Cosmological constraints on SO(10) GUT

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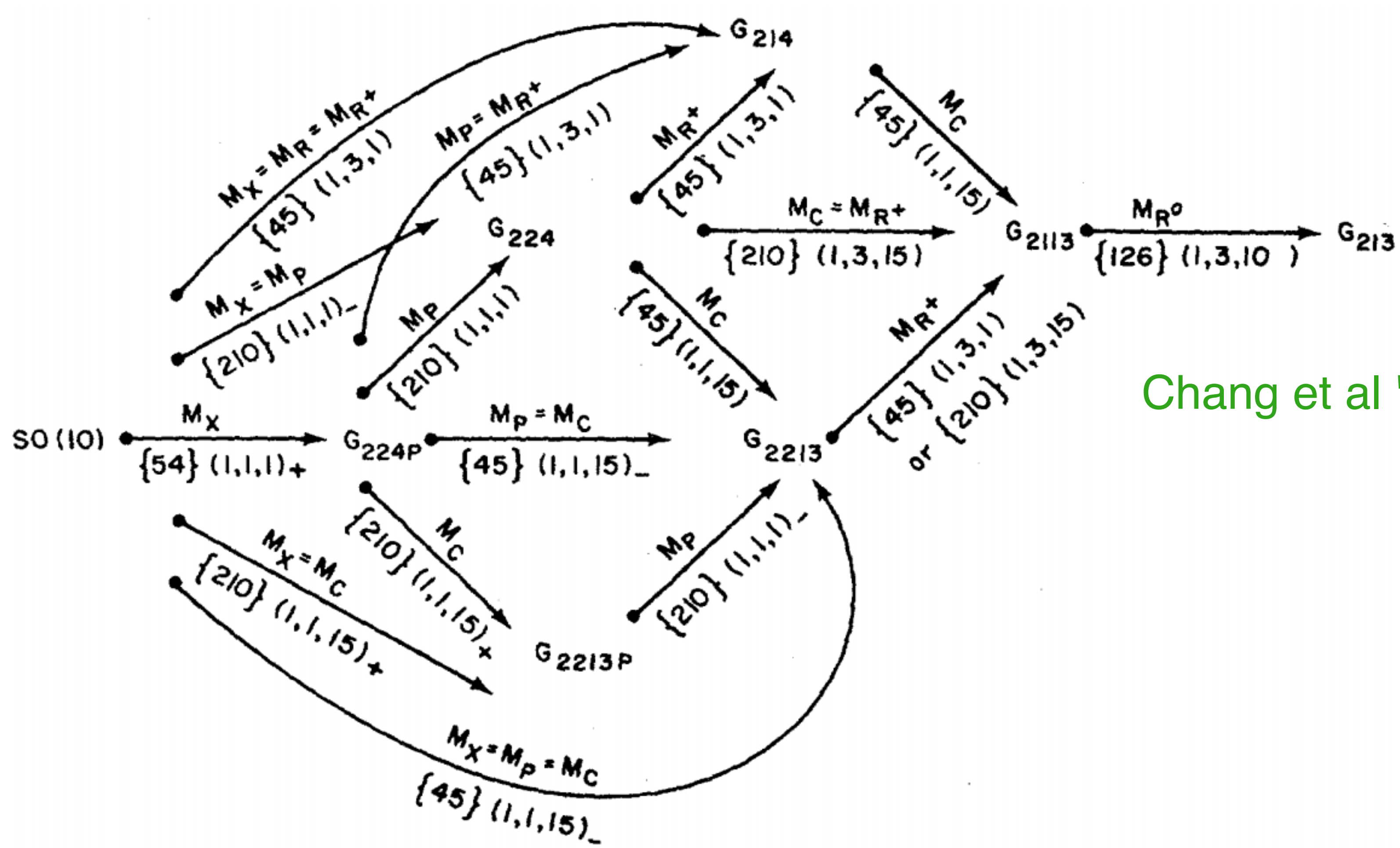
> 1511.02524 (w/ M.Krauss & E.Nardi)
> *in prep* (w/ D.Meloni & Q.Shafi)

SO(10) GUT offer many nice features

- Unification of forces, and of quarks and leptons
- Charge quantization
- Top inspired
- Fermions masses and mixings
- Intermediate physical scales, e.g., LR
- Axions
- **GUT Inflation**
- **baryogenesis via leptogenesis**
- **Dark matter**
- ...

Problem of choice

SO(10) can go to the SM via various routes & scales



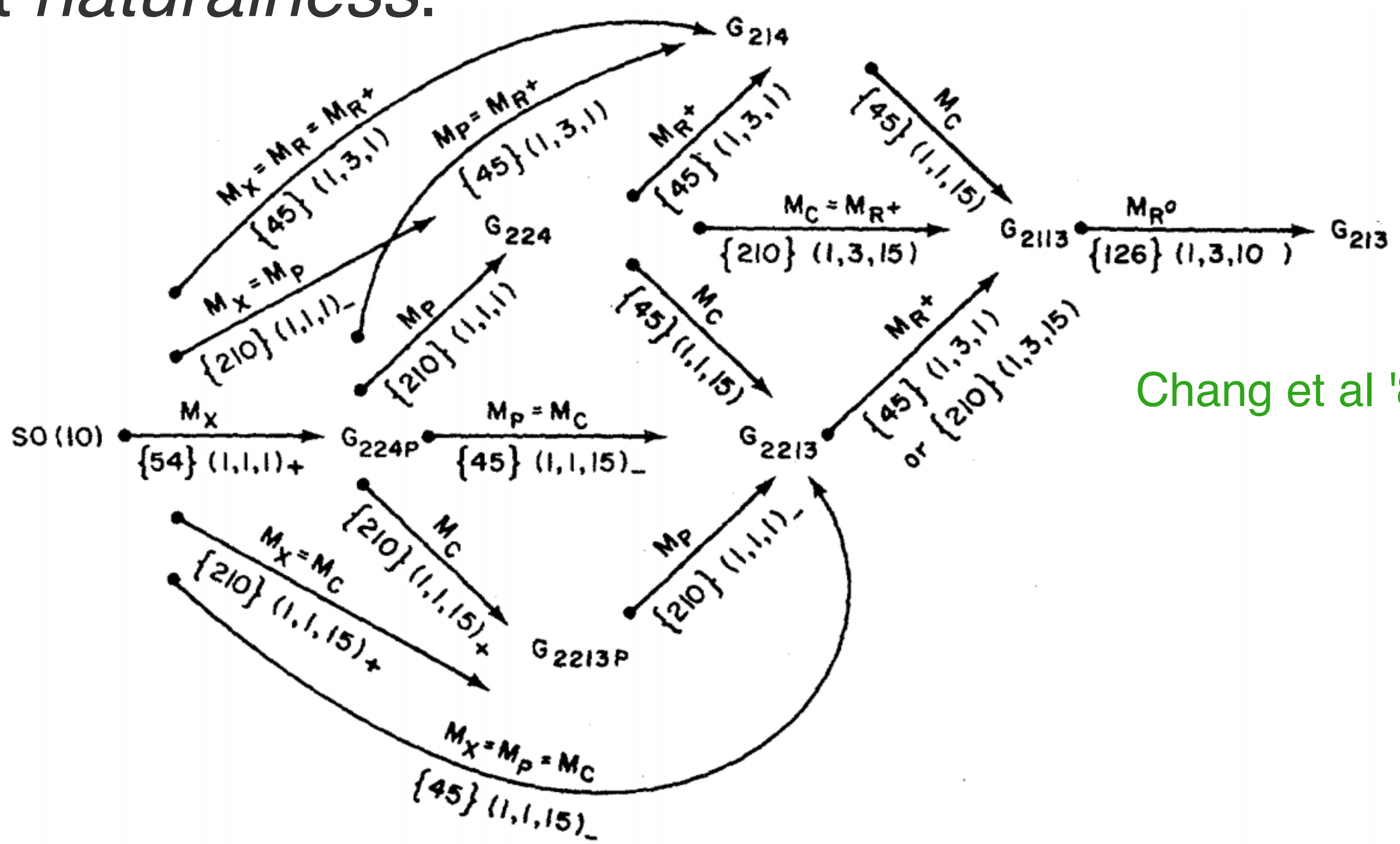
Chang et al '85

ICE CREAM

We now produce more than 150 flavors, every day.
Here you can enjoy more than twenty varieties of chocolate: from the dark chocolate obtained thanks to the processing of the Brazilian cocoa in the State of Bahia to a timeless classic flavor like the Nutella chocolate.

Problem of choice

SO(10) can go to the SM via various routes & scales
Let's maximize **minimality/predictivity**, and forget about *naturalness*.



Chang et al '85

Use cosmo (DM, inflation, BAU) to constrain SO(10) scales and make the models more testable.

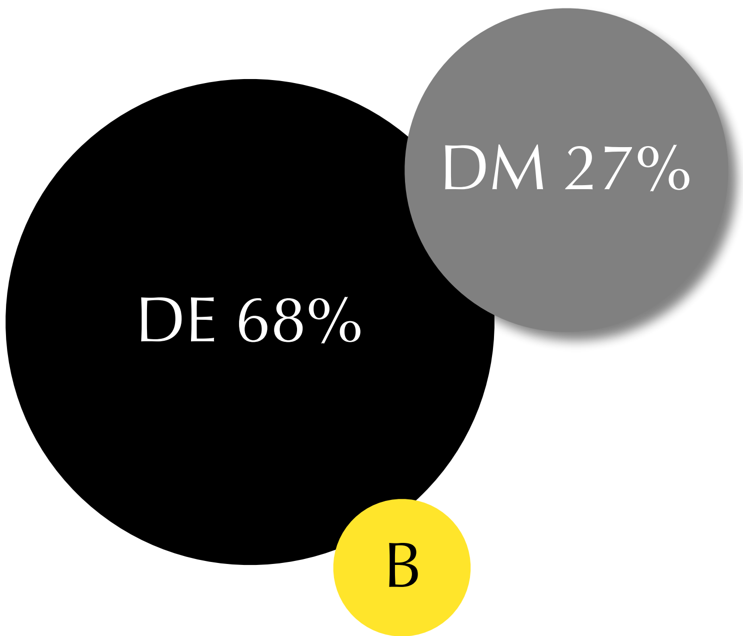
Plan

- Introduction and motivation
- Dark Matter and Left-Right scale
- Inflation and Pati-Salam scale

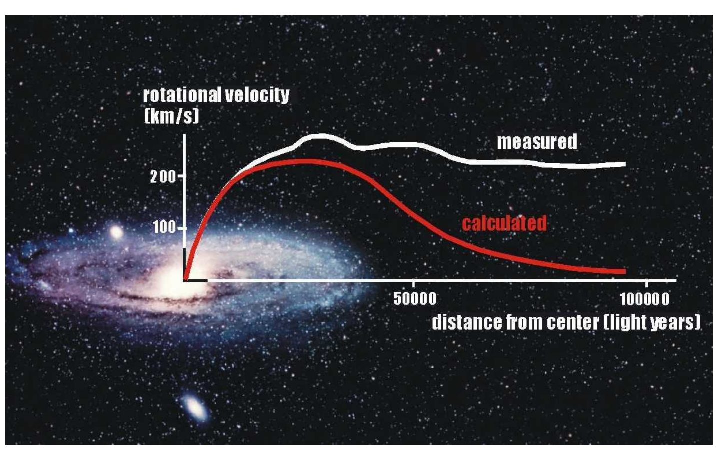
Dark Matter and Left-Right

We live in a pretty dark place

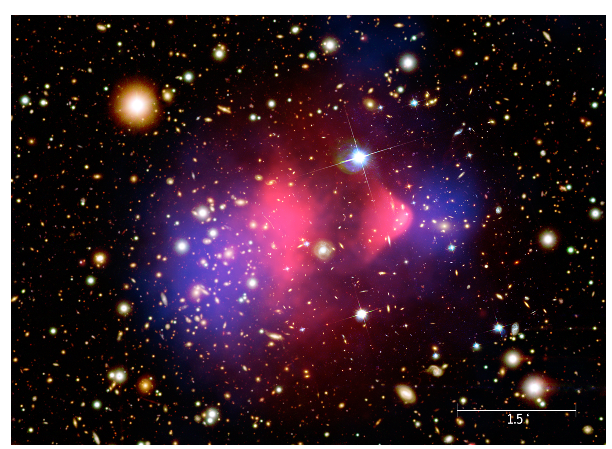
By now, we have a wide array of evidences for a nonbaryonic, clustering component.



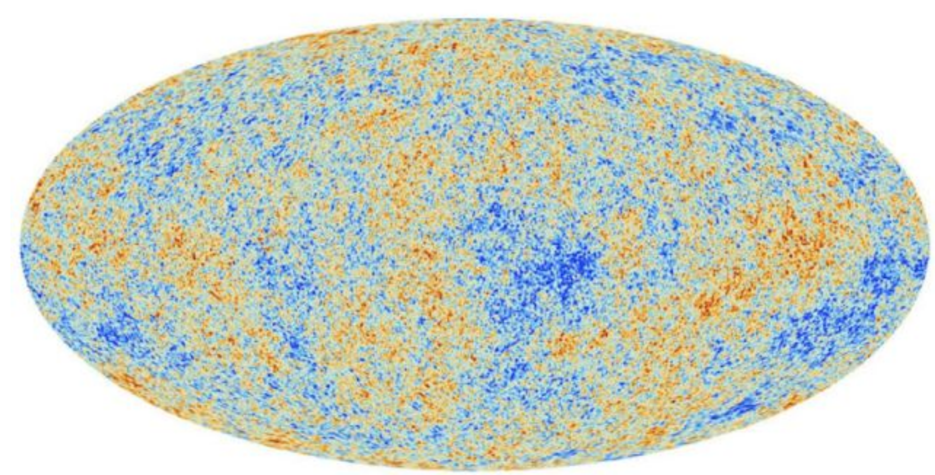
Most interesting particle candidates relate DM to other BSM problems, e.g. axions, majorons, ADM, and **WIMPs**.



(10 kpc)



(Mpc)

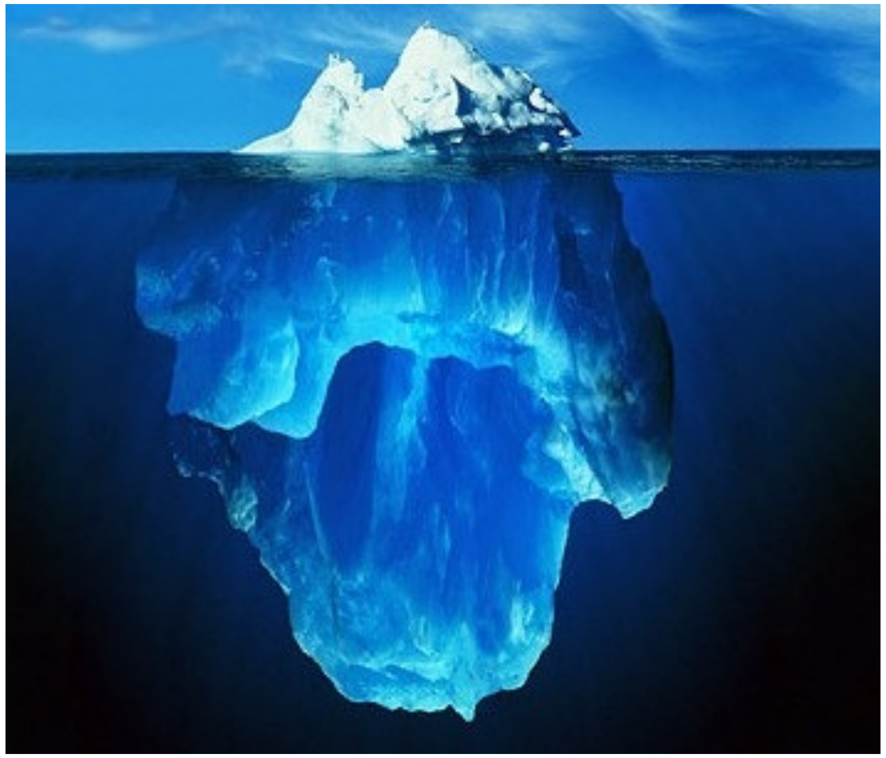


(10 Gpc)

Known knowns about DM

An acceptable candidate should not only reproduce observed abundance but also be

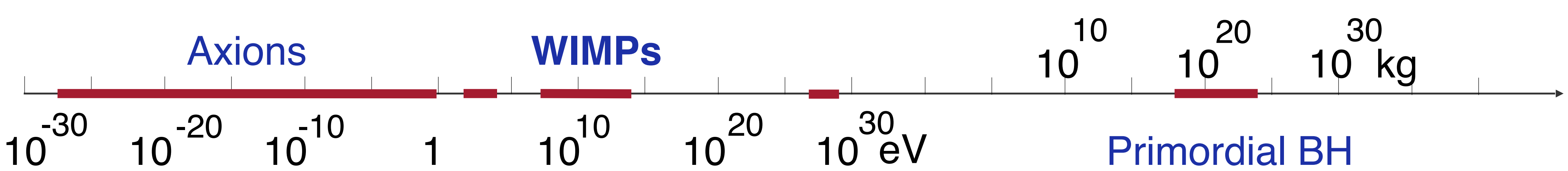
- neutral-ish,
- cold-ish
- quasi-stable
- OK with BBN and astro
- collisionless
- OK with search limits



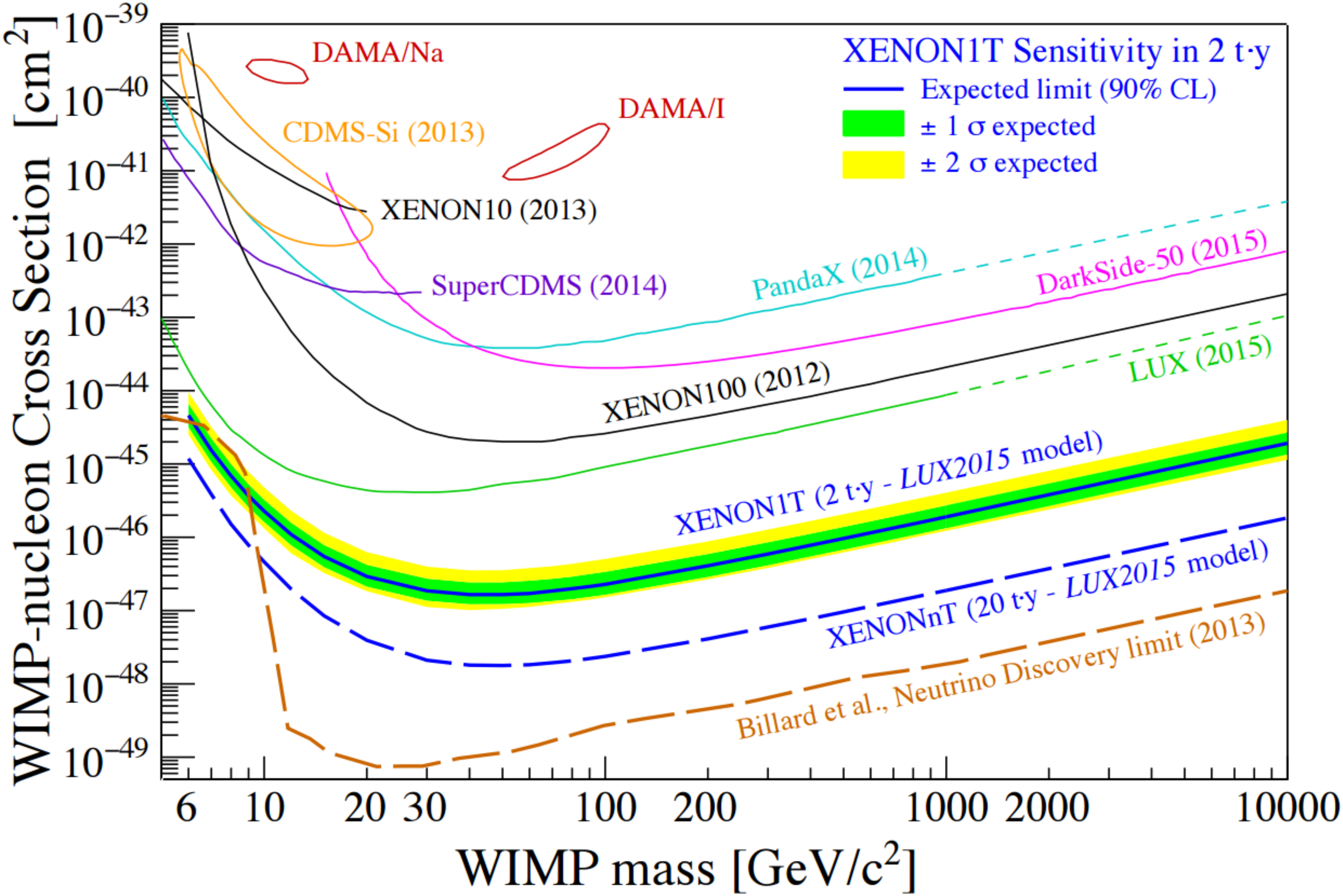
But how about its nature?

- Simple (single particle) or complex (dark chemistry)?
- Does it carry a new charge?
- Is it self-interacting?
- What is stabilizing it and how?
- Is it decaying?
- How is related to other BSM sectors?
- Is it asymmetric?
- How is it produced?

This is where model-building comes in.



Why wimps?



XENON collab. JCAP04(2016)027

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DM is <u>very</u> stable!

DM should be at least older than the Universe:

$$\tau_{\rm DM} \gtrsim H^{-1} \sim 10^{18}\mathrm{s}$$

However, it usually emits *gammas, e+, p,* etc, and to avoid bounds, the limit becomes:

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

How to stabilize DM?

From HEP viewpoint, this stability points to a new preserved symmetry. Straightforward solution is to impose a parity by hand. However, more motivated stabilization mechanisms exist, e.g.,

- accidental Cirelli et al. 05';...
- due to a new (unbroken) gauge group Ackerman et al. 08'; Foot at al. 06'-10'; Pospelov et al. 07'; ...
- remnant from a flavour symmetry Hirsch et al. 10'; SB et al. 11'-12'; ...
- **remnant from SO(10) GUT** Mohapatra 86'; Martin 92'; Frigerio-Hambye 09'; Kadastik et al. 09'
- ...

[For a short review, see Hambye's 1012.4587]

Why SO(10)?

SO(10) is a group of rank 5; SM gauge group is rank 4 → 1 extra U(1). If charges are chosen carefully, a spontaneously broken U(1) leaves a remnant discrete symmetry

$$U(1) \xrightarrow[\text{[with N units of charge]}]{\phi} Z_N$$

In **SO(10)** this **U(1)** is identified with $U(1)_{B-L}$, and the smallest *irreps.* with *N*>1 is **126**, therefore: [Think e.g. of seesaw I and II from **16.126.16**]

$$\boxed{U(1)_{B-L} \xrightarrow{\langle 126 \rangle} Z_2 \equiv (-1)^{3(B-L)}}$$

Kibble, Lazarides, Shafi 82'
Krauss, Wilczek 89'

The possible dark *reps.* are:

	SO(10) reps.	DM candidate (SM)	$\mathbb{Z}_2$
Fermions	**10,** **45, 54, 210** **126** **...**	**(1,2,1/2)** **(1,1,0)+(1,3,0)** **(1,1,1/2)**	**+**
Scalars	**16, 144** **...**	**(1,1,0)**	**-**

[From **16.10.16**, with **16** odd and **10** even:
new fermions (scalars) are stable if even (odd)]

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Fermions	10,	(1,2,1/2)	
	45, 54, 210	(1,1,0)+(1,3,0)	Frigerio, Hambye 09’
	126	(1,1,1/2)	
	...		
Scalars	16, 144	(1,1,0)	Kadastik, Kannike, Raidal 09’
	...		

See also:
Mambrini et al. 15'
Nagata et al. 15'
Arbelaez et al. 15'

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Let's assume a simple setup

We consider a minimal **SO(10)** fields content: 3 generations of fermion **16**, and scalars in **126**, **45** and complex **10**.

$$SO(10) \xrightarrow{\langle \mathbf{45}_H \rangle} 3_C 2_L 2_R 1_{B-L}$$

$$\xrightarrow{\langle \overline{\mathbf{126}}_H \rangle} 3_C 2_L 1_Y \otimes \mathbb{Z}_2$$

$$\xrightarrow{\langle \mathbf{10}_H \rangle} 3_C 1_Q \otimes \mathbb{Z}_2 .$$

Bertolini, di Luzio, Malinsky '11
SB, Krauss, Nardi 15'

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$$-\mathcal{L}_{\rm SM} = \mathbf{16}_i \left(h_{ij} \mathbf{10}_H + g_{ij} \mathbf{10}^*_H + f_{ij} \overline{\mathbf{126}}_H \right) \mathbf{16}_j$$

The **45** breaks the group (first stage to PS), and splits the **10's**

$$\mathbf{45}_H = \mathrm{diag}(a, a, a, b, b) \otimes i\sigma_2$$

~GUT ~TeV

[Dimopoulos, Wilczek]

Let's assume a simple setup

We consider a minimal **SO(10)** fields content: 3 generations of fermion **16**, and scalars in **126**, **45** and complex **10**.

We now add the DM rep; fermionic **10**. The DM candidate is then

$$\mathbf{10} \supset (\mathbf{1}, \mathbf{2}, \mathbf{2}, 0) \equiv \begin{pmatrix} \xi^{+-} & \xi^{++} \\ \xi^{--} & \xi^{-+} \end{pmatrix}$$

... which at EW scale is a $SU(2)_L$ doublet!

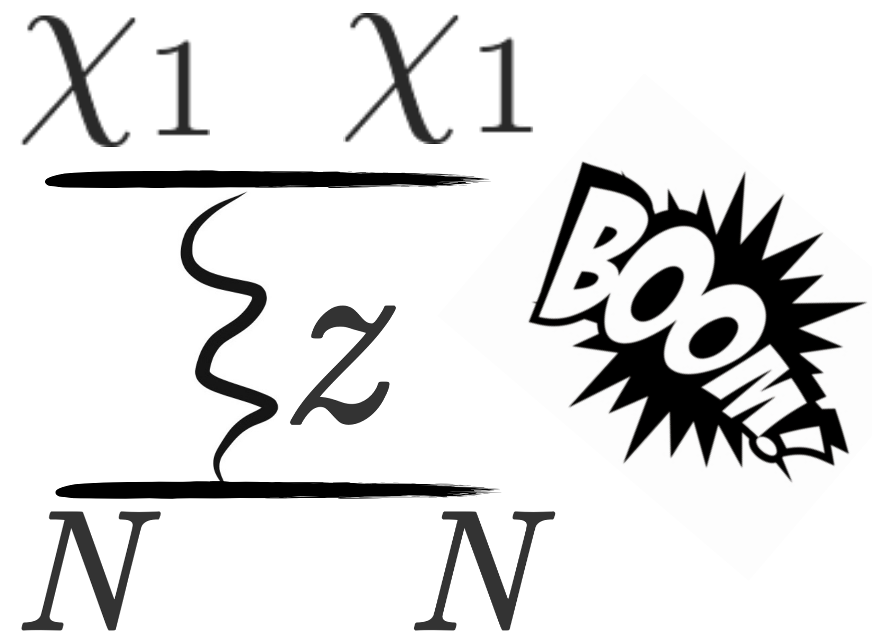
Some direct consequences

Hypercharged DM:

→ $SU(2)_L$ multiplet

→ Z mediated interactions

→ Direct detection problem!



To fix this, one may

- go to very high DM mass (~EeV)
- mix it with a majorana fermion
- have off-diagonal Z interactions
- split the neutral Dirac state to two Majorana fermions

Some direct consequences

Hypercharged DM:

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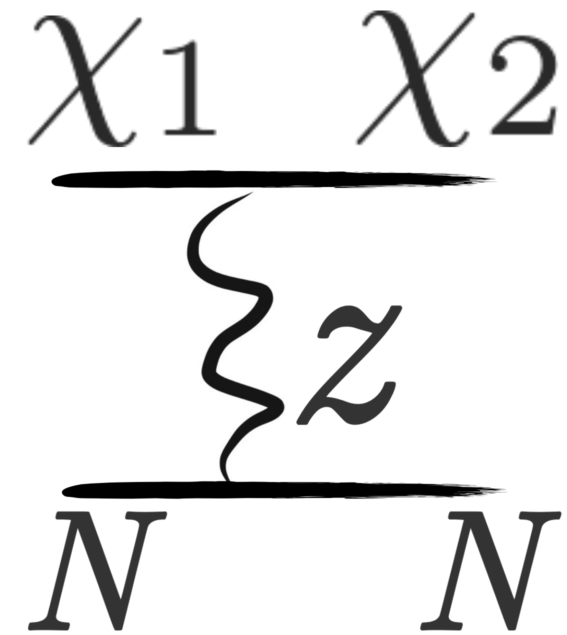

$$\boxed{E_{kin} < \Delta M}$$

To fix this, one may

- ~~go to very high DM mass (~EeV)~~ Can't be WIMP
- ~~mix it with a majorana fermion~~ Usually added by hand; not so nice
- have off-diagonal Z interactions
- split the neutral Dirac state to two Majorana fermions

Let's assume a simple setup

We consider a minimal **SO(10)** fields content: 3 generations of fermion **16**, and scalars in **126**, **45** and complex **10**.

We now add the DM rep; fermionic **10**.

$$-\mathcal{L}_{\rm DM} = \sum_{a=L,R} \mathbf{10}_a\,(M_a + \lambda_a\,\mathbf{54}_H)\,\mathbf{10}_a + [\mathbf{10}_L\,(M + y\,\mathbf{45}_H + \lambda\,\mathbf{54}_H)\,\mathbf{10}_R + \text{H.c.}]$$

$$\mathbf{10} \otimes \mathbf{10} = (\mathbf{1} \oplus \mathbf{54})_s \oplus \mathbf{45}_a$$

Let's assume a simple setup

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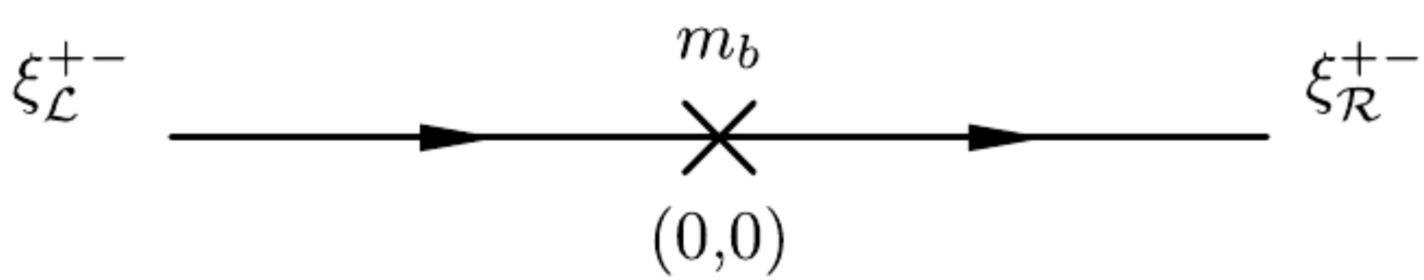
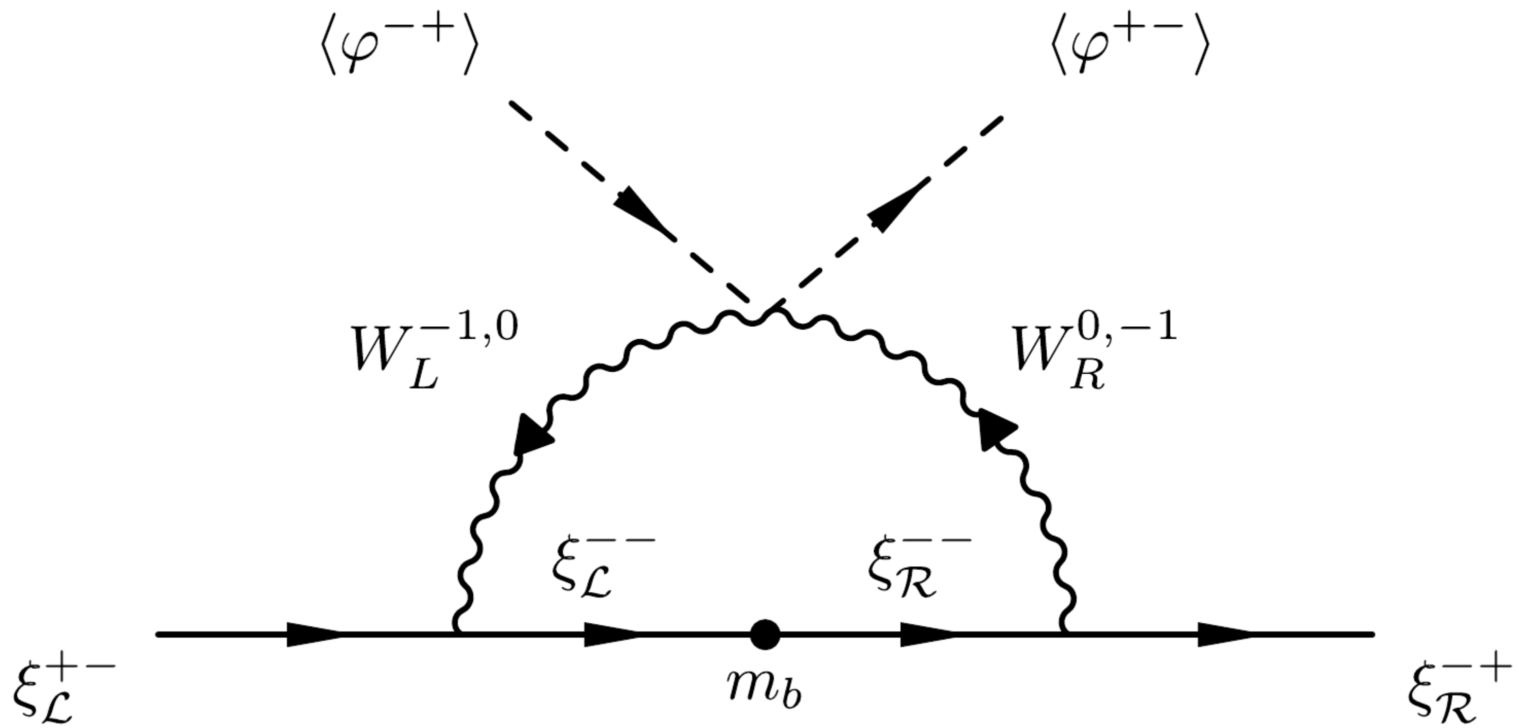
The mass is simply



Bidoublet DM

After EWSB, an effective $(\mathbf{1},\mathbf{3})_1$ can be generated, leading to two, maximally mixed, Dirac particles with $m_{h,l} = m_b \pm \delta_m$

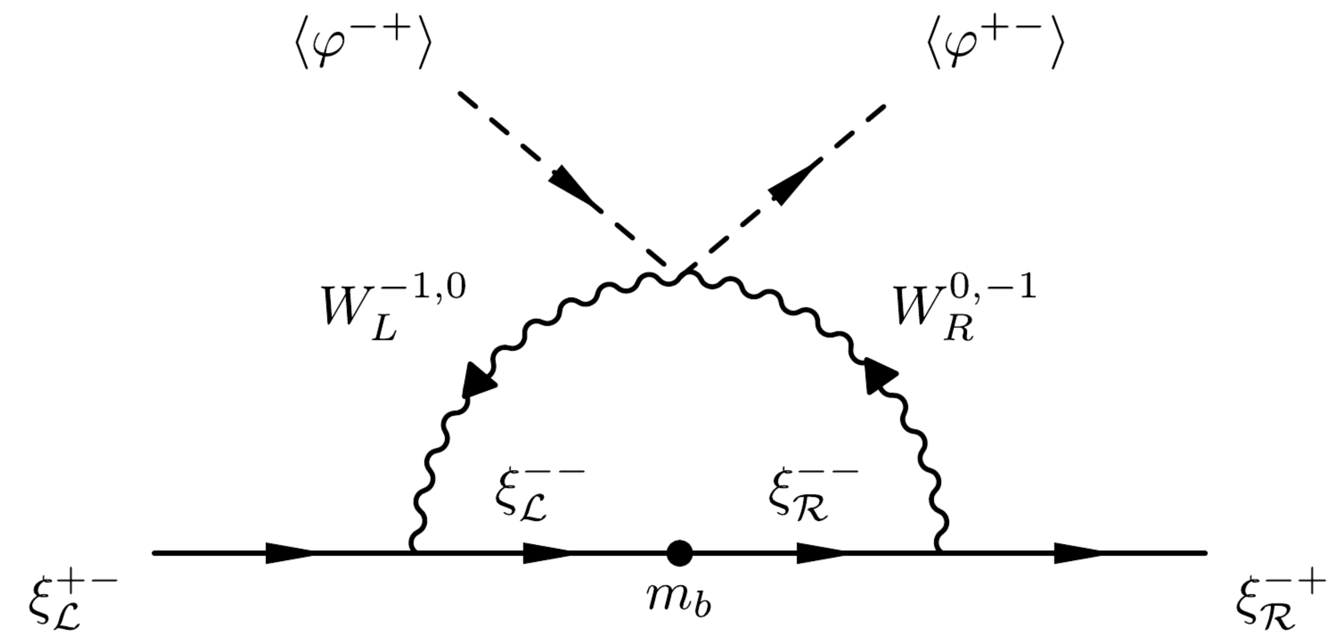


Maximal mixing + iso-spin difference implies off-diagonal Z interactions:

$$\begin{aligned} J_\mu^{nc} &= -\sum_{i=1,2} \chi_i^\dagger i\bar{\sigma}_\mu \left(V\, T_3 V^\dagger\right) \chi_i \\ &= \frac{1}{2}\, \overline{\chi_h} \gamma_\mu\, \chi_l + \text{H.c.}, \end{aligned}$$

DM direct detection and WR

The radiative mass splitting should exceed the kinetic energy of DM; E ~ 200 keV



$$\frac{1}{2}\delta_m \sim \frac{g_L^2 g_R^2}{16\pi^2}\frac{v_u v_d}{M_{W_R}^2} m_b \sim 5\times 10^{-3}\,\vartheta_{LR}\, m_b$$

< ~ 0.001

Interestingly, DD bounds require a low scale LR step:

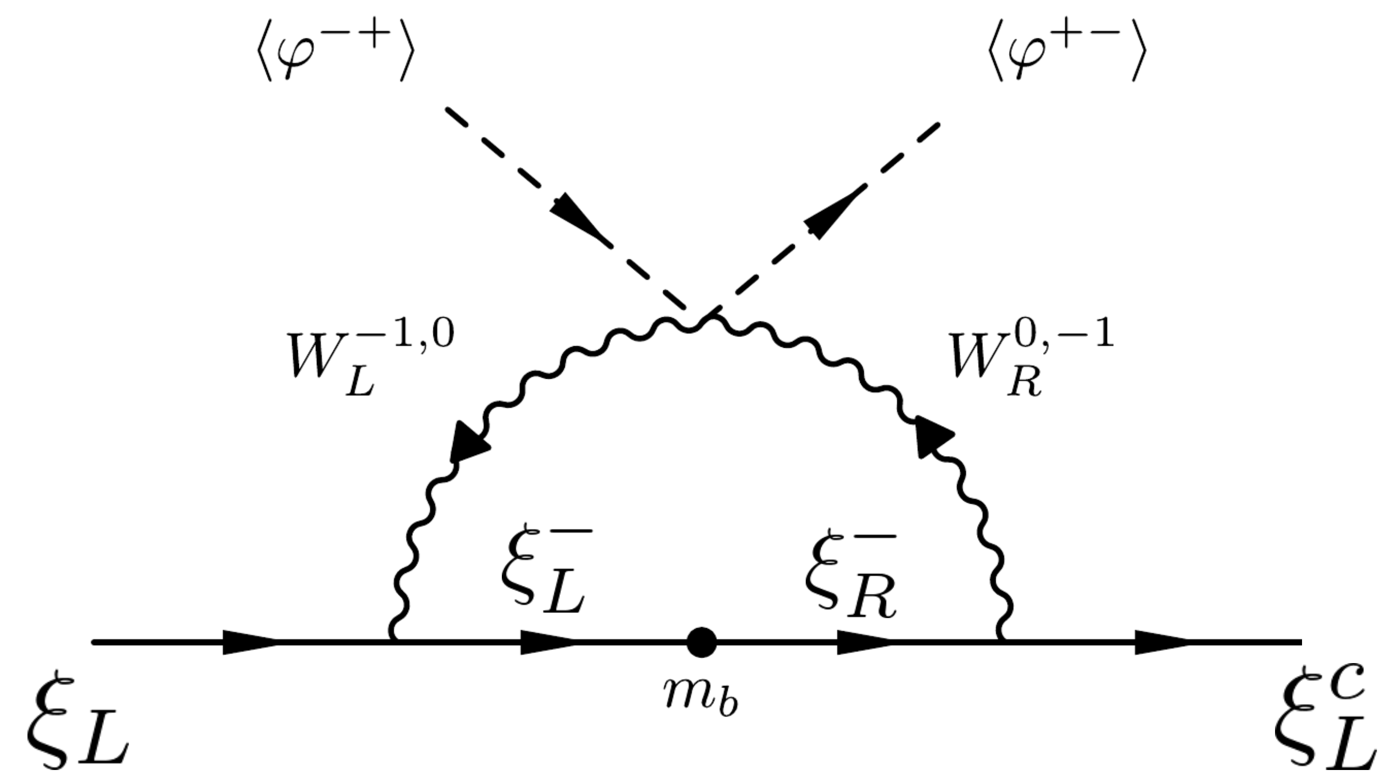
$$\boxed{M_{W_R} \lesssim 25\left(\frac{m_b}{\mathrm{TeV}}\right)^{1/2}}$$

Even simpler

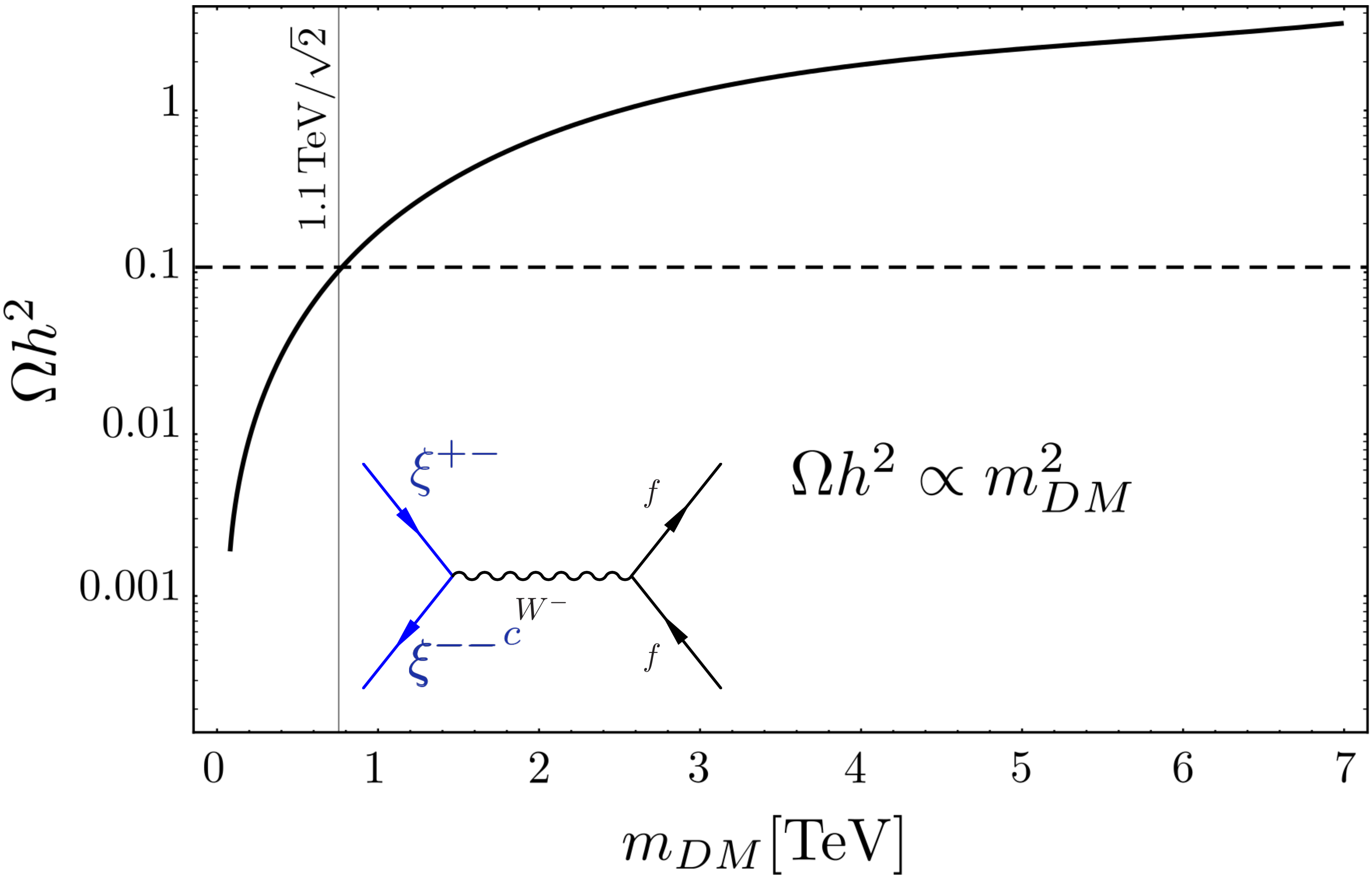
We can achieve similar results with only one, self-conjugated, **10**. Direct detection would be avoided by inducing a majorana splitting to the Dirac state. The DM is then pseudo-Dirac.

$$-\mathcal{L}_{\rm DM} = \cancel{\sum_{a=L,R}} \mathbf{10}_a \left(M_a + \lambda_a \cancel{\mathbf{54}_H}\right) \mathbf{10}_a + \left[\mathbf{10}_L \left(\cancel{M} + \cancel{y\,\mathbf{45}_H} + \cancel{\lambda\,\mathbf{54}_H}\right) \mathbf{10}_R + \text{H.c.}\right]$$

$$\begin{pmatrix} \xi & \xi^+ \\ \xi^- & -\xi^c \end{pmatrix}_L$$



DM relic density



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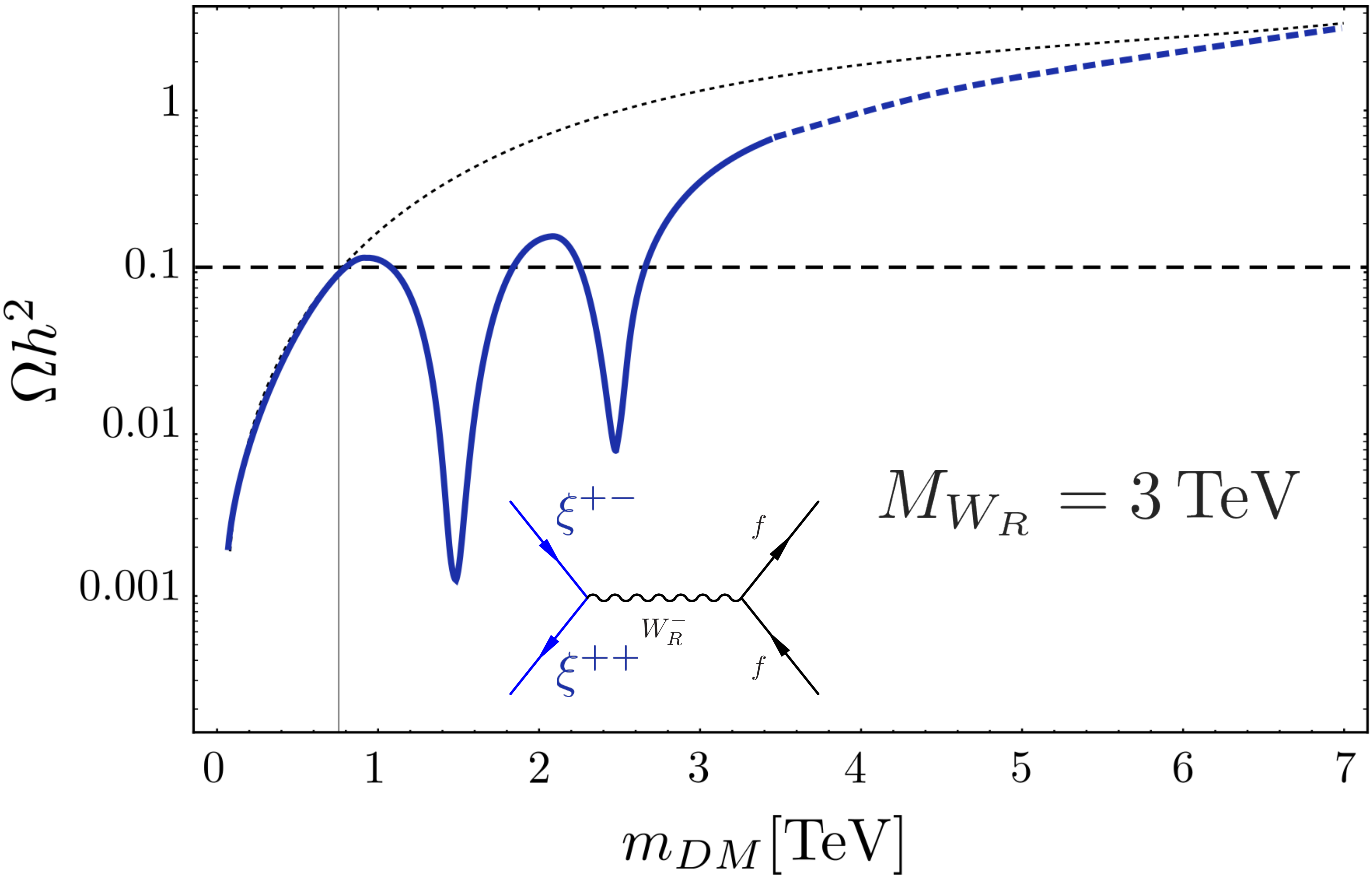

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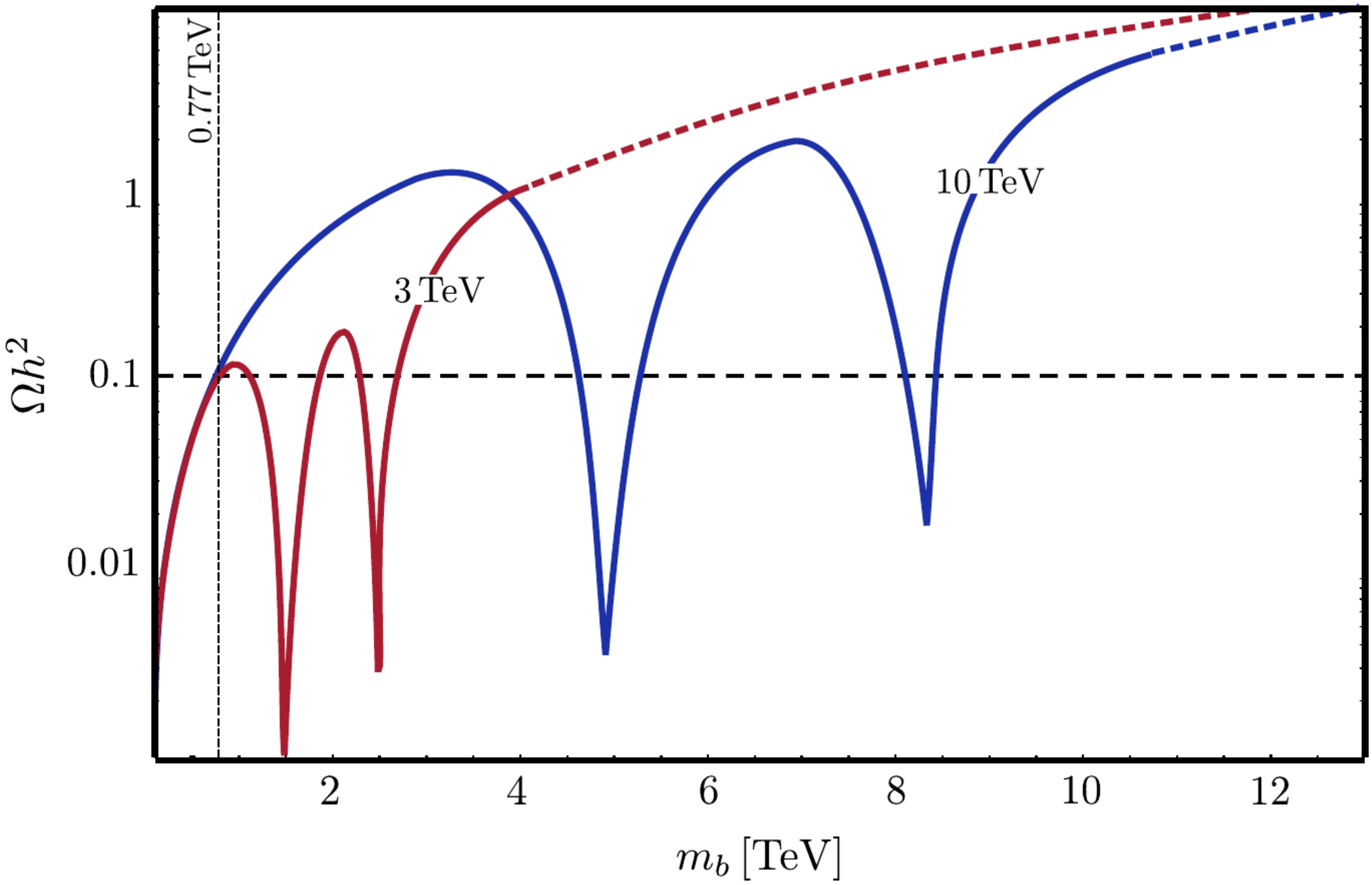


Inflation and Pati-Salam

A simple model

Let's take a minimal, fully consistent, nonsusy **SO(10)** model which goes to SM via PS. We need 4 scalar representations:

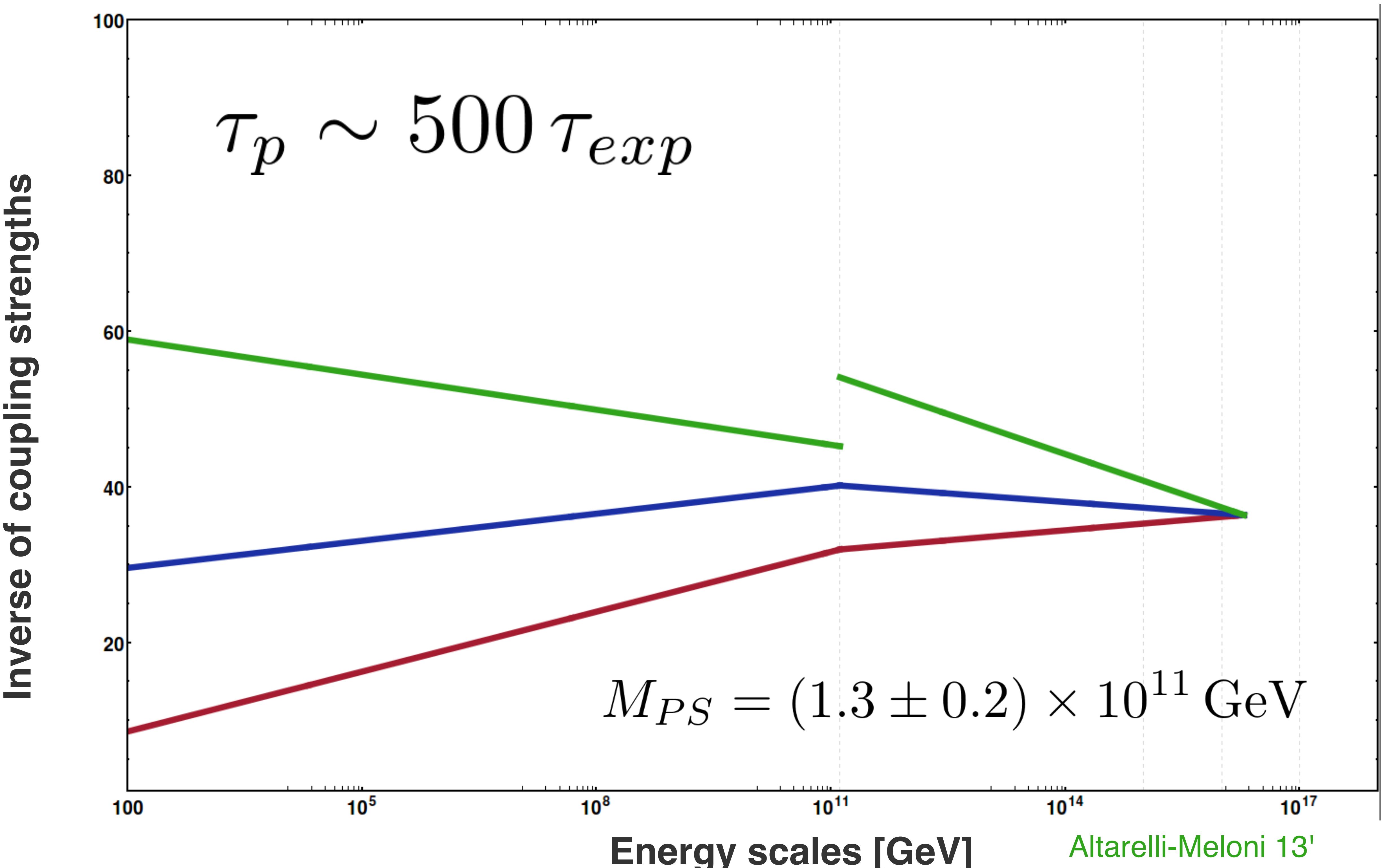
210 to break **SO(10)**
45 to break **U(1)**$_{PQ}$
$\mathbf{\overline{126}}$ and **10** for masses
(the Higgs doublets of the **126** get small vevs via **45.126.10.210**)

This gives:
Fermion masses/mixing, GCU, Leptogenesis, and Axion DM.

$$SO(10)$$
$$\Big\downarrow \ \mathbf{210}$$
$$SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$$
$$\Big\downarrow \ \mathbf{45},\ \mathbf{\overline{126}}$$
$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$
$$\Big\downarrow \ \mathbf{10}$$
$$SU(3)_C \otimes U(1)_Q$$

Altarelli-Meloni 13'

A simple model



Altarelli-Meloni 13'
Lee,Mohapatra,Parida, Rani, 95'

But ...

The PS breaking yields monopoles (2 Dirac charges), whose mass is about 10 M_{PS}. In a simple GUT inflation model, the potential involves at the intermediate scale

$$V \supset \frac{1}{2} T_H^2 \chi_{PS}^2 - \frac{1}{2}\left(\frac{M_{PS}}{M}\right)^2 \phi^2 \chi_{PS}^2$$

$T_H \equiv H/2\pi$

Symmetry breaking occurs (and therefore, monopoles are frozen-in) for

$$\phi \sim T_{H_*} \frac{M}{M_{PS}} \rightarrow M_{PS} \sim T_{H_*} \sim 10^{13}\mathrm{GeV}$$

*=when the scale related to the pivot exists the horizon

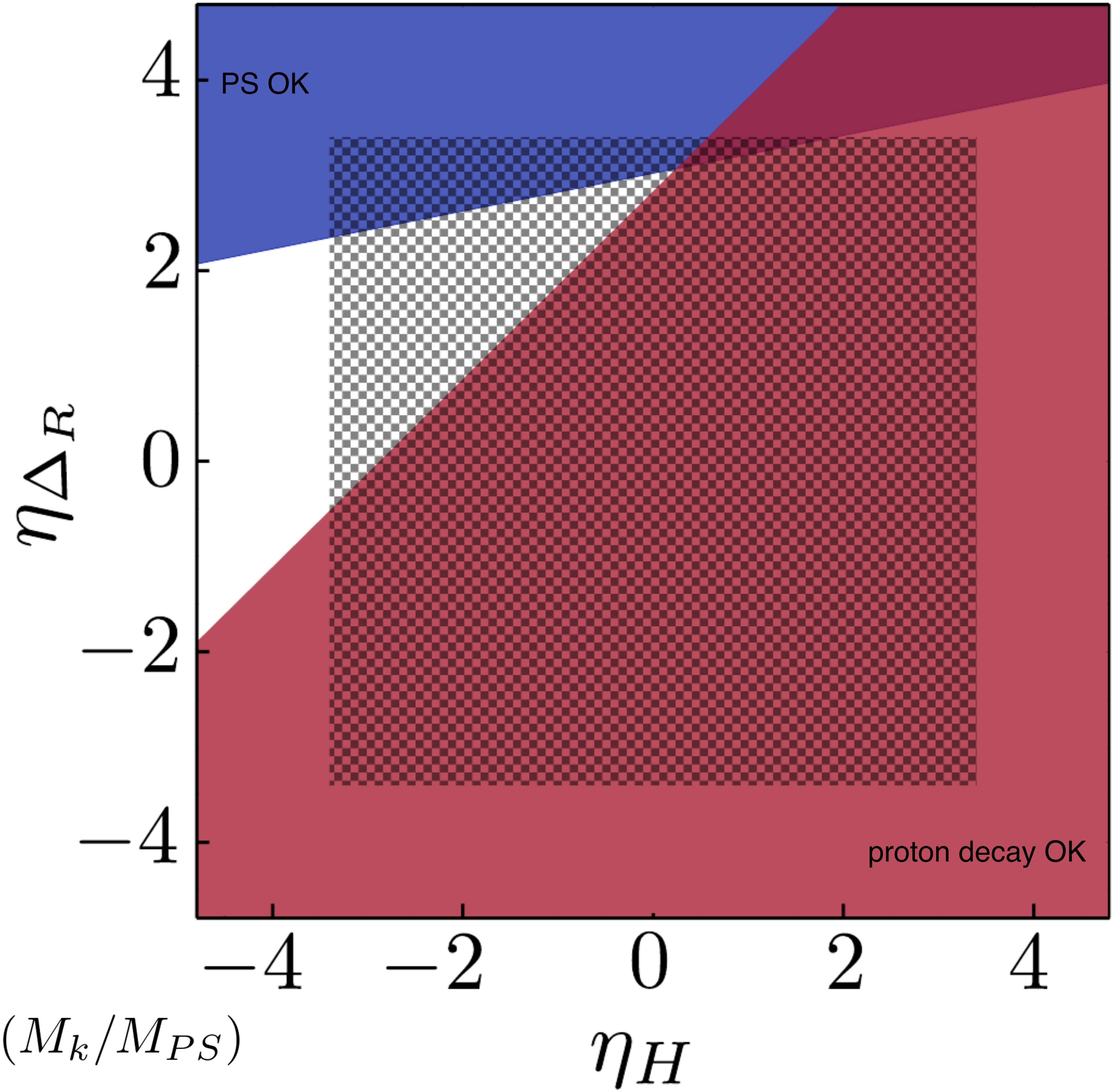
Lazarides, Magg, Shafi 80'
Senoguz, Shafi 15'

How to increase PS scale?

$SO(10)$ *irreps*	PS *irreps*	SM sub-multiplets
$\overline{\mathbf{126}}$	$H(\mathbf{15},\mathbf{2},\mathbf{2})$	$H_1(\mathbf{3},\mathbf{2})_{1/6}$, $H_2(\overline{\mathbf{3}},\mathbf{2})_{-1/6}$, $H_3(\mathbf{3},\mathbf{2})_{7/6}$,$H_4(\overline{\mathbf{3}},\mathbf{2})_{-7/6}$ $H_5(\mathbf{1},\mathbf{2})_{1/2}$, $H_6(\mathbf{1},\mathbf{2})_{-1/2}$ $H_7(\mathbf{8},\mathbf{2})_{1/2}$, $H_8(\mathbf{8},\mathbf{2})_{-1/2}$
	$\Delta_R(\mathbf{10},\mathbf{1},\mathbf{3})$	$\Delta_{R_1}(\mathbf{3},\mathbf{1})_{-1/3}$, $\Delta_{R_2}(\mathbf{3},\mathbf{1})_{-4/3}$, $\Delta_{R_3}(\mathbf{3},\mathbf{1})_{2/3}$ $\Delta_{R_4}(\overline{\mathbf{6}},\mathbf{1})_{+1/3}$, $\Delta_{R_5}(\overline{\mathbf{6}},\mathbf{1})_{+4/3}$, $\Delta_{R_6}(\overline{\mathbf{6}},\mathbf{1})_{-2/3}$ $\Delta_{R_7}(\mathbf{1},\mathbf{1})_{-2}$, $\Delta_{R_8}(\mathbf{1},\mathbf{1})_{-1}$, $\Delta_{R_9}(\mathbf{1},\mathbf{1})_{0}$
$\mathbf{45}$	$\delta_R(\mathbf{1},\mathbf{1},\mathbf{3})$	$\delta_{R_1}(\mathbf{1},\mathbf{1})_{+1}$, $\delta_{R_2}(\mathbf{1},\mathbf{1})_{-1}$, $\delta_{R_3}(\mathbf{1},\mathbf{1})_{0}$

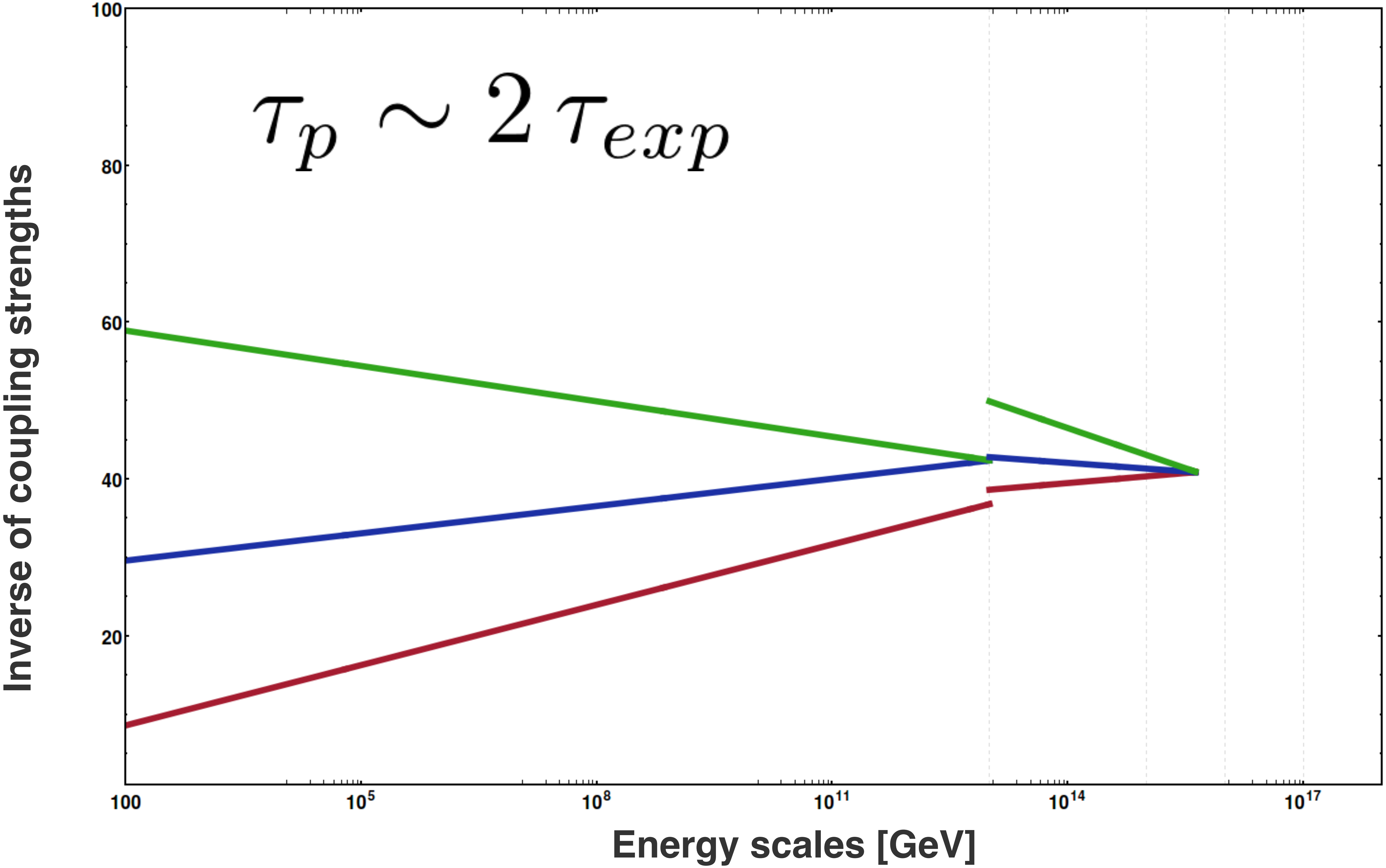
$$
\begin{aligned}
\lambda^I_{3C} &= 1 + 16\,\eta_H + 18\,\eta_{\Delta_R} \\
\lambda^I_{2L} &= 30\,\eta_H \\
5\,\lambda^I_{Y} &= 14 + 154\,\eta_H + 142\,\eta_{\Delta_R}
\end{aligned}
$$

$$
\frac{1}{\alpha_i(M_I)} = \frac{1}{a_I(M_I)} - \frac{\lambda^I_i}{12\pi}
$$



$\eta_k \equiv \ln(M_k/M_{PS})$

Larger PS = More predictivity



Conclusions

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Thanks for your attention !