Physics Beyond the Standard Model and Dark Matter

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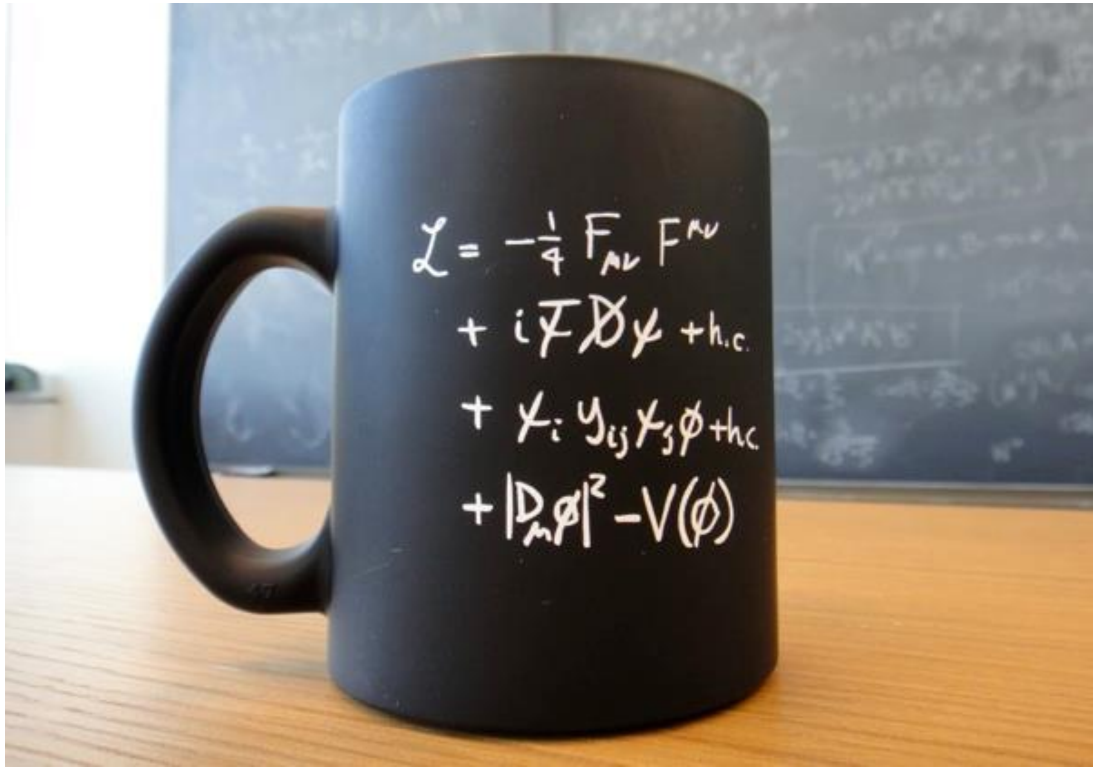
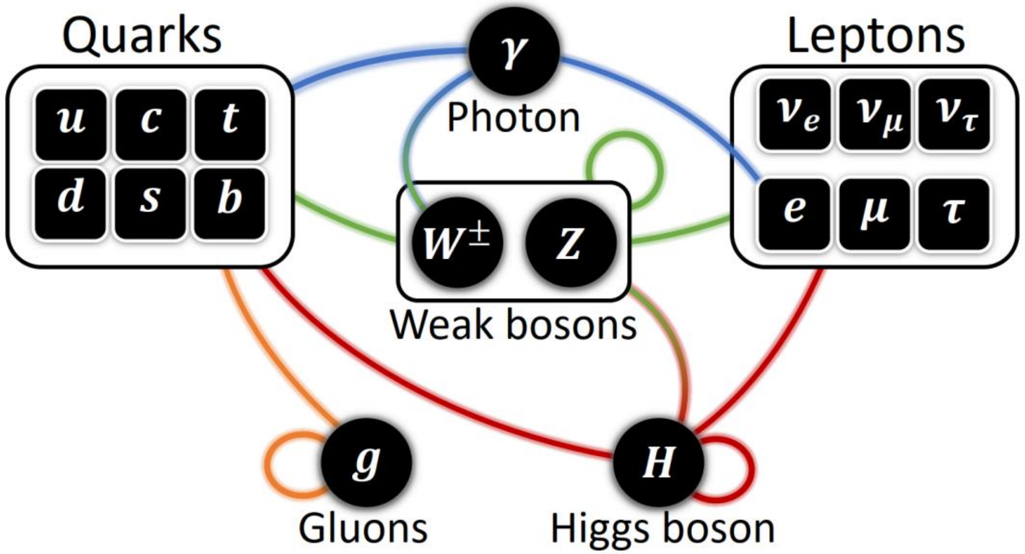
Standard Model

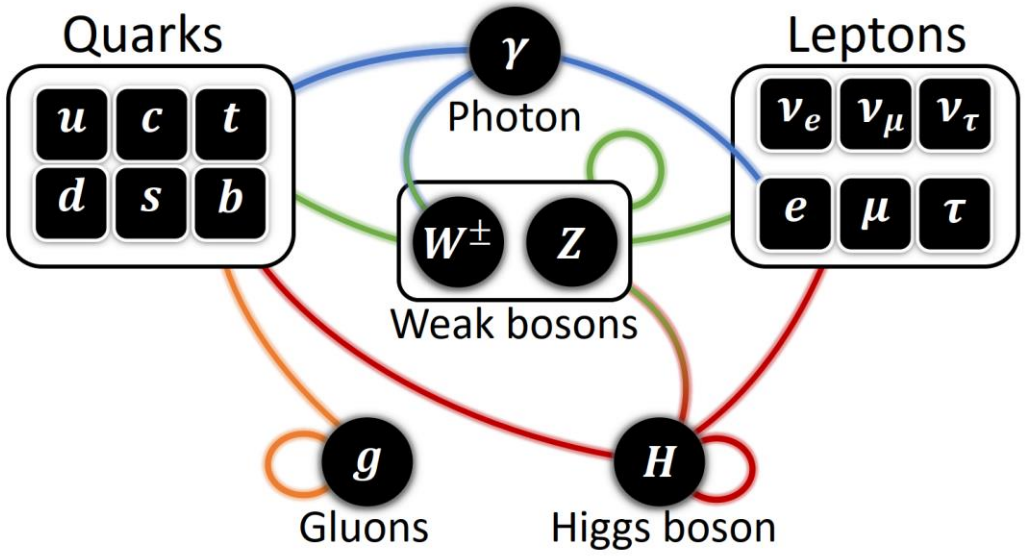




Standard Model

Fundamental constants have to be determined by experiment

26 parameters of the Standard Model:	
6 quark masses	m_u, m_c, m_t, m_d, m_s and m_b
4 quark mixing angles	θ_{12}, θ_{23}, θ_{13} and δ
6 lepton masses	m_{ν_e}, m_{ν_μ}, m_{ν_τ}, m_e, m_μ and m_τ
4 lepton mixing angles	θ'_{12}, θ'_{23}, θ'_{13} and δ'
3 gauge couplings	$g_1(\alpha)$, $g_2(G_F)$ and g_3
1 Higgs vacuum expectation value	$v(M_Z)$
1 Higgs mass	m_H
1 strong CP violating phase	θ



Standard Model – Open Issues & Beyond

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- The strong CP problem: CP violating θ-term in Lagrangian is suppressed by 9 orders of magnitude. Why?
- Possible solution: There is a particle called the axion, which makes this parameter small because of a spontaneously broken symmetry (Peccei-Quinn)
- Candidate for dark matter

Standard Model – Open Issues & Beyond

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- Hierarchy problem: why is the Higgs mass so low?
- Quantum corrections would make the mass huge!
- Proposed solution is supersymmetry: fermionic and bosonic loop corrections cancel each other out
- Lightest SUSY particle is candidate for dark matter

Standard Model – Open Issues & Beyond

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- What about the neutrino masses?
- Are these fundamental constants really constant? (see next talk)

Standard Model – Open Issues & Beyond

- Why is there so much more matter than antimatter in the universe?
  Baryon asymmetry parameter:

Observed: $$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10}$$

Standard Model prediction: $\sim 10^{-18}$

Standard Model – Open Issues & Beyond

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- Conditions for baryon asymmetry by Sakharov:
  - Baryon number violation
  - C and **CP violation**
  - Departure from local equilibrium (or **CPT violation**)

Standard Model – Open Issues & Beyond

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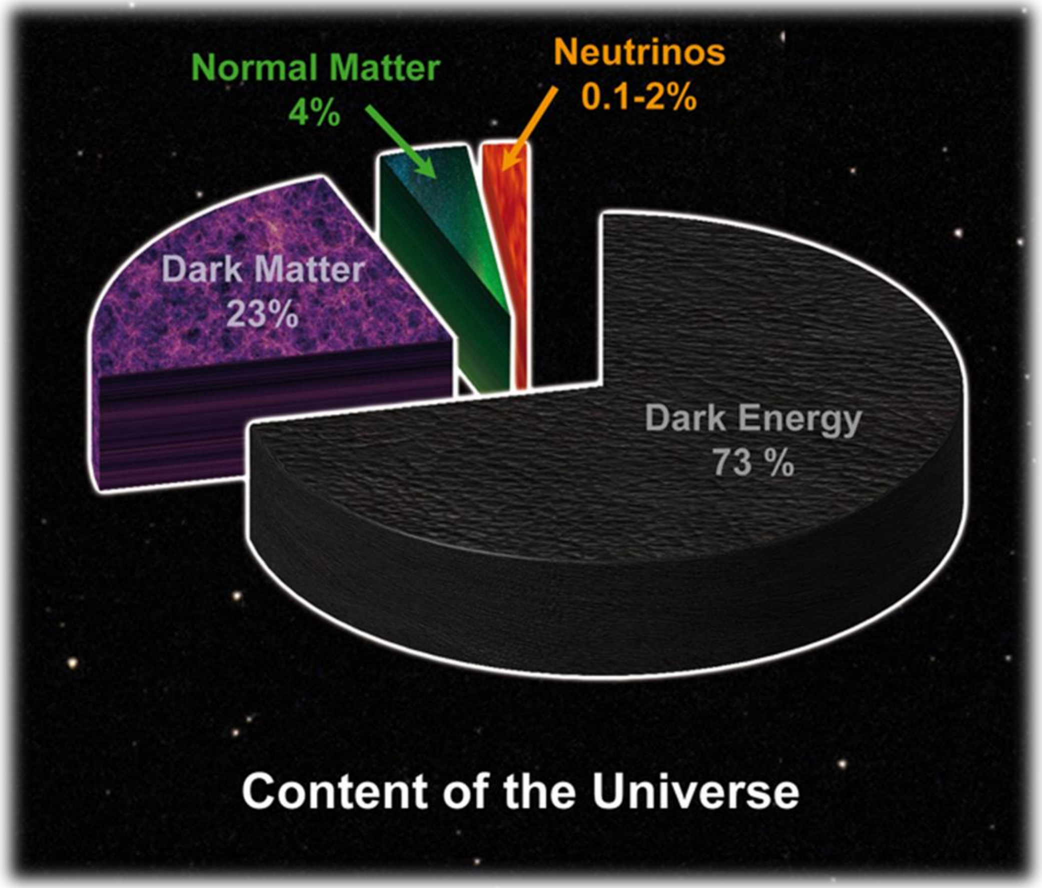
CP violation:
Electric Dipole Moment Searches, see talks of Tuesday

CPT violation:
Antimatter experiments, see several other talks this week!

Standard Model – Open Issues & Beyond

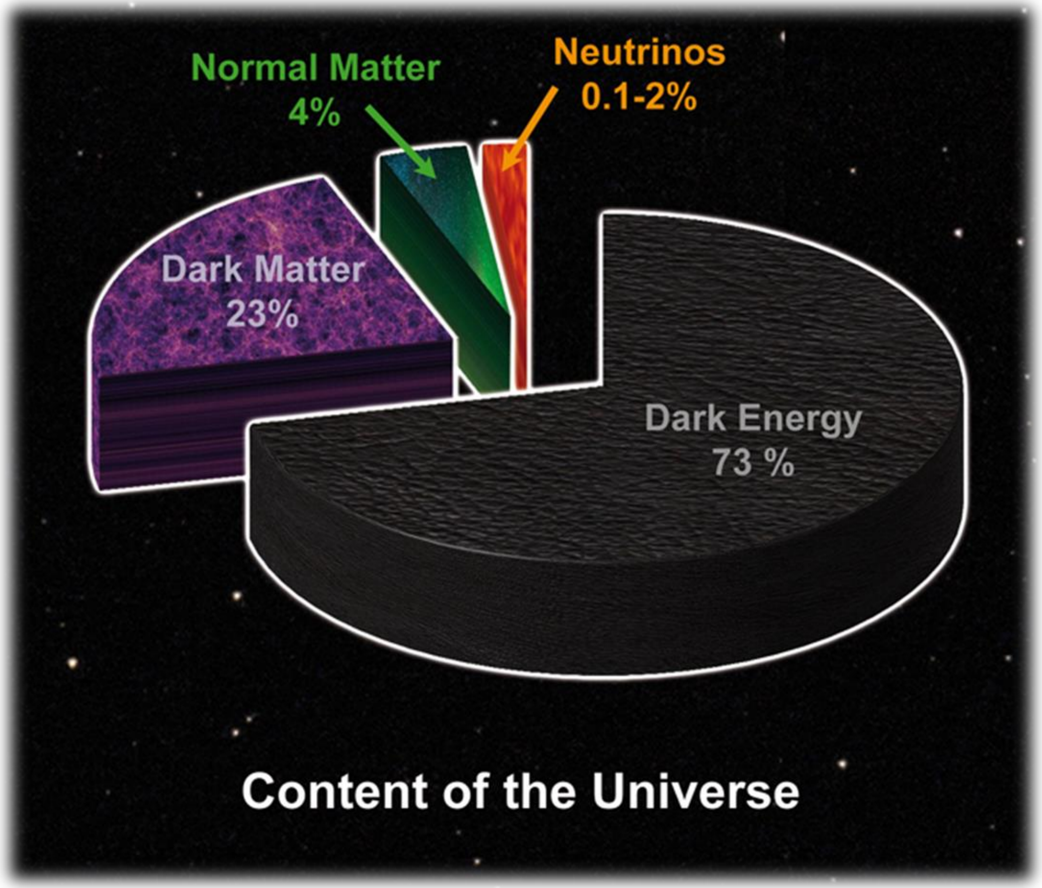


Other open issues:

- SM only describes 5% of the Universe! What is dark matter and dark energy?

The universe is expanding at an accelerated rate. This is only possible according to our Standard Model of Cosmology if there is dark energy, which is an intrinsic property of space, that has a constant energy density regardless of the volume (no dilution with expansion of space)

Standard Model – Open Issues & Beyond



Other open issues:

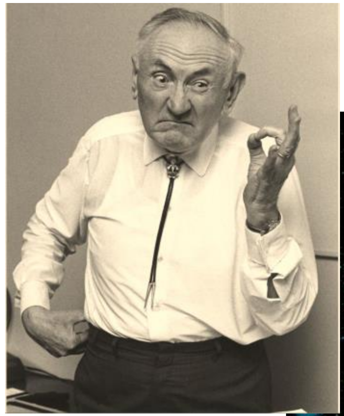
- SM only describes 5% of the Universe! What is dark matter and dark energy?

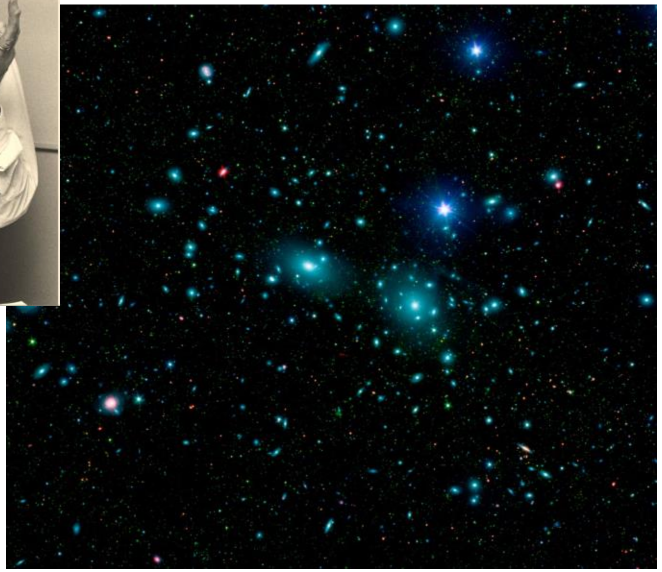
The presence of dark matter is implied by astrophysical observations, including gravitational effects that cannot be explained unless more matter is present!

Dark Matter – Why do we think it exists?

Rotation curves of galaxies and clusters

- In the 1930s Fritz Zwicky studied the Coma Cluster of galaxies
- He finds that the individual galaxies move faster than expected from the gravitational pull of the observed stars in the cluster
- Proposes "Dunkle Materie", dark matter, where the "dark" simply refers to the fact that it does not produce light of any kind



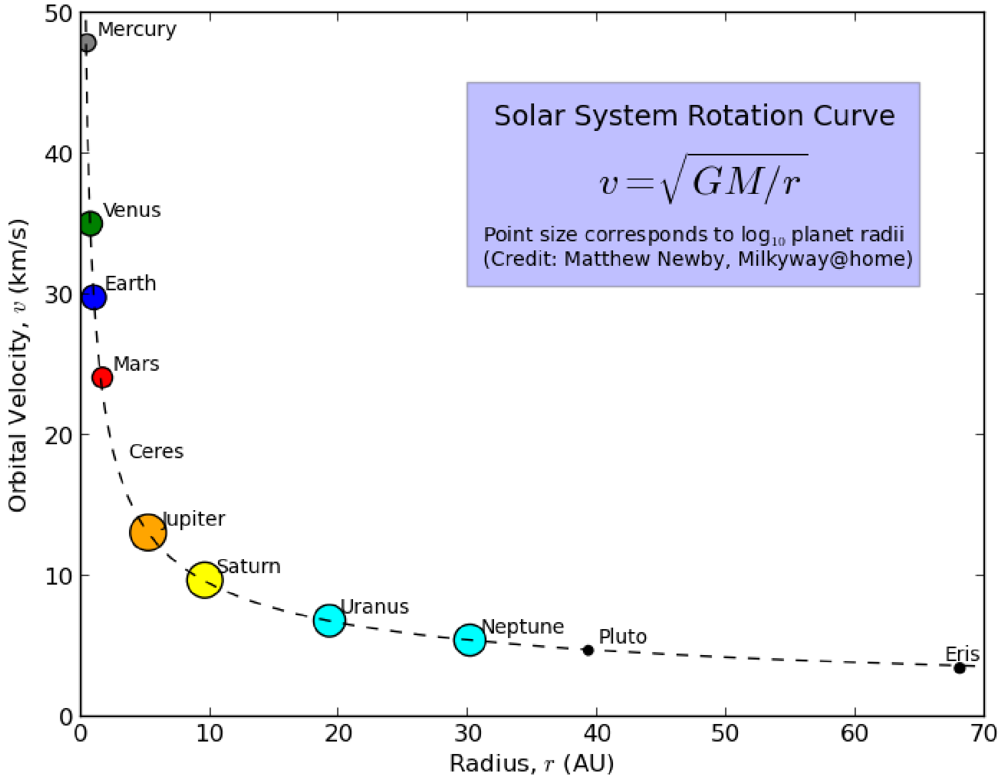


Dark Matter – Why do we think it exists?

Rotation curves of galaxies and clusters

- Example: Our Solar System
- Orbital speed scales as $v = \sqrt{\frac{GM}{r}}$

  M: total mass inside the orbit
  r: distance to Sun



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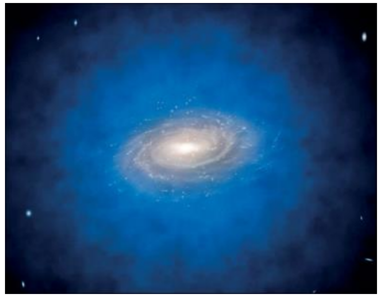
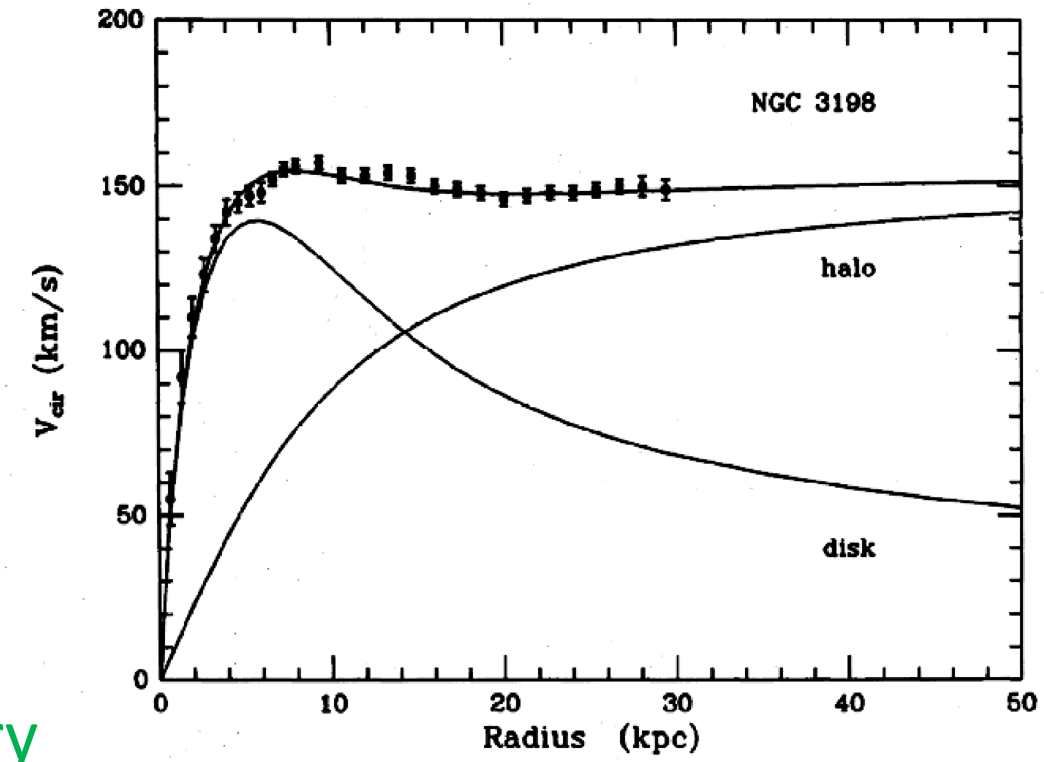


Rotation curves of galaxies and clusters

- Rotation curve of galaxy NGC 3198
- Orbital speed scales as $v = \sqrt{\frac{GM}{r}}$
  M: total mass inside the orbit
  r: distance to Sun
- Galactic rotation curves are flat!
  => spherical dark matter halo is necessary

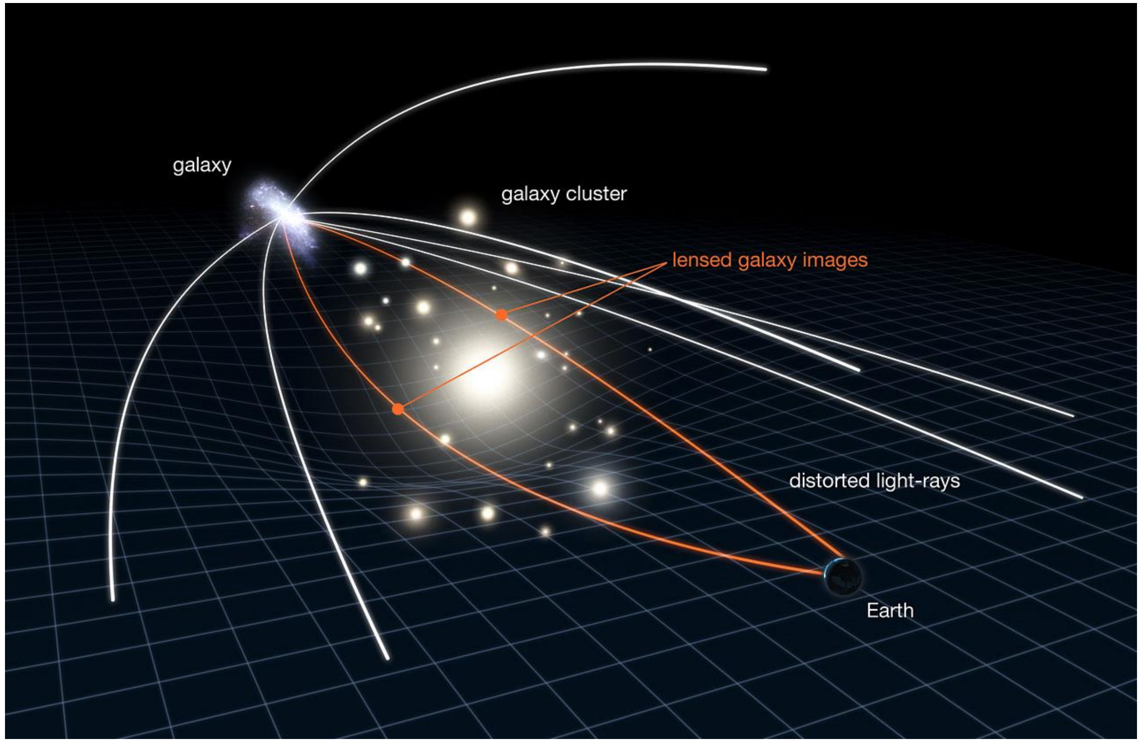


Dark Matter – Why do we think it exists?

Gravitational Lensing

- Background galaxy emits light
- Galaxy cluster acts as a lens
- Light observed on Earth is distorted
  - Can produce multiple images of the same galaxy
  - Or the galaxy appears brighter if the telescope cannot resolve the image (microlensing)

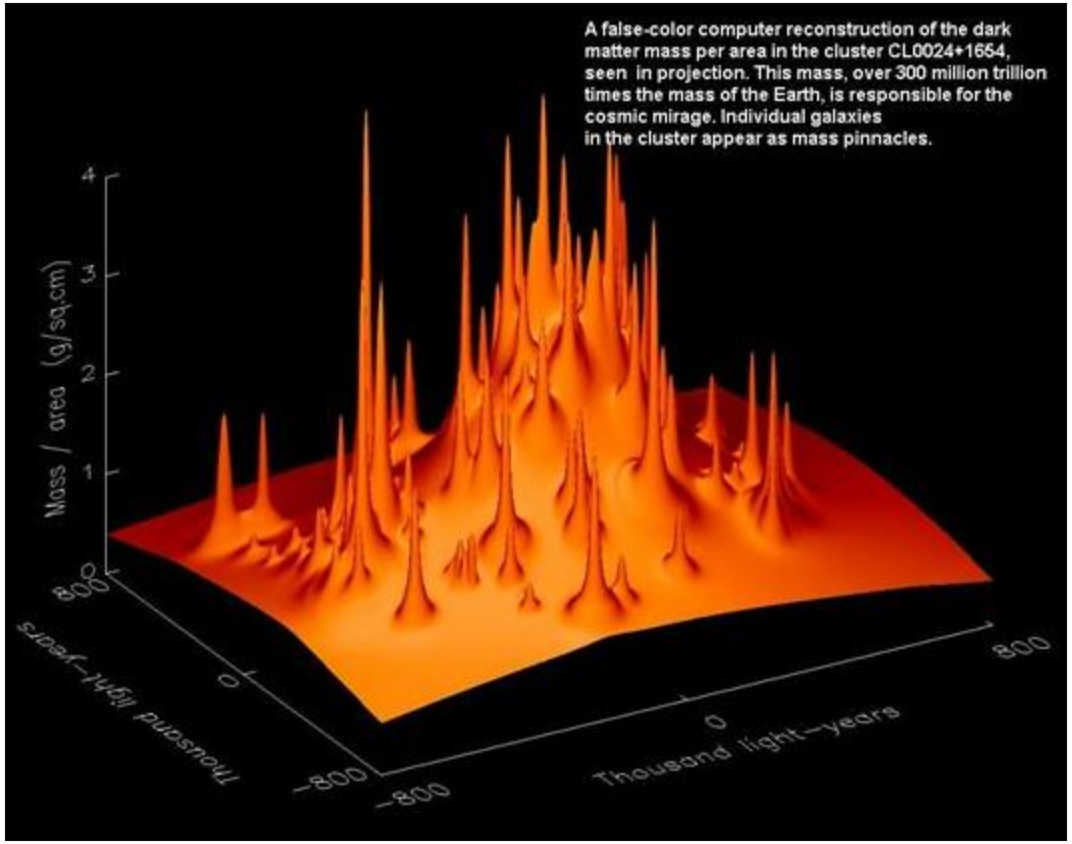
Gravitational lensing is a powerful tool for locating mass in the Universe



Dark Matter – Why do we think it exists?

Gravitational Lensing

Cluster of Galaxies: CL0024+1654



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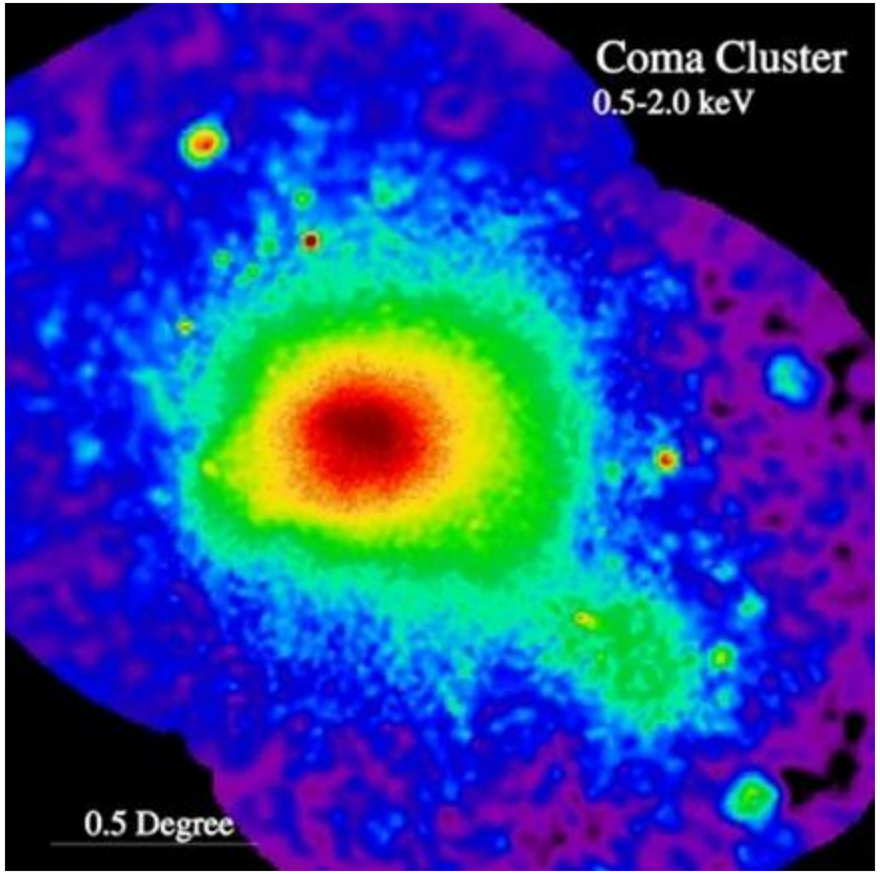
Gravitational lensing is a powerful tool for locating mass in the Universe

Dark Matter – Why do we think it exists?

Hot gas in clusters

- X-rays are emitted by the gas in the cluster (10-100 million K)
- Need gravitational pull of dark matter to keep this gas bound to the cluster

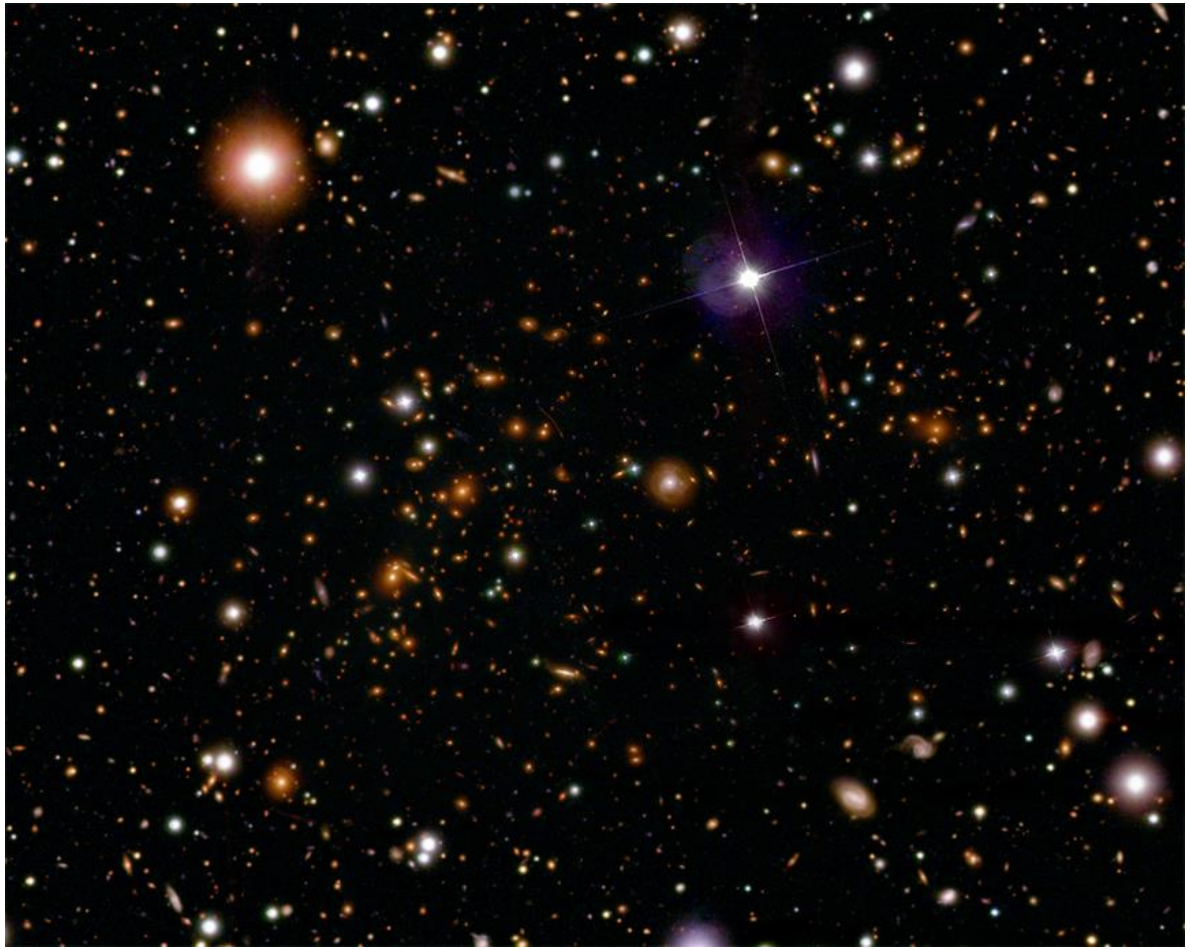
X-ray image



Dark Matter – Why do we think it exists?

Bullet cluster

- Merger of two clusters
  - Visible light image

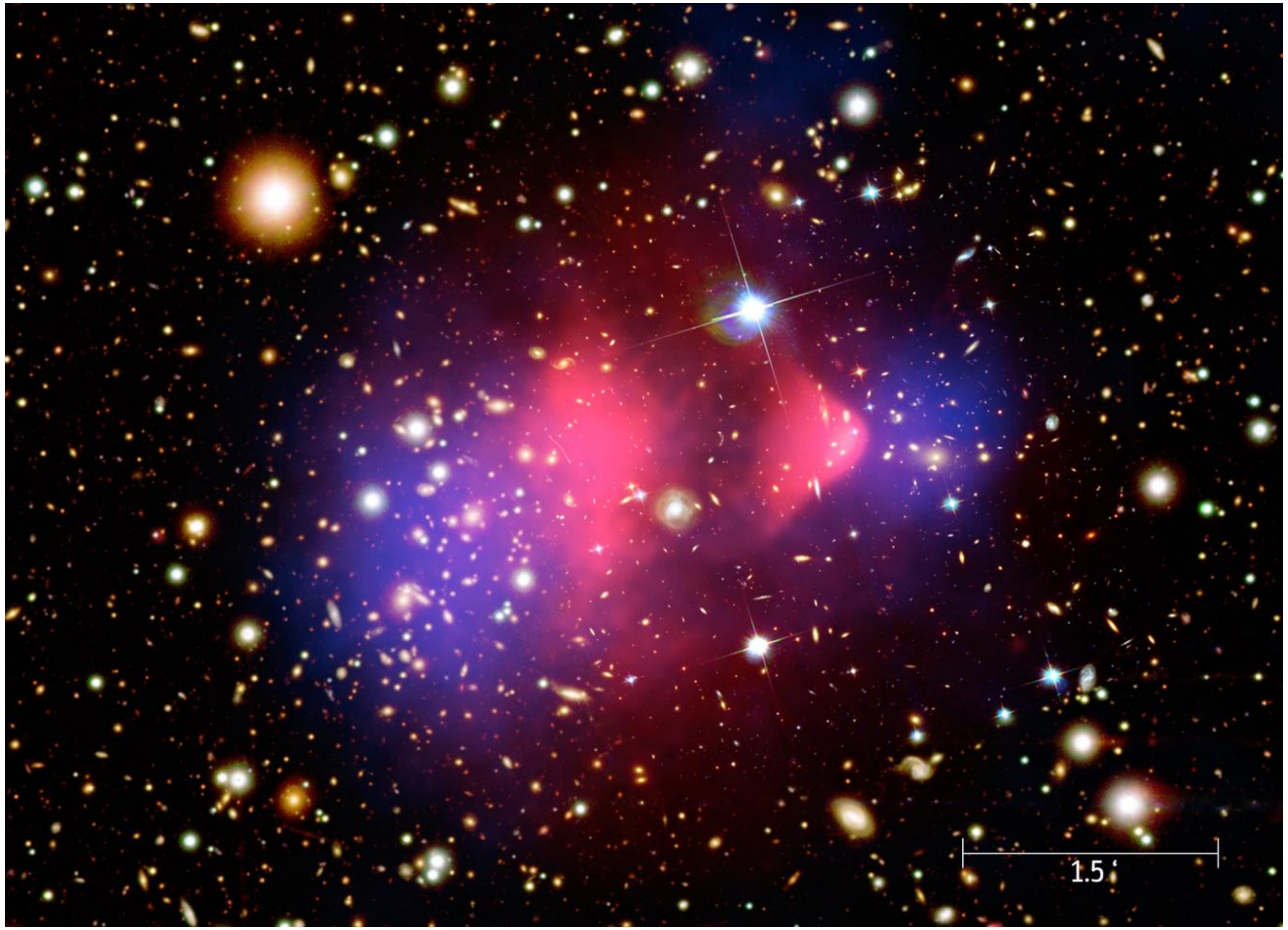


Dark Matter – Why do we think it exists?

Bullet cluster

- Merger of two clusters
  - Visible light image
  - X-ray image (pink)
  - Matter distribution from gravitational lensing (blue)

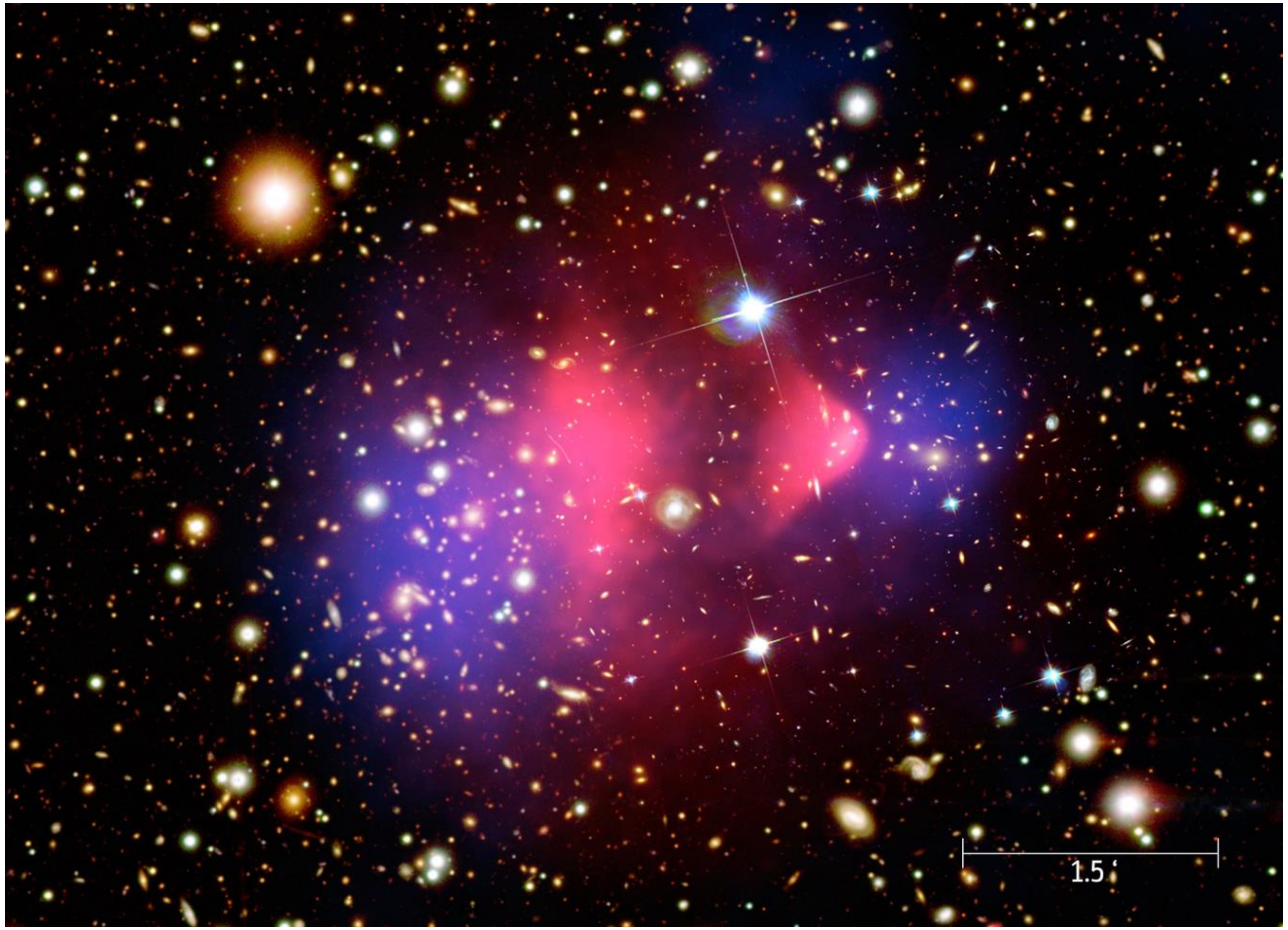
- Atomic matter in hot gas is slowed down during collision
- Dark matter passes through the centre without any interactions



Dark Matter – Why do we think it exists?

Bullet cluster

Modified Newtonian Dynamics models that were proposed to explain flat rotation curves without dark matter have great difficulty explaining this!

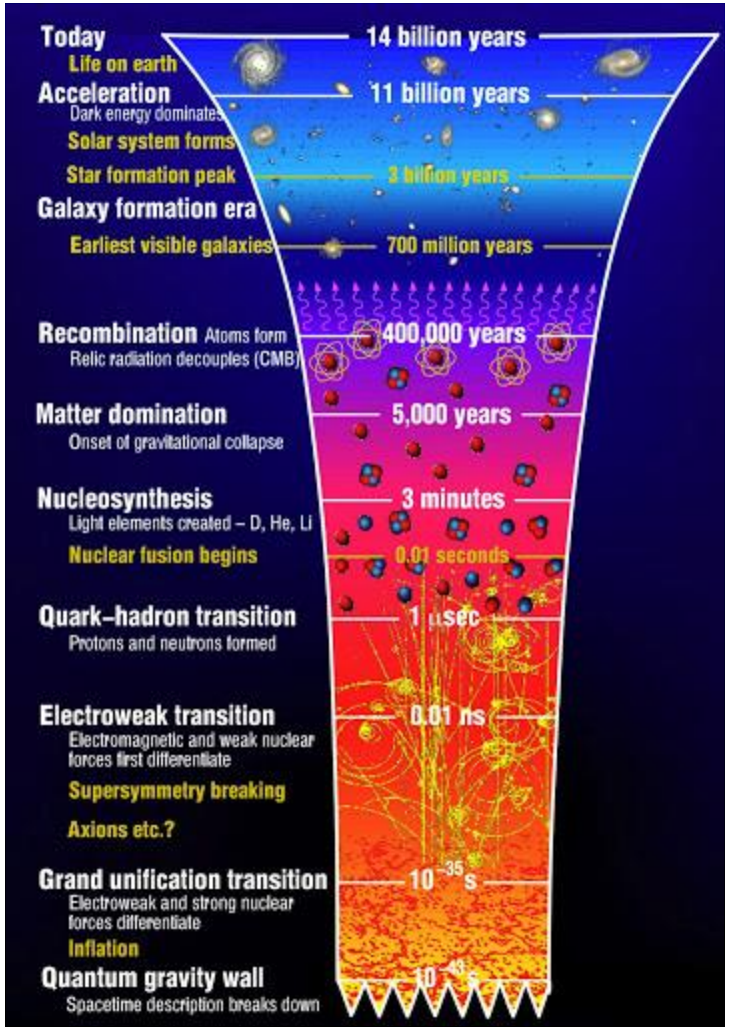


Dark Matter – Why do we think it exists?

Big Bang Nucleosynthesis

Timeline of early universe:

- Primordial soup of subatomic particles
- Universe expands, soup cools
- 10^{-6} s: quark-hadron transition, protons and neutrons formed
- 3 min: nucleosynthesis creates light elements D, ^3He, ^4He and Li



Only after star formation can other elements be created due to fusion (requires 3 body interaction, so high density needed)

Dark Matter – Why do we think it exists?

Big Bang Nucleosynthesis

Primordial abundance is determined by the frozen n/p ratio (beta decay vs expansion)

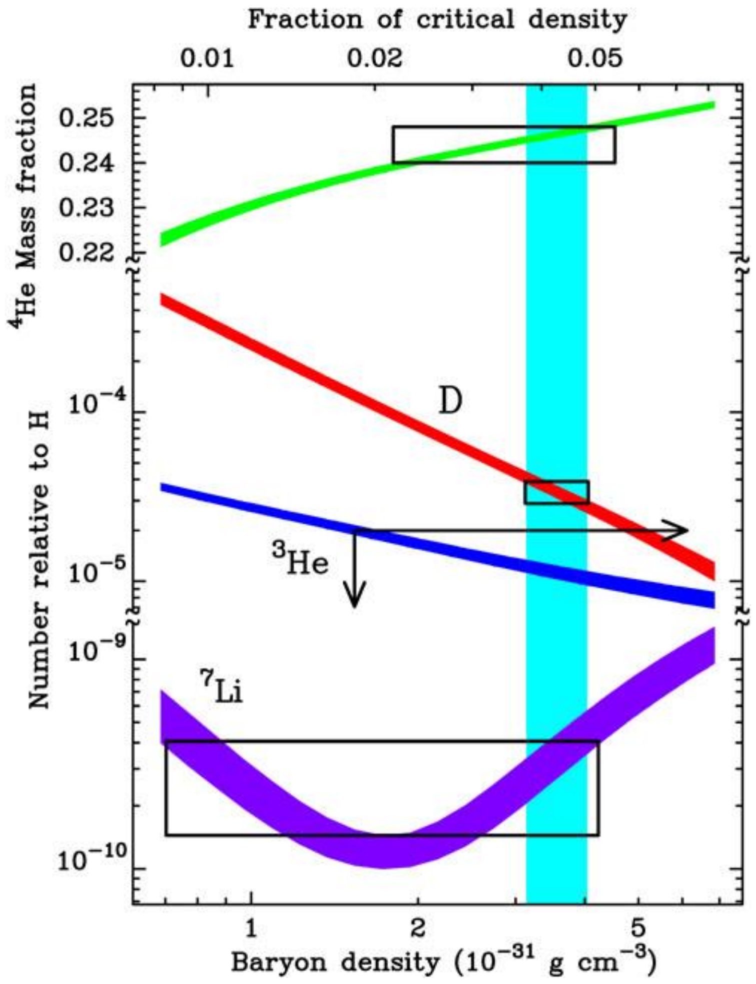
Observed:

25% ^{4}He,

10^{-4} D and ^{3}He

10^{-10} Li

Baryonic matter fraction is 5% of total energy content of the Universe



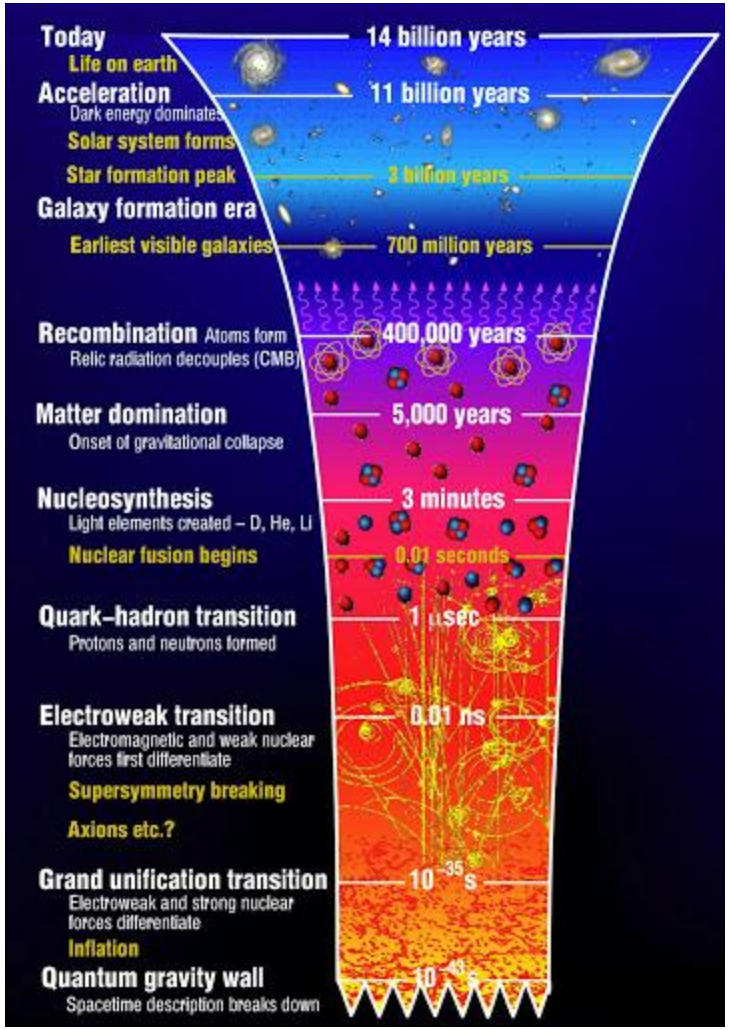
Dark Matter – Why do we think it exists?

Structure formation

Hierarchical structure formation:

- After inflation, all particles are spread out almost uniformly
- Dark matter accumulates first, creates deep potential wells
- Ordinary matter is in ionised state, no clumping together
- After recombination, the ordinary atoms are pulled into existing dark matter structures
- Then formation of minihalos, stars, galaxies, clusters, superclusters

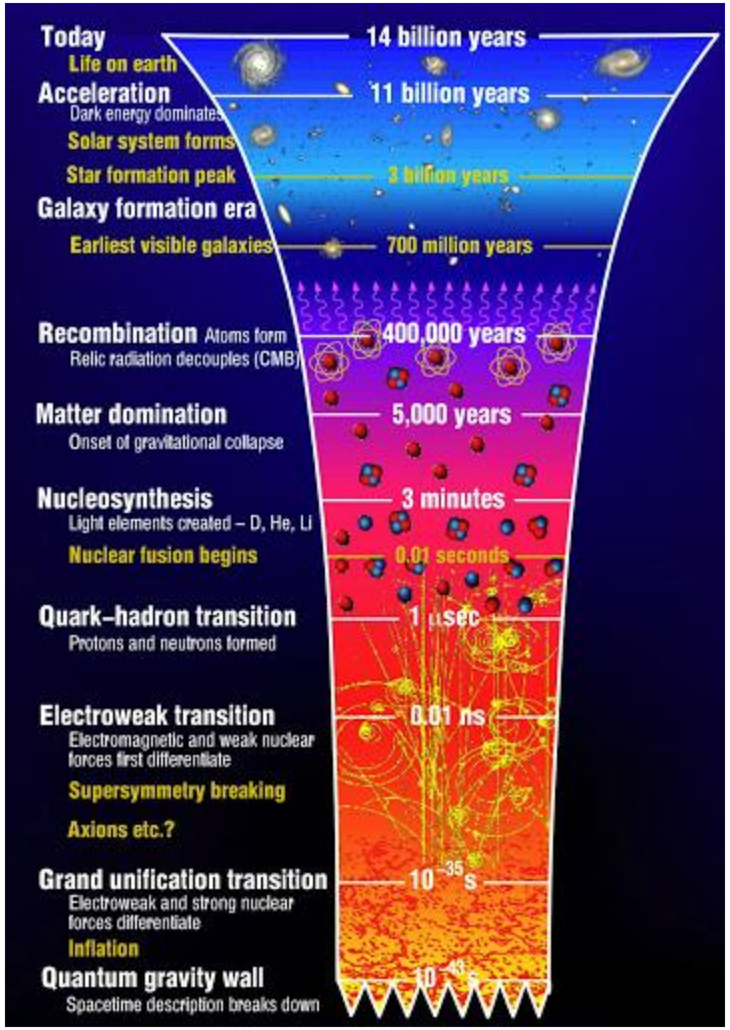
We need cold dark matter for structure formation!



Dark Matter – Why do we think it exists?

Cosmic Microwave Background

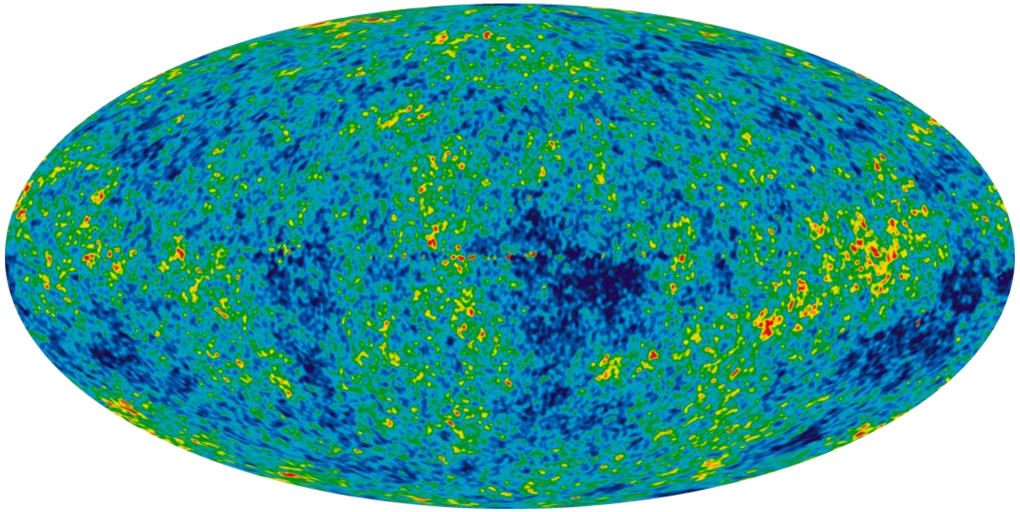
- Before 400 000 years, photons are constrained to short paths due to scattering with free electrons in the photon-baryon-electron plasma
- At 3000K Universe, 400 000 years old, free electrons are bound to protons and He
- Hydrogen atom is neutral, so no more scattering
- Average photon in the Universe has never interacted again since last scattering with free electrons at 3000K
- Now Universe is 1000 times bigger, so temperature of the Cosmic Microwave Background is 2.76K



Dark Matter – Why do we think it exists?

Cosmic Microwave Background

- Prior to last scattering, as matter falls into overdense regions, photons were pulled along as well (plasma)
- These photons are slightly hotter than surroundings
- Density fluctuations leave an imprint on the CMB
- They show the early stages of structure formation



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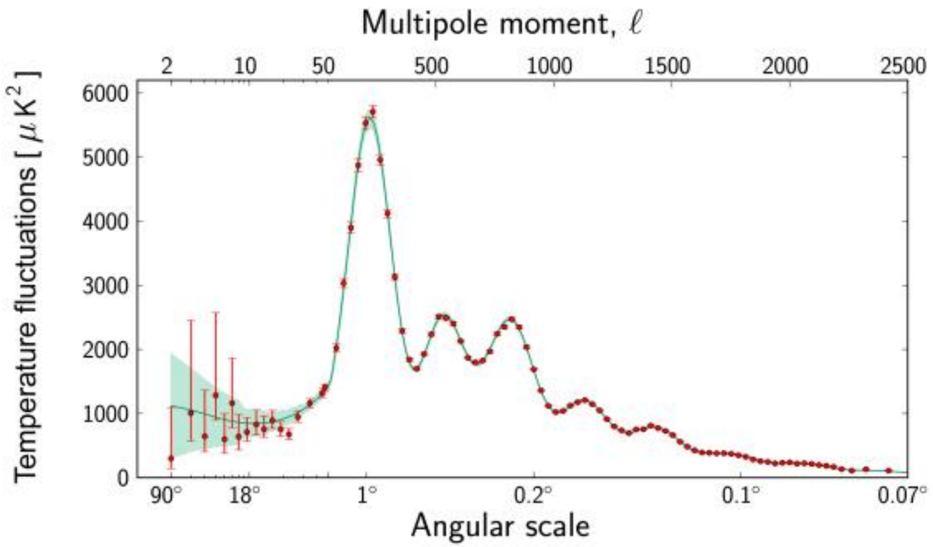
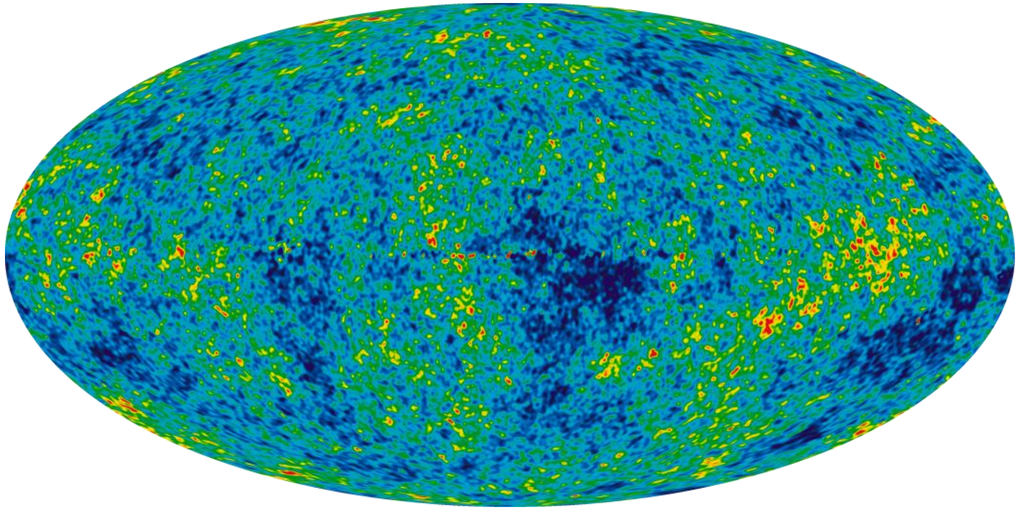


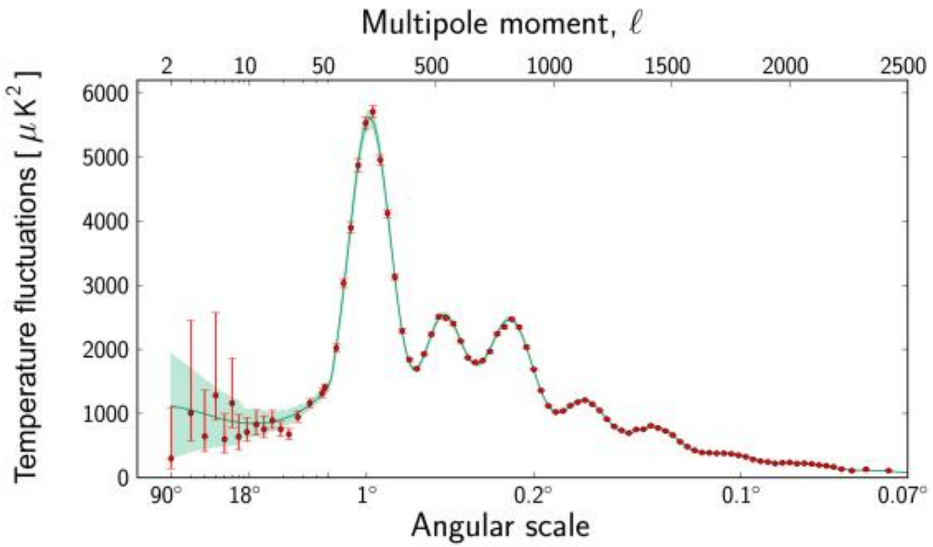


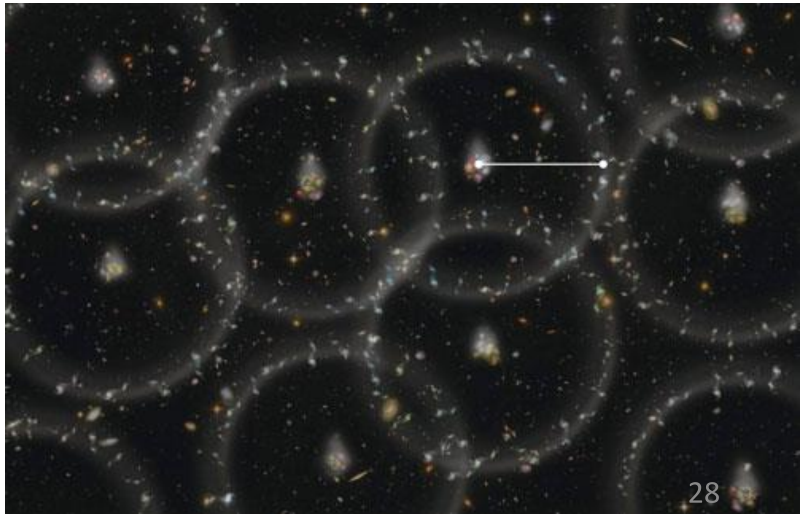
Dark Matter – Why do we think it exists?

Cosmic Microwave Background

Baryon acoustic oscillations:

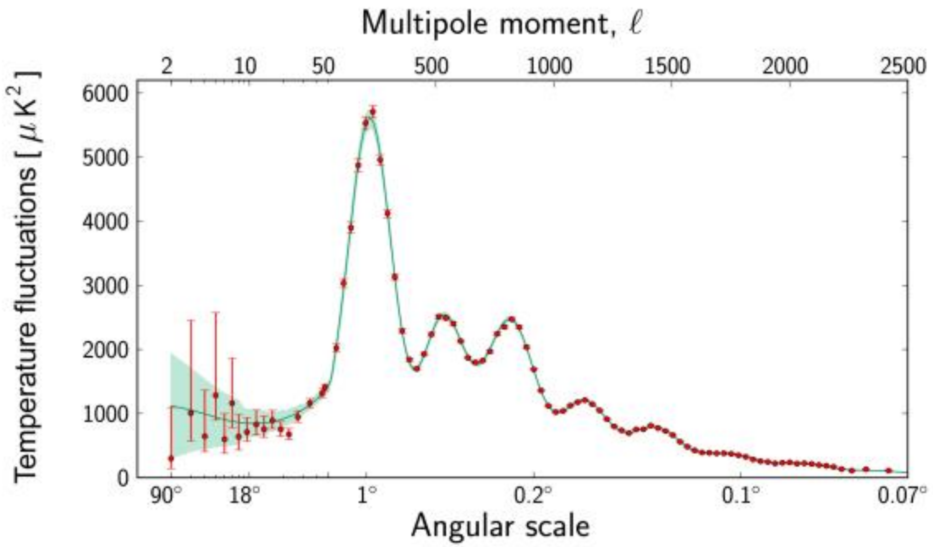
- Before recombination, photons, electrons and baryons form a high pressure fluid
- In a region with high initial density, there will be a high pressure in the baryon-photon fluid, which will propagate as an expanding spherical sound wave
- After recombination, the photons go off at speed of light, and the baryons are sitting in a spherical shell around the initial excess density of dark matter
- Sound wave travels 400 000 years before recombination at a large fraction of the speed of light, so at recombination the shell has a radius of 450 000 light years (sound horizon)
- This expands to 500 million light years, thus we expect to see an enhanced number of galaxy pairs separated by 500 million light years





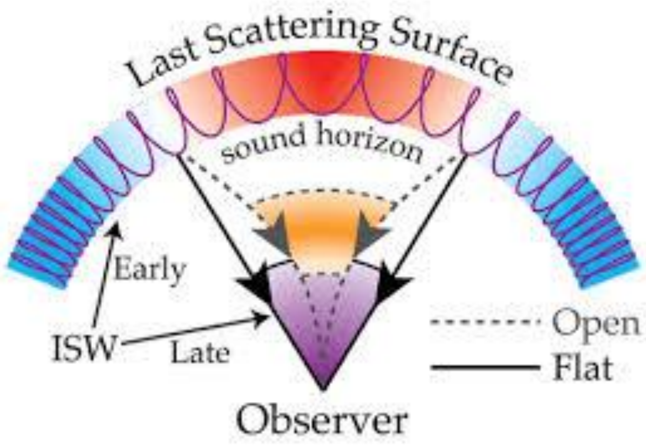
Dark Matter – Why do we think it exists?

Cosmic Microwave Background



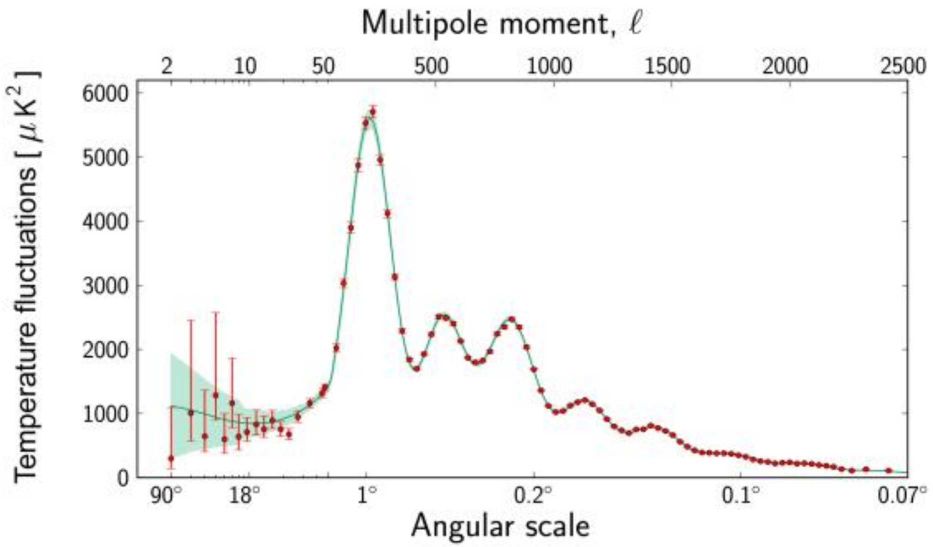
Baryon acoustic oscillations:

- This expands to 500 million light years, thus we expect to see an enhanced number of galaxy pairs separated by 500 million light years
- In angular scale, this is:
  - 1 deg if the Universe is flat
  - Less than 1deg if hyperboloid
  - More than 1deg if spherical



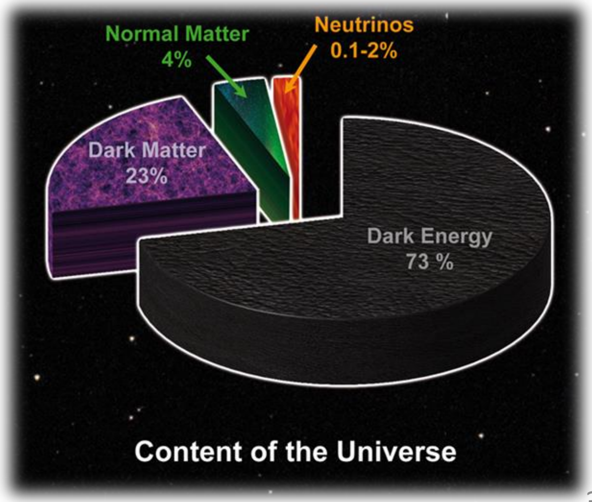
Dark Matter – Why do we think it exists?

Cosmic Microwave Background



Baryon acoustic oscillations:

- The green line is a fit to the red data points
- Model includes 6 parameters including baryonic matter, dark matter and dark energy content and curvature of the Universe
- Result: 5% baryonic matter, 26% dark matter, 69% dark energy and the Universe is very close to flat!



Dark Matter Candidates

Things we already know?

- Hydrogen based:
  - Frozen lumps of Hydrogen would evaporate
  - Diffuse hot gas would produce X-rays we would have seen
  - Cool neutral H would absorb background light

- Rocks & dust:
  - If predominant matter was this type, starts should have more metals, yet earliest stars are almost only H
  - BBN tells us it should be something else

- Neutrino's:
  - Only feel gravity and weak force (don't count in 5%)
  - Don't have restriction from BBN because weak force neutrino interactions had already stopped before BBN
  - Relic abundance shows there's a lot of them: 400/cm^3, if mass was 100eV it would be perfect
  - Is not Cold Dark Matter, but Hot, prevents structure formation
  - Measured masses are less than 1eV summed, so only small fraction of matter content
  - Maybe a sterile neutrino???

Dark Matter Candidates

Things we already know?

- MACHOs (Massive Compact Halo Objects)
  - Faint starts, planetary objects, stellar remnants (white dwarfs, neutron stars, black holes)
  - Extrapolations of what was seen by Hubble Space Telescope, faint starts and substellar objects are <3% of mass Milky Way
  - Galactic halo could contain large numbers of white dwarfs, neutron stars and stellar black holes, but no evidence for their progenitors, not seen with micro lensing in sufficient numbers
  - Primordial black holes? Formed in first min of Universe, very small, fraction of mass of the Sun. Hard to rule out, but also difficult to prove!

Dark Matter Candidates

Things we don't know?

- Axions:
  - Solve strong CP problem
  - Very light, slow, abundant

- WIMPs: Weakly Interacting Massive Particles:
  - Mass of 10-1000GeV
  - Gravity and Weak Force
  - WIMP miracle: if WIMPs are their own antiparticle, they annihilate in the primordial soup with strength determined by the weak force. The residual numbers are coincidentally the right abundance for Dark Matter
  - Arise naturally in SUSY as the lightest supersymmetric particle
  - Arise when including extra dimensions (enable unification of Gravity with other forces, String Theory)

Dark Matter – Searches

3 approaches:

- Create dark matter:
  - Collisions of high energy proton beams at LHC
  - Search for missing transverse momentum
  - So far WIMPs seem very unlikely

- Direct detection:
  - Dark matter from galaxy might interact with atomic nuclei

- Indirect detection:
  - Products of dark matter annihilation in the galaxy might be detected

Dark Matter – Searches

Direct detection:

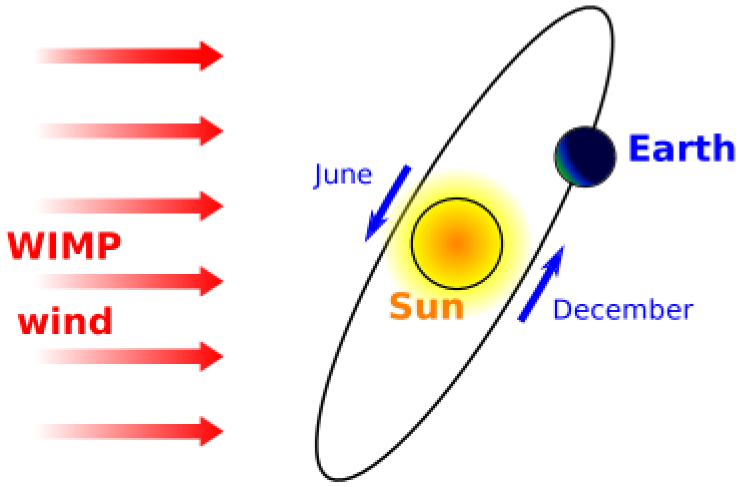
- Standard Halo Model:
  - Dark matter is essentially collisionless
  - Gaseous sphere characterised by “temperature” set by typical speeds of the particles (250km/s)
  - Density profile: peak at galactic centre, falls of with distance
- Solar System moves on an orbit around the galactic centre with speed of 220km/s, traversing the dark matter halo, so we see a dark matter wind!

Dark Matter – Searches

Direct detection:

- WIMPs:
  - Experiment should be extremely sensitive to weak interactions
  - Aim to observe low-energy recoils of nuclei induced by interaction with WIMP
  - Maintain a very low background, often the experiments are operated in mines or tunnels beneath mountains
  - Annual variation is expected

  - So far, no conclusive signs of WIMPs
  - Seem less and less likely



Dark Matter – Searches

Direct detection:

- Bosonic ultralight dark matter:
  - These particles have large mode occupation numbers and their phenomenology is described by a classical field
  - Mass range 10^{-24}eV to 10^{-3}eV (de Broglie wavelength smaller than size of galaxy)
  - Effect of classical field on Standard Model particles:
    - Precession of nuclear and electron spins
    - Drive currents in EM systems
    - Induce equivalence-principle-violating accelerations of matter
    - Modulate the values of the fundamental constants of nature

Dark Matter – Searches

Example 1: Search for axionlike dark matter with neutron Electric Dipole Moment (nEDM)

- ALPs as dark matter would form a coherent classical field
- We pass through a cloud of dark matter as we move throughout the Milky Way
- The following Lagrangian has been proposed to describe the interaction between axions *a*, and gluons *G* and fermions *f*

$$\mathcal{L}_{\text{int}} = \frac{C_G}{f_a}\frac{g^2}{32\pi^2} a G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - \sum_{f=n,p,e}\frac{C_f}{2f_a}\partial_\mu a \ \bar{f}\gamma^\mu\gamma^5 f$$

Dark Matter – Searches

Example 1: Search for axionlike dark matter with nEDM

$$\mathcal{L}_{\text{int}} = \frac{C_G}{f_a}\frac{g^2}{32\pi^2} a G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - \sum_{f=n,p,e} \frac{C_f}{2f_a}\partial_\mu a\ \bar{f}\gamma^\mu\gamma^5 f$$

- The first term in the Lagrangian behaves as the QCD $\bar{\theta}$ term, resulting in an oscillating EDM signal

$$d_n(t) \approx +2.4 \times 10^{-16} \frac{C_G a_0}{f_a} \cos(m_a t)\, e\,\text{cm}$$

- The second term generates spin-dependent anomalous precession

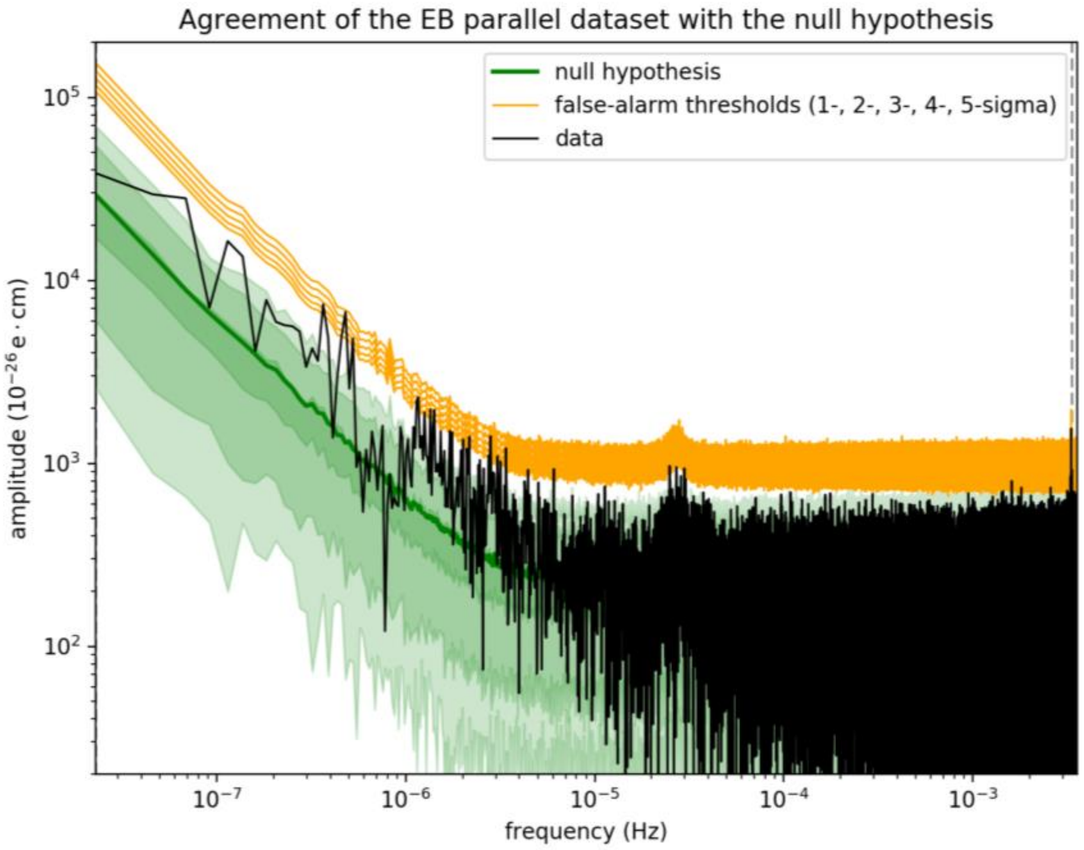
$$H_{\text{int}}(t) = \frac{C_N a_0}{2f_a} \sin(m_a t)\, \boldsymbol{\sigma}_N \cdot \boldsymbol{p}_a$$

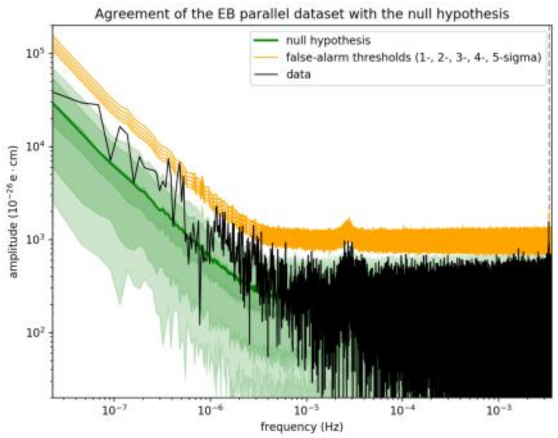
Dark Matter – Searches

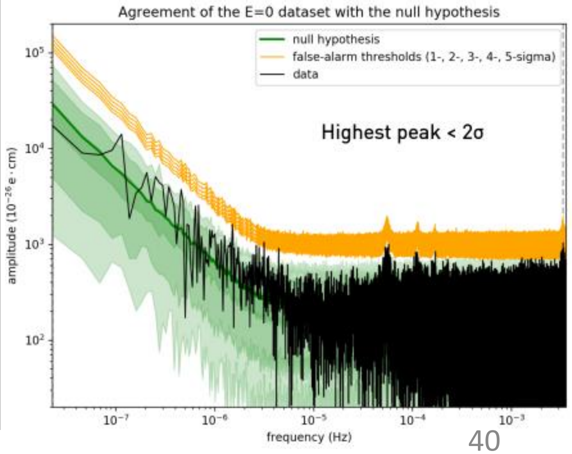
Example 1: Search for axionlike dark matter with nEDM

Oscillating nEDM:

Detection plot

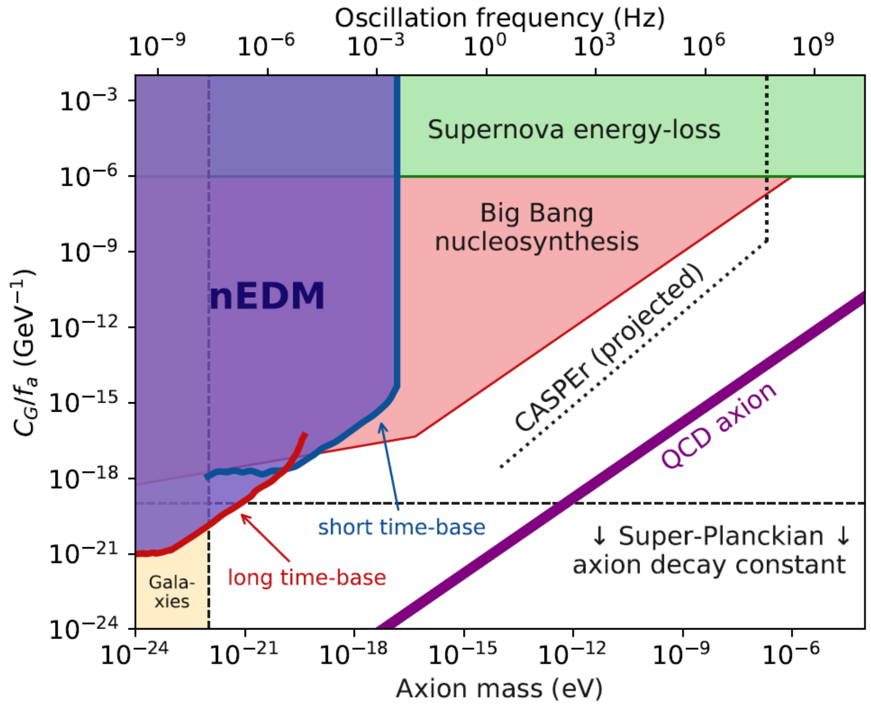






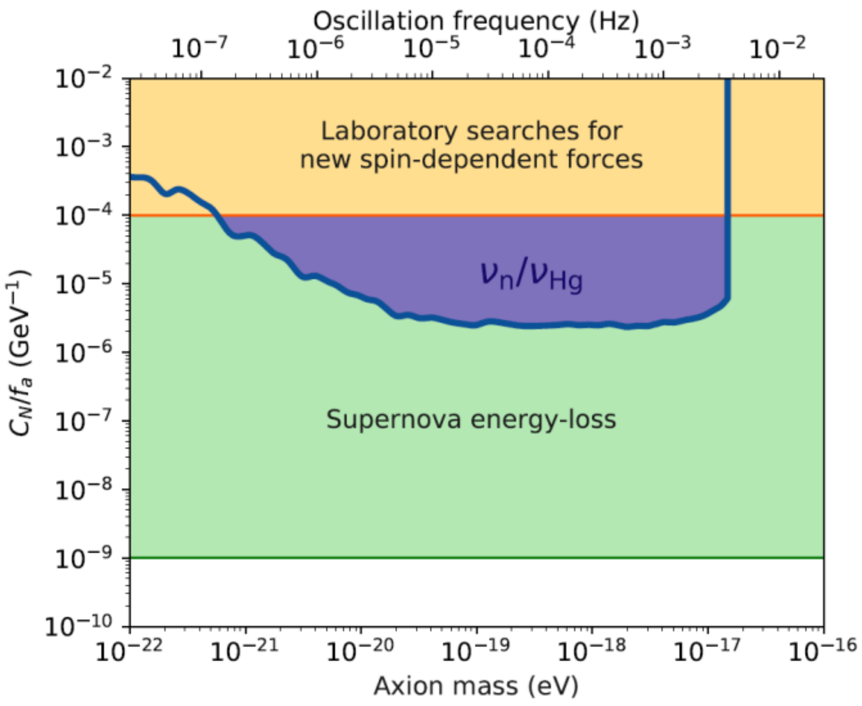
Dark Matter – Searches

Example 1: Search for axionlike dark matter with nEDM



C. Abel *et al.*, PRX7(2017)041034

First experimental limits
on gluonic coupling



40 times better limit
on fermionic coupling

Dark Matter – Searches

Example 2: Search for axionlike dark matter with antimatter at BASE

Same Lagrangian as before induces spin-dependent anomalous precession

$$H_{\rm int}(t) = \frac{C_N a_0}{2 f_a} \sin(m_a t)\, \boldsymbol{\sigma}_N \cdot \boldsymbol{p}_a$$

For the antiproton, this would mean an oscillating g-factor:

$$\left(\frac{\omega_L + \delta\omega_L^{\bar{p}}(t)}{\omega_c}\right)_{\overline{p}} = \frac{\mu_{\overline{p}}}{\mu_N}\left[1 + \sum_{i=1}^{3} b_i \sin\left(\omega_i t + \phi_i\right)\right]$$

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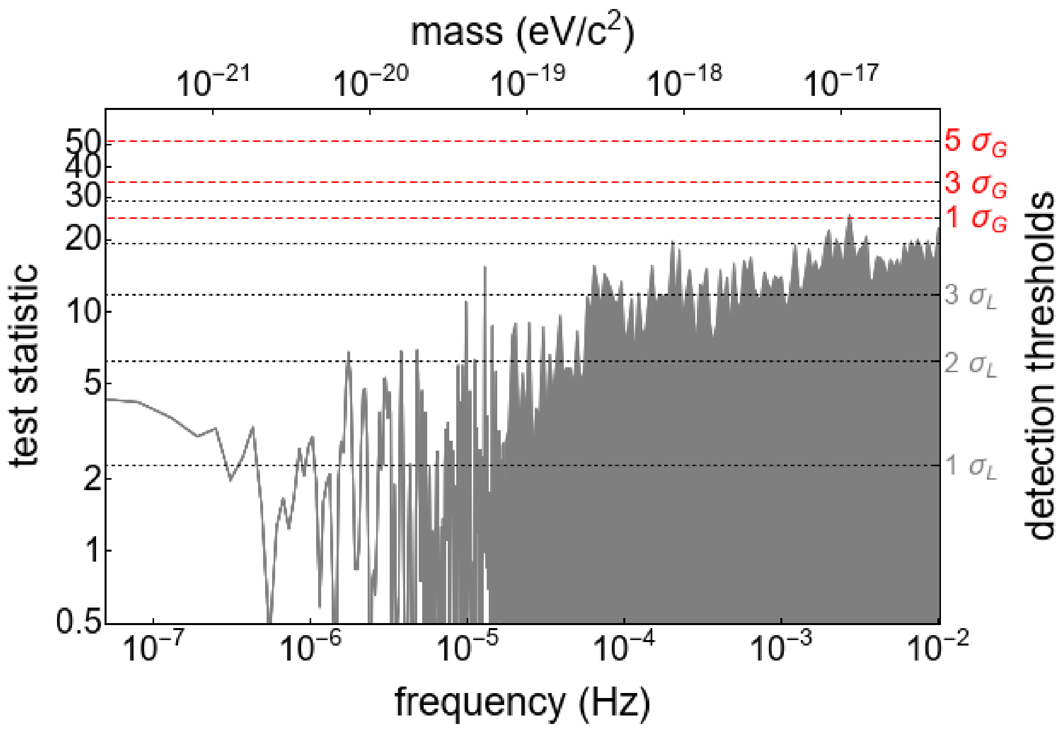
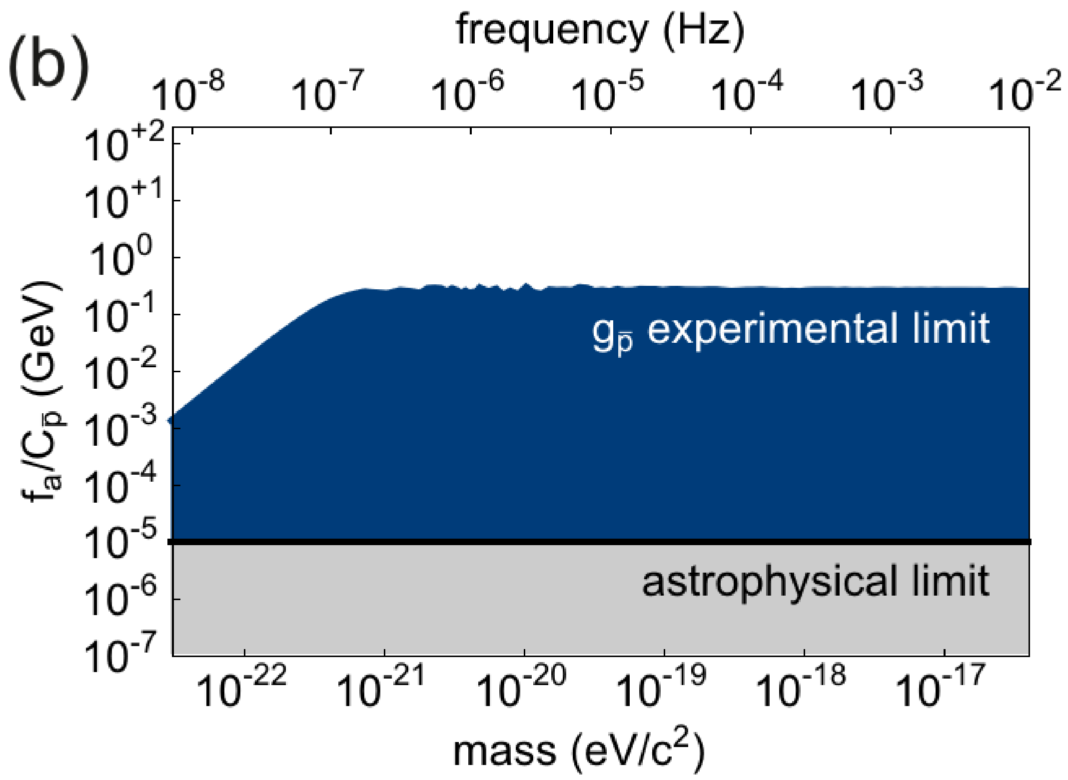
Example 2: Search for axionlike dark matter with antimatter at BASE





Dark Matter – Searches

Example 3: Search for clumpy dark matter

- Search for deviations from the Standard Halo Model: “dark stars”, “Q balls”, “topological defects”
- Would be observed as a transient event associated with the passage of the detector through the dark matter object
- Network of spatially separated sensors is needed, for example:
  - A network of clocks, they are sensitive to a variation of fundamental constants!
  - Network of magnetometer can measure transient anomalous precession effects

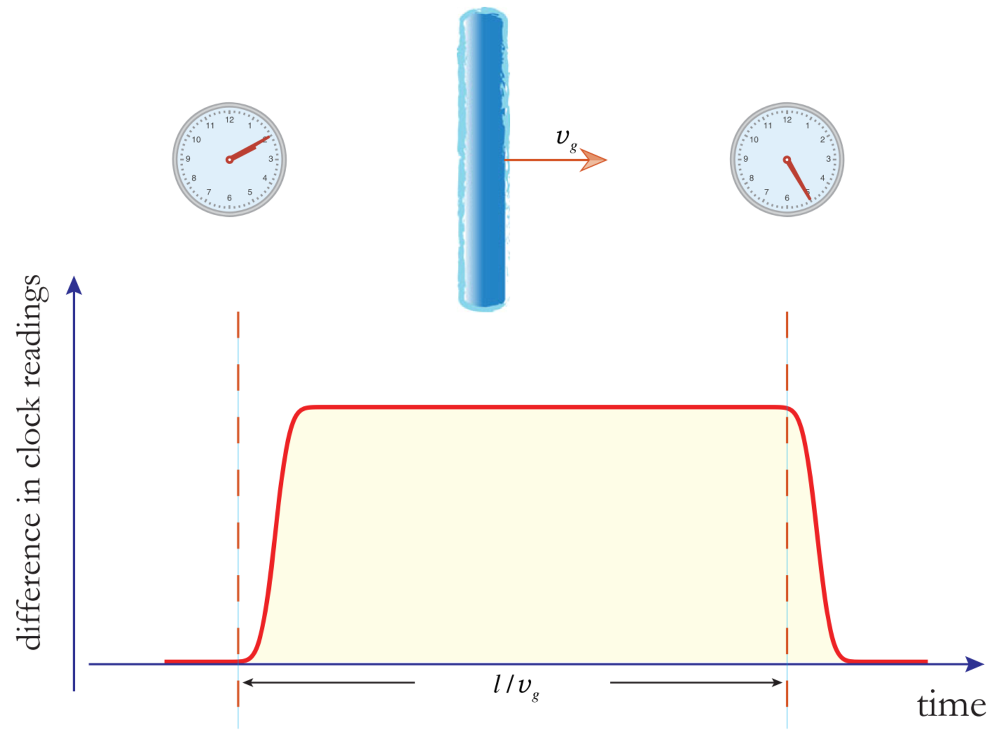


FIG. 21. Spatially separated and initially synchronized identical clocks are expected to exhibit a distinct desynchronization and resynchronization pattern due to an encounter with a DM object. Two clocks are separated by a distance ℓ, and because the wall propagates through the network with a speed $v_g \approx 300$ km/s, the characteristic “hump” persists over time ℓ/v_g. Adapted from Derevianko and Pospelov, 2014.

Conclusions

The Standard Model has had many successes, but many open questions remain. Some of the experiments discussed during this school try to answer these questions.

On the dark matter front:

- Evidence seems overwhelming
- MACHOs are excluded, WIMPs are less and less likely
- Axions and other bosonic ultralight particles are current hot topic
- So far no detections...