# Enlightening the Dark

# Outline:

- **SM and BSM problems** *(Ukraine-Norway School, CERN, 2017)*
- **Evidence for Dark Matter** *(ICTP Summer School Trieste, 2016)*
  - Astrophysical
  - Cosmological
- **The Nature of Dark Matter** *(International School "Relativistic Heavy Ion Collisions, Cosmology and Dark Matter", Oslo, Norway, 2017")*
  - MACHOs
  - Mond/modifided gravity
  - DM partilce
- **Model-independent classifications of DM candidates** *(International School "Relativistic Heavy Ion Collisions, Cosmology and Dark Matter", Oslo, Norway, 2017")*
  - Cold/warm

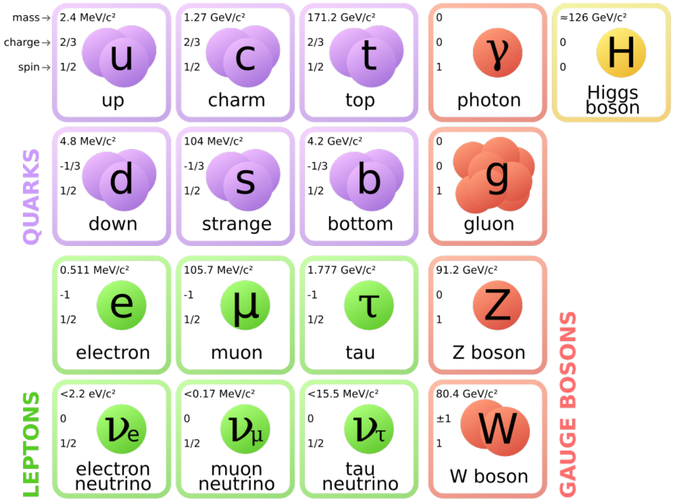
# Outline:

- Stable/decaying
- Ballistic/self-interacting

- **Searching for Dark Matter** *(The Dark and Visible Side of the Universe ISAPP school, Texel Island, The Netherlands, 2017)*
  - direct searches
  - indirect searches
  - accelerator searches

# SM and BSM problems

# The Standard Model of particle physics



- *The Standard Model* (SM) describes **all the confirmed data** obtained using particle accelerators and has enabled many successful theoretical predictions

- The **last prediction** of the SM is the Higgs, that was discovered in 2012

- LCH analyzed from 2012 to 2018 all the SM **decay and production channels** for the Higgs boson and confirmed that the new particle is the SM Higgs, not just Higgs-like particle

# Beyond the SM problems

- Particle physics is facing a great challenge: **We are sure that the SM does not explain all phenomena in Nature**

- Indeed, a number of experimentally established evidence **cannot be explained by the Standard Model**, including:
  - **Neutrino masses**: *Why do neutrinos have mass which is prohibited within the Standard Model?*
  - **Baryon asymmetry of the Universe**: *What mechanism had created a tiny matter-antimatter imbalance in the early Universe?*
  - **Dark Matter**: *What is the prevalent kind of matter in the Universe?*
  - **Dark Energy**: *Constant in the Einstein equation?*

- The era of guaranteed discoveries in particle physics has finished: the last particle with firmly predicted properties was detected and **no signature of new physics** was found, no explanation of the big puzzles was provided

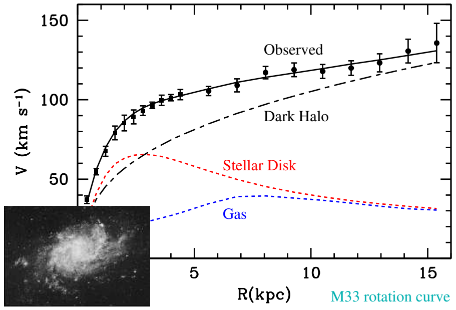
- In this talk I will mainly concentrate on the **DM problem**

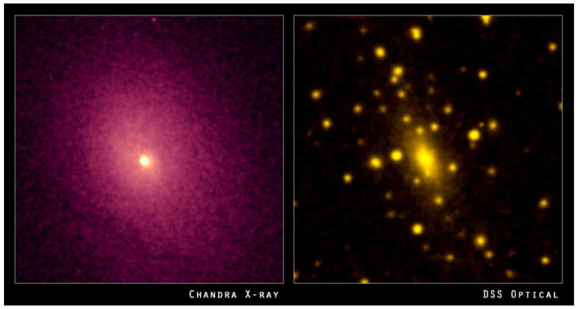
# Evidence for Dark Matter

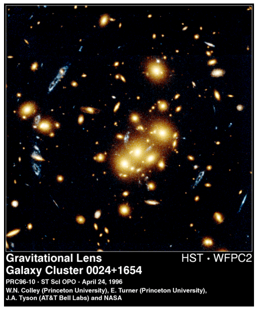
# Three parts of astrophysical evidence for Dark Matter in the Universe

- **Rotation curves** of stars in galaxies and of galaxies in clusters
- **Distribution of intracluster gas**
- **Gravitational lensing** data (strong and weak)

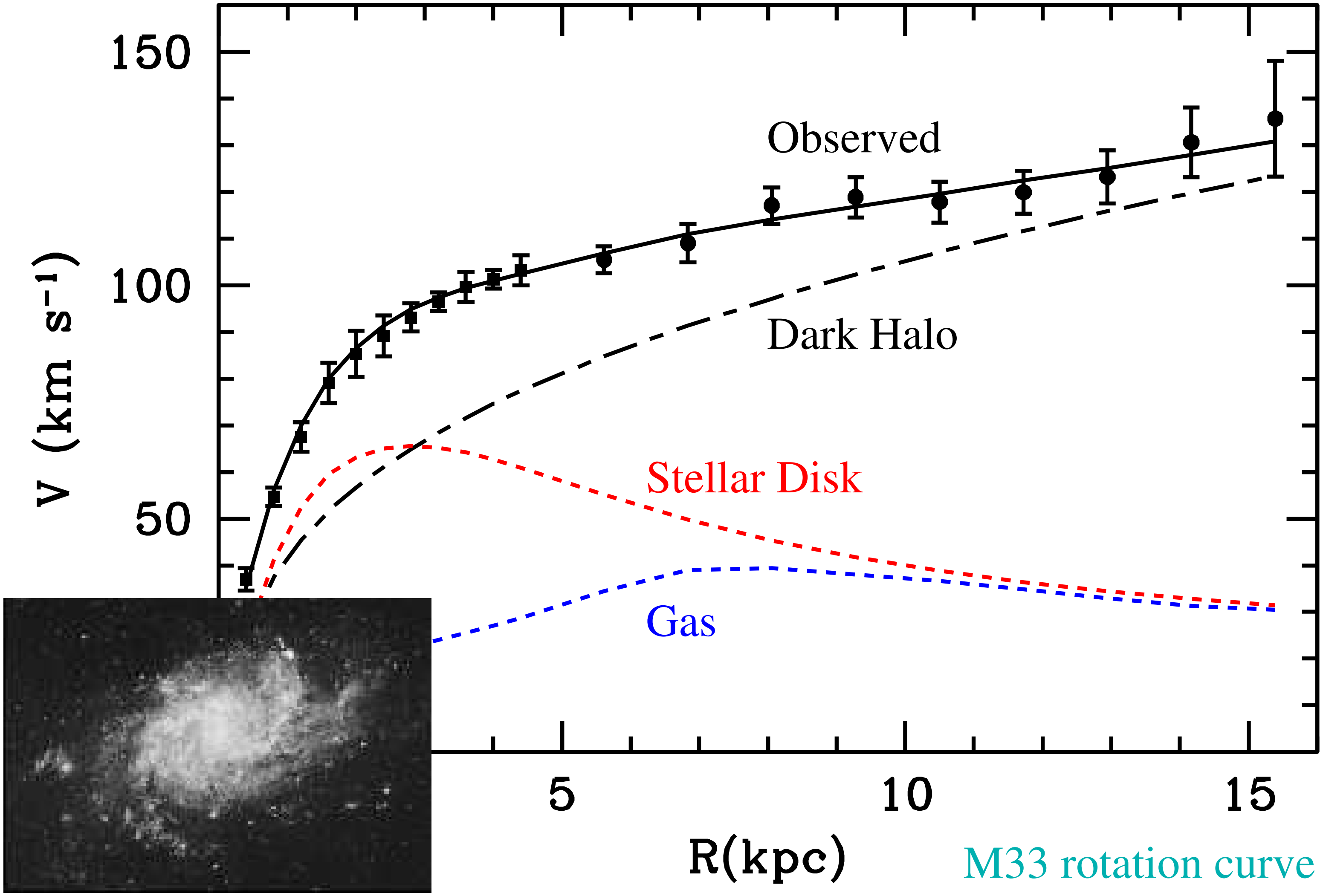
These phenomena are **independent tracers** of gravitational potentials in astrophysical systems. They all show that dynamics is dominated by a matter that is **not observed** in any part of the electromagnetic spectrum







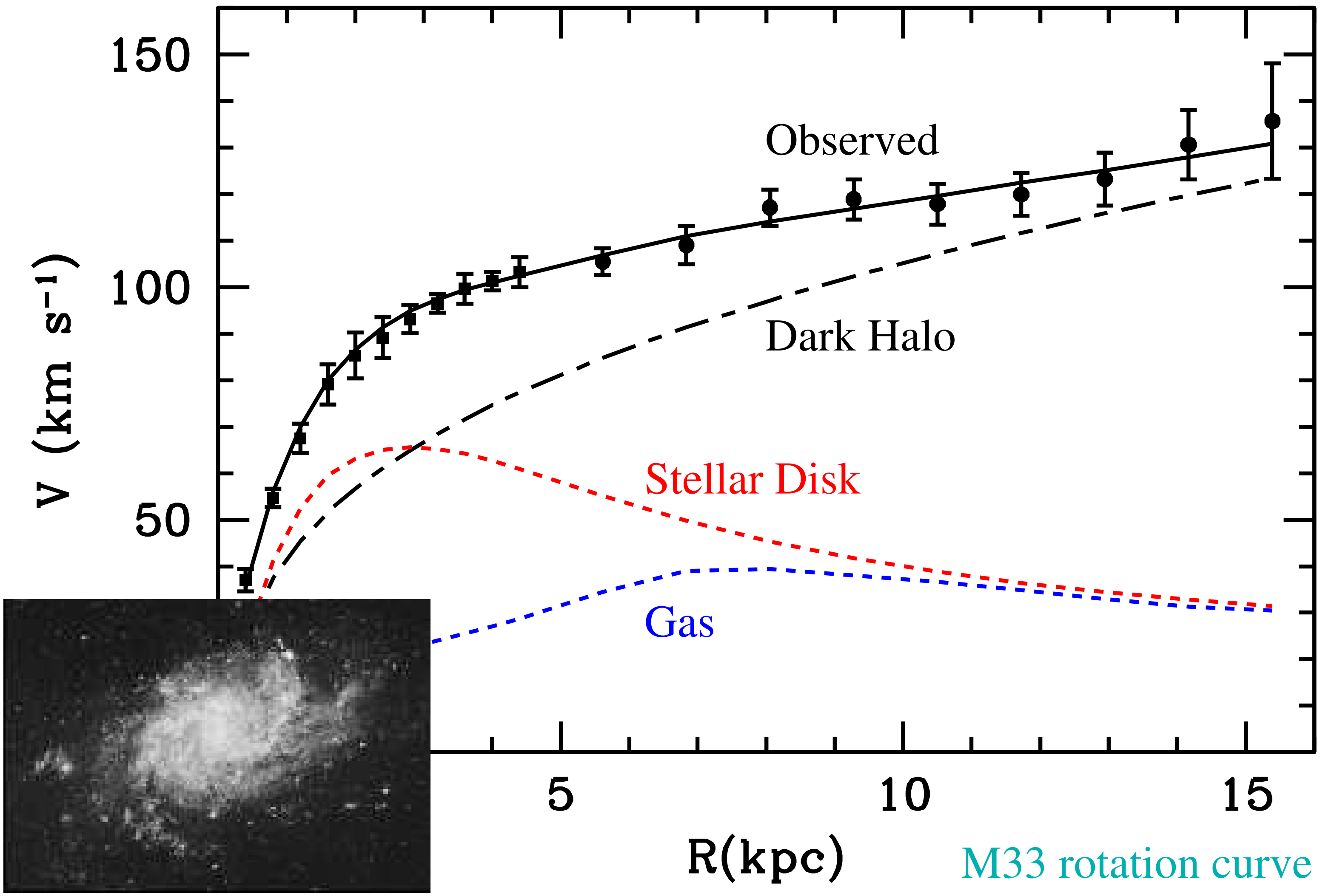
# Evidence I: Rotation curve



M33 rotation curve

Newton dynamics: $$\frac{GM(R)}{R^2} = \frac{V^2(R)}{R} \rightarrow \mathrm{V}(R) \sim \frac{1}{\sqrt{R}}$$

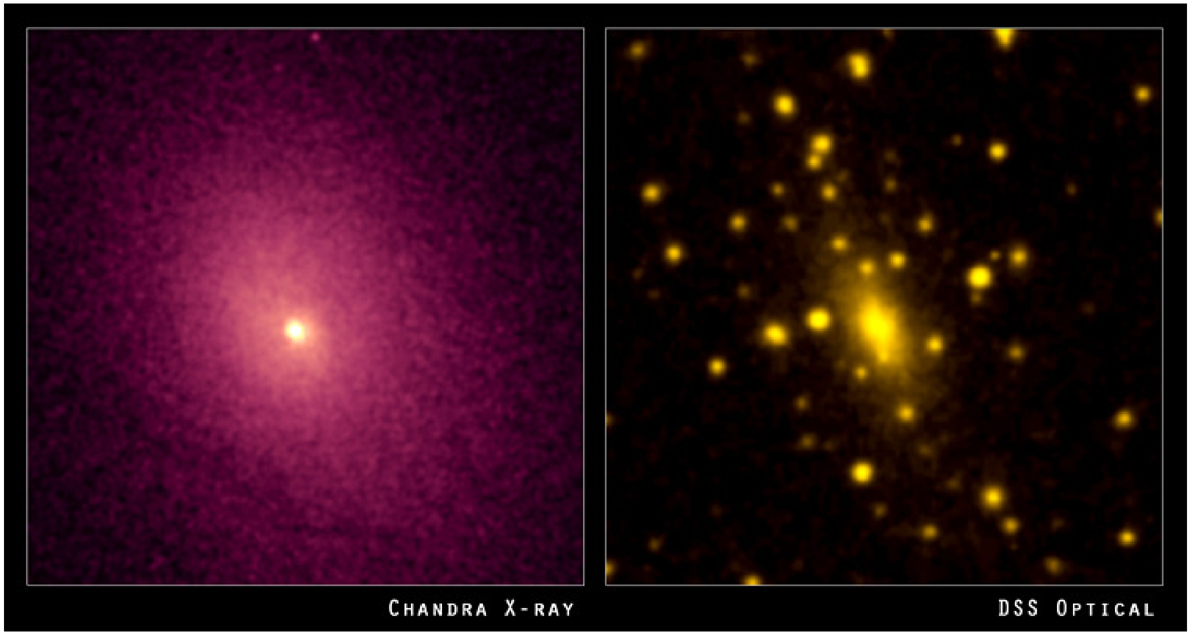
# Evidence I: Rotation curve



M33 rotation curve

Rotation velocities do not decrease when visible matter disappears!

# Evidence II: Intracluster gas



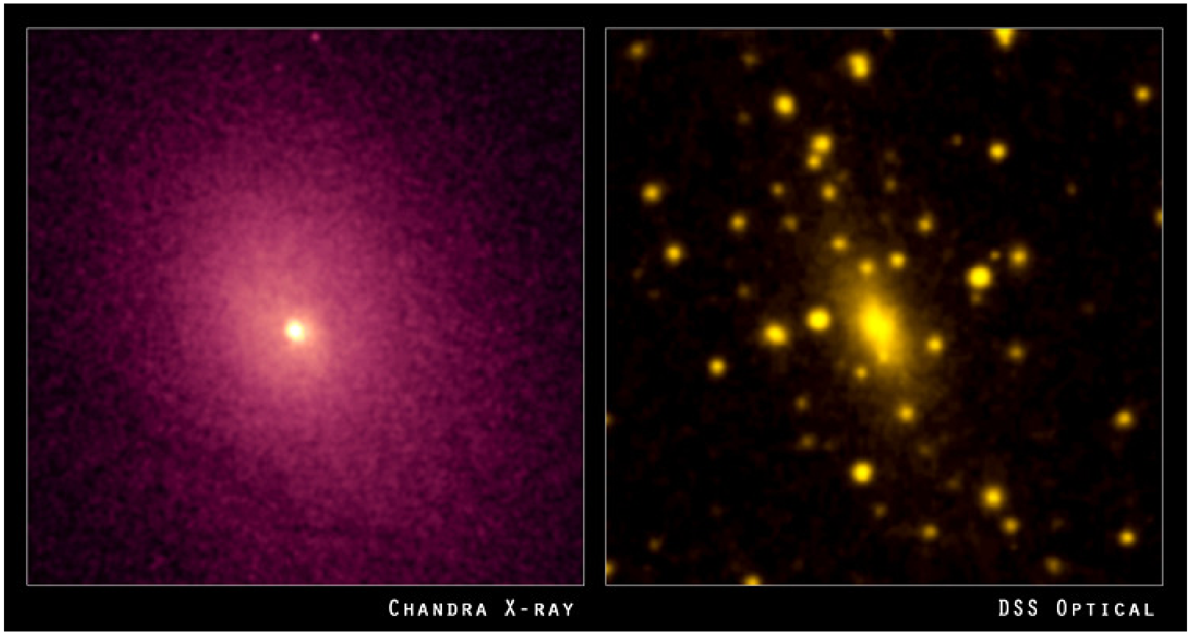
Cluster Abell 2029

- **Clusters of galaxies** look like collections of **point sources in optics** and as **diffuse sources in X-rays**

- X-rays are emitted by the intergalactic gas. X-ray **brightness** is defined by the **temperature** of the gas

- The **temperature** (average kinetic energy) is related to the **potential energy** and therefore to the **mass**

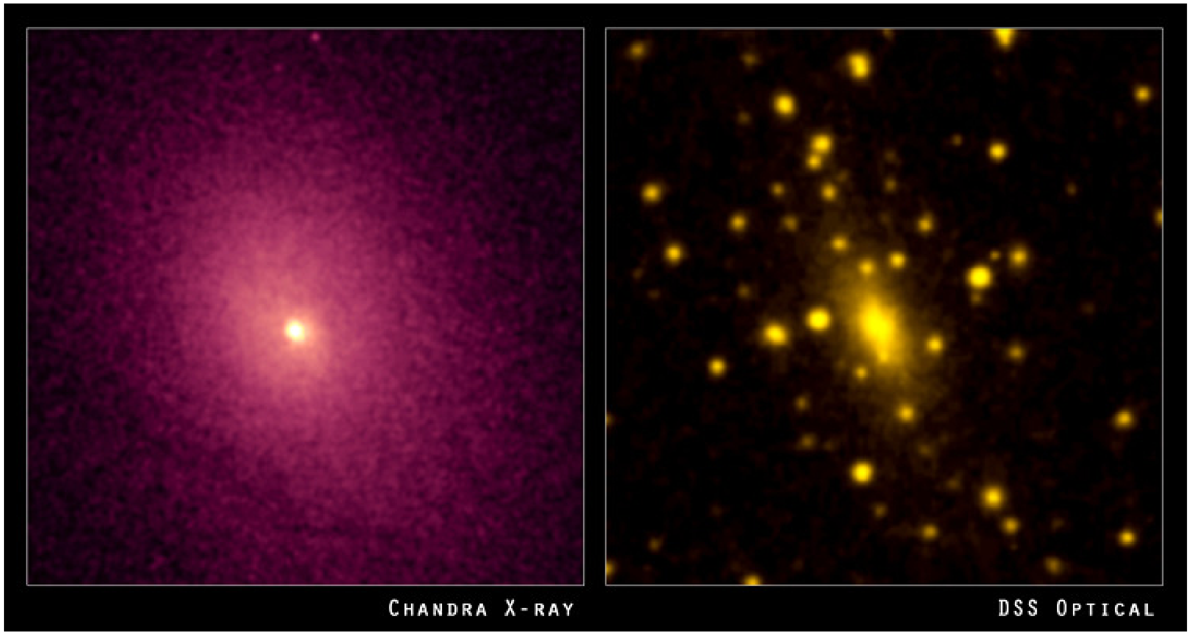
# Evidence II: Intracluster gas



Cluster Abell 2029. Credit: X-ray: NASA/CXC/UCI/A.Lewis et al. Optical: Pal.Obs. DSS

$$\frac{dp}{dr} = n_{\text{gas}}(r)\frac{dT(r)}{dr} + T(r)\frac{dn_{\text{gas}}(r)}{dr} = -\frac{GM(r)n_{\text{gas}}(r)}{r^2}$$

# Evidence II: Intracluster gas



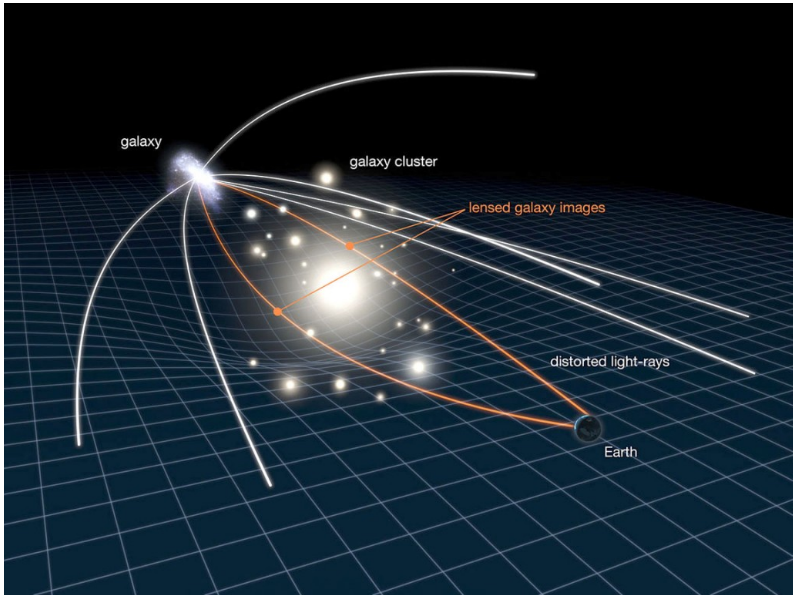
Cluster Abell 2029. **Credit: X-ray: NASA/CXC/UCI/A.Lewis et al. Optical: Pal.Obs. DSS**

| | |
|---|---|
| Dark Matter | $\sim 85\%$ |
| Intracluster gas | $\sim 15\%$ |
| Galaxies | $\sim 1\%$ |

$$\frac{\text{DM in cluster}}{\text{Baryons in cluster}} \approx \frac{\Omega_{\text{DM}}}{\Omega_{\text{baryons}}}$$

**Temperature of ICM:** $1 - 10$ keV $\sim 10^7 - 10^8$ K

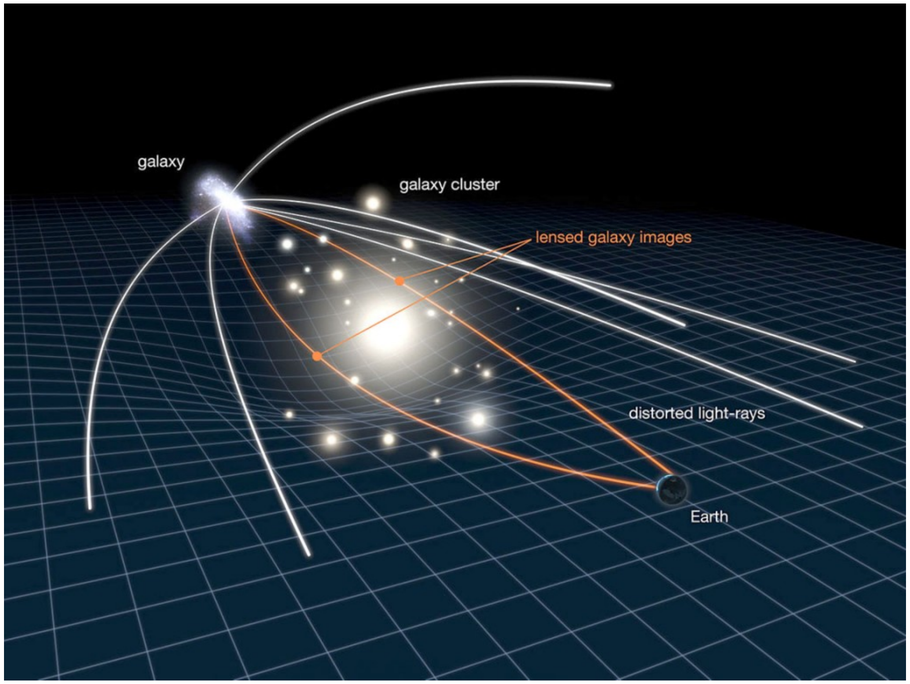
# Evidence III: Gravitational lensing

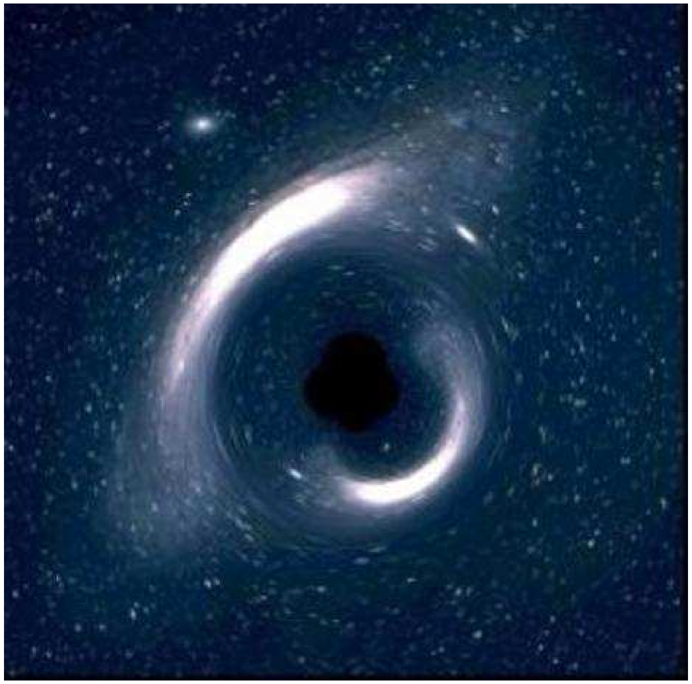


- **Gravitational lensing** works in an analogous way to **normal lenses** – an effect of Einstein's theory of general relativity:
  **mass bends light!**

- **Gravitational lensing allows measuring masses of objects**. There are three types of gravitational lensing:
  - *Strong lensing*
  - *Weak lensing*
  - *Microlensing*

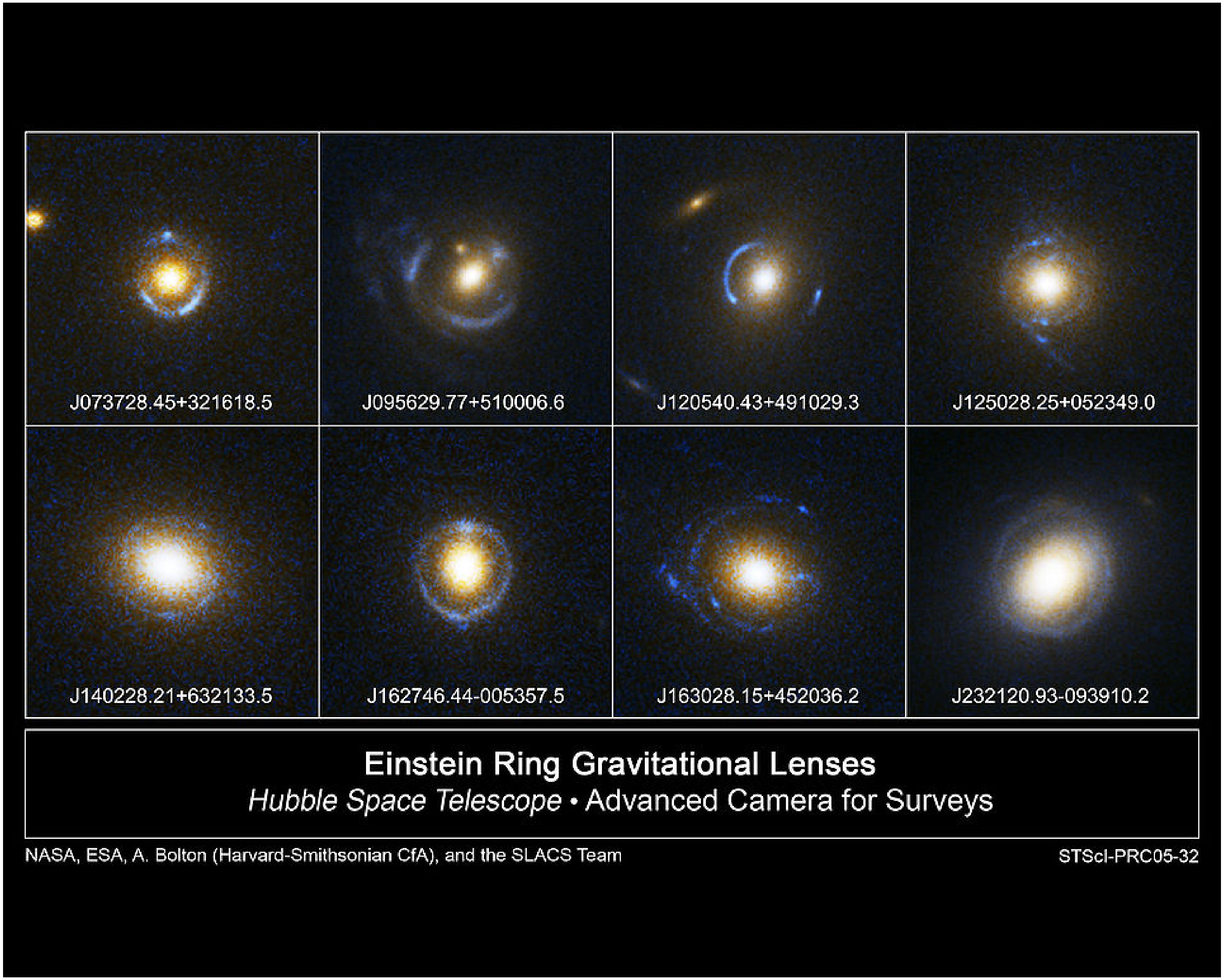
# Evidence III: Gravitational lensing (strong)





- If the lensing effect (Einstein rings) is strong enough, we call this **strong lensing**
- Strong lensing only happens when a **massive cluster of galaxies** lies between us and **some galaxy**
- However, there are not that many clusters that cause such a large lensing effect. So, **strong lensing are very rare!**

# Evidence III: Gravitational lensing (strong)



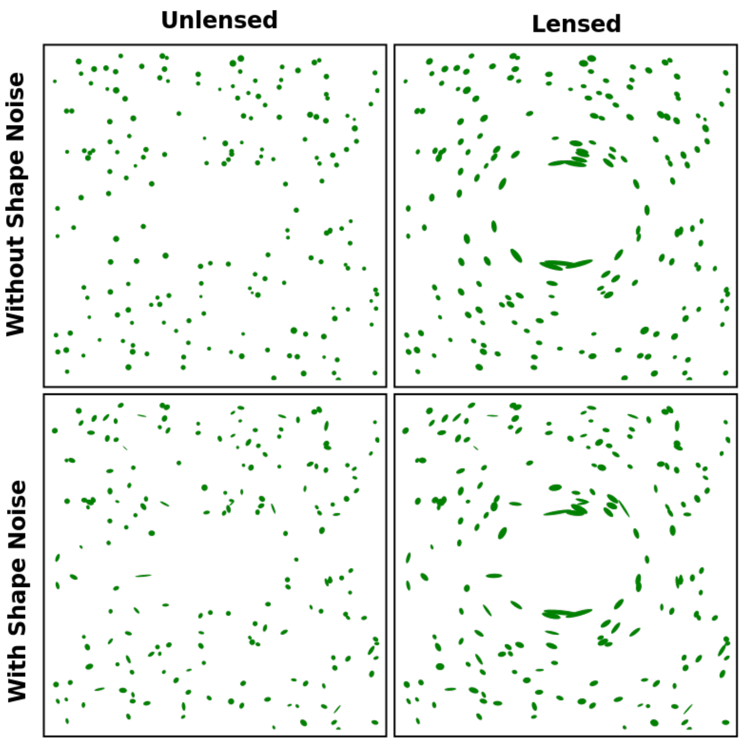
Einstein Ring Gravitational Lenses

*Hubble Space Telescope* • Advanced Camera for Surveys

NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

STScI-PRC05-32

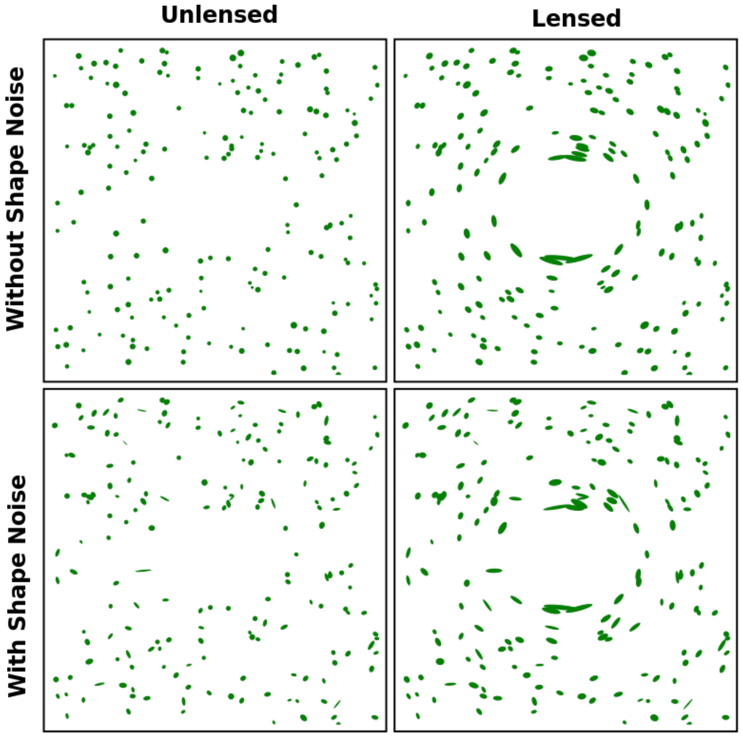
# Evidence III: Gravitational lensing (weak)



- Massive object acting as a lens that **distorts light** (overall shear and magnification) **from many distant objects**. Measuring average shear one can reconstruct the projected mass of the lens

- *ALL* galaxies are lensed - even if only slightly. Usually, we can not see this shape modification by eye because it is too small

# Evidence III: Gravitational lensing (weak)



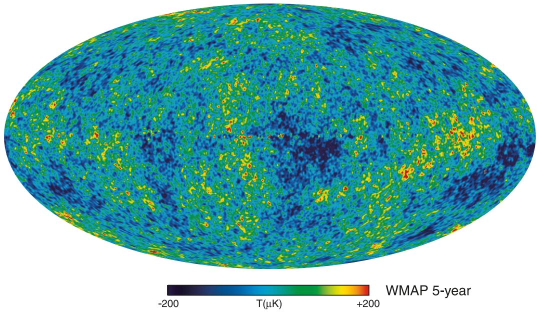
- **How do we measure it?** Cosmologists make 2 *assumptions*:
  - all galaxies are roughly elliptical in overall shape
  - they are orientated randomly on the sky

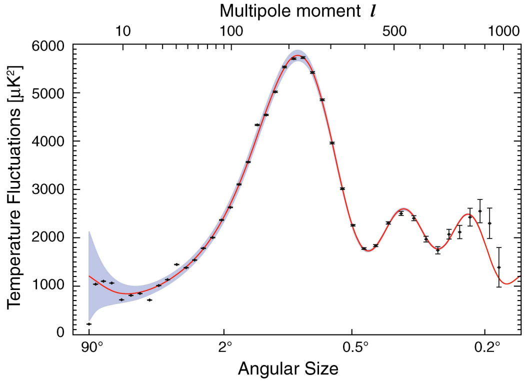
- Any **deviation from a random distribution** of galaxy shape orientations is a **direct measure of the lensing signal** that can be converted to the **mass**

# Cosmological evidence for dark matter

- **Structure formation**: *If there was only baryonic matter in the Universe, density perturbations would not have enough time to grow into galaxies and clusters*

$$\delta\rho/\rho = 10^{-5}\cdot\left(\frac{1+z_{\rm CMB}}{1+z_0}\right) \qquad z_{\rm CMB}\approx 10^3$$





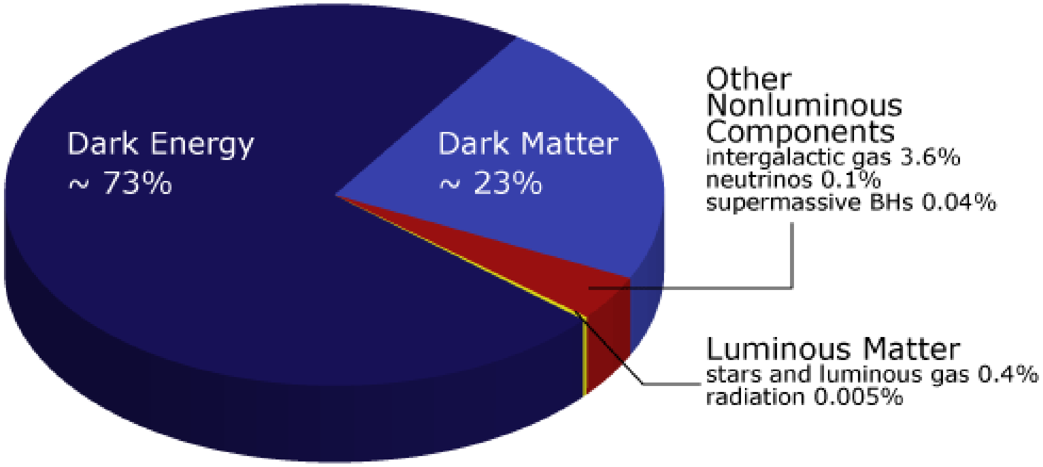
- Approximate isotropy of the **Cosmic Microwave Background** provides strong evidence of the existence of Dark Matter

- The **spectrum of its tiny anisotropies** contains a lot of information about the evolution of the early Universe and allows to measure the abundance of Dark Matter with impressively high precision

- The latest results from Planck shows that the baryon matter is more than 5 times smaller than the total amount of matter

# The Nature of Dark Matter

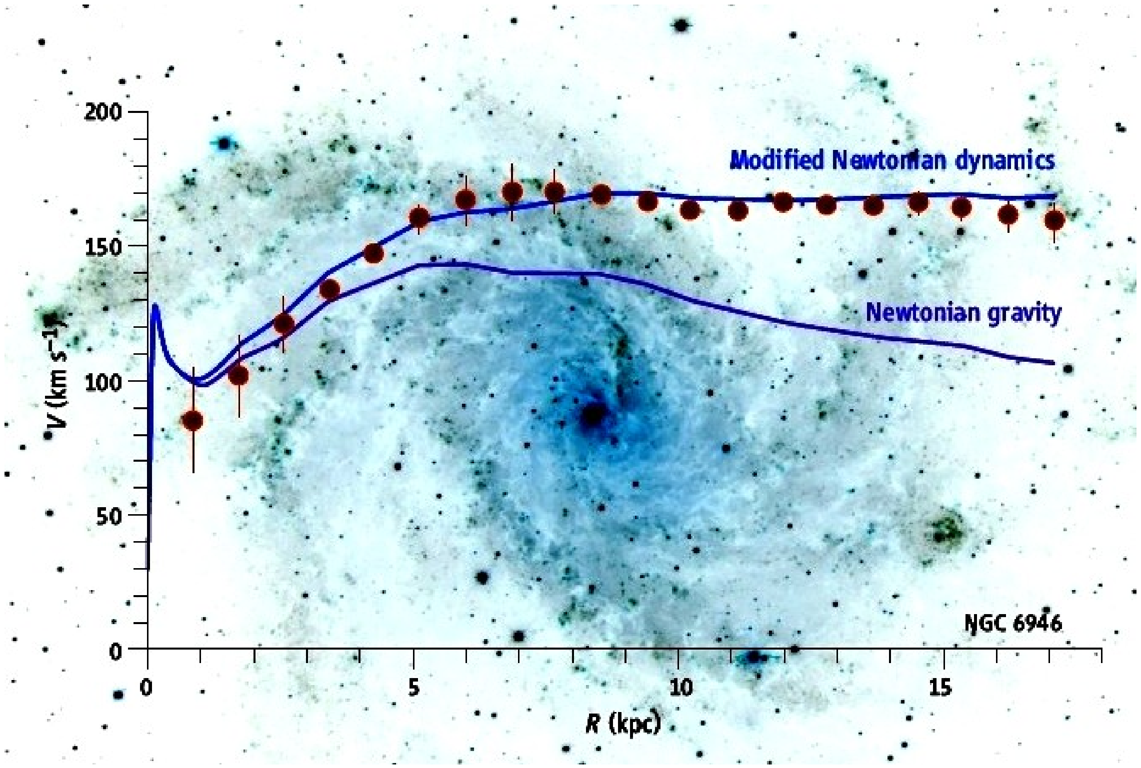
# Three possibilities



- DM is known to be necessary for our understanding of the formation and evolution of galaxies. Having so many evidence that DM exists, **what can we say about the nature of DM?**

- There are 3 possibilities:
  - **Modified Gravity** or Newtonian Dynamics
  - **Compact objects** (MACHOs)
  - **New particles**

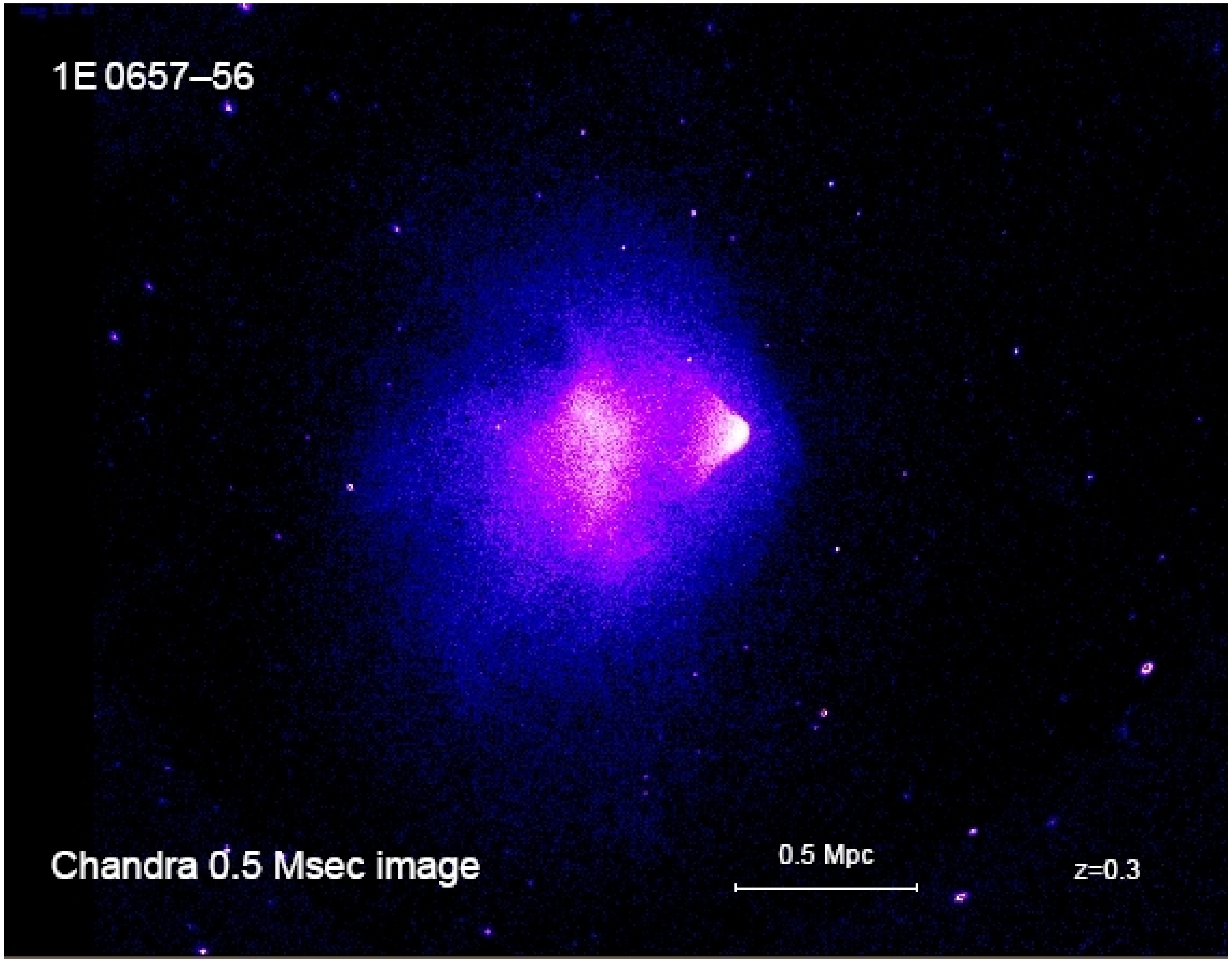
# MOND and Bullet cluster



- **Modified Newtonian Dynamics** (MOND) is a theory that assumes a modification of Newton's second law for very **small accelerations**

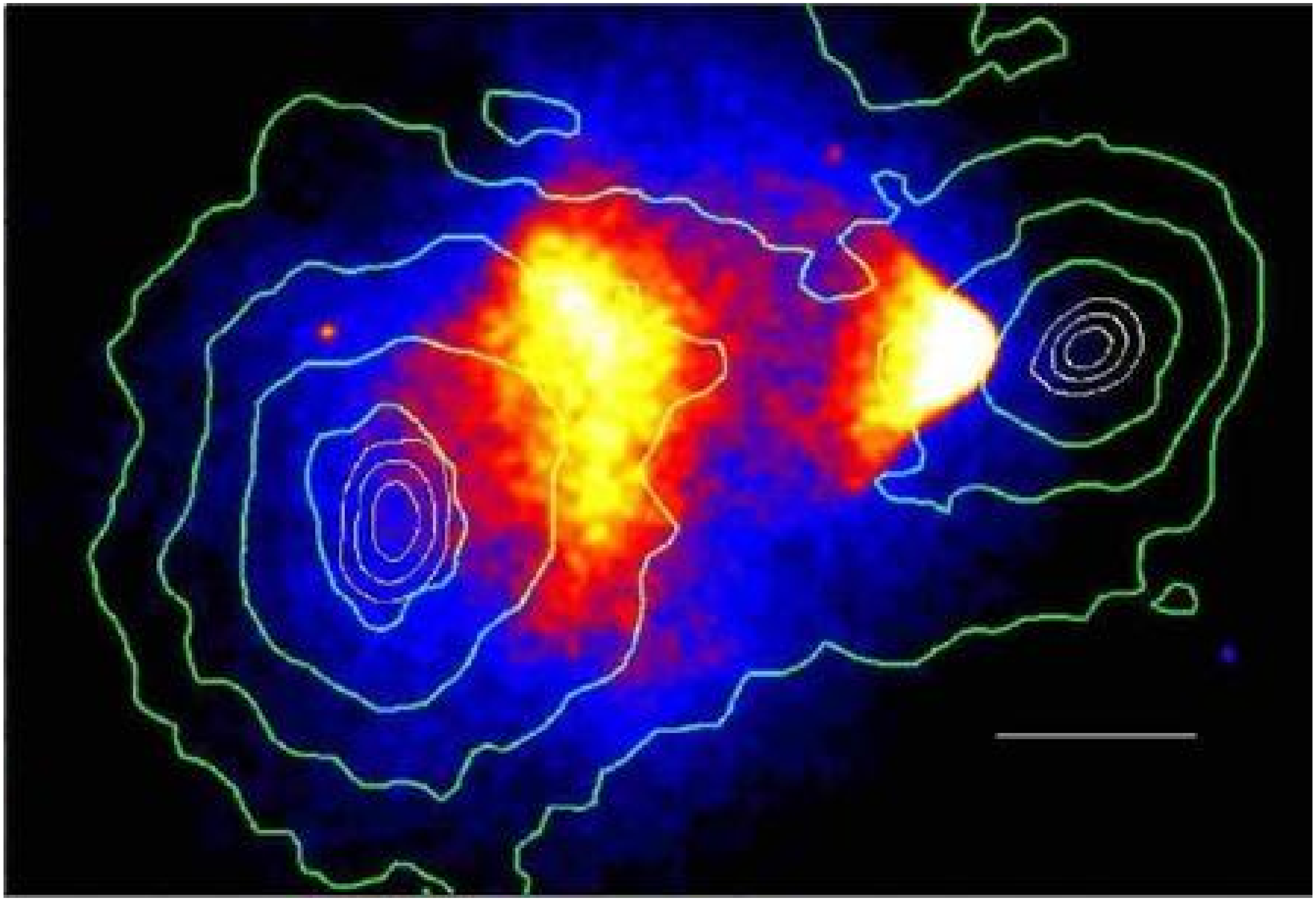
- MOND explains only **rotation curves in galaxies** and does not explain all other evidence of DM, in particular, the Bullet cluster

# MOND and Bullet cluster



- Subcluster passed through the center of the main cluster
- Gas has been stripped away and heated ($T_{\rm gas} \sim 30$ keV)

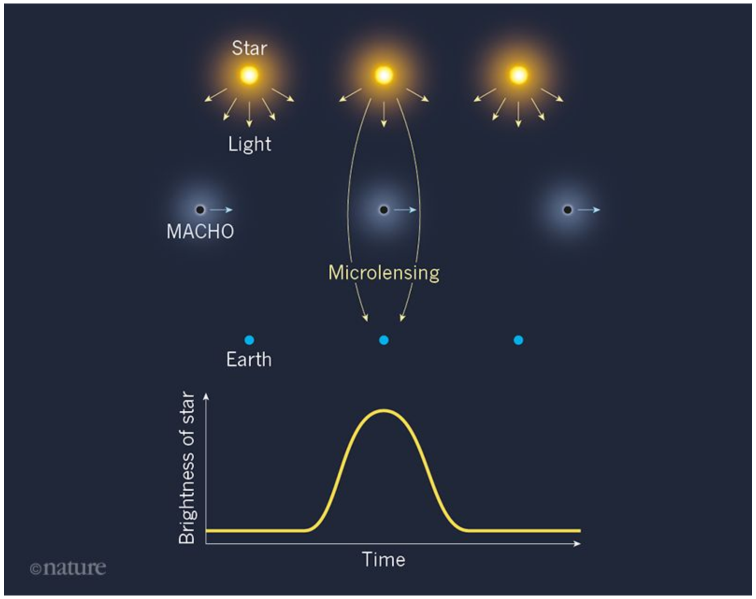
# MOND and Bullet cluster



- DM and stars in galaxies are collisionless
- Centers of mass and gas are clearly separated

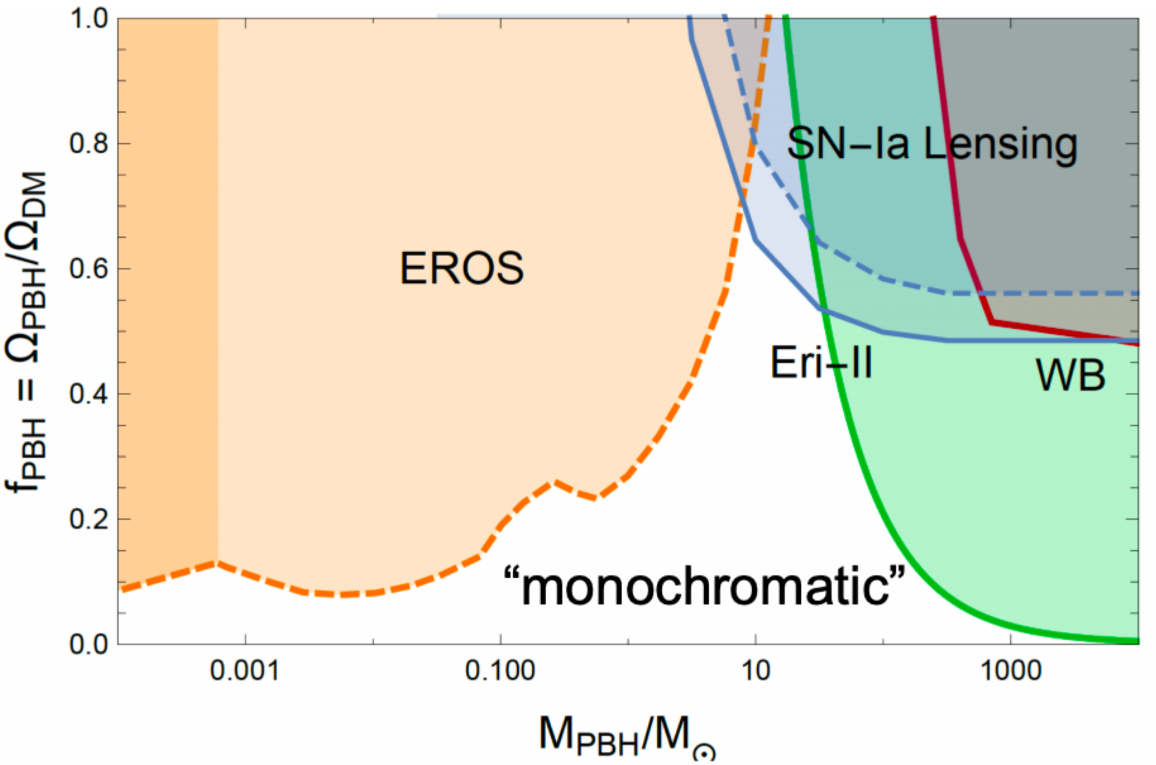
# MACHOs and primordial black holes

- MACHO (Massive Astrophysical Compact Halo Object) was one of the first proposed candidates for dark matter
- These objects include: neutron stars, brown and white dwarfs, black holes etc
- These objects are invisible as they emit very little to no light
- One way to observe them is by monitoring the brightness of distant stars via gravitational microlensing



# MACHOs and primordial black holes

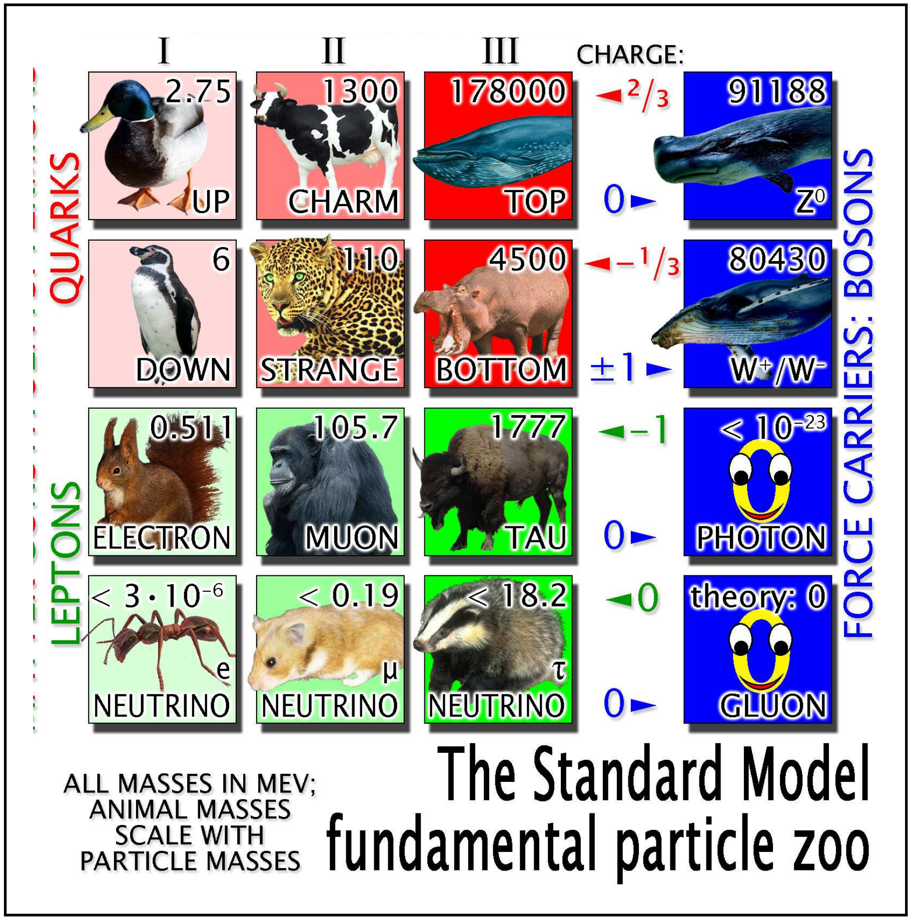
- However, these scenarios have two important challenges
  - It is difficult to explain how these object were created
  - There are strong constrains from gravitational microlensing



**Below we concentrate on the assumption that DM is made of particles**

# Dark Matter particles: Properties

- DM particle should be **massive**
- DM particles should be **neutral** (not to interact with photons)
- DM particles should be **stable** or have cosmologically **long lifetime**



# SM candidates?

**Do we have any such a candidate in the Standard Model?**

- The answer is yes!
- The only possible candidate is **neutrino**
- However, there are two arguments ruling out $\nu$ as the main DM candidate:
  - **Tremaine - Gunn** bound
  - **Top-down structure formation**

# Neutrino Dark Matter: Tremaine-Gunn bound

- *If dark matter is made of fermions – its mass is bounded from below*
- Consider a DM dominated object (dwarf galaxy). One can constrain the size of this object, its mass and velocity of DM particles
- This allows to put a **lower bound on the phase-space density** as it should not exceed the maximal phase-space density given by the Pauli exclusion principle
- This means that there exists the smallest mass that is possible for any fermionic DM particle:

$$\frac{M_{\text{gal}}}{\frac{4\pi}{3}R_{\text{gal}}^3}\frac{1}{\frac{4\pi}{3}v^3} \leq \frac{2{m_{\text{DM}}}^4}{(2\pi\hbar)^3}$$

[0808.3902]

- From dwarf spheroidal galaxies, the **lower bound** on the fermionic DM mass

$$\boxed{m_{\text{DM}} \gtrsim 300 - 400\ \text{eV}}$$

# Neutrino Dark Matter: Tremaine-Gunn bound

- We can compute contribution to DM density from massive neutrinos
- The number density for neutrinos is given by

$$n_{\nu,0} = \int f_F(p) \frac{d^3p}{(2\pi)^3} \sim T_\nu^3(t_0) \simeq 112\ \text{cm}^{-3}$$

- So the contribution to DM is

$$\Omega_{\nu\text{DM}} h^2 = \frac{1}{\rho_{c,100}} \sum m_\nu n_{\nu,0} = \frac{\sum m_\nu\ \text{eV}}{94\ \text{eV}}$$

- For $m_{\text{DM}} = 300$ eV one gets $\Omega_{\text{DM}} h^2 \sim 3$ (**wrong by a factor of 30!**)
- Sum of masses to have the correct abundance $\boxed{\sum m_\nu \approx 11\ \text{eV}}$

**Massive neutrinos cannot be simultaneously "astrophysical" and "cosmological" dark matter**

# Neutrino Dark Matter: Structure formation

- Next blow to neutrino DM came around 1983–1985 when M. Davis, G. Efstathiou, C. Frenk, S. White, *et al.* "*Clustering in a neutrino-dominated universe*"

- They argued that structure formation in the neutrino dominated Universe (with masses around $100$ eV would be incompatible with the observations)

`http://www.adsabs.harvard.edu/abs/1983ApJ...274L...1W`

**Abstract**

The nonlinear growth of structure in a universe dominated by massive neutrinos using initial conditions derived from detailed linear calculations of earlier evolution have been simulated .................. **The conventional neutrino-dominated picture appears to be ruled out.**

# Model-independent classifications of DM candidates

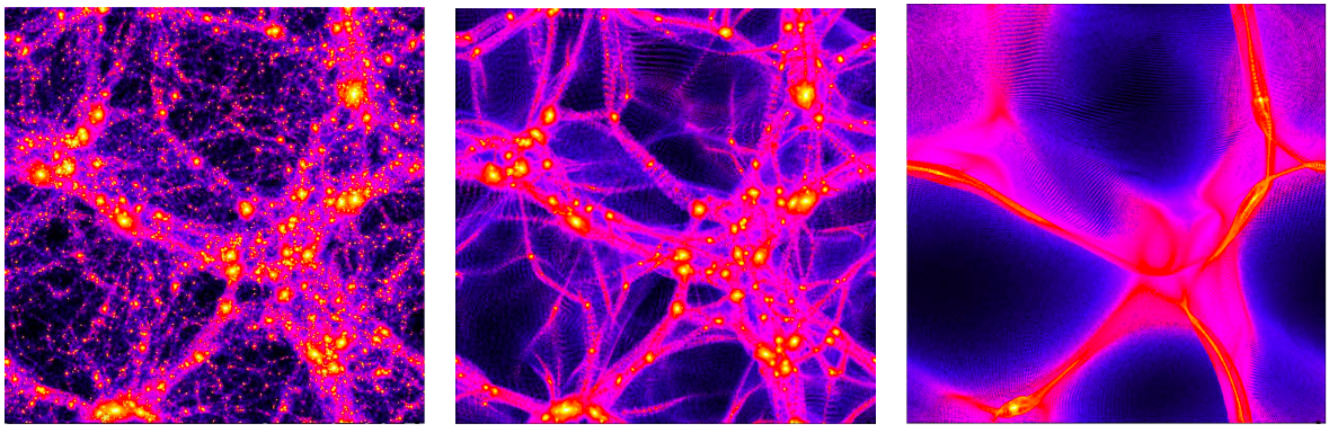
# DM classification

## DM particles can be classified by

- **Initial velocity:** Cold, warm and hot
- **Interaction with SM:** Stable, decaying or annihilating
- **Interaction with itself:** Ballistic or self-interacting

# Initial velocity

- If DM particles are created *non-relativistic* we call them **Cold Dark Matter** (CDM). They can fall on any over-density and form halos of all sizes
- **Warm Dark Matter** (WDM) and **Hot Dark Matter** (HDM) are particles that were created *relativistic*. They cannot be confined by an over-density as long as they are still relativistic and their velocities are close to the speed of light
- The distance that a particle travels from the place where it was *created* to the place where it was *gravitationally bound* is called the **free streaming length**



# Observational differences between CDM and WDM

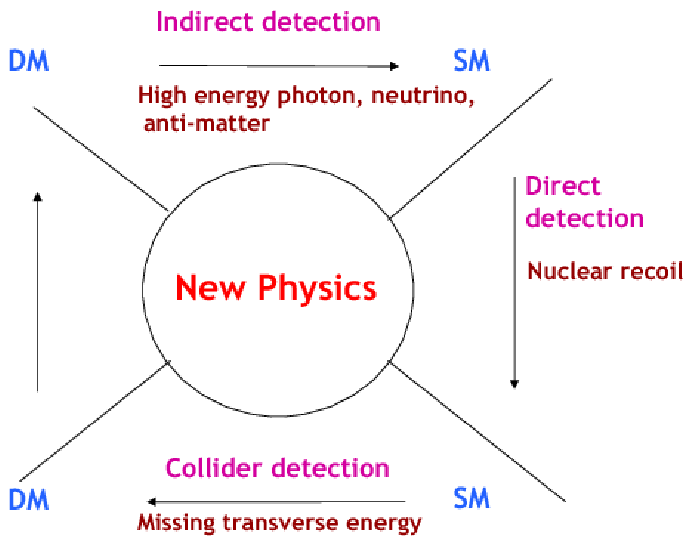
- The *main difference* between **CDM and WDM** is that in CDM there are clumps of DM of **all sizes**, galaxies like Milky Way have more and more substructures of smaller and smaller sizes
- *In WDM model*, the number of structures of the size close to the free streaming length quickly **drops to zero**
- The **problem** is that *small halos are very difficult to observe*
- Primordial hydrogen is *heated* during reionisation and falls into a halo *only if the halo is massive enough*
- We expect that small halos contain **only DM** and can be observed only via **gravitational lensing**
- New telescope Euclid (will be launched in 2021), will be able to prove/exclude the existence of small DM only halos and either exclude CDM or very severely constrain WDM

# Ballistic and self-interacting

- An interaction of Dark Matter with the Standard Model particles is **very strongly constrained by observations**
- The constraints on the cross-section of **the DM self-interaction** are many orders of magnitude **less stringent**
- The robust constraint on the self-interacting dark matter comes from the Bullet cluster and other merging systems
- One possible observable effect comes from the inner structure of the halos: scatterings of DM particles prevent them from collapsing and **reduce the central densities** of DM halos
- This effect is difficult to *predict* quantitatively and to *observe*. Also, it is difficult to distinguish from *baryons effects* in the ballistic CDM
- Robust constraints on DM self-interaction can be obtained by direct comparison of large ensembles of the observed and simulated families of all sizes, from clusters to dwarfs

# Searching for Dark Matter

# Different search strategies



- **Direct detection:** find a signal of the interaction of DM with a nucleus in the laboratory

- **Indirect detection:** find a signal from decay/annihilation of DM from space

- **Search at accelerators:** find an event with DM at accelerators

# Direct detection: WIMPs at XENON

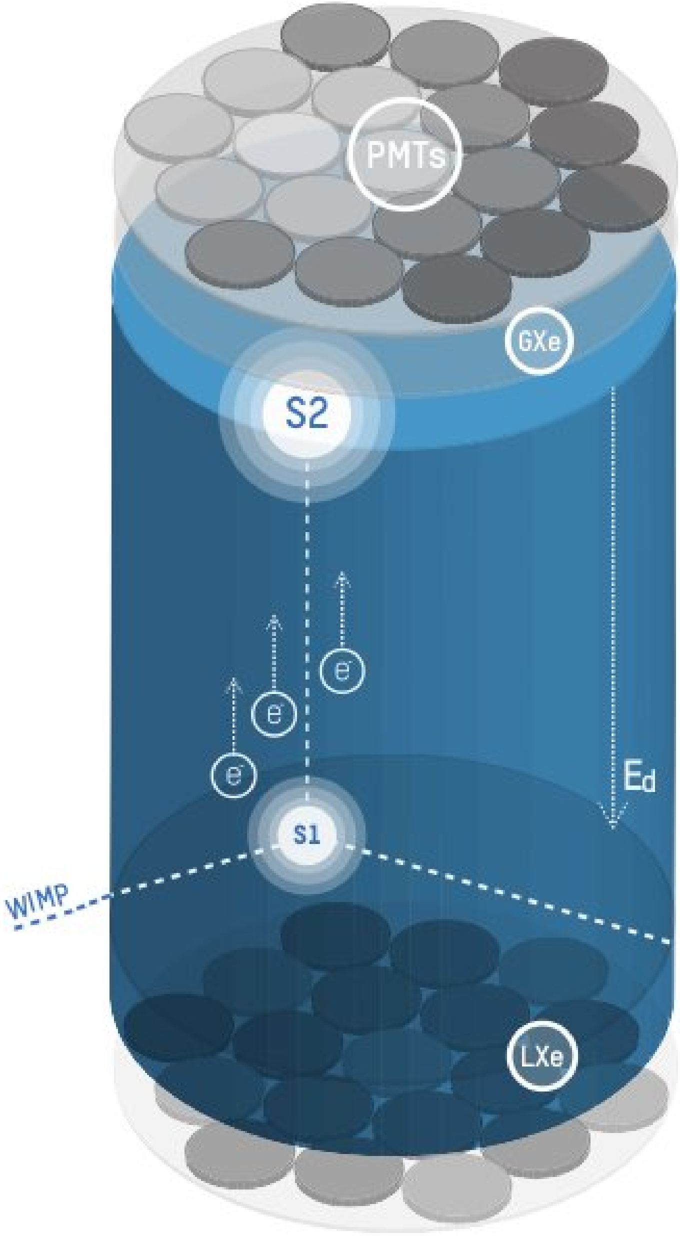
- The cross-section of the scattering on **nucleons** is **much larger** than on electrons

- A galactic WIMP that scatters on a nucleus **ionizes** its atom

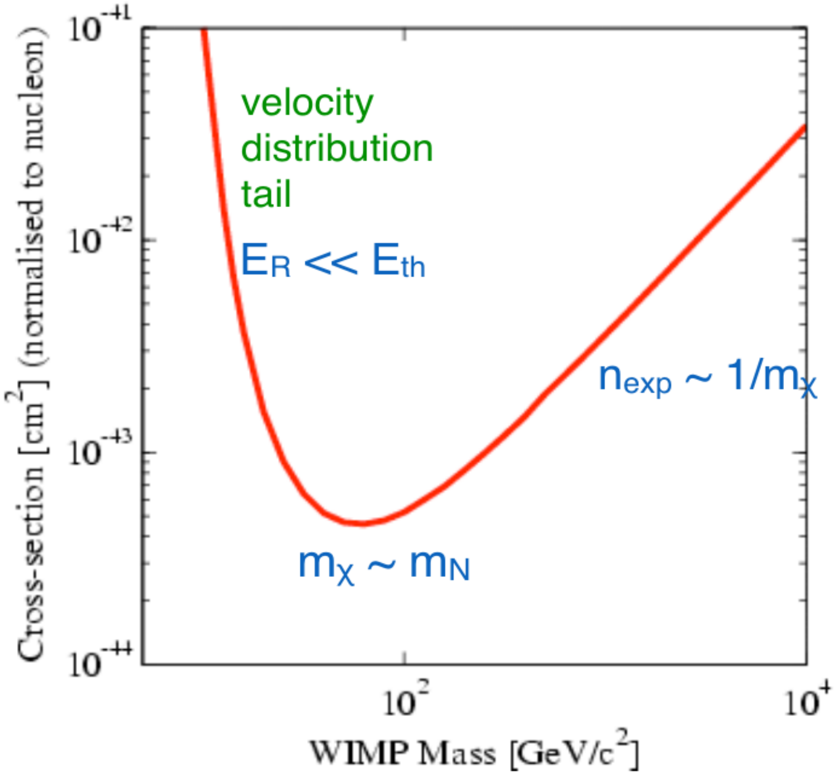
- Ion propagates in xenon and **creates ultraviolet photons**, that are detected by photo-multipliers (PMTs)

- **Electrons** in the electric field drift to the detectors

- The **combination of S1 and S2** signals is sufficient to distinguish the *DM signal* from the background

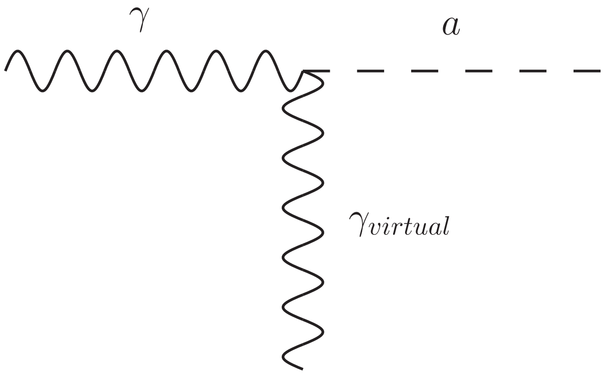


# Direct detection: WIMPs at XENON



- **At low WIMP masses**, the sensitivity decays when the recoil energy $E_R$ is smaller than the ionization threshold energy $E_{\text{th}}$
- **For large WIMP masses**, the sensitivity decays because the DM number density $n_{\text{exp}} \sim 1/m_\chi$

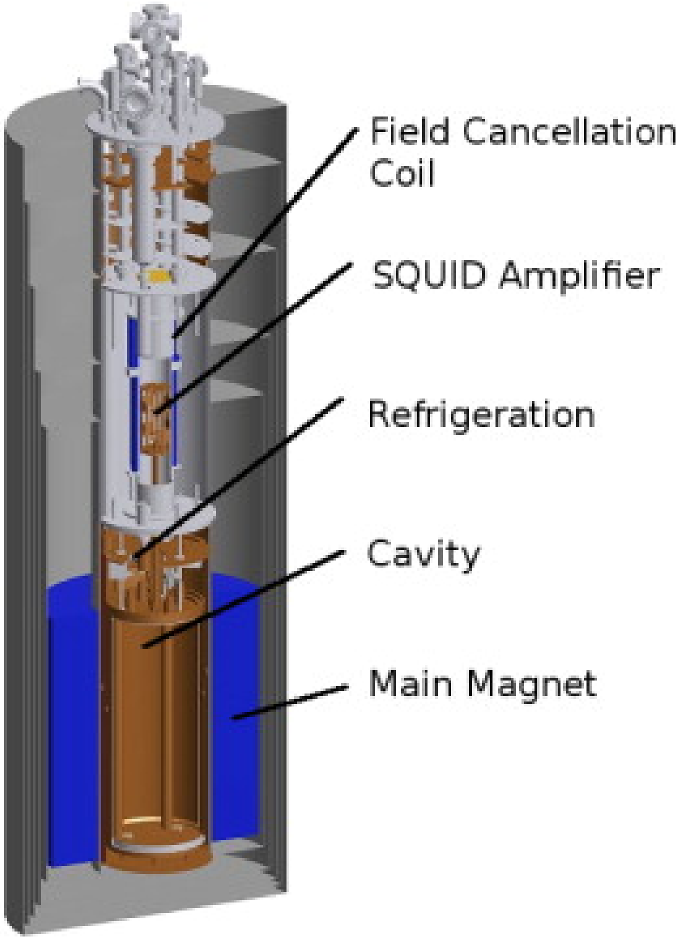
# Direct detection: Axions



- Axion is a **very light** CDM candidate ($m_a \ll 1$ eV)

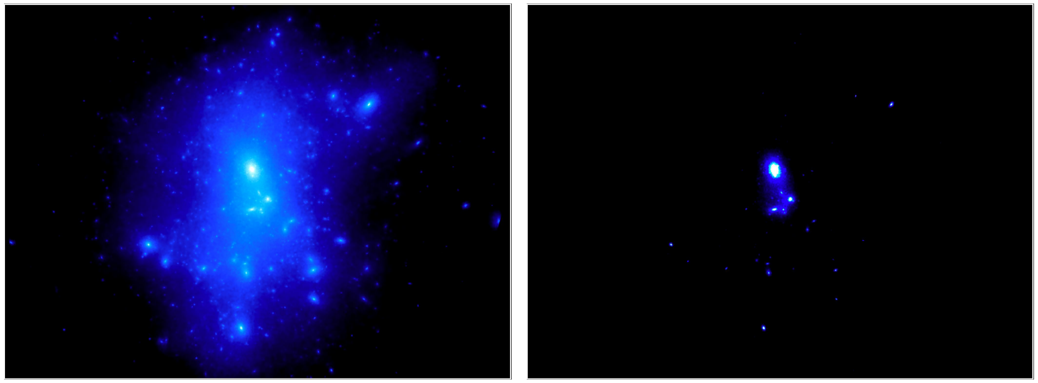
$$\mathcal{L}_{\text{int}} = g_a a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- Axions can be detected using the *Primakoff effect*, that **converts axions into photons** in the external EM field



- The ADMX experiment uses *microwave photons* to **increase** axion conversion rate and **measure the power** of converted photons

# Indirect detection



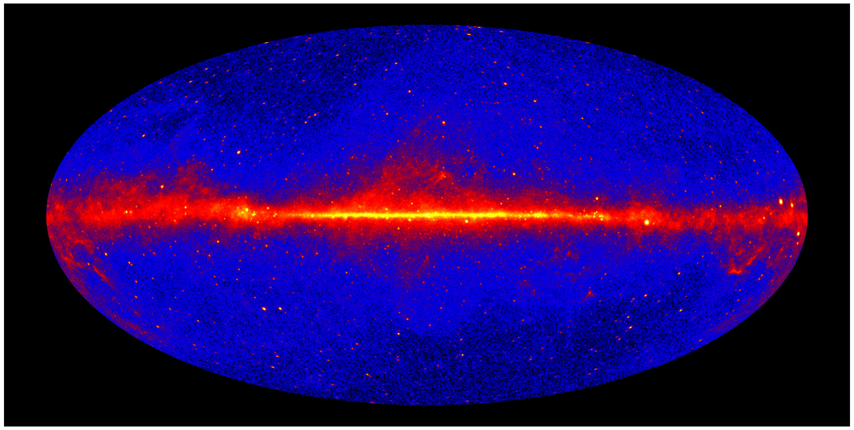
- In the *center of a galaxy*, there are more DM particles than at the edges. So we expect the **strongest signal from the center**

- **For an annihilating dark matter**, the signal is proportional to $\rho^2$

- **For decaying DM**, only one particle is needed to produce a signal, therefore the is linearly proportional to the density

- *The signal for the annihilating DM is much more concentrated in the center, while the signal of the decaying DM is wider.*

# Indirect detection

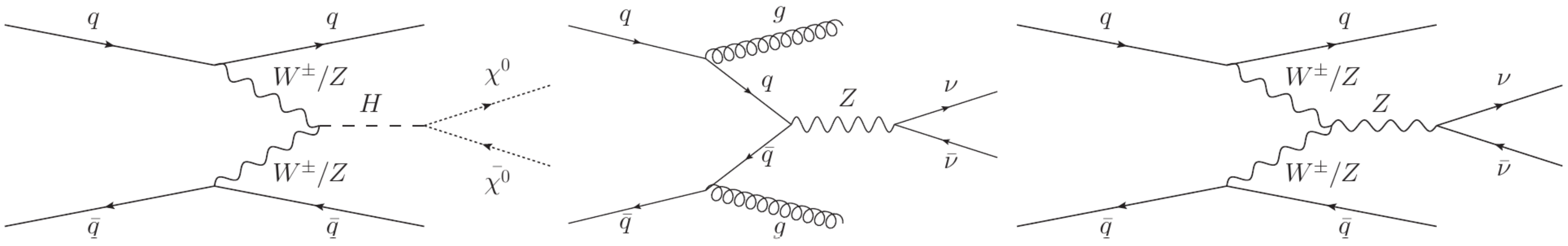


- *Spectral properties* of the signal are **not unique** and depend on particle physics model and available annihilation (decay) channels

- There are two scenarios of $\gamma$ photons creation:
  - **prompt emission**: photons produced directly or from very fast decay of secondary particles
  - **secondary emission**: initially, charged particles were produced. They travel some distance and produce photons for example via Inverse Compton process

- **The main challenge – the astrophysical background**

# Search at accelerators



(a) Signal

(b) Strongly produced (QCD) $Z$+jets

(c) Weakly produced (EW) $Z$+jets

- If DM is produced at *accelerators*, the expected signature is **missing energy** and/or **missing momentum**
- For the LHC, the background is given by the evens with **SM neutrinos**
- It is possible to **reduce** the background assuming a **certain model** and **introducing cuts** on the initial and final states that reduce significantly the number of SM events and *do not affect the signal*
- An example – a search for a model, where Dark Matter couples to the Standard Model via **mixing with the Higgs boson** (the so-called *”scalar portal”*)