Title: A voyage through undulating dark matter and the GUTs of u(48)

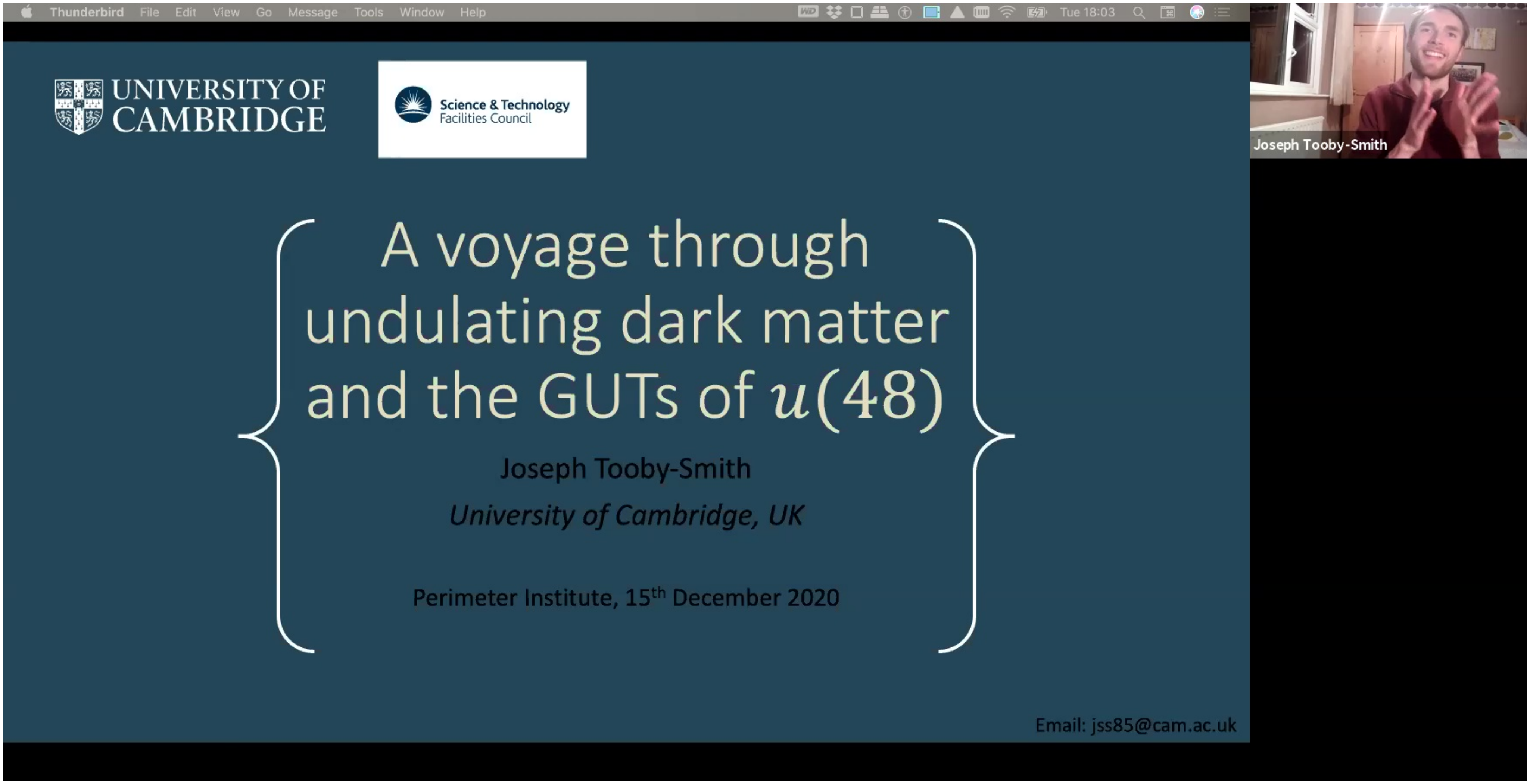
Speakers: Joseph Tooby-Smith

Series: Particle Physics

Date: December 15, 2020 - 1:00 PM

URL: http://pirsa.org/20120025

Abstract: This talk will be split into two distinct halves: The first half will be based on the paper arxiv:2007.03662 and suggest that an interplay between microscopic and macroscopic physics can lead to an undulation on time scales not related to celestial dynamics. By searching for such undulations, the discovery potential of light DM search experiments can be enhanced.
The second half will look at some currently unpublished work into finding all the semi-simple subalgebras of u(48) which contain the SM. Such algebras (in a loose sense of the term) form GUTs and studying them has relevance to family unification, proton decay etc. Although there has been previous work into the classification of GUTs, we believe this is the first this broad question has been answered.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UNIVERSITY OF CAMBRIDGE
Science & Technology Facilities Council
A voyage through undulating dark matter and the GUTs of $u(48)$
Joseph Tooby-Smith
University of Cambridge, UK
Perimeter Institute, 15th December 2020
Email: jss85@cam.ac.uk
Joseph Tooby-Smith

The 1^{st} half: Undulating DM

- Motivation
- Model
- UV extensions

The 2^{nd} half: GUTs of $u(48)$

- The problem
- Why it's interesting
- The solution

Overview

Undulating DM based on:

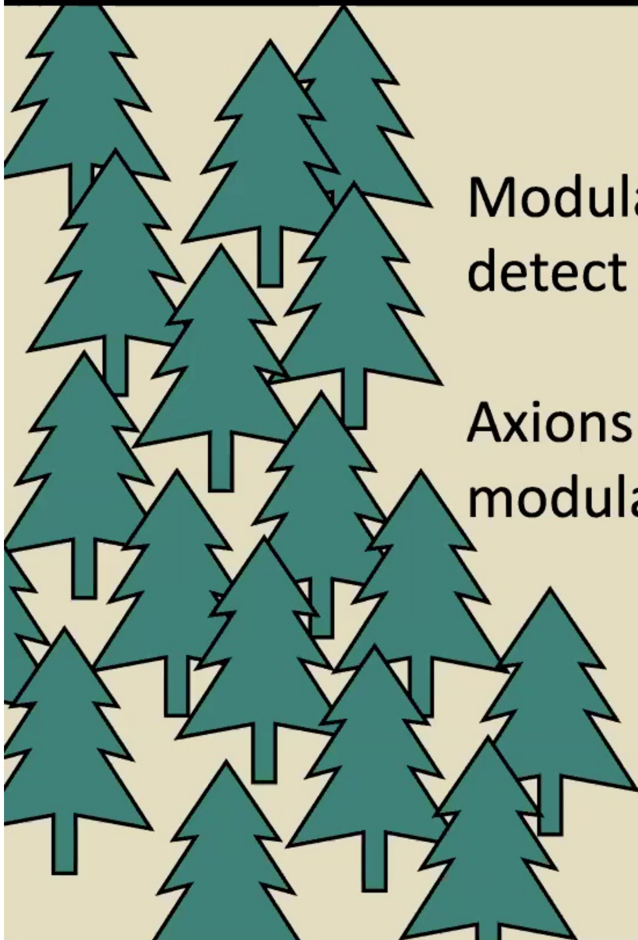
2007.03662

with Joe Davighi and Matthew McCullough.

GUTs of $u(48)$

21xx.xxxxx

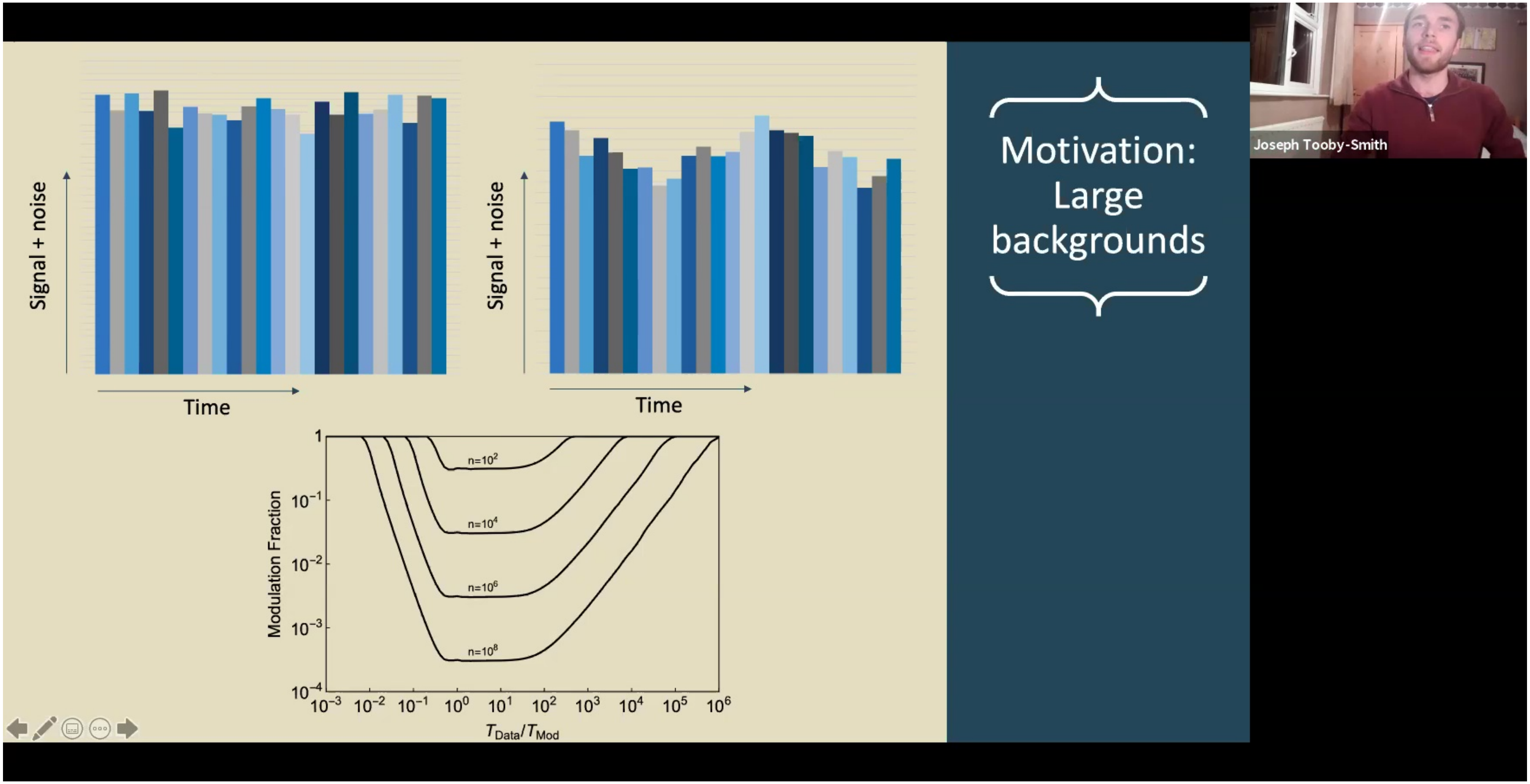
with Ben Gripaios and Ben Allanach.

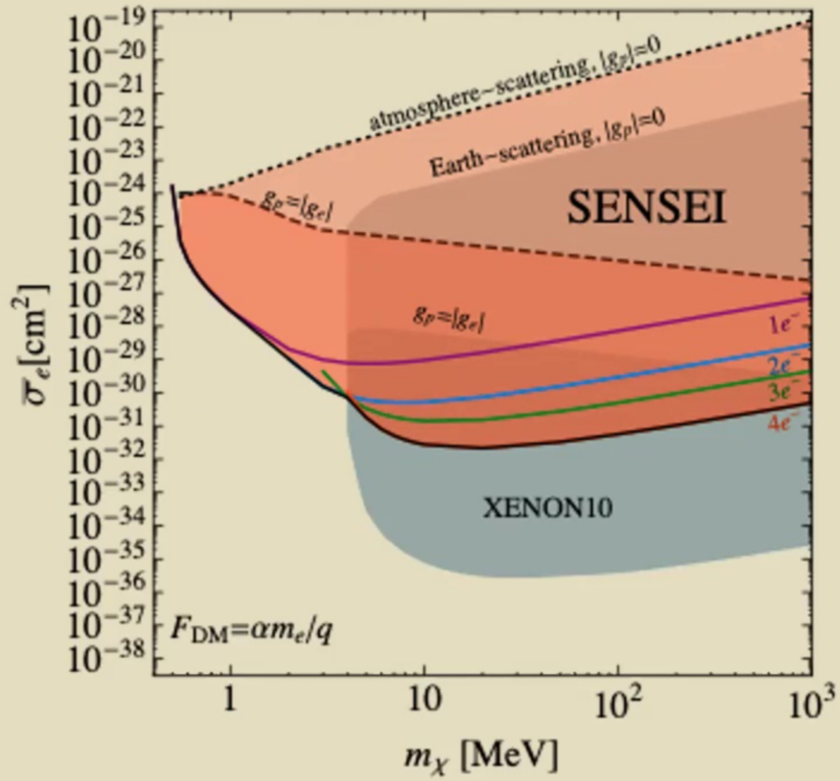


Modulations are easier to detect

Axions plus EDMs cause a modulation

The forest for the trees


Signal + noise
Time
Signal + noise
Time
Modulation Fraction
n=10^2
n=10^4
n=10^6
n=10^8
T_{Data}/T_{Mod}
Motivation: Large backgrounds
Joseph Tooby-Smith



Motivation: Direct detection

- Plot taken from: 1804.00088 (SENSEI collab)

The Model: Copying QCD

CP-odd axion like particle

$$\phi \rightarrow -\phi$$

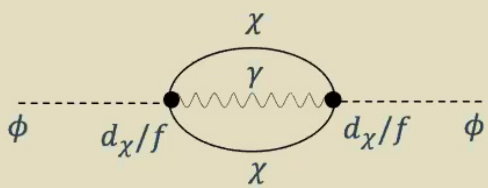
Cosmologically abundant

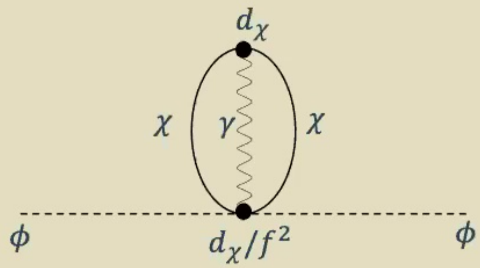
$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$

Gives a dark fermion EDM

$$\mathcal{L}_{DM} \supset -c\,\underbrace{\underbrace{\frac{e}{2\Lambda}}_{d_\chi}\sin\left(\frac{\phi}{f}\right)}_{d_\chi^{eff}}\bar{\chi}\sigma^{\mu\nu}i\gamma_5\chi F_{\mu\nu} + \mathrm{MDM}$$

Corrections to axion mass

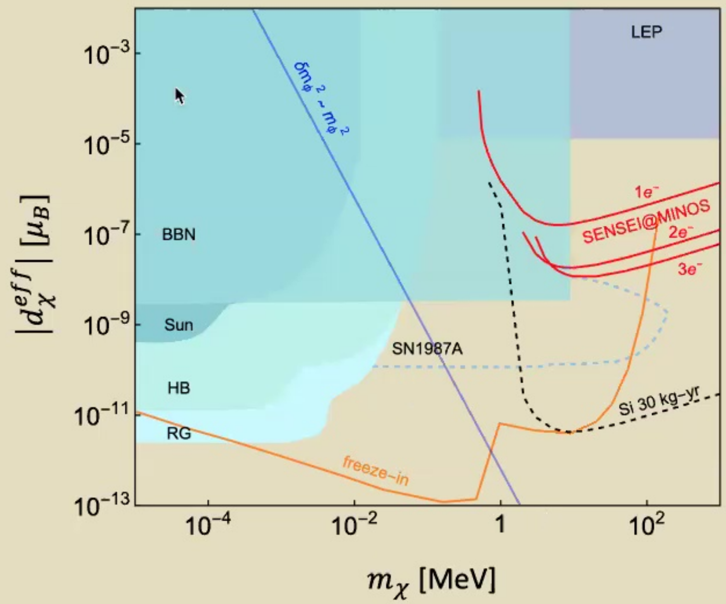




Fine tuning condition

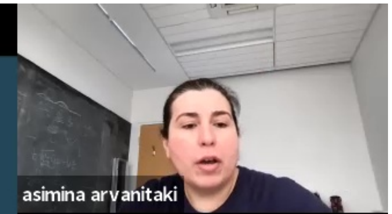
$$\delta m_\phi^2 \lesssim m_\phi^2 \quad \Longrightarrow \quad \frac{|d_\chi^{eff}|}{\mu_B} \lesssim 2 \times 10^{-12} \left(\frac{\text{MeV}}{m_\chi}\right)^3 \sqrt{r}$$

The Model: Fine tuning

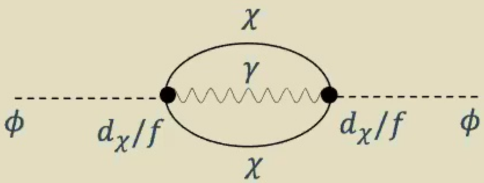


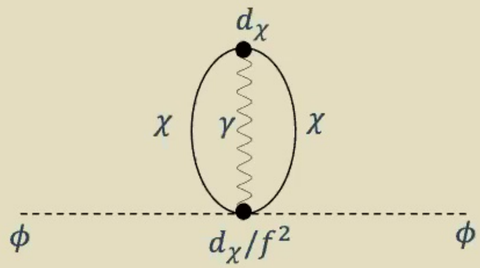
The Model: Other constraints

- 1911.03389 (Chang, Essig, Reinert)
- 1811.04095 (Chu, Pradler, Semmelrock)
- 2004.11378 (SENSEI collab)



Corrections to axion mass





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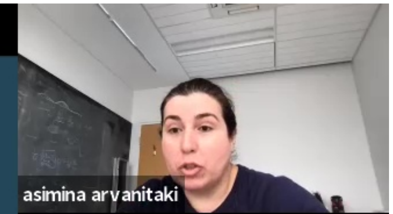


CP-odd axion like particle

$$\phi \to -\phi$$

Cosmologically abundant

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi = 0$$

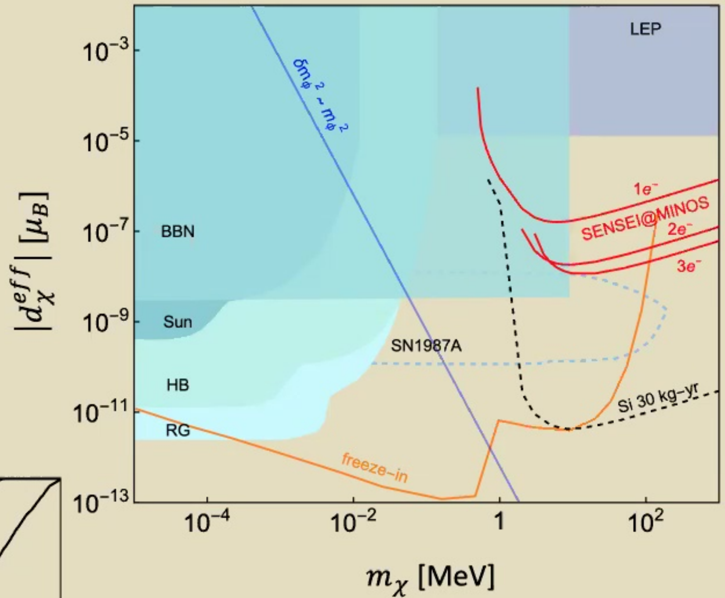
Gives a dark fermion EDM

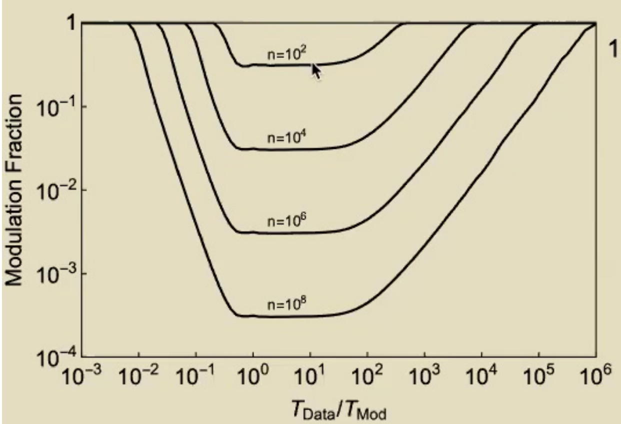
$$\mathcal{L}_{DM} \supset -c\,\frac{e}{2\Lambda}\sin\left(\frac{\phi}{f}\right)\bar{\chi}\sigma^{\mu\nu}i\gamma_5\chi F_{\mu\nu} + \text{MDM}$$

d_χ

d_χ^{eff}

The Model: Copying QCD





The Model: Other constraints

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- 2004.11378 (SENSEI collab)

EDM to take the form

$$d_\chi \approx \frac{e}{m_\chi^2} \frac{m_q^{\text{dark}}}{2}$$

Dark axion mass and fermionic

$$m_\phi^2 \approx \frac{m_q^{\text{dark}} |\langle \bar{q} q \rangle_d|}{f^2} \qquad m_\chi^3 \approx 8\pi^2 \langle \bar{q} q \rangle_d$$

Overall

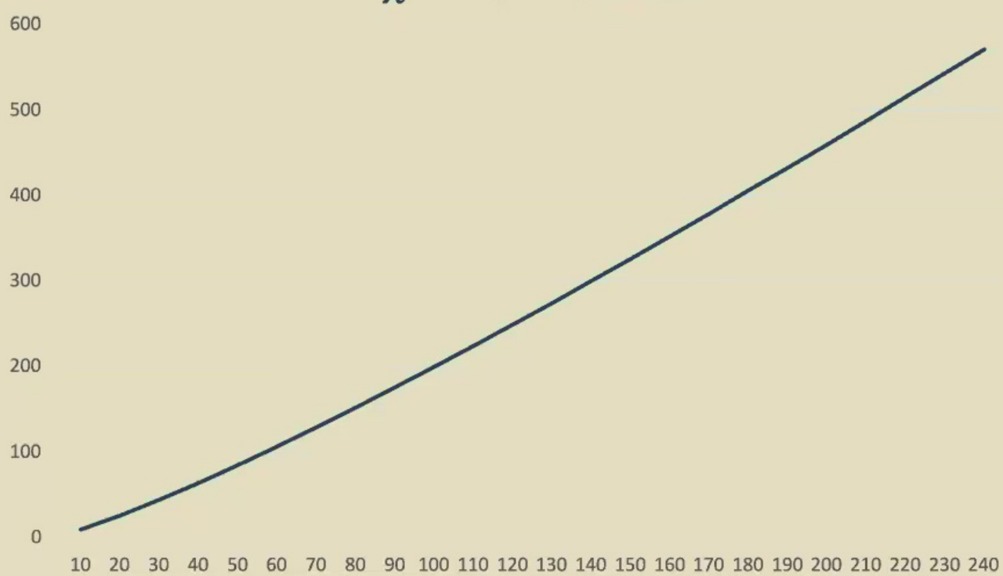
$$d_\chi \approx 4\pi^2 e \frac{m_\phi^2 f^2}{m_\chi^5}$$

UV Extensions: QCD-like baryon

- /hep-ph/0504231 (Pospelov, Ritz)
- Ioffe 1981
- $10^{-20} eV \leq m_\phi \leq 10^{-15} eV$

Large Nc and chiral limit

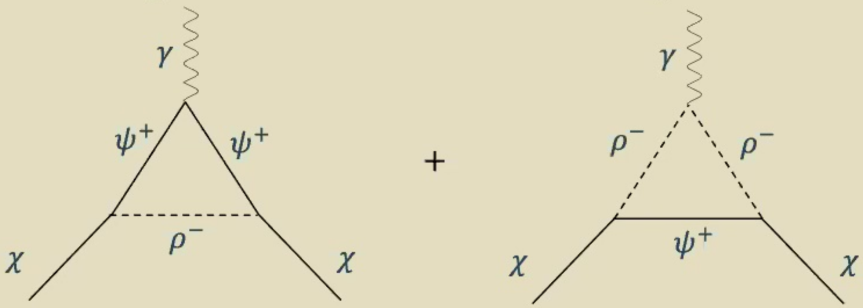
$$d_\chi \sim N_c \log(N_c)$$



UV Completions: Large N_C

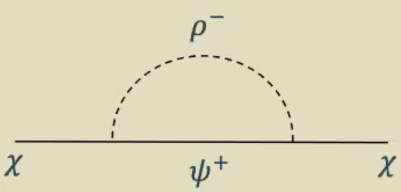
- /hep-ph/9212273 (Riggs, Schnitzer)

Charged scalar and fermion, mass ~ M



$$\Longrightarrow d_\chi \approx \frac{eg^2}{8\pi^2 M}$$

Fine tuning



$$\Longrightarrow \delta m_\chi \approx \frac{g^2 M}{16\pi^2}$$

UV completions: Elementary Fermion

- 1203.2531 (Graham et al)

Modulations are easy to detect

Coupling of ALP to fermion EDM creates such modulations

1st half summary

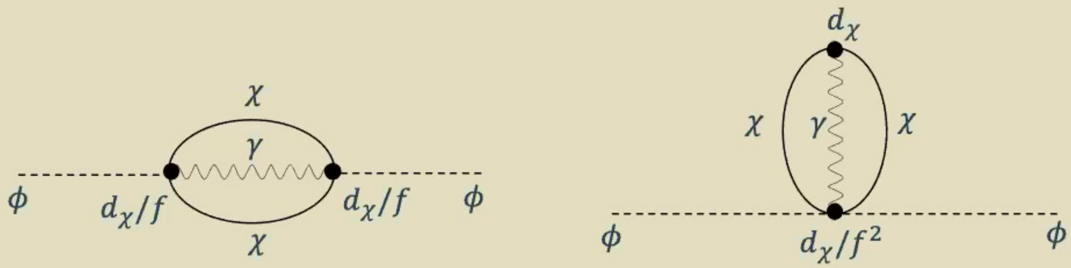
Time to stop thinking

Modulations are easy to detect

Coupling of ALP to fermion EDM creates such modulations

1st half summary

Corrections to axion mass



Fine tuning condition

$$\delta m_\phi^2 \lesssim m_\phi^2 \quad \Longrightarrow \quad \frac{\left|d_\chi^{eff}\right|}{\mu_B} \lesssim 2 \times 10^{-12} \left(\frac{\text{MeV}}{m_\chi}\right)^3 \sqrt{r}$$

The Model: Fine tuning

The origin of the word 'Academy'

- Gymnasiums were where Greek boys studied, and fought.
- Athens had three gymnasiums: the Lyceum, the Cynosarges, and the Academy
- After meeting Socrates, Plato formed a school of philosophy at the Academy.
- His student, Aristotle, later formed one at the Lyceum.

The GUTs of $u(48)$

The forest for the trees

Find every semi-simple subalgebra of $u(48)$ containing the SM

Setup: Anomaly Work

- See my BSM Pandemic talk (indico:950669)

Z' model – extend SM by u(1)

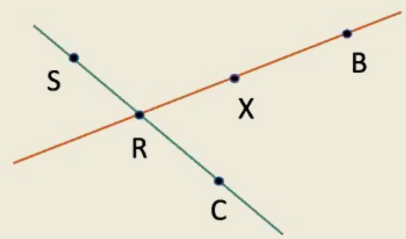
$$su(2) \oplus su(3) \oplus u(1) \oplus u(1)$$

Get a set of Diophantine equations

$$0 = \sum_{j=1}^{3}(2Q_j + U_j + D_j), 0 = \sum_{j=1}^{3}(3Q_j + L_j), 0 = \sum_{j=1}^{3}(Q_j + 8U_j + 2D_j + 3L_j + 6E_j), \quad 0 = \sum_{j=1}^{3}(6\,Q_j + 3U_j + 3D_j + 2L_j + E_j + N_j)$$

$$0 = \sum_{j=1}^{3}(Q_j^2 - 2U_j^2 + D_j^2 - L_j^2 + E_j^2), 0 = \sum_{j=1}^{3}(6\,Q_j^3 + 3U_j^3 + 3D_j^3 + 2L_j^3 + E_j^3 + N_j^3)$$

Use number theory



Setup: Algebras

Sub-algebras of u(48)

Allows for e.g. a kinetic term

Reductive

$$g_1 \oplus g_2 \oplus g_3 \oplus u(1) \oplus u(1)$$

Setup: Algebras

Sub-algebras of u(48)

Allows for e.g. a kinetic term

Reductive

$$g_1 \oplus g_2 \oplus g_3 \oplus u(1) \oplus u(1)$$

Semi-simple

$$g_1 \oplus g_2 \oplus g_3$$

Setup: The Problem

Find every anomaly free semi-simple subalgebra of $u(48)$ which contains the SM

What has been done before?

e.g. Gell-Mann, Ramond and Slansky: one independent gauge coupling

$$g \text{ or } g \oplus g$$

Method: The two steps

1) Find every semi-simple subalgebra of $u(48)$

2) Which of these contain the SM

Method: Subalgebras

Find every irrep dim≤48 of simple algebras

$$g_n\colon (a_1, a_2, \dots, a_n)$$

Combine reducible reps dim≤48

$$g_n\colon \quad (a_1, a_2, \dots, a_n), (b_1, b_2, \dots, b_n)$$
$$g_n \oplus g'_l\colon \quad (a_1, a_2, \dots, a_n, b_1, b_2, \dots, b_l)$$
$$g_n \oplus g'_l\colon \quad (a_1, a_2, \dots, a_n, 0, \dots, 0), (0, . . , 0 b_1, b_2, \dots, b_l)$$

Method: Subalgebras

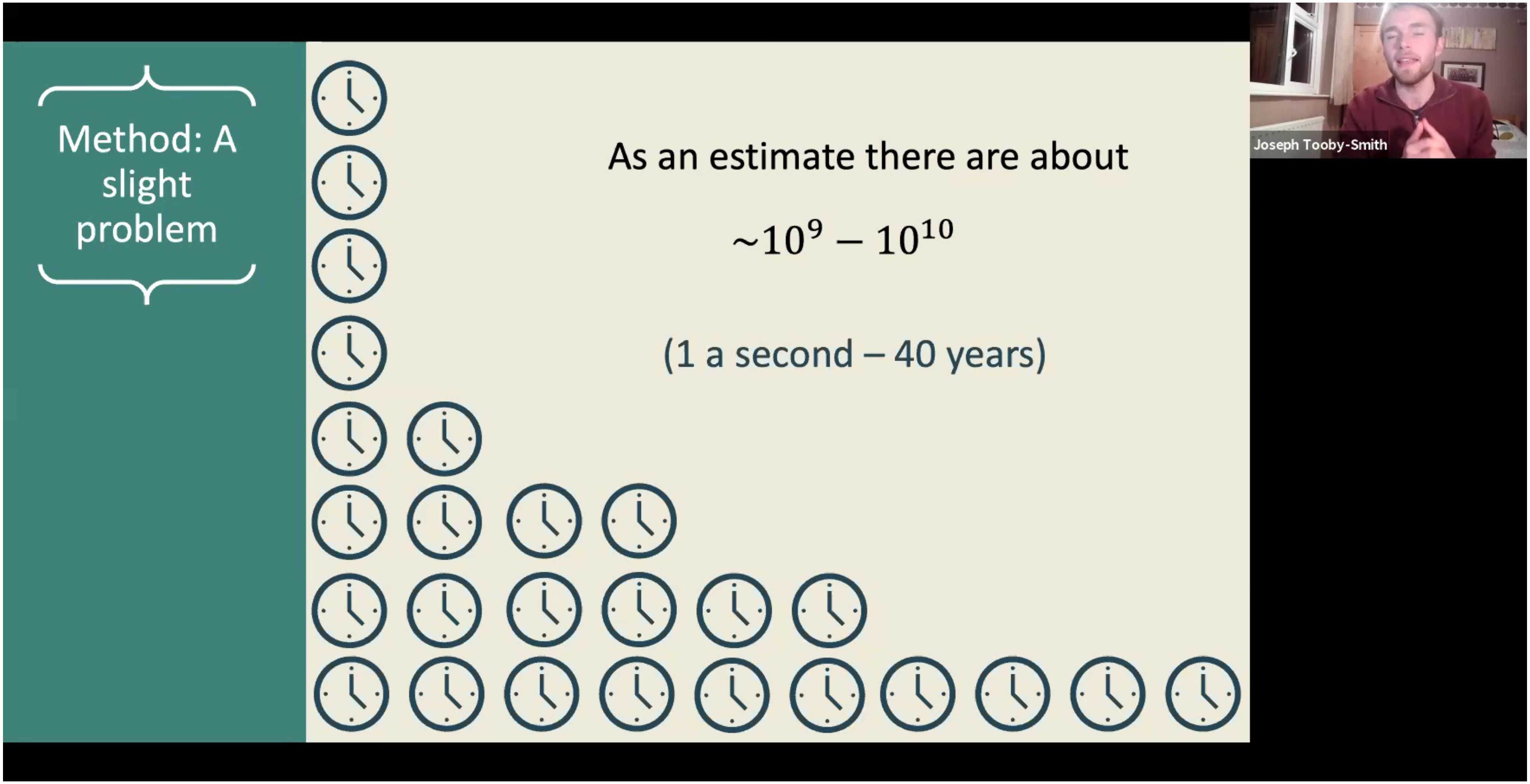
Find every irrep dim≤48 of simple algebras

$$g_n: (a_1, a_2, \dots, a_n)$$

Combine reducible reps dim≤48

$$g_n: \quad (a_1, a_2, \dots, a_n), (b_1, b_2, \dots, b_n)$$
$$g_n \oplus g'_l: \quad (a_1, a_2, \dots, a_n, b_1, b_2, \dots, b_l)$$
$$g_n \oplus g'_l: \quad (a_1, a_2, \dots, a_n, 0, \dots, 0), (0, \dots, 0 b_1, b_2, \dots, b_l)$$

Anomaly free


Method: A slight problem
As an estimate there are about
~10^9 – 10^10
(1 a second – 40 years)
Joseph Tooby-Smith

Method: Solution to problem

~~1) Find every semi-simple subalgebra of $u(48)$~~

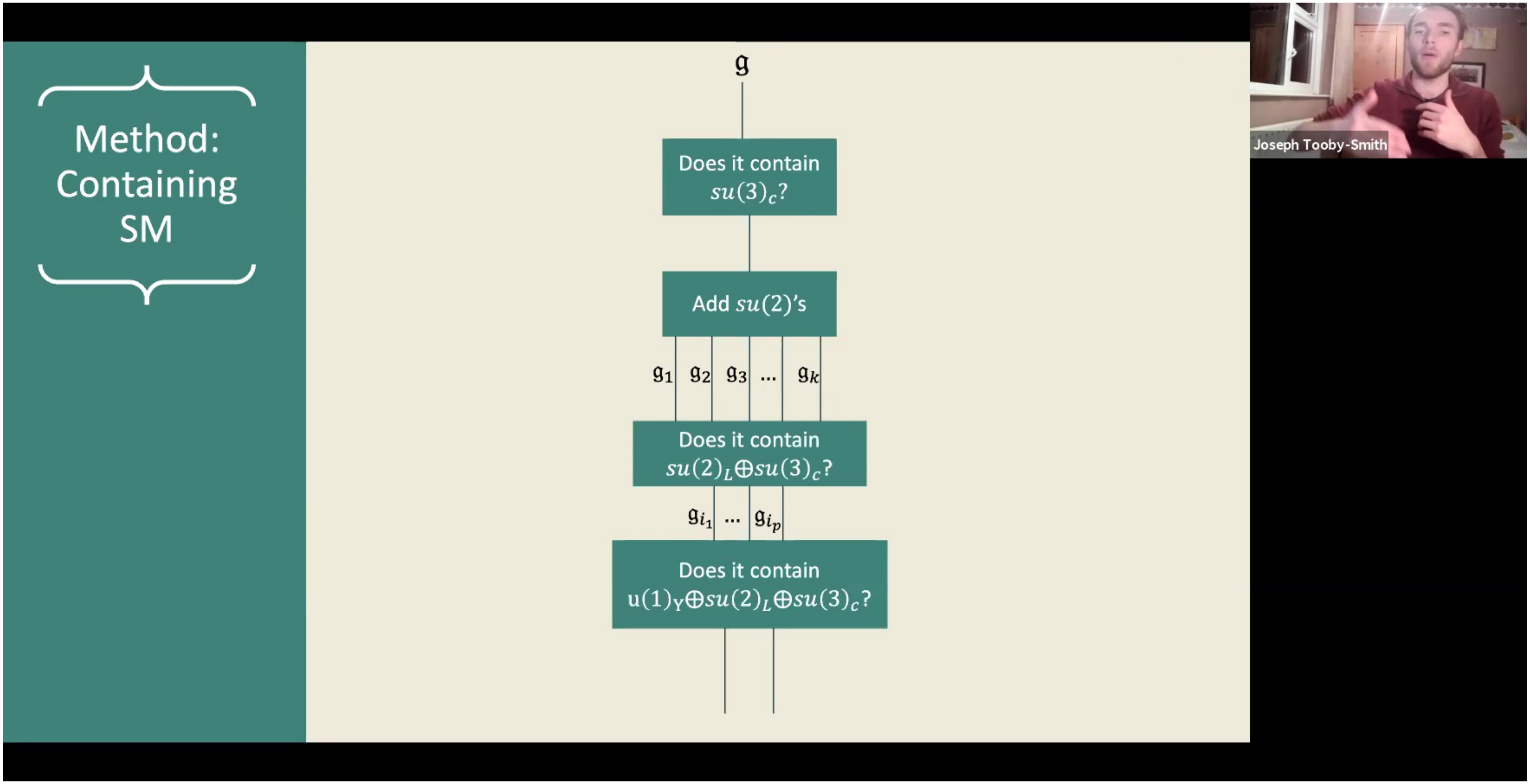
1) Find every semi-simple subalgebra of $u(48)$ without $su(2)$ ideals

$$g_1 \oplus g_2 \oplus g_3$$

SM+RHN

Q	$(2,3)_{1}$	$(2,3)_{1}$	$(2,3)_{1}$
U	$(1,\overline{3})_{-4}$	$(1,\overline{3})_{-4}$	$(1,\overline{3})_{-4}$
D	$(1,\overline{3})_{2}$	$(1,\overline{3})_{2}$	$(1,\overline{3})_{2}$
L	$(2,1)_{-3}$	$(2,1)_{-3}$	$(2,1)_{-3}$
E	$(1,1)_{6}$	$(1,1)_{6}$	$(1,1)_{6}$
N	$(1,1)_{0}$	$(1,1)_{0}$	$(1,1)_{0}$

$$su(2)\oplus su(3)\oplus u(1)$$


Method: Containing SM
$\mathfrak{g}$
Does it contain $su(3)_c$?
Add $su(2)$'s
$\mathfrak{g}_1$ $\mathfrak{g}_2$ $\mathfrak{g}_3$ ... $\mathfrak{g}_k$
Does it contain $su(2)_L \oplus su(3)_c$?
$\mathfrak{g}_{i_1}$ ... $\mathfrak{g}_{i_p}$
Does it contain $u(1)_Y \oplus su(2)_L \oplus su(3)_c$?
Joseph Tooby-Smith

Results: The full results

- An=su(n)
- Bn=so(2n+1)
- Cn=sp(2n)
- Dn=so(2n)
- (Q,U,D,L,E,N)

1) $\mathbf{A_4}$ $3(\bar{5} \to (0,0,1,1,0,0))$ $3(10 \to (1,1,0,0,1,0))$	2) $\mathbf{D_5}$ $3(\bar{16} \to (1,1,1,1,1,1))$	3) $\mathbf{D_5}$ $3(16 \to (1,1,1,1,1,1))$
4) $\mathbf{A_4A_1}$ $\bar{5},1 \to (0,0,1,1,0,0)$ $\bar{5},2 \to (0,0,2,2,0,0)$ $10,3 \to (3,3,0,0,3,0)$	5) $\mathbf{A_4A_1}$ $\bar{5},3 \to (0,0,3,3,0,0)$ $10,3 \to (3,3,0,0,3,0)$	6) $\mathbf{A_4A_1}$ $\bar{5},1 \to (0,0,1,1,0,0)$ $\bar{5},2 \to (0,0,2,2,0,0)$ $3(10,1 \to (1,1,0,0,1,0))$
7) $\mathbf{A_4A_1}$ $3(\bar{5},1 \to (0,0,1,1,0,0))$ $10,1 \to (1,1,0,0,1,0)$ $10,2 \to (2,2,0,0,2,0)$	8) $\mathbf{A_4A_1}$ $3(\bar{5},1 \to (0,0,1,1,0,0))$ $10,3 \to (3,3,0,0,3,0)$	9) $\mathbf{A_4A_1}$ $\bar{5},3 \to (0,0,3,3,0,0)$ $10,1 \to (1,1,0,0,1,0)$ $10,2 \to (2,2,0,0,2,0)$
10) $\mathbf{A_4A_1}$ $\bar{5},3 \to (0,0,3,3,0,0)$ $3(10,1 \to (1,1,0,0,1,0))$	11) $\mathbf{A_4A_1}$ $\bar{5},1 \to (0,0,1,1,0,0)$ $\bar{5},2 \to (0,0,2,2,0,0)$ $10,1 \to (1,1,0,0,1,0)$ $10,2 \to (2,2,0,0,2,0)$	12) $\mathbf{A_4A_4}$ $2(1,\bar{5} \to (0,0,1,1,0,0))$ $2(1,10 \to (1,1,0,0,1,0))$ $5,1 \to (0,0,1,1,0,0)$ $10,1 \to (1,1,0,0,1,0)$
13) $\mathbf{A_4D_5}$ $1,16 \to (1,1,1,1,1,1)$ $2(\bar{5},1 \to (0,0,1,1,0,0))$ $2(10,1 \to (1,1,0,0,1,0))$	14) $\mathbf{A_4D_5}$ $2(1,\bar{16} \to (1,1,1,1,1,1))$ $\bar{5},1 \to (0,0,1,1,0,0)$ $10,1 \to (1,1,0,0,1,0)$	15) $\mathbf{A_4D_5}$ $1,\bar{16} \to (1,1,1,1,1,1)$ $2(\bar{5},1 \to (0,0,1,1,0,0))$ $2(10,1 \to (1,1,0,0,1,0))$
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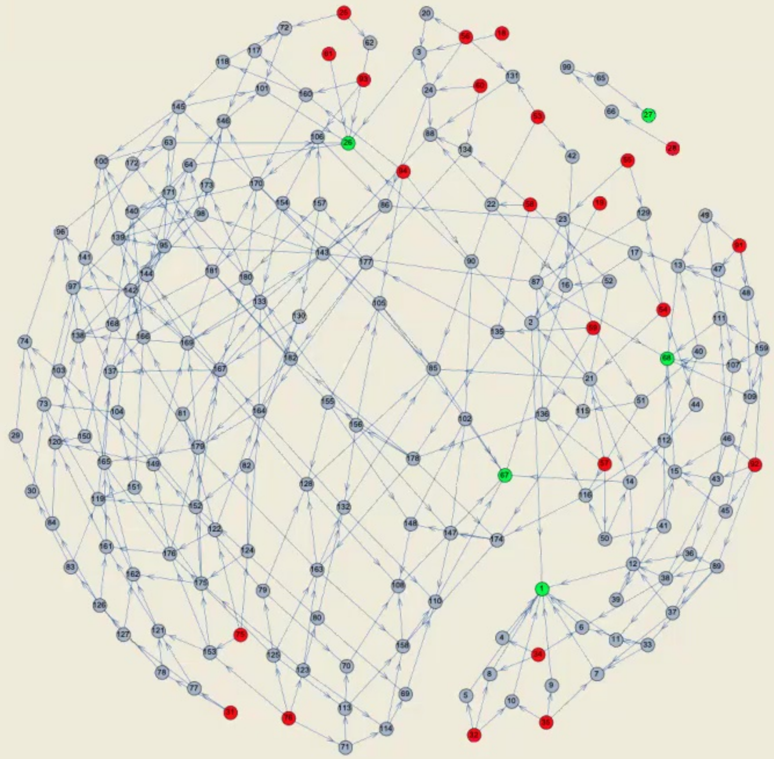
22) $\mathbf{D_5D_5}$ $2(1,16 \to (1,1,1,1,1,1))$ $\bar{16},1 \to (1,1,1,1,1,1)$	23) $\mathbf{D_5D_5}$ $2(1,\bar{16} \to (1,1,1,1,1,1))$ $16,1 \to (1,1,1,1,1,1)$	24) $\mathbf{D_5D_5}$ $2(1,16 \to (1,1,1,1,1,1))$ $16,1 \to (1,1,1,1,1,1)$
25) $\mathbf{A_{11}A_1A_1}$ $\bar{12},2,1 \to (0,3,3,0,3,3)$ $12,1,2 \to (3,0,0,3,0,0)$	26) $\mathbf{A_3A_1A_1}$ $3(\bar{4},2,1 \to (0,1,1,0,1,1))$ $3(4,1,2 \to (1,0,0,1,0,0))$	27) $\mathbf{A_3A_3A_1}$ $3(1,4,2 \to (1,0,0,1,0,0))$ $6,\bar{4},1 \to (0,3,3,0,3,3)$
28) $\mathbf{A_3A_3C_3}$ $1,4,6 \to (3,0,0,3,0,0)$ $6,\bar{4},1 \to (0,3,3,0,3,3)$	29) $\mathbf{A_3C_3A_1}$ $\bar{4},6,1 \to (0,3,3,0,3,3)$ $3(4,1,2 \to (1,0,0,1,0,0))$	30) $\mathbf{A_3C_3A_1}$ $3(\bar{4},1,2 \to (0,1,1,0,1,1))$ $4,6,1 \to (3,0,0,3,0,0)$
31) $\mathbf{A_3C_3C_3}$ $\bar{4},1,6 \to (0,3,3,0,3,3)$ $4,6,1 \to (3,0,0,3,0,0)$	32) $\mathbf{A_4A_1A_1}$ $\bar{5},3,1 \to (0,0,3,3,0,0)$ $10,1,3 \to (3,3,0,0,3,0)$	33) $\mathbf{A_4A_1A_1}$ $\bar{5},1,1 \to (0,0,1,1,0,0)$ $\bar{5},2,1 \to (0,0,2,2,0,0)$ $10,1,1 \to (1,1,0,0,1,0)$ $10,1,2 \to (2,2,0,0,2,0)$

182 all together

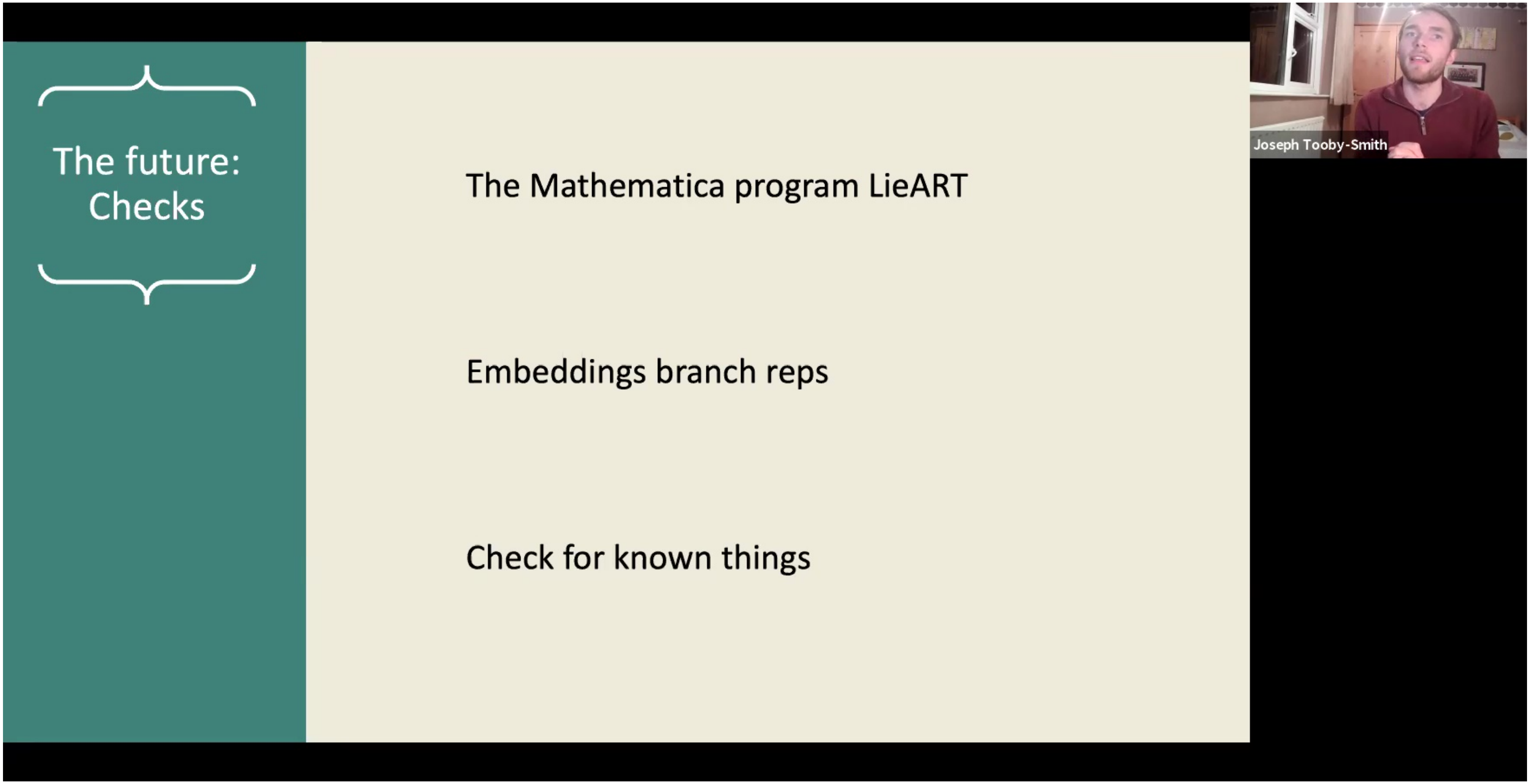
Results: Maximal and Minimal

Maximal: no g' such that $g \subset g' \subset u(48)$
Minimal: no g' such that $g' \subset g \subset u(48)$



Maximal
28) A3A3C3
31) A3C3C3
58) D5D5D5
94) A7D5A1A1

Minimal
1) A4
27) A3A3A1
67) A3A4A1A1


The future: Checks
The Mathematica program LieART
Embeddings branch reps
Check for known things
Joseph Tooby-Smith

The future: Further analysis

Relationship to the unification group $U(3)^6$

Proton decay

Analytic approach

2nd half summary

Aim: Find all semi-simple subalgebras of $u(48)$ which contain the SM

Conclusion: There are 182 of them

Thank you for your attention!