The Quest for Dark Matter in the era of the latest experimental observations: PAMELA, ATIC, DAMA/LIBRA, Fermi-GLAST, INTEGRAL

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Evidence for Dark Matter

- Spiral galaxies
  - rotation curves
- Clusters & Superclusters
  - Weak gravitational lensing
  - Strong gravitational lensing
  - Galaxy velocities
  - X rays
- Large scale structure
  - Structure formation
- CMB anisotropy: WMAP
  - $\Omega_{\text{tot}} = 1$
  - $\Omega_{\text{dark energy}} \sim 0.7$
  - $\Omega_{\text{matter}} \sim 0.27$
  - $\Omega_{\text{baryons}} \sim 0.05$
  - $\Omega_{\text{visible}} \sim 0.005$
  - $\Omega_{\text{dark matter}} \sim 0.22$
The dreams of an astroparticle physicist (actually, of ALL physicists!):

- discover Dark Matter @ LHC
- and confirm it's existence @ DM searches on Earth and in Space...
- work out the details later @ ILC

is it possible/conceivable?
Nature has recently unveiled some of her secrets…:

\[ w > -\frac{1}{3} \]

\[ \Omega < 1 \quad \Omega = 1 \quad \Omega > 1 \]

\[ w < -\frac{1}{3} \]

(open, decelerating) (flat, decelerating) (closed, decelerating)

(open, accelerating) (flat, accelerating) (closed, accelerating)

(unexpected!) outcome from observation
Over-constrained scenario: the concordance model
<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>WMAP-only</th>
<th>WMAP+BAO+SN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age of universe</td>
<td>$t_0$</td>
<td>$13.69 \pm 0.13$ Gyr</td>
<td>$13.73 \pm 0.12$ Gyr</td>
</tr>
<tr>
<td>Hubble constant</td>
<td>$H_0$</td>
<td>$71.9^{+2.6}_{-2.5}$ km/s/Mpc</td>
<td>$70.1 \pm 1.3$ km/s/Mpc</td>
</tr>
<tr>
<td>Baryon density</td>
<td>$\Omega_b$</td>
<td>0.0441 $\pm 0.0030$</td>
<td>0.0462 $\pm 0.0015$</td>
</tr>
<tr>
<td>Physical baryon density</td>
<td>$\Omega_b h^2$</td>
<td>0.02273 $\pm 0.00062$</td>
<td>0.02285 $\pm 0.00059$</td>
</tr>
<tr>
<td>Dark matter density</td>
<td>$\Omega_c$</td>
<td>0.214 $\pm 0.027$</td>
<td>0.233 $\pm 0.013$</td>
</tr>
<tr>
<td>Physical dark matter density</td>
<td>$\Omega_c h^2$</td>
<td>0.1099 $\pm 0.0062$</td>
<td>0.1143 $\pm 0.0034$</td>
</tr>
<tr>
<td>Dark energy density</td>
<td>$\Omega_{\Lambda}$</td>
<td>0.742 $\pm 0.030$</td>
<td>0.721 $\pm 0.015$</td>
</tr>
<tr>
<td>Curvature fluctuation amplitude, $k_0 = 0.002$ Mpc$^{-1}$ b</td>
<td>$\Delta^2_N$ $\rho_c$</td>
<td>$(2.41 \pm 0.11) \times 10^{-9}$</td>
<td>$(2.457^{+0.092}_{-0.098}) \times 10^{-9}$</td>
</tr>
<tr>
<td>Fluctuation amplitude at $8h^{-1}$ Mpc</td>
<td>$\sigma_8$</td>
<td>0.796 $\pm 0.036$</td>
<td>0.817 $\pm 0.028$</td>
</tr>
<tr>
<td>$l(l+1)C_{20}^T/2\pi$</td>
<td>$C_{20}$</td>
<td>5756 $\pm 42$ $\mu$K$^2$</td>
<td>5748 $\pm 41$ $\mu$K$^2$</td>
</tr>
<tr>
<td>Scalar spectral index</td>
<td>$n_s$</td>
<td>0.963$^{+0.018}_{-0.015}$</td>
<td>0.960$^{+0.014}_{-0.013}$</td>
</tr>
<tr>
<td>Redshift of matter-radiation equality</td>
<td>$z_{eq}$</td>
<td>$3178_{-150}^{+151}$</td>
<td>3280$^{+88}_{-89}$</td>
</tr>
<tr>
<td>Angular diameter distance to matter-radiation eq.</td>
<td>$d_A(z_{eq})$</td>
<td>$14279_{-189}^{+188}$ Mpc</td>
<td>14172$^{+141}_{-138}$ Mpc</td>
</tr>
<tr>
<td>Redshift of decoupling</td>
<td>$z_*$</td>
<td>1090.5 $\pm$ 0.95</td>
<td>1091.00$^{+0.72}_{-0.73}$</td>
</tr>
<tr>
<td>Age at decoupling</td>
<td>$t_*$</td>
<td>$380081_{-5841}^{+5845}$ yr</td>
<td>375938$^{+5148}_{-5115}$ yr</td>
</tr>
<tr>
<td>Angular diameter distance to decoupling</td>
<td>$d_A(z_*)$</td>
<td>$14115_{-191}^{+188}$ Mpc</td>
<td>14006$^{+142}_{-141}$ Mpc</td>
</tr>
<tr>
<td>Sound horizon at decoupling</td>
<td>$r_*$</td>
<td>145.8 $\pm$ 1.8 Mpc</td>
<td>145.8 $\pm$ 1.2 Mpc</td>
</tr>
<tr>
<td>Acoustic scale at decoupling</td>
<td>$l_A(z_*)$</td>
<td>302.08$^{+0.83}_{-0.84}$</td>
<td>302.11$^{+0.84}_{-0.82}$</td>
</tr>
<tr>
<td>Reionization optical depth</td>
<td>$\tau$</td>
<td>0.087 $\pm$ 0.017</td>
<td>0.084 $\pm$ 0.016</td>
</tr>
<tr>
<td>Redshift of reionization</td>
<td>$z_{\text{reion}}$</td>
<td>11.0 $\pm$ 1.4</td>
<td>10.8 $\pm$ 1.4</td>
</tr>
<tr>
<td>Age at reionization</td>
<td>$t_{\text{reion}}$</td>
<td>$427_{-67}^{+90}$ Myr</td>
<td>432$^{+90}_{-67}$ Myr</td>
</tr>
</tbody>
</table>

Parameters for Extended Models

| Total density $f$                                | $\Omega_{\text{tot}}$ | $1.099_{-0.085}^{+0.100}$ | $1.0052 \pm 0.0054$ |
| Equation of state $g$                            | $w$ | $-1.06_{-0.42}^{+0.41}$ | $-0.972_{-0.060}^{+0.061}$ |
| Tensor to scalar ratio, $k_0 = 0.002$ Mpc$^{-1}$ b,h | $r$ | $< 0.43$ (95% CL) | $< 0.20$ (95% CL) |
| Running of spectral index, $k_0 = 0.002$ Mpc$^{-1}$ b,i | $dn_s/d\ln k$ | $-0.037 \pm 0.028$ | $-0.032_{-0.020}^{+0.021}$ |
| Neutrino density $i$                             | $\Omega_{\nu} h^2$ | $< 0.014$ (95% CL) | $< 0.0065$ (95% CL) |
| Neutrino mass $j$                                | $\sum m_{\nu}$ | $< 1.3$ eV (95% CL) | $< 0.61$ eV (95% CL) |
| Number of light neutrino families $k$            | $N_{\text{eff}}$ | $> 2.3$ (95% CL) | $4.4 \pm 1.5$ |
A disturbing picture: we don’t know what more than 95% of the Universe is made of…

can we shed some light on this?
Kowalski et al, arXiv:0804.4142

Evolution of equation of state

\[ w(z) = w_0 + w_a \frac{z}{1 + z} \]

\((w = p/\rho)\)

Fig. 16. — 68.3 %, 95.4 % and 99.7% confidence level contours on \(w_a\) and \(w_0\) for a flat Universe. Left: The Union SN set was combined with CMB or BAO constraints. Right: Combination of SNe, CMB and BAO data, with and without systematic uncertainties included. The diagonal line represents \(w_0 + w_a = 0\); note how the likelihoods based on observational data remain below it, favoring matter domination at \(z \gg 1\).
A second problem: today $\Omega_\lambda$ and $\Omega_{\text{matter}}$ are of the same order

$\rho_\lambda = \text{constant}$

$\rho_{\text{matter}} \sim a^{-3}$

today

Coincidence problem: WHY NOW??

(remember: $w(z) = w_0 + w_a \frac{z}{1+z}$, data seem to point to $w_0 + w_a = 0$, vacuum domination seems quite a recent event…)

quintessence field instead of cosmological constant can explain it more naturally through tracking solutions (i.e. solutions where the vacuum energy tracks the other components irrespective of the initial conditions)
The energy-momentum tensor of a scalar (quintessence) field

Noether’s theorem: symmetry of the action $\rightarrow$ conservation law

the energy-momentum tensor is the quantity which is conserved due to invariance of the action through translations in space and time

$$S_\phi = \int g \, d^4x \, \mathcal{L}_\phi$$

(N.B.: $g=\text{constant}=R^3$

$$\mathcal{L}_\phi = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi)$$

$$\delta S = 0 \rightarrow \partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = \partial_\mu \left( \frac{\partial \mathcal{L}}{\partial (\partial_\nu \phi)} \right) - g^{\mu\nu} \mathcal{L} = \begin{pmatrix}
\rho & 0 & 0 & 0 & 0 \\
0 & p & 0 & 0 & 0 \\
0 & 0 & p & 0 & 0 \\
0 & 0 & 0 & p & 0 \\
0 & 0 & 0 & 0 & p
\end{pmatrix}$$
for a field constant in space ($\partial \phi / \partial x^k = 0$):

$$\rho = \frac{\dot{\phi}^2}{2} + V(\phi)$$

$$p = \frac{\dot{\phi}^2}{2} - V(\phi)$$

so that the equation of state is in the range:

$$-1 < w = \frac{p}{\rho} = \frac{\dot{\phi}^2}{2} + V(\phi) \ll \frac{\dot{\phi}^2}{2} - V(\phi) < 1$$

$$\frac{\dot{\phi}^2}{2} \gg V(\phi) \rightarrow w = 1$$ ("kination" regime)

$$\frac{\dot{\phi}^2}{2} \ll V(\phi) \rightarrow w = -1$$ ("vacuum energy" regime)
So, including a cosmological constant and/or a quintessence field, during the history of the Universe the equation of state is expected to lie in the range:

\[-1 < w = p/\rho < 1\]

-1 < w = p/\rho < 1

w <- 1?

“Phantom” models

- interaction between dark matter and dark energy (Farrar, Peebles, Astroph. J. 604(2004)1)
- interaction between neutrinos and dark energy (Ichiki, Keum, JHEP06(2008)058)
- non-canonical kinetic term
- …
N.B.: using a scalar field wide range of possibilities \(-1<w<1\) for the equation of state, including matter and dark energy

matter \((p=0)\) from (coherent) scalar field?
Assume that the scalar field oscillates at the bottom of a potential well:

\[ V(\phi) = \frac{1}{2}m\phi^2, \quad m \gg H^{-1} \]

\[ \ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} \simeq \ddot{\phi} + m^2\phi^2 = 0 \]

**Harmonic oscillator with:**

kinetic energy and potential energy are the same

\[ \left\langle \frac{\dot{\phi}^2}{2} \right\rangle = \left\langle V \right\rangle \quad (<\cdot\cdot\cdot>=time\ average) \]

\[ \left\langle p \right\rangle = \left\langle \frac{\dot{\phi}^2}{2} \right\rangle - \left\langle V \right\rangle = 0 \quad =\text{matter} \]
Quintessence: quinta essentia = fifth element, additional element postulated by Aristotle (also aether=the element of Gods)

In the middle ages considered the main ingredient of the Philosopher’s stone - believed by alchemists to convert elements and to turn inexpensive metals into gold.
many scalars proposed as the Dark Matter. If the scalar field is coupled to the surrounding plasma it reaches thermal equilibrium and coherence is lost (quantum excitations are continuously created and destroyed). This is the case of the sneutrino (the scalar partner of neutrinos in supersymmetry) and of heavy axions ($m_a \gtrapprox$eV).

on the other hand, a light axion ($m \approx 10^{-5}$ eV) is the most popular dark matter candidate for which $\rho=0$ due to its coherent oscillations.

N.B. in all the above examples the Compton wavelength $\lambda=\hbar/mc$ is either smaller than the distance between particles (sneutrino, $m \approx 100$ GeV) or much smaller than a typical Dark Matter halo ($\lambda \approx 100$ km) so in both cases their phase space is that of a gas of individual particles.

More exotic proposal: when $m \approx 10^{-23}$ eV, $\lambda \approx 10-100$ kpc and galactic halos are weird boson-star like objects described by coherent bosonic condensates?

Boson star: localized, asymptotically flat configurations of gravitationally bound zero temperature bosons. Mathematically, the boson field is described by a complex wave function whose lagrangian possesses an internal U(1) that gives rise to a conserved charge \( N \), interpreted as the total number of bosons.

Complex scalar field:

\[
\mathcal{L} = g^{\mu\nu} \partial_\mu \phi^\dagger \partial_\nu \phi - V(\phi)
\]

\[
V(\phi) = m^2 \phi^\dagger \phi + \ldots
\]

Action:

\[
S = \int \sqrt{-g} \, d^4x \, \mathcal{L} [\phi, \partial \phi]
\]

\[
d\tau^2 = e^{2u} dt^2 - e^{2v} \left\{ dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \right\}
\]

static solutions, \( u, v \) only functions of \( r \)
Boson star model of DM Halos

JW Lee and IG Koh (PRD 53, 2236 (1996))

Action

\[ S = \int \sqrt{-g} d^4 x \left[ \frac{-R}{16\pi G} - \frac{g^{\mu\nu}}{2} \partial_\mu \phi \partial_\nu \phi - \frac{m^2}{2} |\phi|^2 - \frac{\lambda}{4} |\phi|^4 \right] \]

Metric

\[ ds^2 = -B(r)dt^2 + A(r)dr^2 + r^2 d\Omega \]

Field

\[ \phi(r, t) = (4\pi G')^{-\frac{1}{2}} \sigma(r) e^{-i\omega t} \]

Equation

\[
\left\{ \begin{align*}
\frac{A'}{A^2 x} + \frac{1}{x^2} \left[ 1 - \frac{1}{A} \right] &= \left[ \frac{\Omega^2}{B} + 1 \right] \sigma^2 + \frac{\Lambda}{2} \sigma^4 + \frac{\sigma^2}{A}, \\
\frac{B'}{ABx} - \frac{1}{x^2} \left[ 1 - \frac{1}{A} \right] &= \left[ \frac{\Omega^2}{B} - 1 \right] \sigma^2 - \frac{\Lambda}{2} \sigma^4 + \frac{\sigma^2}{A}, \\
\sigma'' + \left[ \frac{2}{x} + \frac{B'}{2B} - \frac{A'}{2A} \right] \sigma' + A \left[ \frac{\Omega^2}{B} - 1 \right] \sigma - \Lambda \sigma^3 &= 0,
\end{align*} \right.
\]

\[ v_{\text{rot}} = \sqrt{\frac{x B'(x)}{2B(x)}} \]

Gives similar curve of BEC model for weak

\[ v_{\text{rot}} \sim 10^{-3} c \]
BEC & Boson star models explain rotation curve of Dwarf Galaxies

Recently, it was shown that BEC (thus boson star) model reproduces rotation curves of 12 LSB & dwarf galaxies very well (Bohmer & Harko, JCAP 06 (2007) 025)
For instance take: [Arbey, Lesgourges and Salati, PRD68(2003)023511]

\[ V(\phi) = m^2 \phi^\dagger \phi + \lambda [\phi^\dagger \phi]^2 \]

explains DM at cluster scales
so in principle quintessence can describe both the Dark Matter and the Dark Energy…
can it be our Philosopher’s stone unifying the two?

hard, but maybe not completely impossible!
alchemy has never been easy…

difficult to achieve in practice, but an intriguing scenario
A more conventional scenario: in galaxies and clusters there is more matter than what is observed with telescopes

Baryons are the most common form of matter

Some non-visible baryonic matter is possible:

- non-luminous gas
- brown dwarfs ("failed stars" with not enough mass for nuclear fusion to begin)
- black holes
- neutron stars
Apart from being unable to drive galaxy formation (they decouple too late from photons, not enough time for gravitational instabilities to grow) baryons are too few in the Universe in order to explain the dark matter because of nucleosynthesis.

Observations give $0.6 < h < 0.8$

Big Bang nucleosynthesis (deuterium abundance) and cosmic microwave background (WMAP) determine baryon contribution $\Omega_B h^2 \approx 0.023$, so $\Omega_B \approx 0.04$

$\Omega_{\text{lum}} \approx (4 \pm 2) \cdot 10^{-3}$ (stars, gas, dust) $\Rightarrow$ baryonic dark matter has to exist (maybe as warm intergalactic gas?)

But, now we know that $\Omega_M > 0.2$, so there has to exist non-baryonic dark matter

Lithium underabundant?

Fields & Sarkar, 2004
A lot of matter in the Universe is dark and non-baryonic
The properties of a good Dark Matter candidate:

- stable (protected by a conserved quantum number)
- no charge, no colour (weakly interacting)
- cold, non dissipative
- relic abundance compatible to observation *
- motivated by theory (vs. “ad hoc”)

Subdominant candidates – variety is common in Nature → may be easier to detect
Neutrinos don’t’s work also because they are hot dark matter (=relativistic at decoupling, erase density perturbation through free-streaming):

(from Mark Tegmark home page)
CLUSTERING IN A NEUTRINO-DOMINATED UNIVERSE

SIMON D. M. WHITE,1, 2 CARLOS S. FRENK,1 AND MARC DAVIS1,3
University of California, Berkeley
Received 1983 June 17; accepted 1983 July 1


ABSTRACT

We have simulated the nonlinear growth of structure in a universe dominated by massive neutrinos using initial conditions derived from detailed linear calculations of earlier evolution. Codes based on a direct $N$-body integrator and on a fast Fourier transform Poisson solver produce very similar results. The coherence length of the neutrino distribution at early times is directly related to the mass of the neutrino and thence to the present density of the universe. We find this length to be too large to be consistent with the observed clustering scale of galaxies if other cosmological parameters are to remain within their accepted ranges. The conventional neutrino-dominated picture appears to be ruled out.
Structure formation (i.e.: the very existence of galaxies) needs Cold Dark Matter and Cold Dark Matter implies physics beyond the Standard Model (light neutrinos don’t work)
Have to go **non-baryonic** and beyond the **Standard Model**

Two main guiding principles:

1. simplicity
2. theoretical motivation

not always coinciding!
(Incomplete) List of DM candidates

- Neutrinos
- Axions
- Lightest Supersymmetric particle (LSP) – neutralino, sneutrino, axino
- Lightest Kaluza-Klein Particle (LKP)
- Heavy photon in Little Higgs Models
- Solitons (Q-balls, B-balls)
- Black Hole remnants
- Hidden-sector tecnipions
- BEC/scalar field
- ...
WIMP=Weakly Interacting Massive Particle
most popular thermal WIMP candidates from particle physics (solve hierarchy problem: $M_W/M_{Pl} \sim 10^{-16}$)

<table>
<thead>
<tr>
<th>conserved symmetry</th>
<th>DM candidate</th>
</tr>
</thead>
<tbody>
<tr>
<td>susy *</td>
<td>R-parity</td>
</tr>
<tr>
<td>extra dimensions</td>
<td>K-parity</td>
</tr>
<tr>
<td>little Higgs</td>
<td>T-parity</td>
</tr>
</tbody>
</table>

all thermal candidates, massive, with weak-type interactions (WIMPs)

the most popular
thermal cosmological density of a WIMP $X$

$$\Omega_X h^2 \sim 1/\langle \sigma_{\text{ann}} v \rangle_{\text{int}}$$

$$\langle \sigma_{\text{ann}} v \rangle_{\text{int}} = \int_{x_f}^{x_0} \langle \sigma_{\text{ann}} v \rangle dx$$

$x_0 = M/T_0$

$T_0 =$ present (CMB) temperature

$x_f = M/T_f$

$T_f =$ freeze-out temperature

$x_f >> 1$, $X$ non relativistic at decoupling, low temp expansion for

$$\langle \sigma_{\text{ann}} v \rangle: \langle \sigma_{\text{ann}} v \rangle \sim a + b/x$$

if $\sigma_{\text{ann}}$ is given by weak-type interactions $\rightarrow \Omega_X \sim 0.1-1$

...+ coannihilations with other particle(s) close in mass + resonant annihilations
\[ \Omega_{WIMP} \equiv \frac{\rho_{WIMP}}{\rho_c} = \frac{m \, n_{WIMP}}{\rho_c} = \frac{mS_0 Y_0}{\rho_c} \]

\[ S_0 = 2970 \text{ cm}^{-3} \quad \text{today's entropy} \]

\[ \rho_c = 1.054h^2 \times 10^{-5} \frac{\text{GeV}}{\text{cm}^3} \quad \text{critical density} \]

\[ x_f \approx 20 \quad \text{freeze-out temperature} \]

\[ g^{1/2}_* \approx 10 \quad \# \text{ of degrees of freedom} \]

\[ m = \text{WIMP mass} \]

\[ Y_0 : \text{from Boltzmann equation} \]

\[ \Omega_{WIMP} h^2 = \frac{x_f}{g^{1/2}_*} \frac{3.45 \times 10^{-38}}{\langle \tilde{\sigma} \tilde{v} \rangle} \approx \frac{0.1 \text{ pbarn}}{\langle \tilde{\sigma} \tilde{v} \rangle} \]

\[ h \equiv \frac{H_0}{100 \text{ km sec}^{-1}\text{Mpc}^{-1}} \]
N.B. Very different scales conjure up to lead to the weak scale!

\[ T_0 \approx K \approx 10^{-13} \text{ GeV} \]

\[ H_{100} = 100 \text{ km sec}^{-1} \text{ Mpc} \approx 10^{-42} \text{ GeV} \]

\[ m_{\text{Planck}} = \frac{1}{G^{1/2}} = 10^{19} \text{ GeV} \]

\[
\frac{x_f}{g^*_{1/2}} \left( \frac{45G}{\pi} \right)^{1/2} \frac{S_0}{\rho_c} G^{1/2} \approx 10^2 \frac{T_0^3}{H_{100}^2 m_{\text{Planck}}^3}
\]

\[
\approx 10^2 \frac{10^{-39}}{10^{-84} \times 10^{57}} \text{ GeV}^{-2} \approx 10^{-9} \text{ GeV}^{-2} \approx 1 \text{ pbarn}
\]

the WIMP “miracle”???
**Searches for relic WIMPs**

- **Direct searches.** Elastic scattering of $\chi$ off nuclei ($\propto$ WIMP local density)
  \[
  \chi + N \rightarrow \chi + N
  \]

- **Indirect searches.** Signals due to $\chi - \chi$ annihilations
  \[
  g g \\
  f f \\
  W^+ W^- \\
  ZZ
  \]

  \[
  \chi + \chi \rightarrow \ HH, hh, AA, hH, hA, HA, H^+ H^- \rightarrow \ \nu, \bar{\nu}, \gamma, \bar{p}, e^+, d
  \]

  \[
  W^+ H^-, W^- H^+ \\
  Zh, ZH, ZA
  \]

- Annihilations taking place in celestial bodies where $\chi$’s have been accumulated: $\nu$’s $\rightarrow$ up-going $\mu$’s from Earth and Sun

- Annihilations taking place in the Halo of the Milky Way or that of external galaxies: enhanced in high density regions ($\propto (\text{WIMP density})^2$) $\Rightarrow$ Galactic center, clumpiness
Annual modulation of WIMP direct detection in a nutshell

Expected rate: \( R = R_0 + R_m \cos[\omega(t-t_0)] \)

\( \omega = \frac{2\pi}{(1 \text{ year})} \)

\( t_0 = 2 \text{ june} \)

\( \frac{R_m}{R_0} \sim 5\div10 \% \) (few percent effect)

If \( N = \# \) of events, assuming a 5\% effect a 5 \( \sigma \) discovery requires:

\[
\frac{5}{100} \times N > 5 \times N^{\frac{1}{2}}
\]

\( N \sim (\text{incoming flux}) \times N_{\text{targets}} \times (\text{cross section}) \times (\text{exposition time}) \)

expected rates \( \leq 0.1 \) events/kg/day

\( \Rightarrow \) a few \( \times 100 \) kg \( \times \) day required

hard to do: need large masses, low backgrounds, operational stability over long times…
First proposed in late '80s
The DAMA/LIBRA result (Bernabei et al., arXiv:0804.2741) (presented at “Neutrino Oscillations in Venice”, 16 april 2008) 0.53 ton x year (0.82 ton x year combining previous data) 8.2 σ C.L. effect

$$A \cos[\omega (t-t_0)]$$

$$\omega = 2\pi/T_0$$
The peak is only in the 2-6 keV energy interval, absent in the 6-14 keV interval just above.

The WIMP signal decays exponentially with energy and is expected near threshold.
Effect is “spread out” on all 24 detectors (and affects only “single hits”)
each panel: distribution of $x = (S_m - \langle S_m \rangle) / \sigma$ in one DAMA/LIBRA detector over 4 years

$\chi^2 = \sum x^2$ (64 d.o.f: 16 x 0.5 keV energy bins x 4 years)

$\chi^2$/d.o.f. distribution

5% upper tail

$\langle \chi^2$/d.o.f.$ \rangle = 1.072$
Hard to think of a systematic effect (temperature fluctuation, radon, etc seem under control, and anyway would not affect only single hits or would also influence energies just above the WIMP window)

Modulation seems to be there with $T=1$ year and $\text{phase}=2$ june

Seems to be due to some physics outside the detector

But has it anything to do with Dark Matter?
DAMA disfavoured by other direct searches

small viable window with $M_{\text{WIMP}} \leq 10$ GeV

From Savage et al., arXiv:0901.2713
KIMS spin independent limits (CsI)

\[ \rho_D = 0.3 \text{ GeV/c}^2/\text{cm}^3 \]
\[ v_o = 220 \text{ km/s} \]
\[ v_{\text{esc}} = 650 \text{ km/s} \]

Systematic uncertainty Fitting, Quenching factor energy resolution... combined in quadrature ~ 15% higher than w/o syst.

Nuclear recoil of $^{127}\text{I}$ of DAMA signal region ruled out

PRL 99, 091301 (2007)

for \( m_{\text{wimpo}} \gtrsim 20 \text{ GeV} \) KIMS limit does not depend on scaling law for cross sections
Neutralino - nucleon cross section

\[ \Omega_\chi h^2 \leq (\Omega_{CDM} h^2)_{\text{max}} \]

\[ \sigma_{\text{scalar}}^{(\text{nucleon})} \gtrsim 10^{-40}\text{cm}^2 \left( \frac{m_\chi^2}{\Omega_{CDM} h^2} \right) \left( \frac{\text{GeV}}{m_\chi^2 \left[ 1 - m_b^2/m_\chi^2 \right]^{1/2}} \right) \text{ for } m_\chi \lesssim 20\text{ GeV} \]

The elastic cross section is bounded from below:

\[ \rightarrow \text{“funnel” at low mass} \]

allowed in an effective MSSM scenario where gaugino masses are not universal at the GUT scale
Neutralino-nucleon cross section & CDMS limit (including astrophysical uncertainties) [exp. data: Ahmed et al., arXiv:0802.3530]

- **solid:** $v_{esc} = 650 \text{ km/sec}$
- **long dashes:** $v_{esc} = 450 \text{ km/sec}$

**eff-MSSM** (including uncertainties due to hadronic matrix elements)

**scatter plot:** reference choice of hadronic matrix elements
Examples of alternative explanations

- pseudoscalar and scalar light bosons (axion-like) (Bernabei et al., PRD73(2006)063522)

  (total conversion of incoming particle, no nuclear recoil involved → rejection of other experiments ineffective, “high quenching” DM)

- inelastic Dark Matter (Smith, Weiner, PRD64 (2001) 043502)

\[ \chi^- \chi^+ \]

\[ m_{\chi^-} < m_{\chi^+} \]

\[ \delta = m_{\chi^-} - m_{\chi^+} \]

\[ \delta \approx 15 \text{ keV} \] may reconcile DAMA with other constraints

- mirror matter (Foot, arXiv:0804.4518)

  He’ (H’) dominated halo with small O’ component

\[ \frac{d\sigma}{dE_R} \propto \frac{1}{E_R^2} \] enhances sensitivity to lower threshold compared to WIMPS
Present and future searches of antimatter and gamma rays:
Annihilations taking place in the Halo
($\propto$ WIMP (local density)$^2$)

$\chi + \chi \rightarrow$ 

$\nu, \bar{\nu}$ 

$\gamma$ (continuum) 

$\gamma$ line ($Z\gamma$) 

$\bar{p}, e^+, D^-$ 

keep directionality 

searches for rare components in cosmic rays (diffusion)
WIMP indirect detection: annihilations in the halo

Example:

\[ \chi \rightarrow_{\gamma, e^+} \bar{p}, \bar{d} \]
Radiation: a multi-wavelength approach (see for instance, Colafrancesco, Profumo, Ullio, astro-ph/0507575)

\[ \chi \xrightarrow{\pi^0} \text{radiation} \quad \text{OR} \quad \chi \xrightarrow{\pi^0} \text{radiation} \quad \text{“prompt”} \]

sincrotron emission from e^+e^- (including WMAP haze)

Inverse Compton of e^\pm on CMB and starlight (including INTEGRAL) soft gammas from non-thermal bremsstrahlung

“usual” mechanism: prompt hard gammas, mainly from $\pi^0 \rightarrow \gamma \gamma$ (also one-loop monochromatic line)

<table>
<thead>
<tr>
<th>Region</th>
<th>Energy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>&lt; 10^{-5}</td>
</tr>
<tr>
<td>Microwave</td>
<td>10^{-5} - 0.01</td>
</tr>
<tr>
<td>Infrared</td>
<td>0.01 - 2</td>
</tr>
<tr>
<td>Visible</td>
<td>2 - 3</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>3 - 10^3</td>
</tr>
<tr>
<td>X-rays</td>
<td>10^3 - 10^5</td>
</tr>
<tr>
<td>Gamma rays</td>
<td>&gt; 10^5</td>
</tr>
</tbody>
</table>
The lesson from EGRET and fermi/GLAST: gamma excess is gone...

- GeV excess has gone (at least at intermediate latitudes) - one excess less!

![Graph showing gamma ray emission vs energy with data points and curves indicating model fits.]

$E \gamma^2 J(E_\gamma)$ (MeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$)

$0^\circ \leq l \leq 360^\circ$, $10^\circ \leq |b| \leq 20^\circ$

- EGRET
- LAT

Model $(\pi^0 + IC + Brem) + EG + instr$

(GALPROP conventional)
exotic component in cosmic rays
$e^+/(e^++e^-)$ arXiv:0810.4995, 4994 [astro-ph] $\bar{p}/p$

positron excess above 10 GeV, but no excess in antiprotons
• Balloon experiments measured the spectrum of $e^+ + e^-$ at energies higher than PAMELA
• if PAMELA excess keeps rising with energy positron fraction becomes of order unity at a few hundreds GeV
• data from ATIC-2 and PPB-BETS show a hint of an excess at those energies, and can anyway put constraints

Fig. 12. Electron energy spectrum observed with PPB-BETS (solid circles) in comparison with the energy spectra of BETS (solid squares) and the other observations. The dash line shows the best fit power-law function of the combined spectrum of PPB-BETS and BETS with an index of $-3.05 \pm 0.05$. (arXiv:0809.0760)
ATIC & HESS: electrons

- A feature in the electron spectrum (ATIC) and a sharp cutoff above ~1 TeV

N.B. no discrimination between electrons and positrons
DM with $M_{DM}$ $\sim$ TeV decaying only to leptons just fine
Puzzles for DM interpretation

• Excesses in $e^+/e^{-}$; not in $\bar{p}$.

• Observed fluxes $=(100-1000) \times$ predicted flux for thermal DM:

$$\text{Observed Flux} = \left( \frac{\rho_{\text{DM}}}{0.3 \text{GeV/cm}^3} \right)^2 \left( \frac{\langle \sigma v \rangle_{\text{GAL}}}{10^{-6} \text{GeV}^{-2}} \right)$$

$$\langle \sigma v \rangle_{FO} \sim 10^{-9} \text{GeV}^{-2}$$

Local clumpiness in DM distribution: ‘Boost Factor’ $< 10$

Lavalle et.al., 0709.3634 [astro-ph]

enhancement of $<\sigma v>$ at small velocities?
The Standard Lore about a steep rise in positrons from DM annihilation:

- most likely from direct annihilation to leptons. In this case \textit{neutralino disfavored} - due to chirality flip Born cross section suppressed by $m_e^2/m_{\text{susy}}^2$ – but spin-1 DM particles from UED or little Higgs models are OK, as well as Dirac fermions from mirror DM
- production and decay of heavy bosons marginally OK (play with uncertainties). Compatible to a neutralino. Constraints from antiprotons?
- Instead, $b$ quarks and tau leptons spectra too soft
- anyway, typically large boost factors required (clumpiness? – maybe unreasonably too large according to recent numerical simulations)
- otherwise large $\langle \sigma v \rangle \rightarrow$ (1) non-thermal DM; (2) constraints from other indirect searches (gammas, antiprotons) – however astrophysical uncertainties are larger for the latter (positrons usually come from nearby)
Large theoretical activity triggered by PAMELA
[51] K. Hamaguchi, S. Shirai and T. T. Yanagida,


and more....
“One day, all these will be LHC phenomenology papers”
a small appetizer of the (near!) future awaiting us?
• 511 keV radiation from galactic bulge detected by INTEGRAL
• Positrons from galactic center annihilate with electrons.
• Low mass X ray binary.
• eXiting DM:
  \[ \chi^* \rightarrow \chi \, e^+ \, e^- \]
  \[ \Delta E = 1-2 \text{ MeV} \]

Finkbeiner & Weiner, astro-ph/0702587
New DM ideas

• Leptophilic property:
  1) DM couplings to leptons only.
  2) DM annihilates to sub-GeV particles that is forbidden kinematically to decay to proton/anti-p.

• Boosted annihilation in galaxy:
  1) Non-thermal DM.
  2) Assumed local clumpiness.
  3) Breit-Wigner resonance.
  4) Sommerfeld enhancement.
Sommerfeld enhancement

- Attractive (Coulomb) potential produced by a light force carrier ($m_\phi < \alpha m_\chi$):

- Sufficiently slow incident particles feel potential more at $r=0$ and their wave-function is more distorted $\Rightarrow$ enhanced cross-section.

$$V = \frac{\alpha}{r} e^{-m_\phi r}$$
A Theory of Everything

A Theory of Dark Matter

Nima Arkani-Hamed, Douglas P. Finkbeiner, Tracy R. Slatyer, and Neal Weiner


- **PAMELA/ATIC**: TeV DM with GeV boson for Sommerfeld effect.
- **XDM** for INTEGRAL: 1-2 MeV mass gap.
- **iDM** for DAMA: 0.1 MeV mass gap.

Smith, Weiner, hep-ph/0101138
CR Positron measurements are challenging

- Flux of CR protons in the energy range 1 – 50 GeV exceeds that of positrons by a factor of $>10^4$
- Proton rejection of $10^6$ is required for a positron sample with less than 1% proton contamination.

The single largest challenge in measuring CR positrons is the discrimination against the vast proton background!
CR positron measurements
The early years: 1965 - 1984

What caused the dramatic rise at high energies at that time?
proton misidentification!
What a little dash of protons can do!

PAMELA claims $p$ rejection of $10^{-5}$. CAUTION! This is not verified using independent technique in flight.
More data expected!

- **ATIC and CREAM**
  - Elemental abundances up to \(10^{15}\) eV

- **PAMELA**
  - Absolute positron flux
  - More on absolute antiproton flux
  - Electrons
  - Light nuclei

- **Fermi Large Area Telescope**
  - Electrons up to \(1\) TeV
  - Diffuse emission (Galactic and extragalactic)
  - A probe of electron spectrum from the solar surface to Saturn's orbit
  - A probe of CR proton spectrum beyond the heliospheric boundary

- **AMS - will it fly?**
anyway the many indications/excesses for astroparticle physics are teaching us a lesson…
anyway the many indications/excesses for astroparticle physics are teaching us a lesson…

confirmation needed from accelerator physics!