

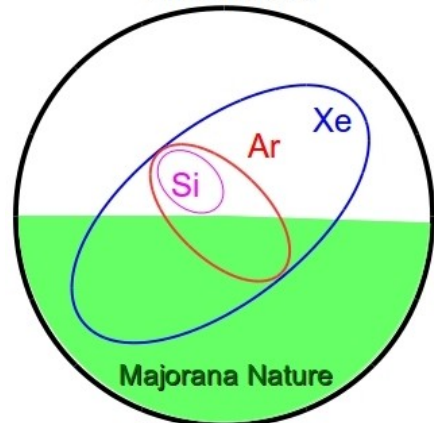
Oslo



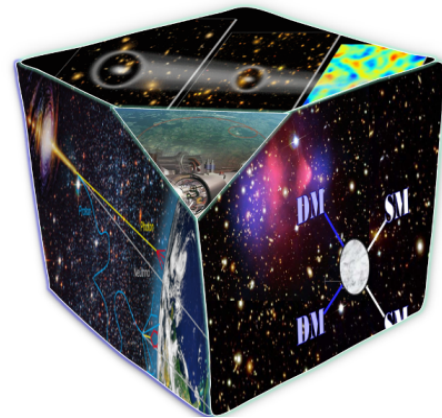
Probing the Nature of Dark Matter

University of Oslo 18/01/17

Dirac Nature



Farinaldo Queiroz
Max Planck Institute for Nuclear Physics - Heidelberg

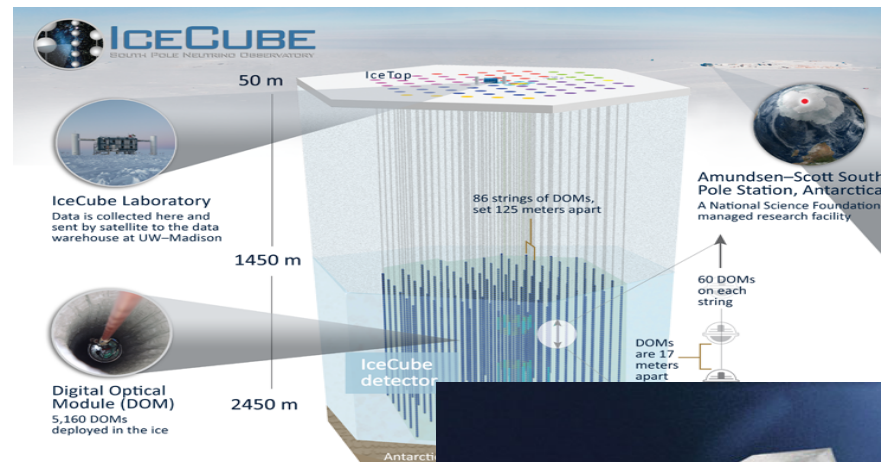
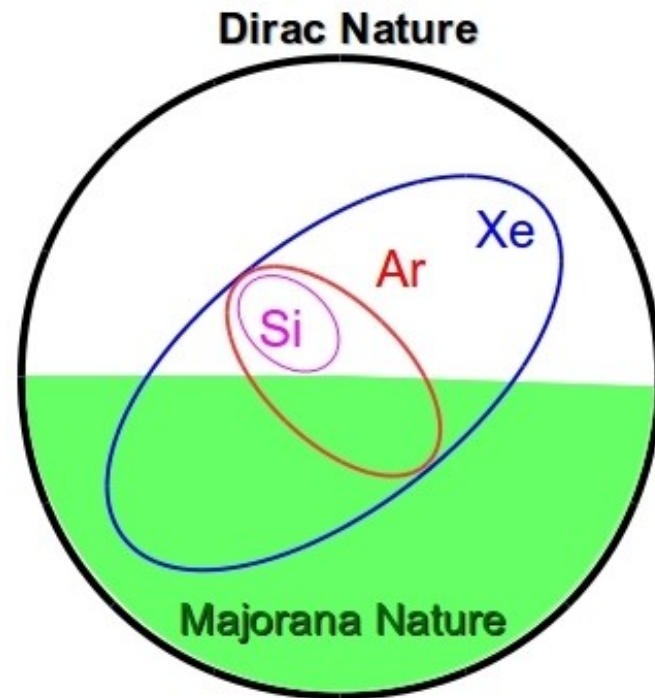


Outline

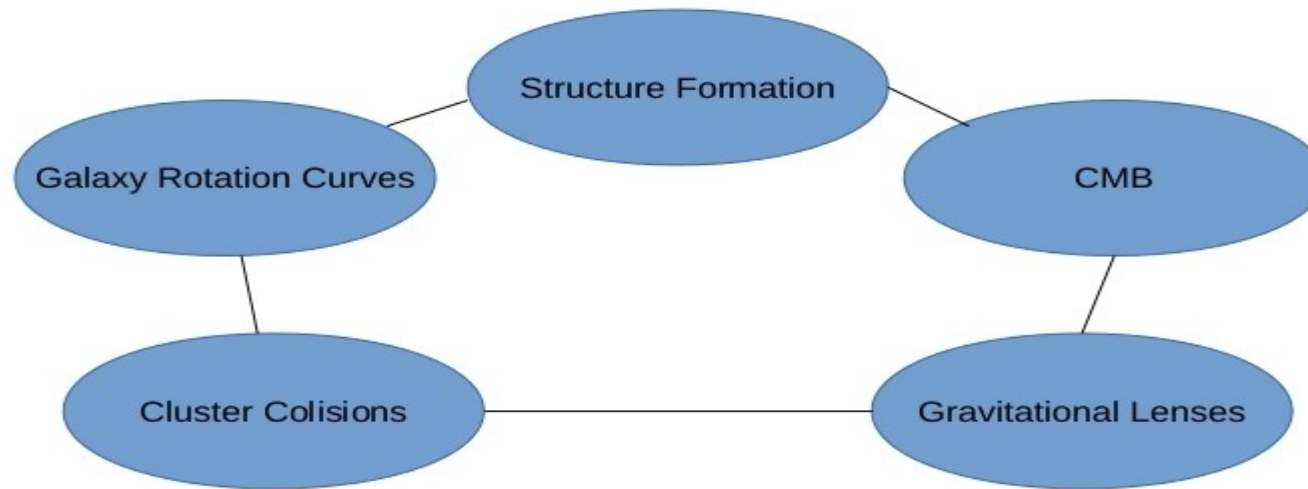
- 1. Take home messages**
- 2. Brief Review**
- 3. Probing Neutrinos Lines with Gamma-rays**
- 4. Probing the nature of dark matter**
- 1. Conclusions/Take home messages**

Take home messages

1. Beginning of a **NEW ERA**: Gamma-rays telescopes are more sensitive than neutrino detectors to neutrino lines from dark matter annihilation
2. There is a way to determine the fundamental nature of dark matter using direct detection data only.



Evidences for Dark Matter



First Evidence for Dark Matter

In 1933 Fritz Zwick used the virial theorem to **infer the existence of unseen matter** in the Coma galaxy cluster



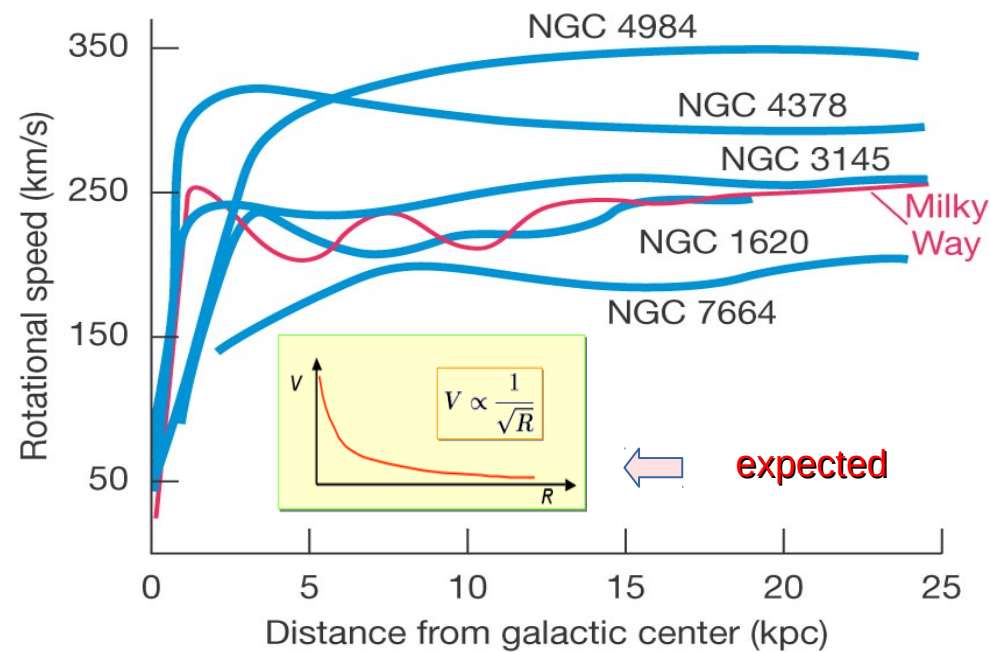
Coma galaxy cluster



“Spherical Bastards”

Galaxy Rotation Curves

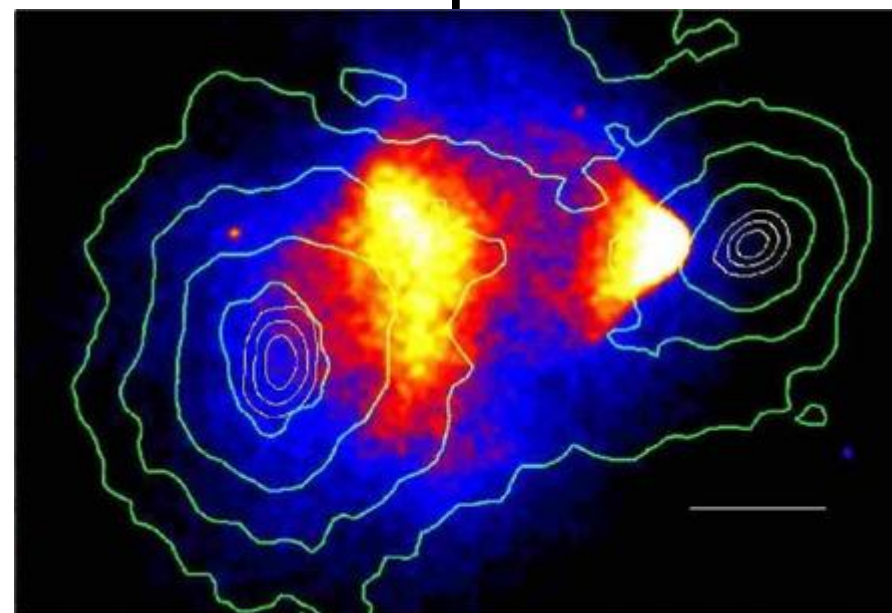
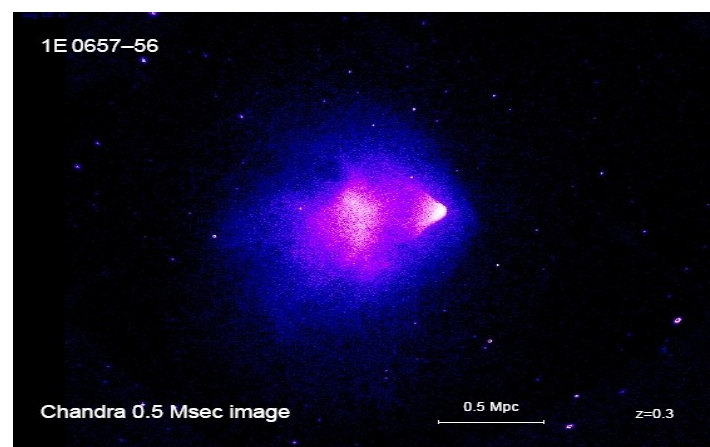
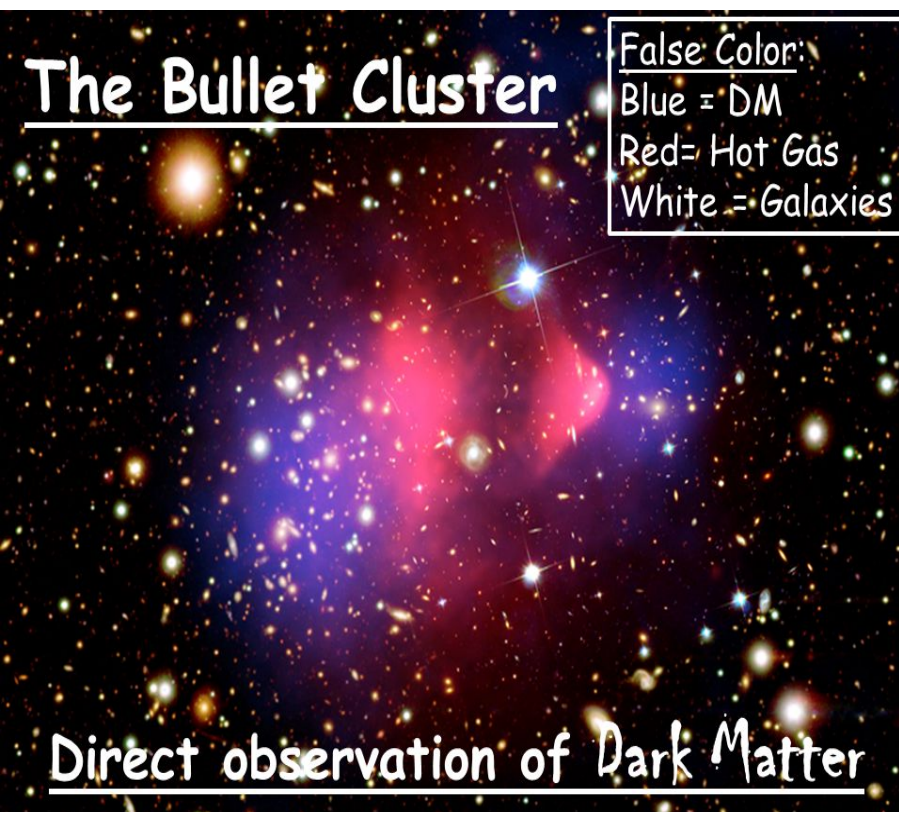
In 1970s Vera Rubin+, **established the existence of dark matter** in galaxies by studying galaxy rotation curves



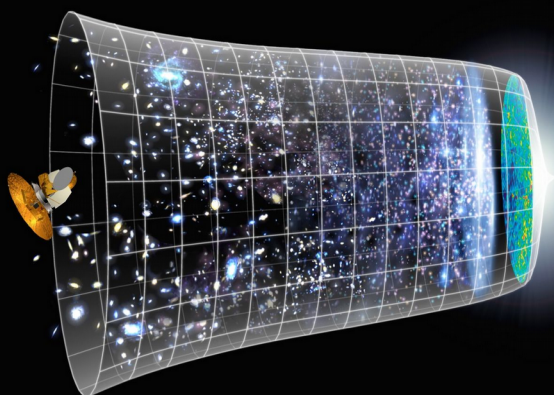
From then on the dark matter search took off

Cluster Collisions

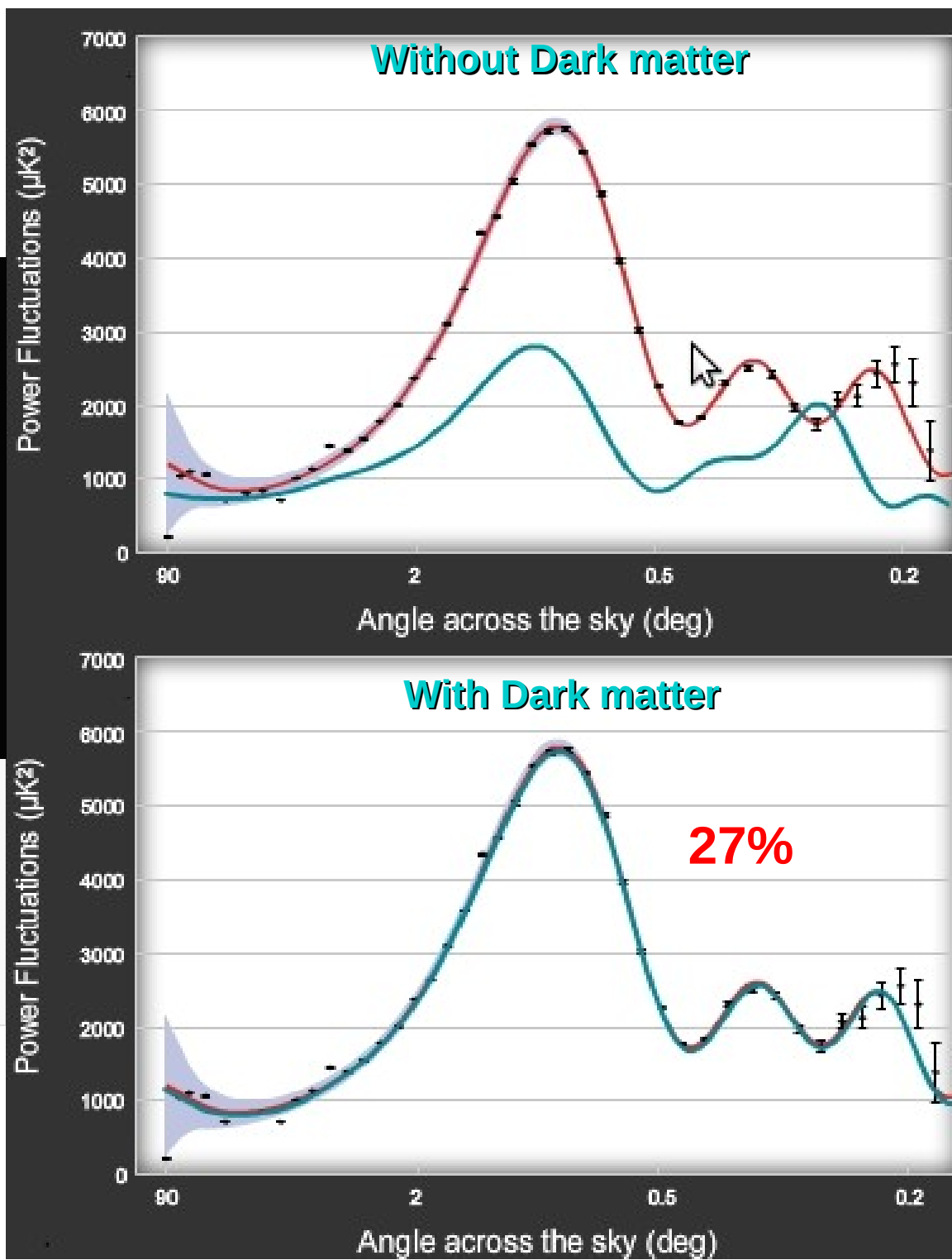
In 2006 Douglas Cowe+, **established the existence of dark matter** in cluster of galaxies and “excluded” classical MOND theories



CMB



2013-2015 Planck satellite has confirmed the existence of dark matter in early times of the universe history

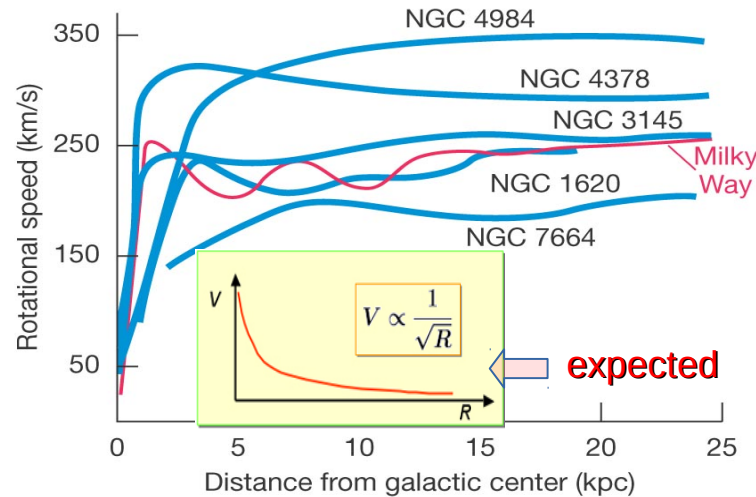


Thus, the need for Dark Matter

In 1933 Fritz Zwick used the virial theorem to infer the existence of unseen matter in the Coma galaxy cluster



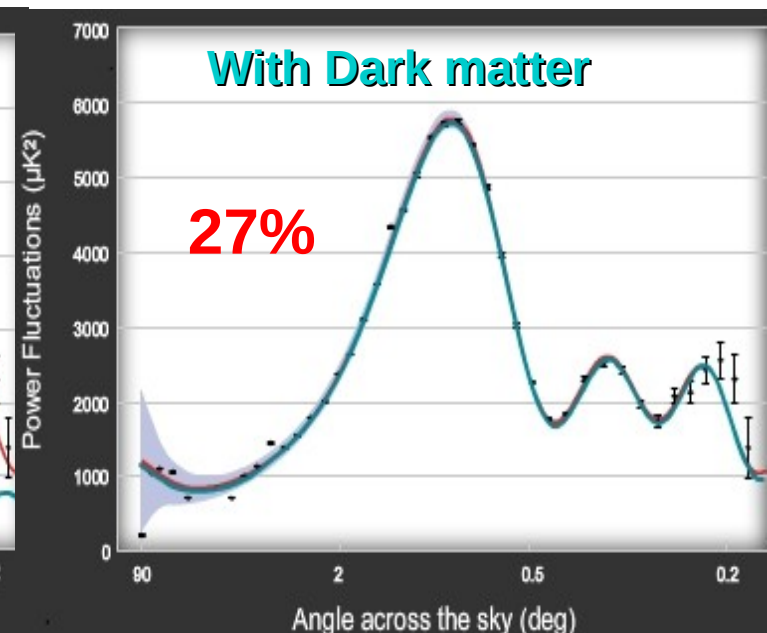
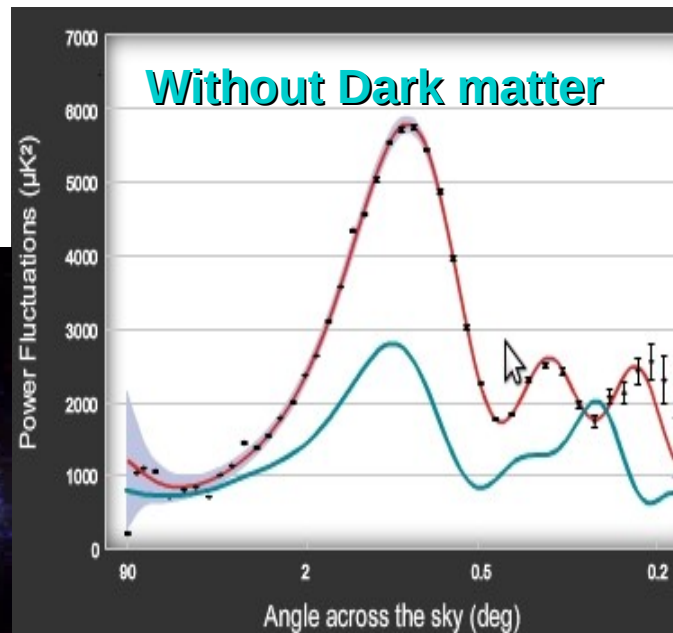
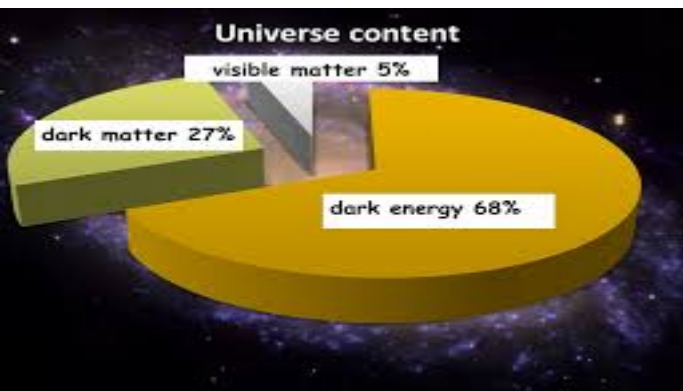
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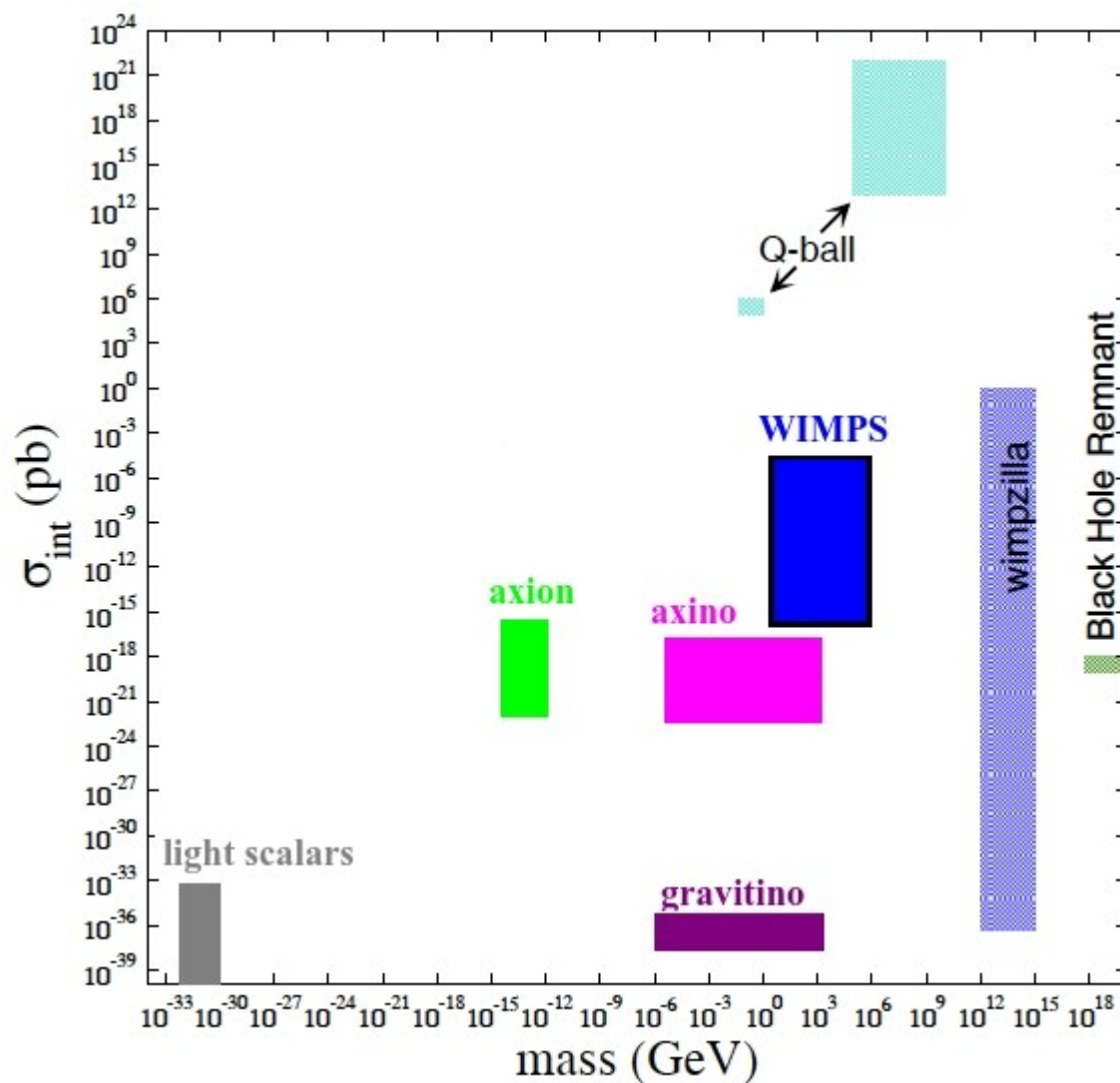
In 2003 the observation of the bullet cluster by Maxim Markevitch+



COBE (1990s), WMAP (2000s), PLANCK (2013) confirmed the existence of dark matter using CMB data



What is the Nature of Dark Matter?



Ultralight scalar

Stadnik, Flambaum PRL 115 (2015)

Sterile Neutrino

M. Drewes et al, 1602.04816 (white paper)s

Neutralino

T. Bringmann, F. Calore, 1308.1089

Axions

[F. S. Queiroz](#), K. Sinha, W. Wester PRD 2014

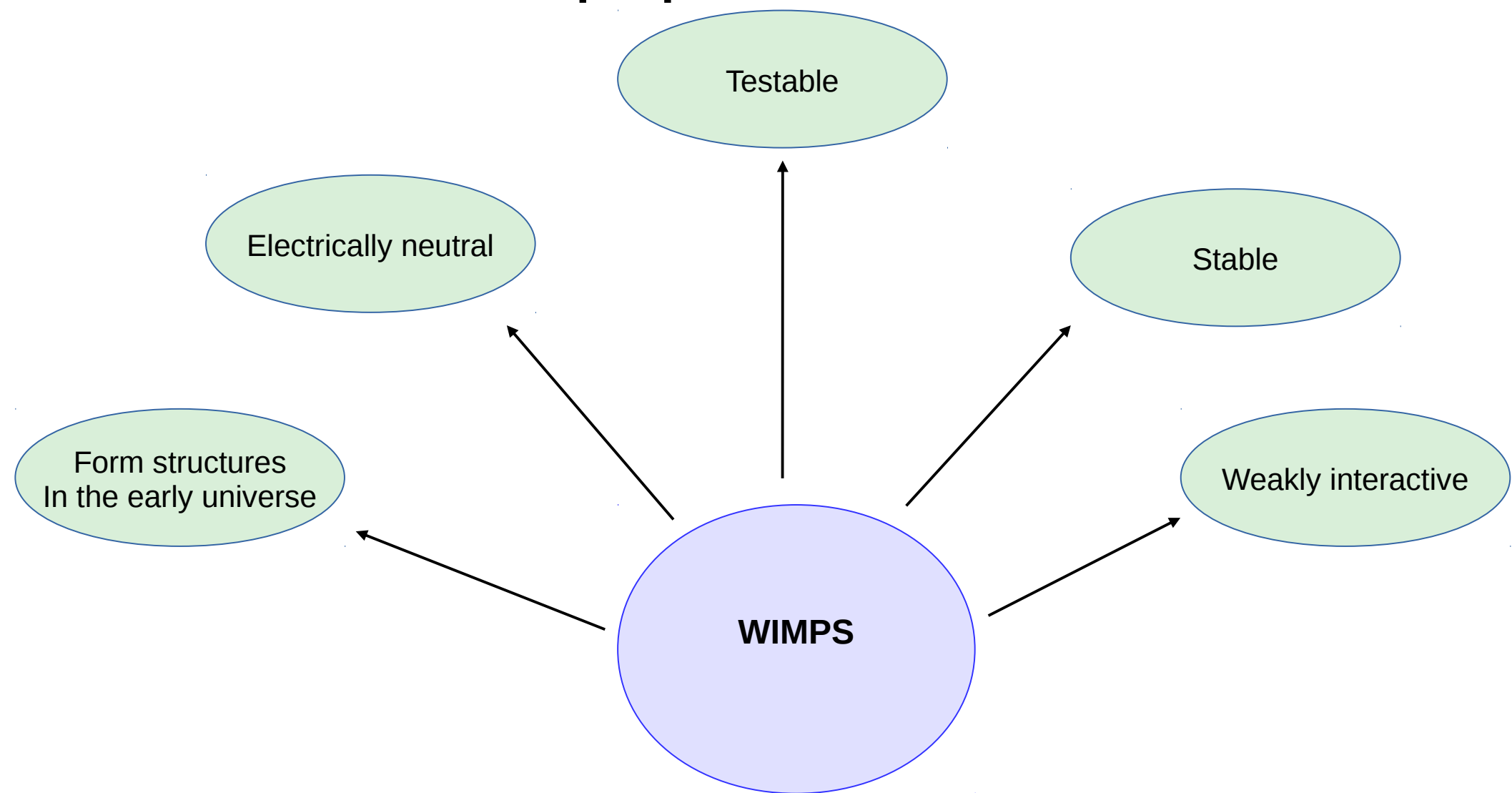
Asymmetric Dark Matter

Petraki, Volkas. IJMPA 28 (2013)

Dark Matter - flavor physics

M. Lindner, M. Platscher, [F. S. Queiroz](#) –
To appear in Physics Reports 2017

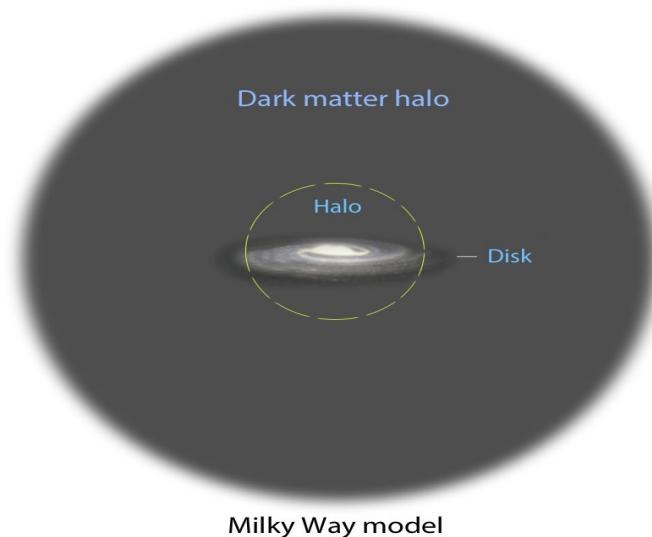
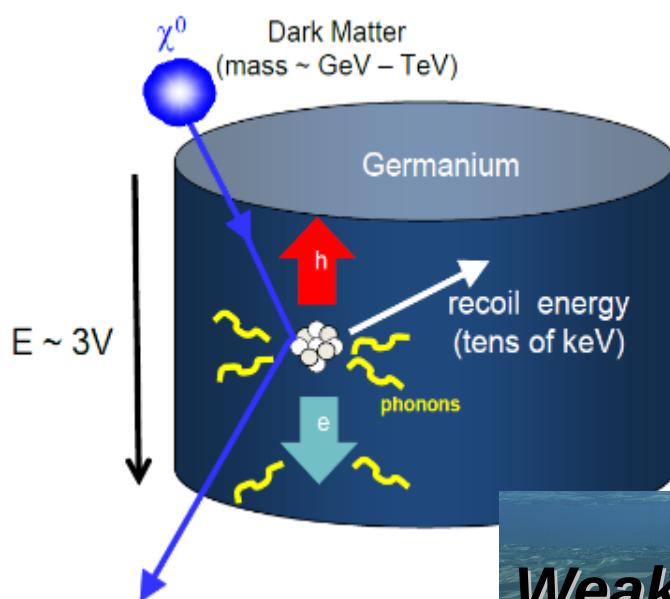
Most popular candidate



WIMPs can naturally fulfill all these requirements

How do we search for WIMPs ?

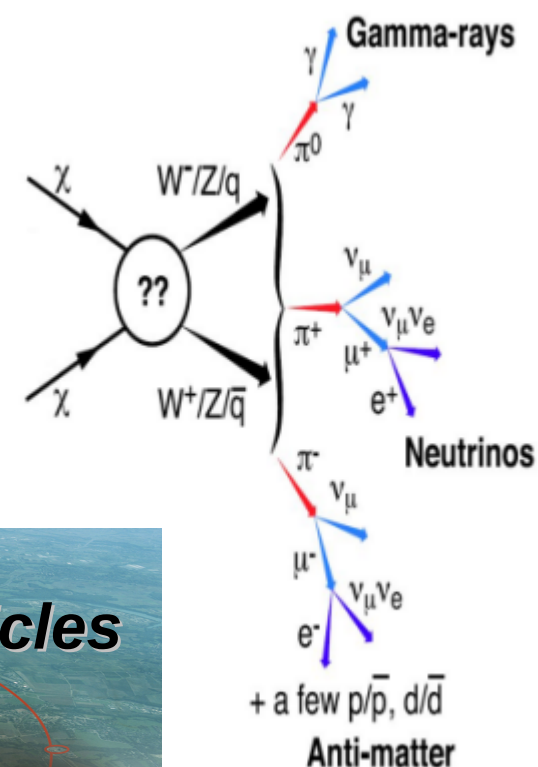
Direct Detection



Collider



Indirect Detection



Experiments searching for Dark Matter

The nature of dark matter is one the most important open problems in science

We might be on the verge of unveiling it

Colliders

Direct detection

Indirect detection

DarkOSLO

CMS

ATLAS

BABAR

MiniBooNE

DAMA

PICO

XENON1T

XENONnT

DM Ice

LZ

ADMX

DarkSide

DRIFT

DAMIC

DMTPC

XMASS

PANDAX

E137- SLAC

EDELWEISS-III

VEPP-III

CTA

DAMPE

MAGIC

XMM-Newton

H.E.S.S.

Fermi-LAT

HAWC

AMS-02

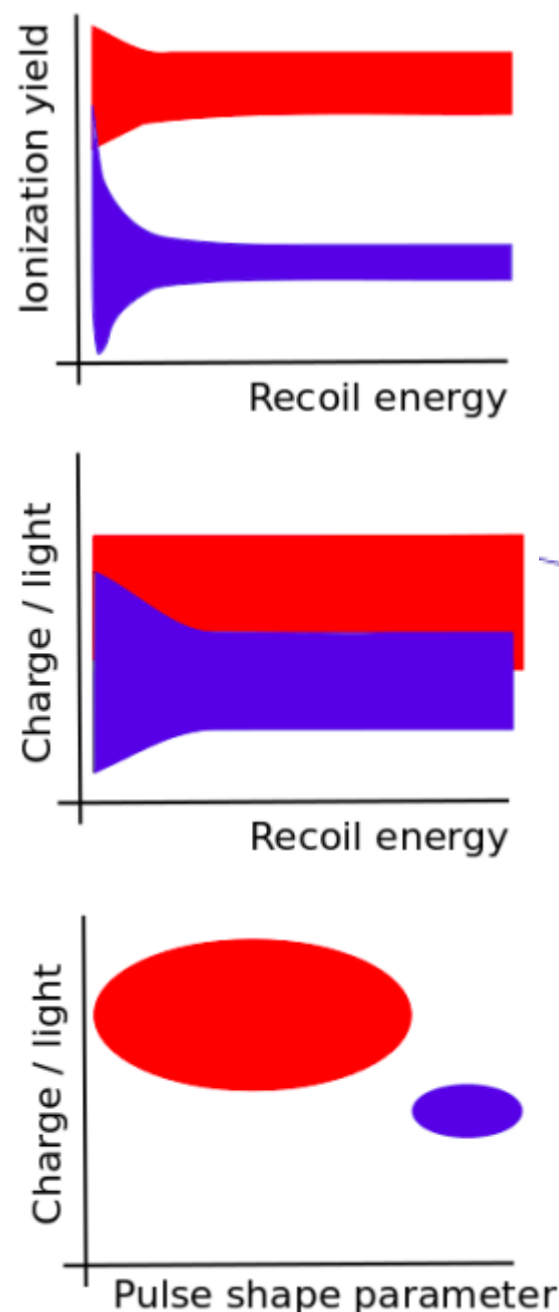
VERITAS

Basic Concepts

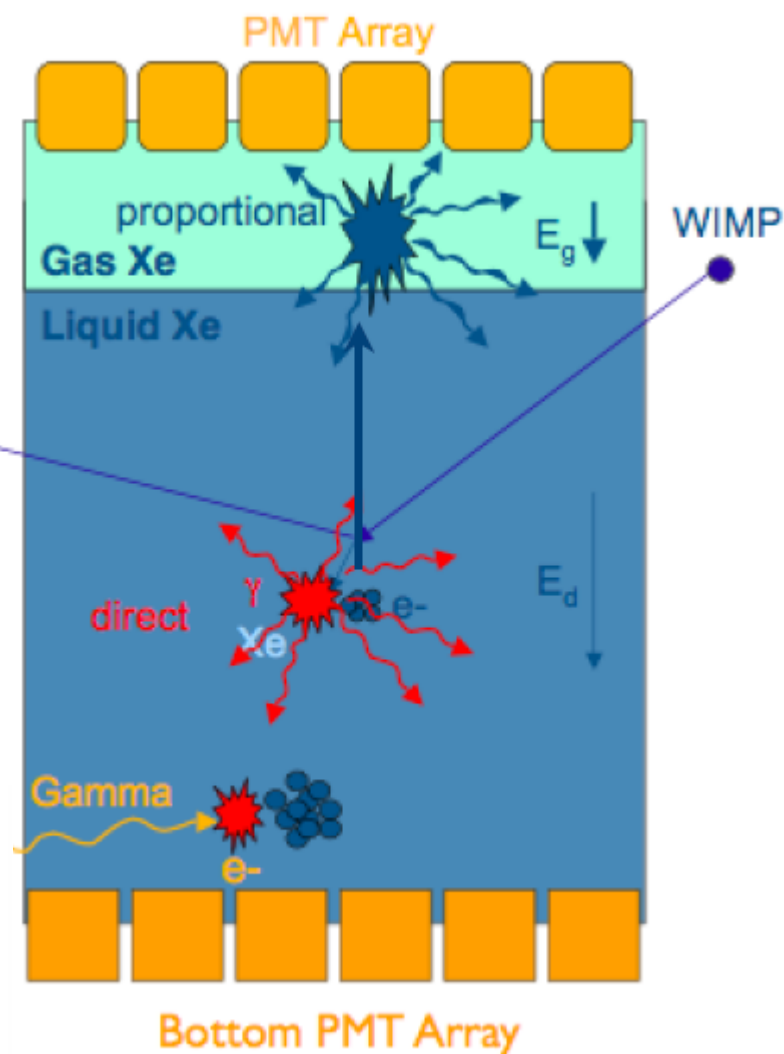
A. There is a smooth halo of dark matter particles in our galaxy described by a Maxwell Velocity distribution.

B. Due to the rotation of the Galactic Disk the solar system experiences an effective WIMP Wind, which lead to an annual Modulation due to Earth's orbital motion.

C. The nucleus is treated as a hard sphere described by the Helm form factor.

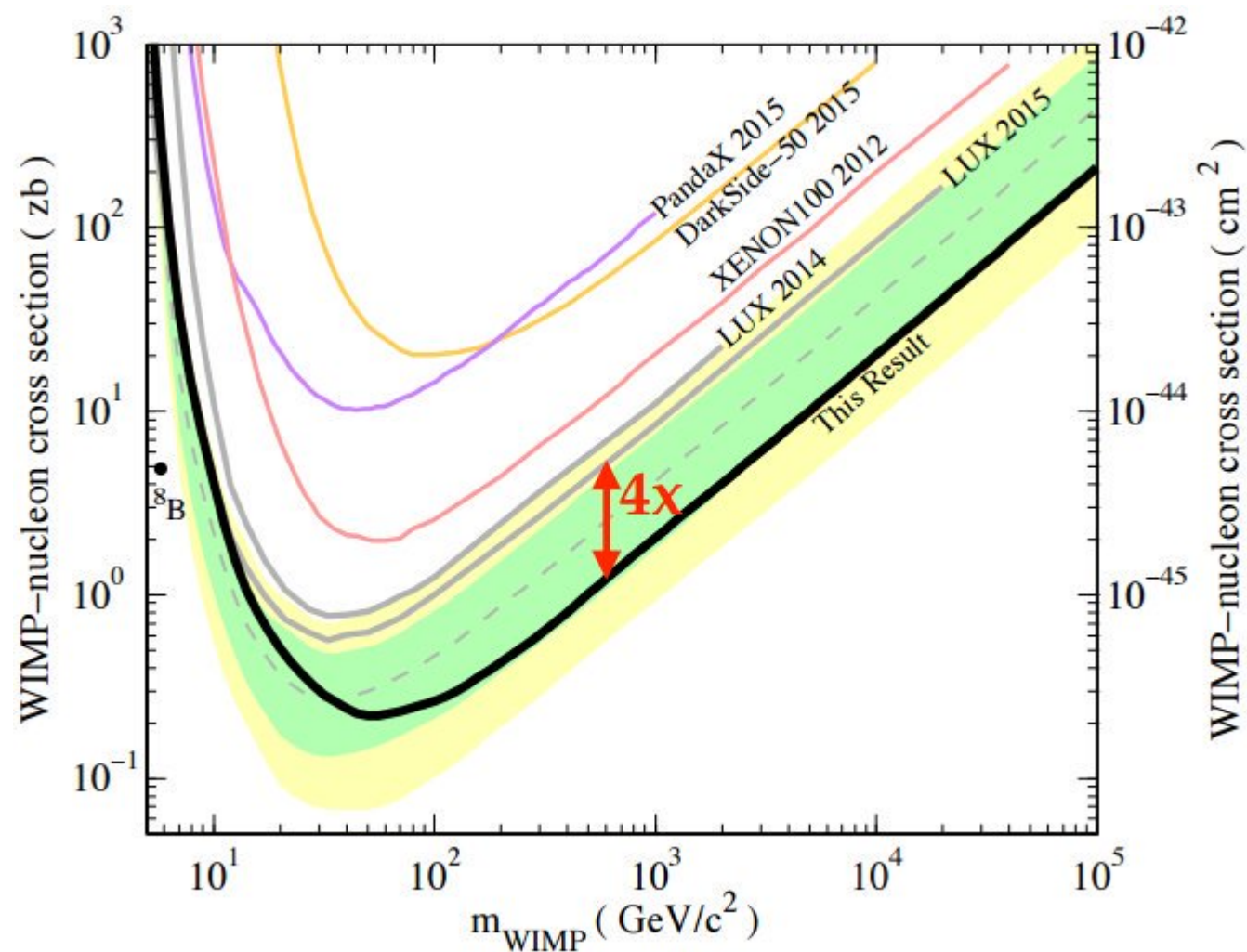


Direct Detection



$$\frac{dR}{dE}(E, t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v}, t) \cdot \frac{d\sigma}{dE}(E, v) d^3v$$

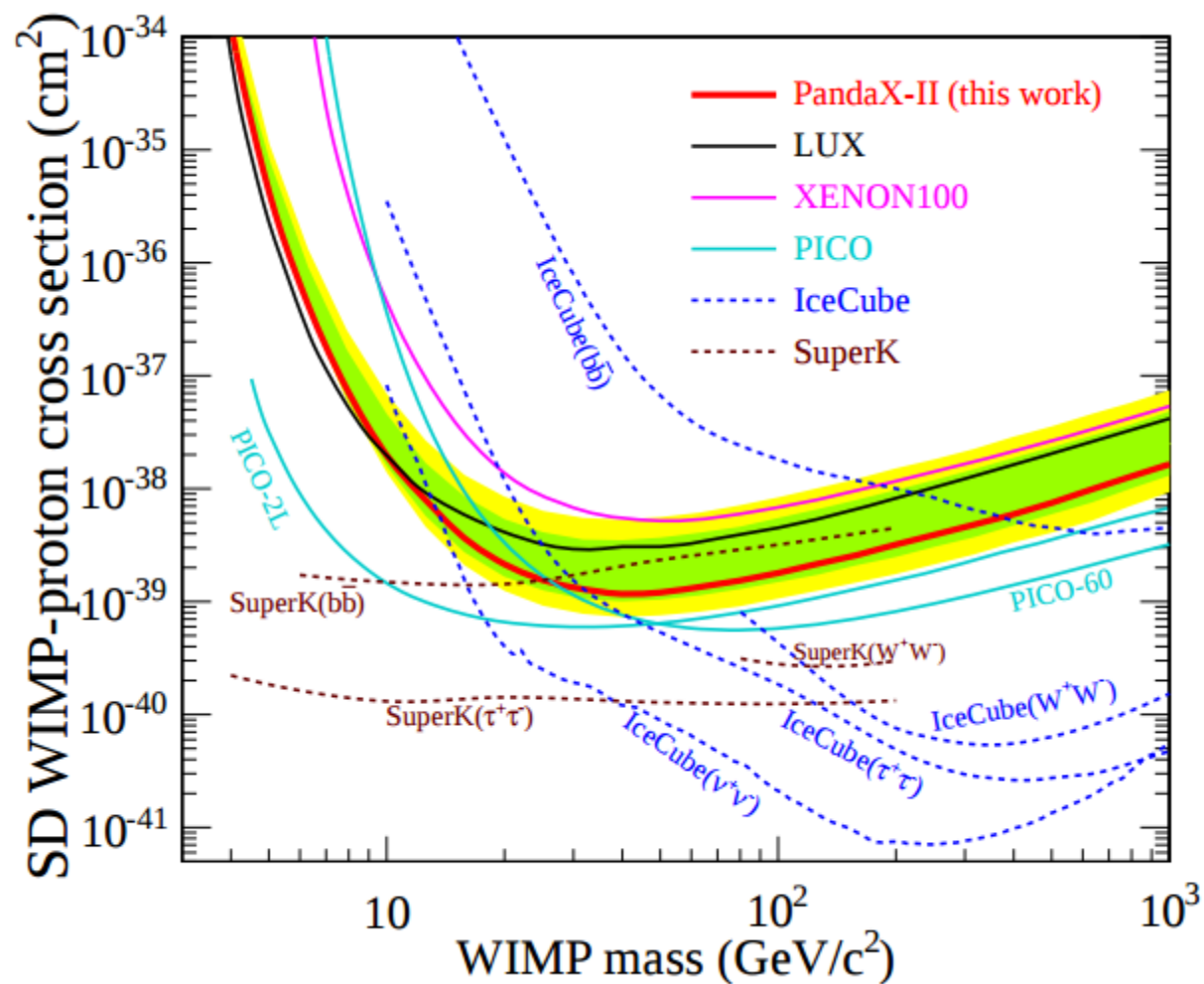
LUX collaboration: Spin-Independent Scattering



IDM conference in UK – July 21, 2016

PANDA-II collaboration: Spin-Dependent Scattering

1611.06553



Collider Searches

Basic Concepts

A. Dark matter is cosmologically stable, therefore is “seen” as missing energy at colliders, mono-X searches.

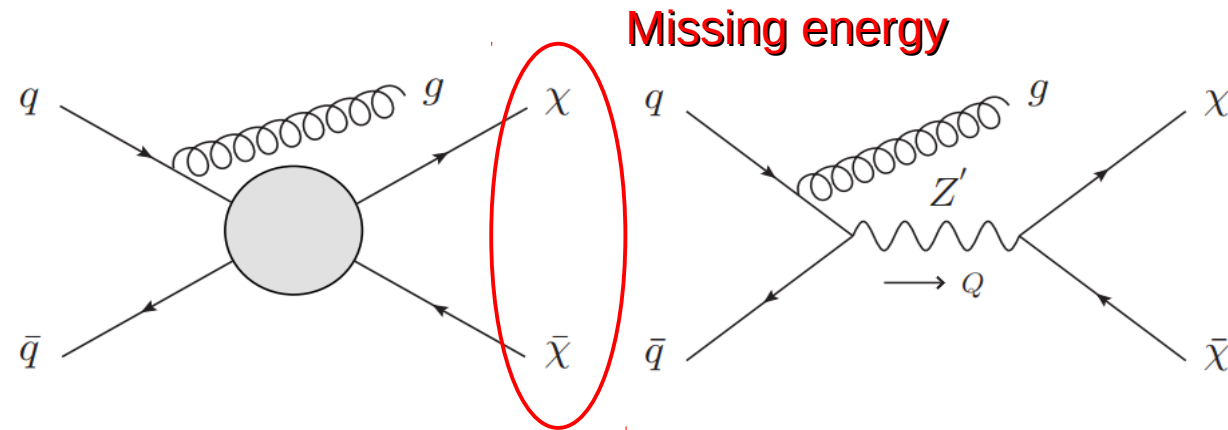
B. The observation relies on the detection of the accompanying particles/jets

C. Effective theory typically assumed. Use it wisely.

For a scan over several simplified dark matter models see:

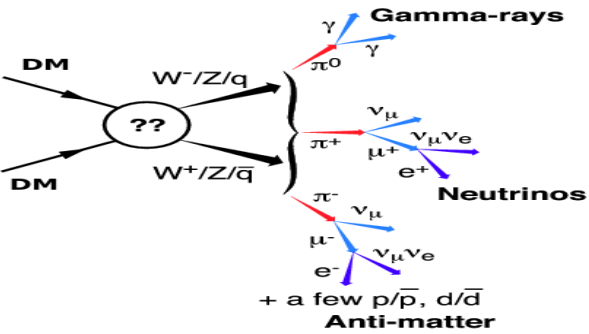
The ATLAS/CMS Dark Matter Forum, 1507.00966

Note: New resonance searches provide Stringent limits on new gauge bosons - often used as mediators between the dark and visible sectors.



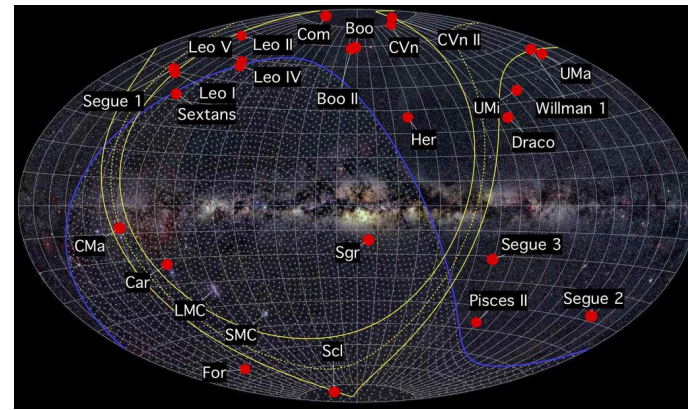
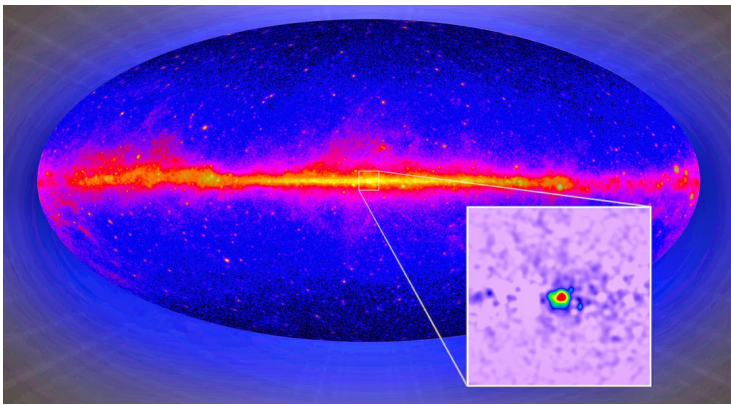
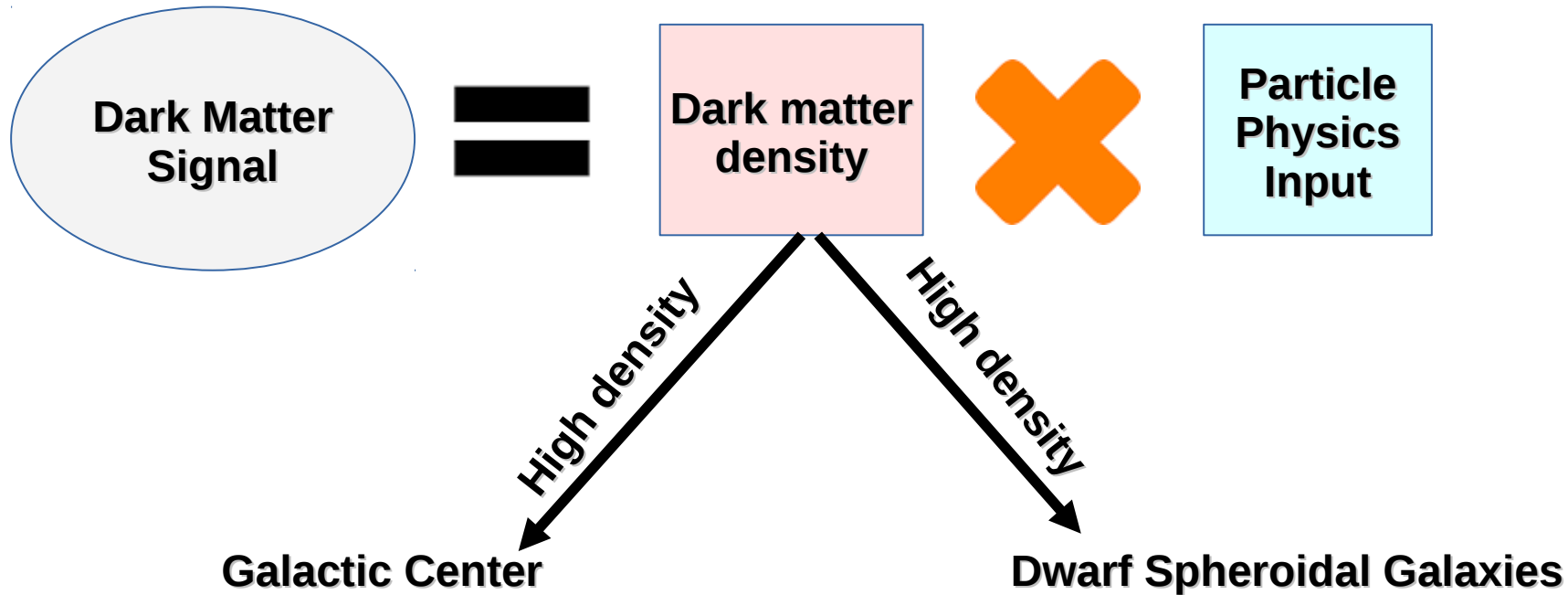
F. S. Queiroz, 1605.08788

Indirect Dark Matter Detection



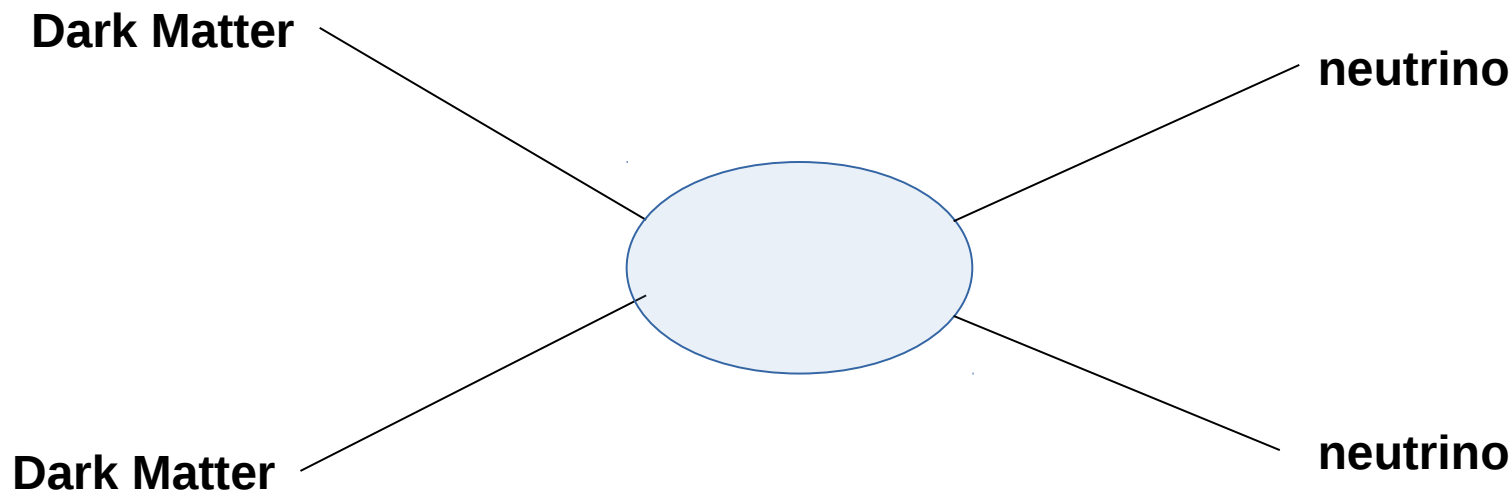
Dark Matter Indirect Detection

Review: T. Bringmann, C. Weniger, 1208.5481

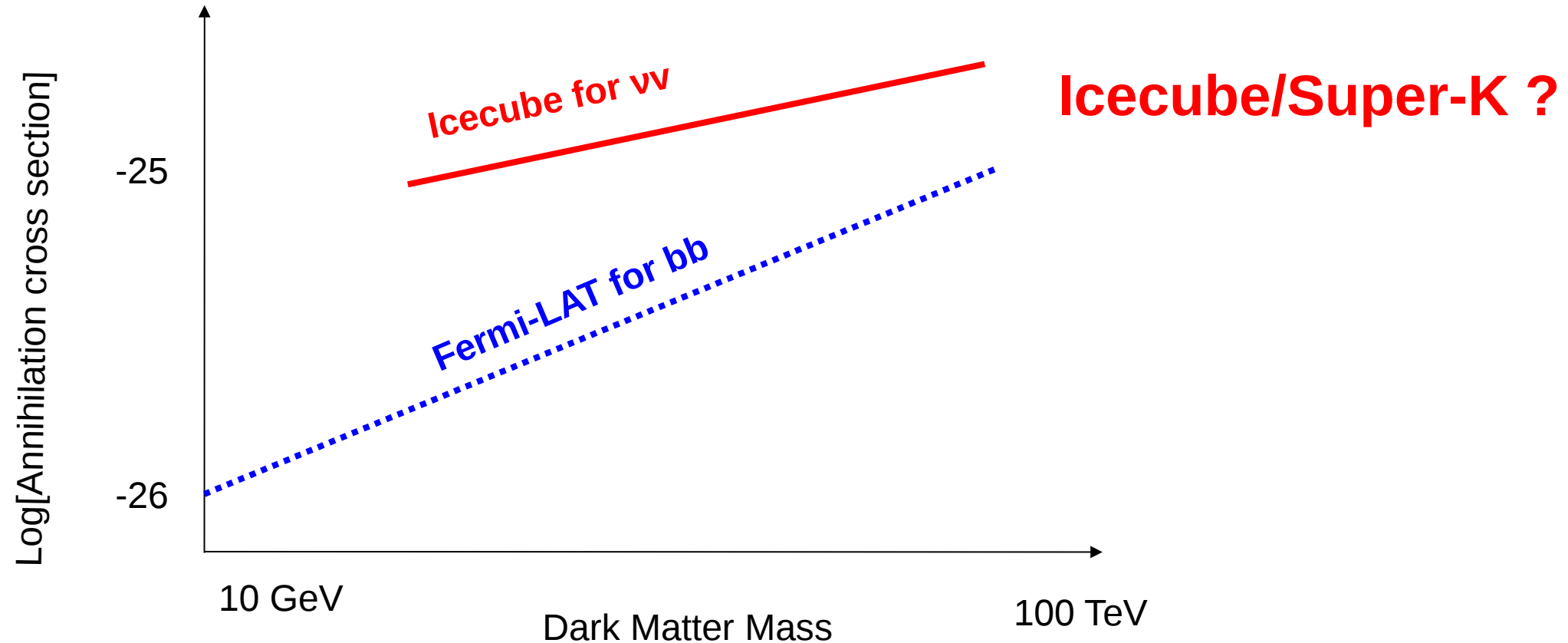


If you have a pair of dark matter particles annihilating purely into neutrinos. Which detector would you use to search for this dark matter particle?

Icecube/Super-K ?



If you have a pair of dark matter particles annihilating purely into neutrinos. Which detector would you use to search for this dark matter particle? Info: Mass in the 1GeV-100TeV range.



The best limits from Icecube are ~ 1 order of magnitude weaker than best limits from Fermi-LAT.....

But it's a neutrino line so I should Icecube/Super-K anyways, right?

**Well, actually both
gamma-ray and
neutrino telescopes!**

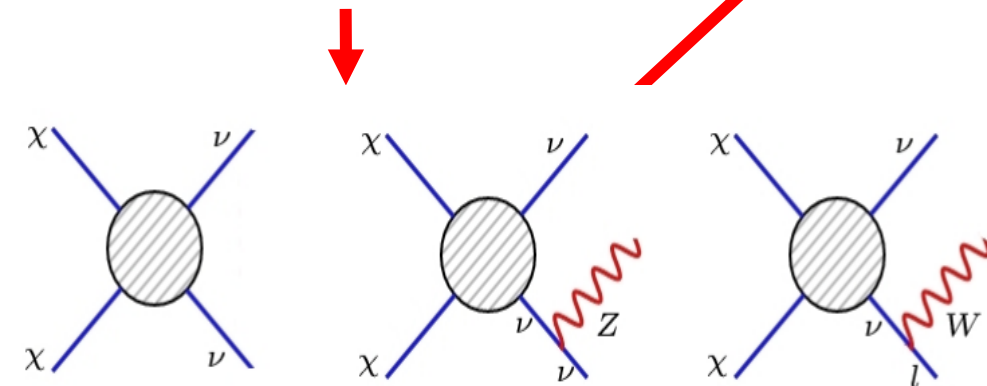
Searches for Dark Matter Annihilation into Neutrino Lines

Farinaldo Queiroz, C. Yaguna, C. Weniger - 1602.05966

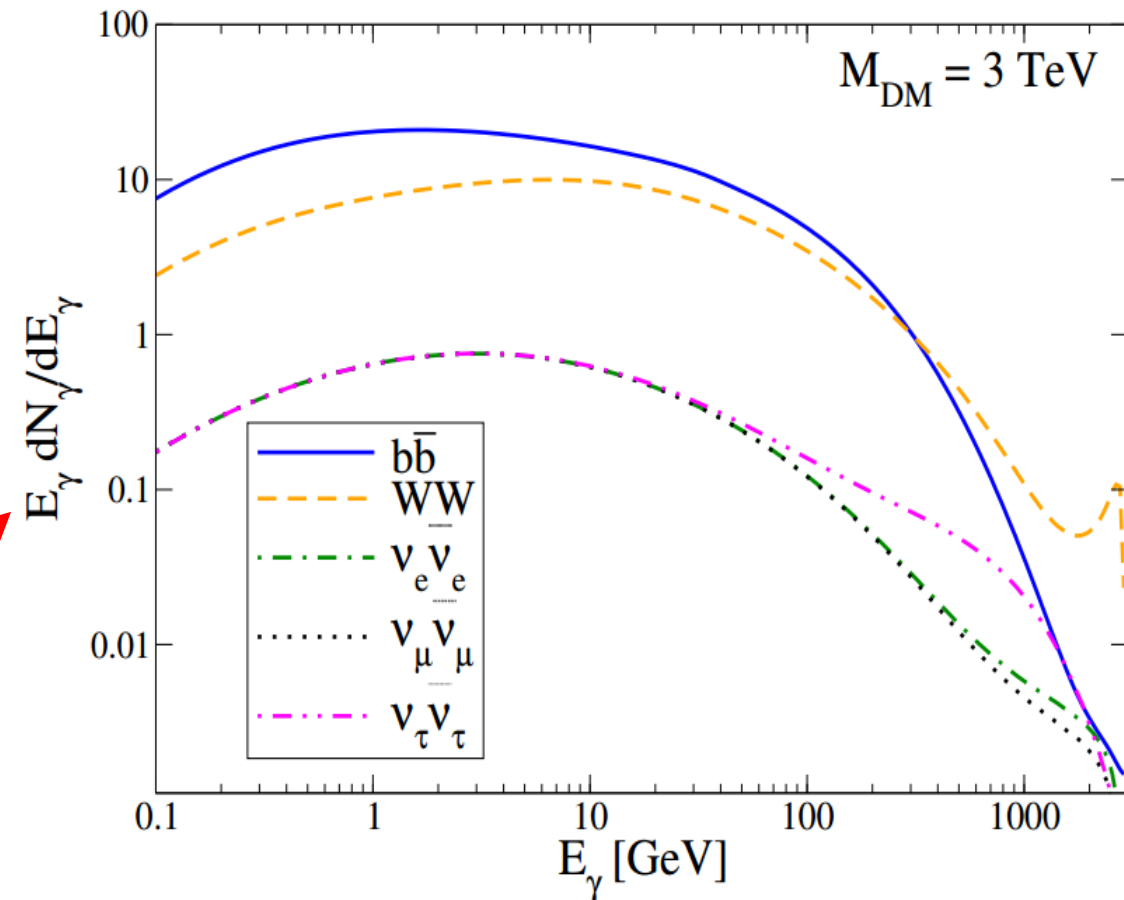
Neutrino telescopes have the advantage of being sensitive to both the WIMP-nucleus scattering and dark matter self-annihilation cross section.

Several searches for neutrinos flavors from dark matter annihilations have been Conducted by Super-K, IceCube and ANTARES collab. as well as by independent groups.

Please notice that weak corrections are important and a neutrino final state also gives rise to a gamma-ray emission which can be probed by Fermi-LAT/H.E.S.S. instruments.



Distinguishing neutrino flavors with gamma-rays

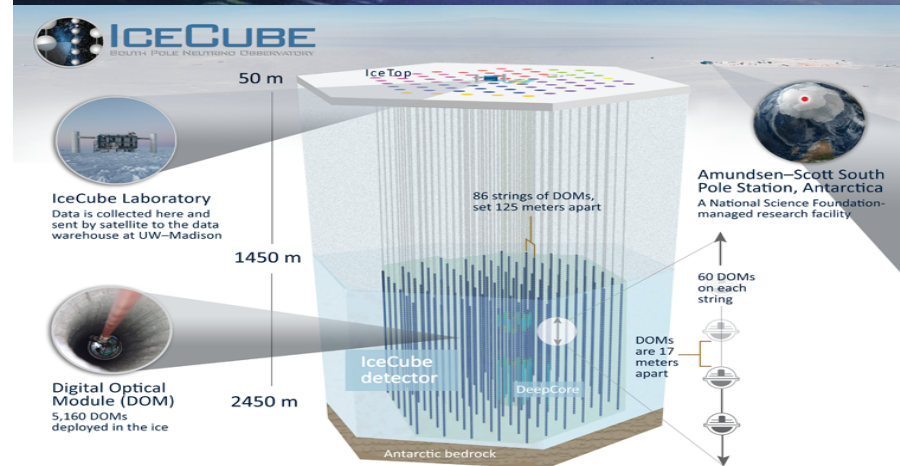
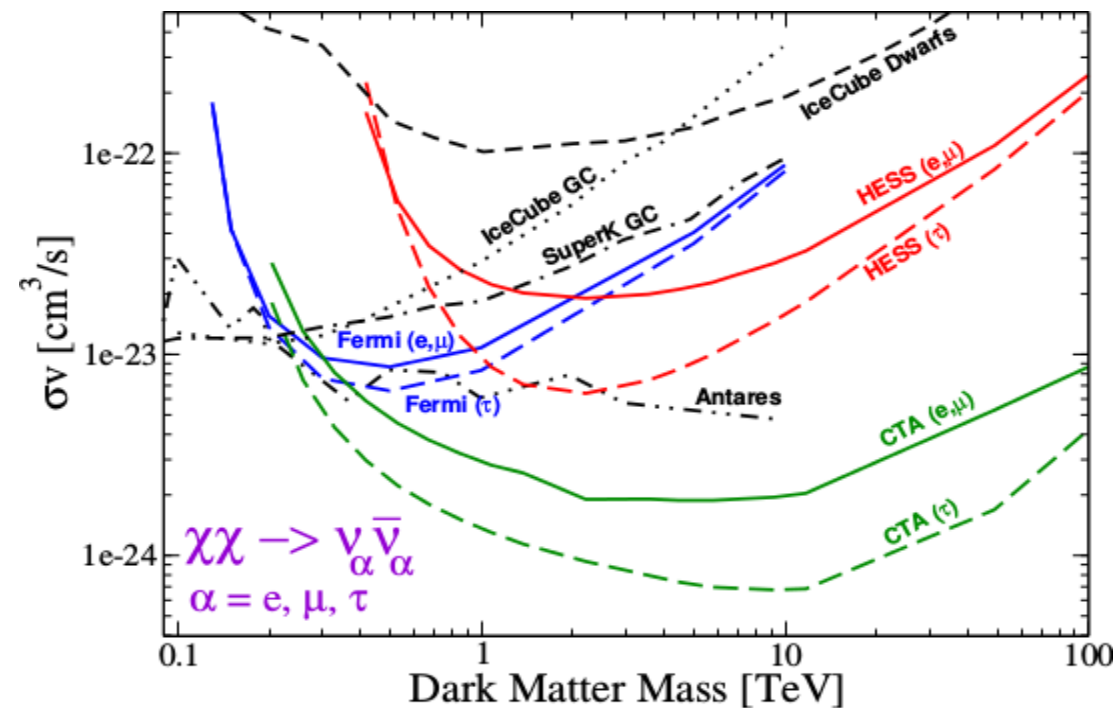
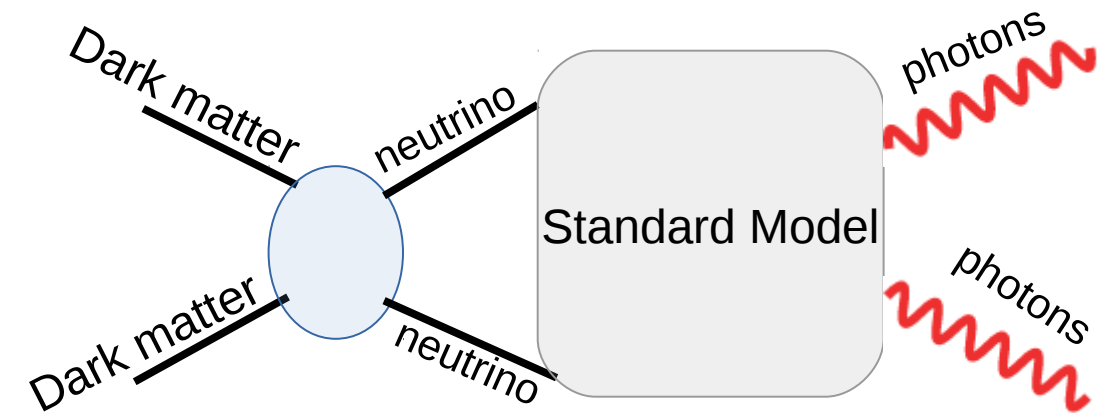


Notice that all three annihilation modes produce sizable continuous gamma-ray emission.

Dark Matter Annihilation

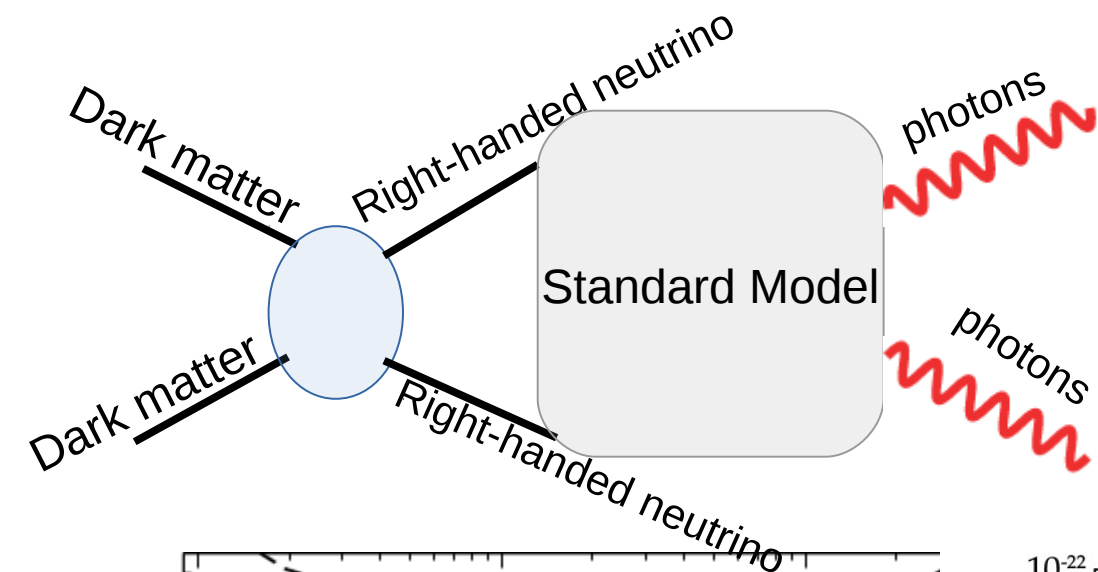
BEGINNING OF A NEW ERA: gamma-ray telescopes are more sensitive than neutrino detectors to neutrino signals from Dark matter annihilation.

The Cherenkov Telescope Array

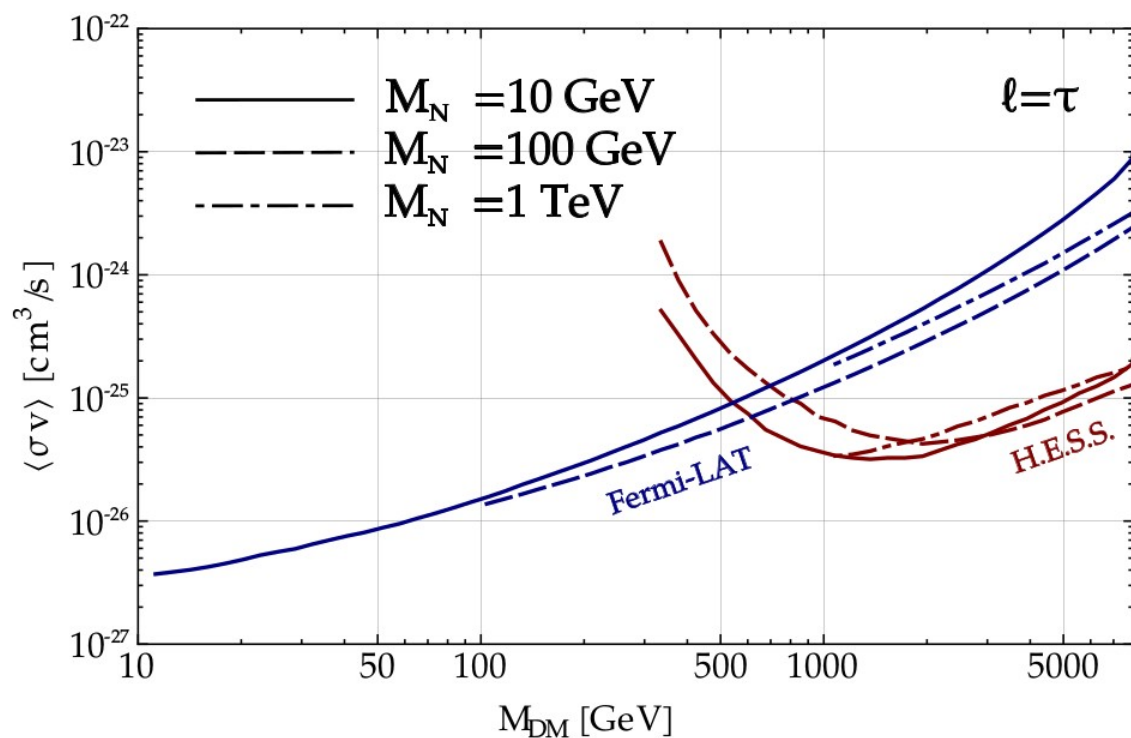
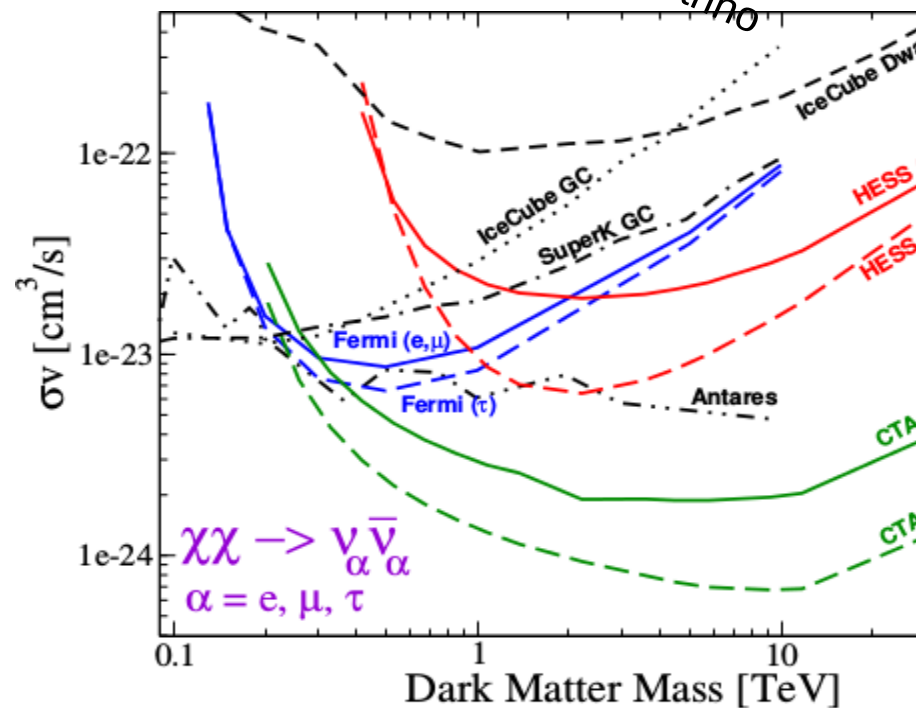


Dark Matter Annihilation

Let's restore SU(2) please!



Dark matter annihilations into right-handed neutrinos



So what's the nature of dark matter?

$$\mathcal{L}_{SI}^F = \lambda_{N,e} \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N + \lambda_{N,o} \bar{\psi}_\chi \gamma_\mu \psi_\chi \bar{\psi}_N \gamma^\mu \psi_N$$



Assuming only one operator dominates

$$\sigma_{SI}^M = \frac{4\mu_\chi^2}{\pi} [\lambda_p^M Z + \lambda_n^M (A - Z)]^2$$

Two measurements lead to

$$\begin{cases} [\lambda_p^M Z_X + \lambda_n^M (A_X - Z_X)]^2 = \frac{\pi \tilde{\sigma}_X}{4\mu_\chi^2}, \\ [\lambda_p^M Z_Y + \lambda_n^M (A_Y - Z_Y)]^2 = \frac{\pi \tilde{\sigma}_Y}{4\mu_\chi^2}. \end{cases}$$

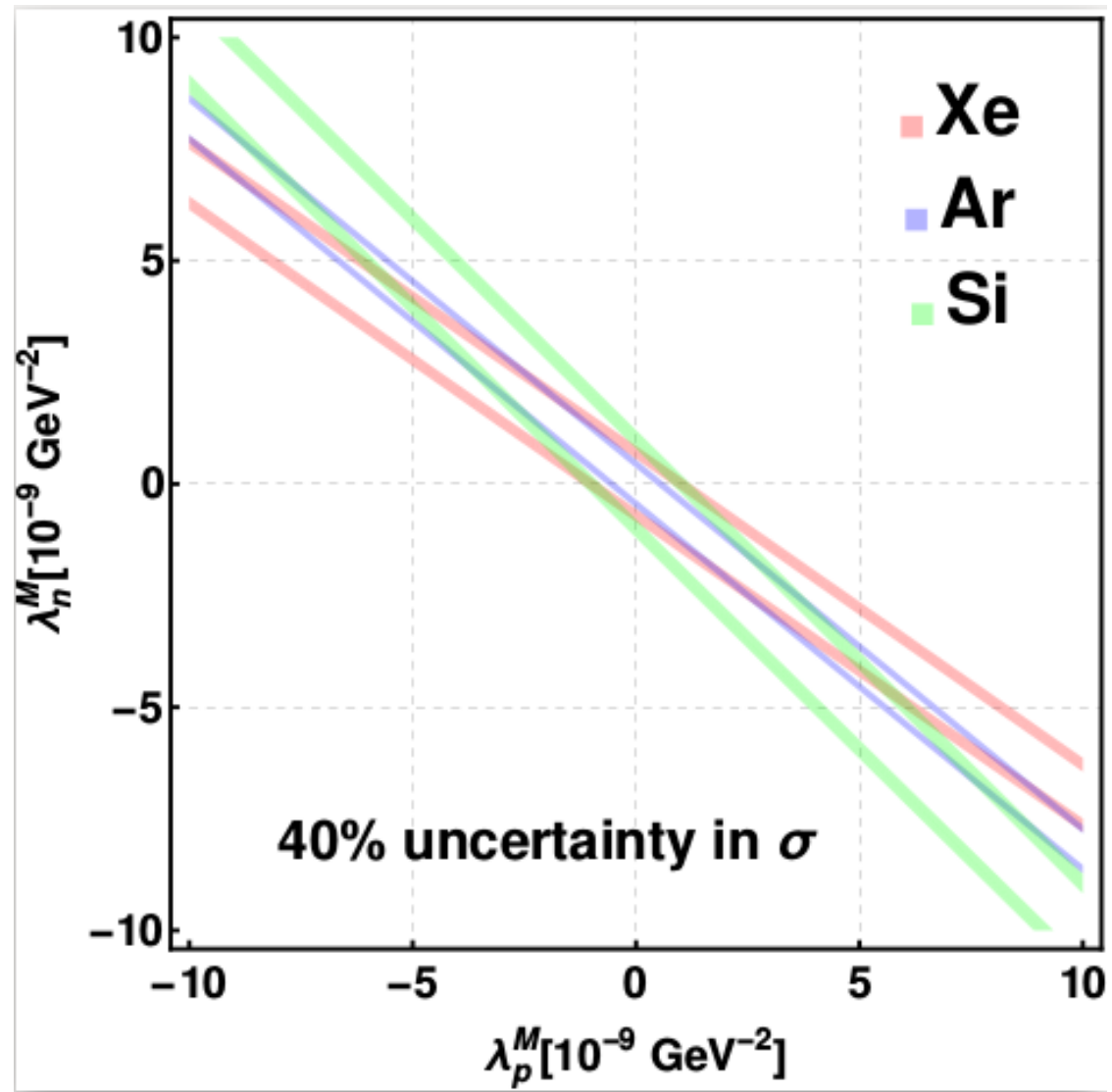
**Solution:
two parallel lines with slopes**

$$\begin{cases} m_X = Z_X / (A_X - Z_X) \\ m_Y = Z_Y / (A_Y - Z_Y) \end{cases}$$

So what's the nature of dark matter?

As for three measurements

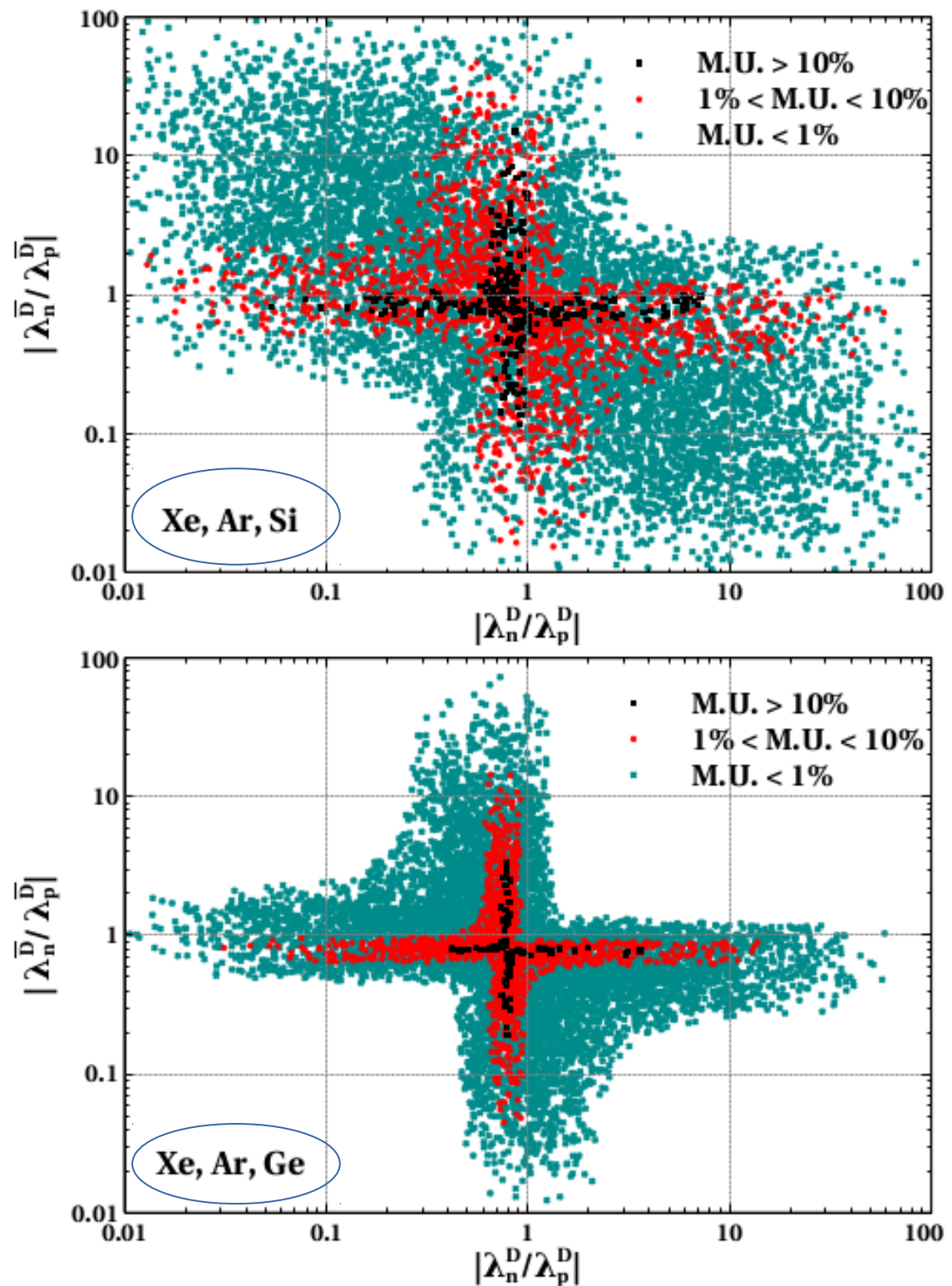
1. If there are is no overlapping region between the three lines
2. Our interpretation in terms of a Majorana DM particle must be wrong.
3. We would conclude, therefore, that the DM is a Dirac particle.



So what's

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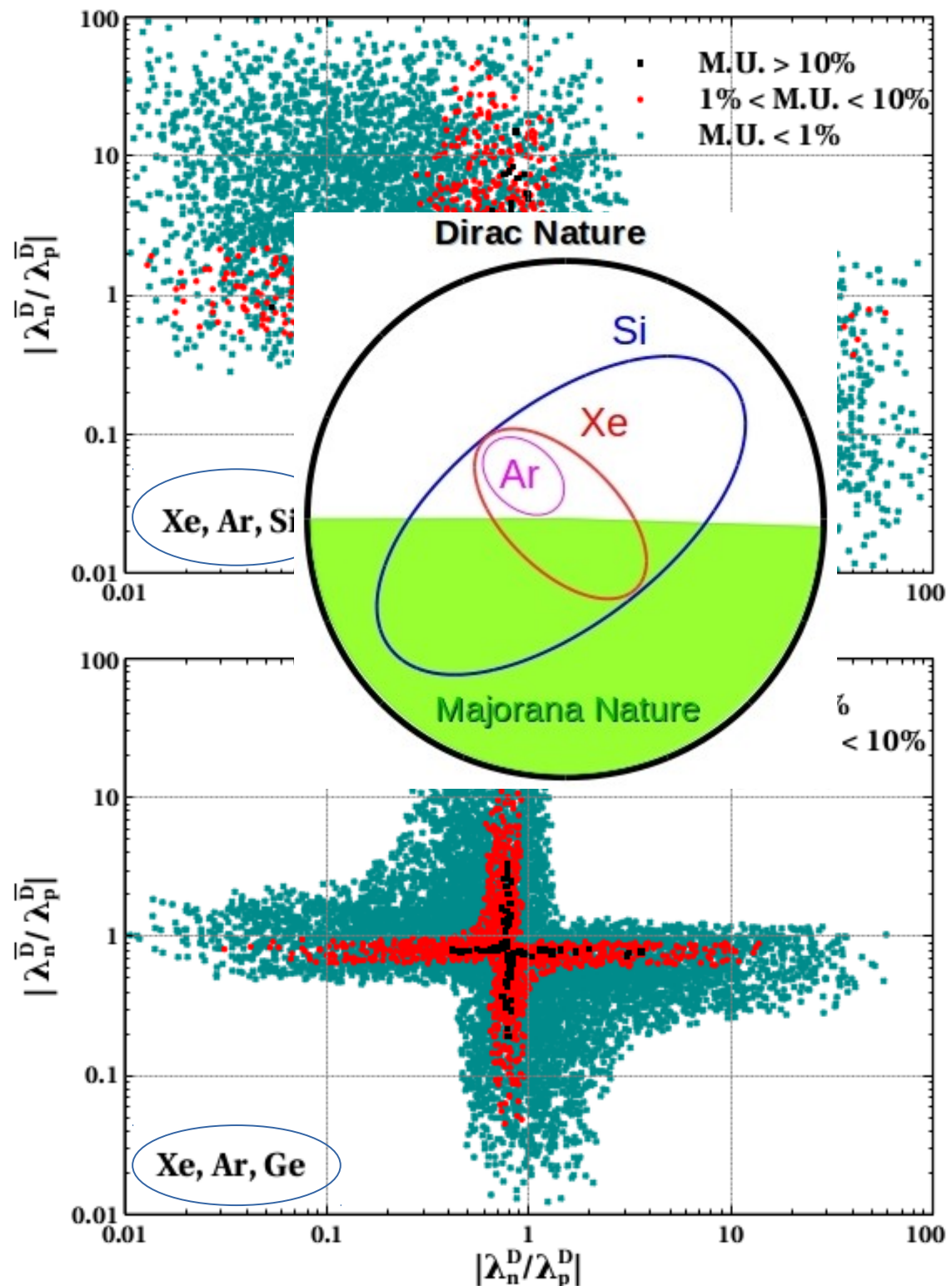
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As for three measurements

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3. We would conclude, therefore, that the DM is a Dirac particle.

A new test where the
fundamental nature of
dark matter may be
unveiled!

Uncertainties on the scattering CS
need to be less than 50%.



Conclusions/Take home messages

1. Beginning of a **NEW ERA**: Gamma-rays telescopes are more sensitive than neutrino detectors to neutrino lines from dark matter annihilation
2. There is a way to determine the fundamental nature of dark matter

Let's be Optimistic