Particle physics

International teachers program
July 2017
part III

European Organisation for Nuclear Research

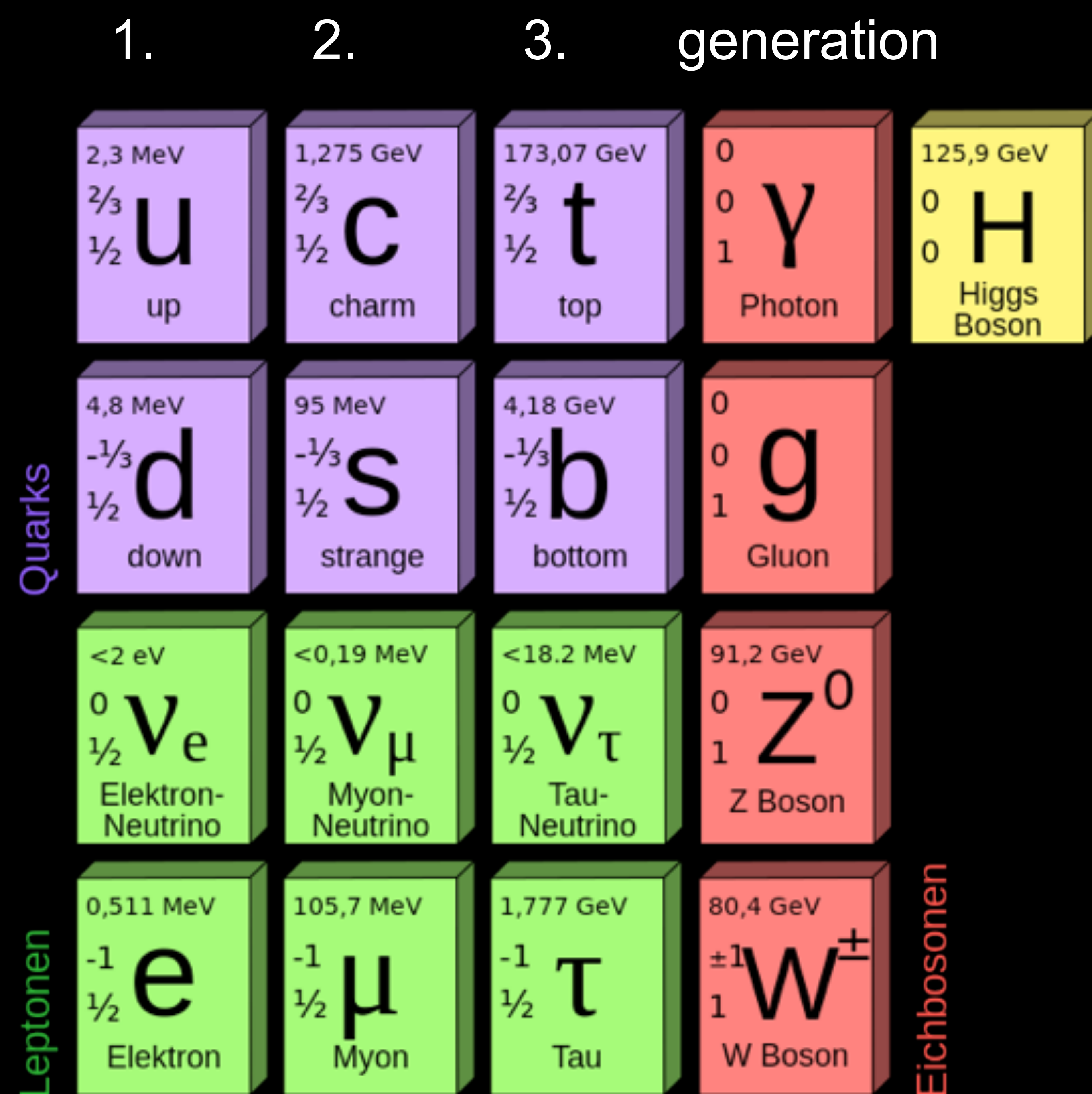
„Magic is not happening at CERN, magic is explained at CERN“ - Tom Hanks

Kristof Schmieden
EP Department

kristof.schmieden@cern.ch

Standard model of particle physics

- **Elementary particles**
  - Constituents of matter
    - Fermions (S=1/2)
  - Force carries
    - Bosons (S=1)



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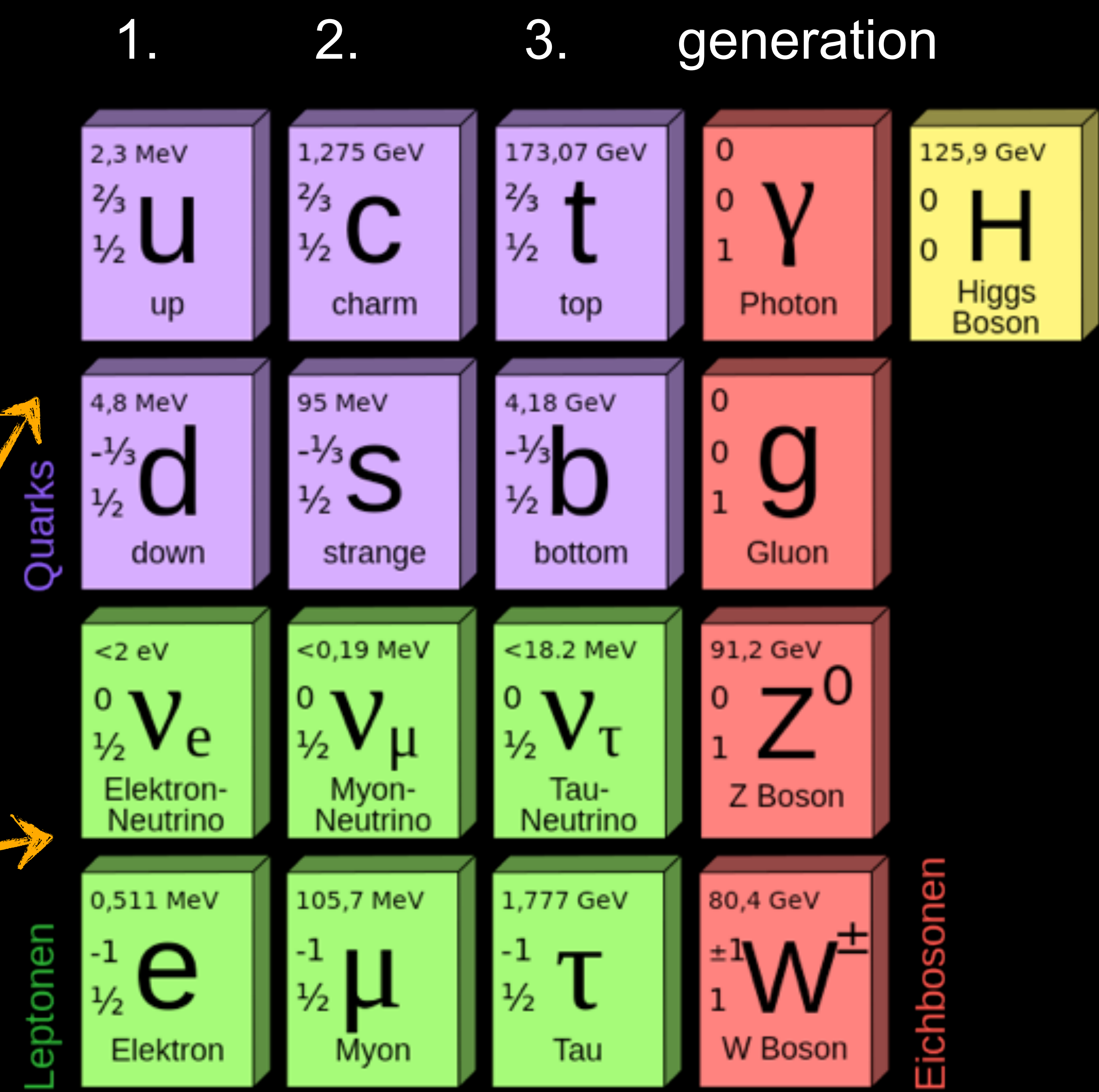

Doublets under weak interaction

Higgs

Higgs

- Higgs mechanism has essential role in theory of electroweak interactions

Higgs, Englert, Brout: 1964

- Why is Higgs mechanism so import for particle physics?

- All gauge bosons massless in standard model!
  - However, W & Z Bosons are massive particles!
- Conservation of probability!

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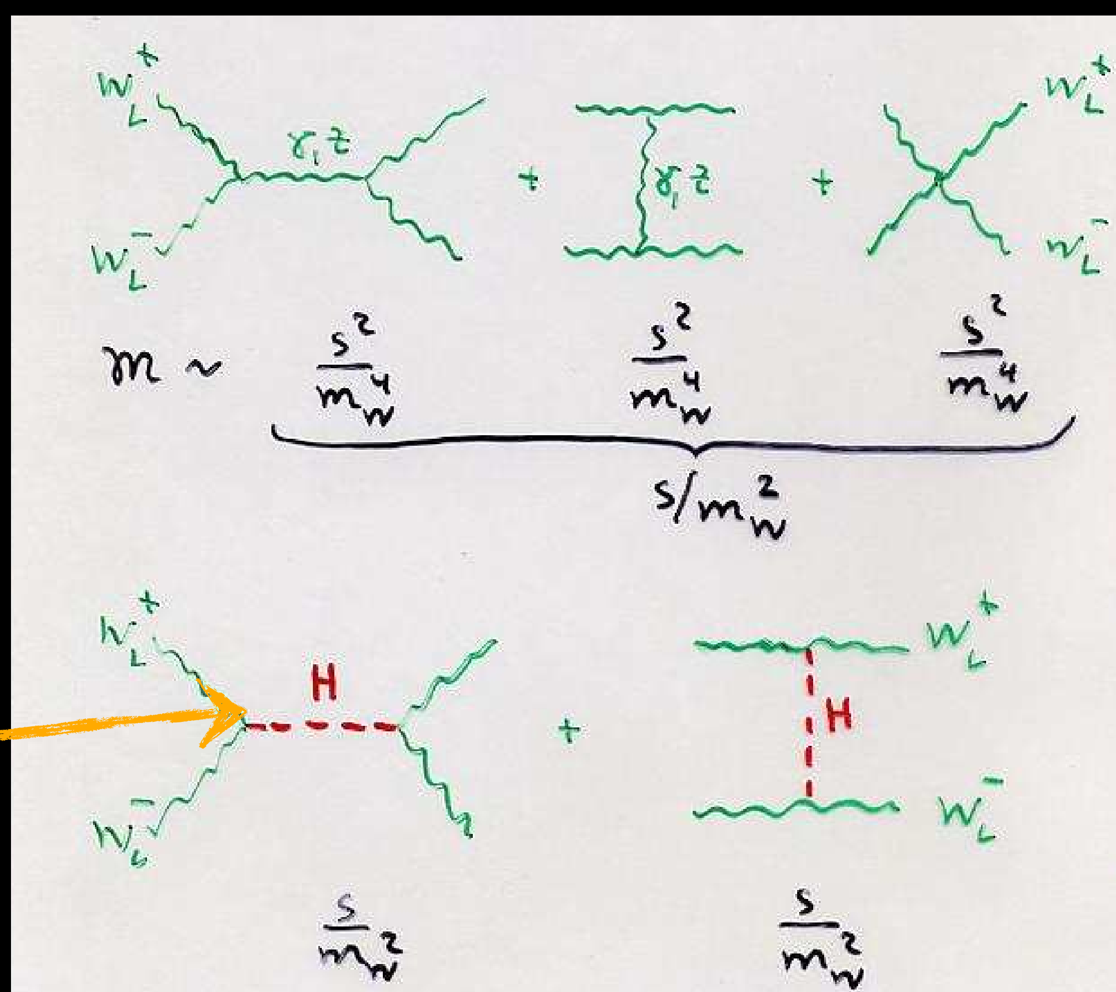
Has to be ‚scalar': Spin = 0



Scattering of longitudinally polarised W bosons:

Interaction probability > 1 for large Q^2!

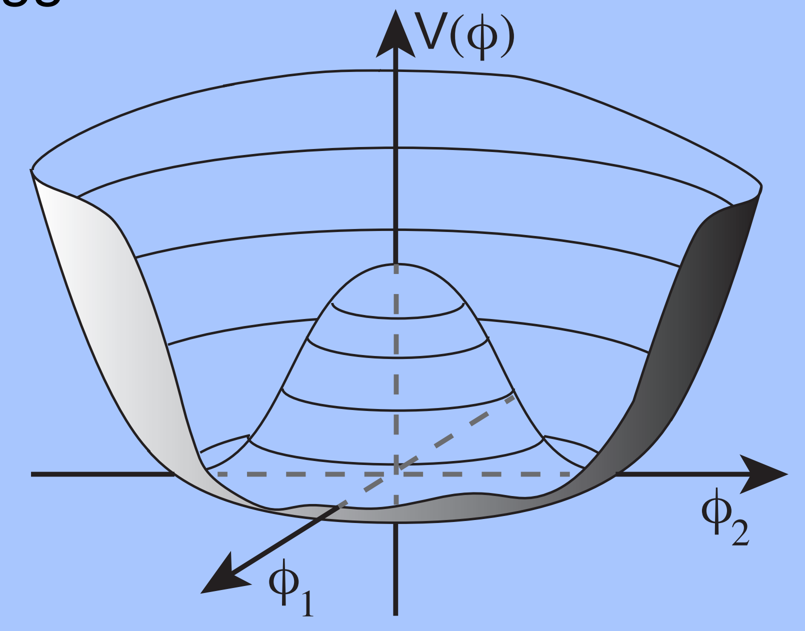
Destructive interference → probability < 1

Masses of gauge bosons

- All gauge bosons are massless within theory!
  - If mass added explicitly: breakdown of theory!!
    - $\rightarrow$ Gauge invariance is lost
- Dynamic emergence of mass:
  - Interaction with scalar field
    - Field spreads through entire universe
  - Leads to mass terms in equations

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

Higgs - Potential



- Symmetry of potential minimum ‚spontaneously' broken
  - Breaking of electroweak symmetry!
    - Manifestation of electromagnetism & weak interactions

- Similar processes known from solid state physics (superconductivity)

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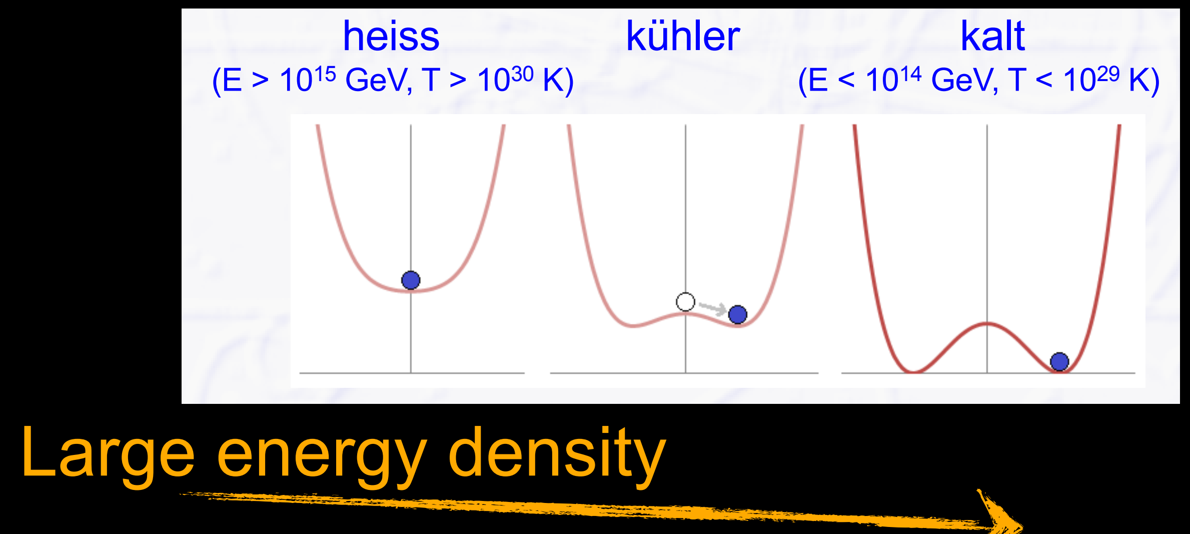

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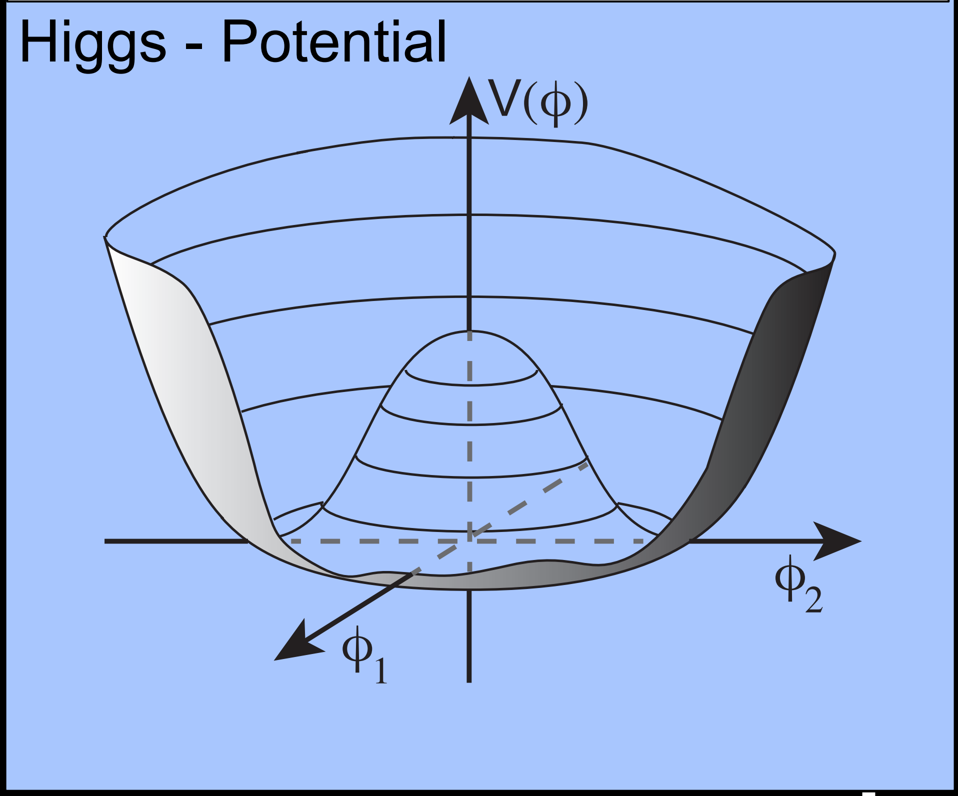

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The Higgs particle

- Higgs mechanism requires particle with spin = 0 (scalar)
  - Boson of higgs field, mediator of interactions with Higgs field

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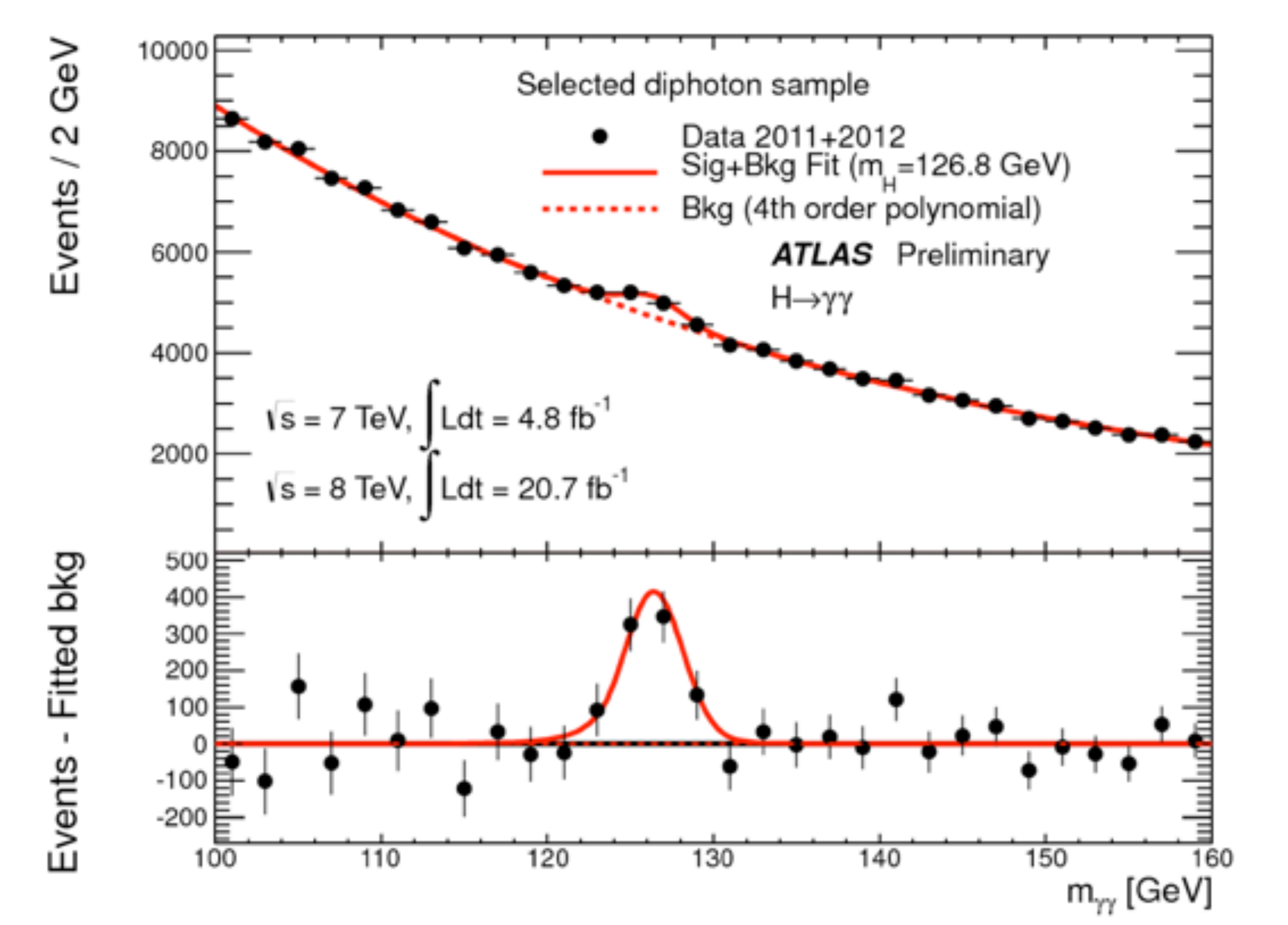
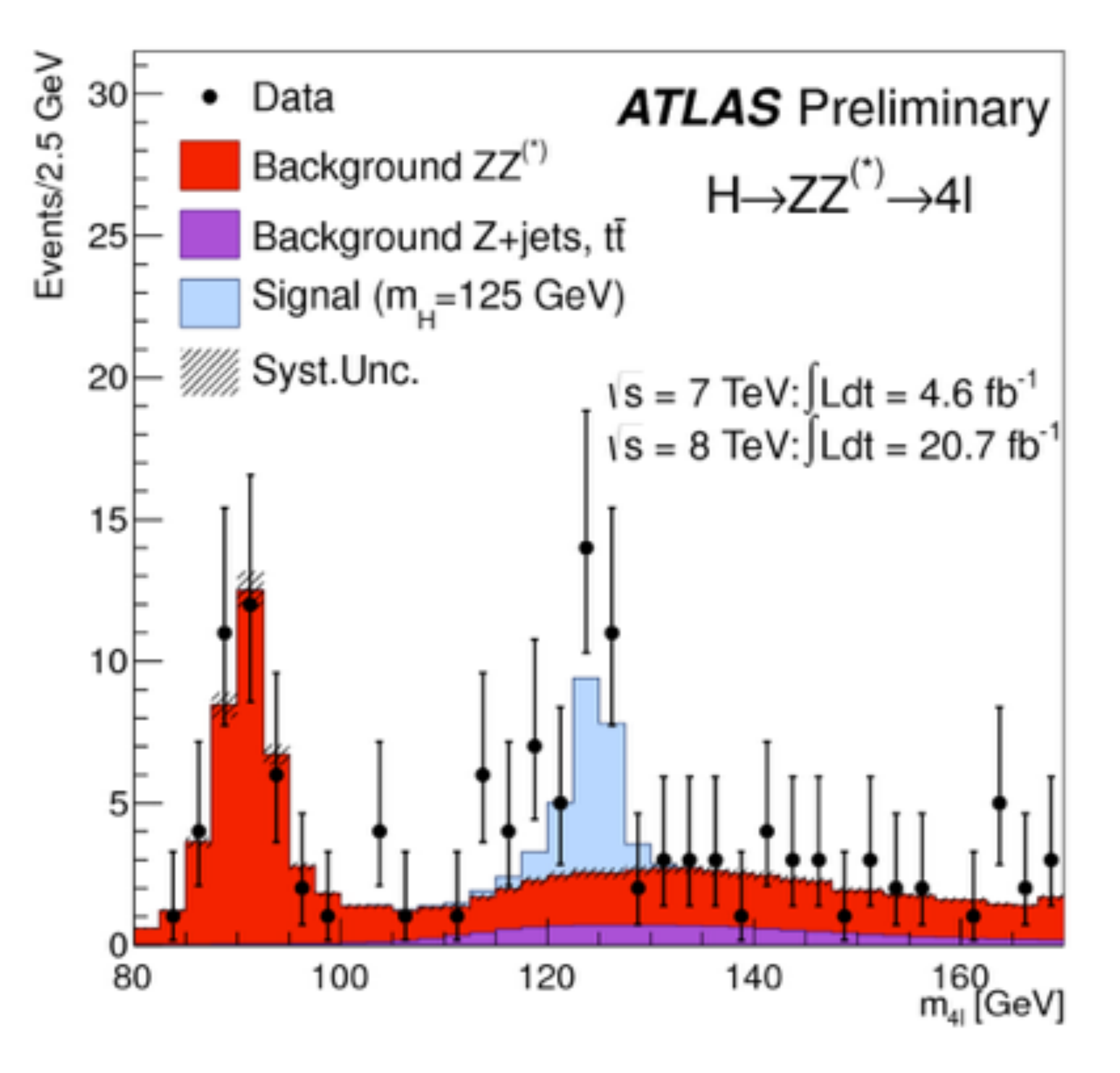
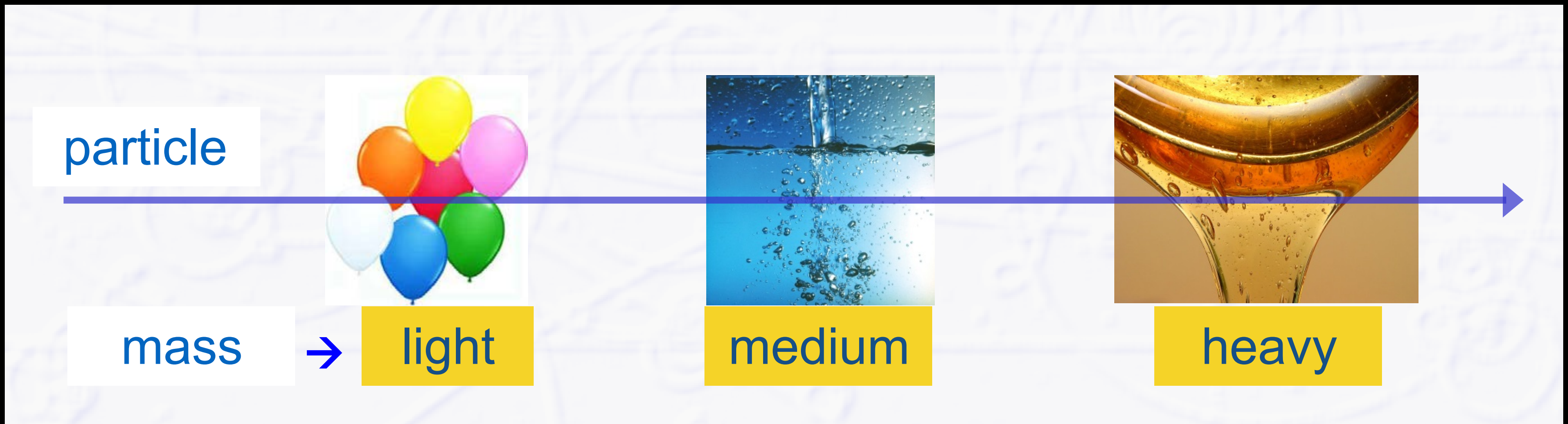
CERN (ATLAS & CMS): 2012





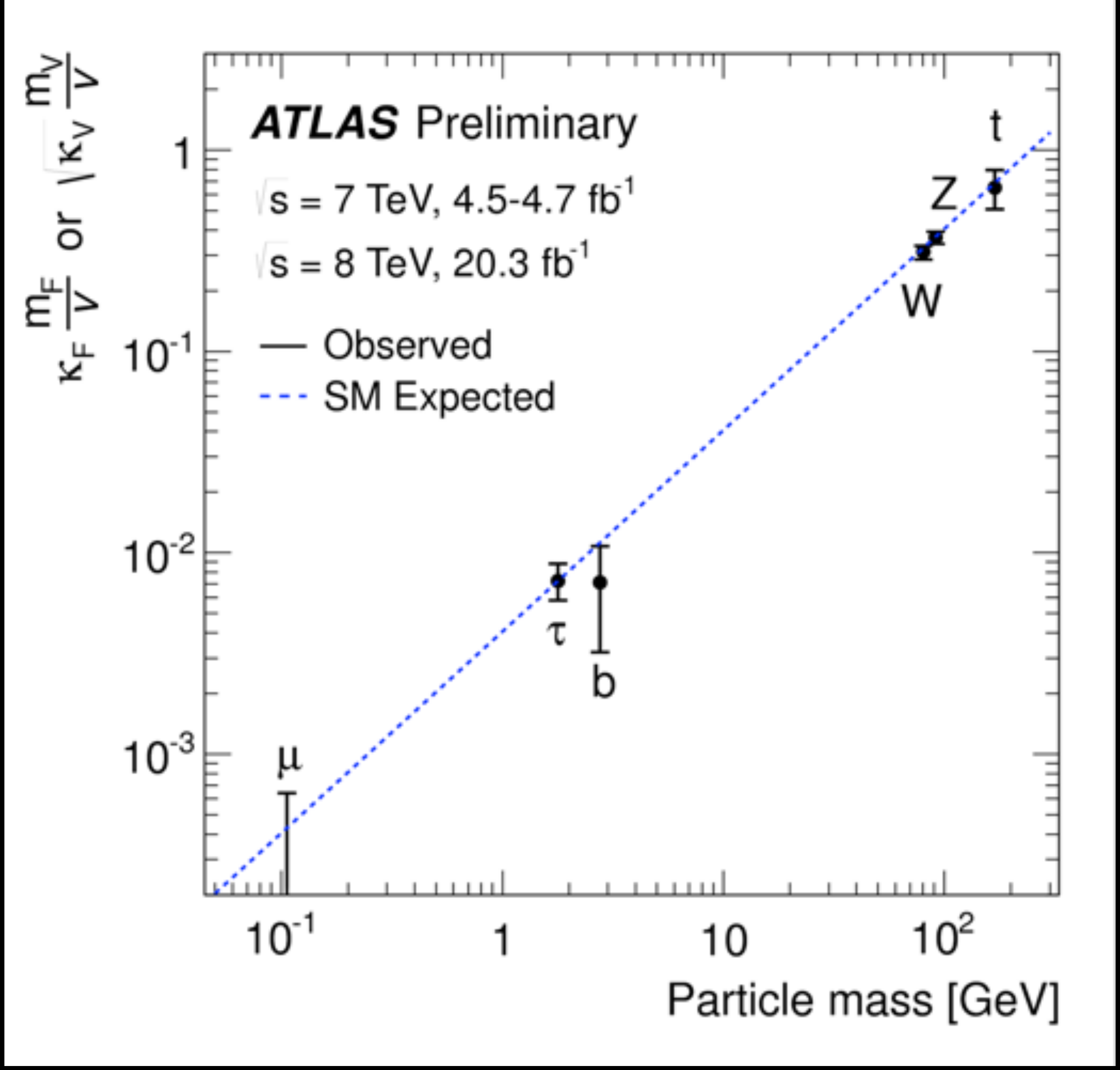
How the particles grew massive

- Mass of particles depends on coupling strength with Higgs field:
  - Directly responsible for masses of vector bosons: $g_V \sim m_V^2$
    - Broken symmetry → goldstone bosons → available degrees of freedom absorbed in 3 massive and 1 massless gauge boson (=> base rotation)
  - What about fermions?
    - Yukawa interaction with Higgs field
    - Explicitly added
    - $g_F \sim m_F$



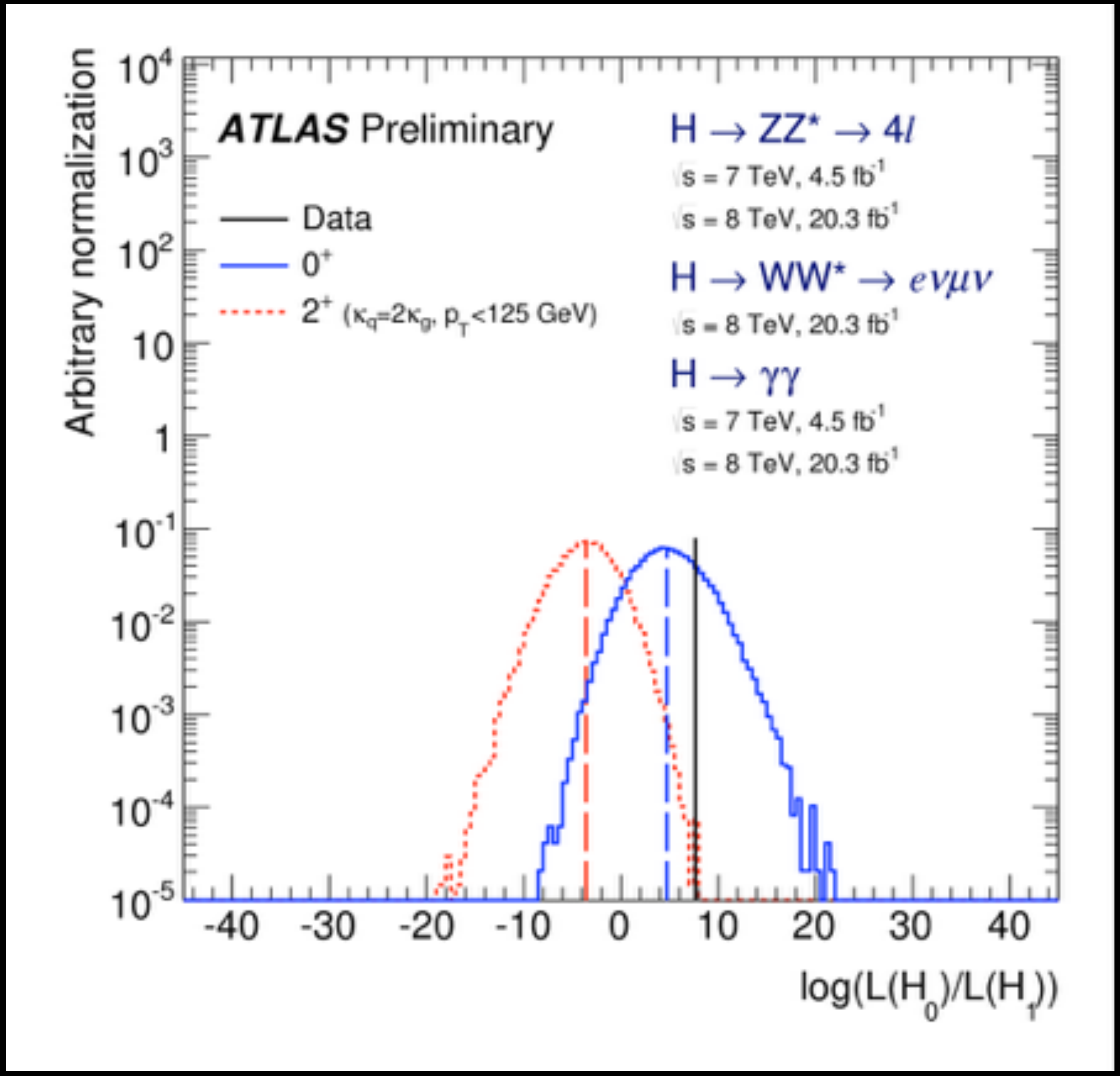
Higgs coupling - mass dependence

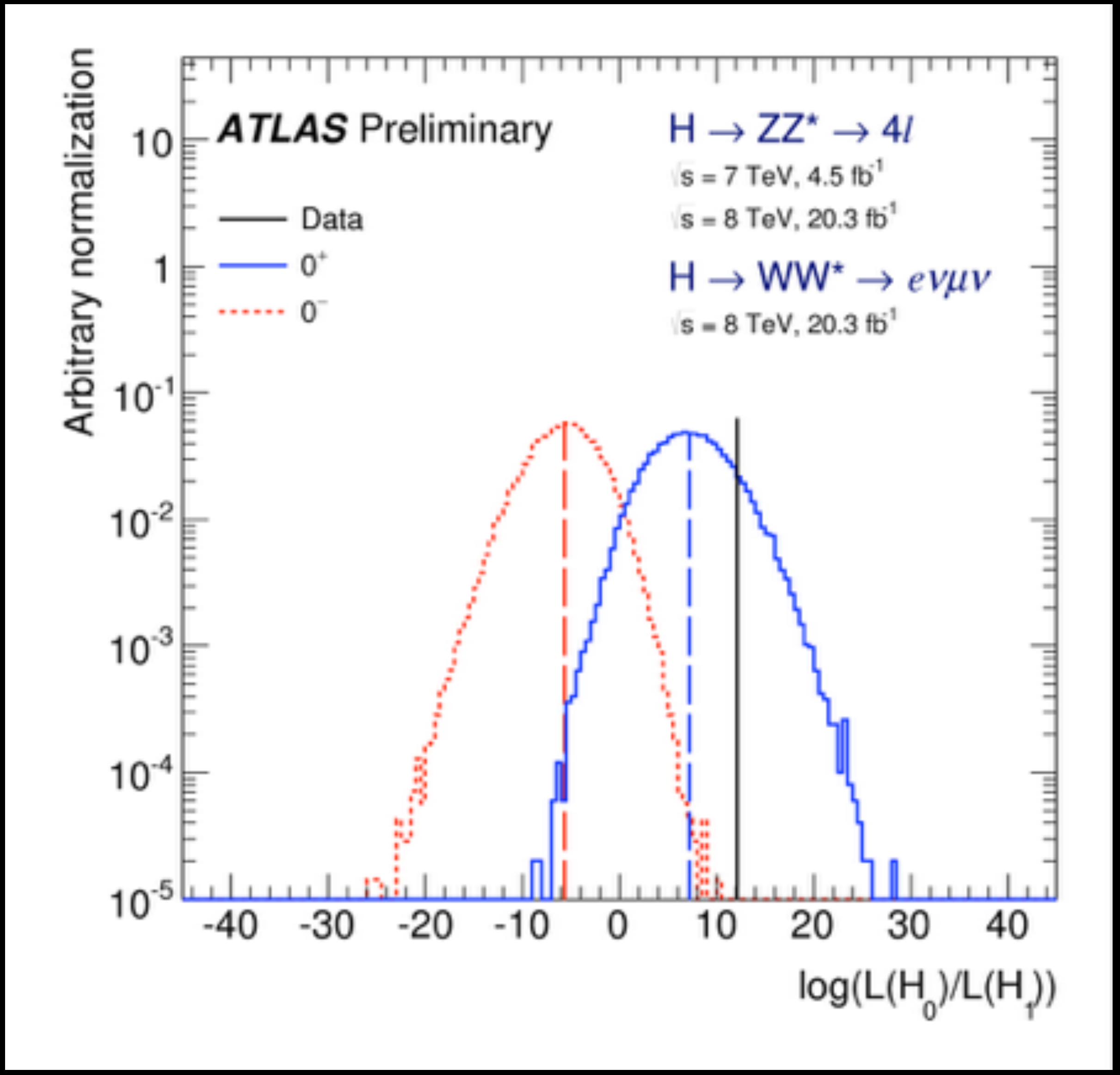
- Coupling or sqrt{coupling}
  - V & F on straight line



Properties of the Higgs boson - Spin & Parity

- Is it really the standard model Higgs particle?
  - Spin:
    - integer, as decaying to $\gamma\gamma$
  - Parity:
    - Even or Odd?





- Comparison of measurement with various predictions!
  - Agreement displayed as ‚likelihood‘
  - Many ‚pseudo experiments‘ => random fluctuations of predictions

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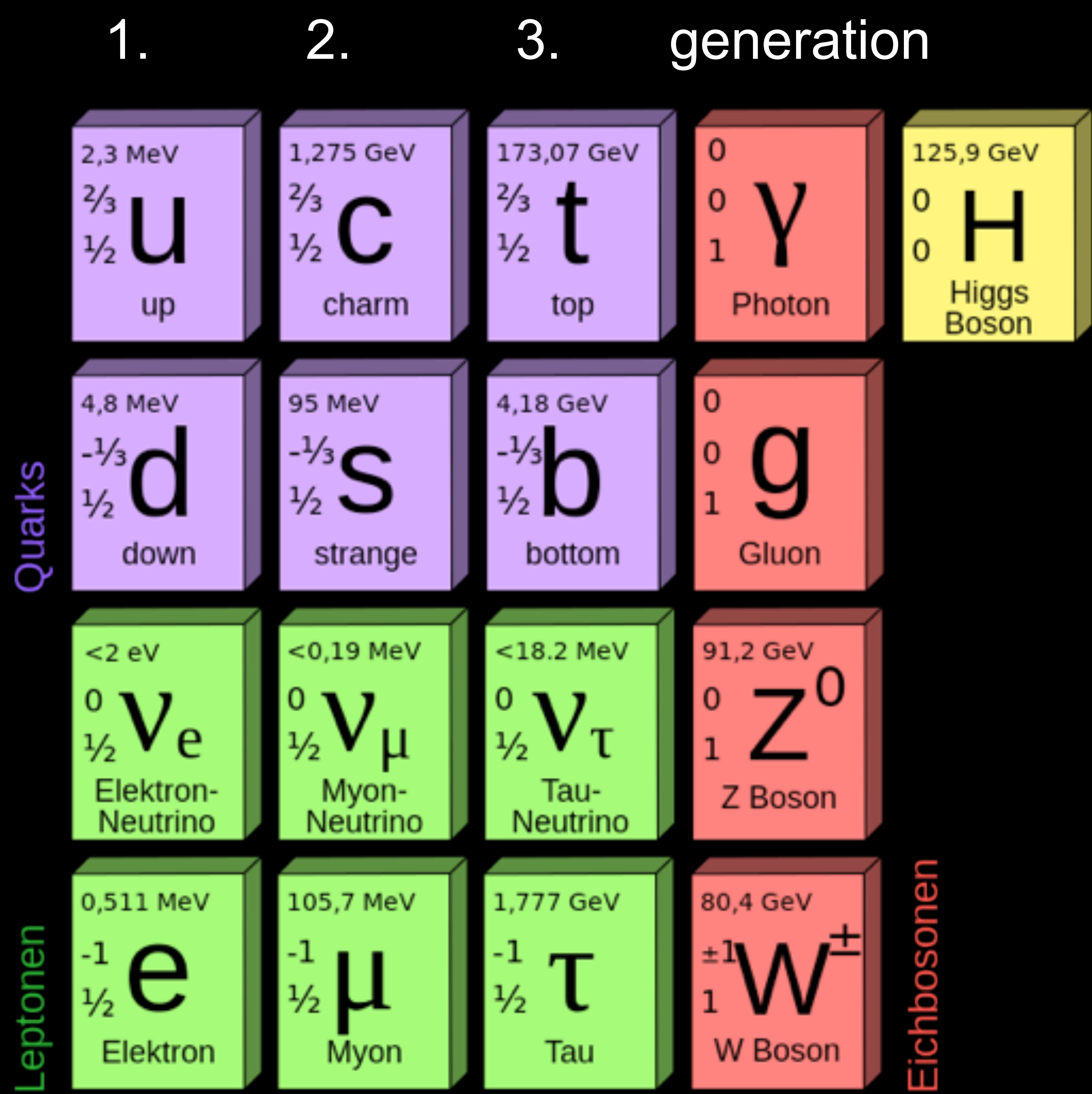

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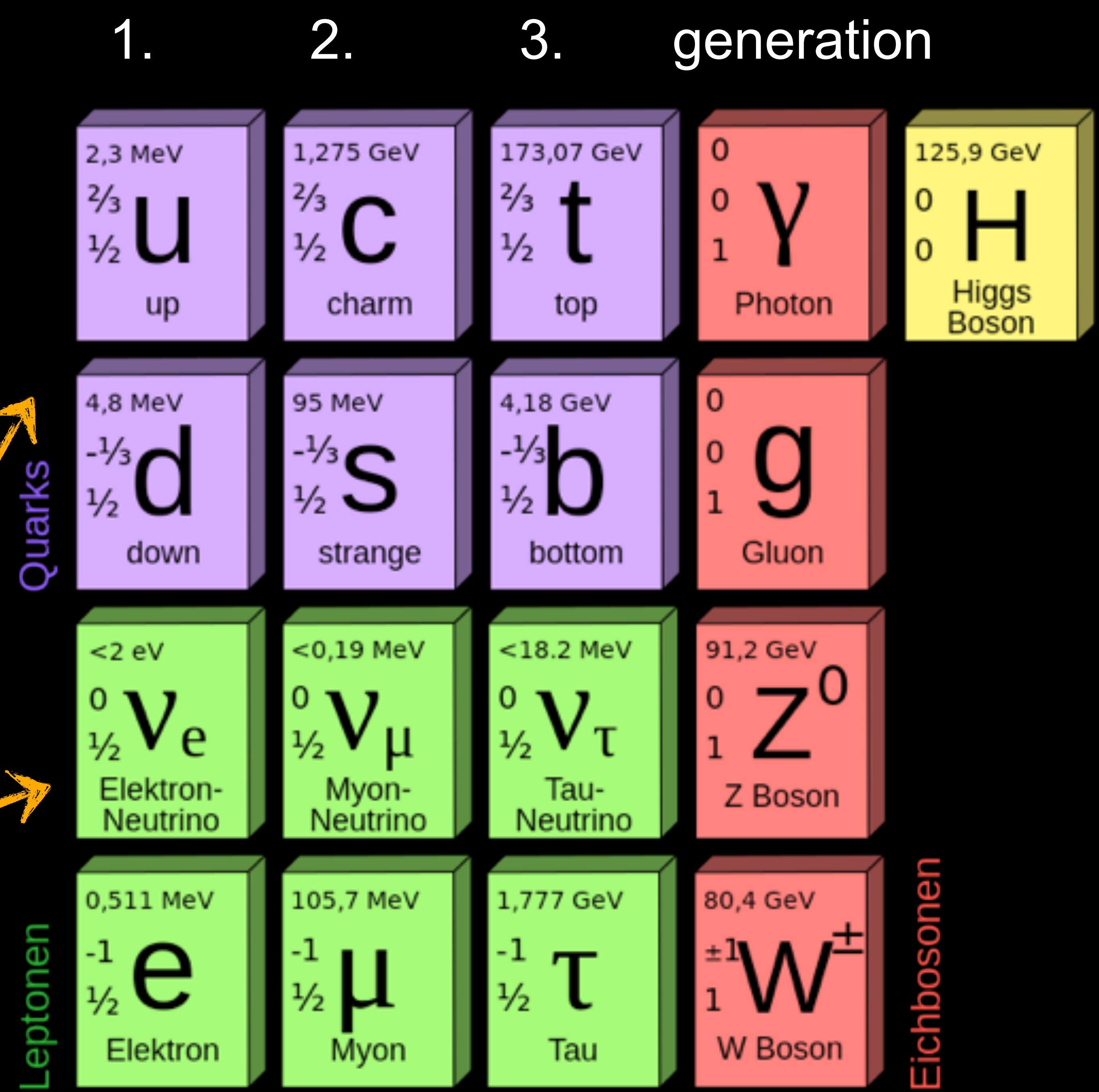

Doublets under weak interaction

In summary

- Masses are dynamically generated
- Unification of electromagnetic & weak interactions
- Breaking of electroweak symmetry consistently described
- Massive & Massless gauge bosons
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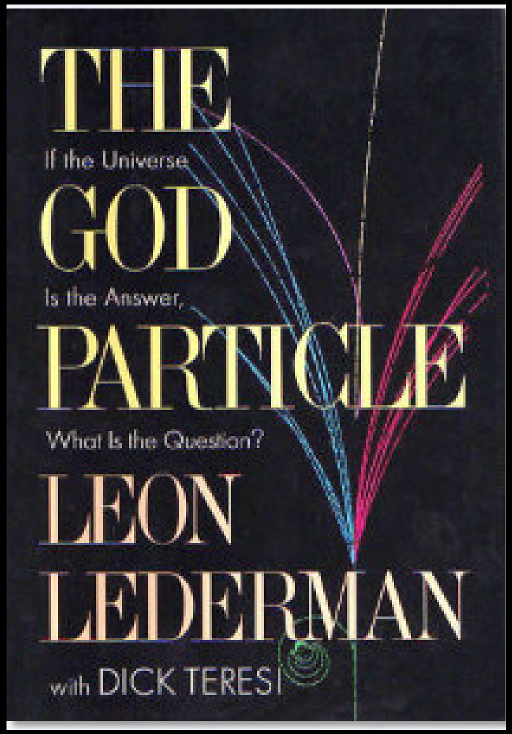
- Why is fermion mass != 0 ?
- Why are fermion masses so different from each other?
- What determines „mass hierarchy"? [2 MeV (u) -- 173 GeV (t)]

One more statement on the Higgs particle

- Leon Lederman (ex director general of Fermilab), Nobelprice 1988
  - Published book on particle physics & the Higgs particle (1993)
  - Introduced „God particle“



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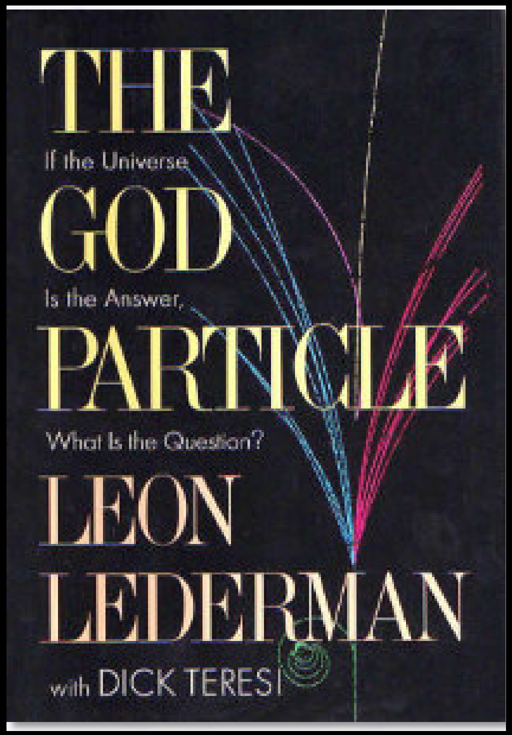

- But why?

"so central to the state of physics today, so crucial to our final understanding of the structure of matter, yet so elusive”

but "the publisher wouldn't let us call it the **Goddamn Particle**, though that might be a more appropriate title, given its villainous nature and the expense it is causing."

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

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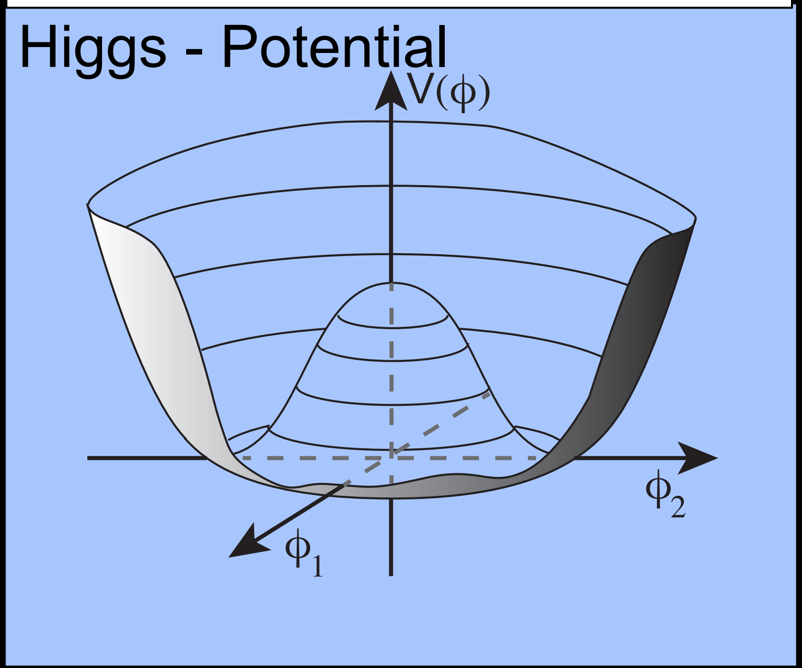

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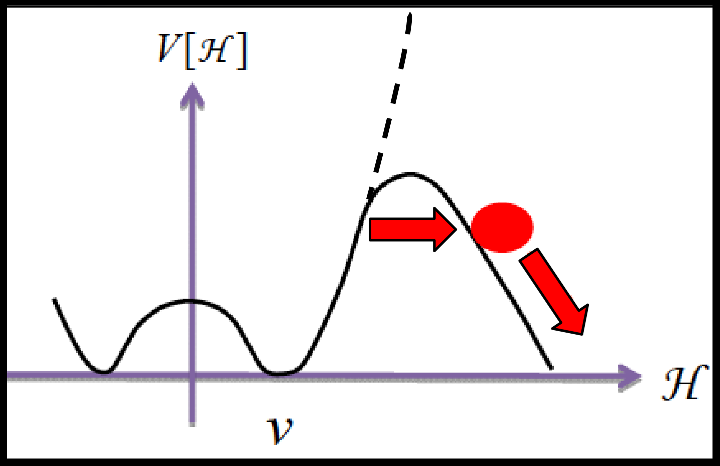

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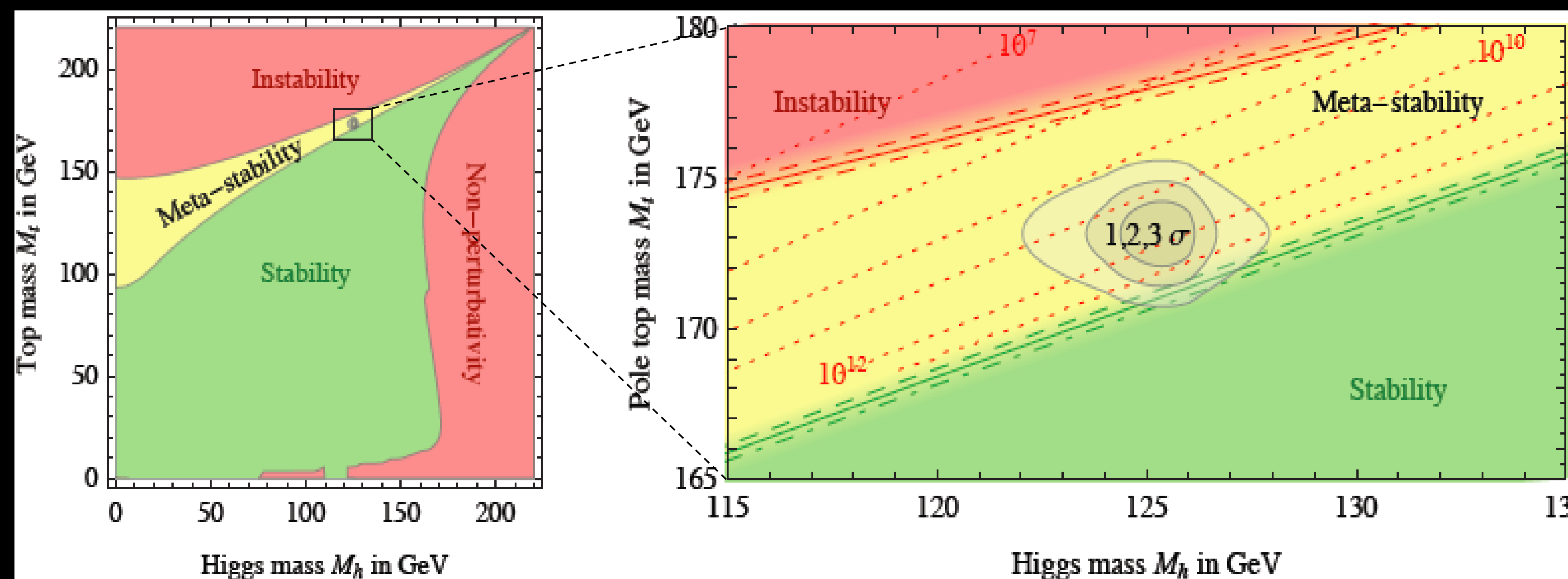

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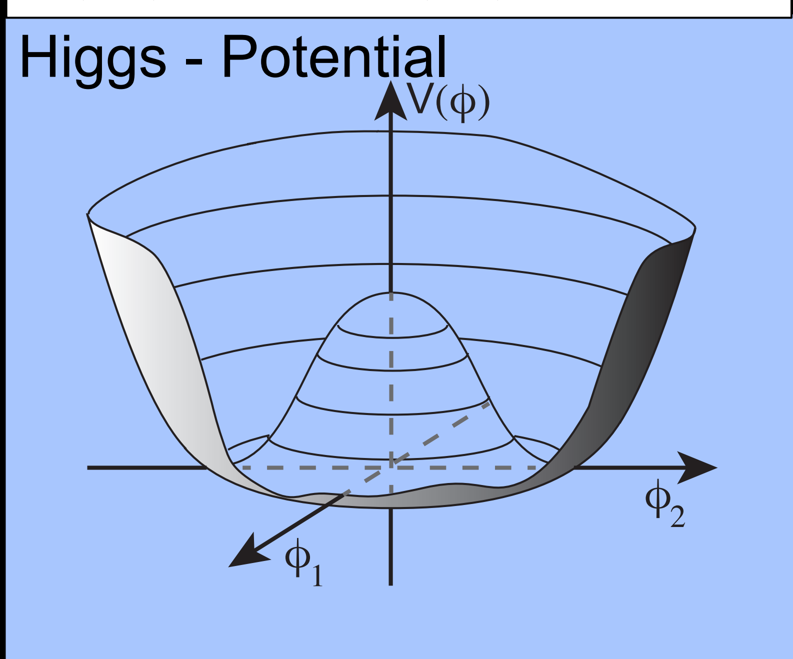

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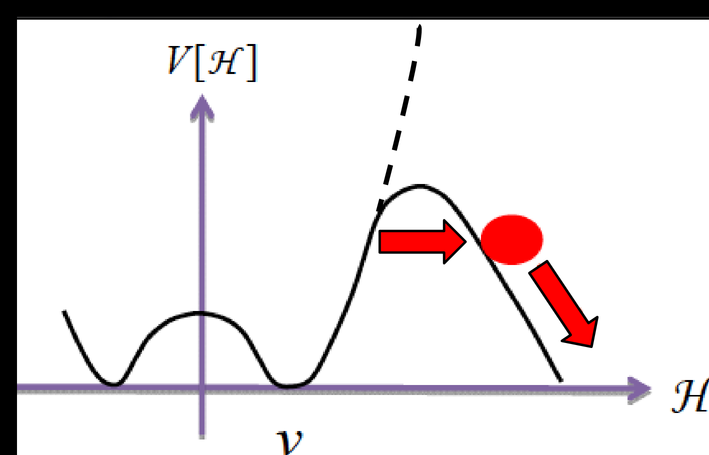

- Average tunnel time ~ 10^{100} years
- probably OK for us ;)

Neutrinos

Sources of neutrinos

- Sun / Supernovae: Nuclear fusion

$$^{1}H +^{1} H \rightarrow^{2} H + e^{+} + \nu_e + 0,42\,\mathrm{MeV}$$

- 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

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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?

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- Neutrinos can oscillate from one flavour to another!
  - Note: only electron & muon neutrinos are detected in those experiments

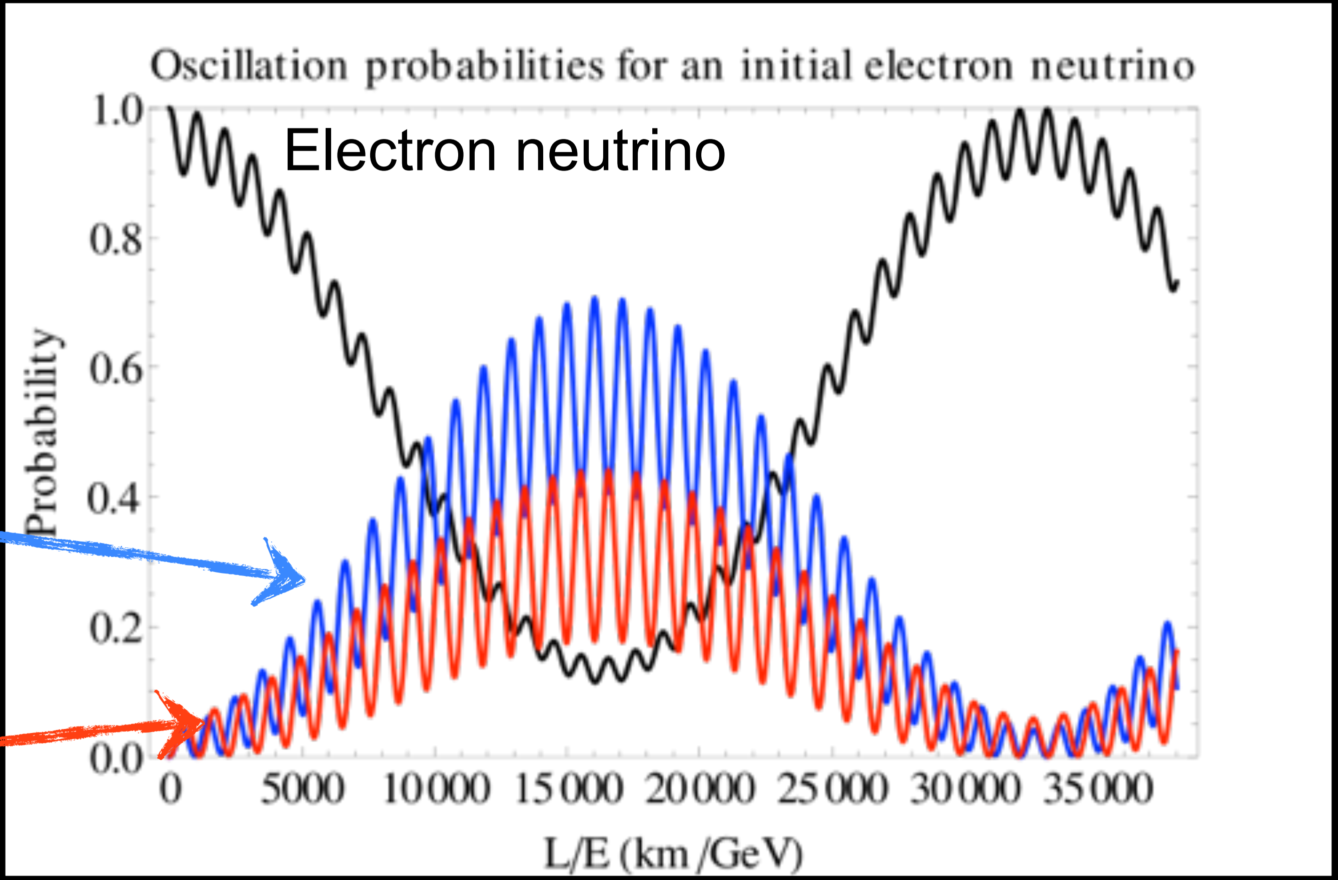
Neutrino oscillations

- Analogy to quark sector

=> Maki-Nakagawa-Sakata-Matrix

  - **Mass eigenstates != flavour eigenstates**
  - Mixing allowed → oscillations
  - Requires: $m_\nu > 0$ & $m_{\nu 1} \neq m_{\nu 2} \neq m_{\nu 3}$

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



Muon neutrino

Tau neutrino

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

Neutrino oscillations - detection

- Various reactor and accelerator based experiments
  - Detectors in varying distance to sources
    - Double Chooz, KamLand, DayaBay / T2K, Opera, Minos
  - Measurement: disappearance of neutrino flux

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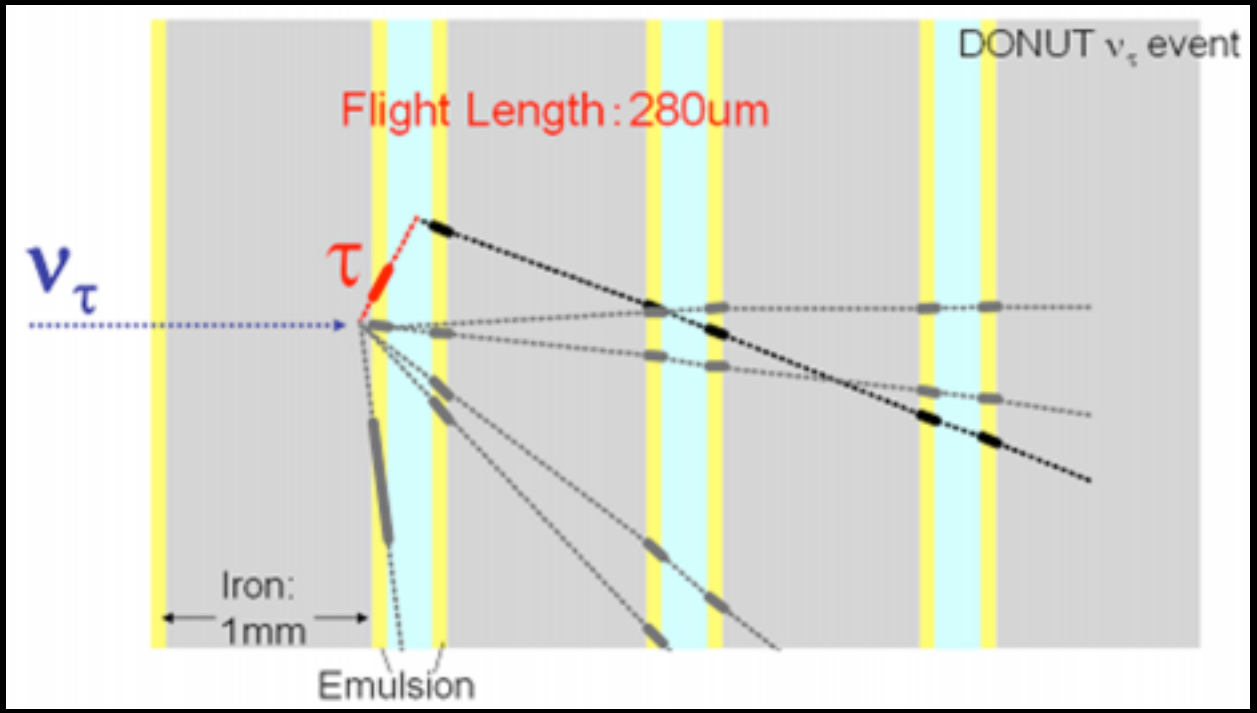
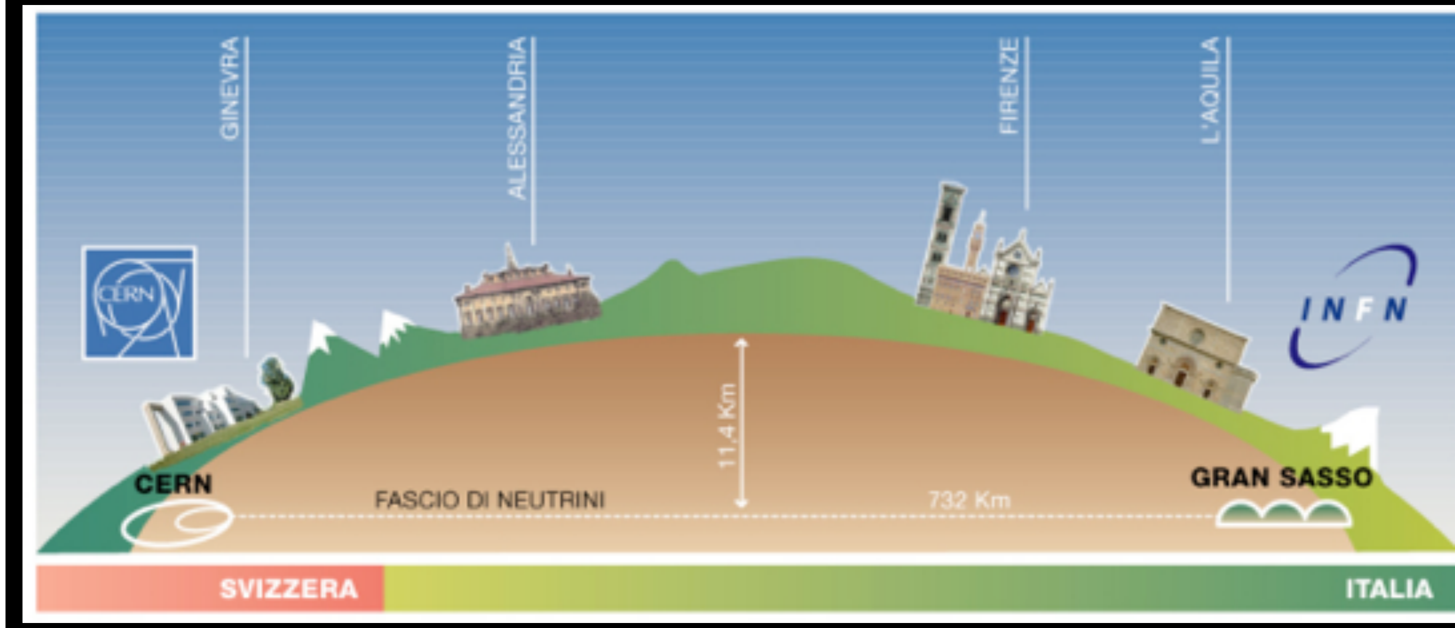
- **Opera**: Detected appearance of tau-neutrinos!

Opera: 2010-2014

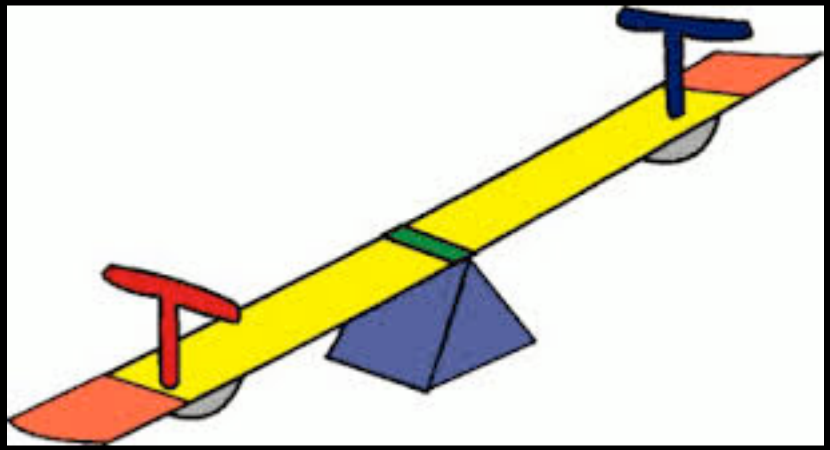
  - Neutrino beam (μ, e) from CERN sent 740km to Gran Sasso (IT)
  - Detection of tau-neutrinos in neutrino beam (5x)





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 genration between sterile and Dirac neutrinos:

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

Dirac mass ~ EW scale

Majorana mass ~GUT scale

B >> M

Eigenvalues ~ Neutrino masses:

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

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

$$\lambda_+ \approx B$$ ~ 1eV

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

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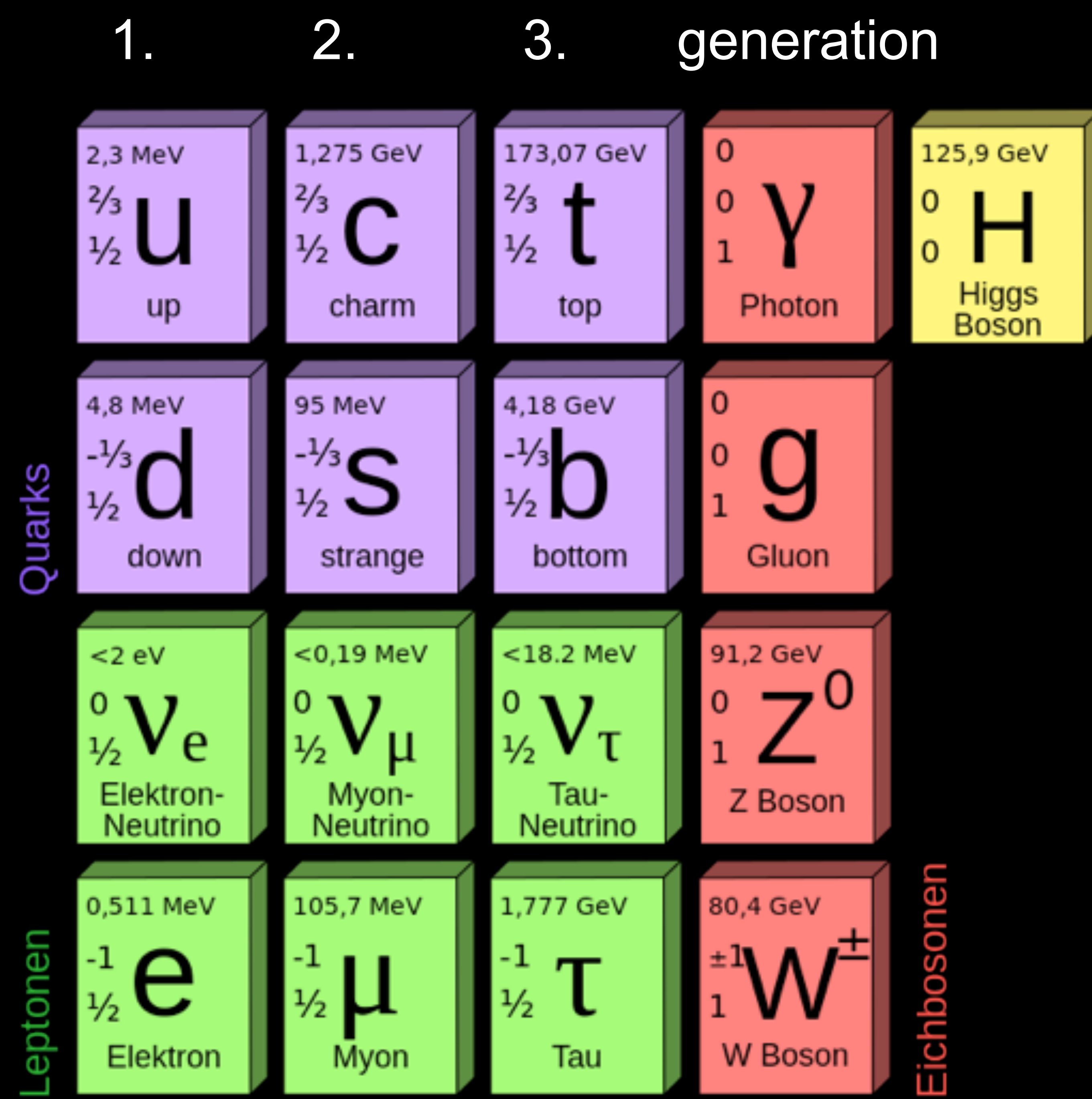

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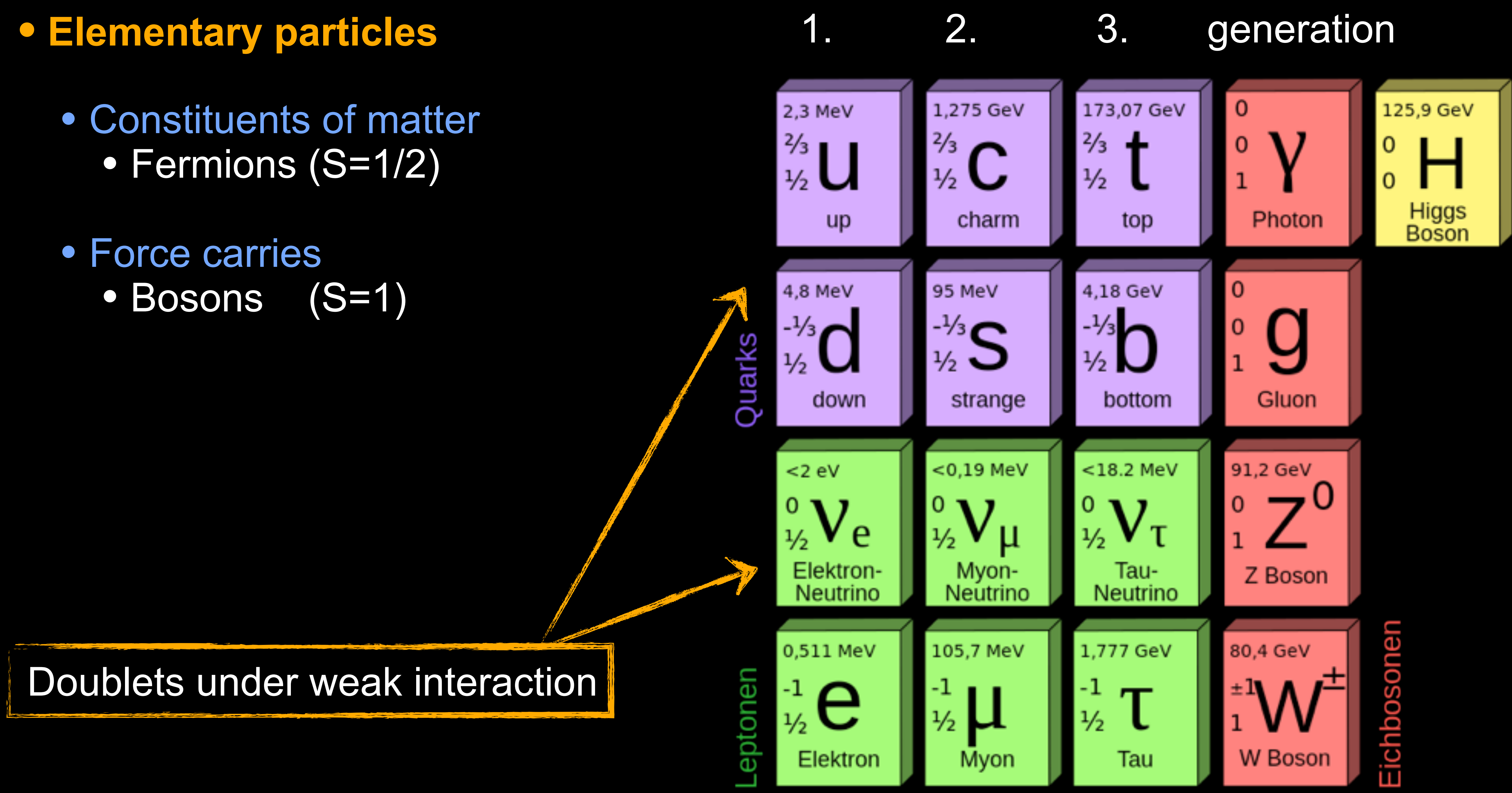
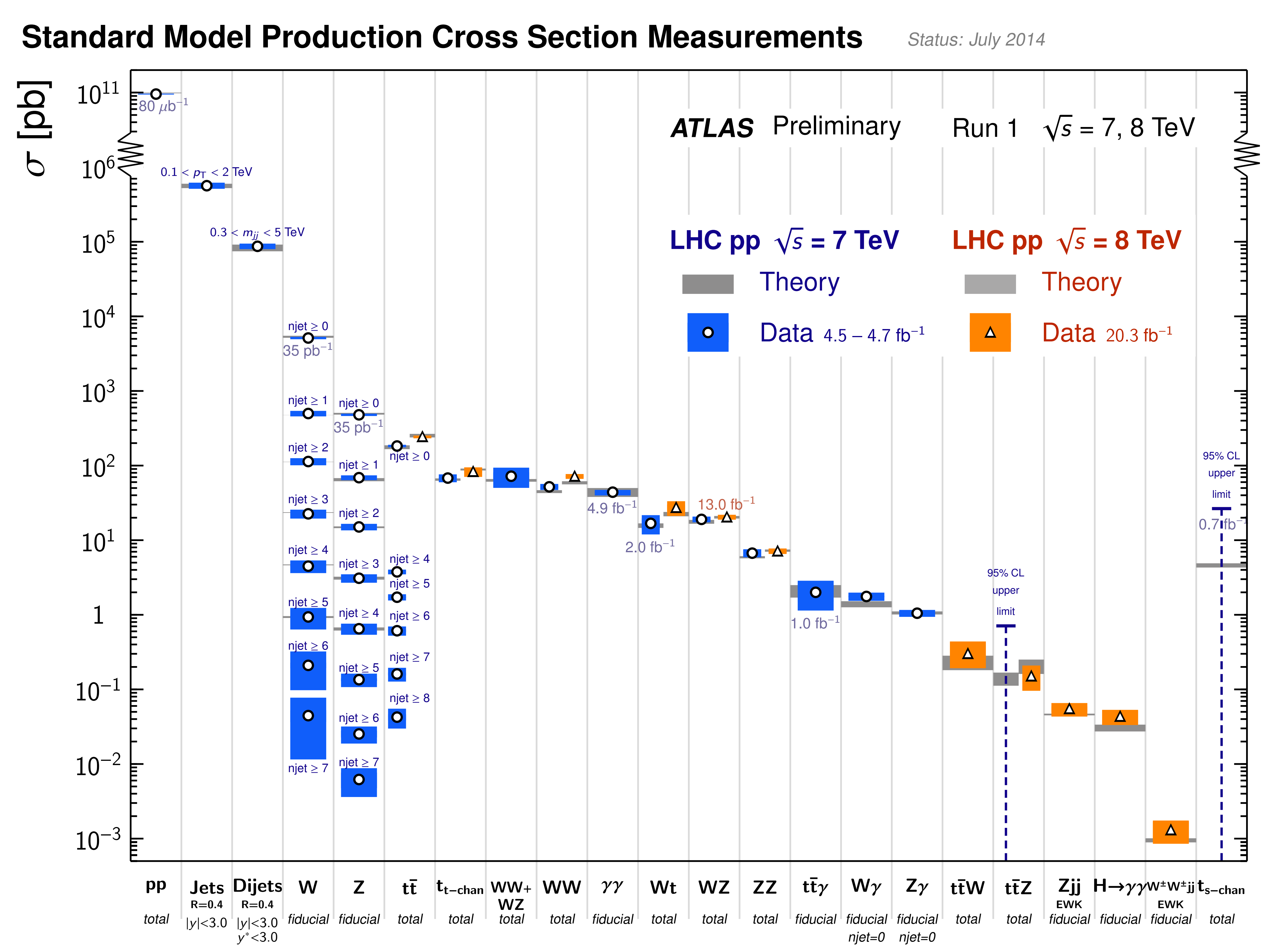


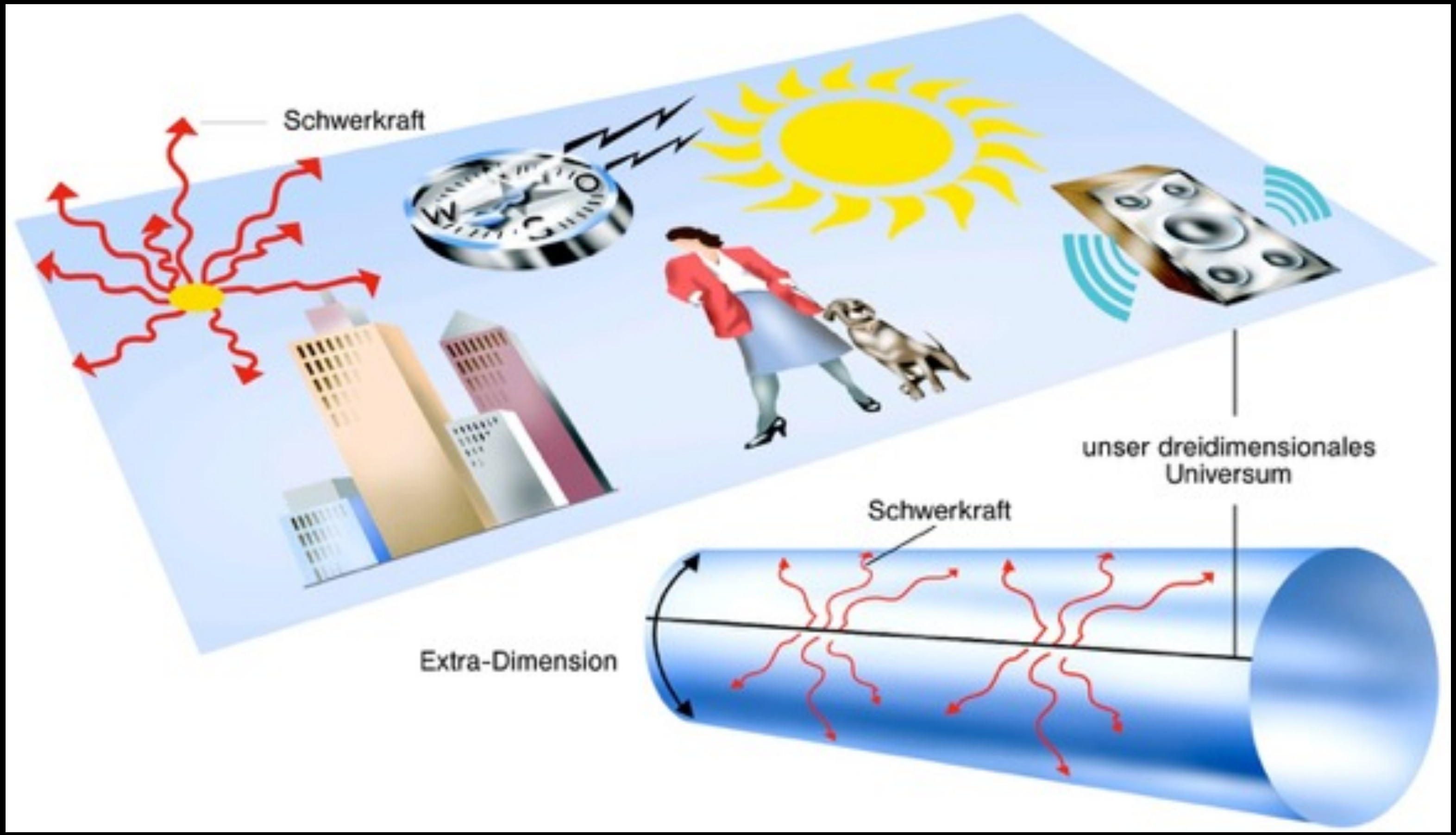
Success of SM



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
    - Neglectable on particle level!
    - 10^{-38} weaker as electromagnetic interaction!

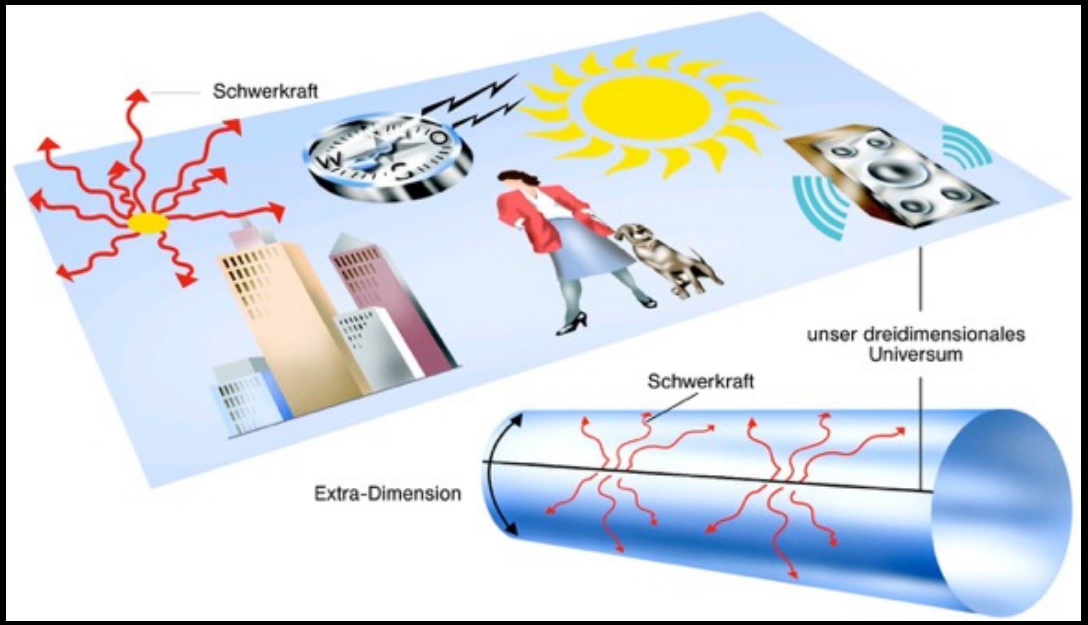


- Extra dimensions?

Gravitation

- Why is gravitation so weak?

- Extra dimensions?



- Predictions of ‚black holes'
  - Particles that could be created at the LHC

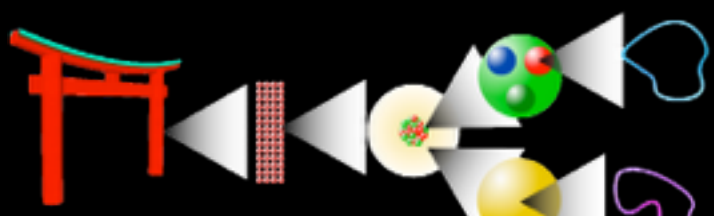
- Scattering off compact dimensions
  - Kaluza-Klein towers / exitations

(= standing wave in extra dimension)

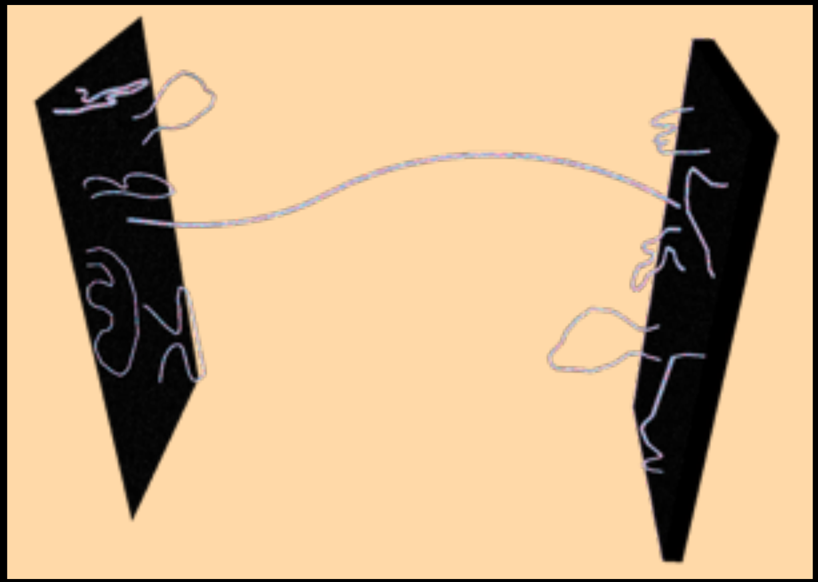
Not observed to date :(

Gravitation - String Theory

- **One** fundamental object:
  - String
  - Size ~ Planck length: 10^{-35}m



~1980 till today



- 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!

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- => 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**

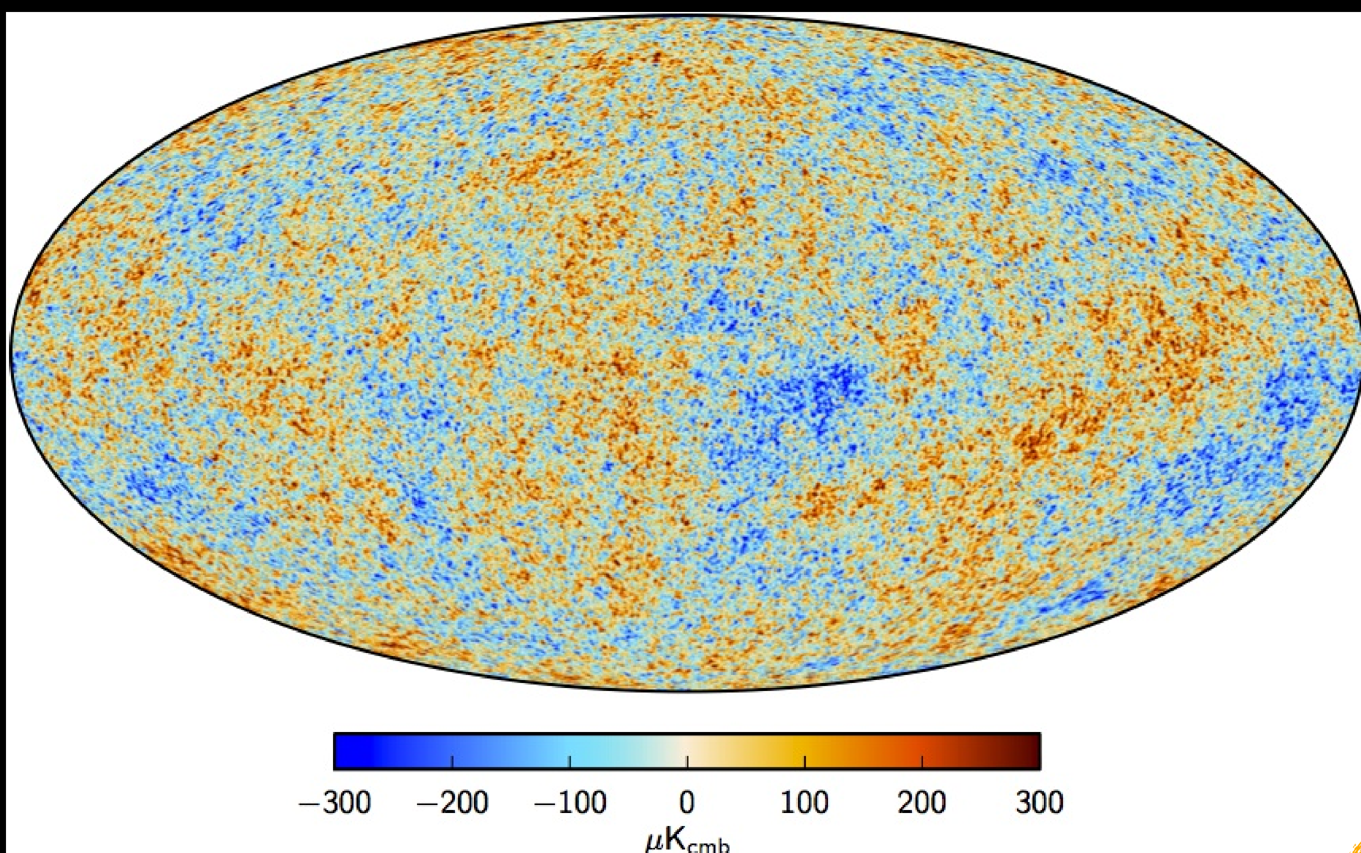
Intermezzo - Cosmology

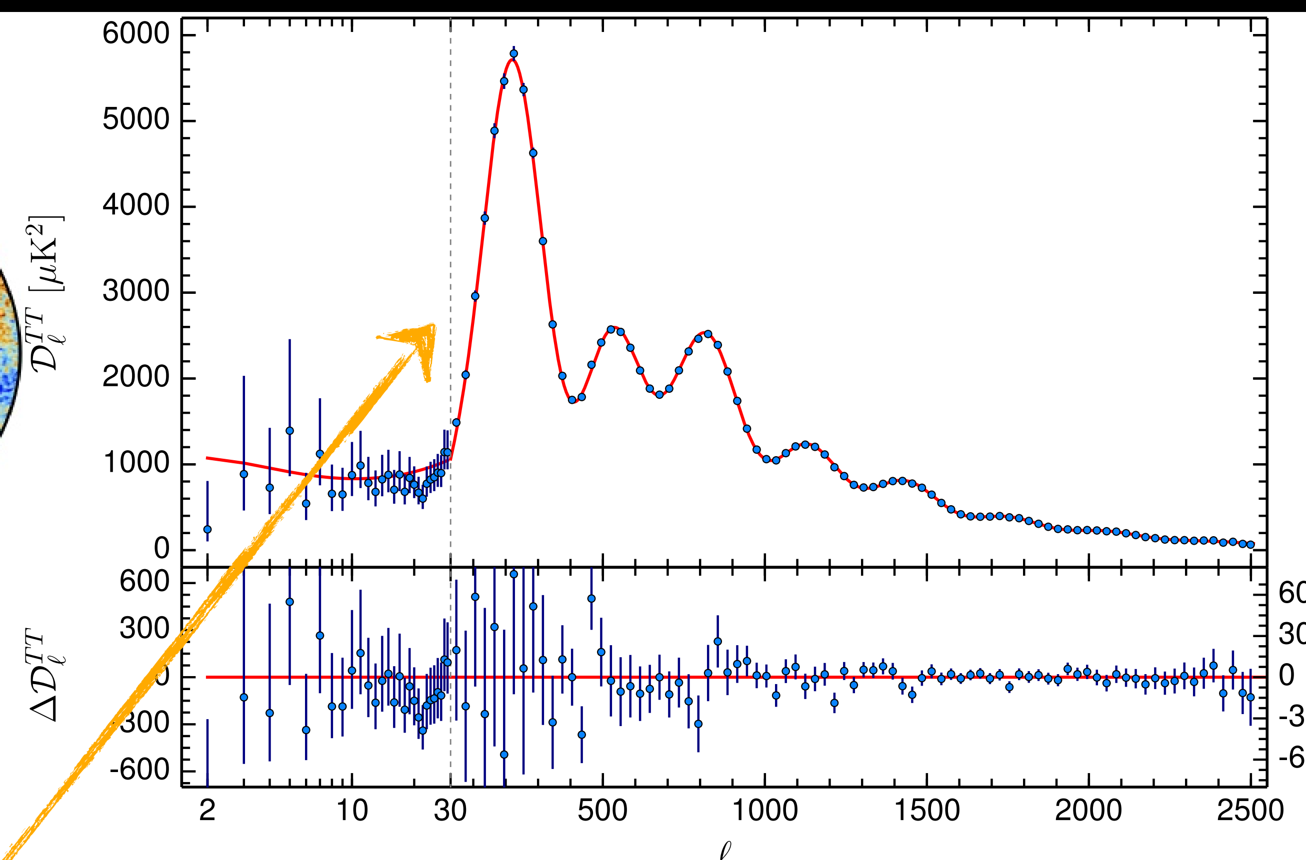
Cosmology lecture by Sarah Aretz (11/07)

- Study of cosmic microwave background:

WMAP / Planck: 2010 / 2015

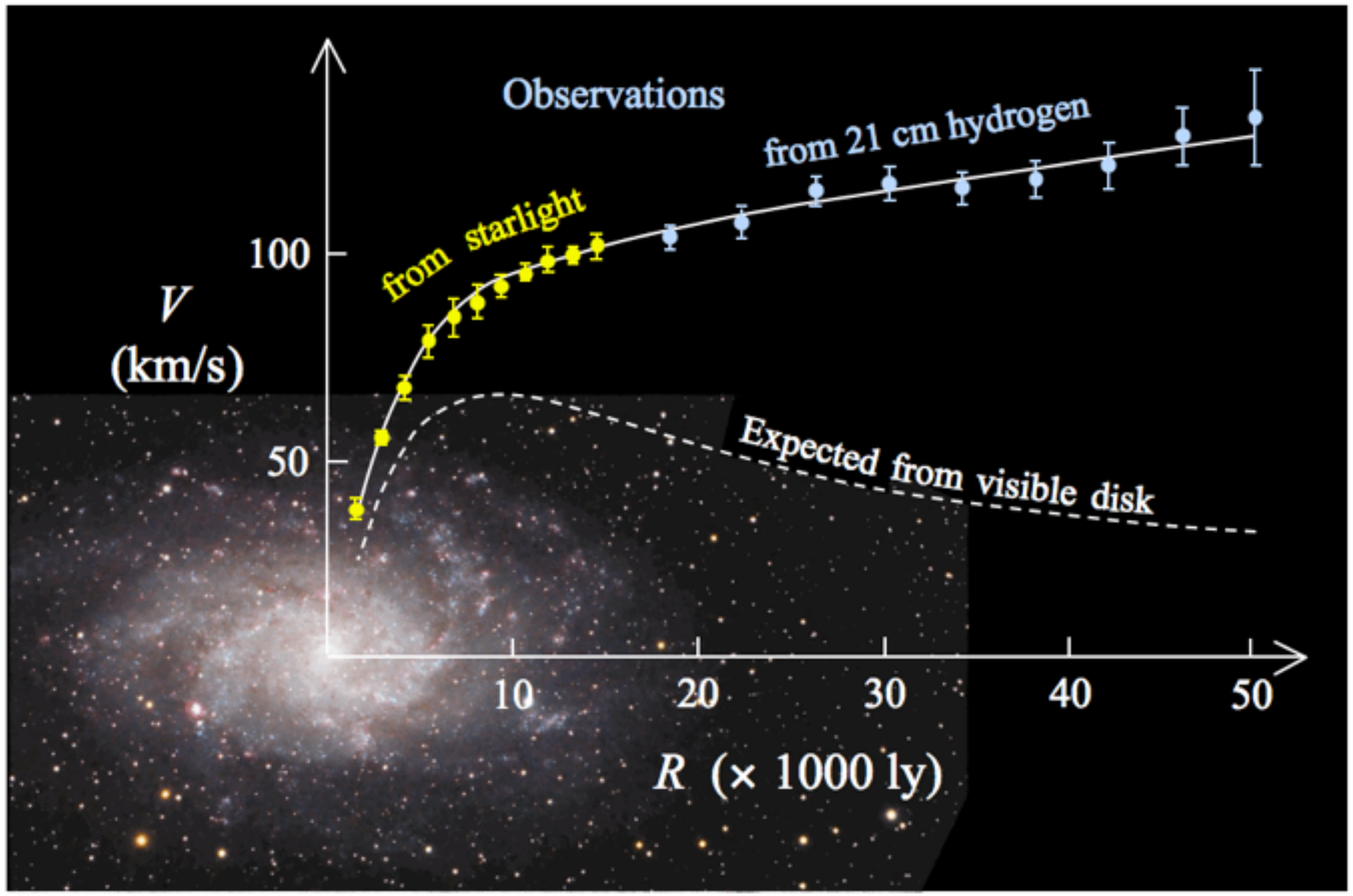
  - Universe cools down → neutral atoms → transparent for em. rad.
  - Radiation from this era: while traveling through the universe, wavelength stretched with expansion of space itself
    - x-rays → microwaves





- Fit of ΛCDM model to data. Parameters:
  - Baryon-density, matter density, curvature of space, ...

Apropos: dark matter



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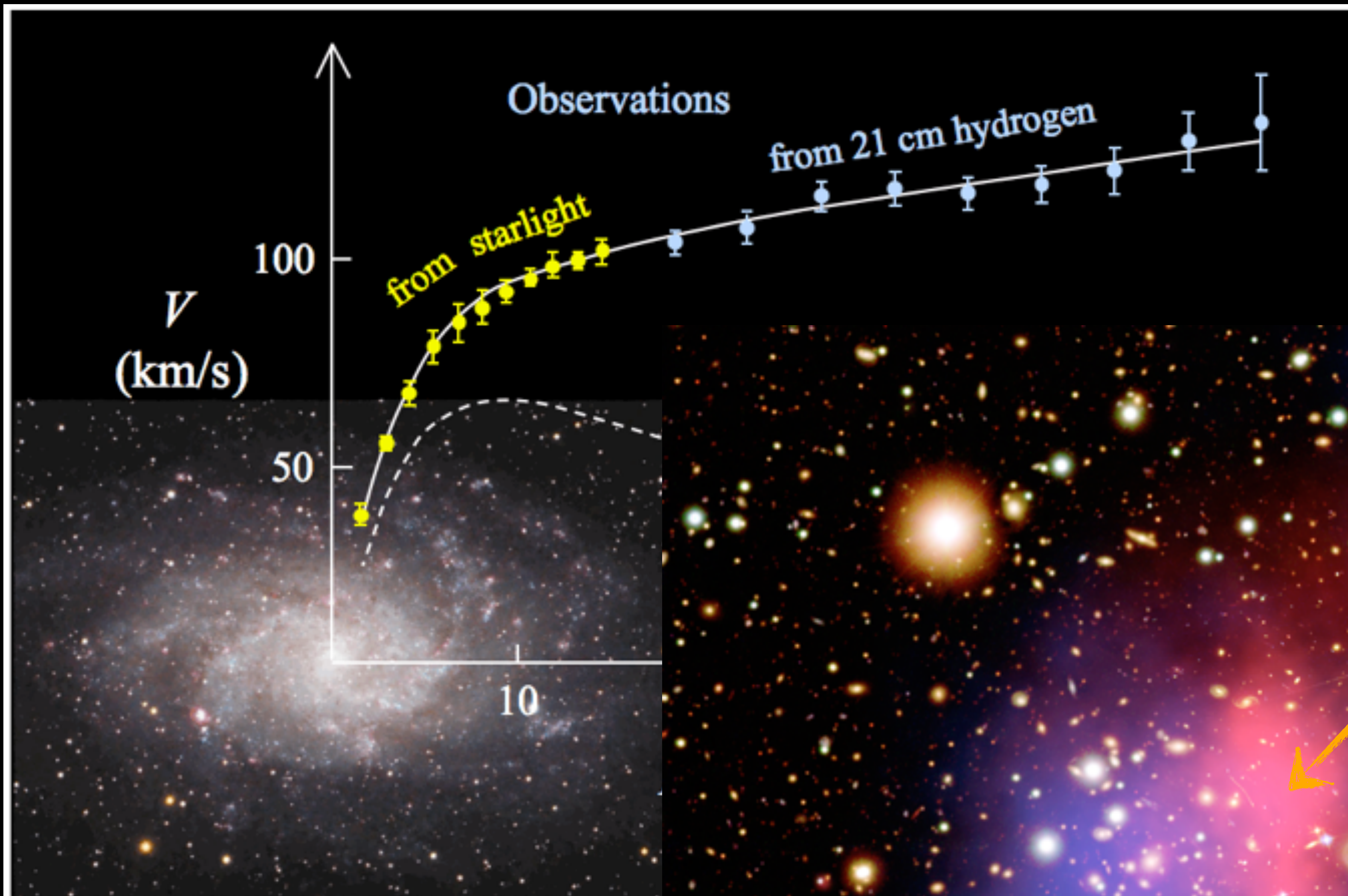

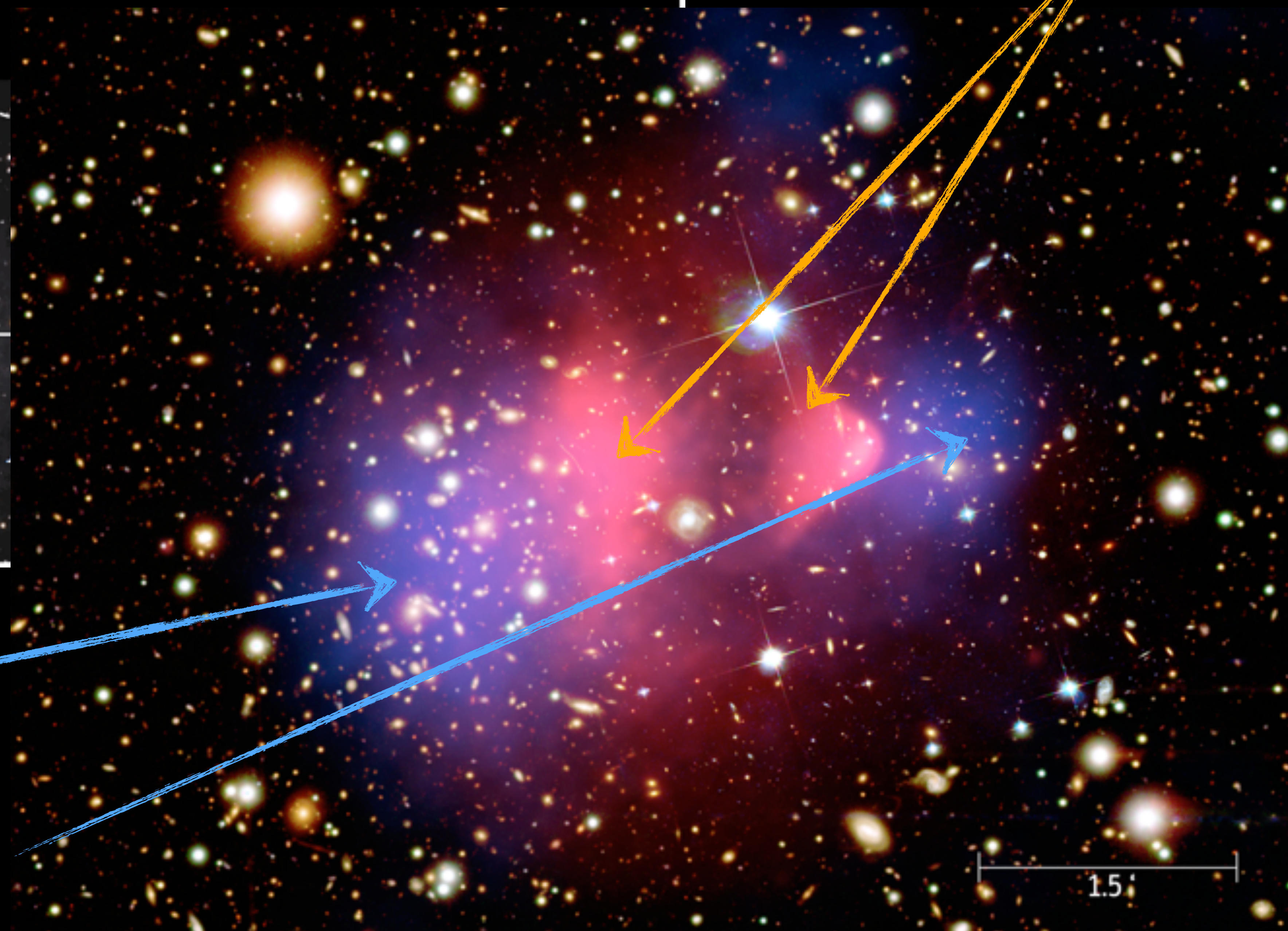

- gravitational centre
  - Per „weak-lensing“

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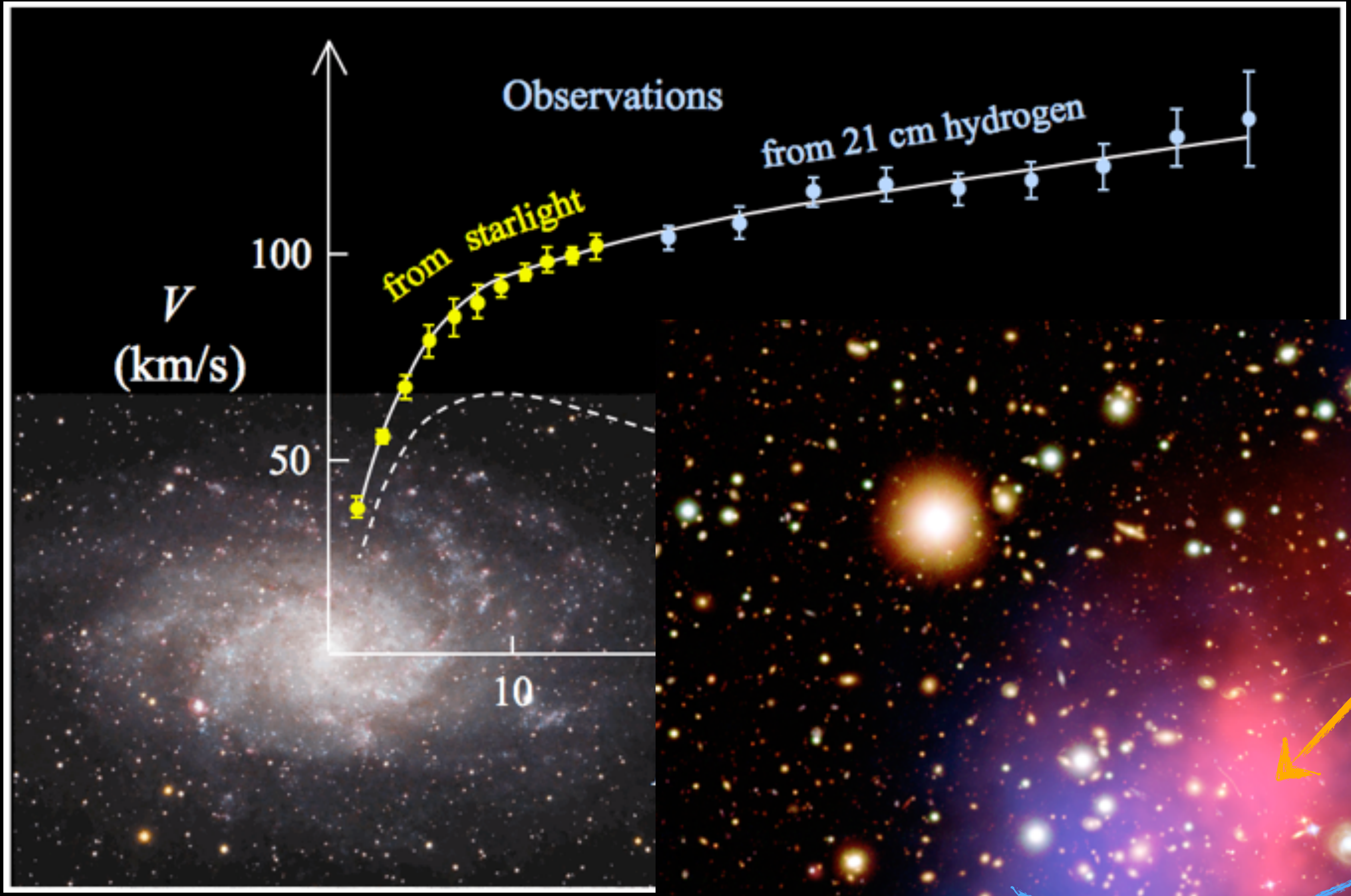
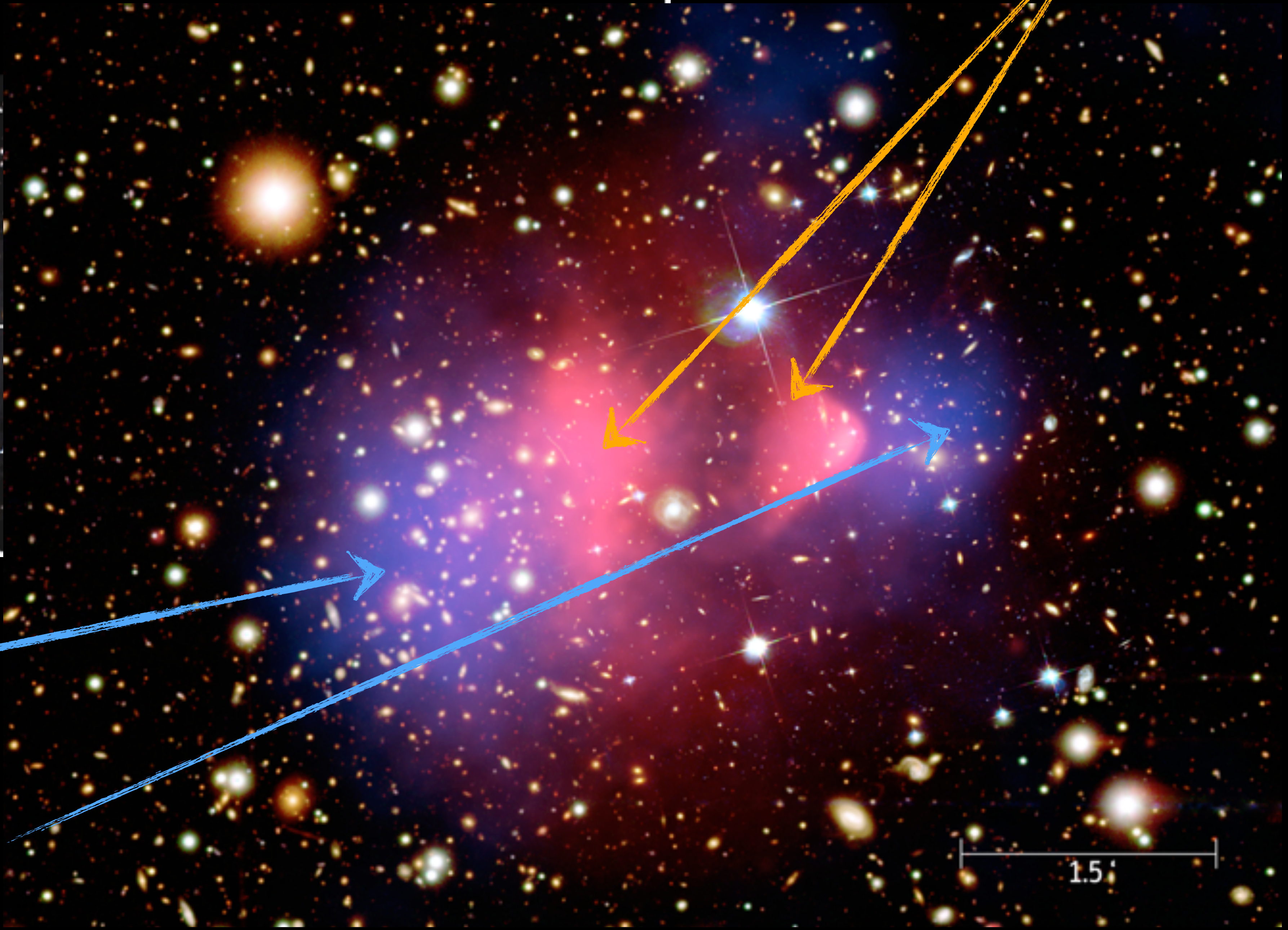


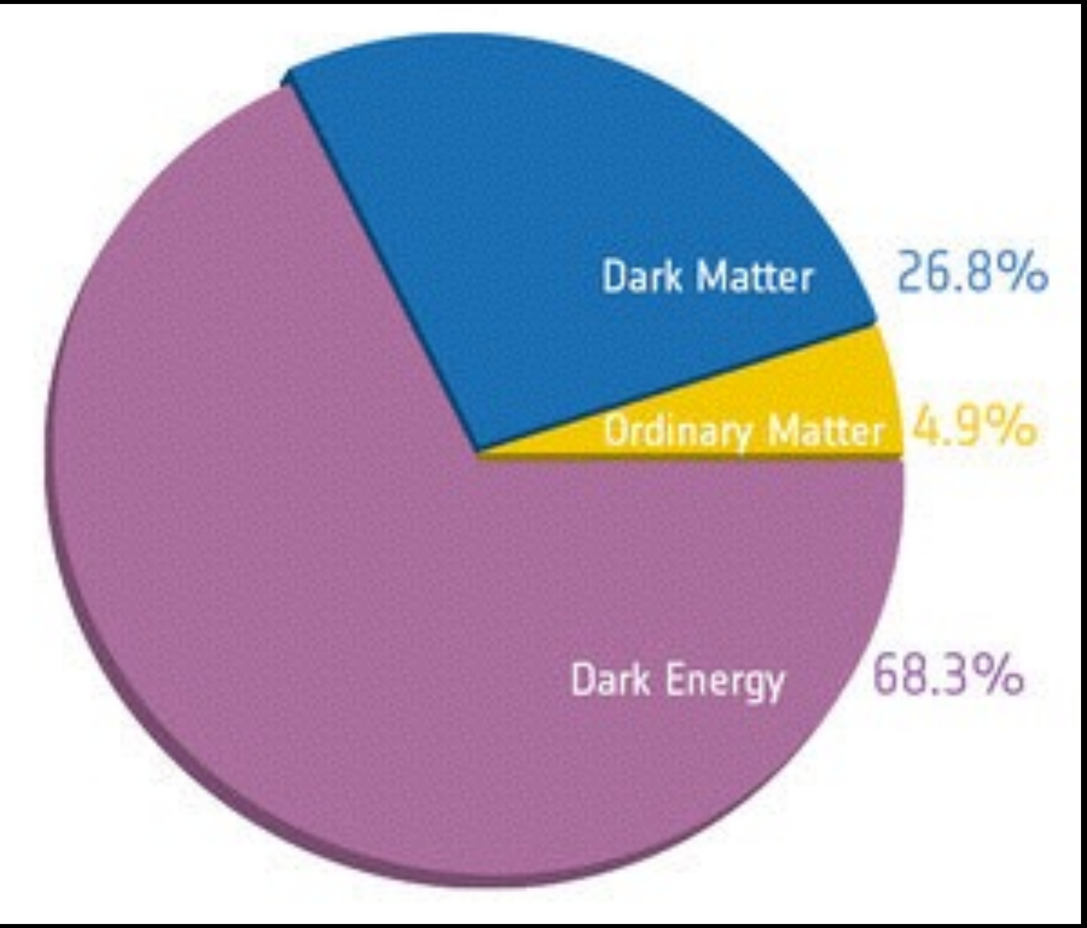


- X-ray emission from hot gas
- highest baryon desnity

- gravitational centre
  - Per „weak-lensing“

Apropos: dark matter

Planck: 2015



dark matter ?

baryons

dark energy ???

- Several candidates + extensions of SM trying to describe DM

Apropos: dark matter

- Properties:
  - Massive (gravitation)
  - Weak interaction

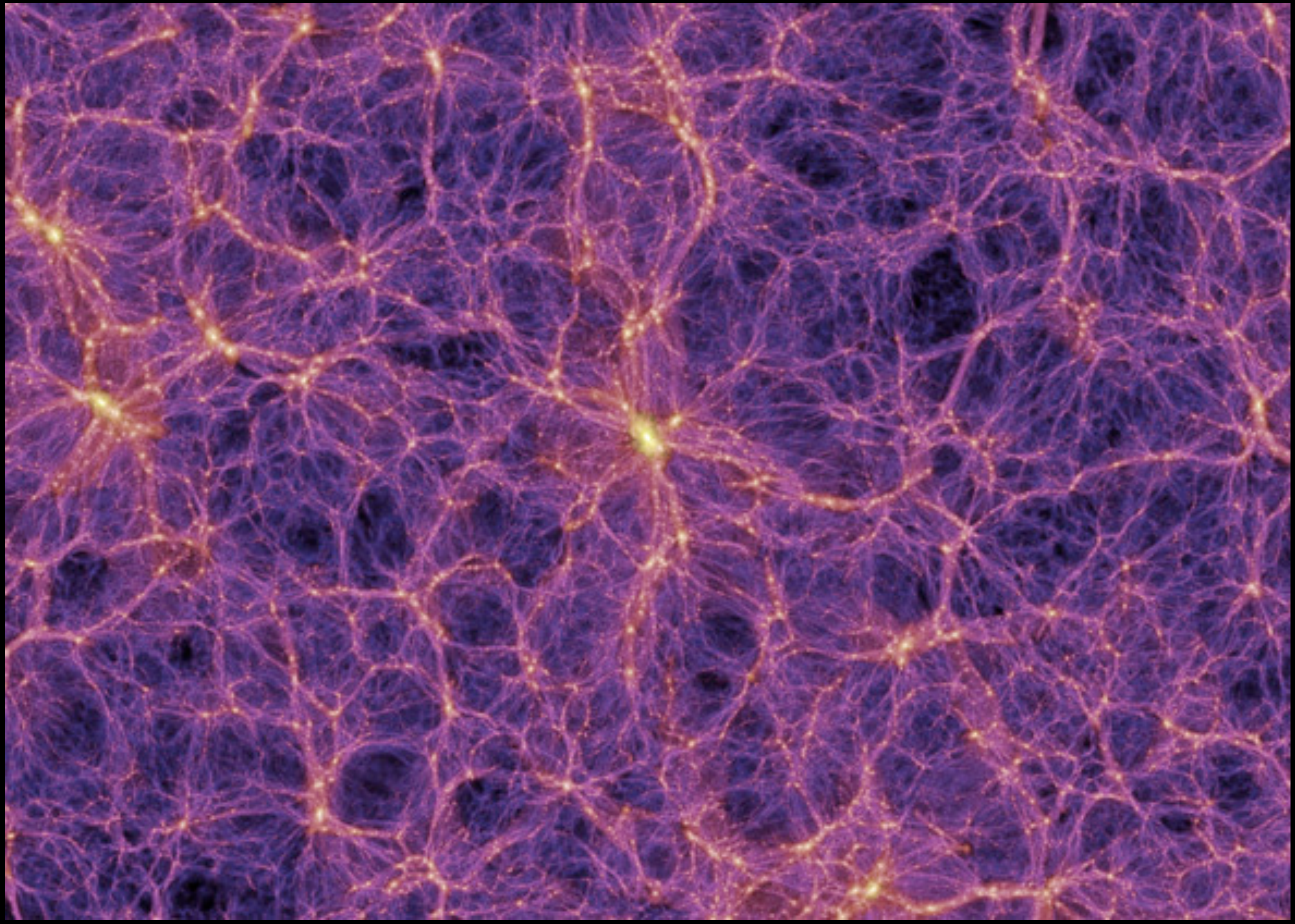
Apropos: dark matter

- Properties:
  - Massive (gravitation) → Neutrinos?
  - Weak interaction

Apropos: dark matter

- Properties:
  - Massive (gravitation) → Neutrinos?
  - Weak interaction

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

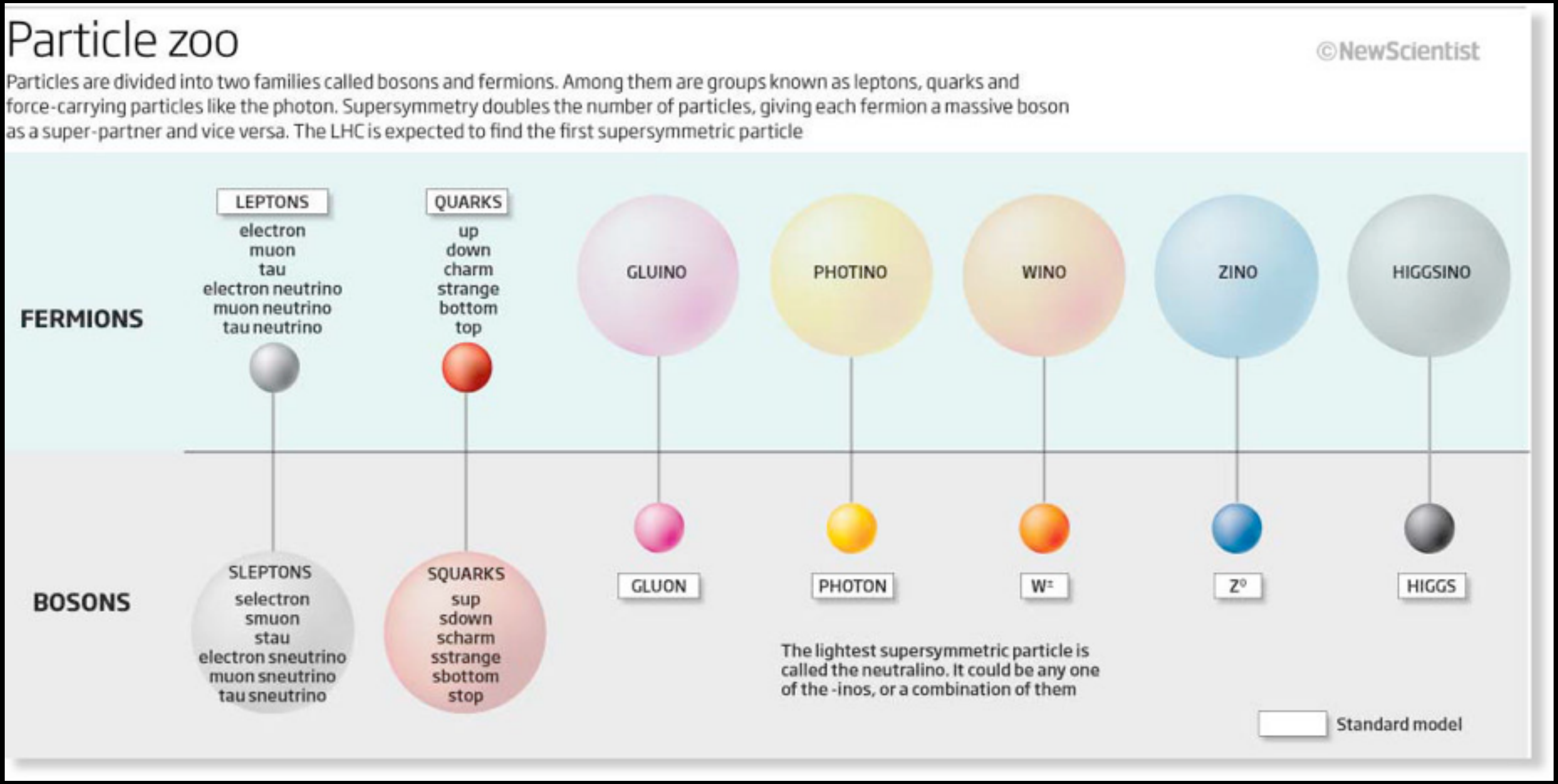


Apropos: dark matter

- Properties:
  - Massive (gravitation)
  - Weak interaction
  - ~non relativistic
- Candidates:
  - WIMPs (Lightest supersymmetric particle?)
  - Axions
  - Sterile neutrinos

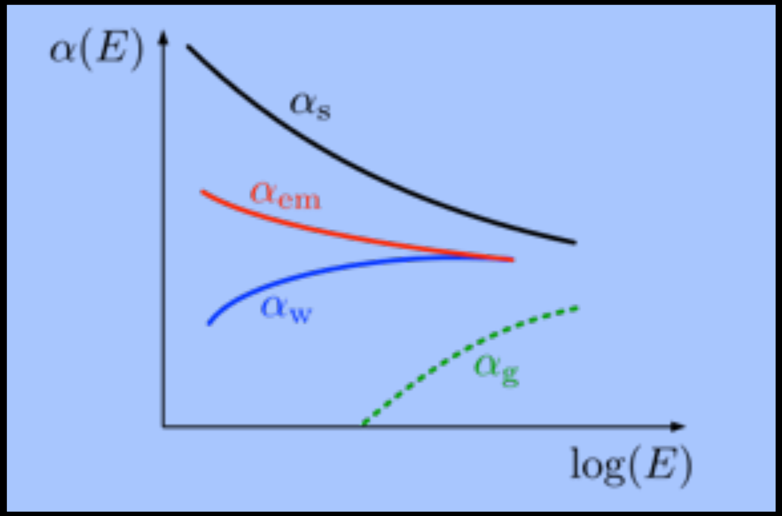
A word on super symmetry

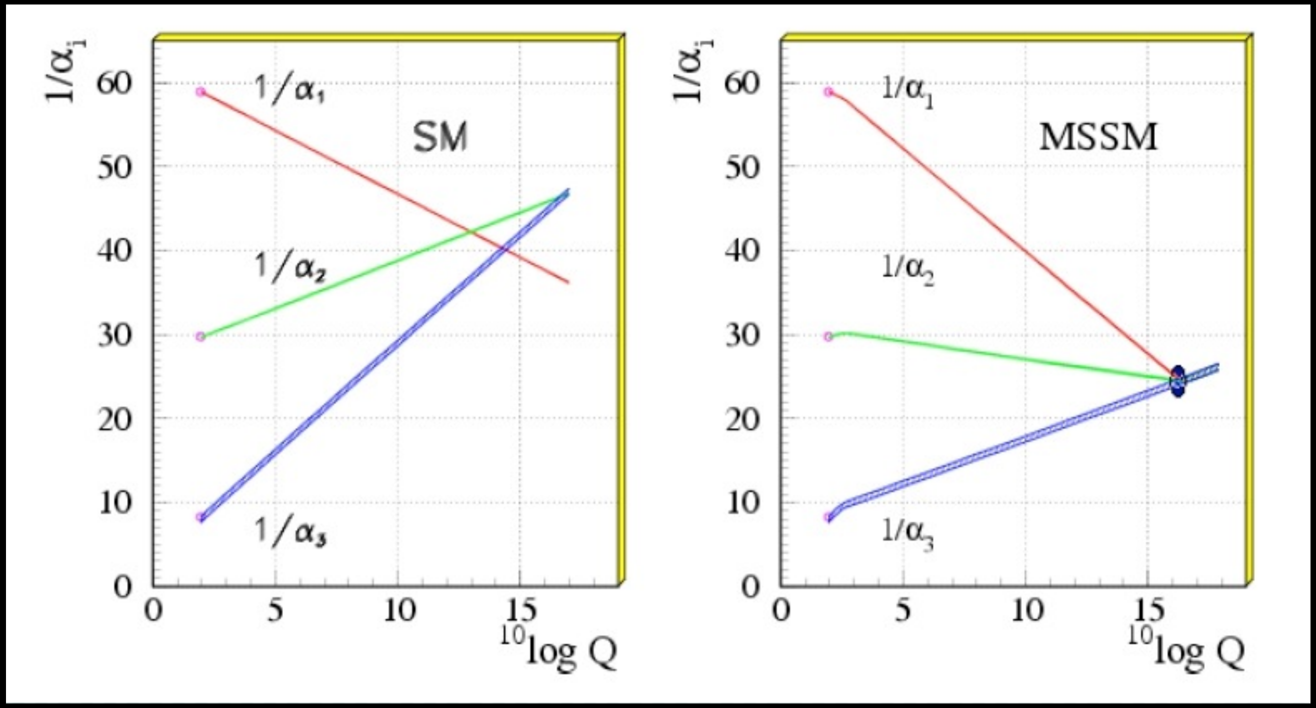
- New symmetry:
  - Each Boson (S=0,1) is assigned a fermion (S=1/2) and vice versa



A word on super symmetry … or two

- „Completes“ SM → all possible symmetries utilised
  - New particles influence „running“ of couplings
    - Grand unification possible





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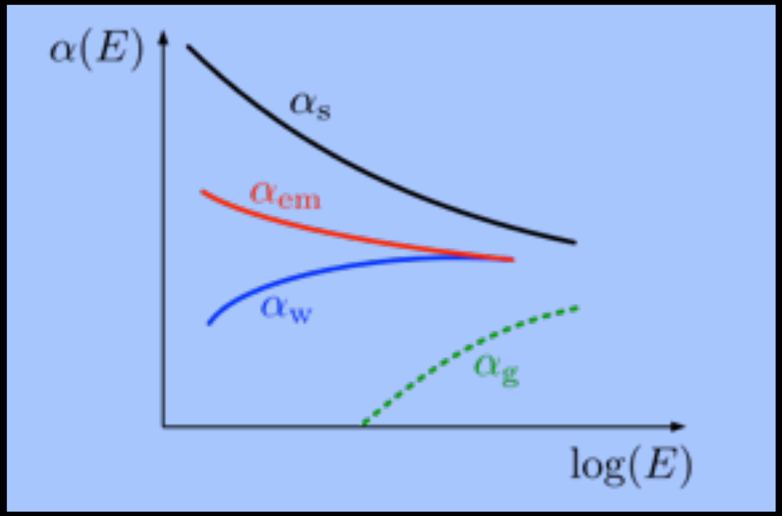

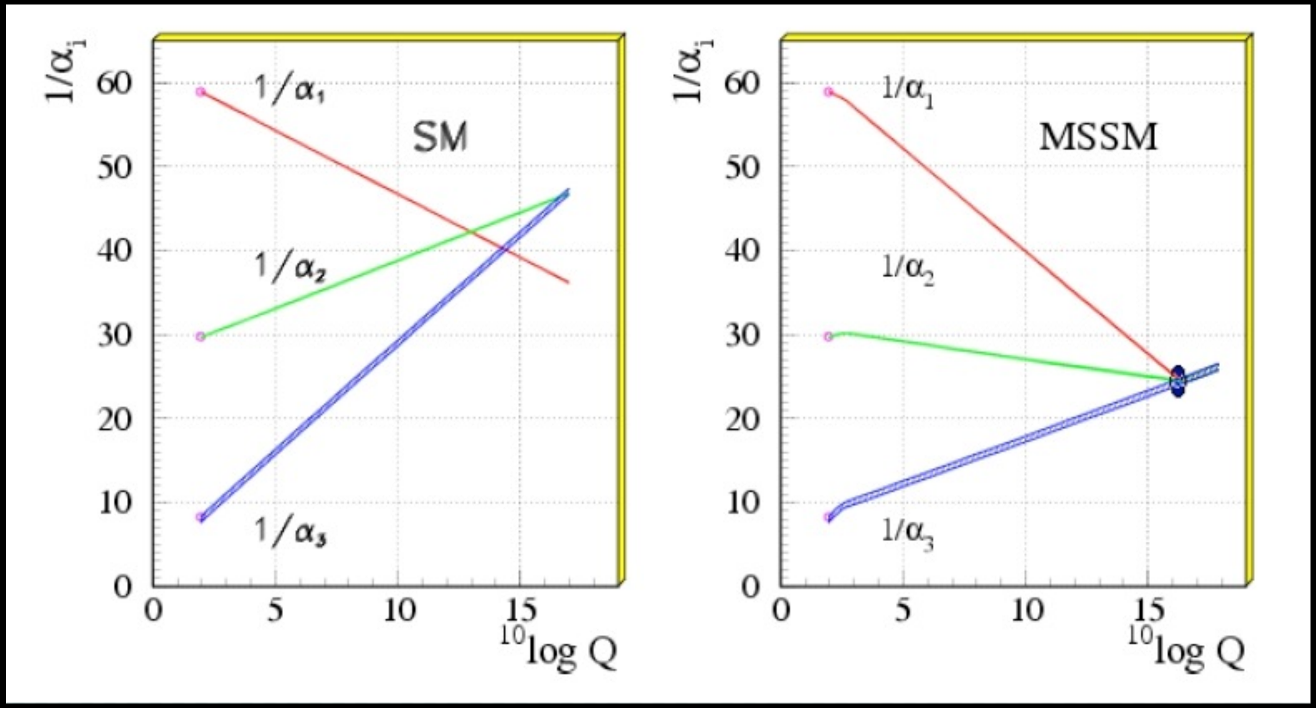

- New conserved quantity: R-parity (+1 for particles, -1 for super-partners)
  - Lightest super symmetric particle must be stable!
  - Candidate for dark matter

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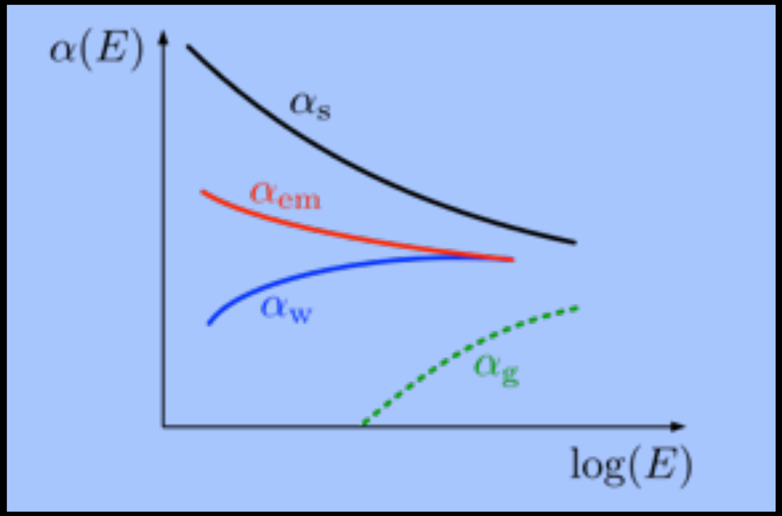

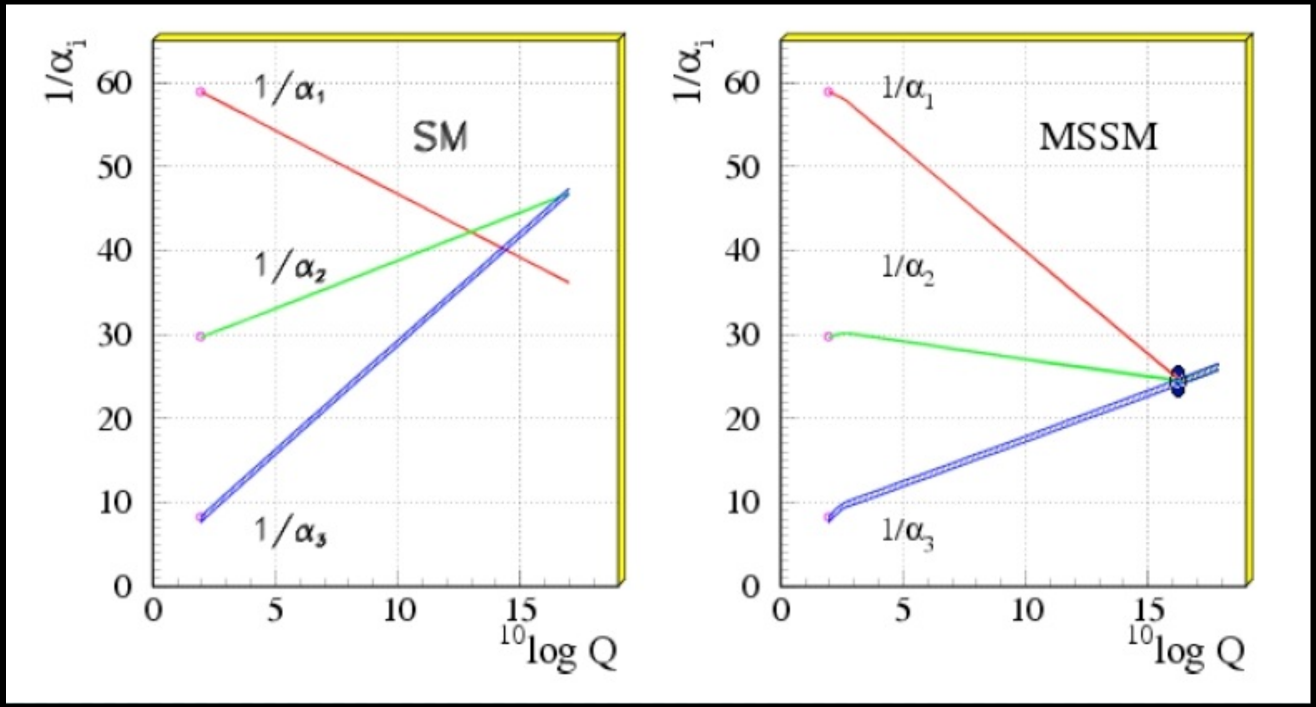

- New conserved quantity: R-parity (+1 for particles, -1 for super-partners)
  - Lightest super symmetric particle must be stable!
  - Candidate for dark matter

> - 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)

Axions

- Solve „strong CP problem“
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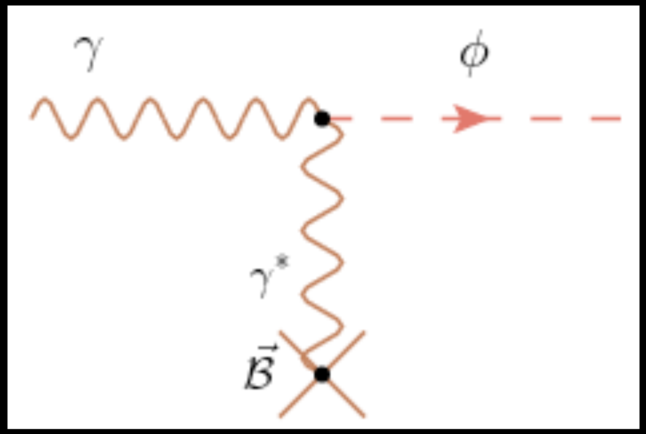
Peccei, Quinn: 1977

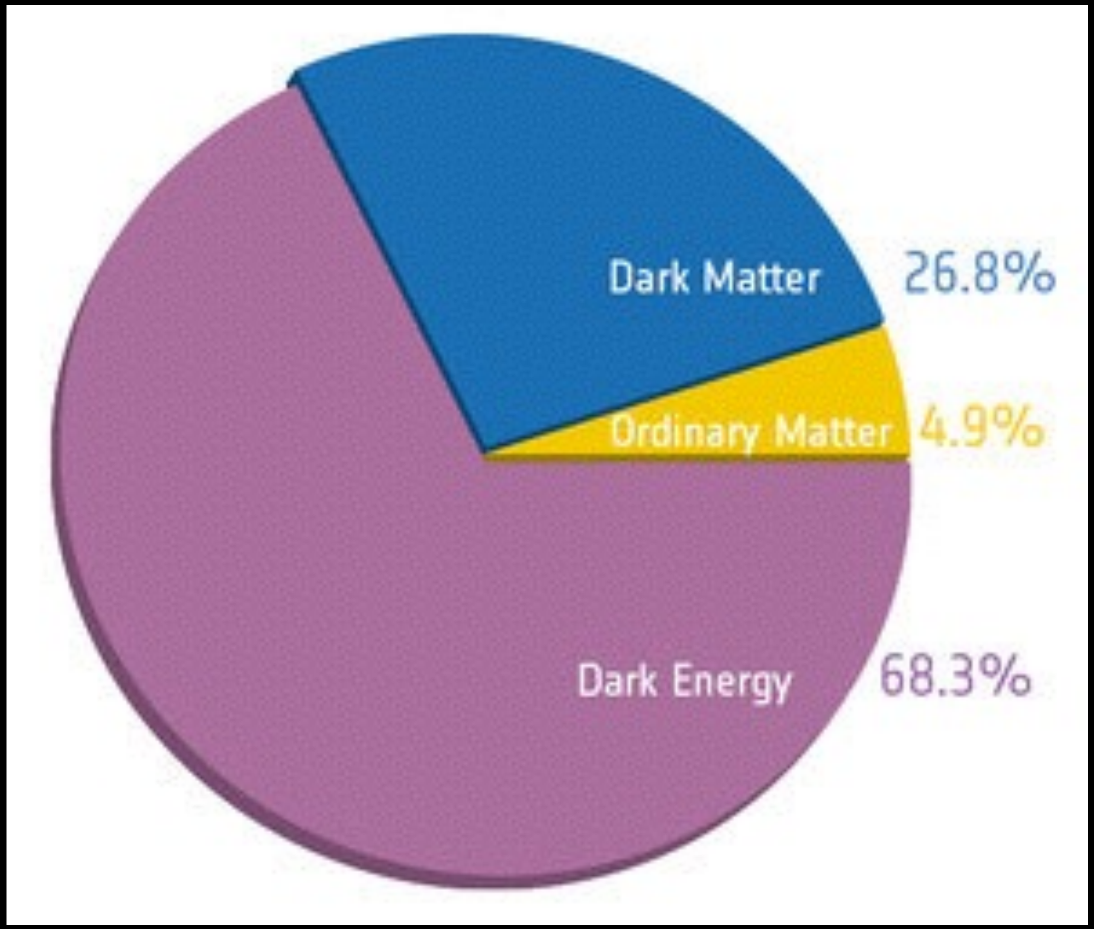
- Introducing yet another complex scalar field
  - Corresponding symmetry is spontaneously broken (as in Higgs mechanism)
  - θ becomes ‚dynamically‘ exactly 0
  - Requires additional massive particle: **Axion**
    - Candidate for dark matter



Primakov Effekt

All dark is intriguing

Planck: 2015



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

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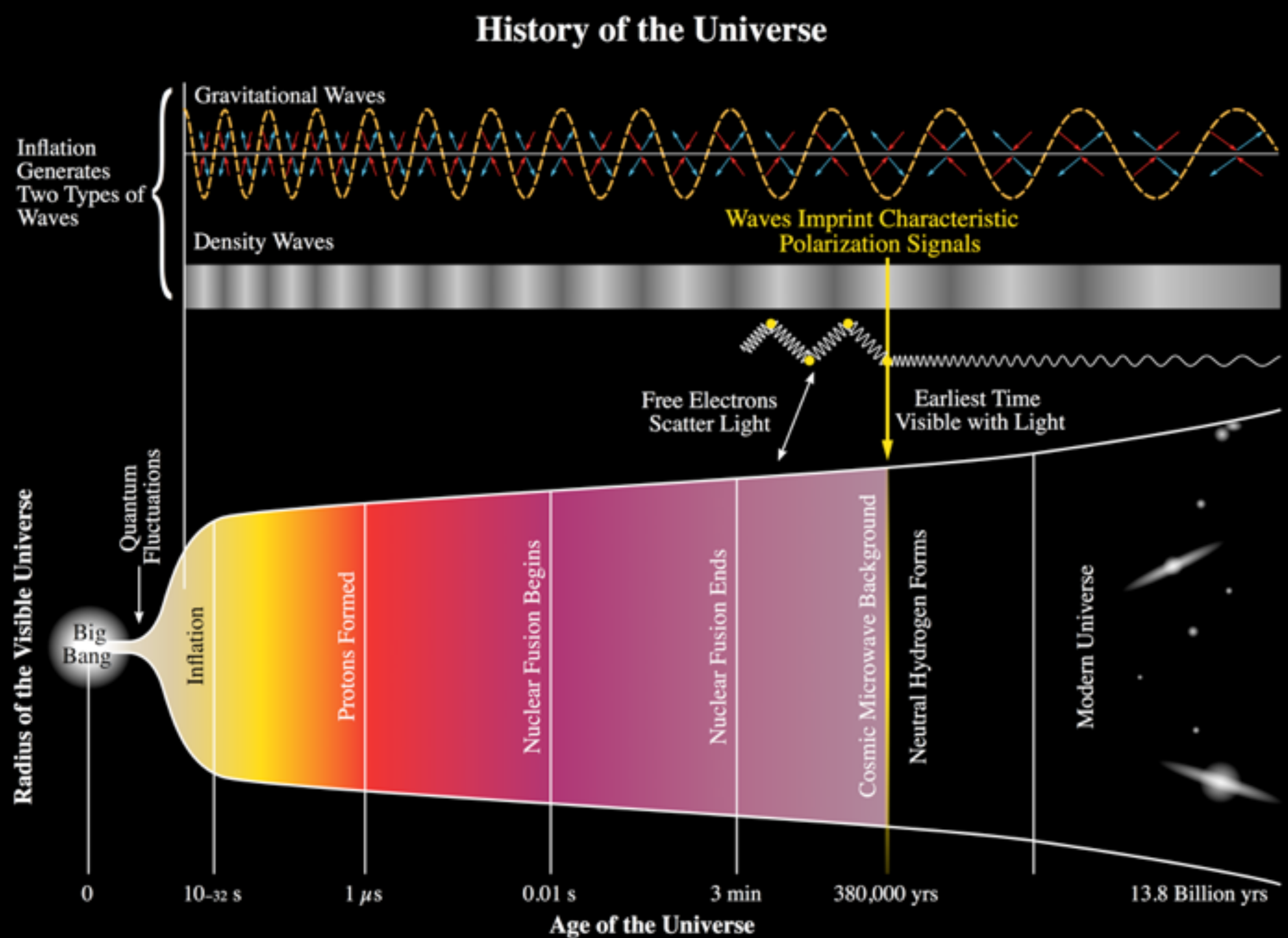
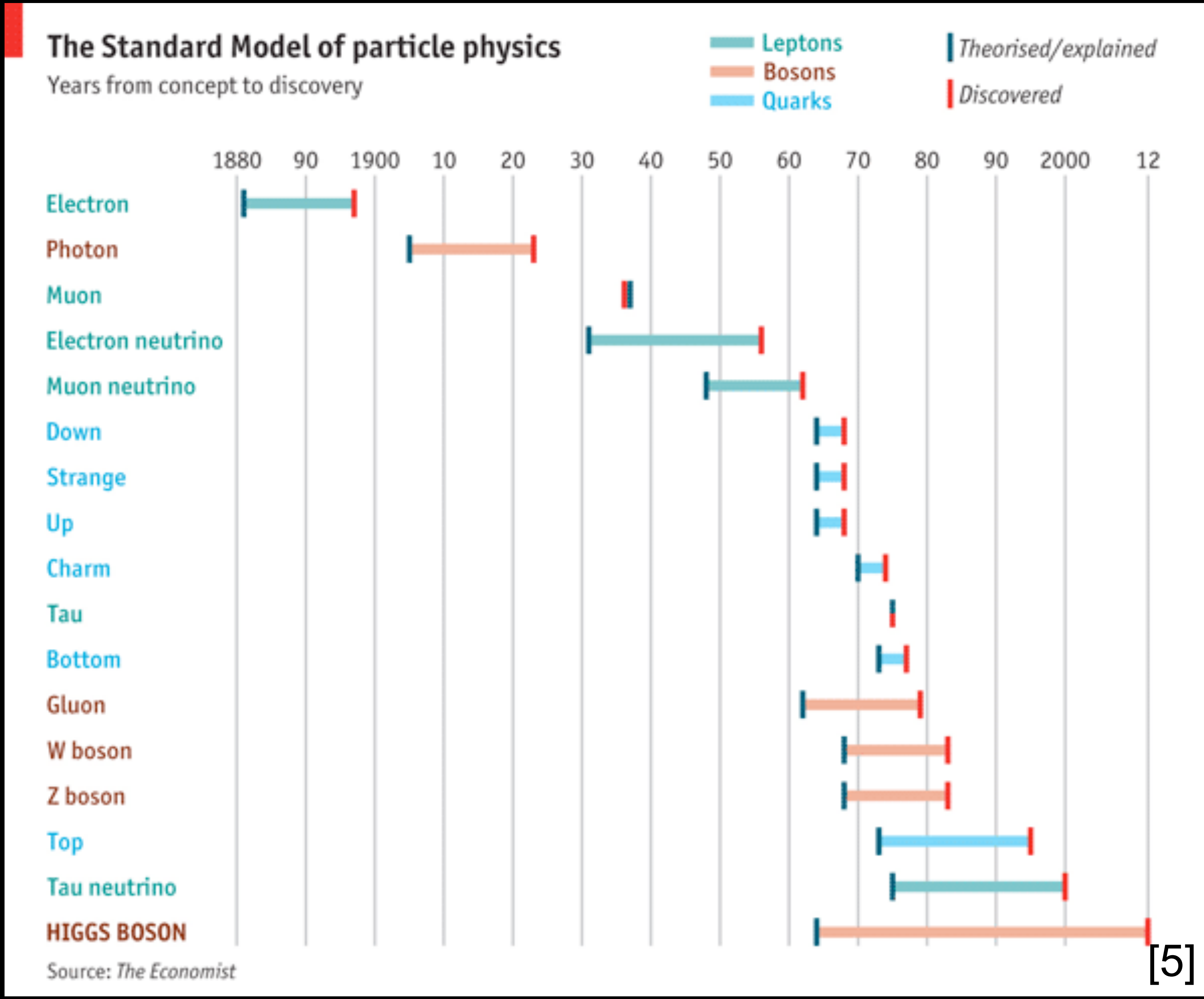
Inflation



History of the Universe
Gravitational Waves
Inflation Generates Two Types of Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10-32 s
1 μs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe


The Standard Model of particle physics
Years from concept to discovery
Leptons
Bosons
Quarks
Theorised/explained
Discovered
1880
90
1900
10
20
30
40
50
60
70
80
90
2000
12
Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino
HIGGS BOSON
Source: The Economist
[5]