Dark Matter

Axel Lindner

with contributions from Elena Mazzeo

DESY Summer Student Lecture, August 8th, 2018

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

DESY.

Our dark matter menu

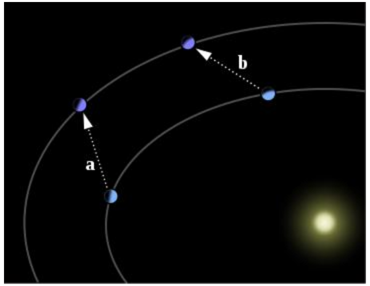
- Starters
  - Historical annotations: how to discover new stuff?
  - Our anchor: the Standard Model of particle physics
- Main course 1
  - The necessity of Dark Matter
  - Alternatives and hidden assumptions
- Main course 2
  - Dark matter candidates
  - Searching for Dark Matter candidate particles
  - Direct searches for Dark Matter particles
- Dessert
  - Astrophysical puzzles
- Doggy bag
  - Summary and outlook

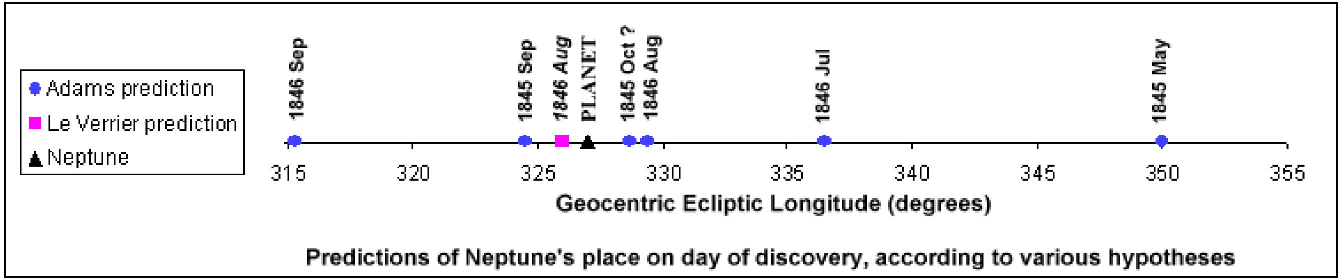
Dark Matter is not open to the public; therefore we do not offer tours or tastings.
info@darkmatterwines.com
707.548.9651
PO BOX 342
ST HELENA, CA 94574

Is there additional stuff around?

Some reminders from history:

- Discovery of Neptune by irregularities of the Uranus orbit:
Sept. 24th 1846 by Johann Gottfried Galle at the Berlin Observatory.





http://en.wikipedia.org/wiki/Discovery_of_Neptune

- An application of the known laws of nature (gravitation) led to the discovery of previously "invisible" mass.

Is there additional stuff around?

Some reminders from history:

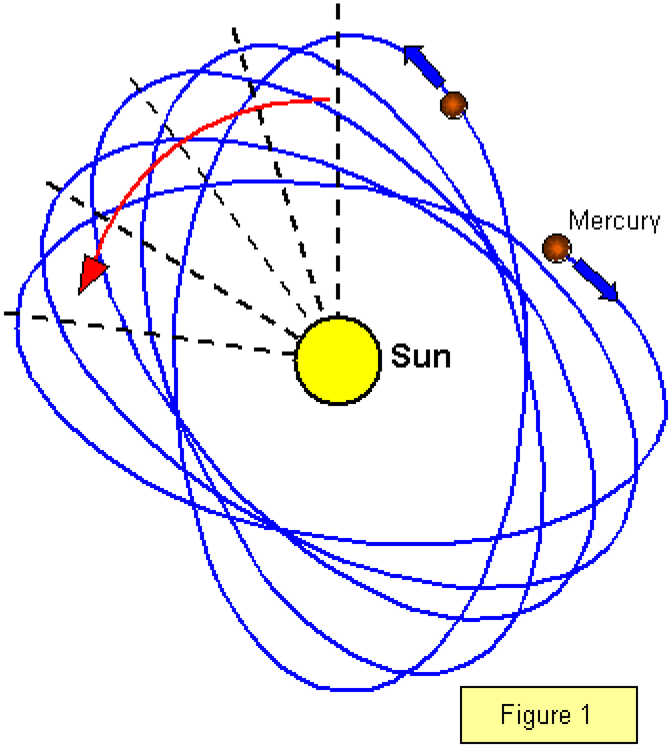
> Motion of the perihelion of Mercury:

http://www.schoolphysics.co.uk/age16-19/Relativity/text/Perihelion_of_mercury/index.html

Attempts to describe this by the gravitational pull of a new planet “Vulcan” failed (in spite of numerous “observations”).

Finally the explanation was given by General Relativity.

> A failed search for an “invisible” mass strongly supported an improved theory of gravitation.



A recipe for discoveries

Apply known laws of nature in regions
where they have not been tested before.

> New regions of time and space	Quantum mechanics
> New regions of time and space	Cosmology
> More energetic particle collisions	LHC
> More precise experiments	ALPS II @ DESY

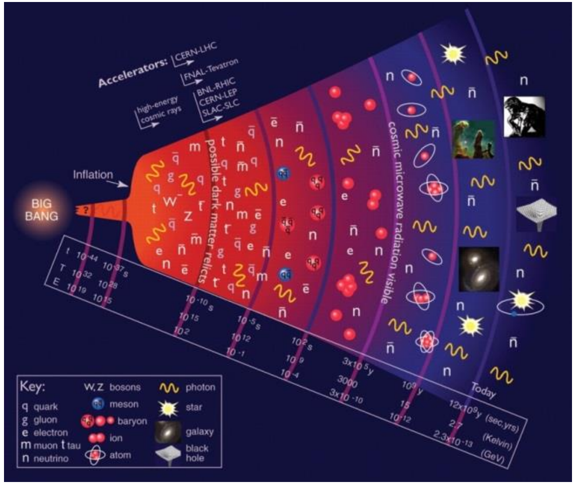
You might find deviations from expectations hinting at

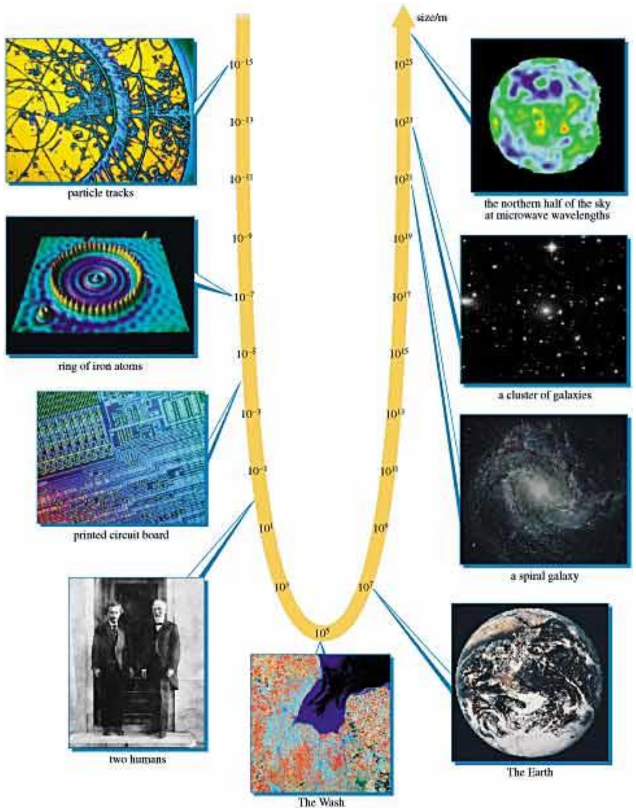
> New stuff	Neptune discovery
> More fundamental laws of nature	General relativity

Our starting point: what we know

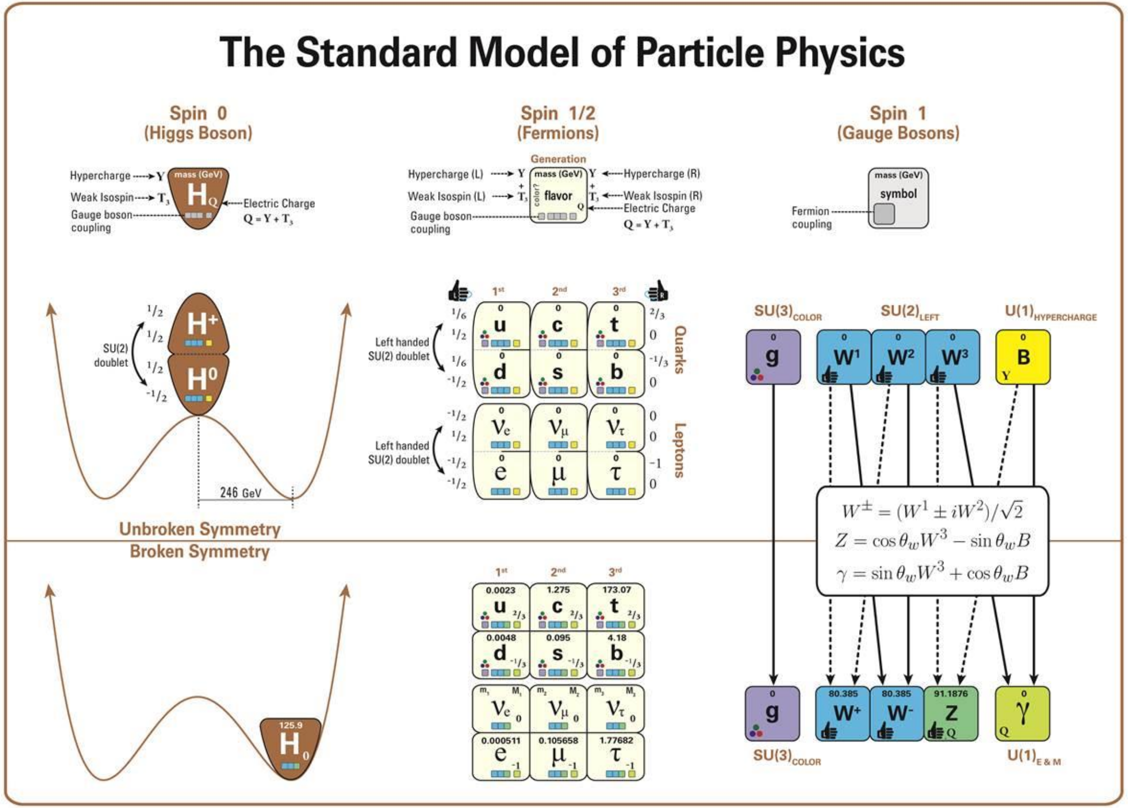
- Microcosm: down to 10^{-18} m
- Macrocosm: up to 10^{26} m

- And we even know about how connecting quarks and the cosmos.





Cornerstone I: the Standard Model of particle physics



https://en.wikipedia.org/wiki/Standard_Model

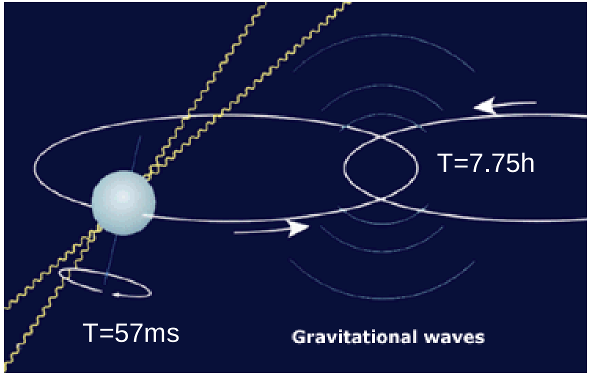
With these few constituents and forces all phenomena observed on earth can be described (in principle).

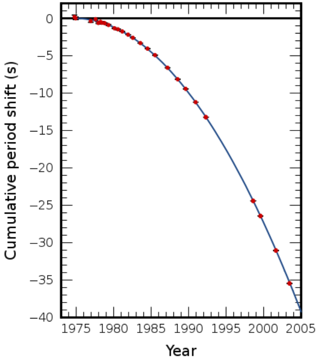
Only the non-zero masses of neutrinos call for “new physics” beyond the Standard Model.

Unfortunately data do not tell us the scale of the “new physics”.

Cornerstone II: understanding gravity

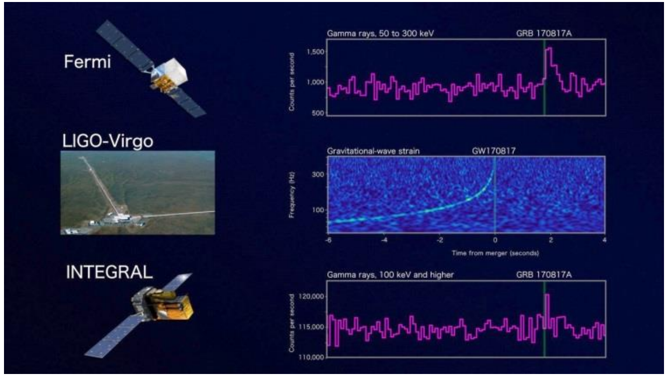
- General relativity paved the way to understand the universe.





Evidence for gravitational waves at PSR1913+16
(Nobel prize 1993 to Hulse and Taylor)

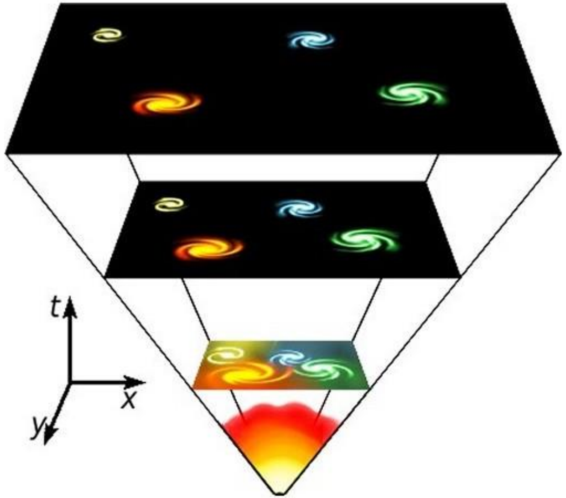
- Since 11 February 2016:
gravitational waves measured
by aLIGO and VIRGO:
Black holes and neutron star merger
(Nobel prize 2017 to Weiss, Thorne and Barish).



Cornerstone III: the quark-cosmos connection

- The universe started as a tiny point (a quantum fluctuation?), has expanded to its present size and keeps on expanding.
- It cools down during this expansion.

Cosmology lectures by
A. Westphal
on 20 August!

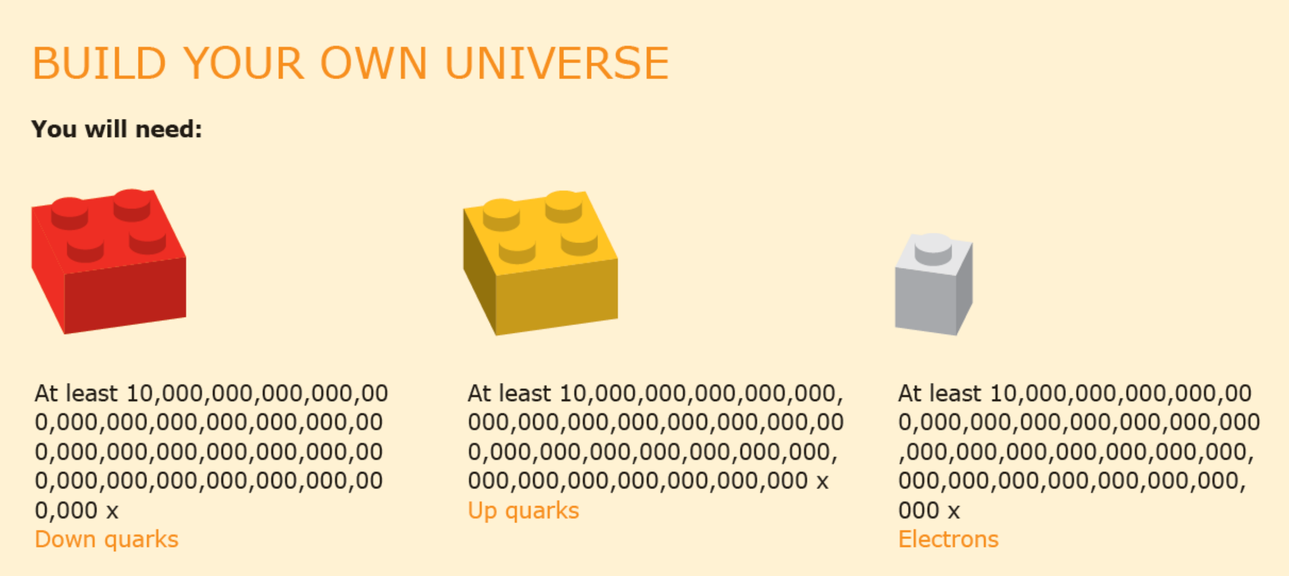


http://www.physicsoftheuniverse.com/topics_bigbang_expanding.html

- Thus high energy particle physics gives an insight to the early universe.
- Thus the universe might teach us about particle physics.

Cornerstone III: the quark-cosmos connection

- We (seem to ?) understand how “everything” evolved.



https://www.qmul.ac.uk/spa/outreach/in-school/teacher-resources/lego-physics/

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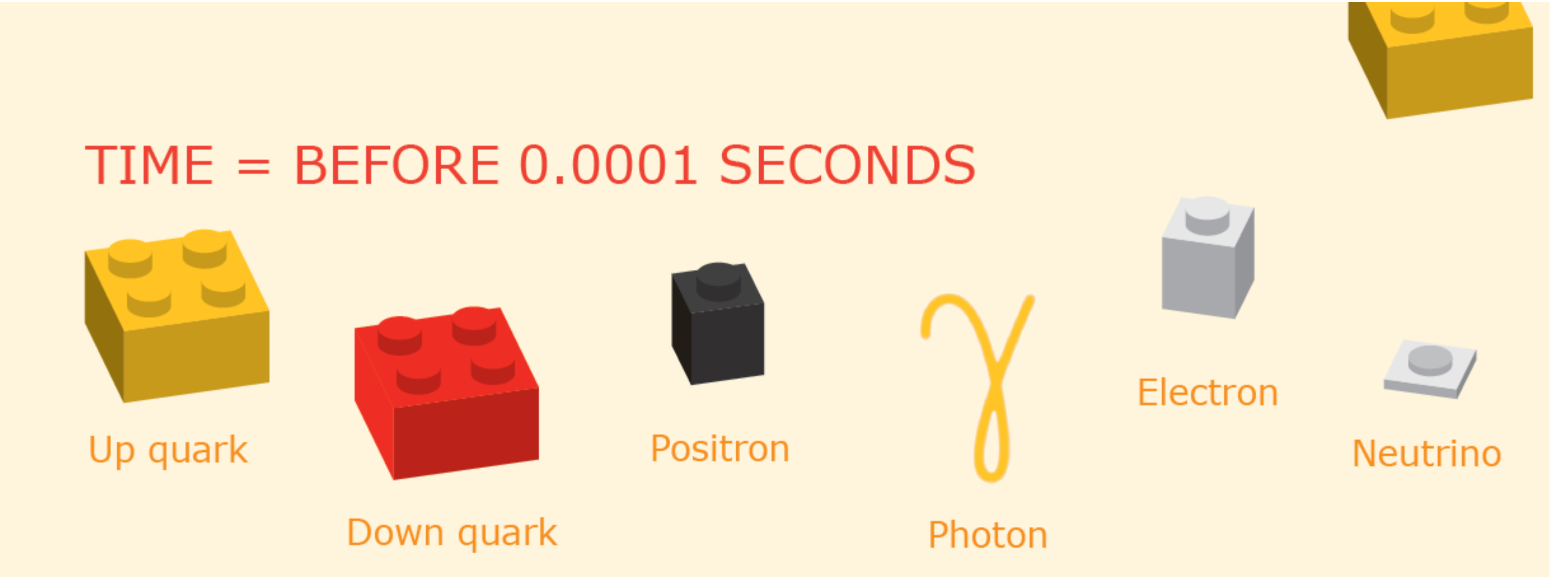

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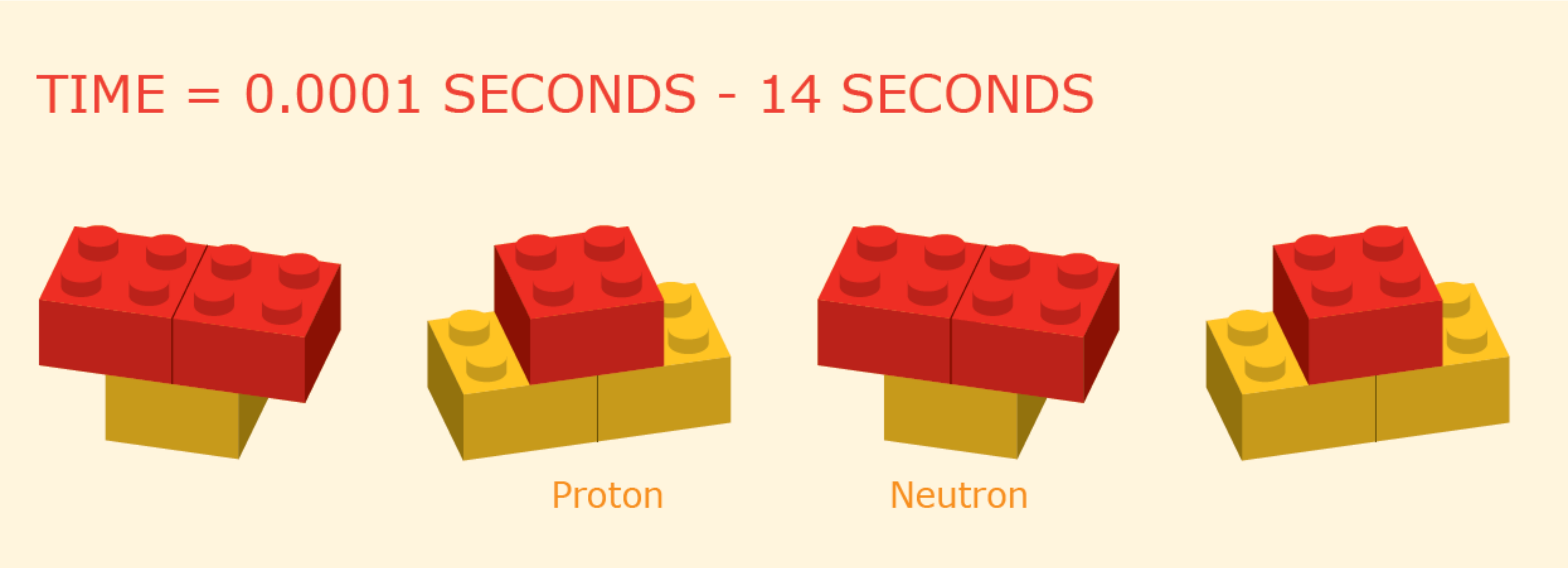

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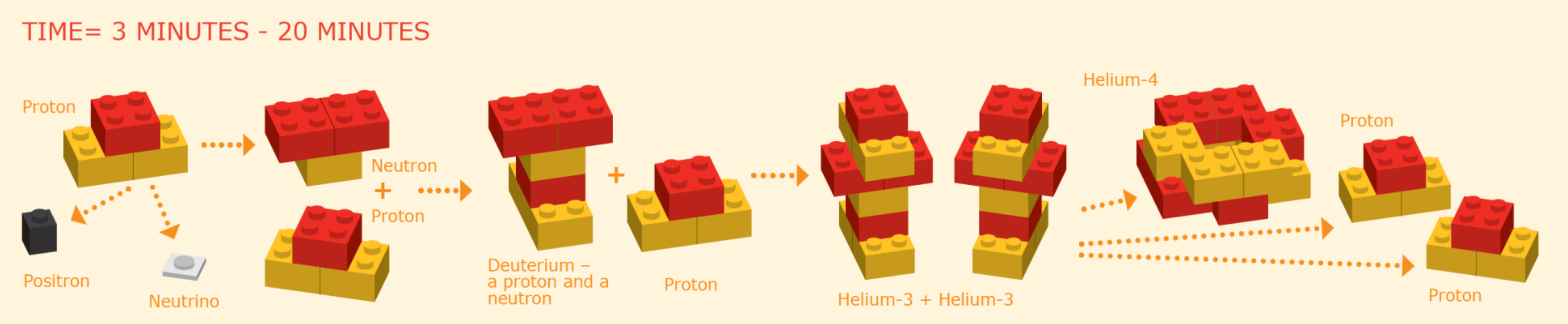

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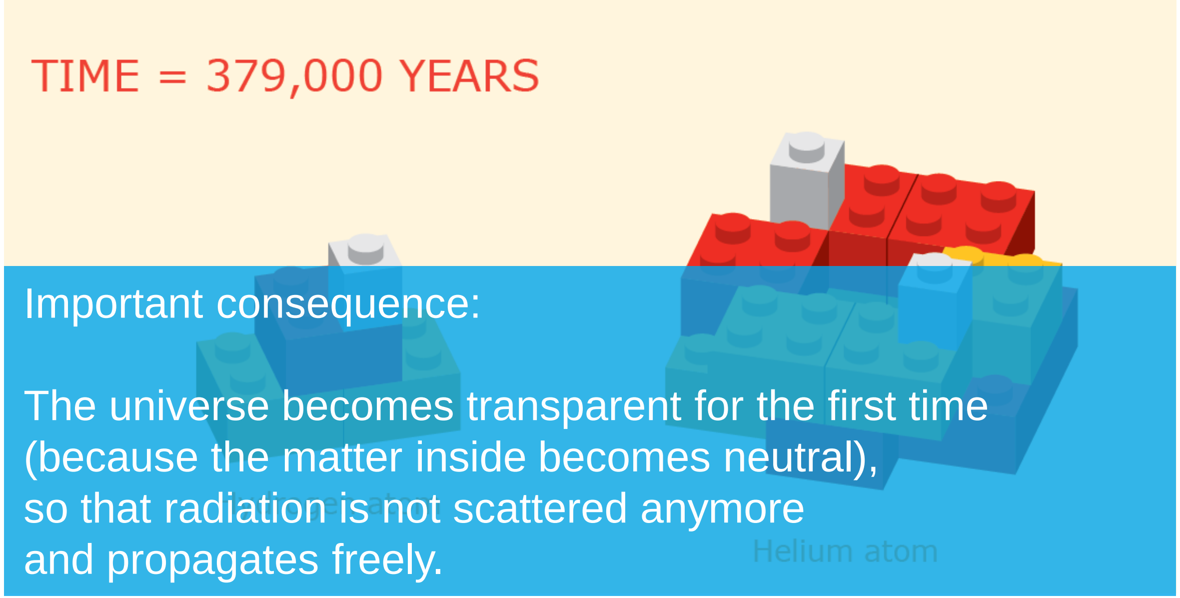

Important consequence:

The universe becomes transparent for the first time
(because the matter inside becomes neutral),
so that radiation is not scattered anymore
and propagates freely.

https://www.qmul.ac.uk/spa/outreach/in-school/teacher-resources/lego-physics/

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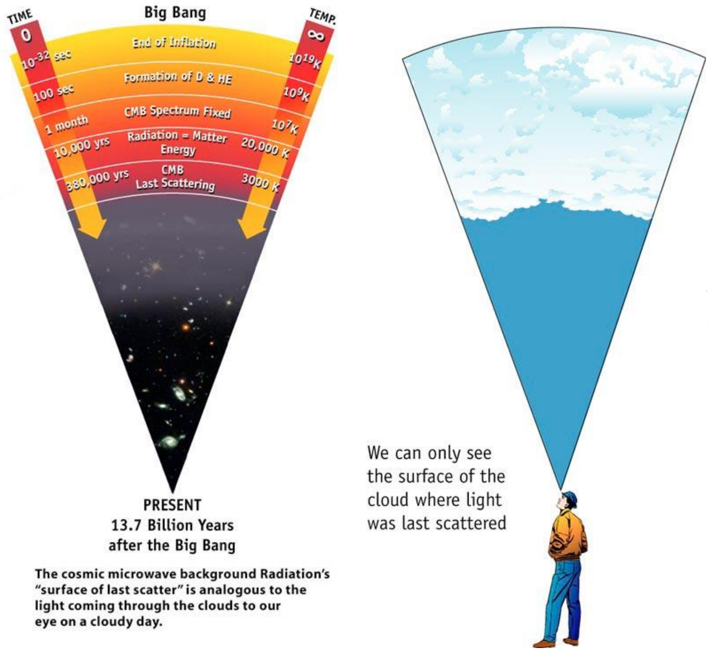
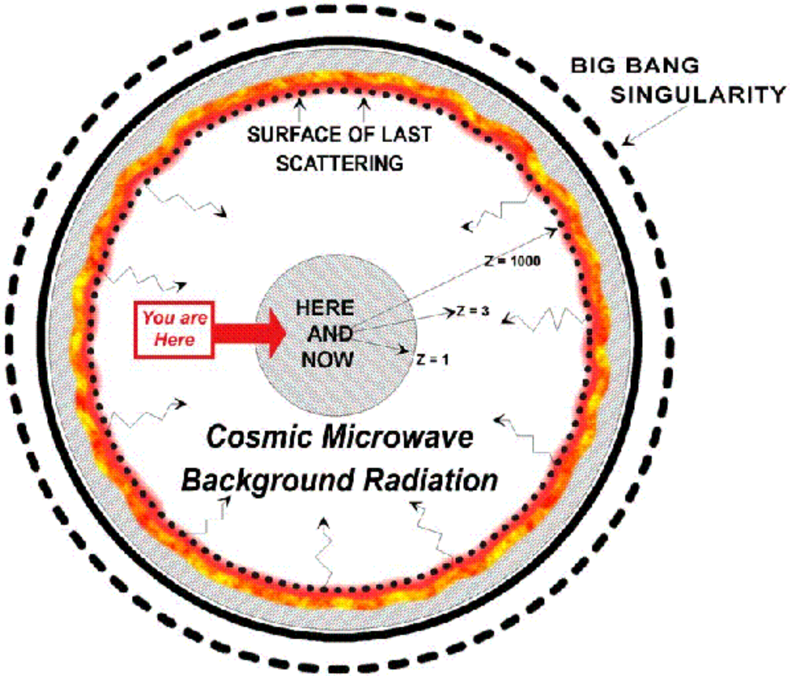
http://map.gsfc.nasa.gov/media/990053/990053sb.jpg



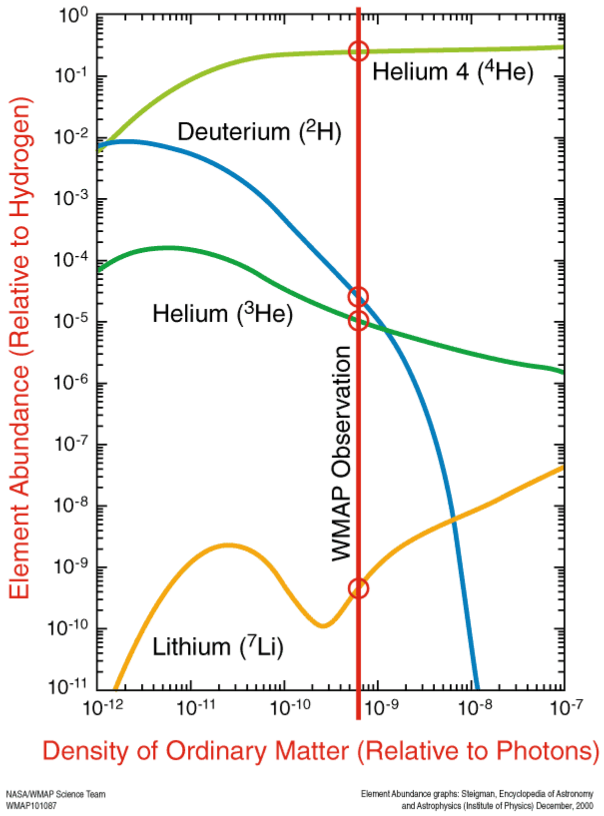


http://planck.caltech.edu/epo/images/CMBfromAllDirections.gif

Cornerstone III: the quark-cosmos connection

- This became precision physics since about 2000!

What does the Universe teach us on elementary particle physics?



Challenges of the standard model of particle physics

In spite of the successes, physicists are nor satisfied with the present picture. Some very fundamental questions still escape any explanation:

- How to include non-zero neutrino masses?
- How can we understand the (values of the) masses and the numbers of the SM particles?
- How does particle physics work in strong gravitational fields?
- How to understand “unnatural” fine-tuning phenomena in the SM?
- Why do we not find large amounts of antimatter in the Universe?
- ….

A brief review of the Standard Model

There exist numerous theories for “beyond standard model (BSM) physics”.

Experimental guidance is required to figure out which of these theories is realized in nature.

At present the non-zero neutrino masses doubtlessly hint at BSM physics,
but they do not pinpoint the underlying theory!

Again:

What does the Universe teach us on elementary particle physics?

Our dark matter menu

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  - Historical annotations: how to discover new stuff?
  - Our anchor: the Standard Model of particle physics
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  - Alternatives and hidden assumptions
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Discussion time: what do you know about dark matter?

https://www.darkmatterday.com/educational-resources-dark-matter-day/

Let's have a look at the structure and dynamics of the Universe.

Structure and dynamics in the Universe

DESY in Hamburg:

Apart from the problem of non-zero neutrino masses,
the standard model of particle physics describes all phenomena and experiments.

In principle.

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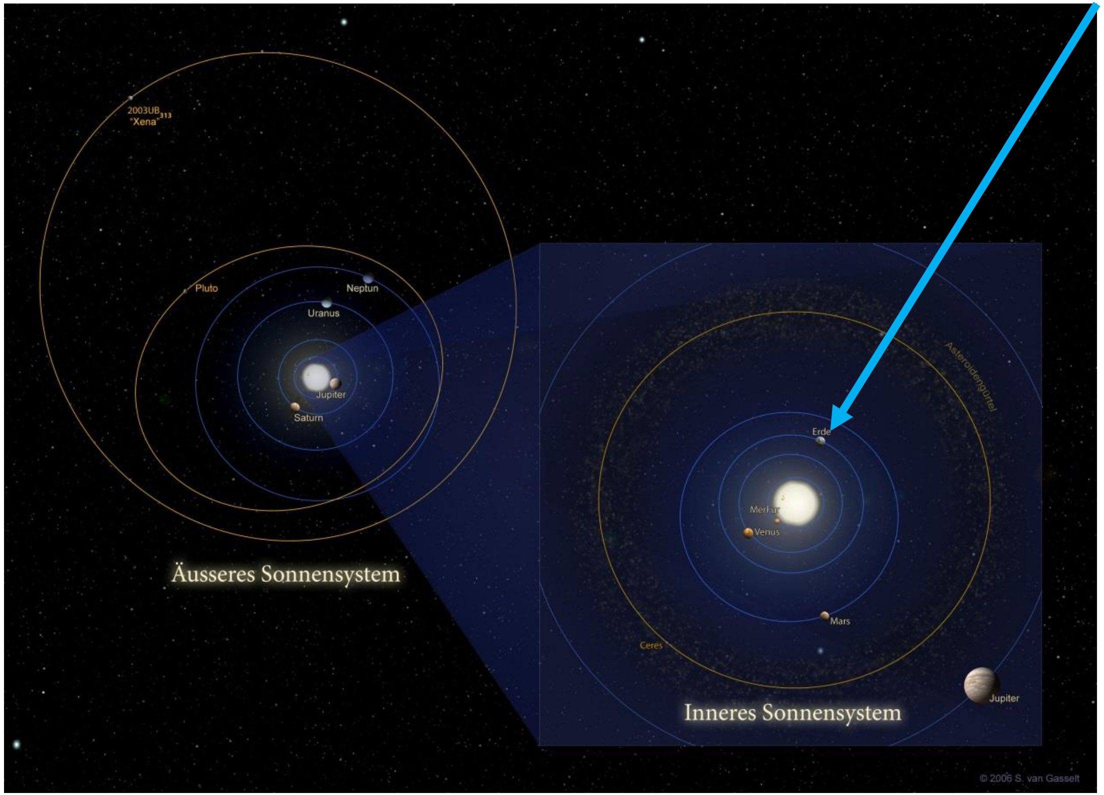
DESY.

Solar system:

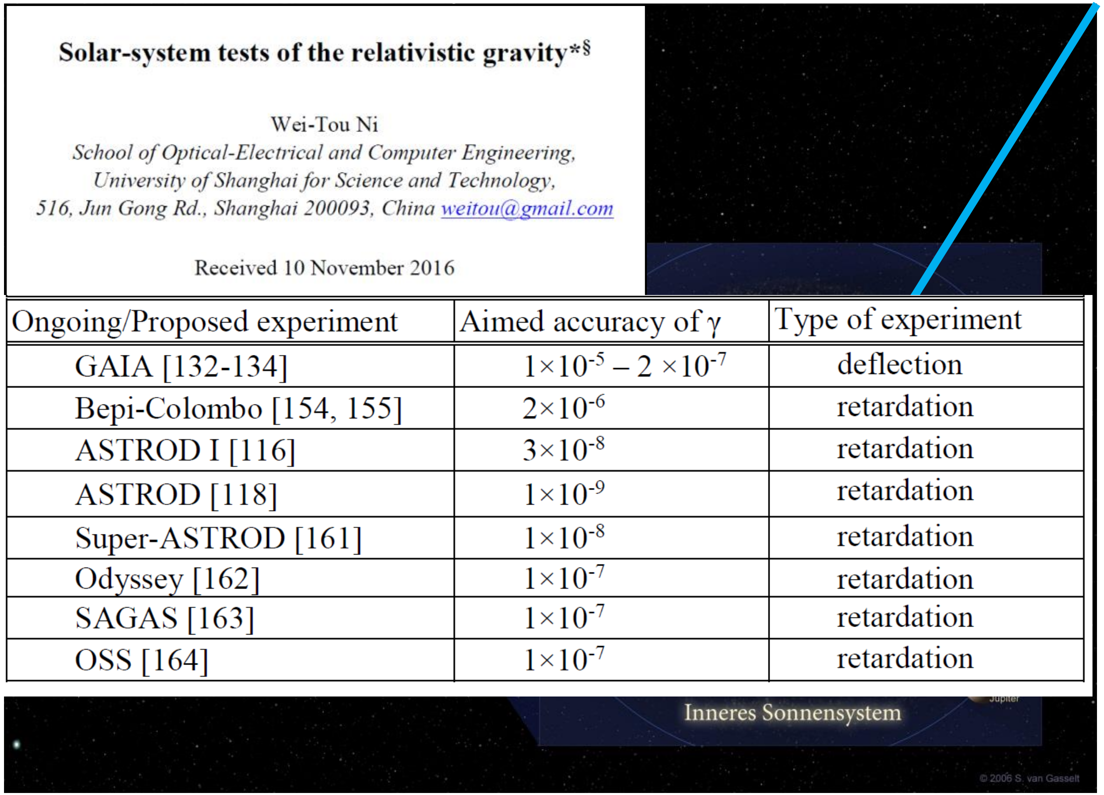
Again no need for anything beyond the standard model.



Solar system:

Again no need for anything beyond the standard model.

Gravitation works perfectly on the 10^{-3} to 10^{-4} level and will be tested at 10^{-8} precision in future.



Solar-system tests of the relativistic gravity*§

Wei-Tou Ni
School of Optical-Electrical and Computer Engineering,
University of Shanghai for Science and Technology,
516, Jun Gong Rd., Shanghai 200093, China weitou@gmail.com

Received 10 November 2016

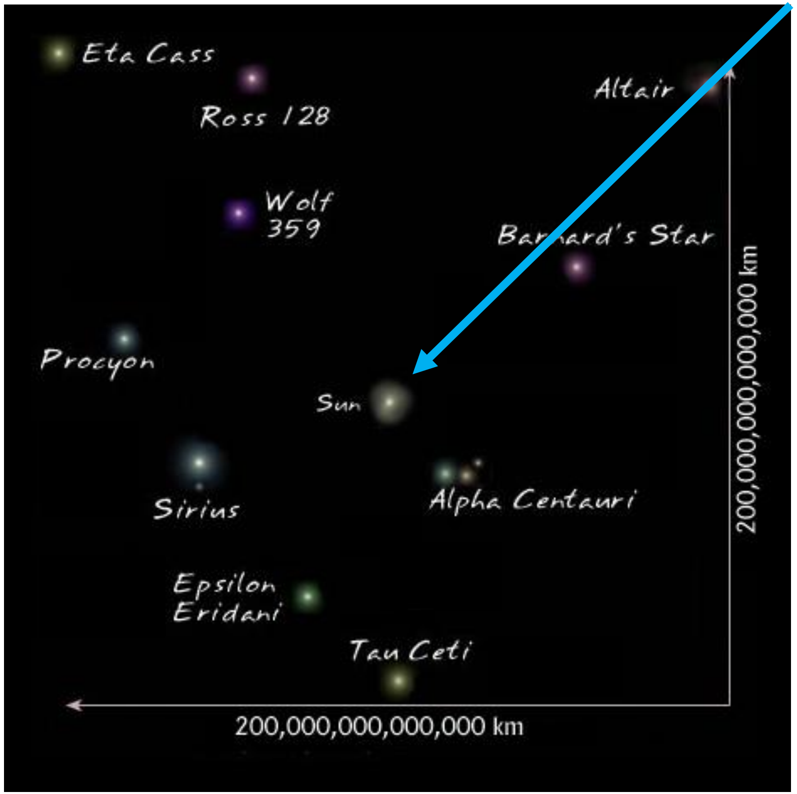
Ongoing/Proposed experiment	Aimed accuracy of γ	Type of experiment
GAIA [132-134]	$1\times10^{-5} - 2\times10^{-7}$	deflection
Bepi-Colombo [154, 155]	2×10^{-6}	retardation
ASTROD I [116]	3×10^{-8}	retardation
ASTROD [118]	1×10^{-9}	retardation
Super-ASTROD [161]	1×10^{-8}	retardation
Odyssey [162]	1×10^{-7}	retardation
SAGAS [163]	1×10^{-7}	retardation
OSS [164]	1×10^{-7}	retardation

https://arxiv.org/abs/1611.06025

Solar neighborhood:

Typical distances about 200.000.000.000.000 km (21 lightyears).

Studies on kinematics are ongoing, but systematic uncertainties prevent at present a clear evidence for dark matter. However, observations are compatible with the dark matter amount discussed later.



Structure and dynamics in the Universe

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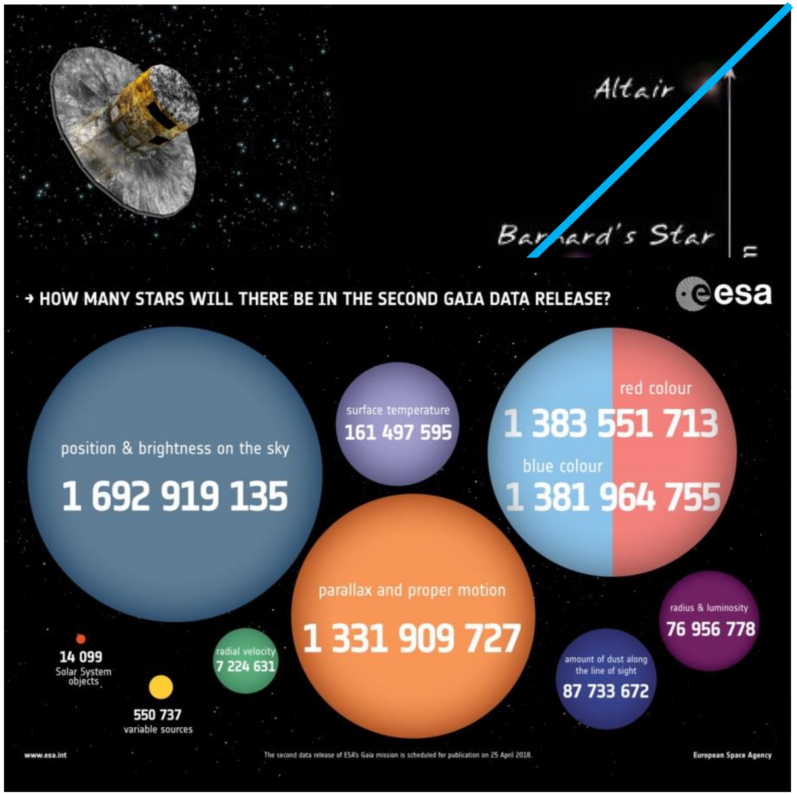
Improvements with more GAIA data?

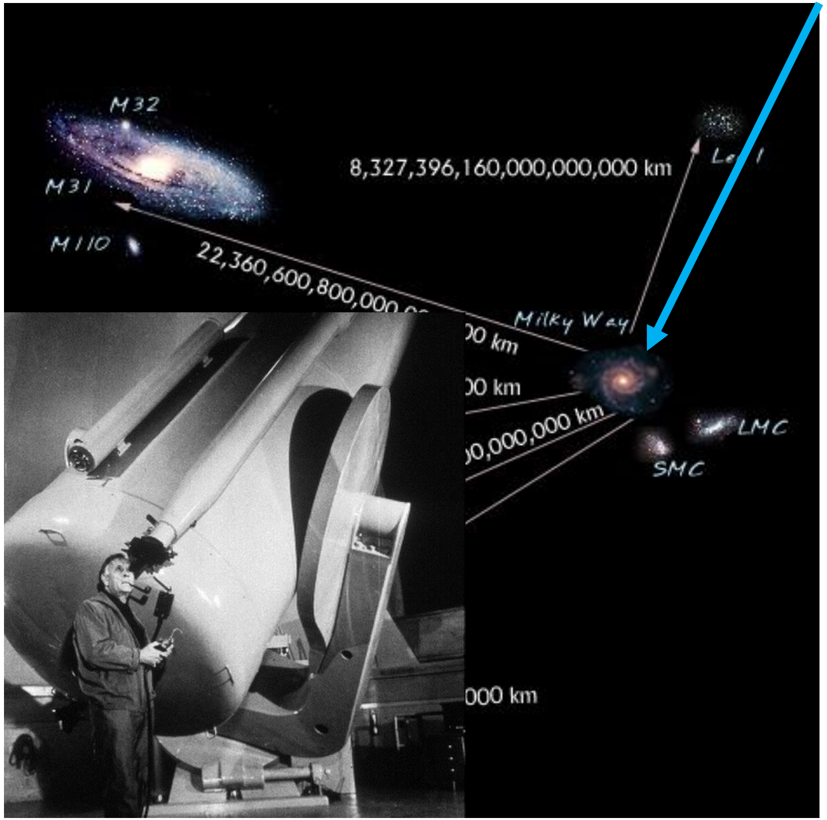


http://sci.esa.int/gaia/60147-waiting-for-gaia-s-second-data-release/

Structure and dynamics in the Universe

Galaxies:

M31 at 2,500,000 lightyears identified as a distant galaxy by E. Hubble in 1932.



Structure and dynamics in the Universe

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Andromeda (M31) with the human eye.

Structure and dynamics in the Universe

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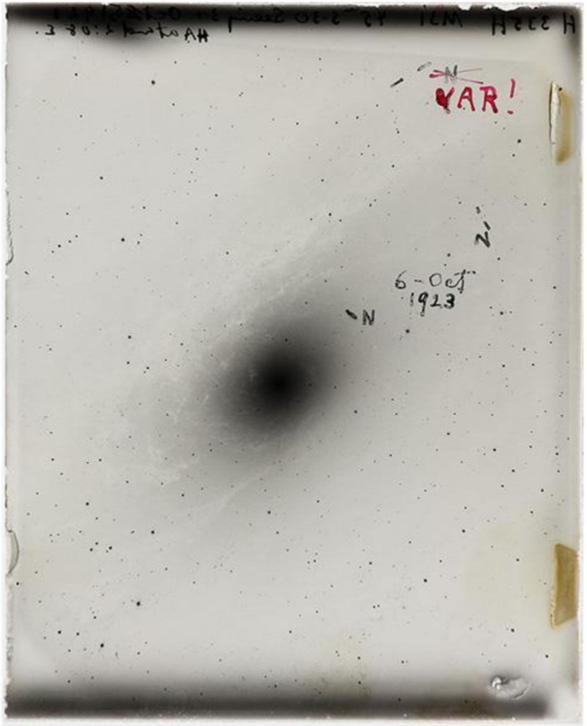

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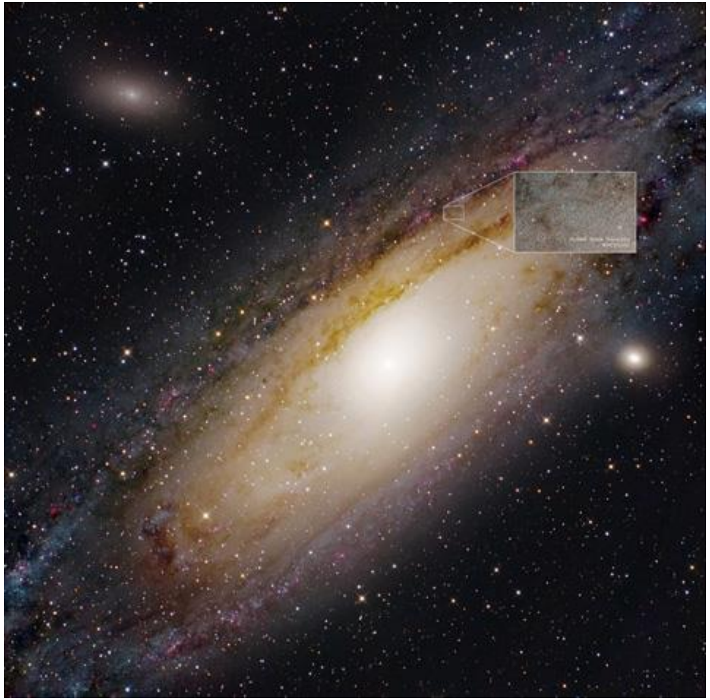
Andromeda (M31) with the Hubble space telescope.




Hubble Space Telescope
WFC3/UVIS

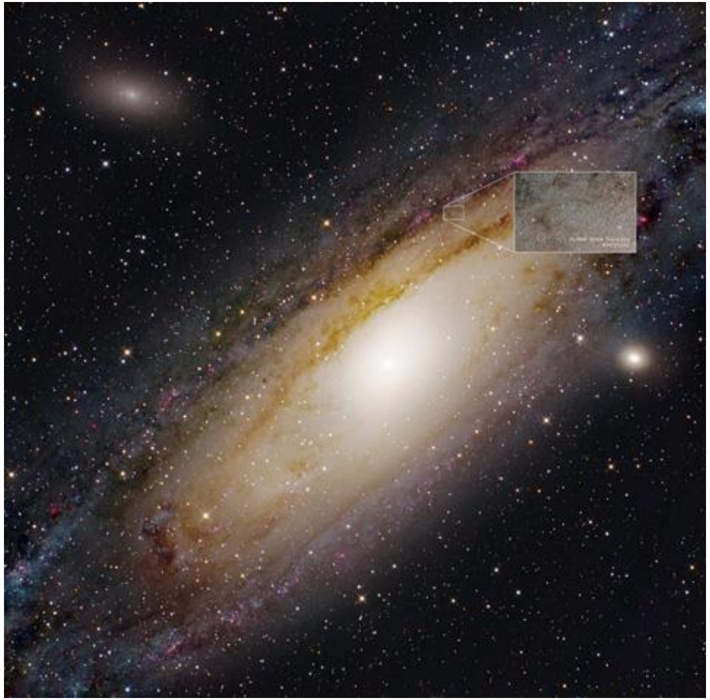
Structure and dynamics in the Universe

Galaxies:

M31 at 2,500,000 lightyears identified as a distant galaxy by E. Hubble in 1923.

Andromeda (M31) with the Hubble space telescope.

Astronomy and cosmology are strongly driven by new experimental technologies!



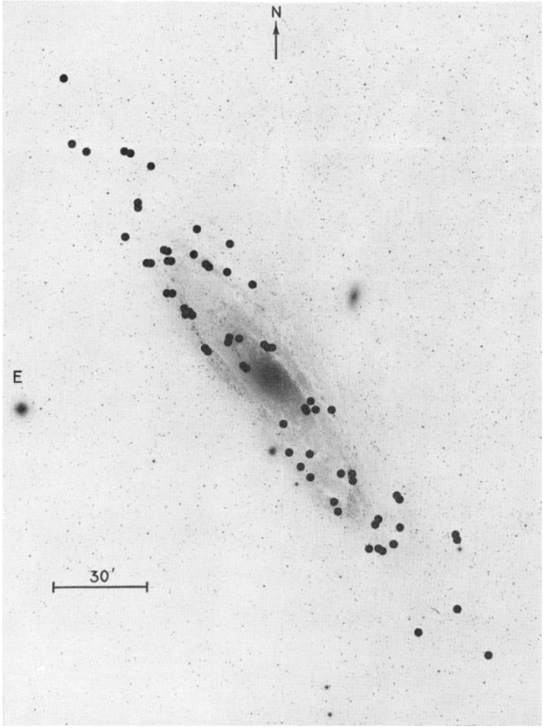
Structure and dynamics in the Universe

Galaxies:

Distant galaxies allow to map their mass distribution by measuring the rotation velocity of stars as a function of their distance to the galaxies' centers.

Andromeda (M31): things get weird.

Vera Rubin, 1972



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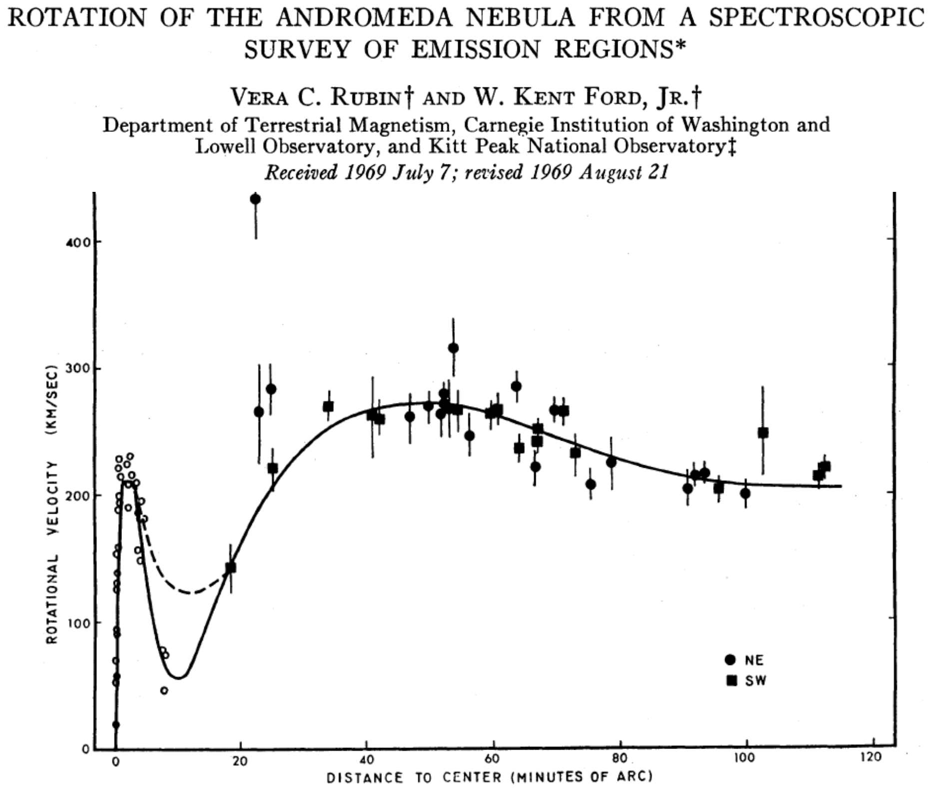

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†

Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

Received 1969 July 7; revised 1969 August 21

Galaxies:

What is your expectation for the rotation curve of a galaxy?

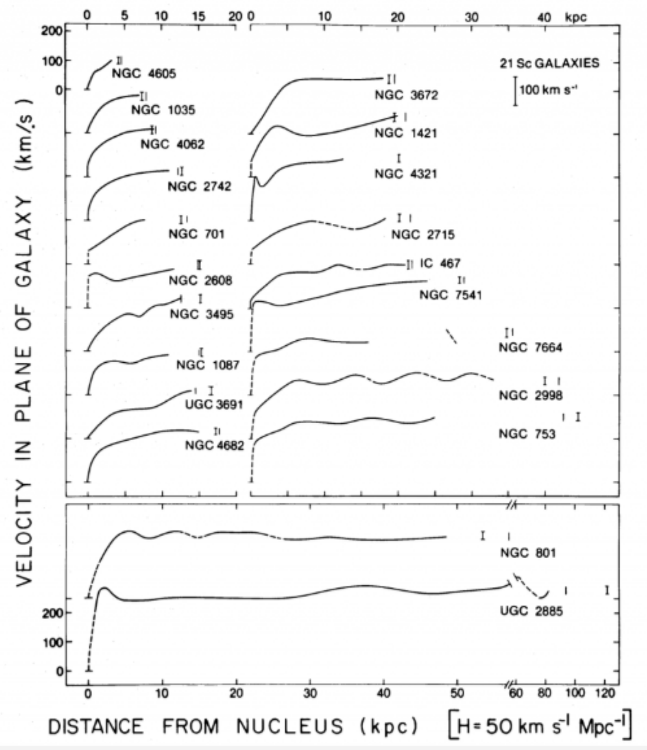
We assume that in the radial direction, our system is at equilibrium: $F_R = 0$

The total force in the radial direction is the sum of the gravitational force and the centripetal force: $-\frac{GMm}{R^2} + m\frac{v^2}{R} = 0$ ⇒ $v(R) \sim \frac{1}{\sqrt{R}}$

In the outskirts of the galaxy, we can assume that the gravitational force is Newtonian

Keplerian decrease

Structure and dynamics in the Universe: discussion



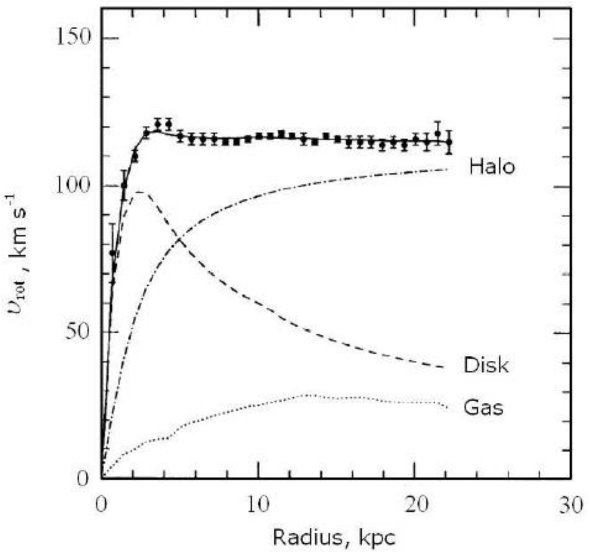
Flat rotation curves → More **mass** than expected!

Larger distance probed by these measurements → **R = 120 kpc**

It's ¼ of the distance between the Milky Way and Andromeda!

Mass density distribution of Dark Matter: a simple model

Model of mass density distribution: $\rho(r) = \rho_0 \frac{r_0^2}{r^2+r_0^2}$



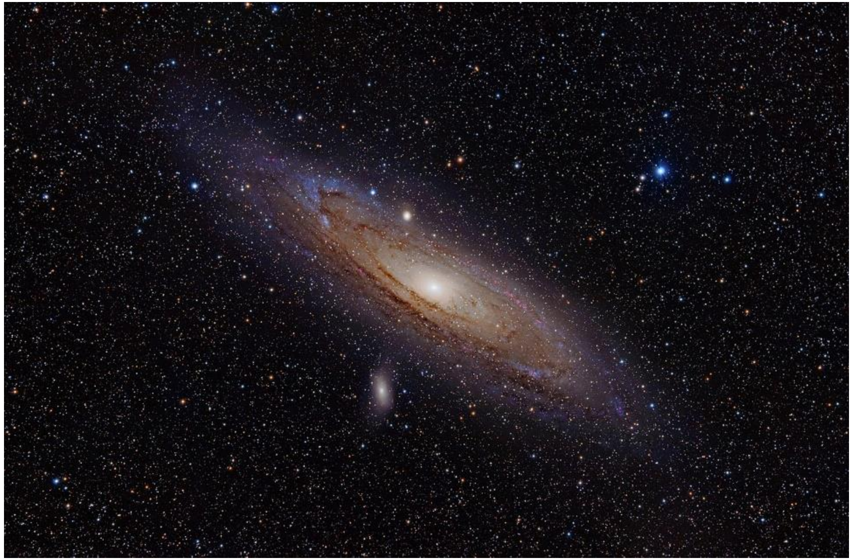
Data and theoretical predictions for galaxy NGC 6503

$$M_{DM}(R) = \int_0^R 4\pi r^2 \rho(r) dr$$
$$= 4\pi\rho_0\, r_0^2 \int_0^R \frac{r^2}{r^2+r_0^2} dr \sim 4\pi\rho_0\, r_0^2 \int_0^R \frac{r^2}{r^2} dr$$
$$= 4\pi\rho_0\, r_0^2 R$$

$$\boldsymbol{M_{DM}(R) = cost \times R}$$

$$\boldsymbol{v_{DM}^2 \sim R \frac{GM_{DM}}{R^2} = \text{cost!}}$$

Structure and dynamics in the Universe: discussion



Picture of Andromeda (Hubble Space Telescope)

Stellar mass: $\sim 10^{11}$ M⊙

Total mass: $\sim 10^{12}$ M⊙

Atomic hydrogen mass: $\sim 10^{8}$ M⊙

Molecular hydrogen mass: $\sim 10^{7}$ M⊙

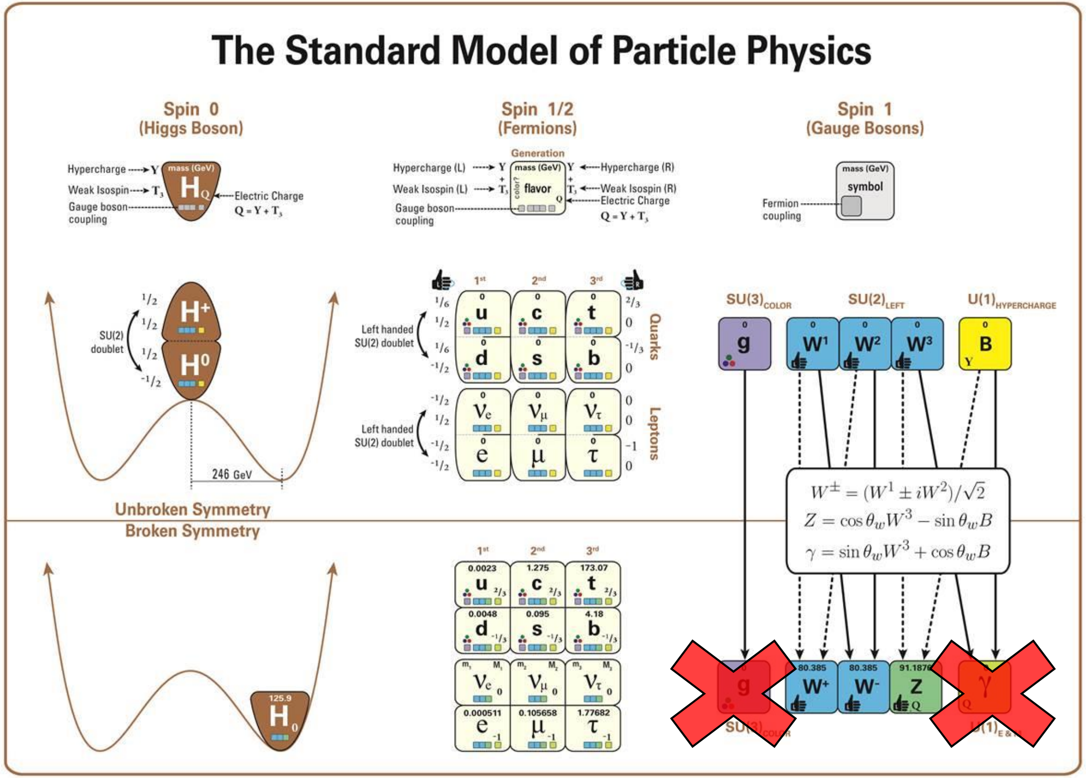
There's **a lot** of mass missing!

Vera Rubin: the astronomer who made the discovery

A picture of Vera Rubin at Carnegie Institution (Washington)

Discussion time: can we quantify “dark“?

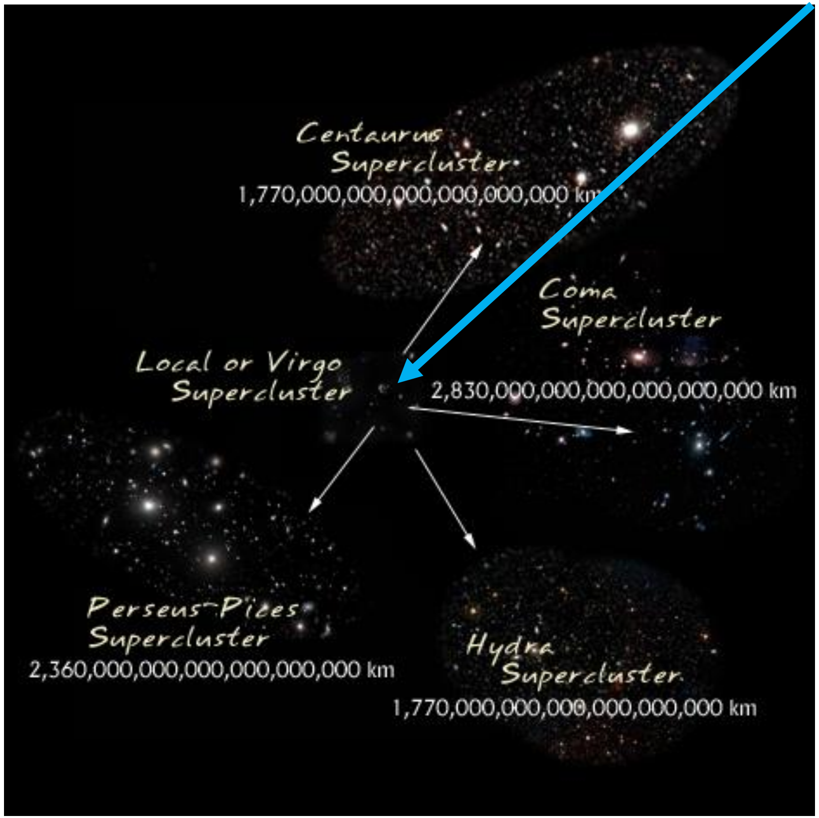
- No interaction with light.
- No strong interaction with “ordinary matter”.
- At maximum weak-scale interaction with “ordinary matter” and with dark matter (self interaction).
- And - of course – gravitation with all kinds of matter.



Structure and dynamics in the Universe: clusters

Cluster of galaxies:

Galaxies come in groups with typical distances of 100,000,000 lightyears.



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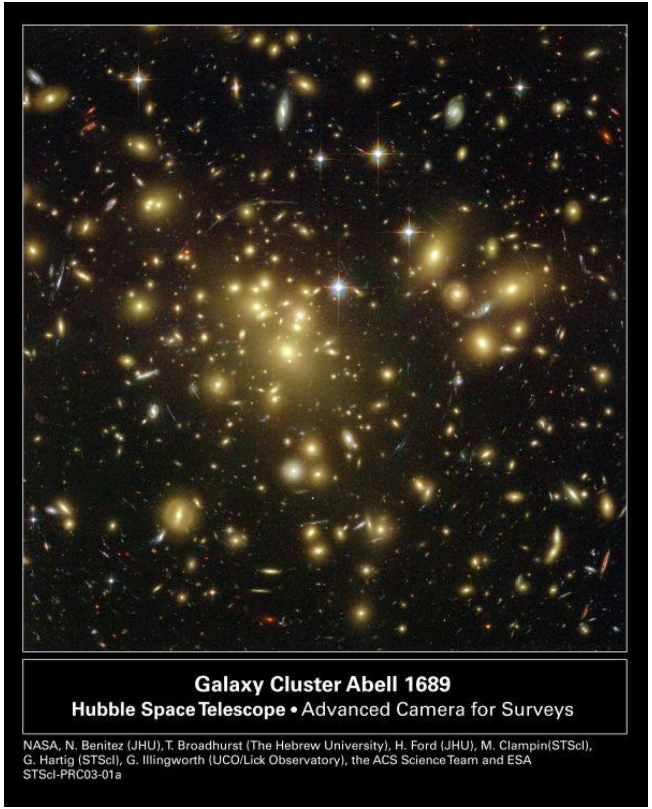

Structure and dynamics in the Universe: clusters

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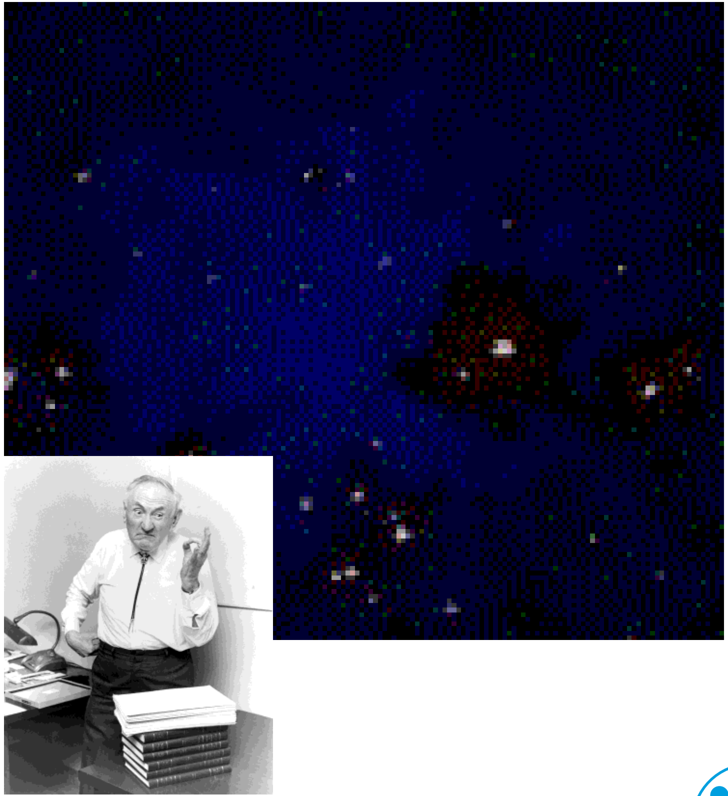
Galaxies come in groups with typical distances of 100,000,000 lightyears.

Galaxies within clusters move much too fast to be bound by the gravitation of the visible mass. Clusters do not diffuse in spite of the high speed of the galaxies.

Some dark matter has to provide the necessary gravitational potential.

This dark component was first proposed 1933 by F. Zwicky after analysis of the Coma cluster.

Dark matter $\approx$ 30 · visible matter!



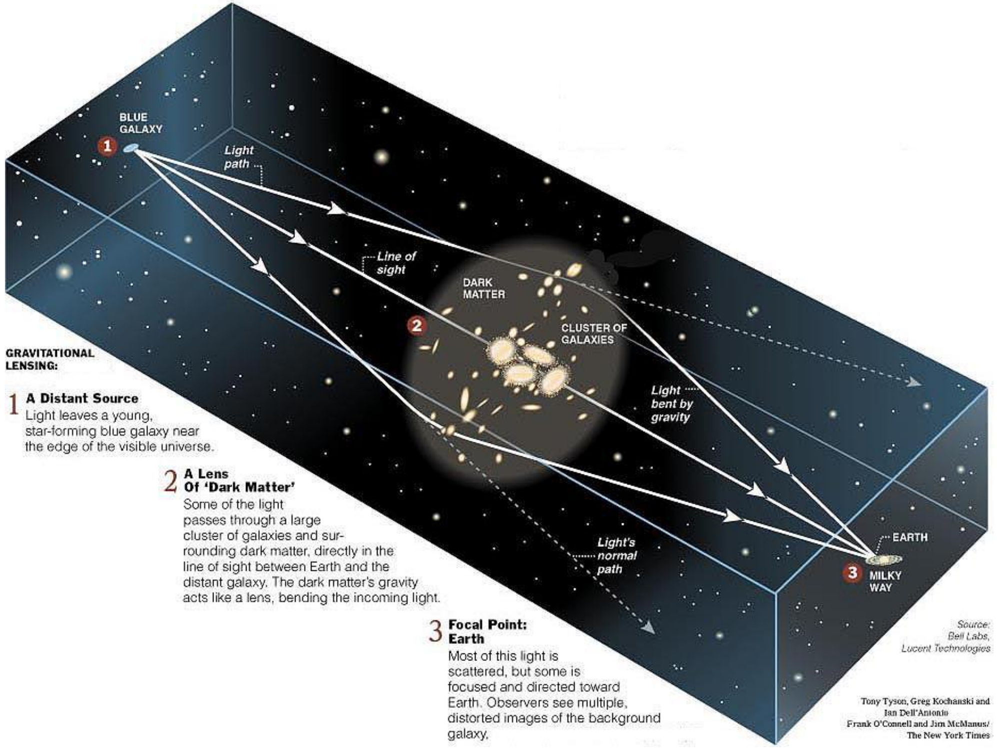
http://ircamera.as.arizona.edu/NatSci102/lectures/galaxydist.htm

More dark matter evidence: gravitational lensing

Gravitational lensing:

Light is bent by mass and hence can trace also “invisible” mass.

If one knows how the undistorted image looks like, one can determine the properties (mass) of the gravitational lens.



http://www.lsst.org/files/img/xxnyt.jpg

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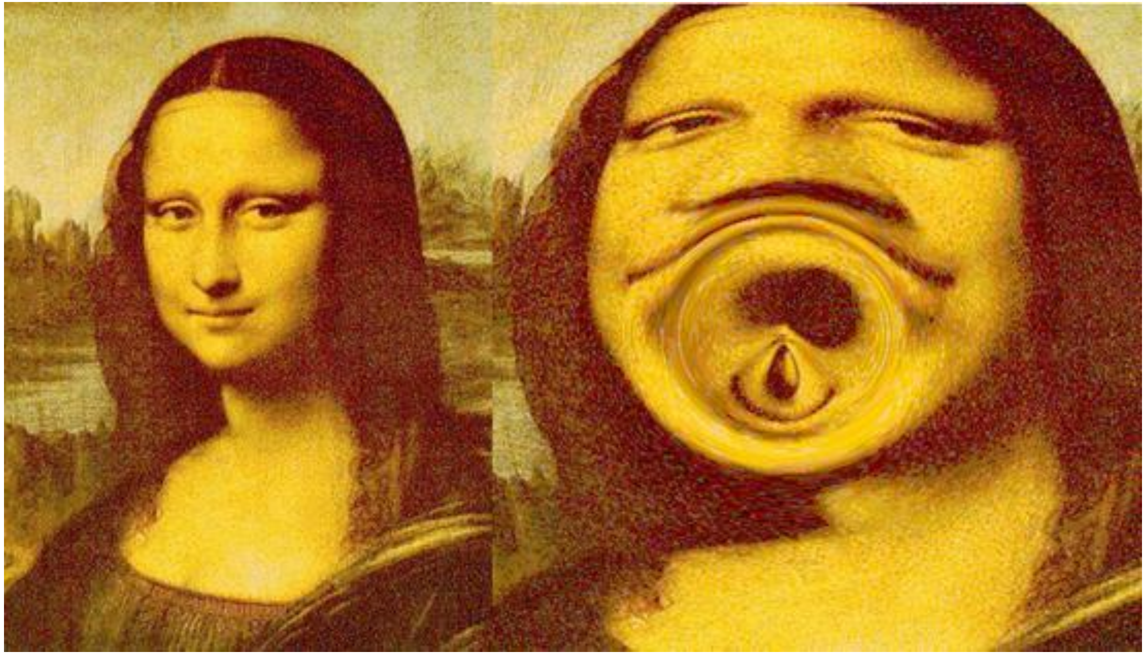
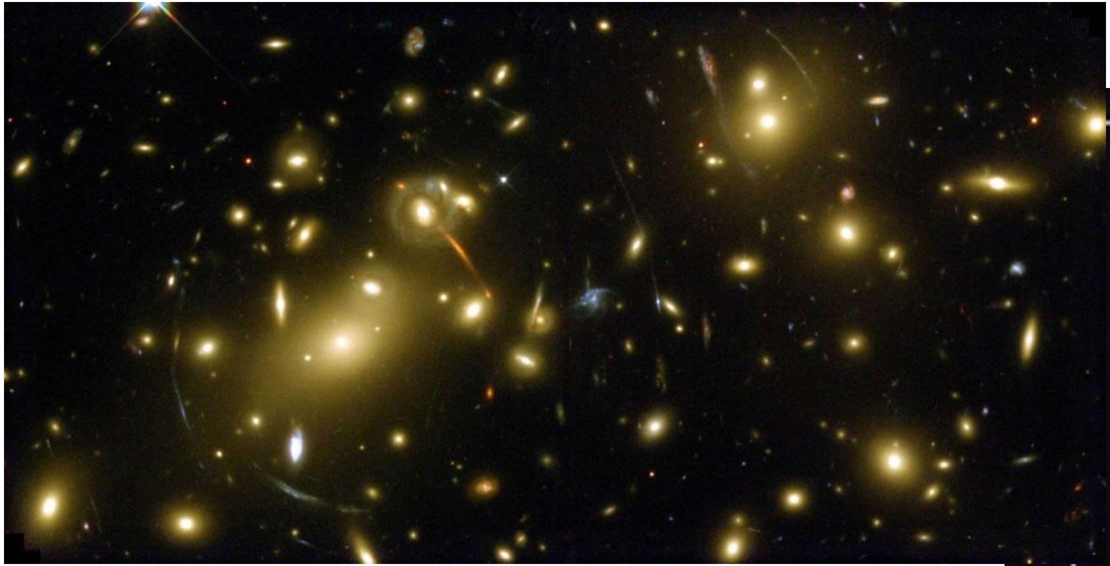
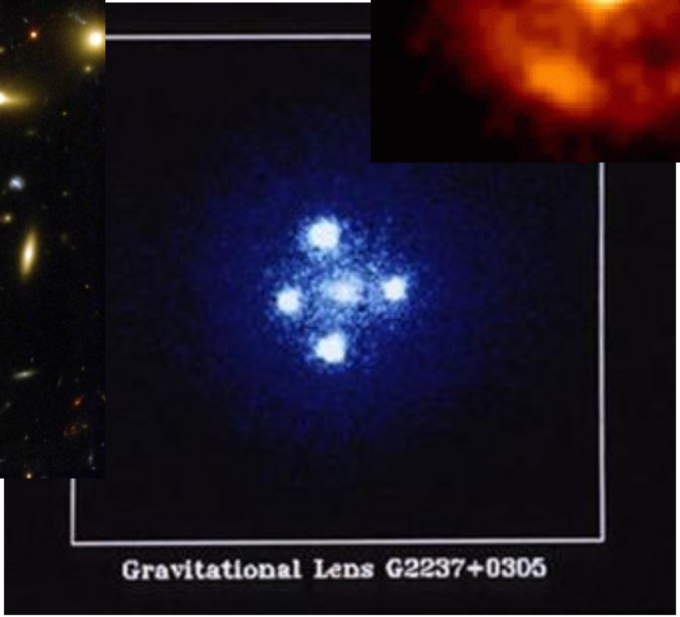


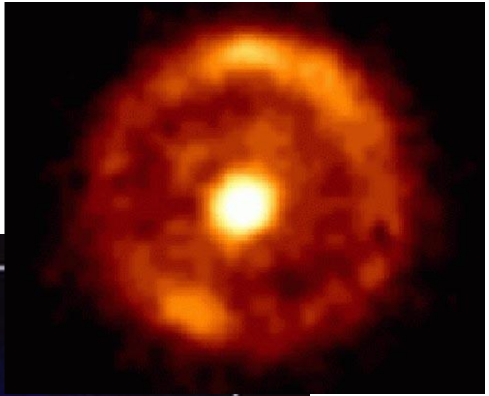
http://astronomyonline.org/Cosmology/GravitationalLensing.asp

More dark matter evidence: gravitational lensing

Gravitational lensing is real:

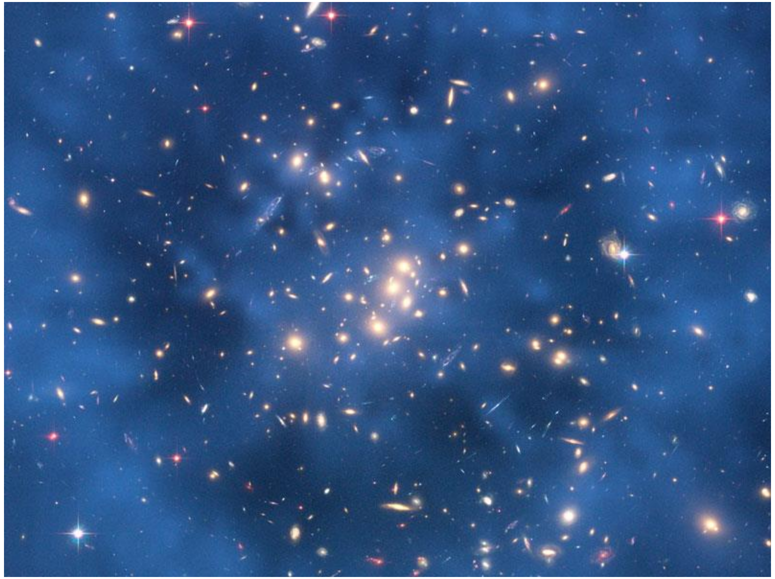


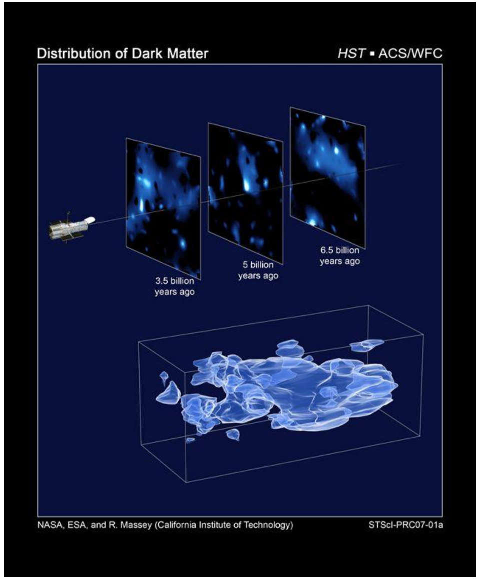




More dark matter evidence: gravitational lensing

Gravitational lensing is real:





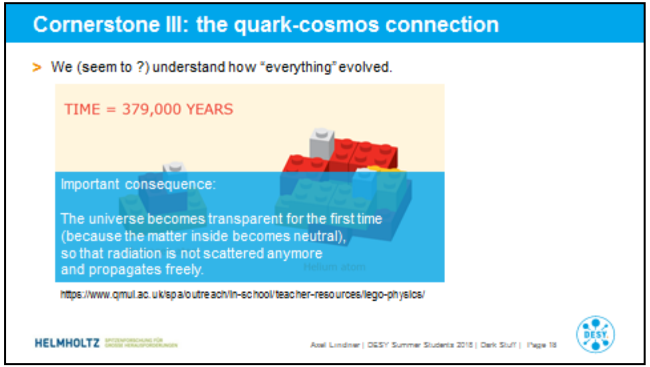
Dark matter ≈ 30 · visible matter!

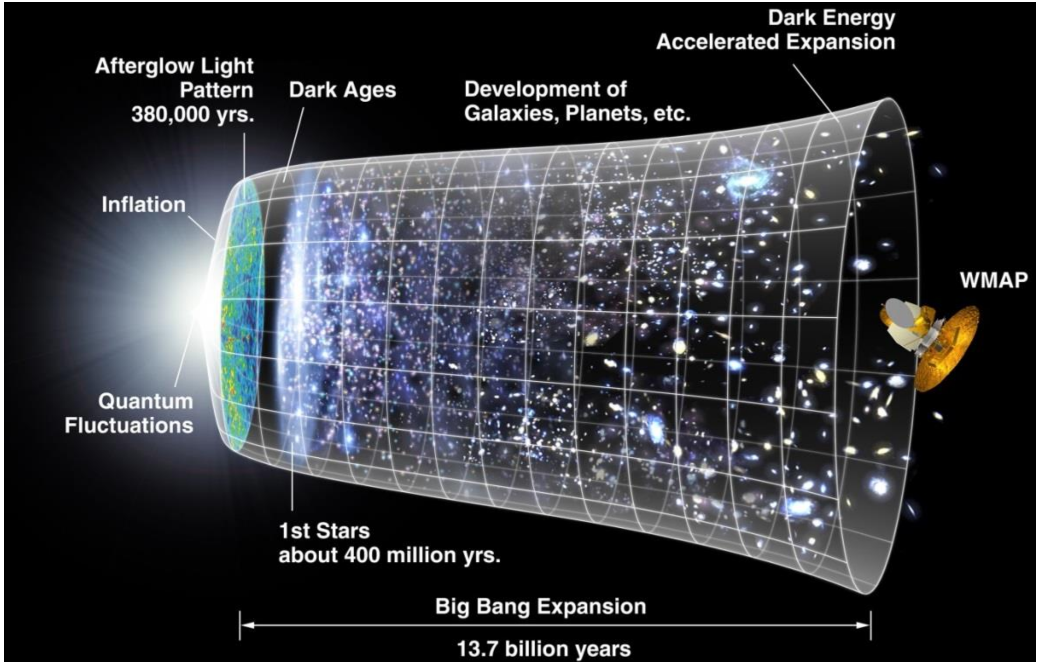
Structure and dynamics in the Universe: the farthest light

Edge of the visible universe:

Cosmic microwave background:

Observe light originating from the recombination of electrons and nuclei in the early universe well before any other structures have emerged.

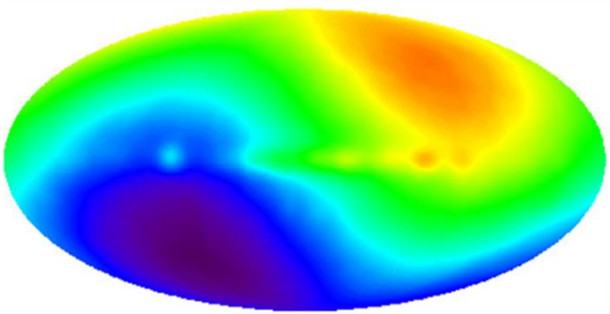




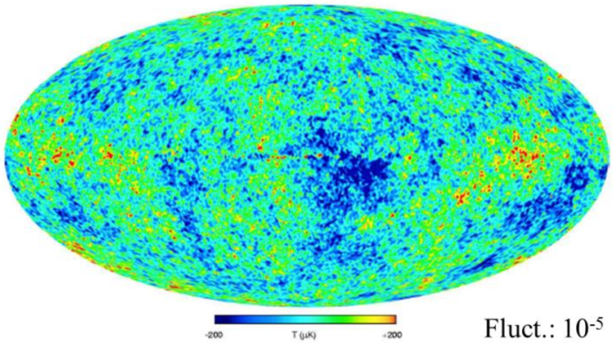
Structure and dynamics in the Universe: the farthest light

An all-sky view of the cosmic microwave background radiation:

Perfect black body radiation
T = 2.735 K



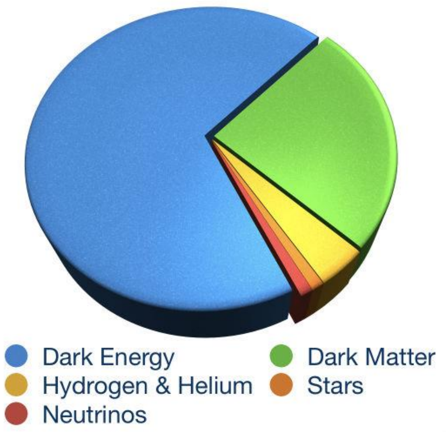
Fluctuations: 10^{-3}
Dipole radiation
(v = 600 km/s)

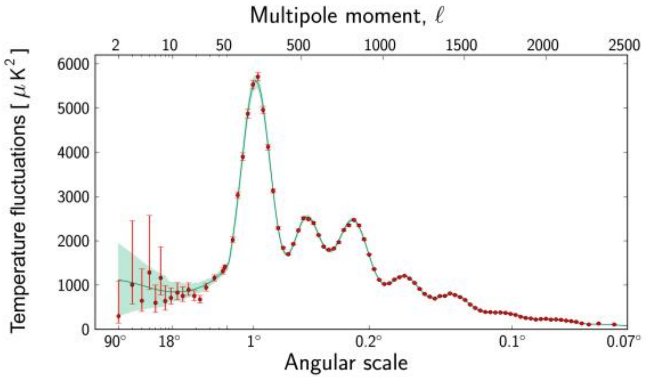


Fluct.: 10^{-5}

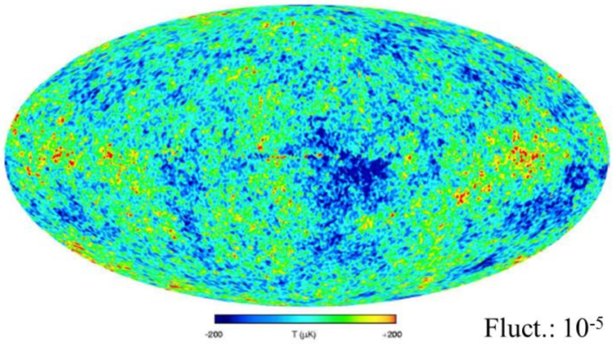
Structure and dynamics in the Universe: the farthest light

An all-sky view of the cosmic microwave background radiation:





http://sci.esa.int/planck/



Matter: 5%
Dark matter: 27%
Dark energy: 68%

Dark energy drives the universe apart

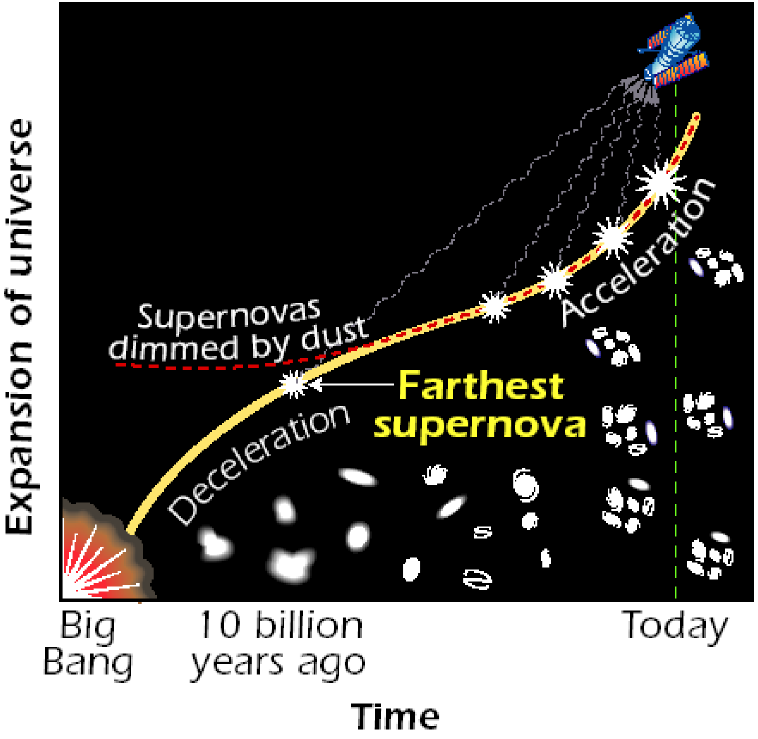
Measurements of Supernovae Ia by the Hubble Space Telescope and others:

> There is a repulsive force ("anti-gravitation") best explained by "dark energy" (Einstein's Λ).

> Dark energy is an attribute of space.
> Dark energy per volume is constant.
> The larger the universe, the larger the fraction of dark energy!

> The universe expands with increasing speed!

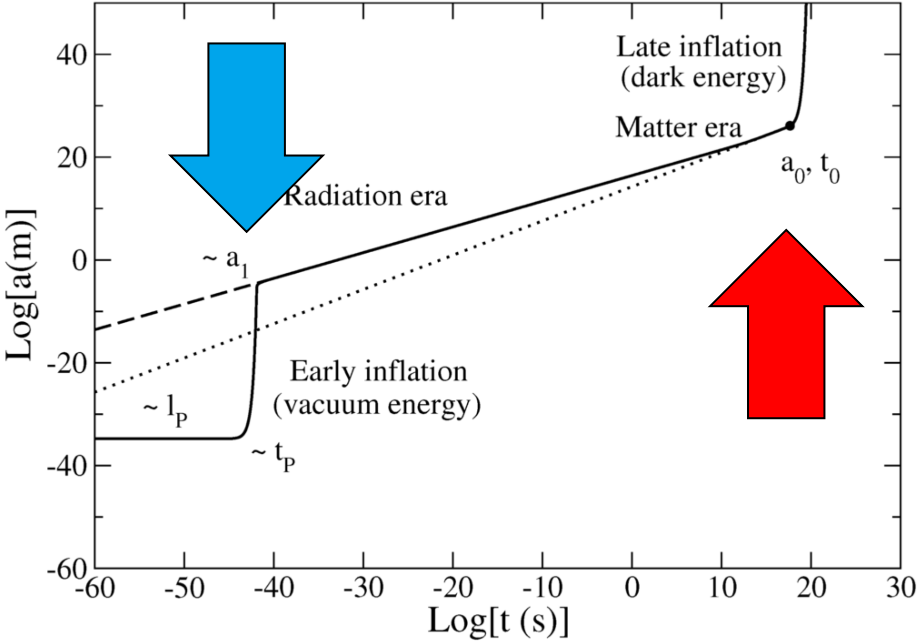
> This scenario is strongly confirmed by analyses of the cosmic microwave background radiation and many other data!



Speedy expansions of the universe

- Many problems to understand the early universe can be solved by predicting an inflation epoch about 10^{-40} s after the big bang.

- Dark energy seems to indicate a new inflation epoch right now!



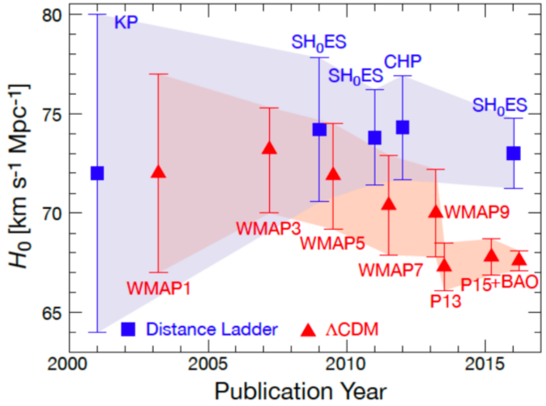
Universe 2015, 1(3), 357-411; doi:10.3390/universe1030357

Cosmology has turned into precision science

- Geometry of the Universe: flat
- Age of the Universe: 13.787 ± 0.020 Gyr
- Hubble Constant: 67.66 ± 0.42 km s^{-1} Mpc^{-1}
- Ω_M (matter): 0.3111 ± 0.0056
- Ω_Λ (dark energy): 0.6889 ± 0.0056

https://arxiv.org/pdf/1807.06209.pdf

A very consistent picture between many different measurements?



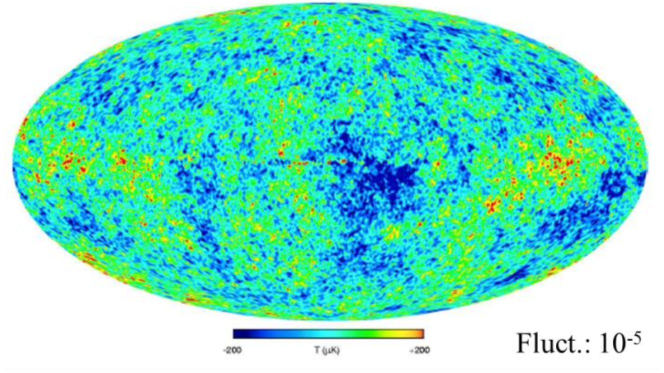
https://astrobites.org/2017/10/13/the-hubble-constants/

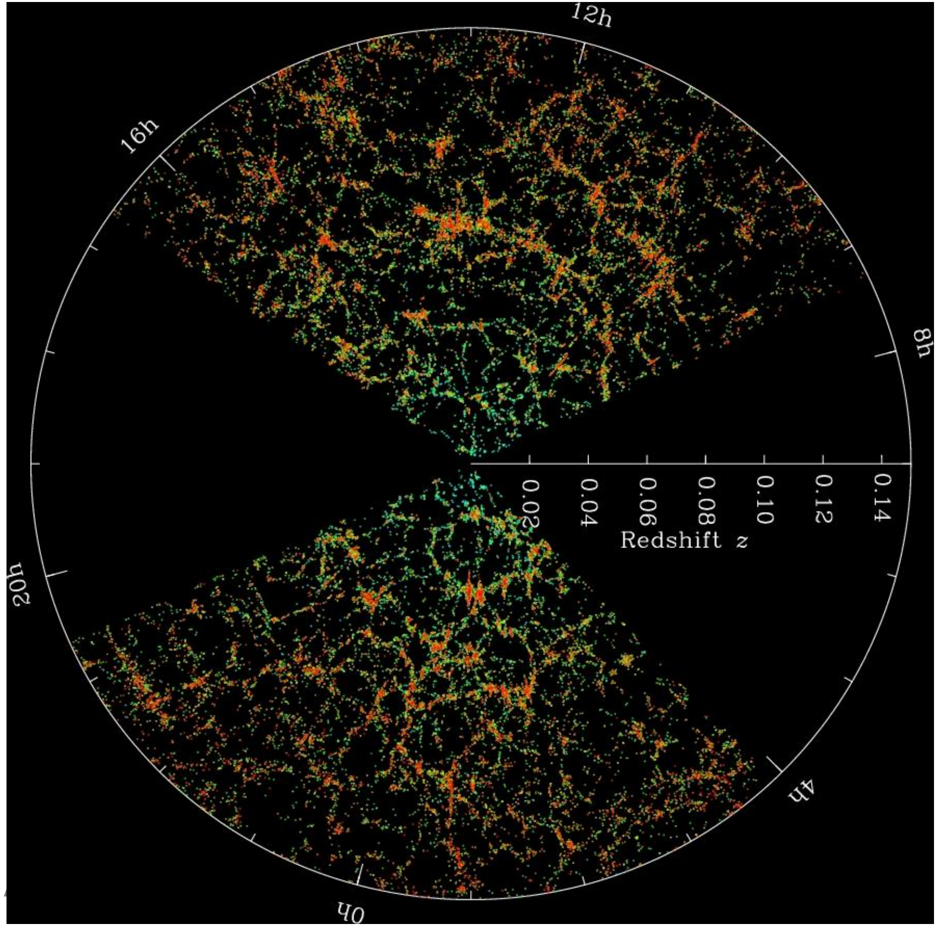
Do we start to see inconsistencies between the local and global measurements of the Hubble constant?

Structure and dynamics in the Universe: the largest scales

Galaxies form clusters arranged in a cosmic web.

How could such structures form out of a
very smooth early universe?

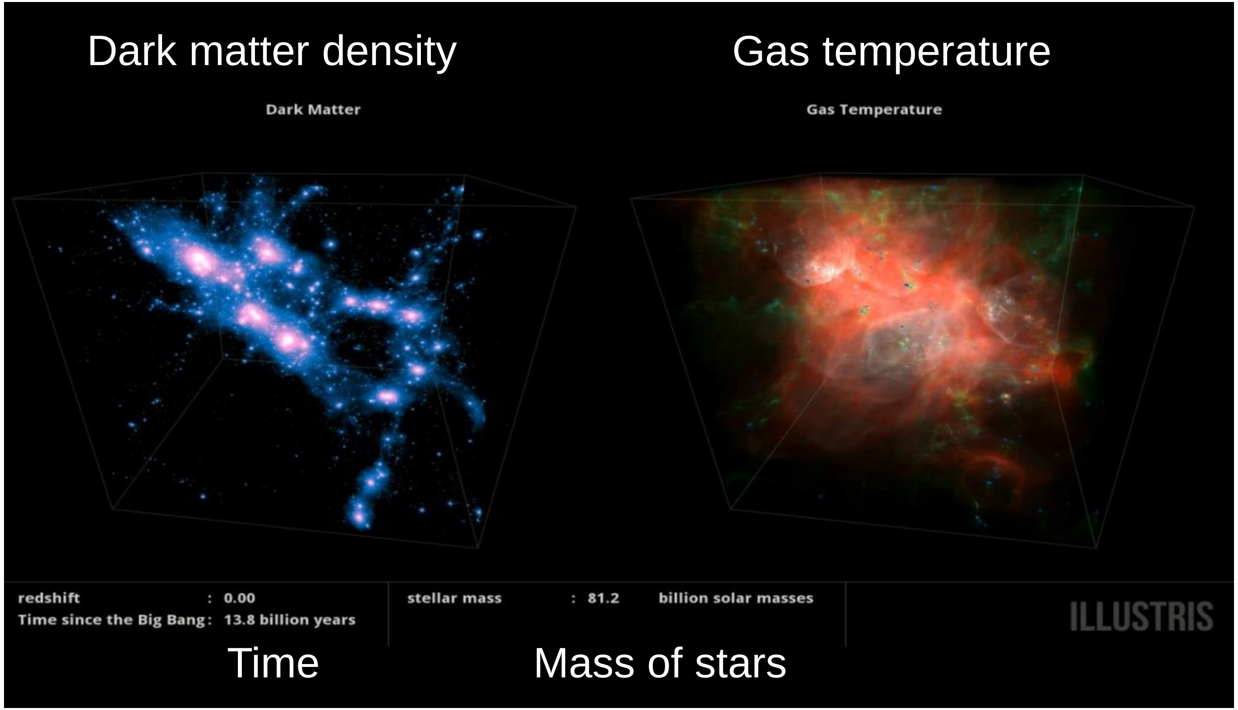




http://classic.sdss.org/includes/sideimages/sdss_pie2.html

Structure and dynamics in the Universe: the largest scales

http://www.illustris-project.org/movies/illustris_movie_cube_sub_frame.mp4

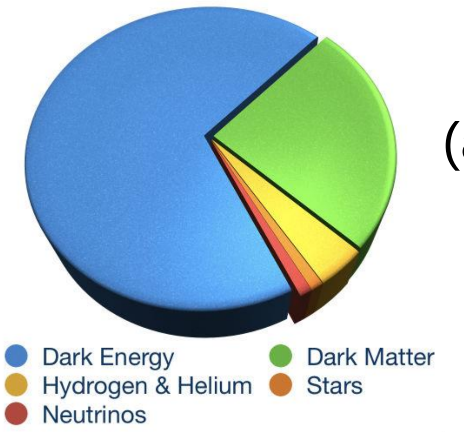


Cubes:
(10 Mpc)^3

Structure and dynamics in the Universe: the largest scales

Galaxies form clusters arranged in a cosmic web.

> This can be simulated quite well assuming



(and its time evolution).

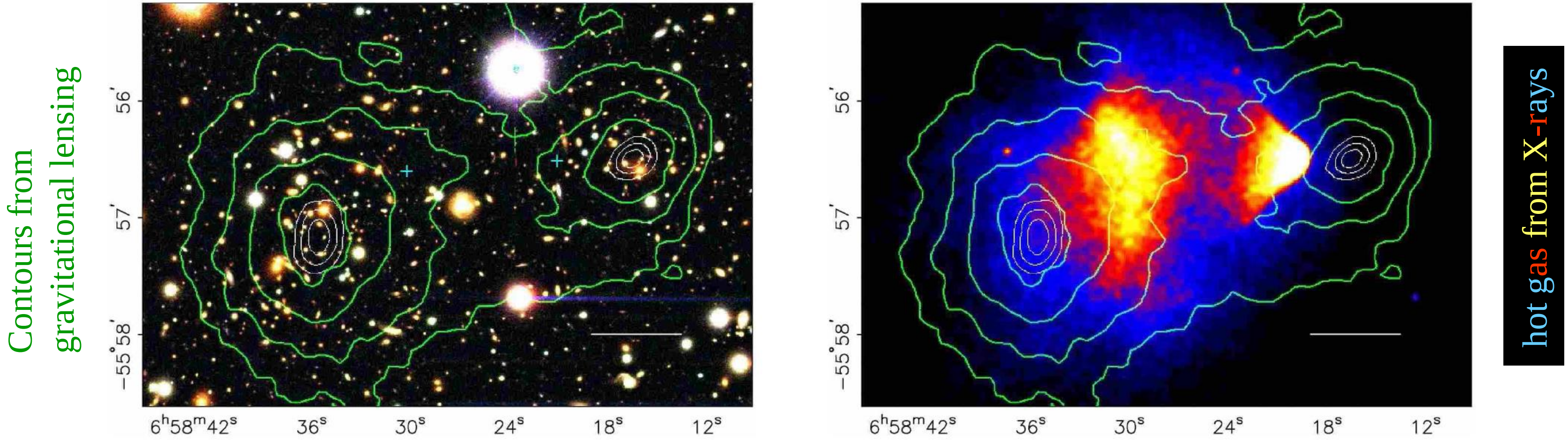
> This can be simulated quite well assuming in addition that dark matter is “cold”:

It has to move at non-relativistic speeds to not “wash out” structures of the universe.

Dark matter interactions (next to gravity)?

Bullet cluster 1E 0657-56: merging of two galaxy clusters

(Clowe et al., astro-ph/0608407v1)



Gases in the clusters have interacted (heated up) during the collision and have been left behind the dark matter: dark matter might interact weakly at most (also from other analyses).

In-between-summary: what we know about dark matter

- It feels gravity.
- Its lifetime is larger than the age of the universe.

- It does not interact via electromagnetism or strong interaction.
- It could have some weak or weak-like interaction.

- In the universe it moves at non-relativistic speeds.

Alternatives to the dark matter paradigm?

A recipe for discoveries

Apply known laws of nature in regions
where they have not been tested before.

> New regions of time and space	Quantum mechanics
> New regions of time and space	Cosmology
> More energetic particle collisions	LHC
> More precise experiments	ALPS II @ DESY

You might find deviations from expectations hinting at

> New stuff	Neptune discovery
> More fundamental laws of nature	General relativity

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

Axel Lindner | DESY Summer Students 2018 | Dark Stuff | Page 7

Alternatives to the dark matter paradigm?

- MoND:
  Modified-Newtonian-Dynamics (Mordehai Milgrom, 1983)
- TeVeS:
  Tensor–Vector–Scalar gravity, a relativistic generalization of MoND
  (Jacob Bekenstein, 2004)

Modified Newtonian dynamics

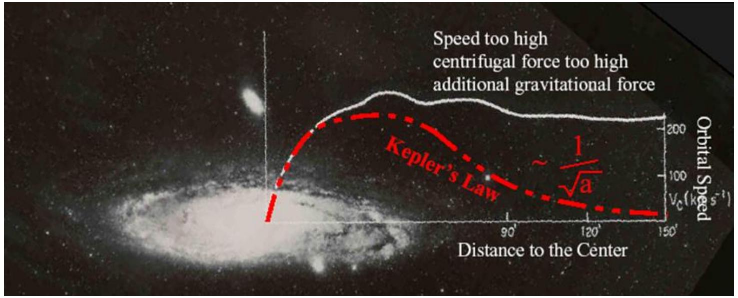
Explain the observed galaxy rotation by modifying Newton‘s 2nd law:

$$F = \mu\, m a \qquad \mu = \begin{cases} 1 & if\ a \gg a_0 \\ \frac{a}{a_0} & if\ a \ll a_0 \end{cases}$$

$$\text{for } a \ll a_0 \qquad F = \mu\, m a = m \frac{a^2}{a_0}$$

$$\frac{GmM}{r^2} = m \frac{a^2}{a_0} \qquad and\ with\ a = \frac{v^2}{r} \quad \Rightarrow \quad v = \sqrt[4]{GM\, a_0} = \text{constant}$$

Value of a_0 obtained from fitting known galaxies’ data ⇒ $a_0 \sim 10^{-8}\ {cm}/{s^2}$



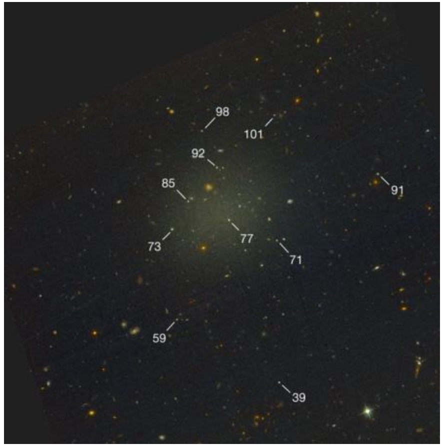
MoND versus dark matter: a decision?

LETTER

doi:10.1038/nature25767

A galaxy lacking dark matter

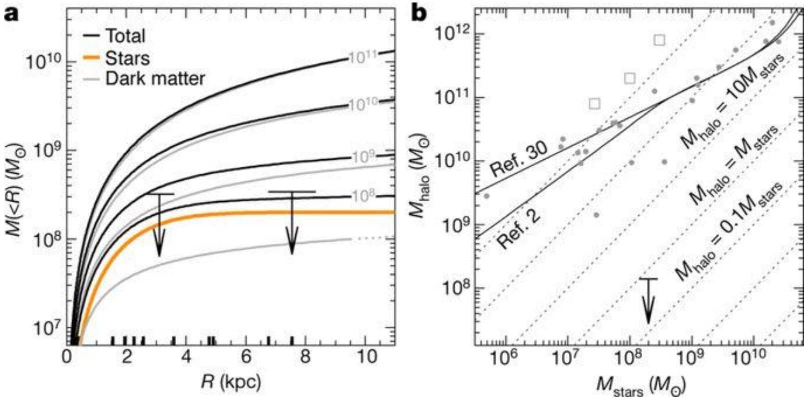
Pieter van Dokkum[1], Shany Danieli[1], Yotam Cohen[1], Allison Merritt[1,2], Aaron J. Romanowsky[3,4], Roberto Abraham[5], Jean Brodie[4], Charlie Conroy[6], Deborah Lokhorst[5], Lamiya Mowla[1], Ewan O'Sullivan[6] & Jielai Zhang[5]



Measure velocity distribution at NGC1052-DF2:

No dark matter is required!

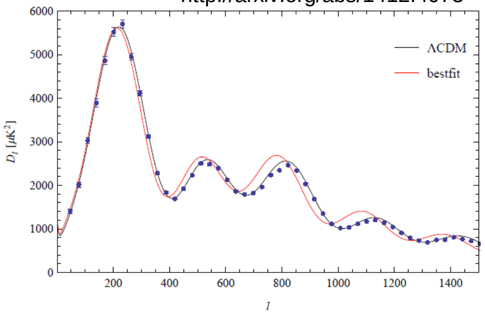
Thus Newton's 2nd law holds true even for galaxies!



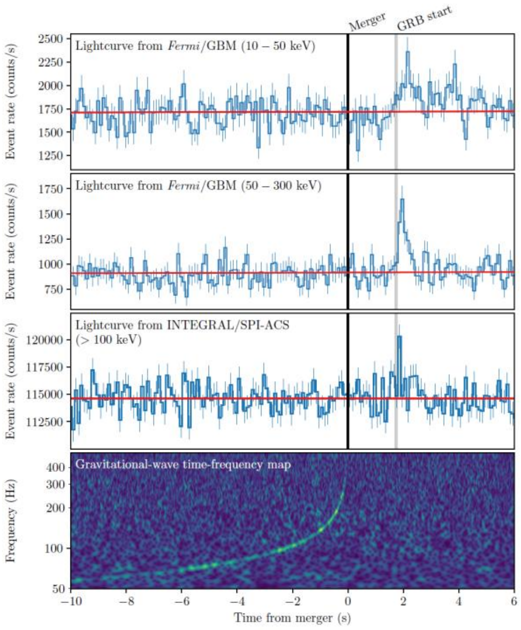
MoND versus dark matter

- One galaxy without dark matter disfavors MoND.
- MoND has difficulties to explain the CMBR spectrum.

http://arxiv.org/abs/1412.4073



- Neutron star merger GW170817 and GRB 1708: Gravitational waves move at the speed of light! Hard / impossible to explain by MoND!



https://www.ligo.org/science/Publication-GW170817GRB/index.php

Let's stick to dark matter searches!

In-between-summary

- Beyond the scale of the solar system evidences for the existence of dark matter are overwhelming.
- There is strong evidence also for a dark energy component.
- Our models to describe the present universe
  as well as its development since the big bang work nicely

  provide that

  95% of the present matter-energy budget of the universe is made out of
  yet unknown components.
- There is no real promising alternative to this interpretation.

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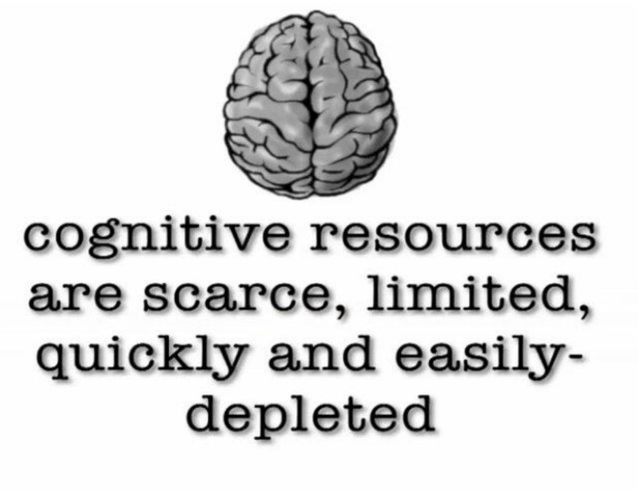
  95% of the present matter-energy budget of the universe is made out of yet unknown components.
- There is no real promising alternative to this interpretation.

However:

It is all about gravity, the only fundamental interaction not included in the Standard Model of particle physics!



.. let‘s have a short break!

Our dark matter menu

- Starters
  - Historical annotations: how to discover new stuff?
  - Our anchor: the Standard Model of particle physics
- Main course 1
  - The necessity of Dark Matter
  - Alternatives and hidden assumptions
- Main course 2
  - Dark matter candidates
  - Searching for Dark Matter candidate particles
  - Direct searches for Dark Matter particles
- Dessert
  - Astrophysical puzzles
- Doggy bag
  - Summary and outlook

Discussion time: dark matter and dark energy here

Why did physics overlook dark matter and dark energy so long?

Densities in this room:

- Matter (earth‘s crust): 3 g/cm^3
- Dark matter (DM): 0.0000000000000000000000005 g/cm^3 = 0.3 GeV/cm^3
- Dark energy (DE): 0.00000000000000000000000000001 g/cm^3

Why dominates matter here and DM und DE in the Universe?

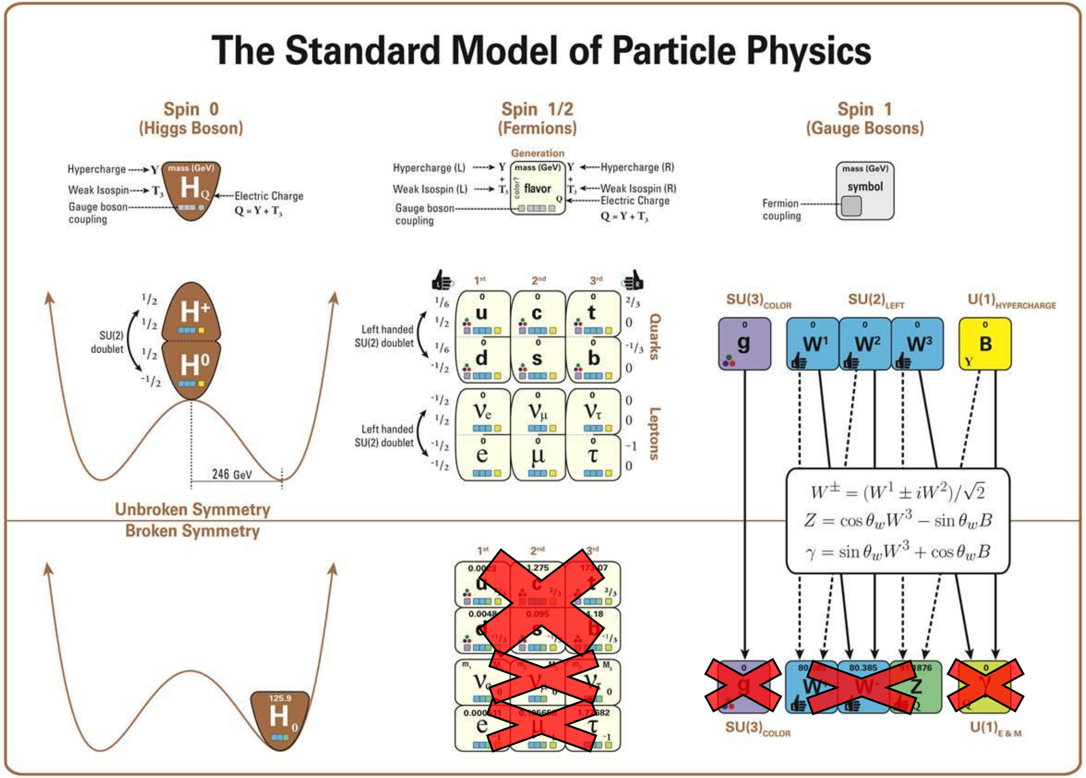
- Matter is “clumpy“, interacts strongly: planets are formed.
- Dark matter interacts only gravitationally: halos around galaxies.
- Dark energy is distributed uniformly all over the universe.

What is dark matter?

Dark matter

- shows no strong or electromagnetic interaction (some weak interaction could have escaped detection by now).
- has not decayed during the evolution of the universe.
- in the universe should be “cold”, moving with non-relativistic speed .

Neutrinos could make up 7% of the dark matter.



Dark matter properties

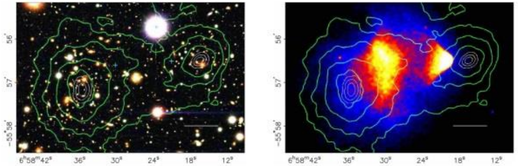
> The dark matter density around us is of about $0.3\ \mathrm{GeV/cm^3} = 5\cdot10^{-25}\ \mathrm{g/cm^3}$.

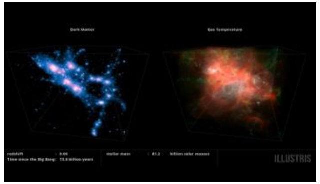
> It has negligible interactions with our "visible" world and negligible self-interaction. The couplings is "weakly" at maximum.

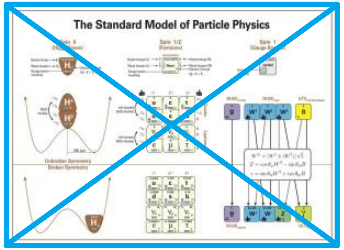
> It is "cold", moving at non-relativistic speeds only.

> The dark matter constituents must have a lifetime much longer than the age of the universe.

None of the known particles within the Standard Model fulfills all these requirements!







Theory: dark matter candidates

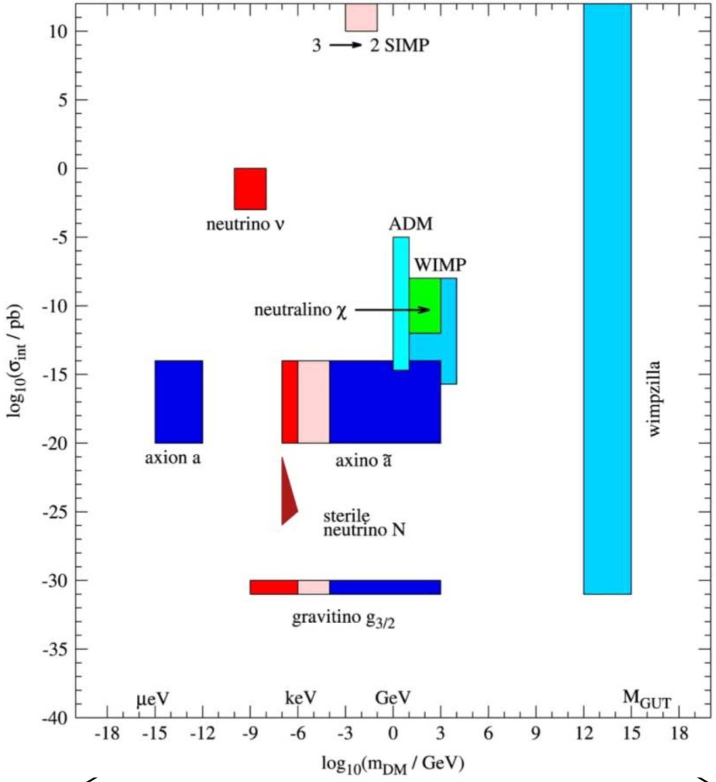
There is a plentitude of theories predicting dark matter candidates

covering more than
30 orders of magnitude in mass range

and

predicting interaction strengths with normal matter orders of magnitude below neutrino cross sections.

50 orders of magnitude



36 orders of magnitude

Dark matter detection (Laura Baudis), http://iopscience.iop.org/article/10.1088/0954-3899/43/4/044001

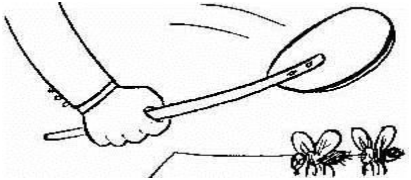
Dark matter candidates: where to focus experimentally?

Selection criteria:

> Are experimental options in reach to either
  - identify dark matter candidates in laboratory experiments,
  - find directly of indirectly the particles composing the dark matter halo we are living in?

> Does the theory explain “just” dark matter or is it embedded
in a more general extension of the standard model of particle physics?

“I’m searching for my keys.”



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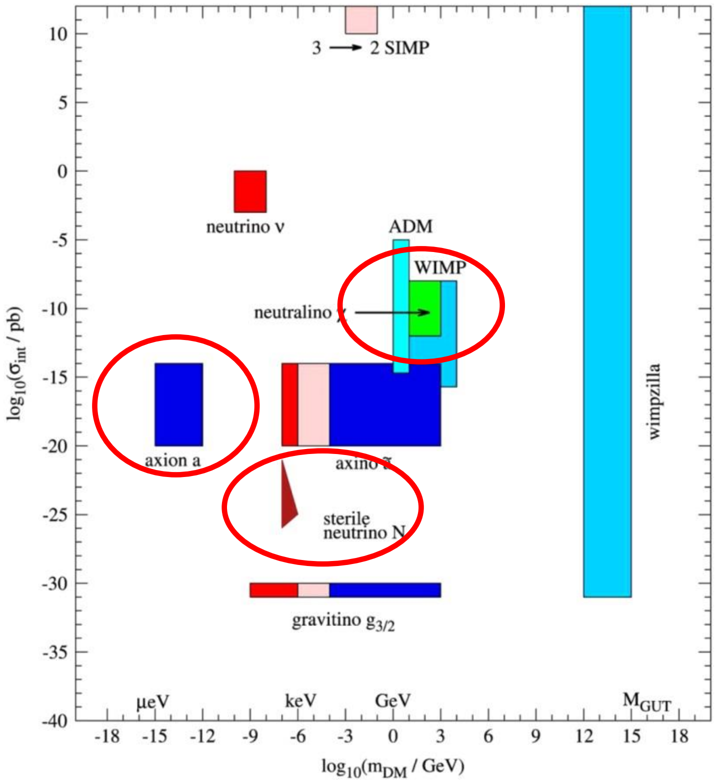


Dark matter detection (Laura Baudis), http://iopscience.iop.org/article/10.1088/0954-3899/43/4/044001

Our prime DM Candidates

1. Weakly Interacting Massive Particles: WIMPs
   Most promising candidate: lightest supersymmetric particle
   (neutralino, a linear combination of photino, zino and higgsinos,
   to be found at LHC),
   very heavy (around 10^{11}eV).

2. Sterile neutrinos
   Right-handed neutrinos, could show up indirectly in neutrino oscillations,
   could constitute DM,
   if Dark Matter: medium weight (around 10^{3}eV)

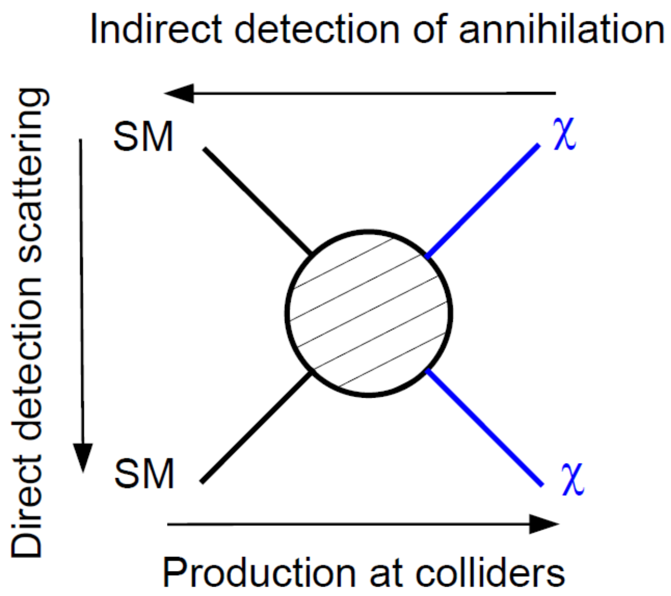
3. Axion or Axion Like Particles: ALPs
   Invented to explain CP conservation in QCD
   ("why is the electric dipole moment of the neutron zero or extremely small?").
   Non-thermal production in the early universe,
   if Dark Matter: very light (around 10^{-5}eV).

Dark matter (DM) search strategies

- **Direct:**
  an experiment detects particles of the DM halo all around us.

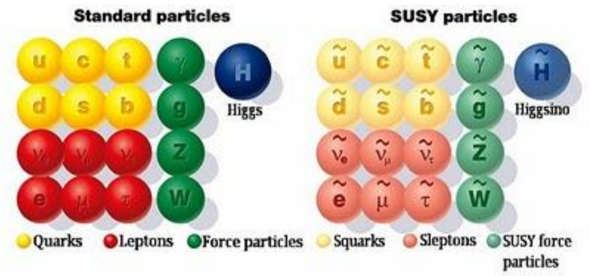
- **Indirect:**
  an experiment finds astrophysical signatures (next to gravitation) of the DM halo particles.

- **Candidates:**
  an experiment identifies new particles which are candidates for the constituents of the DM halo.
  Don't mix this up with finding DM!



Dark matter candidates: WIMPs

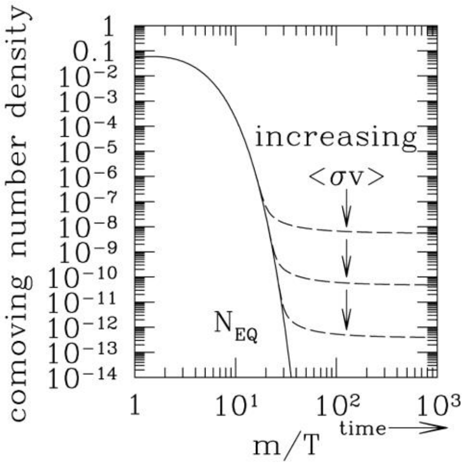
- Weakly Interacting Massive Particles (WIMPs)
  - Theory: a SUperSYmmetry between fermions and bosons might exist. The lightest SUSY particle could make up the dark matter.
  - Dark matter: the lightest stable SUSY particle with an self interaction strengths of the order of the weak interaction would “naturally” be produced as dark matter in the early universe.
  - Additional benefit: if SUSY masses are at the TeV scale one could understand details of the standard model (e.g. Higgs mass) and SUSY could show up at the LHC.



- Prediction:
  Dark matter is composed out of elementary particles with masses O(10 to 100 GeV).
  Its number density is about 0.01 1/cm^3.
  It should interact weakly with SM matter.

WIMP dark matter in the universe

1. When the universe is very hot (hotter than the mass of the WIMP) all particles are in thermal equilibrium:
   the rates of production and annihilation are the same.
2. The universe expands: the particle energy drops,
   WIMP production rates drop, but WIMPs can still annihilate.
3. The universe expands further: the WIMP density drops further,
   WIMPs do not any more meet each other and annihilation stops:
   WIMPs “freeze out”.

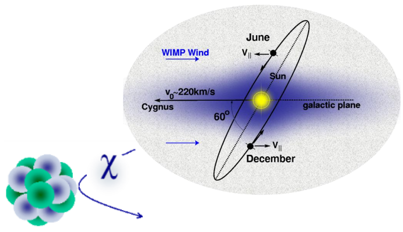


4. Assuming WIMP masses around the electroweak scale (LHC!) and weakly interacting WIMPs gives “automatically” the correct amount of dark matter!

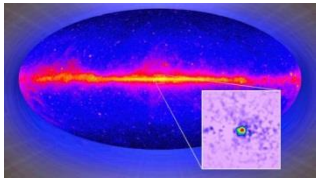
THE WIMP MIRACLE

Dark matter (DM) search strategies: WIMPs

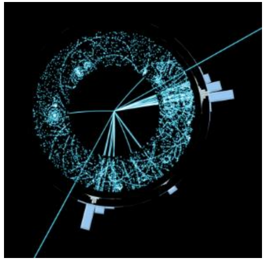
- Direct:
  an experiment detects particles of the DM halo all around us.



- Indirect:
  an experiment finds astrophysical signatures (next to gravitation) of the DM halo particles.



- Candidates:
  an experiment identifies new particles which are candidates for the constituents of the DM halo.



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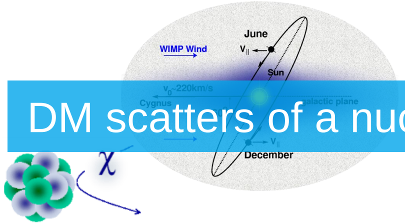
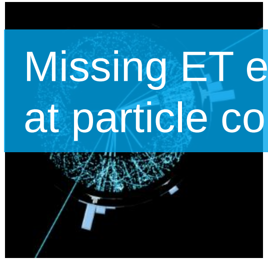


DM scatters of a nucleus

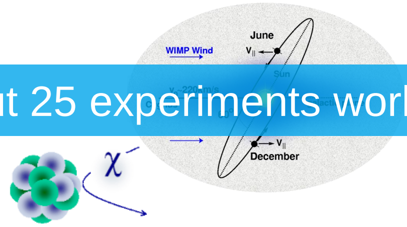
Gamma-rays from DM-DM annihilation



Missing ET events at particle colliders

Dark matter (DM) search strategies: WIMPs

> Direct:
an experiment detects particles of the DM halo all around us.



About 25 experiments world-wide

> Indirect:
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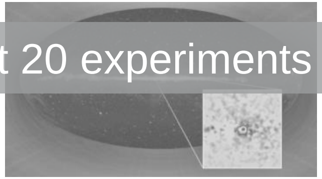


About 20 experiments world-wide

> Candidates:
an experiment identifies new particles which are candidates for the constituents of the DM halo.

LHC, BELLE, …

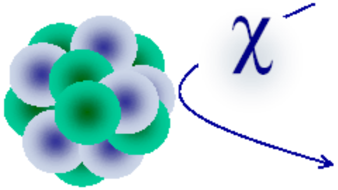
Direct detection of dark matter WIMPs

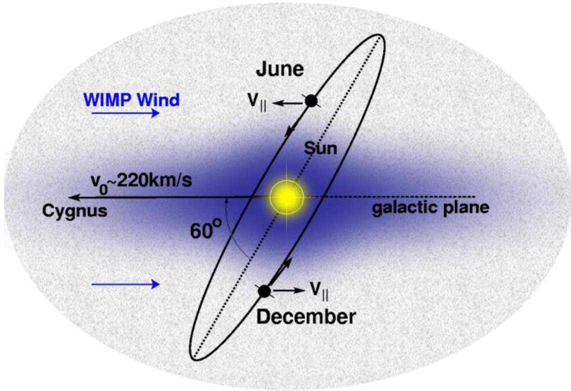
Basic Idea:

> The earth moves through the WIMP halo.

> WIMPs scatter elastically on nuclei.

> Measure nuclear recoils.





Experimental challenge:

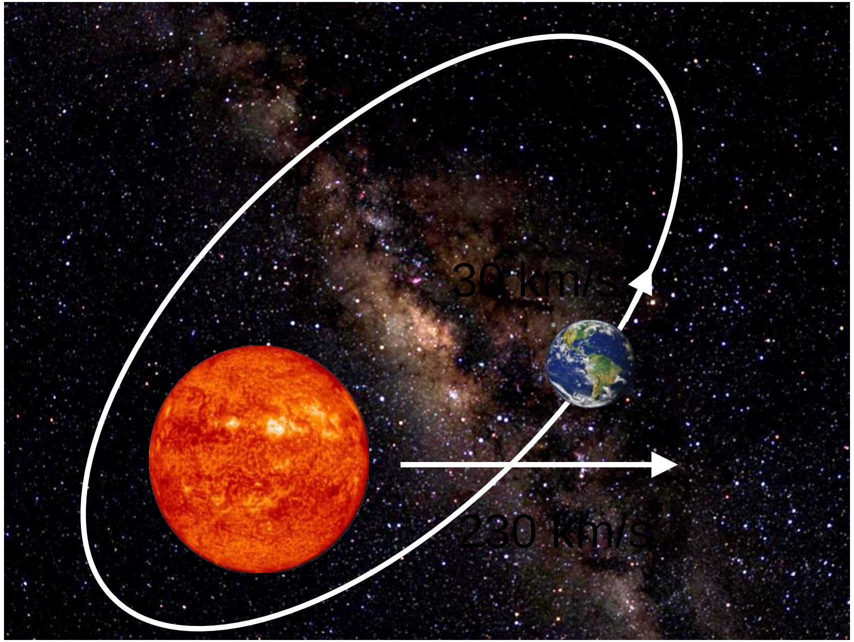
> WIMP mass: 10 GeV to TeV (≈ mass of nuclei)

> Relative speed (earth - WIMP in galactic halo): 250 km/s
> ⇘ kinetic energy ≈ keV

> Very low cross sections: $\sigma_\chi < 10^{-40}$ cm^2 = 10^{-4} pb ≈ $10^{-14}\,\sigma_{pp}$

> Local density ≈ 0.3 GeV / cm^3
> ⇘ Event rate < 0.1 / day / kg (10^{-6} Hz / kg)

The "smoking gun" of WIMP detection

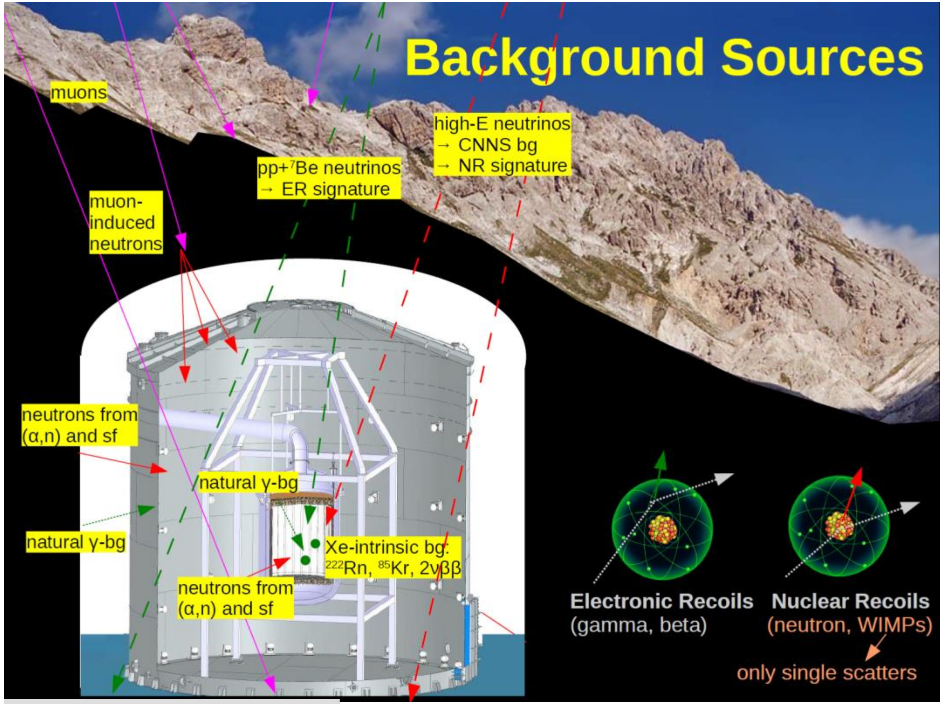


Speed relative to WIMP halo:
(230 ±15) km/s

(10^4 to 10^6 WIMPs/cm^2/s)

Due to varying speed of earth relative to galactic halo:
≈7% annual modulation of WIMP detection rate.

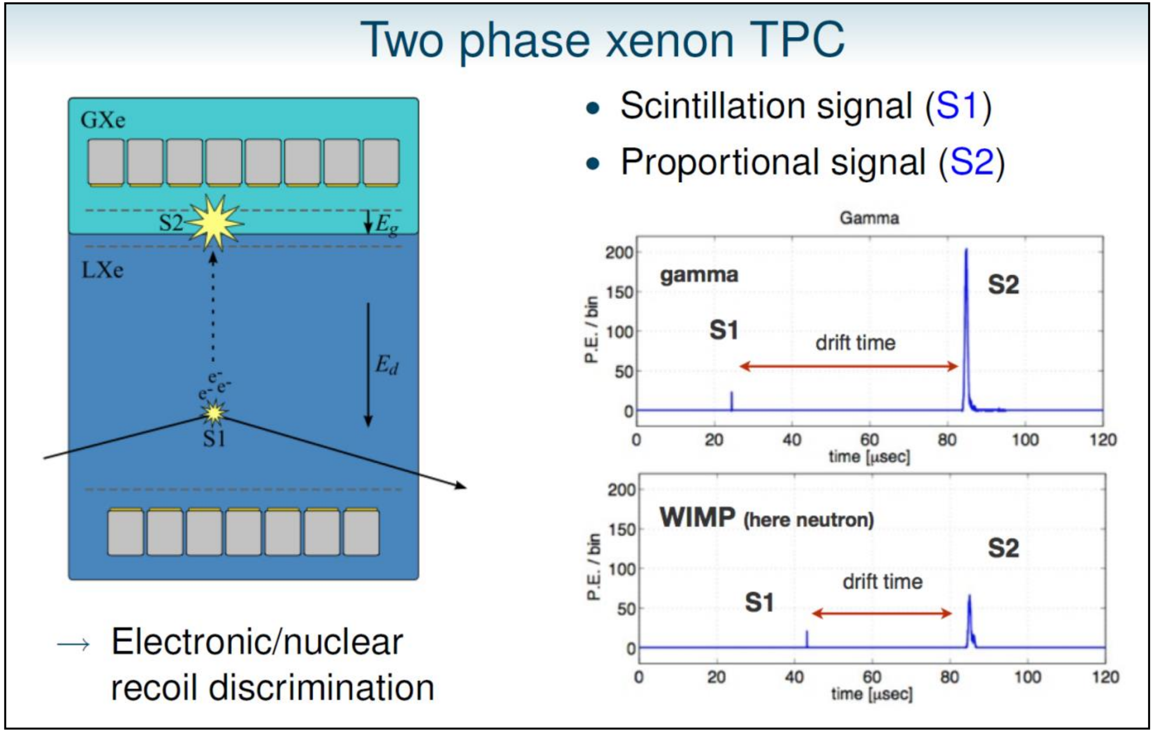
Basic detector considerations



Marc Schumann *U Freiburg*
PATRAS 2017
Thessaloniki, May 19, 2017
marc.schumann@physik.uni-freiburg.de
www.app.uni-freiburg.de

- Large, well shielded detectors to suppress cosmic ray interactions.
- Radio-pure materials to suppress radioactivity.
- Discriminate between electronic and nuclear recoils to further suppress cosmic ray interactions and radioactivity.
- Remaining background: neutron scattering.

Example: the XENON experiment



> Signal S1:
Scintillation light from the scattering process in the liquid Xe.

> Signal S2:
Light produced in the gaseous phase by electrons drifted from primary scatter.

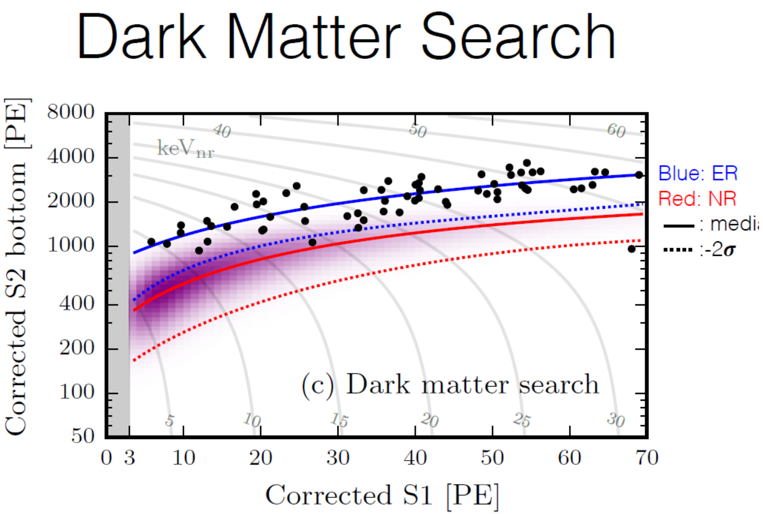
> Ratio S1/S2:
Small for nuclear scatter, larger for electromagnetic scatter.

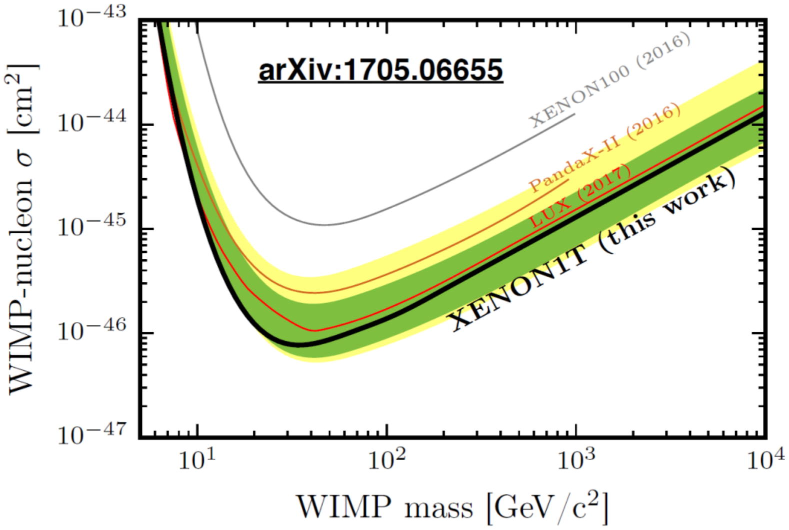
T. Marrodán Undagoitia, PATRAS 2013, Mainz

The XENON experiment

E. Aprile, PATRAS 2017, Thessaloniki

XENON results: https://arxiv.org/abs/1705.06655



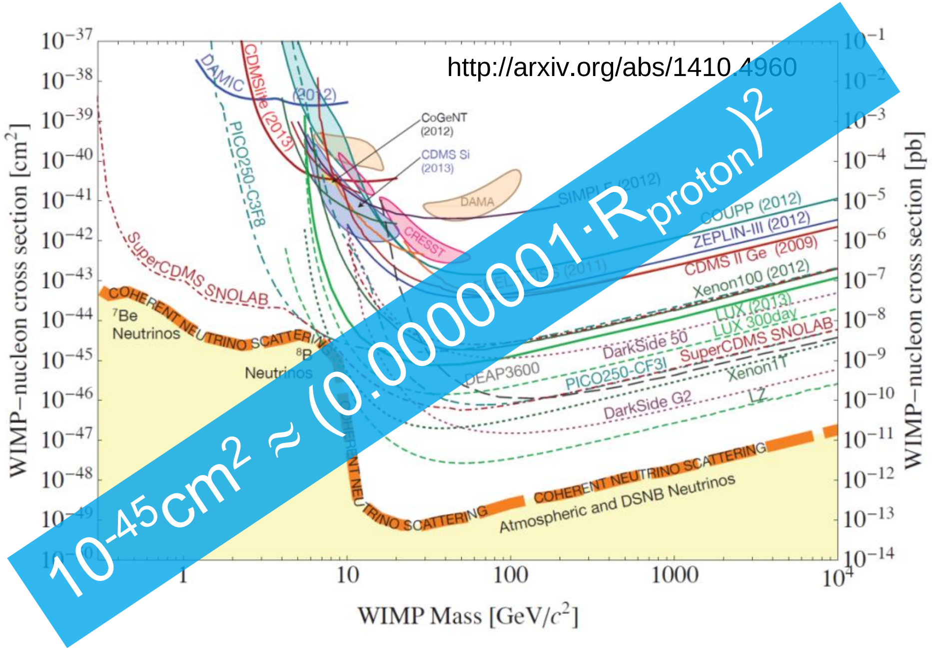


E. Aprile, PATRAS 2017, Thessaloniki

NO WIMP

Status of direct dark matter WIMP searches

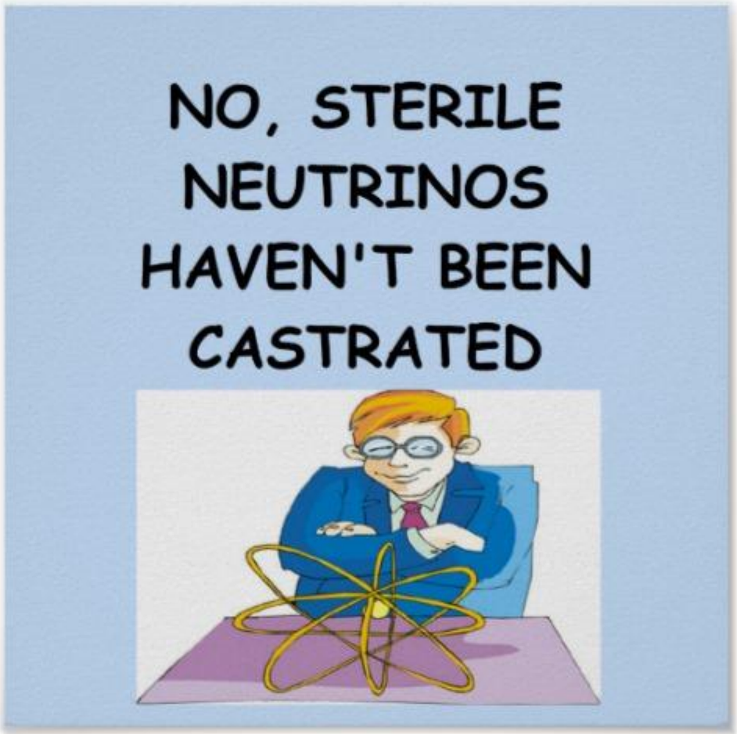
- Dark matter WIMP searches have seen fantastic technological improvements in the past decade.
- However, no convincing indication for the existence of dark matter WIMPs have been found.
- The next generation of experiments will come close to the irreducible background of neutrino interactions.
- At LHC no hint for the existence of WIMPy dark matter candidates has been seen.



$10^{-45} cm^2 \approx (0.0000001 \cdot R_{proton})^2$

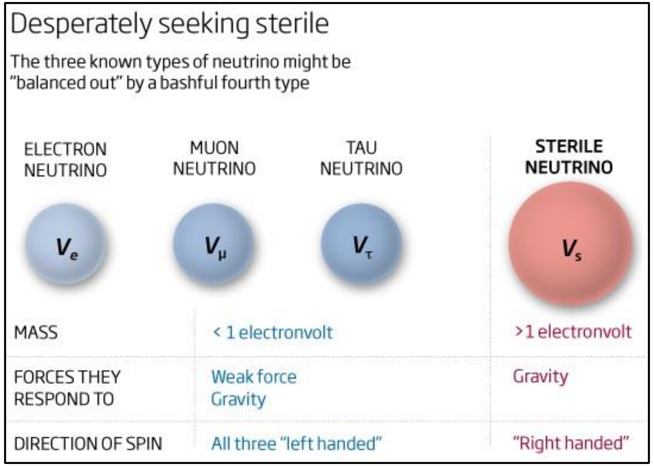
- Are we approaching the final stage of dark matter WIMP searches?

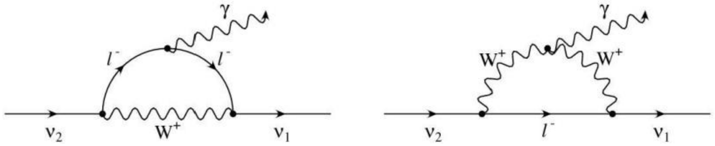
Sterile neutrinos



Sterile neutrino dark matter

- Sterile neutrinos
  - Theory: sterile neutrinos can be very well embedded in theoretical extensions of the standard model.
  - Dark matter: if sterile neutrinos have keV-range masses, they could compose the dark matter in the universe. Sterile neutrinos would compose “warm dark matter”, which could alter structure formation compared to cold dark matter.
  - Additional benefit: sterile neutrinos could explain the non-zero neutrino masses and the baryon / anti-baryon asymmetry in the universe. The might explain puzzling features of X-ray spectra in astrophysics.
- Prediction:
  Dark matter is composed out of elementary particles with masses in the keV range.





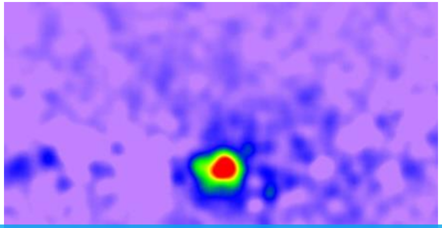
Dark matter (DM) search strategies: sterile neutrinos

- Direct:
  an experiment detects particles of the DM halo all around us.

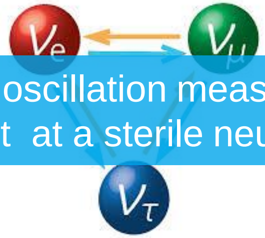
- Indirect:
  an experiment finds astrophysical signatures (next to gravitation) of the DM halo particles.

- Candidates:
  an experiment identifies new particles which are candidates for the constituents of the DM halo.

Hardly possible with sufficient sensitivity



X-rays from DM ν decays in the galactic centre?



Neutrino oscillation measurements could hint at a sterile neutrino.

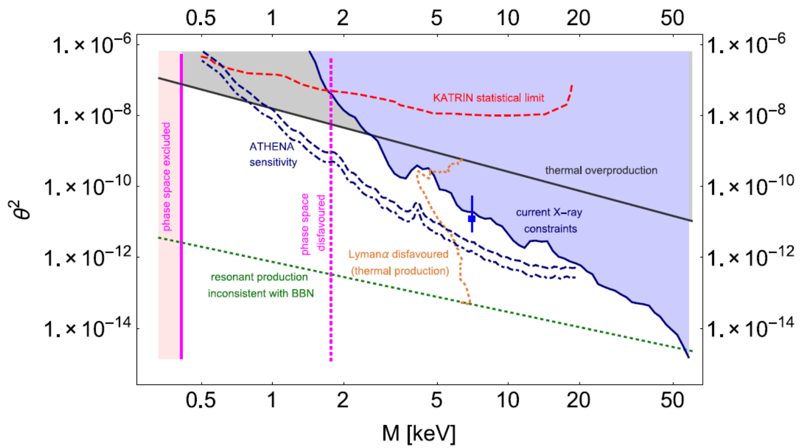
Dark matter (DM) search strategies: sterile neutrinos

Status of searches for sterile neutrinos:

> Some X-ray data might hint at keV dark matter annihilation.

> Data from neutrino oscillation experiments (MiniBoone, LSND) might hint at sterile neutrinos.

> New experiments are planned to probe new parameter regions, including the long standing challenge of detecting cosmic neutrinos (PTOLEMY).



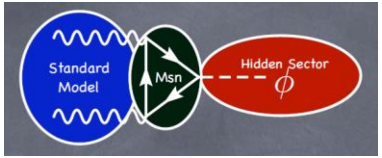
For a review see https://arxiv.org/abs/1807.07938.

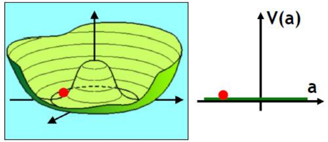
Sterile neutrinos are (still, again) valid dark matter candidates!

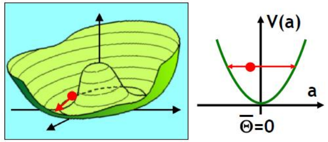
Axions and other Weakly Interacting Slim Particles (WISPs)

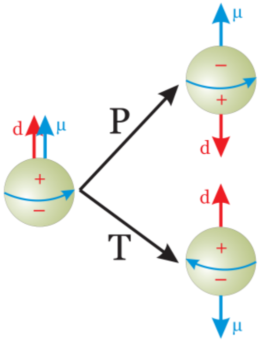
Axions and other WISPs as dark matter

- Weakly Interacting Slim Particles (WISPs)
  - Theory: WISPs might arise as (pseudo) Goldstone bosons related to extra dimensions in theoretical extensions (like string theory) of the standard model.
  - Dark matter: in the early universe WISPs are produced in phase transitions and would compose very cold dark matter in spite of their low mass.
  - Additional benefit: with axions (the longest known WISP) the CP conservation of QCD could be explained, axion-like particles could explain different astrophysical phenomena.
- Prediction:
  Dark matter is composed out of elementary particles with masses below 1 meV.
  Its number density is larger than 10^{12} 1/cm^3.



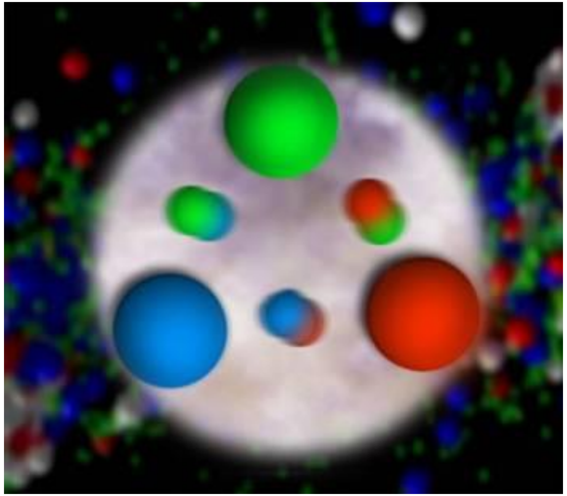






WISP motivation: the axion case

- Why does the static electric dipole moment of the neutron vanish?



Why do the wave functions of the three quarks *exactly* cancel out any observable static charge distribution in the neutron?

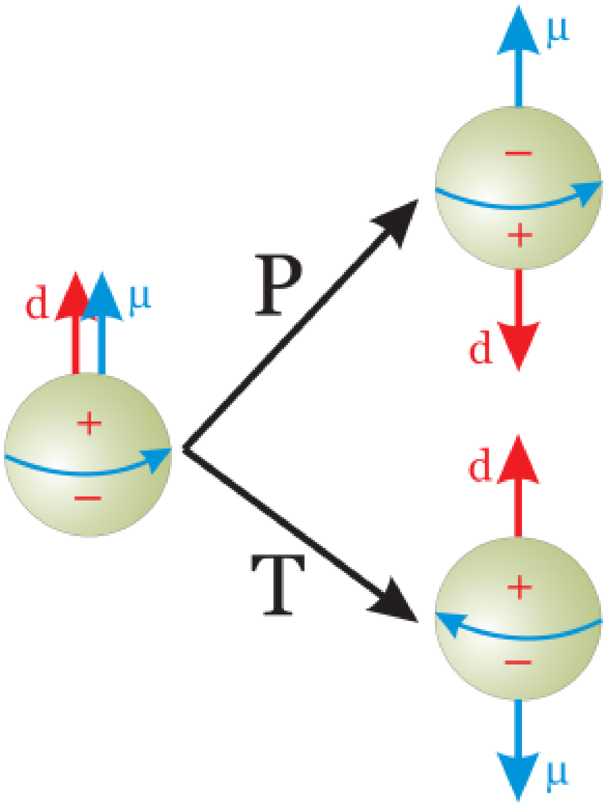
http://www.lbl.gov/Science-Articles/Archive/sabl/2006/Oct/3.html

- This is related to a fundamental property of QCD:

  QCD allows for CP violation, if the quarks have non-zero masses.
  Why does QCD nevertheless conserve CP?

Discussion time

- What is CP violation?



The QCD axion

CP conservation in QCD:

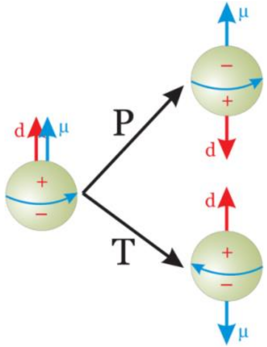
- The QCD Lagrangian includes a CP violating term:

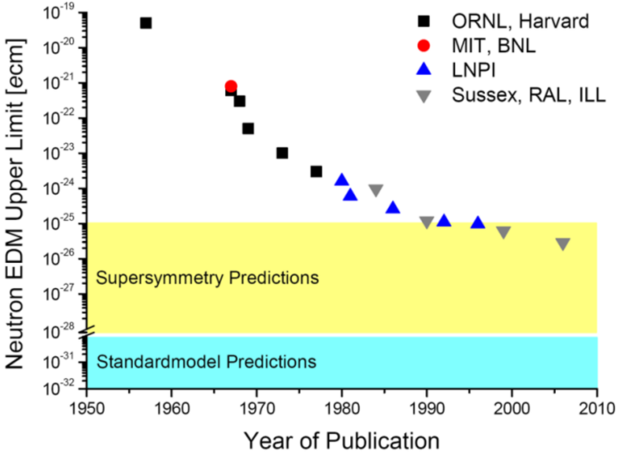
$$L_\theta = -\theta(\alpha_s/8\pi)\, \tilde{G}^a_{\mu\nu} G^a_{\mu\nu}$$

This would impose an electric dipole moment to the neutron for θ ≠ 0:

$$d_n(\theta) = 2.4 \times 10^{-16} \bar{\theta} e \cdot cm$$

Any EDM of the neutron would violate CP:





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  $$L_\theta = -\theta(\alpha_s/8\pi)\,\tilde{G}^a_{\mu\nu}G^a_{\mu\nu}$$

  This would impose an electric dipole moment to the neutron for θ ≠ 0.

- The observable CP-violation is given by

  $$\theta + \arg(\det \mathcal{M})$$

- To our understanding,
  θ (QCD parameter) and
  $\arg(\det \mathcal{M})$ (weak interaction) are not related,

- but experimentally, | $\theta + \arg(\det \mathcal{M})$ | < 10^{-10}.

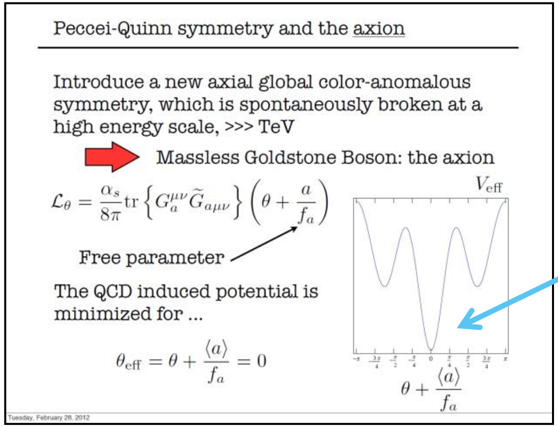
A fine tuning issue?

The QCD axion

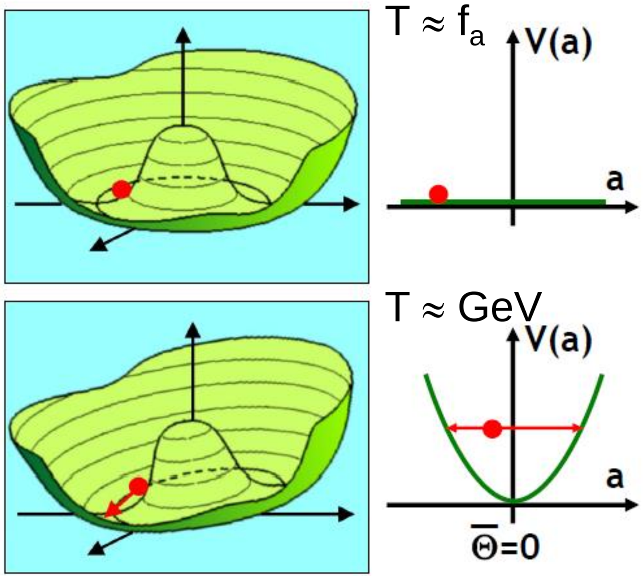
Instead of fine-tuning:

- > Introduce a new symmetry (Peccei-Quinn 1977) so that $\theta + \arg(\det \mathcal{M})$ evolves to zero.

Courtesy J. Redondo



The axion adjusts its v.e.v. to cancel the effects of any theta from QCD



S. Hannestad, presentation at 5th Patras Workshop 2009

- > As the PQ-symmetry is broken: a pseudo Goldstone boson should exist. This axion was predicted in 1978 by Weinberg and Wilczek.

The QCD axion

CP-conservation in QCD:

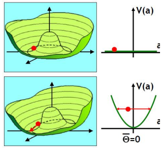
- A dynamic explanation for $\Theta < 10^{-10}$ predicts the axion, which couples very weakly to two photons.
- The axion “wipes out” the CP-conservation problem in QCD.

The axion and dark matter: a brief history of the universe

Ultracold dark matter from phase transition

1. Very high temperatures $T > f_a$:
   Nature picks a random initial θ_i.

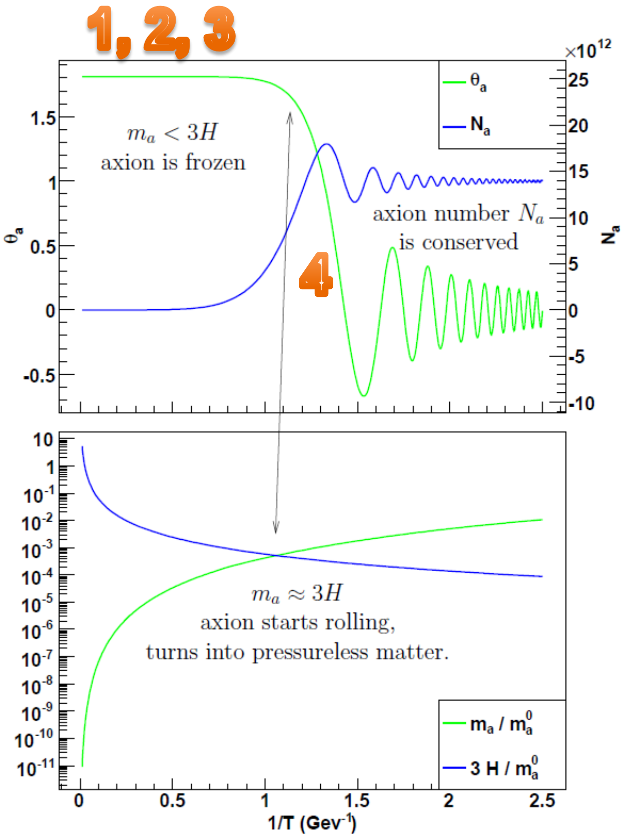
2. For $T < f_a$,
   the "Mexican hat" potential appears.
   The axion field evolves:



$$\ddot{a}_0 + 3H\dot{a}_0 + m_a^2 a_0 = 0$$

3. As long as the size of the universe is smaller than the axion Compton wavelength ($H > m_a$), the axion field is frozen. At this stage, the axion acts like dark energy and might drive inflation.

4. When $H < 3m_a$, the axion field starts to oscillate around $\theta = 0$. The quanta of this oscillating field constitute dark matter.

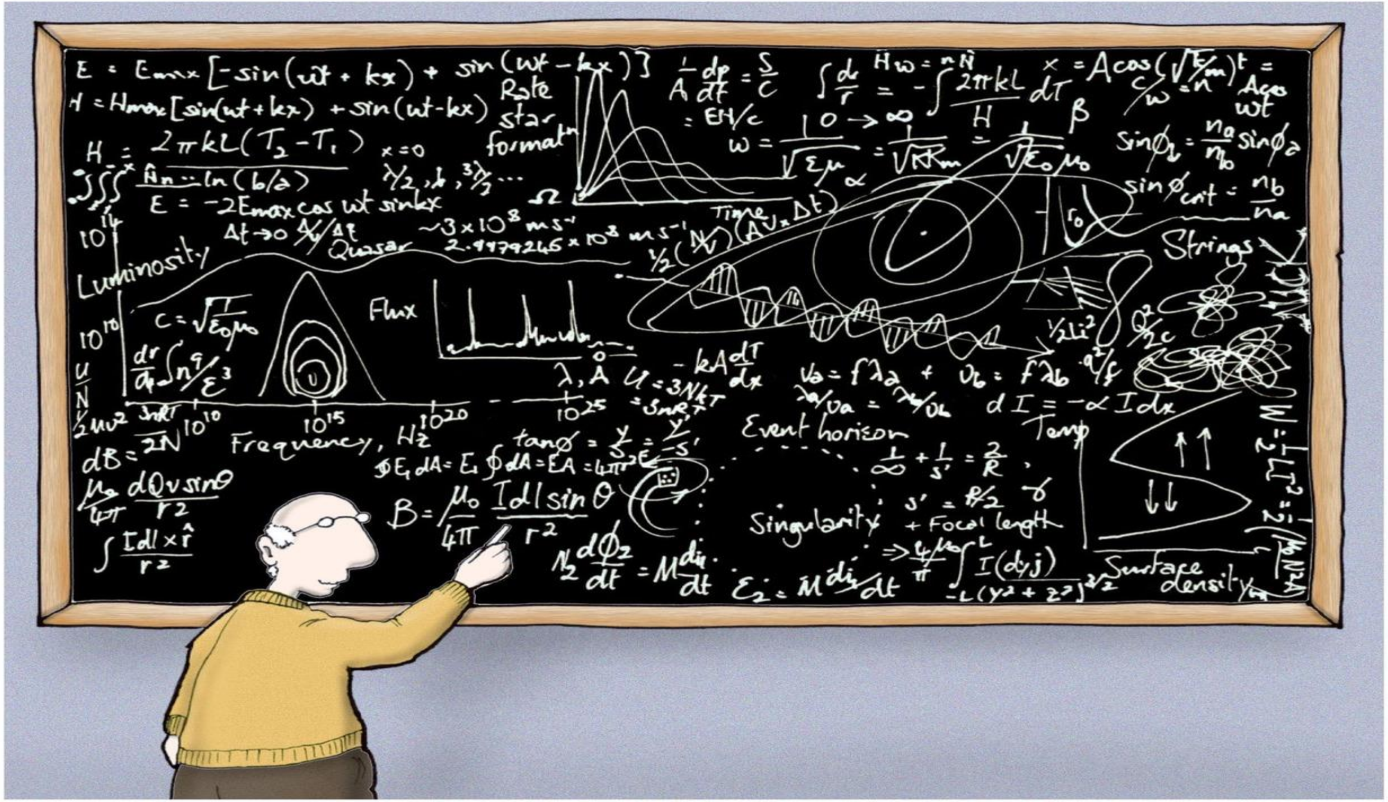


https://arxiv.org/abs/0910.1066

Our dark matter menu

- Starters
  - Historical annotations: how to discover new stuff?
  - Our anchor: the Standard Model of particle physics
- Main course 1
  - The necessity of Dark Matter
  - Alternatives and hidden assumptions
- Main course 2
  - Dark matter candidates
  - Searching for Dark Matter candidate particles
  - Direct searches for Dark Matter particles
- Dessert
  - Astrophysical puzzles
- Doggy bag
  - Summary and outlook

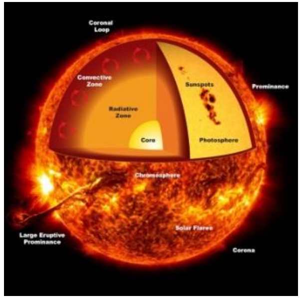
Are there hints from astrophysics on the nature of DM?



Astrophysics made simple

http://www.tumblr.com/photo/1280/jtotheizzoe/13754916531/1/tumblr_lapf0aD7811qaityk

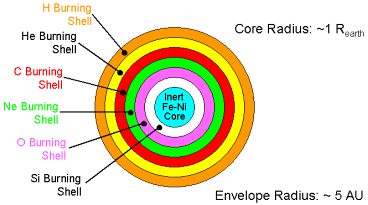
High energies in the present universe



http://spaceplace.nasa.gov/review/solar-tricktionary/photosphere.en.jpg

Using λ=2898μm K/T, E=hc/λ

- Sun, surface temperature: $5.7 \cdot 10^3$ K ↔ 2.4 eV
- Sun, core temperature: $1.6 \cdot 10^7$ K ↔ 6.9 keV



http://www.astronomy.ohio-state.edu/~pogge/Ast162/Unit2/himass.html

- Silicon burning star
  (25 solar masses, 5 days before supernova),
  core temperature: $2.5 \cdot 10^9$ K ↔ 1.1 MeV

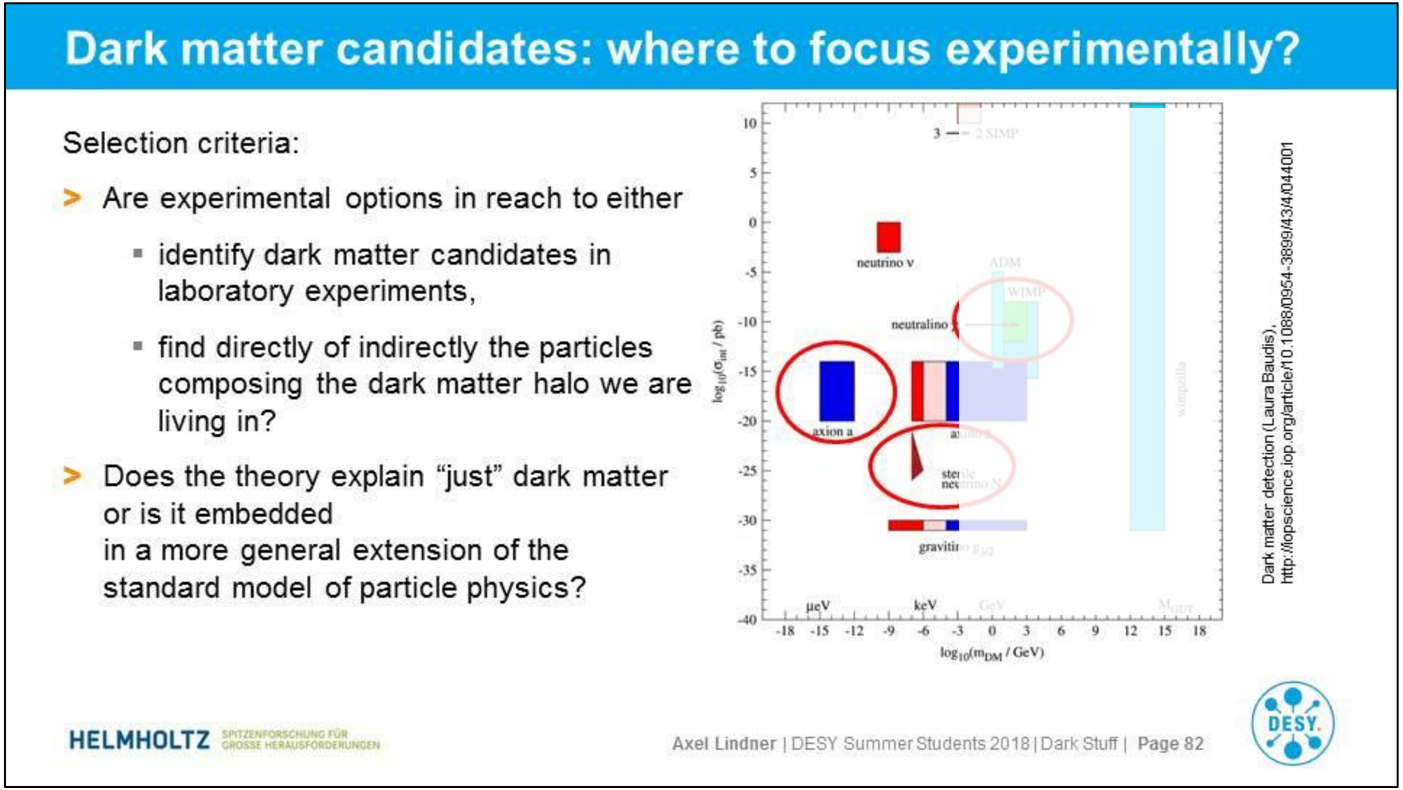
Dark matter production in the present universe

Dark matter with masses below 1 MeV could still be produced (thermally) in our universe today:

> axions, ALPs

> sterile neutrinos.

Come back on Friday to learn about axions, ALPs, stars and photons!



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Summary I

- We claim to understand the deepest structure, the fundamental forces and the early universe.
- However, our knowledge just makes up 5% of the present universe.
- From laboratory experiments we do not have the slightest indication for the constituents of the 95% stuff.
  Despite the huge technical progress in the last 30+ years!
- Is there something fundamentally wrong with our approaches to understand nature?

Discussion time!

Summary II (a more conventional one): to take home

- It is almost certain that Dark Matter of unknown constituents exist.
- It is well possible that in addition Dark Energy exists.
  - We might know just 5% of the universe.

- Constituents making up the Dark Matter in the universe could be essentially anything from ultra-light to extremely heavy.
  - A lot of experiments search for WIMPs at the high energy frontier, also at LHC.
  - A new experimental frontier is developing:
    seachers for axions and similar particles (see Friday lecture).

Outlook

- Next generations of experiments will come and search for dark matter candidates as well as directly and indirectly for dark matter.
- Perhaps we (you!) are lucky like the drunkard who finds his key under the shine of the lantern!
- So one should explore all technical accessible dark matter parameter regions.
- However, according to present-day knowledge it is not excluded that dark matter interacts gravitationally only.
  In this case we will probably never discover it.

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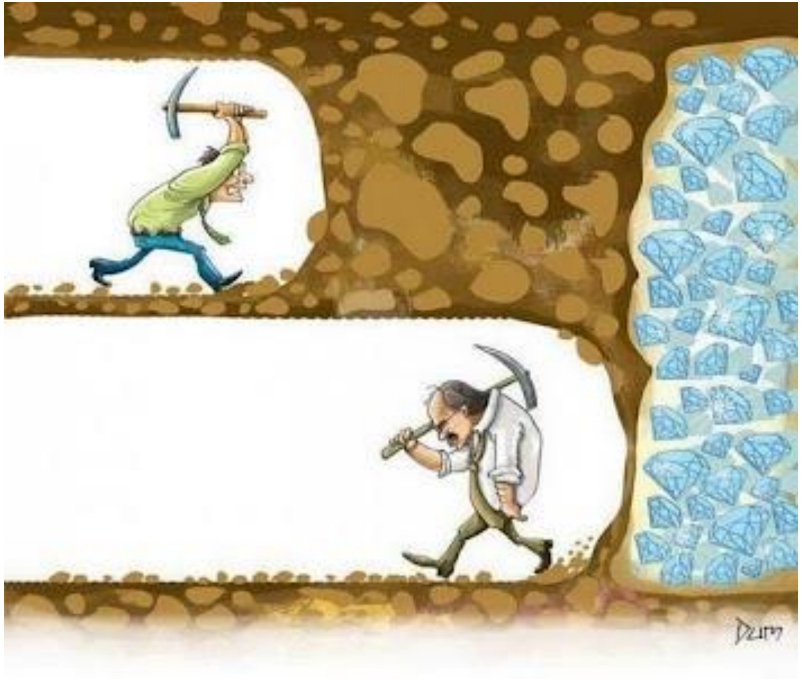

Summary III

> http://www.phdcomics.com/comics.php?f=1430
> http://vimeo.com/22956103