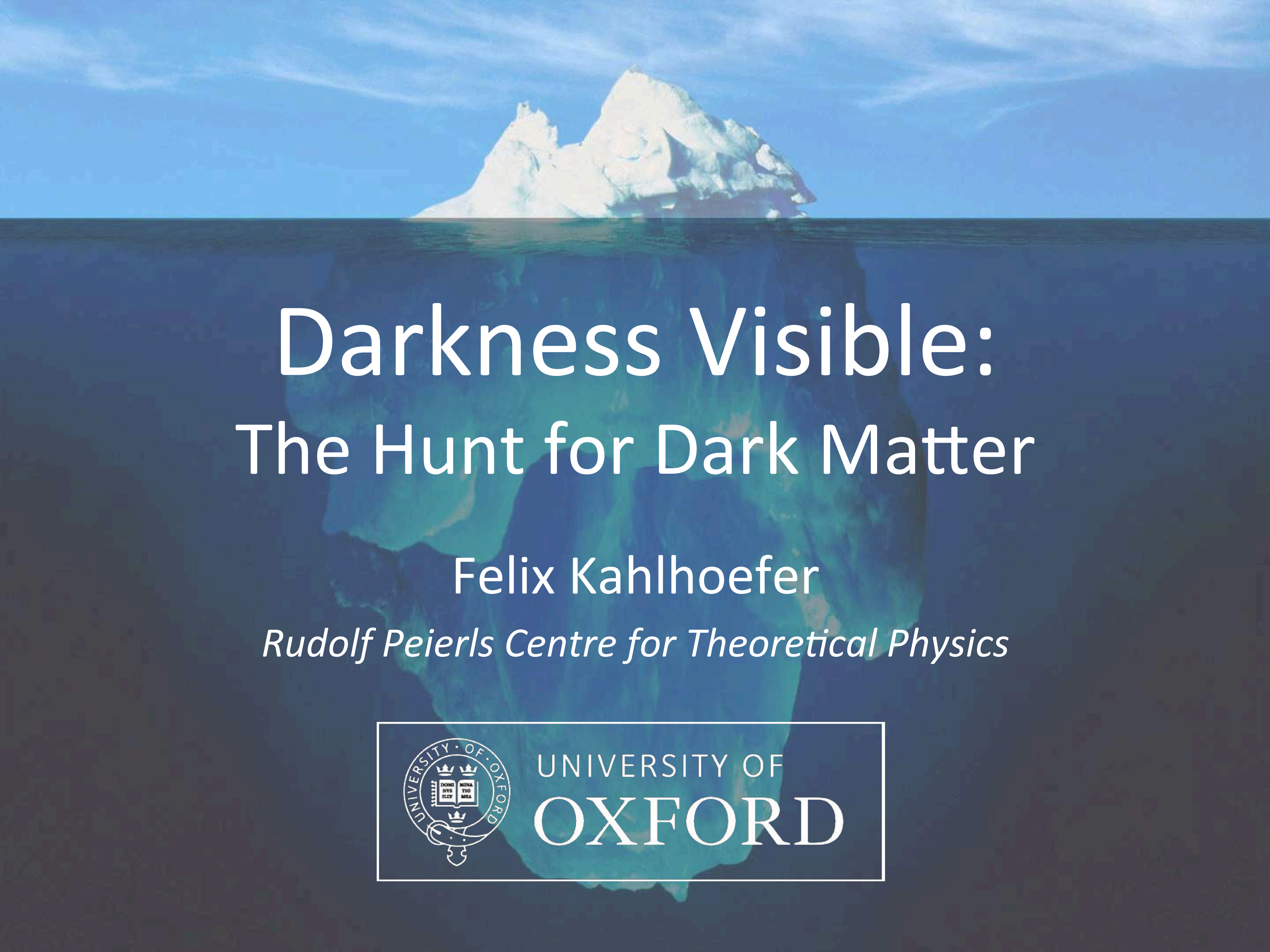

Darkness Visible:

The Hunt for Dark Matter

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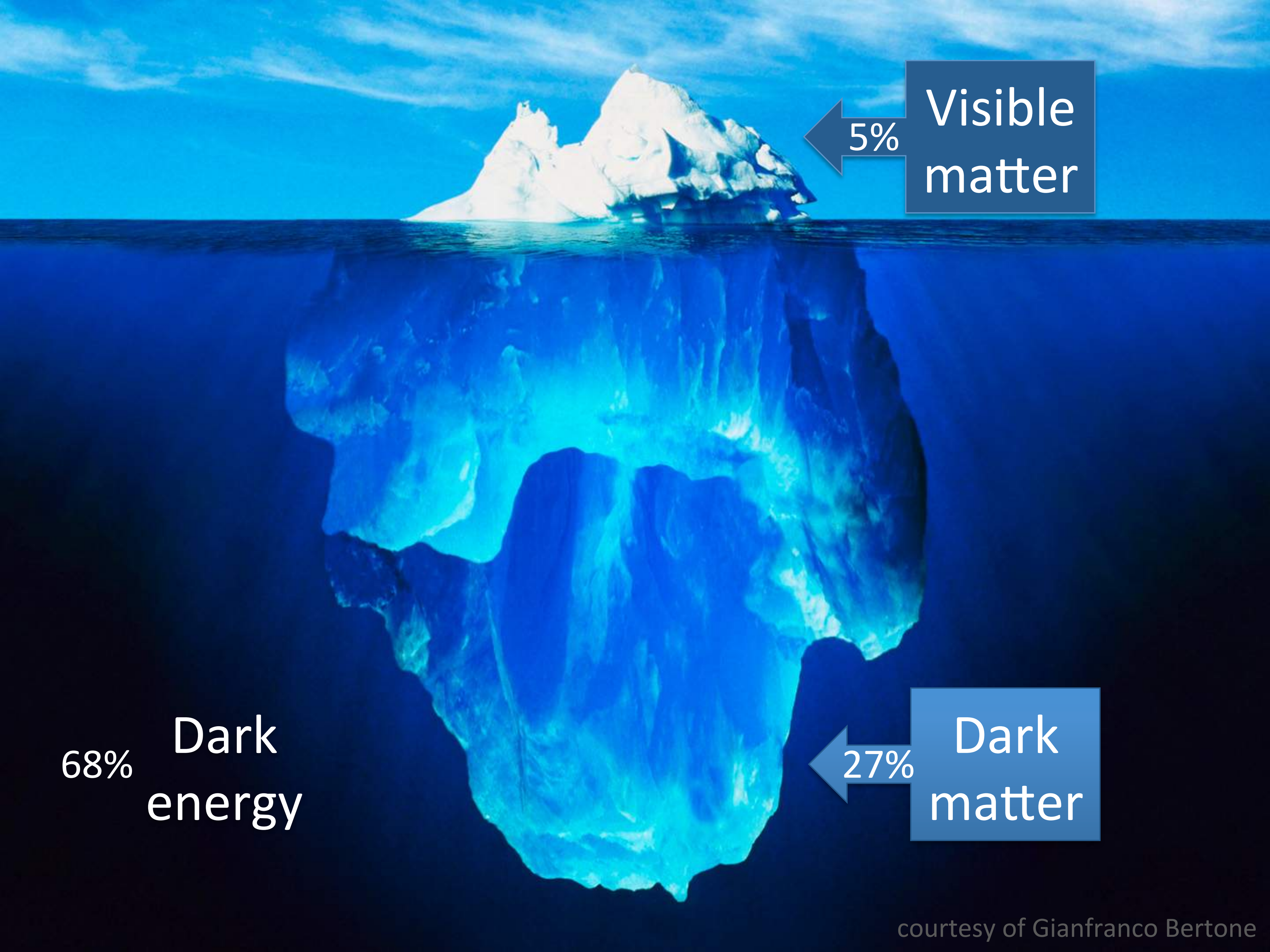


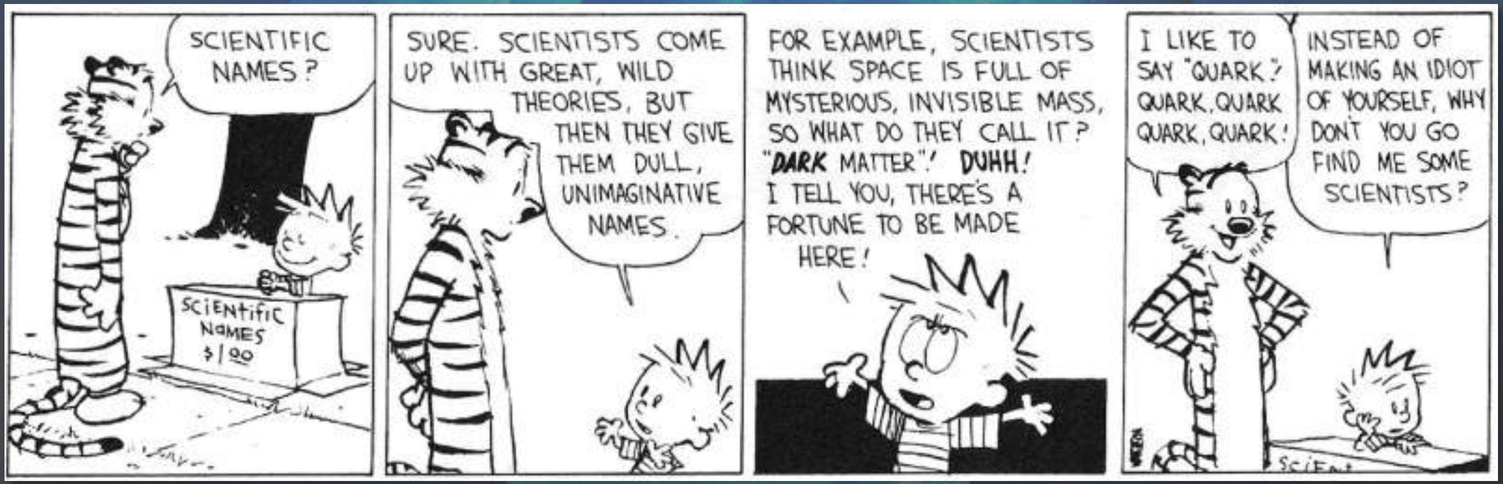
5% Visible matter

27% Dark matter

68% Dark energy

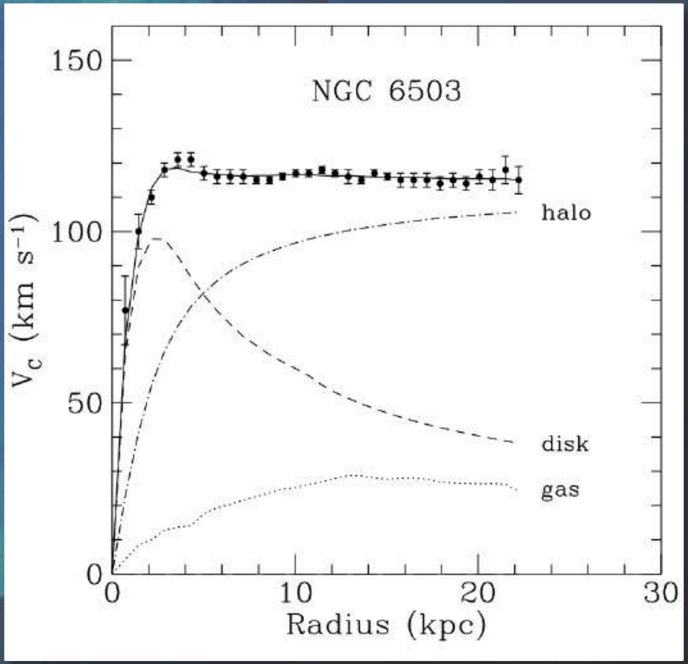
courtesy of Gianfranco Bertone

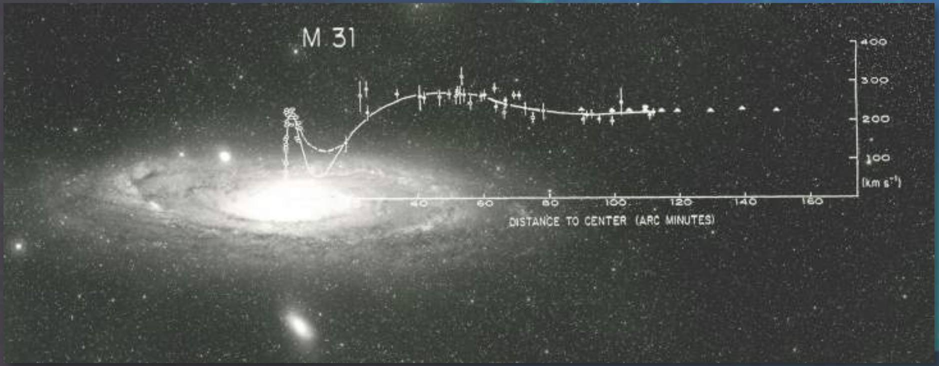
Part I: Darkness



Evidence for dark matter

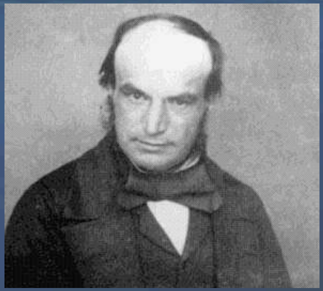
- The indication for dark matter comes from observing gravitational effects which cannot be explained by visible objects.
- For example, we can measure the velocities of stars orbiting the centre of a galaxy. The larger the velocity at a given radius, the larger the amount of mass required within that radius to keep the stars on track.
- Comparing the observed distribution of luminous mass and the inferred distribution of gravitating mass, we find a spectacular mismatch!





How sure can we be?

- This reasoning is in close analogy to the discovery of the planet Neptune, which was predicted by John Adams because the orbit of Uranus deviated slightly from the Newtonian expectations – pointing towards a 'missing mass' in the solar system.

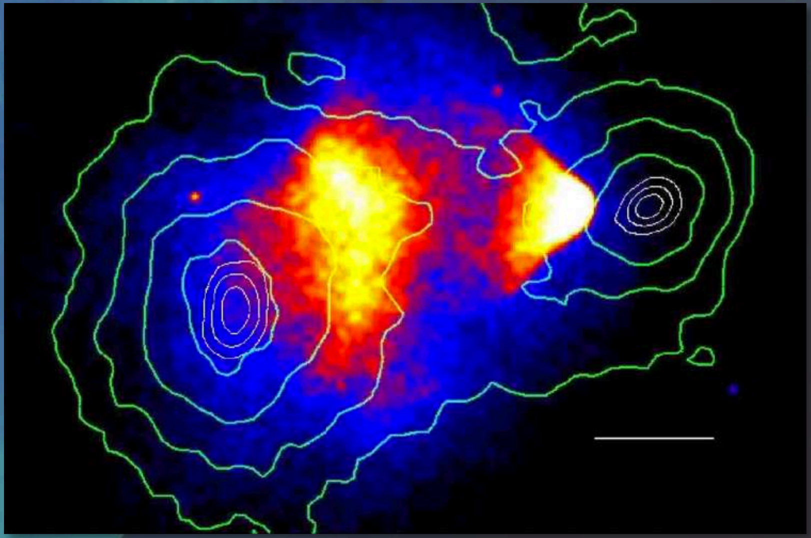


- However, when astronomers observed a similar discrepancy in the motion of Mercury, Urbain Le Verrier incorrectly postulated the existence of a new planet, Vulcan, even closer to the sun.

- This planet does not exist, and a few years later it became clear that the anomalous precession of Mercury is due to the need to use Einstein's theory of general relativity instead of Newtonian dynamics when gravitational fields become strong.

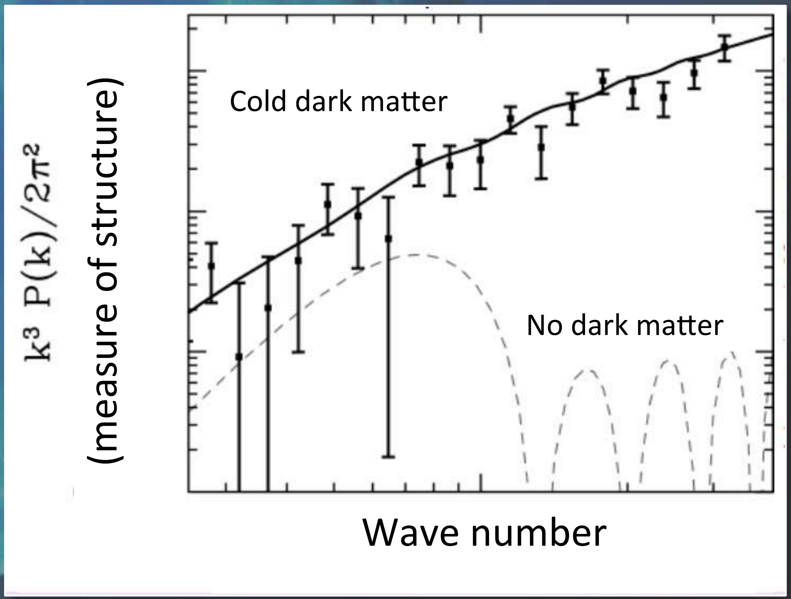
More evidence for dark matter

- In analogy, we may wonder if galactic rotation curves can be explained without need for dark matter, if the theory of gravity is also modified for very weak gravitational fields (so-called Modified Newtonian Dynamics).
- We need an independent measurement of dark matter at different scales!
- According to general relativity, matter bends space-time such that light no longer travels in straight lines, leading to a distortion of the images that we observe. This ‘gravitational lensing’ enables us to determine the total mass (and its distribution) of large objects such as galaxy clusters, which happen to be in front of a distant source e.g. a quasar.



A consistent picture

- We can find further evidence for dark matter on even larger scales by studying the growth of large-scale structure from primordal density perturbations.
- Since particles such as protons and electrons scatter very frequently in the early universe and are heated up by interactions with photons, they are very inefficient in forming structure until (re)combination.
- To explain the observed amount of structure in the Universe, most of its mass must be in the form of 'cold' (i.e. non-relativistic) and very weakly interacting particles.

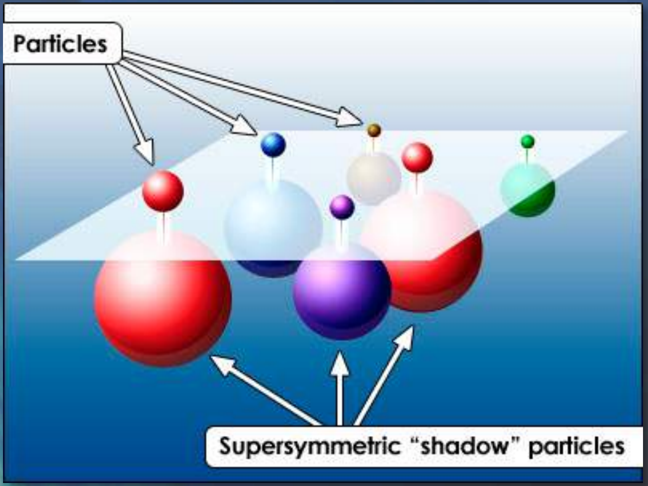


- Hence we conclude that we understand less than 20% of the matter of the universe.
- The only thing we know about dark matter is that it is fundamentally different from the matter we are made of.
- Since its interactions are so weak, we believe that it must be composed of a completely new, yet undiscovered, particle.

Particle candidates for dark matter

- Theories of physics beyond the Standard Model, which have been developed for completely different reasons, predict new particles which have the required properties to be dark matter.

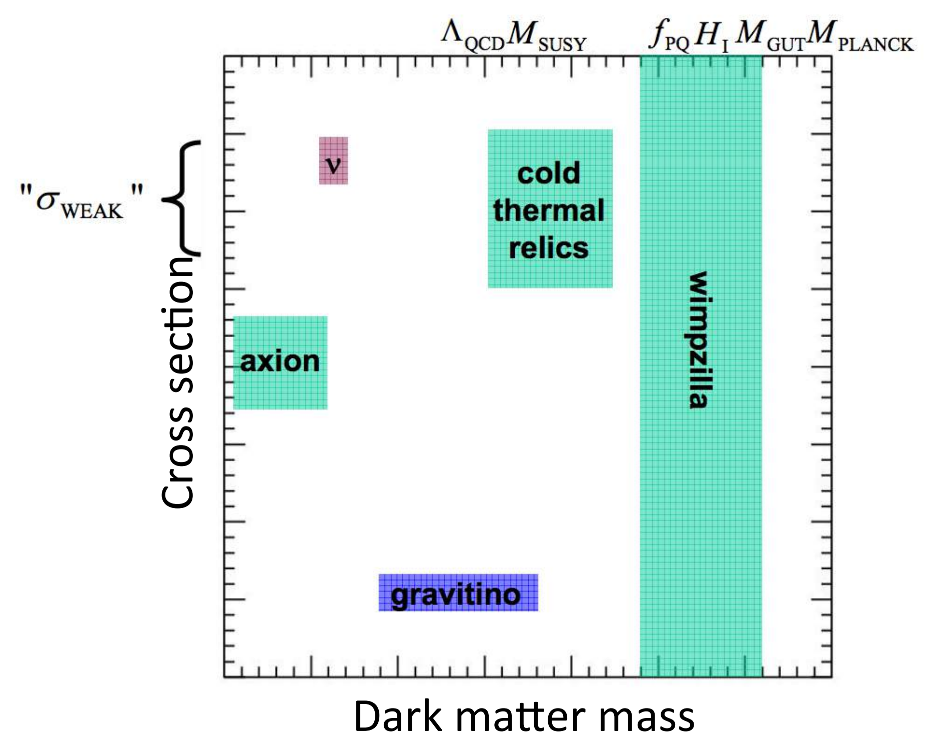
- The most discussed example is a Weakly Interacting Massive Particle (WIMP), which is a generic prediction of many interesting theories such as supersymmetry and extra dimensions.

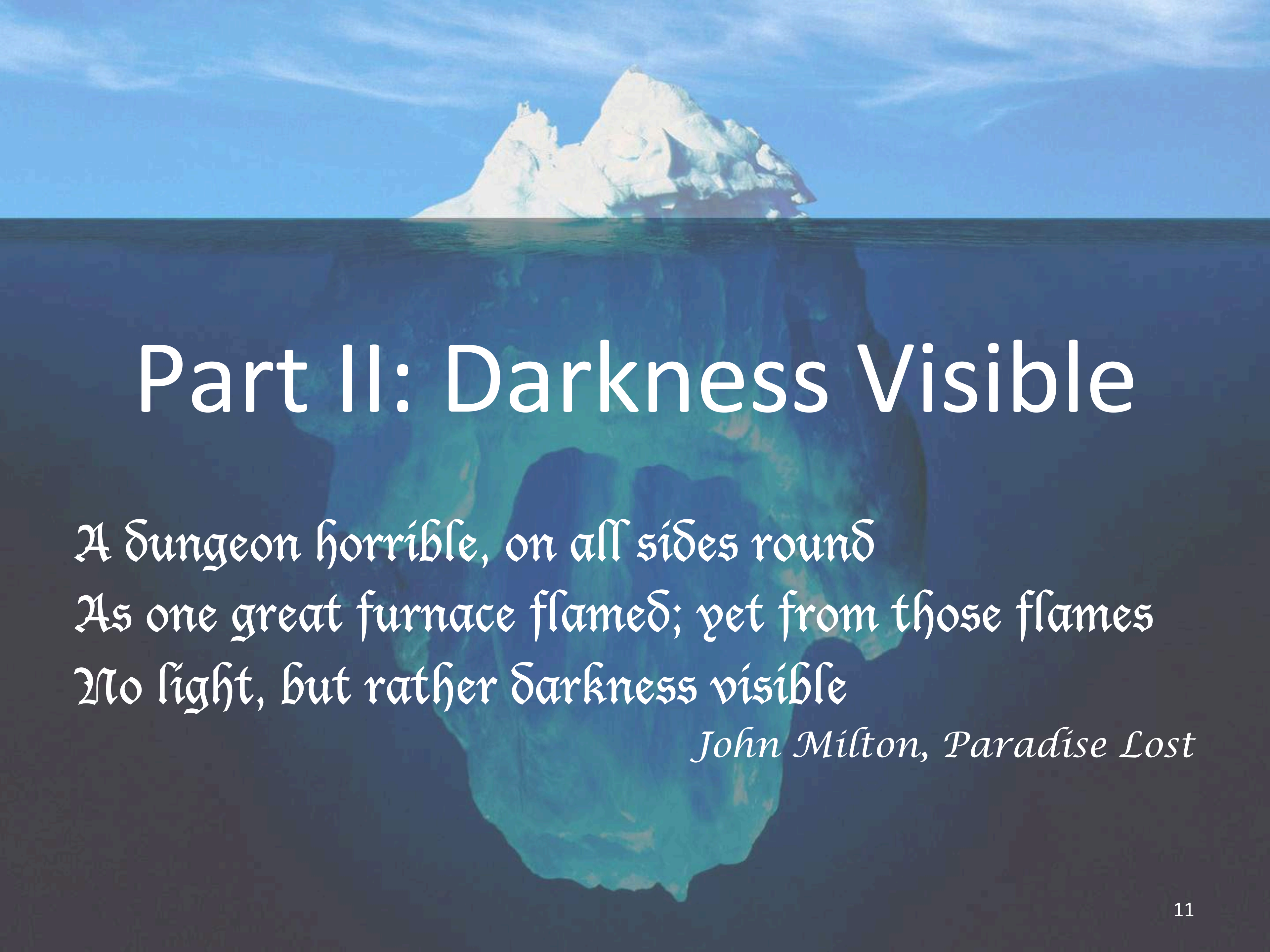


- At high temperatures/densities in the early universe, WIMPs were in thermal equilibrium with all other particles. We can therefore calculate the expected amount of dark matter that remains after thermal decoupling and find that weak-scale particles *naturally* have the required abundance – the ‘WIMP miracle’!

Particle candidates for dark matter

- There are of course other interesting models to explain the observed abundance also for lighter dark matter particles, for example:
  - Non-thermal production of axions
  - Sterile neutrinos as warm dark matter
  - Dark matter with new strong interactions, carrying a matter-antimatter asymmetry (just like baryons)





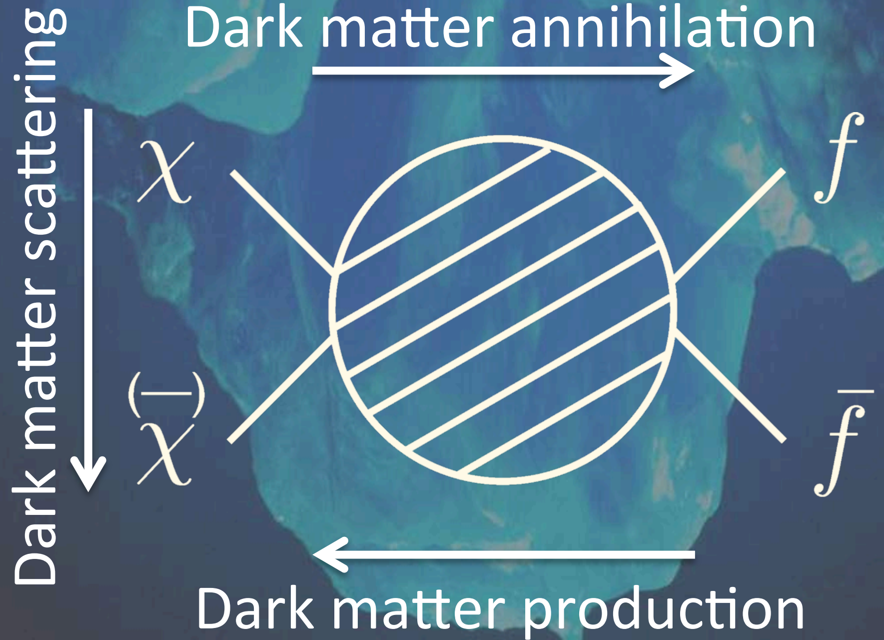
Part II: Darkness Visible

A dungeon horrible, on all sides round
As one great furnace flamed; yet from those flames
No light, but rather darkness visible

John Milton, Paradise Lost

Detecting dark matter particles

- Most dark matter candidates interact at some level with Standard Model particles leading to thermal equilibrium in the early Universe.


Dark matter annihilation

Dark matter scattering

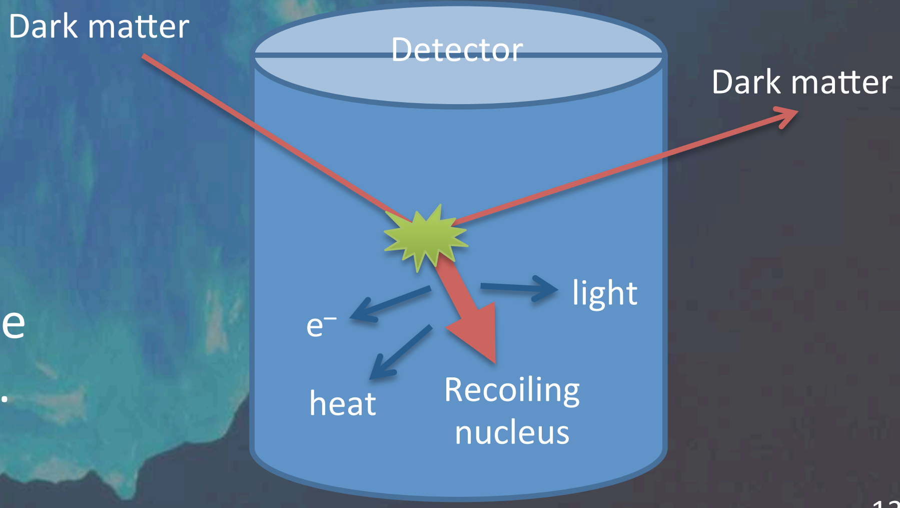
Dark matter production

Direct detection of dark matter


Photo: AP

Dark matter particles from the Galactic halo constantly pass through the Earth: about 10^7 per second through our bodies! As they do so, they have a tiny – but non-zero – probability to scatter off ordinary nuclei.

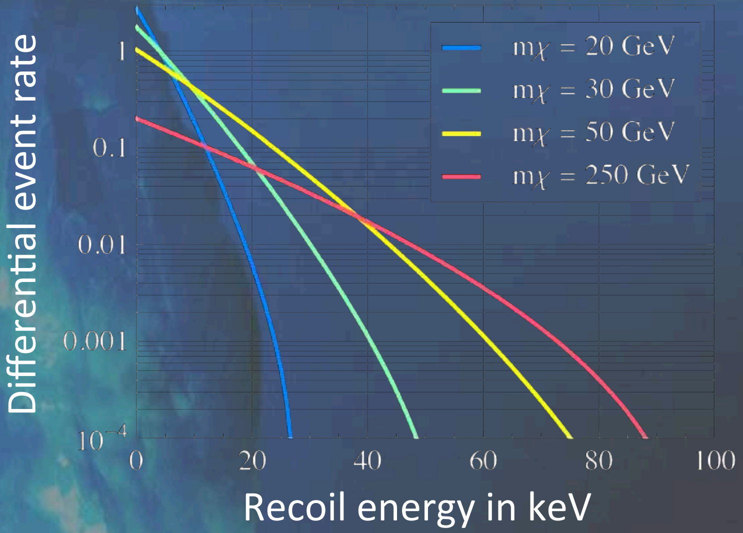
If such a scattering process happens within a dedicated low background detector, the recoiling nucleus can be observed and its energy determined.



Differential event rate

$$\boxed{\frac{\mathrm{d}R}{\mathrm{d}E_{\mathrm{nr}}} = \frac{\rho_0}{m_\chi m_{\mathrm{N}}} \int_{v_{\min}}^{\infty} \mathrm{d}v\, v\, f(v, v_{\mathrm{E}}) \frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{nr}}}}$$

E_{nr}: Nuclear recoil energy
m_χ: Dark matter mass
ρ_0: Local dark matter density
v: Dark matter velocity

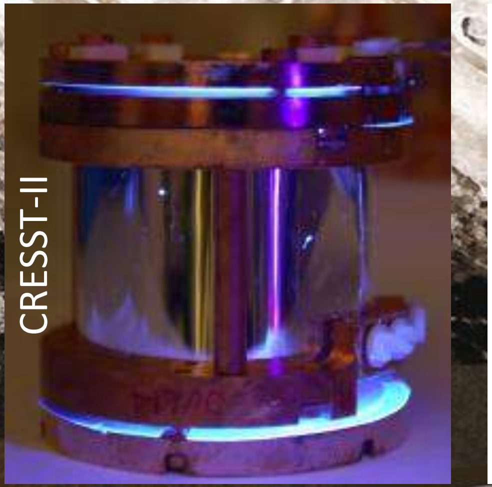


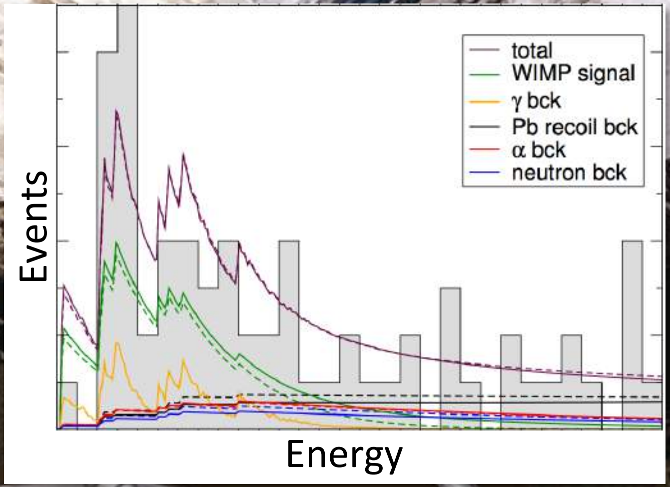
- Typical event rates are less than 1 event per kg per year.
- Even worse, since $v < v_{esc} \approx 650$ km/s, a typical collision will give an energy transfer of ~10 keV, which is less than the energy of a radioactive decay (which happens 10^4 times per second in our bodies).

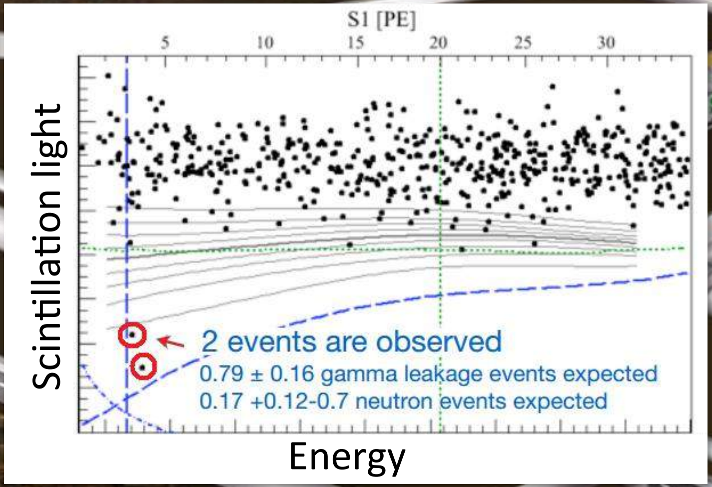
A great experimental challenge!

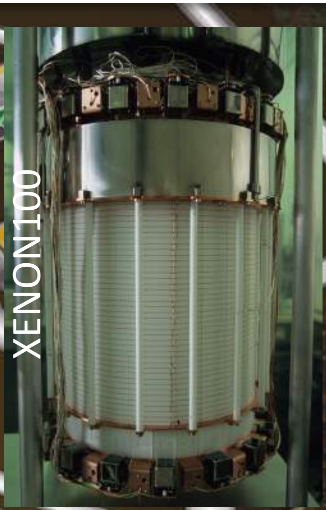
Example: CRESST-II and XENON100

Over the past 30 years, many experiments have attempted to directly detect dark matter. Some (like CRESST-II on the top) have claimed an excess over expected backgrounds, others (like XENON100 on the bottom) see agreement between background and observation.





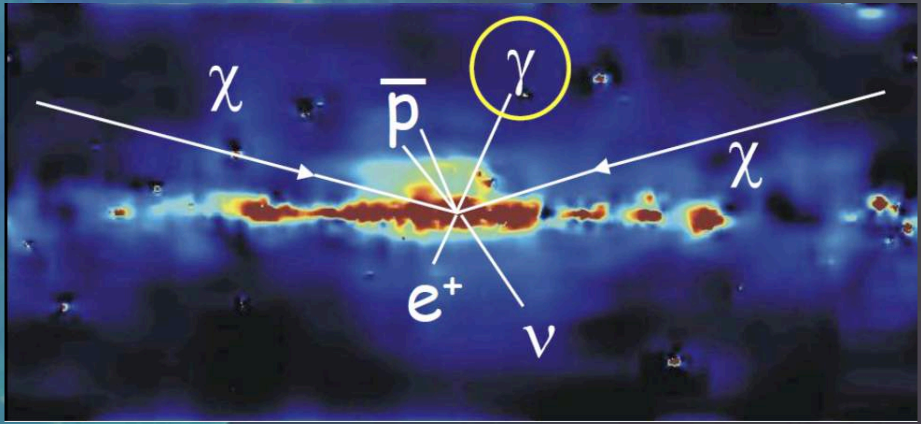




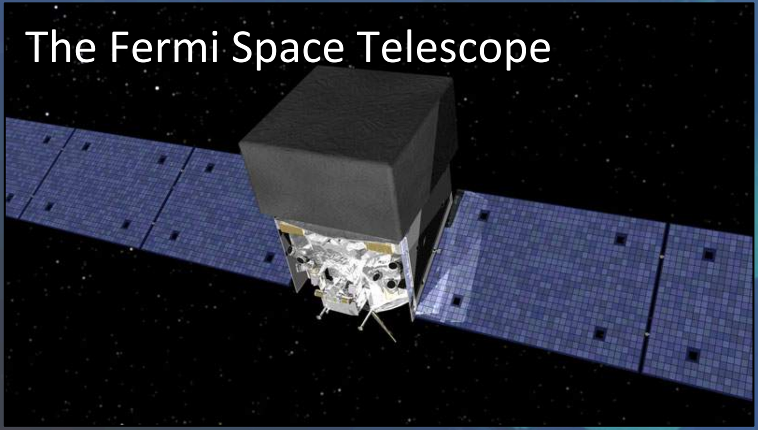
Indirect detection of dark matter

Indirect detection experiments look for the products of dark matter annihilation in regions of large DM density (e.g. the Galactic centre) with satellites, balloons and ground based telescopes.

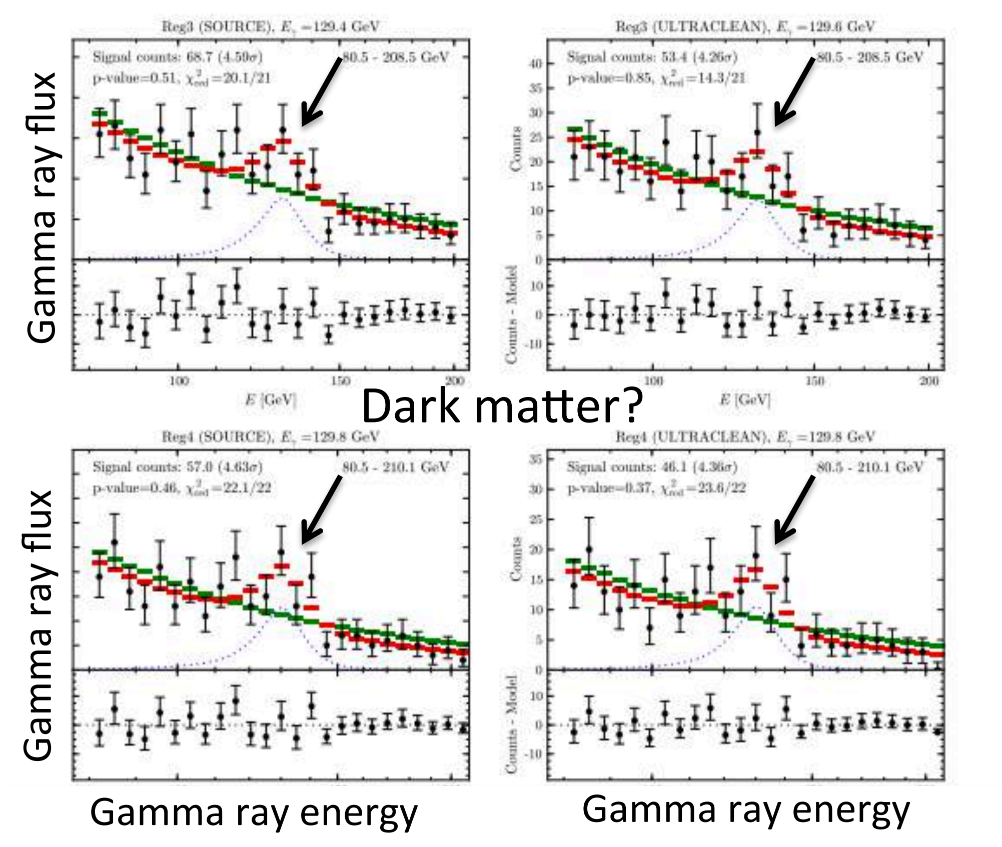
Problem: For these seaches, we need to know where to look (large DM density) and where not to look (large astrophysical backgrounds).



Example: Gamma-ray searches



The Fermi Space Telescope



Dark matter?

A very exciting place to look is the Galactic centre, where the largest density of dark matter is expected. Unfortunately, we do not yet know enough about the Milky Way to understand all astrophysical backgrounds.

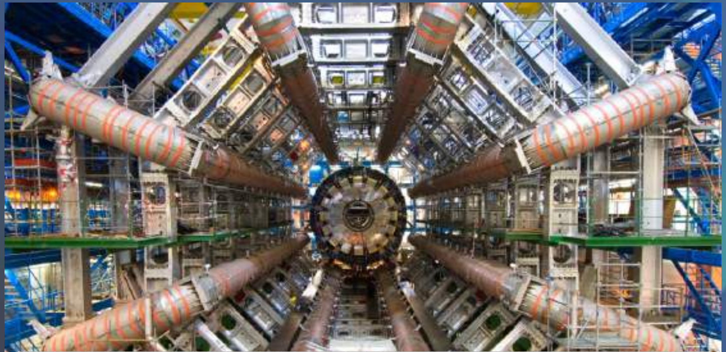
Collider searches

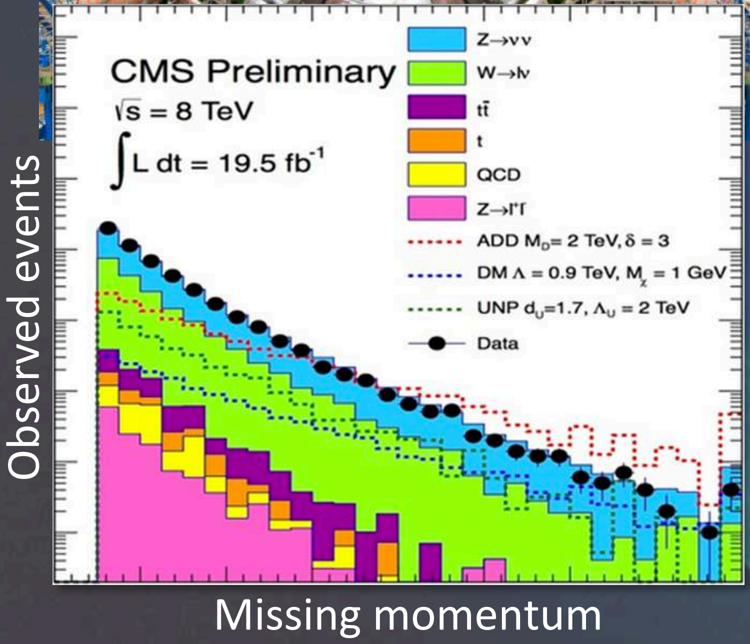
If we collide protons at very high energies, we can hope to produce DM particles just like in the early universe. Unfortunately, any DM particles produced in such collisions will escape from the detector unnoticed.

The LHC: As one great furnace flamed…

But if the collision also produces some visible particles, it will look as if momentum conservation is violated.

Example: Mono-jet searches





The LHC detectors search for events with a single jet of particles (quarks, gluons, etc) and unbalanced momentum on the other end.

Many of these events come from neutrinos, so once again we need to study the backgrounds very carefully and search for an excess over the expectation.

Part III:
The Hunt for Dark Matter

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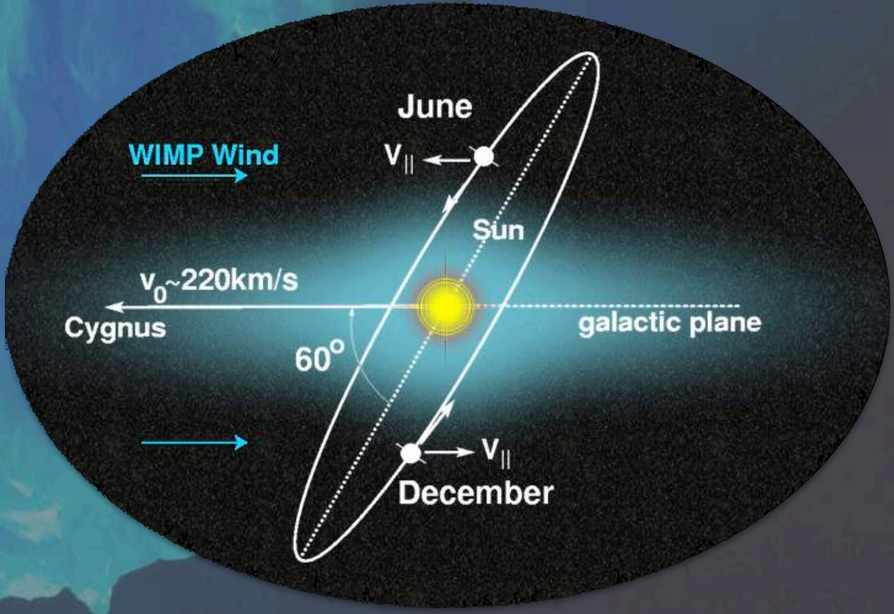
Dark matter annual modulations

- All the different search strategies have in common that we need understand experimental backgrounds (from radioactivity, astrophysical sources, neutrinos…) in order to identify a potential dark matter signal.

- The key challenge is to find new experimental signatures with as little background as possible.

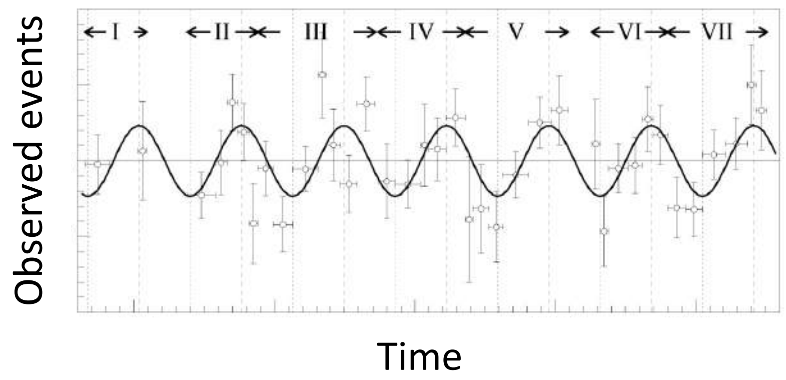
- One particularly interesting option is the annual modulation of direct detection signals due to the motion of the Earth around the Sun.



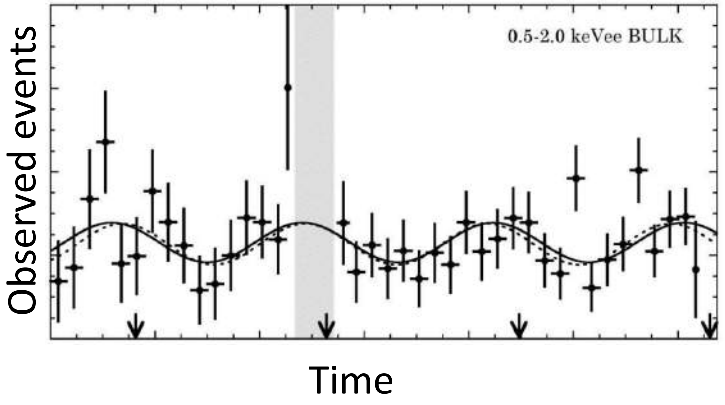
Dark matter annual modulations

- There are two experiments (DAMA and CoGeNT) which search for dark matter annual modulations.
- Both experiments see (some) evidence for a modulating signal with a phase that agrees with expectations.

Seven-year data from DAMA



CoGeNT preprint from 14 January 2014

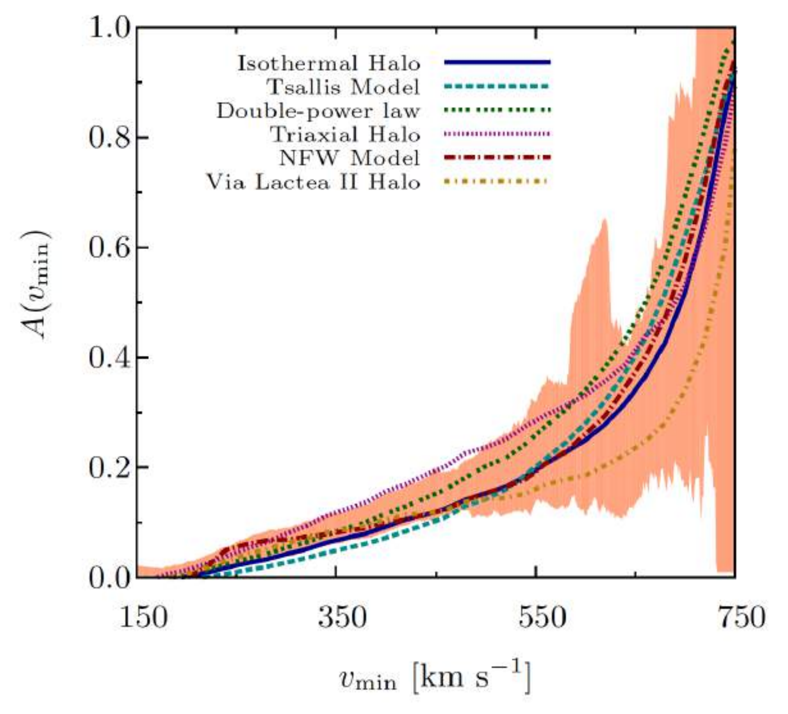


Dark matter annual modulations

- One of the key challenges for interpreting this signal is to make a robust prediction for the modulation fraction *A* (i.e. the ratio of the modulation amplitude to the total signal strength).

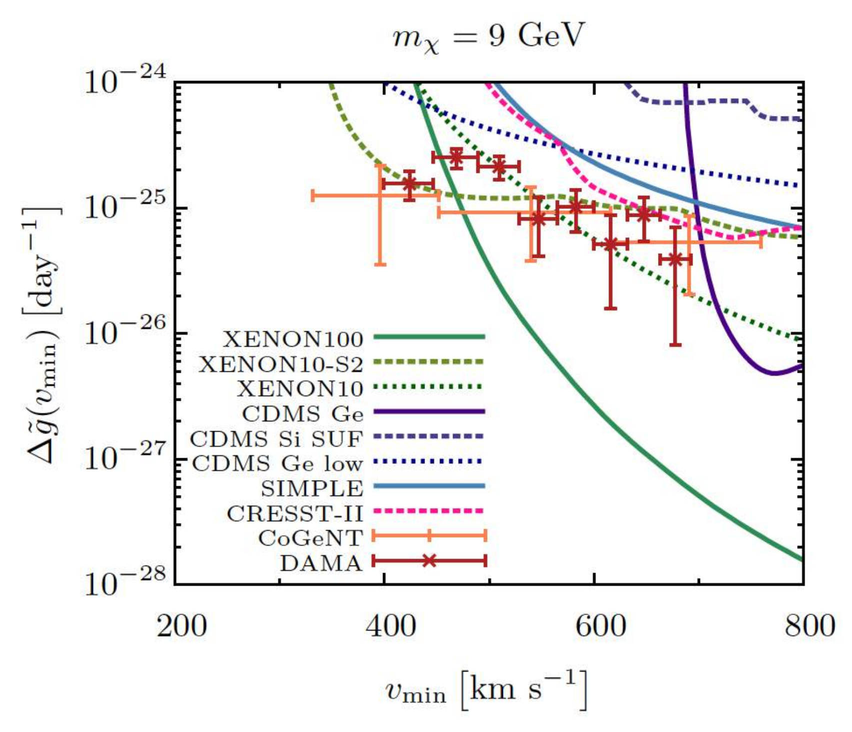
- The expected modulation fraction depends on the velocity of the DM particles, corresponding to the observed recoil energy.

- Moreover, the predictions differ for various models of the Milky Way dark matter halo.



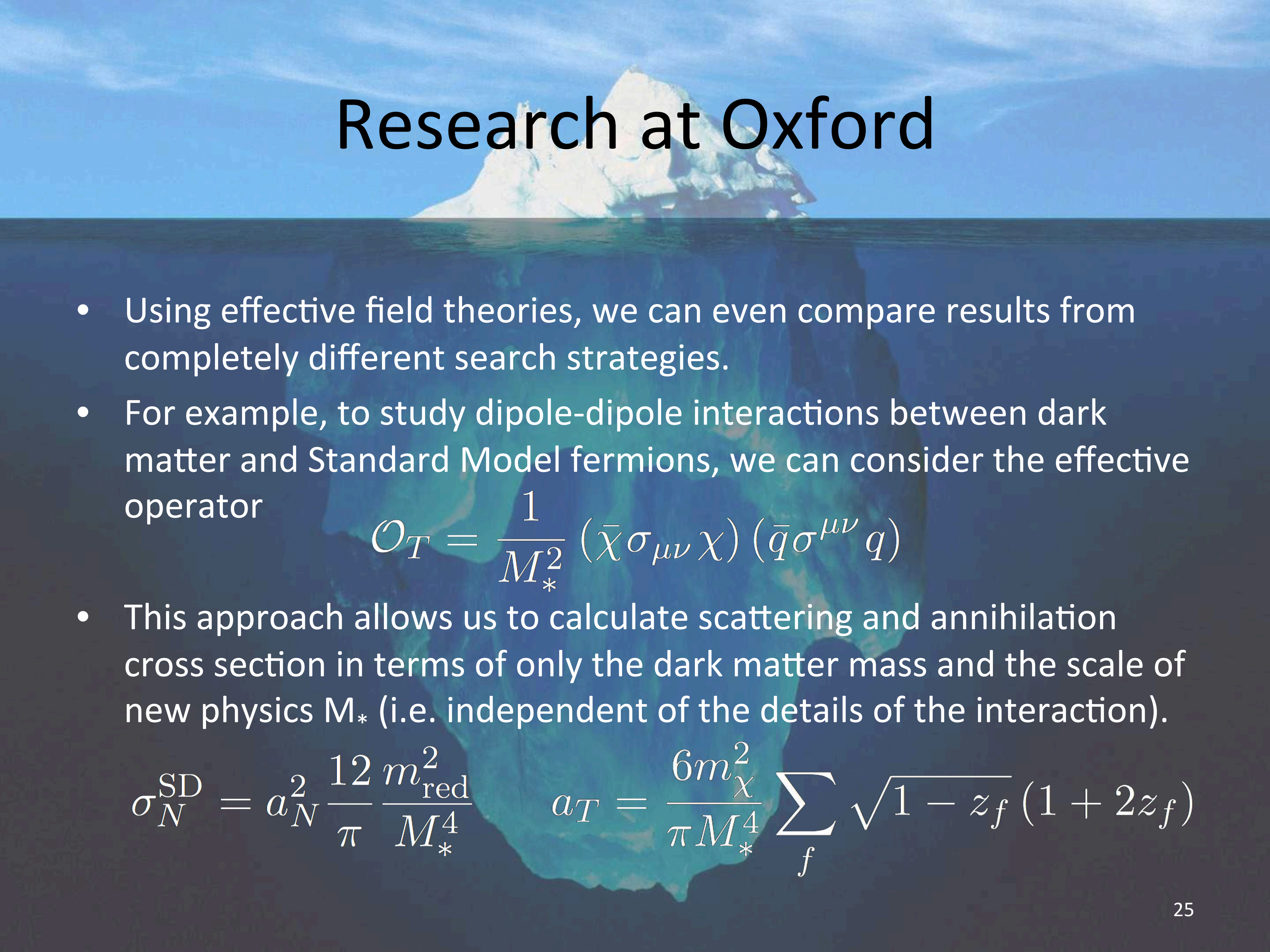
Frandsen, Kahlhoefer *et al.*: JCAP 1201 (2012) 024

Research at Oxford



Frandsen, Kahlhoefer *et al.*: JCAP 1201 (2012) 024

- In the Particle Theory group we have developed methods to compare different direct detection experiments *independently* of the (assumed) properties of the dark matter halo.
- We find that the results from DAMA and CoGeNT are in agreement with each other, but in tension with other experimental data.



Research at Oxford

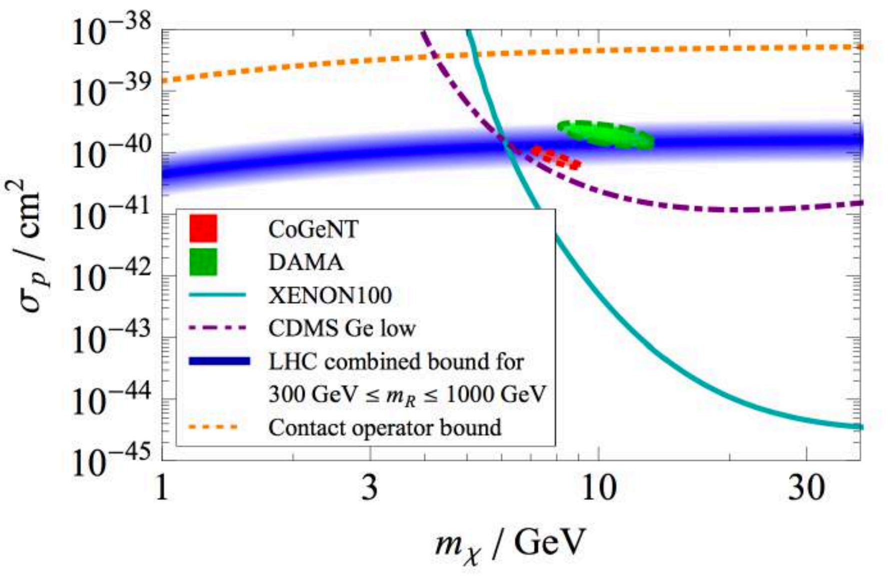
- Using effective field theories, we can even compare results from completely different search strategies.
- For example, to study dipole-dipole interactions between dark matter and Standard Model fermions, we can consider the effective operator

$$\mathcal{O}_T = \frac{1}{M_*^2} \left(\bar{\chi} \sigma_{\mu\nu} \chi\right) \left(\bar{q} \sigma^{\mu\nu} q\right)$$

- This approach allows us to calculate scattering and annihilation cross section in terms of only the dark matter mass and the scale of new physics M* (i.e. independent of the details of the interaction).

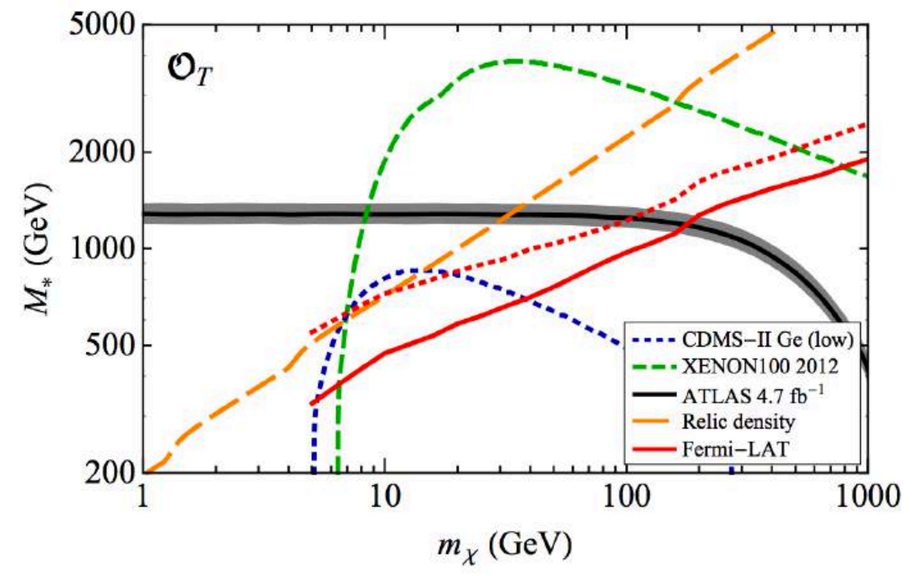
$$\sigma_N^{\mathrm{SD}} = a_N^2 \frac{12}{\pi} \frac{m_{\mathrm{red}}^2}{M_*^4} \qquad a_T = \frac{6 m_\chi^2}{\pi M_*^4} \sum_f \sqrt{1 - z_f} \left(1 + 2 z_f\right)$$

Research at Oxford



Frandsen, Kahlhoefer *et al.*: JHEP 1207 (2012) 123

$$\mathcal{O}_T = \frac{1}{M_*^2}\left(\bar{\chi}\sigma_{\mu\nu}\chi\right)\left(\bar{q}\sigma^{\mu\nu}q\right)$$

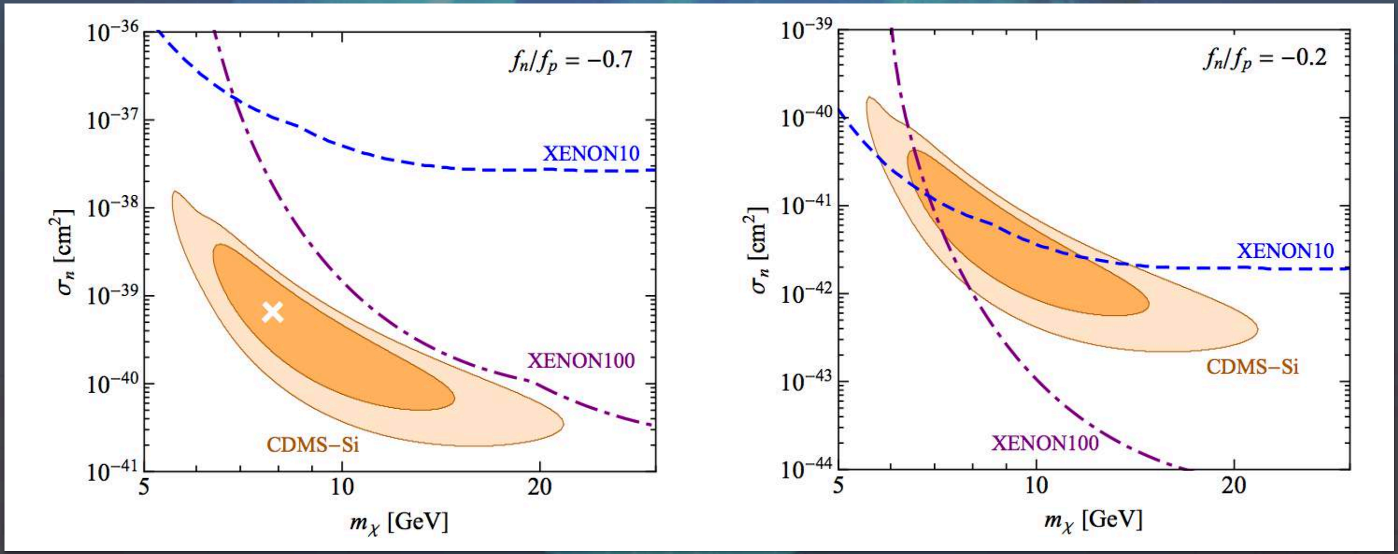


Haisch, Kahlhoefer: JCAP 1304 (2013) 050

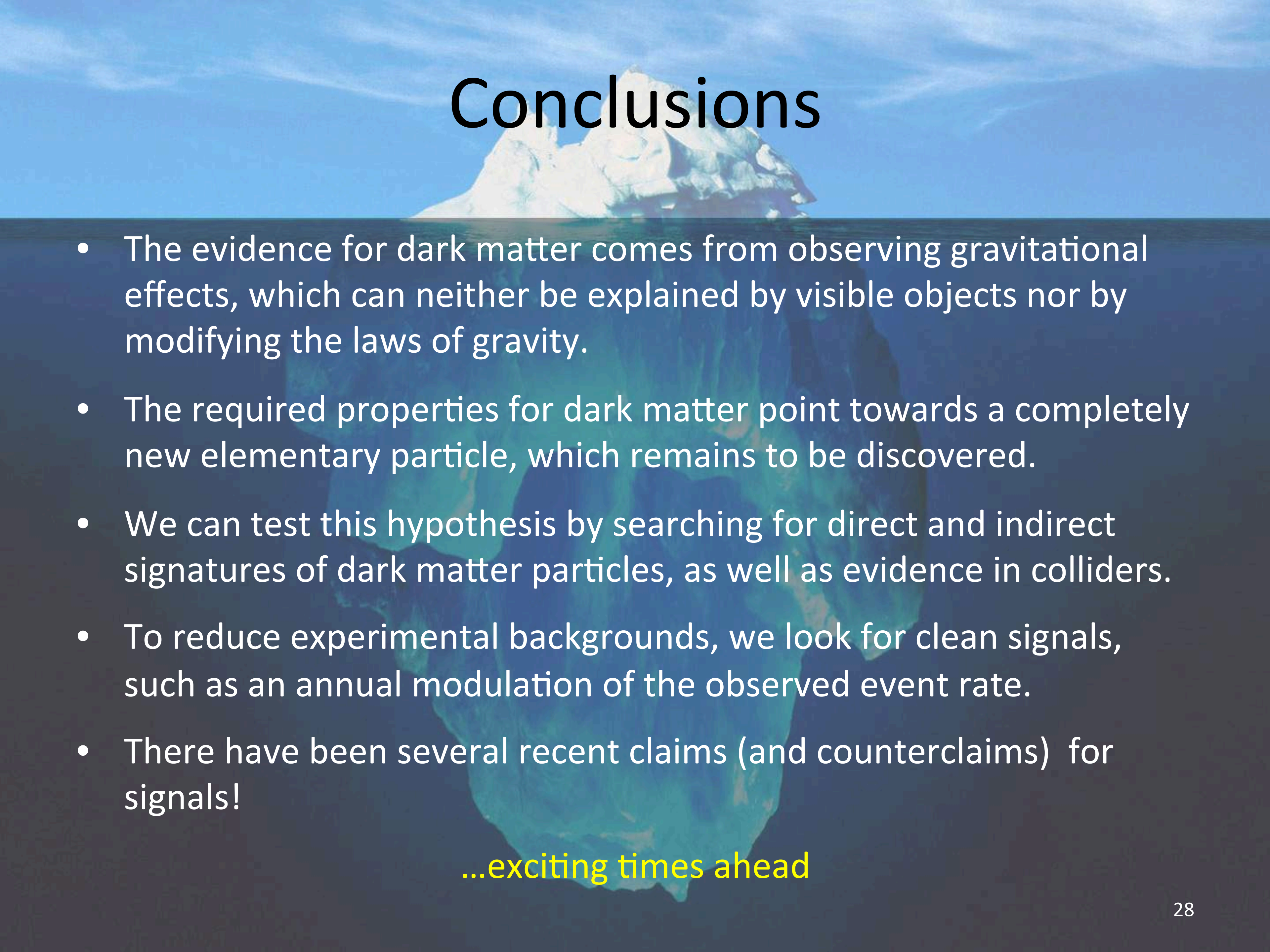
$$\sigma_N^{\mathrm{SD}} = a_N^2\,\frac{12}{\pi}\,\frac{m_{\mathrm{red}}^2}{M_*^4}$$

Research at Oxford

- By comparing different (kinds of) experiments, we can study if several complementary data sets give a consistent picture or if we need to question the theory assumptions made in the signal prediction.
- How would experimental signatures change if dark matter is not a WIMP?
- What types of experiments are needed to cover alternative scenarios?



Frandsen, Kahlhoefer *et al.*: JCAP 1307 (2013) 023



Conclusions

- The evidence for dark matter comes from observing gravitational effects, which can neither be explained by visible objects nor by modifying the laws of gravity.
- The required properties for dark matter point towards a completely new elementary particle, which remains to be discovered.
- We can test this hypothesis by searching for direct and indirect signatures of dark matter particles, as well as evidence in colliders.
- To reduce experimental backgrounds, we look for clean signals, such as an annual modulation of the observed event rate.
- There have been several recent claims (and counterclaims) for signals!

…exciting times ahead