Searches for Dark Matter

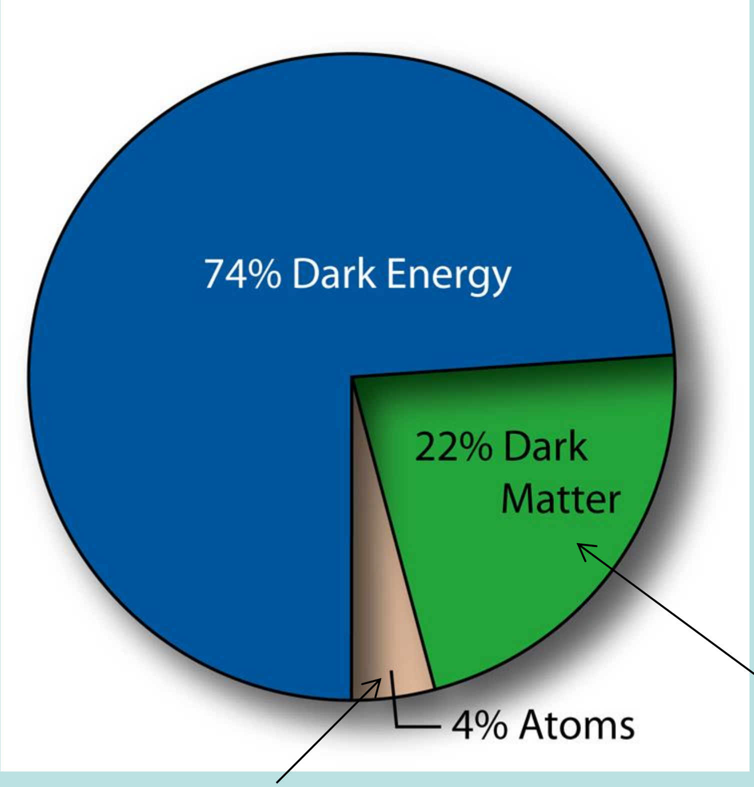
Lecture from the course

“Cosmoparticle Physics”

Outlines

- Search for axions
- Direct search for dark matter particles (WIMPs and SIMPs)
- Effects of DM annihilation in cosmic rays
- DM accumulation and annihilation in Sun and Earth
- Gravitational lensing (macro- and micro-lensing)

Composition of the Universe



$$\Omega \equiv \frac{\rho}{\rho_{cr}}$$

$$\Omega_b \approx 0.044 \qquad \Omega_{CMB} \approx 0.5 \cdot 10^{-4}$$

$$\Omega_{DM} \approx 0.20$$

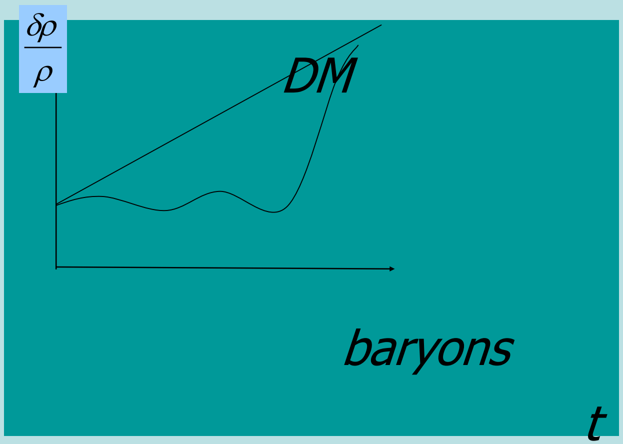
$$\Omega_\Lambda \approx 0.7$$

$$\boxed{\Omega_{tot} \approx 1.0}$$

Baryonic matter consists of atoms

Can dark Matter consist of Dark atoms?

Cosmological Dark Matter



$$\frac{\delta\rho}{\rho} \Rightarrow \frac{\delta T}{T}$$

Cosmological Dark Matter explains:

- ***virial paradox in galaxy clusters,***
- ***rotation curves of galaxies***
- ***dark halos of galaxies***
- ***effects of macro-lensing***

But first of all it provides formation of galaxies from small density fluctuations, corresponding to the observed fluctuations of CMB

To fulfil these duties Dark Matter should interact sufficiently weakly with baryonic matter and radiation and it should be sufficiently stable on cosmological timescale

Dark Matter – Cosmological Reflection of Microworld Structure

Dark Matter should be present in the modern Universe, and thus is stable on cosmological scale.

This stabilty reflects some Conservation Law, which prohibits DM decay.

Following Noether's theorem this conservation law should correspond to a (nearly) strict symmetry of microworld.

Direct dark matter searches

Dark matter and the mass of neutrino

Astrophysical implications of the neutrino rest mass. III. Nonlinear growth of perturbations and the missing mass

A. G. Doroshkevich, Ya. B. Zel'dovich, R. A. Syunyaev, and M. Yu. Khlopov

Keldysh Institute of Applied Mathematics, USSR Academy of Sciences, Moscow, and Institute for Space Research, USSR Academy of Sciences, Moscow

(Submitted May 28, 1980)

Pis'ma Astron. Zh. **6**, 465–469 (August 1980)

A discussion is given of the influence that a finite rest mass for the neutrino would have on the phenomenon of "missing mass" in galaxies and clusters of galaxies, on the nonlinear stage in the evolution of primordial irregularities, and on the problem of observing neutral hydrogen in the spectrum of distant quasars.

In 1980 the experimental claims on the existence of the mass of electron neutrin
about 30 eV lead to immediate cosmological consequence of the
neutrino dominated Universe, In which massive neutrinos play the role of dark m

Direct seaches for Dark Matter

Possibility of detecting relict massive neutrinos

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M. V. Keldysh Institute of Applied Mathematics, Academy of Sciences of the USSR

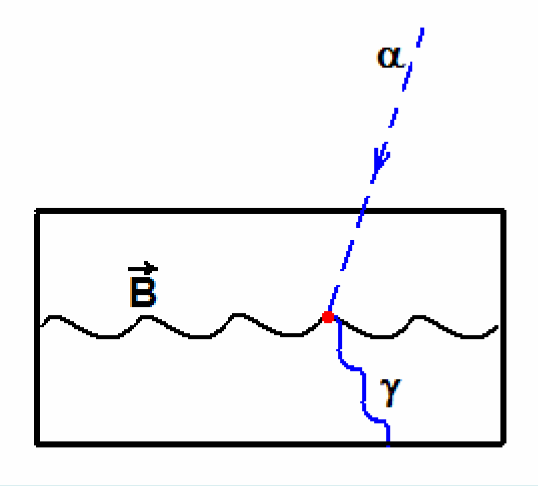
(Submitted 18 August 1982)

Pis'ma Zh. Eksp. Teor. Fiz. **36**, No. 6, 224–226 (20 September 1982)

The coherent intensification of the interaction of relict massive neutrinos with grains of matter with a size on the order of the neutrino wavelength suggests that it might be possible to detect a galactic neutrino sea by virtue of the mechanical pressure which it exerts in the direction opposite that in which the solar system is moving in the galaxy.

Direct search for cosmic axions

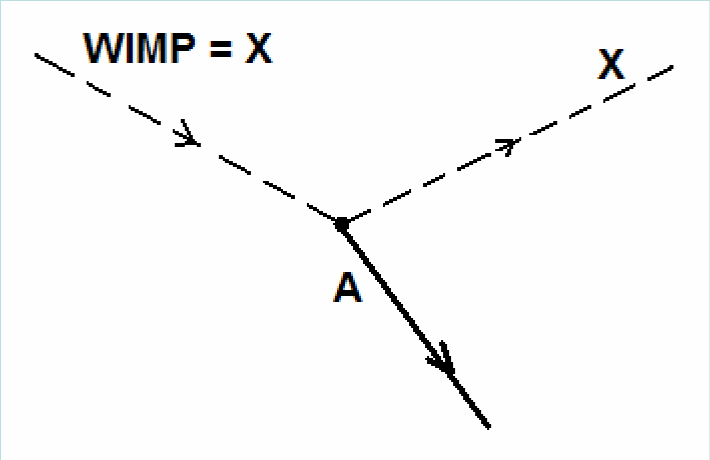
- Searches for cosmic axions use the effect of « light, coming through the walls » - axion conversion in photons in radio-frequency cavity. Axion emission is severely constrained by the observational data on the stellar evolution. Effects of archioles can hardly let axions to be the dominant form of dark matter.



WIMP-nucleus interaction

CDM can consist of Weakly Interacting Massive Particles (WIMPs).

Such particles can be searched by effects of WIMP-nucleus interactions.



$$\Delta T = 0 \div \Delta T_{\max} = \frac{q_{\max}^2}{2m_A} = \frac{2\mu^2 v^2}{m_A} \xrightarrow[m_X >> m_A]{} 2m_A v^2$$

$$v \sim 300 \frac{\mathrm{km}}{\mathrm{s}}, \qquad \Delta T \sim 10\mathrm{keV}$$

$\Delta T_{\max} < E_A^* \Rightarrow$ elastic scattering

$q_{(\max)} R_A > 1 \Rightarrow$ non-pointlike nucleus

$$Interaction\ amplitude \equiv A_{AX} = A_{AX}^{\text{point}} \cdot F_A(q^2)$$

2. Direct search for DM (WIMPs)

***AX*-interaction in nonrelativistic limit**

?

scalar

takes place for Dirac fermions

$$A_{AX}^{\text{point}} = Z \cdot A_{pX} + (A - Z) \cdot A_{nX}$$

$$A_{pX} = g_p A_0 \quad A_{nX} = g_n A_0$$

$$\sigma_{AX} \propto \underbrace{\left[g_p \frac{Z}{A} + g_n \left(1 - \frac{Z}{A} \right) \right]^2}_{} A^2 \mu^2$$

Weakly depends on target-nucleus,

because *Z*/*A*≈const.

spin-spin

takes place for Majorana fermions

$$A_{AX}^{\text{point}} = \langle S_p \rangle_A \cdot A_{pX} + \langle S_n \rangle_A \cdot A_{nX}$$

$$\sigma_{AX} \propto \underbrace{\left[g_p \langle S_p \rangle_A + g_n \langle S_n \rangle_A \right]^2}_{} \mu^2$$

Strongly depends on target-nucleus,

because <$S_{p,n}$> depends on nucleus structure.

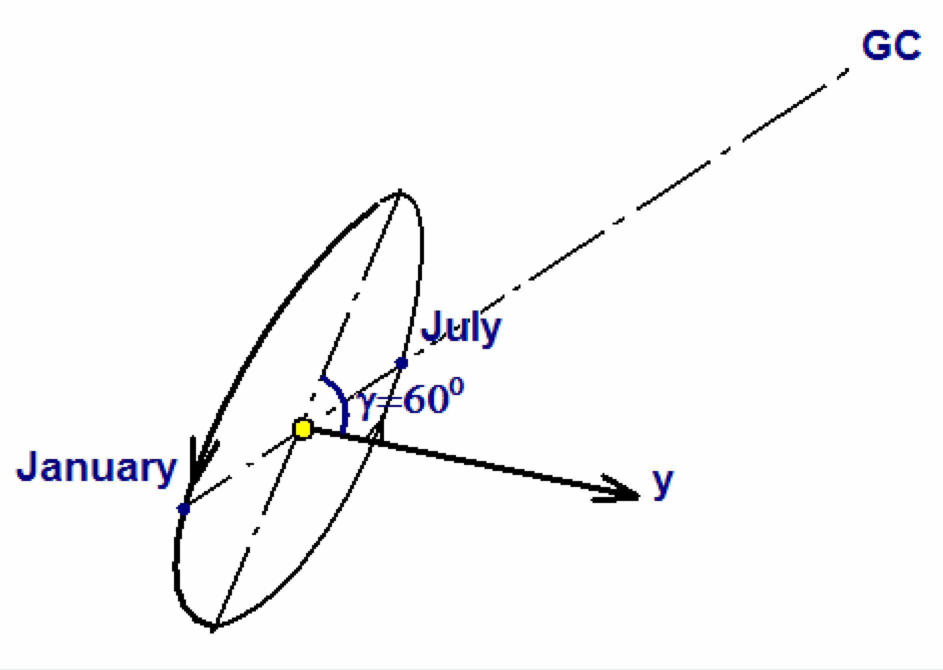
Interpretation of experimental results in terms of spin-spin *AX*-interaction is more dependent on detector material.

Annual modulation of WIMP effects

Minimization of background

- Installation deeply underground
- Radioactively pure materials
- Annual modulation

DM does not participate in rotation around GC.



$$v_{Earth\ y} = v_{Sun\ y} + v_{orb} \cdot \cos\gamma \cdot \cos\omega(t - t_0)$$

$$v_{Sun\ y} = 220 + 16.5 \cdot \cos 25° \cdot \sin 53° \text{ (km/s)}$$

$$t_0 = 2 \text{ June}$$

$$Amplitude <\sim \frac{v_{orb} \cdot \cos\gamma}{v_{Sun\ y}} \sim \frac{15}{232} \sim 7\%$$

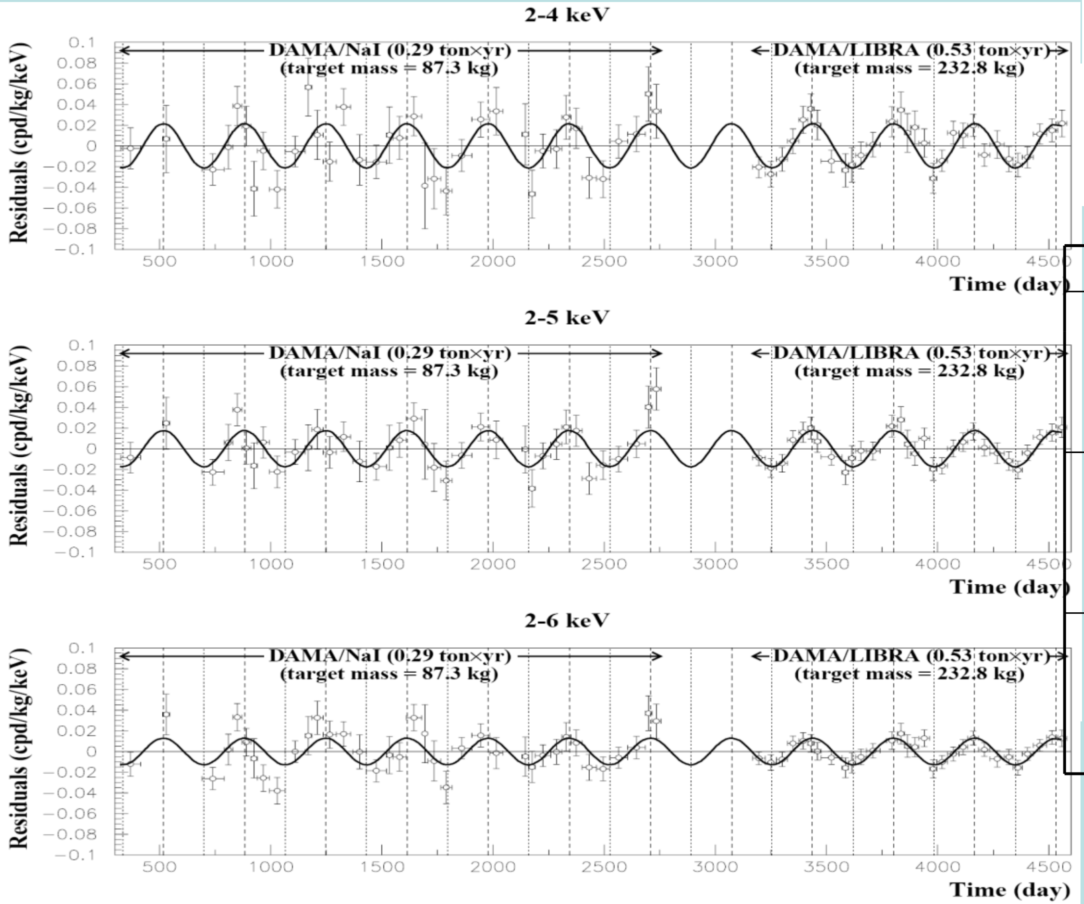
DAMA/NaI and DAMA/LIBRA

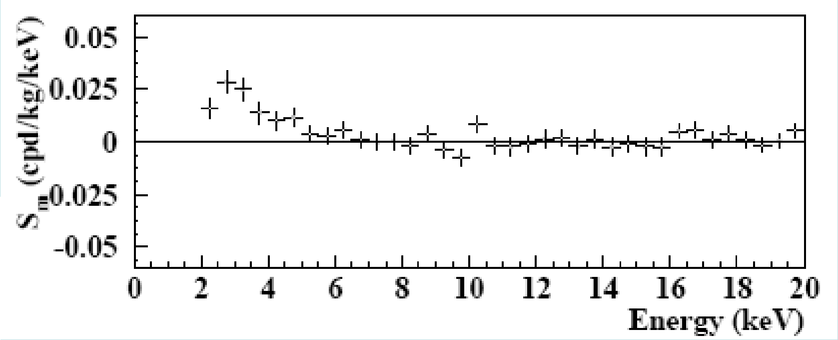
Experiment DAMA (*NaI*)

DAMA/NaI (7 years) + DAMA/LIBRA (4 years) total exposure: 300555 kg×day = 0.82 ton×yr

Results of 7 years of observation (1995-2002).

$$R(t) = S_0 + S_m \cos[\omega(t - t_0)]$$





$t_0 = 21 \text{May} \pm 22 \text{days}$

$T = 1.00 \pm 0.01 \text{year}$

$Amplitude = 0.020(3) \text{ cpd/kg/keV}$

$Confedence\ level = 6.3\sigma$

	A (cpd/kg/keV)	T=2p/? (yr)	t_0 (day)	C.L.
DAMA/NaI (7 years)				
(2÷4) keV	0.0252 ± 0.0050	1.01 ± 0.02	125 ± 30	5.0s
(2÷5) keV	0.0215 ± 0.0039	1.01 ± 0.02	140 ± 30	5.5s
(2÷6) keV	0.0200 ± 0.0032	1.00 ± 0.01	140 ± 22	6.3s
DAMA/LIBRA (4 years)				
(2÷4) keV	0.0213 ± 0.0032	0.997 ± 0.002	139 ± 10	6.7s
(2÷5) keV	0.0165 ± 0.0024	0.998 ± 0.002	143 ± 9	6.9s
(2÷6) keV	0.0107 ± 0.0019	0.998 ± 0.003	144 ± 11	5.6s
DAMA/NaI + DAMA/LIBRA				
(2÷4) keV	0.0223 ± 0.0027	0.996 ± 0.002	138 ± 7	8.3s
(2÷5) keV	0.0178 ± 0.0020	0.998 ± 0.002	145 ± 7	8.9s
(2÷6) keV	0.0131 ± 0.0016	0.998 ± 0.003	144 ± 8	8.2s

Model Independent Annual Modulation Result

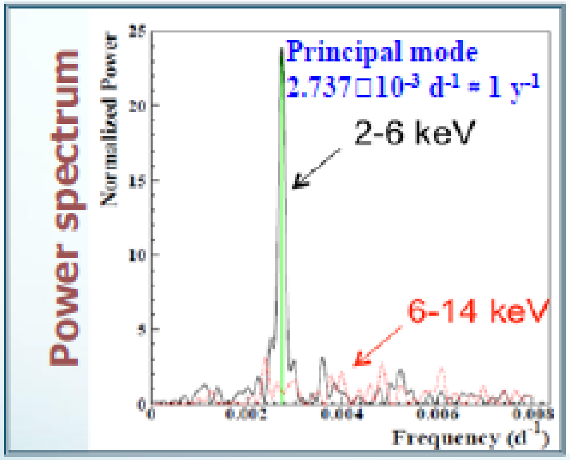
DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = **1.33 ton×yr**

EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

The measured modulation amplitudes (A), period (T) and phase (t_0) from the single-hit residual rate vs time

	A(cpd/kg/keV)	$T=2\pi/\omega$ (yr)	t_0 (day)	C.L.
DAMA/NaI+DAMA/LIBRA-phase1				
(2-4) keV	0.0190 ±0.0020	0.996 ±0.0002	134 ± 6	9.5σ
(2-5) keV	0.0140 ±0.0015	0.996 ±0.0002	140 ± 6	9.3σ
(2-6) keV	0.0112 ±0.0012	0.998 ±0.0002	144 ± 7	9.3σ

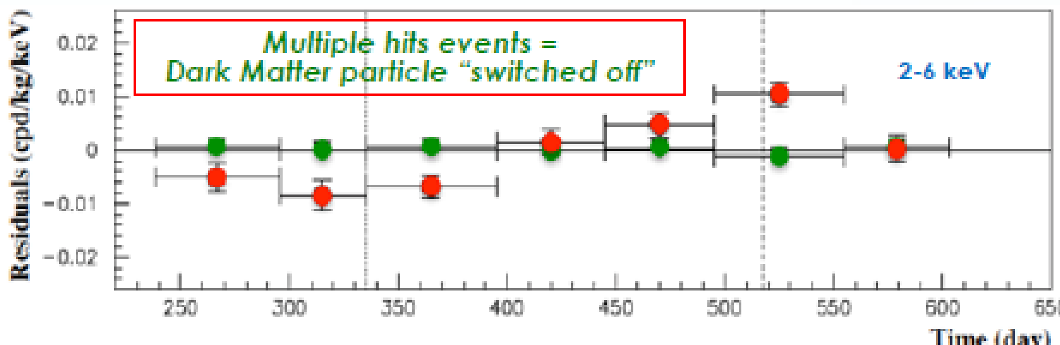
$A\cos[\omega(t-t_0)]$



No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature

Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)**; Clear modulation in the single hit events; No modulation in the residual rate of the multiple hit events

A=-(0.0005±0.0004) cpd/kg/keV



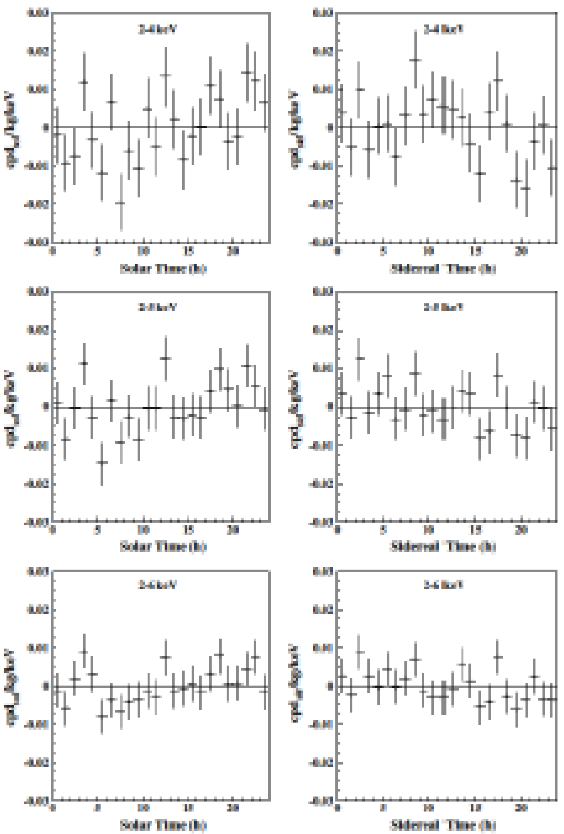
This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9.2σ C.L.

Model independent result on possible diurnal effect in DAMA/LIBRA-phase1

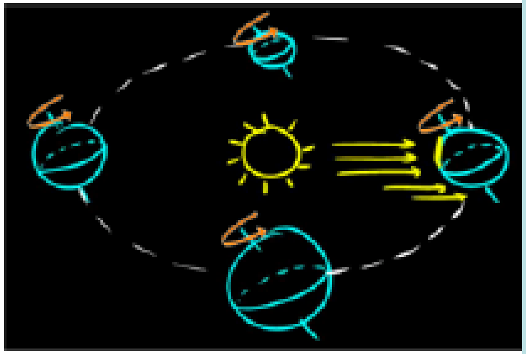
Eur. Phys. J. C 74 (2014) 2827

solar sidereal



2-4 keV

• Experimental *single-hit* residuals rate vs either sidereal and solar time and vs energy.



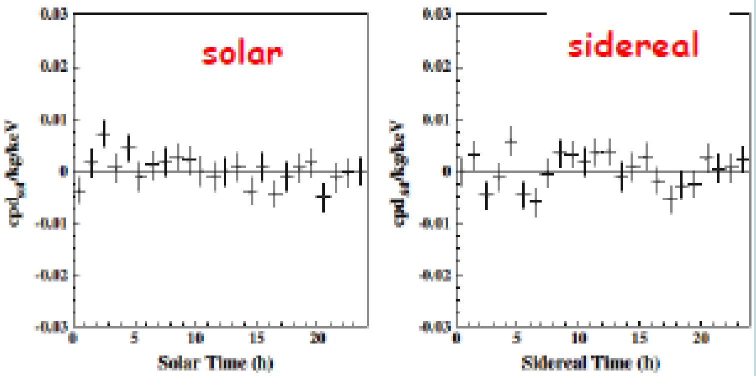
2-5 keV

Energy region where the annual modulation observed.

2-6 keV

Energy region just above.

6-14 keV



Energy	Solar Time	Sidereal Time
2–4 keV	χ^2/d.o.f. = 35.2/24 → P = 7%	χ^2/d.o.f. = 28.7/24 → P = 23%
2–5 keV	χ^2/d.o.f. = 35.5/24 → P = 6%	χ^2/d.o.f. = 24.0/24 → P = 46%
2–6 keV	χ^2/d.o.f. = 25.8/24 → P = 36%	χ^2/d.o.f. = 21.2/24 → P = 63%
6–14 keV	χ^2/d.o.f. = 25.5/24 → P = 38%	χ^2/d.o.f. = 35.9/24 → P = 6%

→ no diurnal variation with significance of 95% C.L.

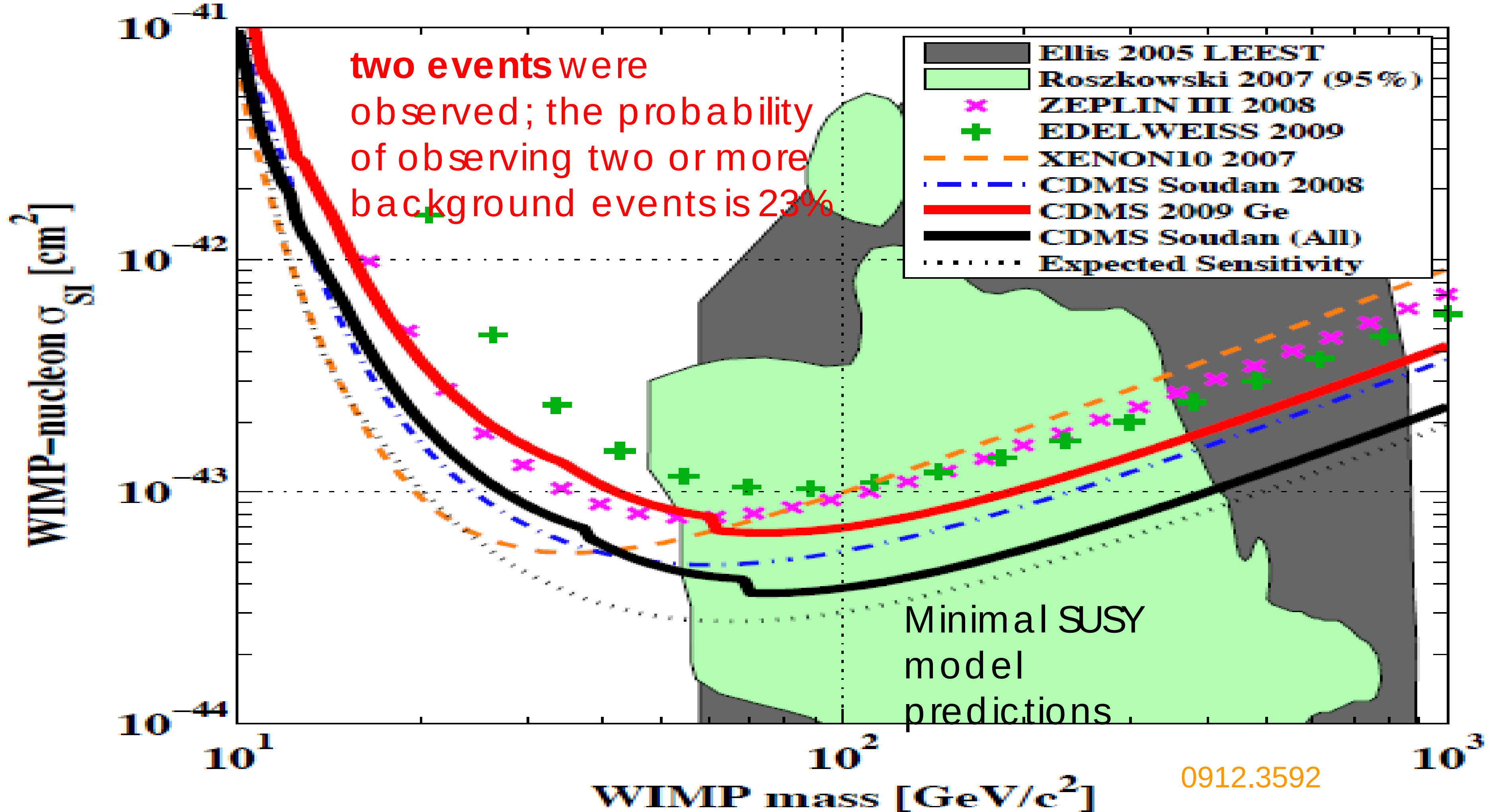
+ run test to verify the hypothesis that the positive and negative data points are randomly distributed: lower tail probabilities (in the four energy regions): 43, 18, 7, 26% for solar case and 54, 84, 78, 16% for sidereal case

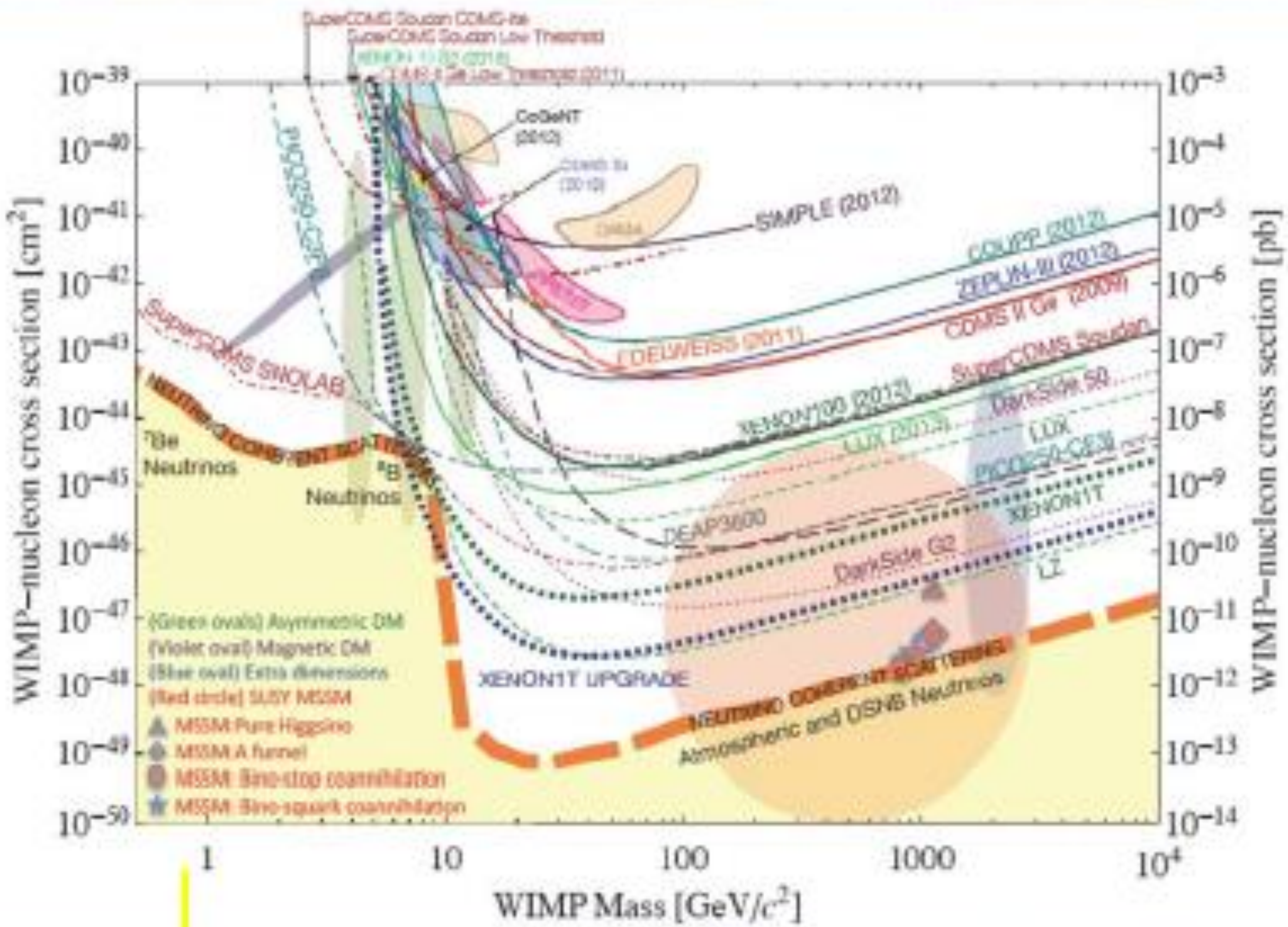
→ presence of any significant diurnal variation and of time structures can be excluded at the reached level of sensitivity

Other searches for DM (WIMPs)

Experiment DAMA (NaI) vs other underground experiments:

Experiment DAMA/NaI+**DAMA/Libra** vs other underground experiments:
Interpretation in terms of ***scalar*** *AX*-interaction.

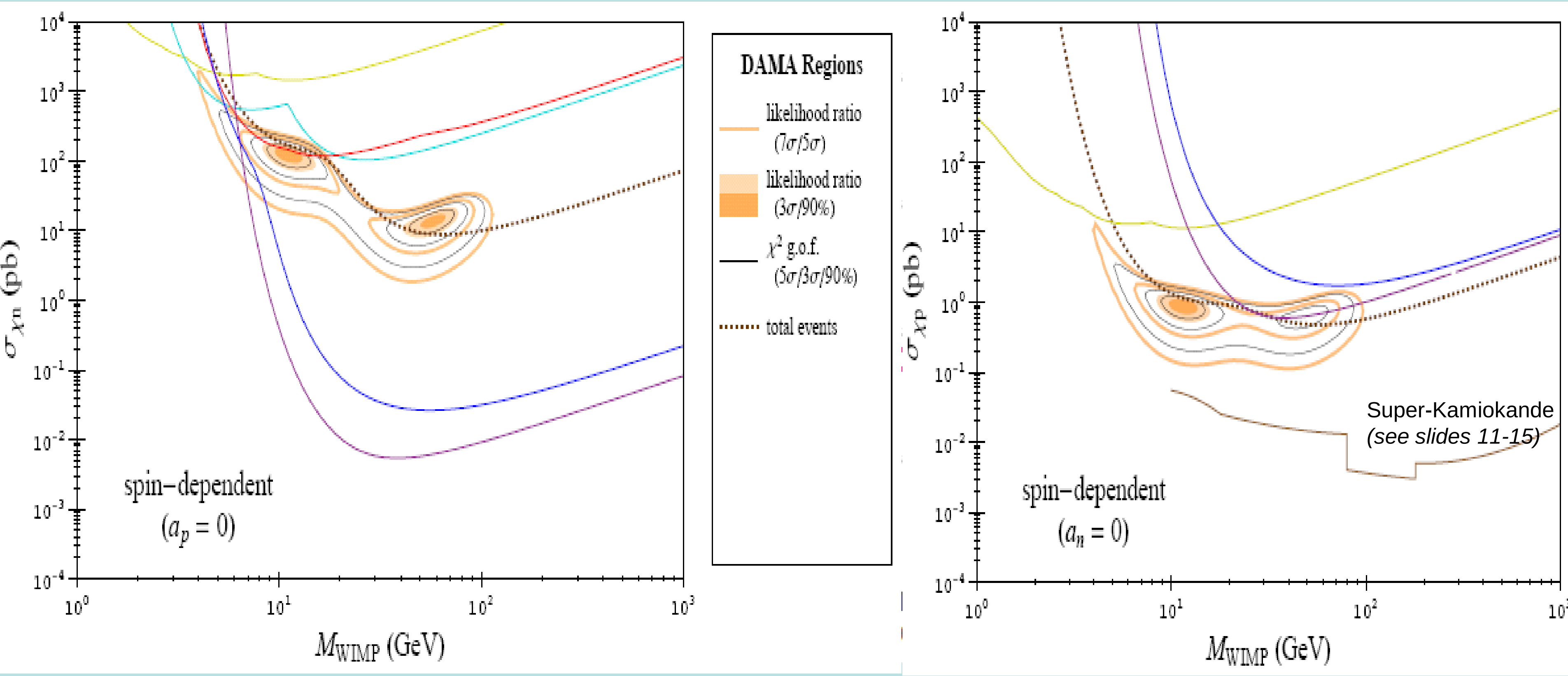




This is just a largely arbitrary, partial, incorrect exercise

Direct search for DM (SDI WIMPs)

Experiment DAMA/NaI + DAMA/Libra vs other underground experiments:
Interpretation in terms of ***spin-spin*** *AX*-interaction.

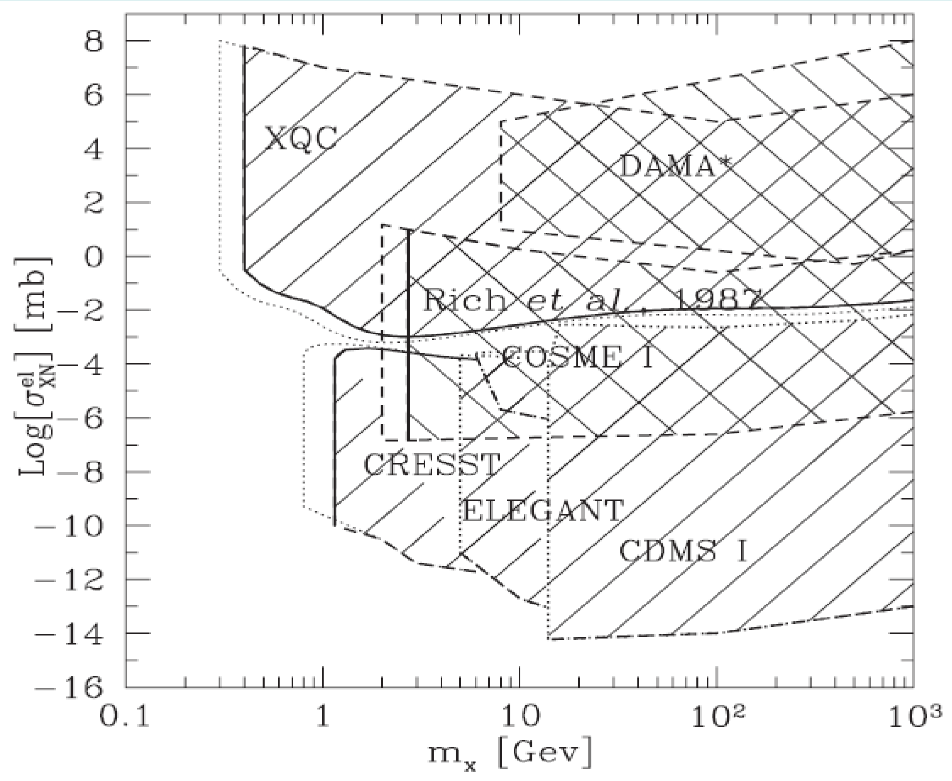


Direct search for SIMPs

Rocket experiment XQC.

If DM consists of *Strongly* Interacting Massive Particles (SIMPs), they could be braked down by ordinary matter and become insensitive for underground detectors.

Such particles could be searched for in X-cosmic ray experiment XQC, aimed at observation of X-rays and realized during a rocket flight.



XQC experiment

data taking time: **~100s**,

material of detector: **Si+HgTe**,

energy deposit range of sensitivity: **25-1000 eV**,

the range being good for extraction of SIMP-nucleus interactions event from background: **25-60 eV**.

For scalar *XA*-interaction

Indirect searches for Dark Matter

Indirect searches for Dark Matter

Astrophysical bounds on the mass of heavy stable neutral leptons

Ya. B. Zel'dovich, A. A. Klypin, M. Yu. Khlopov, and V. M. Chechetkin

Institute of Applied Mathematics, USSR Academy of Sciences
(Submitted 29 November 1979)
Yad. Fiz. **31**, 1286–1294 (May 1980)

Analytical and numerical calculations show that heavy neutral stable leptons are carried along by the collapsing matter during the formation of galaxies and possibly stars as well. The condensation in galaxies and stars results in appreciable annihilation of leptons and antileptons. Modern observations of cosmic-ray and γ-ray fluxes establish a limit $m_\nu \gtrsim 100$ GeV for the mass of neutral leptons, since annihilation of neutral leptons produces γ rays and cosmic rays. The obtained bound, in conjunction with ones established earlier, precludes the existence of stable neutral leptons (neutrinos) with $m_\nu > 30$ eV.

Condensation of Dark Matter in Galaxy

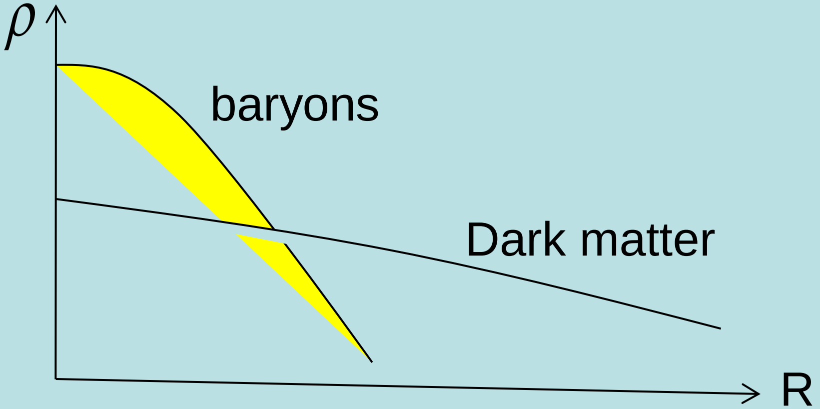
$$\ddot{R} + \omega^2 R = 0$$

$$\omega^2 = 4\pi G\left(\rho_\nu + \rho_b\right)$$

$$I = \frac{E(t)}{\omega(t)} = \frac{\omega^2 R^2}{2\omega} = const$$

$$\rho_\nu(t) \propto R^{-3} \propto \omega^{3/2} \propto \left[\rho_b(t)\right]^{3/4}$$

$$\rho_\nu(t) \propto \left[\rho_b(t)\right]^{3/4}$$



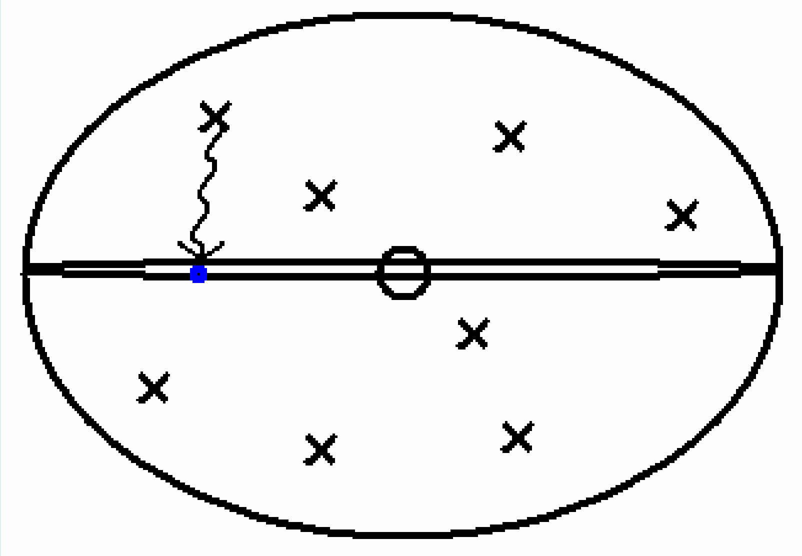
- Motion of collisionless gas in nonstationary field of baryonic matter, contracting owing to dissipation processes, provides effective dissipation and contraction of this gas.
- In result collisionless Dark Matter condences in Galaxy, but it is distributed more steeply, than baryonic matter.
- It qualitatively explains the difference in distribution of baryons and dark matter.
- Due to condensation effects of annihilation in Galaxy can be significant even for subdominant DM components (e.g.4th neutrino).

Annihilation and decays of DM as a source of CR.

Stable DM particles can annihilate

$$\dot{n}_{sources} = n_X n_{\tilde{X}} \langle \sigma_{ann} v \rangle$$

$$X\tilde{X} \to e^+e^- + ...$$



Metastable neutral particles decay with equal amount of positrons and X electrons

$$X \to e^+e^- + ...$$

At the level of elementary process metastable double charged particles can decay to same sign leptons only

$$X^{++} \to l^+l^+$$

Dark atoms can be excited in collisions and emit electron-positron pairs in de-excitation.

The First Five years of AMS on the International Space Station

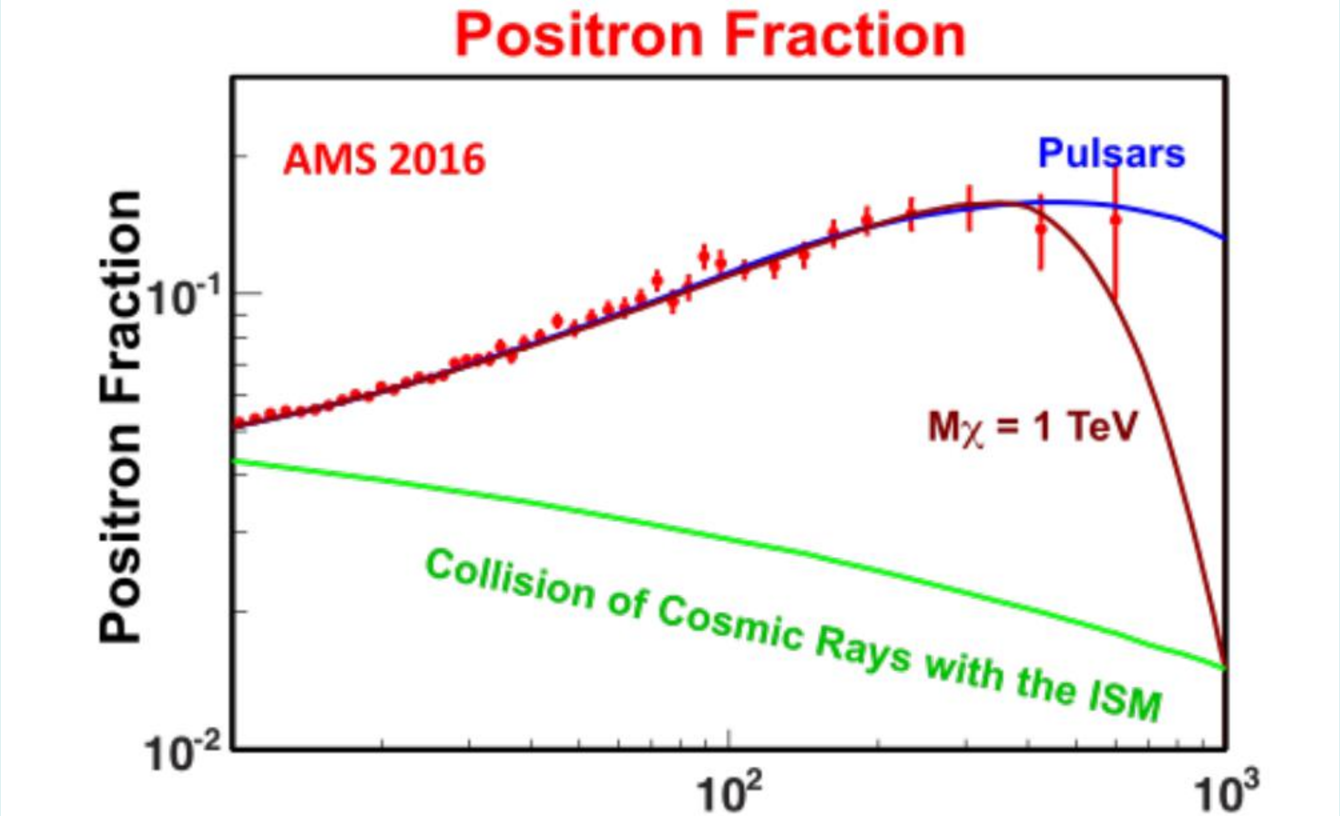
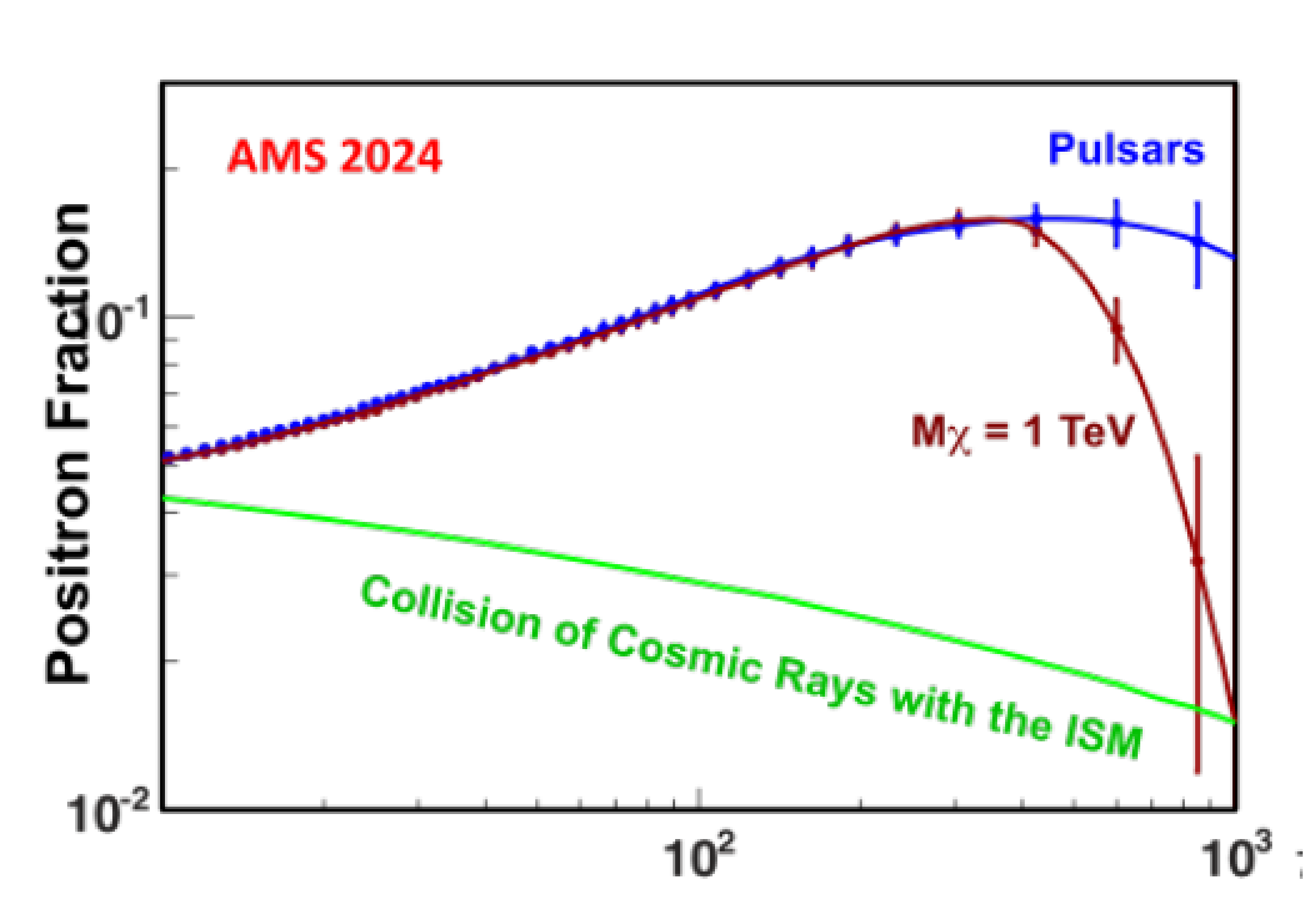


Figure 5. The current AMS positron fraction measurement compared with three theoretical models.

Presented in CERN on 08.12.2016 by Prof. S.Ting

AMS02 in the next decade



Presented in CERN on 08.12.2016 by Prof. S.Ting

Cosmic positron excess from double charged constituents of dark atoms

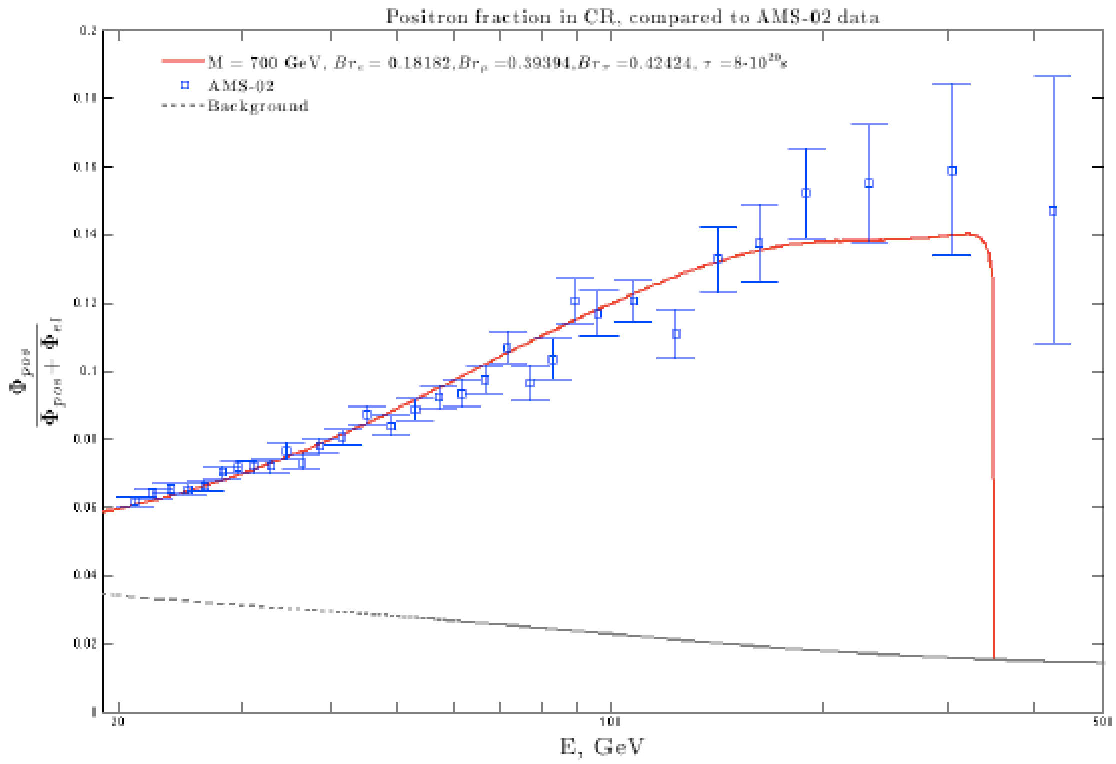


Figure 3: Positron fraction in the cosmic rays from decays of dark matter particles (red curve), corresponding to the best-fit values of model parameters ($M = 700\,\mathrm{GeV}, \tau = 8 \cdot 10^{20}\,\mathrm{s}, Br_{ee} = 0.182, Br_{\mu\mu} = 0.394, Br_{\tau\tau} = 0.424$), and fraction of secondary positrons (gray line), compared to the latest AMS-02 data [34] (blue dots).

Probably such indirect effect is detected in the cosmic positron fluxes.

[figure from K.M.Belotsky et al. Int.J.Mod.Phys. D24 (2015) 1545004 arXiv:1508.02881]

Diffuse Gamma ray background

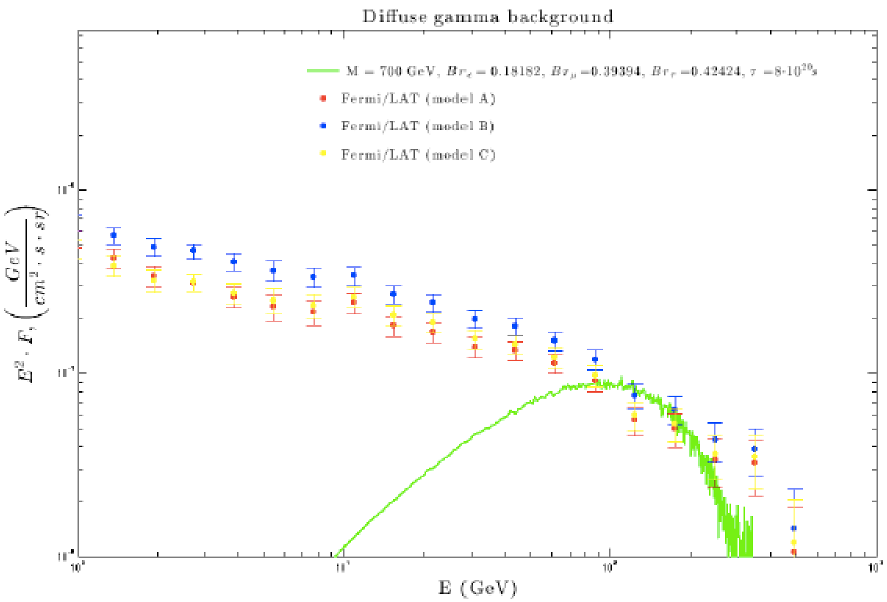
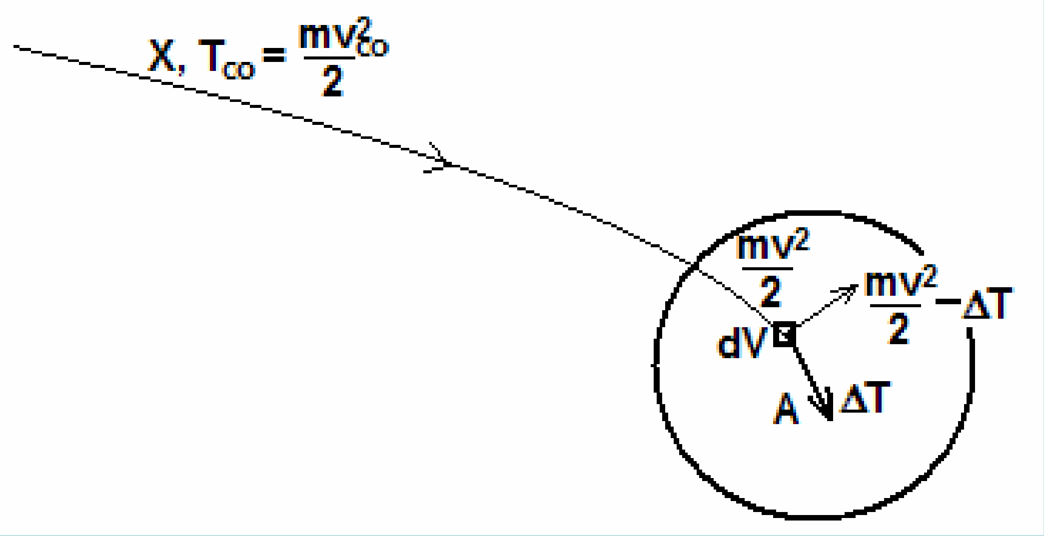


Figure 4: Gamma-ray flux multiplied by E^2 from decays of dark matter particles in the Galaxy and beyond (green curve), corresponding to the best-fit values of model parameters ($M = 700\,\mathrm{GeV}, \tau = 8 \cdot 10^{20}\,\mathrm{s}, Br_{ee} = 0.182, Br_{\mu\mu} = 0.394, Br_{\tau\tau} = 0.424$), compared to the latest FERMI/LAT data on isotropic diffuse gamma-ray background [42] ($|b| > 20°, 0° \leq l < 360°$ with point sources removed and without diffuse emission attributed to the interactions of Galactic cosmic rays with gas and radiation fields (foreground); here three different foreground models A (red dots), B (blue dots) and C (yellow dots) are shown). In our analysis we have used model B.

Neutrinos from DM capture and annihilation in Sun and Earth

DM particles in Sun and Earth

a) Accumulation



$$0 \le \Delta T \le \Delta T_{max} = \frac{2\mu^2 v^2}{m_A}$$

$(v \cong v_X >> v_A)$ relatively to the Earth/Sun

$$\Delta T > T_\infty \Rightarrow capture$$

$$\dot{N}_{capt} = \sum_A \int n_X \langle \sigma_{AX} w v \rangle n_A dV$$

Probability that $\Delta T > T_\infty$ in one collision

Let us estimate given capture rate.

Accumulation in the Sun and Earth.

a) Accumulation

$$v^2 \equiv v_r^2 = v_\infty^2 + v_{\rm II}^2(r) \qquad \frac{mv_{\rm II}^2(r)}{2} \equiv -U(r)$$

From the law of angular momentum conservation one can deduce (see astro-ph/0504216):

$$\frac{\bar{n}_r}{v_r} = \frac{n_\infty}{v_\infty} \qquad \bar{n}_r \equiv \frac{dN_{X\ in\ spheric\ layer}}{4\pi r^2 dr} \qquad \bar{f}_r = \frac{n_\infty}{\bar{n}_r}\frac{v_r^2}{v_\infty^2(v_r)} f_\infty(v_\infty(v_r))\Bigg|_{v_{r\,\min}=v_{\rm II}(r)}^{v_{r\,\max}=\sqrt{v_{\infty\,\max}^2+v_{\rm II}^2(r)}}$$

If cross section of *XA*-interaction depends on transferred momentum (velocity) due to only form-factor of nucleus then:

$$\sigma_{AX} = \sigma_{AX}^{\rm point}\cdot\int_{-1}^{1} F_A^2(q^2)\frac{d\cos\theta^*}{2}$$

$$q^2 = q^{*2} \equiv (\vec{p}^{\,*} - \vec{p}^{\,\prime *})^2 = 2p^*(1-\cos\theta^*) = 2m_A\Delta T$$

$$\frac{d\cos\theta^*}{2}\Bigg|_{-1}^{1} = \frac{d\Delta T}{\Delta T_{\max}}\Bigg|_{0}^{\Delta T_{\max}}$$

$$w = \frac{\int_{T_\infty}^{\Delta T_{\max}} F_A^2(\Delta T)\frac{d\Delta T}{\Delta T_{\max}}}{\int_{0}^{\Delta T_{\max}} F_A^2(\Delta T)\frac{d\Delta T}{\Delta T_{\max}}}$$

$$\sigma_{AX}w = \sigma_{AX}^{\rm point}\cdot\int_{T_\infty}^{\Delta T_{\max}} F_A^2(\Delta T)\frac{d\Delta T}{\Delta T_{\max}} = \sigma_{AX}^{\rm point}\cdot\bar{F}_A^2\,\frac{v_{\rm II}^2(r)-\delta_- v_\infty^2}{v^2},$$

$$\delta_- \equiv \frac{(m_X-m_A)^2}{4m_Xm_A}$$

Capture of DM particles

a) Accumulation

Using results given above and assuming for simplicity $\overline{F}_A^{\,2}(r) \approx const$, one gets:

$$\dot{N}_{capt} \cong n_\infty \sum_A N_{Atot} \sigma_{AX}^{\text{point}} \left\langle \overline{F}_A^{\,2} \frac{\left\langle v_{\text{II}}^2 \right\rangle_A - \delta\_ v_\infty^2}{v_\infty} \right\rangle$$

Averaging over positions of nuclei A.

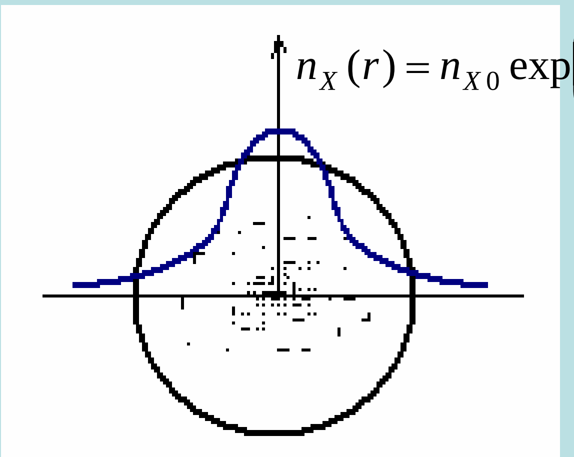
Condition $v_{\text{II}}^2(r) > \delta\_ v_\infty^2$ should be taken into account at the integration in *r* or v_∞.

Note, that for the Earth a nucleus of iron, as a most abundant one from heavy nuclei, is of special importance for heavy WIMPs. Also approximation $\overline{F}_A^{\,2}(r) \approx const$ is good for the Earth, because $v_{\text{II}}(r)$ is small.

Annihilation of DM in the Sun and Earth.

b) Annihilation

Inside the Earth or Sun the captured WIMPs are thermalized.



$$n_X(r) = n_{X0}\exp\left(-\frac{\Delta U}{T}\right)$$

Process of the capture of new WIMPs is competed by process of annihilation (and, for light WIMPs, "evaporation").

$$\dot{N} = \dot{N}_{capt} - \dot{N}_{ann}$$

$$\dot{N}_{ann} = 2\int n_X n_{\tilde{X}} \langle \sigma_{ann} v \rangle dV \equiv CN^2 = \ldots = \dot{N}_{capt}\,\mathrm{th}^2\left(\sqrt{C\dot{N}_{capt}}\,t\right) \xrightarrow{equilibrium} \dot{N}_{capt}$$

In the result of annihilation a <u>flux of light neutrinos</u> is produced, to be registered.

$$\Phi_{\nu_a} = \frac{\dot{N}_{ann}}{2}\frac{\langle multiplicity_{\nu_a} \rangle}{4\pi R^2}$$

Usually, the underground set-ups (Super-Kamiokande, Baksan) register a muon flux. Muon flux induced by muonic neutrinos is roughly

$$\Phi_\mu \approx \Phi_{\nu_\mu}\frac{\lambda_\mu(ionization)}{\lambda_{\nu_\mu}(\nu_\mu A \to \mu X)}$$

No excess of upgoing muons was still observed.

Moreover, there is a deficit of background muons (from atmospheric neutrinos), what can imply physics of neutrino oscillation.

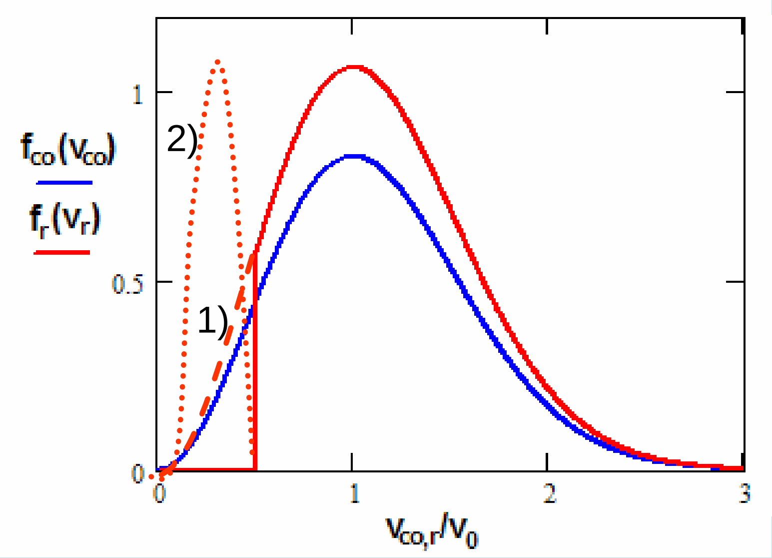
DM capture by the Solar system

c) Solar system component

Solar system (SS) can capture WIMPs due to

1) gravitational scattering off the planets

2) interaction with matter of the Sun and planets.



The question on effectiveness of given mechanisms is still open.
The **first** one acts both on “external” WIMPs and on “internal” (already captured by SS) ones. Acting alone, it would reproduce, after some time, inside SS an “external” WIMP distribution.
The **second** mechanism for the Sun could lead to accumulation of WIMPs inside SS provided a large enough time of their falling on the Sun, escaping SS due to gravities of planets. Modern estimations of that time do not support it.

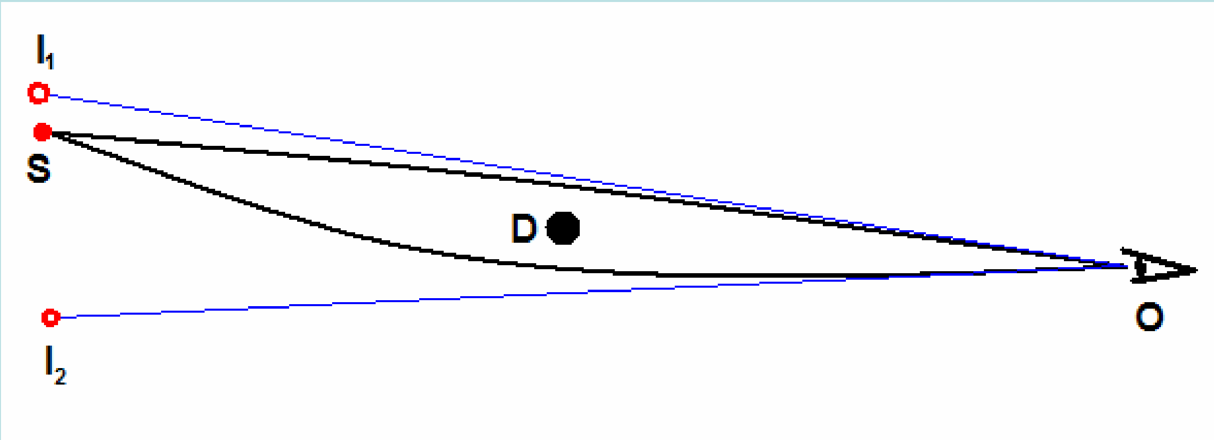
WIMPs captured by Solar system, owing to their relatively low velocities, would be captured more effectively by the Earth. What can be seen from existing estimates

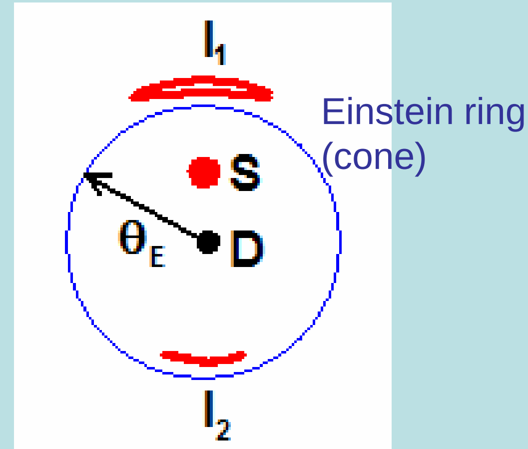
$$\frac{\dot{N}^{SS}_{capt}}{\dot{N}^{gal}_{capt}} \sim \frac{n_{SS}}{n_{gal}} \cdot \frac{v_{gal}}{v_{SS}} \cdot \frac{\langle v^2_{\mathrm{II}} \rangle - \delta_- v^2_{SS}}{\langle v^2_{\mathrm{II}} \rangle - \delta_- v^2_{gal}} \cdot \frac{\overline{F}^2(v_{SS})}{\overline{F}^2(v_{gal})}$$

$$\quad ? \qquad 5\text{-}10 \qquad 1_{\text{(maybe} \gg 1)} \qquad 1$$

Gravitational lensing

Gravitational lensing.





$$\theta_E^2 = \frac{4GM_D}{c^2}\frac{l_{SD}}{l_{DO}l_{SO}} = 2r_{gD}\left(\frac{1}{l_{DO}} - \frac{1}{l_{SO}}\right)$$ Holstein-Einstein formula

$$\mu = \frac{\theta_I d\theta_I}{\theta_S d\theta_S} = \frac{1}{2}\left(\frac{\Delta\theta}{\theta_S} + \frac{\theta_S}{\Delta\theta}\right)$$ - intensity enhancement

$$\Delta\theta = \sqrt{\theta_S^2 + 4\theta_E^2}$$

Note, effect does not depend on the frequency of the light (blue, green, yellow, red…).

Two images appear, as a rule, in case of spherically symmetric **D.**

Macro- and micro- lensing.

(Macro)lensing

$\theta_E \sim 1''$

Kind of “galaxy on galaxy”.

Two images are resolved.

Microlensing

$\theta_E \sim 0.001''$

Kind of “star on star”.

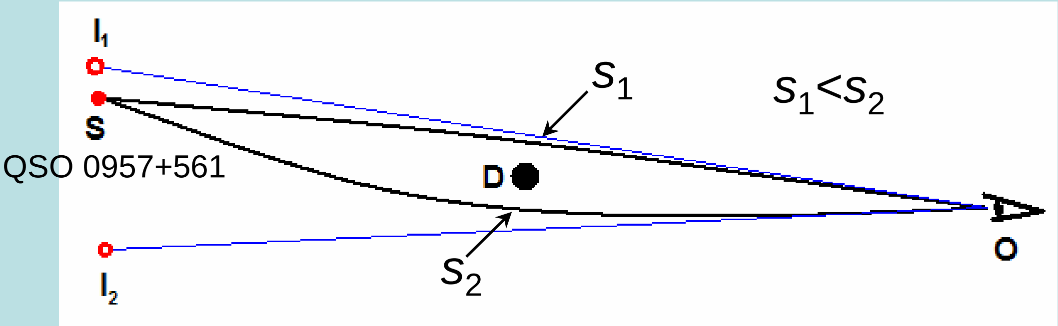
Two images are not resolved.

Gravitational lensing provides an unique tool for studying DM (the matter which does not shine but just gravitates) and, as was found out, for probing basic cosmological parameters and a new physics.

Gravitational Macro-lensing.

(Macro)lensing

+ Allows to measure Hubble constant

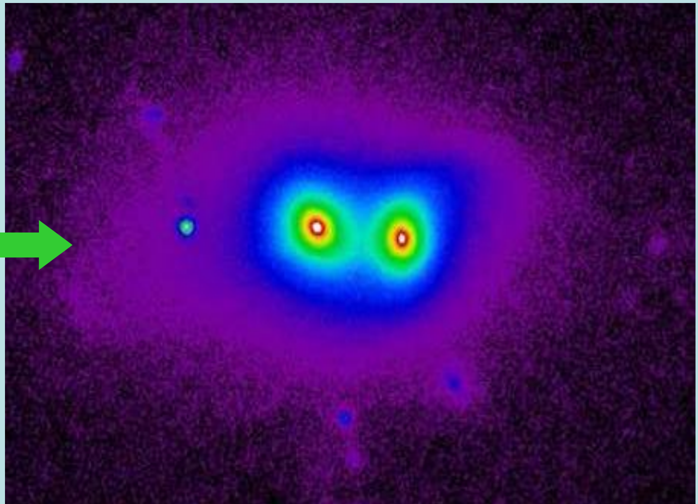


Agree with the cosmological parameters, obtained by other methods

+ Allows to measure distribution of DM in a lensing object **D** (galaxy, cluster of galaxies).

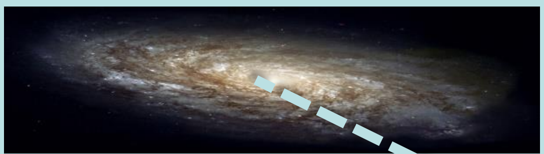
+ There were hints (not confirmed) on an observation of cosmic strings.

- L.Covi et al.: 5 pairs of similar galaxies are observed within region of the size 45''x45''.
- M.Sazhin et al.: two very similar elliptic galaxies are observed (at z=0.46).
- V.Oknyansky found several pairs of QSOs as candidates for lensed by an **Alice string**

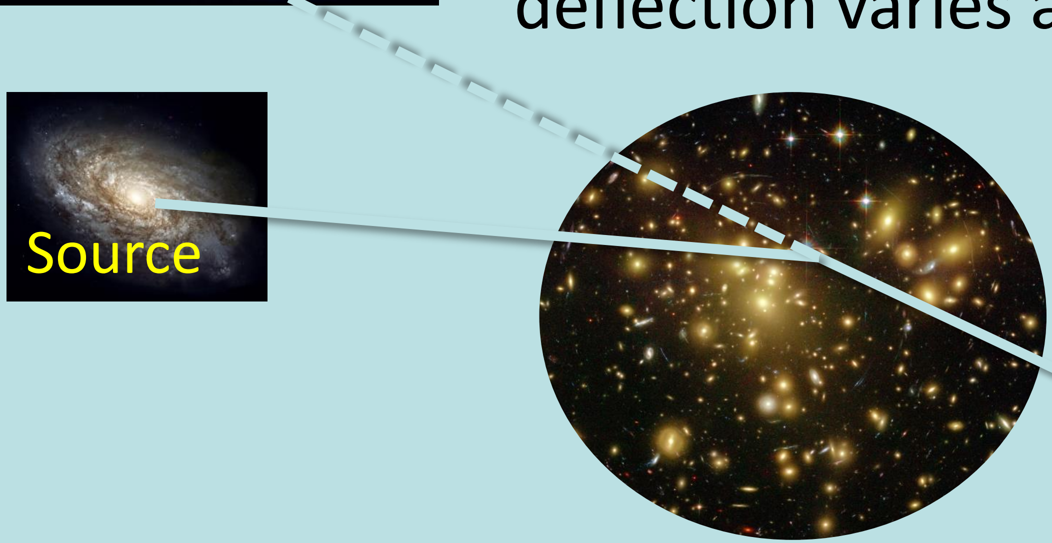


Weak Lensing

The gravity of a galaxy cluster deflects the photons of background sources that pass near it.



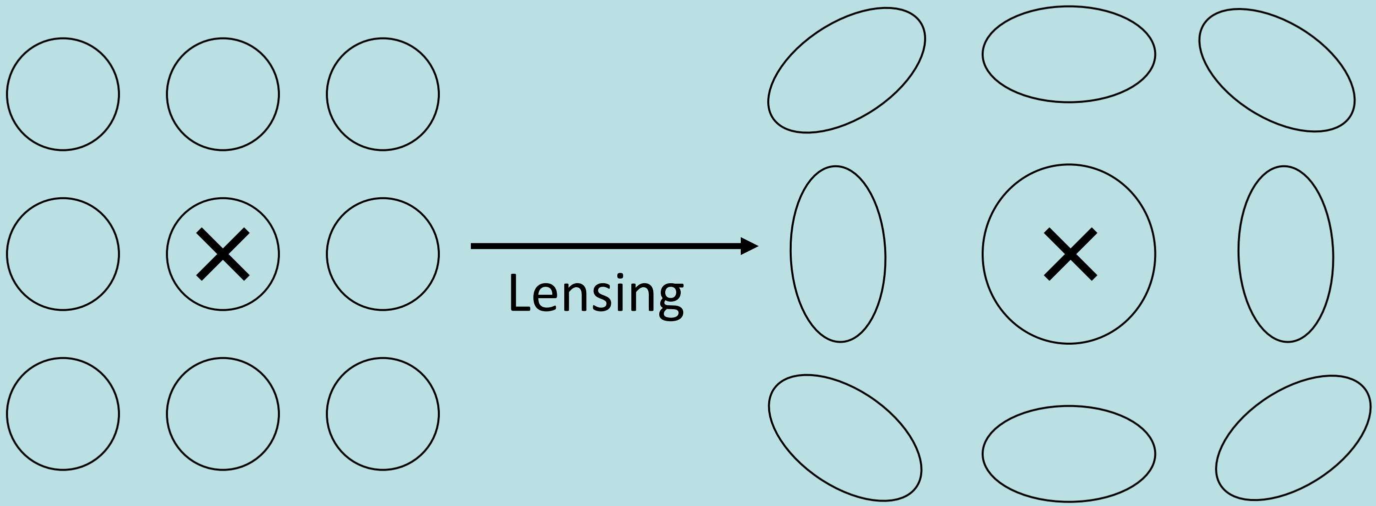
Background glaxies are not points: the deflection varies across the source.



This leads to *shearing* of the image.

Weak Lensing

We can detect *shear* statistically:

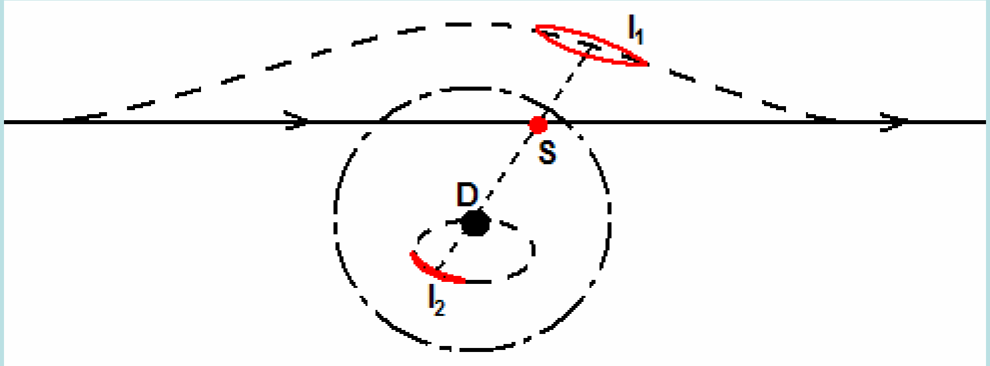


The mean tangential ellipticity of *background* galaxies around galaxy clusters depends on the cluster mass.

Gravitational microlensing.

Microlensing

Effect is registered by a change of integral intensity in time.



(in the rest frame of D)

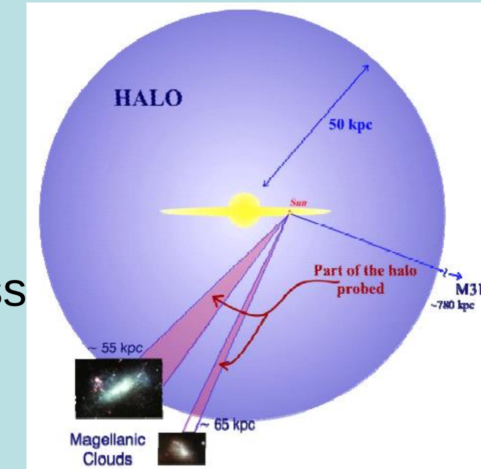
$r_E(l_{DO}$~10kpc$) = \theta_E \cdot l_{DO} \sim 10^9$ km, $\tau = r_E/v \sim$ 1-2 months.

For comparison $R_{clump}(M_{Sun}) \sim 10^{13}$ km.

MACHOs

Microlensing

Collaboration MACHO searched for facts of microlensing by observing stars (about 10^7) in LMO and M31 (during about 6 years).



The results (about 13-17 events were registered) imply an existence of **MACHOs** (Massive Astronomical Compact Halo Objects) with mass

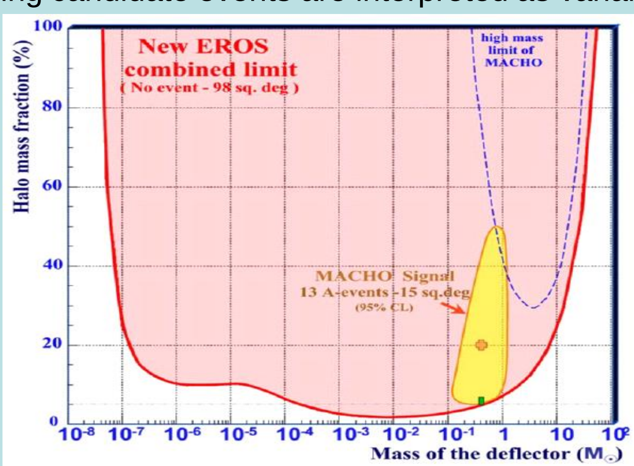
$$M \approx 0.6+0.28-0.20\ M_{Sun}$$

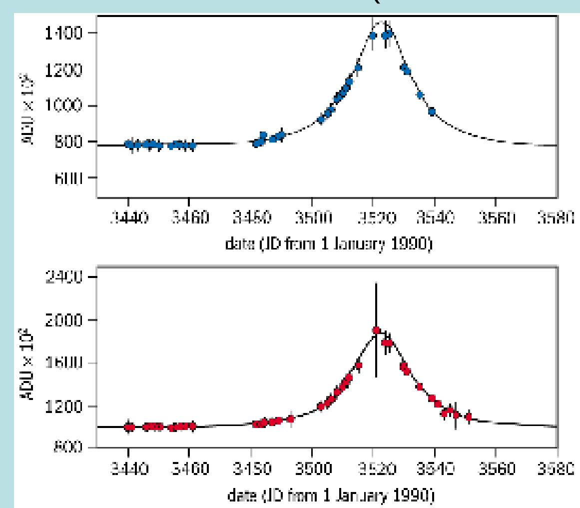
composing halo of our Galaxy in mass fraction

$$f = 0.21+0.10-0.07.$$

Re-analysis of possible background events (D – accidental ordinary stars, S – a star with unknown variability, distant SN) can reduce *f* downto 8%.

Moreover, successive experiments (EROS, OGLE) did not confirm the results of MACHO (all microlensing candidate events are interpreted as variable stars or SN).





5. Gravitational lensing.

Microlensing

Possible nature **(provided MACHO results were confirmed)**

- Red dwarfs
- White dwarfs
- Neutron stars
- Brown dwarfs
- Jupiters

} "frustrated" stars

- Compact non-baryonic (DM) objects (Mirror stars, axionic clumps…?)

Results of the MACHO (provided being confirmed) agree with cosmological estimates of *dark baryon* abundance. They can be evidences for dissipating dark matter (e.g. mirror matter), forming compact objects, but they can not provide more than 20% of dark matter in our Galaxy.

Conclusions

- Experimental searches for dark matter may have already given positive results. Experimental cosmoparticle physics has appeared, in fact!
- It is probable that no single form of dark matter can explain all the data, making us to consider the whole variety of different candidates.
- It stimulates exciting development of cosmoparticle physics.