Five Aspects of Dark Matter

Michel H.G. Tytgat
Brussels University, Belgium

Talk at Brookhaven National Laboratory, April 14th 2009

I. Why Dark Matter ?

II. How Much Dark Matter ?

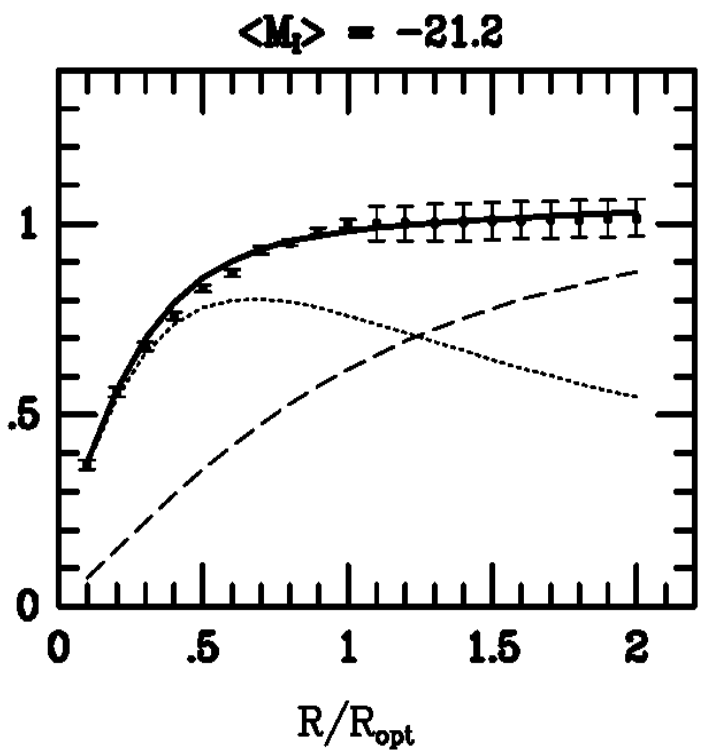
III. Which Dark Matter ?

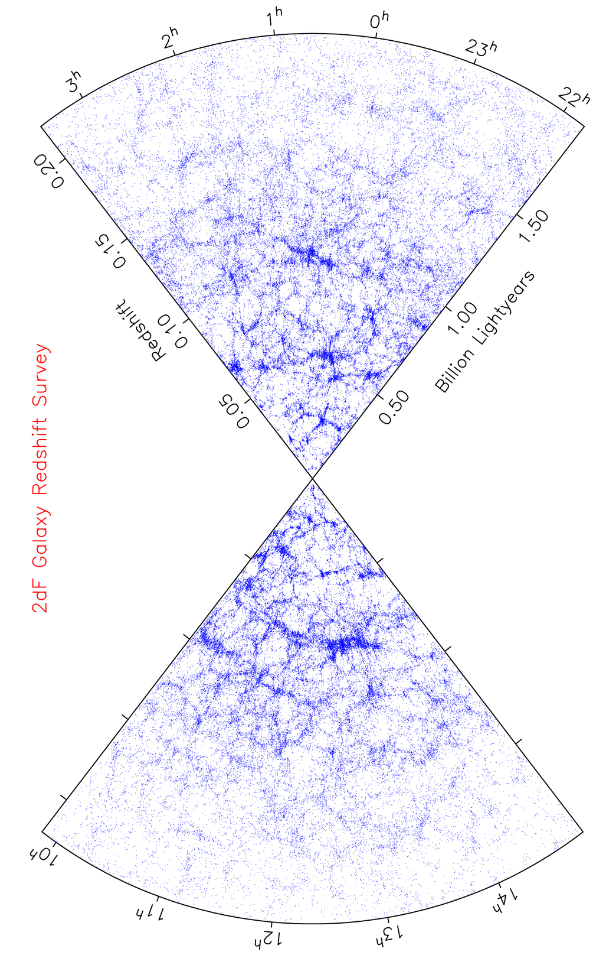
IV. Dark Matter and the Defeat of Antimatter

V. Dark Matter Seen ?

I. Why Dark Matter?

Confidence

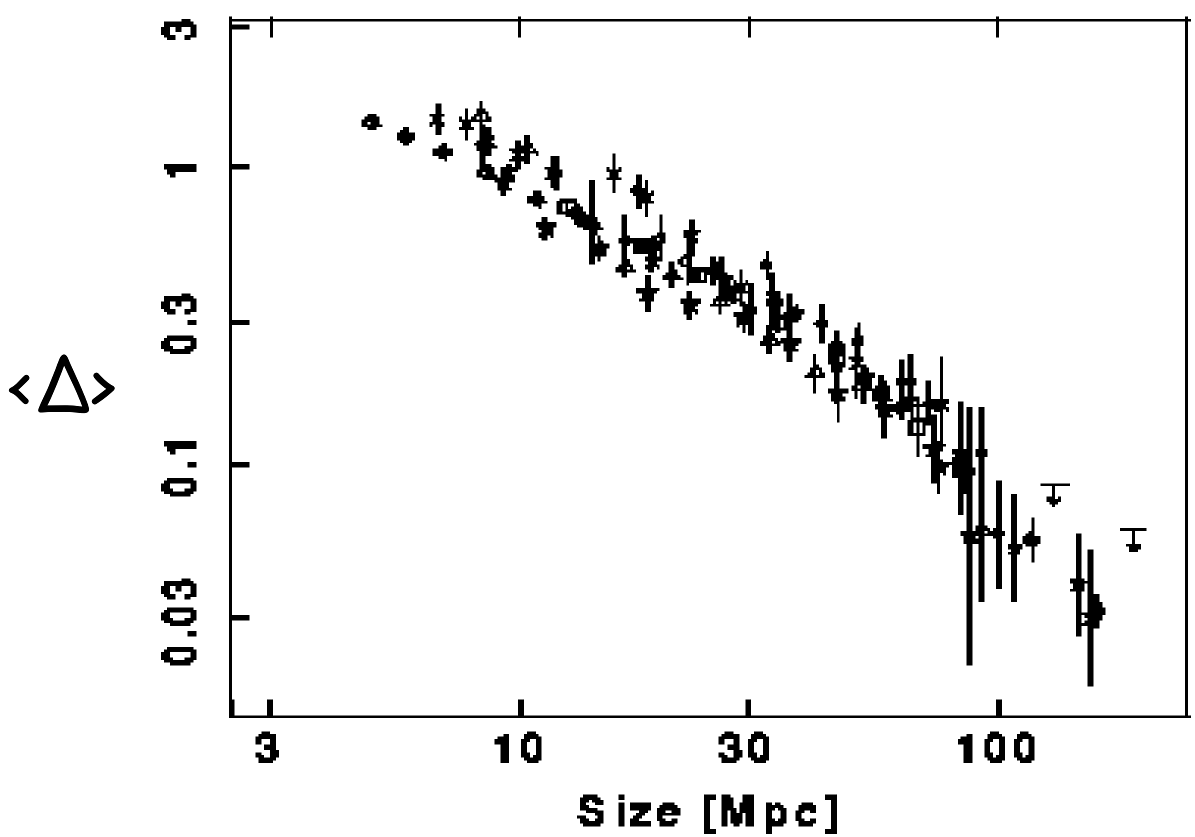




Complexity

Matter inhomogeneities are small on large scales

$$\Delta = |\delta\rho/\rho| \ll 1$$

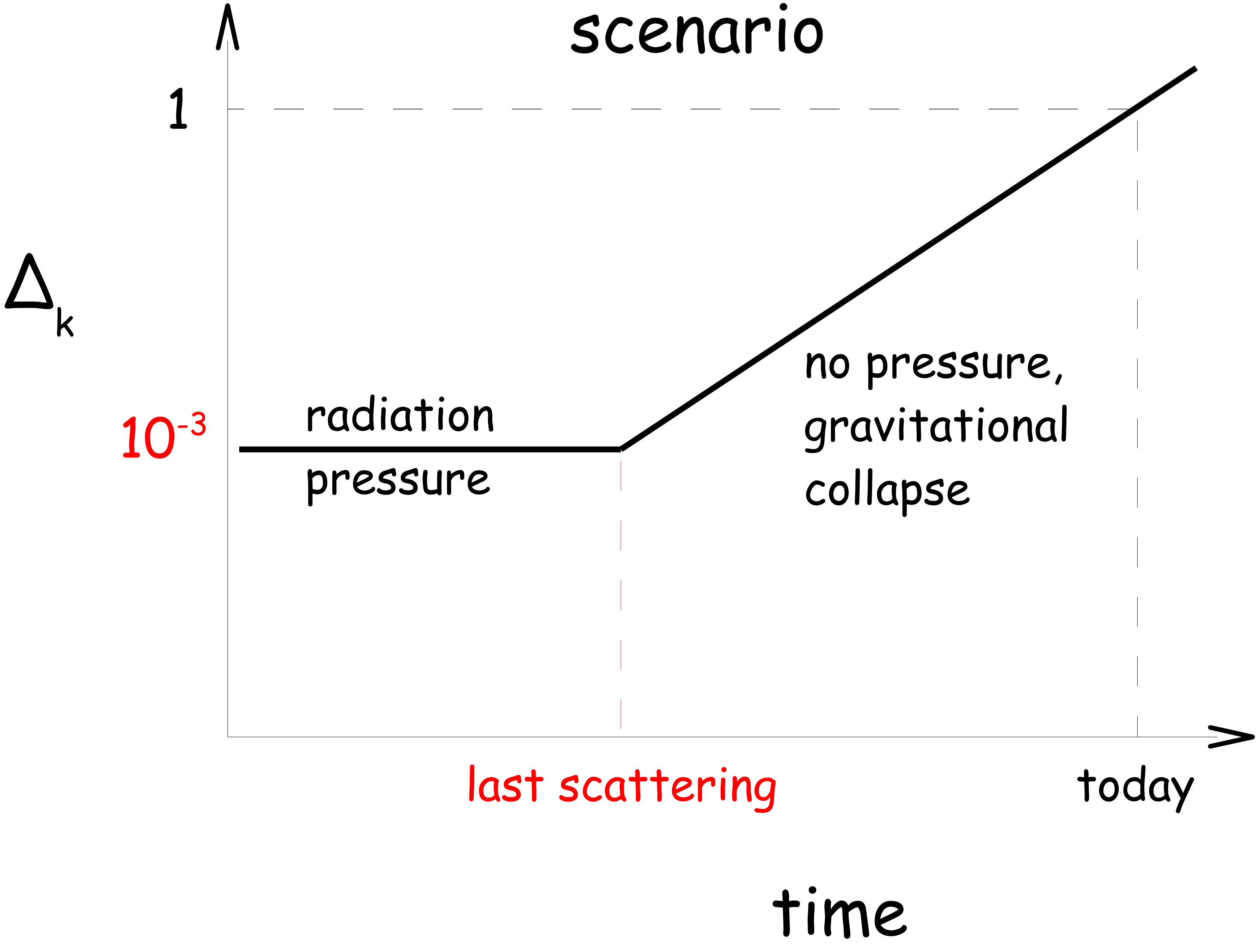


Evolution of inhomogeneities
(Jeans Instability)

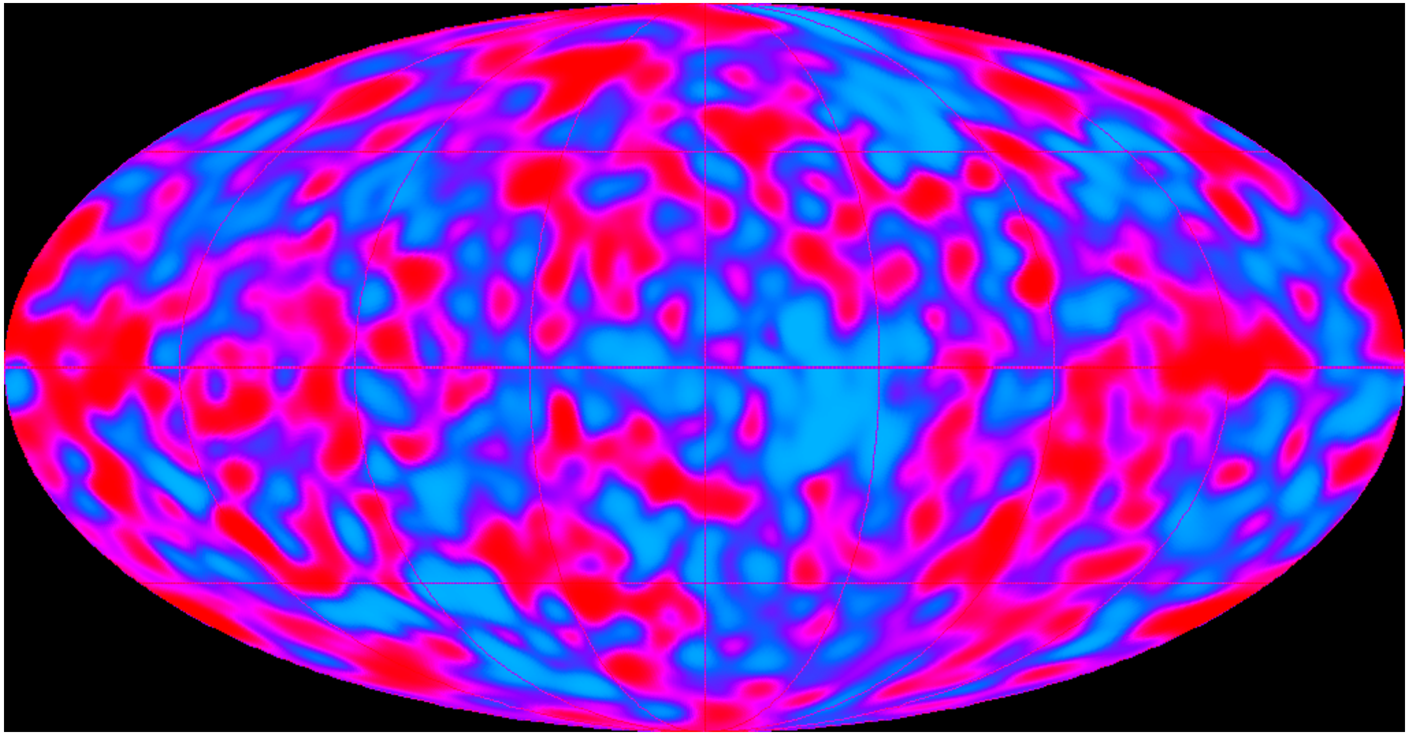
$$\ddot{\Delta} + 2\frac{\dot{a}}{a}\dot{\Delta} + (v_s^2 k^2 - 4\pi G\rho)\Delta = 0$$

pressure vs gravity

Only baryonic matter scenario

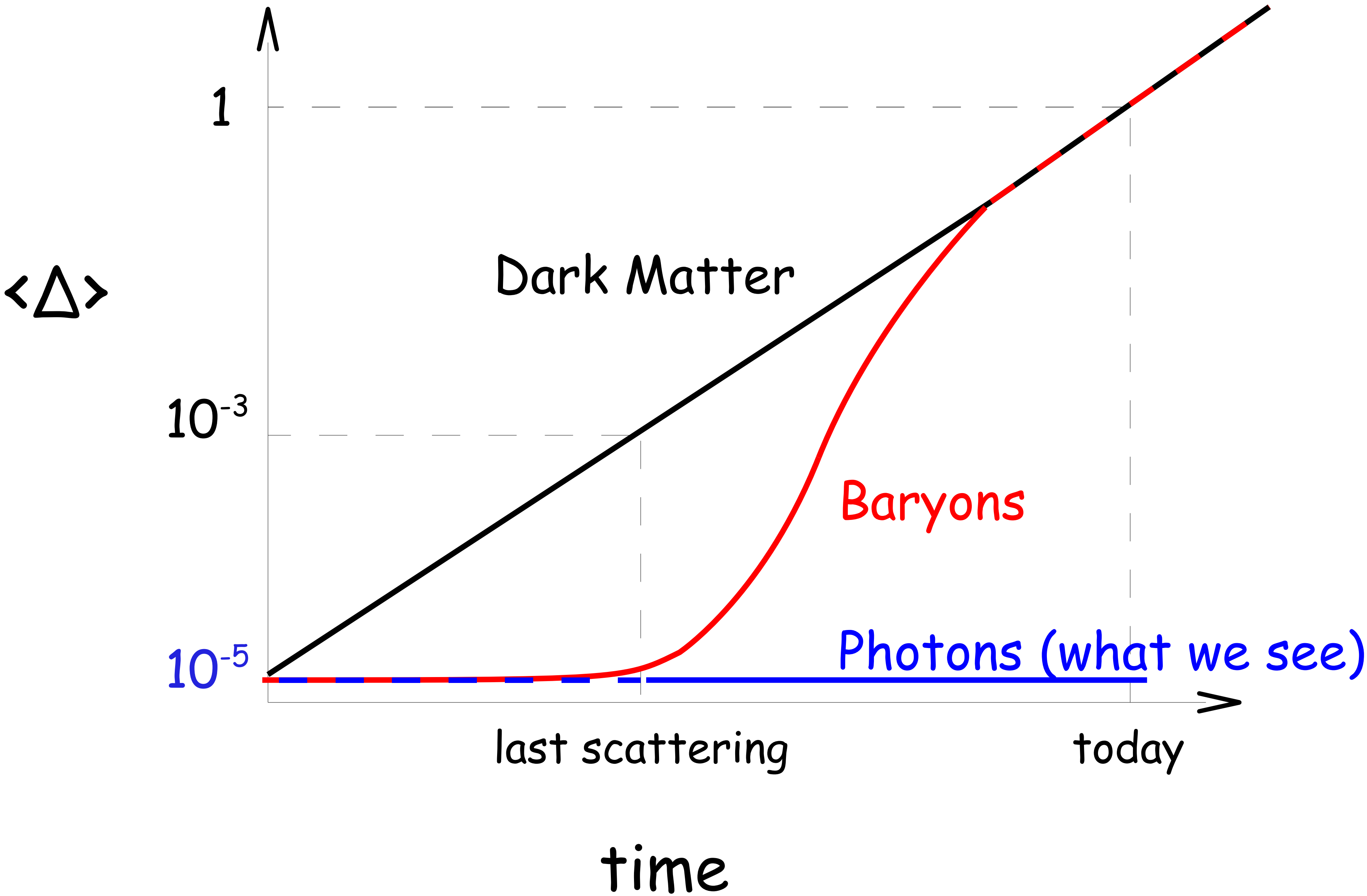


CMBR temperature anisotropies



$$\Delta \approx \delta T/T = O(10^{-5})$$

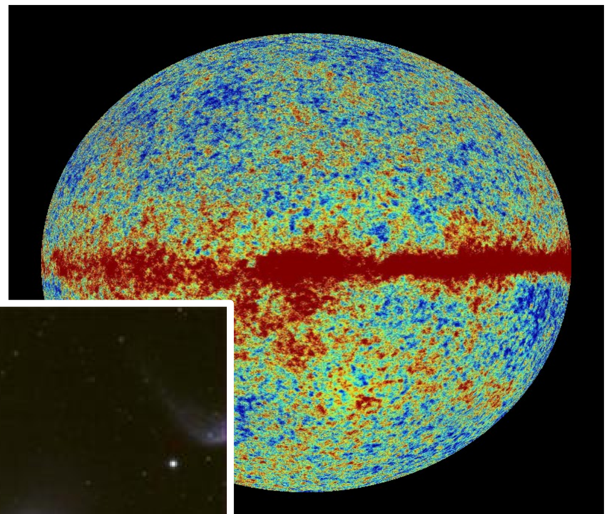
The (cold) dark matter scenario

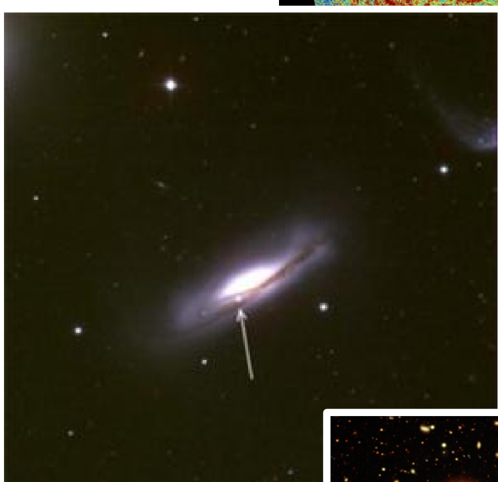


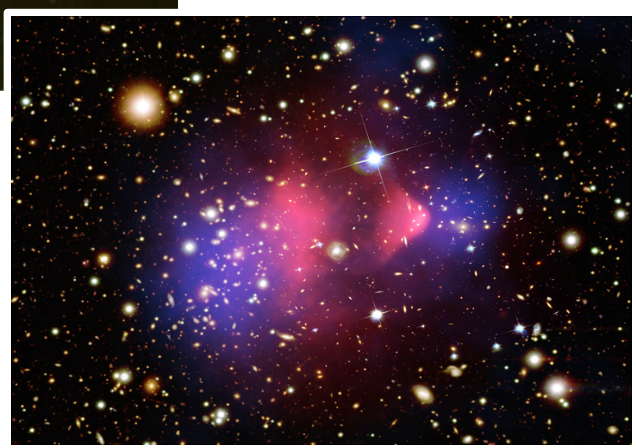
Peebles, 1982

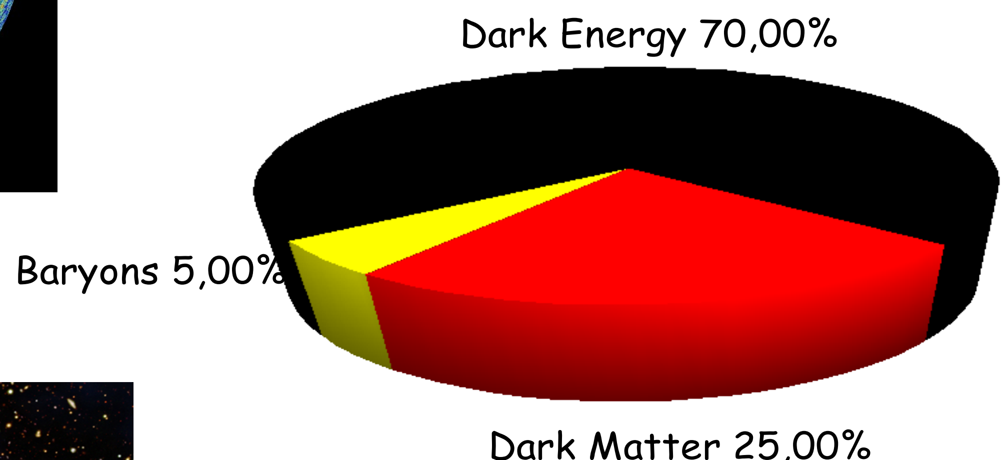
II. How much Dark Matter ?

The Concordance Model

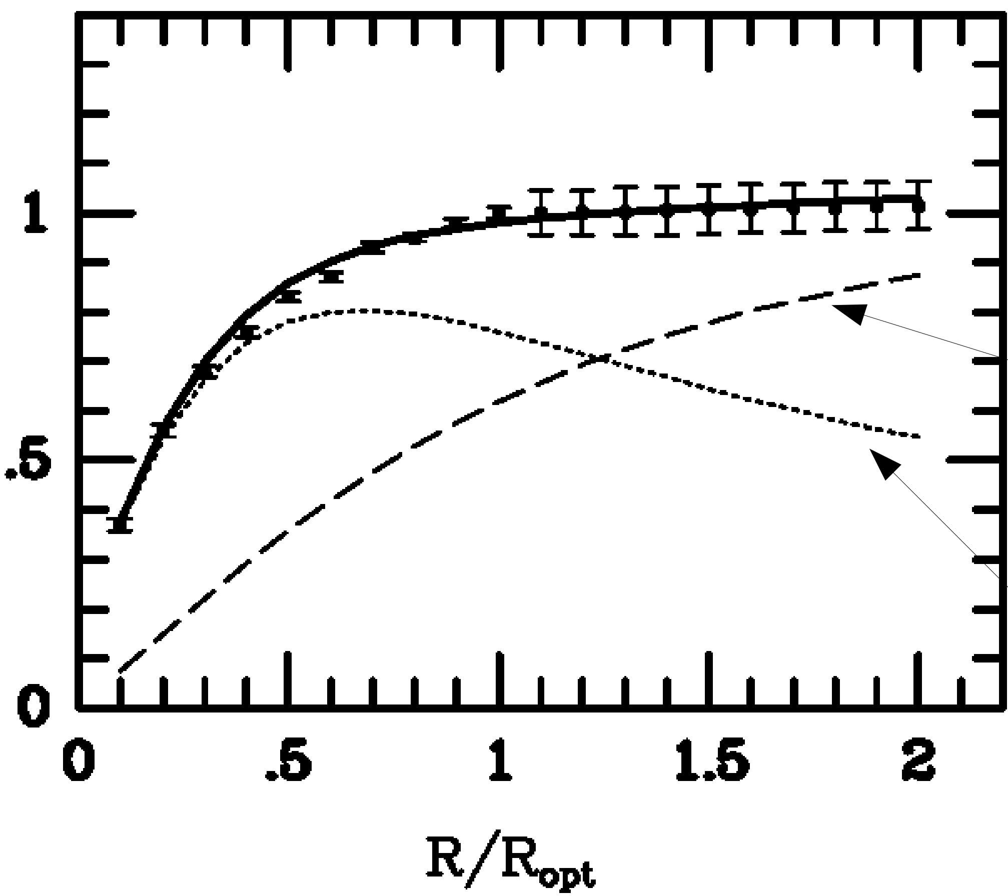








The rotational curve of spiral galaxies (Vera Rubin, 80')



V_{radial}

$v_r^{\,2} \sim G\, M(R)/R$

Contribution of
a Halo of Dark Matter

Contribution of
Ordinary Matter
(bulge + disk)

$R_{optical}$ = 20kpc (for Milky Way)

(Picture is a compilation of 1000 rotation curves, Persic et al, 99)

Abundance of Dark Matter in the Milky Way?

A bold model: cored isothermal spherical halo of dark matter

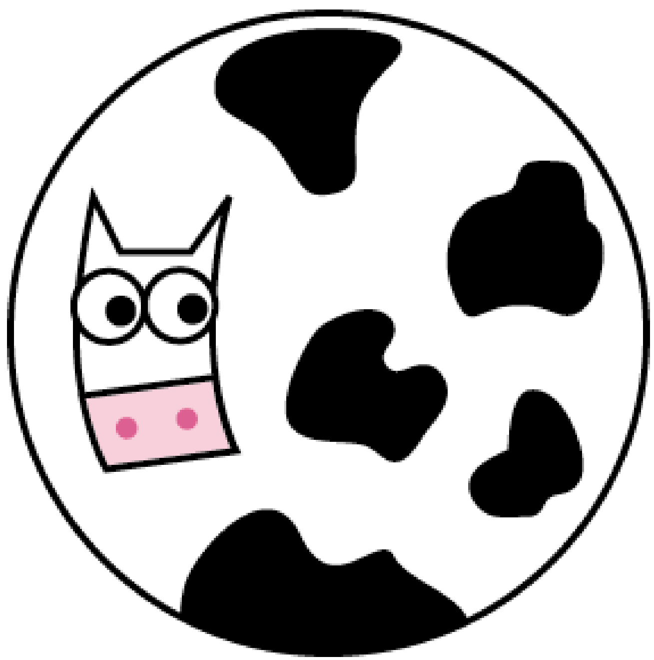
$\rho_h(r) = \rho_0 (a^2 + r_0^2)/(a^2 + r^2)$ $\longrightarrow$ $v_h^2 = v_{h\infty}^2 (1 - a/r \, \mathrm{atan}(r/a))$

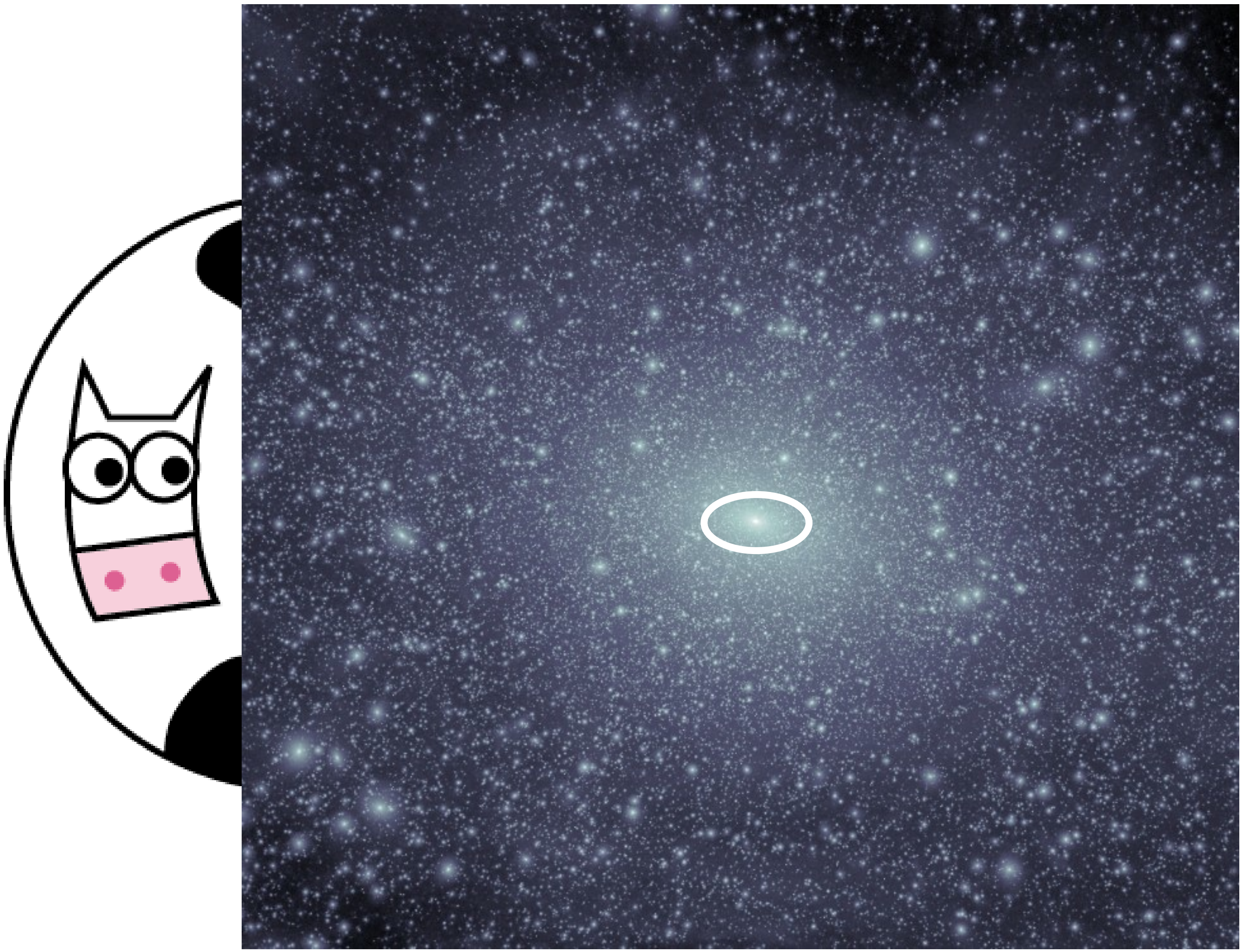
To be fitted to observed velocity curve

Infered local abundance

$$\rho_0 \sim 0.1 - 2 \text{ GeV/cm}^3$$

Fiducial density is $\rho_0 = 0.3$ GeV/cm^3



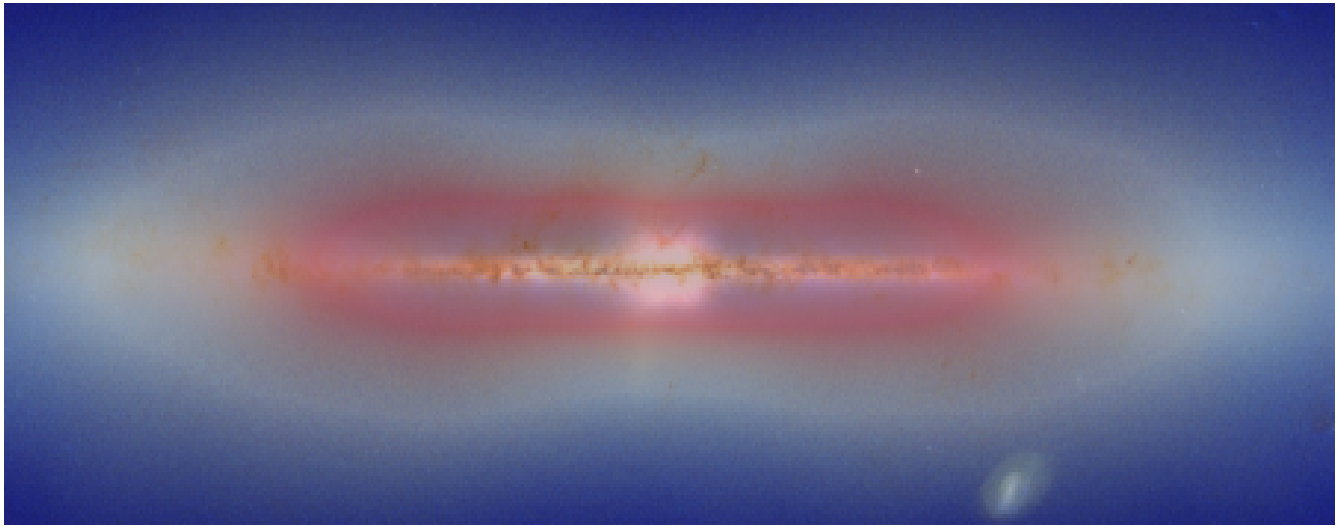


Simulation from the Via Lactea project (Dark matter only)

(Diemand et al)

Thin, thick and dark discs in ΛCDM

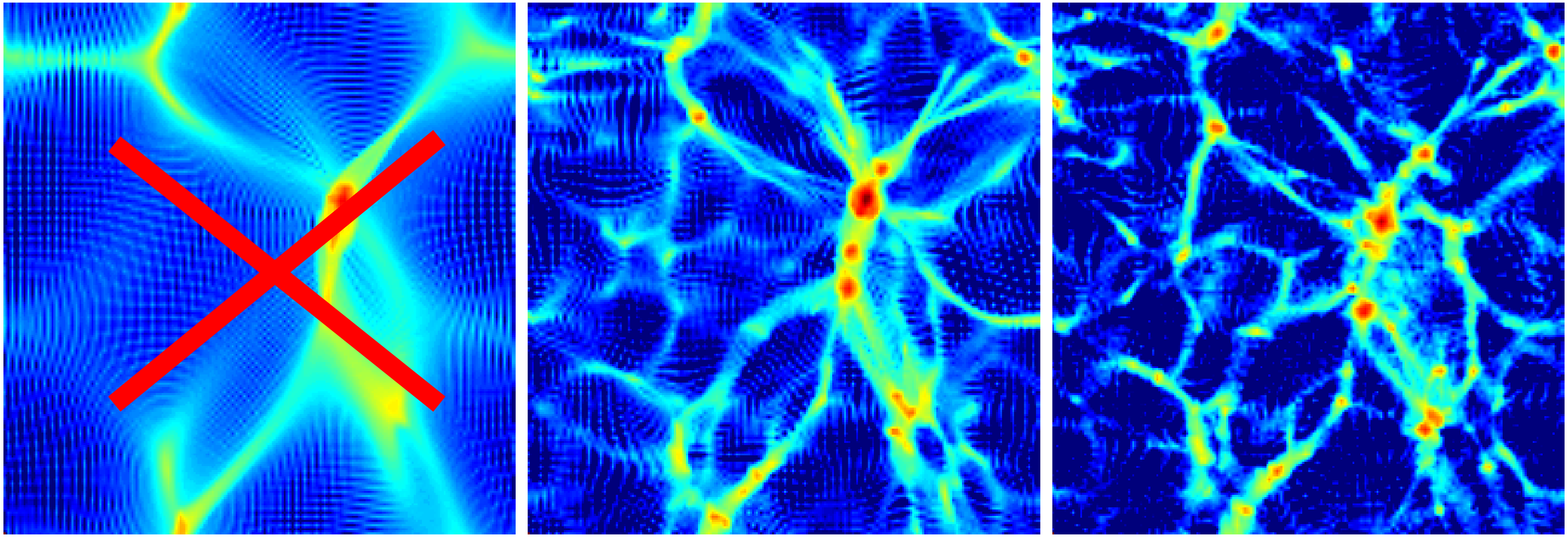
J. I. Read*[1], G. Lake[1], O. Agertz[1] & Victor P. Debattista[2]
[1] Institute of Theoretical Physics, University of Zürich, Winterthurerstrasse 190, 8057 Zürich, Switzerland.
[2] RCUK Fellow; Centre For Astrophysics, University of Central Lancashire, Preston, PR1 2HE, UK.



Impact of gas/star disk on dark matter halo -> dark disk

$$1/2 < \rho_{disk}/\rho_{halo} < 2$$

III. Which Dark Matter ?



Hot Dark Matter

First large structures,
then smaller ones

Not the neutrinos of the Standard Model

Moreover, they are too light

Cold Dark Matter

First galaxies

Then clusters of galaxies, etc...

A stable, Weakly Interacting Massive Particle (or WIMP) ?

DM + DM <-> Known Particles

Freeze-out when

Int. rate ~ Exp. rate

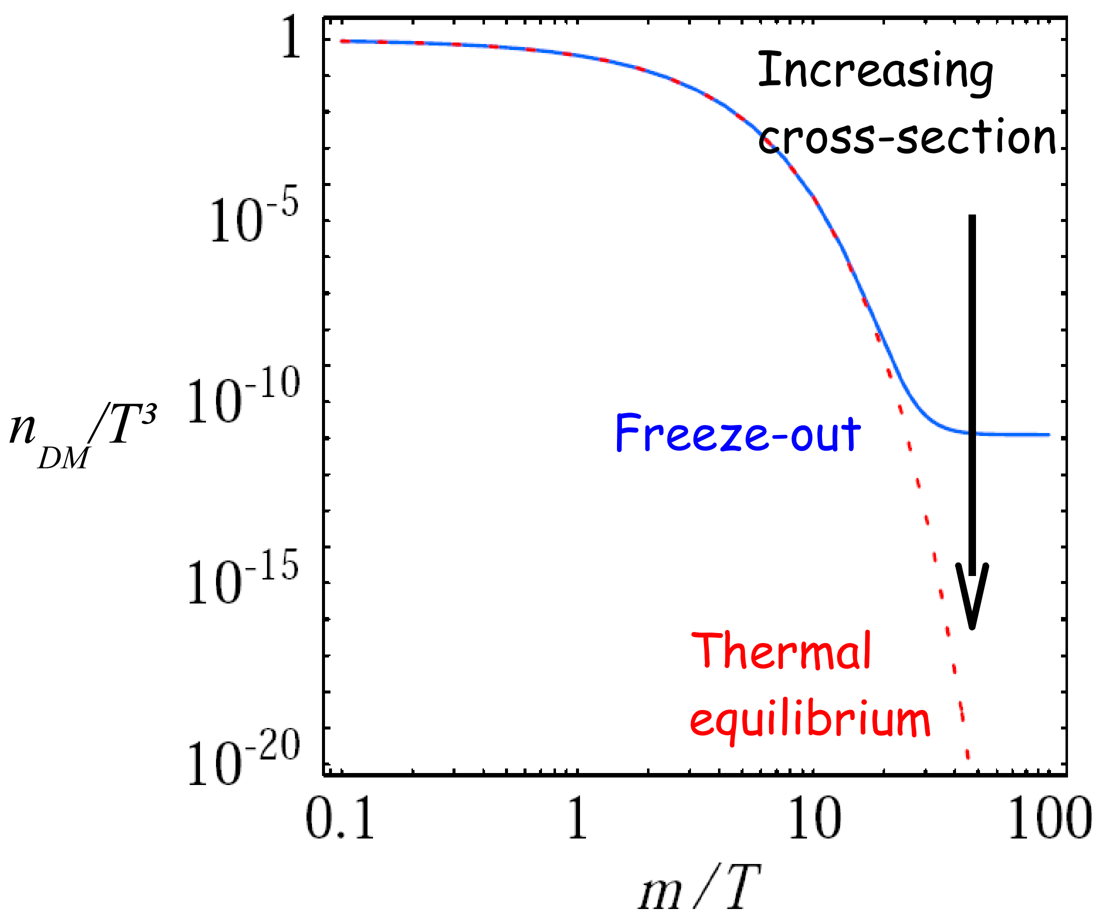
$\langle \sigma v \rangle n_{DM} \sim T_{FO}^2 / m_{Planck}$

Relic abundance

$n_{DM} \sim 1/\langle \sigma v \rangle$

WMAP requires

$\langle \sigma v \rangle \sim 1$ pb



Stability from Symmetry

U(1) symmetry: $\Psi \longrightarrow e^{i\beta}\Psi$

e.g. Proton stability = baryon number conservation

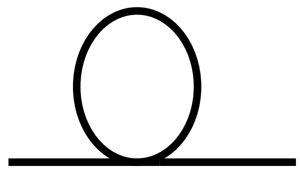
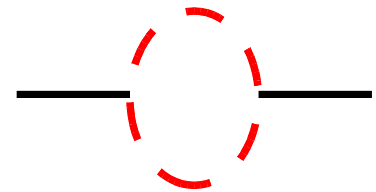
Z_2 symmetry: $\Psi \longrightarrow -\Psi$

e.g. R-parity in Supersymmetric extensions of the Standard Model

Others: e.g. $\Psi_i \longrightarrow \Psi_j + \Psi_k$ with i,j,k in an SU(2)

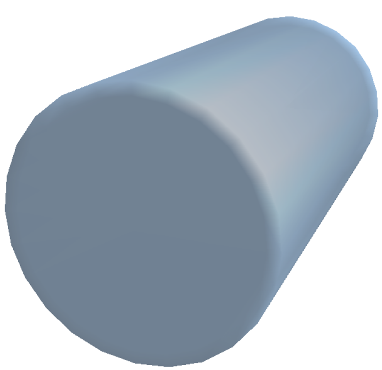
An Electroweak Connection ?

SUSY

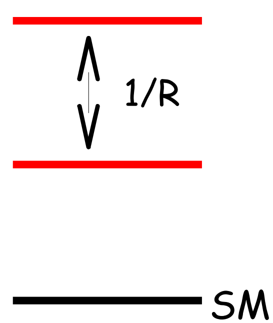
δM^2_{Higgs} =  +  $\sim M^2_{Higgs} \ll M^2_{Planck}$

R-parity: $\Psi_{SM} \rightarrow \Psi_{SM}$ $\quad \Psi_{susy} \rightarrow -\Psi_{susy}$

Extra Dimensions



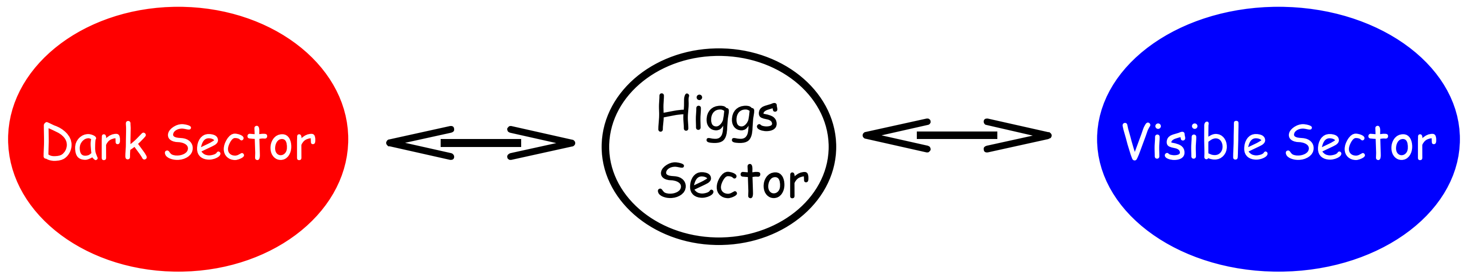
$\Longrightarrow$



KK-parity: $\Psi_{SM} \rightarrow \Psi_{SM}$

$\Psi_{KK} \rightarrow -\Psi_{KK}$

The Brout-Englert-Higgs portal



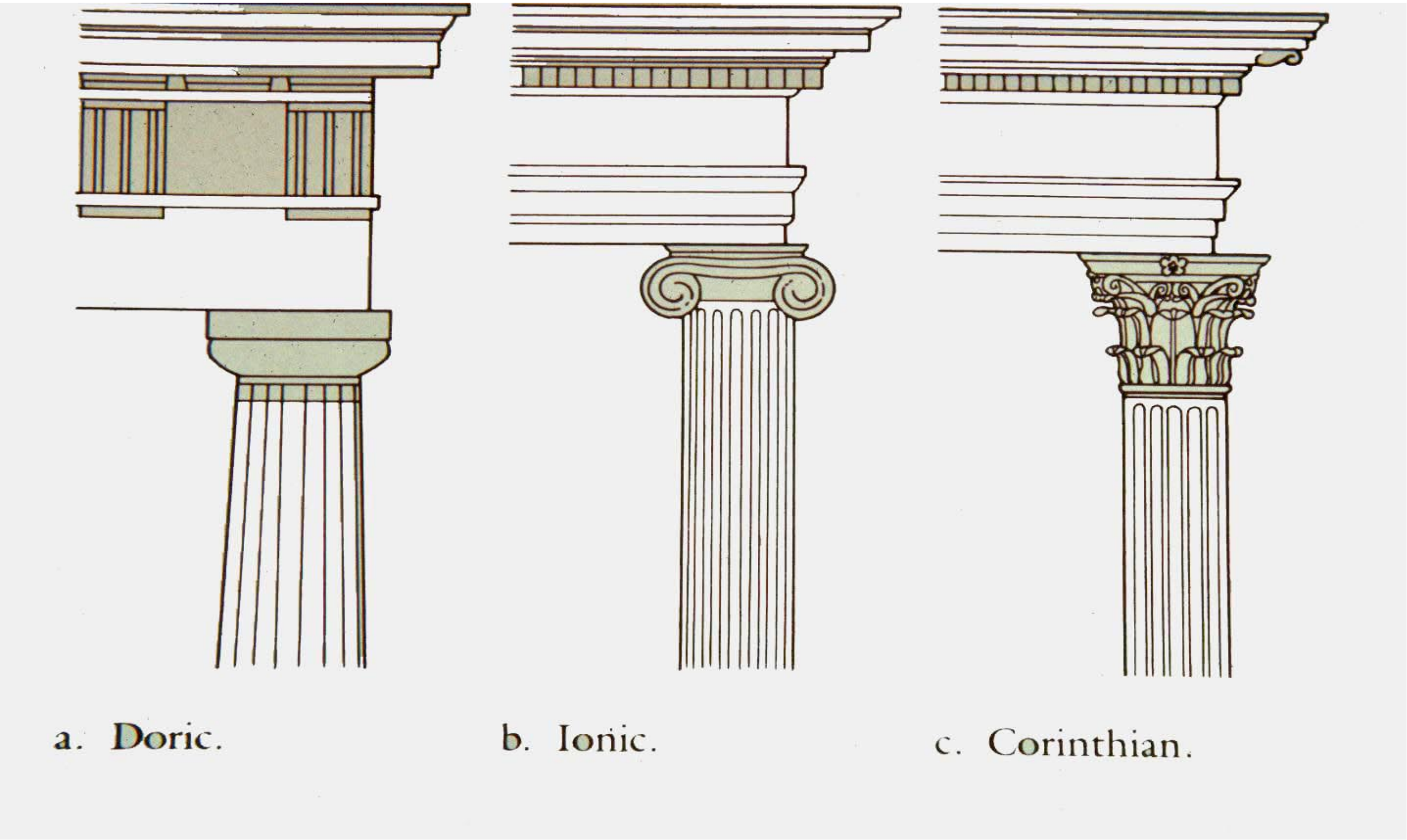
e.g. The Inert Doublet Model

$\Psi_{\text{Higgs}} \longrightarrow \Psi_{\text{Higgs}}$ $\quad$ $\Psi_{\text{Inert Higgs}} \longrightarrow -\Psi_{\text{Inert Higgs}}$

Easy way to prevent FCNC

WIMP Dark Matter Archetypes

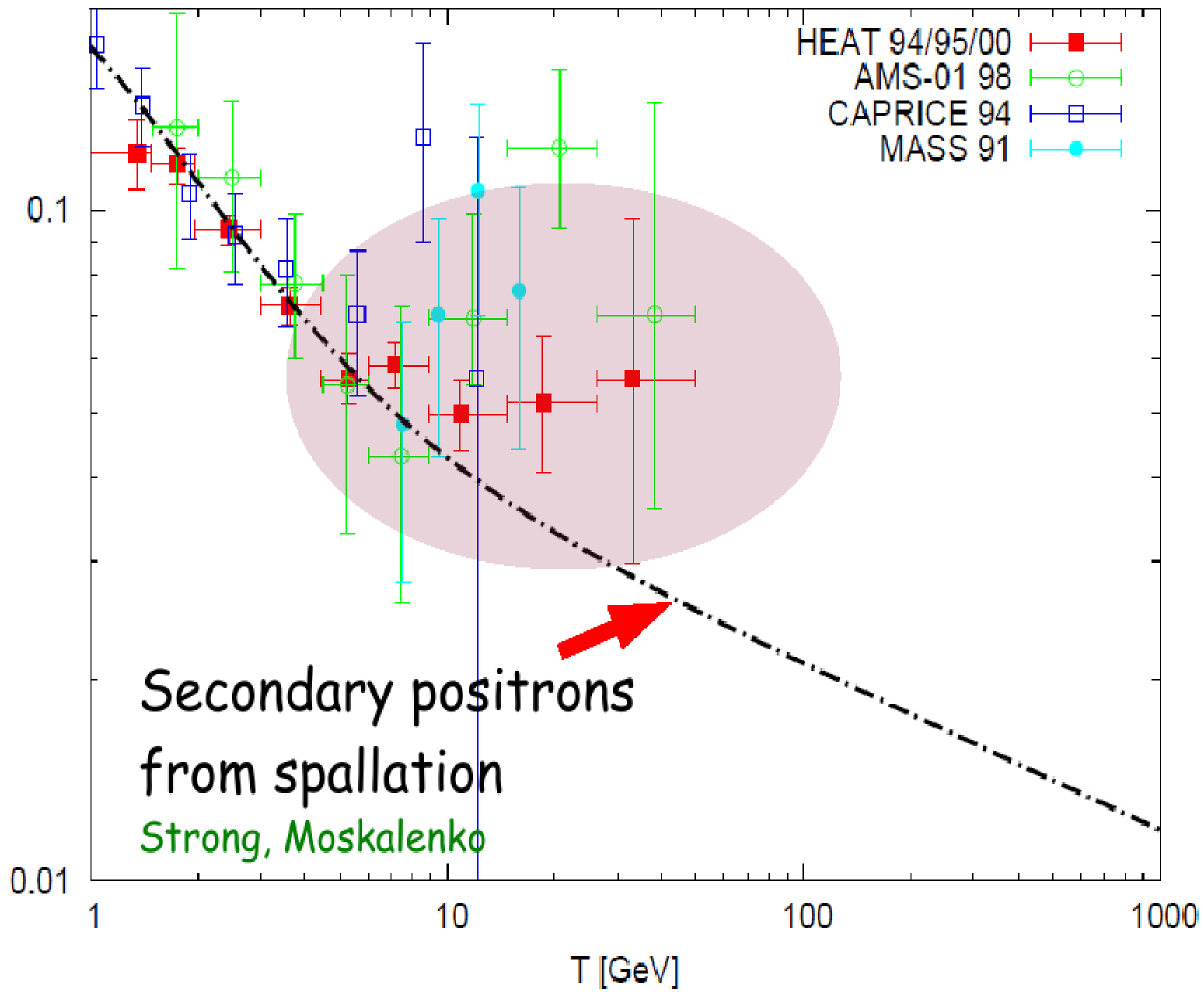
Spin 0	Spin ½	Spin 1
The Inert Doublet	The Neutralino	The Kaluza Klein photon



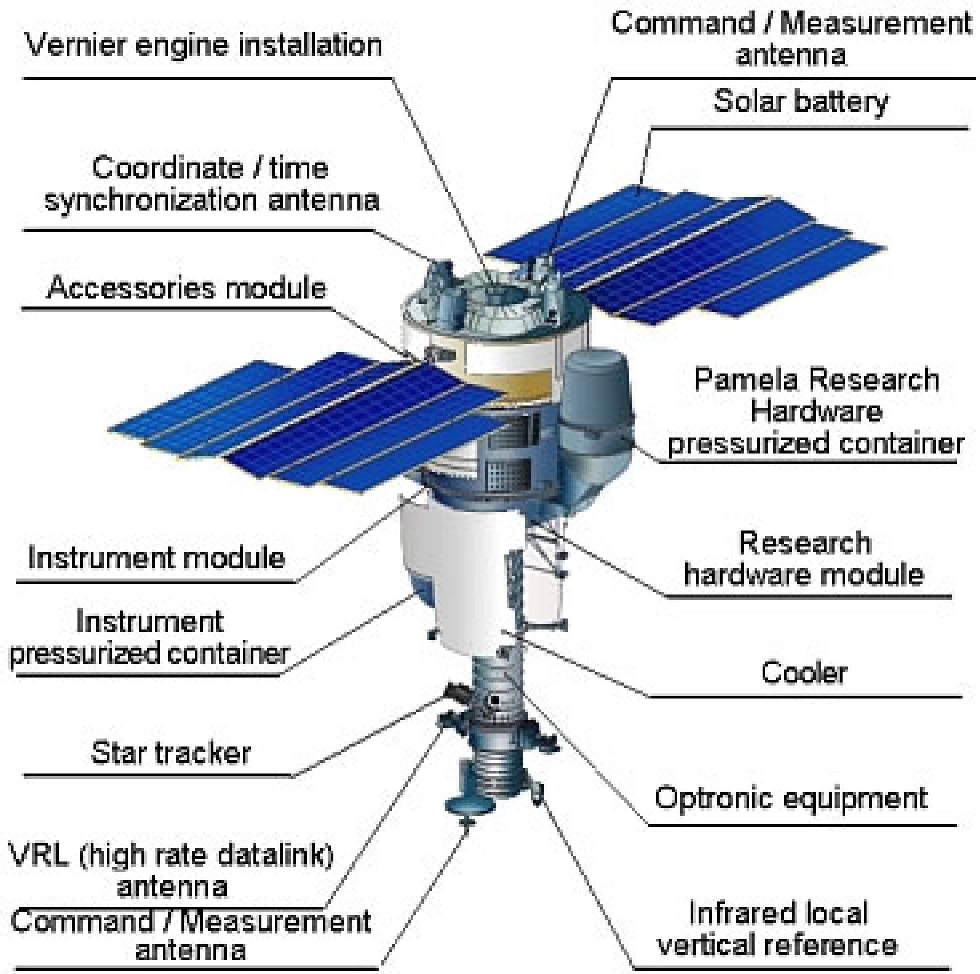
IV. Dark Matter and the defeat of Antimatter

Positron fraction in Cosmic Rays

$$\frac{e^+}{e^+ + e^-}$$

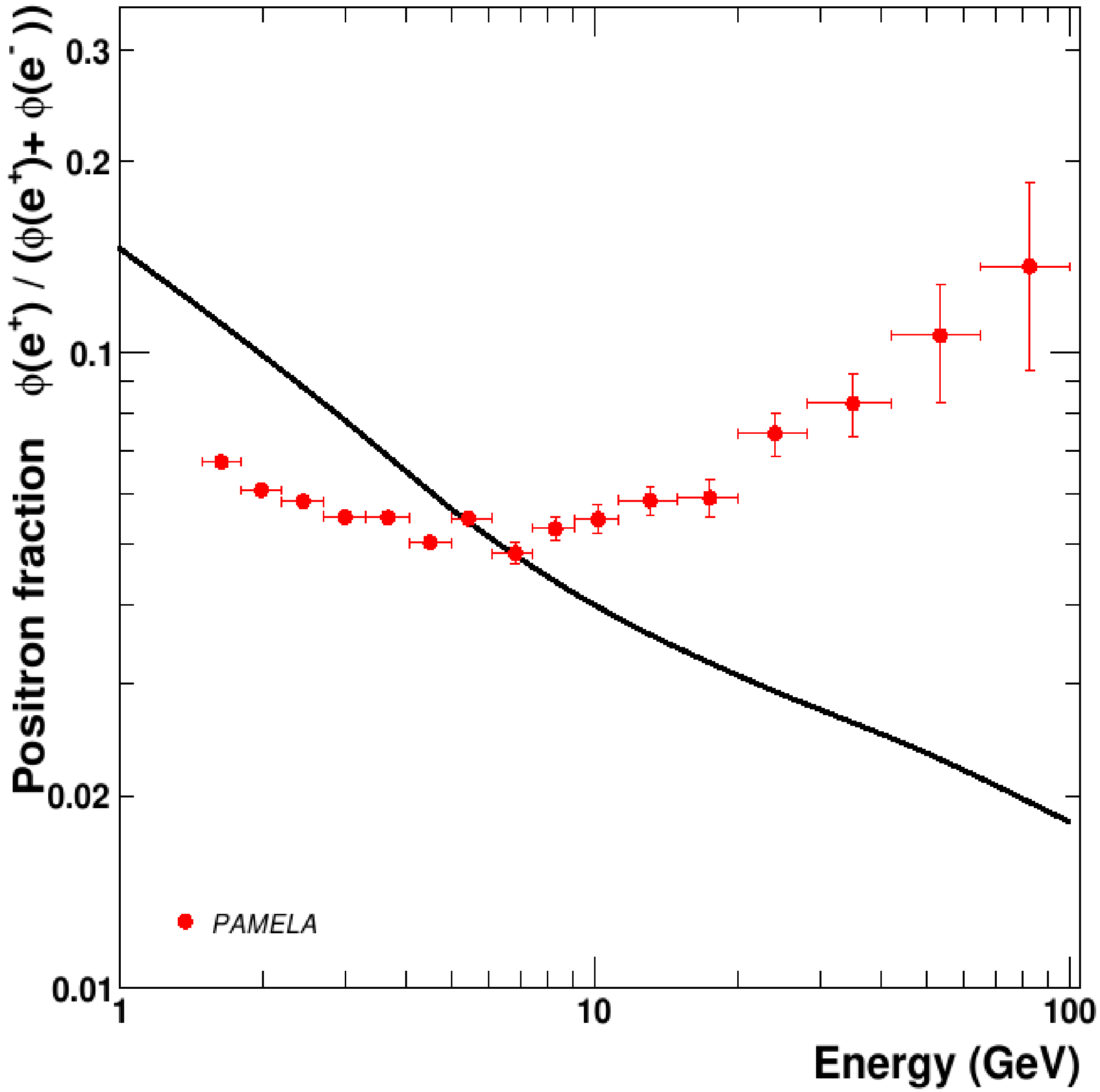


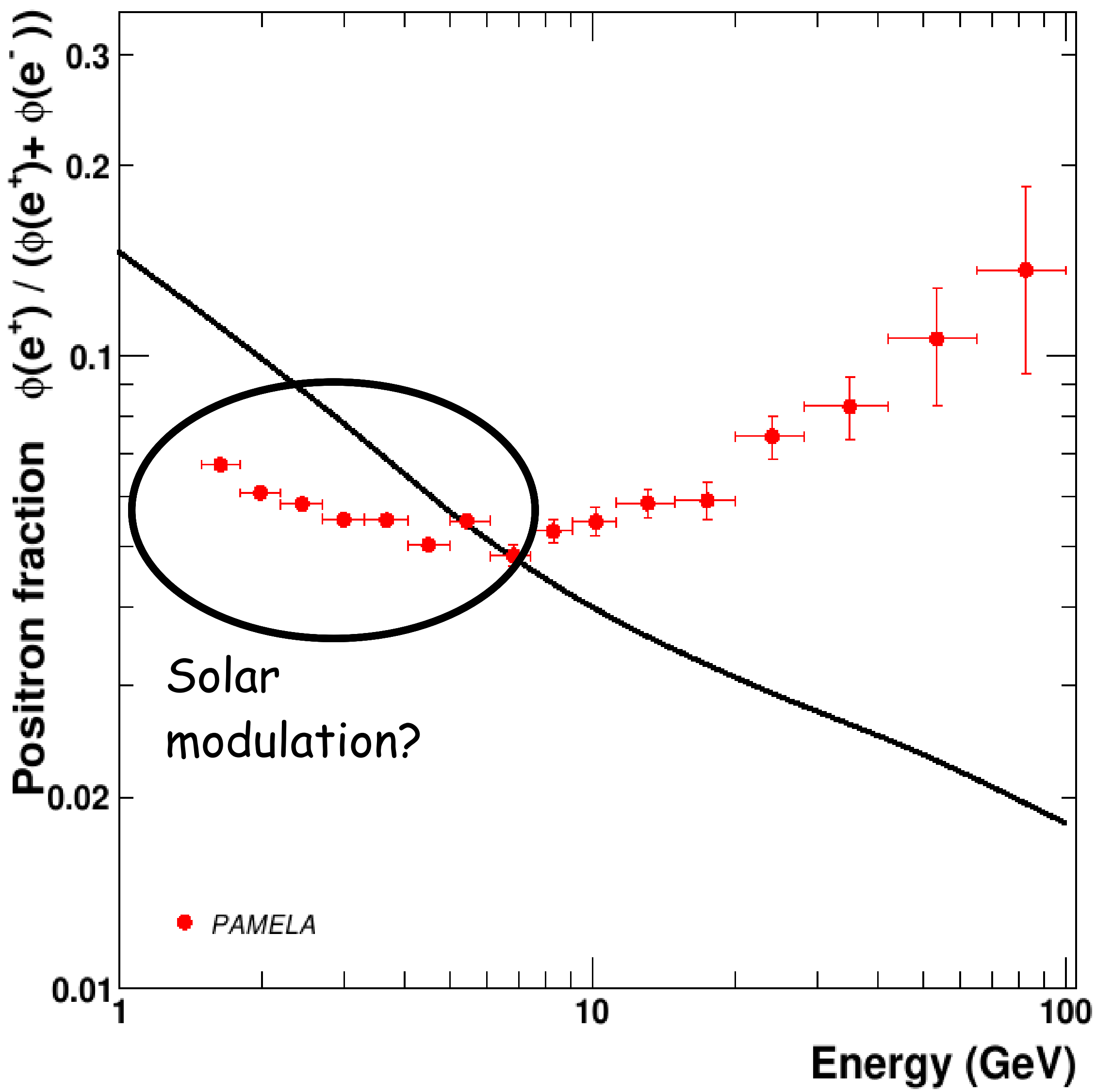
PAMELA, *a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics*



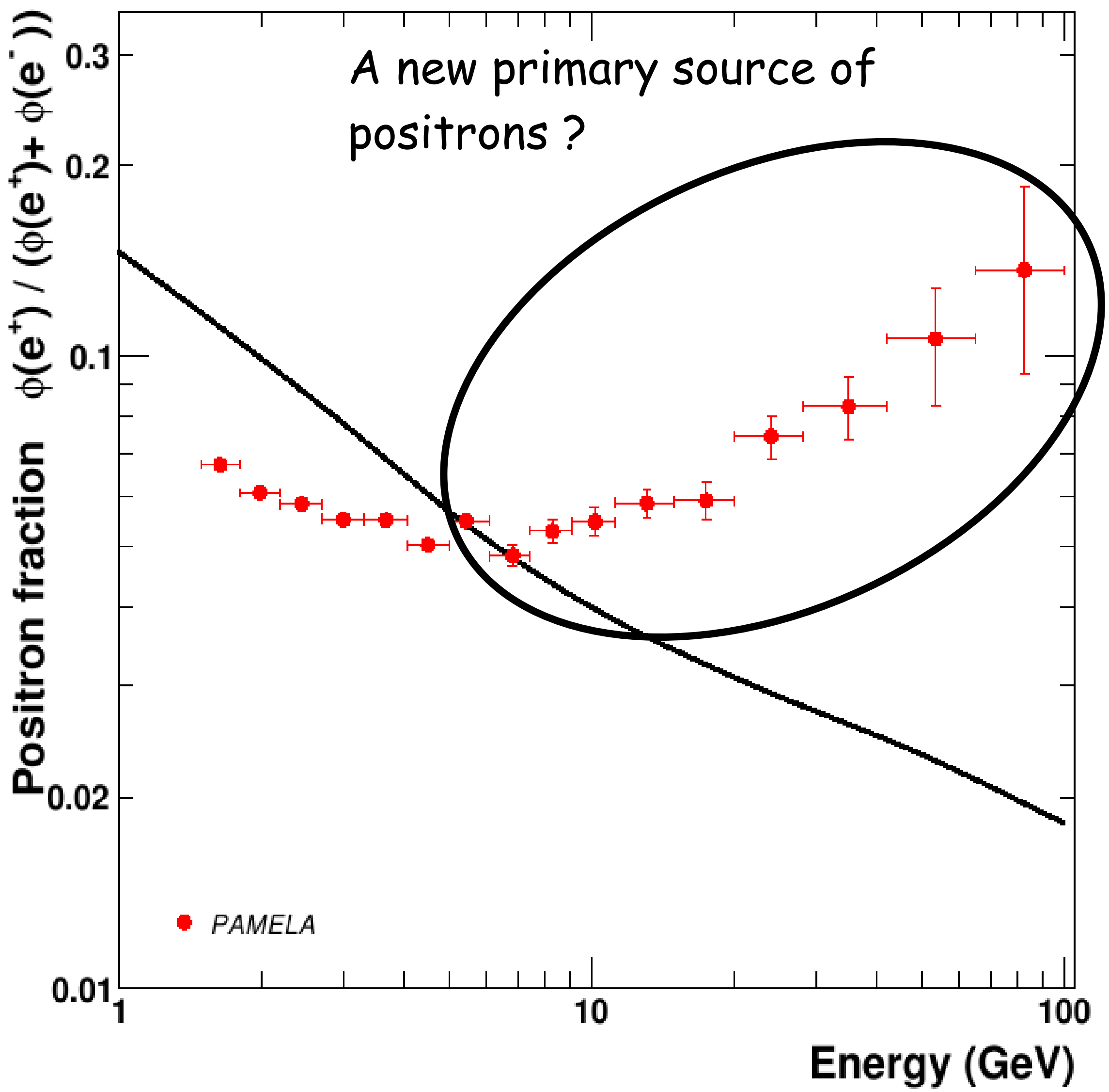
A picture of Pamela

Pamela results (released October 28 2008)



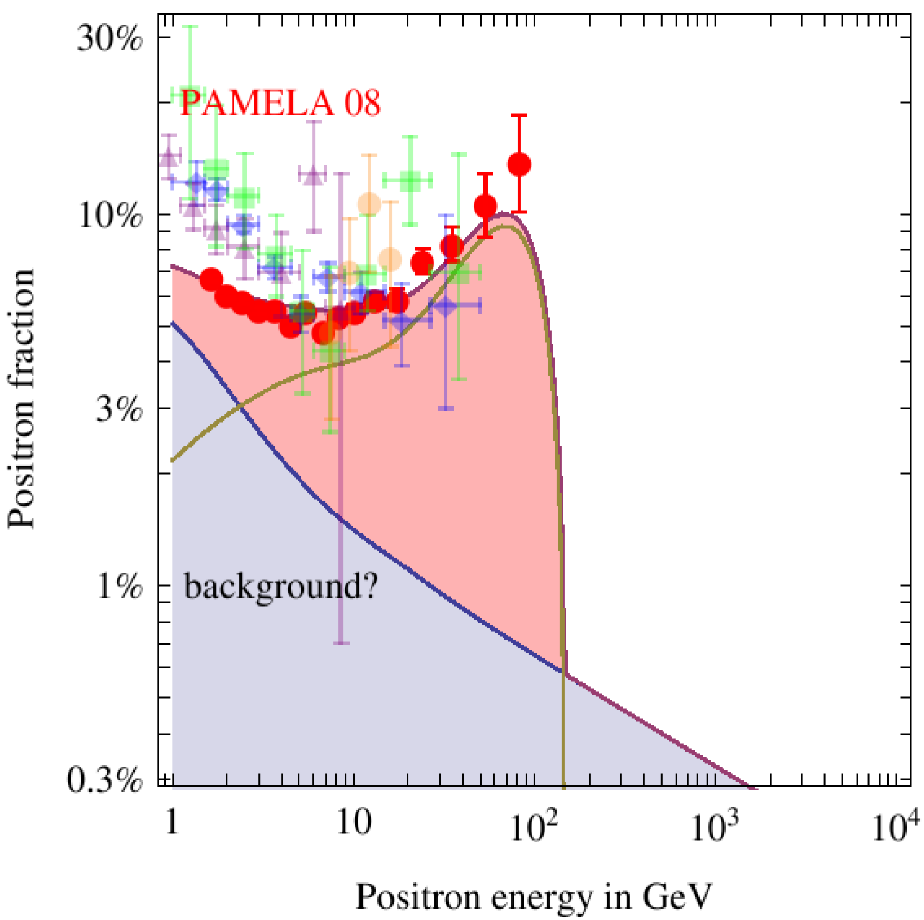


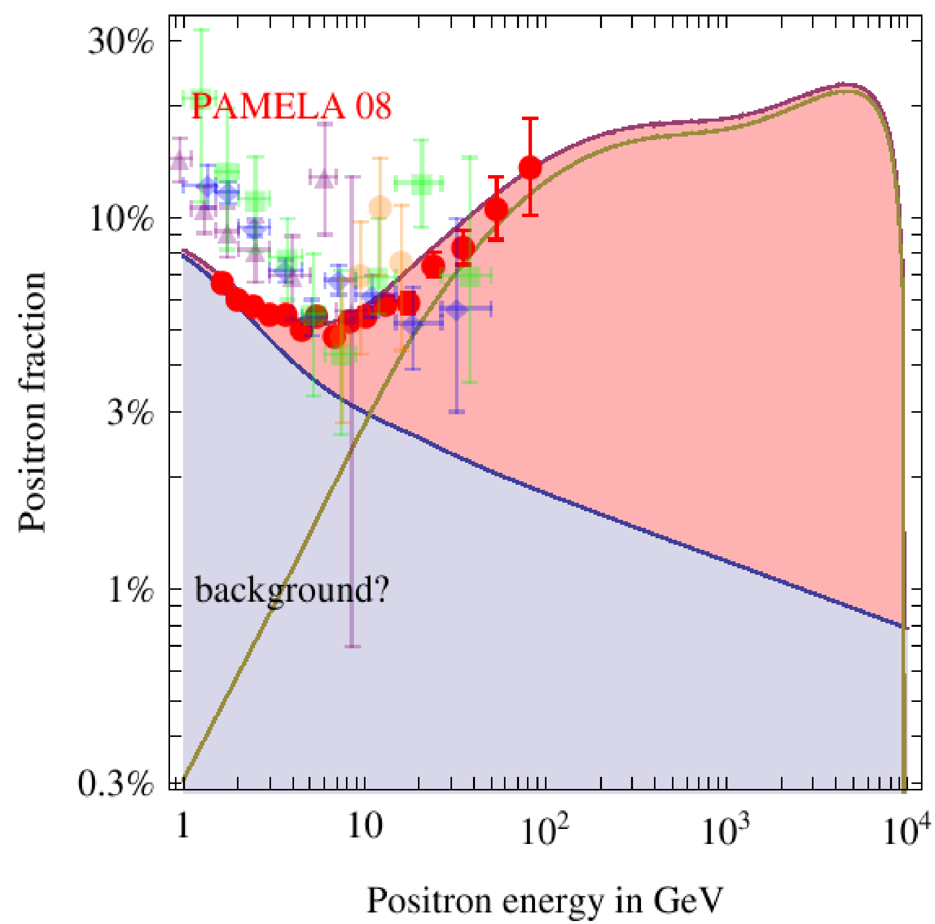
Positron fraction $\phi(e^+) / (\phi(e^+) + \phi(e^-))$
0.3
0.2
0.1
0.02
0.01
1
10
100
Energy (GeV)
Solar
modulation?
PAMELA



A new primary source of positrons ?
Positron fraction φ(e+) / (φ(e+)+ φ(e-))
0.3
0.2
0.1
0.02
0.01
1
10
100
Energy (GeV)
PAMELA

DM + DM —> … —> $e^+ e^-$ …



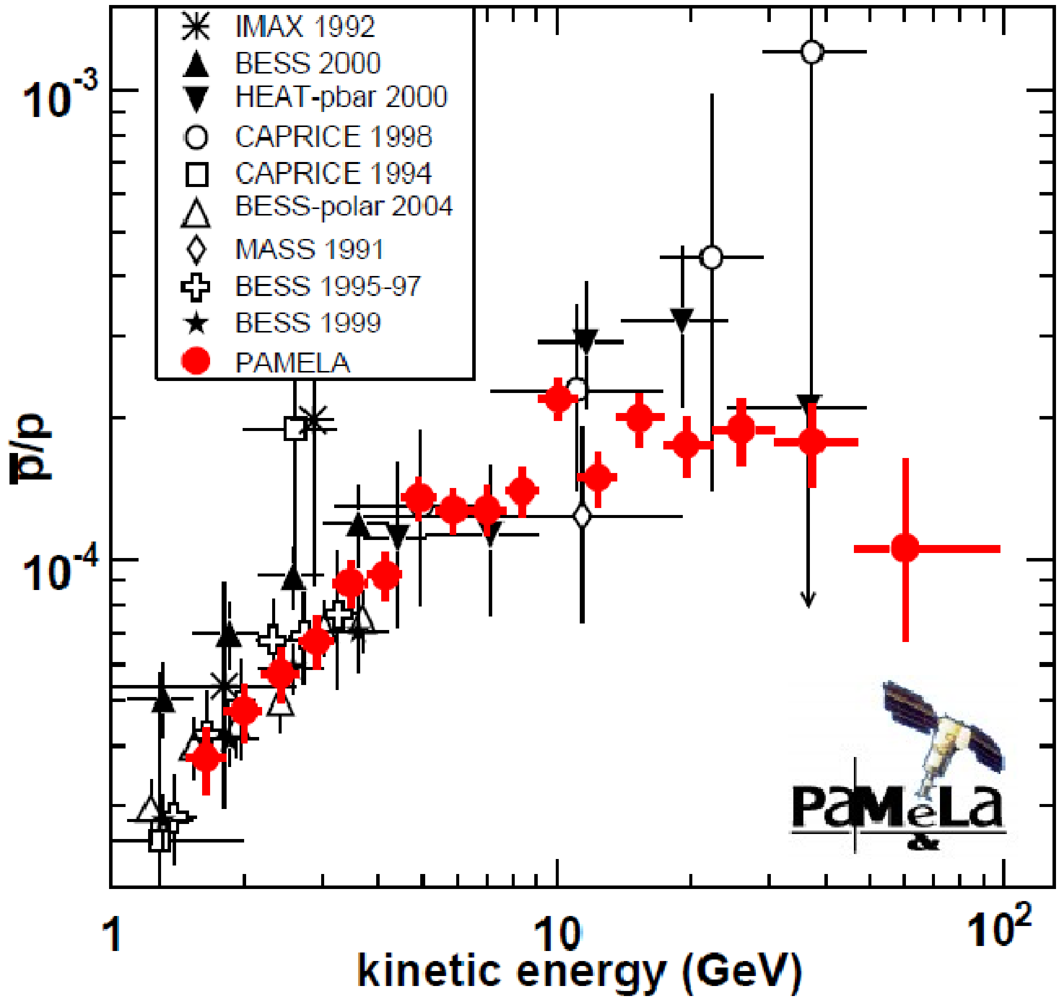


M_{DM} = 150 GeV into W^+W^-

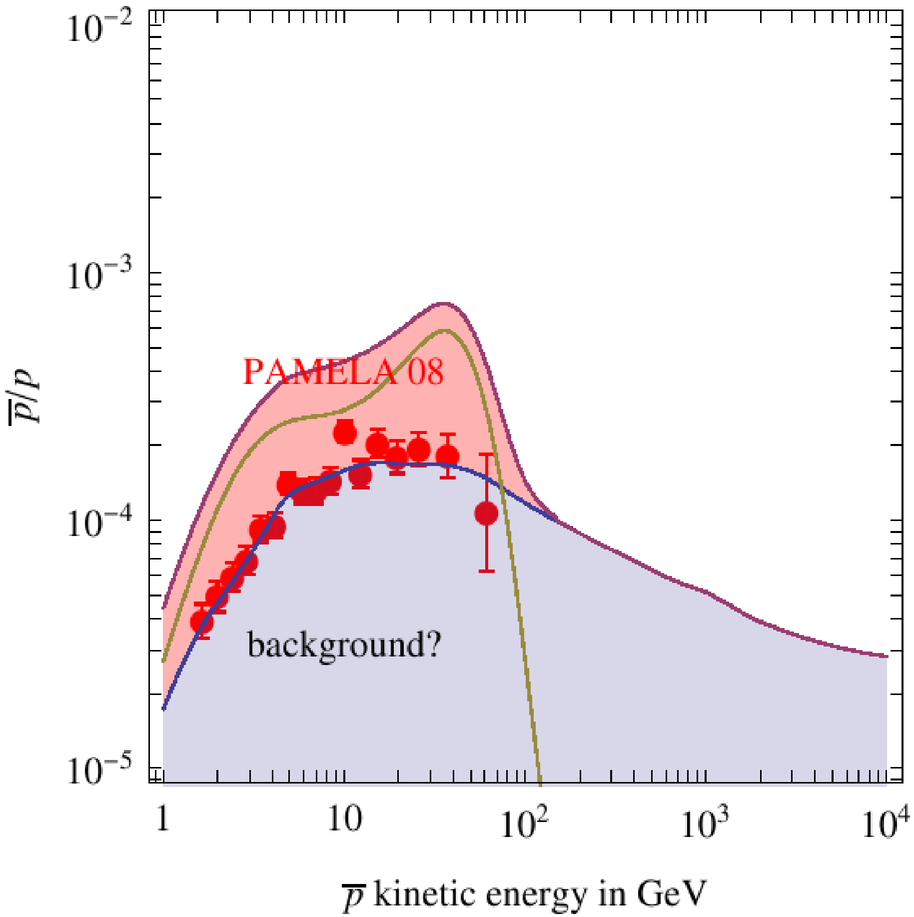
M_{DM} = 10 TeV into W^+W^-

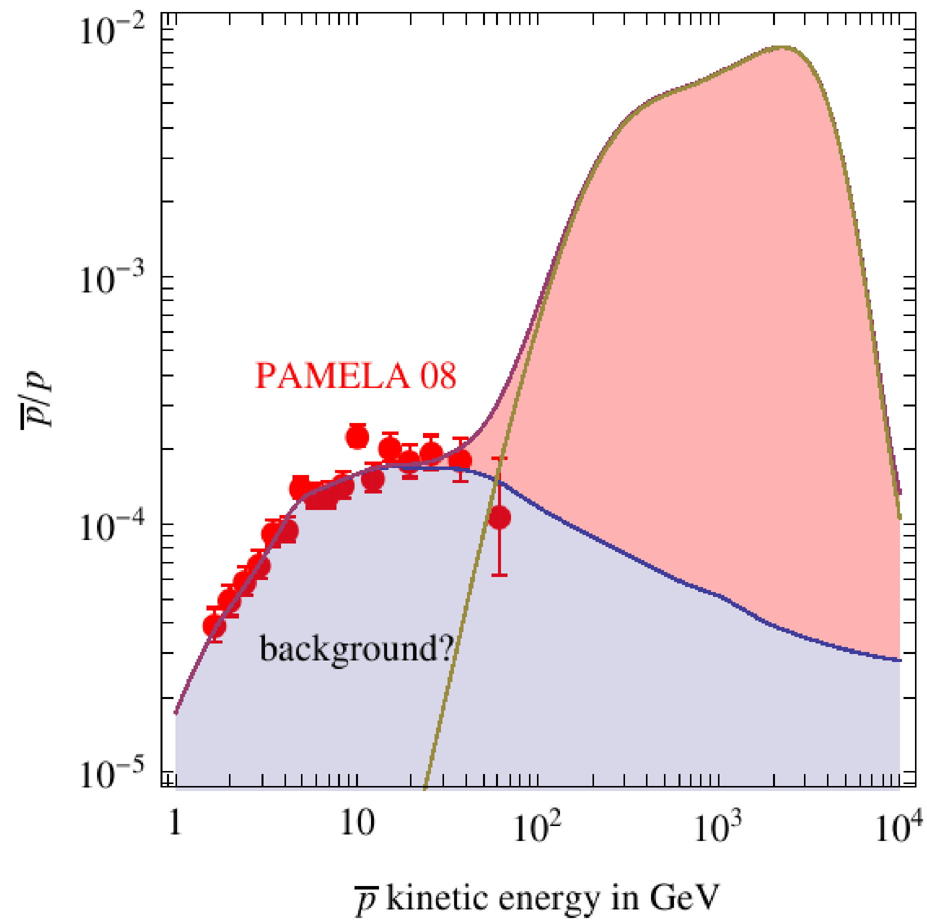
Cirelli, Strumia & Raydal

Antiproton flux from PAMELA



DM + DM —> ... —> $\bar{p}$ p ...





M_{DM} = 150 GeV into W^+W^-

M_{DM} = 10 TeV into W^+W^-

nature Vol 456|20 November 2008|doi:10.1038/nature07477

LETTERS

An excess of cosmic ray electrons at energies of 300–800 GeV

J. Chang[1,2], J. H. Adams Jr[3], H. S. Ahn[4], G. L. Bashindzhagyan[5], M. Christl[3], O. Ganel[4], T. G. Guzik[6], J. Isbert[6], K. C. Kim[4], E. N. Kuznetsov[5], M. I. Panasyuk[5], A. D. Panov[5], W. K. H. Schmidt[2], E. S. Seo[4], N. V. Sokolskaya[5], J. W. Watts[3], J. P. Wefel[6], J. Wu[4] & V. I. Zatsepin[5]

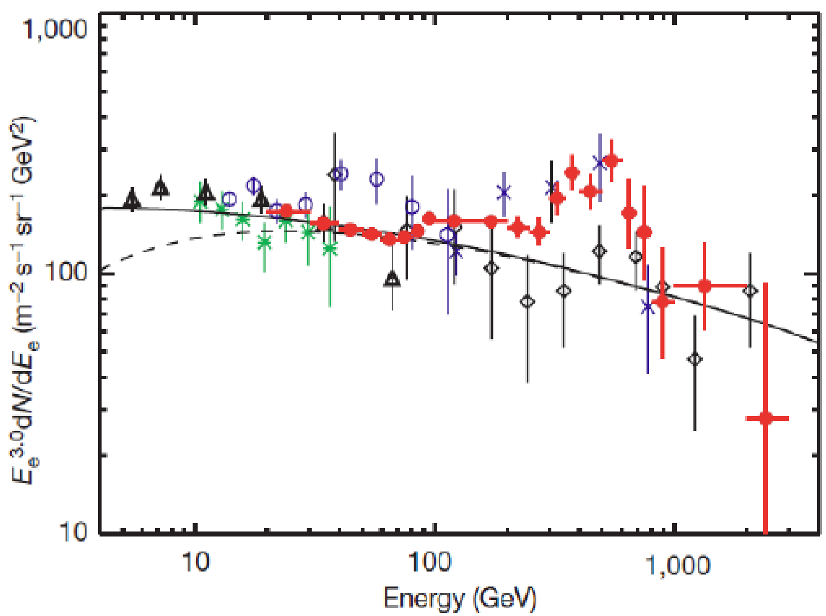
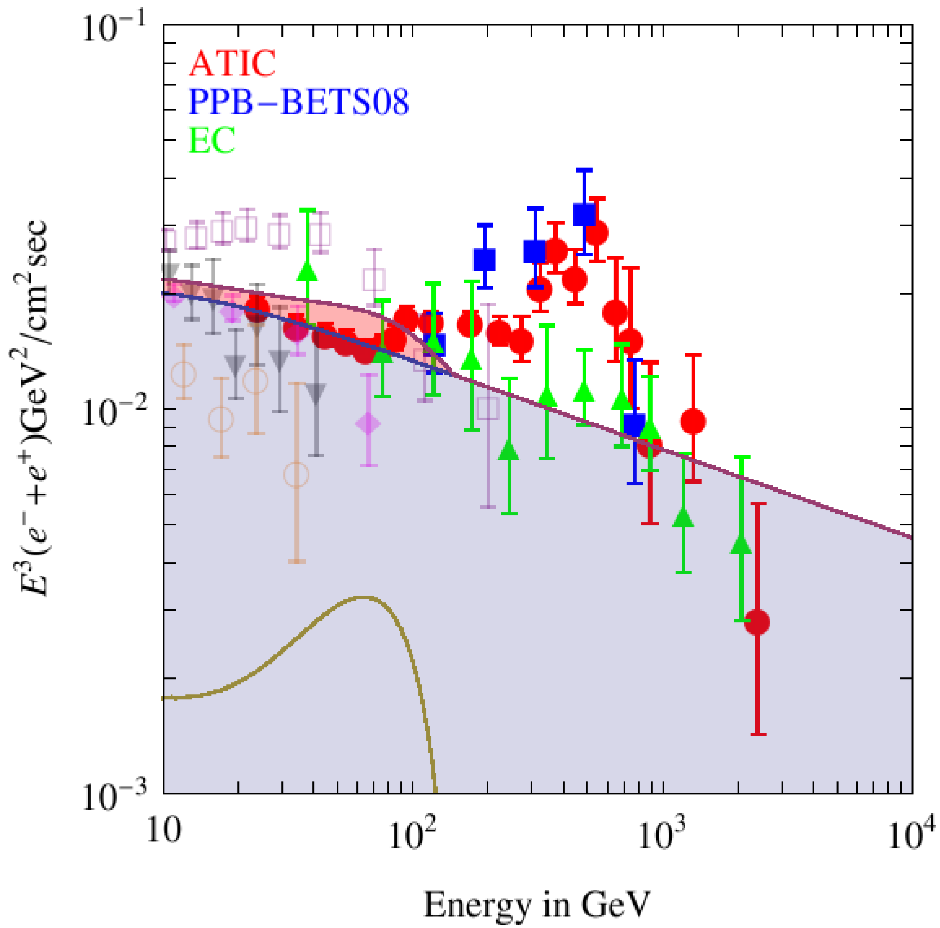
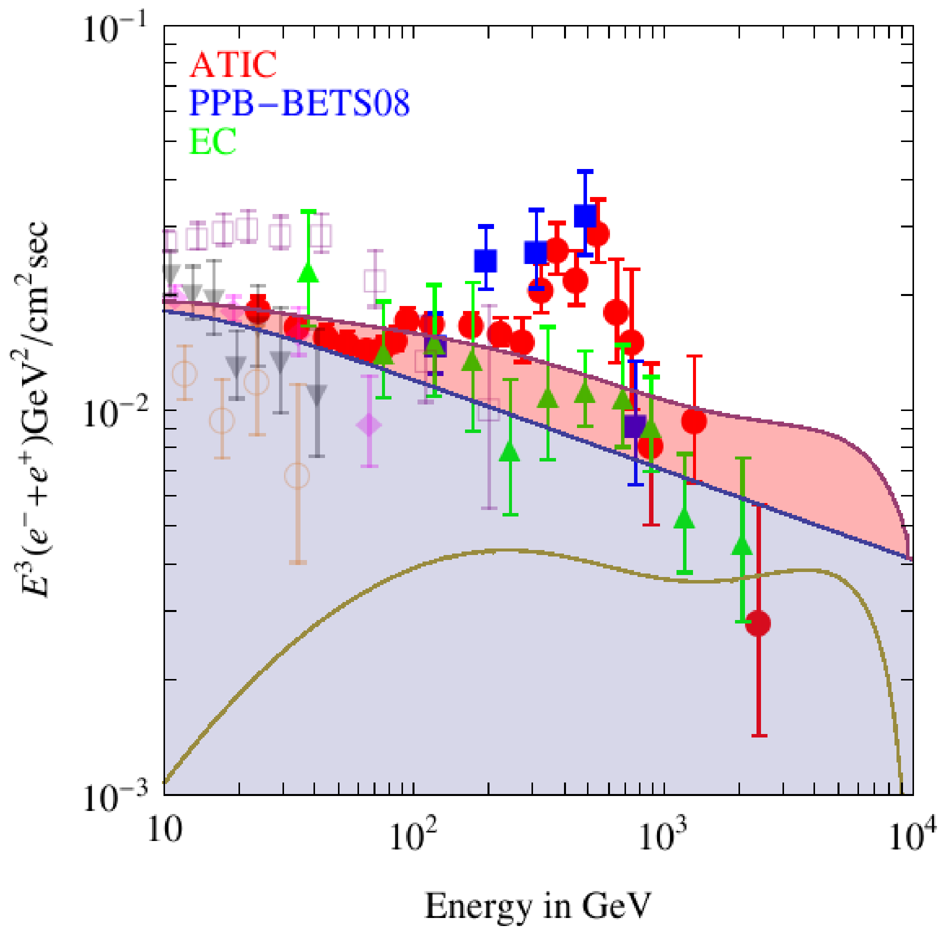


Figure 3 | ATIC results showing agreement with previous data at lower energy and with the imaging calorimeter PPB-BETS at higher energy. The

DM + DM —> … —> e^+ + e^- …

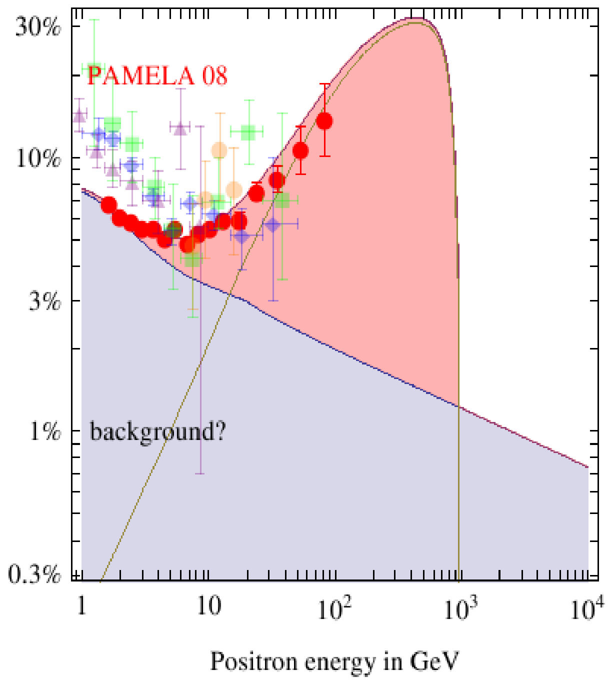


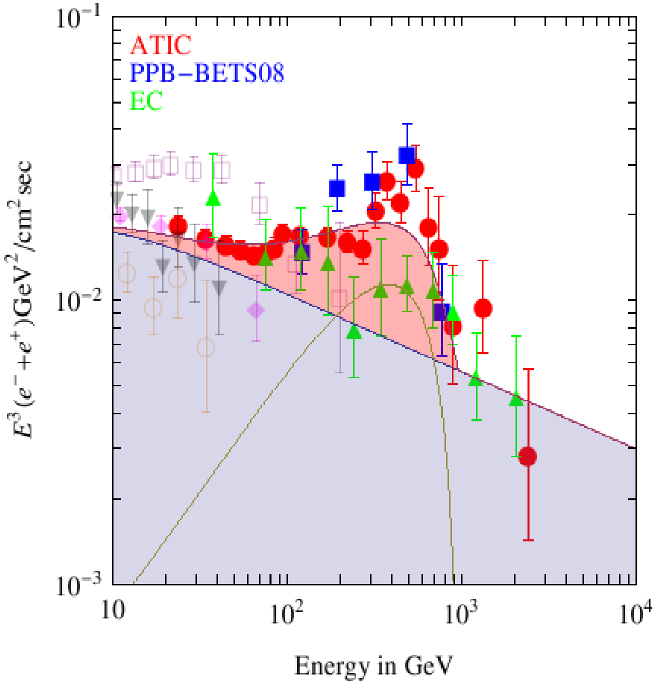
M_{DM} = 150 GeV into W^+W^-

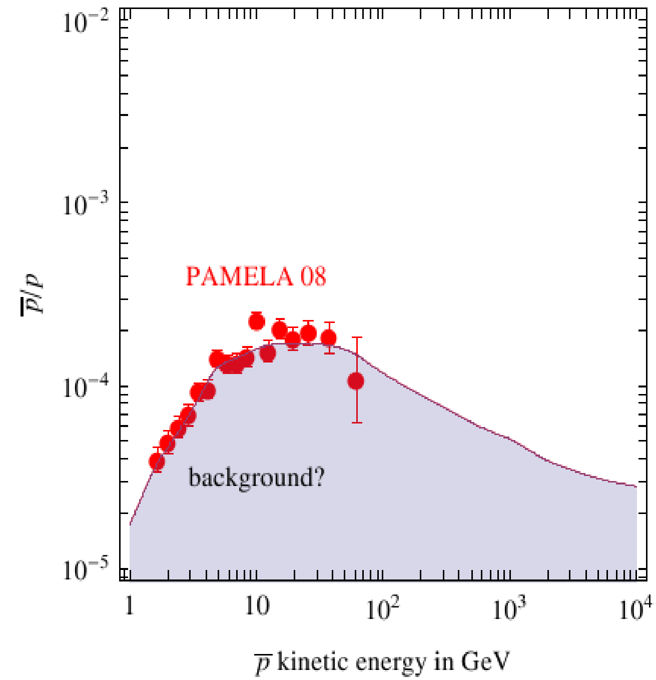


M_{DM} = 10 TeV into W^+W^-

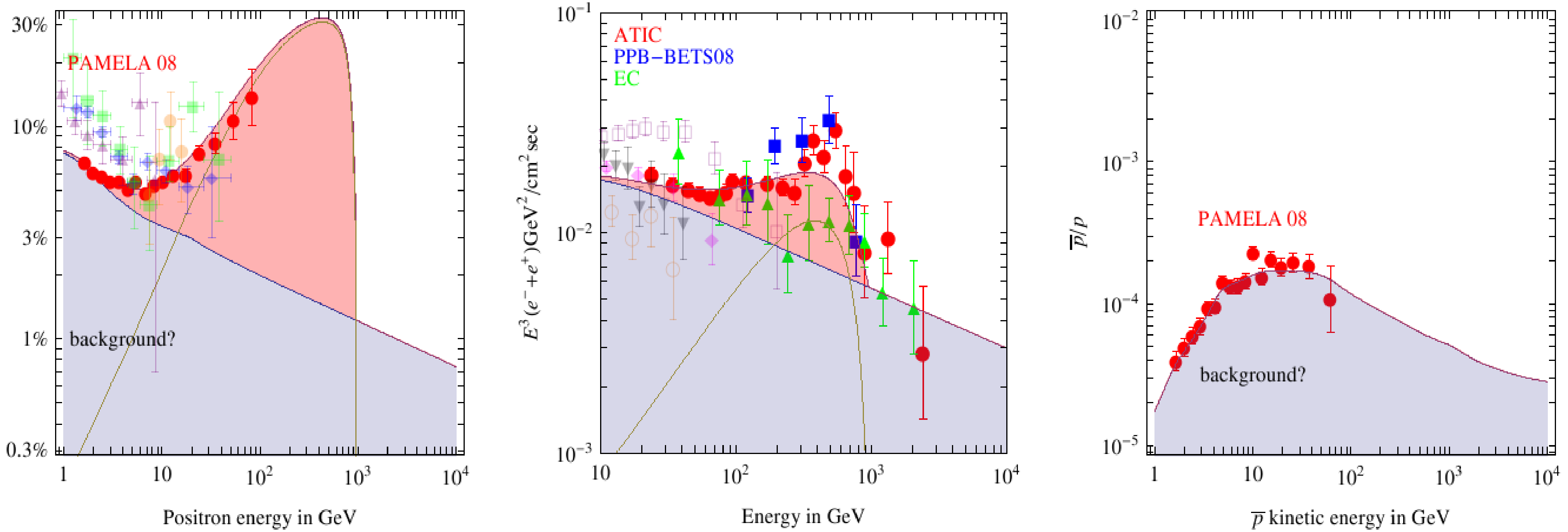
Annihilation of DM with M_{DM} = 1 TeV into $\mu^+ \mu^-$







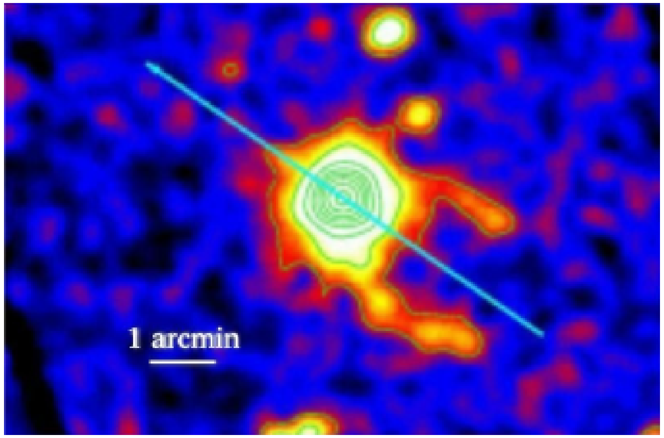
Annihilation of DM with M_{DM} = 1 TeV into $\mu^+ \mu^-$

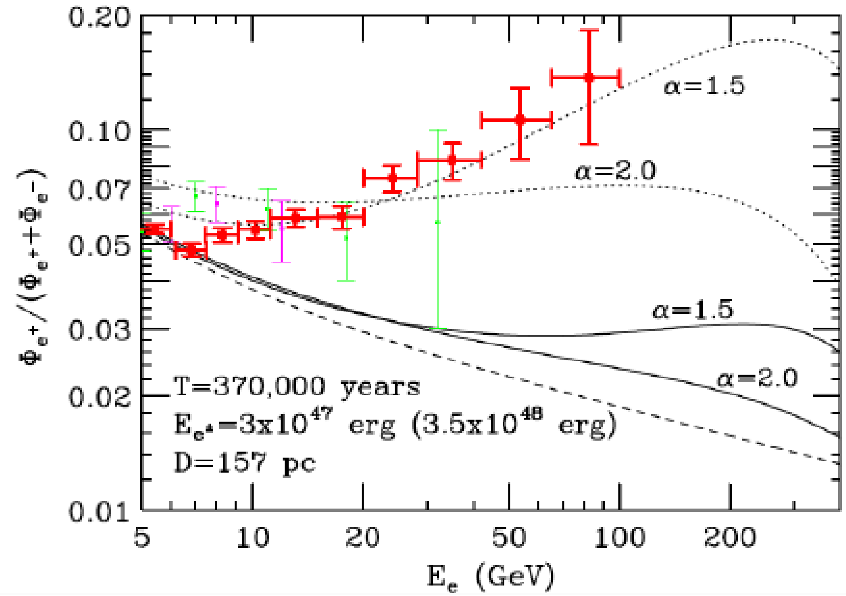


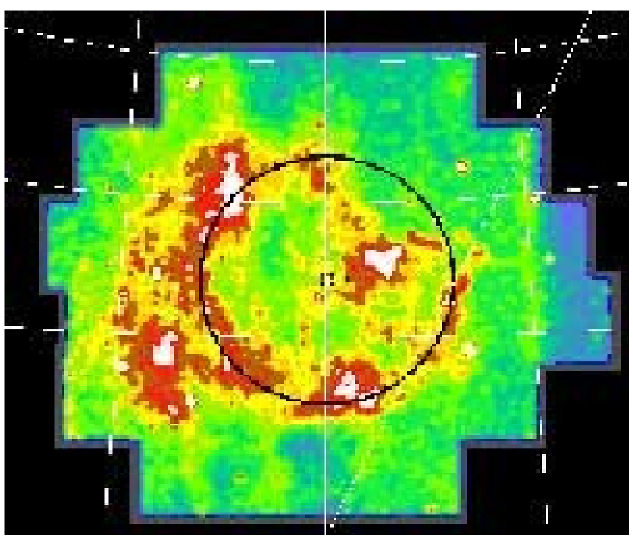
N.B. : need to increase the rate by a factor of 10^3...

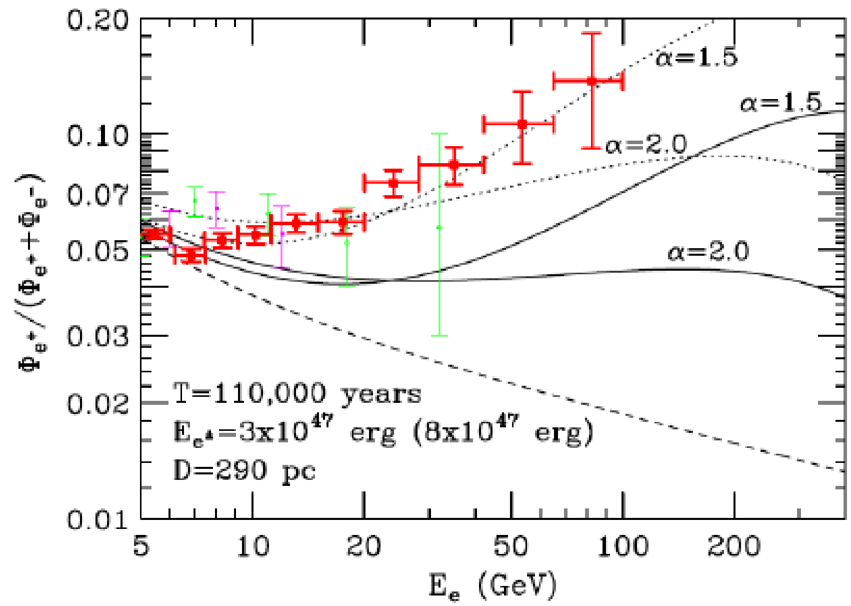
$dN_e/dE_e \propto E_e^{-\alpha} \exp(-E_e/600GeV)$

Geminga





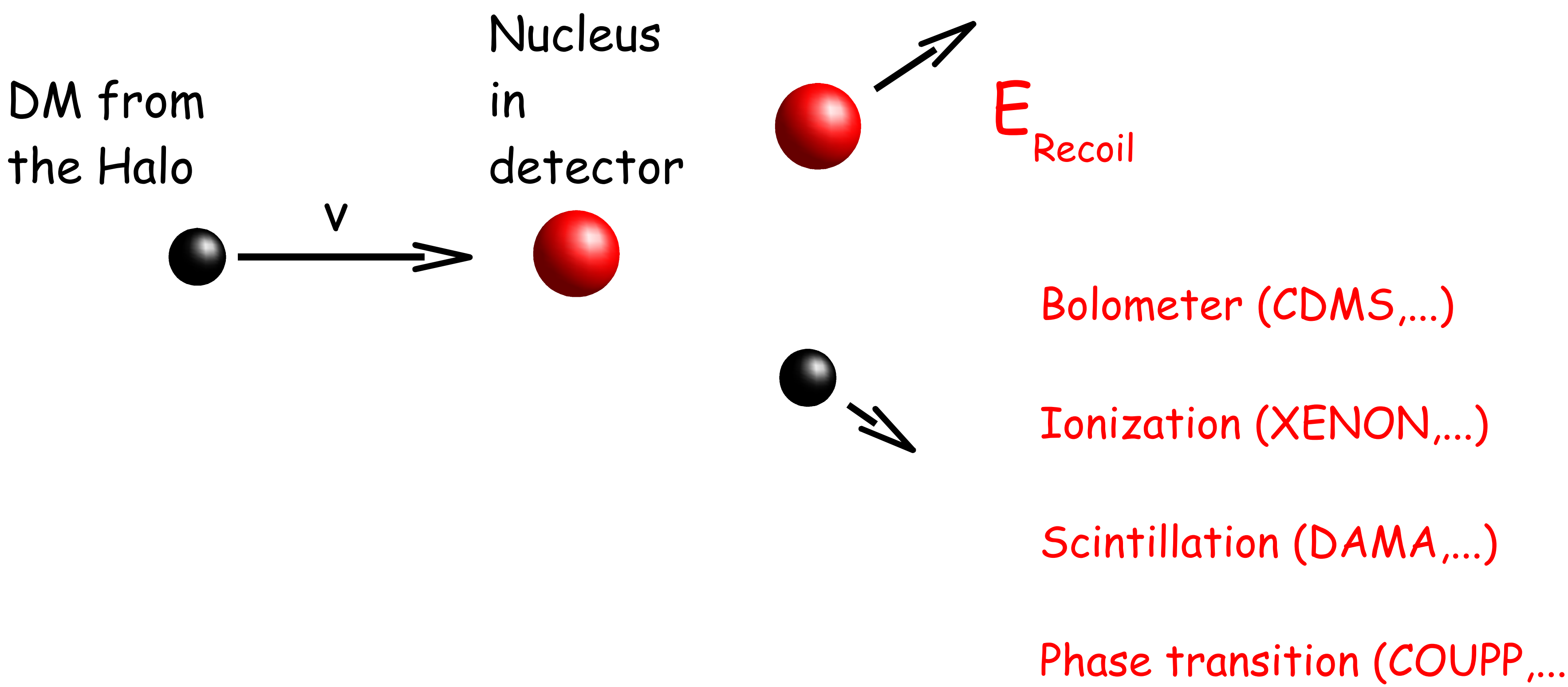


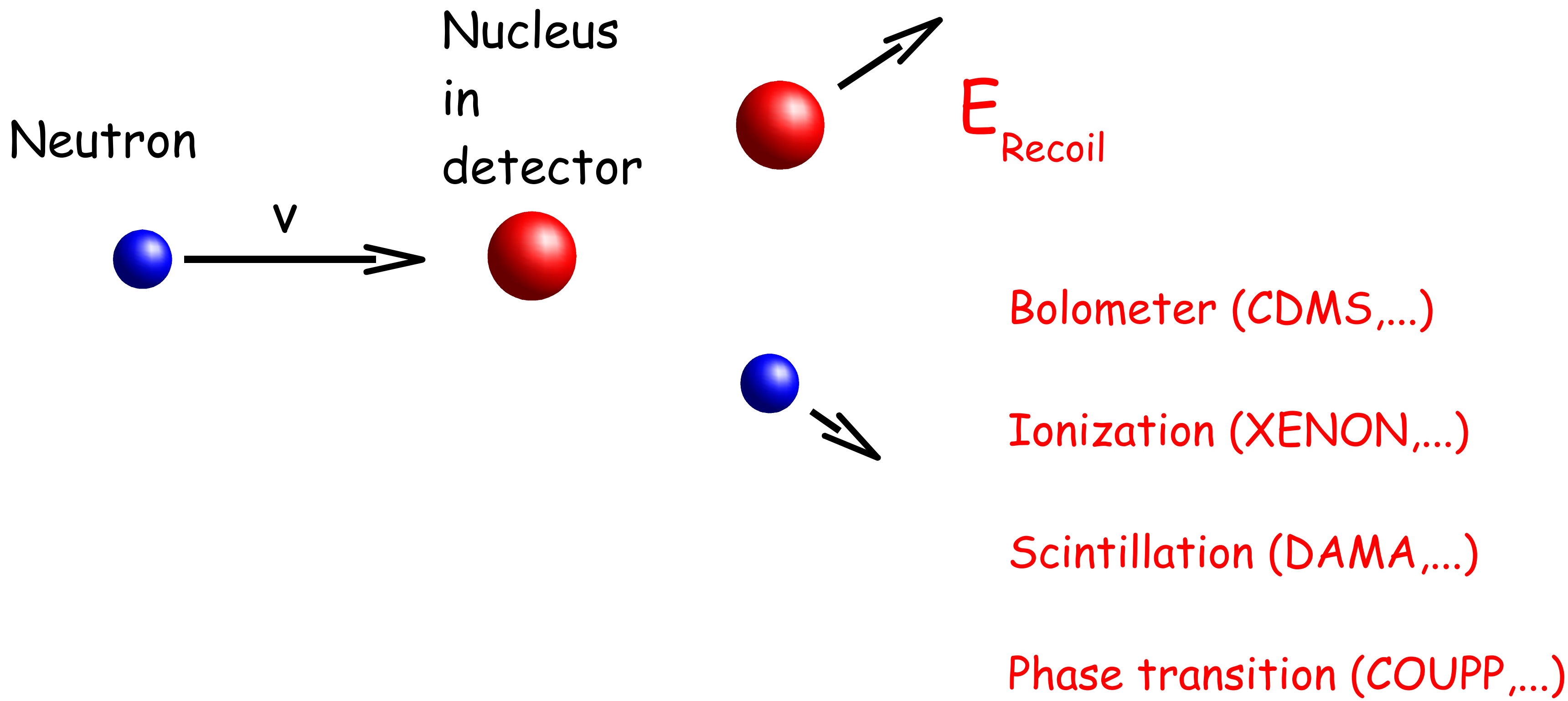


B0656+14

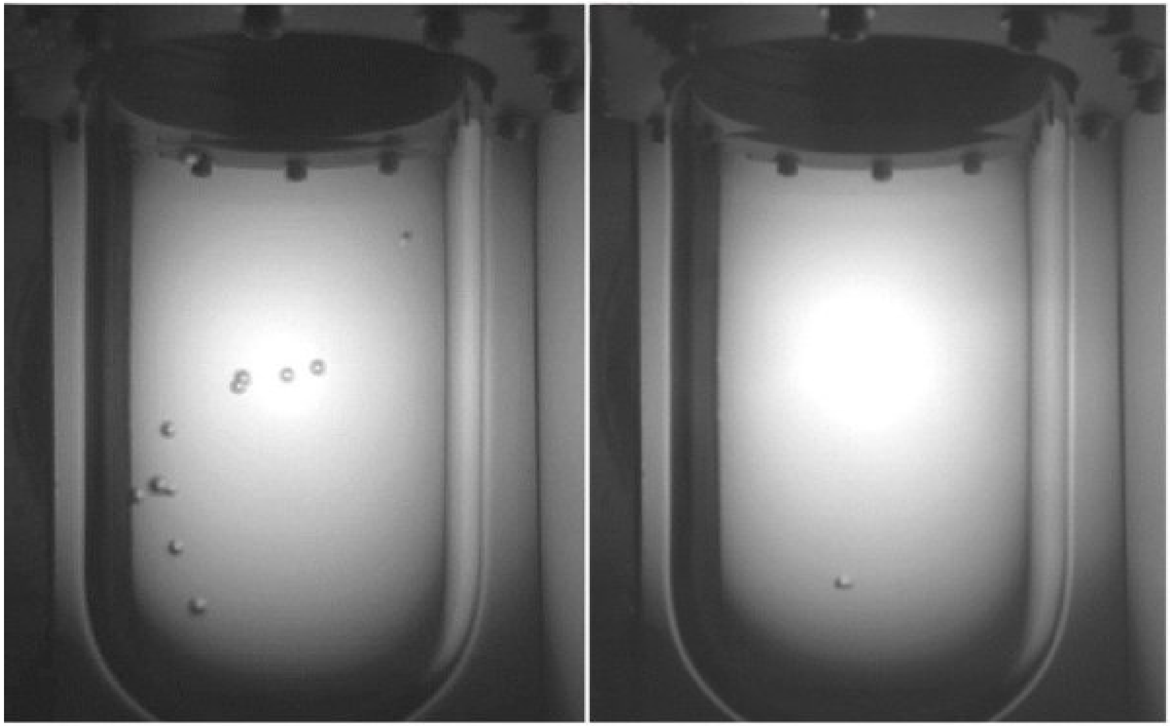
Hooper, Blasi, Serpico

V. Dark Matter Seen ?


DM from
the Halo
v
Nucleus
in
detector
E_{Recoil}
Bolometer (CDMS,...)
Ionization (XENON,...)
Scintillation (DAMA,...)
Phase transition (COUPP,...)

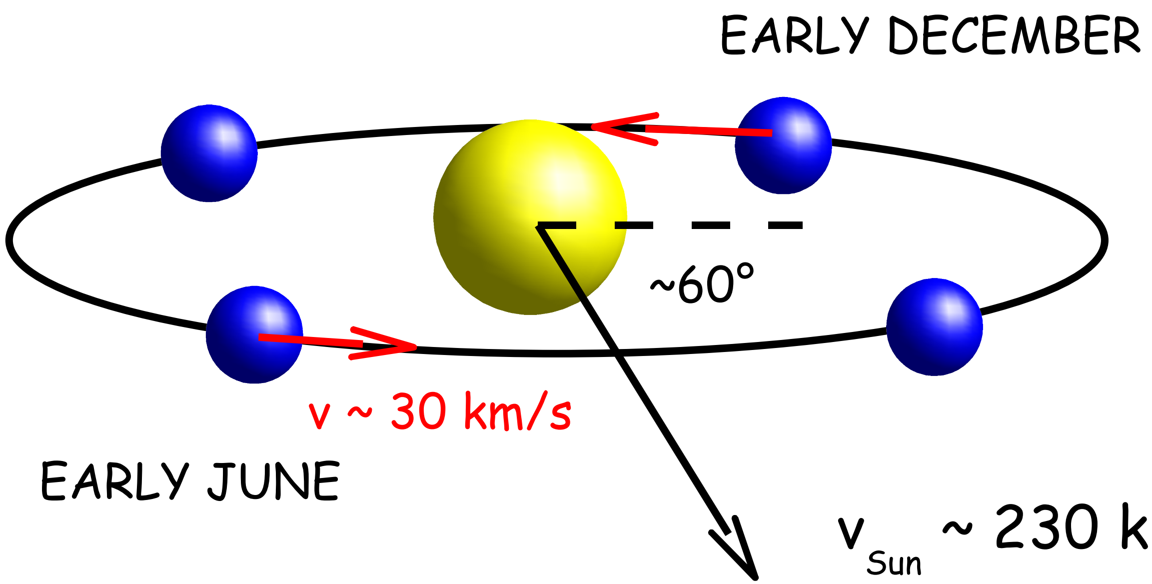

Neutron
v
Nucleus
in
detector
E_{Recoil}
Bolometer (CDMS,...)
Ionization (XENON,...)
Scintillation (DAMA,...)
Phase transition (COUPP,...)

The Chicagoland Observatory for Underground Particle Physics, or COUPP



neutron-like DM-like

Expect Annual Modulation of the Dark Matter Flux

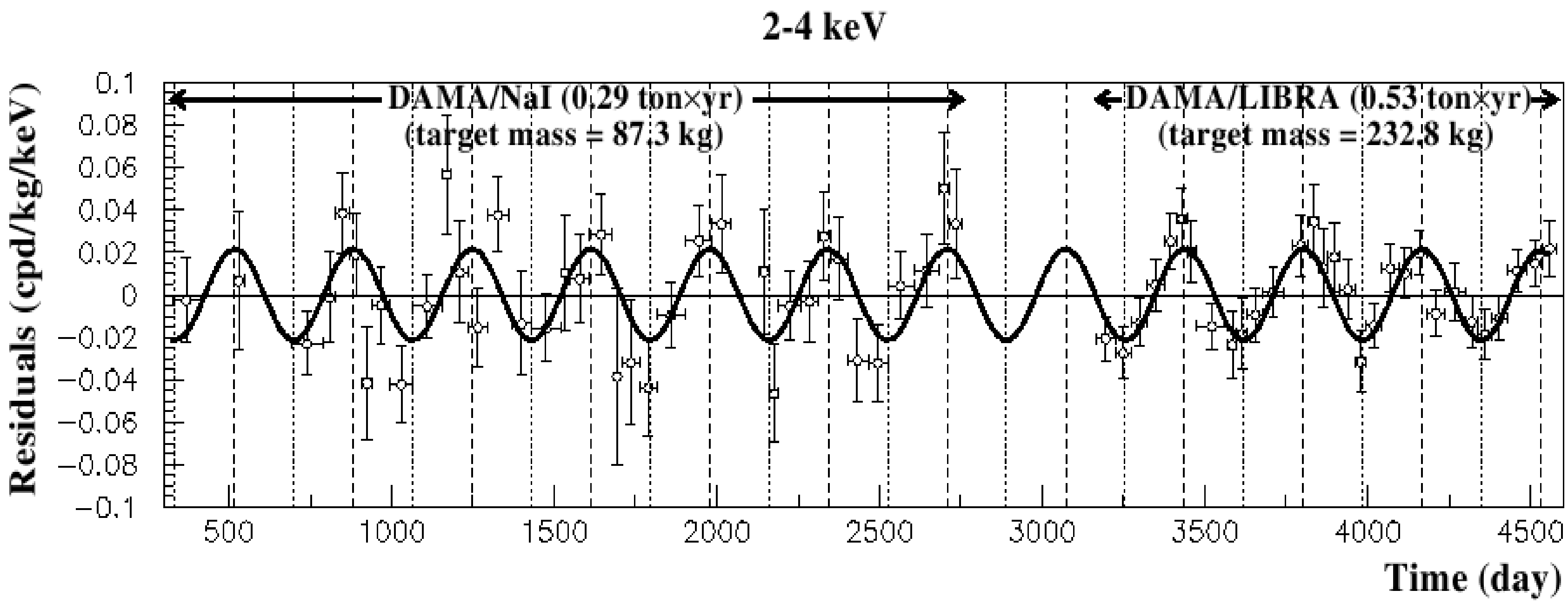


v_{Sun} ~ 230 km/s

= mean velocity of the Sun w.r.t. DM halo (?)

ROM2F/2008/07
April 2008

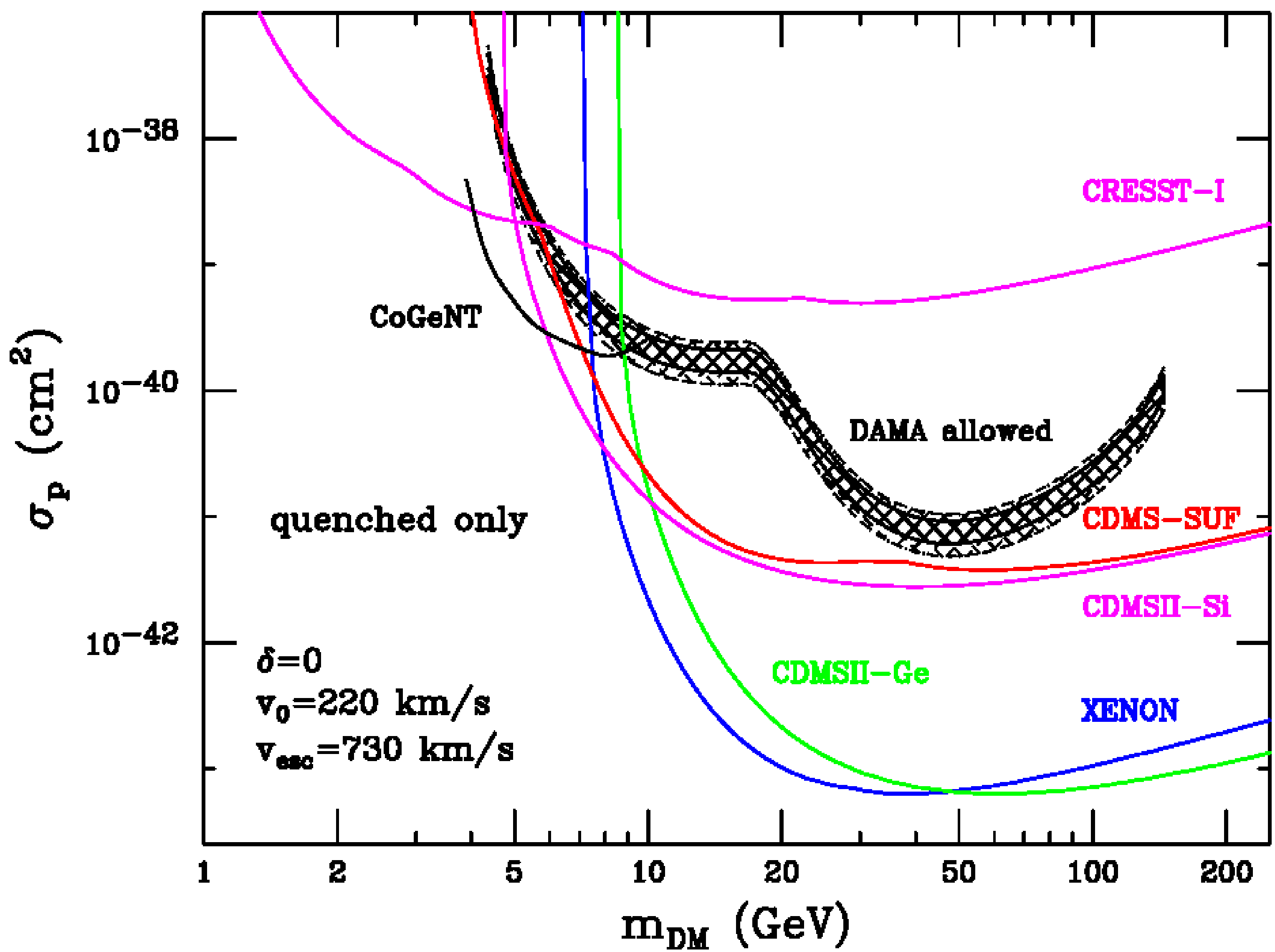
First results from DAMA/LIBRA and the combined results with DAMA/NaI



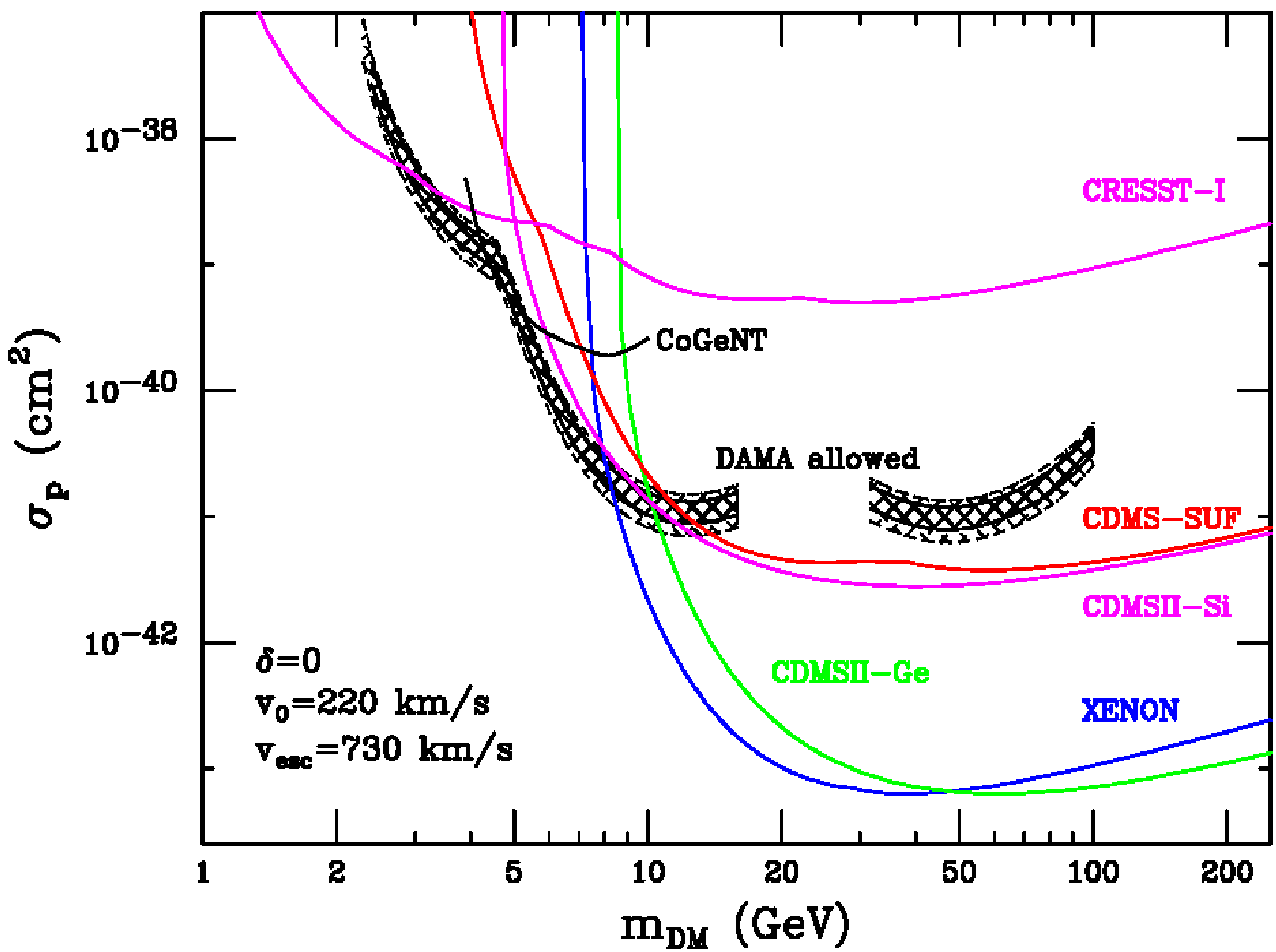
8.2 standard deviation (cumulative exposure of 0.82 ton x year)

Maximum around early June

The Trouble with DAMA

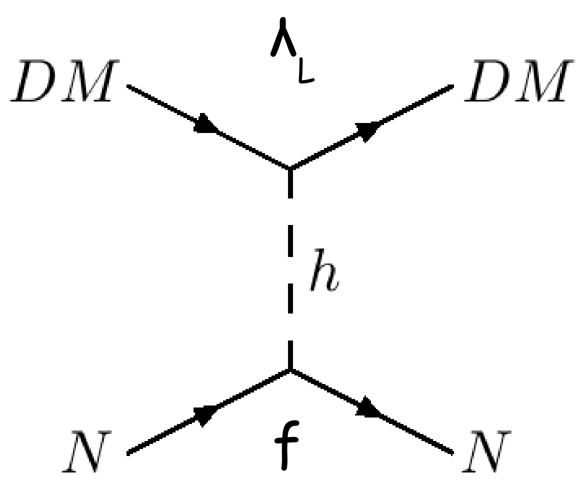


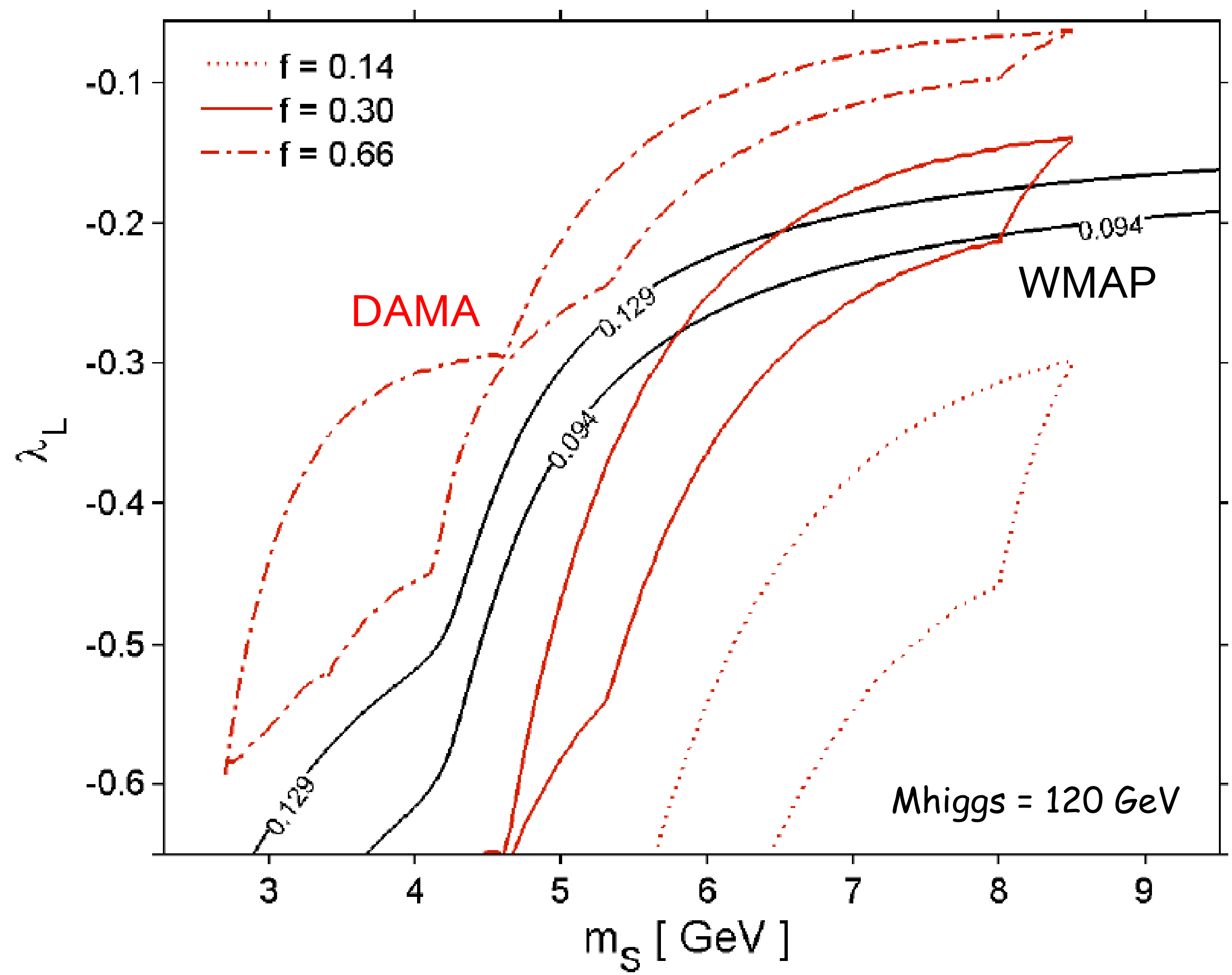
Pietrello & Zurek



Pietrello & Zurek

A light scalar WIMP through the Higgs Portal ?





Sarah Andreas, Thomas Hambye, M.T.

A multi-prong search

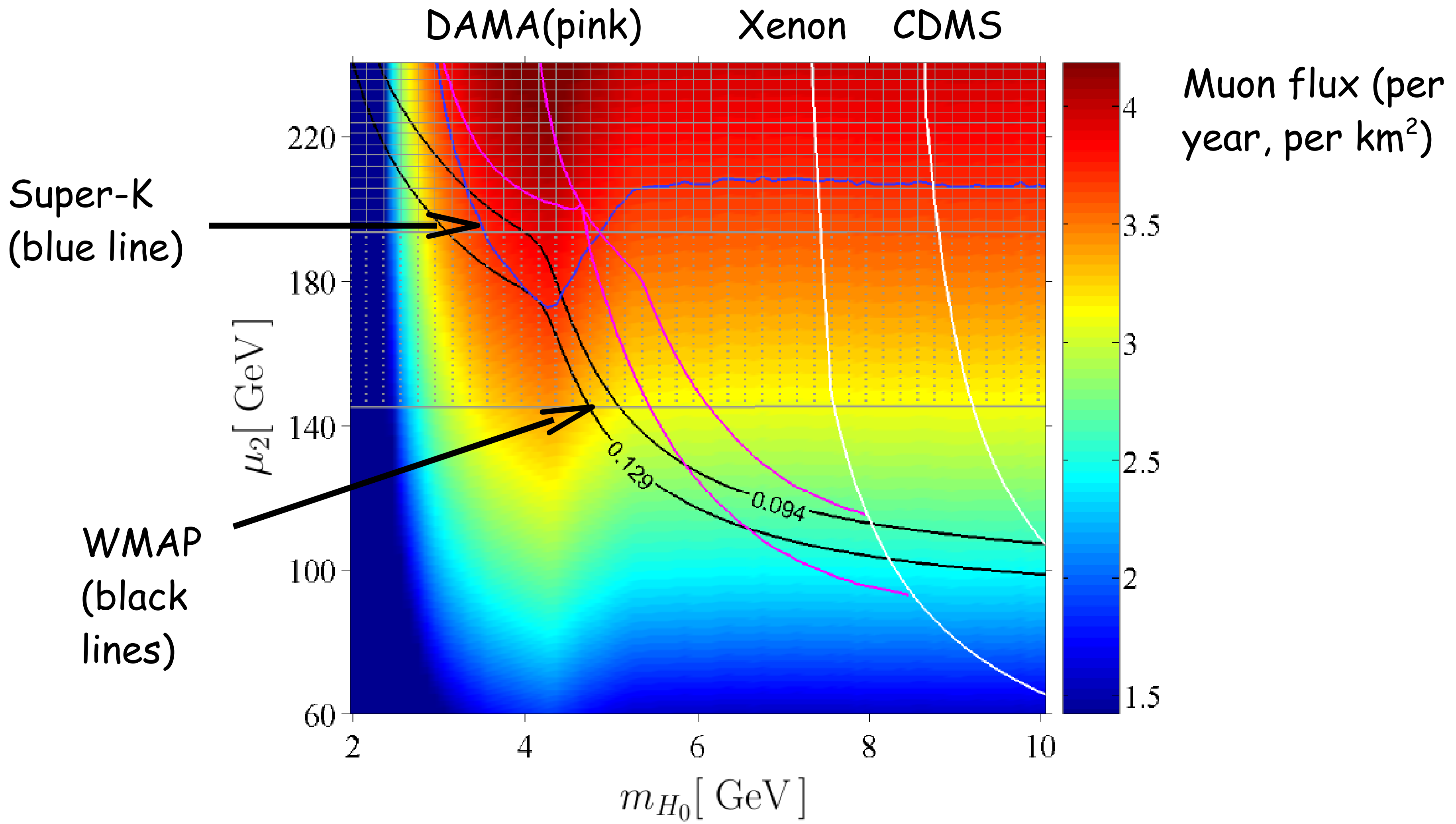
An (almost) invisible Higgs @ the LHC ?

... -> Z -> Z + h

└-> DM + DM

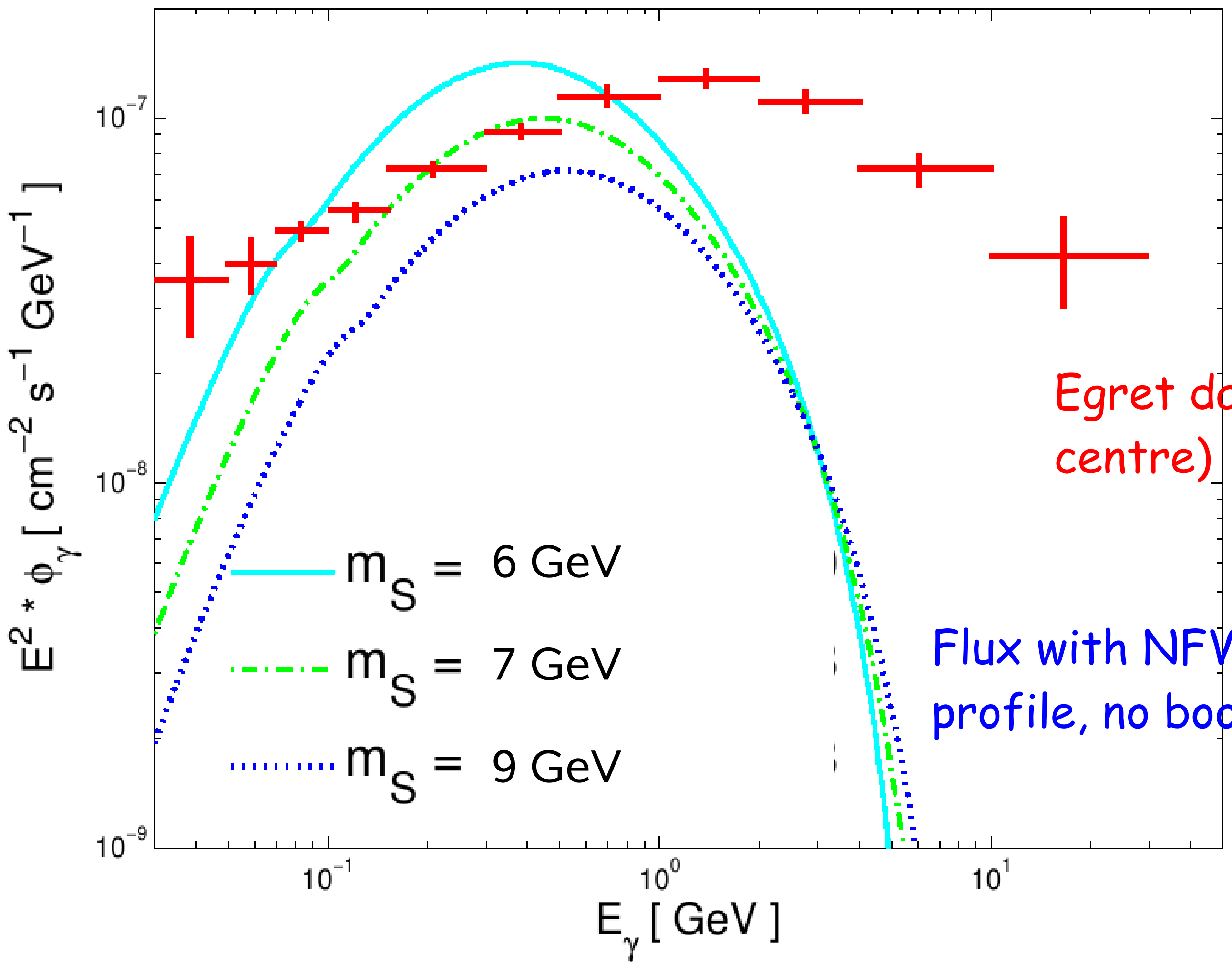
lepton-antilepton pair + missing energy

Neutrinos from DM captured by the Sun



S.Andreas, Q.Swillens,
M.T.   arXiv:0901.1750

Gammas rays from the Galactic centre



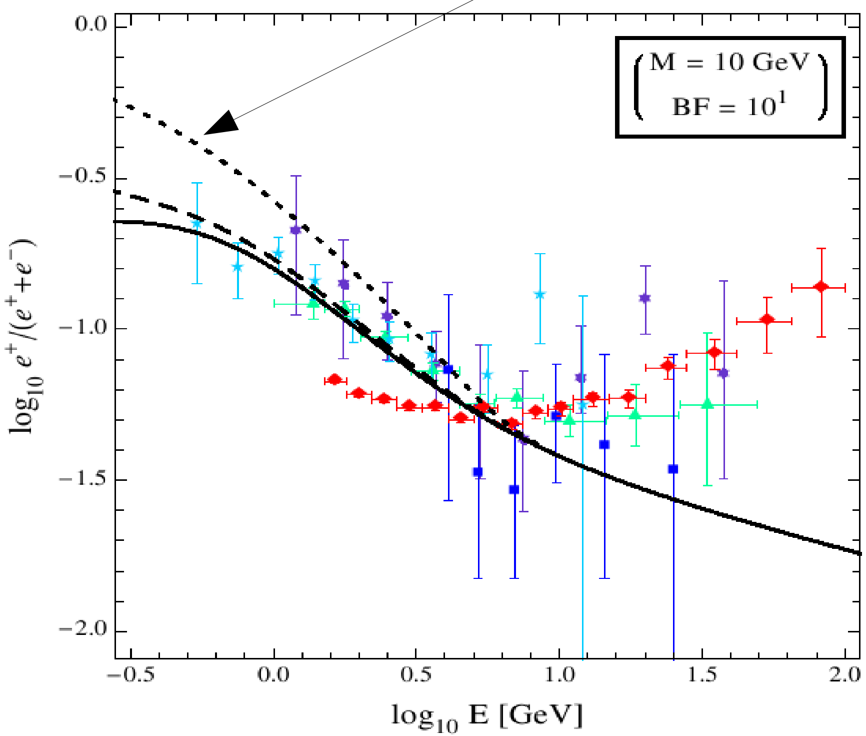
Egret data (Galactic centre)

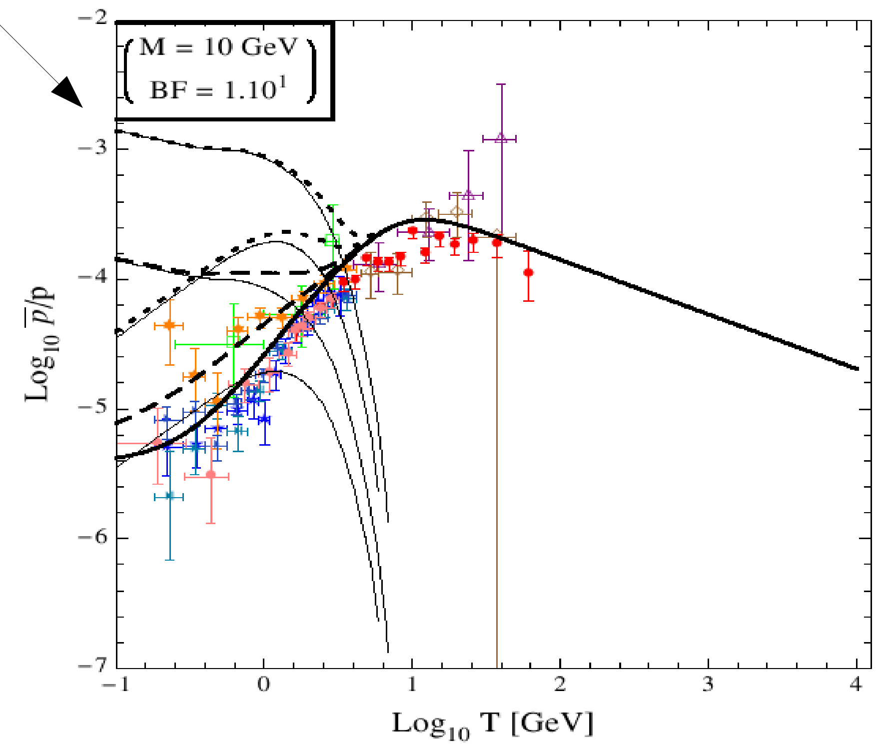
Flux with NFW profile, no boost

S.Andreas, Th. Hambye, M.T.

Positrons and antiprotons excess in cosmic rays

boost=10





E.Nezri, G. Vertongen, M.T.

A large anti-deuteron flux

Spallation production small, and spectrum falling off at low energies: low background

→ good probe of dark matter annihilation

An 8 GeV candidate, 0.3 GeV/cm local density, FRW distribution, gives

Φ = 9 10^{-7} (GeV/nucleon s sr $m^2)^{-1}$ at T=0.25 GeV/n

(expected sensitivity of AMS-02 is

Φ = 4.5 10^{-7} (GeV/nucleon s sr $m^2)^{-1}$ at T=0.25 GeV/n

Conclusions ?

$$\frac{\text{Mass}_{\text{baryon}} \times \text{Density}_{\text{baryon}}}{\text{Mass}_{\text{dark matter}} \times \text{Density}_{\text{dark matter}}} \approx \frac{1}{5}$$

QCD
Dynamics

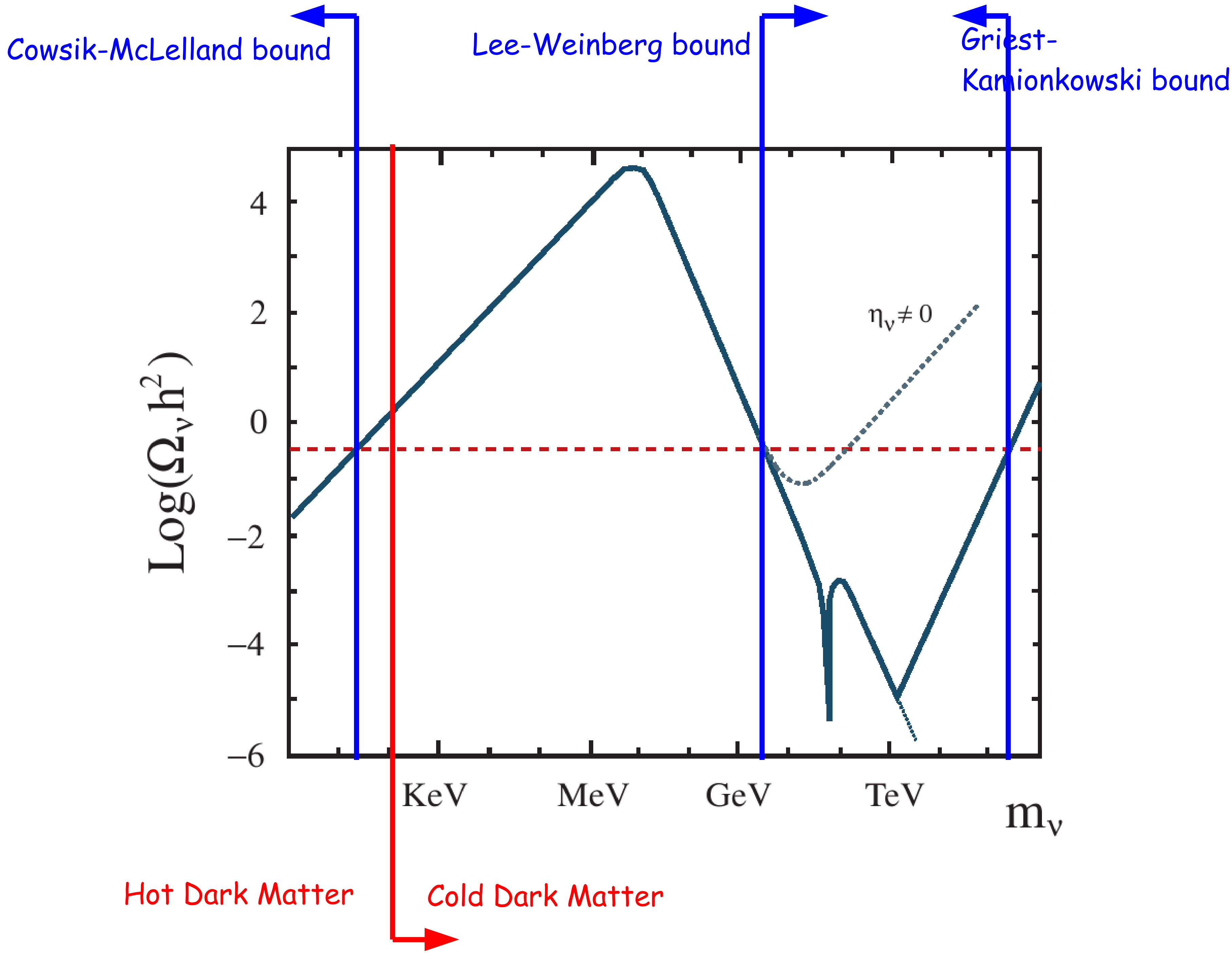
Baryogenesis (CP & B violation)

$$\frac{\text{Mass}_{\text{baryon}} \times \text{Density}_{\text{baryon}}}{\text{Mass}_{\text{dark matter}} \times \text{Density}_{\text{dark matter}}} = O(1)$$

EW Scale
but could be anything
else

Freeze-Out
but really could be anything
else

$$\frac{\text{Density}_{\text{baryon}}}{\text{Density}_{\text{dark matter}}} = O(1)\ ?$$

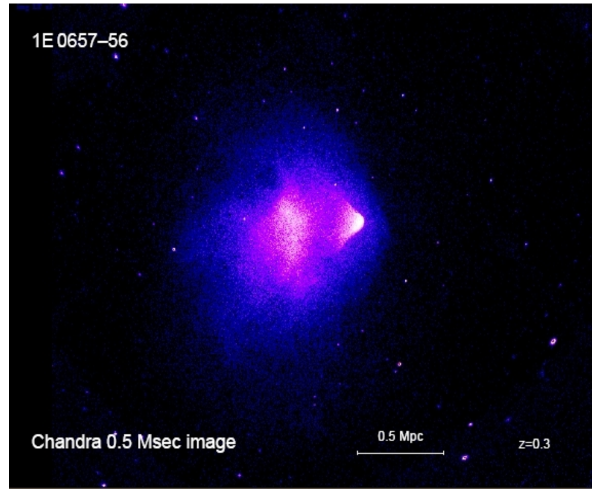


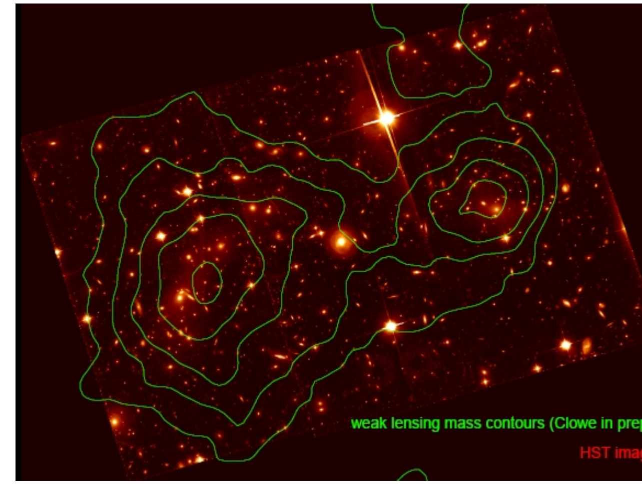
Cowsik-McLelland bound
Lee-Weinberg bound
Griest-
Kamionkowski bound
4
2
0
−2
−4
−6
$\text{Log}(\Omega_\nu h^2)$
$\eta_\nu \neq 0$
KeV
MeV
GeV
TeV
m_ν
Hot Dark Matter
Cold Dark Matter

Visible

X-ray

Gravitational lensing





Galaxies

Intergalactic Hot Gas

Total Mass

$M_{visible} \sim 10^{14}\ M_{\odot}$

$M_{hot\ gas} \sim 10^{15}\ M_{\odot}$

$M_{tot} \sim 10^{16}\ M_{\odot}$

Visible Baryons

Missing Baryons

All Baryons *

Baryons

+

Dark Matter

* consistent with primordial nucleosynthesis

Abundance of Dark Matter in the Milky Way?

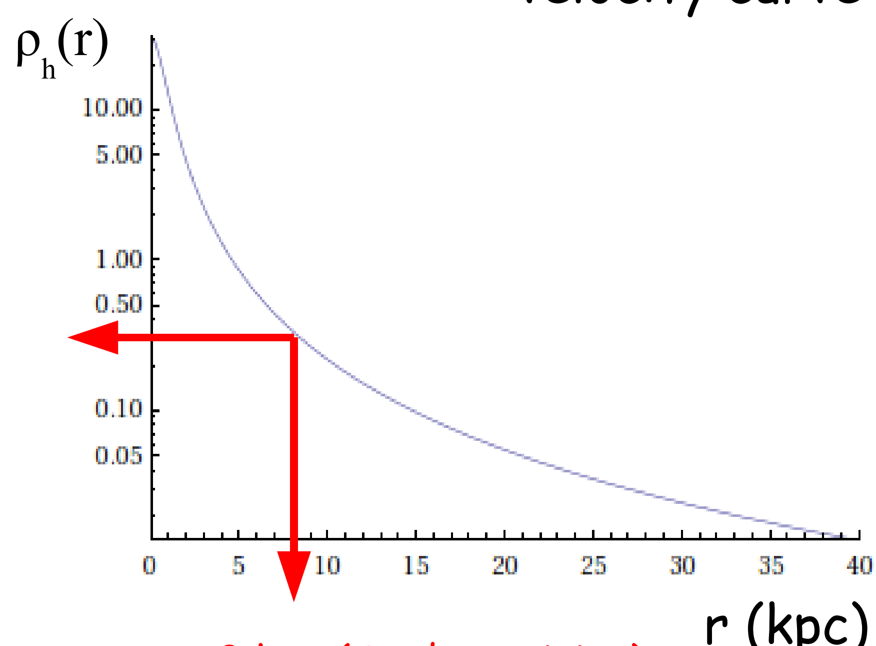
Bold model: a cored isothermal spherical halo of dark matter

$$\rho_h(r) = \rho_0 (a^2 + r_0^2)/(a^2 + r^2) \quad \Rightarrow \quad v_h^2 = v_{h\infty}^2 (1 - a/r \, \mathrm{atan}(r/a))$$

To be fitted to observed velocity curve

Infered local abundance

$\rho_0 = 0.3$ GeV/cm^3



r_0= 8 kpc (Sun's position)

Five Aspects of Dark Matter

Michel H.G. Tytgat
Brussels University, Belgium

Talk at Brookhaven National Laboratory, April 14th 2009

I. Why Dark Matter ?

II. How Much Dark Matter ?

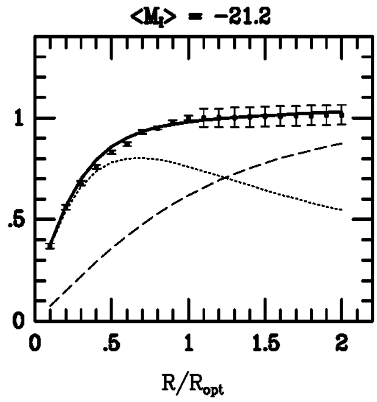
III. Which Dark Matter ?

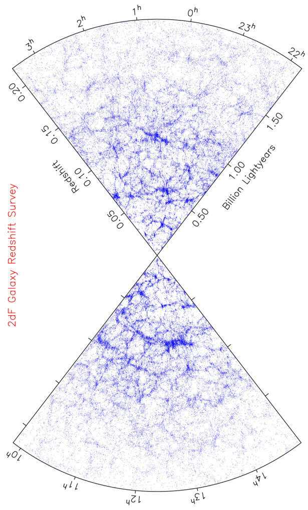
IV. Dark Matter and the Defeat of Antimatter

V. Dark Matter Seen ?

I. Why Dark Matter?

Confidence

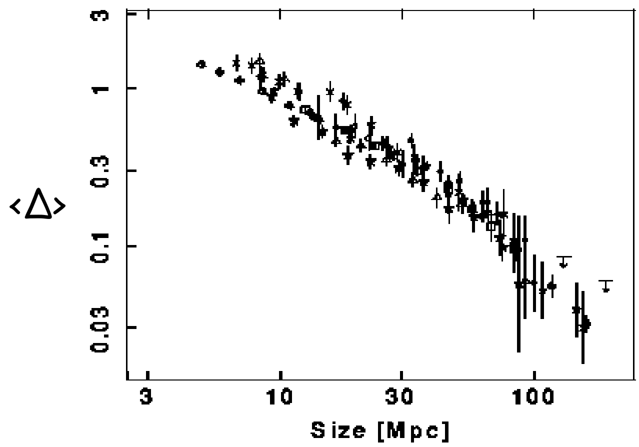




Complexity

Matter inhomogeneities are small on large scales

$$\Delta = |\delta\rho/\rho| \ll 1$$

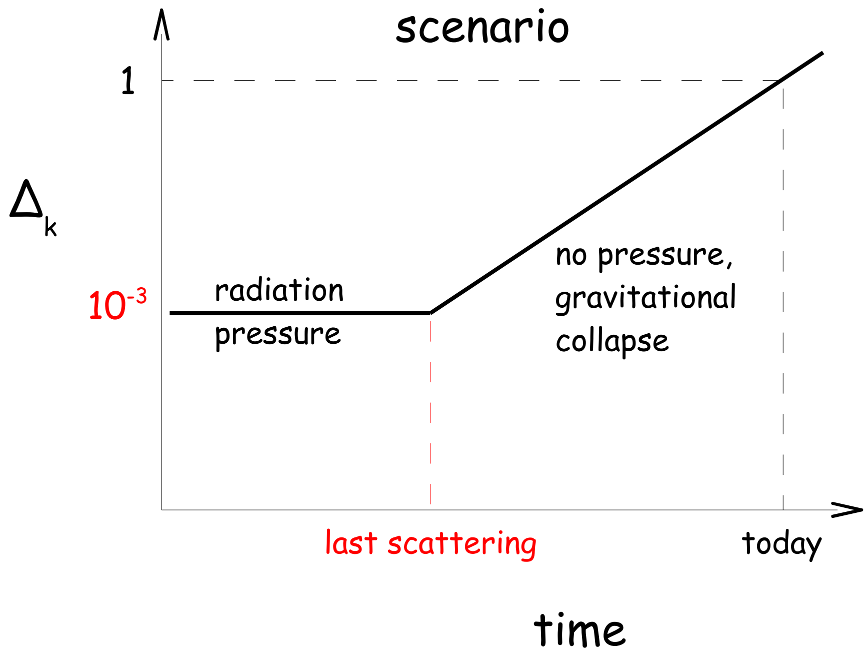


Evolution of inhomogeneities (Jeans Instability)

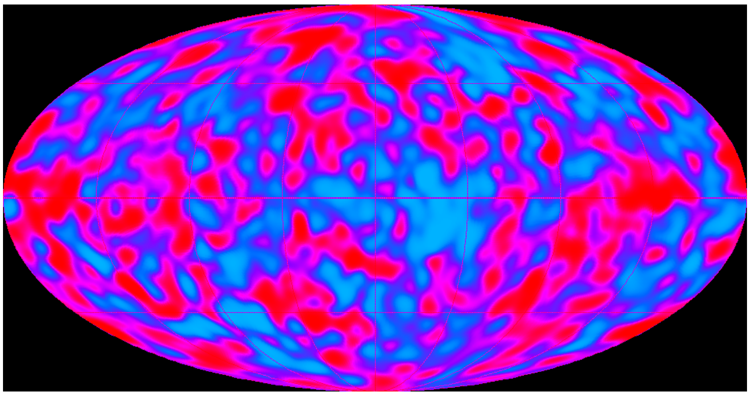
$$\ddot{\Delta} + 2\frac{\dot{a}}{a}\dot{\Delta} + (v_s^2 k^2 - 4\pi G\rho)\Delta = 0$$

pressure vs gravity

Only baryonic matter scenario

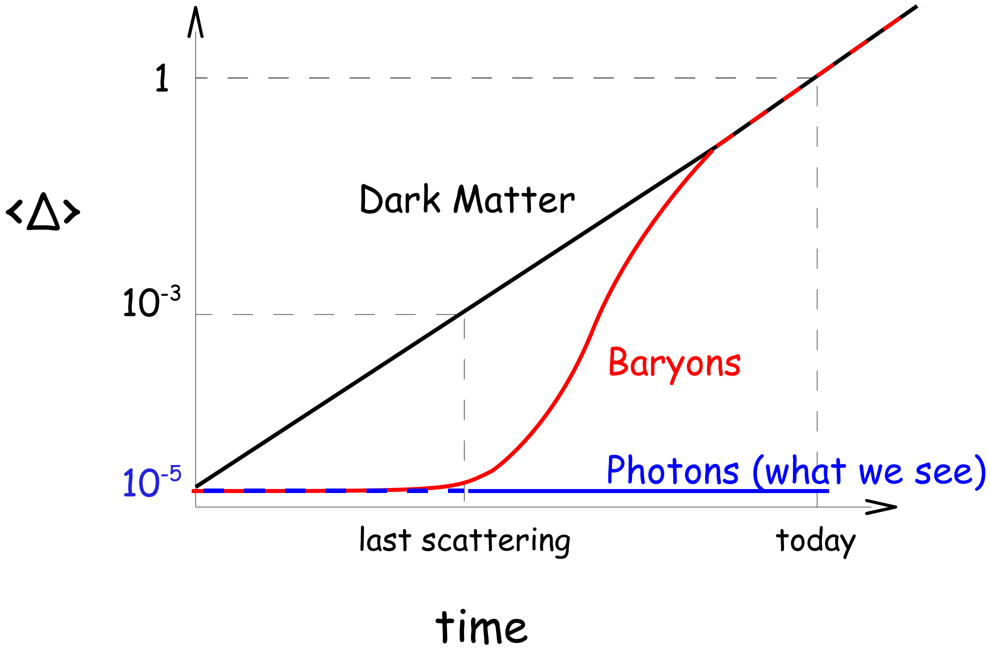


CMBR temperature anisotropies



$$\Delta \approx \delta T/T = O(10^{-5})$$

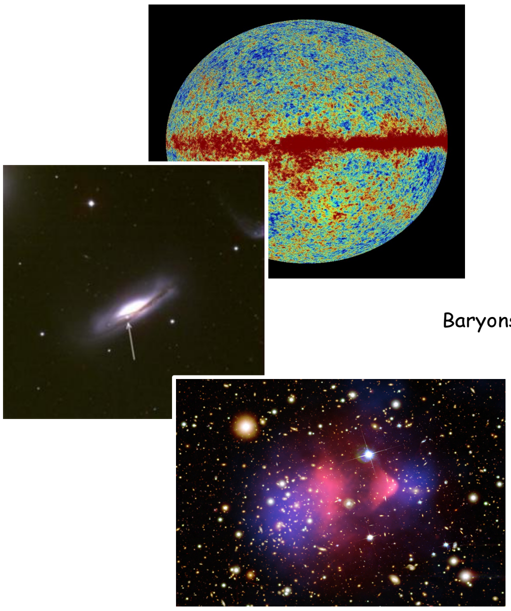
The (cold) dark matter scenario

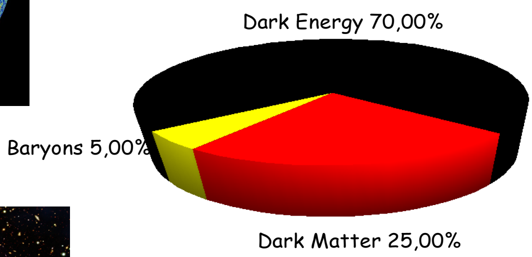


Peebles, 1982

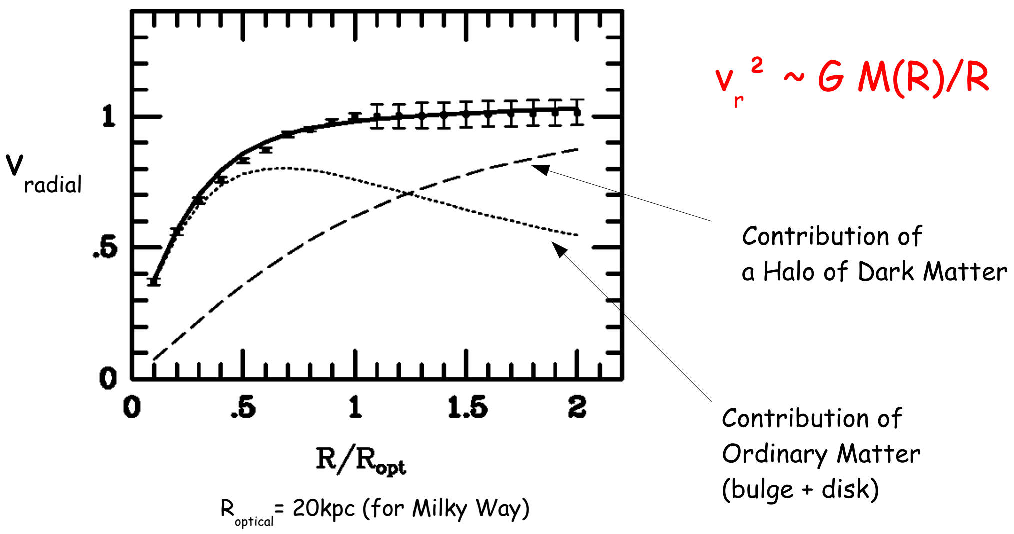
II. How much Dark Matter ?

The Concordance Model





The rotational curve of spiral galaxies (Vera Rubin, 80')



(Picture is a compilation of 1000 rotation curves, Persic et al, 99)

Abundance of Dark Matter in the Milky Way?

A bold model: cored isothermal spherical halo of dark matter

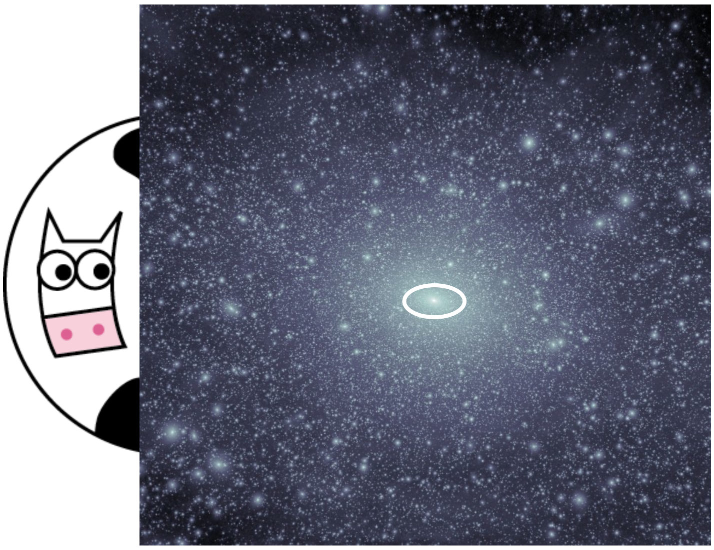
$\rho_h(r) = \rho_0 (a^2 + r_0^2)/(a^2 + r^2)$ $\longrightarrow$ $v_h^2 = v_{h\infty}^2 (1 - a/r \, \mathrm{atan}(r/a))$

To be fitted to observed velocity curve

Infered local abundance

$$\rho_0 \sim 0.1 - 2 \text{ GeV/cm}^3$$

Fiducial density is $\rho_0 = 0.3$ GeV/cm^3



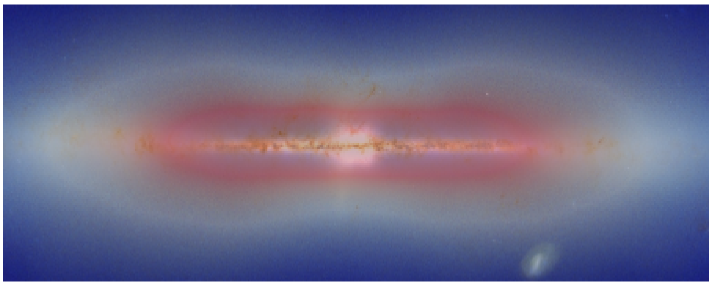
Simulation from the Via Lactea project (Dark matter only)

(Diemand et al)

arXiv:0803.2714v2

Thin, thick and dark discs in ΛCDM

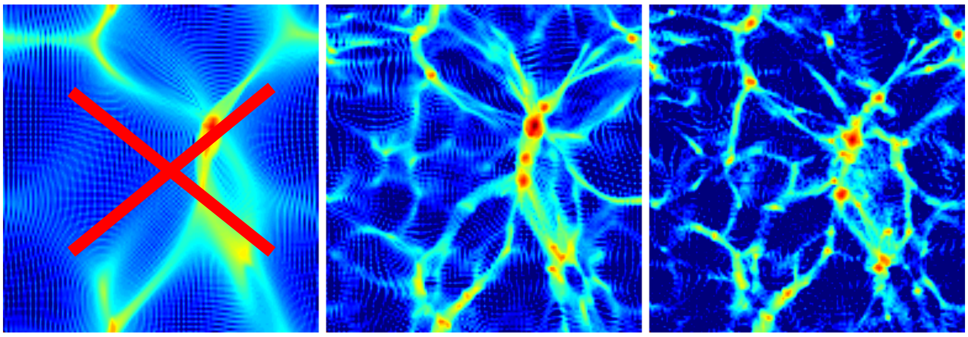
J. I. Read*[1], G. Lake[1], O. Agertz[1] & Victor P. Debattista[2]
[1] *Institute of Theoretical Physics, University of Zürich, Winterthurerstrasse 190, 8057 Zürich, Switzerland.*
[2] *RCUK Fellow; Centre For Astrophysics, University of Central Lancashire, Preston, PR1 2HE, UK.*



Impact of gas/star disk on dark matter halo -> dark disk

$$1/2 < \rho_{disk}/\rho_{halo} < 2$$

III. Which Dark Matter ?



Hot Dark Matter

First large structures,
then smaller ones

Not the neutrinos of the Standard Model

Moreover, they are too light

Cold Dark Matter

First galaxies

Then clusters of galaxies, etc...

A stable, Weakly Interacting Massive Particle (or WIMP) ?

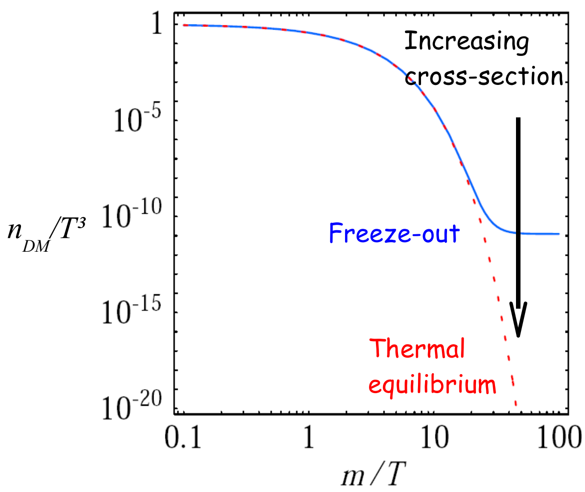
DM + DM <-> Known Particles

Freeze-out when
Int. rate ~ Exp. rate

$\langle \sigma v \rangle n_{DM} \sim T_{FO}^2 / m_{Planck}$

Relic abundance
$n_{DM} \sim 1/\langle \sigma v \rangle$

WMAP requires
$\langle \sigma v \rangle \sim 1$ pb



Stability from Symmetry

U(1) symmetry: $\Psi \rightarrow e^{i\beta}\Psi$

e.g. Proton stability = baryon number conservation

Z_2 symmetry: $\Psi \rightarrow -\Psi$

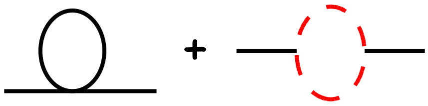
e.g. R-parity in Supersymmetric extensions of the Standard Model

Others: e.g. $\Psi_i \rightarrow \Psi_j + \Psi_k$ with i,j,k in an SU(2)

An Electroweak Connection ?

SUSY

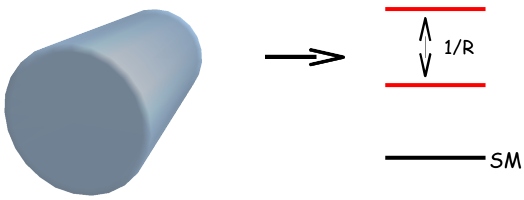
δM^2_{Higgs} =



$\sim M^2_{Higgs} \ll M^2_{Planck}$

R-parity: $\Psi_{SM} \longrightarrow \Psi_{SM}$ $\quad \Psi_{susy} \longrightarrow -\Psi_{susy}$

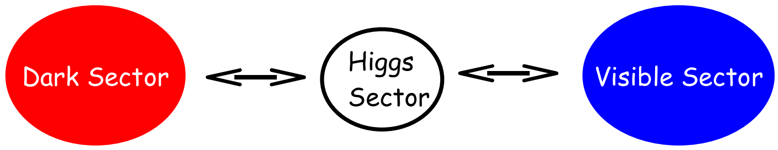
Extra Dimensions



KK-parity: $\Psi_{SM} \longrightarrow \Psi_{SM}$

$\Psi_{KK} \longrightarrow -\Psi_{KK}$

The Brout-Englert-Higgs portal



e.g. The Inert Doublet Model

$\Psi_{\text{Higgs}} \longrightarrow \Psi_{\text{Higgs}}$ $\qquad$ $\Psi_{\text{Inert Higgs}} \longrightarrow -\Psi_{\text{Inert Higgs}}$

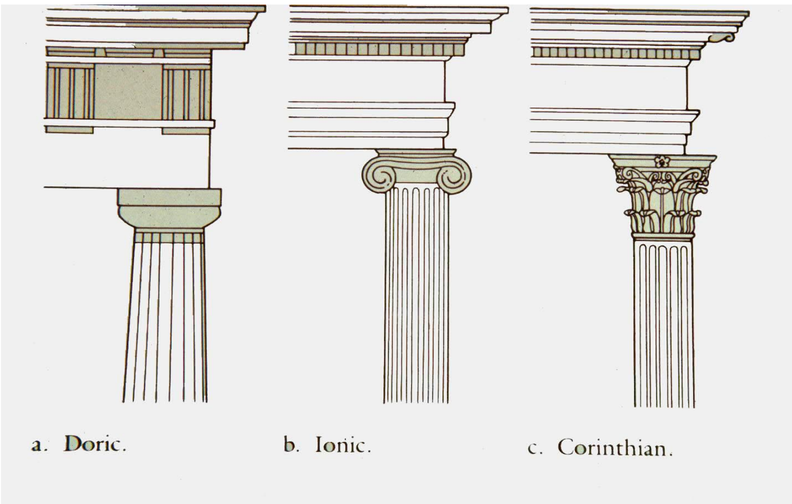
Easy way to prevent FCNC

WIMP Dark Matter Archetypes

Spin 0
The Inert Doublet

Spin $\frac{1}{2}$
The Neutralino

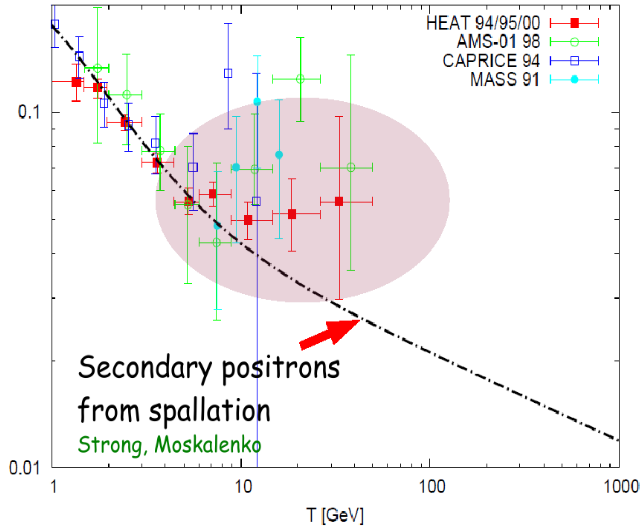
Spin 1
The Kaluza Klein photon



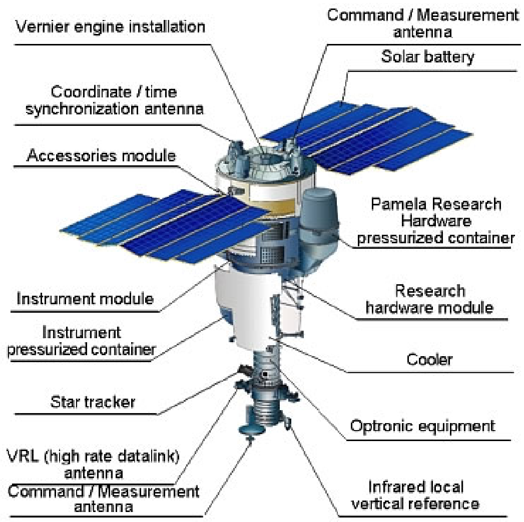
IV. Dark Matter and the defeat of Antimatter

Positron fraction in Cosmic Rays

$$\frac{e^+}{e^+ + e^-}$$

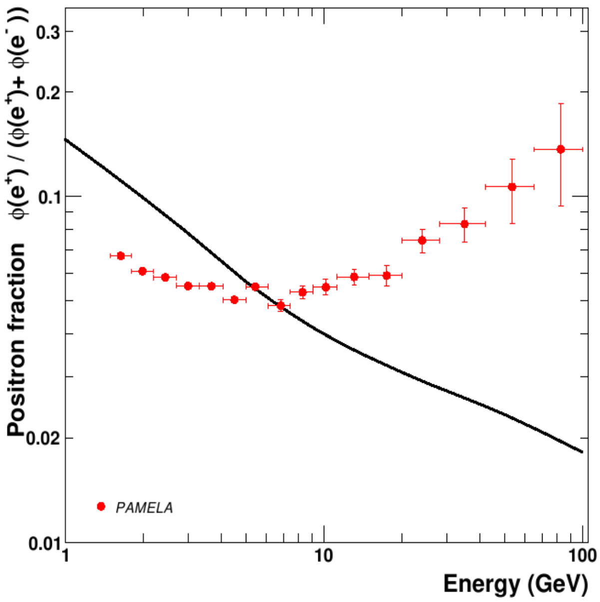


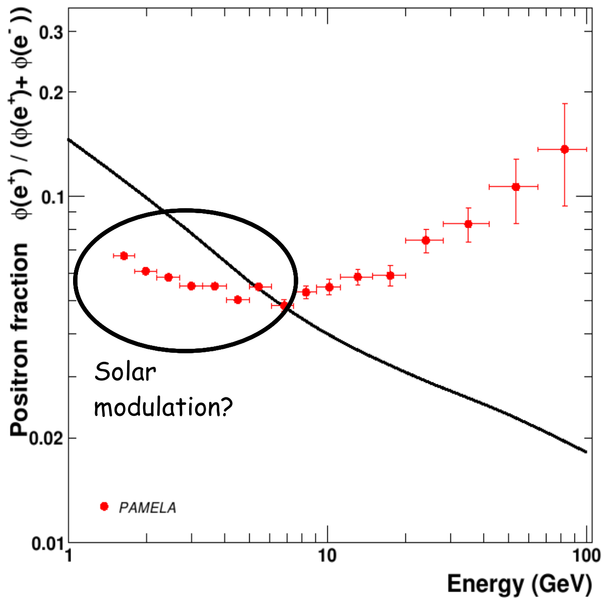
PAMELA, *a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics*

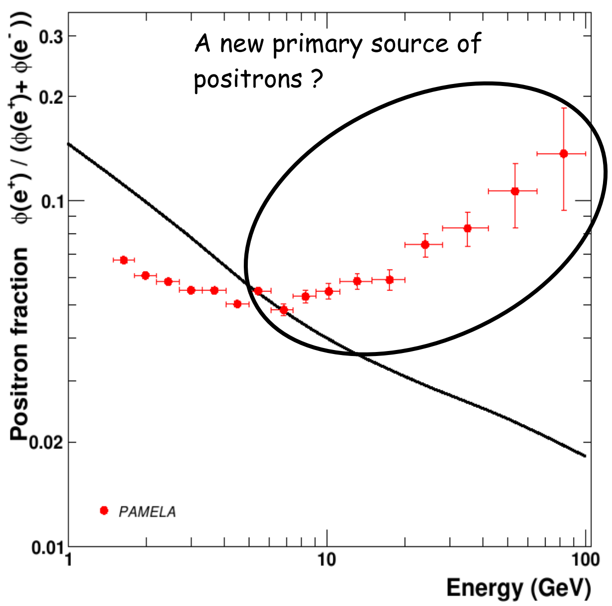


A picture of Pamela

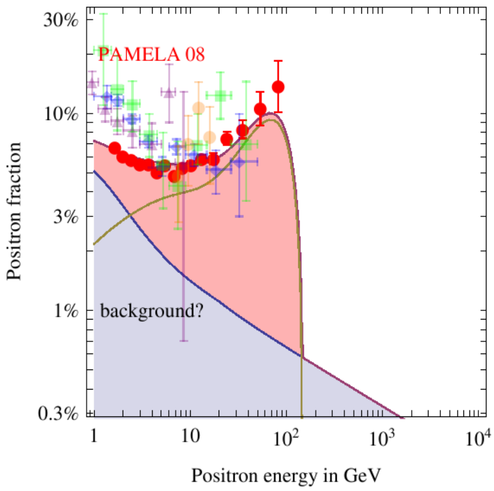
Pamela results (released October 28 2008)



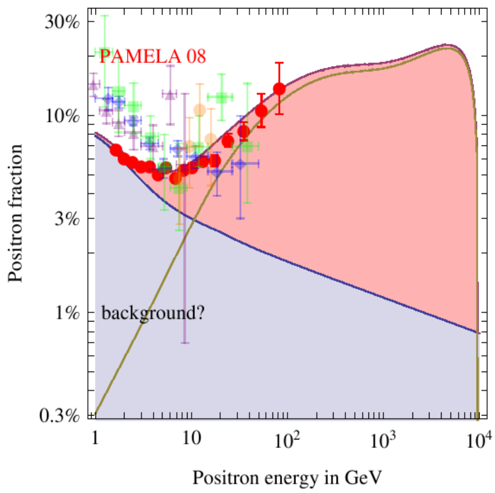

Positron fraction φ(e+) / (φ(e+)+ φ(e-))
0.3
0.2
0.1
0.02
0.01
1
10
100
Energy (GeV)
Solar
modulation?
PAMELA


A new primary source of positrons ?
Positron fraction $\phi(e^+) / (\phi(e^+)+\phi(e^-))$
0.3
0.2
0.1
0.02
0.01
1
10
100
Energy (GeV)
PAMELA

DM + DM —> ... —> $e^+ e^-$ ...



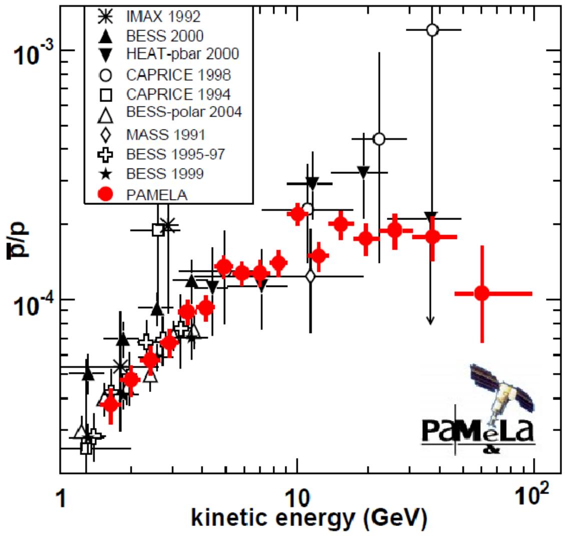
M_{DM} = 150 GeV into W^+W^-



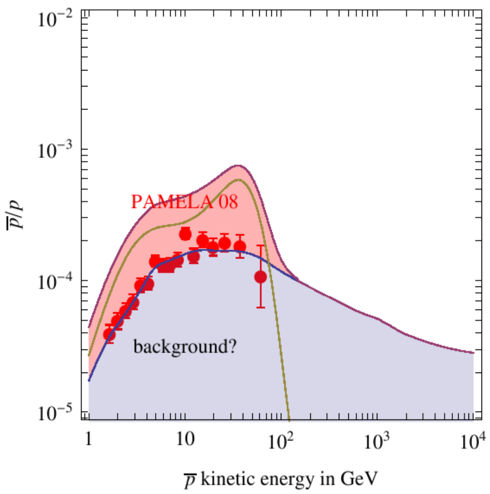
M_{DM} = 10 TeV into W^+W^-

Cirelli, Strumia & Raydal

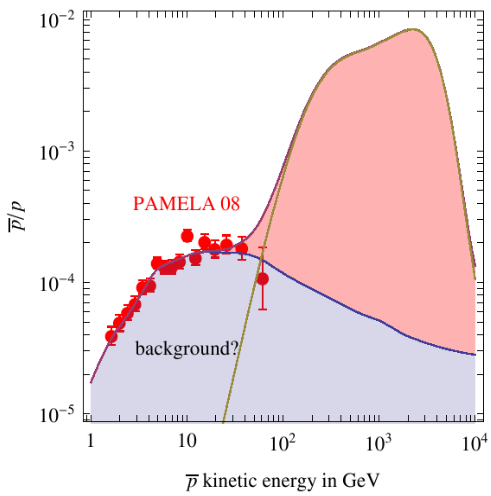
Antiproton flux from PAMELA



DM + DM —> ... —> $\bar{p}$ p ...



M_{DM} = 150 GeV into W^+W^-



M_{DM} = 10 TeV into W^+W^-

nature Vol 456 | 20 November 2008 | doi:10.1038/nature07477

LETTERS

An excess of cosmic ray electrons at energies of 300–800 GeV

J. Chang[1,2], J. H. Adams Jr[3], H. S. Ahn[4], G. L. Bashindzhagyan[5], M. Christl[3], O. Ganel[4], T. G. Guzik[6], J. Isbert[6], K. C. Kim[4], E. N. Kuznetsov[5], M. I. Panasyuk[5], A. D. Panov[5], W. K. H. Schmidt[2], E. S. Seo[4], N. V. Sokolskaya[5], J. W. Watts[3], J. P. Wefel[6], J. Wu[4] & V. I. Zatsepin[5]

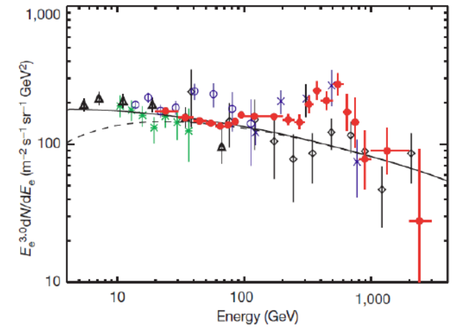
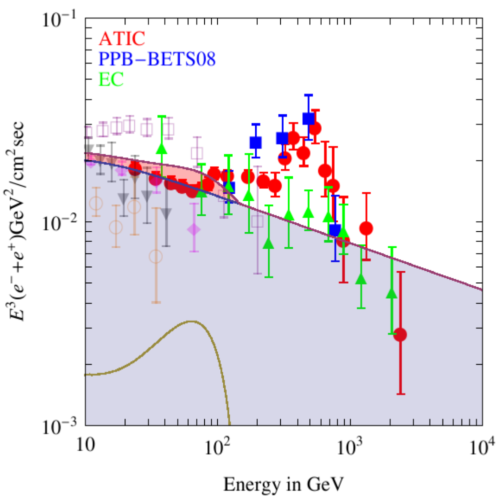
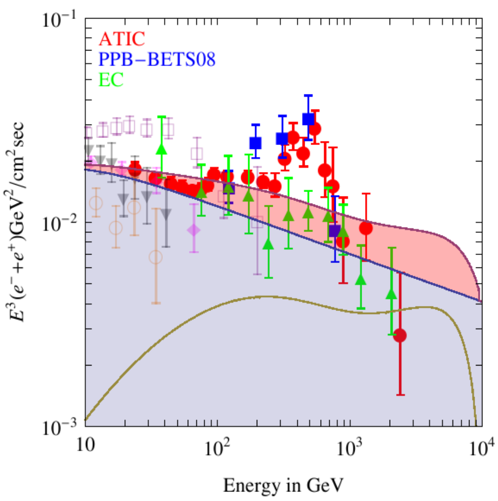


Figure 3 | ATIC results showing agreement with previous data at lower energy and with the imaging calorimeter PPB-BETS at higher energy. The

DM + DM —> … —> e^+ + e^- …

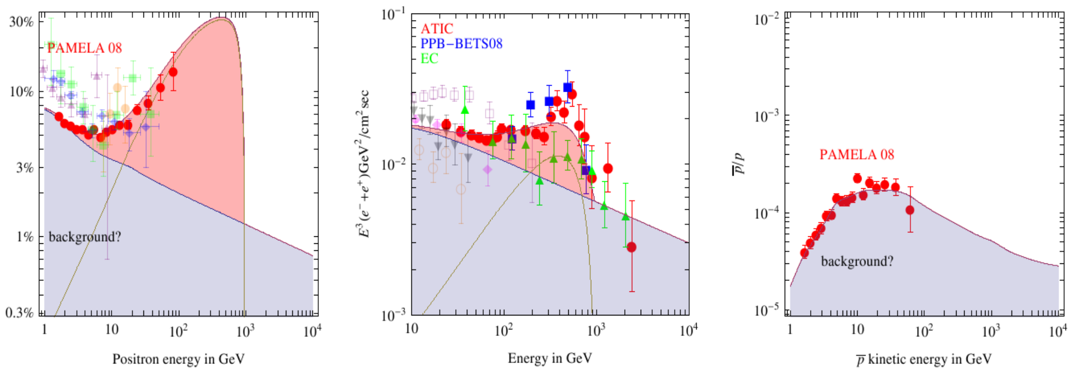


M_{DM} = 150 GeV into W^+W^-

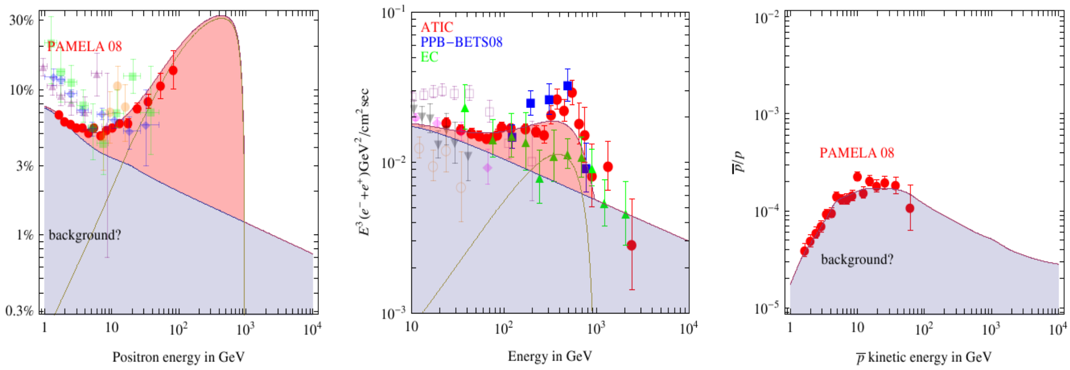


M_{DM} = 10 TeV into W^+W^-

Annihilation of DM with M_{DM} = 1 TeV into $\mu^+ \mu^-$



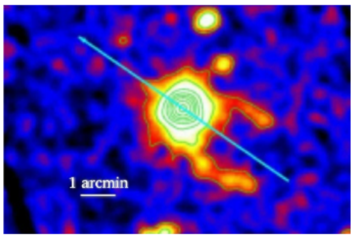
Annihilation of DM with M_{DM} = 1 TeV into $\mu^+ \mu^-$

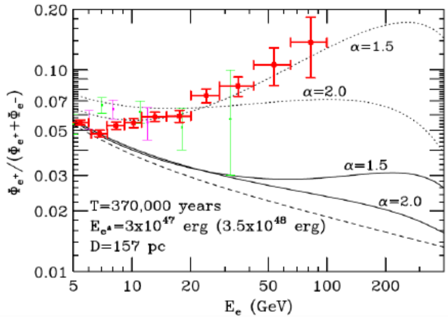


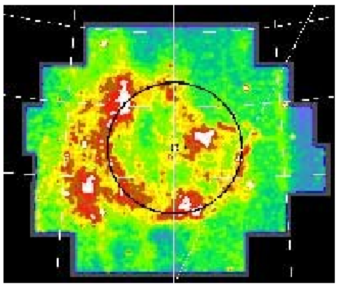
N.B. : need to increase the rate by a factor of 10^3...

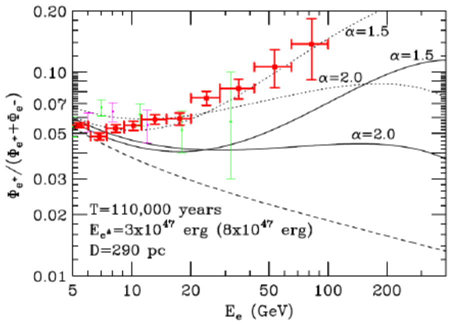
$$dN_e/dE_e \propto E_e^{-\alpha} \exp(-E_e/600\text{GeV})$$

Geminga





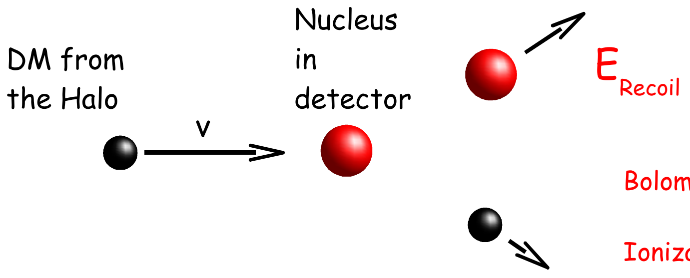




B0656+14

Hooper, Blasi, Serpico

V. Dark Matter Seen ?

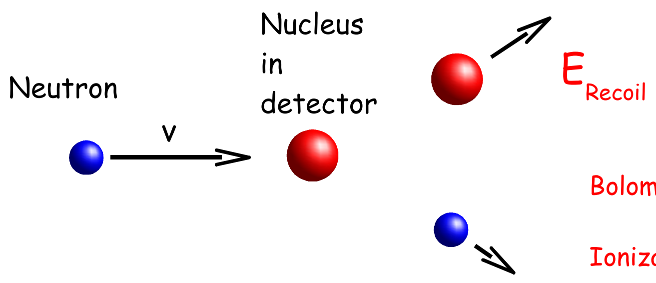


Bolometer (CDMS,...)

Ionization (XENON,...)

Scintillation (DAMA,...)

Phase transition (COUPP,...)



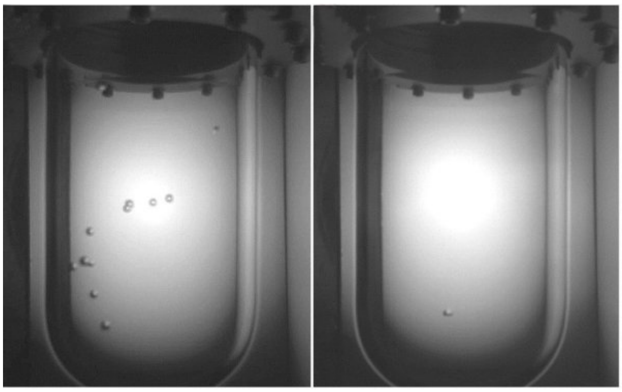
Bolometer (CDMS,...)

Ionization (XENON,...)

Scintillation (DAMA,...)

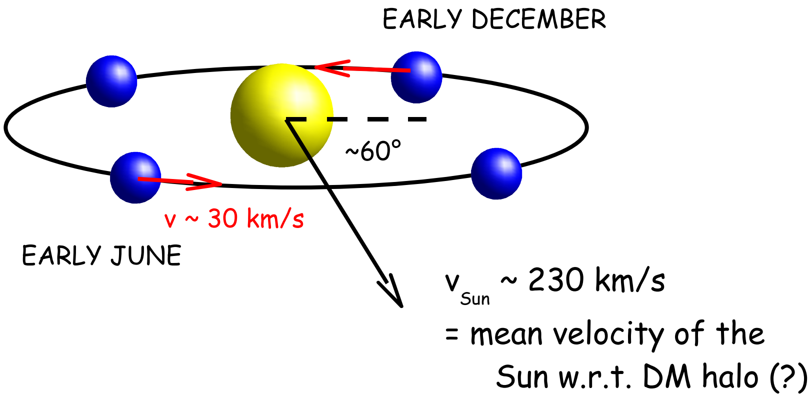
Phase transition (COUPP,...)

The Chicagoland Observatory for Underground Particle Physics, or COUPP



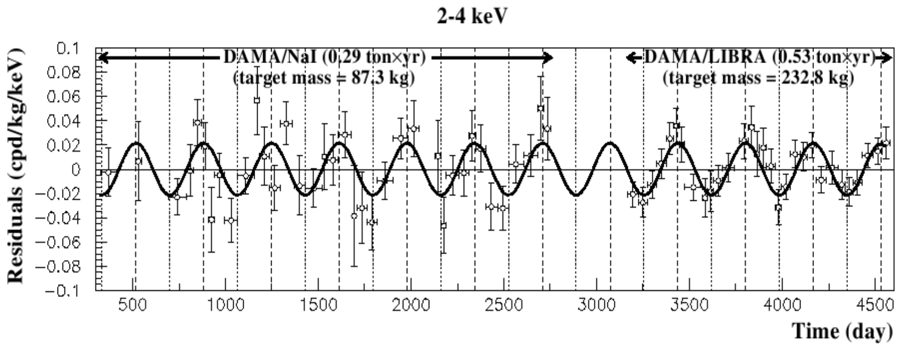
neutron-like DM-like

Expect Annual Modulation of the Dark Matter Flux



ROM2F/2008/07
April 2008

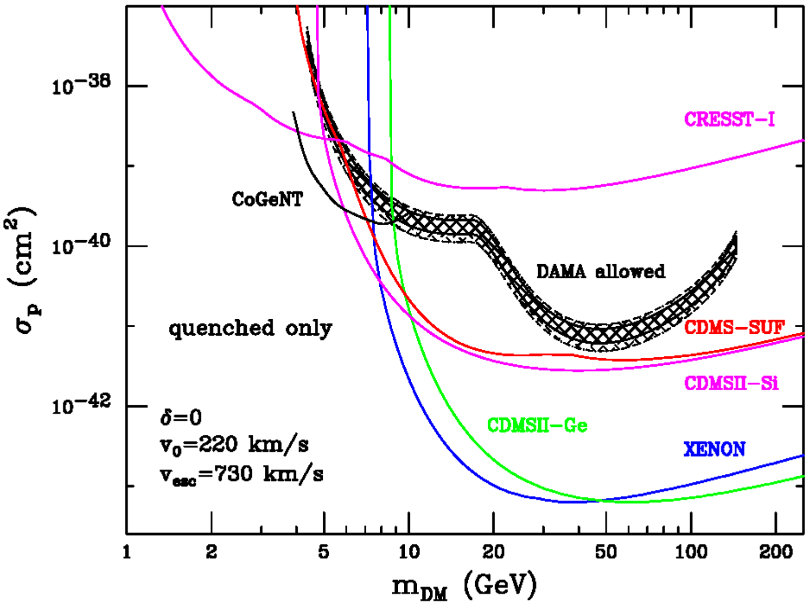
First results from DAMA/LIBRA and the combined results with DAMA/NaI



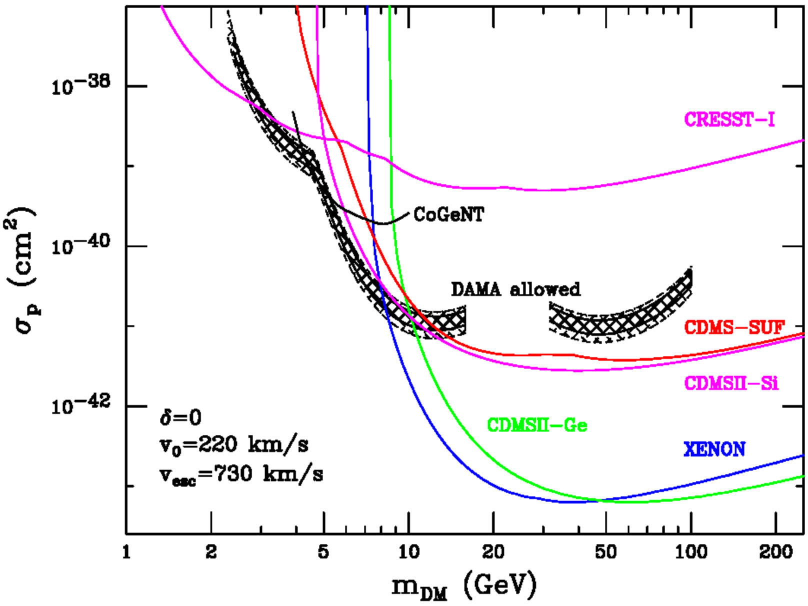
8.2 standard deviation (cumulative exposure of 0.82 ton x year)

Maximum around early June

The Trouble with DAMA

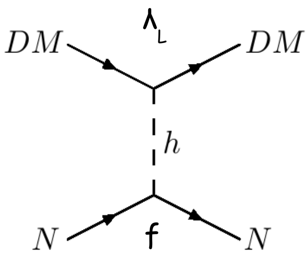


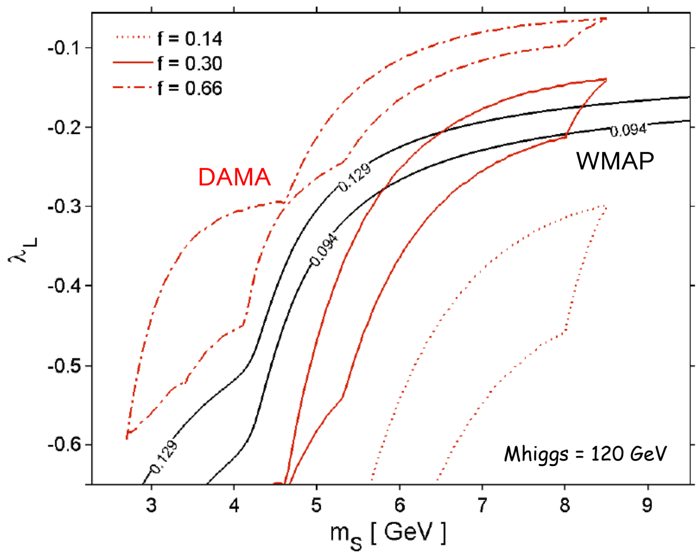
Pietrello & Zurek



Pietrello & Zurek

A light scalar WIMP through the Higgs Portal ?





Sarah Andreas, Thomas Hambye, M.T.

A multi-prong search

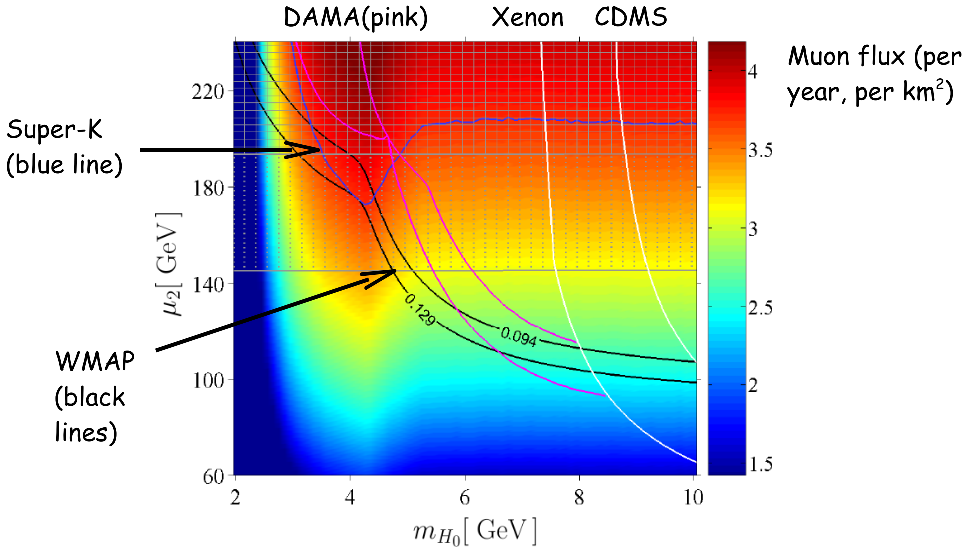
An (almost) invisible Higgs @ the LHC ?

... -> Z -> Z + h

└-> DM + DM

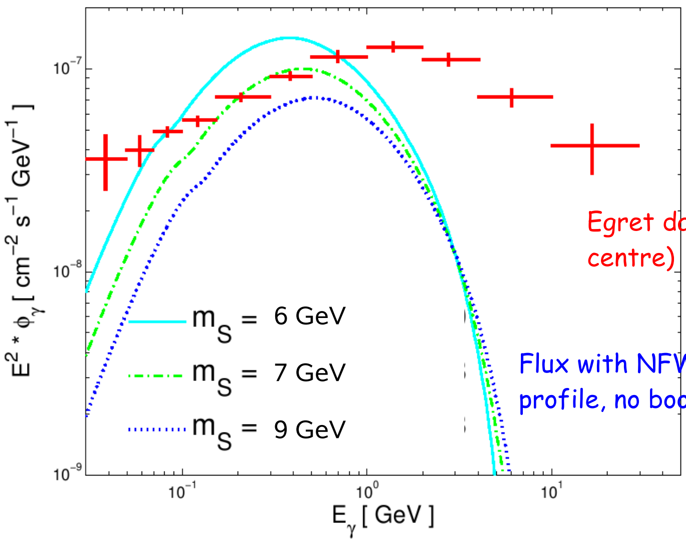
lepton-antilepton pair + missing energy

Neutrinos from DM captured by the Sun



S.Andreas, Q.Swillens, M.T. arXiv:0901.1750

Gammas rays from the Galactic centre



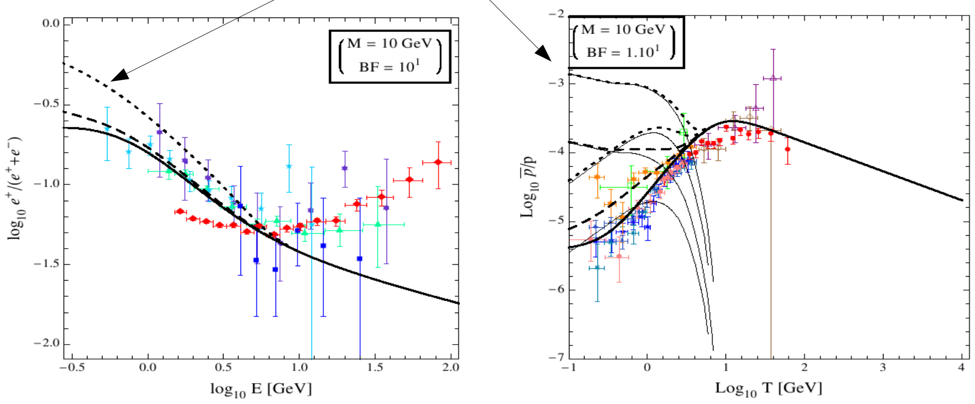
Egret data (Galactic centre)

Flux with NFW profile, no boost

S.Andreas, Th. Hambye, M.T.

Positrons and antiprotons excess in cosmic rays

boost=10



E.Nezri, G. Vertongen, M.T.

A large anti-deuteron flux

Spallation production small, and spectrum falling off at low energies: low background

→ good probe of dark matter annihilation

An 8 GeV candidate, 0.3 GeV/cm local density, FRW distribution, gives

Φ = 9 10^{-7} (GeV/nucleon s sr m^2)$^{-1}$ at T=0.25 GeV/n

(expected sensitivity of AMS-02 is

Φ = 4.5 10^{-7} (GeV/nucleon s sr m^2)$^{-1}$ at T=0.25 GeV/n

Conclusions ?

$$\frac{\text{Mass}_{\text{baryon}} \times \text{Density}_{\text{baryon}}}{\text{Mass}_{\text{dark matter}} \times \text{Density}_{\text{dark matter}}} \approx \frac{1}{5}$$

QCD
Dynamics

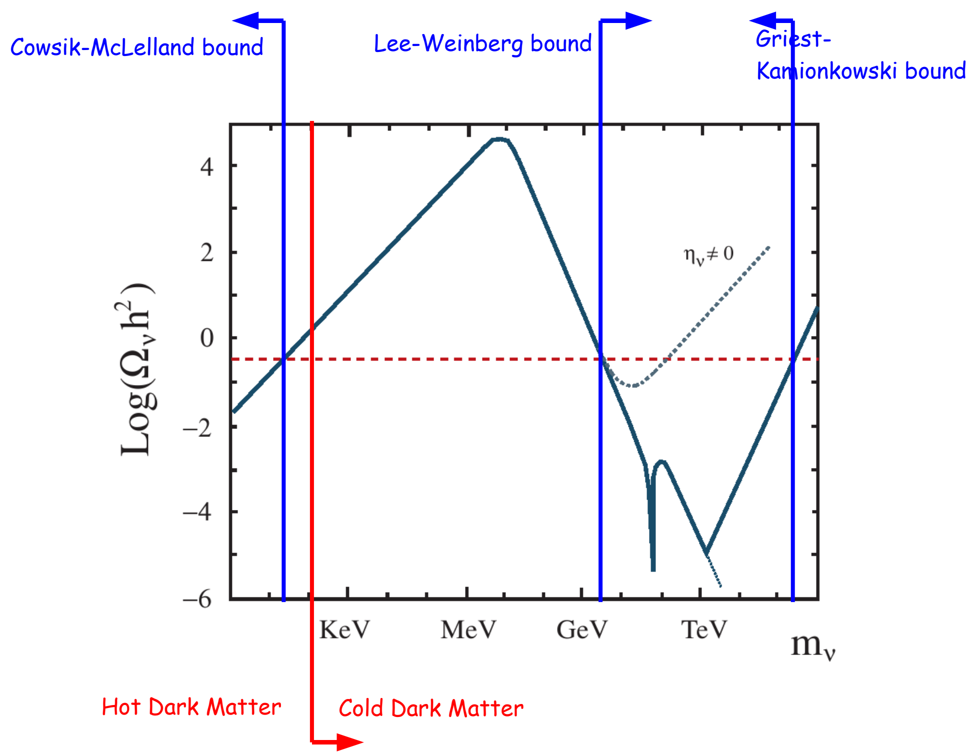
Baryogenesis (CP & B violation)

$$\frac{\text{Mass}_{\text{baryon}} \times \text{Density}_{\text{baryon}}}{\text{Mass}_{\text{dark matter}} \times \text{Density}_{\text{dark matter}}} = O(1)$$

EW Scale
but could be anything
else

Freeze-Out
but really could be anything
else

$$\frac{\text{Density}_{\text{baryon}}}{\text{Density}_{\text{dark matter}}} = O(1)\ ?$$

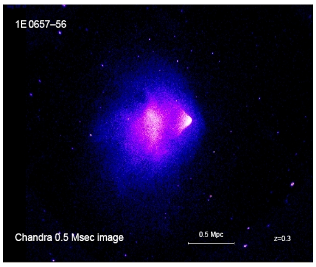


Cowsik-McLelland bound
Lee-Weinberg bound
Griest-
Kamionkowski bound
4
2
0
−2
−4
−6
Log(Ωνh²)
ην≠0
KeV
MeV
GeV
TeV
mν
Hot Dark Matter
Cold Dark Matter

Visible

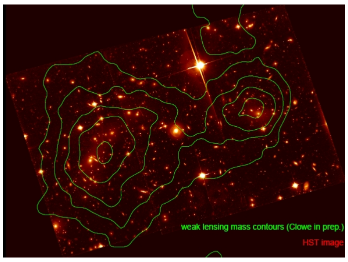
Galaxies

X-ray



Intergalactic Hot Gas

Gravitational lensing



Total Mass

$M_{visible} \sim 10^{14}\ M_\odot$ | $M_{hot\ gas} \sim 10^{15}\ M_\odot$ | $M_{tot} \sim 10^{16}\ M_\odot$

Visible Baryons | Missing Baryons

All Baryons *

Baryons
+
Dark Matter

* consistent with primordial nucleosynthesis

Abundance of Dark Matter in the Milky Way?

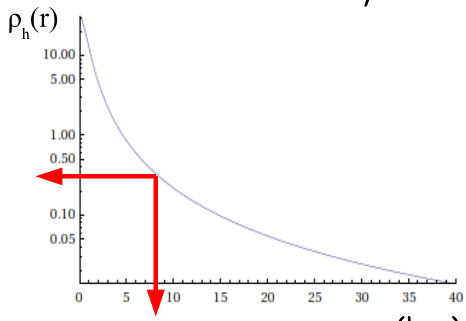
Bold model: a cored isothermal spherical halo of dark matter

$$\rho_h(r) = \rho_0 (a^2 + r_0^2)/(a^2 + r^2) = v_{h\infty}^2 (1 - a/r \, \mathrm{atan}(r/a))$$

To be fitted to observed velocity curve

Infered local abundance

ρ_0=0.3 GeV/cm^3



r (kpc)

r_0= 8 kpc (Sun's position)