Precision Physics and Antimatter

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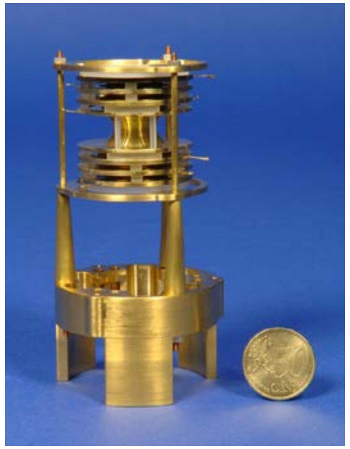
Christian Smorra

master/PhD thesis

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ



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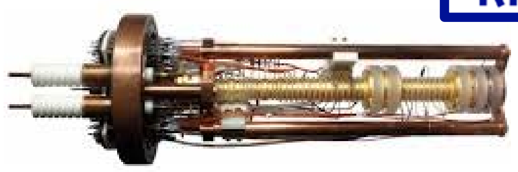
BASE

RIKEN



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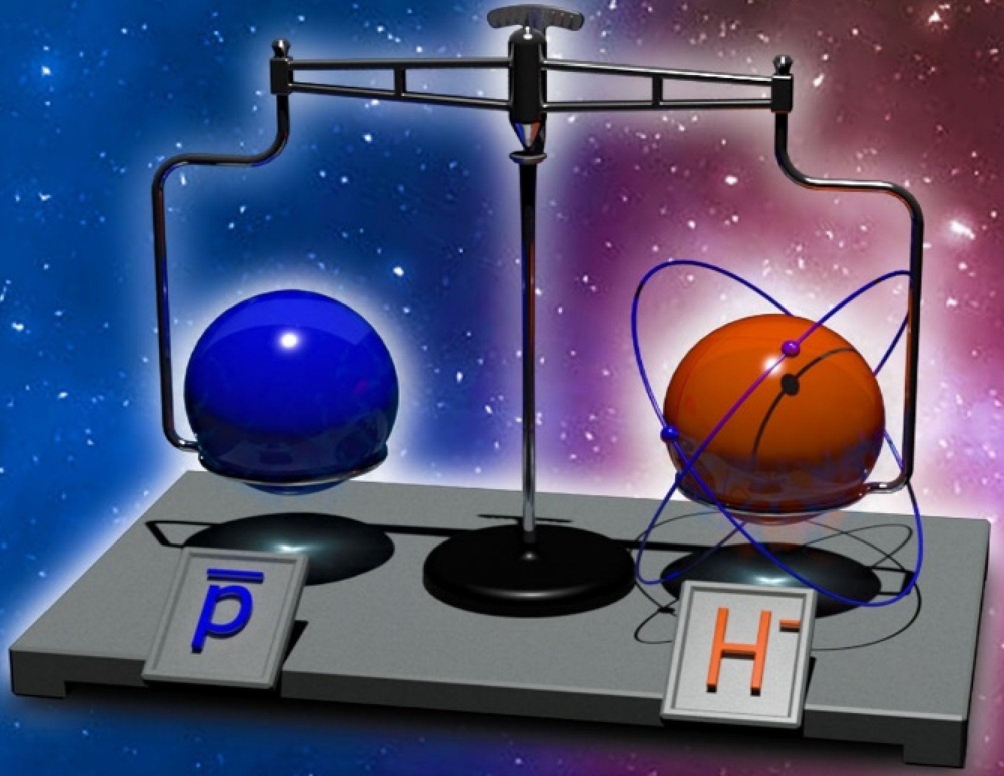
CERN

High precision measurements of the antiproton and proton magnetic moments

C. Smorra et al., A ppb measurement of the antiproton magnetic moment, Nature, doi:10.1038/nature24048 (2017).
A. Mooser et al., High-precision measurement of the magnetic moment of the proton, Nature 509, 596 (2014).

High-Precision Comparison of the



Antiproton-to-Proton Charge-to-Mass Ratio

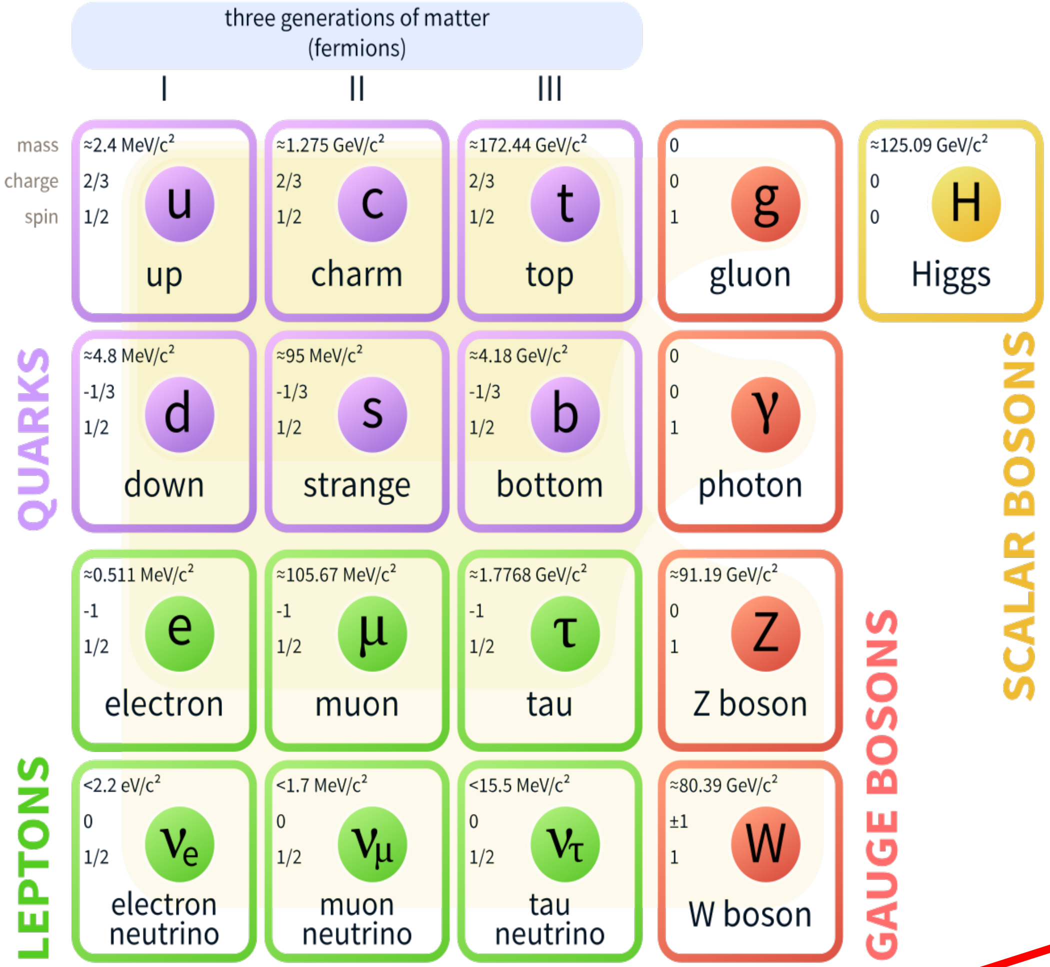
S. Ulmer, C. Smorra, A. Mooser et al., High-precision comparison of the antiproton-to-proton charge-to-mass ratio. Nature 524, 196 (2015).

Index

Monday	Introduction: • Why precision physics?/Why antimatter? • History of antimatter and CPT invariance
Tuesday	• The antiproton decelerator • Stopping and storing antiparticle • Antihydrogen experiments – Part 1
Wednesday	• Antihydrogen experiments – Part 2 • Single-particles in a Penning trap
Thursday	• Magnetic moment measurements
Friday	• Exotic atom spectroscopy • Antiproton lifetime limits • Antiproton charge-to-mass ratio measurement

Precision experiments and antimatter

The Standard Model of Particle Physics



- Based on Quantum Field Theory

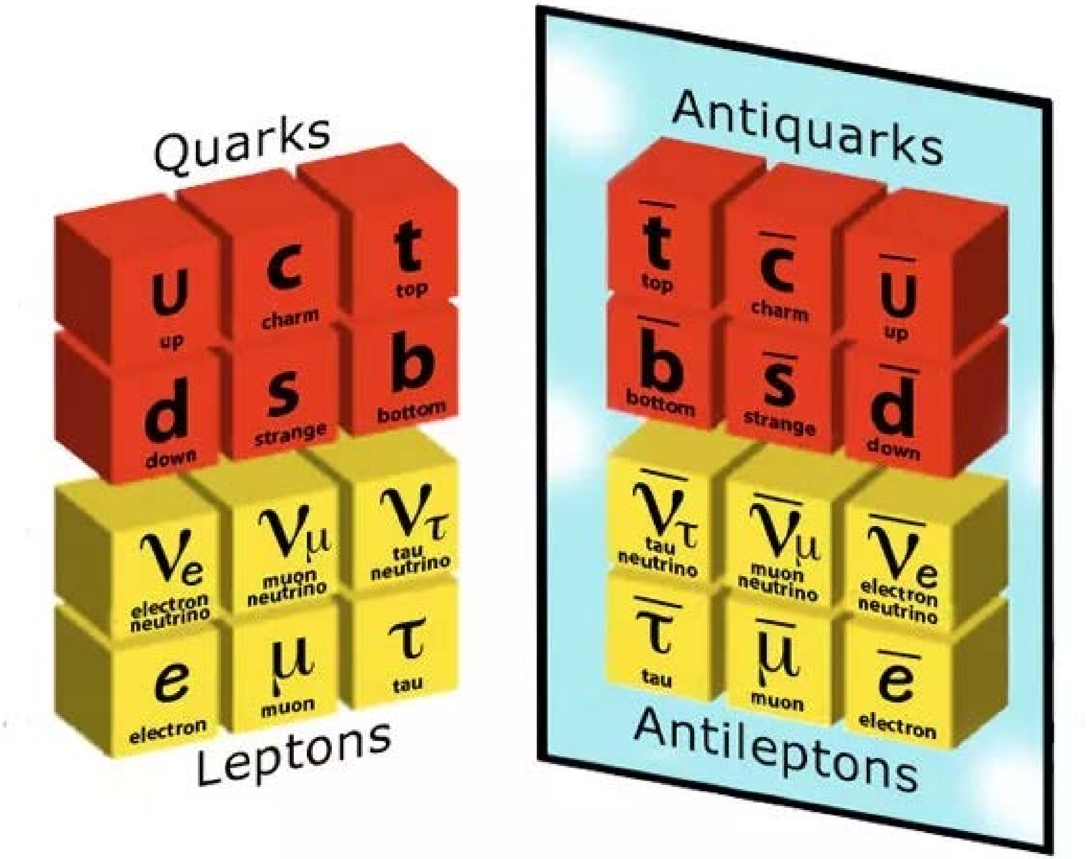
- Fermions as fundamental particles
- Bosons as force carriers
  - Electromagnetic interaction
  - Weak interaction
  - Strong interaction

Unified in the SM

Gravitation/ General Relativity

D. H. Perkins, Introduction to High Energy Physics, ISBN-13: 978-0521621960

Antiparticles/Antimatter



- Each fermion has an antiparticle
  Consequence of Dirac's equation

- Antiparticle are an
  exotic species in our universe

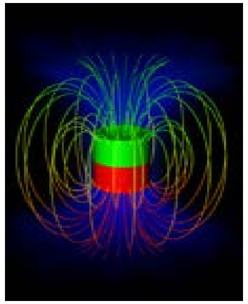
- CPT invariance:
  Fundamental interactions are invariant under the combined charge-parity-time (CPT) reversal transformation

- Conjugate fermions have identical masses(+), lifetimes(+), charges(-) and magnetic moments(-)

How precise can the Standard Model be tested?

- The electron magnetic moment is one of the most precisely predicted quantities by the Standard Model:

Magnetic moment: $\vec{\mu} = \frac{\mu}{\mu_B} \mu_B \frac{\vec{S}}{\hbar/2}$



g-factor: $\frac{g}{2} = \frac{\mu}{\mu_B}$

Bohr magneton: $\mu_B = \frac{e\hbar}{2m_e}$

- Dirac's equation predicts g=2 for fermions with no sub-structure

D. Hanneke et al., Phys. Rev. Lett. 100, 120801 (2008).

Corrections to the electron g-factor

$$\frac{g_{electron}}{2} = C_0 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \cdots + a_{\mu,\tau} + a_{weak} + a_{hadrons}$$

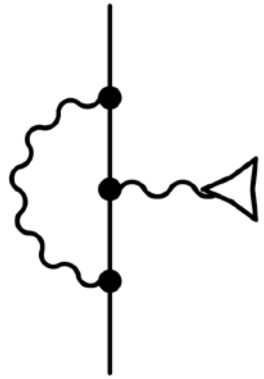
$C_0 = 1$ is obtained from Dirac's equation.

Higher-order corrections stem from the interaction of the electron with the radiation field

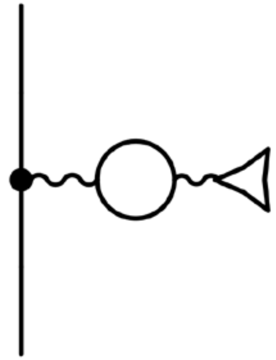
$$(g_{electron}/2)_{exp} = 1.001\,159\,652\,180\,73(28)$$

$$(g_{electron}/2)_{theo} = 1.001\,159\,652\,181\,78(77)$$

Lowest-order QED corrections



Self energy



Vacuum Polarization

The Standard models most precise prediction is accurately tested with $3 \cdot 10^{-13}$ relative precision!

D. Hanneke et al., Phys. Rev. Lett. 100, 120801 (2008).
T. Aoyama et al., Phys. Rev. Lett. 99, 110406 (2007).

Why should we continue to study fundamental physics?

1874: Phillip von Jolly to young Max Planck:

„[Die Physik ist] eine hochentwickelte, nahezu voll ausgereifte Wissenschaft [...], [sie] nähere sich merklich demjenigen Grade der Vollendung, wie ihn etwa die Geometrie schon seit Jahrhunderten besitzt.“

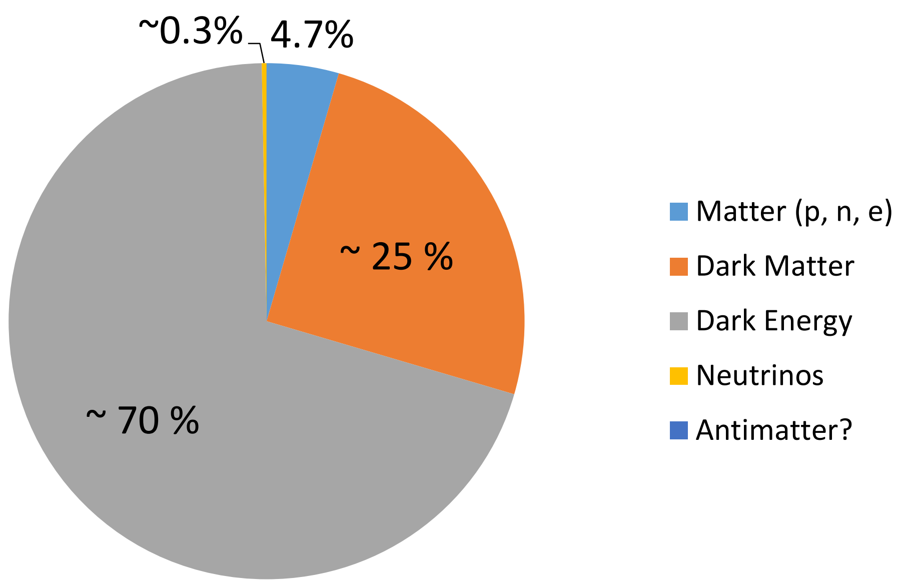
1918: Max Planck received the Nobel price for physics for postulating the energy of electromagnetic radiation is quantized (photon energy: $E=h\nu$)

Today: The situation is completely different.

The Standard Model leaves us with many open questions, to which we have not found any satisfying answers!

The pie chart of the universe

What we think the universe is made of:



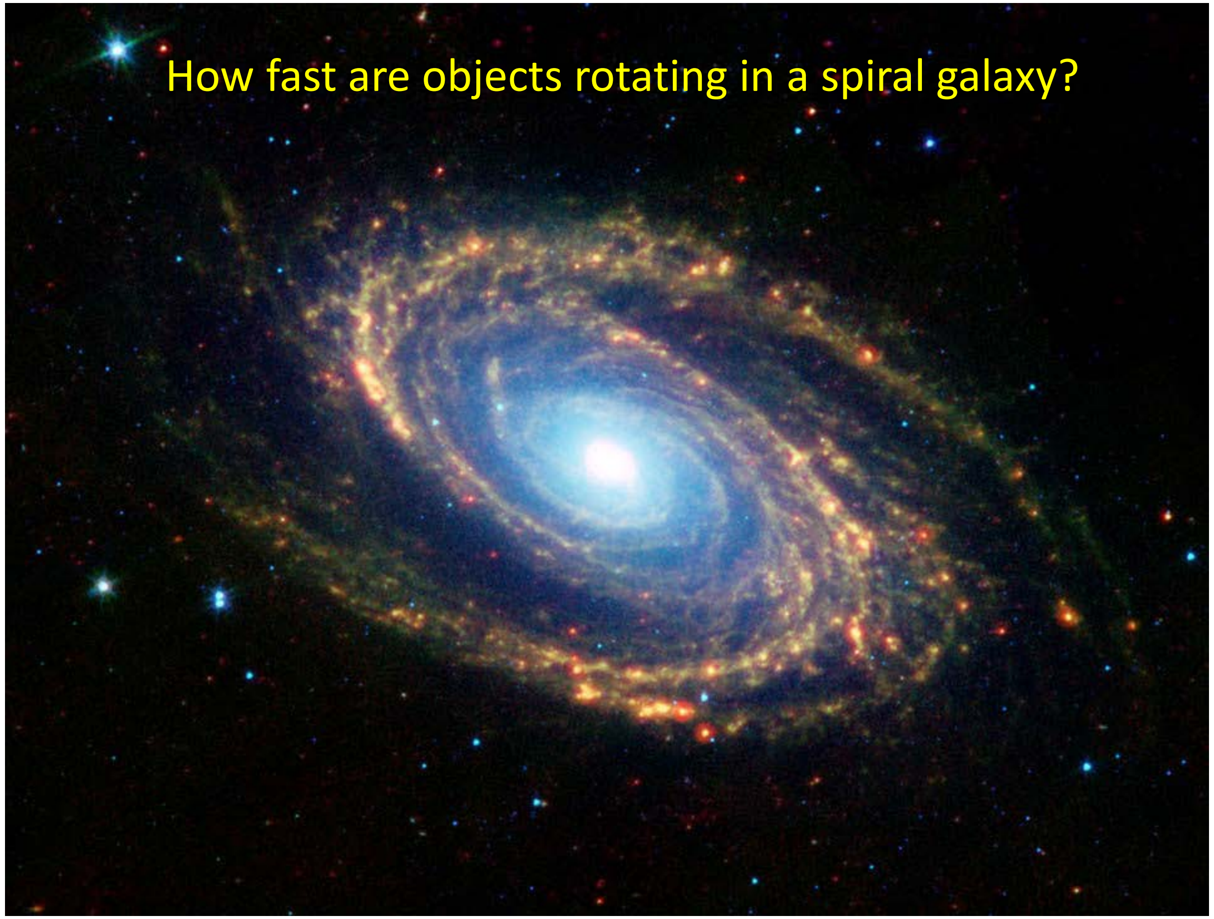
Three examples for phaenomena in cosmology which eluded any explanations verified in any experimental observation:

What is dark matter?

What is dark energy?

Where is all the antimatter?

Why should there be Dark Matter?



Central gravitation potential:

$$m\frac{v^2}{r_0} = \gamma \frac{M(r < r_0)\, m}{r_0^2} \Longrightarrow v \propto r_0^{-1/2}$$

Rigid rotor:

$$v = \omega r_0$$

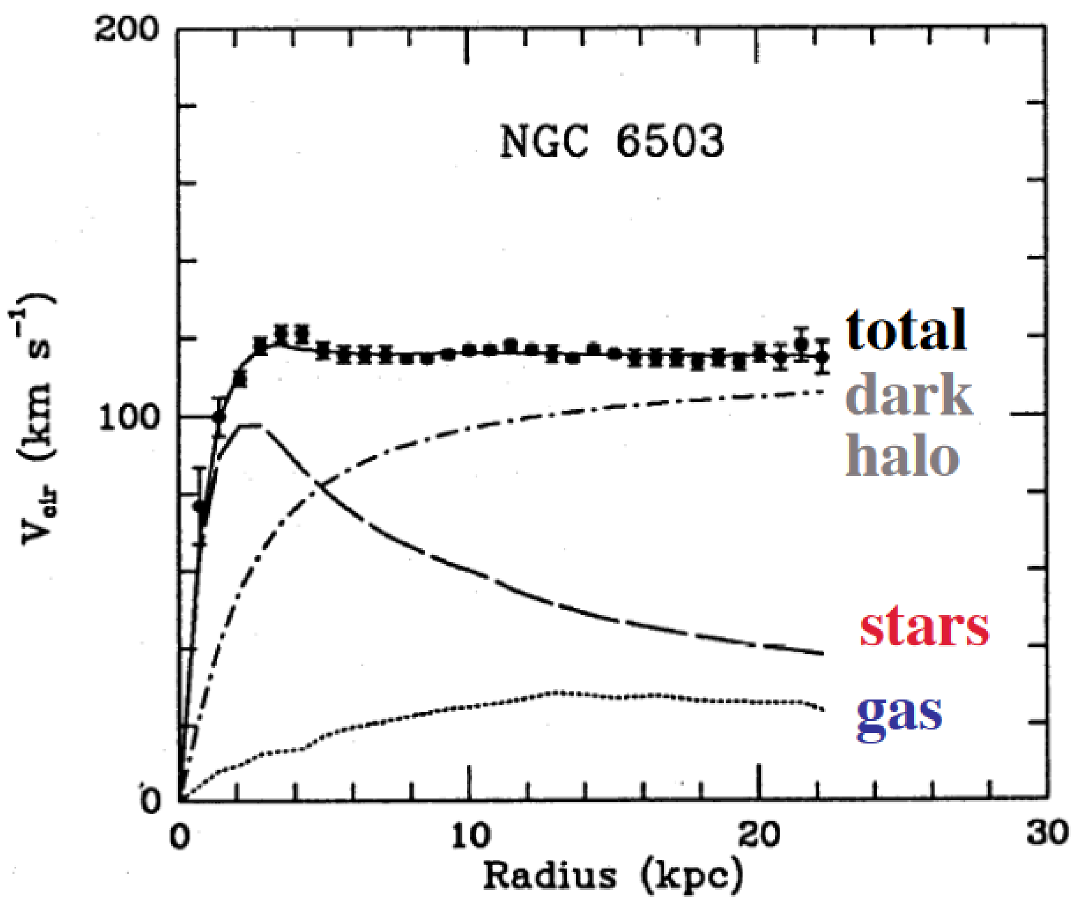
$v(r)$ allows to infer the mass distribution of the galaxy, which can be compared to the baryonic matter distribution of the “luminous matter”.

The velocity can be measured by the redshift of e.g. the 21 cm^{-1} hydrogen line from the ground state hyperfine transition.

Review of particle physics, Particle Data Group, Chapter 26, http://pdg.lbl.gov/
C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).

Why should there be Dark Matter?

A typical observation



Rotation curves require additional mass compared to the observable baryonic matter

What particles is dark matter made of?

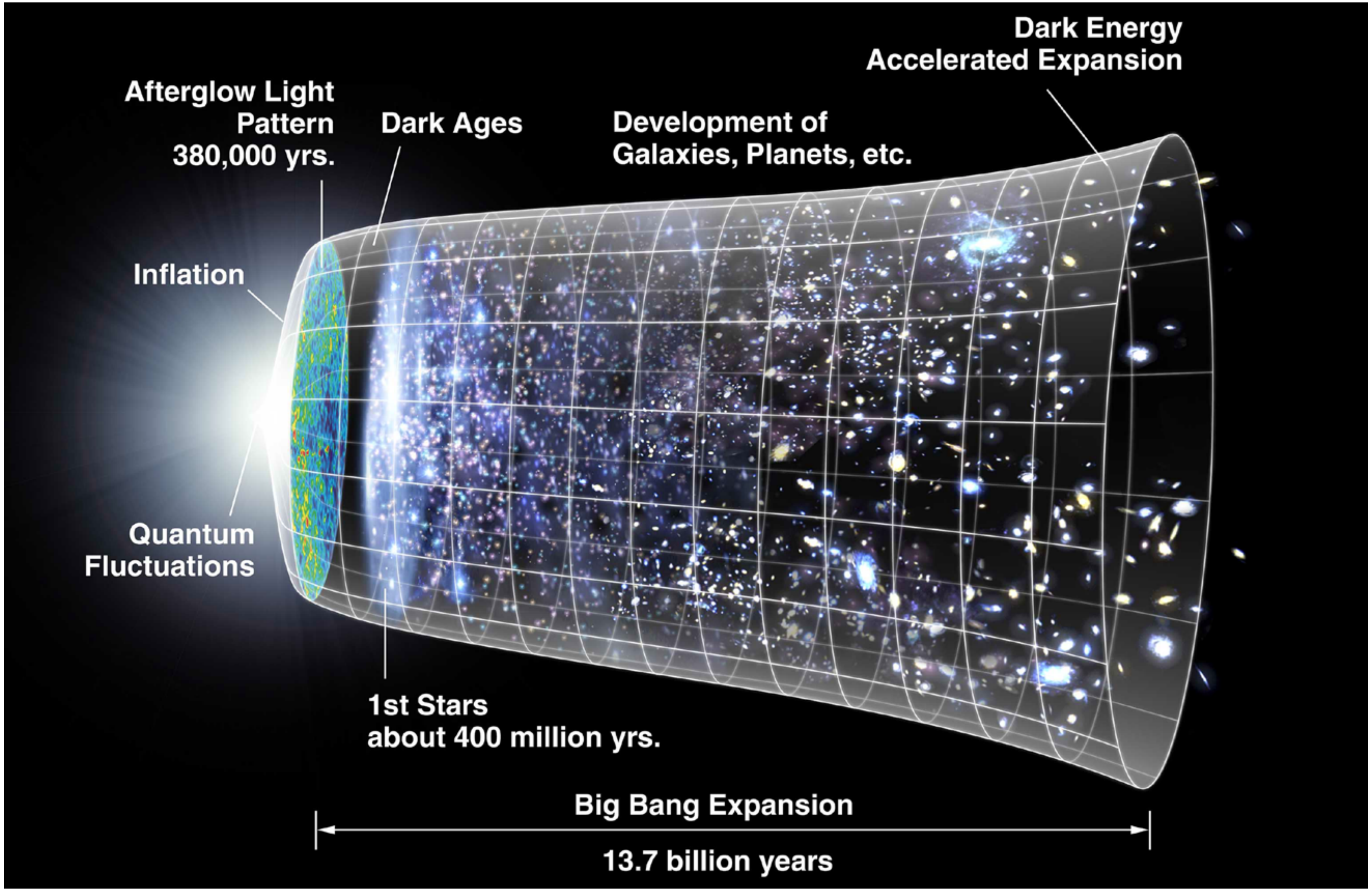
Is our understanding of gravitation correct?

How does dark matter interact with the Standard Model particles?

How can we observe dark matter in laboratory experiments?

Review of particle physics, Particle Data Group, Chapter 26, http://pdg.lbl.gov/
C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).

Our picture of the universe



Big bang model:

1) Hubble's law:* $\mathrm{v} = H \cdot r$
   The universe is expanding

2) The cosmic microwave background radiation (CMB)

3) Abundance of the light elements

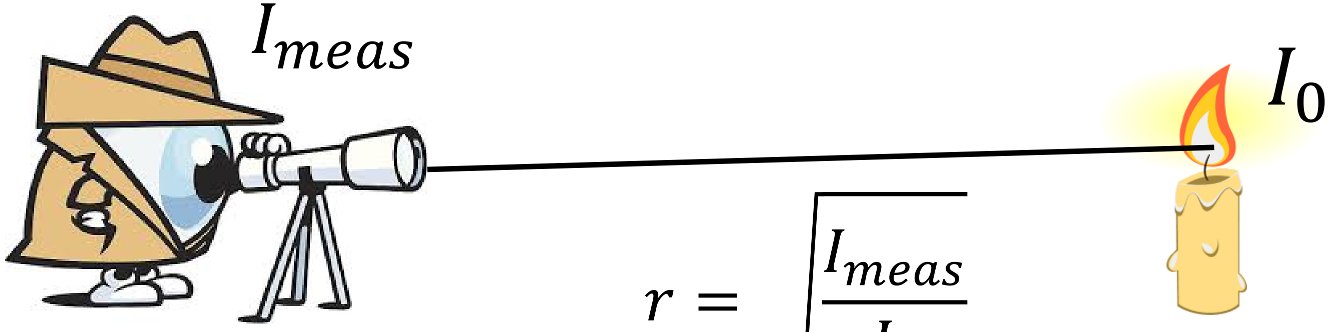
4) Anisotropy of the CMB

D. H. Perkins, Introduction to High Energy Physics, ISBN-13: 978-0521621960

Hubble's law at large distances

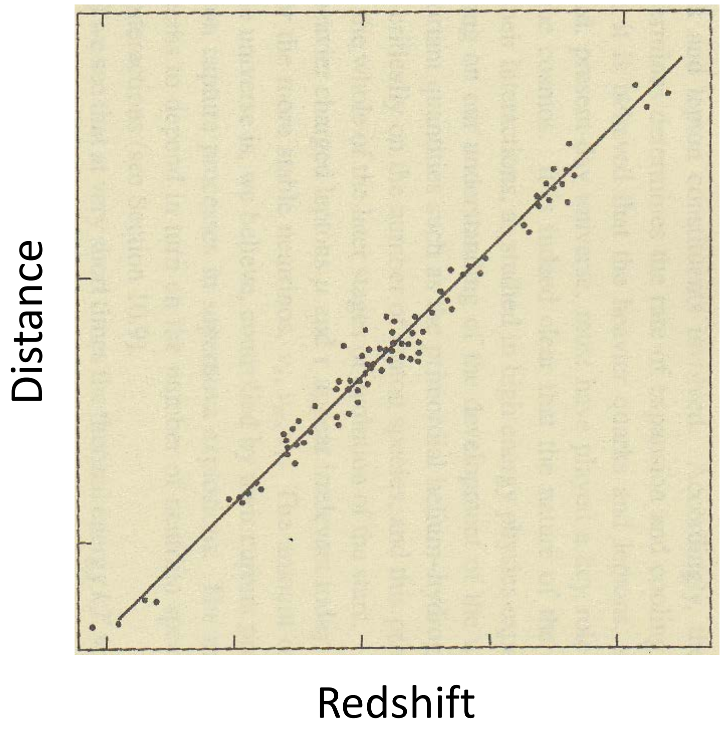
- Gravity is supposed to slow down the expansion of the universe
- Observations until the 1990s were not able to extend Hubble's diagram to large distances to see any gravity effect
- Relative velocity is measured from red-shift of transition lines
- Distance measurements require a "standard candle":

$$\mathrm{v} = H \cdot r$$



$$r = \sqrt{\frac{I_{meas}}{I_0}}$$

Hubble plot



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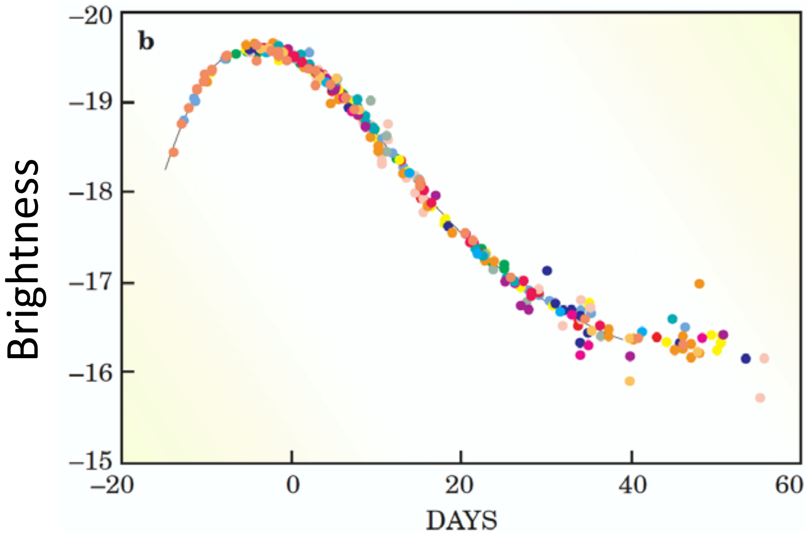
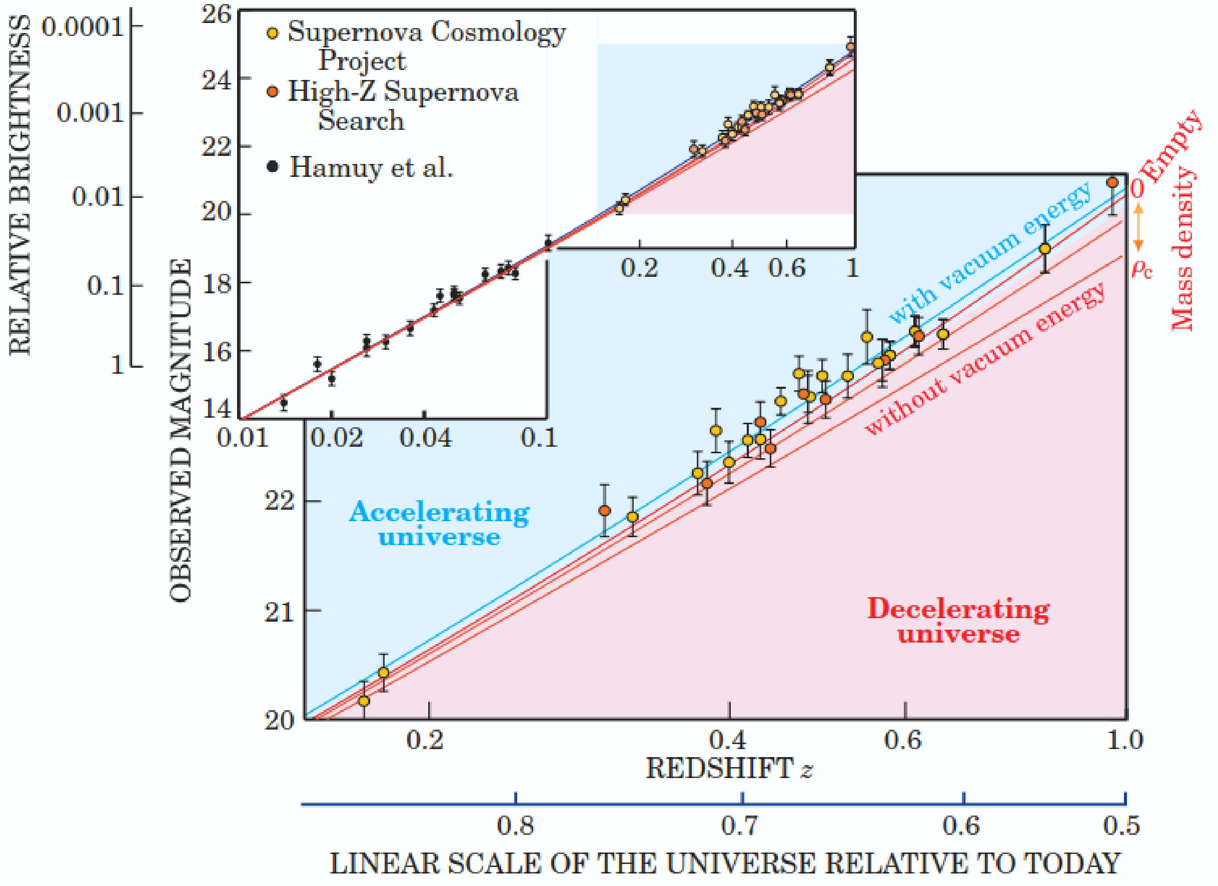
Review of particle physics, Particle Data Group, Chapter 27, http://pdg.lbl.gov/
C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).

Why should there be dark energy?

- A "Standard candle" has been found in Supernovae type Ia.



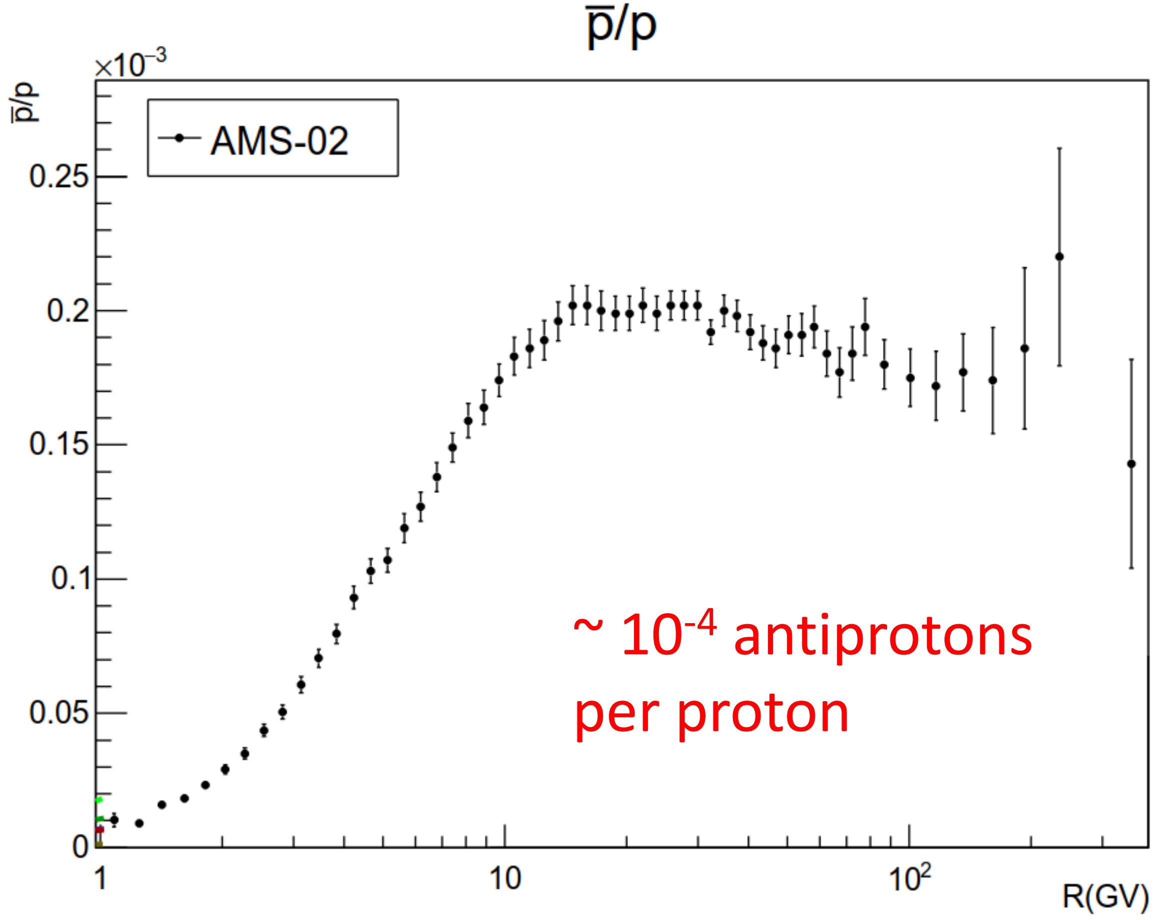
- Observation of distant supernovae show that the redshift for distant supernovae is smaller than expected
- What is the mysterious force accelerating the expansion of the universe?
- Are the laws of physics inferred from laboratory experiments valid at all scales?



S. Perlmutter, Physics Today 56, 4, 53 (2003).
Review of particle physics, Particle Data Group, Chapter 27, http://pdg.lbl.gov/
C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).

Antimatter in the universe

Cosmic ray flux analysed with the Alpha Magnetic Spectrometer (ISS)



R. Kappl et al., JCAP09, 051 (2014).
S.J. Lin et al., arXiV 1612.0400, (2016).

Baryon asymmetry:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6 \times 10^{-10}$$

($n_{\bar{B}}$: ≈ 0)

No annihilation radiation/ No primordial antinuclei

Possibilities:

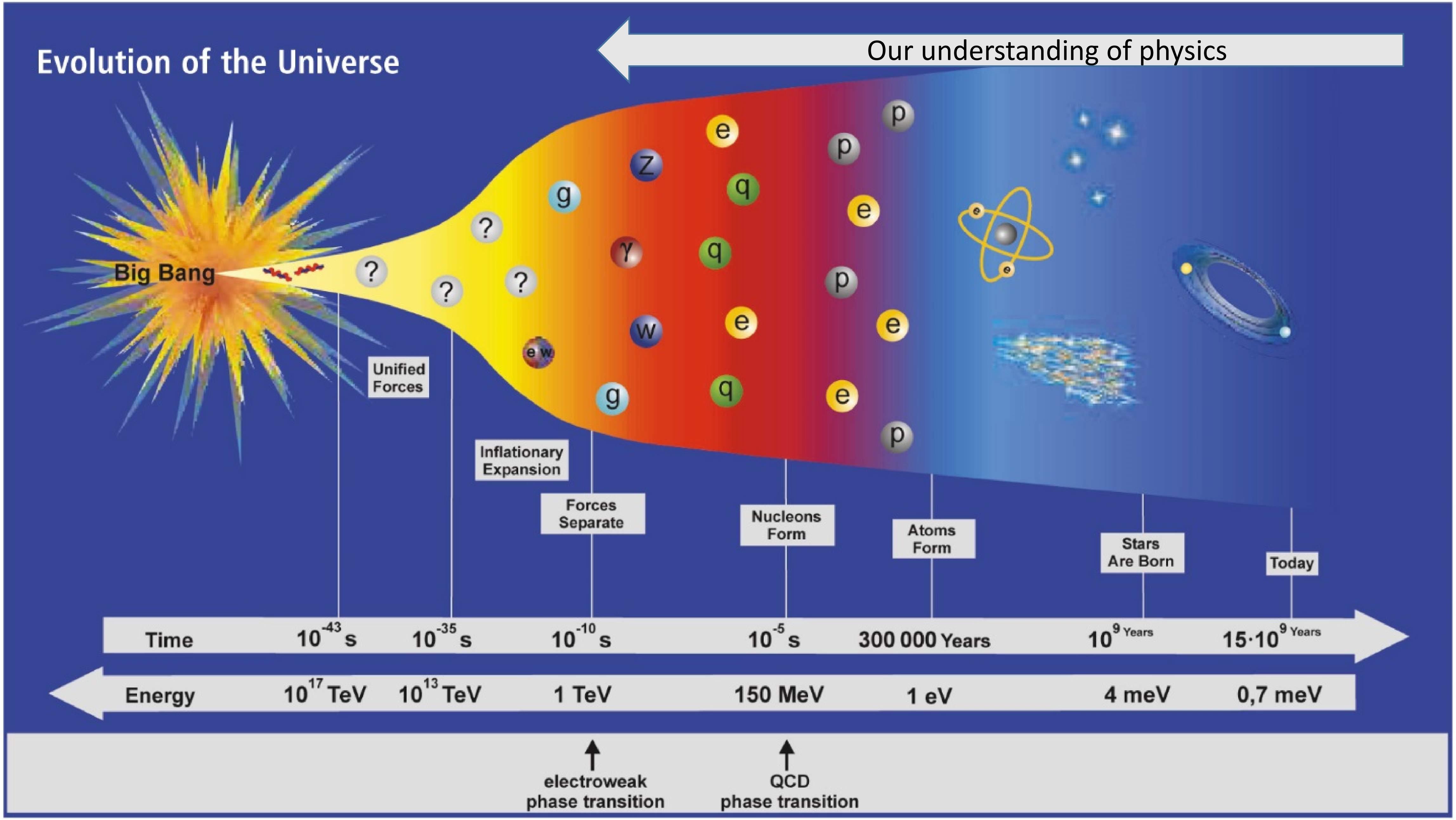
1.) Asymmetric universe,
B > 0 , since the Big Bang (t = 0)

2.) Symmetric universe,
B = 0, separated “matter/antimatter bubbles”
In this scenario: $\eta \approx 10^{-18}$

3.) Baryogenesis
B = 0 (t = 0), and now B > 0

How was this matter-antimatter asymmetry created?

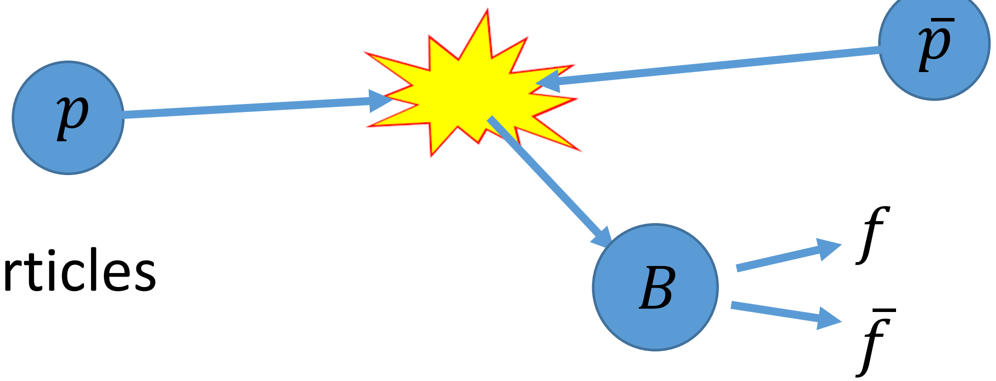
D. V. Perepelitsa, Sakharov Conditions for Baryogenesis, Columbia University



Evolution of the Universe
Our understanding of physics
Big Bang
?
e w
g
Z
γ
W
e
q
p
Unified Forces
Inflationary Expansion
Forces Separate
Nucleons Form
Atoms Form
Stars Are Born
Today
Time
10^{-43} s
10^{-35} s
10^{-10} s
10^{-5} s
300 000 Years
10^{9} Years
$15 \cdot 10^{9}$ Years
Energy
10^{17} TeV
10^{13} TeV
1 TeV
150 MeV
1 eV
4 meV
0,7 meV
electroweak phase transition
QCD phase transition

How to find “Physics beyond the Standard Model?”

- High energy experiments (direct search)
  - Produce and detect new particles in high energy particle collisions
  - High energies needed to make non-virtual particles



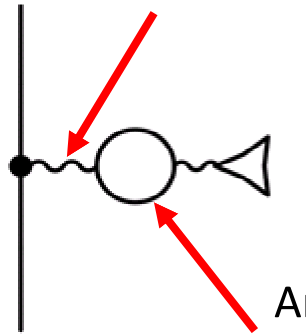
- Precision experiments: (indirect search)

$$\frac{g_{electron}}{2} = 1 + a_{QED} + a_{\mu,\tau} + a_{weak} + a_{hadrons} + a_{New\ physics}$$

Mass dependence for massive bosons: $\approx \frac{1}{k^2 - m^2 + j\varepsilon}$

Mass dependence for fermions: $\frac{1}{\gamma^\mu p_\mu - m + j\varepsilon}$

Any interacting boson



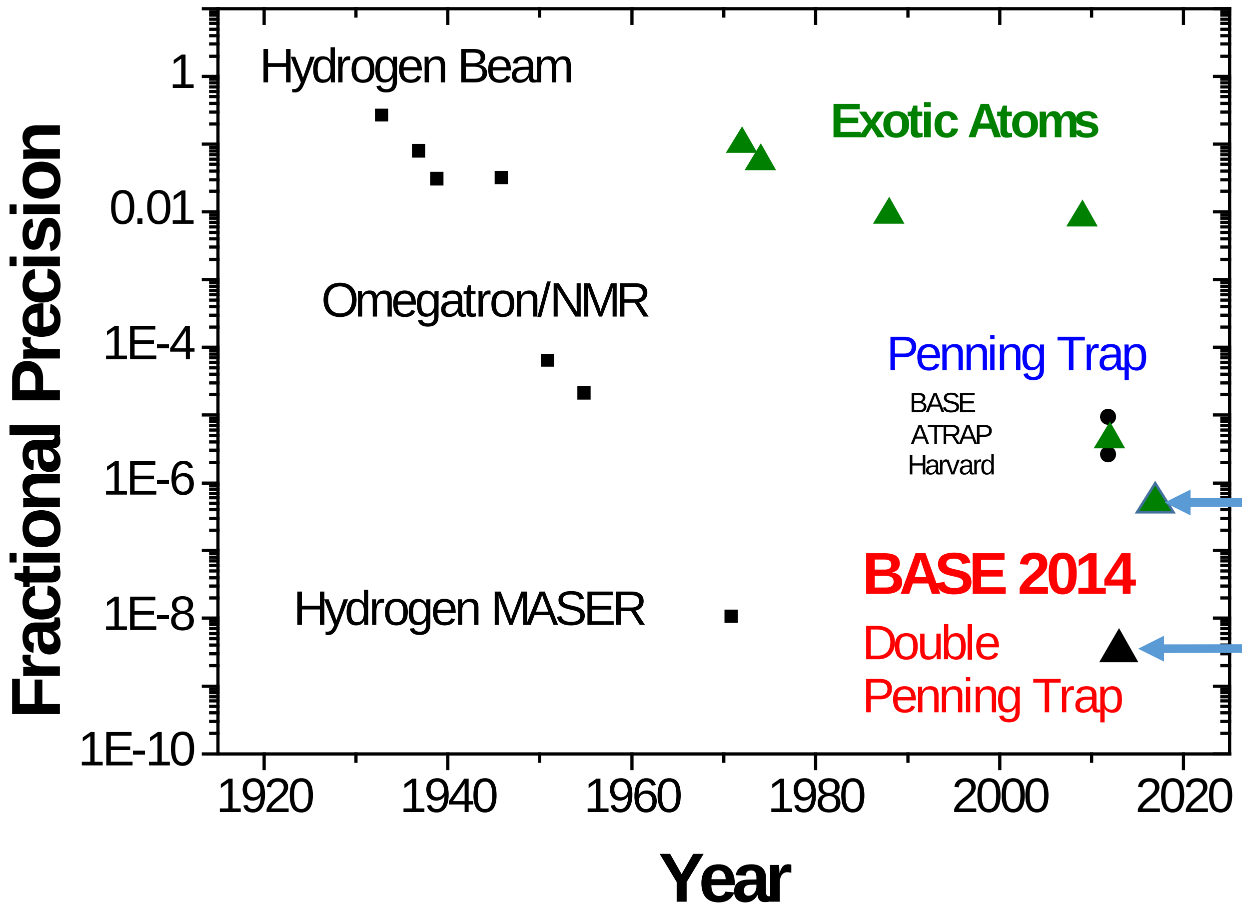
Any fermion/ antifermion pair

Why antimatter?

- Antimatter and antiparticles are exotic species
  - Measuring their properties is a challenge
  - Some antimatter properties are still not well known
- Many of our experimental observations rely on matter-based experiments
  - Gravitation of antimatter has never been observed directly
  - Stringent tests of CPT-invariance from co-magnetometer measurements (He/Xe)
- We rely on CPT invariance and the validity of the weak equivalence principle to predict the behaviour of antimatter

Their validity has to be experimentally confirmed in antimatter experiments

Proton/Antiproton Magnetic Moments



Proton magnetic moment ~160-fold better known than for the antiproton

$$\frac{g_{\bar{p}}}{2} = 2.7928465(14)$$

$$\frac{g_p}{2} = 2.792847350(9)$$

S. Ulmer, A. Mooser, H. Nagahama, C. Smorra, K. Blaum, et al.
C. Smorra et al., Eur. Phys. J ST 224, 3055-3108 (2015).

To be continued

The History of Antimatter and CPT invariance