Search for low-mass dark matter candidates with direct detection experiments

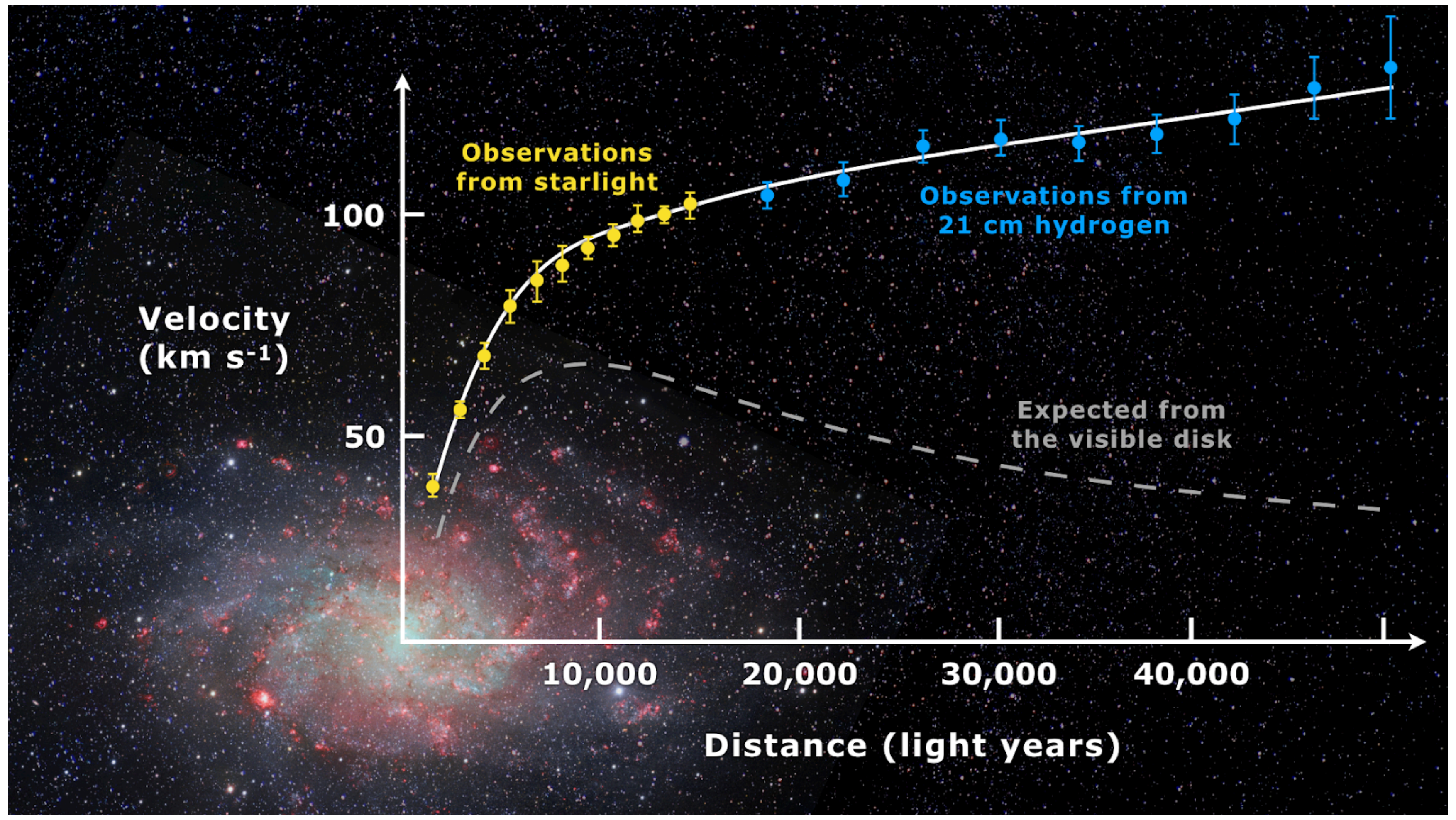
Stefano Piacentini 02 / 03 / 2022

Outline

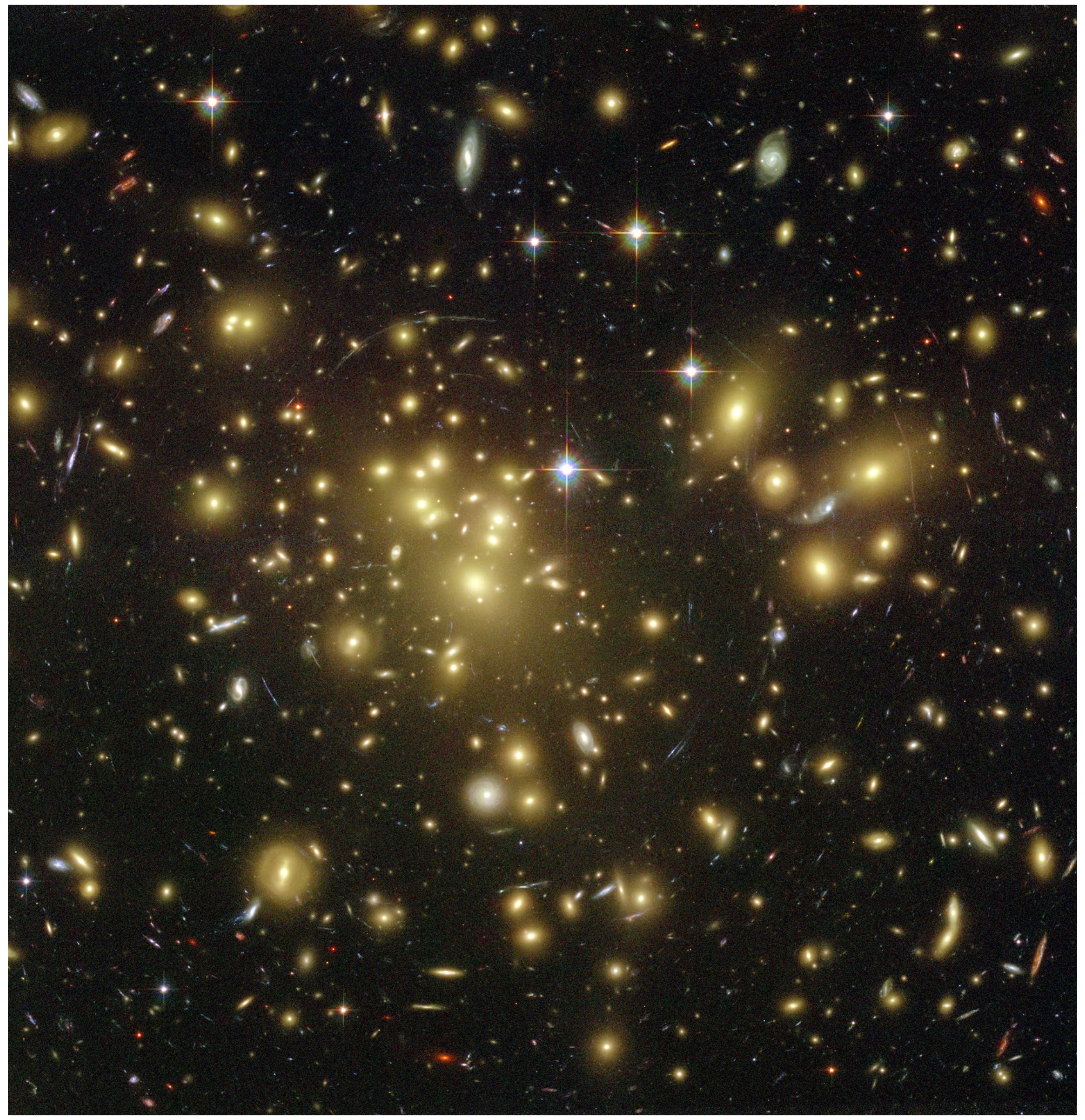
- The dark matter problem:
  - Evidence
  - Candidates

- Direct detection of dark matter
  - State-of-the-art
  - The Migdal effect
  - The problem of the systematic uncertainties

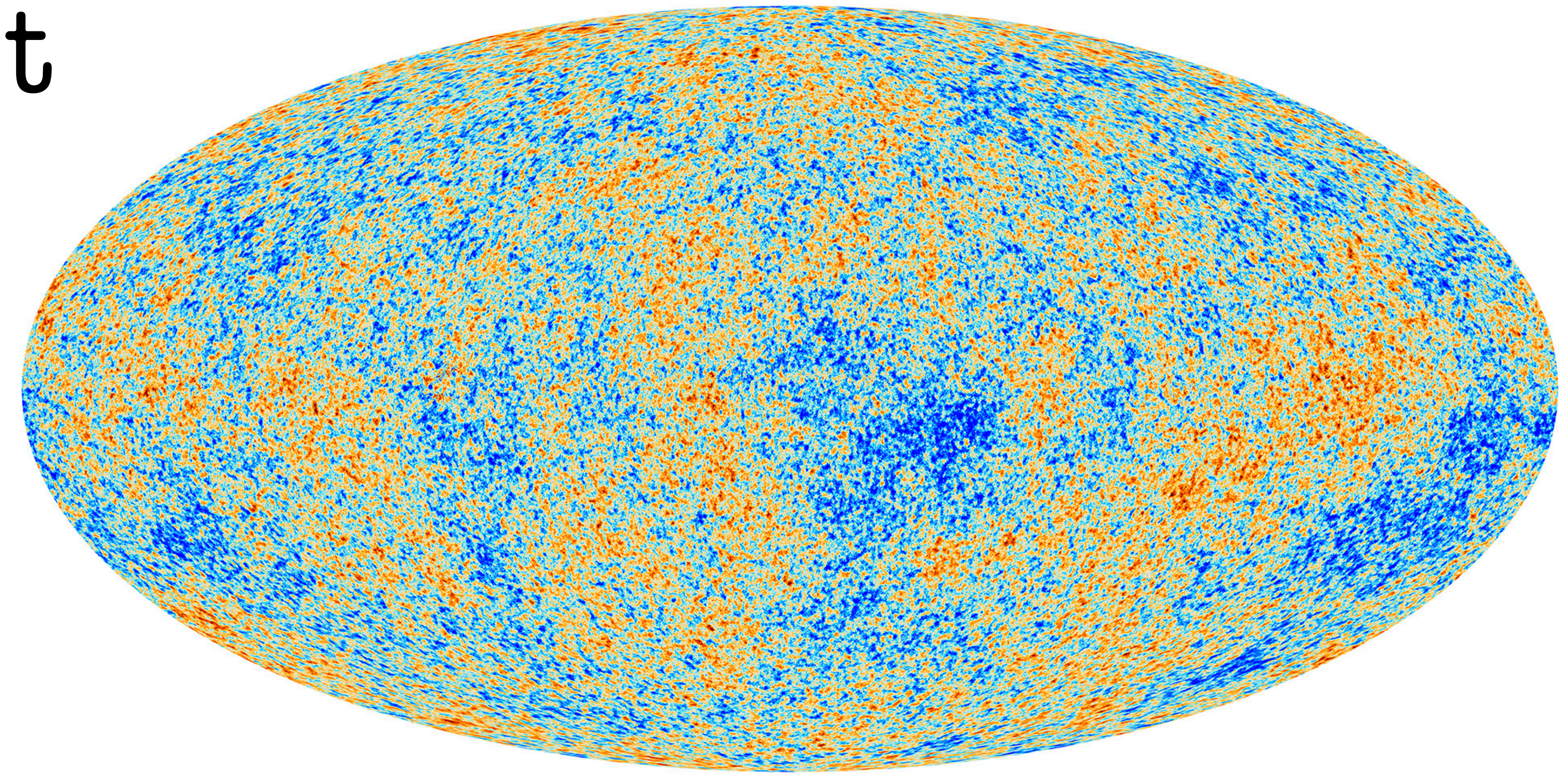
The dark matter problem



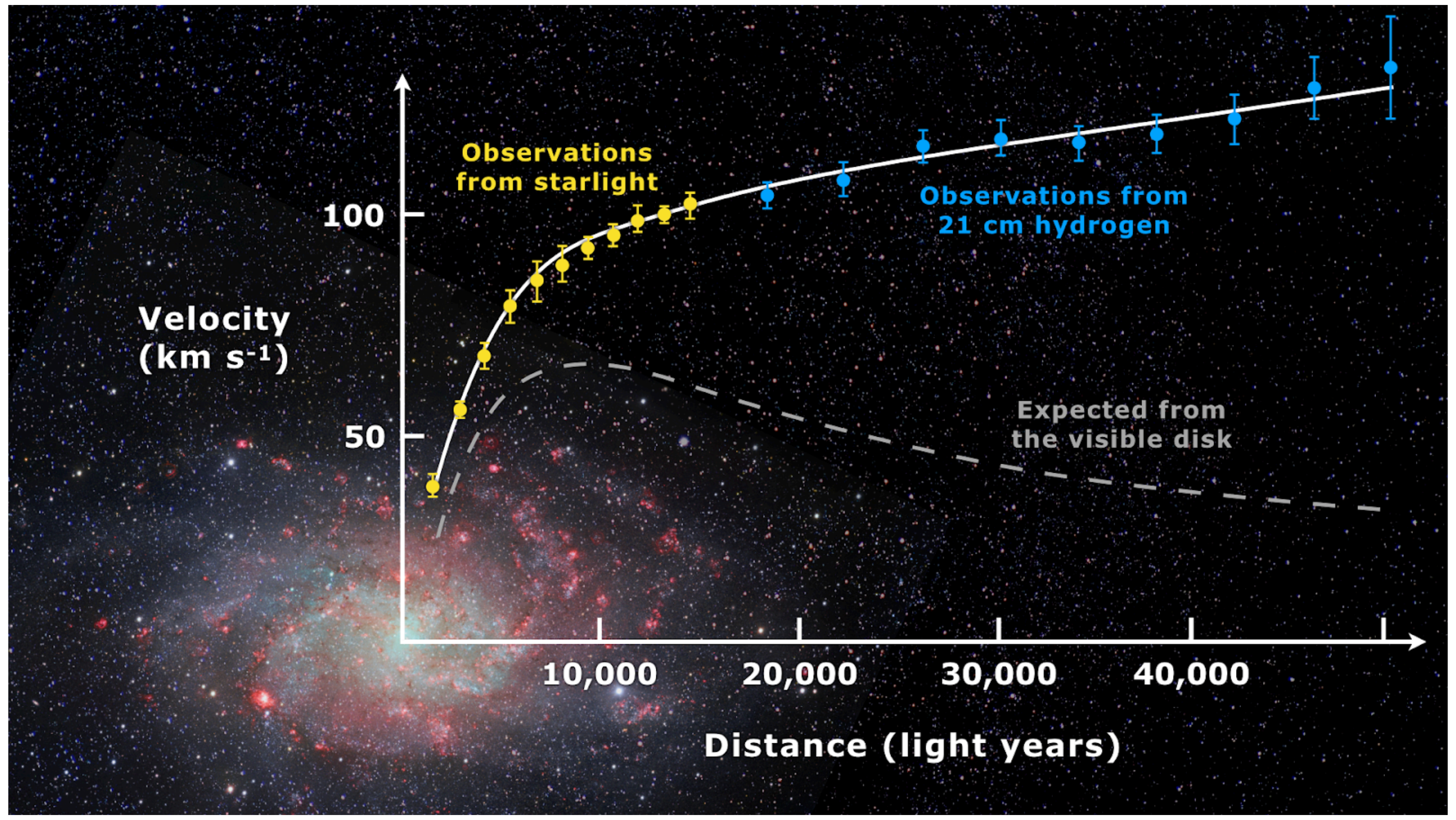
Cosmological and astronomical
observations strongly support
the existence of dark matter (DM)



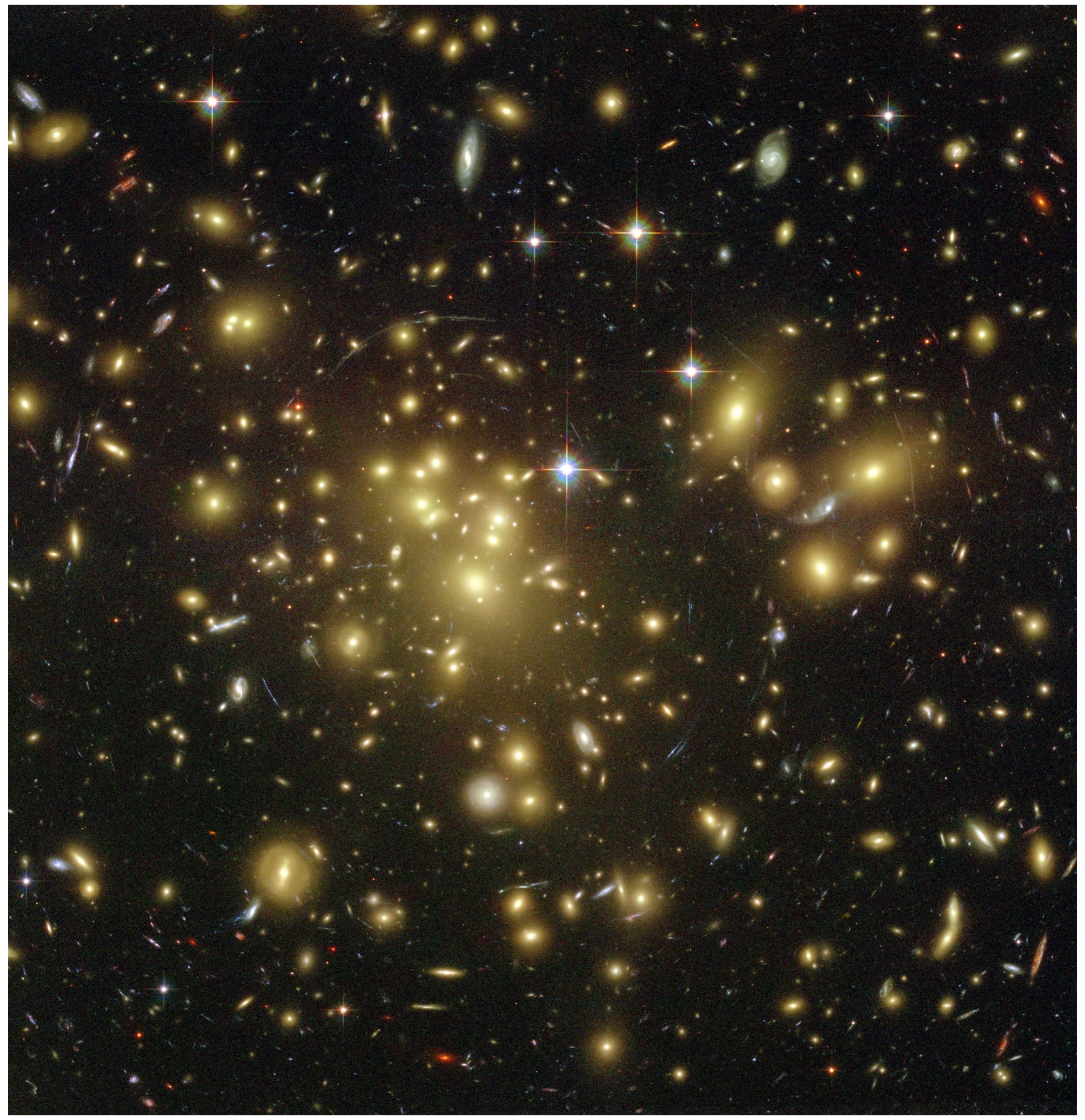
However its nature - i.e. its mass,
interactions with the Standard
Model (SM), etc. - has not
yet been revealed.



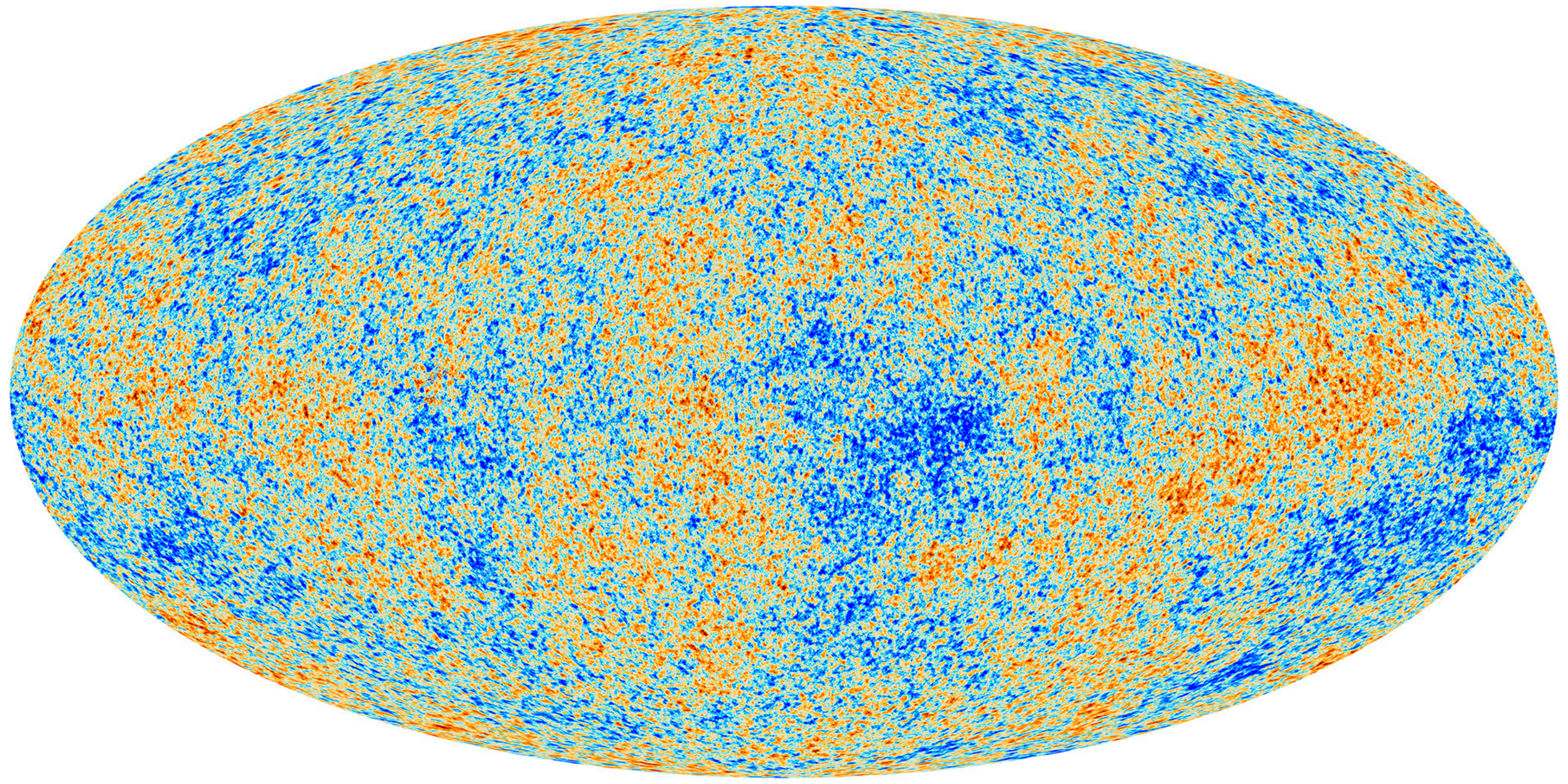
Dark matter evidence



- Spiral galaxy rotation curve [Begeman, Broeils, Sanders]
- Gravitational lensing [arXiv:1003.5567] [arXiv:1411.0115] [Paczynski (1986)]
- Cosmic Microwave Background (CMB) anisotropies [arXiv:1807.06209]
- Large scale structure formation [arXiv:2105.13549]
- Bullet cluster [astro-ph/0608407]



Many observations at very different scales can be explained by the existence of DM



Dark matter candidates

Properties it has to satisfy:

- it has a non-zero **mass**
- it is **not baryonic** (to explain CMB)
- it is **electrically neutral** (it doesn't have EM interactions)
- if coupled to the SM, the **interactions** have to be **weak** (we have not observed them yet)
- it is **stable** on a cosmological timescale (DM is still there and it is not decayed yet)
- it is mainly "**cold**", i.e. non-relativistic

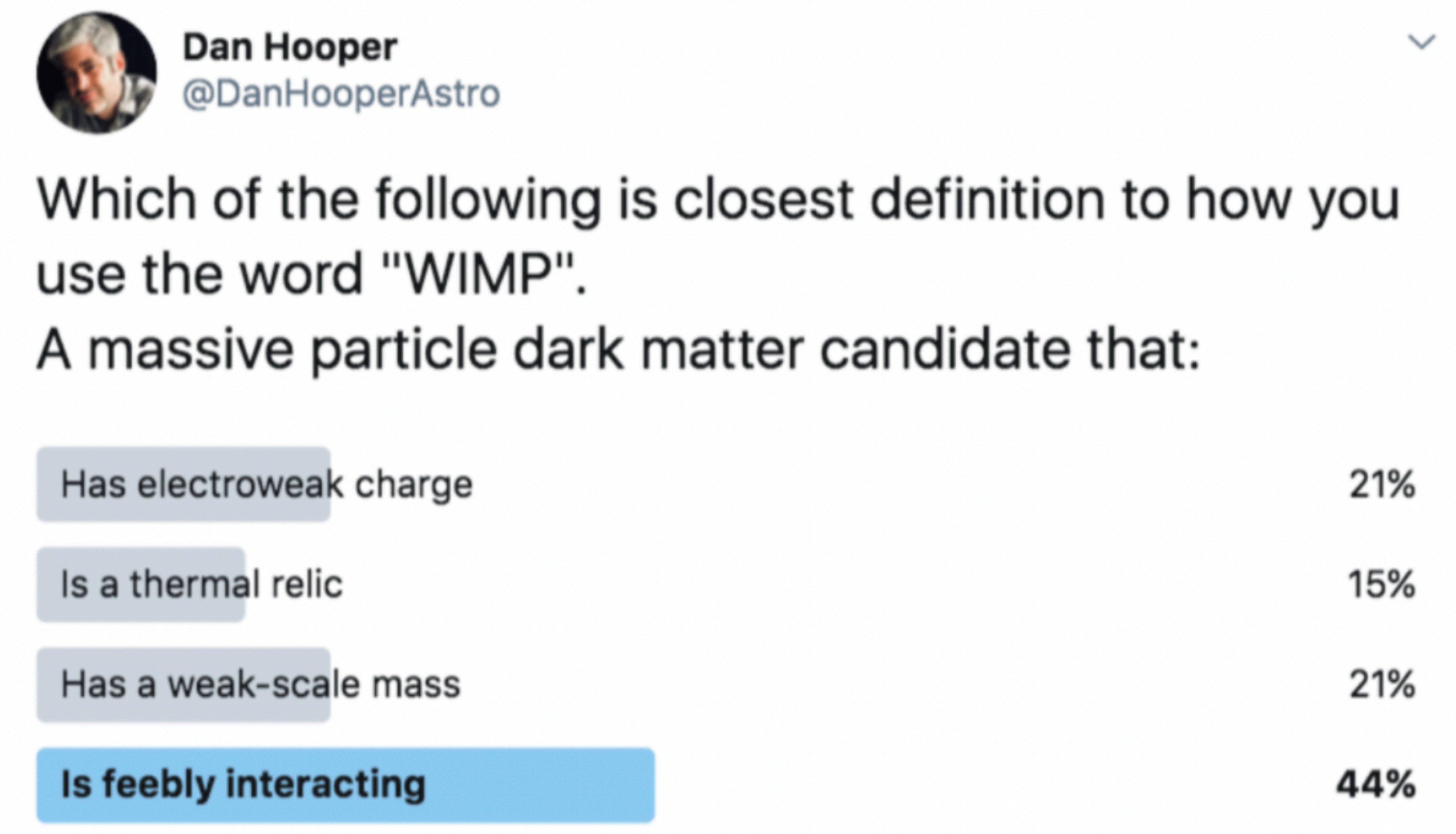
Required to explain large scale structure formation ["hot" component at most $\sim$1% of the total DM]

[arXiv:2105.13549]

Dark matter candidates

arXiv:1810.01668

Weakly Interactive Massive Particles



Dan Hooper
@DanHooperAstro

Which of the following is closest definition to how you use the word "WIMP".
A massive particle dark matter candidate that:

Has electroweak charge	21%
Is a thermal relic	15%
Has a weak-scale mass	21%
Is feebly interacting	**44%**

The precise definition of Weakly Interacting Massive Particle (WIMP) has changed during the years.

In the following we will illustrate the search for a massive stable neutral particle with small couplings to the SM particles.

The most theoretically motivated mass region for this kind of candidate is the EW scale (1 GeV/c^2 - 10 TeV/c^2)

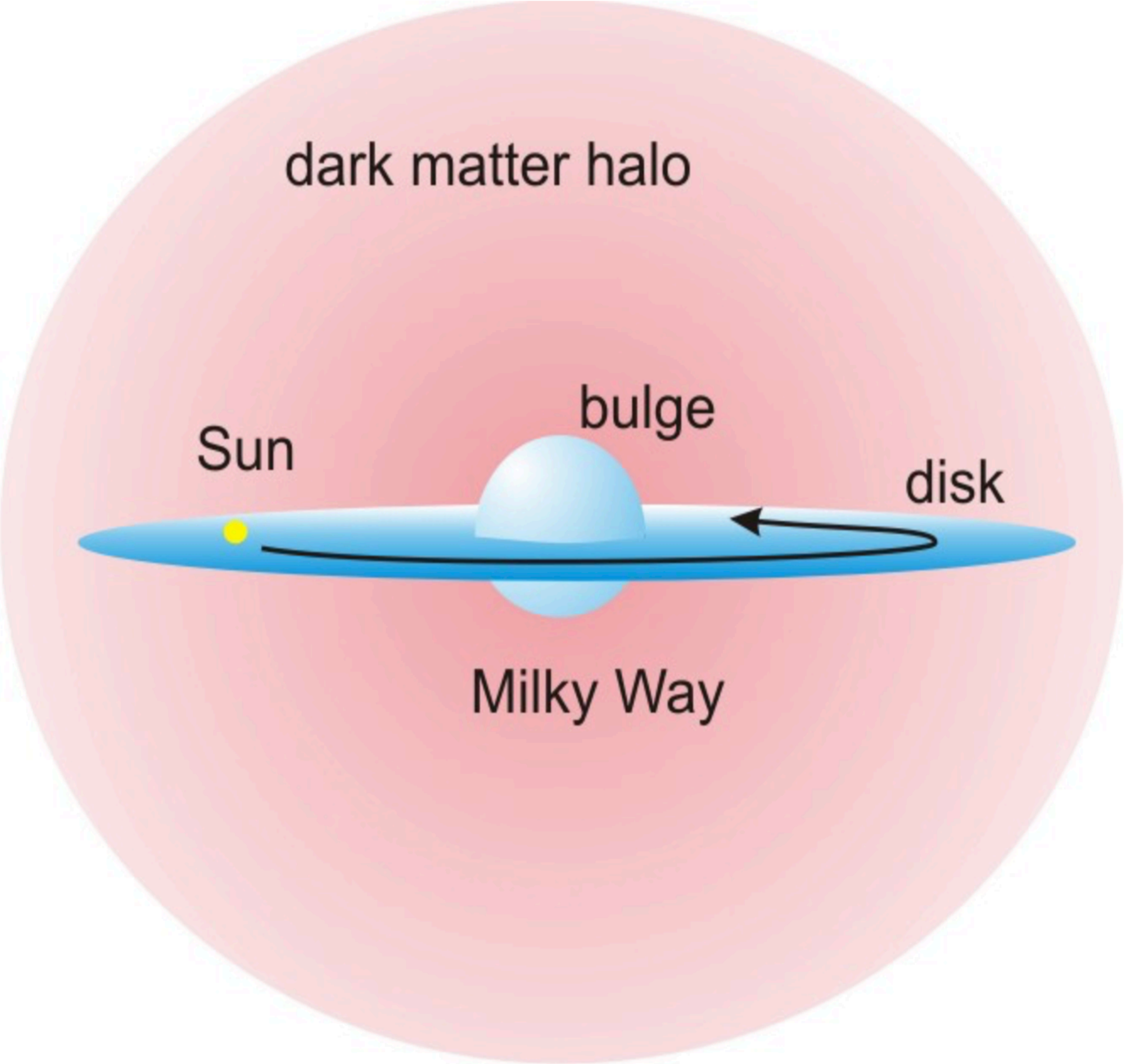
arXiv:2104.07634

Standard Galactic Halo Model

The Standard galactic Halo Model (SHM) is a model describing the DM distribution in the Milky Way.

The DM halo is modeled as an isothermal isotropic collisionless gas-like halo, where the DM velocity follows a Maxwell-Boltzmann distribution.

The solar system is traveling in this halo: in its reference frame it is hit by a DM wind coming from the direction of the Cygnus constellation.



Commonly adopted parameters:

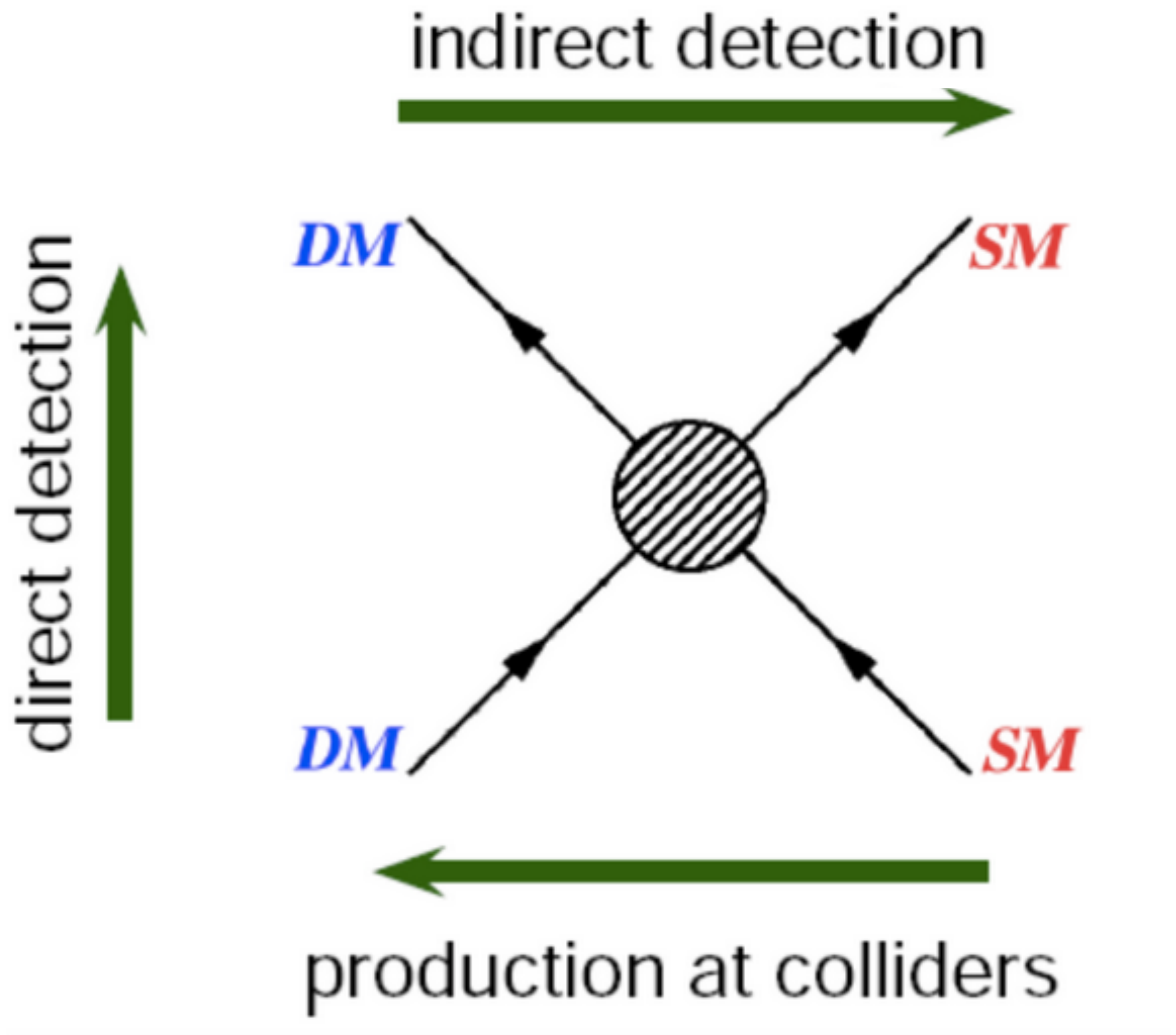
- local DM density $\rho(R_\odot) = 0.3\ \mathrm{GeV cm^{-3}} c^{-2}$
- local circular speed $v_c(R_\odot) = 230\ \mathrm{km\ s^{-1}}$
- local escape speed $v_{esc}(R_\odot) = 544\ \mathrm{km\ s^{-1}}$

How can we detect dark matter?

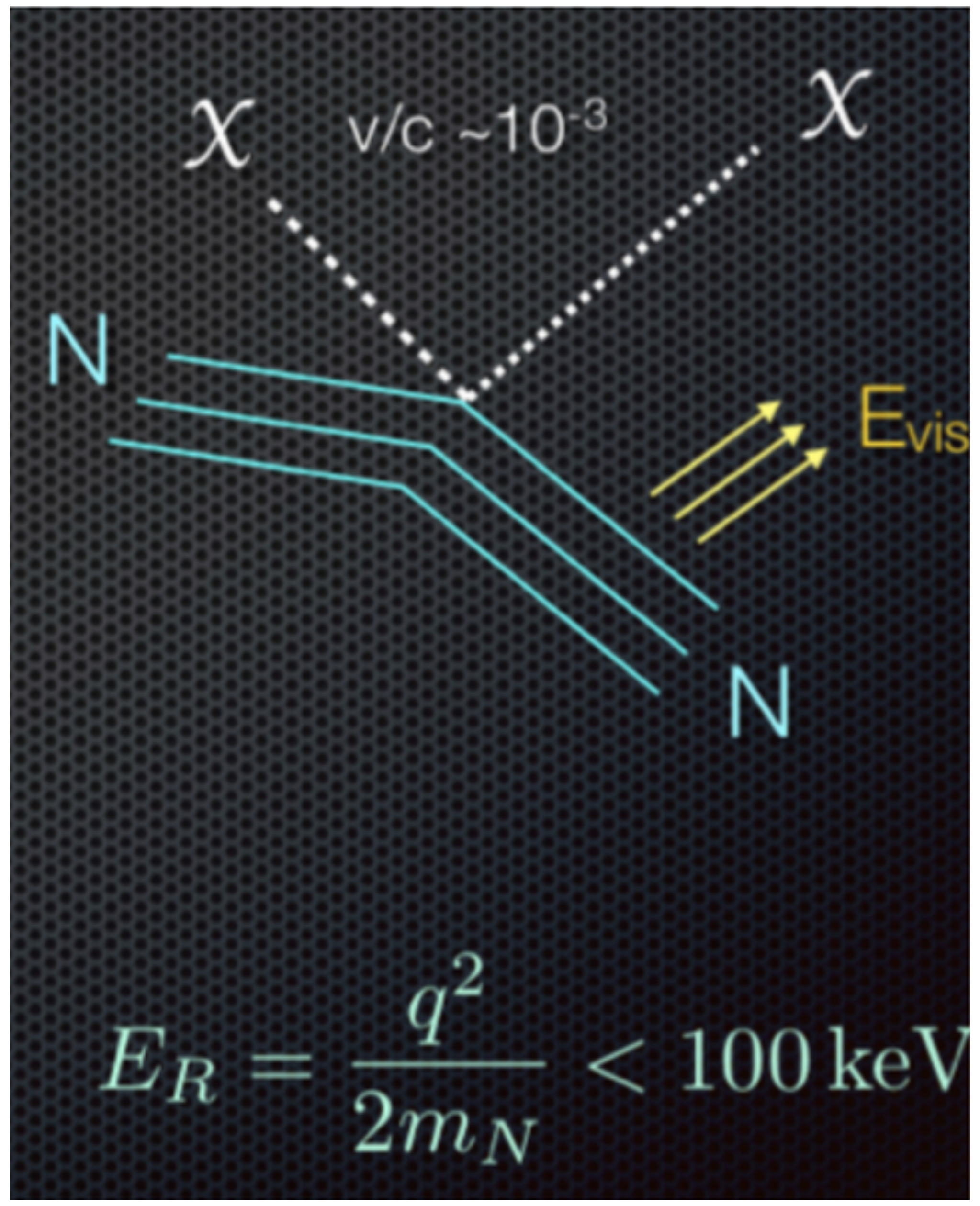
1. Colliders: produce DM particles in an accelerator from the interaction of two SM particles

2. Indirect detection: look for any excess of SM particles or anti- particles produced from DM annihilation or decay

3. Direct detection: look for the recoils that DM particles should induce in the constituents of the ordinary matter (mainly nuclei)



Direct detection experiments



DM-nucleus energy spectrum is
~ exponentially decreasing:

$$\frac{dR}{dE_R} \sim \frac{R_0}{E_0} \exp\left[-\frac{E_R}{E_0}\right]$$

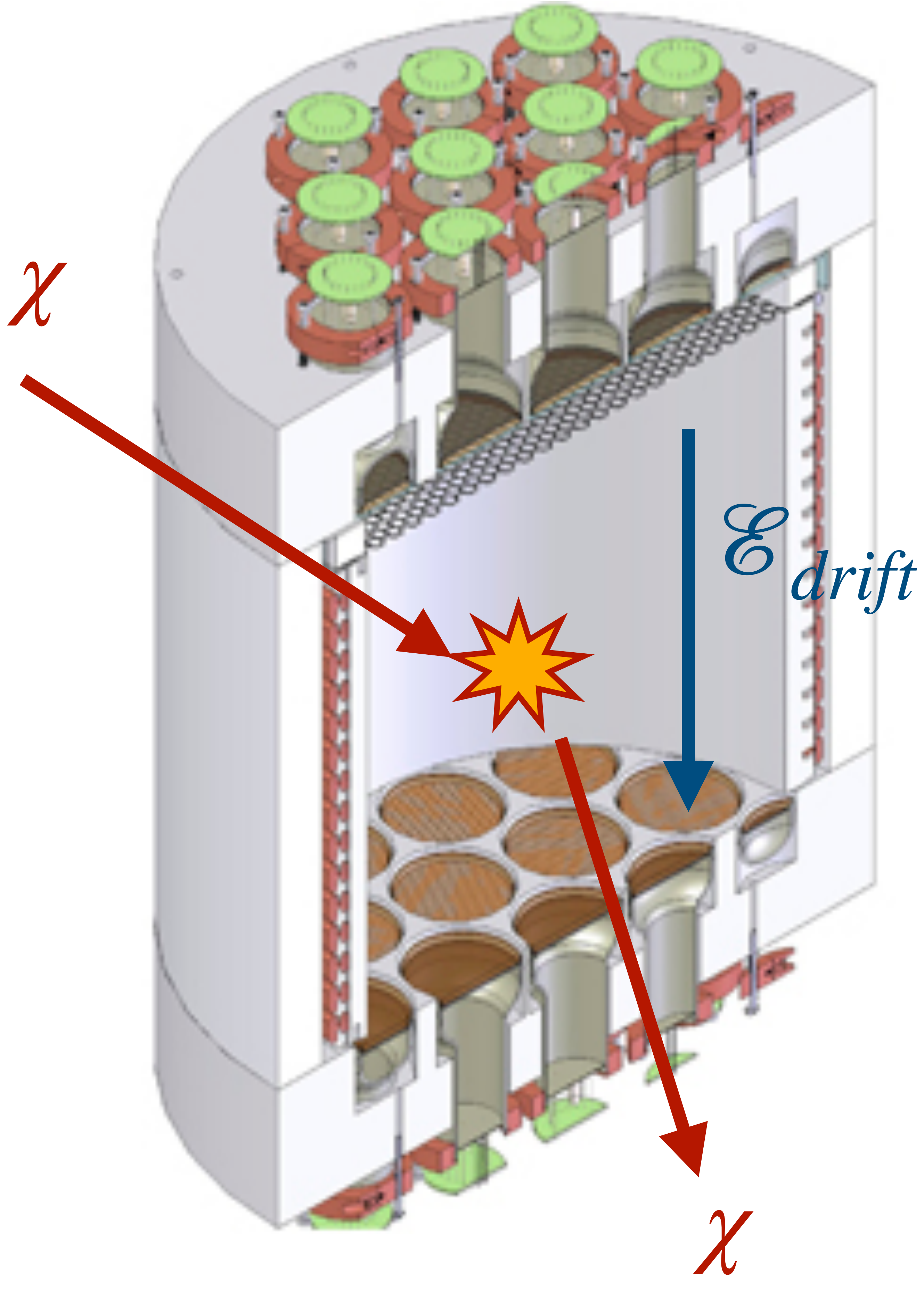
diff. rate

total rate

recoil energy

a constant given by the kinematics

DarkSide-50



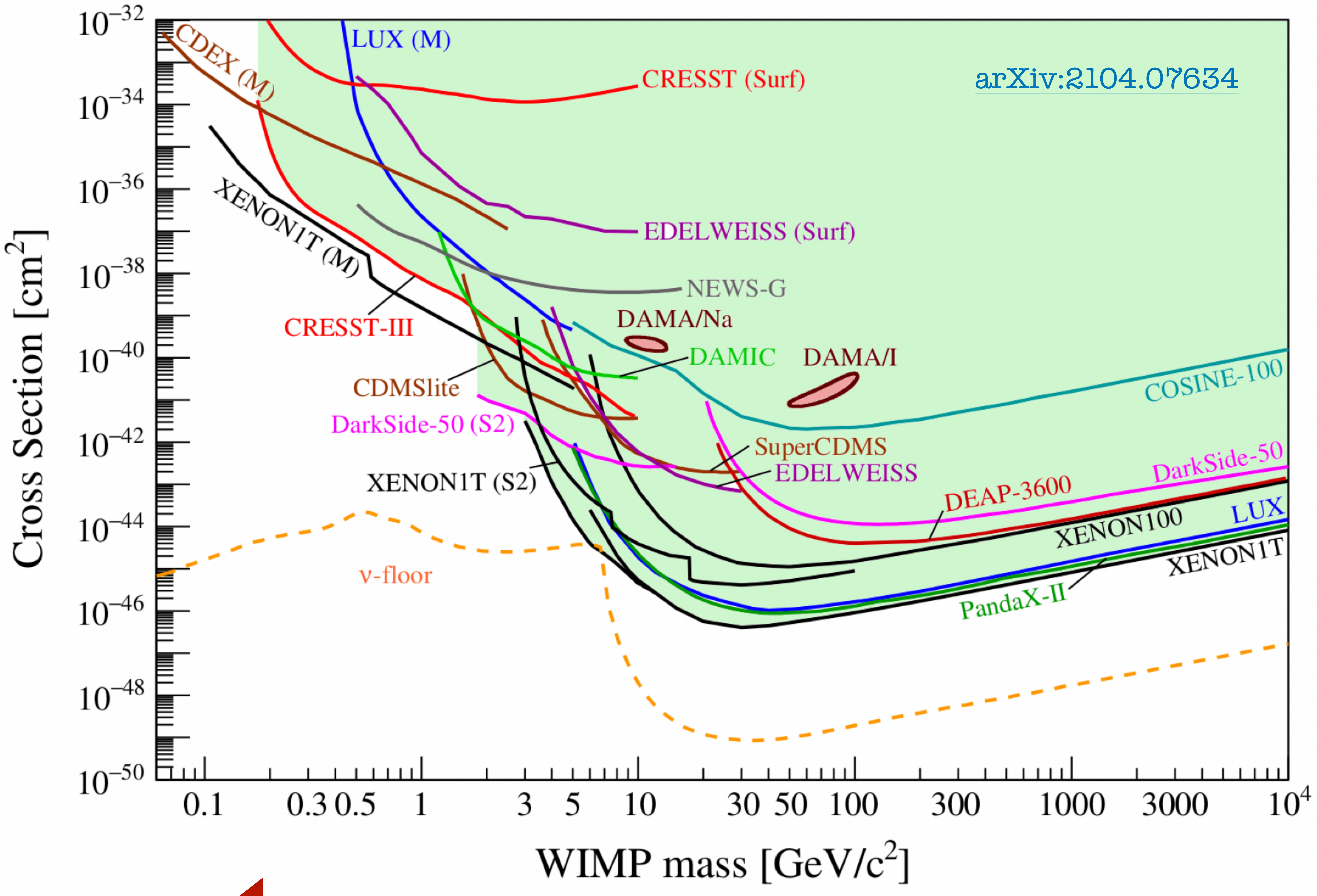
To reach the needed low-energy sensitivity they require a very low background environment.

Main backgrounds

- Cosmic rays or external radioactivity → Put the detector underground
- Internal radioactivity of the detector materials → Use radiopure materials

Direct detection experiments

Exposure



Low energy threshold

From kinematics:

DM-nucleus reduced mass

DM velocity

$$E_R^{\max} = 2\frac{\mu^2}{m_N} v_{DM}^2$$

target nucleus mass

Maximum energy that can be transferred to the recoiling nucleus

DM mass

$$\mu = \frac{m_\chi m_N}{m_\chi + m_N} \sim m_\chi$$

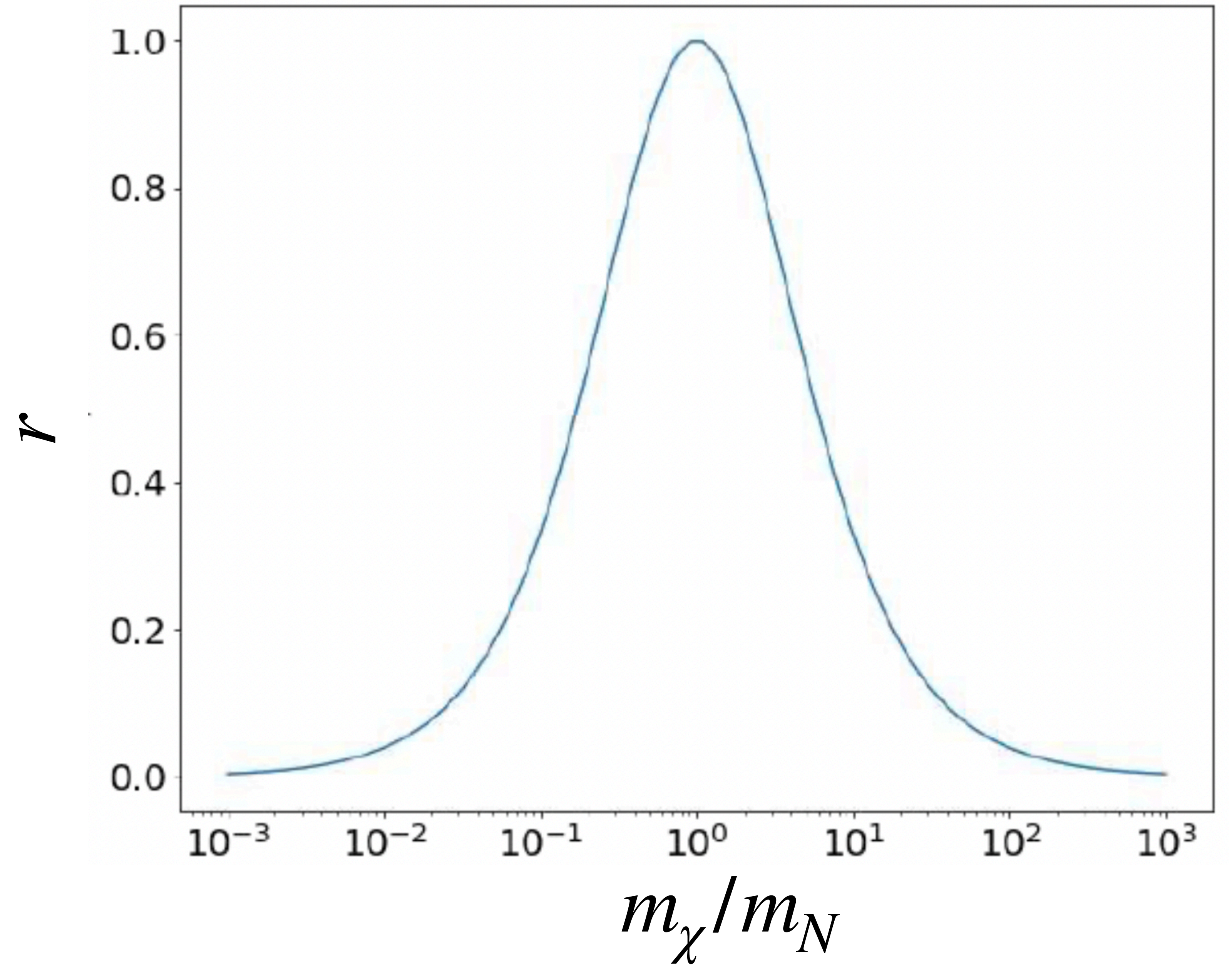
If $m_\chi < m_N$

How can we explore the low mass region?

1. Lowering the energy threshold

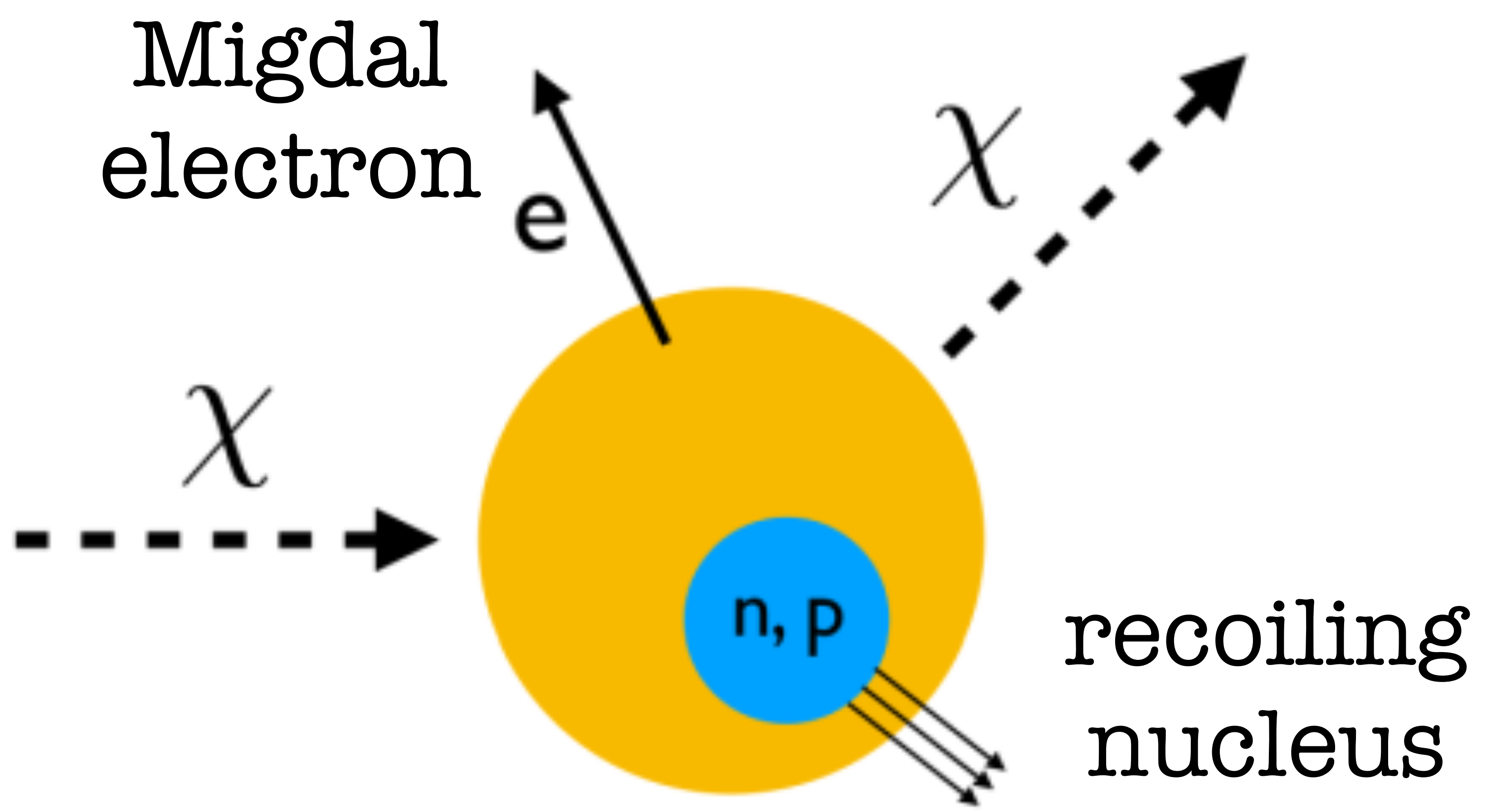
2. Using a lighter target →

$$E_R^{\max} = 2\frac{\mu^2}{m_N}v_{DM}^2 = r\,E_{DM} \quad \text{with} \quad r = \frac{4\,(m_\chi/m_N)}{[1+(m_\chi/m_N)]^2}$$



3. Exploring alternative signals contributions

The Migdal effect



Migdal effect: emission of an **electron** as a consequence of a nuclear recoil.

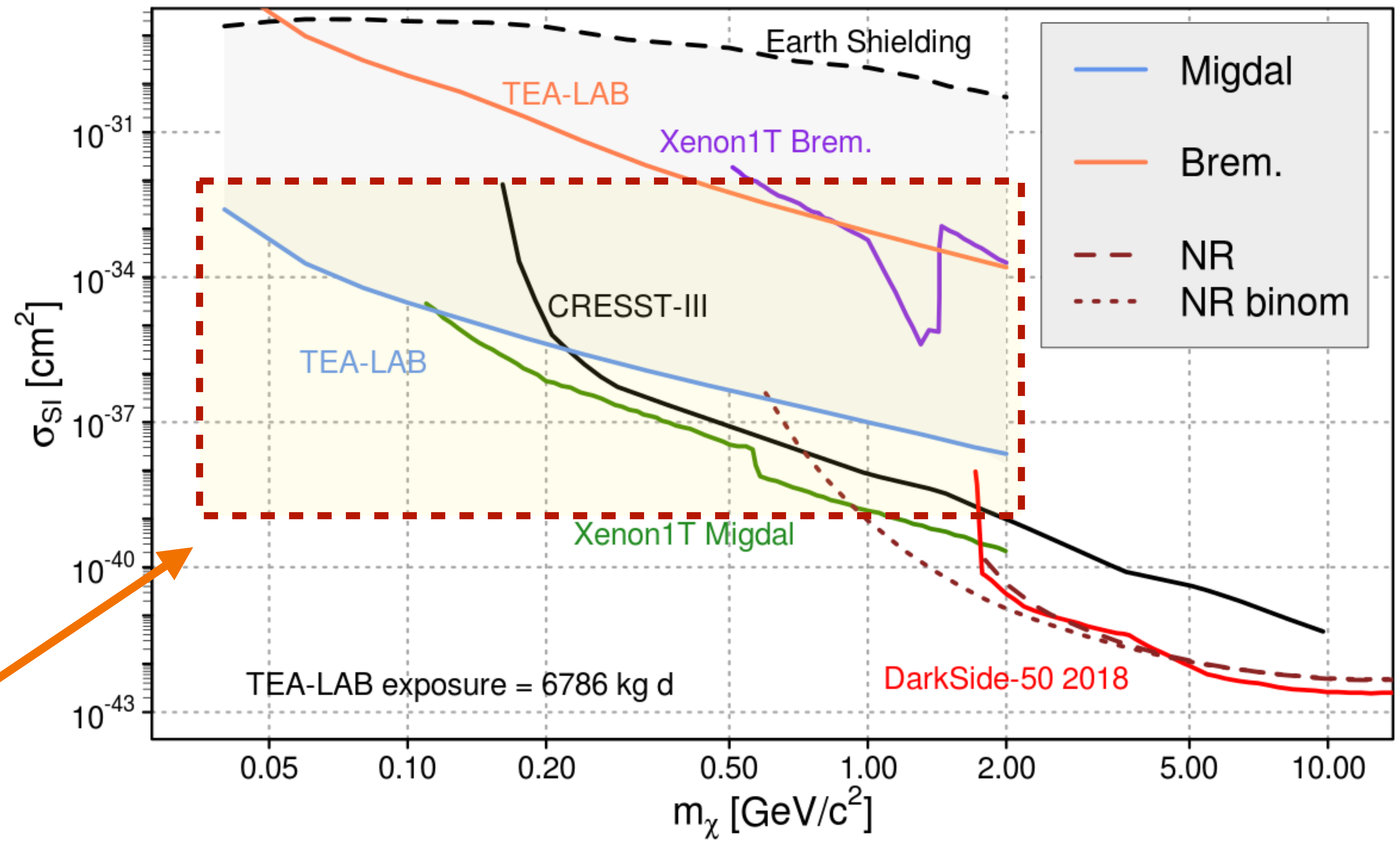
There is a range of DM masses for which **it is easier to detect the electronic energy** originating from the Migdal effect processes rather than nuclear recoils.

$$\boxed{E^{max}_{Migdal}} = \frac{1}{2}\mu v^2_{DM} = \frac{m_N}{4\mu}E^{max}_R \gg E^{max}_R$$

if $m_\chi \ll m_N$

Maximum energy of the Migdal electron

Thanks to the inclusion of the Migdal effect we have access to to the low mass region even with heavy targets like argon



G. Grilli di Cortona, A. Messina, S. Piacentini [JHEP 11 (2020) 034]

The problem of the systematic uncertainties

In frontier physics, the propagation of the **systematic uncertainties** to the final results is often a challenging task:

- there is a general **lack of models** for the description of the detector response to the low energy deposits which are relevant for this search
- even assuming empirical models based on the calibration measurements, the propagation of the uncertainties to the final results is often non trivial, due to the **complexity** and **non-linearity** of the relations connecting the different parameters

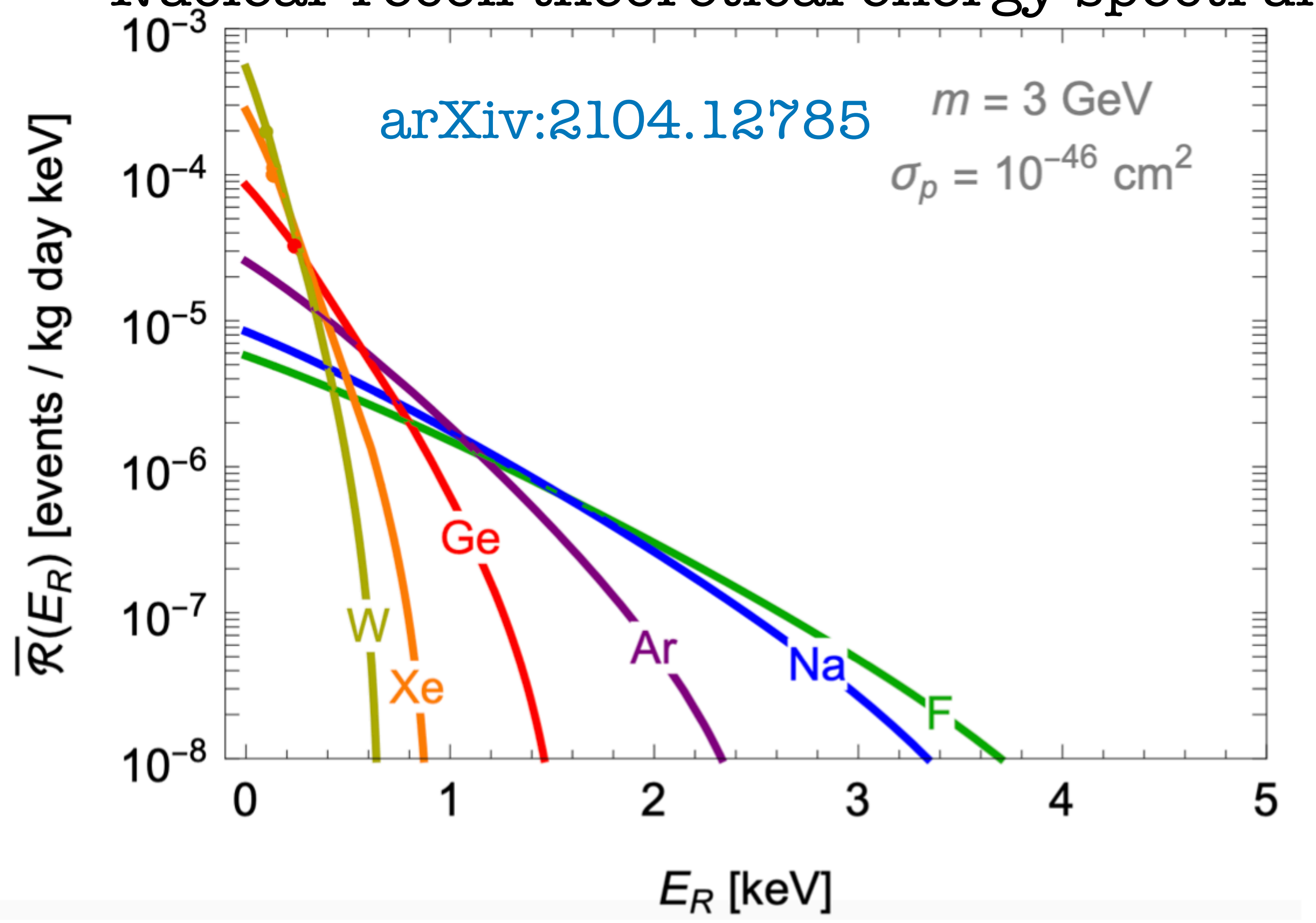
The standard approaches based on the **profiling of the likelihood**, which rely on “Gaussianity” or linearity assumptions, could therefore **not be able** to determine the **propagated uncertainties** on the quantity of interest in an **accurate** way.

Solution: use a method based on the **marginalization** of the likelihood, but, to do that coherently, the dependence of the quantity of interest on the original nuisance parameters on which we are uncertain should be kept in every intermediate step of the analysis.

An innovative solution

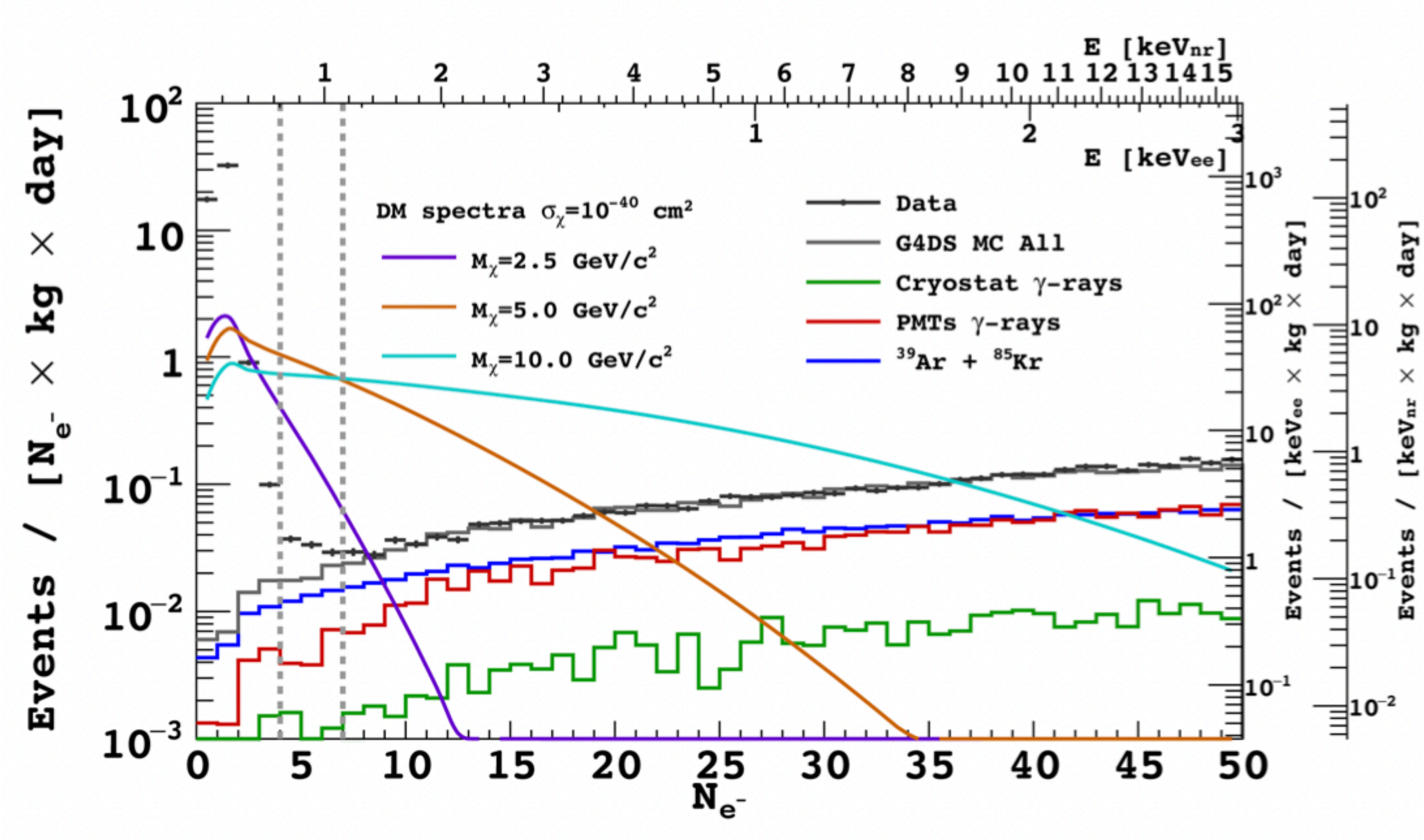
We developed a solution to **implement** the original **detector response model** via **linear algebra** operations and in a semi analytical way.

Nuclear recoil theoretical energy spectrum



[2018, arXiv:1802.06994]

DarkSide-50 preliminary dataset



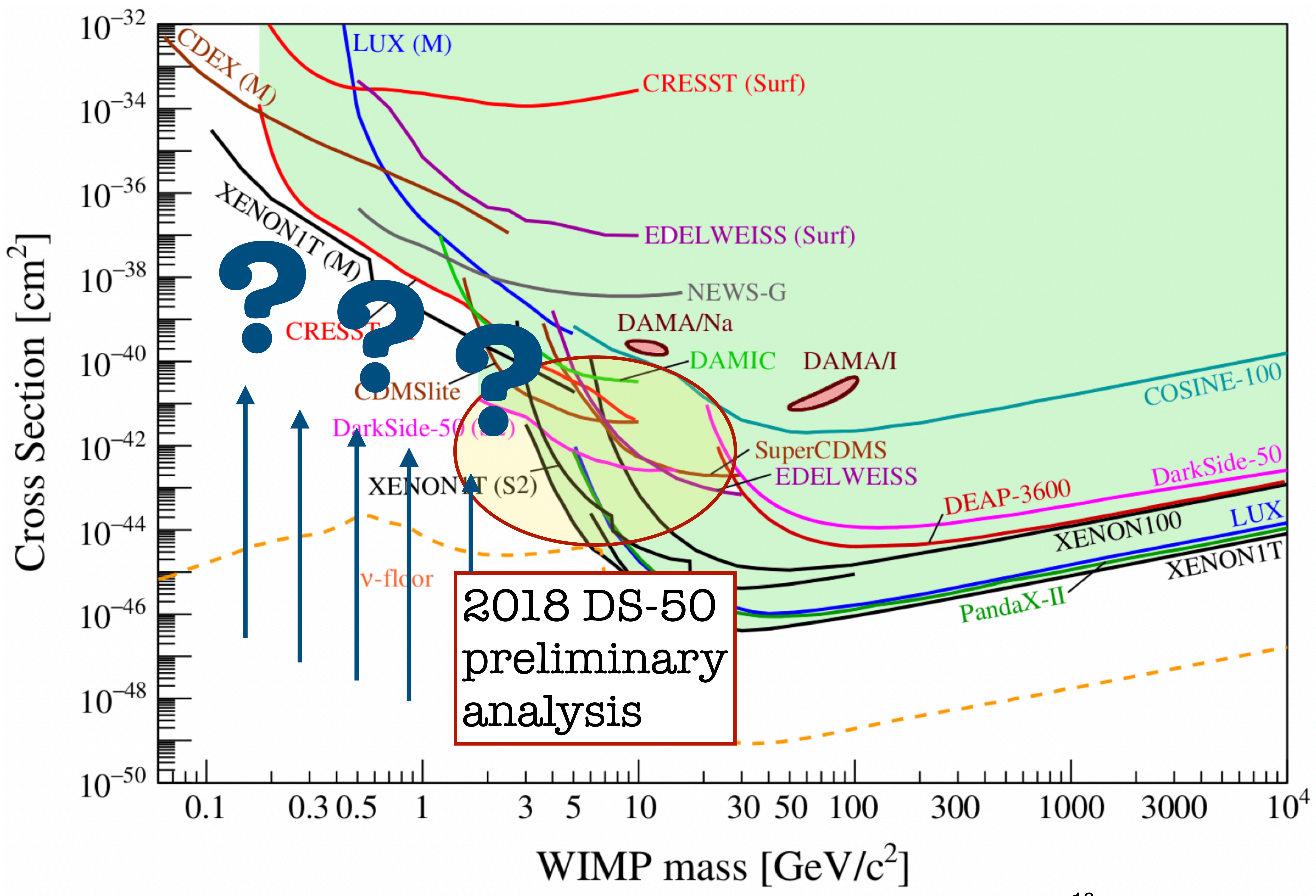
theor. spectrum

observed spectrum

$$S_i(\boldsymbol{\theta}_{syst}) = \sum_j \sum_k \mathscr{M}^1_{ij}(\boldsymbol{\theta}_{syst})\mathscr{M}^2_{jk}(\boldsymbol{\theta}_{syst}) S^{th}_k(\boldsymbol{\theta}_{syst})$$

A set of matrices encoding the detector response model

Stay tuned for upcoming results…



2018 DS-50 preliminary analysis

This method has been employed for the conclusive analysis of the DarkSide-50 experiment.

The papers are currently in the internal review phase and will be published in the next months.

So… stay tuned!

Thanks for the attention!

Backup

Spiral galaxy rotation curve

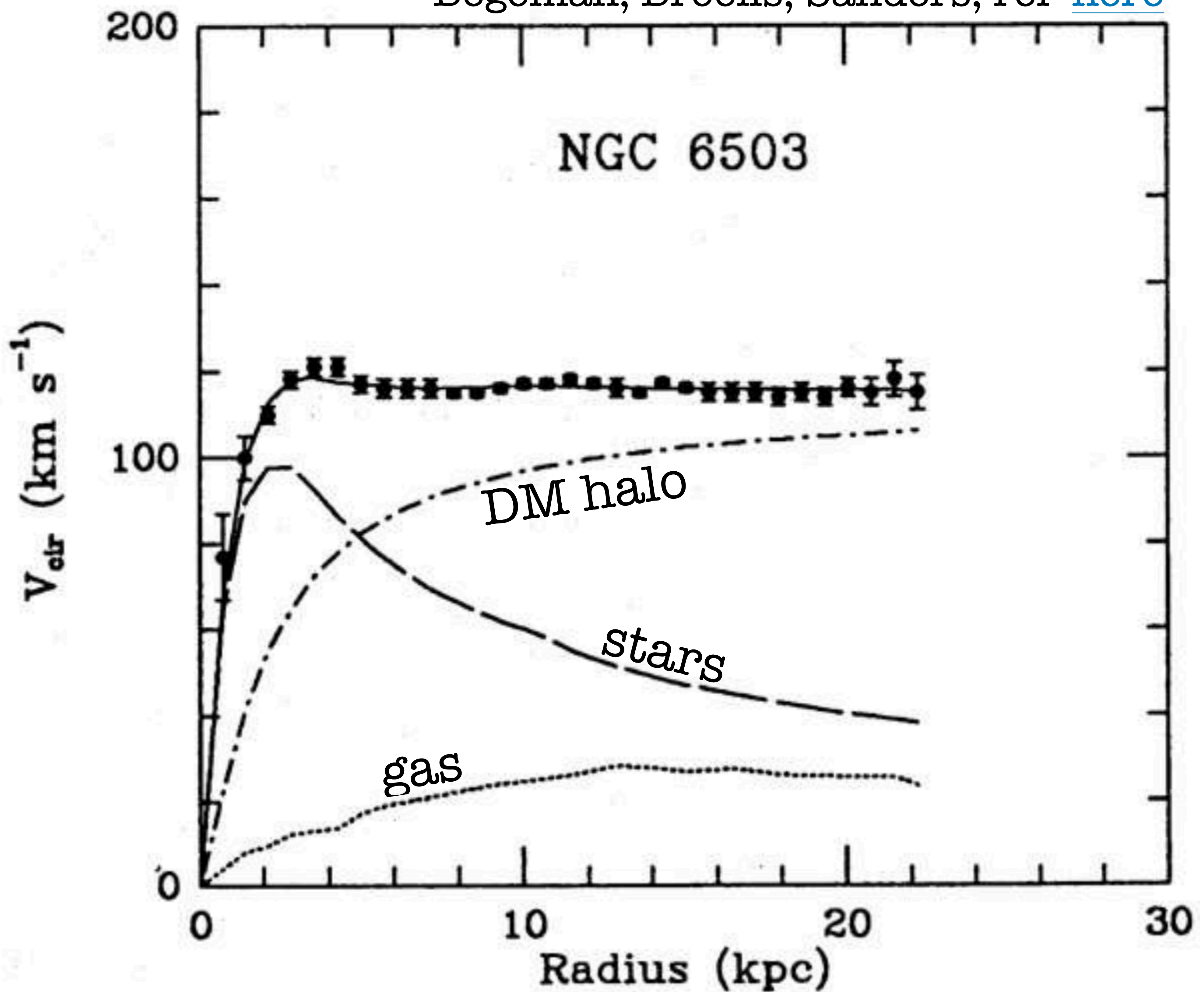
Rotation curve ≡ stars circular speed
vs
distance from center

$$v(R) = \sqrt{\frac{GM(R)}{R}}$$

$$M(R) = \int_{|\boldsymbol{r}|<R} \rho(\boldsymbol{r}) d\boldsymbol{r}$$

At large R: stars component $v(R) \propto 1/\sqrt{R}$

$M(R) \sim const$



Begeman, Broeils, Sanders, ref here

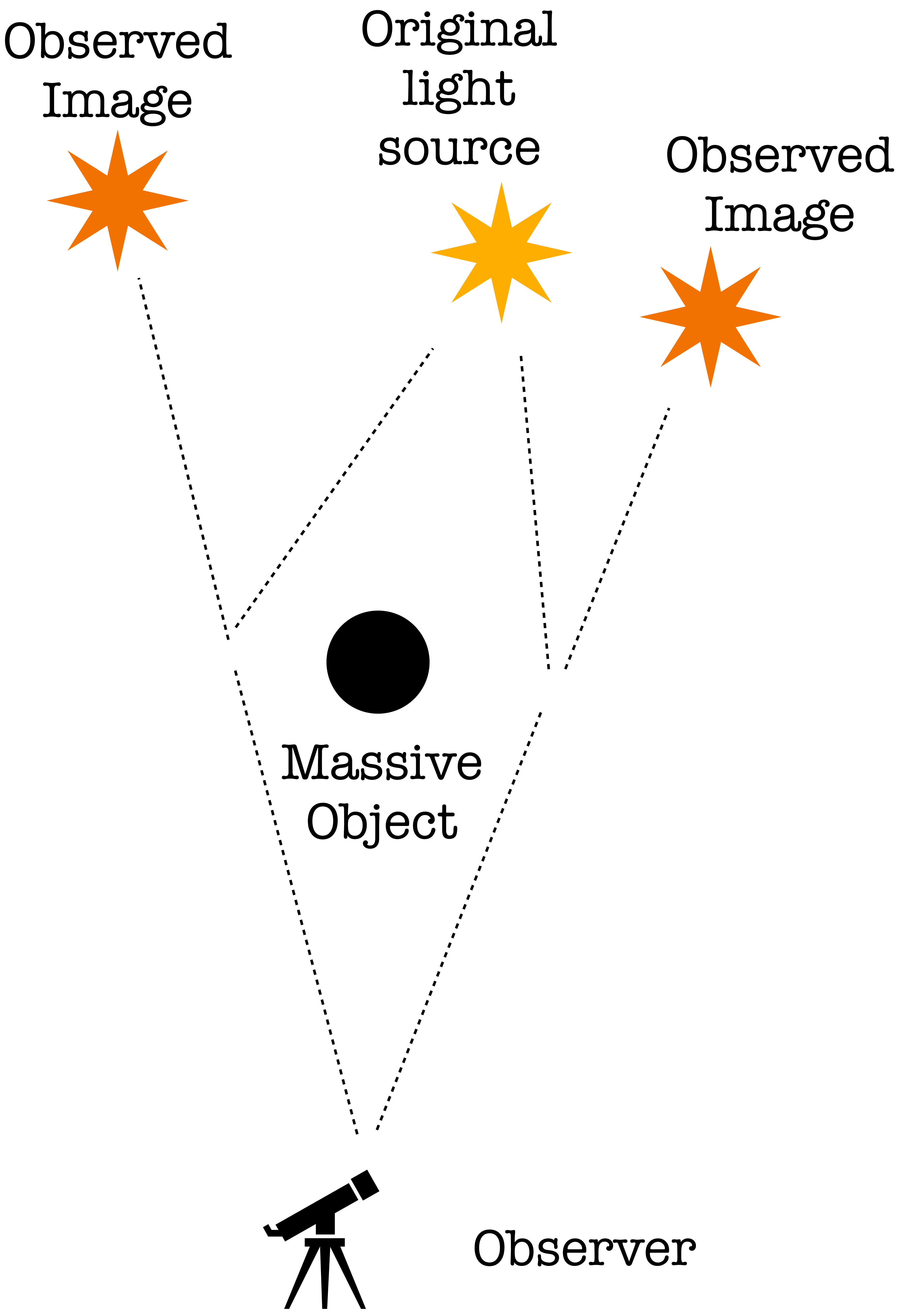
$v(R)$ constant if $\rho(\boldsymbol{r}) \propto r^{-2}$ →

The data can be explained by an invisible DM halo with a density profile $\rho(\boldsymbol{r}) \propto r^{-2}$

Gravitational lensing

- strong lensing: large deflection angles (multiple images, Einstein ring) arXiv:1003.5567
- weak lensing: small deflection angles (distorted images) arXiv:1411.0115
- microlensing: deflection angles below resolution (light source temporarily brightened) Paczynski (1986)

The mass of the stars and the gas composing the galaxies and the galaxy clusters is not enough to explain such big observed gravitational lensing effects



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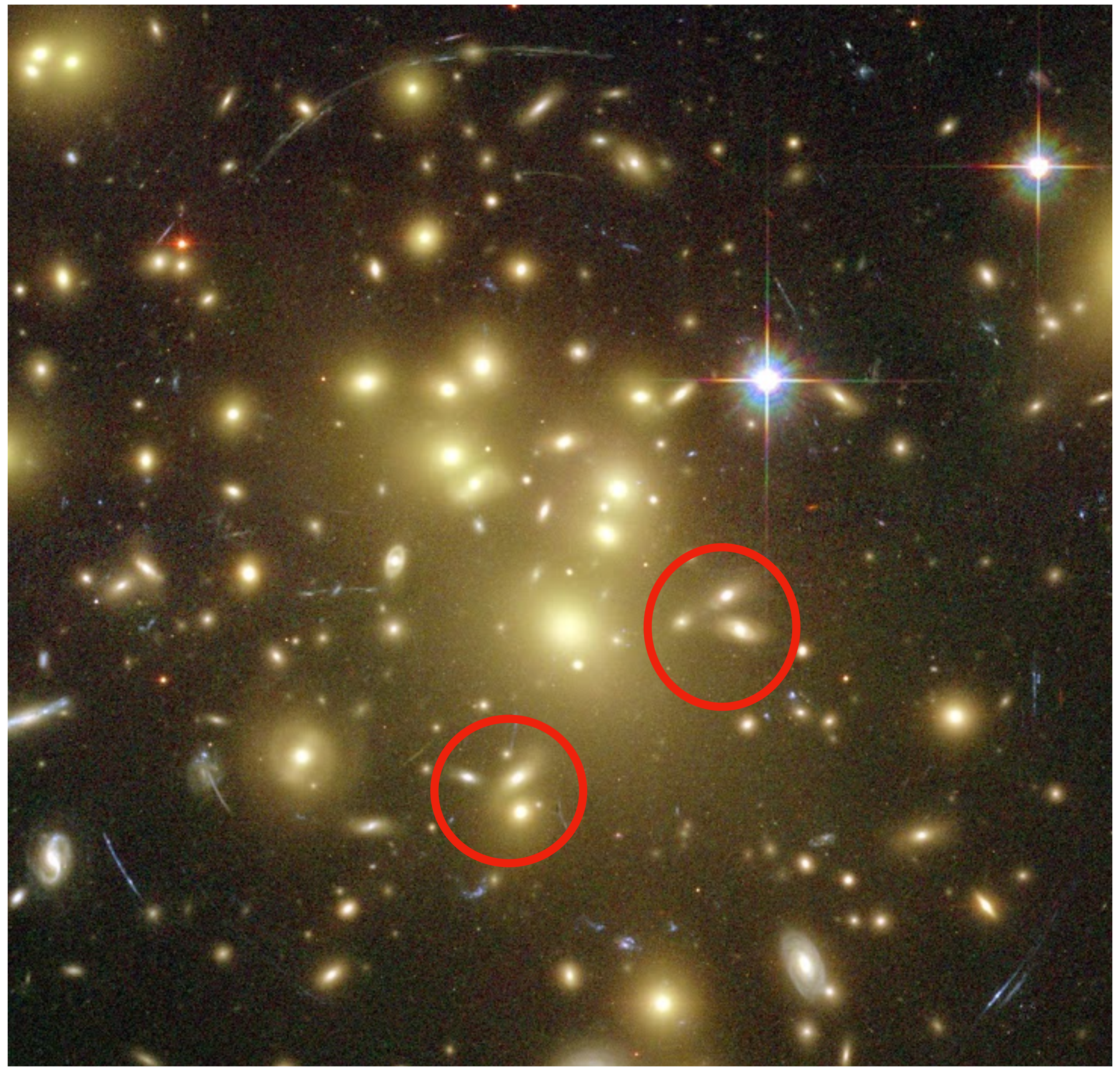
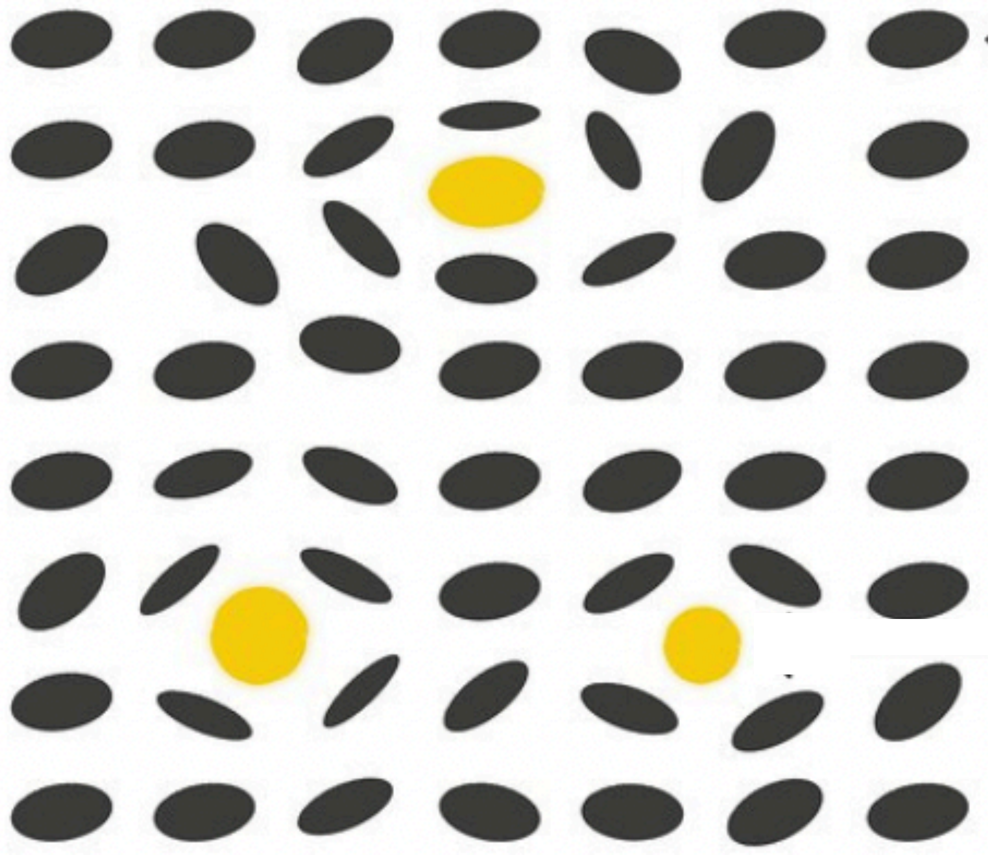
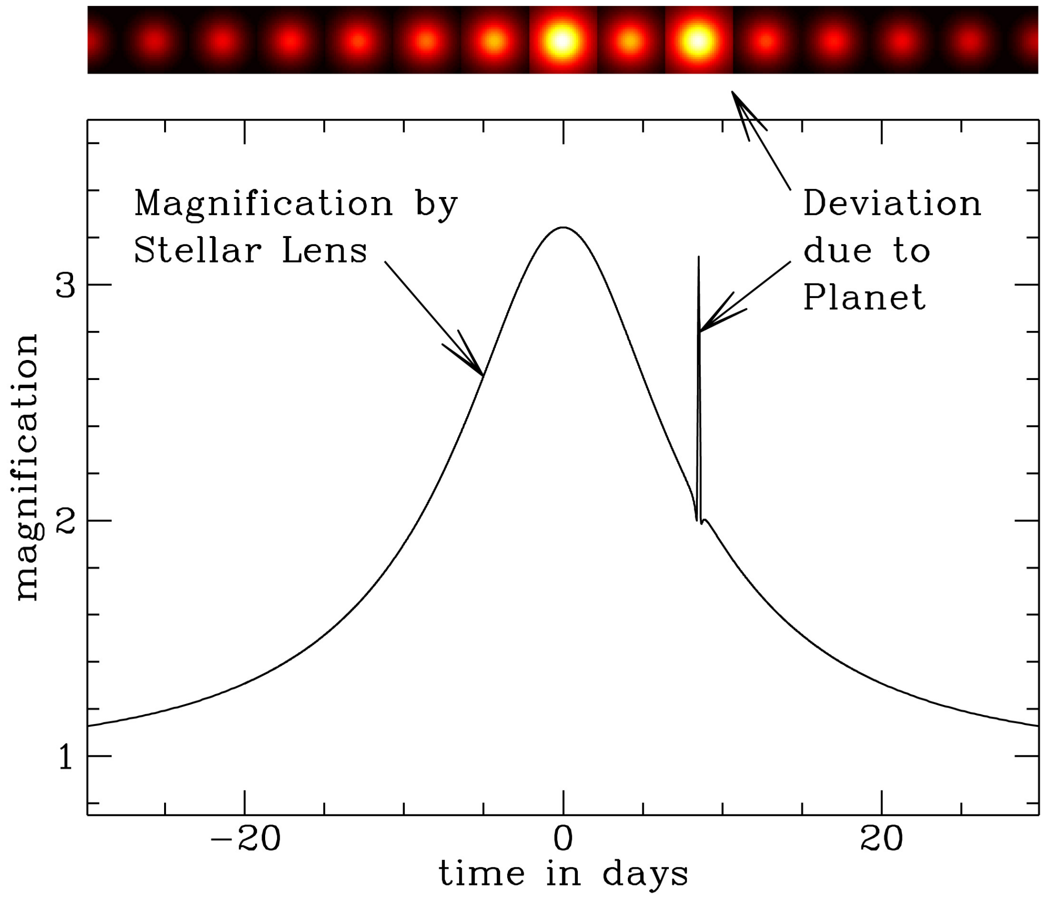
Strong lensing



Weak lensing

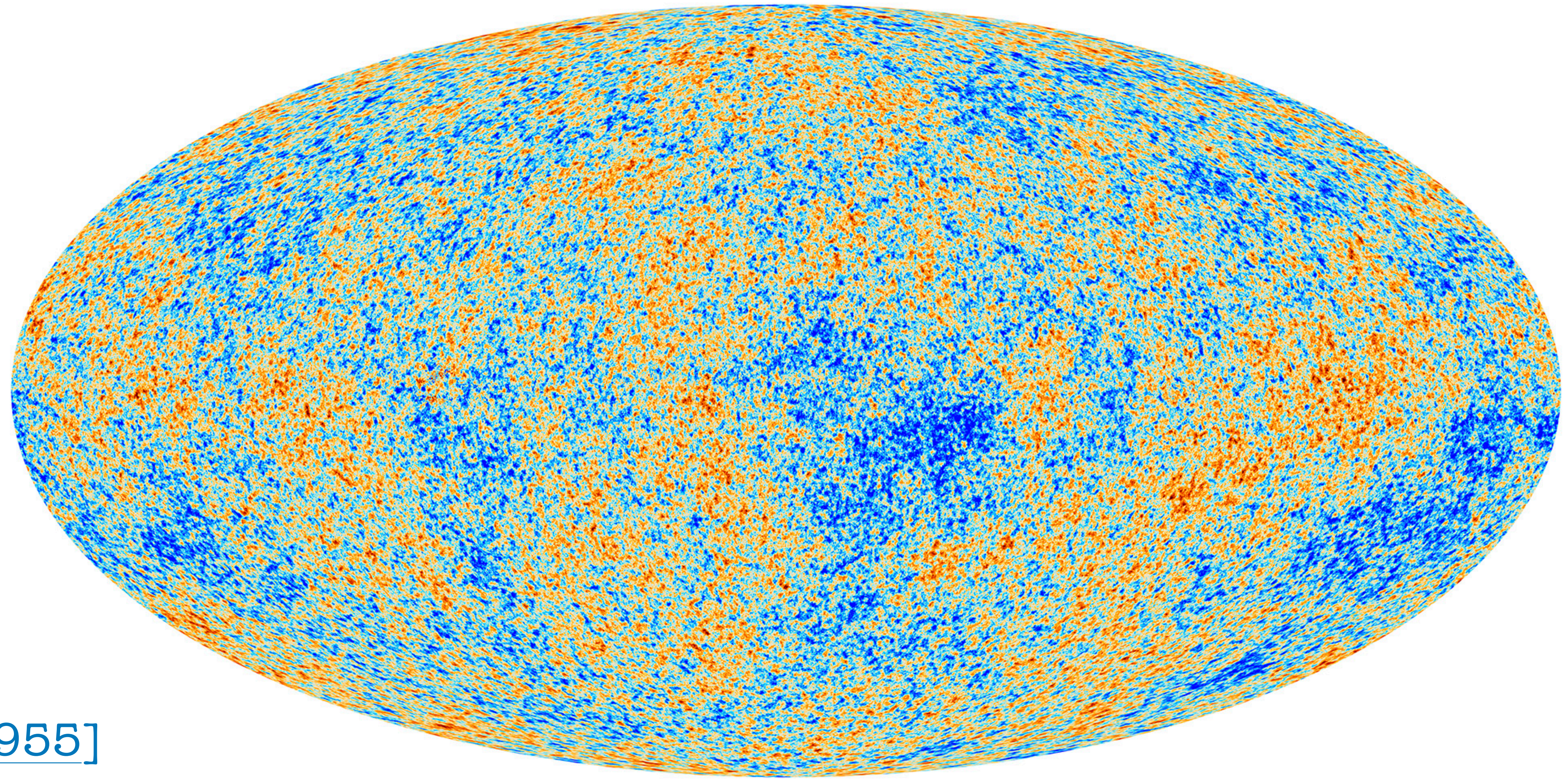


Microlensing



Cosmic Microwave Background

https://www.esa.int/ESA_Multimedia/Images/2013/03/Planck_CMB



When the Universe became transparent to radiation, the photons started to travel freely in the Universe.

These photons are still streaming and we call them Cosmic Microwave Background (CMB)

The CMB appears to be a black body radiation with $T = (2.7255 \pm 0.0006)\ K$ [arXiv:0911.1955]

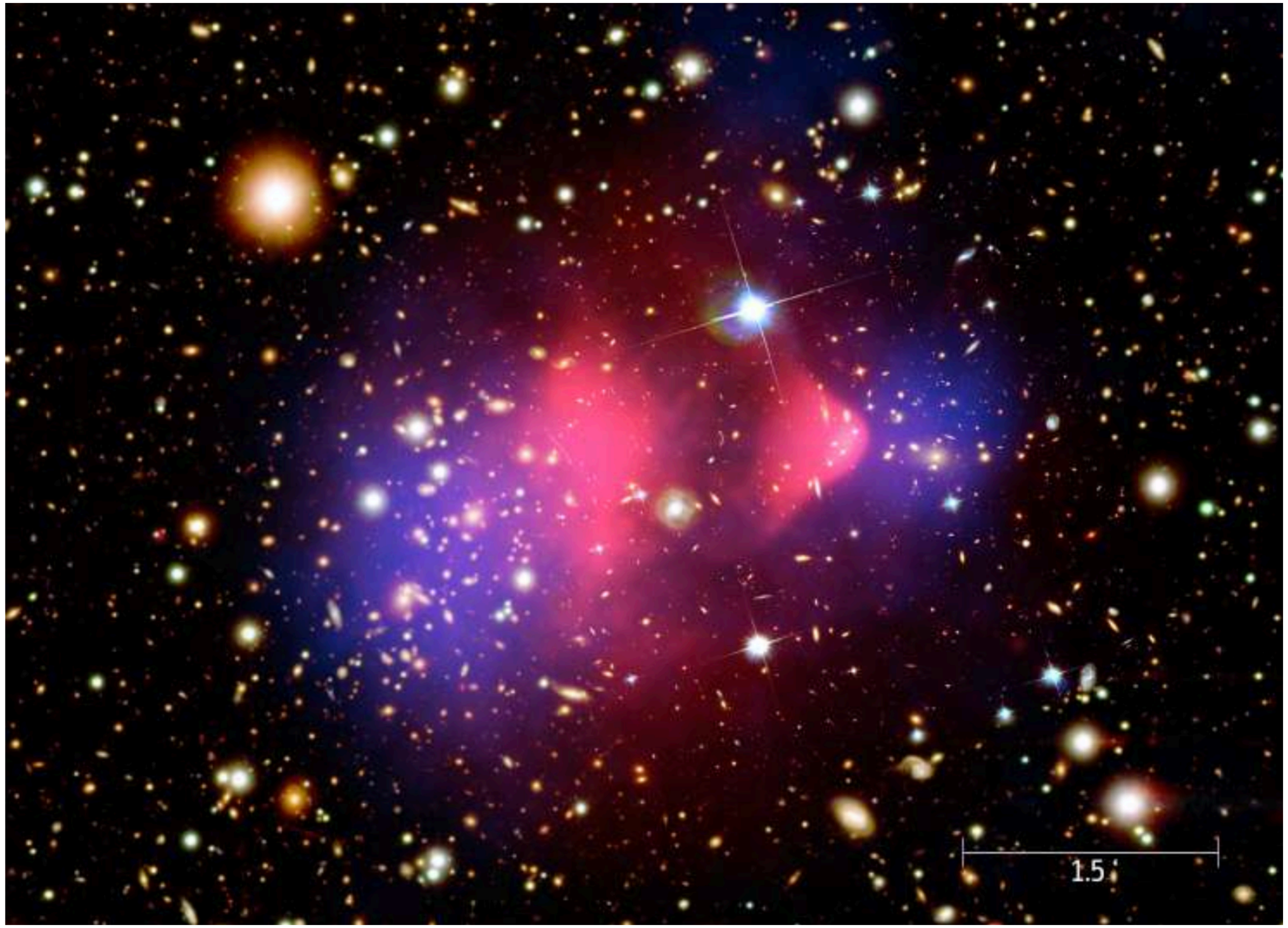
The spectral analysis of the CMB suggests that non only the DM component is not zero, but it is also the main ingredient (~80%) of all the matter in the Universe

arXiv:1807.06209

Bullet cluster

Two clusters right after their collision: the different behavior of the various components of the clusters - stars, gas and hypothetically DM - can be studied.

- **Stars**: unaffected by the clash
- **Gas**: the EM interactions slow down the gas (pink halo is the gas Xray emission)
- **Blue halo**: lensing map (the brighter the blue, the stronger the lensing)

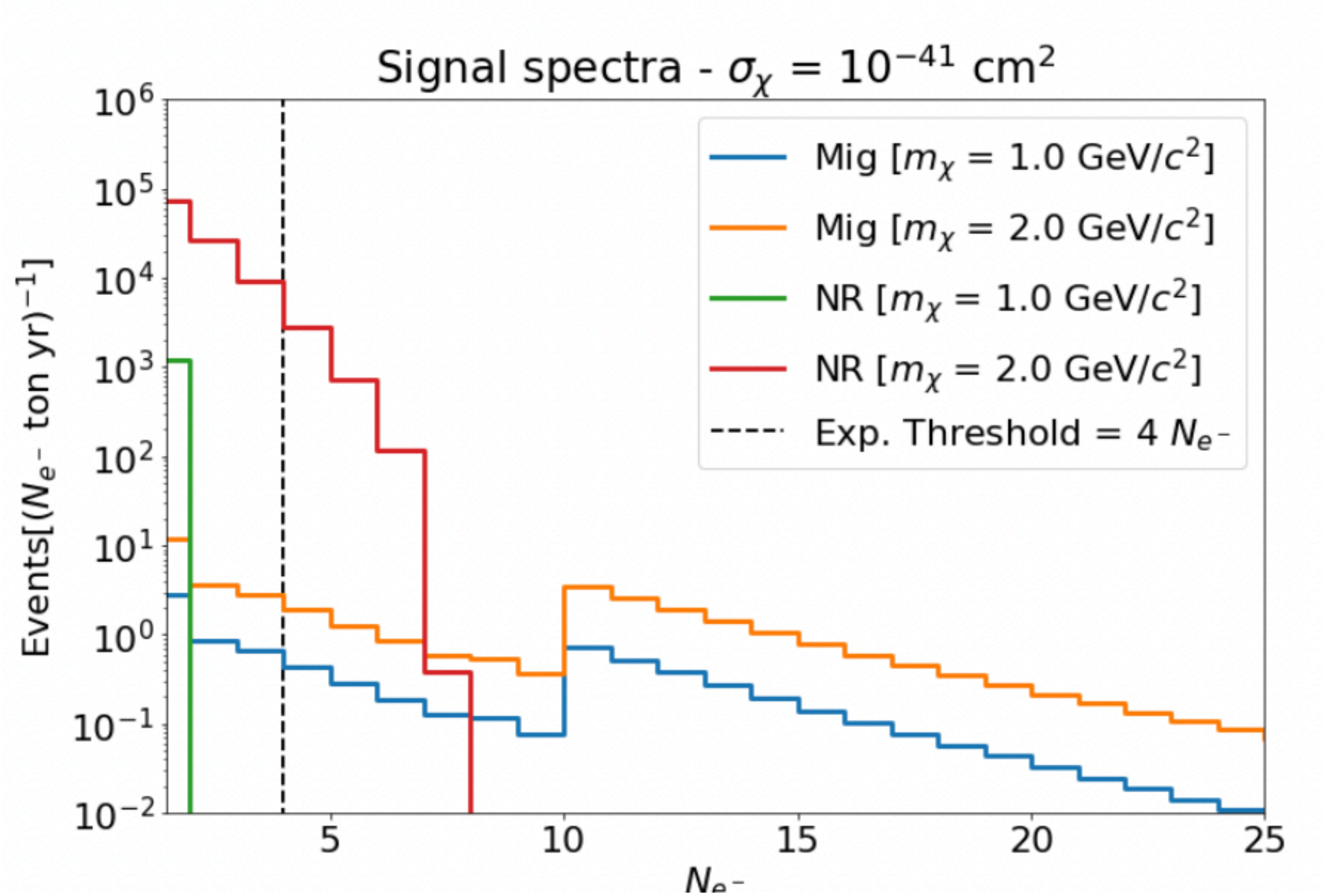


X-ray: NASA/CXC/CfA/M.Markevitch et al.;
Optical: NASA/STScI;
Magellan/U.Arizona/D.Clowe et al.;
Lensing Map: NASA/STScI;
ESO WFI;
Magellan/U.Arizona/D.Clowe et al..

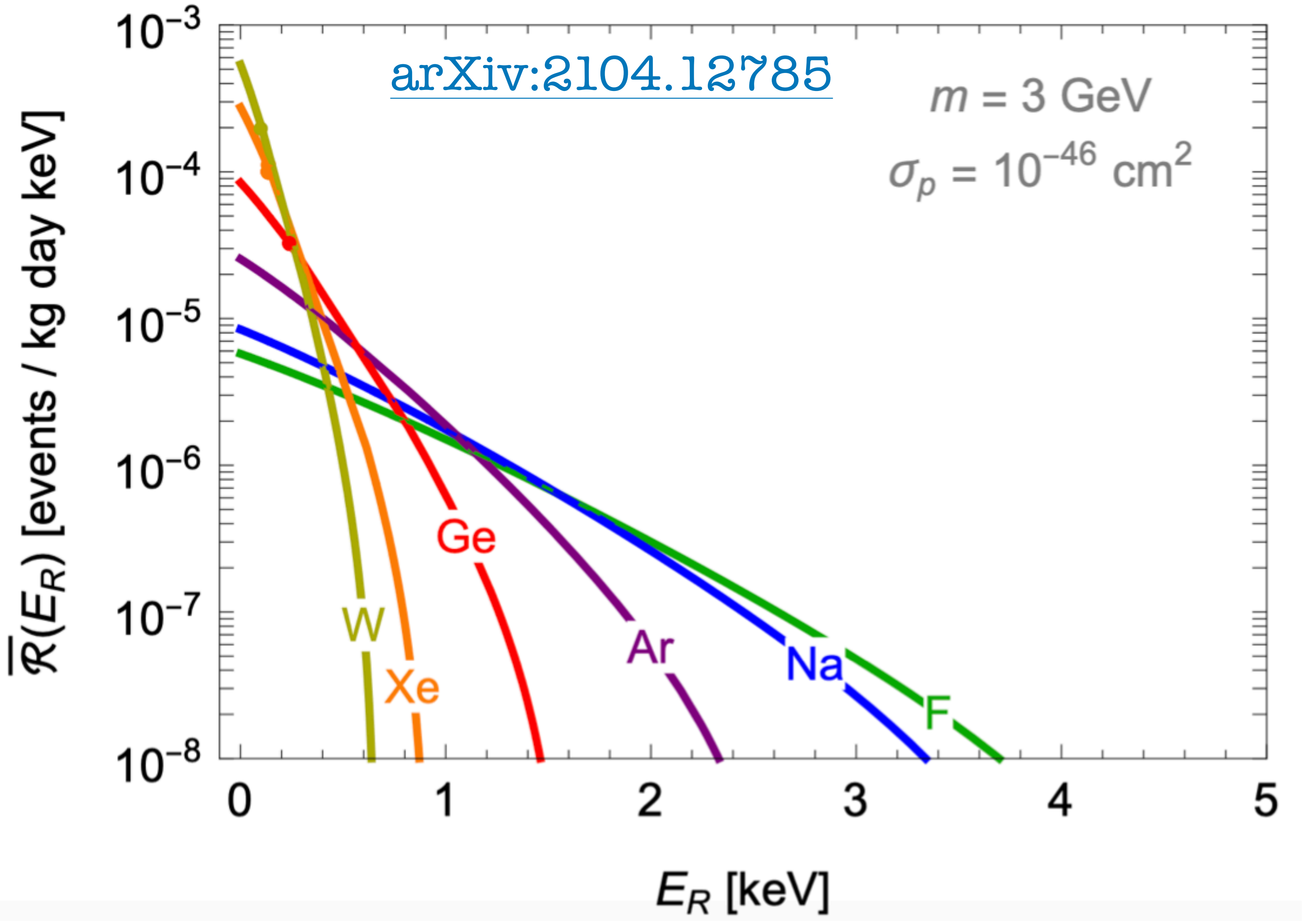
The gravitational lensing does not follow the baryonic matter (whose main component is the gas itself)

This strongly supports the idea of the existence of a non-baryonic DM halo in the two clusters

Migdal effect VS Nuclear recoil



From theoretical to observed spectrum



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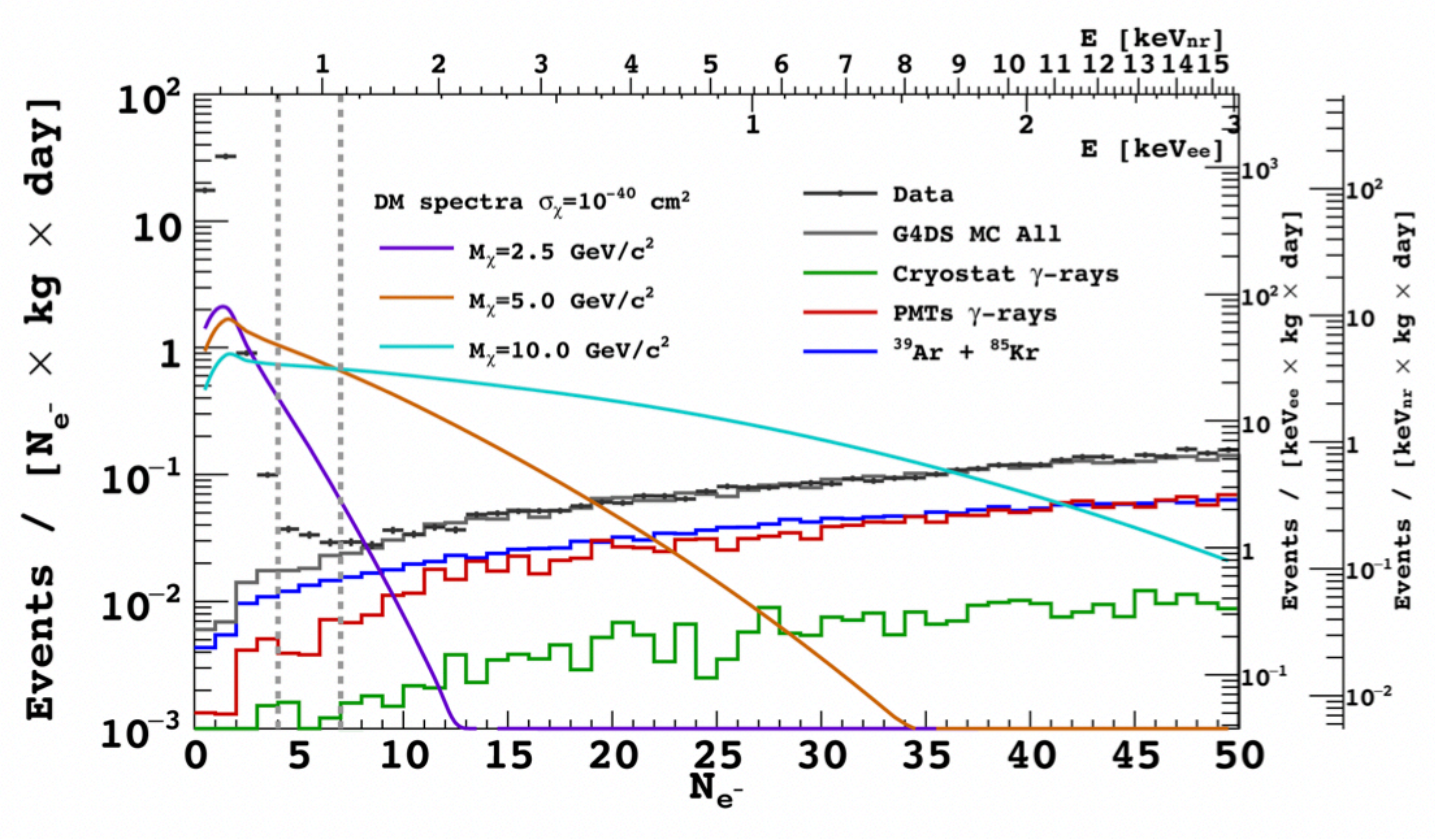

An innovative solution

We developed a solution to **implement**, via linear algebra operations, the original **detector response model** via **linear algebra** operations.

A bit of notation:

- **data** x_i = usually the histogram of the observed events as a function of a certain measured quantity (e.g. the number of ionizations)
- **expected spectrum** S_i = the expected value for the data x_i
- **theoretical spectrum** S_k^{th} = the signal or background rate of the incoming ionizing particle as a **function** of the **recoil energy**

$$S_i(\boldsymbol{\theta}_{syst}) = \sum_j \sum_k \boxed{\mathscr{M}^1_{ij}(\boldsymbol{\theta}_{syst})\mathscr{M}^2_{jk}(\boldsymbol{\theta}_{syst})}\, S^{th}_k(\boldsymbol{\theta}_{syst})$$

A set of matrices encoding the probabilities of observing an event in the bin i given a certain "theoretical" recoil energy E_k (they include quenching fluctuations, Fano factor, resolution, efficiency, etc.)

Smearing matrices

N_q = number of **measured** detectable quanta

$N_q^{(0)}$ = number of **produced** detectable quanta

E_R = recoil energy

$$\mathscr{M}^1_{jk}(\boldsymbol{\theta}) = p(N_q^{(0)} = j \,|\, E_R = E_k, \boldsymbol{\theta})$$

(quenching factor, Fano factor, ionization fluctuations, ...)

$$\mathscr{M}^2_{jk}(\boldsymbol{\theta}) = p(N_q = i \,|\, N_q^{(0)} = j, \boldsymbol{\theta})$$

(efficiency, resolution, ...)