The mystery of the Dark Matter of the Universe

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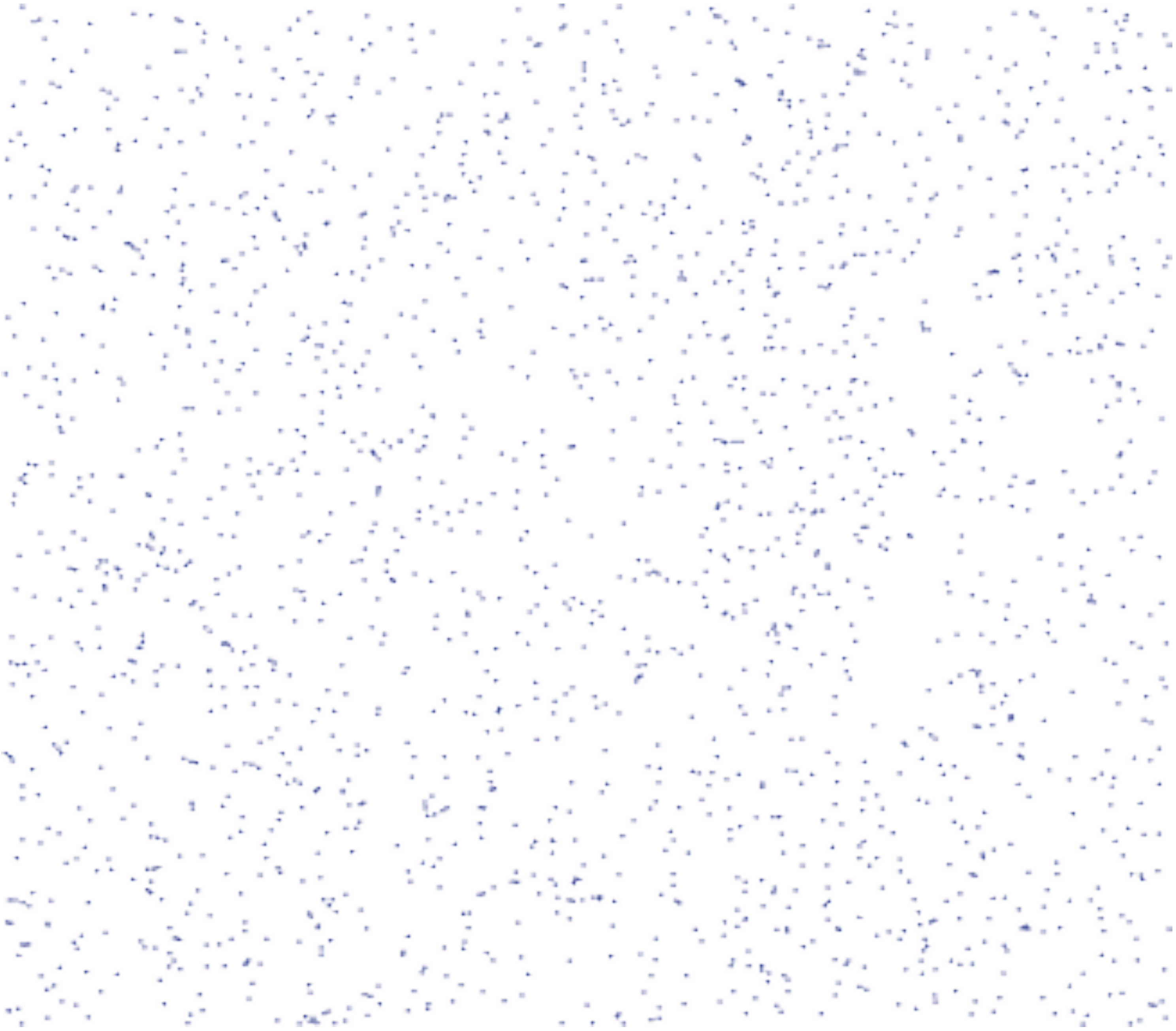
Oskar Klein centre

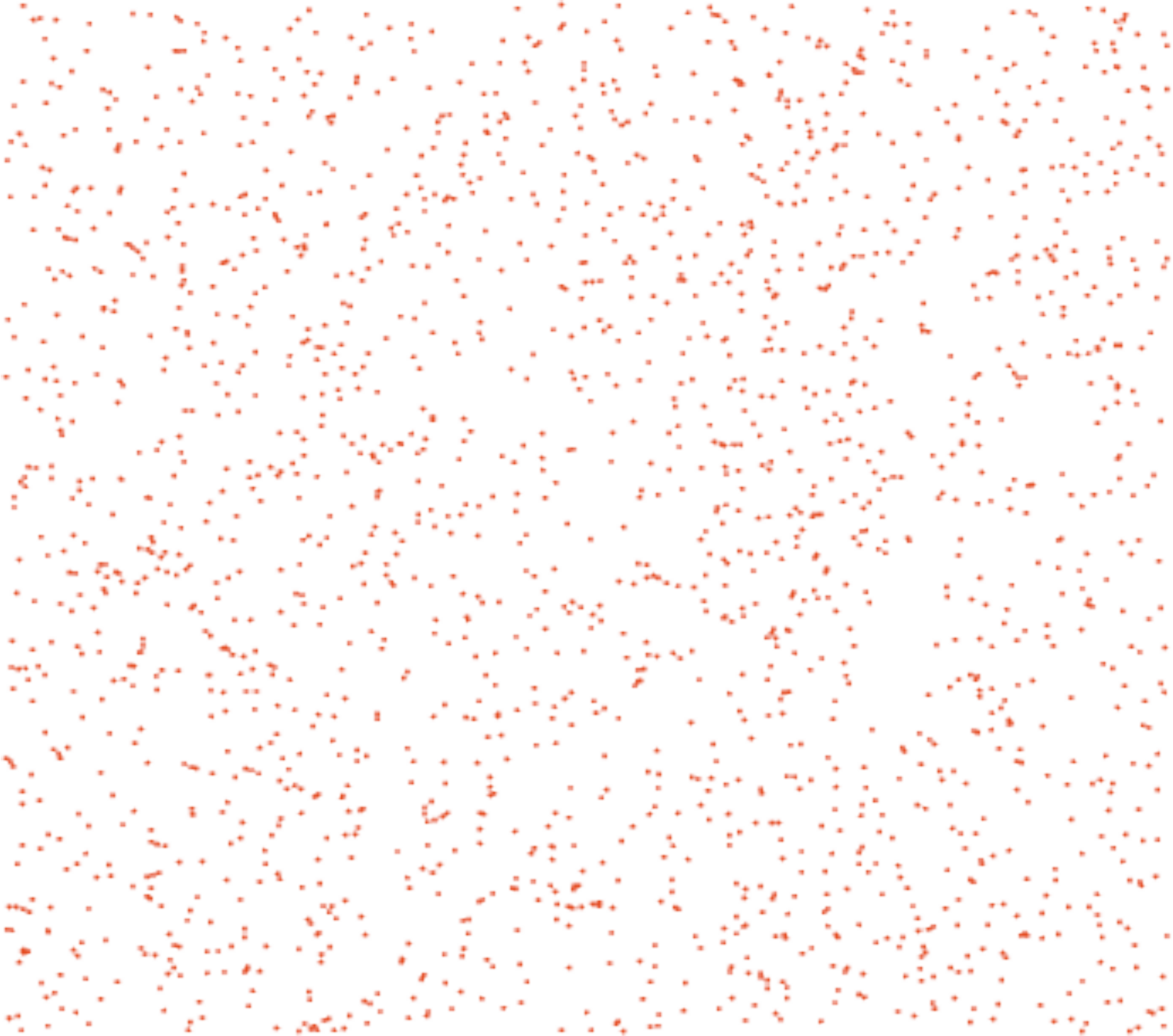
Oskar Klein (1894 – 1977)
Professor at Stockholm University (1930 - 1962)
Klein's paradox, Klein-Nishina formula,
Kaluza-Klein theory of extra dimensions, …

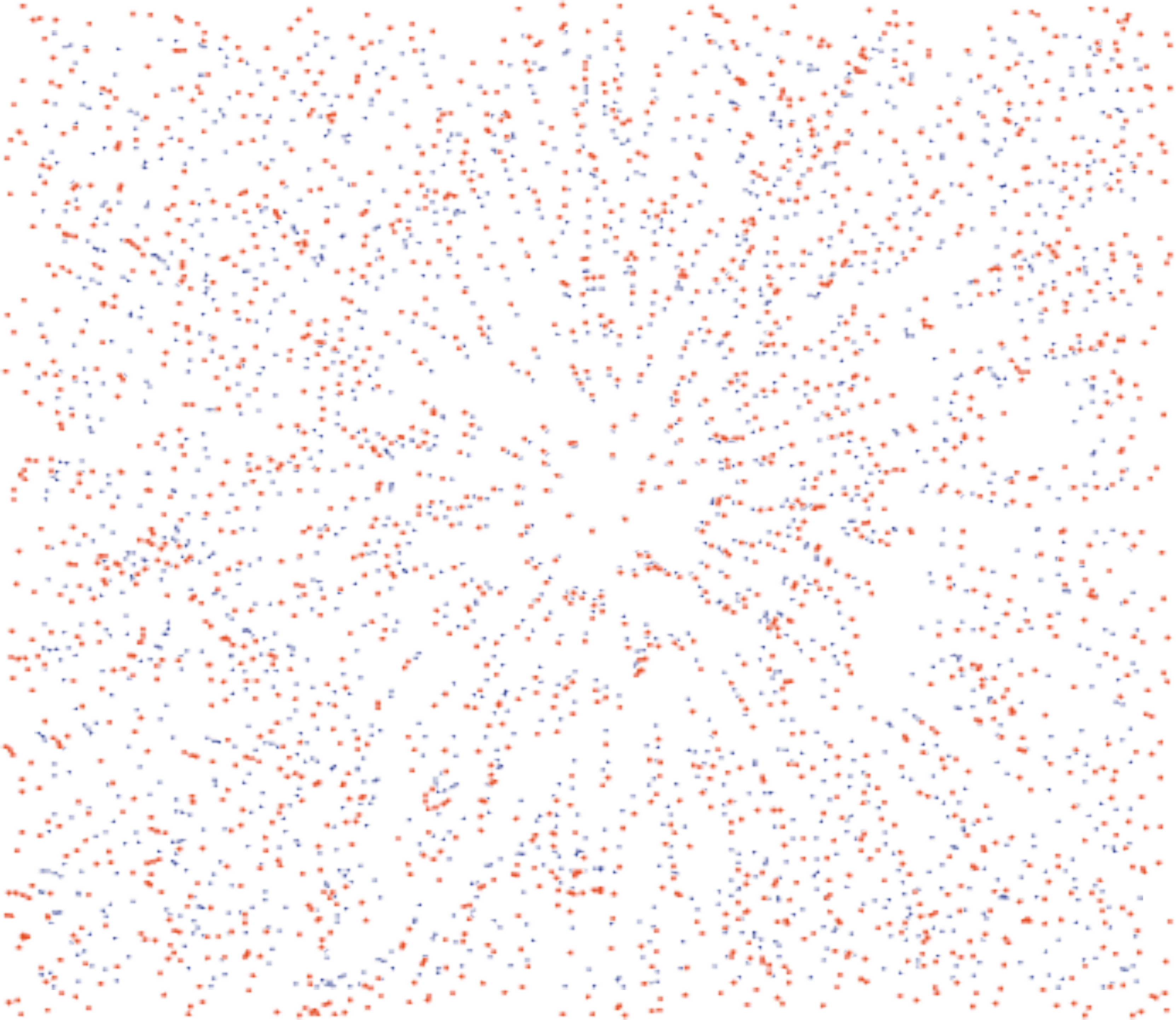
The Oskar Klein Centre for Cosmoparticle Physics (OKC): Centre under the Faculty of Science, located at Fysikum, Stockholm University on the AlbaNova campus. "Linnaeus grant", unique long-term grant from the Swedish Research Council (VR) awarded in mid-2008 in strong national competition. Groups from the Astronomy Department and the experimental astroparticle physics group at KTH are also members.

The grant is for 10 years, 7 MSEK/yr. This was increased by 10%, from July 2010, after successful VR evaluation, to 7.7 MSEK/yr (0.9 MEUR or 1.2 MUSD/yr).

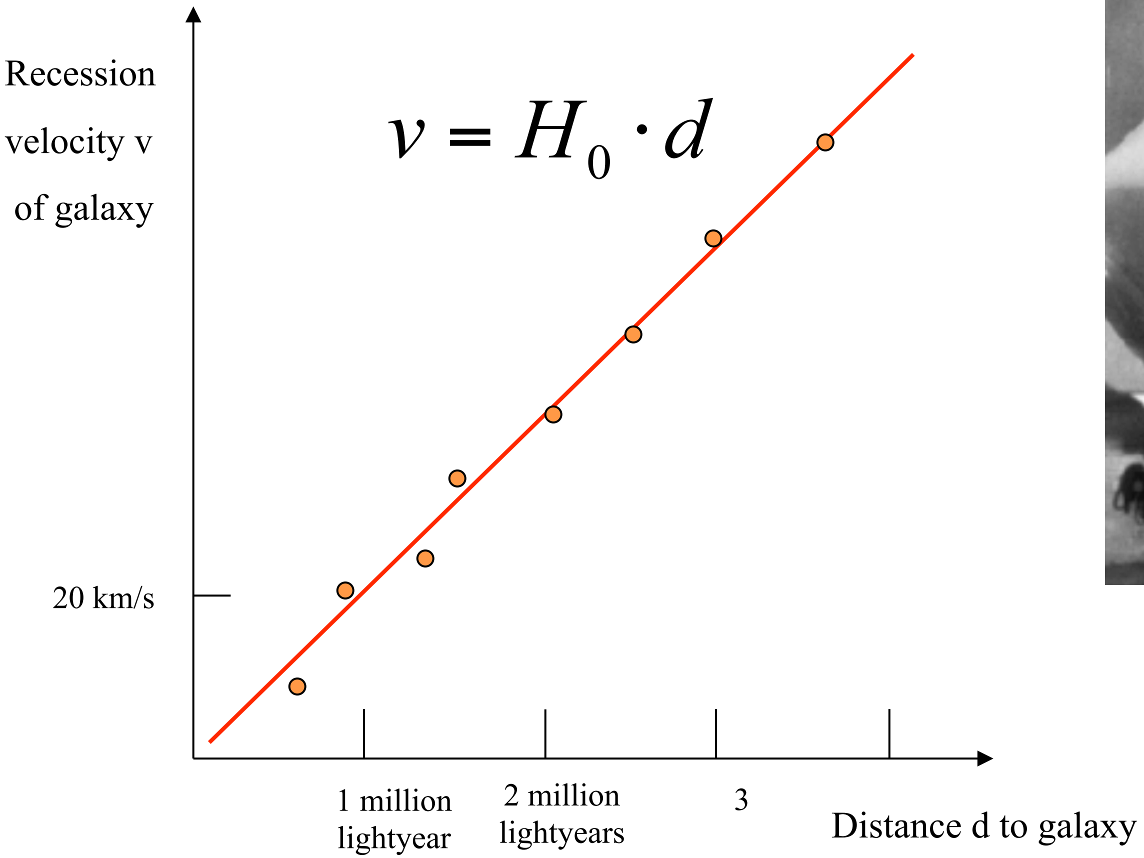
There is a much larger co-funding from the participating Universities (mainly in terms of PhD students and faculty positions).







Hubble's law (really first discovered by Knut Lundmark and George Lemaître in mid-1920´s)



Value of the ”Hubble constant” H_0: 20 km/sek per million lightyears

Modern interpretation based on Einsteins GR: space is expanding

Einstein 1905: Space ***r*** and time *t* become space-time (*t*, ***r***). Simplest assumption: The universe is isotropic and homogeneous on large scales. The Minkowski metric $ds^2 = c^2 dt^2 - dr^2$ will change in the presence of energy and momentum according to Einstein's general relativity equations (1915) and becomes for the standard cosmological model ΛCDM model (put *c* = *1*):

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right)$$

where *a(t)* is the average scale factor, and *k* is related to the overall geometry of the universe, k = 0 for a geometrically flat universe. (The clumpiness of the physical universe seems to have little effect on the averaging assumed.)

The scale factor *a(t)* follows equations derived from Einstein's equations:

$$H(t)^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\left[\rho_B + \rho_{CDM} + \rho_R + \rho_\Lambda\right]$$ Friedmann's equation

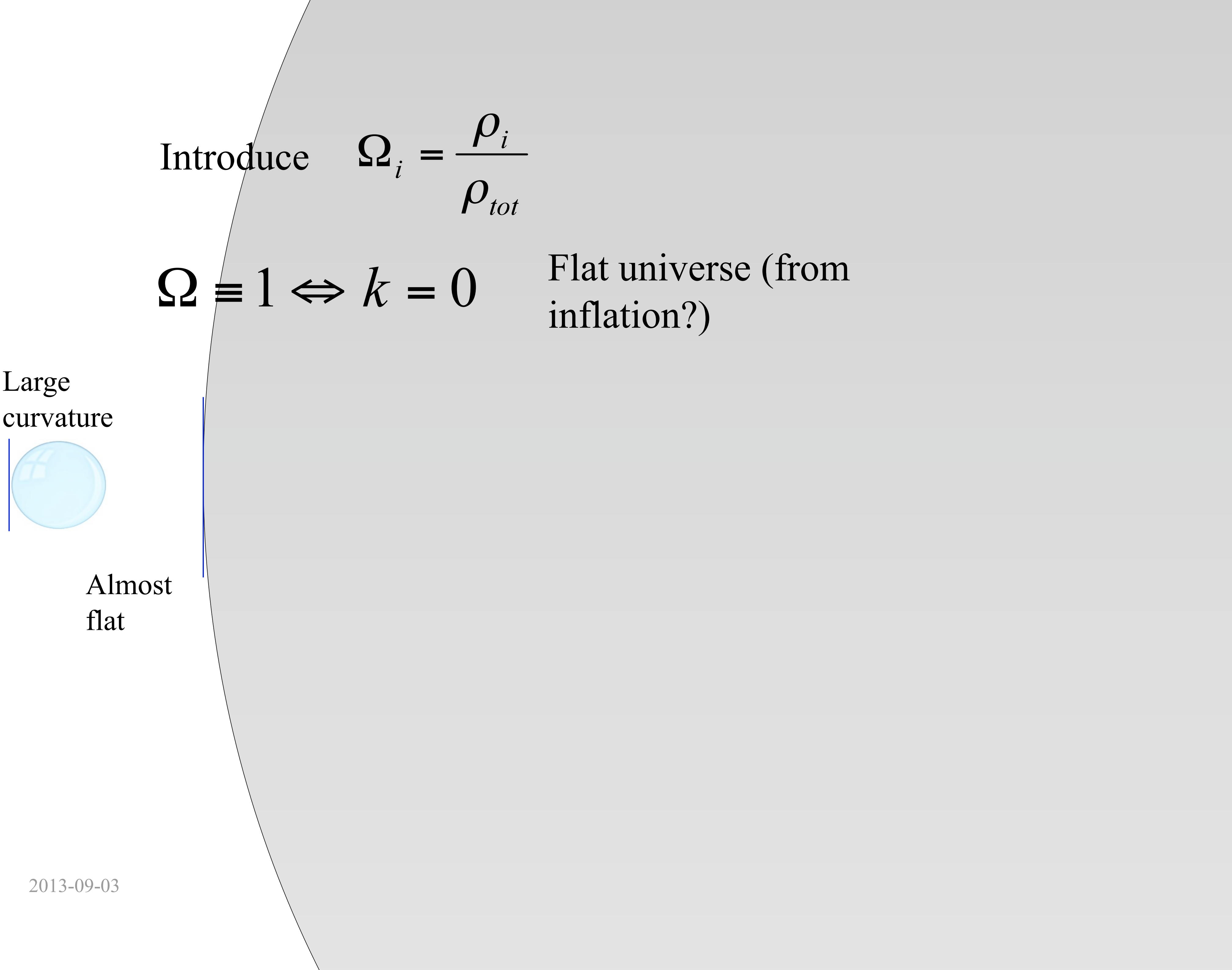
$$H(t_{now}) = h \cdot 100 \text{ kms}^{-1}\text{Mpc}^{-1}$$ with $h \sim 0.67$, $t_{now} \sim 13.8$ Gyr (*Planck* 2013)

$$\frac{2\ddot{a}}{a} + \left(\frac{\dot{a}}{a}\right)^2 = -8\pi G_N p$$ Acceleration equation

Introduce $\Omega_i = \dfrac{\rho_i}{\rho_{tot}}$

$$\Omega \equiv 1 \Leftrightarrow k = 0$$

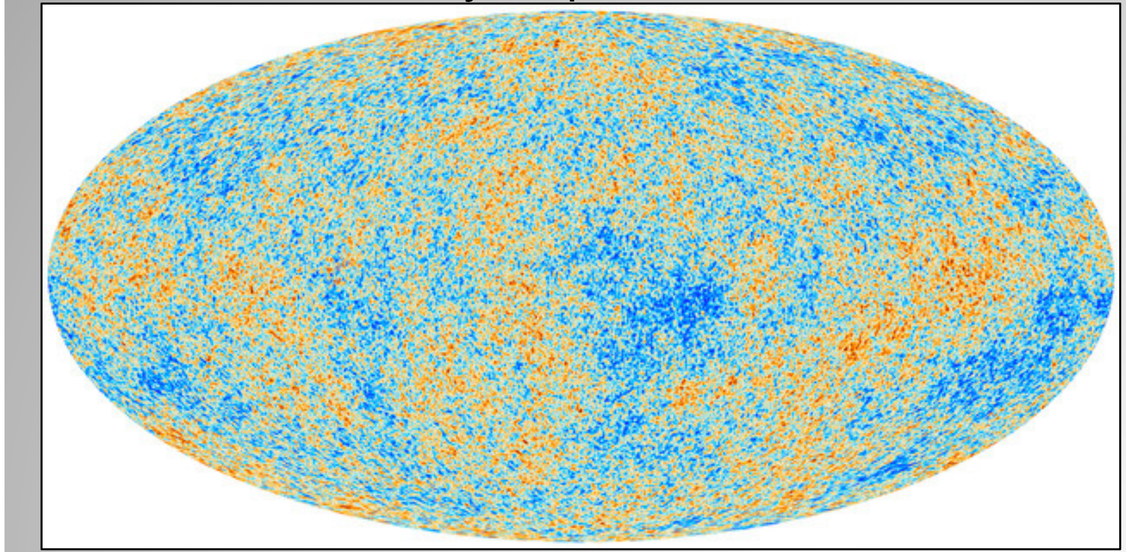
Flat universe (from inflation?)



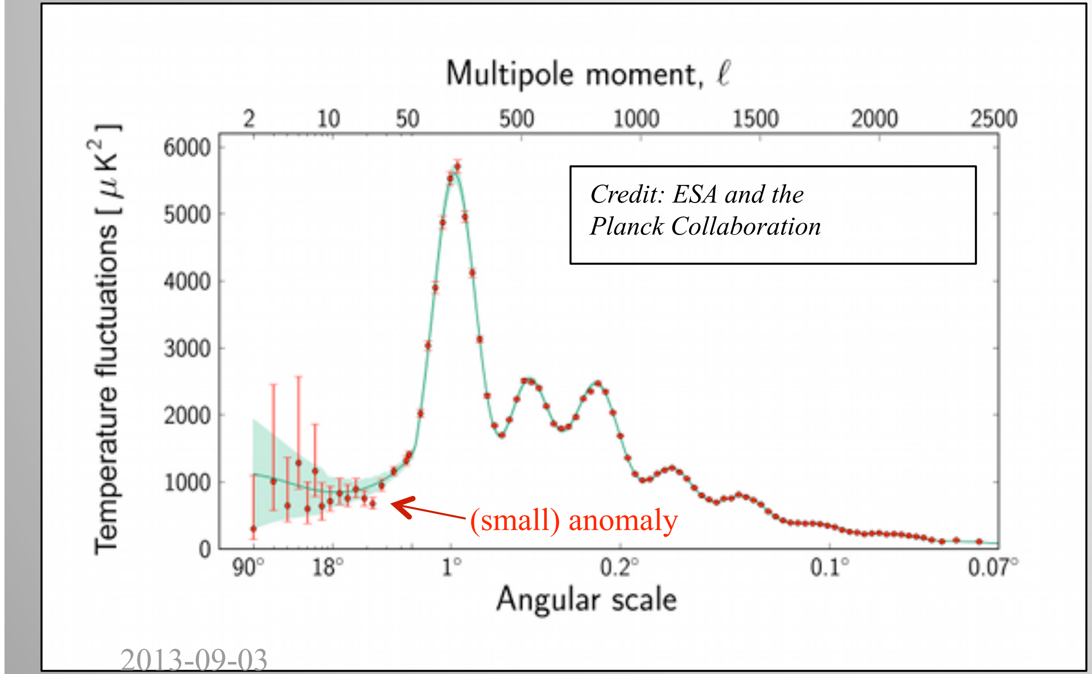
Large curvature

Almost flat

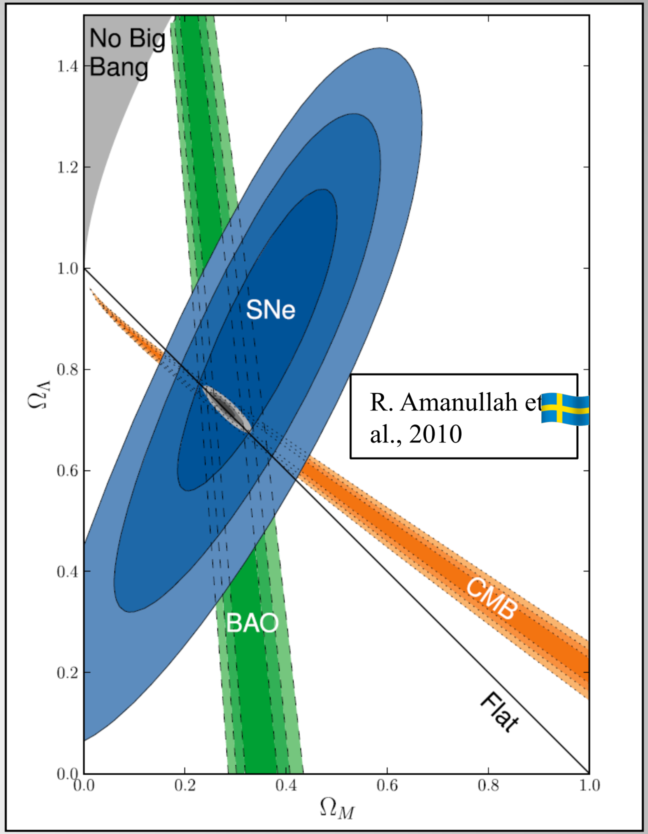
Planck Sky Map, March 2013



The *Planck* Collaboration, 2013



Credit: ESA and the Planck Collaboration



R. Amanullah et al., 2010 🇸🇪

Planck 2013:

$$\Omega_{tot} \equiv \frac{\rho_{tot}}{\rho_{crit}} \approx 1.01 \pm 0.02$$

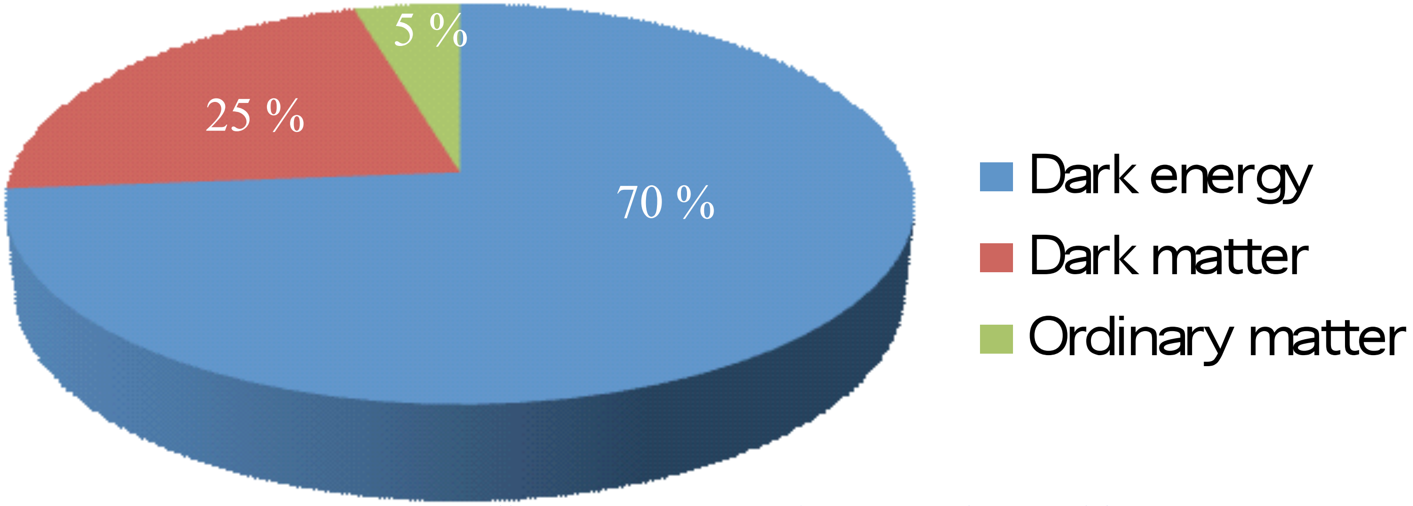
$$\Omega_\Lambda = 0.685 \pm 0.018 \quad \Omega_{CDM} h^2 = 0.1199 \pm 0.0027$$

$$\Omega_B = 0.0489 \pm 0.0018 \quad h = 0.673 \pm 0.012$$

$$\sum m_\nu < \begin{cases} 0.98\,\text{eV} & (95\%;\ \textit{Planck}\text{+WP+highL}) \\ 0.32\,\text{eV} & (95\%;\ \textit{Planck}\text{+WP+highL+BAO}). \end{cases}$$

$$N_{\text{eff}} = 3.30^{+0.54}_{-0.51} \quad (95\%;\ \textit{Planck}\text{+WP+highL+BAO})$$

Composition of the Universe
("Concordance Model")



All measurements so far are consistent with this cosmological model

Look at a simple, spherically symmetric model of the mass density distribution $\rho(r)$ of a galaxy. The enclosed mass at radius r is:

$$M(R) \equiv M(r < R) = 4\pi \int_0^R \rho(r) r^2 dr$$

Consider a model of the galaxy which has a finite extent, $r(r) = 0$ for $r > R$. (In a real galaxy with visible matter only, R would correspond to the ”optical radius”.)

Then for $r > R$, $M(r) = const = M_0$, and if velocities are non-relativistic, we can use the Newtonian expression for the velocity of circular orbits

$$\frac{v^2}{r} = \frac{G_N M_0}{r^2},$$

or

$$v \sim r^{-\frac{1}{2}}$$

Thus, if the galaxy only contains visible material, the rotation curve should decrease beyond the ”optical radius” R of the galaxy.

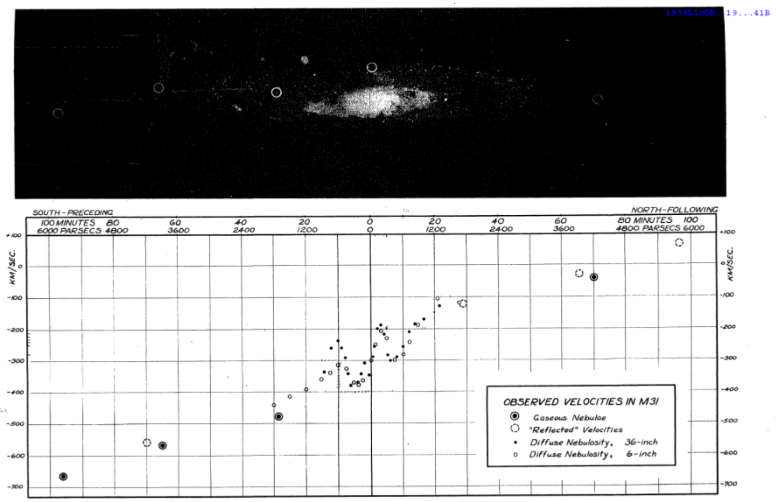
First observations of dark matter:

”If this over-density is confirmed we would arrive at the astonishing conclusion that dark matter is present with a much greater density than luminous matter.” Zwicky 1933

H.W. Babcock (1939) measured the optical rotation curve of M31 (Andromeda); was verified much later by V. Rubin and W.K. Ford (1970).

From Babcock’s paper, 1939:

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.



The Andromeda Nebula, with observed velocities plotted below. Smoothed mean velocities of the unresolved central portion are represented by small dots for observations with the Crossley reflector, and by small open circles for observations with the 6-inch mirror. In the photograph, the bright-line emission nebulosities are encircled, and their velocities, with the exception of the one on the minor axis, are plotted as ringed dots. *(Photograph by Mayall)*

VOL. XIX PLATE III L. O. BULLETIN

Dat during last decade: Dark matter needed on all scales!
⇒ Modified Newtonian Dynamics (MOND) and other *ad hoc* attemps to modify Einstein’s or Newton’s theory of gravitation do not seem viable

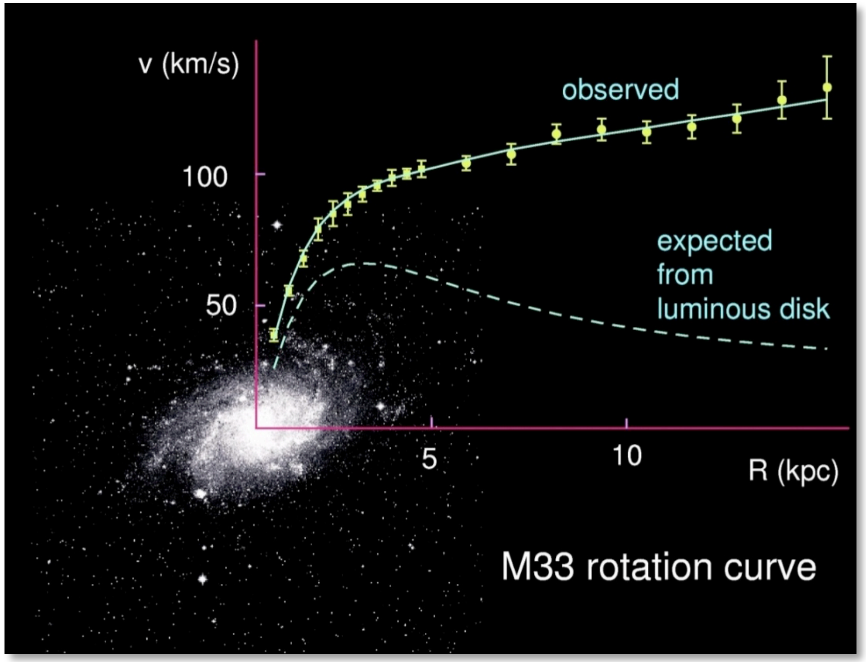
Einstein:
$$\boxed{S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-\tilde{g}}\,R\,.}$$

MOND:
$$\begin{aligned} S \;=\; & \frac{1}{16\pi G}\int d^4x\,\sqrt{-\tilde{g}}\,\Big[\tilde{R} - \frac{1}{2}KF^{ab}F_{ab} + \lambda(A_aA^a + 1) \\ & -\mu(\tilde{g}^{ab} - A^aA^b)\nabla_a\phi\nabla_b\phi - V(\mu)\Big] \end{aligned}$$

where $g^{ab} = e^{2\phi}\tilde{g}^{ab} + 2\sinh(2\phi)A^aA^b\,.$

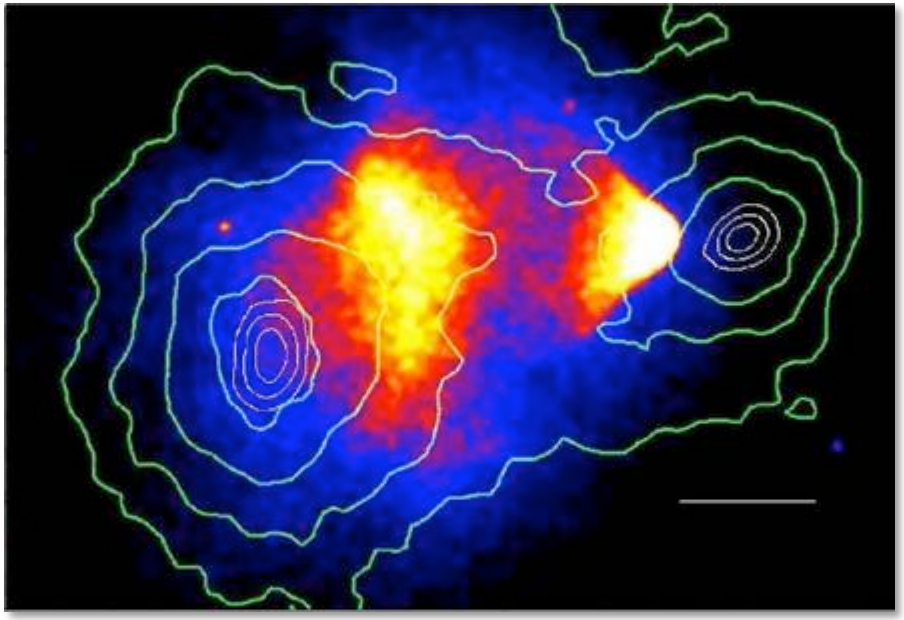
and $\frac{dV}{d\mu} = -\frac{3}{32\pi l_B^2\mu_0^2}\frac{\mu^2(\mu-2\mu_0)^2}{\mu_0-\mu}\,.$

Galaxy rotation curves



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

Colliding galaxy clusters



The bullet cluster, D. Clowe et al., 2006

The ingredients of the Concordance Model can be described and understood by known effects in particle physics and quantum mechanics:

Dark energy is the cosmological constant: the sum of all quantum mechanical zero-point energies (but why is it so small?)

Inflation is driven by the vacuum energy of a scalar field – the inflaton. We know since last year (the Higgs discovery) that fundamental scalar fields do exist. $\Omega_{tot} = 1$ to high accuracy predicted.

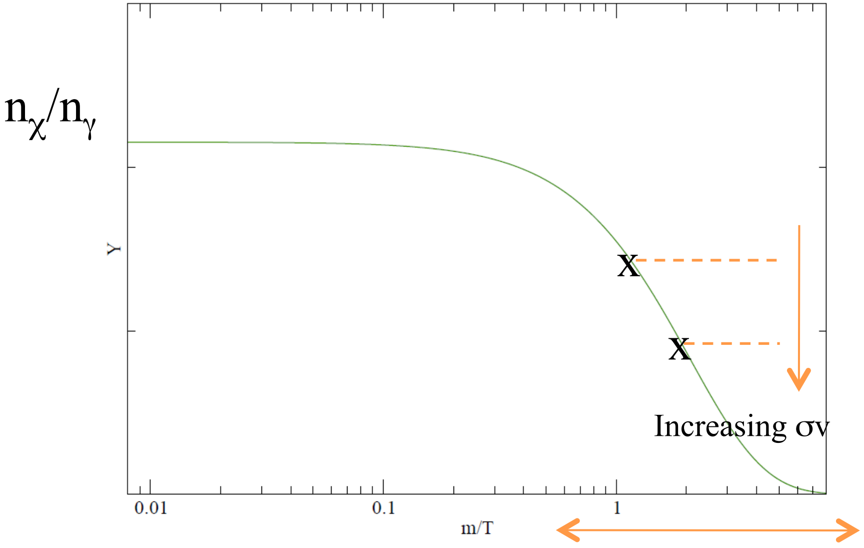
Dark matter can be explained by the existence of an electrically neutral, massive particle (mass a few GeV to a few TeV), stable or with very long lifetime.

Why do we have protons and electrons in the universe? They are the lightest charged lepton and baryon, respectively, and due to conservation of quantum numbers they cannot decay → stability.

We then have a given candidate in the Standard Model: The lightest neutrino!
However, does not work since observationally, the mass is too small ($\sum_{\nu} m_{\nu} \leq 0.98\,\mathrm{eV}$).

But there could exist other neutral particles with a conserved quantum number.
Example: the lightest supersymmetric particle.

Cold Dark Matter (for masses greater than a few GeV): Solving the Boltzmann equation numerically in the non-relativistic decoupling regime one finds ($h \sim 0.5$ is a scaled version of the Hubble constant)



Non-relativistic
Cold dark matter

$$\boxed{\Omega_{\chi^0} h^2 \simeq \frac{3 \cdot 10^{-27}\ \mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma_A v \rangle}}$$

This means that a successful cold dark matter model should have (independently of the mass!):

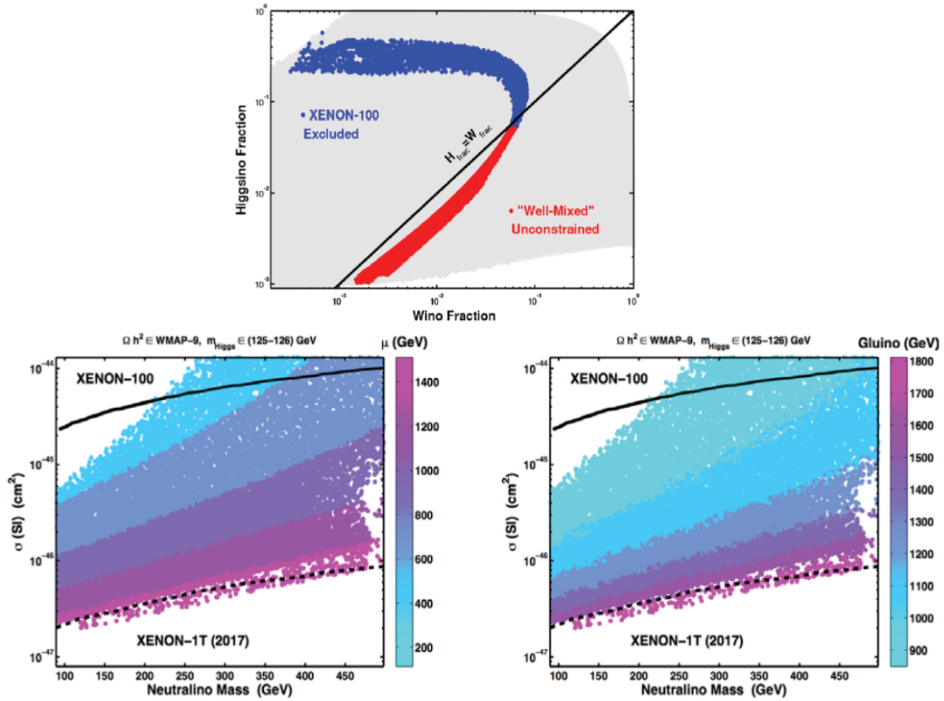
$$\boxed{\langle \sigma_A v \rangle \simeq 3 \cdot 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}}$$

That is, $\sigma_A v \sim 1$ pb. This is a typical weak interaction cross section, so these candidates for dark matter are called WIMPs (Weakly Interacting Massive Particles). The fact that one gets the correct relic density is sometimes called the ”WIMP miracle”. Good template, SUSY WIMP: The lightest neutralino in supersymmetry (H. Goldberg, 1983; J. Ellis, J. Hagelin, D.V. Nanopoulos, K.A. Olive & M. Srednicki, 1984).

One finds typically $T_f \sim \frac{m_\chi}{20}$ for the freeze-out temperature.

Freely available software package, written by
P. Gondolo, J. Edsjö, L. B., P. Ullio, M. Schelke, E. Baltz, T. Bringmann and G. Duda.
http://www.darksusy.org

Example of parameter regions where the MSSM neutralino fullfils all constraints of LHC & Xenon-100 and gives correct relic density. (D. Feldman & P. Sandick, 1303.0329)



One problem for MSSM: While the (lightest) Higgs mass, ~125 GeV, is within the range predicted by SUSY with radiative corrections, it is on the high side which may necessitate some fine-tuning. Also squarks and gluinos (not seen at the LHC) have to have very large masses – not the spectrum one would first have guessed.

Also other interesting non-SUSY WIMPs are worth studying: Lightest Kaluza-Klein particle – mass scale 600 – 1000 GeV, Inert Higgs doublet, Right-handed neutrino, … Non-WIMP: Axion.

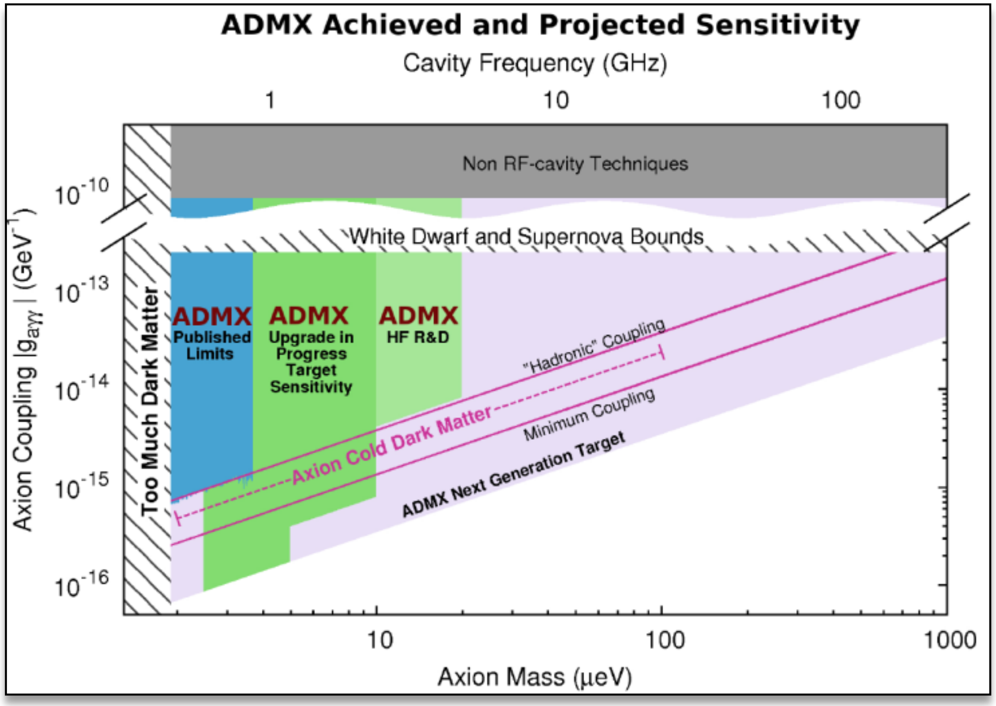
The axion

’t Hooft (1976) pointed out that in the presence of instantons the QCD action is modified with a CP-violating piece (which from experiment, e.g. the EDM of the neutron, is known to be very small):

$$S^q_{eff} = \int d^4x \mathcal{L}_{QCD} + i\theta q \qquad\qquad q = \frac{g_s^2}{32\pi^2}\int G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}d^4x$$

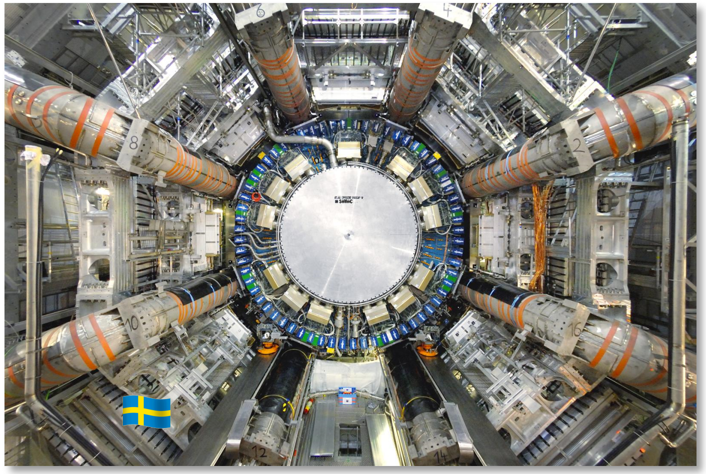
Peccei & Quinn (1977); Weinberg (1978) and Wilczek (1978): Introduce Goldstone-like pseudoscalar field. Very weakly coupled, but behaves like Cold Dark Matter. Modifications (Kim; Shifman, Vainshtein & Zakharov, 1980; Dine, Fischler & Srednicki, 1981) made the axion ”invisible”, but Sikivie (1983) showed that the 2-photon coupling could be used to resonantly convert an axion to a photon in a strong, inhomogeneous magnetic field.

The ADMX experiment in Seattle (L. Rosenberg & al.), will have a greatly improved sensitivity to axions DM (2014-).

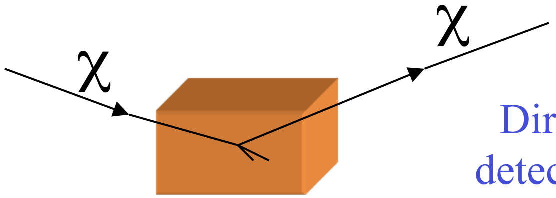


Methods of **WIMP** Dark Matter detection:

- Discovery at accelerators (Fermilab, LHC, ILC…), if kinematically allowed. Can give mass scale, but no proof of required long lifetime.
- Direct detection of halo dark matter particles in terrestrial detectors. (J. Goodman & E. Witten, 1985)
- Indirect detection of particles produced in dark matter annihilation: neutrinos, gamma rays & other e.m. waves, antiprotons, antideuterons, positrons in ground- or space-based experiments. (J. Silk & M.Srednicki, 1984)
- For a convincing determination of the identity of dark matter, plausibly need detection by at least two different methods. For most methods, the background problem is very serious.



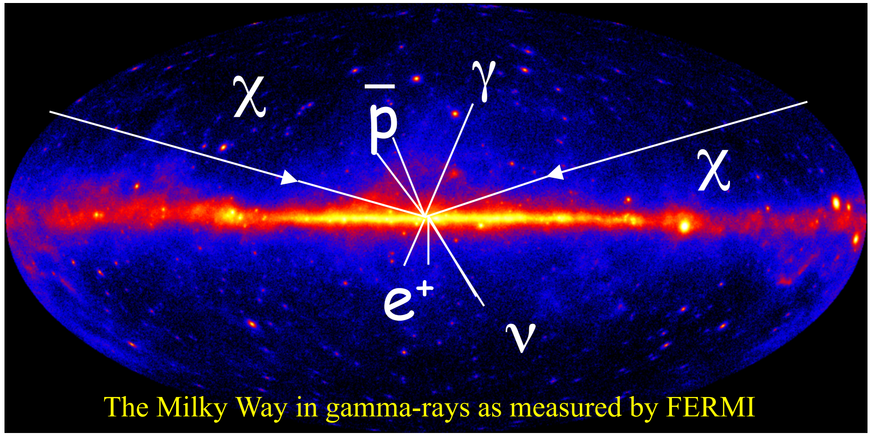
CERN LHC/ATLAS



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 in gamma-rays as measured by FERMI

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

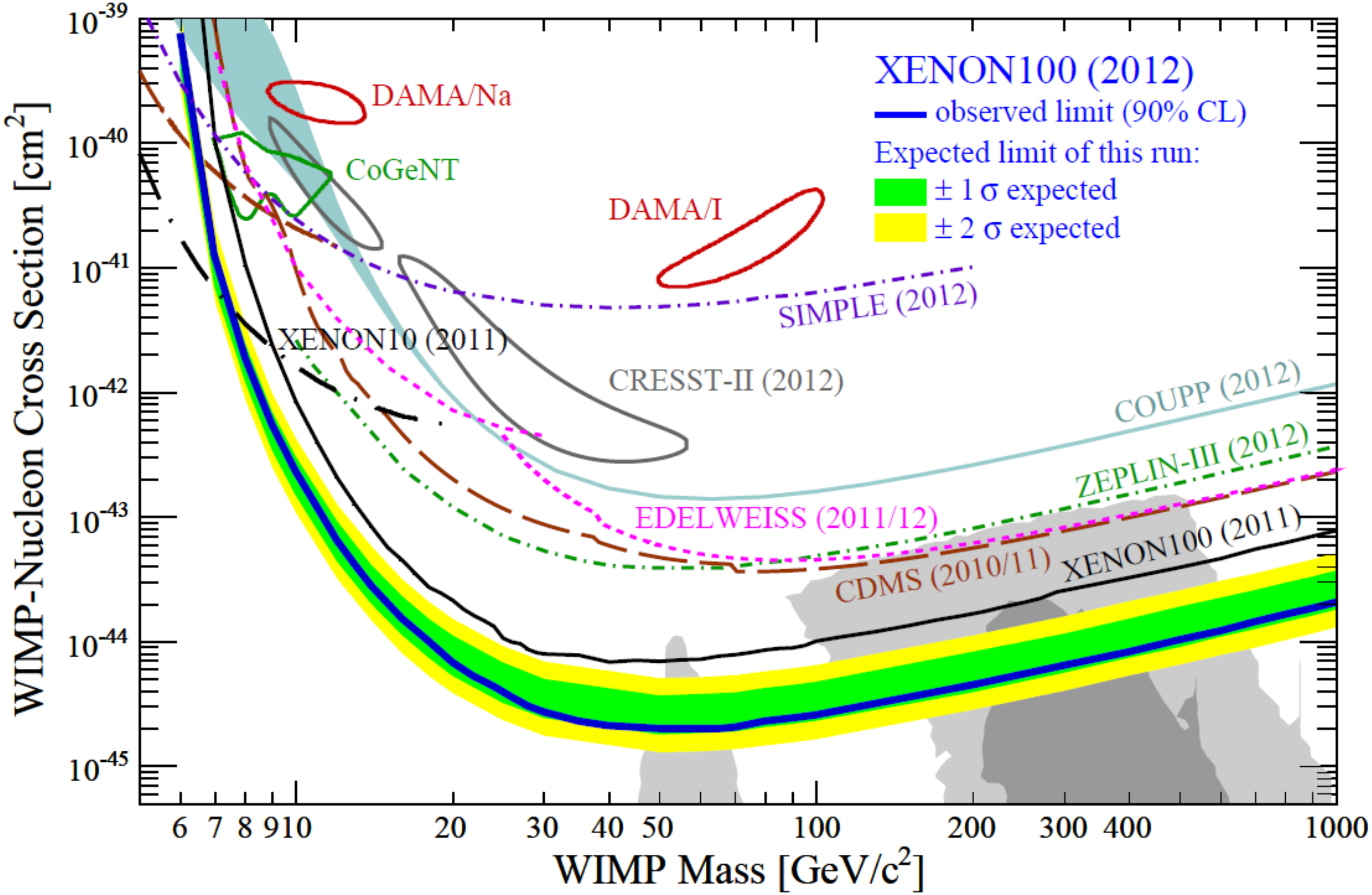
Annihilation rate enhanced for clumpy halo; near galactic centre and in subhalos, also for larger systems like galaxy clusters, cosmological structure (as seen in N-body simulations).

Direct and indirect detection of DM:
There have been many (false?) alarms during the last decade. Many of these phenomena would need contrived (non-WIMP) models for a dark matter explanation.

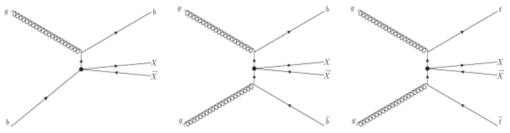
Indication	**Status**
DAMA annual modulation	Unexplained at the moment – in tension with other experiments
CoGeNT and CRESST excess events	Tension with other experiments (CDMS-II, XENON100)
EGRET excess of GeV photons	Due to instrument error (?) - not confirmed by Fermi-LAT collaboration
INTEGRAL 511 keV γ-line from galactic centre	Does not seem to have spherical symmetry - shows an asymmetry following the disk (?)
2009: PAMELA: Anomalous ratio e^+/e^-	May be due to DM, or pulsars - energy signature not unique for DM
Fermi-LAT positrons + electrons	May be due to DM, or pulsars - energy signature not unique for DM
Fermi-LAT γ-ray continuum excess around a few GeV, towards g.c.	Unexplained at the moment – very messy astrophysics
2012: Fermi 130 GeV line (T. Bringmann & al.; C.Weniger ; M. Su & D.Finkbeiner; A.Hektor & al.)	3.1σ – 4.6σ effect, using public data, unexplained, not confirmed by Fermi-LAT
2013, April 3: AMS-02 (S.T.T. Ting & al.) Rising positron ratio confirmed – maybe DM?	May be due to DM, or pulsars - energy signature not unique for DM
2013, April 15: CDMS Si data: 3 events, best fit DM mass is 8.6 GeV	CDMS had 2 events a few years ago, turned out to be background. "… we do not believe this result rises to the level of discovery."

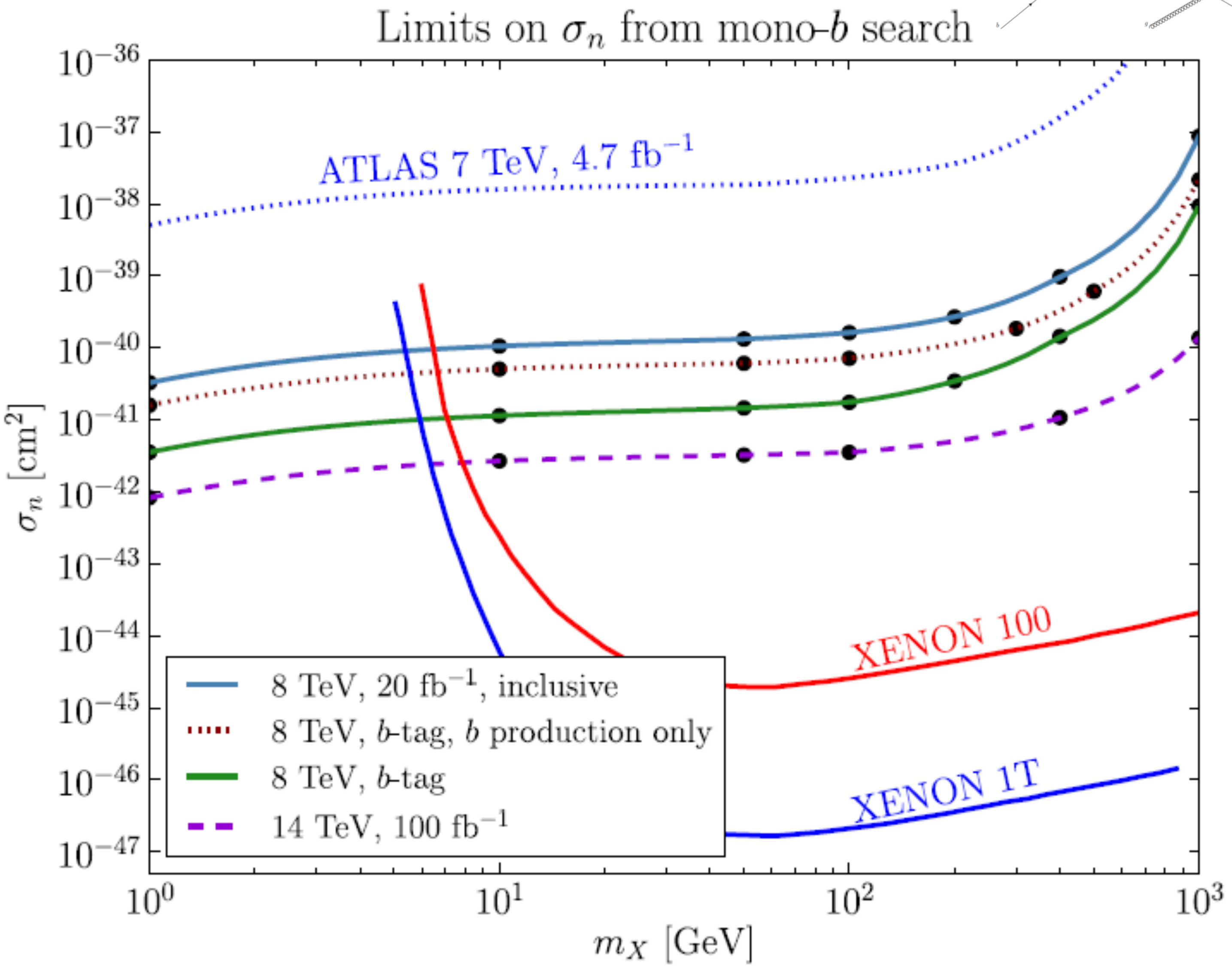
Direct detection limits, Xenon100 data, 2012:

CoGeNT and DAMA seem well excluded…



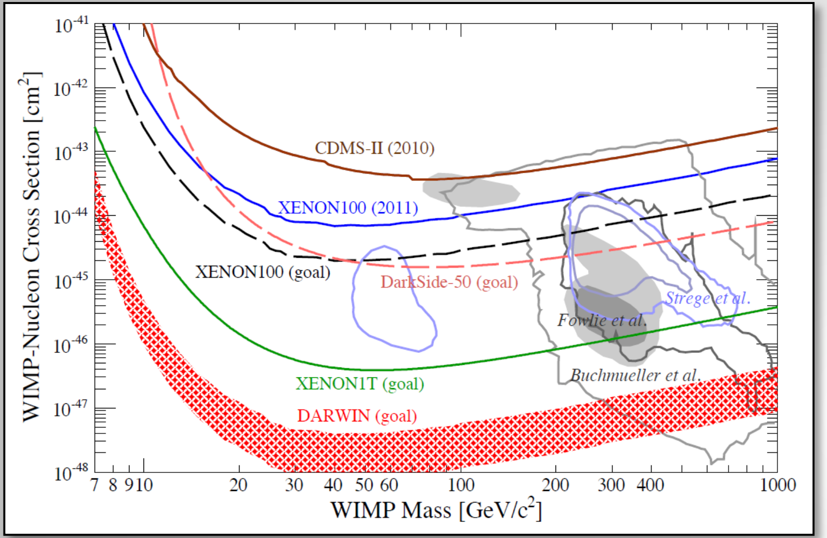
LHC limits may be complementary at low masses:



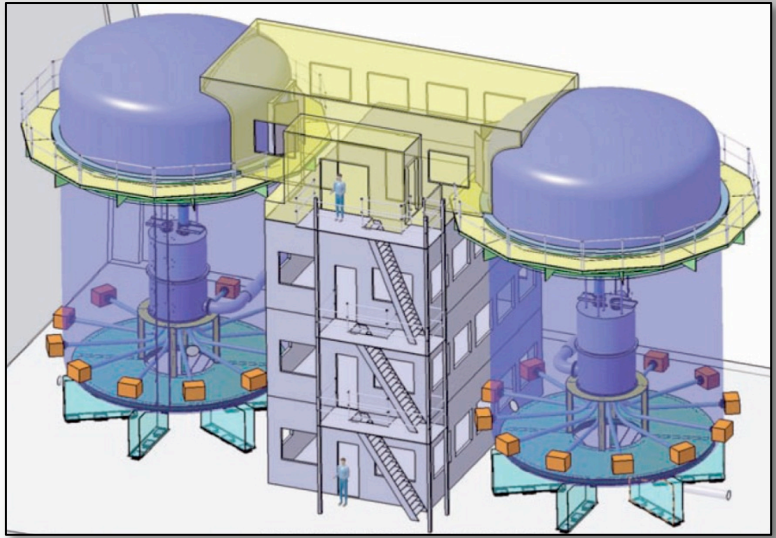

Limits on σ_n from mono-b search

T. Lin, E.W. Kolb & L.-T. Wang, 1303.6638

Direct detection, future:

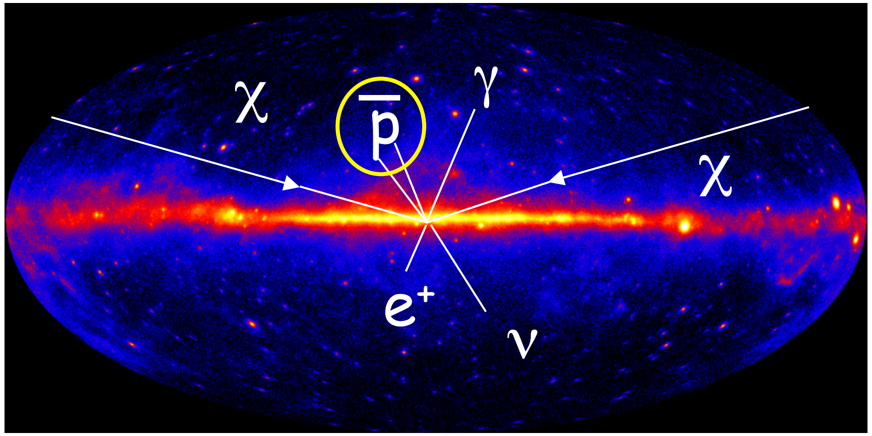


Darwin Collaboration, L. Baudis & al., 2012



EURECA Collaboration, G. Gerbier & al., 2012

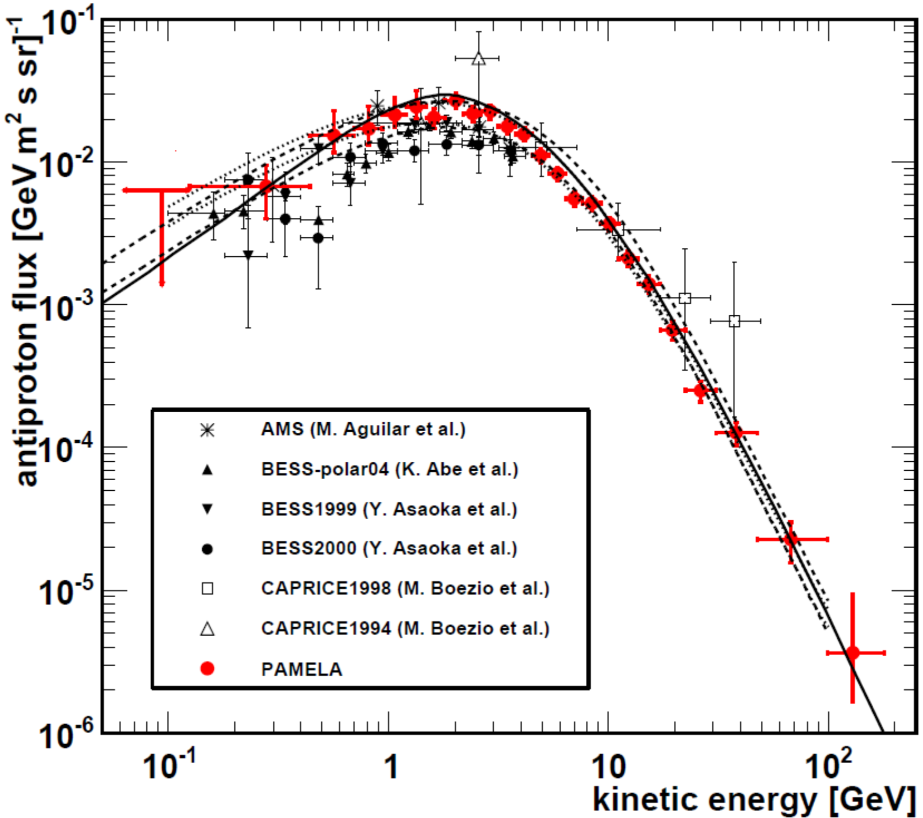
The improvement in sensitivity over the last ~ 15 years has been spectacular (factor of ~ 10 000), and future looks equally promising.

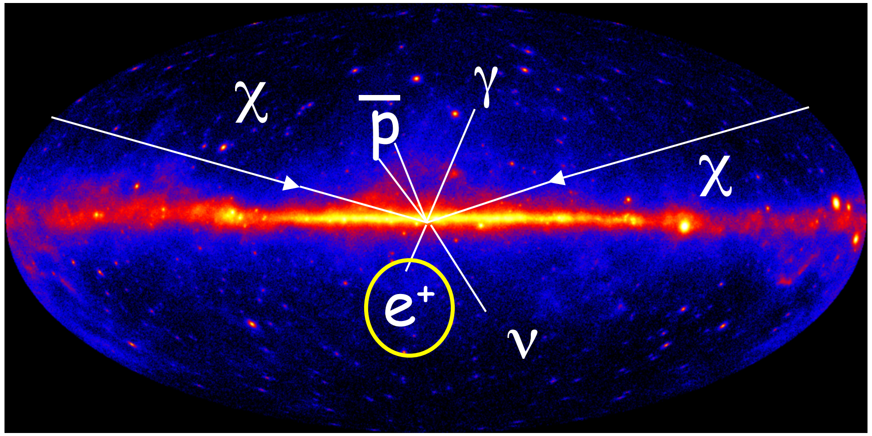


Antiprotons

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

However, p-He reactions and energy losses due to scattering of antiprotons ⇒ low-energy gap is filled in. BESS, AMS, CAPRICE and PAMELA data are compatible with conventional production by cosmic rays. Antideuterons may be a better signal – but rare. (Donato, Fornengo & Salati, 2000; R. Ong & al., GAPS, 2013)





Positrons

The Astrophysical part for positrons has some uncertainty (faster energy loss than antiprotons):
Diffusion equation (see, e.g., Baltz and Edsjö, 1999; T. Delahaye & al., 2010):

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

Energy-dependent diffusion coefficient

Energy loss (mostly synchrotron and Inverse Compton)

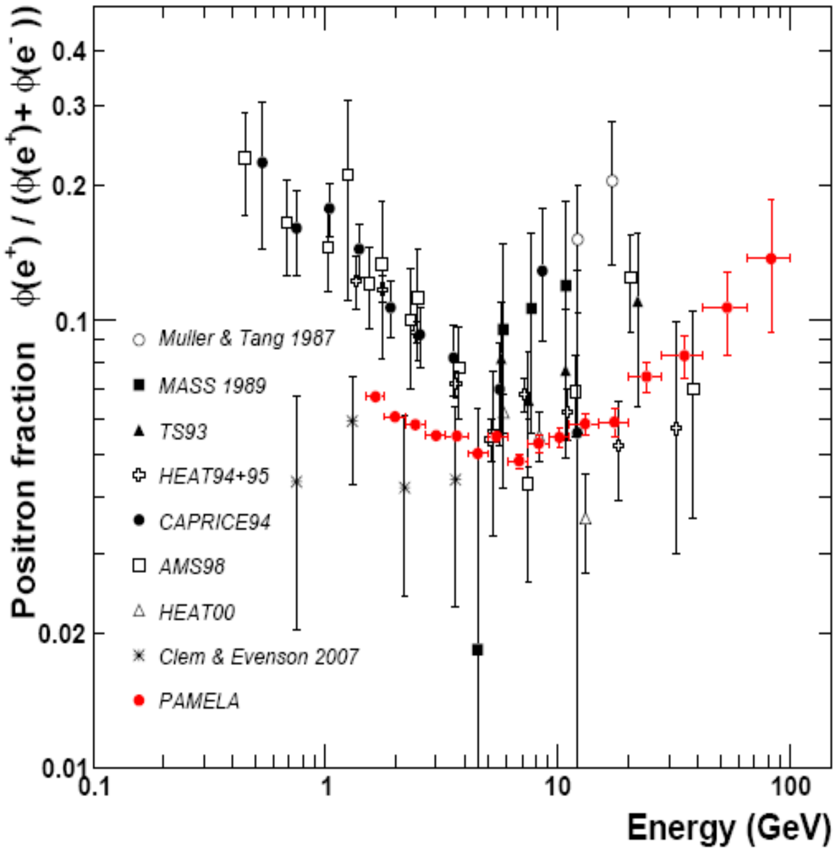
Source term (from dark matter annihilation or e.g. pulsars)

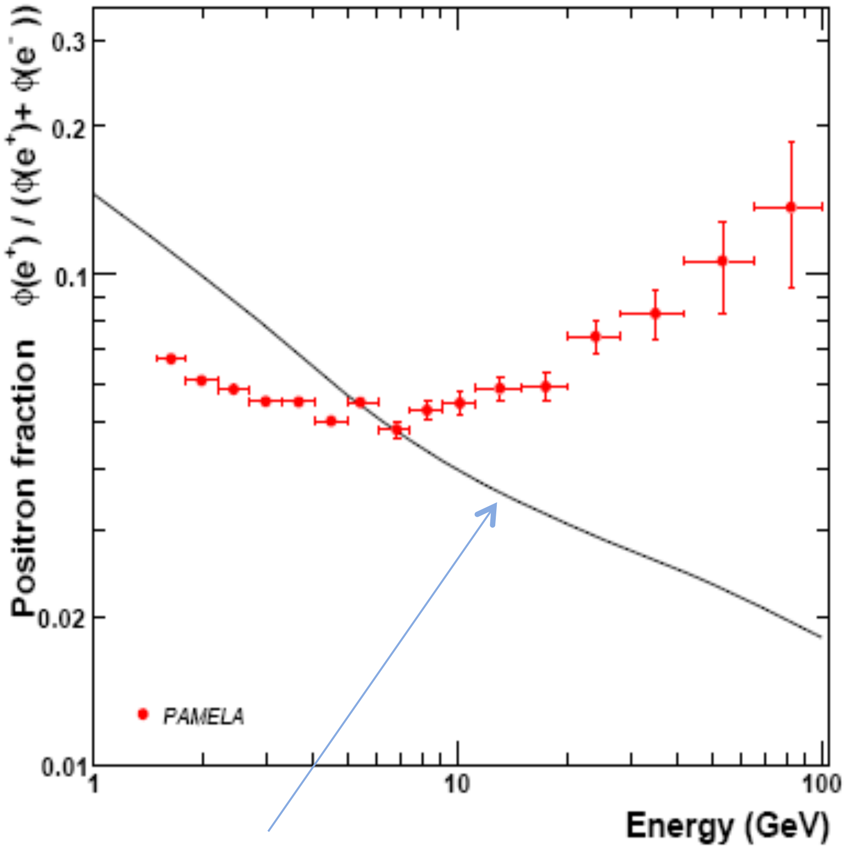
$$\begin{aligned} b(E) &= 10^{-16}(E/1\ \mathrm{GeV})^2 \quad (\mathrm{GeVs}^{-1}) \\ K(E) &= 3.3\times 10^{27}\left[3^{0.6} + (E/1\ \mathrm{GeV})^{0.6}\right] \quad (\mathrm{cm}^2\mathrm{s}^{-1}) \end{aligned}$$

Can be calibrated by fitting light element ratios in cosmic rays.

The surprising PAMELA data on the positron ratio up to 100 GeV.
(O. Adriani et al., Nature 458, 607 (2009))

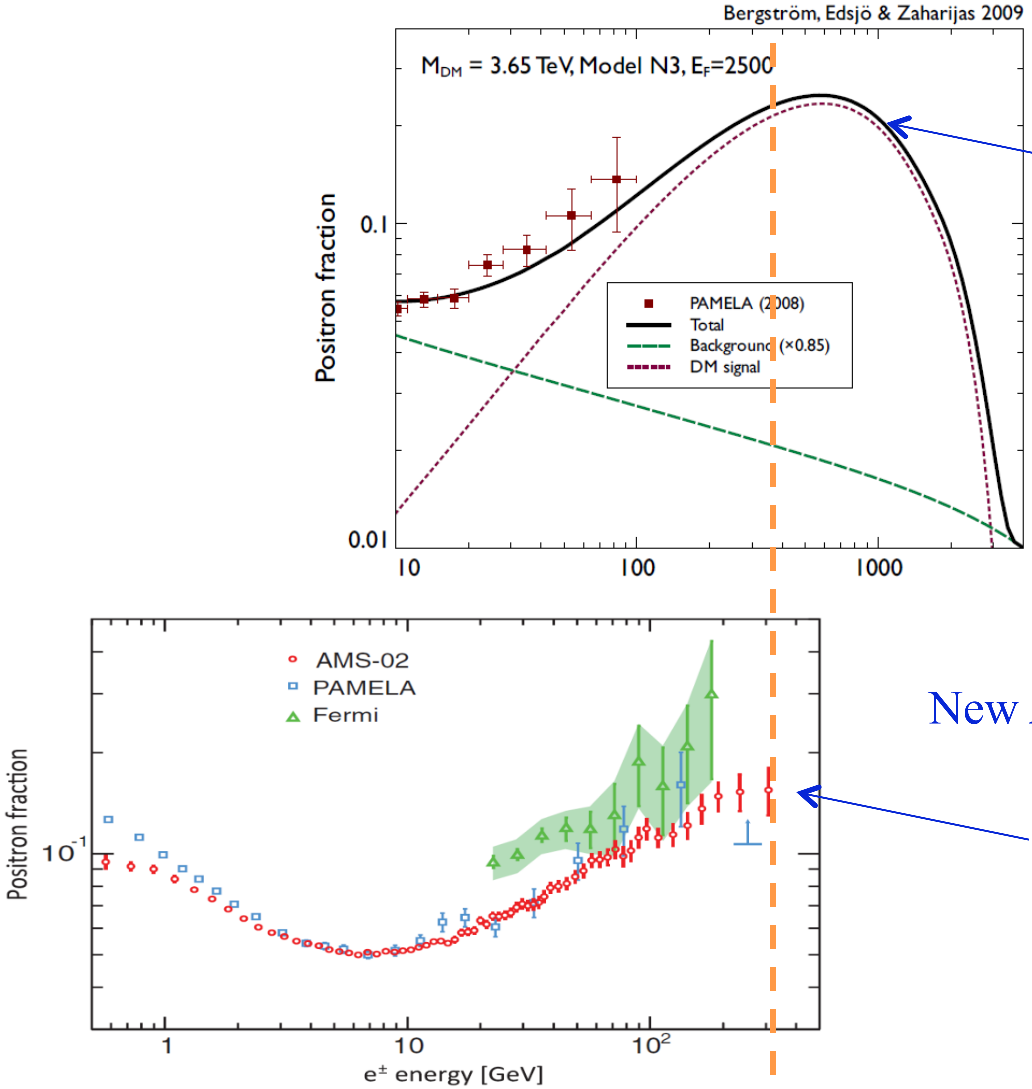
A very important result. An additional, primary source of positrons seems to be needed.





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

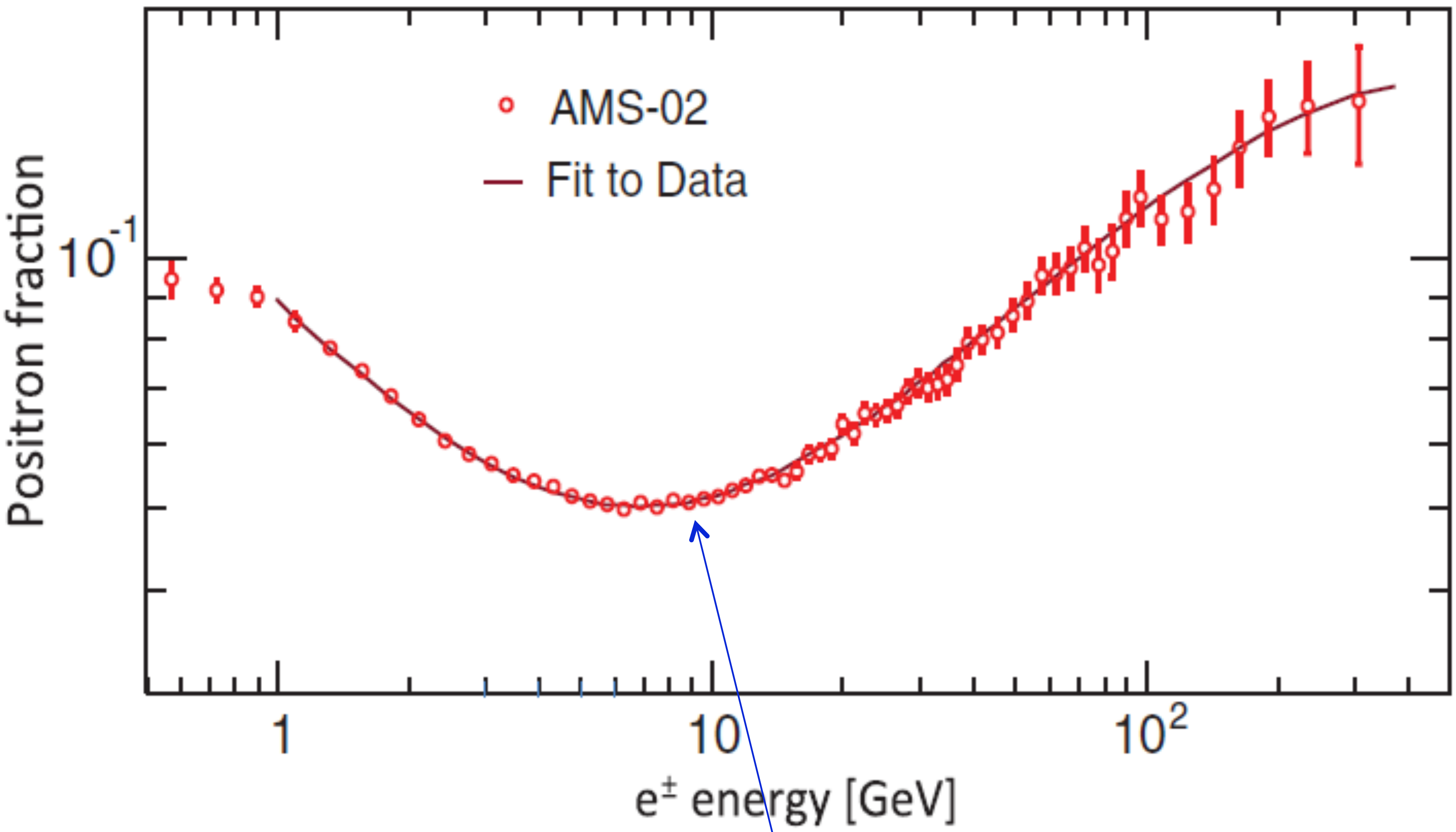
L.B., J. Edsjö, G. Zaharijas, 2009:



Prediction:
fall-off after rise
(Note very large mass,
M_{DM} = 3.65 TeV, and
”boost factor”, E_f =
2500, needed.)

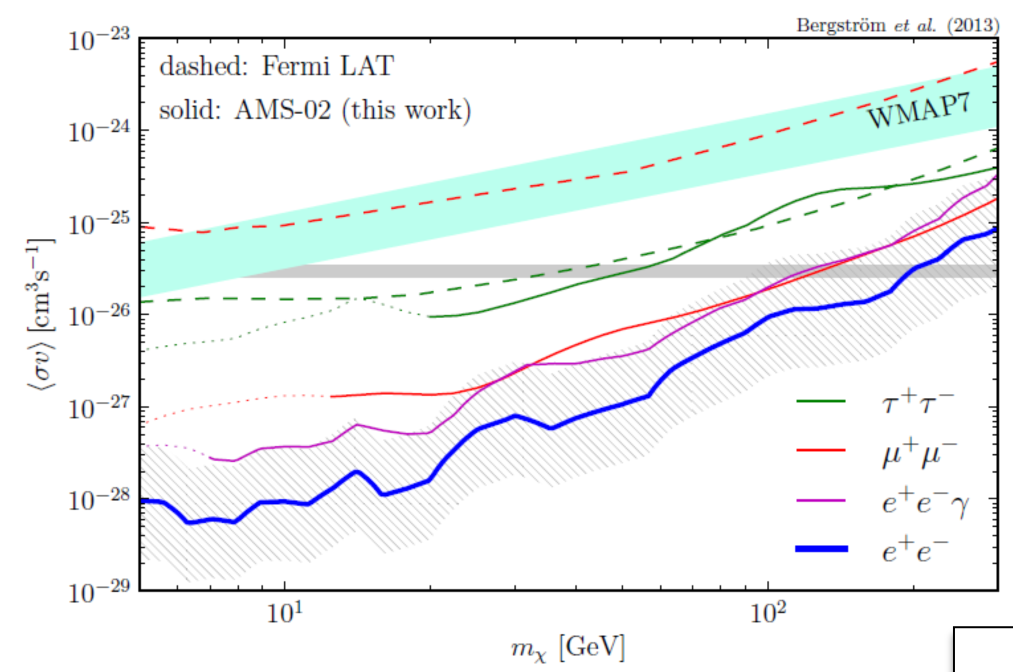
New AMS-02 data 2013

Indications of a
fall-off?



Note high precision of the AMS-02 data.

The experiment will give data for 18 more years…



The precison of the AMS-02 data allow stringent limits on Dark Matter annihilation to positrons, muons, and taus. (L. Bergström, T. Bringmann, I. Cholis, D.Hooper & C. Weniger, 2013.)

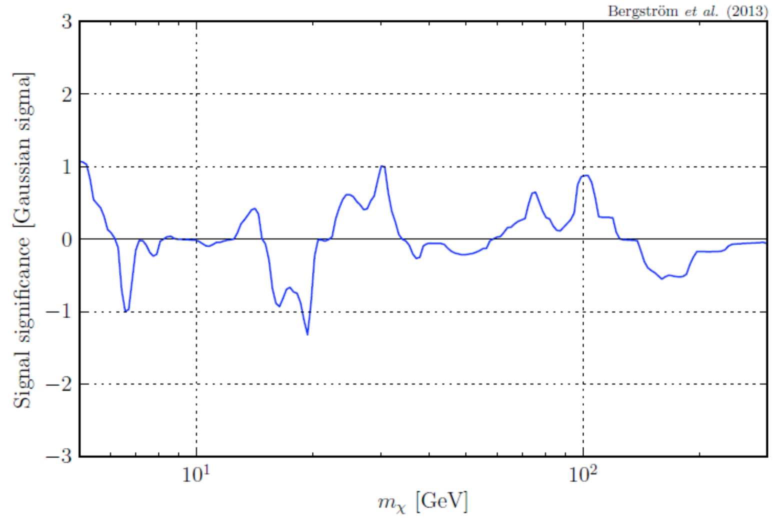
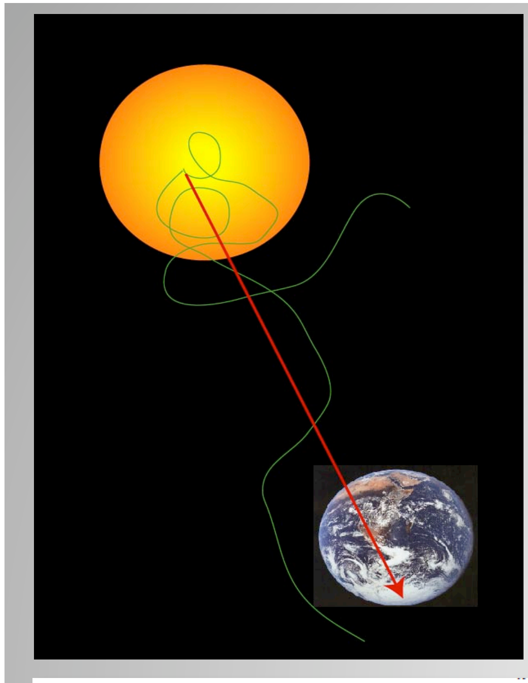


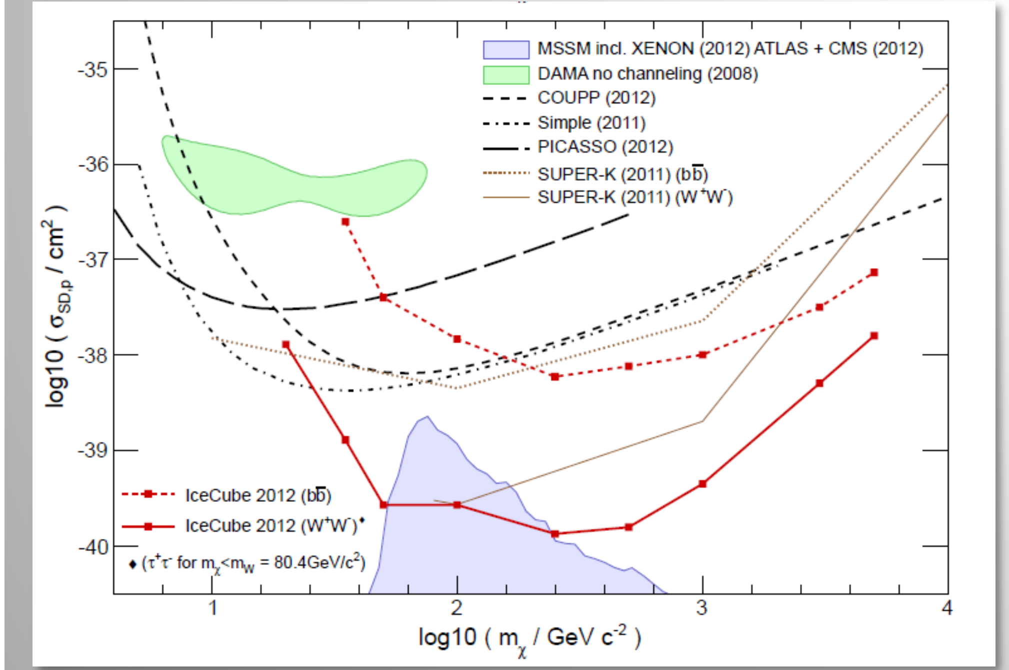
FIG. 6. Significance for a contribution from a e^+e^- DM signal to the AMS-02 positron fraction, for different DM energies, in units of Gaussian sigma. Negative values correspond to negative (but unphysical) signal normalizations.

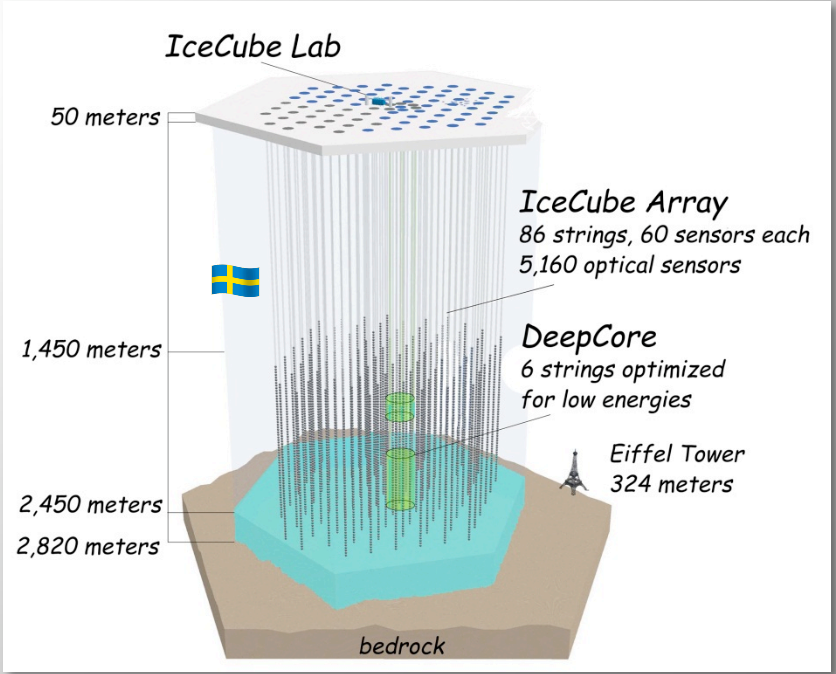
One can also search for ”bumps”, none found so far – wait and see…



Indirect detection by neutrinos from annihilation in the Sun:

Competitive, due to high proton content of the Sun ⇒ sensitive to spin-dependent interactions. With IceCube-79 and DeepCore-6 operational now, a large new region will be probed.





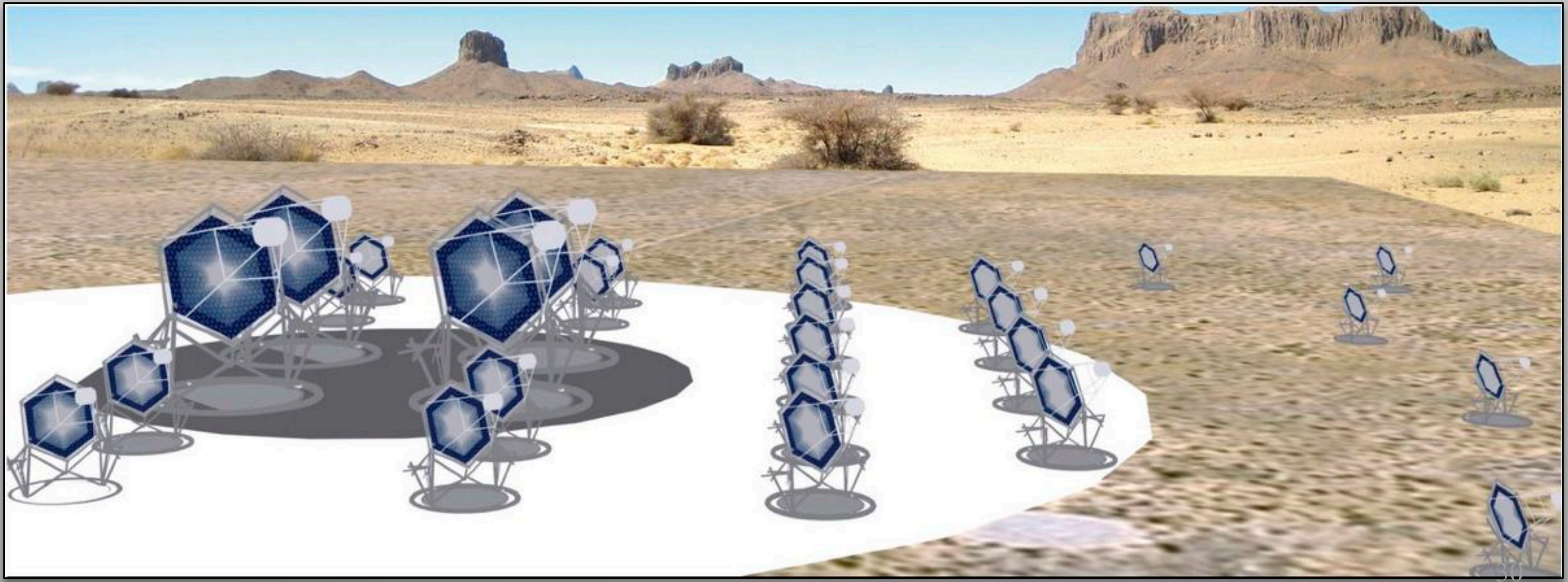
IceCube Collaboration, Phys.Rev.Lett. 110 (2013) 131302

Indirect detection through γ-rays from DM annihilation

Fermi-LAT (Fermi Large Area Telescope)

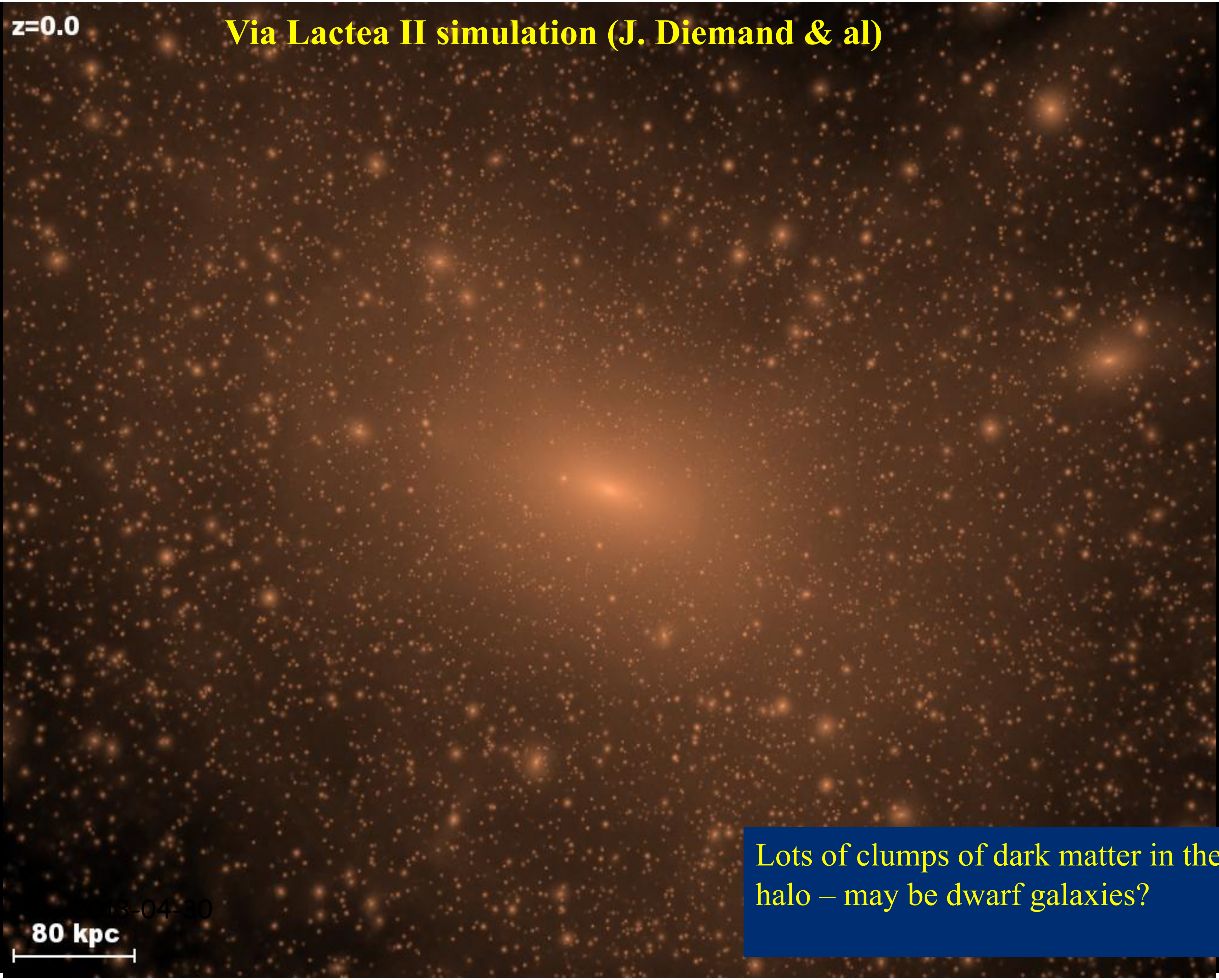
H.E.S.S. & H.E.S.S.-2

VERITAS



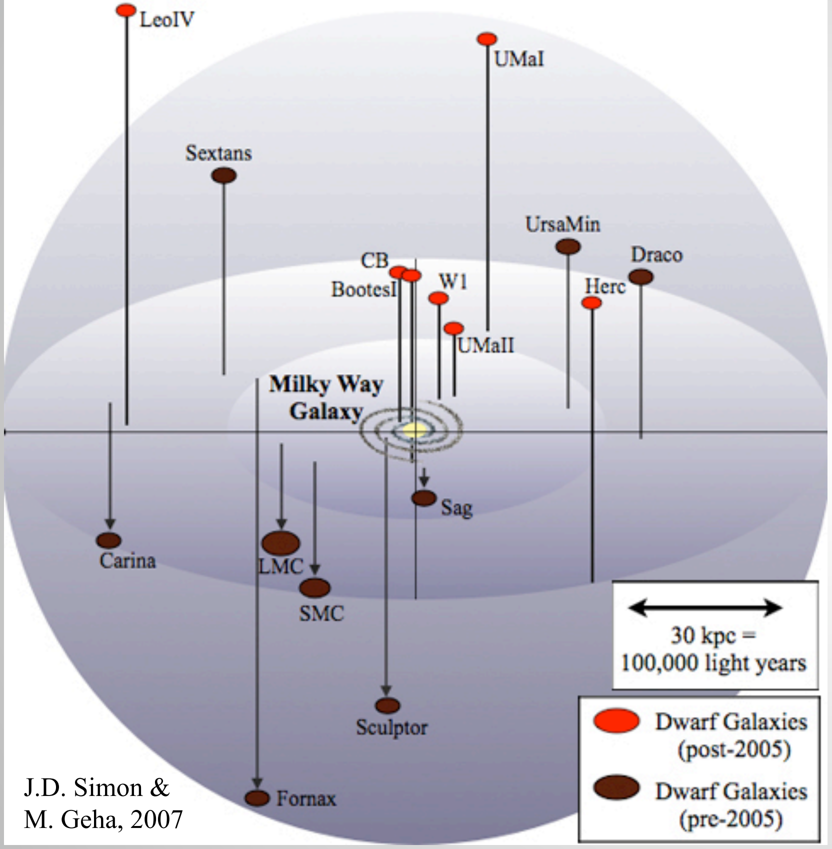
CTA (Cherenkov Telescope Array)

Via Lactea II simulation (J. Diemand & al)



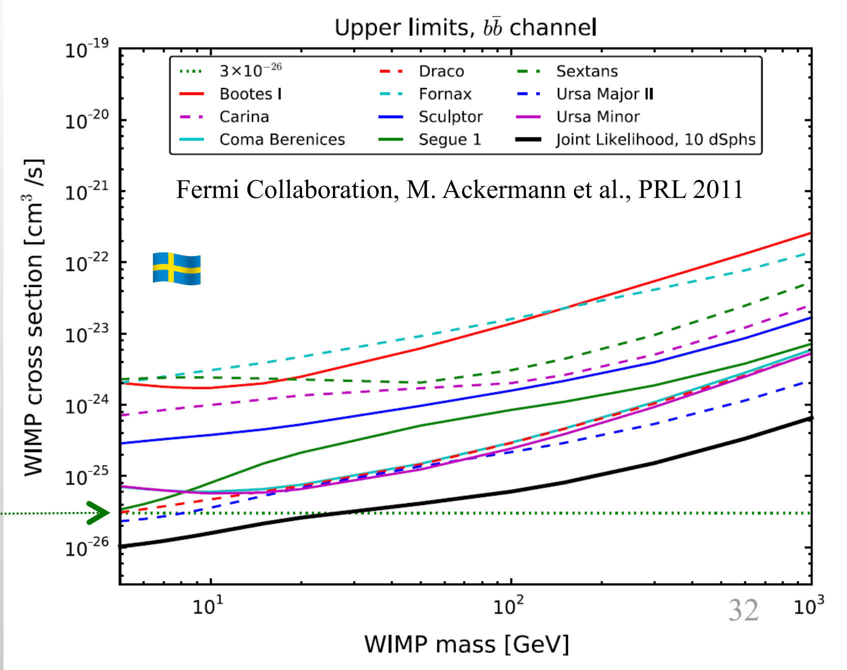
Lots of clumps of dark matter in the halo – may be dwarf galaxies?

New promising experimental DM detection method: Stacking data from many dwarf galaxies, FERMI Collaboration; Maja Garde & Jan Conrad from OKC, (Phys. Rev. Letters, December, 2011). Update soon to be published.



J.D. Simon & M. Geha, 2007

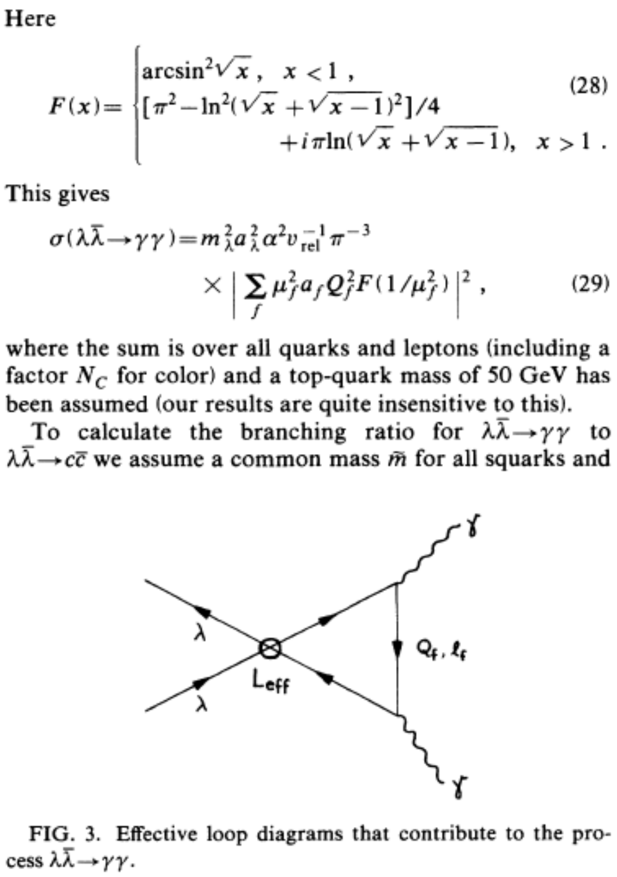
By stacking the data, sensitivity to the dark matter distribution may be minimized



Fermi Collaboration, M. Ackermann et al., PRL 2011

”Canonical” WIMP cross section

A ”smoking gun”? - the gamma-ray line (L.B. & H. Snellman, 1988; L.B. & P. Ullio, 1997):



Here

$$F(x)=\begin{cases}\arcsin^2\sqrt{x}\,, & x<1\,,\\ [\pi^2-\ln^2(\sqrt{x}+\sqrt{x-1})^2]/4 & \\ \quad +i\pi\ln(\sqrt{x}+\sqrt{x-1}), & x>1\,.\end{cases} \tag{28}$$

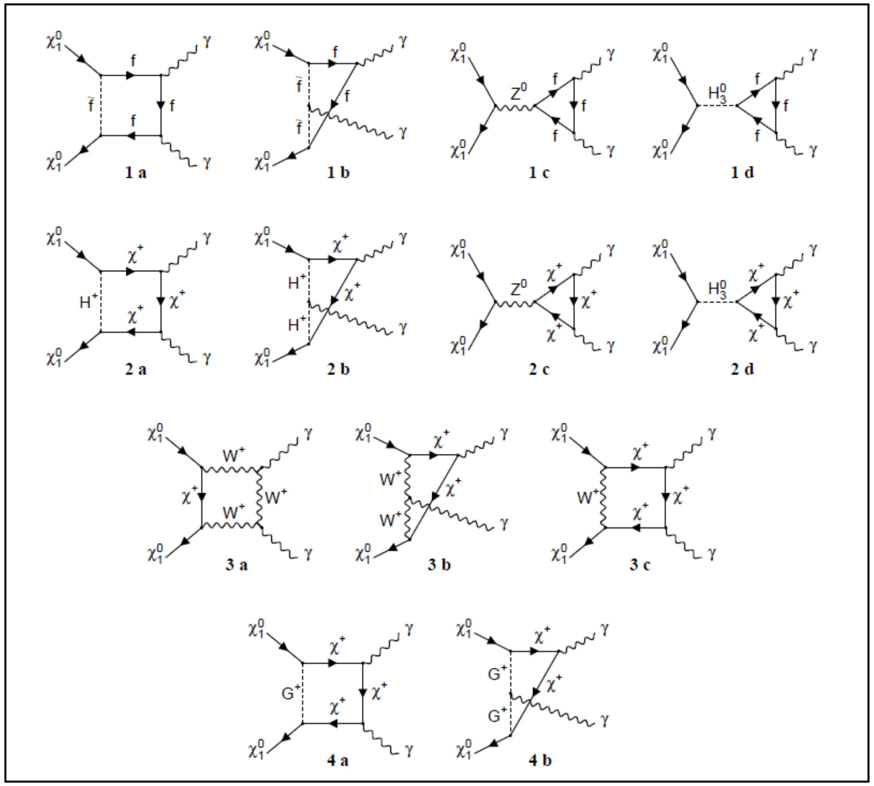
This gives

$$\sigma(\lambda\bar{\lambda}\rightarrow\gamma\gamma)=m_\lambda^2 a_\lambda^2\alpha^2 v_{\mathrm{rel}}^{-1}\pi^{-3} \times\left|\sum_f \mu_f^2 a_f Q_f^2 F(1/\mu_f^2)\right|^2 , \tag{29}$$

where the sum is over all quarks and leptons (including a factor N_C for color) and a top-quark mass of 50 GeV has been assumed (our results are quite insensitive to this).

To calculate the branching ratio for $\lambda\bar{\lambda}\rightarrow\gamma\gamma$ to $\lambda\bar{\lambda}\rightarrow c\bar{c}$ we assume a common mass $\tilde{m}$ for all squarks and

FIG. 3. Effective loop diagrams that contribute to the process $\lambda\bar{\lambda}\rightarrow\gamma\gamma$.

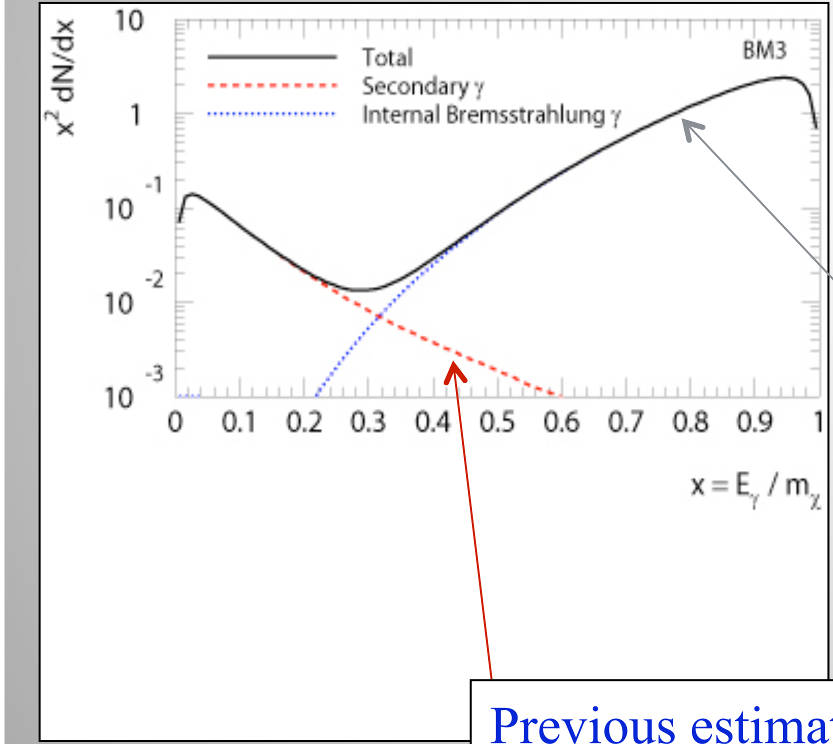


L.B. & H. Snellman, Phys. Rev. D (1988)

L.B. & P. Ullio, Nucl. Phys. B (1997)

Quantum ”corrections” (Internal Bremsstrahlung) in the MSSM – a way to avoid helicity suppression in annihilation to fermions: good news for detection in gamma-rays:

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

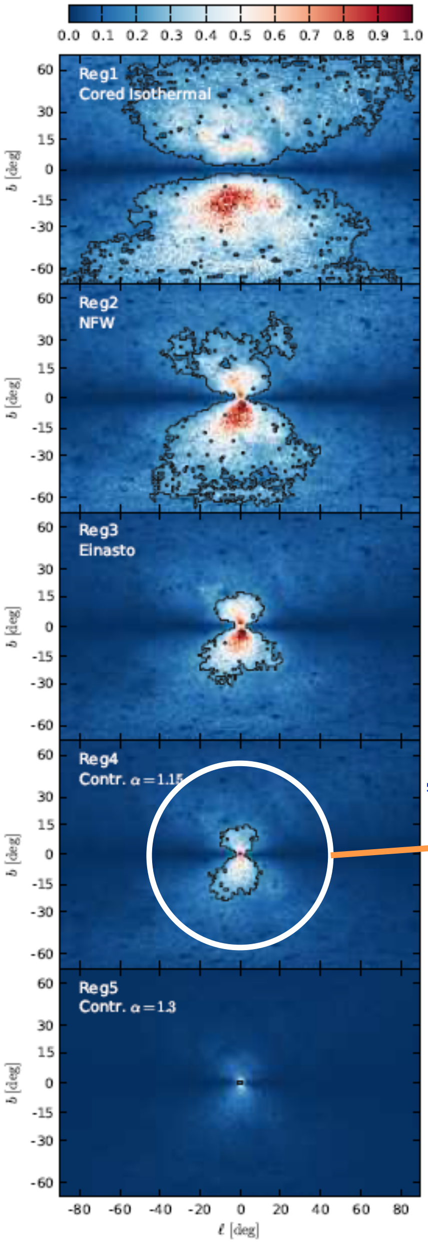


Example: DM mass = 233 GeV, has WMAP-compatible relic density (stau coannihilation region).

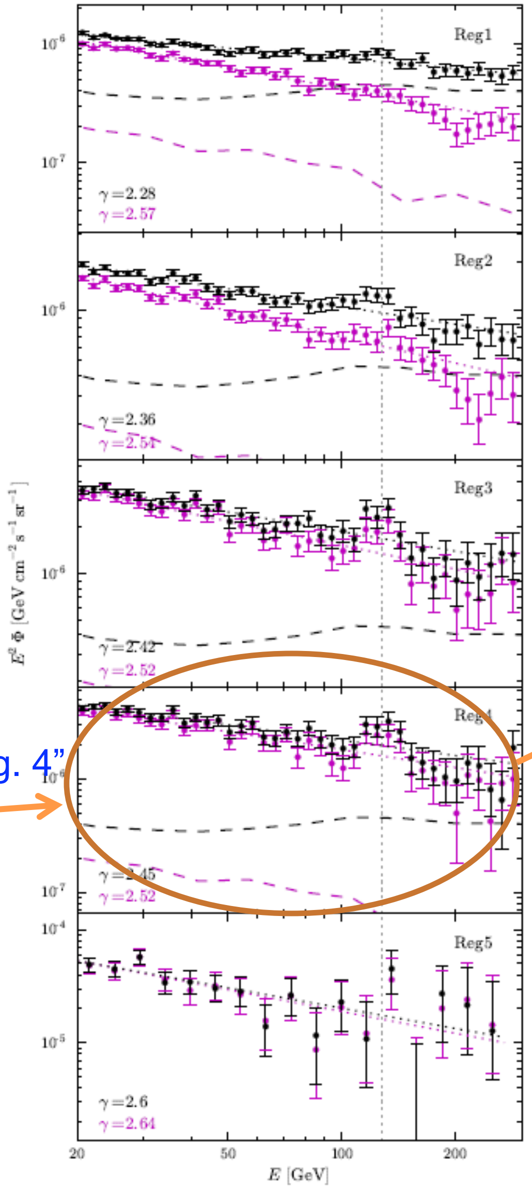
Calculation including Internal Bremsstrahlung (DarkSUSY 5.1).

Previous estimate of gamma-ray spectrum

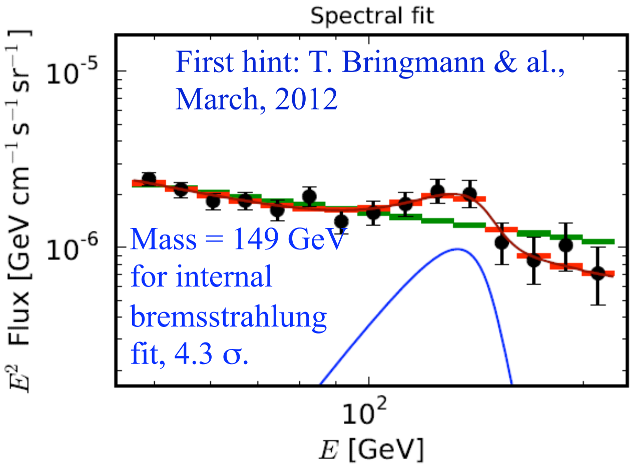
April, 2012: C. Weniger



43 months of (public) Fermi data

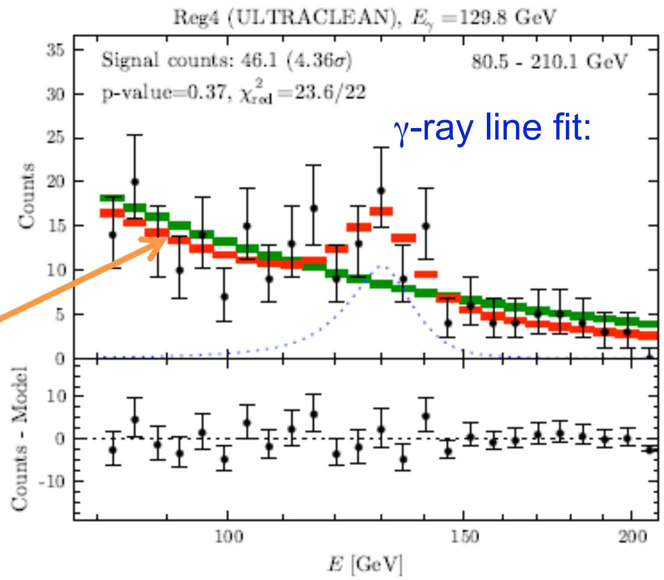


"Reg. 4"



First hint: T. Bringmann & al., March, 2012

Mass = 149 GeV for internal bremsstrahlung fit, 4.3 σ.



γ-ray line fit:

Mass = 130 GeV
Significance 4.6σ (3.3σ if "look elsewhere" effect included)

There have been some 60-70 ”postdictions” of this gamma-ray signature (2012-13). Was anything like this predicted? Yes, example: A leptonic WIMP – a ”LIMP”.

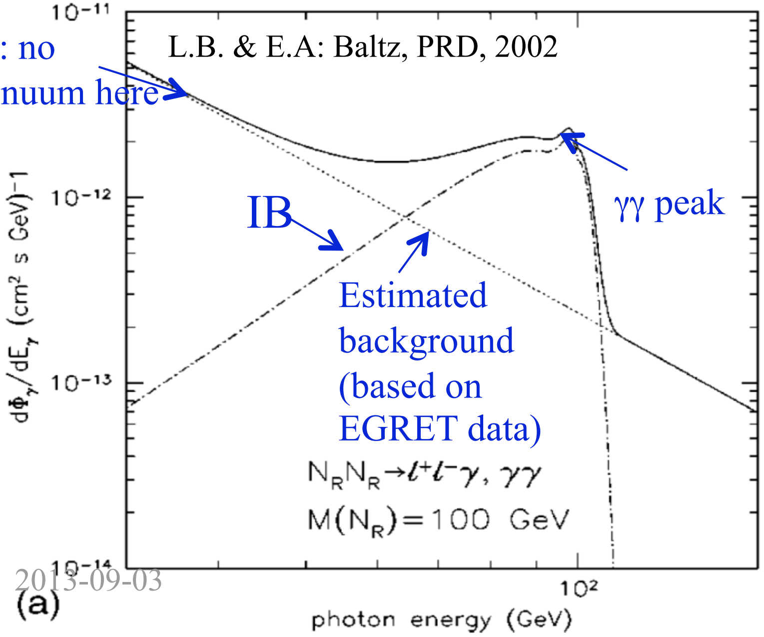
E.A. Baltz & L.B., Phys Rev D, 2002. Well motivated candidate from particle physics: The right-handed neutrino N_R (in ”radiative see-saw” models) as the dark matter candidate – May explain observed ~ 0.1 eV neutrino masses, also muon g-2 anomaly & baryon asymmetry of universe. Internal bremsstrahlung plus γγ and Zγ annihilation will give a peculiar spectrum:

$$\sigma v\left(N_R N_R \to \ell^+\ell^-\right) = \frac{g_\ell^4}{8\pi m_N^4 (1+f^2)^2}\left[\underset{\uparrow}{m_\ell^2} + \underbrace{\frac{2}{3}\left(\frac{1+f^4}{(1+f^2)^2}\right) m_N^2 v^2} + \dots\right]$$

S wave part determines the lowest order cross section today

P wave part sets relic WIMP density in early universe

$f = m_S/m_N$

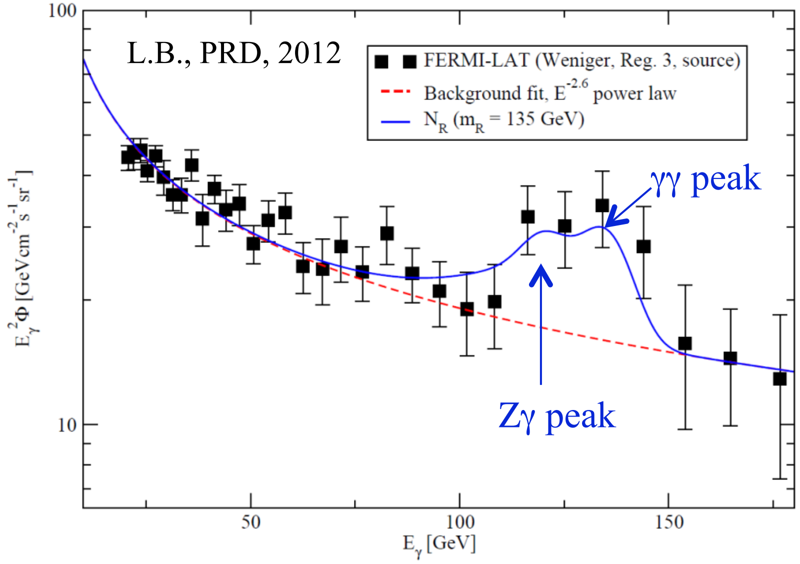


Note: no continuum here

IB

γγ peak

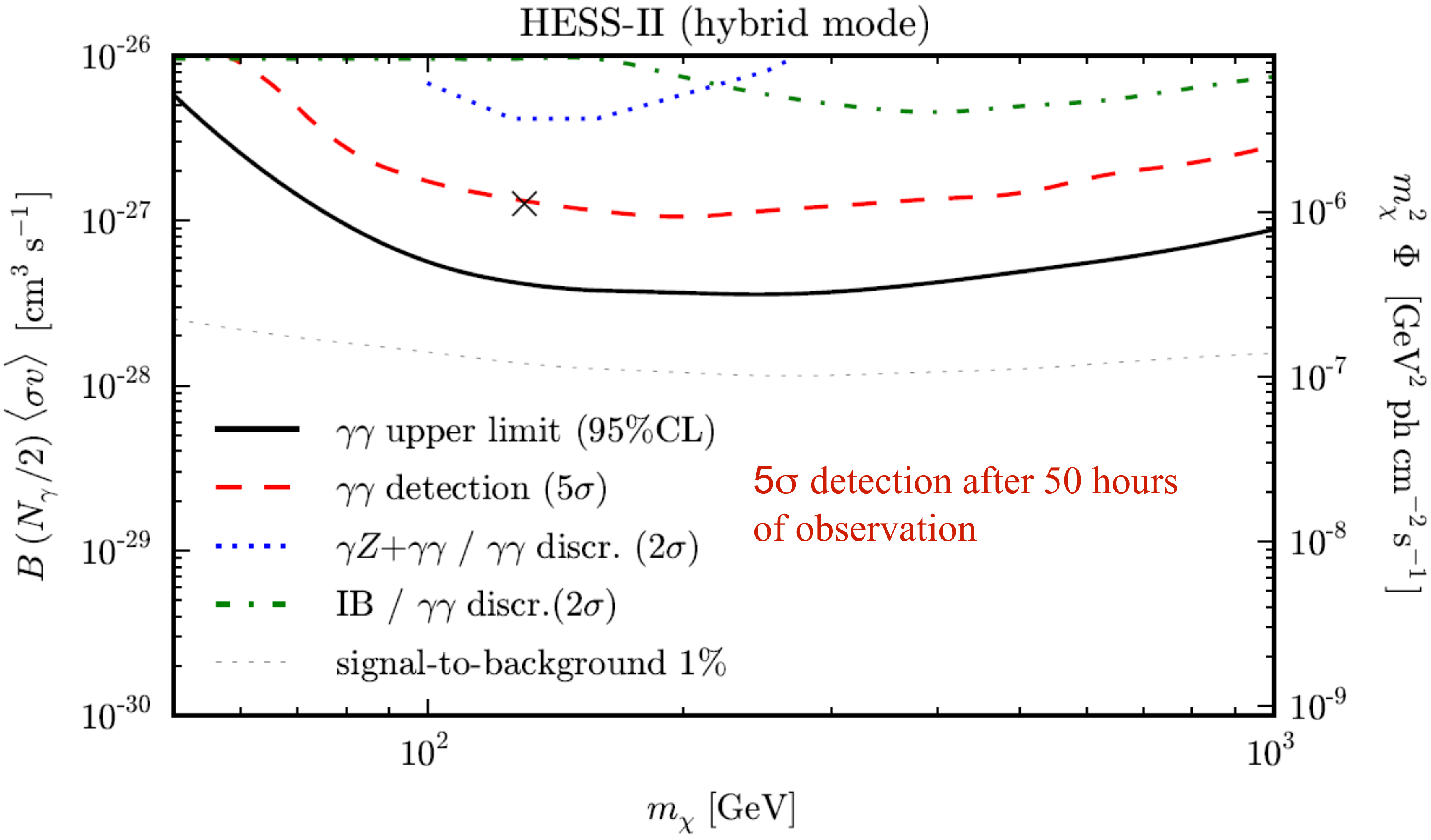
Estimated background (based on EGRET data)



γγ peak

Zγ peak

L.B., G. Bertone, J. Conrad, C. Farnier & C. Weniger, 2012:



5σ detection after 50 hours of observation

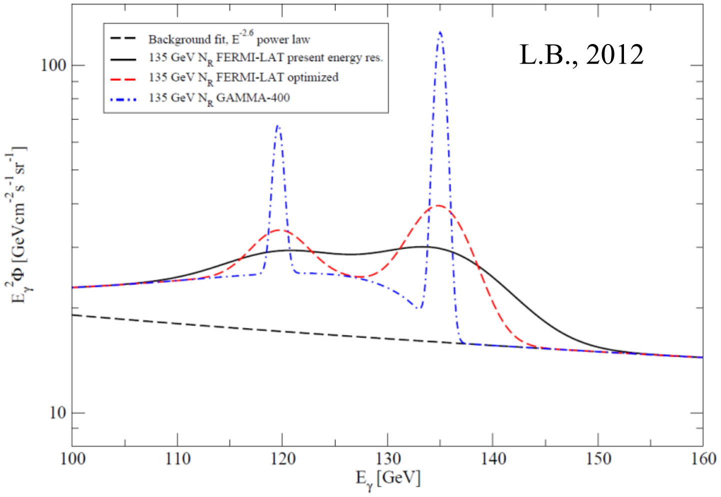
The future for gamma-ray space telescopes:

GAMMA-400, 100 MeV – 3 TeV, an approved Russian γ-ray satellite. Planned launch 2017-18 (an Oskar Klein Centre group will participate).
Energy resolution (100 GeV) ~ 1 %. Effective area ~ 0.4 m^2 . Angular resolution (100 GeV) ~ 0.01°

DAMPE: Satellite of similar performance. An approved Chinese γ-ray satellite. Planned launch 2015-16.

HERD: Instrument on Chinese Space Station. Energy resolution (100 GeV) ~ 1 %. Effective area ~ 1 m^2. Angular resolution (100 GeV) ~ 0.01°. Planned launch around 2020.

All three have detection of dark matter as one key science driver



Ideal, e.g., for looking for spectral DM-induced features, like searching for γ-ray lines! If the 130 - 135 GeV structure exists, it should be seen with more than 10σ significance (L.B. & al., JCAP 2012). Otherwise, the parameter space of viable models will be probed with unprecedented precision.

Conclusions

- There are many experimental DM indications – none is not particularly convincing at the present time.

- Fermi-LAT already has competitive limits for low masses, but maybe indications of line(s) and/or internal bremsstrahlung at 130 - 135 GeV. We will soon know whether it is a real effect.

- IceCube has a window of opportunity for spin-dependent DM scattering.

- The field is entering a very interesting period: CERN LHC has been running at 8 TeV at full luminosity, and in a couple of years at 14 TeV; XENON 1t is being installed; IceCube and DeepCore are operational; Fermi will collect at least 5 more years of data; AMS-02 will collect data for 18 more years, CTA, Gamma-400, DAMPE and HERD may operate by 2018, and perhaps even a dedicated DM array, DMA some years later.

- However, as many experiments now enter regions of parameter space where a DM signal *could* be found, we also have to be prepared for false alarms.

- These are exciting times for dark matter searches !