New Physics in Non-SUSY Grand Unified Theories

Sofiane Boucenna
KTH Royal Institute of Technology & Oskar Klein Center

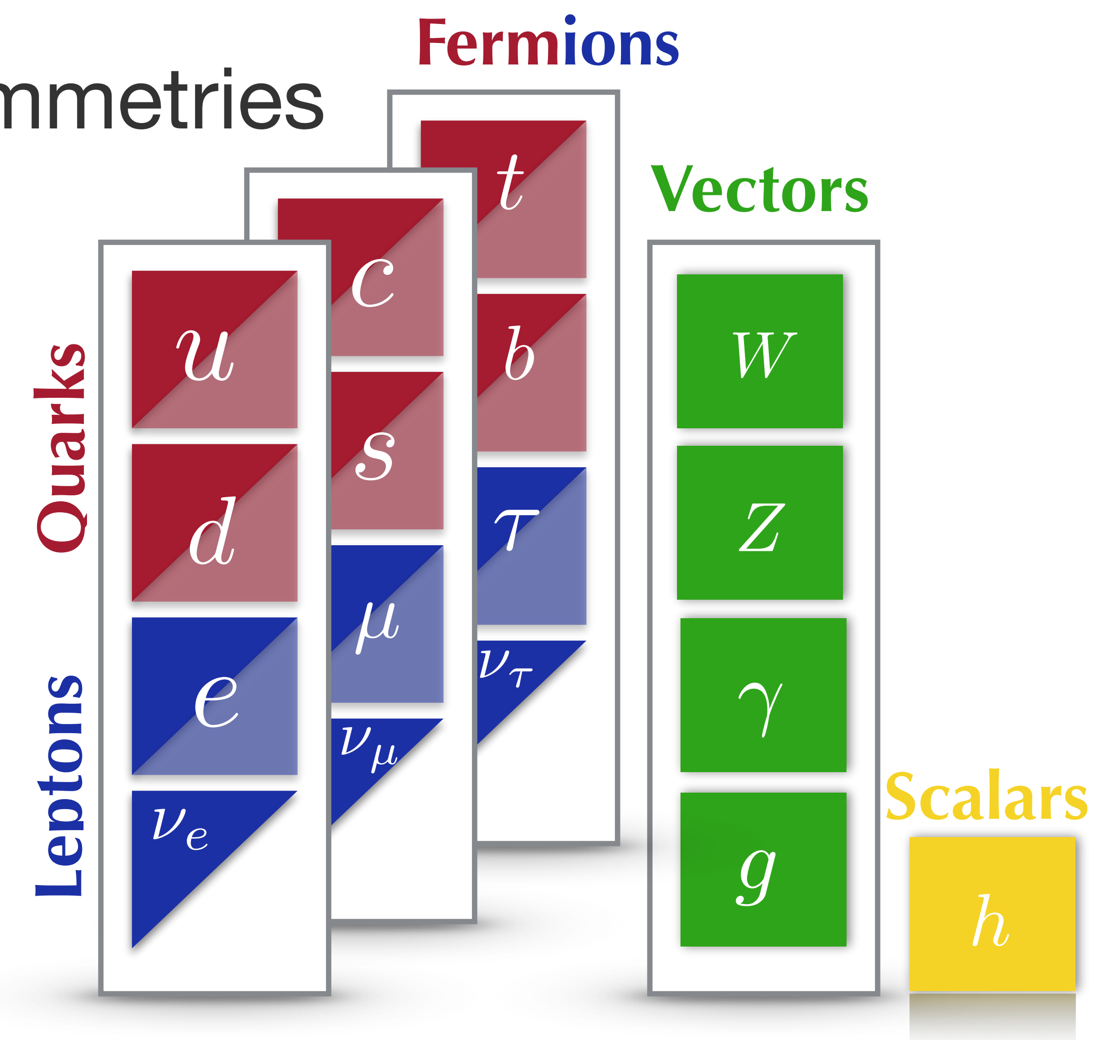
Southampton - 28/09/2018.

The Standard Model explains "everything" down to 10^{-16} cm

It is based on a few core concepts:

- Quantum field theory
- Gauge "symmetries"
- Spontaneous breaking of gauge symmetries
- Quark confinement

$$\begin{pmatrix} e_L \\ \nu_{eL} \end{pmatrix} \quad e_R \quad \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad u_R \quad d_R$$



But on aesthetic and quantitative grounds, the SM looks ad-hoc and incomplete

3 symmetry groups
5 distinct fermionic representations per family
3 distinct families
Fermions mixing patterns unexplained
Charge quantization unexplained
Unexplained anomaly cancellation
Strong CP problem
Unstable electroweak vacuum
Hierarchy problem

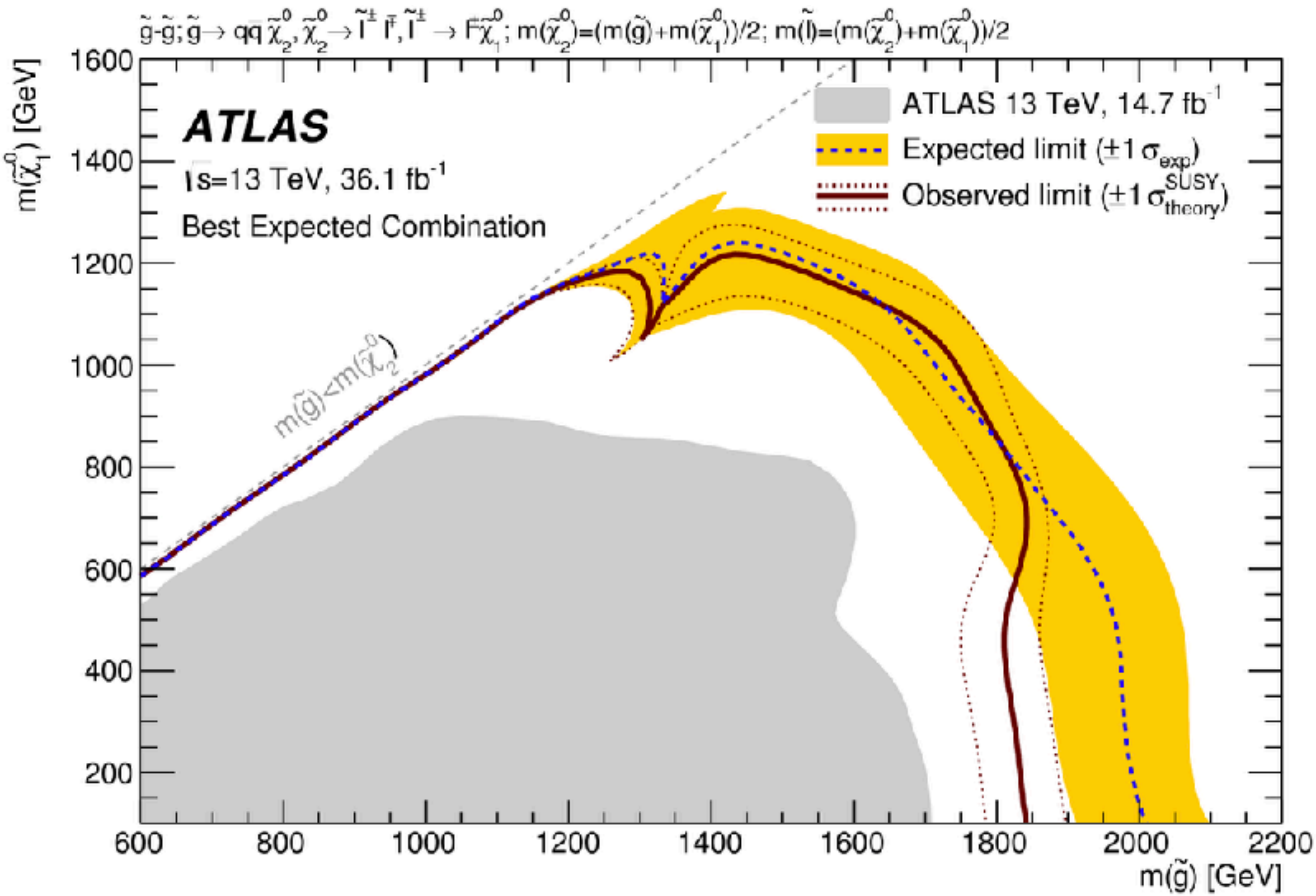
No explanation for neutrino masses
No dark matter candidate
No explanation for matter-antimatter asymmetry
No inflationary phase

Naturalness as a guide. SUSY!

3 symmetry groups
5 distinct fermionic representations per family
3 distinct families
Fermions mixing patterns unexplained
Charge quantization unexplained
Unexplained anomaly cancellation
Strong CP problem
Stabilized electroweak vacuum
Hierarchy problem

Neutrino masses via bilinear R-parity violation
Neutralino WIMP Dark matter
Electroweak baryogenesis
Chaotic inflation model in supergravity

But … where is SUSY?



[ATLAS collab.Eur. Phys. J. C 78 (2018) 625]

Post-naturalness model-building?

There are many idealistic motivations for SUSY: elegance, relation between matter and forces, relation between gravity and the other forces, etc. However, while SUSY is certainly not ruled out … it is becoming increasingly hard to keep it natural.

If we don't take naturalness as a guide for model-building, then what kind of framework could help us uncover the shape of the physics BSM?

Candidates include: EFTs, compositeness, toy models

Non-susy GUTs can explain a lot

3 symmetry groups
5 distinct fermionic representations per family
3 distinct families
Fermions mixing patterns from running
Explain Charge quantization
Explain anomaly cancellation
Strong CP problem
Stabilize electroweak vacuum
Hierarchy problem

Neutrino masses via seesaw
WIMP Dark matter
Baryogenesis via leptogenesis
Inflation via new higgses

This talk:
discussion of some non-susy GUTs as motivation for New Physics phenomena

Plan:

- General introduction
- SU(5) GUT
- SO(10) GUT

1/3
Introduction

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

We present a series of hypotheses and speculations leading inescapably to the conclusion that SU(5) is the gauge group of the world—that all elementary particle forces (strong, weak, and electromagnetic) are different manifestations of the same fundamental interaction involving a single coupling strength, the fine-structure constant. Our hypotheses may be wrong and our speculations idle, but the uniqueness and simplicity of our scheme are reasons enough that it be taken seriously.

Georgi-Glashow's minimal SU(5)

Matter is contained in only 2 representations

$$\mathbf{5} = \begin{pmatrix} e_L \\ \nu_{eL} \end{pmatrix} \oplus d_R \qquad \mathbf{10} = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \oplus u_R \oplus e_R$$

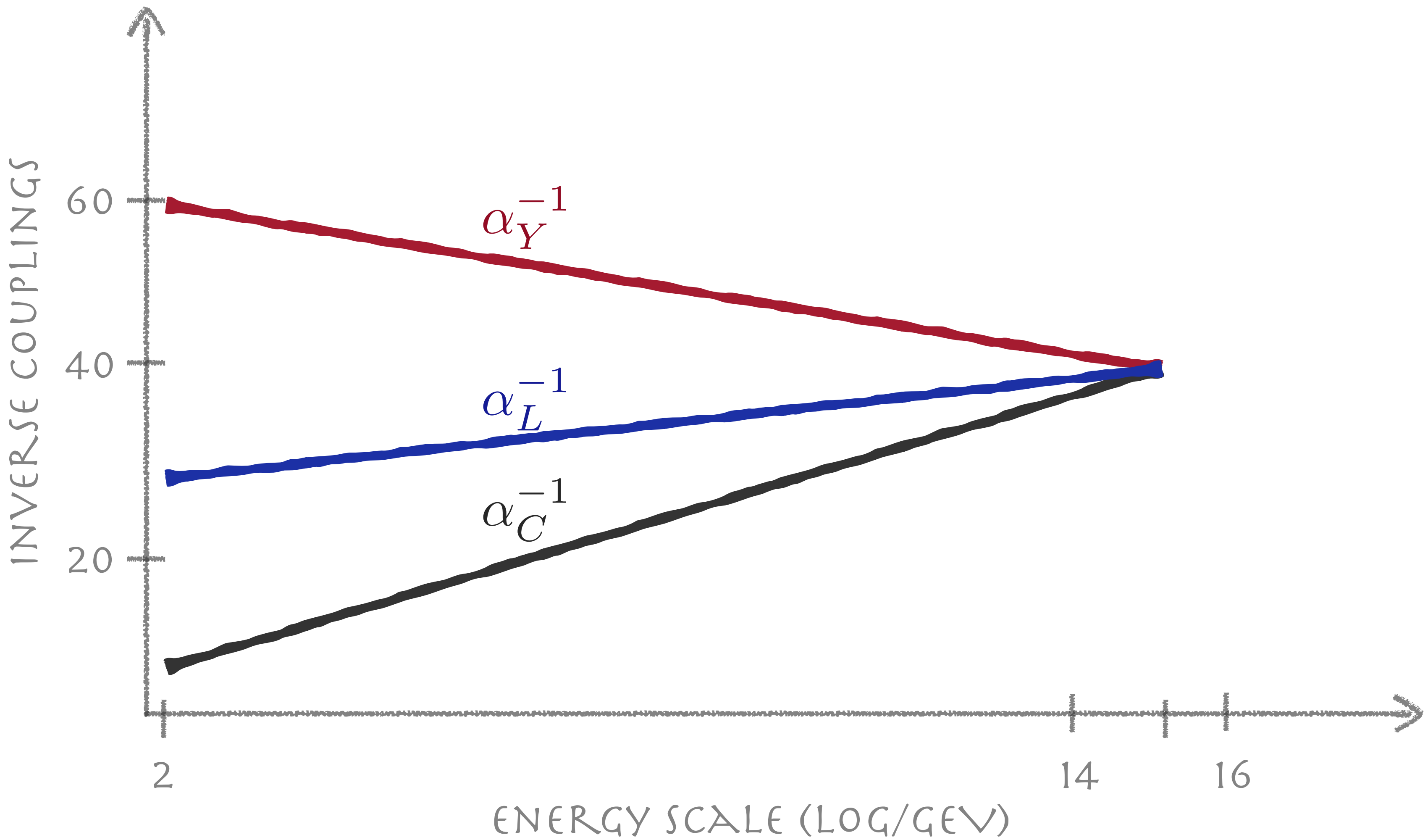
Higgses are in another **5** (Breaks EW)
and in **24** (breaks SU(5))

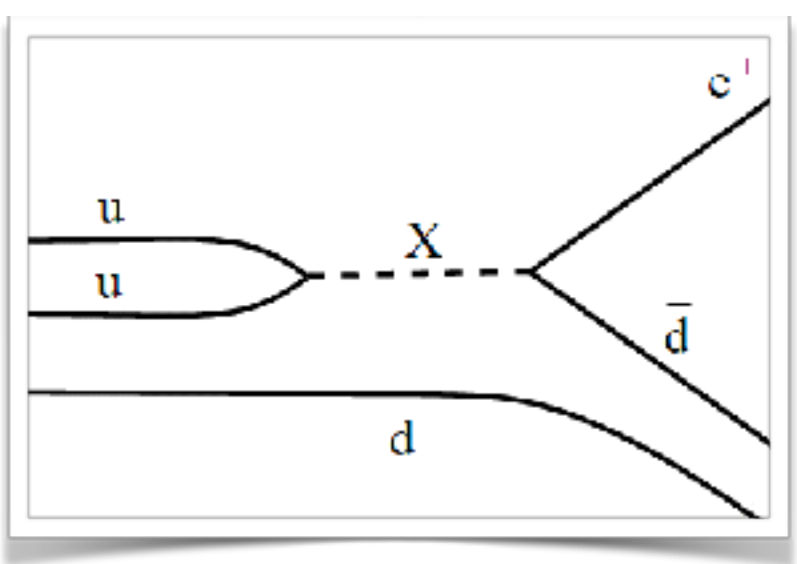
Quarks and leptons are unified

Gauge couplings are unified

Anomaly cancellation and charge quantization are explained

Gauge and matter unification imply protons are not forever!





$$\tau_p \sim \frac{M_X^4}{\alpha_U^2 M_P^5}$$

$$\sim \left(\frac{M_X}{10^{15}\,\mathrm{GeV}}\right)^4 10^{32}\ \mathrm{yrs}$$

Unfortunately, it is ruled out!

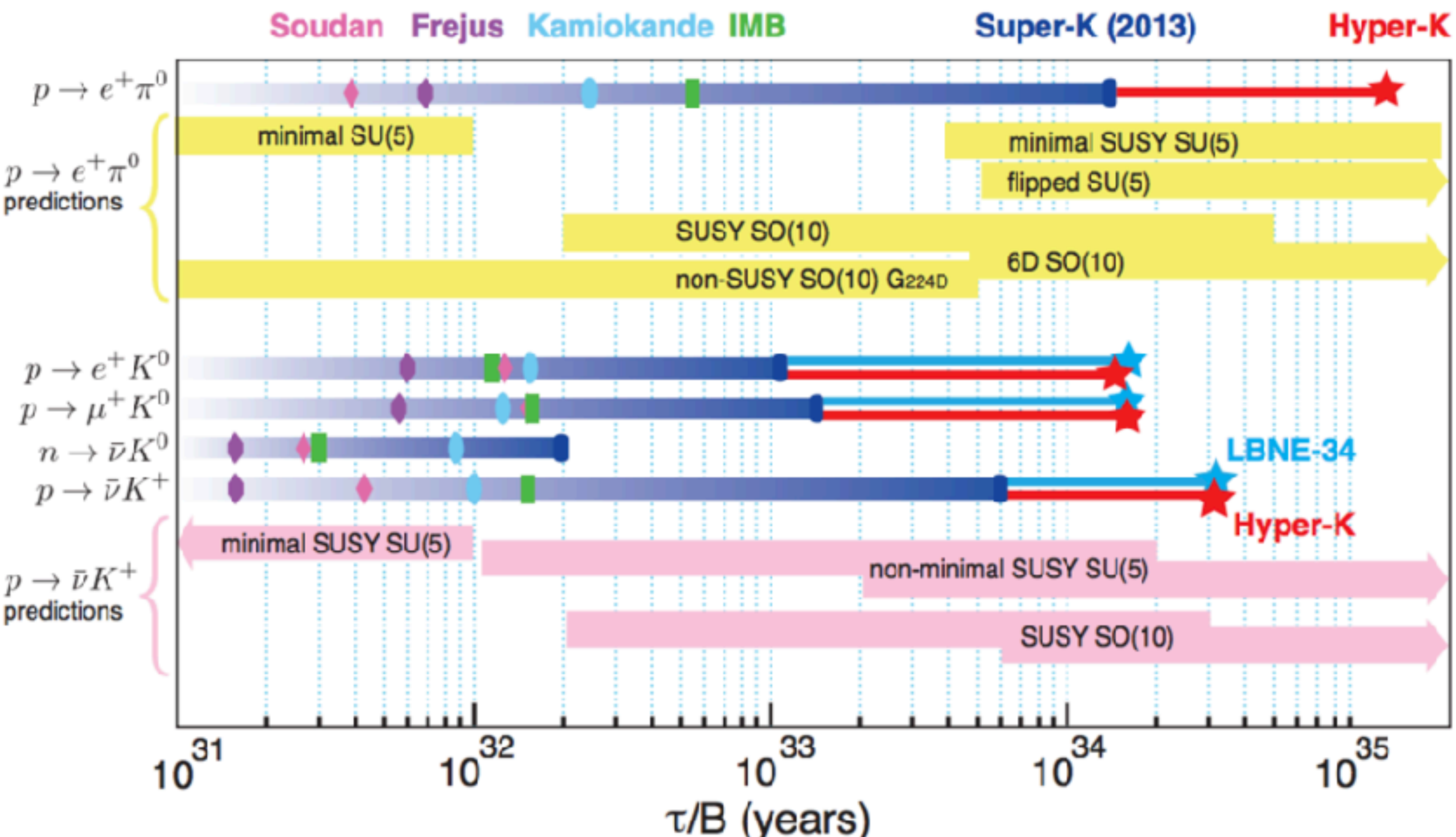
Protons are too short-lived
2 orders below current limits

Wrong mass predictions
M(charged leptons)=M(down quarks)

No solution to neutrino masses, baryon asymmetry, and dark matter.

The end?

Lessons from Georgi-Glashow's SU(5): GUTs are testable!



[Snowmass report '13]

A step further: SO(10)

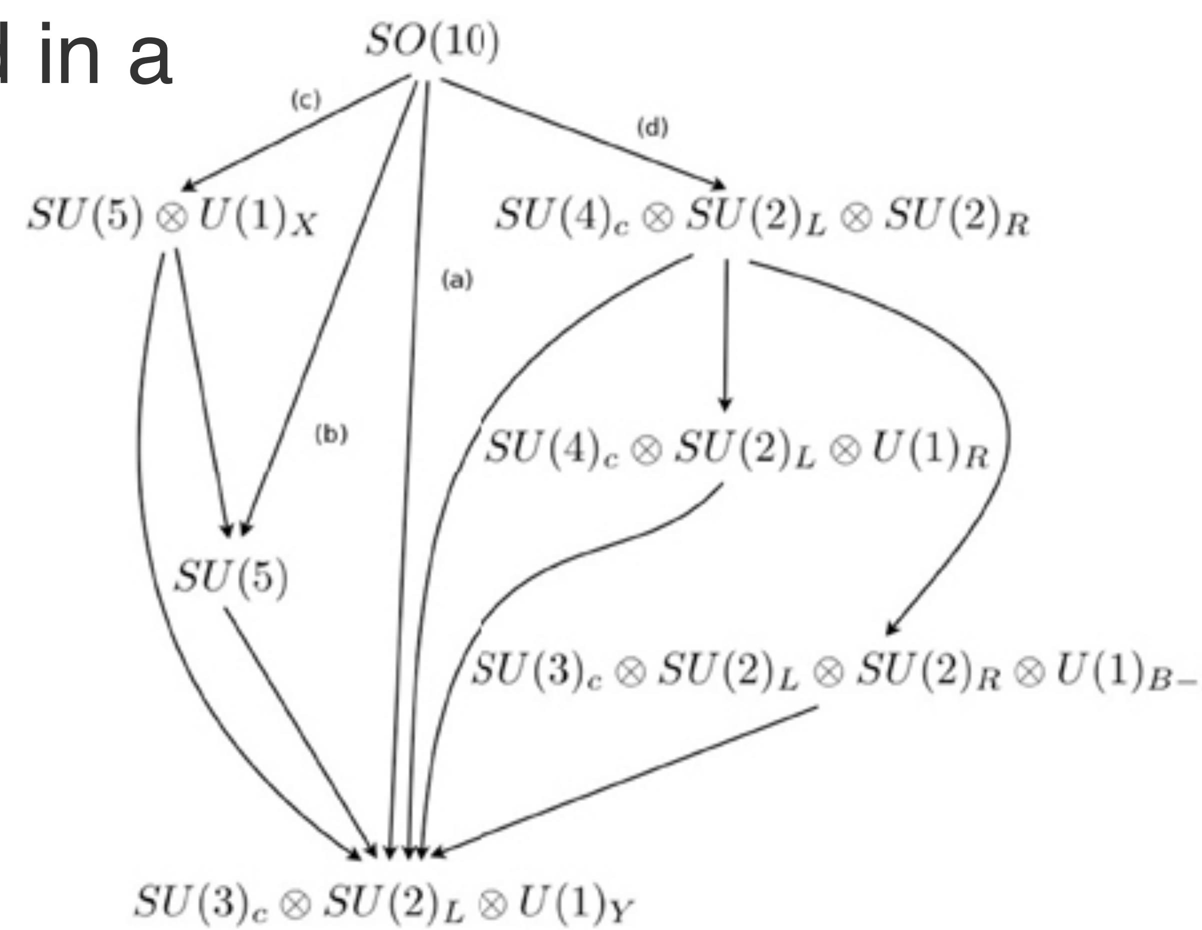
SO(10) is a rank 5 group that contains SU(5);

$$SO(10) \to SU(5) \times U(1)$$

Remarkably, **all** the SM fermions + the right-handed neutrino are included in a single multiplet: **16 = 5 + 10 + 1**

$$\mathbf{16}^T = (Q,\ u^c,\ d^c,\ L,\ \nu^c,\ e^c)$$

New intermediate symmetries are possible!



SO(10) is a very constraining symmetry. Can we fit all the SM with the new data?

We consider a simple Yukawa sector consisting of **10+126**. And run the parameters down from GUT to fit the SM parameters and neutrino masses

$$
\begin{aligned}
Y_u &= \frac{1}{v_{SM}}(v_{10}^u Y_{10} + v_{126}^u Y_{126}) \\
Y_d &= \frac{1}{v_{SM}}(v_{10}^d Y_{10} + v_{126}^d Y_{126}) \\
Y_D &= \frac{1}{v_{SM}}(v_{10}^u Y_{10} - 3v_{126}^u Y_{126}) \\
Y_e &= \frac{1}{v_{SM}}(v_{10}^d Y_{10} - 3v_{126}^d Y_{126}) \\
Y_\Delta &= \frac{v_\Delta}{v_{SM}} Y_{126} \\
M_R &= v_{126}^R Y_{126}.
\end{aligned}
$$

SO(10) is a very constraining symmetry. Can we fit all the SM with the new data?

We consider a simple Yukawa sector consisting of **10+126**. And run the parameters down from GUT to fit the SM parameters and neutrino masses

$$
\begin{aligned}
16\pi^2\beta_\lambda &= 6\lambda^2 - 3\lambda\left(3g_2^2 + \frac{3}{5}g_1^2\right) + 3g_2^4 + \frac{3}{2}\left(\frac{3}{5}g_1^2 + g_2^2\right)^2 \\
&+ 4\lambda\mathrm{Tr}\left[Y_e^\dagger Y_e + Y_D^\dagger Y_D + 3Y_d^\dagger Y_d + 3Y_u^\dagger Y_u\right] \\
&- 8\mathrm{Tr}\left[Y_e^\dagger Y_e Y_e^\dagger Y_e + Y_D^\dagger Y_D Y_D^\dagger Y_D + 3Y_d^\dagger Y_d Y_d^\dagger Y_d + 3Y_u^\dagger Y_u Y_u^\dagger Y_u\right], \\
16\pi^2\beta_{Y_u} &= Y_u\left(\frac{3}{2}Y_u^\dagger Y_u - \frac{3}{2}Y_d^\dagger Y_d - \frac{17}{20}g_1^2 - \frac{9}{4}g_2^2 - 8g_3^2\right. \\
&\left. + \mathrm{Tr}\left[Y_e^\dagger Y_e + Y_D^\dagger Y_D + 3Y_d^\dagger Y_d + 3Y_u^\dagger Y_u\right]\right), \\
16\pi^2\beta_{Y_d} &= Y_d\left(\frac{3}{2}Y_d^\dagger Y_d - \frac{3}{2}Y_u^\dagger Y_u - \frac{1}{4}g_1^2 - \frac{9}{4}g_2^2 - 8g_3^2\right. \\
&\left. + \mathrm{Tr}\left[Y_e^\dagger Y_e + Y_D^\dagger Y_D + 3Y_d^\dagger Y_d + 3Y_u^\dagger Y_u\right]\right),
\end{aligned}
$$

SO(10) is a very constraining symmetry. Can we fit all the SM with the new data?

Observable	Central Value	Error
m_u [MeV]	1.27	0.46
m_c [GeV]	0.619	0.084
m_t [GeV]	171.7	3.0
m_d [GeV]	0.0029	0.0012
m_s [GeV]	0.055	0.016
m_b [GeV]	2.89	0.09
m_e [MeV]	0.487	0.024
m_μ [GeV]	0.103	0.0051
m_τ [GeV]	1.75	0.087
$\sin\theta^q_{12}$	0.225	0.0011
$\sin\theta^q_{13}$	0.0035	0.0003
$\sin\theta^q_{23}$	0.042	0.0013
$\delta_{\rm CKM}$	1.22	0.058
Δm^2_{21} [10^{-5}eV^2]	7.55	0.59
Δm^2_{31} [10^{-3}eV^2]	2.50	0.10
$\sin^2\theta^\ell_{12}$	0.32	0.059
$\sin^2\theta^\ell_{13}$	0.0216	0.0025
$\sin^2\theta^\ell_{23}$	0.547	0.102
λ	0.518	0.01

[Preliminary]

SO(10) is a very constraining symmetry.
Can we fit all the SM with the new data?

We find: $\chi^2 = 13.3/19$

- $M_1(\mu = M_1) = 1.06150 \cdot 10^9\,\mathrm{GeV}$
- $M_2(\mu = M_2) = 7.51645 \cdot 10^{10}\,\mathrm{GeV}$
- $M_3(\mu = M_3) = 1.25043 \cdot 10^{12}\,\mathrm{GeV}$
- $M_\Delta = 1.06150 \cdot 10^9\,\mathrm{GeV}$
- $v_\Delta = 8.32398 \cdot 10^{-5}\,\mathrm{GeV}$
- $\lambda(\mu = M_{\mathrm{GUT}}) = 1.16949 \cdot 10^{-10}$
- $m_{eff} = 5.33 \cdot 10^{-3}\,\mathrm{eV}$
- $m_{\nu 1} = 4.12 \cdot 10^{-3}\,\mathrm{eV}$
- $m_{\nu 2} = 9.62 \cdot 10^{-3}\,\mathrm{eV}$
- $m_{\nu 3} = 5.02 \cdot 10^{-2}\,\mathrm{eV}$
- $\delta_{\mathrm{PMNS}} = 1.14$

Observable	Best Fit	Pull
m_u [MeV]	1.31	0.089
m_c [GeV]	0.615	−0.044
m_t [GeV]	162.4	−3.1
m_d [GeV]	0.000783	−1.74
m_s [GeV]	0.0567	0.11
m_b [GeV]	2.90	0.056
m_e [MeV]	0.485	−0.045
m_μ [GeV]	0.104	0.19
m_τ [GeV]	1.74	−0.069
$\sin\theta^q_{12}$	0.225	0.0074
$\sin\theta^q_{13}$	0.00353	0.10
$\sin\theta^q_{23}$	0.0420	−0.033
δ_{CKM}	1.22	−0.0039
Δm^2_{21} [$10^{-5}\mathrm{eV}^2$]	7.56	0.014
Δm^2_{31} [$10^{-3}\mathrm{eV}^2$]	2.50	−0.015
$\sin^2\theta^\ell_{12}$	0.322	0.032
$\sin^2\theta^\ell_{13}$	0.0210	−0.23
$\sin^2\theta^\ell_{23}$	0.531	−0.16
λ	0.527	0.61

Circumstantial evidence in favor of GUT is very compelling

SM couplings quasi-unify ~ 1e15 GeV

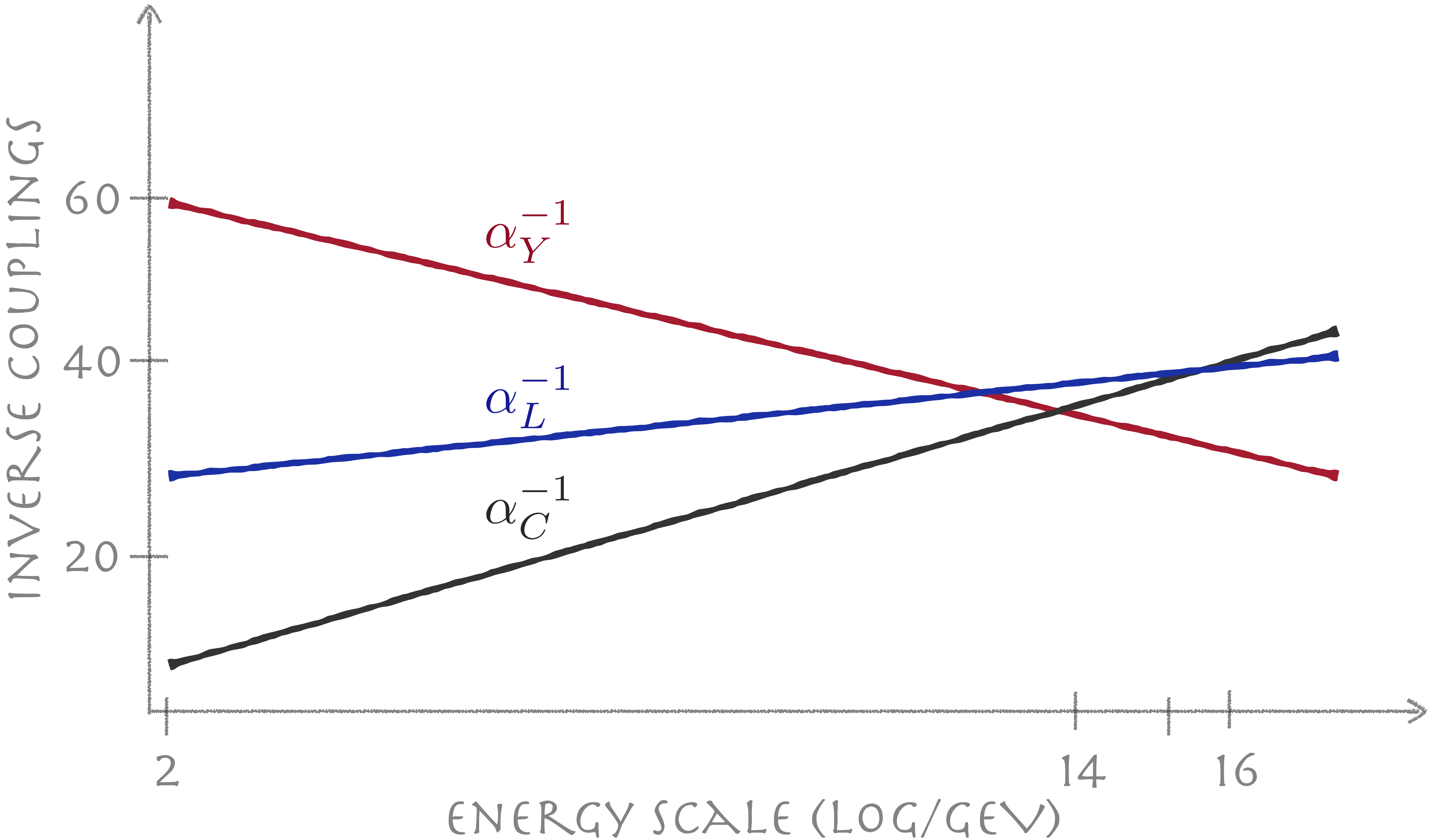
Neutrino mass operator natural scale ~ 1e12 GeV

Leptogenesis works best ~ 1e10-16 GeV

Axions scale ~ 1e10-14 GeV

Energy scale of inflation ~ 1e16 GeV

Coupling "constants" offer a tantalizing hint in favor of GUT



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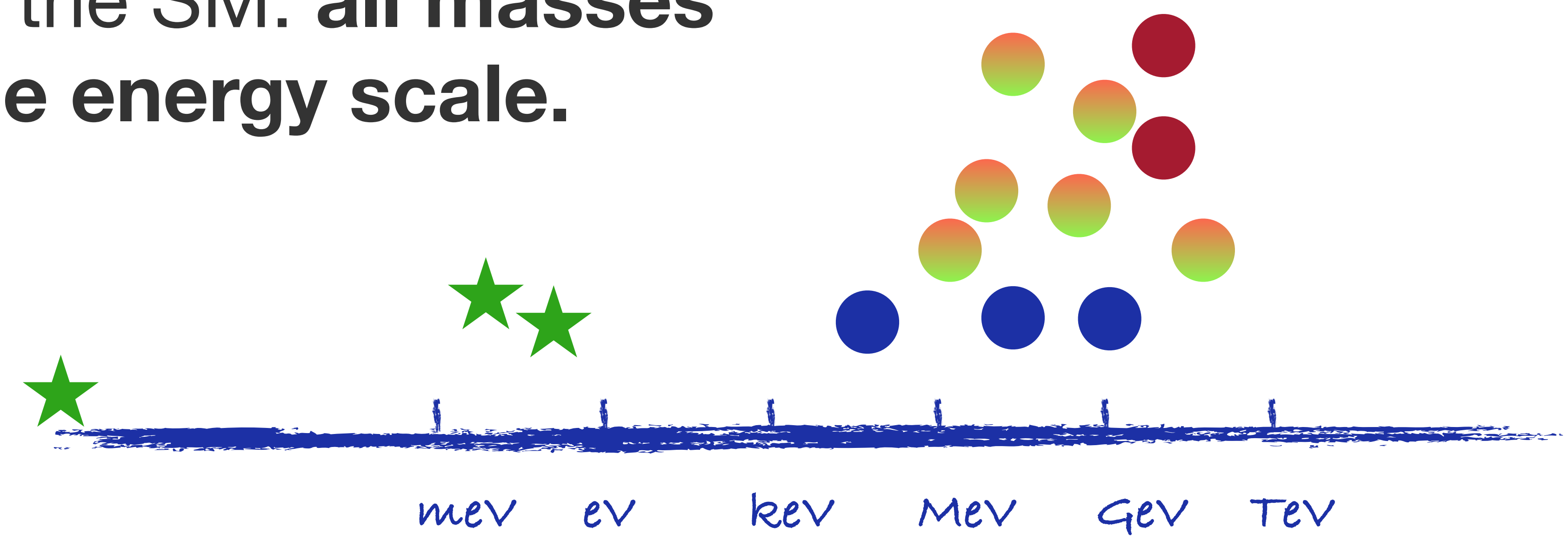
Neutrinos do not really fit into the SM

It is interesting that the same Higgs doublet "gives" mass to all the charged leptons, quarks, and bosons of the SM: **all masses originate from a single energy scale.**



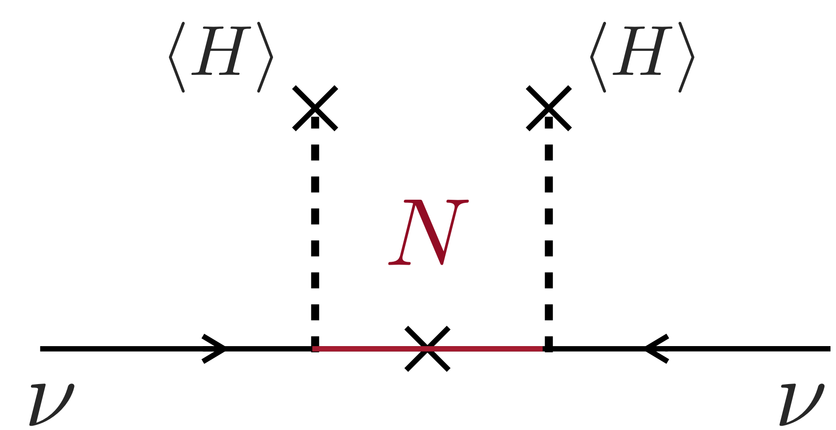
However, if we were to treat neutrinos as the other fermions, the Higgs coupling would be unnaturally small. Origin could be explained by a dim-5 operator

$$\frac{1}{M} LLHH$$

The messengers of high-scale neutrino mass models are remarkably close to Unification energy

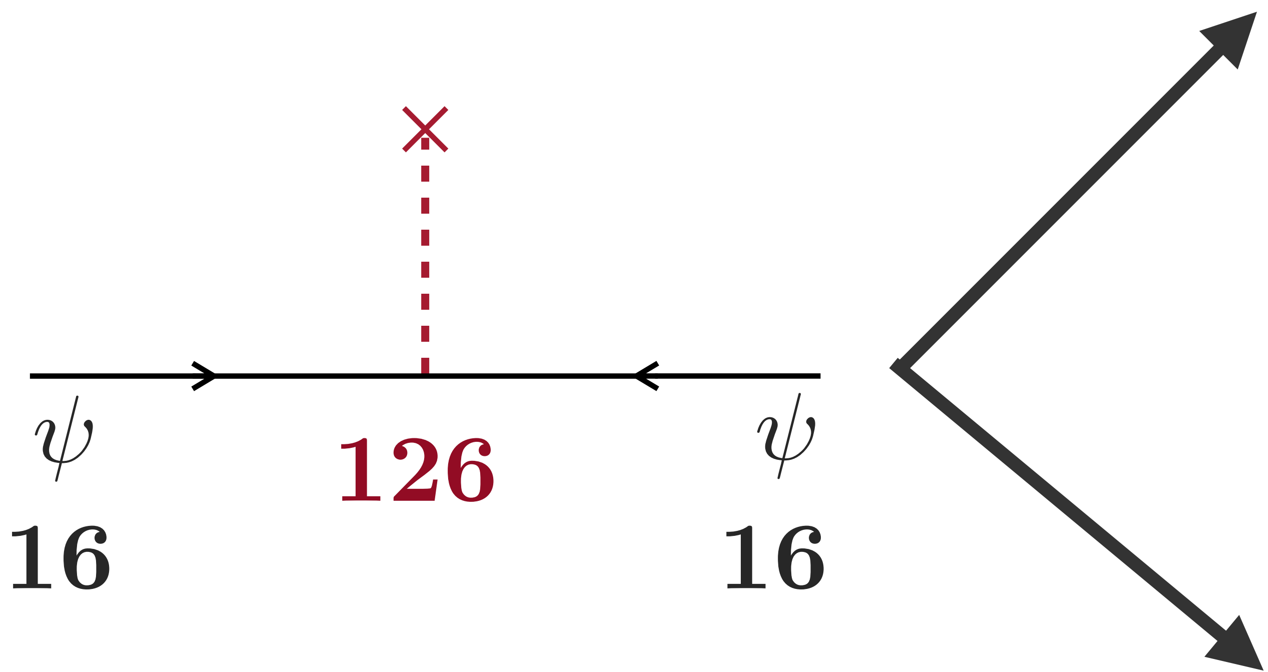
$$m_\nu \approx \frac{\langle H \rangle^2}{M} \approx 0.1 \left(\frac{100^2}{10^{14}} \right) \mathrm{eV}$$

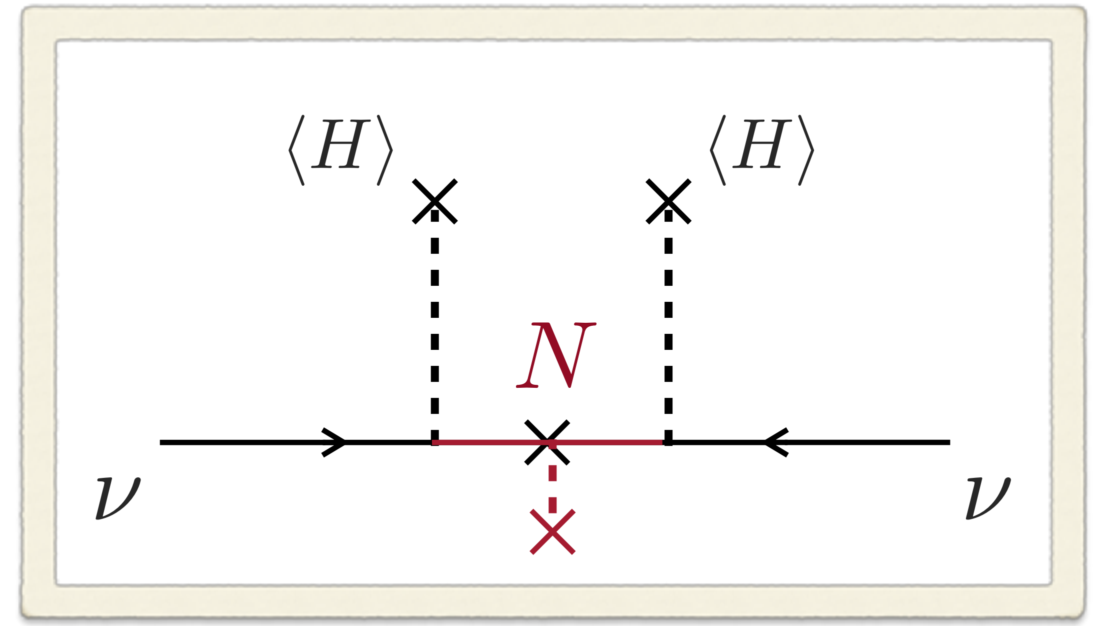
$$\frac{1}{M} LLHH$$

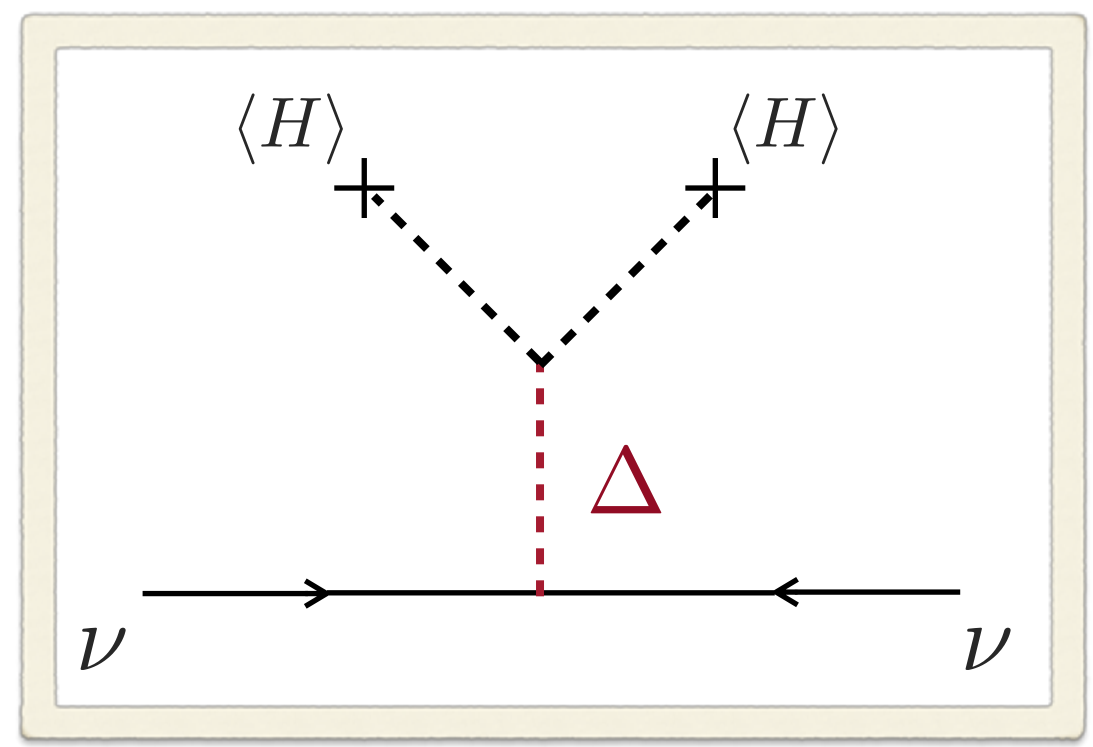


[Minkowski ’77;Yanagida ’79; Gell-Mann, Ramond, Slansky ’79; Glashow ’80; Mohapatra, Senjanovic ’80]

SO(10) is the *raison d'être* of seesaw mechanism







Indeed, seesaw I + II come out of a single SO(10) operator.

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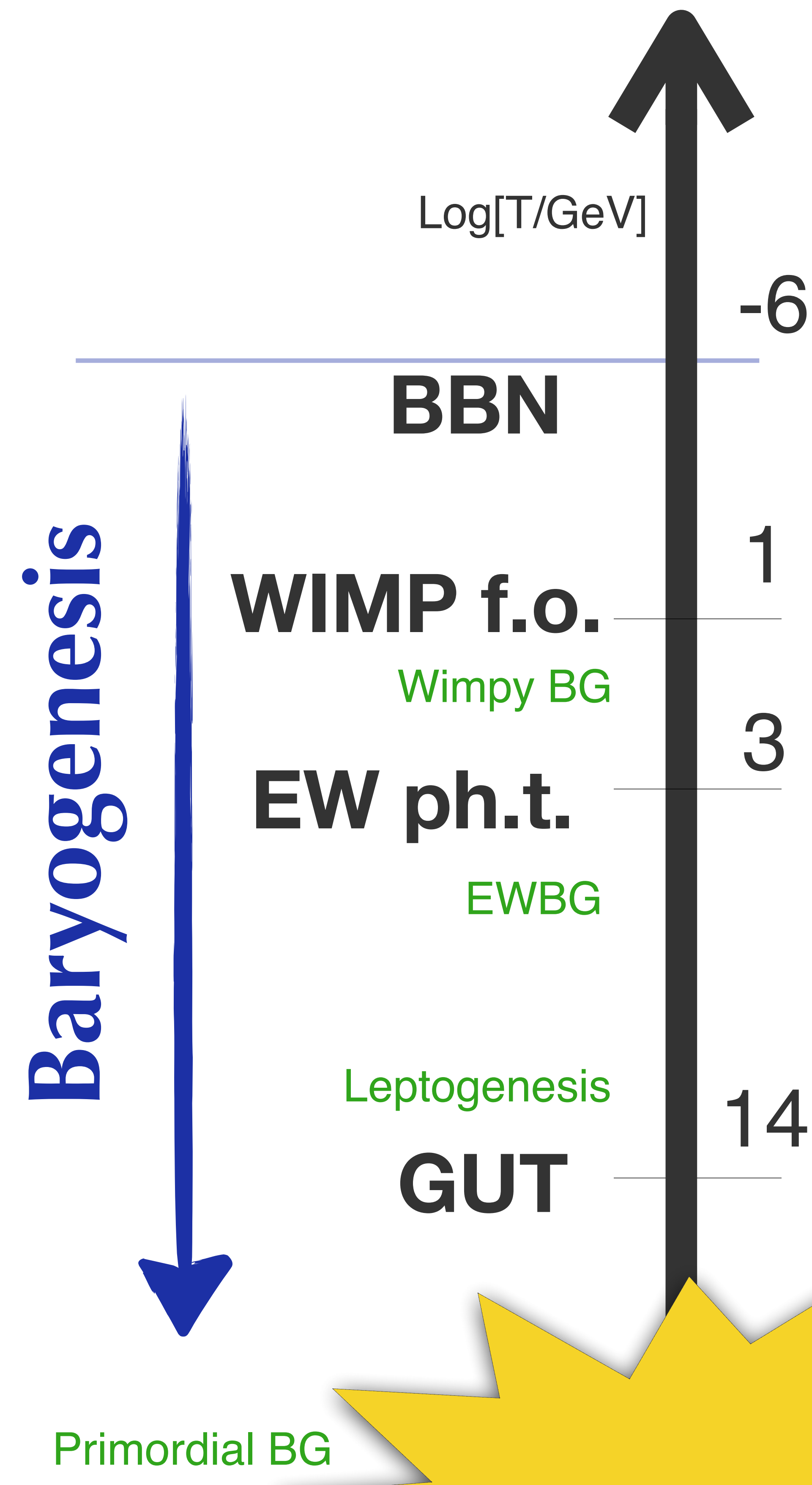
Our Univers is quite asymmetric

- No antimatter on earth, moon, solar system, Galaxy, and cosmic rays (~0.01%); No anti-planets/stars, No annihilation radiation (e.g. from Virgo); No matter-anti-matter patchwork Universe.

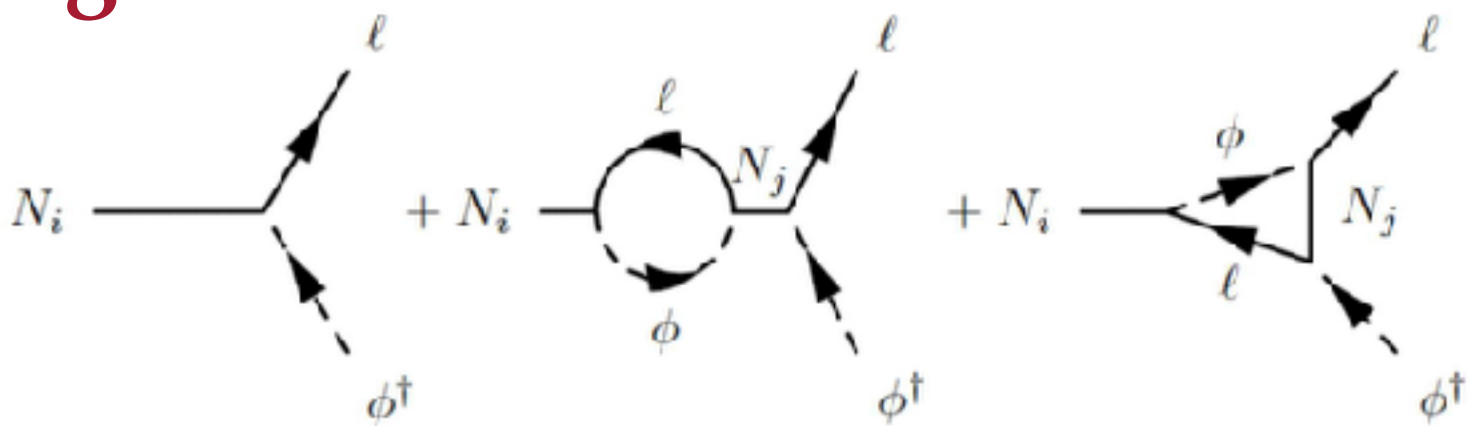
$$\eta_b^{CMB} = 6.2 \times 10^{-10}$$

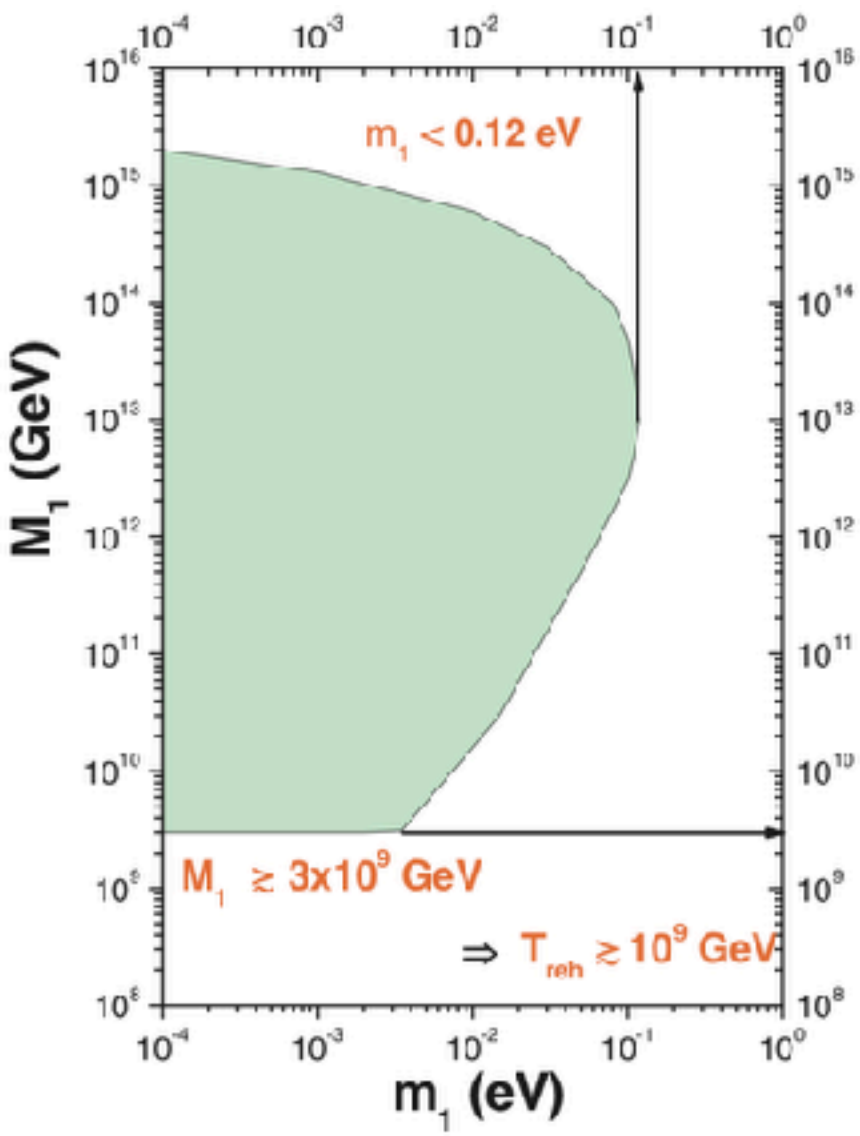
$$\eta_b^{BBN} = 2.6 \div 6.2 \times 10^{-10}$$

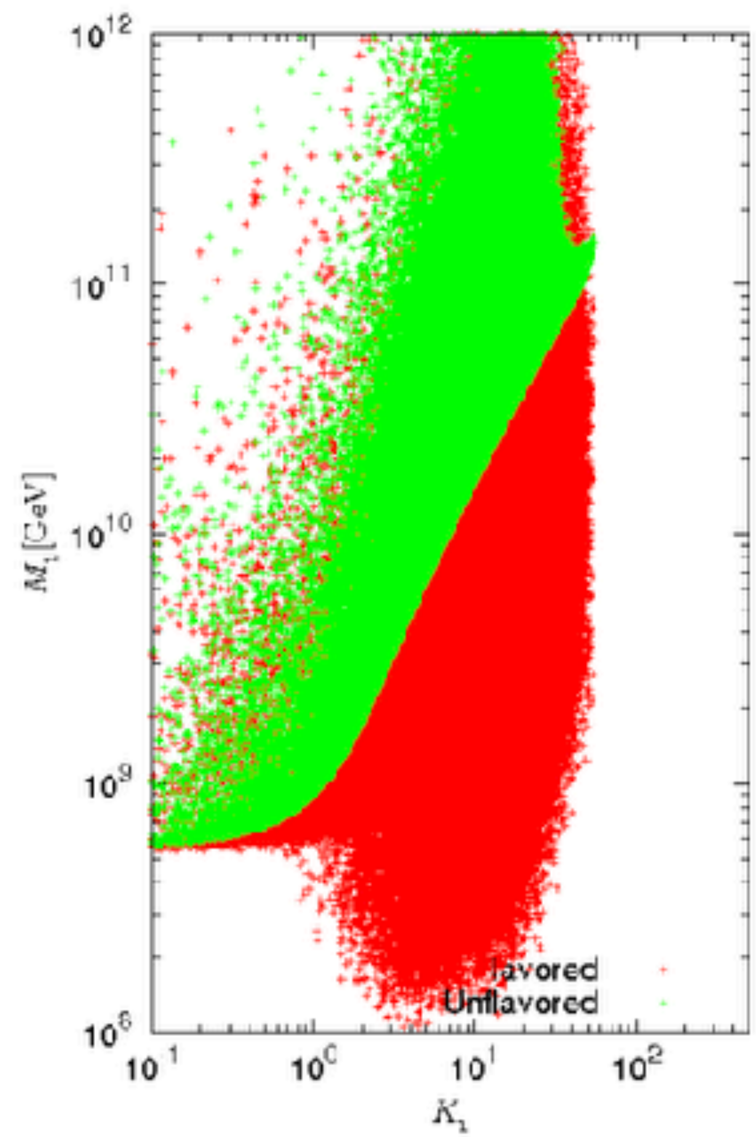
$$\boxed{\eta_b^{obs} \gg \eta_b^{sym} \approx 10^{-18}}$$



Baryogenesis via Leptogenesis works best at high scales







[Di Bari '12]

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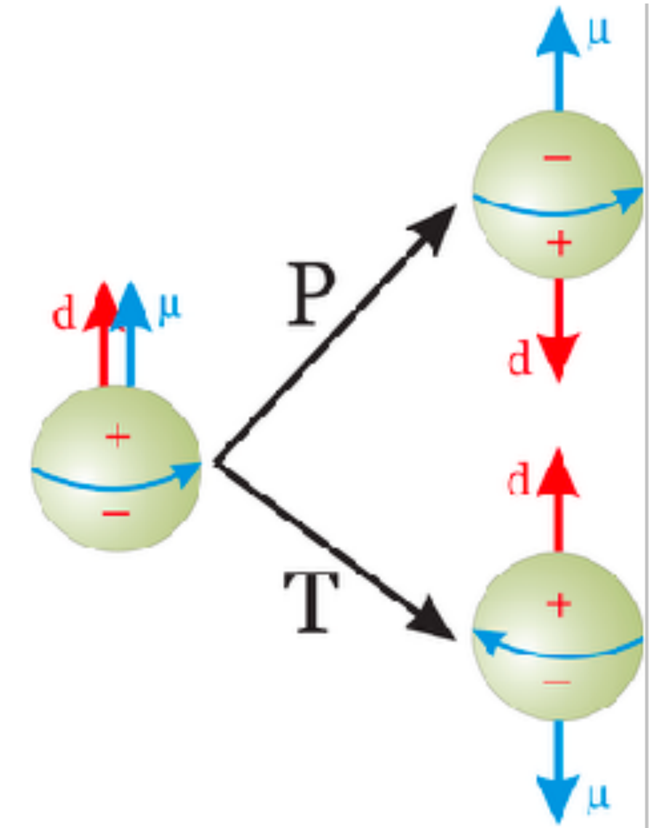
Axions & the strong CP problem



An anomalous symmetry in the SM allows for a physical term

$$\frac{\alpha_S}{8\pi}\theta G\tilde{G}$$

Experimentally, from CP violating observables (e.g., neutron's EDM) we know that $\theta < 10^{-10}$

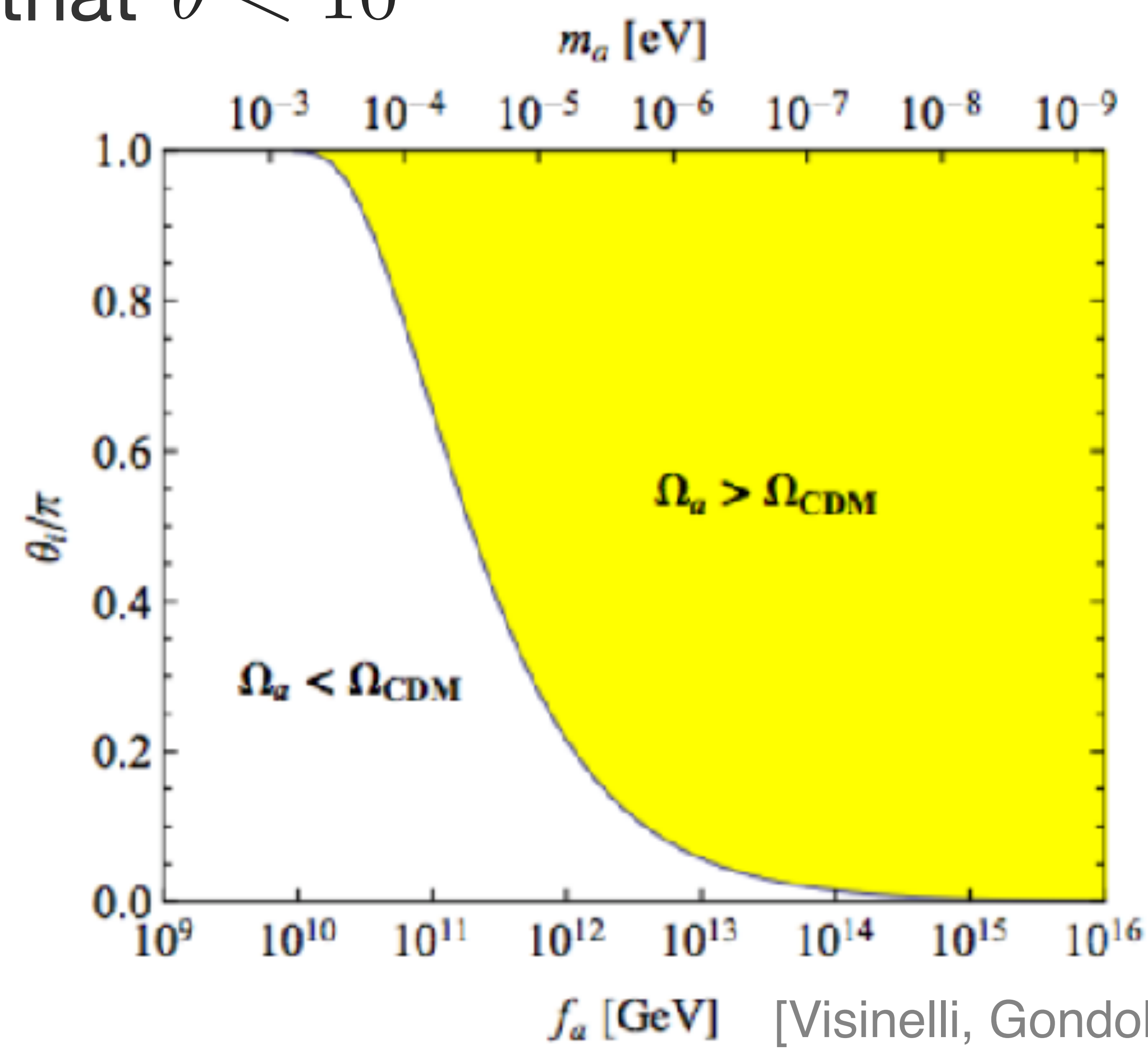
Why so small?

Promote it to a dynamical field which relaxes to zero.
Pseudo-goldsone boson is the **axion**. Excellent DM candidate!

[Peccei-Quinn '77]

[Weinberg '78
Wilczek '78]

[Preskill-Wise-Wilczek '83]



[Visinelli, Gondolo '09]

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Energy scale of inflation ~ 1e16 GeV

A period of accelerated expansion solves cosmic conundrums

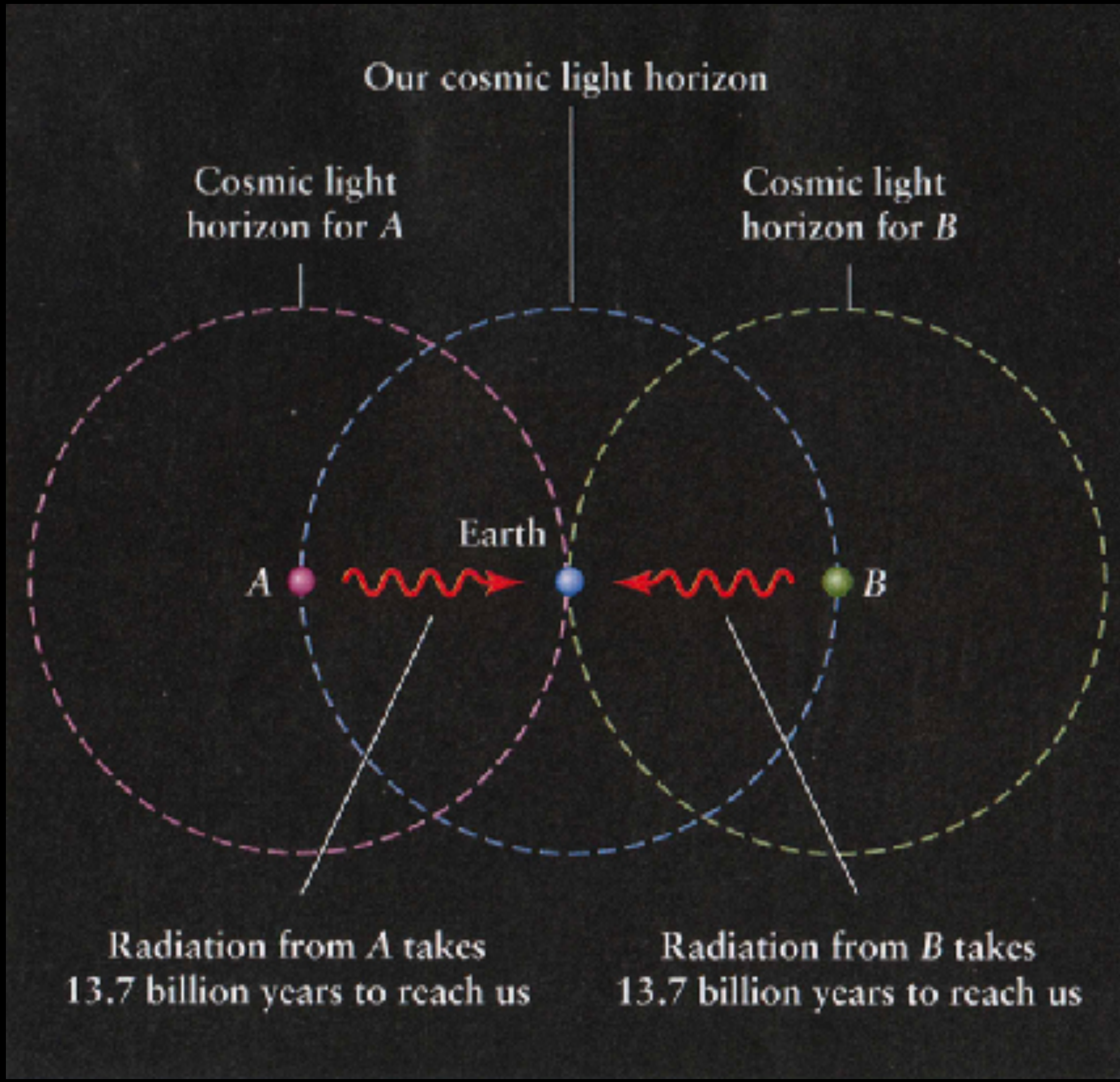
Inflation solves the horizon and flatness problems

seeds cosmological perturbations

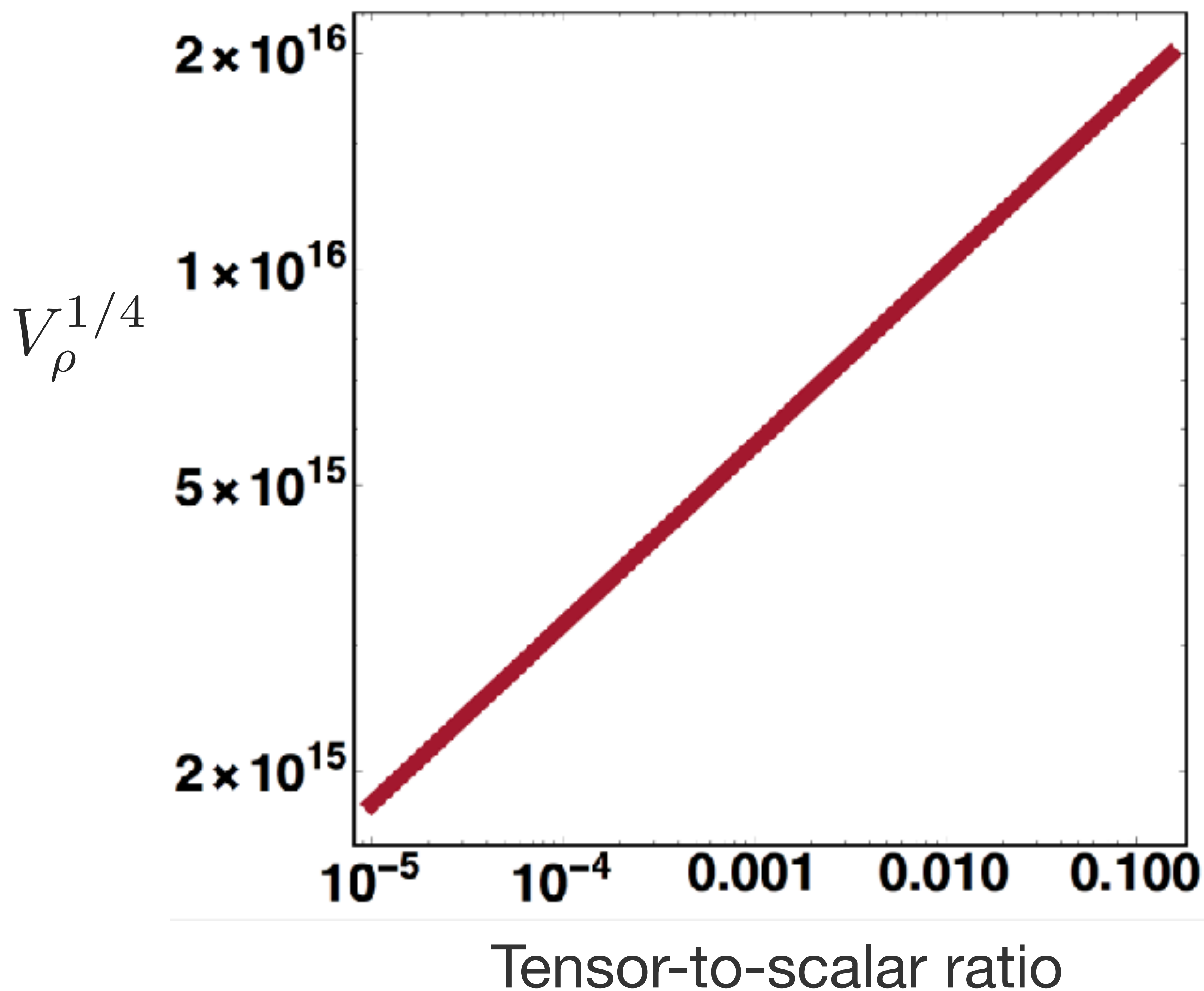
recovers hot Big Bang cosmology

A new scalar fields is needed:
the **inflaton**

In the context of GUT, inflation dilutes the monopoles!



The mass scale driving inflation = Unification scale?



To sum-up this part …

“Numerology” and group-theory provide remarkable hints in favor of GUTs

Neutrino masses, leptogenesis, axions, and inflation are all naturally related to energies at or near Unification scale

Grand unified theories are testable!

Natural question: solve all SM shortcomings with a single GUT model?

2/3
SU(5) revived

[SB, Shafi, ’17]

Our goal

Fix the old SU(5) model

Use SU(5) symmetry as a guide to minimally include solutions to: neutrinos masses, dark matter, inflation, strong CP, and baryogenesis.

SU(5) x U(1)$_{PQ}$
Particle content and symmetries

	T_L	F_L	ν_L^c	H_1	H_2	σ	Φ	χ
$SU(5)$	$\mathbf{10}$	$\overline{\mathbf{5}}$	$\mathbf{1}$	$\mathbf{5}$	$\overline{\mathbf{5}}$	$\mathbf{1}$	$\mathbf{24}$	$\mathbf{45}^\star$
$U(1)_{PQ}$	$\alpha/2$	$\alpha/2$	$\alpha/2$	$-\alpha$	$-\alpha$	$-\alpha$	0	$-\alpha$

SU(5) x U(1)$_{PQ}$

Georgi-Glashow's model

	T_L	F_L	ν_L^c	H_1	H_2	σ	Φ	χ
$SU(5)$	$\mathbf{10}$	$\overline{\mathbf{5}}$	$\mathbf{1}$	$\mathbf{5}$	$\overline{\mathbf{5}}$	$\mathbf{1}$	$\mathbf{24}$	$\mathbf{45}^\star$
$U(1)_{PQ}$	$\alpha/2$	$\alpha/2$	$\alpha/2$	$-\alpha$	$-\alpha$	$-\alpha$	0	$-\alpha$

SU(5) x U(1)$_{PQ}$
Fermions masses are OK!

Generates neutrino masses

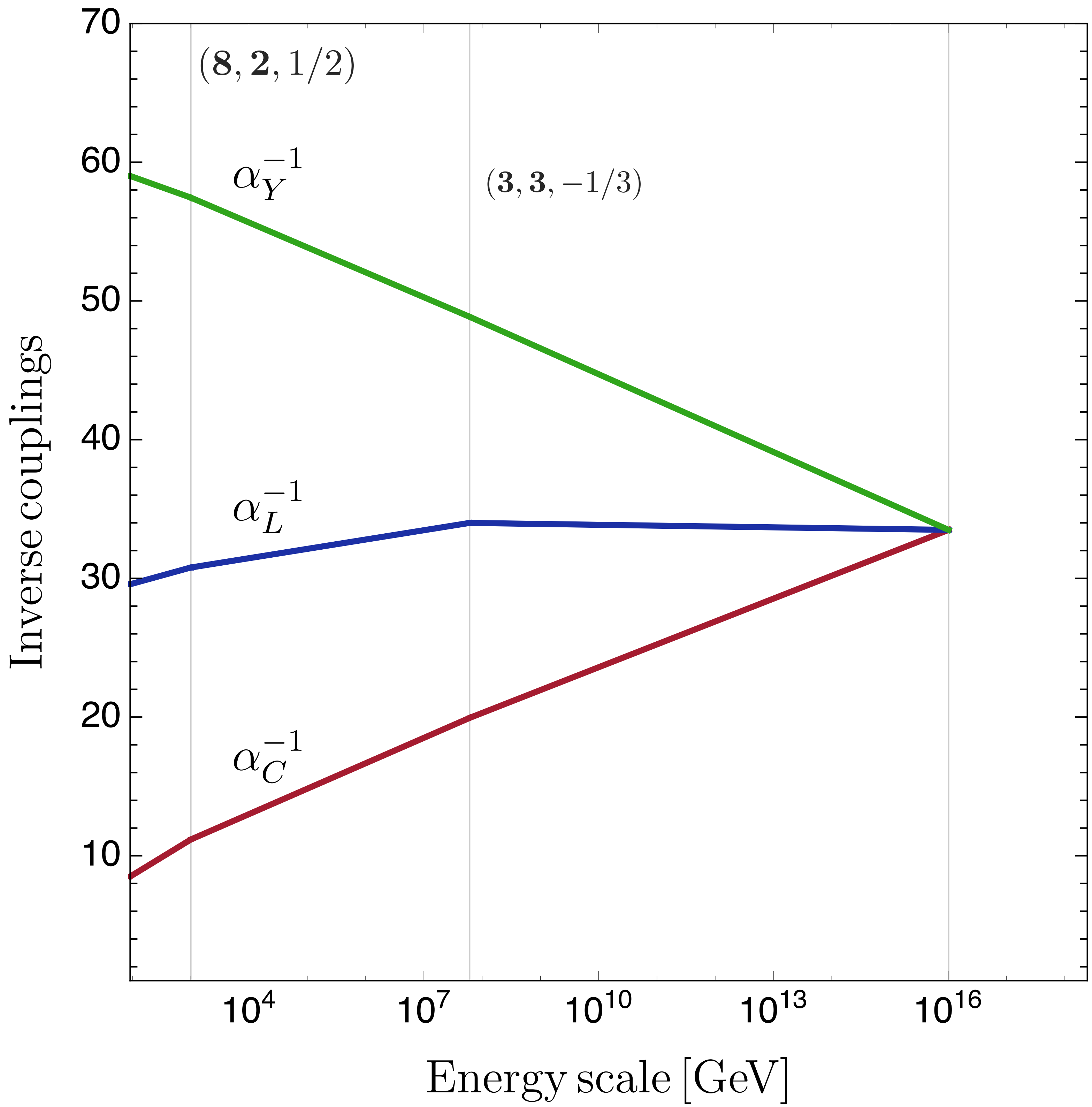
Fixes bad mass relations & GCU

	T_L	F_L	ν_L^c	H_1	H_2	σ	Φ	χ
$SU(5)$	$\mathbf{10}$	$\overline{\mathbf{5}}$	$\mathbf{1}$	$\mathbf{5}$	$\overline{\mathbf{5}}$	$\mathbf{1}$	$\mathbf{24}$	$\mathbf{45}^\star$
$U(1)_{PQ}$	$\alpha/2$	$\alpha/2$	$\alpha/2$	$-\alpha$	$-\alpha$	$-\alpha$	0	$-\alpha$

$$\mathcal{L}_{Yuk} = T_L.\mathbf{Y_{10}}.T_L.H_1 + T_L.\mathbf{Y_5}.F_L.H_2 + T_L.\mathbf{Y_{45}}.F_L.\chi$$
$$F_L.\mathbf{Y}_\nu.\nu_L^c.H_1 + \tfrac{1}{2}\mathbf{Y_N}\nu_L^c.\nu_L^c.\sigma + \text{h.c.}\,,$$

$$M_e = \mathbf{Y_5}\,\langle H_2\rangle + 2\mathbf{Y_{45}}\,\langle\chi\rangle$$
$$M_d = \mathbf{Y_5}^T\,\langle H_2\rangle - 6\mathbf{Y_{45}}^T\,\langle\chi\rangle$$
$$M_u = 4(\mathbf{Y_{10}} + \mathbf{Y_{10}}^T)\,\langle H_1\rangle$$
$$M_\nu \simeq \mathbf{Y}_\nu{}^T.\mathbf{Y_N}^{-1}.\mathbf{Y}_\nu\frac{\langle H_1\rangle^2}{\langle\sigma\rangle}$$

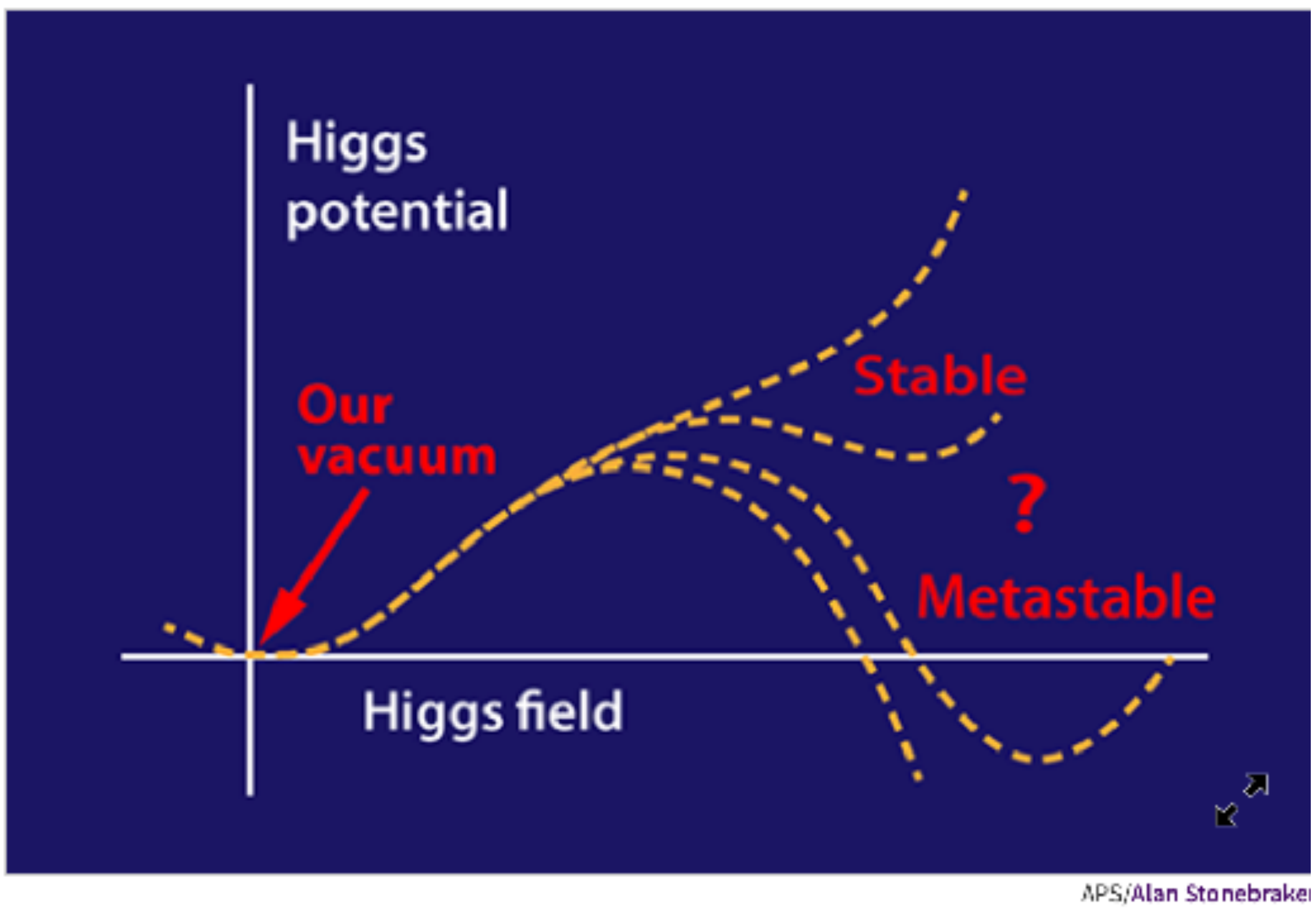
SU(5) x U(1)$_{PQ}$
Successful GCU and testable p decay

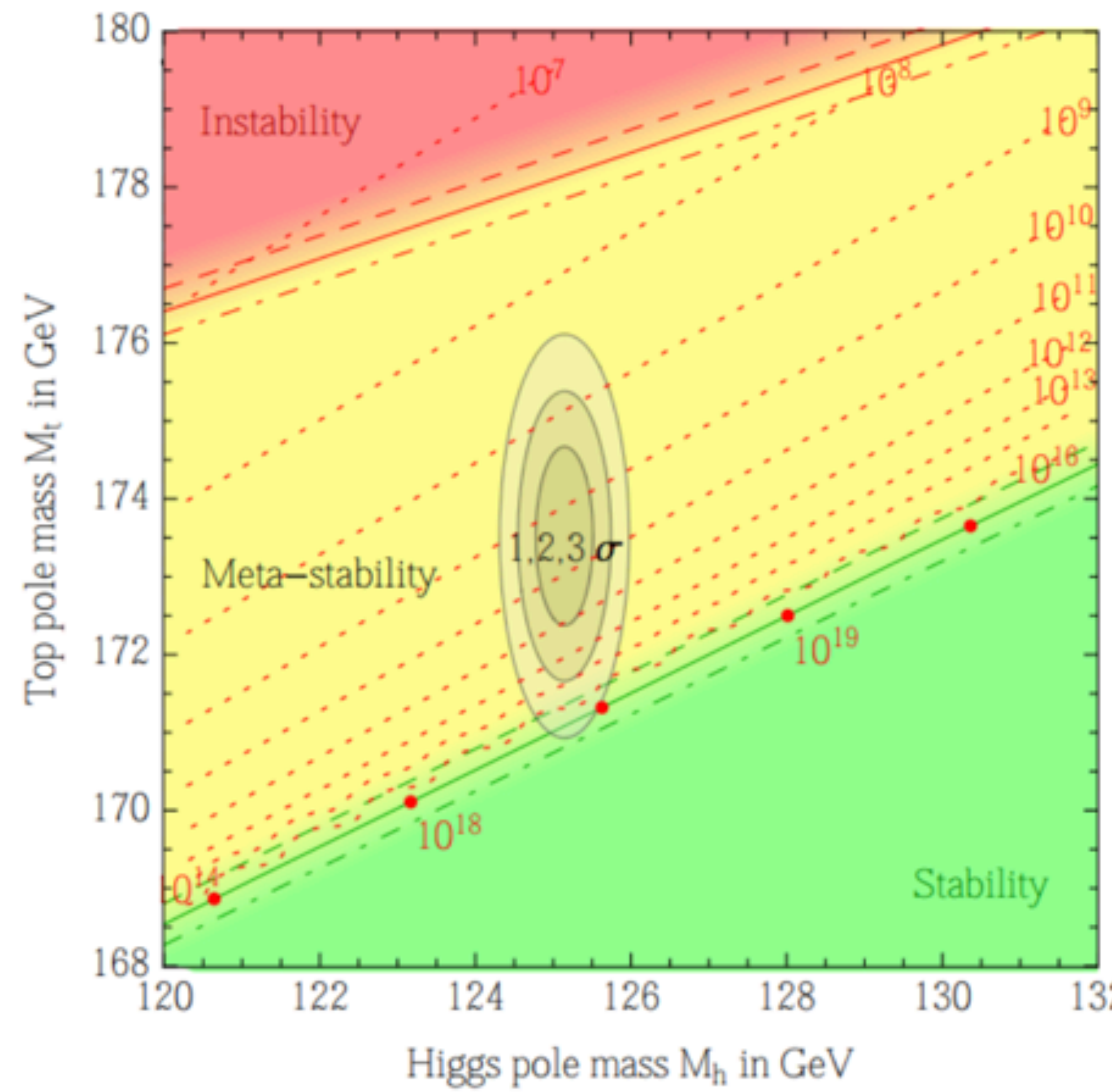


$$M_{GUT} \approx \left(\frac{M_{R_8}}{\mathrm{TeV}}\right)^{-0.126} \times 10^{16}\ \mathrm{GeV}$$

$$\boxed{\tau_p \approx 2.4 \times 10^{35}\ \mathrm{yrs}}$$

SU(5) x U(1)$_{PQ}$
Remarkably, the same fields which make GCU possible stabilize the effective potential of the SM at high energies





[Buttazzo et al '13]

SU(5) x U(1)$_{PQ}$

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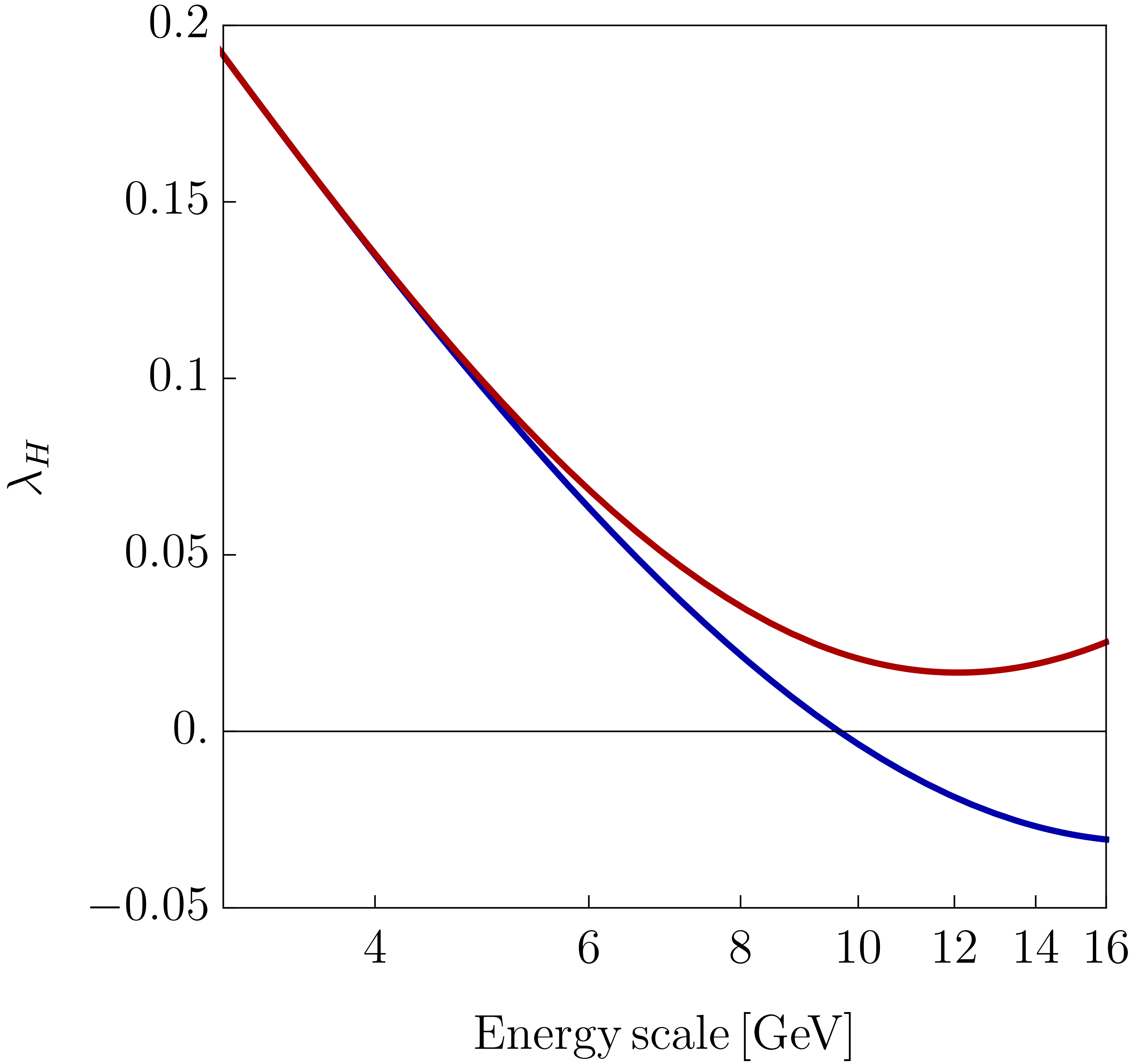

$$M_{R_8} \lesssim 10^4\,\mathrm{GeV}$$

$$\tau_p \gtrsim 7.8 \times 10^{34}\,\mathrm{yrs}$$

SU(5) x U(1)$_{PQ}$
Inflation from the axionic field

	T_L	F_L	ν_L^c	H_1	H_2	σ	Φ	χ
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$U(1)_{PQ}$	$\alpha/2$	$\alpha/2$	$\alpha/2$	$-\alpha$	$-\alpha$	$-\alpha$	0	$-\alpha$

The Peccei-Quinn symmetry.

DFSZ model emerges naturally.

$$\sigma = \rho e^{ia/f_a}$$

The inflaton

The axion field

SU(5) x U(1)$_{PQ}$
Inflation proceeds via the radial part of the anionic field, "raxion"

The raxion has a non-minimal coupling to gravity;

$$V_E(\phi(\rho)) = \frac{\frac{1}{4}\lambda_\sigma(t)\rho^4}{\left(1+\xi\,\rho^2\right)^2}$$

For non-minimal couplings > 0.1, the predicted values of the main cosmological observables converge toward:

	n_s	$r \times 10^3$	$-\alpha \times 10^4$
$N = 50$	0.962	4	7.5
$N = 60$	0.968	3	5.3

$(H_I \simeq 2\pi \times 10^{13}\ \mathrm{GeV}\ )$

SU(5) x U(1)$_{PQ}$
Inflation proceeds via the radial part of the anionic field, "raxion"

The Universe is reheated via $\rho \to 2\nu_L^c$

This imposes constraints on the mass of the RH neutrinos, and the PQ scale. We can estimate the reheat temperature as

$$T_{RH} \lesssim 3 \times 10^8\,\mathrm{GeV}\sqrt{\left(\frac{\lambda_\sigma}{10^{-7}}\right)\left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)} \equiv T_{RH}^{\max}$$

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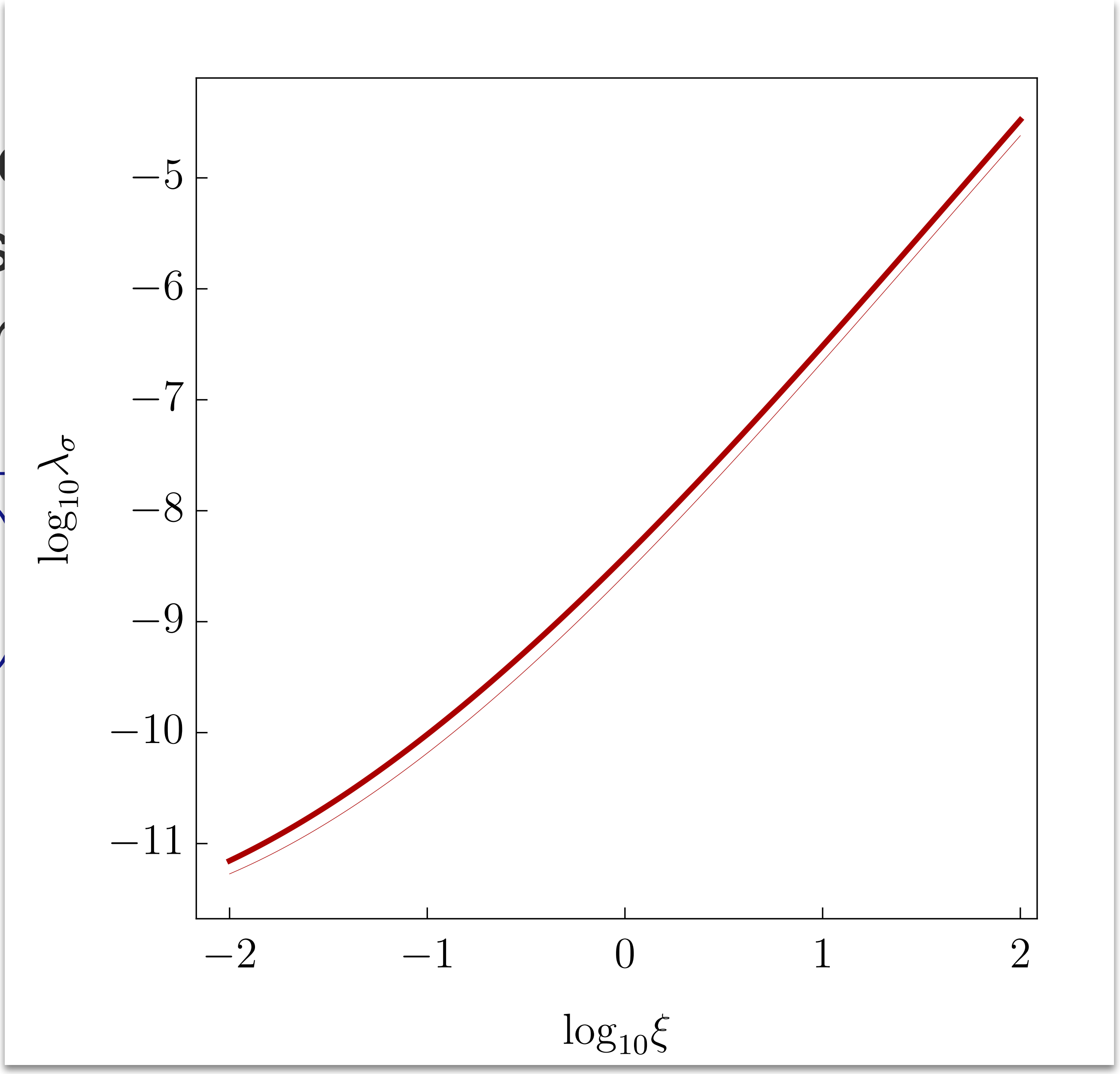


SU(5) x U(1)$_{PQ}$
The asymmetry is obtained via non-thermal leptogenesis

Baryogenesis

	T_L	F_L	ν_L^c	H_1	H_2	σ	Φ	χ
$SU(5)$	$\mathbf{10}$	$\overline{\mathbf{5}}$	$\mathbf{1}$	$\mathbf{5}$	$\overline{\mathbf{5}}$	$\mathbf{1}$	$\mathbf{24}$	$\mathbf{45}^\star$
$U(1)_{PQ}$	$\alpha/2$	$\alpha/2$	$\alpha/2$	$-\alpha$	$-\alpha$	$-\alpha$	0	$-\alpha$

[Lazarides, Shafi '91
Asaka et al '92]

The products of the inflaton, decay non-thermally to the SM particles producing an asymmetry:

$$\eta_L \simeq -10^{-5}\left(\frac{T_{RH}}{10^9\,\mathrm{GeV}}\right)\left(\frac{M_N}{m_\rho}\right) \longrightarrow M_N \simeq 0.3\left(\frac{10^7\,\mathrm{GeV}}{T_{RH}}\right) m_\rho$$

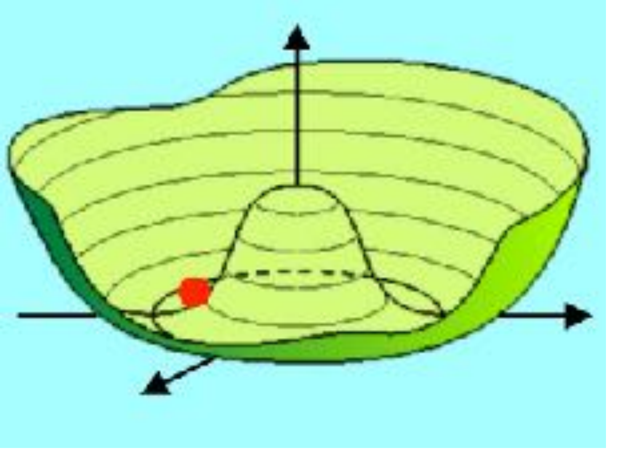
$$m_\rho \simeq \sqrt{2\lambda_\sigma} f_a \to M_N \sim 10^8\,\mathrm{GeV}$$

Revived SU(5)
The Dark matter of the universe is simply the axion itself

$$\sigma = \rho e^{ia/f_a}$$

	T_L	F_L	ν_L^c	H_1	H_2	σ	Φ	χ
$SU(5)$	$\mathbf{10}$	$\overline{\mathbf{5}}$	$\mathbf{1}$	$\mathbf{5}$	$\overline{\mathbf{5}}$	$\mathbf{1}$	$\mathbf{24}$	$\mathbf{45}^\star$
$U(1)_{PQ}$	$\alpha/2$	$\alpha/2$	$\alpha/2$	$-\alpha$	$-\alpha$	$-\alpha$	0	$-\alpha$

At high temperatures, after PQ breaking the axion at some angle



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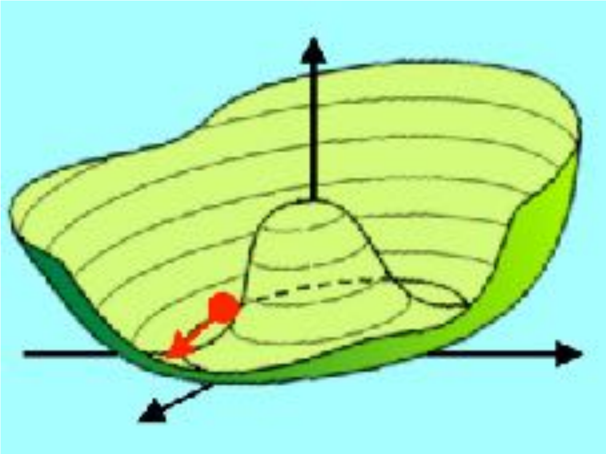
But at T ~ GeV, axion acquires mass and starts oscillating classically



Cold dark matter due to non-relativistic birth

Revived SU(5)
The Dark matter of the universe is simply the axion itself

$$\sigma = \rho e^{ia/f_a}$$

	T_L	F_L	ν_L^c	H_1	H_2	σ	Φ	χ
$SU(5)$	$\mathbf{10}$	$\overline{\mathbf{5}}$	$\mathbf{1}$	$\mathbf{5}$	$\overline{\mathbf{5}}$	$\mathbf{1}$	$\mathbf{24}$	$\mathbf{45}^\star$
$U(1)_{PQ}$	$\alpha/2$	$\alpha/2$	$\alpha/2$	$-\alpha$	$-\alpha$	$-\alpha$	0	$-\alpha$

The axion is produced via the misalignment mechanism

$$\Omega_a h^2 = 0.1199 \left(\frac{\overline{\theta_i^2}}{0.28}\right)\left(\frac{f_a}{10^{12}}\right)^{7/6}$$

[Preskill-Wise-Wilczek ’83]

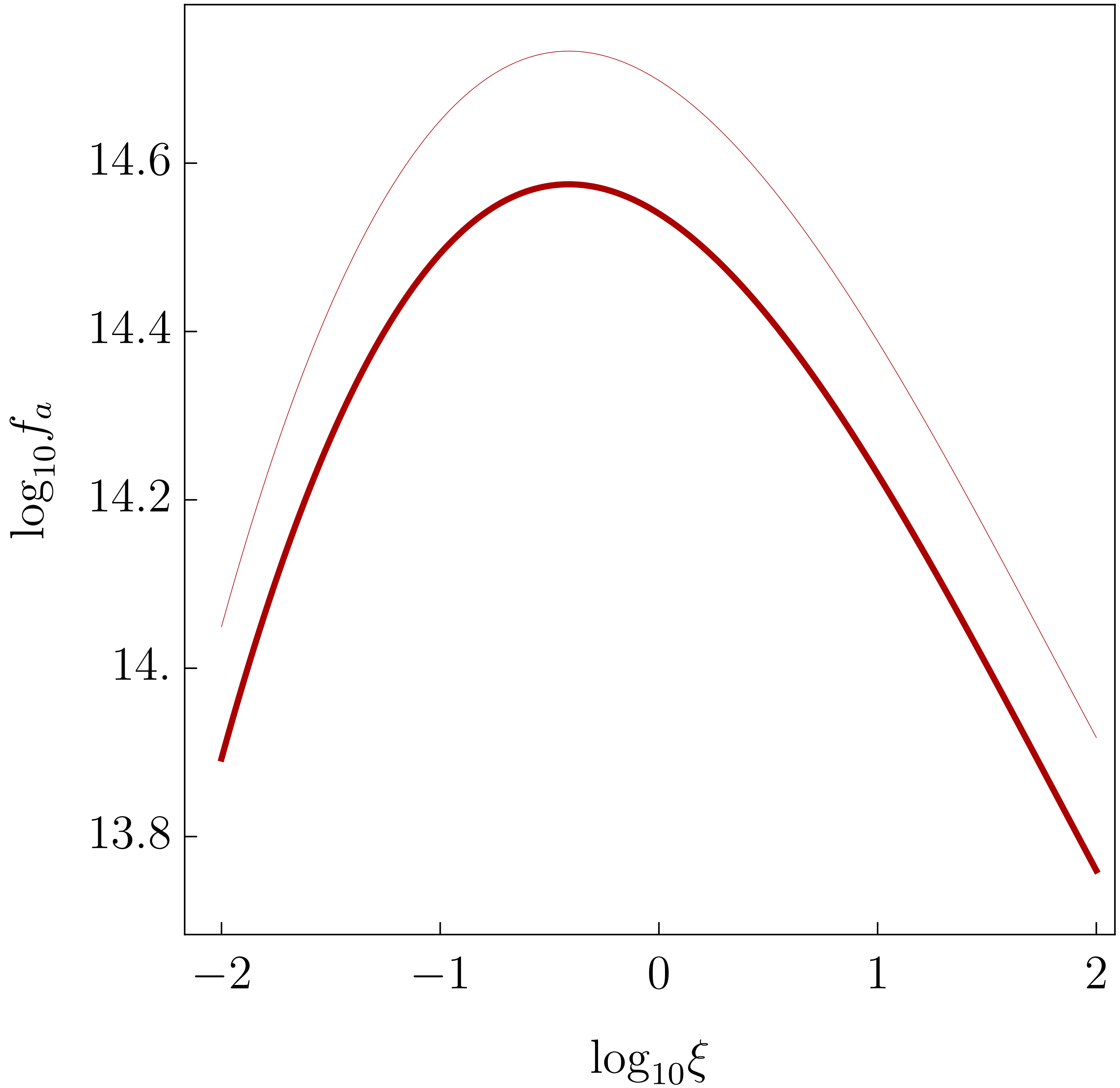
SU(5) x U(1)$_{PQ}$
The Dark matter of the universe is simply the axion itself

Since inflation is driven by the raxion, PQ is always broken during inflation and the axion acquires isothermal (isocurvature) fluctuations

$$\beta_{\text{iso}} = \left(1 + \frac{\pi f_{a,\star}^2 \overline{\theta_i^2}}{\epsilon(\rho)}\right)^{-1} \leq 0.038$$

In the standard scenario this bound implies a large PQ breaking scale. In our case the effective scale is given by the trans-Planckian inflaton field value during inflation. The final PQ scale does not have a direct impact on the isocurvature perturbations and enters only indirectly via the DM requirement.

SU(5) x $U(1)_{PQ}$
The Dark matter of the universe is simply the axion itself



SU(5) x U(1)$_{PQ}$
Summary

A simple theory, with only 3 fermion representations per family, explains a lot and draws links between various BSM areas

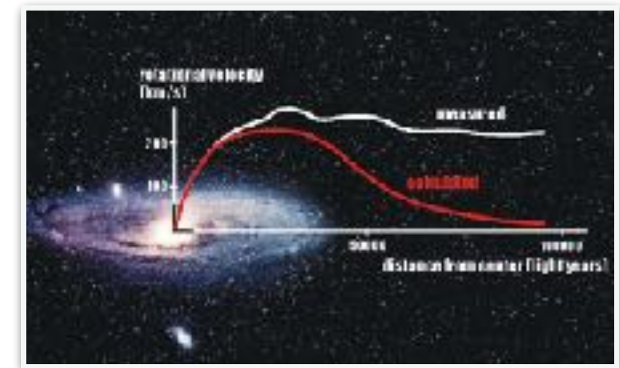
Neutrino masses and mixings, dark matter, baryogenesis, Inflation, and the smallness of the theta term are all explained. The vacuum is stabilized

Predicts: color octet ~ TeV (LHC), proton lifetime close to current limits, axions, small tensor-to-scalar ratio ~ 1e-3

3/3
SO(10) and WIMP DM

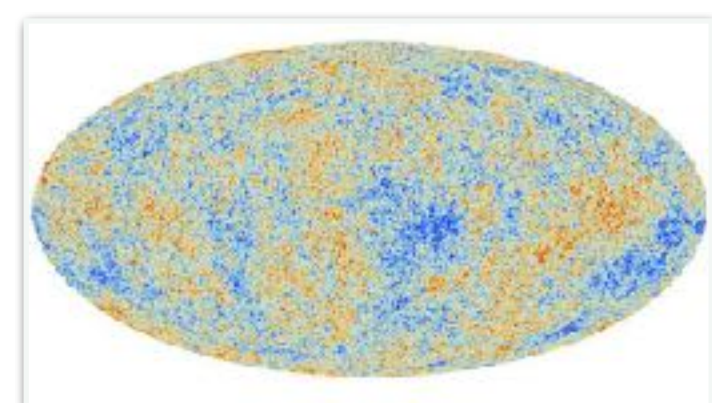
There exists a wide array of evidence for a nonbaryonic, clustering component of the Universe. Most likely new particle(s).

Acceptable candidates are very feebly interacting with SM, reproduce observed abundance, cold-ish, and very stable!



DM should be at least older than the Universe. If it emits cosmic rays the lifetime may become orders of magnitude larger:

$$\tau_{\rm DM} \gtrsim 10^{26}\,\mathrm{s}$$

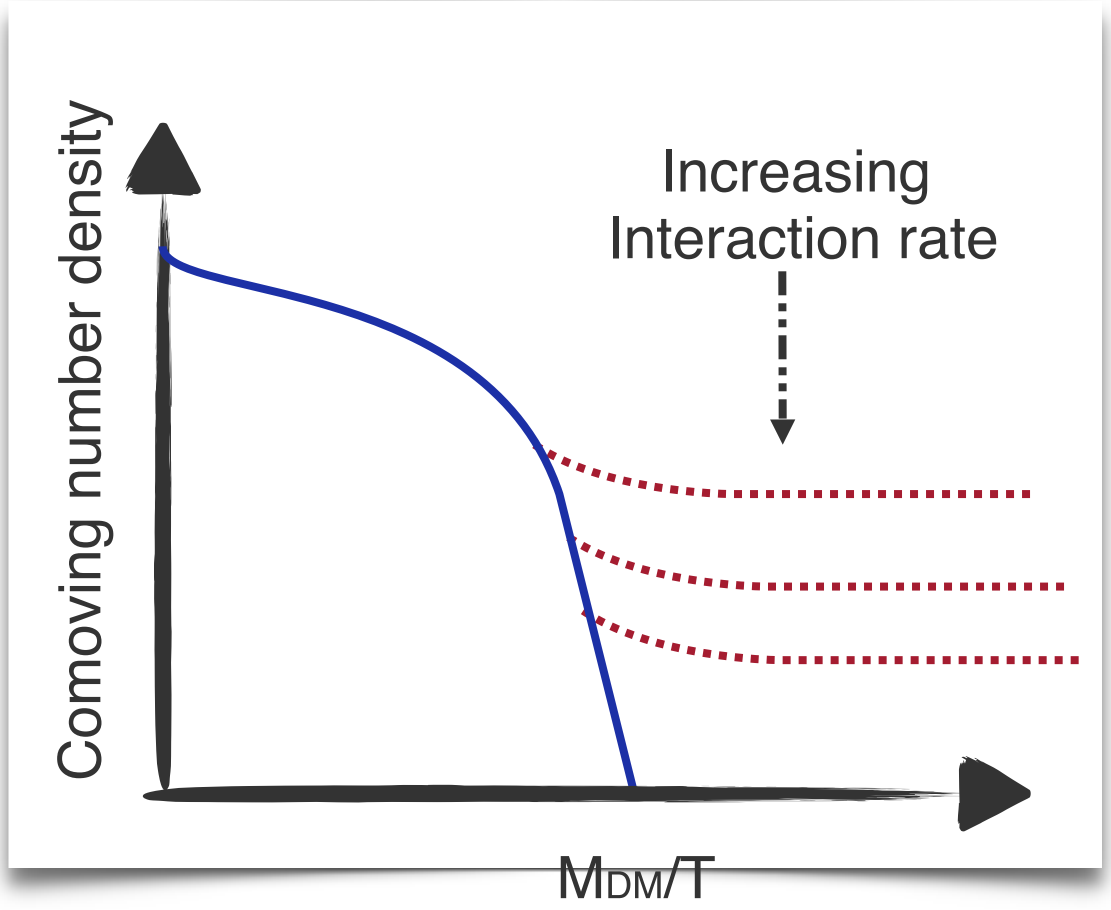


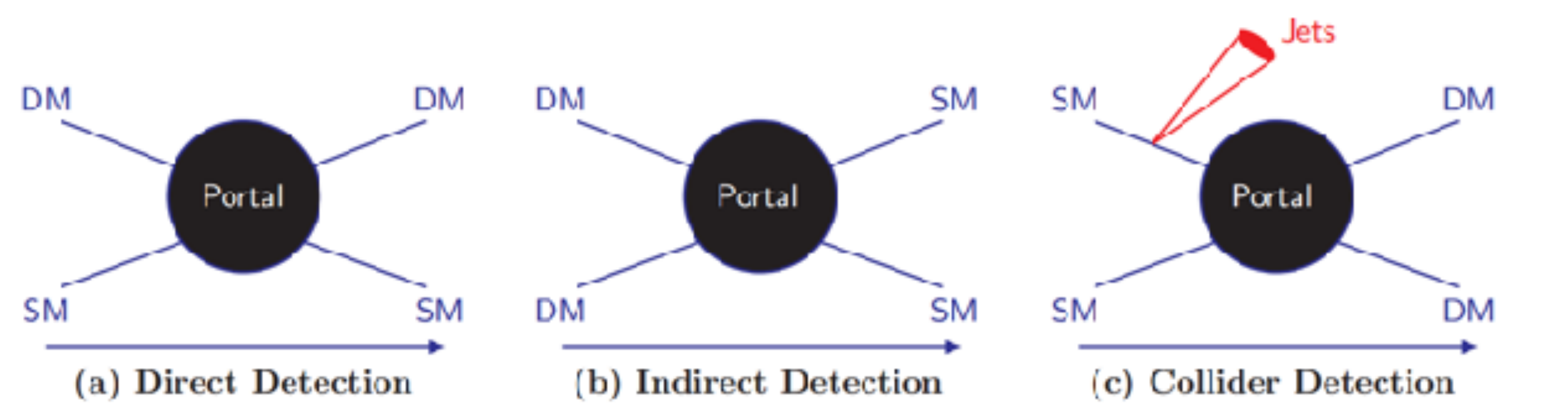
What are WIMPs?

For masses & interactions around the weak scale, the abundance is *naturally* close to observations:

$$\Omega_\chi h^2 \approx 0.1 \, \frac{3\times 10^{-26}\,\mathrm{cm}^2/\mathrm{s}}{\langle \sigma_{\chi\bar{\chi}} |v| \rangle}$$

The WIMP "Miracle". The same portal that produces WIMPs can be used to search for them.
WIMPs are testable!





From HEP viewpoint, stability and electroweak scale point to new symmetries

SUSY (with R parity) offers a natural motivation for WIMPs. Without SUSY, SO(10) makes the best case for WIMPs. **Spin(10)** offers some interesting hidden symmetries. E.g., those appearing in the Yukawa sector could be related to the flavor problem. <u>One symmetry stands out:</u> **Spin(10)** has a ***Z***$_4$ center.

$$\begin{array}{lcccc}
\mathcal{Z} & : & \psi & \to +i & \psi \\
 & : & \overline{\psi} & \to -i & \overline{\psi} \\
 & : & \phi_{2n+1} & \to - & \phi_{2n+1} \\
 & : & \phi_{2n} & \to + & \phi_{2n}
\end{array}$$

$$\begin{array}{lcccc}
\mathcal{Z}^2 & : & \psi & \to & -\psi \\
 & : & \phi & \to & +\phi
\end{array}$$

Non-SUSY SO(10) GUT provide a nice motivation from top for WIMPs in the form of various (admixtures of) multiplets.

	SO(10) reps.	DM candidates (SM)	$\mathbb{Z}_2$
Fermions	**10,**	**(1,2,**1/2**)** [SB, Nardi, Krauss '15]	
	45, 54, 210	**(1,1,**0**)+(1,3,**0**)** [Frigerio, Hambye '09]	**+**
	126	**(1,1,**0**)**	
	…		
Scalars	**16, 144**	**(1,1,**0**)** [Kadastik, Kannike, Raidal '09]	**-**
	...		

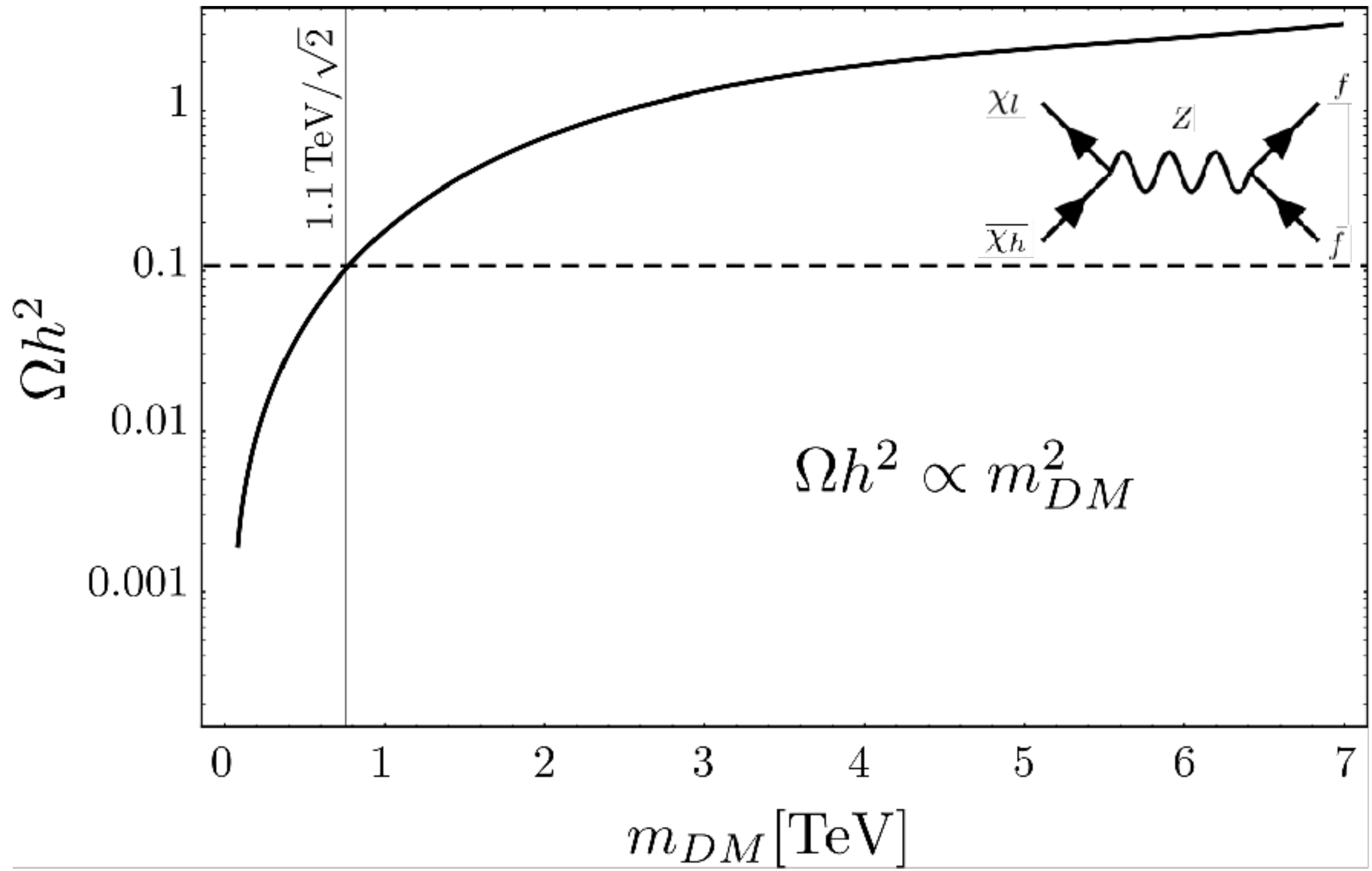
Simplest possibility: 10

The **10** of SO(10) offers the simplest possibility to include DM in realistic models. The fermionic 10 representation contains an SU(2) doublet: higgsino-like DM.

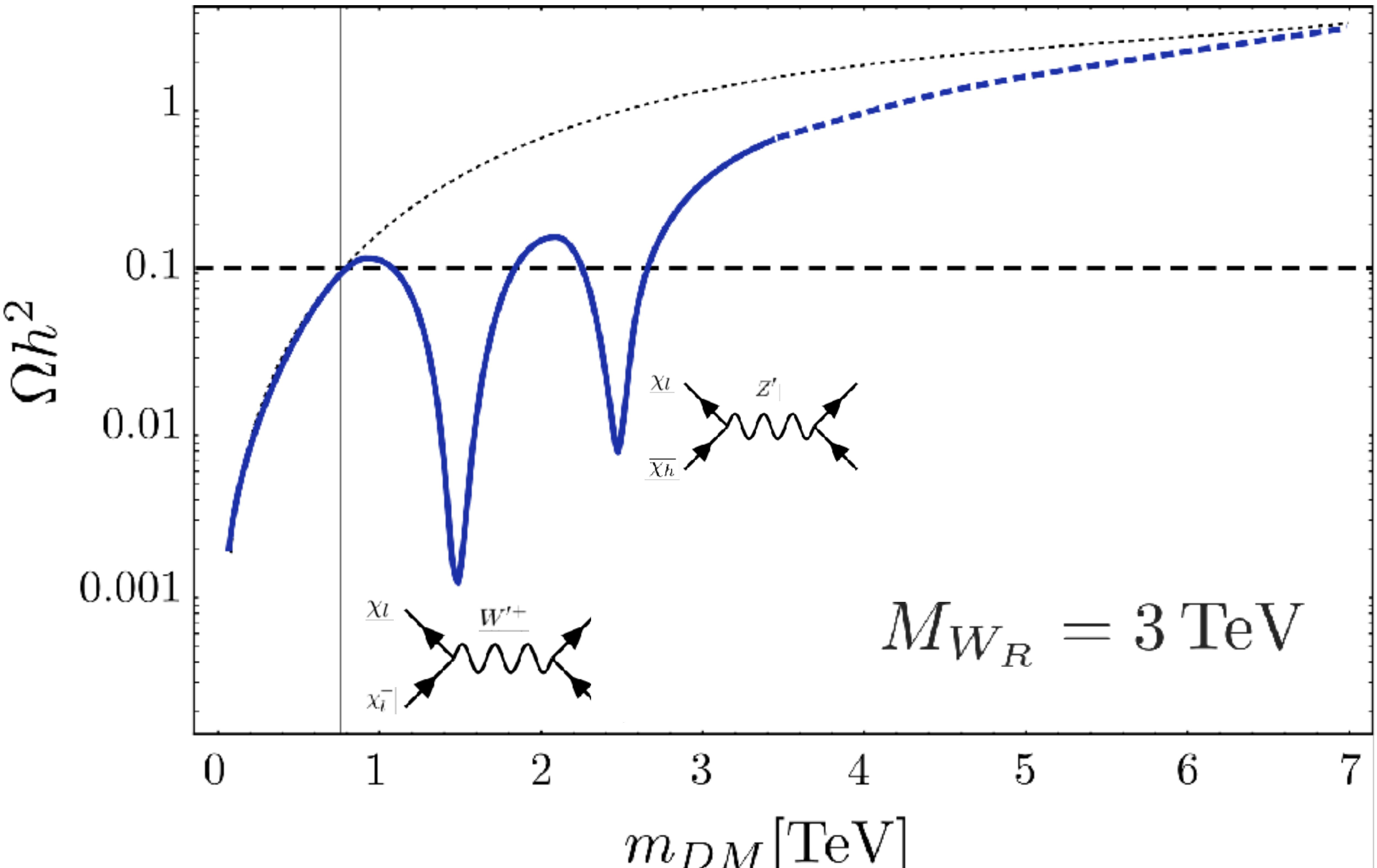
However, due to the rich gauge structure of the GUT, this low energy doublet interacts via new gauge bosons as well.

This leads to enhanced phenomenological predictions.

Simplest possibility: 10



Simplest possibility: 10



Indirect detection

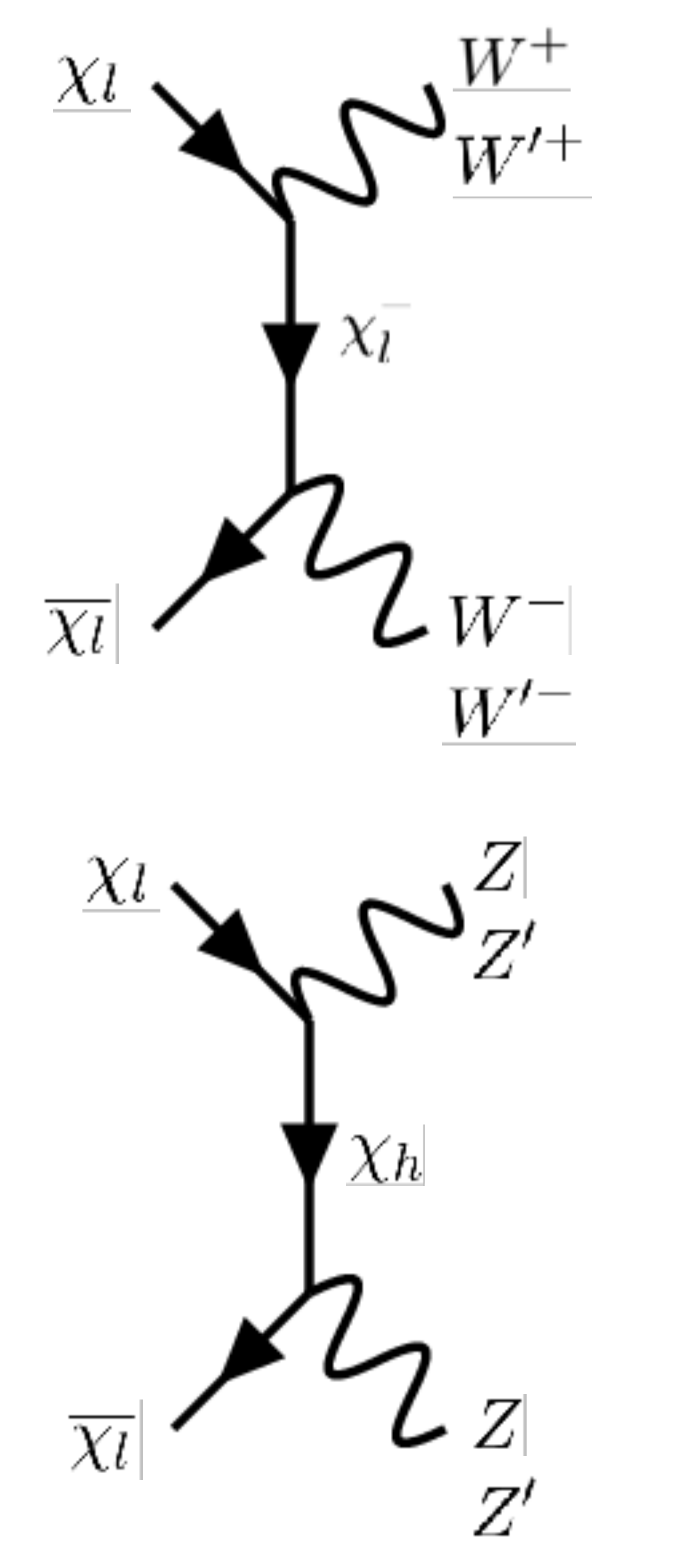
The leading annihilation channel for indirect detection searches is into diboson states.

The signal remains below current limits:

$$\langle \sigma v \rangle \approx 10^{-1.5} \left(\frac{2\,\mathrm{TeV}}{m_{\chi_l}} \right)^2 \langle \sigma v \rangle_{\mathrm{FERMI}}$$

Future observatories like CTA could soon probe some of the allowed regions.

Collider pheno similar to quasi-degenerate Higgsino in split-susy



Origin of the 10

There exist a natural motivation for the use of the **10**.
In E_6:

$$\mathbf{27} = \begin{pmatrix} \mathbf{16} \\ \mathbf{10} \\ \mathbf{1} \end{pmatrix}$$

$SO(10) \times U(1)$ explains the presence of the **10** (anomaly cancellation conditions) and greatly enriches the pheno!

$$\begin{aligned} [E_6 \rightarrow]\, SO(10) \times U(1) \quad &\rightarrow \quad [SU(5) \times U(1)_\chi \times U(1)_\psi] \\ &\rightarrow \quad [...] \\ &\rightarrow \quad SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X \end{aligned}$$

Origin of the 10

The DM sector consists of the **10+1** reps, charged under the U(1)X as

$$Q_X(\theta) = \cos\theta \, Q_\chi + \sin\theta \, Q_\psi$$

$SO(10)$	$SU(5)$	fields	$2\sqrt{6}Q_\psi$	$2\sqrt{10}Q_\chi$
16	**10**	$\{Q, u^c, e^c\} \equiv F_{10}$	1	-1
	$\mathbf{5}^\star$	$\{L, d^c\} \equiv F_{\bar{5}}$		3
	1	ν^c		-5
10	**5**	$\{\mathcal{Q}, \xi\} \equiv \chi$	-2	2
	$\mathbf{5}^\star$	$\{\mathcal{Q}^c, \xi^c\} \equiv \chi^c$		-2
1	**1**	N	4	0

Motivation for various DM possibilities

- **Singlet DM**
  - $M_X \gg \text{TeV}$: E-WIMP
  - $M_X \sim \text{TeV}$: Archetypical Z' portal model
- **Doublet DM**
  - $M_X \gg \text{TeV}$ and $M_{LR} \sim \text{TeV}$: Previous slides
  - $M_X \sim \text{TeV}$ and $M_{LR} \gg \text{TeV}$: Next slide
- **Doublet+Singlet DM**
  - $M_X, M_{LR} \gg \text{TeV}$: The model automatically reproduces a `well-tempered' system which renders the DM OK with DD.
  - $M_X \sim \text{TeV}$ and $M_{LR} \gg \text{TeV}$: The X interactions impact DD/ID rates, and the presence of the D quarks enrich the LHC pheno.
  - $M_X, M_{LR} \sim \text{TeV}$: All the features of the **SO(10)** model + new pheno due to X

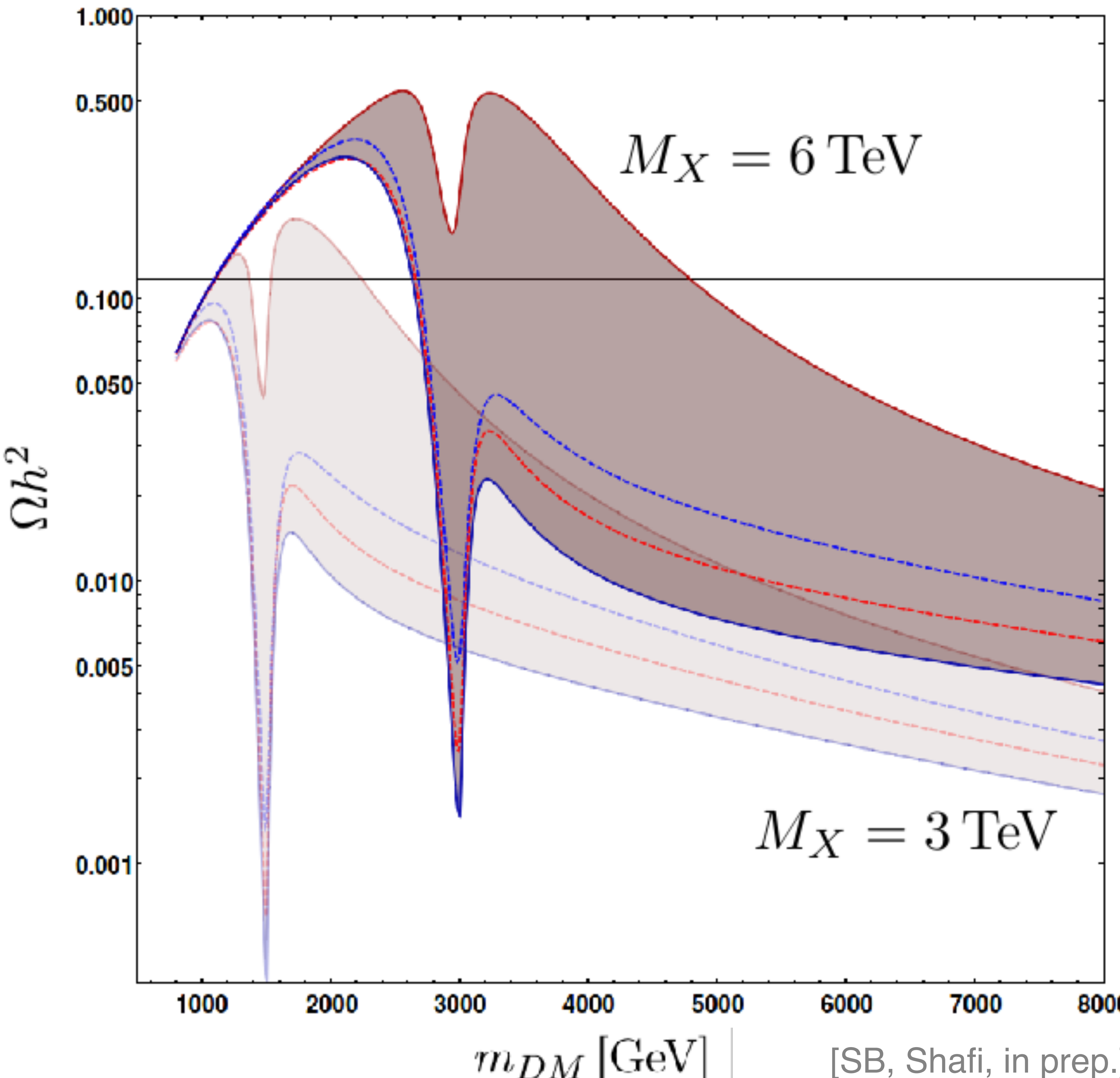
[SB, Shafi, in prep.]

Motivation for various DM possibilities - example

Mostly **2**-blet DM with low scale X and high scale LR.

Band = All possible U(1)X.

DD is evaded via tiny singlet mixing (**2**=pseudo-Dirac pair)



[SB, Shafi, in prep.]

DM in SO(10)
Summary

SO(10) provides a natural framework to motivate WIMP DM. The pheno is rich with possible interplays with neutrino masses, BAU, and new intermediate scales.

Simplest possibility consists of adding a **10**plet, leading to a bi-doublet DM. Direct detection bounds force the LR r scale to be low: testable scenario; interplay DD/ID/LHC. simple theory, using only 3 fermion representations per family explains a lot and draws links between various BSM areas.

SO(10)xU(1) goes a step further and offer various DM scenarios.

General Conclusions

Grand Unified Theories offer a very interesting framework for New Physics