Introduction to astroparticle physics

Part 1: Andrii Neronov

Cosmic ray physics

... direct continuation of research started by V.Hess

Gamma-ray astronomy

.... application of particle physics methods in astronomy

Gravitational waves

Neutrino physics

* neutrino oscillations
* high-energy neutrino astronomy

Dark matter physics

... direct continuation of research started by F.Zwicky

Particle physics in the Early Universe

... direct continuation of research started by Gamow

Dark matter in clusters of galaxies


Coma galaxy cluster in visible light

Galaxies are often found on the sky in groups (of ~ 10s) and clusters (of ~ 100s). Assuming that galaxies are bound by common gravitational field one could apply virial theorem also to velocity dispersion of galaxies in galaxy clusters (the exercise first done by Zwicky, see lecture 1):

$$\frac{m\sigma^2}{2} \sim \frac{G_N M m}{2R}$$

(M is the cumulative mass of galaxies in a cluster, m is the mass of individual galaxy). This gives a mass estimate

$$M \sim \frac{\sigma^2 R}{G_N} \simeq 2 \times 10^{14} M_\odot \left(\frac{\sigma}{10^3\,\frac{\mathrm{km}}{\mathrm{s}}}\right)^2 \left(\frac{R}{1\ \mathrm{Mpc}}\right)$$

This mass estimate is much larger than the sum of (estimated) masses of galaxies forming the cluster.

Average density of baryons and dark matter in the Universe is

$$\rho_b = \Omega_b \rho_0 \simeq 0.05 \times 10^{-29}\,\frac{\mathrm{g}}{\mathrm{cm}^3}; \quad \rho_{dm} = (\Omega_m - \Omega_b)\rho_0 \simeq 0.25 \times 10^{-29}\,\frac{\mathrm{g}}{\mathrm{cm}^3}$$

This is much lower than the density of (mostly dark) matter in galaxy clusters:

$$\rho \sim \frac{M}{R^3} \simeq 10^{-26}\,\frac{\mathrm{g}}{\mathrm{cm}^3}$$

Galaxies and galaxy clusters are large “overdensities” in matter distribution, formed in result of gravitational collapse of inhomogeneities of matter distribution and accretion of dark matter and baryons onto the collapsed inhomogeneities.

Hot gas in galaxy clusters

The virial theorem applied to gas which might have been accreted onto galaxy clusters tells that

$$\frac{3}{2}T \sim \frac{m_p\sigma^2}{2} \sim \frac{G_N M m_p}{2R}$$

The gas should have temperature

$$T \sim \frac{G_N M m_p}{3R} \simeq 2\times 10^7 \left(\frac{M}{10^{14}M_\odot}\right)\left(\frac{R}{1\ \mathrm{Mpc}}\right)^{-1}\ \mathrm{K}$$

Such hot gas is expected to "glow" in X-rays ($k_B T \sim 2$ keV). This X-ray glow is observed.

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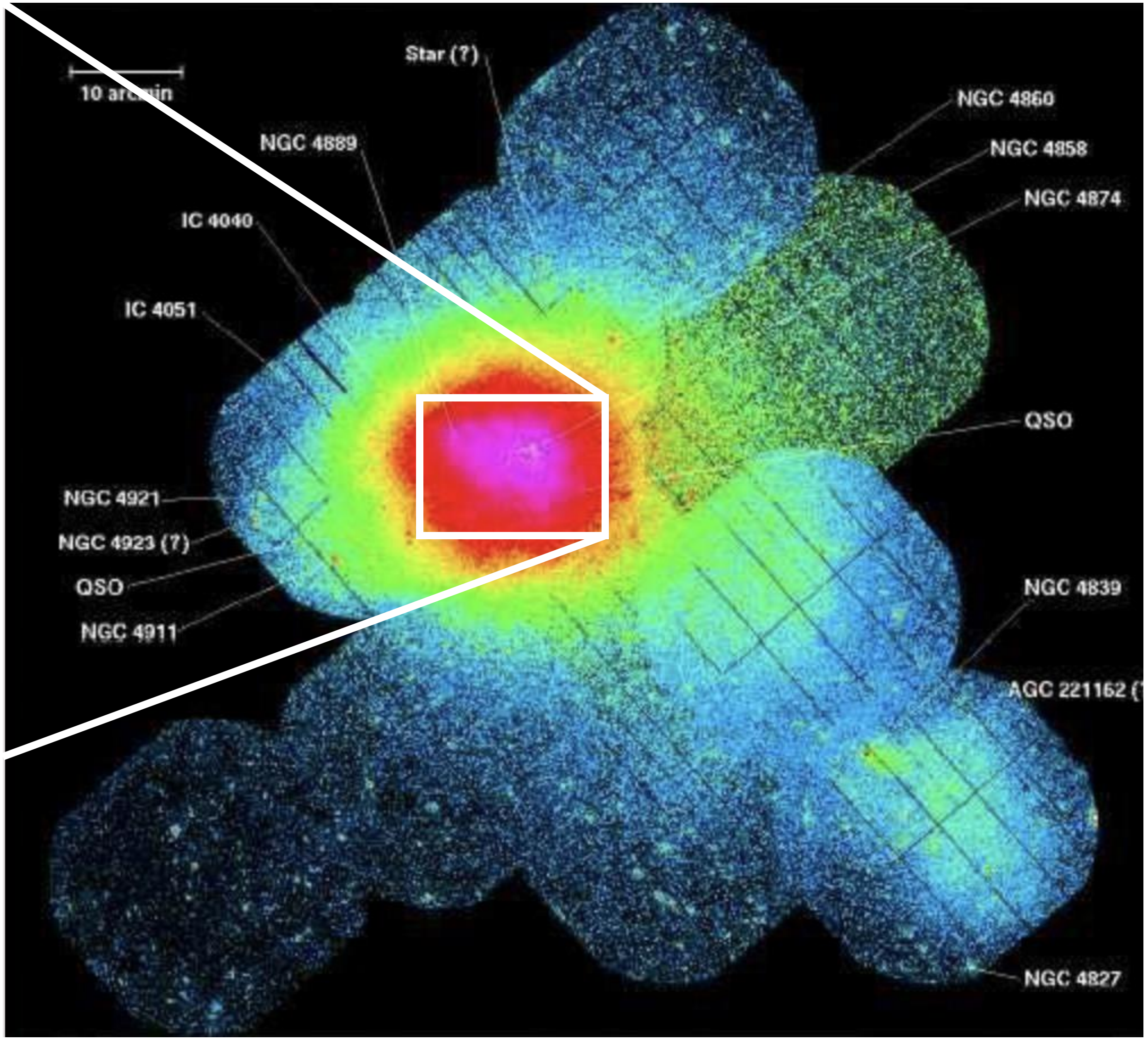


Coma galaxy cluster in X-rays (XMM-Newton "mosaic" image

Dark matter in galaxy clusters

Measurements of distribution of hot gas provide a complementary evidence for the presence of the dark matter. Hydrostatic equilibrium equation for the hot gas:

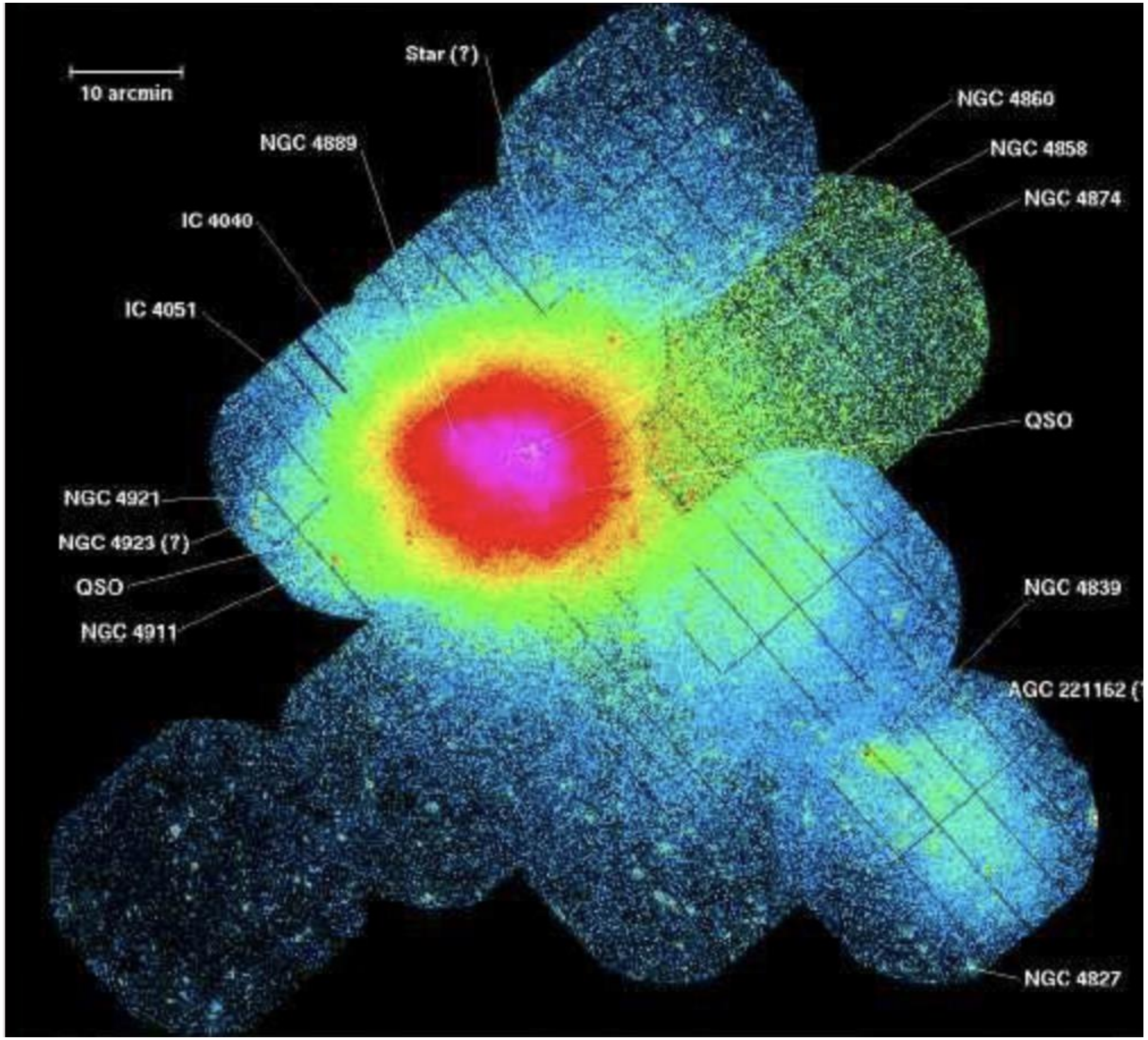
$$\frac{dP}{dr} = \frac{G_N M \rho_{gas}}{r^2}$$

$$P = \left(\frac{\rho_{gas}}{m_p}\right) T_{gas}$$

$$\frac{1}{m_p} \frac{d(\rho_{gas} T_{gas})}{dr} = \frac{G_N M \rho_{gas}}{r^2}$$

$$M(r) = \frac{1}{G_N m_p} \frac{r^2}{\rho_{gas}(r)} \frac{d(\rho_{gas} T_{gas})}{dr}$$

Measurements of radial profile of intensity of X-ray emission (proportional to ρ_{gas}^2) and the emission spectrum (which depends on the temperature T_{gas}) provide measurements of the mass profiles of galaxy clusters $M(r)$. Total mass of the intracluster gas is typically 10 times larger than that of galaxies in the cluster, but it is much smaller than the total mass (dominated by the dark matter).



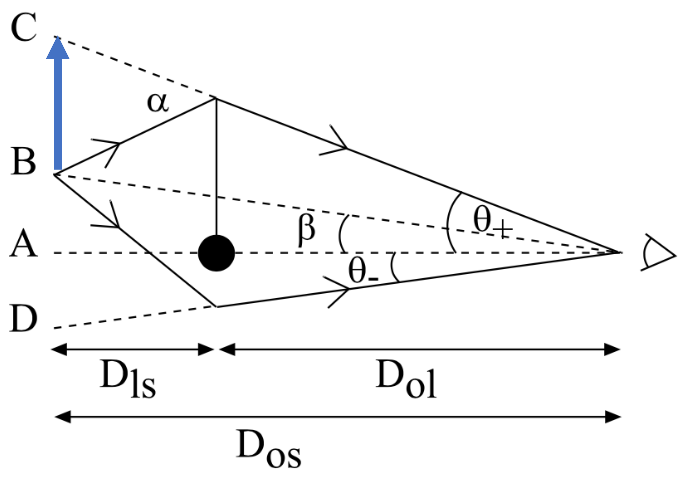
Coma galaxy cluster in X-rays (XMM-Newton “mosaic” image

Gravitational lensing

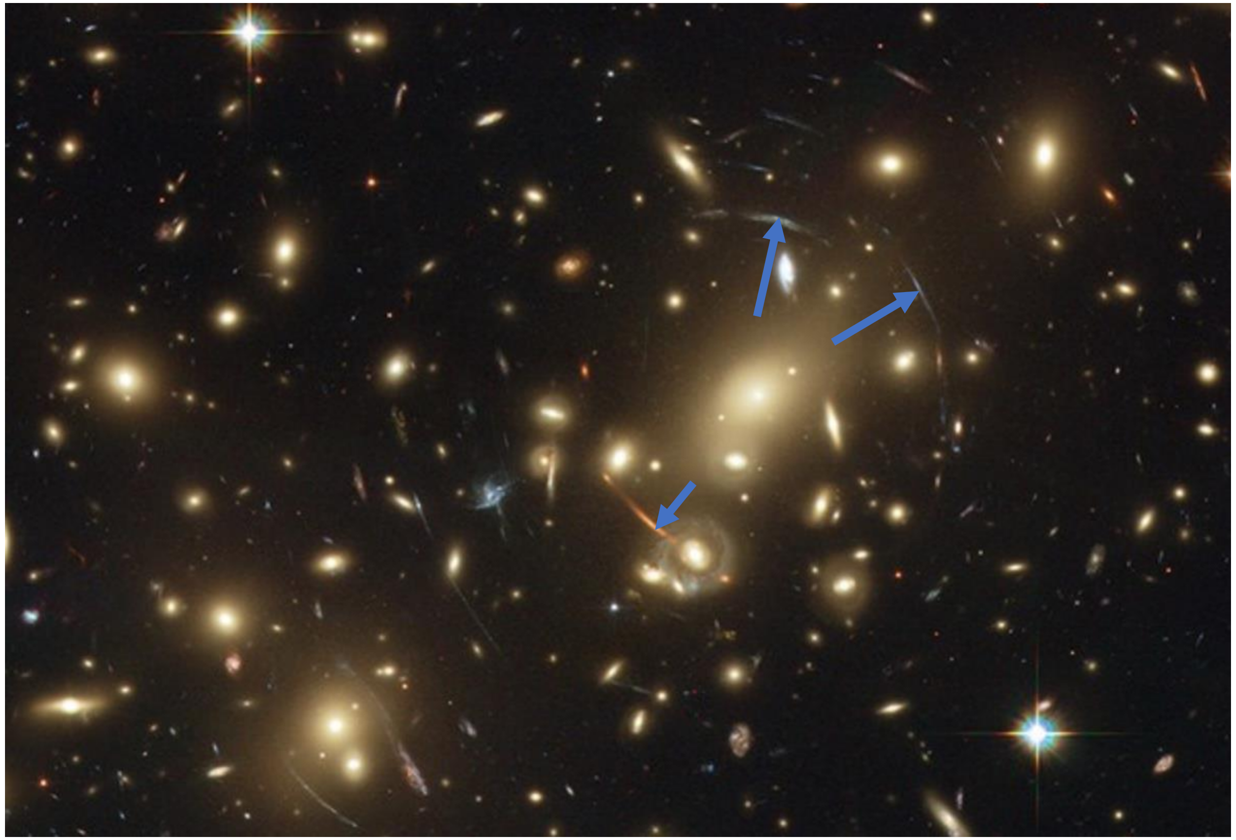
Still one more complementary measurement of the mass of a galaxy cluster is obtained via observation of the effect of gravitational lensing. A mass M deflects light passing at the impact distance d by an angle

$$\alpha = \frac{4G_N M}{c^2 d} \simeq 4'' \left(\frac{M}{10^{14} M_\odot}\right)\left(\frac{d}{1\text{ Mpc}}\right)$$

(a result from General relativity theory). Images of background galaxy B behind galaxy clusters is displaced to the direction C away from the cluster center (direction toward A). Radial displacement also leads to "stretching" of the images in azimuthal direction.

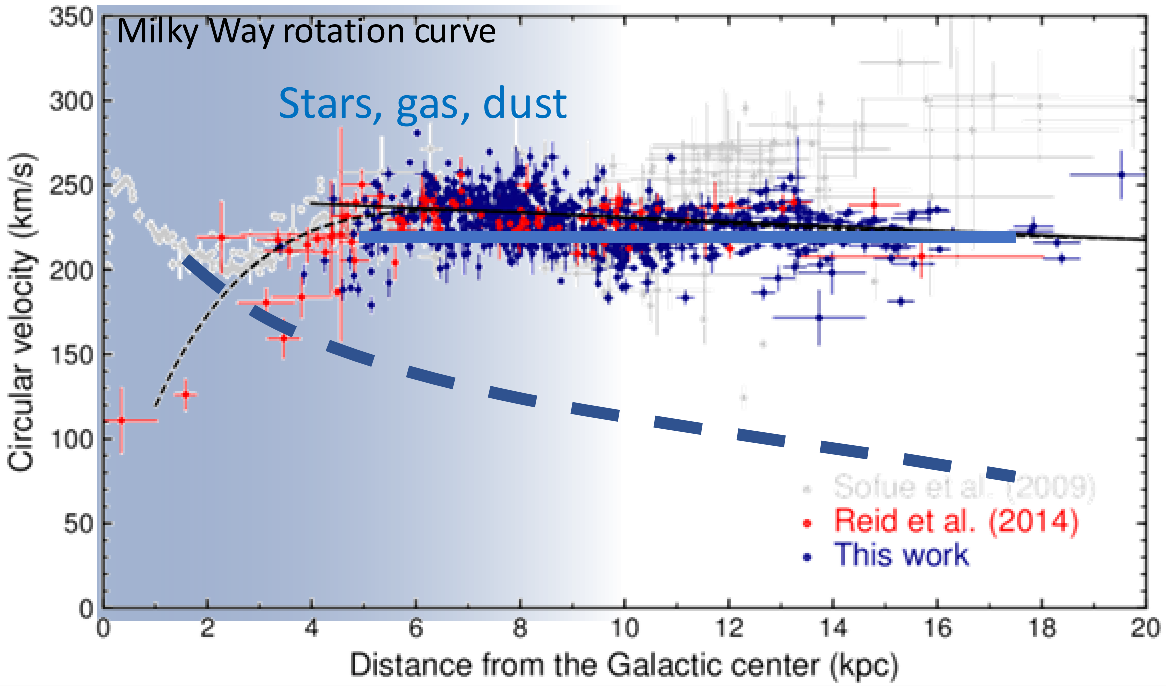


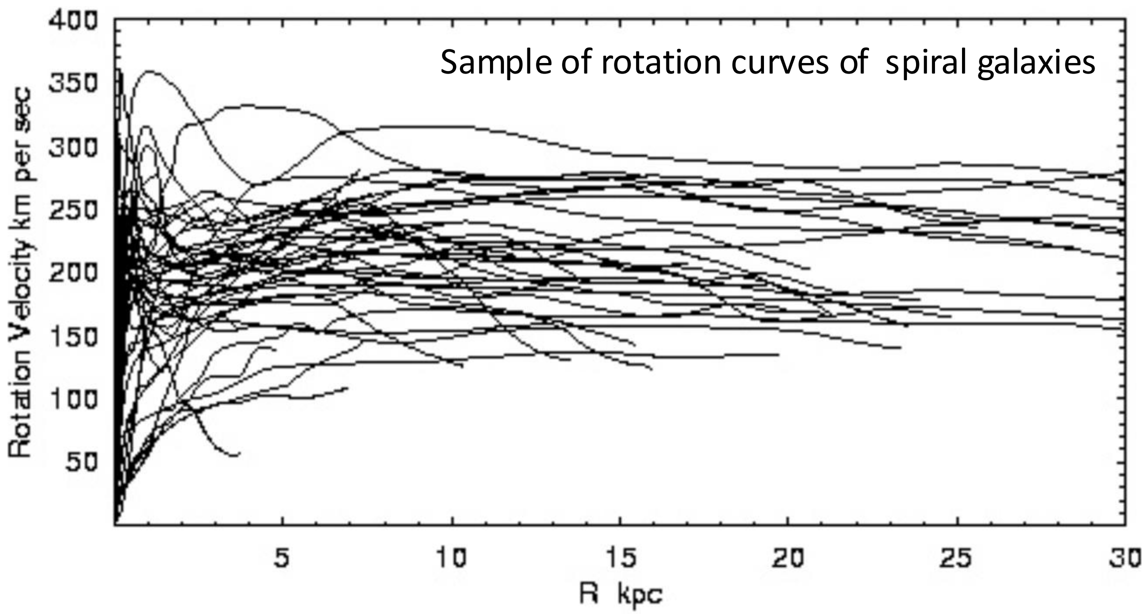
Measurement of the scale of displacement and shear of background galaxy images as a function of distance from the cluster center provides a measurement of $M(r)$.



Visible band image of a galaxy cluster revealing a gravitational lensing effect

Dark matter in the Milky Way and other galaxies





Matter content of disk galaxies can be measured from their rotation pattern

$$m\ \vec{a} = \vec{F}$$

$$\frac{mv^2}{r} = \frac{G_N M(r) m}{r^2}$$

$$v(r) = \sqrt{\frac{G_N M(r)}{r}}$$

Measurements of rotation velocity of a galaxy as a function of distance from its center give mass profile $M(r)$. Outside the galaxy, the rotation velocity is expected to decrease as $r^{-1/2}$.

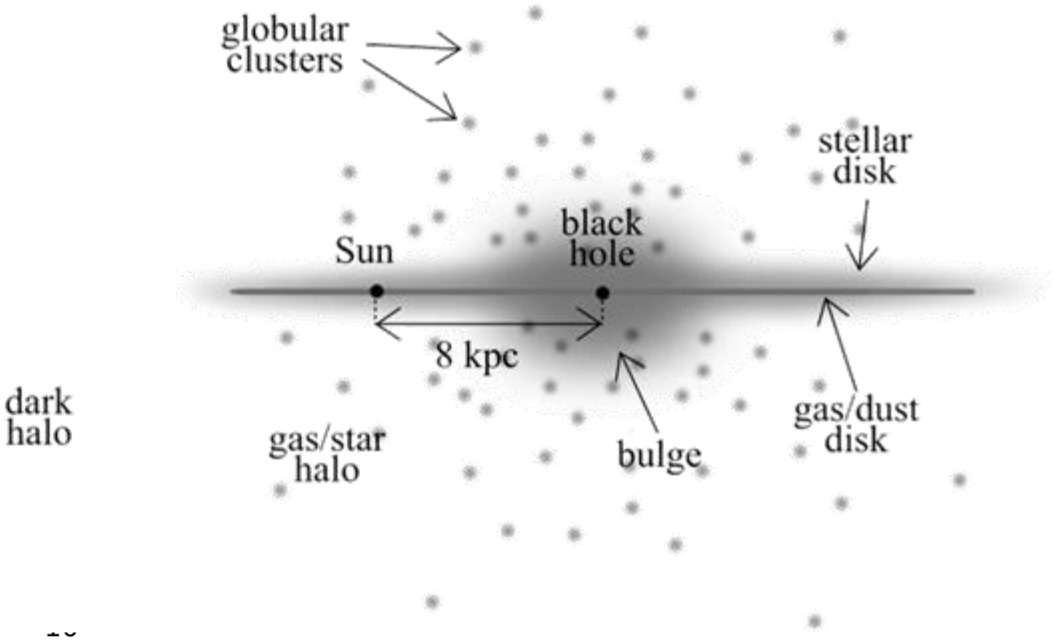
This is not what is observed e.g. in the Milky Way. Instead, its rotation velocity stays approximately at the same level, $v \sim 230\ \mathrm{km/s}$ all the way up to $\sim 30\ \mathrm{kpc}$ from the center.

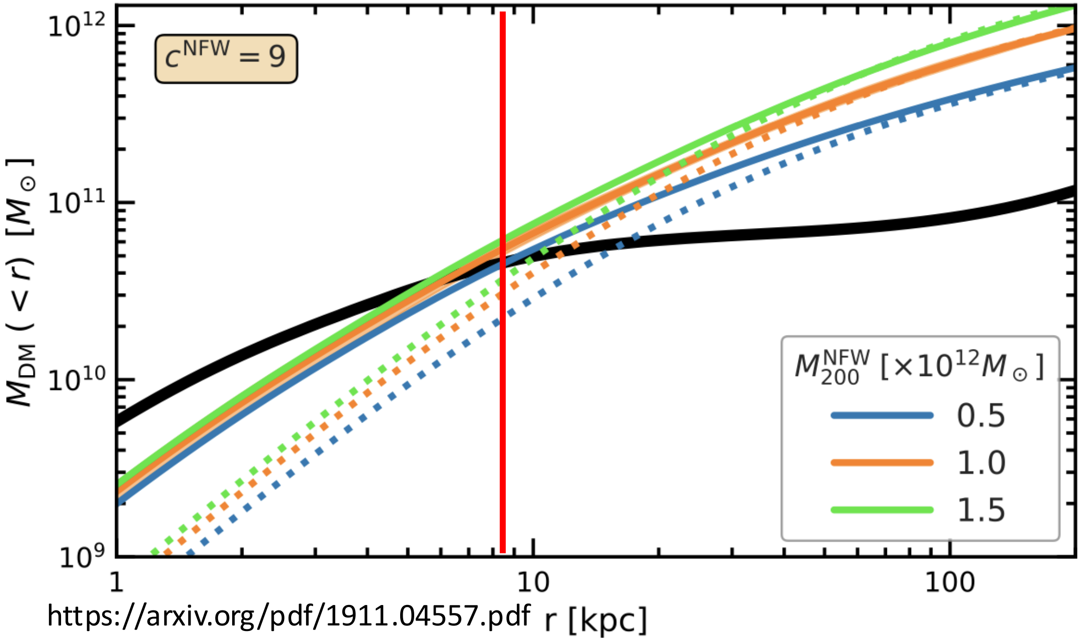
This suggest that the mass grows as $M \propto r$, but there is no visible matter at such large distances. The density of stellar disk decreases exponentially beyond $r_* \simeq 4\ \mathrm{kpc}$ distance

$$\rho_*(r) \propto e^{-\frac{r}{r_*}}$$

The same mass growth $M \propto r$ is observed in most of other spiral galaxies. The rotation curves remain flat well beyond the visible matter distribution.

Dark matter in the Milky Way





https://arxiv.org/pdf/1911.04557.pdf

Numerical models of formation of galaxies suggest a range of analytical approximations for the radial profiles of dark matter halos, such as Navarro Frenk White (NFW):

$$n(r) = \frac{n_0}{\frac{r}{r_0}\left(1 + \left(\frac{r}{r_0}\right)^2\right)}$$

with a characteristic scale r_0 and density n_0 that can be constrained by observations. The NFW dark matter density profile has a "spike" at $r \to 0$, that is difficult to confirm or disprove observationally, as in the central part of the galaxy, the dominant contribution to the mass comes from conventional matter.

Close to the solar distance (8 kpc from the Galactic Center), the density of the dark and conventional (baryonic) matter are comparable,

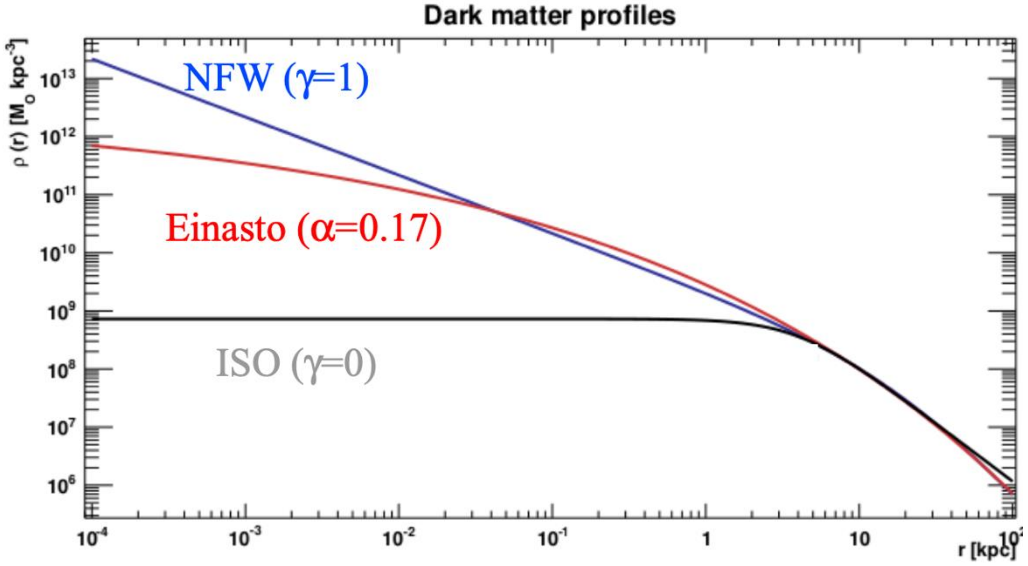
$$\rho_{dm} \sim \rho_b \sim 0.3\frac{\mathrm{GeV}}{\mathrm{cm}^3}; \quad n_{dm} = \frac{\rho_{dm}}{M} \simeq 0.03\left[\frac{M}{10\ \mathrm{GeV}}\right]^{-1}\frac{1}{\mathrm{cm}^3}$$

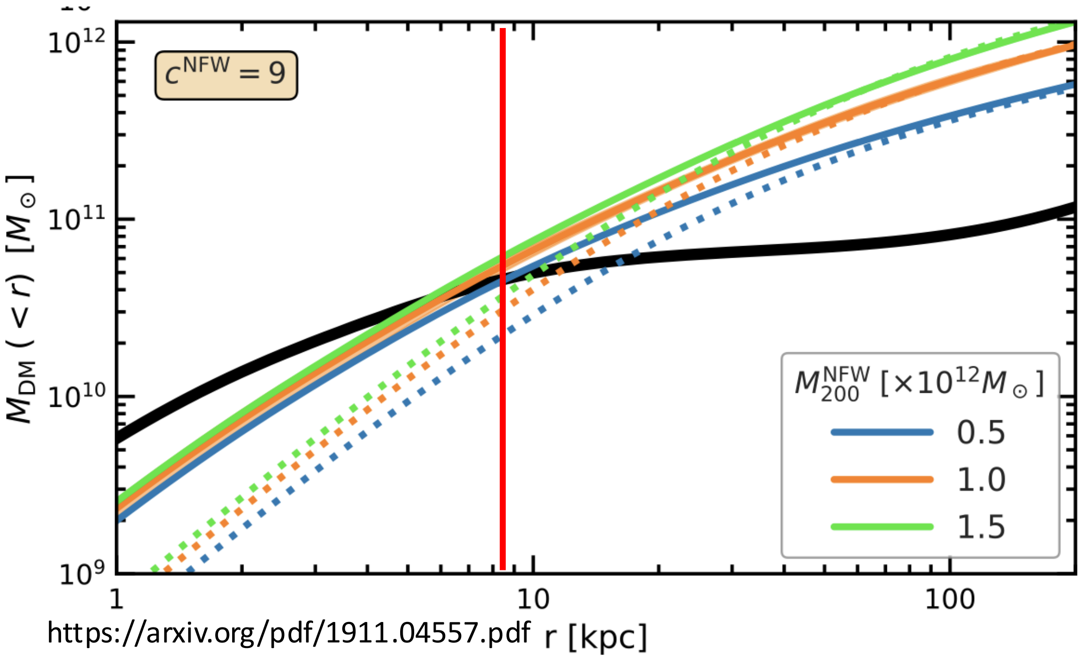
Dark matter particles residing in the Milky Way halo form a virialized gas:

$$E_k = \frac{Mv^2}{2} \sim \frac{G_N M_{tot}(r) M}{2r} = \frac{E_p}{2}$$

$$v \sim \sqrt{\frac{G_N M_{tot}(r)}{r}}$$

Dark matter in the Milky Way





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For each dark matter particle, the time between subsequent interactions is

$$t_{int} = \frac{1}{\sigma v n_{dm}}$$

The rate of interactions per unit volume is thus

$$\frac{n_{dm}}{t_{int}} = \sigma v n_{dm}^2$$

If the density profile of the dark matter has a "spike" in the center (as in the NFW profile), the volume interaction rate increases as r^{-2} as $r \to 0$.

Interactions of the dark matter particles (annihilation, decay) produce conventional Standard Model particles, like in the Early Universe:

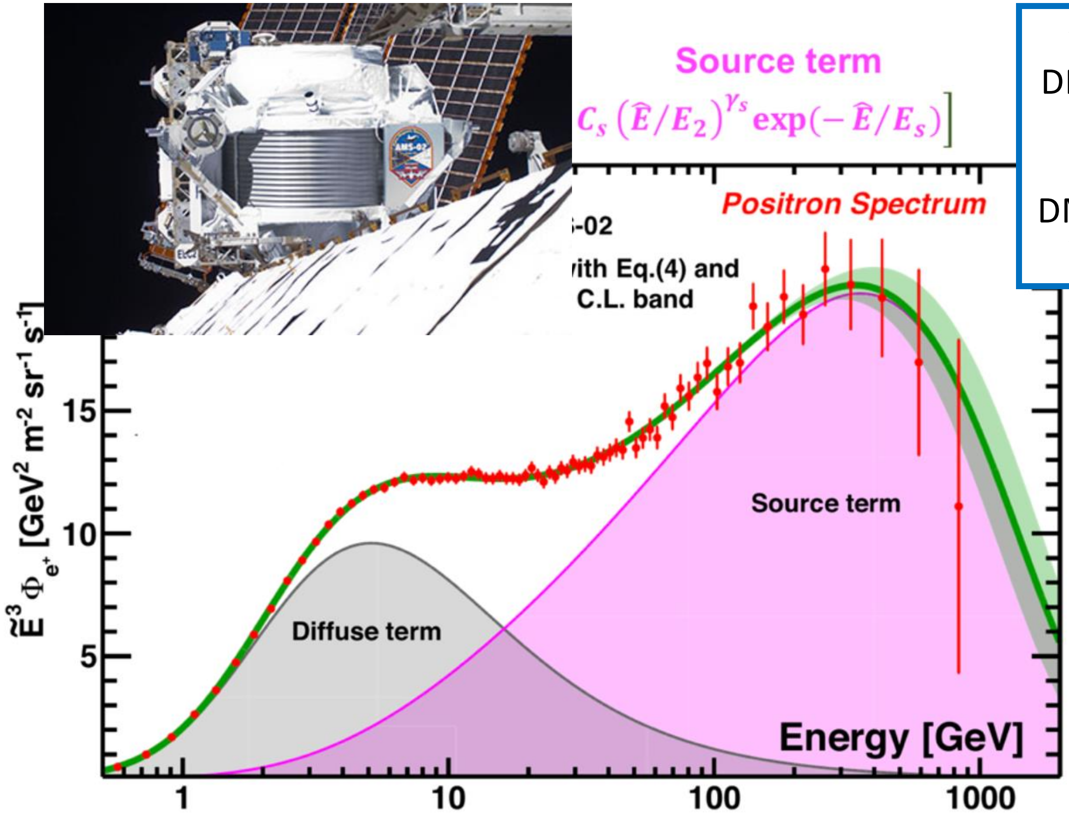
$$DM + DM \to SM + SM$$
$$DM + DM \to q + \overline{q};\ \ q \to hadrons \to \gamma,$$
$$DM + DM \to e^+ + e^-;\ \ \ e^{\pm} \to \gamma$$
$$DM + DM \to \gamma + \gamma$$

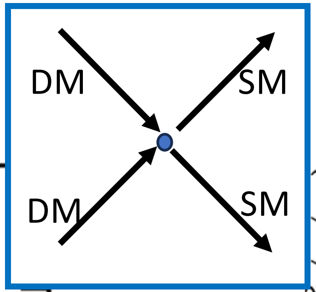
… … … … . .

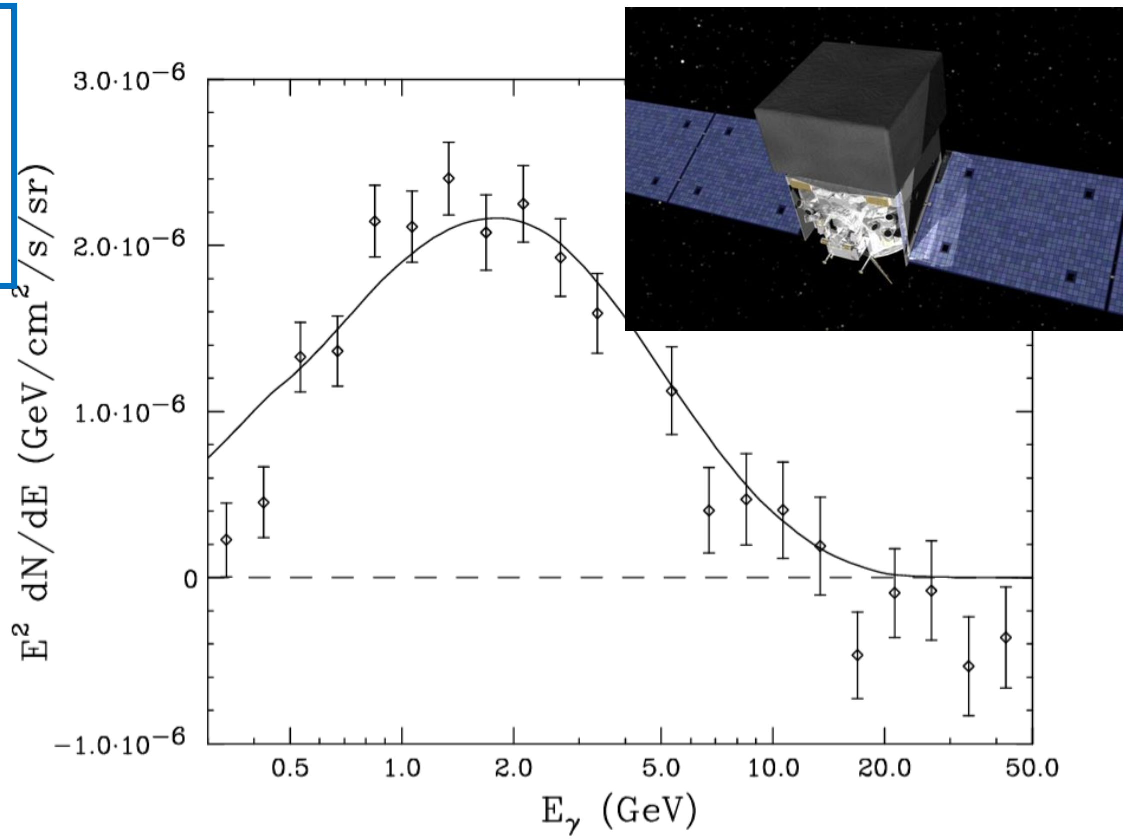
Such interactions convert the rest energy of the dark matter particles into the energy of conventional particles that are detectable with telescopes and particle detectors. The volume luminosity of the Milky Way due to this process is

$$l(r) = 2\,M \frac{n_{dm}}{t_{int}} = \frac{\sigma v \rho_{dm}^2(r)}{M} \propto \frac{1}{r^2}$$

“Indirect detection” of dark matter in the Milky Way?







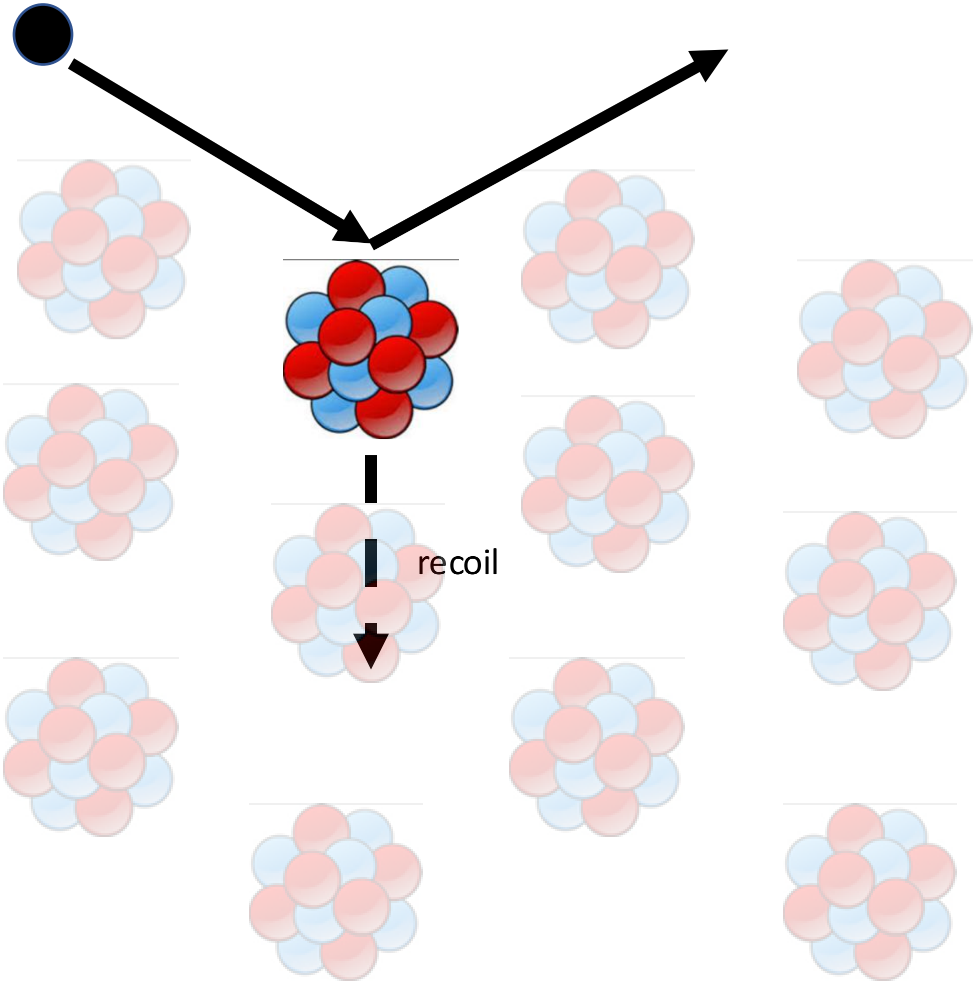
Spectrum of positrons measured by the AMS-02 experiment at the International Space Station

“Excess” gamma-ray flux from the direction of the Galactic Center found in the data of Fermi Large Area Telescope.

Signal from dark matter annihilation / decay may appear as an “anomaly” or “excess” on top of conventional singals measured by detectors of cosmic ray particles (for example, positrons), or telescopes (for example, gamma-ray).

There exists a range of such unexplained “anomalies” in the cosmic ray detector, gamma-ray and X-ray telescope measurements. None of them can currently be unambiguously related to the dark matter: viable alternative explanations involving conventional (astro)physics exist.

Dark matter "direct detection" experiments



Close to the solar distance, the density of the dark and conventional (baryonic) matter are comparable,

$$\rho_{DM} \sim \rho_b \sim 0.3\,\frac{\text{GeV}}{\text{cm}^3}$$

The density of dark matter particles, such as WIMPs of the masses m in the GeV-TeV range is

$$n_{DM} = \frac{\rho_{DM}}{m} \simeq 0.3\left[\frac{m_{DM}}{1\text{ GeV}}\right]^{-1}\frac{1}{\text{cm}^3}$$

These particles are available everywhere (pass through every laboratory setup with velocities $v \sim \sqrt{G_N\, M/r} \sim 230\text{ km/s}$.

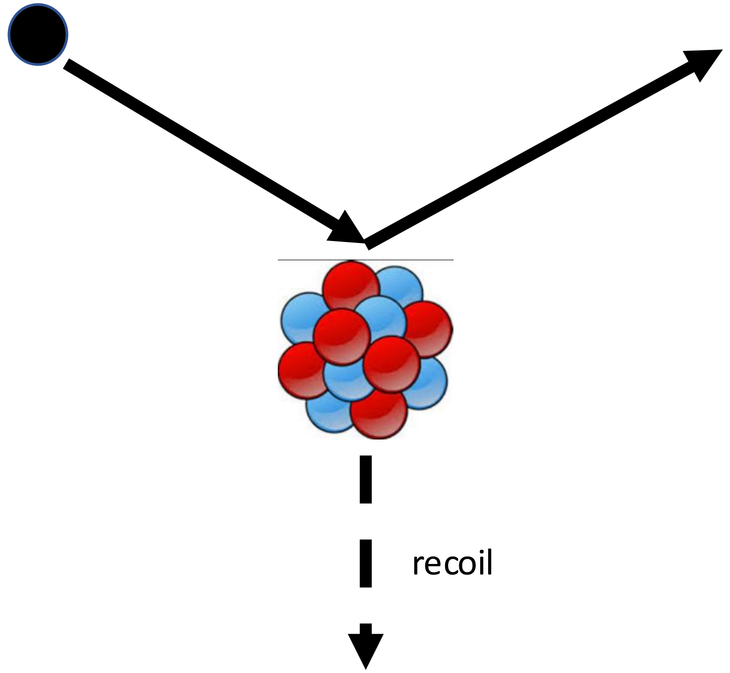
Their kinetic energy is

$$E_{DM} \sim \frac{m_{DM}v^2}{2} \simeq 0.3\left[\frac{m_{DM}}{1\text{ GeV}}\right]\text{ keV}$$

If the dark matter particles occasionally collide with atomic nuclei (or electrons?) they might deposit "recoil" energy up to E_{DM} in detector material.

This energy deposition can be measured.

Dark matter “direct detection” experiments



The kinetic energy of the dark matter particles is

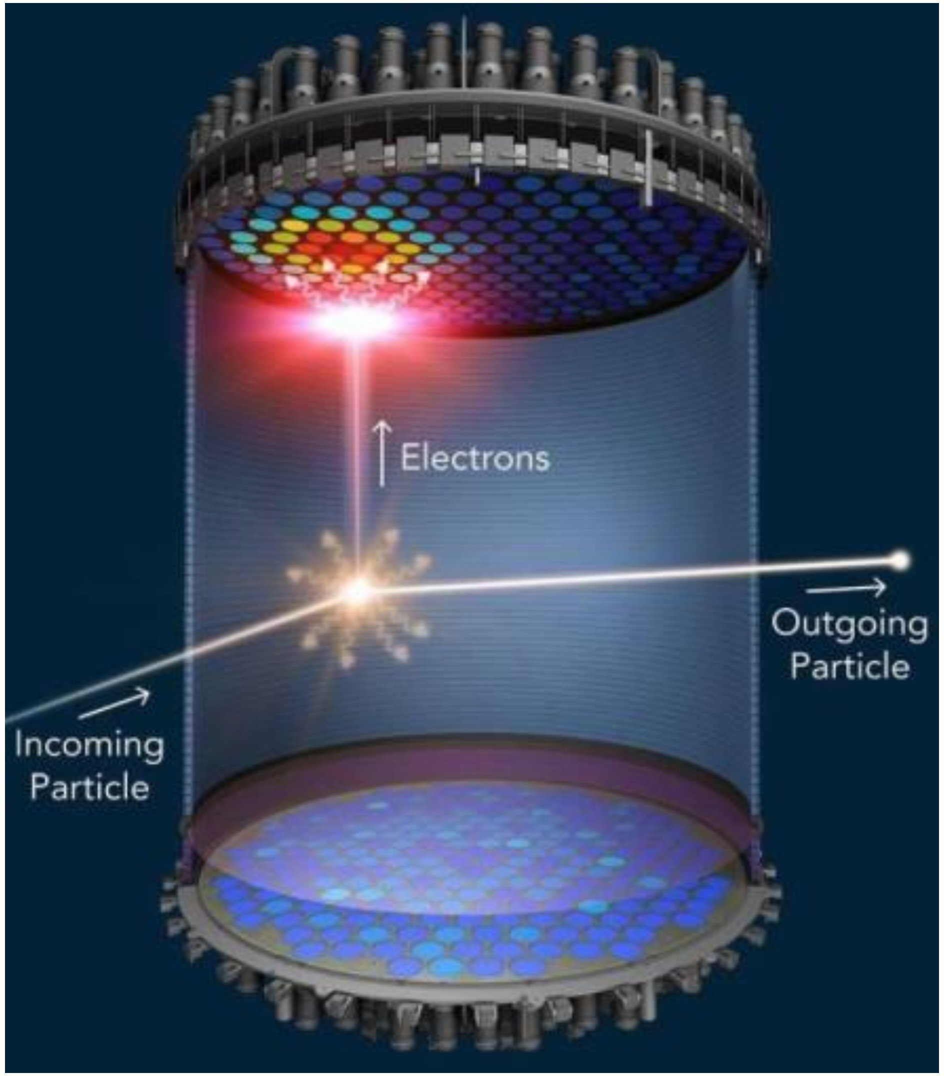
$$E_{dm} \sim \frac{m_{DM} v^2}{2} \simeq 0.3 \left[\frac{m_{DM}}{1 \text{ GeV}}\right] \text{ keV}$$

If the dark matter particles occasionally collide with atomic nuclei (or electrons?) they might deposit “recoil” energy up to E_{DM} in detector material.

This energy deposition can be measured. It is larger than ionisation energy of atoms.

- Dark matter interactions can excite atomic levels. De-exciting atoms would emit detectable **light** pulses.
- Dark matter interactions can produce free charges (e.g. electron-hole pairs in semiconductors). Free charges can be sampled as **current** pulses, if voltage is applied to detector.
- Dark matter interaction can heat the detector causing slight increase in its **temperature**.

Dark matter "direct detection" experiments



XENON experiment for "direct" search of dark matter particles (WIMPs)

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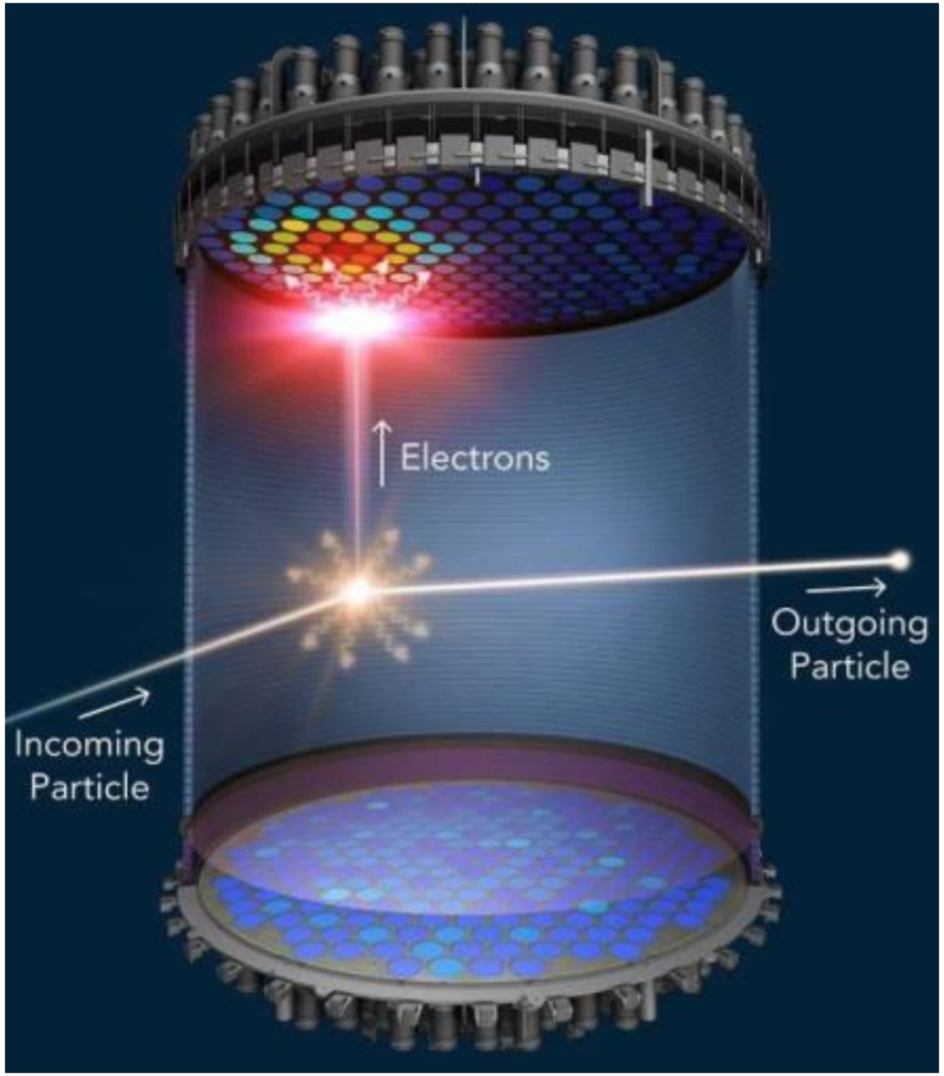
Similar (or larger) energy deposits can be created by interactions of *any* particles (with sufficient energy) with the detector. Dark matter detectors are typically situated deep underground, to reduce the level of conventional particle interactions in the detector (mostly secondary cosmic ray particles and natural radioactivity)

Sampling of many types of signals simultaneously (e.g. light+current pulse) allows to get better identification of the particle which has deposited energy in the detector.

Dark matter “direct detection” experiments



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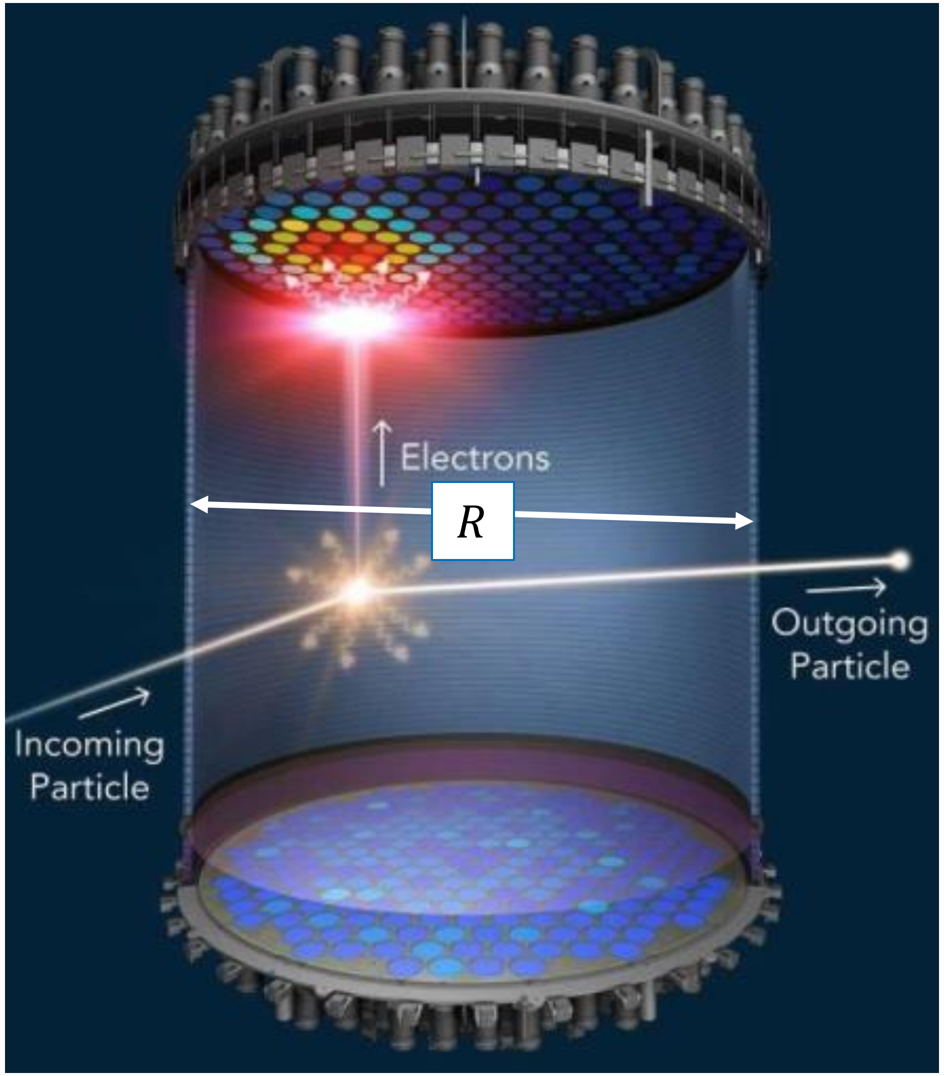
Example: noble liquid + gas “Time Projection Chambers” (TPC).

A dark matter particle interacting in liquid xenon excites Xe_2 molecule. De-excitation leads to emission of photon which is sampled by photomultipliers surrounding the detection barrel.

Dark matter interaction also liberates an electron, which starts to drift upwards through xenon liquid, if high voltage (thousands of volts) is applied in vertical direction.

Electron reaching fluid-gas xenon interface gets accelerated by the high voltage and creates an avalanche of electrons in the gaseous phase. This produces current pulse on the cathode.

Dark matter "direct detection" experiments



XENON experiment for "direct" search of dark matter particles (WIMPs)

Dark matter flux through the detector:

$$F = \frac{\rho_{dm}}{m_{dm}} v_{dm}$$

Number of particles passing through the detector per unit time

$$\frac{dN_{dm}}{dt} = FR^2 = \frac{\rho_{dm}}{m_{dm}} v_{dm} R^2$$

Mean free path of dark matter particles

$$\lambda = \frac{1}{\sigma_{dm-det}\, n_{det}}$$

Probability for a dark matter particle to interact inside the detector

$$p = \frac{R}{\lambda}$$

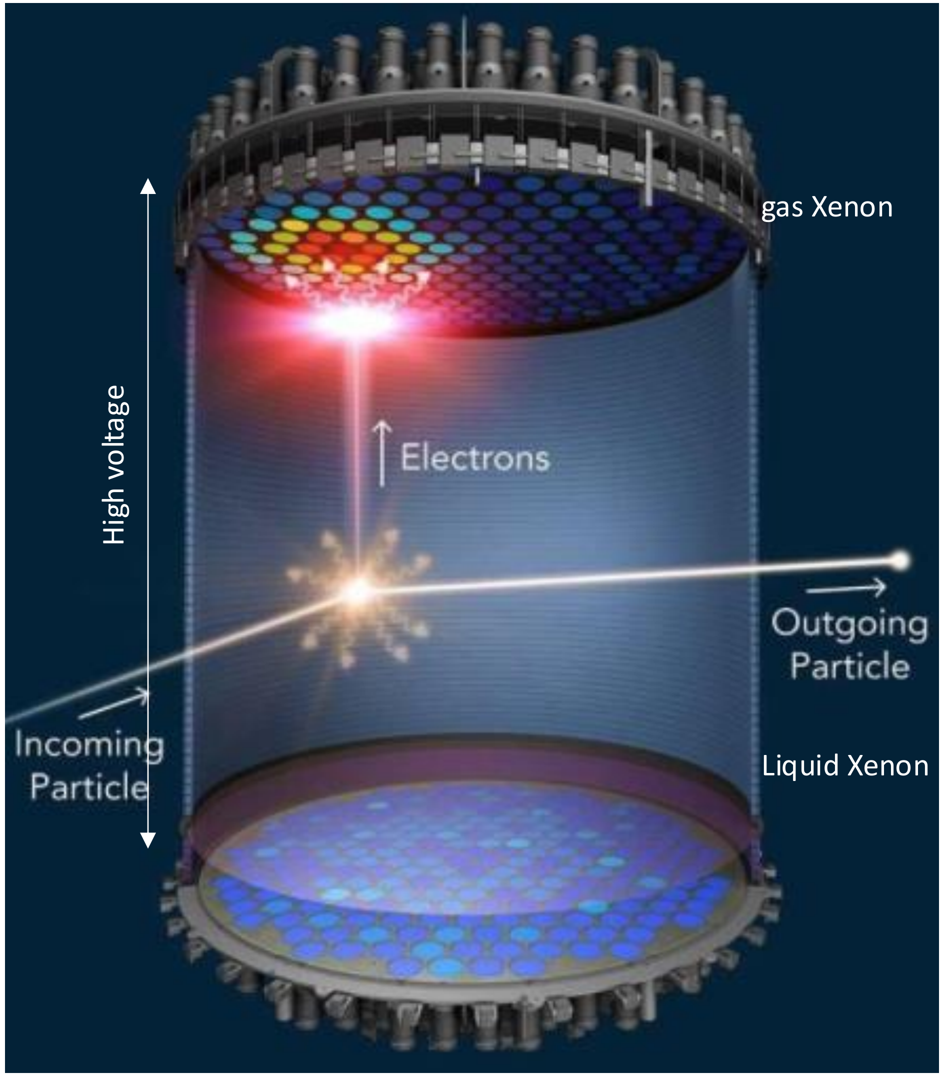
Number of dark matter particles interacting in the detector per unit time

$$\frac{dN_{int}}{dt} = p\frac{dN_{dm}}{dt} = \frac{\rho_{dm}}{m_{dm}} v_{dm} \sigma_{dm-det}\; n_{det}\, R^3$$

Number of detected events within exposure T

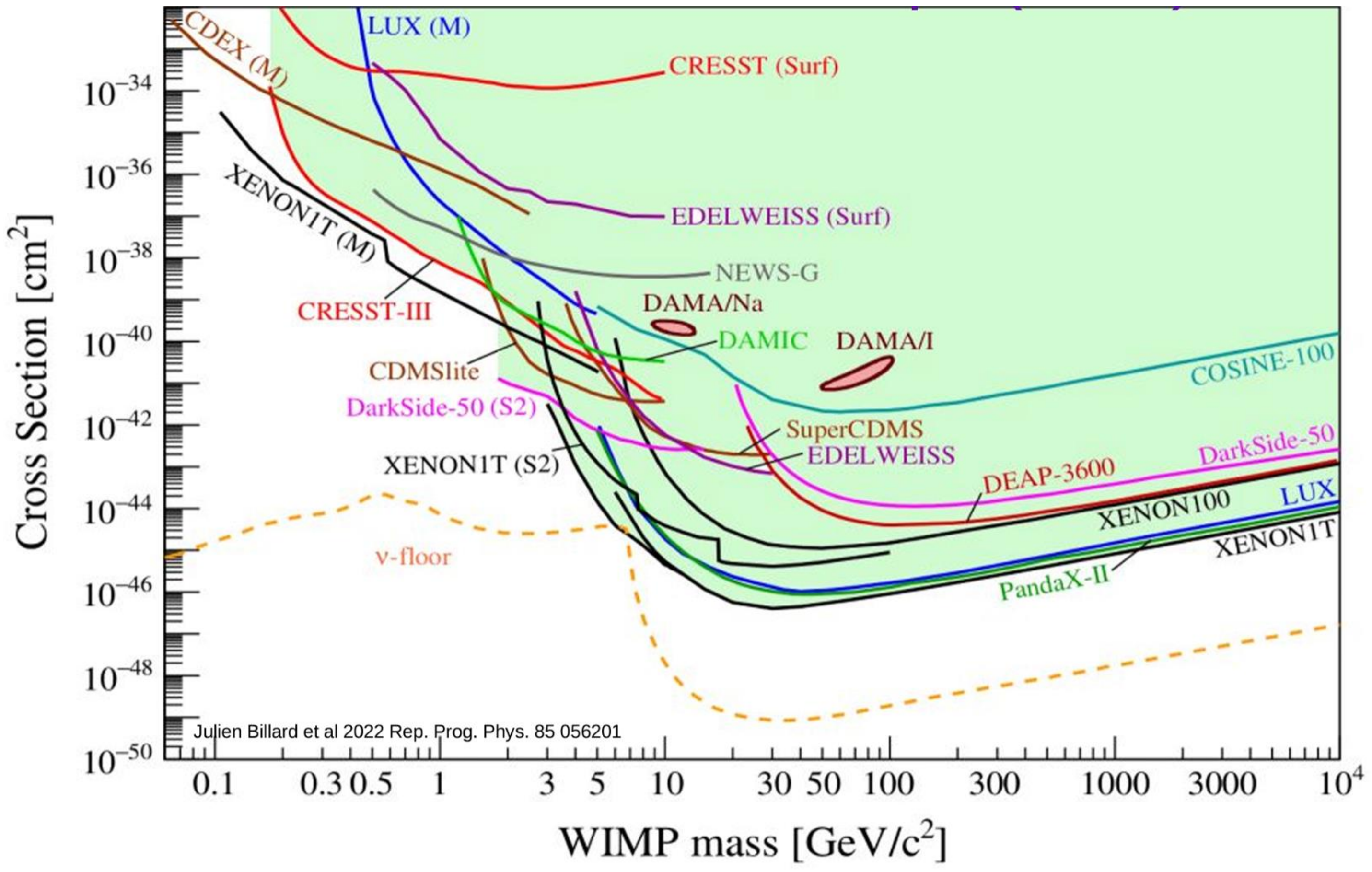
$$N_{int} = \frac{\rho_{dm}}{m_{dm}} \sigma_{det-dm} v_{dm} \frac{M_{det} T}{m_p}$$

Limits on WIMP cross-section

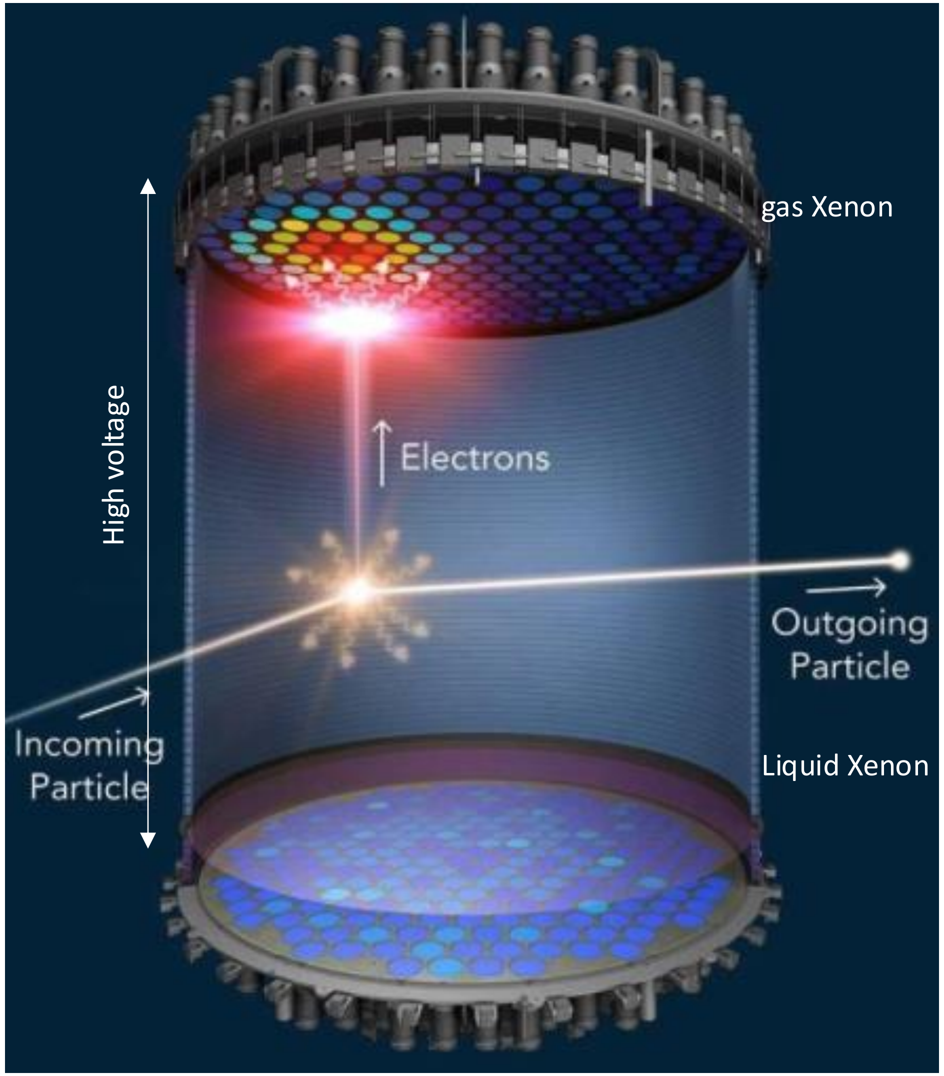


XENON experiment for "direct" search of dark matter particles (WIMPs). "Time projection chamber"

Up to now, no unambiguous signature of dark matter interactions in numerous dark matter detectors has been found. Negative search results imply that WIMP interactions in detectors are rare. This suggests that the WIMP-nuclei interaction cross-section σ_{dm-N} is very small (smaller than certain mass-dependent upper limit).

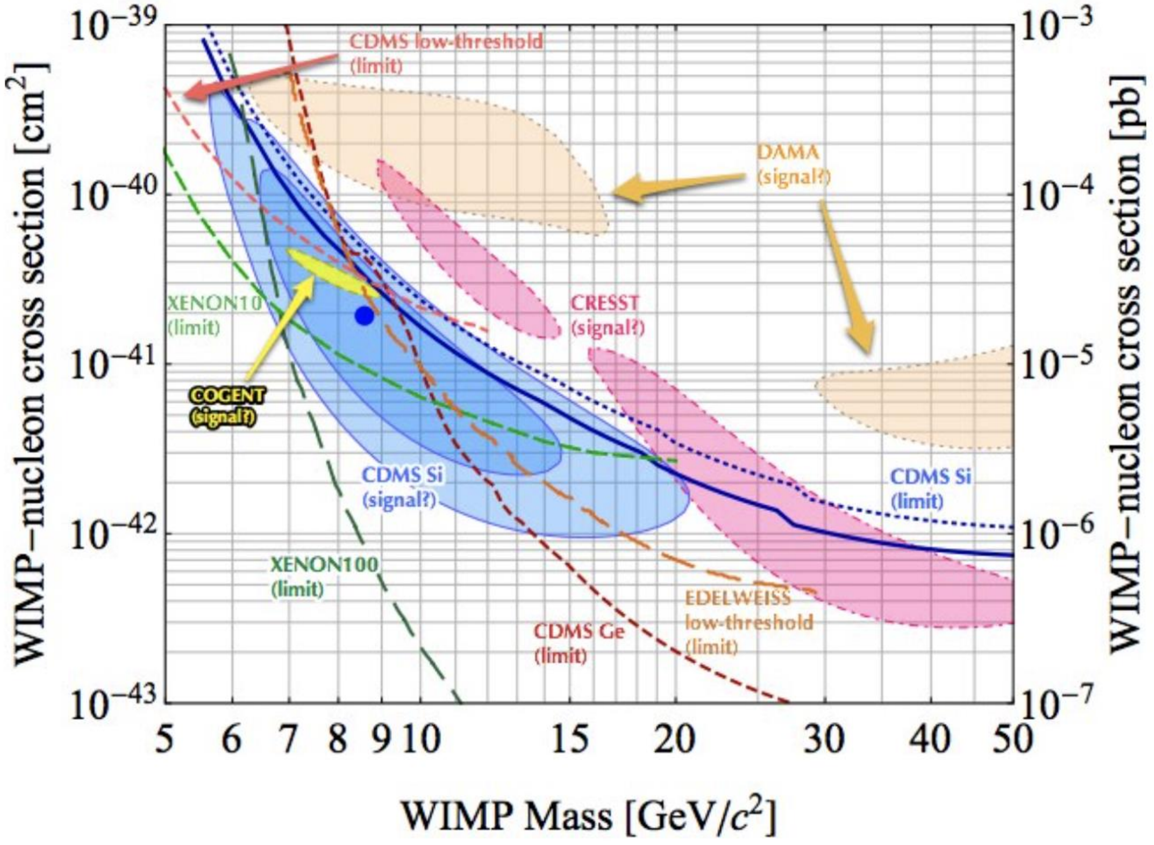


Limits on WIMP cross-section



XENON experiment for "direct" search of dark matter particles (WIMPs). "Time projection chamber"

A number of experiments finds evidence for the signal, either in the form of candidate "events", or in the form of annual modulation of the event rate.

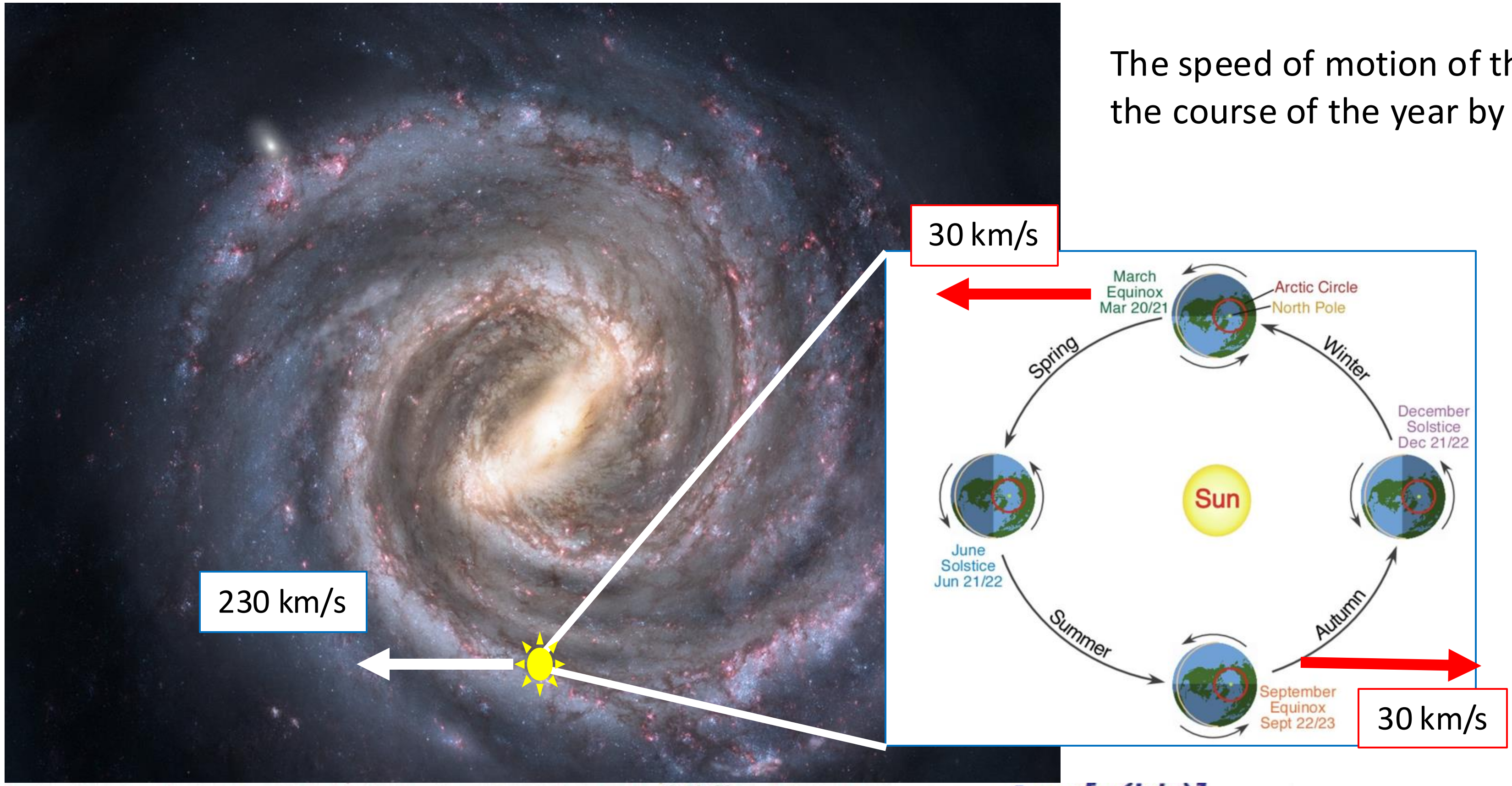


Annual modulation effect

Solar system moves through the dark matter halo,
The Earth moves around the Sun.

The speed of motion of the Earth through the dark matter halo varies in the course of the year by

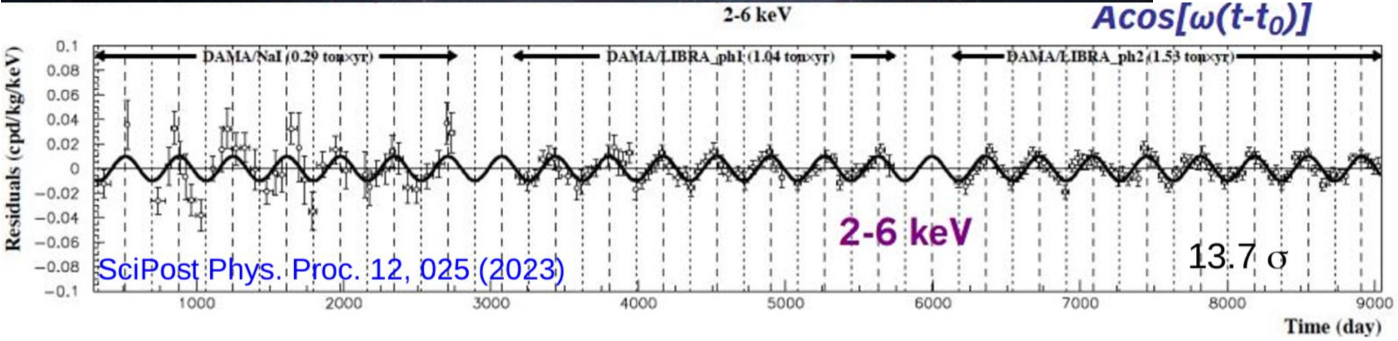
$$\frac{\delta v}{v} \simeq \frac{30\,\frac{\text{km}}{\text{s}}}{230\,\frac{\text{km}}{\text{s}}} \simeq 13\%$$

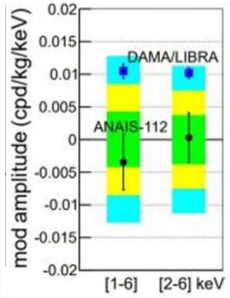


The flux of the dark matter through the detector also varies by $\pm 13\%$.

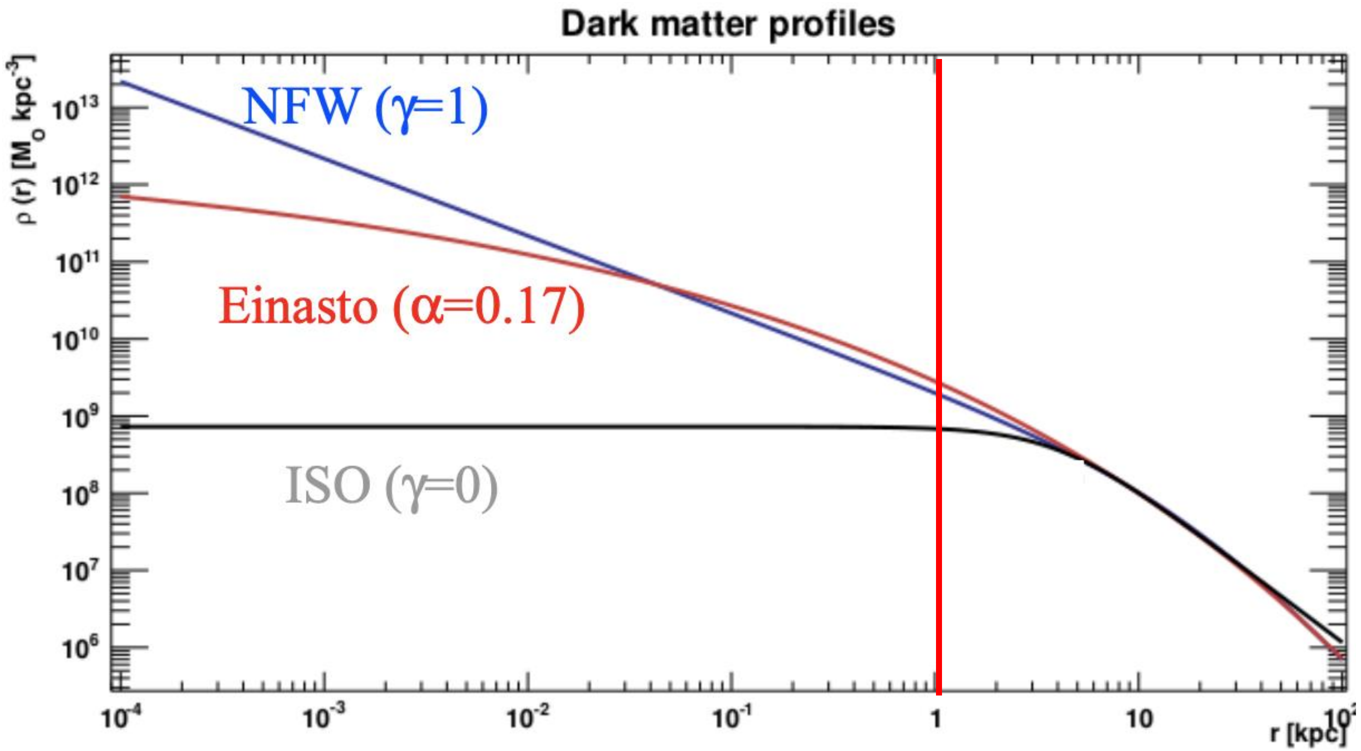
The rate of dark-matter induced nuclear recoil events varies by $\pm 13\%$ with one year period.

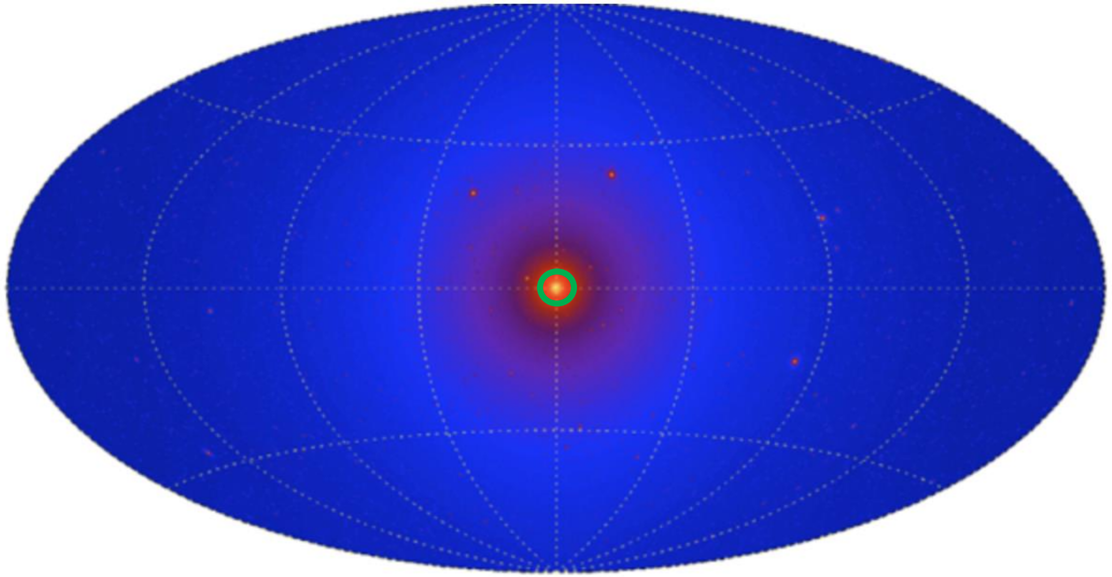
This effect is, in principle, detectable.
DAMA experiment has claimed such a detection in the past. However, DAMA results have not been reproduced by other experiments.





Exercise: dark matter annihilation in the Galactic Center





Estimate the expected WIMP dark matter annihilation flux from a region(s) of 1 pc, 10 pc, 1 kpc around the Galactic Center (assume that all annihilation goes through a channel $\chi + \bar{\chi} \rightarrow \gamma + \gamma$).

The Sun is at the distance 8 kpc from the Galactic Center.