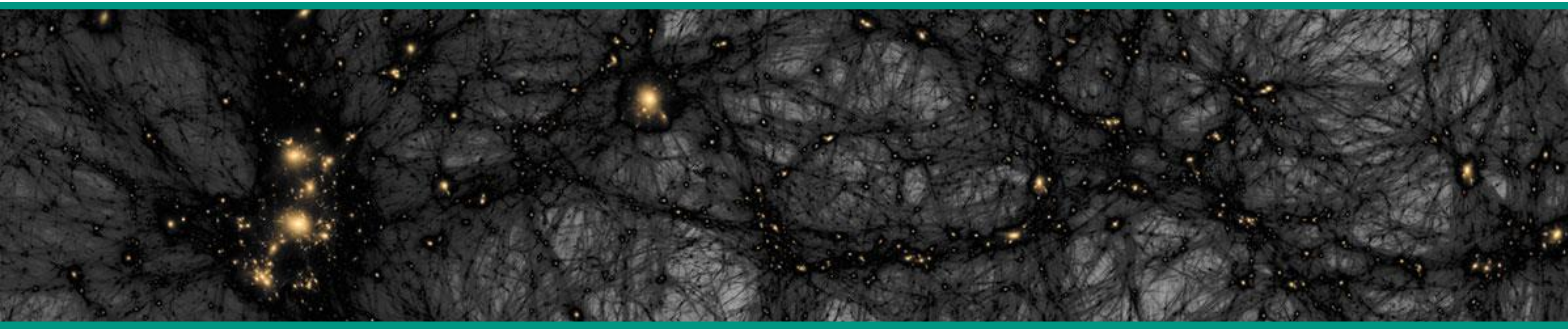
Astroparticle physics I – Dark Matter

WS22/23 Lecture 13 Dec. 21, 2022



Recap of Lecture 12

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

  - key parameters impacting the sensitivity for half-life $t_{½}^{0\nu\beta\beta}$

  - enrichment factor $a = 0 \ldots 1$, exposure $M \cdot t$, energy resolution ΔE

  - most important: extremely low background rate B at Q – value

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

  - DM-evidences: velocity dispersion of galaxy clusters, galactic rotation curves

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

4.2 Dark Matter: candidates

- **A huge variety of candidates – from the very light up to super-massive DM**

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

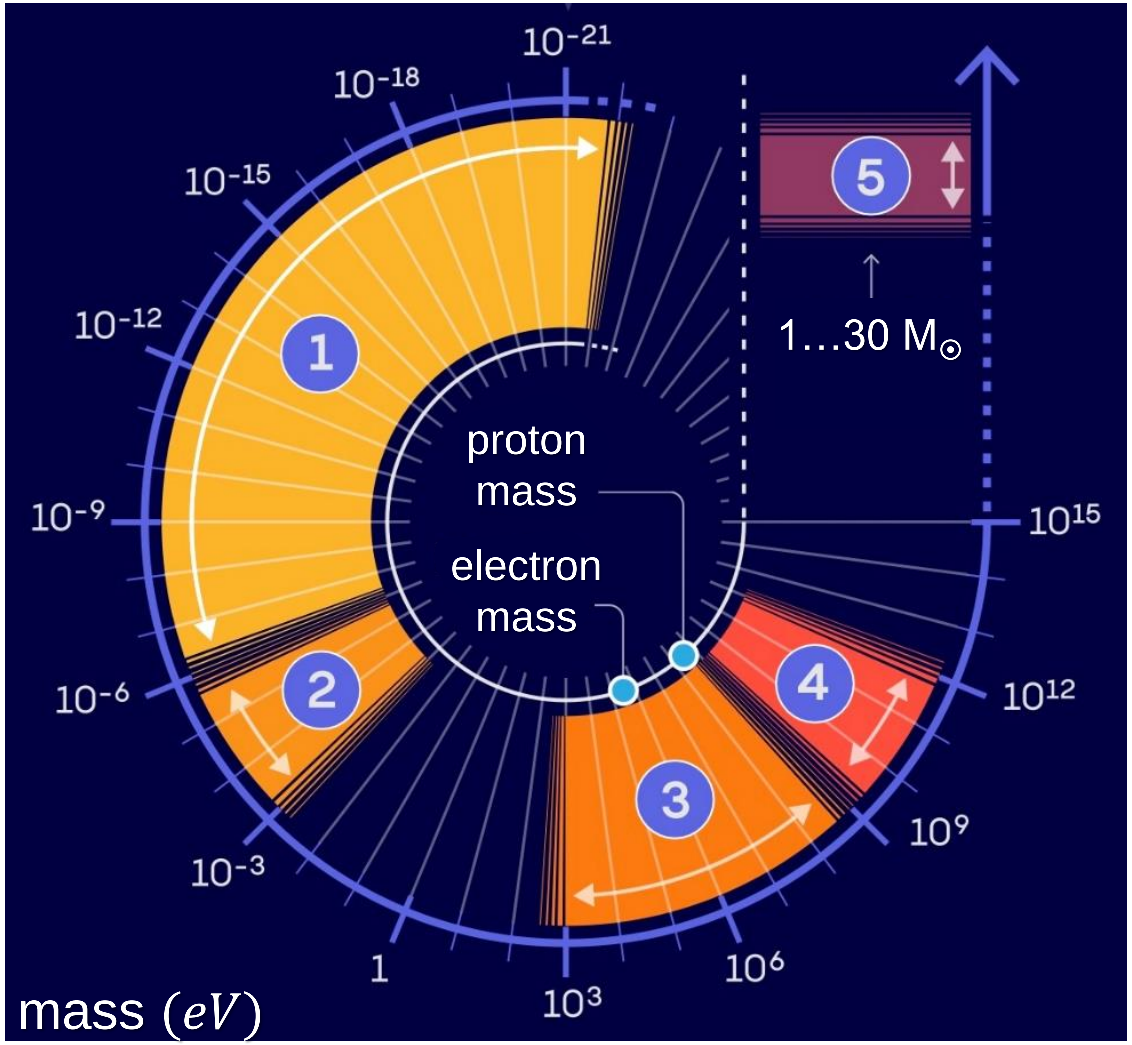
❶ ultra-light DM (**ALPs: a**xion-**l**ike **p**articles, hidden photons,…)

❷ **axions** (strong CP – problem)

❸ DM on $sub - GeV$ – scale

❹ WIMPs: **neutralinos**

❺ primordial black holes (MACHOs)



Dark matter candidates & cosmology

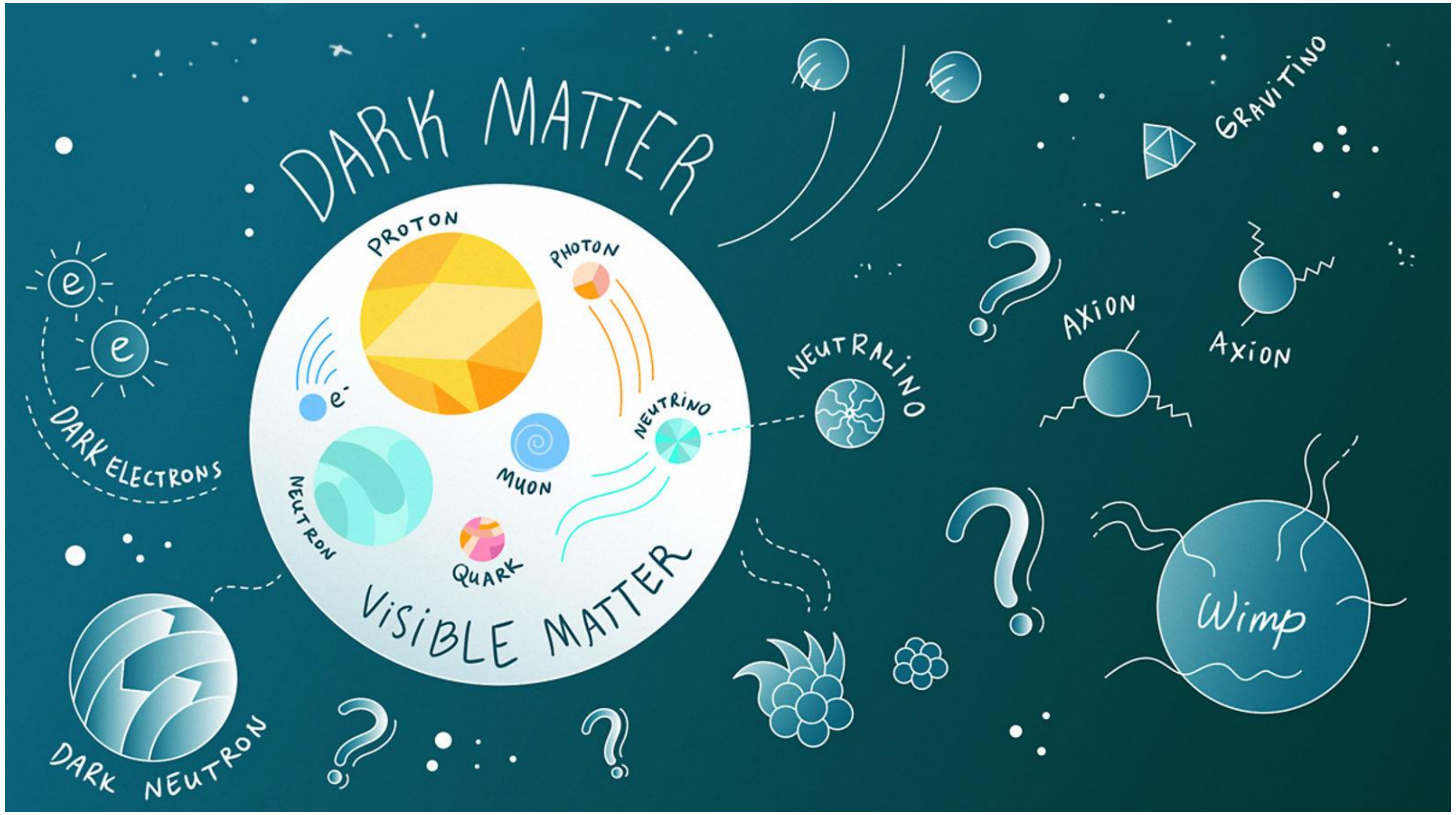
- **Important cross-checks via DM role in early & present universe**

  - no particle in the SM can play the role of Dark Matter candidate: look beyond

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

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

  - weak interactions only (Z^0, h bosons)

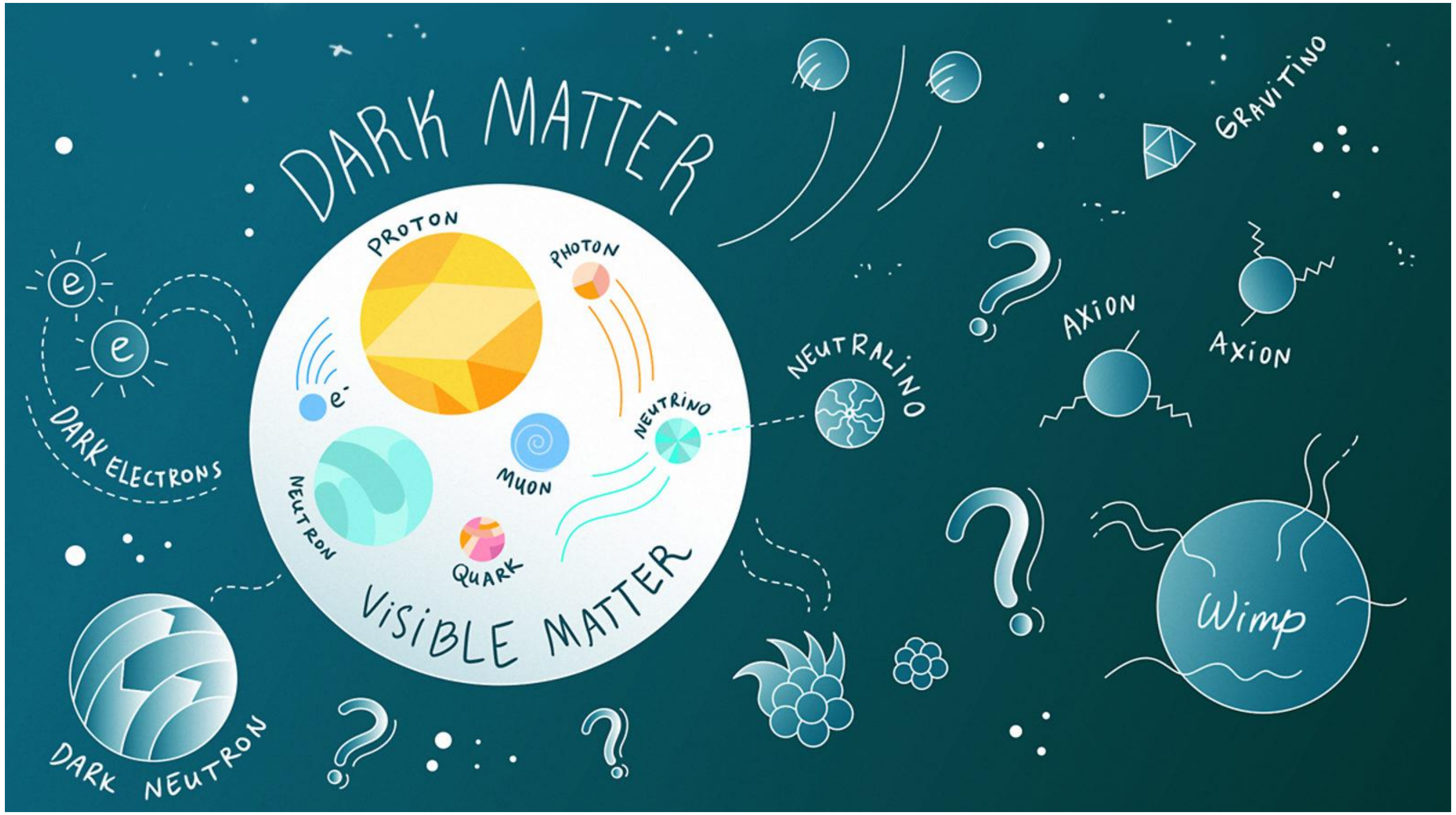


Dark matter candidates & cosmology

■ **Important cross-checks via DM role in early & present universe**

- production in early universe: thermal (WIMPs) or non-thermal processes (axions)

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

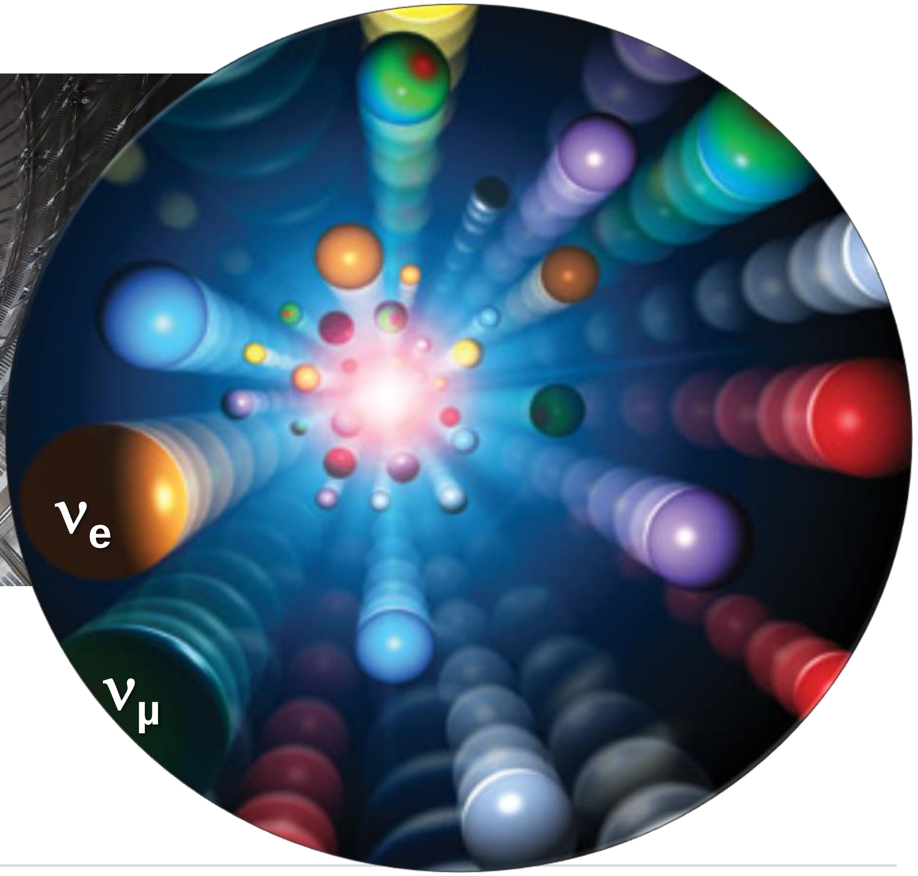


- de-Broglie wavelength $\lambda_{deBroglie} < r_{dg}$ (radius of a dwarf galaxy, $few\ kpc$)

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

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 $W^{\pm}, Z^0$ - $339\ \nu's\ cm^{-3}$
  - are ´hot´, i.e. moving relativistically $(m_\nu < 0.8\ eV)$ ⇨ ´top-down´ formation of large-scale structures
  - de-Broglie wavelength $\lambda_{deBroglie} > r_{dg}$ (radius of a dwarf galaxy, $few\ kpc$)
  - only small part in form of **HDM**, dominant is **CDM**



Dark matter candidates: the case of neutralinos

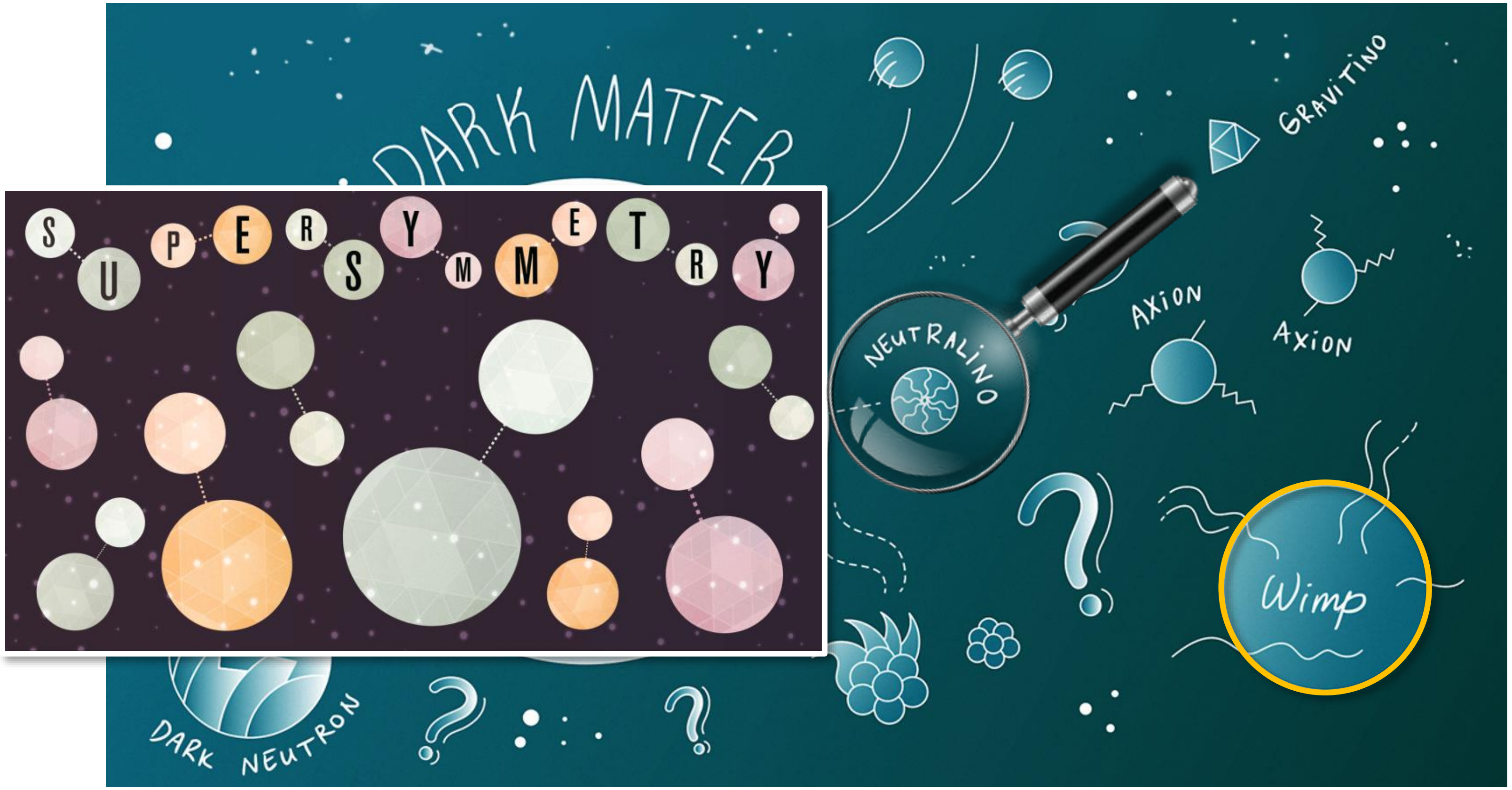
- **Weakly Interacting, Massive Particles: WIMPs or, specifically, neutralinos**

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

  - correct abundance if weak interaction $xsec$

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

  - **CDM**: non-relativistic velocity distribution, allows bottom-up evolution of structures



Dark matter candidates: the case of neutralinos

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- **Weakly Interacting, Massive Particles: WIMPs or, specifically, neutralinos**

  - production in early universe: non-thermal processes via symmetry breakting

  - correct abundance if mass & $xsec$ in region

  - cosmologically stable due to tiny mass (μeV)

  - **CDM**: non-relativistic velocity distribution, allows bottom-up evolution of strucutures

Dark matter candidates: mass vs. cross section

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- **An overview of DM-particles**

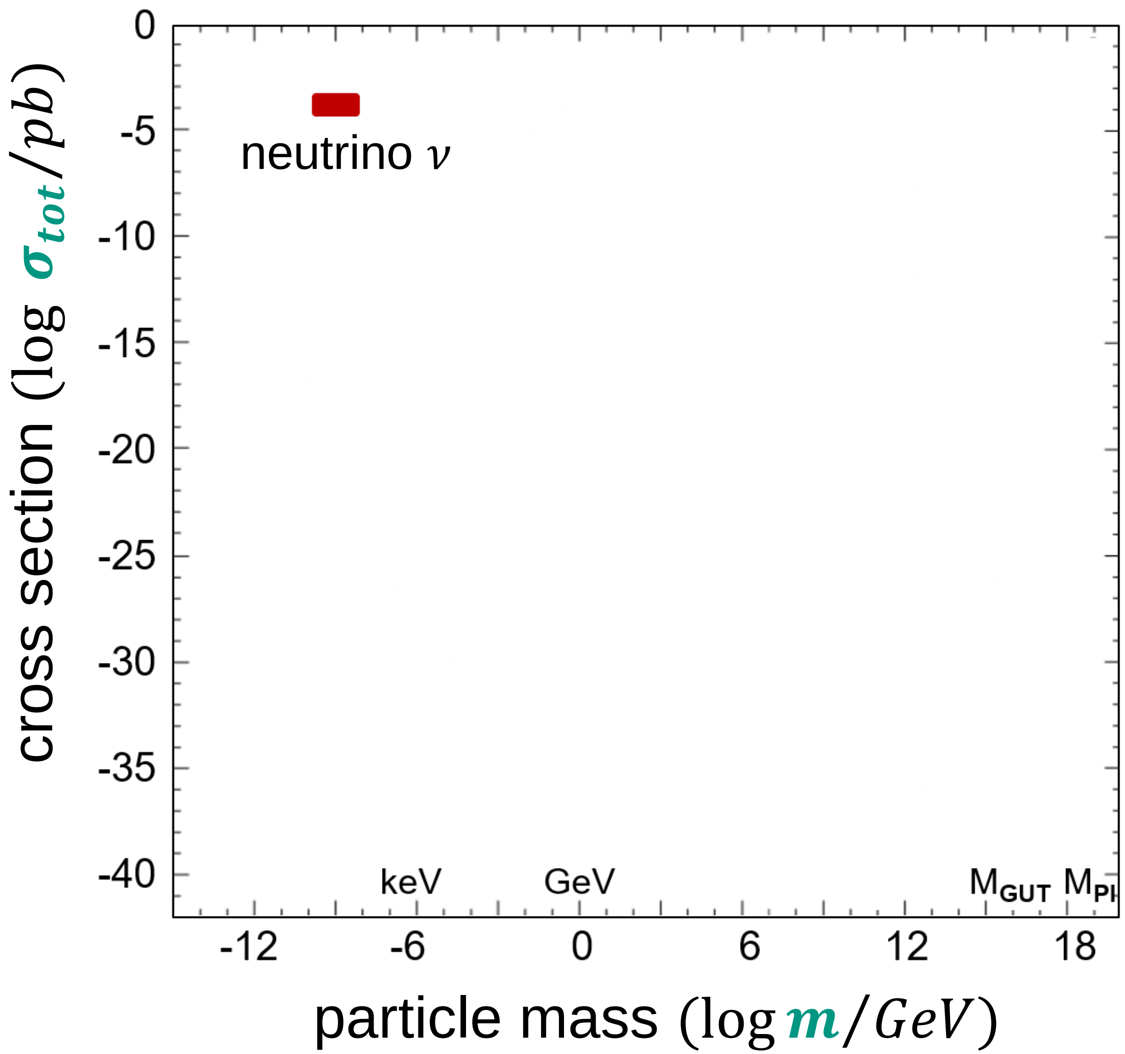
  - two key parameters:
    mass $m\ [GeV]$, $\boldsymbol{\sigma_{tot}}\ [\boldsymbol{pb = 10^{-36}\ cm^2}]$

  - **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 WIMPs

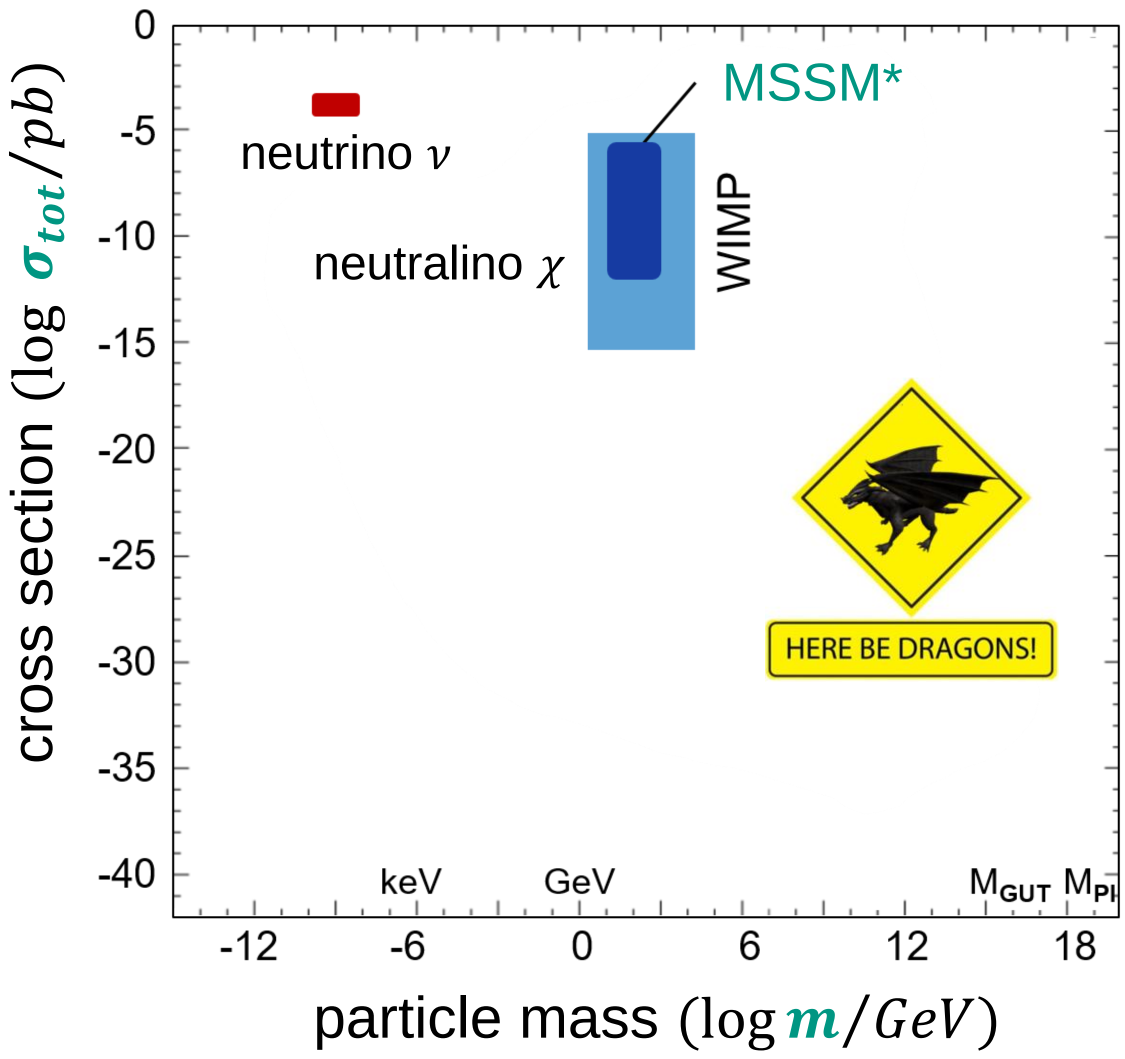
- **neutralino χ**: prototype of a weakly interacting massive particle (WIMP)

- mass $m = GeV \ldots TeV$ scale
  ⇨ determines number density

- neutralinos are superpositions of 4 states: ⇨ mixing efffects reduce σ_{tot}

- electroweak χ – cross section scale:

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



*Minimum Supersymmetric Standard Model

Dark matter candidates: light, but cold DM

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Axions & Axion-Like Particles (ALPs)

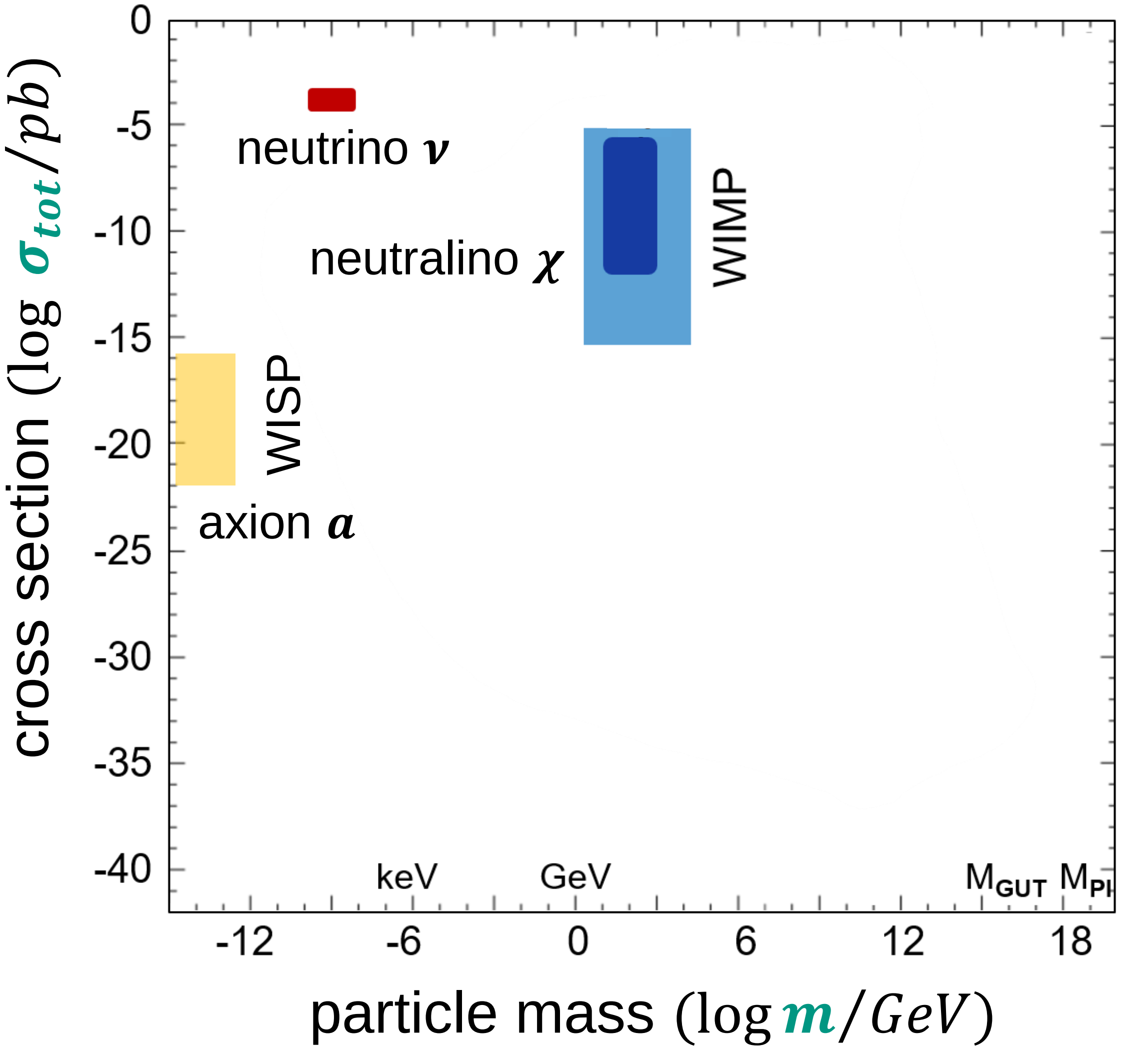
- **axion $\boldsymbol{a}$**: prototype of a weakly interacting slim particle (WISP)

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

- axions ´solve´ the **strong $\boldsymbol{CP}$ – problem** of QCD

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

  B –field: conversion into/from γ´s

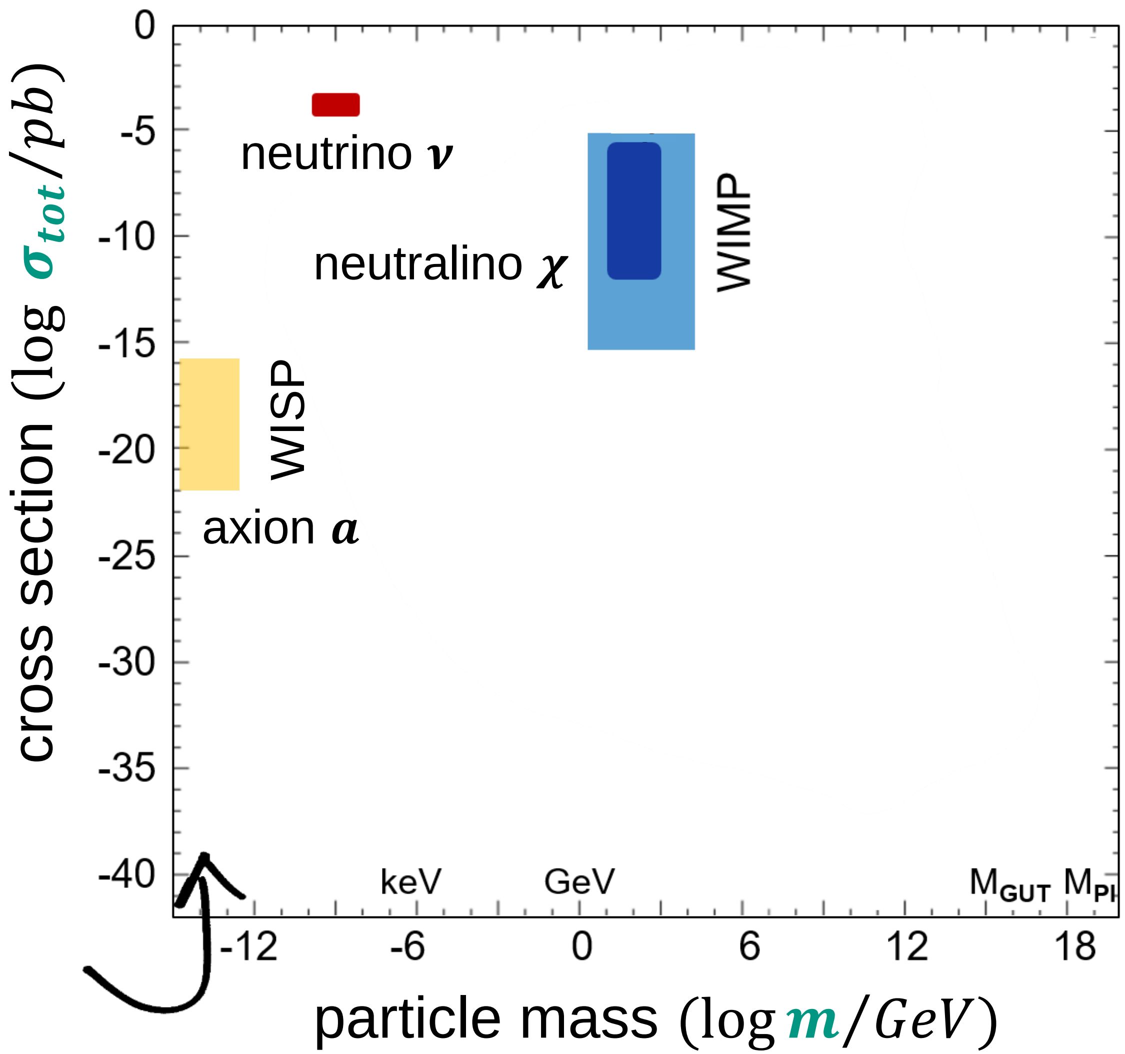


Dark matter candidates: light, lighter, & beyond…

- **ultra-light particles (WISPs)**
  - **axion *a***: prototype of a weakly interacting slim particle (WISP)
  - a large parameter space to cover
  - message from Richard Feynman:

29.12.1959

There´s plenty of room at the bottom



Dark matter candidates: heavy, heavier, GUT –scale

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- **ultra-heavy particles**

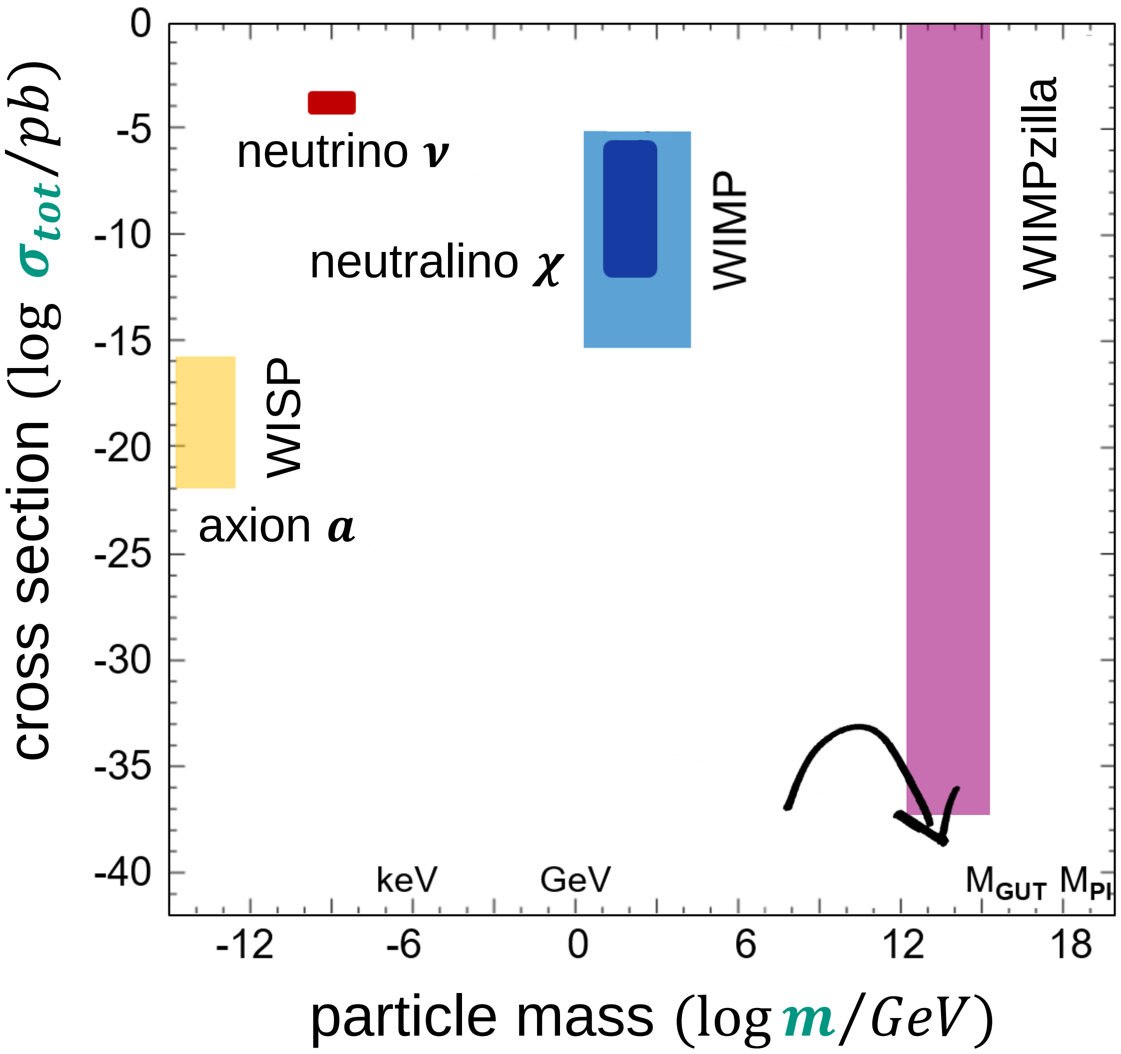
  - ´**WIMPzilla**´: prototype of an extremely massive particle

  - mass $m = \mathbf{10^{12}} \ldots \mathbf{10^{12}}\ GeV$ scale
    ⇨ at GUT –scale & beyond

  - often associated with inflationary, very early phase of the universe

Rocky Kolb

Size does matter



DM-related theories: Super-Symmetry ($SUSY$)

- **A new space-time symmetry between bosons ⬄ fermions**

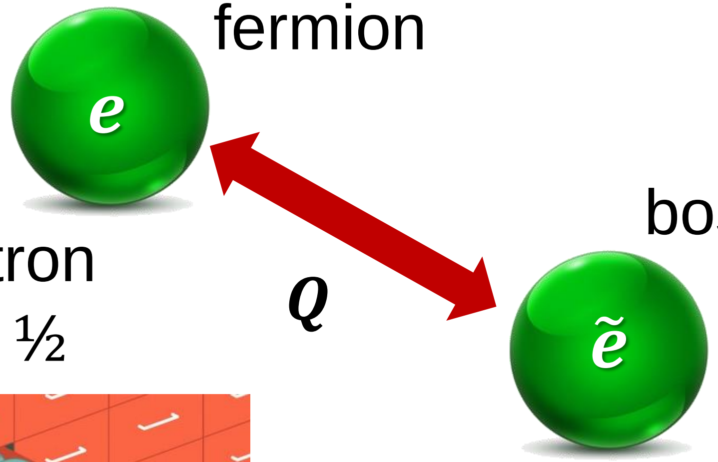
  - $SUSY$ postulate: each SM –particle has a heavy (TeV) $SUSY$ superpartner

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

  - $SUSY$ – operator $\boldsymbol{Q}$:

$$\boldsymbol{Q}\,|\boldsymbol{boson}\rangle = |\boldsymbol{fermion}\rangle$$
$$\boldsymbol{Q}\,|\boldsymbol{fermion}\rangle = |\boldsymbol{boson}\rangle$$

  transforms bosons into fermions & v.v.



DM-related theories: $SUSY$ name conventions

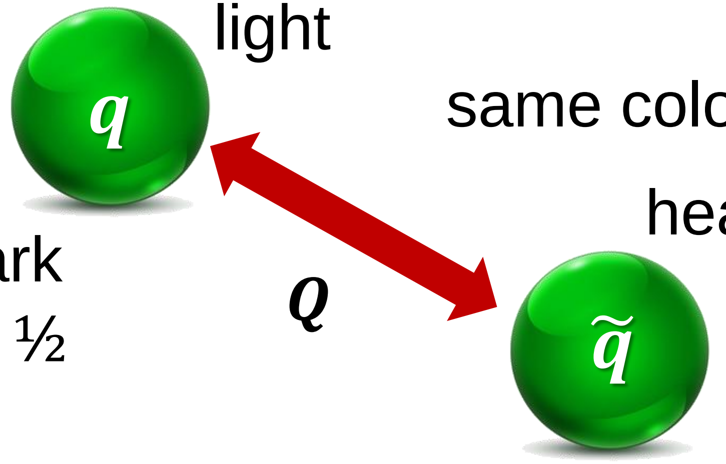
- **$SUSY$ postulate of heavy superpartners with $s = ½$ and $s = 0$**

  - $SUSY$ 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,…)**



DM-related theories: *SUSY* origins at KIT

- 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

- KCETA regularly awards the Julius Wess prize

$SUSY$: a spontaneously broken symmetry

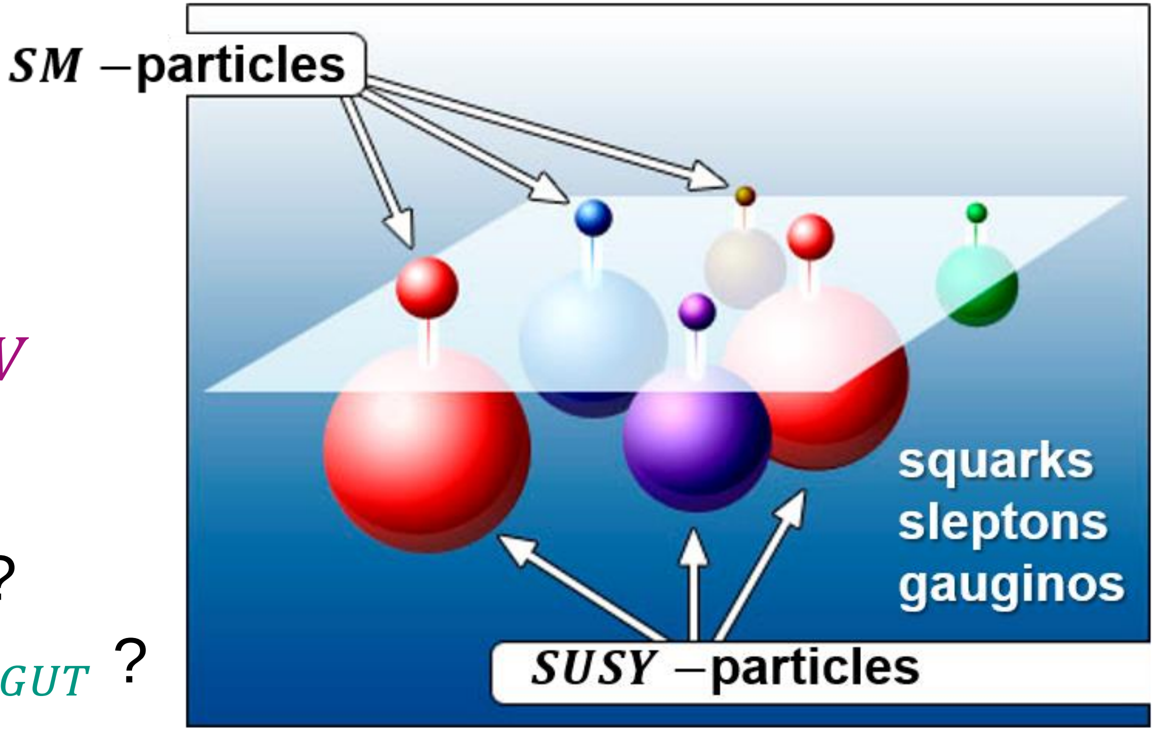
- **Quantum vacuum not invariant under $SUSY$ – transformations**

  - 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 $E_{SUSY} \ll E_{GUT}$?

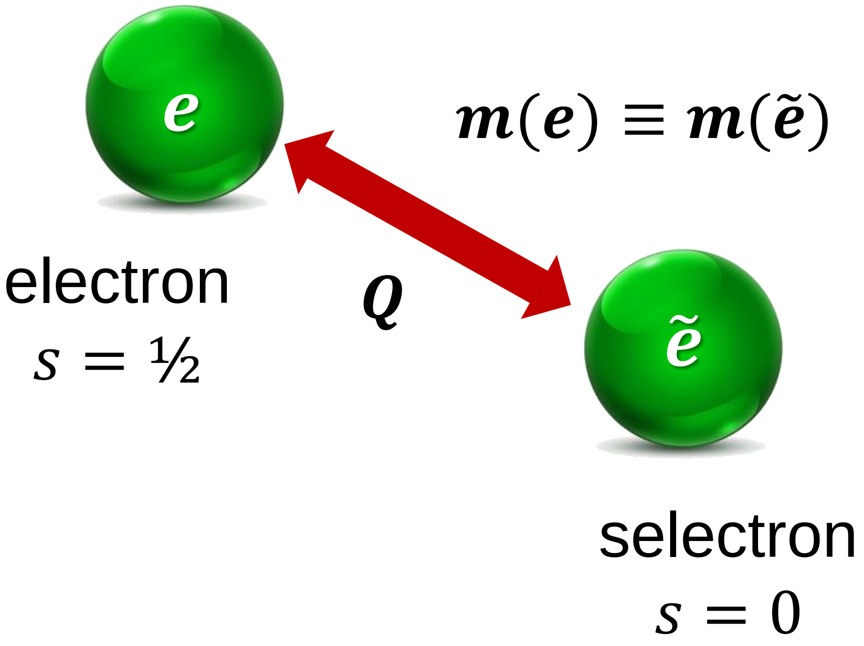


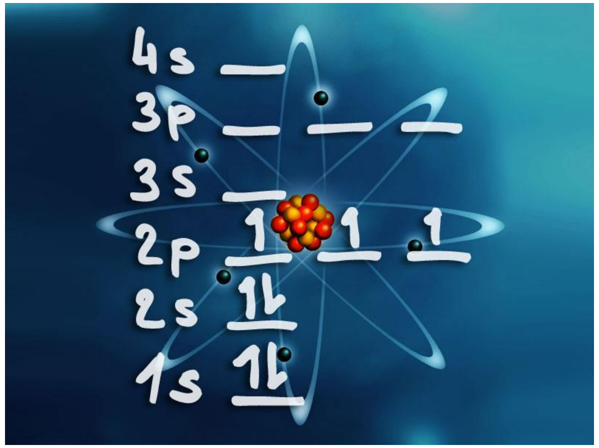
INSERTION: what if … $SUSY$ was NOT broken?

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

  - result:
    masses of SM – particles & $SUSY$ – particles **are** identical

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

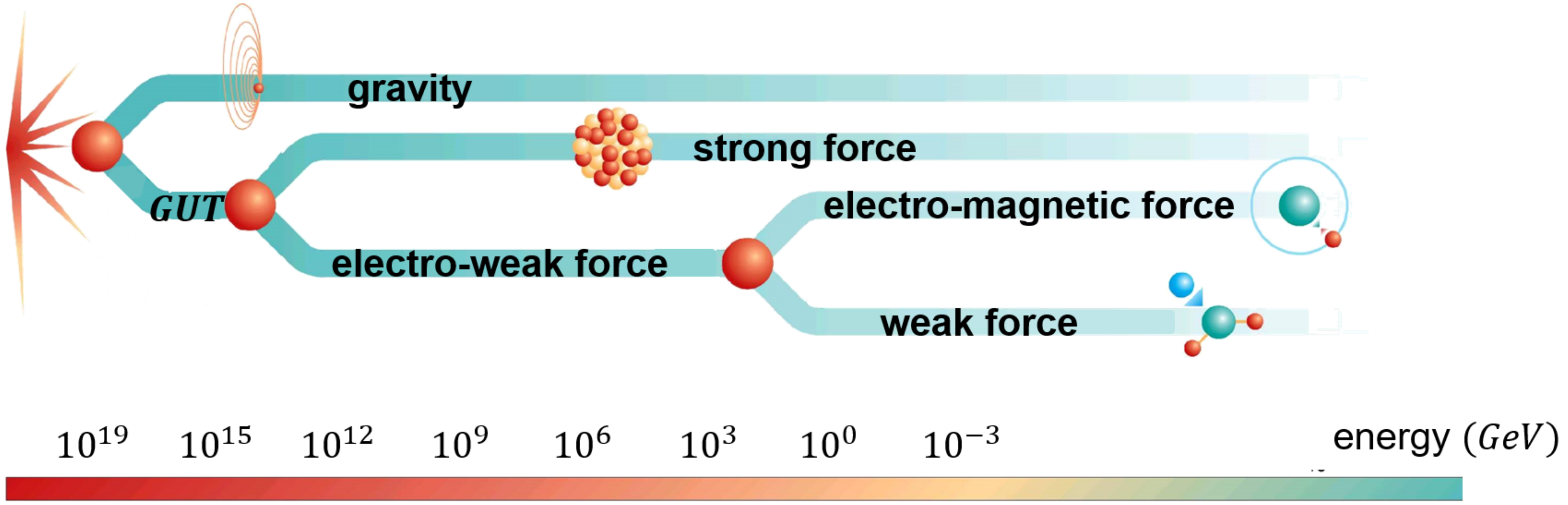




$SUSY$ and gauge unification of interactions

- **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)



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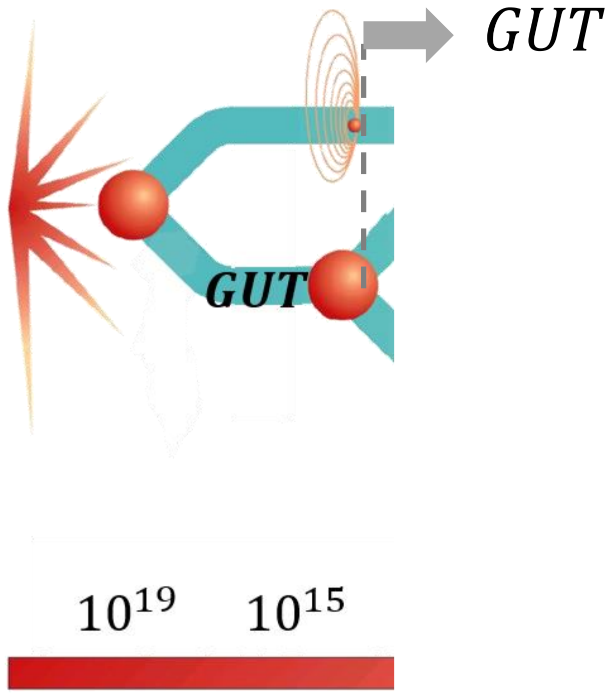
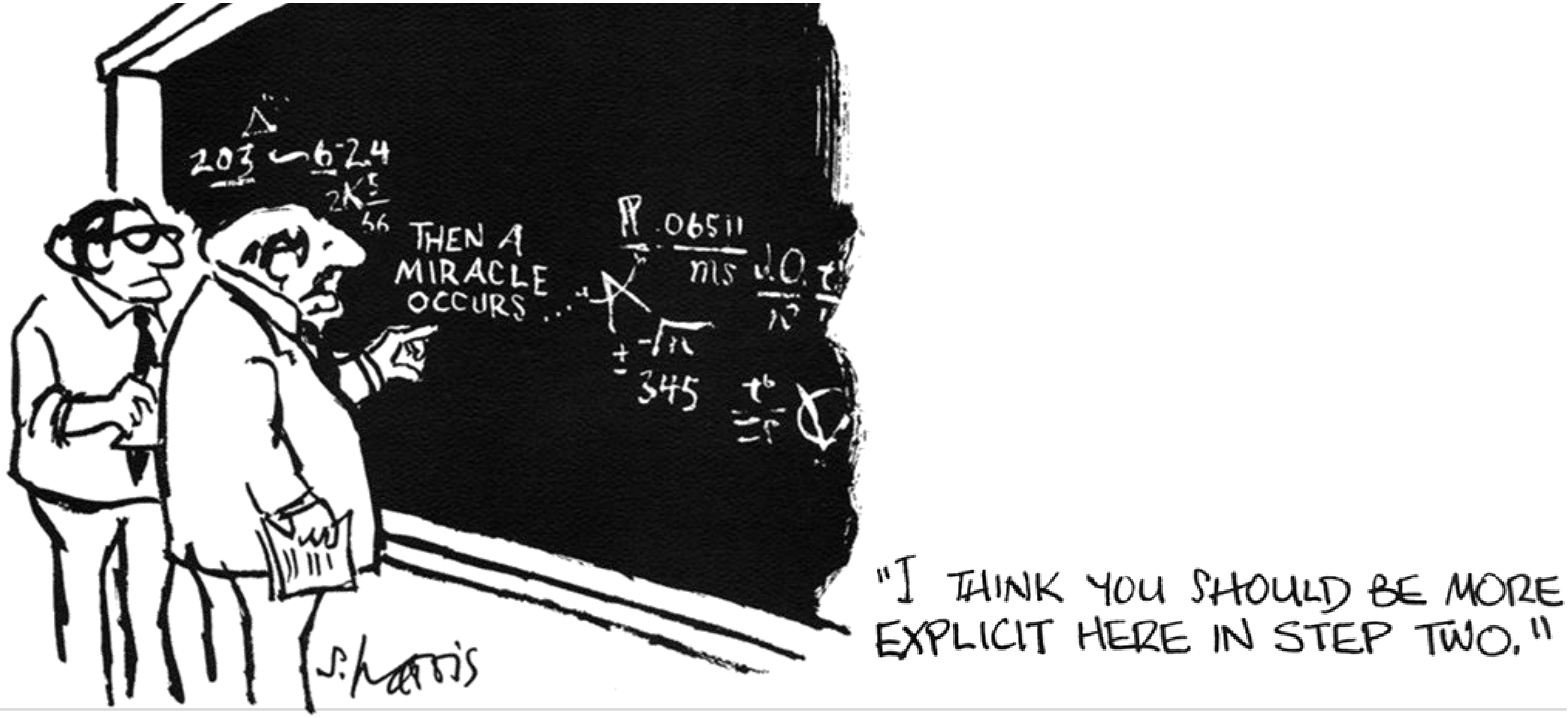
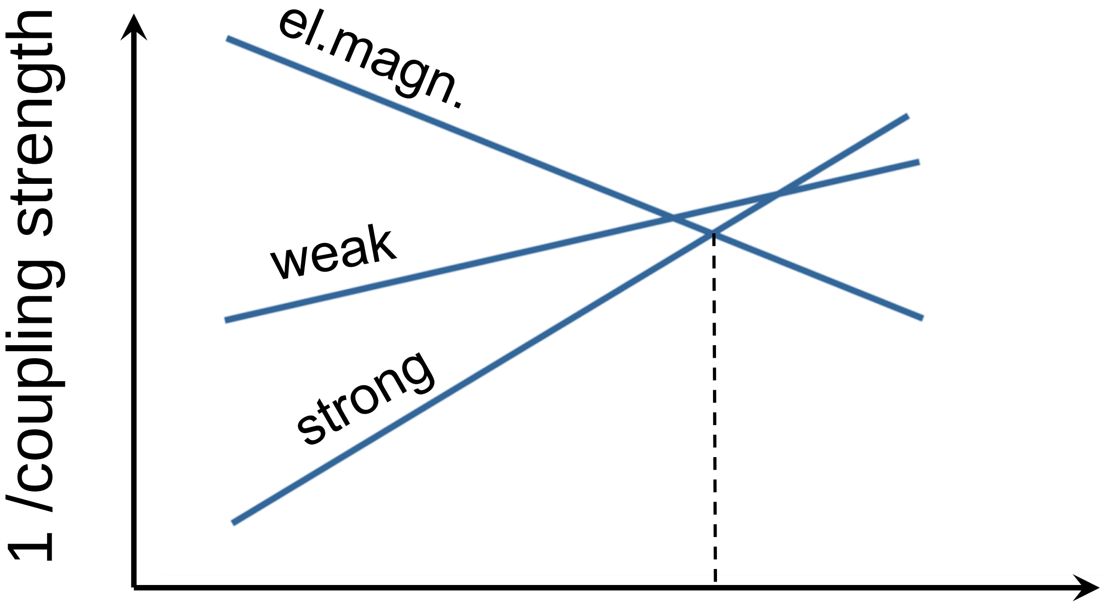




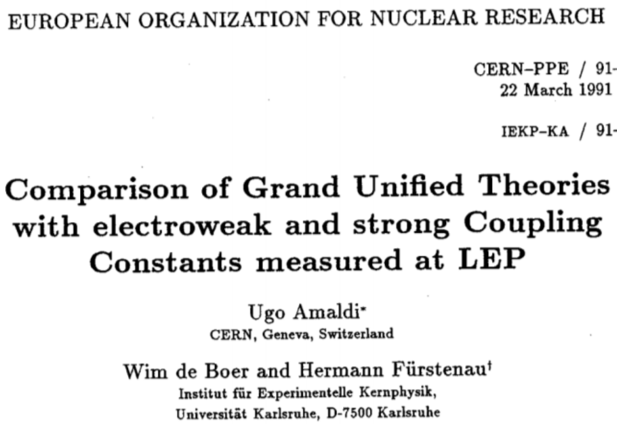
SUSY and gauge unification of interactions

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

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



10^{14} energy (GeV)



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

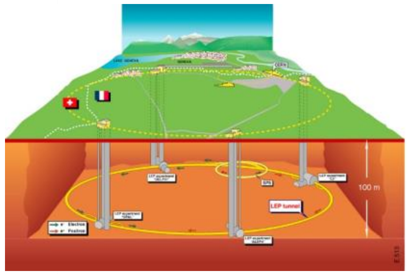
CERN–PPE / 91–44
22 March 1991

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



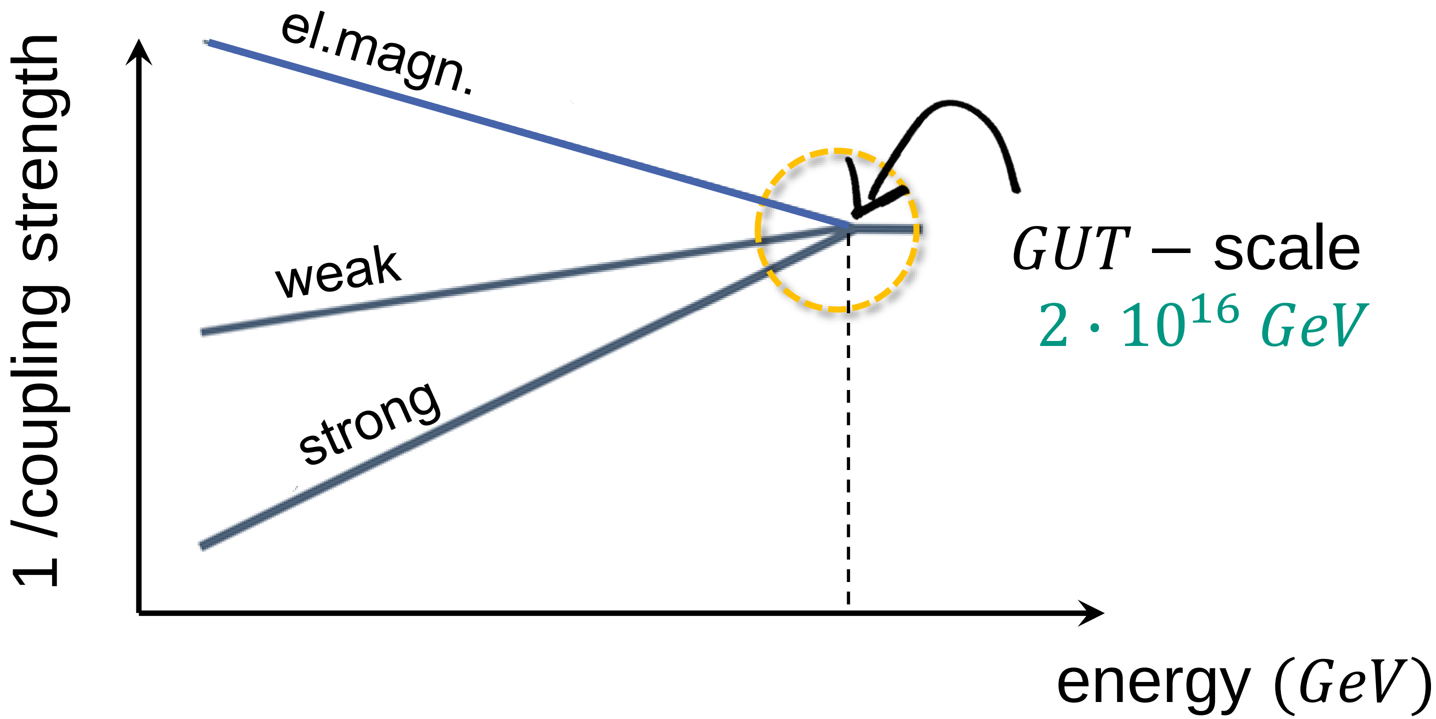
W. De Boer (KIT)

U. Amaldi

$SUSY$ and gauge unification of interactions

- **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

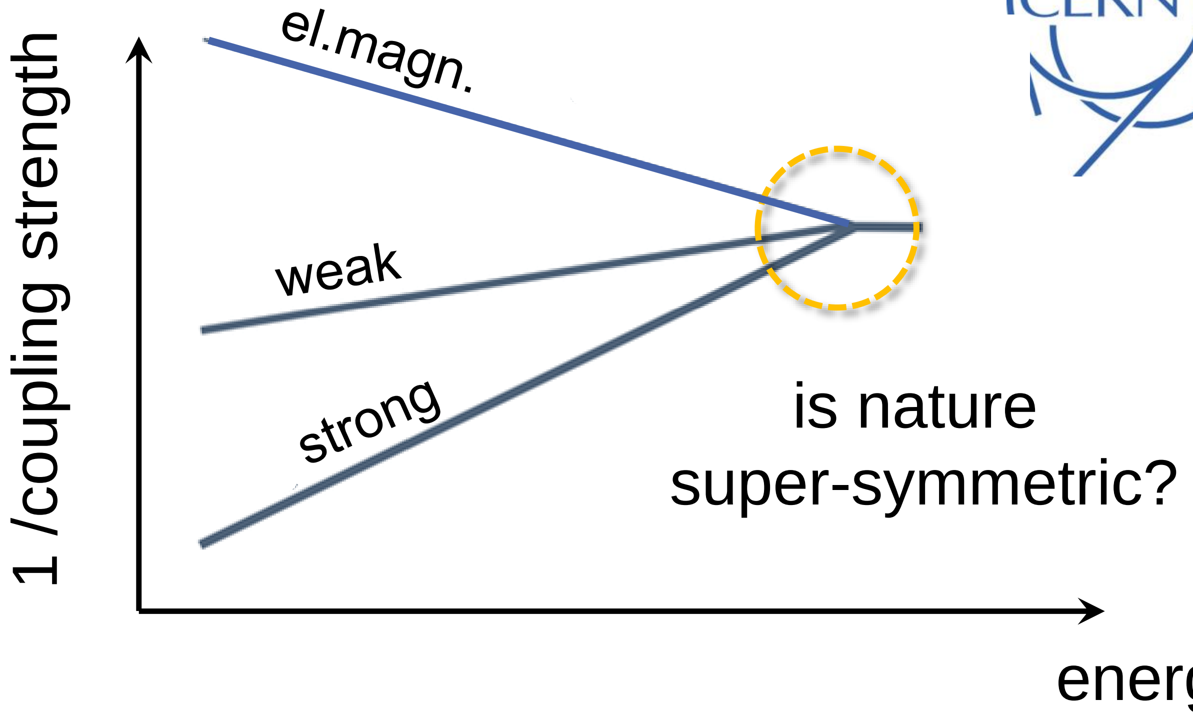
W. De Boer (KIT)

U. Amaldi

$SUSY$ and experimental verification at the LHC

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

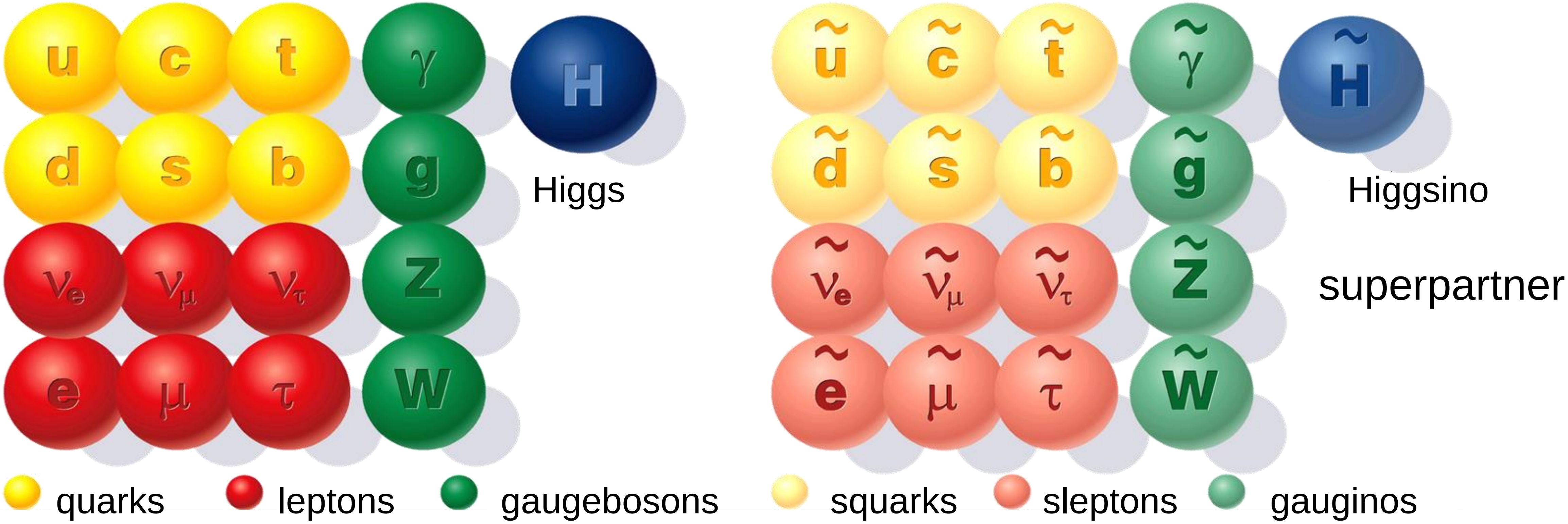
  - search for $SUSY$ – superpartners at the TeV −scale in pp – collisions



$SUSY$: a closer look at the superpartner properties

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

- search for $\boldsymbol{SUSY}$ – superpartners at the TeV –scale in pp –collisions



$SUSY$: a closer look at the superpartner properties

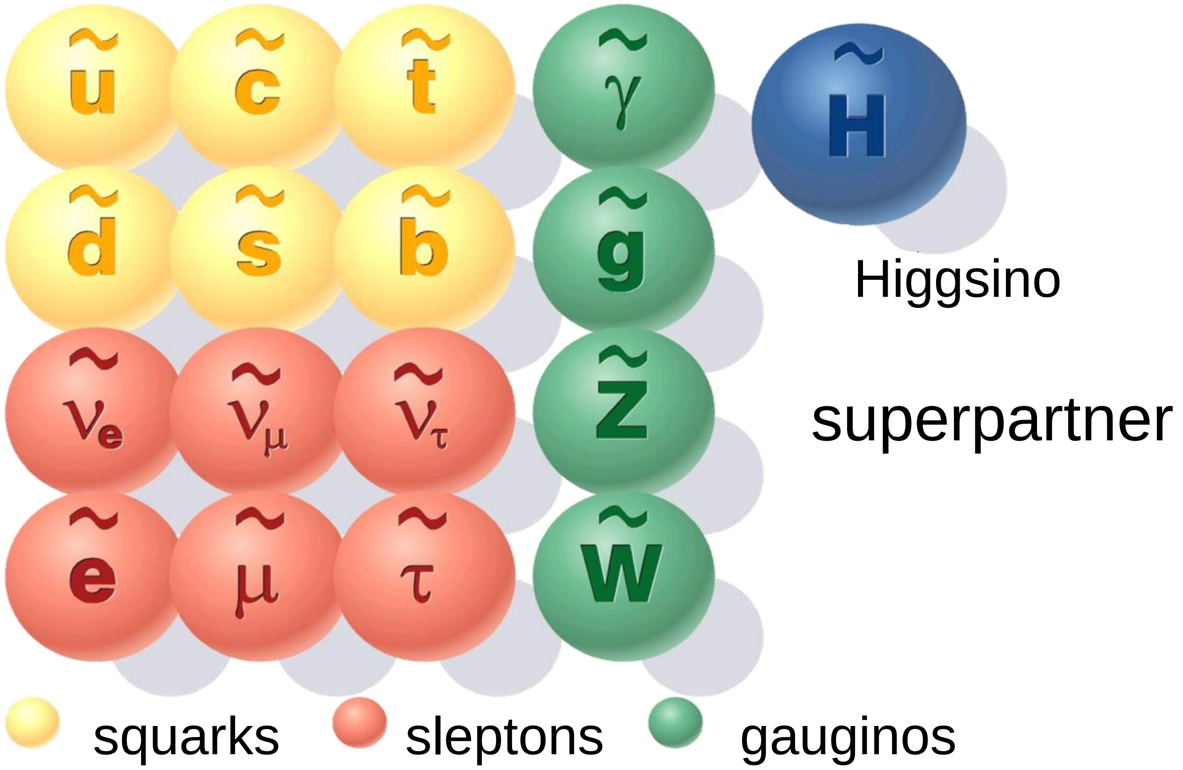
- **Building a viable DM-candidate from $SUSY$ –particles: a how-to approach**

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

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

- **sleptons**: identical electromagnetic interaction as leptons $\boldsymbol{e, \mu, \tau}$

- **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

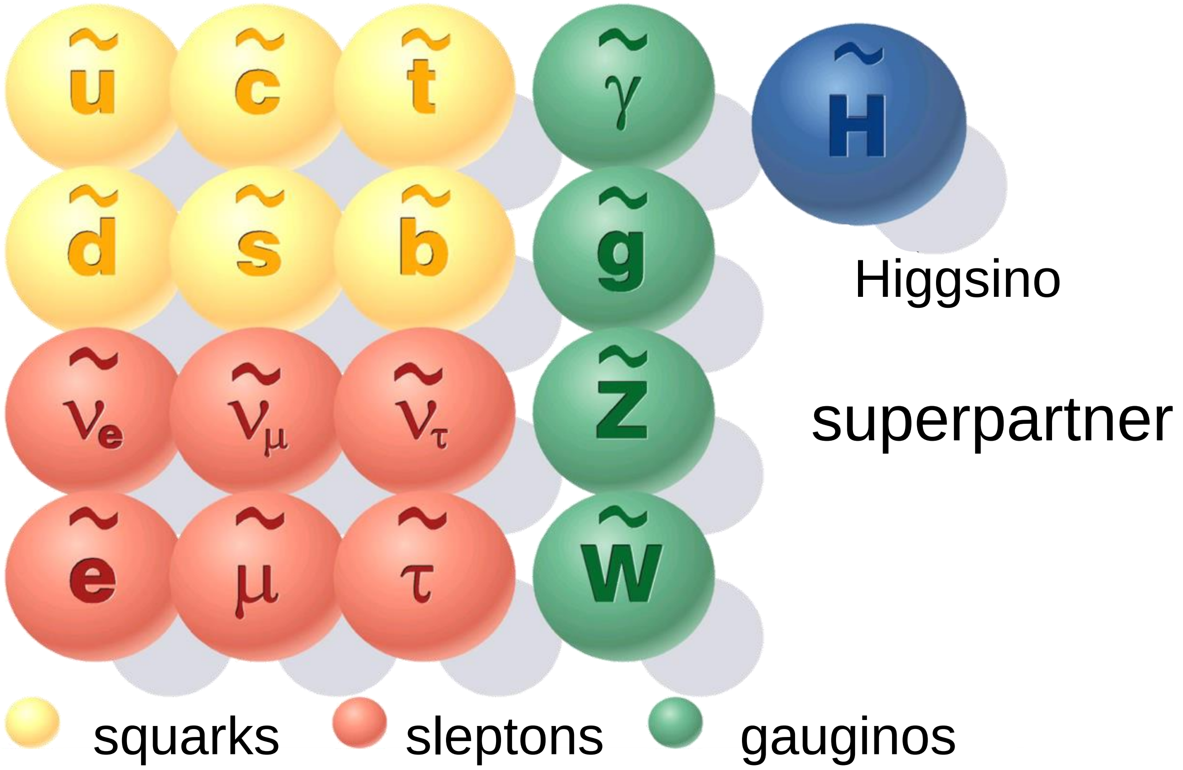
- **Building a viable DM-candidate from $SUSY$ −particles: a how-to approach**

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

- minimal extension of new particles & interaction

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

- $SUSY$ − masses of $MSSM$ expected in **range $\boldsymbol{M = 0.1 \ldots 1\ TeV}$** but: no signal at LHC so far…



$SUSY$: 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

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

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

B: baryon number L: lepton number S: spin

  - $SM-$ particles: $R_P = +1$ (even) - $SUSY-$ particles: $R_P = -1$ (odd)

  - resulting superpartner properties:

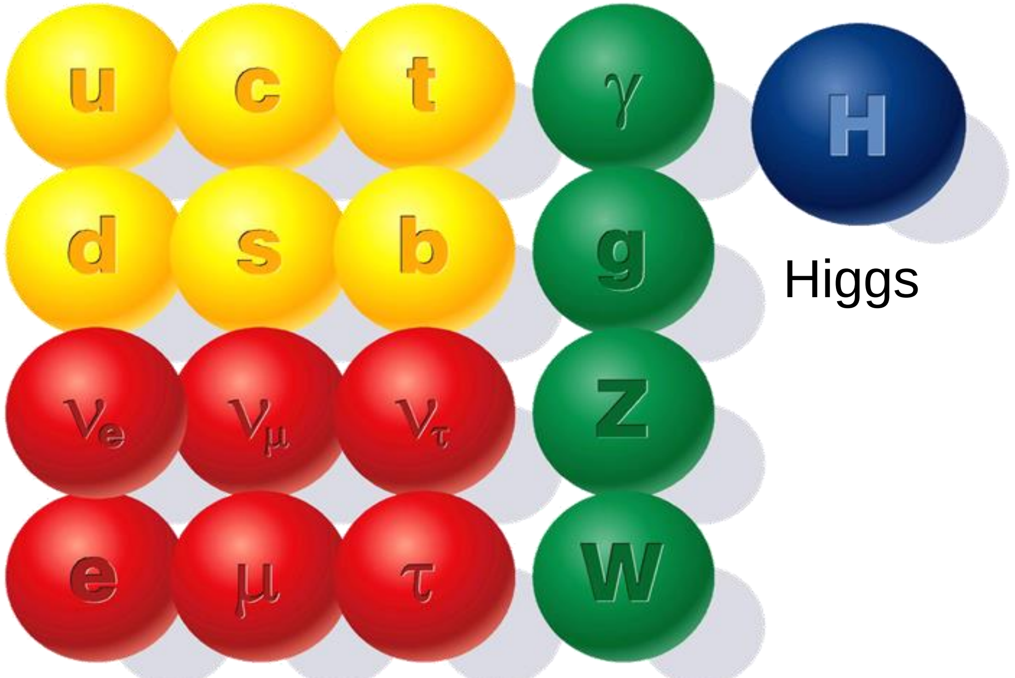
    a) production via $SM-$ particles: only $SUSY-$ **pairs** can be emitted

    b) $SUSY-$ superpartners only decay into superpartners (not $SM-$particles)

$SUSY$: important properties with view to DM

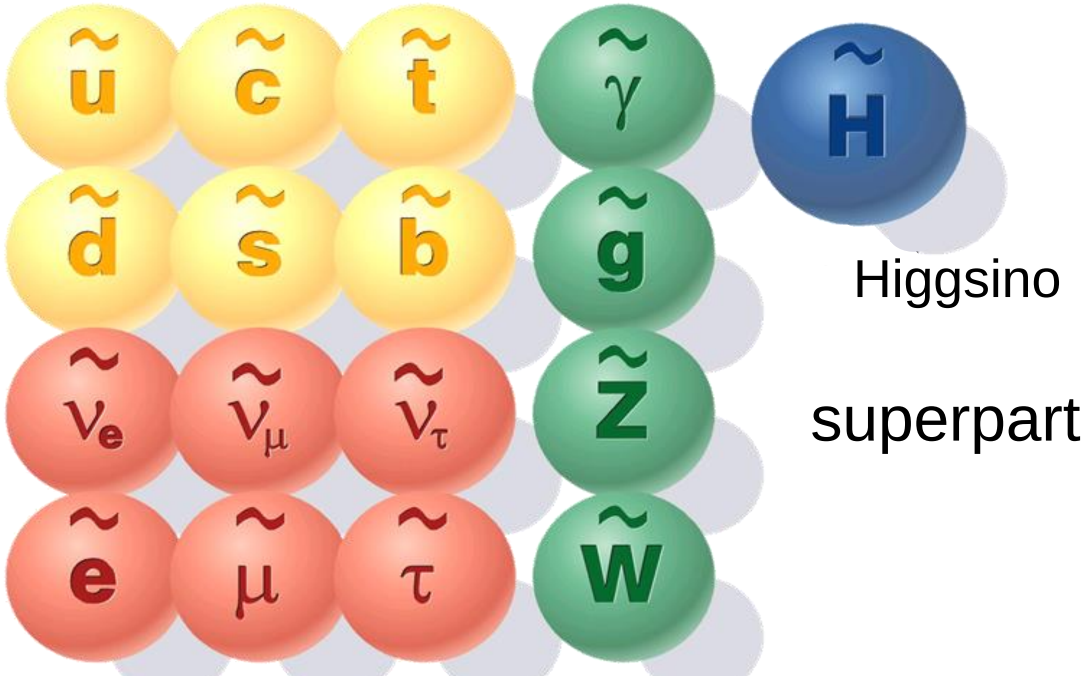
- $R-$ parity: a key property of $SUSY$ for DM & the stability of the proton p

- $SM-$ particles: $R_P = +1$ (even)



quarks leptons gaugebosons

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



superpartner

squarks sleptons gauginos

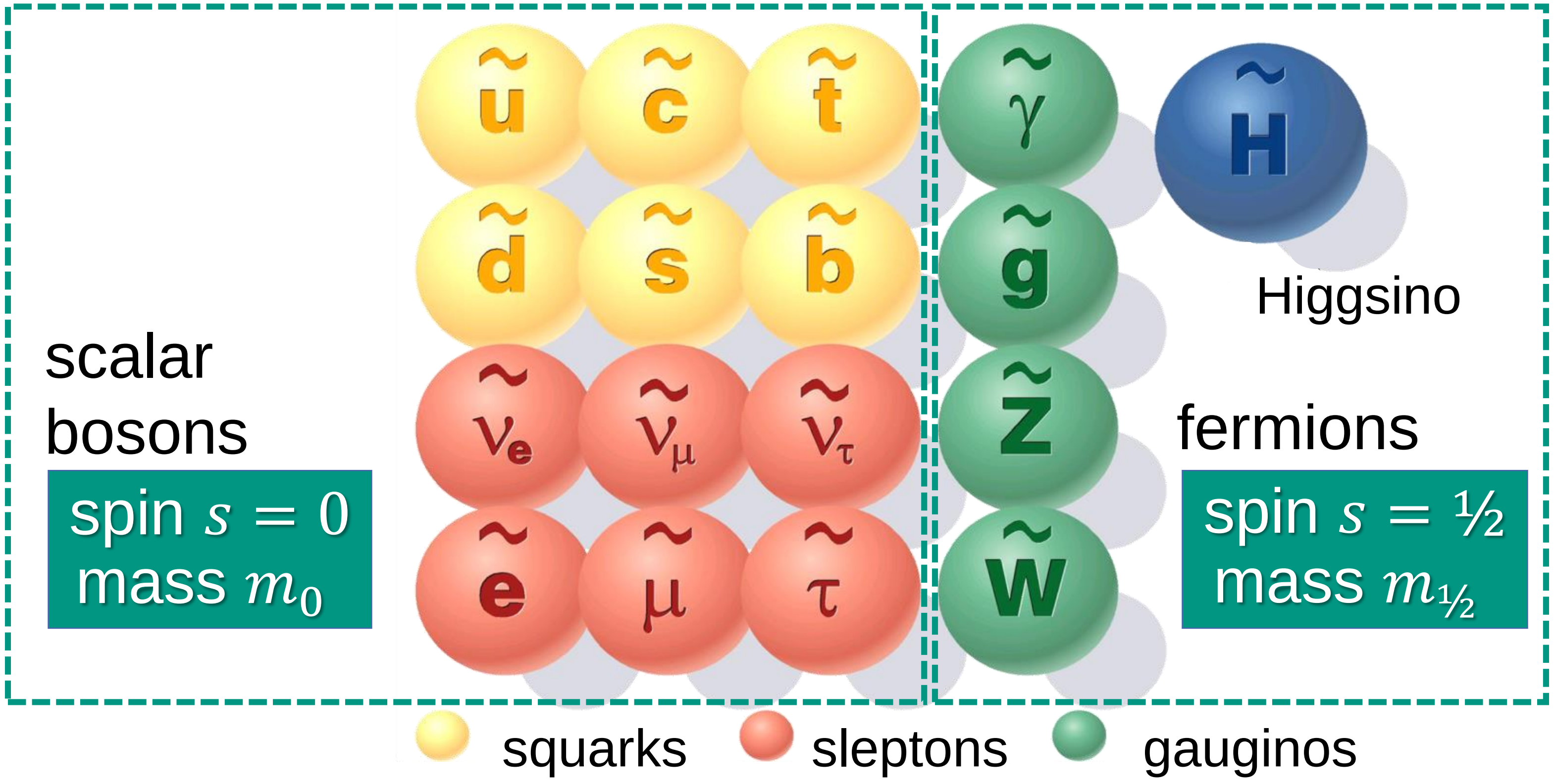
$SUSY$ and the constrained $MSSM$ ($cMSSM$)

- **$cMSSM$: 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 leptons* (charge)

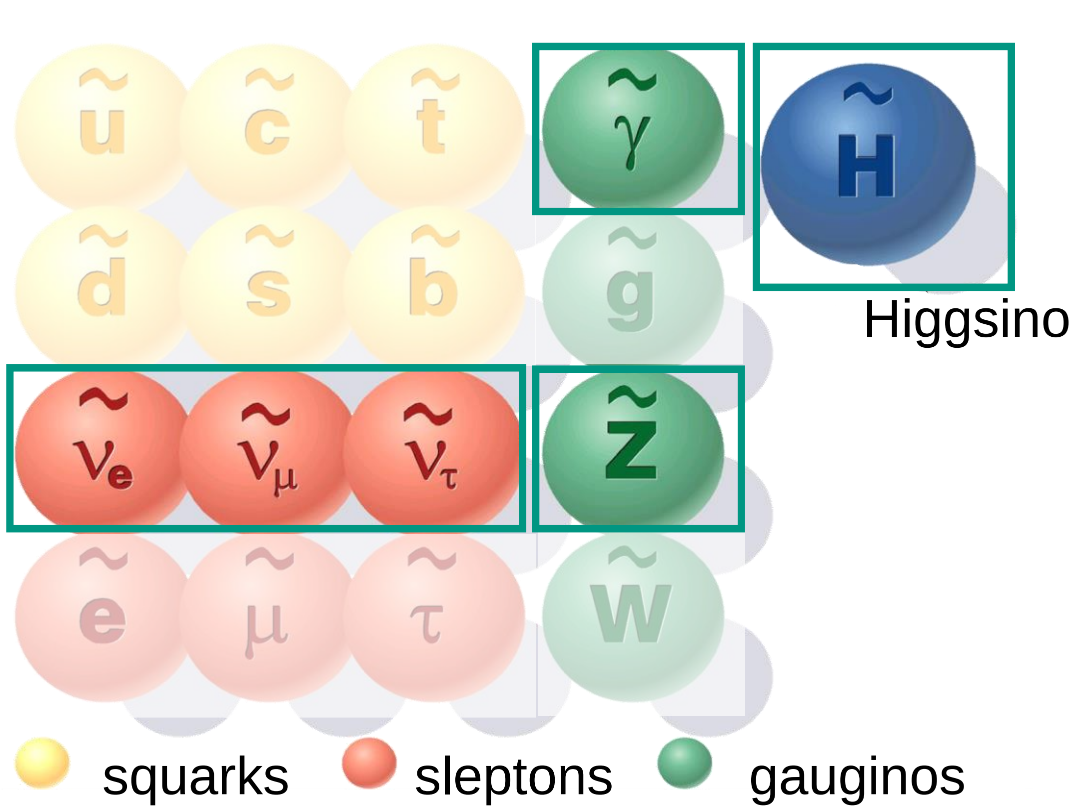
→ no *gluinos* (colour)

→ no *Winos* (charge)

- remaining DM-candidates:

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

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



$cMSSM$: a closer look at sneutrinos

Sneutrinos as superpartners of neutrinos: can they be a DM-candidate?

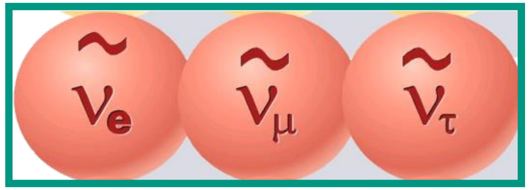
- neutral particles with weak interactions only ☑

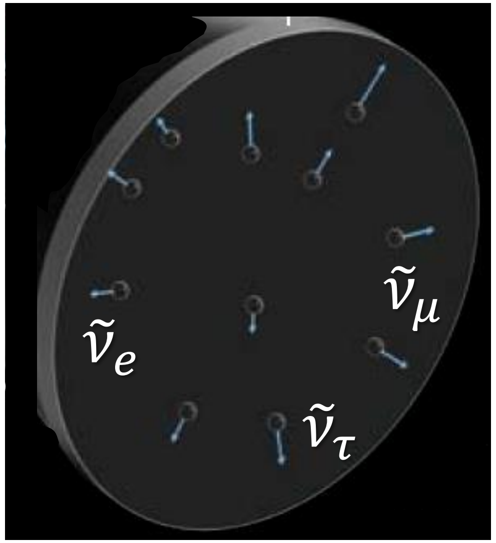
- heavy, scalar particles at the TeV – mass scale (CDM) ☑

- but: weak interaction rates are identical to the ones of ν´s ☒

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

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





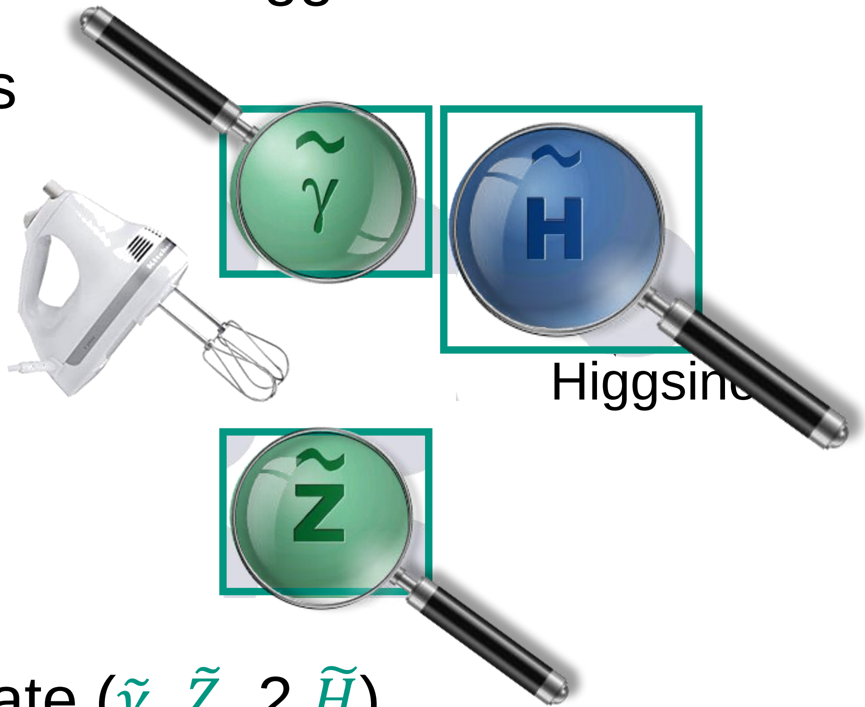
- lesson: **weak interaction rate** of a successful DM-candiate must be **significantly smal**ler than the one neutrinos!

$cMSSM$: a closer look at gauginos & Higgsinos

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

- we have 4 interaction eigenstates : 1 photino $\tilde{\gamma}$ 1 Zino $\tilde{Z}$ 2 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 4 flavour states photino $\tilde{\gamma}$, Zino $\tilde{Z}$ and the 2 Higgsinos $\tilde{H}$ to 4 mass eigenstates: neutralinos

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

$cMSSM$: an even closer look at Higgsinos

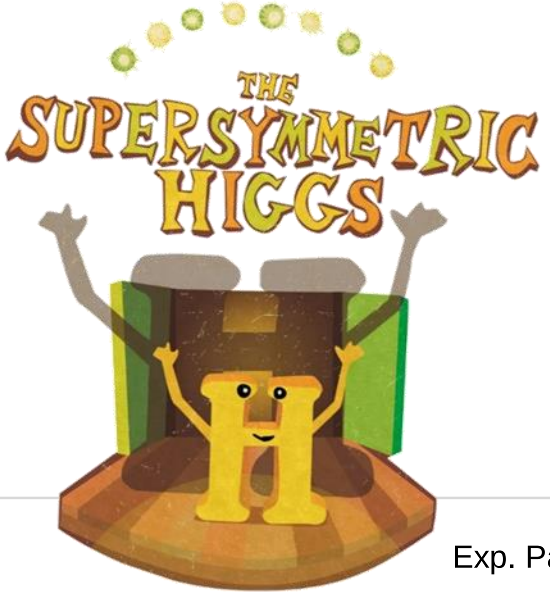
■ How many superpartners for the Higgs boson of the SM?

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

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

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

- for mixing to mass states we now have **4 states**:
  - photino $\boldsymbol{\tilde{\gamma}}$
  - Zino $\boldsymbol{\tilde{Z}}$
  - 2 Higgsinos $\boldsymbol{\tilde{H}_u^0}$ $\boldsymbol{\tilde{H}_d^0}$



$cMSSM$: a comparison of neutralinos & gauginos

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

- we have **4 flavour states**:

gauginos

photino $\tilde{\gamma}$

Zino $\tilde{Z}$

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

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

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

$\mathbf{4} \times \mathbf{4}$ 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 viable DM candidate

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

  - the **LSP** (**L**ightest **S**upersymmetric **P**article) is expected to be stable over cosmological time scales due to its intrinsic $\boldsymbol{R_P = -1}$

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

Neutralino: $\boxed{\tilde{\chi}_1^0 = c_1 \cdot \tilde{\gamma}^0 + c_2 \cdot \tilde{Z}^0 + c_3 \cdot \tilde{H}_u^0 + c_4 \cdot \tilde{H}_d^0}$ flavour states

Photino **Zino** **Higgsinos** (up, down)

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

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

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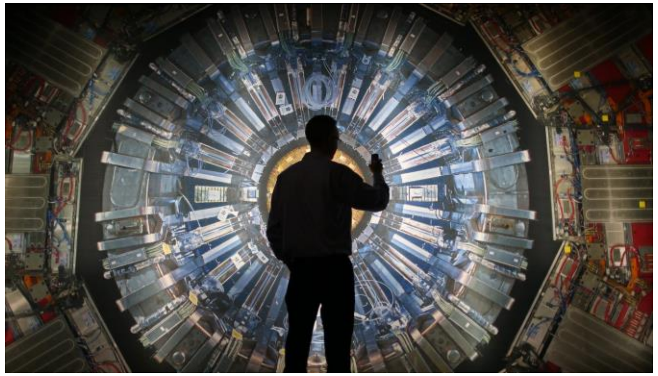
Properties of neutralinos & searches for $SUSY$ –WIMPs

- $SUSY$ 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**, **DM-detectors**

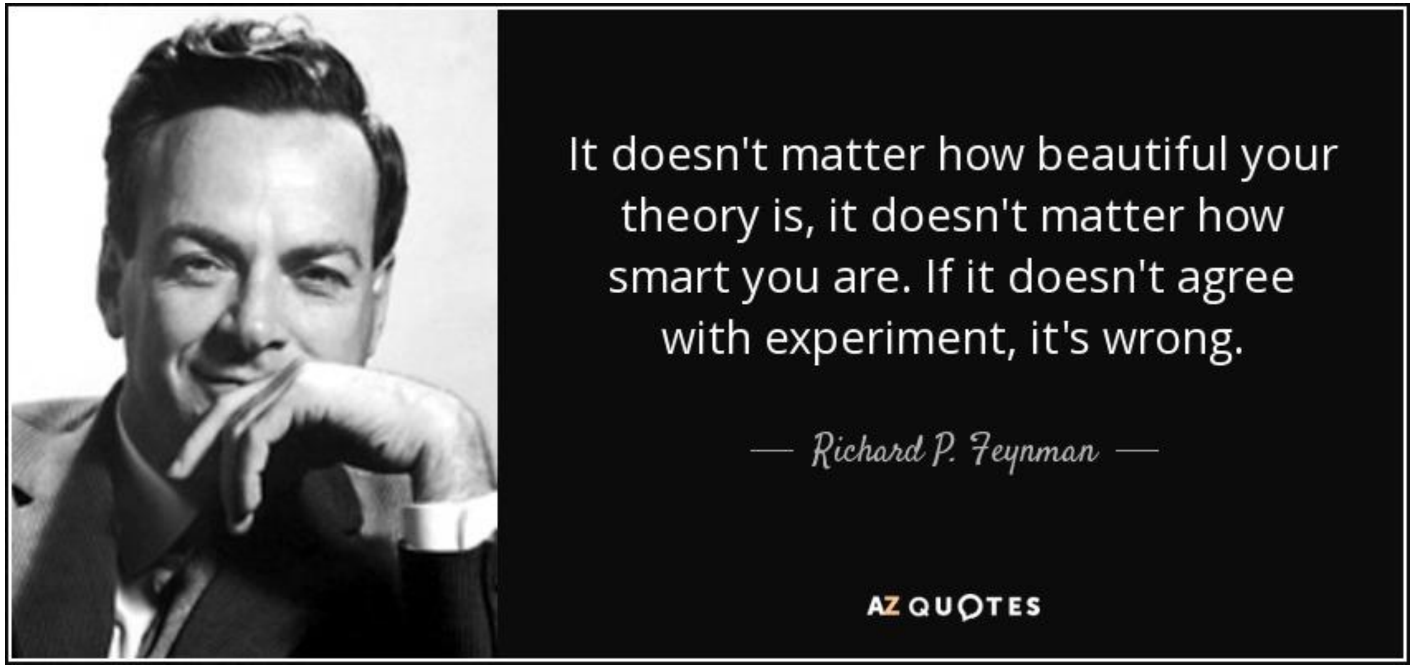


*see lecture #11, p. 27-29

Putting *SUSY* on the experimental testbed

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

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



Geprüfte **S**USY

Putting *SUSY* on the experimental testbed

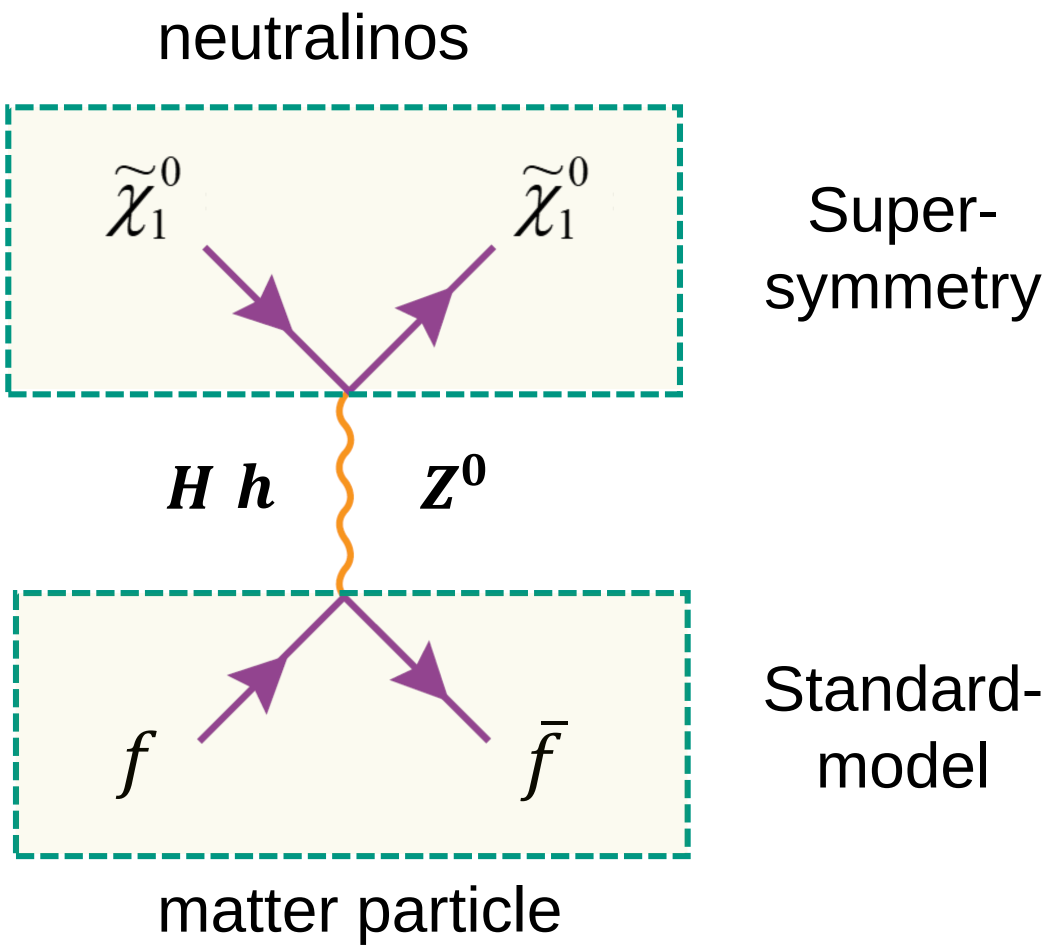
■ Feynman diagrams for WIMP interactions

- 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**)

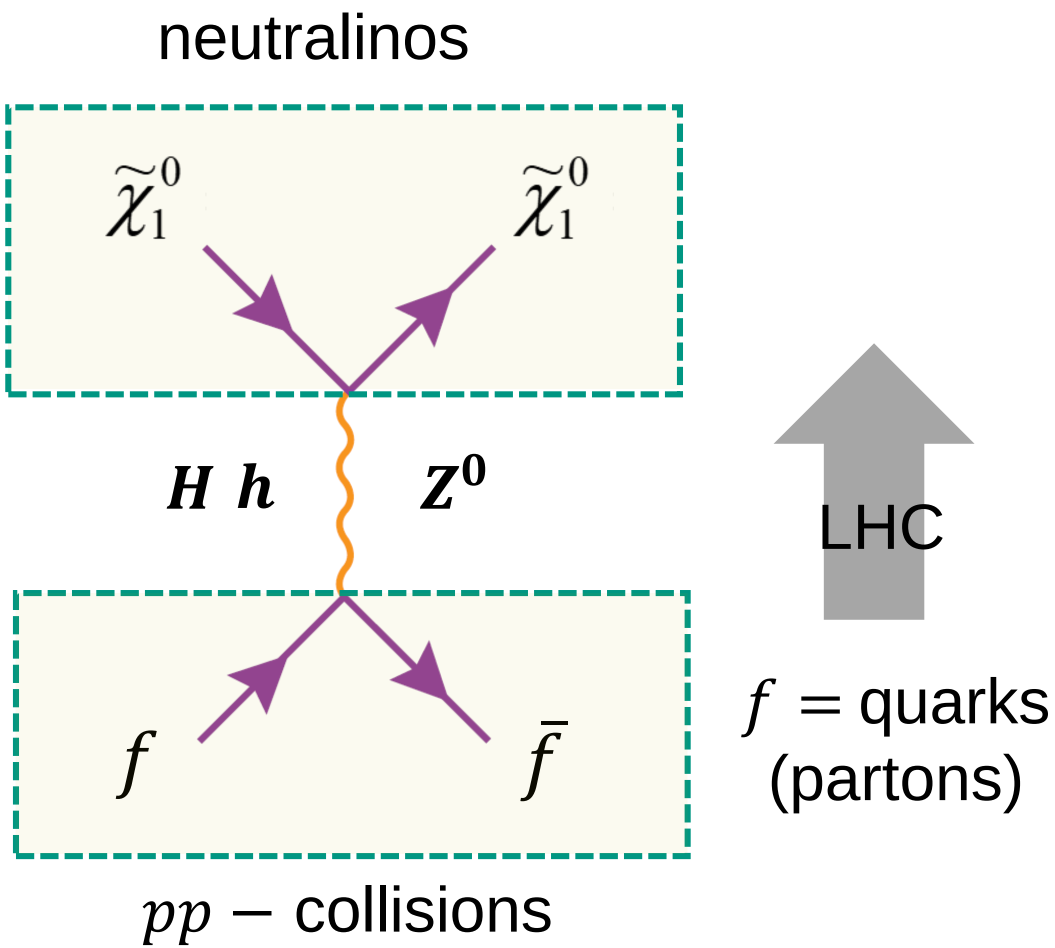
- relative coupling strengths unknown, but very small in both cases



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

- **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)



Putting *SUSY* on the testbed at the galactic halo

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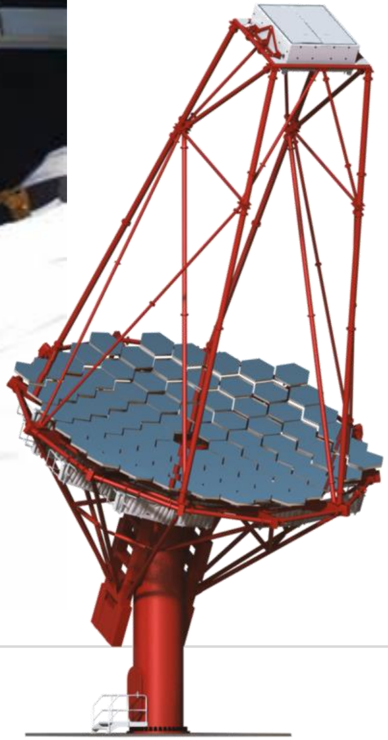
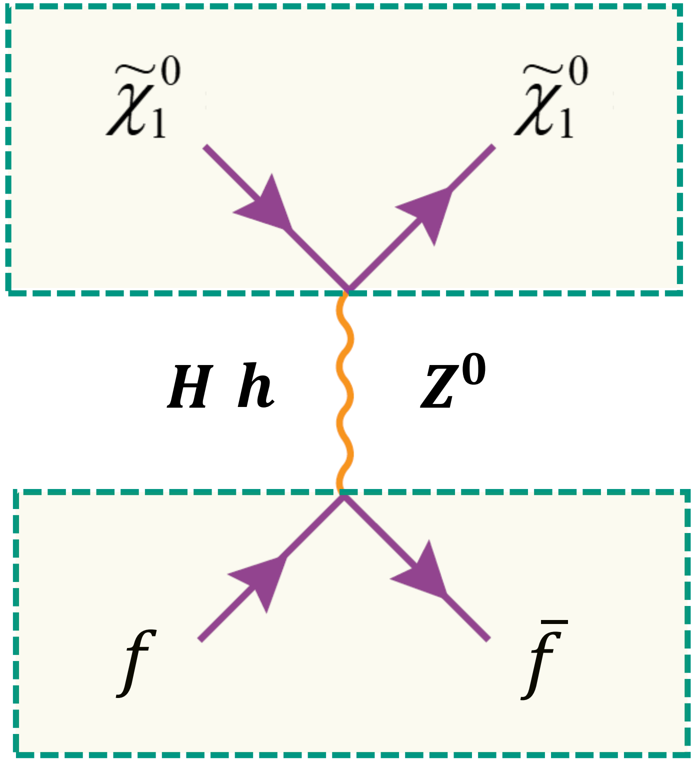
- **Feynman diagram for WIMP annihilation at the center of the galaxy**

  - **indirect searches** for the annihilation reactions of neutralinos at the inner part of the galactic halo (chapter 4.4)



neutralinos



$GeV - TeV -$ energies

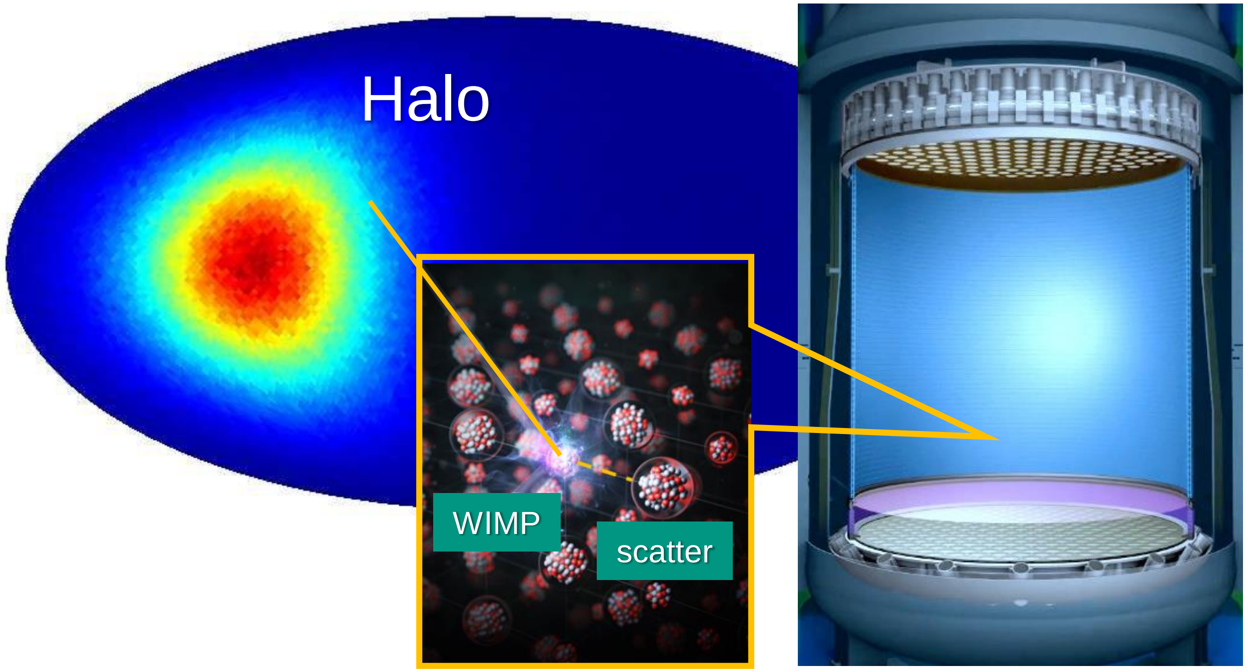
galactic halo

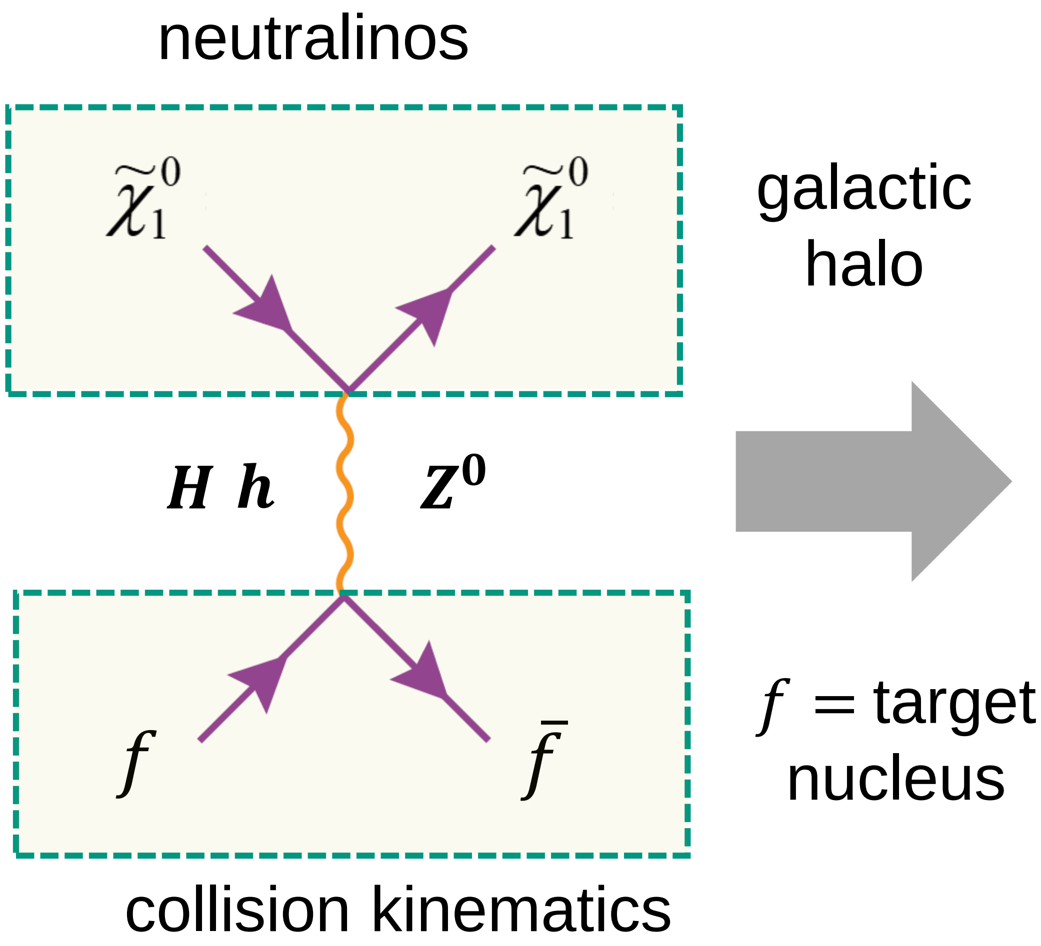
$f =$ multi-messengers

Putting *SUSY* on the testbed at a DM detector

- Feynman diagram for WIMP scattering in an underground DM-detector

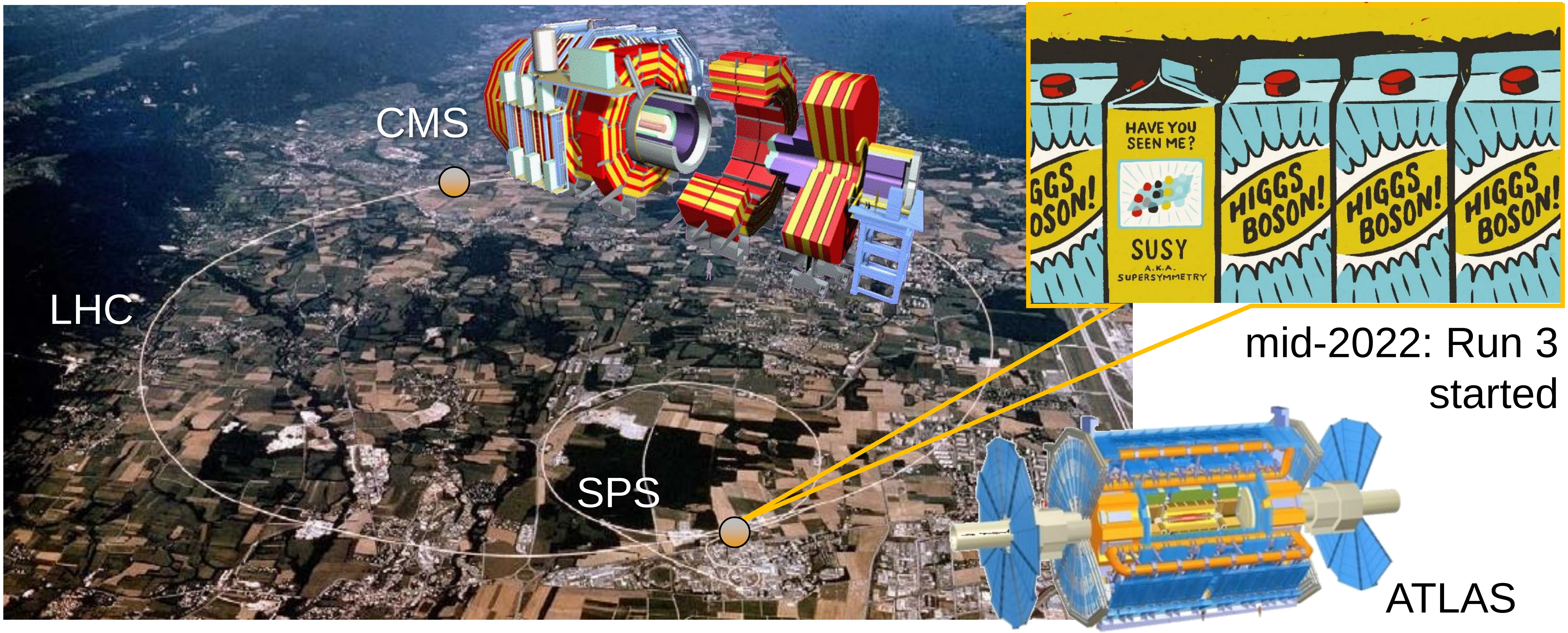
  - direct searches for elastic scattering processes of neutralinos at large DM detectors (chapter 4.5)





4.3 WIMP search at the LHC

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



mid-2022: Run 3 started

RCAP: LHC beam parameters

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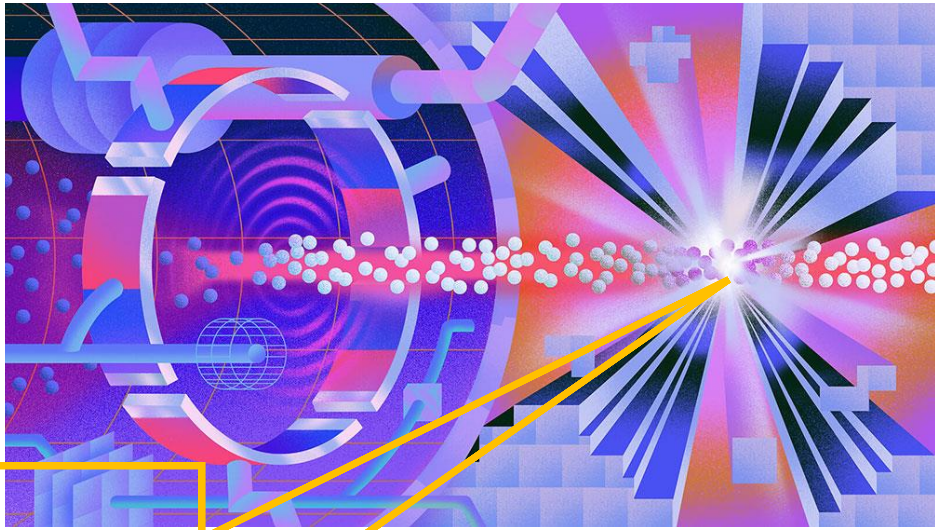
- **Search for rare $SUSY$ – events is boosted by high collider luminosity L**

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

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



  - how to calculate the **luminosity L** from a beam:

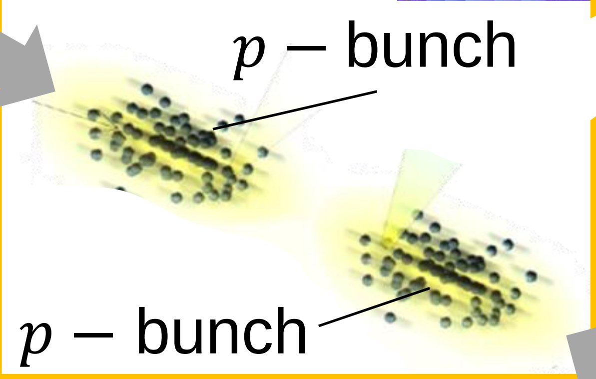
$$\boxed{L = f \cdot n \cdot \frac{N^2}{4\pi \cdot \sigma_b^2}}$$

f: frequency

n: # bunches

N: #p / bunch

σ_b: transversal beam size



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

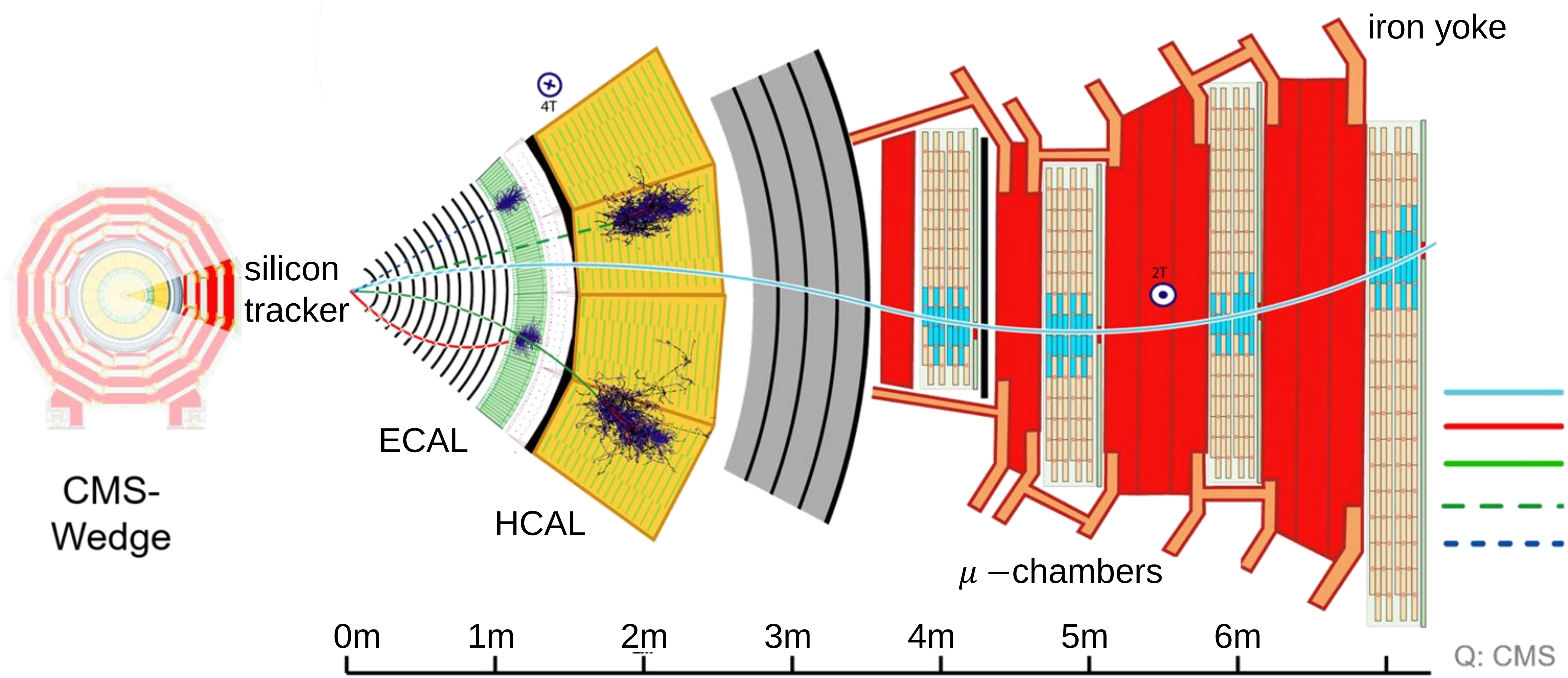
R: rate

σ: cross section

L: lumi

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