How is the intermediate scale axion decay constant become possible?

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Is "intermediate scale" $f_a \sim (v_{ew} M_{Pl})^{1/2}$?

This is possible only after having a spontaneously broken global symmetry far below the Planck mass scale.

1. ’t Hooft mechanism

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Unbroken $X = Q_{global} - Q_{gauge}$

$$\phi \to e^{i\alpha(x)Q_{\text{gauge}}} e^{i\beta Q_{\text{global}}} \phi$$

the α direction becomes the longitudinal mode of heavy gauge boson. The above transformation can be rewritten as

$$\phi \to e^{i(\alpha(x)+\beta)Q_{\text{gauge}}} e^{i\beta(Q_{\text{global}}-Q_{\text{gauge}})} \phi$$

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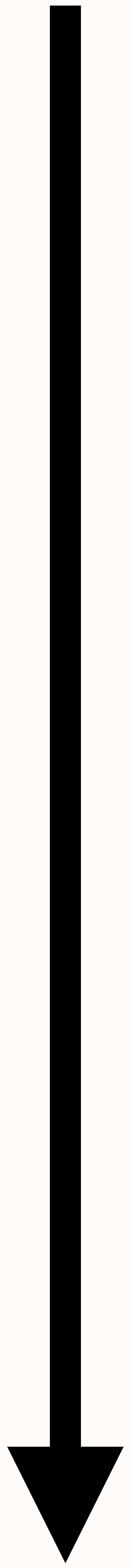
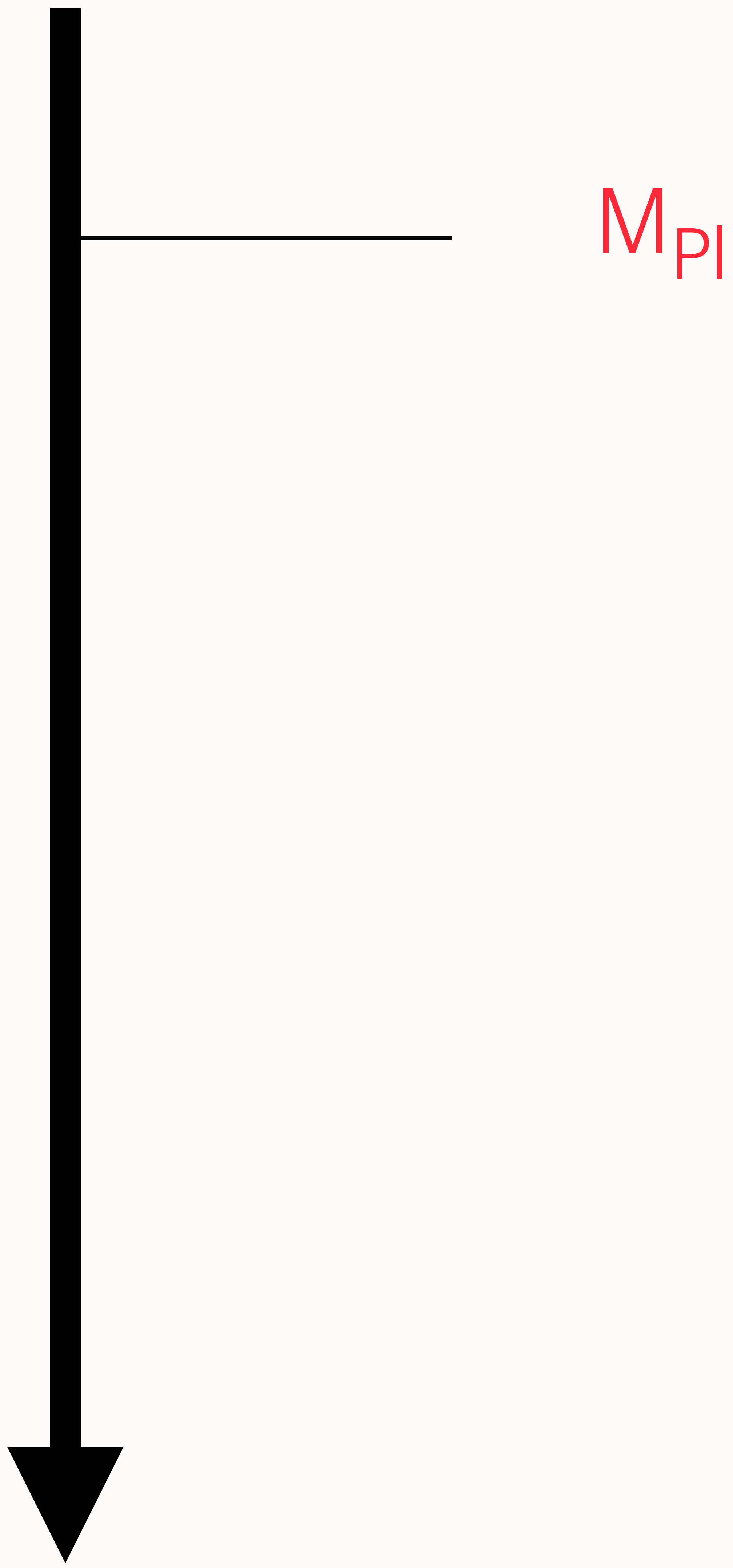
So, the gauge boson becomes heavy and there remains the x-independent transformation parameter beta. The corresponding charge is a combination:

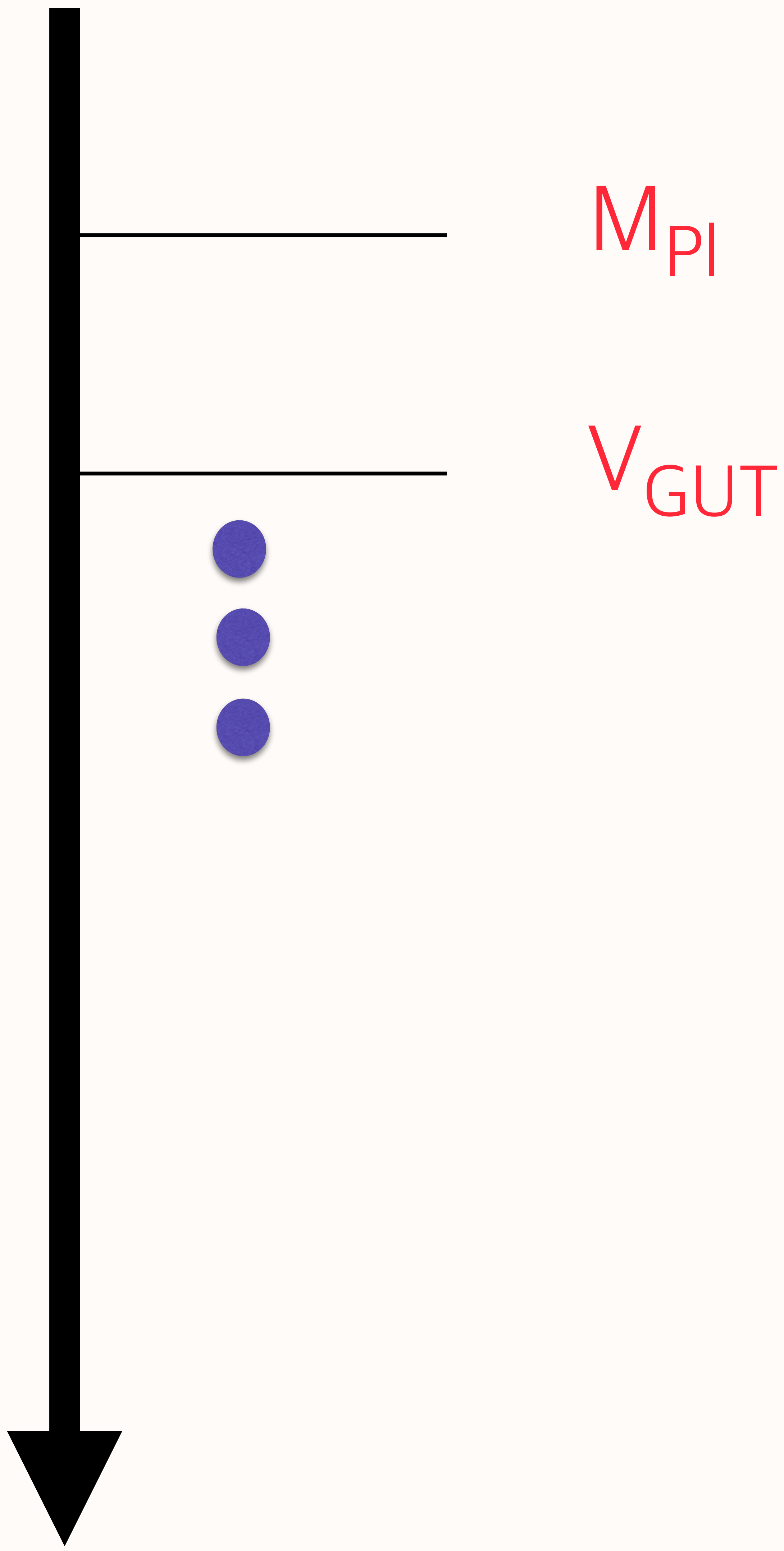
$X = Q_{global} - Q_{gauge}$

This process can be worked out at any step. When one global symmetry survives below a high energy scale, we consider another gauged U(1) and one more complex scalar to break two U(1)'s. Then, one global symmetry survives.





One complex scalar for one gauge symmetry breaking



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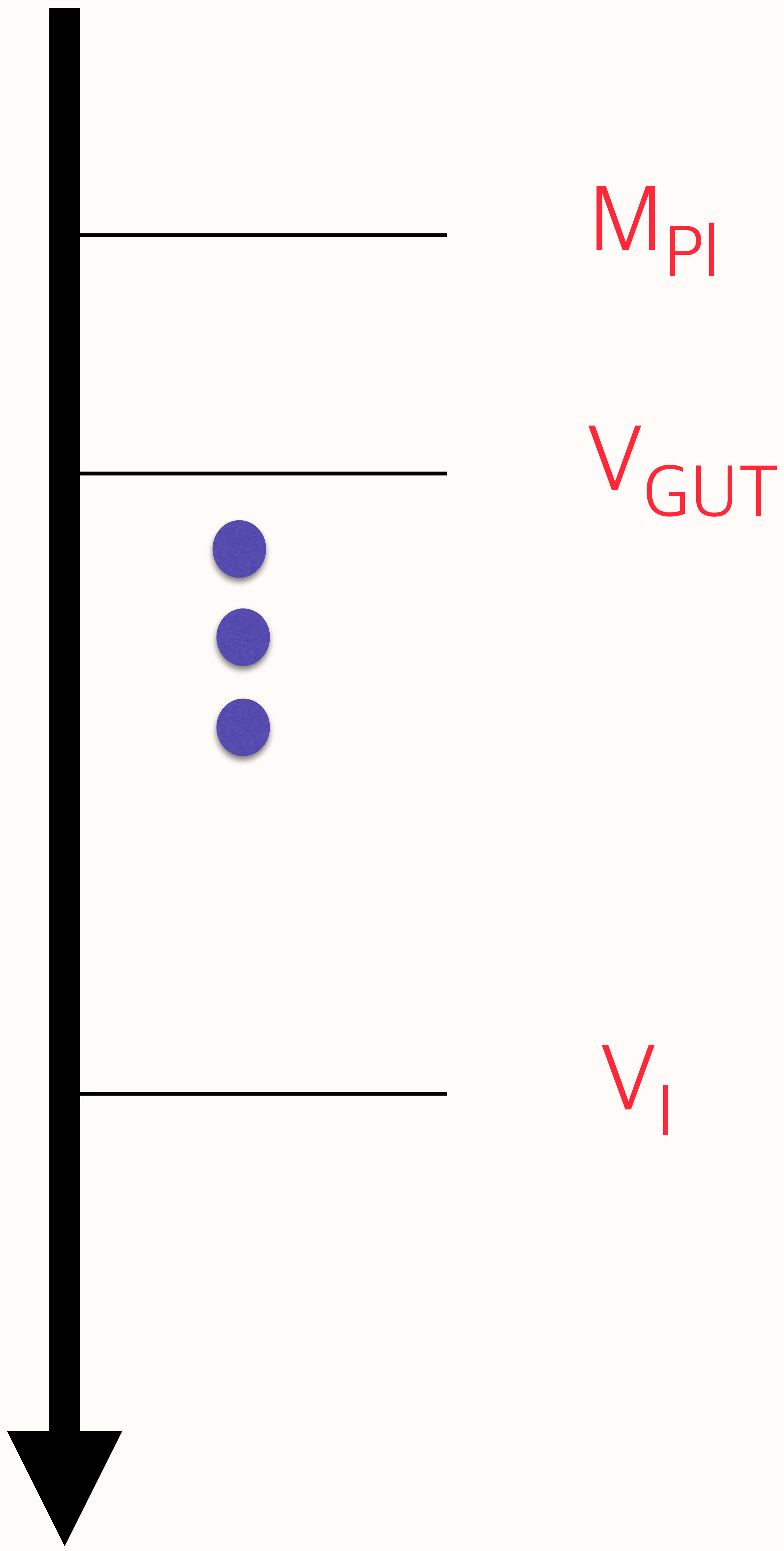
Until all wanted U(1) gauge symmetries are broken.



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Until all wanted U(1) gauge symmetries are broken.

At the next step, a global symmetry is broken

2. Model-independent axion
in string theory

Openning of string theory by the GS term

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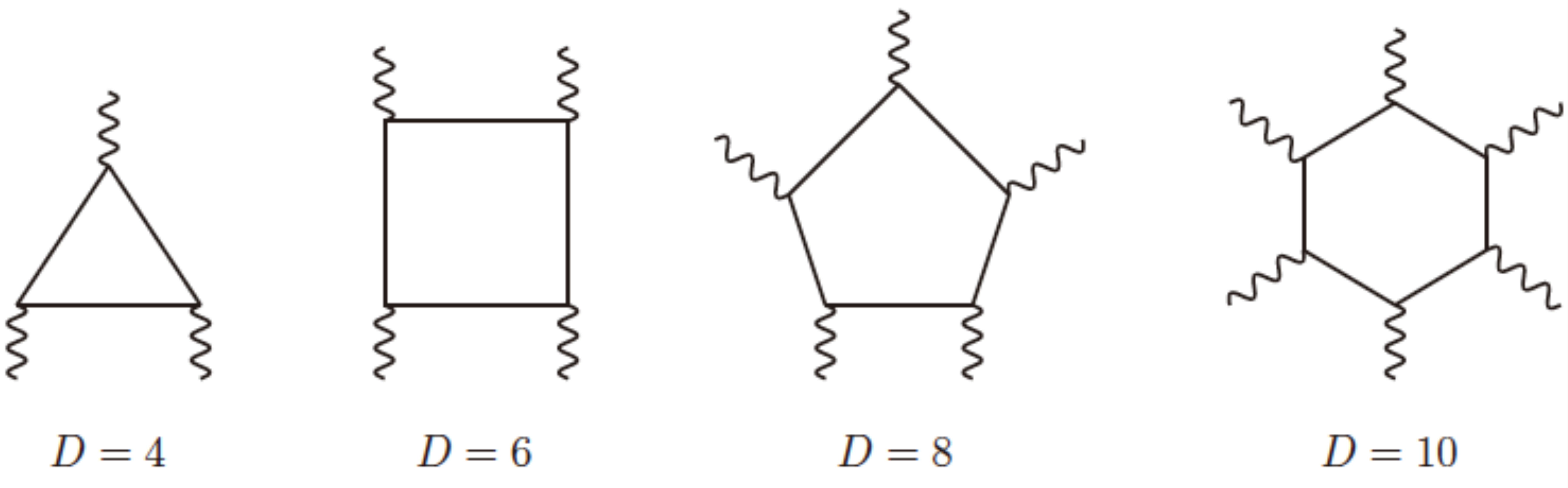
One needs a term (GS-term) to cancel the gauge and gravitational anomalies.

Anomalies: even dimensions



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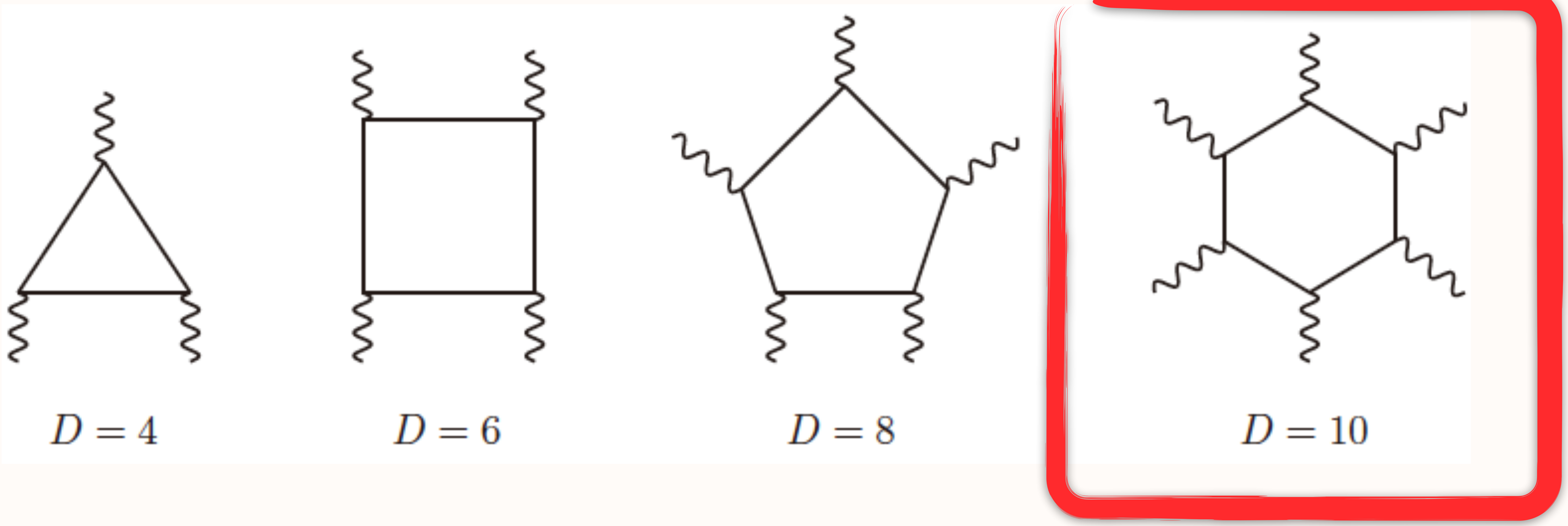

In 10D, the hexagon anomaly. It is cancelled by the previous GS term.

Green-Schwarz mechanism:

The gravity anomaly in 10D requires 496 spin-1/2 fields. Possible non-Abelian gauge groups are rank 16 groups SO(32) and E8xE8'. The anti-symmetric field B_{MN} has field strength (in diff notation), $H= dB+w_{3Y}{}^0-w_{3L}{}^0$:SO(32). Three indices matched.

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$$-\frac{3\kappa^2}{2g^4\,\varphi^2} H_{MNP}H^{MNP}, \text{ with } M,N,P = \{1,2,\cdots,10\}$$

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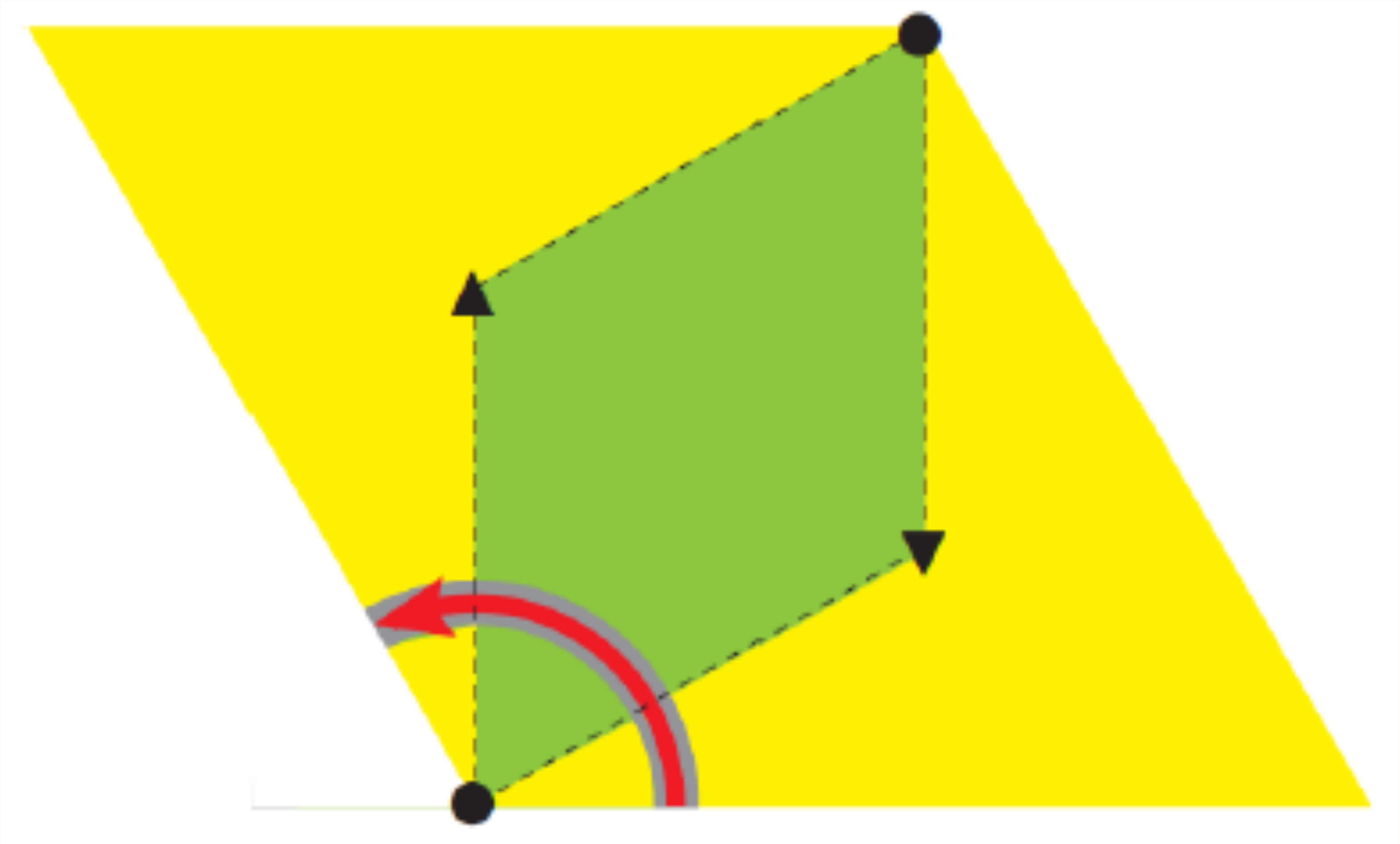

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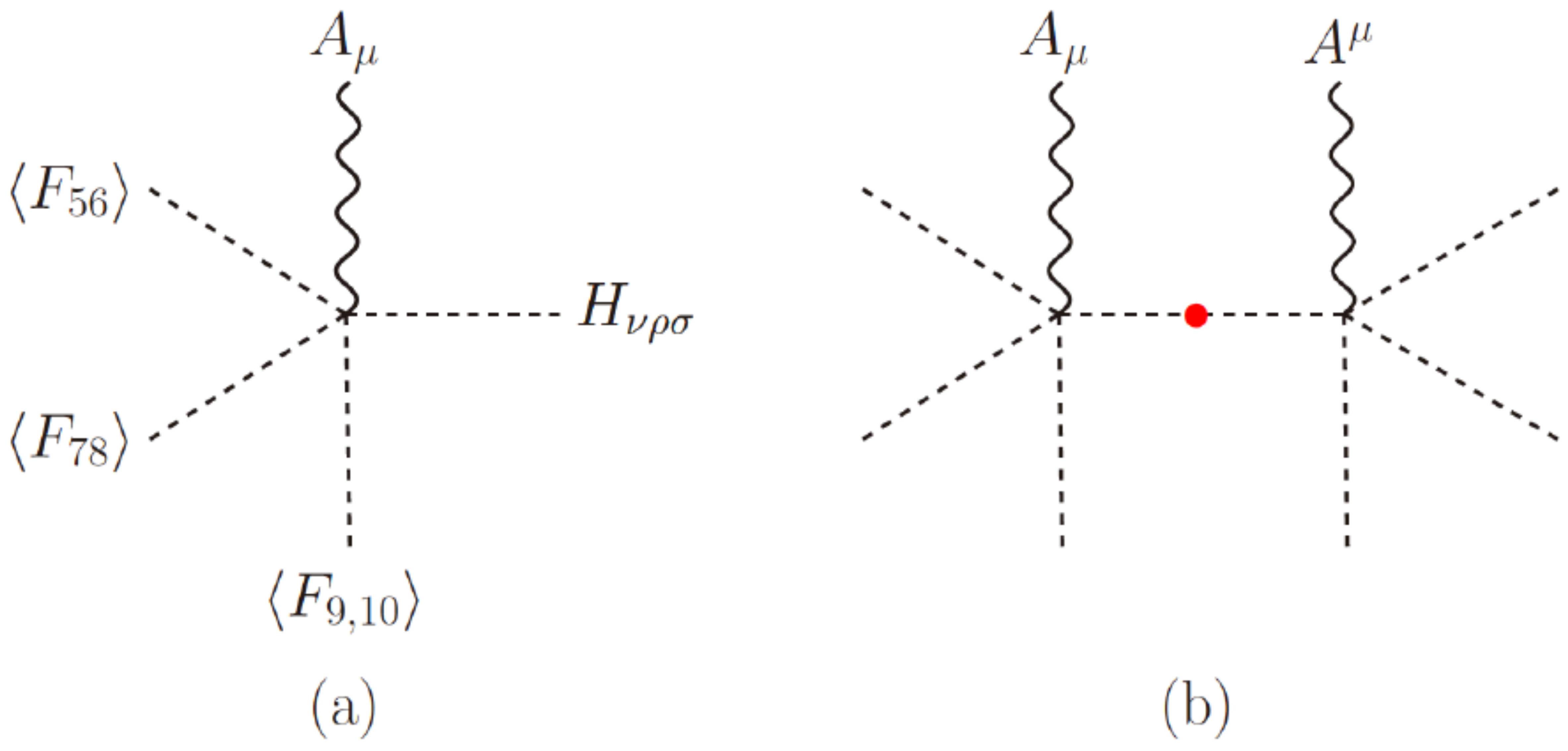
$$\frac{1}{2\cdot 3!M_{MI}^2}H_{\mu\nu\rho}H^{\mu\nu\rho},\ \text{with } \mu,\nu,\rho=\{1,2,3,4\}.$$



$$M_{MI} A_\mu \partial^\mu a_{MI}$$

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One may look this in the following way.

The10 supergravity quantum field theory with SO(32) and E8xE8' gauge groups has gauge and gravity anomalies. Let us believe that string theory is consistent, effectively removing all divergences, i.e. removing all anomalies. The point particle limit of 10D string theory should not allow any anomalies. There must be some term in the string theory removing all these anomalies. It is the GS term. In strong int., breaking chiral symmetry, viz. the Wess-Zumino term removing anomalies by some term involving pseudoscalar fields.

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Thus, since the MI axion is a real spin-0 particle, f_a can be related to the string scale.

I believe that people are confused here. My guess: "String theorists and their followers are confused." Even they calculated the FI D-term for $U(1)_{anom}$ gauge symmetry.

Whether or not there exist the FI D-term or not, counting the number of phases is an INVARIANT one.

All pseudoscalars are phase fields. Count the number of these continuous degrees of freedom. In our case, we consider two phase fields, the MI-axion and some phase of a complex scalar carrying the $U(1)_{anom}$ charge.

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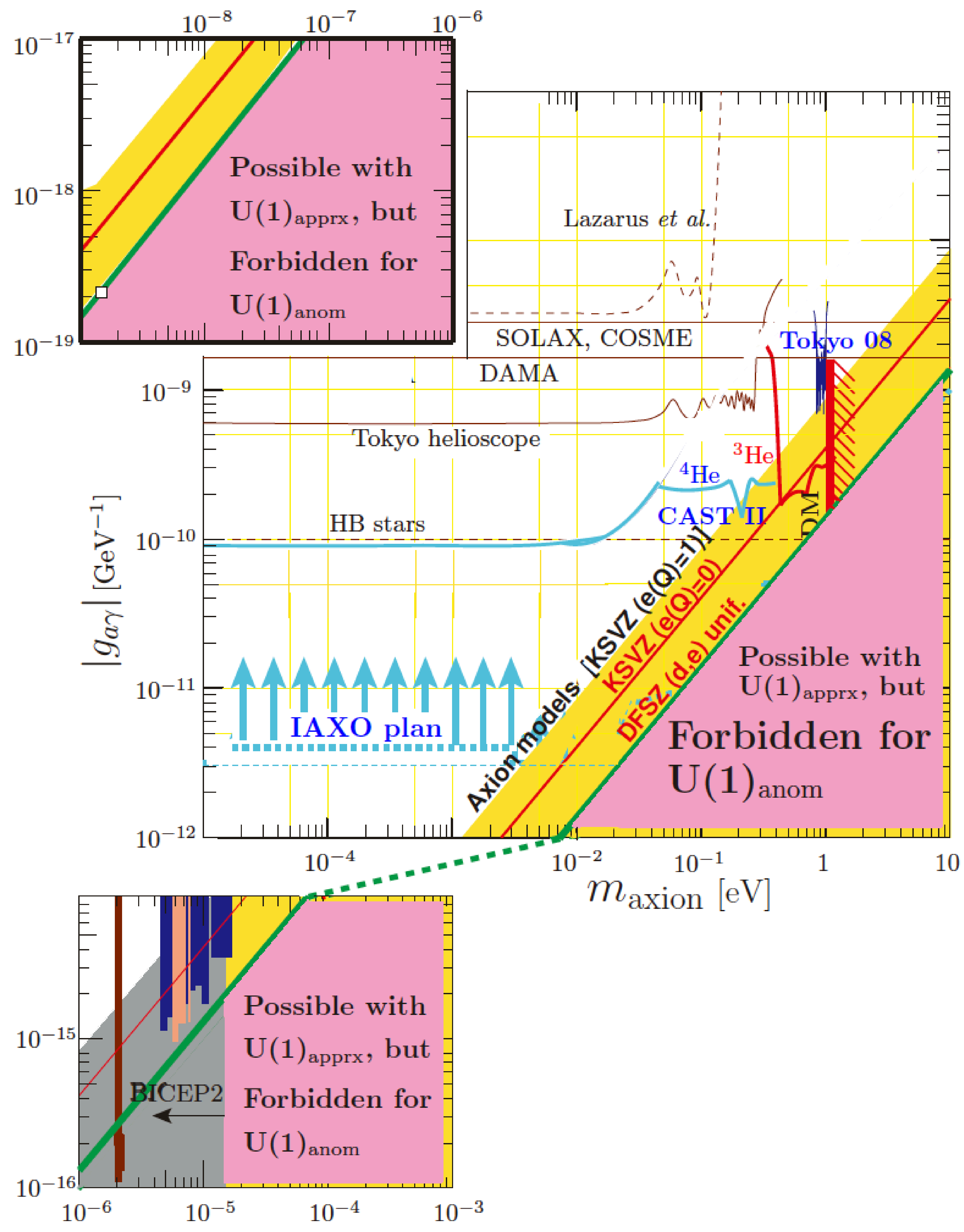
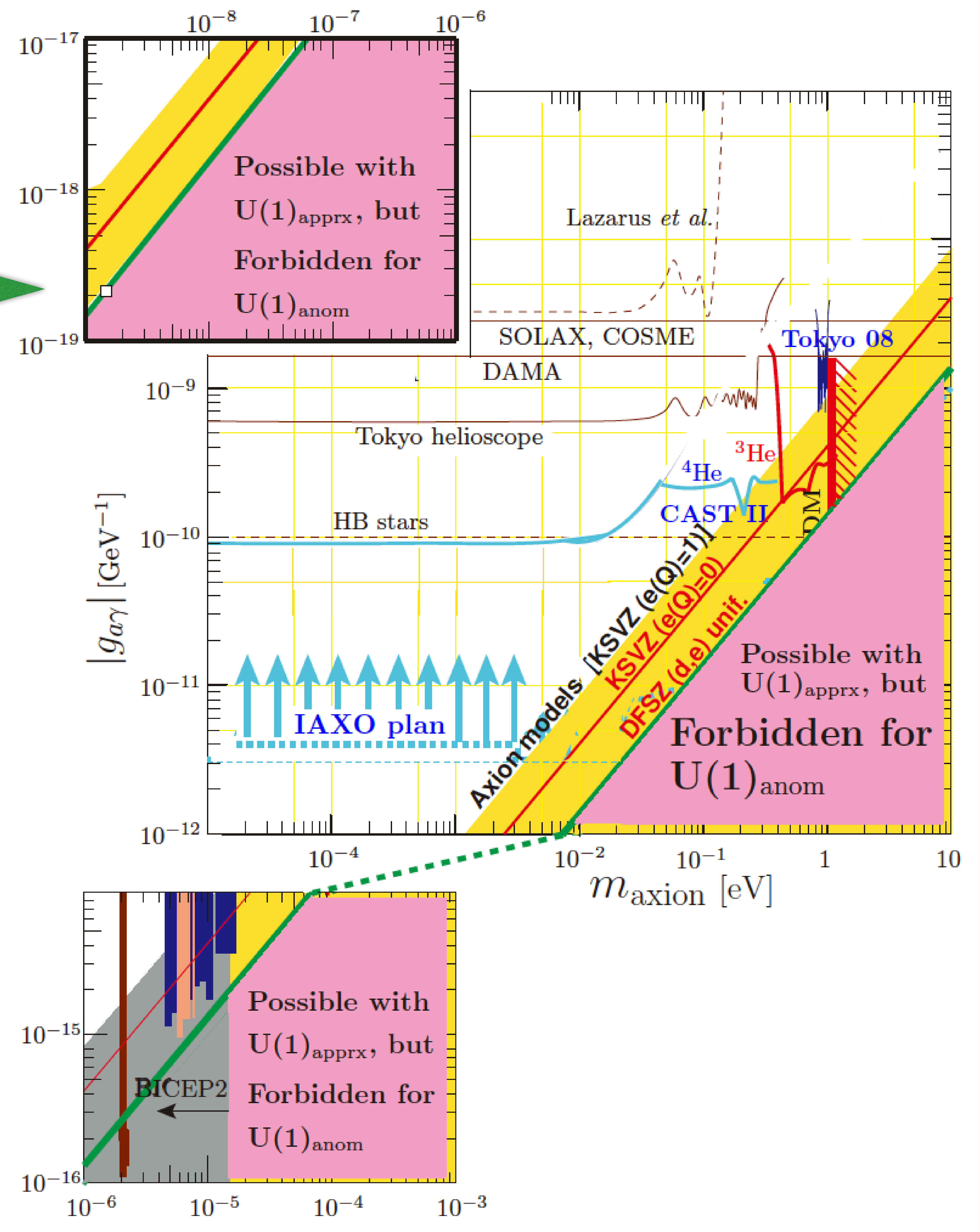


Fig. 8. The $g_{a\gamma}(= 1.57 \times 10^{-10}\, c_{a\gamma\gamma})$ vs. m_a plot.[80,81]

Choi-Kim, 1985

f_{MI}



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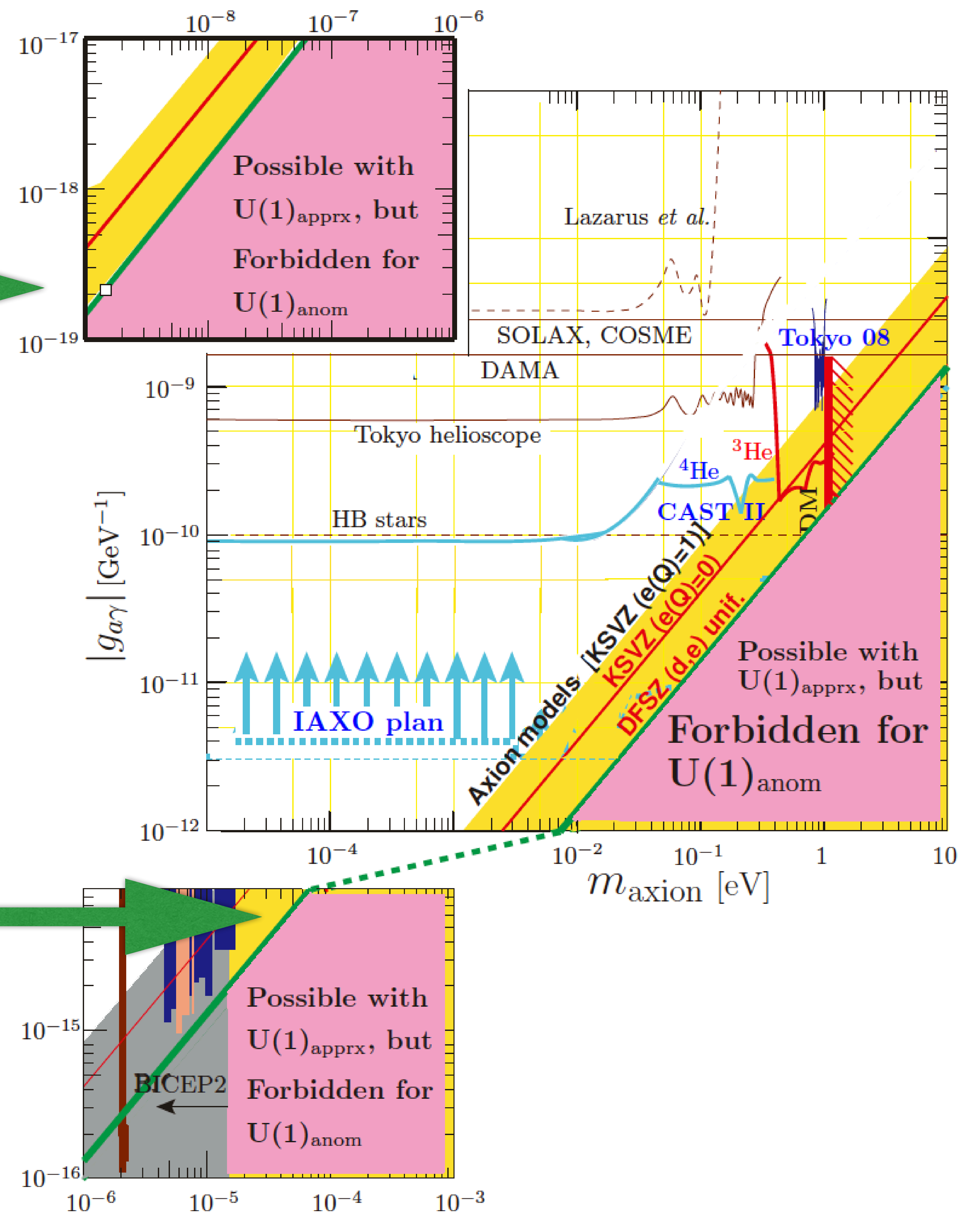
But, we need "invisible" axion here

f_a



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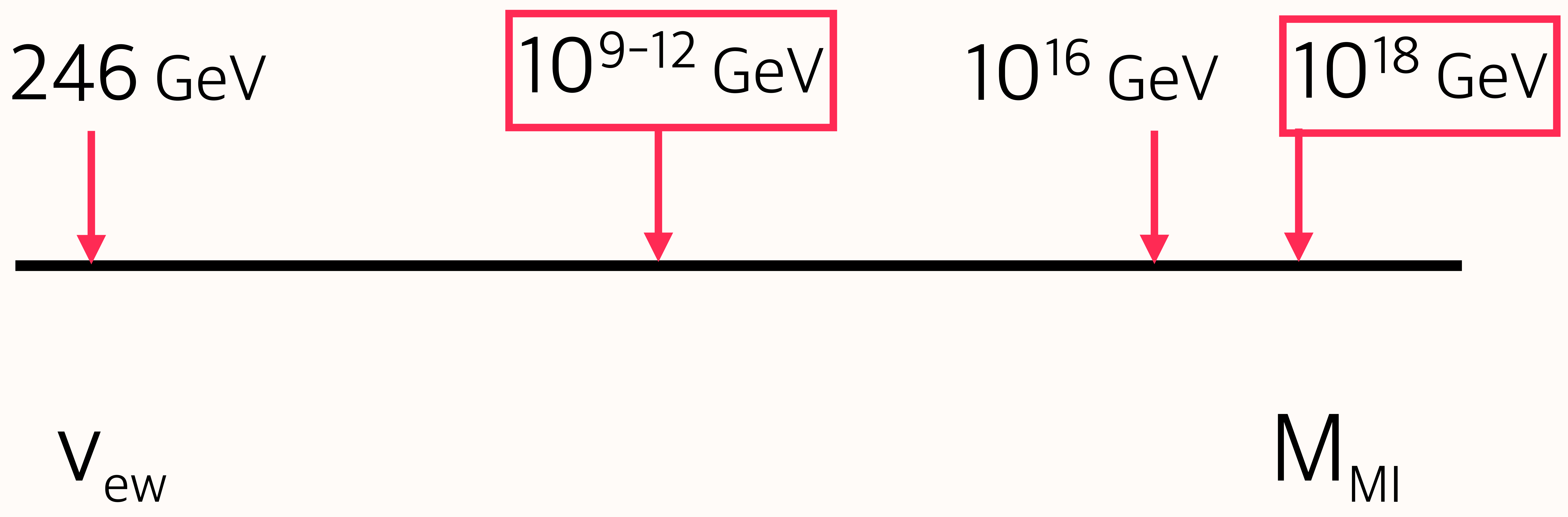
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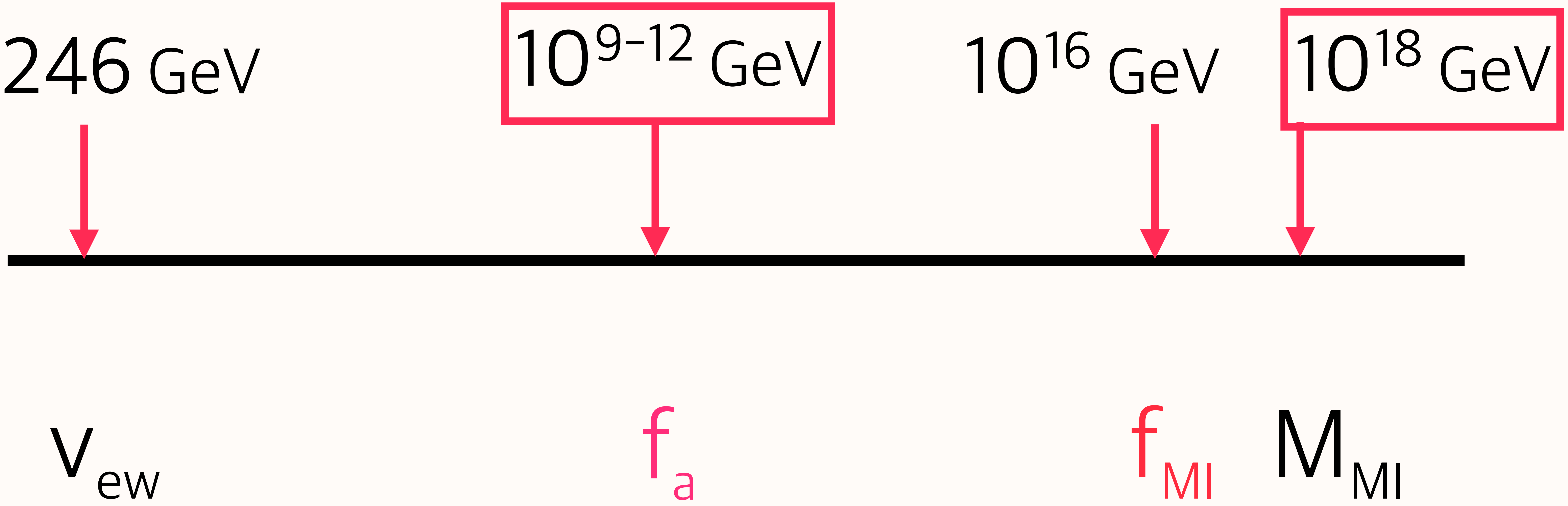
10^{16} GeV
10^{18} GeV
V_{ew}
M_{MI}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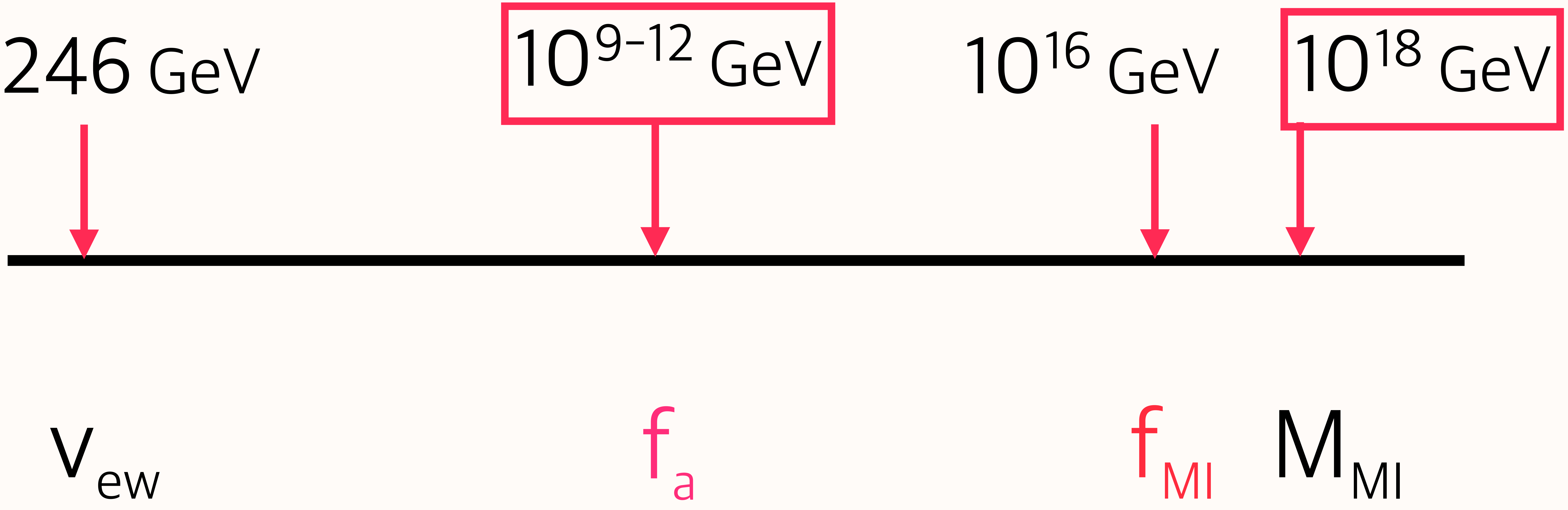

Is "intermediate scale" $f_a \sim (v_{ew} M_{MI})^{1/2}$?

If the VEVs of scalars is much smaller than the string scale, then one can say that the global symmetry survives from string compactification and it is the relevant symmetry. Even if one adds $|\phi^* T^a \phi - \xi|^2$ for $\xi \ll M_{string}^2$, it is not much different from considering the global symmetry with the usual D-term, $|\phi^* T_{\rm anom} \phi|^2$ (as if there is a gauge symmetry) since $\xi \ll M_{string}^2$. This is a hierarchical explanation.

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You may question, "you have only two phases, and one is absorbed to the gauge boson $A^\mu_{\rm anom}$, and the other may become a heavy pseudoscalar." Answer: It does not work that way, because there is no potential term giving the remaining pseudoscalar mass because the charges of gauge U(1) from $E_8 \times E_8'$ and the charge operator in the FI D-term are identical. I.e. there is no mass term generated because the exact Goldstone boson direction (the longitudinal mode of $A^\mu_{\rm anom}$) coincides with the phase in the FI D-term.

Even if we consider the FI term with a non-vanishing \xi and there is no hierarchy between the comp scale and the GUT scale, a global symmetry can be derived:

$$\frac{1}{2}\partial^\mu a_{\rm MI}\partial_\mu a_{\rm MI} + M_{\rm MI}A_\mu\partial^\mu a_{\rm MI} + \left|-\xi + e\sum_a \phi_a^* Q_a \phi_a\right|^2 + \left[|(\partial_\mu - ieA_\mu)\phi_1|^2 + \cdots\right]$$
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Assume: one phi_a is carrying the anomalous charge.

ϕ_1 **develops a VEV,** V_1**, by minimizing the FI term.**

a_1 [= the phase of ϕ_1 (= $(V_1+\rho_1)e^{ia_1/V_1})/\sqrt{2}$] are considered and only one Goldstone boson

$$\sqrt{M_{\rm MI}^2+e^2V_1^2}\,(\cos\theta_G\,a_{\rm MI}-\sin\theta_G\,a_1)$$

re $\tan\theta_G = eV_1/M_{\rm MI}$. The orthogonal Goldestone boson direction

$$a' = \cos\theta_G\,a_1+\sin\theta_G\,a_{\rm MI}$$

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This process can be worked out further below the GUT scale as far as U(1) gauge symmetries (to be broken above the EW scale) are present. Then, one global symmetry survives down to the intermediate scale.

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It is the 't Hooft mechanism working in the string theory. So, the continuous direction a_{MI} –> a_{MI} + (constant) survives as a global symmetry at low energy. "Invisible" axion!!!!!

$$|D_\mu\phi|^2 = |(\partial_\mu - igQ_a A_\mu)\phi|^2_{\rho=0} = \frac{1}{2}(\partial_\mu a_\phi)^2 - gQ_a A_\mu \partial^\mu a_\phi + \frac{g^2}{2}Q_a^2 v^2 A_\mu^2$$

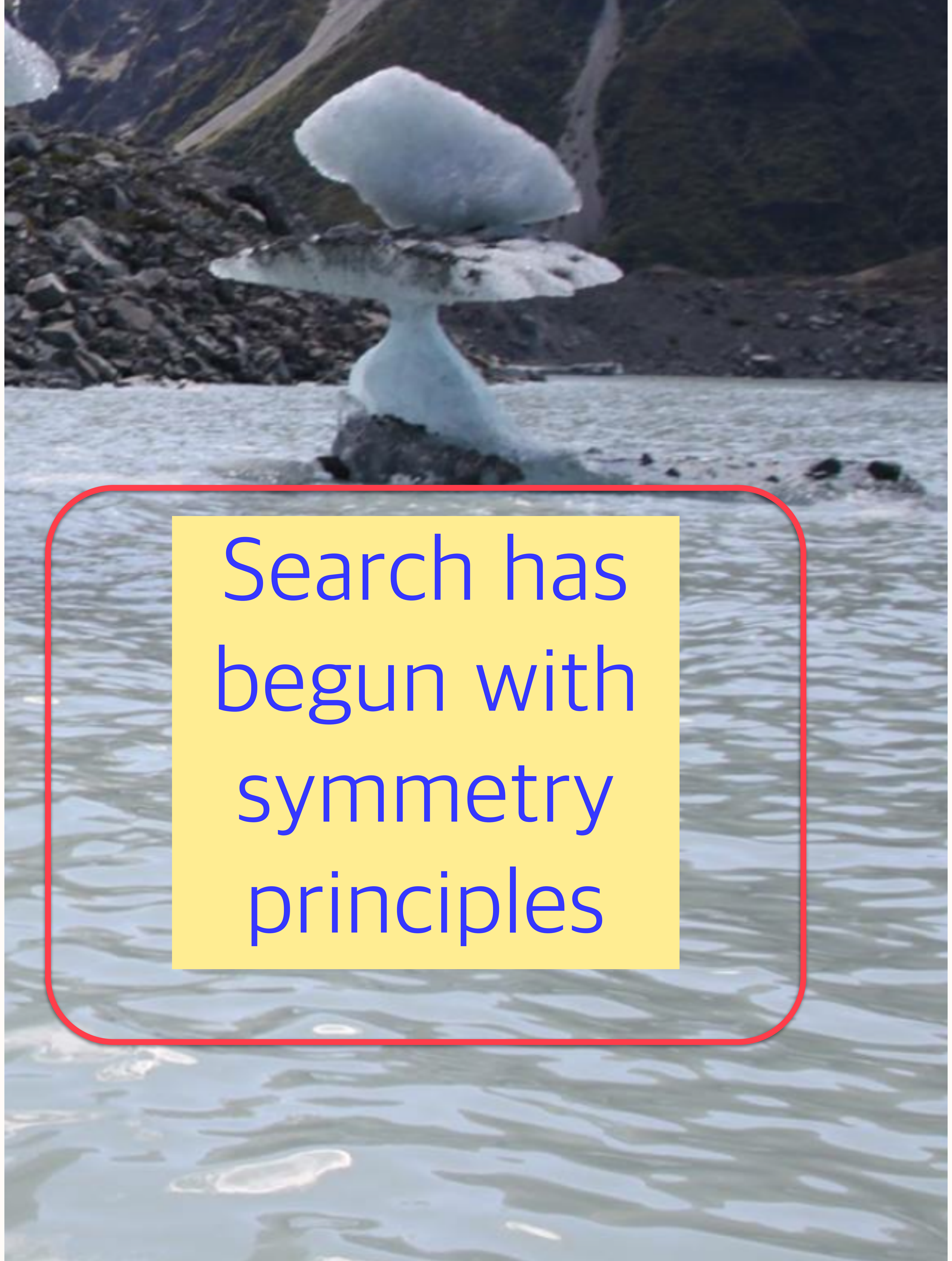
$$= \frac{g^2}{2}Q_a^2 v^2 (A_\mu - \frac{1}{gQ_a v}\partial^\mu a_\phi)^2$$

$$\frac{1}{2}\left(M_{MI}^2 + g^2 Q_a^2 v^2\right)(A_\mu)^2 + A_\mu(M_{MI}\partial^\mu a_{MI} - gQ_a v \partial^\mu a_\phi) + \frac{1}{2}\left[(\partial_\mu a_{MI})^2 + (\partial^\mu a_\phi)^2\right]$$

$$a = \cos\theta\, a_\phi + \sin\theta\, a_{MI}$$

$$\sin\theta = \frac{gQ_a v}{\sqrt{M_{MI}^2 + g^2 Q_a^2 v^2}}.$$

3. Approximate global symmetry


Search has begun with symmetry principles

Symmetry is beautiful: a framework, beginning with Gross' grand design.

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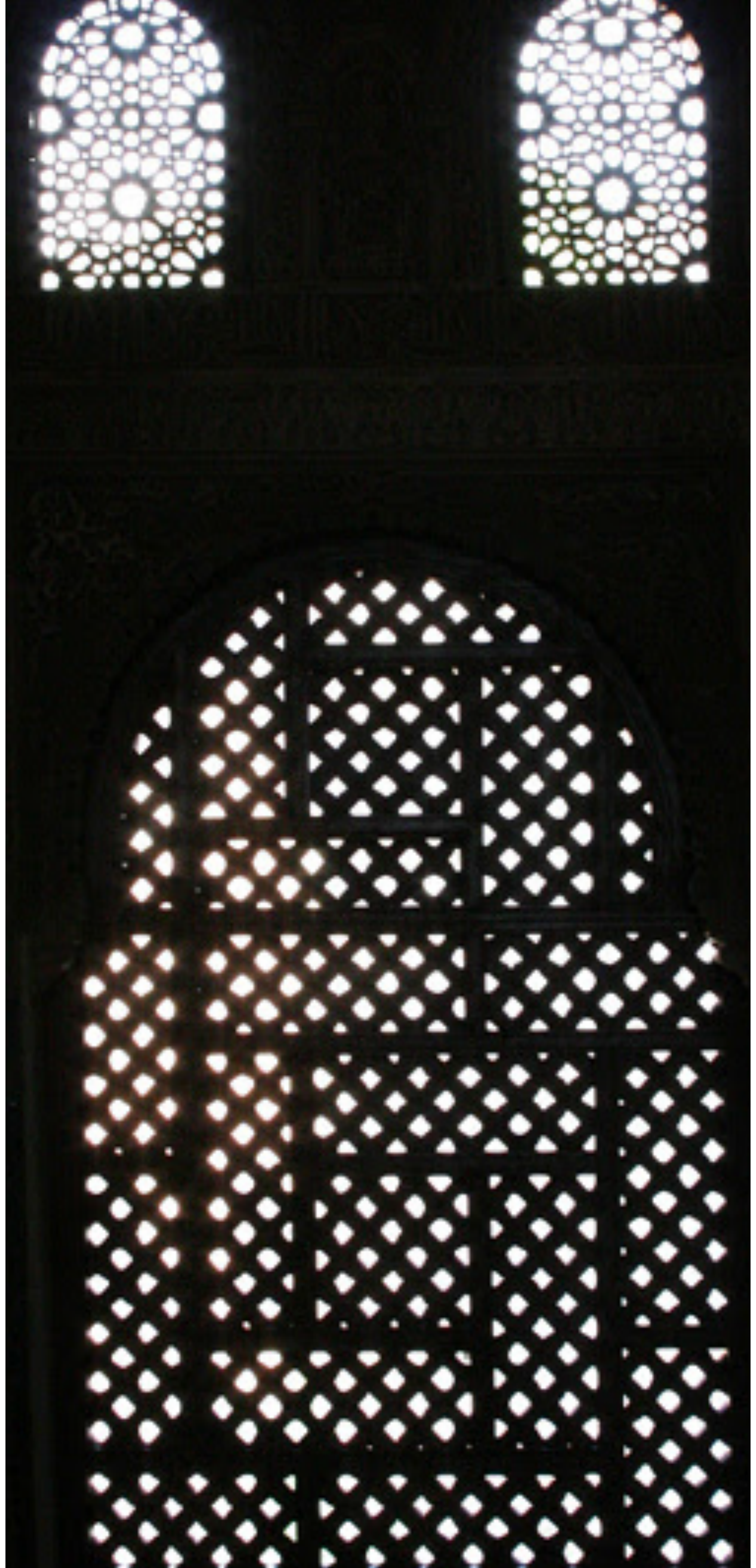
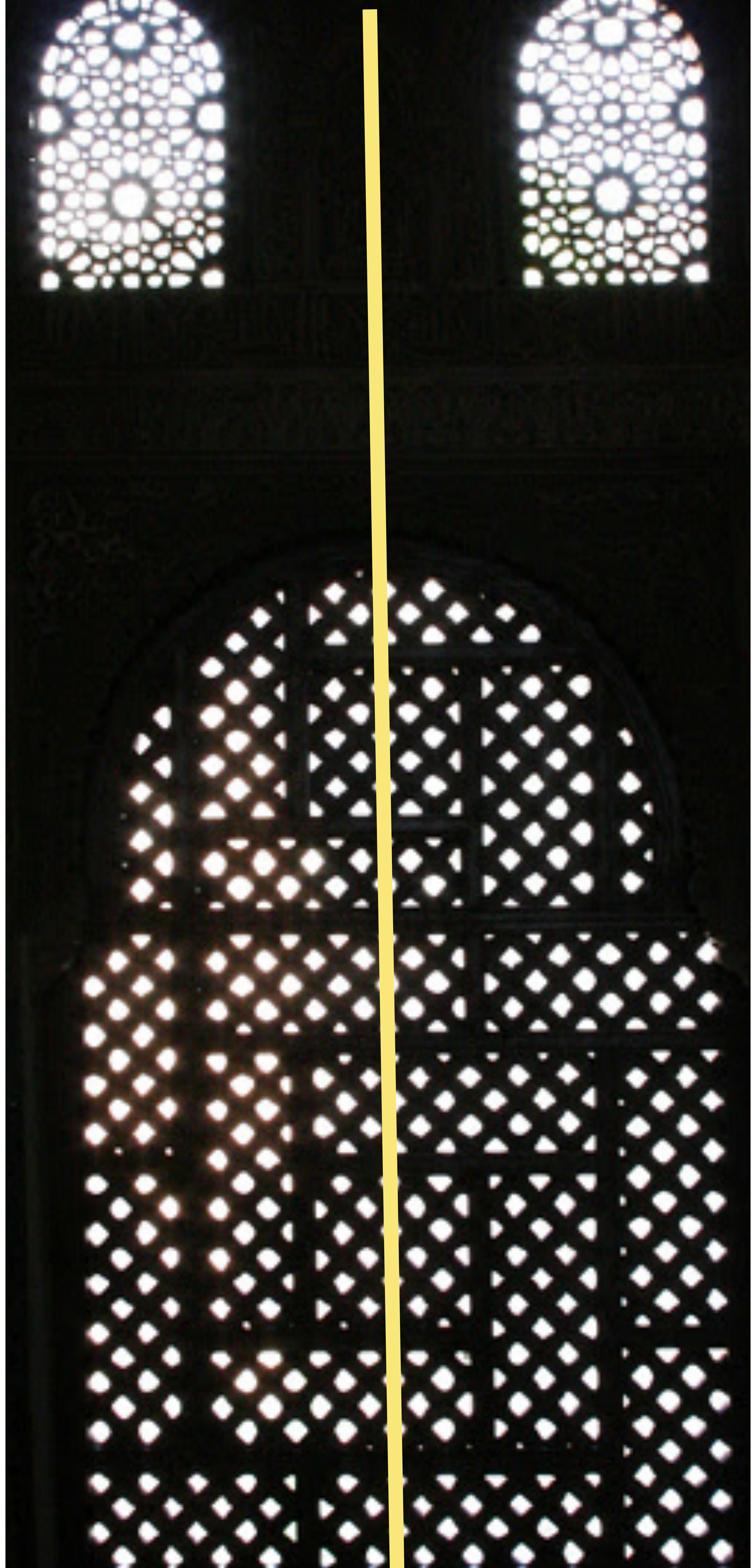


Symmetry is beautiful: a framework, beginning with Gross’ grand design.

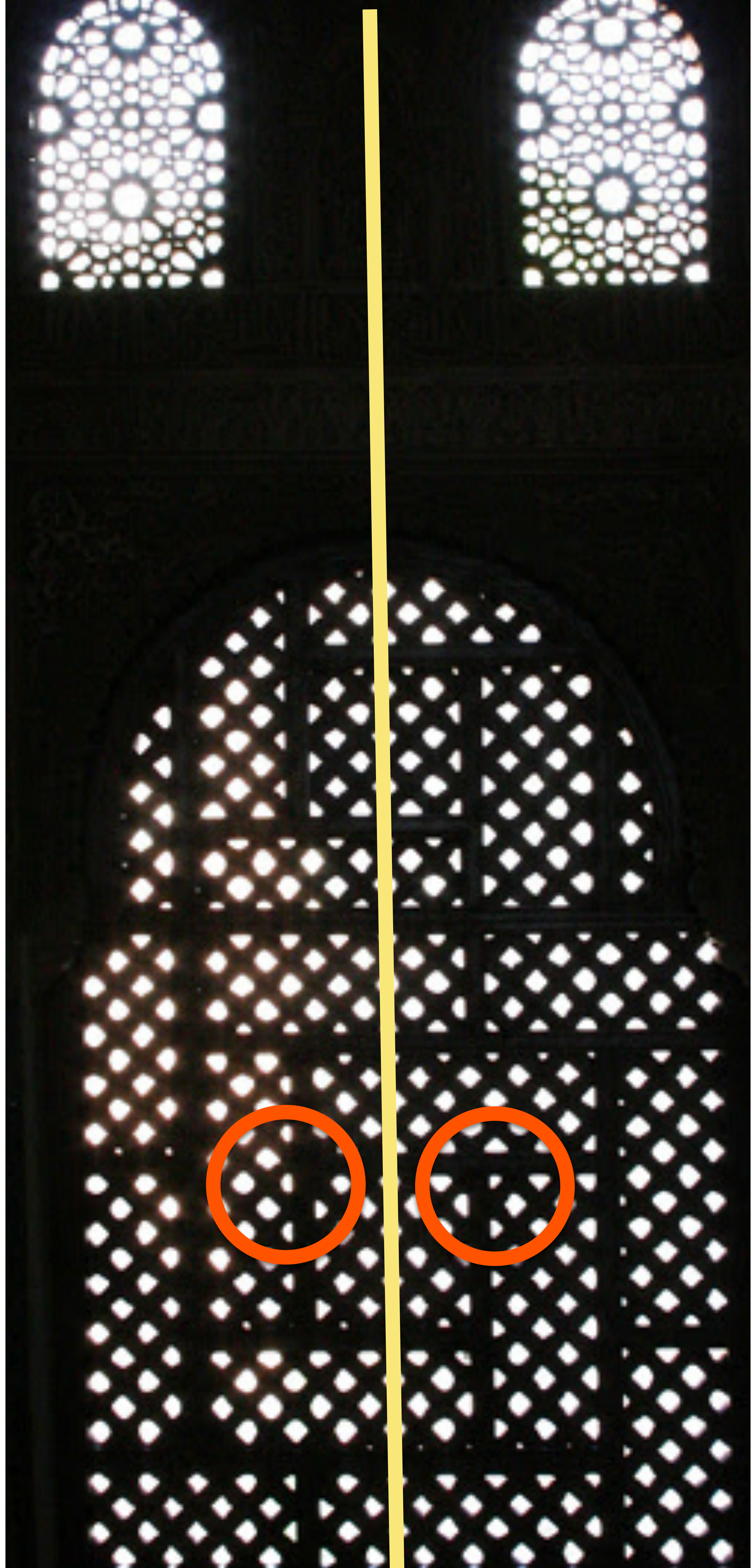
Parity:

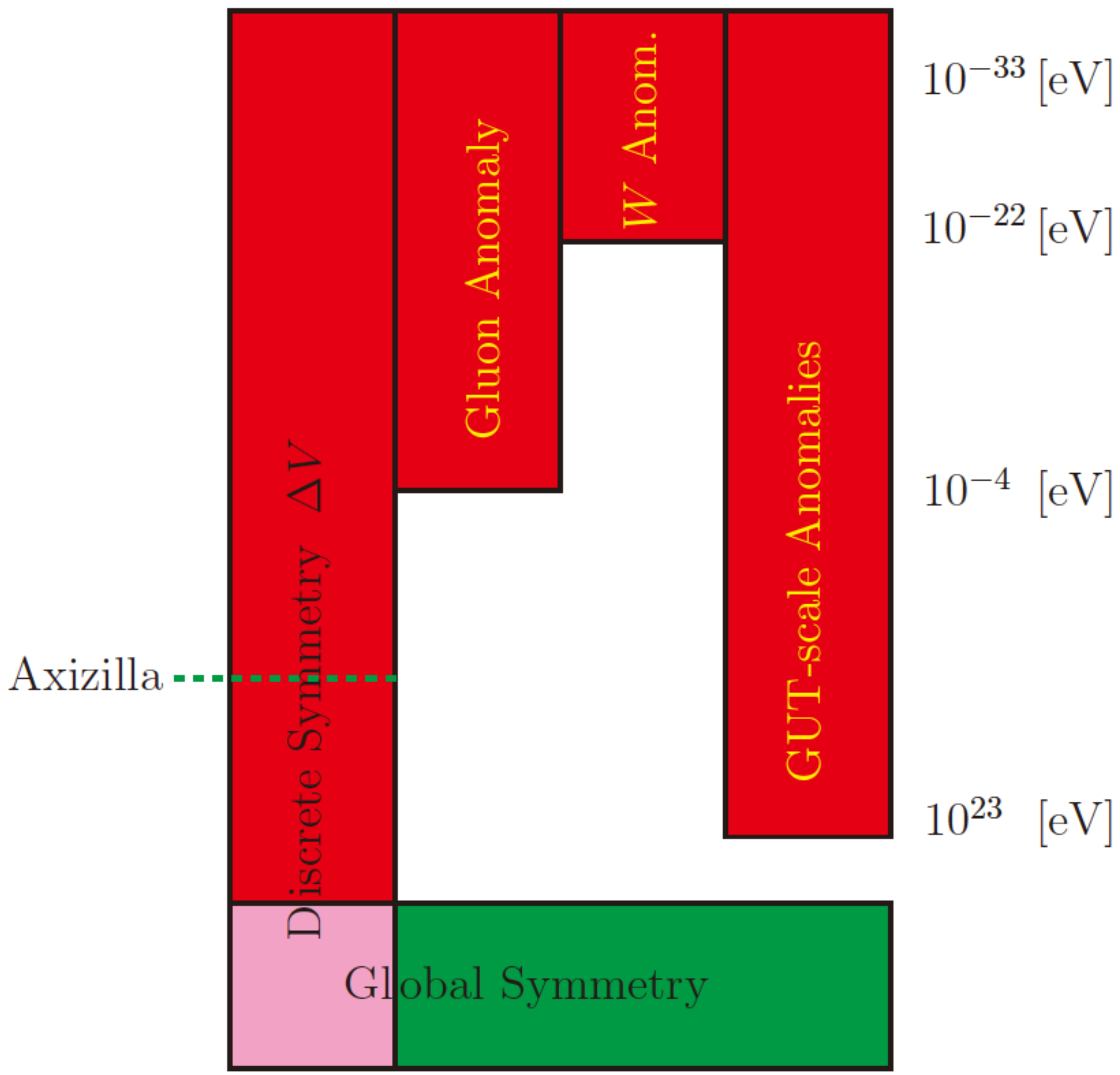


Symmetry is beautiful: a framework, beginning with Gross' grand design.

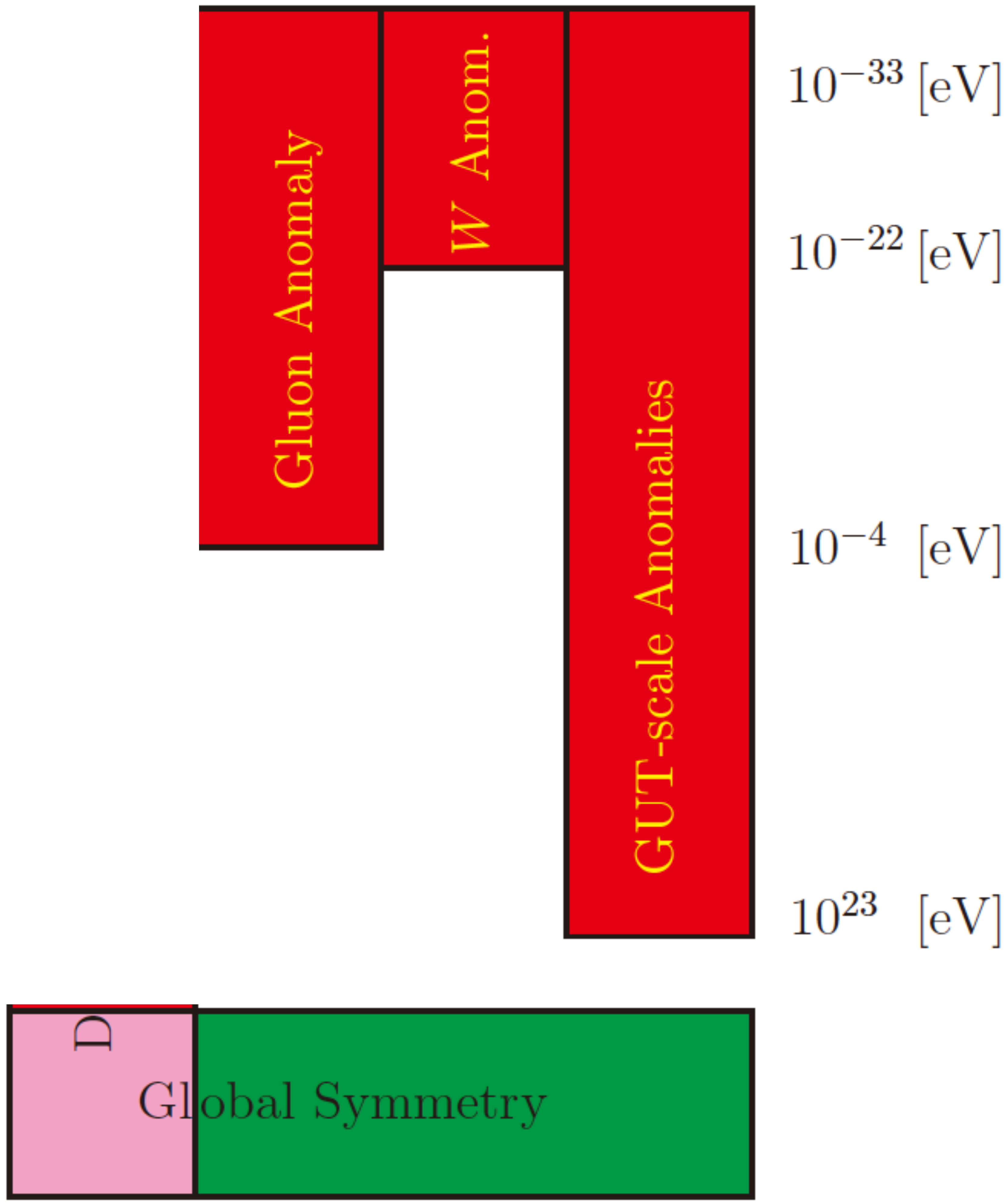
Parity:

Slightly broken!





W Anom.
Gluon Anomaly
GUT-scale Anomalies
Discrete Symmetry ΔV
Axizilla
Global Symmetry
10^{-33} [eV]
10^{-22} [eV]
10^{-4} [eV]
10^{23} [eV]



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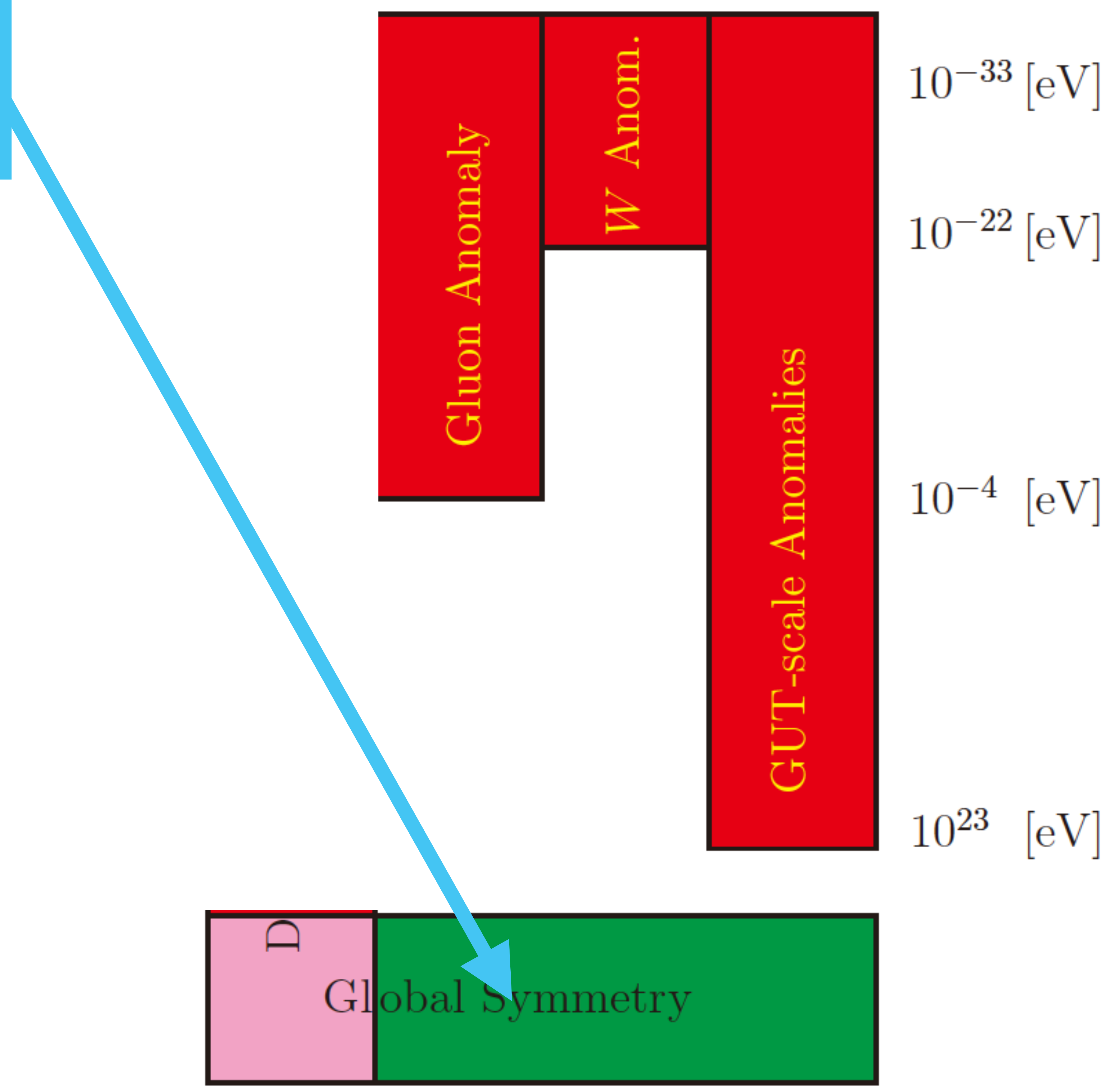
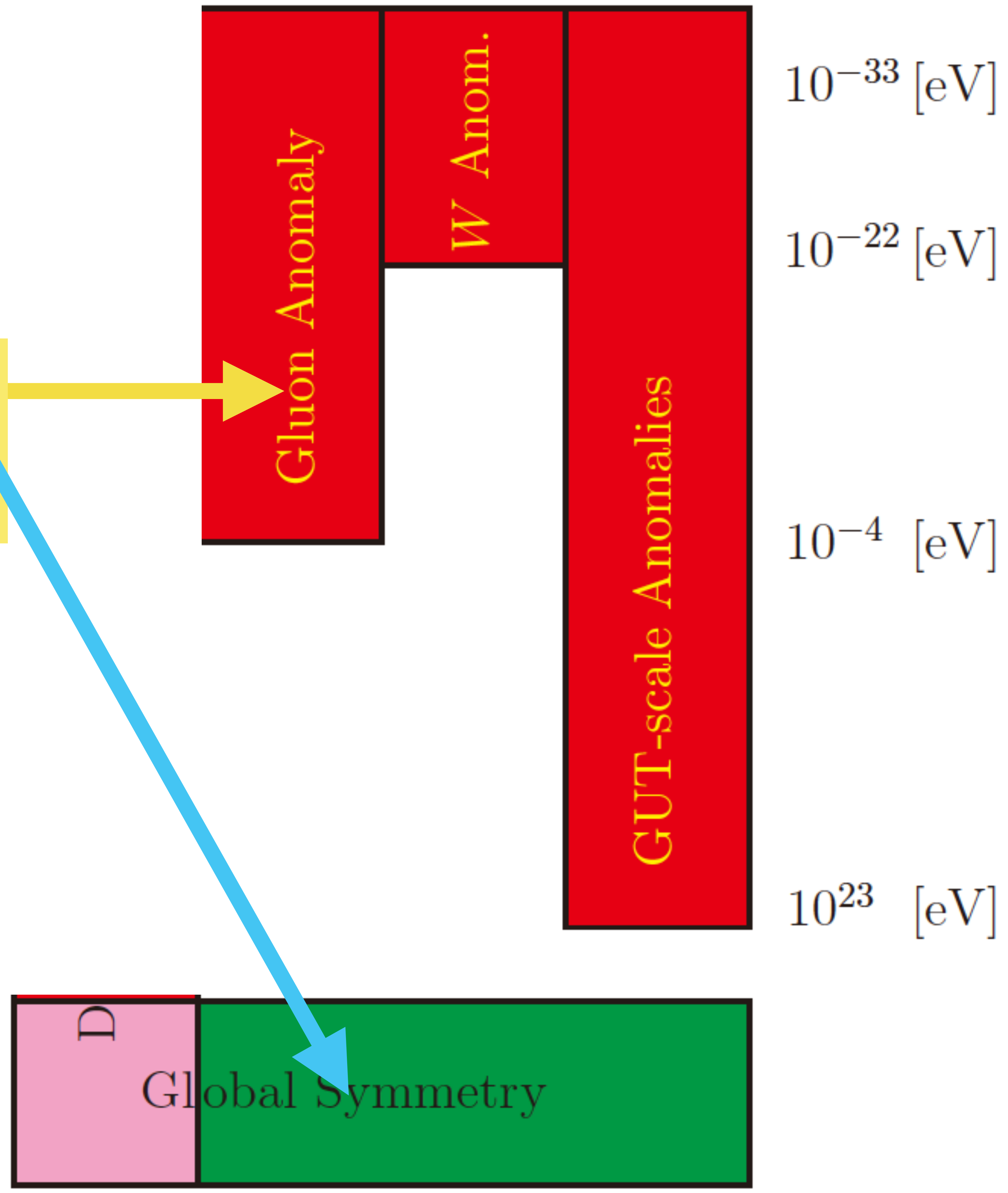
D
Global Symmetry

From the exact global symmetry.



From the exact global symmetry.

This anomaly breaks the PQ symmetry.



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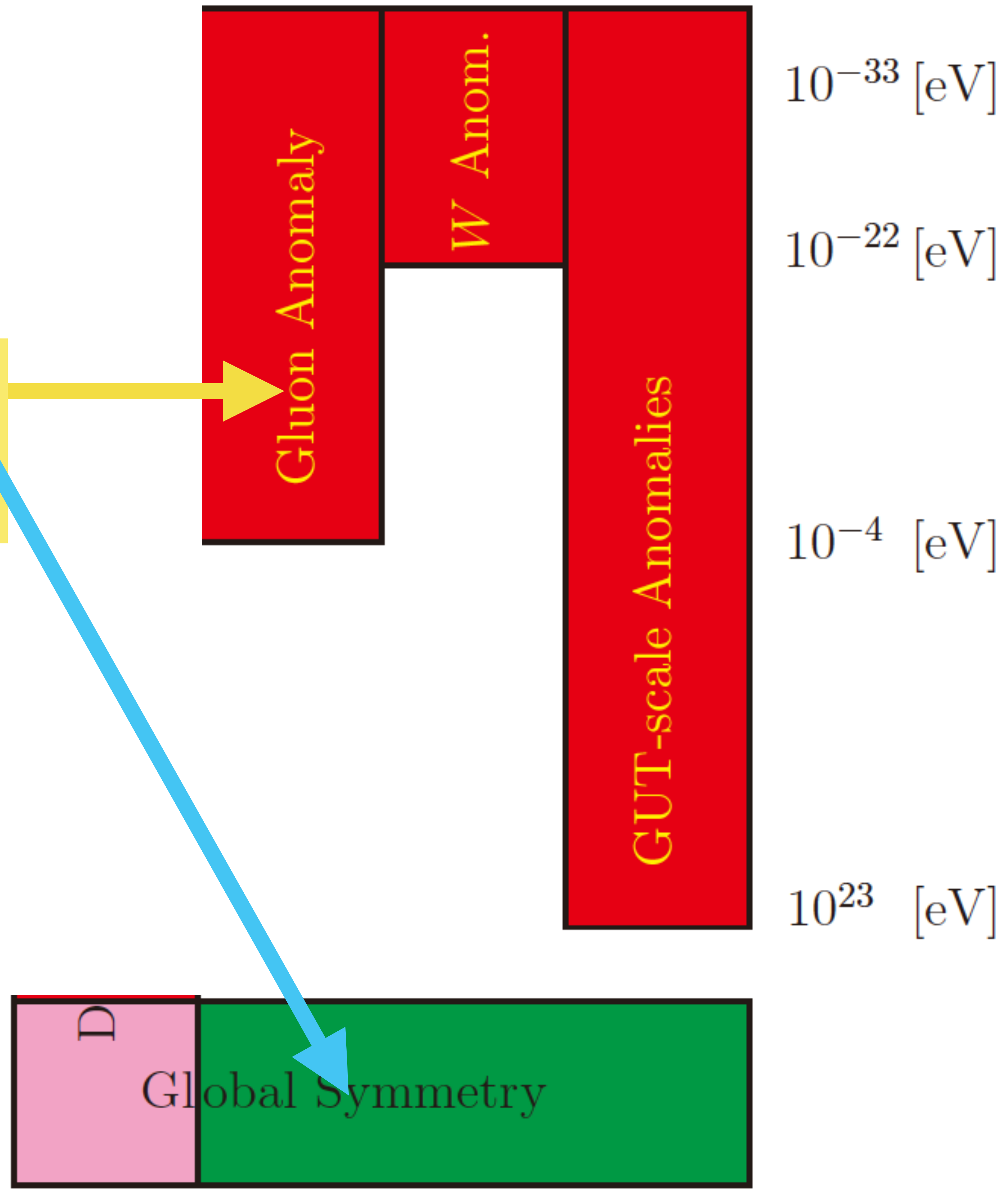
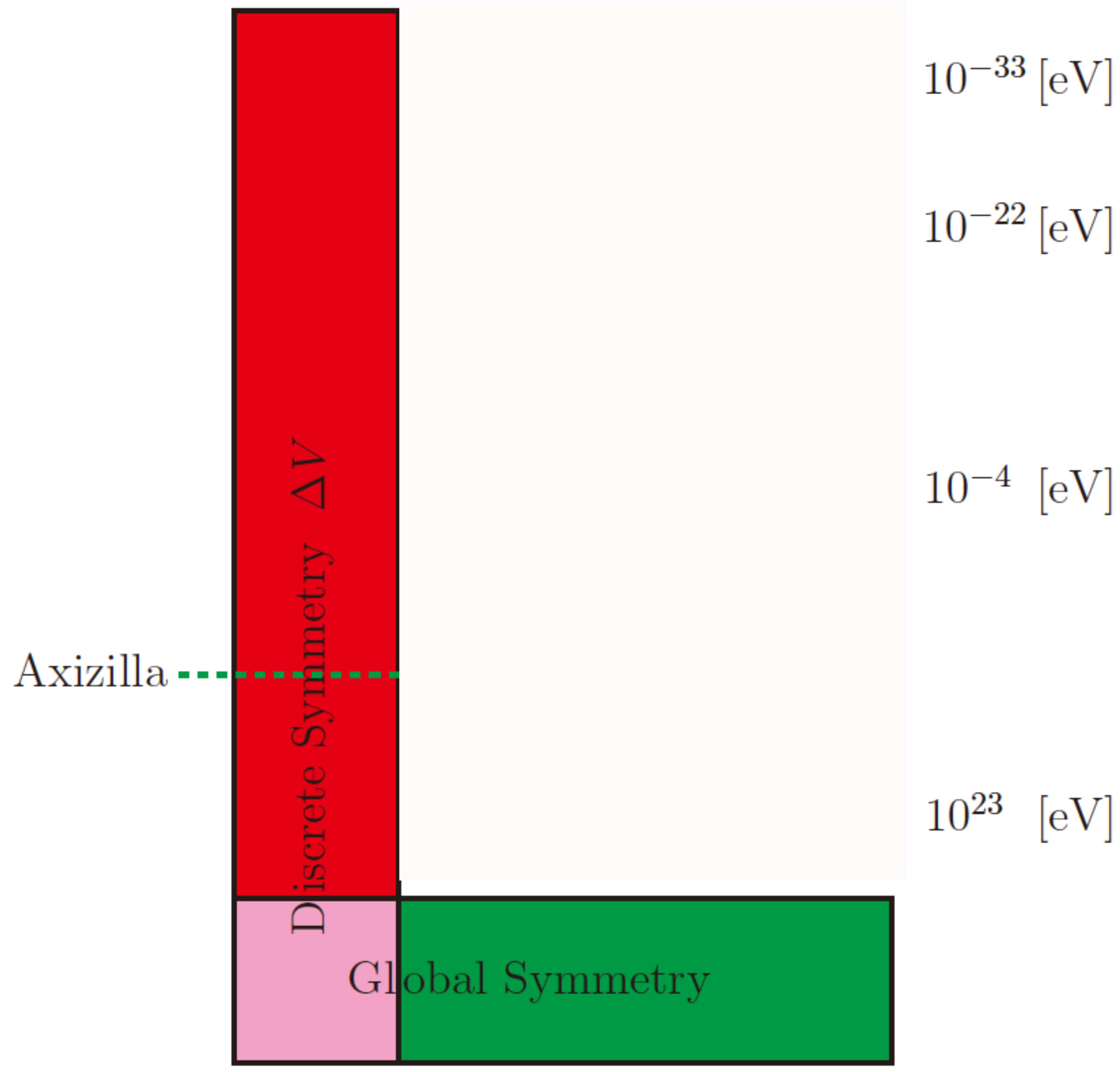


VEV of scalar phi gives the f_a scale.



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Axizilla
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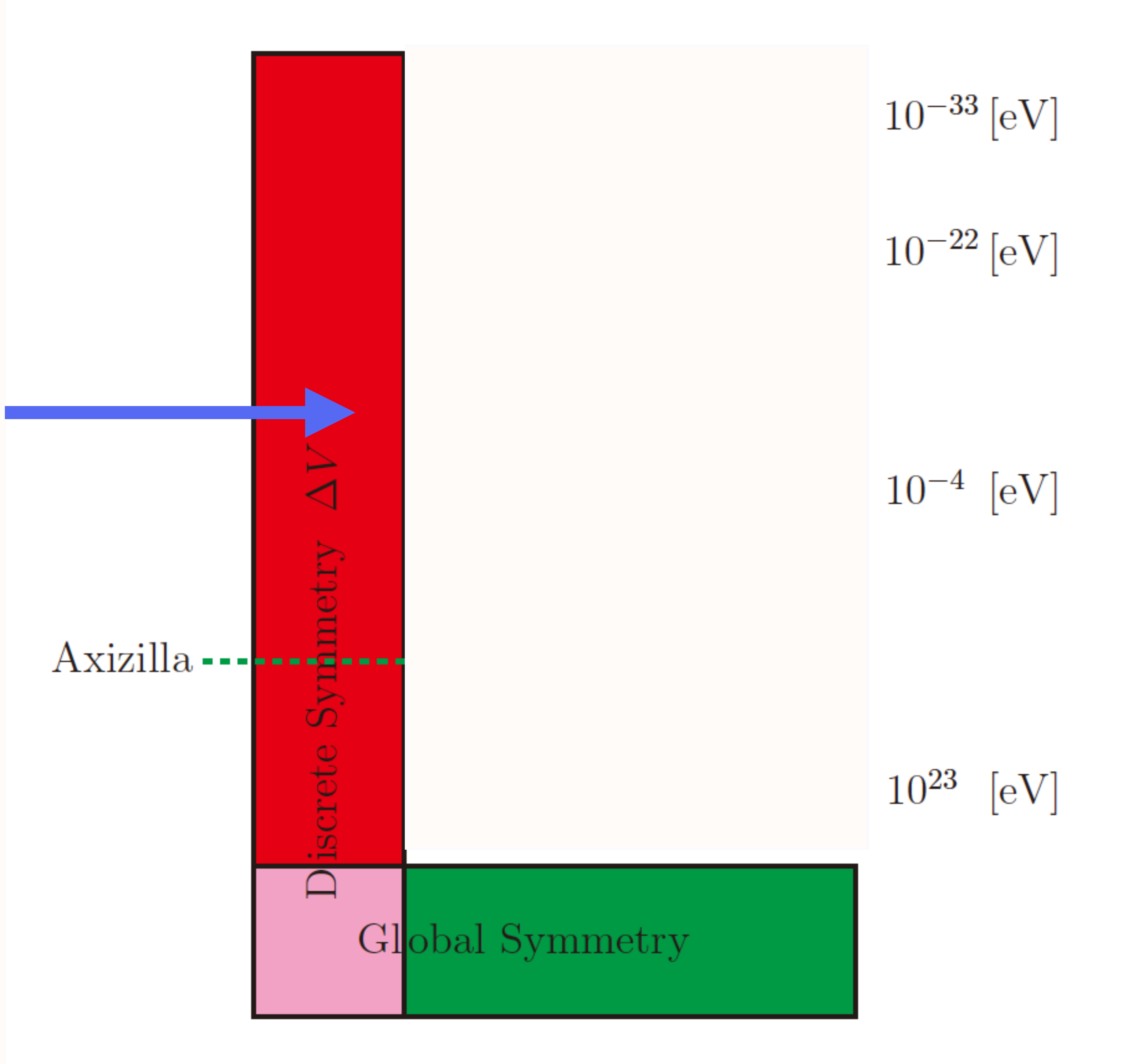

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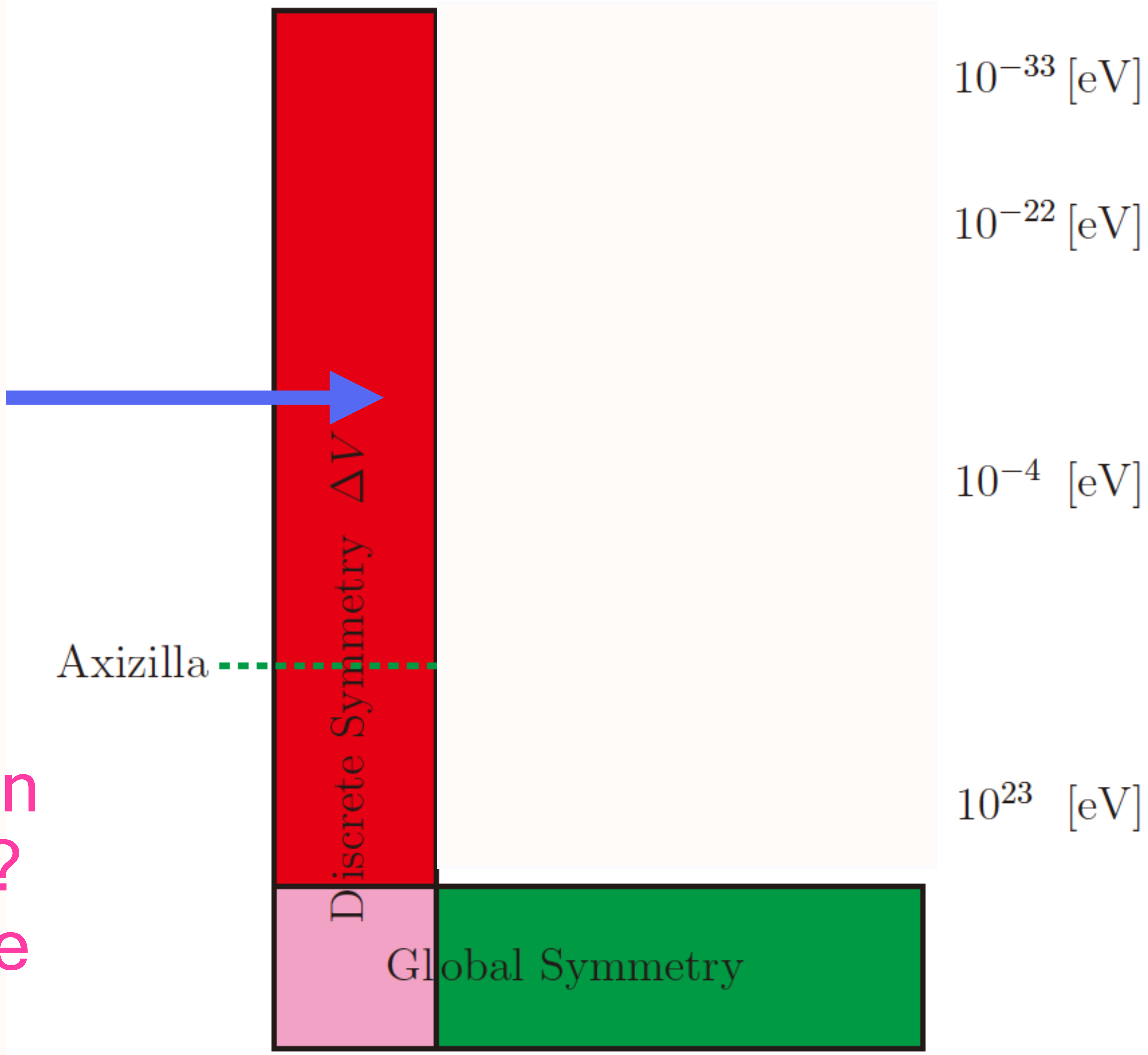

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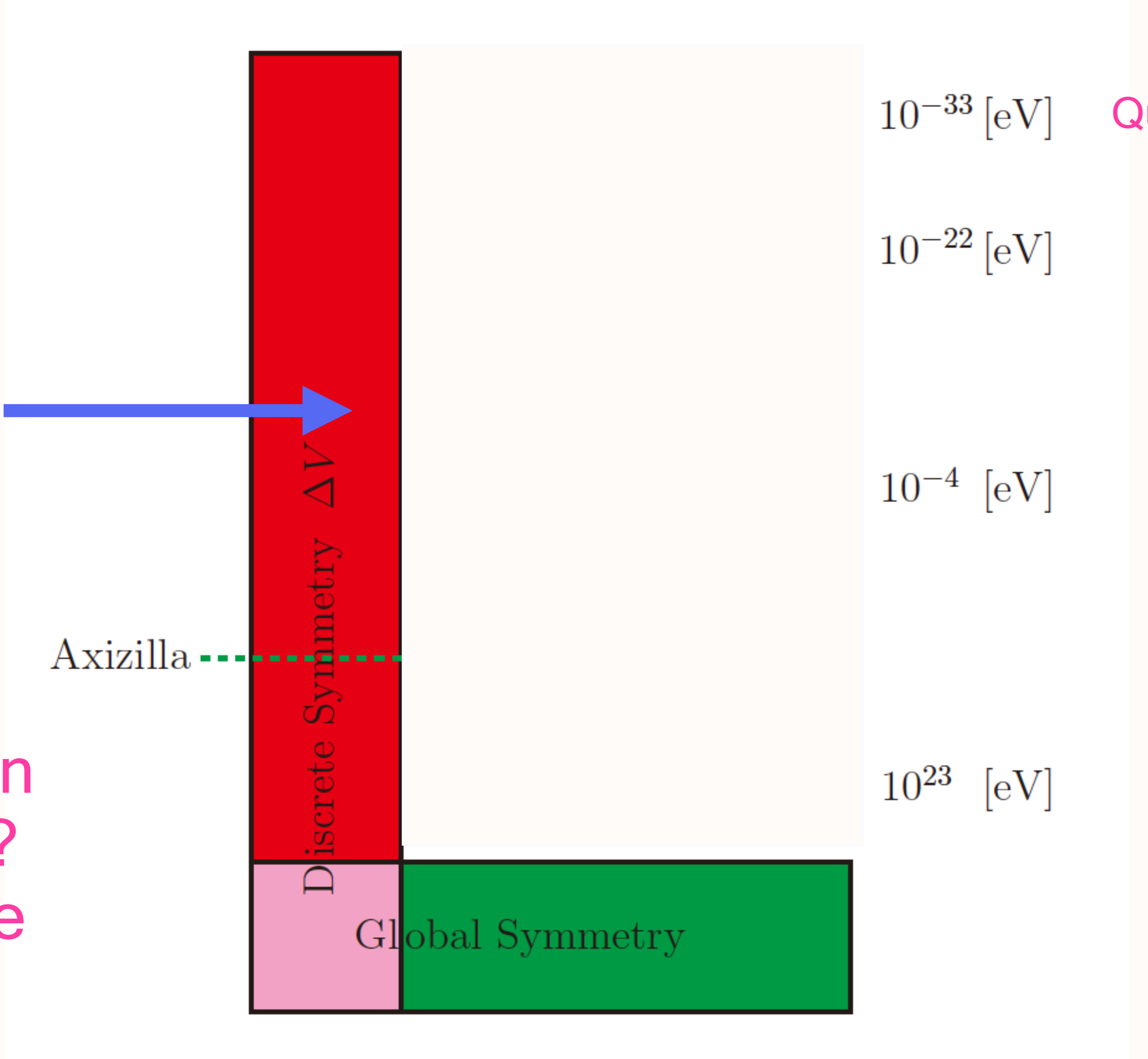

Quintessential axion

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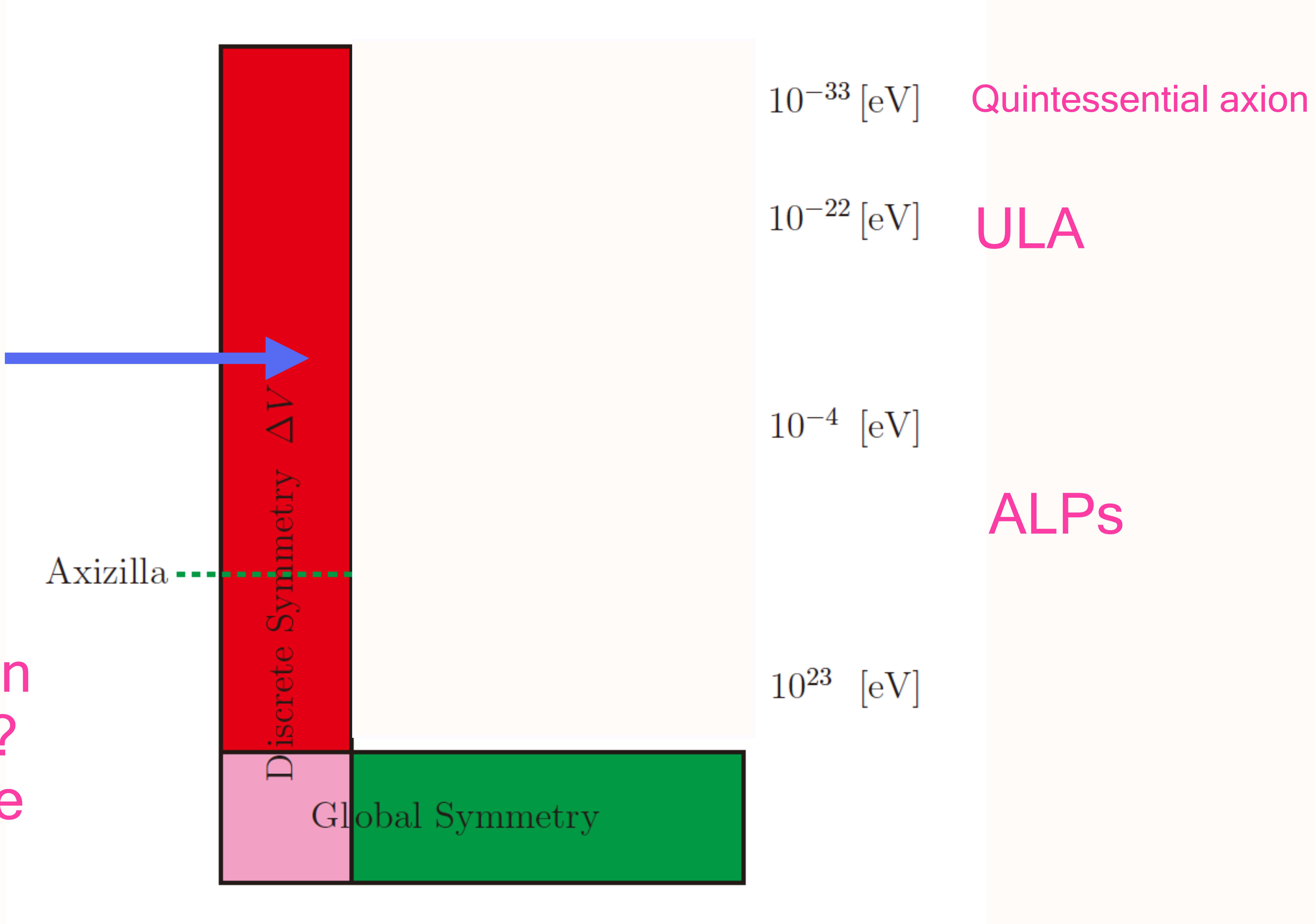

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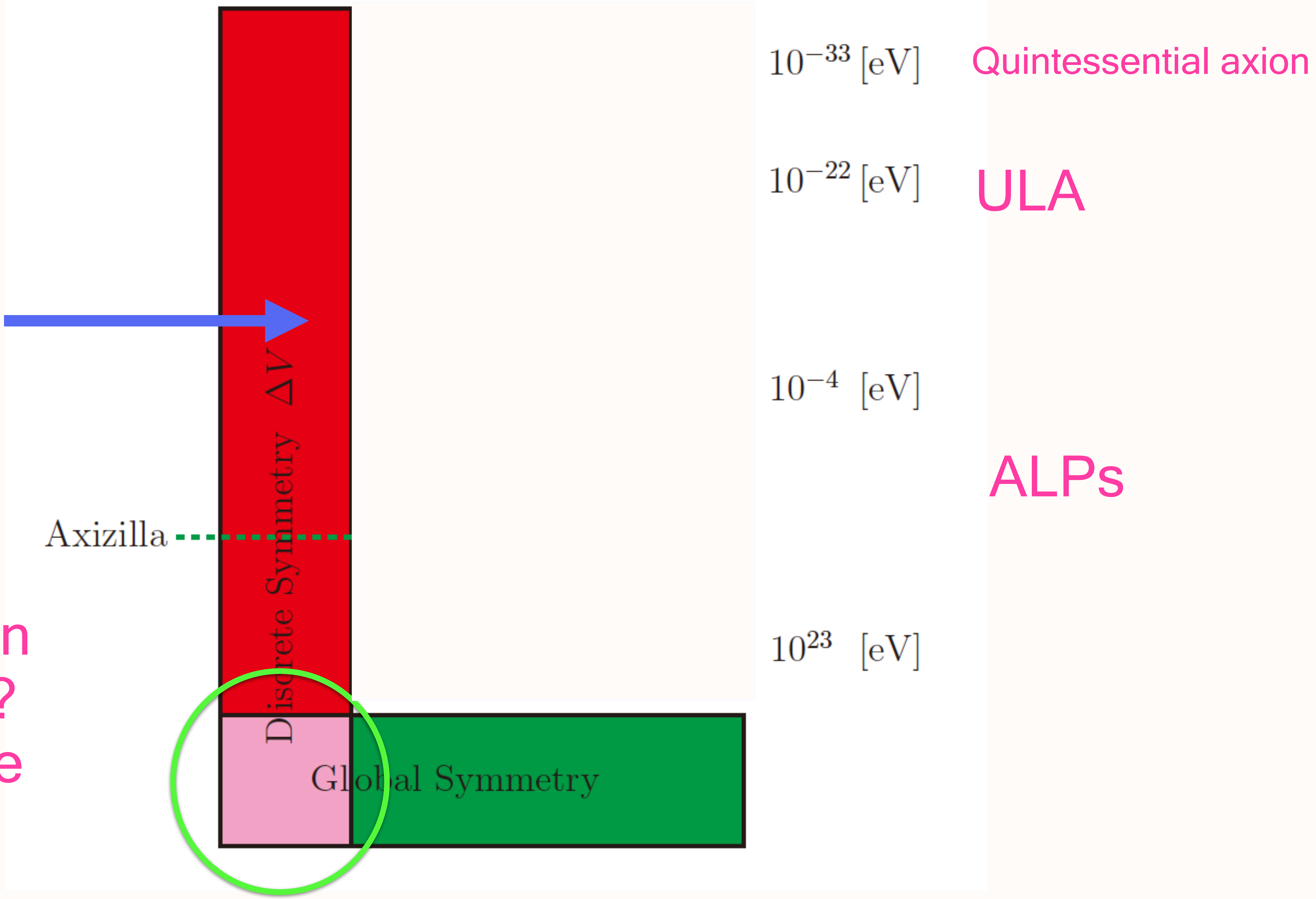

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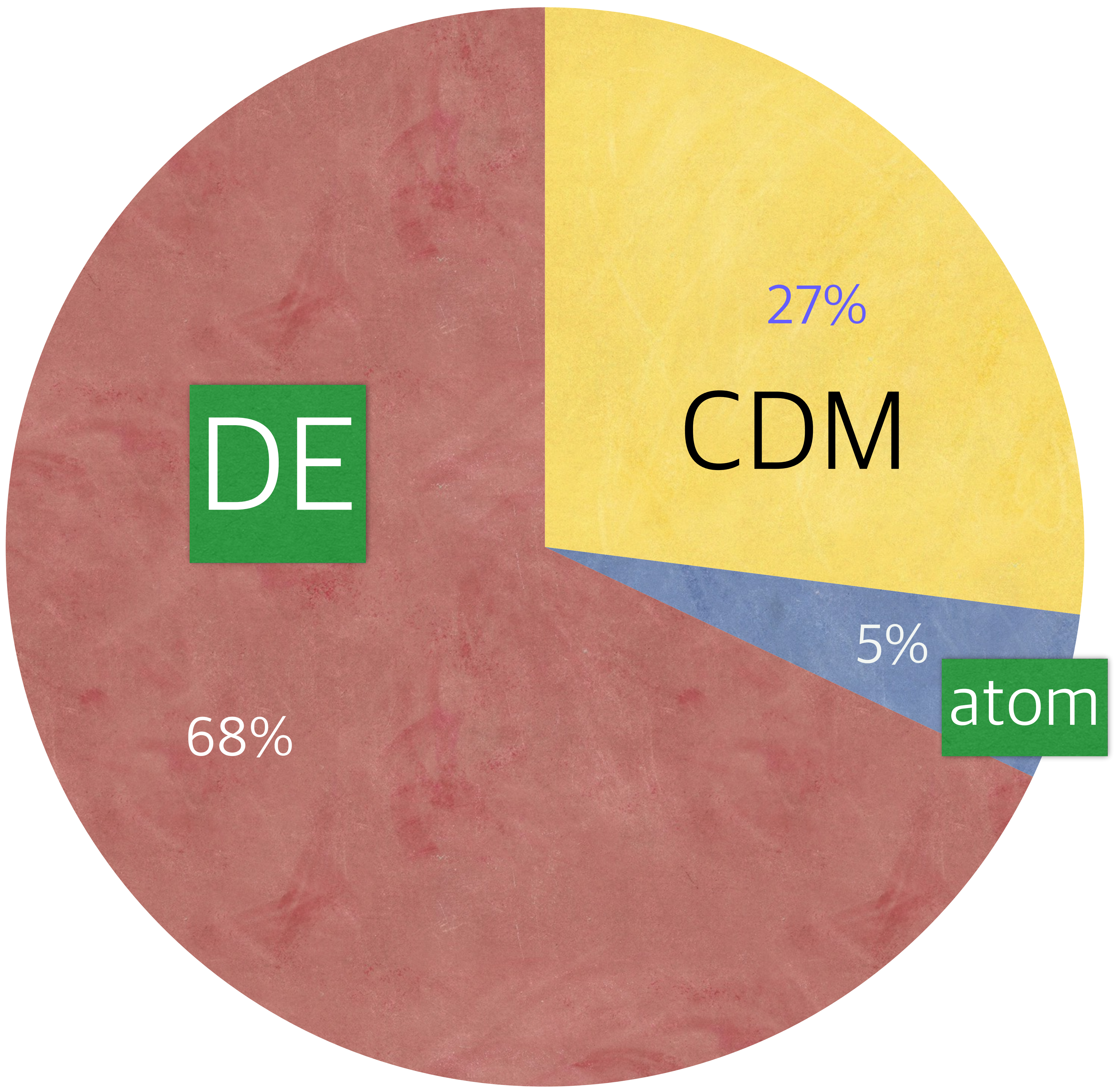
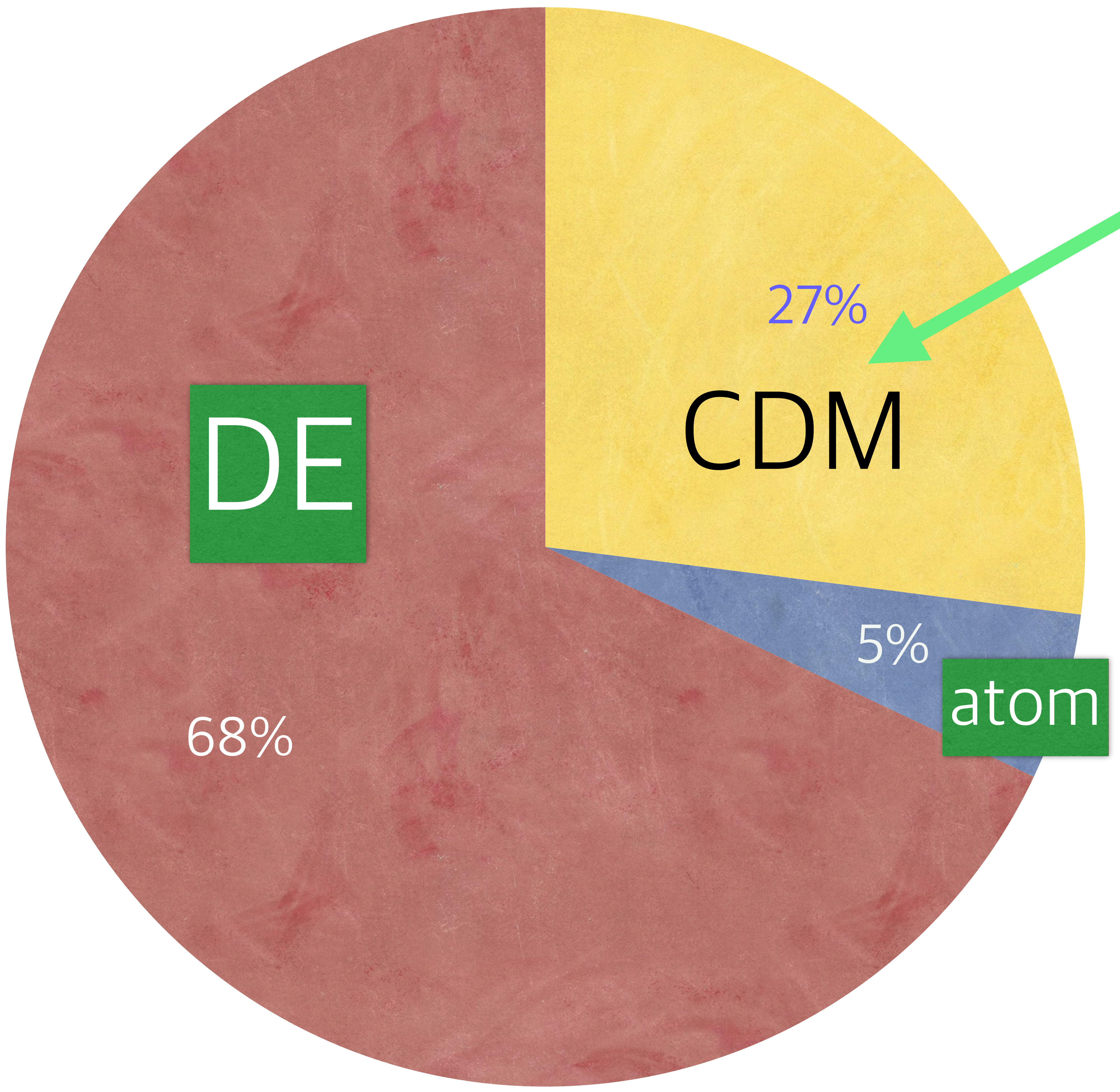

27%
CDM
DE
5%
atom
68%



Detection of “invisible” axion CDM by cavity detectors: CAPP, Yale, ADMX, etc.

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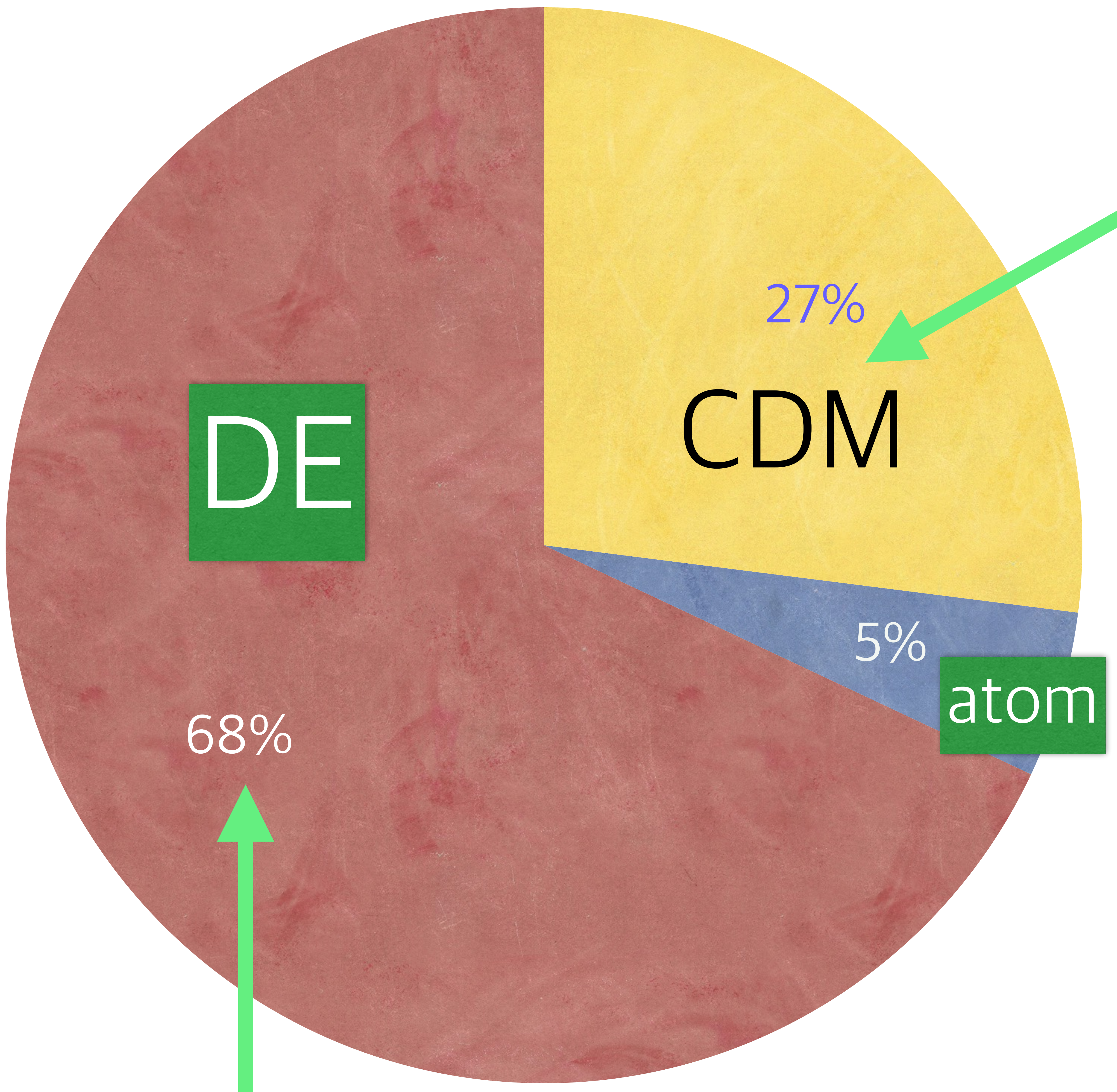
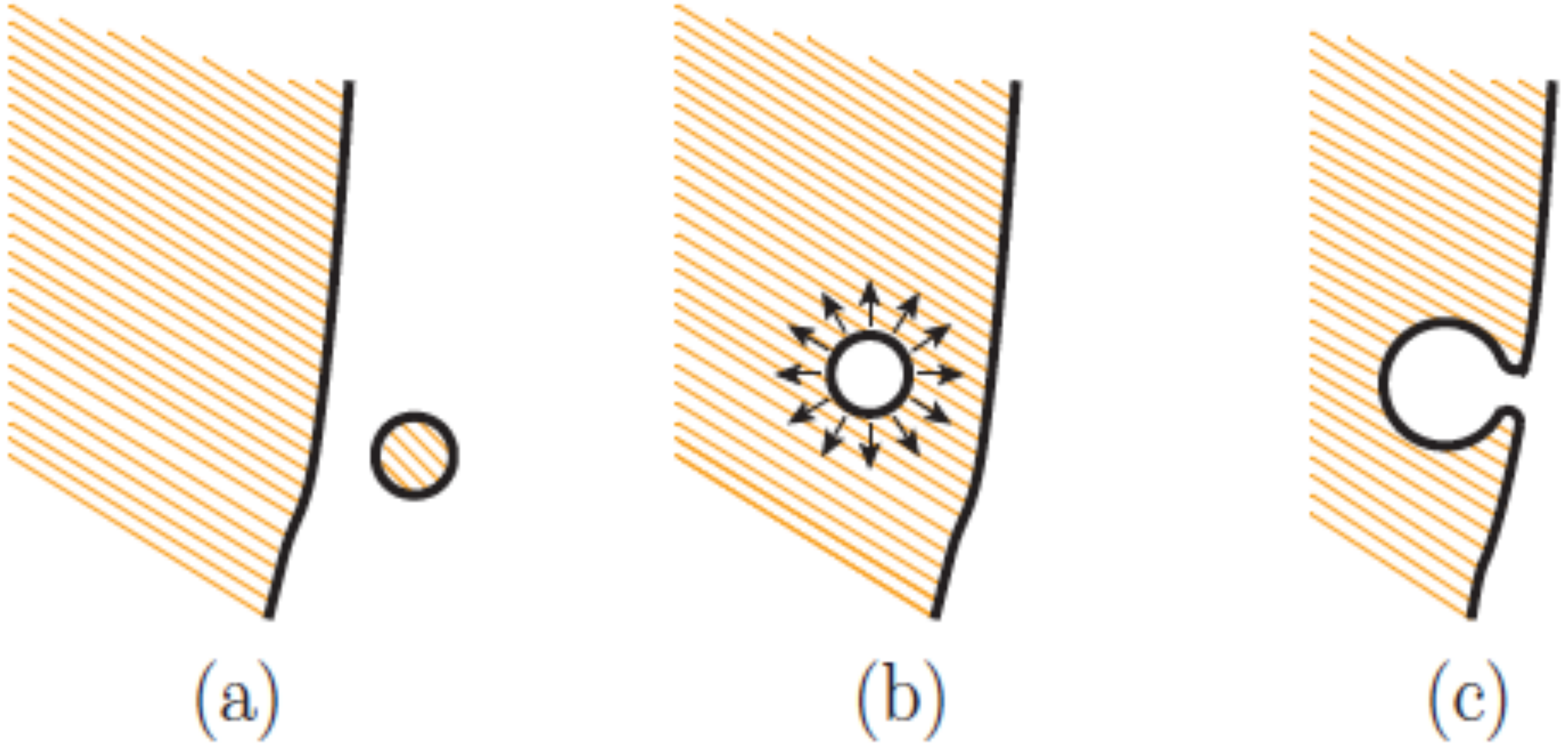
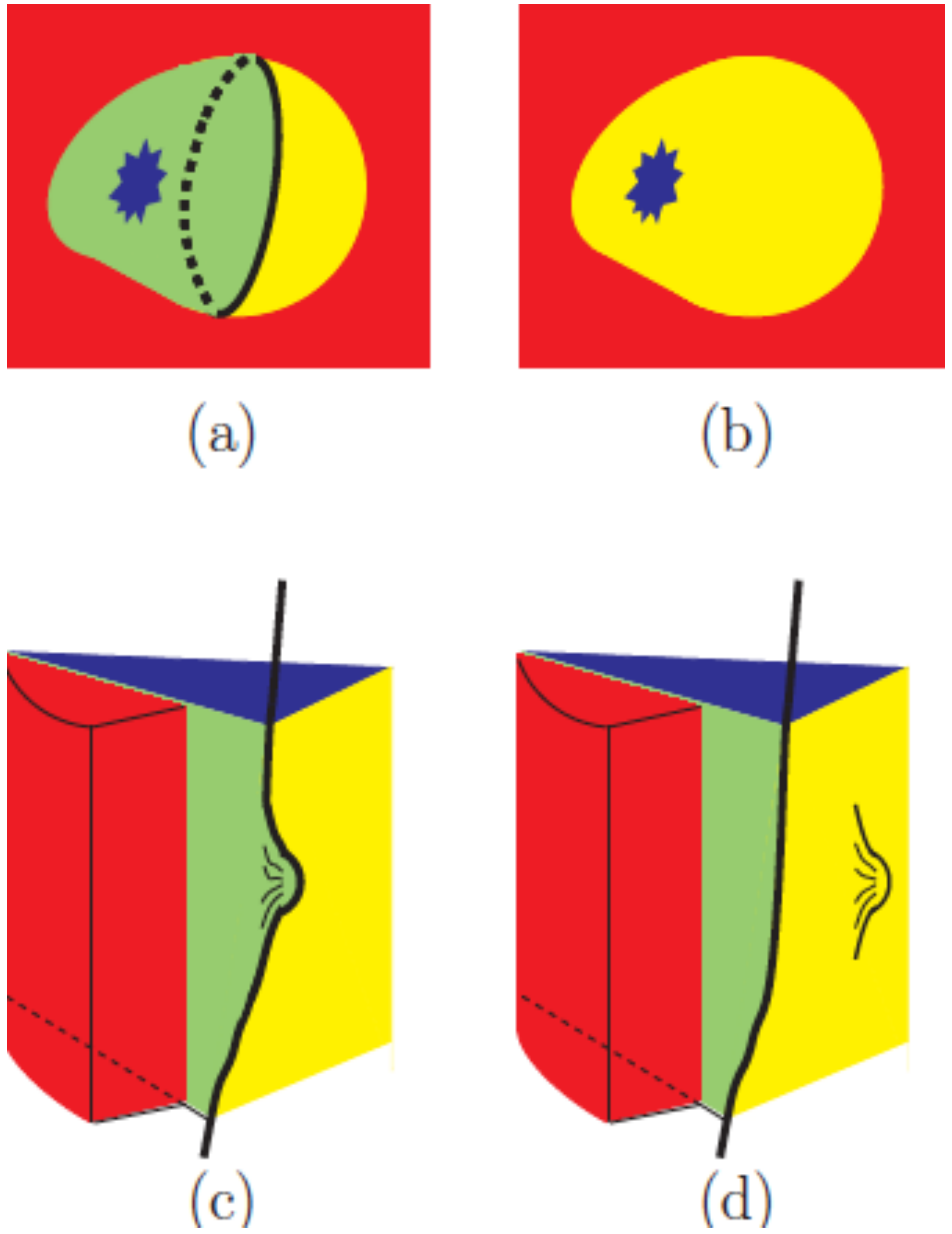


Quintessential axion

4. N_{DW}=1 needed



Vilenkin-Everett (1982);
Barr-Choi-Kim (1987)



Sikivie (1982)

Top-down approach, using string compactification

1. The global U(1) is broken at the axion window.
2. DW number given here.
3. By giving a VEV to Q_{PQ}=1 field, we obtain N_{DW}=1.
4. Example: 1 heavy quark model. But, effectively, all PQ charged quarks should add up their contributions to makeN_{DW}=1.
5. Anomalous U(1) gauge symmetry.
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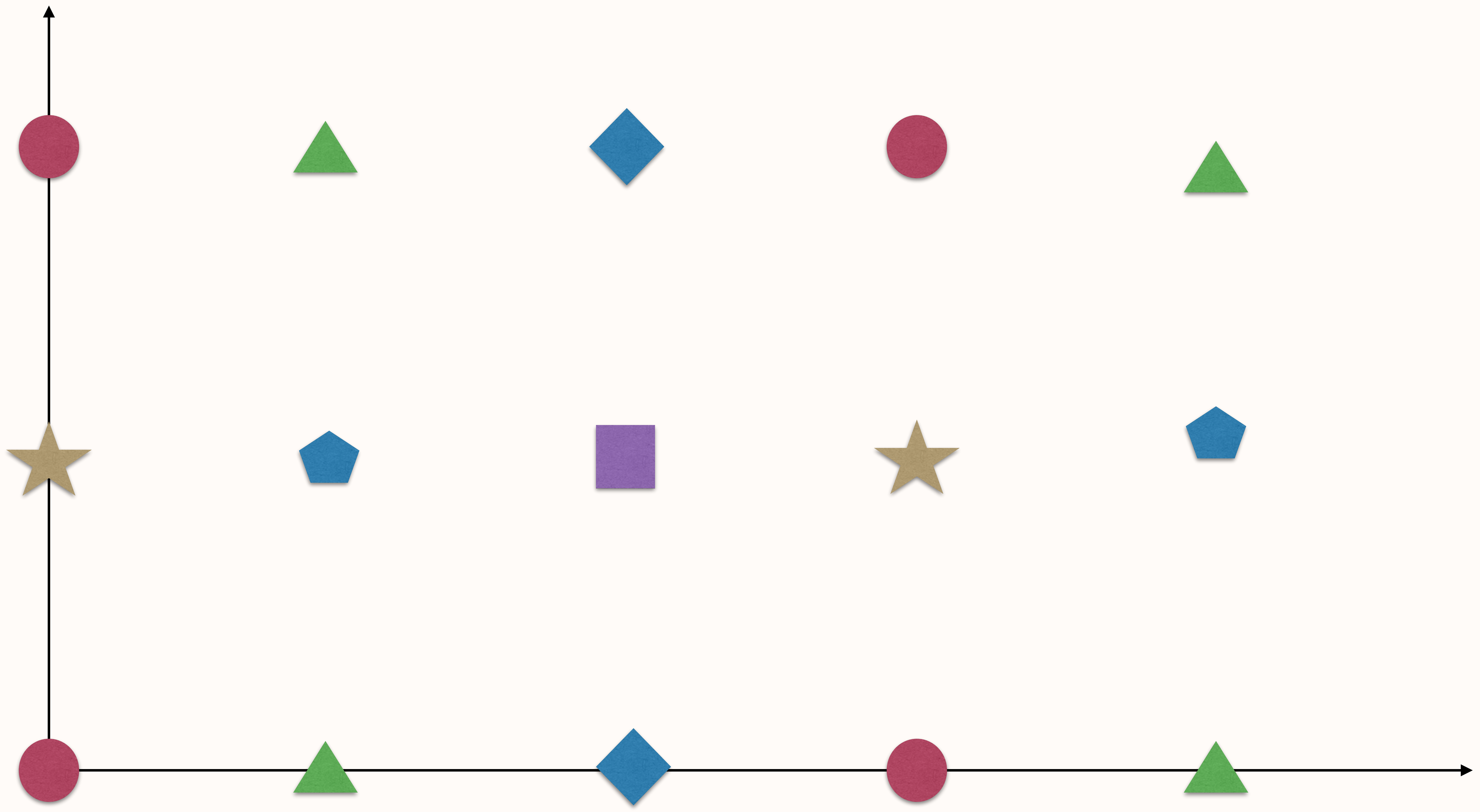
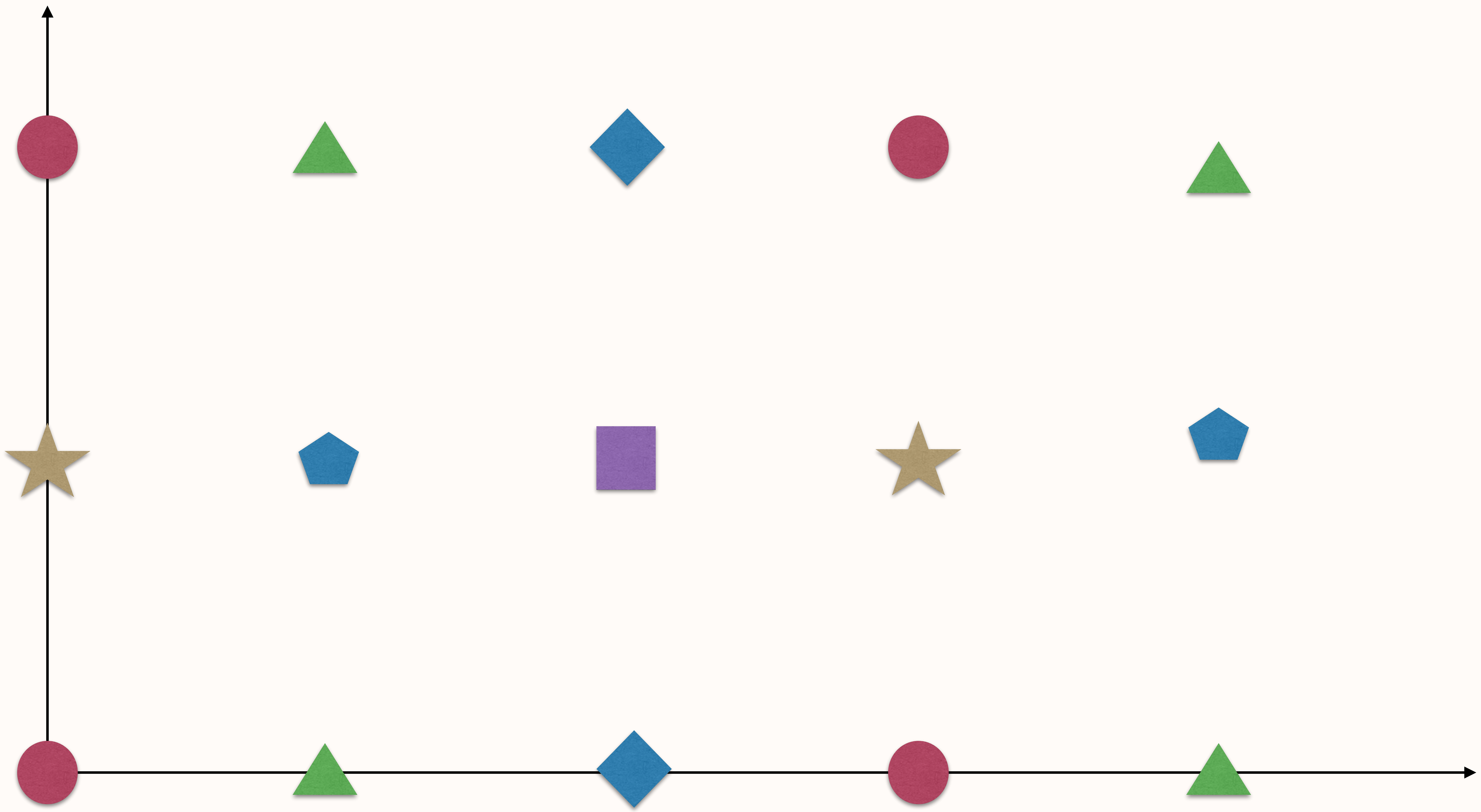
Better way than Lazarides-Shafi: we need a Goldstone boson direction

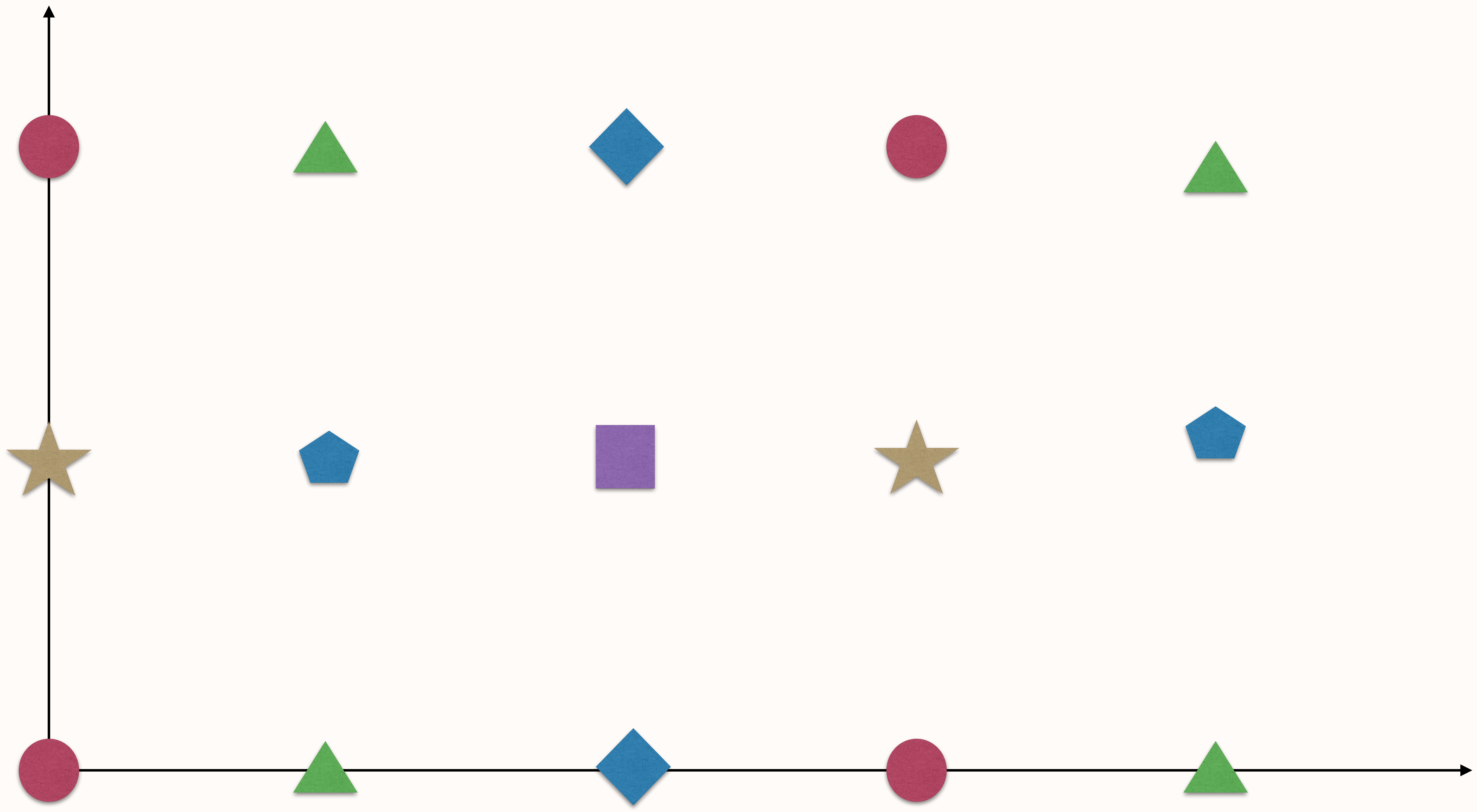


For the center of GUT group, Lazarides-Shafi (1982).
But, the following ideas are more widely applicable.



Choi-Kim, PRL55 (1985) 2637

with two confining forces



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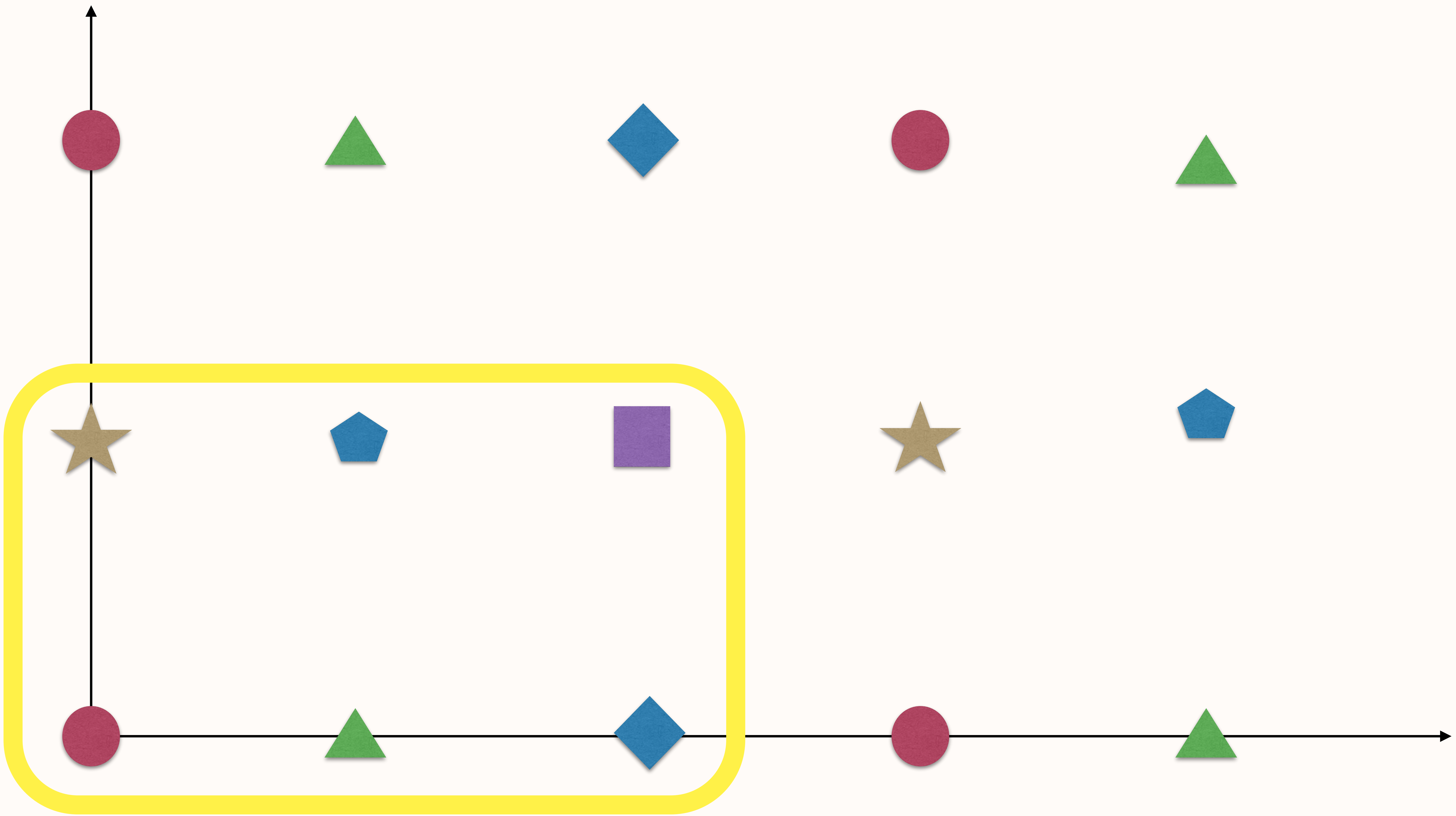

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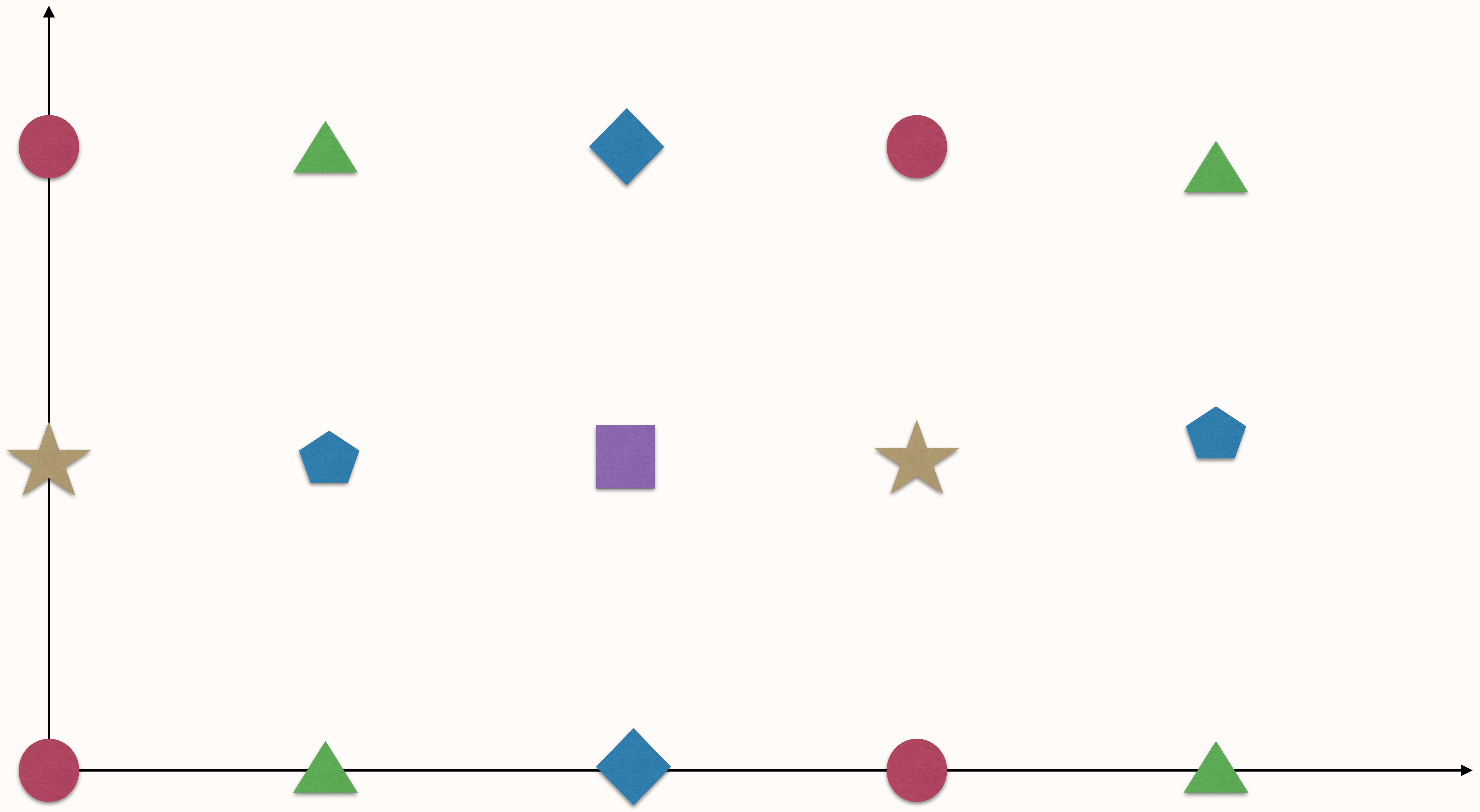

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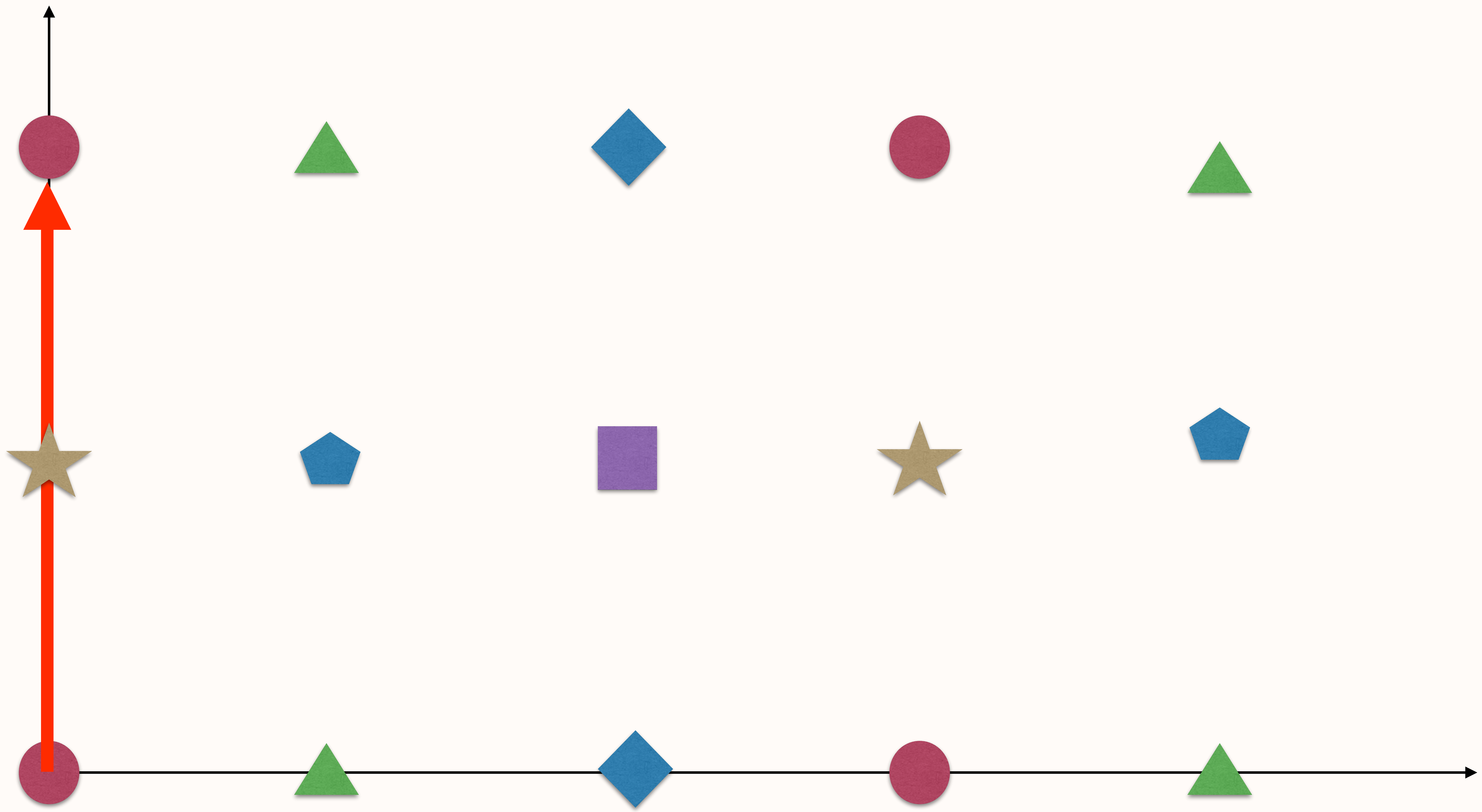

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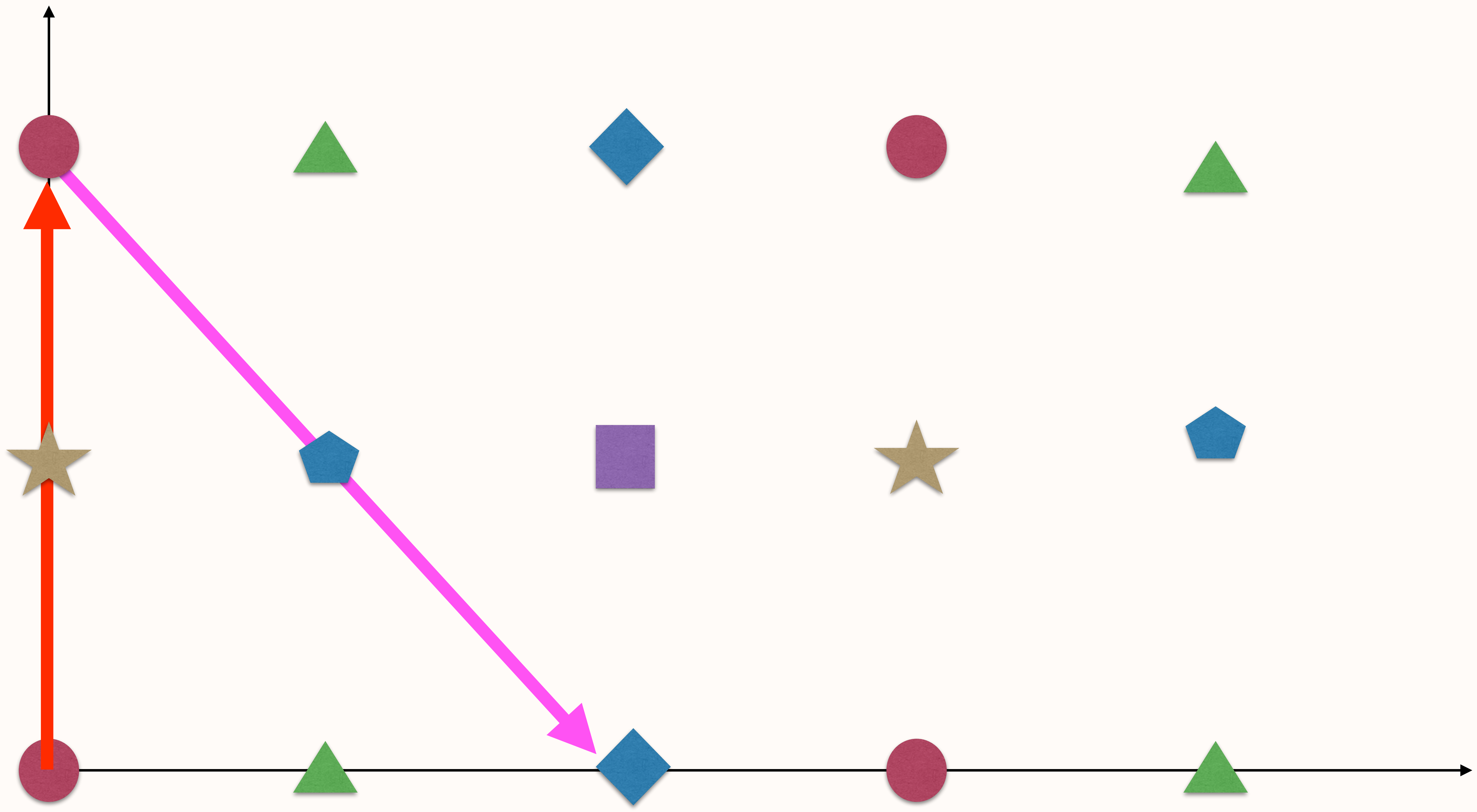

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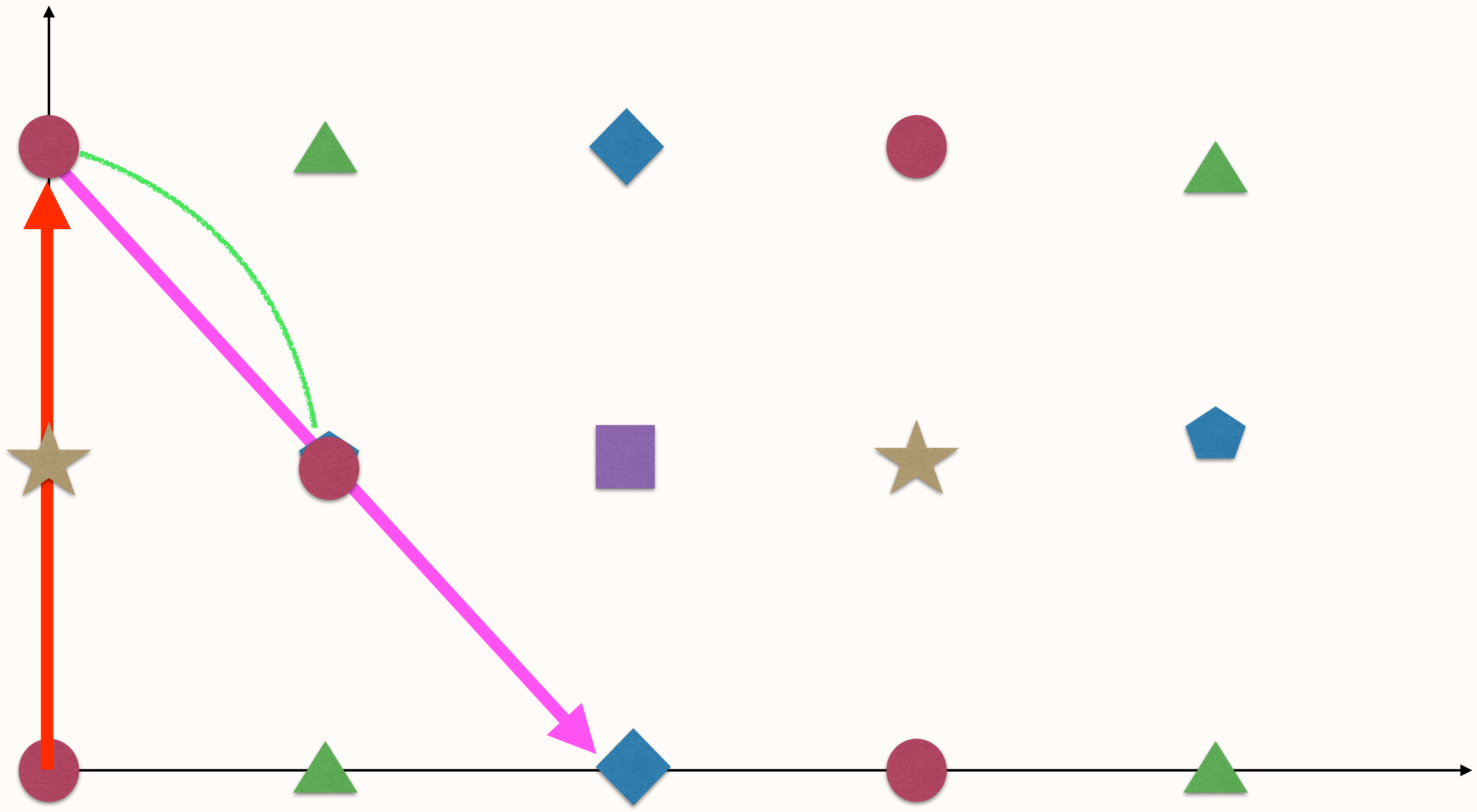

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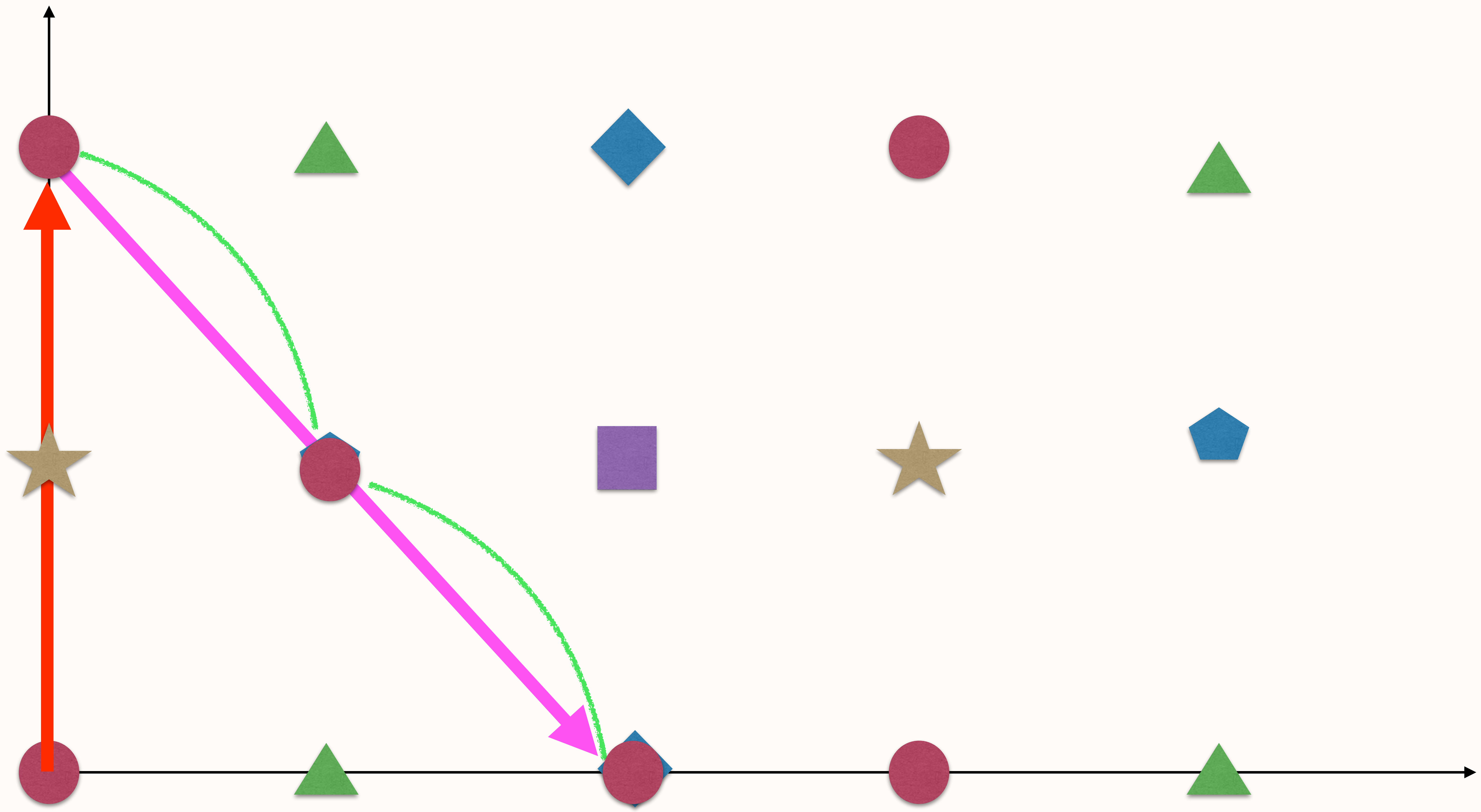

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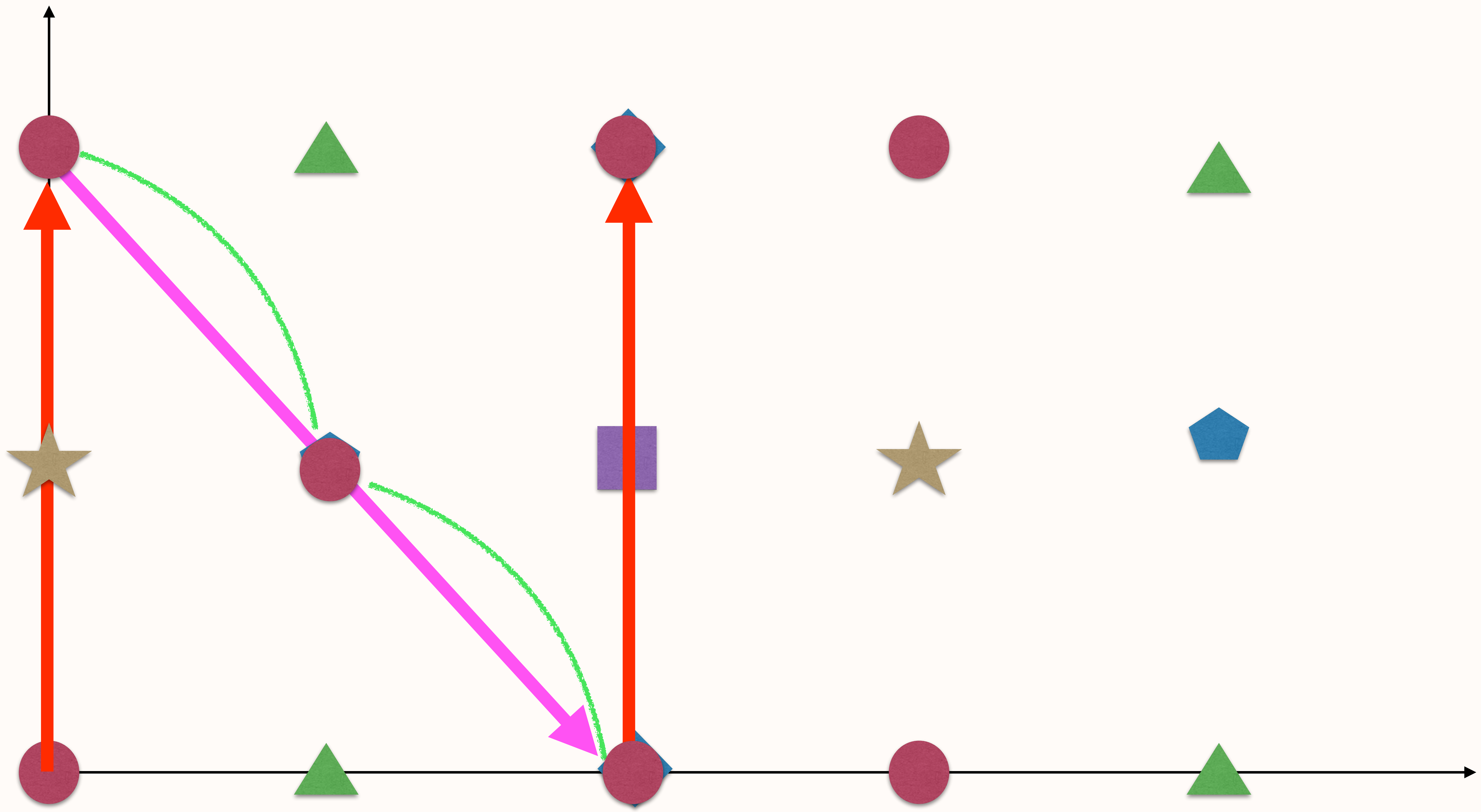

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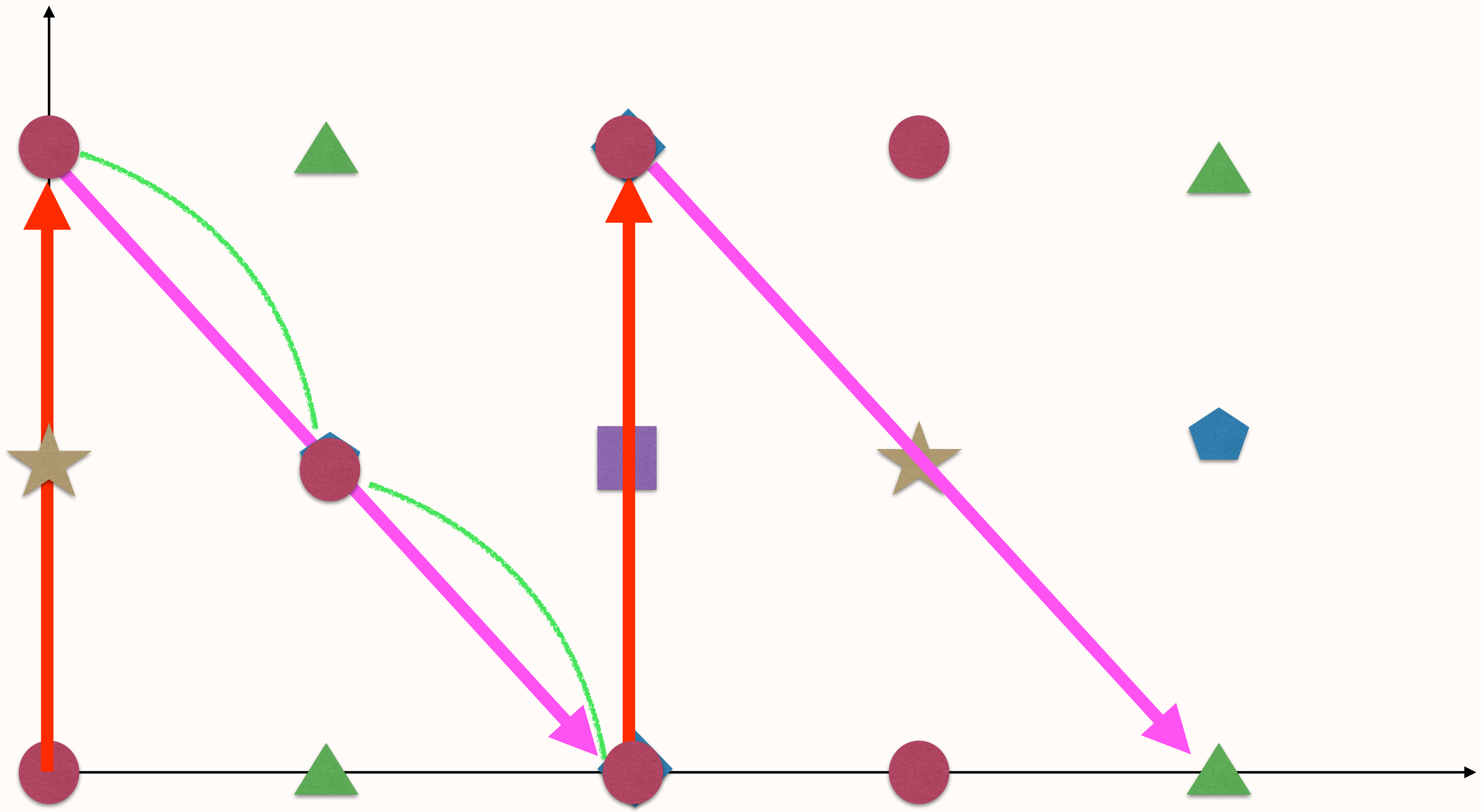

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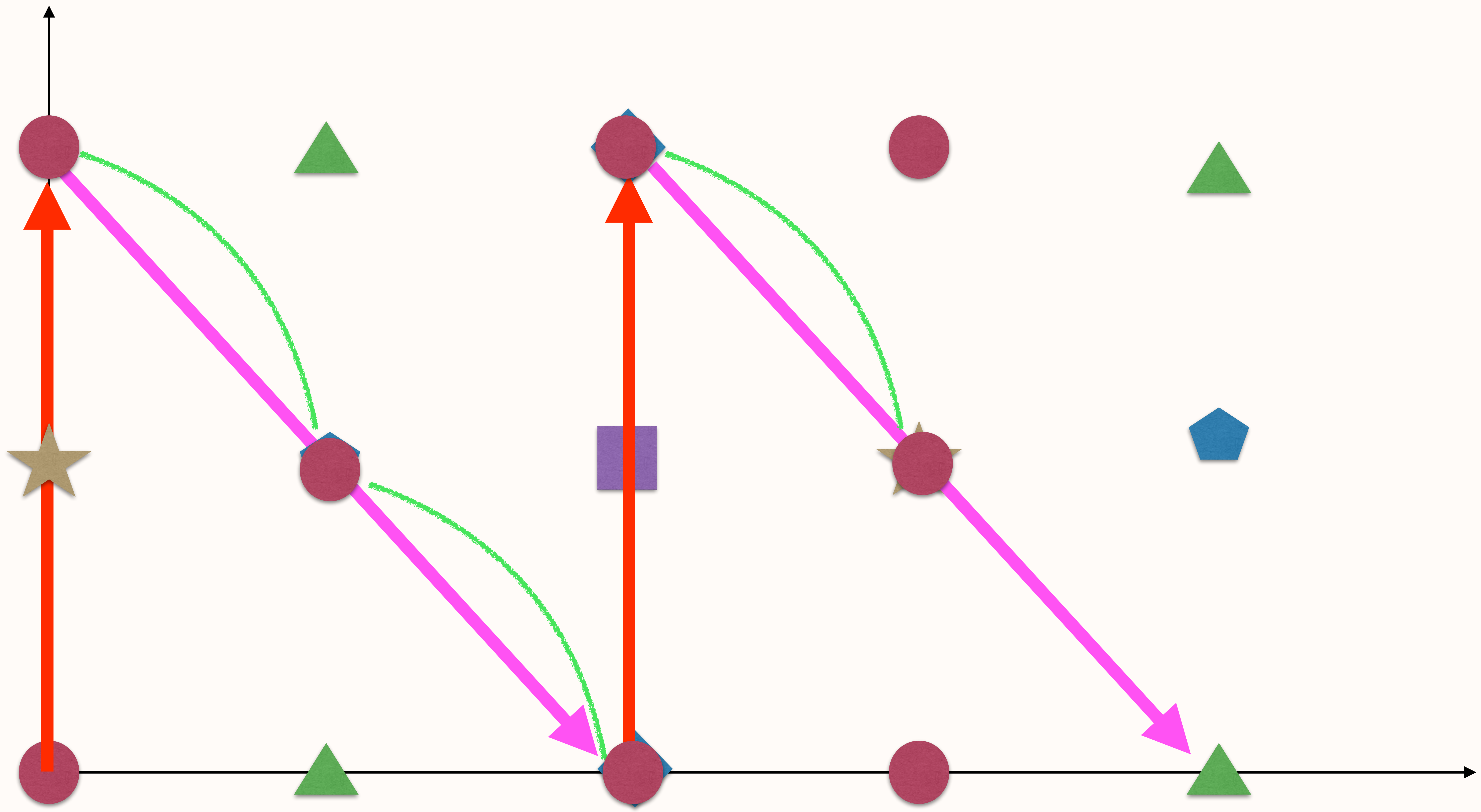

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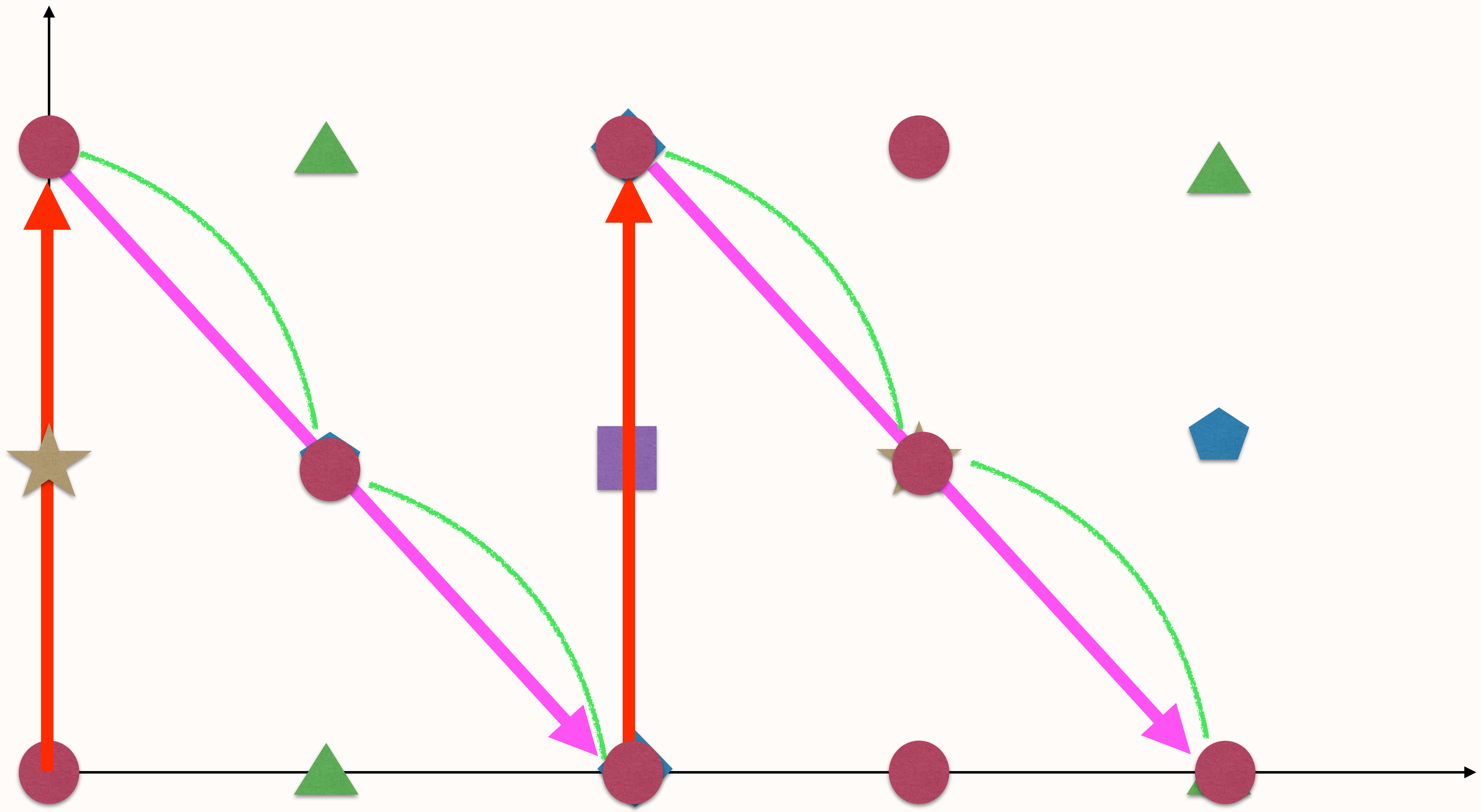

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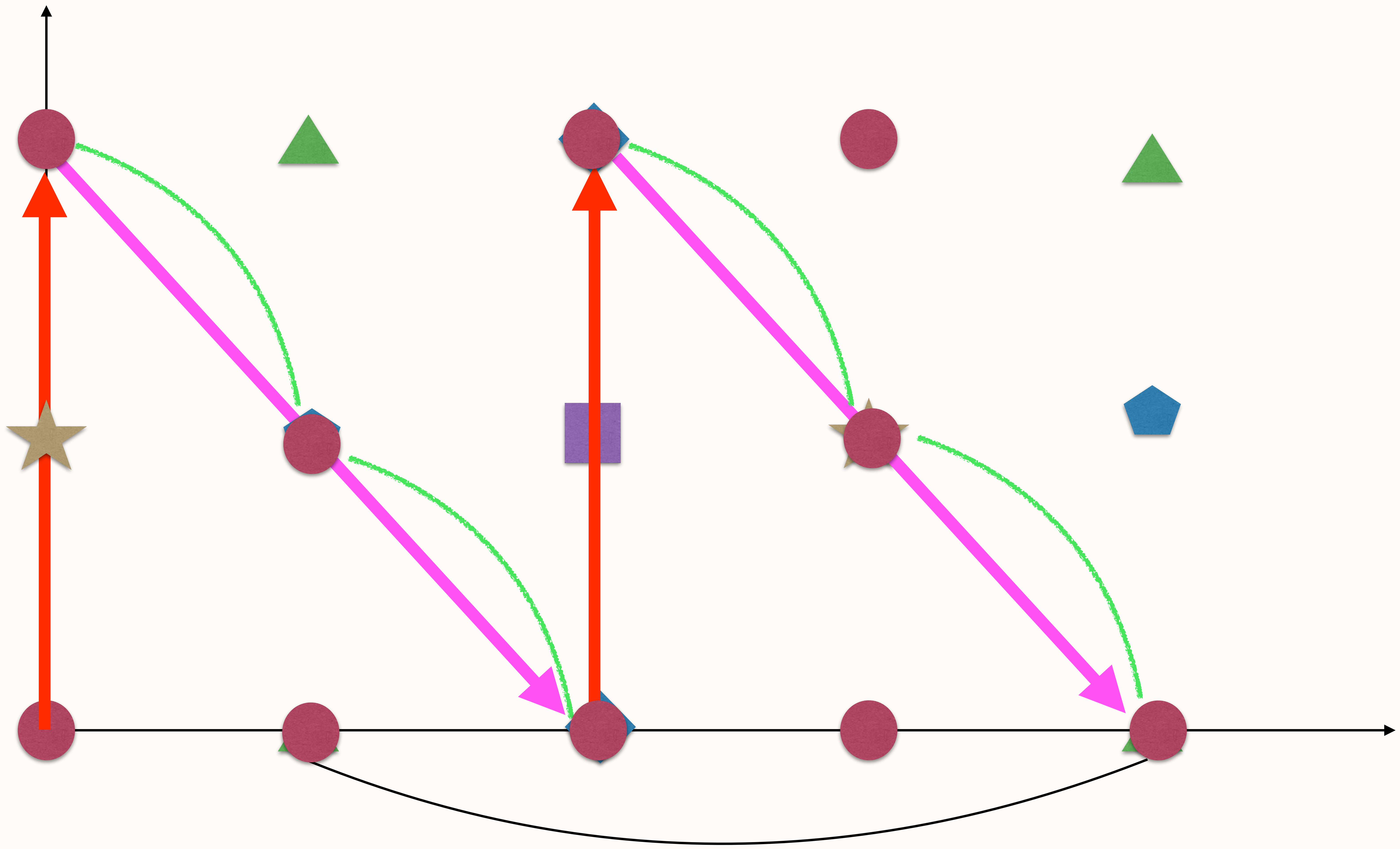

Torus identification

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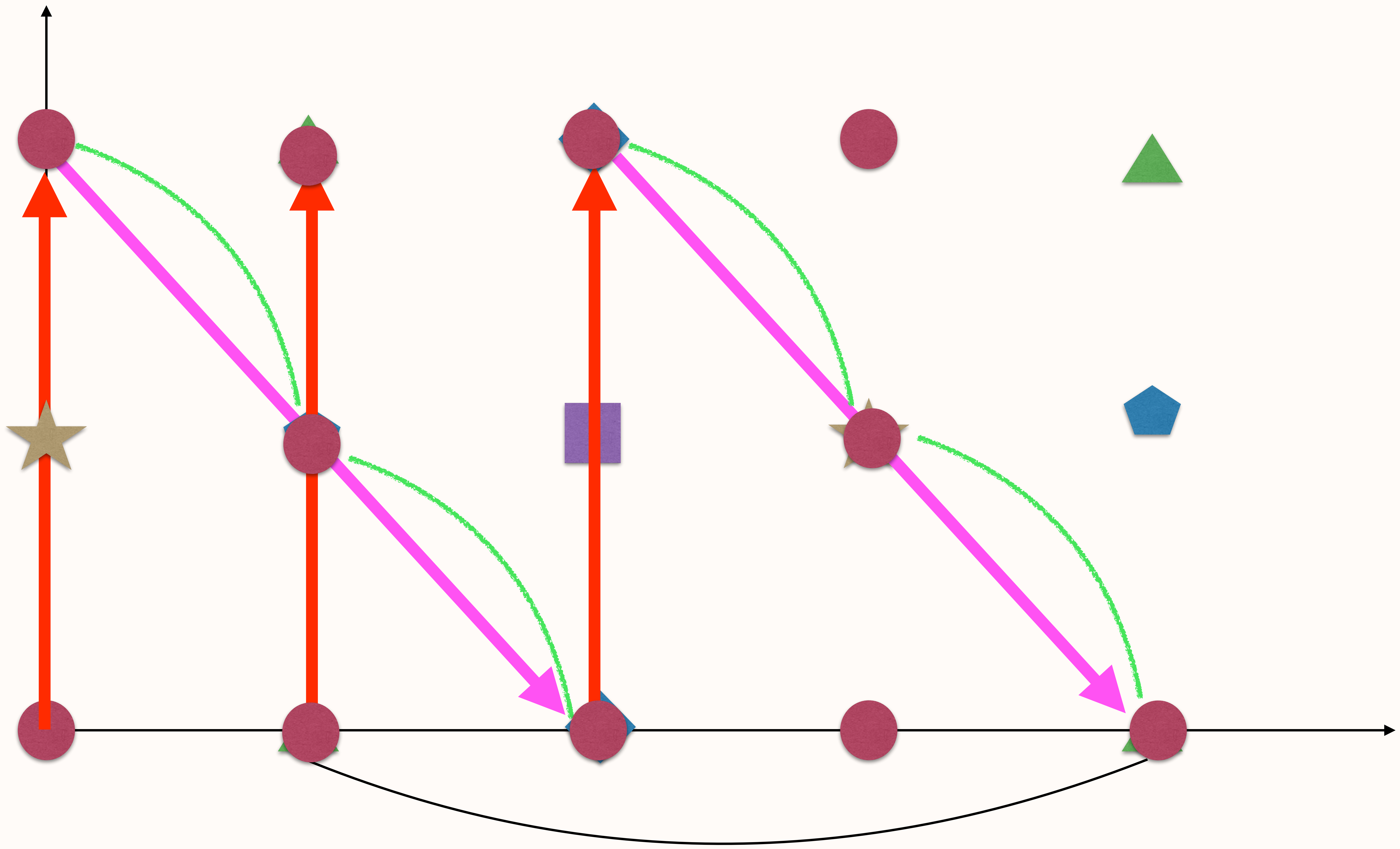

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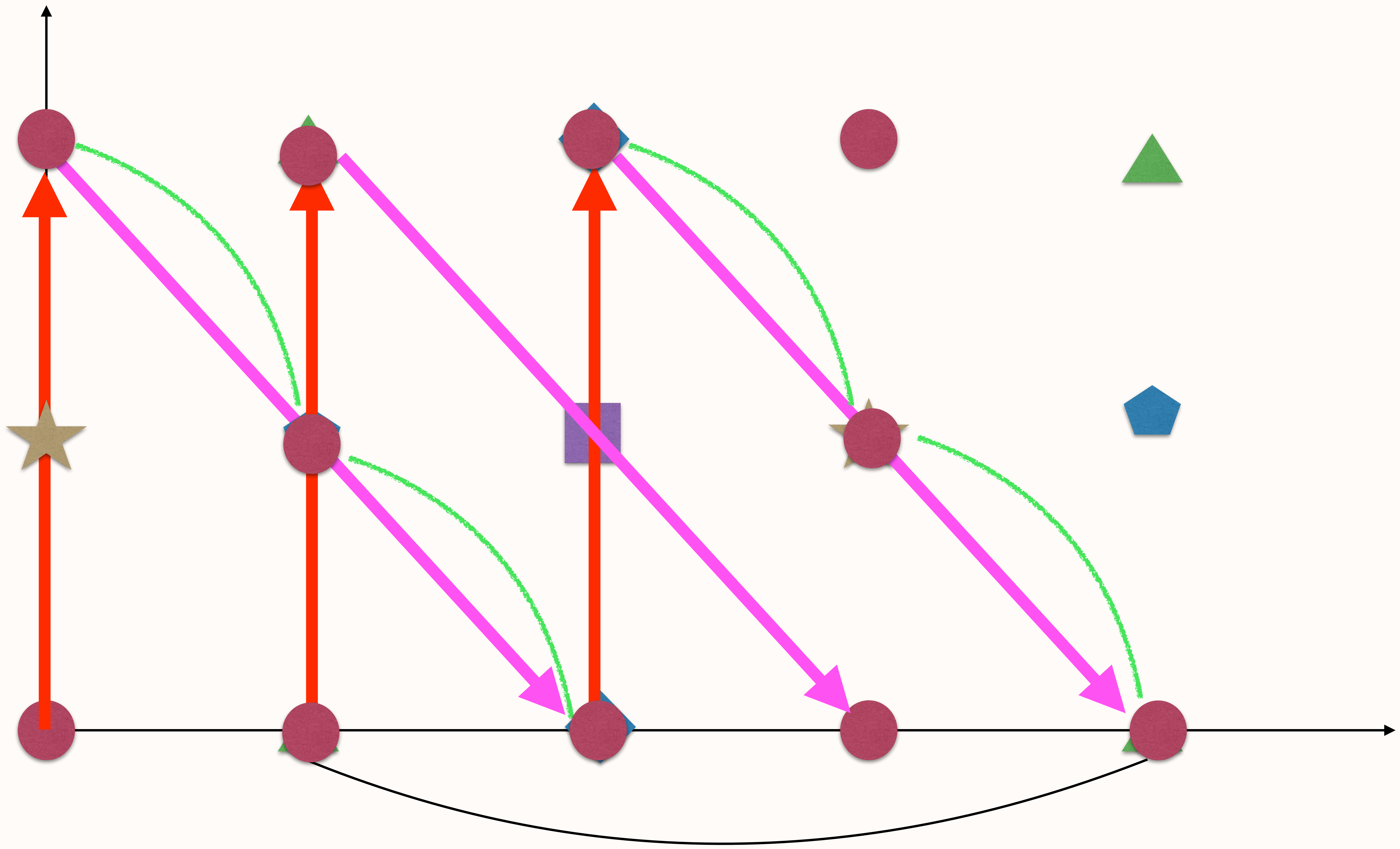

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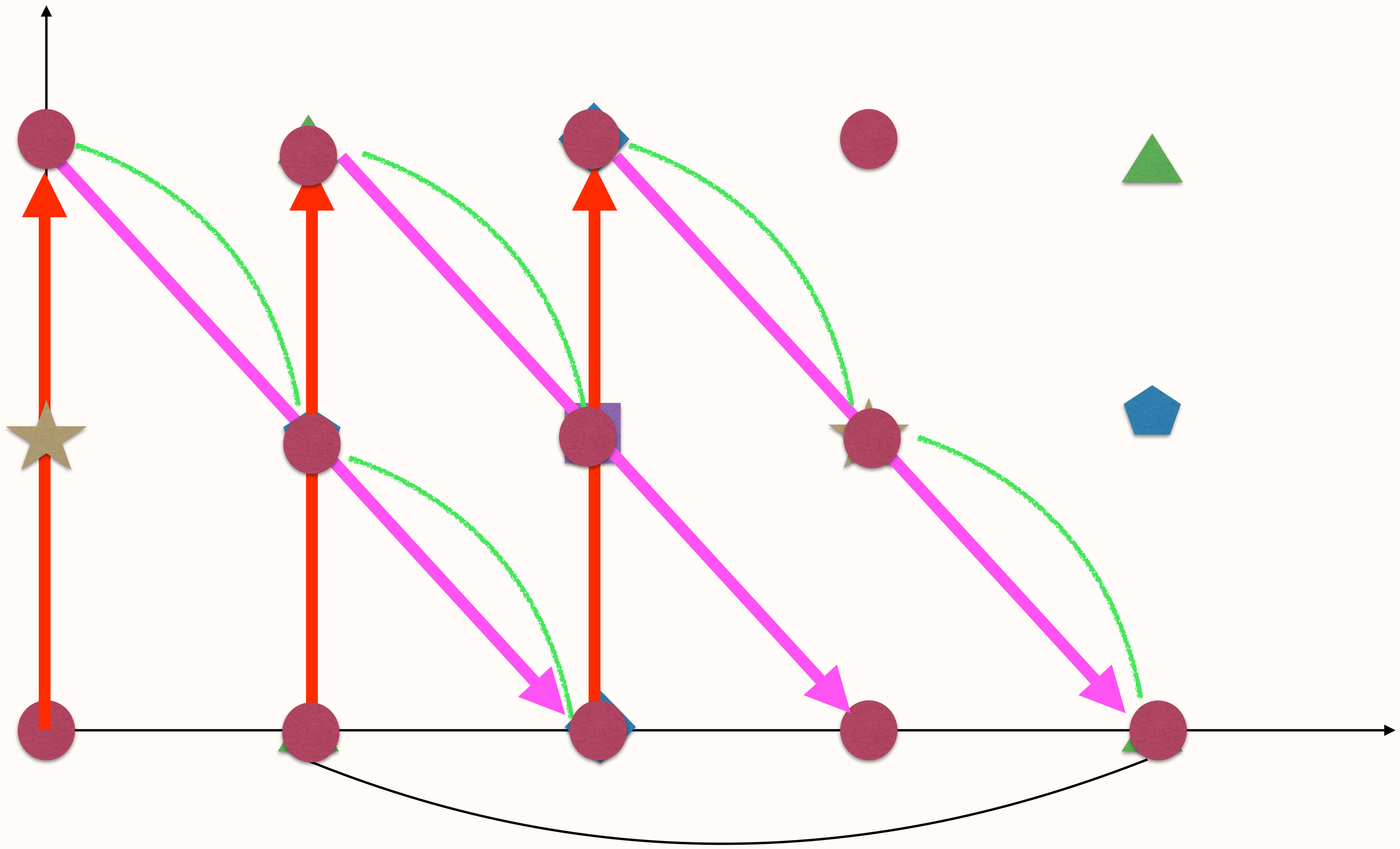

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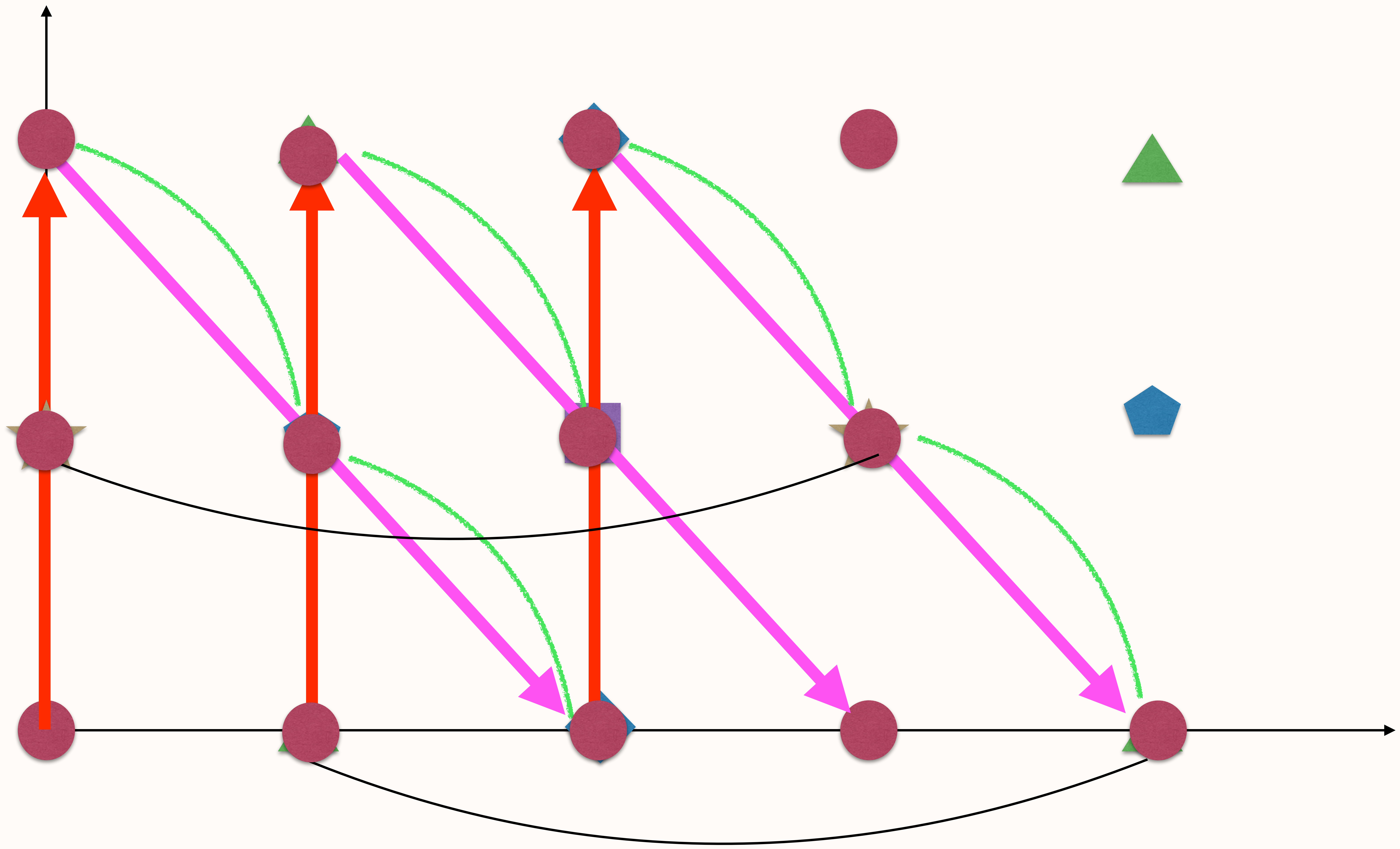

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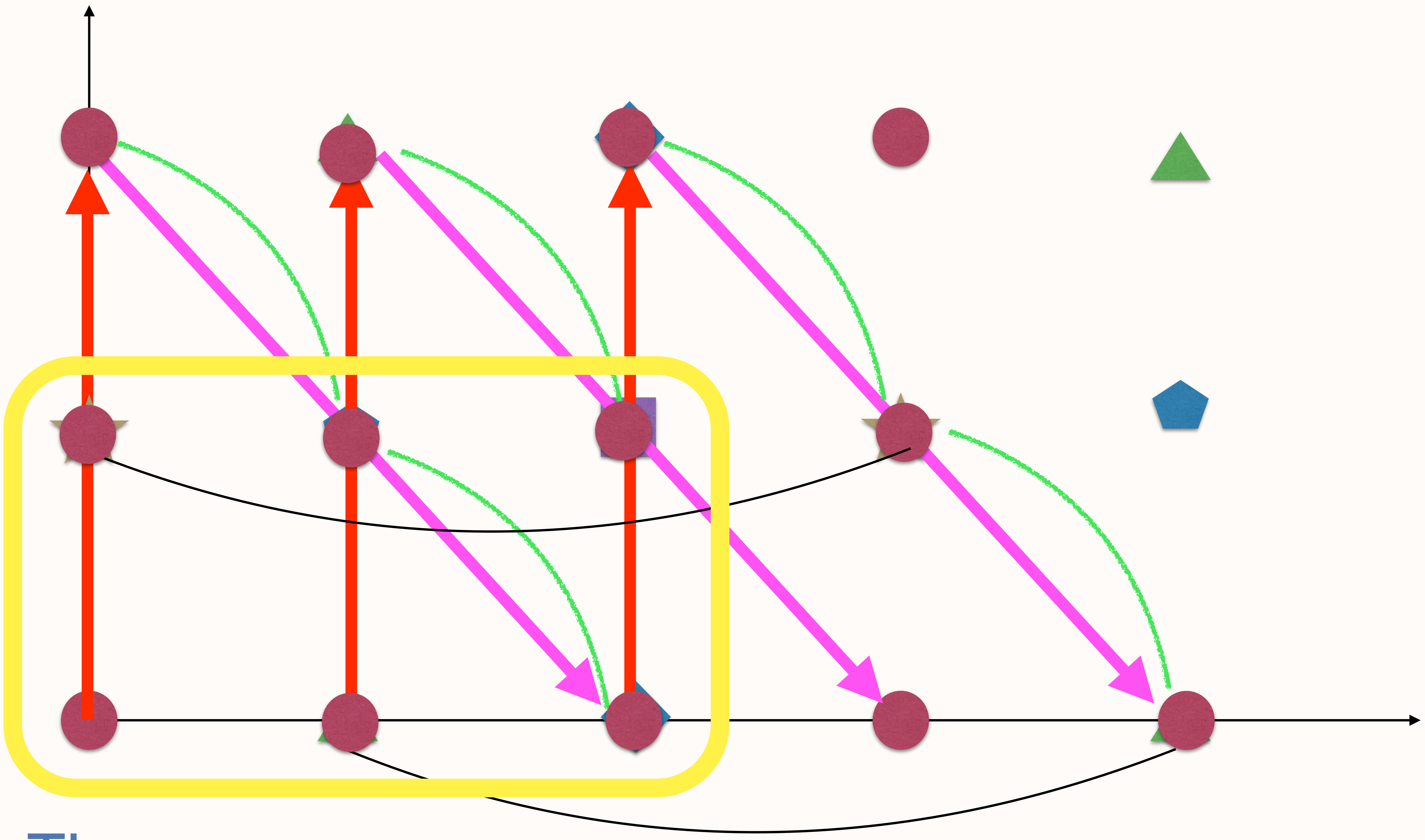
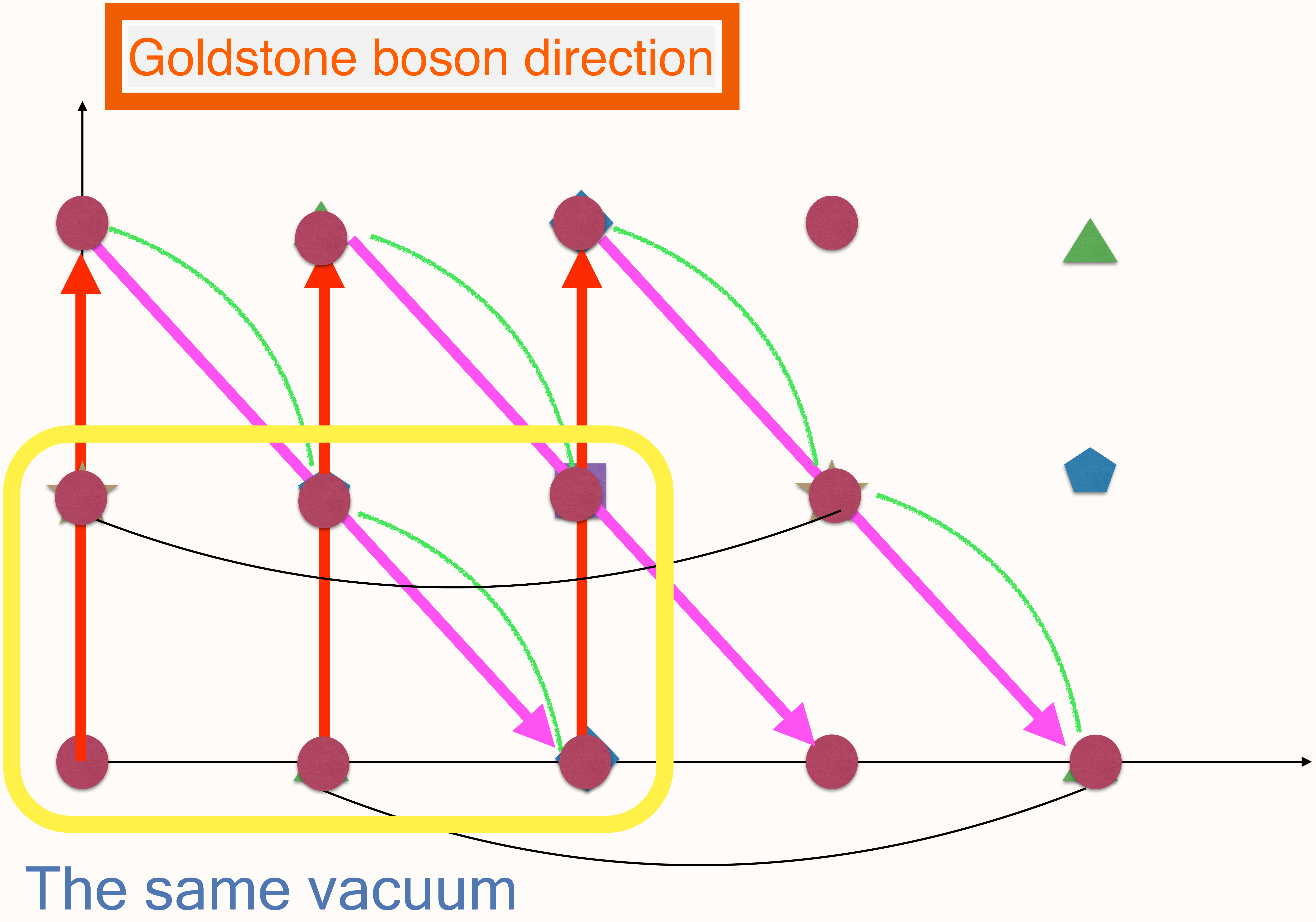
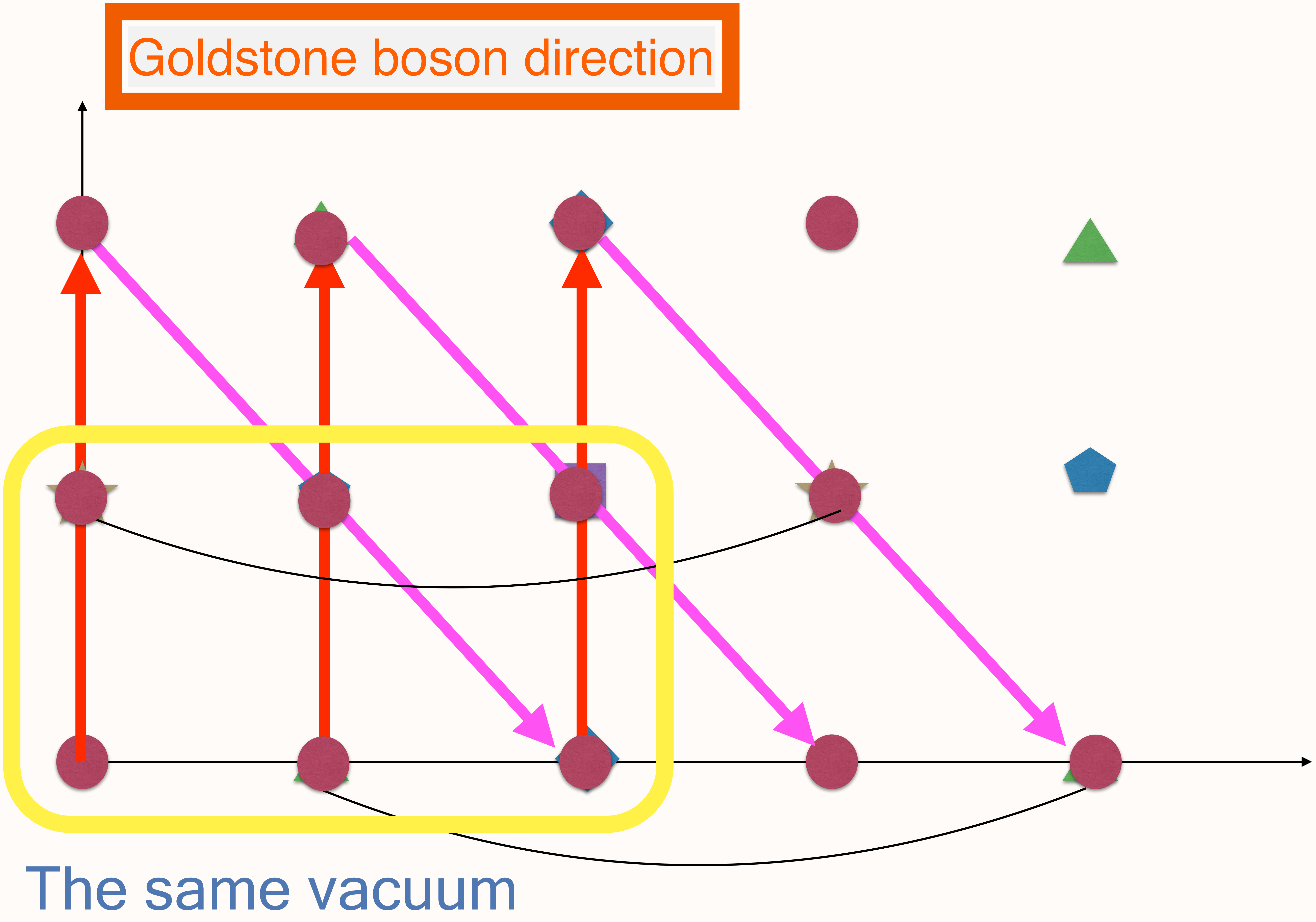


The same vacuum


Goldstone boson direction
The same vacuum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2. Choi-Kim mechanism

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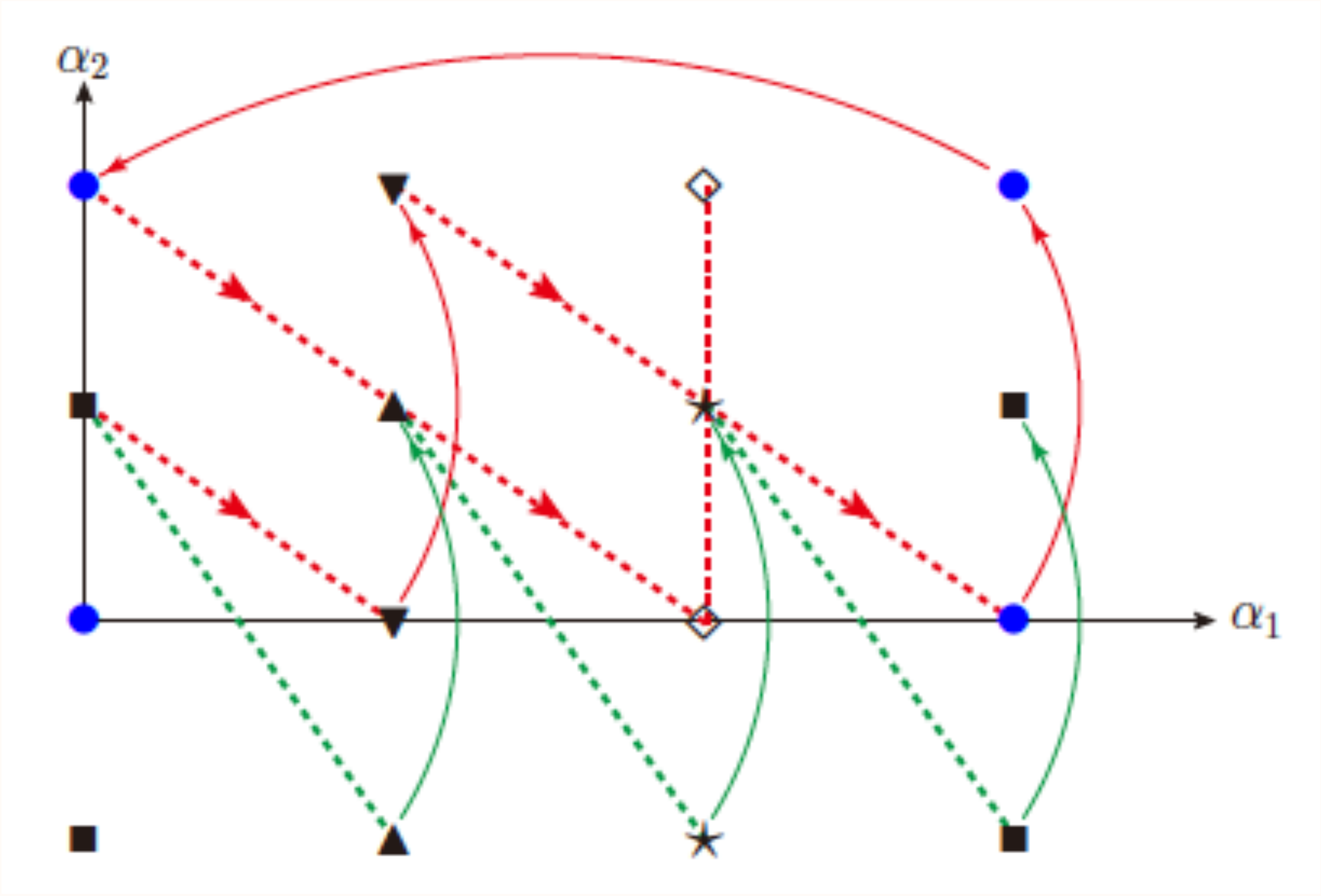

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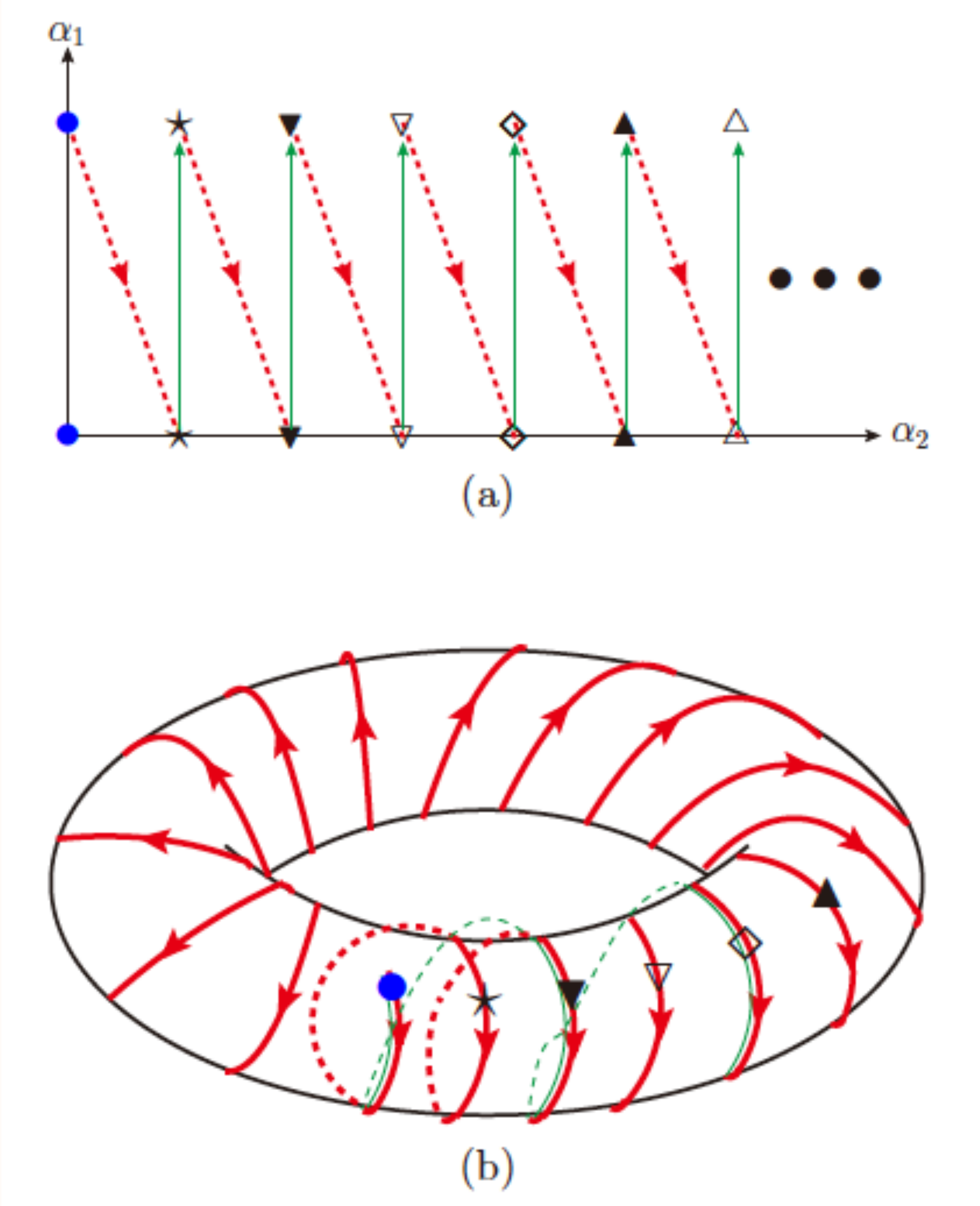
3. Relation of prime numbers: For N_2=17



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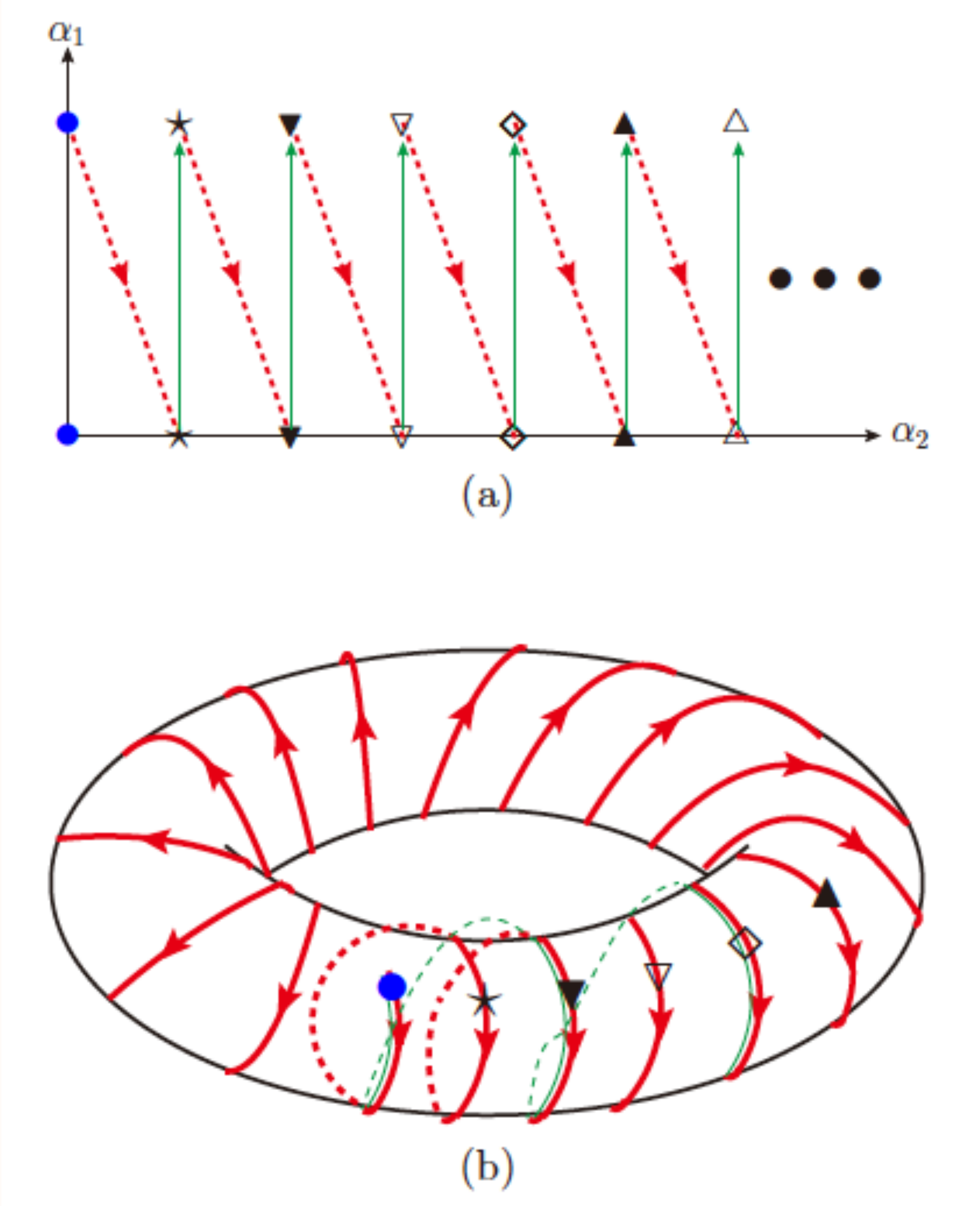

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4. In the example of 1710.08454, based on the model of Huh-Kim-Kyae, sum of U(1)-SU(3)$_c{}^2$ anomaly is $3492=2^2 \times 3^2 \times 97$. So, there is a great chance that

M_{MI} : $f_{\text{phi at st scale}}$ of 3491: 3493, 3497, 3499 etc will lead to N_{DW}=1 because they are relatively prime. Thus, the global symmetry is determined purely from the VEVs at the string scale.

Thus “invisible” axion from anomalous U(1) satisfies the requirements for the intermediate f_a.

4. Conclusion

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In the compactification, if an anomalous gauge U(1) is created, then
the ’t Hooft mechanism works and a global PQ symmetry comes down to the low energy scale.

1. ’t Hooft mechanism.

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2. MI-axion.

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3. Approximate global symmetries