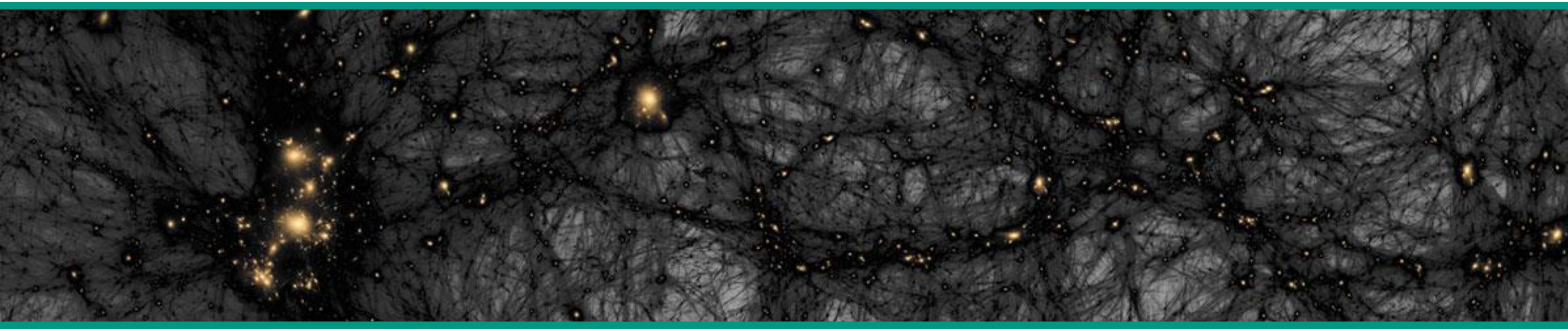
Astroparticle physics I – Dark Matter

Winter term 23/24 Lecture 13 Dec. 20, 2023



Recap of Lecture 12

- **Searches for $\boldsymbol{0\nu\beta\beta}$ – decay and astrophysical evidences for $\boldsymbol{DM}$**

  - $\mathbf{5}$ key parameters impact the sensitivity to half–life $\boldsymbol{t_{1/2}^{0\nu\beta\beta}}$: $\boldsymbol{a}$, $\boldsymbol{M}$, $\boldsymbol{t}$, $\boldsymbol{\Delta E}$, $\boldsymbol{B}$

  - enrichment factor $\boldsymbol{a = 0 \dots 1}$, exposure $\boldsymbol{M \cdot t}$, energy resolution $\boldsymbol{\Delta E}$

  - most important: extremely low background rate $\boldsymbol{B}$ at $\boldsymbol{Q}$ – value

  - current ($\boldsymbol{MAJORANA}$, $\boldsymbol{GERDA}$) & future ($\boldsymbol{LEGEND}$) experiments: ⇨ $\boldsymbol{10^{28}\ yr}$

  - $\boldsymbol{DM}$ – evidences: **velocity dispersion** of clusters, galactic **rotation curves**

  - local $\boldsymbol{DM}$ – density: $\boldsymbol{\rho_{DM,local} = 0.3\ GeV/cm^3}$ [$\boldsymbol{1\ WIMP(50\ GeV)}$ / coffee cup]

4.2 Dark Matter: candidates

- **A broad variety of candidates – from ultra–light up to super–massive DM**

  - **mass scale**: from $\mathbf{10^{-21}} \ldots \mathbf{10^{25}}\ eV$

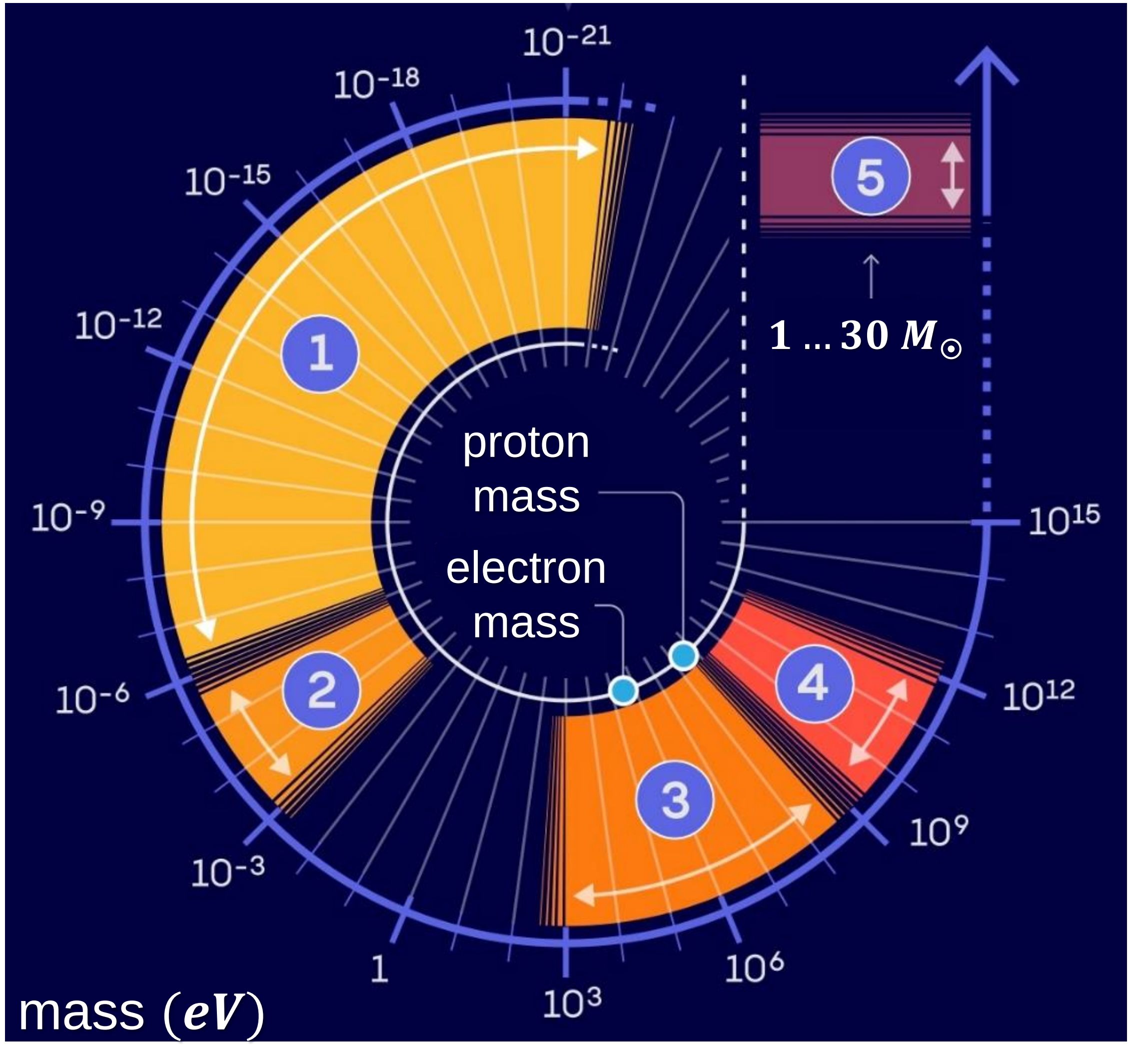
❶ ultra–light DM ($ALPs$: Axion–Like Particles, hidden photons,…)

❷ **axions** (strong CP – problem)

❸ light DM on $sub - GeV$ – scale

❹ $GeV \ldots TeV - WIMP$s: **neutralinos**

❺ primordial black holes ($MACHOs$*)



*MAssive Compact Halo Object$s$

Dark matter candidates & cosmology

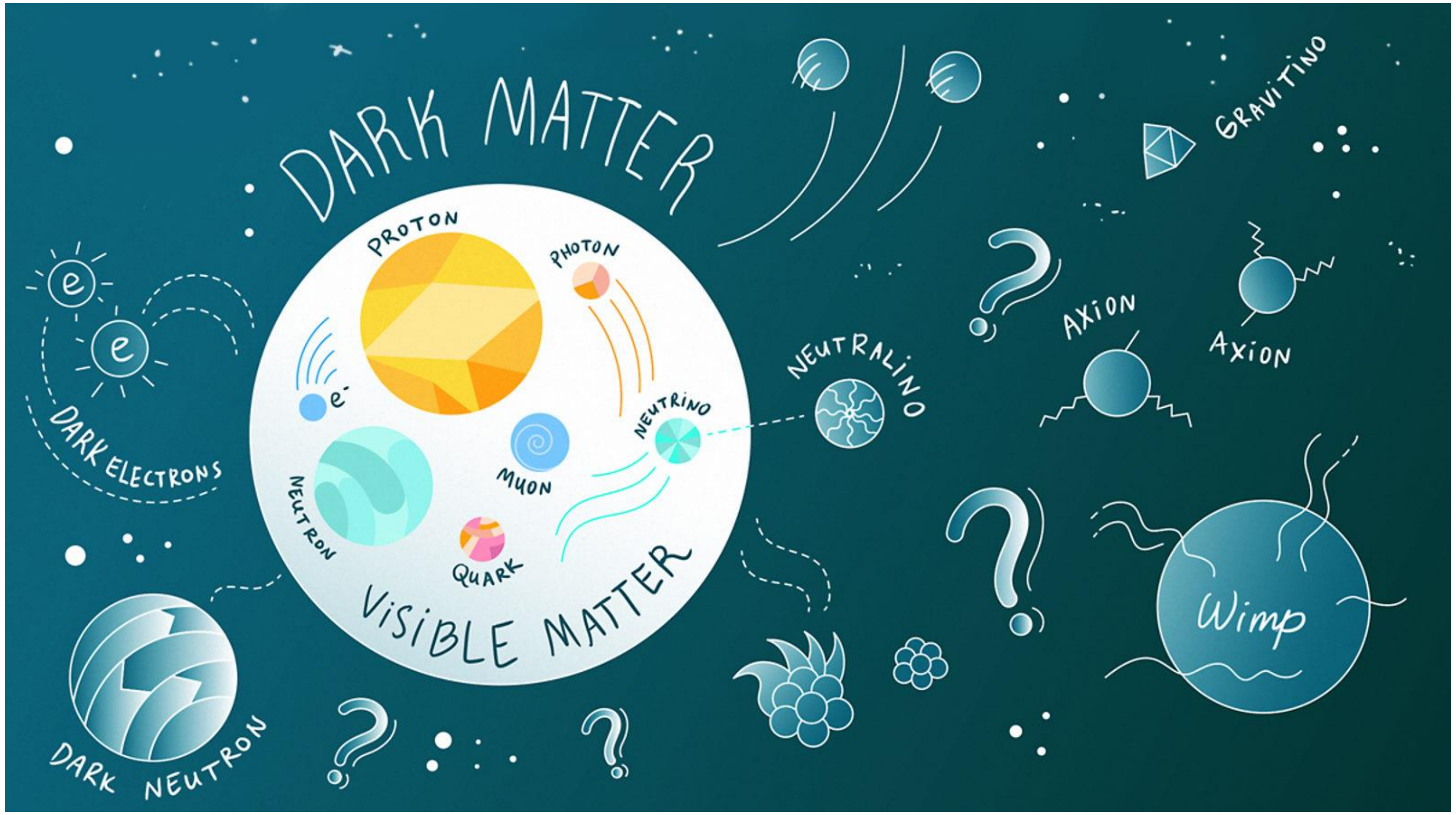
- **Important** **cross–checks** **via impact of** $\boldsymbol{DM}$ **in early & present universe**

- no particle in the $\boldsymbol{SM}$ can play the role of Dark Matter: ⇨ **look beyond** ($\boldsymbol{BSM}$)

- stable over $\boldsymbol{Hubble}$ – time $\boldsymbol{t_H = 13.8 \cdot 10^9\ yr}$ against decay: $\boldsymbol{\tau_{decay} \gg t_H}$ or *wrt.* radiative emission ($\boldsymbol{BH}$)

- current number density must reproduce the $\boldsymbol{DM}$ – density $\boldsymbol{\Omega_{DM} = 1\ GeV\ m^{-3}}$

- weak interactions only ($\boldsymbol{Z^0}$, $\boldsymbol{h}$ bosons,...), + gravity



Dark matter candidates & cosmology

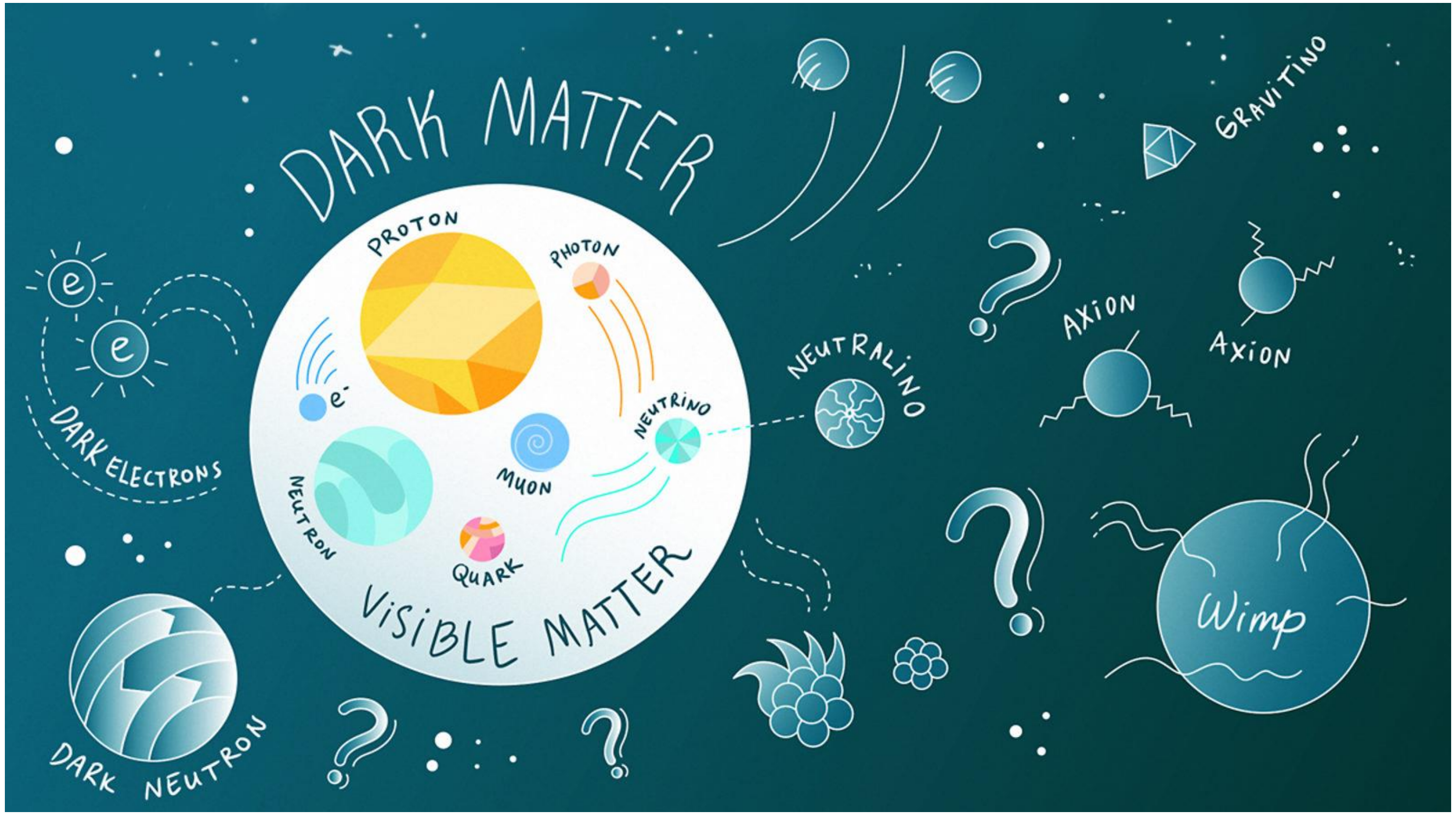
- **Important cross−checks via impact of DM in early & present universe**

  - production in early universe: thermal ($\boldsymbol{WIMPs}$) or non−thermal processes (**axions**)

  - must be ´**cold**´, i.e. moving non−relativistically
    ⇨ ´**bottom−up**´ formation of large−scale structures

  - de−Broglie wavelength $\boldsymbol{\lambda_{deBroglie} < r_{dw\,gal}}$ (radius of a dwarf galaxy, $\boldsymbol{few\ kpc}$)

  - reproduce observed ***local*** $\boldsymbol{DM}$ – density ($\boldsymbol{0.3\ GeV\ cm^{-3}}$)



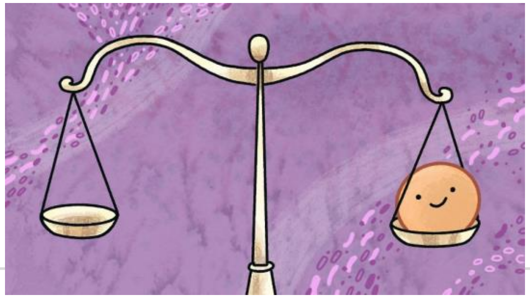
Dark matter candidates: the case of neutrinos

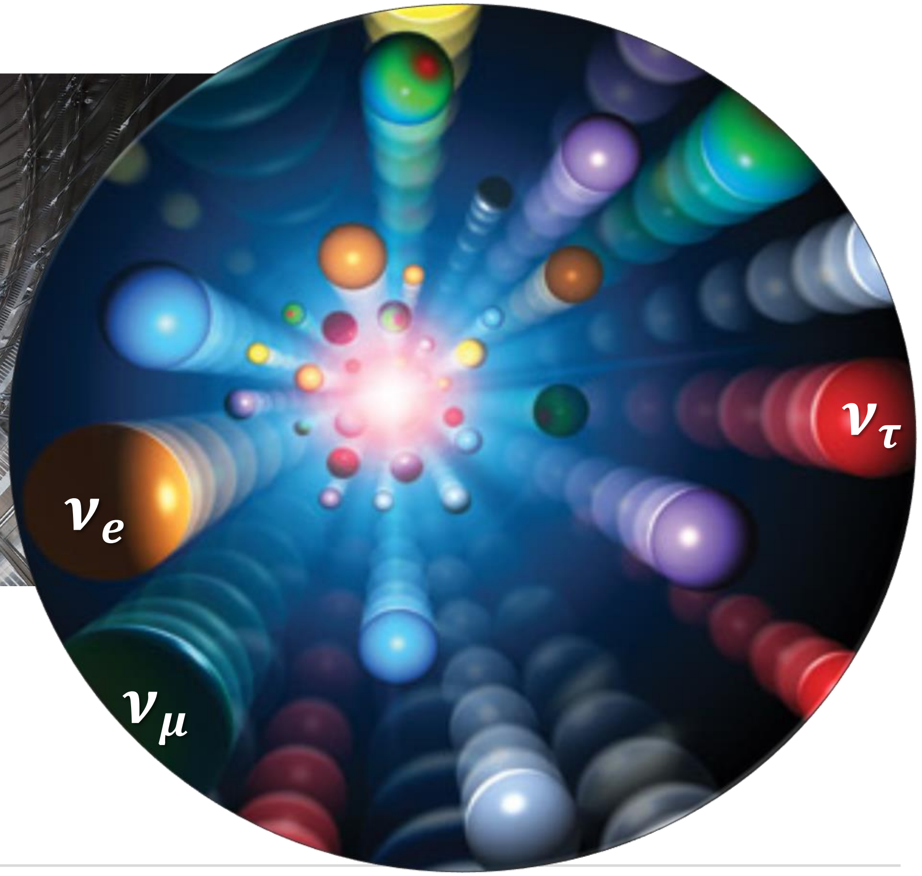
- **Massive neutrinos are part of the Dark Matter in the universe**

- production in early universe: **thermal** processes via $W^{\pm}, Z^{0}$ – $339\ \nu\text{´}s\ cm^{-3}$

- $\nu\text{´}s$ are ´**hot**´, i.e. moving relativistically ($m_{\nu} < 0.8\ eV$)
  ⇨ ´**top–down**´ formation of large–scale structures

- de–Broglie wavelength $\lambda_{deBroglie} > r_{dw\ gal}$ (radius of a dwarf galaxy, $few\ kpc$)





Dark matter candidates: the case of neutralinos

- $\boldsymbol{W}$**eakly** $\boldsymbol{I}$**nteracting,** $\boldsymbol{M}$**assive** $\boldsymbol{P}$**articles:** $\boldsymbol{WIMP}$**s or, specifically,** $\boldsymbol{neutralinos}$

  - production in early universe: **thermal** processes via $W^{\pm}, Z^{0}$ – bosons

  - correct abundance if **weak interaction** $\boldsymbol{xsec}$

  - cosmologically **stable** due to new intrinsic quantum number (R_P)

  - $\boldsymbol{CDM}$: non–relativistic velocity distribution, allows **bottom–up** evolution of structures

Dark matter candidates: the case of axions

- $\boldsymbol{W}$**eakly** $\boldsymbol{I}$**nteracting,** $\boldsymbol{S}$**lim** $\boldsymbol{P}$**articles:** $\boldsymbol{WISP}$**s or, specifically, axions**

- production in early universe: **non–thermal** processes via **symmetry breaking**

- correct abundance if **mass** & $\boldsymbol{xsec}$ within specific range

- cosmologically **stable** due to tiny mass ($\sim\boldsymbol{\mu eV}$)

- $\boldsymbol{CDM}$: non–relativistic velocity distribution, allows **bottom–up** evolution of structures

Dark matter candidates: mass *vs.* cross section

- **An overview of DM – candidates**

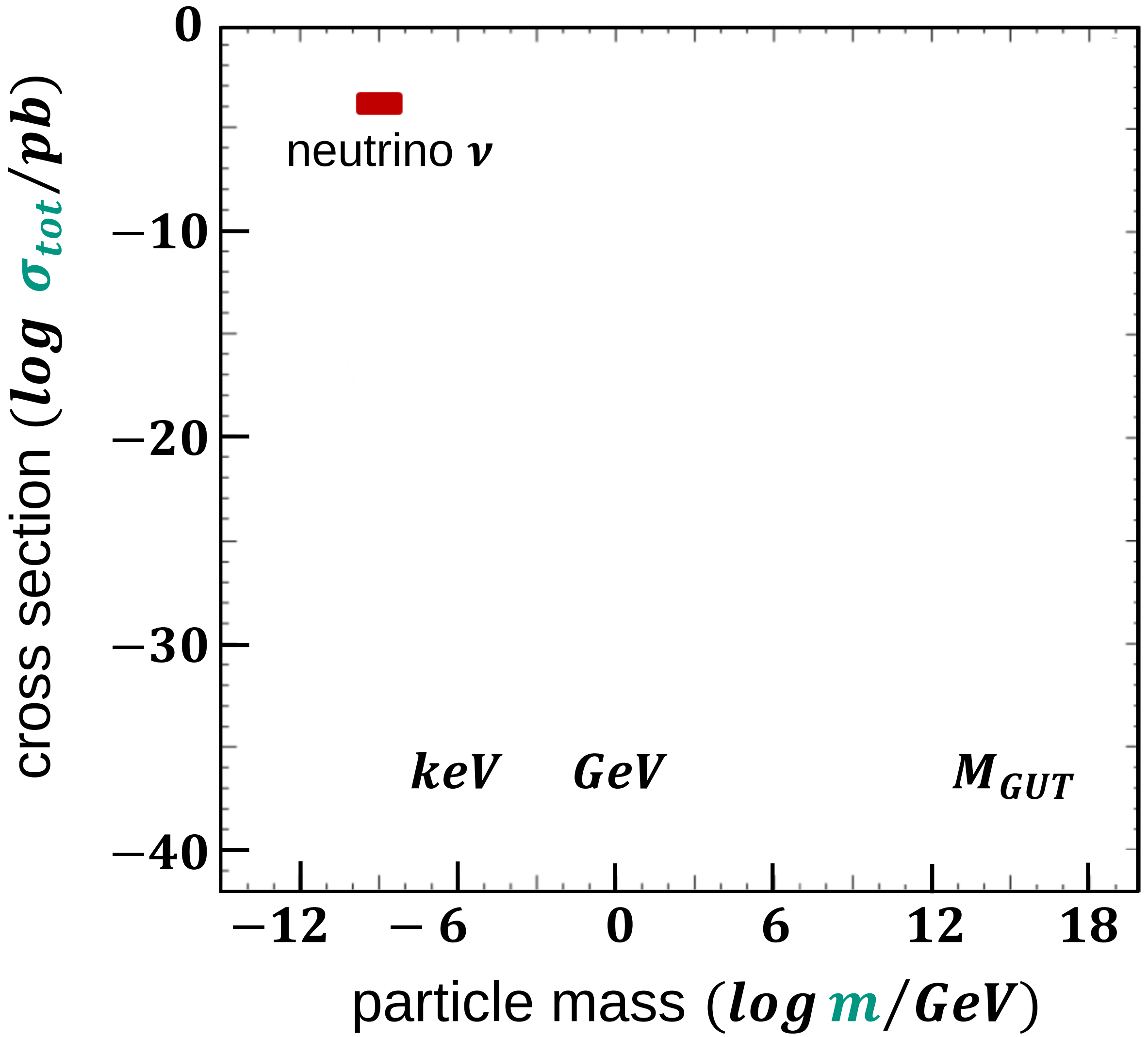
  - two key parameters:
    mass $m\ [GeV], \sigma_{tot}\ [pb = 10^{-36}\ cm^2]$

  - **neutrino**: prototype of a weakly interacting particle

  - only LH states interact via $W^{\pm}, Z^0$ bosons

  - electroweak ν – cross section scale:

$$\sigma_{\nu,tot} = 10^{-8} \dots 10^{-4}\ pb$$



Dark matter candidates: heavy, cold DM

- **Neutralinos** & **other** $\boldsymbol{WIMPs}$

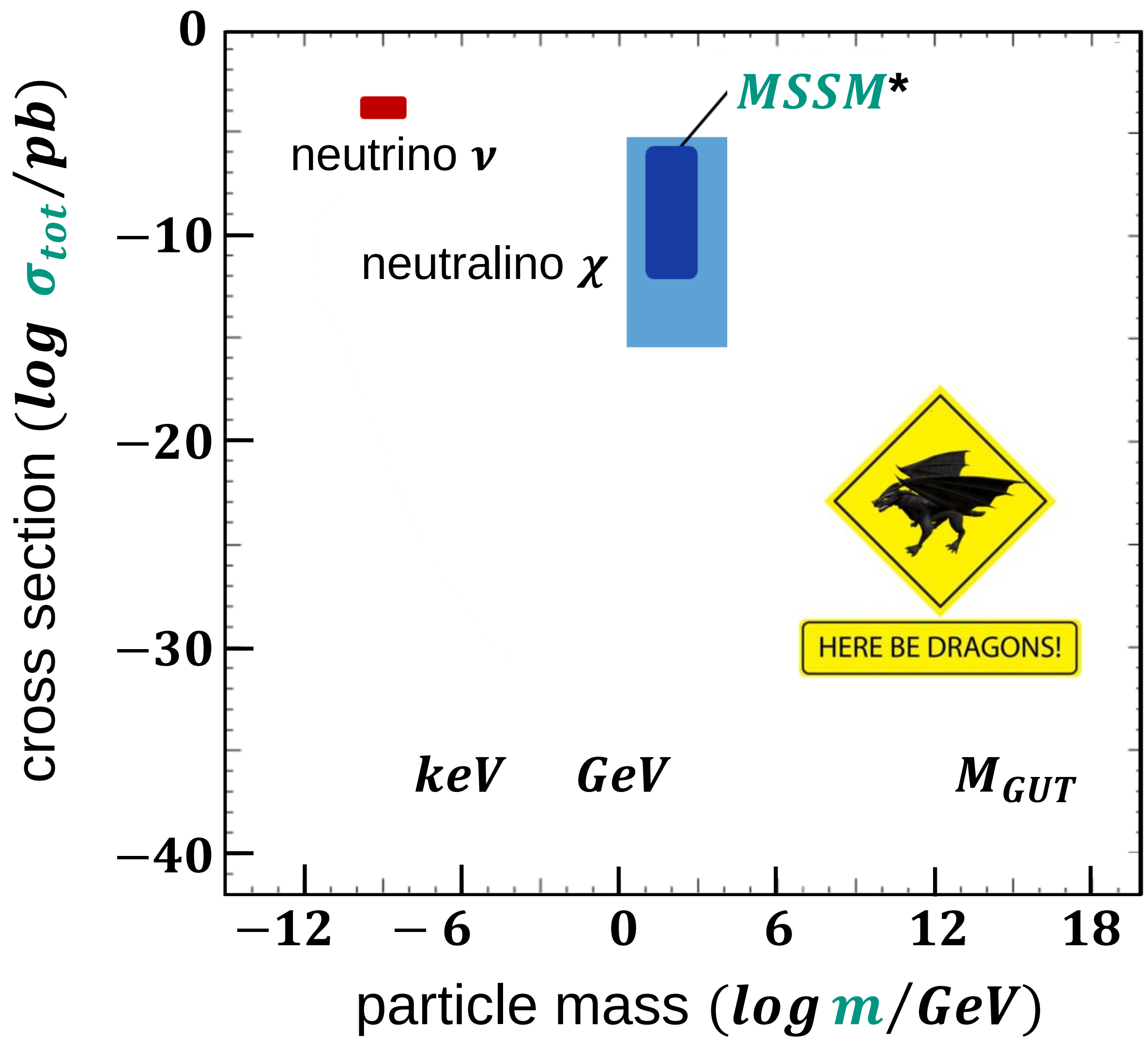
- **neutralino** χ: prototype of a $\boldsymbol{W}$eakly $\boldsymbol{I}$nteracting $\boldsymbol{M}$assive $\boldsymbol{P}$article ($\boldsymbol{WIMP}$)

- mass $\boldsymbol{m = GeV \dots TeV}$ scale
  ⇨ determines its number density

- neutralinos are superpositions of $\mathbf{4}$ **states**: ⇨ **mixing** efffects reduce $\boldsymbol{\sigma_{tot}}$

- electroweak χ – cross section scale:

$$\sigma_{\chi,tot} = 10^{-12} \dots 10^{-6}\, pb$$



*$\boldsymbol{M}$inimum $\boldsymbol{S}$upersymmetric $\boldsymbol{S}$tandard $\boldsymbol{M}$odel

Dark matter candidates: light, but cold DM

- **Axions** & A**xion**–L**ike** P**articles** (ALP**s)**

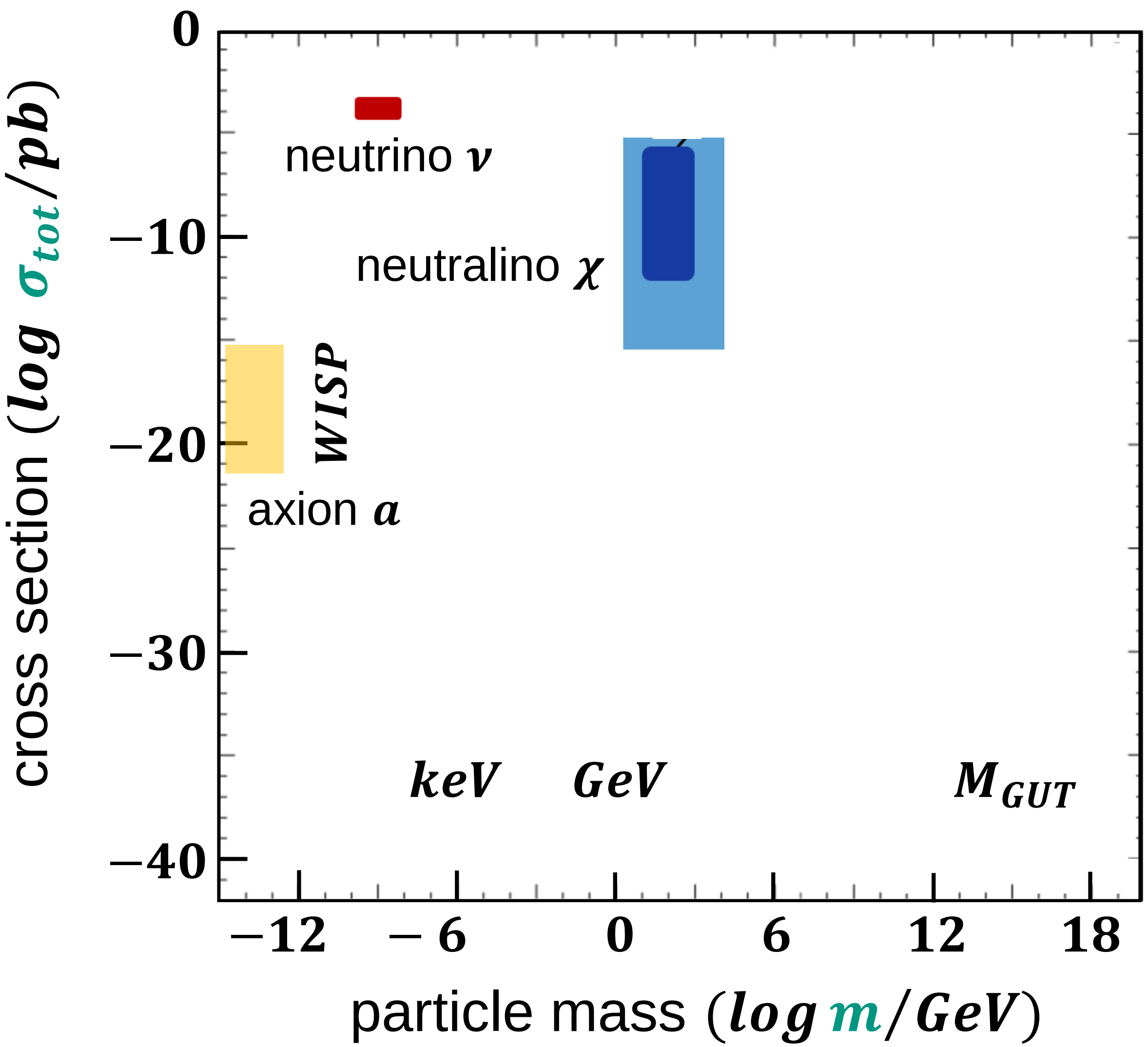
- **axion** a: prototype of a Weakly Interacting Slim Particle ($WISP$)

- mass $m = neV \ldots meV$ scale
  ⇨ determines interaction rate

- axions ´solve´ the **strong** CP – **problem** of QCD

- interaction via ´**Primakoff effect**´:

  B – field: conversion into/from γ´s



Dark matter candidates: light, but cold DM

- **Axions** & ***A*xion–*L*ike *P*articles (*ALP*s)**

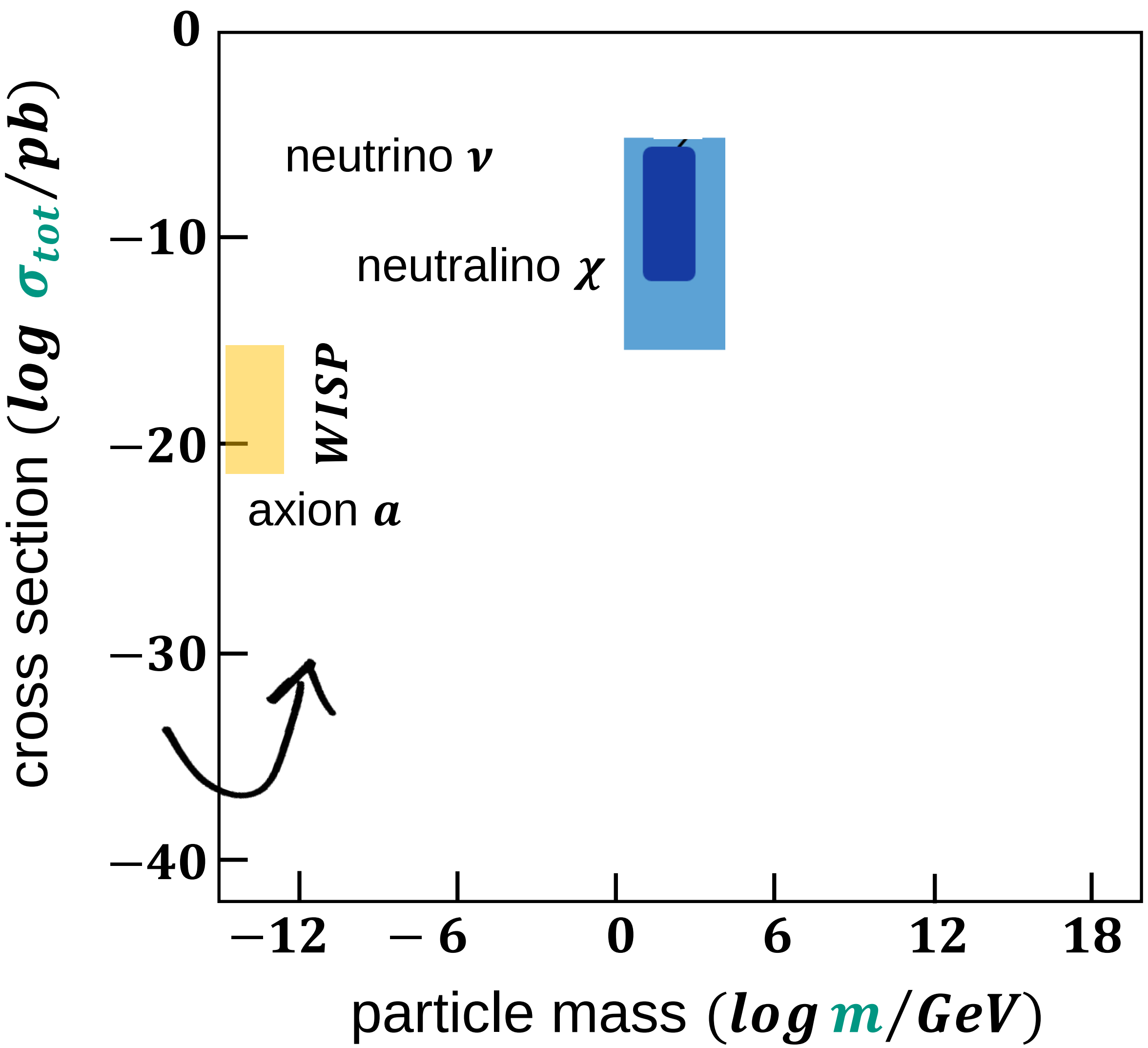
  - **axion a**: prototype of a ***W***eakly ***I***nteracting ***S***lim ***P***article (***WISP***)

  - a large parameter space to cover

  - a message from ***Richard Feynman***:

29.12.1959

There´s plenty of room at the bottom



Dark matter candidates: ultra–heavy DM

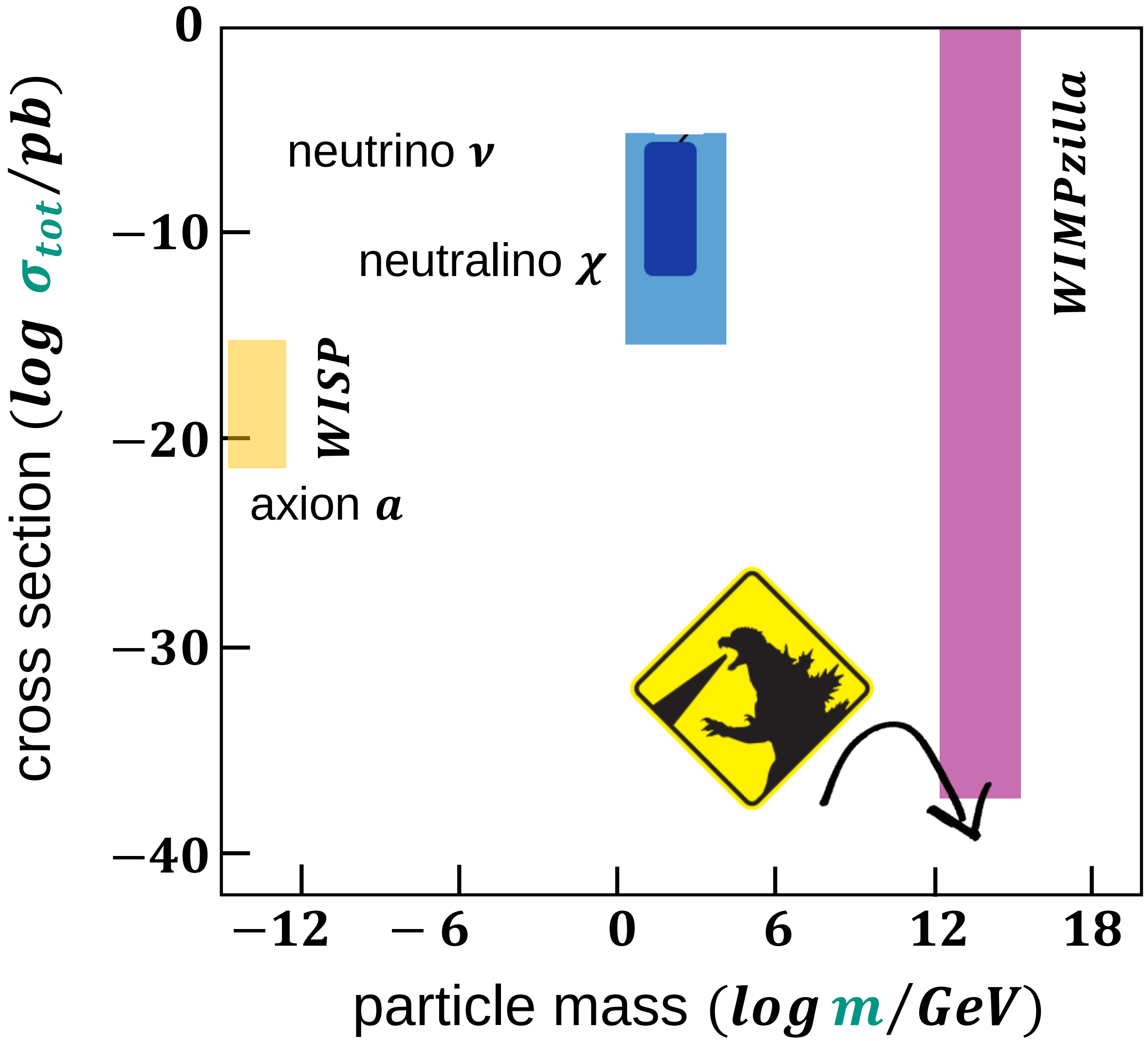
- **ultra–heavy particles: $WIMPzilla$**

- ´$WIMPzilla$´: prototype of an **extremely massive particle**

- mass $m = 10^{12} \dots 10^{12}\ GeV$ scale
  ⇨ at GUT – scale (inflation!)

- a message from ***Rock Kolb***:

Size does matter



DM – related theories: SUper–SYmmetry ($SUSY$)

- **A new space–time symmetry between bosons ⇔ fermions**

  - $SUSY$ postulate: each SM – particle has a heavy (TeV) $SUSY$ superpartner

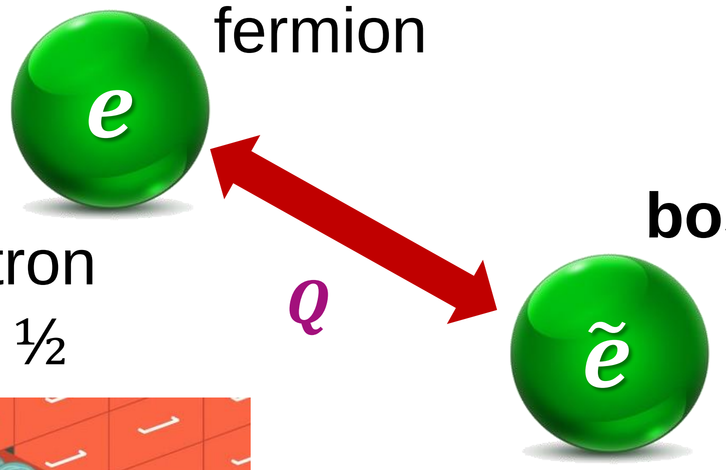
  - $SUSY$ & SM – particles obey **different spin statistics** (fermions ⇔ bosons), as spin differs by $\Delta s = ½$

  - $SUSY$ – operator Q:

$$Q\,|boson\rangle = |fermion\rangle$$

$$Q\,|fermion\rangle = |boson\rangle$$

transforms bosons into fermions & $v.v.$



DM – related theories: $SUSY$ name conventions

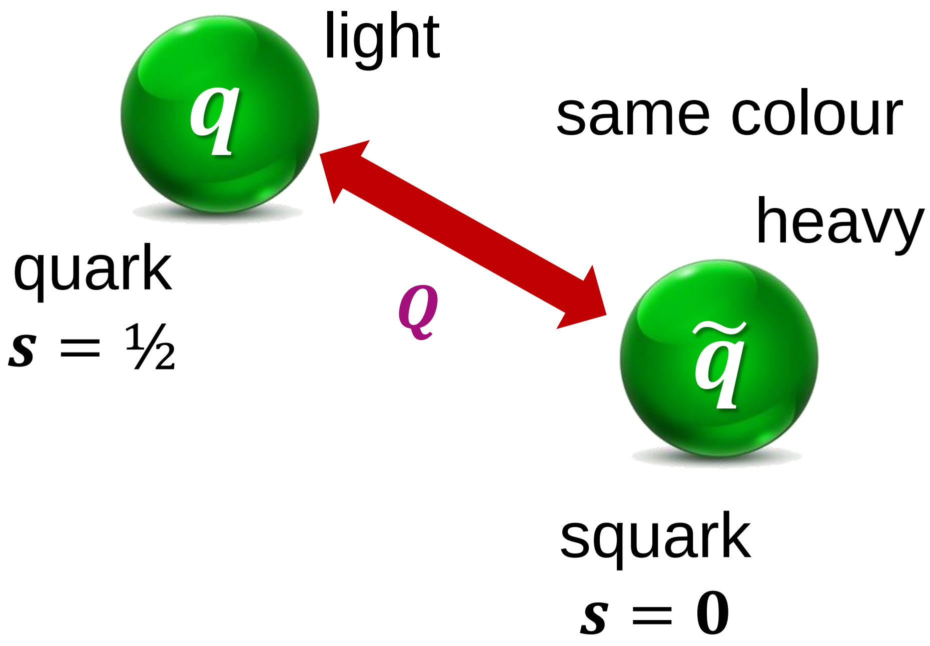
- **$SUSY$ postulates heavy superpartners with $s = ½$ and $s = 0$**

  - $SUSY$ postulate: each SM – particle has a heavy (TeV) $SUSY$ **superpartner**

  - $SUSY$ & SM – particles: identical properties, except **mass & spin statistics**

  - $SUSY$ – **bosonic** superpartners
    $sfermion$ $(\tilde{q}: squark, \tilde{\ell}: slepton)$

  - $SUSY$ – **fermionic** superpartners
    … – $inos$ $(\tilde{\gamma}: photino, \tilde{g}: gluino,$
    $\tilde{H}: Higgsino, \ldots)$



DM – related theories: $SUSY$ origins at KIT

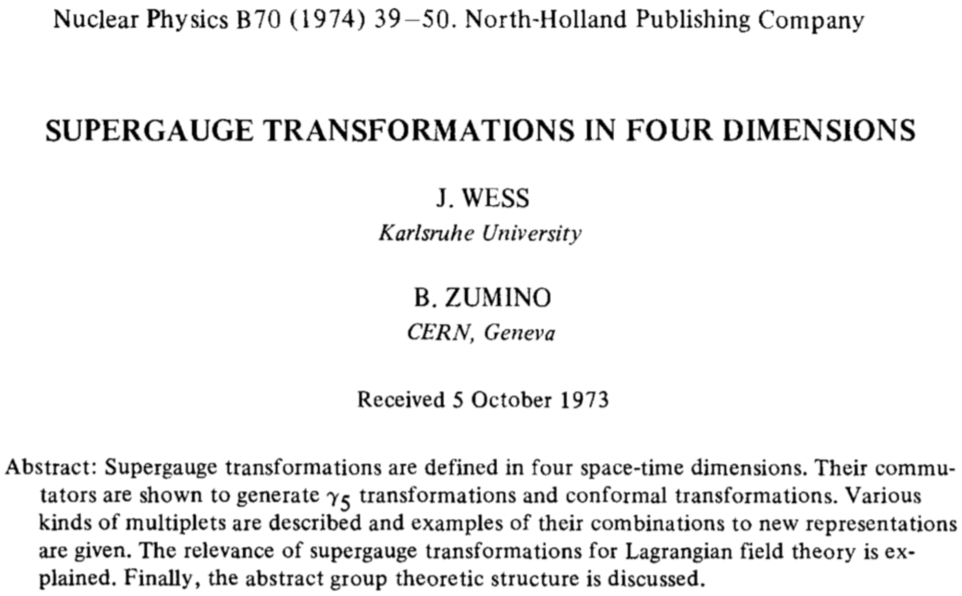
Karlsruhe Institute of Technology

- **1973: *Wess* & *Zumino* postulate the first supersymmetric quantum theory**

  - Wess–Zumino model
    Julius Wess (**KIT**)
    Bruno Zumino (**$CERN$**)

    director of the **KIT** institute
    for Theoretical Physics
    from **1968 – 1990**

Julius Wess
(1934 – 2007)


Nuclear Physics B70 (1974) 39–50. North-Holland Publishing Company

SUPERGAUGE TRANSFORMATIONS IN FOUR DIMENSIONS

J. WESS
Karlsruhe University

B. ZUMINO
CERN, Geneva

Received 5 October 1973

Abstract: Supergauge transformations are defined in four space-time dimensions. Their commutators are shown to generate γ_5 transformations and conformal transformations. Various kinds of multiplets are described and examples of their combinations to new representations are given. The relevance of supergauge transformations for Lagrangian field theory is explained. Finally, the abstract group theoretic structure is discussed.

  - **$KCETA$** regularly awards the **Julius Wess** prize*

 *KIT - KCETA - Julius Wess Award

$SUSY$: a spontaneously broken symmetry

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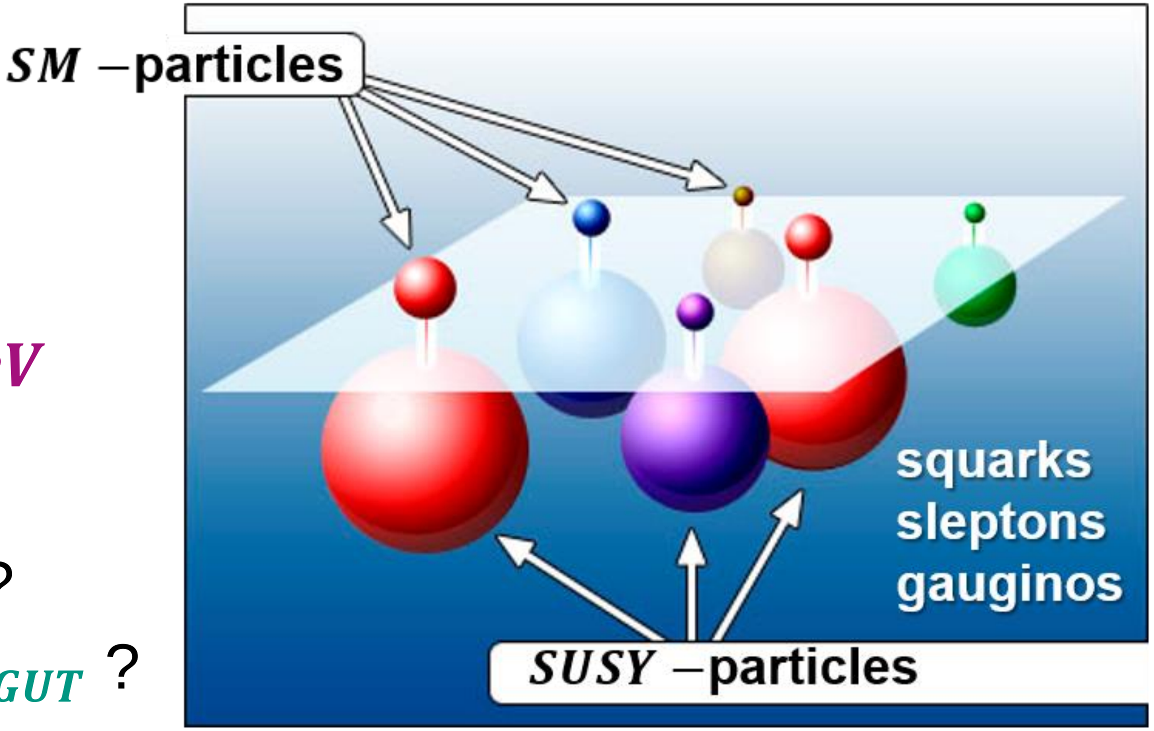
- **Quantum vacuum not invariant under $SUSY$ – transformations**

  - result:
    masses of SM – particles & $SUSY$ – particles **not** identical

  - mass–relation:
    $m(SM) \ll m(SUSY) = 0.1 \ldots 10\ TeV$

  - **scale** of $SUSY$ – symmetry breaking:
    expected at energies $E_{SUSY} = 0.1 \ldots 10\ TeV$

  - **origin** of $SUSY$ – symmetry breaking:
    unknown, why the scale $E_{SUSY} < 10\ TeV$?
    further hierarchy problem: why $E_{SUSY} \ll E_{GUT}$?

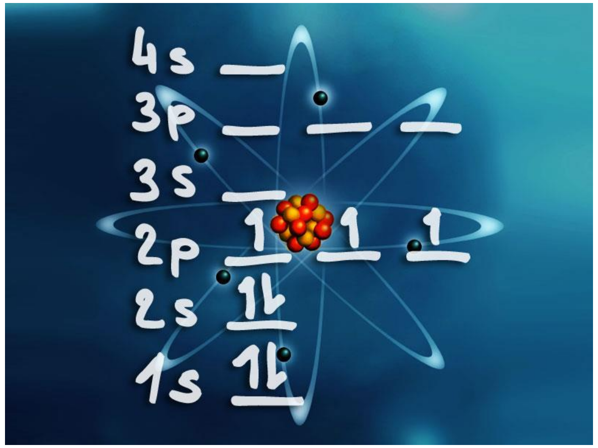


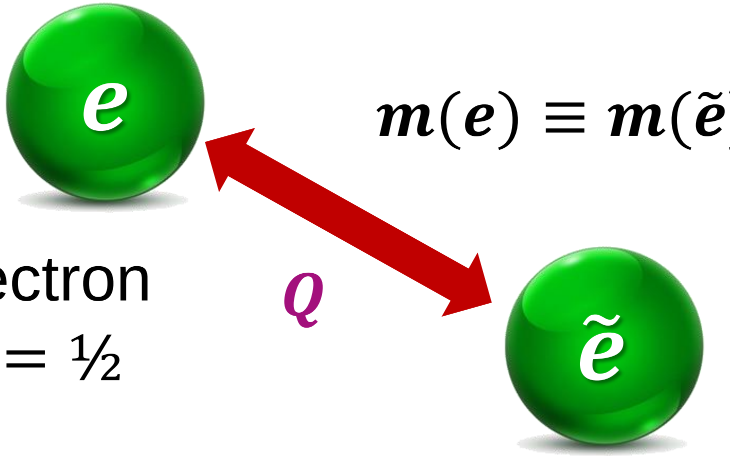
EXCURSION: what if ... $SUSY$ was NOT broken?

- **assumption: quantum vacuum is invariant under $SUSY$ – transformations**

  - **result**:
    masses of $\boldsymbol{SM}$ – particles & $\boldsymbol{SUSY}$ – particles **are** identical

  - **Pauli exclusion principle** not valid for bosonic superpartner selectron $(\tilde{e})$ of electron $(\boldsymbol{e})$:
    no extended Bohr orbitals possible…





$\boldsymbol{m(e) \equiv m(\tilde{e})}$

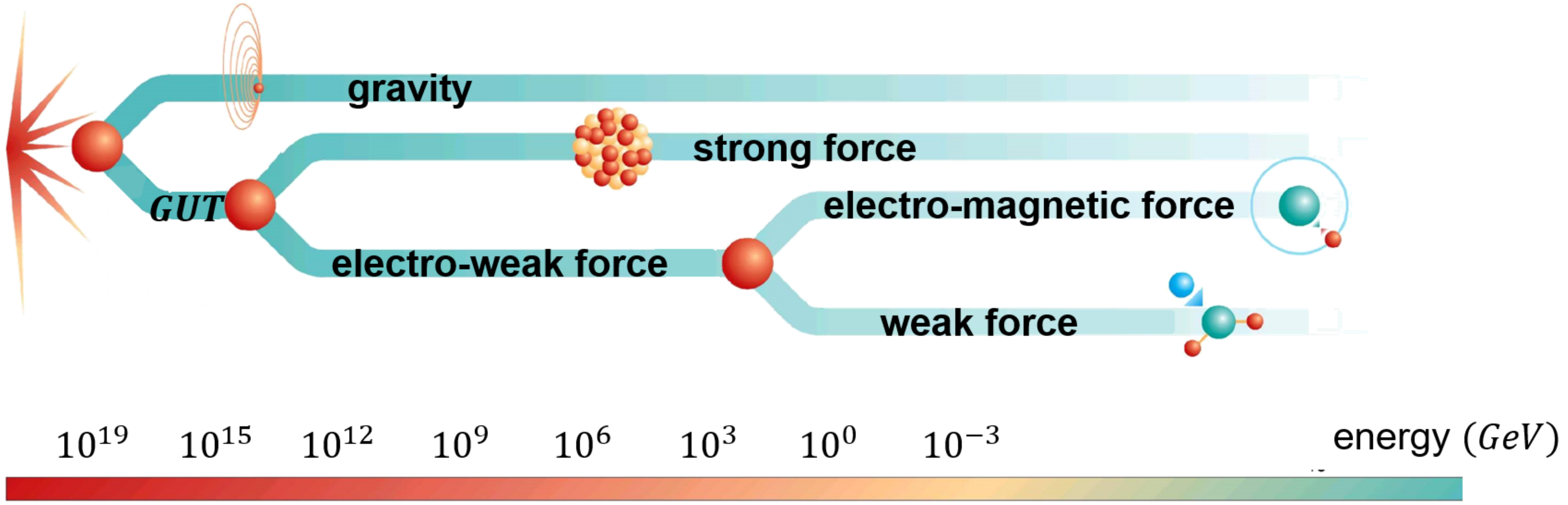
electron
$\boldsymbol{s = ½}$

selectron
$\boldsymbol{s = 0}$

$SUSY$ and gauge unification of interactions

- **Indirect hints for $SUSY$ comes from the running of coupling constants α_i**

  - GUT (Grand Unified Theory) – based scenarios expect a unfication of forces at large scale $\Lambda_{GUT} \sim 10^{16}\ GeV$ (*S. Glashow*, *H. Georgi*, **1974**)



SUSY and gauge unification of interactions

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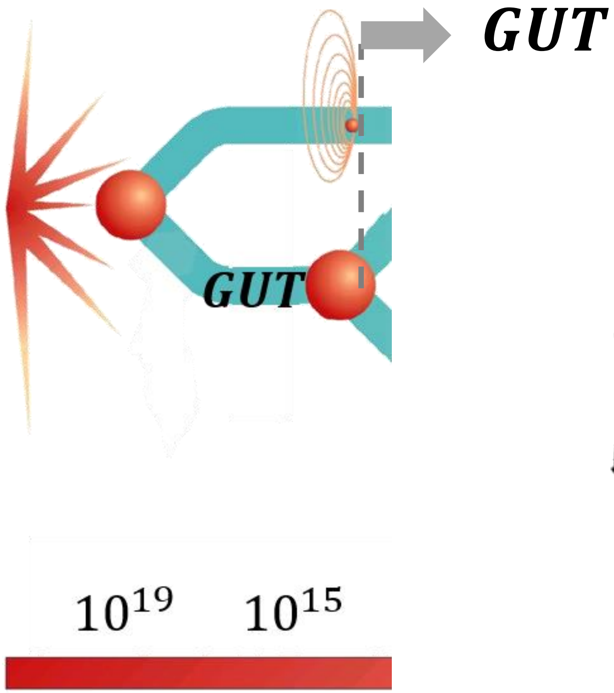
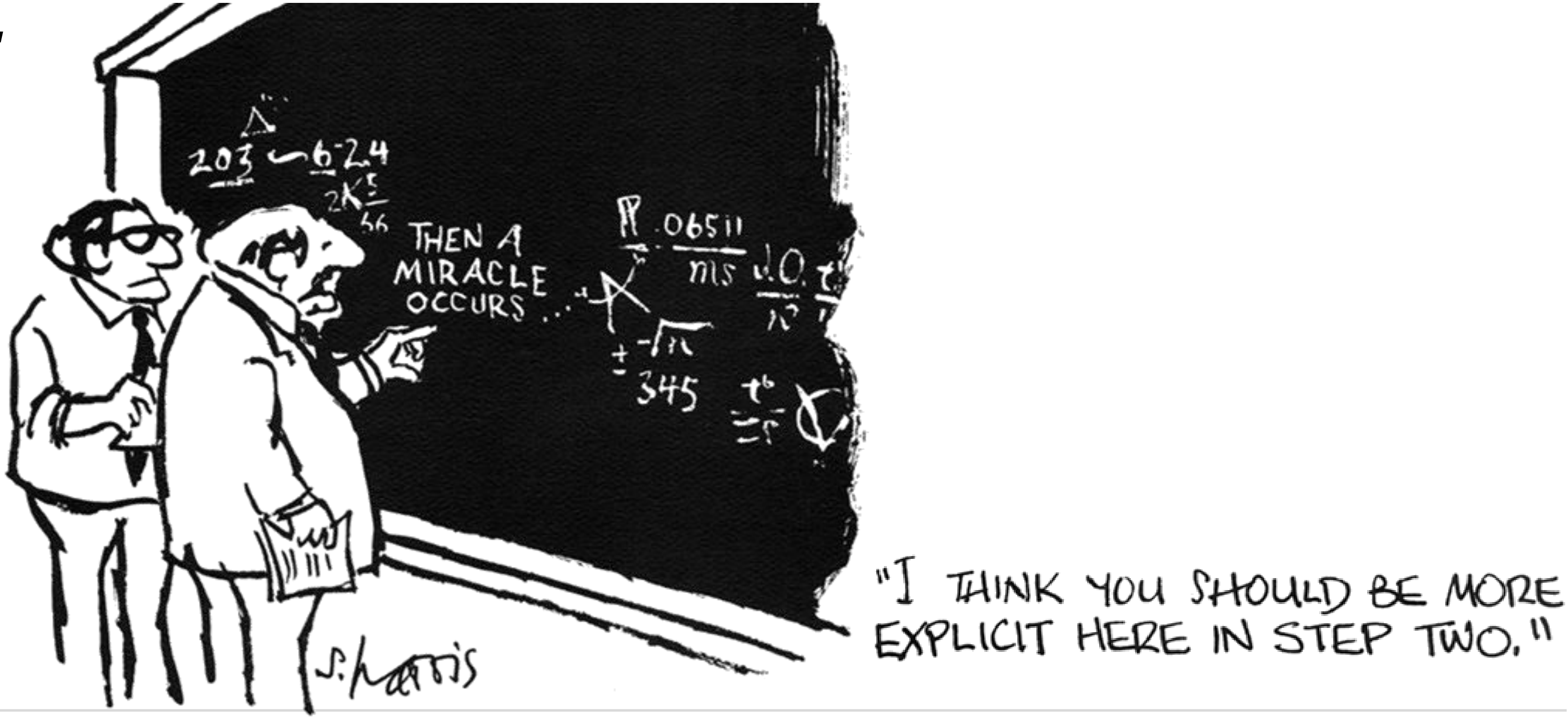
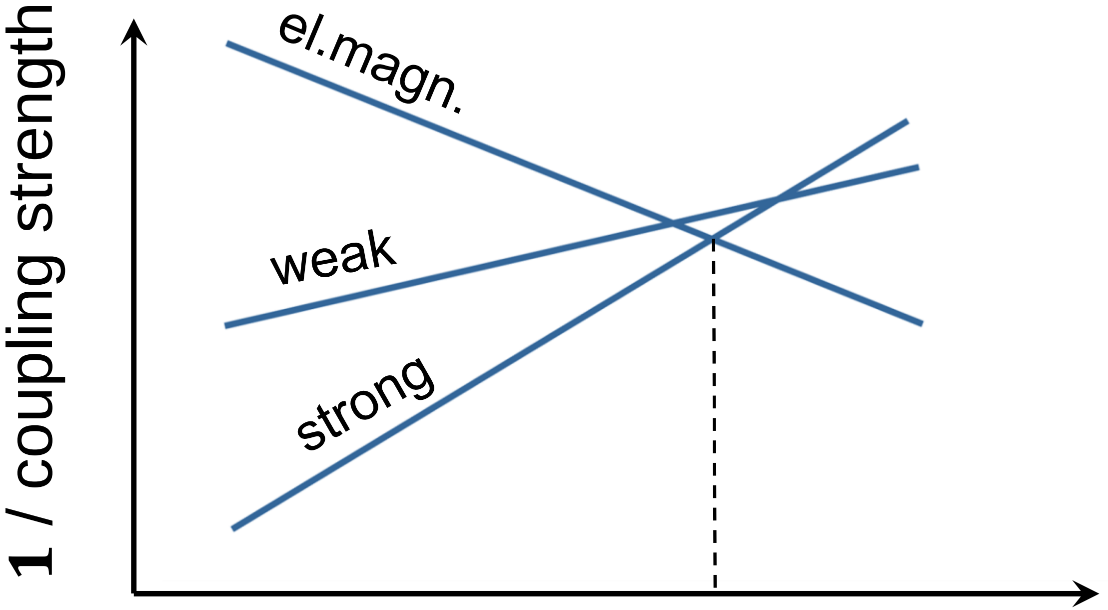




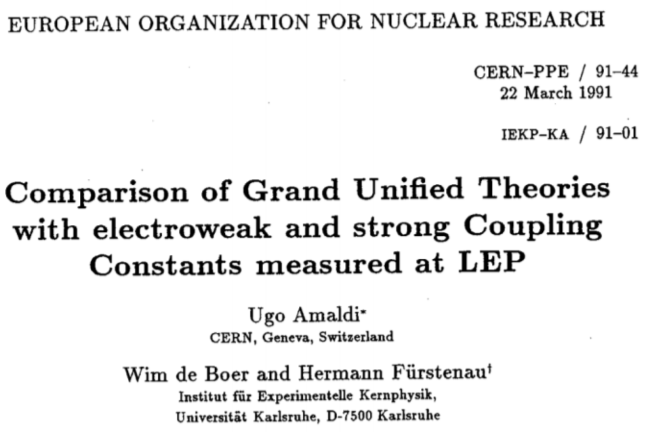
SUSY and gauge unification of interactions

- ***SM***: **no gauge unification observed in running of coupling constants** α_i

  - *Wim de Boer* (***ETP***) *et al.* perform a **fit** to couplings:
    ´in the ***SM*** the couplings do NOT meet…!´



10^{14} energy (GeV)



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

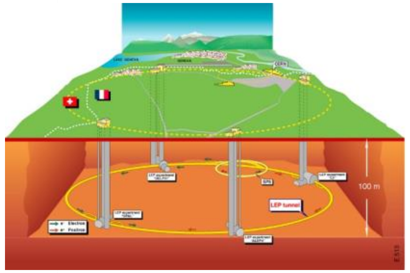
CERN–PPE / 91–44
22 March 1991

IEKP–KA / 91–01

Comparison of Grand Unified Theories with electroweak and strong Coupling Constants measured at LEP

Ugo Amaldi*
CERN, Geneva, Switzerland

Wim de Boer and Hermann Fürstenau†
Institut für Experimentelle Kernphysik,
Universität Karlsruhe, D-7500 Karlsruhe



W. De Boer (***KIT***)

U. Amaldi

$SUSY$ and gauge unification of interactions

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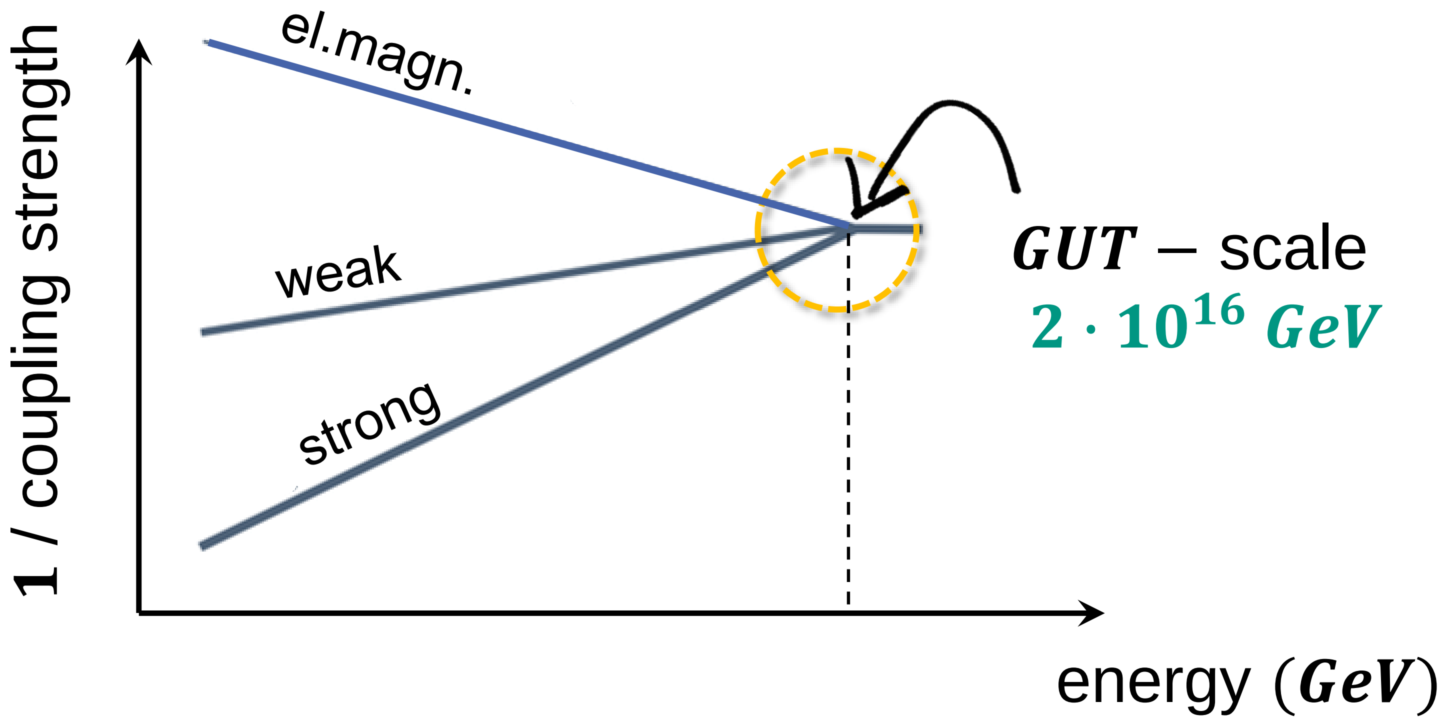
- SM: **no gauge unification observed in running of coupling constants α_i**

  - *Wim*: ´we find: **only in a $SUSY$ – scenario** all couplings meet at one energy scale!´



  - *Julius*: ´my $SUSY$ – scenario fits!´

J. Wess (KIT) & *B. Zumino*

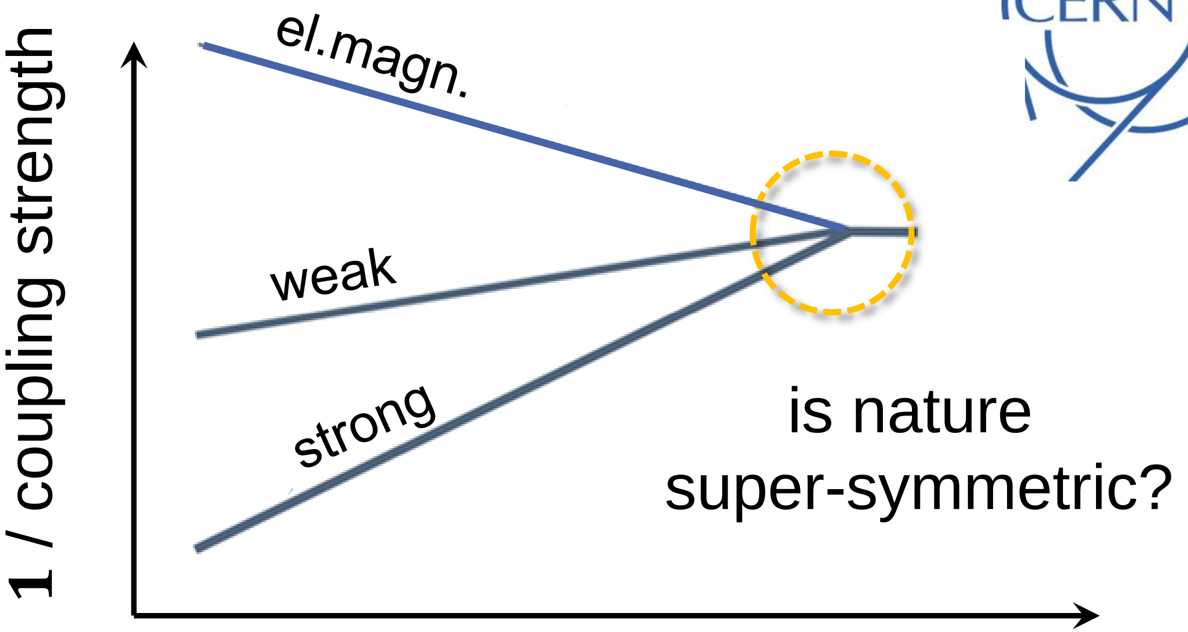
W. De Boer (KIT)

U. Amaldi

$SUSY$ and experimental verification at the LHC

- LHC **with** cms – **energy of** $\sqrt{s} = 13.6\ TeV$ **allows dedicated** $SUSY$ –**searches**

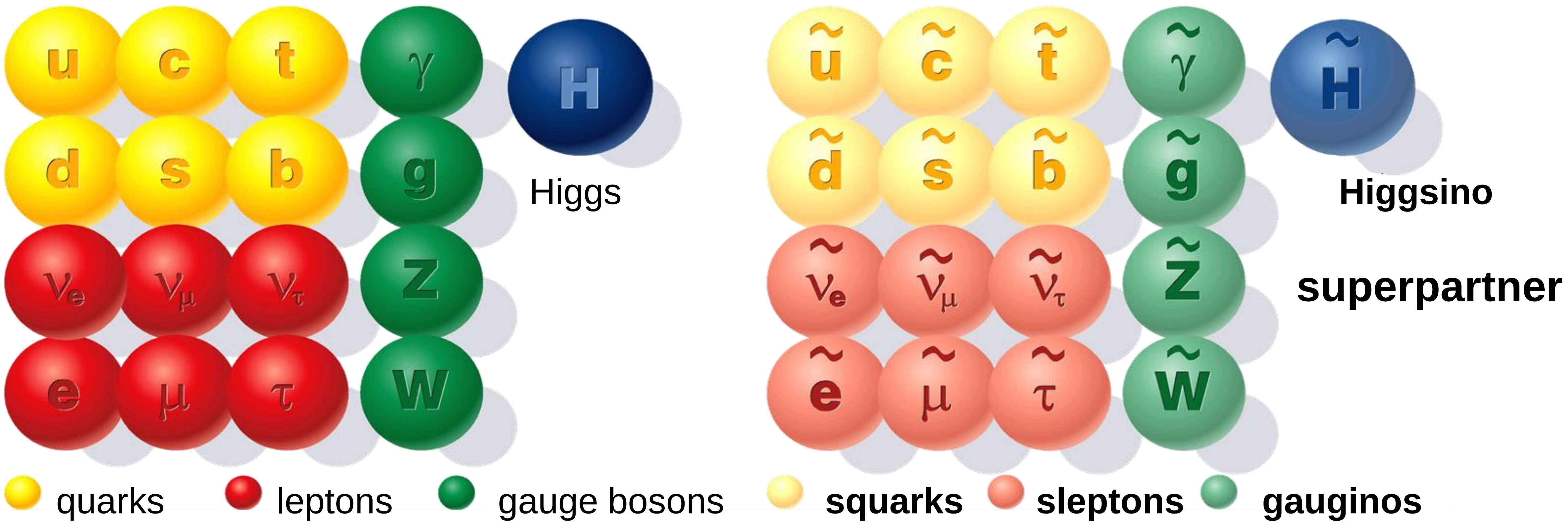
  - search for $SUSY$ – superpartners at the TeV – scale in pp – collisions



$SUSY$: a closer look at the superpartner properties

- **Building a viable DM – candidate from $SUSY$ – particles:** a how–to approach

- search for $SUSY$ – superpartners at the TeV – scale in pp – collisions



$SUSY$: a closer look at the superpartner properties

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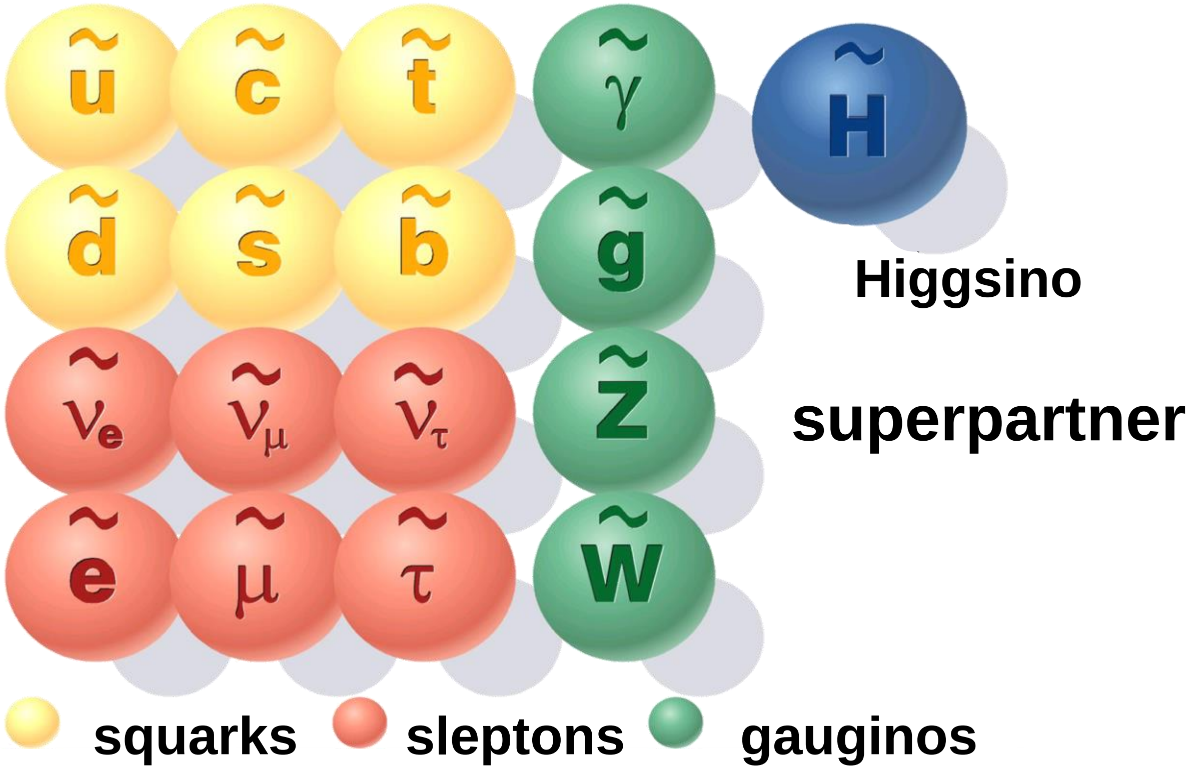
- **Building a viable DM – candidate from $SUSY$ – particles:** a how–to approach

- $SUSY$ – superpartners: identical properties, except **mass** m & instrinsic **spin** s

- $squarks$: identical strong interaction as quarks (**3** colours)

- $sleptons$: identical electromagnetic interaction as leptons e, μ, τ

- $sneutrinos, neutral\ gauginos$: mixing effects as in case of ν´s
  - ⇨ **mass** states for propagation
  - ⇨ **flavour** states for interaction



$SUSY$: $MSSM$, the minimum extension of the SM

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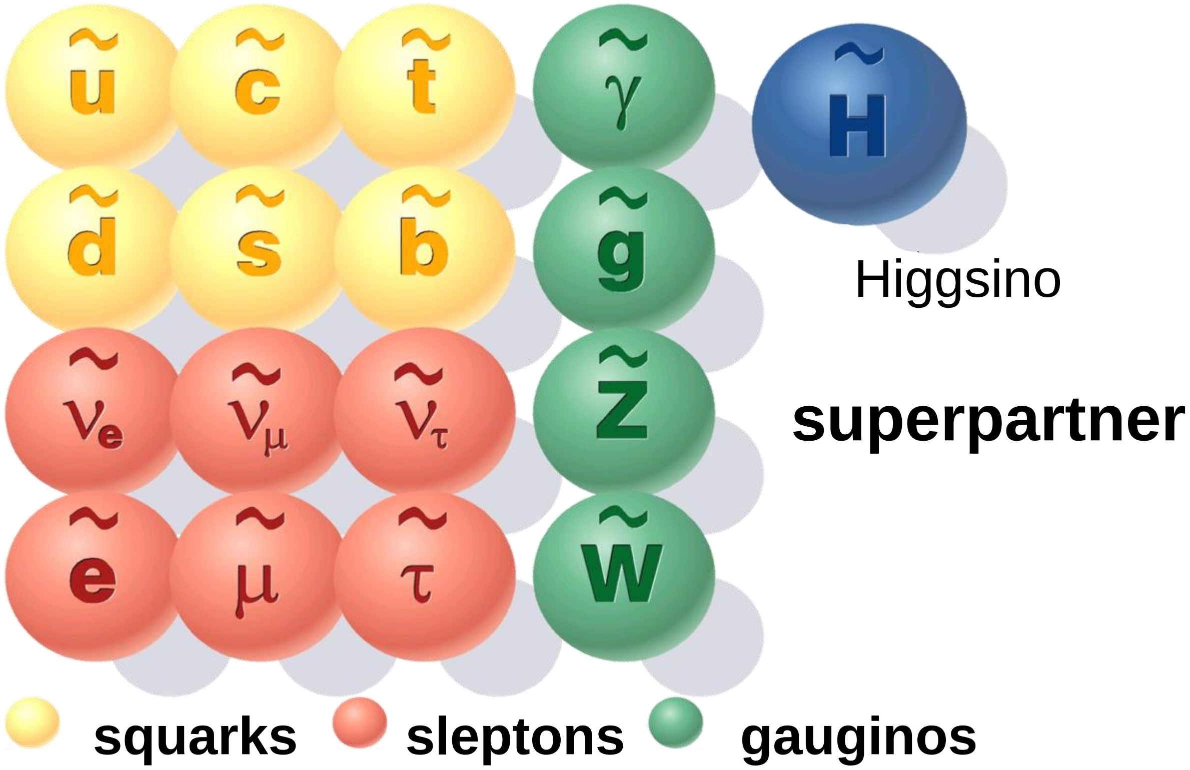
- **Building a viable DM – candidate from $SUSY$ – particles:** a how–to approach

- $MSSM$: Minimal Supersymmetric Standard Model: **105 new parameters** – particle masses, mixing angles, CP – phases, life–times,...

- minimal extension of new particles & interactions

- motivation: **stabilisation** of the **light Higgs boson** at $125\ GeV$ against quantum–loop–corrections

- $SUSY$ – masses of $MSSM$ expected in **range** $M = 0.1 \dots 1\ TeV$ but: no signal at LHC so far…



$SUSY$: important properties with view to DM

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- $\boldsymbol{R}$ **– parity: a key property of** $\boldsymbol{SUSY}$ **for** $\boldsymbol{DM}$ **& the stability of the proton** $\boldsymbol{p}$

  - introduction of a new, **multiplicative** quantum number for all particles

$\boldsymbol{R}$ – parity $\boldsymbol{R_P}$: $\boxed{\boldsymbol{R_P = (-1)^{3\cdot B+L+2S}}}$ or $\boxed{\boldsymbol{R_P = (-1)^{3\cdot(B-L)+2S}}}$

$\boldsymbol{B}$: baryon number $\boldsymbol{L}$: lepton number $\boldsymbol{S}$: spin

  - $\boldsymbol{SM}$ – particles: $\boldsymbol{R_P = +1}$ $(\boldsymbol{even})$ - $\boldsymbol{SUSY}$ – particles: $\boldsymbol{R_P = -1}$ $(\boldsymbol{odd})$

  - resulting superpartner properties:

    a) production via $\boldsymbol{SM}$ – particles: only $\boldsymbol{SUSY}$ – **pairs** can be emitted

    b) $\boldsymbol{SUSY}$ – superpartners only decay into superpartners (not $\boldsymbol{SM}$ – particles)

$SUSY$: important properties with view to DM

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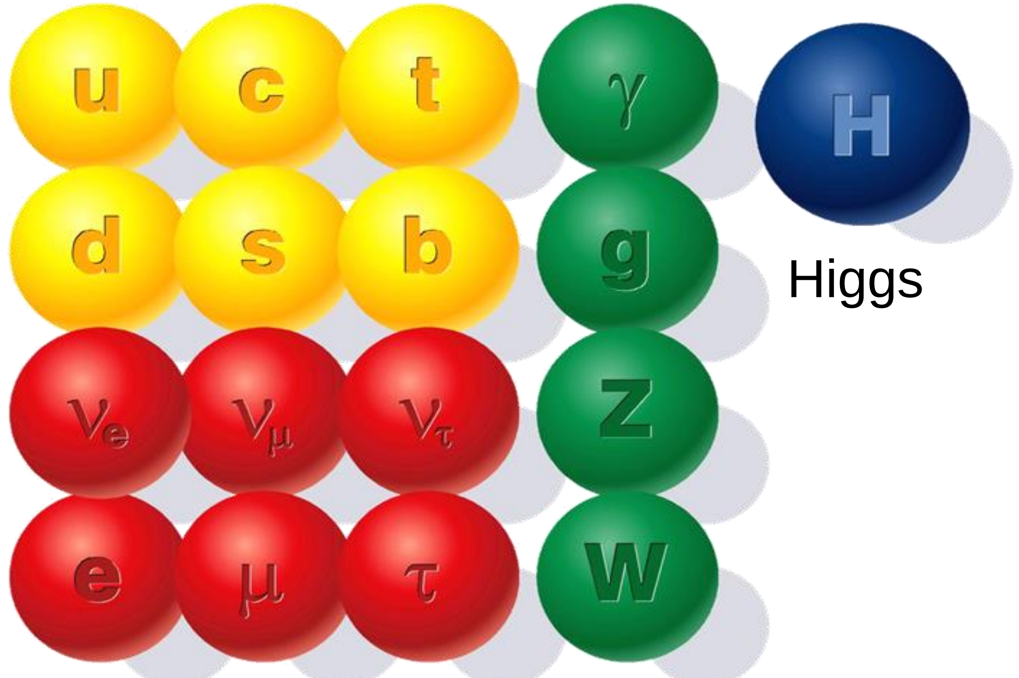
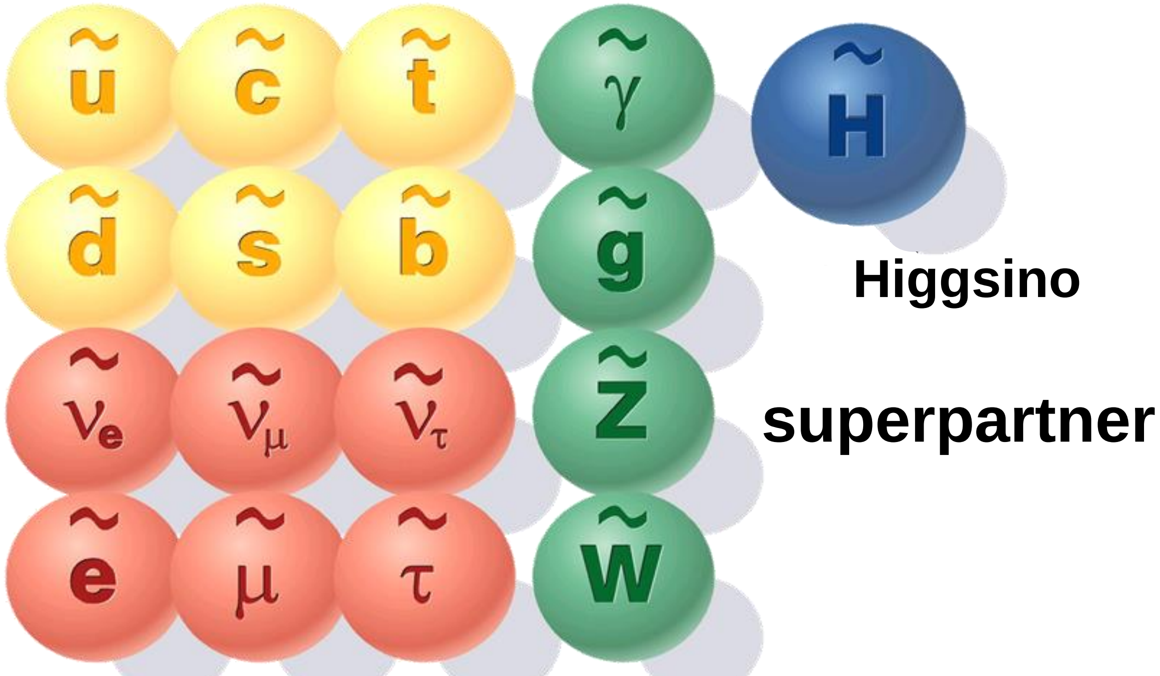
- R – parity: a key property of $SUSY$ for DM & the stability of the proton p

- SM – particles: $R_P = +1$ $(even)$



quarks leptons gauge bosons

- $SUSY$ – particles: $R_P = -1$ (odd)



squarks sleptons gauginos

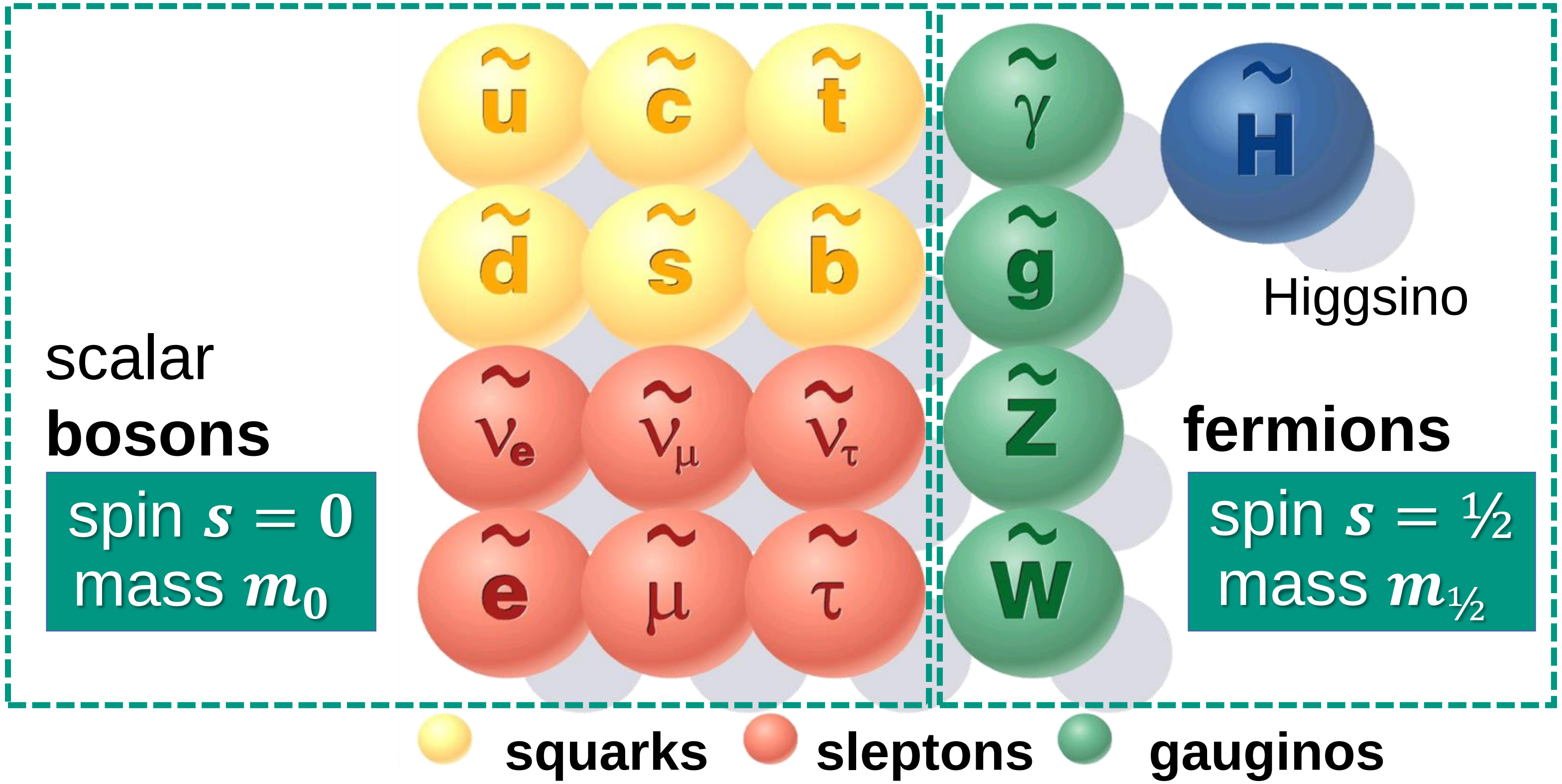
$SUSY$ and the constrained $MSSM$ ($cMSSM$)

- $cMSSM$: the most ´economic´ $SUSY$ – model with only 5 new parameters

  - all superpartner masses are assumed to be identical at the GUT scale

m_0 : mass of all superpartners with spin $s = 0$
scalar bosons:
squarks, sleptons

$m_{½}$: mass of all superpartners with spin $s = ½$
fermions:
4 gauginos, Higgsino



$cMSSM$: building of a viable DM – candidate

- A **weakly interacting** massive, mixed DM – particle (which is also stable)

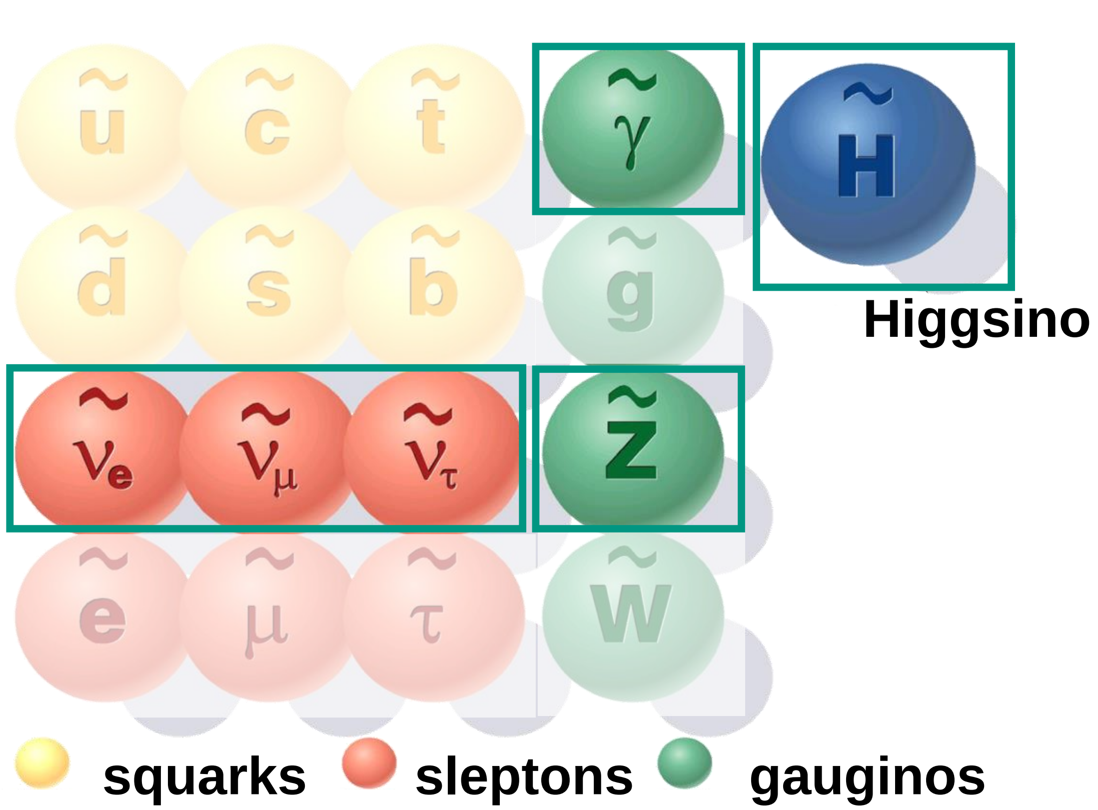
- **neutral particles** with weak interactions only, as no exotic isotopes were observed

  → no $squarks$ (charge, colour)

  → no $charged\ sleptons$ (charge)

  → no $gluinos$ (colour)

  → no $Winos$ (charge)



- remaining DM – candidates:

  → **gauginos**: $photino\ \tilde{\gamma},\ Zino\ \tilde{Z}$

  $Higgsino\ \tilde{H}$

  → $sneutrinos$: $\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$

$cMSSM$: a closer look at $sneutrinos$

- $\boldsymbol{Sneutrinos}$ **as superpartners of neutrinos: can they be a $\boldsymbol{DM}$ – candidate?**

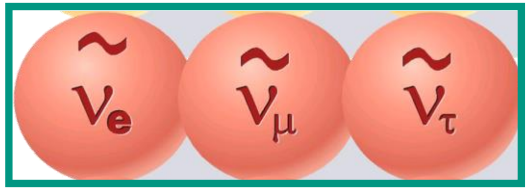
- neutral particles with **weak interactions** only ☑

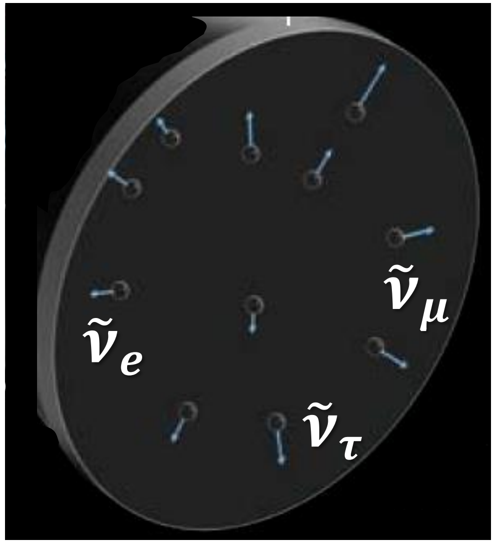
- heavy, scalar particles at the $\boldsymbol{TeV}$ – mass scale ($\boldsymbol{CDM}$) ☑

- but: weak interaction rates are **identical** to the ones of $\boldsymbol{\nu\acute{}s}$ ☒

⇨ very early universe: **too large annihilation rate**!

⇨ present density in the universe is much too small ($\boldsymbol{\Omega_{DM}} \ll \mathbf{0.27}$)





- lesson: **weak interaction rate** of a successful $\boldsymbol{DM}$ – candidate must be **significantly smaller** than the one of neutrinos!

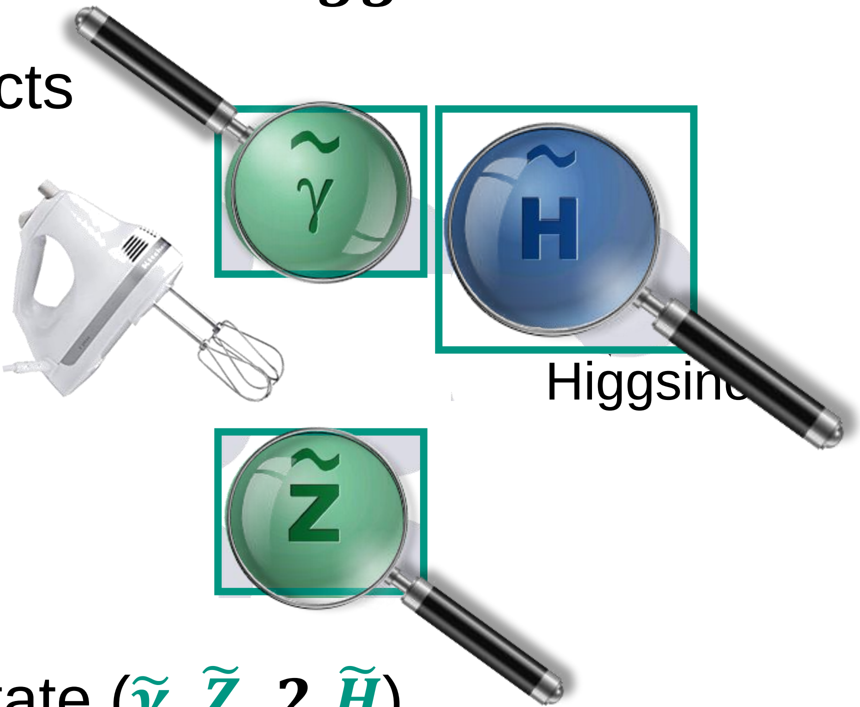
$cMSSM$: a closer look at $gauginos$ & $Higgsinos$

- **Neutral fermionic superpartners: can they be a DM – candidate?**

- we have $\mathbf{4}$ interaction eigenstates : $\mathbf{1}$ $\boldsymbol{photino}$ $\tilde{\gamma}$ $\mathbf{1}$ $\boldsymbol{Zino}$ $\tilde{Z}$ $\mathbf{2}$ $\boldsymbol{Higgsinos}$ $\tilde{H}$

- remember **neutrino oscillations**: strong mixing effects due to identical quantum numbers
flavour states ν_e, ν_μ, ν_τ ⇔ mass states m_1, m_2, m_3

- we now mix the $\mathbf{4}$ flavour states $\boldsymbol{photino}$ $\tilde{\gamma}$, $\boldsymbol{Zino}$ $\tilde{Z}$ and the $\mathbf{2}$ $\boldsymbol{Higgsinos}$ $\tilde{H}$ to **$\mathbf{4}$ mass eigenstates**:
neutralinos



- $\boldsymbol{´WIMP´}$ **miracle**: weak interaction rate of a mixed state ($\tilde{\gamma}$, $\tilde{Z}$, $\mathbf{2}$ $\tilde{H}$) possesses just the required (**annihilation**) interaction rate for $\boldsymbol{\Omega_{DM}} \approx \mathbf{0.27}$ (!!!!)

$cMSSM$: an even closer look at $Higgsinos$

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- **How many superpartners for the Higgs boson of the SM?**

- we have **5** physical $\boldsymbol{Higgsino}$ states in the $\boldsymbol{MSSM}$: $\tilde{h}$, $\tilde{H}^0$, $\tilde{A}$, $\tilde{H}^{\pm}$

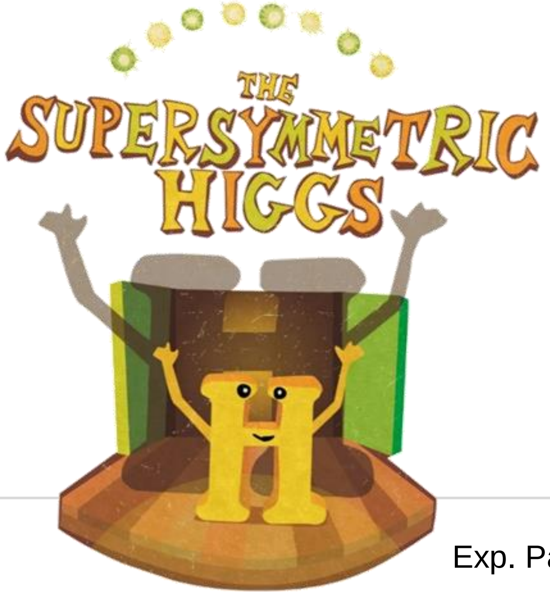
- **1** rather light ($\boldsymbol{SM}$ – like) state : $\tilde{h}$**,** plus others (charged $\tilde{H}^{\pm}$
  do **not** mix, as well as pseudoscalar $\tilde{A}$)

Higgsin

- in $\boldsymbol{SUSY}$ we have to consider **2** Higgsinos $\tilde{H}^0$:
  for $\boldsymbol{u}$ – type particles $\tilde{H}_u^0$, for $\boldsymbol{d}$ – type particles $\tilde{H}_d^0$

- for mixing to mass states we thus have **4 states**:

  $\boldsymbol{photino}$ $\tilde{\gamma}$
  $\boldsymbol{Zino}$ $\tilde{Z}$
  2 $\boldsymbol{Higgsinos}$ $\tilde{H}_u^0$ $\tilde{H}_d^0$



$cMSSM$: comparing $neutralinos$ & $gauginos$

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- **Due to mixing: we have flavour eigenstates & mass eigenstates**

- we have **4 flavour states**:

$gauginos$

$photino\ \tilde{\gamma}$

$Zino\ \tilde{Z}$

$2\ Higgsinos\ \tilde{H}_u^0\ \tilde{H}_d^0$

these states do **interact**, but have no well–defined masses & thus do not propagate

$\tilde{\gamma}\ \tilde{Z}\ \tilde{H}_u^0\ \tilde{H}_d^0$

4×4 mixing matrix

$\tilde{\chi}_1^0\ \tilde{\chi}_2^0\ \tilde{\chi}_3^0\ \tilde{\chi}_4^0$

- we have **4 mass states**:

$neutralinos$

lightest … heaviest

$\tilde{\chi}_1^0\ \tilde{\chi}_2^0\ \tilde{\chi}_3^0\ \tilde{\chi}_4^0$

these states **propagate in space** with well–defined masses, but have to mix to interact

And finally: the $neutralino$ as DM candidate

- **Stabilising the lightest neutralino $\tilde{\chi}_1^0$ via its intrinsic R – parity R_P as DM**

  - the LSP (Lightest Supersymmetric Particle) is expected to be stable over cosmological time scales due to its intrinsic $R_P = -1$

  - accordingly, if the lightest $neutralino$ $\tilde{\chi}_1^0$ is the LSP of $SUSY$, it is an excellent DM – candidate at the TeV – scale

$$neutralino: \boxed{\tilde{\chi}_1^0 = \underbrace{c_1 \cdot \tilde{\gamma}^0}_{photino} + \underbrace{c_2 \cdot \tilde{Z}^0}_{Zino} + \underbrace{c_3 \cdot \tilde{H}_u^0 + c_4 \cdot \tilde{H}_d^0}_{Higgsinos}}$$

flavour states

$Higgsinos$ (up, down)

  - the (unknown) flavour ratios c_i determine interaction rates of the $\tilde{\chi}_1^0$

the lightest neutralino $\tilde{\chi}_1^0$ as $WIMP - DM$

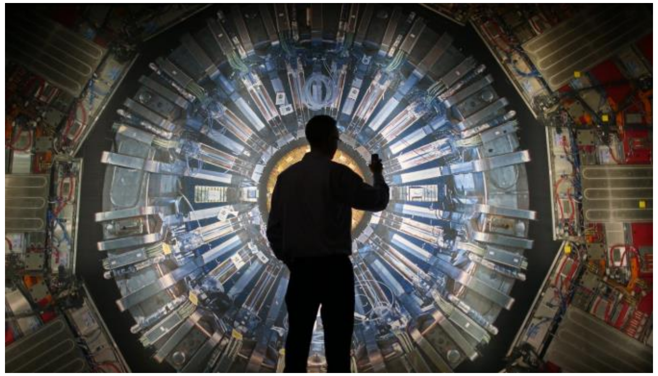
- **Properties of $neutralinos$ & searches for $SUSY - WIMPs$**

  - $SUSY$ expects $neutralinos$ to be **Majorana**–type* particles

  - it can **annihilate** with itself (no anti–neutralinos)

  - mass on TeV – scale, very weakly interacting

  - searches at LHC, galactic DM – **halo**, direct DM – **detectors**



*see lecture #11

Putting $SUSY$ on the experimental testbed

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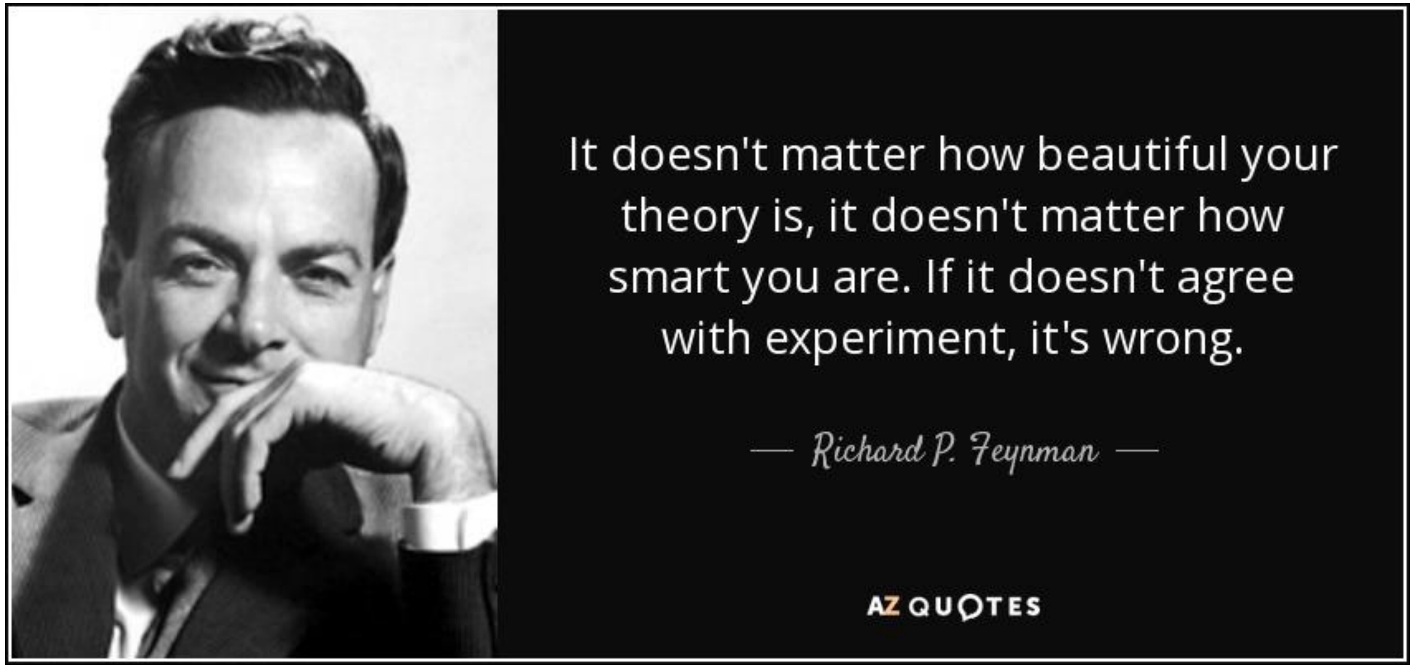
- **Feynman diagrams for $WIMP$ searches at LHC, galactic halo & DM – detectors**

- before we start to discuss DM – searches, we quote ***Richard Feynman*** himself



TÜV SÜD geprüfte Sicherheit

Geprüfte ***S***USY

Putting $SUSY$ on the experimental testbed

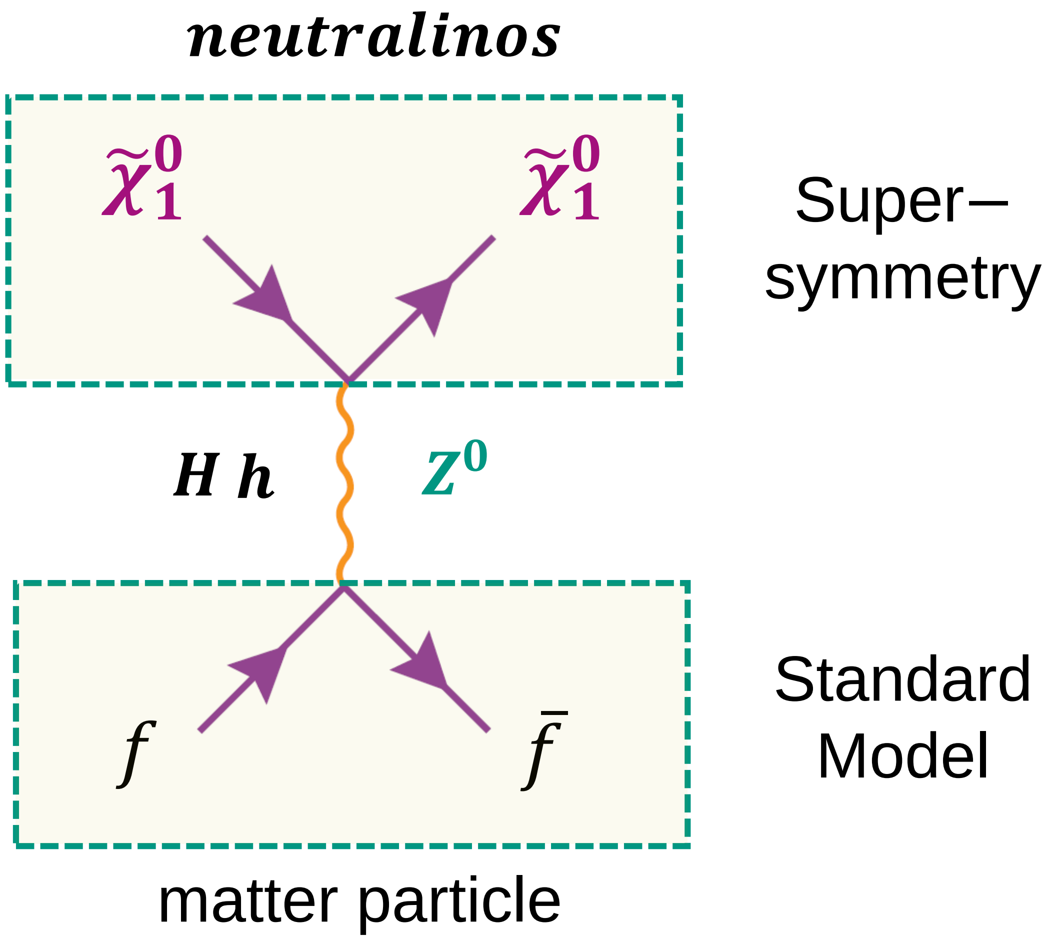
Feynman diagrams for $WIMP$ interactions

- flavour components of the lightest neutralino $\tilde{\chi}_1^0$ will interact via **two exchange bosons**

  a) **neutral vector boson Z^0**
  = **spin–dependent** process

  b) **neutral Higgs bosons H, h**
  = **spin–independent** process
  (**scalar interaction**)

- relative coupling strengths unknown, but very small in both cases

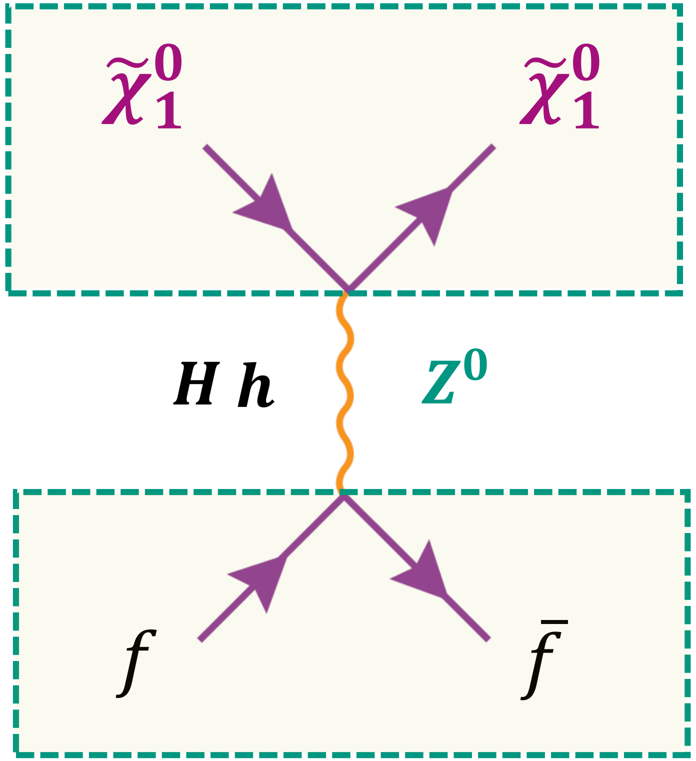


Putting $SUSY$ on the LHC testbed at $CERN$

- **Feynman diagram for $WIMP$ production from partons inside a proton**

  - direct production of neutralinos at a **high$-$luminosity collider** at the TeV $-$ scale (chapter 4.3)

$neutralinos$



pp $-$ collisions

LHC

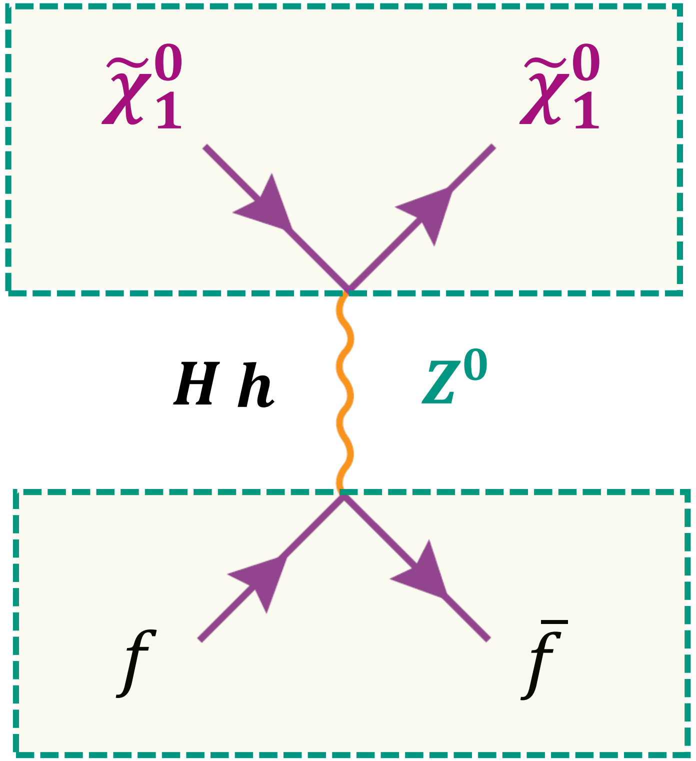
f = quarks (partons)

Putting $SUSY$ on the testbed at the galactic halo

- **Feynman diagram for $WIMP$ annihilation at the center of the galaxy**

  - **indirect searches** for the **annihilation** reactions of $\boldsymbol{neutralinos}$ at the inner part of the galactic halo (chapter $\mathbf{4.4}$)

$\boldsymbol{neutralinos}$



galactic halo

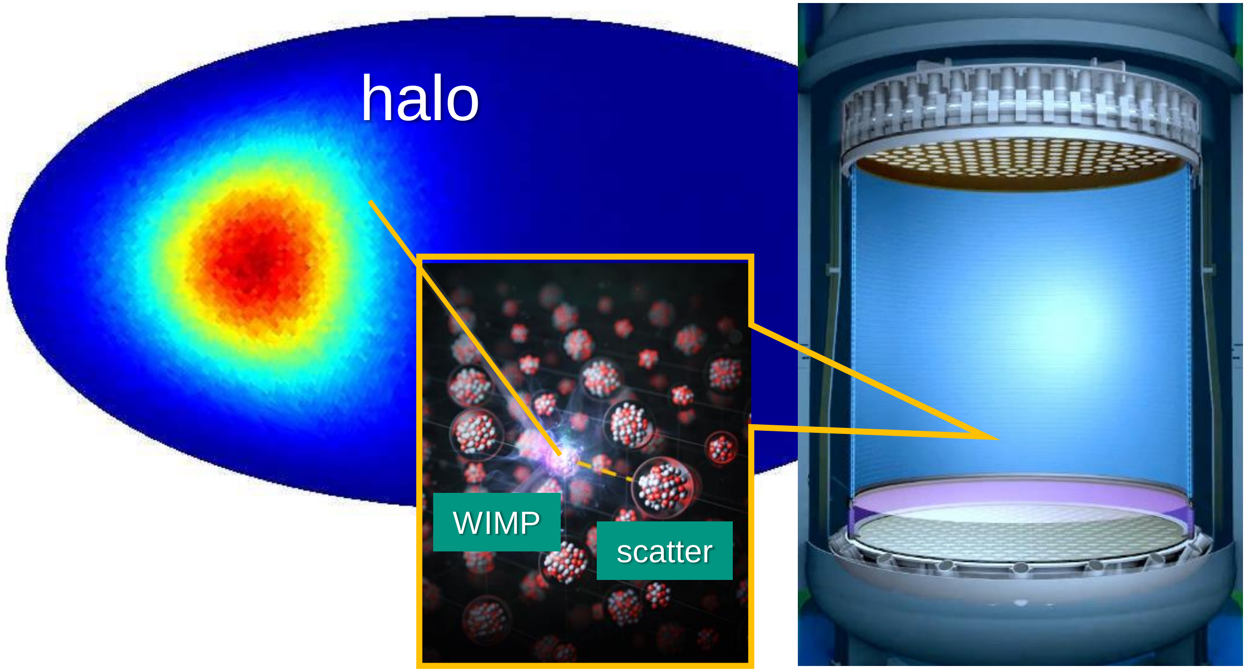
$\boldsymbol{f}$ = multi-messengers

$\boldsymbol{GeV - TeV}$ – energies

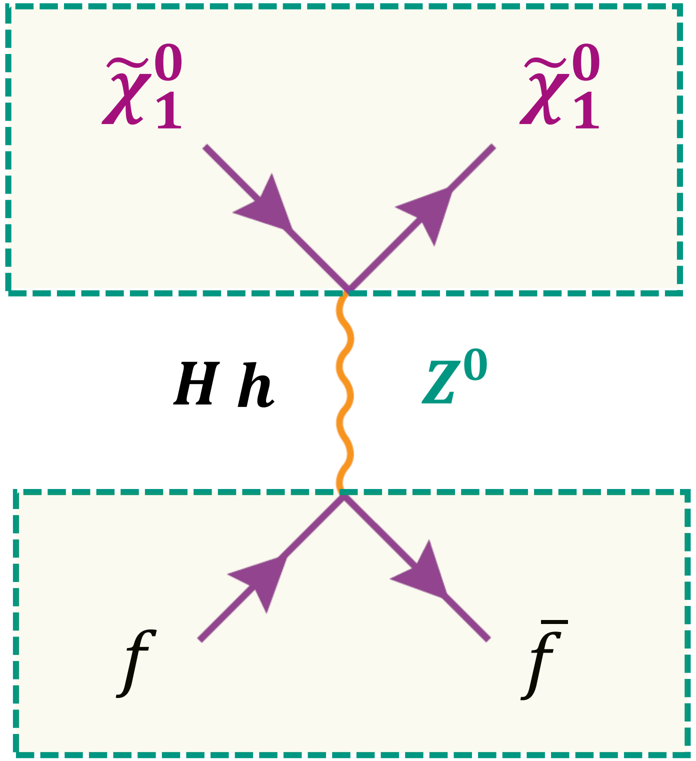
Putting $SUSY$ on the testbed at a DM detector

- **Feynman diagram for $WIMP$ scattering in an underground DM – detector**

  - direct searches for **elastic scattering** processes of $\boldsymbol{neutralinos}$ at large $\boldsymbol{DM}$ detectors (chapter $\mathbf{4.5}$)



$\boldsymbol{neutralinos}$



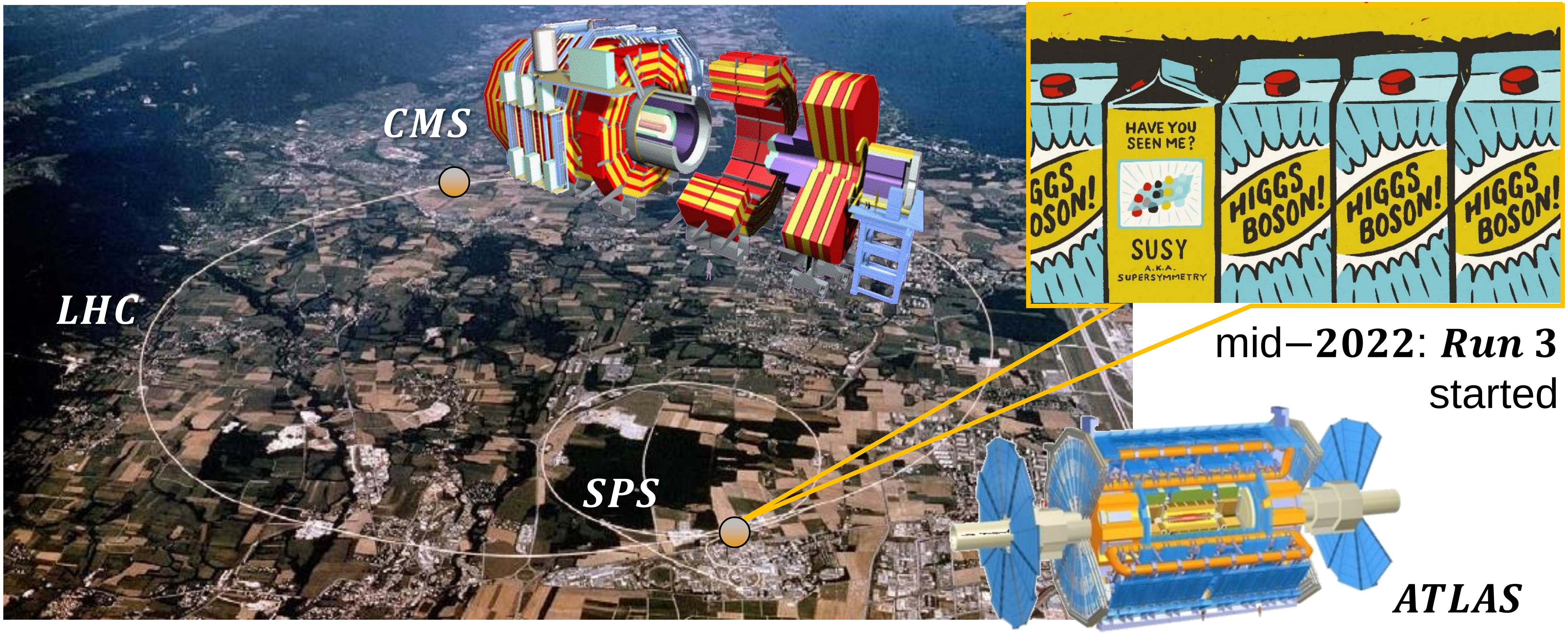
galactic halo

$\boldsymbol{f}$ = target nucleus

collision kinematics

4.3 $WIMP$ search at the LHC

- **Direct production of $WIMPs$ in $pp-$ collisions at $\sqrt{s} = 13.6\ TeV$**



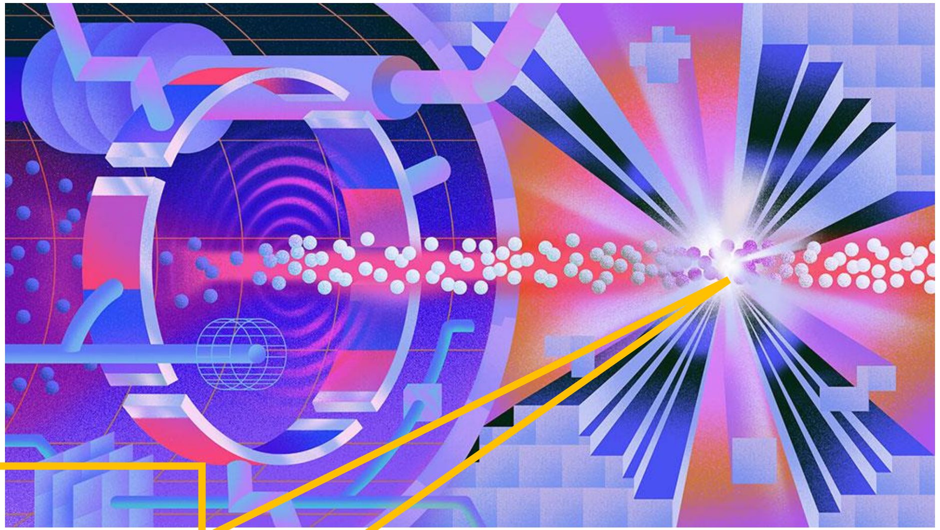
mid$-\mathbf{2022}$: $\boldsymbol{Run\ 3}$ started

RCAP: LHC beam parameters

- Search for rare $SUSY -$ events is boosted by high **collider luminosity L**

  - LHC: a huge step forward in increasing the luminosity of particle collisions – design value

$$L = 10^{34}\ cm^{-2} s^{-1}$$



  - calculating the beam **luminosity L**:

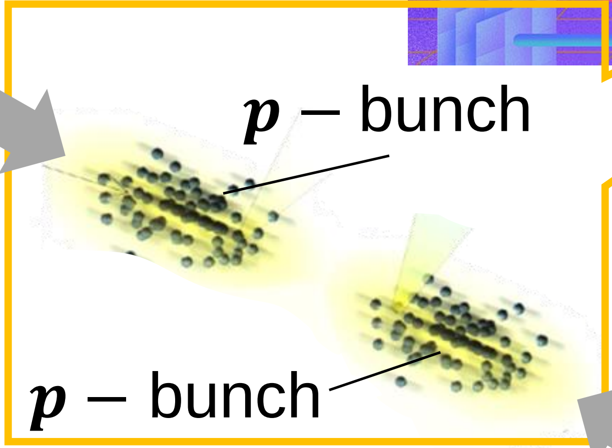
$$\boxed{L = f \cdot n \cdot \frac{N^2}{4\pi \cdot \sigma_b^2}}$$

f: frequency

n: # bunches

N: #p / bunch

σ_b: transversal beam size



$$\boxed{R = \frac{dN}{dt} = L \cdot \sigma}$$

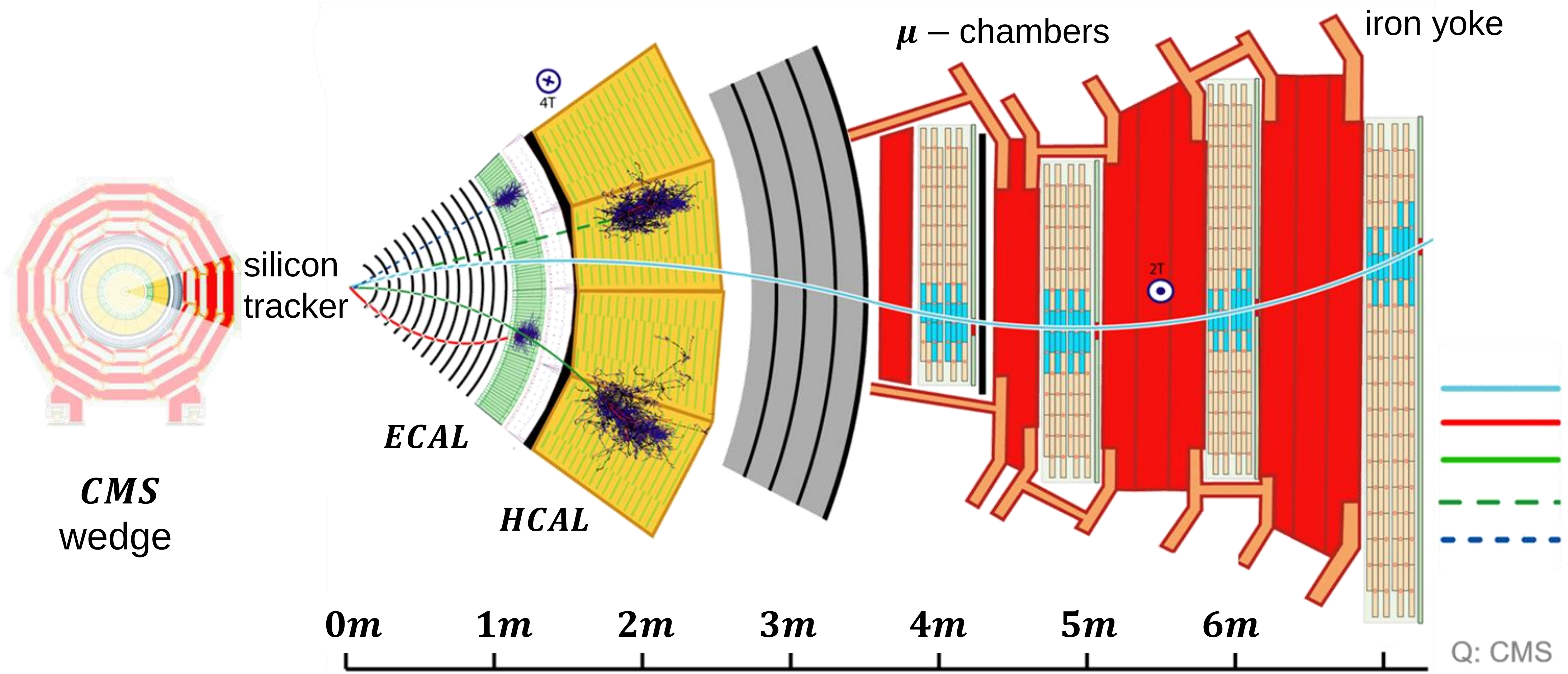
R: rate

L: lumi

σ: cross section

RECAP: detector components of CMS experiment

- **Transversal view of inner tracker, $ECAL$, $HCAL$, muon chambers**



Outlook: hunting for signatures of $SUSY$

- Signatures of $neutralinos$: missing energy / transversal momentum