Recent developments in dark matter

Arjun Berera

The University of Edinburgh

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Overview

- Review observational evidence for dark matter (DM)
- Basic properties required of DM
- Candidate DM particles
- Problems with DM as particles and alternative theory MOND
- Direct detection experiments and recent CDMSII results
- Indirect detection experiments
- Recent results finding universal scales in galaxies

Methods for detecting dark matter

- Observation
- Direct detection
- Indirect detection
- Collider

Observational evidence for dark matter

- Galaxy rotation curves
- Galaxy clusters
- Gravitational lensing
- Cosmic background radiation

Galaxy rotation curves

Rotation velocity of matter moving around a galaxy

Keplerian relation:

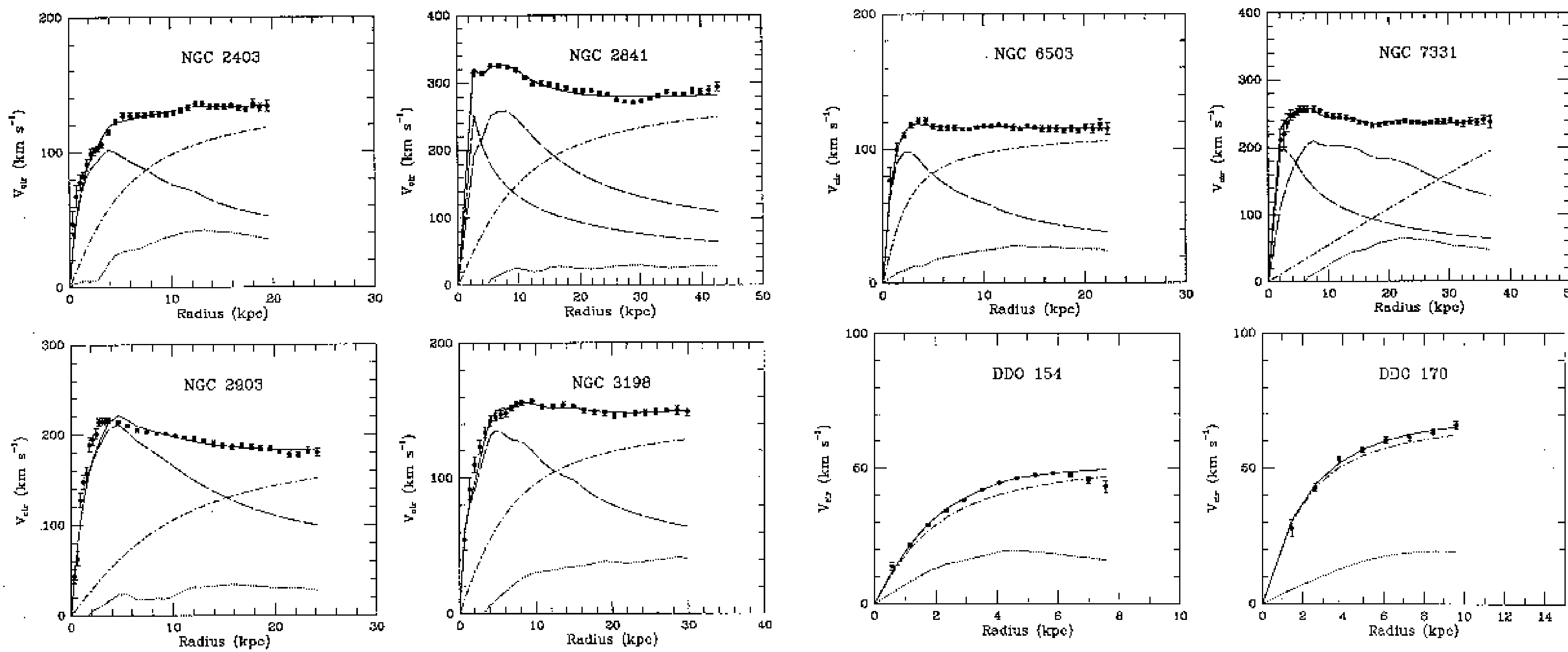
$$v_c^2(r) = \frac{GM(r)}{r}$$

If galaxy mass comprised only of visible matter, expect $v_c^2 \sim 1/r$ at distance beyond where there is no visible matter (~ 10 kpc for a typical spiral galaxy)

Instead find v_c flattens at large distance.

Measured rotation curves

Three parameter fits (solid) to measured rotation curves, with individual components, visible component (dashed), gas (dotted), and dark halo (dash-dot)

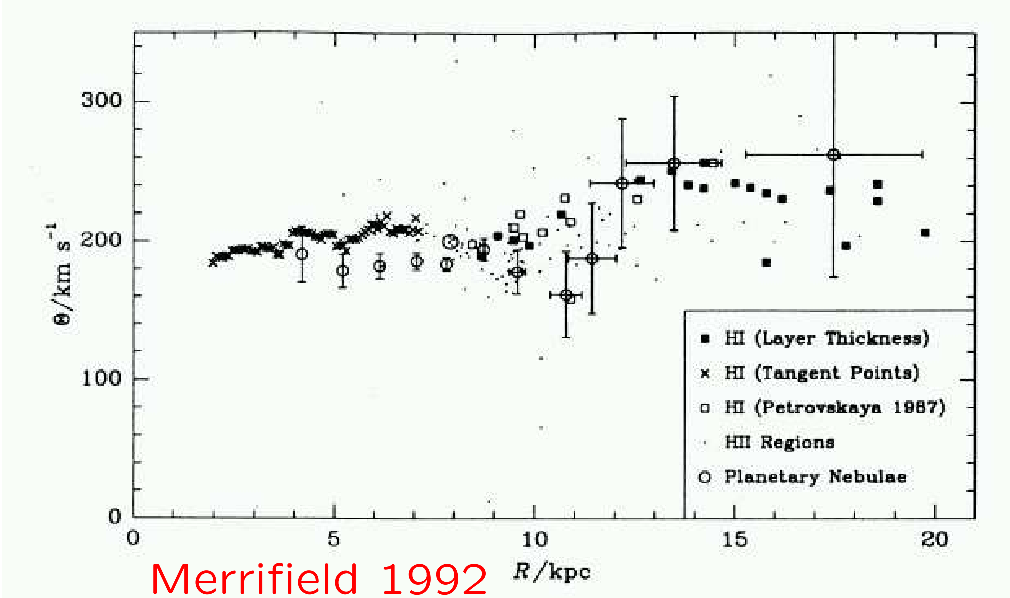


Begeman *et al.* 1991

Local dark matter density

Assuming matter is distributed
with spherical symmetry,
the mass inside radius r is:

$M_<(r) = 4\pi \int_0^r r'^2 dr' \rho(r')$



Merrifield 1992

Fit Milky Way rotation data with two parameter density profile (cored isothermal sphere):

$$\rho(r) = \rho_0 \frac{R^2 + a^2}{r^2 + a^2}$$

ρ_0 - local dark matter density
$R \sim 8.5\text{kpc}$, distance from our Galaxy center,

Fit to data suggests $a \sim 3 - 5\text{kpc}$ and $\rho_0 \sim 3 - 4\text{GeVcm}^{-3}$

Galaxy clusters

Largest gravitationally bound objects in the Universe

Early observations of concentrations of thousands of galaxies applied the virial theorem $v^2 = GM/R$ where v^2 is velocity dispersion and R observed radius of cluster and suggested more matter than just the stellar components

$2K + V = 0$ self-gravitating system in equilibrium

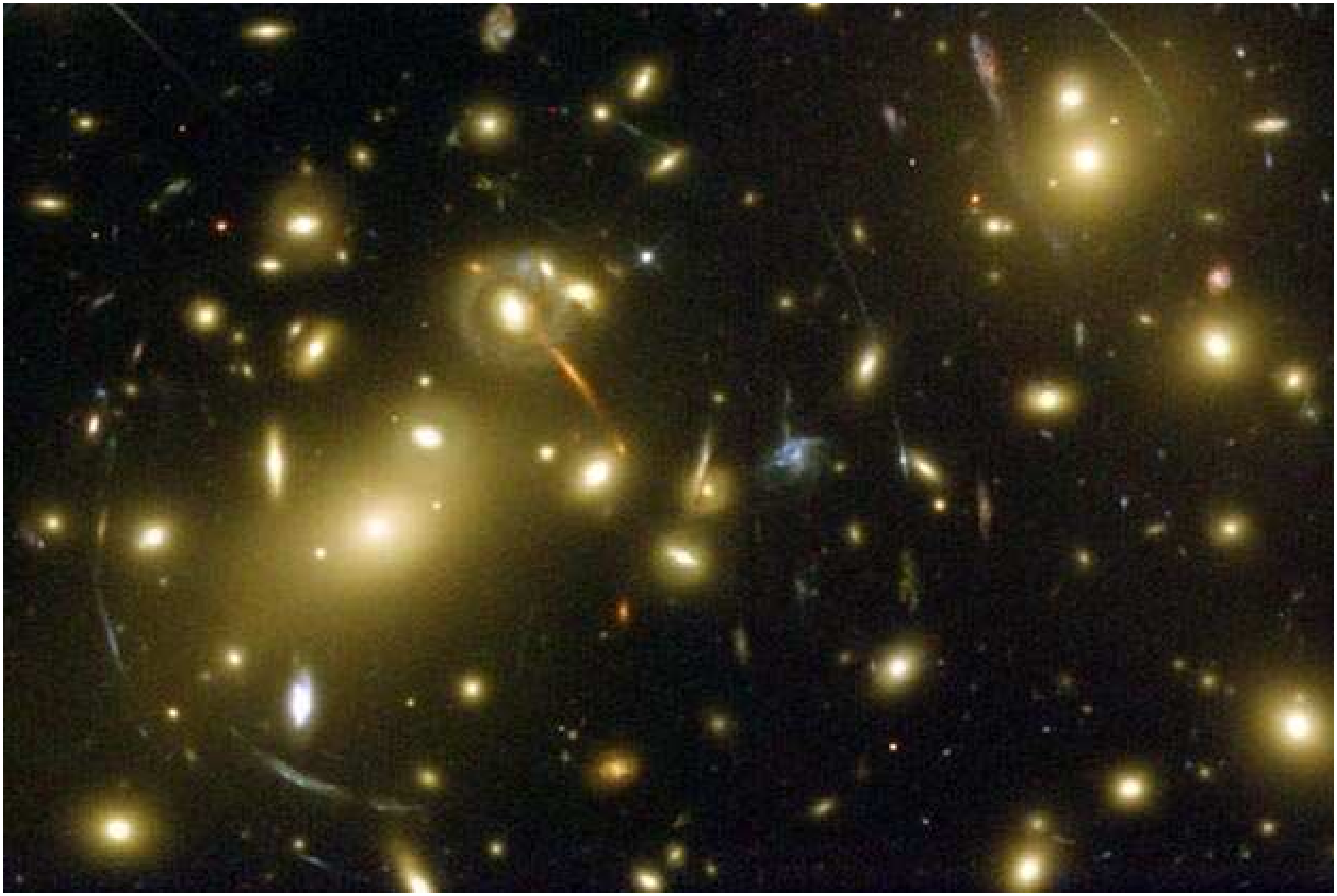
$$K = \frac{1}{2}\sum_i m_i v_i^2 \qquad V = -\frac{1}{2}\sum_i \sum_{j\neq i} \frac{G m_i m_j}{r_{ij}}$$

$$\langle v^2 \rangle \equiv \frac{\sum_i m_i v_i^2}{\sum_i m_i} \qquad R_{cluster} \equiv 2\left(\sum_i m_i\right)\left(\sum_{i,j} \frac{m_i m_j}{r_{ij}}\right)^{-1}$$

$$\frac{GM}{R_{cluster}} = \langle v^2 \rangle$$ where $M \equiv \sum_i m_i \Rightarrow \Omega_m \sim 0.4$

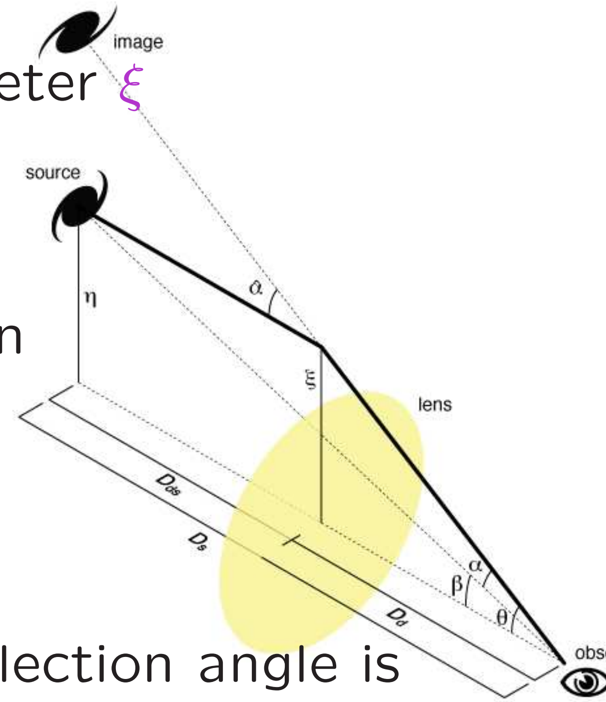
Gravitational lensing

Abell 2218



Hubble Space Telescope, Couch 1995

Gravitational lensing - Basics



Light from source incident on lens at impact parameter ξ

Crossing lens plane $\Rightarrow$ deflection angle $\hat{\alpha}(\xi)$

Deflected ray reaches observer, who sees image of source apparently at position θ whereas true position (in absence of lens) is β

Can cause elongation, arcing and for strong enough lensing multiple images

Lensing cluster of mass M, impact parameter ξ, deflection angle is

$$\hat{\alpha} \sim \left(\frac{GM}{dc^2}\right)^{1/2}$$

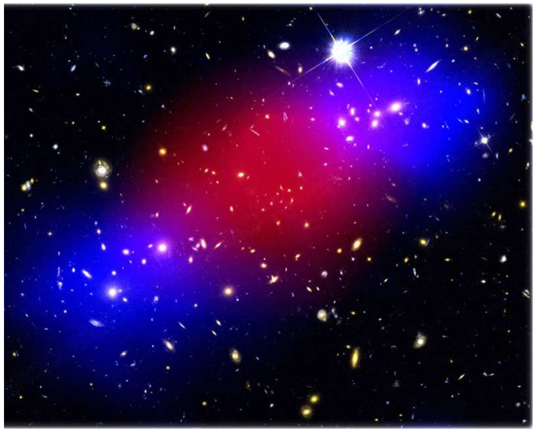
Measure impact parameter indirectly by knowing redshift of source and lensing cluster

From this can obtain cluster mass M

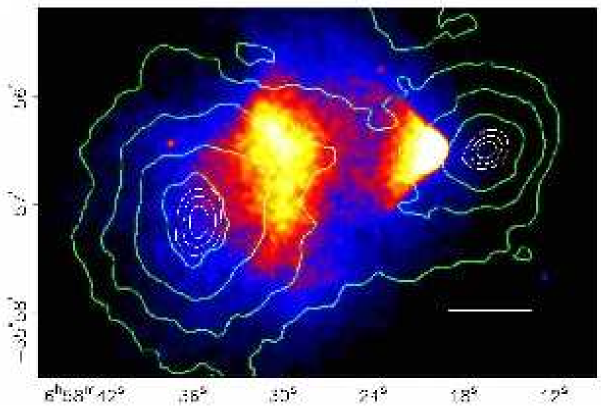
Observation finds M for clusters bigger than observed baryonic mass

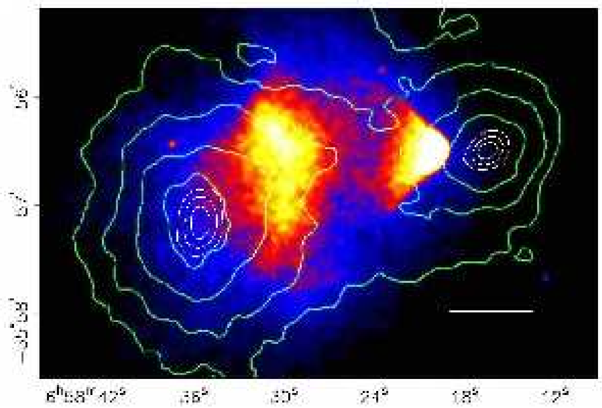
Bullet cluster

Direct evidence of dark matter, Clowe *et. al.* 2006



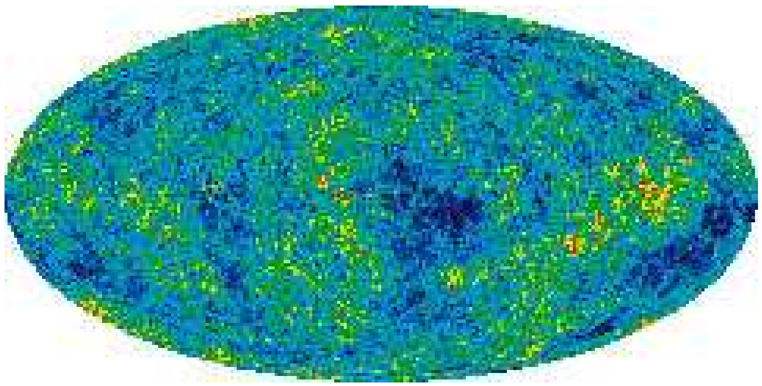
Weak lensing observation of cluster merger

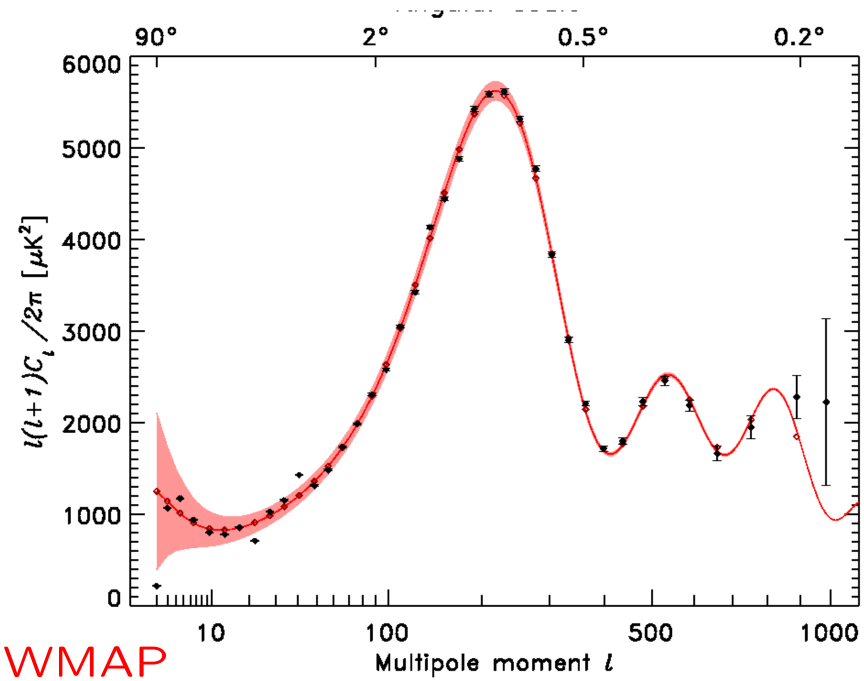




Gravitational lensing map is created showing gravitational potential does not trace plasma distribution (dominant baryonic mass component) - rather approximately traces distribution of galaxies

Cosmic microwave background anisotropies





WMAP

Fluctuation distribution of CMB depends on content of Universe and primordial fluctuations

$$\Omega_b h^2 = 0.02267^{+0.00058}_{-0.00059}$$

$$\Omega_c h^2 = 0.1131 \pm 0.0034$$

$$-0.0179 < \Omega_k < 0.0081$$

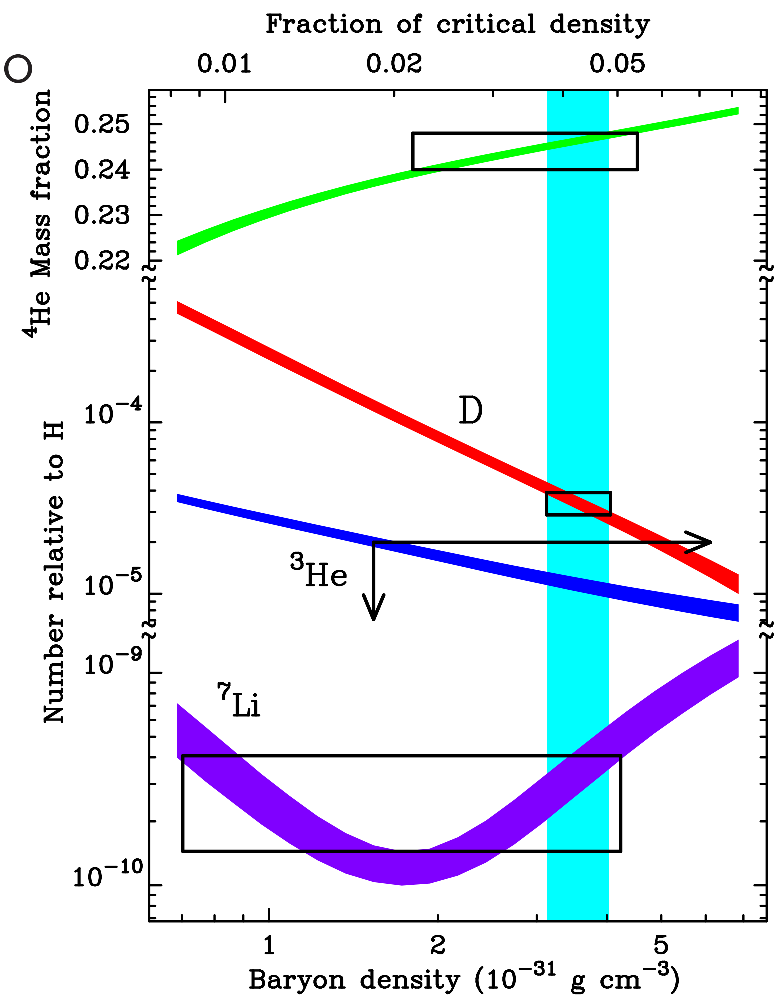
Nucleosynthesis

$T \lesssim 1$MeV ($t \lesssim 1$s) weak interactions changing neutrons and protons becomes negligible, n and p start binding into nuclei

Abundance depends on photon to baryon ratio

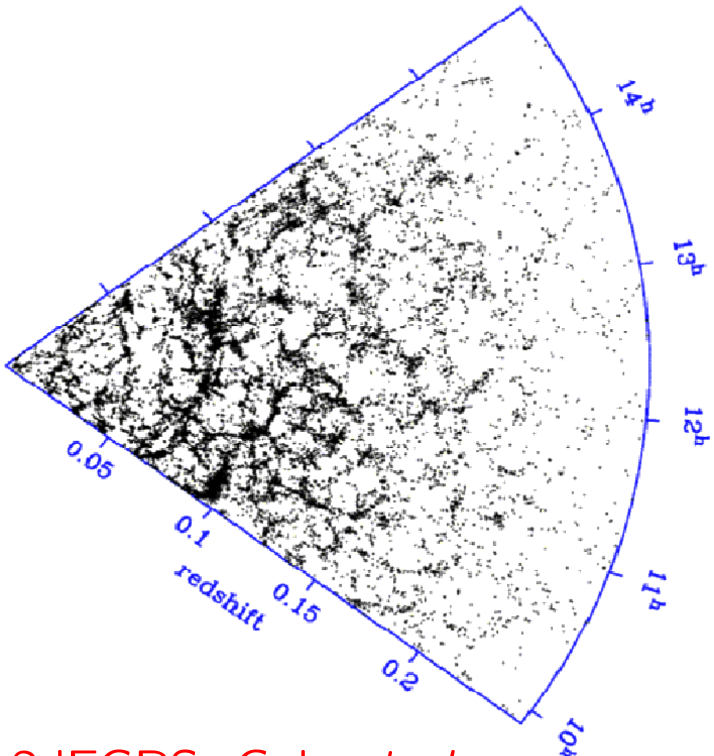
Can measure high redshift abundances of baryons can compare to theory

Consistent with measurement of baryon density from CMB temperature fluctuations

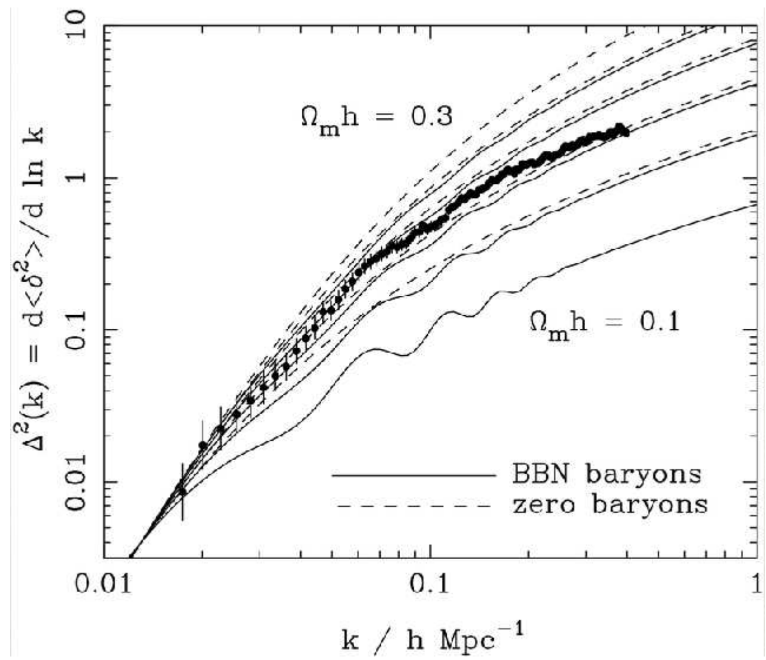


Large scale structure

Governed by density perturbations at late time, which depend on content of Universe

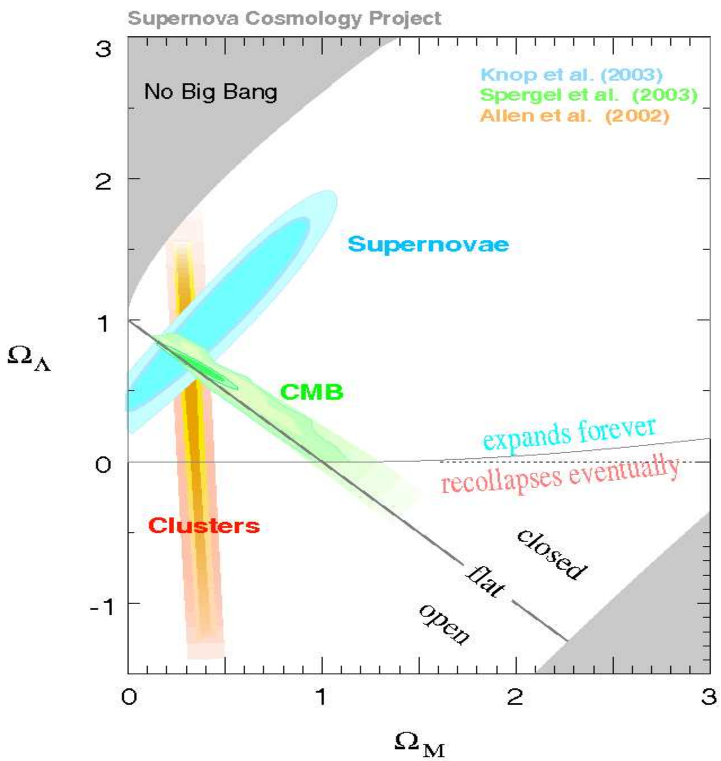


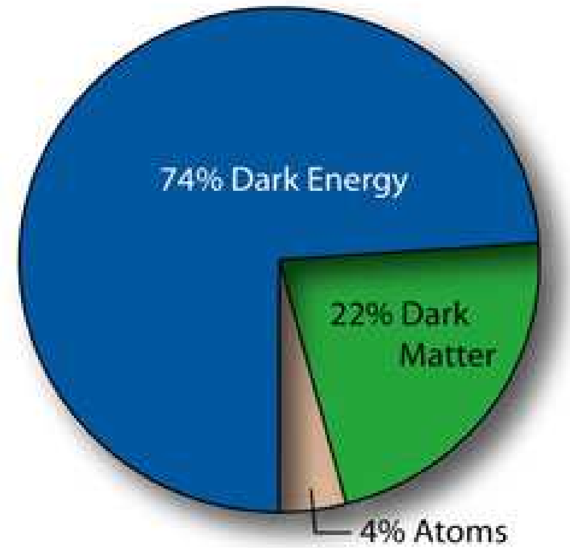
2dFGRS, Cole *et al.*



$$\Omega_m h = 0.168 \pm 0.016$$
$$\frac{\Omega_b}{\Omega_m} = 0.185 \pm 0.046$$

Cosmic budget





4% Baryonic Matter -
Matter asymmetry?

22% Dark Matter - No candidate in the Standard Model,
No direct evidence

74% Dark Energy - Accelerated expansion in present Universe
Candidates? - Cosmological constant, Quintessence field ...

Properties of dark matter

- No (extremely weak) interaction with photons - otherwise would contribute to dimming of quasars, create absorption lines in spectra of distant quasars

- Self interaction of dark matter must be small - otherwise gravothermal collapse, i.e. halo would evaporate. Bullet Cluster evidence of low interaction

- Interaction of dark matter and baryons must be small - otherwise as overdense regions collapse to form a galaxy, dark matter and baryons would fall together, resulting in baryon-DM disk rather than more diffuse DM halo. Also DM-baryon non-gravitational interactions would modify baryon acoustic oscillations.

- Can not be Standard Model particle - only possibility, neutrino, ruled out due to Gunn-Tremaine bound

Types of dark matter

Kinematic properties

- Hot dark matter - dark matter particles which are relativistic at time of structure formation (so very light or massless particles). Ruled out as the major component of dark matter, can only be at most a few percent of universe content.

- Cold dark matter (CDM) - dark matter particles that are non-relativistic at time of structure formation. Most successful dark matter theory

Interaction properties

- Baryonic dark matter - composed of protons and neutrons such as nonemitting ordinary atoms

- Nonbaryonic dark matter - composed of particles that are not baryons. So contains no atoms and does not interact with ordinary matter via electromagnetic forces

Candidates for cold dark matter

- WIMP - Weakly interacting massive particles - a heavy unknown particle that has a weak interaction strength with ordinary matter, most promising candidate for dark matter

- EWIP - Extremely weakly interacting particle below weak interaction scale. Such particles can be very light but still CDM since interacted so less in early universe that could not thermalize

- MACHOs - Massive Compact Halo Objects - composed of normal baryonic mattercondensed objects such as black holes, neutron stars, white dwarfs, and planets. Microlensing observations suggest as much as 20% of dark matter in the Milky Way could be MACHOs.

Case against neutrinos

Gunn-Tremaine bound imposes lower bound required for dark matter particle that decoupled when relativistic, $m_{DM} \gtrsim 100\text{eV}$

Momentum distribution in Galactic halo Maxwell-Boltzmann, $\Delta p \sim m_{DM}\langle v\rangle \sim 300\text{km/sec}$

Mean spacing $\Delta x \sim n_{DM}^{-1/3} \sim (\rho_{DM}/m_{DM})^{-1/3}$

$\Delta x \Delta p \gtrsim \hbar \Rightarrow m_{DM} \gtrsim 50\text{eV}$

Much too massive for SM neutrinos

Total relic density from neutrinos is:

$$\Omega_\nu h^2 = \sum_{i=1}^{3} \frac{m_i}{93\text{eV}}$$

Upper bound of neutrino masses from β-decay experiments: $m_\nu < 2.05\text{eV}$

$$\Rightarrow \Omega_\nu h^2 \lesssim 0.07$$

Neutrinos not abundant enough to dominate dark matter.

CMB + LSS constraints even more stringent, giving $\Omega_\nu h^2 \lesssim 0.0067$

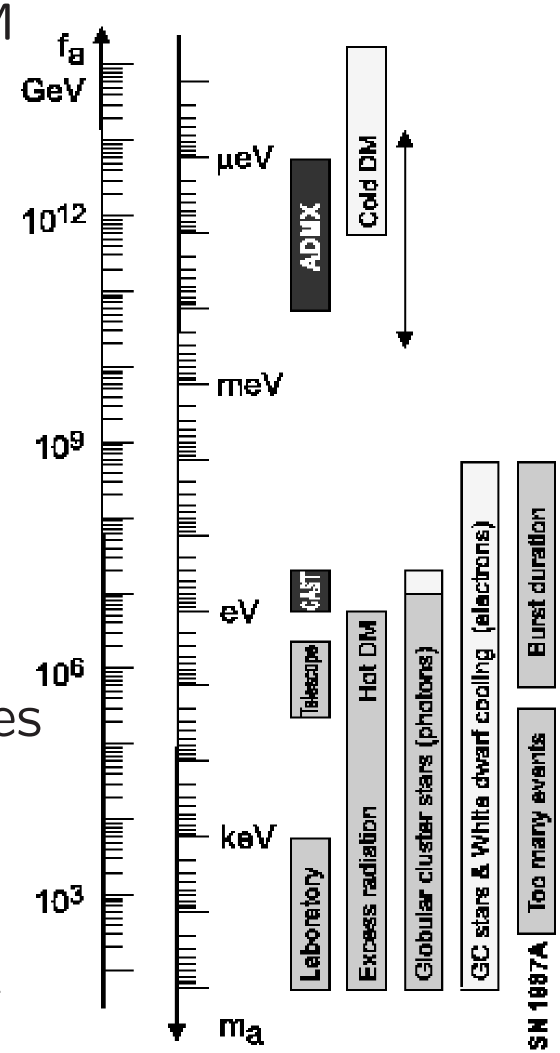
Possible dark matter particles

- Axion
- Neutralino
- Gravitino
- Klein-Kaluza particles

Also, Inert Higgs, axino, wimpzilla, sterile neutrino, . . .

Axion

One of earliest suggestions for DM



Pseudo-Goldstone boson arising from the spontaneous breaking of the U(1) symmetry of Pecci-Quinn suggested to solve the strong CP problem

Very weak EM and strong interactions, extremely weakly interacting particle (EWIP)

Axion typically is very light $\lesssim 0.01\text{eV}$ but couples so weakly to other matter that it never thermalizes in the early universe and behaves as CDM

Still remains mass range $10^{-5} - 10^{-2}\text{eV}$ where axion passes all observational tests and would not overclose the universe

Neutralino

Spin 1/2 particle with weak interactions

Mixture of bino, wino and neutral higgsino states

In appealing SUSY-breaking schemes neutralino appears as the lightest supersymmetry particle (LSP) $\Rightarrow$ stable so good candidate for DM. These breaking schemes motivated by grand unification and experimental constraints on flavor mixing and CP violation.

Typical mass range of neutralino $\sim$ 100GeV, is the most common example of a WIMP

Another possibly more obvious choice, sneutrino turns out to have too strong a coupling and should already have been observed if it were the LSP

Gravitino

Spin-3/2 field, superpartner to the Spin-1 graviton

Interaction suppressed by M_{Pl}^{-1} $\Rightarrow$ early universe interaction could be enhanced but today a EWIP

Mass can range from eV to TeV range depending of SUSY breaking scenario

Extremely weak coupling means inaccessible to direct and indirect searches

Direct production at colliders highly suppressed for masses $\gtrsim$ 0.1keV due to extremely weak coupling

Kaluza-Klein

Arise from extra dimensional extensions of Standard Model

SM particles propagate in higher dimensional bulk, universal extra dimensions

Lightest KK particle (LKP) turns out to be a WIMP

Unlike the case of SUSY, this model has small parameter space testable entirely by LHC

Typical feature, model has tower of states

$$m^{(n)} = \sqrt{(n/R)^2 + m_{EW}^2}$$

m_{EW} is zero mode mass

KK dark matter is spin-1 $\Rightarrow$ interesting new direct annihilation channels into $\nu\bar{\nu}$ and e^+e^- appear not found for fermion dark matter (these channels usually heavily suppressed for neutralinos)

Recently of interest as positron source as explanation of excess seen in PAMELA

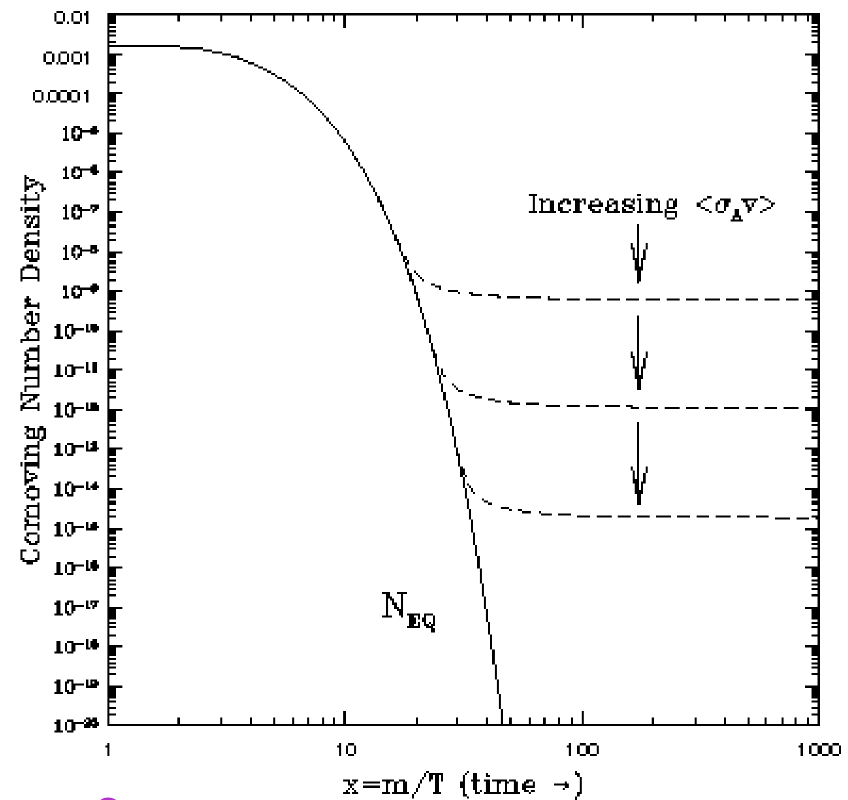
WIMP relic abundance

WIMP annihilation rate: $\Gamma(\chi\chi \leftrightarrow l\bar{l}, \ldots) = n_\chi \langle \sigma v \rangle$
- σ cross section for annihilation of two WIMPs, v relative velocity

At early times, when $T \gg M_\chi$, $n_\chi \sim T^3$, $\Gamma \gg H$, considerable scattering, equilibrium maintained

At late times, when $T \ll M_\chi$, $\Gamma \ll H$, $n_\chi \sim T^{3/2} e^{-M_\chi/T}$, abundance freezes out

Freezeout at $\Gamma(T_f) \sim H(T_f)$ and for nonrelativistic particles
$n_\chi = g_\chi (M_\chi T/2\pi)^{3/2} e^{-M_\chi/T} \Longrightarrow$



$$\langle \sigma v \rangle (M_\chi T_f)^{3/2} e^{-M_\chi/T_f} \sim \frac{T_f^2}{M_{pl}}$$

for $T_f \sim M_\chi \Rightarrow T_f/M_\chi \sim 1/25$ with electroweak-scale parameters $\sigma \sim 10^{-8}$GeV, $M_\chi \sim 100$GeV

WIMP relic abundance - cont.

Freezeout abundance

$$\frac{n_\chi}{n_\gamma} \sim \frac{\Gamma(T_f)/\langle\sigma v\rangle}{T_f^3} \sim \frac{25}{M_{pl}\langle\sigma v\rangle M_\chi}$$

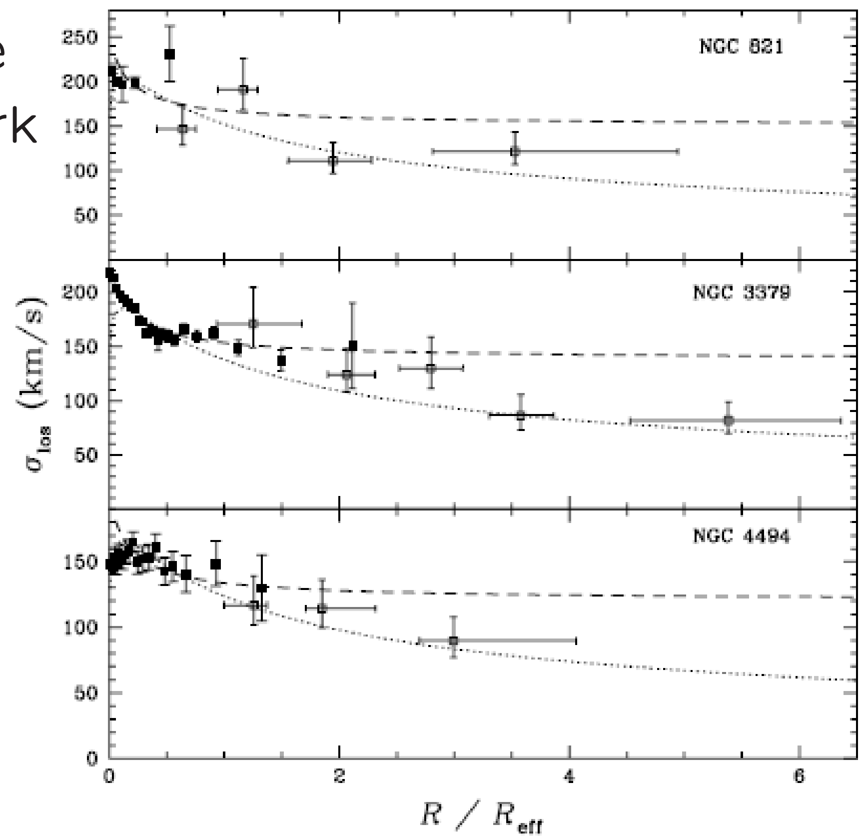
$\Longrightarrow \quad \Omega_\chi = \rho_\chi/\rho_c \sim 25/(M_{pl}\rangle\sigma v\rangle)400cm^{-3}/(10^{-6}\mathrm{GeVcm}^{-3}$

$\Longrightarrow \quad \Omega_\chi h^2 \sim 0.1$

Get required dark matter density for weak interaction cross section and particle around electroweak scale - "WIMP miracle"

Problems with dark matter paradigm

- Halo model is basically has three free parameters, velocity dispersion of dark matter particles, inner cutoff radius and mass to luminosity ratio. Needs to be fine tuned to avoid unobserved cusp in rotation curve



- Giant elliptical galaxies reveal no evidence for a dark halo Romanowsky *et. al.* 2003

- No direct observation of a dark matter particle

Modified Newtonian Dynamics (MOND)

Milgrom, APJ **270**, 365 (1983)

Modification in Newtonian dynamics governed by acceleration scale

$$-\nabla\mathbf{\Phi}_N = \mu(|\mathbf{a}|/a_0)\mathbf{a}$$

$\mathbf{\Phi}_N$ - Newtonian gravitational field, $\mathbf{a}$ - acceleration

$a_0 \sim 10^{-8}\mathbf{cms}^{-2}$ - acceleration scale

$\mu(x) \approx x$ for $x \ll 1$ $\quad \mu(x) \to 1$ for $x \gg 1$

At very low acceleration, much below laboratory scales, dynamics gets modified - Outskirts of galaxies, often very low acceleration

Successful in fitting many spiral galaxies

Problem with MOND: does not conserve momentum or angular momentum

Correct with nonrelativistic field theory of MOND,

AQUAdratic Lagrangian theory (AQUAL) Bekenstein and Milgrom, '84

Relativistic version (RAQUAL) and GR version tensor-vector-scalar (TeVeS) Bekenstein 2004

Experimental status of MOND theories

- MOND in the NR limit explains rotation curves of spiral galaxies

  For elliptical galaxies, the MOND explanation is these galaxies have accelerations exceeding a_0 well outside the core

- Can explain CMB and galaxy distributions Skordis *et al.* 2006

- Gravitational lensing, different predictions to GR in some cases, but no conclusion Chiu *et al.* 2006, Bekenstein 2007

Direct detection: WIMP-nucleus collisions

Elastic collision of WIMPs off nuclei

$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_{wimp}} \int_{v_{min}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}.$$

LHS measured spectrum in detector $\Longleftrightarrow$ RHS theoretical prediction

Differential cross section, 2 components:

Scalar coupling between WIMP (χ) and nucleus (N): $\mathcal{L}_{scalar} \propto \bar{\chi}\chi\bar{q}q$

Axial coupling between WIMP and nucleus spins:
$\mathcal{L}_{axial} \propto \bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{q}\gamma_{\mu}\gamma_5 q$

Elastic collision estimate

If WIMPs make up our Galaxy's halo $\Rightarrow$ local spatial density $n_\chi \sim 0.004(M_\chi/100\text{GeV})^{-1}\text{cm}^{-3}$ (roughly one per liter) and moving with velocity $v \sim 200\text{km/sec}$

Typical WIMP cross section for elastic scattering off quarks, say for neutralino, $\sigma \sim 10^{-41} - 10^{-36}\text{cm}^2$ Suppose similar also for nuclei.

Interaction rate:

$R \sim n_{chi}\sigma v \sim (0.004\text{cm}^{-3})(10^{-36}\text{cm}^2)(2 \times 10^7\text{cm/sec}) \sim 10^{-24}\text{yr}^{-1}$

So $10^{23}M/(Ag)$ nuclei in the detector, for $A \sim 100$, expect $R \sim 1/\text{kg/yr}$ events.

Direct detection results

Current status of null results

- **CDMS**
  Ge, 150 kg-days,
  E_R=5/10 keV
  ionisation & heat

- **Xenon10**
  2-phase Xe, 140 kg-days,
  E_R = 4.5 keV
  scintillation & ionisation

- **Edelweiss**
  Ge, 60 kg-days,
  E_R=13 keV
  ionisation & heat

- **Zeplin III**
  liquid Xe, 847 kg-days,
  E_M = 5 keV
  scintillation & ionisation

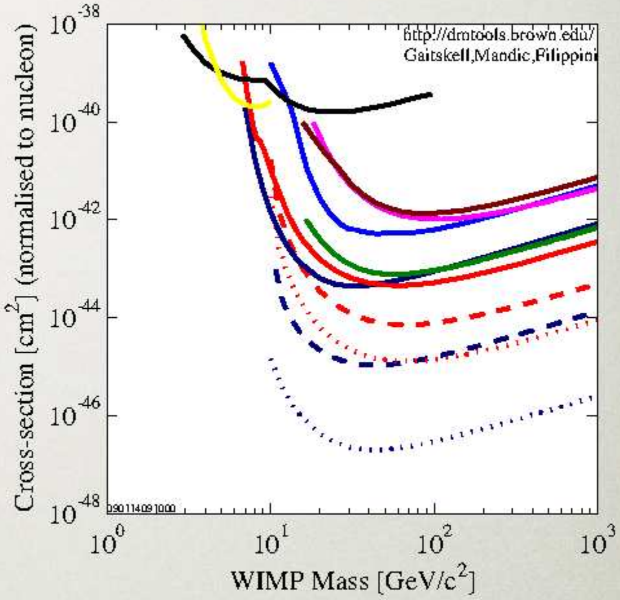
- **WARP**
  Ar, 96.5 kg-days,
  E_R=55 keV
  scintillation & ionisation

- **CRESST**
  $CaWO_4$, 20 kg-days,
  E_R=10 keV
  scintillation & heat

- **CoGENT**
  Ge, 8.4 kg-days,
  E_M= 0.23 keV
  ionisation

- **TEXONO**
  Ge, 0.337 kg-days,
  E_M=0.23 keV
  ionisation

spin-independent coupling



Assuming 'standard' halo model
(Maxwellian speed distribution
local density 0.3 GeV / cm^{-3})

CDMS II recent results

Cryogenic Dark Matter Search experiment Ahmed *et. al.*, 18 Dec 2009

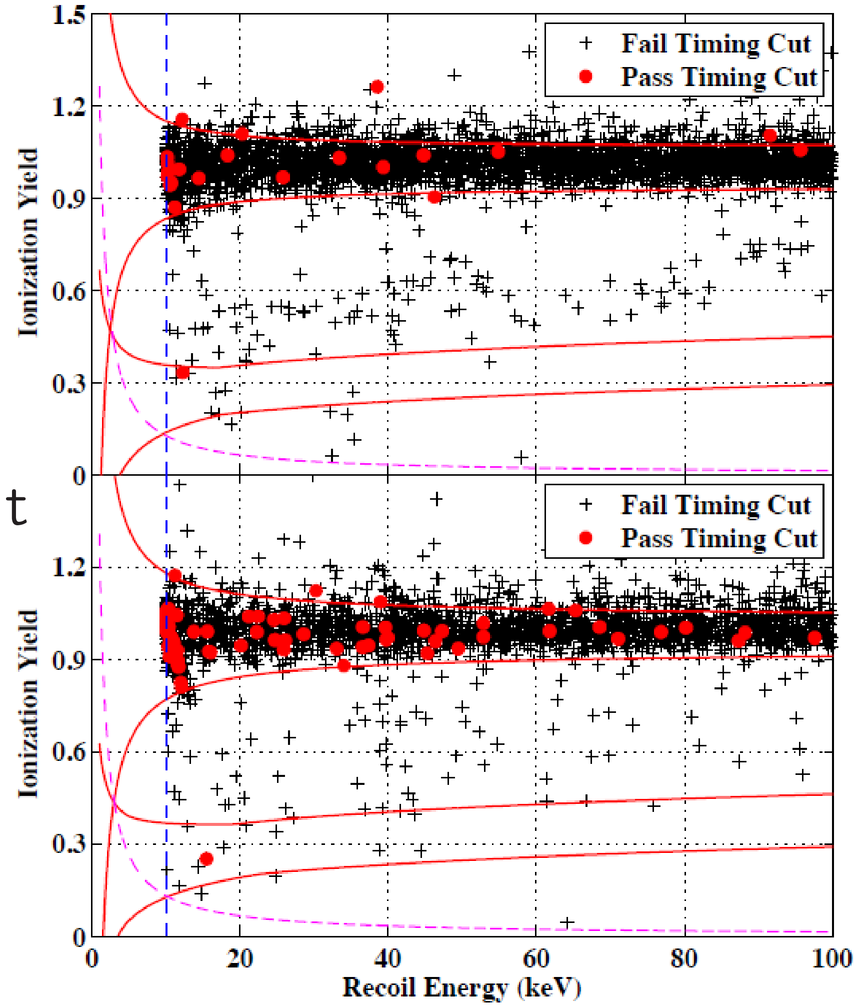
612 kg-days

Two events observed in signal region

Estimate of observing 2 or more background events is 23%

Sets upper limit at 90%-CL on WIMP-nucleon elastic scattering spin-independent cross-section $7.0 \times 10^{-44}\text{cm}^2$ for WIMP mass 70GeV

Combined CDMSII upper limit $3.8 \times 10^{-44}\text{cm}^2$ for 70GeV WIMP mass



(only narrow region within allowed range by DAMA)

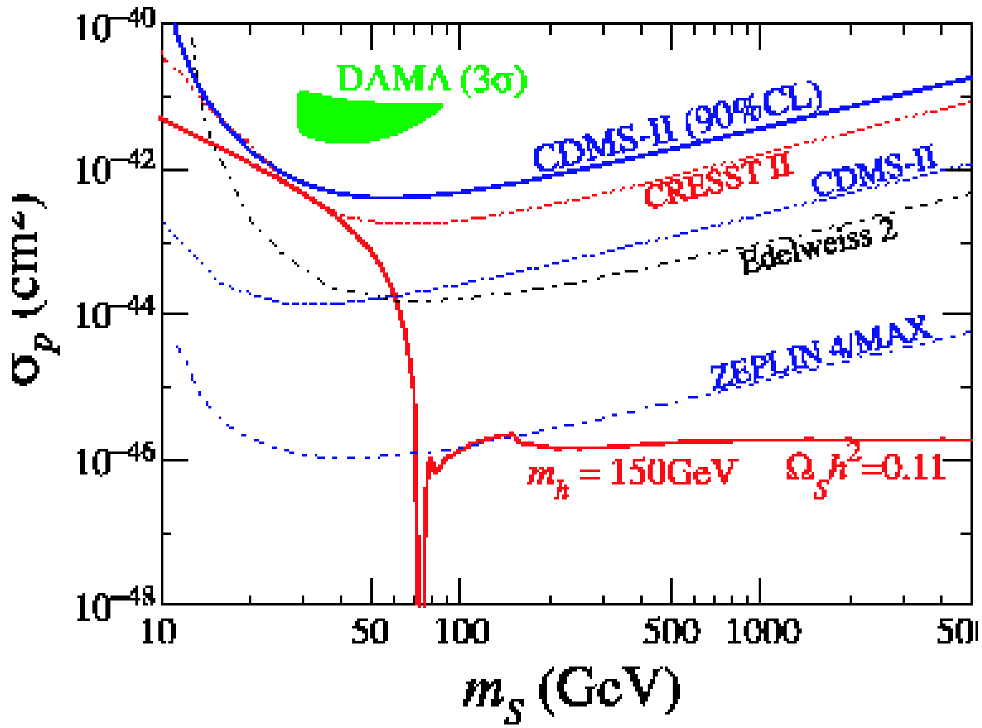
Interpretation of CDMSII findings

And theories pour in ...

- In a MSSM version with light neutralino, $\sim$ 10GeV CDMSII and DAMA/LIBRA results consistent Bottino *et. al.* 20 Dec 2009
- Scalar DM model based on SO(10) non-SUSY GUT model with DM mass $\sim$ 100GeV and prediction for jet properties at LHC Kadastik *et. al.*, 21 Dec 2009
- Attempt model independent analysis using crossing symmetry to study relation between the elastic scattering results from of CDMSII and the annihilation results implied by PAMELA and determine necessary boost factor as function of DM mass Cao *et. al.*, 22 Dec 2009
- Implications of results to neutralino MSSM scenario Hisano *et al.*, 23 Dec 2009

Etc...

Direct detection future measurements



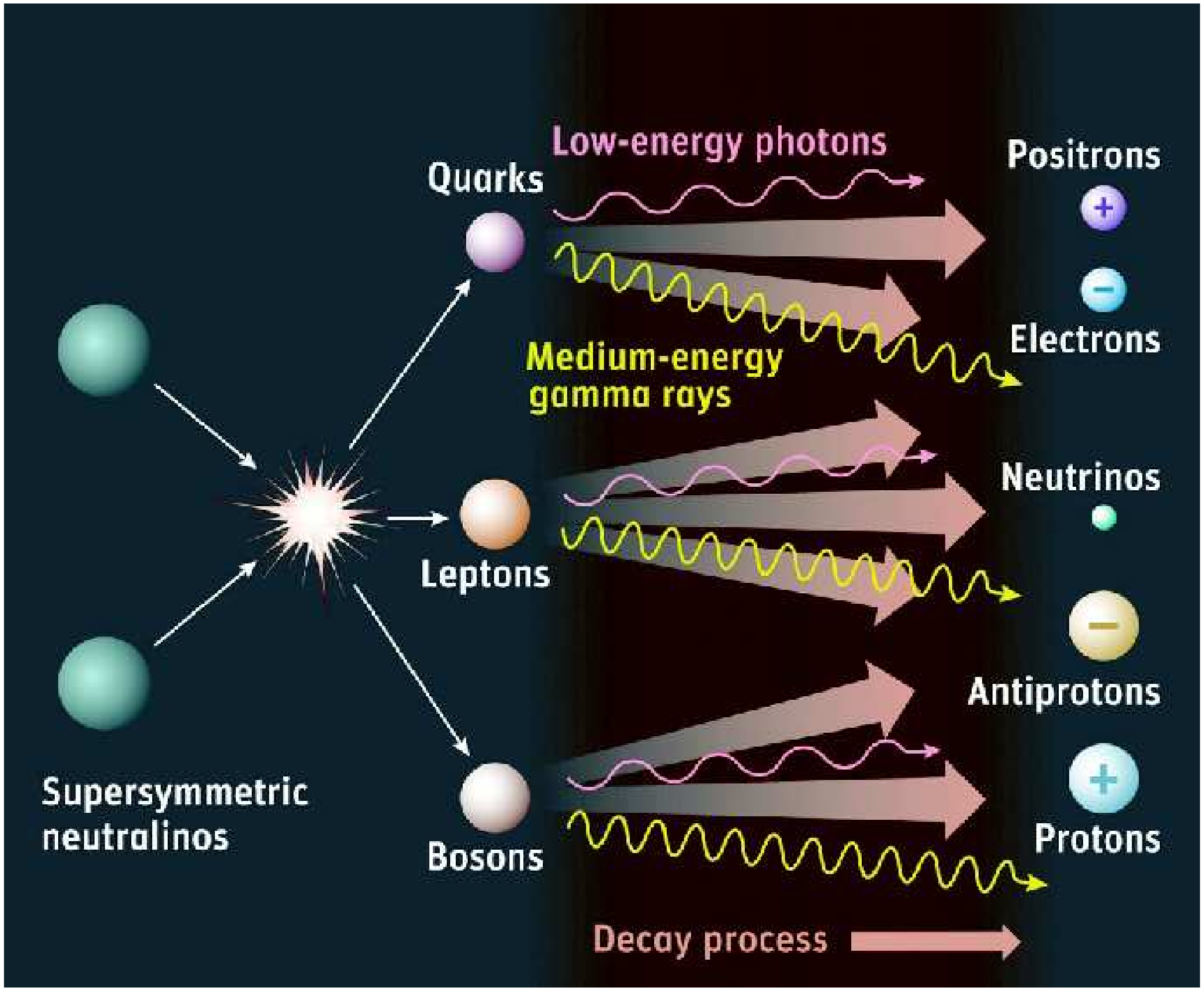
Solid red curve example theoretical prediction for particular model

DAMA - based on expected annual modulation of dark matter flux, does not use background elimination techniques like the other experiments. Reports a signal, but inconsistent with bounds set by other experiments. CDMS has a possible signal but only within narrow region consistent with DAMA results.

Indirect detection

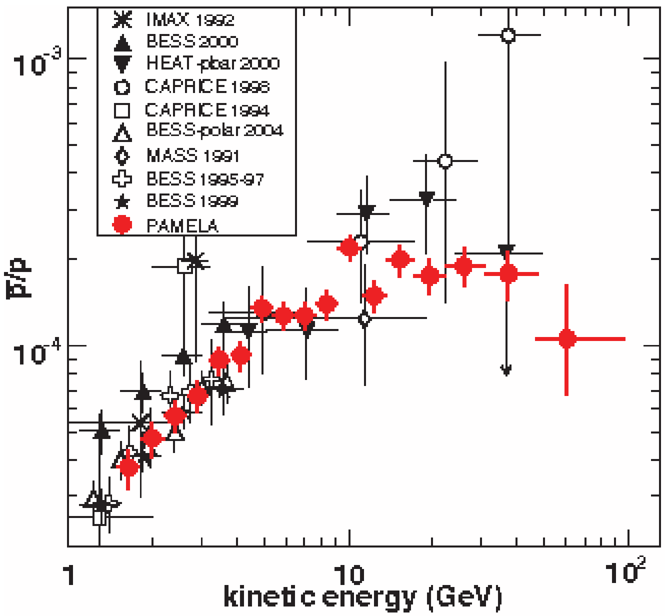
Flux measurement of

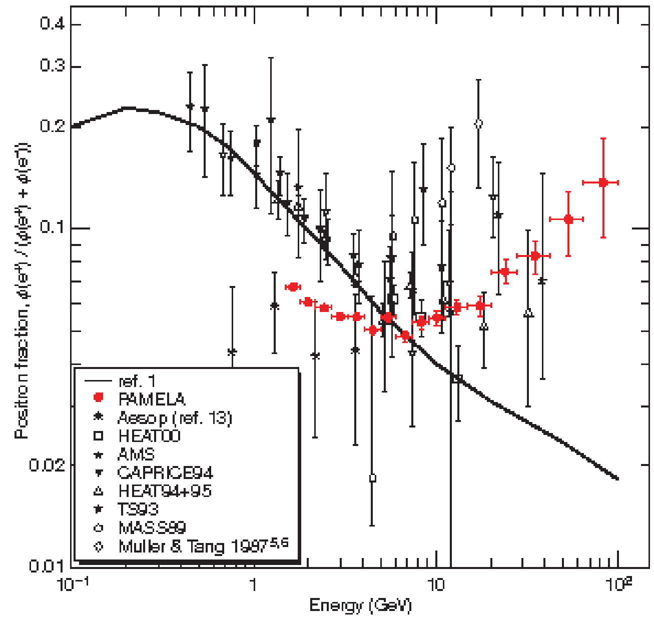
- electrons, positrons
- protons, antiprotons
- neutrinos



PAMELA experiment

Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics Adriani *et al.* 2009





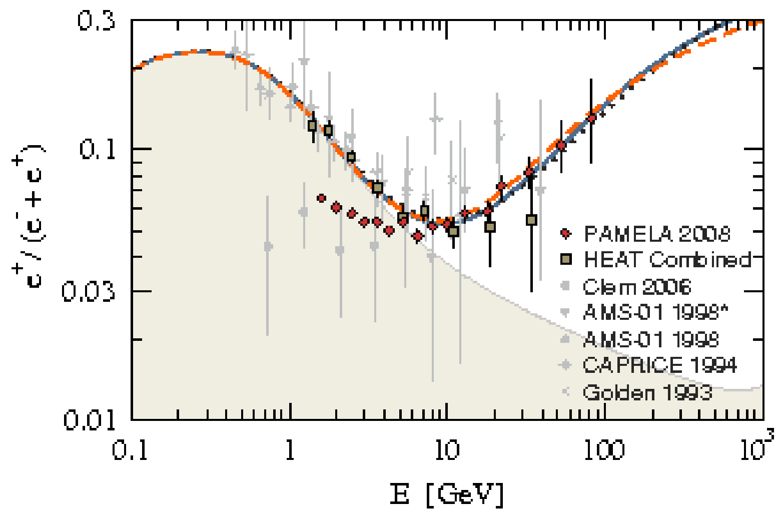
Satellite-borne experiment detects electrons, positrons, protons, antiprotons in energy range < 100GeV

Positron fraction: Lower at low energy < 5GeV - due to charge dependent solar modulation, excess at energy > 10GeV

Antiproton-proton flux ratio consistent with secondary production

Interpretation of PAMELA results

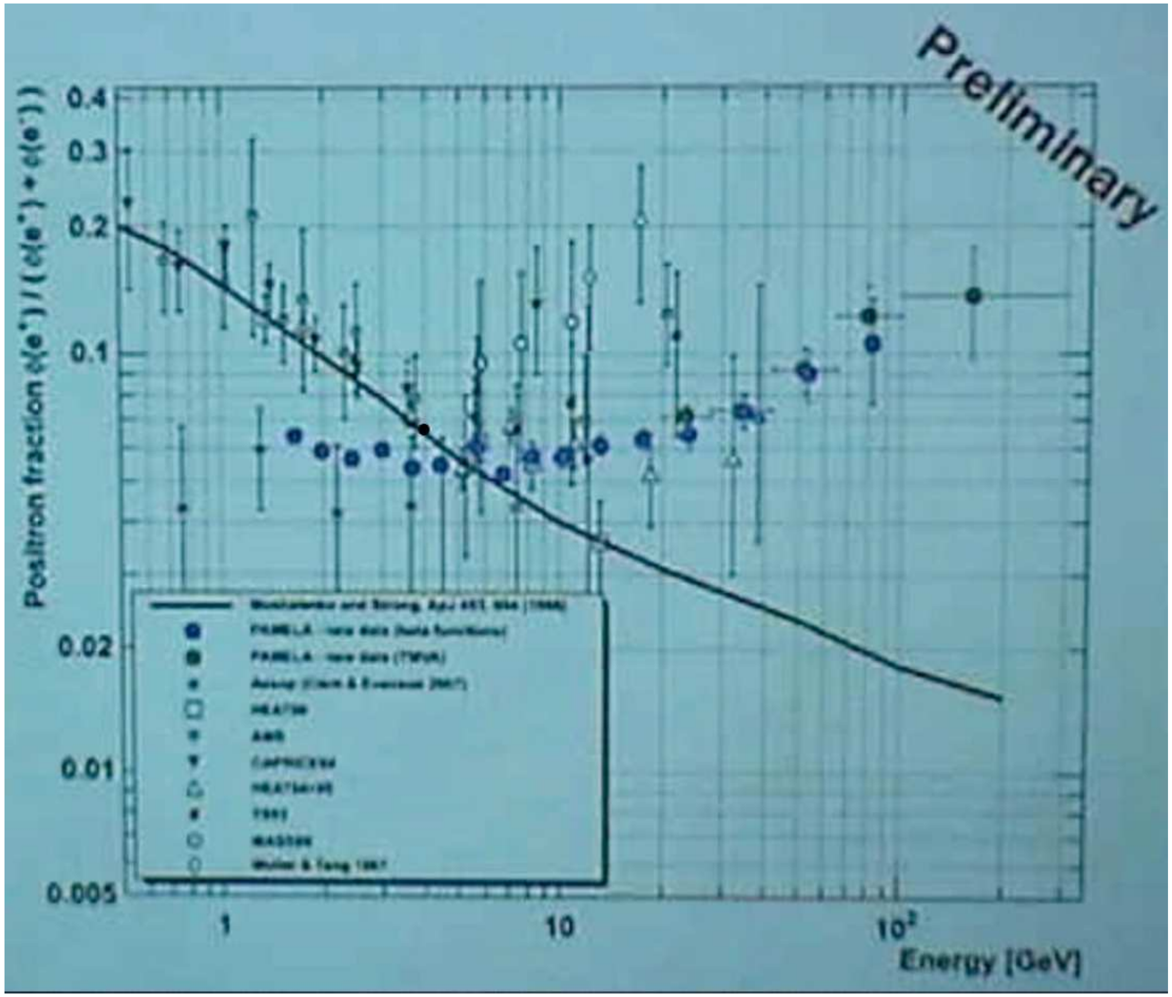
- WIMP annihilation (Bergström, *et. al.* 2008; Cholis, *et. al.* 2009)
- Gamma-ray astrophysical source - Geminga pulsar (Hooper *et. al.*, 2008; Yüksel *et. al.*, 2009; Profumo, 2009), Fermi LAT should be able to determine



- Supernova explosion of massive star (Wolf-Rayet, Biermann, *et. al.*, 2009)

Preliminary PAMELA results

New results for positron spectrum to 200GeV

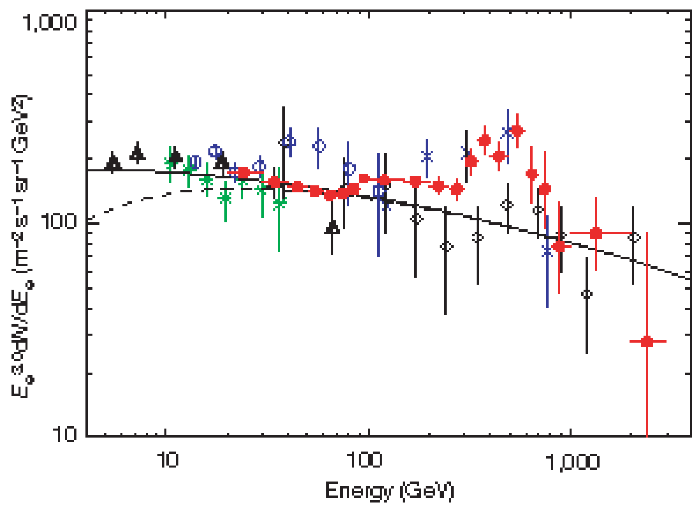


From Marfatia, Miami 2009 talk

Continuing rise in positron spectrum unclear

ATIC balloon based experiment

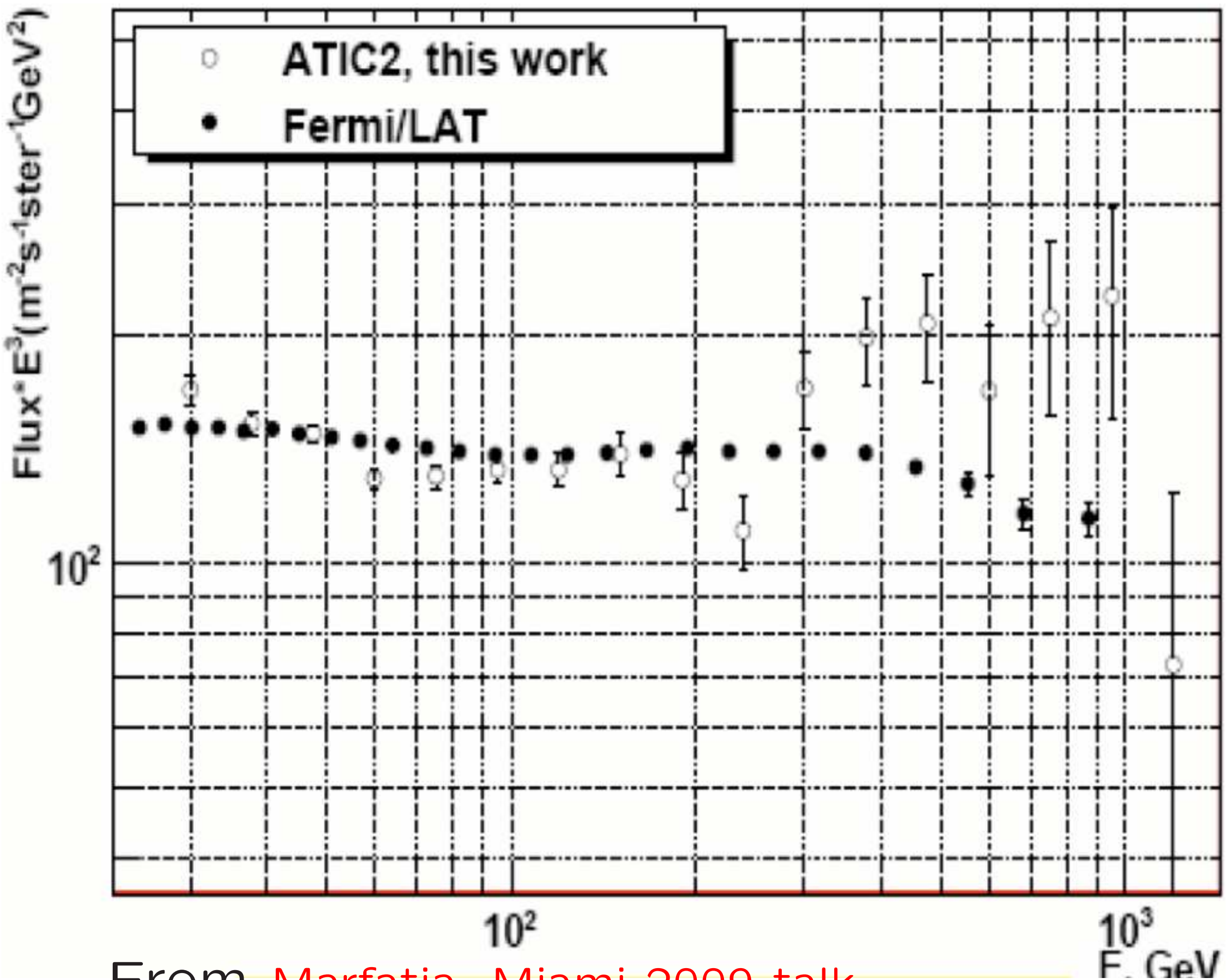
Advanced Thin Ionization Calorimeter (ATIC) (Chang *et al.* 2008)



Electron ($e^+ + e^-$) differential energy spectrum (scaled by E^3)

Find excess of galactic cosmic-ray electrons in range $\sim 300 - 800\mathrm{GeV}$

New ATIC analysis



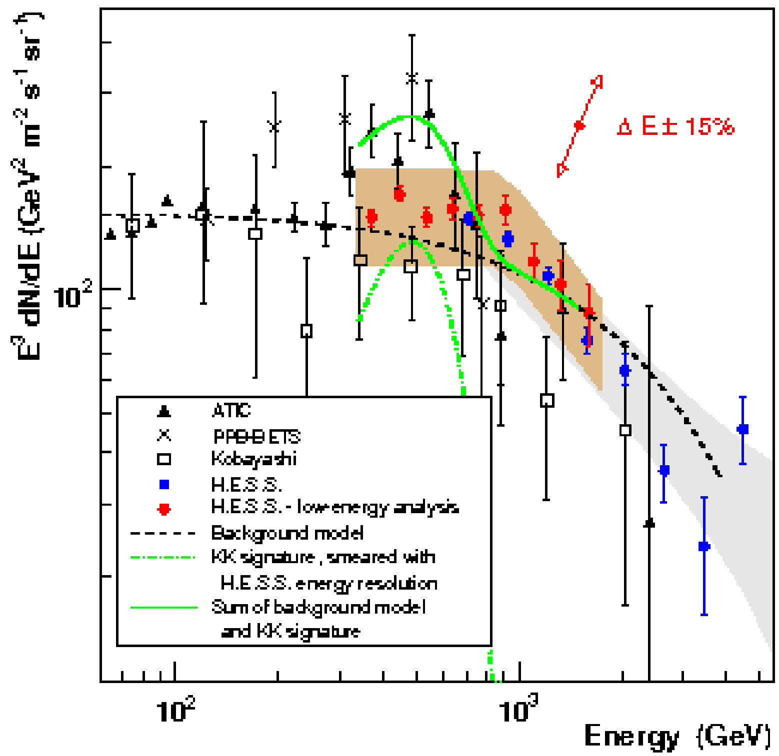
From Marfatia, Miami 2009 talk

$e^+ + e^-$ spectrum shows less steep bump compared to their original analysis

HESS Cherenkov ground telescope system

High Energy Steroscopic System (HESS) (Aharonian *et al.* 2009)

$e^+ + e^-$ energy spectrum



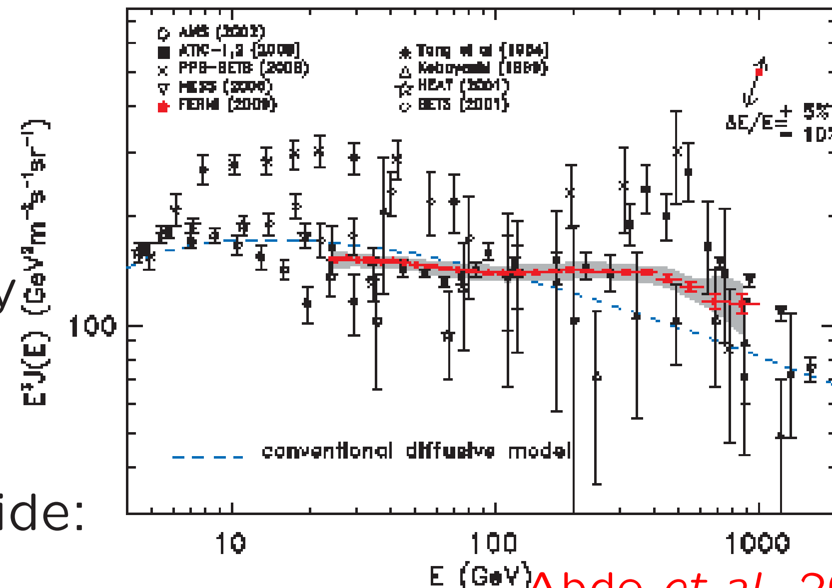
Spectrum appears to steepen at about $1TeV$ but near the end shows possible flattening (not expected for Klein-Kaluza dark matter scenario) - compatible with astrophysical origin

Does not rule out ATIC excess due to a possible energy scale shift inherent to the data

Fermi Large Area Telescope (LAT)

Satellite observatory to survey the variable gamma-ray sky between 20MeV and 300GeV

Electromagnetic cascades are closely related to electron/positron interactions in matter $\Rightarrow$ LAT also is an $e^+ \; e^-$ detector which will provide:



Abdo *et al.* 2009

(a) excellent measurement of $e^- - e^+$ flux

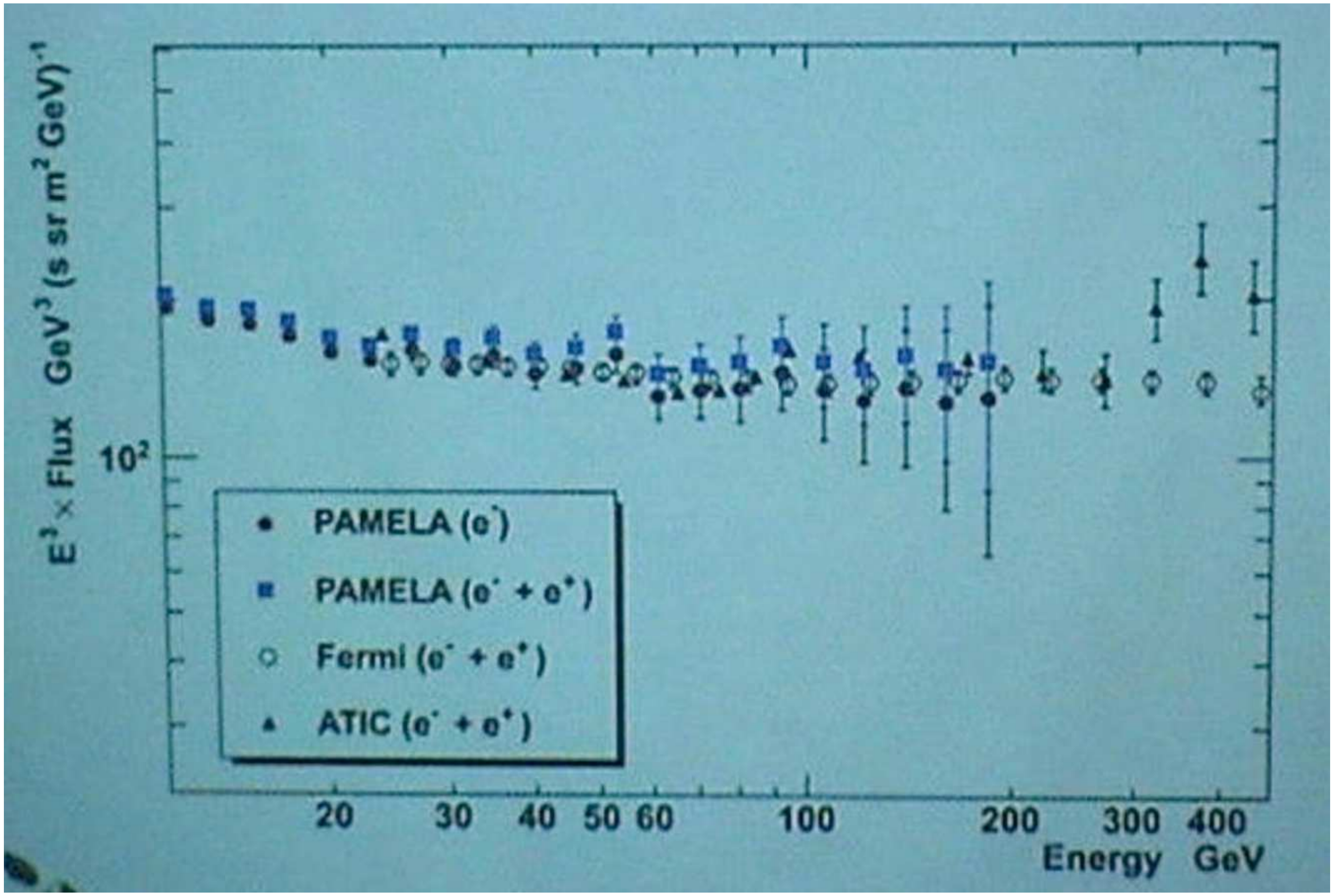
(b) detection of yet undiscovered gamma-ray pulsars

(c) search for anisotropies in arrival direction of high-energy $e^- - e^+$

Flattening of LAT data above model predictions for $E \geq 70$GeV suggests presence of one or more local sources of high-energy cosmic ray electrons

As yet dark matter scenarios not ruled out by LAT

Preliminary PAMELA electron spectrum



From Marfatia, Miami 2009 talk

New $e^+ + e^-$ spectrum data to 200GeV, consistent with Fermi LAT

Dark matter interpretation of results

- PAMELA and ATIC positron data suggest high dark matter mass
- Decay channel for dark matter must be leptonic
- Local average dark matter number density decreases a $1/M_{DM}$ So the annihilation rate decreases as $1/M_{DM}^2$
- $\Longrightarrow$ standard annihilation rate for thermally produced halo WIMPs $\langle \sigma v \rangle = 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}$ is too small to explain measured result

Such a model predicts an e^- and e^+ combined flux

$$E^3 \frac{d\phi}{dE} = 6 \times 10^{-4} E \left(\frac{1 \text{TeV}}{M_{DM}} \right) \theta(M_{DM} - E) B_{tot} \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^2$$

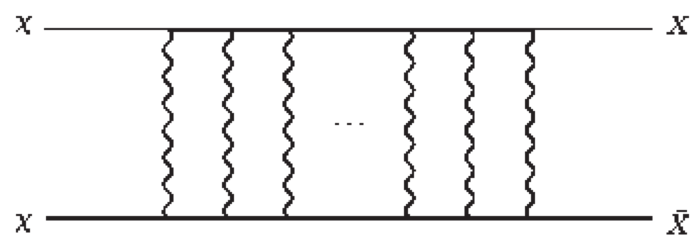
and would require a boost factor $B_{tot} \sim 200$.

Sommerfeld enhancement

Nonrelativistic quantum effect between particles interacting via a force (ladder diagrams)

leads to correction in annihilation cross section

$$\sigma v = S \langle \sigma v \rangle_0$$



$\langle \sigma v \rangle_0$ tree level cross section times velocity

S - Sommerfeld boost factor

Obtain from Schrödinger equation

$$\frac{1}{m} \frac{d^2 \psi(r)}{dr^2} - V(r)\psi(r) = -m\beta^2 \psi(r)$$

β - particle velocity

$V(r) = -(\alpha/r)\exp(-m_V r)$ - attractive Yukawa potential mediated by boson on mass m_V

Boundary conditions, particle free at large $r \Rightarrow d\psi/dr = im\beta\phi$ for $r \rightarrow \infty$

Sommerfeld enhancement - cont.

For $m_V = 0$, Coulomb potential, can solve analytically, gives:

$$S = \frac{\pi\alpha}{\beta}[1 - \exp(-\pi\alpha/\beta)]^{-1}$$

As $\beta \to 0 \Rightarrow S \approx \pi\alpha/\beta$

$\Longrightarrow$ Sommerfeld enhancement $1/v$ effect

Low velocity regime of Sommerfeld enhancement

$1/v$ behavior breaks down at very low velocity, since approximation in which Yukawa part of interaction ignored is $m\beta^2 \gg \alpha m_V$

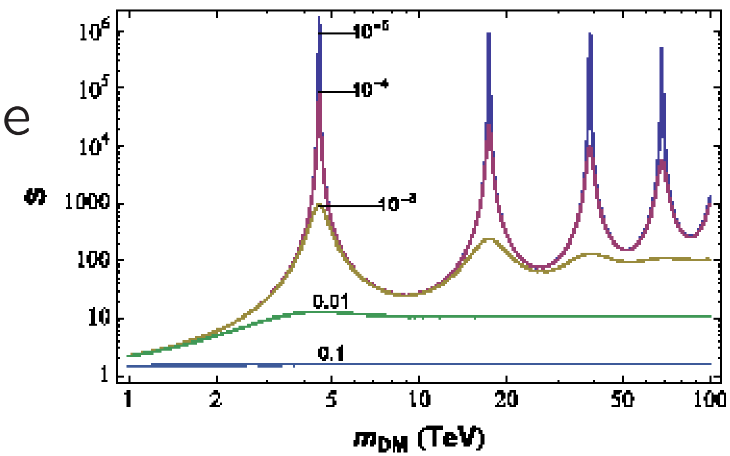
At very low velocity $m\beta^2 \ll \alpha m_V$ can expand in powers of $x \equiv m_V r$, Schrödinger equation becomes

$$\frac{d^2\psi(x)}{dx^2} + \frac{\alpha}{\delta}\frac{\psi}{x} = \frac{\alpha}{\delta}\psi(x)$$

with $\delta \equiv m_V/m$

RHS positive $\Rightarrow$ bound states (equation same as describing hydrogen atom), bound states for $\sqrt{\alpha/\delta}$ even integer, meaning

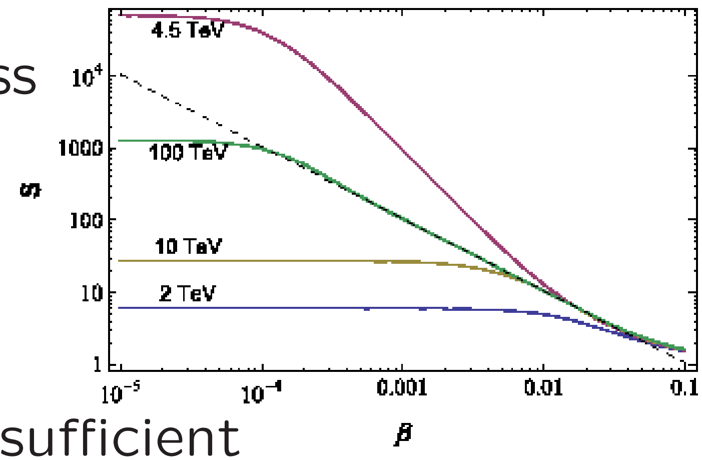
$$m = 4m_V n^2/\alpha,\ n = 1, 2, \ldots$$



Sommerfeld enhancement in SUSY interactions

During the annihilation of neutralinos into lepton pairs, multiple exchanges can occur of W or Z gauge boson mass (quasi) degeneracy with other components in multiplet lead to transitions mediated by weak gauge boson exchange Hisano *et. al.* 2004

Boost factors of ~ 30 for $m_{DM} \leq 10$TeV unless near mass near resonance, which for $m_V \sim 90$GeV implies $m_{DM} \sim 4.5$TeV Lattanzi and Silk 2009

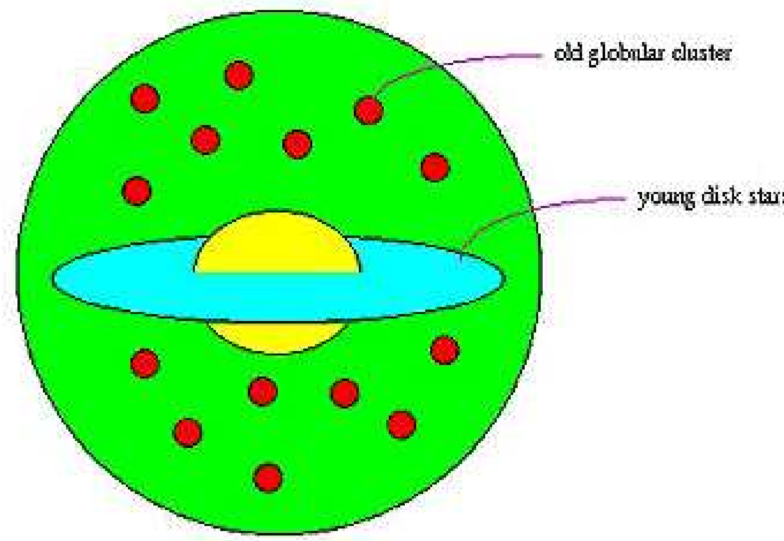


Aside from near resonances, boost factor is insufficient

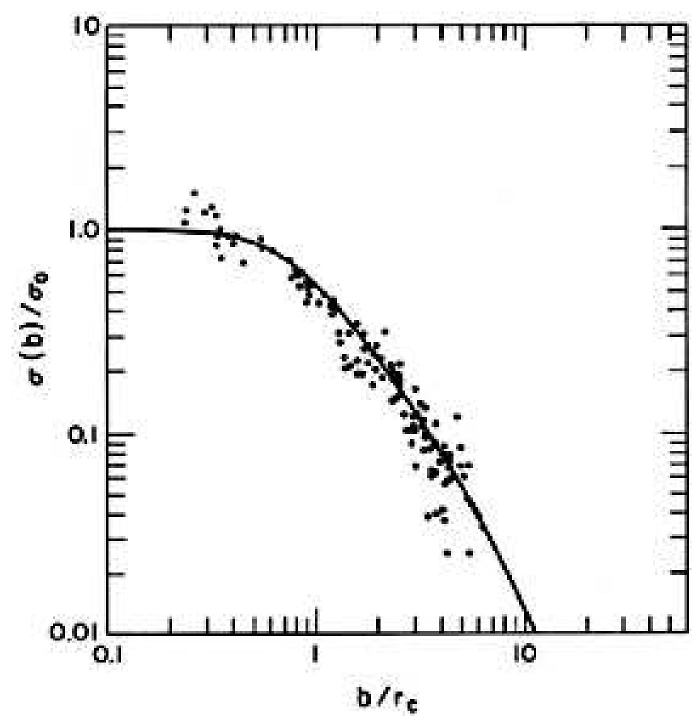
Other examples of Sommerfeld enhancement: Goldstone pseudo-scalar exchange Bedaque *et. al.* 2009, excited states Slatyer 2009, unparticle exchange Chen and Kim 2009, generic l-partial wave Lengo 2009

Examine effect for bosonic DM particles such as KK or Inert Higgs

Galaxy halo

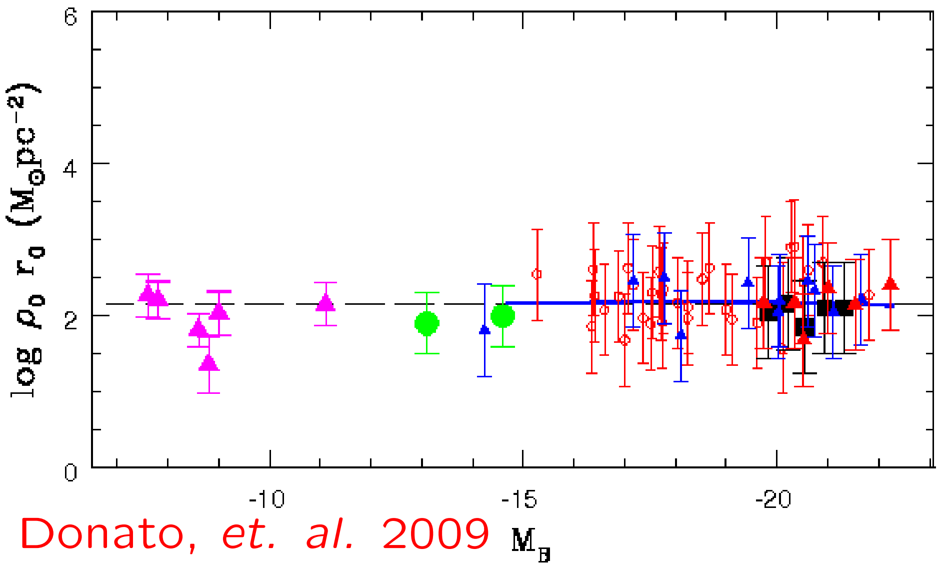


Dark matter distributed around galaxy in large region called galaxy halo



There is a core region where dark matter density approximately constant and then drops of for $r > r_0$

Universal galaxy scale



Donato, *et. al.* 2009

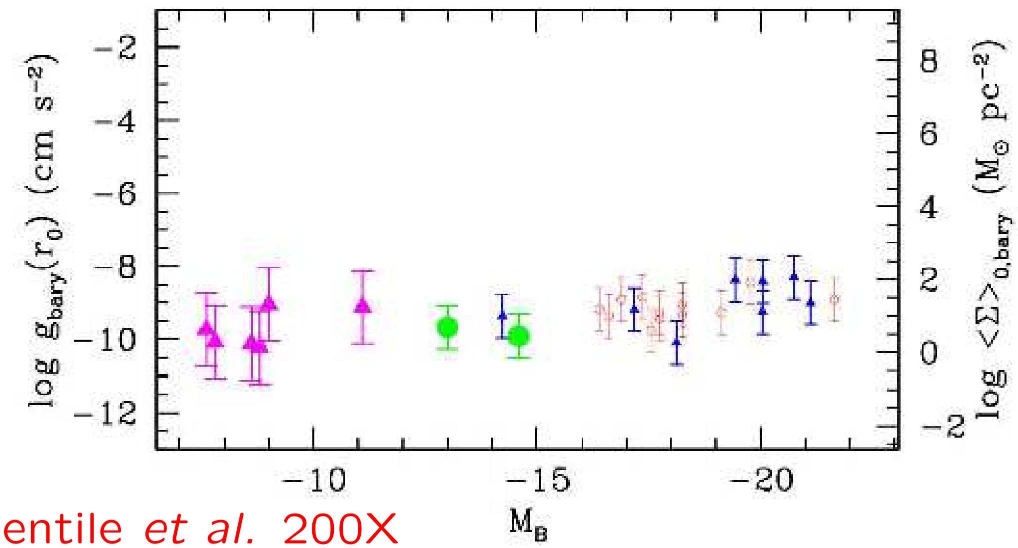
Constant surface density of galaxy halo $\mu_0 \equiv r_0 \rho_0$

r_0 - core radius, ρ_0 - core density

μ_{0D} nearly constant and independent of galaxy type

Over ~ 1000 galaxies surveyed found $\log \mu_{0D} = 2.15 \pm 0.2$

Another universal galaxy scale



Gentile *et al.* 200X

Luminous matter surface density is also constant

$$g_{bary}(r_0)(\sim \rho_{0L} r_0) = 5.7^{+3.8}_{-2.8} \times 10^{-10} \text{cms}^{-1}$$

Central baryonic surface density is correlated with core radius

Possible explanation via MOND

NR field theory MOND equation:

$$\nabla \cdot [\mu(|\nabla|/\phi/a_0)\nabla\phi] = 4\pi G\rho$$

MOND picture: different between MOND acceleration field $\nabla\phi$ and Newtonian one, is expressed as "dark matter", which called "phantom matter"

$$\rho_p \;=\; \frac{1}{4\pi G}\nabla^2\phi - \rho = -\frac{a_0}{4\pi G}\mathbf{e}\cdot\nabla\mathcal{U}(|\nabla\phi|/a_0) + (\mu^{-1} - 1)\rho$$

$\mathcal{U}(x) = \int L(x)dx,\ L(x) = x\mu'/\mu$, and $\mathbf{e}$ unit vector in direction of $\nabla\phi$

Central surface density of phantom matter halo surrounding a point mass

$$\Sigma(0) = \int_{infty}^{\infty} \rho_p dz = \Sigma_M[\mathcal{U}(\infty) - \mathcal{U}(0)] = \Sigma_M \int_0^{\infty} L(x)dx = \lambda\Sigma_M$$

with $\Sigma_M = a_0/(2\pi G)$

Using standard value $a_0 = 1.2 \times 10^{-8}\text{cms}^{-2}$ gives $\mu_{MOND} = 2.14$, Milgrom 2009 (Compare to Donato *et. al.*)

Can this also explain the universal luminous surface density scale?

Examine other explanations via MOND or f(R) gravity

Perspective

Optimistic view for dark matter particles: PAMELA positron enhancement is due to DM annihilation to mainly leptonic channel and CDMSII has seen the precursor of direct detection of dark matter

Pessimistic view for dark matter particles: All indirect detection results have astrophysical explanation. CDMSII results are not convincing and may not be verified with further data. Universal galaxy scale results are suggestive of a MOND-type explanation.

Conclusion

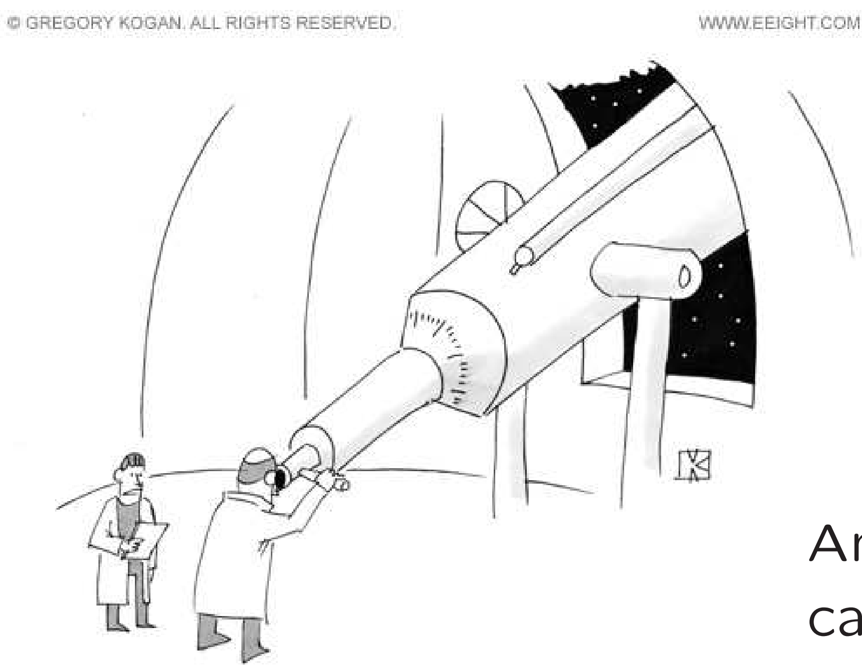
Dark matter is in an era of data interpretation and the working group should focus on this.

There is vast amount of new data on dark matter. Important to carefully review all data and form an interpretation of likely candidates for dark matter particles or MOND or alternative astrophysical explanations for what has been observed so far.

And the search goes on . . .

Continue to look for what exactly, we don't know

"LOTS OF THINGS ARE INVISIBLE, BUT WE DON'T KNOW HOW MANY BECAUSE WE CAN'T SEE THEM."



"That isn't dark matter, sir—you just forgot to take off the lens cap."

And must be careful not to make any careless conclusions