FROM BOTTOM-UP TO TOP-DOWN: THE RÔLE OF SYMMETRIES IN FLAVOR PHYSICS

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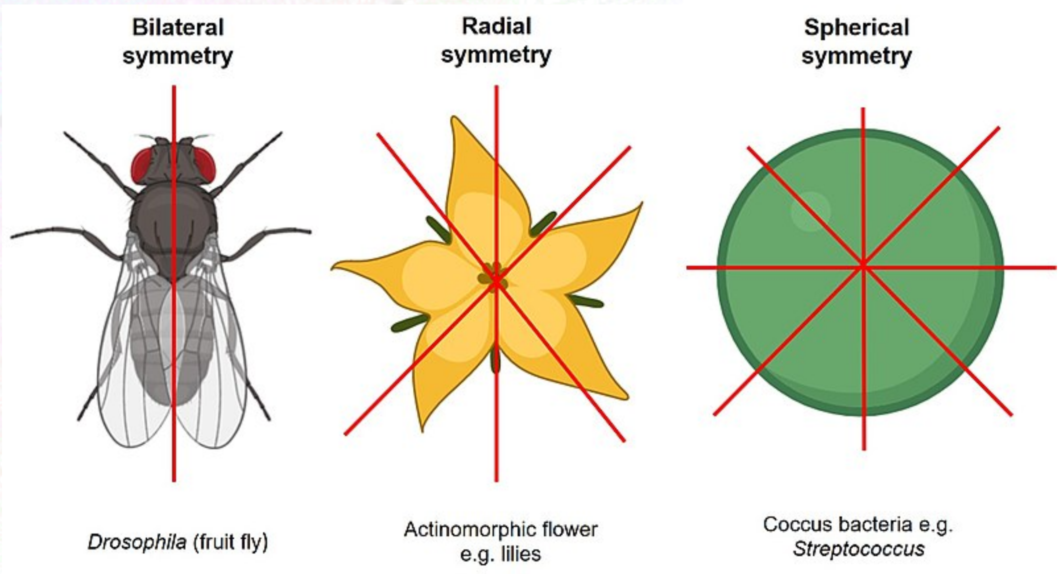
SYMMETRIES

Standard Model built on symmetries: exact or broken

- Space-time symmetries: rotations, translations, Lorenz and Poincaré transformations
- Internal symmetries: transformation of the fields in the theory → gauge symmetries
- Global → spacetime momentum, angular momentum, spin
- Local → gauge symmetries
- Continuous symmetries→ conserved quantities
  - rotational symmetry angular momentum conservation
  - translational symmetry momentum and energy conservation
- Discrete → charge and parity conjugation CP

- Label and classify particles
- Determine interactions among particles → they must respect the symmetries
- Exact, broken, a little bit broken (softly), hidden



WHY GO BEYOND?

- The hierarchy problem
- Neutrino masses
- All masses
- Origin of gauge interactions
- Dark matter
- Matter over anti-matter abundance
- Cosmological constant
- Inflation
- …

Higgs sector not natural

Fermion masses vastly different

Origin of electroweak symmetry breaking unknown

Dirac or Majorana neutrinos

Strong CP problem

Not enough CP in SM for Baryogengesis
Value of cosmological constant
Inflation inconsistent with non-zero baryon number
Is DM a particle, then which, is it only one

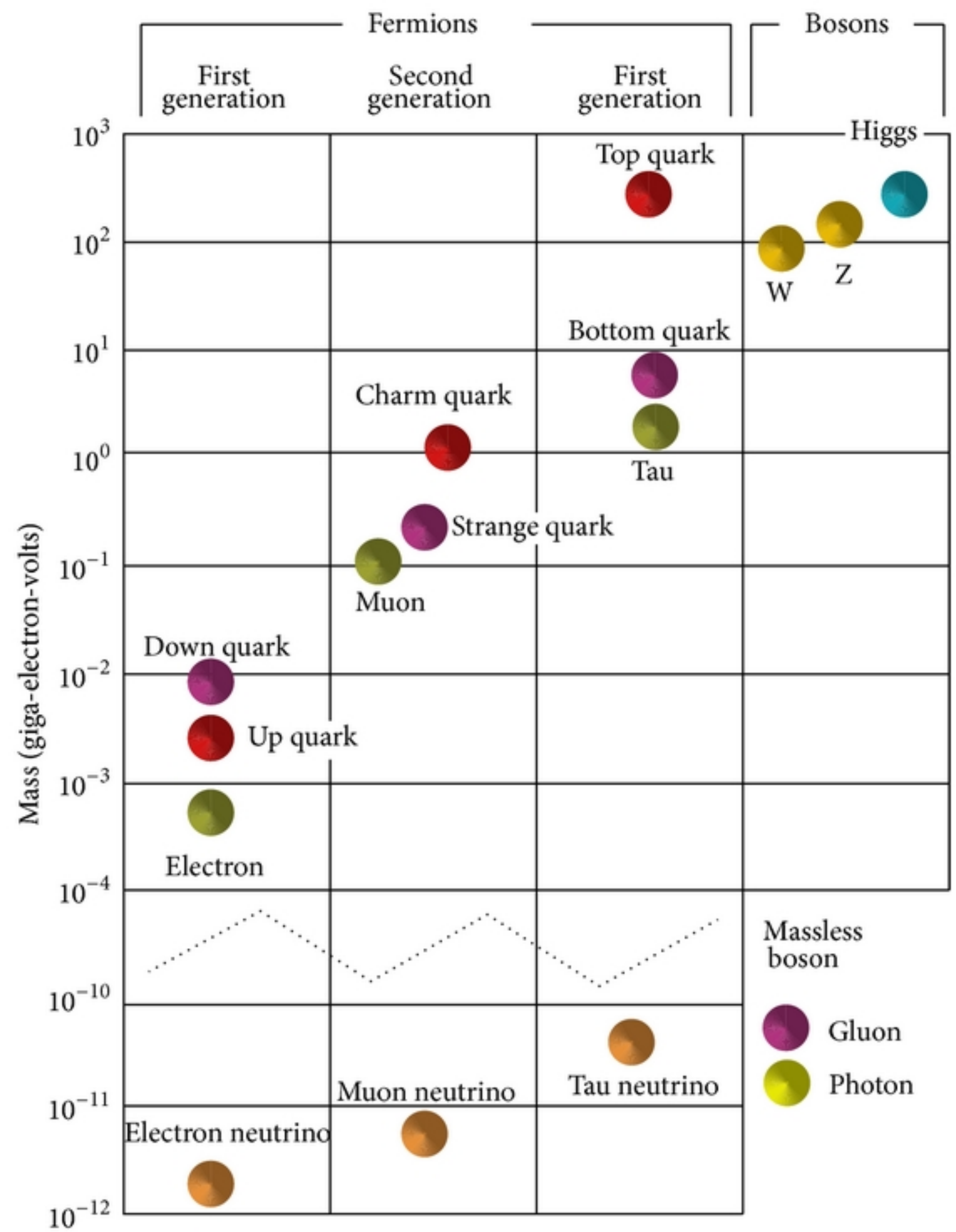
HOW TO GO BEYOND THE STANDARD MODEL (BSM)?

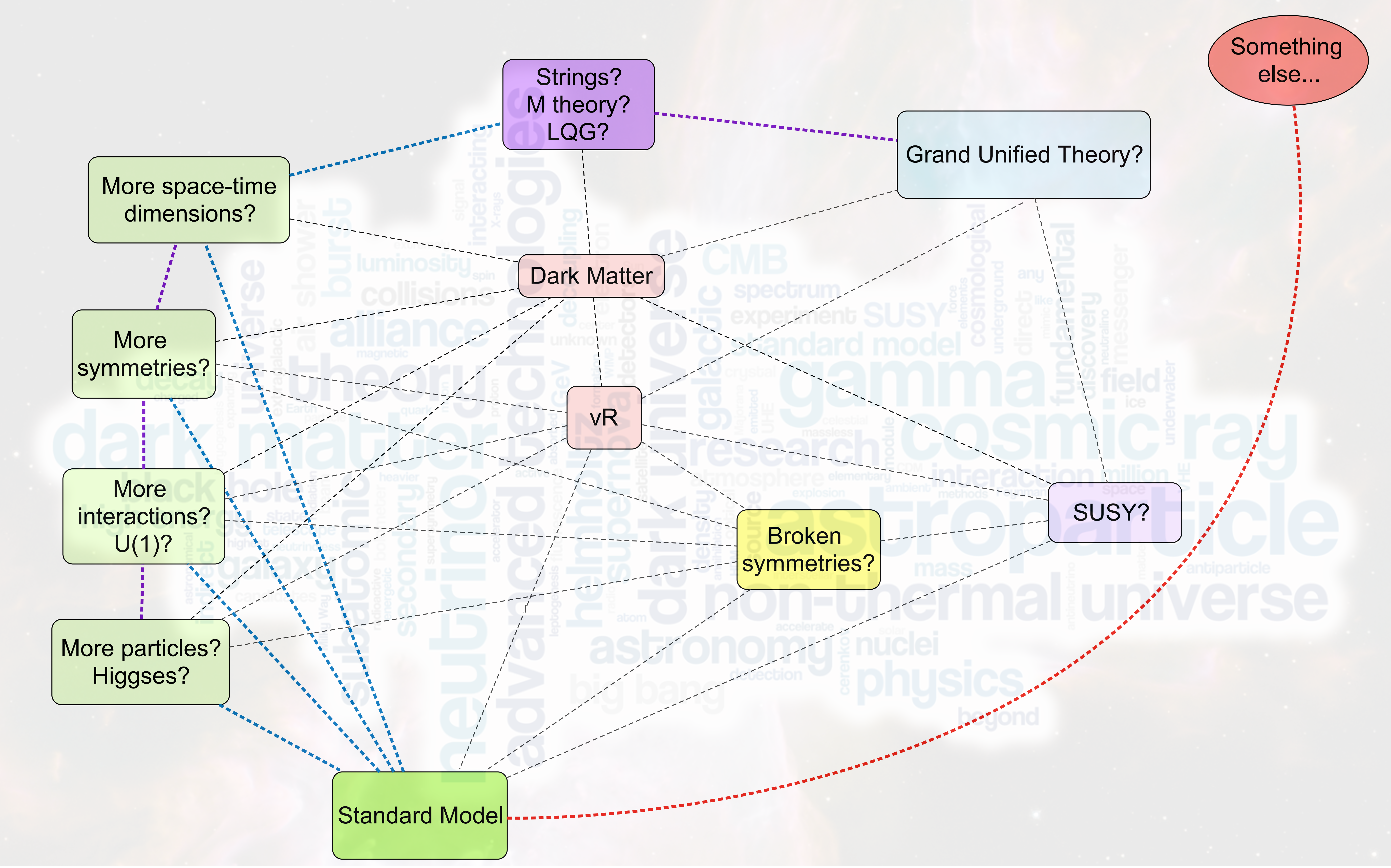
- Addition of symmetries
- Addition of particles
- Addition of interactions
- Addition of space-time dimensions
- All of the above…

I will concentrate on masses and mixings.

And perhaps dark matter and leptogenesis, and…

Can get messy…




Strings?
M theory?
LQG?
Something else...
Grand Unified Theory?
More space-time dimensions?
Dark Matter
More symmetries?
νR
More interactions? U(1)?
SUSY?
Broken symmetries?
More particles? Higgses?
Standard Model

HOW DO WE MOVE UP (OR DOWN) IN ENERGY?

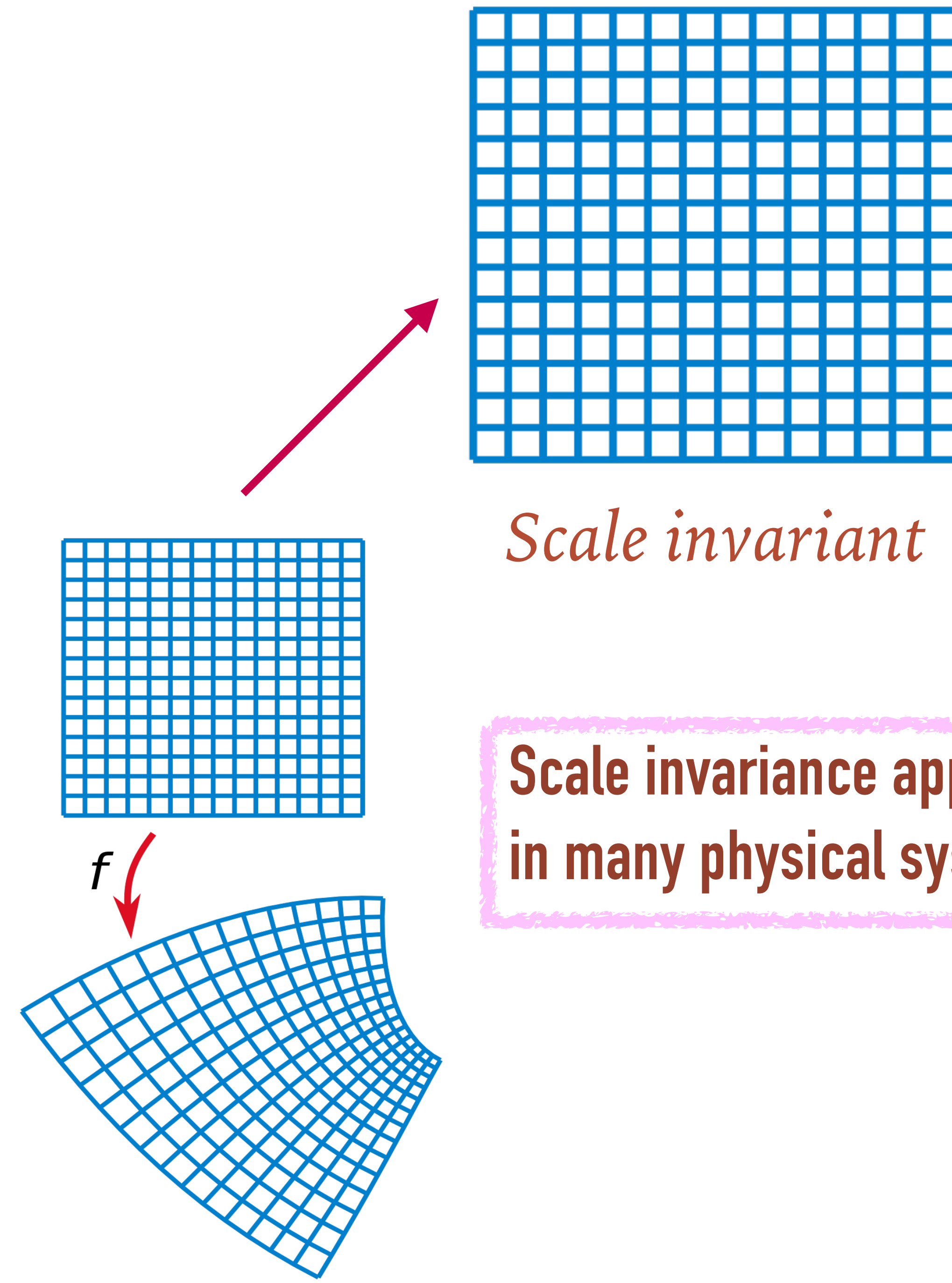
- We know how a QFT behaves at different scales through the renormalization group RG
- The theory has the same structure at different energy scales, but the parameters — couplings and masses — change with energy
- Related to scale invariance and conformal invariance

$$\beta(g) = \mu \frac{\partial g}{\partial \mu} \qquad \gamma(\phi) = \mu \frac{\partial \ln Z}{\partial \mu}$$

Set of differential equations that describe the bahaviour of the theory at different scales — Renormalization Group Equations RGE

FINITENESS

- Finiteness ⇒ $\beta = 0$ to all orders in perturbation theory
- Scale or conformal invariance
- Couplings do not depend on energy scale
- Based on RGI and reduction of couplings
- Reduces greatly the number of free parameters
  → new symmetries
- Partial reduction → predictions for 3rd generation masses



Scale invariant

Conformally invariant

Scale invariance appears in many physical systems

FINITESS $\Longrightarrow$ GAUGE YUKAWA UNIFICATION

Grand Unified SUSY N=1, no gauge anomalies:

$$W = \frac{1}{2} m^{ij}\, \Phi_i\, \Phi_j + \frac{1}{6} C^{ijk}\, \Phi_i\, \Phi_j\, \Phi_k$$

$$\beta_g^{(1)} = 0 = \gamma_i^{j\,(1)}$$

$$\sum_i T(R_i) = 3C_2(G)\,, \qquad \frac{1}{2} C_{ipq} C^{jpq} = 2\delta_i^j g^2 C_2(R_i)$$

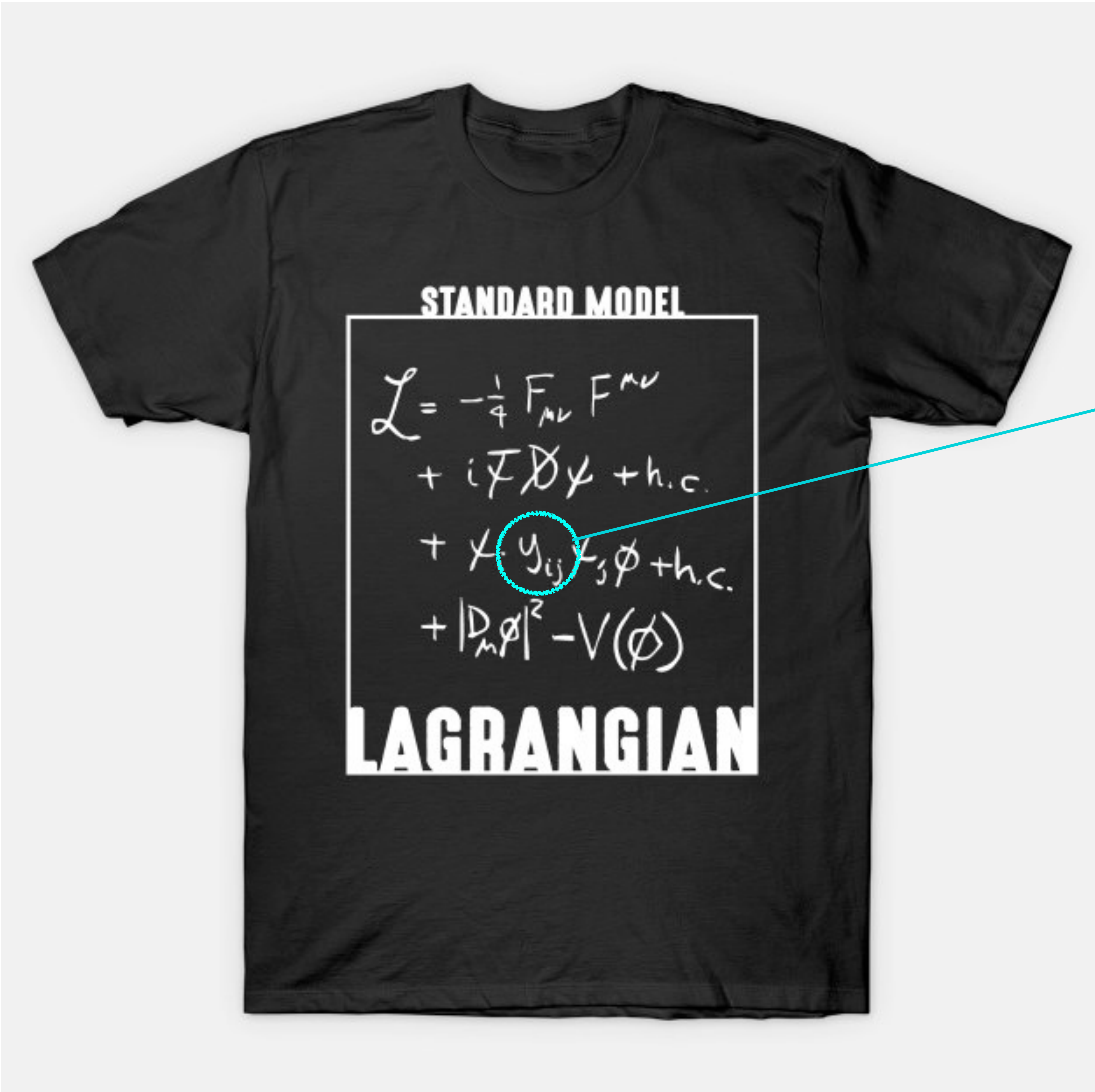
T Dynkin index of irrep, C_2 Casimir invariant of group   *C_{ijk} Yukawa couplings, g gauge coupling*

- Restricts the gauge group
- Relates gauge and Yukawa couplings
- Can be made finite to all orders

Conformal invariance

- Just analyze one-loop solution
- Isolated and non-degenerate solution
  Lucchesi, Piguet, Sibold
- Implies extra symmetries, in this case discrete

β= 0 non-renormalization of coupling constants, not complete UV finiteness where field renormalization is absent



Yukawa couplings free parameters

$$M_H^2 = \lambda v^2$$

$$m_f = g_f v/\sqrt{2}$$

MANY ASPECTS OF FINITENESS STUDIED

- $SU(5)$ models extensively studied — Rabi et al; Kazakov et al; Quirós et al; MM, Zoupanos et al
- One coincides with a non-standard Calabi-Yau — MM, Zoupanos
- Finite string theories and criteria for branes — Ibáñez
- Models with three generations — Babu, Enkhbat, Gogoladze; MM & Jiménez
- $SU(N)^k$ models finite $\Longleftrightarrow$ 3 generations
  $SU(3)^3$ finite — MM, Ma, Zoupanos
- Relations non-commutative theories and finiteness — Jack, Jones
- Proof of conformal invariance (dimensionless part) — Kazakov, Bork; MM & Reyes
- Relation between finiteness and QFT in curved space-time & inflation
  Elizalde et al
- Recent reviews — Heinemeyer, M.M, Tracas, Zoupanos, Phys.Rept. 814 (2019); Fortsch.Phys. 68 (2020)

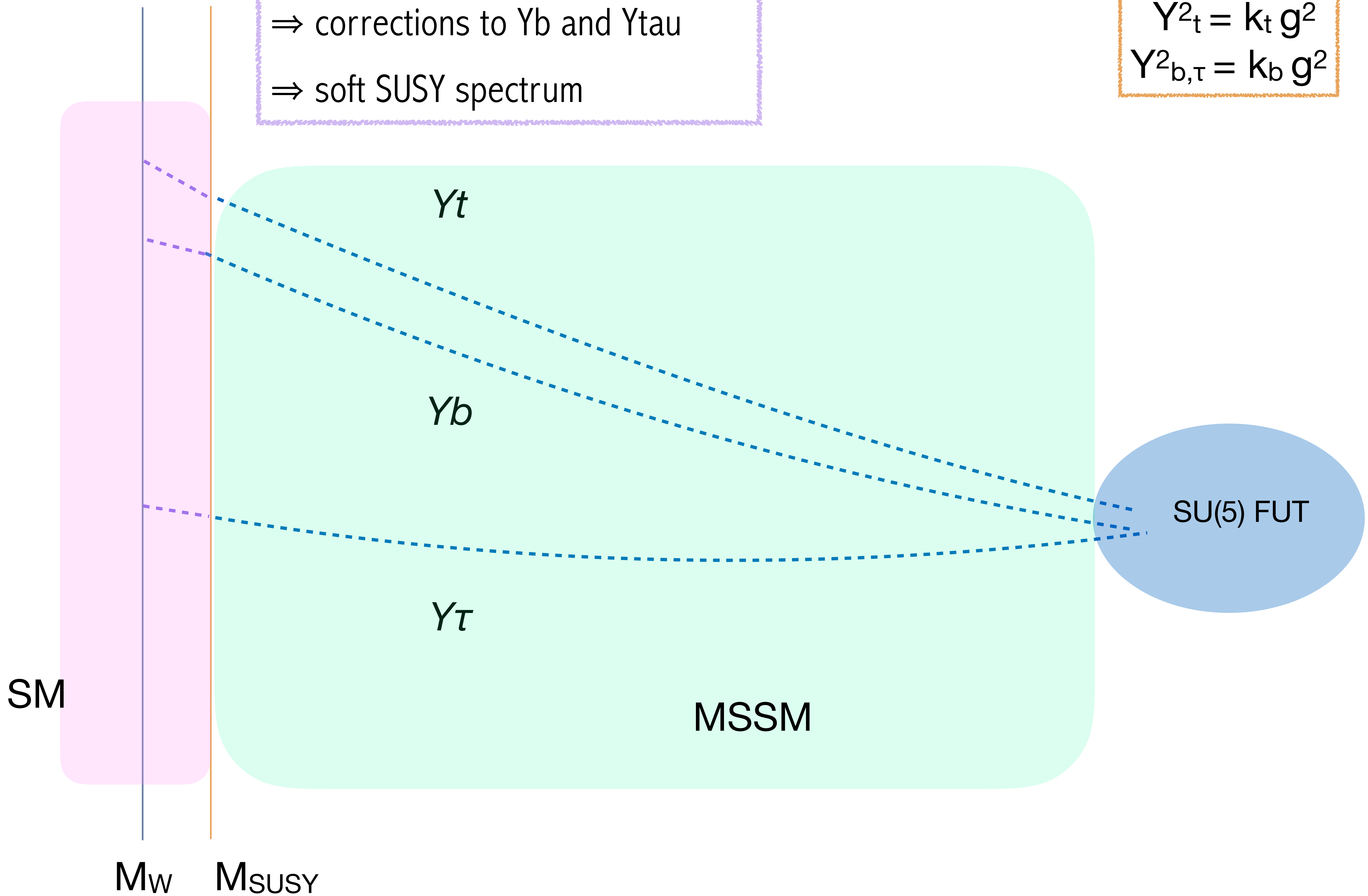
Finite soft breaking terms included

⇒ corrections to Yb and Ytau

⇒ soft SUSY spectrum

$Y^2_t = k_t\, g^2$

$Y^2_{b,\tau} = k_b\, g^2$



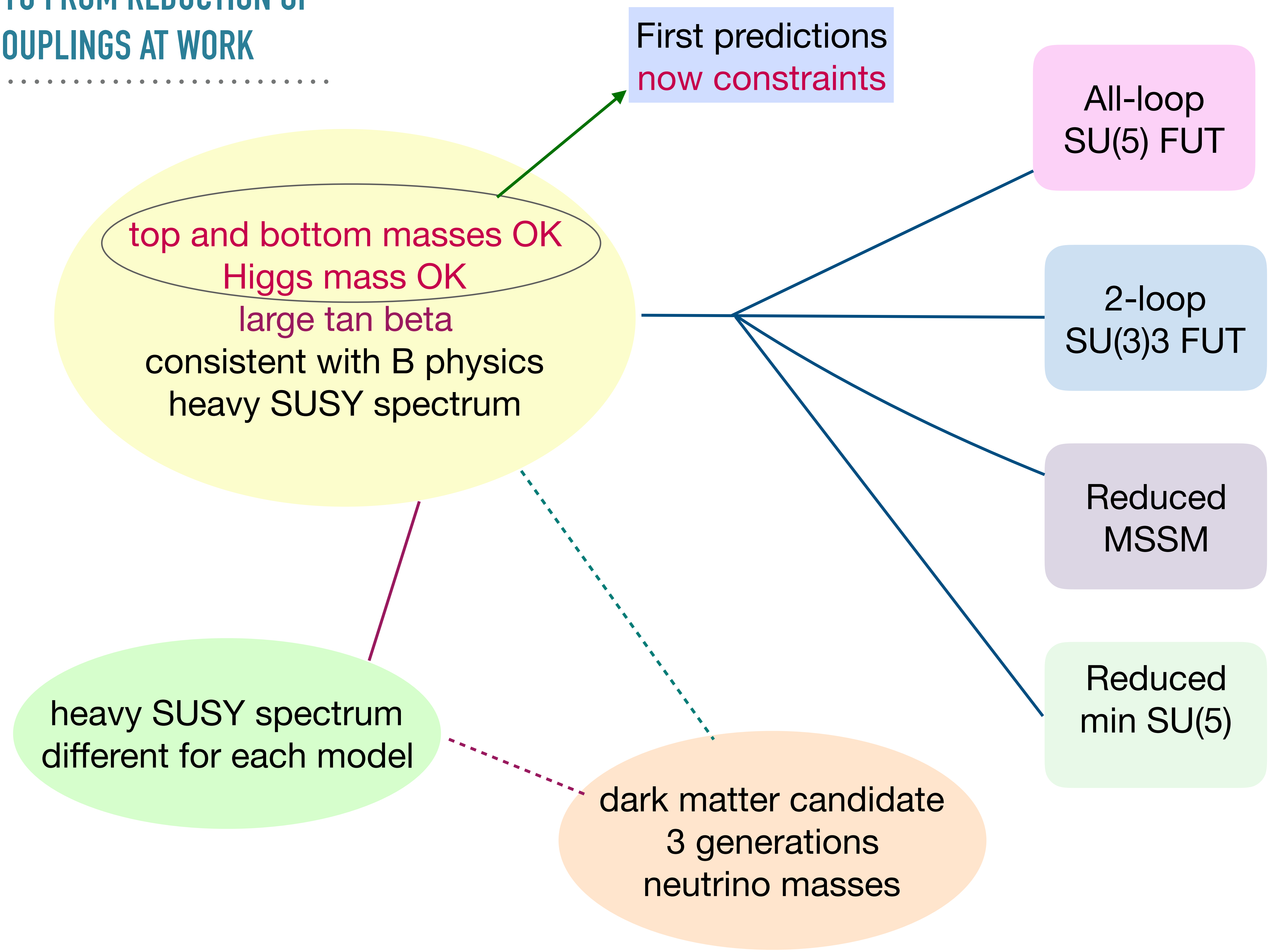
Results confronted to experimental constraints ⇒

gives available parameter space

$m_t = Y_t\, v_u \qquad v_u / v_d = \tan\beta$

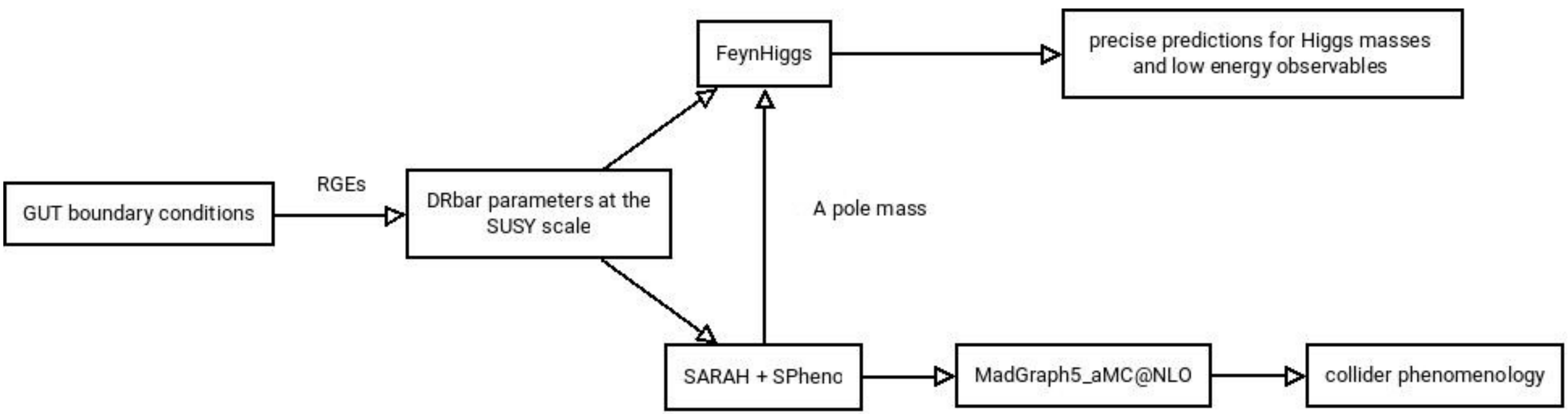
$m_{b,\tau} = Y_{b,\tau}\, v_d \qquad v_d = m_\tau^{exp} / Y_\tau$

GYU FROM REDUCTION OF COUPLINGS AT WORK



PREDICTIONS – NEW 2018 AND 2022 ANALYSES

- Results consistent with B physics constraints (not trivial)
- Predictions for top and bottom quark masses in experimental range
  M_{top} - 171-174 GeV exp 173.3 ± 0.76 GeV
  M_{bot} - 2.6-2.9 (M_Z) GeV exp 2.8 ± 0.1 GeV
- Large tanβ 48-52
- Higgs mass 122-129 GeV exp 125.1 ± 0.3
- Heavy SUSY spectrum in TeV region — Collider phenomenology, challenging even for FCC
- Not all models survive, non minimal FUT SU(5) and SU(3) ^ 3 FUT do



RECENT DEVELOPMENTS

- Updated phenomenological analysis still consistent with 3rd generation masses, large tanβ and **very heavy SUSY spectrum**
  S. Heinemeyer, J. Malinowski, W. Kotlarski, M. Mondragón, N. Tracas, G. Zoupanos 2018 and 2022
- Finiteness implies conformal invariance and phase transition
  L.E. Reyes Rodríguez, Lic. Thesis (2018)
- Three generation analysis SU(5):
  Diagonal quark mass matrix compatible with data and proton decay
  Luis Odín Estrada, M.Sc. Thesis (2018)
- Three generation solution for SU(5) with Z symmetries compatible with good textures at high energies
  Luis Odín Estrada, Ph.D. Thesis
- Finiteness in Soft breaking terms lead to anomaly mediated type breaking
  L.E. Reyes Rodríguez, M.Sc.Thesis (2021)
- Reduction of couplings in multi-Higgs models M.A. May Pech, M.Sc. Thesis (2023)
- SU(3) ^ 3 finite split susy model in progress L.E. Reyes Rodríguez, Ph. D. Thesis

OUTLOOK AND TO PACK…

- Inclusion of neutrino masses through $\not{R}$
- Will not change much the collider phenomenology presented
- Will impact the DM candidate $\Rightarrow$ gravitino + ?
- Detailed analysis of three gen solutions with discrete symmetries
- Detailed analysis of phase transition and SUSY breaking
- Lately: FUTs in curved space time $\Rightarrow$ successful inflation
  E. Elizalde, S. Odintsov, E. Pozdeeva, S. Vernov (2015)
- New type of finite theories imply duality between UV and IR fixed points. Connection to FUTs? Y. Kawamura (2015)

AND AT LOWER ENERGIES….?

HOW DO WE CHOOSE A FLAVOUR SYMMETRY?

- Several ways:
- Look for inspiration in a high energy extension of SM, i.e. strings or GUTs
- Look at low energy phenomenology
- At some point they should intersect…
- In here:
  - Find the smallest flavour symmetry suggested by data
  - Explore how generally it can be applied (universally)
  - Follow it to the end
  - Compare it with the data

SOME ASPECTS OF THE FLAVOR PROBLEM

- Quark and charged lepton masses very different, very hierarchical

$$m_u : m_c : m_t \sim 10^{-6} : 10^{-3} : 1$$

$$m_d : m_s : m_b \sim 10^{-4} : 10^{-2} : 1$$

$$m_e : m_\mu : m_\tau \sim 10^{-5} : 10^{-2} : 1$$

- Neutrino masses unknown, only difference of squared masses.
- Type of hierarchy (normal or inverted) also unknown
- Higgs sector under study

- Quark mixing angles

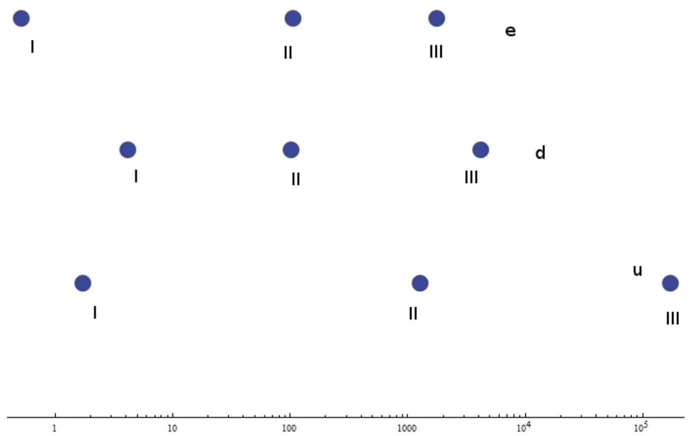
$$\theta_{12} \approx 13.0^o$$
$$\theta_{23} \approx 2.4^o$$
$$\theta_{13} \approx 0.2^o$$

- Neutrino mixing angles

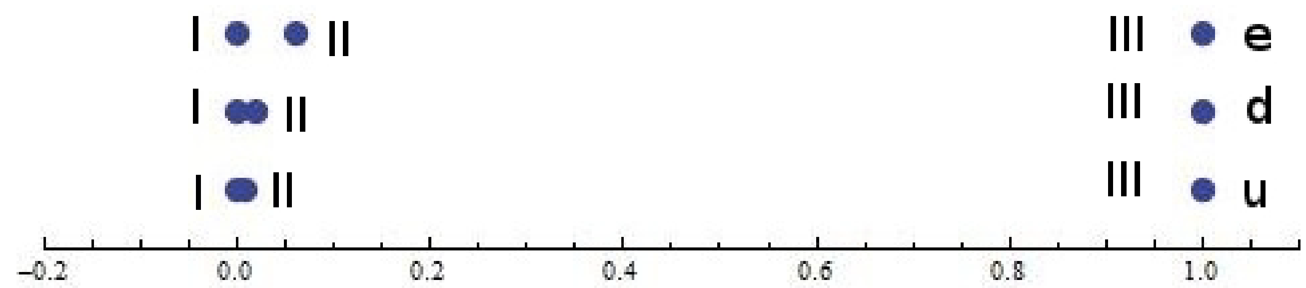
$$\Theta_{12} \approx 33.8^\circ$$
$$\Theta_{23} \approx 48.6^\circ$$
$$\Theta_{13} \approx 8.6^\circ$$

- Small mixing in quarks, large mixing in neutrinos. Very different
- Is there an underlying symmetry?

?



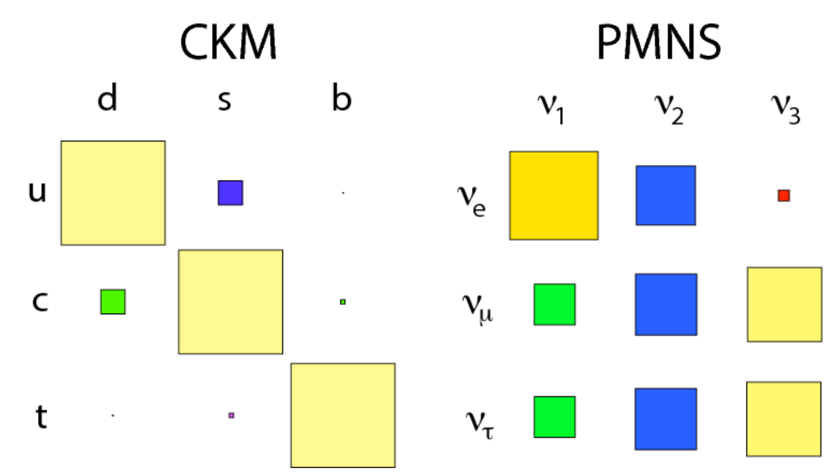
Plot of mass ratios



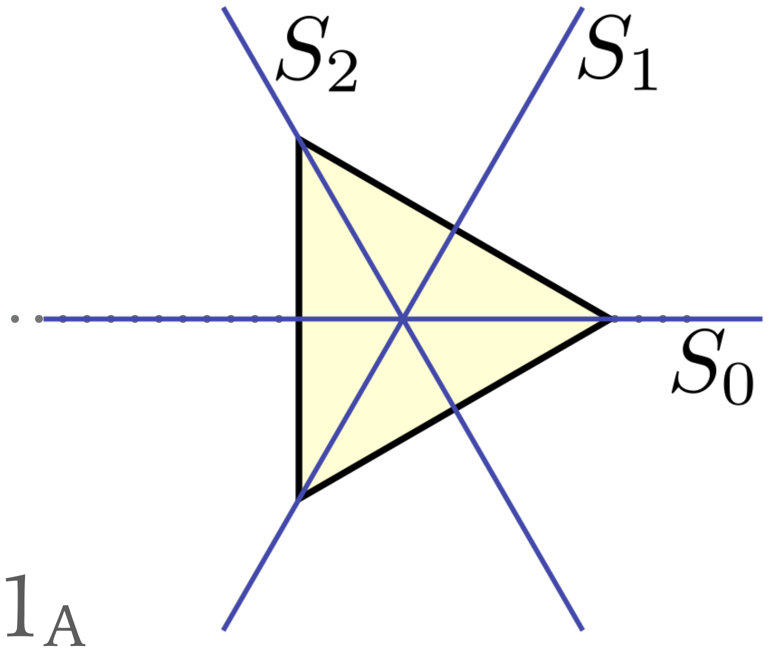
Logarithmic plot of quark masses

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} \approx \begin{bmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{bmatrix},$$

Suggests a 2⊕1 structure



S3–3HDM



- Smallest non-Abelian discrete group
- Has irreducible representations, 2, 1_S and 1_A
- We add three right-handed neutrinos to implement the see-saw mechanism
- We apply the symmetry "universally" to quarks, leptons and Higgs-es
  - First two families in the doublet
  - Third family in symmetric singlet
- Three sectors related, we treat them simultaneously

PREDICTIONS, ADVANTAGES?

- Possible to reparametrize mixing matrices in terms of mass ratios, successfully
- CKM has NNI and Fritzsch textures
- PMNS → fix one mixing angle, predictions for the other two within experimental range
- Reactor mixing angle $\theta_{13} \neq 0$
- Some FCNCs suppressed by symmetry
- Higgs potential has 8 couplings
- Underlying symmetry in quark, leptons and Higgs → residual symmetry of a more fundamental one?
- Lots of Higgses: 3 neutral, 4 charged, 2 pseudoscalars
- Further predictions will come from Higgs sector: decays, branching ratios

A. Mondragón, M. M., F. González, E. Peinado, U. Saldaña, O. Félix, E. Rodríguez, A. Pérez, H. Reyes, C. Espinoza, E. Garcés,...; Das, Dey et al; Teshima et al; E. Barradas, O. Félix, E. Rodríguez; M. Rebelo, P. Osland et al; many many more

NEW RESULTS S3-3H

- Adriana's talk: full scalar potential analysis
- 2 scenarios:
  - A: SM Higgs lightest one
  - B: Neutral scalar lighter than SM~100 GeV possible neutral scalar signal?
- Both compatible with SM limit for trilinear and quartic couplings
- Small deviations from SM in trilinear and quartic couplings compatible with recent phenomenological analyses in the modifier or κ framework

$$g_{H_2H_2H_2} \equiv \lambda_{SM}\kappa_\lambda = \frac{m_{H_2}^2}{2v}\left[(1+2\delta^2)\sqrt{1-\delta^2}+\delta^3(\tan\theta-\cot\theta)-\frac{m_{h_0}^2}{m_{H_2}^2}\frac{\delta^3}{9s_\theta c_\theta^3}\right]$$

S3–3H FUTURE ANALYSIS

- Mass spectrum in reach of future runs of the LHC
  - Inclusion of one-loop corrections necessary
  - Calculation of decays and branching rations of scalars
- New neutral scalar not coupled to gauge bosons, DM?
- Residual symmetry ⇒ problematic in fermionic sector
  Solutions:
  - break S3
  - **modular S3**
  - high energy sector terms
  - 4 Higgs doublets
  - Higgs singlets

Possible to return to good previous results for mixing matrices

S3-4H

- “Saturate” the irreps: add an extra inert Higgs doublet in the $\mathbf{1}_A$
- Natural DM candidates from inert part
  the non-inert part same as S3-3H in SM alignment limit
- Full analysis for DM, with Higgs bounds, relic density, indirect detection done
  E. Garcés, C. Espinoza, M.M, H. Reyes, PLB (2018), M.Sc. Thesis H. Reyes
- Multi-component DM in progress
  With scalar and neutrino M. Valenzuela, Ph.D. Thesis in progress, with E. Espinoza, A. Ramírez
  With 2 scalars J. Pacheco, Ph.D. Thesis in progress, with E. Espinoza, E. Barradas, T. Valencia
- Neutrino portal in progress with E. Espinoza, E. Barradas, T. Valencia
- LFV analysis in progress J. Pacheco, Ph.D. Thesis in progress
- S3 with 3H and $U(1)_{B-L}$ multi component DM in progress
  L. E. Gutiérrez-Luna, Ph.D. Thesis in progress with J.C. Gómez-Izquierdo, C. Espinoza

S3–4H DM

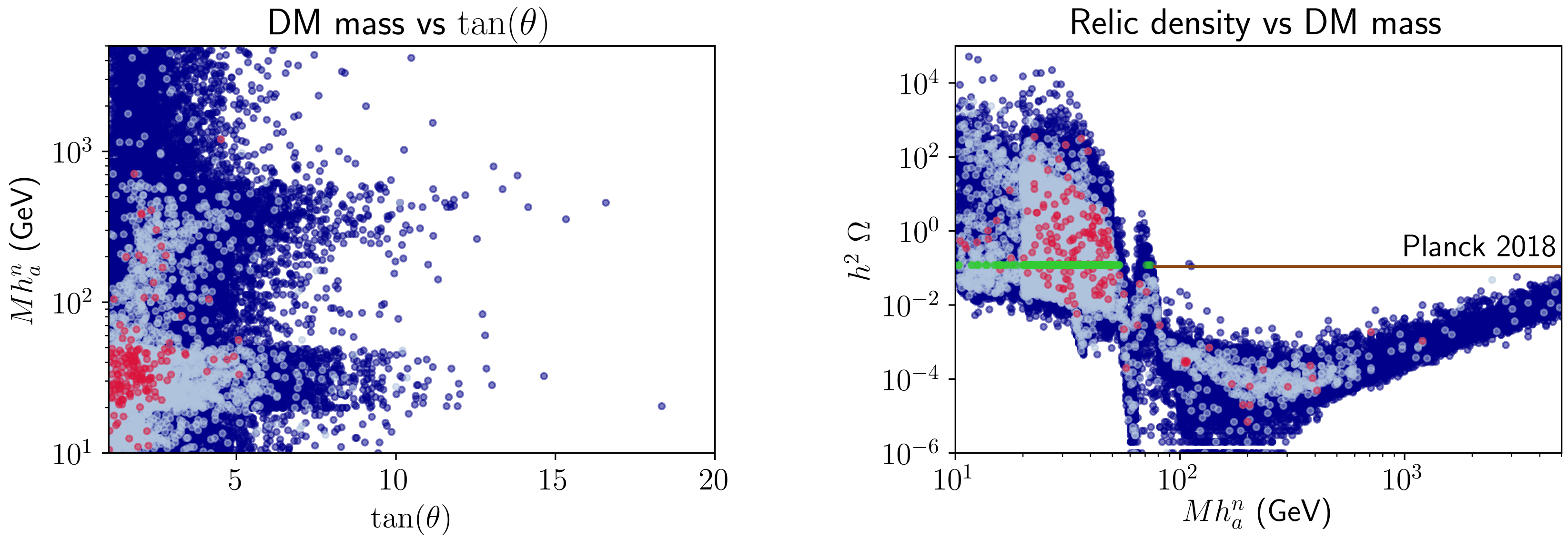


Figure 1: Mass of the DM candidate as a function of $\tan\theta$ (left panel), and value of the DM relic density as a function of the DM mass. The dark blue points (set A) are the ones that comply with stability and unitarity constraints, the light blue points (set B) are also compatible with the experimental bounds for extra scalar searches (see text), the red points also satisfy the decoupling limit and the green points in the right panel lie within the experimental Planck bound.

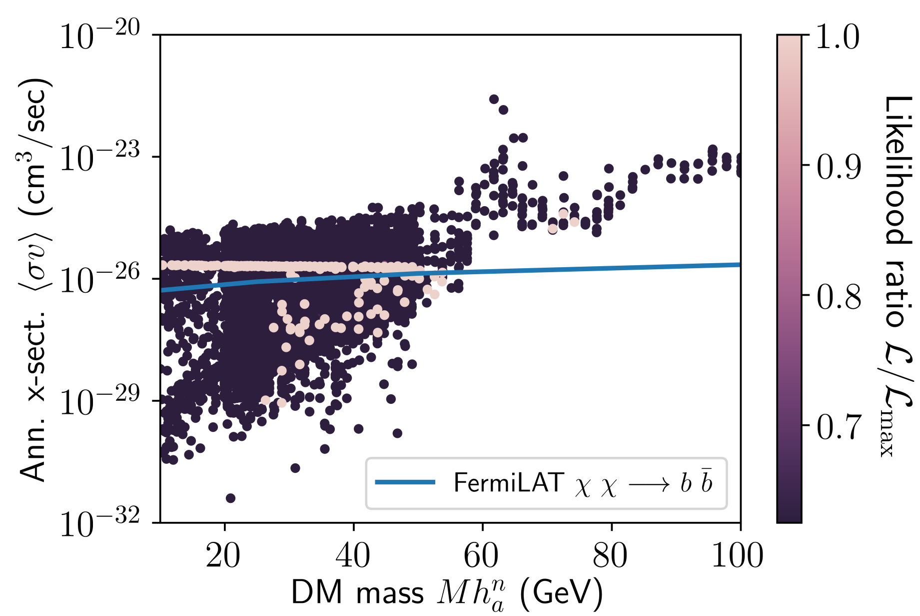


Figure 3: Annihilation cross section as a function of the DM mass for small DM masses, the points are colored according to their (normalized) likelihood (with respect to the relic density) value. Also shown is the FermiLAT dwarf spheroidal combined DM exclusion curve.

C. Espinoza, E. Garcés, M.M., H Reyes-González
Phys.Lett.B 788 (2019) 185-191

WHAT CAN GUIDE US IN BETWEEN?

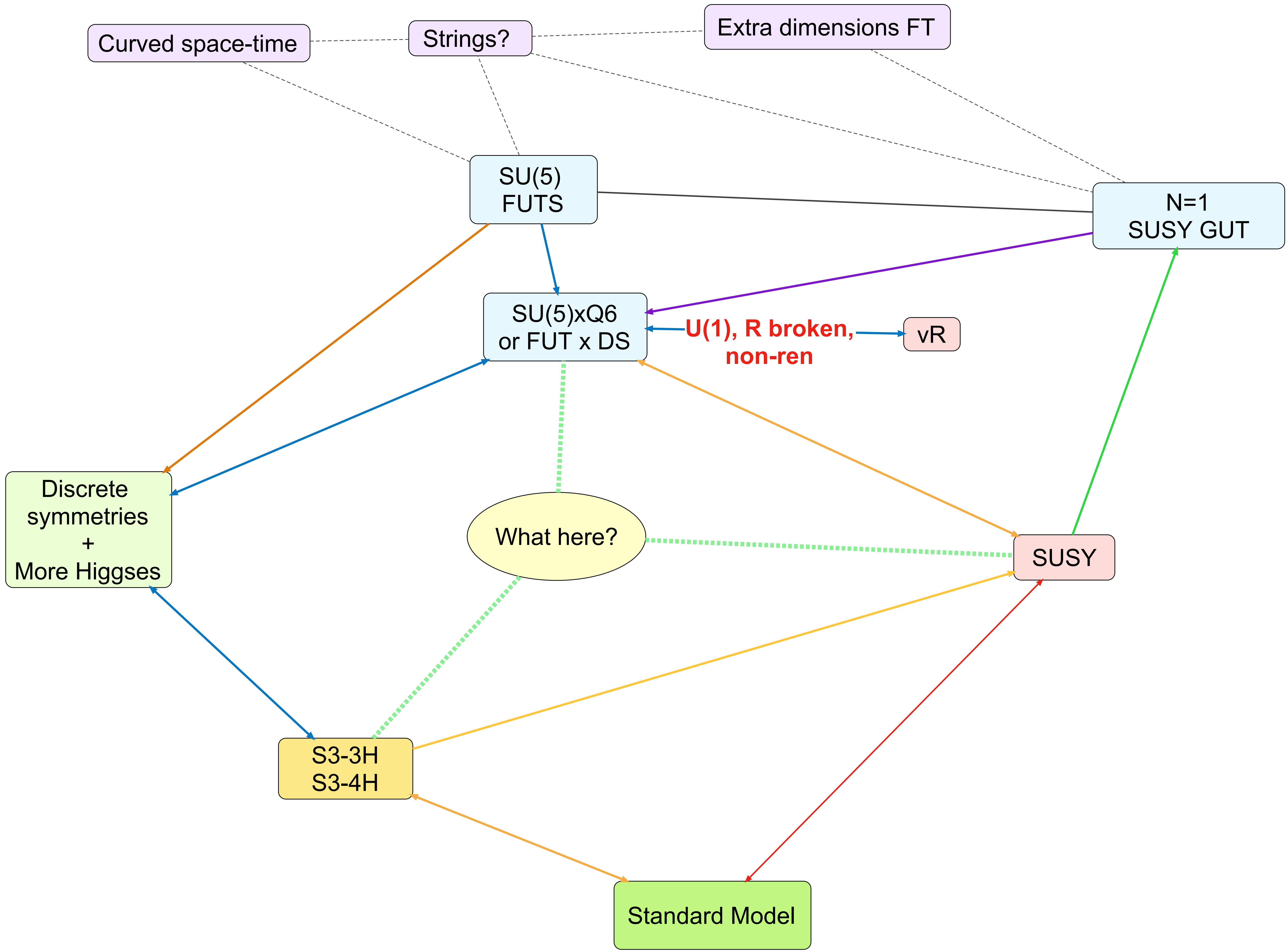
- SU(5) x Q6 (non-FUT) $\Longrightarrow$ good CKM, similar predictions to S3-3H for neutrino sector
  J.C. Gómez-Izquierdo, F. González-Canales, MM (2015)
- Breaking of mu-tau symmetry through Q6 SUSY and S3 non-SUSY
  J.C. Gómez-Izquierdo, F. González-Canales, M.M. (2017);(2018)
- g-2 solution through LFV in extended MSSM, with discrete symmetry inspired terms M. Gómez-Bock, F. Flores-Báez, MM (2016)
- LFV violating processes Jorge Pacheco, Ph.D. Thesis
- And of course experimental data and observations…

MORE MODELS?

Explore other models

- 2+1 successful in quark sector
- Neutrino sector also: more flexibility
- Q4 2HDM and singlets
  quarks, leptons, DM, leptogenesis, g-2
  Gatto-Sartori-Tonin relation between quark masses and mixing angles

  A. Cárcamo, E. Espinoza, J.C. Gómez-Izquierdo, M.M. *Eur.Phys.J.Plus* 137 (2022) 11, 1224
- S4xZ4xZ2 3HDM and 4HDM, plus singlets, with very predictive neutrino sector, also interesting scalar sector, scalar and sermonic DM candidates
  A. Cárcamo, C. Espinoza, J.C. Gomez, J. Marchant, M.M.
- S3-3H with S3 as modular symmetry, nice results without residual Z2 in quark sector
  M.C. Cerón, M.Sc. Thesis (2021)
- SUSY SU(5) non-minimal with modular S3 A.C. Samaniego, M.Sc. Thesis
- Also: combined approach from particle physics and cosmology. An ultra-light scalar plus a Higgs-like or axion-like DM particles L.E. Gutiérrez-Luna, Ph.D. Thesis
- Bi-component DM M. Valenzuela, Ph.D. Thesis



Curved space-time
Strings?
Extra dimensions FT
SU(5)
FUTS
N=1
SUSY GUT
SU(5)xQ6
or FUT x DS
U(1), R broken,
non-ren
vR
Discrete
symmetries
+
More Higgses
What here?
SUSY
S3-3H
S3-4H
Standard Model

OUTLOOK AND CONCLUSIONS

- Among the different ways to go BSM finiteness proves to be a good guiding principle.
  Reduces greatly the number of free parameters, RG flow of the third family in the right direction
- Needs extended Higgs sector and discrete flavor symmetries
- At low energies S3, S4, Q4, Q6 theories with extended Higgs sector explain well CKM and have predictions for neutrino sector
  - Provide baryogenesis through leptogenesis
  - Good DM candidates
- Maybe is possible to connect both approaches
- How do astroparticle physics and cosmology help?

¡GRACIAS!