Gamma Rays from WIMP Dark Matter Annihilations

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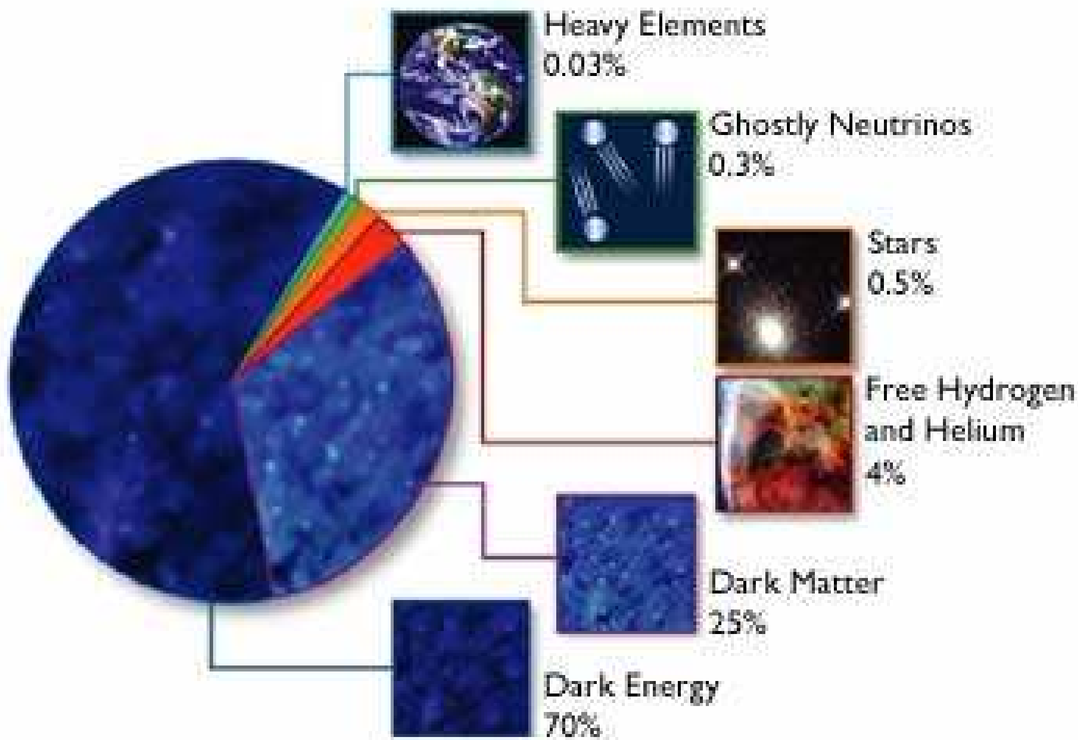
Dictionary meaning of **Wimp**: (Mariam-Webster's Online Dictionary):

1. *A weak, cowardly, ineffectual, timid person* (Americanism)
Origin: around 1915 - 20; source: unknown

Examples:
"George Bush is President Wimp"
"President Wimp is hooked on doing nothing"
"Bush insisted today that he is not a wimp"
...
— Chicago Sun - Times

2. **W**(eakly) **I**(nteracting) **M**(assive) **P**(article)
Origin: 1985 – 90; Source : Physics.

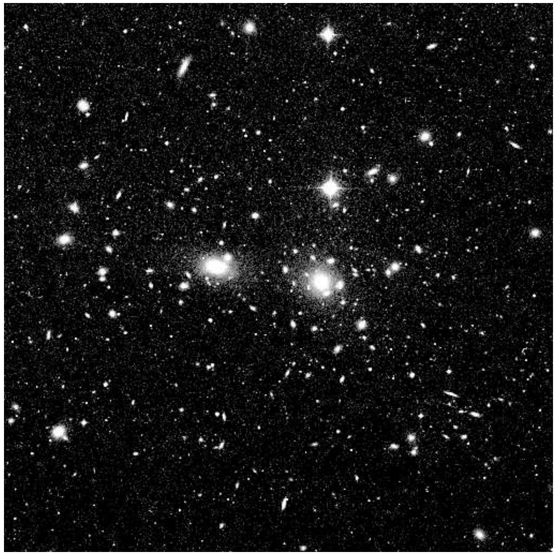
Contents of the Universe



The Standard Model contains 3 neutrinos of definite flavor, and a set of corresponding anti-particles.

Dark Matter

"Discovered" by Fritz Zwicky in 1933 : "Virial discrepancy" in the Coma cluster :



Coma Cluster

Virial Theorem $\Rightarrow \langle v^2 \rangle \sim \frac{1}{2}\frac{GM}{\langle r \rangle}$

Measured $\langle v^2 \rangle^{\frac{1}{2}} \sim 1000\,\mathrm{km\,s^{-1}} \Rightarrow M \sim 400 M_{\mathrm{visible}}$!!

— Radial velocities of galaxies in the Coma cluster are too large to be bound in the cluster with the known "visible" mass of the cluster.

Note: Zwicky used (wrong!) $H_0 = 558\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (as measured by Hubble!). Correct result $M_{\mathrm{Coma\ cluster}} \sim 50 M_{\mathrm{visible}}$

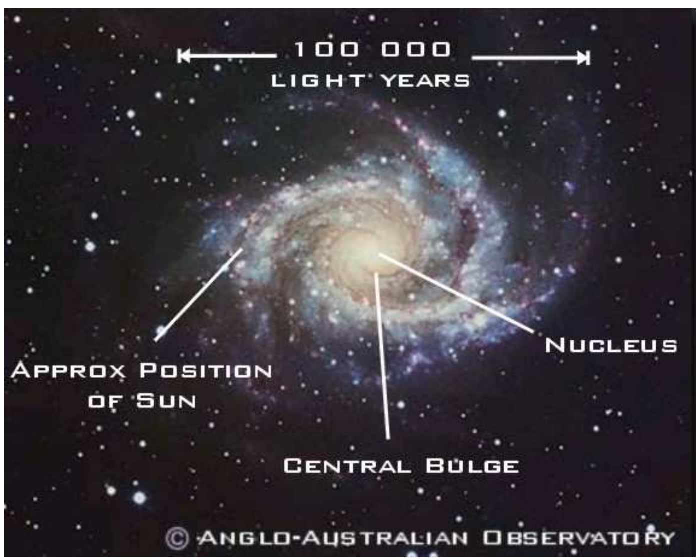
Rotation Curve of Spiral Galaxies and Dark Matter

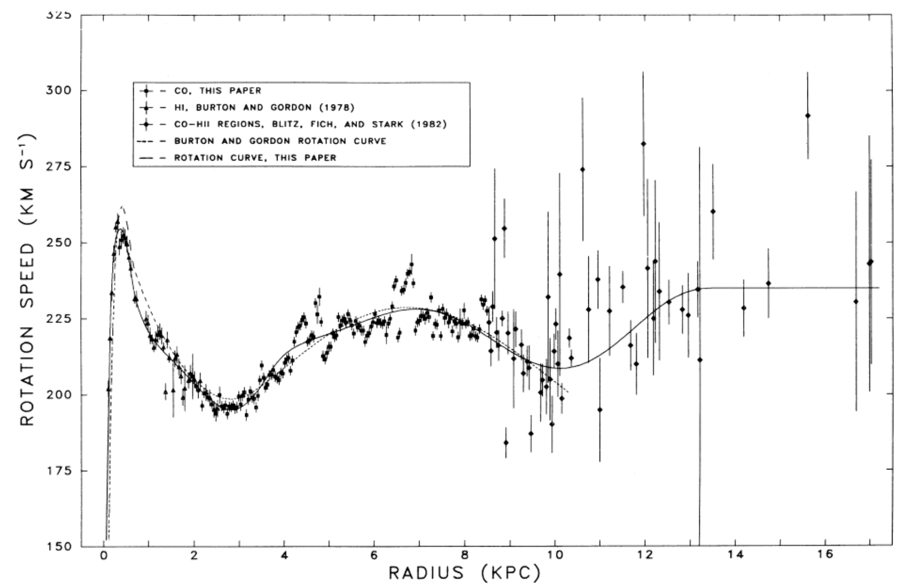
Galactic scale Dark Matter seriously studied only begining early 1970s: Vera Rubin:

Rotation Curve of Spiral galaxies.

Circular Rotation Speed: $v_c^2(R) = R\frac{\partial\phi}{\partial R} = G\frac{M(R)}{R}$

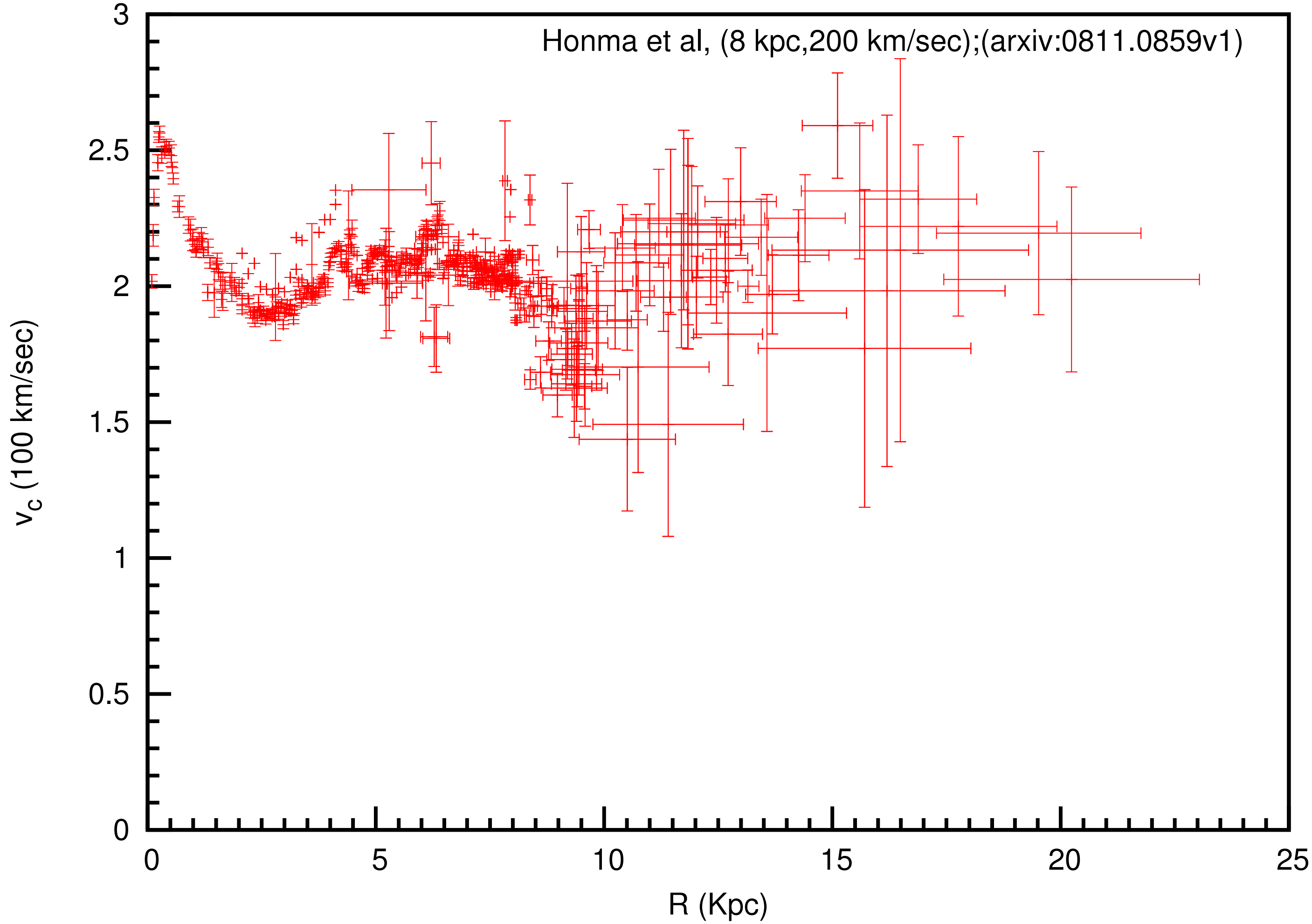
Rotation Curve of Milky Way

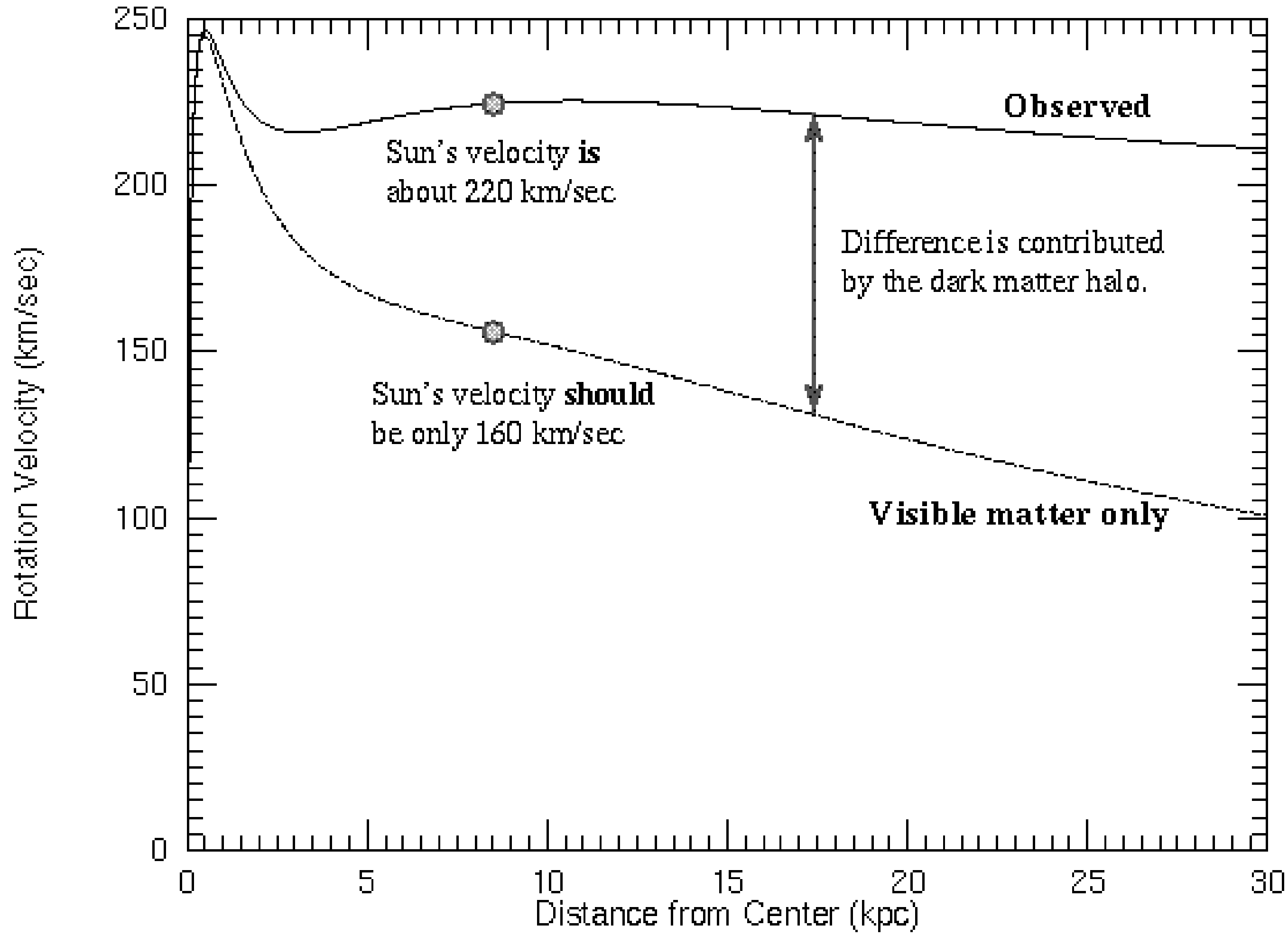




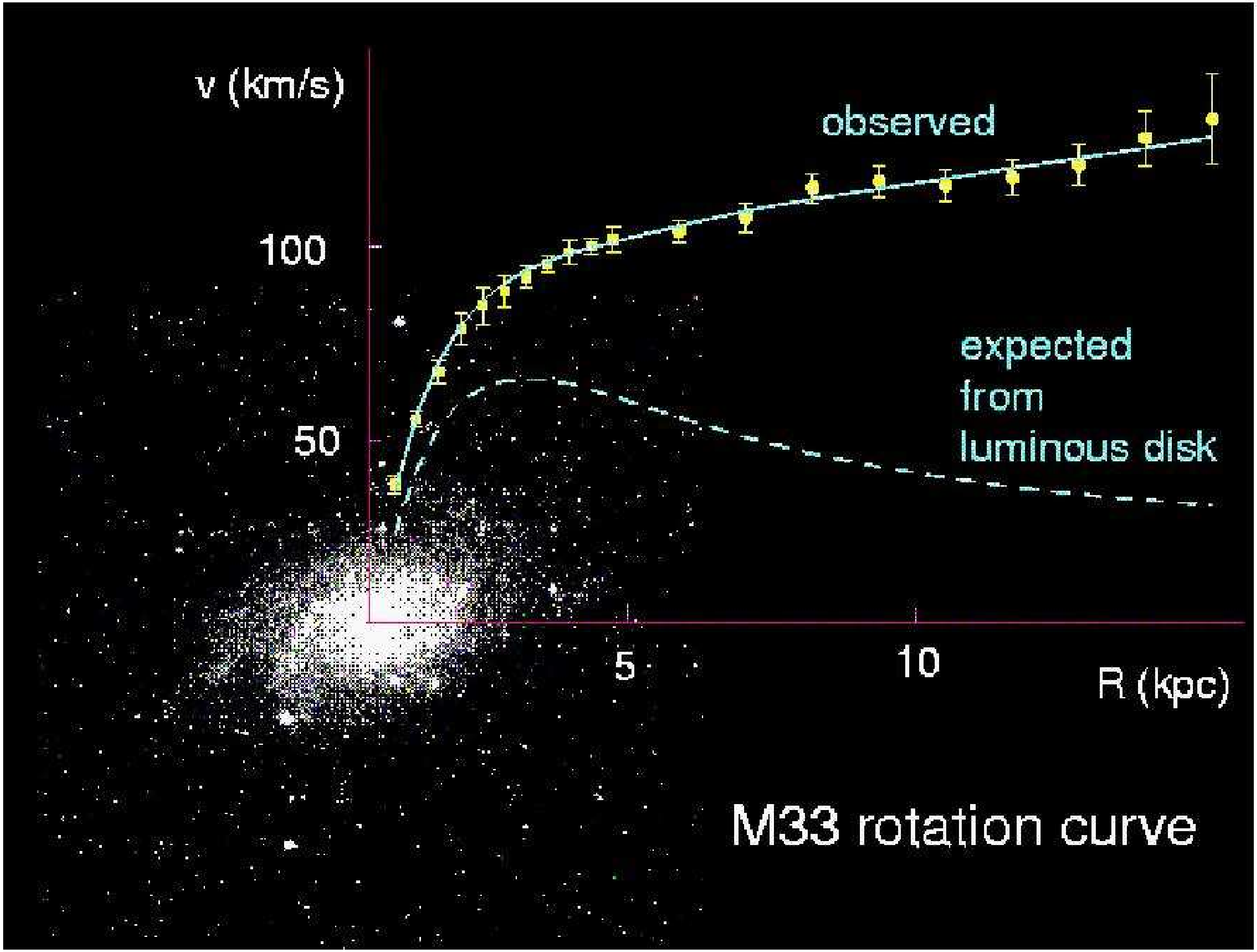
Clemens (1985)

Milky Way's Rotation Curve

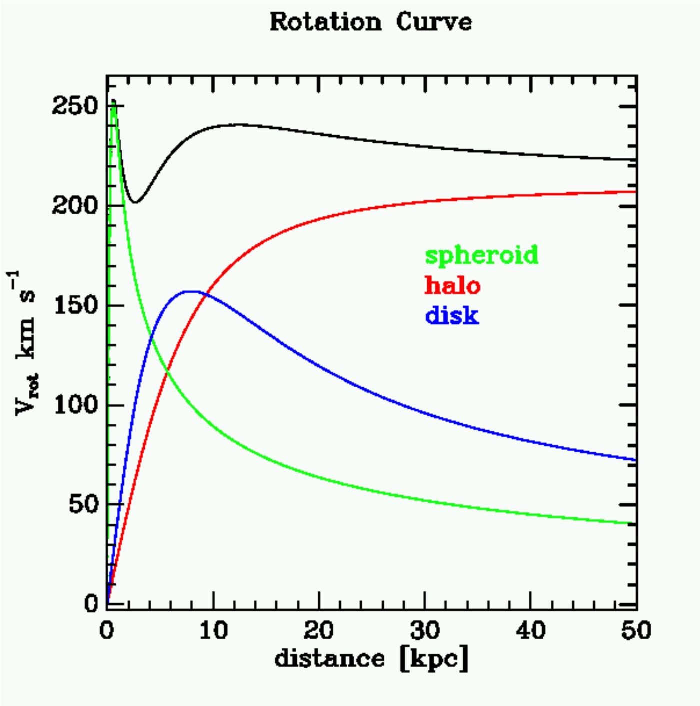




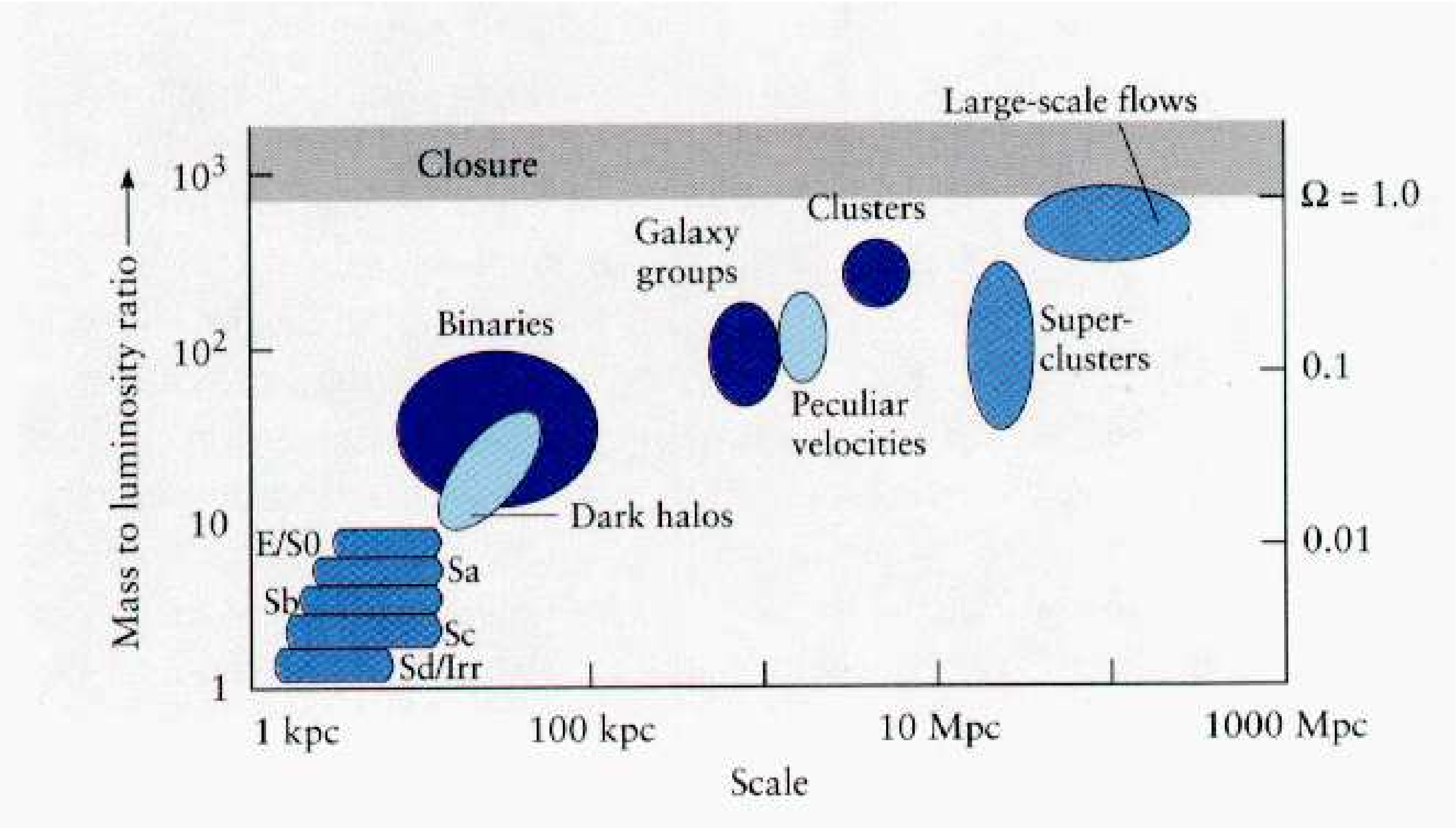
The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo.**


v (km/s)
observed
100
expected
from
luminous disk
50
5
10
R (kpc)
M33 rotation curve

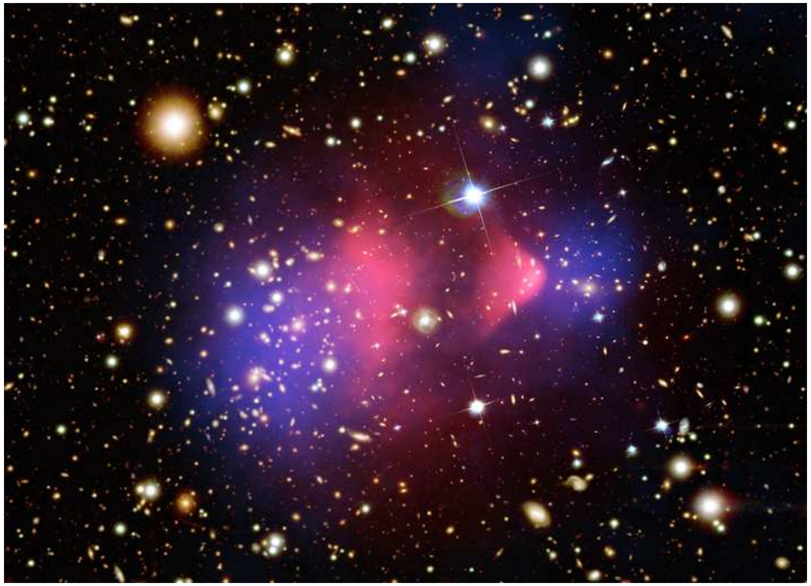
Mass Models : Dark Matter Halo



Dark Matter in the large scale Universe



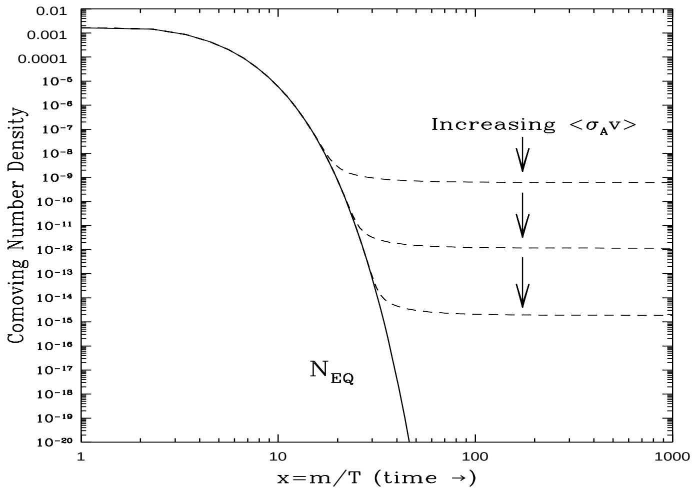
The Nature of Dark Matter



- DM must be non-baryonic, dissipationless $\Rightarrow$ very weakly interacting
- Clustered on small (sub-galactic) scale $\Rightarrow$ Must be cold

  $\Rightarrow$ Weakly Interacting Massive Particles

- In thermal equilibrium, $(n/s)^{\rm eq} \propto (m/T)^{3/2} e^{-m/T} \Rightarrow$ negligible abundance today!
- But WIMPs can decouple ("freeze out") when $\Gamma_{\rm int} < H$ in the early universe and survive with $\Omega_{\rm WIMP} \propto \langle \sigma_{\rm ann} v \rangle^{-1}$ today.



WIMP abundance today:

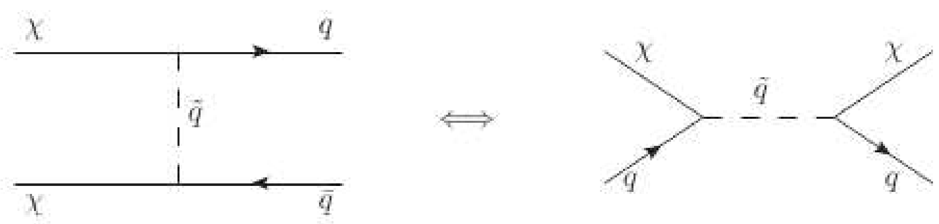
$\Omega_\chi h^2 \sim 0.1 \left(\frac{3\times10^{-26}\,\mathrm{cm}^3/\,\mathrm{sec}}{\langle\sigma v\rangle}\right) + \log \;\; \mathrm{corrections}$

Typically, $\sigma \sim \alpha^2/\,\mathrm{m}_\chi \sim 10^{-8}\,\mathrm{GeV}^{-2} \sim 4\times10^{-36}\,\mathrm{cm}^2$ (with $\alpha \sim 10^{-2}$ $m_\chi \sim 100\,\mathrm{GeV}$), and $\langle v\rangle_f \sim 0.25c$. Also, $h \sim 0.7$.

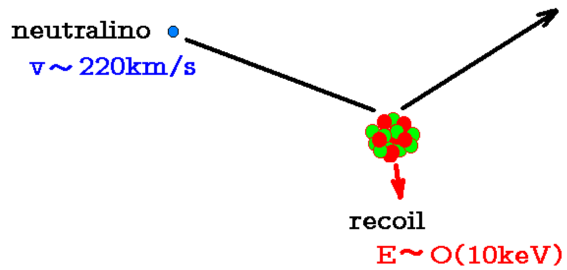
Thus, if there is a WIMP, it is the natural DM candidate!

WIMP annihilation into SM particles $\Rightarrow$ WIMPs must also have some (weak) interaction (albeit small) with nuclei, via crossing symmetry $\Rightarrow$ Direct detection of WIMPs may be possible.

Also, WIMPs captured within astrophysical bodies (e.g., Sun) would annihilate $\Rightarrow$ annihilation products (e.g., neutrinos) may be detectable.



Direct Detection: Order-of-magnitude Estimates



Event rate :

For a single detector nucleus, the rate of WIMP scatterings, $R \sim n_\chi v \sigma_{\chi N}$, gives

$$R \sim 2.7 \times 10^{-24}\,\mathrm{yr}^{-1} \left(\frac{\rho_\chi}{0.3\,\mathrm{GeV\,cm}^{-3}}\right)\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)\left(\frac{v}{300\,\mathrm{km\,s}^{-1}}\right)\left(\frac{\sigma_{\chi N}}{10^{-36}\,\mathrm{cm}^2}\right)$$

No. of nuclei of atomic number A in 1 gm is $6 \times 10^{23}/A$. So, total rate

$$R_{\rm total} \sim 16\ \ \mathrm{events\,kg}^{-1}\,\mathrm{yr}^{-1} \left(\frac{100}{A}\right)\left(\frac{\rho_\chi}{0.3\,\mathrm{GeV\,cm}^{-3}}\right)\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)\left(\frac{v}{300\,\mathrm{km\,s}^{-1}}\right)\left(\frac{\sigma_{\chi N}}{10^{-36}\,\mathrm{cm}^2}\right)$$

Recoil Energy :

For a WIMP of mass m_χ and velocity v striking a nucleus of mass M at rest, $\Delta p \sim m_\chi v$. $\Rightarrow$ Recoil energy of nucleus,

$$E_r \sim (\Delta p)^2/2M \sim 50\,\mathrm{keV} \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^2 \left(\frac{v}{300\,\mathrm{km\,s}^{-1}}\right)^2 \left(\frac{100\,\mathrm{GeV}}{M}\right) .$$

Proper calculations :

Recoil energy: $E = (\mu^2 v^2/M)(1 - \cos\theta^*)$, where $\mu \equiv m_\chi M/(m_\chi + M) =$ reduced mass, $v =$ WIMP speed relative to the nucleus, and $\theta^* =$ scattering angle in the center of mass frame.

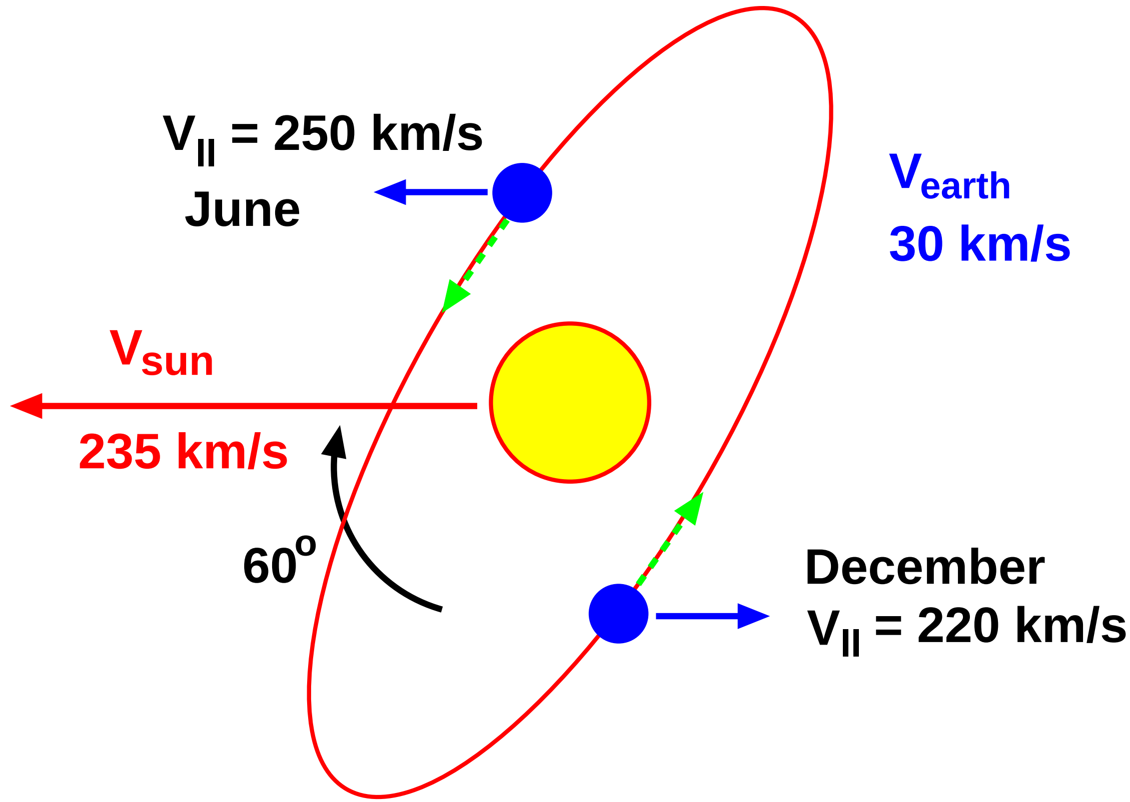
Differential recoil rate per unit detector mass, in units of counts/day/kg/keV : $\frac{\mathrm{d}R}{\mathrm{d}E} = \frac{\sigma(q)}{2\, m_\chi \mu^2}\, \rho\, \eta(E,t)$, with $q = \sqrt{2ME} =$ nucleus recoil momentum, $\sigma(q) =$ WIMP-nucleus cross-section,

$\eta(E,t) = \int_{v > v_{\min}} \frac{f(\mathbf{v},t)}{v}\, \mathrm{d}^3 v$,

$v_{\min} = \sqrt{\frac{ME}{2\mu^2}} =$ minimum WIMP velocity that can result in a recoil energy E.

$f(\mathbf{v},t)$ is the (time-dependent) velocity distribution of the WIMPs relative to detector at rest on Earth.

Modulation Signal



$$f(\mathbf{v},t) = f_{\mathrm{Galaxy}}(\mathbf{v} + \mathbf{v}^{\mathrm{Earth}}(t))\,.$$

Recoil rate R per unit detector mass: $R(t) = \int_{E_1/Q}^{E_2/Q} \mathrm{d}E\, \epsilon(QE) \frac{dR}{dE}$.

$\epsilon(QE) =$ the (energy dependent) efficiency of the experiment, $Q =$ quenching factor: $E_{det} = QE_{rec}$

For detectors with multiple elements and/or isotopes: $R_{tot}(t) = \sum_i f_i R_i(t)\,,$ where f_i is the mass fraction and R_i is the rate for element/isotope i.

The expected number of recoils: $N_{rec} = M_{det} T R$ where M_{det} is the detector mass and T is the exposure time.

Cross Section

In general, σ has contributions from spin-independent (SI) (scalar) and spin-dependent (SD) (axial vector) couplings:

$$\sigma = \sigma_{\rm SI} + \sigma_{\rm SD}$$

Spin-independent (SI) interactions :

$\sigma = \sigma_0 \, |F(E)|^2$ where $\sigma_0 =$ zero-momentum WIMP-nuclear cross-section and $F(E) =$ nuclear form factor, normalized to $F(0) = 1$.

For purely scalar interactions,

$\sigma_{0,\rm SI} = \frac{4\mu^2}{\pi}[Zf_{\rm p} + (A-Z)f_{\rm n}]^2 \, .$

$Z =$ number of protons, $A - Z =$ number of neutrons, and $f_{\rm p}$ and $f_{\rm n}$ are the WIMP couplings to the proton and nucleon, respectively. ($f_{\rm n} \sim f_{\rm p}$);

$\sigma_{0,\rm SI} = \sigma_{\rm p,SI} \left(\frac{\mu}{\mu_{\rm p}}\right)^2 A^2 \, ,$

$\mu_{\rm p} =$ proton-WIMP reduced mass, and $A =$ atomic mass of the target nucleus.

Spin-dependent (SD) interactions :

$$\sigma_{SD}(q) = \frac{32\mu^2 G_F^2}{2J+1}\left[a_p^2 S_{pp}(q) + a_p a_n S_{pn}(q) + a_n^2 S_{nn}(q)\right].$$

where $a_p(a_n)$ = WIMP-proton (neutron) couplings, and the nuclear structure functions $S_{pp}(q)$, $S_{nn}(q)$, and $S_{pn}(q)$ are functions of the exchange momentum q and are specific to each nucleus.

Detection claim by DAMA/LIBRA Experiment

DAMA + DAMA/LIBRA claimed detection based on a claimed positive modulation signal

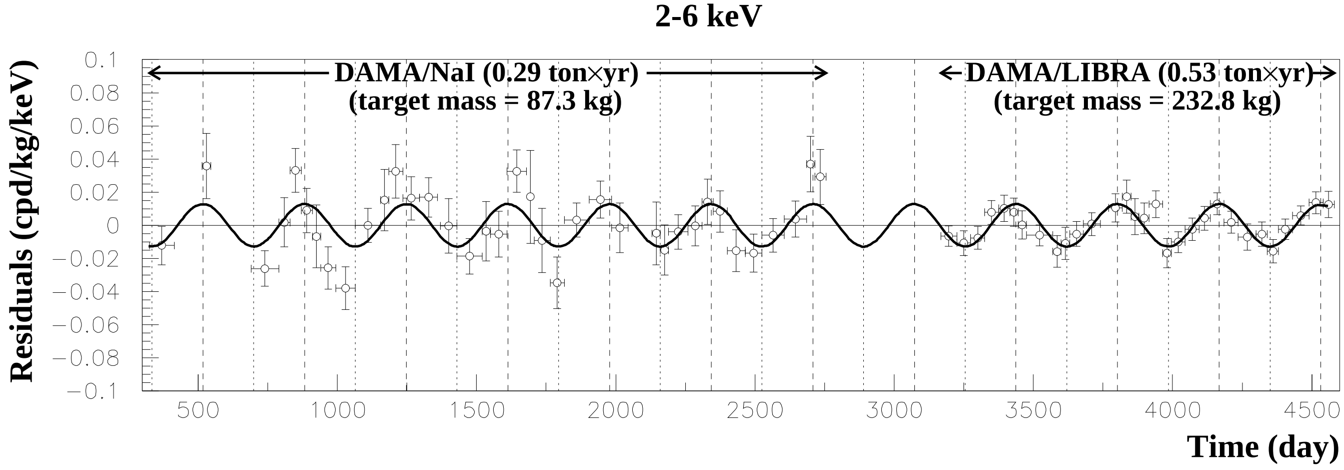
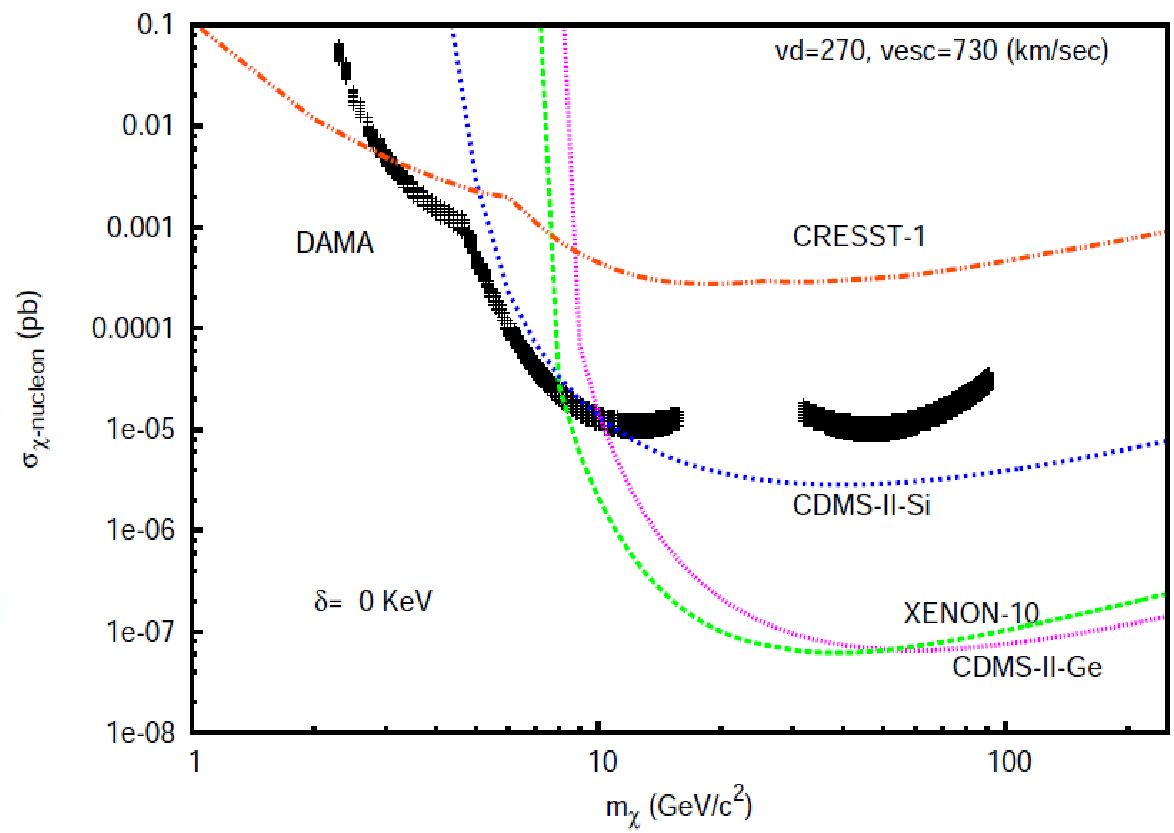


Fig. 9. Annual modulation observed by DAMA NaI and DAMA/LIBRA experiments with recoil energy between 2-6keV. The amplitude is (0.0129 ± 0.0016) cpd/kg/keV against an overall background counting rate of about 1 cpd/kg/keV (corresponding to a relative amplitude of about 1.3 ± 0.1 %). The phase is 144 ± 8 days, with maximum in early June. Details can be found in [108].

Exclusion Plot



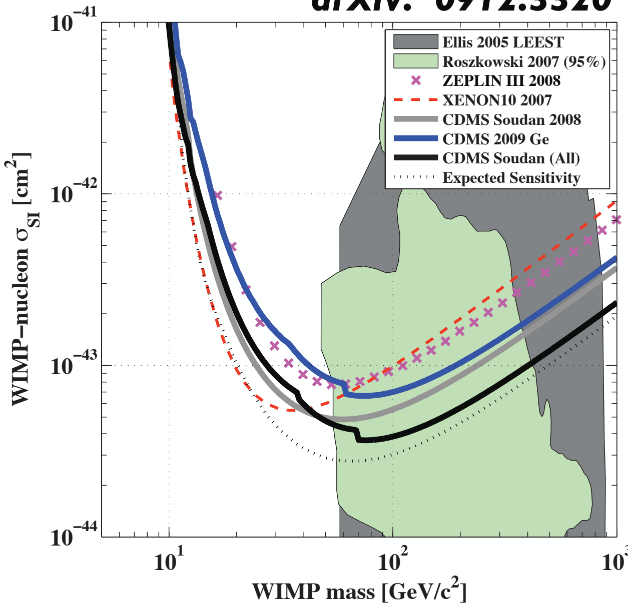
Direct Detection: CDMS Limits

CDMS II Results

Upper limit at the 90% C.L. on the WIMP-nucleon cross-section is **3.8×10^{-44} cm^2** for a WIMP of mass **70 GeV/c^2**

Note: An improved estimate of our detector masses (~9% decrease) was used in calculating these limits.

arXiv: 0912.3320



SLAC, Dec. 17, 2009

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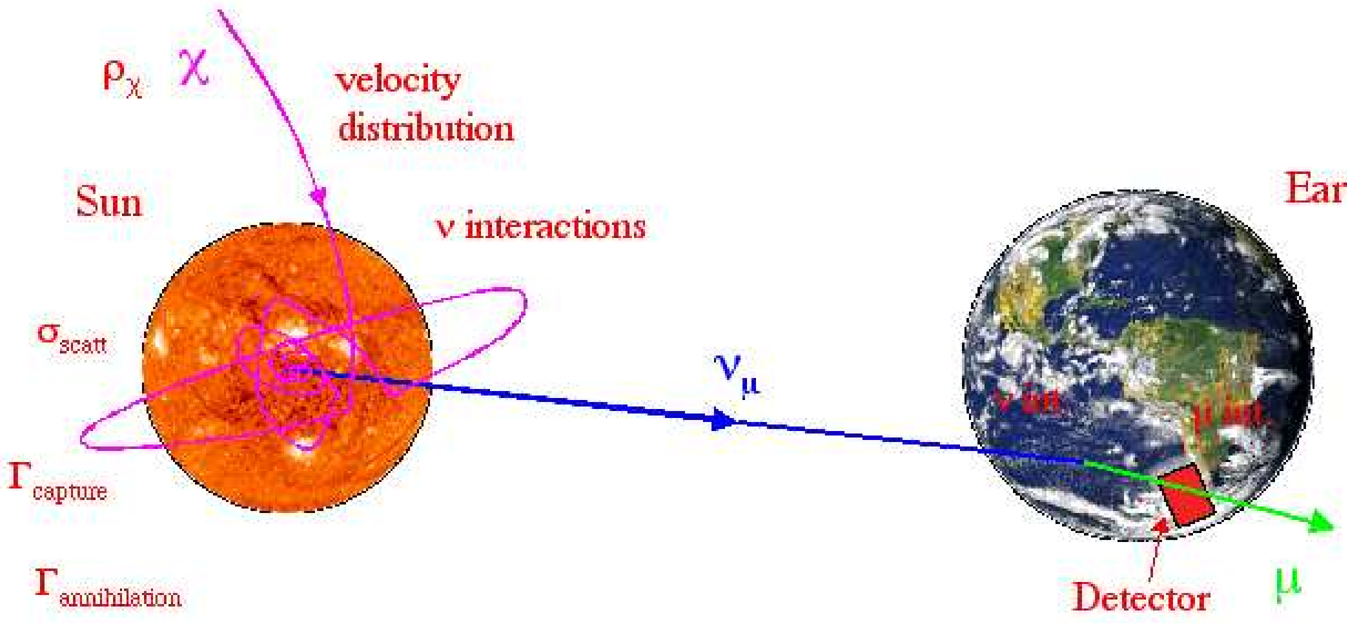
Jodi Cooley, SMU, CDMS Collaboration

Indirect Detection: WIMP Capture and Annihilation in Sun



WIMP Capture and Annihilation Rates: Order-of-magnitude Estimates

Capture rate by Sun:

$C^{\odot} \sim \left(\frac{\rho_\chi}{m_\chi} v_\chi\right)\left(\frac{\mathrm{M}_\odot}{m_p}\right)\sigma_{\chi p} \Rightarrow$

$C^{\odot} \approx 10^{20}\,\mathrm{sec}^{-1}\left(\frac{\rho_{\mathrm{local}}}{0.3\ \mathrm{GeV/\,cm^3}}\right)\left(\frac{300\,\mathrm{km\,s^{-1}}}{v_\chi}\right)\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)\left(\frac{\sigma_{\chi p}}{10^{-6}\,\mathrm{pb}}\right)$

Proper calculations should include (1) Gravitational focussing of WIMPs towards Sun; (2) not every scattered WIMP will be captured; (3) WIMPs have a velocity distribution; (4) sun has other elements (He, O, . . .), . . . $\Rightarrow$

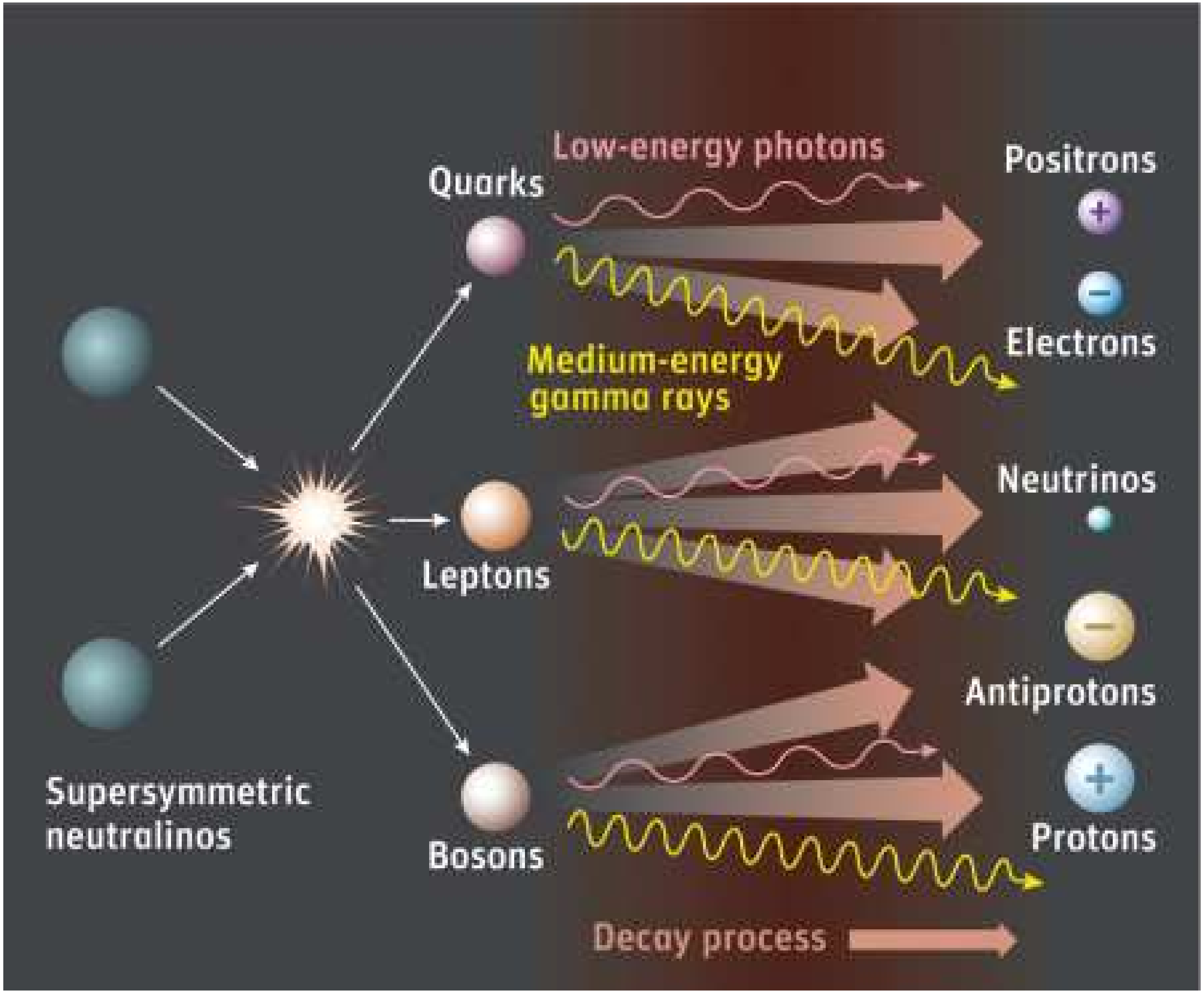
$$C^{\odot} \approx 3.4\times 10^{20}\ \mathrm{sec}^{-1}\left(\frac{\rho_{\mathrm{local}}}{0.3\ \mathrm{GeV/\,cm^3}}\right)\left(\frac{270\,\mathrm{km\,s^{-1}}}{\bar{v}_{\mathrm{local}}}\right)^3\times\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^2 \left(\frac{\sigma_{\chi\mathrm{H,SD}}+\sigma_{\chi\mathrm{H,SI}}+0.07\sigma_{\chi\mathrm{He,SI}}}{10^{-6}\,\mathrm{pb}}\right)$$

Annihilation rate $(\Gamma^{\odot}_{\mathrm{ann}})$:

$\frac{dN_\chi}{dt} \approx C^{\odot} - 2\Gamma^{\odot}_{\mathrm{ann}}$

In equilibrium, $\frac{dN_\chi}{dt} = 0 \quad \Rightarrow C^{\odot} = \frac{1}{2}\Gamma^{\odot}_{\mathrm{ann}}$

WIMP Annihilation Products



Is WIMP Annihilation Already Detected in Cosmic Rays?

Excess positrons in cosmic rays:

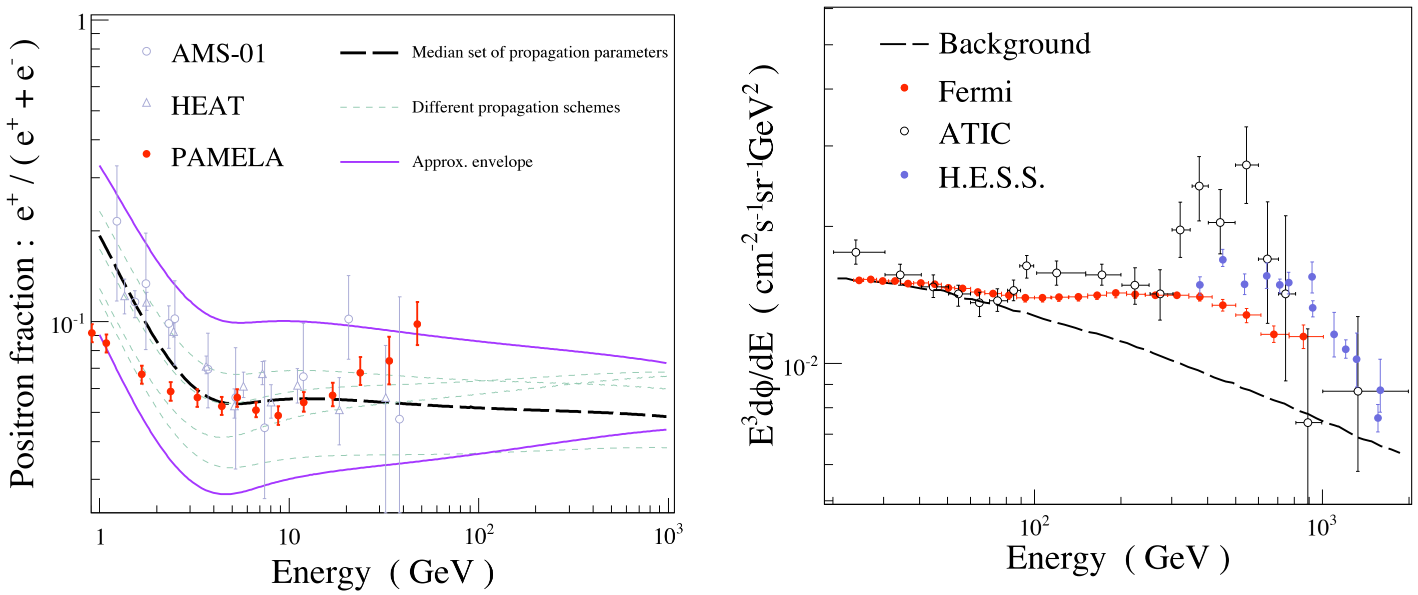


FIG. 1: Cosmic ray positron fraction (left) and electrons+positrons fluxes (right) (figure from P. Brun & T. Delahaye, CERN Courier Sep. 2009 issue).

But no excess is seen in antiprotons!

Fitting the excess positron data with WIMP annihilations or decay :

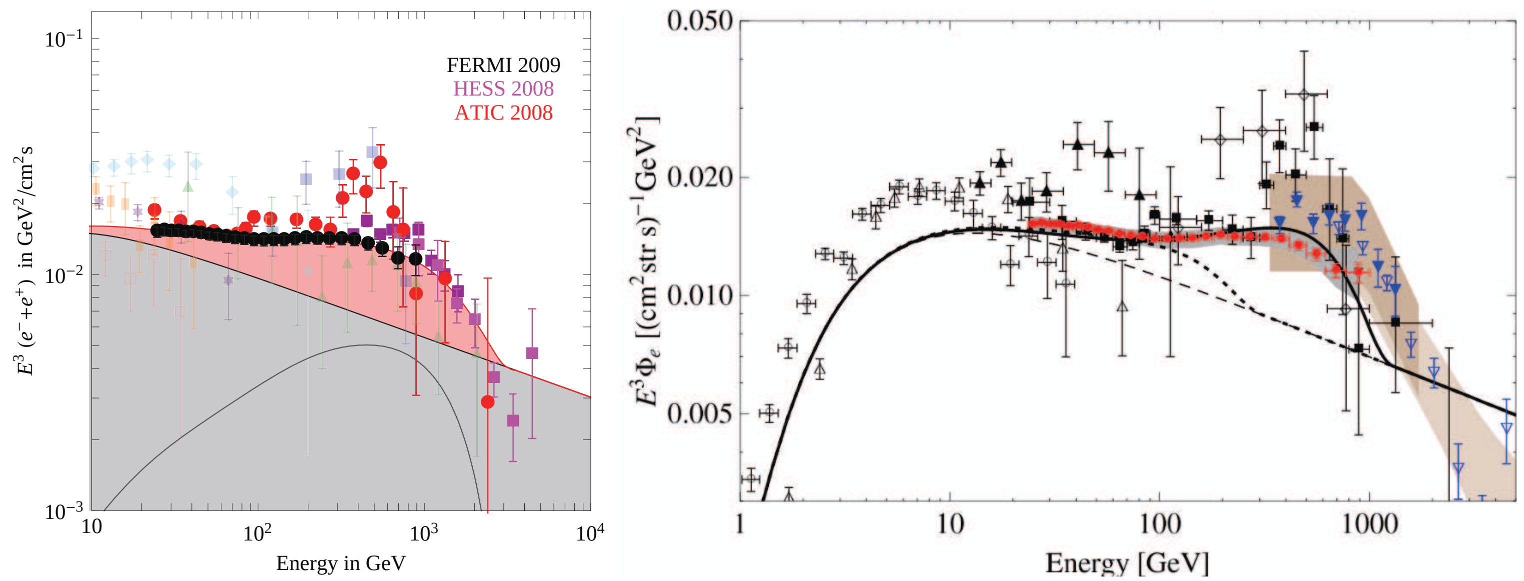


FIG. 3: Fit of the electron data with annihilating dark matter (M.Cirelli), decaying dark matter (A.Ib

To avoid $\bar{p}$-excess, can allow only “leptophilic” (and “hadrophobic”) WIMP coupling to SM particles. Also need a “boost” in the annihilation x-section

Disappointingly, there are more conventional, astrophysical explanations! The e^{+}-excess without $\bar{p}$-excess can be well-explained in terms of pulsars as sources and/or a few nearby sources of cosmic rays

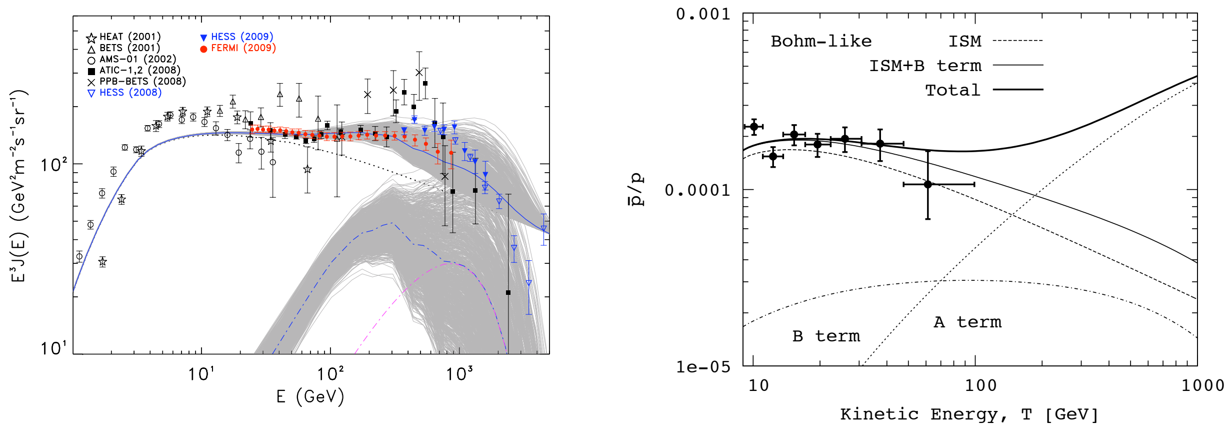
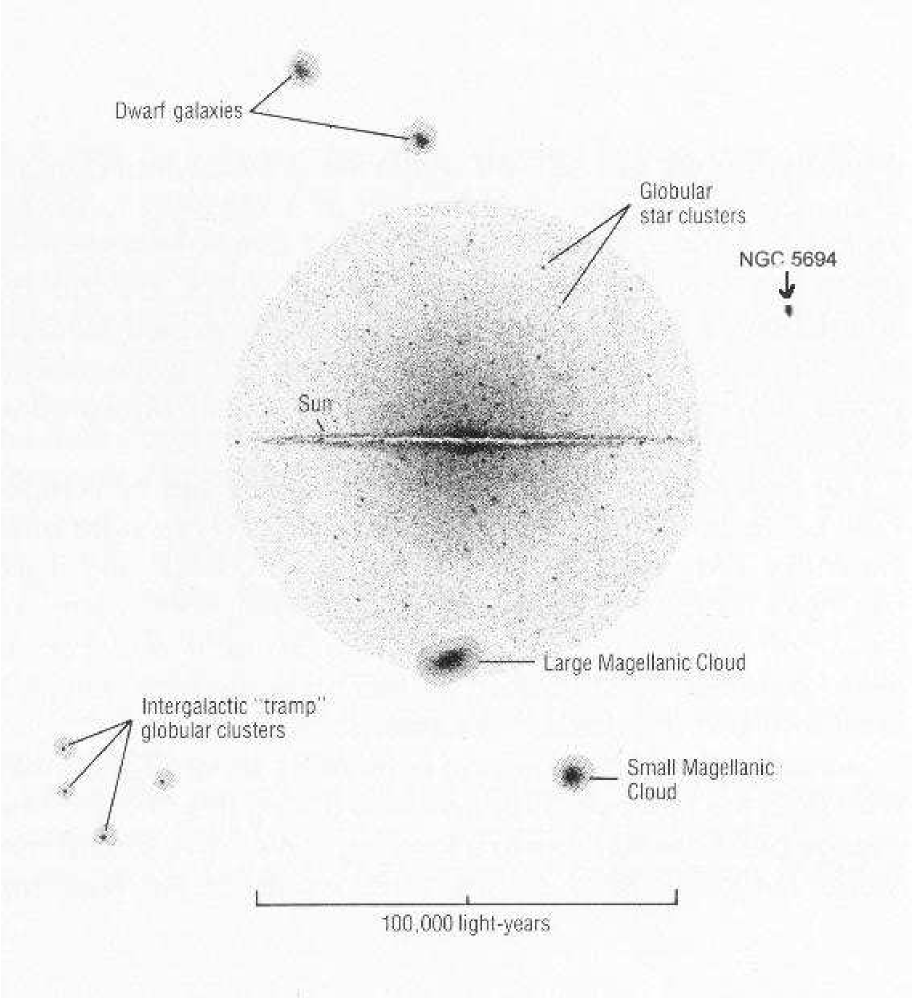


FIG. 2: Fit of the electron data with pulsars (J.Bregeon) and $\bar{p}$ predictions in case of secondary production within a supernovae remnant (P. Blasi).

Gamma Rays from WIMP DM Annihilations in DM Dominated Objects

There are Dark Matter sub-structures within DM halos, e.g., dwarf galaxies within the Milky Way's DM Halo with $M/L > 100$: DM dominated objects. Expect significant DM annihilations, hence γ-rays



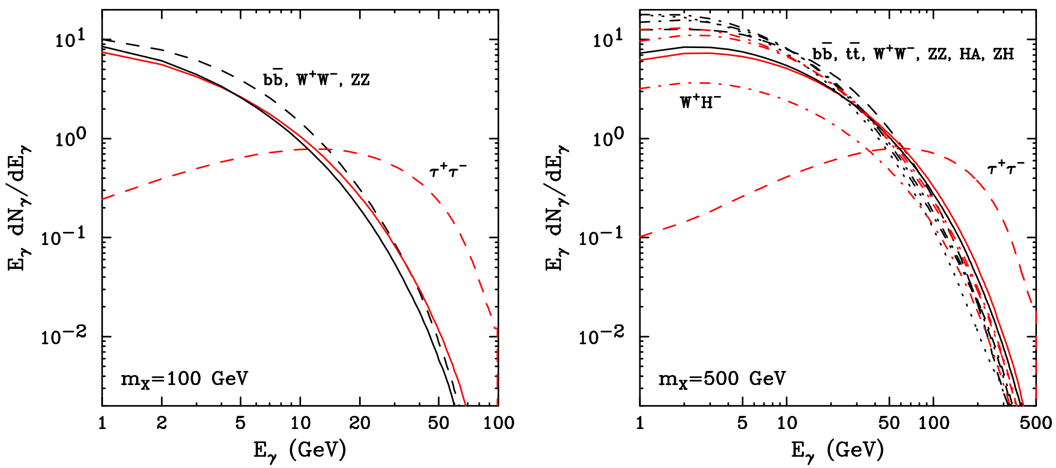
Photon Flux from WIMP Annihilations

$\Phi_\gamma(E_\gamma, \Omega) \equiv$ photons/area/time/energy/sterradian along direction Ω:

$$\Phi_\gamma(E_\gamma, \Omega) = \left[\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}(E_\gamma)\frac{\langle\sigma v\rangle}{8\pi m_X^2}\right]\int_{\mathrm{los}} \rho^2(\ell, \Omega)\,\mathrm{d}\ell,$$

$$\frac{\Phi_\gamma(E_\gamma, \Omega)}{\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}} \approx 2.8\times 10^{-10}\, J(\Omega)\,\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}(E_\gamma)\frac{\langle\sigma v\rangle}{\mathrm{pb}}\left(\frac{100\,\mathrm{GeV}}{m_{\mathrm{X}}}\right)^2.$$

$$J(\Omega) = \frac{1}{8.5\,\mathrm{kpc}}\left(\frac{1}{0.3\,\mathrm{GeV/cm^3}}\right)^2 \int_{\mathrm{los}} \rho^2(\ell, \Omega)\mathrm{d}\ell\,.$$



Flux Upper limits from Dwarf Spheroidals

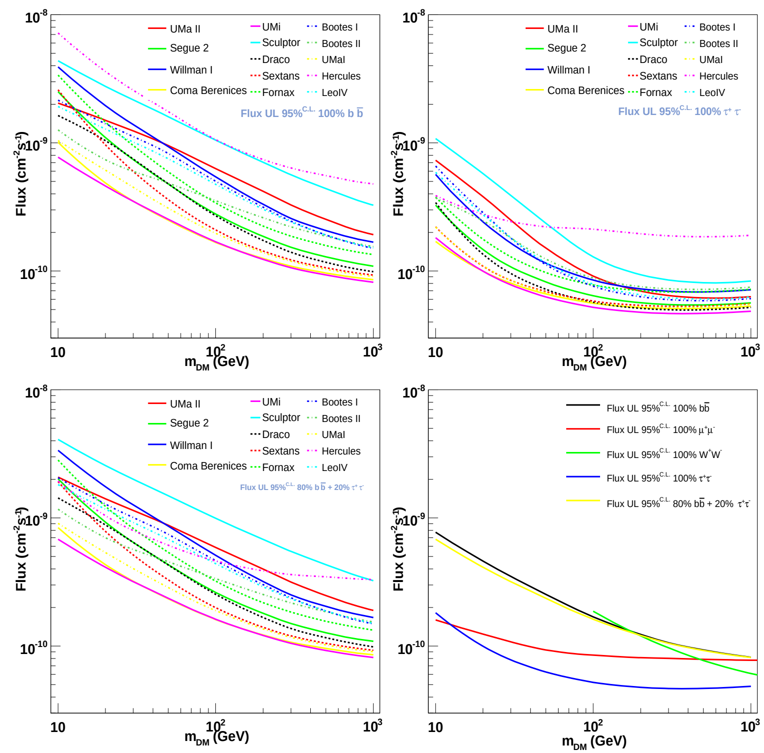


Fig. 2.— Derived upper limits on fluxes for all selected dwarfs and for various branching ratios: 100% $b\bar{b}$ (upper left), 100% $\tau^+\tau^-$ (upper right) and mixed 80% $b\bar{b}$ + 20%$\tau^+\tau^-$ (lower left) final state. Lower right plot gives an illustration of how the upper limits on the fluxes can change depending on the selected final state (here for the Ursa Minor dSph).

(From arXiv:1001.4531)

The predicted flux is subject to a lot of astrophysical uncertainties.
DM density profile and velocity distribution not known — "Standard Halo Model" or "NFW-Halo" are used.