# Astroparticles and Dark Matter (from production to detection)

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**TAE2019 Benasque**


The dark side

# Contents (Astroparticles and Dark Matter)

1) Motivation for dark matter

   Some basic Cosmology: Boltzmann equation and Freezeout of massive particles

2) Dark Matter Production Mechanisms:
   Freezout (WIMPs) versus Freeze-in. Out of equilibrium decays
   Axions and axion like particles

3) Dark matter detection
   direct detection
   indirect searches

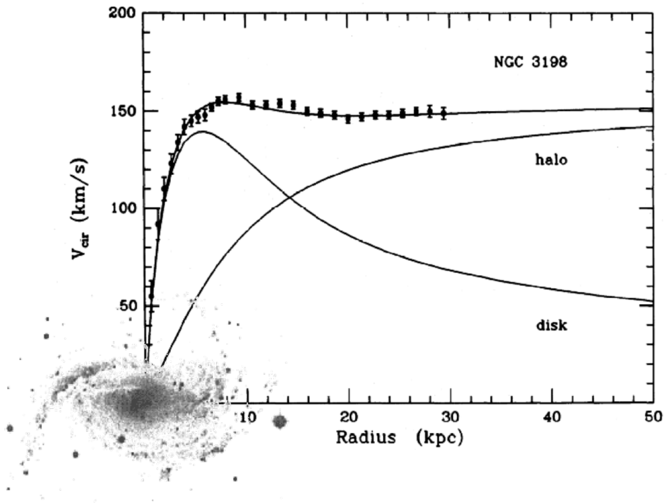
4) (some) DM models

# Dark Matter is a necessary (and abundant) ingredient in the Universe

It is one of the clearest hints of Physics Beyond the SM

## Galaxies

- Rotation curves of spiral galaxies
- Gas temperature in elliptical galaxies



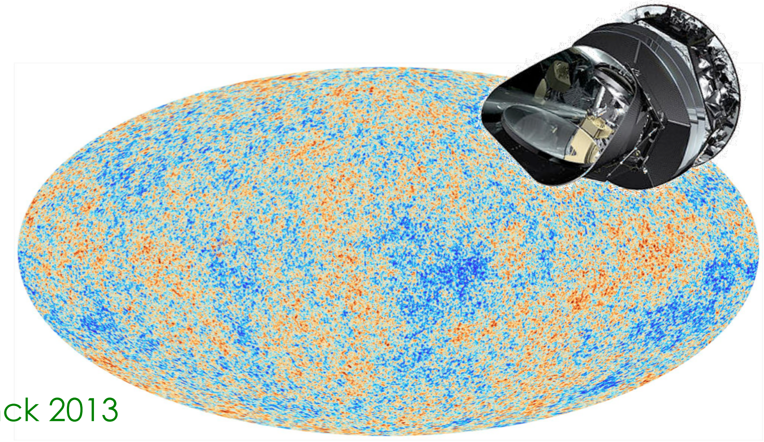

## Clusters of galaxies

- Peculiar velocities and gas temperature
- Weak lensing
- Dynamics of cluster collision
- Filaments between galaxy clusters

## Cosmological scales

Anisotropies in the Cosmic Microwave Background

$$\Omega_{CDM}\, h^2 = 0.1196 \pm 0.003$$



Planck 2013

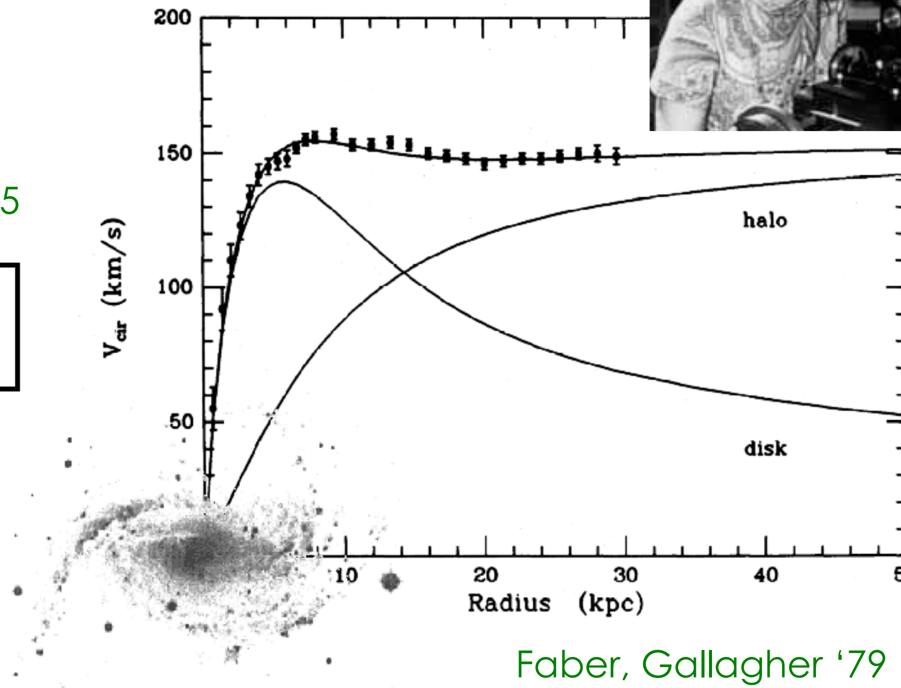
# Rotation curves of spiral galaxies become flat for large distances

From the luminous matter of the disc one would expect a decrease in the velocity that is not observed

Rubin '75

$$\frac{v_{\text{rot}}^2}{r} = \frac{G\ M(r)}{r^2} \rightarrow v_{\text{rot}} = \sqrt{\frac{G\ M(r)}{r}}$$

$$M(r) = cte \rightarrow v_{\text{rot}} \propto \frac{1}{\sqrt{r}}$$




Faber, Gallagher '79
Bosma '78, '81
van Albada, Bahcall, Begeman, Sancisi '84

Galaxies contain vast amounts of non-luminous matter $M \gg M_*$

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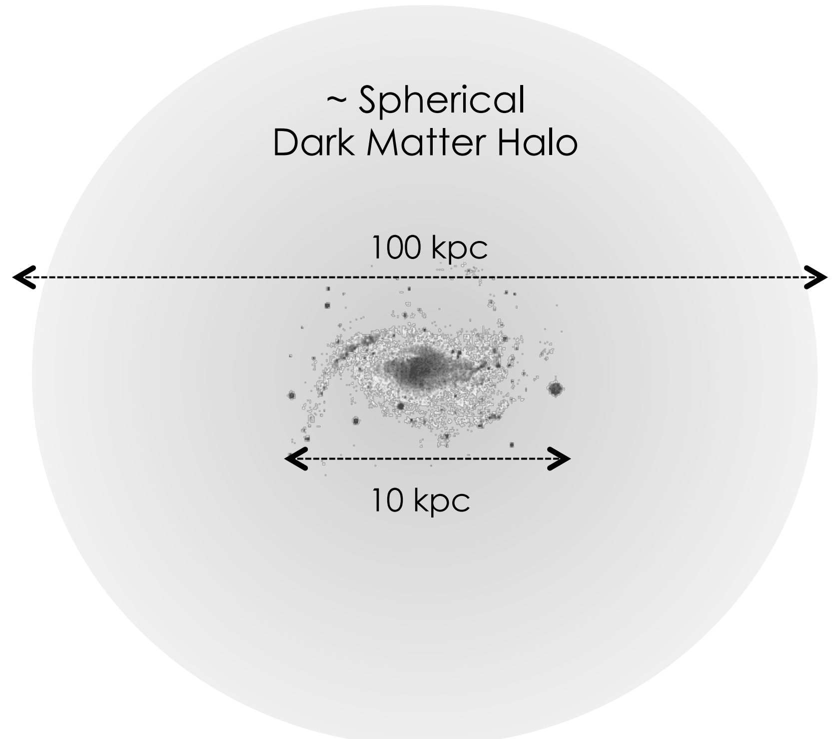


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Isothermal Spherical ~~Cow~~ Halo (a.k.a. Standard Halo Model)

Isotropic

density distribution $\rho(r) \propto r^{-2}$

it has reached a steady state (Maxwell-Bolzmann distribution of velocities)

# Rotation curves have also been measured for a large number of spiral galaxies

The mismatch in the shape cannot be compensated by modifying the contribution from luminous components (disk and bulge)

Faber, Gallagher '79
Bosma '78, '81
van Albada, Bahcall, Begeman, Sancisi '84

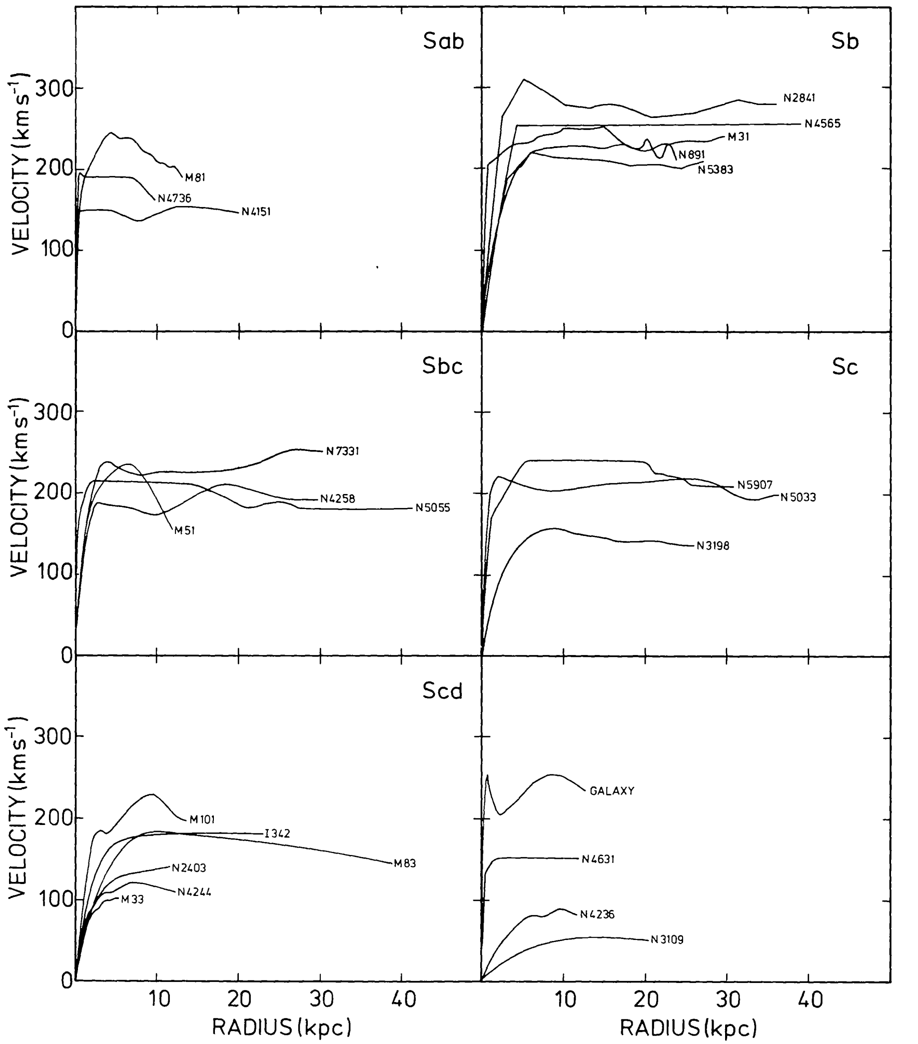
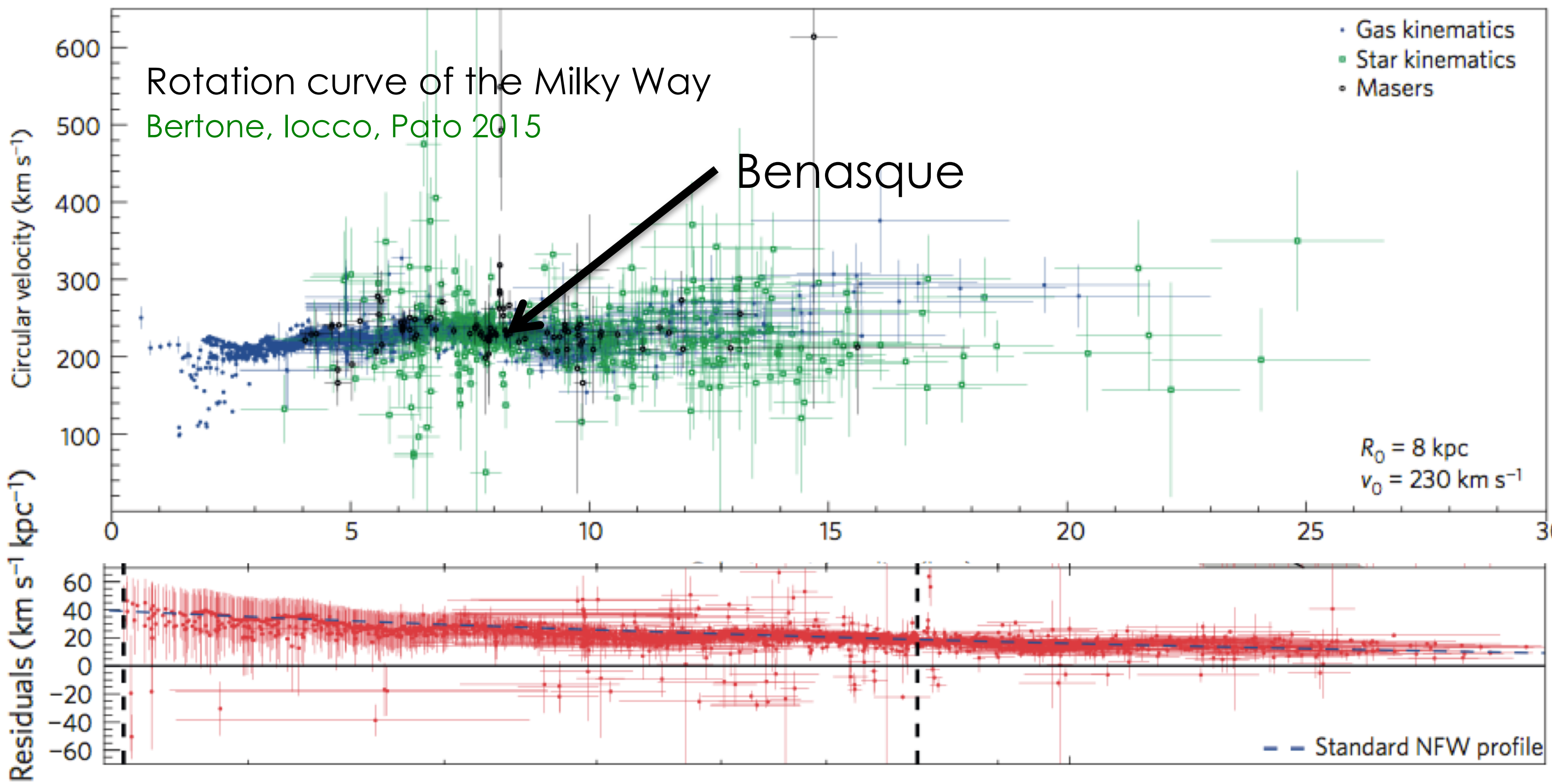



*Figure 2* Rotation curves of 25 galaxies of various morphological types from Bosma (1978).

# The effect of DM has also been observed in the Milky Way...

- There is DM in the centre of our Galaxy




- Observations also show that there is need for DM in the solar neighbourhood

Bovy, Tremaine 2012

# There are substantial uncertainties in the description of our DM halo

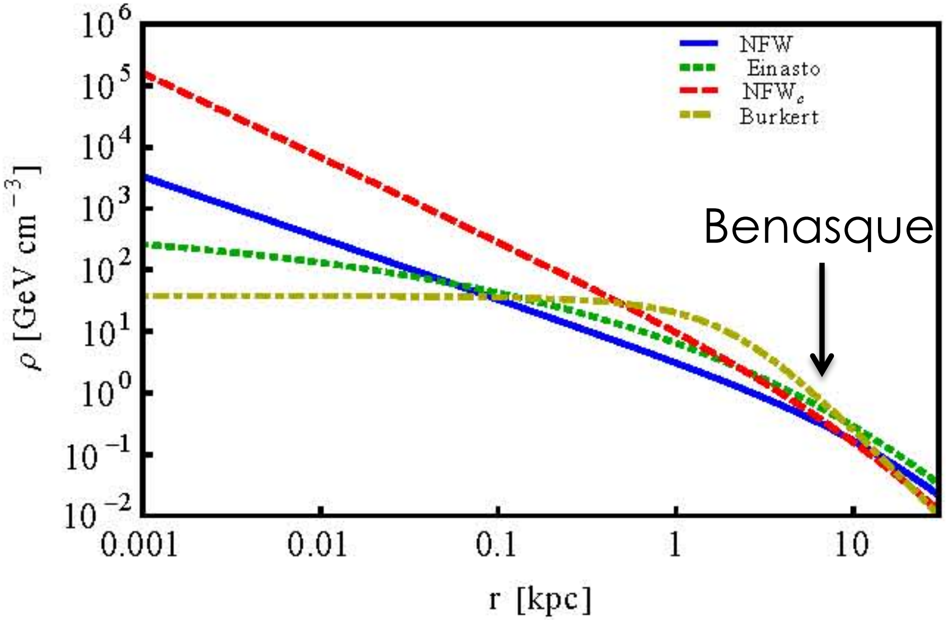
- local DM density

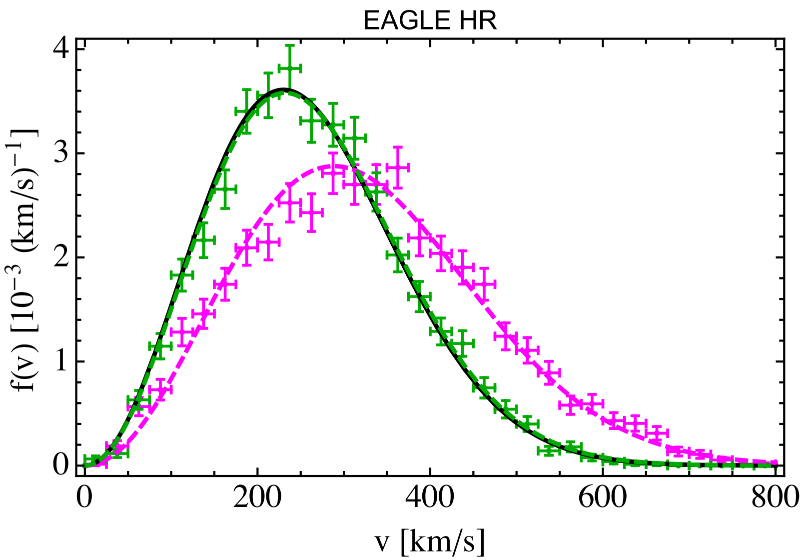
$$\rho_{DM}(R_0) = 0.43(0.11)(0.10)\,\mathrm{GeV/cm^3}$$ Nesti, Salucci 2012

$$\rho_{DM}(R_0) = 0.32 \pm 0.07\ \mathrm{GeV/cm^3}$$ Strigari, Trotta 2009

$$\rho_{DM}(R_0) = 1.3 \pm 0.3\ \mathrm{GeV/cm^3}$$ De Boer, Webber 2011

- DM density profile
  (DM density at the galactic centre)



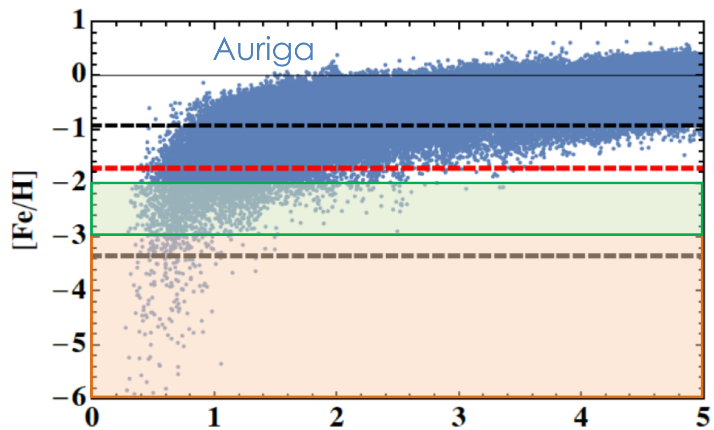




- Velocity distribution of DM particles

Maxwellian distribution is a good fit in the Milky Way
Uncertainty in astrophysical parameters

Bozorgnia et al. 1601.04707

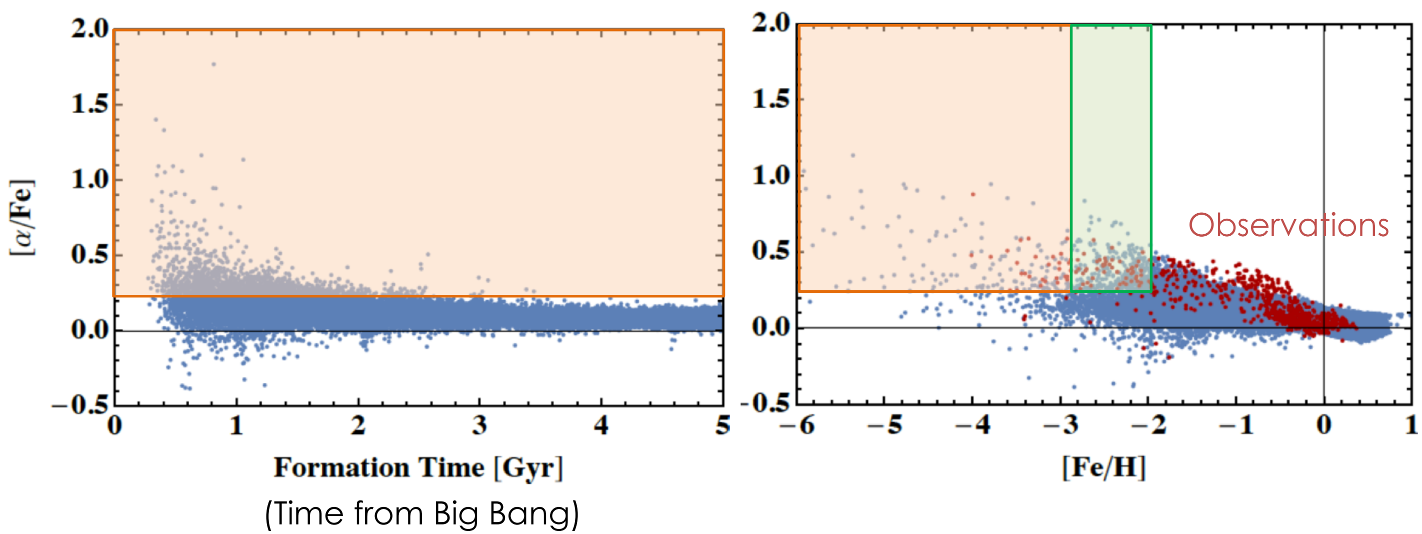
# Can we use stars to trace the DM velocity distribution?




Old stars are deposited in the Galactic inner regions by disruption events.

DM and metal-poor stars in the Solar neighbourhood could share similar kinematics due to their common origin

We can use the metallicity as a proxy for the star's formation time.

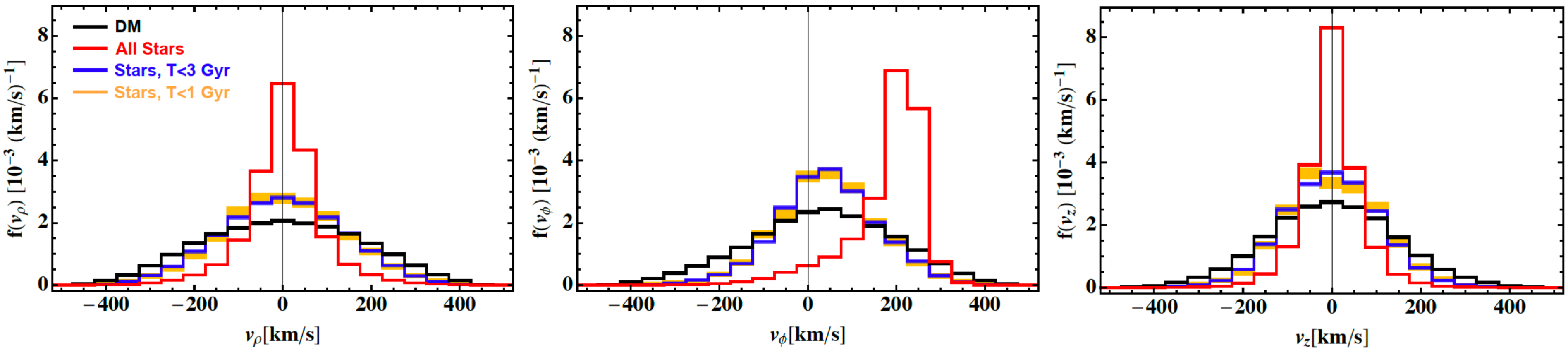


# Can we use stars to trace the DM velocity distribution?

It has been suggested that the local dark matter velocity distribution can be inferred from that of **old** or **metal-poor** stars

Herzog-Arbeitman, Lisanti, Necib 1704.04499

Results from high resolution magneto-hydrodynamical simulations of Milky Way-like galaxies of the Auriga project do not show a strong correlation




Bozorgnia et al. 1811.11763

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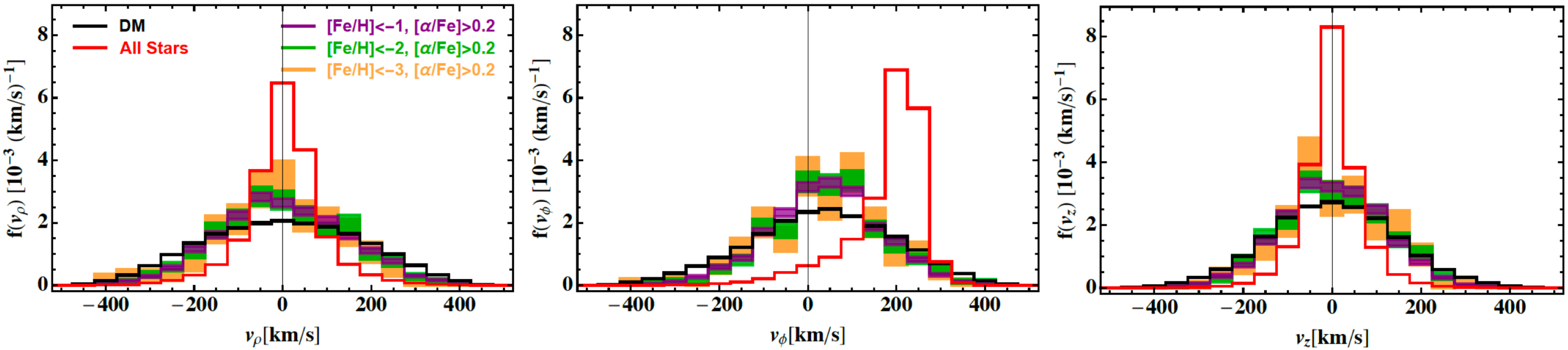


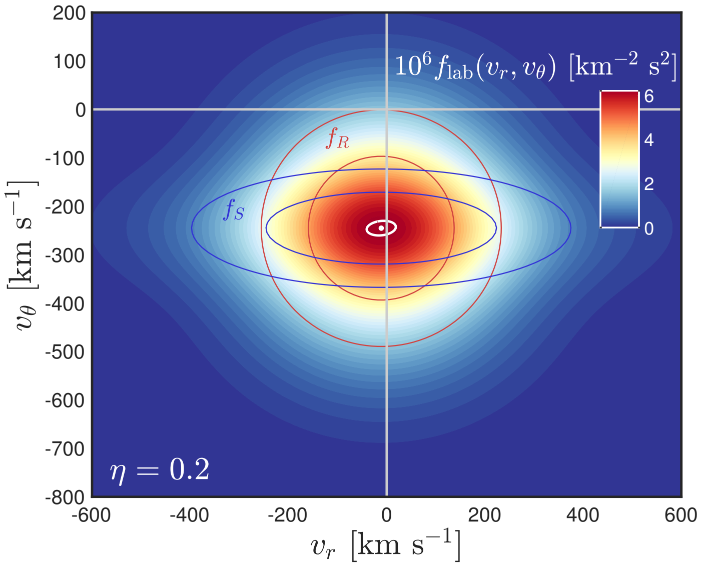

Bozorgnia et al. 1811.11763

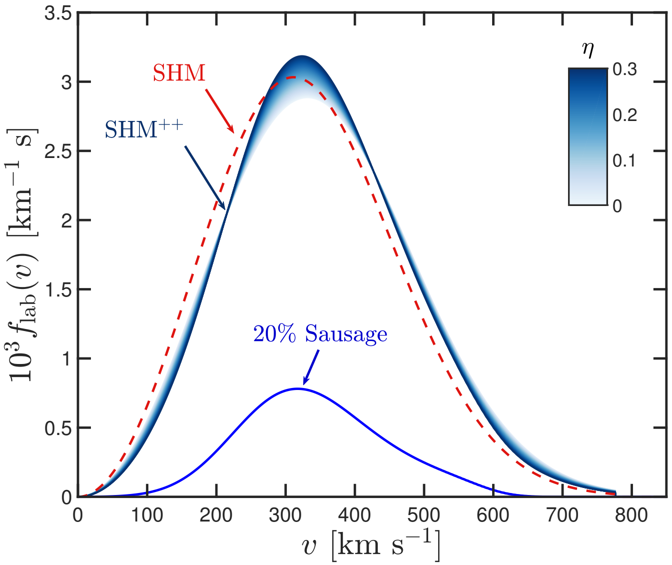
# A sausage in our Galaxy??

The DM (and stars) velocity distribution function is sensitive to the merging history.

Evans, et al. 2018

A head-on collision with a smaller object left a characteristic imprint in the angular and radial velocities.



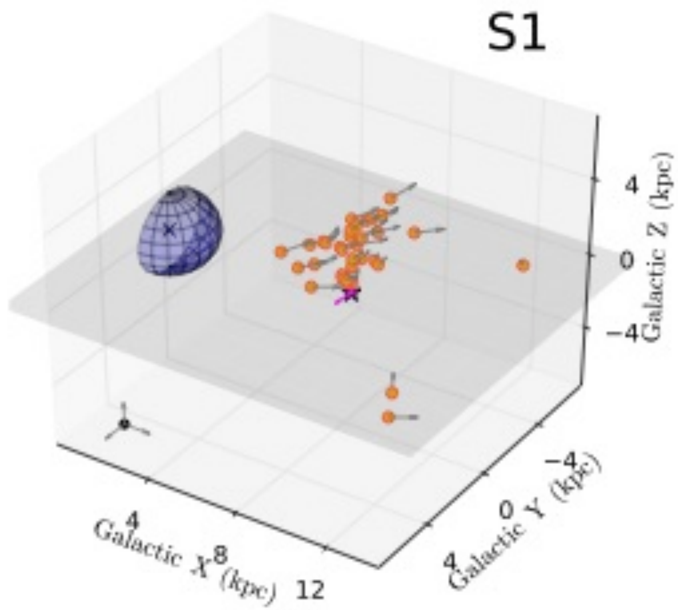



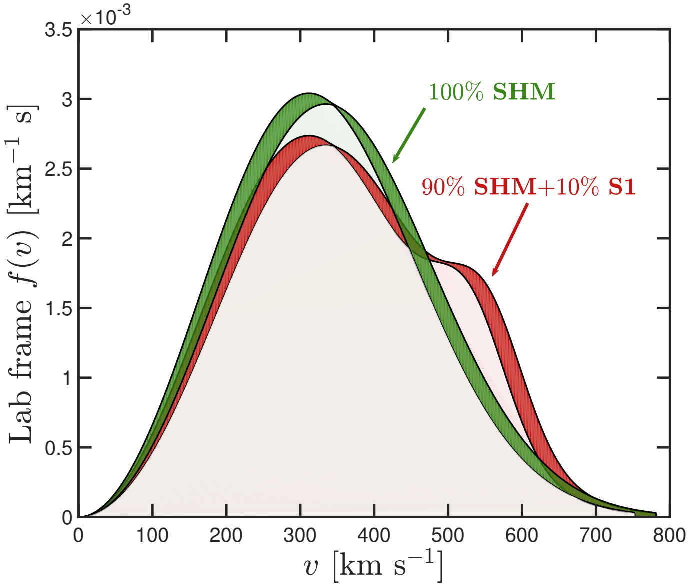

Evans, O'Hare, McCabe 1810.11468

# There can also be streams of Dark Matter

Using Gaia data, a stream (in visible starts), S1, has also been found in the Milky Way

If DM is also present in the stream it will modify the local velocity distribution function



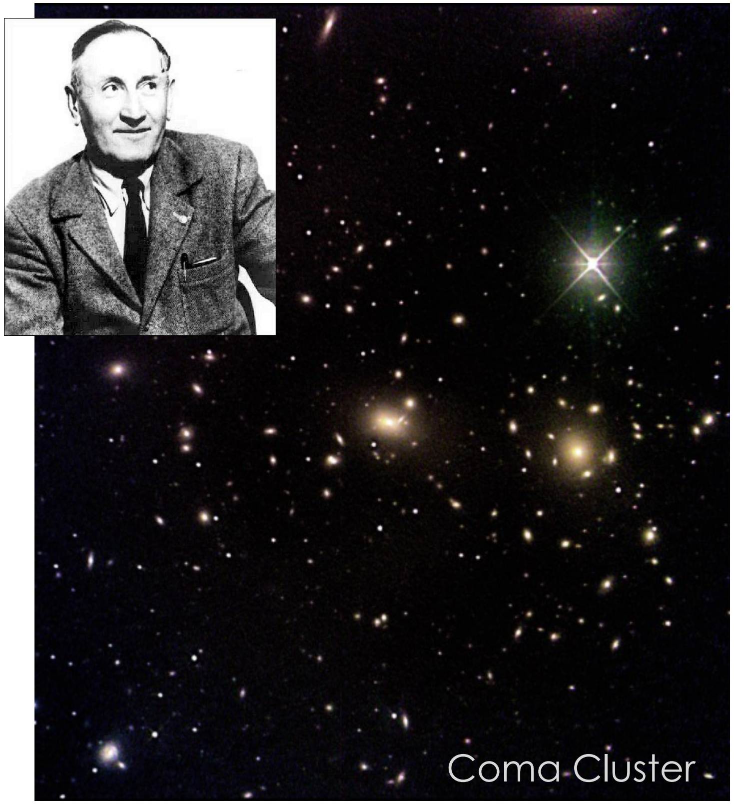

O'Hare, McCabe, Evans, Myeong, Berlokurov 1807.0900

Picture by Stephen Rahn


Andromeda (M31)
2.5 million light years away
Edited by Tom Buckley Houston

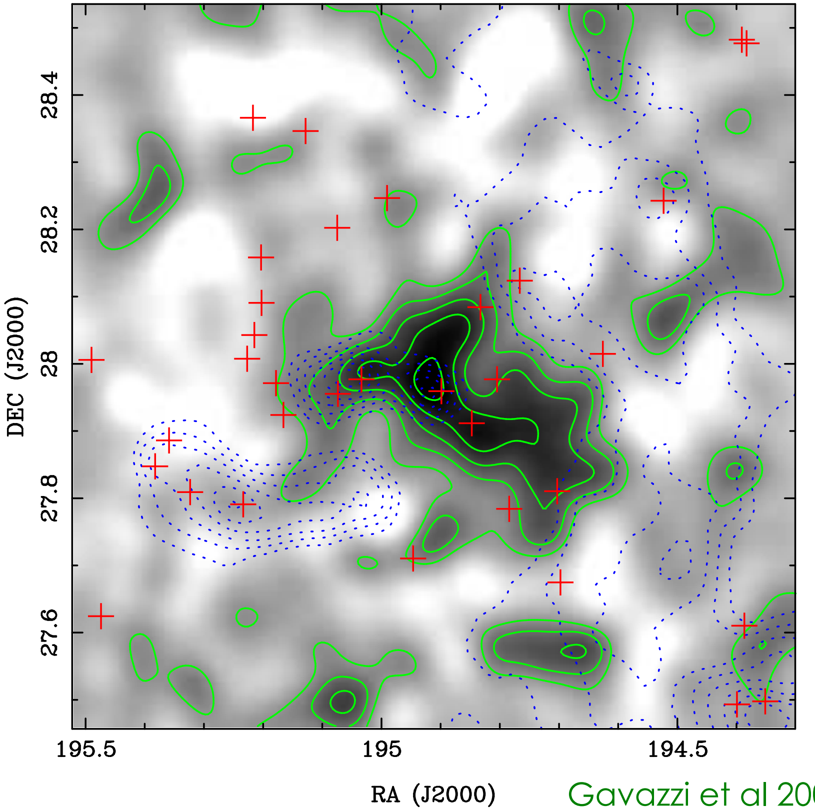

Andromeda (M31)
Sample Dark Matter halo from the Aquarius DM simulation

# Galaxy clusters also contain large amounts of non-luminous matter




Peculiar motions of galaxies in the Coma cluster show that the total mass is much larger than the luminous one

Zwicky 1933, 1937

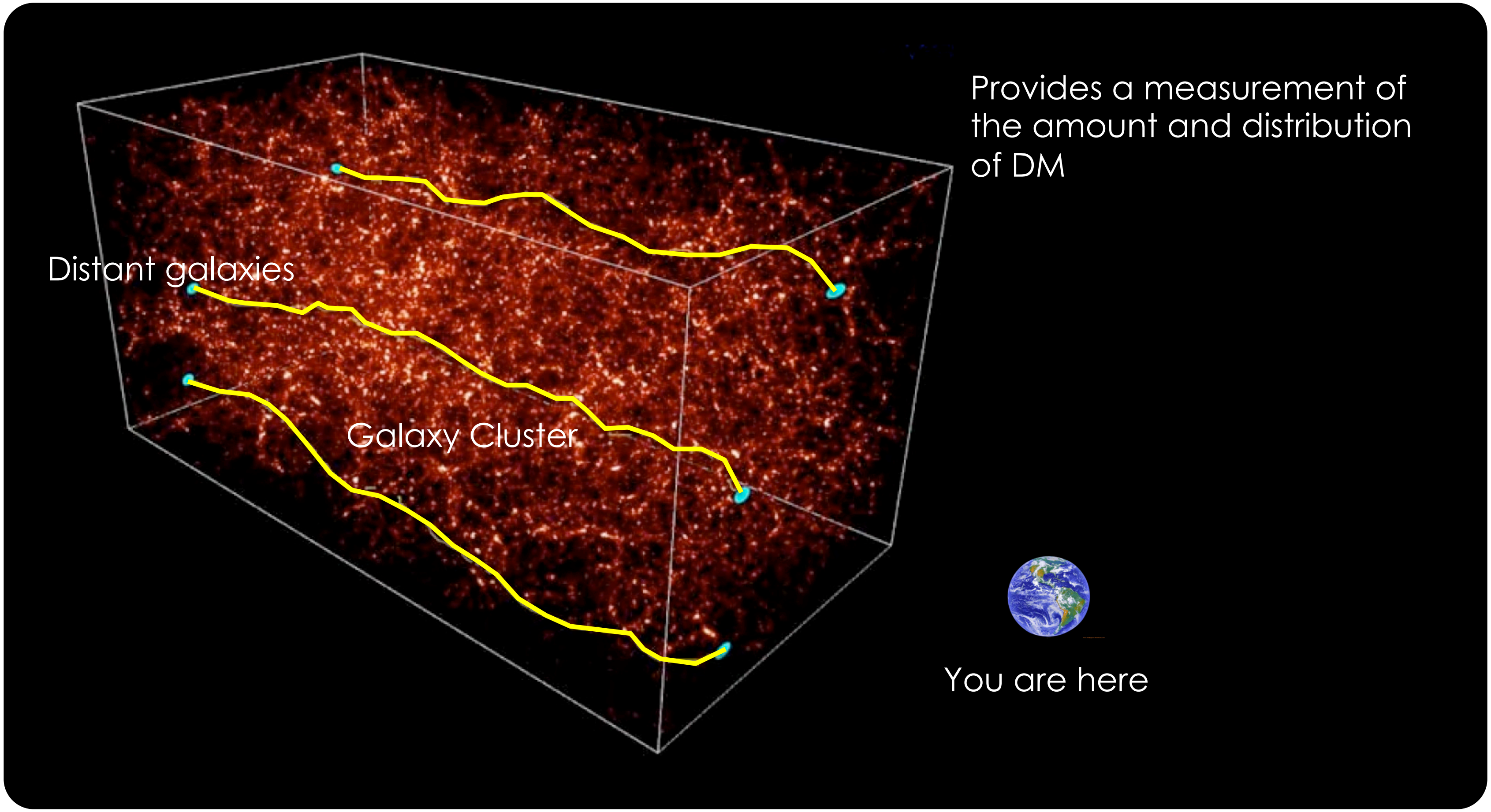



Weak lensing techniques also allow to "weigh" galaxy clusters by measuring the distortion (shear) of distant galaxies behind the cluster.

Gavazzi et al 2009
Kubo et al. 2007

# The DM in Galaxy clusters can also be observed through weak gravitational lensing

Observe collective distortions in the shape of distant galaxies whose light has crossed a heavy object ( such as a galaxy cluster)



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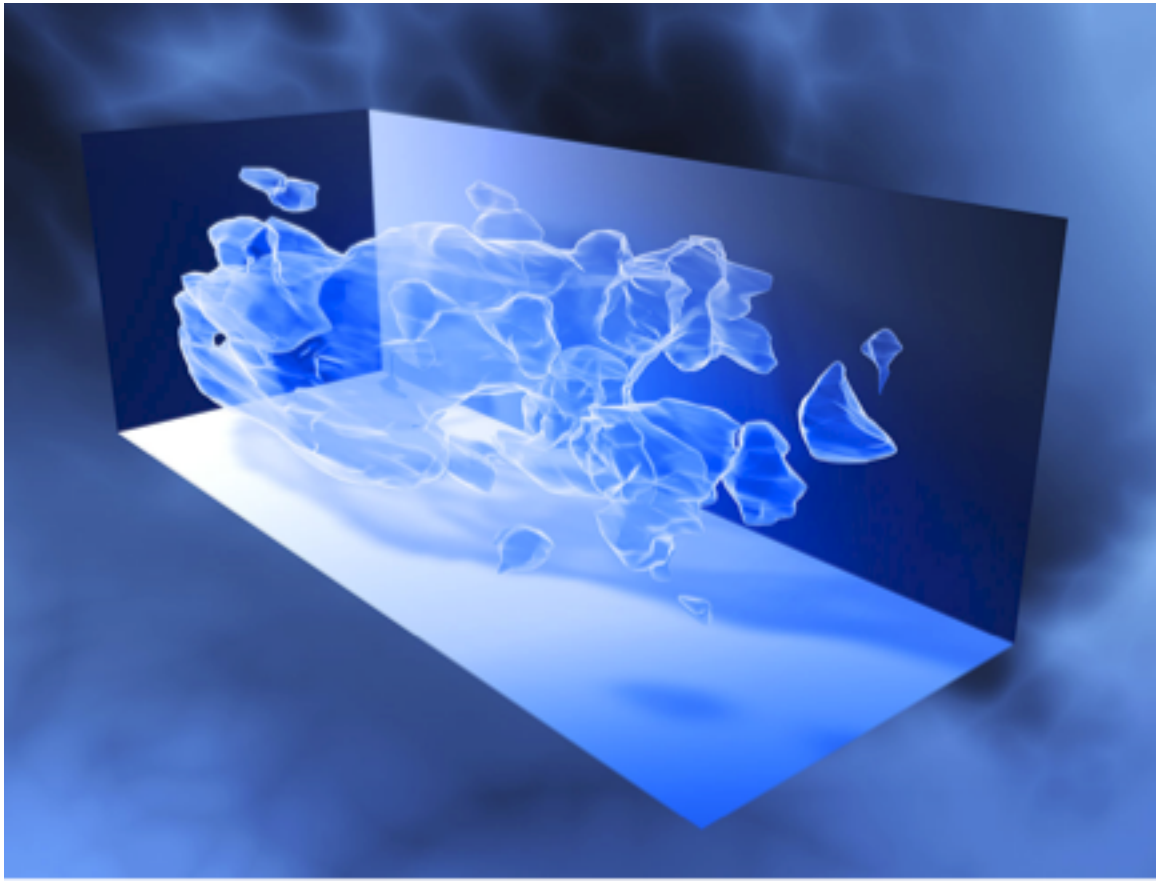
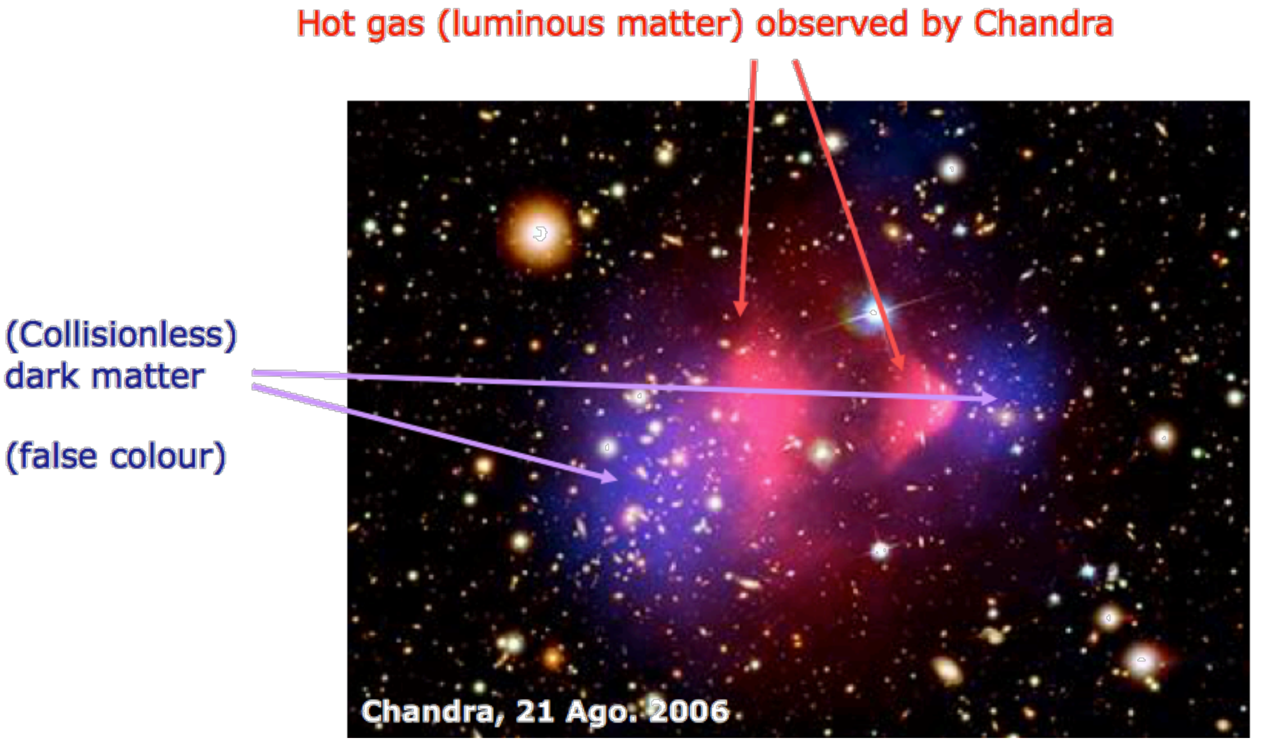


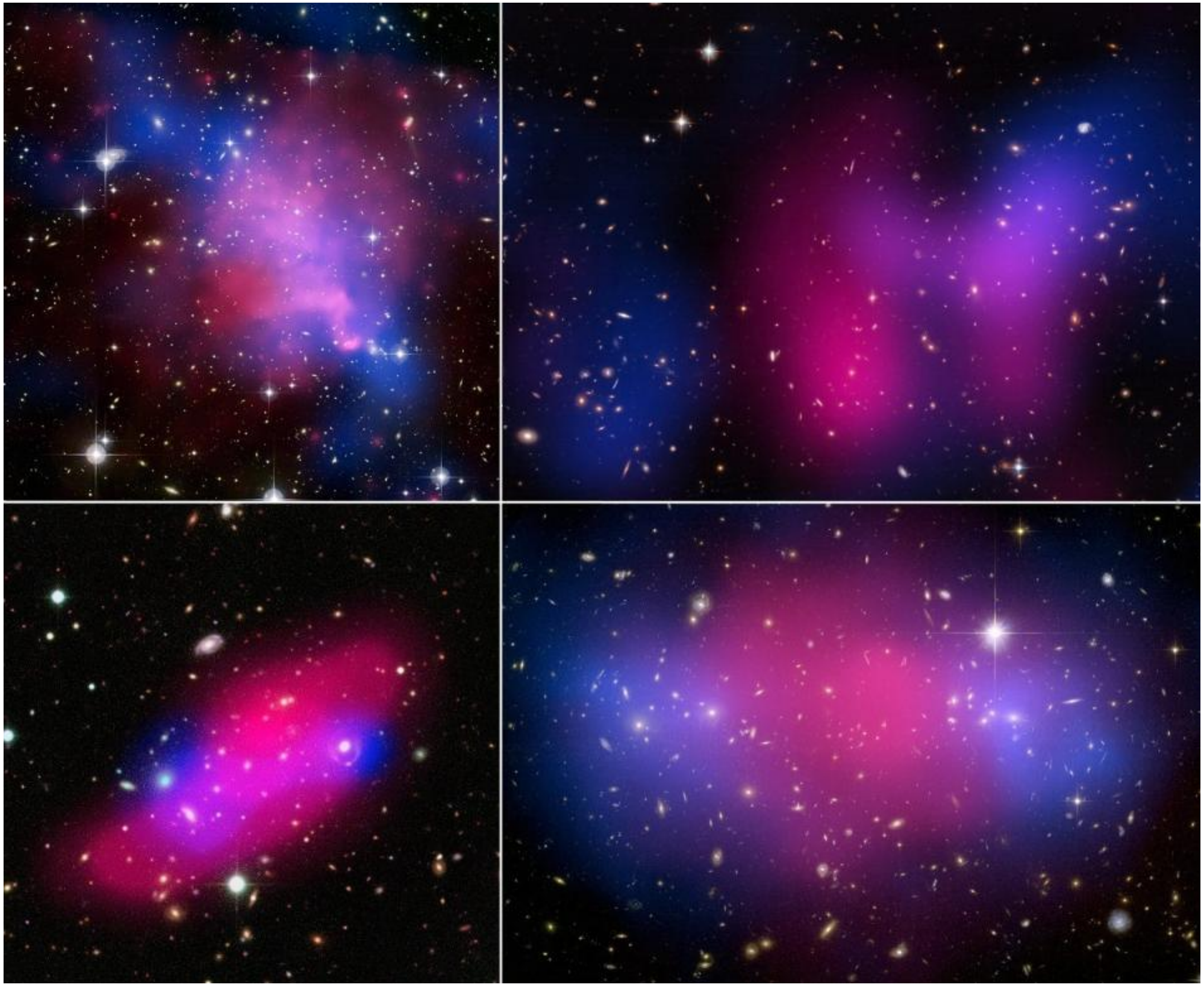
E.g., reconstruction of the DM distribution using Hubble observations.

# The bullet cluster (a.k.a. merging galaxy cluster 1E0657-56)

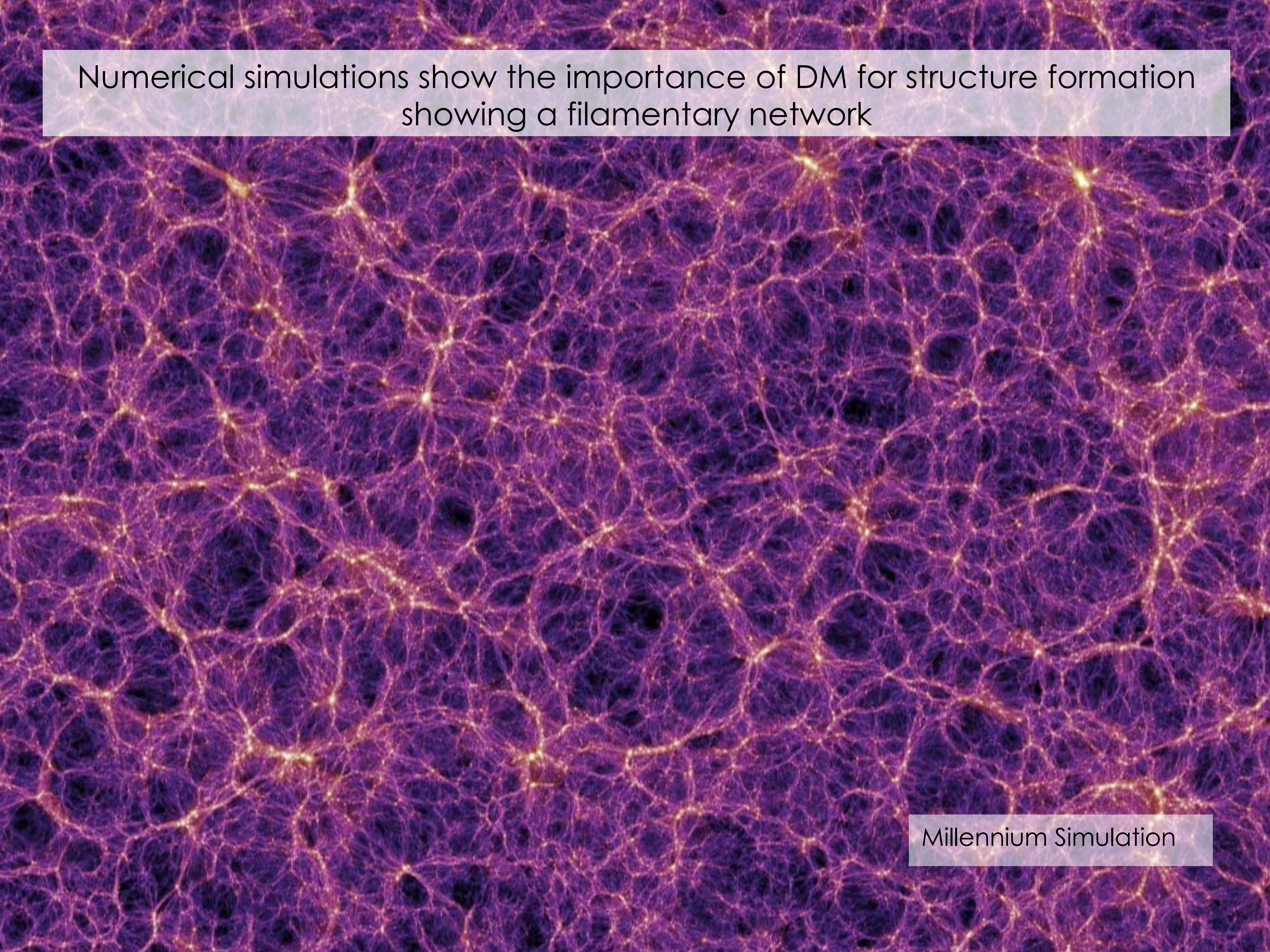



Clowe, González, Markevitch 2003
Clowe et al. 2006
Bradac et al. 2006

The observed displacement between the bulk of the baryons and the gravitational potential favours the dark matter hypothesis versus modifications of gravity.

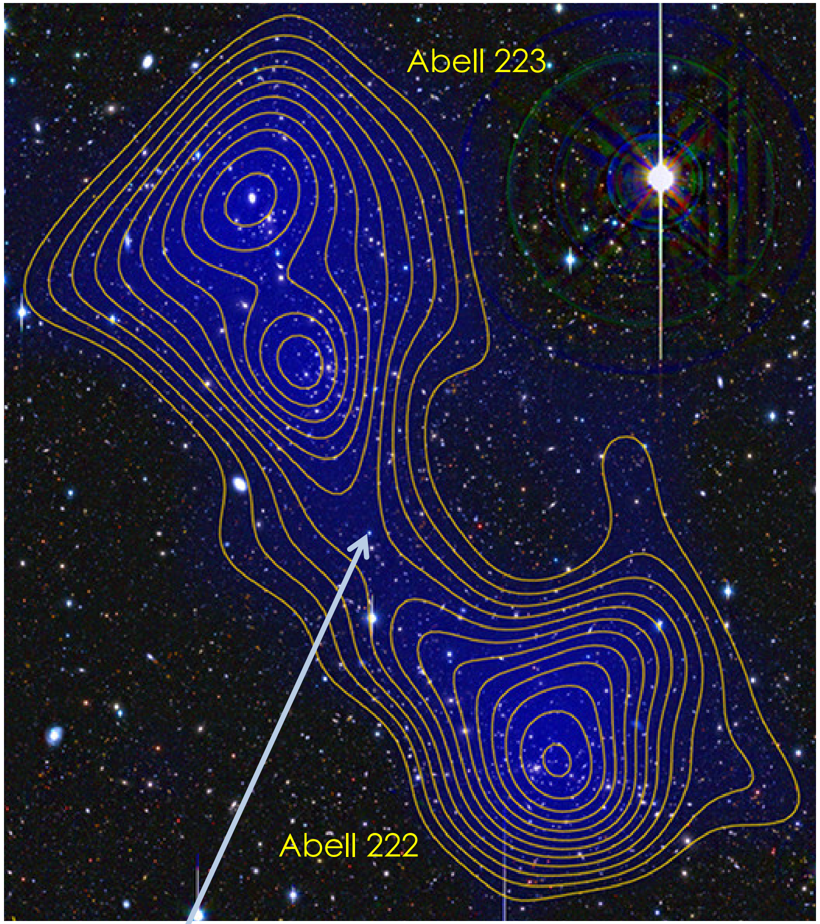


Numerical simulations show the importance of DM for structure formation showing a filamentary network



Millennium Simulation

# ... and dark matter filaments might have been recently observed

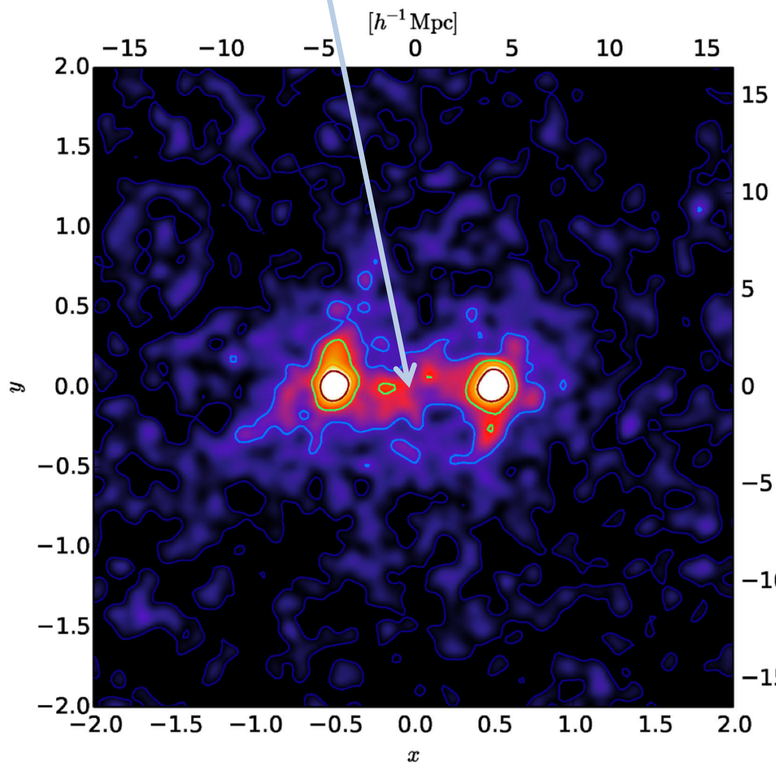



Dietrich et al. 2012

Dark matter filament between two galaxy clusters

Dark matter bridge between two galaxies

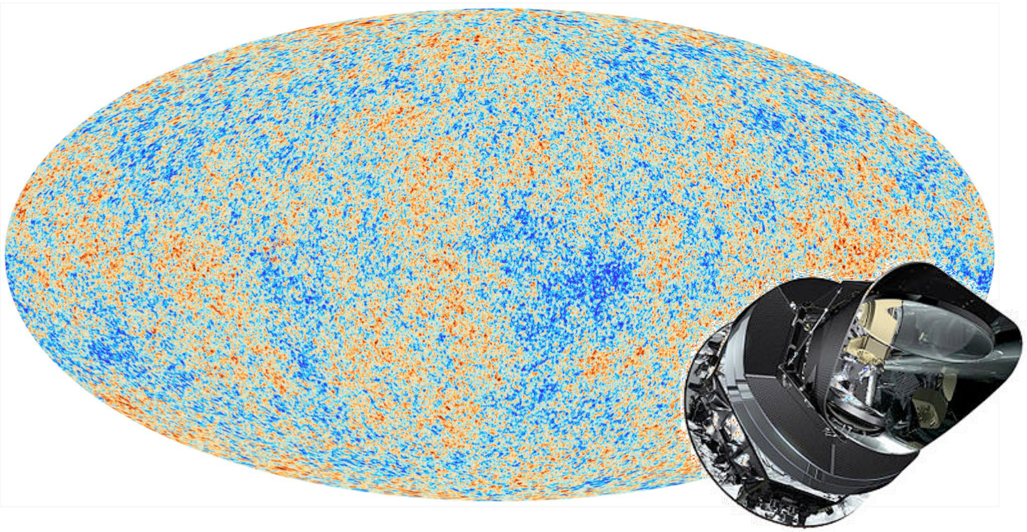
Epps, Hudson 2017

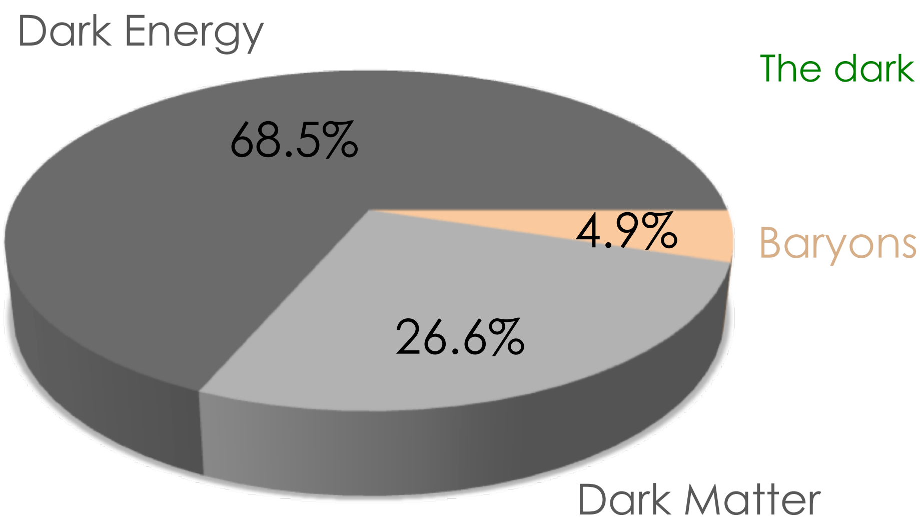


# Observations of the Cosmic microwave Background can be used to determine the components of our Universe

WMAP and Planck precision data of the CMB anisotropies allow the determination of cosmological parameters

COBE, WMAP, Planck






The dark matter abundance is measured accurately

$$\Omega_\Lambda h^2 = 0.3116 \pm 0.009$$

$$\Omega_c h^2 = 0.1196 \pm 0.003$$

$$\Omega_b h^2 = 0.02207 \pm 0.00033$$

Planck 2013

## Challenges for DARK MATTER in the 80's

The main questions concerning dark matter are whether it is really present in the first place and, if so, how much is there, where is it and what does it consist of.

How much. In general one wants to know the amount of dark matter relative to luminous matter. For cosmology the main issue is whether there is enough dark matter to close the universe. Is the density parameter $\Omega$ equal to 1?

Where. The problem of the distribution of dark matter with respect to luminous matter is fundamental for understanding its origin and composition. Is it associated with individual galaxies or is it spread out in intergalactic and intracluster space? If associated with galaxies how is it distributed with respect to the stars?

What. What is the nature of dark matter? Is it baryonic or non-baryonic or is it both?

van Albada, Sancisi '87

## Current challenges for DARK MATTER

- **Experimental detection:**
  Does DM feel other interactions apart from Gravity?
  Is the Electro-Weak scale related somehow related to DM?
  How is DM distributed?

- **Determination of the DM particle parameters:**
  Mass, interaction cross section, etc…

- **What is the theory for Physics beyond the SM:**
  DM as a window for new Physics
  Can we identify the DM candidate?

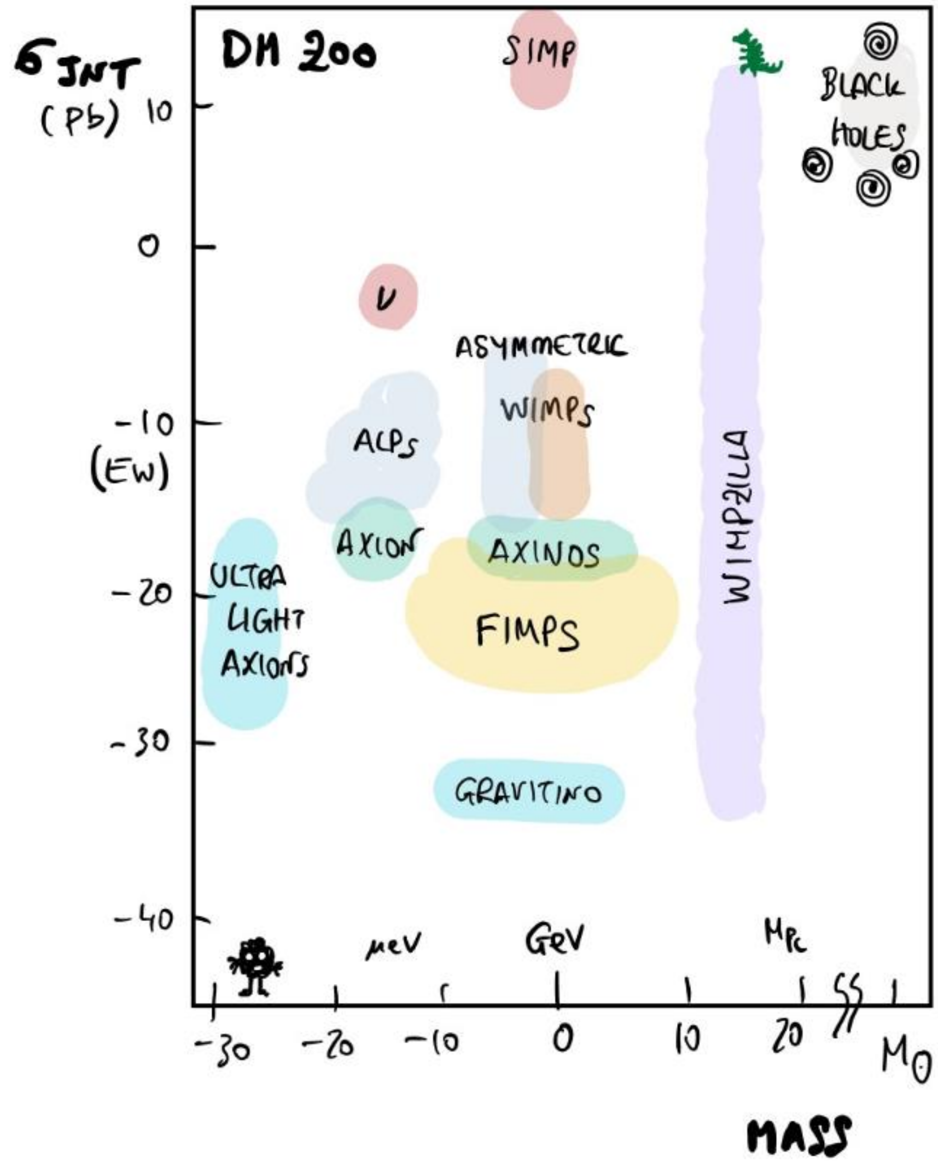
## We don't know yet what DM is... but we do know many of its properties

It is a NEW particle

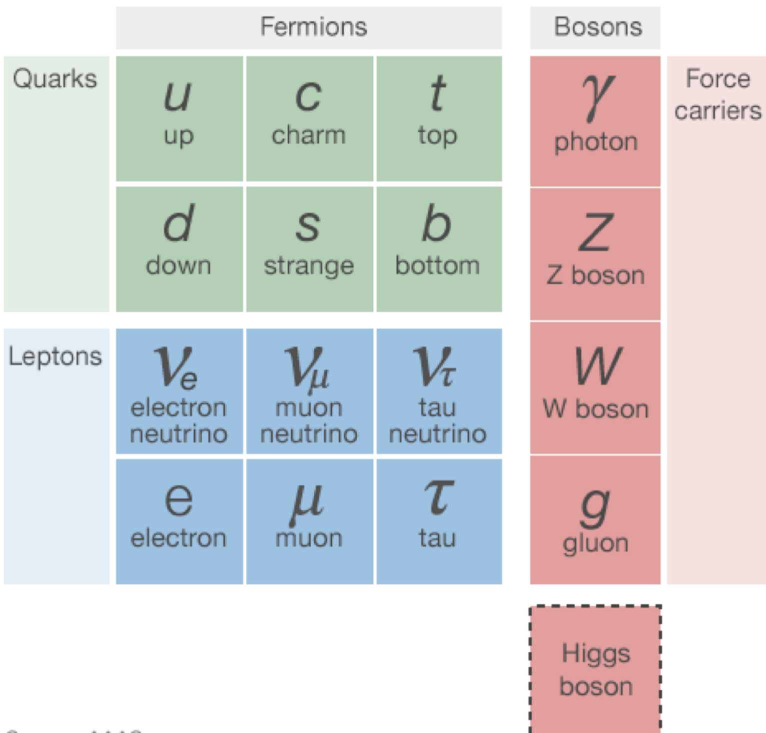
- Neutral
- Stable on cosmological scales
- Reproduce the correct relic abundanc
- Not excluded by current searches
- No conflicts with BBN or stellar evolutior

Many candidates in Particle Physics

- Axions
- Weakly Interacting Massive Particles (W
- SuperWIMPs and Decaying DM
- WIMPzillas
- Asymmetric DM
- SIMPs, CHAMPs, SIDMs, ETCs...



# The Standard Model does not contain any viable candidate for DM




Source: AAAS

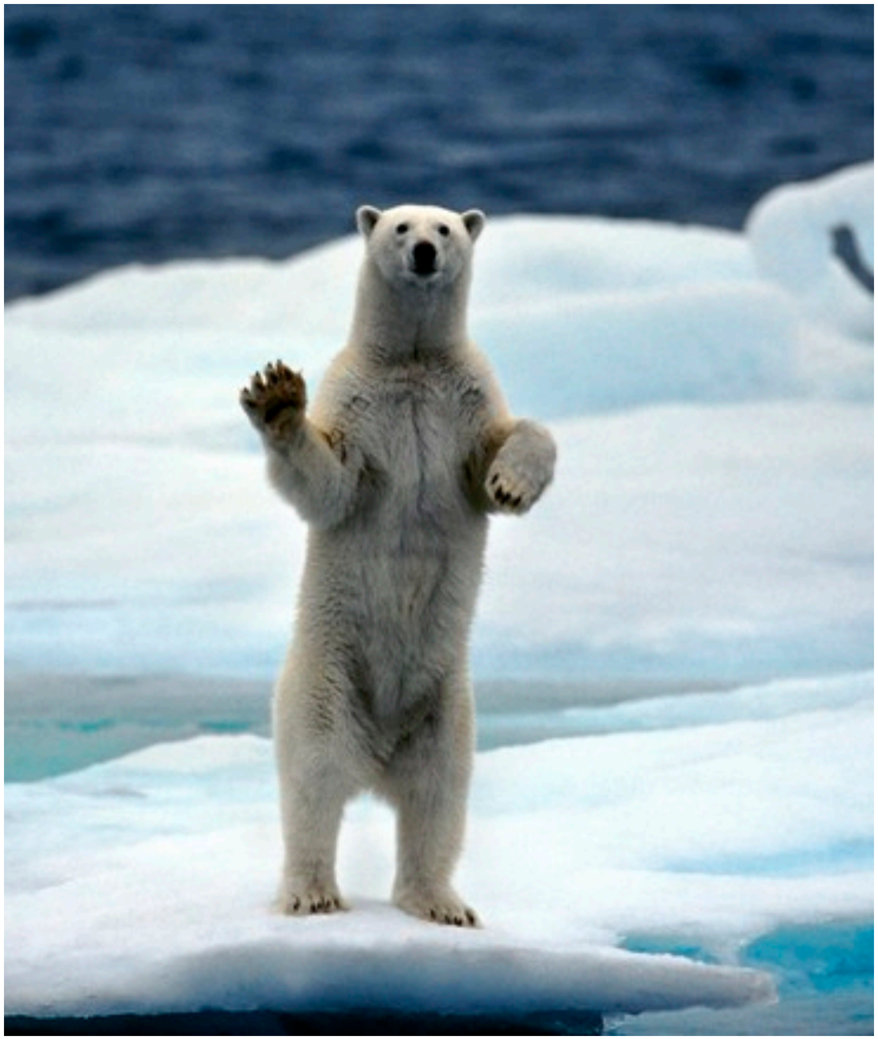
Neutrinos constitute a tiny part of (Hot) dark matter

$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{91.5\mathrm{eV}} \lesssim 0.003$$

Hot dark matter not consistent with observations on structure formation.

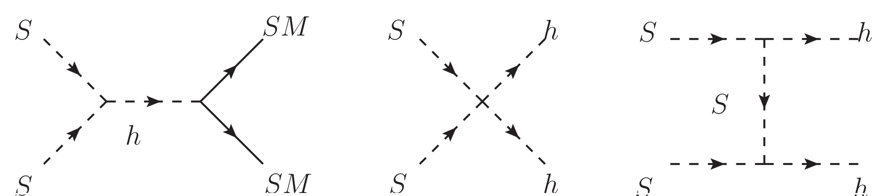
Dark Matter is one of the clearest hints of Physics Beyond the SM

# DM ZOO



**"Lone DM"**

- The DM particle is the only exotic addition to the Standard Model
- For example: **Higgs-portal DM**

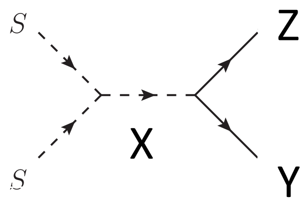



- Or **axions…**

# DM ZOO

**"Dark sector"**

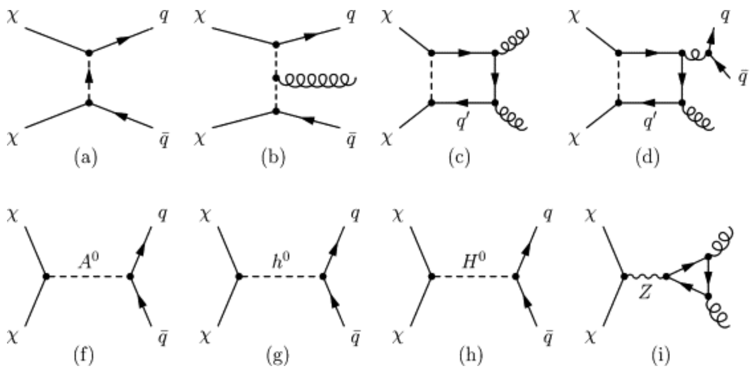
- The DM particle is accompanied by other **new exotics**.
- New **"mediators"** would connect the dark sector to the Standard Model.




# DM ZOO

## “Dark sector”

- The DM particle is accompanied by other **new exotics**.
- New **“mediators”** would connect the dark sector to the Standard Model.
- For example, **SUSY**




**Supersymmetric rave**

# Some basics on Dark Matter Production

Dark matter was present in the Early Universe and it is present now, however, there are many different mechanisms to account for its correct abundance

- Thermal production (freeze-out)
- Out of equilibrium production (freeze-in)
- Late decays of unstable exotics
- Vacuum misalignment (axions)
- Asymmetry