Particle physics

International teachers program
July 2018
part III

European Organisation for Nuclear Research

„*Magic is not happening at CERN, magic is explained at CERN*" - Tom Hanks

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- **Elementary particles**

  - Constituents of matter
    - Fermions (S=1/2)

  - Force carries
    - Bosons   (S=1)

Doublets under weak interaction
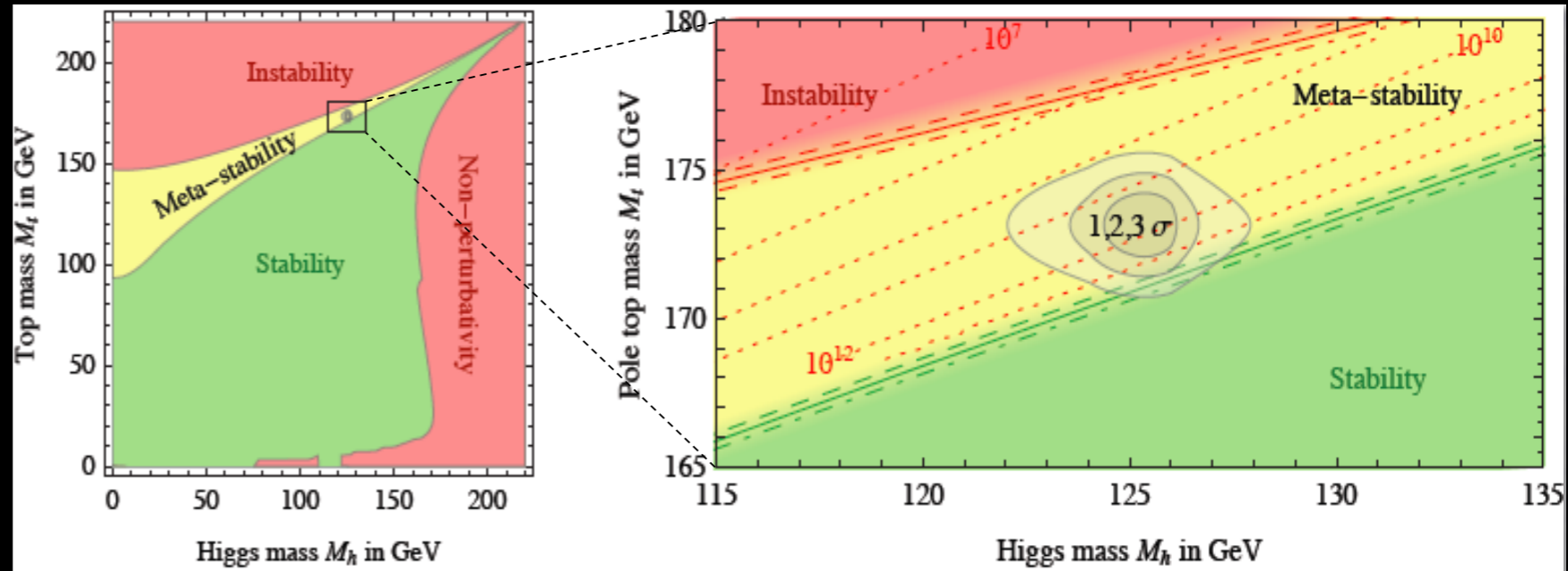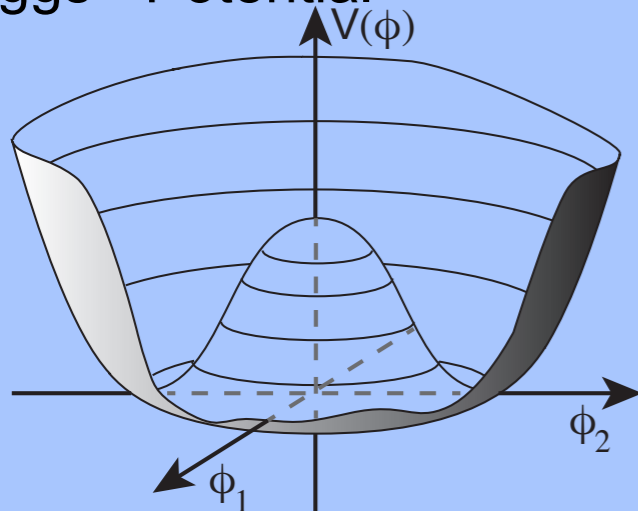
Is the universe stable until the end of time?

- Does vacuum energy of Higgs field correspond to local or global minimum?

  - If local: is there a state of lower energy?
  - Could the universe tunnel into the lower energy state?

- Depends on masses of top quark & Higgs boson

$$V(\phi^\dagger\phi) = m^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2, \quad m, \lambda \in \mathbb{R}.$$
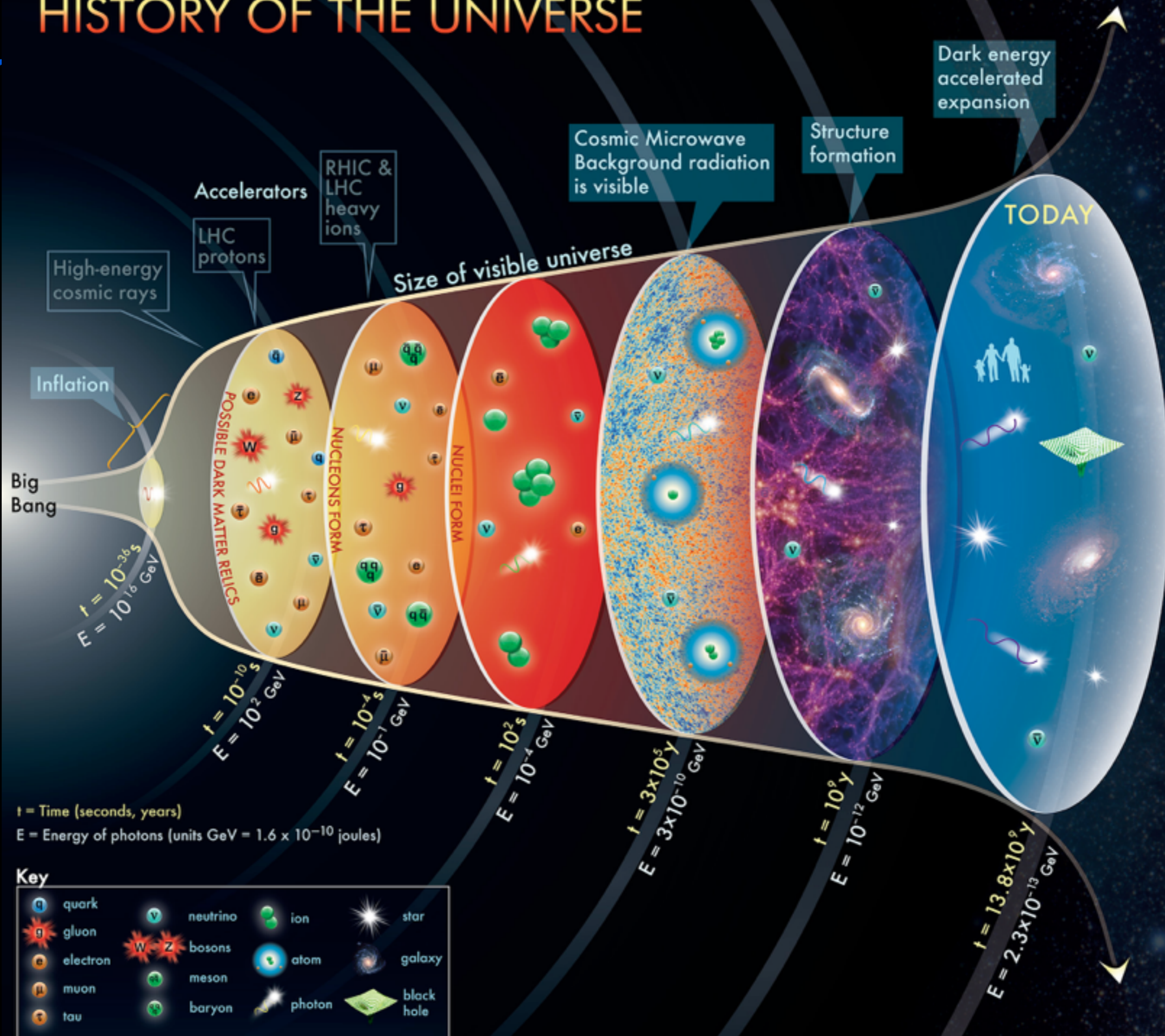
Higgs - Potential

?
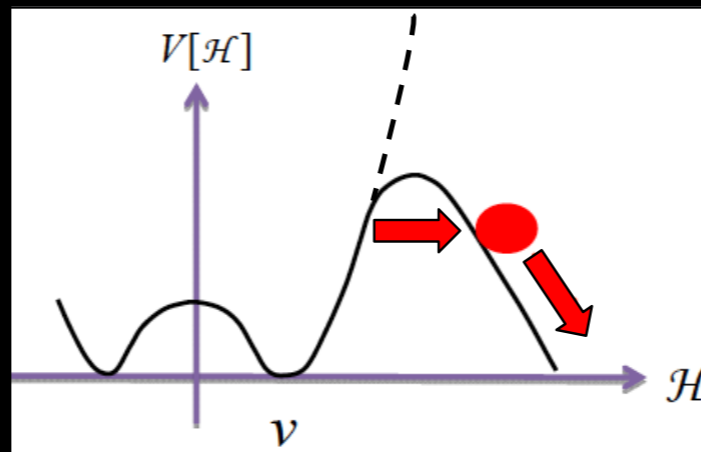
- Average tunnel time ~ 10^{100} years
- probably OK for us ;)

HISTORY OF THE UNIVERSE

Dark energy accelerated expansion

Structure formation

Cosmic Microwave Background radiation is visible

Accelerators

RHIC & LHC heavy ions

LHC protons

High-energy cosmic rays

Size of visible universe

TODAY

Inflation

Big Bang

POSSIBLE DARK MATTER RELICS

NUCLEONS FORM

NUCLEI FORM

$t = 10^{-36}$s
$E = 10^{16}$ GeV

$t = 10^{-10}$s
$E = 10^2$ GeV

$t = 10^{-4}$s
$E = 10^{-1}$ GeV

$t = 10^2$s
$E = 10^{-4}$ GeV

$t = 3 \times 10^5$y
$E = 3 \times 10^{-10}$ GeV

$t = 10^9$y
$E = 10^{-12}$ GeV

$t = 13.8 \times 10^9$y
$E = 2.3 \times 10^{-13}$ GeV

t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6×10^{-10} joules)

Key

q	quark	ν	neutrino		ion	star
g	gluon	W Z	bosons			galaxy
e	electron		meson		atom	
μ	muon				photon	black hole
τ	tau		baryon			

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The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

Supported by DOE

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Neutrinos

Sources of neutrinos

- Sun / Supernovae: Nuclear fusion
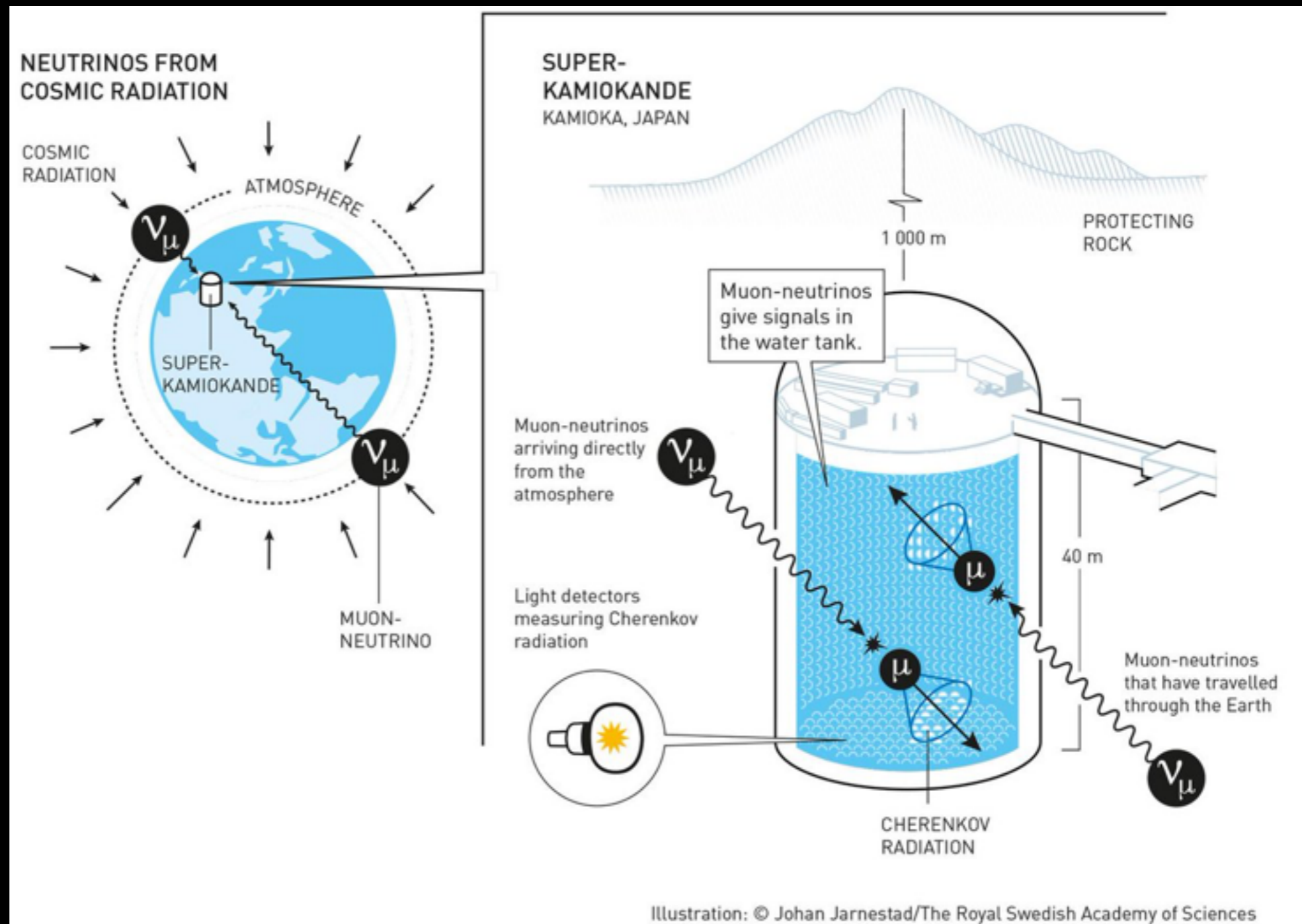
$$^1H + ^1H \to\, ^2H + e^+ + \nu_e + 0,42\,\mathrm{MeV}$$
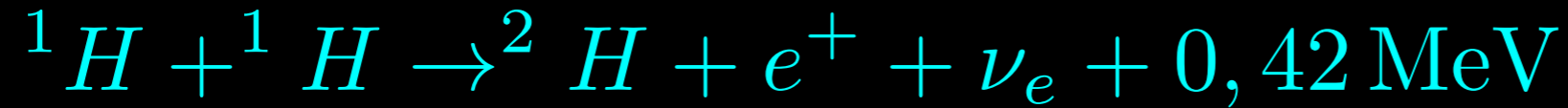
- Nuclear reactors: fission
  - β - decay of spallation products and neutrons → ν_e

- Atmosphere:
  - Decaying muons from cosmic rays → ν_μ, ν_e

- Accelerators:
  - Muon decays → ν_μ, ν_e

Neutrino oscillations

- Detection of stellar neutrinos in Homestake experiment: Davis Jr.: 1960ies

  - Measured neutrino flux 50% of expectation from sun's luminosity

- Detection of stellar neutrinos in Kamiokande
  - Confirms Homestake results   Super Kamiokande: 1998

- Detection of atmospheric neutrinos

  - Flux of neutrinos arriving from „top" and „bottom" differs by ~50%
  - What happens to the neutrinos within the earth?

- Neutrinos can oscillate from one flavour to another!

  - Note: only electron & muon neutrinos are detected in those experiments

Superkamiokande

- 40m x 40m
  - 50 kt of purified water

- Solar & Atmospheric neutrinos

- 4k Solar neutrinos / year
  - -> 10 per day

NEUTRINOS FROM COSMIC RADIATION

COSMIC RADIATION

ATMOSPHERE

ν_μ

SUPER-KAMIOKANDE

MUON-NEUTRINO

SUPER-KAMIOKANDE
KAMIOKA, JAPAN

1 000 m

PROTECTING ROCK

Muon-neutrinos give signals in the water tank.

Muon-neutrinos arriving directly from the atmosphere

Light detectors measuring Cherenkov radiation

40 m

Muon-neutrinos that have travelled through the Earth

CHERENKOV RADIATION

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

Neutrino oscillations

- Analogy to quark sector   => Maki-Nakagawa-Sakata-Matrix
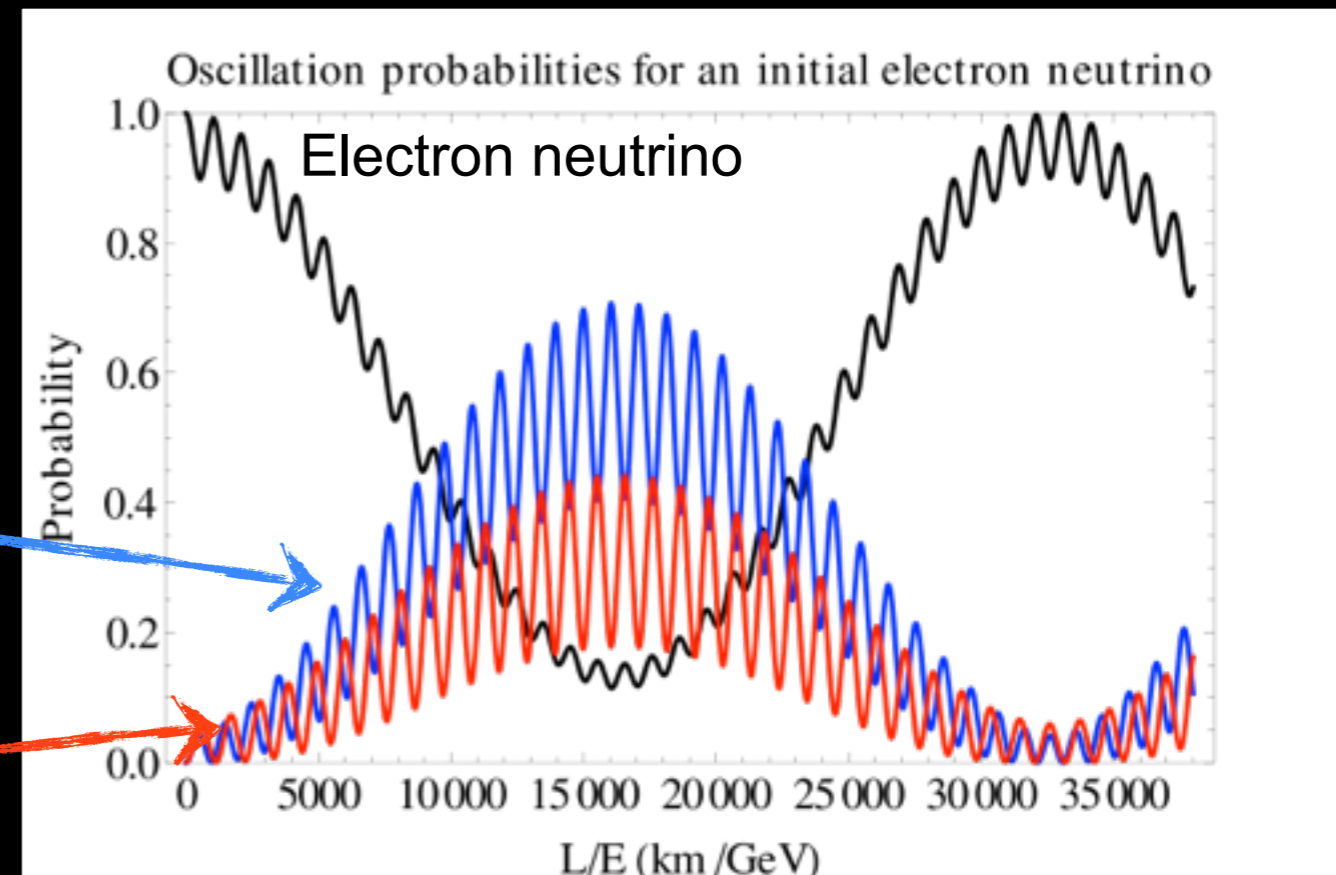
  - **Mass eigenstates != flavour eigenstates**

  - Mixing allowed → oscillations

  - Requires: $m_\nu > 0$ & $m_{\nu 1} \ne m_{\nu 2} \ne m_{\nu 3}$

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\Theta_m & \sin\Theta_m \\ -\sin\Theta_m & \cos\Theta_m \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix},$$

Oscillation probabilities for an initial electron neutrino

Electron neutrino

Muon neutrino

Tau neutrino

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta(0) | \nu_\alpha(L) \rangle|^2 \approx \sin^2\left(\frac{\Delta m^2 c^4}{4E} \frac{L}{\hbar c}\right) \cdot \sin^2(2\Theta_m)$$

Neutrino oscillations - detection

- Various reactor and accelerator based experiments

  - Detectors in varying distance to sources
    - Double Chooz, KamLand, DayaBay / T2K, Opera, Minos, DUNE

  - Measurement: disappearance of neutrino flux

- **Opera**: Detected appearance of tau-neutrinos!   Opera: 2010-2014

  - Neutrino beam (μ, e) from CERN sent 740km to Gran Sasso (IT)

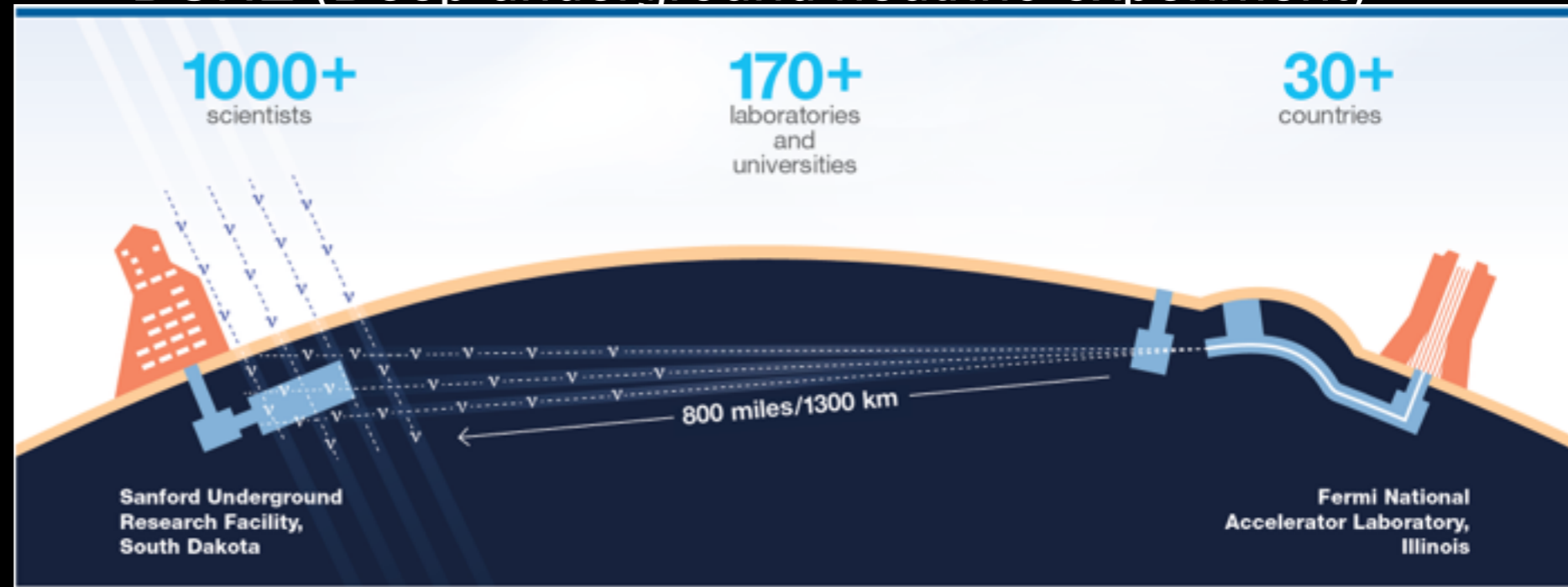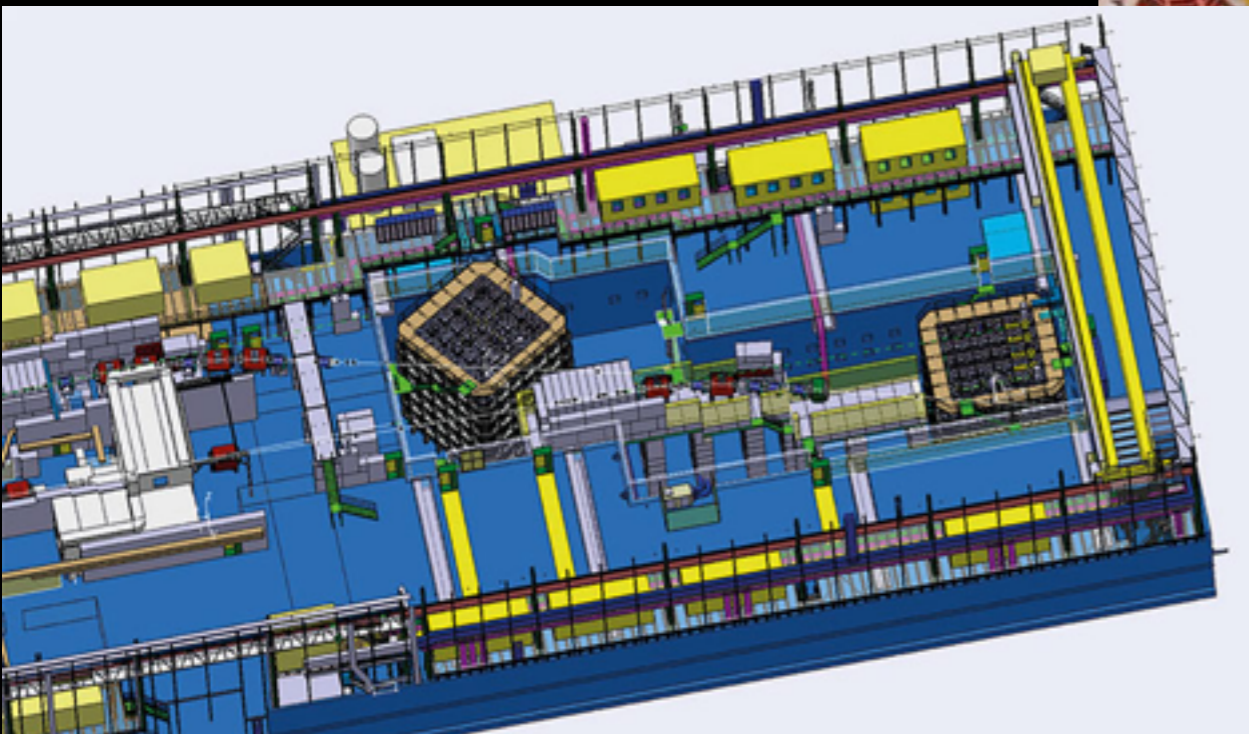 - Detection of tau-neutrinos in neutrino beam (5x)

Neutrino Detectors

• DUNE (Deep underground neutrino experiment)
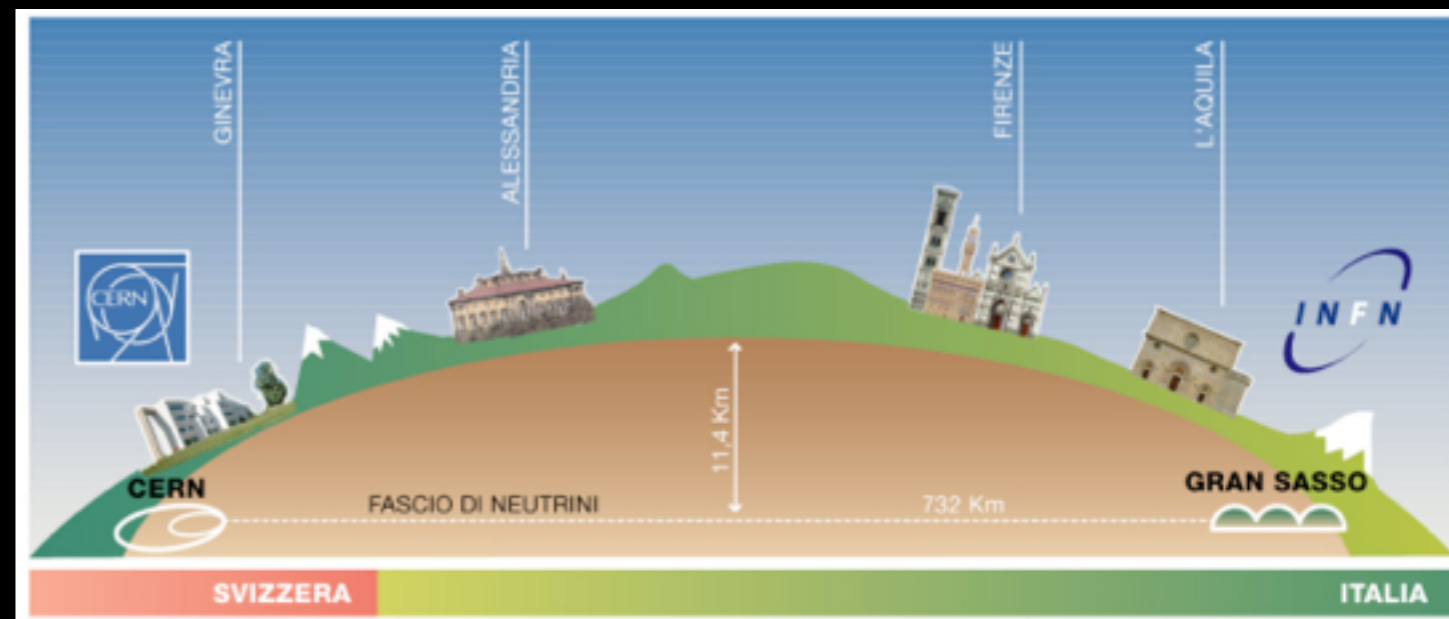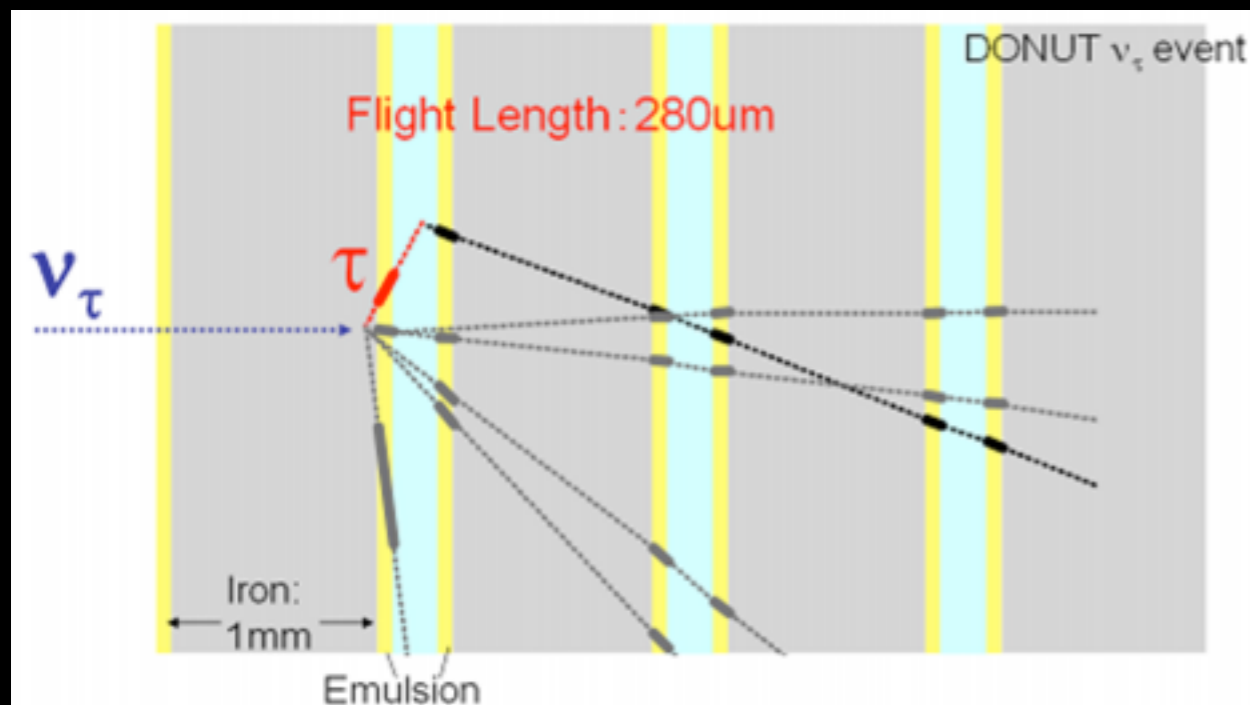
CERN neutrino platform:

Test facility for future neutrino detectors.

How do neutrinos gain mass?

- And why is mass so little? (< 2eV)

- Like fermions: coupling to Higgs field?

  - Requires left & right handed neutrinos

    - Only left-handed neutrinos observed!

- Other mechanism?

- One option: **See-Saw mechanism**:

  - Neutrinos are Majorana particles (their own anti-particles)
  - In addition very heavy right handed neutrinos (sterile Neutrinos)
    - Require very small mass for known neutrinos

  - Violated lepton number conservation & B-L
    - Possible explanation of the existence of matter via lepto-genesis
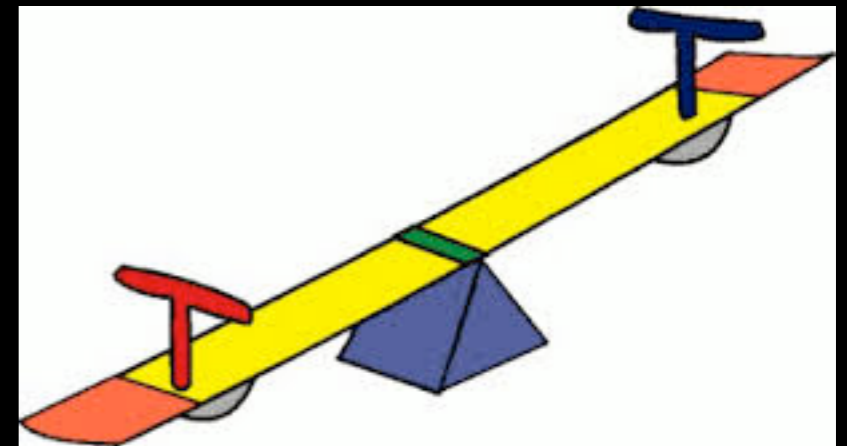
See saw mechanism

- **Idea**: one or more right handed neutrino fields, inert under weak interaction (sterile)
  - Mass matrix in 1 generation between sterile and Dirac neutrinos:

$$\begin{pmatrix} 0 & M \\ M & B \end{pmatrix}$$

Dirac mass ~ EW scale (246 GeV)

B >> M

Majorana mass ~GUT scale (10^{19} GeV)

Eigenvalues ~ Neutrino masses:

$$\lambda_{\pm} = \frac{B \pm \sqrt{B^2 + 4M^2}}{2}$$

$$\lambda_- \approx -\frac{M^2}{B}$$ ~ 1eV

$$\lambda_+ \approx B$$

If one eigenvalue goes up, the other goes down => see saw

- **Elementary particles**

  - Constituents of matter
    - Fermions (S=1/2)

  - Force carries
    - Bosons   (S=1)

Doublets under weak interaction

1.   2.   3.   generation

	1.	2.	3.		
Quarks	2,3 MeV $\frac{2}{3}$ $\frac{1}{2}$ **u** up	1,275 GeV $\frac{2}{3}$ $\frac{1}{2}$ **c** charm	173,07 GeV $\frac{2}{3}$ $\frac{1}{2}$ **t** top	0 0 1 **γ** Photon	125,9 GeV 0 0 **H** Higgs Boson
	4,8 MeV $-\frac{1}{3}$ $\frac{1}{2}$ **d** down	95 MeV $-\frac{1}{3}$ $\frac{1}{2}$ **s** strange	4,18 GeV $-\frac{1}{3}$ $\frac{1}{2}$ **b** bottom	0 0 1 **g** Gluon	
Leptonen	<2 eV 0 $\frac{1}{2}$ **ν_e** Elektron-Neutrino	<0,19 MeV 0 $\frac{1}{2}$ **ν_μ** Myon-Neutrino	<18.2 MeV 0 $\frac{1}{2}$ **ν_τ** Tau-Neutrino	91,2 GeV 0 1 **Z^0** Z Boson	
	0,511 MeV -1 $\frac{1}{2}$ **e** Elektron	105,7 MeV -1 $\frac{1}{2}$ **μ** Myon	1,777 GeV -1 $\frac{1}{2}$ **τ** Tau	80,4 GeV ±1 1 **$W^\pm$** W Boson	Eichbosonen

Standard Model Production Cross Section Measurements — Status: March 2018. ATLAS Preliminary, Run 1,2 $\sqrt{s} = 7, 8, 13$ TeV.
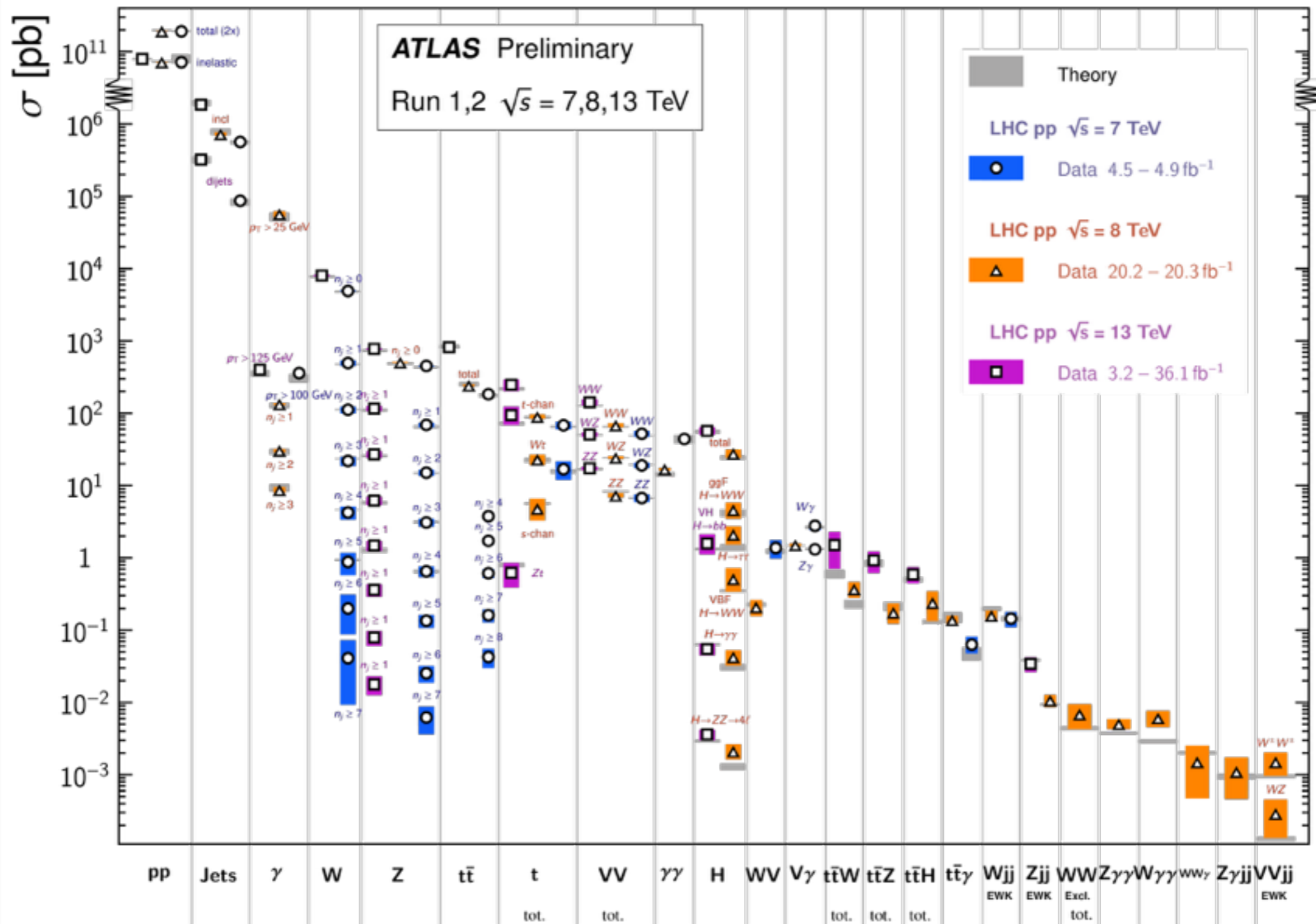
Few loose ends to tie up ...

Gravitation

- Gravitation con not be described within the standard model

  - **Problem in theories:** general relativity and quantum mechanics can not me merged consistently

- Wy is gravity so weak?

  - Dominates on macroscopic skales
    - Neglectacble on particle level!
    - 10^{-38} weaker as electromagnetic interaction!
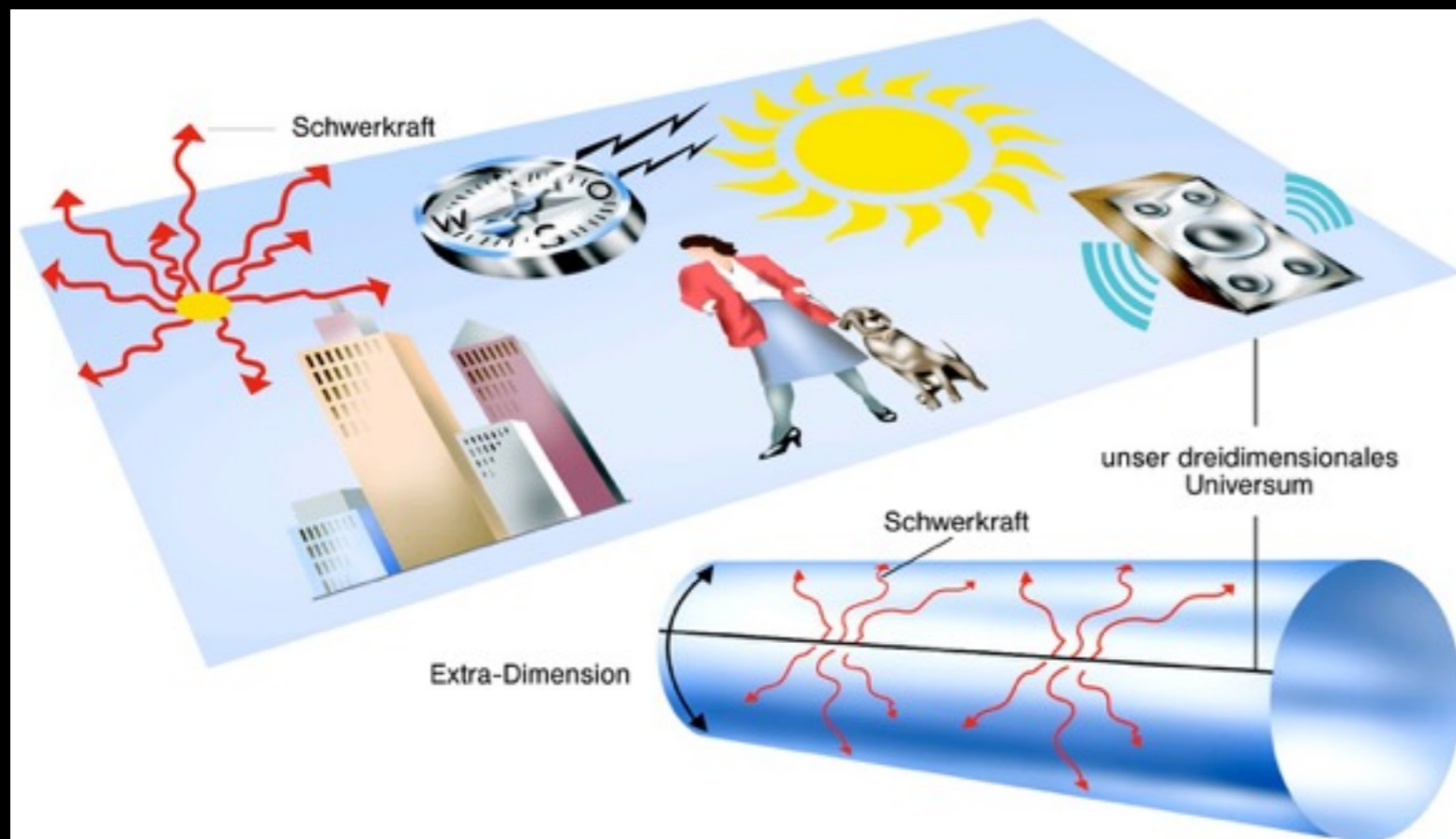
- Extra dimensions?

Gravitation

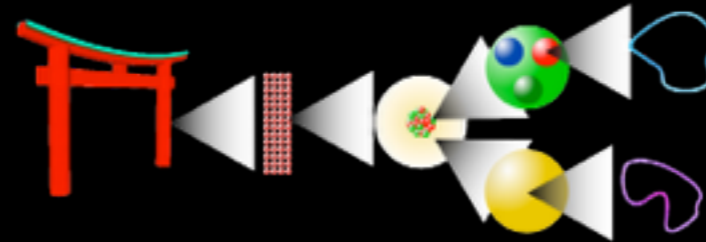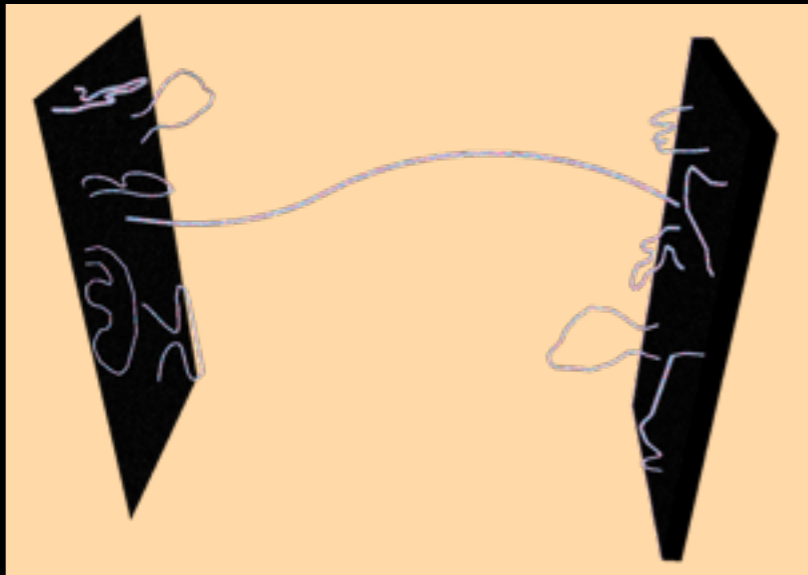- Why is gravitation so weak?
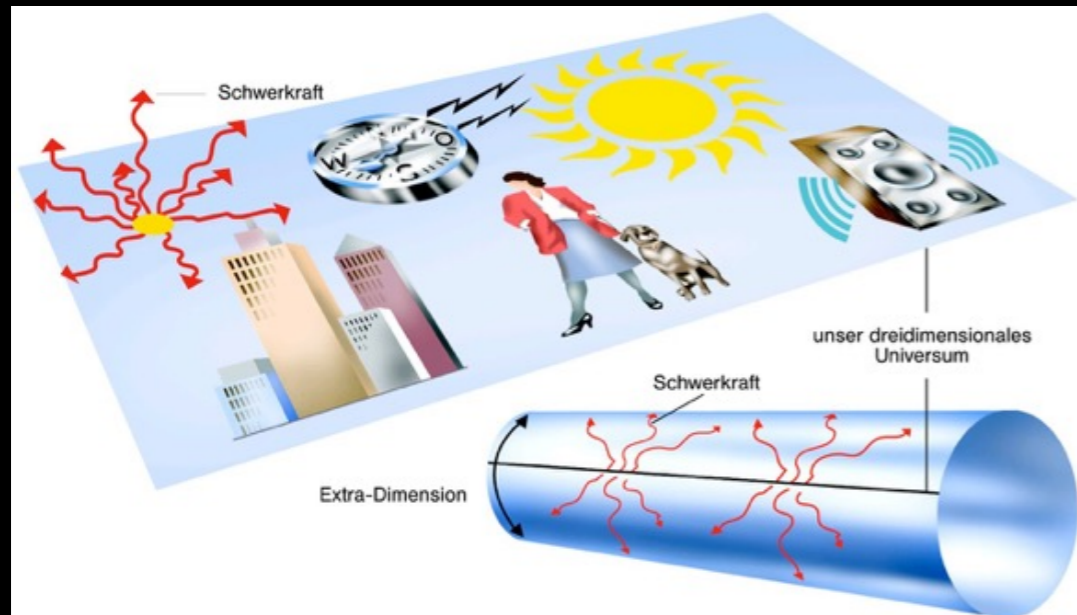
- Extra dimensions?

- Predictions of ‚black holes'

  - Particles that could be created at the LHC

- Scattering off compact dimensions

  - Kaluza-Klein towers / excitations
(= standing wave in extra dimension)

Not observed to date :(

Gravitation - String Theory

- **One** fundamental object:
  - String

  - Size ~ Planck length: 10^{-35} m

- Could be open or closed

- Attached to „world-Brane"

- Oscillation mode corresponds to observable particles

- Branes live in 11 dimensional space

  - M-theory

- Very simple & elegant approach
  - Unification of all forces (including quantum description of gravitation)

  - Extremely hard to calculate. Until today no predictions that could be verified

What about anti-matter?

- Known asymmetry between matter & anti-matter can not explain matter anti-matter asymmetry in the universe

- CP - violation in weak interaction

  - physics processes distinguish between matter & anti-matter

  - LHCb investigates this

- There has to be a yet unknown interaction in addition to the SM ones!

 - => How much energy contains the universe?
    - Cosmology lecture

assuming only known asymmetry between particles & anti-particles:
  generated matter / anti-matter in big bang **> total energy density of universe**

Intermezzo - Cosmology

- Study of cosmic microwave background:

  - Universe cools down → neutral atoms → transparent for em. rad.

  - Radiation from this era: while traveling through the universe, wavelength stretched with expansion of space itself
    - x-rays → microwaves
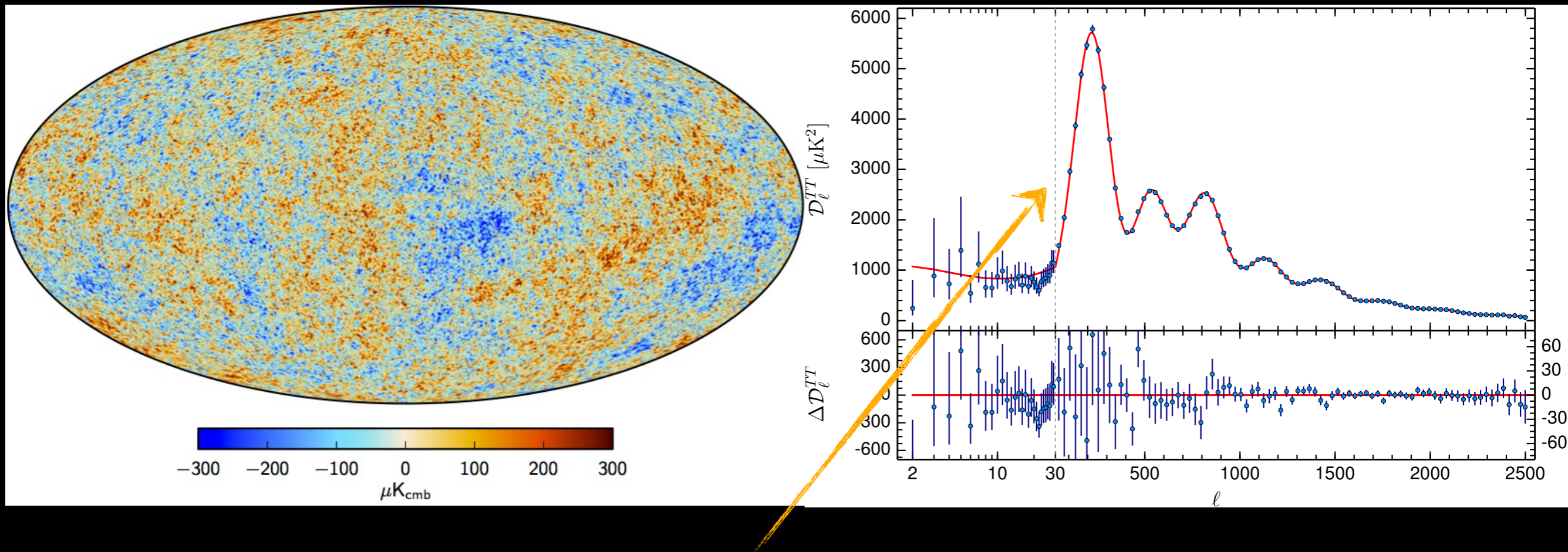
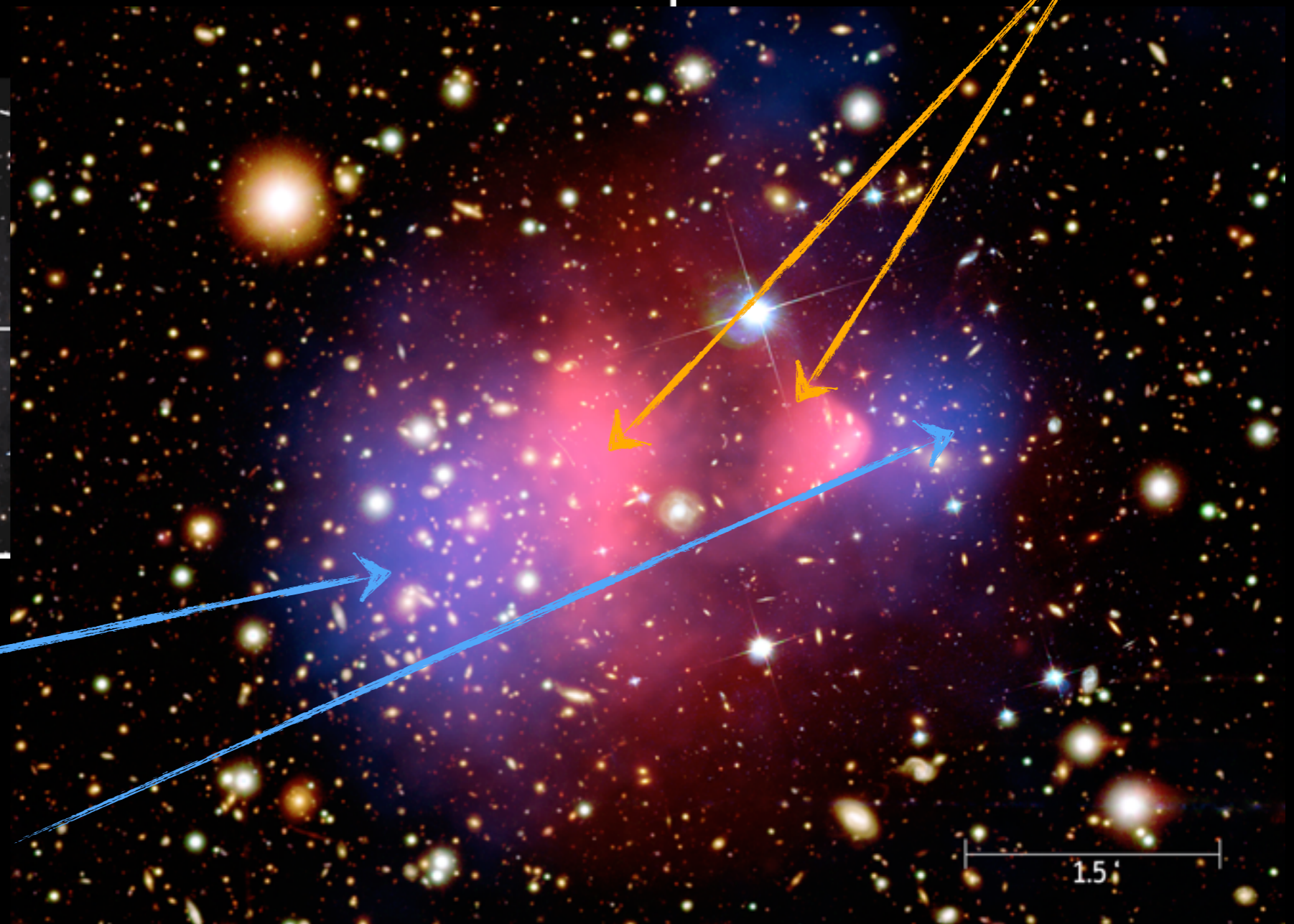- Fit of ΛCDM model to data. Parameters:
  - Baryon-density, matter density, curvature of space, ...

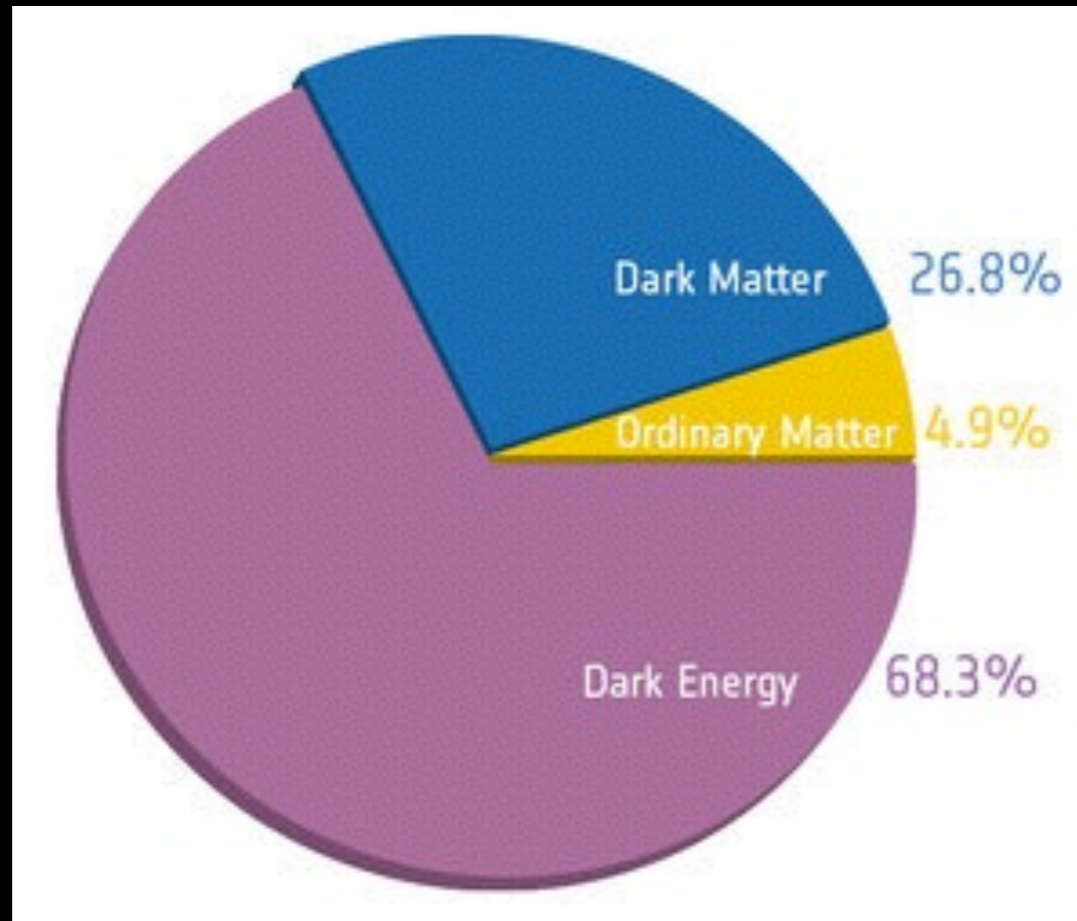# Apropos: dark matter
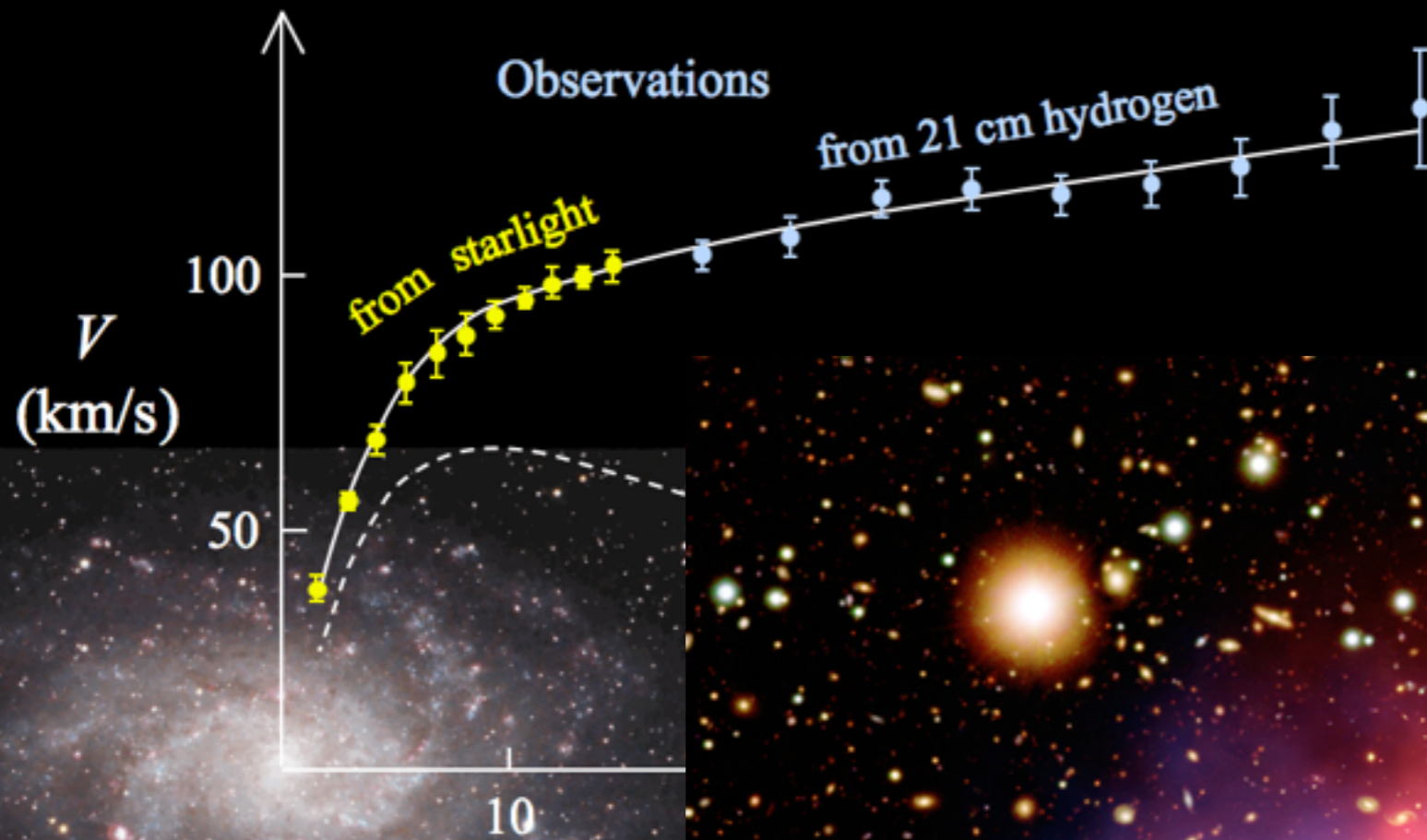
- X-ray emission from hot gas
- highest baryon desnity

- gravitational centre
  - Per „weak-lensing"

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Apropos: dark matter

Dark Matter 26.8%

Ordinary Matter 4.9%

Dark Energy 68.3%

dark matter ?

baryons

dark energy ???

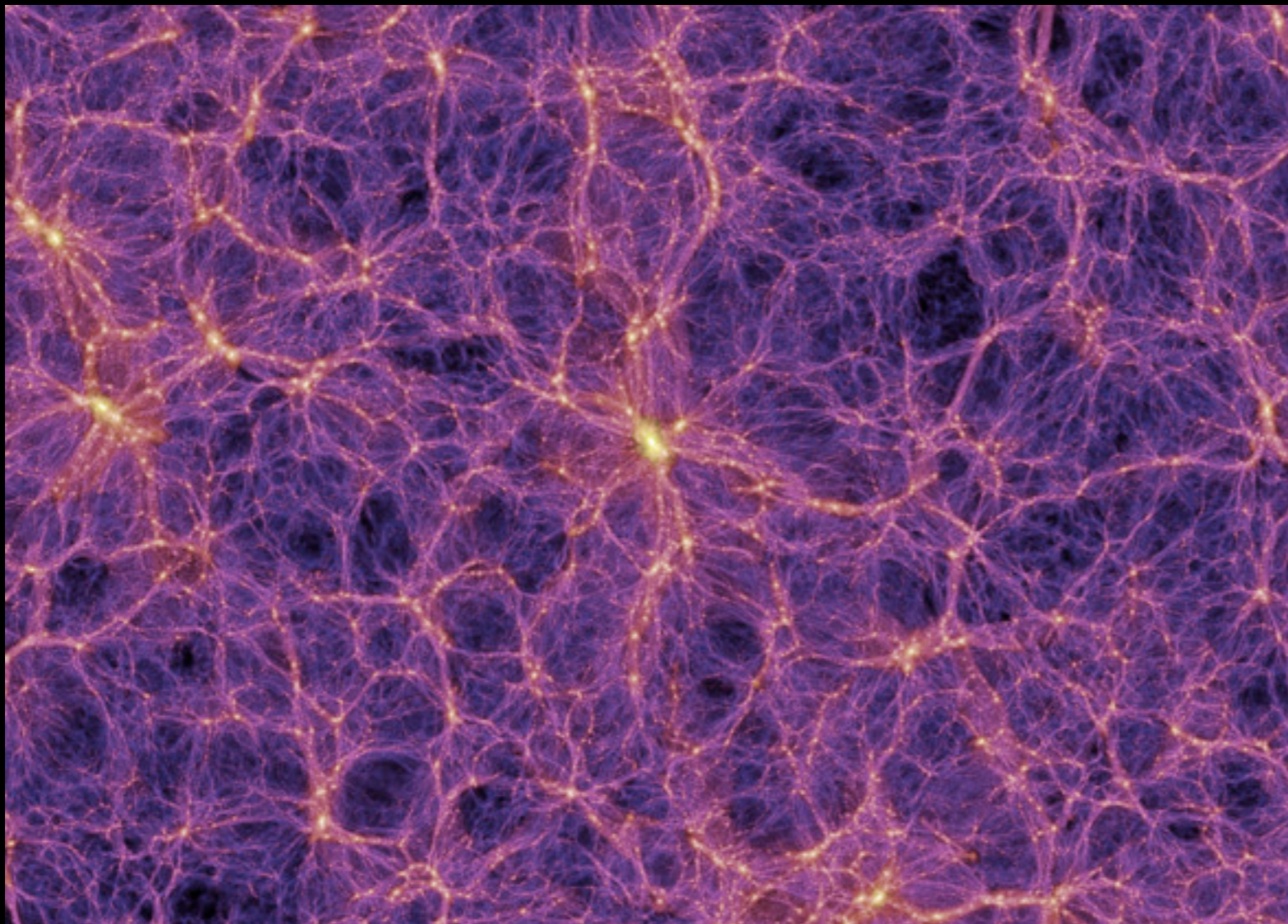- Several candidates + extensions of SM trying to describe DM

- Properties:

  - Massive (gravitation)

  - Weak interaction

→ Neutrinos?

Nope! Only non-relativistic particles contribute to structure formation in the universe

Apropos: dark matter

- Properties:

  - Massive (gravitation)

  - Weak interaction

  - ~non relativistic

- Candidates:

  - WIMPs (Lightest supersymmetric particle?)
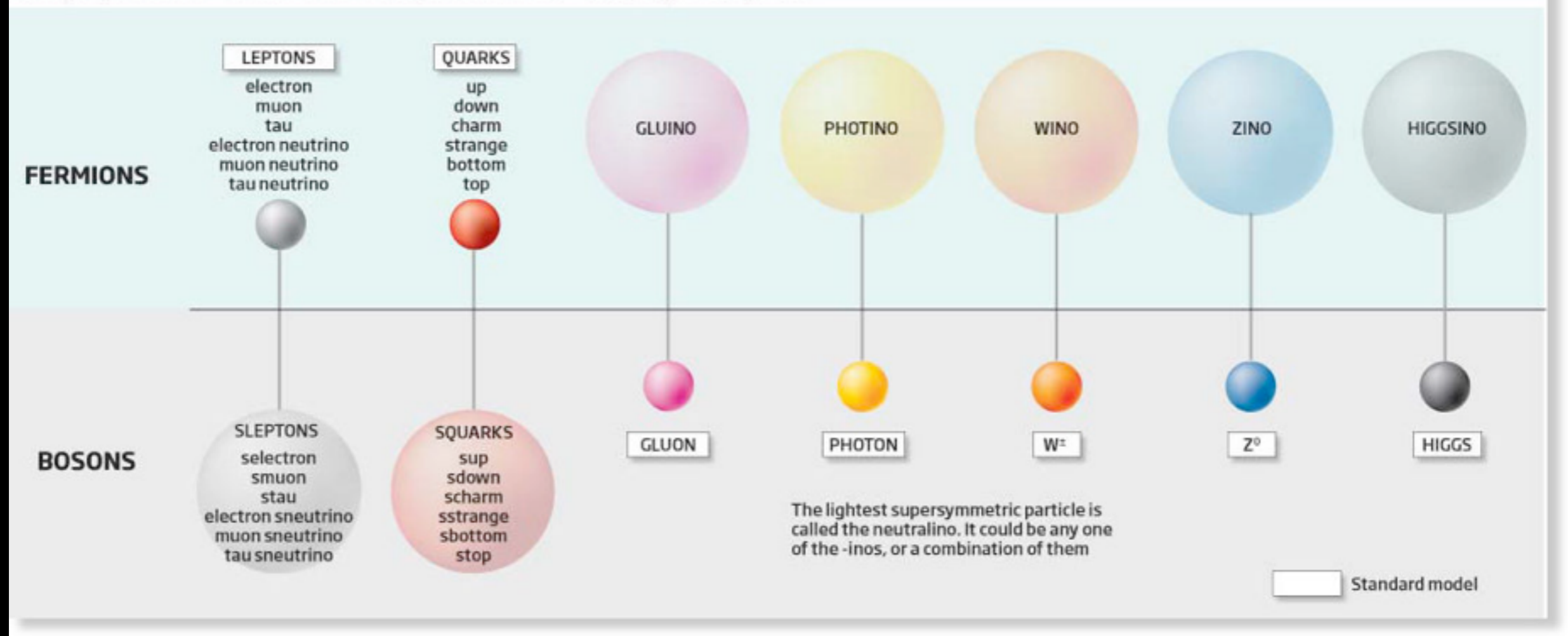
  - Axions

  - Sterile neutrinos

A word on super symmetry

- **New symmetry:**
 - Each Boson (S=0,1) is assigned a fermion (S=1/2) and vice versa

Particle zoo

©NewScientist

Particles are divided into two families called bosons and fermions. Among them are groups known as leptons, quarks and force-carrying particles like the photon. Supersymmetry doubles the number of particles, giving each fermion a massive boson as a super-partner and vice versa. The LHC is expected to find the first supersymmetric particle

FERMIONS

LEPTONS
electron
muon
tau
electron neutrino
muon neutrino
tau neutrino

QUARKS
up
down
charm
strange
bottom
top

GLUINO   PHOTINO   WINO   ZINO   HIGGSINO

GLUON   PHOTON   W±   Z⁰   HIGGS

BOSONS

SLEPTONS
selectron
smuon
stau
electron sneutrino
muon sneutrino
tau sneutrino

SQUARKS
sup
sdown
scharm
sstrange
sbottom
stop

The lightest supersymmetric particle is called the neutralino. It could be any one of the -inos, or a combination of them
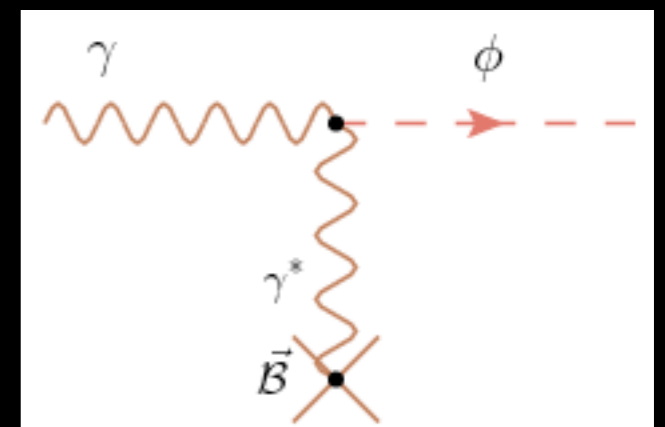
Standard model

- „Completes" SM → all possible symmetries utilized

  - New particles influence „running" of couplings
    - Grand unification possible
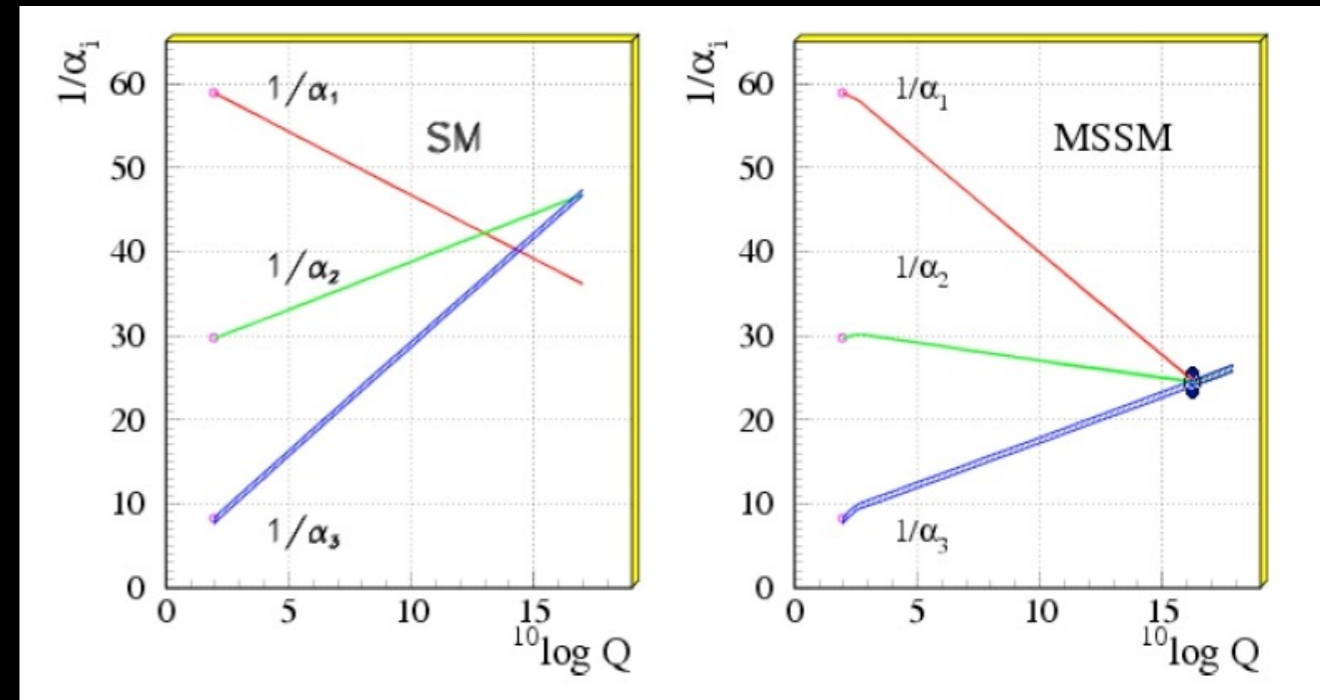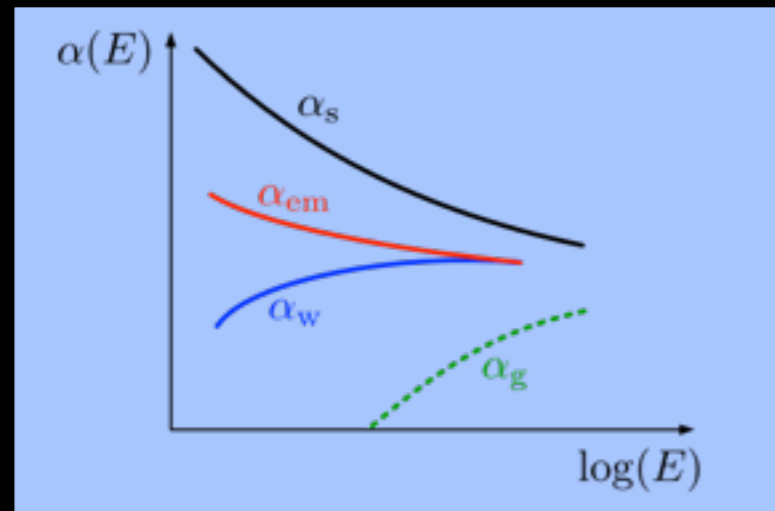
- New conserved quantity: R-parity (+1 for particles, -1 for super-partners)

  - Lightest super symmetric particle must be stable!
  - Candidate for dark matter

  - Parameter space for super symmetry is huge
    - Parameters determine particle masses, **can be (nearly) arbitrary**
   - Can not be excluded

Axions

- Solve „strong CP problem"

- QCD allows CP violating reactions. Strength parametrised by parameter θ

  - CP violation → electric dipole moment of the neutron

  - Experimentally: EDM(n) < 10^{-25} e·cm

    - Why? Seems non „natural" (fine tuning)

Peccei, Quinn: 1977

- Introducing yet another complex scalar field
  - Corresponding symmetry is spontaneously broken
    (as in Higgs mechanism)

  - θ becomes ‚dynamically' exactly 0

  - Requires additional massive particle: **Axion**

    - Candidate for dark matter

Primakov Effekt

CAST (Cern Axion TeleScope)

Prototype LHC dipole

Micromegas

Micromegas
CCD
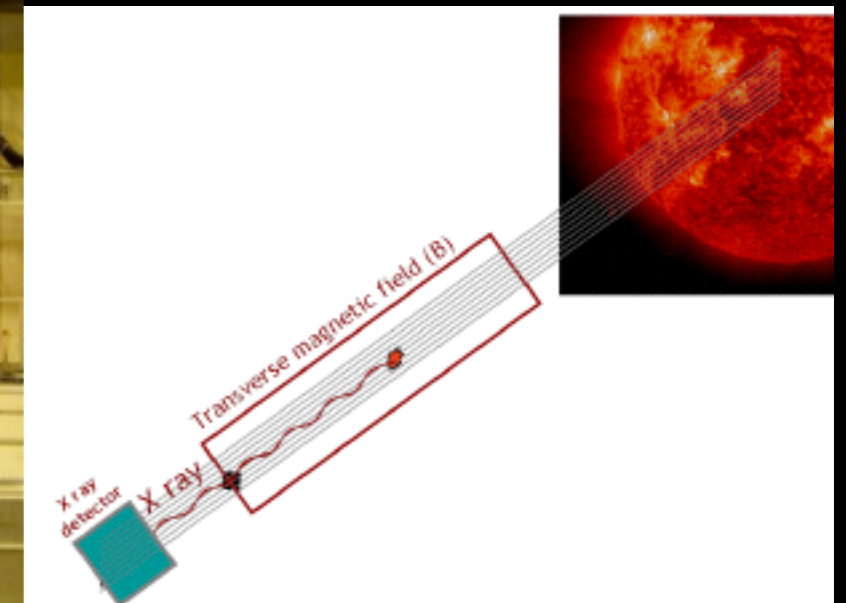
Prototype x-ray telescope
(Abrixa)

All dark is intriguing
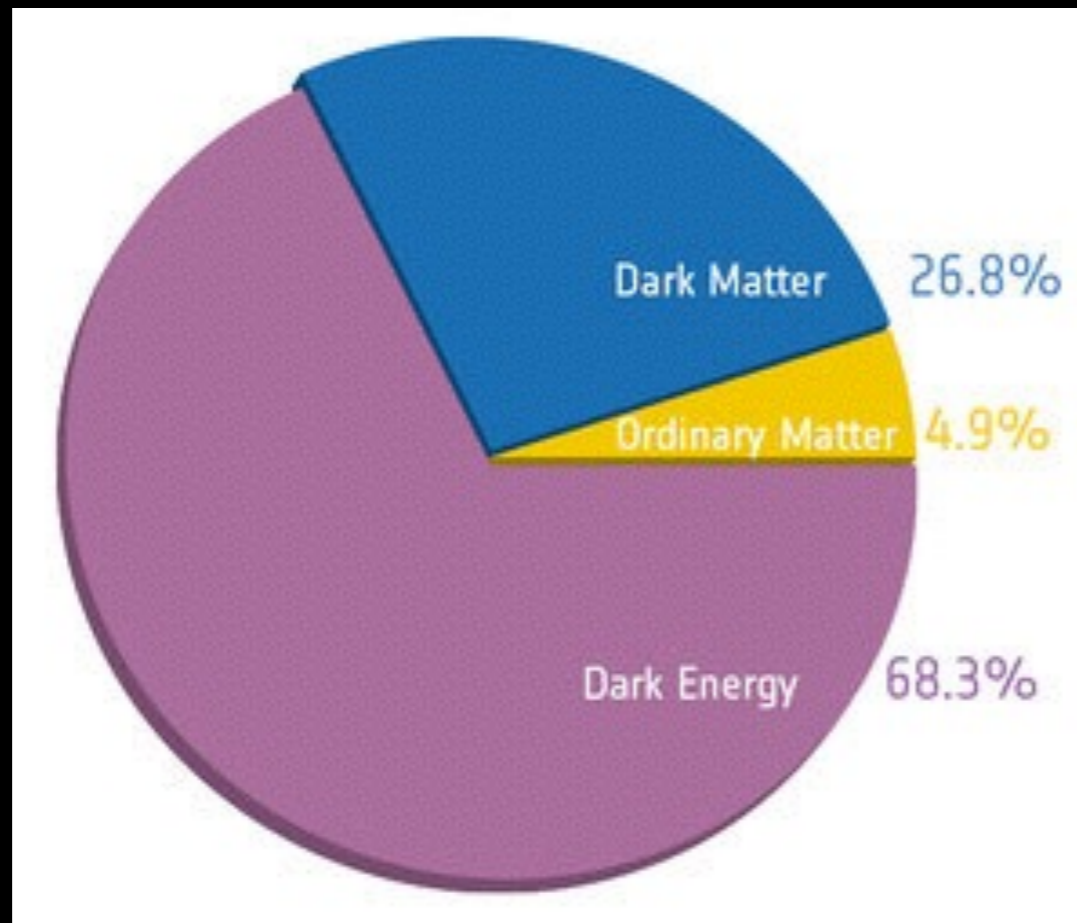
Dark matter?

Baryons

Dark energy ???

- Dark energy is completely not understood

  - Connection to theory of inflation?
  - Vacuum fluctuations?
  - Quintessence ?

Many open question / issues

- **Gravitation!**

  - Why is gravitation so weak?

- Why is there no anti matter in the universe?

- Dark sector? (dark matter, dark energy)

- What is the nature of neutrinos?

- Why do we have exactly 3 particle generations?

- Why do particles have different masses?

-
-

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

The End

Literaturverzeichnis

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[4] By Sch (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0) or GFDL (http://www.gnu.org/copyleft/fdl.html)], via Wikimedia Commons

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History of the Universe