The (in-)visible Axiverse:

Axion-photon couplings in string theory

Naomi Gendler, Harvard University

based on hep-th/2112.04503 with Mehmet Demirtas, Cody Long, Liam McAllister, and Jakob Moritz and WIP with Doddy Marsh, Liam McAllister, and Jakob Moritz

July 4, 2023, String Phenomenology, Daejeon, South Korea

Summary

We analyze axion-photon couplings in the type IIB axiverse and compare to known observational bounds.

Axion-photon couplings are more suppressed than one might think.

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Axion experiments can teach us about where we live in the string theory landscape.

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We have: $\theta_{QCD}, \theta_{QED}, \theta_3, \ldots \theta_N$

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φ_i: phases set by UV physics (generally assumed O(1))

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- I will now present some preliminary results on studying **axion-photon couplings** in this axiverse. [NG, Marsh, McAllister, Moritz WIP]

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Start with axion Lagrangian in terms of Calabi-Yau data:

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See Jakob's talk on Friday to see these suppression mechanisms in detail!

Axion detection

- Primary constraints come from the axion coupling to photons: $\mathcal{L}_{a\gamma\gamma} \sim g_{a\gamma\gamma}\theta F\tilde{F}$

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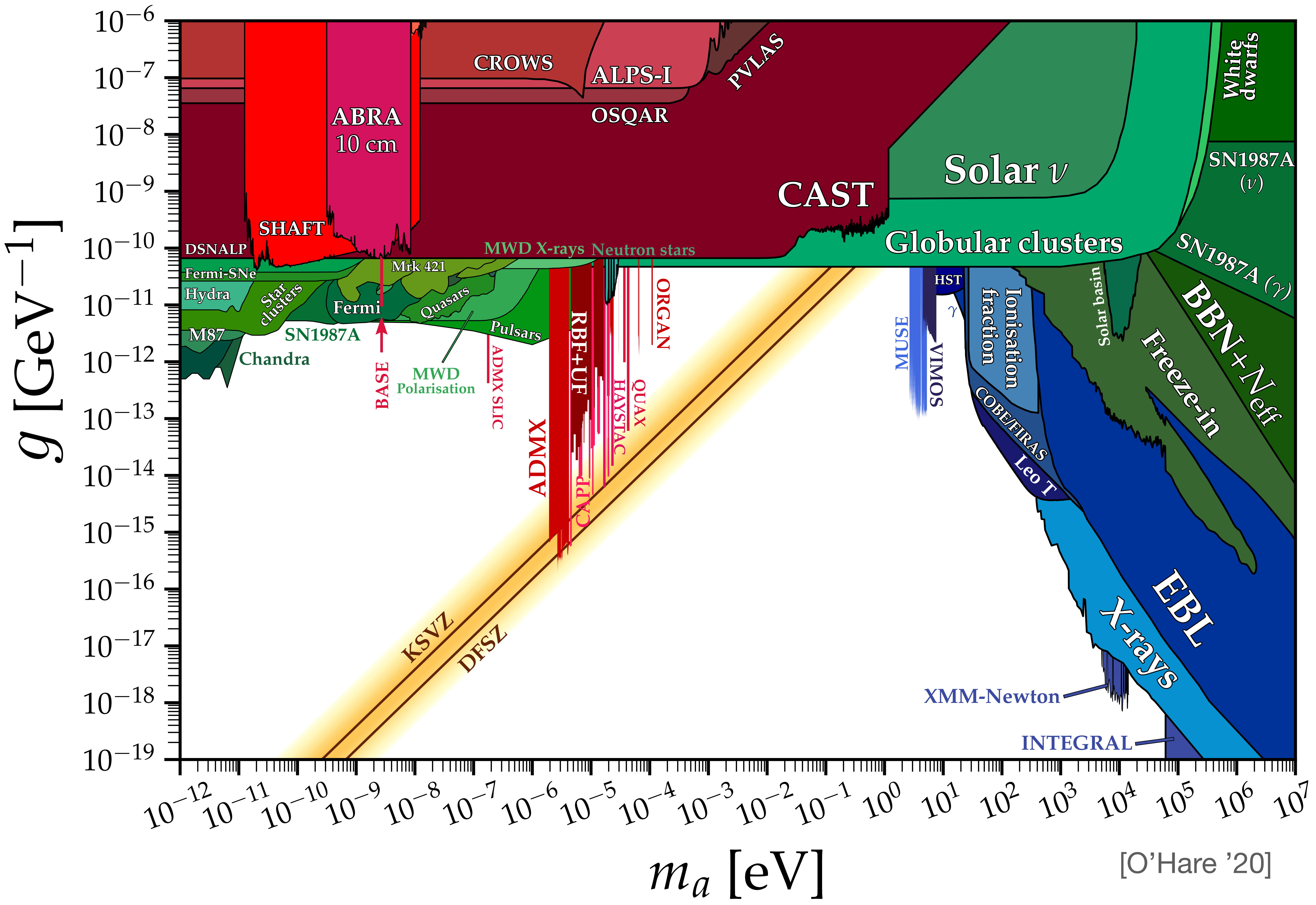
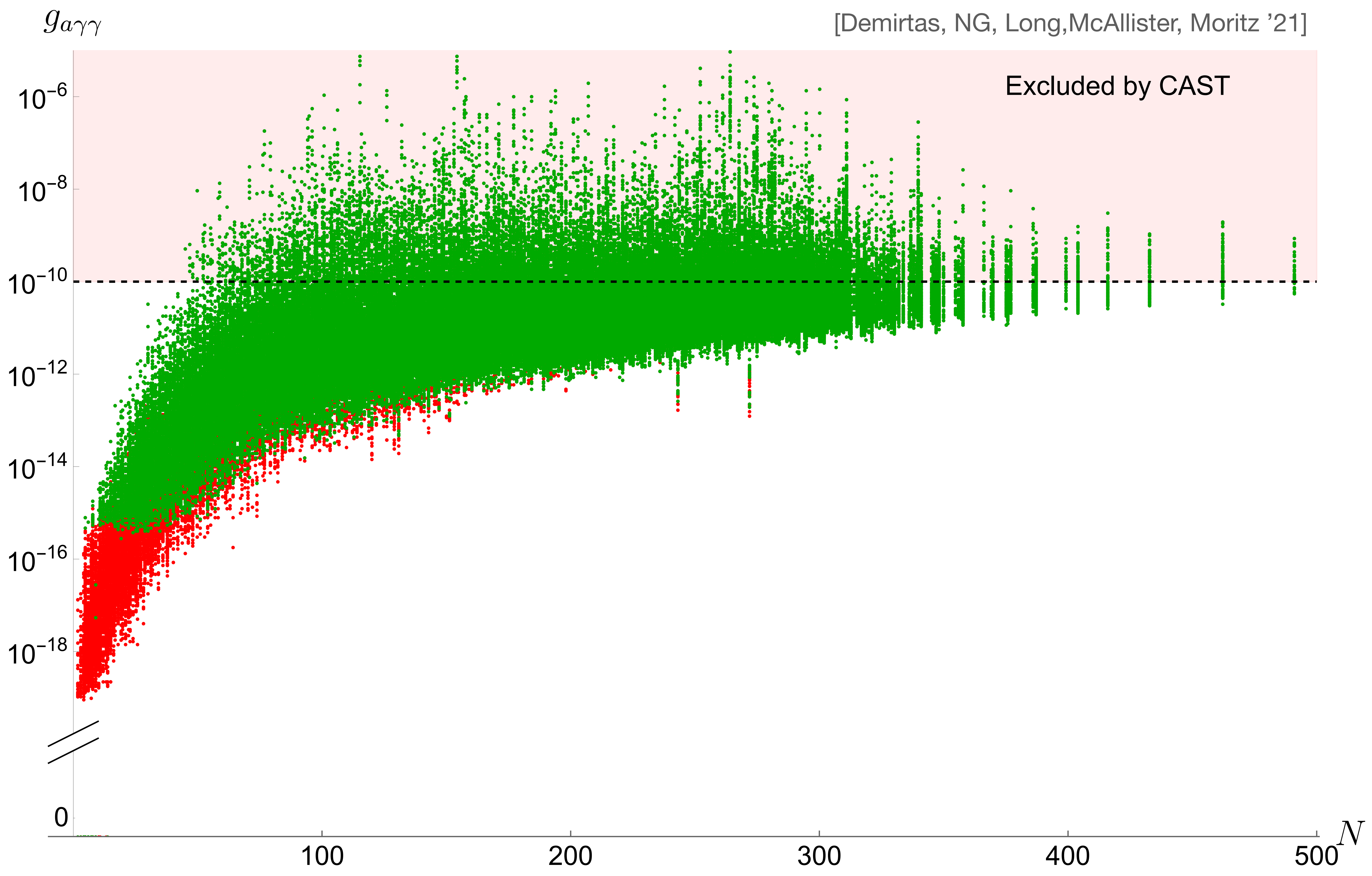


[O'Hare '20]

solid colors = regions that are ruled out

diagonal line = region where the QCD axion would live

Suppression of axion-photon couplings



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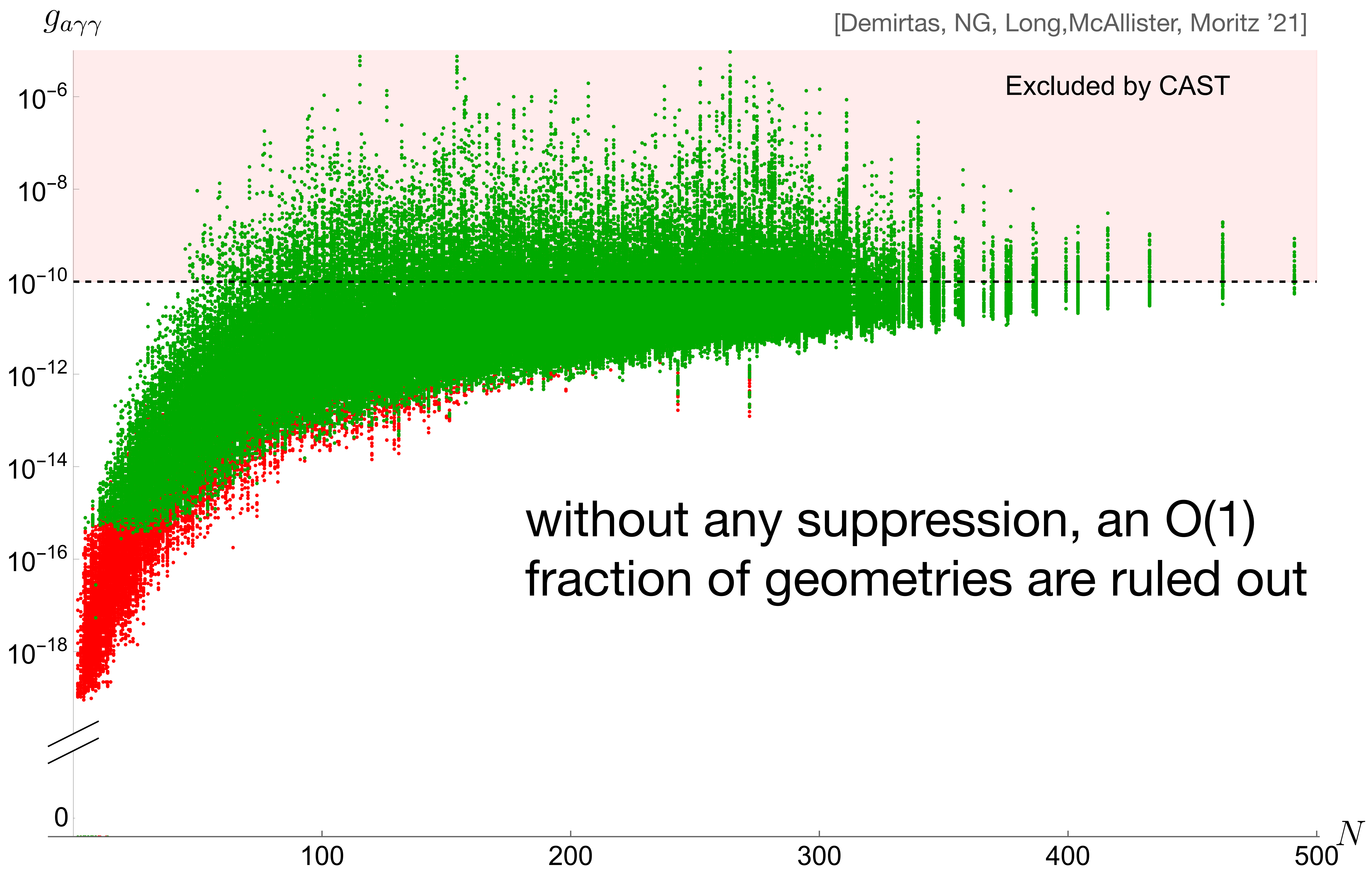

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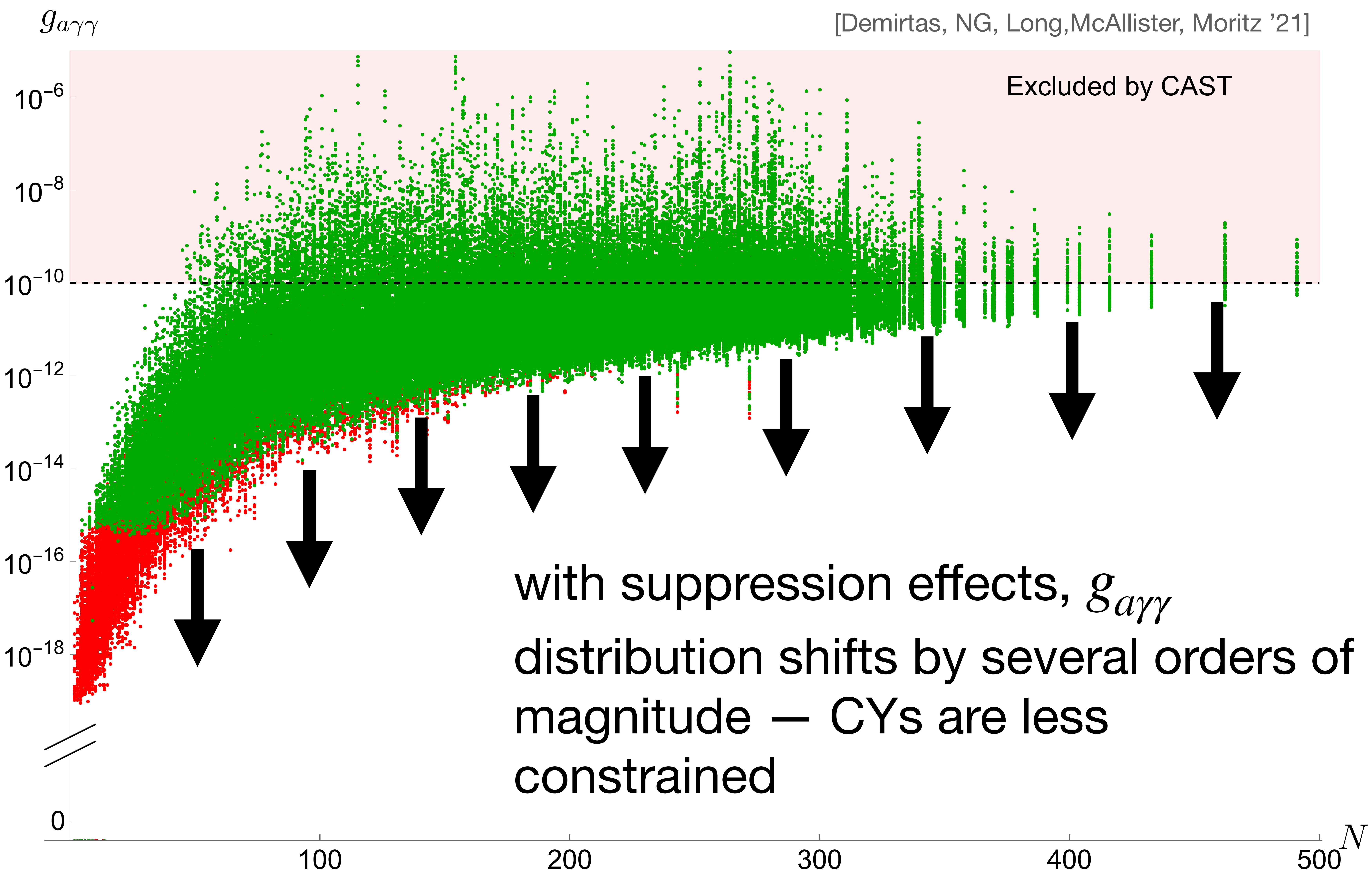

with suppression effects, $g_{a\gamma\gamma}$ distribution shifts by several orders of magnitude — CYs are less constrained

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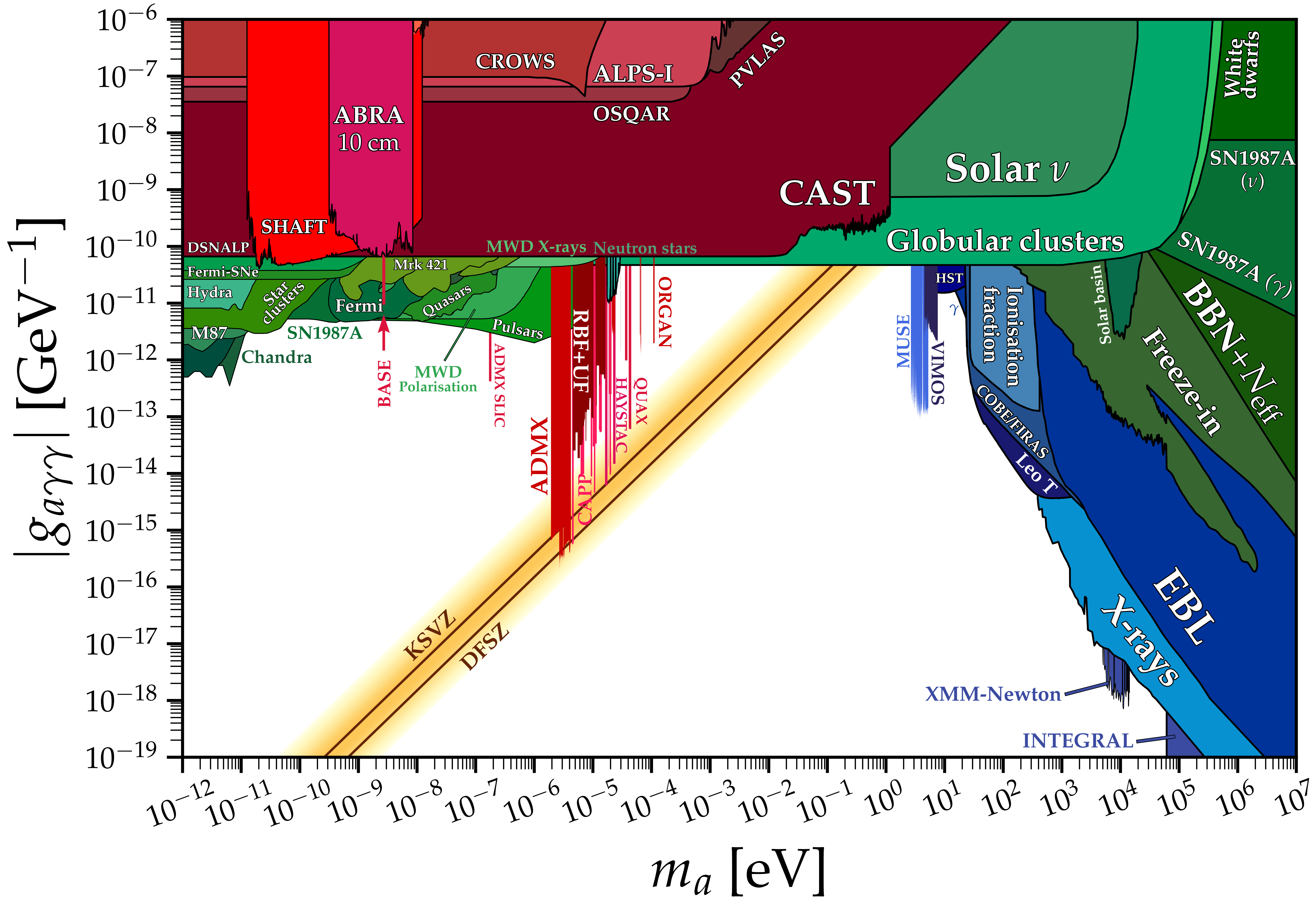
- Where do string theory axions sit on this plot?

Preliminary data: 300 CYs with $h^{1,1} = 50,100,200$



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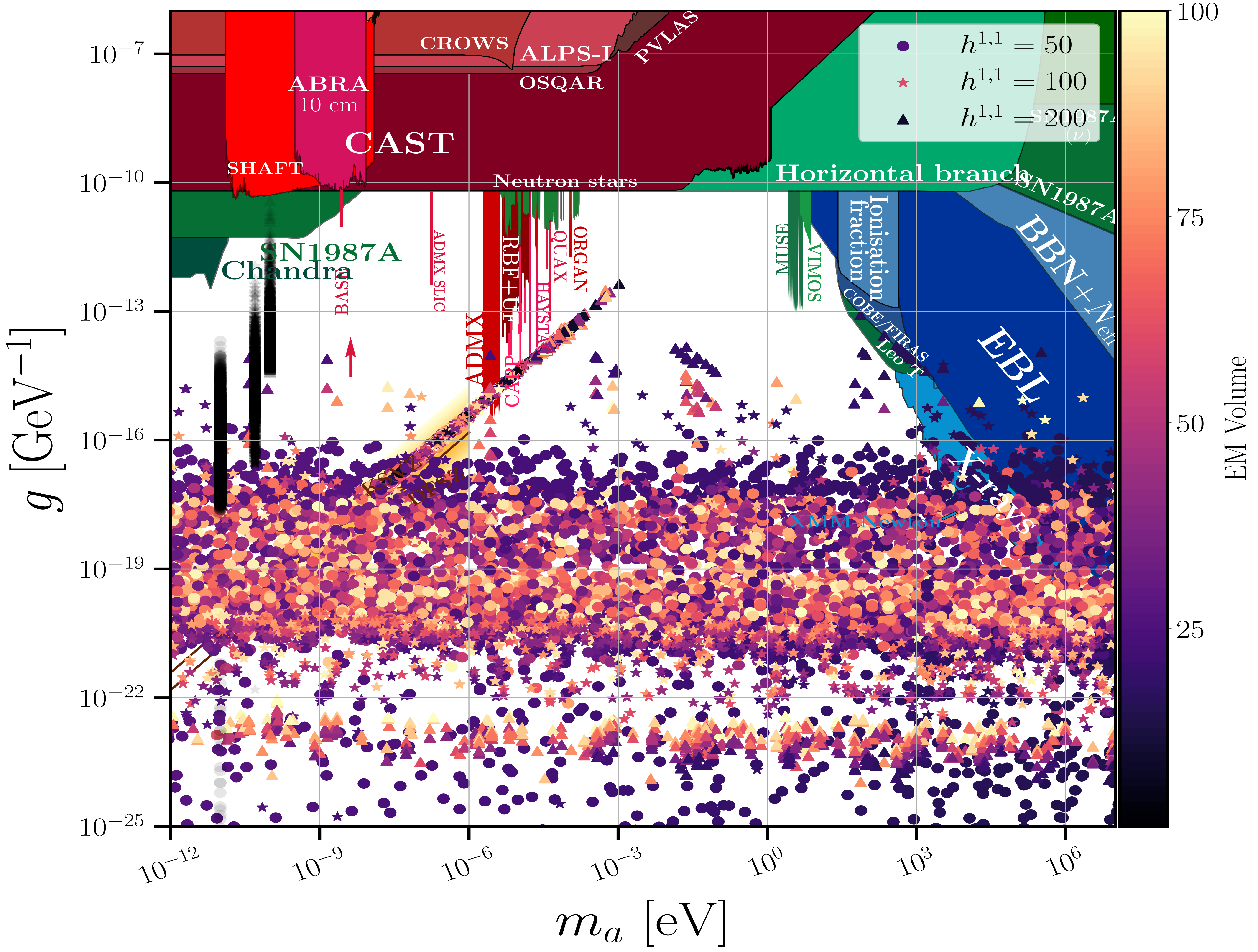

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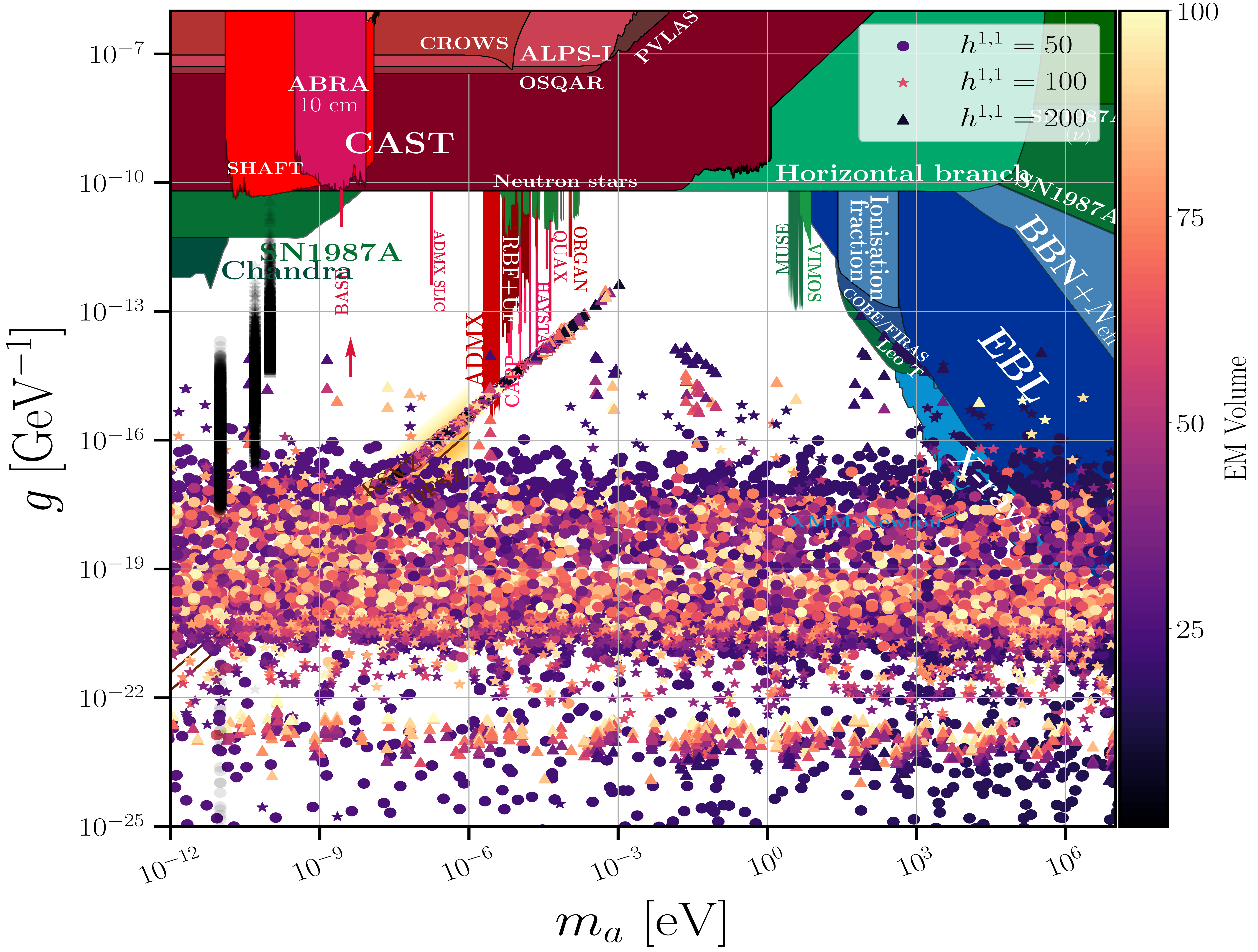

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Lessons:

1. String theory axions fill the ALP parameter region
2. Couplings don't reach current constraints

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- Hierarchies in Calabi-Yau geometries led to new expectations for the scales of the problem: **as the number of axions increases, the decay constants decrease.**
- In the models we studies, we also calculated the effective axion-photon couplings.
- We found a mechanism that generically suppresses axion-photon couplings, compared to the naive expectation.

Thank you!

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F5

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$$S_{10\mathrm{D}} \supset \int d^{10}x \, F_{MNPQR}F^{MNPQR} \qquad M,\, N \in 0, \ldots 9$$

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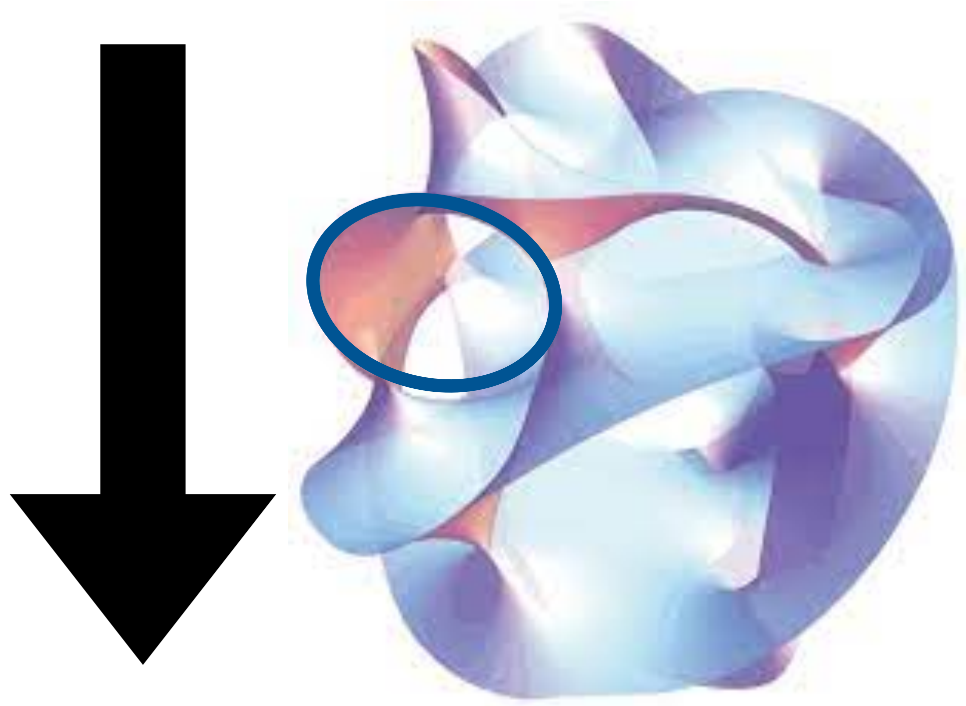

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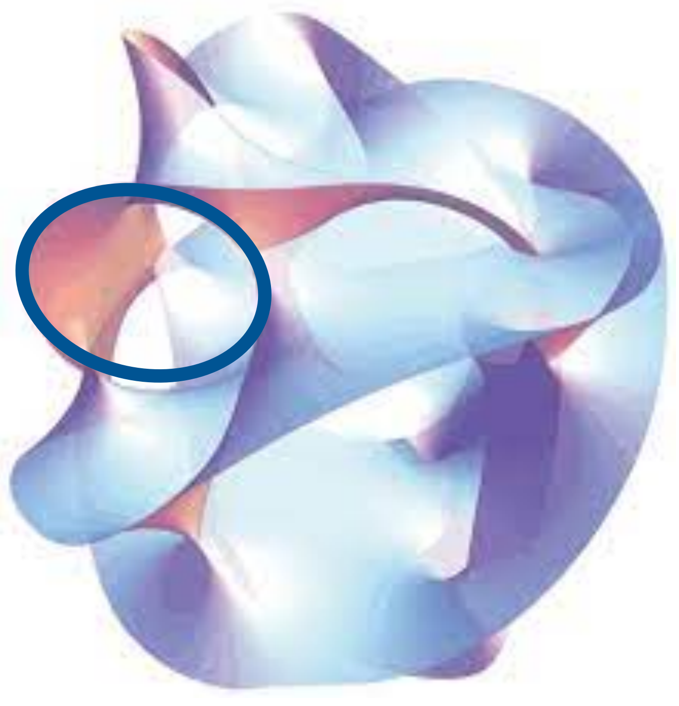

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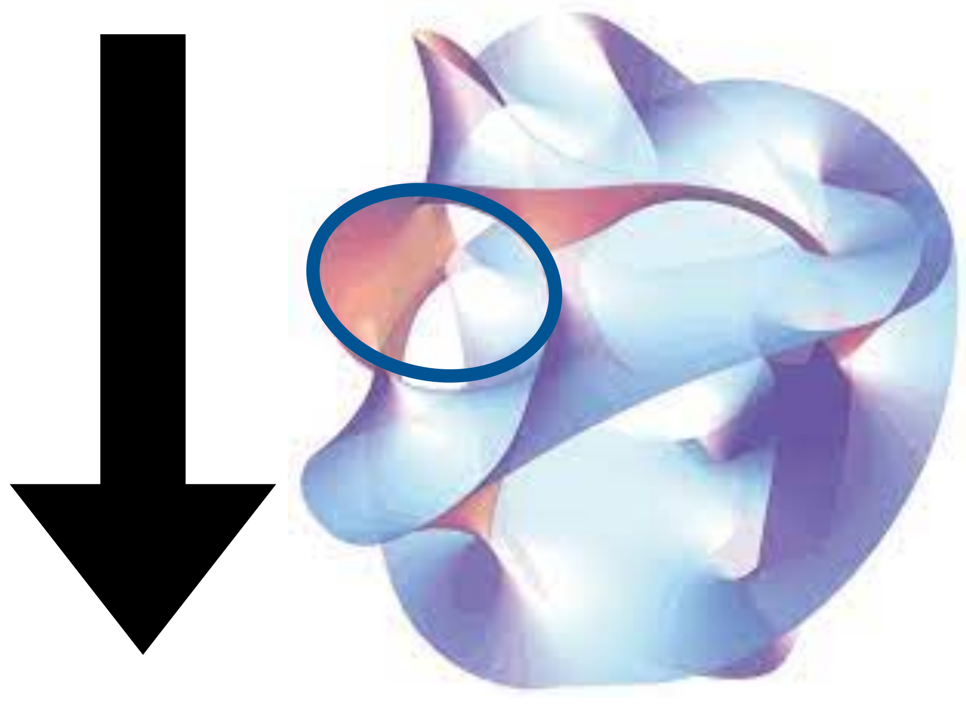

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These manifolds can have hundreds of four-cycles → hundreds of axions!

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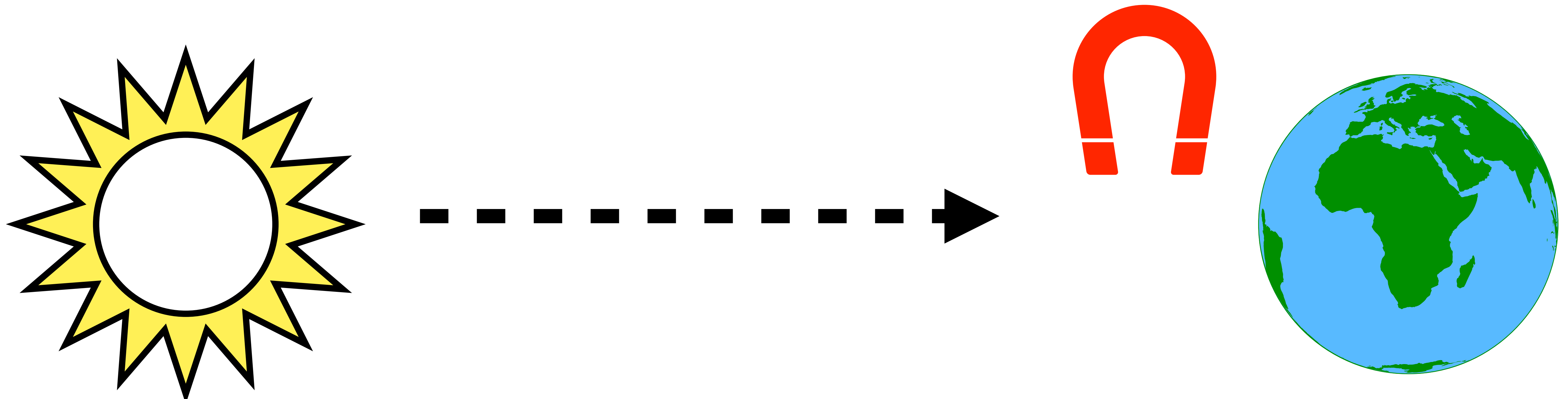

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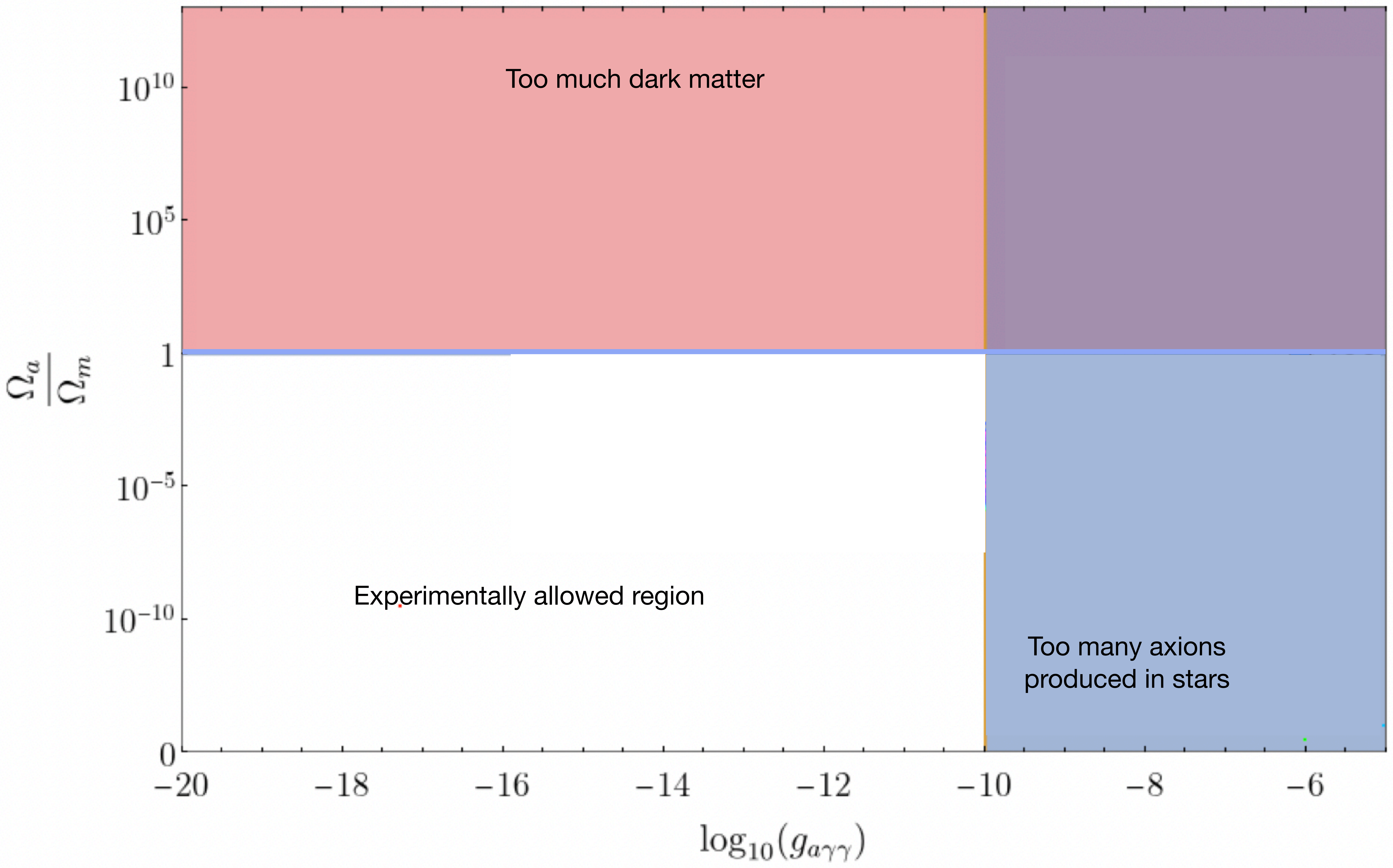

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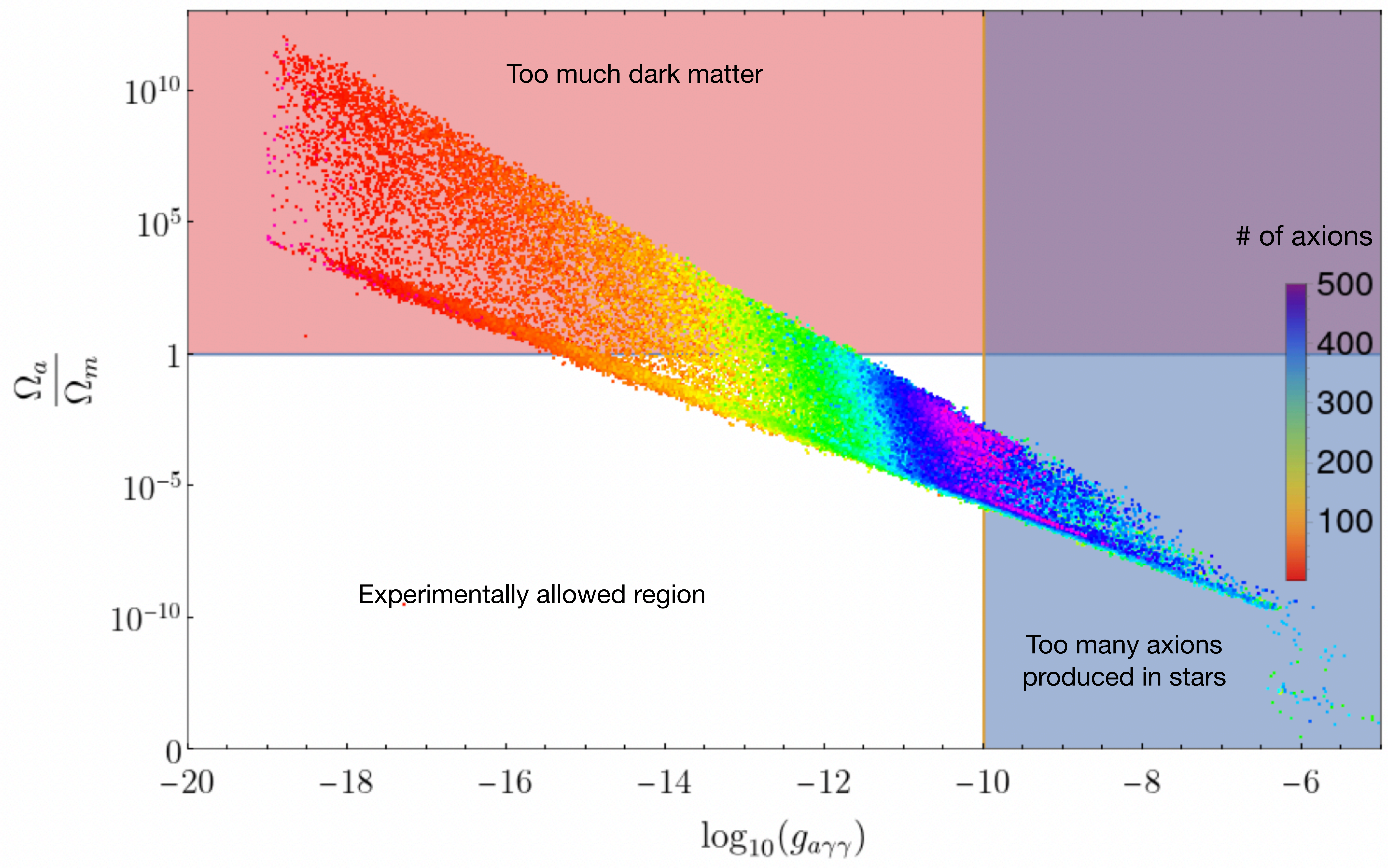

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Strong CP problem: why is this number so small?

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Axion particles are excellent candidates for dark matter and dark energy!

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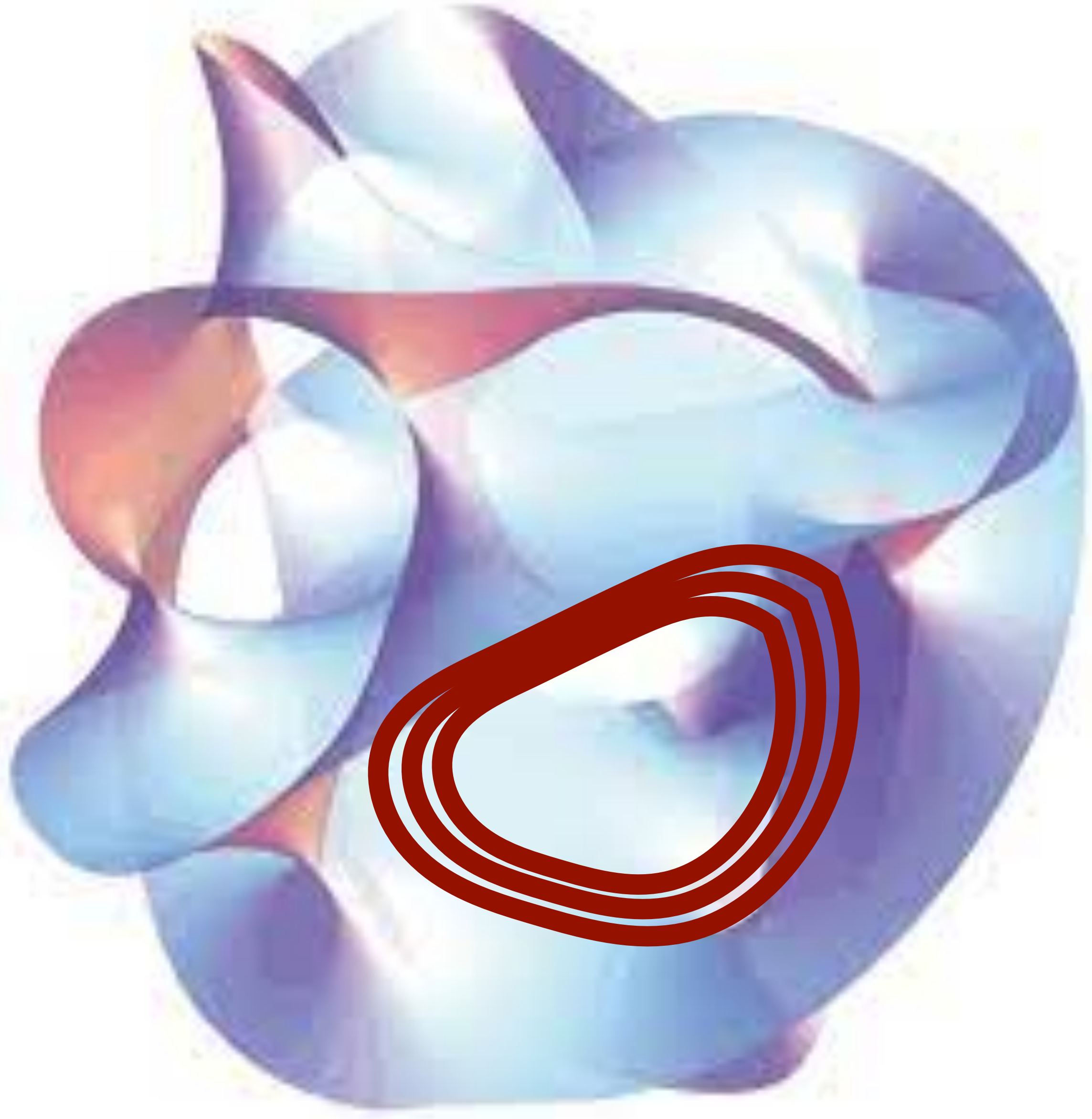

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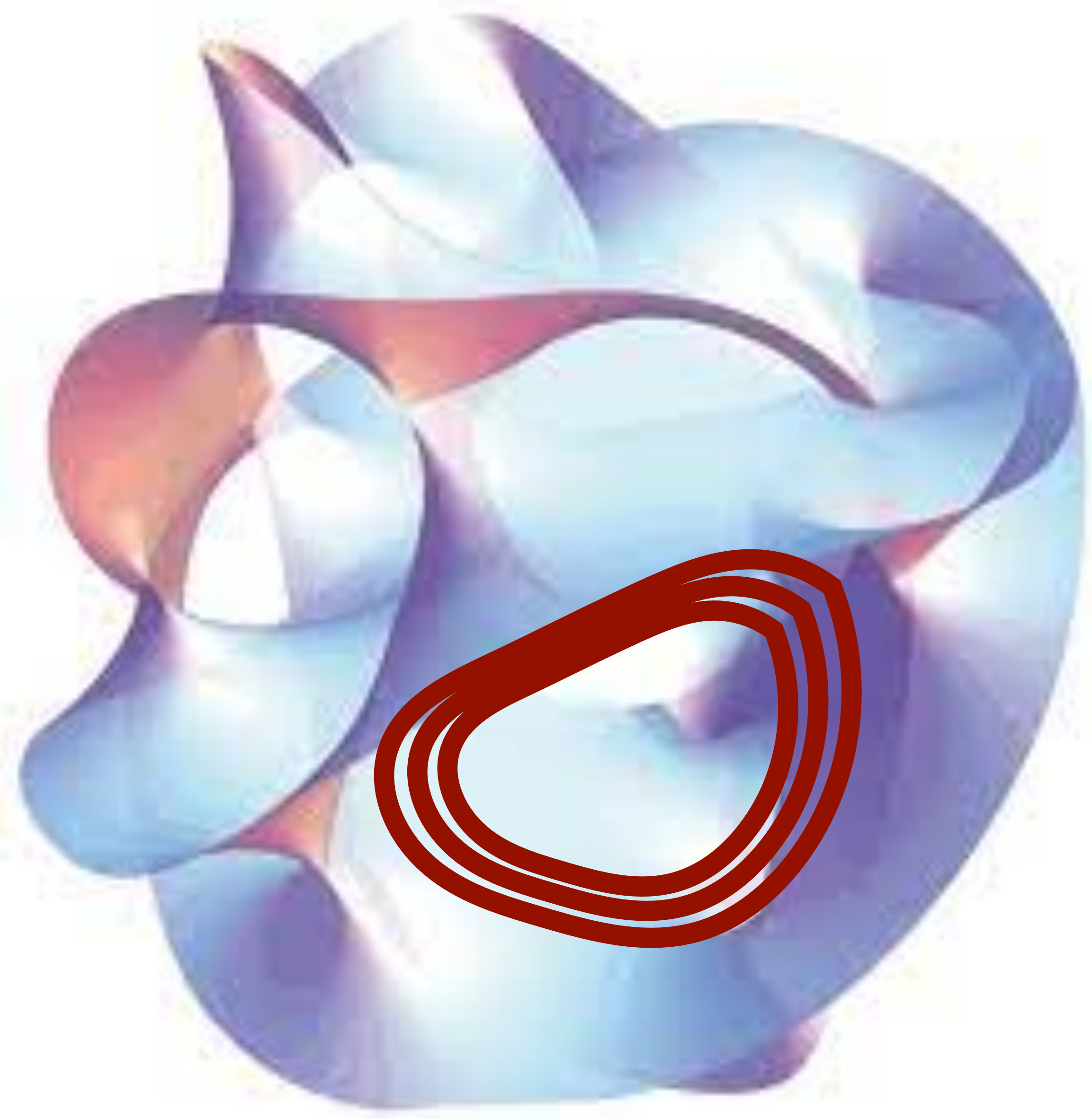

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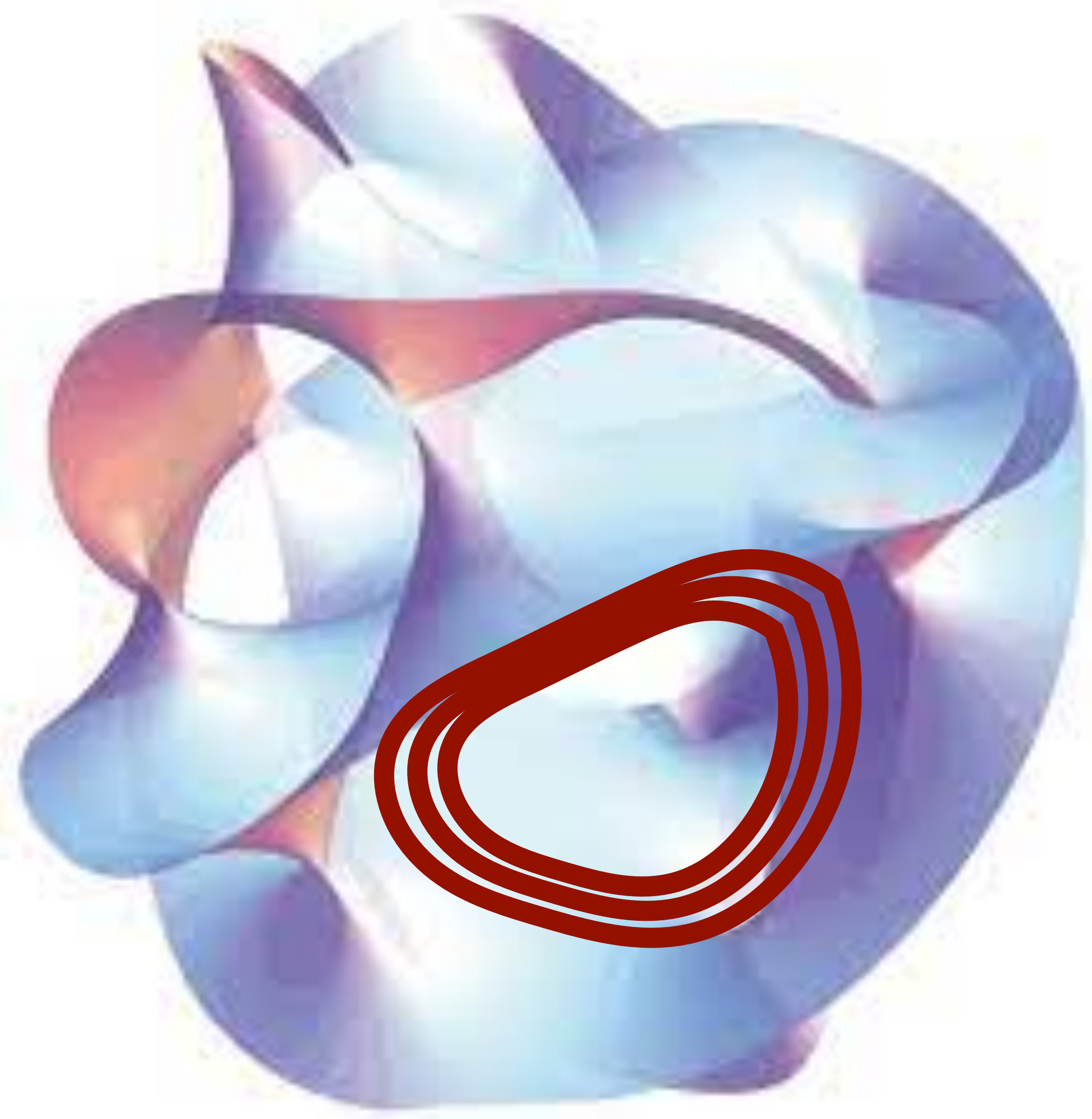

We will not explicitly engineer the SM in this work: rather, we will simply choose a cycle Σ_i and ensure that vol(Σ_i) reproduces (i.e.) the correct g_{QCD} that we observe.

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1. What is W_0? ← what is the scale of SUSY breaking?

2. What is $\mathcal{V}$? ← what is the KK scale?

3. What are the q^A and associated T_A? ← actions of contributing instantons?

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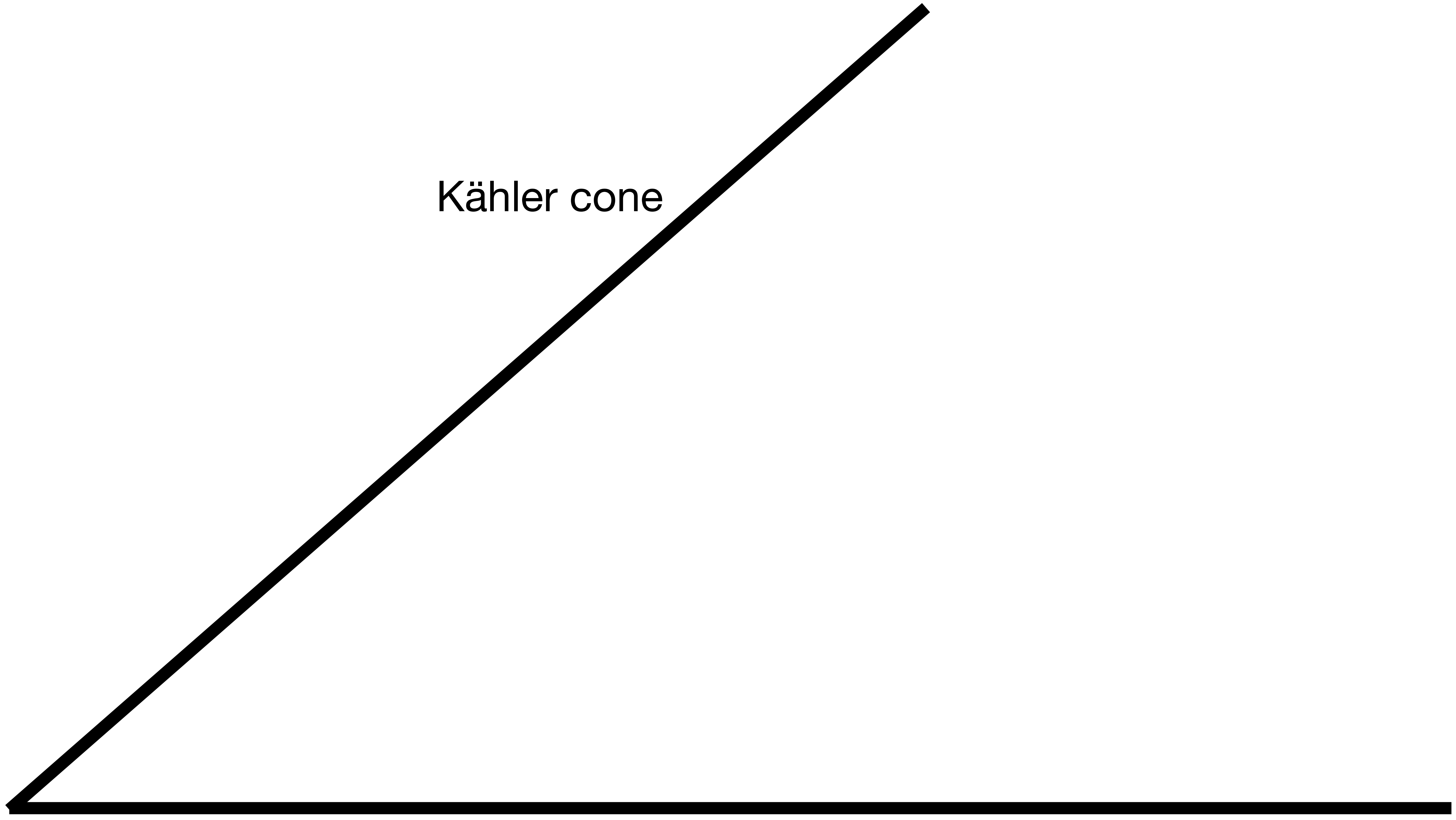

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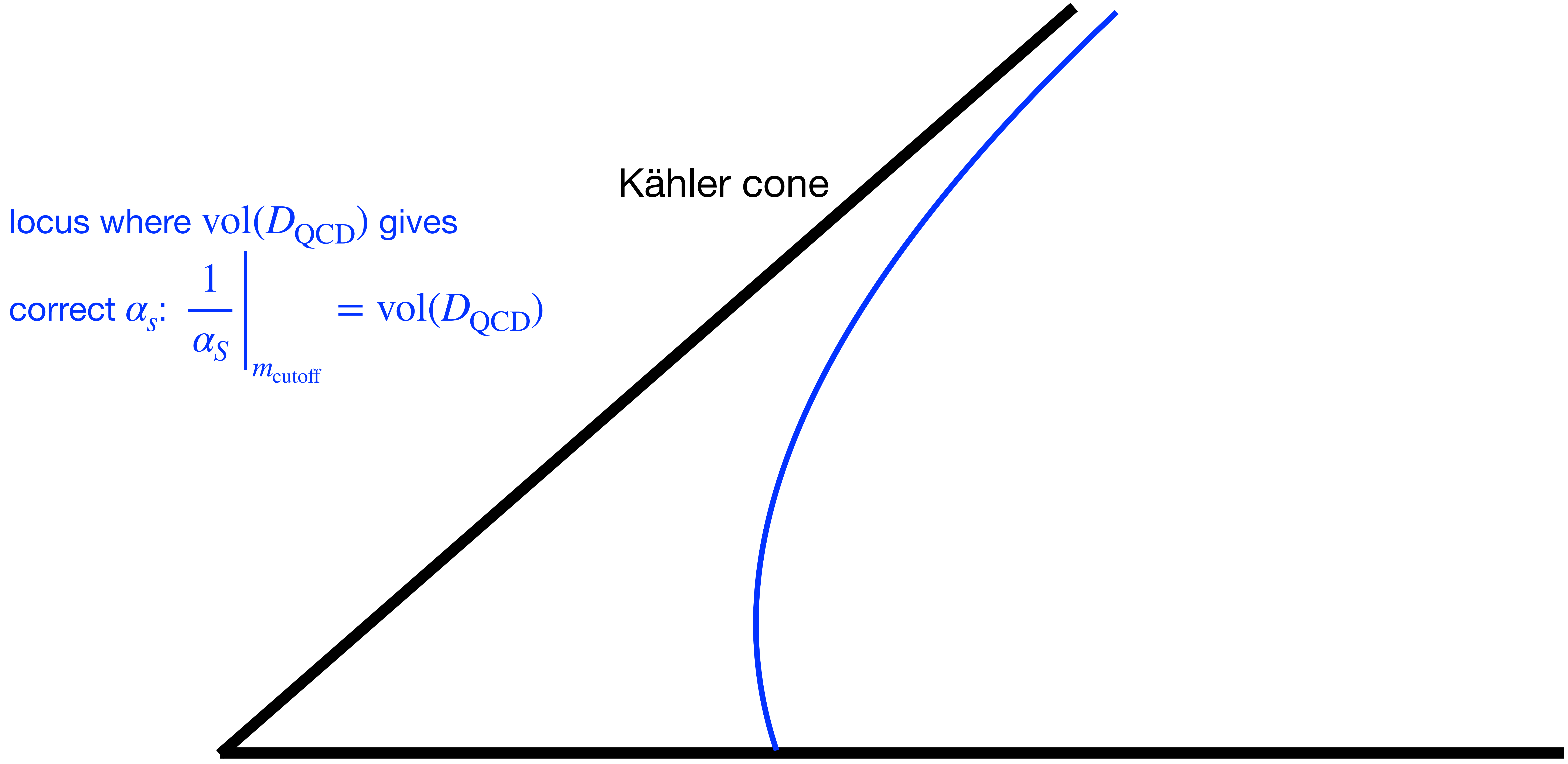

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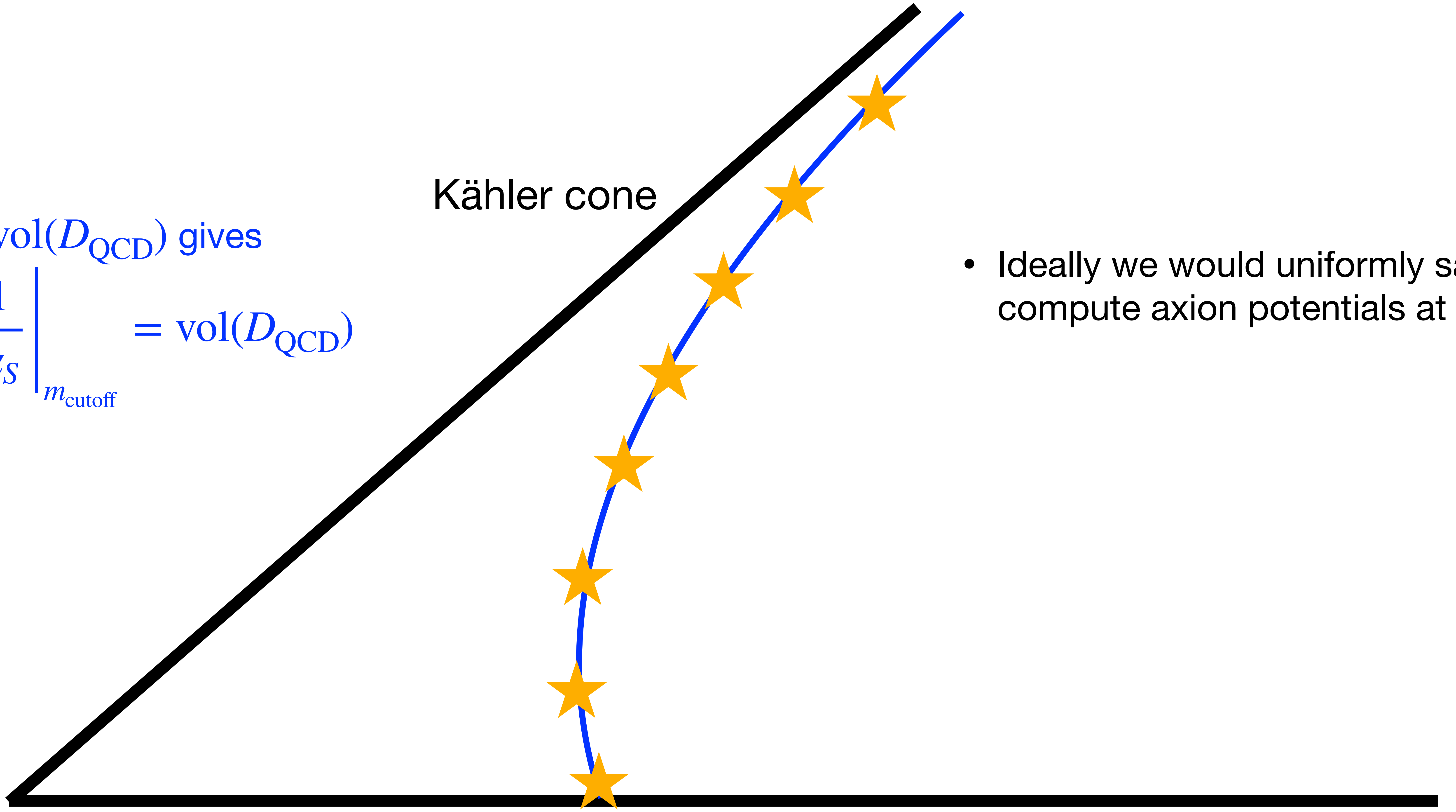

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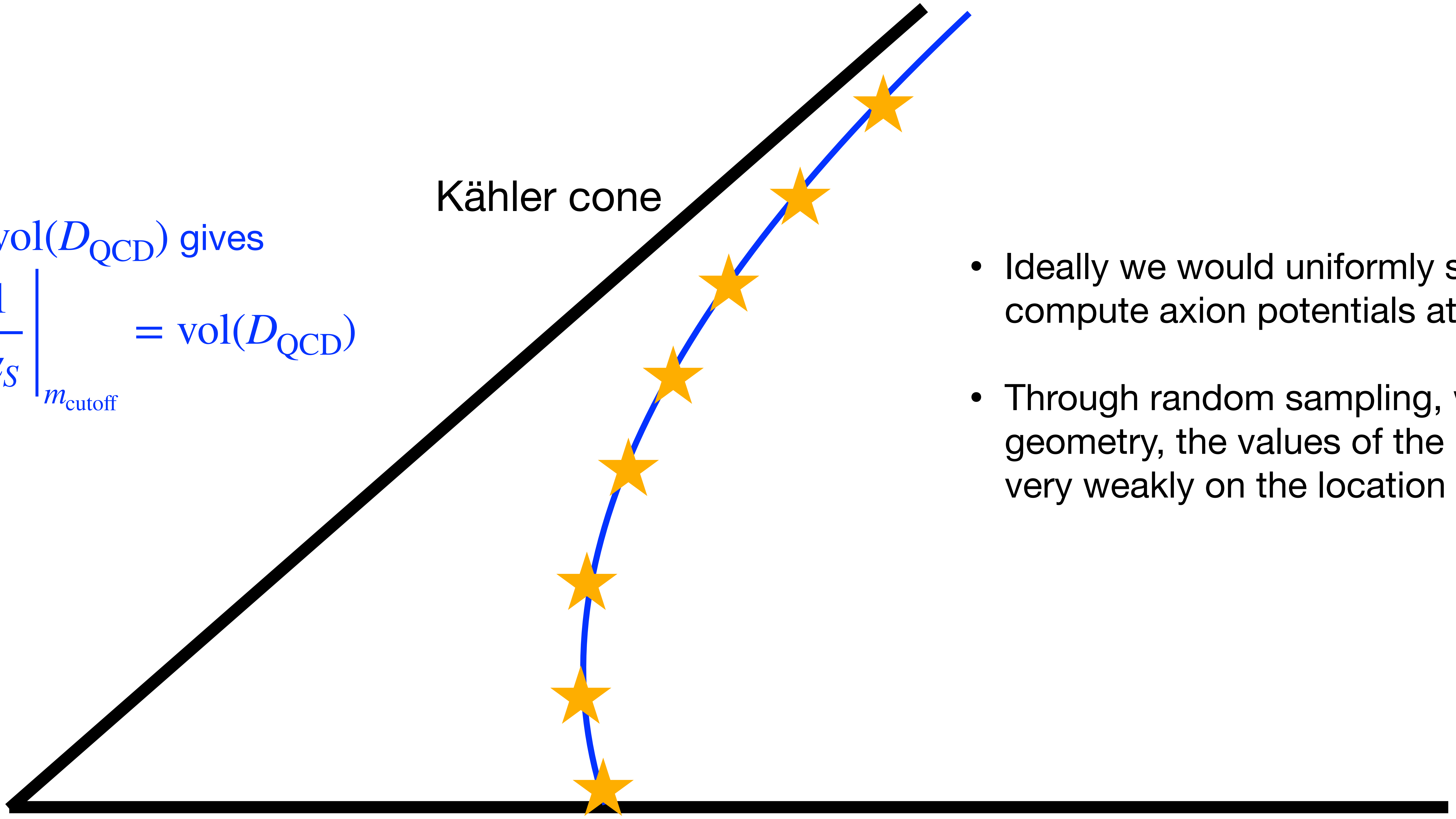

- Ideally we would uniformly sample this locus and compute axion potentials at each point.
- Through random sampling, we found that for a given geometry, the values of the moduli (divisor volumes) depend very weakly on the location on this locus.

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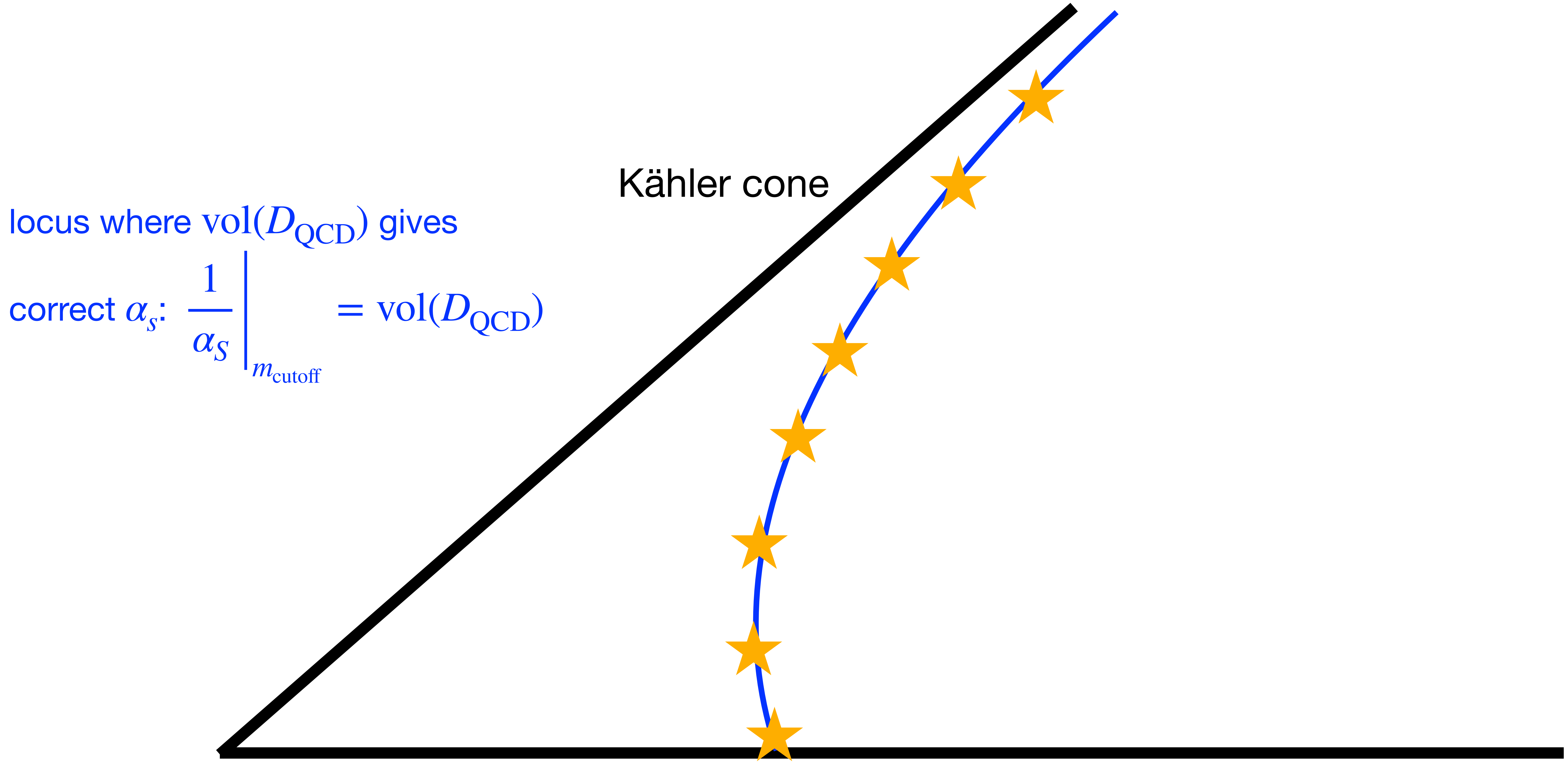

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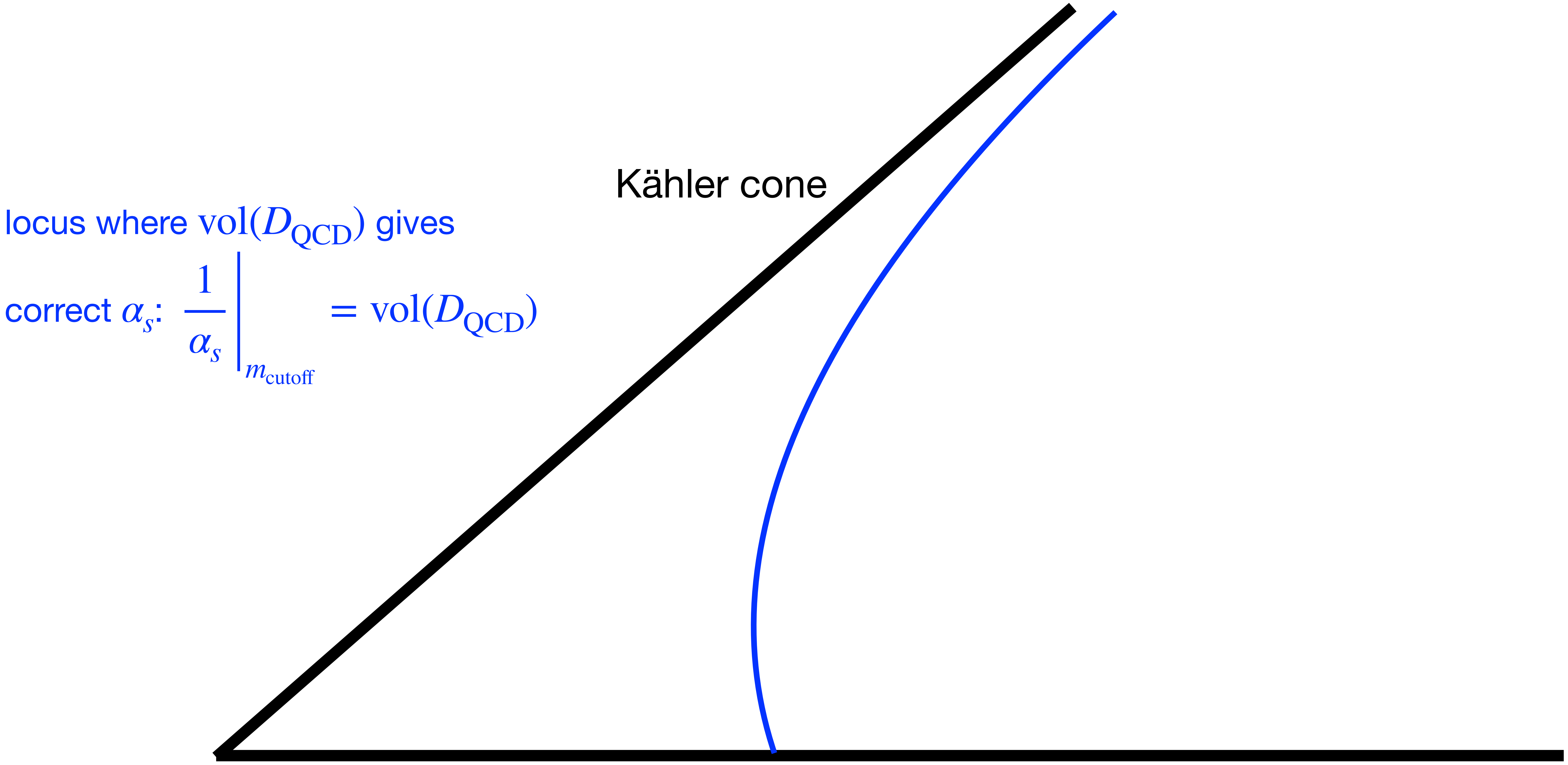

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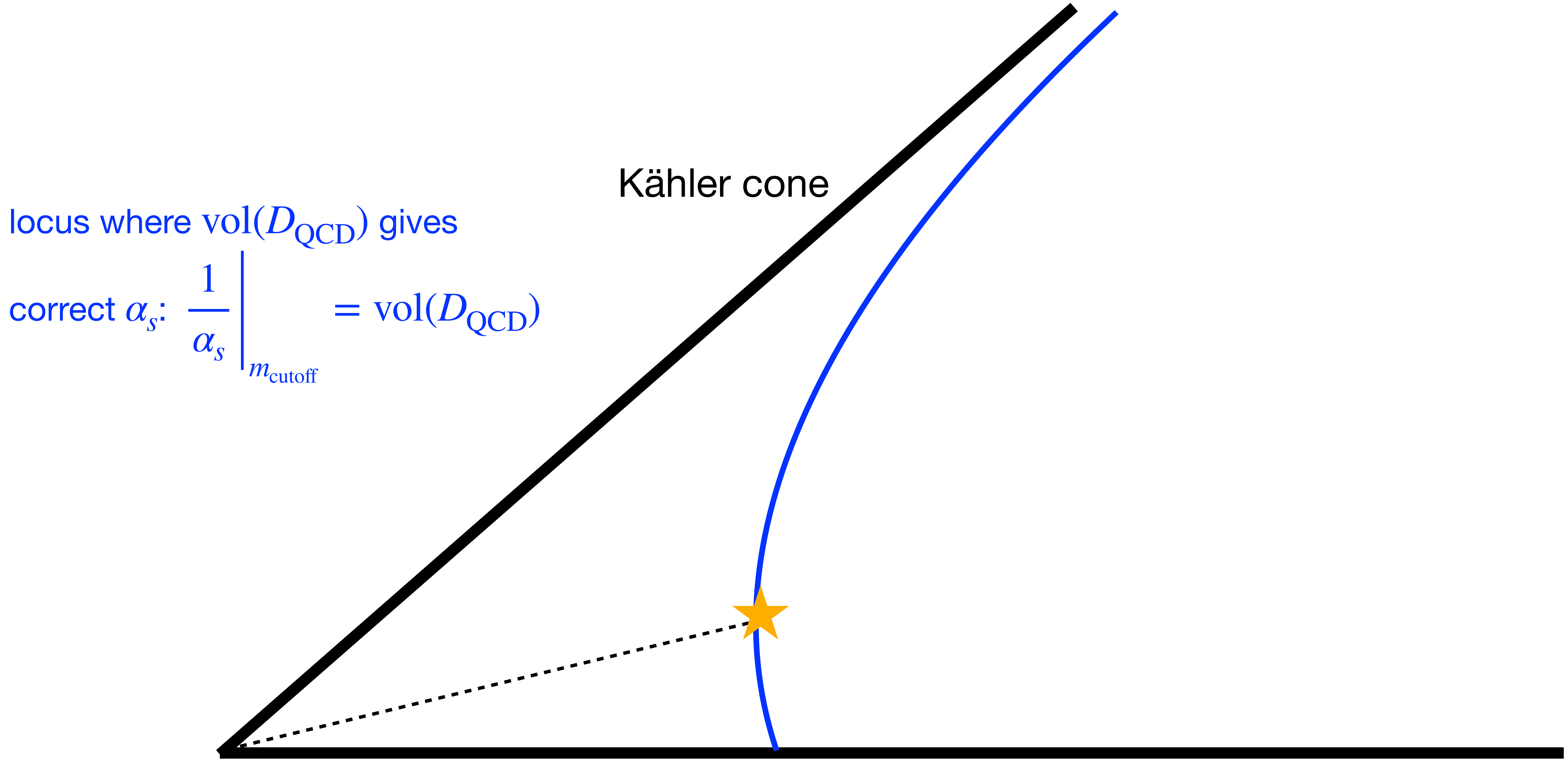

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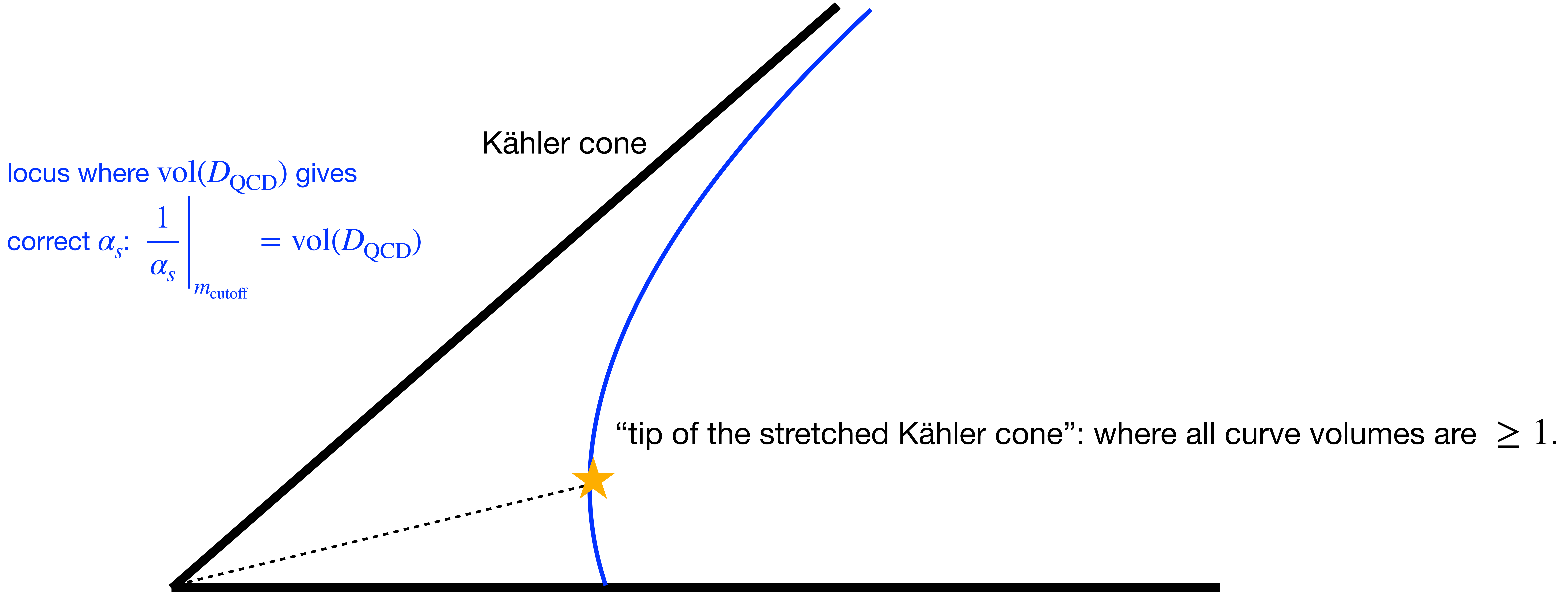

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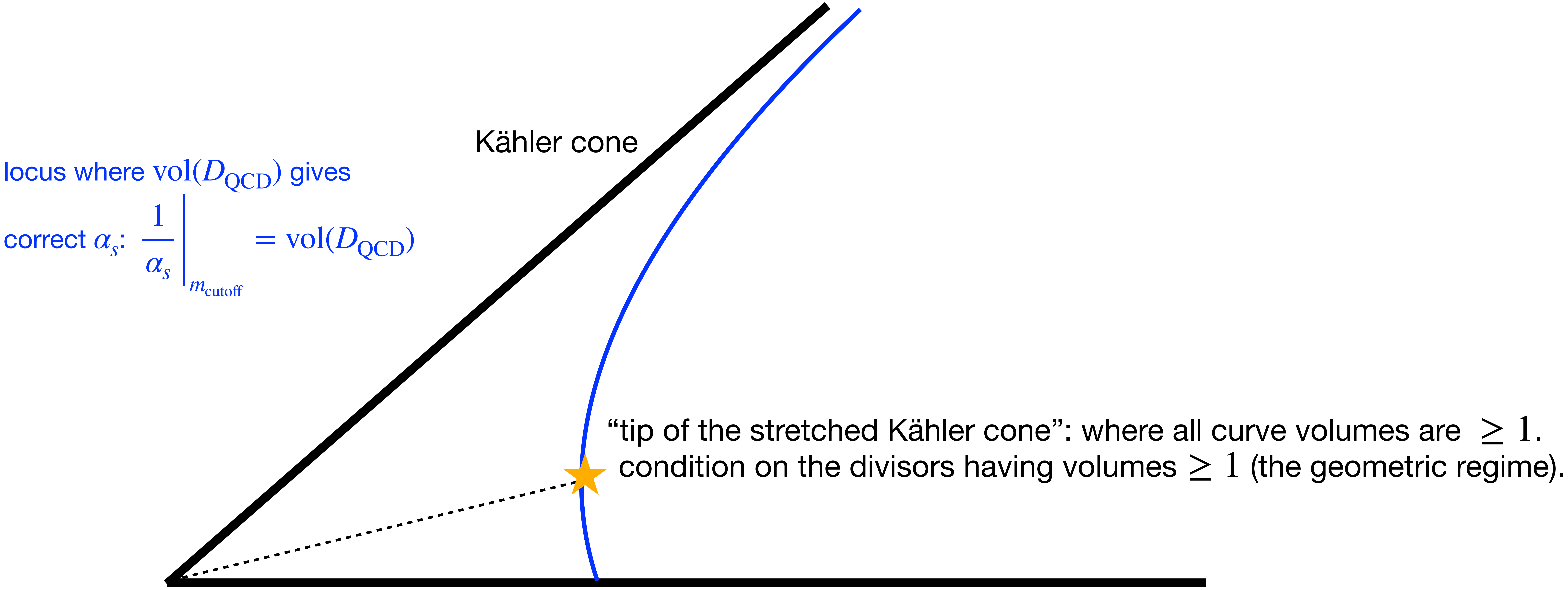

A first test: θ-angles in type IIB string theory

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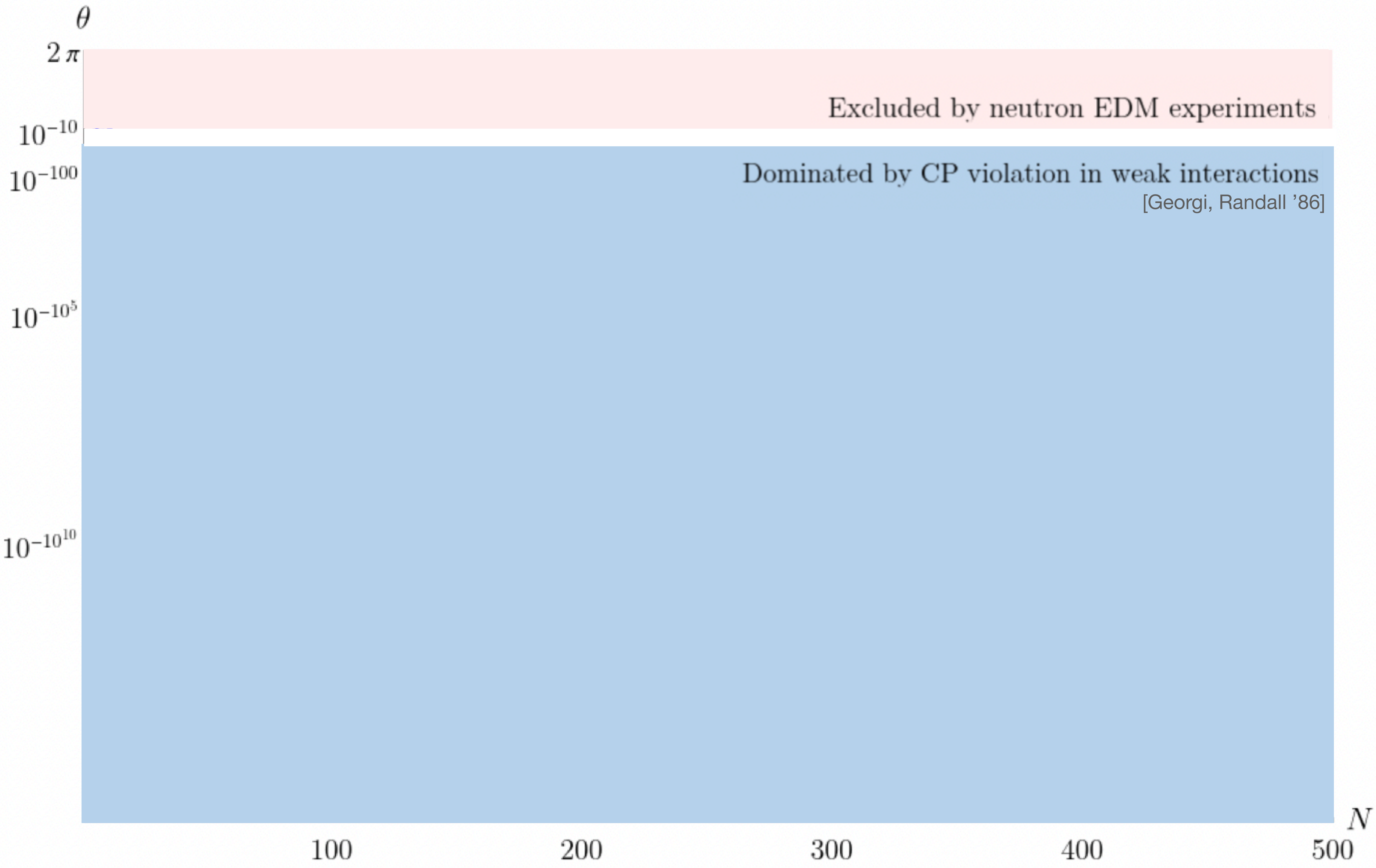
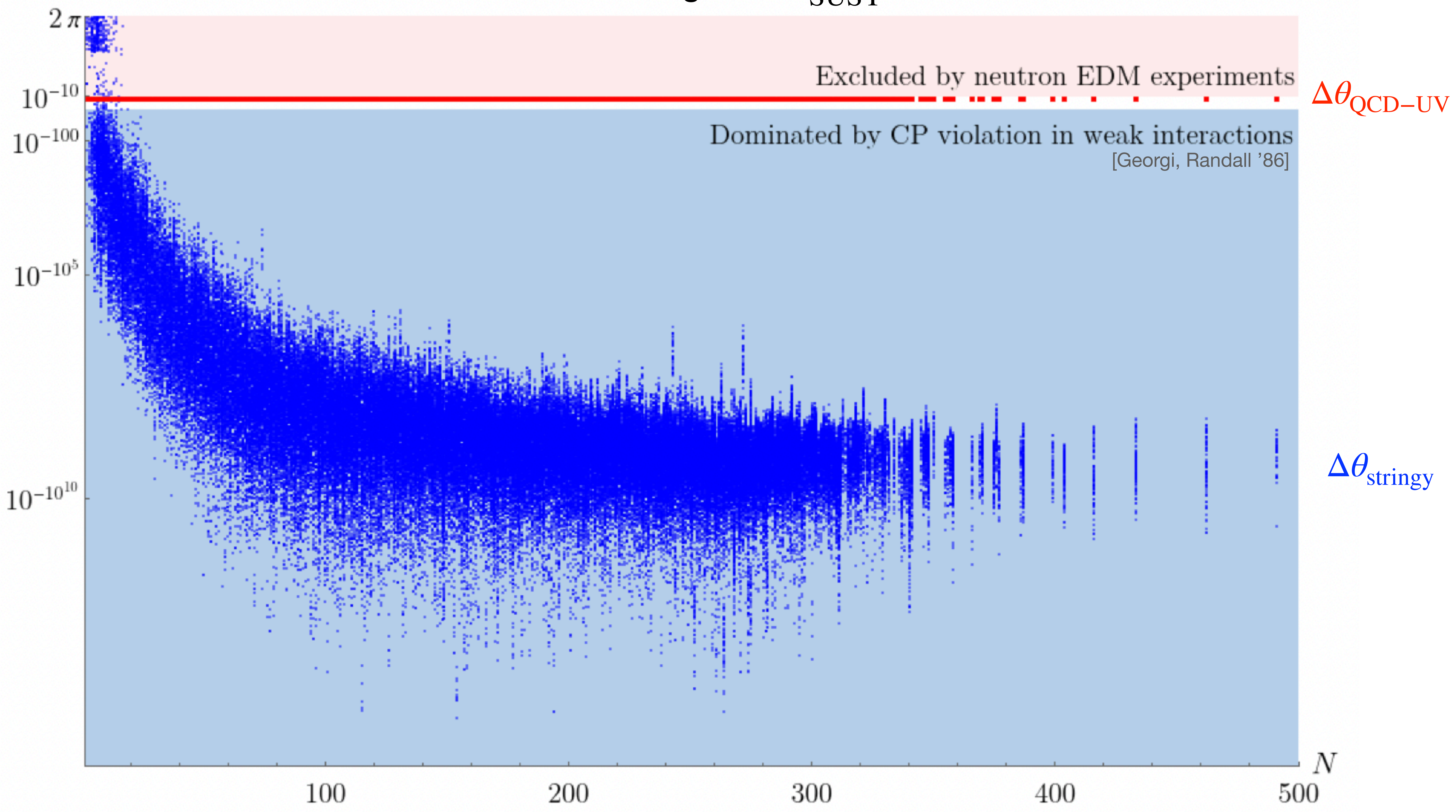
- **The search space:** 32,040 Calabi-Yau manifolds obtained as triangulations of 4d reflexive polytopes with $h^{1,1} \leq 491$ randomly selected from the Kreuzer-Skarke database.



θ
2 π
10^{-10}
10^{-100}
10^{-10^5}
10^{-10^{10}}
Excluded by neutron EDM experiments
Dominated by CP violation in weak interactions
[Georgi, Randall '86]
N
100
200
300
400
500

The QCD θ-angle at $M_{\text{SUSY}} = 1$ TeV



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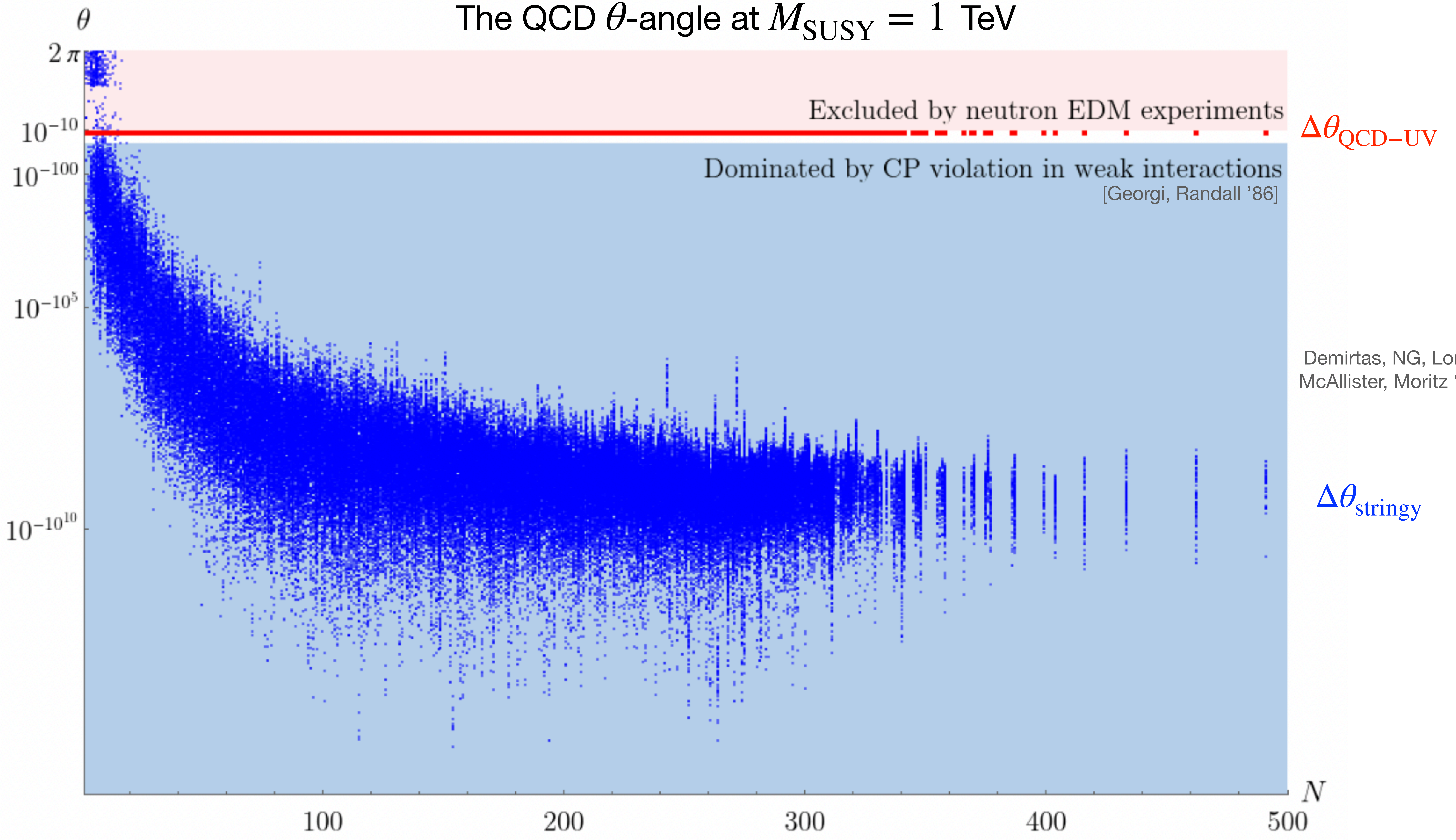


Demirtas, NG, Long
McAllister, Moritz '21

High-scale instantons

CP-breaking operators of dimension 6 or higher in SMEFT can lift fermion zero modes, e.g.

$$S_{\text{eff}} \supset \int d^4x \, \lambda_{ijkl} M^{-2} \mathcal{O}_6^{ijkl} + c.c.$$

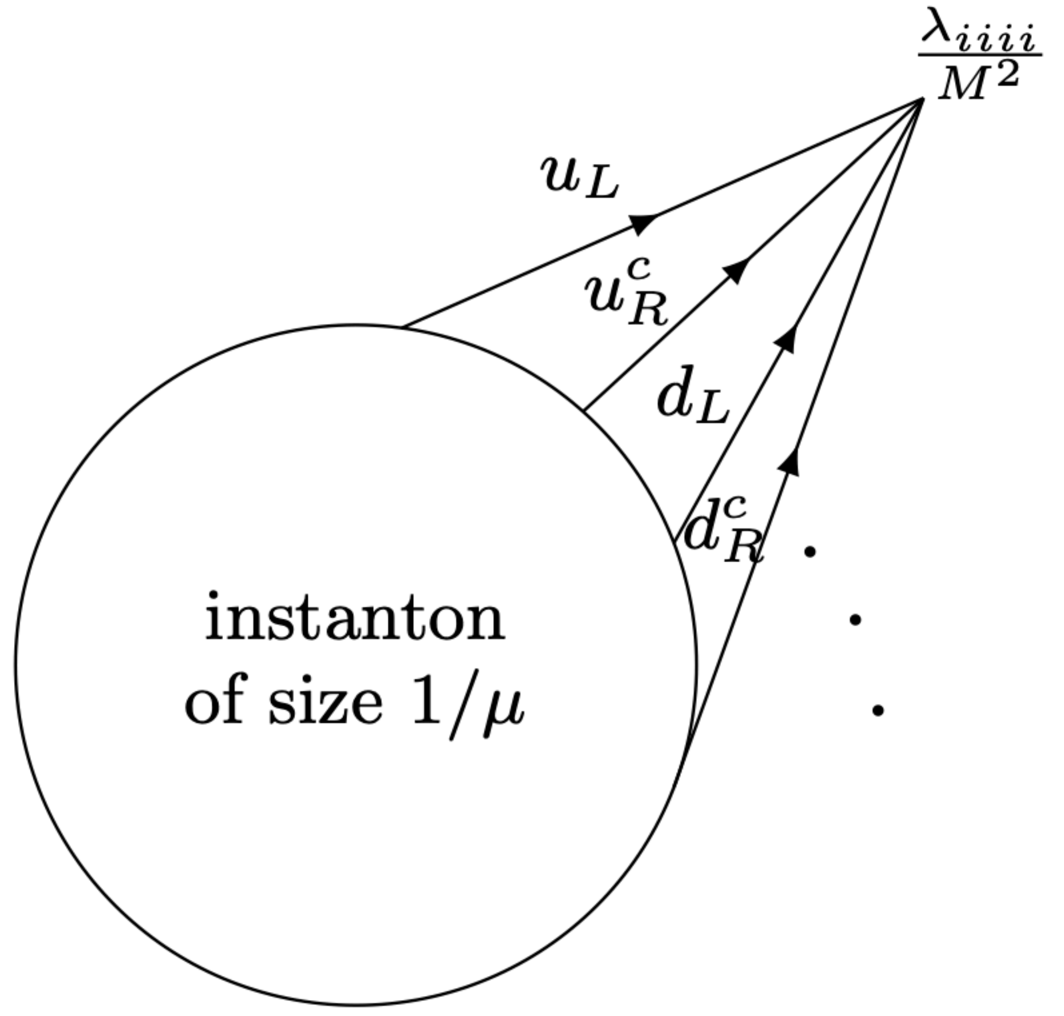
$$Q^i \equiv \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}, \; i = 1, 2, 3,$$

$$U^i \equiv (u_R^i)^c \qquad D^i \equiv (d_R^i)^c$$

With

$$\mathcal{O}_6^{ijkl} := \epsilon_{ab} D^i Q^{j,a} U^k Q^{l,b}$$

$$\delta V_{\text{inst.}}^{UV} \sim \int \frac{d\mu}{\mu} \mu^4 \prod_{i=1}^{3} \frac{\mu^2 \lambda_{iiii}}{M^2} e^{-\frac{2\pi}{\alpha_\mu} - i\theta} + c.c.$$



With SUSY breaking:

$$\delta V_{\rm inst.}(M) \sim \frac{8\pi}{\alpha_M} M_{\rm SUSY} M^3\, e^{-\frac{2\pi}{\alpha_M} - i(\theta - \phi_M)} + c.c.$$

Matching the gauge coupling at the mass of the Z:

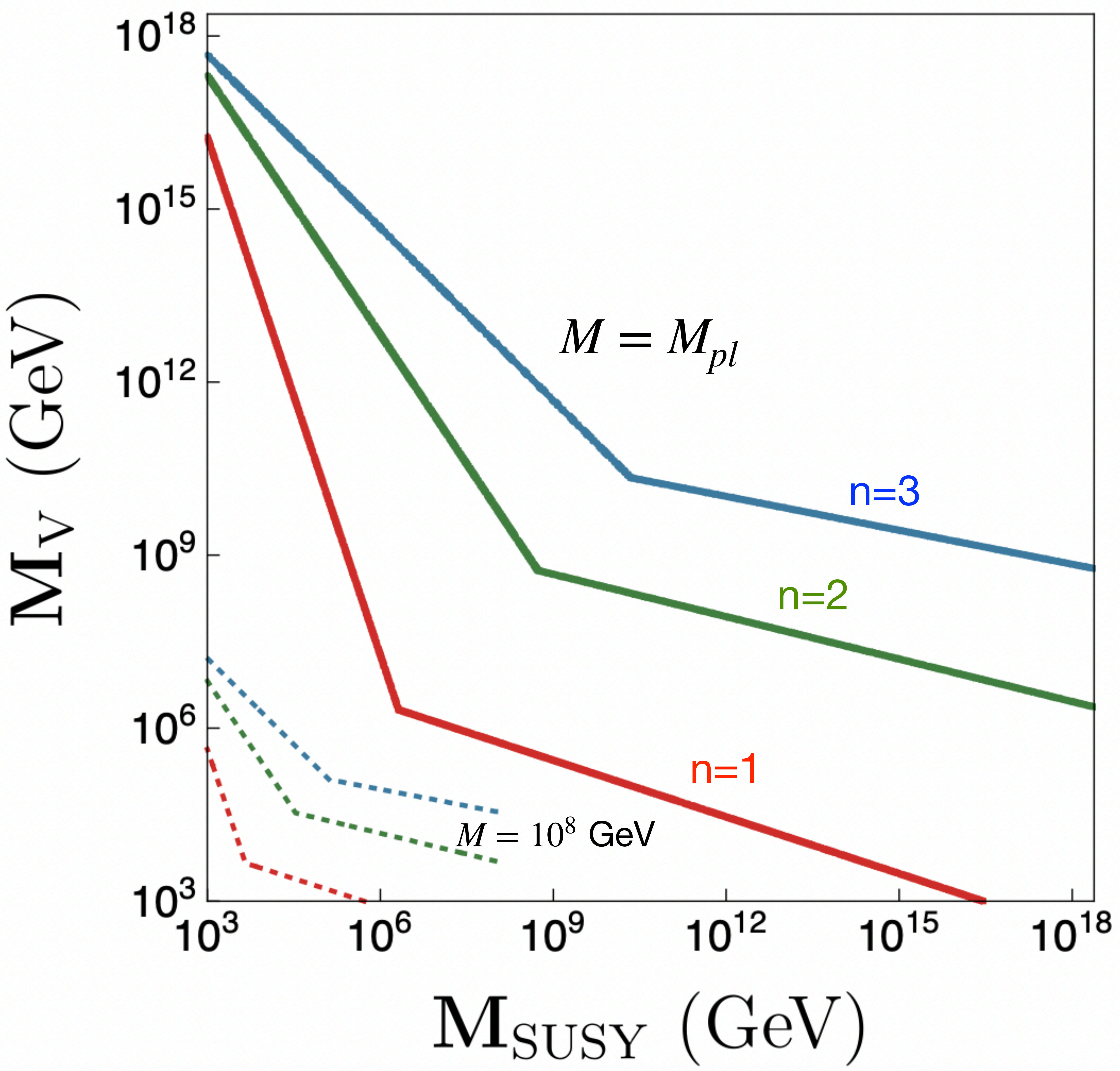
$$\delta V_{\rm inst.}^{M > M_{\rm SUSY}} \sim \frac{8\pi}{\alpha_M} \left(\frac{m_Z}{M_{\rm SUSY}}\right)^3 m_Z^4 e^{-\frac{2\pi}{\alpha_Z}}\, e^{-i(\theta - \phi_M)}$$

Plugging in numbers:

$$\Delta\theta_{\rm QCD} \sim 10^{-12} \left(\frac{1\,{\rm TeV}}{M_{\rm SUSY}}\right)^3$$

Vector-like matter

$$\delta V_{\text{inst.}}(M) \sim \left(\frac{m_Z}{M_{susy}}\right)^3 \left(\frac{M}{M_V}\right)^n m_Z^4 e^{-\frac{2\pi}{\alpha(m_Z)}} e^{i(\bar\theta+\phi_M)} + cc\,.$$



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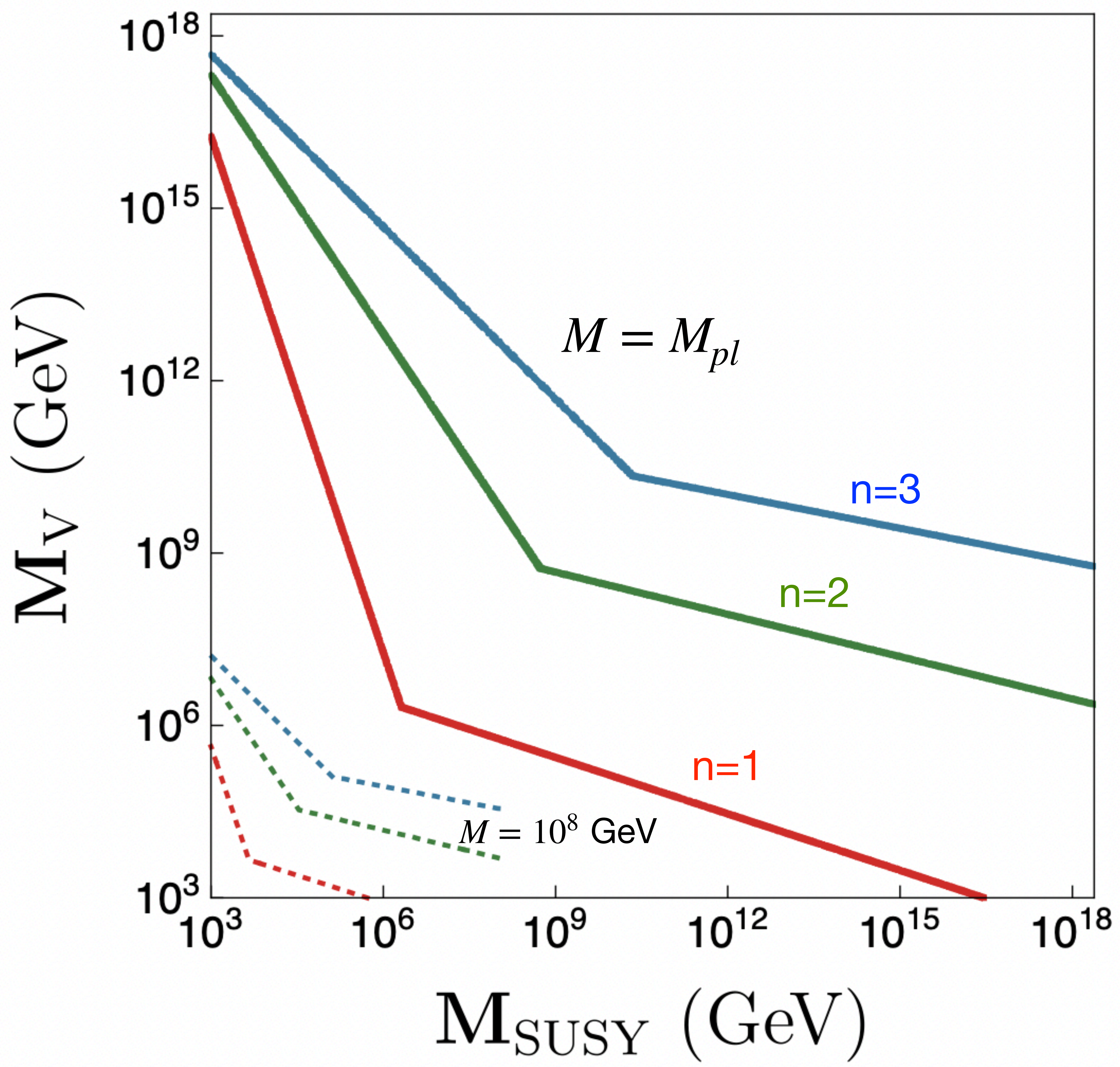

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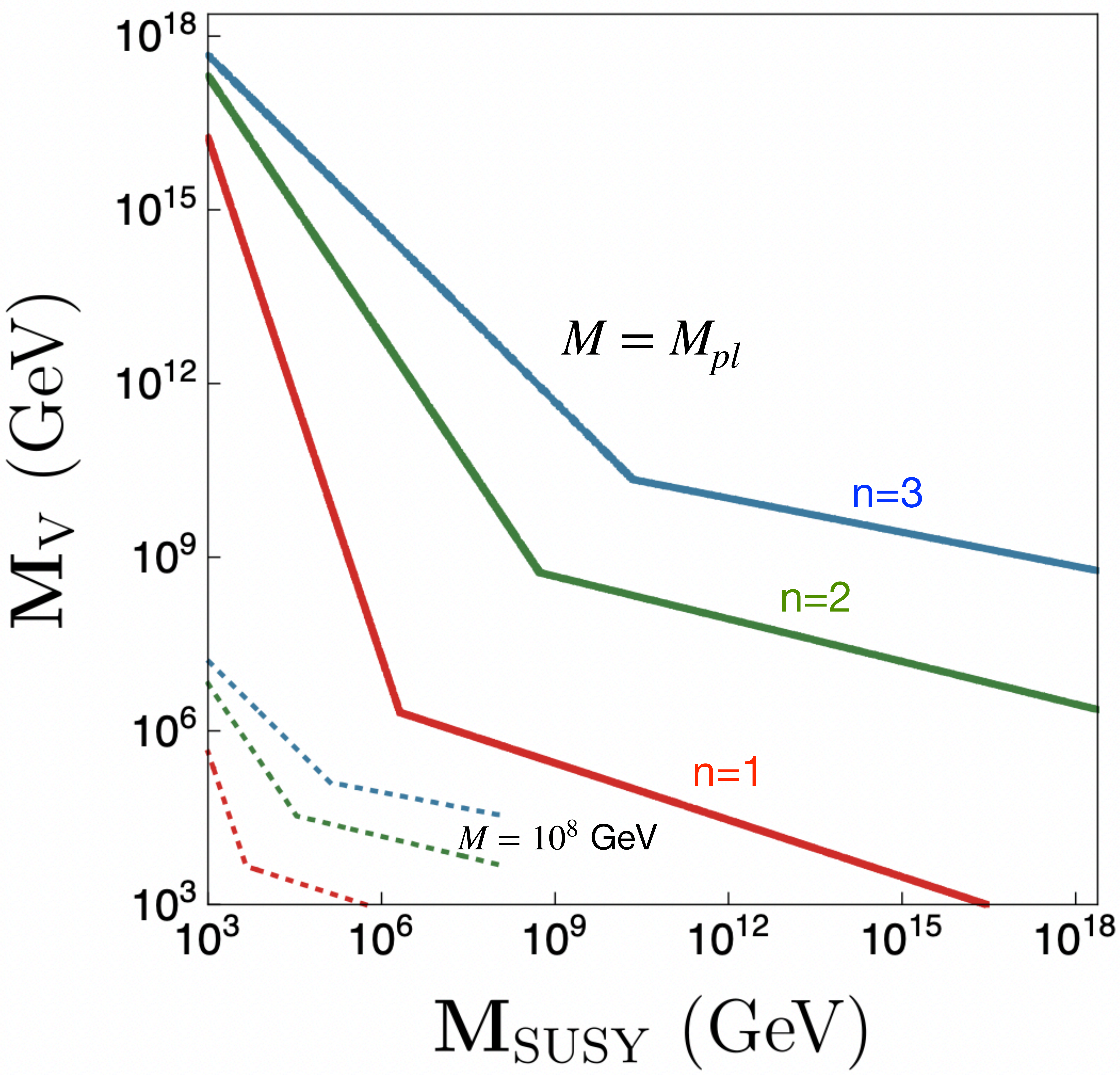
Can give lower bound on M_{SUSY} in order to not spoil PQ



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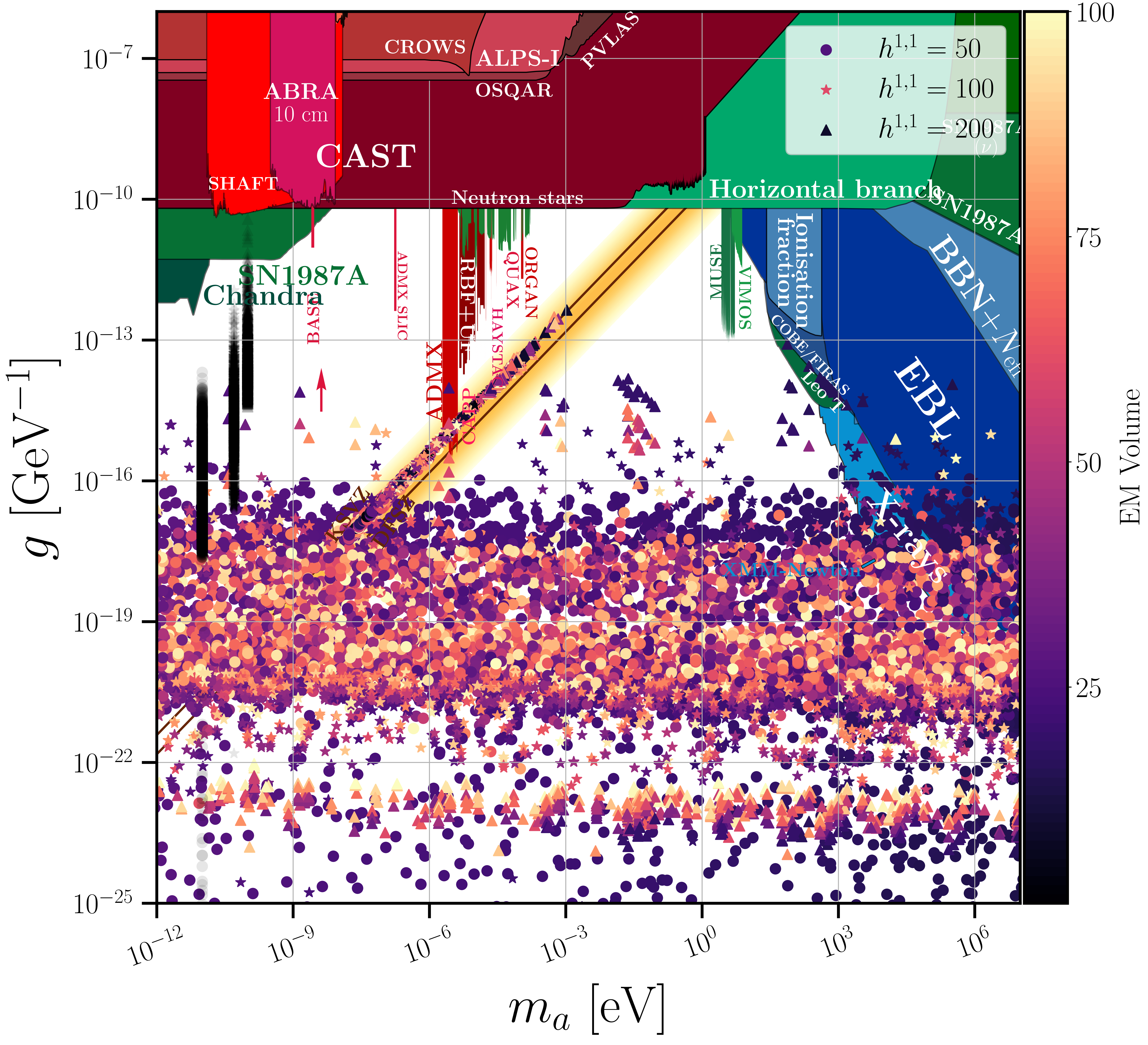
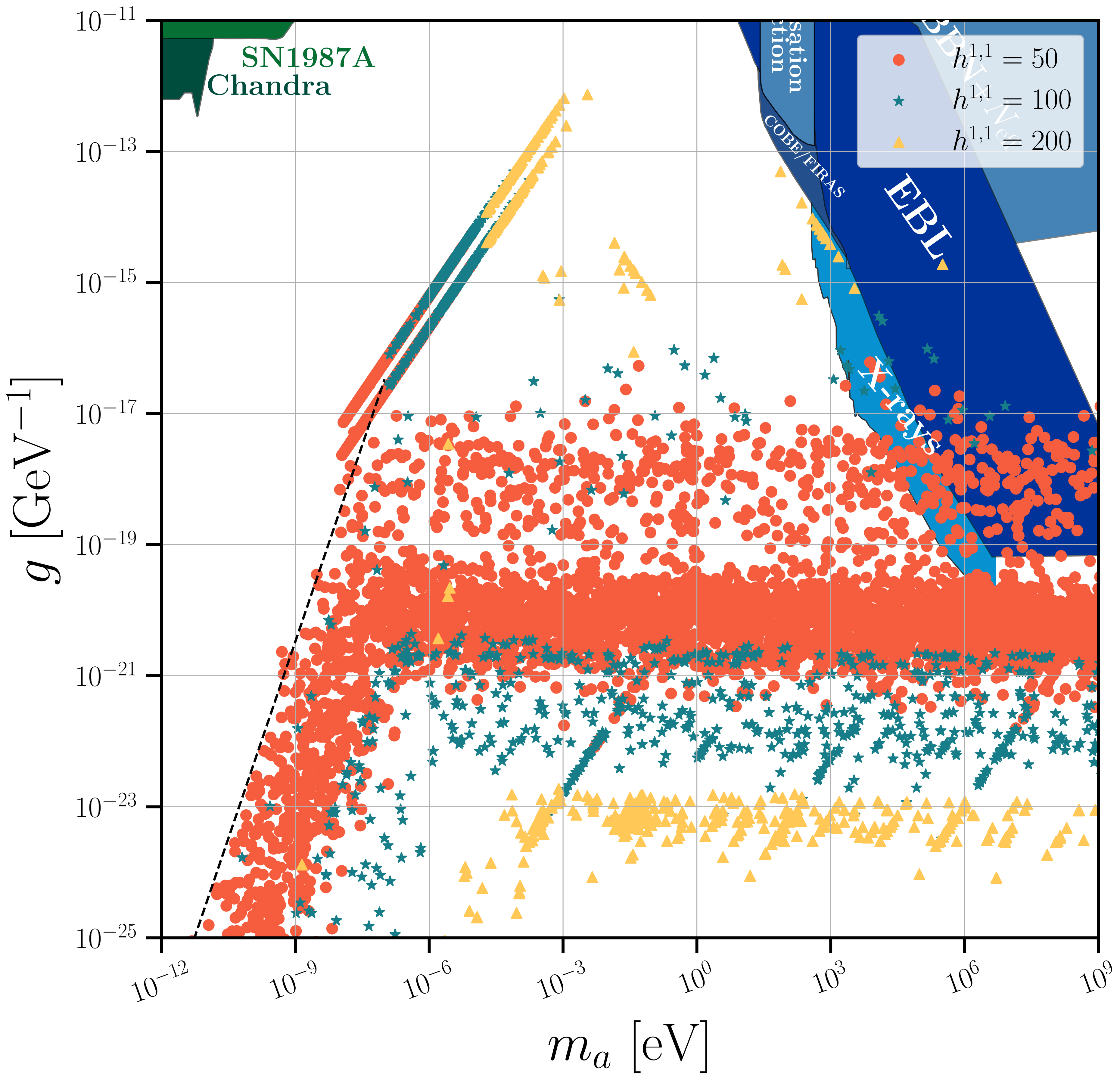
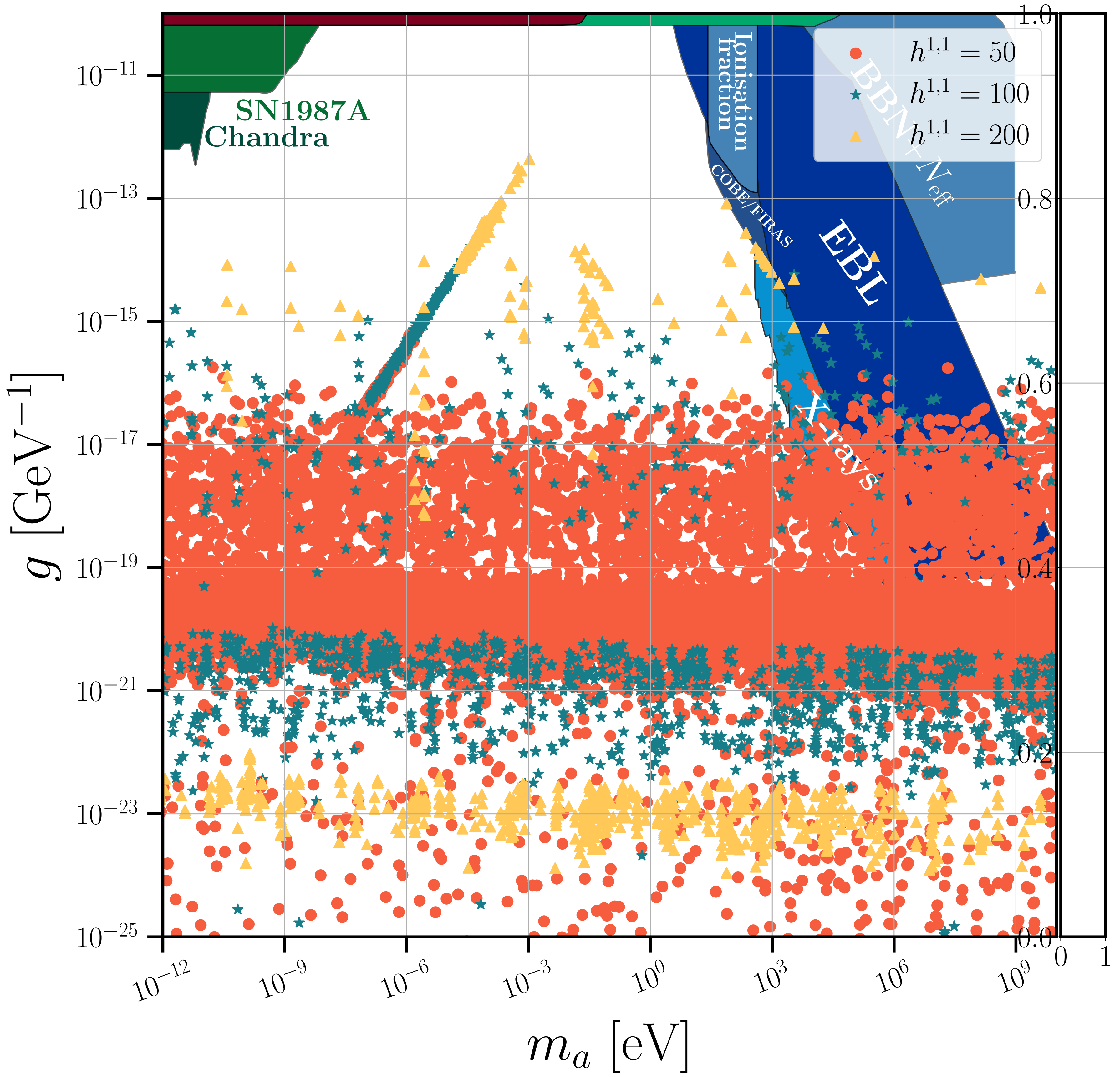
With this in mind, we will now move on to calculating the axion dark matter relic abundance.



CROWS
ALPS-I
PVLAS
OSQAR
ABRA
10 cm
CAST
SHAFT
Neutron stars
Horizontal branch
SN1987A
Chandra
ADMX SLIC
BASE
ADMX
RBF+UF
QUAX
ORGAN
HAYSTAC
CAPP
MUSE
VIMOS
Ionisation fraction
COBE/FIRAS
Leo T
BBN+N_{eff}
EBL
X-rays
XMM-Newton
$h^{1,1} = 50$
$h^{1,1} = 100$
$h^{1,1} = 200$
EM Volume
g [GeV^{-1}]
m_a [eV]

Axion-photon couplings in the string axiverse





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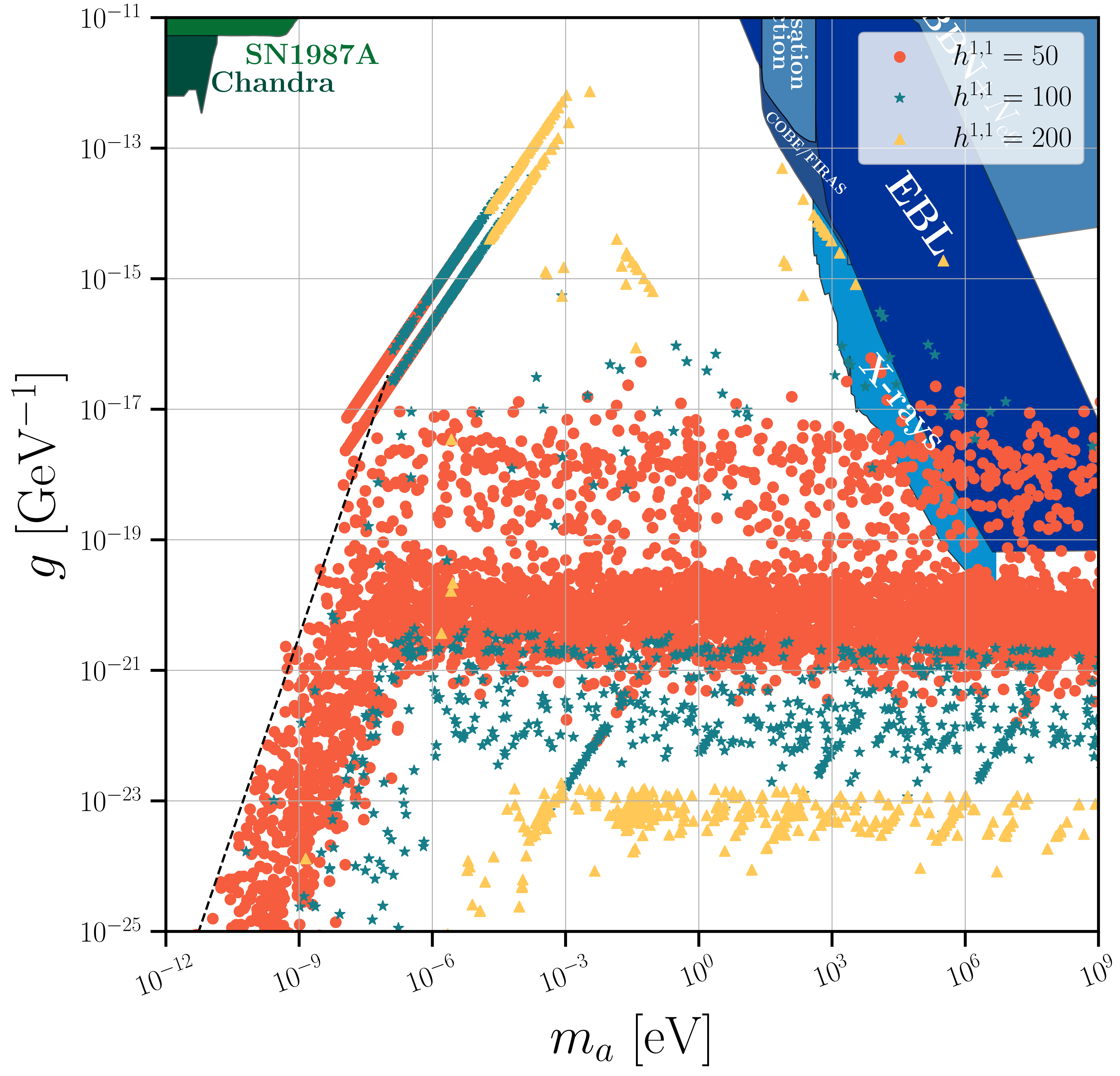

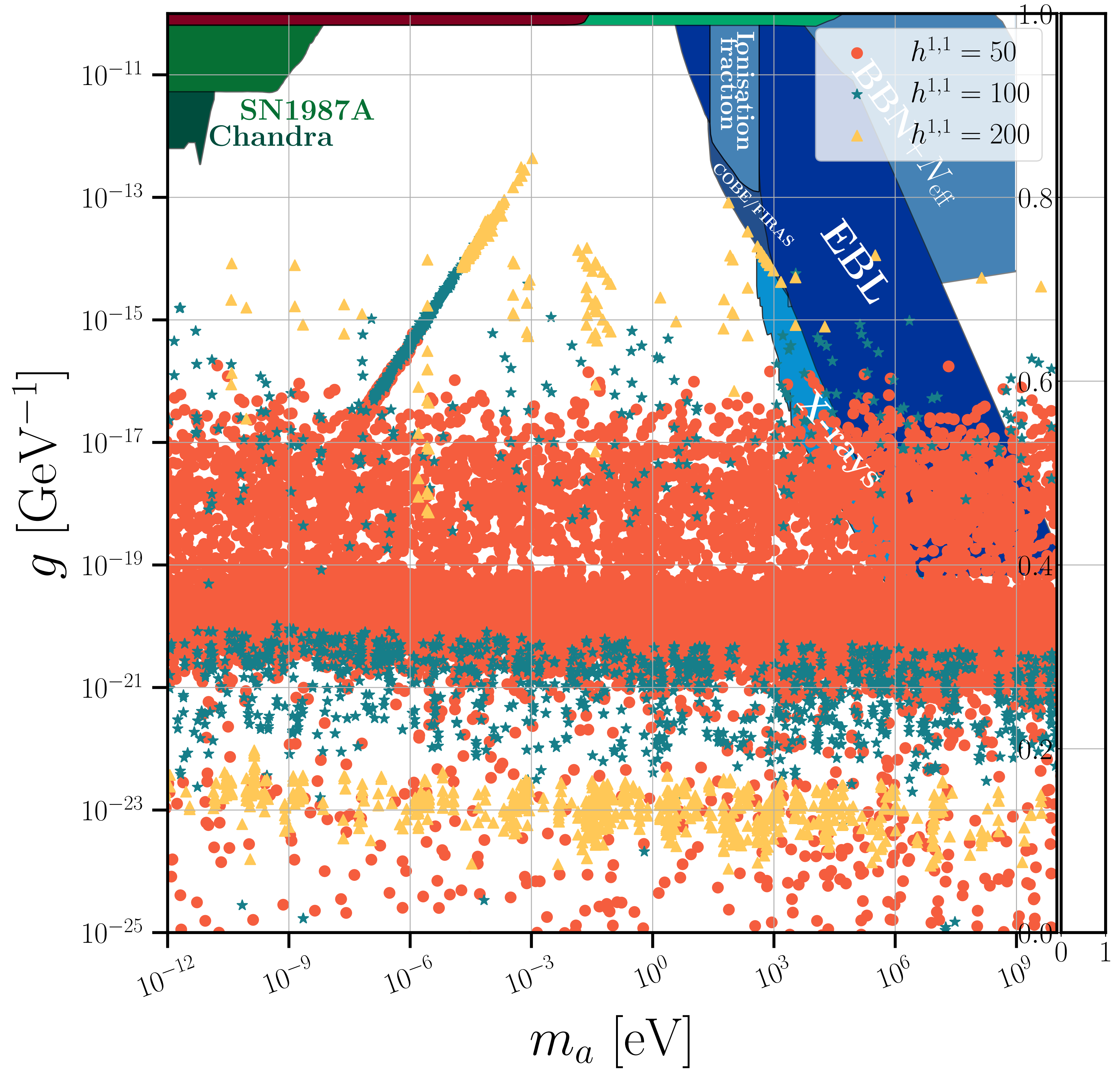

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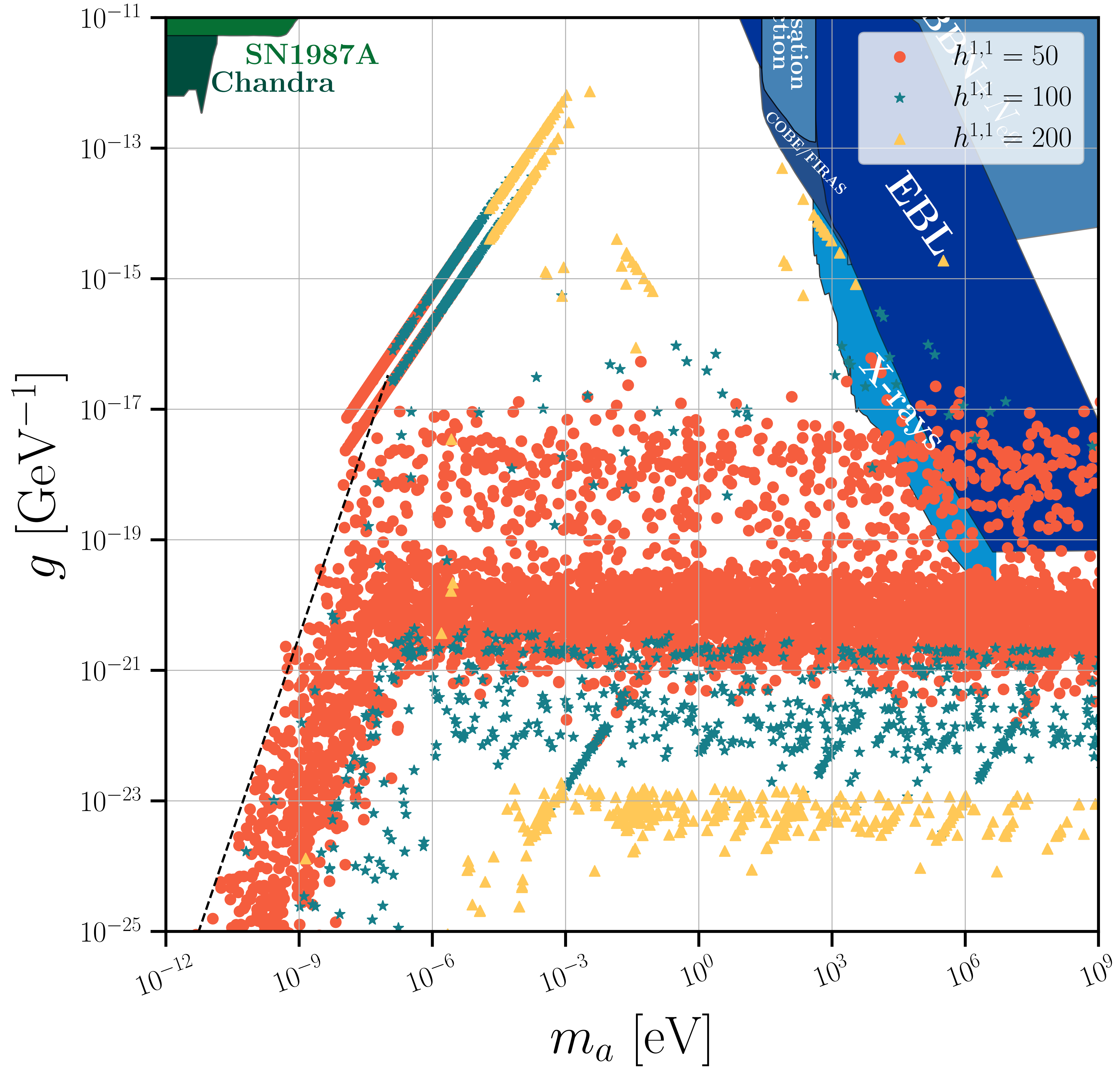

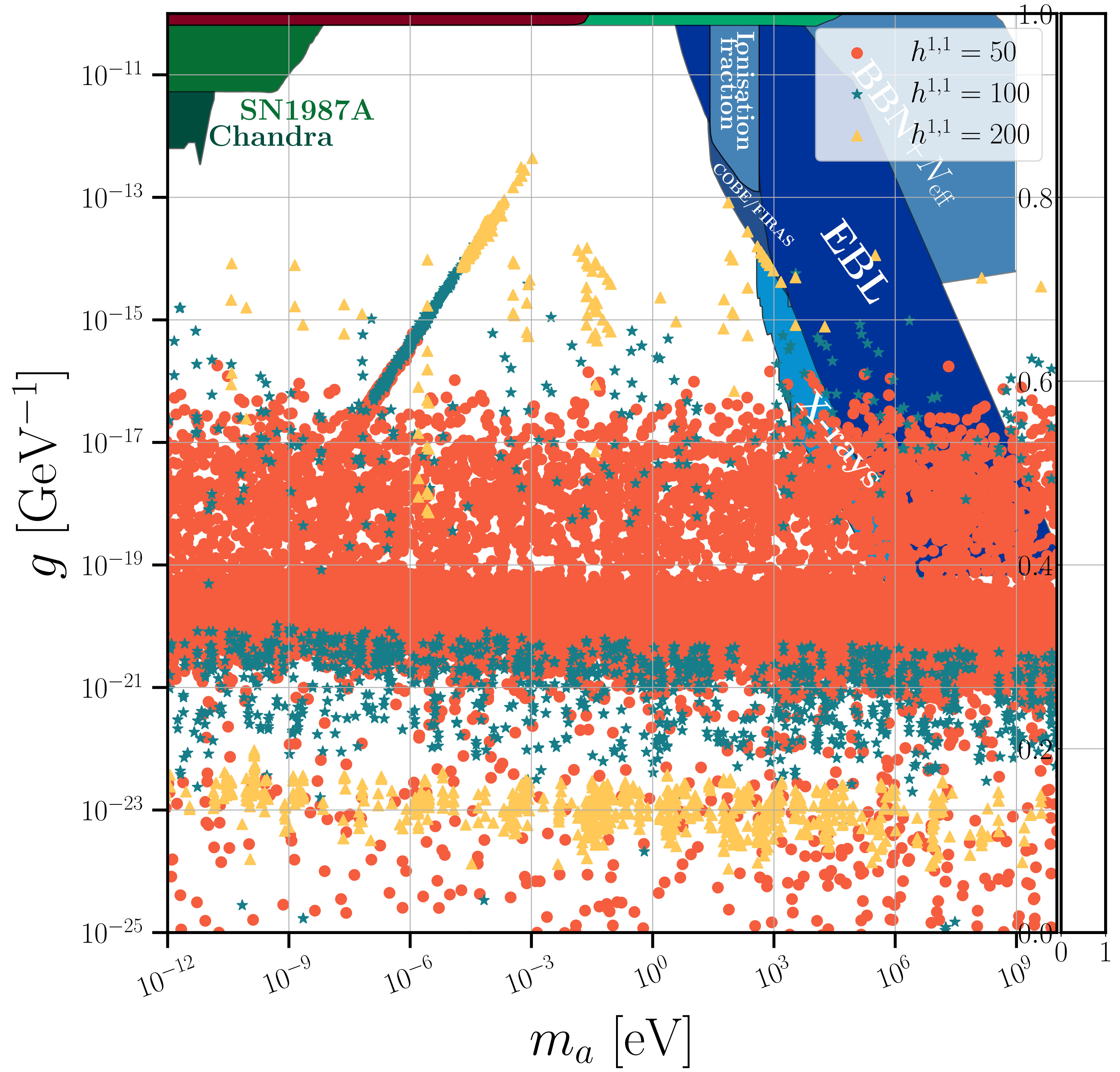

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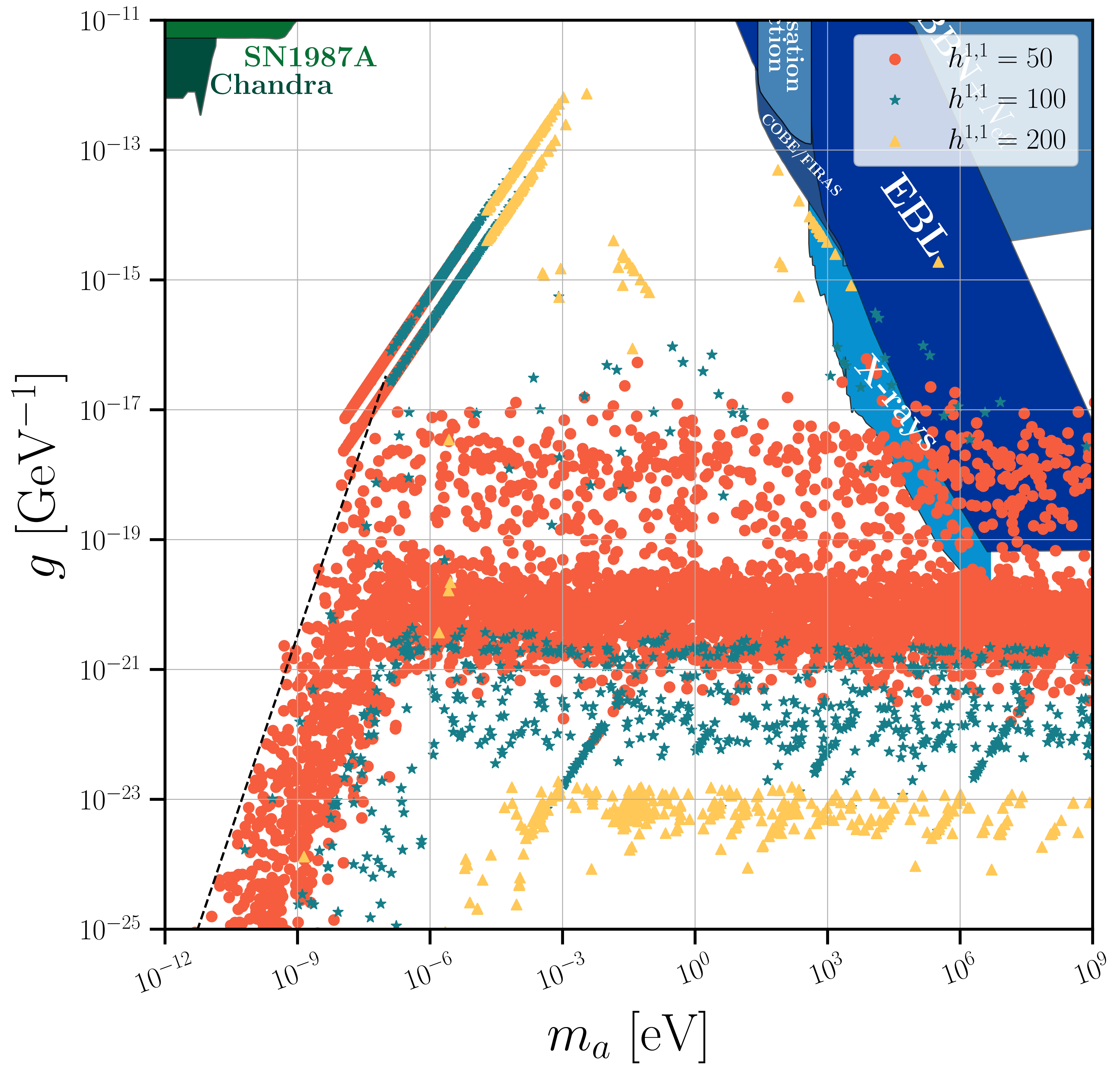
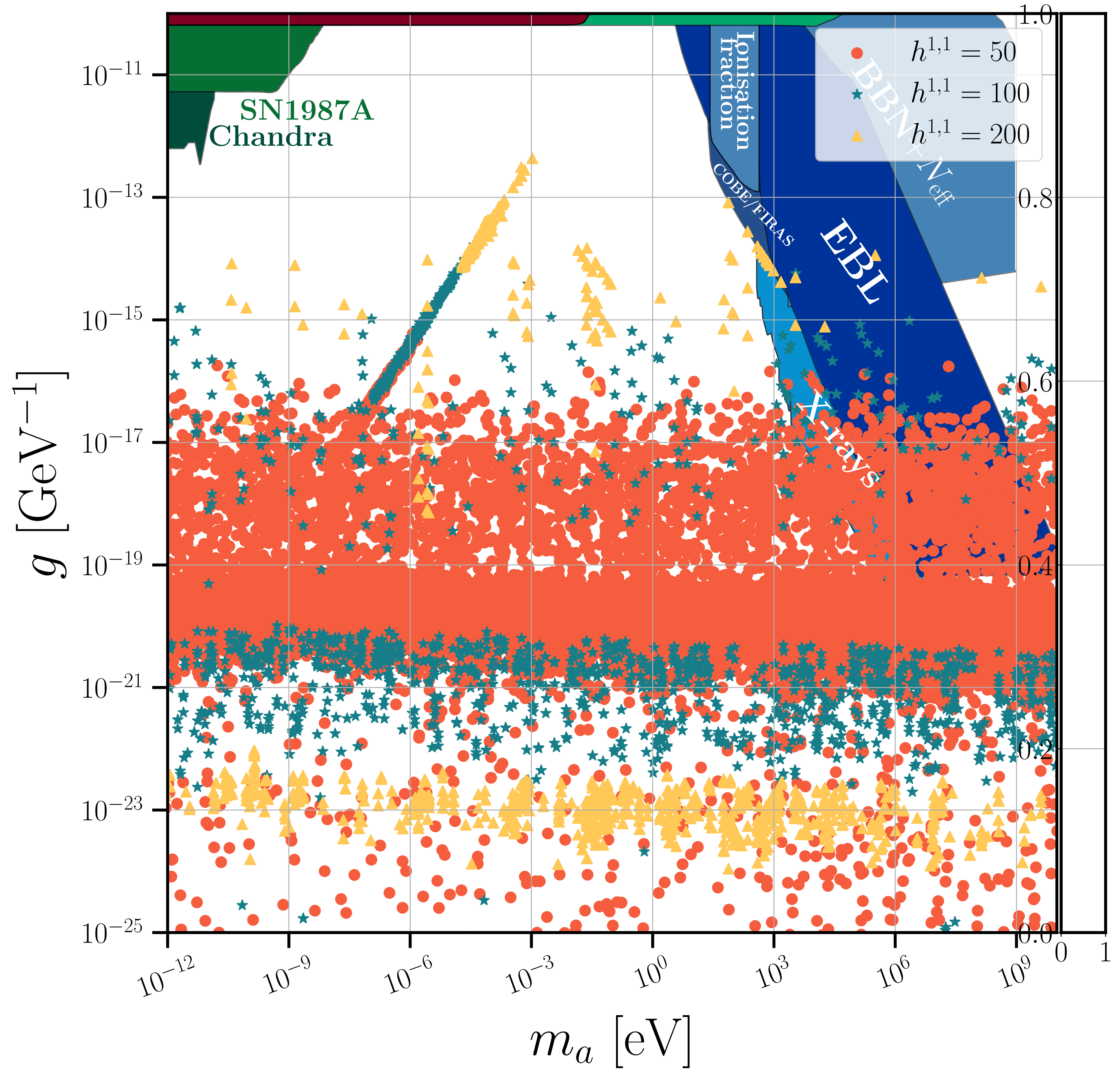


non-GUT



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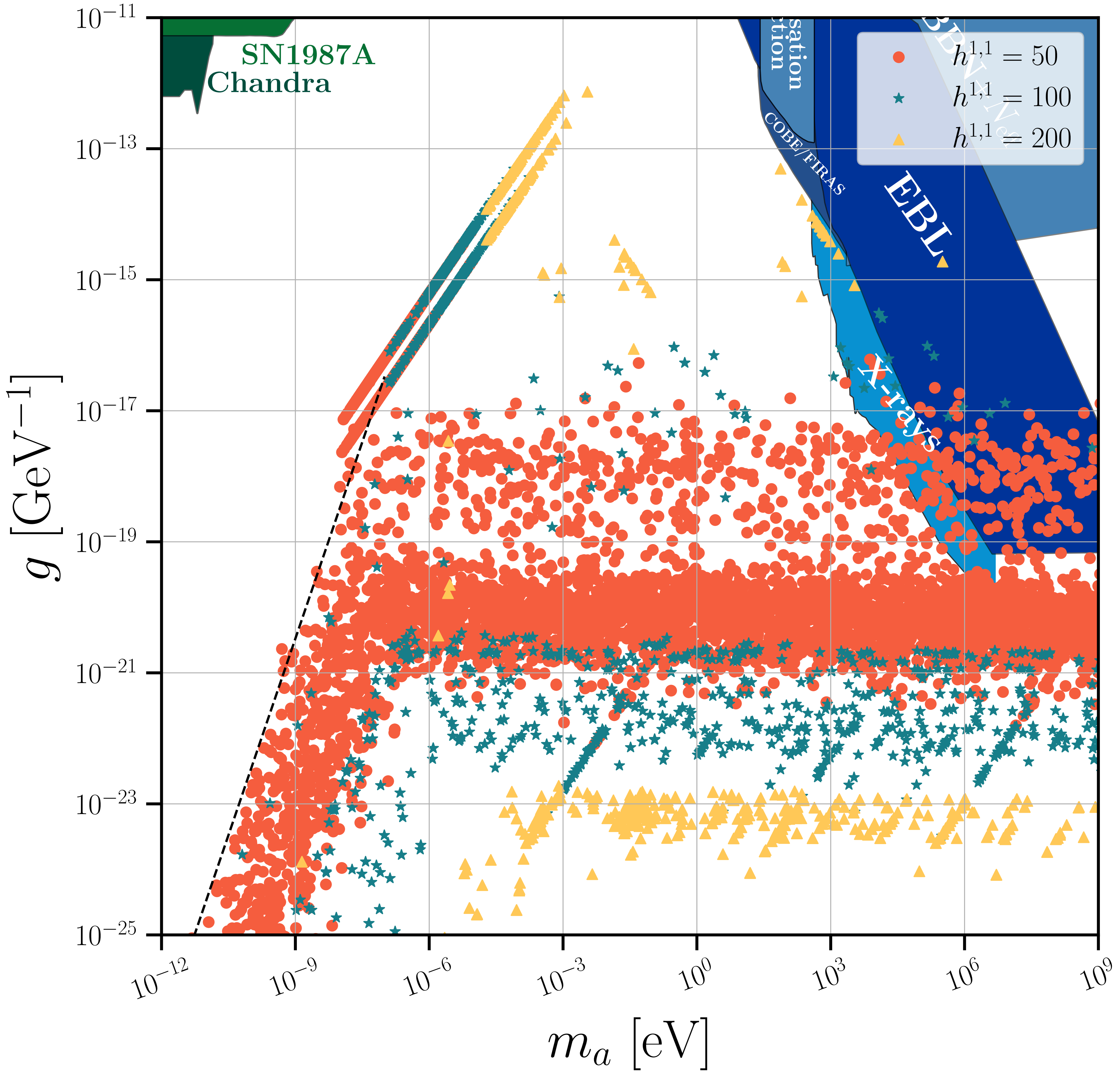

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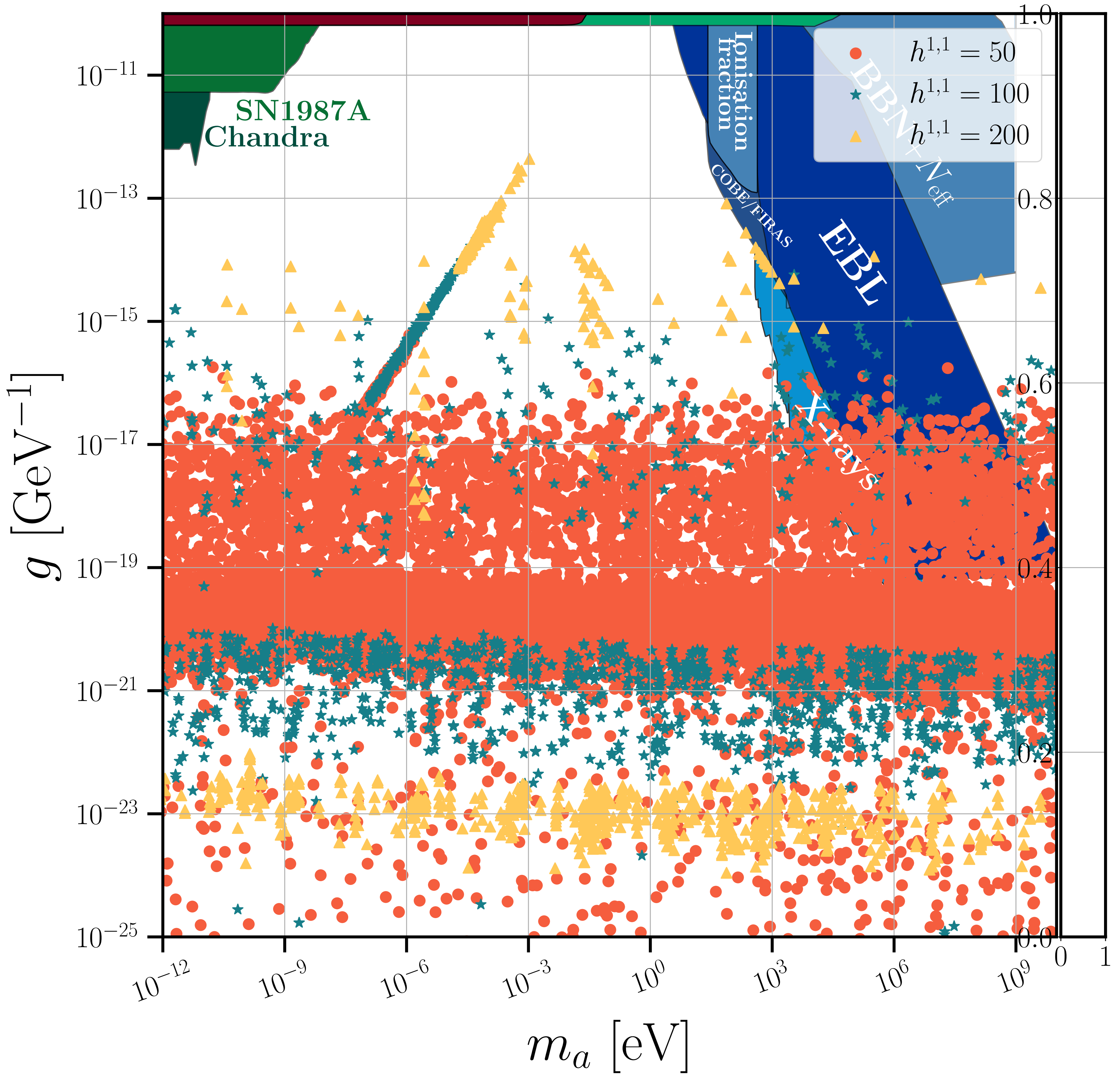

c.f. [Agrawal, Nee, Reig '22]