Searches for Dark Matter signals

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Outline

Lecture #1: content

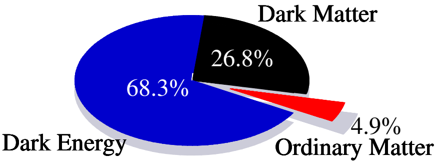
1. Introduction: dark matter, basic facts and properties
2. Direct searches for the dark matter
3. Indirect searches for dark matter (photons)

Lecture #2: content

1. Indirect detection for dark matter (neutrinos and antiparticles)
2. Dark matter at colliders
3. Particular models (asymmetric dark matter, axions...)

Dark Matter

- Evidences: galaxy rotation curves, weak gravitational lensing, Universe evolution: CMB anisotropy, structure formation, nucleosynthesis etc.



Dark matter properties:

- has attractive gravitational interaction
- no electric or color charge (no interaction with light)
- stable at cosmological scale, $t_D \gg t_U$
- not-HDM, nonrelativistic today (CDM or WDM)
- dissipationless
- collisionless, $\sigma_{self}/m \lesssim 2 \cdot 10^{-24}$ cm^2/GeV
- requires new physics!

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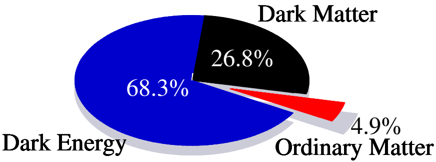

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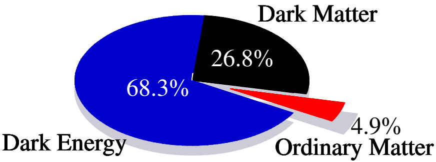

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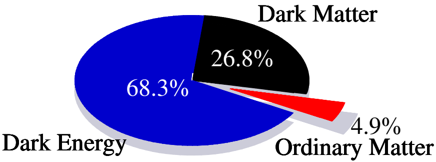

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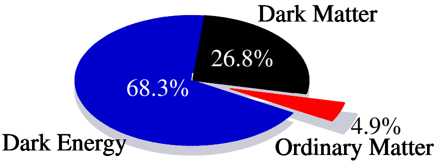

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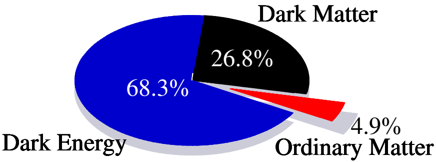

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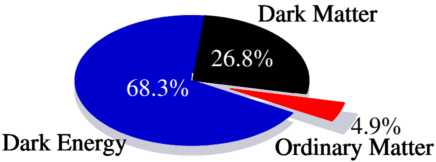

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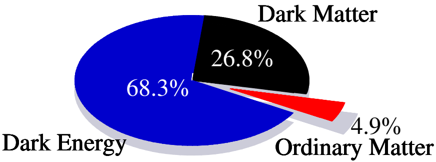

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Dark Matter Candidates Zoo

Different dark matter production mechanisms...
Different dark matter models...

- supersymmetry (neutralinos)
- extra dimensions (Kaluza-Klein states)
- heavy neutrino
- axion-like particles
- ...

- supersymmetry (gravitinos)
- sterile neutrinos
- nonthermal WIMPs
- Q-balls
- ...

WIMPs

- WIMPs - unify several types of dark matter models
- Thermal equilibrium in the Early Universe
- Annihilation to SM particles: $\chi_{DM}\bar{\chi}_{DM} \leftrightarrow X_{SM}\bar{X}_{SM}$
- For DM masses 1 GeV – 100 TeV

$$\Omega_{DM}h^2 \sim \frac{3 \times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma_A v \rangle_{freeze-out}} \sim 0.1$$

- $\langle \sigma_A v \rangle_{freeze-out} \sim 3 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$ - "natural" scale
- In WIMP models this value appears naturally - "WIMP miracle"
- WIMPs serve as a reference point for dark matter searches

Dark matter detection (three pillars)

- Direct detection:

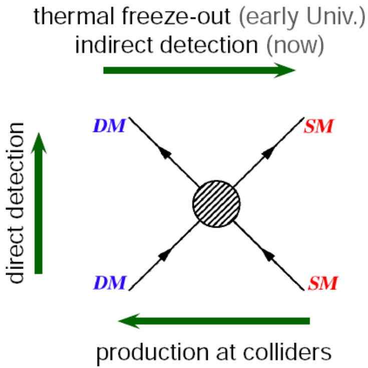
$$\text{DM} + \text{Nucleus} \to \text{DM} + \text{Nucleus}$$

- Indirect detection:

$$\text{DM} + \text{DM} \to \gamma\gamma,\ e^+e^-\ , \nu\bar{\nu},\ \dots$$

- Production at colliders

$$p + p \to \text{DM} + \text{DM}$$



Problem with indirect detection and collider searches – how to prove that the signal is from dark matter?

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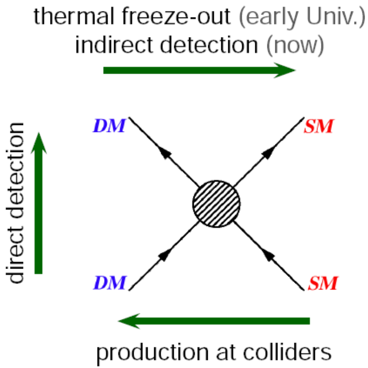

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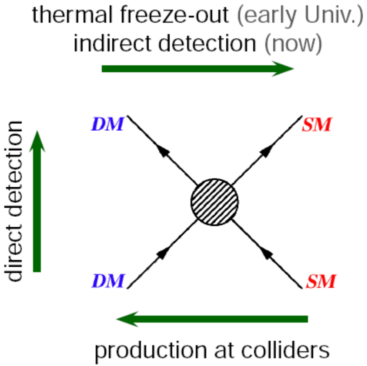

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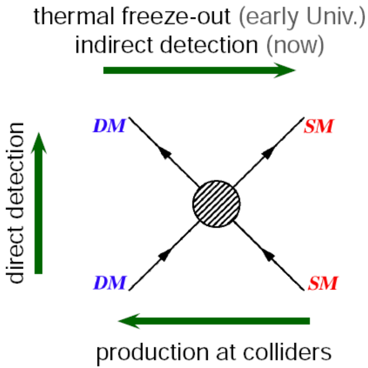
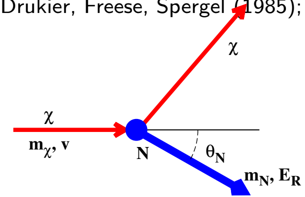


Problem with indirect detection and collider searches – how to prove that the signal is from dark matter?

Direct detection: basic

Drukier, Stodolsky (1984);
Goodman, Witten (1985);
Drukier, Freese, Spergel (1985);



Local dark matter density:
$\rho_{DM} \sim 0.3$ GeV/cm^3
Flux of DM particles ($v_S \approx 220$km/s):
$nv_S = \rho_{DM} v_S/m \sim 10^7 \left(\frac{\text{GeV}}{m}\right)/\text{cm}^2\text{s}$

Momentum transfer : $|\vec{q}| = 2\mu_N v \cos\theta_N$
Maximal recoil energy

$$E_R^{max} = \frac{q_{max}^2}{2m_N}, \quad q_{max} = 2\mu_N v, \quad \mu_N = \frac{m_\chi m_N}{m_\chi + m_N}.$$

Experiments are able to detect recoiling events with sufficiently large value of recoil energy. Typical recoil energy threshold E_R^{th} is $\mathcal{O}$(several keVs).

- for $m_\chi \ll m_N$, $\mu_N \simeq m_\chi$ and $E_R^{max} = 2$ keV $\left(\frac{m}{10\ \text{GeV}}\right)^2 \left(\frac{100\ \text{GeV}}{m_N}\right)$; the smallest value of m_χ which can be probed is $m_\chi^{min} \simeq \left(\frac{E_R^{th} m_N}{2v^2}\right)^{1/2} \sim \mathcal{O}(\text{GeV})$
- for $m_\chi \gg m_N$, $\mu_N \simeq m_N$ and $E_R^{max} = 2$ keV $\left(\frac{m_N}{\text{GeV}}\right)$

Direct detection: event rate

Expected recoil rate (per unit mass of detector, per unit of time)

$$\frac{dR}{dE_R} = \sum_N \frac{\epsilon_N}{m_N} \int_{v>v_{min}} \frac{d\sigma_N}{dE_R} n_\chi v \, f(\vec{v}, t) \, d^3 v$$

$\frac{\epsilon_N}{m_N}$ – number of nuclides of a type N with mass fraction ϵ_N per unit of detector mass; $\frac{d\sigma_N}{dE_R}$ – differential cross section

$n_\chi \equiv \frac{\rho_\chi}{m_\chi}$ – local dark matter number density;

$\tilde{f}(\vec{v}, r)$ – local dark matter velocity distribution

$v_{min} = \sqrt{\frac{M_N E_R}{2\mu_N^2}}$ – for elastic scattering

Remark: "inelastic" dark matter: $\chi(m) + N \to \chi'(m') + N \, , \quad m' = m + \delta$

For a typical momentum transfer $q \sim \mu_N v$:

– for $m_\chi \ll m_N \quad q \sim \mathcal{O}(\text{MeV}) \left(\frac{m_\chi}{\text{GeV}}\right)$

– for $m_\chi \gg m_N \quad q \sim \mathcal{O}(\text{MeV}) \left(\frac{m_N}{\text{GeV}}\right) \sim A \cdot \mathcal{O}(\text{MeV})$

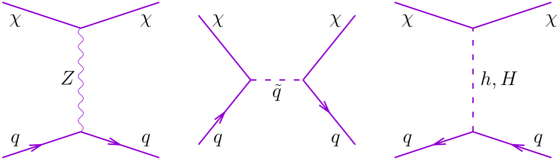
In both cases $\frac{1}{q} > R_{nuclei} \sim 1.25 \cdot A^{1/3}$ fm $\qquad (1 \text{ MeV}^{-1} \sim 2 \cdot 10^{-11} \text{ cm})$

Coherent scattering – when $1/q \gg R_{nuclei}$; otherwise one should take into account a nuclear form-factor

Direct detection: particle physics input

Steps to calculate σ_N (supersymmetric neutralino as an example)

- Calculation of interactions of DM with quarks and gluons



$$\mathcal{L}_{eff} = f_q \bar{\chi}\chi\bar{q}q + d_q \bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q + b\alpha_s\bar{\chi}\chi G^{a\mu\nu}G^a_{\mu\nu} + \ldots$$

- Translation of the microscopic interactions with quarks and gluons into interactions with nucleons using nucleon matrix elements (hadronic models, experimental data)
- Obtaining dark matter - nucleus cross section (coherent summation of contribution from different nucleons, formfactors)

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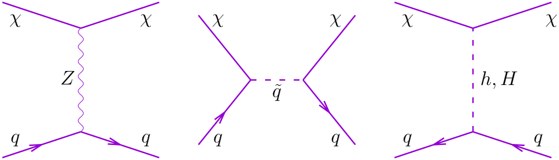

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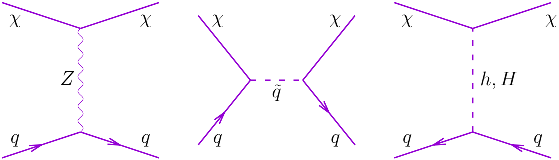

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Direct detection: spin-independent (SI) cross section

$\mathcal{L}_S = \sum_q f_q \, \bar{\chi}\chi \, \bar{q}q \,, \quad f_q$ – model-dependent coefficients

The nucleon matrix elements:
$\langle N | m_q \bar{q}q | N \rangle \equiv m_N f^N_{T_q}$

numbers from MicrOmega

Nucleon	$f^N_{T_u}$	$f^N_{T_d}$	$f^N_{T_u}$
n	0.011	0.027	0.045
p	0.015	0.019	0.045

Lagrangian for interaction with nucleons (heavy quarks contribute through QCD trace anomaly):

$\mathcal{L}_S = f_N \, \bar{N}N \, \bar{\chi}\chi$, where $f_N = m_N \left\{ \sum_{u,d,s} \frac{f_q}{m_q} f^N_{T_q} + \frac{2}{27} (1 - \sum_{u,d,s} f^N_{T_q}) \sum_{c,b,t} \frac{f_Q}{m_Q} \right\}$

Spin-independent cross section:

$$\frac{d\sigma^{SI}_{\chi N}}{dE_R} = \frac{2m_N}{\pi v^2} \left\{ Z f_p + (A - Z) f_n \right\}^2 \, F^2_{SI}(E_R), \qquad \sigma^{SI}_{\chi N} = \frac{2\mu_N^2 v^2}{m_N} \frac{d\sigma_{SI}}{dE_R}$$

Different experiments – different target nucleus

Isospin symmetry: $f_p = f_n$, one obtains (apart from formfactor):

$$\sigma^{SI}_{\chi A} = A^2 \frac{\mu_N^2}{\mu_p^2} \sigma^{SI}_{\chi p} = A^2 \frac{m_N^2 (m_p + m_\chi)^2}{m_p^2 (m_N + m_\chi)^2} \, \sigma^{SI}_{\chi p}$$

Without isospin symmetry - there can be cancellations in the amplitude

Direct detection: spin-dependent (SD) part

$\mathcal{L}_A = \sum_q d_q \, \bar{\chi}\gamma^\mu\gamma^5\chi \, \bar{q}\gamma_\mu\gamma^5 q \,,$ d_q – model-dependent coefficients

The nucleon matrix elements:
$\langle N|\bar{q}\gamma_\mu\gamma^5 q|N\rangle = 2s_\mu^N \Delta q^N$

HERMES collaboration

Nucleon	Δu^N	Δd^N	Δs^N
n	-0.427	0.842	-0.085
p	0.842	-0.427	-0.085

Lagrangian for interaction with nucleons:

$$\mathcal{L}_A = \sum_{u,d,s} 2d_q \Delta q^N \, (\bar{N}\, s_\mu N)(\bar{\chi}\gamma^\mu\gamma^5\chi) \equiv 2\sqrt{2} G_F \, a_N \, (\bar{N}\, s_\mu N)(\bar{\chi}\gamma^\mu\gamma^5\chi)$$

Spin-dependent cross section:

$$\frac{d\sigma^{SD}}{dE_R} = \frac{16 m_N}{\pi v^2} G_F^2 J(J+1)\Lambda^2 F_{SD}^2(E_R),$$

where $\Lambda = \frac{1}{J}(a_p\langle S_p\rangle + a_n\langle S_n\rangle)$ – requires knowledge of the average spin carried by protons and neutrons which depends on nucleus

SD cross section does not scale as A^2!

Remark: other interactions – different dependence on E_R

Direct detection: astrophysical input (I)

There are different models of DM density profile

The most simplest – model of isothermal sphere

Dark matter distribution function:

$$f(\vec{r},\vec{v}) = \mathcal{N}\exp\left(-\frac{E}{\sigma^2}\right) \equiv \mathcal{N}\exp\left(-\frac{v^2}{\sigma^2} - \frac{\Phi(r)}{\sigma^2}\right)$$

Φ – gravitational potential

Dark matter number density:

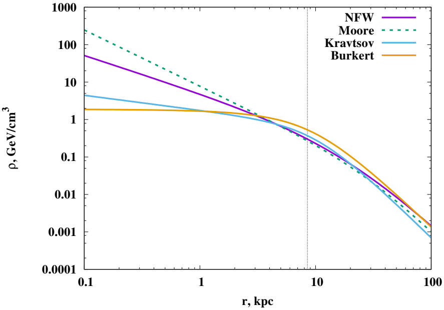
$$\rho(r) = \mathcal{N}\exp\left(-\frac{\Phi(r)}{\sigma^2}\right)\ , \quad \frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\Phi}{dr}\right) = 4\pi G\,\rho(r)$$

One obtains the dark matter density profile:

$$\rho(r) = \frac{\sigma^2}{2\pi G}\,\frac{1}{r^2}$$

Flat rotation curve with $v_r = \sqrt{2}\sigma$! Infinite mass of the Galaxy...

Direct detection: astrophysical input (II)



- Almost spherical Halo
- *N*-body simulations without baryons - cusp, $\rho(r) \sim r^{-1}$, $r \to 0$
- Large uncertainties for $\rho(r)$ near the GC
- Direct observations fail (baryon dominance)
- Local dark matter density - from fits of dark matter density profiles and microlensing $\rho_0 \sim 0.2 - 0.6$ GeV/cm^3

$$\rho(r) = \frac{\rho_0}{\left(\delta + \frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$

Model	α	β	γ	δ	r_s, kpc	ρ_0, GeV/cm^3
NFW	1	3	1	0	20	0.3
Kravtsov	2	3	0.4	0	10	0.37
Moore	1.5	3	1.5	0	28	0.27
Burkert	2	3	1	1	9.26	1.88

Direct detection: astrophysical input (III)

Gaussian velocity distribution (truncated) is used

$$f(\vec{v}) = \begin{cases} \mathcal{N} \exp\left(-\frac{\vec{v}^2}{2\sigma^2}\right), & \text{if } |\vec{v}| < v_{esc} \\ 0, & \text{if } |\vec{v}| > v_{esc} \end{cases}$$

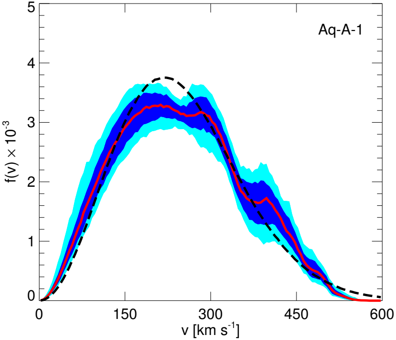
with $\sqrt{2}\sigma \approx 220$ km/s – rotation circular speed, $v_{esc} \approx 544$ km/s

Motion of the Sun and Earth:

$$f(\vec{v}, t) = f_G(\vec{v} + \vec{v}_{Sun} + \vec{v}_{Earth}(t))$$

results in annual modulation of the signal

Results of numerical simulations (arXiv:0812.0362 [astro-ph])



Remark: dark matter can have substructure:

- Clumps (local overdensity of DM)
- Streams (peaks in velocity distribution from certain directions)
- Dark Disk

Direct detection: experiments and techniques

Methods to detect energy deposition in keV range:

- Phonons - increase of the temperature (cryogenic technique)
- Ionization - production of electron-hole pairs in semiconductors and change of conductivity
- Scintillation - light produced by atoms

Expected recoil rate is small – around $0.01 - 0.1$ events/kg/day

The main problem – background suppression:

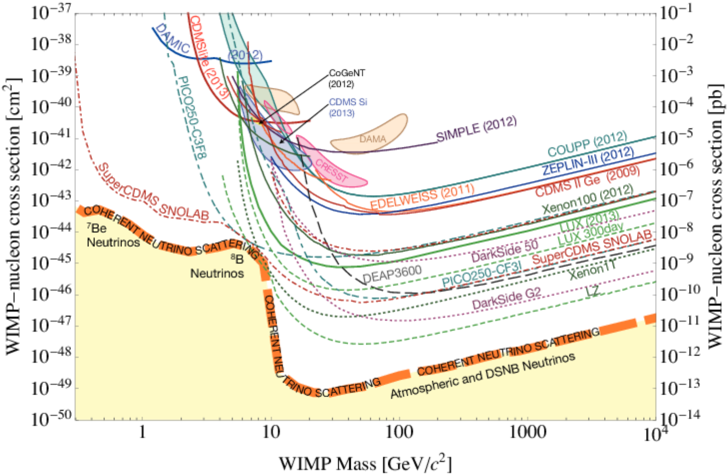
- Placed underground (cosmic rays)
- Passive shield (protection from natural underground radioactivity)
- Decreasing radioactivity of the detector (material stored underground)

To suppress the background typically the techniques used in combination:

- phonons and ionization (CDMS, Edelweiss)
- ionization and scintillation (XENON)
- phonons and scintillation (CRESST II)

Direct detection: results (SI)

from arXiv:1310.8327



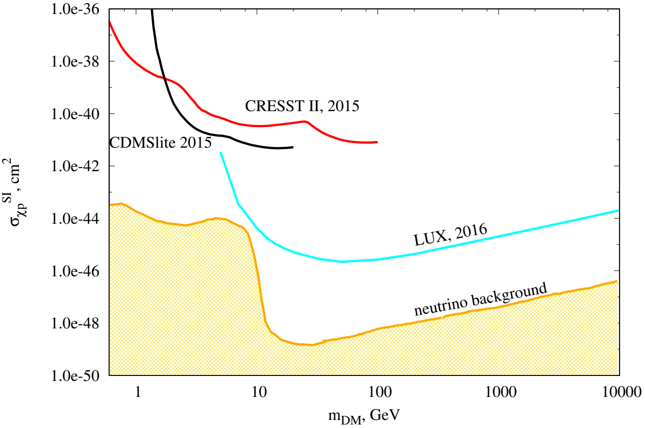
Solid lines – upper limits recalculated to $\sigma_{\chi p}^{SI}$

Dashed lines – sensitivities

Signal regions – still are not conclusive

Direct detection: results (SI)

Best limits



LUX – Xe, scintillation
SuperCDMS – Ge,Si, ionization+phonons
CRESST-II – CaWO$_4$, scintillation+phonons

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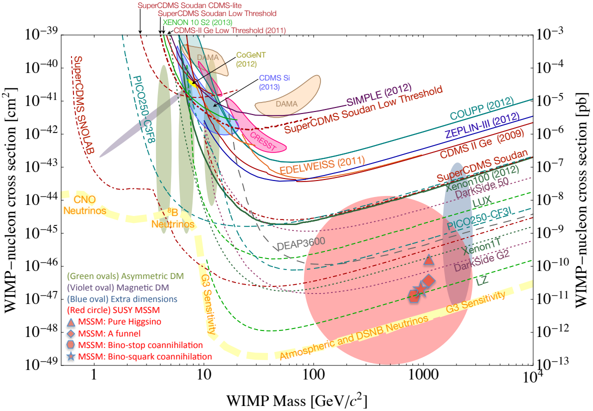
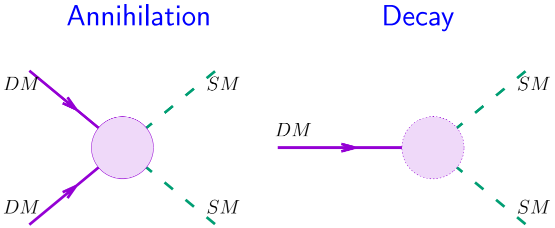


Coherent neutrino scattering – imitation of dark matter signal

- annual modulation
- directional detection
- understanding of the energy spectra of neutrino background

Indirect methods: a review



- DM annihilation is expected in WIMP models
- Regions with very high DM density
- Messengers: photons (γ), neutrinos (ν), antimatter (e^+, $\bar{p}$...)
- Annihilation (decay) channels

$$\chi\chi \to W^+W^-, \bar{b}b, \tau^+\tau^- \text{or metastable states}$$

- Signal from dark matter – significant excess of the fluxes above the background

Messengers: photons

Photons γ – most expected, easy to detect, no deflection, absorbed for $E \gtrsim 100$ TeV

Searches for DM signal with photons are performed with ground and space experiments (satellites and atmospheric Cherenkov telescopes):

Fermi-LAT (20 MeV – 300 GeV) H.E.S.S. (up to 10 TeV)

MAGIC, VERITAS, CTA (future project)

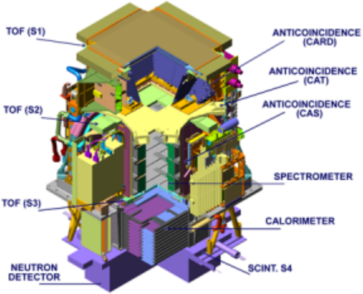
Messengers: cosmic rays

Charged particles – easy to detect, energy loss (ICS or synchrotron), deflected by magnetic fields

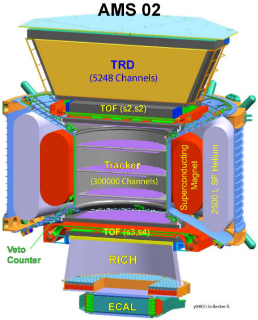
Can be detected by most of the gamma-experiments

Dedicated experiments: in space and balloon experiments

PAMELA



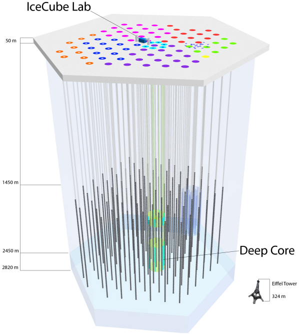
AMS-02



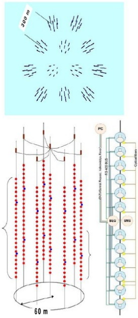
Messengers: neutrinos

Neutrinos ν – hard to detect, no deflection, point to sources, small astrophysical background

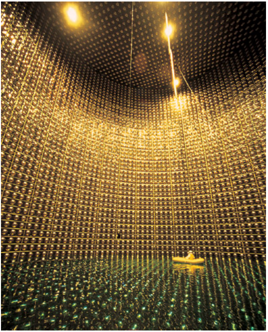
IceCube



Baikal-GVD



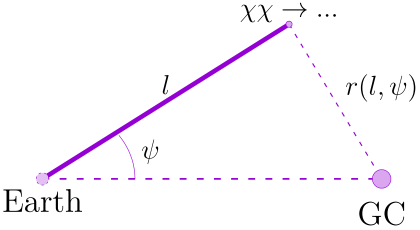
Super-Kamiokande



ANTARES (KM3NET), Baksan

Signal from DM annihilations

Flux of γ or ν from an extended source



Annihilation rate per particle:

$\sum_i \frac{\rho[r(l,\psi)]}{m_\chi} \langle \sigma_i v \rangle$

Total annihilation rate:

$\frac{1}{2} \left(\sum_i \frac{\rho[r(l,\psi)]}{m_\chi} \langle \sigma_i v \rangle \right) \left(\frac{\rho[r(l,\psi)]}{m_\chi} dV \right)$

$$\frac{d\phi}{dEd\Omega}(E,\psi) = \frac{1}{4\pi} \int_0^{l_{max}} dl\ \rho^2(l)\ \frac{\langle \sigma_A v \rangle_0}{2m_{DM}^2}\ \frac{dN}{dE}.$$

Particle physics factor:

1. $\langle \sigma_A v \rangle_0$ – annihilation cross section
2. $\frac{dN}{dE}$ – energy spectra

Astrophysical factor

$$J_2(\psi) = \int_0^{l_{max}} dl\ \rho^2(l),$$

Indirect searches for DM

Case of dark matter decay:

- Expected γ or ν flux

$$\frac{d\phi}{dEd\Omega} = \int_0^{l_{max}} dl\ \rho(l)\ \frac{1}{\tau_{DM}}\ \frac{1}{4\pi m_{DM}}\ \frac{dN}{dE},$$

- Astrophysical factor

$$J_1(\psi) = \int_0^{l_{max}} dl\ \rho(l).$$

- For an extended source DM decay signal is wider

The case of charge particles - propagation should carefully accounted for.

Annihilation cross section

WIMP's models: annihilation at freeze-out ($v \sim 0.3c$)

$$\Omega_{DM} h^2 \sim \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma_A v \rangle_{freeze-out}} \sim 0.1$$

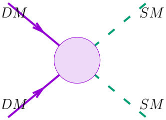
Annihilation cross section today can be different!
Nonrelativistic regime $v \sim 10^{-3} c \ll c$: s- or p-wave annihilation

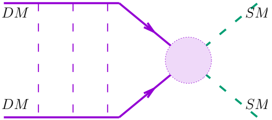
$$\langle \sigma_A v \rangle_0 = a + b \bar{v}^2$$

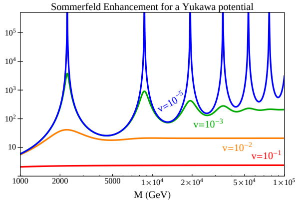
DM models with long-range self-interaction: Sommerfeld enhancement

$S = |\psi(0)|^2 / |\psi_0(0)|^2$

$V = \frac{\alpha}{r} \mathrm{e}^{-m_\phi r}$, arxiv:1307.1129



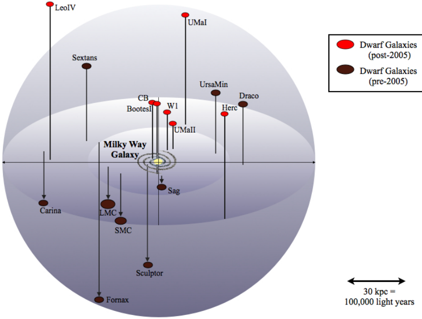




Signal from DM annihilations

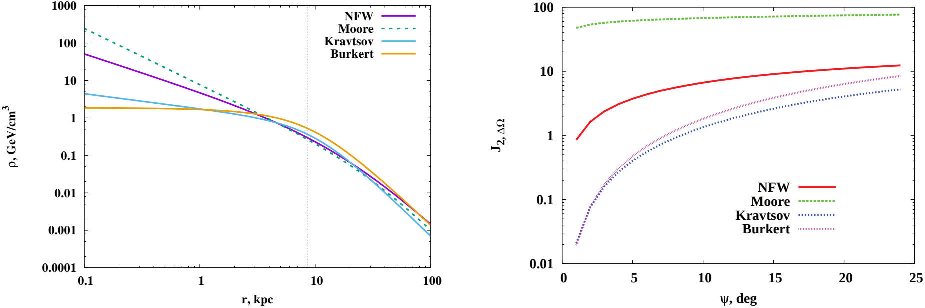
Potential sources of neutrino signal from DM include many objects:

- Galactic Center
  $J_2 \sim 10^{22-25}$ GeV^2/cm^5 within 0.1°
- Andromeda galaxy
  $J_2 \sim 10^{20}$ GeV^2/cm^5
- Milky Way satellite galaxies (dSphs) – proximity, high dark matter content, small astrophysical background
  $J_2 \sim 10^{19-20}$ GeV^2/cm^5
- galaxy clusters

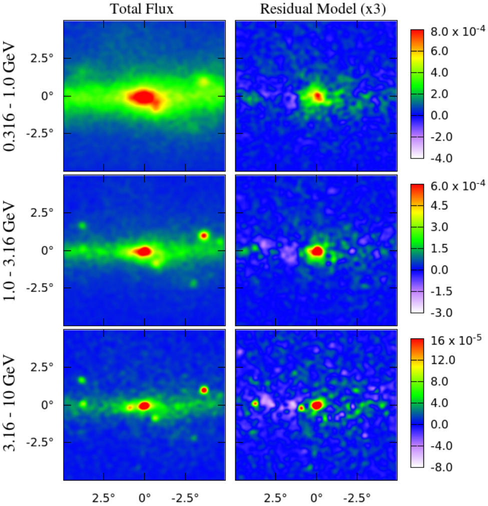


Galactic Center

- Huge dark matter content
- Huge uncertainties related to DM density profile,
- Huge astrophysical background



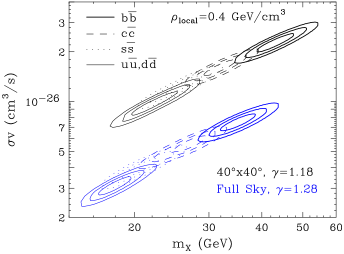
Galactic Center: FERMI excess Hooper, Linden (2011)



observed photon excess from GC in GeV range

Possible explanations:

–signal from dark matter (see, e.g.T. Daylan et.al. arXiv:1402.6703)

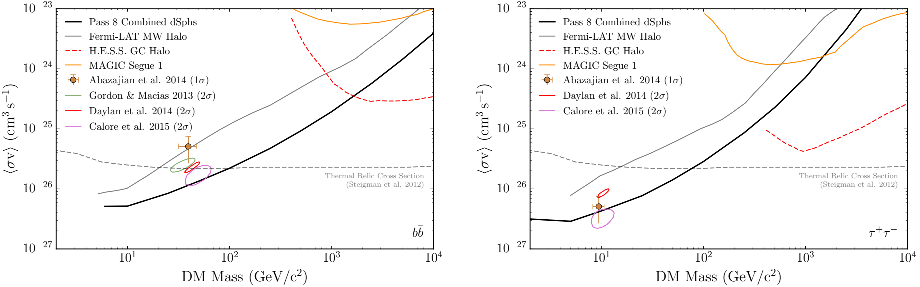


– unaccounted background (millisecond pulsars)

How to check that this signal is due to dark matter?

Dwarf Galaxies

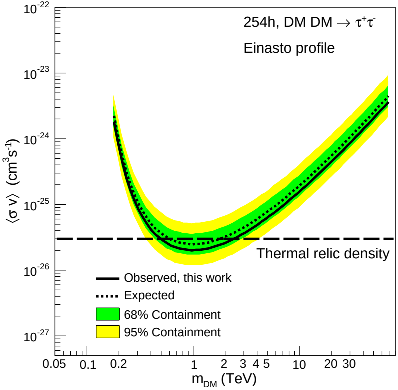
dSphs of the Milky Way – dark matter dominated objects – give the most stringent constraints!
Results by FERMI-LAT (arXiv:1503.02641): Combined analysis of 15 Milky Way dSphs

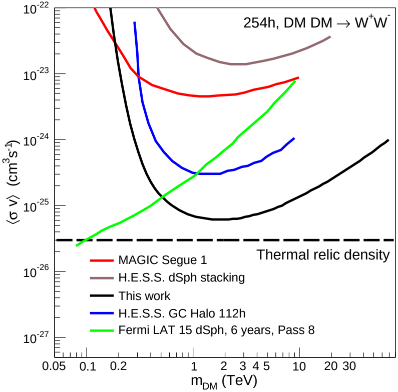


Starting to exclude dark matter with thermal annihilation cross section and possible dark matter interpretation of the FERMI GeV excess

Heavier dark matter candidates?

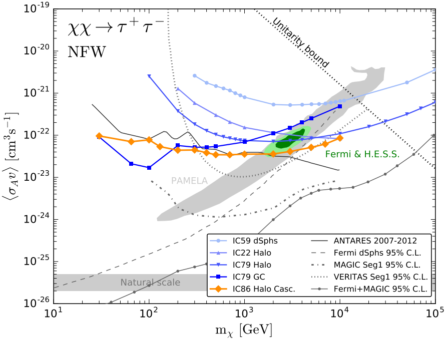
Heavier dark matter candidates can be probed with ACTs.
H.E.S.S. observations (10 years) of inner Halo (arXiv:1607.08142)
(in the region 0.3-0.9° from GC)





Neutrinos from DM annihilations

from arXiv:1606.00209



from arXiv:1512.01198