Accidentally Light Scalars

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Accidentally light scalars from large representations
with **Felix Brümmer, Giacomo Ferrante, Thomas Hambye**
JHEP 01 (2024) 075 [arXiv:2307.10092]

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Searching for new physics ...

Joe Penhall, THE ROAD, 2009

Two accidental phenomena

(I) Familiar : **accidental symmetries → light scalars**

- A given gauge theory → accidental global symmetries

$$\begin{array}{lcl} \text{Spontaneous symmetry breaking (SSB)} & & G \to H \\ \text{Nambu Goldstone bosons (NGBs)} & \in & G/H \end{array}$$

- NGB masses controlled by explicit-symmetry-breaking sources

(II) Unfamiliar: **accidentally light scalars, without a symmetry**

- For some special choices of scalar representations

$$\langle \phi \rangle : \; G \to H \quad \text{but vacuum manifold larger than} \quad G/H$$

- Unexpected, still natural hierarchy among scalar masses

Accidental symmetries: hyper-QCD

Gauge theory with several fermion flavours $G_C \qquad \psi^a \sim R_C^a$

Confinement scale generated dynamically $\langle \psi^a \psi^b \rangle \sim \Lambda_C^3$

Flavour symmetries $G_F \to H_F$ for $m_\psi \to 0$ light $(\pi_1, \pi_2, \dots)$

Anomalous symmetries $U(1)_A$ for $N_C \to \infty$ light η'

$U(1)_{PQ}$ for $f_{PQ} \gg \Lambda_C$ light axion

Scale invariance $SO(4,2)$ if "slightly" broken light dilaton

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Scale invariance $\quad SO(4,2) \quad$ if "slightly" broken $\quad$ light dilaton

Holography well-suited to model strong dynamics in these regimes

Elander, Frigerio, Knecht, Kneur, 2020-21

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Scale invariance $SO(4,2)$ if "slightly" broken light dilaton

Higgs boson may be identified e.g. with one hyper-pion,
but Higgs couplings heavily break the NGB shift symmetry ...

$m_h \ll \Lambda_C \qquad \frac{y_t}{4\pi} \sim 0.1$

Accidental symmetries: hyper-QCD

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Cacciapaglia De Andrea Fuks et al. 2015-20

Anomalous symmetries $U(1)_A \quad \text{for } N_C \to \infty$ light η'

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Bonnefoy Dudas et al. 2018-20, D'Agnolo et al. 2023

Scale invariance $SO(4,2)$ if "slightly" broken light dilaton

Bellazzini et al. 2012, Mariotti et al. 2019, Pomarol et al. 2019

Extensive model-building activity & rich experimental signatures

Accidentally light scalars : outline

- *Setting* : field theory of elementary scalar fields

  with a given symmetry group

  transforming in a large representation

$\phi = (\phi_1, \ldots, \phi_n)$

G

$\phi \sim R_G$

- *Outcome* : after SSB, accidents may occur

  i.e. some scalar components, beside NGBs,

  remain massless

$a = (a_1, \ldots, a_m)$

➔ Understand accidental hierarchy among scalar masses

➔ Study phenomenological applications in particles & cosmology

Spontaneous symmetry breaking

Common lore for SSB : $G : V(\phi) \to V(\phi) \qquad \langle\phi\rangle : G \to H$

$$dim(G/H) = n_{NGB} = n_{massless}$$

Not always true: additional states may remain massless by accident (approximately) :

$$dim(G/H) = n_{NGB} < n_{massless}$$

These are not isolated points in field space, rather flat directions of non-equivalent vacua :

$$dim(\text{vacuum manifold}) = dim(\{\phi : V(\phi) = V_{min}\}) > n_{NGB}$$

We find that accidents occur as soon as the G-representation of ϕ is sufficiently large :

$$G = SU(2) \qquad \text{not for } \phi \sim \mathbf{2}\ ,\ \phi \sim \mathbf{3}\ ,\ \phi \sim \mathbf{4}\ ,\ \text{but for } \phi \sim \mathbf{5}$$

Analogous phenomenon has been long known, in somewhat baroque models with small reps
(sequence of gauge groups, ad-hoc discrete symmetries, multiple ϕ representations)

Georgi & Pais, 1975

Building models for accidents

John Carpenter, CHRISTINE, 1983

Minimal model with accidents

$$G = U(2) = SU(2) \times U(1)$$

$$\phi \sim (\mathbf{5}_{SU(2)}, \mathbf{1}_{U(1)})$$

$$V(\phi) = -\mu^2(\phi\phi^*) + \frac{\lambda}{2}(\phi\phi^*)^2 + \frac{\kappa}{2}[(\phi\phi^*)^2 - (\phi\phi)(\phi^*\phi^*)] + 2\delta[(\phi\phi^*\phi\phi^*) - (\phi\phi\phi^*\phi^*)]$$

$$\left[\phi \equiv \frac{1}{\sqrt{2}}\lambda_a\phi_a \ , \ a = 1,3,4,6,8\right]$$

Gell-Mann matrices

This is most general renormalisable potential.

It has no accidental symmetry beside *U(2)*.

For $\mu^2, \lambda, \kappa, \delta > 0$ minimum at $\langle\phi_a\rangle = \frac{v_a}{\sqrt{2}}e^{i\theta} \ , \quad v^2 \equiv v_a v_a = \frac{2\mu^2}{\lambda}$

10 d.o.f. − 5 constraints = 5D vacuum

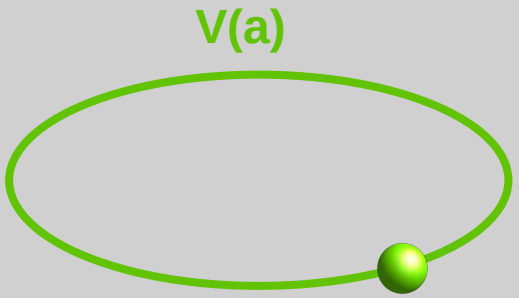
$U(2)$ fully broken : 4 NGBs + 1 accident

V(a)

One compact flat direction : *a(x)*

$$\left[\langle\phi\rangle \equiv \frac{v}{\sqrt{2}}\left(\lambda_3 \sin\frac{a}{v} + \lambda_8 \cos\frac{a}{v}\right)\right]$$

Minimal model with accidents

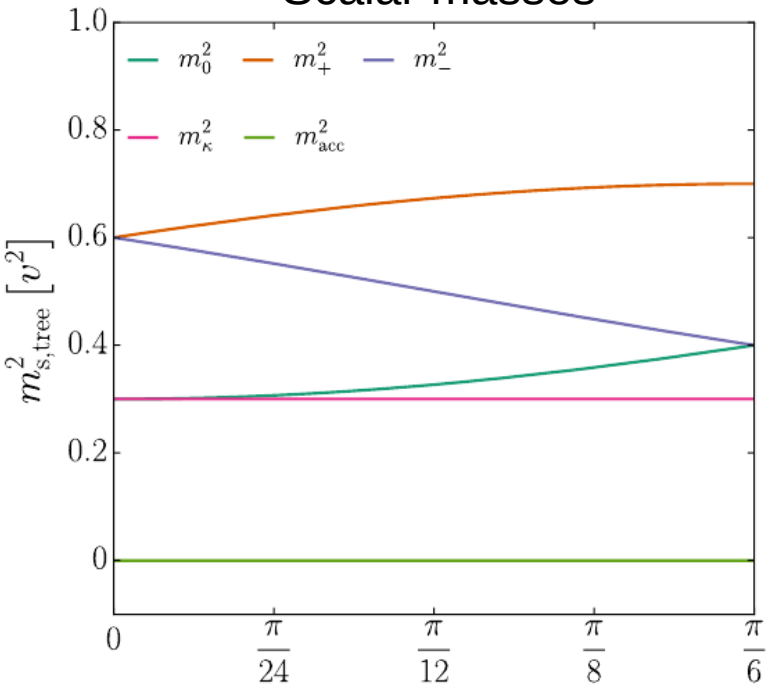


Points around accident direction are NOT gauge equivalent.

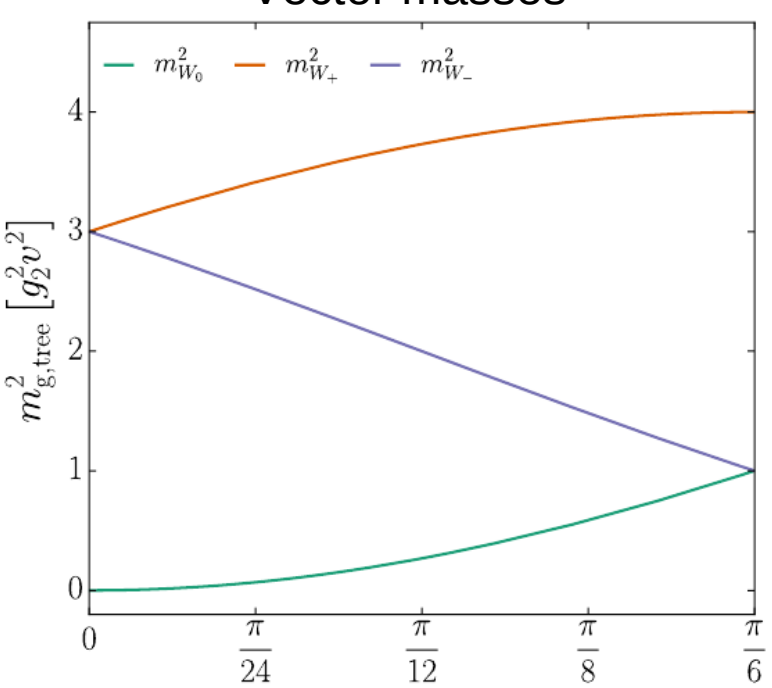
True minimum is undetermined (at tree level).

$$a = 0 \ : \ \text{special point with } U(2) \to U(1)' \ \Rightarrow \ 3 \text{ NGBs} + 2 \text{ accidents !}$$

Scalar masses



Vector masses



Mass spectrum varies along accident direction.

$\kappa = 0.3$

$\delta = 0.1$

What is the accident scale ?

To recapitulate :

Vectors : $m_W^2 \sim g^2 v^2$ $\quad m_A^2 = 0$

Scalars : $m_\rho^2 \sim \lambda v^2$ $\quad m_a^2 = 0$

For the most general **gauge-invariant, renormalisable, tree-level** potential

QFT ⇒ Accidents should receive mass from **higher-order corrections :**

$$m_a^2 = \lambda v^2 \times O\left(\frac{\lambda'}{16\pi^2} \, , \, \frac{v^2}{\Lambda^2} \, , \, \frac{m^2_{\cancel{SUSY}}}{m^2_{SUSY}} \, , \, \dots \right)$$

loops

higher-dim operators

if G holds in supersymmetric limit

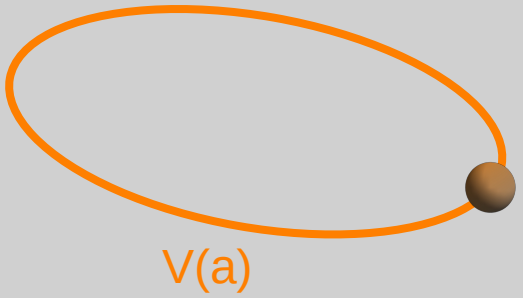
Effective potential

Accidents may receive a mass from one-loop corrections :

$$V_{CW}(\phi) = \frac{1}{64\pi^2}\mathrm{Str}\left[\mathcal{M}(\phi)^4 \log(\mathcal{M}(\phi)^2/\Lambda^2)\right]$$

- apply to minimal U(2) model with SSB at scale *v*
- compute scalar and gauge loops
- fix Λ subtracting tadpole in radial mode

→ U(1)'-preserving point selected as true minimum



$$m_{acc}^2 = \frac{v^2}{4\pi^2}\left(9g_2^4 + 3\delta^2 + \delta\kappa \log\frac{\kappa}{\kappa + 3\delta}\right) > 0$$

$$V_{CW}(a) \simeq -\frac{m_{acc}^2 v^2}{36}\cos\frac{6a}{v}$$

Open question : are there models where accidents remain massless even at one loop ?

$$m_{acc}^2 \sim \lambda v^2 \left(\frac{\lambda'}{16\pi^2}\right)^n$$

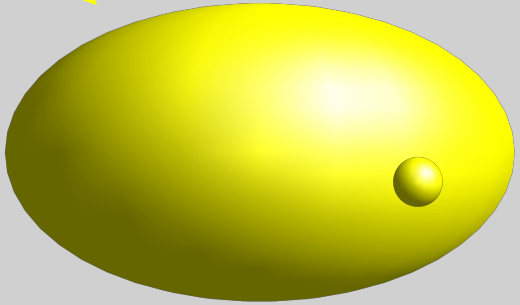
Charting accidents

Accidents seem **generic for large representations :**

n-index symmetric representation of SU(N) [with U(1) charge]

# flat directions	ϕ^i	ϕ^{ij}	ϕ^{ijk}	ϕ^{ijkl}	...
$SU(2) \times U(1)$	0	0	0	**1**	...
$SU(3) \times U(1)$	0	0	**2**	...	
$SU(4) \times U(1)$	0	0	**8**	...	
$SU(N) \times U(1)$	0	0	$\frac{\mathbf{N(N-1)(N-2)}}{\mathbf{3}}$	...	

Hic
Sunt
Leones



More possibilities to explore :

- different region in coupling space,
- different representation,
- different symmetry group,
- more than one representation,

...

Brummer, Ferrante, Frigerio, Hambye 2023
see also **Luhn 2011** &
Frigerio, Grimbaum-Tanimoto, Hambye 2022

Phenomenology of accidents

David Cronenberg, CRASH, 1996

Higgs as an accident ?

$$\langle \phi \rangle = v : SU(2) \to U(1)'$$

Can one break U(1)' at scale v' << v ?
It would be ***toy model*** for electroweak SSB :
address little hierarchy problem by realising $v_{weak} << v_{new}$

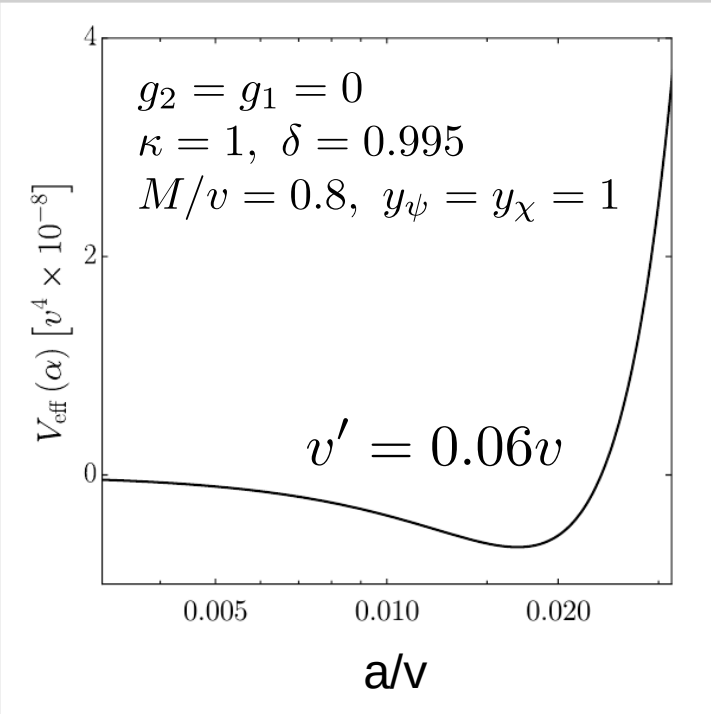
When Yukawa couplings to fermions are added,
fermion loops can misalign the vacuum

$$\phi \sim 5_1 \quad \psi \sim 3_{-1/2} \quad \chi \sim 3_{+1/2}$$

$$\mathcal{L} = y_\psi \psi^T \phi \psi + y_\chi \chi^T \phi^* \chi + M \chi^T \psi + h.c.$$

$$V_{CW}(a) \simeq -\Lambda^4 \left[\cos \frac{6a}{v} + c_2 \cos \frac{12a}{v} \right]$$

Fine-tuning needed to obtain v' << v



Higgs as an accident ?

$\langle \phi \rangle = v : SU(2) \to U(1)'$ One can break U(1)' at scale v' << v

Open question : realistic accident model for electroweak SSB ? Wish list :

$$\langle \phi \rangle = v_{new} : G \to SU(2)_w \ , \quad a(x) \sim \mathbf{2}_w \ , \quad V_{CW}(a) : \ v_w \ll v_{new}$$

Analogies & differences with known models of pseudo-NGB Higgs :

Bellazzini Csaki Serra 2014

- Little Higgs : larger global symmetry broken collectively by several couplings **Schmaltz Tucker-Smith 2005**
- Composite Higgs : exact global symmetry of composite sector, broken by external couplings **Panico Wulzer 2015**
- **Accident Higgs :**
  - potential can be induced by a single self-interaction
  - whole group G can be gauged

Supersymmetric accidents

Large hierarchy problem: need to promote ϕ to *composite* or *supersymmetric* field

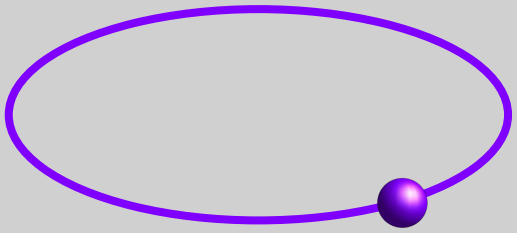
In a supersymmetric world, tree-level accidents are all-order accidents !
(non-renormalisation theorems)

$$SUSY: \ m_a = 0 \qquad \cancel{SUSY}: \ m_a \sim m_{\cancel{SUSY}}$$

U(2) model can be successfully supersymmetrised: $\phi \sim \mathbf{5}_1 \ , \ \bar{\phi} \sim \mathbf{5}_{-1}$

$$W = M(\phi\bar{\phi}) + \frac{1}{M}\left\{\lambda(\phi\bar{\phi})^2 + \frac{\kappa}{4}[(\phi\bar{\phi})^2 - (\phi\phi)(\bar{\phi}\bar{\phi})] + \frac{\delta}{6}[(\phi\bar{\phi}\phi\bar{\phi}) - (\phi\phi\bar{\phi}\bar{\phi})]\right\}$$

$$SUSY \text{ vacua} \ : \ 0 = F_i = \partial W/\partial\varphi^i \ \ , \ \ 0 = D_a = \varphi_i^*(t_a)^i_j\varphi^j$$



Solution is one compact flat direction:
1 massless chiral superfield
At special point with enhanced U(1)' symmetry:
2 massless superfields with conjugate charge

Supersymmetric accidents

Grand Unification scale

Consider SUSY Grand Unification Theories :
Accident mechanism is promising
to realise natural doublet-triplet splitting

$$\langle \phi \rangle = v_{GUT} : G_{GUT} \rightarrow SU(3)_c \times SU(2)_w \times U(1)_y$$

$$T(x) \sim \mathbf{3}_c \ : \ m_T \sim v_{GUT}$$

$$a(x) \equiv H(x) \sim \mathbf{2}_w \ : \ m_H \sim m_{\cancel{SUSY}}$$

SUSY breaking scale

Study interplay of accident mechanism
& SUSY breaking mediation:
could Higgs mass be loop-suppressed
w.r.t. mass of SUSY partners ?

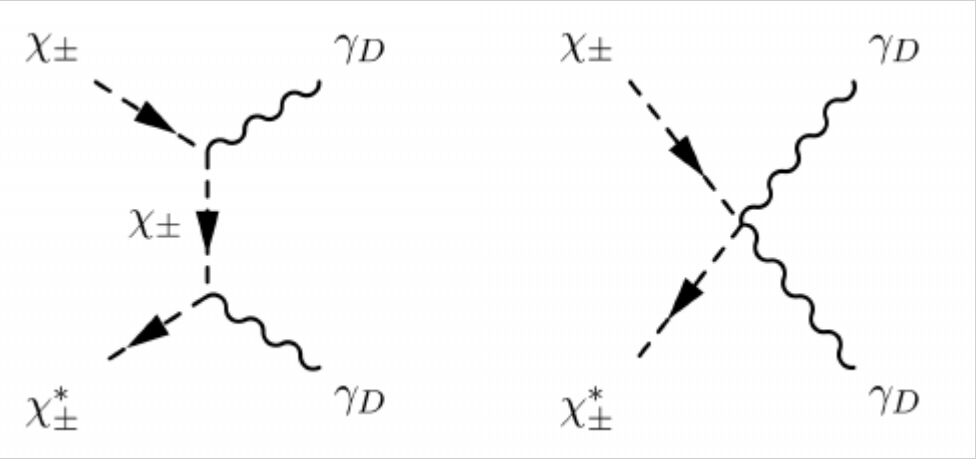
Accident dark matter

- Dark sector with gauge symmetry G_D and $\langle\phi\rangle$: $G_D \rightarrow H_D$
- Exactly massless dark photon(s) A_D
- *T*ree-level massless dark accident(s) a_D *:*

  a_D is the lightest particle charged under $H_D \rightarrow$ **automatically stable**
- Thermalisation via Higgs portal $\lambda_{H\phi}(H^\dagger H)(\phi^\dagger \phi)$
- Annihilations to SM: Higgs-portal freeze-out , strongly constrained
- **Annihilations to dark photons A_D** : dark-sector freeze-out

$$\phi \sim \mathbf{5}_{SU(2)_D}$$

$$\langle\phi\rangle \;:\; SU(2)_D \rightarrow U(1)_D$$



Accident dark matter

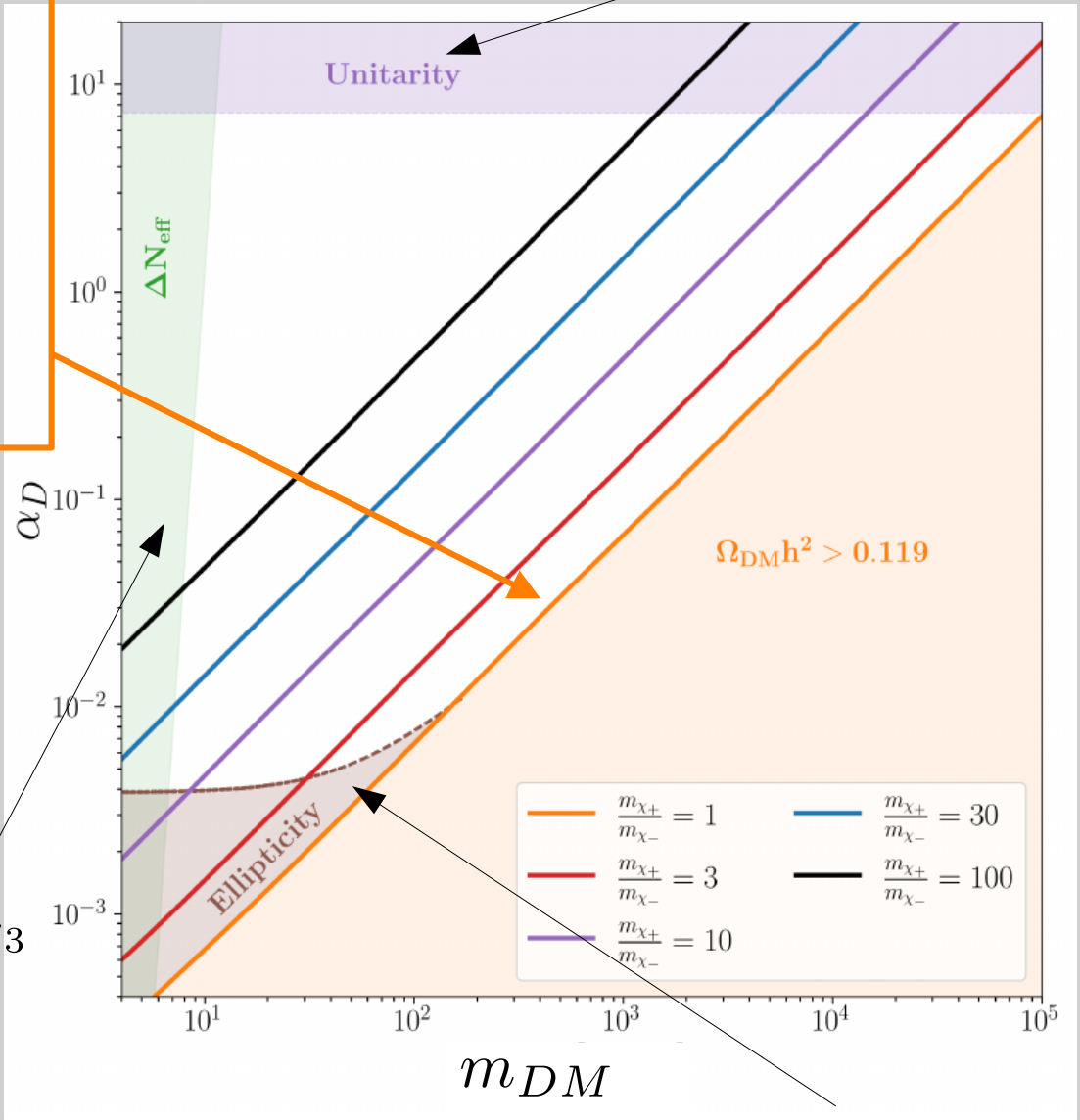
Dark sector freeze-out by

$$\alpha_D \equiv \frac{g_D^2}{4\pi}$$

Correct relic density for

$$\alpha_D \simeq 0.4 \cdot 10^{-5} \left(\frac{m_{DM}}{\text{GeV}}\right)$$

Perturbative unitarity : $\langle \sigma v \rangle \lesssim \frac{4\pi}{m_{DM}^2 v}$



Frigerio, Grimbaum--Tanimoto, Hambye 2022 *(analogous DM model, up to order one factors)*

Dark radiation :

$$\Delta N_{eff}^{CMB+BBN} \lesssim 0.135$$

$$\Delta N_{eff}^{\gamma_D} \simeq 0.05 \left[\frac{100}{g^{\star s}(T_{dec})}\right]^{4/3}$$

$$T_{dec} \gtrsim 300 \text{ MeV}$$

Long-range force : galactic-scale structure formation requires

$$\alpha_D \lesssim 3 \cdot 10^{-7} \left(\frac{m_{DM}}{\text{GeV}}\right)^{3/2}$$

Cosmology along accident potential

Accident has tree-level shift symmetry: **approximately flat potential**

- Natural inflation: accident as inflaton with slow-roll potential

see next talk by Giacomo Ferrante

- Likely first-order phase transitions : symmetry restored at high temperature T, and broken only radiatively at low T

- Possible built-in mechanism for reheating : as accident oscillates around minimum, massless dark photons can be efficiently produced

Summary

- When scalar fields sit in large group representations, some components may remain accidentally light
- Accidents: approximately flat potential, carry conserved charges
- Robust dark-matter candidates: stabilised by gauge symmetry and naturally light
- May address fine-tuning problems: from electroweak little/large hierarchy, to slow roll in cosmology
- Worth to search for other models with accidents, to answer theoretical & phenomenological open questions