Chapter 2

Finding the underlying symmetries behind the fundamental components of matter

Theory

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Workshop Strategic Theme 9

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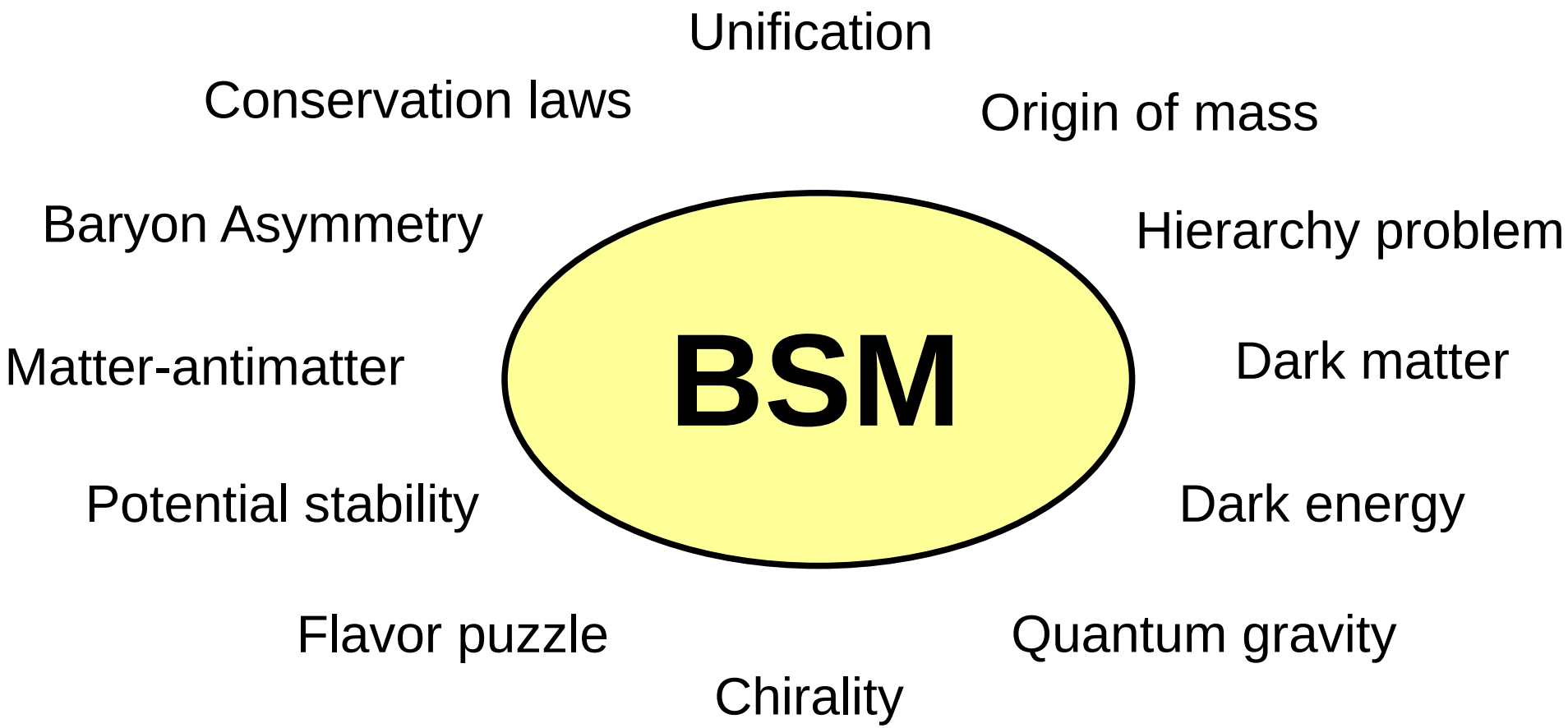
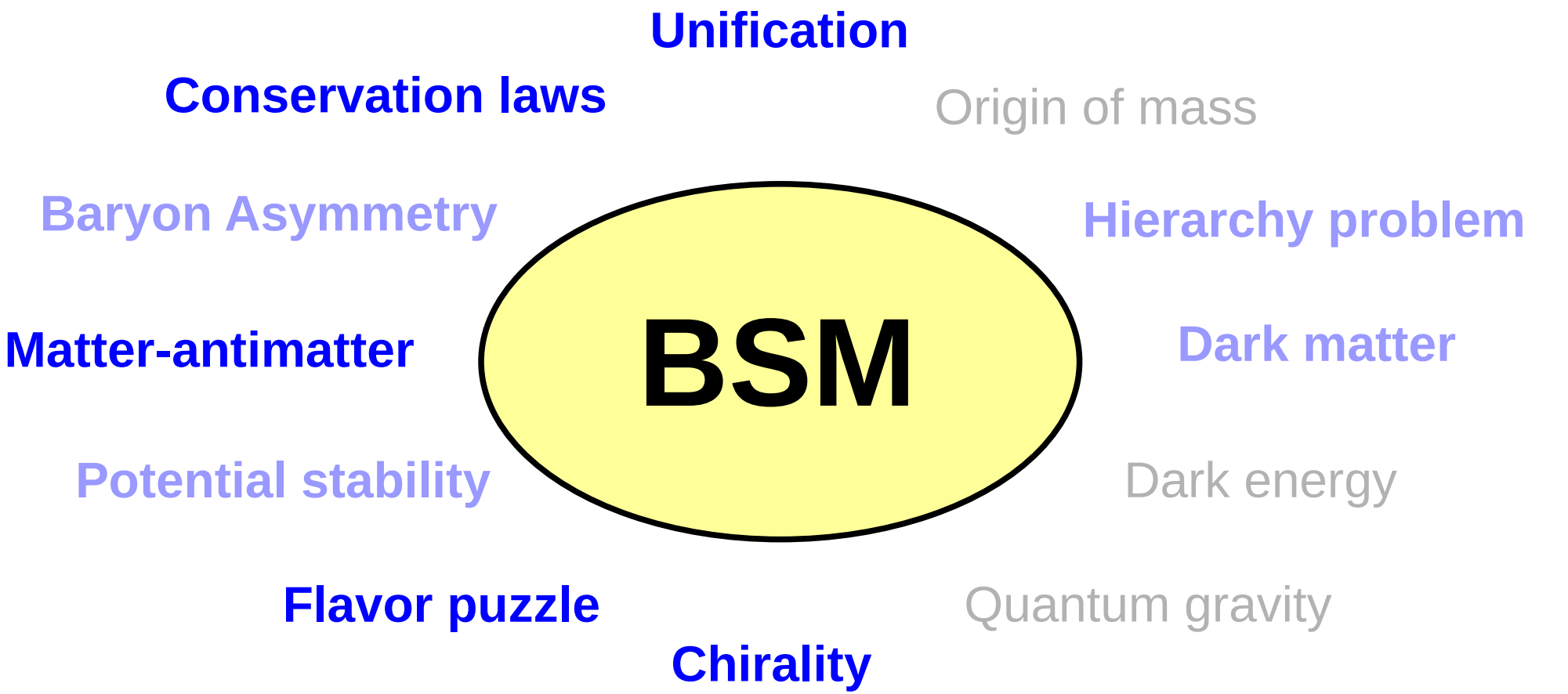
Consejo Superior de Investigaciones Científicas

Beyond the Standard Model



Beyond the Standard Model



The challenge

Possibly some of these questions are connected and their resolution is related to underlying symmetries

Gauge symmetry

Space-time symmetry

Flavor symmetry

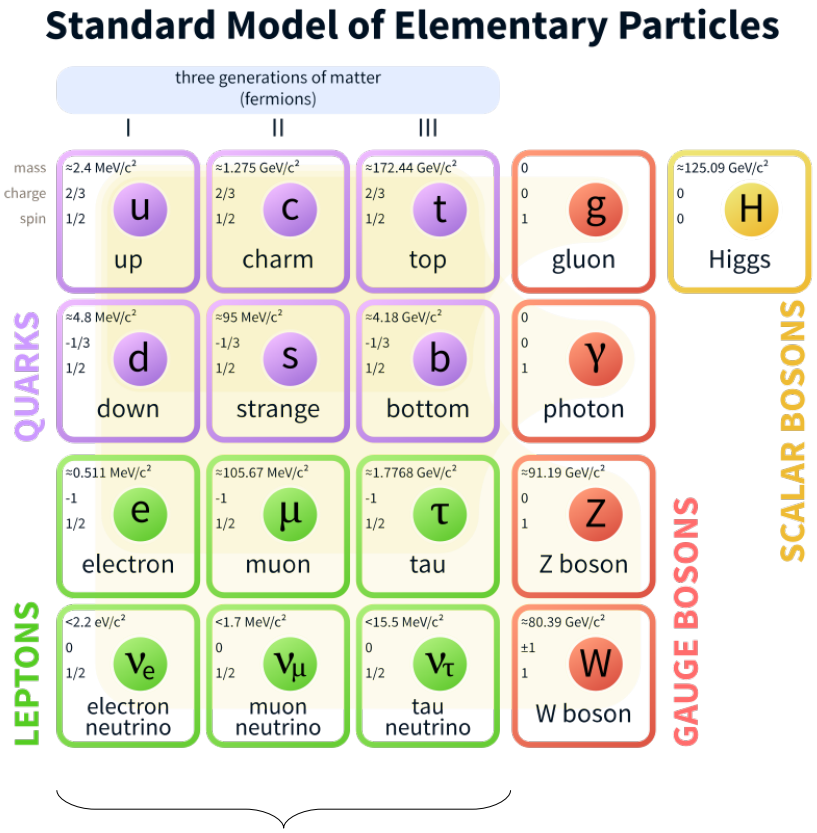
Global symmetries

Discrete symmetries

...

Example: the breaking of lepton number could be related to both the origin of neutrino masses and the baryon asymmetry of the universe (via leptogenesis or otherwise)

The flavor puzzle



3 replicas

Mass & mixing pattern

The fermionic components of matter display an intriguing family structure that is not yet understood

- **Why are there 3 fermion families?**
- **What is the origin of their mass and mixing patterns?**

→ Chapter 1

The flavor puzzle

The flavour puzzle is an intriguing fundamental question and thus a clear area of research in particle physics.

However...

- **We still do not have a convincing or preferred theoretical framework to explain it**
- **We still do not have experimental hints, apart from exclusion limits**

The flavor puzzle and...

Actually, a similar situation occurs for other fundamental questions:

Nature of dark matter	Chapters 4 & 7
Origin of neutrino masses	Chapter 1
Baryon asymmetry of the universe	Chapter 4
...	

It is essential to keep acquiring experimental data. In the absence of clear theoretical hints, experimental constraints (and hopefully potential signals) are crucial to guide the theoretical research.

The flavor puzzle and...

Two basic approaches for the theoretical research:

- **Bottom-up.** Work with a generic (SM)EFT and find constraints and preferred regions on EFT parameters. This may give in turn hints on the underlying theory.

- **Top-down.** Build consistent (UV complete) models, e.g. Inspired in GUT or string symmetries.

→ Chapter 9

The flavor puzzle and...

Bottom-up  **Top-down**

Both approaches are complementary

- The bottom-up approach is more appropriate to study the impact of the experimental constraints in the absence of a preferred theoretical framework. Precise and reliable theoretical predictions are required.

  → Chapter 3

- The top-down approach is appropriate to look for connections between the various fundamental questions: flavor puzzle, dark matter, BAU, ν-masses, etc.

  → Chapters 1 & 4

The flavor puzzle and...

Examples of recents directions:

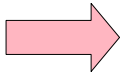
- Consider (string-inspired) modular symmetries to describe the structure of fermionic masses and mixing angles
- Connection to spontaneously-broken CP
- Models of QCD-axions free from the usual axion coupling/mass relation
- Construction and exploration of axion-EFTs
- Models addressing two or several questions at the same time
- Heavy neutral leptons (~ sterile neutrinos)

The flavor puzzle and...

Besides, it is essential to think of new ideas to e.g. detect axions and other types of dark matter. This effort is both experimental and theoretical.

In recent times new ideas are arising, e.g.

- Different types od cavity (axion) resonators
- Search for oscillating nuclear EDMs
- Solid-state detectors for very light DM (based on phonon production)
- Astrophysical hints (e.g. DM in neutron stars or white dwarfs)



Chapters
8 & 10

Chirality, symmetry and unification

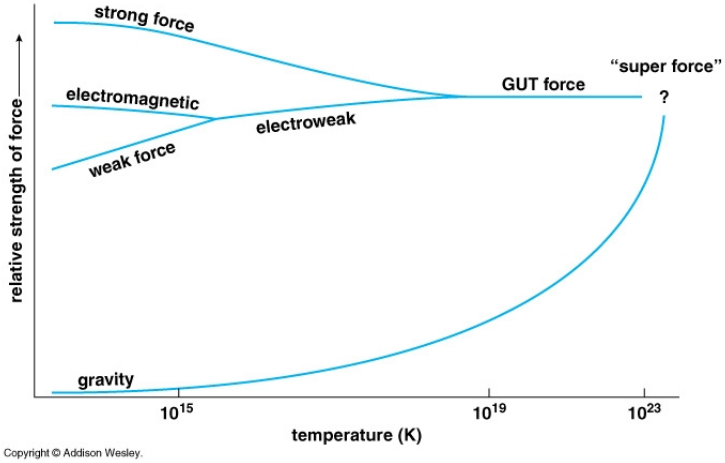
- **Why are the SM gauge interactions chiral?**
- **Can the SM be embedded in a larger symmetry group? Perhaps with left and right fermionic sectors? Addressing other open questions?**

Extended symmetry groups may explain the chirality of the SM interactions (left-right models), the number of fermion families (331 models), dark matter stability (parities), the origin of baryon and lepton numbers (local symmetries) ...

→ High-energy (LHC) phenomenology

- **Do all the SM gauge interactions unify at very high energies? Does supersymmetry play role in this unification?**
- **Can gravity be merged in a consistent theoretical framework?**

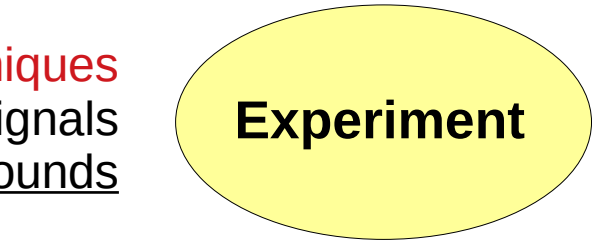
Deep origin of the SM interactions and the forces of Nature



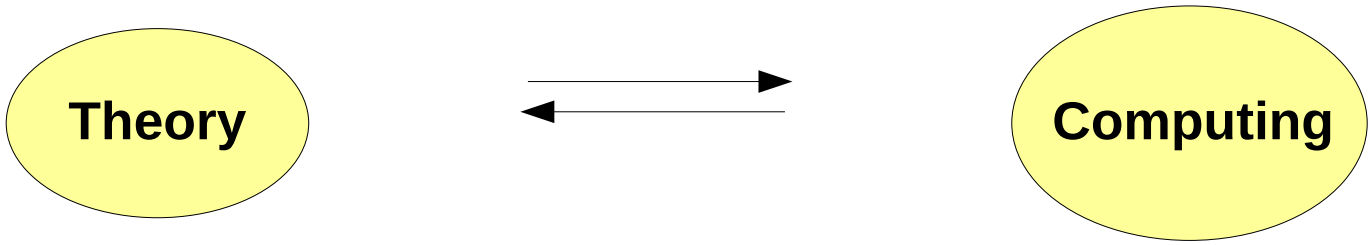
Multidisciplinarity

This challenge requires a multidisciplinary approach

New data-taking techniques to pin down small signals from huge backgrounds



The (possible) violation of certain symmetries is expected to be tiny, hence leading to very small rates for the associated processes (lepton flavor violation, proton decay, neutrinoless double beta decay...)



The most advanced theoretical tools: model building & phenomenology

Powerful computing resources both for data analysis as well as for theoretical calculations and simulations

Strategic plan

- **Flavor experiments:**
  Consolidate CSIC's position in LHCb and Belle II & support theory groups
- **Higgs, top, CP & flavor:**
  Maintain CSIC's leading role in ATLAS and CMS
- **Search for new symmetries:**
  Pursue new theoretical lines of research
- **Axion physics:**
  Reinforce theory groups
- **Machine-learning techniques:**
  Upgrade computing facilities and establish knowledge-sharing platforms
- **Underlying mathematical structure:**
  Reinforce CSIC's position and establish external collaborations

Resources

Maintain CSIC's current strategic position and support its participation in experimental collaborations with the required funding

- Collaboration fees, regular visits and hardware expenses

Be actively involved in the ongoing discussions about the future of particle physics

- Participation in meetings and invitation of international experts

Reinforce theoretical and experimental groups

- New permanent, postdoctoral and PhD positions

Promote interactions with the international community

- Host meetings and fund visits

Thanks to:

Guillermo Ballesteros, IFT-CSIC/UAM

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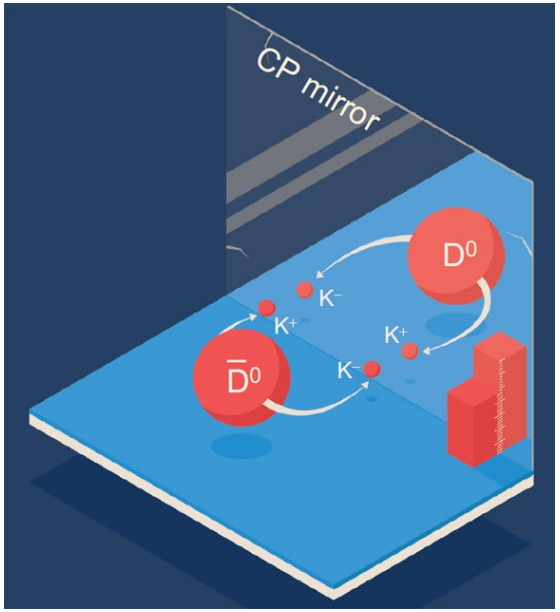
Sven Heinemeyer, IFT-CSIC/UAM

....

Backup slides

Other open questions

How are matter and antimatter related?



Related to the baryon asymmetry problem, but completely different question: what is the fundamental difference between matter and antimatter?

Discrete symmetries: C & P, CP, CPT

With two fermion families, CP remains conserved, while three families allow for CP violation

→ Possible relation to the flavor puzzle

Is CP broken in the strong interactions?

→ Possible relation to the dark matter problem: the axion

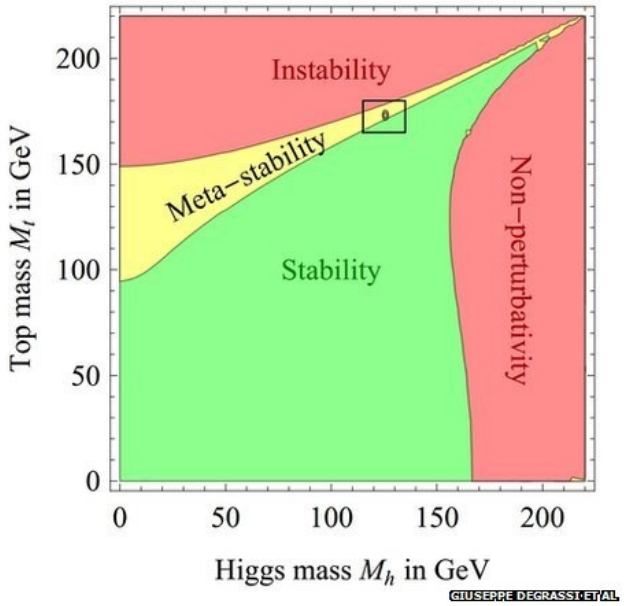
CPT theorem: CP violation implies T (time reversal) violation

Is CPT an exact symmetry? → Lorentz symmetry

Other open questions

What sets the electroweak scale? Is there a hierarchy problem? Can it be cured with new symmetries (supersymmetry) or space-time dimensions?

Profound implications for the other open issues of the SM: origin of mass, flavor puzzle, dark matter, ...



Is the Higgs potential completely stable? Do new symmetries/dynamics play a role in its stabilization at high energies?

New dynamics (perhaps related to the flavor puzzle?) would alter the shape of the Higgs potential