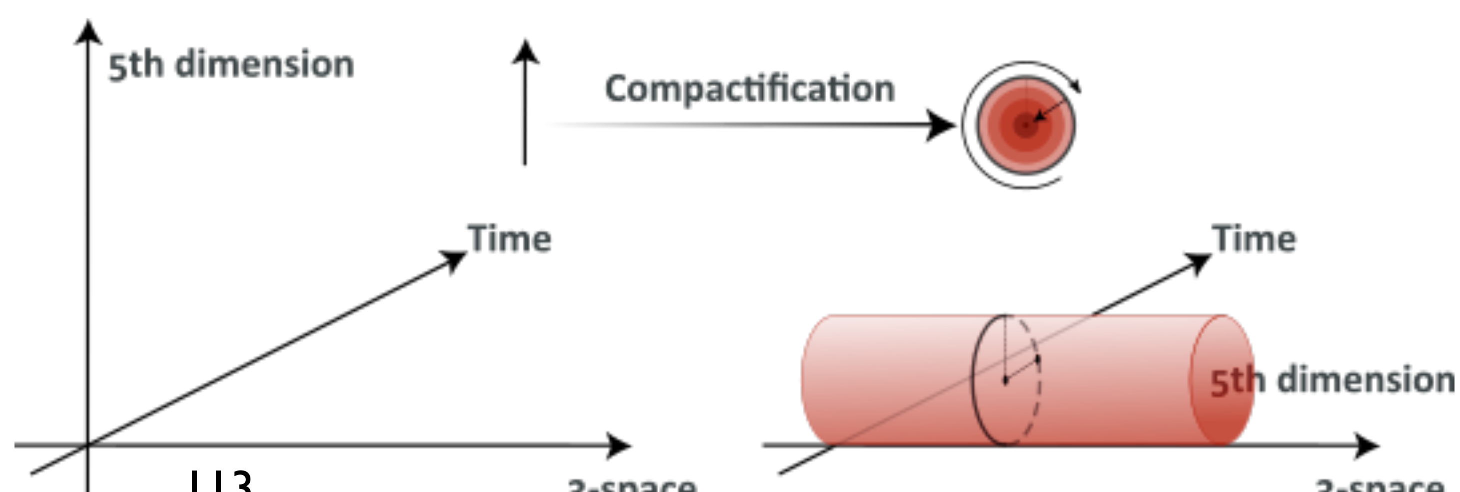
Kaluza-Klein theories

- Add extra space-time dimensions to unify gravity and electromagnetism (T. Kaluza 1921)
- The fifth dimension is compact, periodic, very small (O. Klein 1926)
- Start with a theory of Einstein gravity in 5-D. One of the dimensions is compactified in a very small circle
- Tower of massive scalars

$$M_{KK}^2 \propto n/R^2$$

- The 5-D general coordinate invariance broken in ground state $\rightarrow$ ordinary gravity in 4-D plus an Abelian gauge field
- U(1) gauge symmetry appears associated with coordinate transformations on circle
- Parameters of the two theories connected, since they have same origin



Kaluza theory

- Consider a 5D theory only with gravity, the gravitons are

$$h_{MN} \quad M, N = \mu, 5$$

- Correspond to fluctuations around flat space

$$g_{MN} = \eta_{MN} + h_{MN}$$

which decompose into a spin 2 $h_{\mu\nu}$, identified with a graviton,
a spin 0, $h_{\mu 5}$ identified with a photon, and a scalar h_{55}

- The first proposal did not include massless charged matter particles

Kaluza-Klein theories

- The action in 5D, y is fifth-dimension. Only scalars

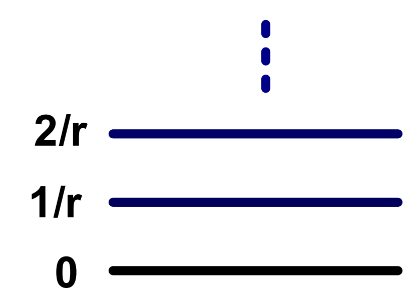
$$S_5 = -\int d^4x\, dy\, M_* \left[|\partial_\mu \phi|^2 + |\partial_y \phi|^2 + g_5^2 |\phi|^4 \right] .$$

- y compactified in a circle $y = y + 2\pi R$

- Expand the complex scalar in a Fourier series

$$\phi(x,y) = \sum_{n=-\infty}^{\infty} e^{iny/R} \phi^{(n)}(x) = \phi^{(0)}(x) + \sum_{n\neq 0} e^{iny/R} \phi^{(n)}(x) .$$

- Integrating over y gives $S_5 = S_4^{(0)} + S_4^{(n)}$



massless scalar

$$S_4^{(0)} = -\int d^4x\, 2\pi R M_* \left[|\partial_\mu \phi^{(0)}|^2 + g_5^2 |\phi^{(0)}|^4 \right] ,$$

$$S_4^{(n)} = -\int d^4x\, 2\pi R M_* \sum_{n\neq 0} \left[|\partial_\mu \phi^{(n)}|^2 + \left(\frac{n}{R}\right)^2 |\phi^{(n)}|^2 \right] + \text{quartic} - \text{couplings}$$

tower of massive modes

- We can describe 5D theories as 4D ones

$$S_4^{(0)} = -\int d^4x \left[|\partial_\mu \phi^{(0)}|^2 + g_4^2 |\phi^{(0)}|^4 \right] \qquad g_4^2 = \frac{g_5^2}{2\pi R M_*} .$$

- Same for gauge fields and graviton:

$$-\int d^4x \left[\frac{1}{16\pi G_N} \mathcal{R}^{(0)} + \frac{1}{4g_4^2} F^{(0)\,\mu\nu} F^{(0)}_{\mu\nu} \right] + \dots ,$$

$$g_4^2 = \frac{g_5^2}{2\pi R M_*} ,$$

$$G_N = \frac{1}{16\pi^2 R M_*^3}$$

g_4 is 4D gauge coupling
G_N is 4D Newton constant

strength of interaction suppressed by radius of extra dimension

- If we lived in 5D, then g5 should be perturbative, but from the 4D perspective g4 should be strongly interacting $\rightarrow$

$$R \sim 1/M_*$$

$$M_P^2 = 2\pi R M_*^3\,.$$

$$R \sim \frac{1}{M_P} = l_P \sim 10^{-32}\ \mathrm{cm}$$

- The compactification radius is of the order of the Planck length (reduced Planck mass)

- Gauge coupling in 5D has negative mass dimension
  $\rightarrow$ non-renormalizable
  From 4D perspective this is due to the K-K modes accesible at the energy scale

- M_* is the cut-off of the theory, which we treat as an effective field theory below this mass scale

- Gauss' law for the electric field and potential of a point charge

$$\oint_{S^2} \vec{E}\cdot d\vec{S} = Q \Rightarrow \|\vec{E}\| \propto \frac{1}{R^2}, \Phi \propto \frac{1}{R} :\ 4D$$

$$\oint_{S^3} \vec{E}\cdot d\vec{S} = Q \Rightarrow \|\vec{E}\| \propto \frac{1}{R^3}, \Phi \propto \frac{1}{R^2} :\ 5D$$

$$\|\vec{E}\| \propto \begin{cases} \frac{1}{R^3} & : R < r \\ \frac{1}{R^2} & : R \gg r \end{cases}$$

- At small distances E falls as $1/R^3$

- When the extra dimension is small compared to the distances then it falls as $1/R^2$, as usual

Large extra dimensions

- Similarly for the gravitational fields
  G_{MN} in 5D becomes the graviton $g_{\mu\nu}$, gravivectors $G_{\mu n}$ and graviscalars G_{mn}
- Is it possible to solve the hierarchy problem with large extra dimensions?
- The Planck mass is now a derived quantity, in d dimensions, V is the volume

$$M_P^2 = V^d M_*^{2+d}$$

$$M_P^2 = (RM_*)^d M_*^2 \,.$$

- Gravity lives in more dimensions than the gauge bosons, it propagates in the extra dimensions, thus explaining the gravitational couplings smallness compared to the other couplings

- KK tower of graviton → new forces

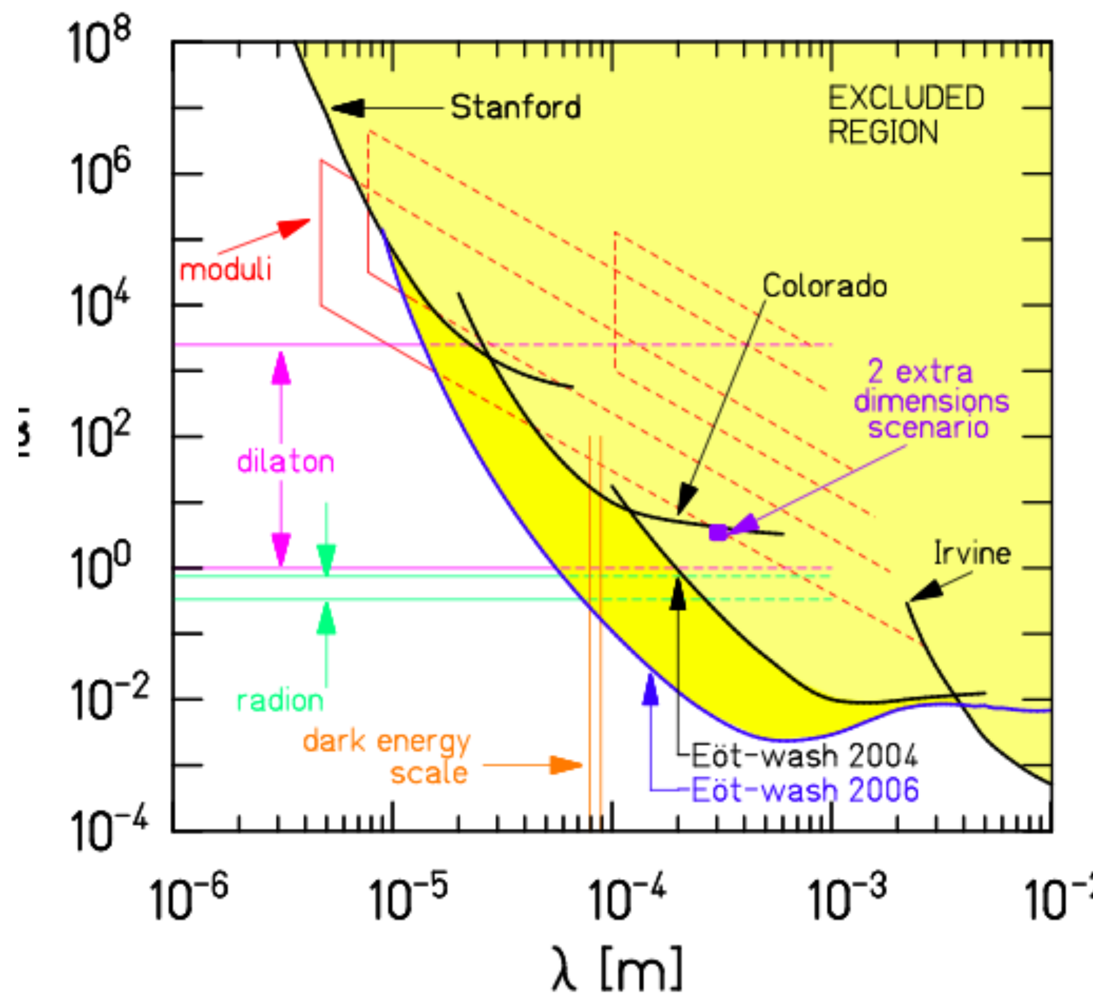
$$F_{KK}(r) = -\alpha G_N \frac{m_1 m_2}{r} e^{-r/\lambda},$$

λ= R, α constant of compactification type

- If we assume M* above 1TeV:

- For d=1 → R~ 10^9 km
  d=2 → R~ 0.5 mm

- d = 2 is ruled out, unless M* > 3 TeV



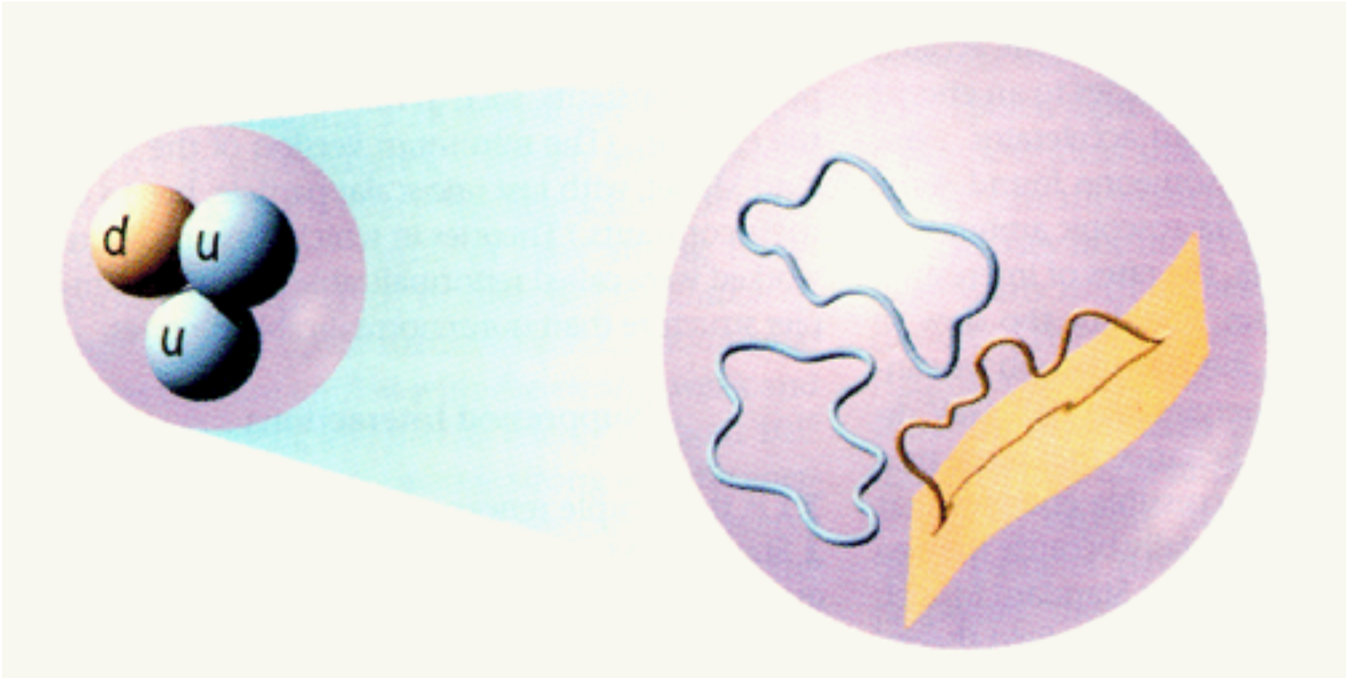
E. G. Adelberger, J. H. Gundlach, B. R. Heckel et al., Prog. Part. Nucl. Phys. 62 (2009) 102–134.

Superstrings and branes

more symmetries, more unification, more particles, more dimensions

- Particles are excitations of vibrating strings
- Branes are p-dimensional surfaces in space time
- Many require SUSY
- Require extra space-time dimensions for consistency
- Similar idea as K-K compactification
- Many ways to compactify these extra dimensions
- Spectrum includes a graviton

- Duality relates strongly coupled to weakly coupled theories
- Could be ultimate unification

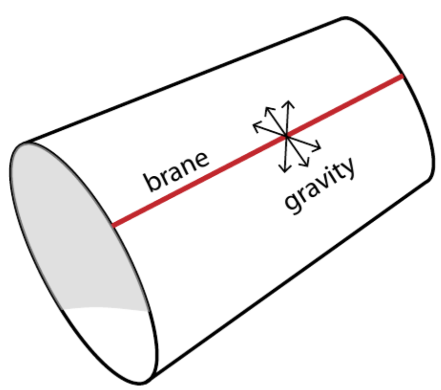


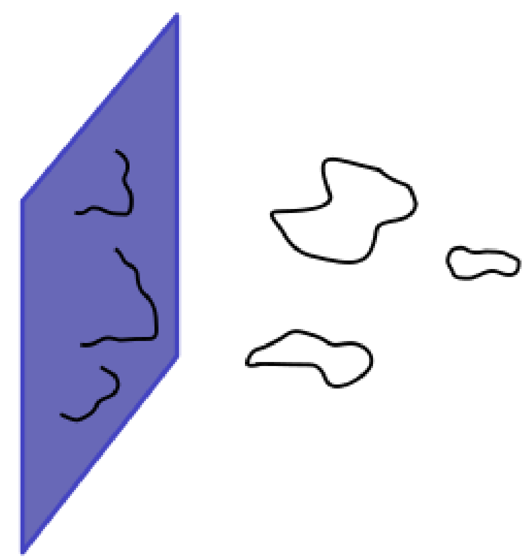
- Adding more dimensions we extend the Poincaré symmetries of SM and general coordinate transformations of general relativity, to each

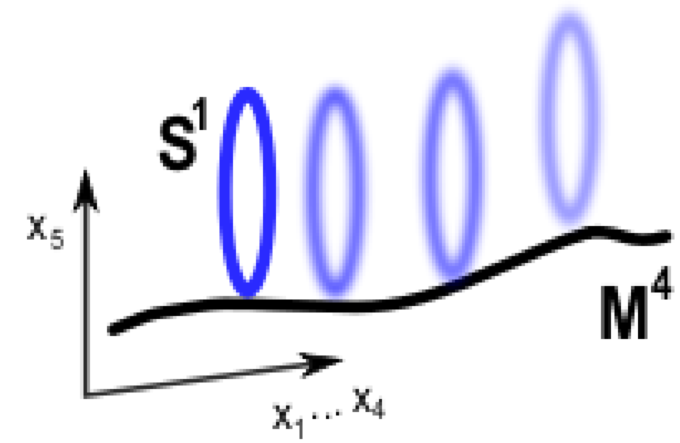
- Superstring theory also requires extra dimensions 10 for heterotic string, 11 for supergravity and M theory

- Why don't we perceive them?

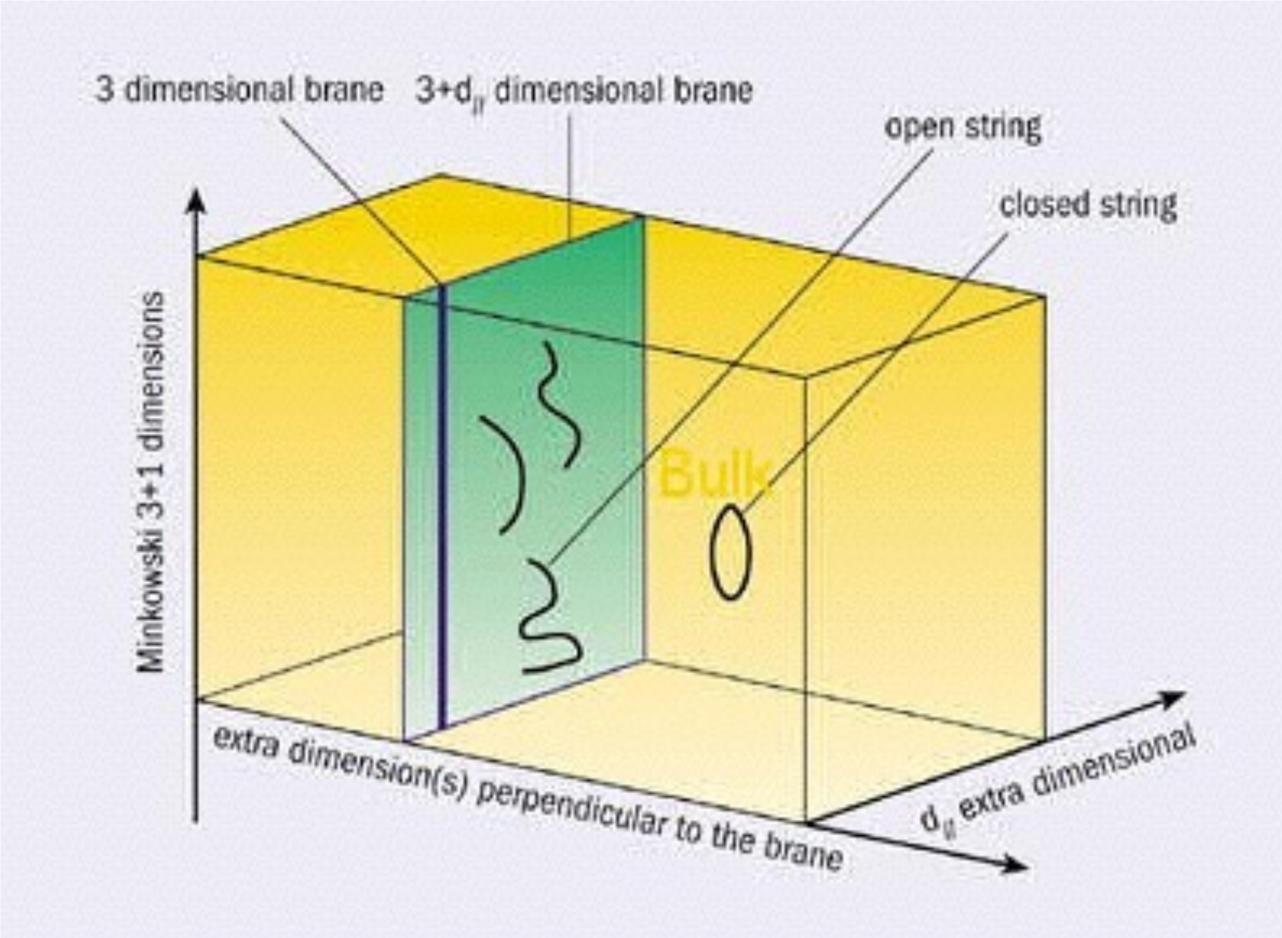
  - They are compactified or

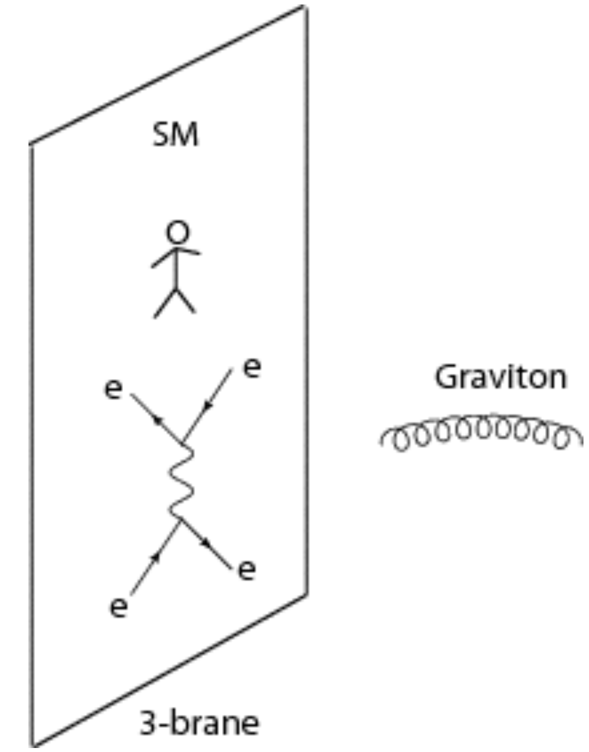


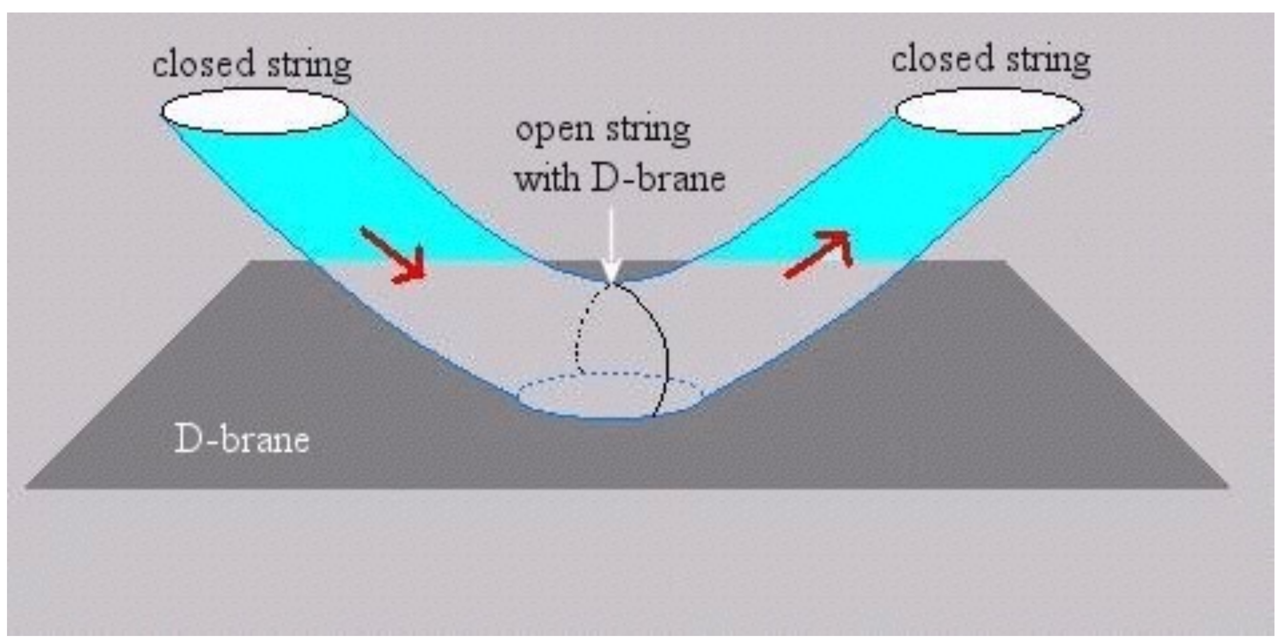




  - We live on a brane — bulk of space time lives in D+3+1 dimensions, but SM (us) are fixed to a brane = 3+1 dimensional hyper surface. Gravity moves through space-time, i.e. all dimensions. We don't.


3 dimensional brane
3+d// dimensional brane
open string
closed string
Bulk
Minkowski 3+1 dimensions
extra dimension(s) perpendicular to the brane
d// extra dimensional


SM
e
e
e
e
Graviton
3-brane


closed string
closed string
open string
with D-brane
D-brane

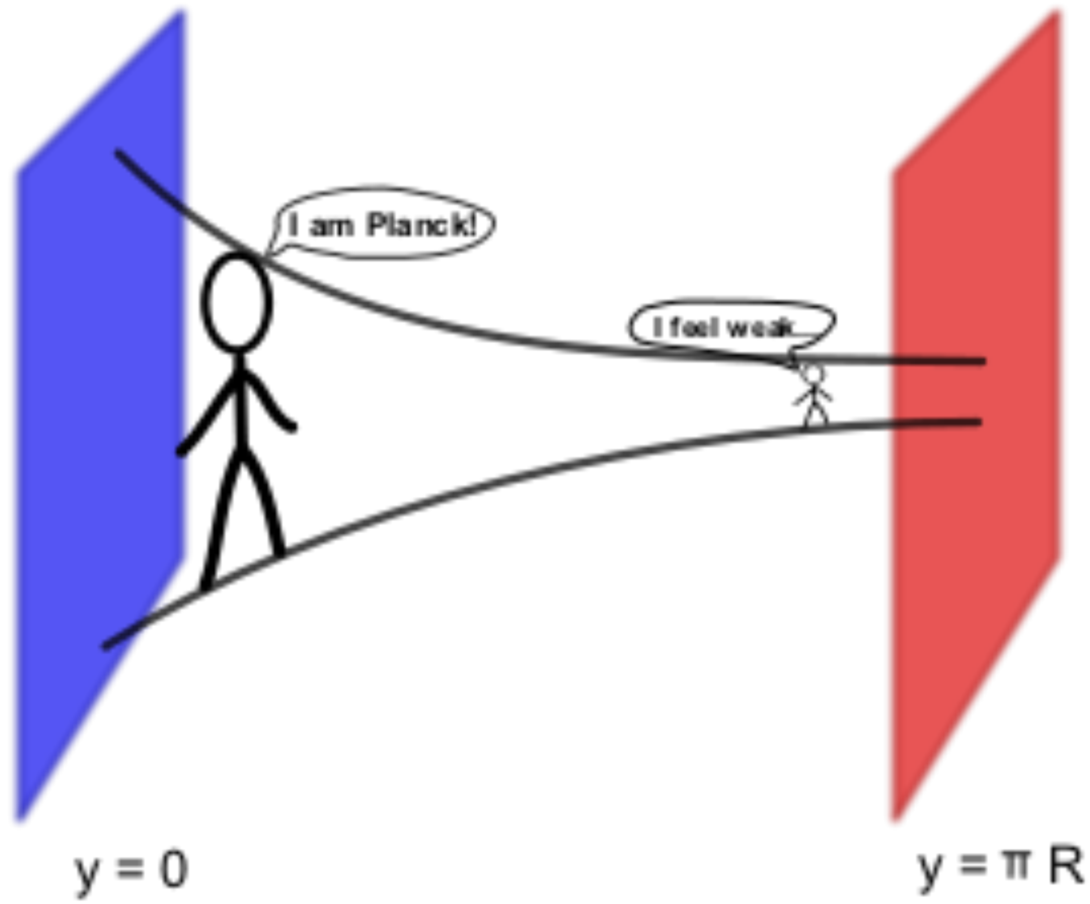
Warped extra dimensions

- 5th dimension bounded by two (3+1) branes
- Warped space-times, the metric warps exponentially along the extra dimension

$$ds^2 = e^{-|ky|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2.$$

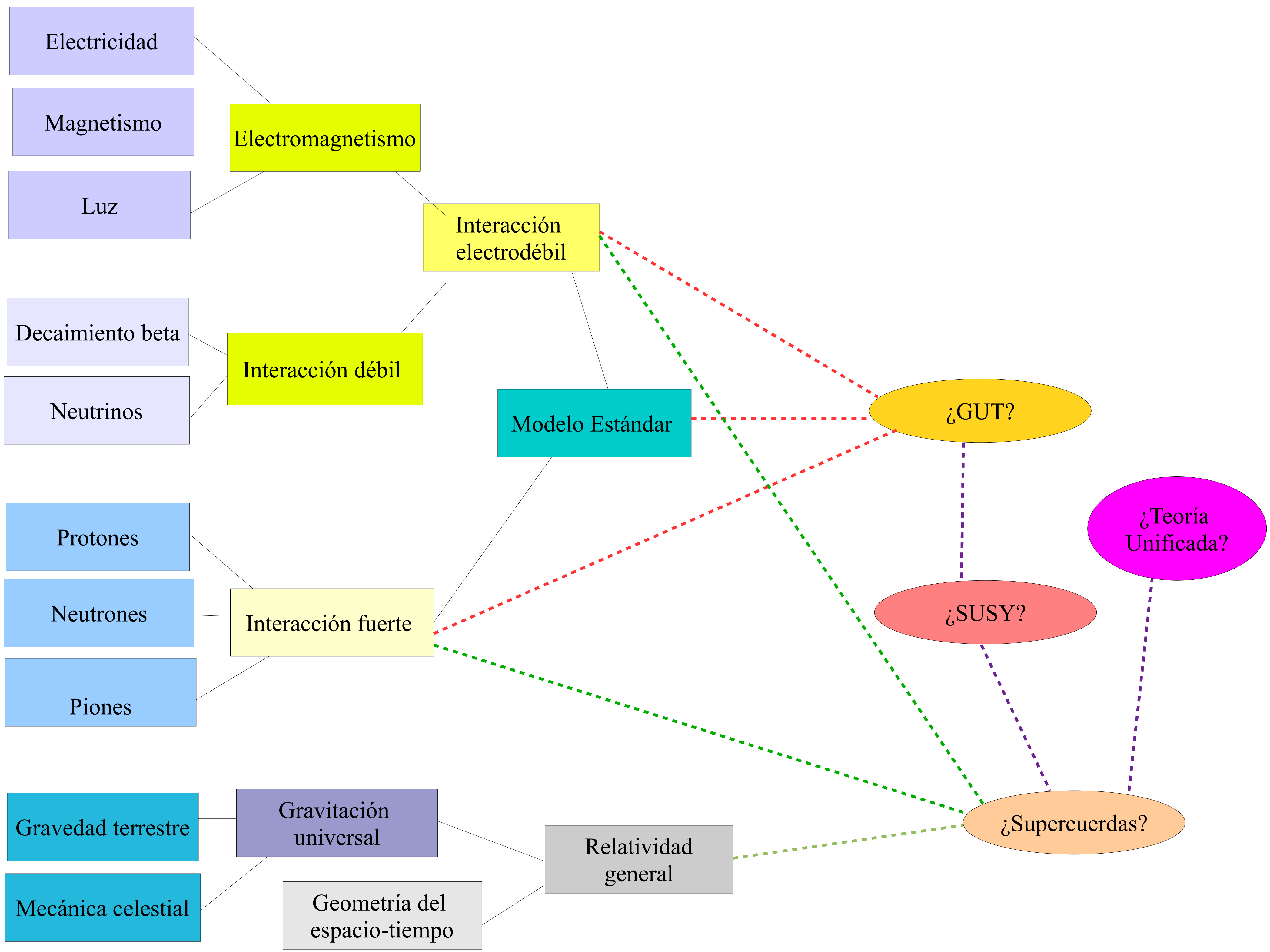
- MD = MPlanck, but it gets warped down to eW scale, r~10/k, k~ Planck scale $\Longrightarrow$ small extra dimension

$$\Lambda_\pi \sim M_{Pl}e^{-k\pi r} \sim \mathcal{O}(\mathrm{TeV})$$



Planck brane is warped down to weak brane. Higgs and other fields live on the weak brane

Gravity may propagate in the extra dimension $\Longrightarrow$ might produce a TeV resonance that is detectable — "RS graviton"


Electricidad
Magnetismo
Luz
Electromagnetismo
Interacción electrodébil
Decaimiento beta
Neutrinos
Interacción débil
Modelo Estándar
¿GUT?
¿Teoría Unificada?
Protones
Neutrones
Piones
Interacción fuerte
¿SUSY?
Gravedad terrestre
Mecánica celestial
Gravitación universal
Geometría del espacio-tiempo
Relatividad general
¿Supercuerdas?

Multi-Higgs models more particles

- 2HDM without SUSY
  - widely studied
  - different versions depending on how they couple to the other SM particles
- 3 or more HDM also possible
- Extra singlet Higgs models NMSSM

- Complex MSSM
  ℂMSSM

- More sources of CP violation
- Candidates for dark matter, with some discrete symmetry
- Might give explanation for the mass hierarchies and mixing of quarks and leptons

N-Higgs doublet models — NHDM

- Add more complex scleras electroweak doublets
  All with same hyper charge Y=1

$$V(\phi) = Y_{ij}\phi_i^\dagger\phi_j + Z_{ijkl}(\phi_i^\dagger\phi_j)(\phi_k^\dagger\phi_l)\,.$$

- $N^2 + N^2(N^2+1)/2$ real parameters:
  12 for 2HDM, 54 for 3HDM…
- Potential must be bounded by below, no charge or colour breaking minima
- Must respect unitarity bounds
- Can have CP breaking minima → baryogenesis (or disaster)

2HDM

- Most studied, experimental limits exist
- 4 parameters in the quadratic part
  10 parameters (6 real, 4 complex) in the quartic part
- Again: minimum must be bounded from below, neutral and satisfy perturbative unitarity bounds

$$\begin{aligned} V \;=\; & \underline{m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2 - m_{12}^2\phi_1^\dagger\phi_2 - (m_{12}^2)^*\phi_2^\dagger\phi_1} + \underline{\frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2} \\ & \underline{+\lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{\lambda_5}{2}(\phi_1^\dagger\phi_2)^2} + \underline{\frac{\lambda_5^*}{2}(\phi_2^\dagger\phi_1)^2} \\ & \underline{+\left[\lambda_6(\phi_1^\dagger\phi_1)(\phi_1^\dagger\phi_2) + \lambda_7(\phi_2^\dagger\phi_2)(\phi_1^\dagger\phi_2) + h.c.\right]}. \end{aligned}$$

- To analyse it: usually impose symmetries

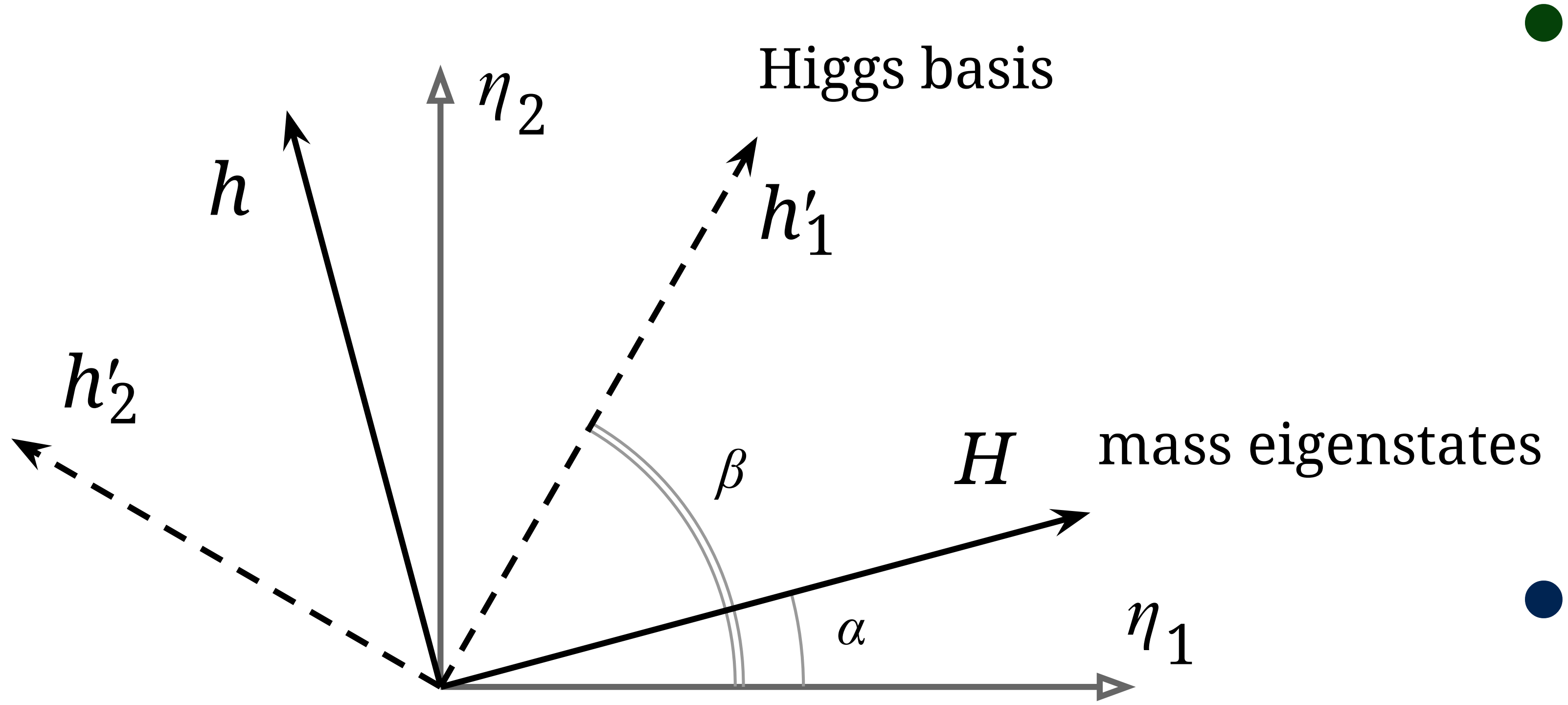
- Not all parameters are physical, only 11.

- Add more symmetries: No FCNC → Z_2 symmetry, softly broken by m_{12}^2 term

- Mainly two types of 2HDM analysed, 8 parameters:

  Type I: all fermions couple only to one doublet
  Type II: up quarks couple to one doublet, down quarks and leptons couple to the second doublet

- After eW symmetry breaking there are five massive physical Higgs bosons m_h, m_H, m_A, $m_{H^\pm}$, $\tan\beta$ (v1/v2), m_{12}^2, sen(β-α)
  α mixing angle between scalars



- (n1,n2) original basis in which there is natural flavour conservation
- (h1',h2') Higgs basis, all the vev is in one of the Higgses, rotated by β from original
- (h,H) physical Higgs bases, rotated by α from original, and by (β-α) from Higgs one

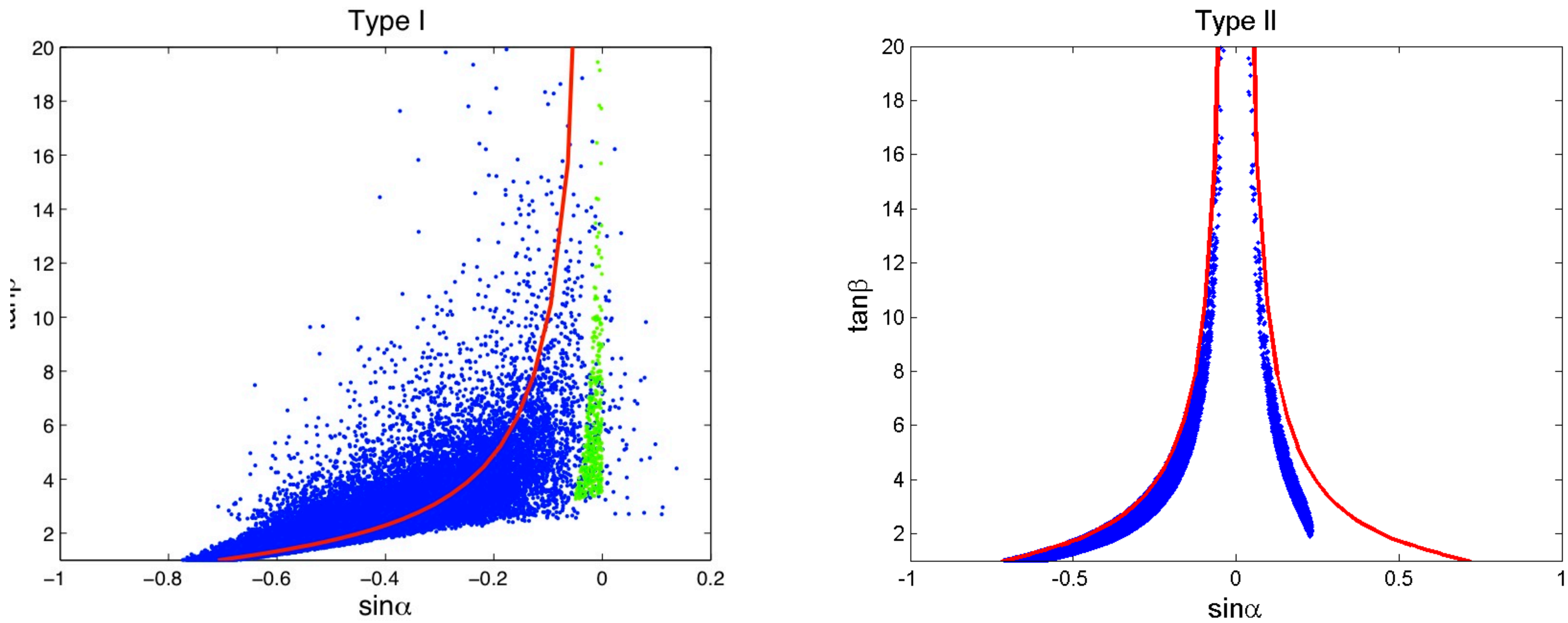
- How to test them? Look for signals of new physics

- Usual test focus on 2HDM type I and II, and on MSSM

- Heavy extra Higgs usually decoupled, difficult to discard the 2HDM

- Other new scalars would give similar results, so searches for new Higgses and scalars are complementary

- LEP excluded charge scalars M_H >80 GeV, and b—>sγ places stringer constraints M_H>480 GeV



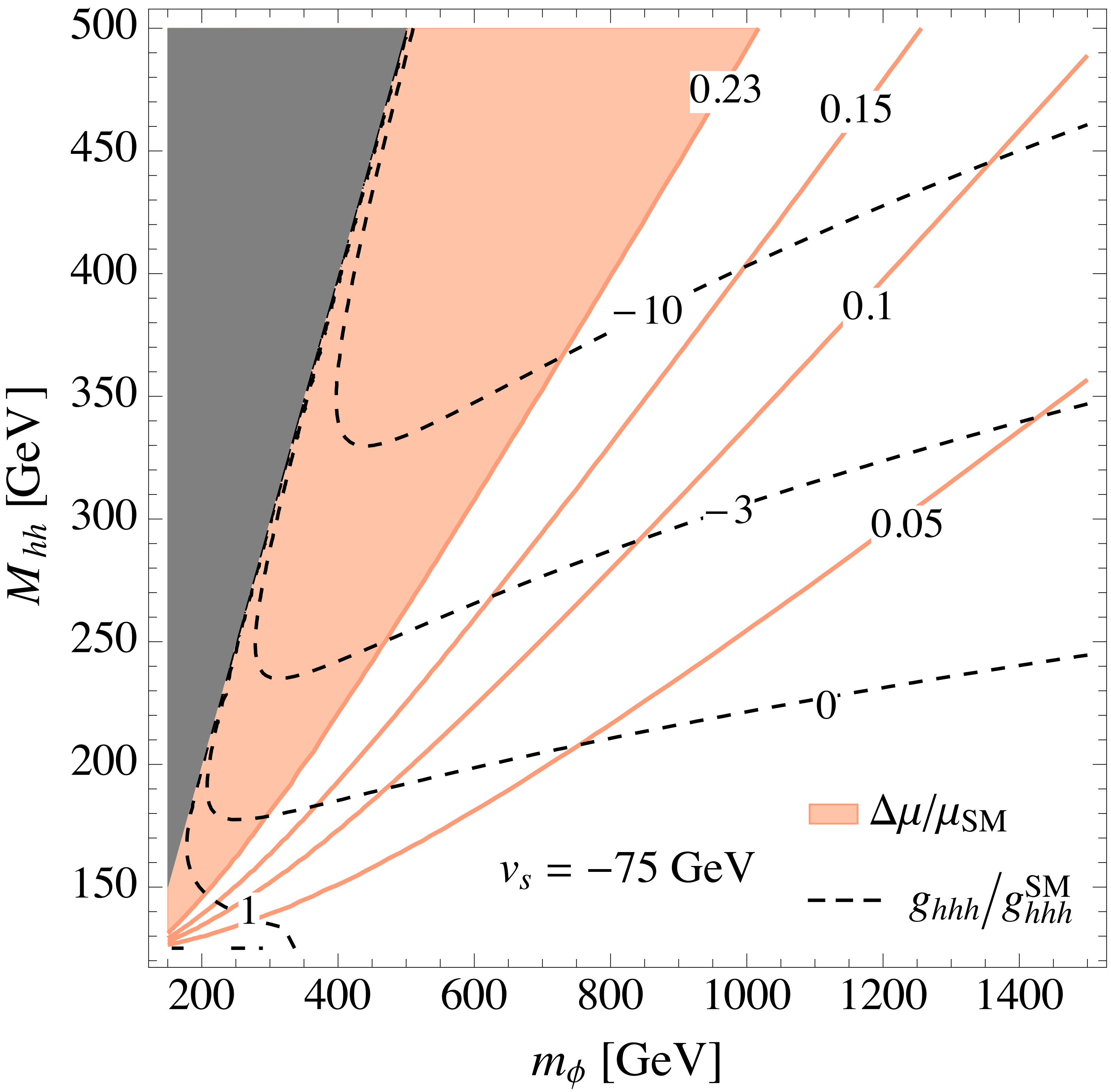
$$R_f = \frac{\sigma(pp \to h)_{\mathrm{2HDM}}\ \mathrm{BR}(h \to f)_{\mathrm{2HDM}}}{\sigma(pp \to h_{\mathrm{SM}})\ \mathrm{BR}(h_{\mathrm{SM}} \to f)}$$

Points that pass all constraints: Rf is the ratio of events predicted by 2HDM to the ones from SM, f is the final state particle
Green 1 sigma, blue 2 sigma, red SM limit

A. Barroso, P. M. Ferreira, R. Santos, M. Sher, J. P. Silva, 2HDM at the LHC - the story so far, in: Proceedings, 1st Toyama International Workshop on Higgs as a Probe of New Physics 2013 (HPNP2013): Toyama, Japan, February 13-16, 2013, 2013. arXiv:1304.5225.
URL http://inspirehep.net/record/1228915/files/arXiv:1304.5225.pdf

Adding singlets

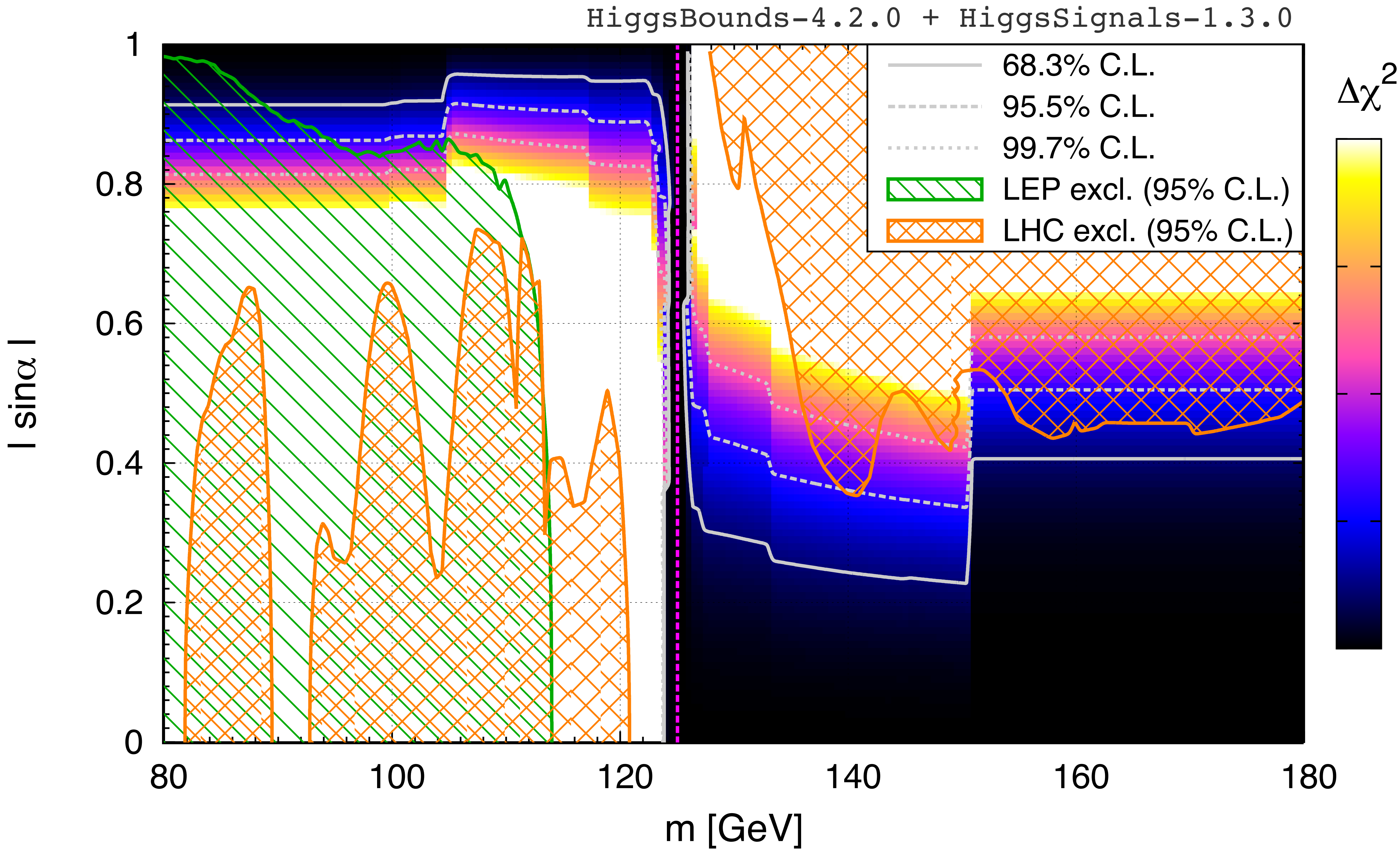
- Add only one scalar singlet, either real or complex
- Transforms trivially under SM, i.e. is a singlet
- Only couples to SM via the phi phi operator
- Could be there is a whole hidden sector, SM blind to it
- $V_{int} = \lambda_{hs}\phi^\dagger\phi S^2$, for a real scalar
- In the quartic interaction, the self-interaction of S can get a non-zero vev, which is equal to the $\mu^2\phi^\dagger\phi$ term in SM. This mass scale is normally put by hand
- They can give a natural candidate for dark matter, complex ones can give the right DM relic abundance



Parameters of real singlet extension:
v, tanbeta = v/vs, mh, mH, alpha (mixing angle of hs hSM)

Ratio of trilinear coupling to SM value, for vs = -75 GeV
Grey unphysical
Pink, exclusion at 95% from Higgs signal
Pink lines, different values of the mixing angle sin^2
Mhh (1,1) of the mass matrix before diagonalization

D. Buttazzo, F. Sala, A. Tesi, Singlet-like Higgs bosons at present and future colliders, JHEP 11 (2015) 158. arXiv:1505.05488, doi:10.1007/JHEP11(2015)158.



Constraints on mH, |sinalpha| plane, and from Higgs signal \Delta\chi^2
magenta line is the normal Higgs

T. Robens, T. Stefaniak, Status of the Higgs Singlet Extension of the Standard Model after LHC Run 1, Eur. Phys. J. C75 (2015) 104. arXiv:1501.02234, doi:10.1140/epjc/s10052-015-3323-y.

NMSSM

- Add a singlet to the MSSM → Next to MSSM
- The super potential gets modified, where f(S) is a polynomial of at most order three

$$\mathcal{W}_{\text{NMSSM}} = \mathcal{W}_{\text{MSSM}} + \lambda S H_u H_d + f(S)$$

- The superpotential is

$$V_{\text{soft}}^{\text{NMSSM}} \supset m_S^2 |S|^2 + \left(\lambda A_\lambda H_u H_d S + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.} \right)$$

- The Higgs mass is now

$$m_h^2 \lesssim \frac{\lambda^2 v^2}{2} s_{2\beta}^2 + m_Z^2 c_{2\beta}^2 + \Delta^2$$

- 7 physical Higgs bosons

- Large SUSY contribution to the Higgs mass → possible to achieve Mh = 125 GeV at tree level

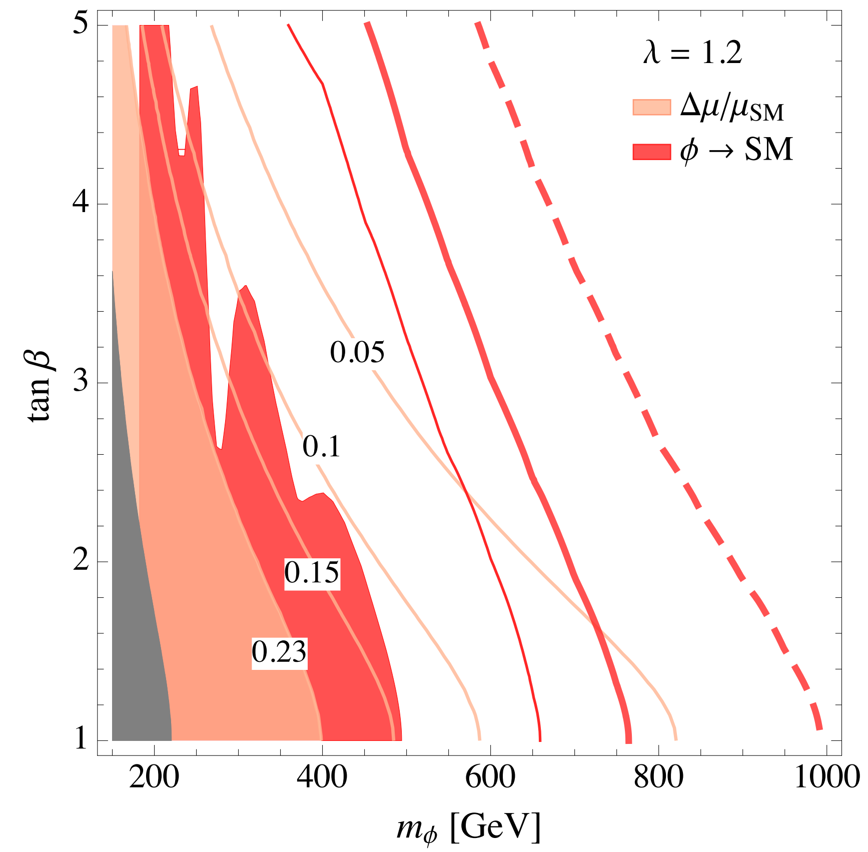
- Allows larger masses for stops and gluinos O(λ/g)

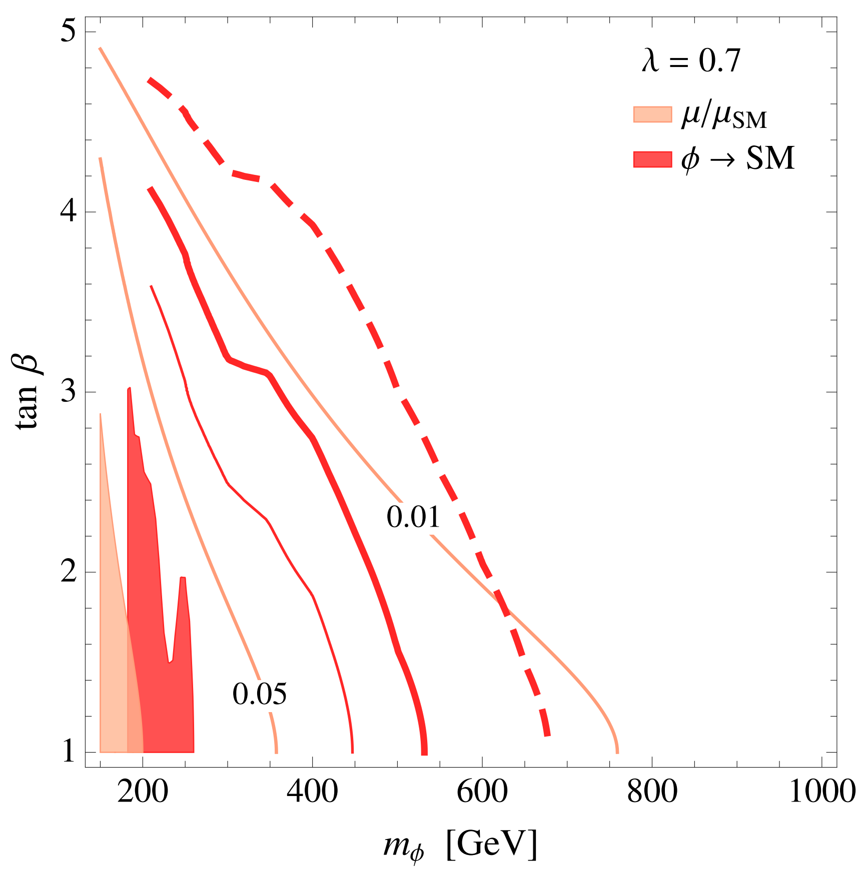
- The coupling λ is not asymptotically free, $\lambda > 0.7$ theory becomes strongly coupled, below the GUT scale

- λ ~ 1.2 strong coupling regime
  λ ~ 0.7 still perturbative at GUT scale

- If λ is sizeable → lightest new particles are the extra scalar bosons of the Higgs sector

Grey unphysical, pink and red excluded regions
Contours of fixed s2gamma





Projected: thin solid red LHC13
thick solid red LHC14
dashed red 14 HL-LHC

D. Buttazzo, F. Sala, A. Tesi, Singlet-like Higgs bosons at present and future colliders, JHEP 11 (2015) 158. arXiv:1505.05488, doi:10.1007/JHEP11(2015)158.

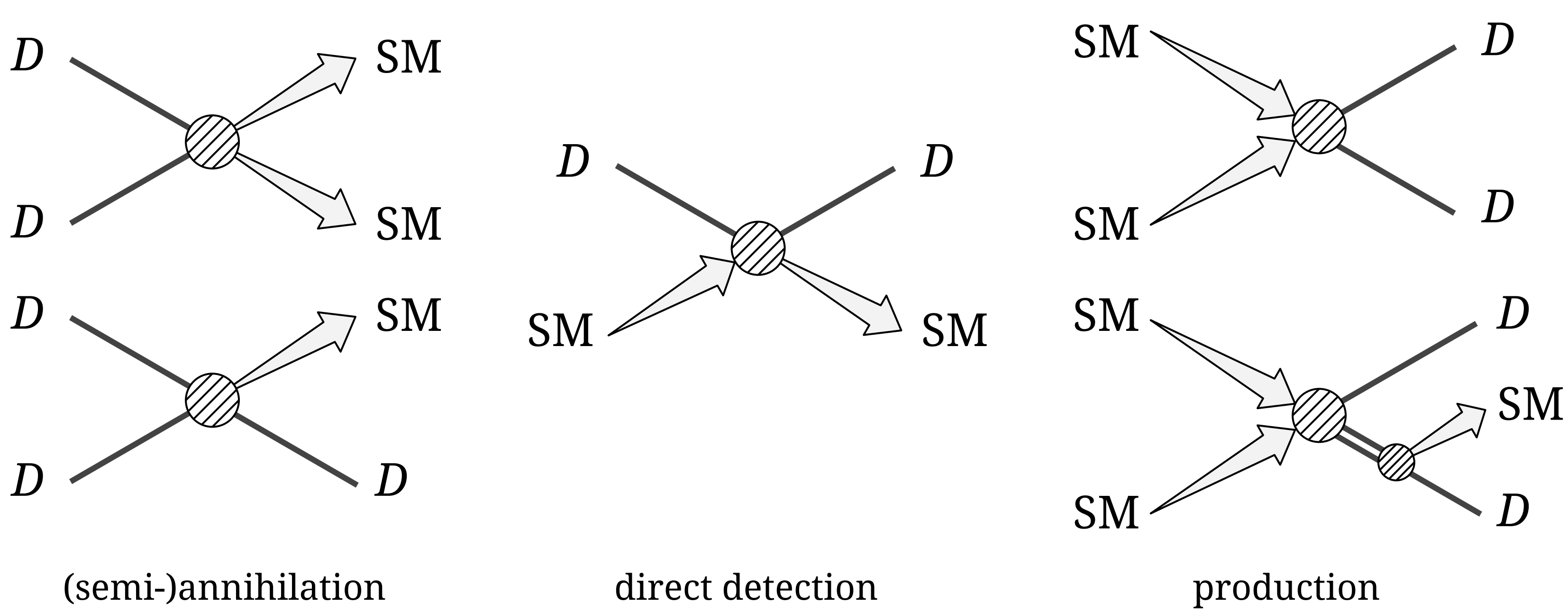
Dark Matter?

- Many models provide candidates for DM
  - sterile neutrinos, neutrinos
  - scalars, Higgses, K-K scalars, others
  - axion (solution to the strong CP problem), pseudoscalar
  - SUSY particles, neutralino, sneutrino, axino
  - Decaying DM

- DM-DM interactions
- Most models assume WIMP
- Usually require a discrete symmetry to make them stable
- Constraints from cosmology: relic density, structure formation, BBN
- DM could be more than one type of particle

Scalar dark matter popular now

- Natural in models with extended Higgs sectors and global symmetries, like Z2
- These symmetries may remain unbroken after eW symmetry breaking $\Longrightarrow$ DM candidate stable

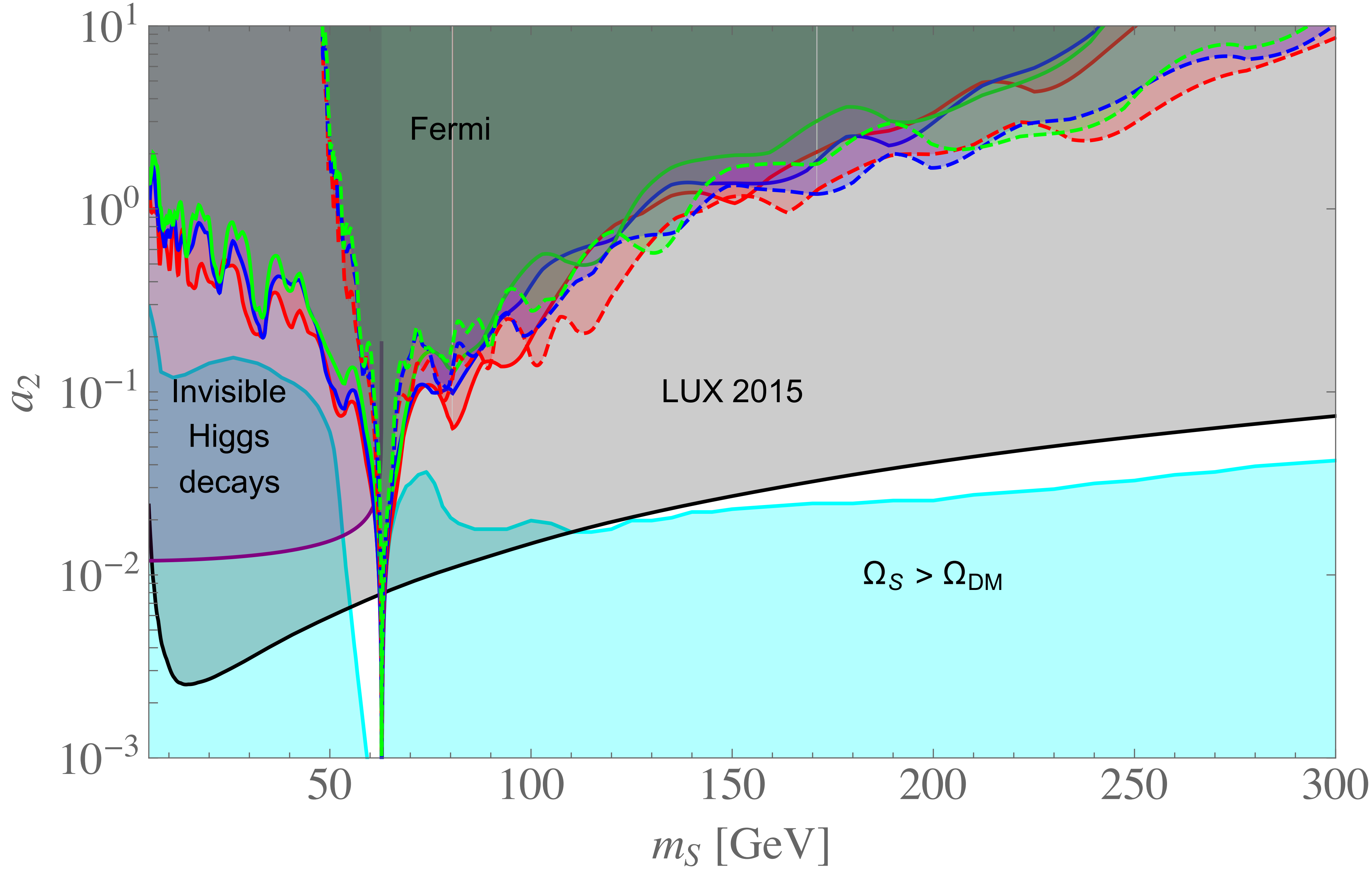


Building and testing models with extended Higgs sectors
Igor P. Ivanov, arXiv:1702.03776 [hep-ph].

- annihilation, co-annihilation and semi-annihilation will determine DM abundance
- also missing energy signature in colliders
- Example: minimal dark matter. Add extra scalars in higher dimensional reps of SU(2), only renormalizable interactions in Lagrangian.
- If lightest component neutral $\Longrightarrow$ DM candidate
- They are used also to explain small neutrino masses

Real singlet extension

- One real gauge singlet and a Z2 symmetry
- Symmetry makes DM stable and prevents it from mixing with neutral part of the doublet
- Correct DM relic abundance for some values of the coupling λ between SM-DM
- Cannot be too heavy (above TeV), or runs into trouble with perturbative constraints



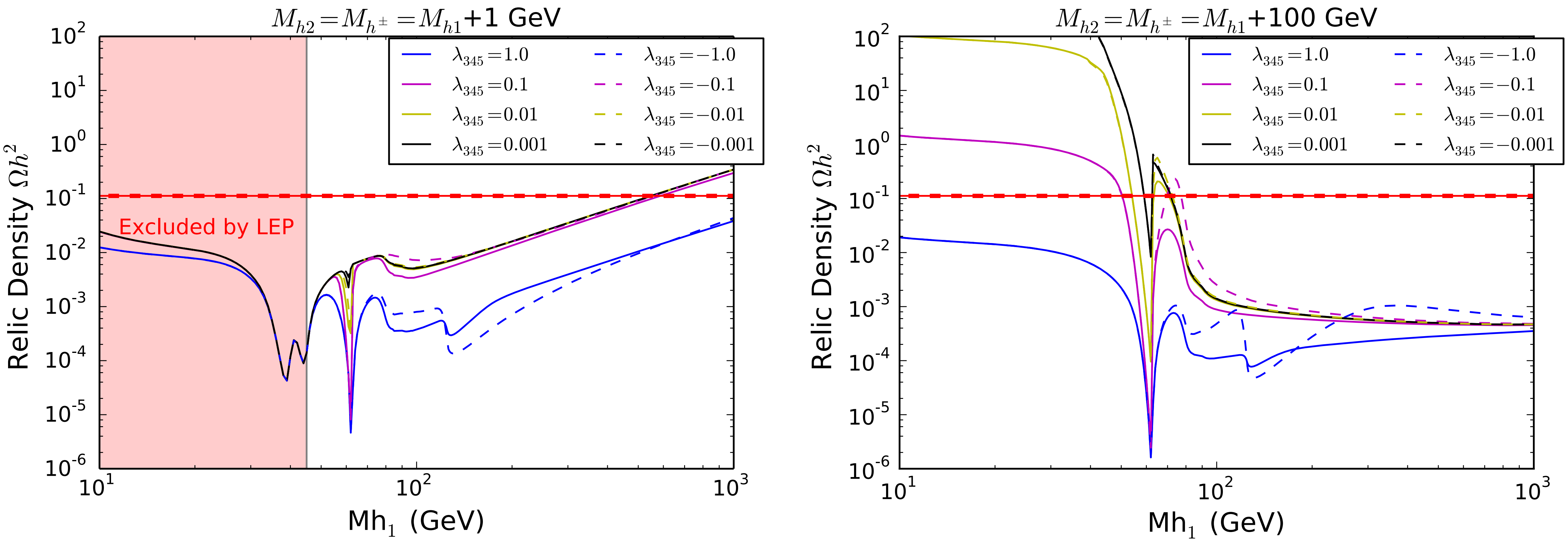
singlet DM: almost excluded by LHC, Planck, Fermi and LUX
white region still allowed

L. Feng, S. Profumo, L. Ubaldi, Closing in on singlet scalar dark matter: LUX, invisible Higgs decays and gamma-ray lines, JHEP 03 (2015) 045. arXiv:1412.1105, doi:10.1007/JHEP03(2015) 045.

Inert doublet model

- 2HDM type 1 with Z2 symmetry has natural DM candidate
- <H2> = 0, i.e. inert, in large parts of parameter space, odd under Z2
- Heavier scalars from this doublet decay into the lightest one
- DM annihilation, co-annihilation and collider signatures possible
- Masses are

$$M_{h^+}^2 = \frac{1}{2}\lambda_3 v^2 + m_{22}^2\,, \quad M_{h_1}^2, M_{h_2}^2 = \frac{1}{2}(\lambda_3 + \lambda_4 \mp |\lambda_5|)v^2 + m_{22}^2\,.$$



quasi degenerate and large mass splitting limits in IDM
small mass region ruled out by LHC and Planck
red line: relic density

A. Belyaev, G. Cacciapaglia, I. P. Ivanov, F. Rojas, M. Thomas, Anatomy of the Inert Two Higgs Doublet Model in the light of the LHC and non-LHC Dark Matter Searches`arXiv:1612.00511`.

Flavour/family symmetries more symmetries

- Add the flavour symmetry of your choice

- Continuous → upon breaking might generate massless Goldstone bosons U(1), SU(3)...

- Discrete Z_N, A4, S3, S4, Q6, Δ27...
  → might also generate accidental continuous symmetries

- Explain masses and mixings of quarks and leptons

- Usually also add more particles → Higgs

Flavour symmetries

- Mass hierarchy of quarks and charged leptons very hierarchical
- Mass hierarchy also in neutrino sector, but whether normal or inverted hierarchy unknown
- Small mixing in quarks, but large mixing in leptons
- Perhaps there is an underlying flavour/family symmetry

- Abelian or non-Abelian?
- Abelian symmetries have all uni-dimensional irreps
- Need non-Abelian symmetries, have irreps of more than one dimension $\Longrightarrow$ possible to explain the patterns of masses and mixings

- Discrete or continuous?
- Breaking of continuous symmetries leads to Goldstone bosons
- Discrete symmetries have several representations of small dimension $\Longrightarrow$ appropriate to describe three generations

- Non-Abelian, discrete groups widely studied recently

- Permutational symmetries: S_N, A_N

- Dihedral symmetries: D_N

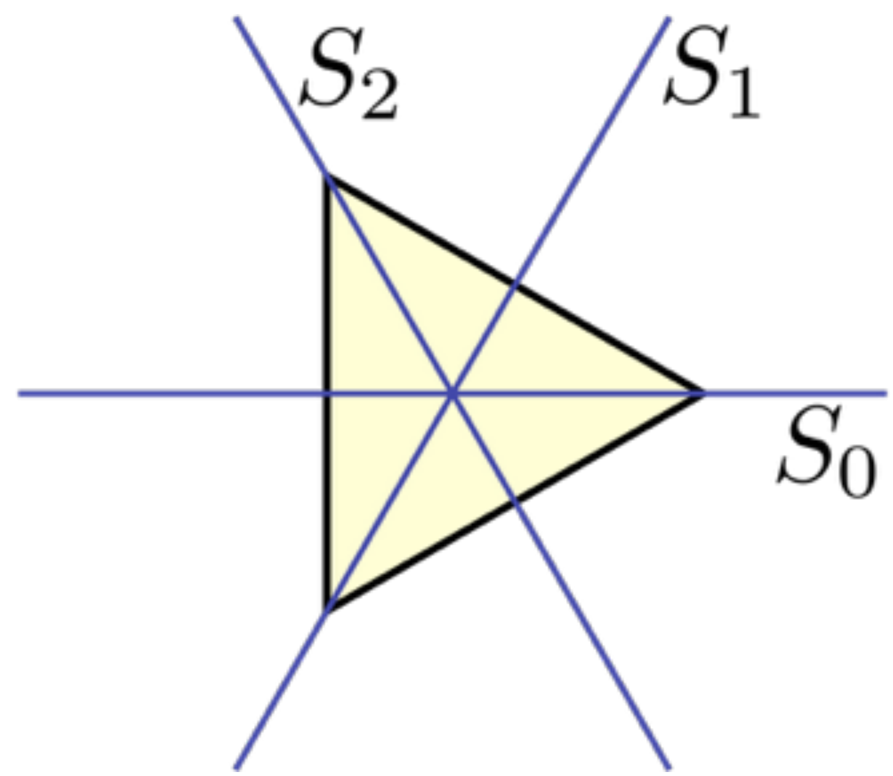
- Double valued dihedral symmetries: D_N'
  Other double valued groups: T', O'

- Subgroups of SU(3): $\Delta(3n^2)$, $\Delta(6n^2)$

3HDM with S3

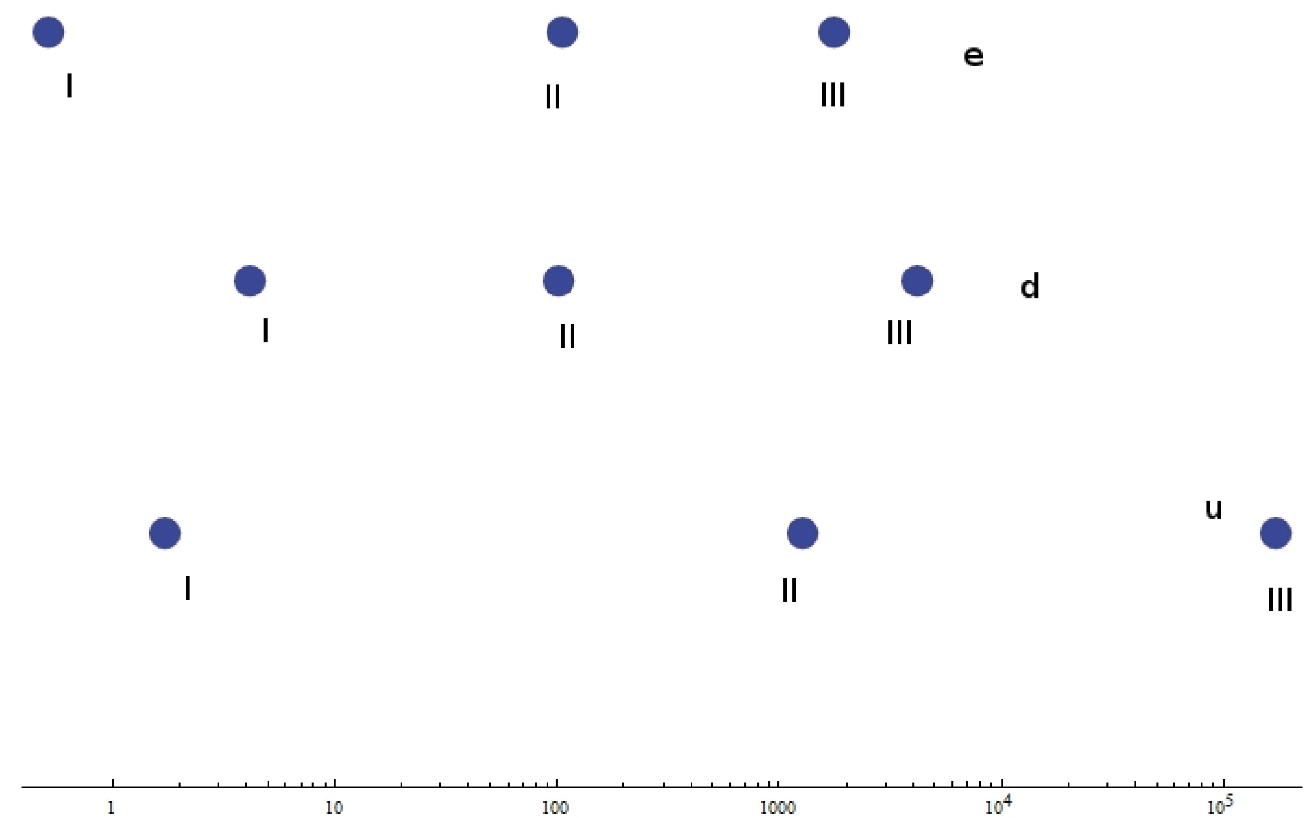
- Low-energy model
- Extend the concept of flavour to the Higgs sector by adding two more eW doublets
- Add symmetry: permutation symmetry of three objects, symmetry operations (reflections and rotations) that leave an equilateral triangle invariant

- 3HDM without symmetry: 57 couplings in the Higgs potential

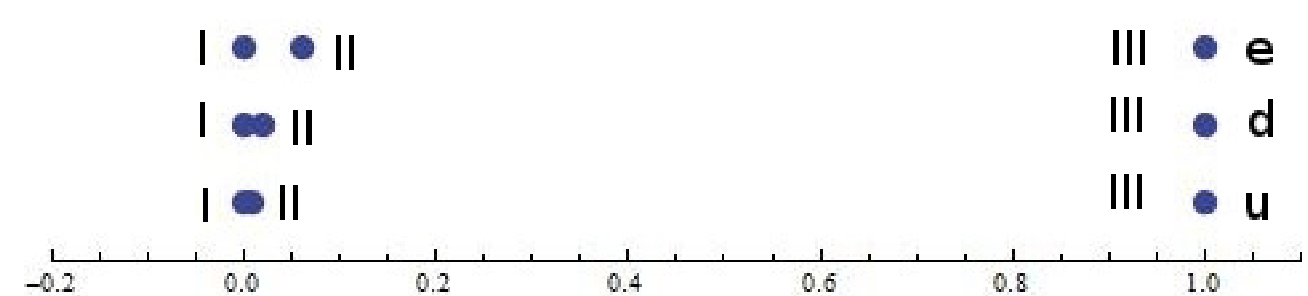


Why a particular symmetry?

- Prior to the eW symmetry breaking all families look the same → permutation symmetry
- Smallest non-Abelian group discrete group S3
- Has irreducible representations: 2, 1_S, 1_A



Logarithmic plot of fermions



Mass ratios

Predictions, advantages?

- Possible to reparametrize mixing matrices in terms of mass ratios, successfuly
- Reproduces well CKM → one less parameter as SM
- PMNS → fix one mixing angle, predictions for the other two within experimental range
- Predicts reactor angle $\theta 13 \neq 0$
- No extra flavons
- 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
  Natural decoupling limit
- Further predictions will come from Higgs sector:
  decays, branching ratios

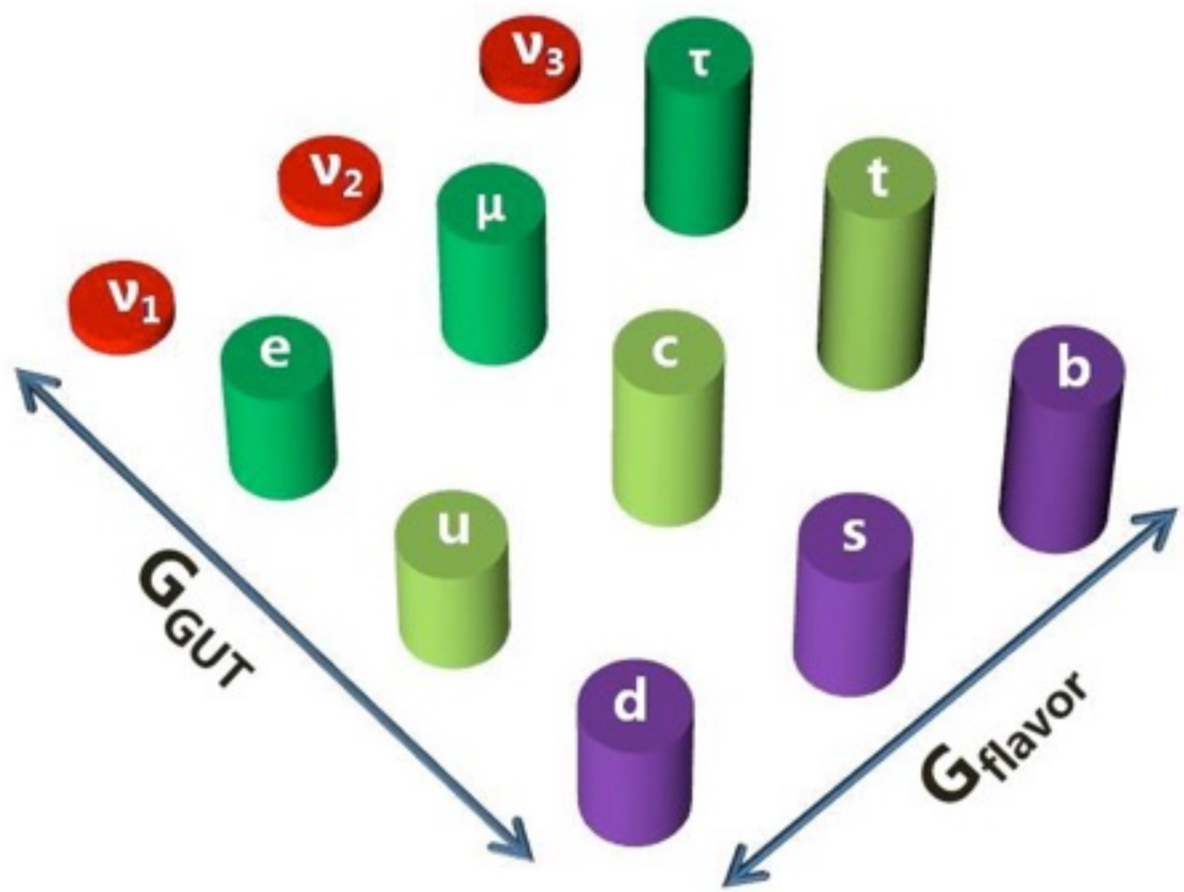
A. Mondragón, M. M., F. González, E. Peinado, U. Saldaña, O. Félix, E. Rodríguez, A. Pérez, H. Reyes...

A4 symmetry

- Symmetry group of a tetrahedron, even permutations of four objects
- Four irreducible representations: 1, 1', 1", 3
- Fermions can be nicely assigned to the 3
- It predicts the tri-bimaximal mixing, which is now ruled out by experiment
- Symmetry has to be broken softly to reproduce the mixing pattern
- Deviations from tri-bimaximal mixing may come from higher dimensional operators from neutrino sector

$$\sin^2(\theta_{12}^{TB}) = \frac{1}{3}\,, \quad \sin^2(\theta_{23}^{TB}) = \frac{1}{2}\,, \quad \sin^2(\theta_{13}^{TB}) = 0.$$

Add a discrete flavour symmetry to a SUSY GUT theory



Interplay between
the different symmetries
(and their breaking)
would lead to an explanation
of the fermionmass hierarchies

- SU(5)xA4, SU(5)xQ6, SU(5)xS4xU(1), SU(5)xT7…

- SO(10)xS3, SO(10)xS4, SO(10)xD4, SO(10)xA4, SO(10)xΔ(54)…

- Many of these models also have extra Abelian discrete symmetries Z_N, besides the GUT and the flavour symmetries

- The addition of discrete symmetries might lead to accidental continuous symmetries

- After eW symmetry breaking there might be surprises $\Longrightarrow$ unwanted Goldstone bosons from the continuous symmetries

- There might also be residual discrete symmetries $\Longrightarrow$ can spoil the pattern of masses and mixings

Extra U(1)'s

- Well motivated, they appear naturally when breaking large unification groups to SM
- Also appear in string compactifications
- In SUSY GUTs and string compactifications U(1)' and SU(2)xU(1) breaking tied to soft SUSY breaking
- At TeV, proposed to alleviate the quadratic divergences in the Higgs mass
  - Dynamical symmetry breaking models often include U(1)'s
  - In some models associated with almost-hidden sectors

How do we sieve through models/ideas

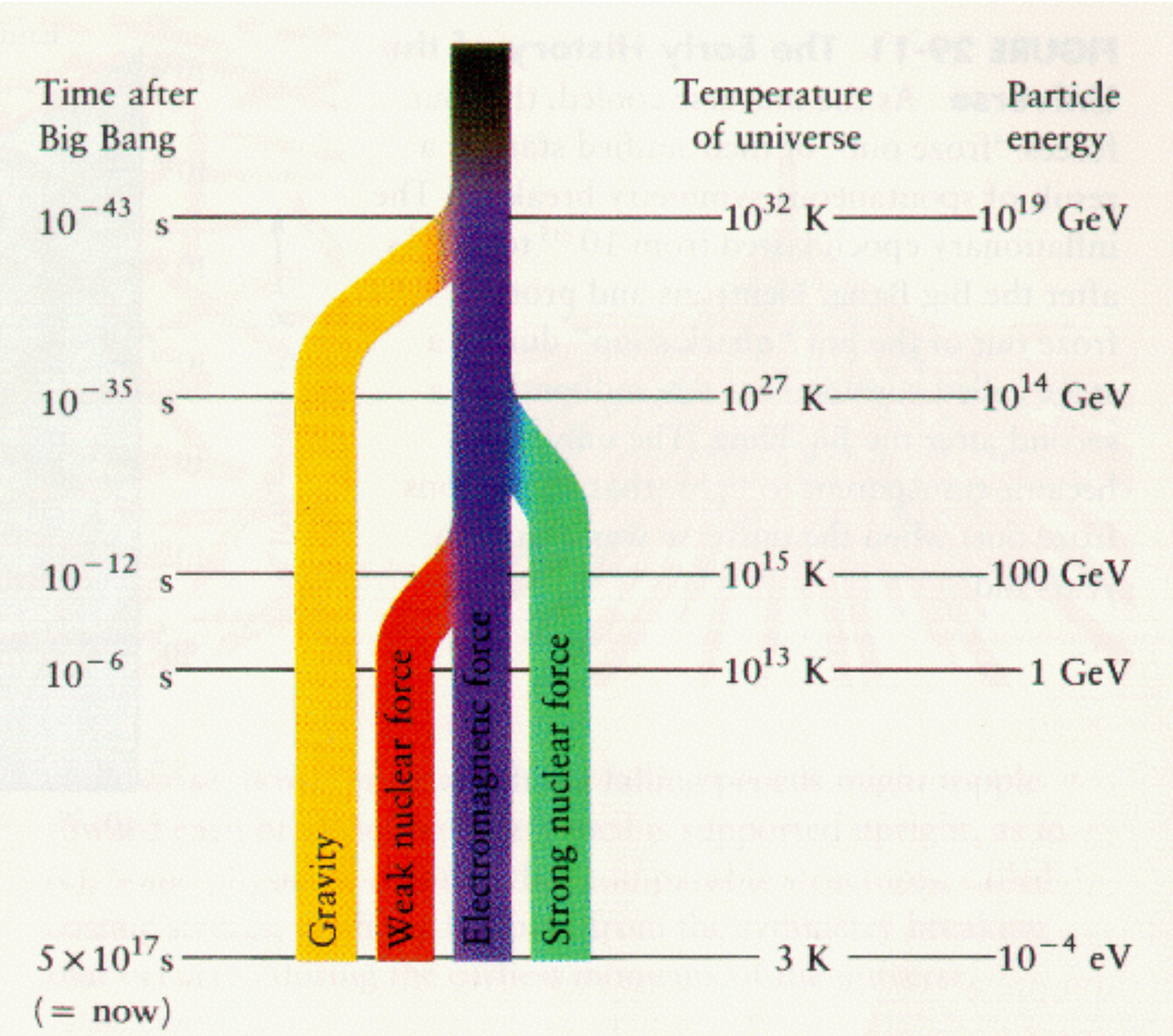
- Interplay between theory and experiment
- Models have to provide predictions and/or explanations to the SM open questions
- Each extension BSM has assumptions that have to be spelled out explicitly to be able to test it
- Applies to theory and experiment
- Theoretical uncertainties have to be taken into account (not only experimental)
- Most successful models combine more than one idea

Going BSM — assumptions

- Usually do not break Lorentz or gauge invariance
  These symmetries are too fundamental to mess around with…
- Respect experimental results (not everybody likes to)
  These are facts of life, even if for some of them origin not understood
- Guiding principles: mathematical consistency and experimental compatibility
- Many assumptions are a matter of "taste", acknowledge it

Where (in energy) are these models realized?

- Depends...
  - some models are valid around few TeV and a “bit” above
  - some models assumed valid to TeV to the GUT or Planck scale
  - some models valid only at GUT or Planck scale
- If they are described by a QFT we can use Renormalization Group Equations (RGE) to test them at different scales



String theory

GUTS

ν_R

SUSY

Extra Higgses

other symmetries

Conclusions

- There is unknown physics to explore $\rightarrow$ BSM
- To discover it we need an interplay between mathematical consistency (theories), experiments and observations in particle physics, cosmology and astrophysics
- There is a lot of work to do...