Caltech

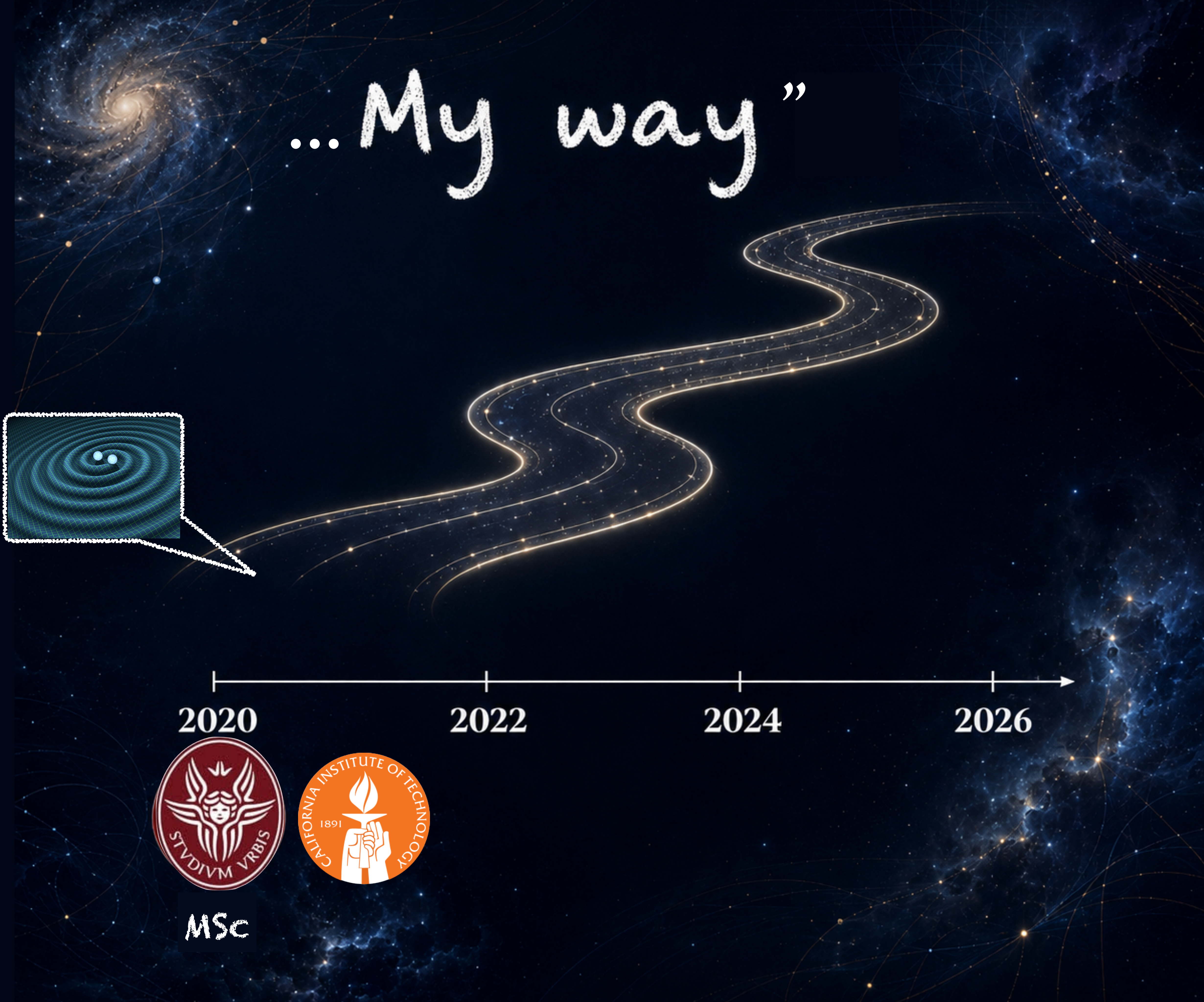
Tracing *New Physics*: From Symmetry to Observation

Samuel Patrone

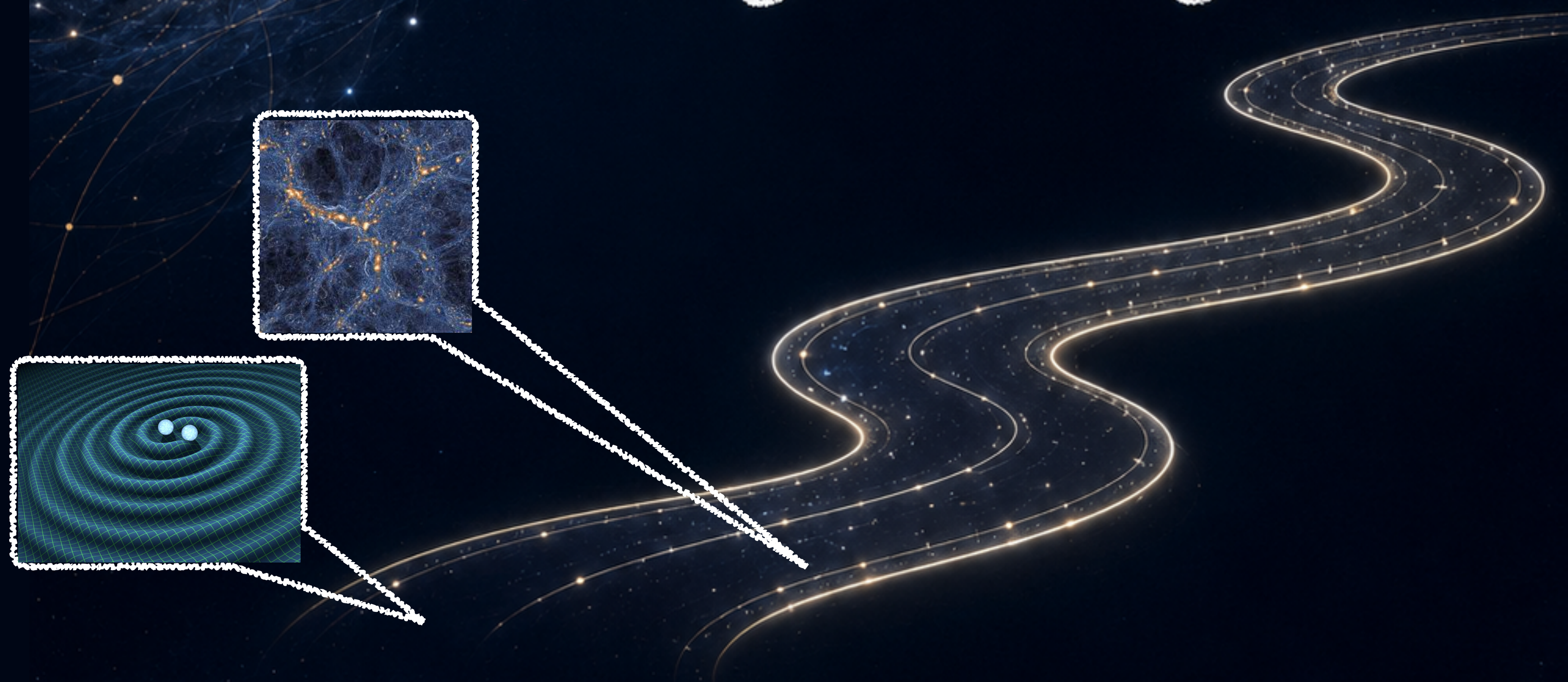
PhD Defense
May 27th, 2026

BURKE INSTITUTE

“And now, the end is near
And so I face the final curtain
My friend, I'll say it clear
I'll state my case, of which I'm certain
I've lived a life that's full I traveled each and every highway
And more, much more than this I did it ...


...My way”
2020
2022
2024
2026
STVDIVM VRBIS
CALIFORNIA INSTITUTE OF TECHNOLOGY
1891
MSc

…My way"



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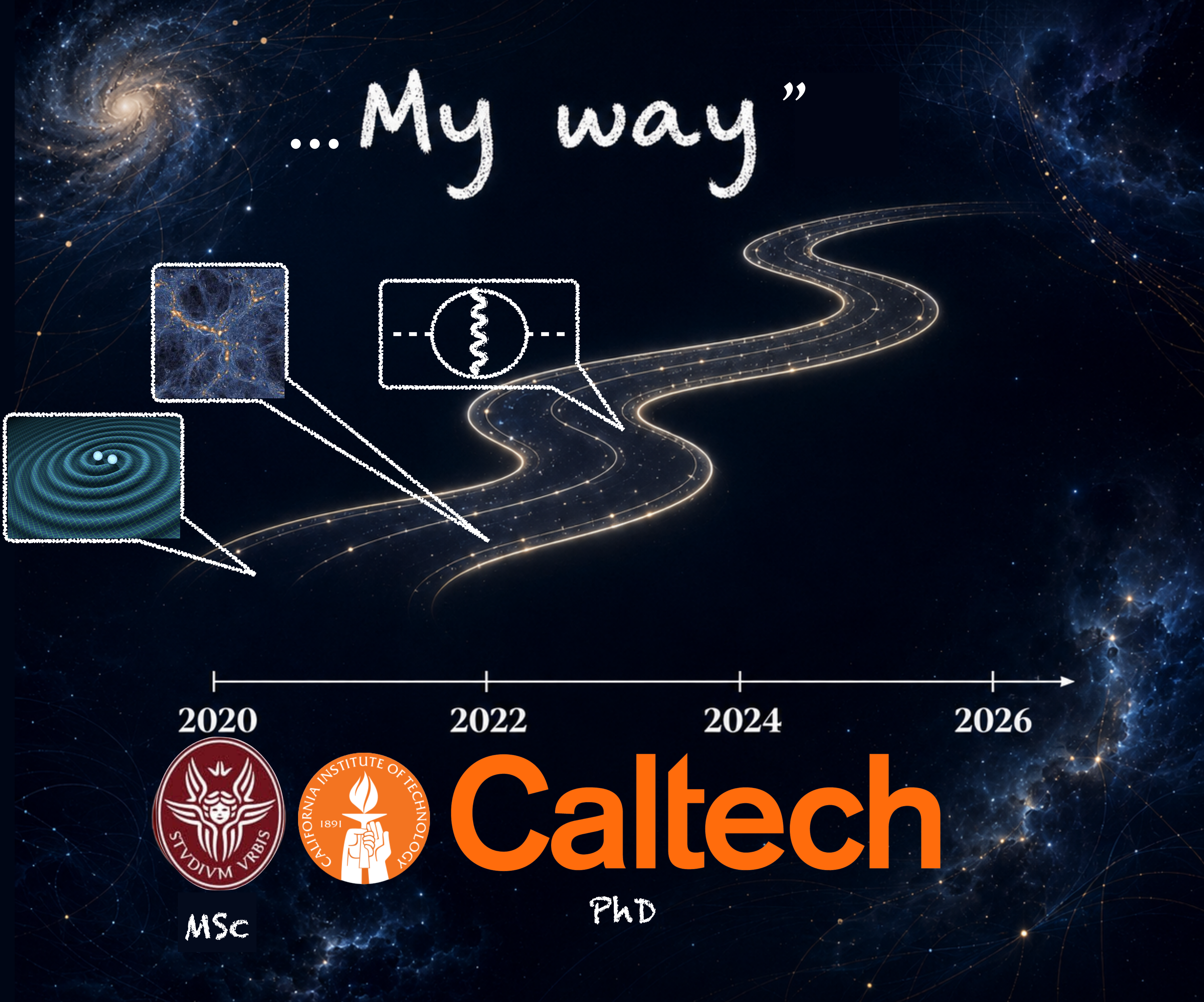

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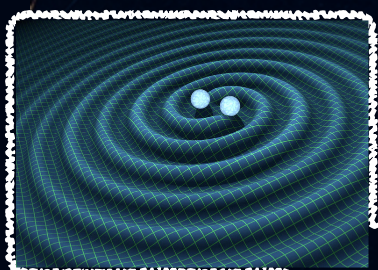

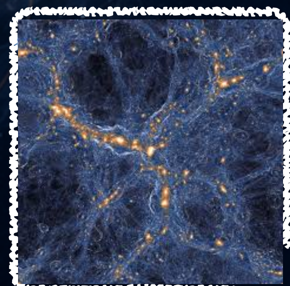

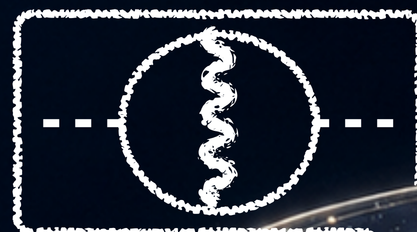

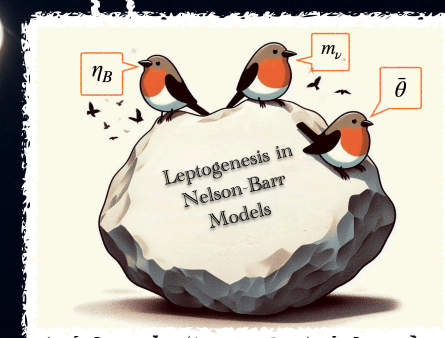

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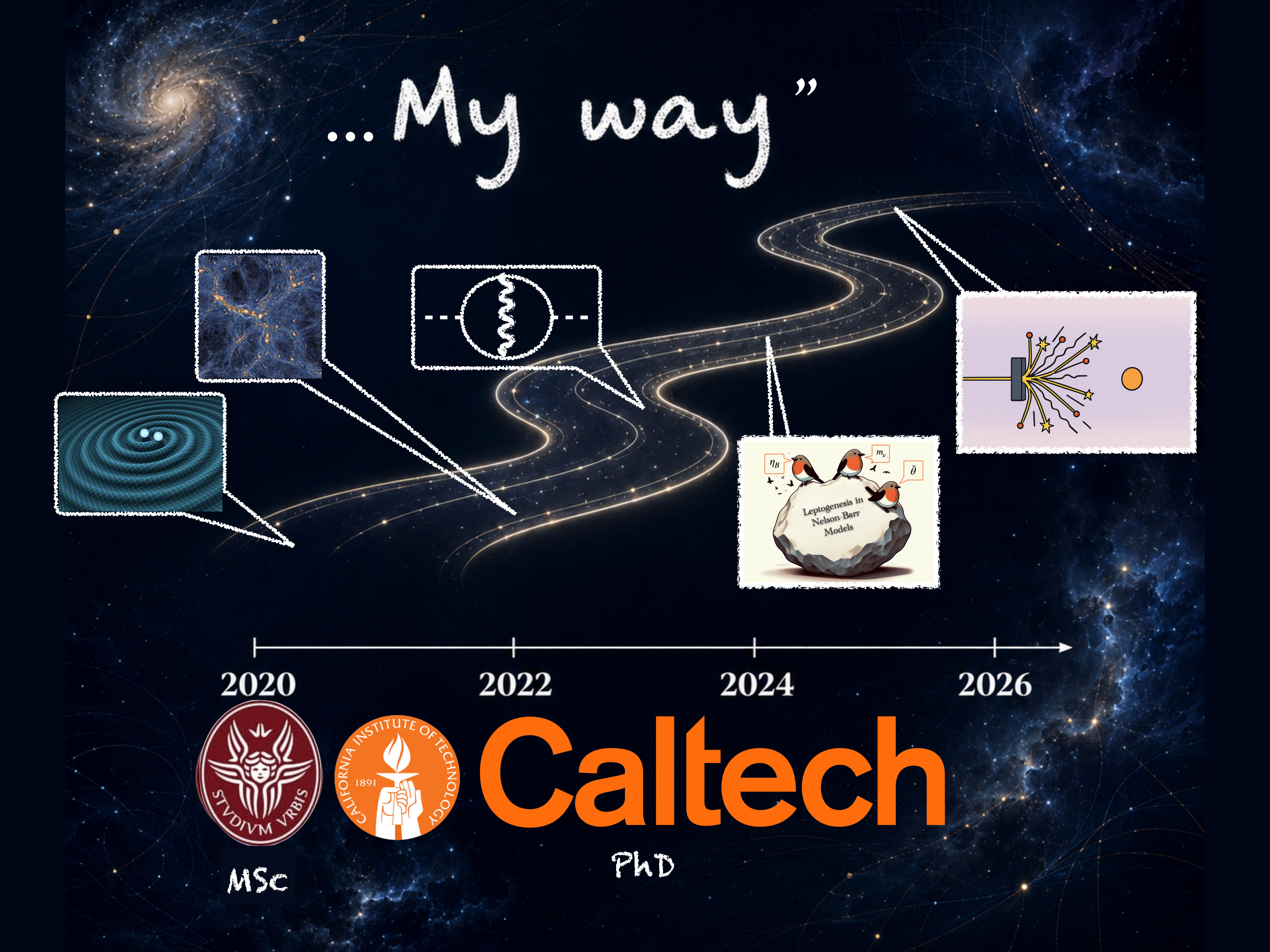

…My way”
Leptogenesis in Nelson-Barr Models
η_B
m_ν
$\bar{\theta}$
2020
2022
2024
2026
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MSc
CALIFORNIA INSTITUTE OF TECHNOLOGY
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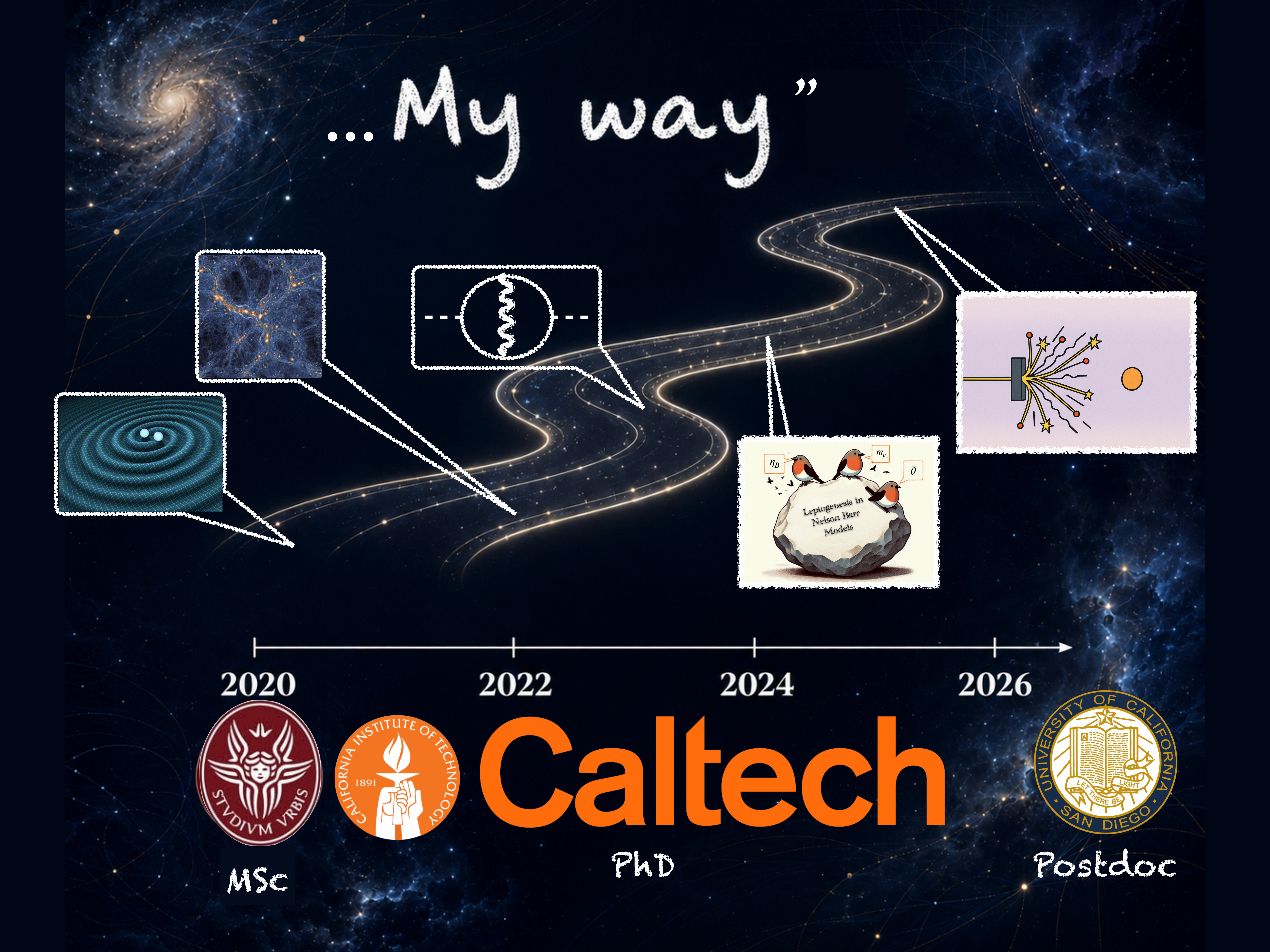
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SAN DIEGO
LET THERE BE LIGHT
MSc
PhD
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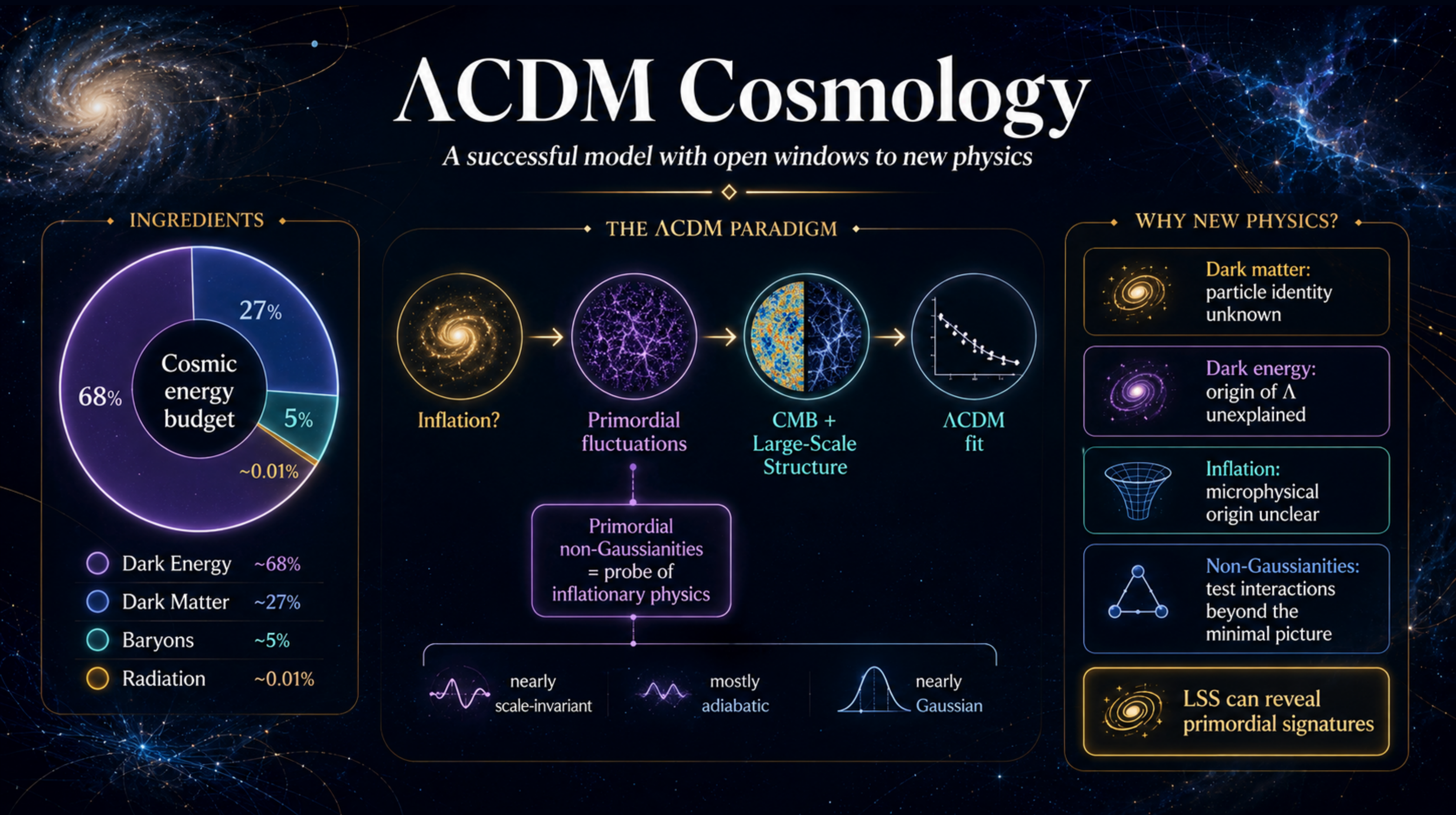
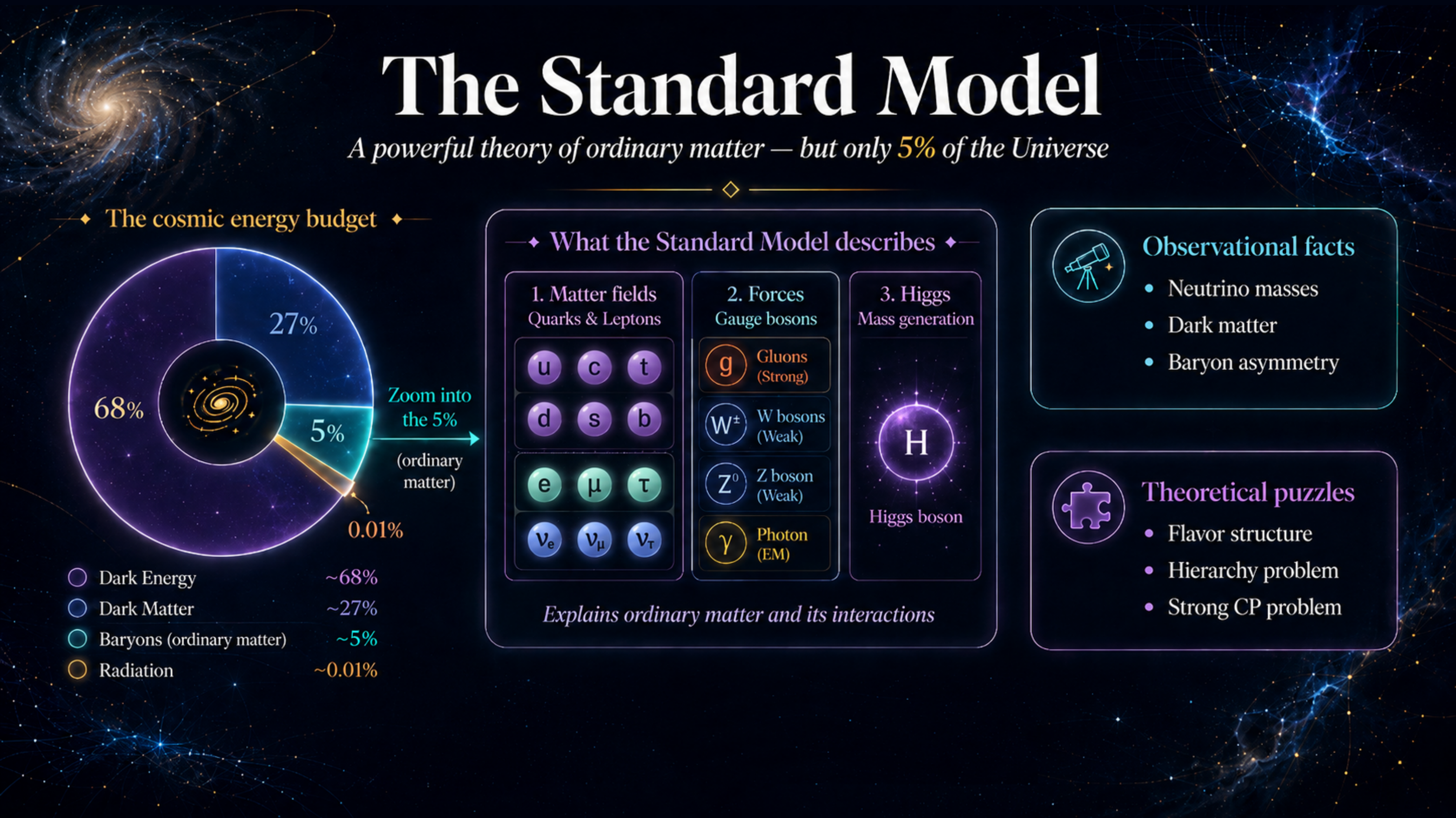
Prologue

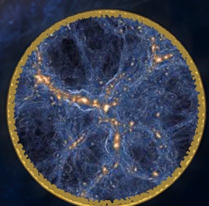
Tracing *New Physics*


ΛCDM Cosmology
A successful model with open windows to new physics
INGREDIENTS
27%
68%
Cosmic energy budget
5%
~0.01%
Dark Energy ~68%
Dark Matter ~27%
Baryons ~5%
Radiation ~0.01%
THE ΛCDM PARADIGM
Inflation?
Primordial fluctuations
CMB + Large-Scale Structure
ΛCDM fit
Primordial non-Gaussianities = probe of inflationary physics
nearly scale-invariant
mostly adiabatic
nearly Gaussian
WHY NEW PHYSICS?
Dark matter: particle identity unknown
Dark energy: origin of Λ unexplained
Inflation: microphysical origin unclear
Non-Gaussianities: test interactions beyond the minimal picture
LSS can reveal primordial signatures



The Standard Model
A powerful theory of ordinary matter — but only 5% of the Universe
The cosmic energy budget
27%
68%
5%
0.01%
Zoom into the 5%
(ordinary matter)
Dark Energy ~68%
Dark Matter ~27%
Baryons (ordinary matter) ~5%
Radiation ~0.01%
What the Standard Model describes
1. Matter fields
Quarks & Leptons
u c t
d s b
e μ τ
νe νμ ντ
2. Forces
Gauge bosons
g Gluons (Strong)
W± W bosons (Weak)
Z0 Z boson (Weak)
γ Photon (EM)
3. Higgs
Mass generation
H
Higgs boson
Explains ordinary matter and its interactions
Observational facts
Neutrino masses
Dark matter
Baryon asymmetry
Theoretical puzzles
Flavor structure
Hierarchy problem
Strong CP problem

Where new physics hides



Long ago / Far away

Regularization Scheme Dependence of the Counterterms in the Galaxy Bias Expansion

JCAP (2023)

High energies

Finite Naturalness and Quark-Lepton Unification

Phys. Rev. D (2024)

New Physics

Weak coupling

Long-lived Axion-like Particles from Electromagnetic Cascades

Phys. Rev. D (2026)

High precision

Leptogenesis in Automatic Nelson-Barr Models

JHEP (2025)

From symmetry principles to observable signatures

...My way"

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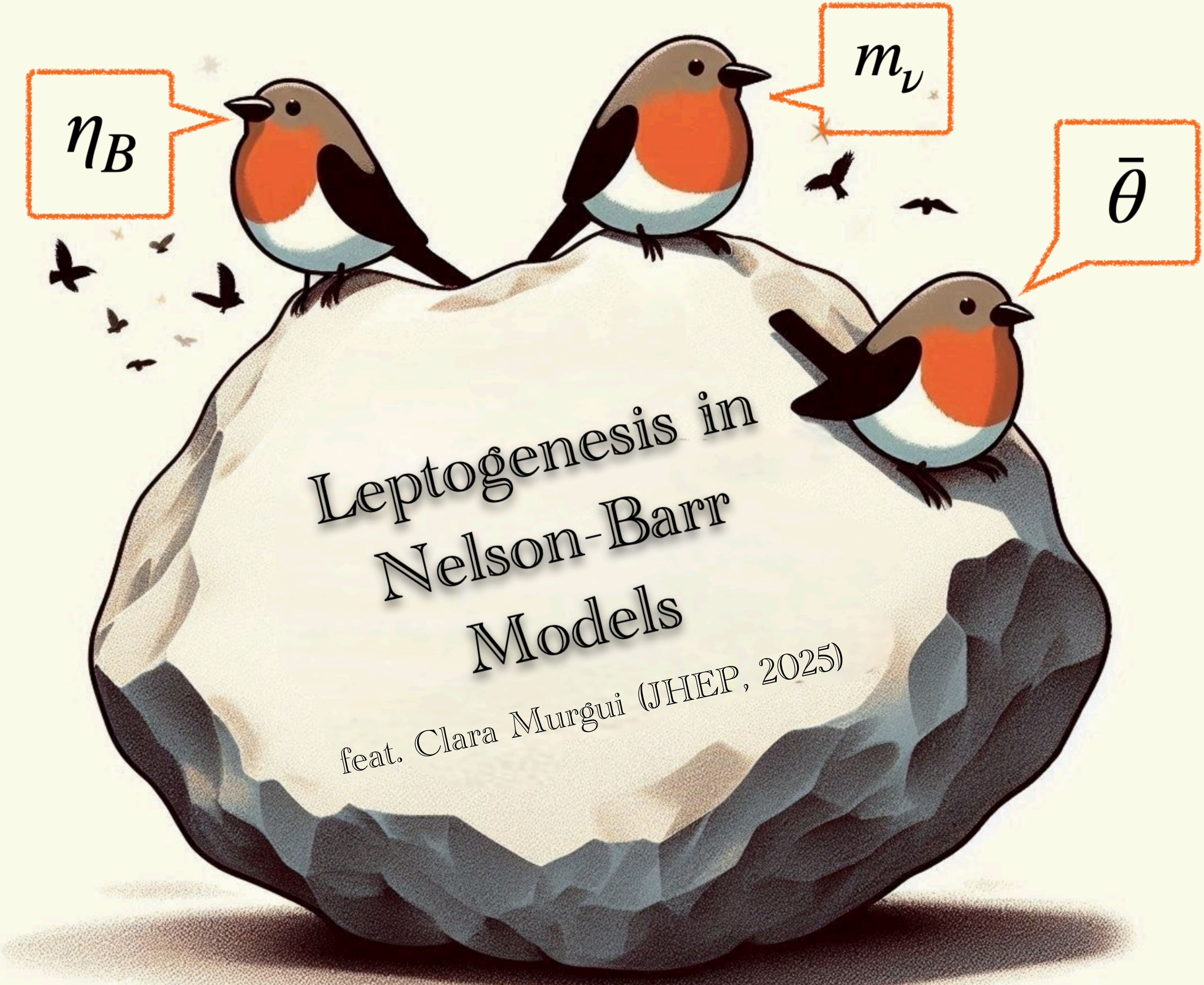


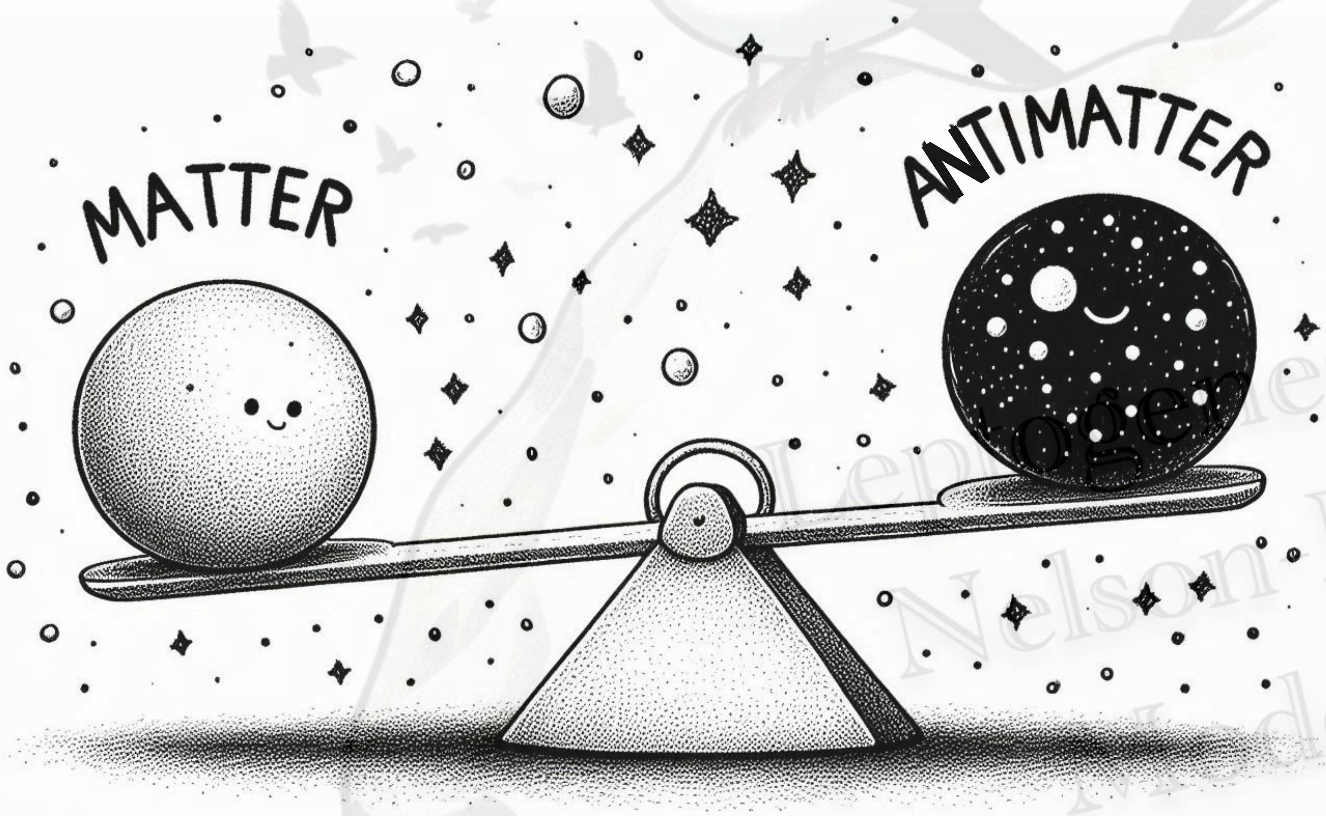
η_B
m_ν
$\bar{\theta}$
Leptogenesis in Nelson-Barr Models
feat. Clara Murgui (JHEP, 2025)

How unique are you?

$$1 \text{ in } 10^{10}$$

… humans is you!
… photons is a baryon!

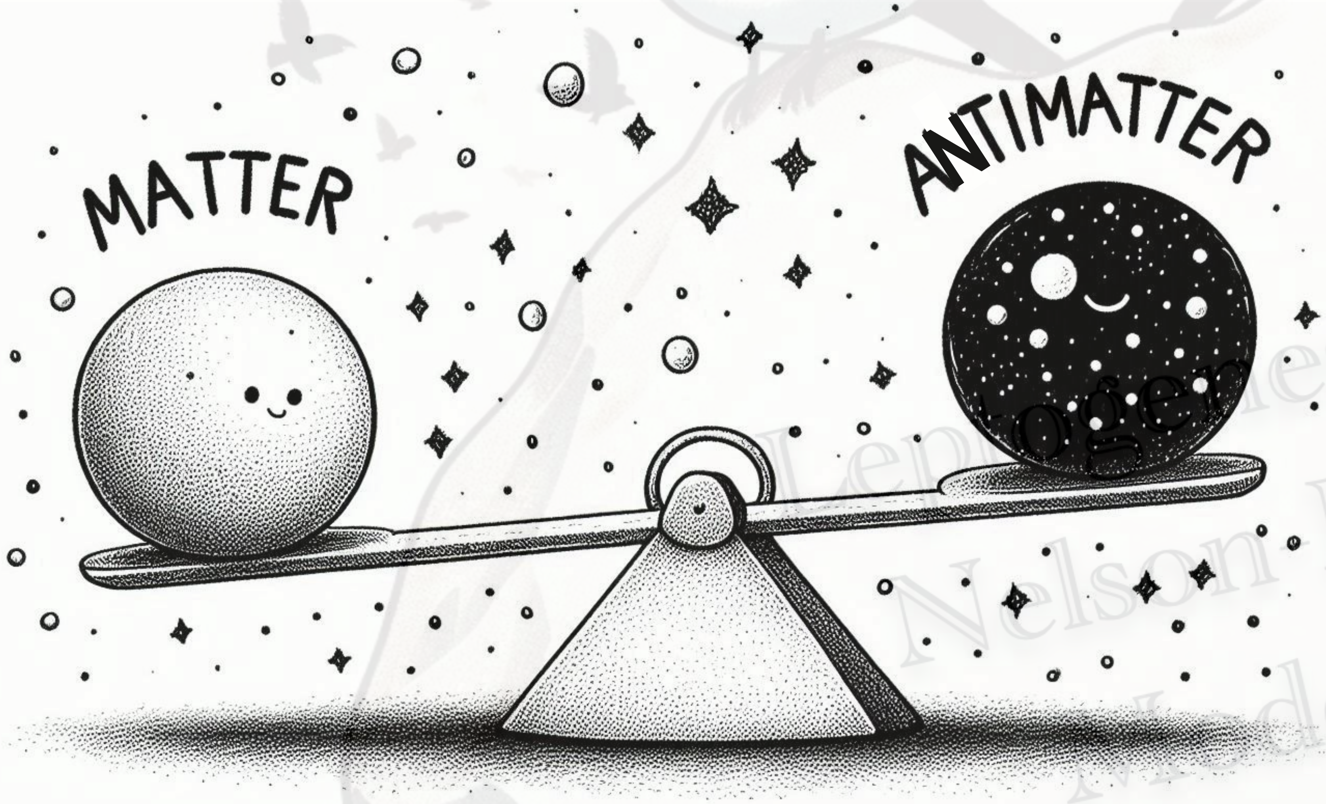
The matter-antimatter asymmetry



10.000.000.001 VS 10.000.000.000

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \times 10^{-10}$$

The matter-antimatter asymmetry



HOW DO WE MEASURE IT?

- BBN

  $n(\mathrm{H}) \propto \eta \quad n(\mathrm{He}) \propto \eta^2$

- CMB

  Odd peaks enhancement

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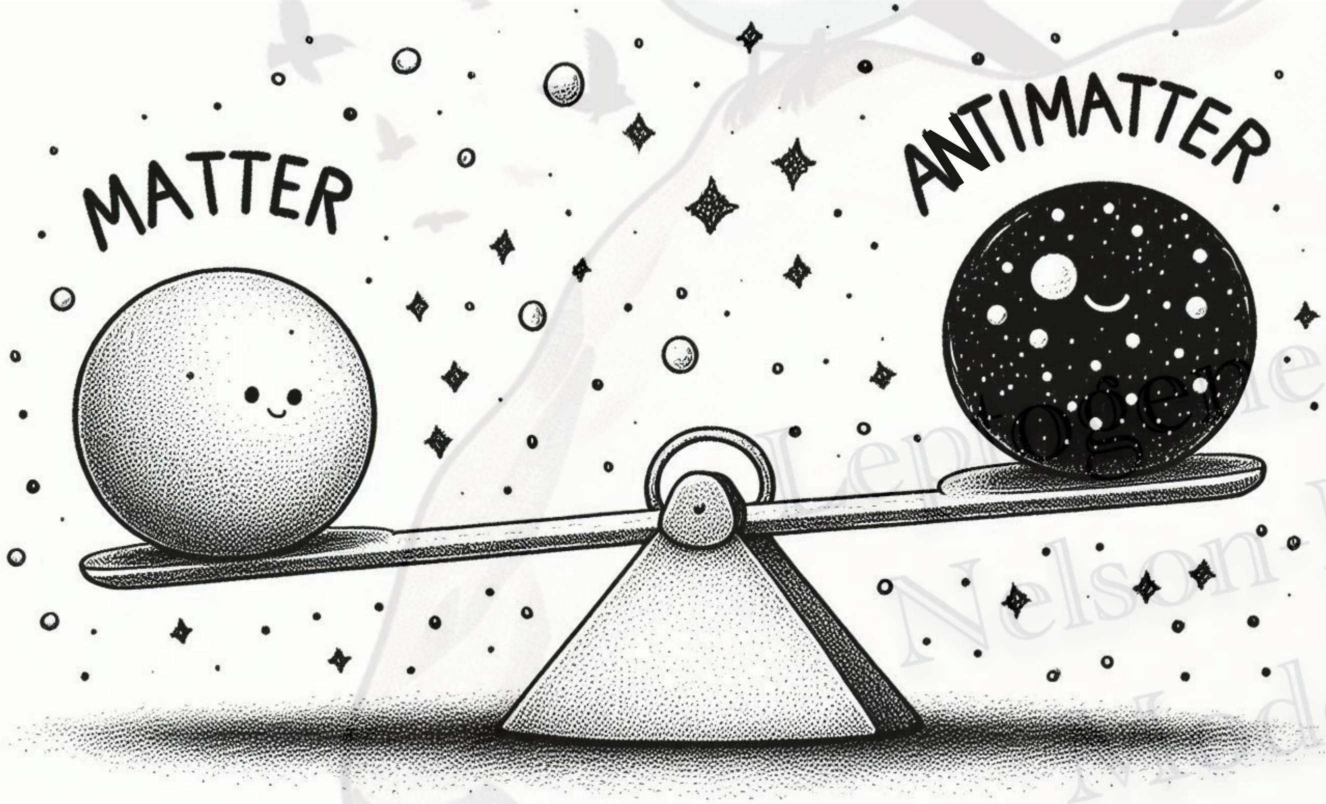
The matter-antimatter asymmetry



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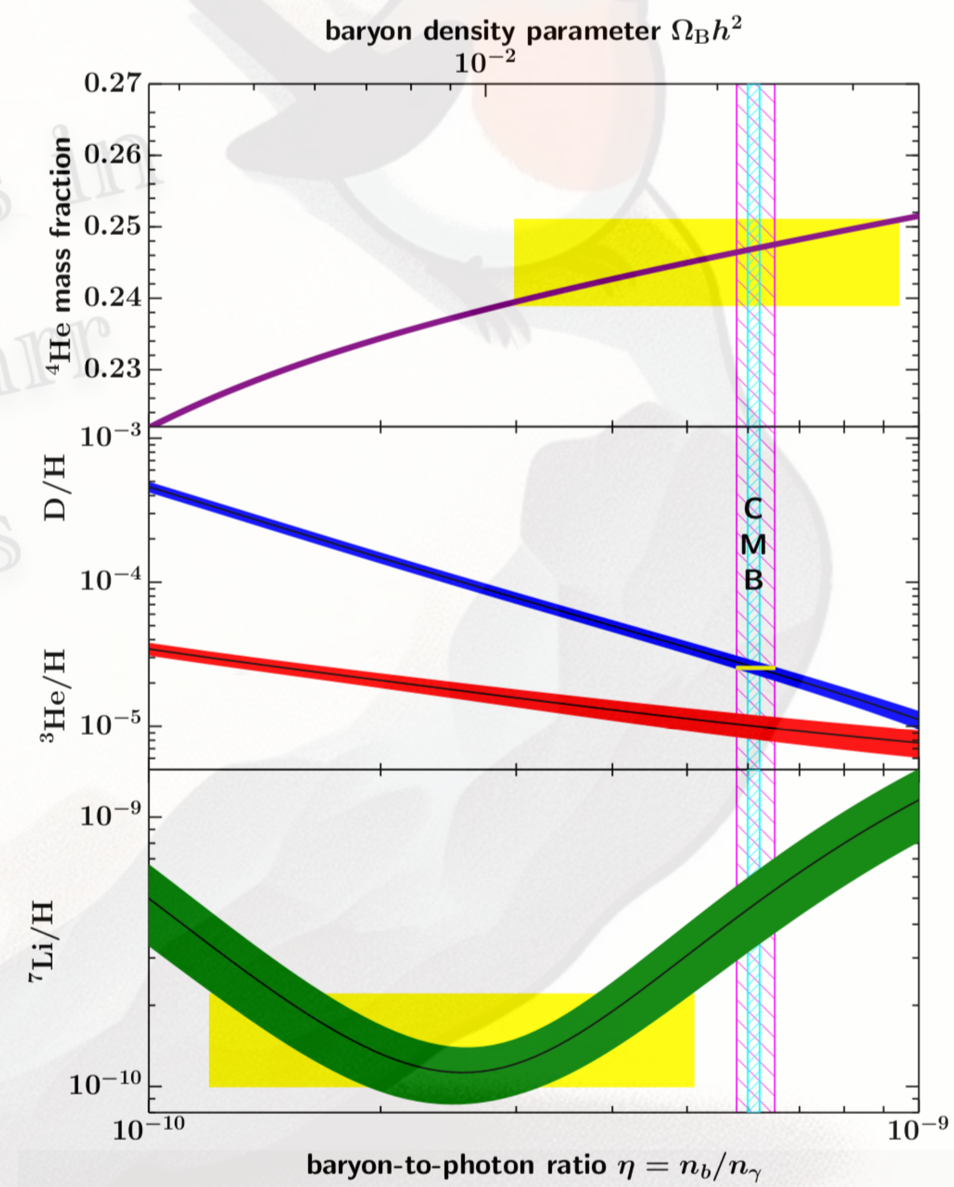
WHAT WE SEE ...



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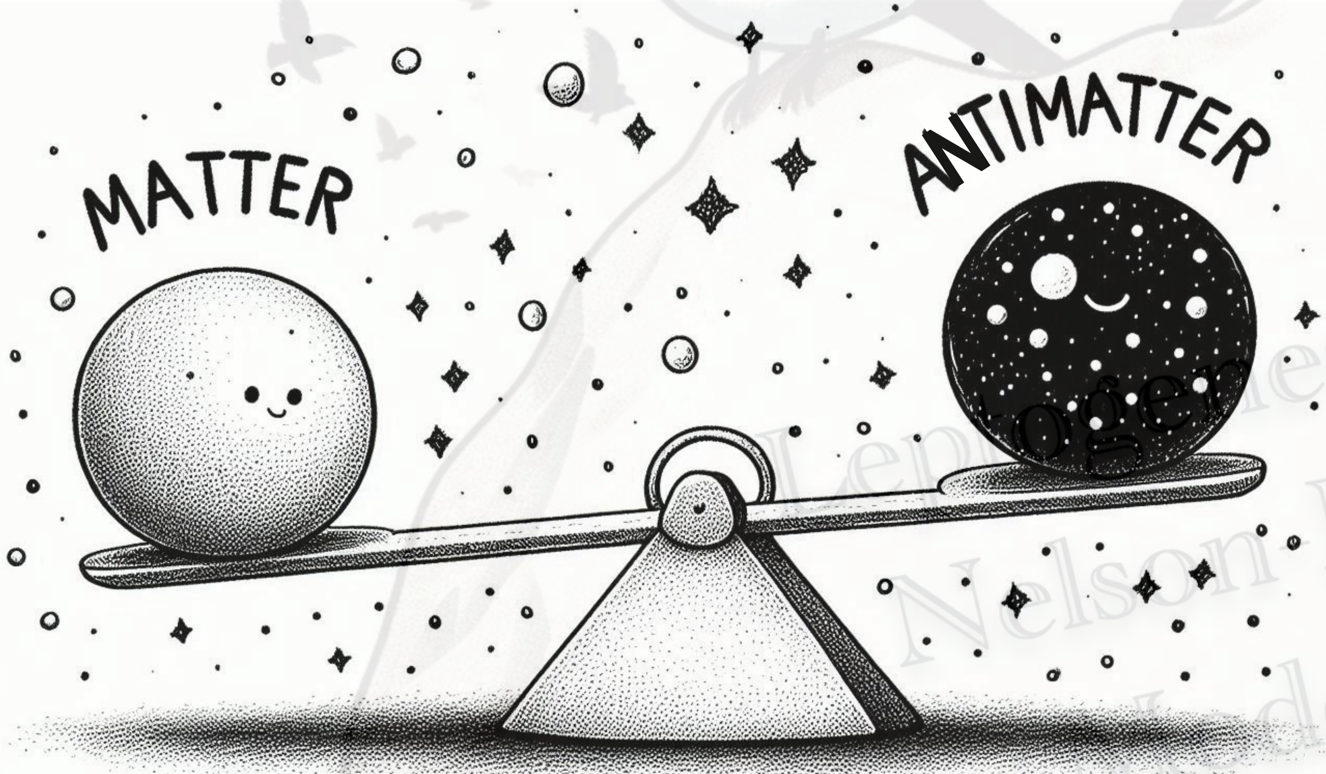
The matter-antimatter asymmetry



HOW DO WE MAKE IT?

 $\not{B}$

 $\not{C}$, $\not{CP}$

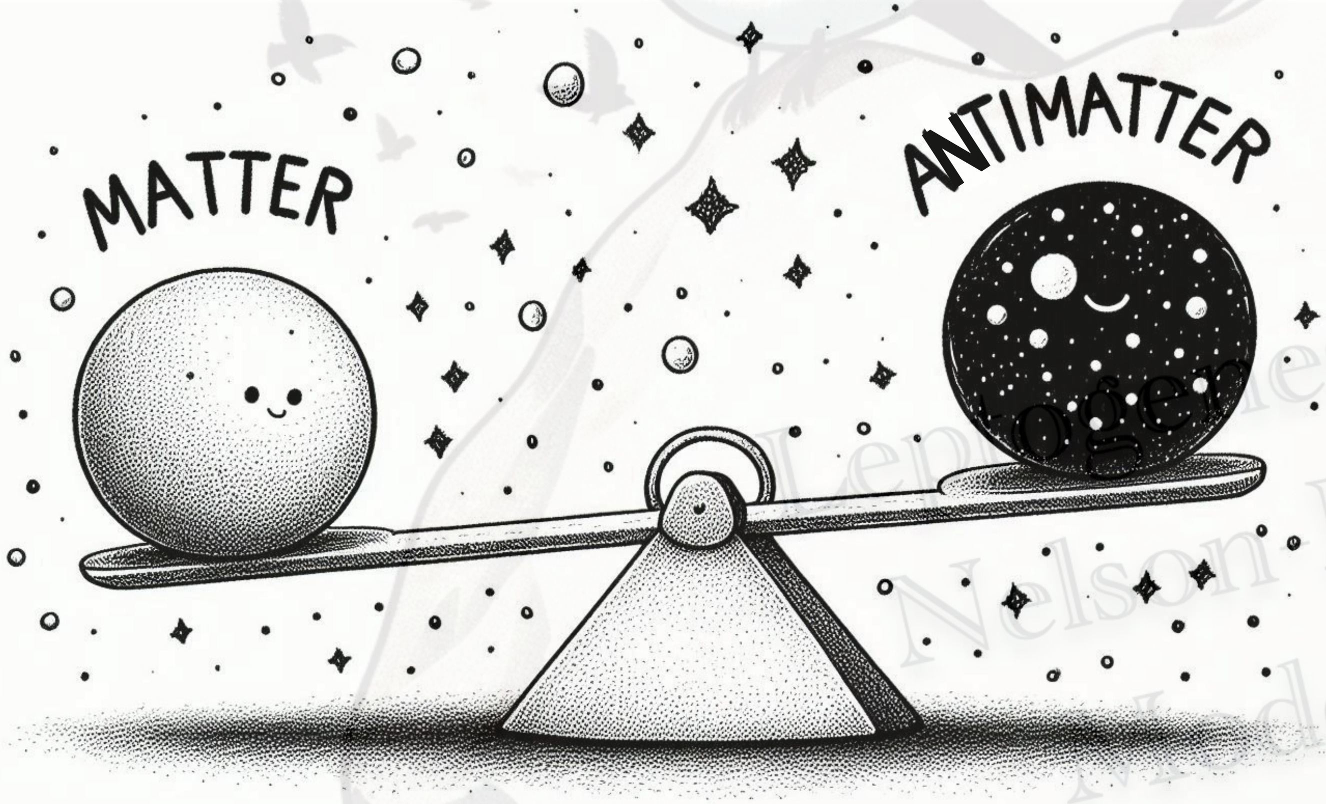
 Out-of-equilibrium

[Shakarov, 1967]

10.000.000.001 VS 10.000.000.000

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \times 10^{-10}$$

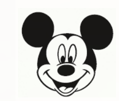
The matter-antimatter asymmetry



10.000.000.001 vs 10.000.000.000

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \times 10^{-10}$$

HOW DO WE MAKE IT?

 $\not B$

 $\not C$, $\not{CP}$

 Out-of-equilibrium

[Shakarov, 1967]

IS SM ENOUGH?

$$\eta_{SM} \sim 10^{-20}$$

[Gavela et al. , 1993]

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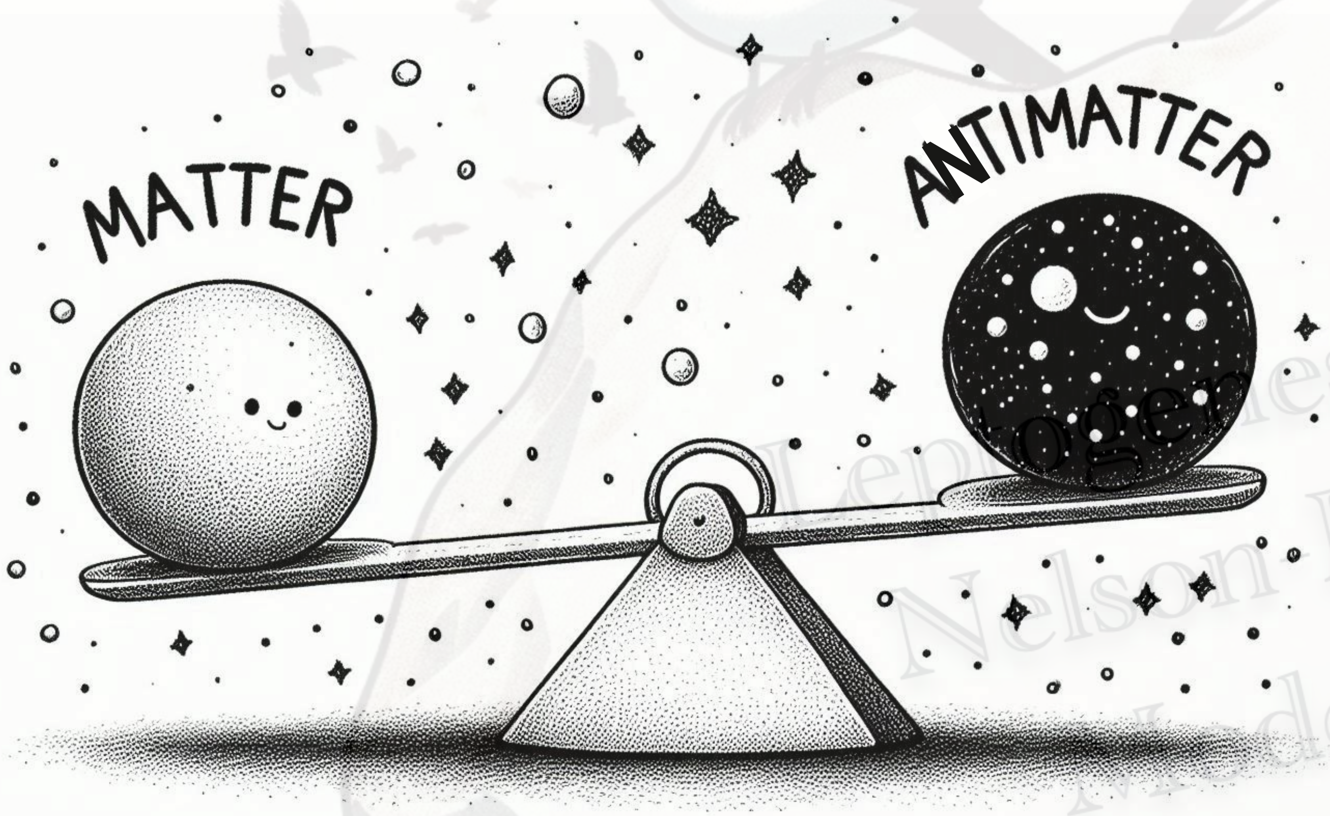
The matter-antimatter asymmetry *problem*



10.000.000.001 VS 10.000.000.000

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \times 10^{-10}$$

HOW DO WE MAKE IT?

- $\not{B}$
- $\not{C}$, $\not{CP}$
- Out-of-equilibrium

[Shakarov, 1967]

IS SM ENOUGH?

$$\eta_{SM} \sim 10^{-20}$$

[Gavela et al. , 1993]

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The Strong CP *problem*

Meanwhile, in the QCD Lagrangian...

$$\mathcal{L}_{\not{CP}}(\bar{\theta}) = -\frac{g_s^2}{32\pi^2}\underbrace{\left(\arg(\text{Det}\, M) + \theta_{\text{QCD}}\right)}_{\bar{\theta}} G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

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The Strong CP *problem*

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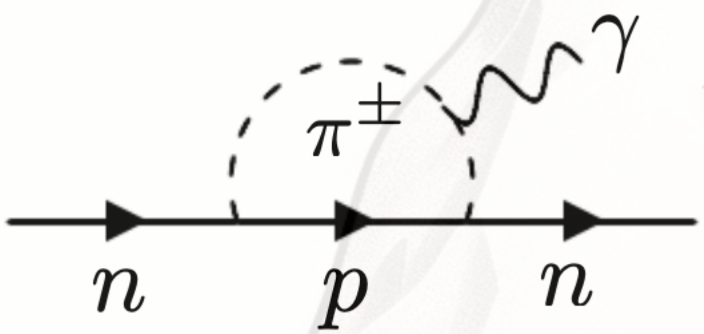
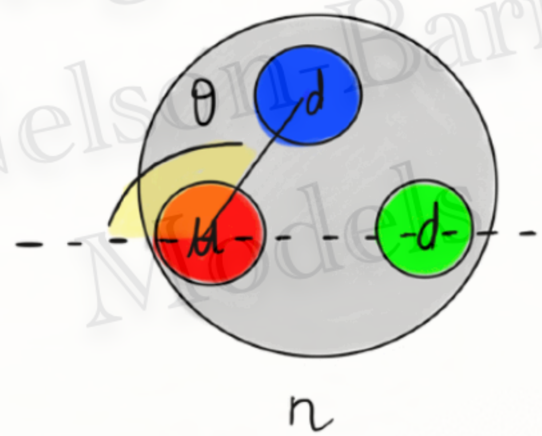


[A. Hook, TASI 18]



$$d_n = \mathcal{O}(1)\bar\theta \times 10^3 \text{ e fm}$$

The Strong CP *problem*

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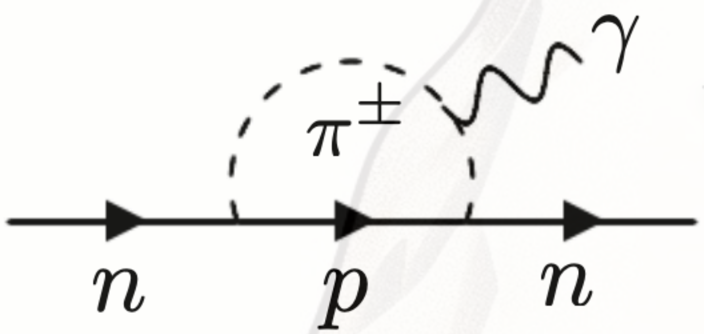
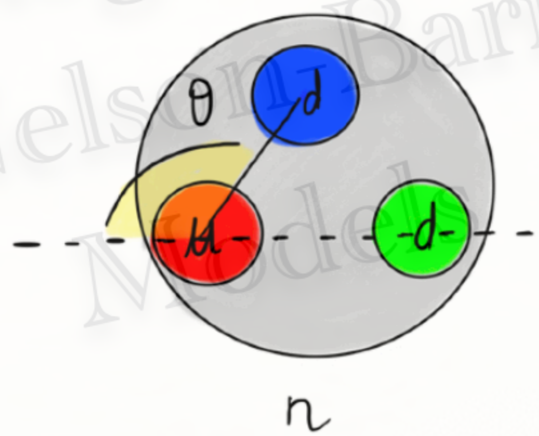
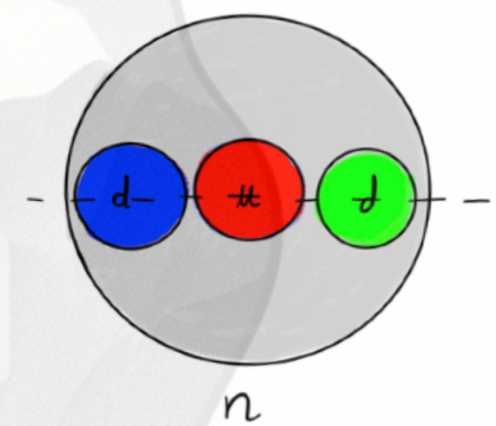




instead



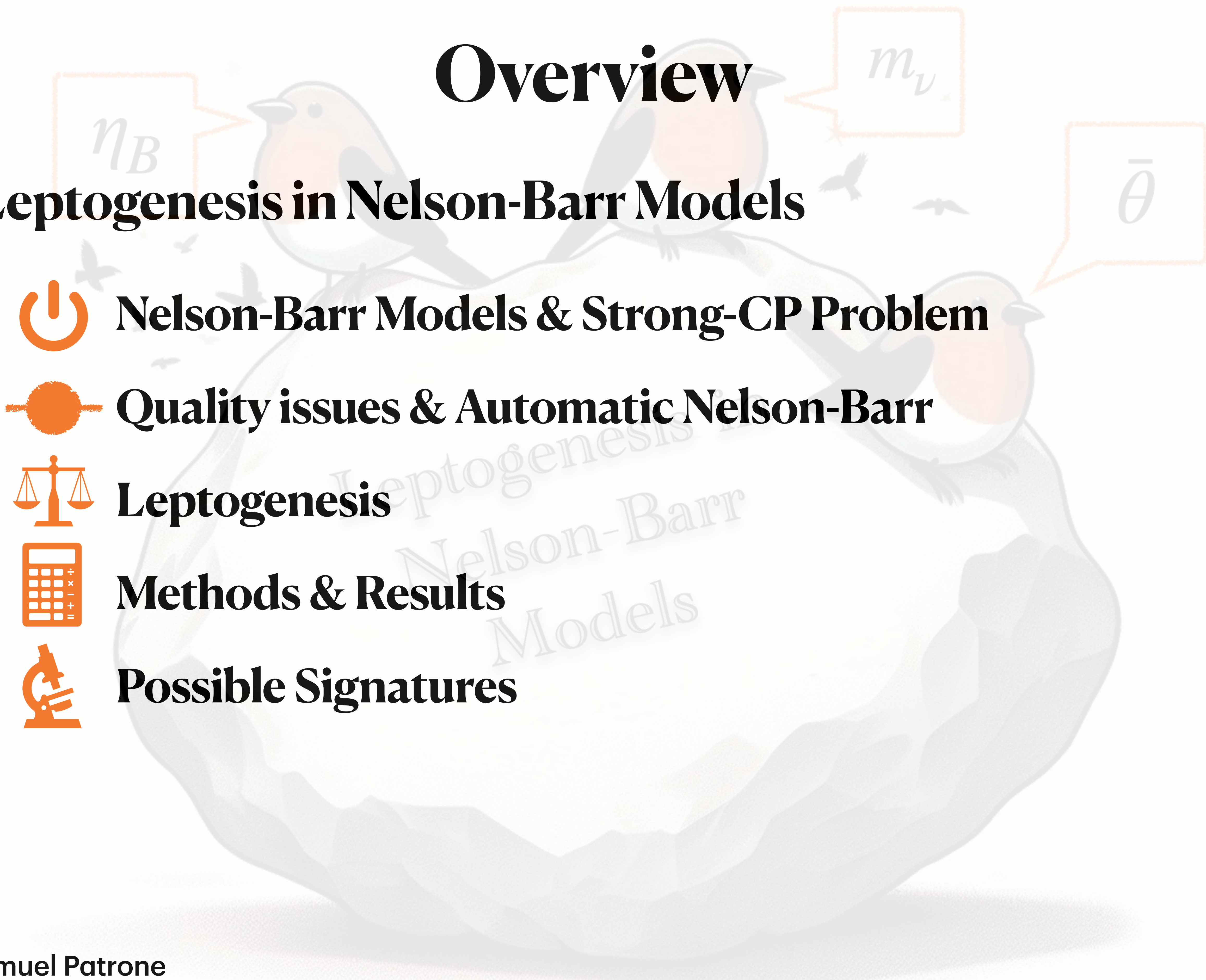
$$d_n = \mathcal{O}(1)\bar\theta \times 10^3 \text{ e fm}$$

$$|d_n|^{\text{exp}} < 3.0 \times 10^{-13} \text{ e fm} \quad \Rightarrow \quad \boxed{\bar\theta \lesssim 10^{-10}}$$

Overview

Leptogenesis in Nelson-Barr Models

- Nelson-Barr Models & Strong-CP Problem
- Quality issues & Automatic Nelson-Barr
- Leptogenesis
- Methods & Results
- Possible Signatures



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Nelson-Barr Models

as solutions to the Strong-CP problem

$$\mathcal{L}_{\not{C}\not{P}}(\bar{\theta}) = -\frac{g_s^2}{32\pi^2}\underbrace{\left(\arg(\mathrm{Det}\, M) + \theta_{\mathrm{QCD}}\right)}_{\bar{\theta} \leq 10^{-10}} G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

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<u>Ingredients:</u>

- CP is... spontaneously broken! [Nelson, 84] [Barr, 84]

$$\langle X \rangle = e^{i\alpha} v_{CP}$$

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$$\langle X \rangle = e^{i\alpha} v_{CP}$$

- Add an extra colored VL fermion D_L, D_R [Bento, Branco, Parada, 1991]

$$-\mathscr{L}_Y = \bar{Q}_L Y_d H d_R + M_D \bar{D}_L D_R + Y' \bar{Q}_L H D_R + M_{dD} \bar{D}_L d_R + \text{h.c.}$$

$$\supset \left(\bar{d}_L \bar{D}_L\right) \begin{pmatrix} Y_d \frac{v_H}{\sqrt{2}} & Y_i' \frac{v_H}{\sqrt{2}} \\ M_{dD} & M_D \end{pmatrix} \begin{pmatrix} d_R \\ D_R \end{pmatrix} + \text{h.c.}$$

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Nelson-Barr Models

as solutions to the Strong-CP problem

$$\mathcal{L}_{\cancel{CP}}(\bar{\theta}) = -\frac{g_s^2}{32\pi^2}\underbrace{\left(\arg(\cancel{\mathrm{D}}\mathrm{et}\, M) + \theta_{\cancel{\mathrm{Q}}\mathrm{CD}}\right)}_{\bar{\theta} \leq 10^{-10}} G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

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- Charge X, D_L, D_R under $\mathbb{Z}_2$

$$-\mathscr{L}_Y = \bar{Q}_L Y_d H d_R + M_D \bar{D}_L D_R + (\lambda_d^i X + \lambda_d^{\prime i} X^*)\bar{D}_L d_R + \text{h.c.}$$

$$\supset (\bar{d}_L \bar{D}_L)\begin{pmatrix} Y_d \frac{v_H}{\sqrt{2}} & \cancel{0} \\ (\lambda_d^i e^{i\alpha} + \lambda_d^{\prime i} e^{-i\alpha})\frac{v_{CP}}{\sqrt{2}} & M_D \end{pmatrix}\begin{pmatrix} d_R \\ D_R \end{pmatrix} + \text{h.c.}$$

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Nelson-Barr Models

as solutions to the Strong-CP problem

$$\mathcal{L}_{\cancel{CP}}(\bar\theta) = -\frac{g_s^2}{32\pi^2}\underbrace{\left(\arg(\cancel{\text{D}}\text{et}\, M) + \theta_{\cancel{\text{Q}}\text{CD}}\right)}_{\bar\theta \leq 10^{-10}} G^a_{\mu\nu}\tilde G^{\mu\nu}_a$$

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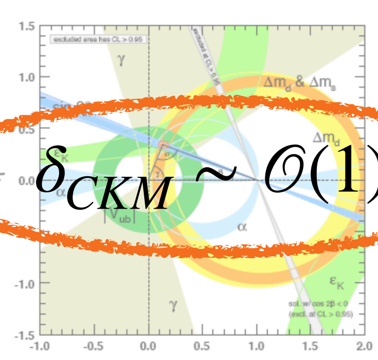

$\delta_{CKM} \sim \mathcal{O}(1)$

$$\supset (\bar d_L \bar D_L)\begin{pmatrix} Y_d \frac{v_H}{\sqrt{2}} & 0 \\ (\lambda_d^i e^{i\alpha} + \lambda_d^{\prime i} e^{-i\alpha})\frac{v_{CP}}{\sqrt{2}} & M_D \end{pmatrix}\begin{pmatrix} d_R \\ D_R \end{pmatrix} + \text{h.c.}$$

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Nelson-Barr Models

as solutions to the Strong-CP problem

$\bar{\theta} = 0$ @ tree - level

Ingredients:

- CP is... spontaneously broken! [Nelson, 84] [Barr, 84]

$$\langle X \rangle = e^{i\alpha} v_{CP}$$

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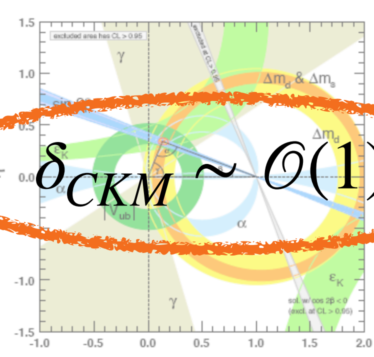

$$\delta_{CKM} \sim \mathcal{O}(1)$$

$$\supset (\bar{d}_L \bar{D}_L) \begin{pmatrix} Y_d \frac{v_H}{\sqrt{2}} & 0 \\ (\lambda_d^i e^{i\alpha} + \lambda_d^{\prime i} e^{-i\alpha}) \frac{v_{CP}}{\sqrt{2}} & M_D \end{pmatrix} \begin{pmatrix} d_R \\ D_R \end{pmatrix} + \text{h.c.}$$

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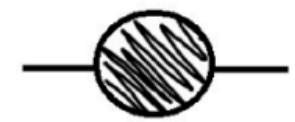
The Nelson-Barr Quality (Problem ?)

Loops



H.D.O.

$$\sum_{n>4} \frac{\mathcal{O}_n}{\Lambda_{\text{EFT}}^{n-4}}$$

$$\tilde{\mathcal{M}}_q = \mathcal{M}_q + \delta\mathcal{M}_q$$

$$\Delta\bar{\theta}_{\text{QCD}} = \text{Im}\{\text{Tr}\{\mathcal{M}_q^{-1}\delta\mathcal{M}_q\}\} + \mathcal{O}(\delta\mathcal{M}_q^2) \lesssim 10^{-10}$$

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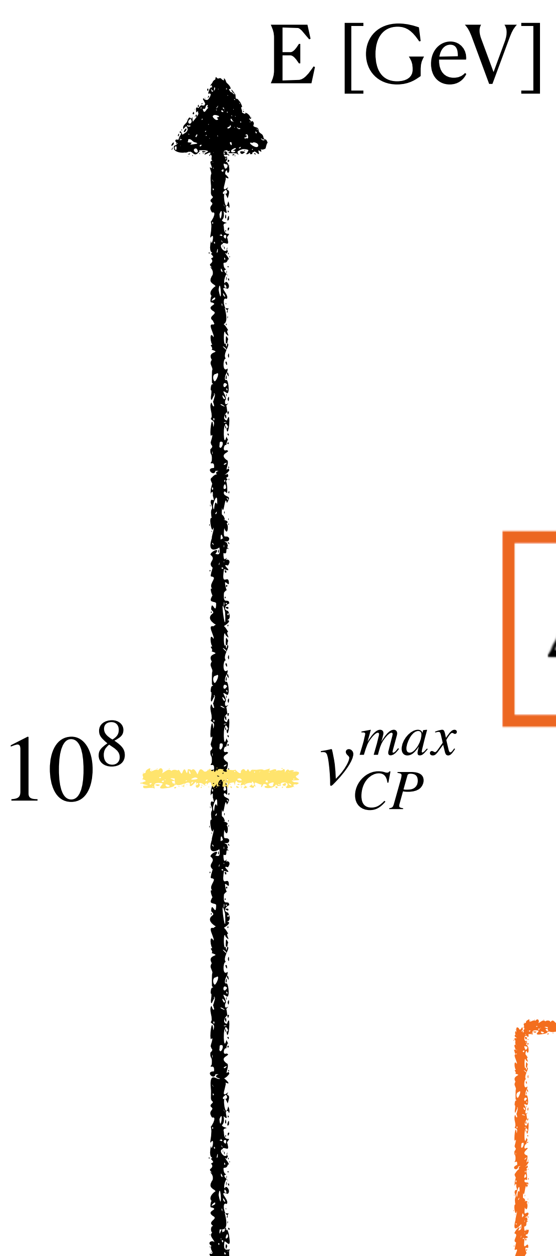
The Nelson-Barr Quality (Problem ?)



H.D.O.

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$$\boxed{\Delta\bar{\theta}_{\text{QCD}} = \text{Im}\{\text{Tr}\{\mathcal{M}_q^{-1}\delta\mathcal{M}_q\}\} + \mathcal{O}(\delta\mathcal{M}_q^2)} \lesssim 10^{-10}$$

$\mathbb{Z}_2$: 5-dim operators $\left(\frac{\xi_1}{\Lambda}\bar{Q}_L H D_R X + \frac{\xi_2}{\Lambda}\bar{D}_L D_R X^2\right)$

$$\boxed{v_{\text{CP}} < 10^8\ \text{GeV}\left(\frac{1}{\xi \sin\theta_{\text{CP}}}\right)\left(\frac{\Delta\bar{\theta}_{\text{QCD}}}{10^{-10}}\right)\left(\frac{M_D/\mu}{1}\right)^*}$$

*= MFV case

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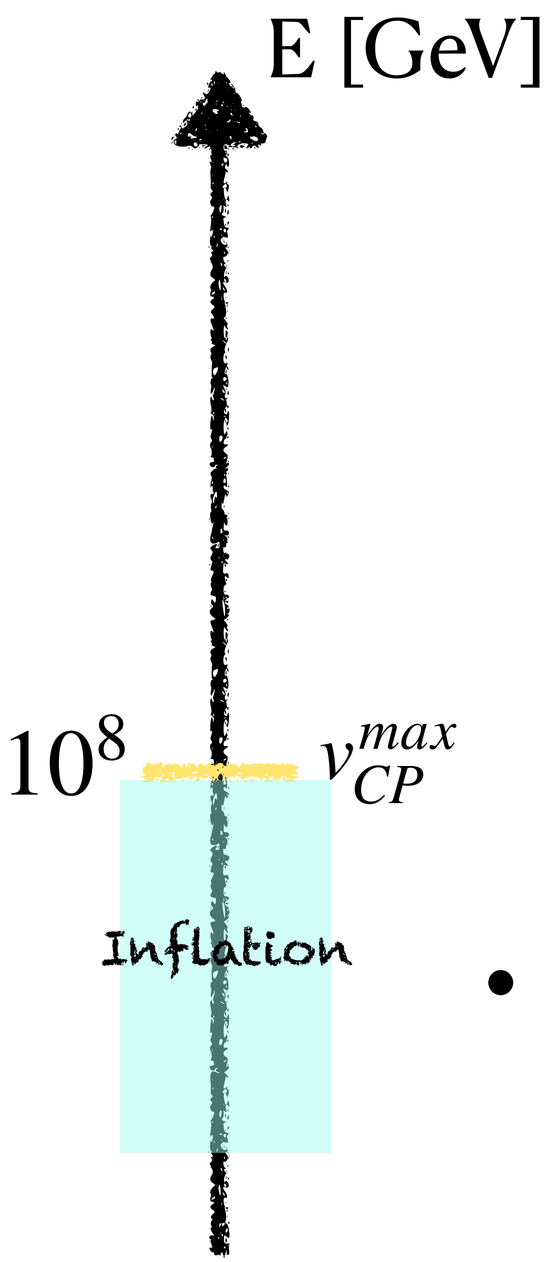
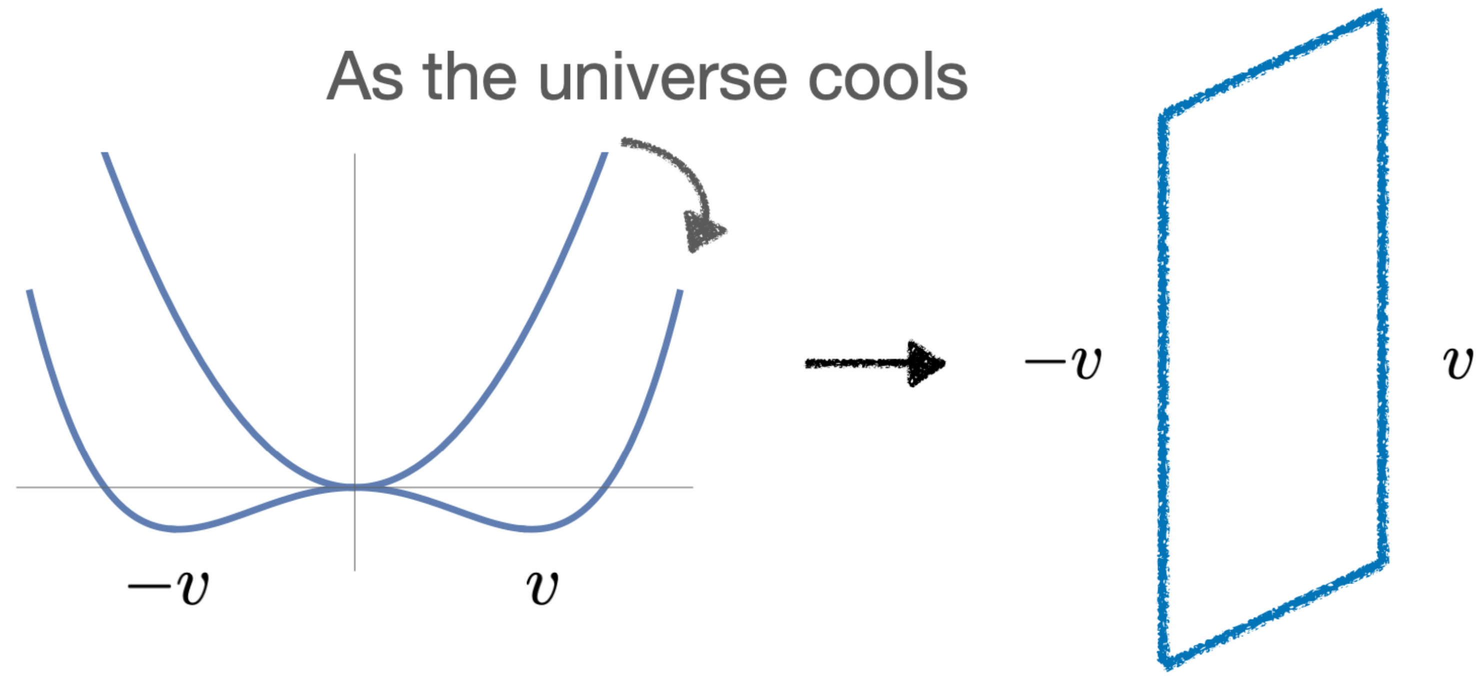
Domain Walls from SSB of a discrete symmetry





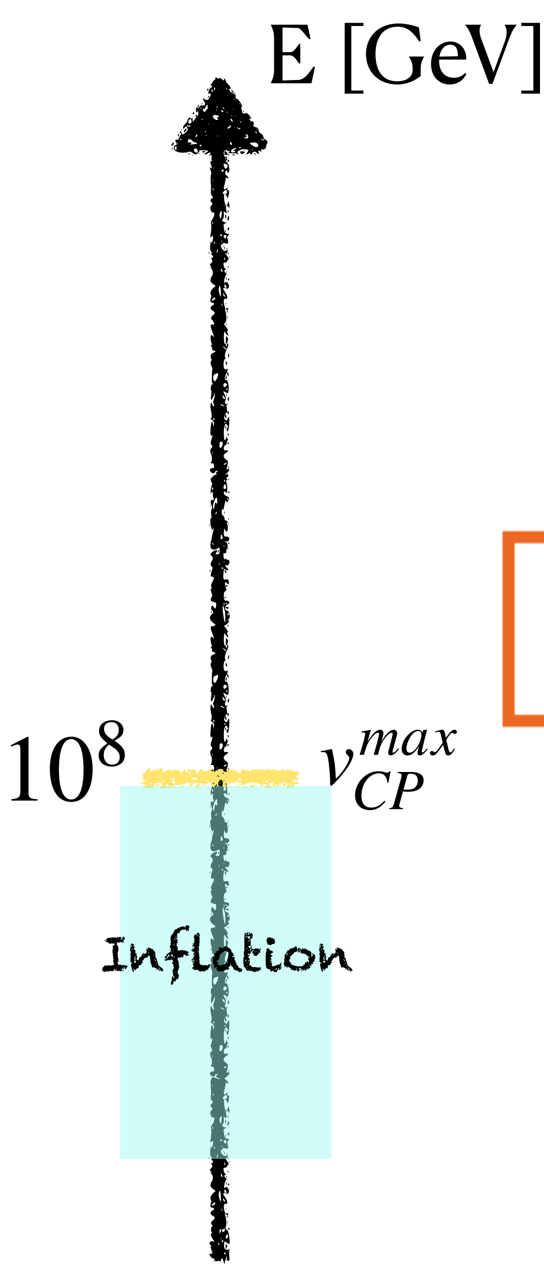
$\sigma \equiv \frac{E}{A} \sim v^3$

- The energy density $\rho_{DW}(t) \propto a^{-1}(t)$

  $\Rightarrow$ it dominates over matter&radiation quickly

  $\Rightarrow$ for $v > 1$ MeV, we have to destroy them $\begin{cases} \text{dynamics} \\ \text{inflation} \end{cases}$

Automatic Nelson-Barr



H.D.O.

$$\sum_{n>4} \frac{\mathcal{O}_n}{\Lambda_{\text{EFT}}^{n-4}}$$

$$\tilde{\mathcal{M}}_q = \mathcal{M}_q + \delta\mathcal{M}_q$$

$$\boxed{\Delta\bar{\theta}_{\text{QCD}} = \text{Im}\{\text{Tr}\{\mathcal{M}_q^{-1}\delta\mathcal{M}_q\}\} + \mathcal{O}(\delta\mathcal{M}_q^2)} \lesssim 10^{-10}$$

- $U(1)$ such that the new fermions are *chiral*

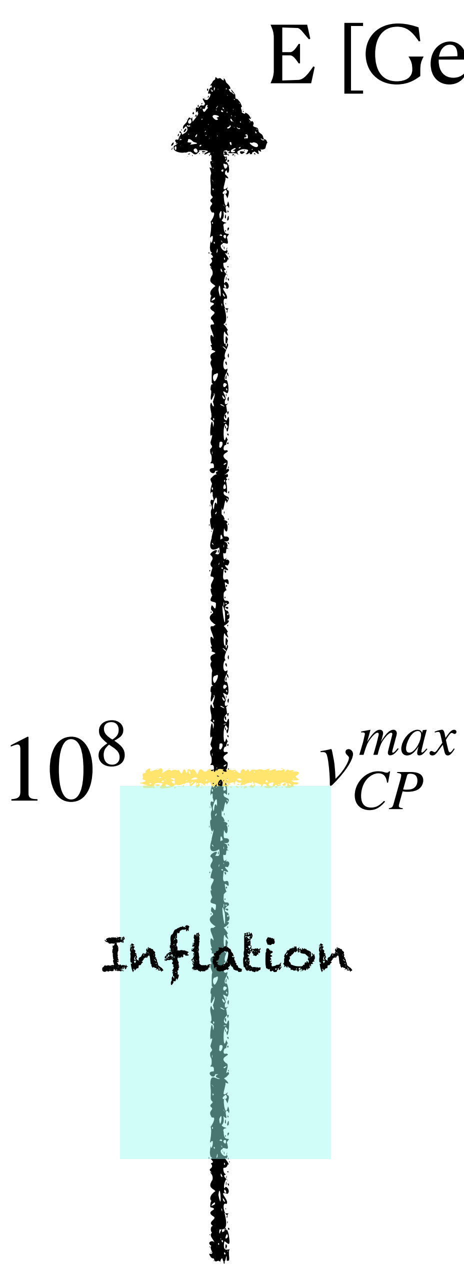
"No-bare-mass" policy
exceptions: the bridge term

⇨ Charge 'Em All!

[A. Valenti, L. Vecchi, 2021]
[P. Asadi, S. Homiller, Q. Lu, M. Reece, 2022]
[Fileviez-Perez, Murgui, Wise, 2023]

Samuel Patrone

Automatic Nelson-Barr



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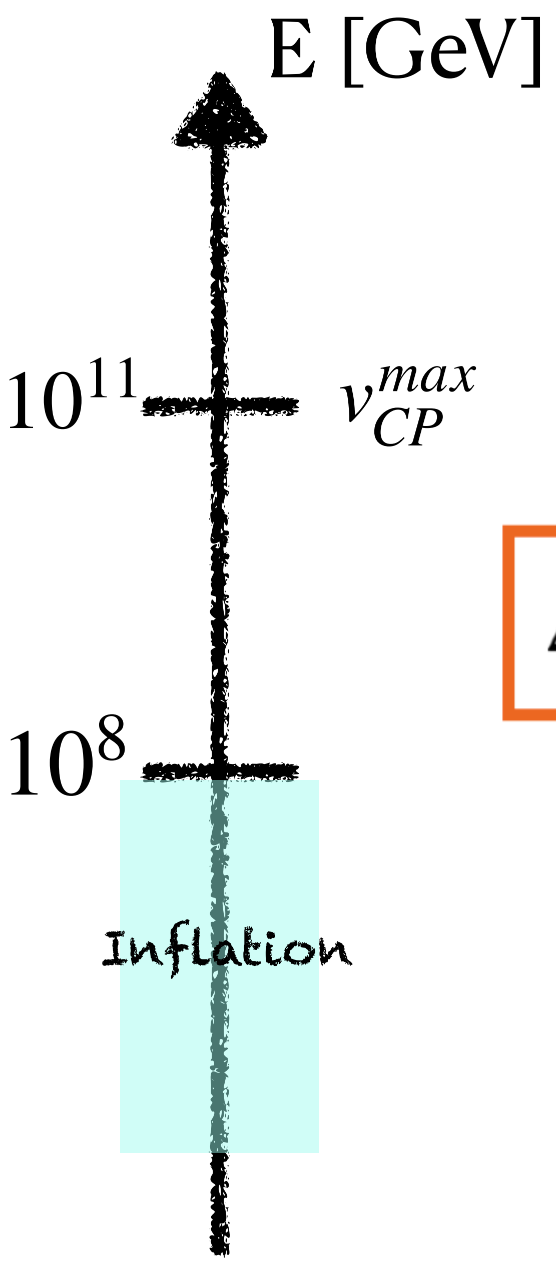
$U(1)$: 6-dim operators $\left(\frac{\xi}{\Lambda_{EFT}^2} S\,\bar{D}_L D_R\, X_i X_j^*\right)$

Samuel Patrone

Automatic Nelson-Barr



H.D.O.

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$U(1)$: 6-dim operators $\left(\frac{\xi}{\Lambda_{EFT}^2} S\,\bar{D}_L D_R\, X_i X_j^*\right)$

$$v_{\rm CP} \lesssim 3\times 10^{11}\,{\rm GeV}\left(\frac{\Delta\theta_{\rm QCD}}{10^{-10}}\right)^{1/2}\left(\frac{1}{\xi\sin\theta_{\rm CP}}\right)^{1/2}$$

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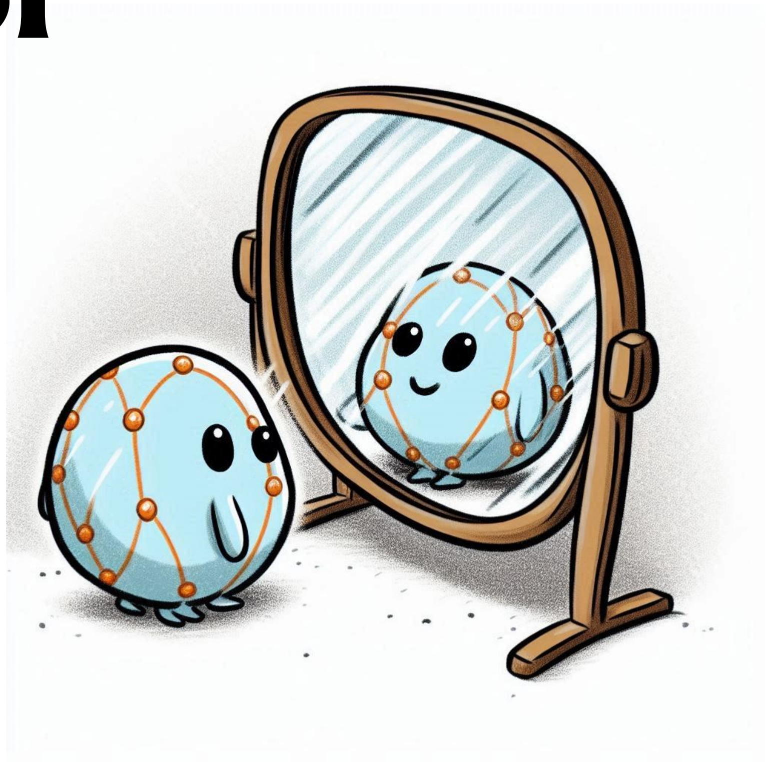
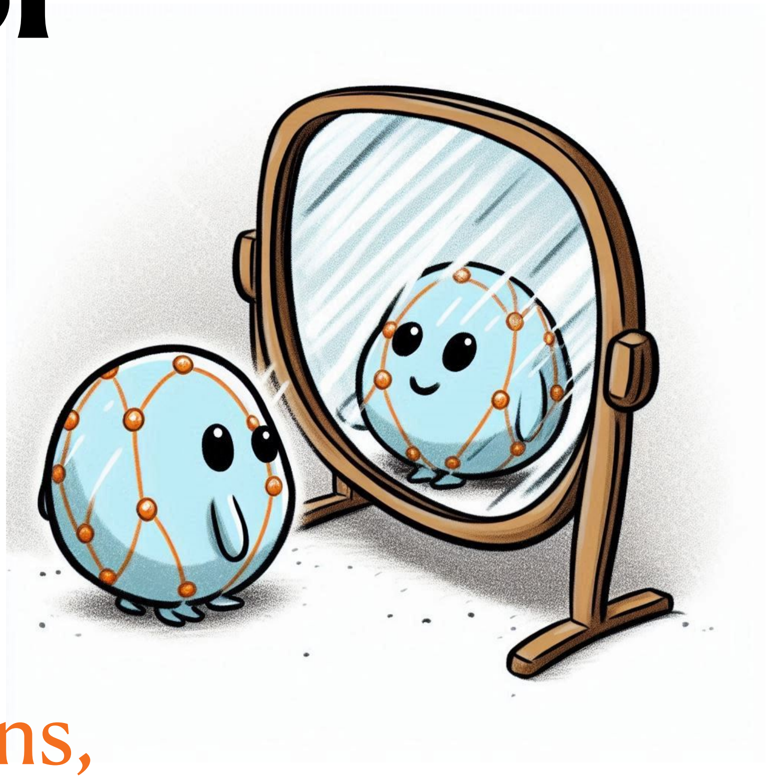
Leptonic sector



Mirroring the quark sector...

- We add 3 $\nu_R + N_L, N_R$ (5 HNLs)

Leptonic sector



Mirroring the quark sector...

- We add $3\ \nu_R + N_L, N_R$ (5 HNLs)

- Mirroring the Quark Sector charge relations, we assume the following simplified model

$$-\mathscr{L} \supset \bar{L}_L \mathsf{Y}_\nu \tilde{H} \nu_R + (\lambda_{\nu 1} X_1 + \lambda_{\nu 2} X_2)\, \bar{N}_L \nu_R + \lambda_N S \bar{N}_L N_R + S\, \overline{\nu_R^c}\, \mathsf{Y}_R \nu_R + \mathrm{h.c.},$$

$$\xrightarrow[\langle S \rangle, \langle X_{1,2} \rangle]{} \bar{L}_L \mathsf{Y}_\nu \tilde{H} \nu_R + \bar{N}_L \mu\, \nu_R + m_N \bar{N}_L N_R + \overline{\nu_R^c}\, \mathsf{M}_R \nu_R + \mathrm{h.c.},$$

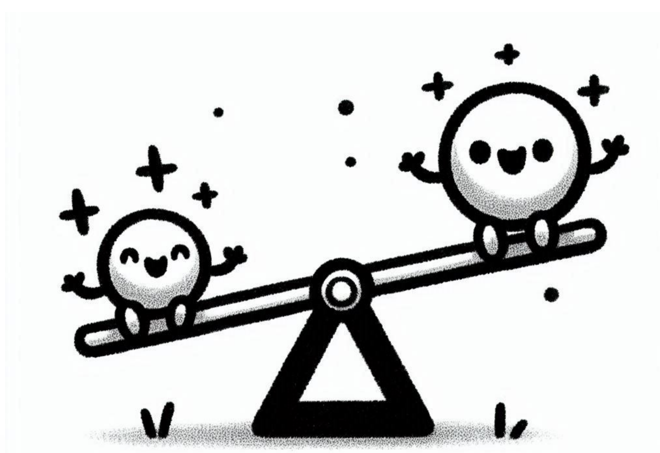
Type-I See-saw

- The Neutral Lepton Mass Matrix $\begin{pmatrix} 0^{3\times3} & M_D^{3\times5} \\ (M_D^T)^{5\times3} & M_H^{5\times5} \end{pmatrix}$

$$M_D = \begin{pmatrix} 0 & & 0 \\ 0 & (Y_\nu O_R)\frac{v_H}{\sqrt{2}} & 0 \\ 0 & & 0 \end{pmatrix} \qquad M_H = \begin{pmatrix} 0 & \mu_1 & \mu_2 & \mu_3 & m_N \\ \mu_1 & m_{R1} & 0 & 0 & 0 \\ \mu_2 & 0 & m_{R2} & 0 & 0 \\ \mu_3 & 0 & 0 & m_{R3} & 0 \\ m_N & 0 & 0 & 0 & 0 \end{pmatrix}$$

where $\begin{cases} \mu \sim v_{CP} \in \mathbb{C} \\ m_{Ri} \sim v_S \in \mathbb{R} \\ m_N \sim v_S \in \mathbb{R} \end{cases}$

and $v_H \ll v_{CP} \leq v_S$



$$\begin{cases} \bar{M}_L &= -U_L^T M_D M_H^{-1} M_D^T U_L + \mathcal{O}\left(\frac{|m_D|^3}{m_{Ri}^2}\right) \\ \bar{M}_H &= U_H^T M_H U_H + \mathcal{O}\left(\frac{|m_D|^2}{m_{Ri}}\right) \end{cases}$$

$$M_{N_1} \simeq \mathrm{Min}\left[m_N, m_R\left(\frac{m_N^2}{m_N^2 + |\mu|^2}\right)\right]$$

$$m_{\nu_i} \simeq \frac{Y_\nu^2 v_H^2}{2 m_{Ri}} \lesssim 0.1 \text{ eV}$$

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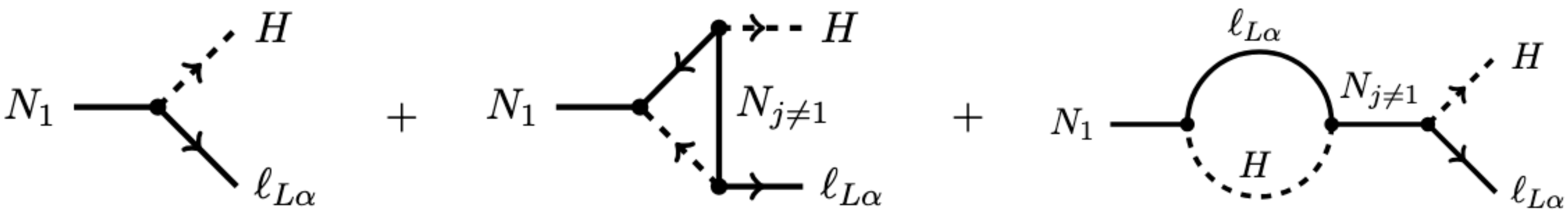
Leptogenesis: a crash course

- For Hierarchical HNL $\quad \mathrm{h}^{i\ell} \equiv (\mathrm{Y}_\nu \mathrm{O}_R)^{ik} \mathrm{U}_H^{*k\ell}$



$$\epsilon_{\mathrm{CP}} \equiv \sum_\alpha \frac{\Gamma_{N_1 \to H\ell_\alpha} - \Gamma_{N_1 \to H^\dagger \bar{\ell}_\alpha}}{\Gamma_D} = \sum_{j\neq 1} \frac{\mathrm{Im}\{[\mathrm{h}^\dagger \mathrm{h}]^2_{1j}\}}{8\pi [\mathrm{h}^\dagger \mathrm{h}]_{11}} f_{\mathrm{loop}} \left[\frac{M^2_{N_j}}{M^2_{N_1}} \right]$$

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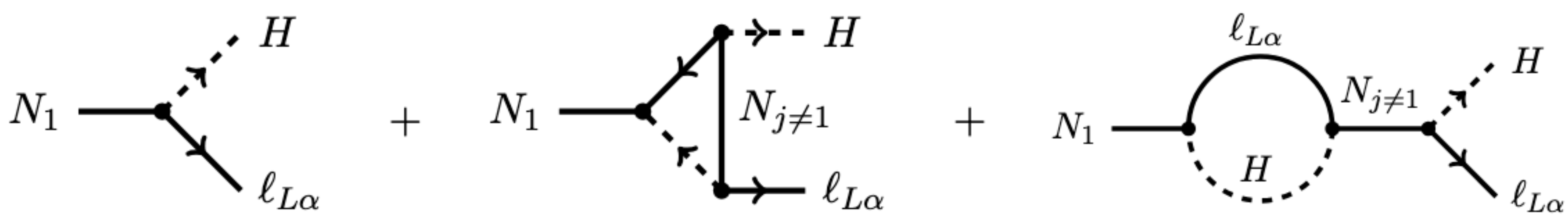

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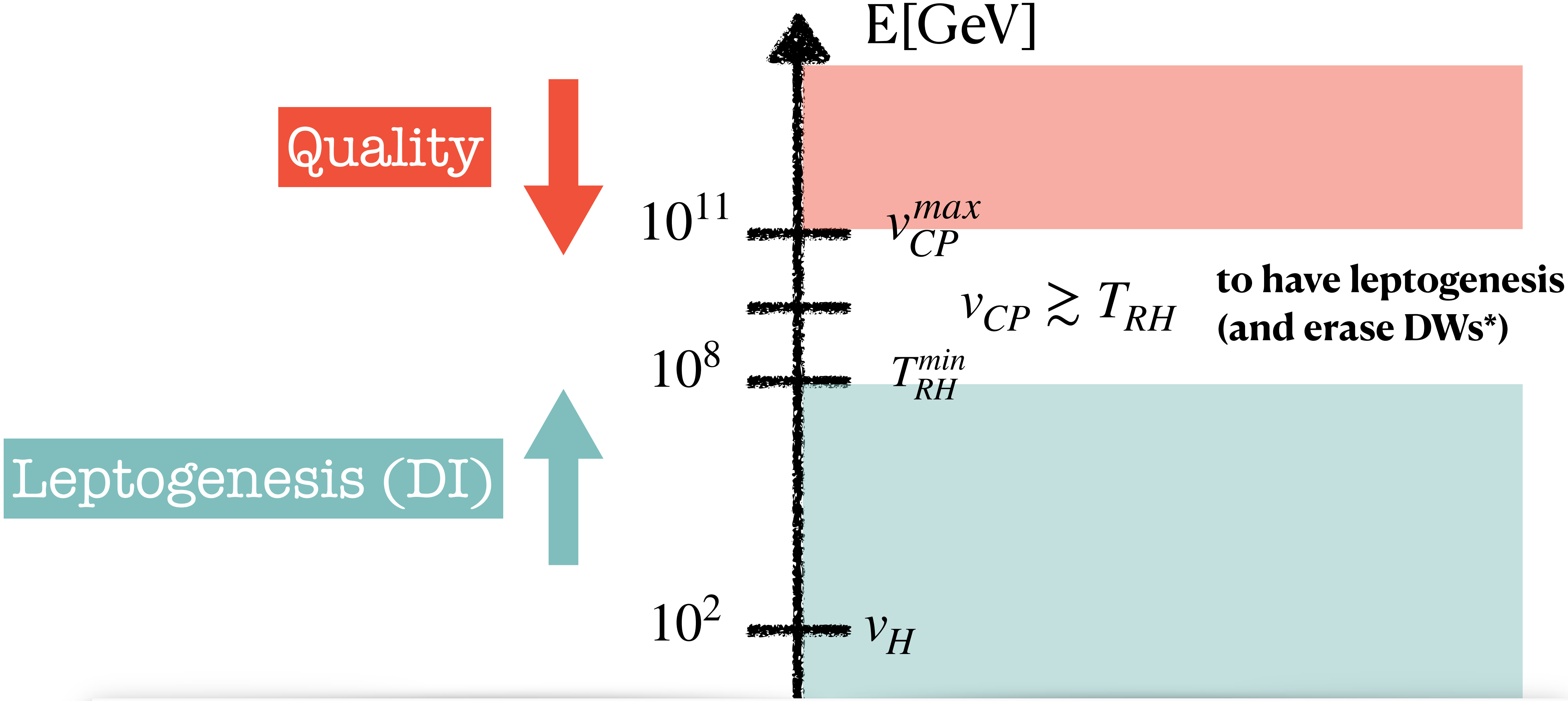
- Davidson-Ibarra bound [Davidson and Ibarra, 2002]

$$|\epsilon_{\rm CP}| \leq \frac{3}{8\pi}\frac{M_{N_1}}{v_H^2} m_\nu^{\rm heavy}$$

$\eta_B \sim 10^{-10}$ →

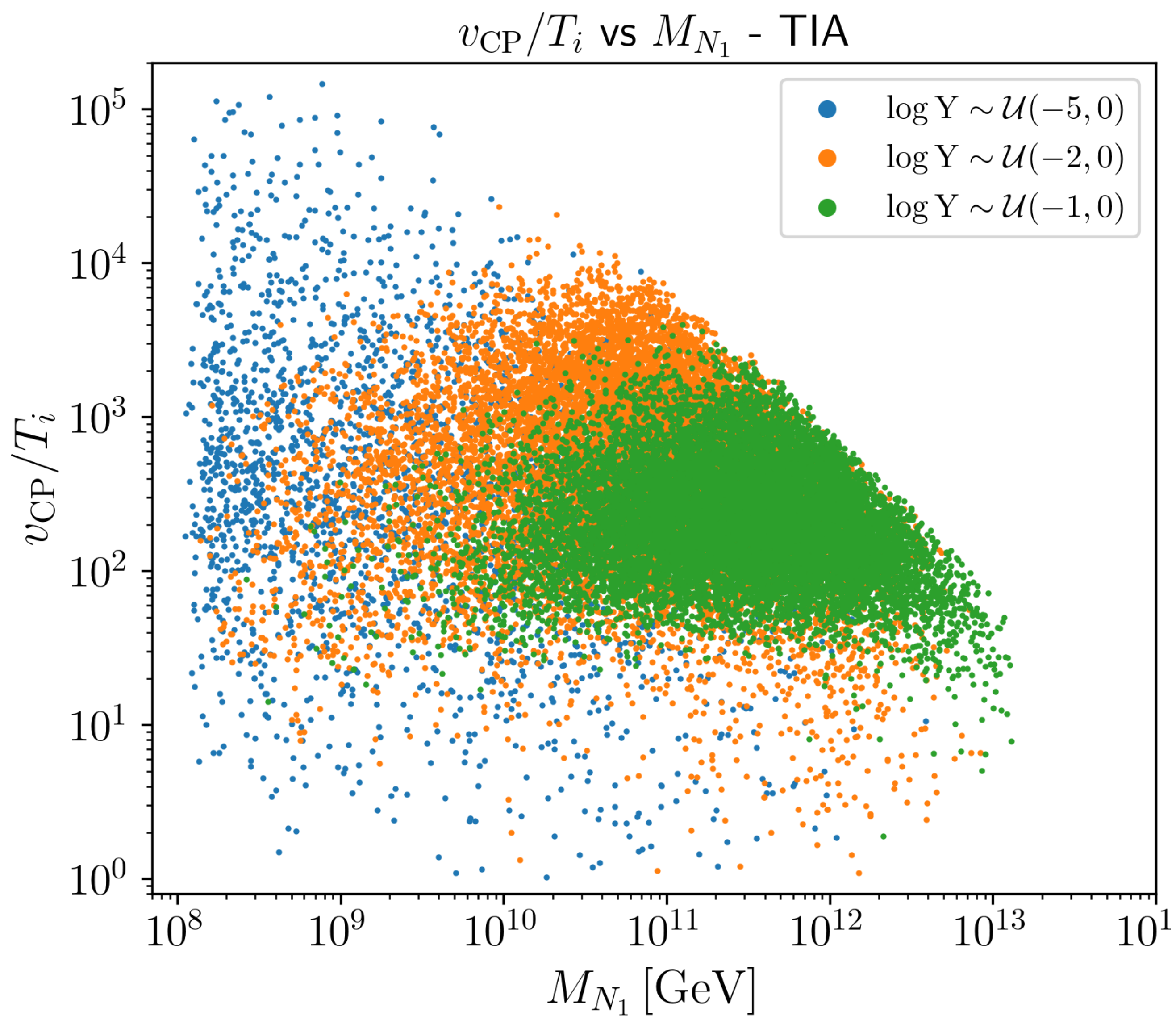
$$T_{RH} \gtrsim M_{N_1} \gtrsim \begin{cases} 10^8\ \mathrm{GeV} & \text{thermal} \\ 10^9\ \mathrm{GeV} & \text{dynamical} \end{cases}$$

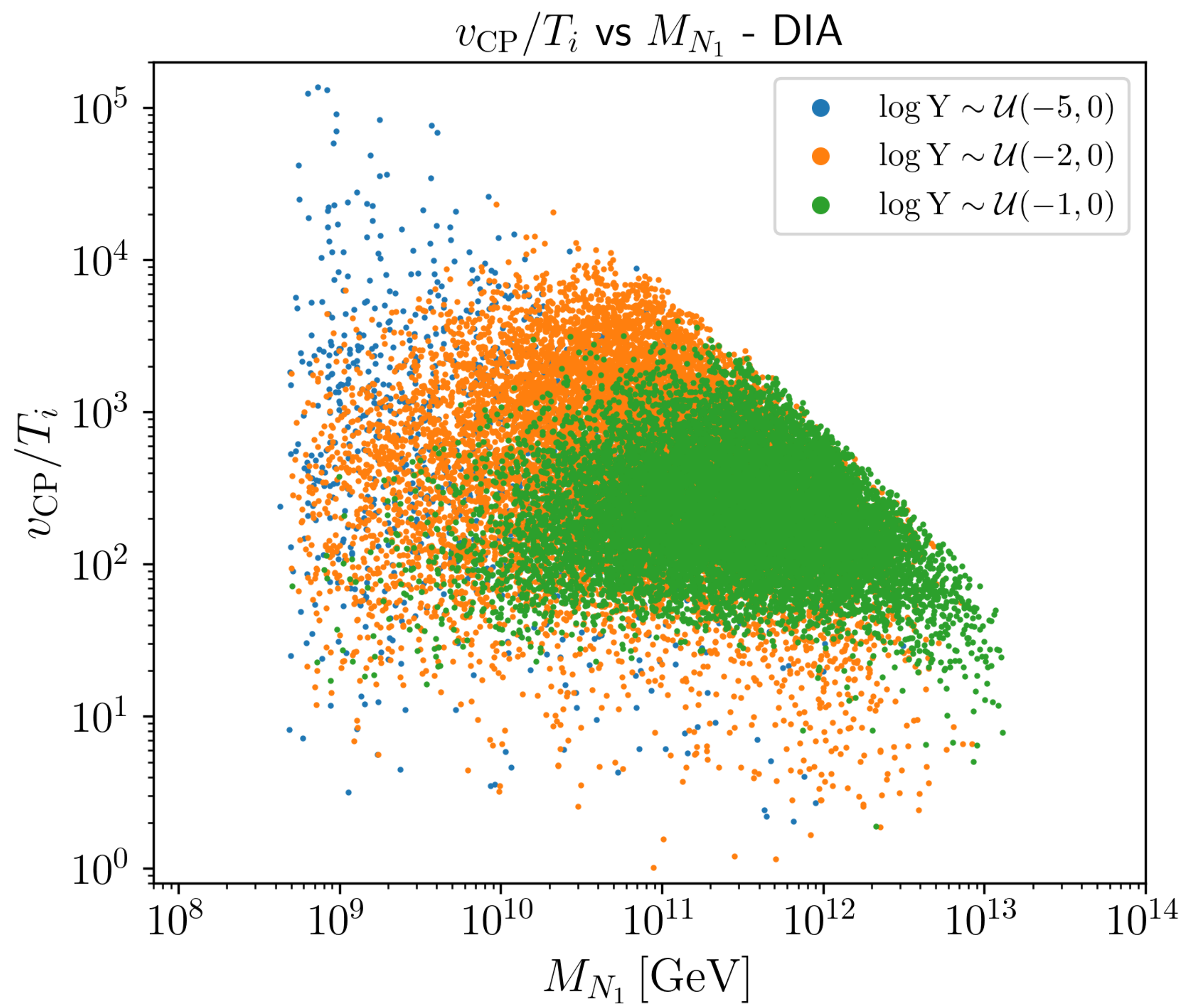
Wya, v_{CP} ?



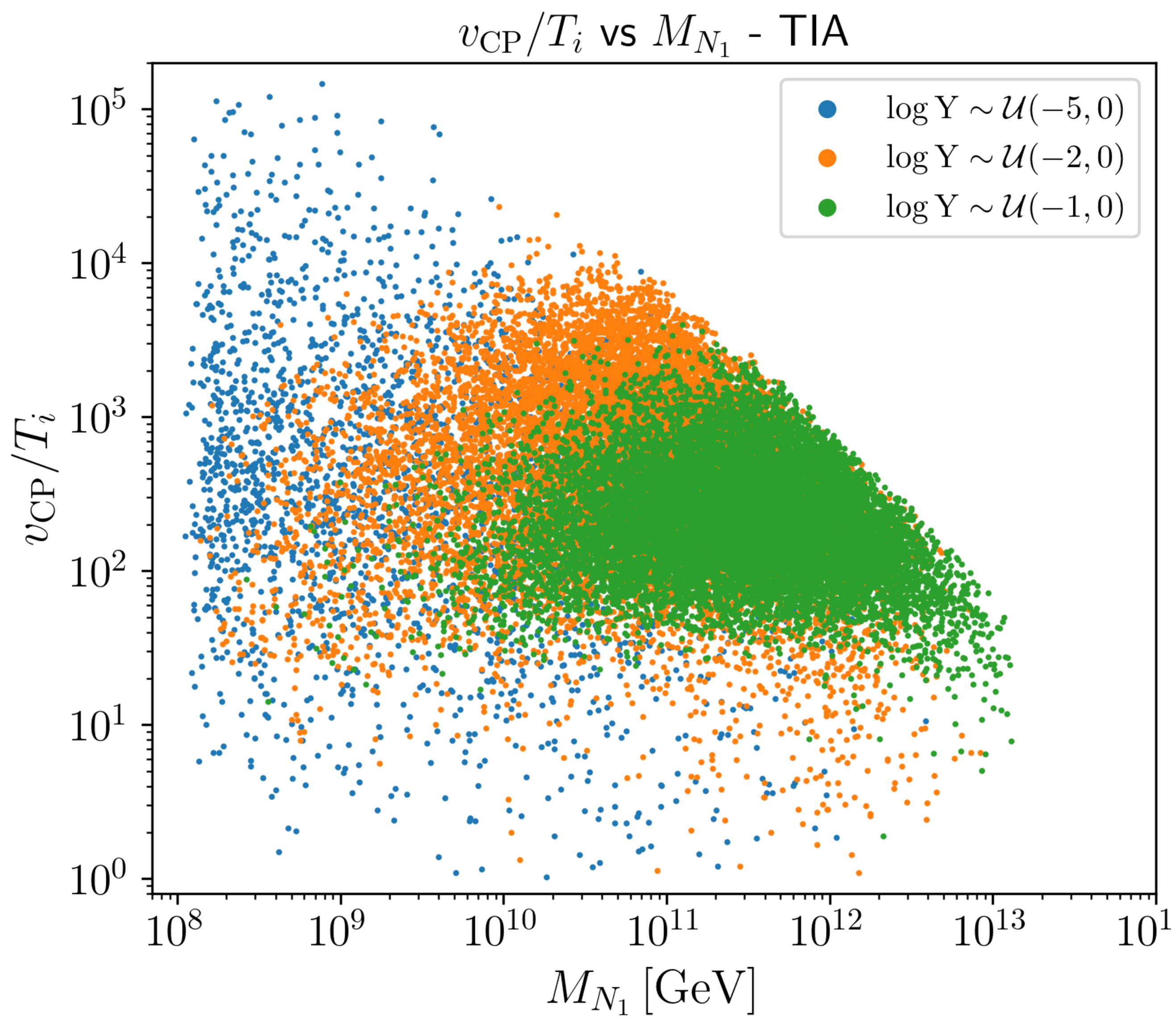
Is it possible to realize thermal leptogenesis?
Is there any potential signature?

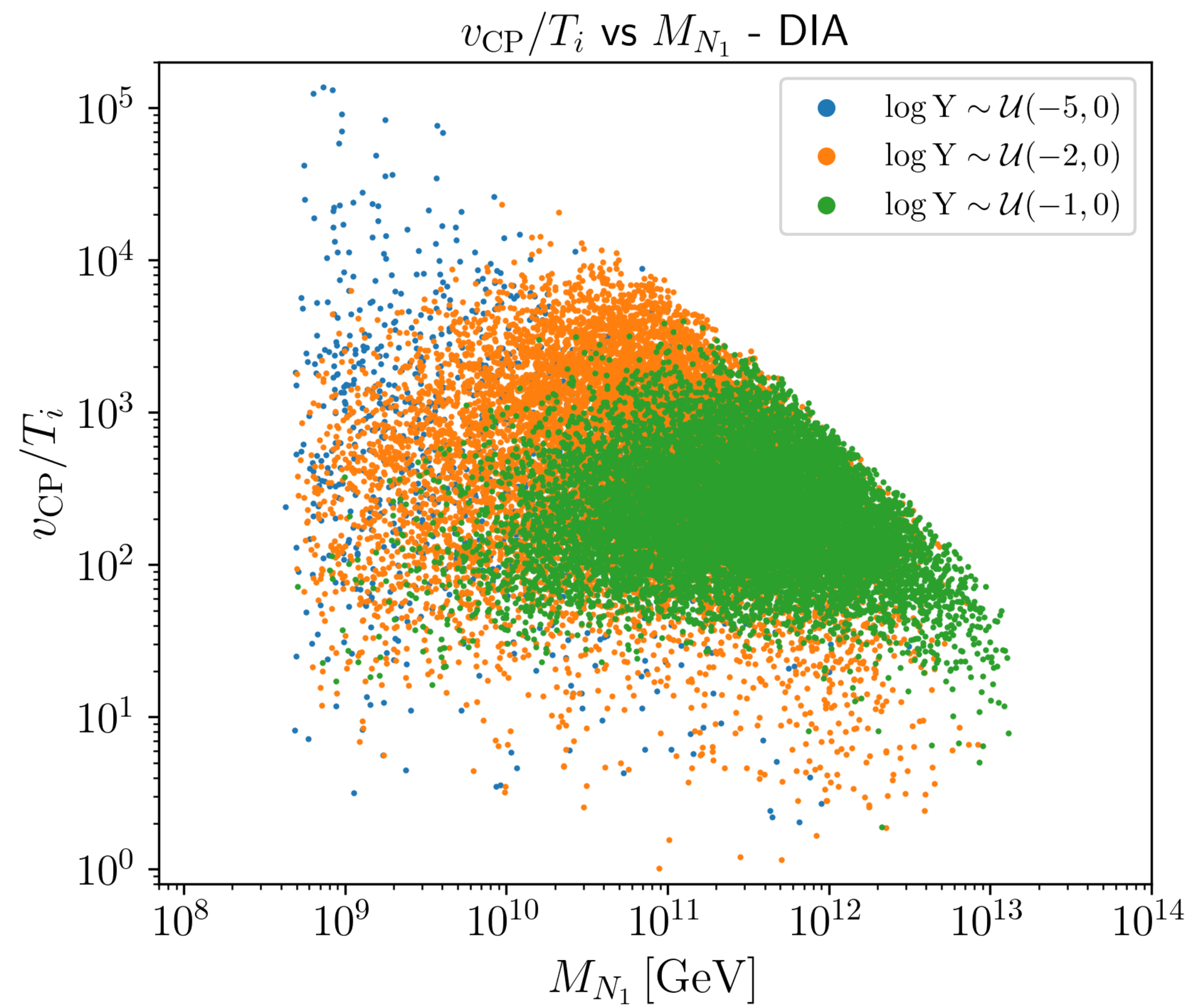
Numerical study





Vector-like Quality

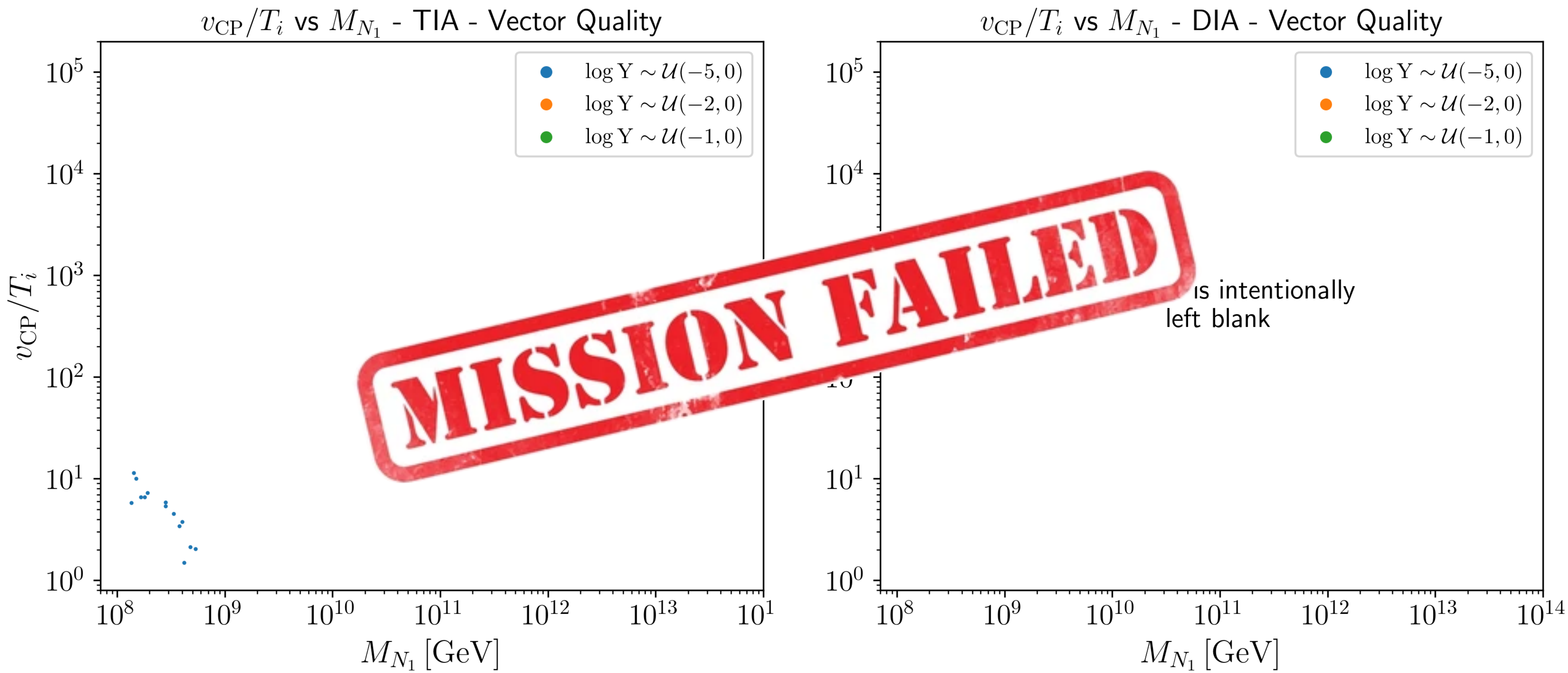




Checking quality for vectors...

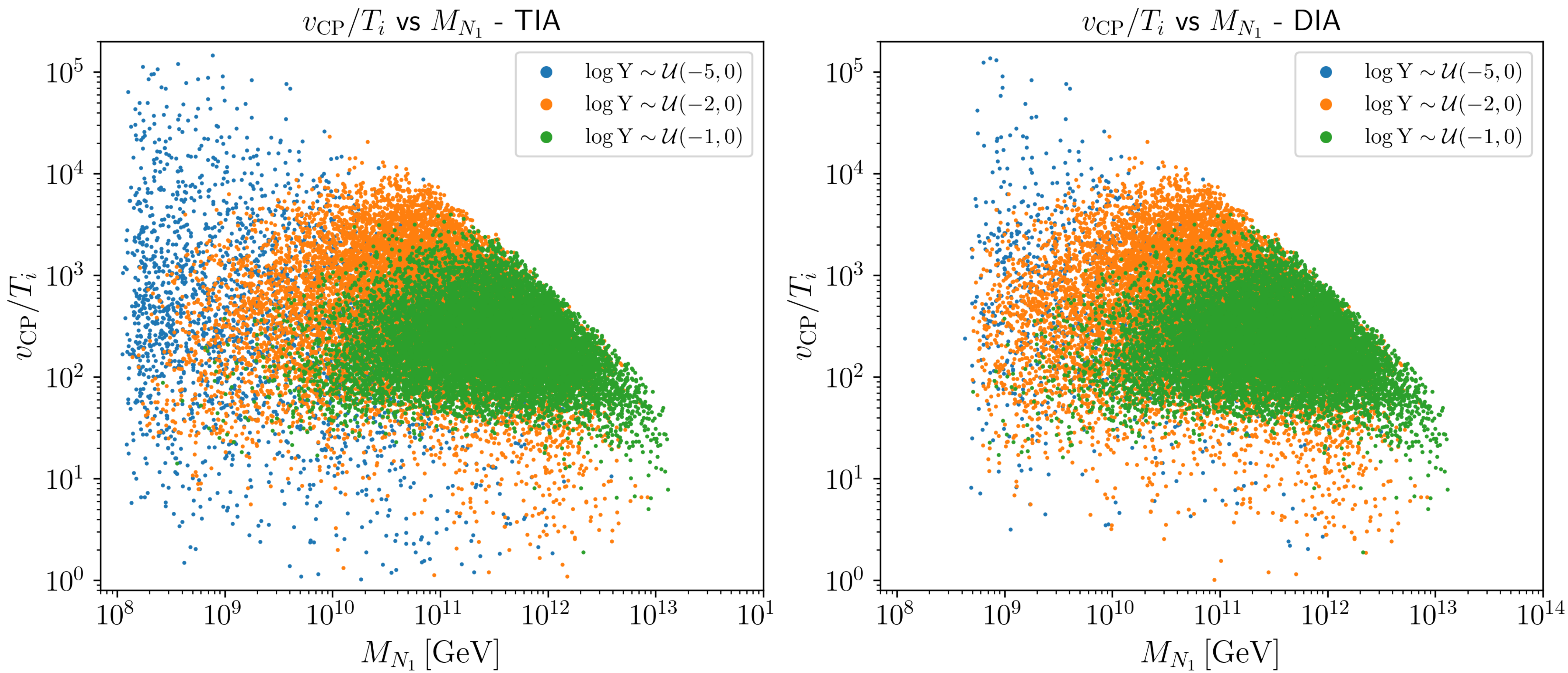
($v_{CP} < 10^8$ GeV)

Vector-like Quality



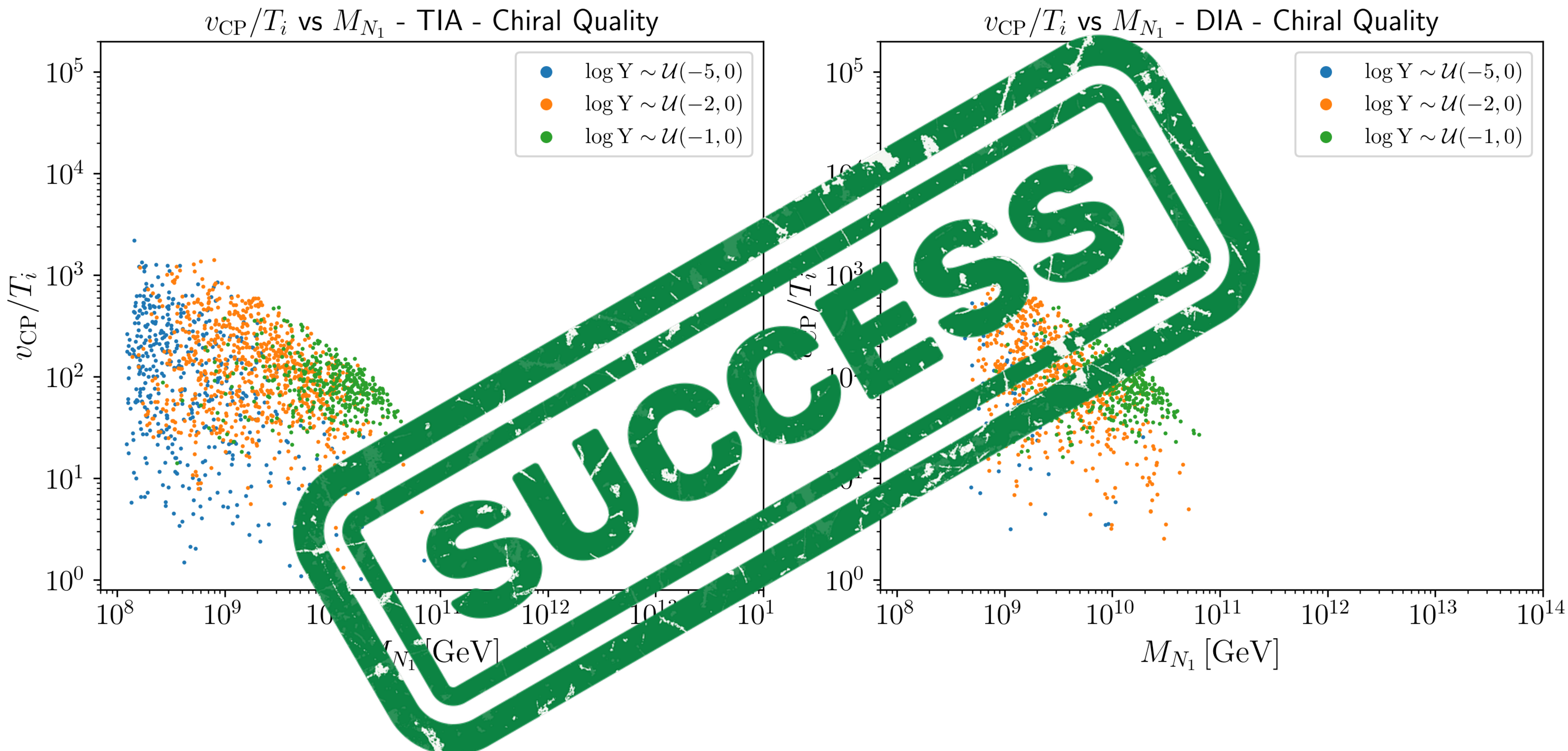
- NB models with **vector-like** heavy quarks face tension with leptogenesis [Asadi, Homiller, Lu, Reece, 2023]

Chiral Quality



Checking quality for chiral fermions (automatic NB)...

Chiral Quality

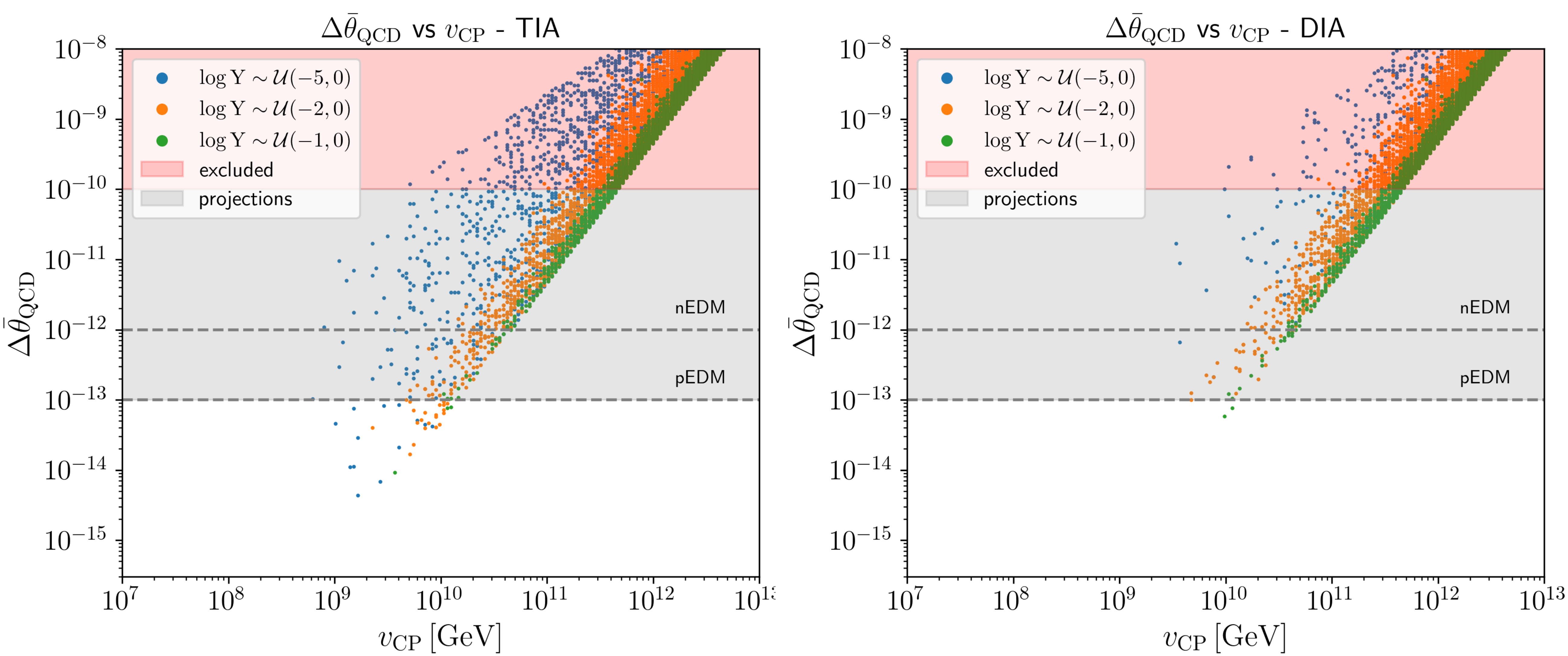


- NB models with **chiral** heavy quarks are **high-quality** solutions to the strong CP problem and achieve **successful** leptogenesis

Signatures

Leptogenesis & Quality

$$\Delta\bar{\theta}_{\rm QCD} \simeq 10^{-17} \times \left(\frac{\xi \sin\theta_{\rm CP}}{1}\right)\left(\frac{v_{CP}}{10^8\ {\rm GeV}}\right)^2\left(1+\frac{v_S}{v_{\rm CP}}\right)$$



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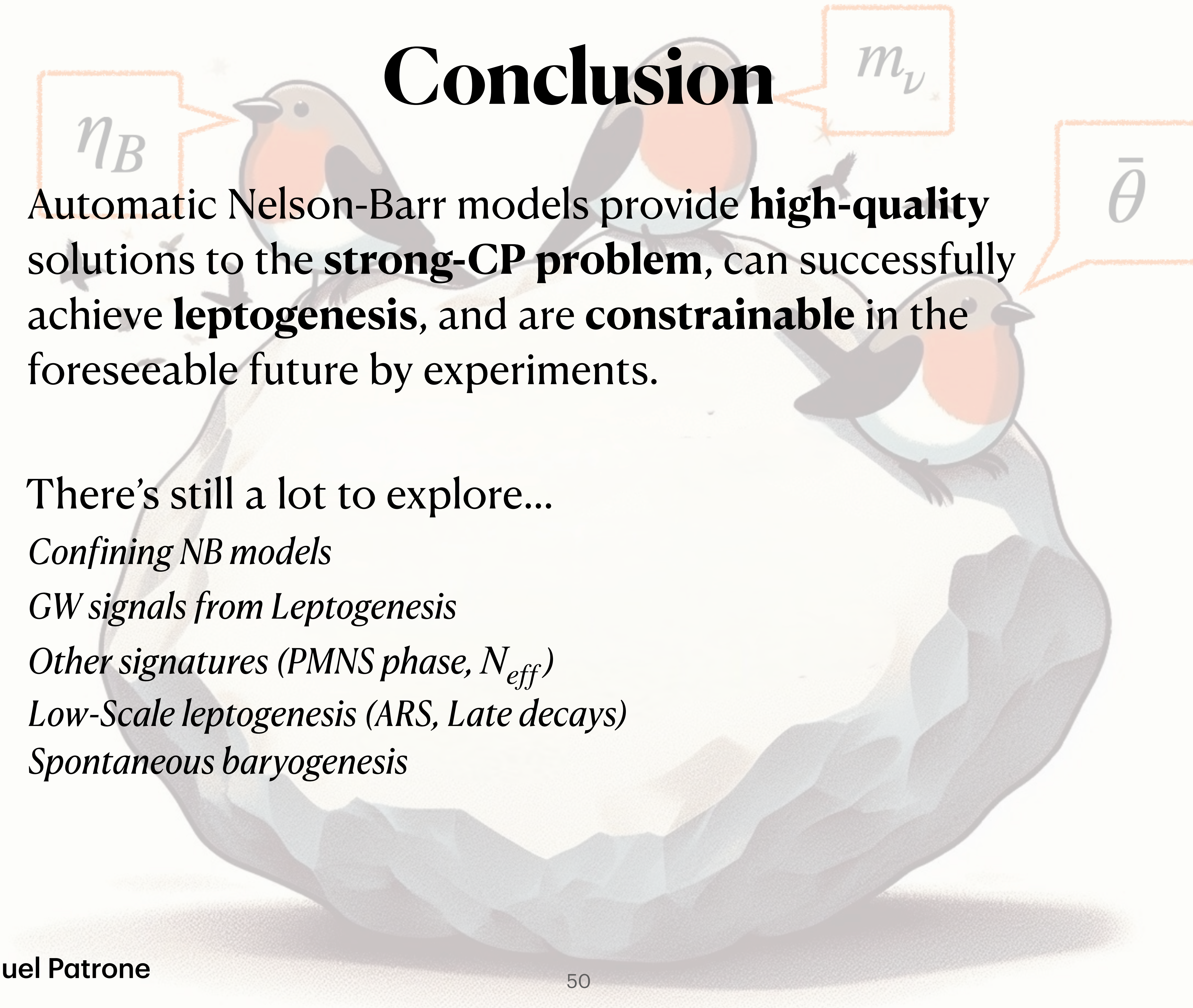
Conclusion



- Automatic Nelson-Barr models provide **high-quality** solutions to the **strong-CP problem**, can successfully achieve **leptogenesis**, and are **constrainable** in the foreseeable future by experiments.

- There's still a lot to explore…

  Confining NB models

  GW signals from Leptogenesis

  Other signatures (PMNS phase, N_{eff})

  Low-Scale leptogenesis (ARS, Late decays)

  Spontaneous baryogenesis

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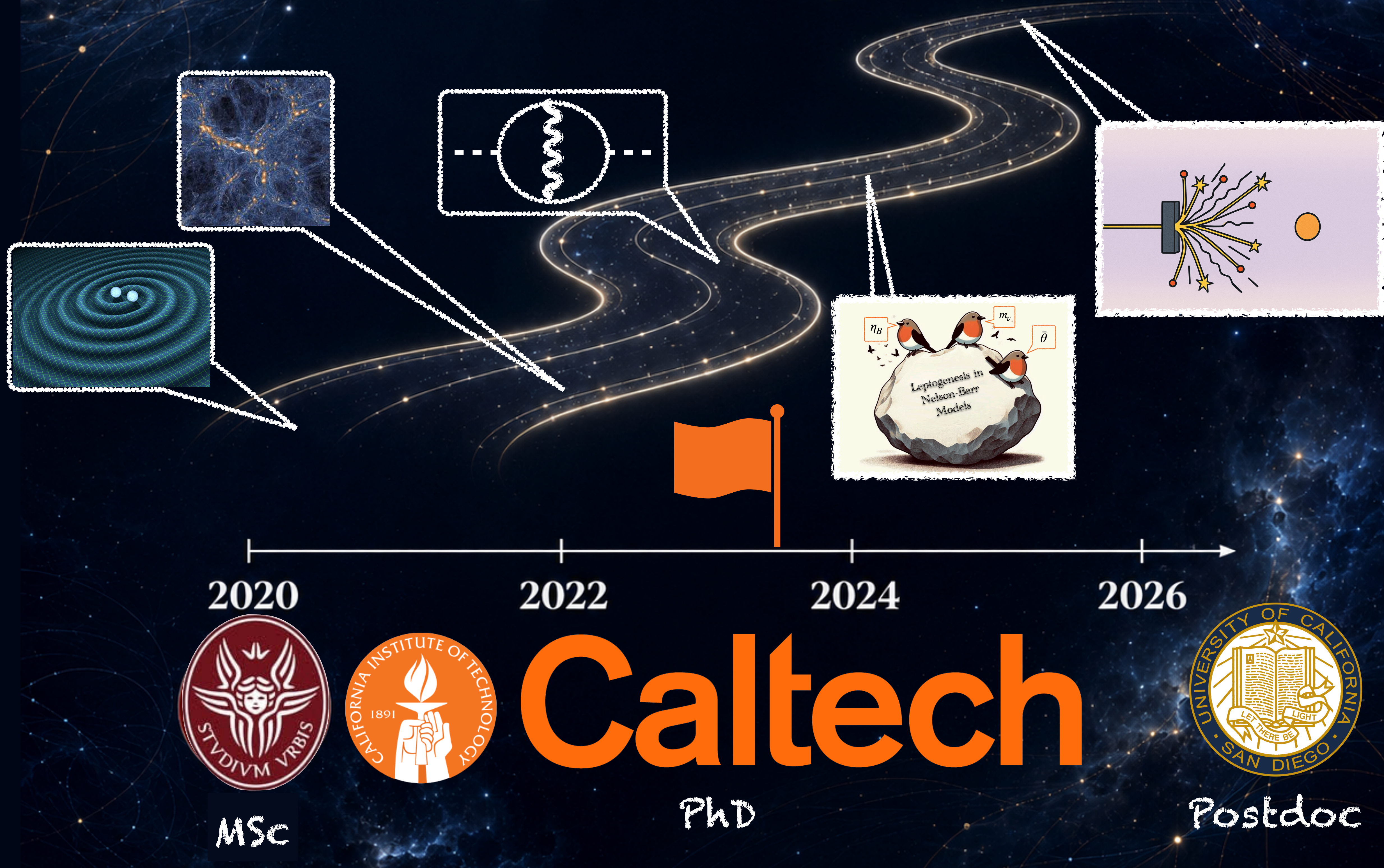
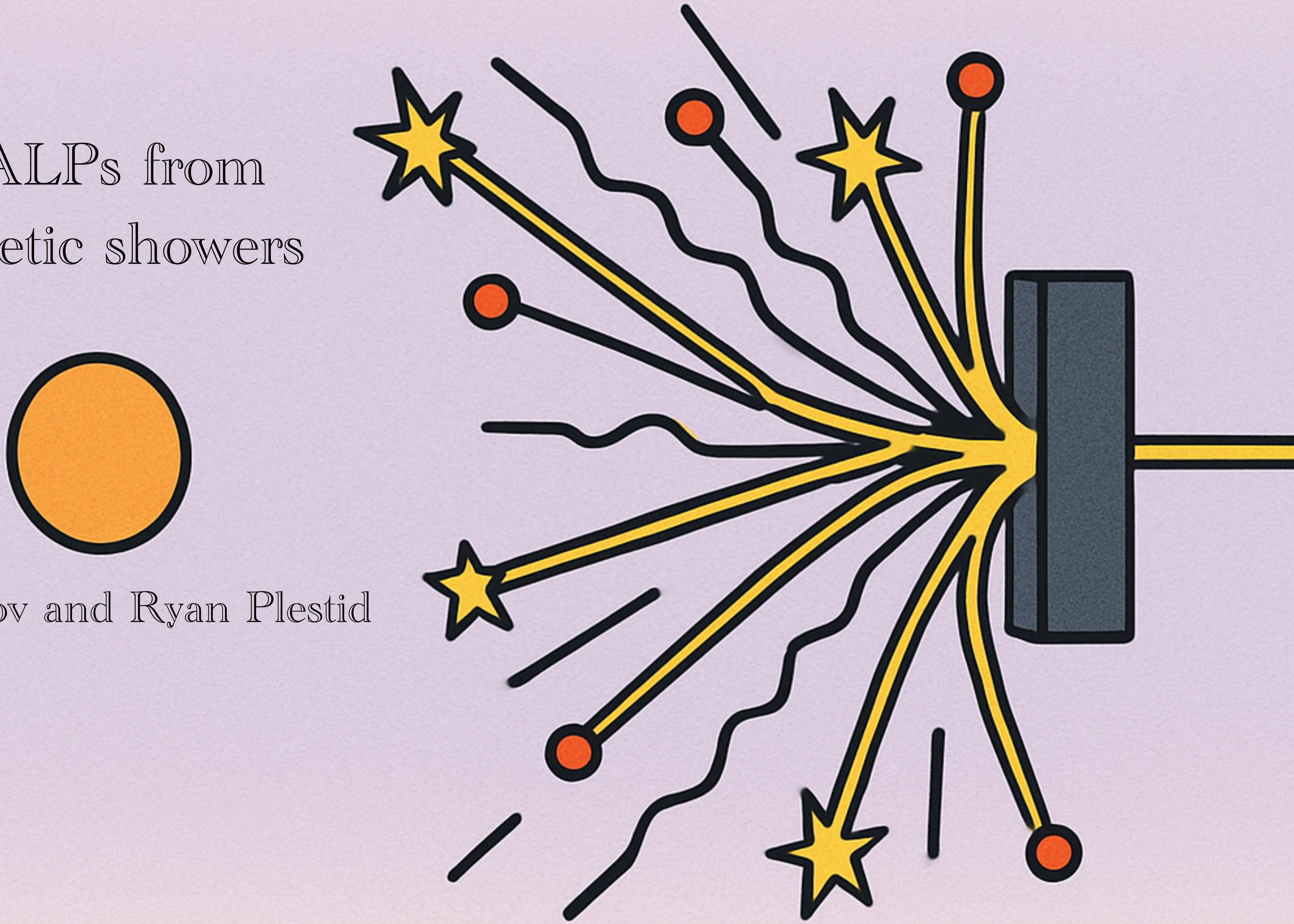
…My way”



η_B
m_ν
$\bar{\theta}$
Leptogenesis in Nelson-Barr Models
2020
2022
2024
2026
STVDIVM VRBIS
CALIFORNIA INSTITUTE OF TECHNOLOGY
1891
Caltech
UNIVERSITY OF CALIFORNIA
SAN DIEGO
LET THERE BE LIGHT
MSc
PhD
Postdoc

Long-lived ALPs from electromagnetic showers



feat. Nikita Blinov and Ryan Plestid
(PRD, 2026)

Motivation

- State-of-the-art ALPs Beam Dump Sensitivity projections **do not** include **EM showers** in the target [1904.02091, 2201.05170]

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- Accurate sensitivity curves can change the **selection criteria** experiments should optimize for.

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Overview

Long-lived ALPs from Electromagnetic Cascades

- ALPs in the wild
- ALPs-genesis
- ALPs in the dump
- ALPETITE
- Results
- Conclusion & Outlook

ALPs in the wild

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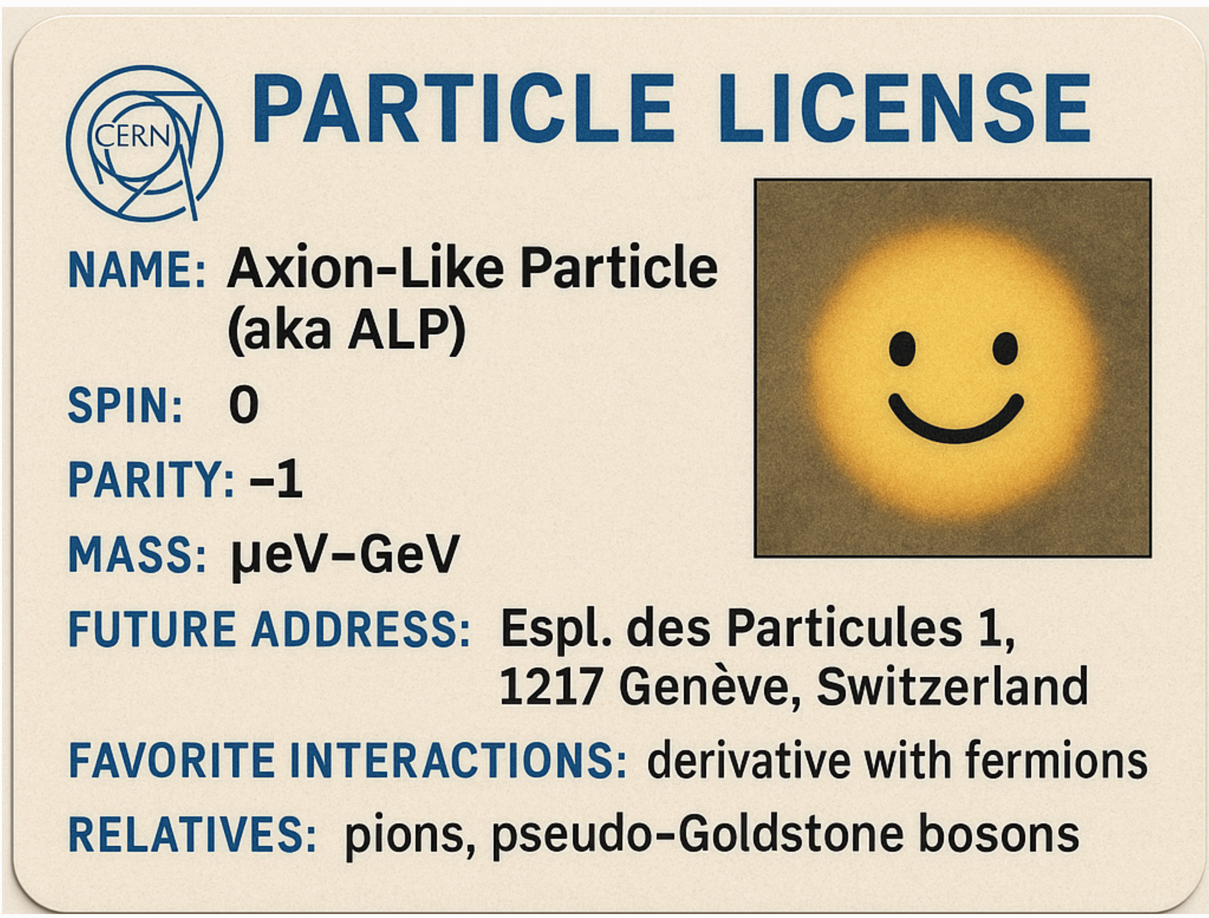
Axion-Like Particles
In the Wild



[ChatGPT 4]

- **Model building:** Any dynamics with a spontaneously broken (approximate) global symmetry will produce light, spinless particles (Goldstone theorem).
- **Light New Physics:** ALP (spin 0), dark photon, Z' (spin 1), HNL (spin 1/2), gravitino (spin 3/2)

- **Model independent:** Don't need to know the UV physics to study ALPs

Axion-Like Particles

In the Wild

$$\mathscr{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\, a^2 + \frac{\partial^\mu a}{f} \sum_F \bar{\psi}_F\, \mathbf{c}_F\, \gamma_\mu \psi_F$$

$$+ c_{GG}\, \frac{\alpha_s}{4\pi}\, \frac{a}{f}\, G^a_{\mu\nu}\, \tilde{G}^{\mu\nu,a} + c_{WW}\, \frac{\alpha_2}{4\pi}\, \frac{a}{f}\, W^A_{\mu\nu}\, \tilde{W}^{\mu\nu,A} + c_{BB}\, \frac{\alpha_1}{4\pi}\, \frac{a}{f}\, B_{\mu\nu}\, \tilde{B}^{\mu\nu}\,.$$

[Georgi, Kaplan, Randall (1986)]

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[Georgi, Kaplan, Randall (1986)]

Weakly - coupled

- **Model independent:** Don't need to know the UV physics to study ALPs

Axion-Like Particles
In the Wild

Shift symmetry -> derivatively coupled

$$\mathscr{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \frac{\partial^\mu a}{f}\sum_F \bar{\Psi}_F \mathbf{c}_F \gamma_\mu \Psi_F$$

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[Georgi, Kaplan, Randall (1986)]

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Axion-Like Particles
In the Wild

ALPs: explicit symmetry breaking term

QCD axions: generated by instantons, $m_a \approx 10^{12}\,\mathrm{GeV}/f_a \times \mu\mathrm{eV}$

$$\mathscr{L}_{\rm eff}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \frac{\partial^\mu a}{f}\sum_F \bar{\psi}_F\,\mathbf{c}_F\,\gamma_\mu \psi_F$$

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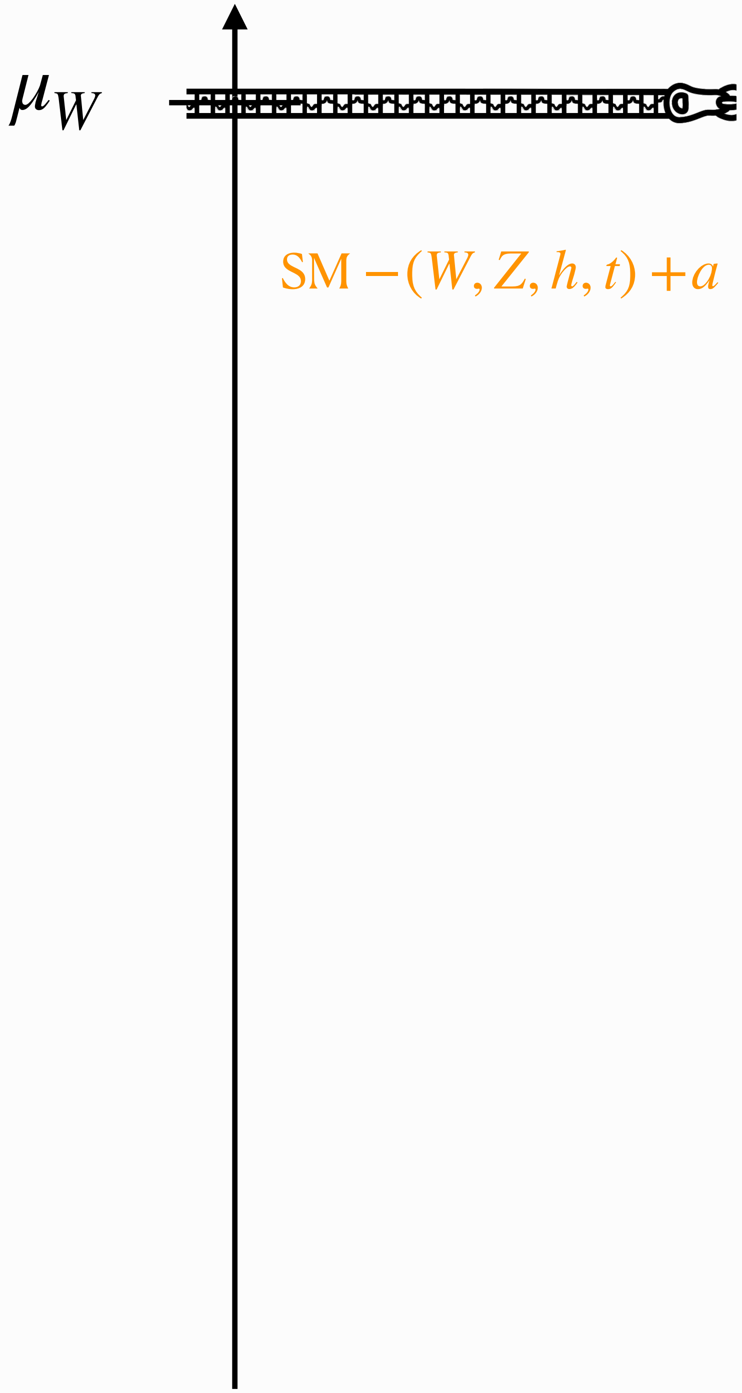
Axion-Like Particles

In the Wild



[ArXiv 2012.12272]

$$\mathcal{L}_{\rm eff}^{D\leq 5}(\mu \lesssim \mu_w) = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\, a^2 + \sum_{f\neq t} \frac{c_{aff}(\mu)}{2}\, \frac{\partial^\mu a}{f}\, \bar{f}\gamma_\mu\gamma_5 f$$
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Axion-Like Particles

In the Wild

μ_W

[ArXiv 2012.12272]

SM $-(W, Z, h, t) + a$

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"Hadrophobic" ALPs

γ dominated

$c_{a\gamma\gamma} = 1$

e^- dominated

$c_{aee}(\mu_w) = 1$

Samuel Patrone

Axion-Like Particles

In the Wild

μ_W

[ArXiv 2012.12272]

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"*Hadrophobic*" ALPs

γ dominated ← *e^- dominated*

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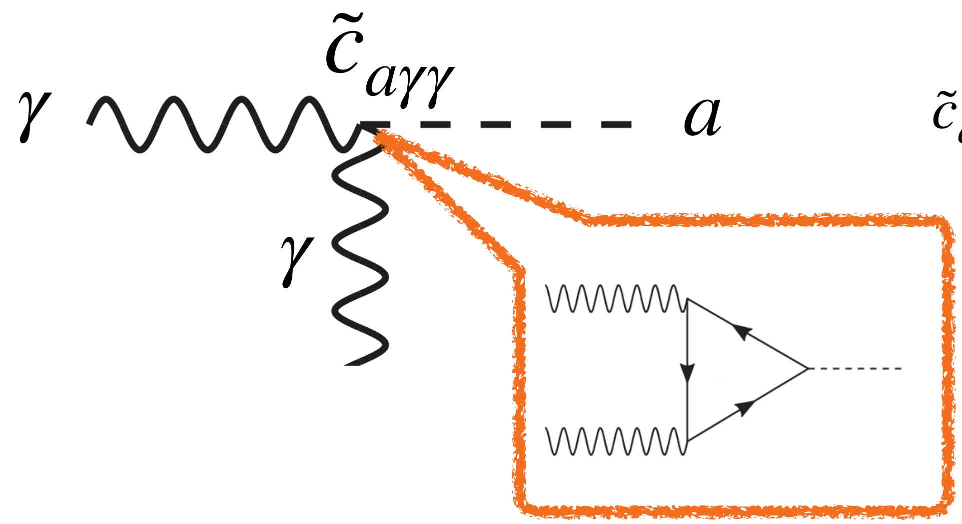

$$\tilde{c}_{a\gamma\gamma}(\mu) = c_{a\gamma\gamma} + \sum_f N_c Q_f^2 c_{aff}(\mu)\Theta(\mu - m_f)$$

$$\equiv c_{a\gamma\gamma} + c_{aee}(\mu)$$

Axion-Like Particles

In the Wild

[ArXiv 2012.12272]

μ_W

SM $-(W, Z, h, t) + a$

$$\mathscr{L}_{\text{eff}}^{D\le 5}(\mu \lesssim \mu_w) = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + \sum_{f\neq t} \frac{c_{aff}(\mu)}{2} \frac{\partial^\mu a}{f} \bar{f}\gamma_\mu \gamma_5 f$$
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"Hadrophobic" ALPs

γ dominated → *e^- dominated*

$c_{a\gamma\gamma} = 1$ | $c_{aee}(\mu_w) = 1$

$$\begin{cases} \tilde{c}_{a\gamma\gamma}(\mu) = c_{a\gamma\gamma} + \sum_f N_c Q_f^2 c_{aff}(\mu)\Theta(\mu - m_f) \\ c_{aee}(\mu_L) = c_{aee}(\mu_H) + \frac{3\tilde{c}_{a\gamma\gamma}(\mu_H)}{\beta_0^{\text{QED}}} \frac{\alpha(\mu_H) - \alpha(\mu_L)}{\pi} \end{cases}$$

$$\begin{cases} \tilde{c}_{a\gamma\gamma}(m_a) \approx 1 \\ c_{aee}(m_a) \approx 3.6 \times 10^{-5} \end{cases}$$

$$\begin{cases} \tilde{c}_{a\gamma\gamma}(m_a) \approx 1 \\ c_{aee}(m_a) \approx 1 \end{cases}$$

m_a

(3 MeV - 1 GeV)

Samuel Patrone

Axion-Like Particles

In the Wild

[ArXiv 2012.12272]

μ_W

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γ dominated → *e^- dominated*

$c_{a\gamma\gamma} = 1$ | $c_{aee}(\mu_w) = 1$

$$\begin{cases} \tilde{c}_{a\gamma\gamma}(\mu) = c_{a\gamma\gamma} + \sum_f N_c Q_f^2 c_{aff}(\mu)\Theta(\mu - m_f) \\ c_{aee}(\mu_L) = c_{aee}(\mu_H) + \dfrac{3\tilde{c}_{a\gamma\gamma}(\mu_H)}{\beta_0^{\text{QED}}}\, \dfrac{\alpha(\mu_H) - \alpha(\mu_L)}{\pi} \end{cases}$$

$$\begin{cases} \tilde{c}_{a\gamma\gamma}(m_a) \approx 1 \\ c_{aee}(m_a) \approx 3.6 \times 10^{-5} \end{cases} \qquad \begin{cases} \tilde{c}_{a\gamma\gamma}(m_a) \approx 1 \\ c_{aee}(m_a) \approx 1 \end{cases}$$

m_a

(3 MeV - 1 GeV)

$$\mathscr{L}_{EFT} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 + \frac{\alpha}{4\pi}\frac{c_{a\gamma\gamma}}{f} a F\tilde{F} + \frac{c_{aee}(m_a)}{f}(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e$$

Samuel Patrone

Axion-Like Particles

In the Wild

[ArXiv 2012.12272]

μ_W

SM $-(W, Z, h, t) + a$

$$\mathscr{L}_{\rm eff}^{D\leq 5}(\mu \lesssim \mu_w) = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \sum_{f\neq t}\frac{c_{aff}(\mu)}{2}\frac{\partial^\mu a}{f}\bar{f}\gamma_\mu\gamma_5 f + c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + c_{a\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f}F_{\mu\nu}\tilde{F}^{\mu\nu},$$

"*Hadrophobic*" ALPs

γ dominated → *e^- dominated*

$c_{a\gamma\gamma} = 1$ $\qquad$ $c_{aee}(\mu_w) = 1$

$$\begin{cases} \tilde{c}_{a\gamma\gamma}(\mu) = c_{a\gamma\gamma} + \sum_f N_c Q_f^2 c_{aff}(\mu)\Theta(\mu - m_f) \\ c_{aee}(\mu_L) = c_{aee}(\mu_H) + \frac{3\tilde{c}_{a\gamma\gamma}(\mu_H)}{\beta_0^{\rm QED}}\frac{\alpha(\mu_H) - \alpha(\mu_L)}{\pi} \end{cases}$$

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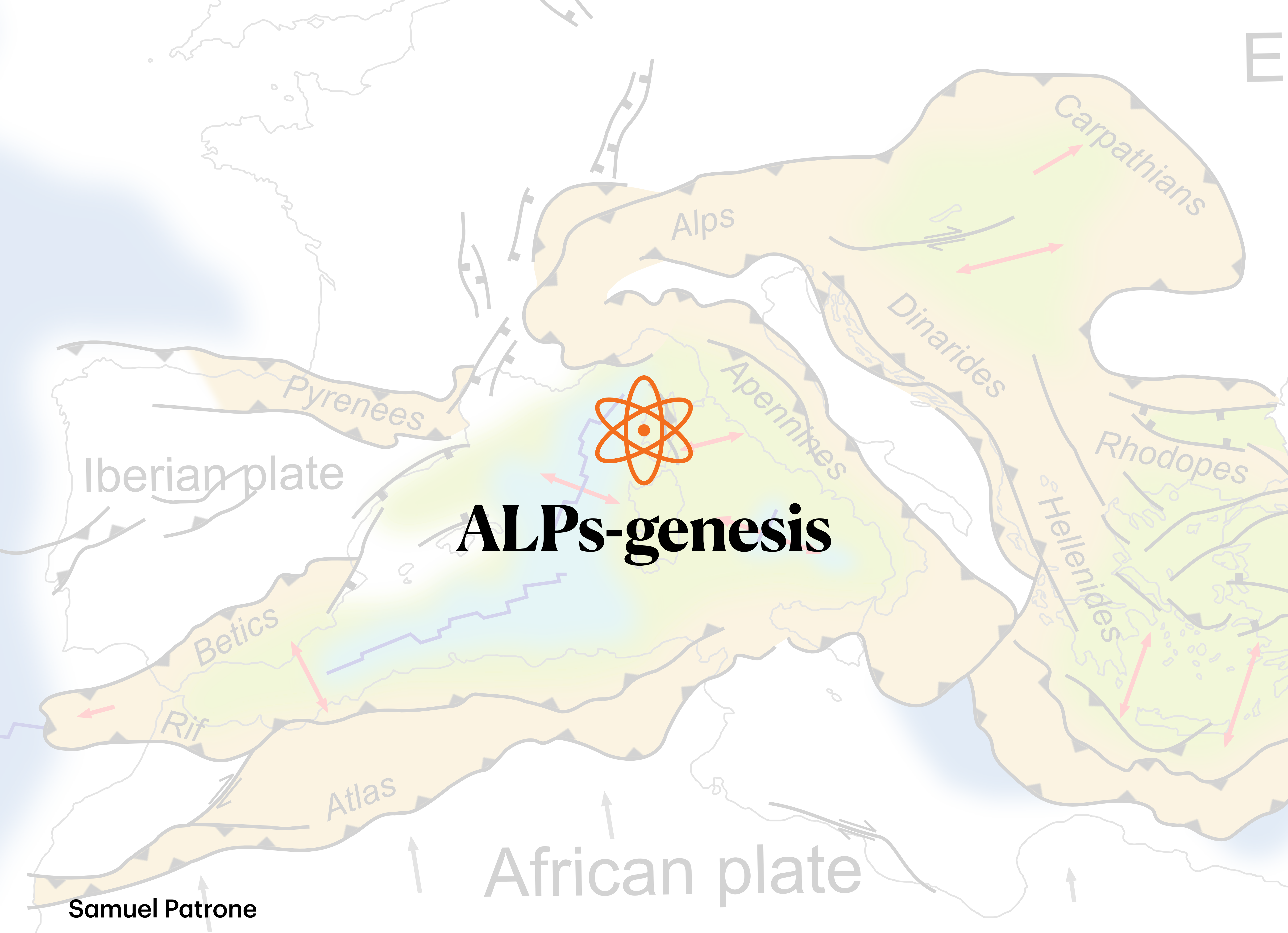
m_a

(3 MeV - 1 GeV)

$$\mathscr{L}_{EFT} = \frac{1}{2}\partial_\mu a\partial^\mu a - \frac{1}{2}m_a^2 a^2 + \frac{\alpha}{4\pi}\frac{(1,0)}{f}aF\tilde{F} + \frac{(10^{-5},1)}{f}(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e$$

Samuel Patrone

ALPs-genesis



Samuel Patrone

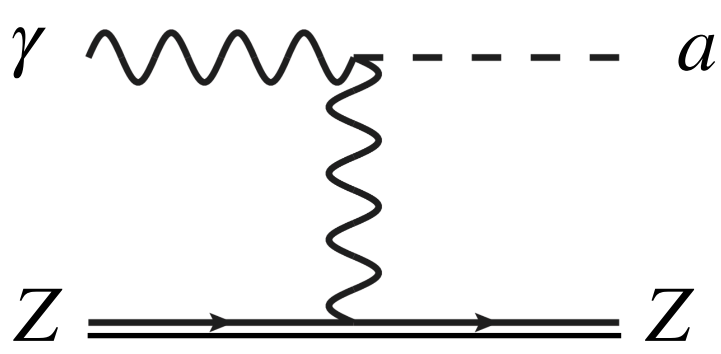
Production

$$\mathscr{L} \supset \frac{\alpha}{4\pi}\frac{c_{a\gamma\gamma}}{f_a}aF\tilde{F} + \frac{c_{aee}}{f_a}(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e$$

Production

$$\mathscr{L} \supset \frac{\alpha}{4\pi}\frac{c_{a\gamma\gamma}}{f_a}aF\tilde{F} + \frac{c_{aee}}{f_a}(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e$$

$\propto \tilde{c}_{a\gamma\gamma}$

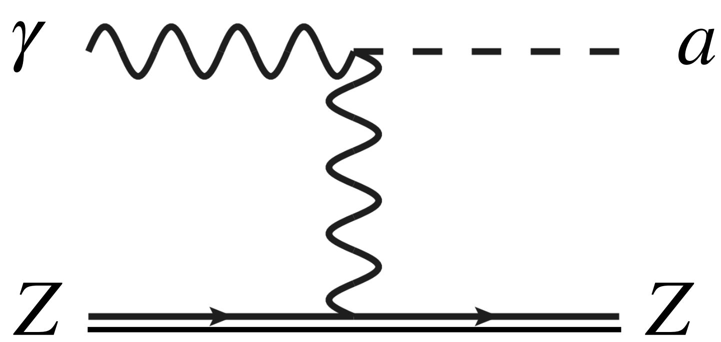


Primakoff

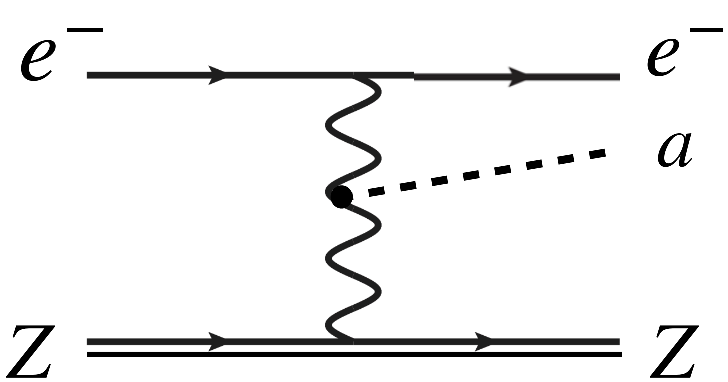
Production

$$\mathscr{L} \supset \frac{\alpha}{4\pi}\frac{c_{a\gamma\gamma}}{f_a} aF\tilde{F} + \frac{c_{aee}}{f_a}(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e$$

$\propto \tilde{c}_{a\gamma\gamma}$



Primakoff



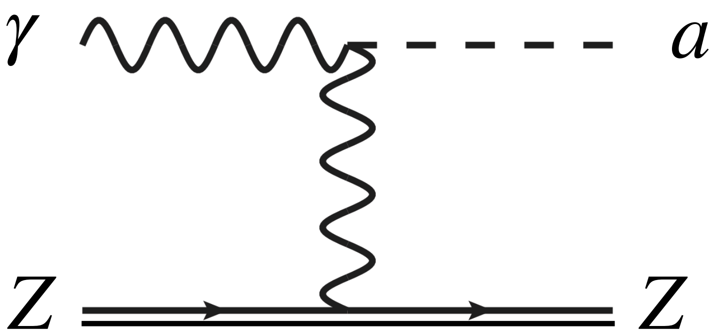
Photon-fusion

Samuel Patrone

Production

$$\mathscr{L} \supset \frac{\alpha}{4\pi}\frac{c_{a\gamma\gamma}}{f_a} aF\tilde{F} + \frac{c_{aee}}{f_a}(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e$$

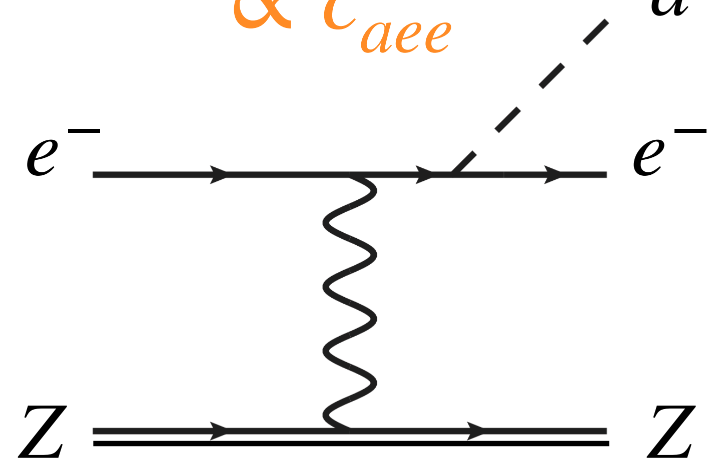
$\propto \tilde{c}_{a\gamma\gamma}$



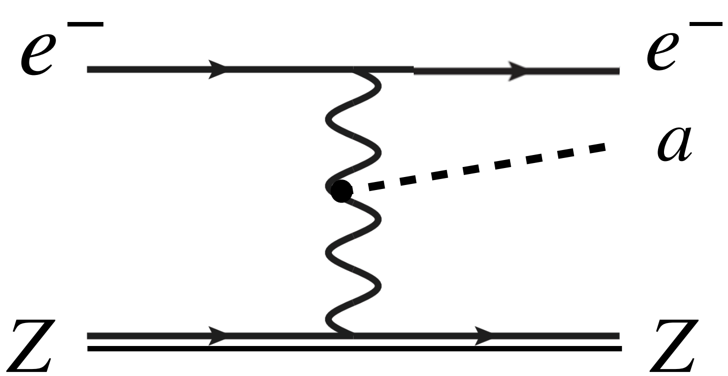
Primakoff

$\propto c_{aee}$

a



Bremsstrahlung

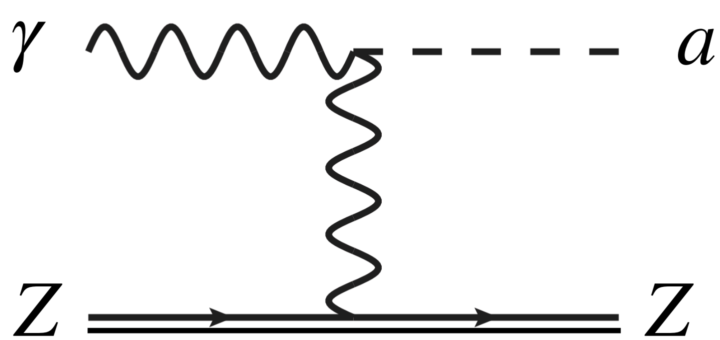


Photon-fusion

Production

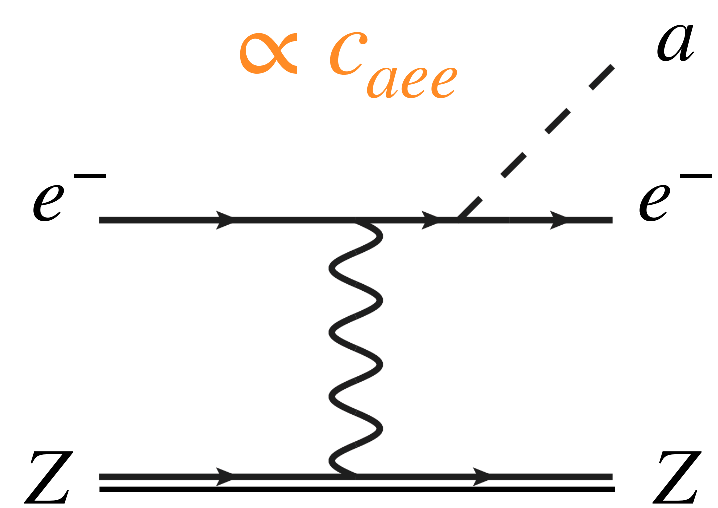
$$\mathscr{L} \supset \frac{\alpha}{4\pi}\frac{c_{a\gamma\gamma}}{f_a} aF\tilde{F} + \frac{c_{aee}}{f_a}(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e$$

$\propto \tilde{c}_{a\gamma\gamma}$

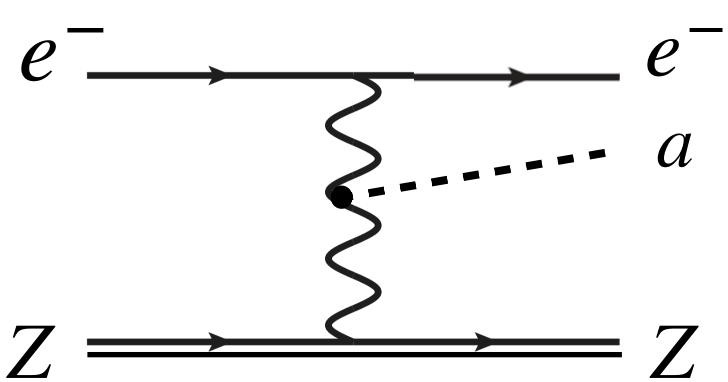


Primakoff

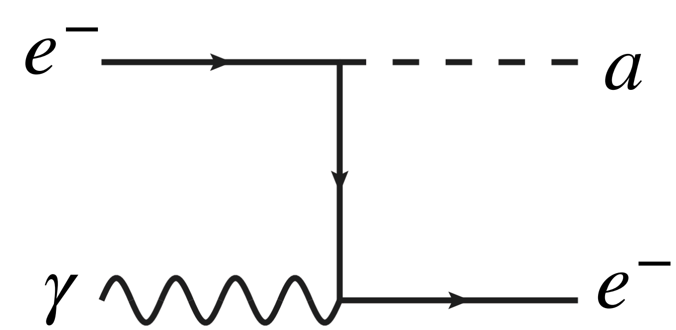
$\propto c_{aee}$



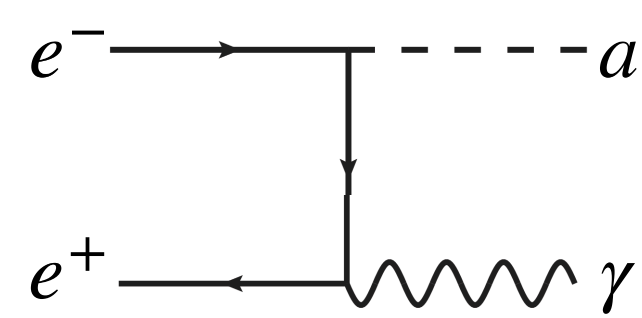
Bremsstrahlung



Photon-fusion



Compton

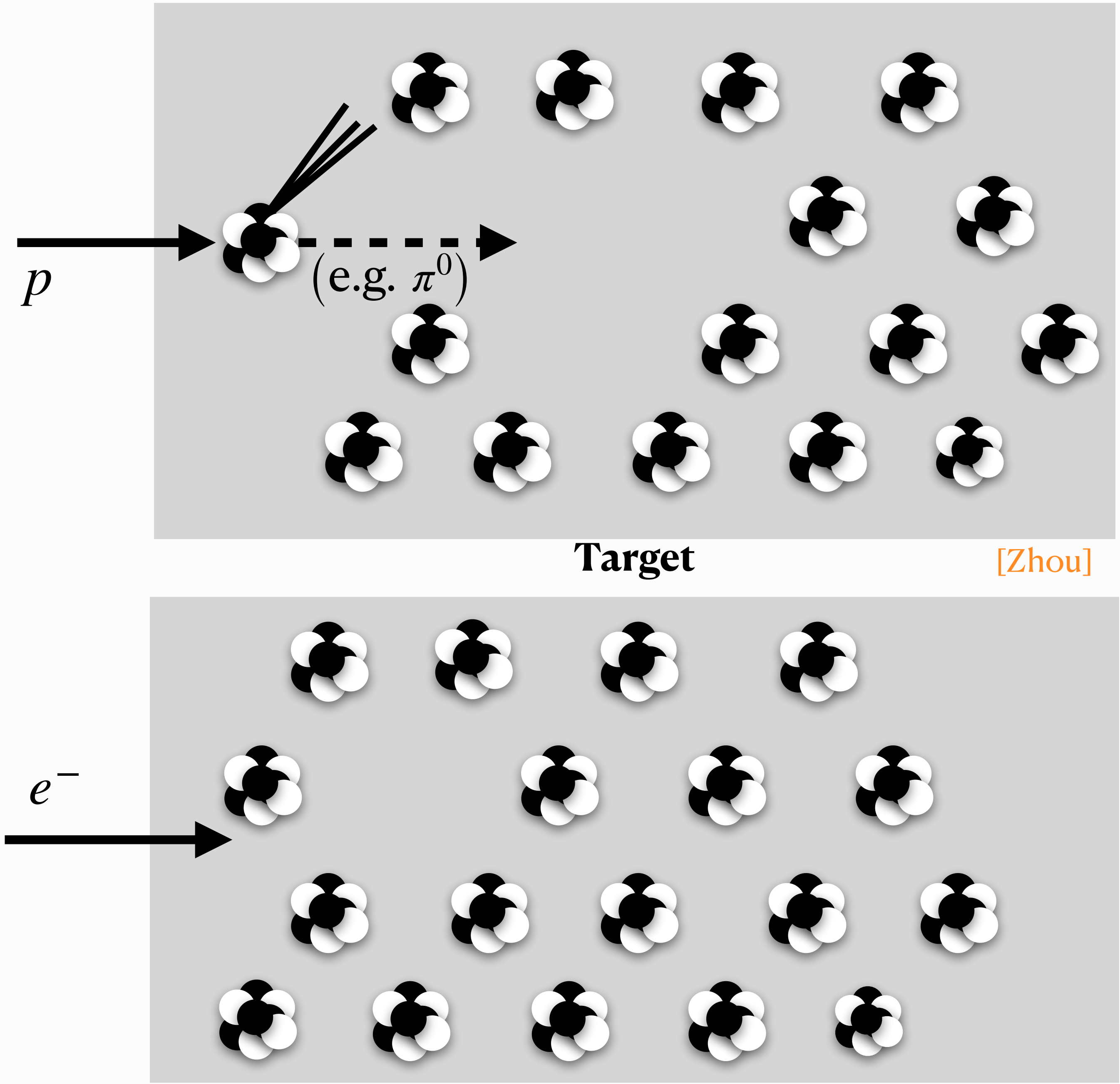


Annihilation

Samuel Patrone

Production

$$\mathscr{L} \supset \frac{\alpha}{4\pi}\frac{c_{a\gamma\gamma}}{f_a}aF\tilde{F} + \frac{c_{aee}}{f_a}(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e$$

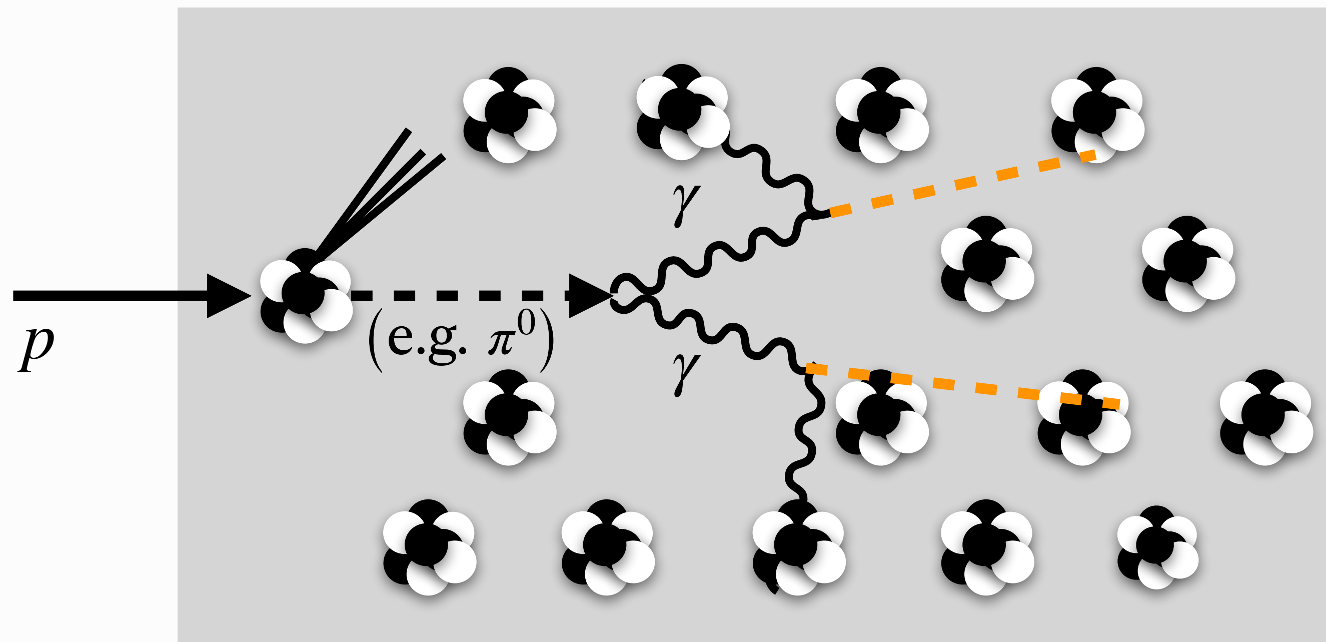


Proton Beam Dump

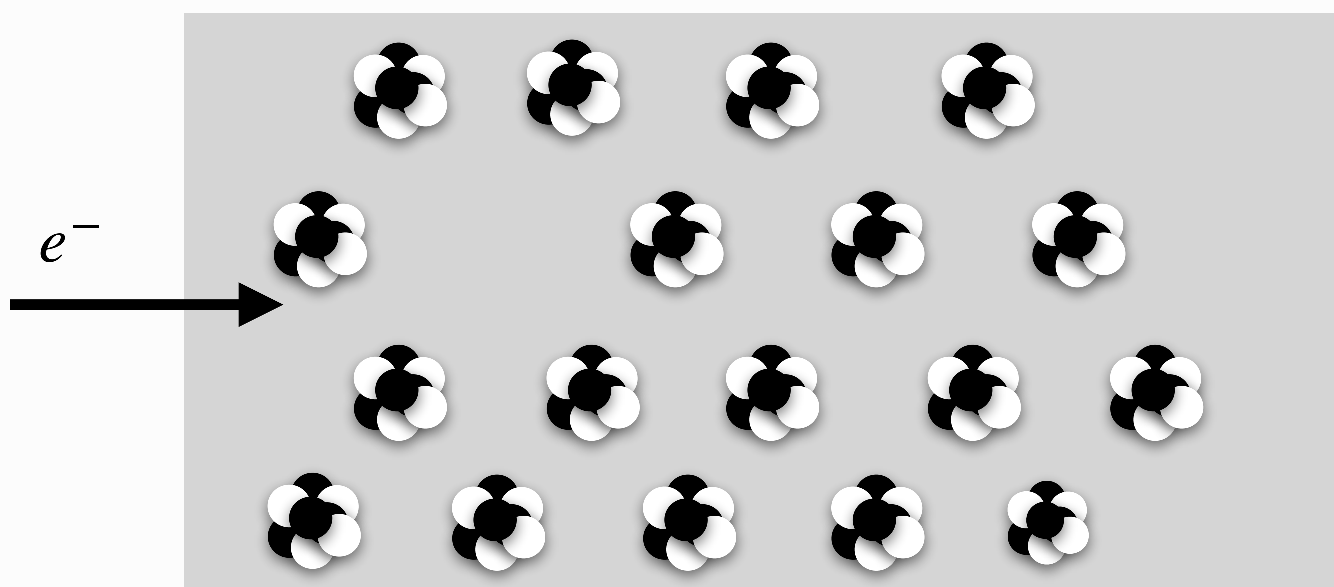
(SHiP)

Production

$$\mathscr{L} \supset \frac{\alpha}{4\pi}\frac{c_{a\gamma\gamma}}{f_a} aF\tilde{F} + \frac{c_{aee}}{f_a}(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e$$



Target [Zhou]



Proton Beam Dump

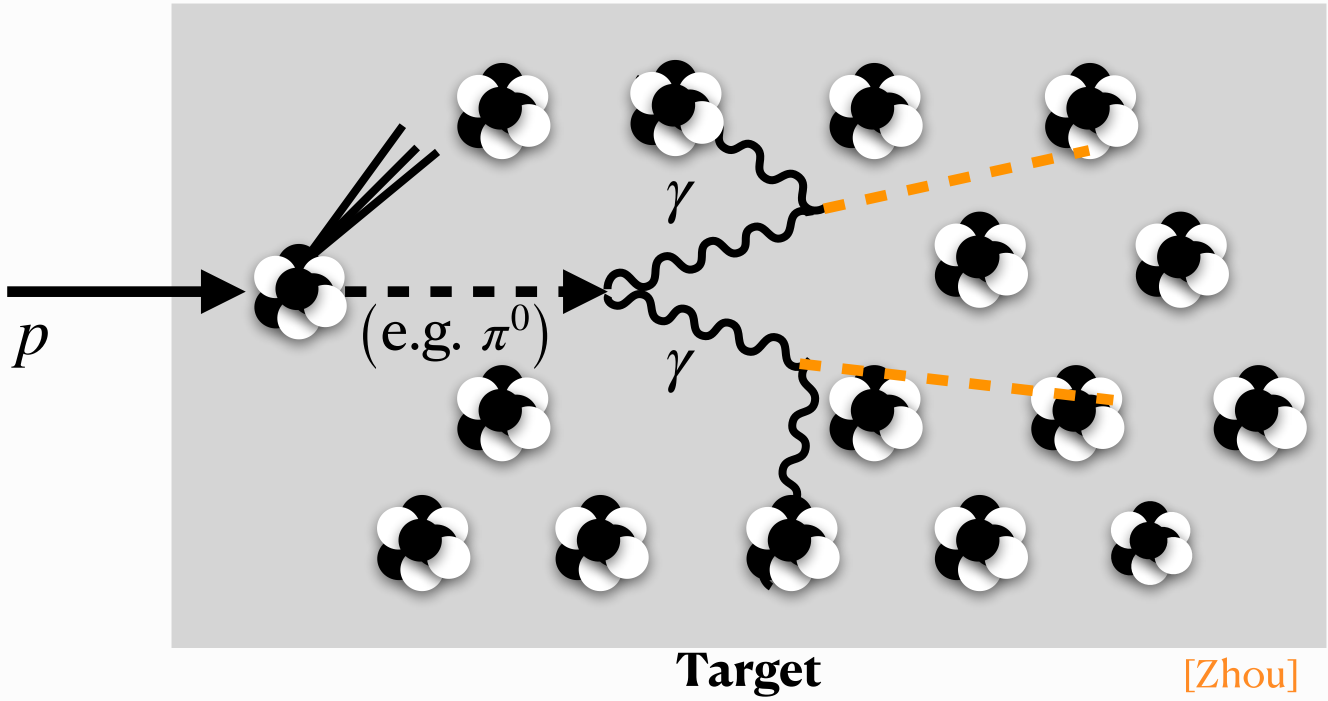
(SHiP)

- **Primary process:** Primakoff [1904.02091, 2201.05170]

Samuel Patrone

Production

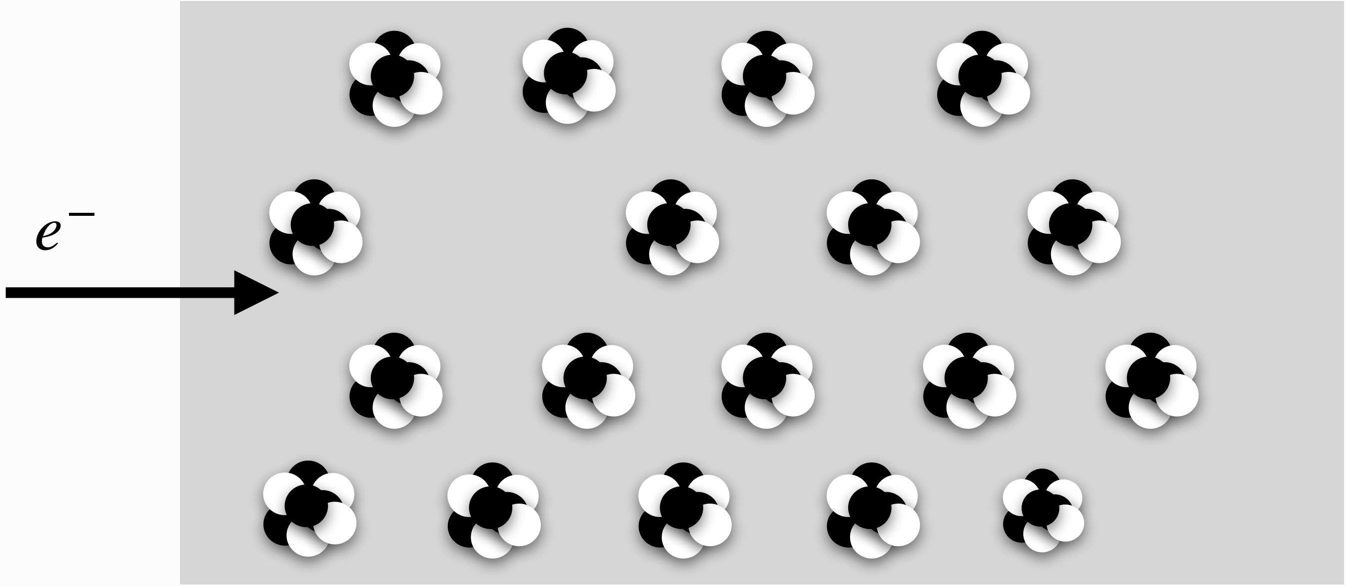
$$\mathscr{L} \supset \frac{\alpha}{4\pi}\frac{c_{a\gamma\gamma}}{f_a}aF\tilde{F} + \frac{c_{aee}}{f_a}(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e$$



Proton Beam Dump

(SHiP)

- **Primary process:** Primakoff [1904.02091, 2201.05170]

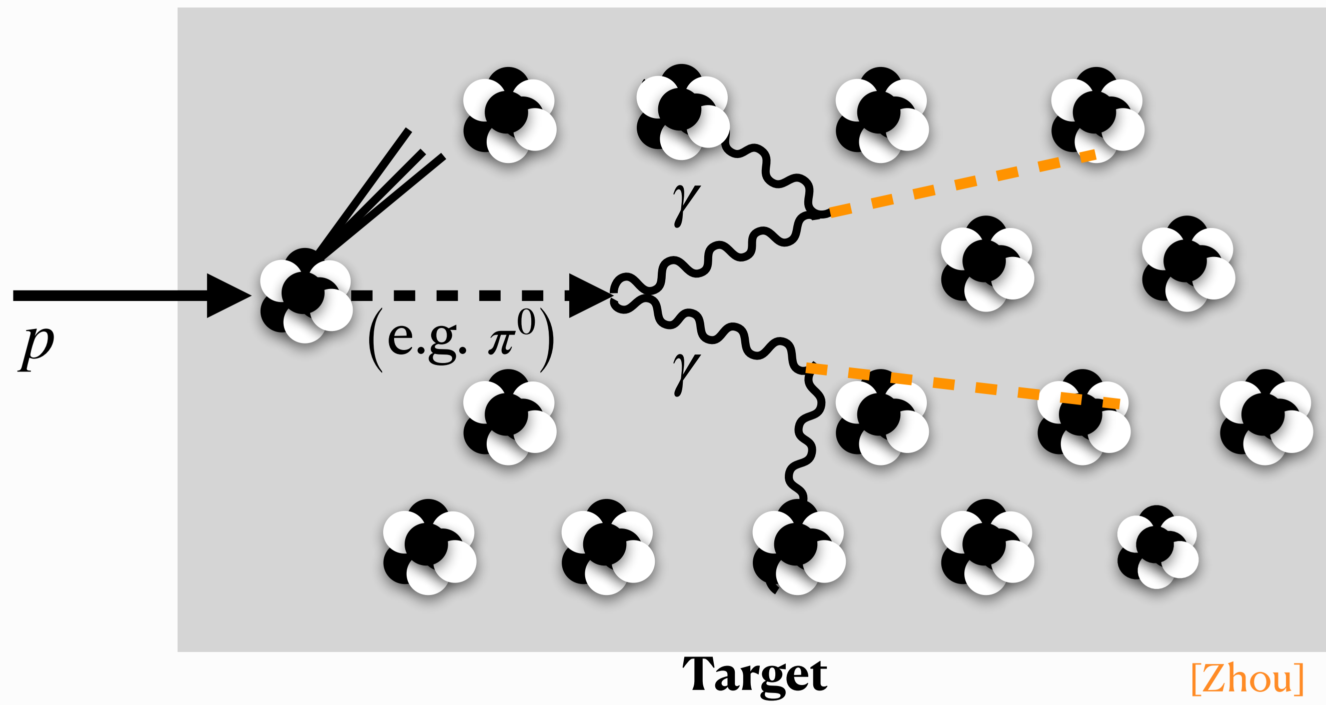


Electron Beam Dump

(BDX)

Production

$$\mathscr{L} \supset \frac{\alpha}{4\pi}\frac{c_{a\gamma\gamma}}{f_a} aF\tilde{F} + \frac{c_{aee}}{f_a}(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e$$

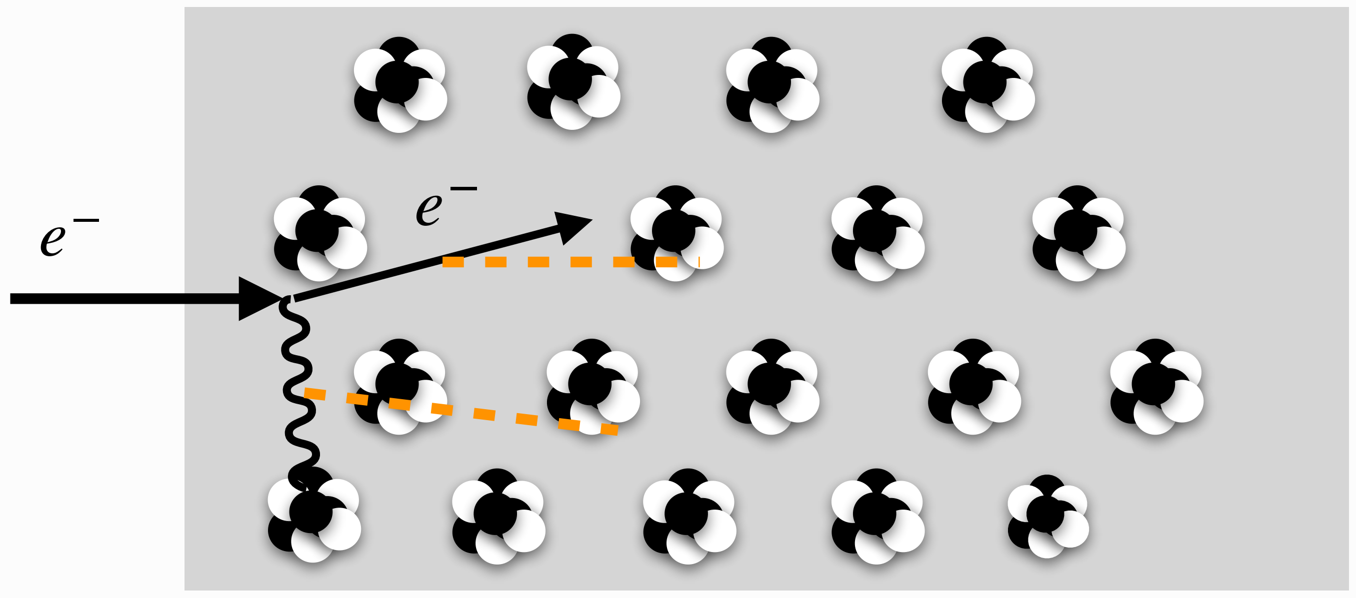


[Zhou]

Proton Beam Dump

(SHiP)

- **Primary process:**
  Primakoff [1904.02091, 2201.05170]



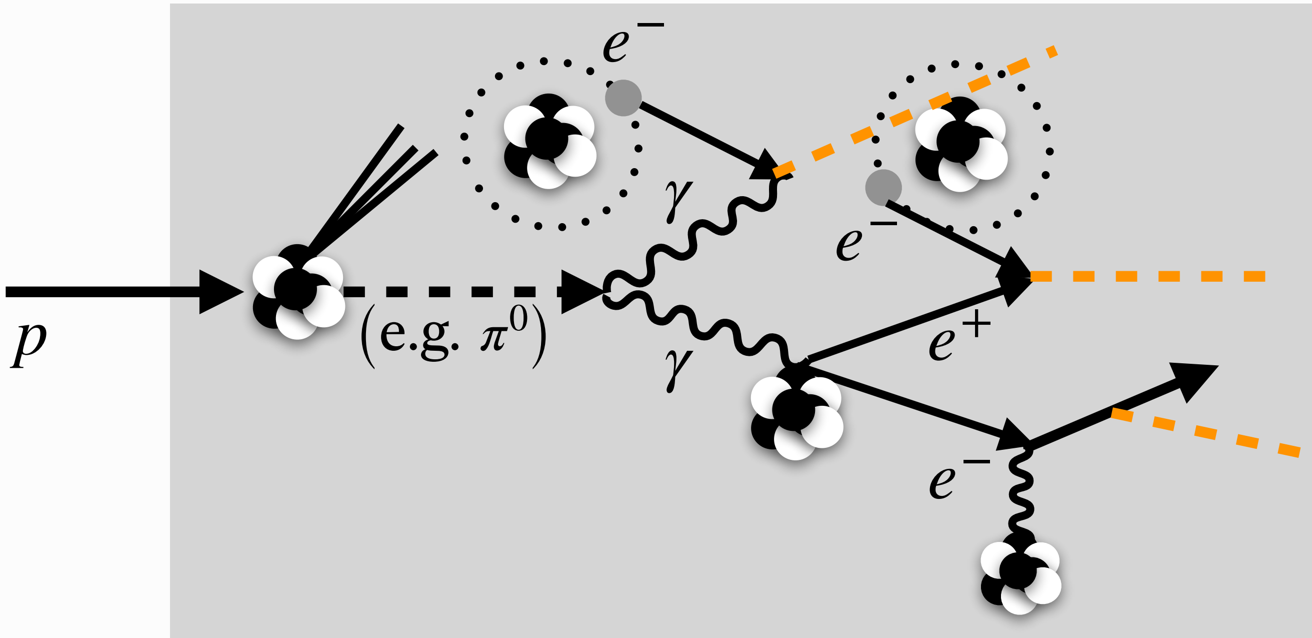
Electron Beam Dump

(BDX)

- **Primary process:**
  Brem/Photon-fusion [This Work]

Production

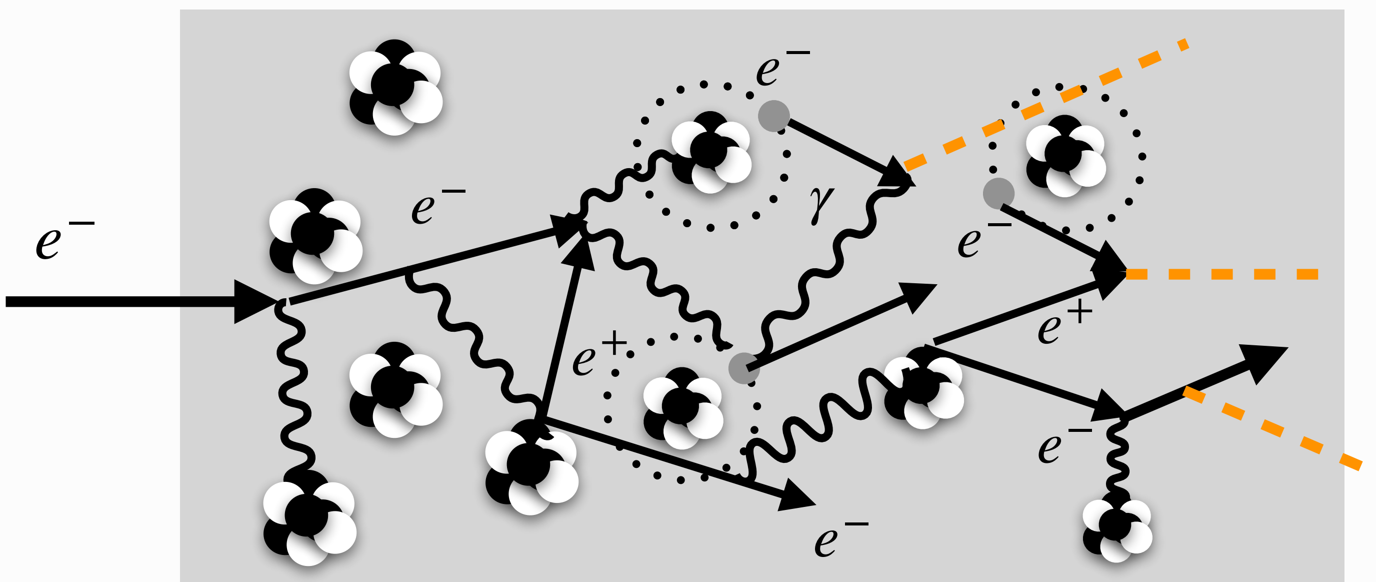
$$\mathscr{L} \supset \frac{\alpha}{4\pi}\frac{c_{a\gamma\gamma}}{f_a}aF\tilde{F} + \frac{c_{aee}}{f_a}(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e$$



Target [Zhou]

Proton Beam Dump
(SHiP)

- **Primary process:** Primakoff [1904.02091, 2201.05170]
- **Shower:** Primakoff, Brem, Ann, Compton [This Work]



Electron Beam Dump
(BDX)

- **Primary process:** Brem/Photon-fusion [This Work]
- **Shower:** Primakoff, Brem, Ann, Compton [This Work]

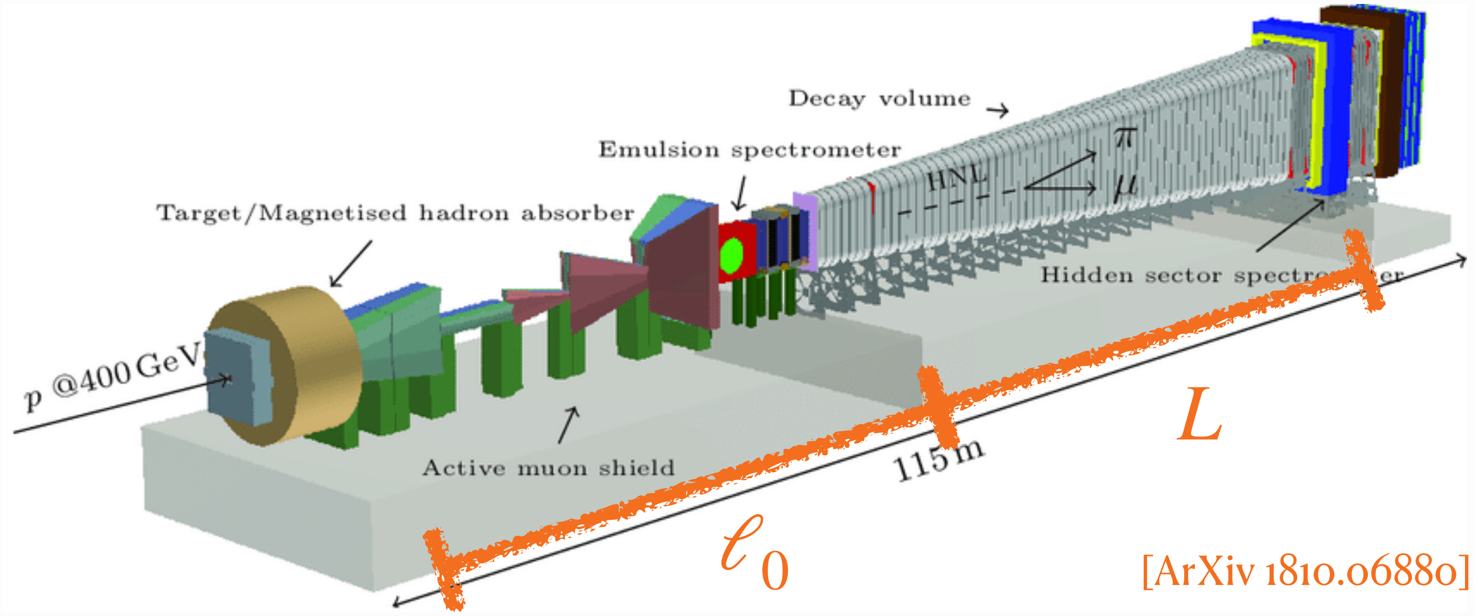
Samuel Patrone

ALPs in the dump

Samuel Patrone

Axion-Like Particles

In the dump



$$P(a_{det}|\text{beam}) = P(a_{det}|a_{decay})P(a_{decay}|a_{prod})P(a_{prod}|\text{beam})$$

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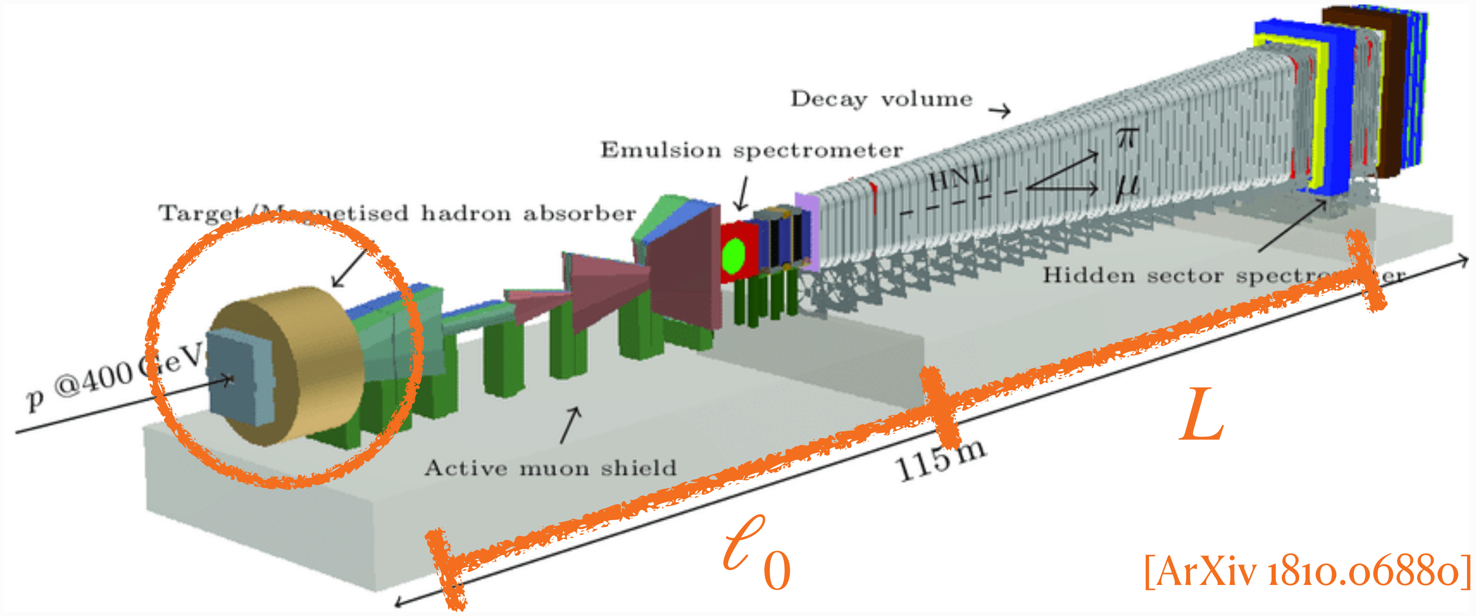
Axion-Like Particles

In the dump

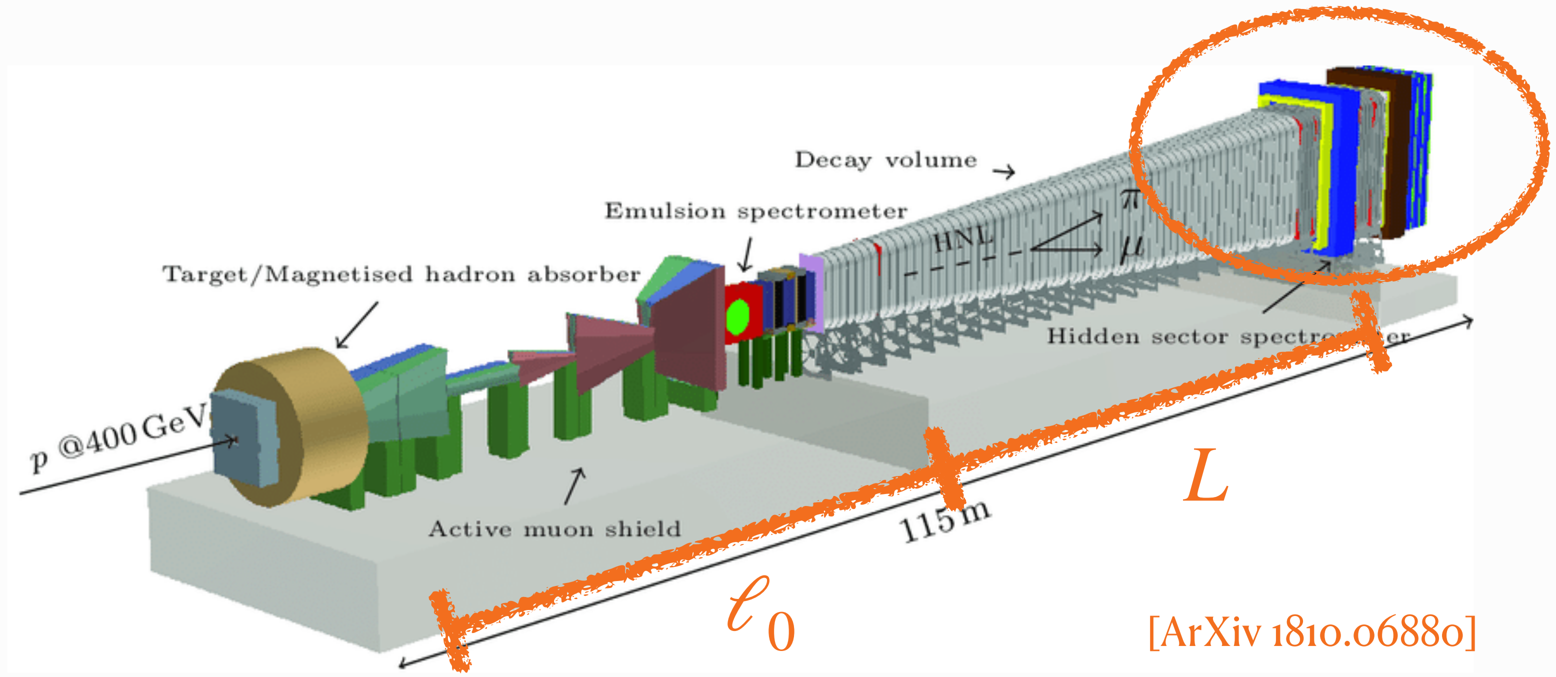


$$P(a_{det} | \text{beam}) = P(a_{det} | a_{decay}) P(a_{decay} | a_{prod}) P(a_{prod} | \text{beam})$$

$$\frac{\sigma_a}{\sigma_{SM}} \propto \frac{1}{f^2}$$

Axion-Like Particles

In the dump



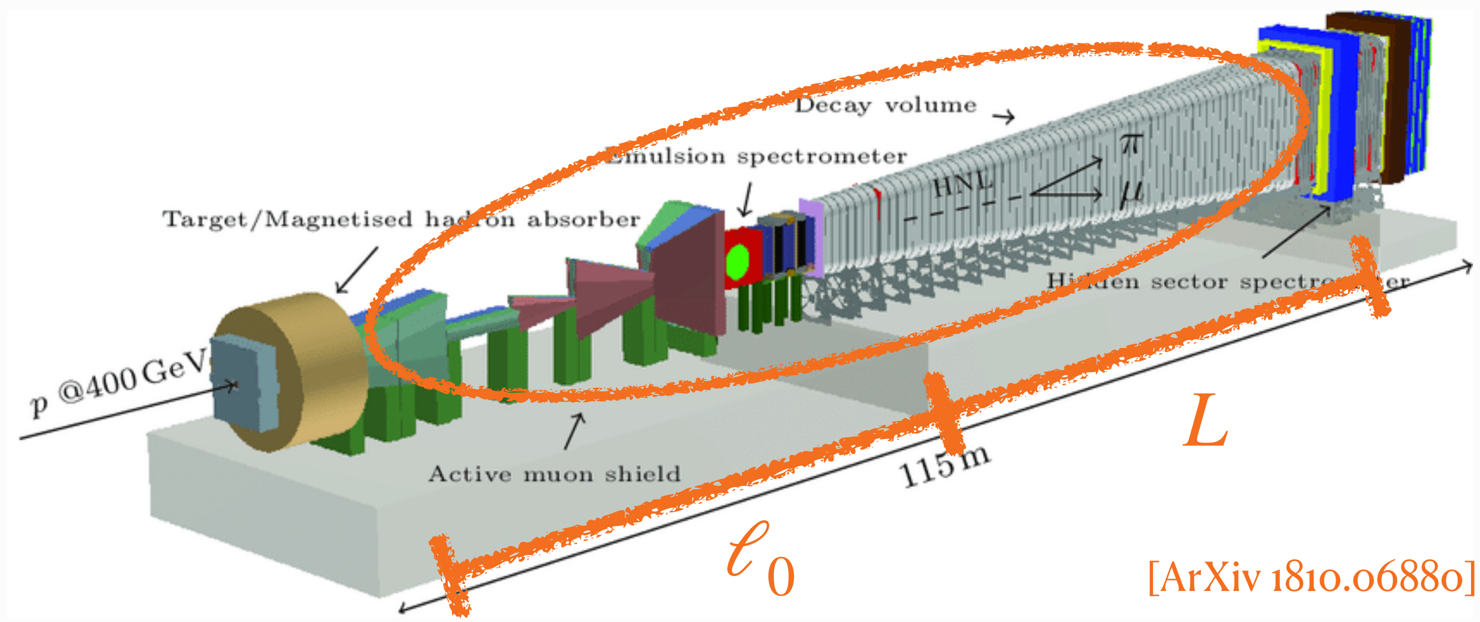
[ArXiv 1810.06880]

$$P(a_{det} \,|\, \text{beam}) = P(a_{det} \,|\, a_{decay}) P(a_{decay} \,|\, a_{prod}) P(a_{prod} \,|\, \text{beam})$$

Geometric
Factor &
Energy cutoff

Axion-Like Particles

In the dump

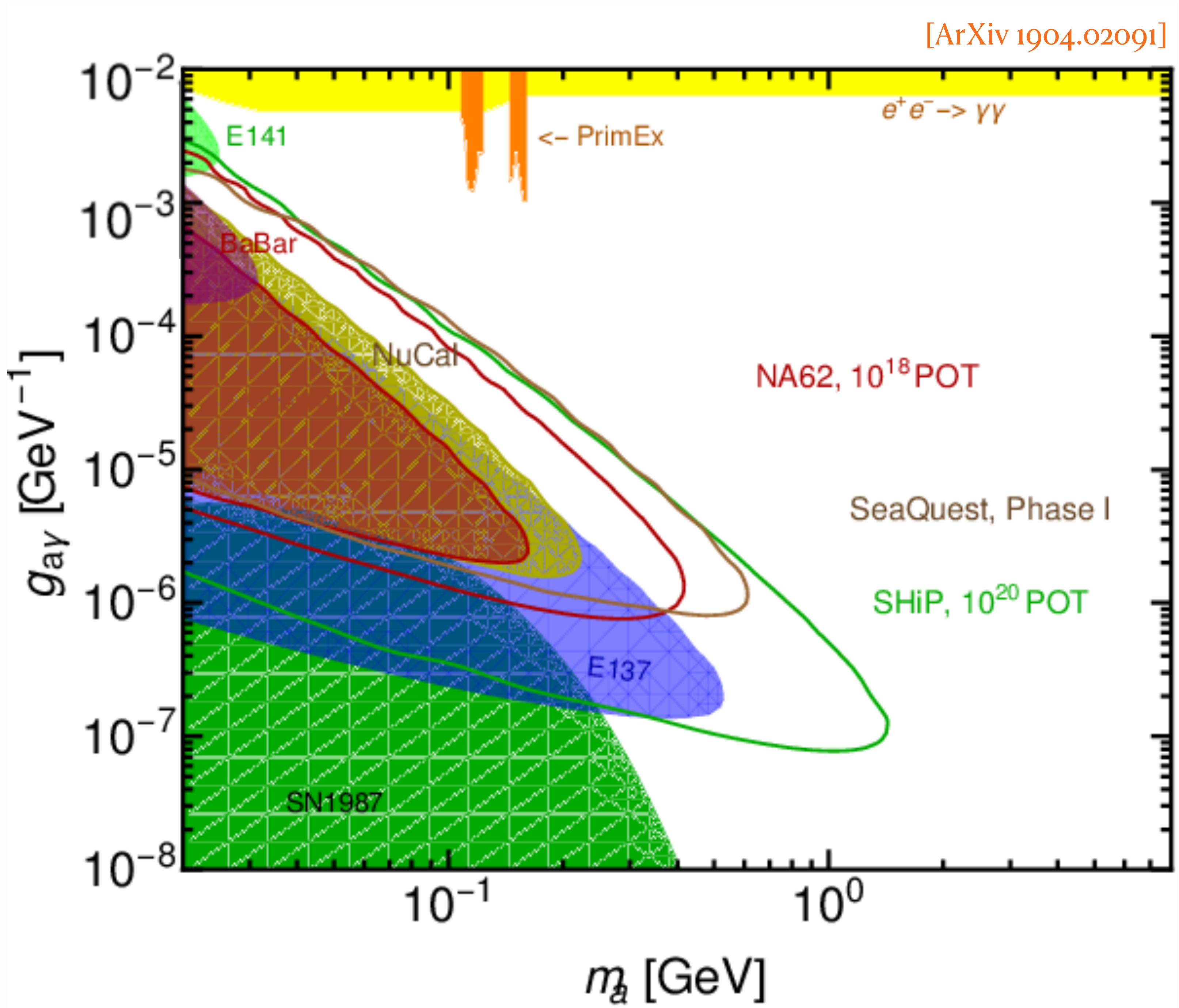


$$P(a_{det} \,|\, \text{beam}) = P(a_{det} \,|\, a_{decay}) P(a_{decay} \,|\, a_{prod}) P(a_{prod} \,|\, \text{beam})$$

$$\lambda^-(\ell_0, L) < \lambda < \lambda^+(\ell_0, L)$$ to be detected/excluded

Axion-Like Particles

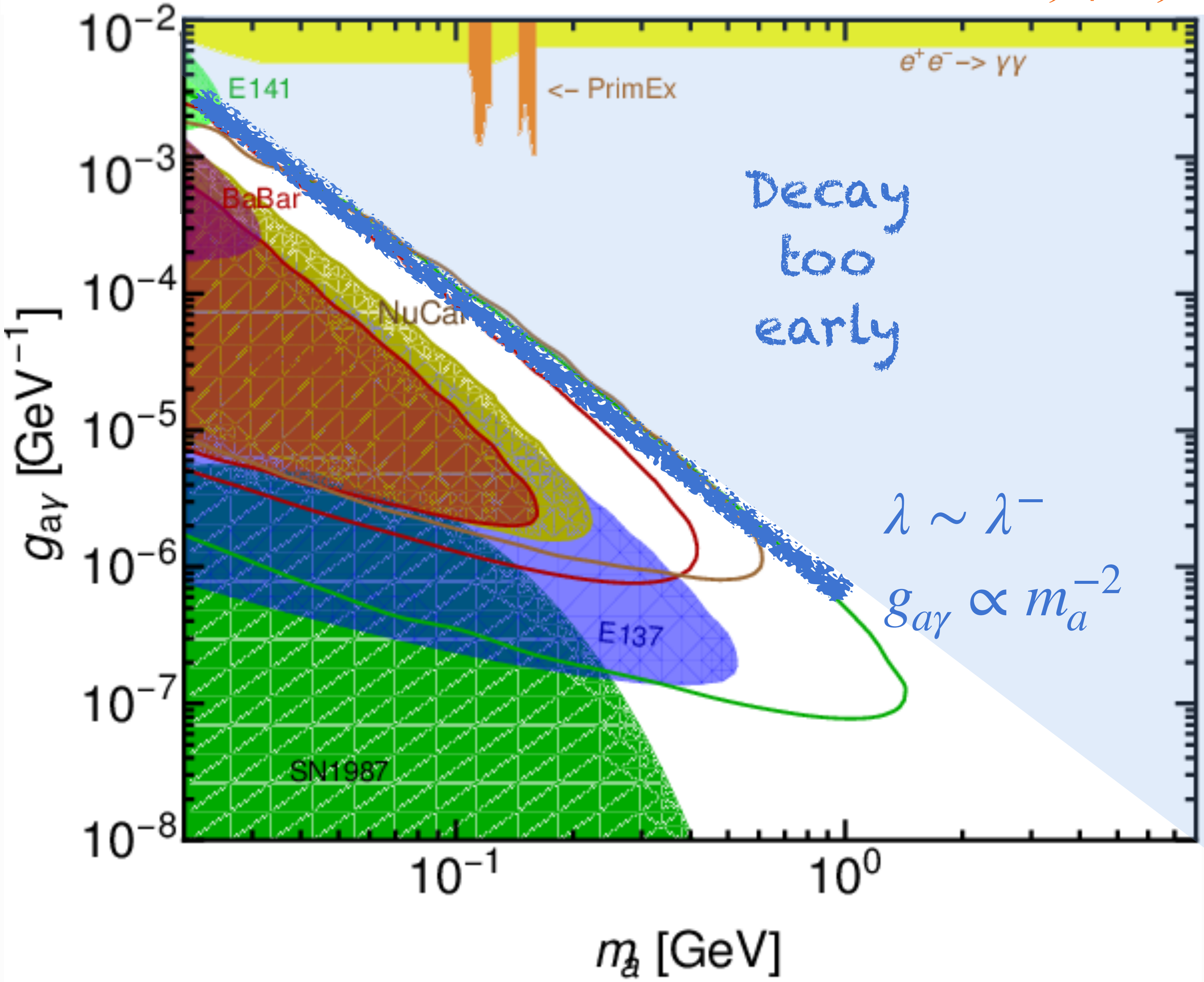
In the dump



Axion-Like Particles

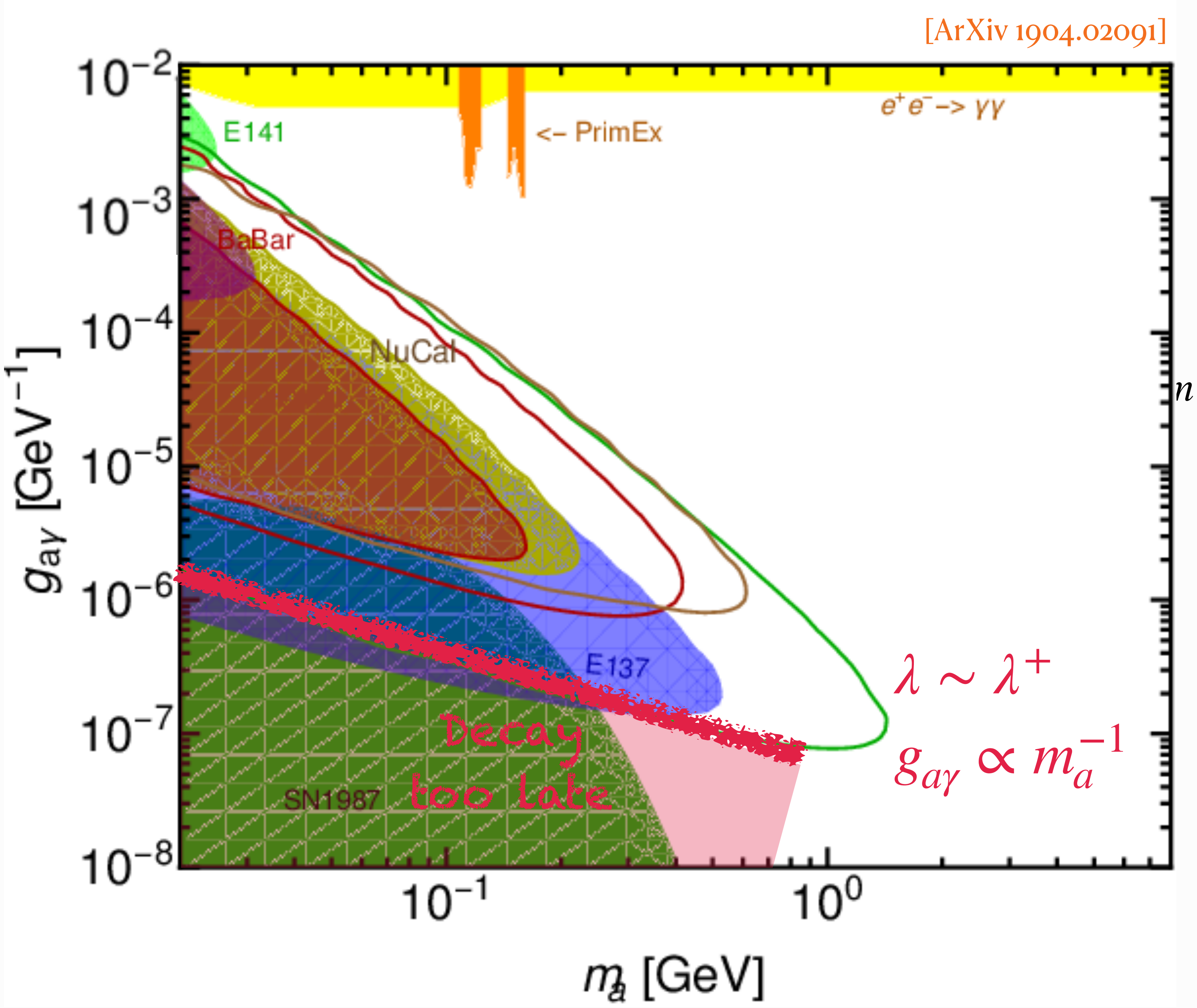
In the dump

[ArXiv 1904.02091]



Axion-Like Particles

In the dump



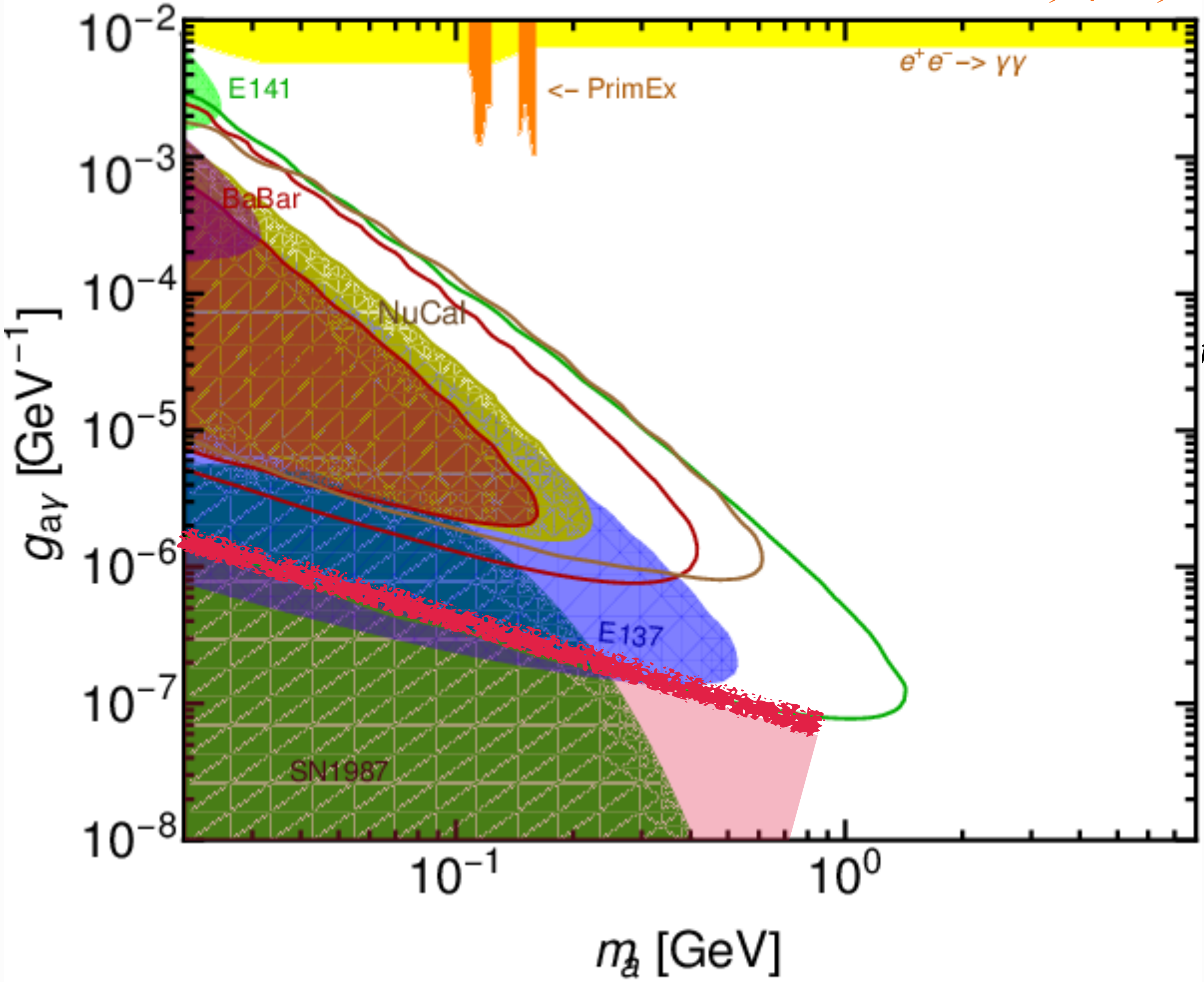
Samuel Patrone

Axion-Like Particles

In the dump

What about EM showers?

$$\lambda^+ \sim \frac{\beta\gamma}{\Gamma_{dec}} \sim \frac{\beta\gamma}{g_{a\gamma}^2 m_a^3}$$



Samuel Patrone

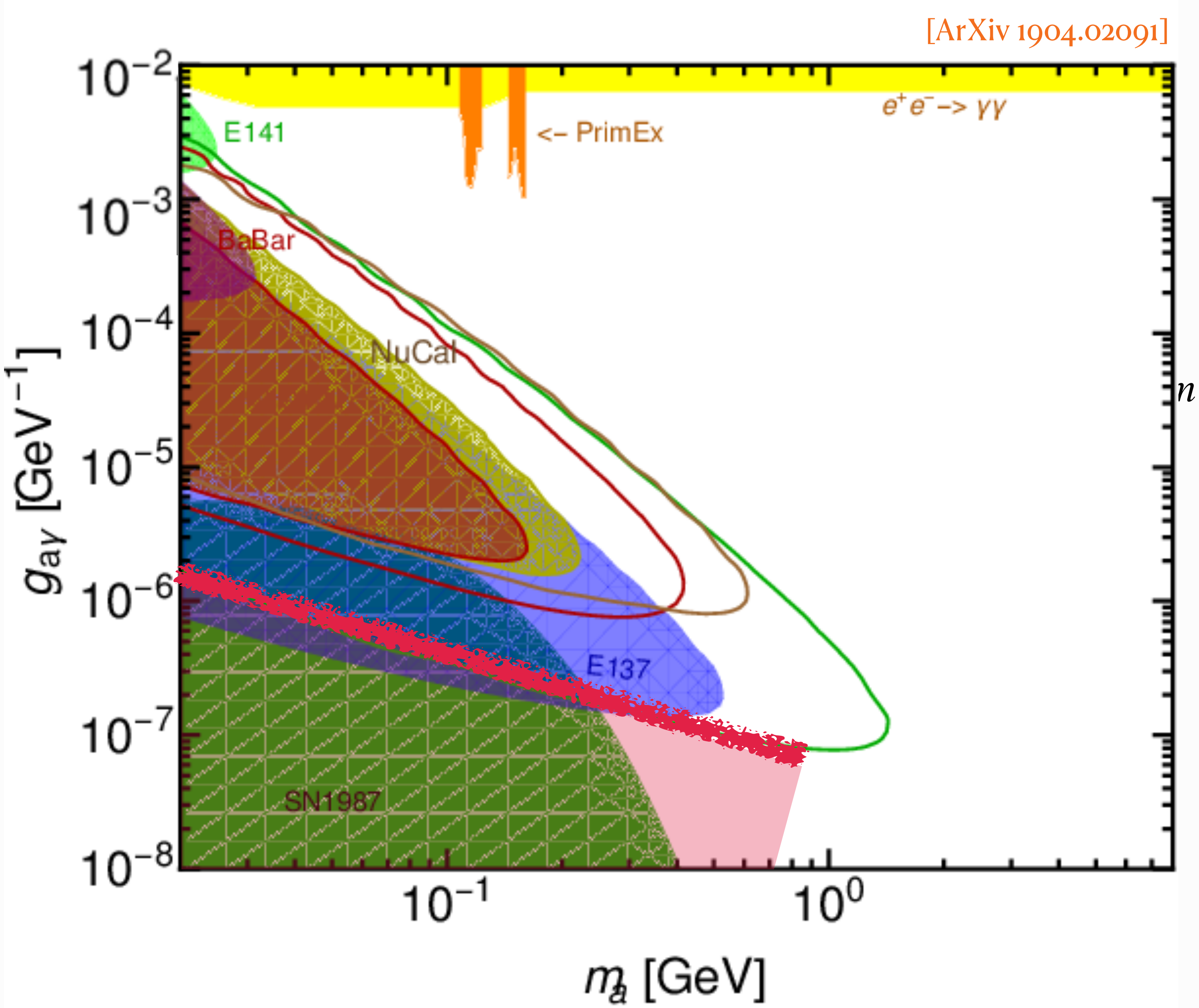
Axion-Like Particles

In the dump

What about EM showers?

$$\lambda^{+} \sim \frac{\beta\gamma}{\Gamma_{dec}} \sim \frac{\beta\gamma}{g_{a\gamma}^{2} m_{a}^{3}}$$

- Smaller $\beta\gamma$
- Smaller $g_{a\gamma}$ probed



Samuel Patrone

Axion-Like Particles

In the dump

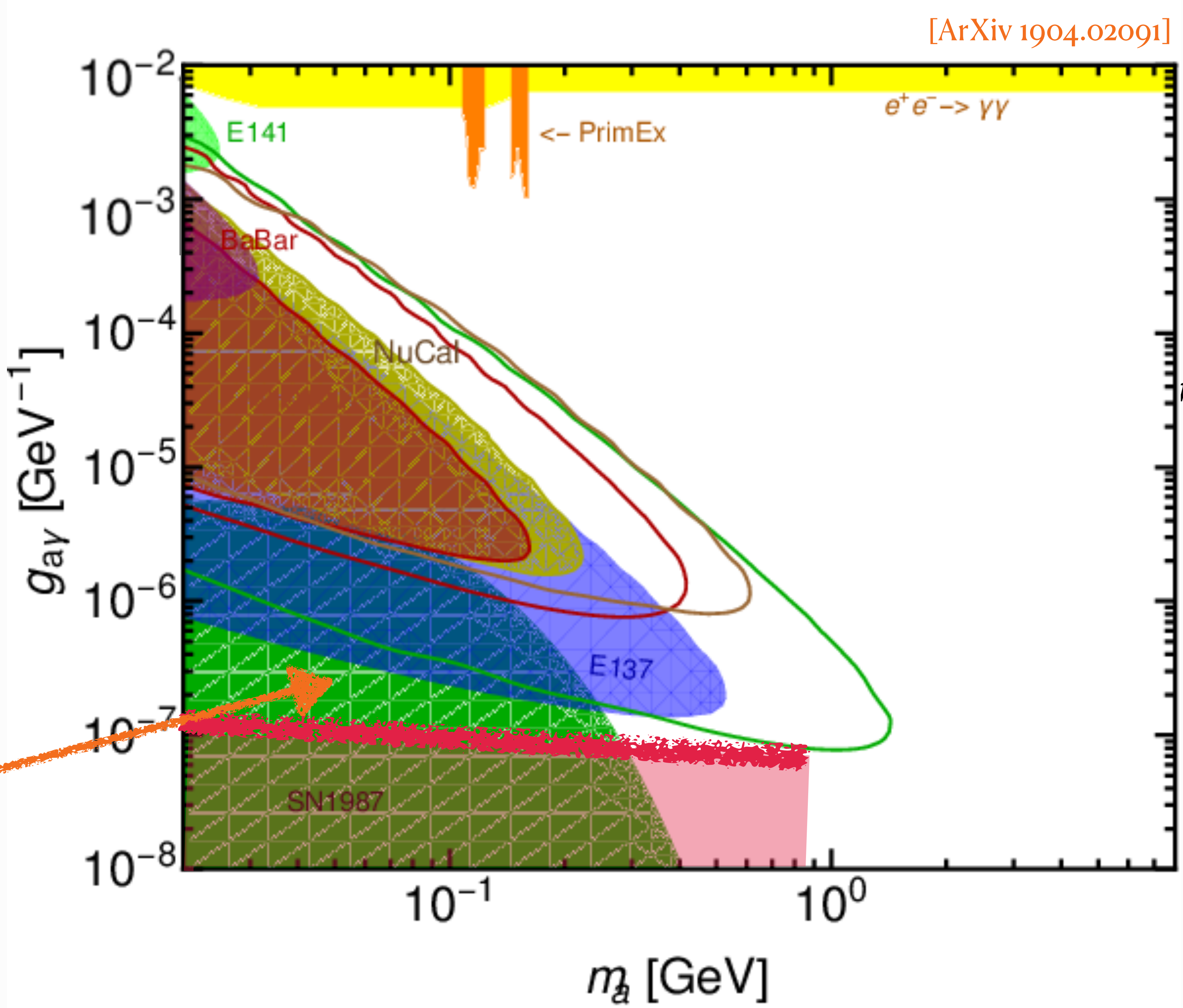
What about EM showers?

$$\lambda^+ \sim \frac{\beta\gamma}{\Gamma_{dec}} \sim \frac{\beta\gamma}{g_{a\gamma}^2 m_a^3}$$

- Smaller $\beta\gamma$
- Smaller $g_{a\gamma}$ probed

Exp are sensitive here!

[ArXiv 1904.02091]



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Experiments

BDX	SHiP
Aluminum	Molybdenum
10.6 GeV electrons	400 GeV protons
10^22 EOT	6 x 10^20 POT
lo = 20 m	lo = 33 m
Lpipe = n/a	Lpipe = 50 m
Ecut = 300 MeV	Ecut = 200 MeV
Jefferson Lab	CERN

ALPETITE

Samuel Patrone

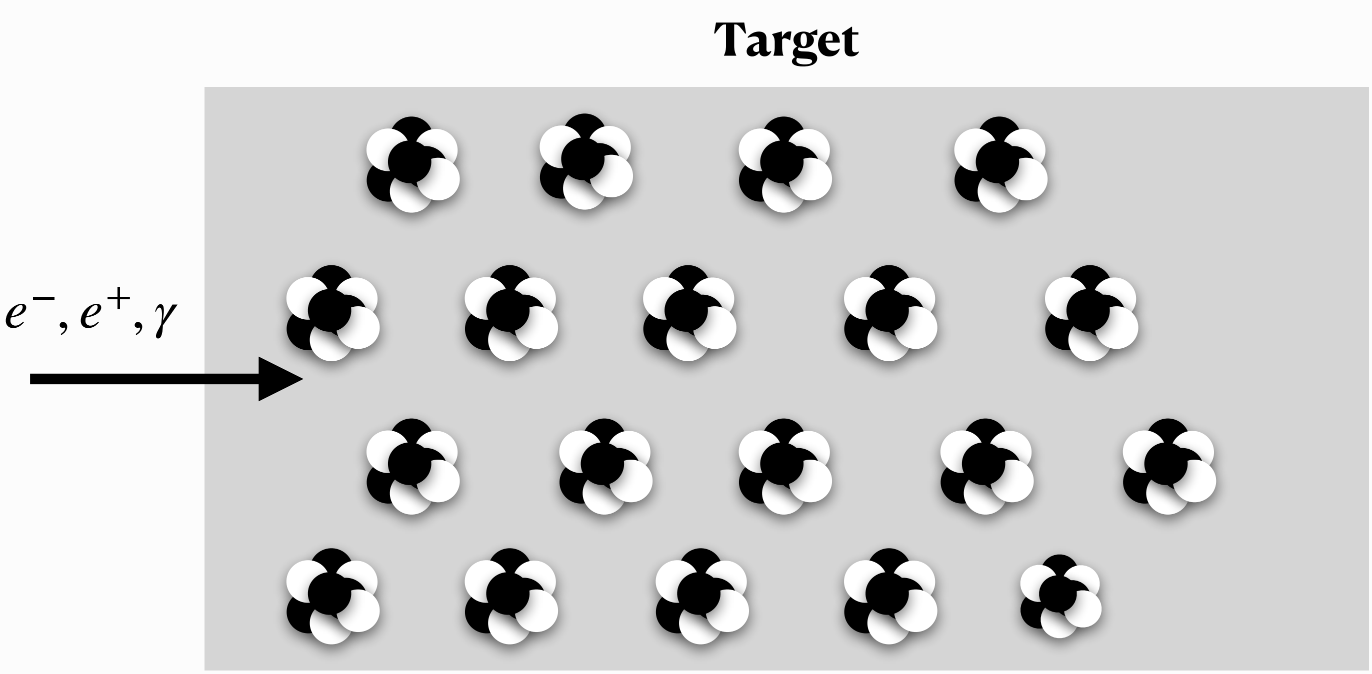
ALPETITE

https://github.com/spatrone/ALPETITE

- ALPETITE is an extension of the PETITE package

Package for Electromagnetic Transitions In Thick-target Environments (PETITE)
[Blinov, Fox, Kelly, Machado, Plestid 2401.06843]

- **Fast** and **lightweight** Monte Carlo generator for production of dark sector objects in thick-target experiments.



[Zhou]

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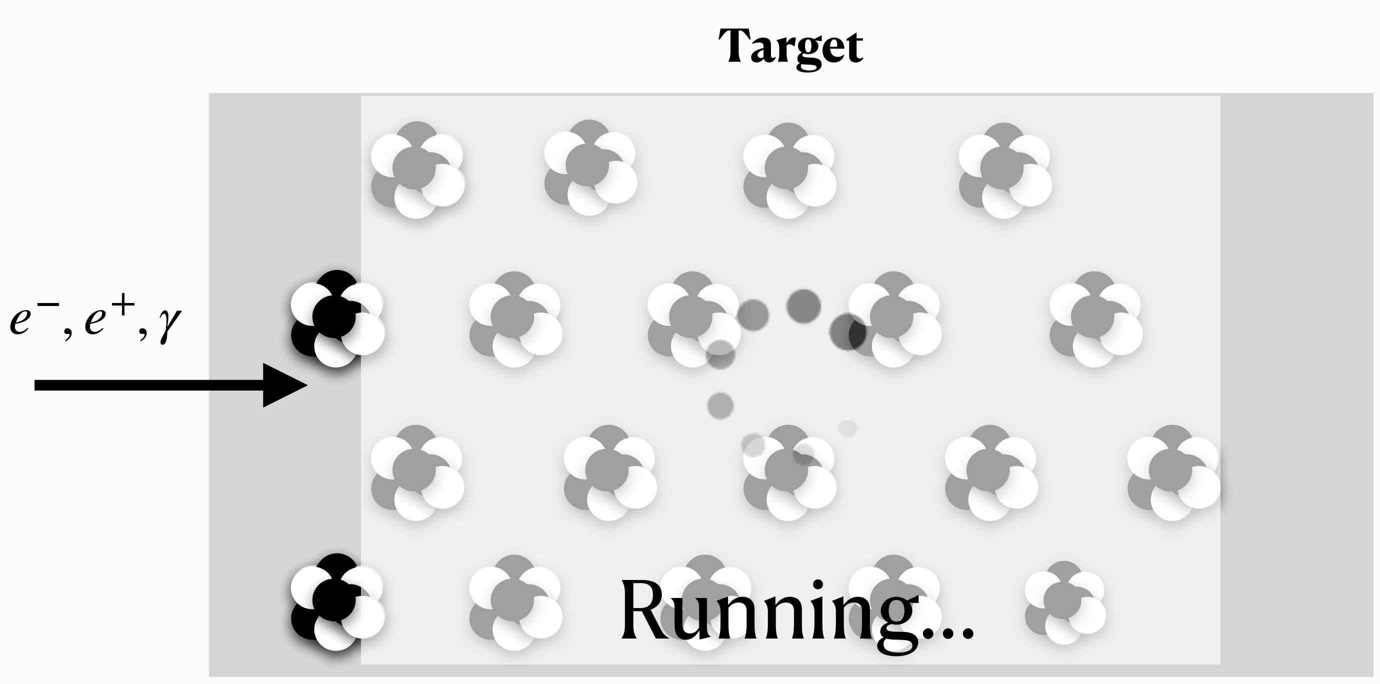

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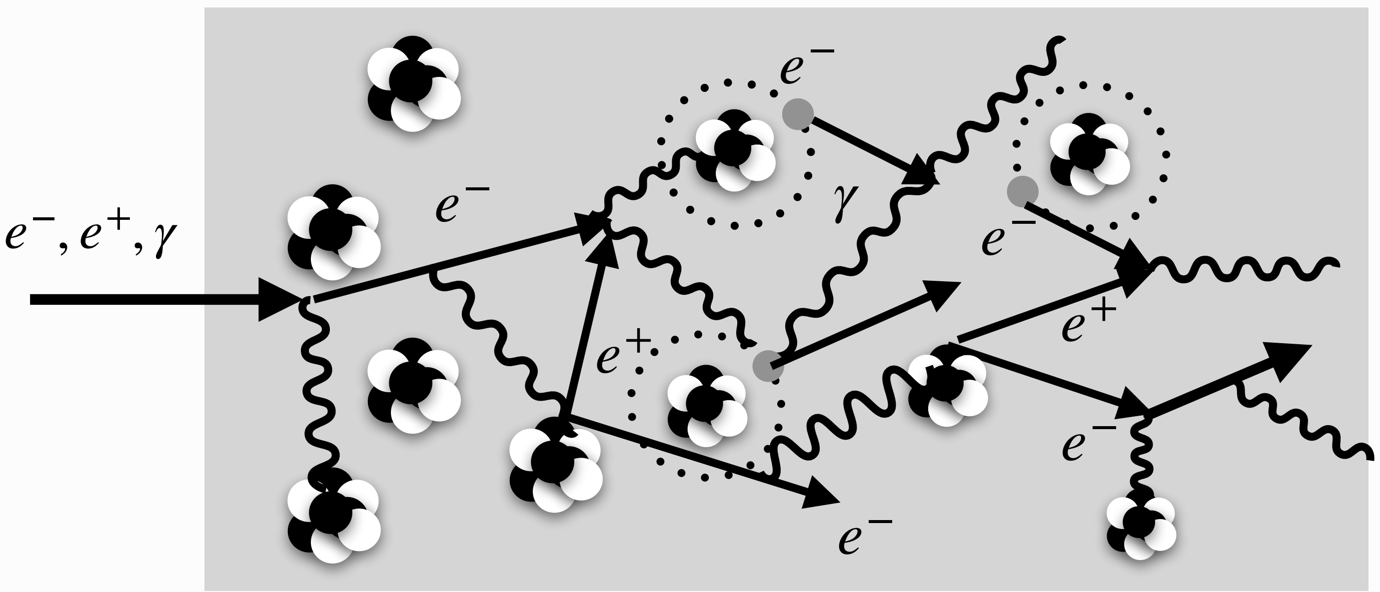
Target



[Zhou]

SM processes

Bremsstrahlung $e^{\pm}Z \to e^{\pm}\gamma Z$
Pair production $\gamma Z \to e^+e^-Z.$
Compton scattering $\gamma e^- \to \gamma e^-$
Pair-annihilation $e^+e^- \to \gamma\gamma$
Moller/Bhabha Scattering $e^{\mp}e^- \to e^{\mp}e^-$
Continuous energy loss for electron/positrons, $|dE/dx|$
Multiple-Coulomb scattering for angular deflection

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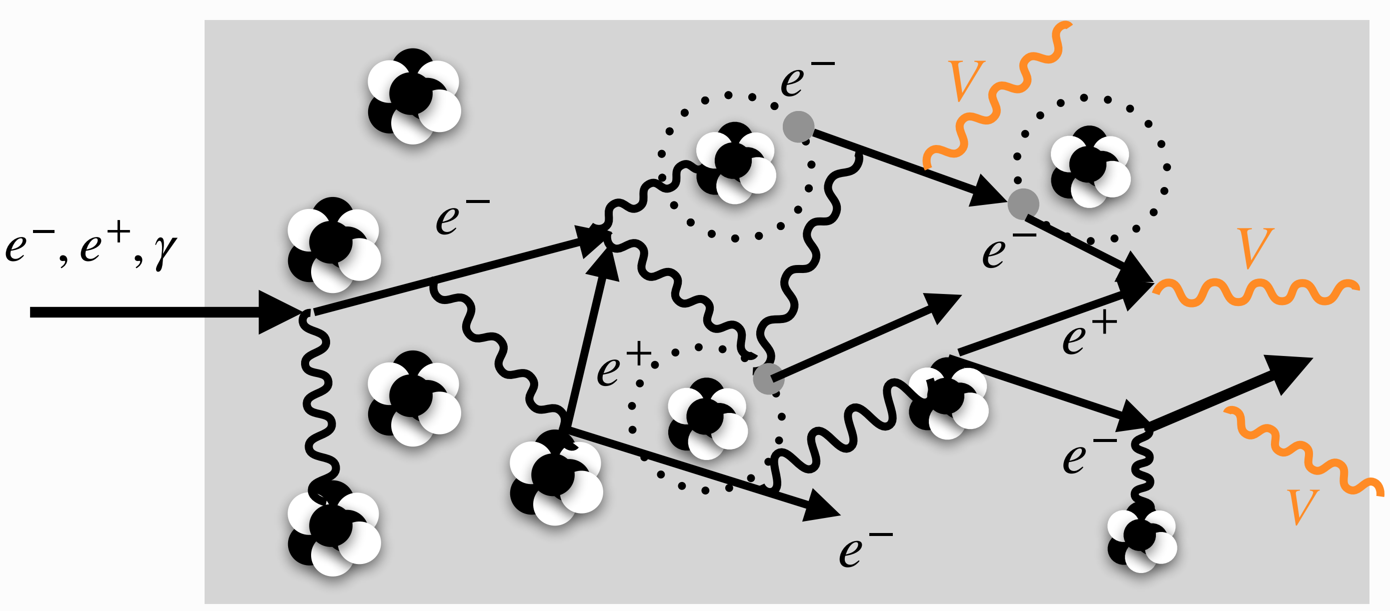

[Zhou]

Dark Vector processes

Bremsstrahlung $Ze^\pm \to Ze^\pm V$

Compton scattering $\gamma e^- \to e^- V$

Pair-annihilation $e^+e^- \to (\gamma)V$

Samuel Patrone

ALPETITE

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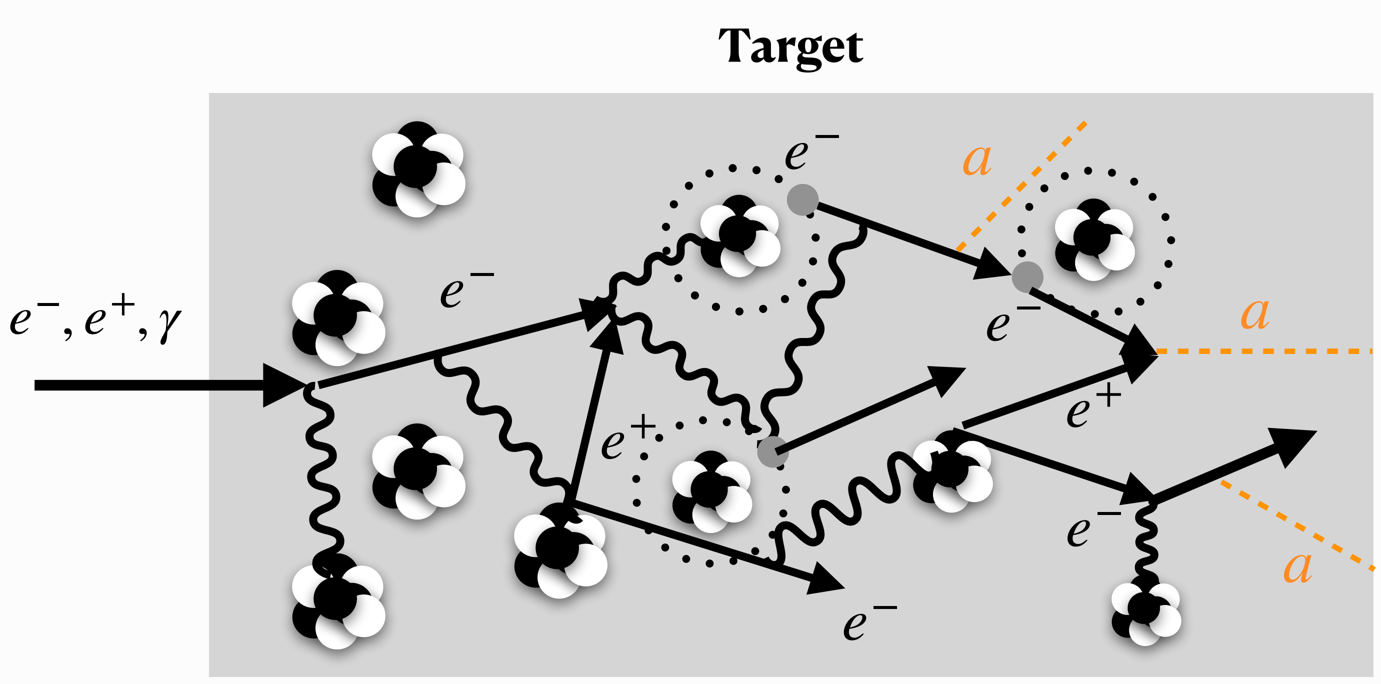

Axion ~~Dark Vector~~ processes

Bremsstrahlung $Ze^\pm \to Ze^\pm a$

Compton scattering $\gamma e^- \to e^- a$

Pair-annihilation $e^+e^- \to (\gamma)a$

By rescaling $w_V \times \frac{d\sigma_a}{d\sigma_V}$

ALPETITE

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Package for Electromagnetic Transitions In Thick-target Environments (PETITE)
[Blinov, Fox, Kelly, Machado, Plestid 2401.06843]

- **Montecarlo generators** were implemented to sample ALPs from the SM shower
    - **Brem/Compton/Annihilation** were obtained by rescaling the dark vector fluxes produced by PETITE (pre-trained VEGAS generators)
    - **Primakoff(-like)** was obtained from scratch, using the photons from the SM shower/primary electrons

Results

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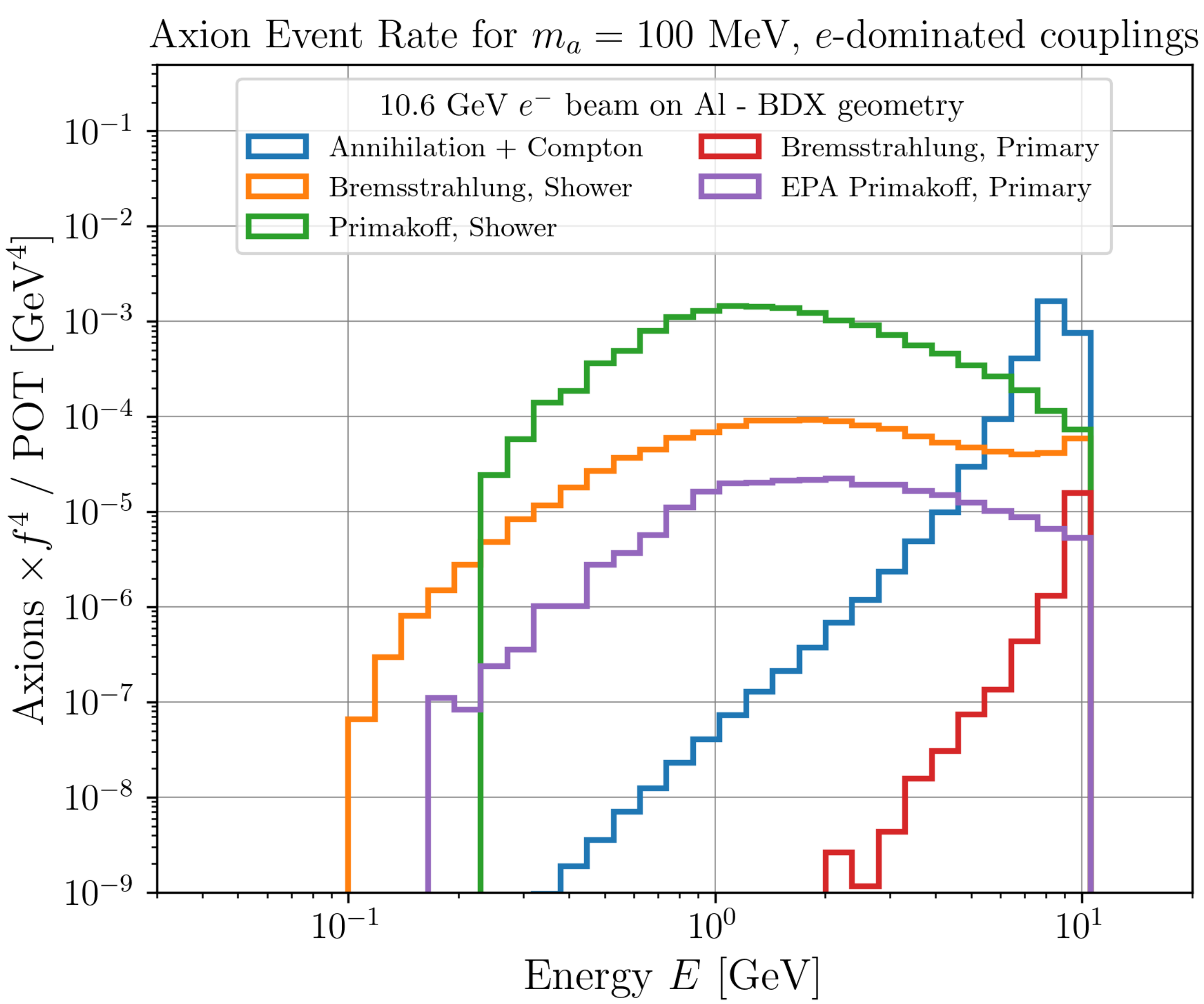
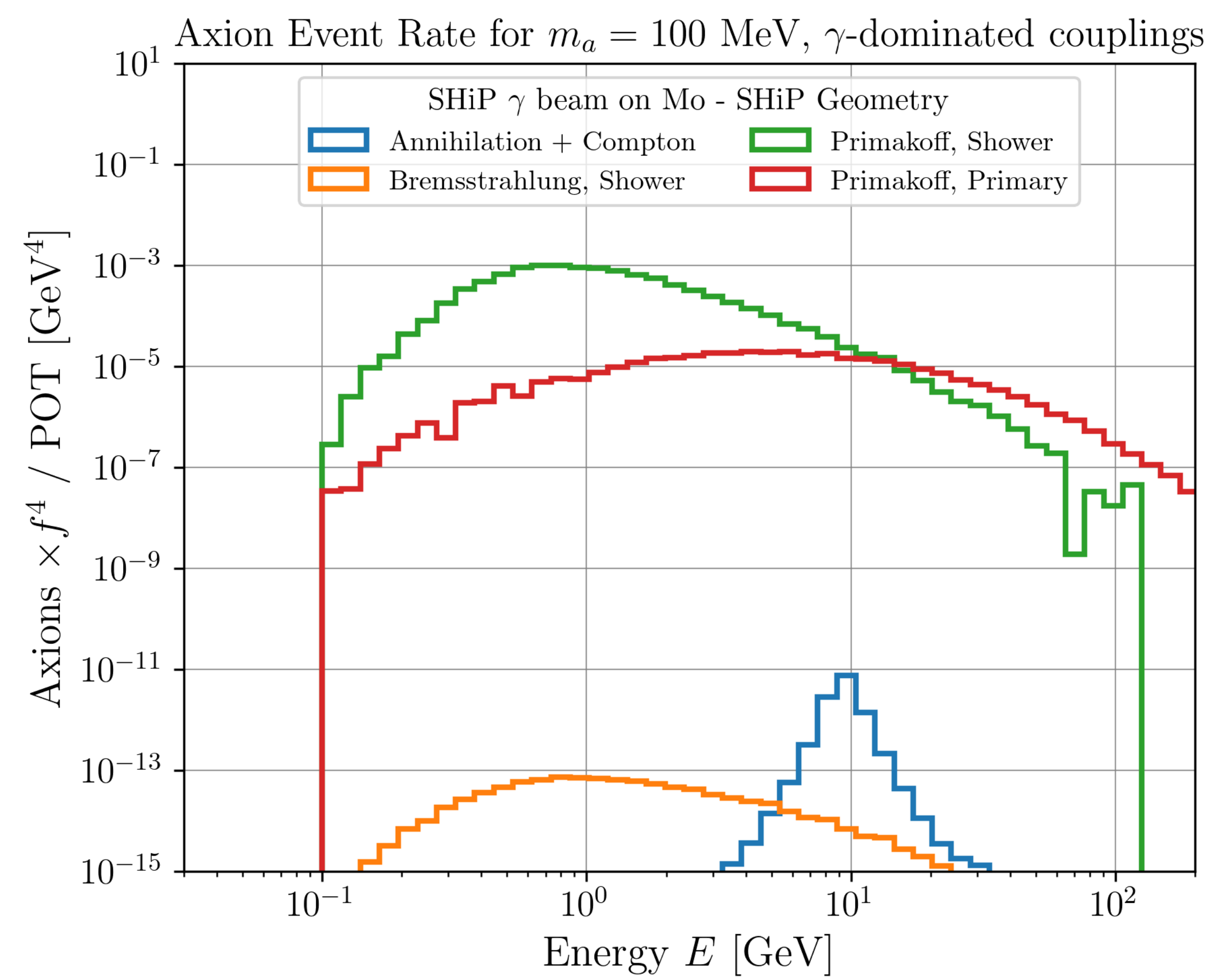
Fluxes

BDX

SHiP





Photon-fusion, Brem — **Primaries** — Primakoff

Ann+Comp, Primakoff, Brem — **Shower** — Ann+Comp, Primakoff, Brem

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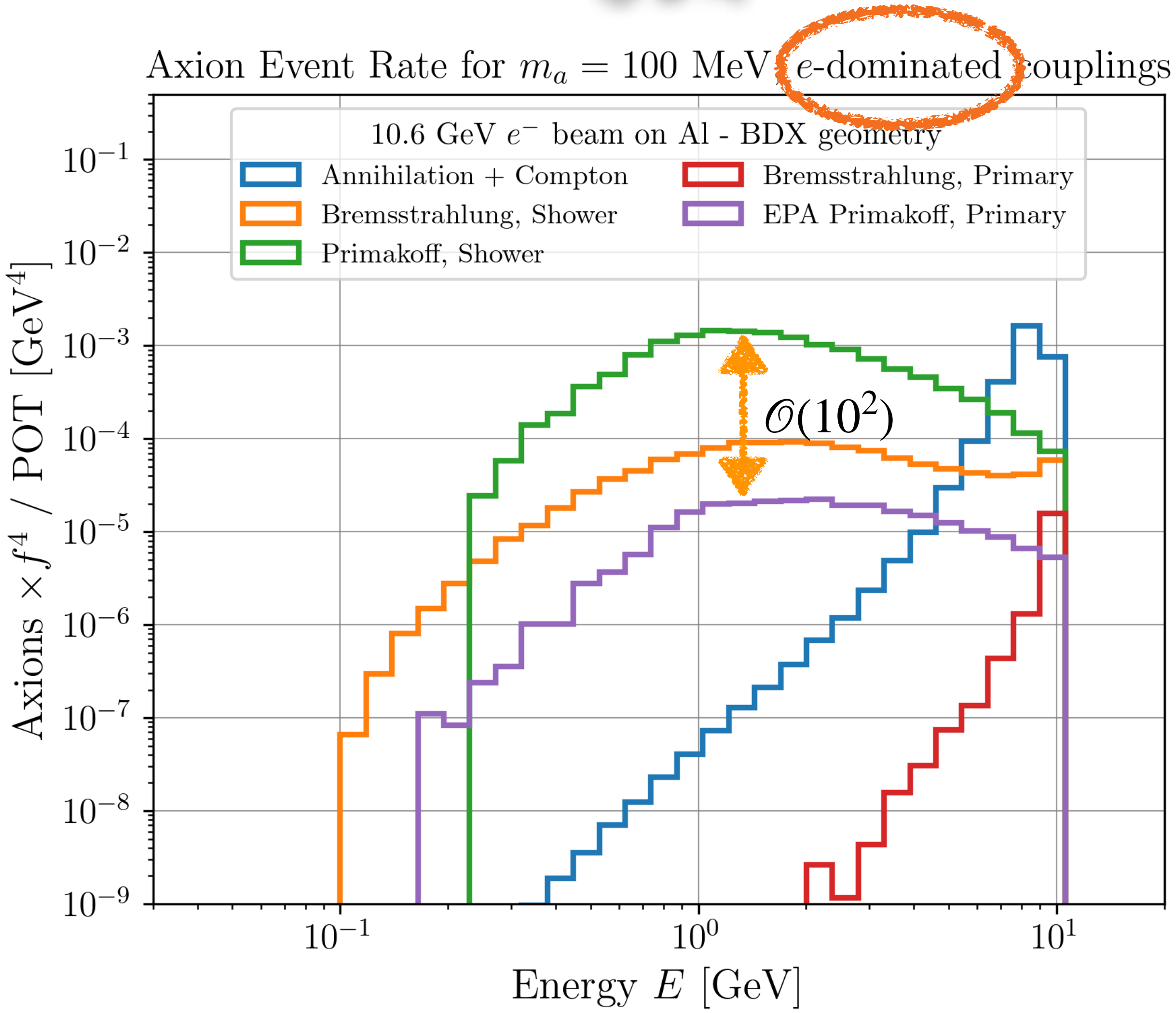
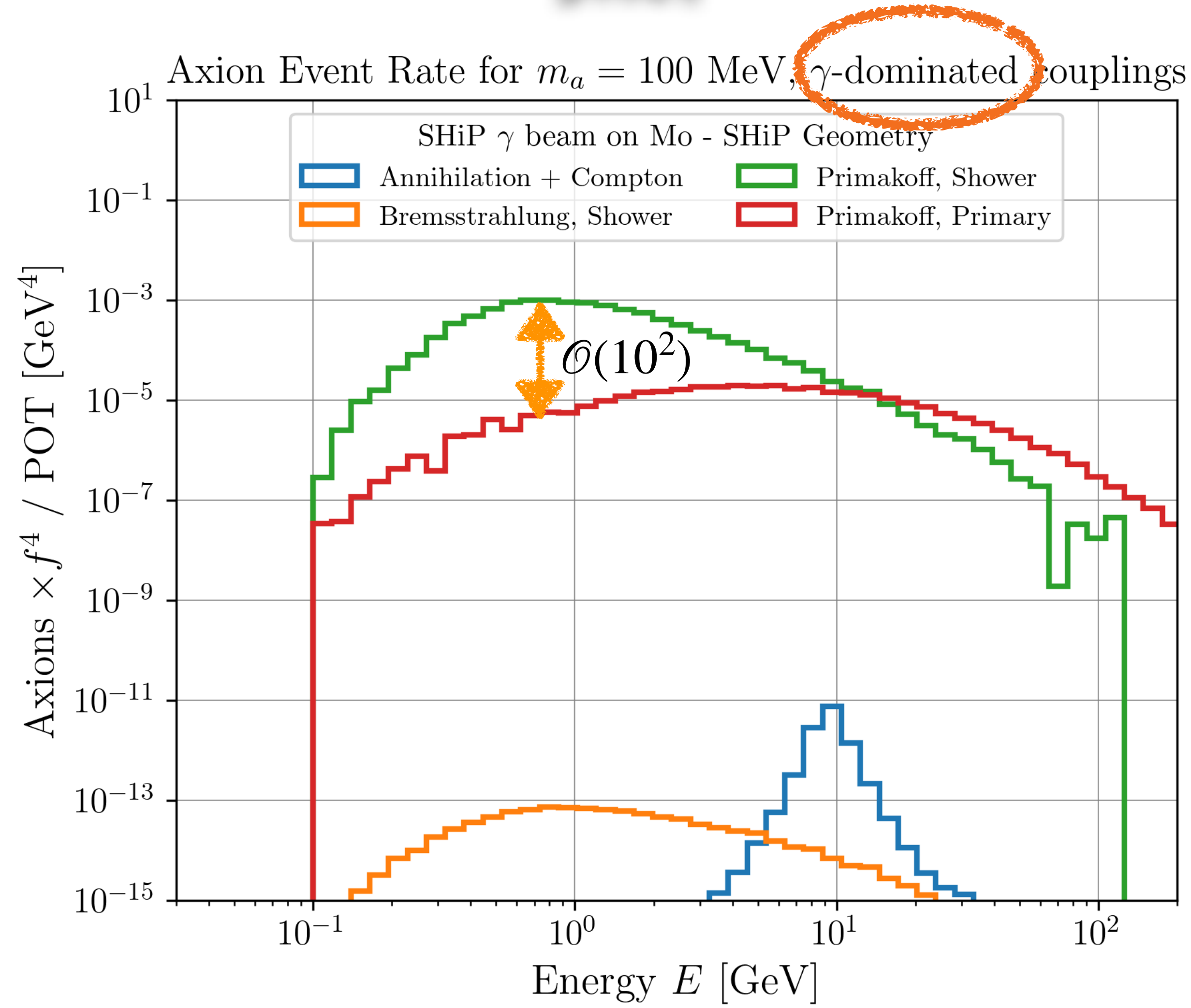
Fluxes

BDX



SHiP



Photon-fusion, Brem — **Primaries** — Primakoff

Ann+Comp, Primakoff, Brem — **Shower** — Ann+Comp, Primakoff, Brem

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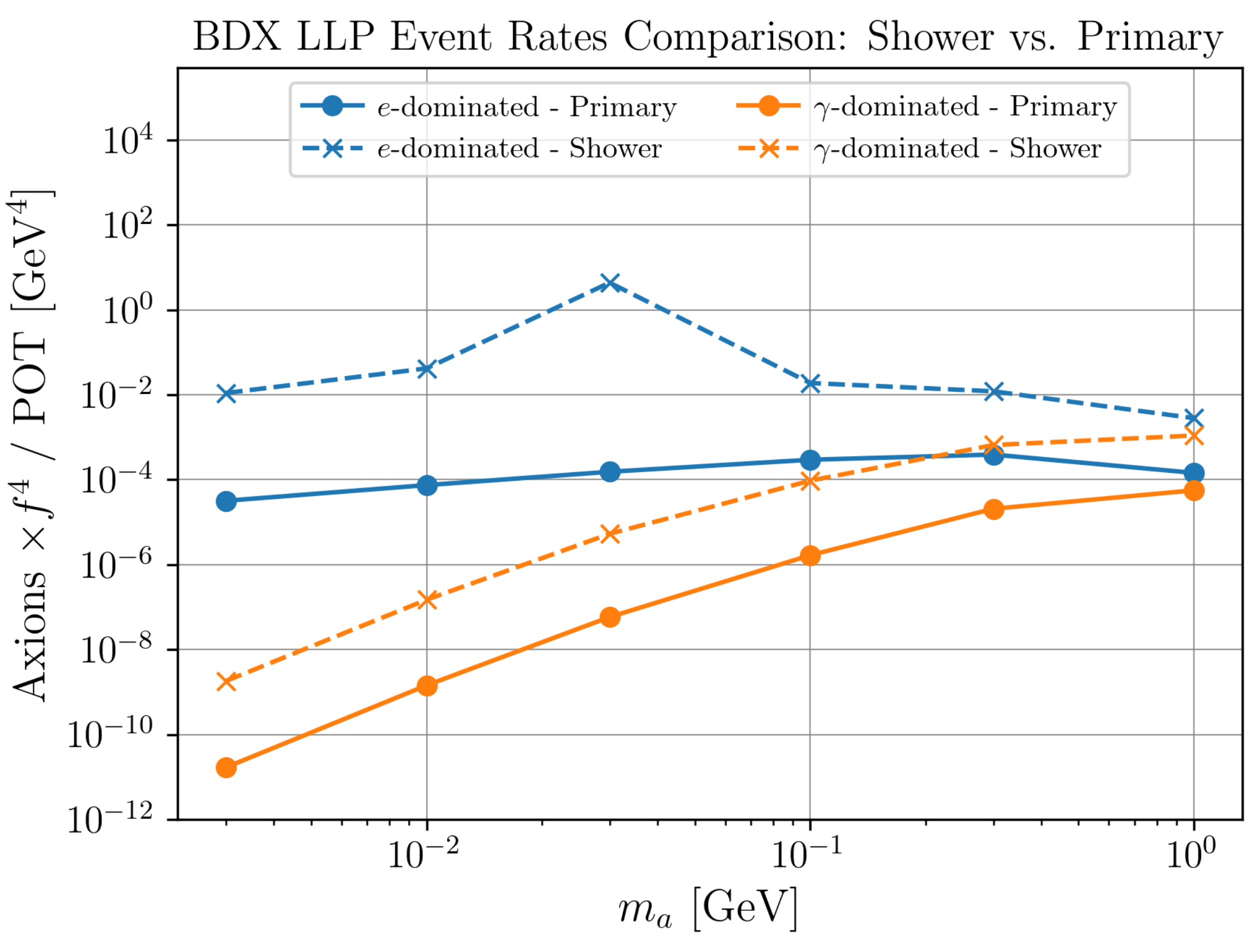
Fluxes

BDX



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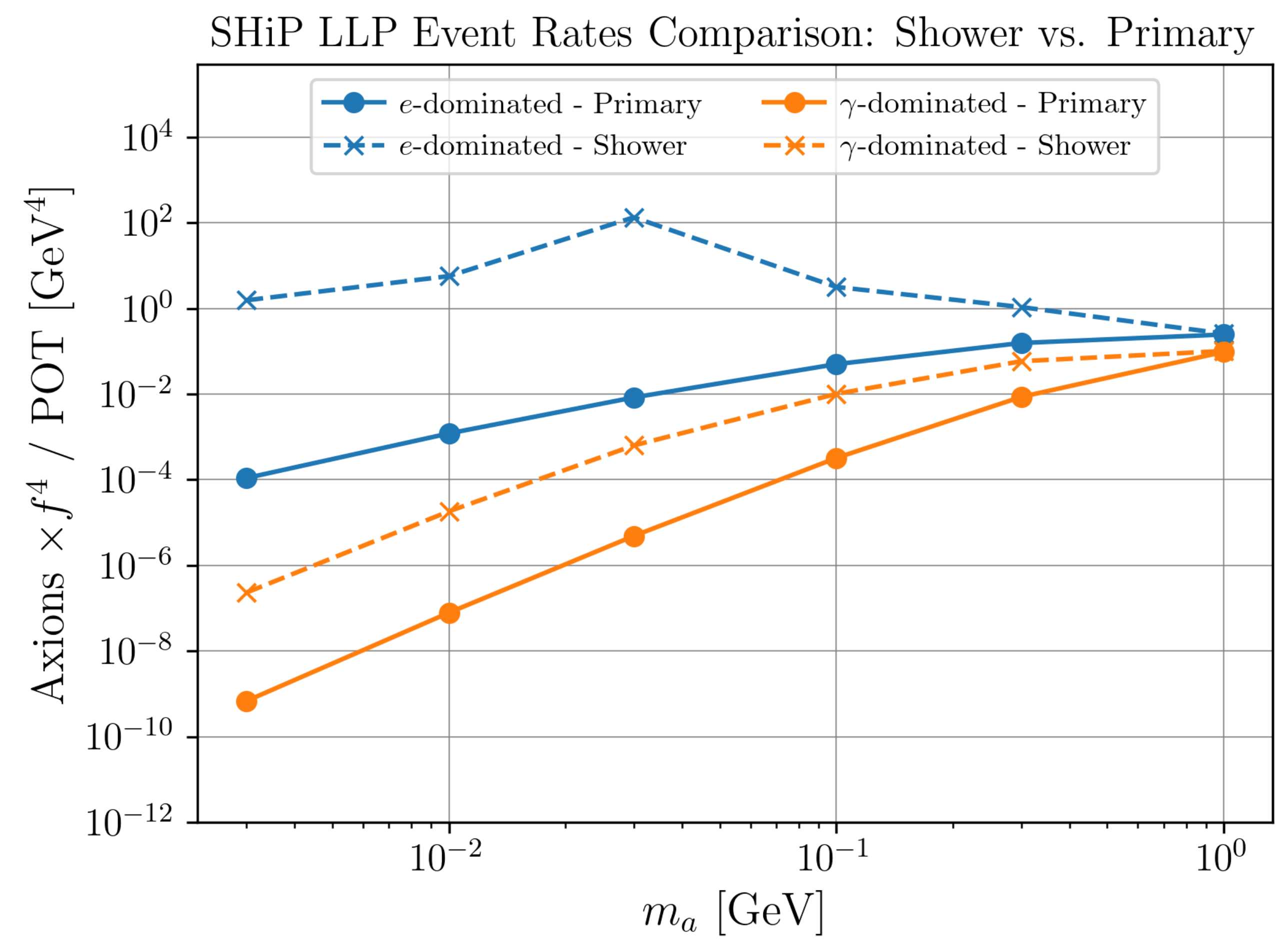
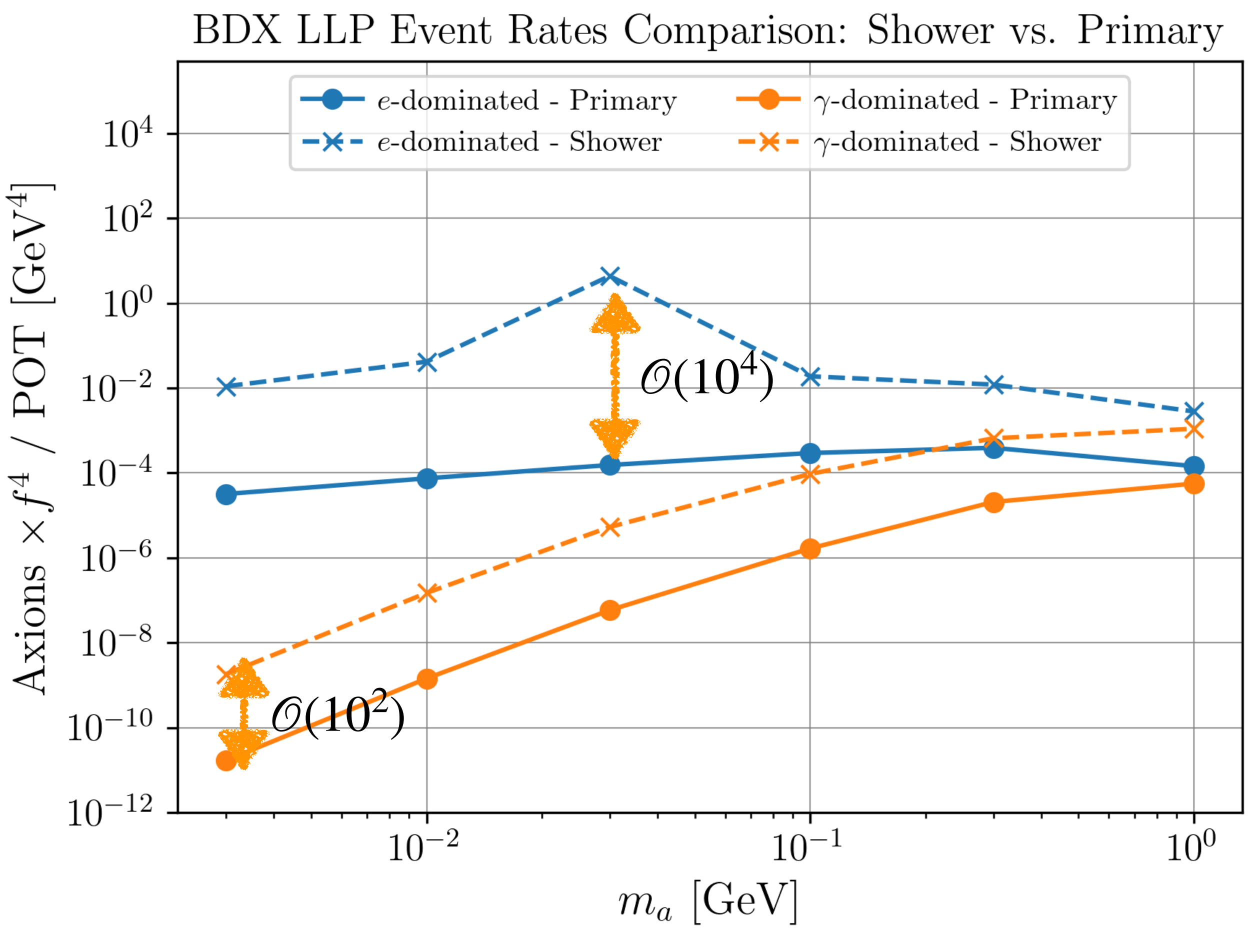


Fluxes

BDX



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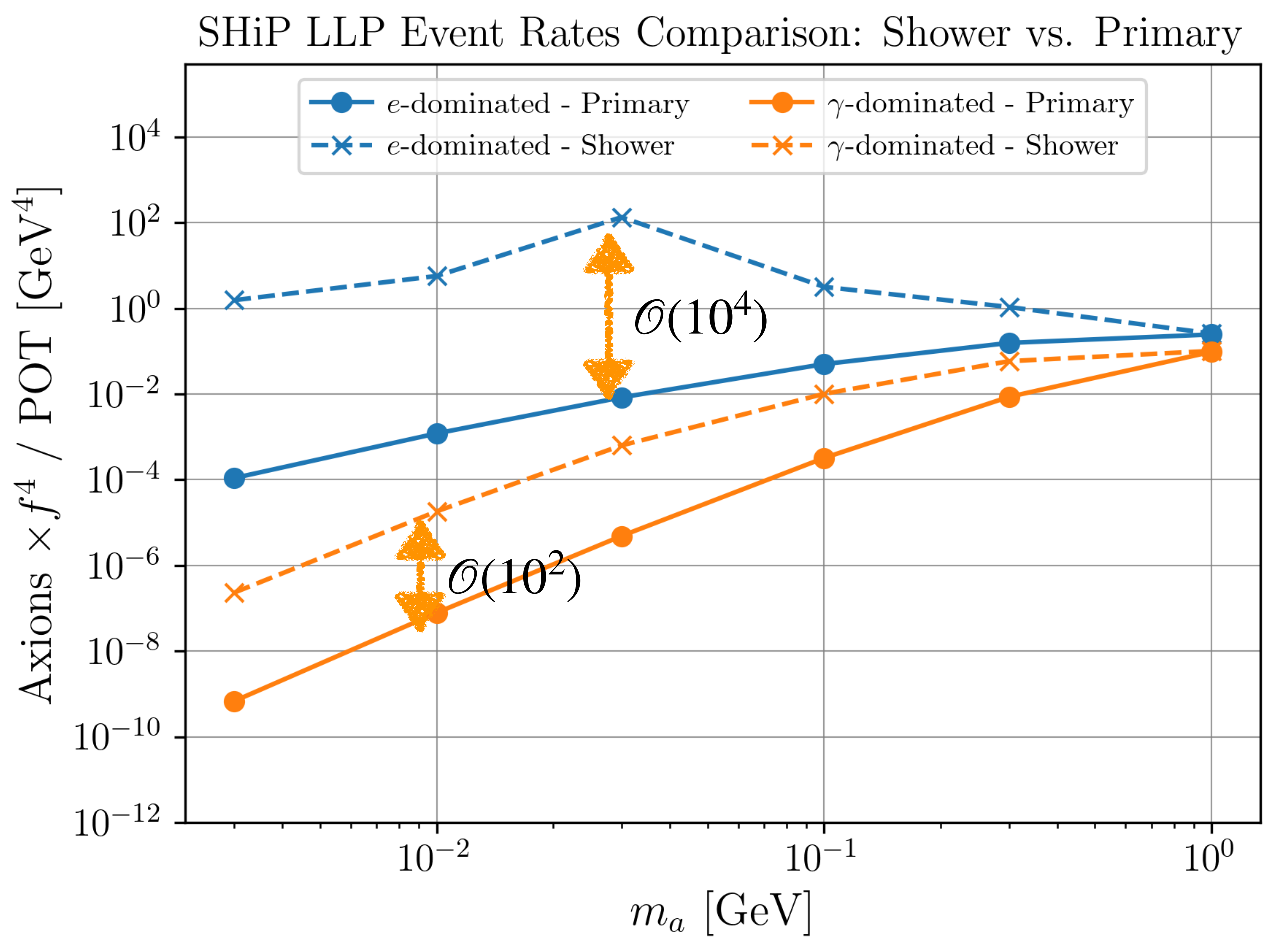

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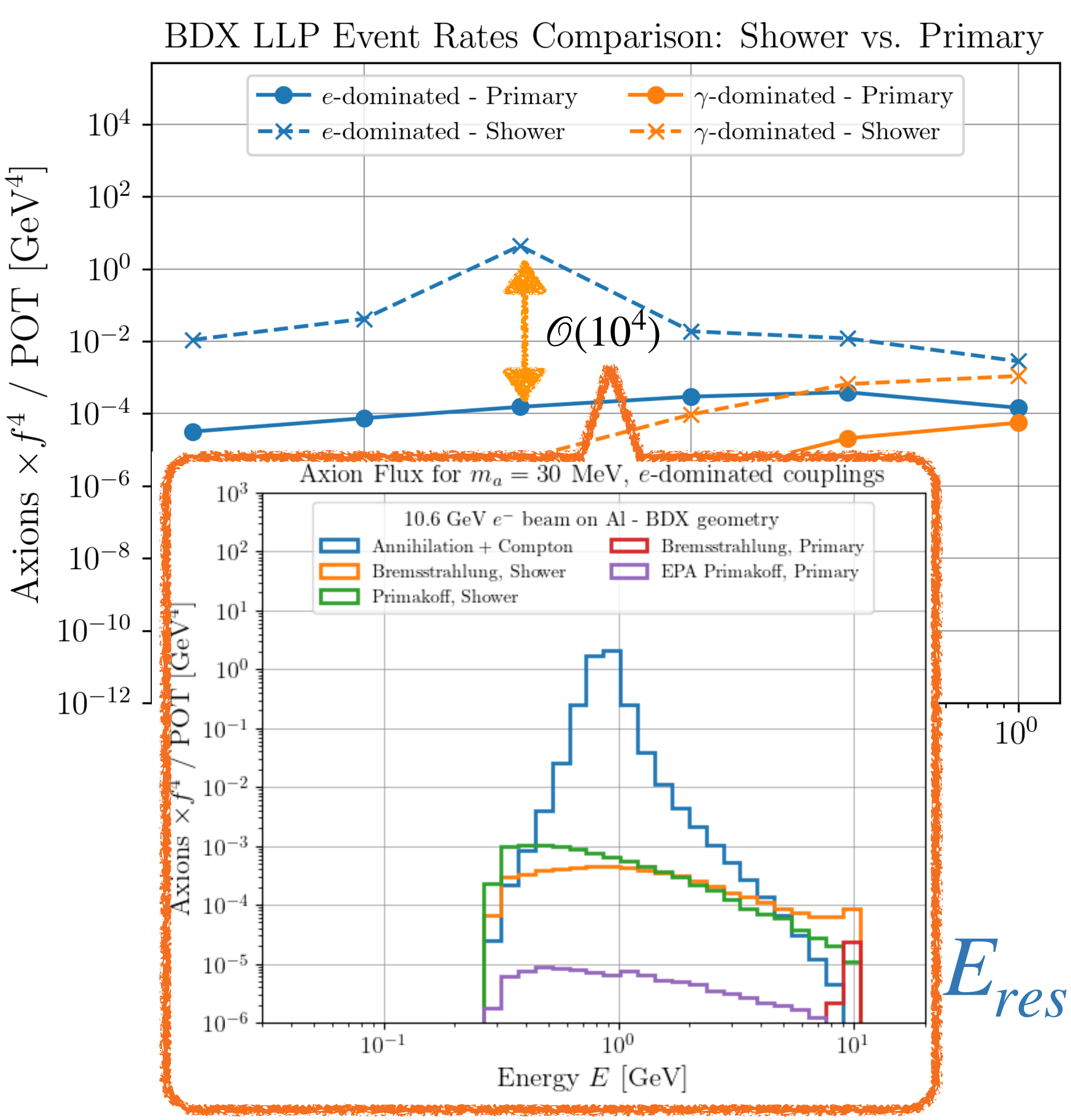
Fluxes

BDX



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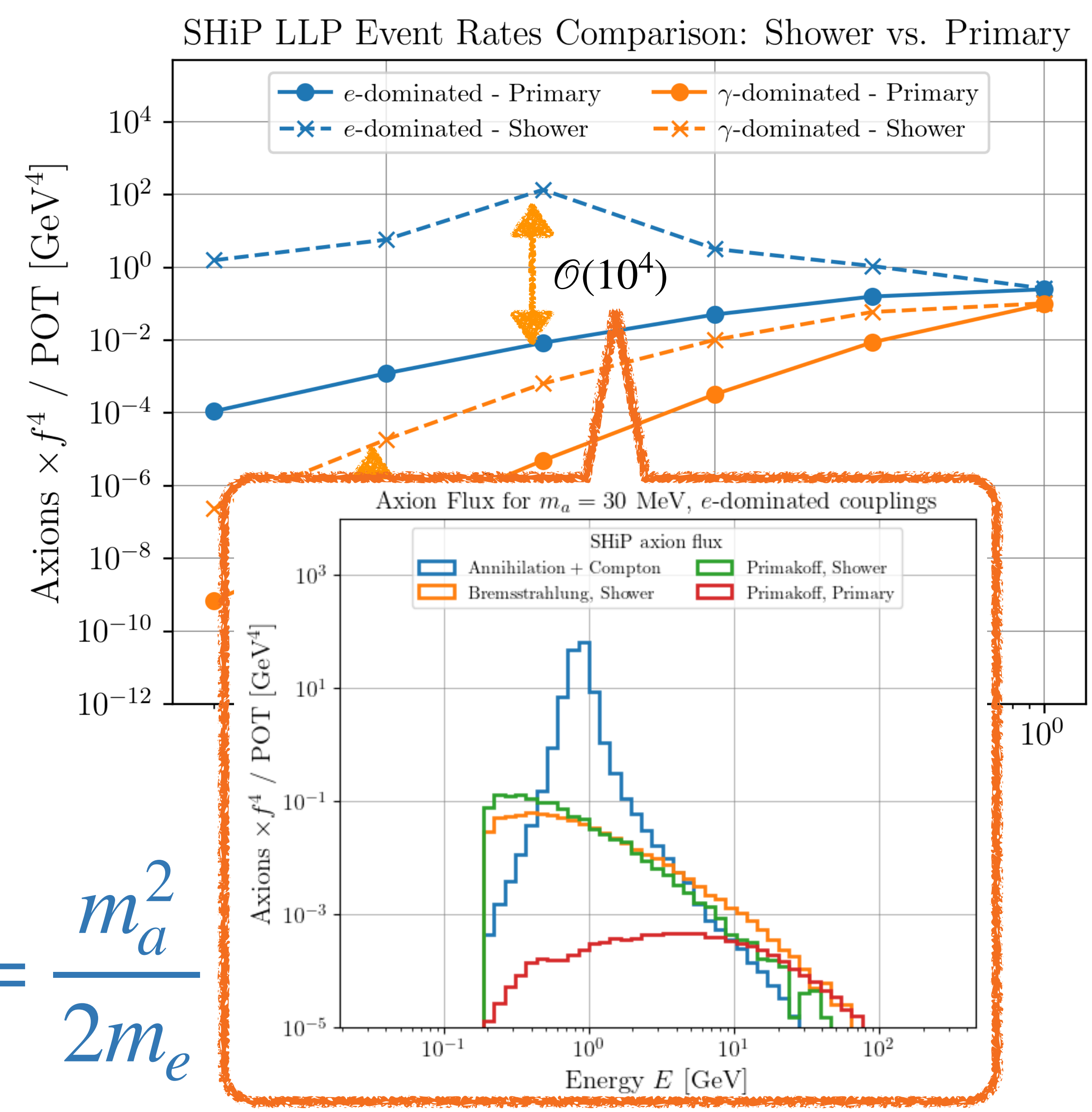

$$E_{res} = \frac{m_a^2}{2m_e}$$

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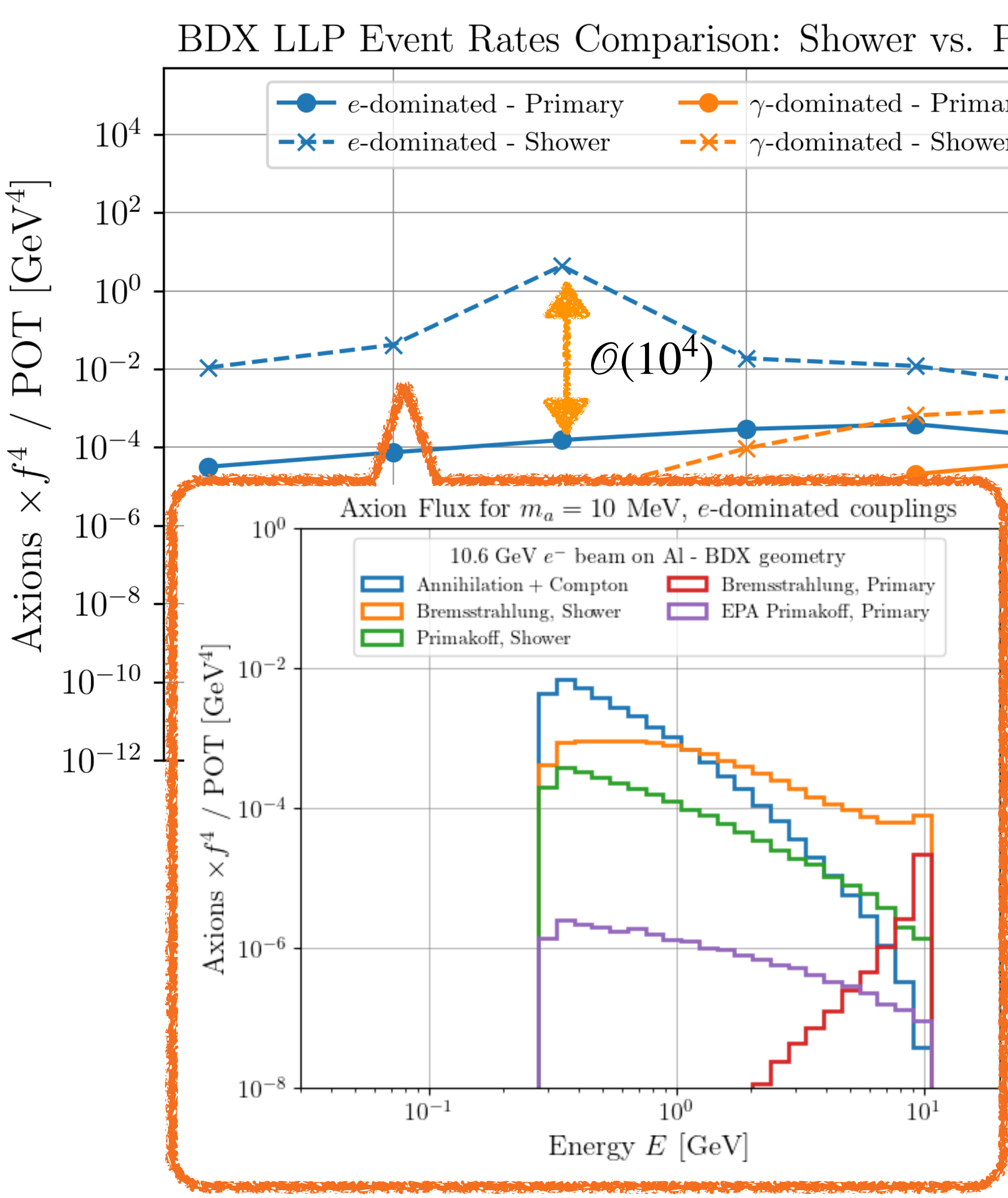
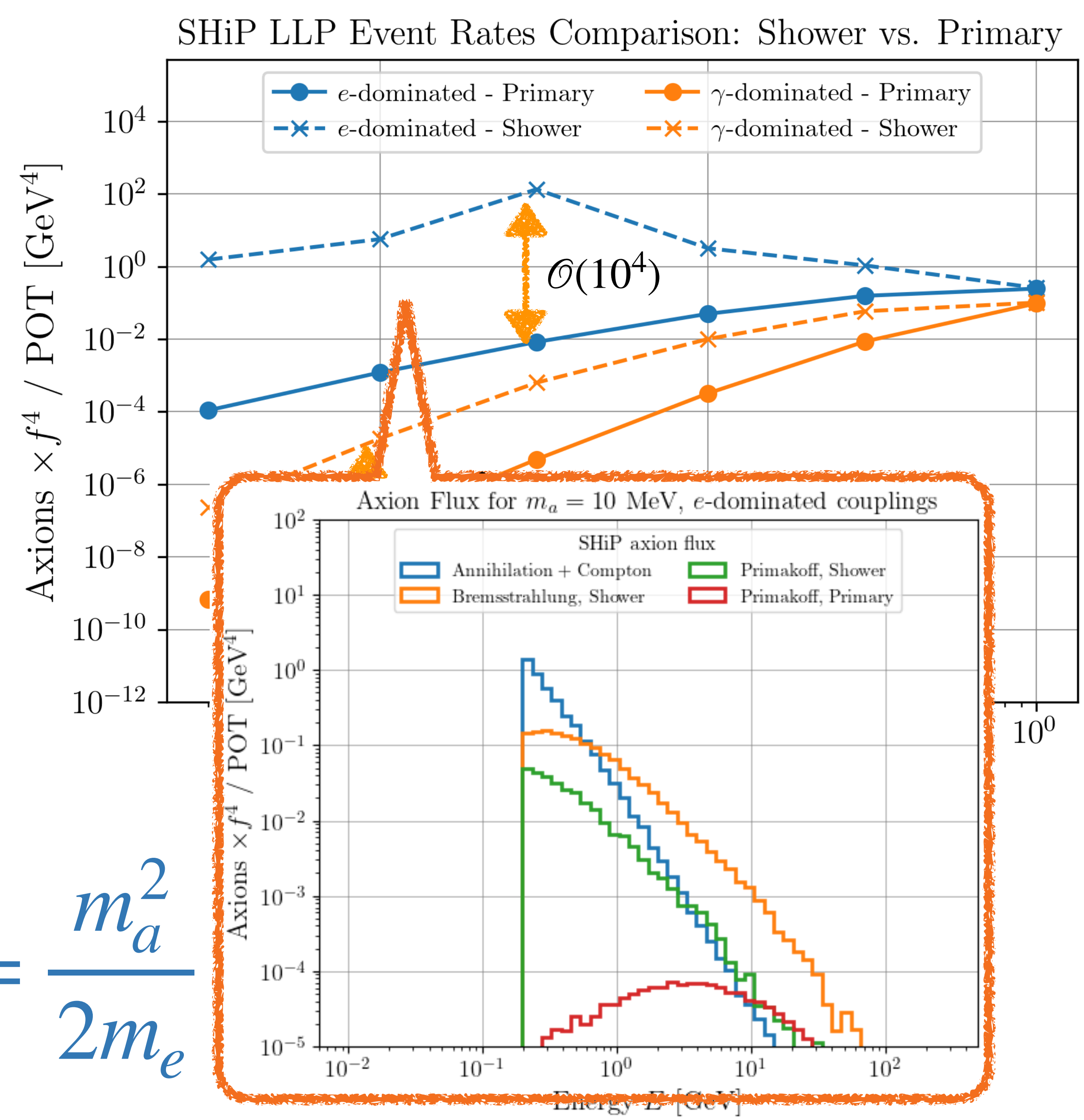
Fluxes

BDX

SHiP



$$E_{res} = \frac{m_a^2}{2m_e}$$



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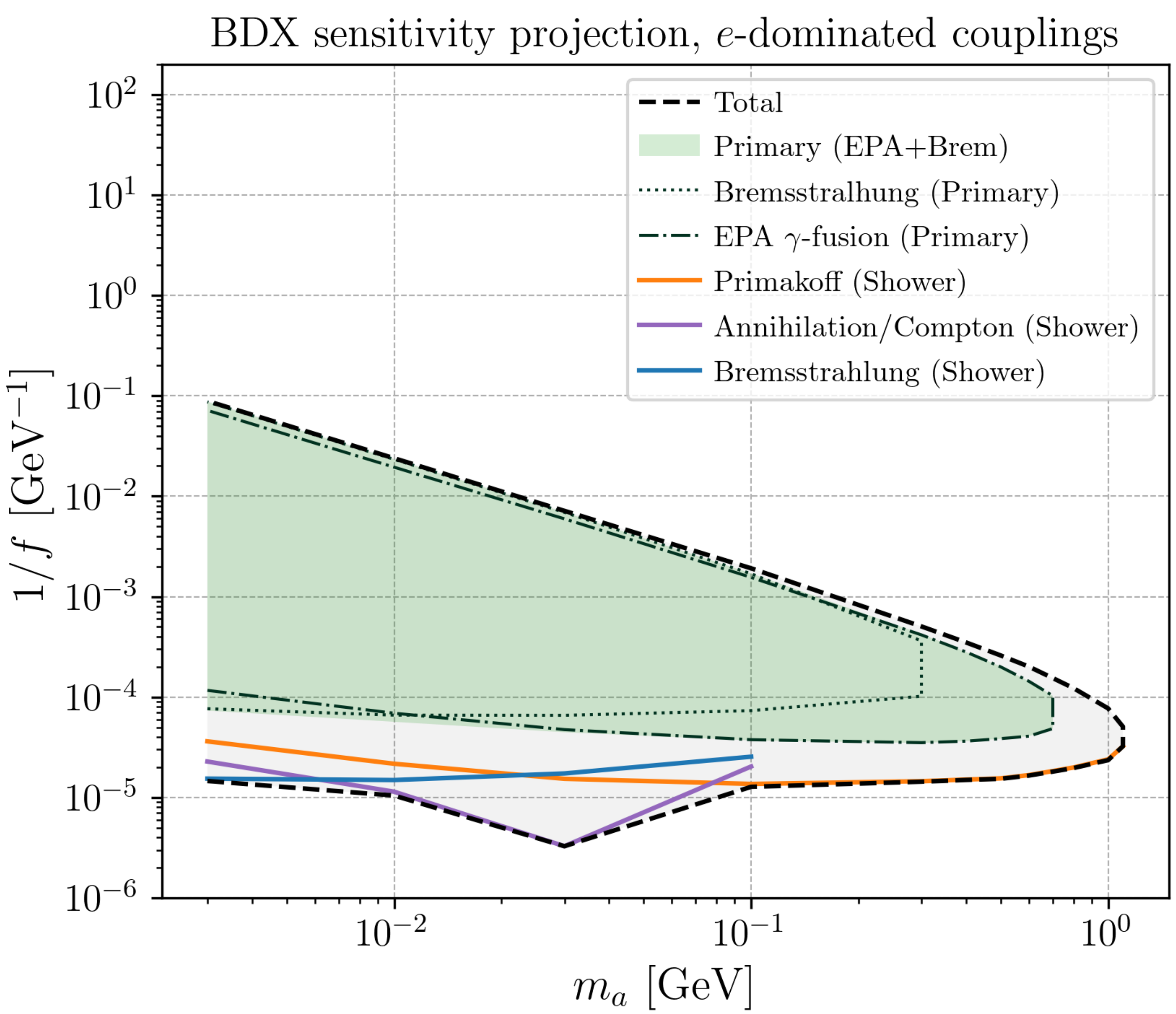
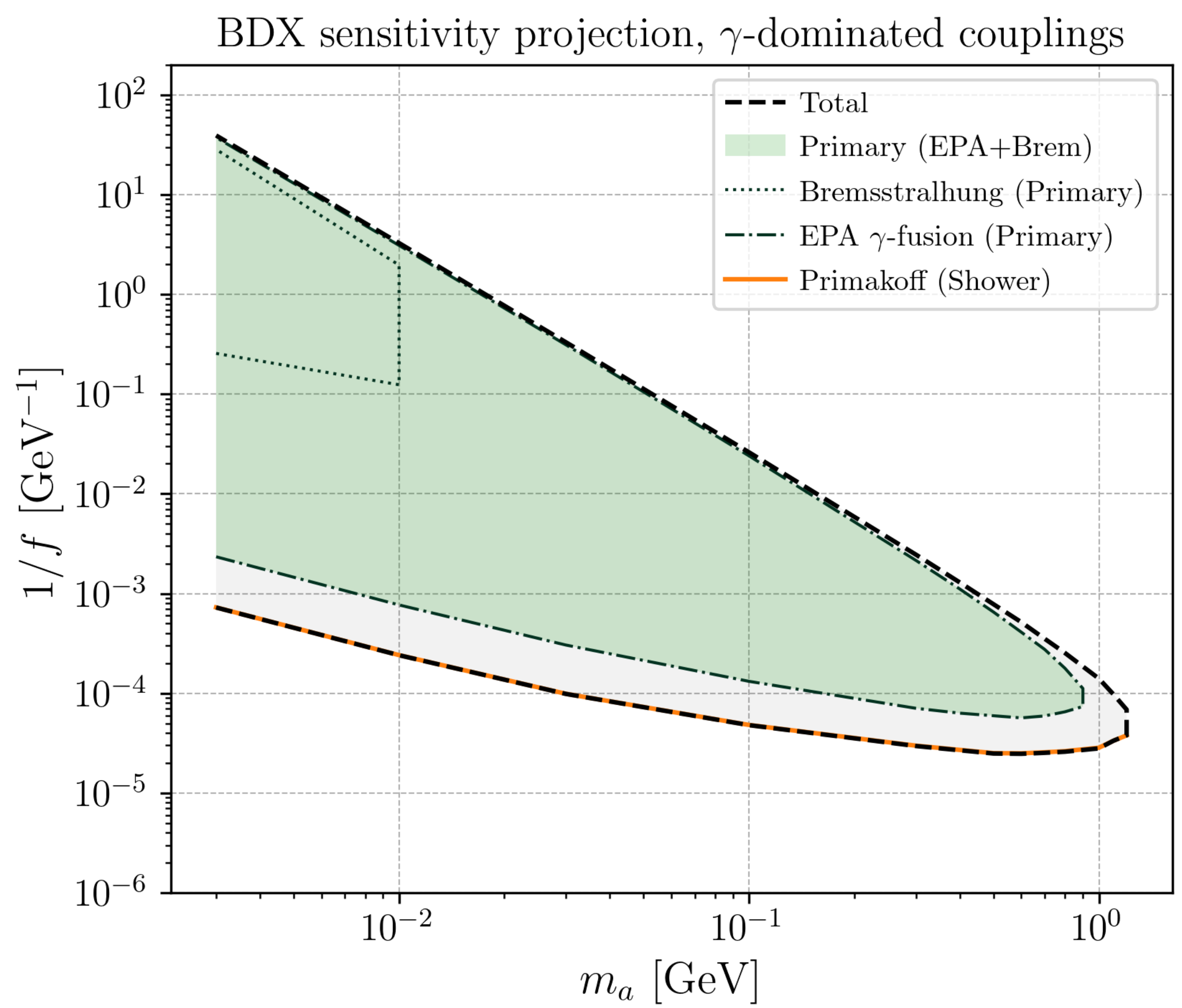
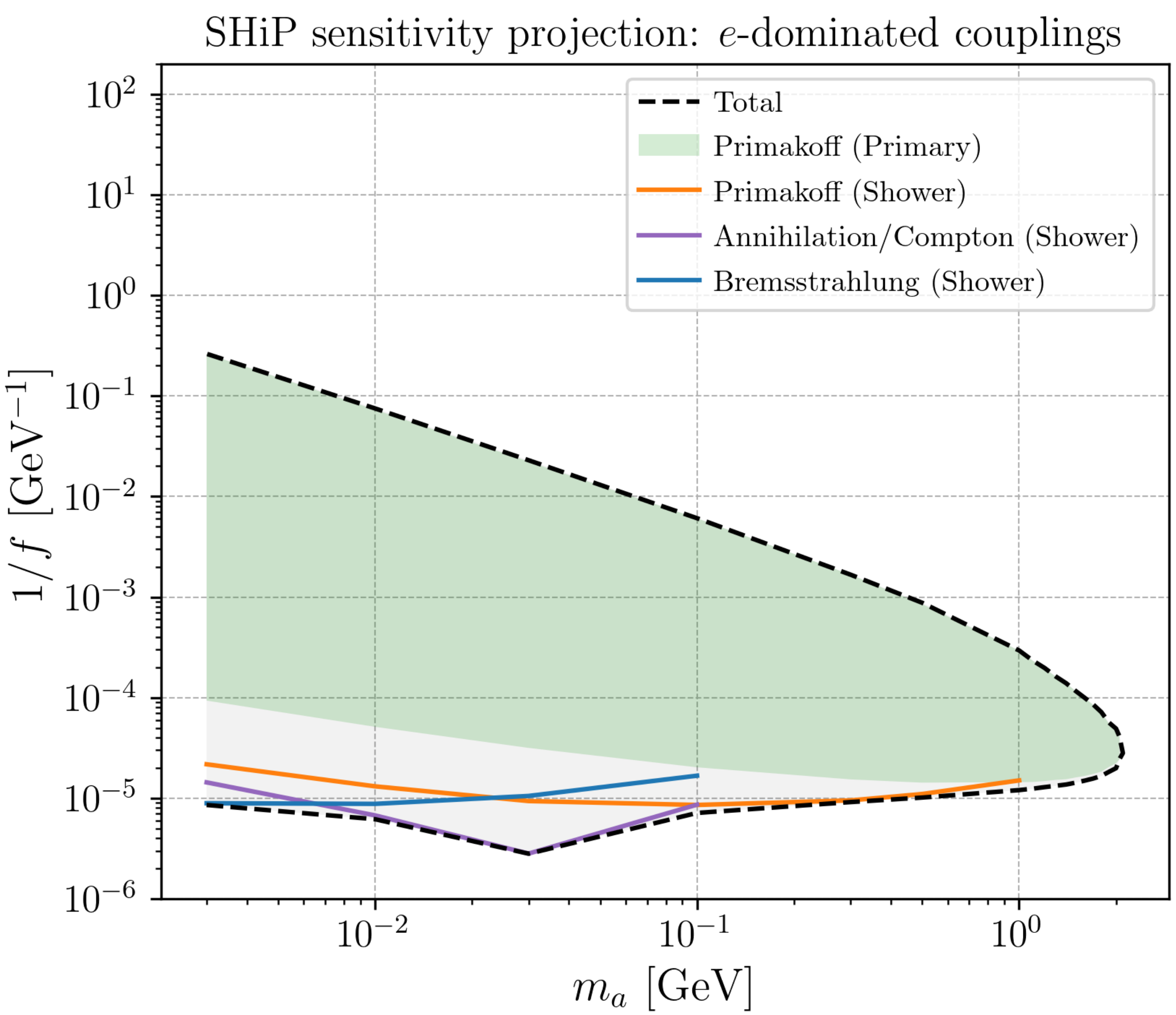
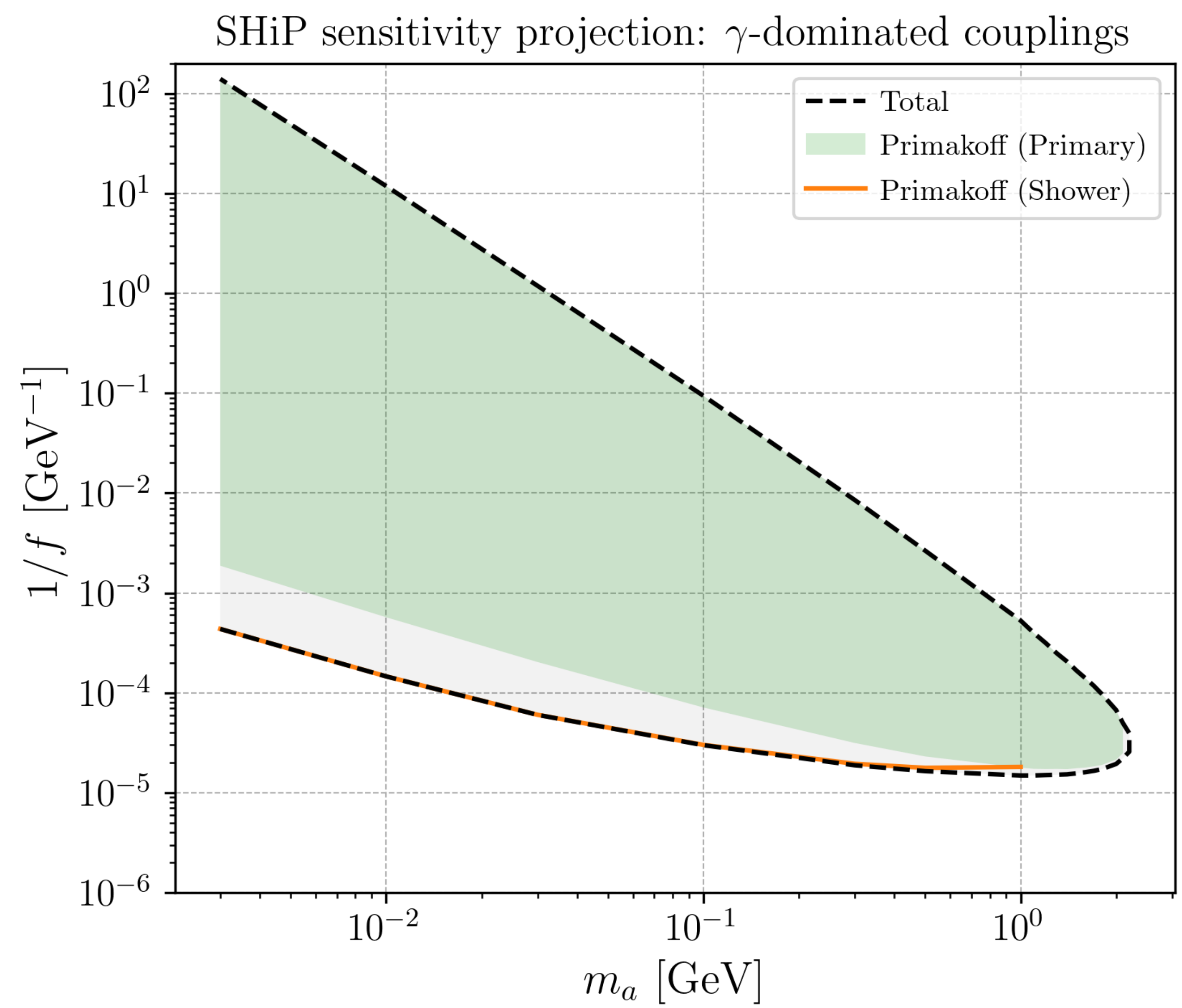
BDX Sensitivity



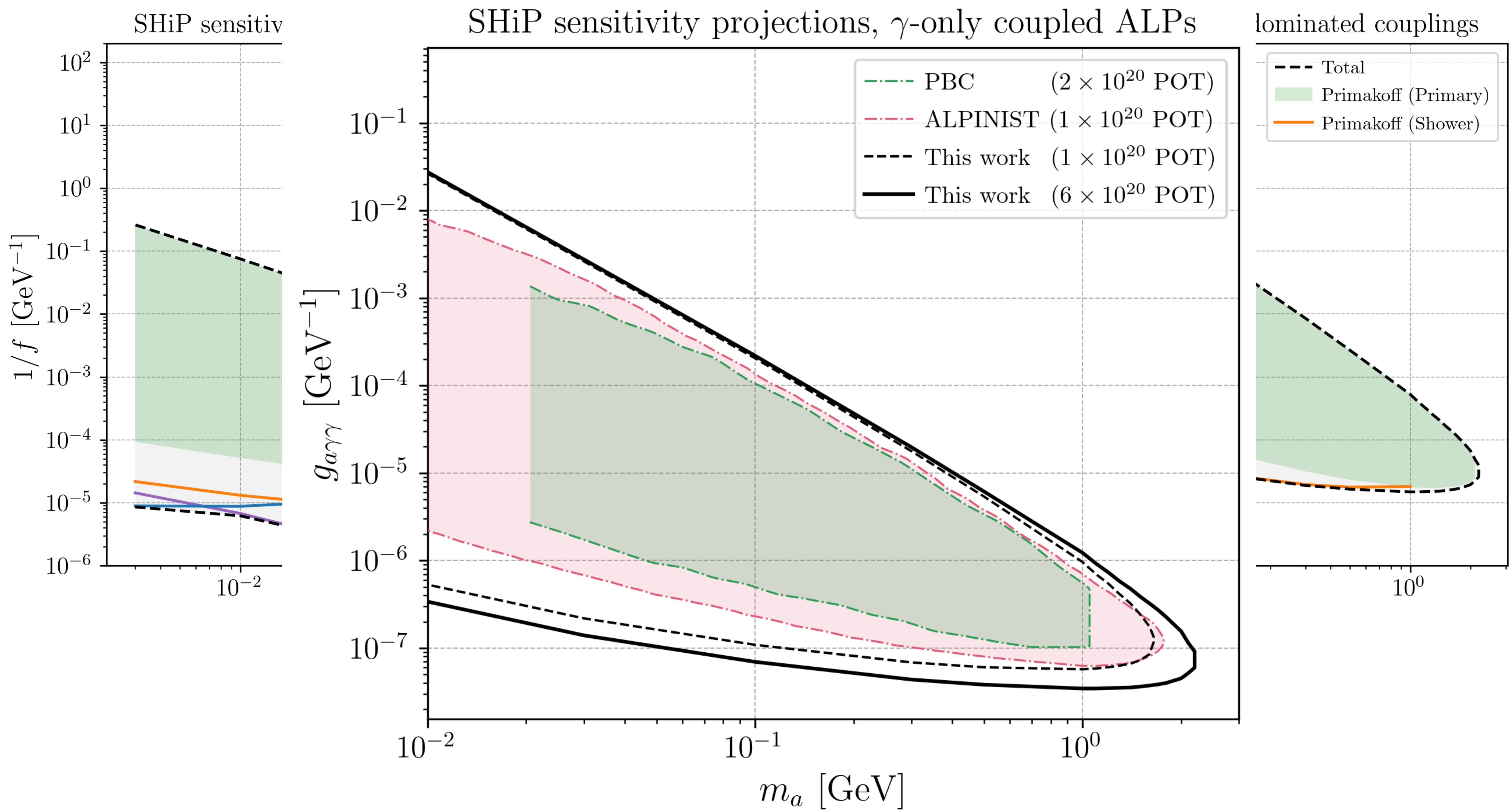


SHiP Sensitivity





SHiP Sensitivity



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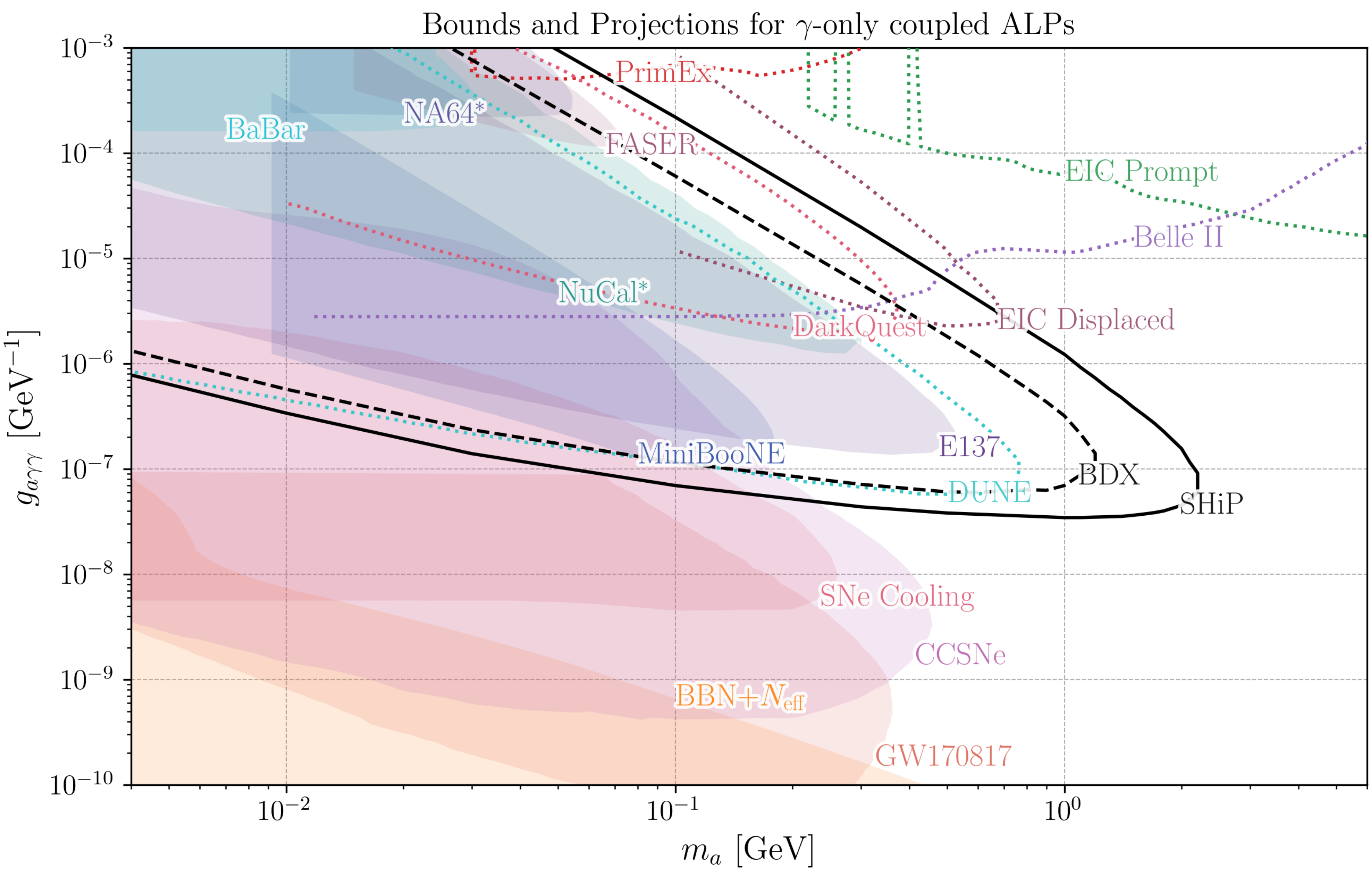
ALPs Bounds



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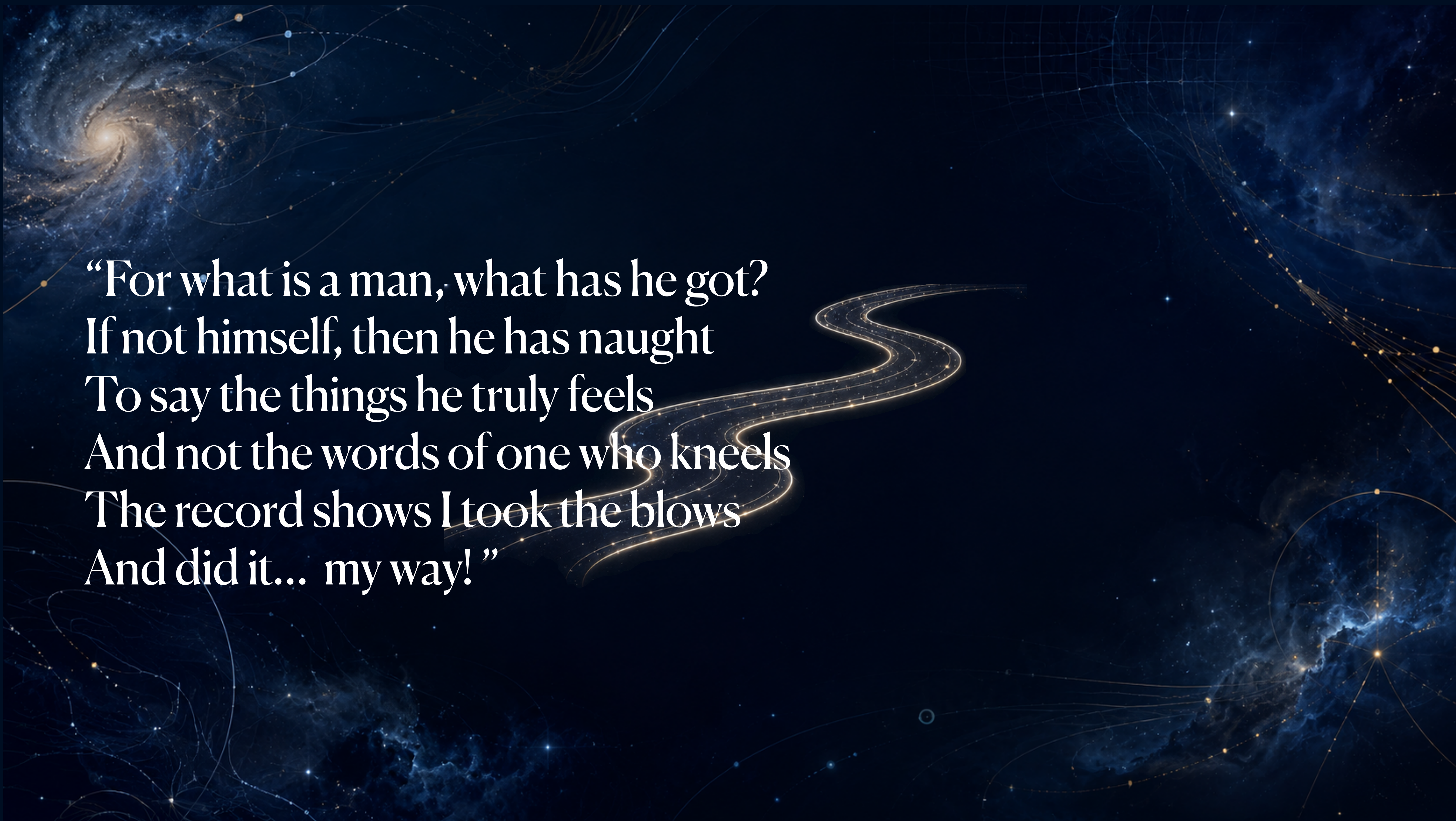
Conclusion

- **Electromagnetic cascades** significantly **enhance** the hypothetical **flux of ALPs** in **beam dump experiments** and must be taken into account -> Old bounds can be recasted

- **Primakoff** production is the dominant channel, together with **Resonant Annihilation** (for e-dominated benchmark) when $m_a < 100\ MeV$

- **Future directions:**
  - improve angular selection criteria
  - study interplay with hadronic production
  - extend the framework to other BSM particles (HNL, Higgs-mixed Scalar)


"For what is a man, what has he got?
If not himself, then he has naught
To say the things he truly feels
And not the words of one who kneels
The record shows I took the blows
And did it... my way! "

Caltech

BURKE INSTITUTE

Thank you!

(Dr. ?) Samuel Patrone

PhD Defense

May 27th, 2026

Tracing *New Physics*

From Symmetry To Observation

Question Time