

Open Questions in Fundamental Physics

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Try 1609.06941 for
Wilczek's view

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Open Questions: 1900 to Today

Open Questions from Data

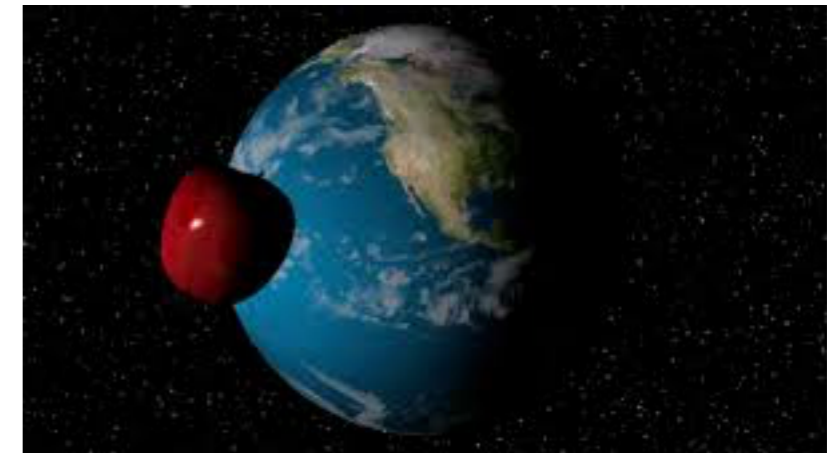
Open Questions from Theory

Open Questions: 1900 to Today

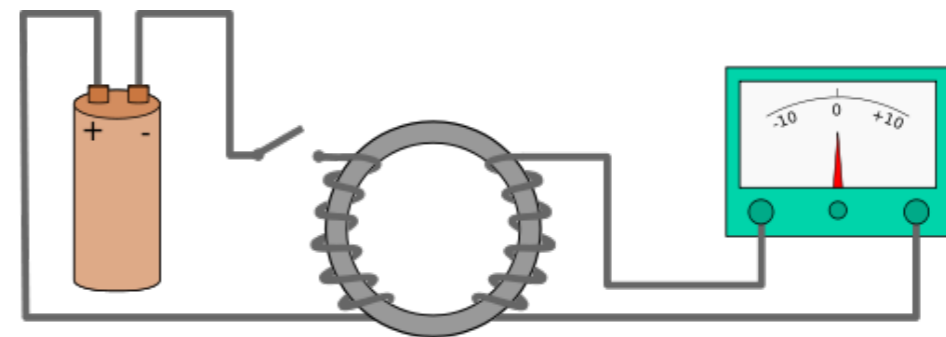
Fundamental Physics - XIX century

The fundamental **interactions**

1686



1861



Fundamental Physics - XIX century

The fundamental **constituents of matter**

1869



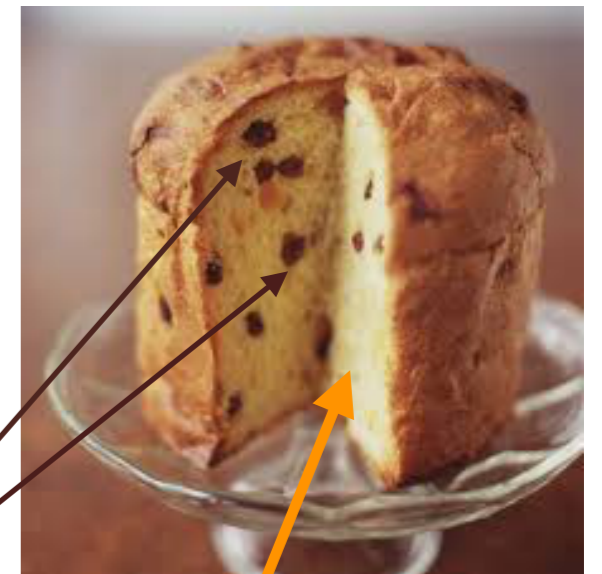
Atoms “by definition” smallest existing thing

Really known from chemistry, smallest atom = Hydrogen (Mendeleiev table was in 1869)

1897



J.J. Thomson discovers **electron** and proposes "panettone" atom model to fit with Maxwell's electromagnetism



negatively charged electrons

positively charged medium

“It seems probable that most of the grand underlying principles have been firmly established [...] the future truths of physical science are to be looked for in the sixth place of decimals”



attributed to Lord Kelvin (wrongly, Wikipedia says)

Two little clouds

1900



We understand ~ everything
except two clouds

Black Body
radiation problem

Michelson-Morley
fail to detect "aether"

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Birth of:

Quantum Mechanics

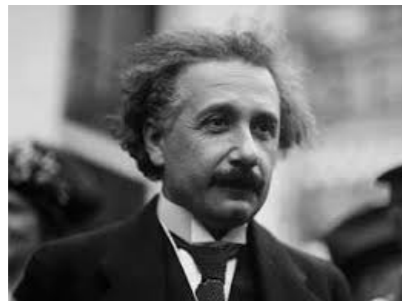
Special Relativity

1900



Planck solves black body
by postulating quanta of light

1905



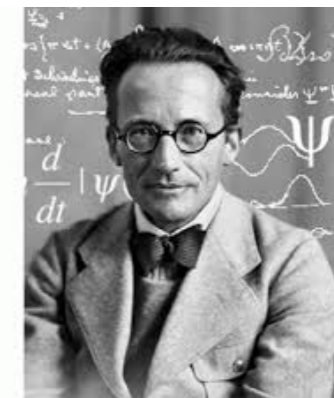
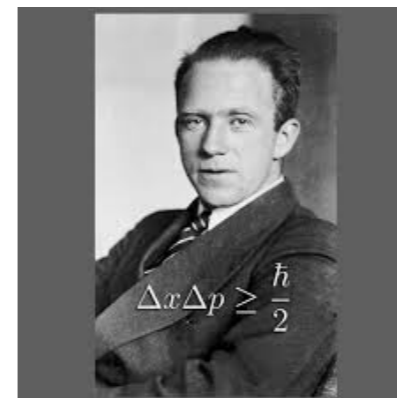
Einstein uses same hypothesis
to explain photoelectric effect

Speed of light is frame-independent
Lorentz-invariance of physical laws

... ~ 1930



Prince Louis - Victor de Broglie

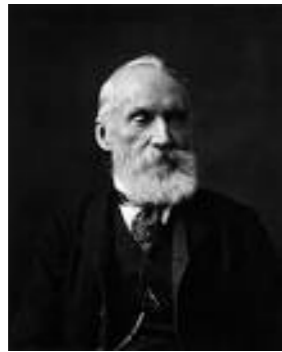


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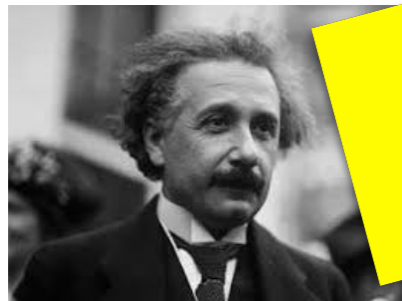
1900



Planck solves black body by postulating

NB: still same **interactions** and **matter** constituents

1905



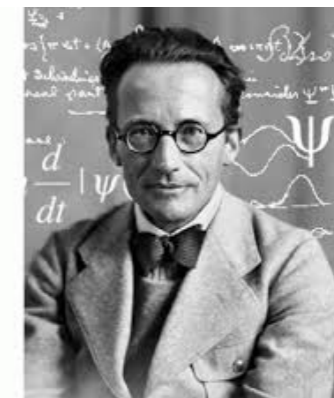
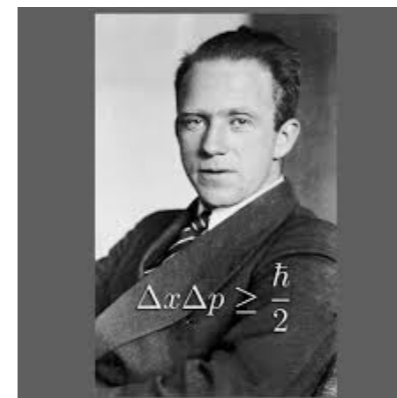
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Quantum Mechanics + Special Relativity = ?

~ 1930 ...today **Quantum Field Theory (QFT)**

Field = set of values, or operators, assigned to every location in space and time

1 value: Temperature, “scalar” fields (like the Higgs boson, H)

>1 values: Wind, “fermion” (like electron e) and “vector” (like photon A_μ) fields

Particle = “quantum” of excitation of a quantum field $H|\text{vacuum}\rangle \simeq$ Higgs particle

(like the smallest possible wave on the “field” of a lake surface)

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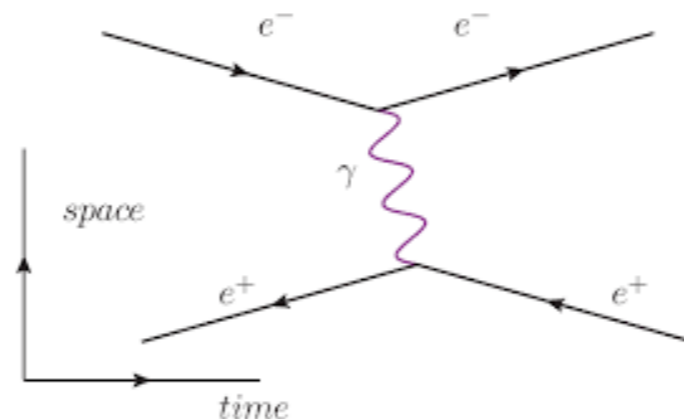
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(g = coupling, γ^μ = Dirac matrices acting on spin)

Pictorially: Feynman diagrams



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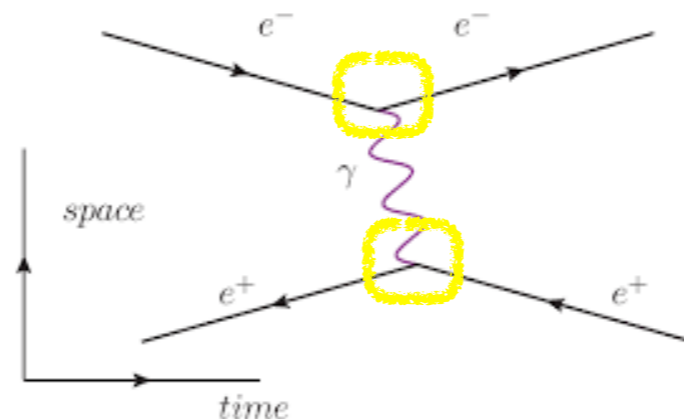
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Vertex ~ insertion of a Lagrangian **interaction** with 3 or more **fields**

In and out **particles** have to match quantum **field** operators

More on QFTs

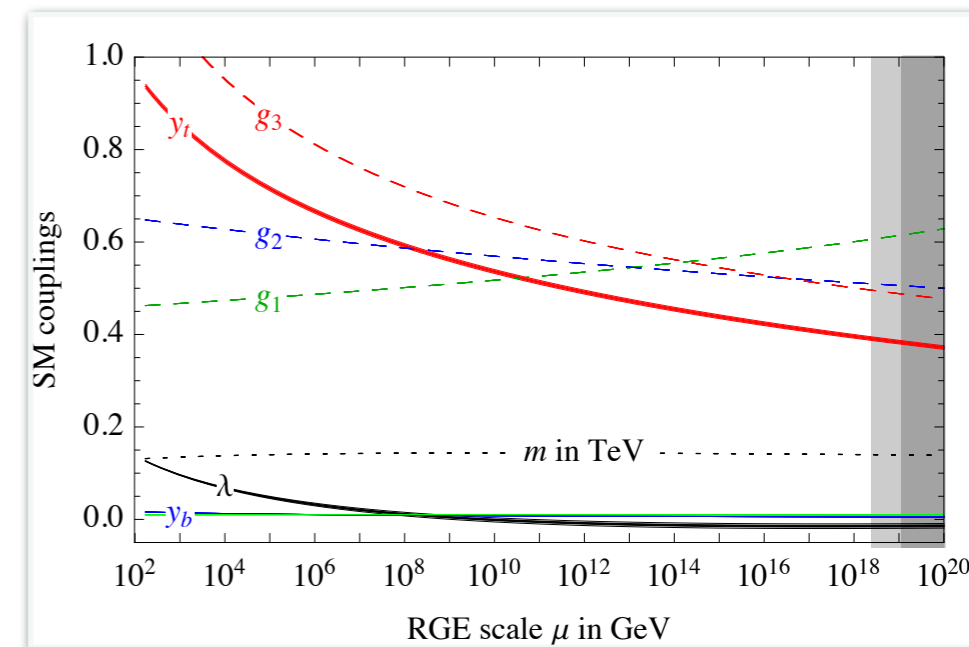
QFT ~ QM in 3 (space) + 1 (time) dimensions, instead of 1 (time), to incorporate Lorentz
[Schrodinger equation is evolution in time]

Couplings “run”

Fix value of coupling at a given energy, from measurements
then QFT predicts its value at different energies!

$$\alpha_{\text{em}} \simeq \frac{1}{137} \quad @ \text{ energies } \sim 0$$

$$\alpha_{\text{em}} \simeq \frac{1}{130} \quad @ \text{ energies } \sim 100 \text{ GeV } (\sim Z, W, h)$$



Perturbative Expansions

Extracting predictions for “observables” from QFTs

(most often) assumes one can Taylor-expand in **small** couplings

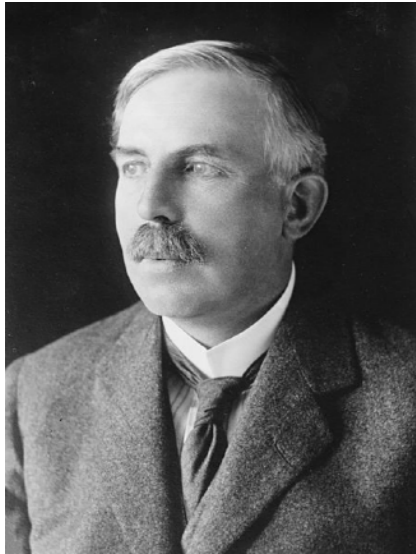
when this is not the case other techniques needed, “lattice”...

$$\frac{g^2}{16\pi^2} \equiv \frac{\alpha_{\text{em}}}{4\pi}$$

$$\mathcal{L}_{\text{QED}} = g \bar{e} \gamma^\mu e A_\mu$$

New Interactions and New Matter

Back to 1900...

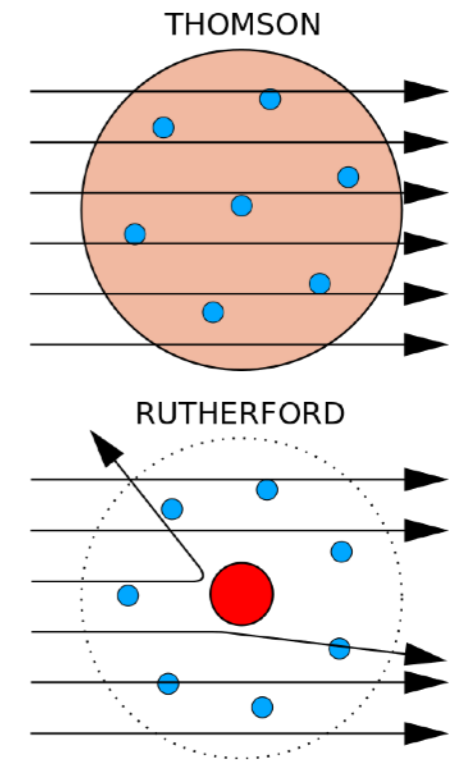


E. Rutherford (Thomson's student)

1908 Nobel for studies on radiation
(new particles: alpha, beta, ...)

1909-1911 Alpha particles on gold foils
kill the model of his mentor!

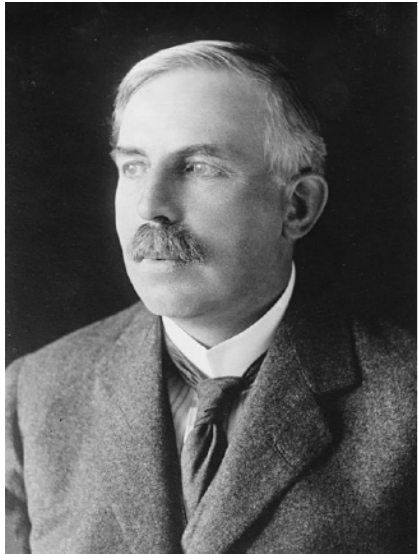
(another important lesson: we can learn from colliding particles!)



Nuclei made of **protons** (= Hydrogen nucleus) and **neutrons** (**1932**, James Chadwick)

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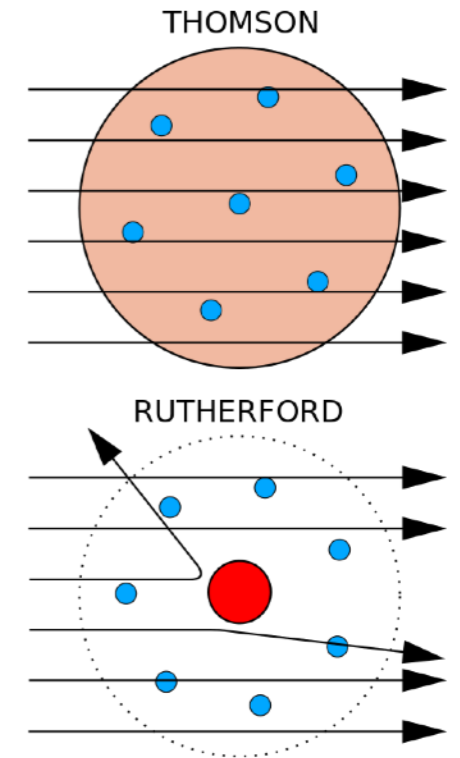


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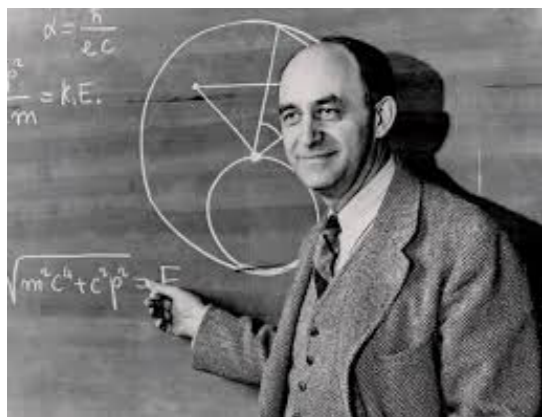
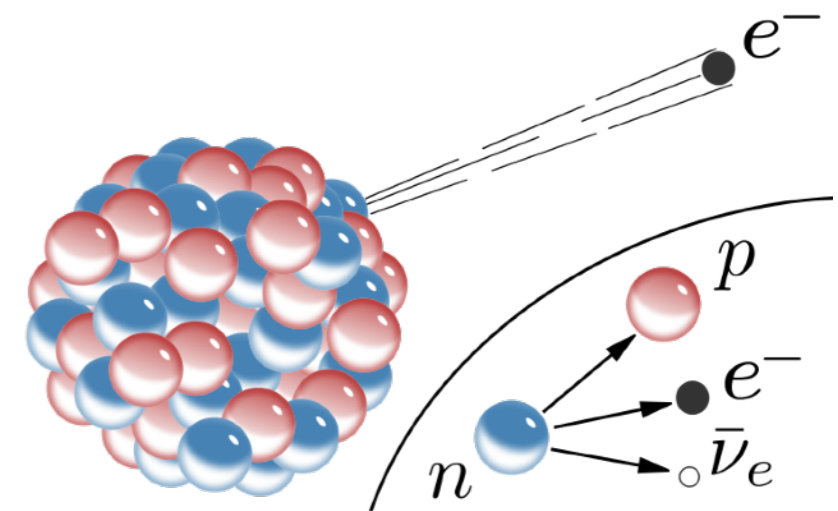


1930 Wolfgang Pauli theorises **neutrinos** to explain beta decays

1933 Enrico Fermi explains beta decays with

$$\mathcal{L}_{\text{Fermi}} = G_F (\bar{n} \gamma_\mu p) (\bar{\nu} \gamma^\mu e)$$

precursor of the **weak interactions**!



New Interactions and Loads of New Matter

1936 **Muon** a “new electron”, with mass ~ 200 times larger, discovered in cosmic rays

40's to 70's dozens of new particles discovered at colliders, chaotic situation

New Interactions and Loads of New Matter

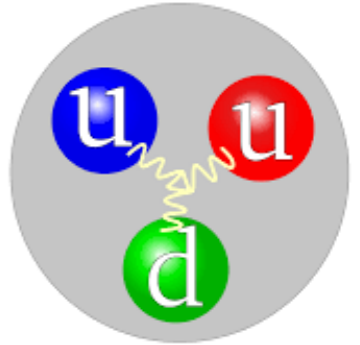
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lead to **Quantum Chromodynamics (QCD)** theory of **Strong Interactions**

Mediators = **gluons**

Felt by **quarks** that constitute protons, neutrons and all the above p.



New Interactions and Loads of New Matter

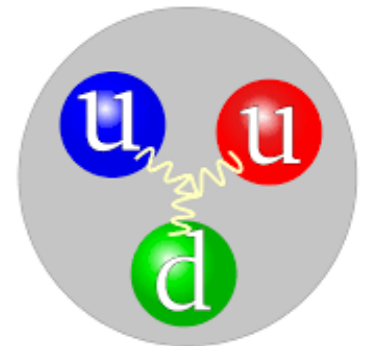
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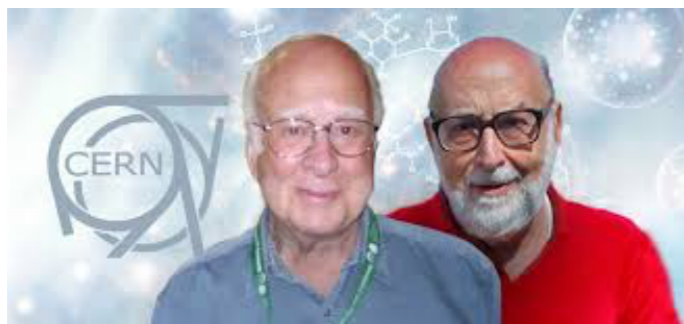
1968-83 What is the origin of Fermi Lagrangian (and of other phenomena)?

ElectroWeak Interaction developed by Glashow, Salam and Weinberg

Mediators = **W & Z bosons**

Felt by **W, Z, Higgs bosons, quarks, leptons** (= electron, muon,...)

2012



Higgs boson discovered at the Large Hadron Collider (LHC)!

Proposed in the 60's by Brout, Englert and Higgs

The Standard Model (SM)

Mathematical framework: **Quantum Field Theory**

Interactions

Local symmetries $G_{\text{SM}} = SU(3)_c \times SU(2)_w \times U(1)_y$
QCD weak hypercharge

broken via Higgs to electromagnetism $SU(2)_w \times U(1)_y \rightarrow U(1)_{\text{em}}$

Spin 0 and spin 1 fields specified from the interactions $W, Z, h, \gamma, \text{gluons}$

Matter

Spin 1/2 fields observed, in some representation of G_{SM}

$$3 \times \Psi = Q(3, 2)_{1/6} \quad u(\bar{3}, 1)_{-2/3} \quad d(\bar{3}, 1)_{1/3} \quad L(1, 2)_{-1/2} \quad e(1, 1)_1$$

quarks leptons

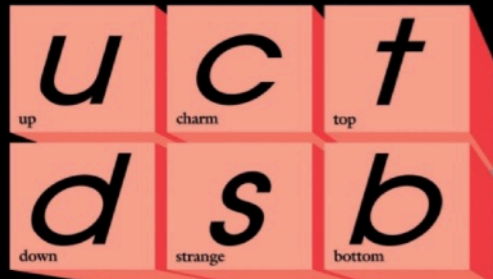
“Recipe”

Write down all possible operators involving those fields, compatible with G_{SM}

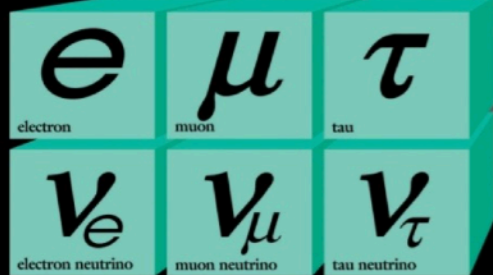
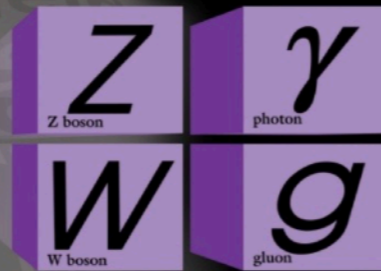
and up to dimension 4 in the fields (otherwise non-renormalizable, not in these lectures...)

The Standard Model

Quarks



Forces



Leptons

$$u + d + g = \text{nuclei} \\ + e + \gamma = \text{atoms}$$

$$+ \nu_e + Z + W \rightarrow \text{radioactivity}$$

$$\text{multiply } (u + d + e + \nu_e) \times 3$$

2012: Higgs boson! [LHC, Geneva]
gives mass to all elementary particles

NB most "baryonic" mass from $u + d + g$

The greatest success of reductionism

Successes of the Standard Model

Not only the SM predicts **incredibly many** phenomena starting from only 18 inputs
but it also predicts these phenomena with an **incredible precision!**

Never in the history of all science has a model performed so well

Most precise test of a theory ever:

g_e factor \sim proportionality between magnetic moment and angular momentum

$$\vec{\mu}_e = g_e \frac{\sqrt{4\pi\alpha}}{2m_e} \vec{S}_e, \quad g_e \equiv 2(1 + a_e), \quad a_e = \frac{\alpha}{2\pi} + \dots$$

$$a_e^{\text{exp.}} = 0.00115965218073(28)$$

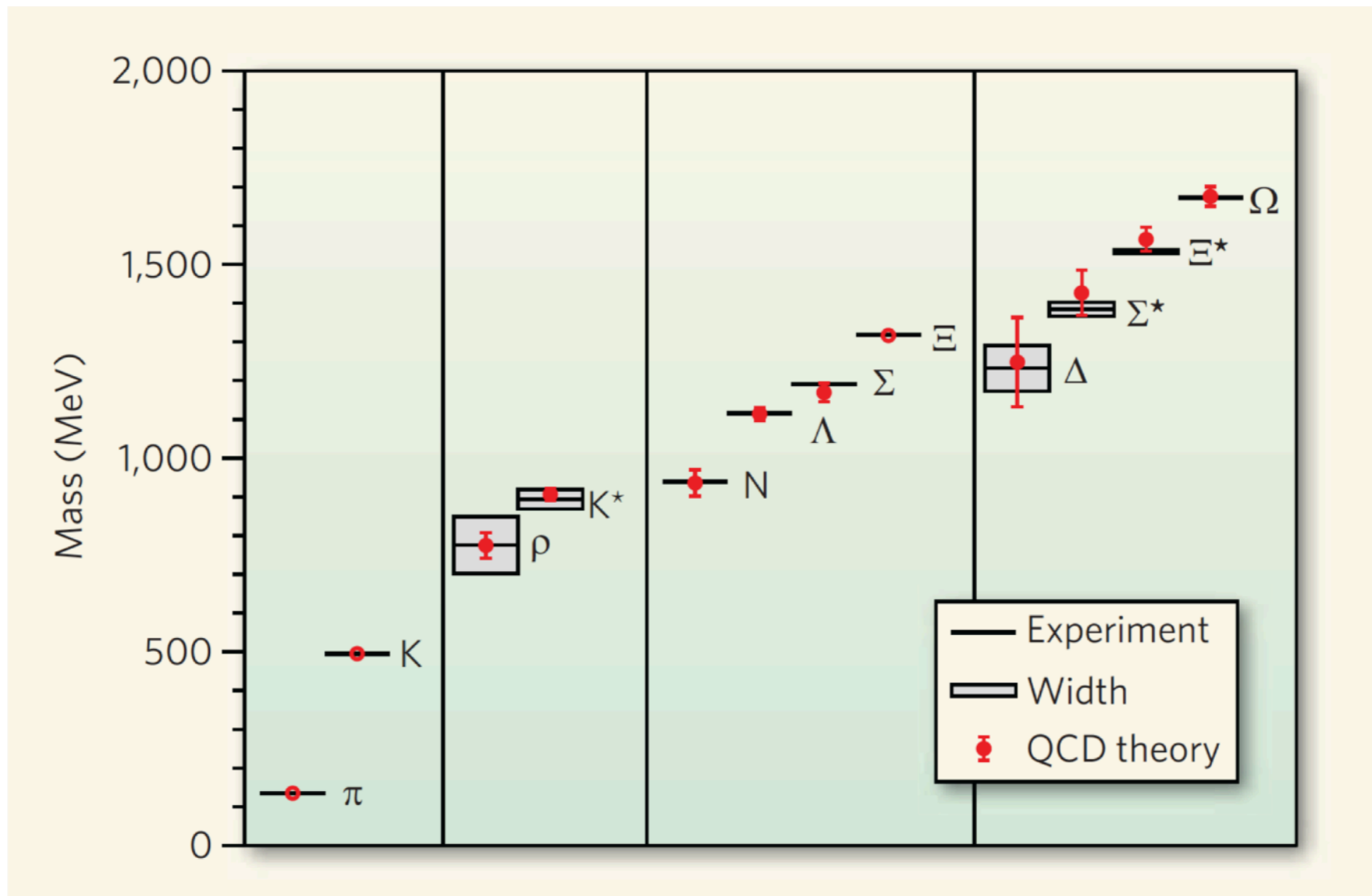
$$a_e^{\text{theory}} = 0.00115965218203(72)$$

See the recent resonaances.blogspot.com for more details

Successes of the Standard Model

3 Input Parameters: 2 quark masses and a coupling strength
 $(m_u + m_d)/2$
 m_s
 α_s

Outputs: Masses of tens of hadrons!



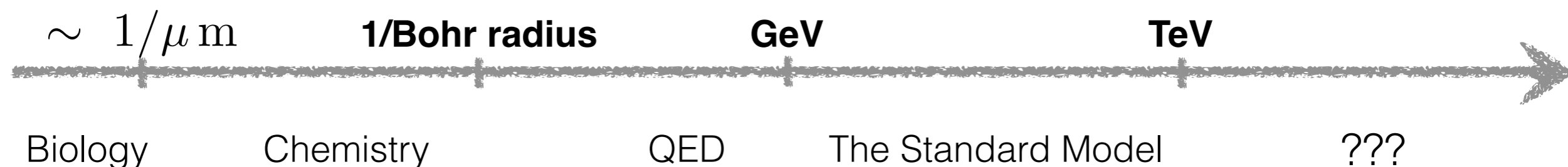
One could fill a year of lectures with precise tests of the SM....

Energy Scales

Natural Units $\hbar = c = 1$

Energy = Mass = 1/Length = 1/Time

Domains of validity



If you are not familiar...:

$$\text{Rydberg} \simeq 13 \text{ eV} \quad \text{Bohr Radius} = \frac{1}{\alpha_{\text{em}} m_e} \simeq 5 \times 10^{-2} \text{ nm} \simeq \frac{1}{5 \text{ keV}}$$

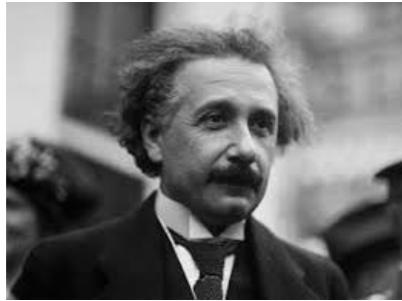
$$m_{\text{proton}} \simeq \text{GeV} \quad \text{Heaviest particle in the Standard Model } m_{\text{top}} \simeq 173 \text{ GeV}$$

Energy of collision of protons at the LHC 13 TeV

Back to Early 1900

General Relativity (GR)

~ 1915



Einstein proposes theory of General Relativity, generalises Newton
(just from theory considerations!)

1919

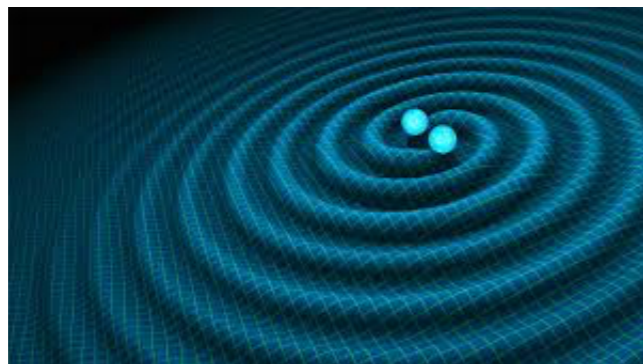


Eddington's expedition to Africa's island to observe solar eclipse
measures deflection of light by the Sun's gravitational field
and confirms General Relativity!

....

precession of Mercury, tons of lensing systems, GPS,...standard cosmological model

2015



LIGO detects gravitational waves

first *direct* observation ever!

(*indirect* evidence came from pulsars)

The Standard Model could have been formulated even if GR did not exist!

Standard Model + GR = ?

= **Standard Cosmological Model** Next slides, but before

= **open question of fundamental physics**

Gravitational Interaction contains a new fundamental scale

$$M_{\text{Planck}} \equiv 1/G_{\text{Newton}} \simeq 10^{19} \text{ GeV}$$

At those scales one needs to go beyond
(GR is non-renormalizable) either **SM + GR**
or **QFT**
possibly **both**

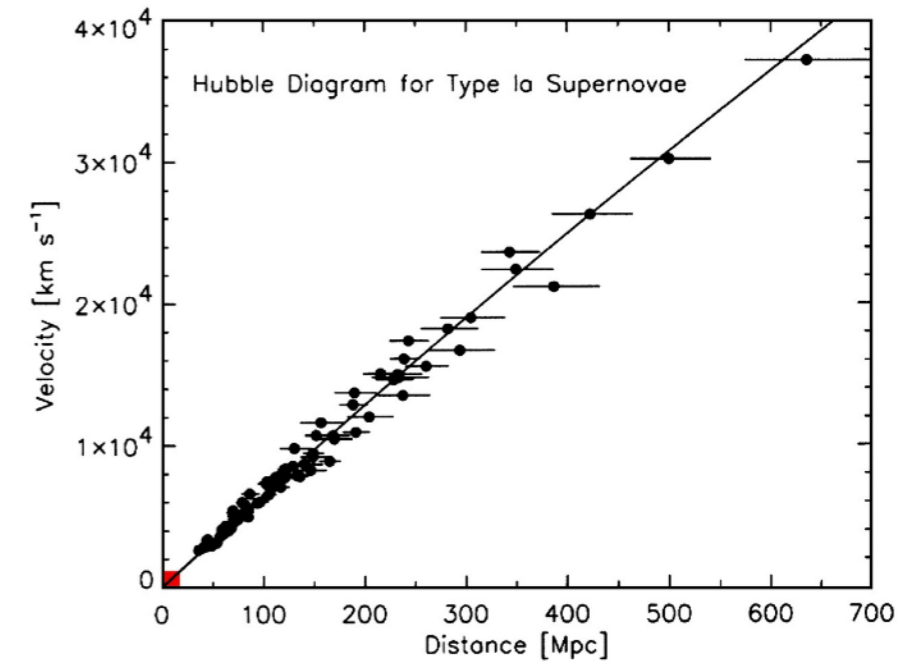
Domains of validity



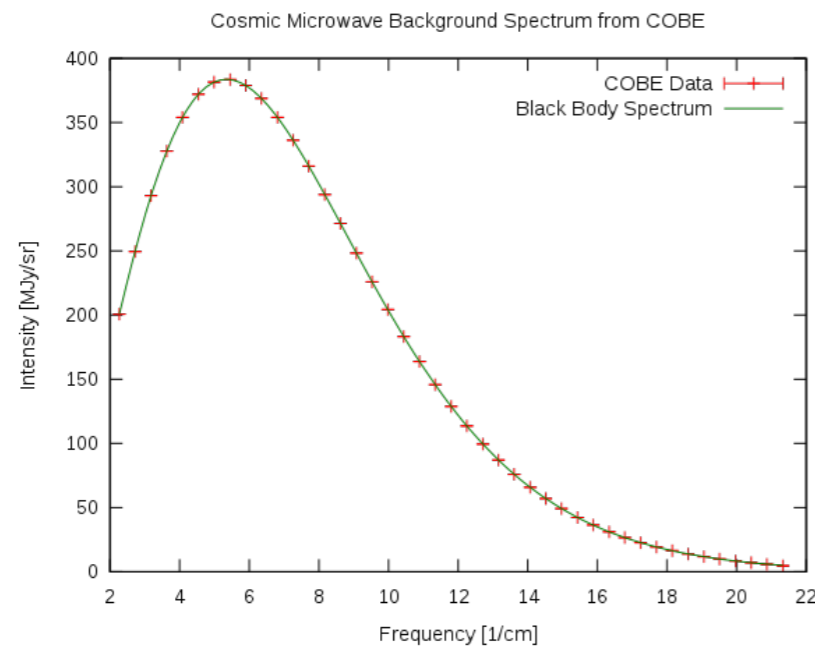
Some key observations

1929

Edwin **Hubble** observes distant galaxies and relates their distance with their redshift
Other galaxies are ~ escaping from us!



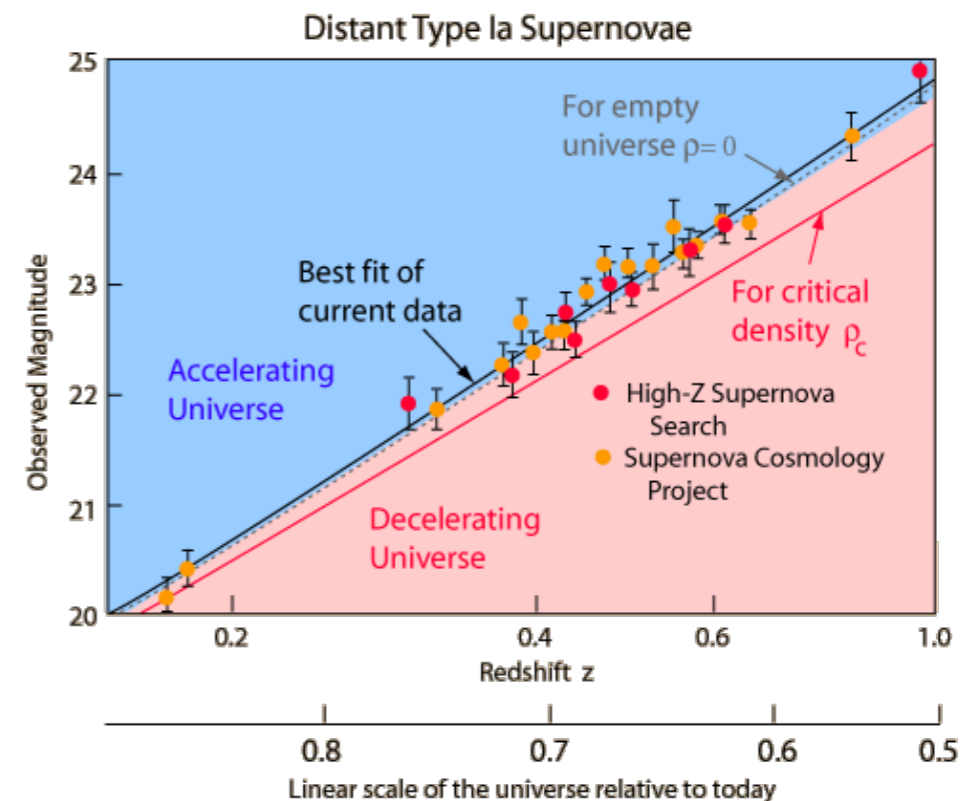
1964



Electromagnetic Radiation with perfect black-body observed from all Sky directions
Cosmic Microwave Background (CMB)

1998

Not only the Universe expands but its expansion is **accelerating!**
(from 2 independent US groups)



Lambda Cold Dark Matter (Λ CDM)

General Relativity applied to entire Universe predicts properties of space-time from its content

like expansion or contraction curvature or flatness

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like expansion or contraction curvature or flatness

Density parameter $\Omega_X \equiv \frac{\rho_X}{\rho_{cr}}$, ρ_{cr} = density to have flat universe

X = **matter** (Mass > Temperature), **radiation** (Mass < Temperature), **cosmological constant** Λ

“**Baryonic**” **matter** = interacts with SM plasma

~ fluid with negative pressure

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Inputs: Ω_{matter} Ω_{baryon} Ω_r Ω_Λ + particle physics

Outputs:

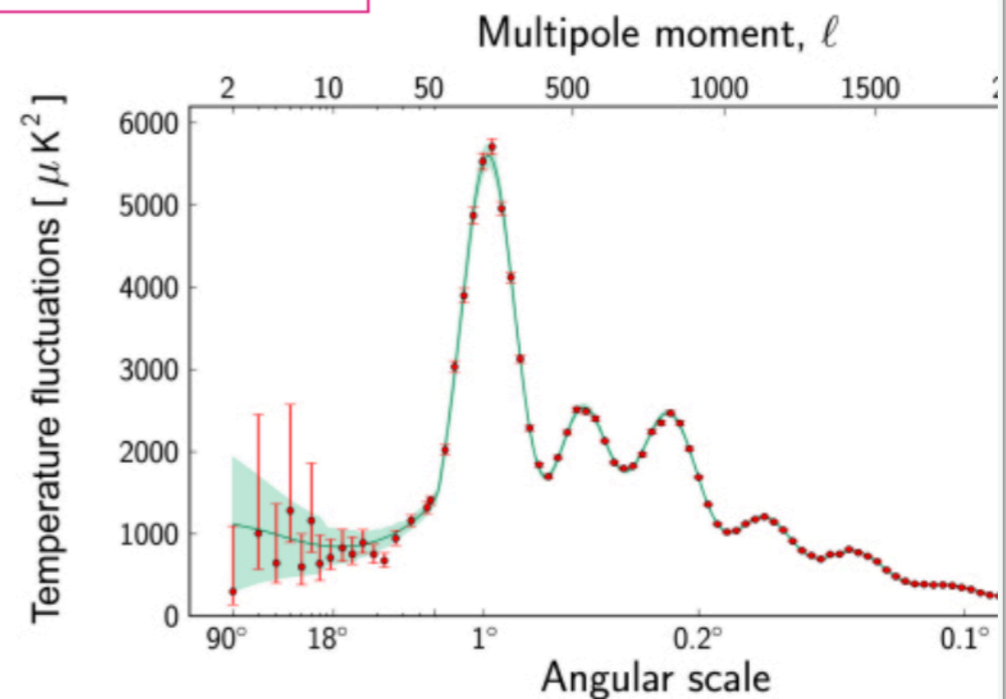
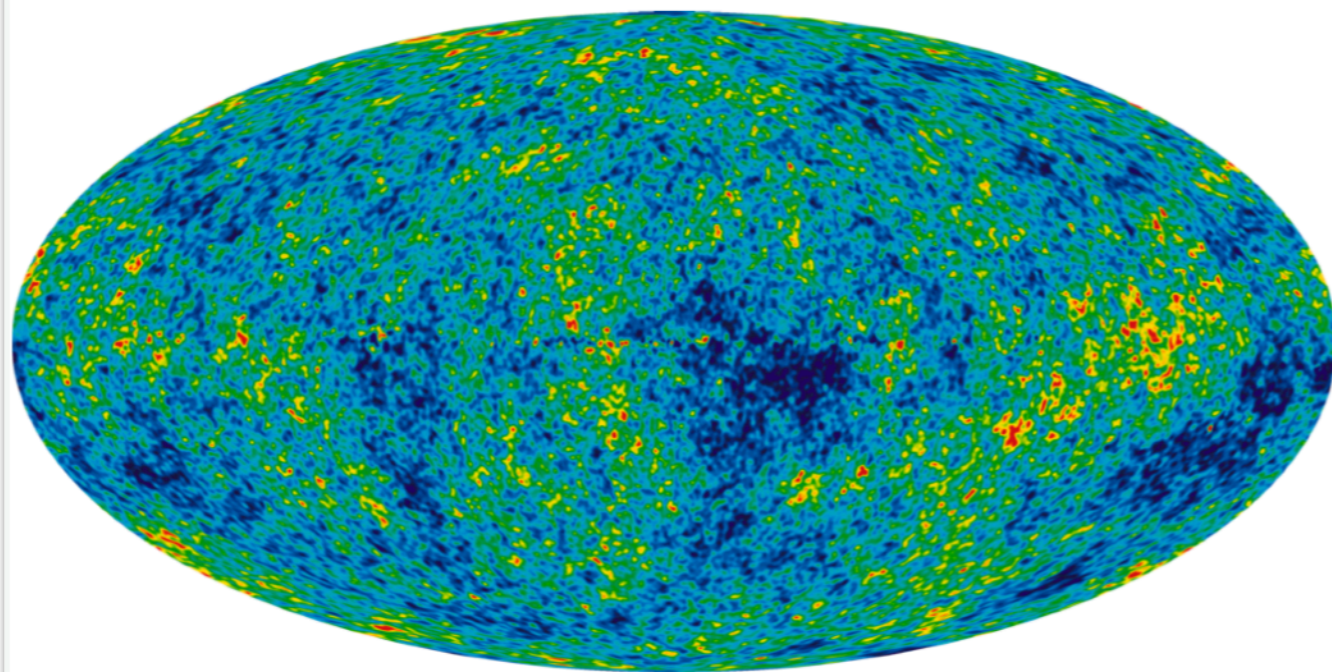
- synthesis of light (H,...) nuclei: “Big Bang Nucleosynthesis” (BBN)
- cosmic microwave background (CMB) properties
- initial conditions for evolution of structures (galaxies, clusters,...)
- ...

The Dark side of the Universe

BBN: $\Omega_{\text{baryons}} \simeq 0.05$ gives correct abundance of H, ^2H , ^3He , ^4He ...!

CMB anisotropies $\Omega_{\text{tot}} = 1$

What is the 95% of the Universe made of??



$$\Omega_{\text{baryon}} = 0.05$$

$$\Omega_{\text{DM}} \simeq 0.27$$

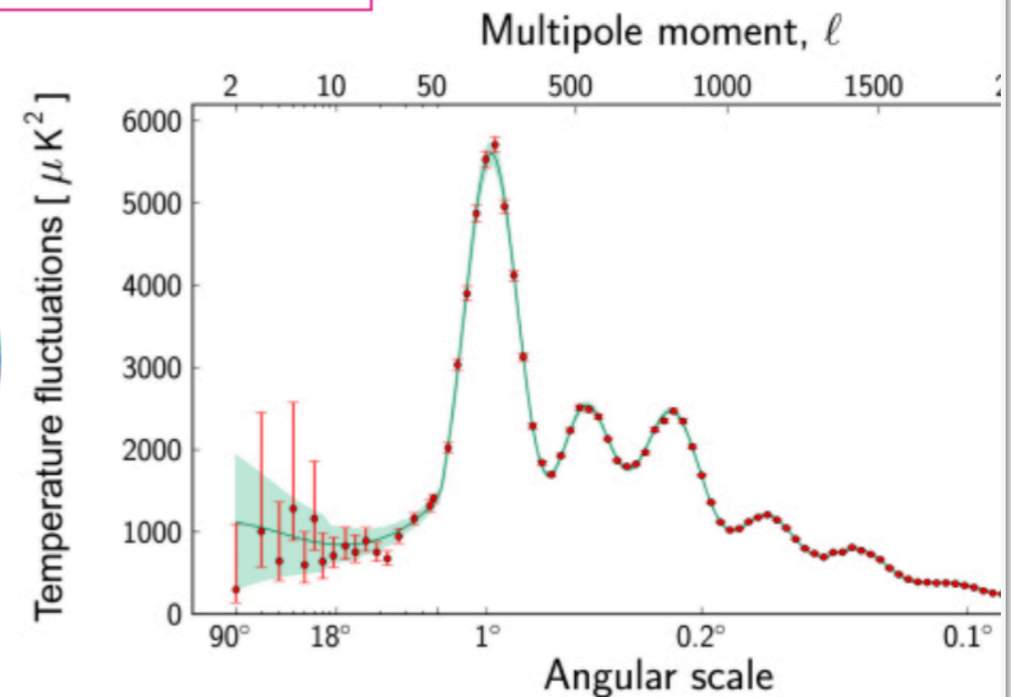
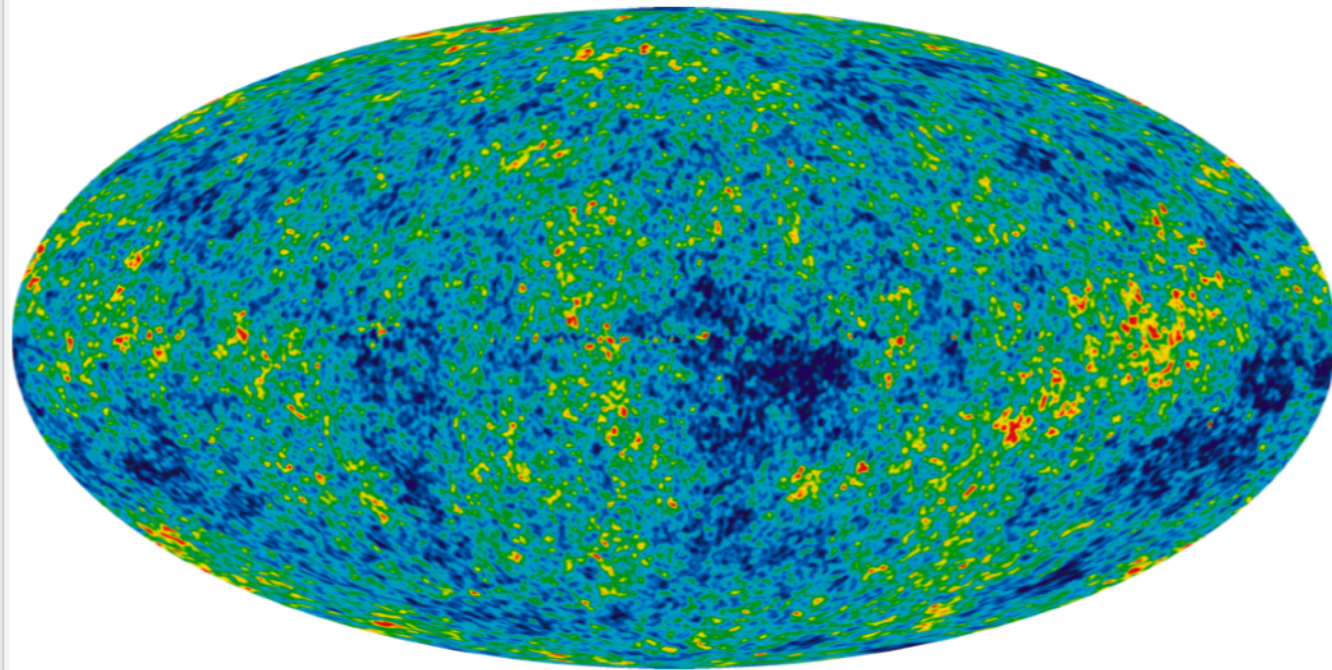
More than 80% of matter in the Universe is **non baryonic** (and **non luminous**)!

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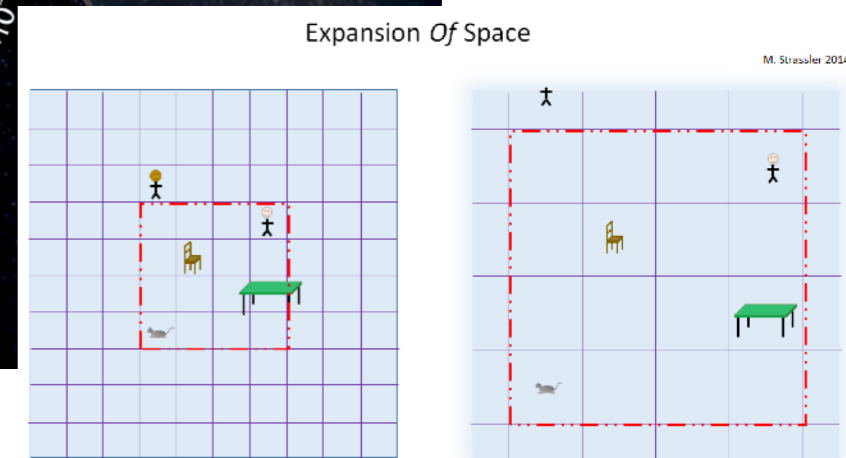
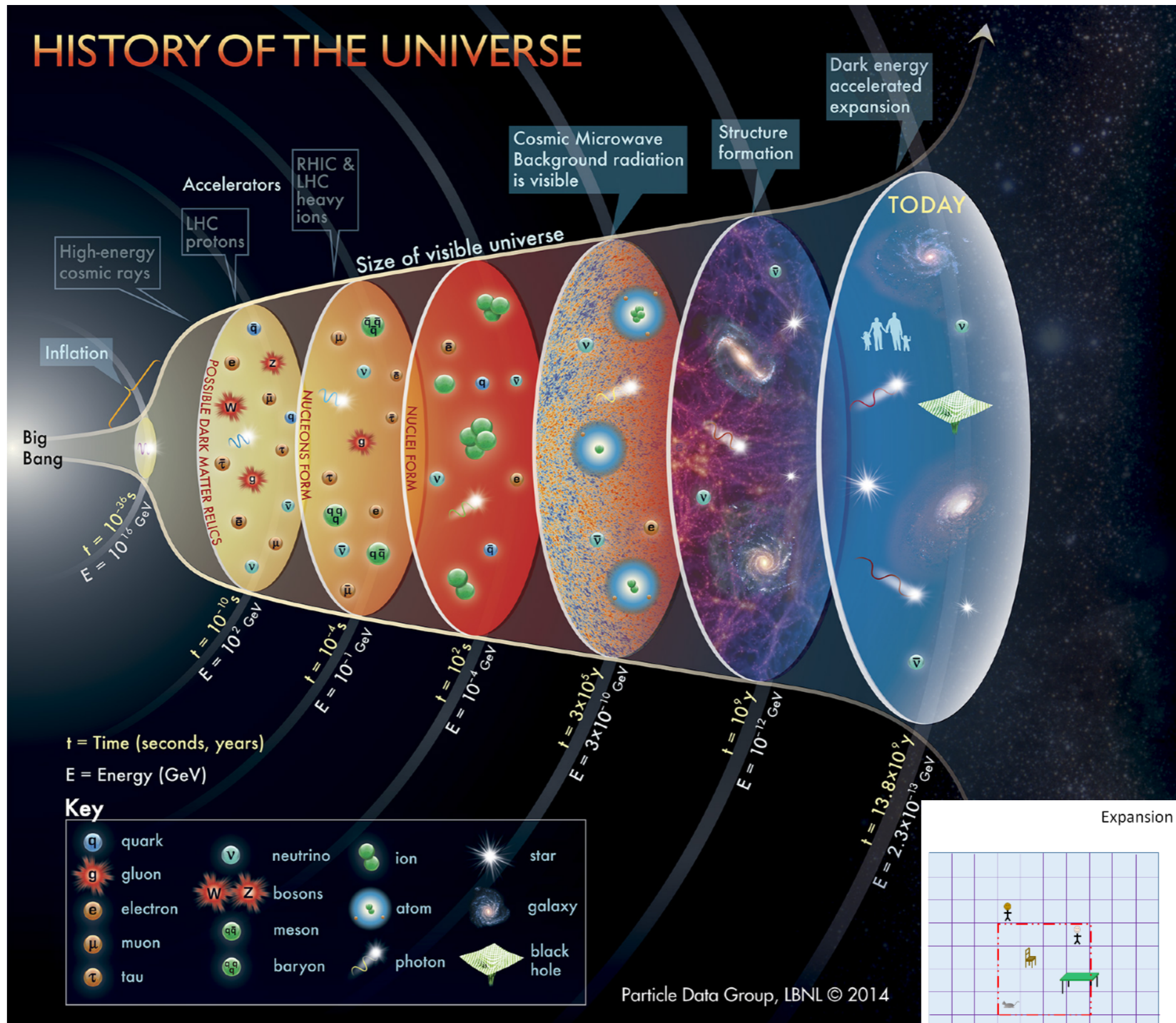
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27% of the Universe is **Dark Matter**

Remaining 68% is **Dark Energy**

(explains observed **accelerated expansion**!)

History of the Universe



Open Questions: 1900 to Today

Open Questions from Data

Open Questions from Theory

Open Questions from Data

Dark Matter

Baryon Asymmetry

Neutrino Oscillations

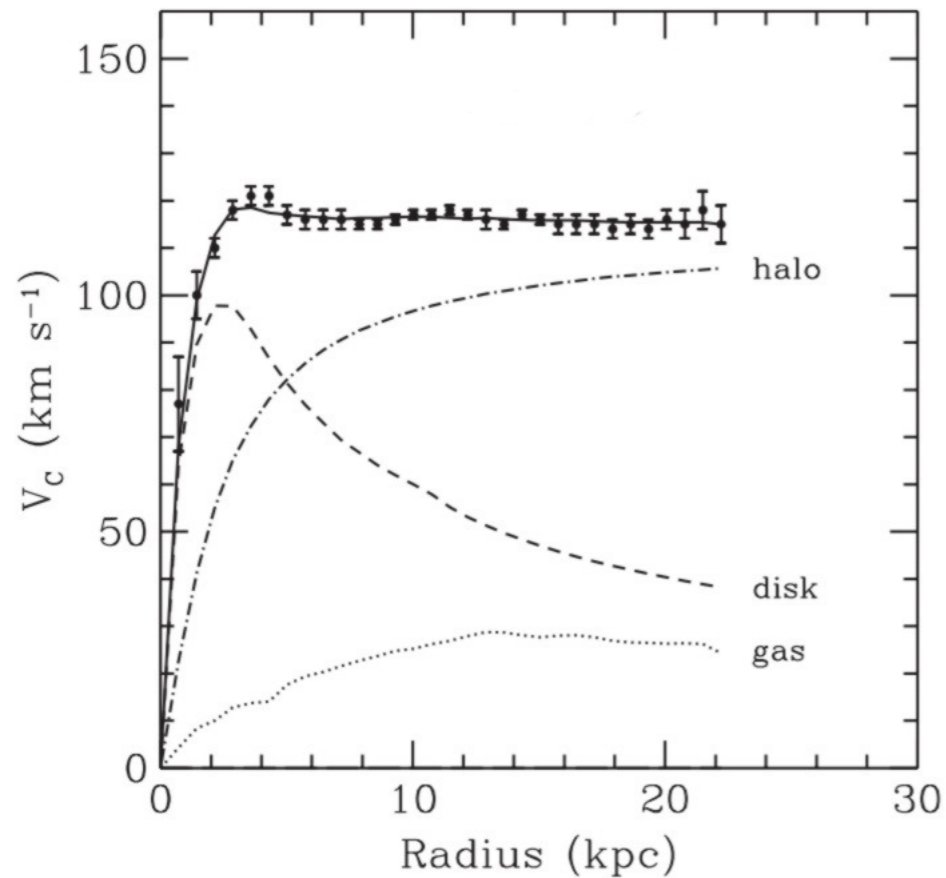
Open Questions from Data

Dark Matter

More Evidences for Dark Matter

see [Bertone Hooper 1605.04909](#) for a historical review

All from **Gravity**, all from Astrophysics Observations

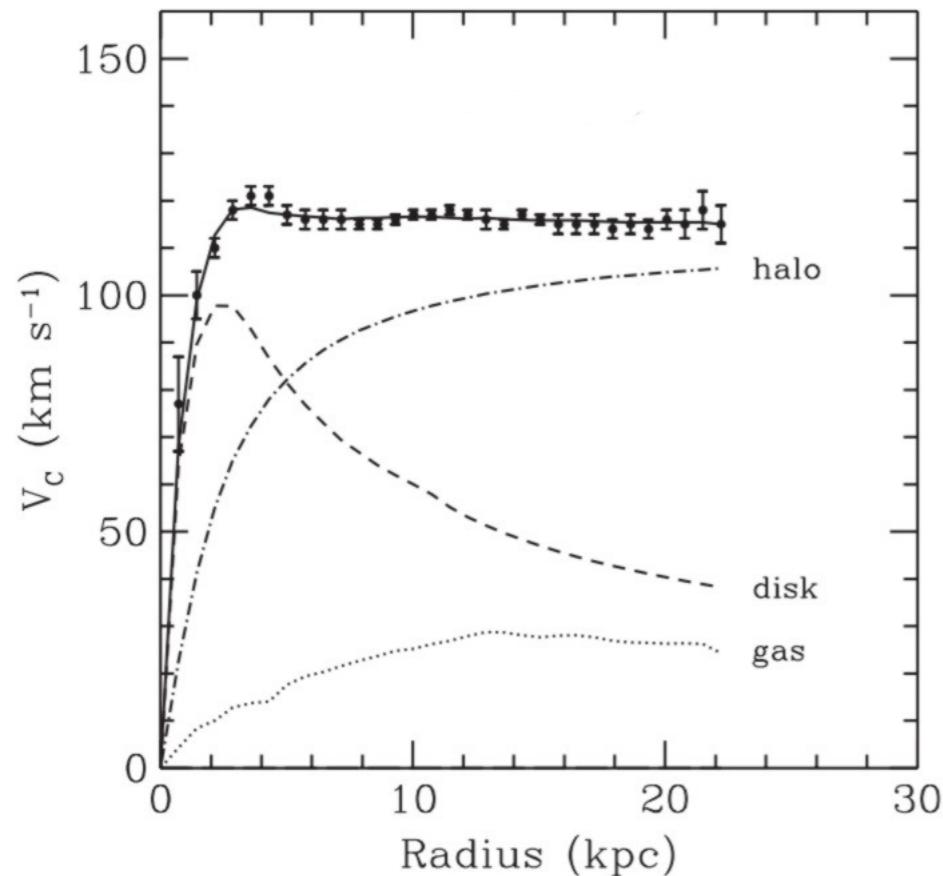


- galaxy rotation curves: $\frac{v^2}{r} > \frac{GM_{\text{visible}}}{r^2}$
- velocity dispersion in clusters:
 $\langle \text{Kinetic energy} \rangle \neq -\langle \text{Potential energy} \rangle$
- gravitational lensing

More Evidences for Dark Matter

see [Bertone Hooper 1605.04909](#) for a historical review

All from **Gravity**, all from Astrophysics Observations



- galaxy rotation curves: $\frac{v^2}{r} > \frac{GM_{\text{visible}}}{r^2}$
- velocity dispersion in clusters:
 $\langle \text{Kinetic energy} \rangle \neq -\langle \text{Potential energy} \rangle$
- gravitational lensing

All these observations are robust! Different techniques → same results

dynamical analyses of i) luminous objects, ii) cold nubes of H_2 , ...

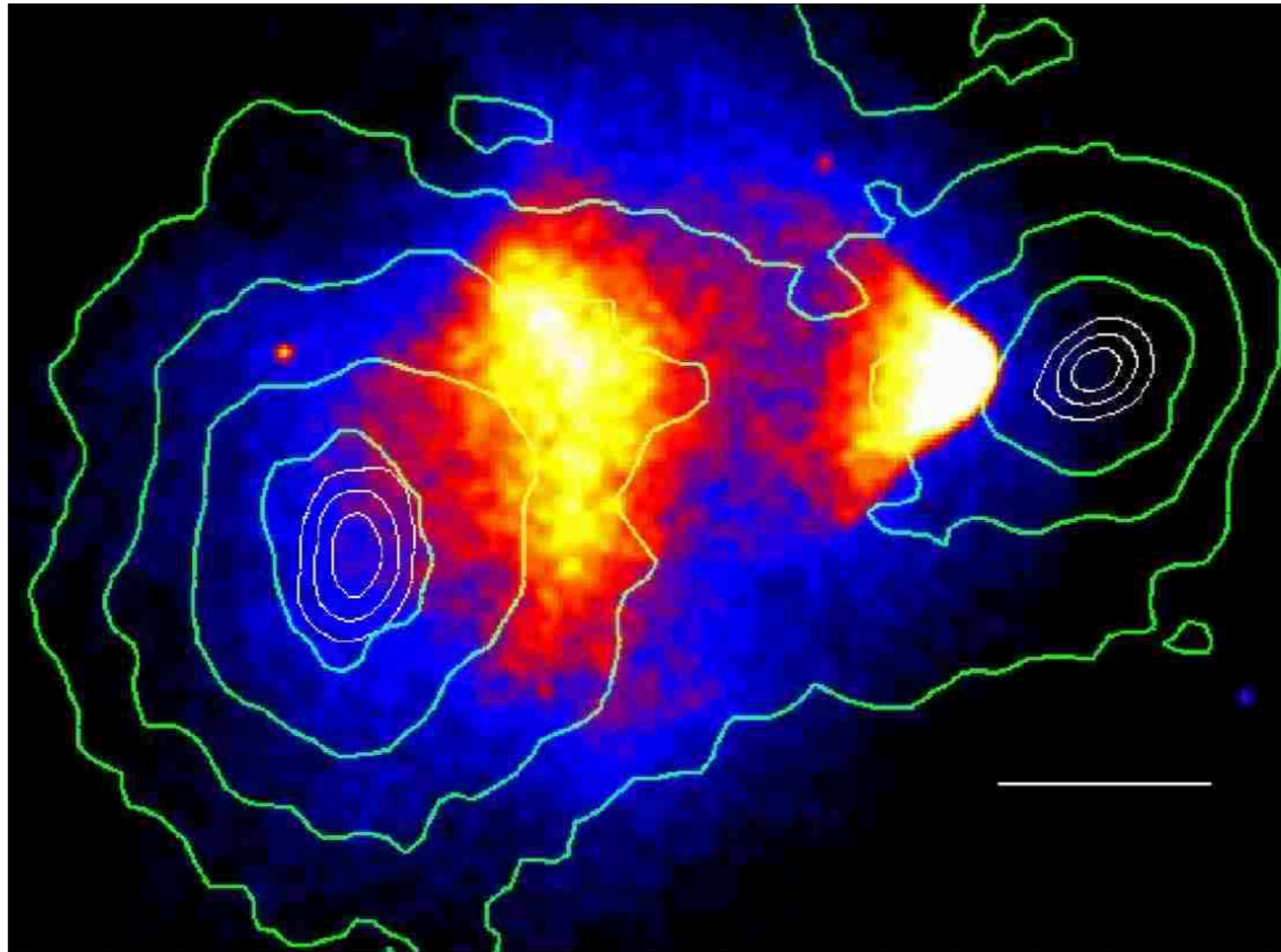
X-ray emission of hot gases

gravitational lensing

...

“Seeing” the Dark Matter

The **Bullet Cluster** [astro-ph/0608407](#)

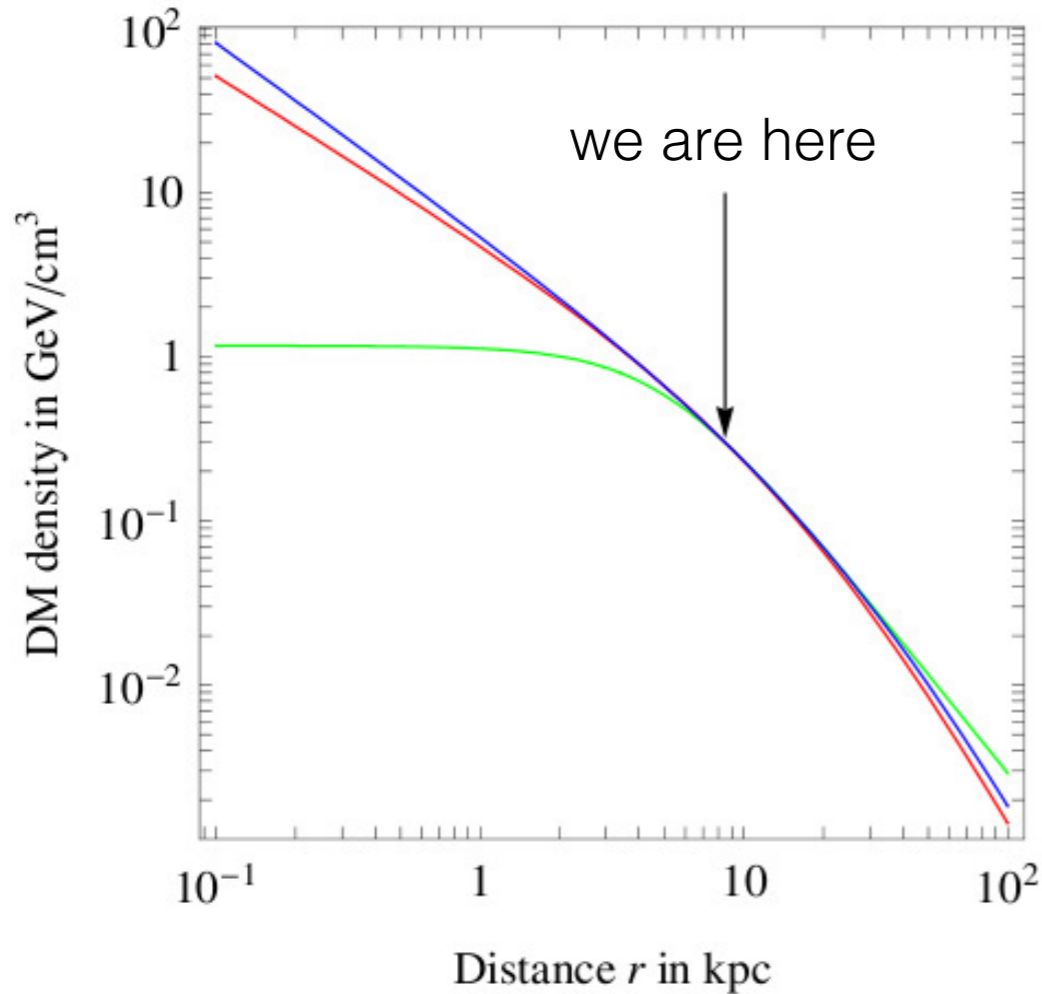


X-ray emission maps distribution of baryonic matter

Gravitational Lensing maps distribution of all matter

Since then many more collisions of clusters observed, confirming the same picture

Properties of Dark Matter

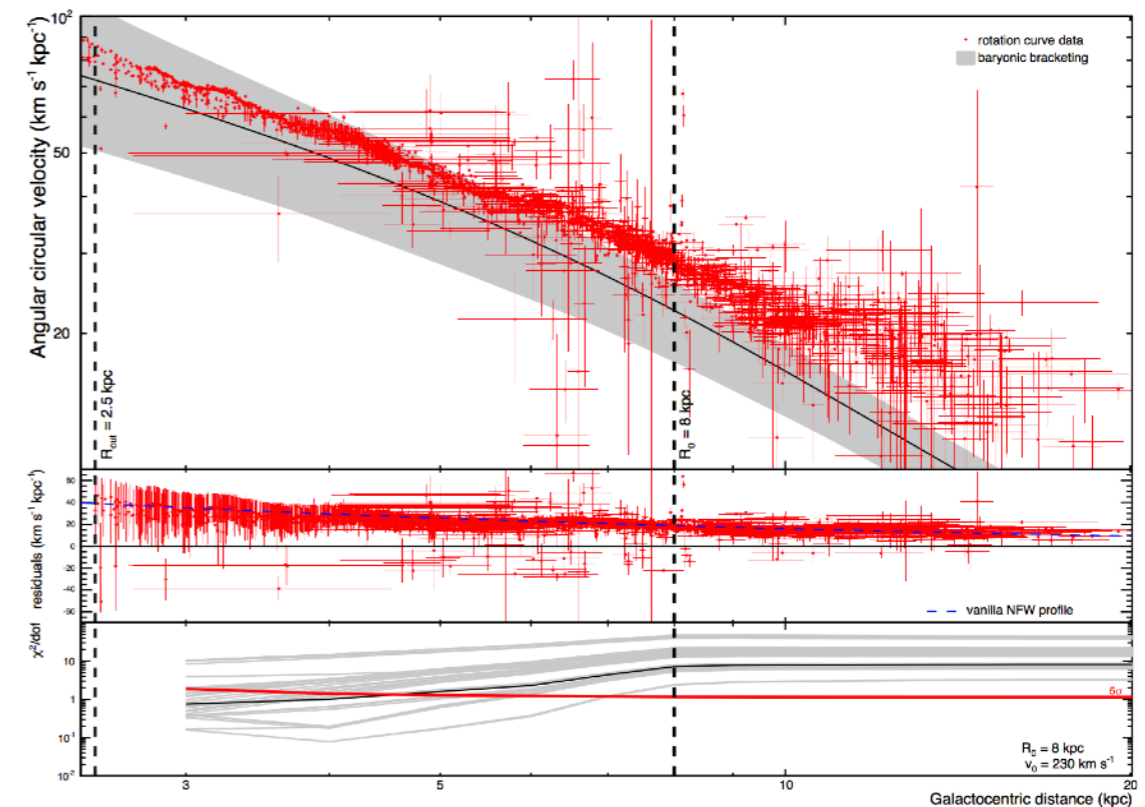


Astrophysics + N-body simulations

- In a galaxy: $R_{DM} \sim 10R_{lumi}$
 $M_{DM} \sim 10M_{lumi}$
- In a cluster:
DM almost absent between galaxies
- Distribution: we do not know yet!
see e.g. [Macciò 1503.04814](#)

- Density at sun position
 $\rho|_{DM}(8.3\text{kpc}) \sim 0.4 \frac{\text{GeV}}{\text{cm}^3}$

[Bertone Iocco Pato 1502.03821](#) →



What could it be?

Q: Why not non-luminous astronomical objects?

(white and brown dwarves, cold gas, black holes,...)

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DM has to be there before Big Bang Nucleosynthesis

(weaker evidence from astrophysics: if all DM were astronomical objects then more heavy elements in halos → more electromagnetic emission)

Besides this, DM could be anything!!

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Example Density of $\rho|_{\text{DM}}(8.3\text{kpc}) \simeq 0.4 \frac{\text{GeV}}{\text{cm}^3}$ is just average!

\rightarrow Neither observations nor N-body simulations resolve solar system they average over thousands of stars

\rightarrow **Exercise:** Integrate $\rho|_{\text{DM}}$ within Saturn orbit: how much DM?

Measurement: $M_{\text{DM}} < 1.7 \times 10^{-10} M_{\text{sun}}$ Pitjev Pitjeva 1306.5534

Dark Matter in the Standard Model?

Requirements for **particle Dark Matter**

- 0 must be **stable**
- 1 must have (almost) **zero electric charge**
otherwise it would not be Dark!
- 2 must **not interact with gluons**, and little with Z, W
otherwise we would have already seen it in experiments (see last slides)

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Another candidate that might not require BSM physics: a di-baryon *uuddss*

Farrar 1711.10971 & refs therein

Long-known it could be very bound (isospin singlet) Jaffe NPPS 24B (1991)

Turns out that its abundance would be way too small Gross+ 1803.10242