Dark Matter: Observational Status and Theoretical Challenges

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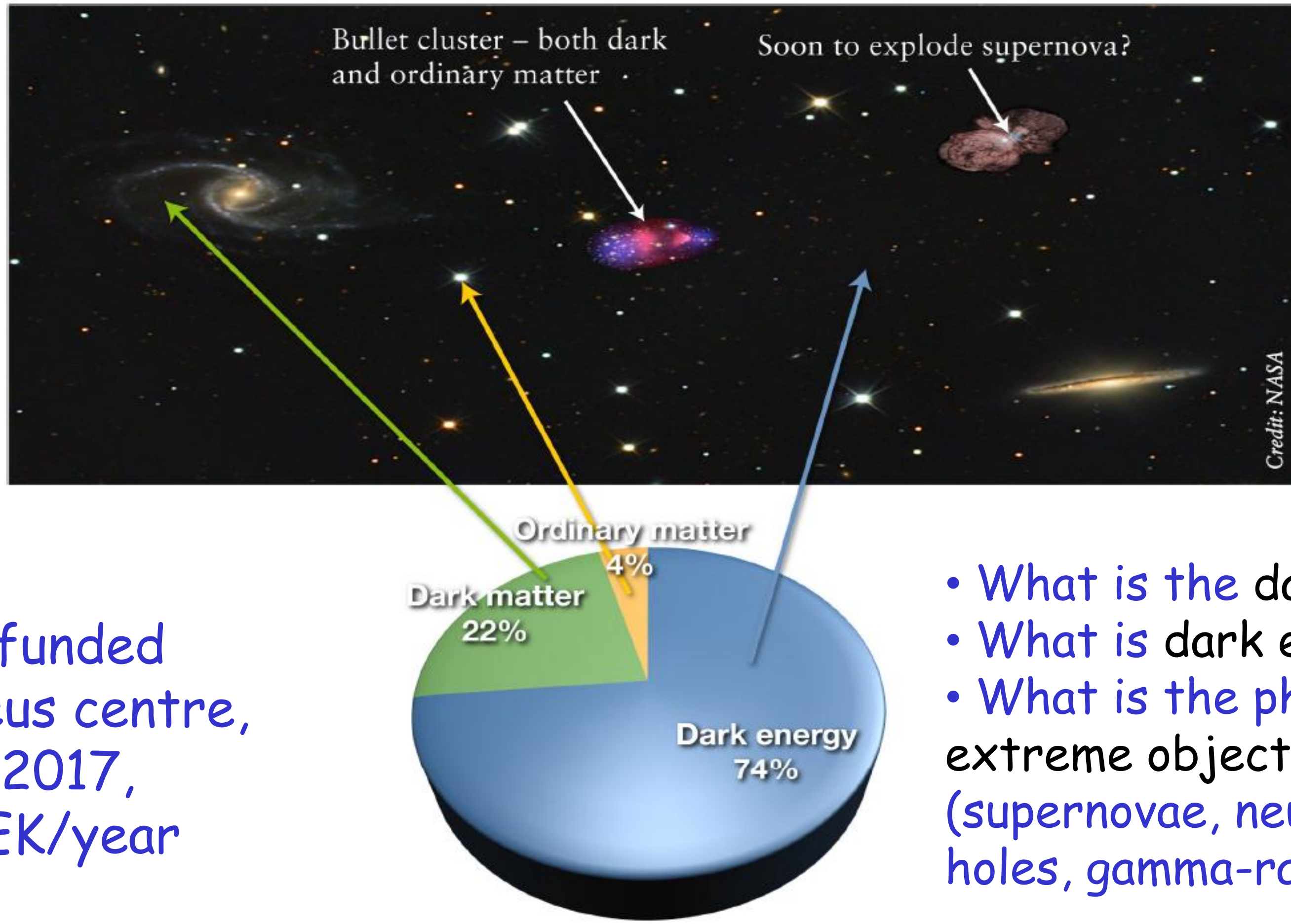
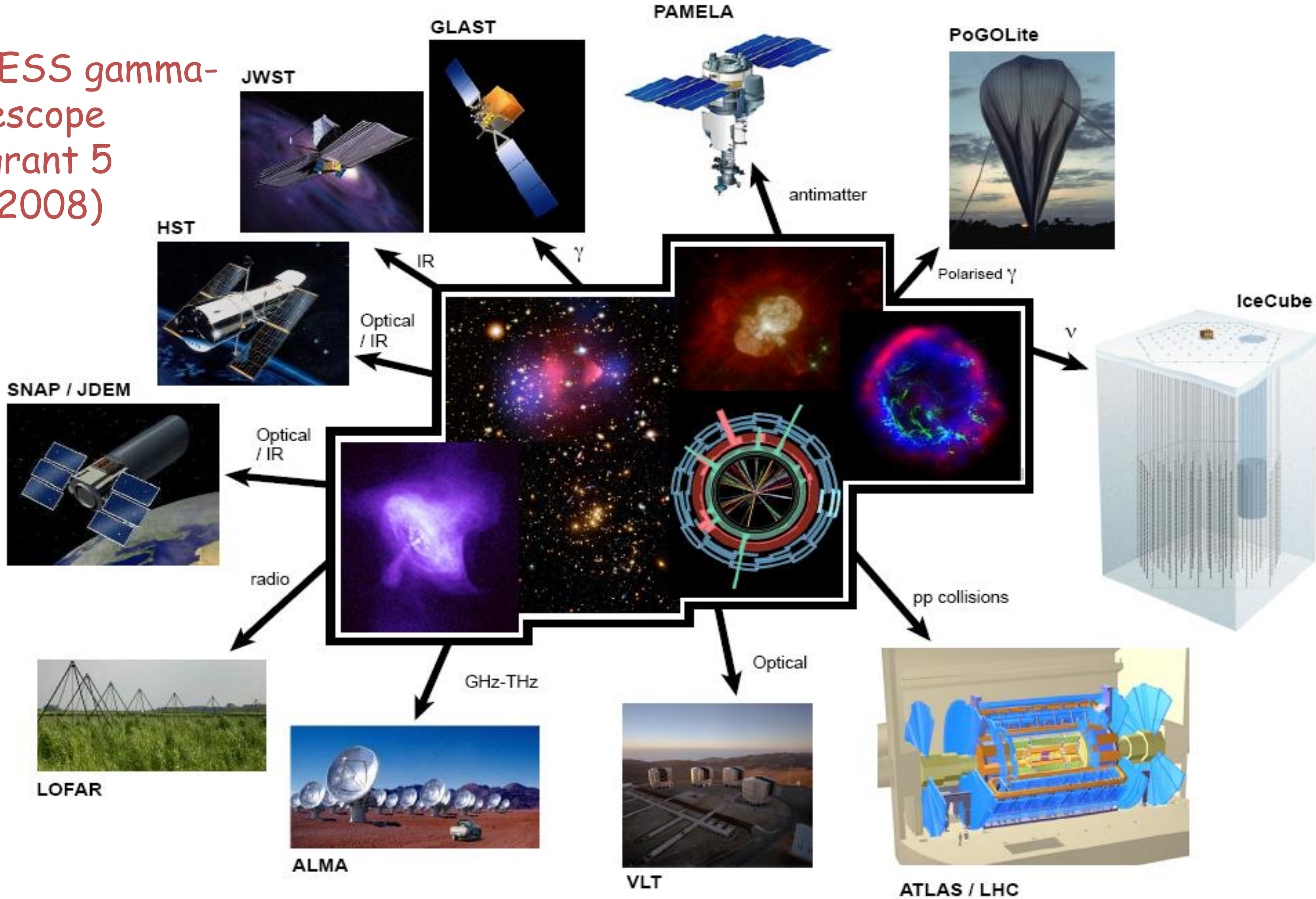


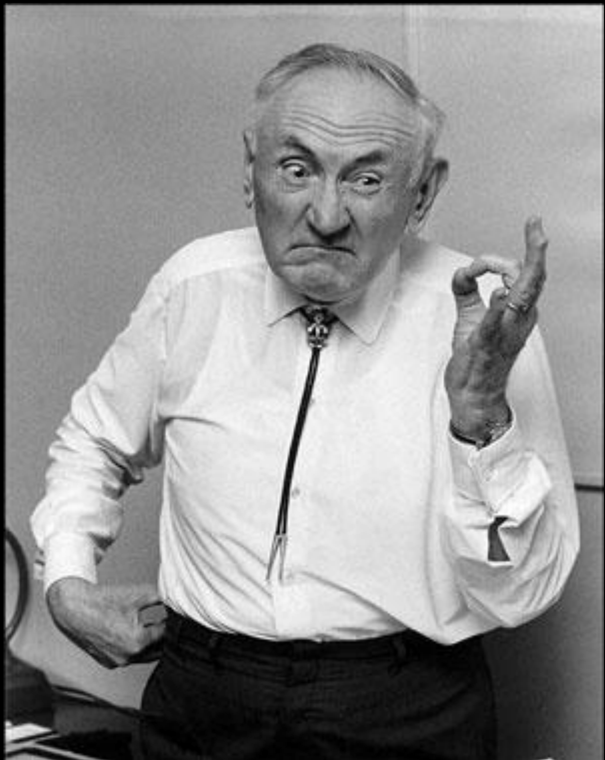
A VR-funded Linnaeus centre, 2008-2017, 7 MSEK/year

- What is the dark matter?
- What is dark energy?
- What is the physics of the extreme objects in the Universe (supernovae, neutron stars, black holes, gamma-ray bursts…)?

How will we do it?

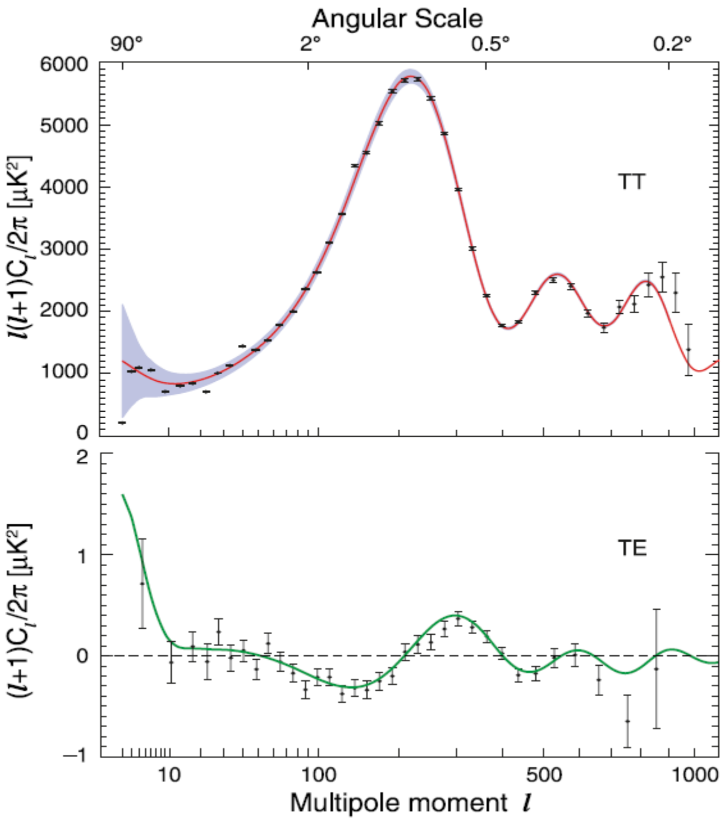
New: HESS gamma-ray telescope (KAW grant 5 MSEK, 2008)

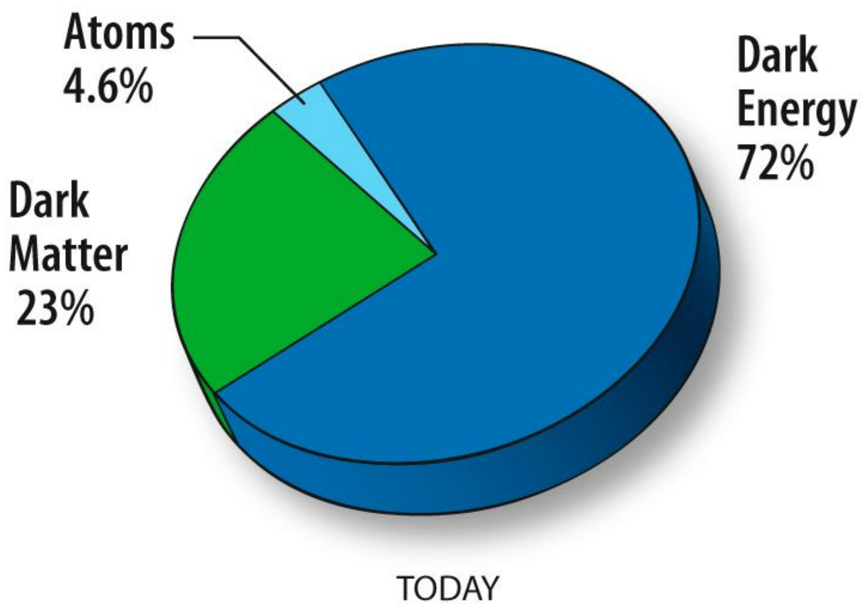




Fritz Zwicky, 1933: Velocity dispersion of galaxies in Coma cluster indicates presence of Dark Matter, $\sigma \sim 1000$ km/s $\Rightarrow$ $M/L \sim 50$

"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."





WMAP 2008:

$$\Omega = \frac{\rho_{tot}}{\rho_{crit}} = 1 \pm 0.01$$

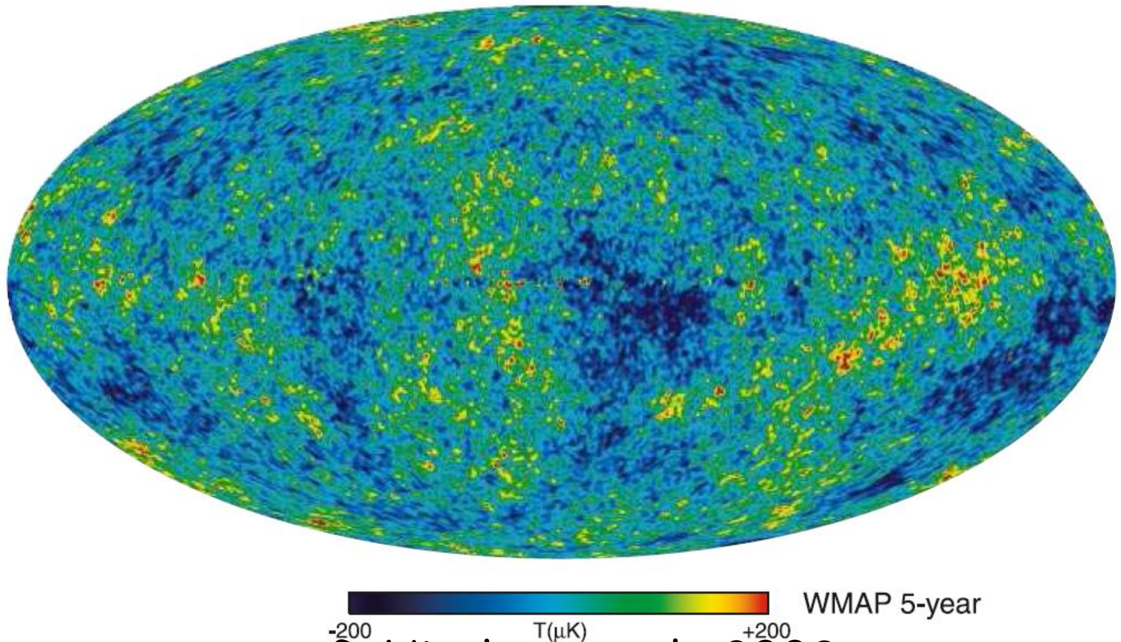
$$\Omega_\Lambda \approx 0.72; \quad \Omega_{CDM} \approx 0.23;$$

$$\Omega_B \approx 0.046 \quad h \approx 0.70$$

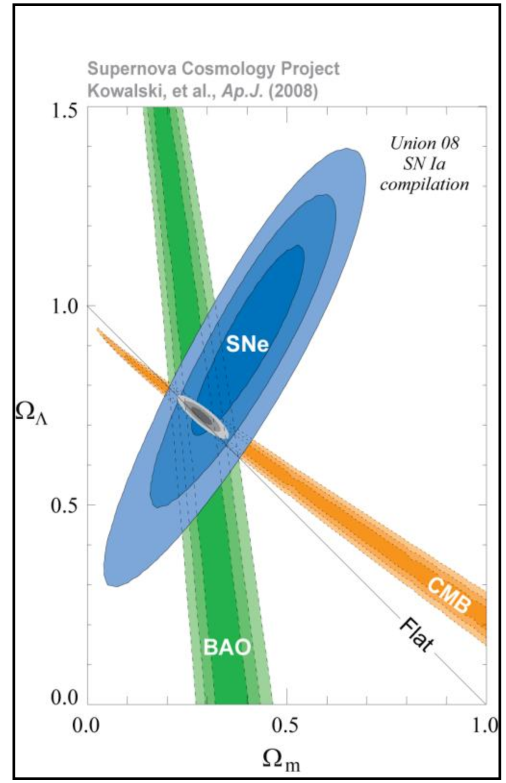
The energy densities now (13.7 billion years after the big bang).

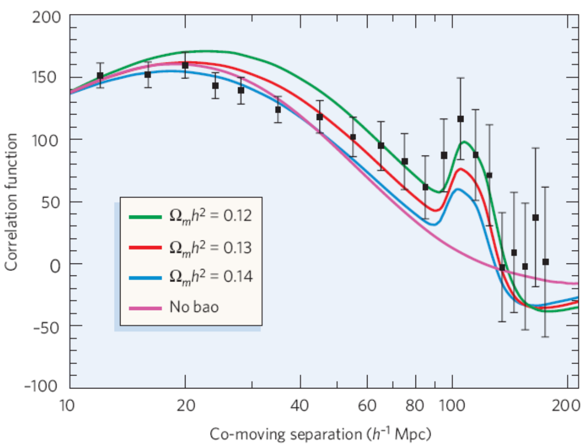
The ΛCDM Model:

Cold Dark Matter Model (meaning the particles move non-relativistically, i.e., slowly) with a Cosmological Constant Λ being the dark energy.

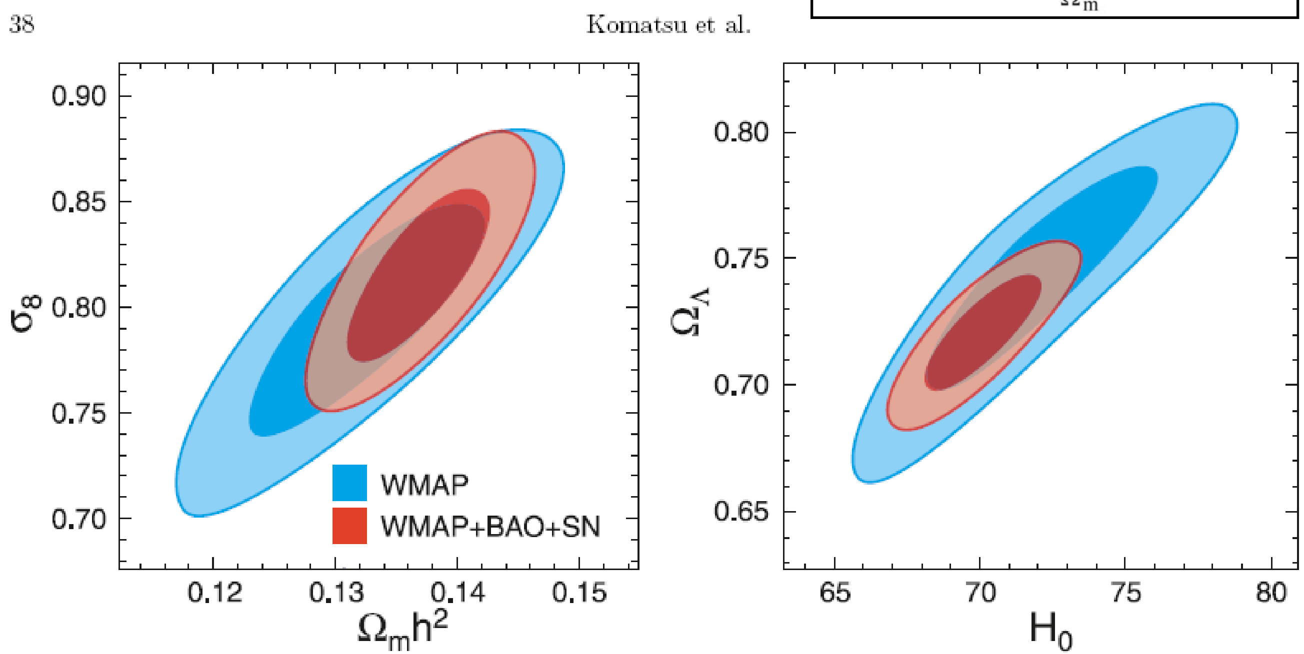


G. Hinshaw et al., 2008





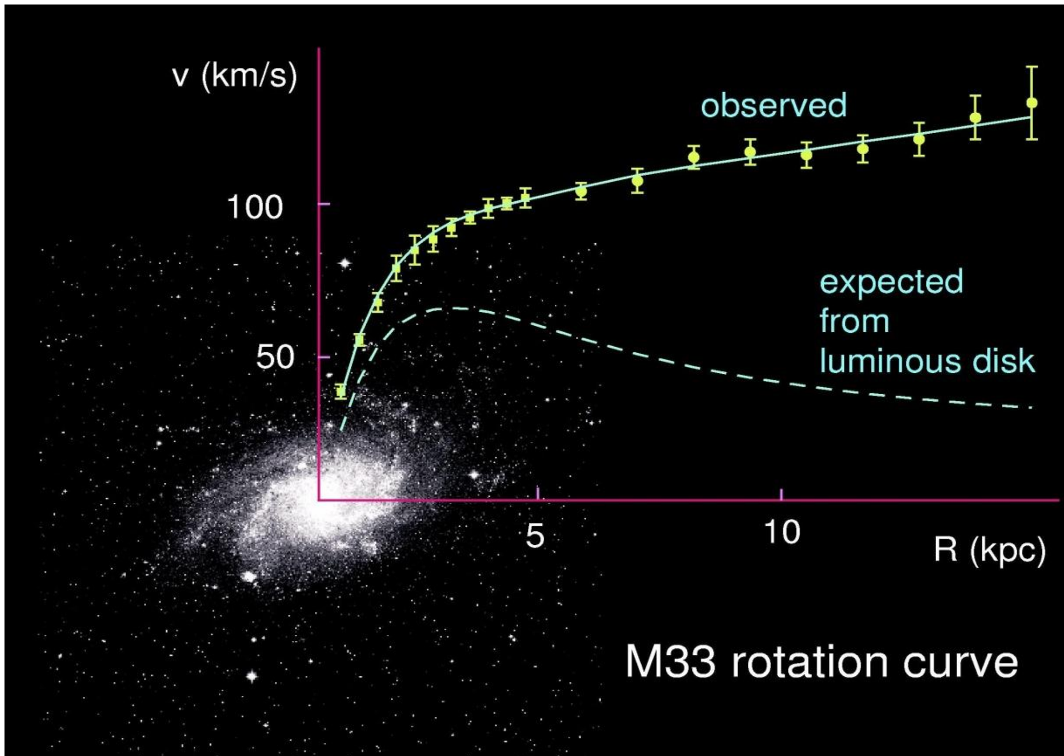
Baryon Acoustic Oscillations
(BAO) SDSS, 2005



WMAP 5-year, Komatsu & al., 2008

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

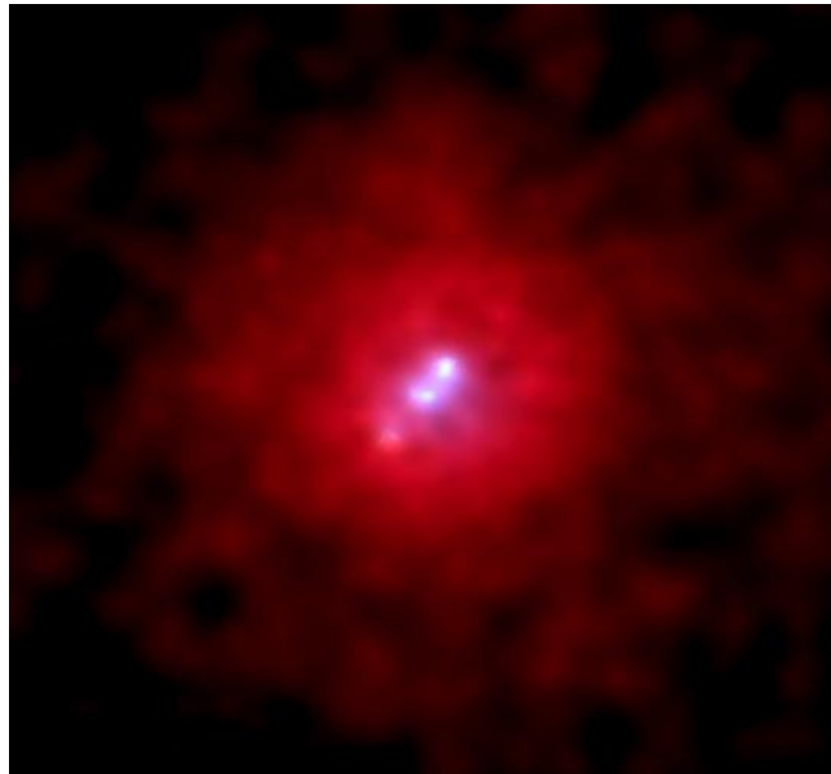
Galaxy rotation curves



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

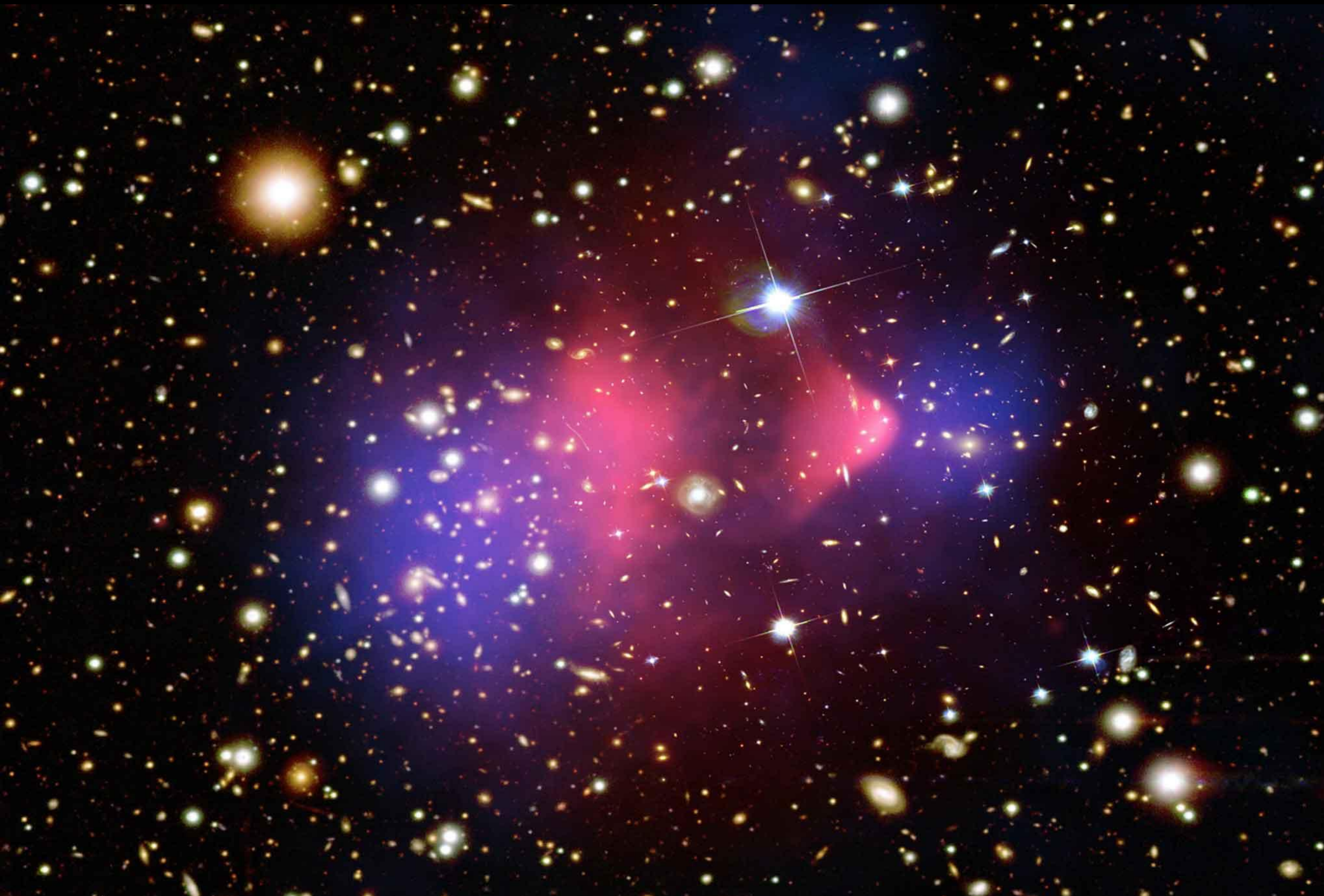
cf. Babcock, 1939

X-ray emitting clusters
(also gravitational lensing)



Cluster 3C295 (Chandra)

cf. Zwicky, 1933

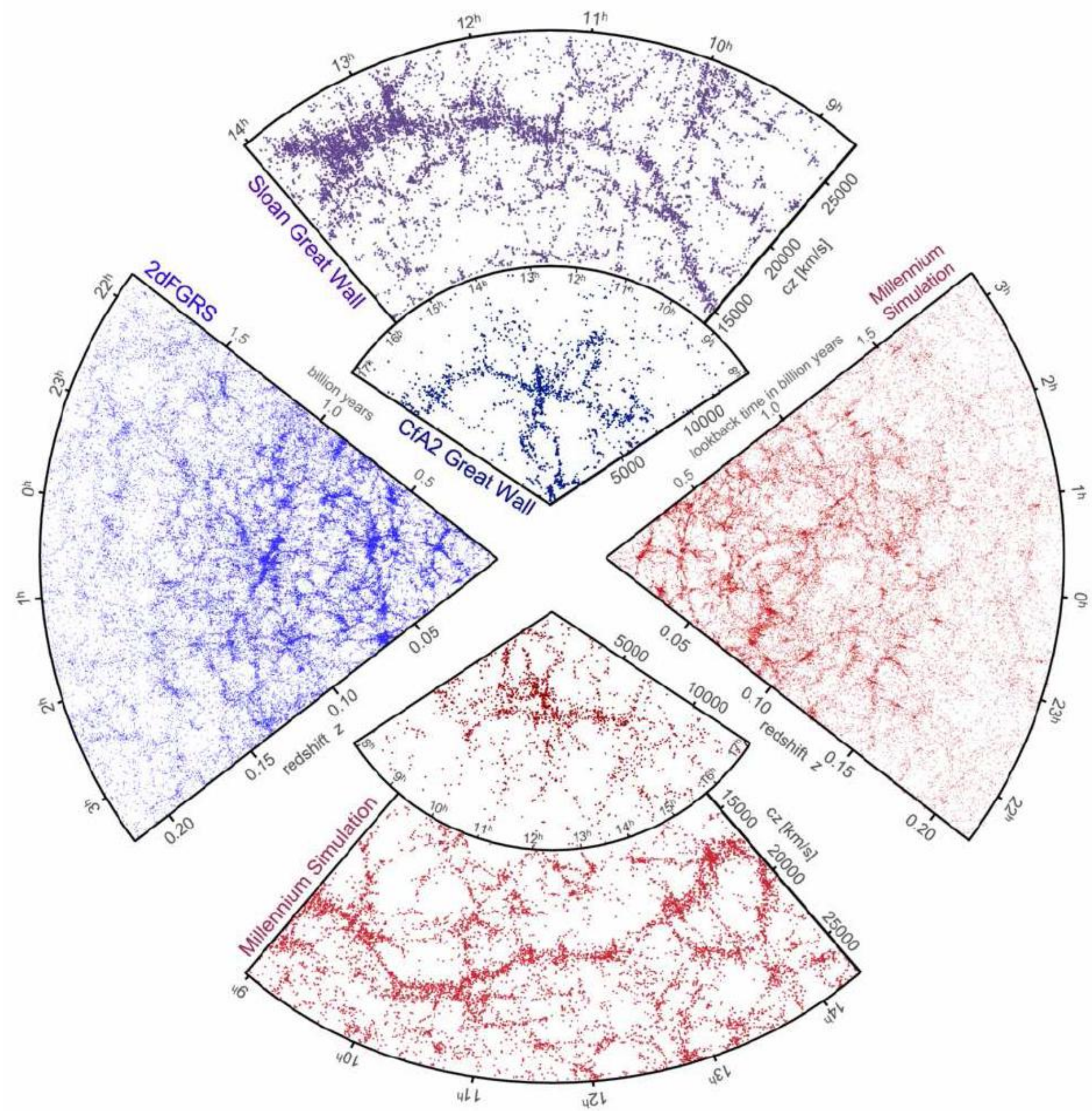


The Bullet cluster

"A direct empirical proof of the existence of dark matter" Ap. J. 2006

2008: Another such system found, MACS J0025.4-1222

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

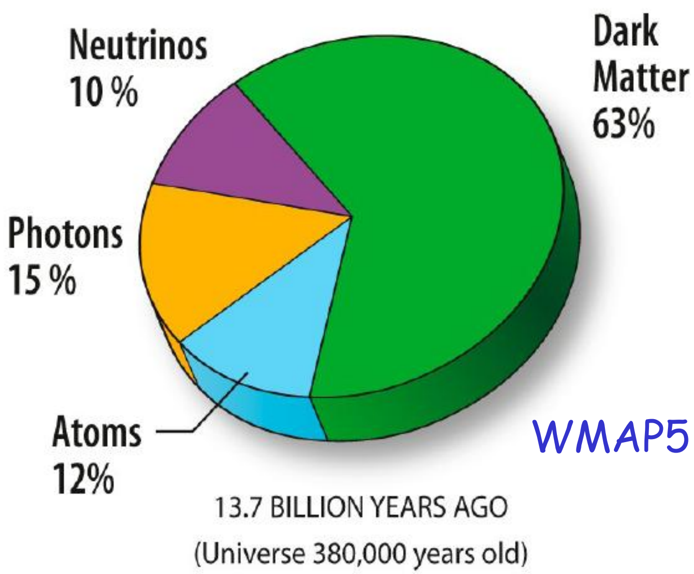


Comparing the distribution of mass on the largest scales (CfA, Sloan and 2dF data), with numerical, dark matter only, simulations in a ΛCDM model (Millennium simulation)

Springel, Frenk & White, 2006

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

Since 1998 (Super-K, T. Kajita et al), we know that non-baryonic dark matter exists! $\Delta m_\nu \neq 0 \Rightarrow m_\nu \neq 0$
In 2008, WMAP (J. Dunkley et al) found direct evidence for neutrinos at the epoch of the CMBR (380 000 years after the big bang):



WMAP5

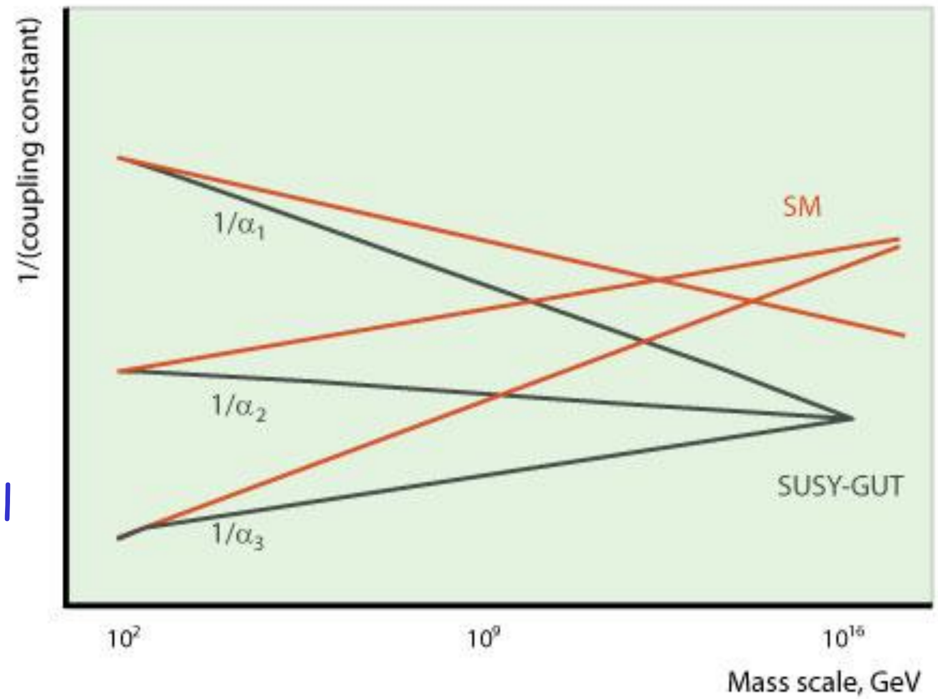
However, neutrinos are not the main component of dark matter (10% at most)

- Pauli principle $\Rightarrow$ cannot clump in dwarf halos
- Galaxy distribution $\Rightarrow$ limit on sum of ν masses

WMAP 2008: $\Sigma\, m_\nu < 1.3$ eV, using CMB data only
Goobar, Hannestad, Mörtsell, Tu 2006:
$\Sigma\, m_\nu < 0.3$ eV (including limit from Ly-a and baryon acoustic oscillations, otherwise 0.5-0.6 eV). U. Seljak & al., 2006: 0.17 eV (?)
Future galaxy surveys + Planck satellite (CMBR) + weak lensing $\Rightarrow$ perhaps $m_\nu \approx \Delta m_\nu^{atm} \approx 0.06$ eV may be detectable! (Hu, Eisenstein & Tegmark, 1998)

Supersymmetry

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



The lightest neutralino: The most natural SUSY dark matter candidate

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

Gaugino part Higgsino part

Good particle physics candidates for Cold Dark Matter:

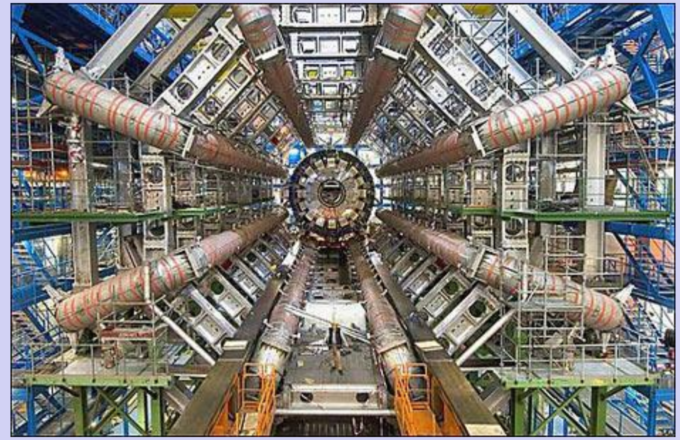
Independent motivation from particle physics

- 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, …

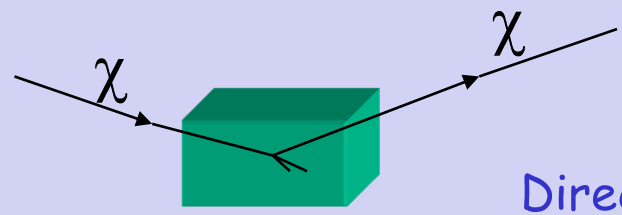
"The WIMP miracle": for typical gauge couplings and masses of order the electroweak scale, $\Omega_{wimp}h^2 \approx 0.1$ (within factor of 10 or so)

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.



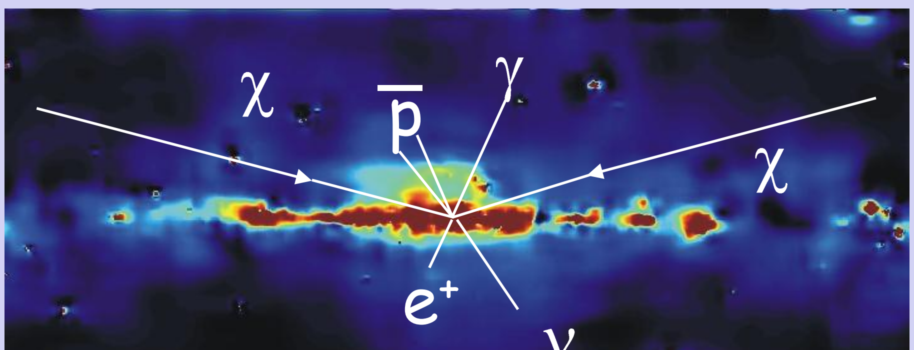
CERN/Atlas



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

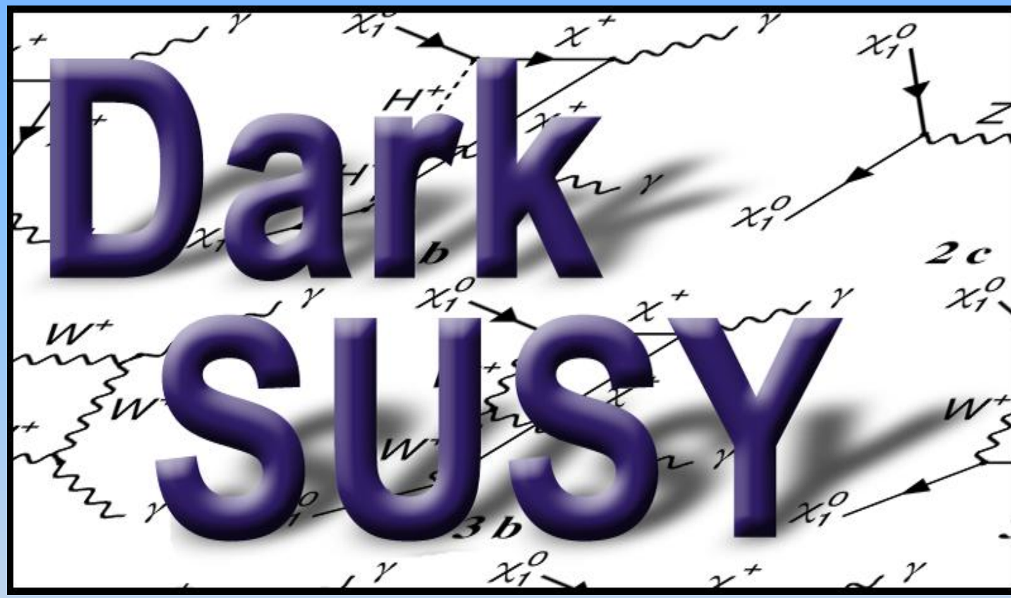


The Milky Way halo in gamma-rays as measured by EGRET (D.Dixon et al, 1997)

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

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

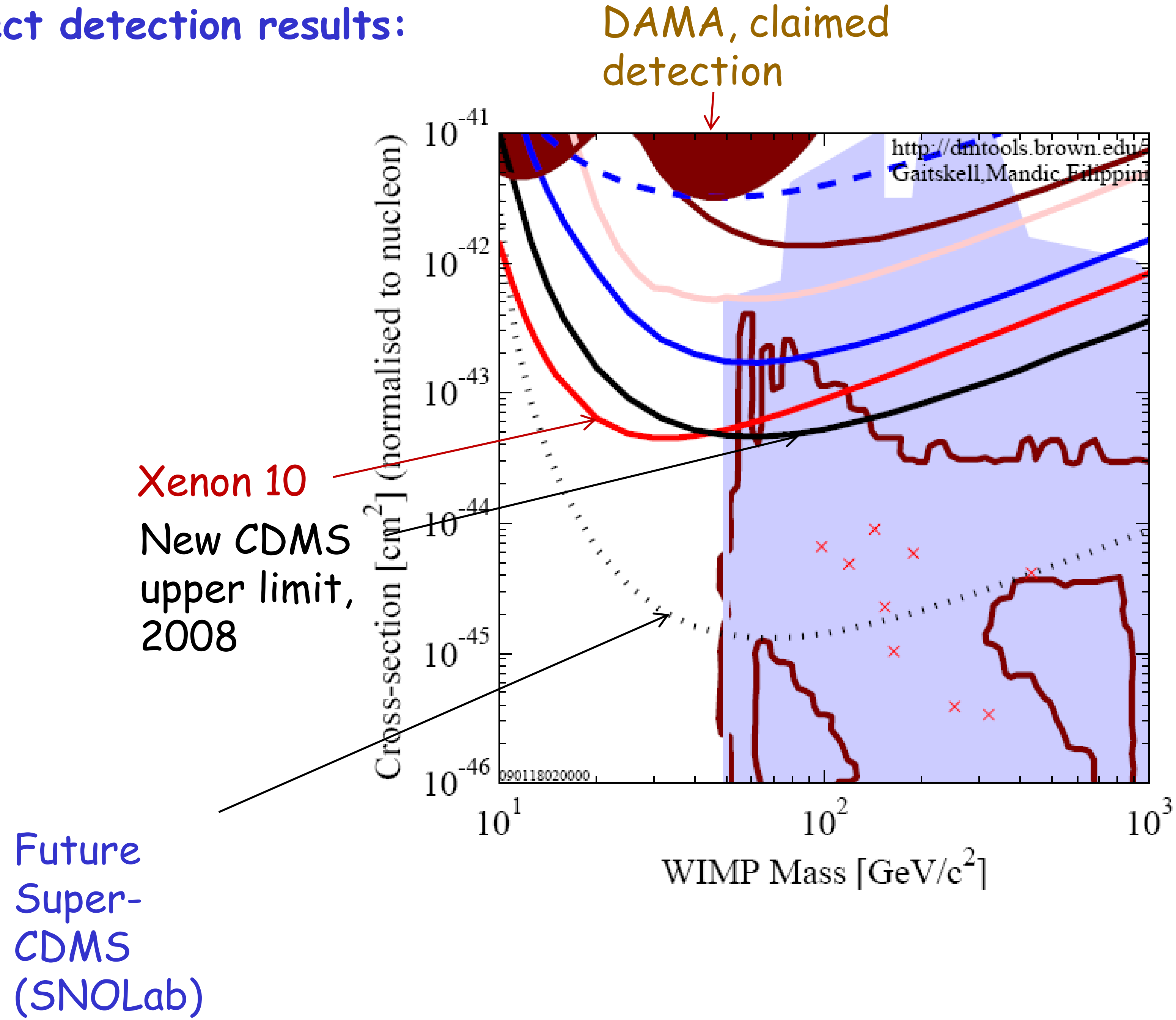
Tool for computing cosmological relic density, masses, branching ratios, direct and indirect detection cross sections for general WIMPs, especially super-symmetric ones:

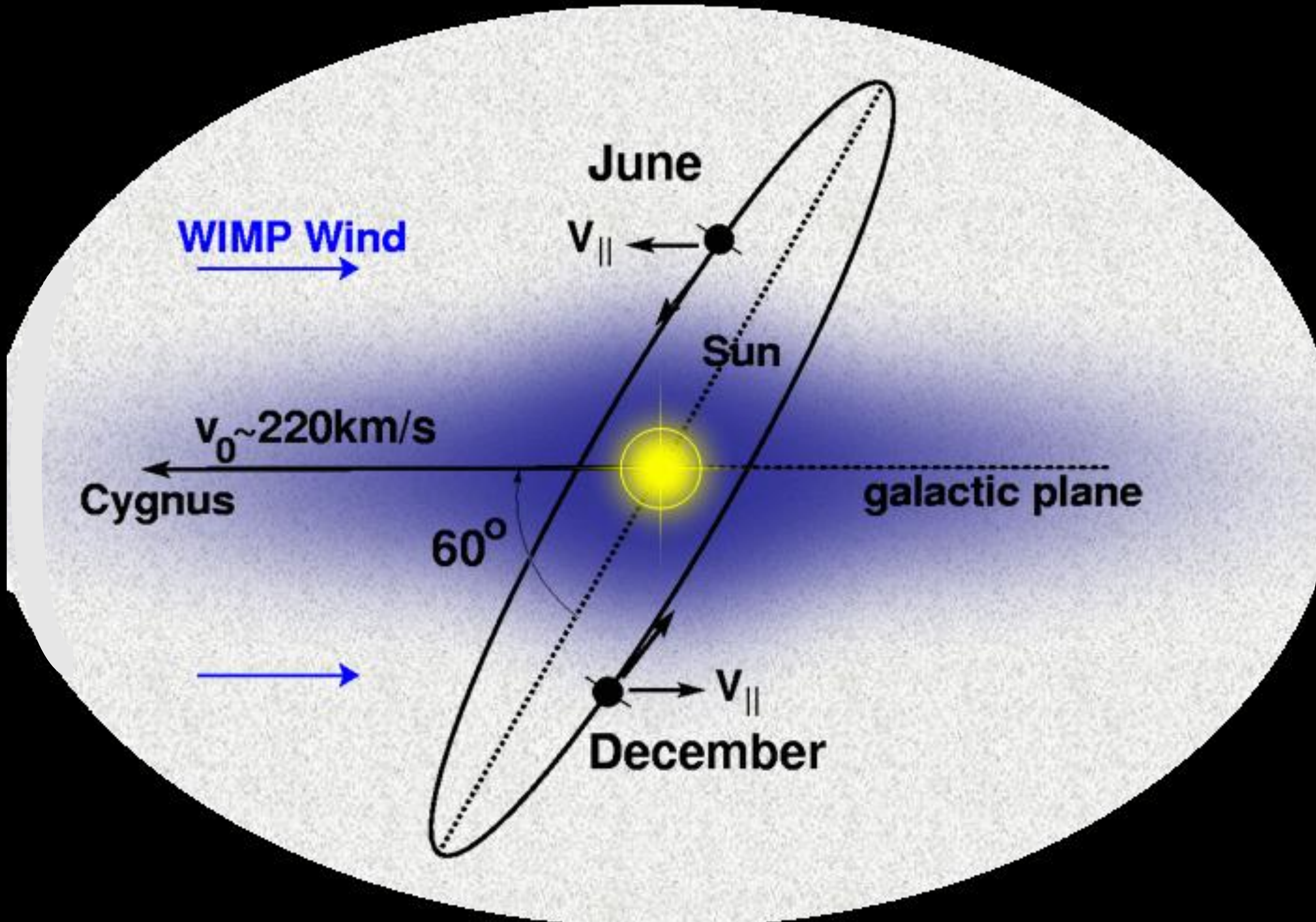


P. Gondolo, J. Edsjö, L.B., P. Ullio, Mia Schelke and E. A. Baltz, JCAP 2004

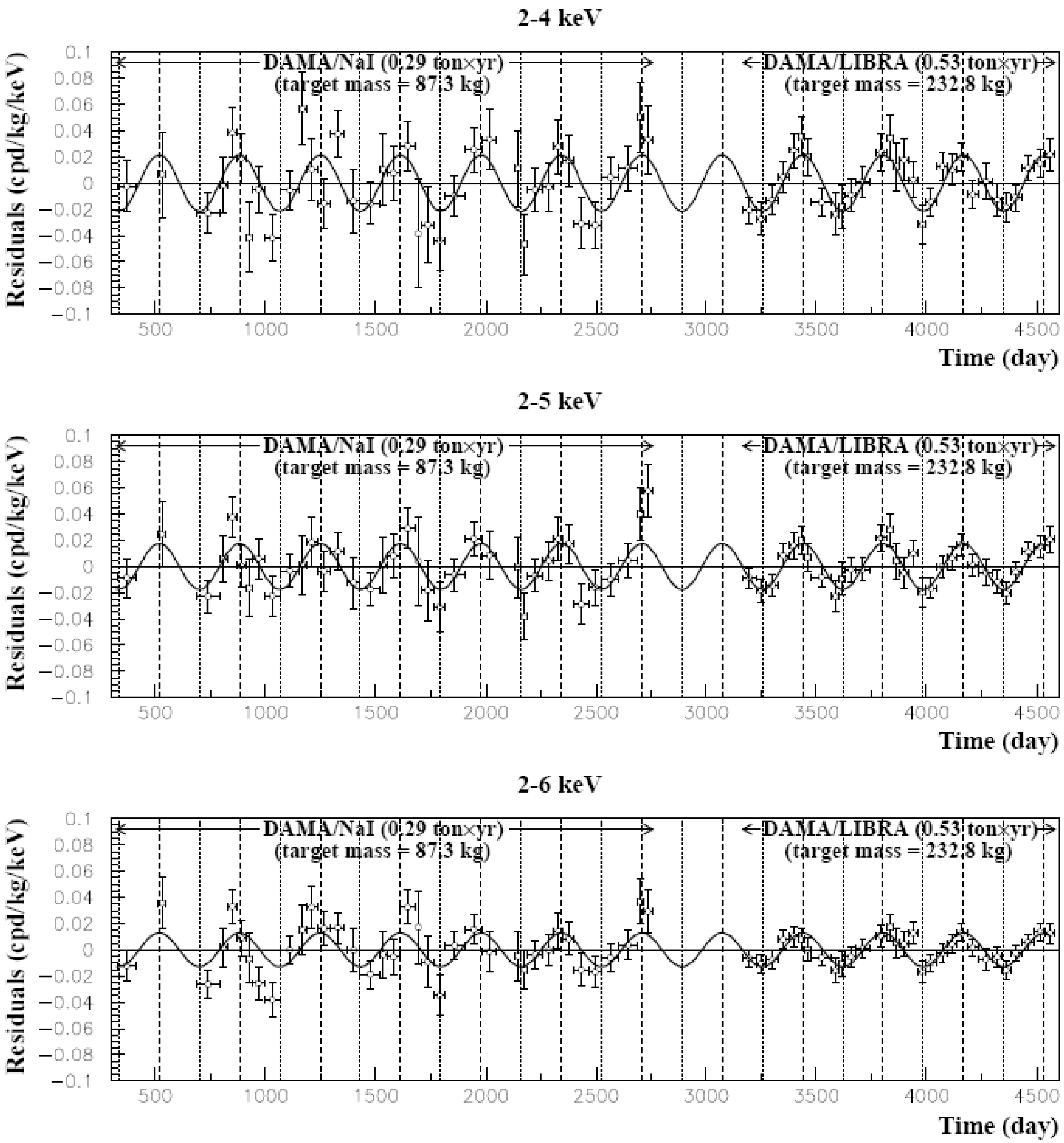
(with additions by T. Bringmann and G. Dudas)

Direct detection results:





Drukier, Freese, Spergel, 1986

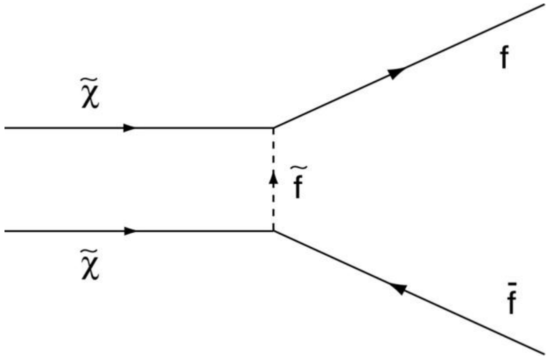


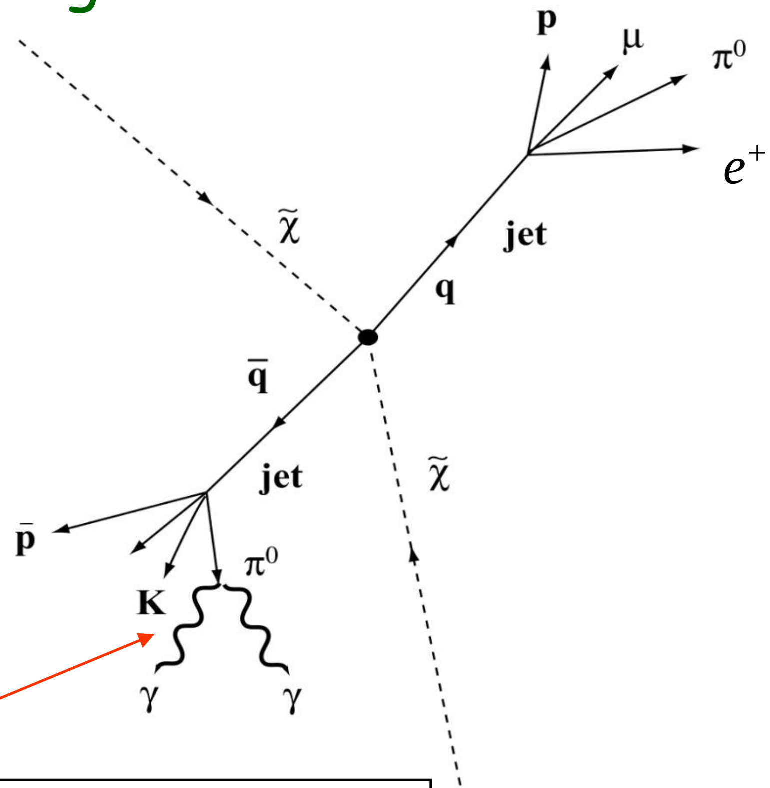
DAMA/LIBRA: Annual modulation of unknown cause. Consistent with dark matter signal (but not confirmed by any other experiment).

Claimed significance: More than 8σ !

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

Indirect detection, example: annihilation of neutralinos in the galactic halo



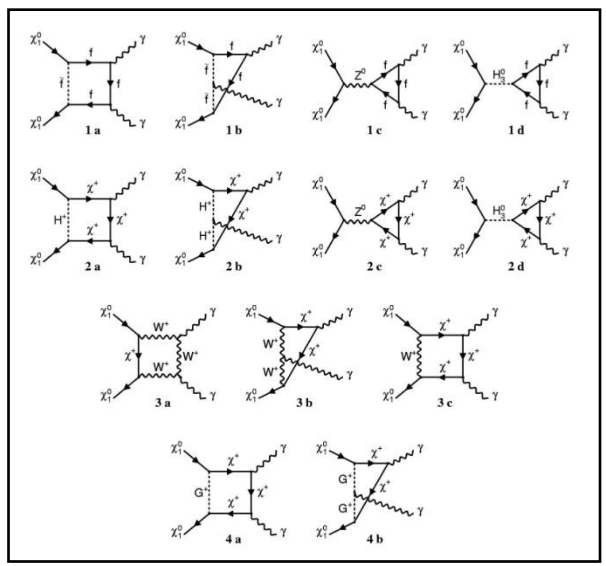


Majorana particles: helicity factor for fermions $\sigma v \sim m_f^2$

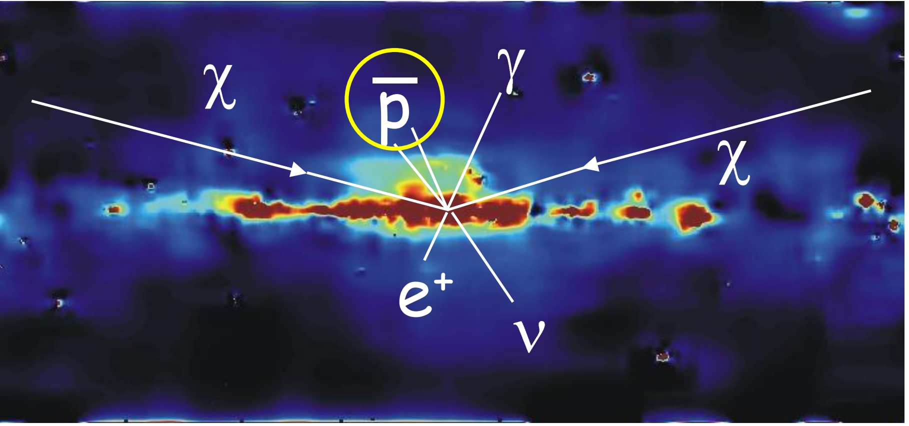
Note: equal amounts of matter and antimatter in annihilations

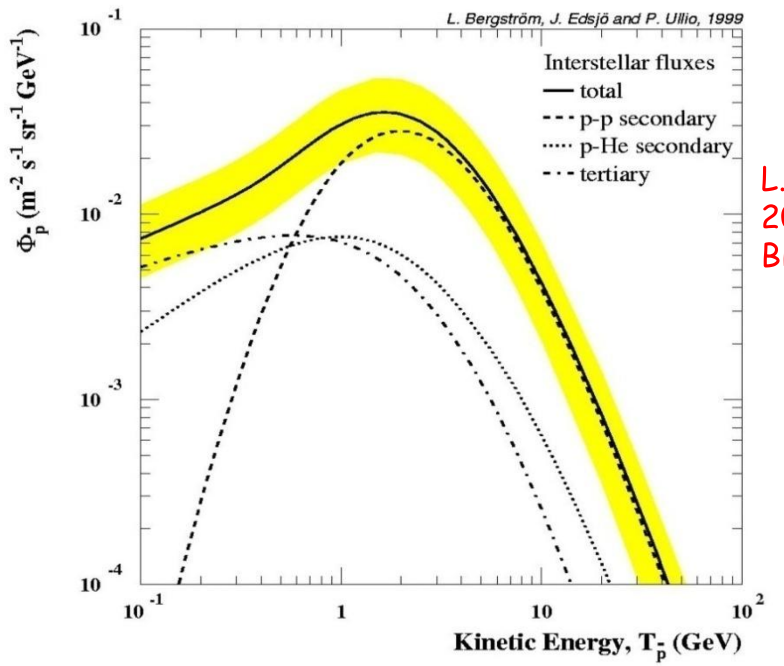
Decays from neutral pions, kaons etc:
DarkSUSY uses PYTHIA.

One-loop effect: 2γ or $Z\gamma$ final state gives narrow lines (L.B. & P. Ullio, 1998).
Internal bremsstrahlung also contributes to high-energy gammas (Bringmann, L.B., Edsjö, 2007-8)



Antiprotons





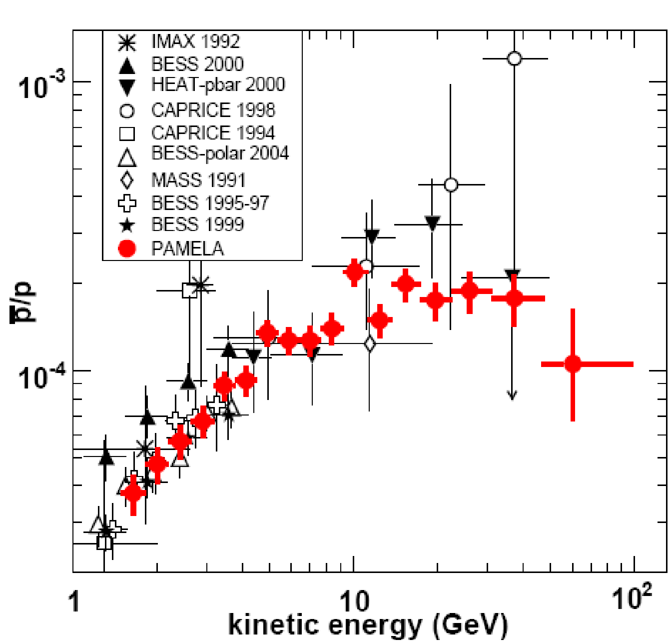
L.B., J. Edsjö and P. Ullio, 2000;
Bieber & Gaisser, 2000

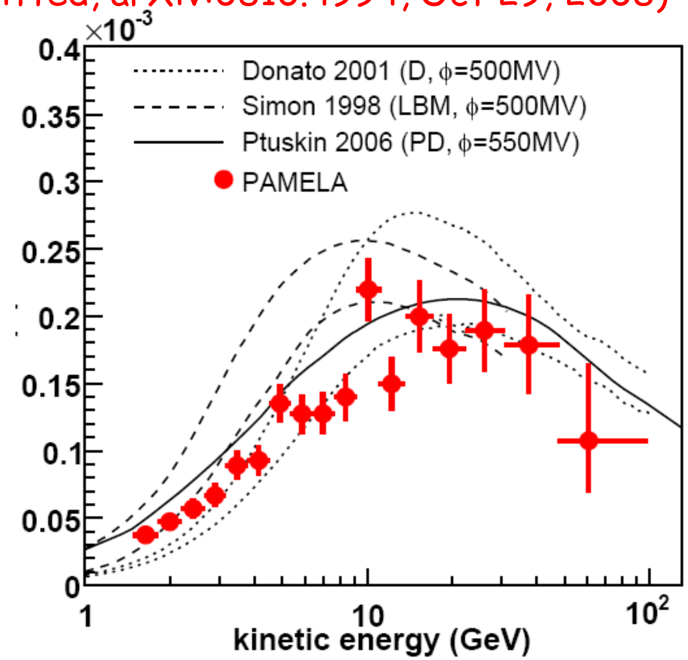
Antiprotons rarely produced in pp collisions in the galaxy, so that may be DM signal?

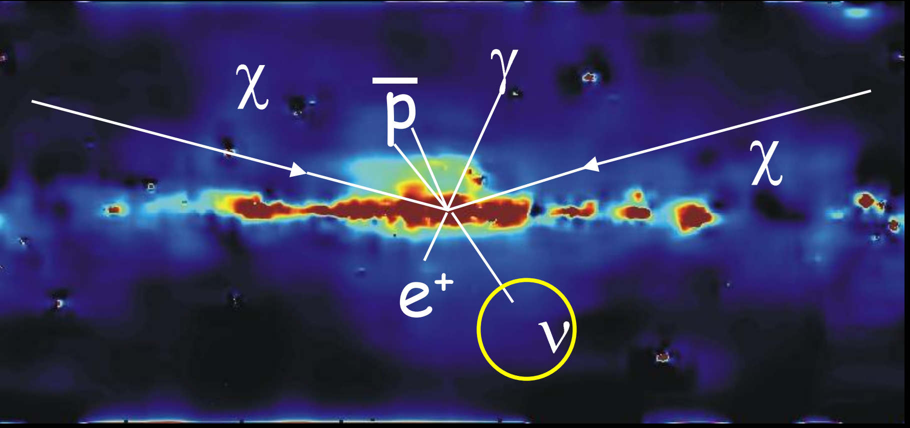
Earlier experiments and new results of PAMELA (with participation from OKC-KTH) give no hint of any "exotic" component

⇒ Stringent limits on Dark Matter models which have quark jets as important annihilation final states

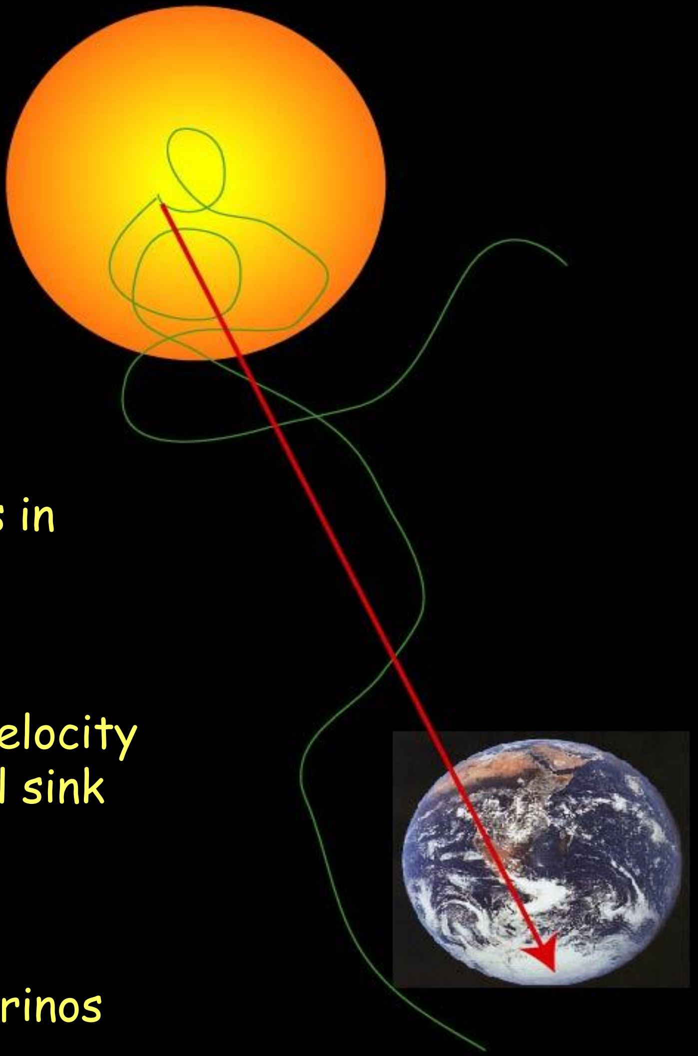
PAMELA 2008 (O. Adriani et al, PRL, submitted, arXiv:0810.4994, Oct 29, 2008)







Neutrinos

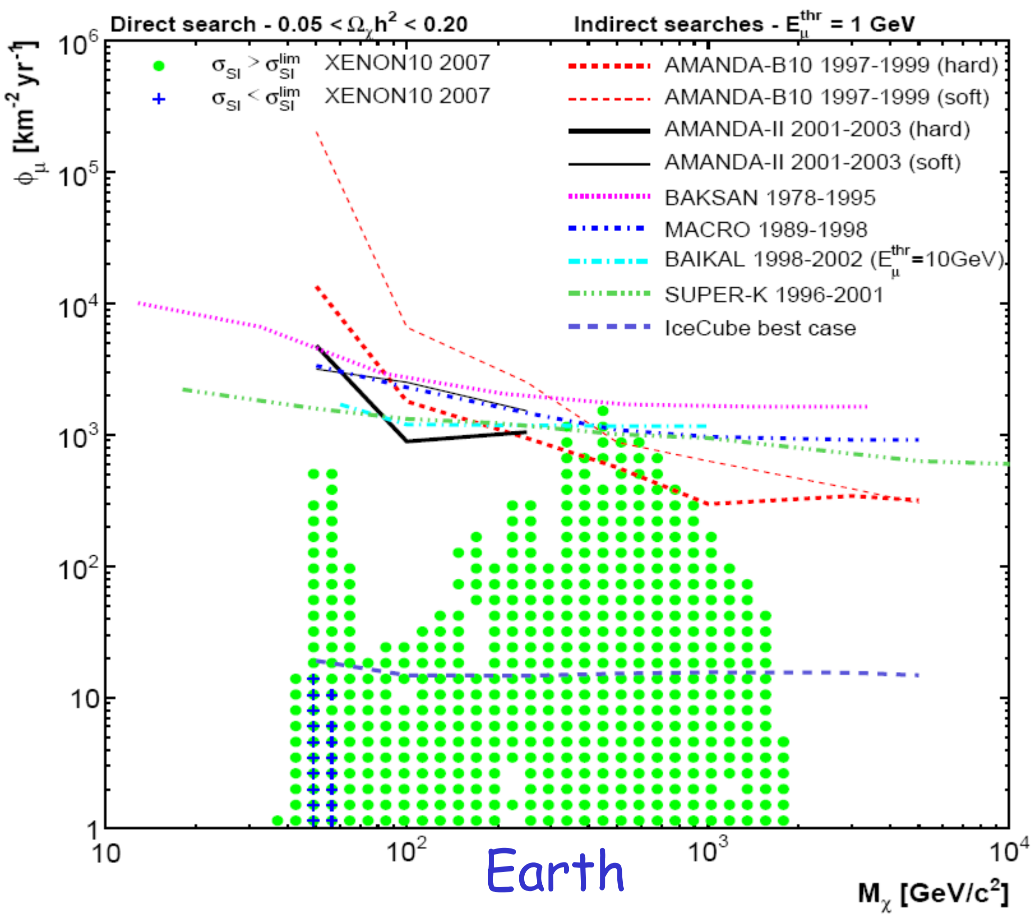


Neutrinos from the center of the Earth or Sun in large neutrino telescopes: IceCUBE at the South Pole, Antares in Mediterranean, KM3…

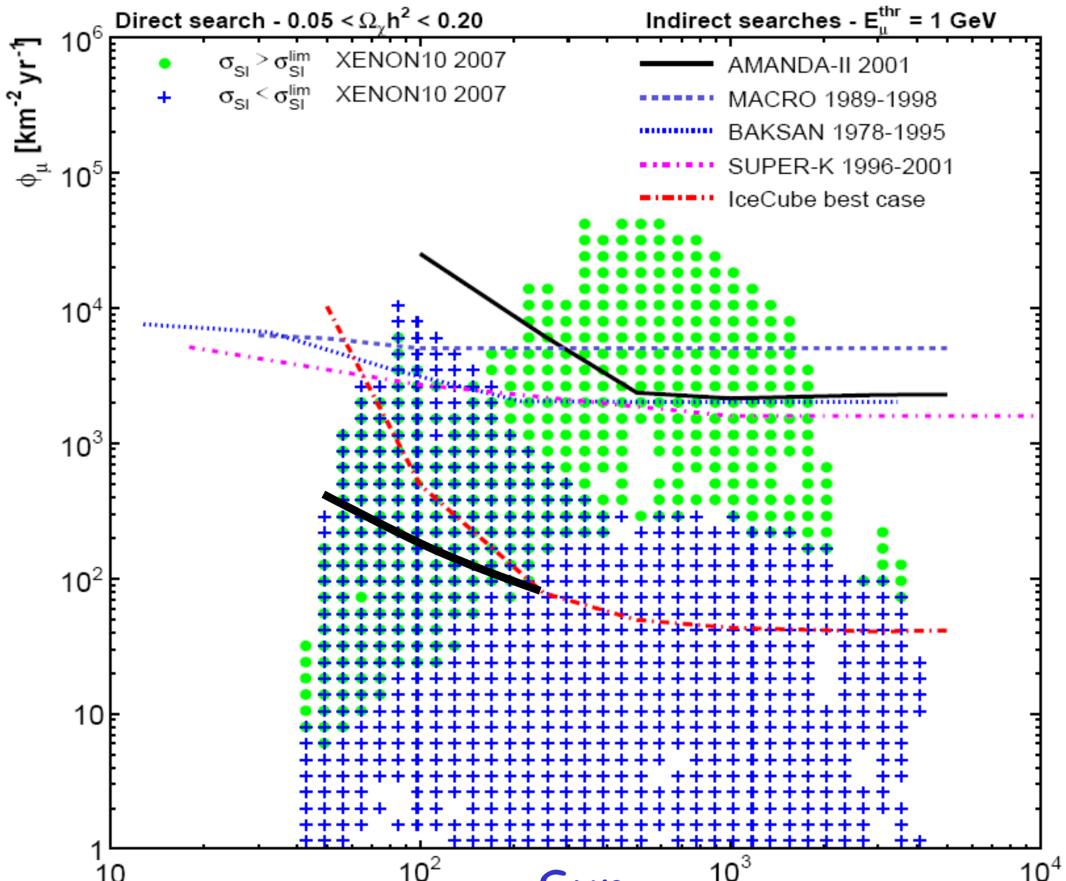
WIMPs are trapped gravitationally by scattering; when velocity after scattering is below escape velocity, the WIMPs will sink down to the center

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

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. The Deep Core extension (proposed by the OKC-Icecube group in Sweden, funded by KAW grant, will improve sensitivity at low mass).



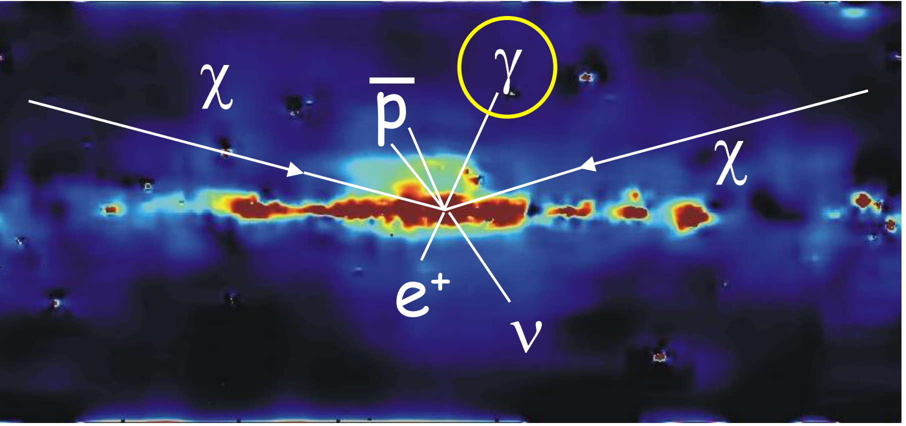
Earth



Sun

J. Edsjö, 2007

Rates computed with DarkSUSY

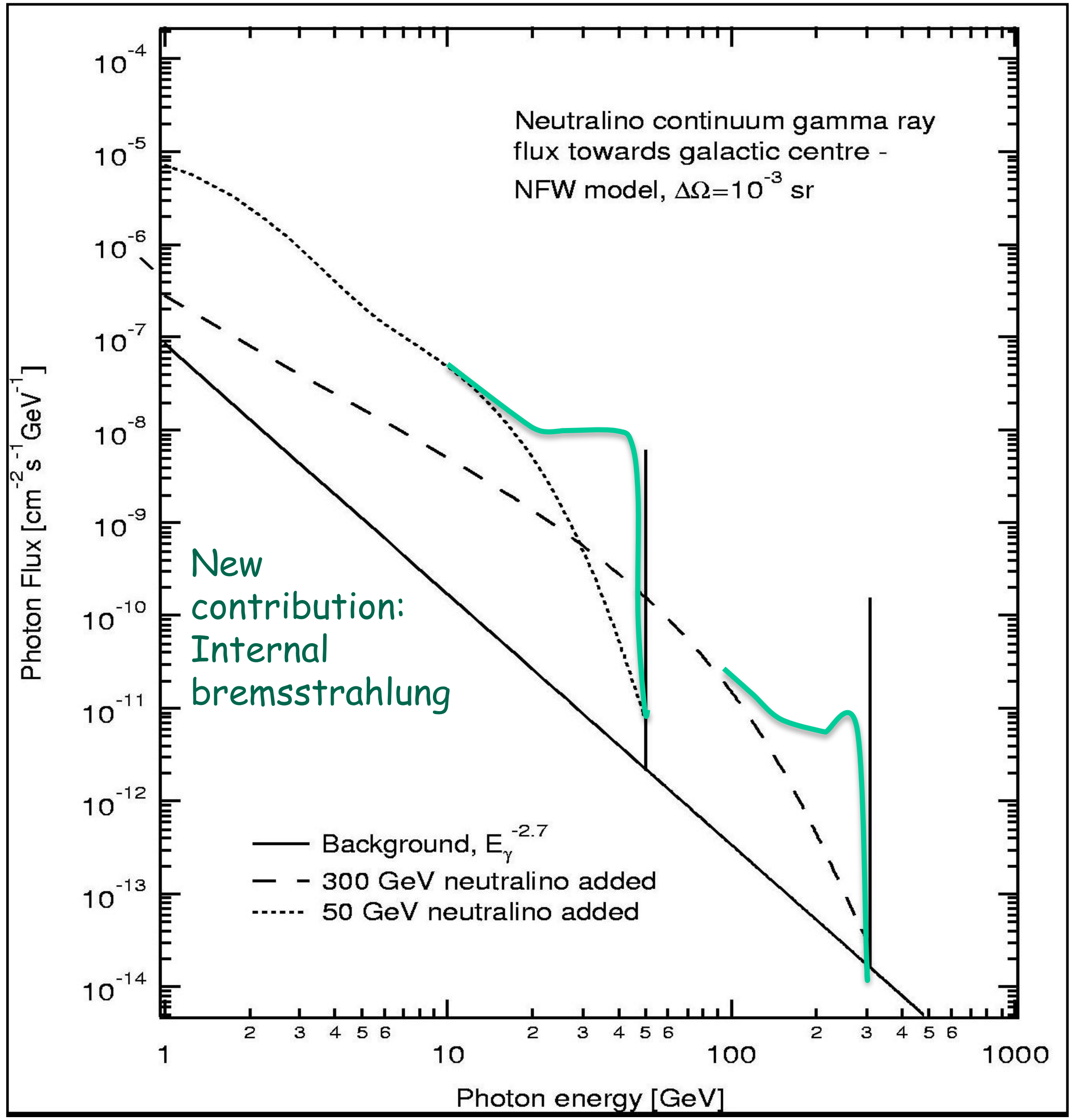


Gamma-rays (one of OKC's key areas, both for theory and observations)

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

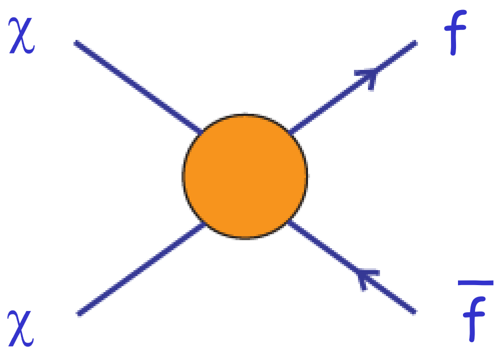
- Continuous from π^0, K^0, … decays
  and
- Monoenergetic line
  and
- Internal bremsstrahlung from QED process.

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



L.B., P.Ullio & J. Buckley 1998 T. Bringmann, L.B., J. Edsjö, 2007

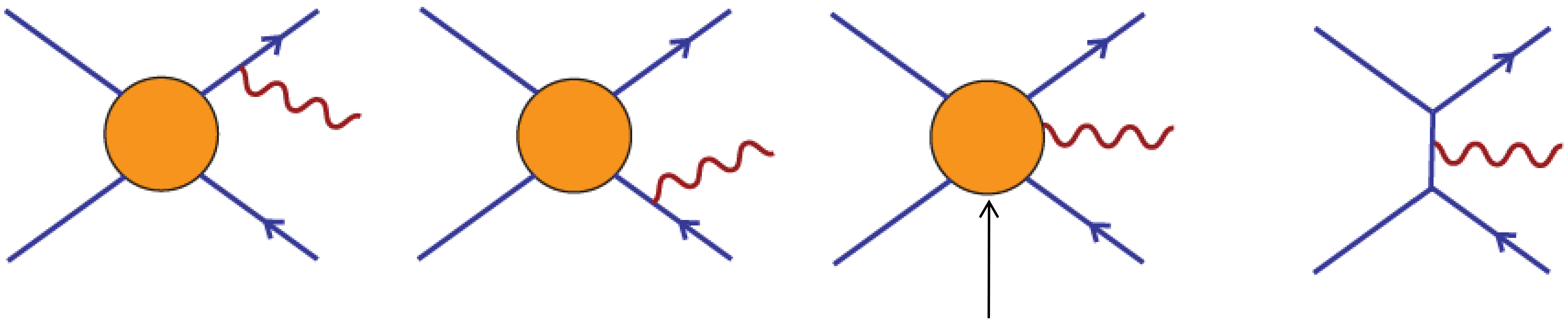
Recent development: New observational signature for Majorana particles (as most dark matter candidates are)



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

"Final state radiation"

"Internal bremsstrahlung", IB

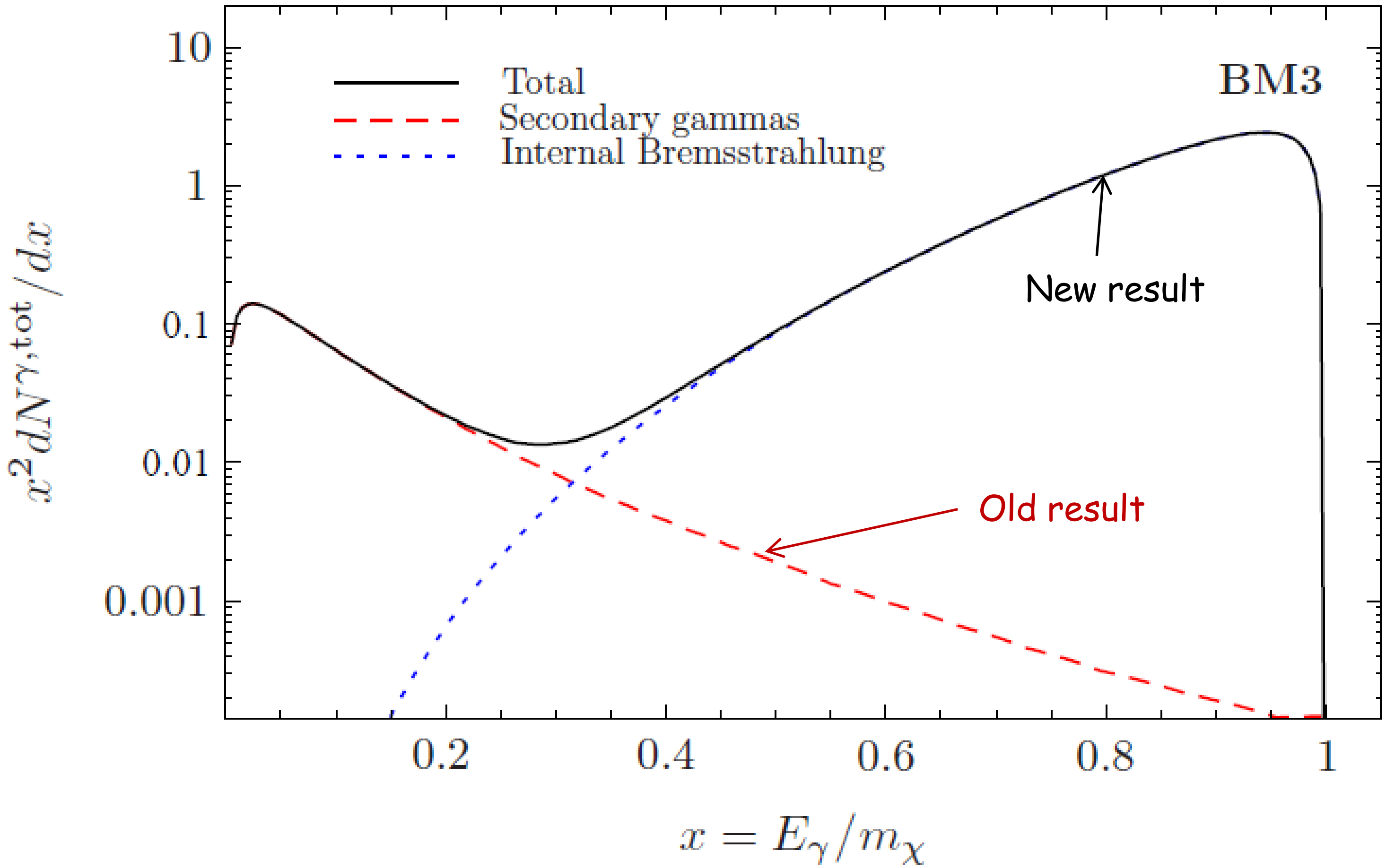


$\sim m_f$ $\sim m_f$ No m_f suppression! Simplest example

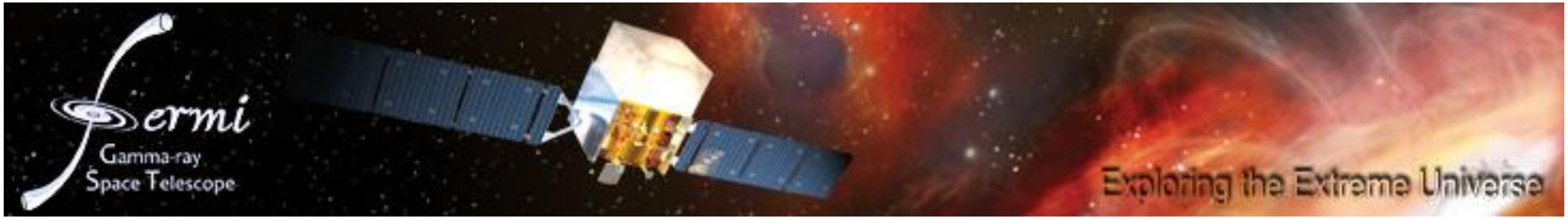
This new QED "correction" can enhance the rate by many orders of magnitude!

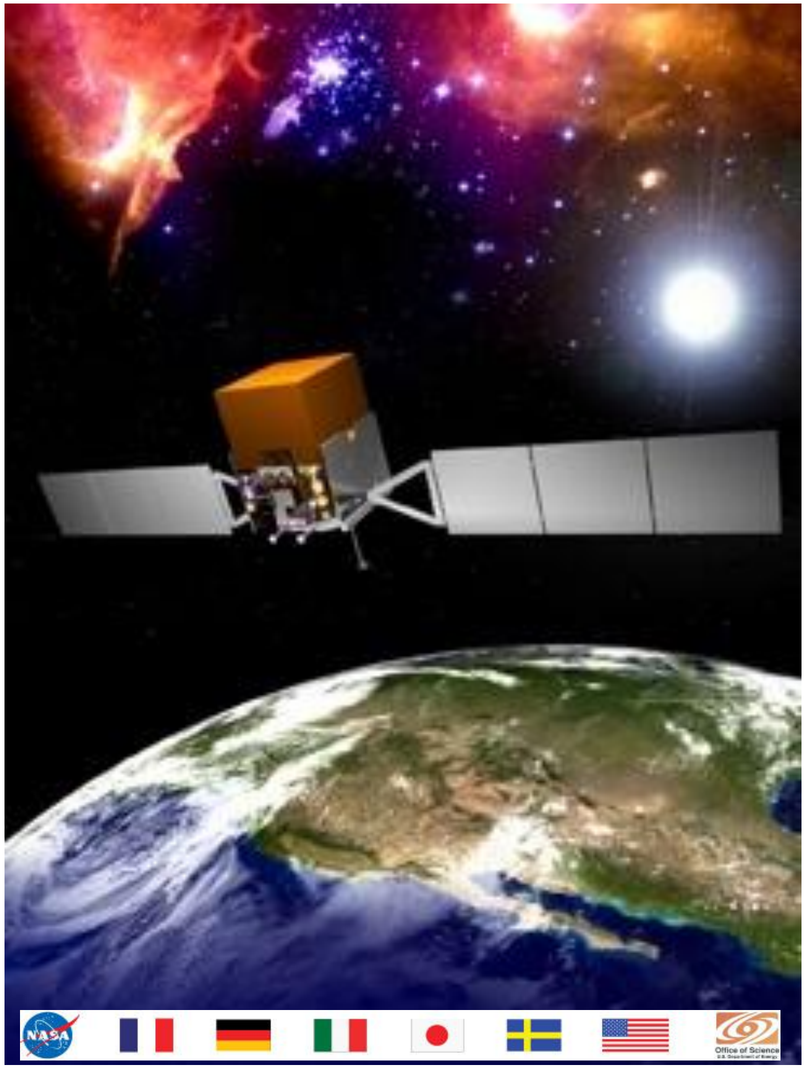
L.B., 1989; T. Bringmann, L.B., J. Edsjö , 2007-8

Example of SUSY benchmark model where this effect is very important:

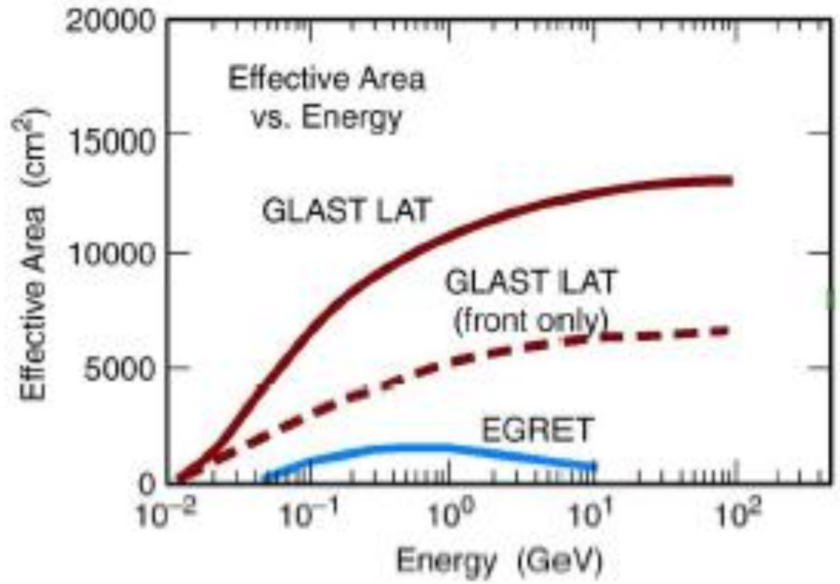


T. Bringmann, L.B., J. Edsjö, JHEP 0801:049,2008.



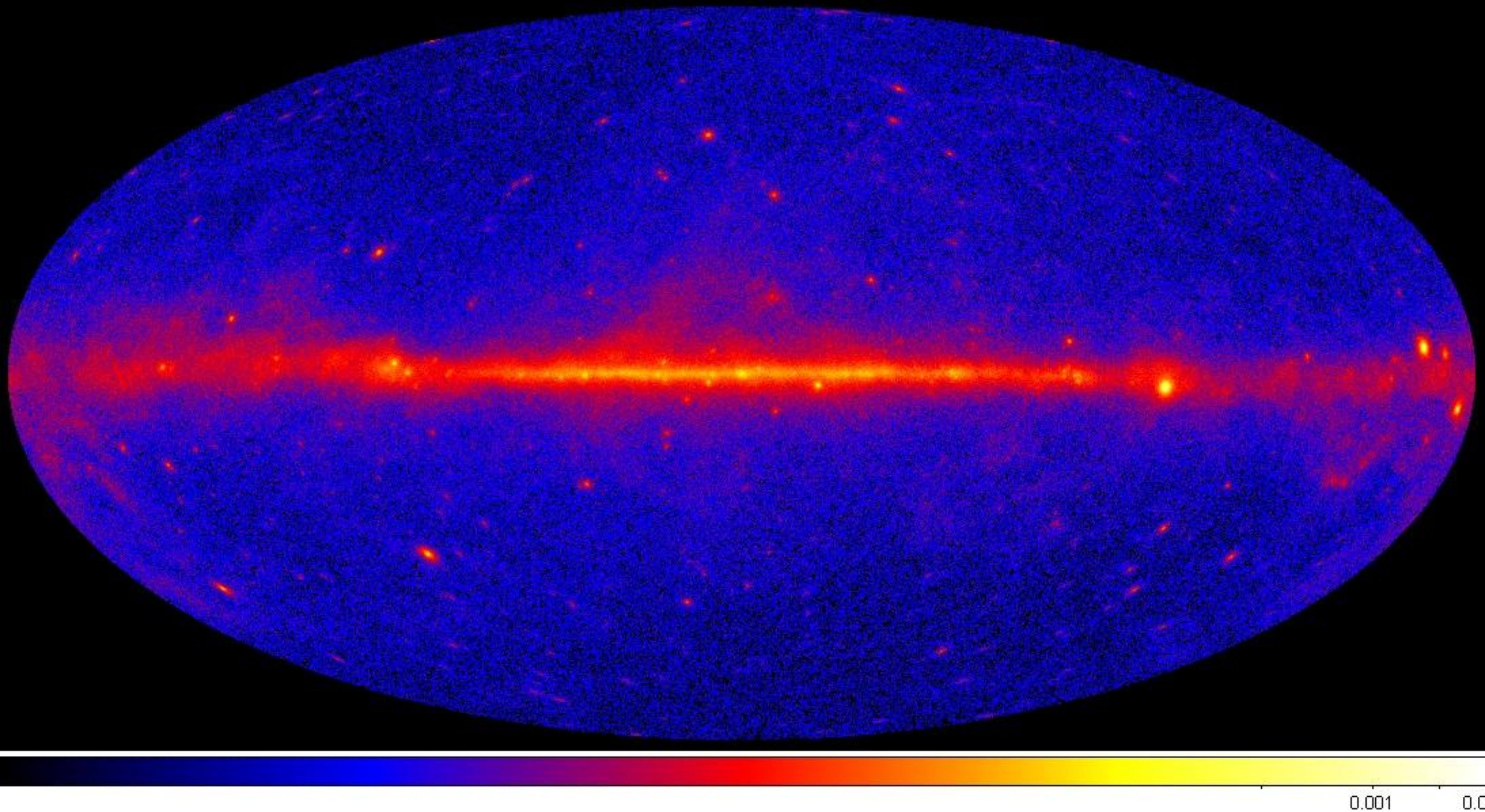


USA-France-Italy-Sweden-Japan – Germany collaboration, Fermi/GLAST launched June 2008 –taking data!



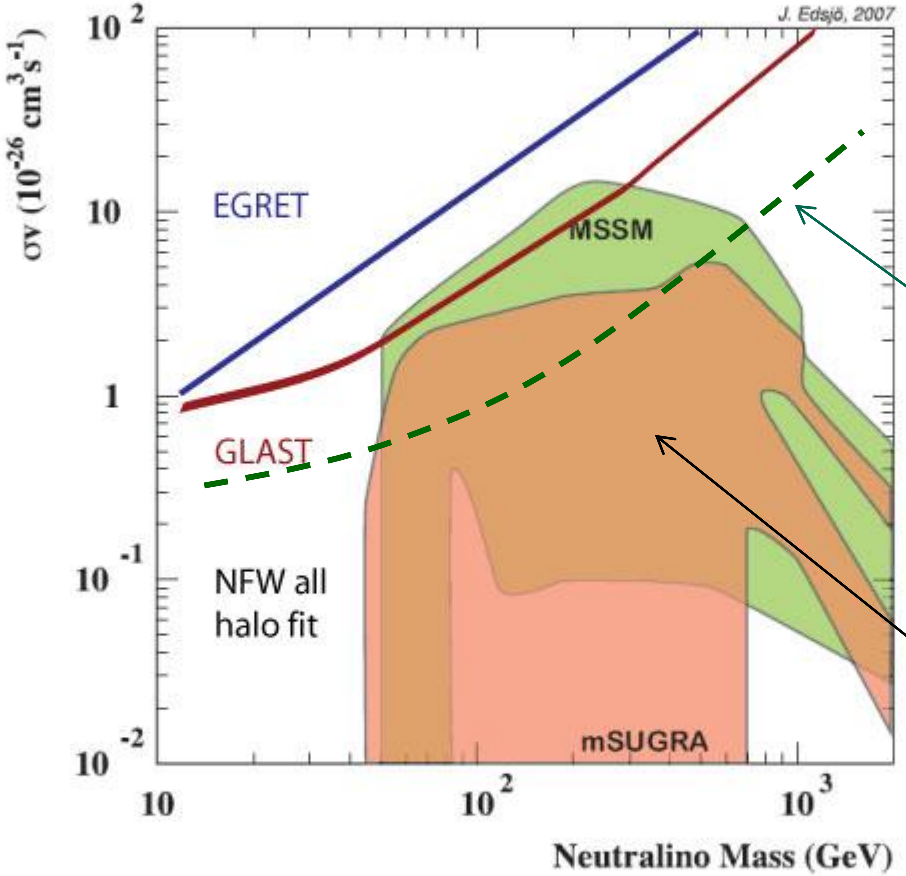
Fermi/GLAST can search for dark matter signals up to 300 GeV. It is also likely to detect a thousand new AGNs (GeV blazars). J. Conrad from OKC leads the dark matter effort of Fermi at present.

After a few days, the Fermi sky map was superior to that of EGRET after several years! Several new sources detected. Here is the 3 month-map:



Potential for discovery by Fermi

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

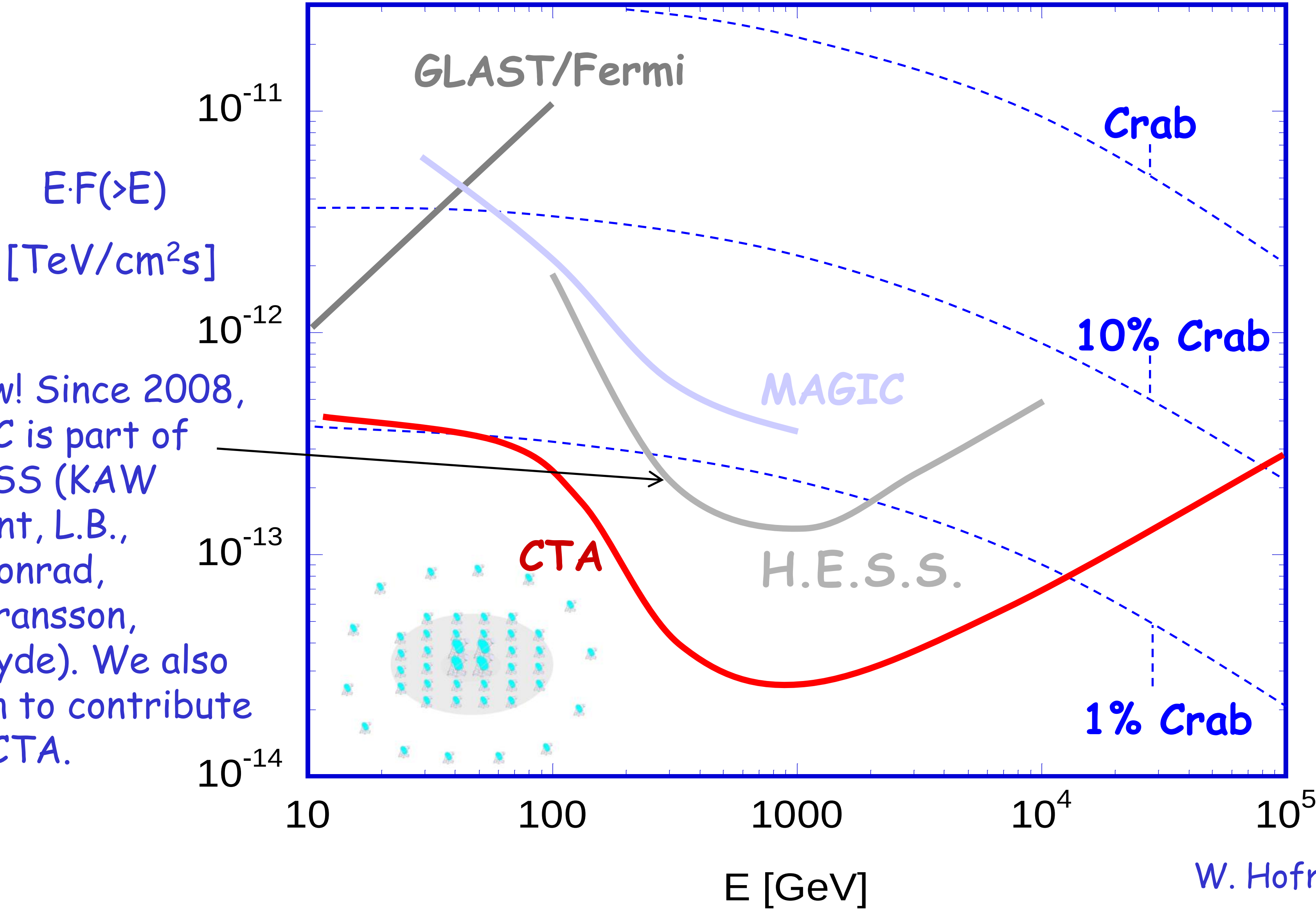


Including all halo, with substructure

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

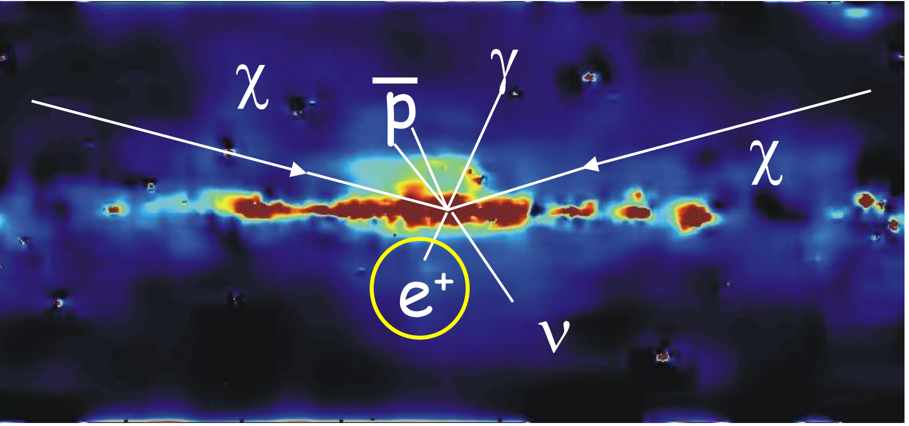
GLAST working group on Dark Matter and New Physics, E.A. Baltz, L. B., G. Bertone, T. Bringmann, ..., J. Conrad, J. Edsjö & al., JCAP, 2008.

The future? Possible Cherenkov Telescope Array (CTA) sensitivity



New! Since 2008, OKC is part of HESS (KAW grant, L.B., J.Conrad, C.Fransson, F.Ryde). We also plan to contribute to CTA.

W. Hofmann



Positrons

The Astrophysical part for positrons has some uncertainty (faster energy loss than antiprotons): Positrons lose direction almost immediately, and lose energy continuously. 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)

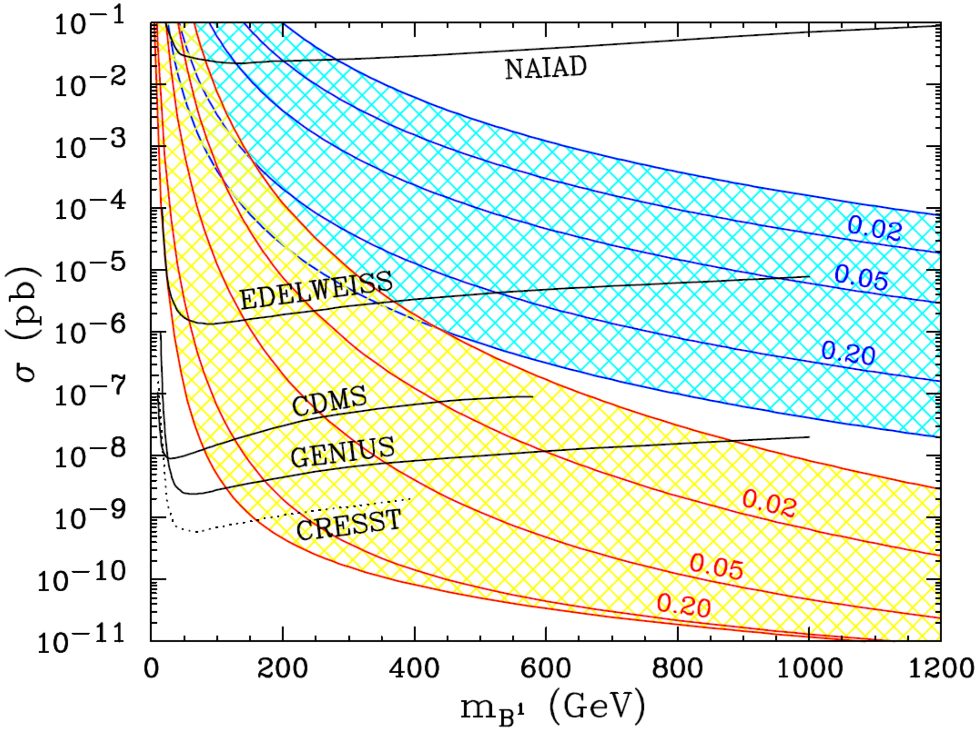
$$b(E) = 10^{-16}(E/1\ \mathrm{GeV})^2 \quad (\mathrm{GeV s^{-1}})$$

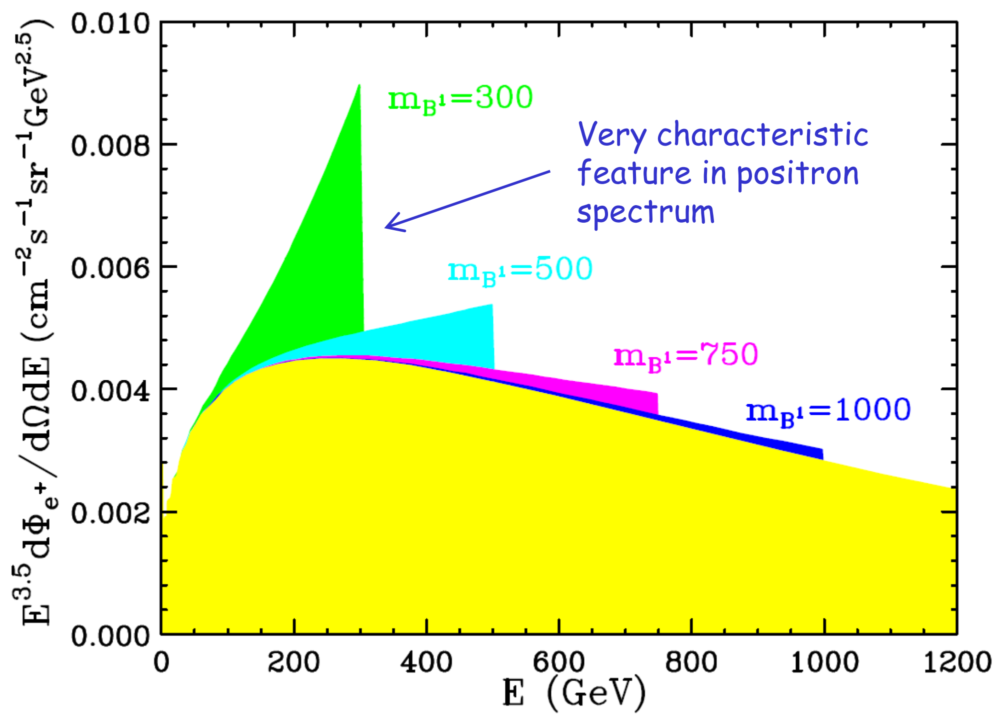
$$K(E) = 3.3\times 10^{27}\left[3^{0.6} + (E/1\ \mathrm{GeV})^{0.6}\right] \quad (\mathrm{cm^2 s^{-1}})$$

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

Yes, Oskar Klein!

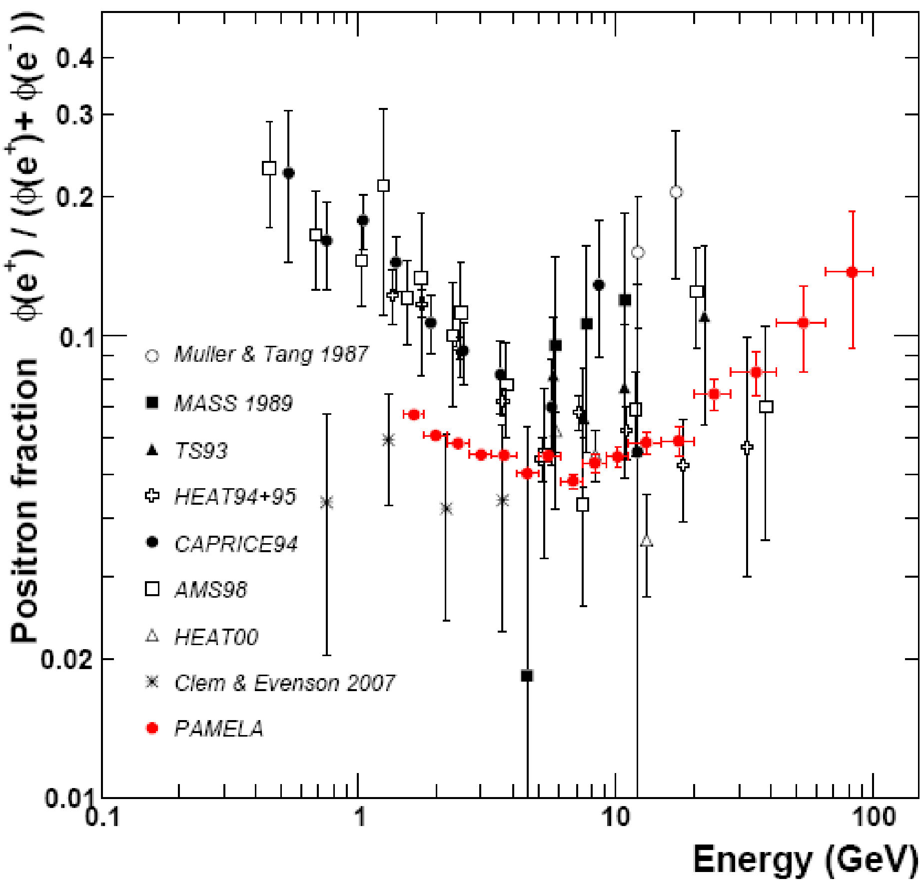
DM particle is a neutral spin 1 particle: the first KK excitaton of the B-field of the standard model.
This gives somewhat different phenomenology. For instance, direct annnihilation to light fermions (like electrons and positrons; neutrinos) is not helicity suppressed.

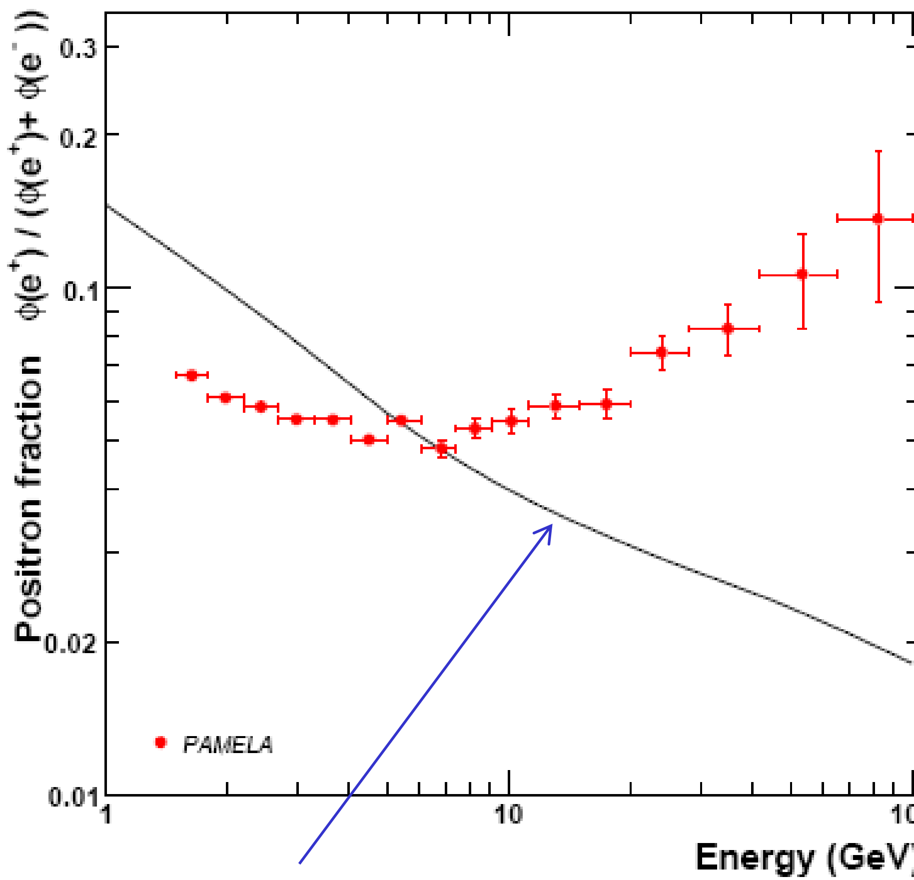




Cheng, Feng & Matchev, 2002

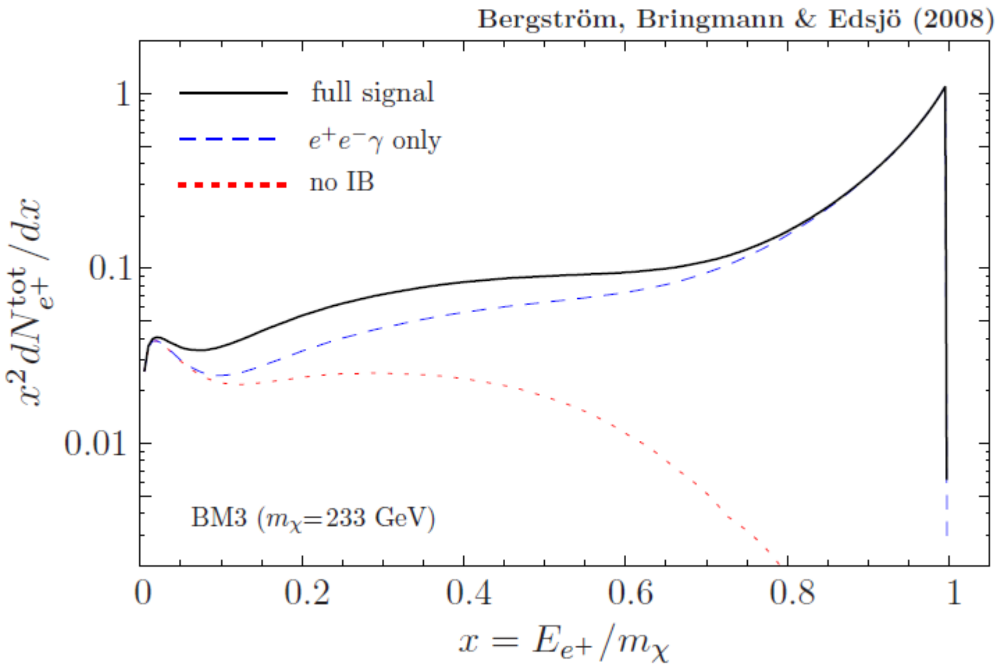
Oct 2008: The awaited PAMELA data on the positron ratio up to 100 GeV (first presented in a "paparazzi session" at the Identification of Dark Matter Conference at AlbaNova in August) is now public!
O. Adriani et al., Nature, submitted, arXiv:0810.4995

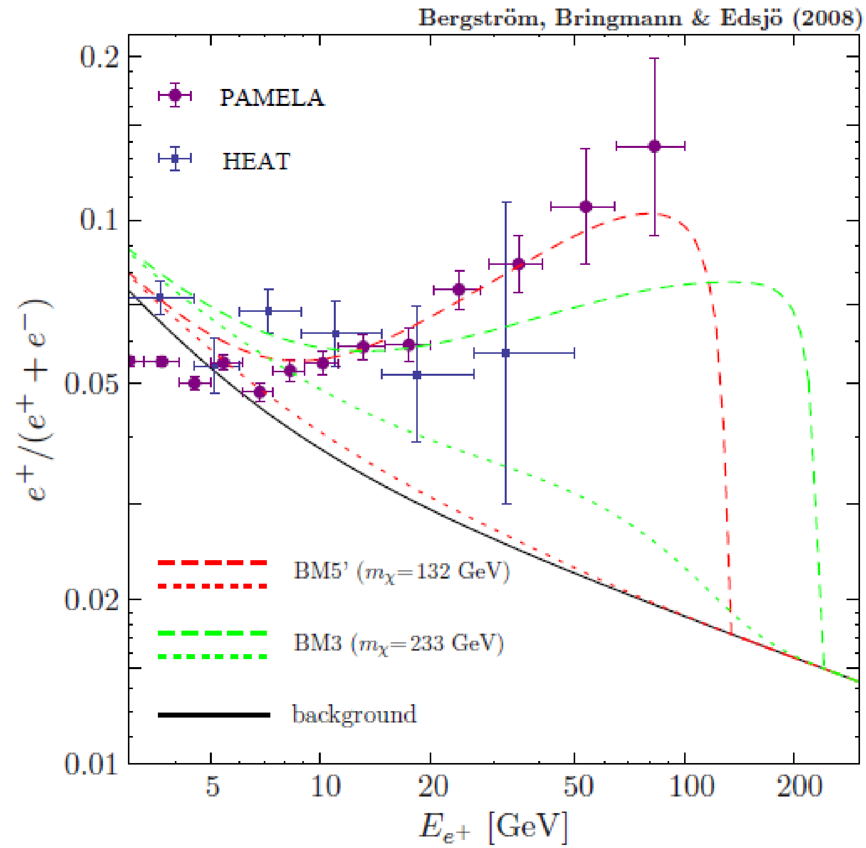




Prediction from secondary production by cosmic rays: Moskalenko & Strong, 1998

Good news: Susy with internal bremsstrahlung can give the right spectrum:





Bad news: one needs to artificially enhance the annihilation cross section by a "boost factor" of more than 1000. For KK-like models which go directly to electron-positron pairs, only a factor of a few – 10 is needed

Boost factor:

$$B_{\Delta V} = B_n^{\Delta V} \times B_{\sigma v} = \frac{\left\langle n^2(\vec{r}) \right\rangle_{\Delta V}}{\left\langle n_{NFW}^2(\vec{r}) \right\rangle_{\Delta V}} \times \frac{\left\langle \sigma v \right\rangle_{v/c \approx 10^{-3}}}{\left\langle \sigma v \right\rangle_{v/c \approx 0.3}}$$

Cosmology Particle physics

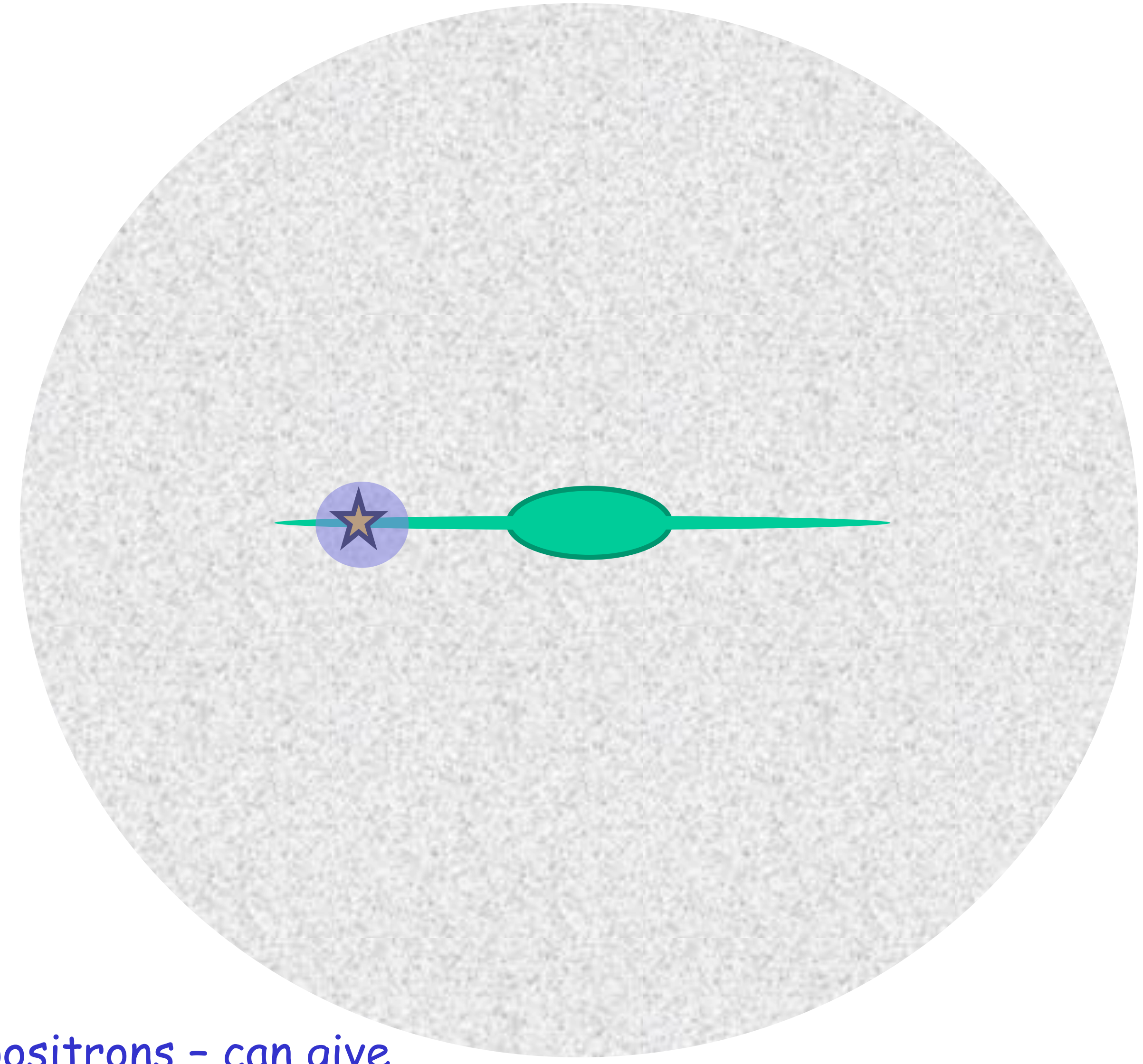
For explaining PAMELA positrons in terms of conventional Dark Matter models, need B ~ 100 – 10000

The cosmology B-factor for $\Delta V \sim (10\text{ kpc})^3$, such as for antiprotons, is between a few (Springel & al, 2008) and 20 (Diemand & al, 2008)

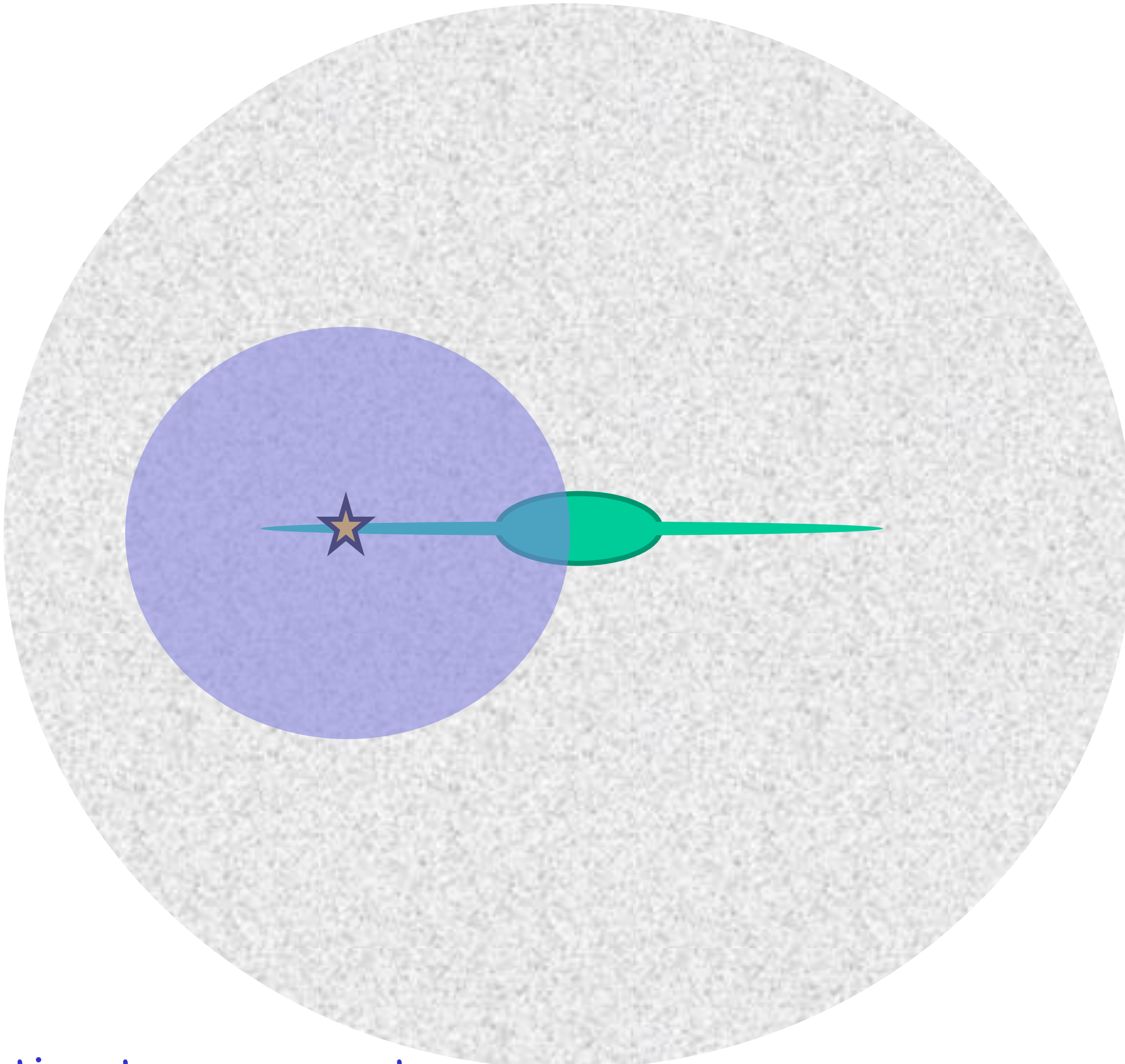
However, $\Delta V \sim (0.1 - 1\text{ kpc})^3$ for high energy positrons

$\Rightarrow$The solution is either to assume a strong local source (DM clump, intermediate mass black hole, etc) or to increase σv

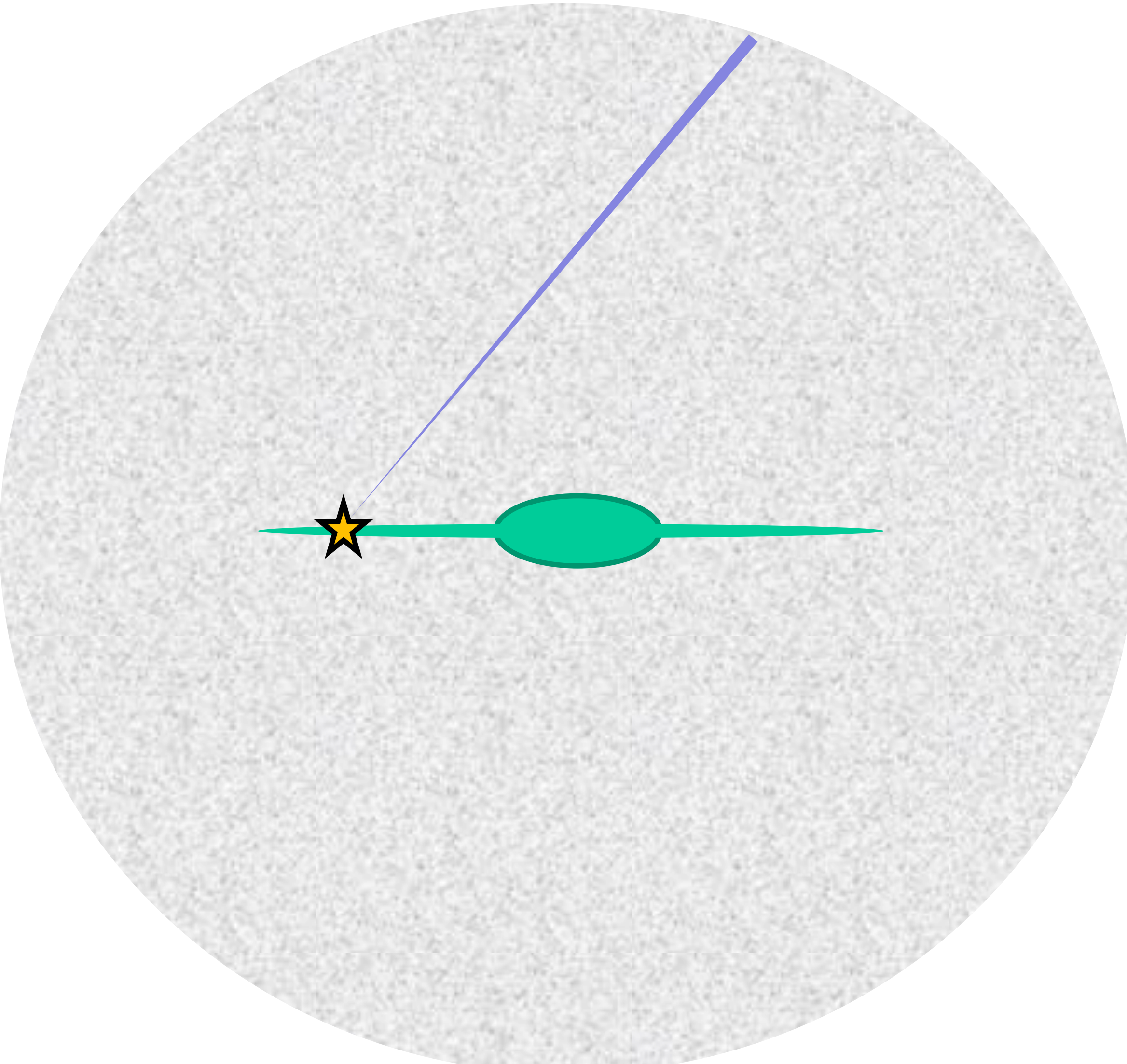
(Note that for gamma-ray detection in a given direction, e.g., the galactic centre, ΔV is very small, and therefore the boost can be very large.)



ΔV for positrons – can give large boost if nearby dark matter clump (unlikely)



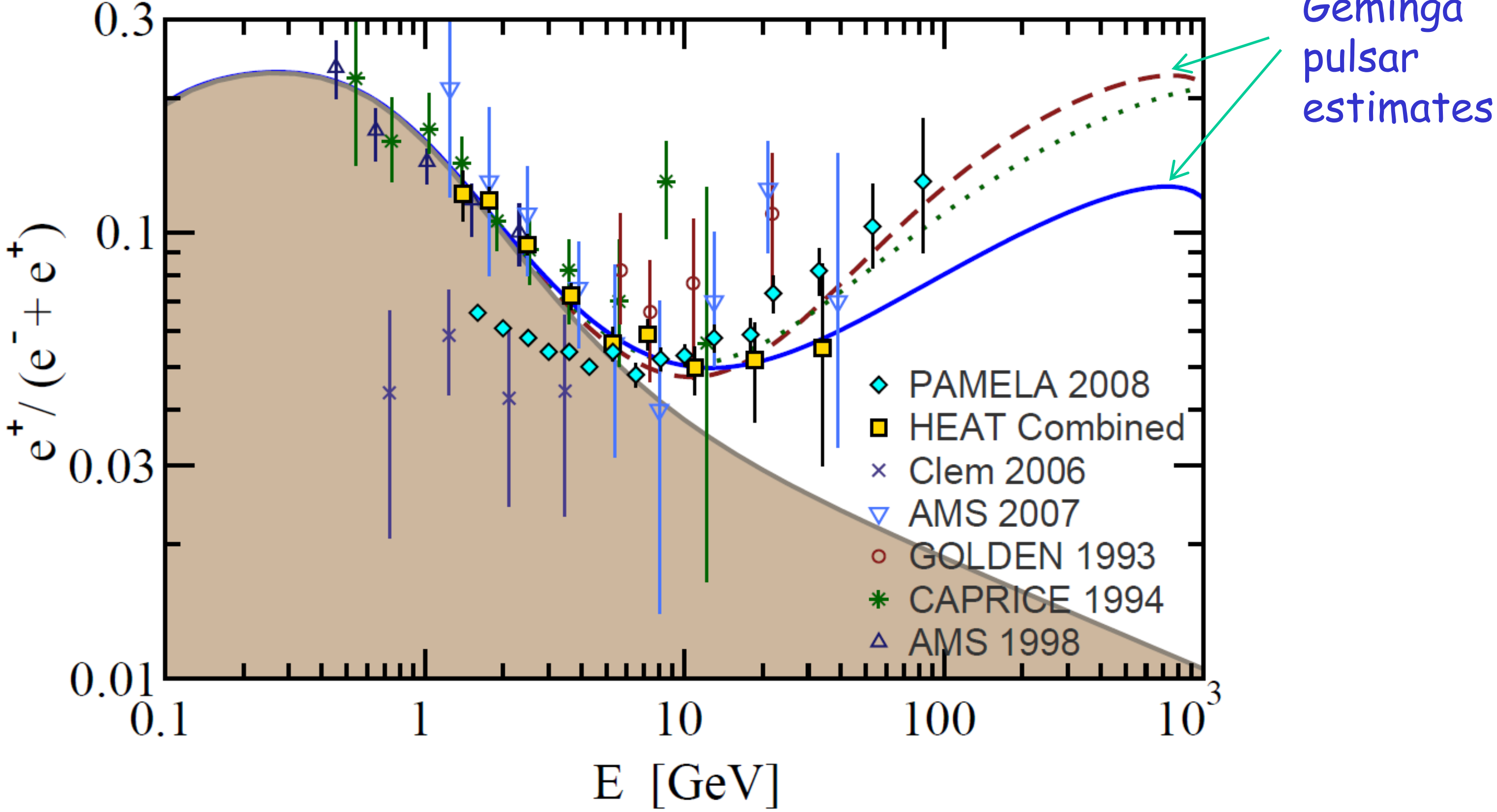
ΔV for antiprotons – can not give large boost factor for realistic halo models



ΔV for gamma-rays – can give very large boost factors in directions where dark matter is concentrated (the galactic center; subhalos)

Alternative explanation for high positron flux: positrons generated by a class of extreme objects: supernova remnants (pulsars)

Vela pulsar (supernova remnant)



Yuksel, Kistler, Stanev, 2008 (cf. Aharonian, Atoyan and Völk, 1995; Kobayashi et al., 2004; Hooper, Blasi, Serpico, 2008; Profumo 2008;…)

Nature, November 19, 2008
ATIC: Balloon experiment which measures sum of electron and positron flux

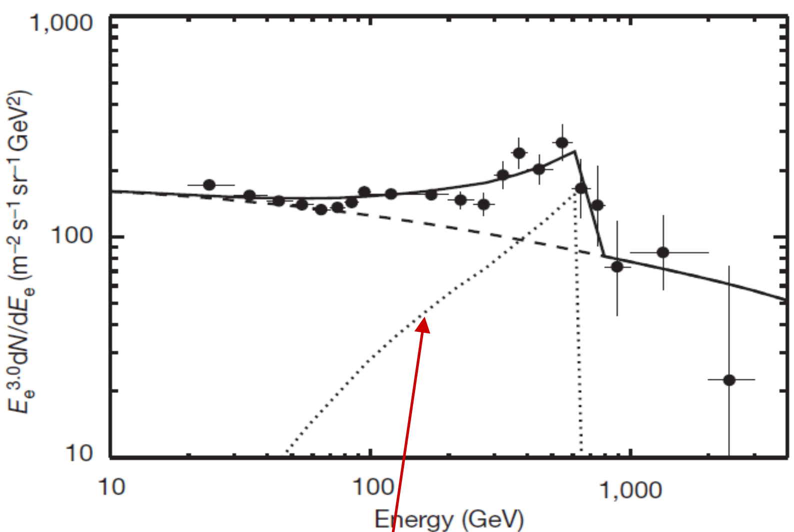


Figure 4 | Assuming an annihilation signature of Kaluza–Klein dark matter, all the data can be reproduced. The GALPROP general electron

Boost factor of order 1000 needed!

HESS, Nov. 24, 2008

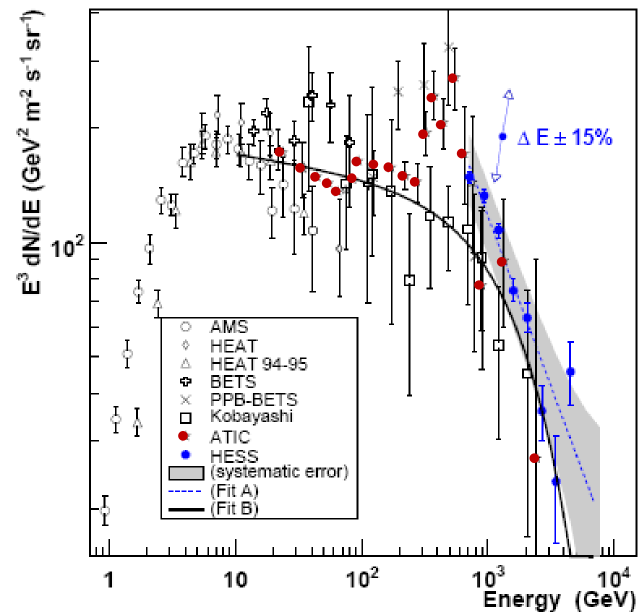
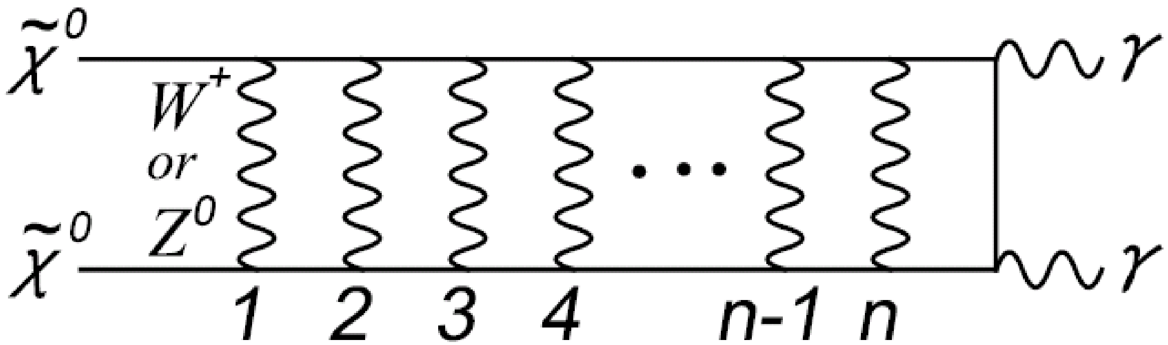


FIG. 3: The energy spectrum E^3 dN/dE of CR electrons as measured by H.E.S.S. in comparison with previous measurements. The H.E.S.S. data are shown as solid points. The two fit functions (A and B) are described in the main text. The shaded band indicates the approximate systematic error arising from uncertainties in the modeling of hadronic interactions and in the atmospheric model. The double arrow indicates the effect of an energy scale shift of 15%, the approximate systematic uncertainty on the H.E.S.S. points. Previous data are reproduced from: AMS [18], HEAT [19], HEAT 94-95 [20], BETS [21], PPB-BETS [22], Kobayashi [2] and ATIC [23].

Is the dark matter feature really there? Or is the true distribution a smooth curve (indications of a pulsar origin). Fermi can measure this spectrum to 1 TeV with superior accuracy. The results should appear shortly (within a few months)…

Interesting possibility to boost annihilation of high-mass WIMPs:

Hisano, Matsumoto and Nojiri, 2003; Hisano, Matsumoto, Nojiri and Saito, 2004, expanding on the 2γ calculation of L.B. and P. Ullio (1998)



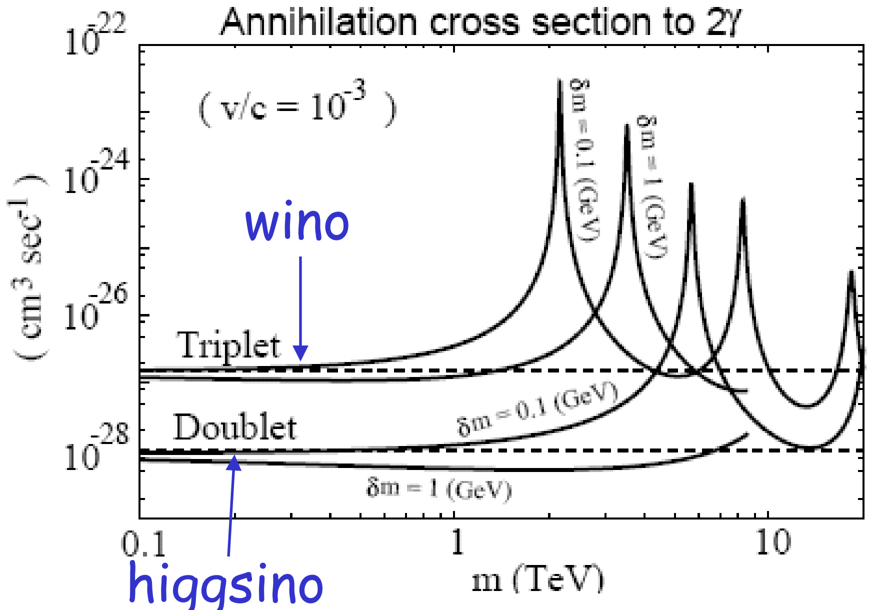
$$\mathcal{S}^{(II)} = \int d^4x d^3r \; \Phi^\dagger(x,\vec{r}) \left\{ \left(i\partial_{x^0} + \frac{\nabla_x^2}{4m} + \frac{\nabla_r^2}{m} \right) - \mathbf{V}(\vec{r}) + 2i\mathbf{\Gamma}\delta(\vec{r}) \right\} \Phi(x,\vec{r})$$

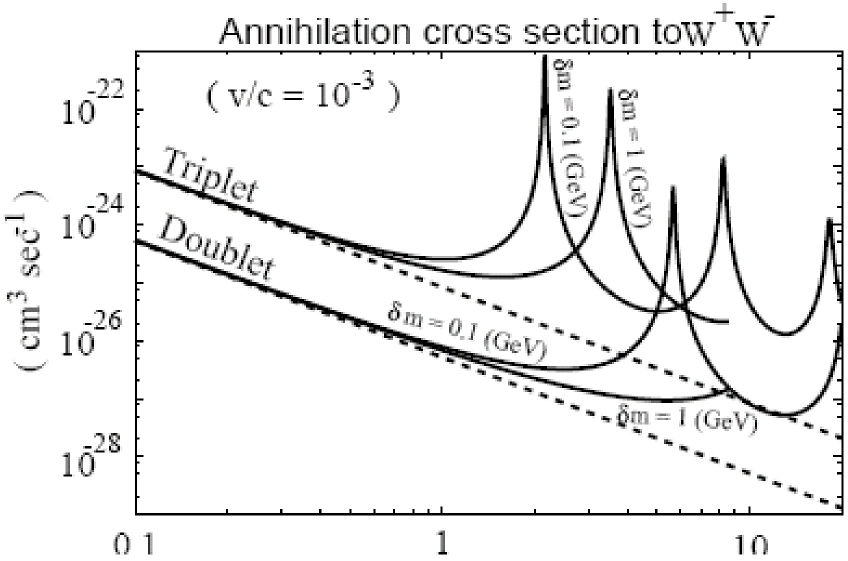
$$\mathbf{V}(r) = \begin{pmatrix} 2\delta m - \frac{\alpha}{r} - \alpha_2 c_W^2 \frac{e^{-m_Z r}}{r} & -\sqrt{2}\alpha_2 \frac{e^{-m_W r}}{r} \\ -\sqrt{2}\alpha_2 \frac{e^{-m_W r}}{r} & 0 \end{pmatrix}$$

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

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

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

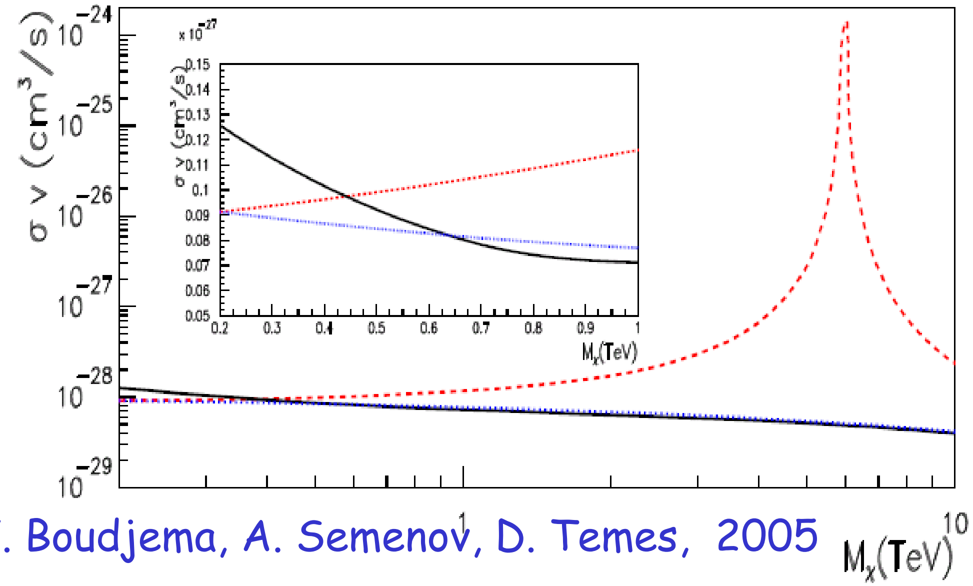




In MSSM without standard GUT condition (AMSB; split SUSY) m_{wino} ~ 2 – 3 TeV; δm ~ 0.2 GeV

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

See also M. Cirelli & A. Strumia, 2008, N. Arkani-Hamed, D. Finkbeiner, T. Slatyer and N. Weiner, 2008

A Theory of Dark Matter arXiv:0810.0713v1 [hep-ph] 6 Oct 2008

Nima Arkani-Hamed,[1] Douglas P. Finkbeiner,[2] Tracy Slatyer,[3] and Neal Weiner[4]

$$\mathcal{L}_{\rm Dark} = \mathcal{L}_{\rm Gauge\ Kin.} + \frac{1}{2} m_{ij}^2 a_i^\mu a_{\mu j} + \cdots$$

- Take a model with TeV-scale Dark Matter forming a multiplet with very small mass splitting (100 keV – 1 MeV)
- Let the DM interact with a new gauge group, e.g. a new SU(2)xU(1), with gauge bosons of mass around a GeV, and maybe some new Higgses
- Let the gauge boson couple weakly to SM particles
- Adjust couplings and masses so that the Sommerfeld condition for resonance is met

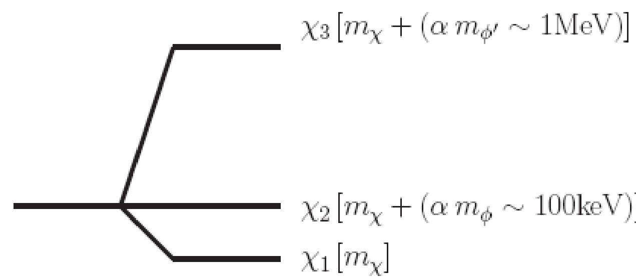


FIG. 4: Spectrum of exciting dark matter.

Then one may simultaneously explain the experimental results of:

- ~~INTEGRAL 511 keV positrons~~ asymmetry detected
- WMAP haze
- PAMELA preliminary high energy positrons
- PPB-BETS, ATIC electrons + positrons
- ~~EGRET excess~~ Fermi sees no excess!
- DAMA

Too good to be true??

Experiment	DM interpretation	Conventional explanation	Summary
DAMA annual modulation	Not a conventional WIMP. Maybe excitation of DM?	None found, but also no independent confirmation of effect.	Should be performed at other location, with other materials
HEAT excess of positrons (**PAMELA**, **PPB-BETS and ATIC** preliminary excesses)	Needs huge boost factors for conventional WIMPs. Maybe Sommerfeld enhancement?	Pulsars, like Geminga, can give flux with right properties.	New circumpolar balloon flights will be performed. Fermi/GLAST may give data on sum of e^+ and e^- flux
EGRET GeV excess	Standard SUSY WIMP with unusual halo model (W. de Boer). May be in conflict with antiprotons (L.B. J.Edsjö, M. Gustafsson & P. Salati).	Maybe EGRET had calibration error (Stecker, Hunter & Kniffen, 2007)?	Fermi/GLAST has just released data (Jan. 2009) which do not show the "EGRET excess"
INTEGRAL MeV positrons near Galactic Centre	Annihilation of very small mass DM candidate. Or decay of particles with small mass splitting	The distribution seems to have some spatial anisotropy. Astrophysical sources?	INTEGRAL is getting more and more data. If anisotropy confirmed, DM interpretation less likely.
WMAP "haze"	DM source with NFW distribution, annihilating with large B.R. into electrons.	Dangerous to subtract many components with unknown errors. Polarisation data seems not to confirm the need for extra component.	Planck will get more accurate data.

Has Dark Matter been seen?

Better wait for forthcoming data, in particular from Fermi...

We may soon have the answer to the exciting question - what is the dark matter?