1: Building non-vanilla QCD axion models & 2: Perspectives on DEI from an American Scientist in Germany

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Based on

*Kivel, Laux, FY, JHEP **11** (2022) 88, [2207.08740]*

*Elahi, Elor, Kivel, Laux, Najjari, FY, PRD **108** (2023) 3, L031701 [2301.08760]*

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Brookhaven Forum 2023
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PRISMA+

Intro: Axions and strong CP

- nEDM constraint gives severe constraint on $|\bar{\theta}| < 7.5 \times 10^{-11}$

  See, e.g. FY [2308.08612], published in Annalen der Physik

  - $|d_n| < 1.8 \times 10^{-26} e\text{cm}$

  Abel, et. al. [nEDM collaboration], 2001.11966

- Most attractive current solution is QCD axion
  - PNGB of U(1) Peccei-Quinn global anomalous symmetry gains instanton-induced potential

    Peccei, Quinn PRL 38, 1440 (1977)

    - QCD axion acts as spurion for $\bar{\theta}$, rolls to cancel $\bar{\theta}$
  - Two canonical (vanilla) models – functionally generate $U(1)_{PQ}$ anomaly with QCD
    - **KSVZ** – Add heavy VLQs; **DFSZ** – Adopt 2HDM

    Kim (1979), Shifman, Vainshtein, Zakharov (1980); Dine, Fischler, Srednicki (1981), Zhitnitsky (1980)

Basic axion phenomenology

- Vanilla axion mass driven by topological susceptibility of QCD: $m_a f_a = \sqrt{\chi} \approx m_\pi f_\pi$ in SM
  - Also need mixing with SM neutral mesons

$$\mathcal{L} \simeq \Lambda_{\rm QCD}^4 \cos\left(\frac{a}{f_a}\right)$$

- Main consequence: Vanilla QCD axion physics is essentially a one-parameter model
  – Primary target: axion-photon coupling
  – Some residual dependence on UV model via EM and color anomaly factors

Very active experimental program

$$m_a = 5.70 \pm 0.06 \pm 0.04\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

$$g_{a\gamma\gamma} = \frac{\alpha_{EM}}{2\pi f_a}\left(\frac{E}{N} - 1.92(4)\right)$$

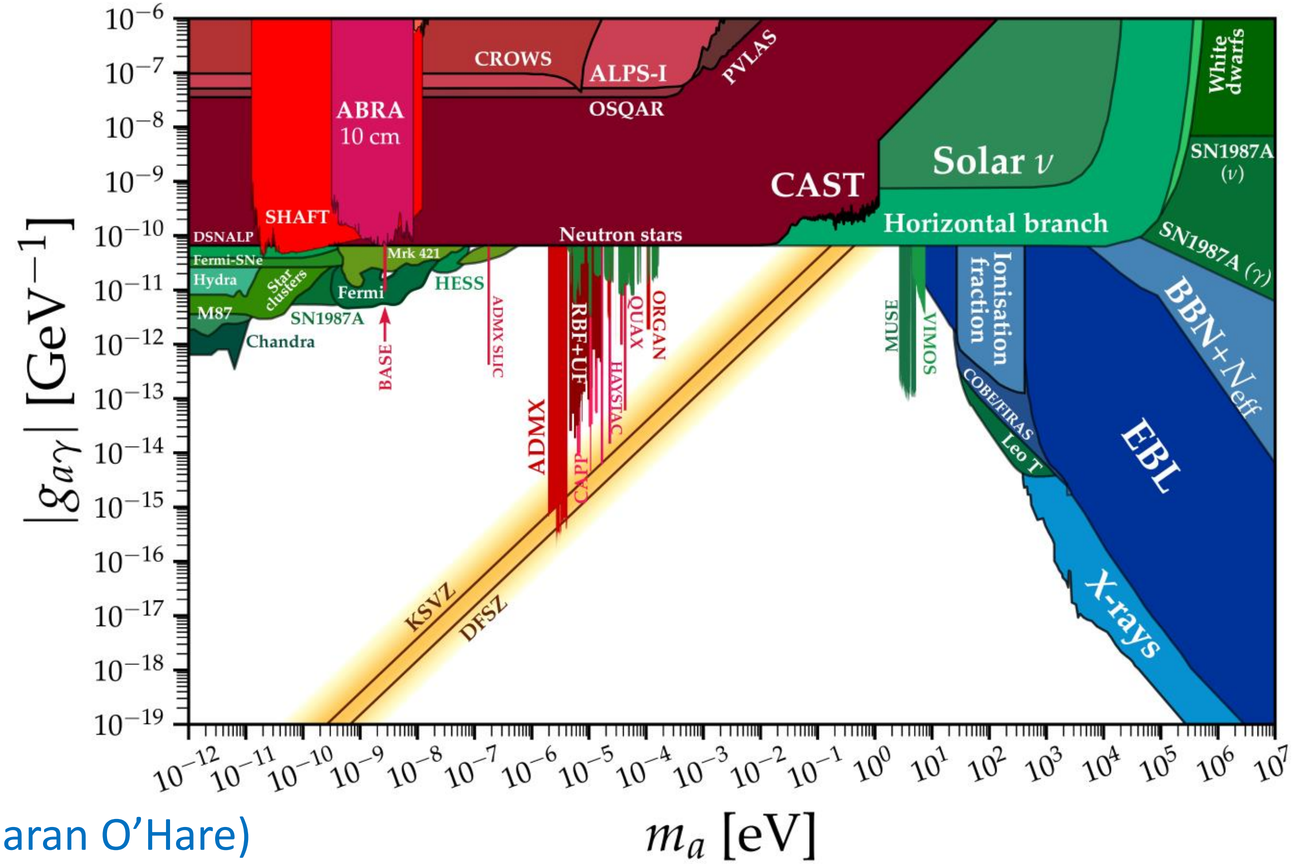
m_a: quark mass and higher order uncertainties

$g_{a\gamma\gamma}$: O(α) in QED and NNLO in χPT

Gorghetto, Villadoro [1812.01008]

The standard QCD axion band focuses on sub-eV axion masses and tiny axion-photon couplings

Width of band roughly given by E/N = 44/3 and E/N = 5/3 as boundary values



PDG (from AxionLimits by Ciaran O'Hare)

Motivating PNGB field theory

- Axions are interesting objects for field theory
  - PQ mechanism transforms strong CP problem into vacuum energetics problem
    - PNGBs have no preferred origin in field space
  - Global PQ symmetries and axion PNGBs are cousins of flavor symmetries and chiral Lagrangians
    - Anomalous and explicit symmetry breaking on equal footing
      - Can also study effects of gauging U(1) subgroup: see Kivel, Laux, FY, JHEP 03 (2023) 078 [2211.12155]
- Reconceptualize axion quality problem as new example of non-decoupling in EFTs
  - UV-IR matching of Theta terms and CP symmetry

Supersizing axions with small-size instantons

Kivel, Laux, FY, JHEP **11** (2022) 88 [2207.08740]

Small-size instanton effects

- Key insight: Use axion sensitivity to UV physics to enhance quality of axion solution

Agrawal, Howe [1710.04213, 1712.05803]

  – Embed $SU(3)_C$ in larger UV gauge group
    - Confinement of extended color gauge group will give additional instanton-induced potential terms to light axion
    - Requires non-trivial book-keeping to trace PQ symmetry from IR to UV
  – Practical consequence: Extended color groups typically involve coloron/axigluon color octet vectors and additional collider signatures

See, e.g. Dobrescu, FY [1306.2629]

Refresher: SM instanton effects

- SM + axion Lagrangian

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{\partial_\mu a}{F_a}\left(\sum_{i=1}^{N_f} c_1^i \bar{q}_i \gamma_\mu \gamma_5 q_i\right) - \left(\sum_{i=1}^{N_f} m_i \bar{q}_L^i e^{ic_2^i a/F_a} q_R^i + \text{h.c.}\right)$$

$$- \frac{a}{F_a}\left(c_3^G \frac{g_s^2}{32\pi^2} G\tilde{G} + c_3^W \frac{g^2}{32\pi^2} W\tilde{W} + c_3^B \frac{g'^2}{32\pi^2} B\tilde{B}\right) \ ,$$

Kim, Carosi (2008)

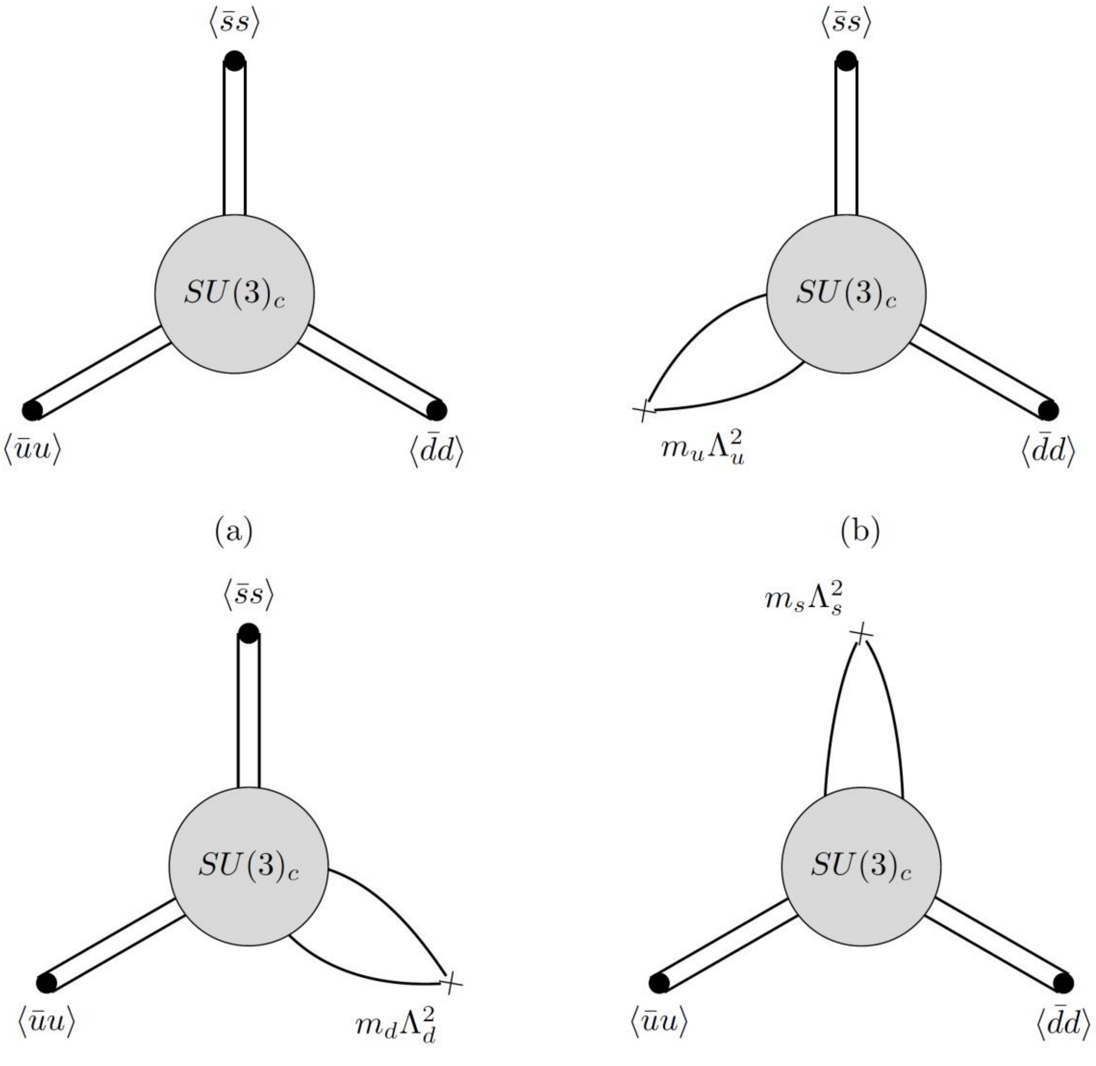
- Axion mass is generated by gluon operator
  - Via index theorem, instanton action induces 't Hooft determinantal operator according to PQ color anomaly

$$\mathcal{L}_{\text{det}} = (-1)^{N_f} K^{4-3N_f} \left(\prod_{i=1}^{N_f} \det\left(\bar{q}_L^i q_R^i\right)\right) e^{-ic_3^G \frac{a}{F_a}} + \text{h.c.}$$

Refresher: SM instanton effects

- Calculate leading determinantal operators
  - Correspond to "instanton flower" diagrams
  - Power counting in chiral symmetry breaking parameters

$$\mathcal{L}_{\rm det} = -\frac{1}{K^5}\sum_i A_i$$



Refresher: SM instanton effects

- Operators lead to mixing of π^0, η, η' and axion

$$A_1 = \left(\prod_i \det(\bar{q}_{i,L}\, q_{i,R})\right) e^{-ic_3^G \theta_a} + \text{ h.c. },$$

$$\sim \left(\frac{v^3}{2}\exp\big(i(\theta_{\pi^0} + \theta_{\eta'})\big)\right)\left(\frac{v^3}{2}\exp\big(i(-\theta_{\pi^0} + \theta_{\eta'})\big)\right)\left(\frac{v^3}{2}\right) e^{-ic_3^G \theta_a} + \text{ h.c. },$$

$$= \frac{v^9}{8}\left(\exp\big(i(2\theta_{\eta'} - c_3^G \theta_a)\big) + \text{h.c.}\right) = \frac{v^9}{4}\cos\big(2\theta_{\eta'} - c_3^G\theta_a\big),$$

$$A_2 = \frac{v^6}{2} m_u \Lambda_u^2 \cos\big(\theta_{\pi^0} + \theta_{\eta'} - c_3^G \theta_a\big),$$

$$A_3 = \frac{v^6}{2} m_d \Lambda_d^2 \cos\big(-\theta_{\pi^0} + \theta_{\eta'} - c_3^G \theta_a\big),$$

$$A_4 = \frac{v^6}{2} m_s \Lambda_s^2 \cos\big(2\theta_{\eta'} - c_3^G \theta_a\big).$$

  - Encapsulate relevant instanton effects via chiral insertions

Color-Unified SU(6) x SU(3)' model

Gaillard, Gavela, Houtz, Quilez, del Rey [1805.064365]

- Embed $SU(3)_c$ into SU(6) at high scales, SU(6) has massless Q fermion to solve θ_6
  - Use SU(3)' to make SM-charged exotic multiplets decouple at Λ_{CUT} scale by bifundamental scalar Δ

$$SU(6) \times SU(3') \xrightarrow{\Lambda_{\rm CUT}} SU(3)_c \times SU(3)_{\rm diag} \xrightarrow{v_{\rm diag}} SU(3)_c$$

– M1 (KSVZ-like) or M2 (DFSZ-like) variants solve θ'

	$SU(3)_{\rm diag}$	$SU(3)_c$	$SU(3')$	$SU(6)$
Q	$\bar{\square}$	$\square$	1	20
q	$\square$	1	$\square$	1

	$SU(3)_{\rm diag}$	$SU(3)_c$	$SU(3')$	$SU(6)$
Q	$\bar{\square}$	$\square$	1	20
Δ_2	-	-	$\bar{\square}$	$\square$

– $v_{\rm diag}$ separates exotic colored states from EW scale

M1 variant – SSI amplitudes

$$\mathcal{L}_{\text{det}} = -K' A_1 - \frac{1}{K_{\text{diag}}^2} A_2 - \frac{1}{K^8}(A_3 + A_4 + A_5)$$

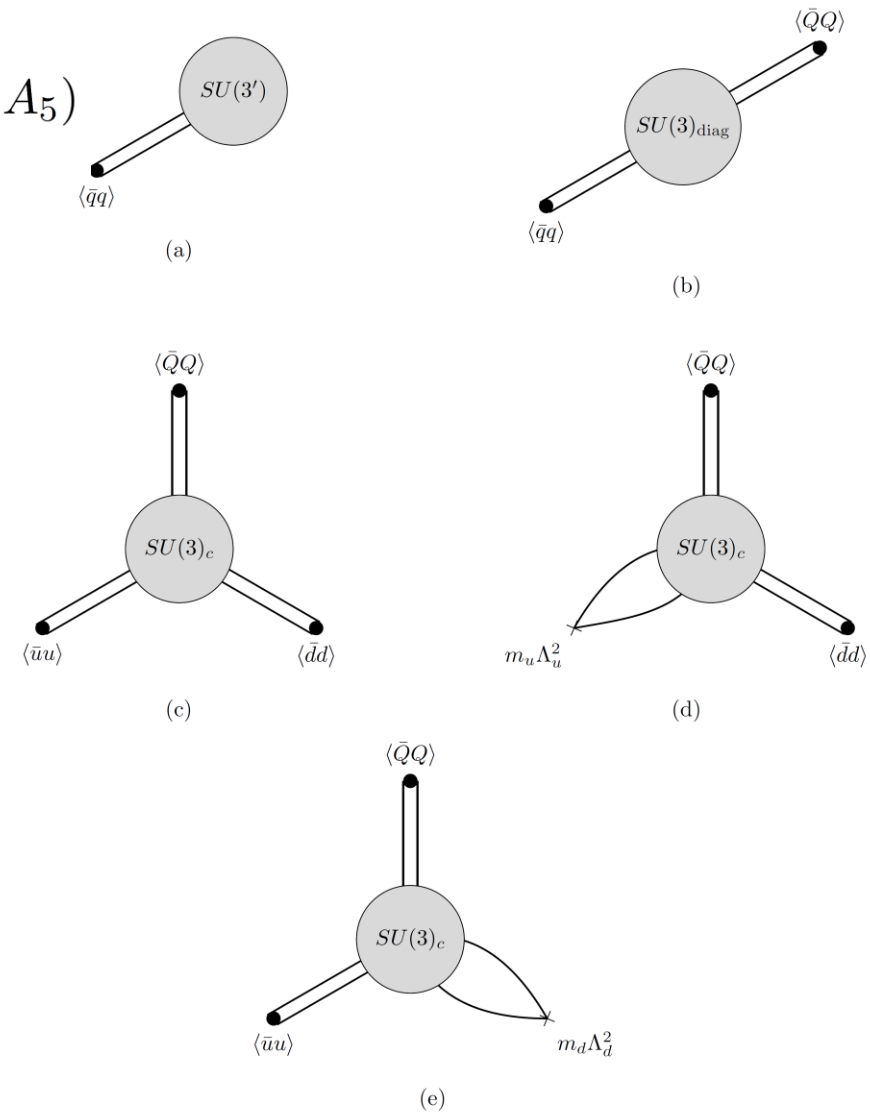
$$A_1 = v_{\text{diag}}^3 \cos\left(\frac{2\eta_d}{F_a}\right) ,$$

$$A_2 = \frac{v_{\text{diag}}^6}{2} \cos\left(\frac{2\eta_d}{F_a} + \frac{\sqrt{6}a}{F_a}\right) ,$$

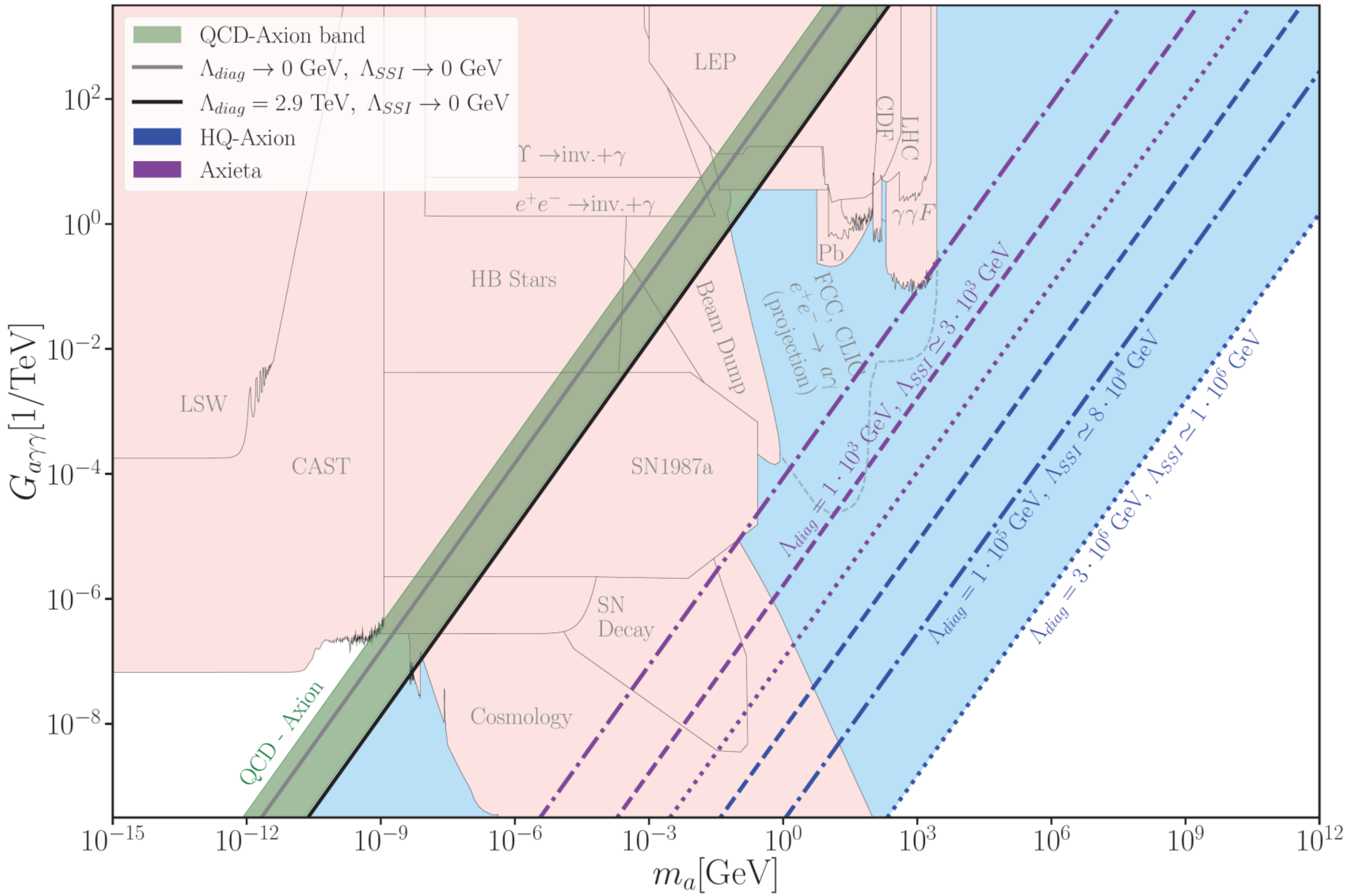
$$A_3 = \frac{v_{\text{diag}}^3 v^9}{4} \cos\left(\frac{\sqrt{6}a}{F_a} + 2\frac{\eta'}{F_{\eta'}}\right) ,$$

$$A_4 = \frac{v_{\text{diag}}^3 v^6}{2} m_u \Lambda_u^2 \cos\left(\frac{\sqrt{6}a}{F_a} + \frac{\eta'}{F_{\eta'}} + \frac{\pi^0}{F_{\pi^0}}\right)$$

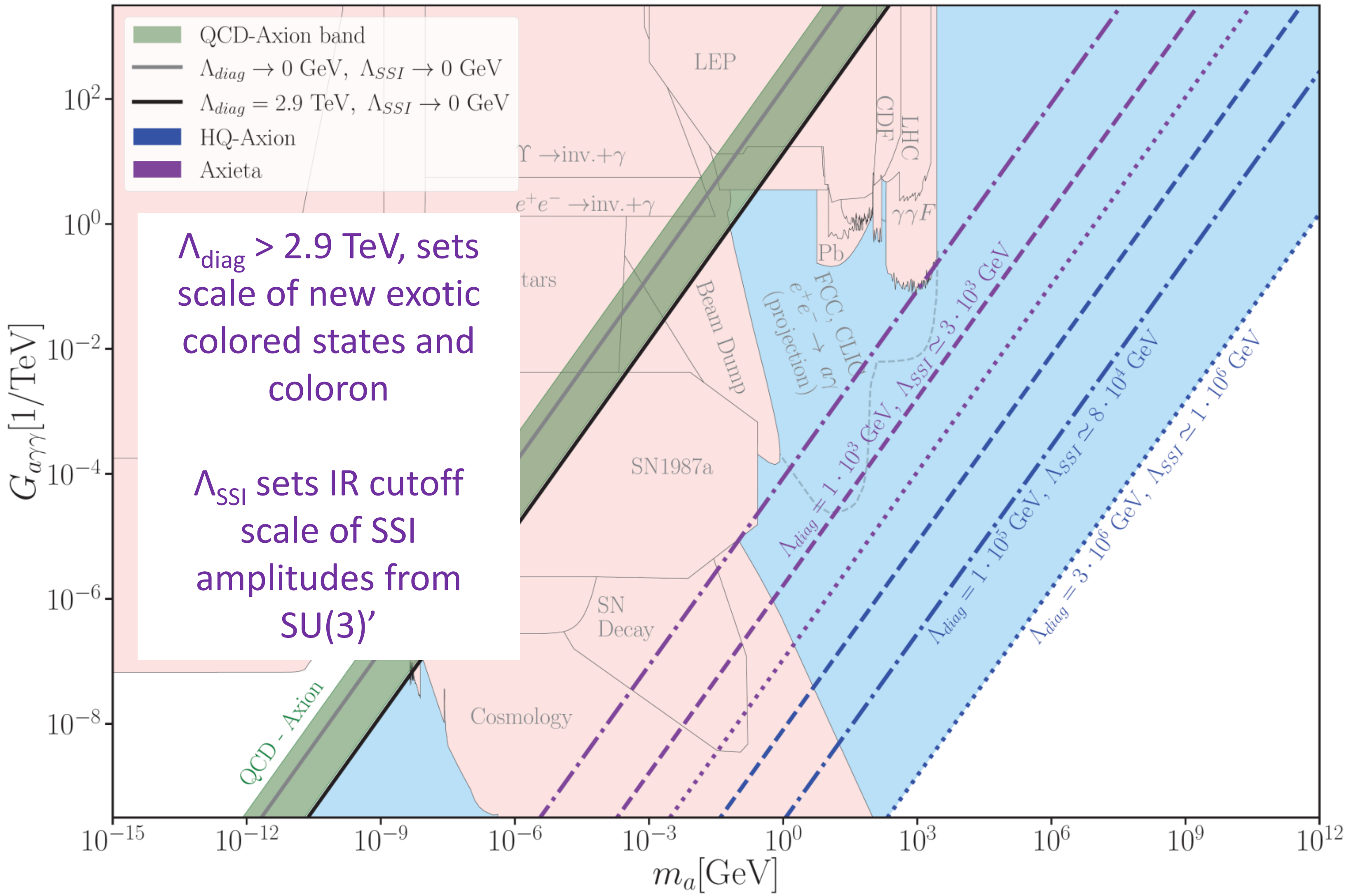
$$A_5 = \frac{v_{\text{diag}}^3 v^6}{2} m_d \Lambda_d^2 \cos\left(\frac{\sqrt{6}a}{F_a} + \frac{\eta'}{F_{\eta'}} - \frac{\pi^0}{F_{\pi^0}}\right)$$



SSI-driven mass enhancements – M1 variant



SSI-driven mass enhancements – M1 variant



Λ_{diag} > 2.9 TeV, sets scale of new exotic colored states and coloron

Λ_{SSI} sets IR cutoff scale of SSI amplitudes from SU(3)'

Beyond vanilla axions

- How to make axions heavier?
  - Smoothly match Theta parameter in IR with vanishing Theta in UV
  - Use BSM topological susceptibility to enhance axion potential
- How to make axions lighter?
  - Need to cancel off instanton-induced potential but keep vacuum energetics aligned
  - Inevitably fine-tuned?

The anarchic axion

Elahi, Elor, Kivel, Laux, Najjari, FY, PRD **108** (2023) 3, L031701 [2301.08760]

Anarchic axion

- Revisit fundamental origin of PQ symmetry: anomalous global symmetry
  - In general, global symmetries stem from field content multiplicity, explicit breaking by Lagrangian interaction terms
    - Not necessarily renormalizable
- Vanilla axion: sole source of PQ breaking arises from $U(1)_{PQ} \times SU(3)^2$ anomaly
  - But no generally rigorous embedding between low-scale PQ symmetry and UV PQ symmetries = quality problem
- Consequence of soft PQ breaking understudied

Building anarchy

- Break PQ softly
- Begin with DFSZ axion

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_5$	$U(1)_{PQ}$
Q_L^i	3	2	1/6	0	X_Q
u_R^i	3	1	2/3	1	X_Q-X_1
d_R^i	3	1	-1/3	0	X_Q-X_2
L_L^i	1	2	-1/2	0	X_L
e_R^i	1	1	-1	0	X_L-X_2
H_1	1	2	-1/2	4	X_1
H_2	1	2	1/2	0	X_2
Φ	1	1	0	1	X_3

- Scalar potential (1a) leaves global $U(1)_{H1} \times U(1)_{H2} \times U(1)_{\Phi}$ symmetry charges undefined
- Canonical DFSZ scalar term (1b) defines PQ charges

$$V = \sum_{i=1,2} \left(\mu_i^2 |H_i|^2 + \lambda_i |H_i|^4\right) + \lambda |H_1|^2 |H_2|^2 + \lambda' |H_1 H_2|^2 + \mu_3^2 |\Phi|^2 + \lambda_3 |\Phi|^4 + \lambda_{13} |H_1|^2 |\Phi|^2 + \lambda_{23} |H_2|^2 |\Phi|^2 \,, \tag{1a}$$

$$V_{\text{break}}^{C_\lambda} = -C_\lambda H_1 H_2 \Phi + \text{h.c.} \,, \tag{1b}$$

Building anarchy

$$V = \sum_{i=1,2} \left(\mu_i^2 |H_i|^2 + \lambda_i |H_i|^4\right) + \lambda |H_1|^2 |H_2|^2 + \lambda' |H_1 H_2|^2$$
$$+ \mu_3^2 |\Phi|^2 + \lambda_3 |\Phi|^4 + \lambda_{13} |H_1|^2 |\Phi|^2 + \lambda_{23} |H_2|^2 |\Phi|^2 \,, \qquad (1a)$$

$$V_{\text{break}}^{C_\lambda} = -C_\lambda H_1 H_2 \Phi + \text{h.c.} \,, \qquad (1b)$$

- With global PQ symmetry set, now add PQ soft breaking term

$$V_{\text{break}}^{B_\mu} = -B_\mu H_1 H_2 + \text{h.c.} \,,$$

- Two sources of PQ breaking: color anomaly and B_μ
  - Three neutral Goldstones: one for SM Z, one 2HDM A, one axion
  - "Standard" 2HDM potential terms forbidden by Z_5 symmetry

Building anarchy

- Define angular fields $\alpha \equiv a/v_a, \; \alpha' \equiv A/v_A$
- Use C_λ to effectively decouple 2HDM A

$$
\begin{aligned}
-V_{\rm ang} = \; & \Lambda_{\rm QCD}^4 \cos\left(N_g \left(\alpha + \alpha'\delta^2\right)\right) \\
& + \Lambda_{\rm QCD}^4 \frac{v_a}{v_{\rm max}} \cos\left(\alpha + \alpha'\delta^2 + \bar\theta\right) \\
& + \frac{|C_\lambda| v v_A^2}{\sqrt{2}\delta(1+\delta^2)} \cos\left(\alpha'(1+\delta^2)\right)
\end{aligned}
$$

$$
\begin{aligned}
v_{\rm max} &\equiv \frac{\Lambda_{\rm QCD}^4}{|B_\mu| v}\sqrt{1+\delta^2} \\
\delta &= v_A/v_a
\end{aligned}
$$

  - Second line is effect of finite B_μ
  - v_{max} = maximal value of PQ vev v_a

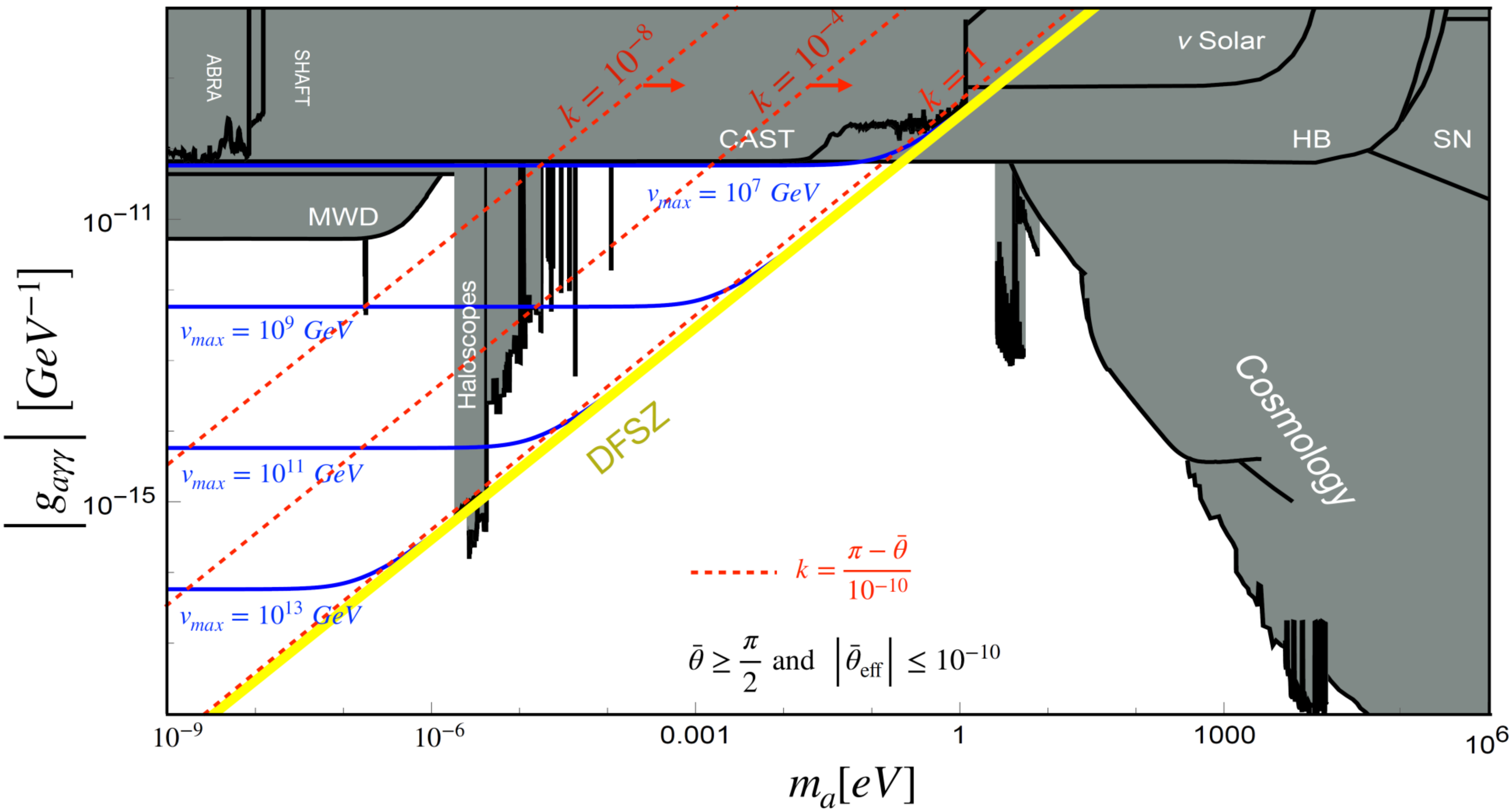
Building anarchy

- UV phases shuffled into $N_g\,\bar{\theta} = \theta_{SM} - N_g\theta_\mu$
- Tadpole of axion = observable $|\theta_{eff}|$
- Axion mass arises from canonical DFSZ contribution and soft-breaking B_μ piece

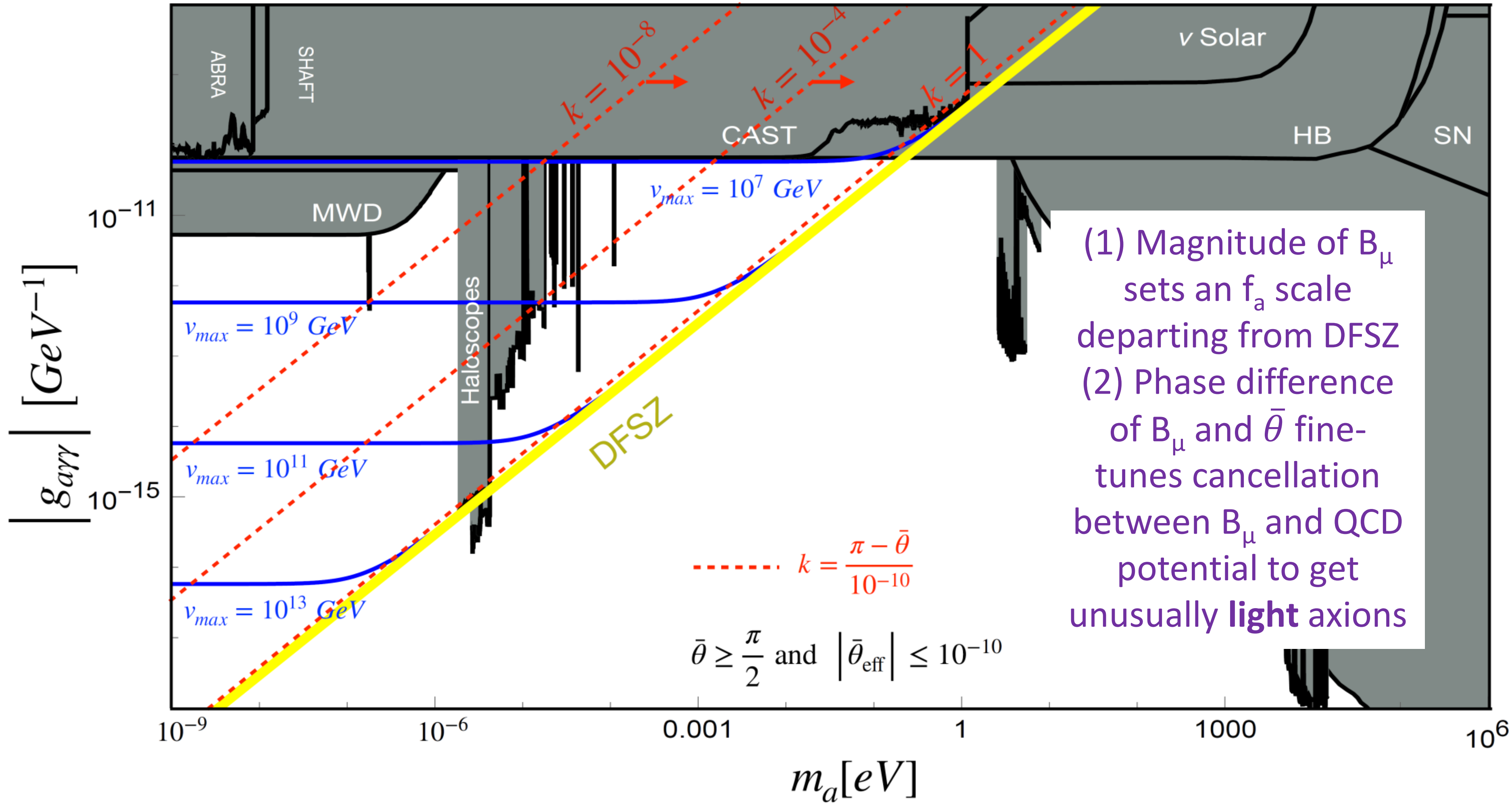
$$m_a^2 = \frac{\Lambda_{\rm QCD}^4}{v_a^2}\left(N_g^2 \cos\left(N_g\bar{\theta}_{\rm eff}\right) + \frac{v_a}{v_{\rm max}}\cos\left(\bar{\theta} - \bar{\theta}_{\rm eff}\right)\right)$$

$$\frac{1}{f_a} \equiv \frac{N_g}{v_a} = -\frac{\cos\left(\bar{\theta}-\bar{\theta}_{\rm eff}\right)}{2N_g v_{\rm max}\cos\left(N_g\bar{\theta}_{\rm eff}\right)} + \sqrt{\frac{m_a^2}{\Lambda_{\rm QCD}^4\cos\left(N_g\bar{\theta}_{\rm eff}\right)} + \left(\frac{\cos\left(\bar{\theta}-\bar{\theta}_{\rm eff}\right)}{2N_g v_{\rm max}\cos\left(N_g\bar{\theta}_{\rm eff}\right)}\right)^2}\,. \quad (11)$$

Anarchic axion deviates from DFSZ band



Anarchic axion deviates from DFSZ band

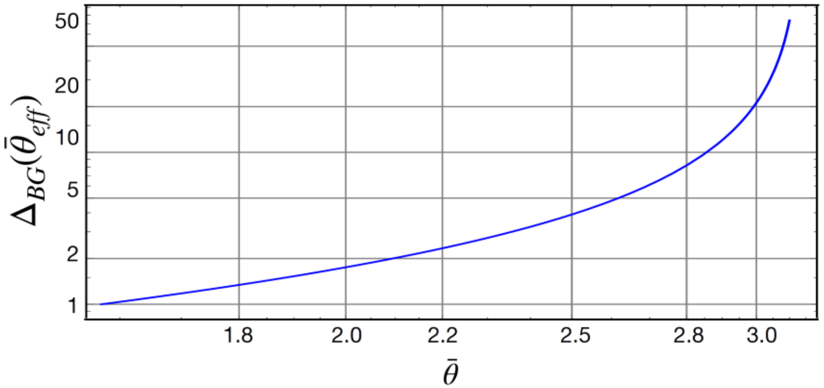


(1) Magnitude of B_μ sets an f_a scale departing from DFSZ
(2) Phase difference of B_μ and $\bar{\theta}$ fine-tunes cancellation between B_μ and QCD potential to get unusually **light** axions

Fine-tuning measure

- Since finite residual nEDM is *calculable*, can use Giudice-Barbieri fine-tuning measure

$$\Delta_{\rm BG}(\bar\theta_{\rm eff}) \equiv \left| \frac{\bar\theta}{\bar\theta_{\rm eff}} \frac{\partial \bar\theta_{\rm eff}}{\partial \bar\theta} \right|$$



- Open model-building question whether more complicated UV model can reduce fine-tuning
  - Ongoing work with Nelson-Barr origin of B_μ term
- Anarchic axion model serves as target toy effective description aiming for light axions

Part 1 Conclusions – Non-vanilla axions

- Axion field theory is rich with phenomenological applications and diverse model-building tools
  - Viable strong CP axion models with SSIs **enhance axion mass** into collider reach and beyond
  - Soft-breaking PQ symmetry motivates **unusually light** axions – prime targets for host of experiments
- Future work will focus on Goldstone field theories and their breaking (beyond CCWZ)
  - Field theoretic synthesis of other PNGB EFTs
    - Relaxion, clockwork, linear dilaton, etc.
  - Connections to generalized global symmetries

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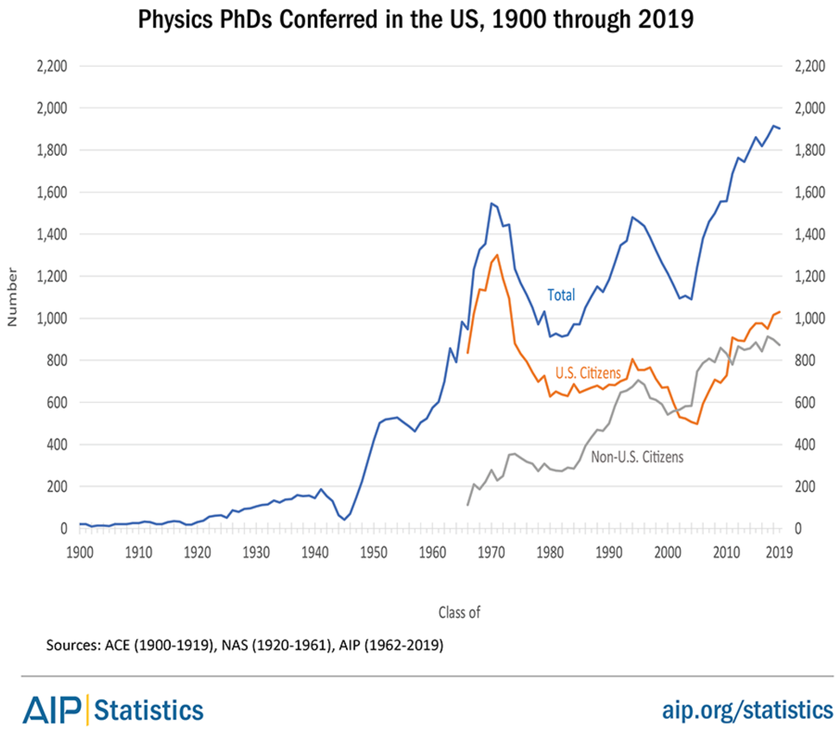
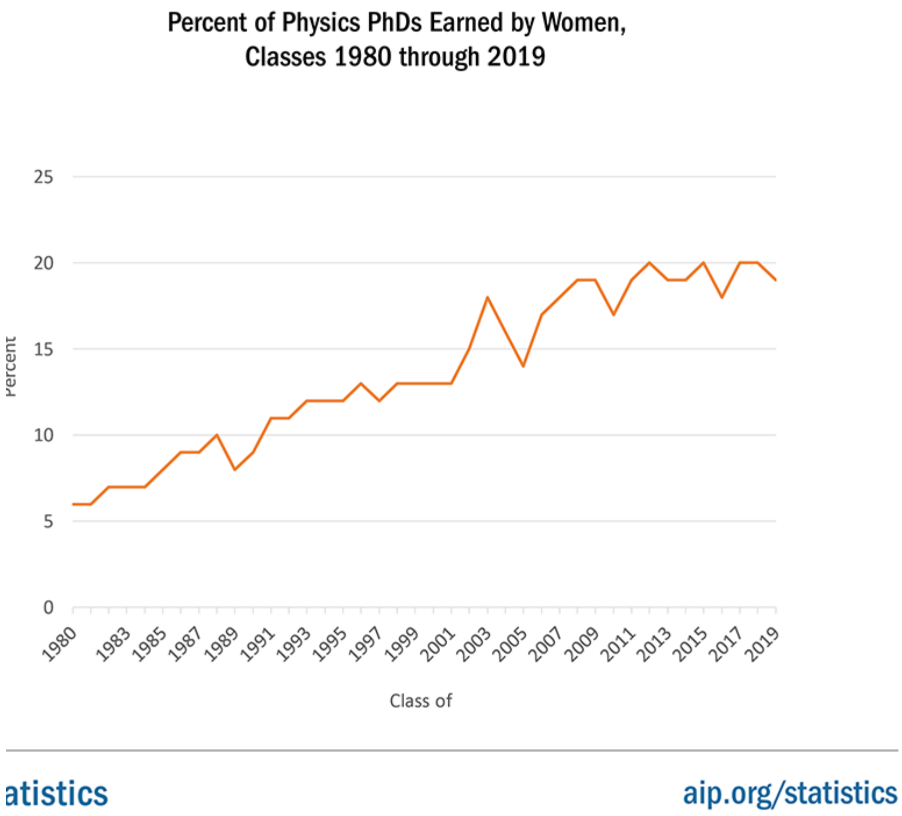
Perspective on Diversity, Equity, and Inclusion

Current status for physics as a field – US

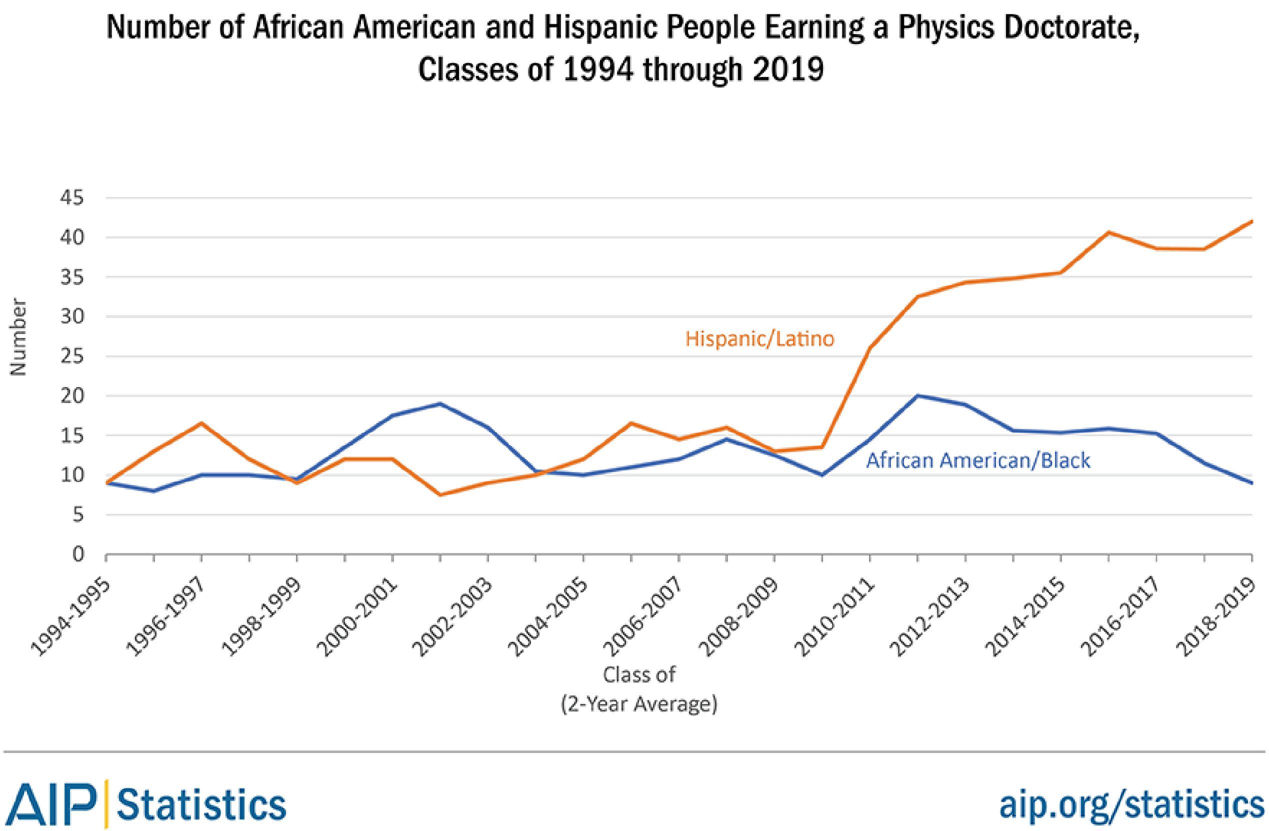
- Progress in gender balance has stalled





Current status for physics as a field – US

- Uneven improvement in ethnic diversity



Current status for physics as a field – US

- Uneven improvement in ethnic diversity

Race and Ethnicity of Physics PhDs, Classes of 2018 and 2019 Combined.

	Number (2-Year Average)	Percent of all Physics PhDs	Percent of US Physics PhDs*
White	860	45%	84%
Asian American	92	5%	9%
Hispanic American	42	2%	4%
African American	9	<1%	1%
Other US Citizens	20	1%	2%
Non-US Citizens	887	47%	-
Total	1,910	100%	100%

*Based on a 2-year average of 1,022 US Citizens.

US Census
58.9%
6.3%
19.1%
13.6%
4.3%

AIP | Statistics   aip.org/statistics

Current status for physics as a field – US

- Numerical breakdown into categories for reference

The Number of Doctorates Earned in Physics, 2014–15 to 2018–19

Number of Doctorates Earned in Physics by People who are:	2014–15	2015–16	2016–17	2017–18	2018–19
American Indian or Alaska Native men	5	0	1	2	2
American Indian or Alaska Native women	0	1	0	0	0
Asian men	56	55	61	66	70
Asian women	17	20	19	18	27
Black or African American men	13	15	16	8	8
Black or African American women	5	9	3	4	1
Hispanic or Latino men	34	40	50	42	40
Hispanic or Latino women	10	5	7	11	10
Native Hawaiian or Other Pacific Islander men	2	1	1	1	1
Native Hawaiian or Other Pacific Islander women	0	0	0	1	0
White men	639	650	648	609	651
White women	135	142	115	165	123
Two or more races men	9	11	11	24	22
Two or more races women	1	8	6	6	6
All Other Race/Ethnicity and Gender Combinations (NonResident Alien and Unknown)	915	889	894	923	914
Totals:					
Non-White Only	152	165	175	183	187
White Only	774	792	763	774	774
Grand Totals:					
Men	1,474	1,489	1,511	1,478	1,497
Women	367	357	321	402	378
All	**1,841**	**1,846**	**1,832**	**1,880**	**1,875**

These data are publicly available from the National Center for Education Statistics (NCES) here: https://nces.ed.gov/ipeds/use-the-data.

AIP | Statistics   aip.org/statistics

Current status – United States as attractor

- Addressing geographic diversity

Regions and Countries of Citizenship for Non-US Physics PhD Degree Recipients, Classes of 2017 and 2018 Combined

Asia	70%
China	30%
India	15%
Nepal	7%
Taiwan	4%
Sri Lanka	3%
Other Asian Countries	11%
Europe	11%
Americas	5%
Middle East	9%
Africa	4%
Australia, New Zealand	1%

AIP | Statistics   aip.org/statistics

Current status for physics as a field – US

- Aside: Physics as a career

Response to the Question: "If You Had to Do it Over Again, Would You Still Get a PhD in Physics?" Classes of 2017 and 2018 Combined

	US Citizens	Non-US Citizens
Yes, at the same institution	70%	53%
Yes, at a different institution	13%	24%
No, I would get a PhD in another subject	5%	15%
No, I would not get a PhD	12%	8%

AIP | Statistics aip.org/statistics

  - Do not know the reason for the other answers

Current status – Germany

- No equivalent demographic survey information
- More specialized survey was conducted by KET (roughly the German equivalent to APS Particles and Fields Section)
  - Target group for survey were people who moved to a permanent position in particle physics in Germany since 2010 and are working in particle physics in Germany – 92 responses

https://www.ketweb.de/veroeffentlichungen/karrieren_2023/

Current status – Germany

- Gender balance

2.2 How is the gender balance?

33% of those who obtained a permanent position since 2010 are women. An earlier survey conducted by KET in 2021 in the *full* community showed that the fraction of women in each of the three categories doctoral researchers, postdoctoral researchers, and leading and permanent positions is around 22%. In the third category of leading and permanent positions this represented a significant increase from about 10% in 2014. The recent hires since 2010 have therefore significantly increased the share of women in permanent positions in particle physics. The fraction of hired women is higher than their share in doctoral and postdoctoral researchers, and also beyond the share of women in bachelor graduates in physics of 24% in 2020. The fraction of hired women is very different between hires at universities (23%, excluding joint appointments with research laboratories) and at research laboratories (45%). Therefore the increase is, at least on average, mainly due to hires at research laboratories while universities hire women roughly according to their share in earlier career levels. The Helmholtz Association has two programs to recruit excellent female scientists to their laboratories with an association to a German university, see Section 4.2.3. These positions likely contribute to a higher fraction of women hired at the laboratories.

https://www.ketweb.de/veroeffentlichungen/karrieren_2023/

Current status – Germany

- Personal view: takes longer to get to permanent jobs in Germany (in theory)

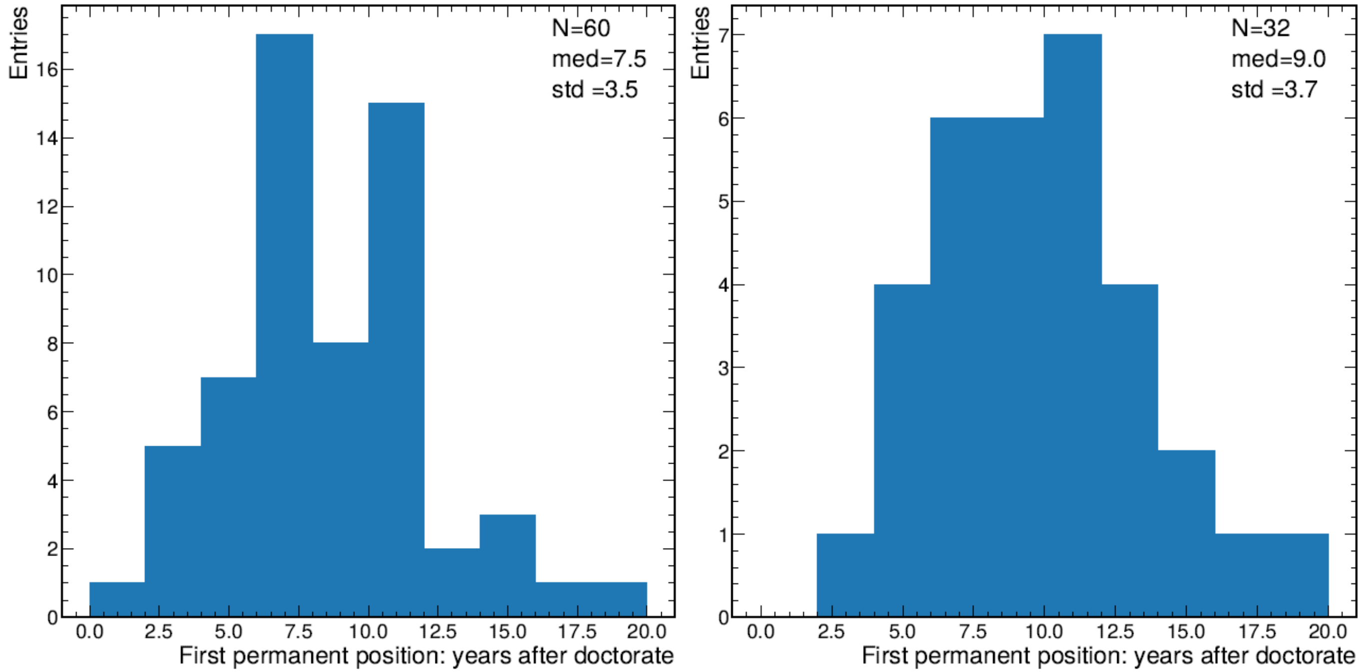


Figure 3: *Number of years between conclusion of doctorate and first permanent position in experimental particle physics (left) and in theoretical particle physics (right).*

https://www.ketweb.de/veroeffentlichungen/karrieren_2023/

Current status – Germany

- Some significant (co-)dependence on "feeder" programs

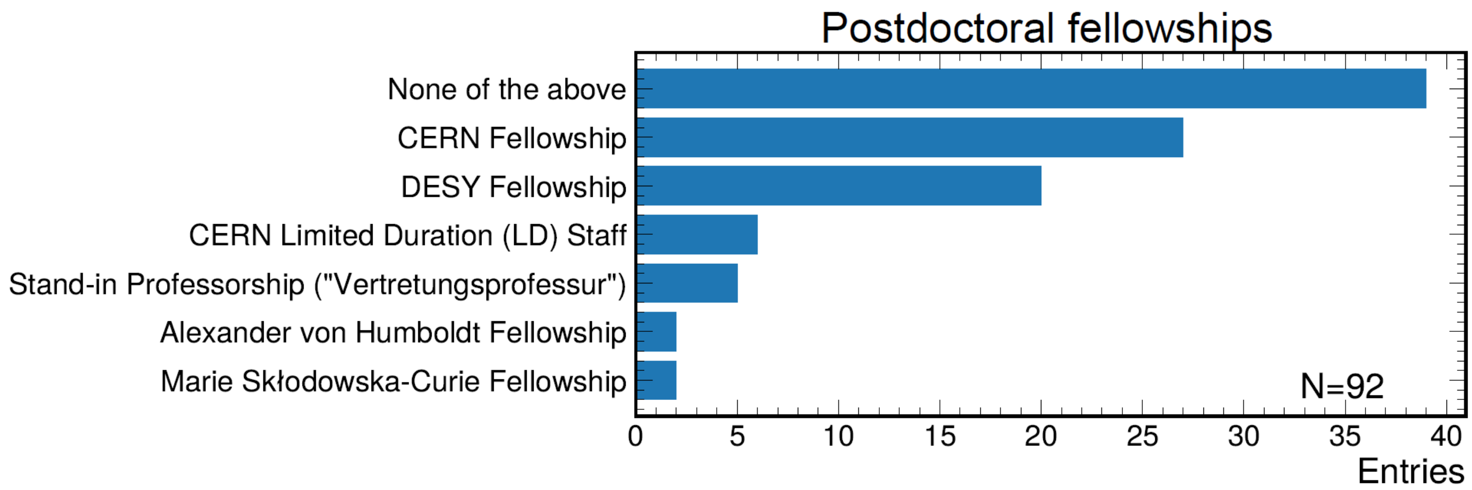


Figure 4: *Types of fellowships granted to members of the target group prior to assuming their permanent position in Germany (multiple answers were possible).*

https://www.ketweb.de/veroeffentlichungen/karrieren_2023/

Current status – Germany

- Self-reflection: "What seems most significant to a permanent job in Germany?" (1 to 5 scale)

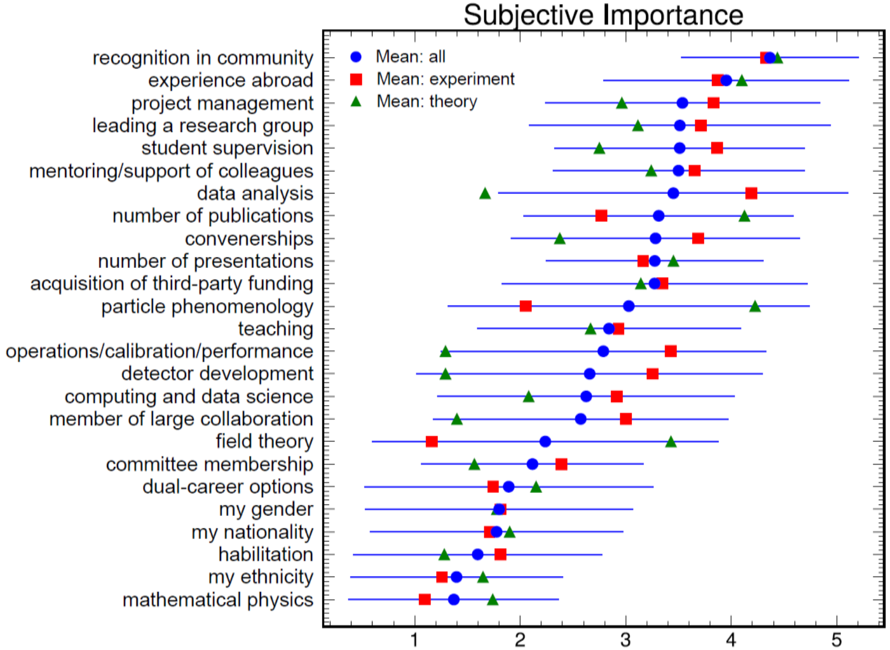


Figure 7: *Subjective importance assigned to various factors for obtaining a permanent position, on a scale from 1 (not important) to 5 (very important). The factors are sorted by the mean importance of the entire target group (blue circles). In addition the plot shows the standard deviation of the entire group (error bar) as well as the mean for colleagues currently working in experimental physics (red squares) and in theoretical physics (green triangles).*

https://www.ketweb.de/veroeffentlichungen/karrieren_2023/

Current status – Germany

- Self-reflection: “What seems most significant to a permanent job in Germany?” (1 to 5 scale)

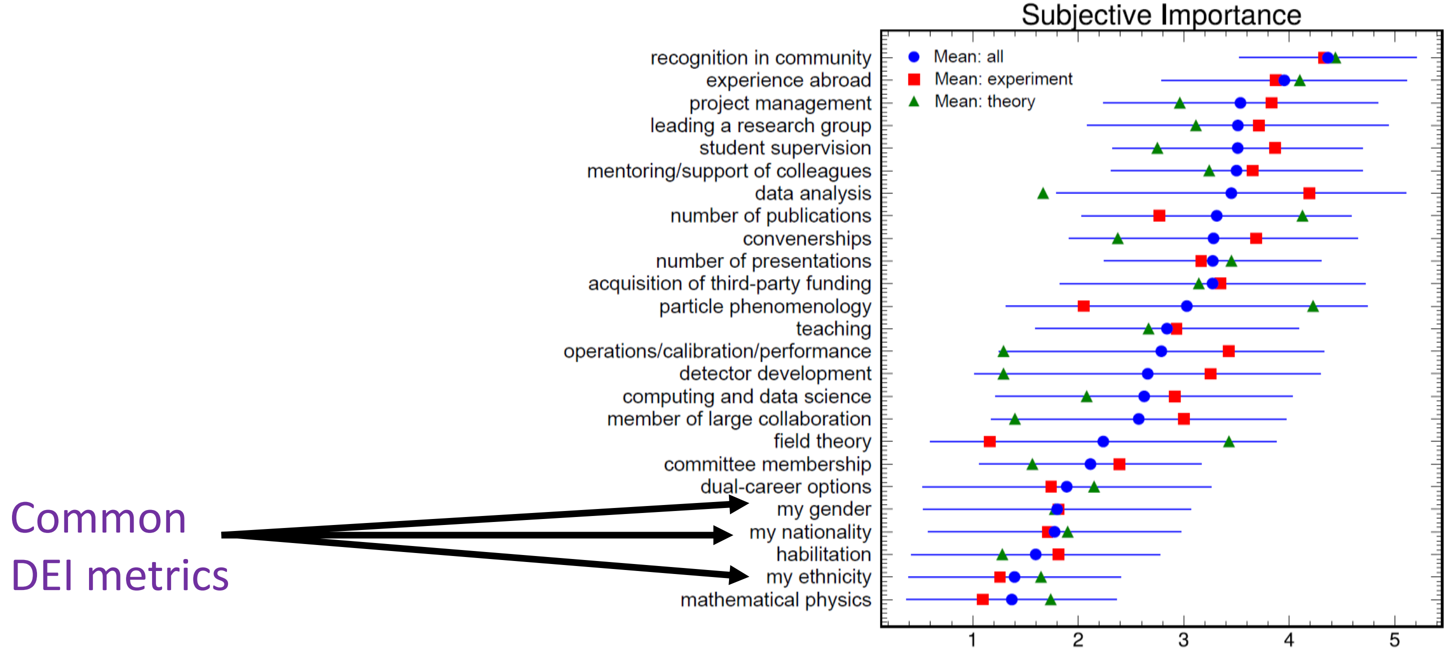


Figure 7: *Subjective importance assigned to various factors for obtaining a permanent position, on a scale from 1 (not important) to 5 (very important). The factors are sorted by the mean importance of the entire target group (blue circles). In addition the plot shows the standard deviation of the entire group (error bar) as well as the mean for colleagues currently working in experimental physics (red squares) and in theoretical physics (green triangles).*

https://www.ketweb.de/veroeffentlichungen/karrieren_2023/

Survey takeaways

- Leaky pipeline is intact
- Selection is a fact
- Diversity means different things in USA and Germany
  - Visibility is important, sociological data is lacking

- I will not address the leaky pipeline or selection
  - Thorny issue: perception/reality of a zero-sum game in faculty hiring

A personal best practice to help DEI

- I am not a policy maker, but I want to do my part in helping DEI

A personal best practice to help DEI

- I am not a policy maker, but I want to do my part in helping DEI
- Engage people outside your comfort zone at workshops, seminars, conferences, schools
  - Everyone has a shared interest in physics
  - Can invariably learn something new
  - Avoid prejudice – poor physics knowledge becomes teachable moment

Science transcends barriers

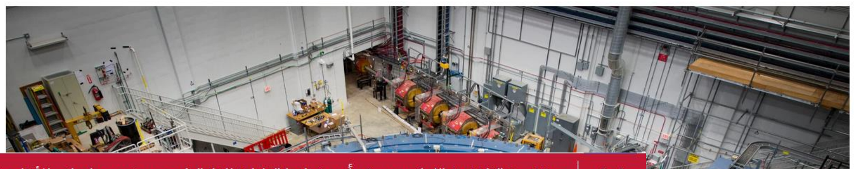
The New York Times

OUT THERE

A Tiny Particle's Wobble Could Upend the Known Laws of Physics

Experiments with particles known as muons suggest that there are forms of matter and energy vital to the nature and evolution of the cosmos that are not yet known to science.

535



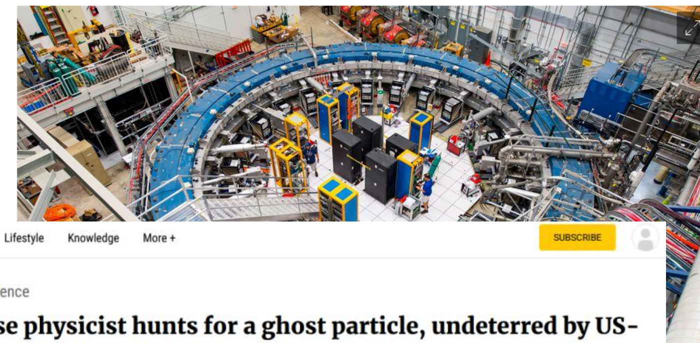
SPIEGEL Wissenschaft

Neue Erkenntnisse in der Teilchenphysik

Kundschafter ins Unbekannte

Seit 50 Jahren ersehnen Forscher Einblicke in die Welt jenseits der bekannten Naturgesetze. Jetzt öffnet sich das Tor zu einer neuen Physik.

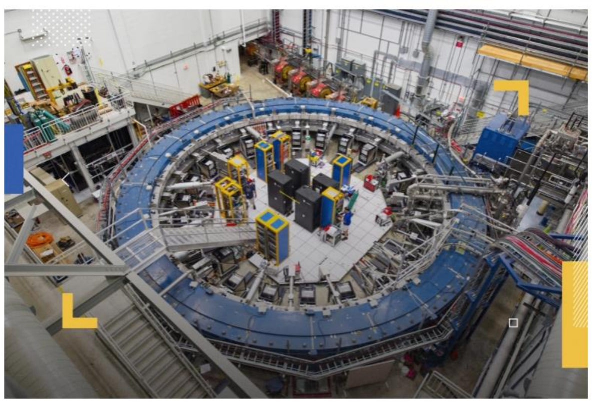
Von **Johann Grolle**
07.04.2021, 16.48 Uhr



عاجل | رويترز عن التلفزيون الإيراني: حريق بأحد خطوط الطوارئ للغاز الطبيعي جنوبي طهران ولا أنباء عن خسائر بشرية

ميدان

نتائج أهم تجربة في العالم.. هل نحن على مشارف فيزياء جديدة تماما؟!



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Chinese physicist hunts for a ghost particle, undeterred by US-China friction

- Li Liang has worked for nearly a decade on the Muon g-2 experiment involving 200 researchers from seven countries at Fermilab in the US
- Teams in China are working on the blueprint for a muon collider with sites in Guangdong province among candidates to host the potential project

Stephen Chen in Beijing + FOLLOW
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