Probing quantum gravity at all scales

Bridging high and low energies in search of quantum gravity
COST Action CA23130 Annual Conference, July 8, 2025

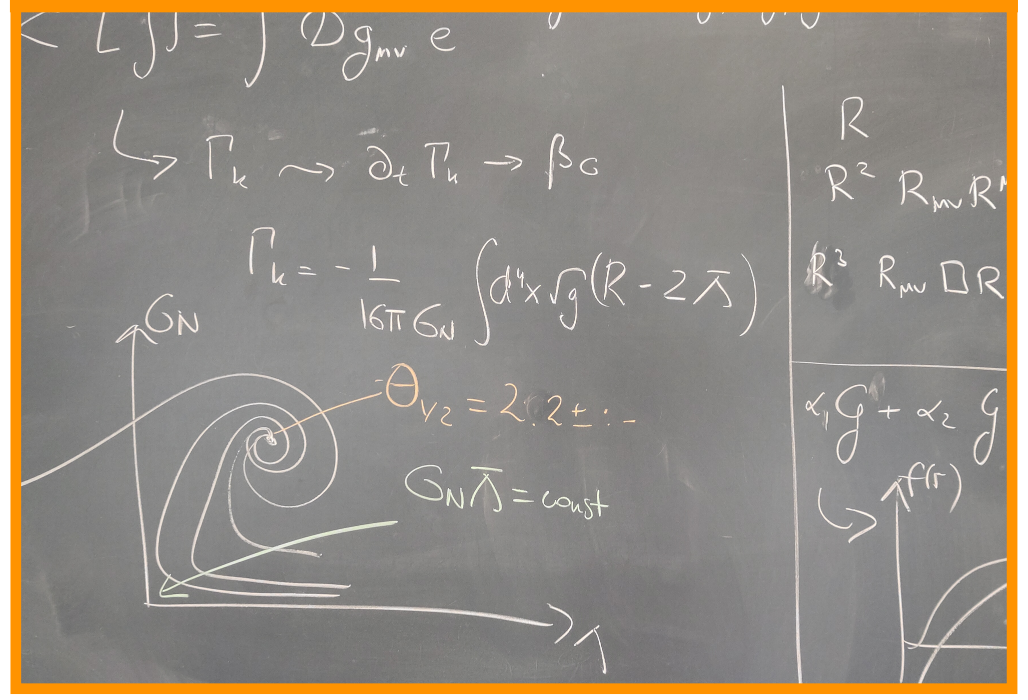
Astrid Eichhorn, Heidelberg University

European Research Council

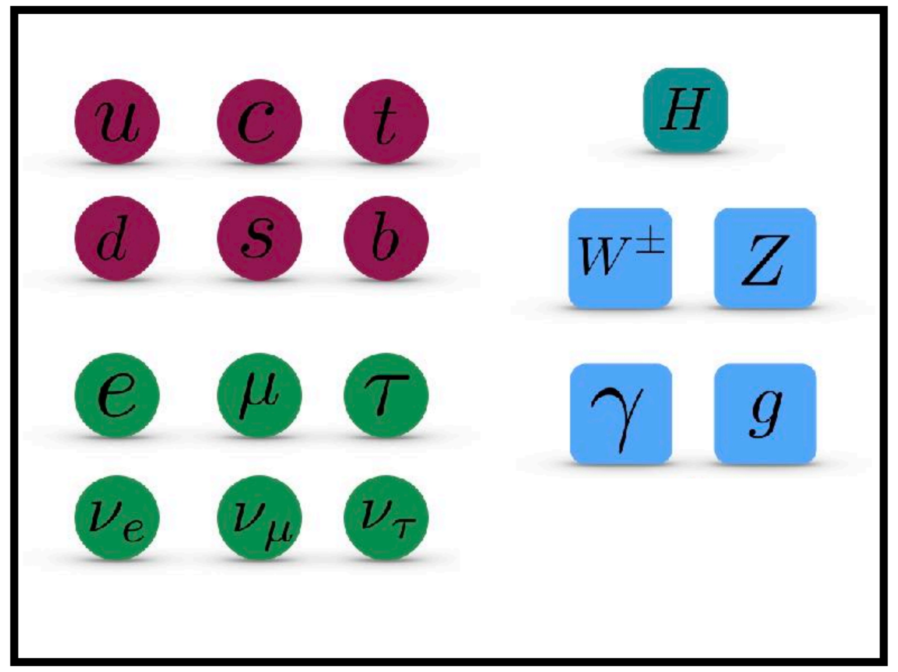
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

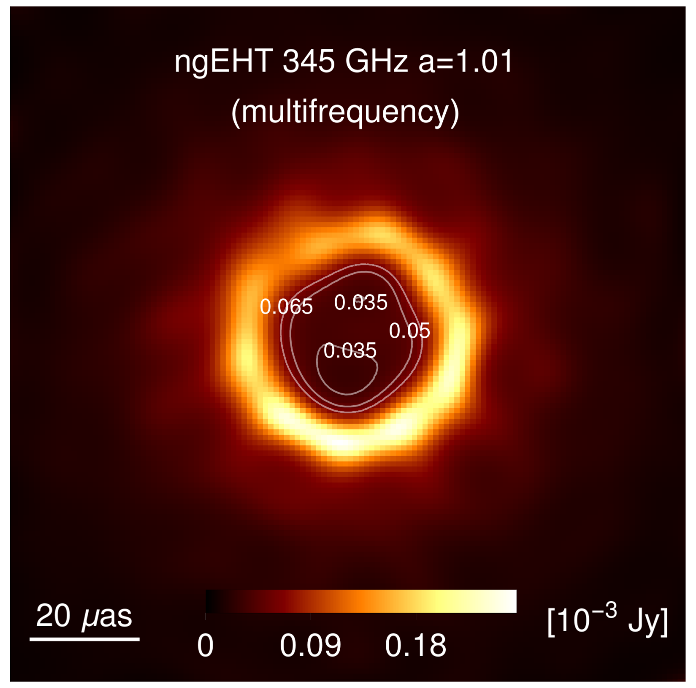
Motivation: How to test proposed theories of quantum gravity?

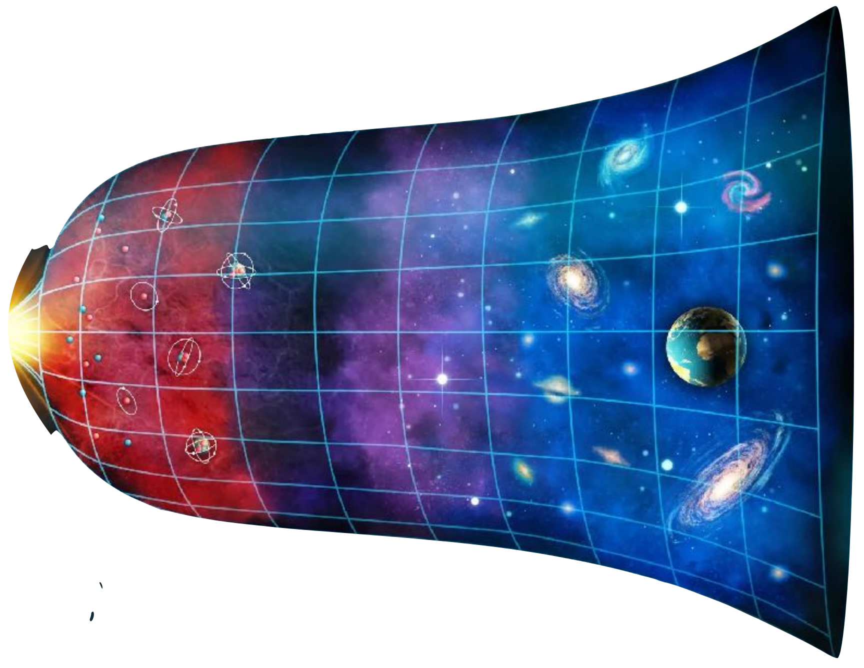
Theory of quantum gravity



Key challenge: gap in scales







Planckian scales $10^{-35}\,\mathrm{m}$

Particle physics scales $10^{-17}\,\mathrm{m}$

Black-hole scales $10^{11}\,\mathrm{m}$

Cosmological scales $> 10^{20}\,\mathrm{m}$

distance scale

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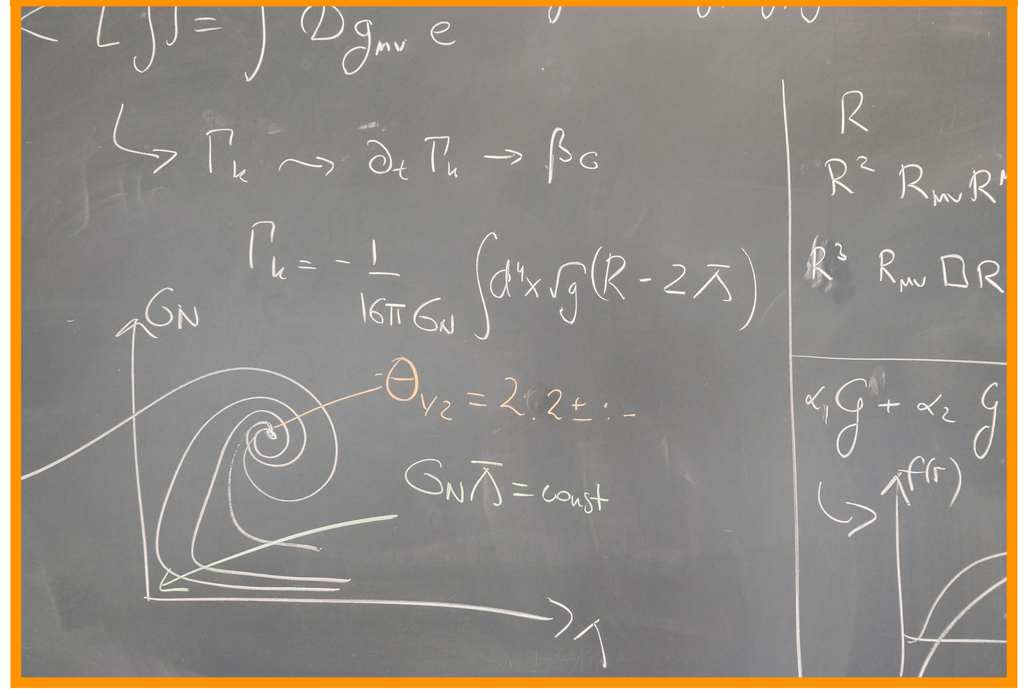

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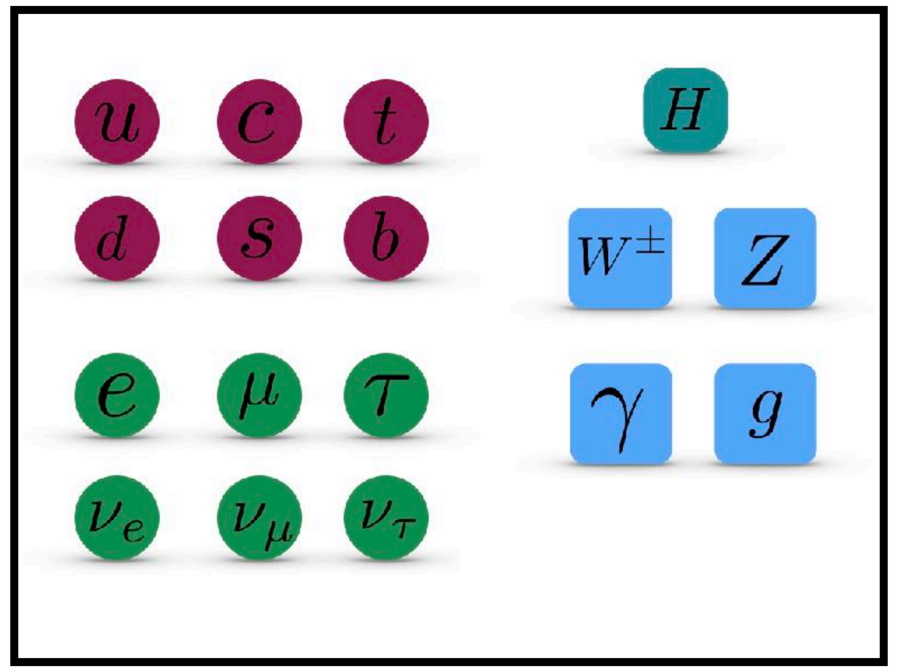

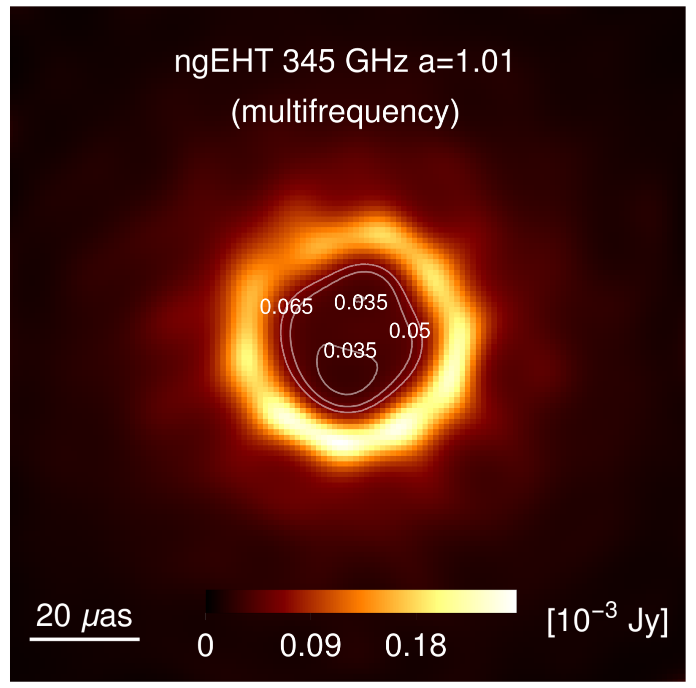

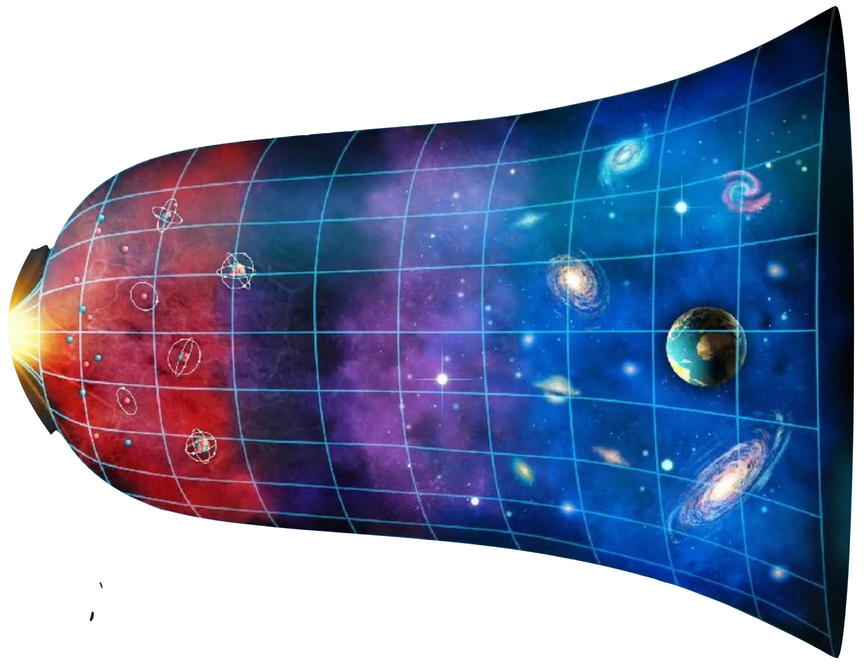

Planckian scales	Particle physics scales	Black-hole scales	Cosmological scales
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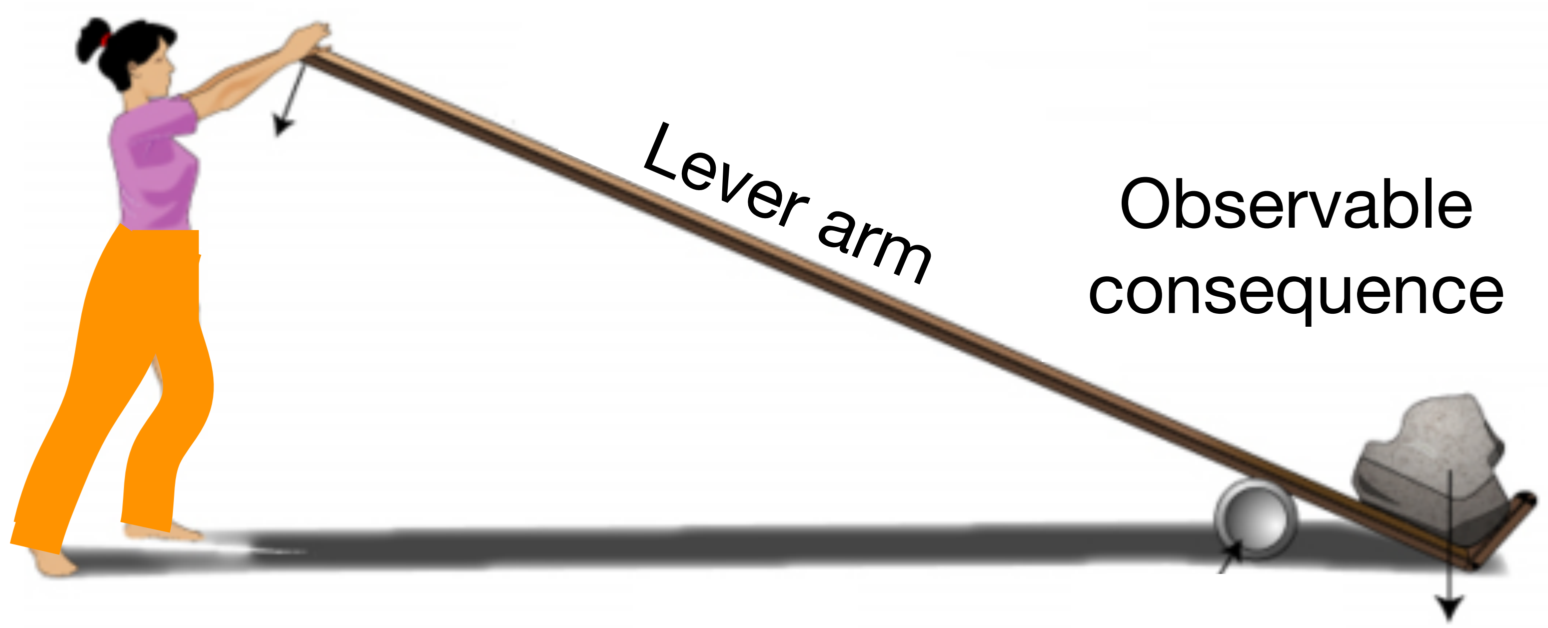
Quantum-gravity effect



Examples:

- Accumulation of Lorentz-Invariance-Violation over astrophysical distances of photons from short Gamma-Ray-Bursts

  [Amelino-Camelia, Ellis, Mavromatos Nanopoulos, Sakar '97]

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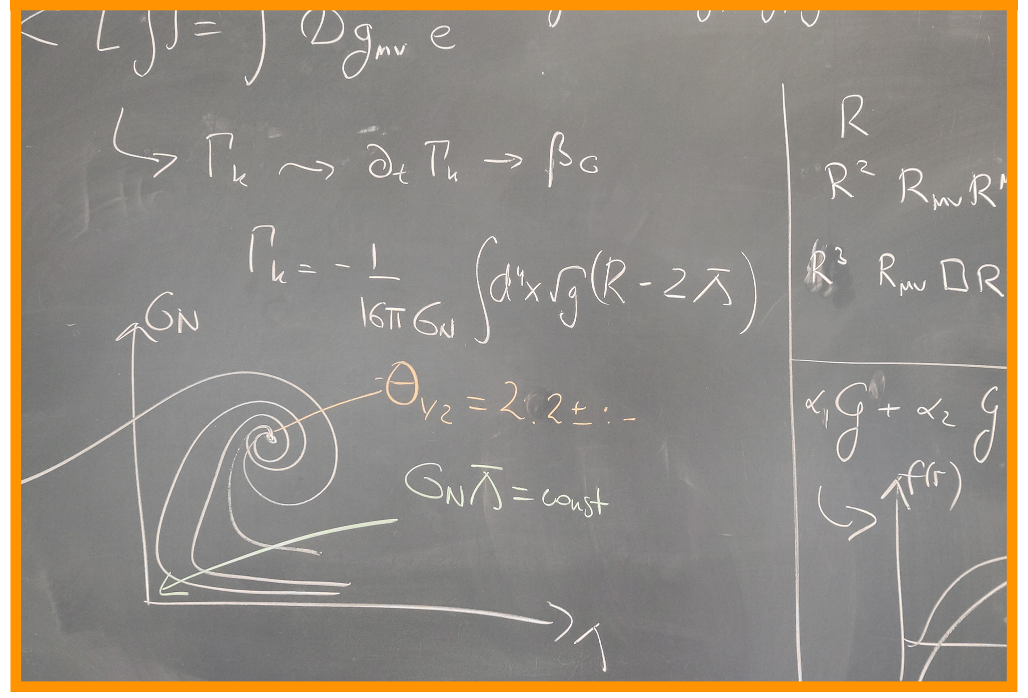

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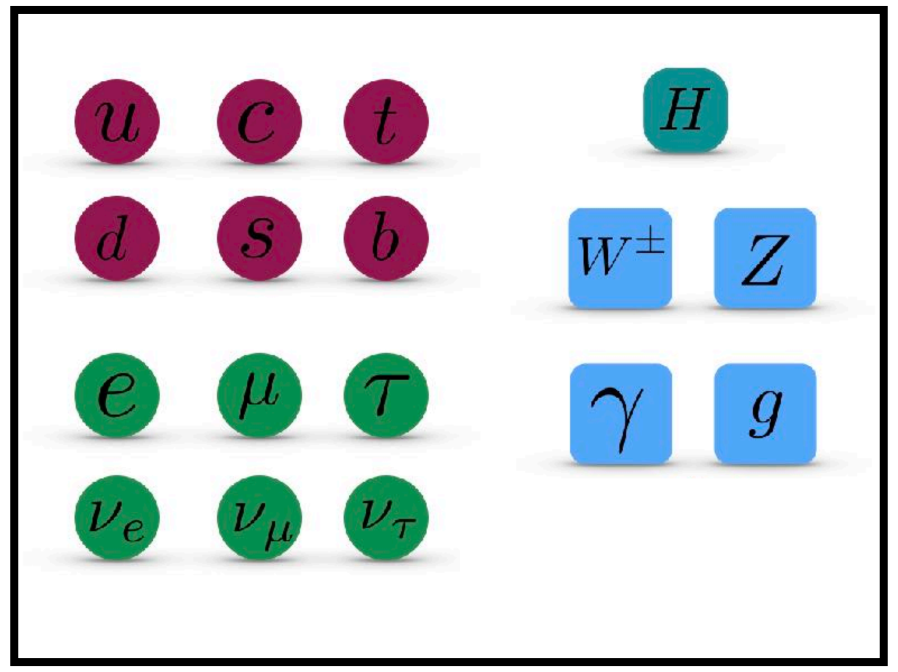

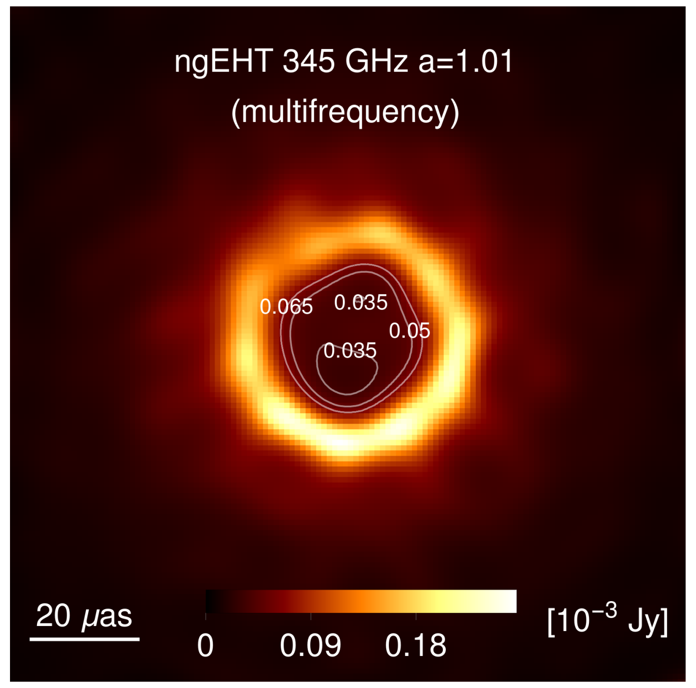

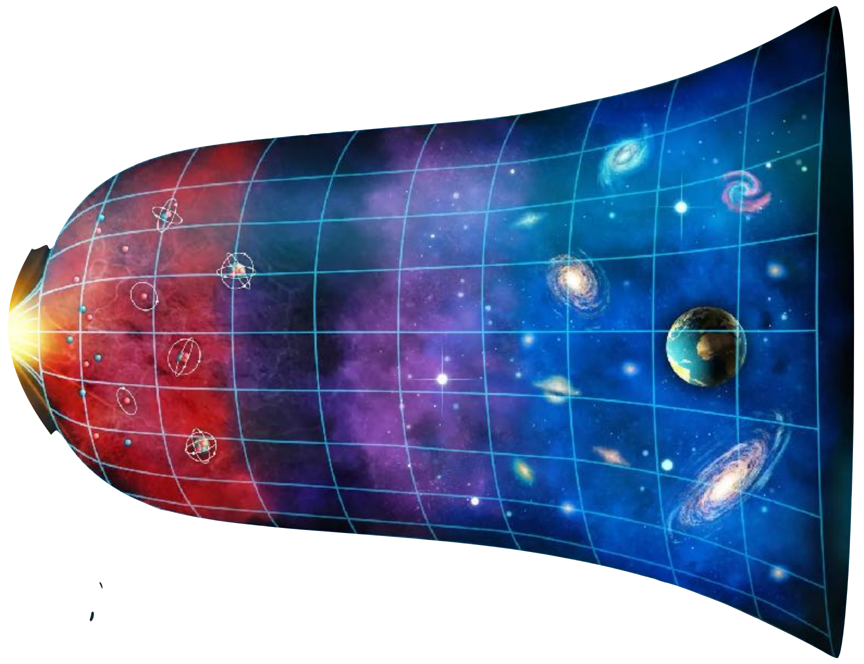

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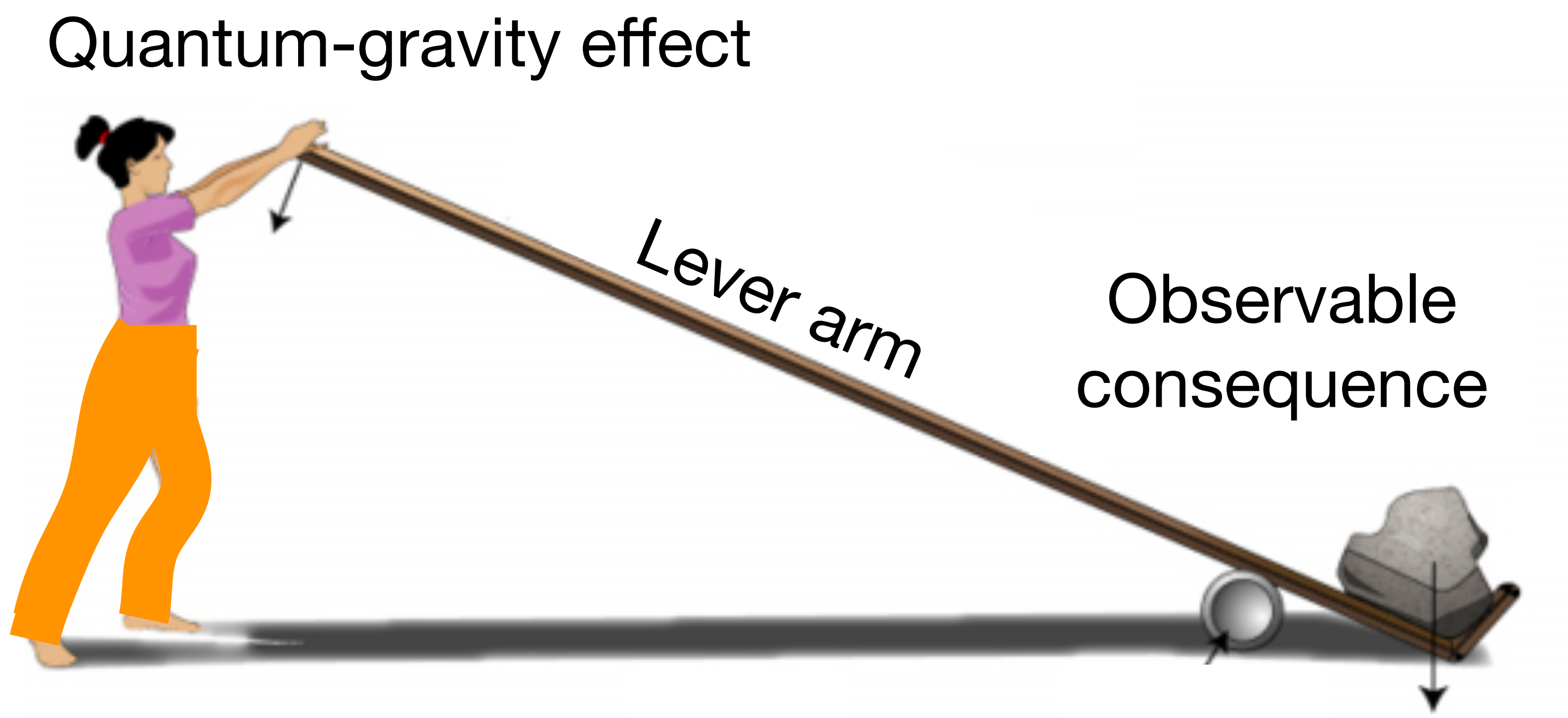

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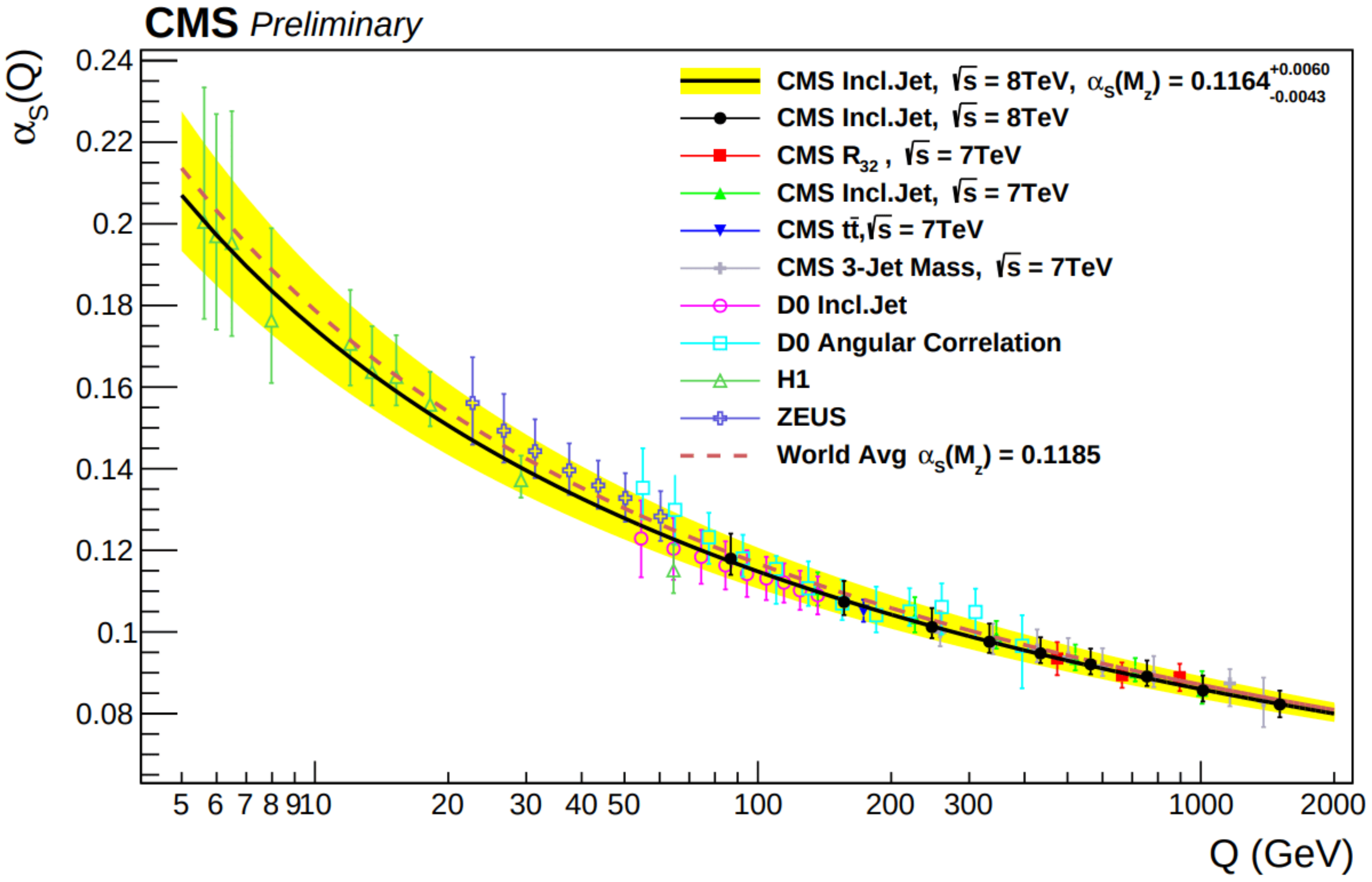
- Renormalization Group flow of couplings

Renormalization Group flow

Coupling constants are not constant, instead they *run* as a function of scale due to quantum fluctuations



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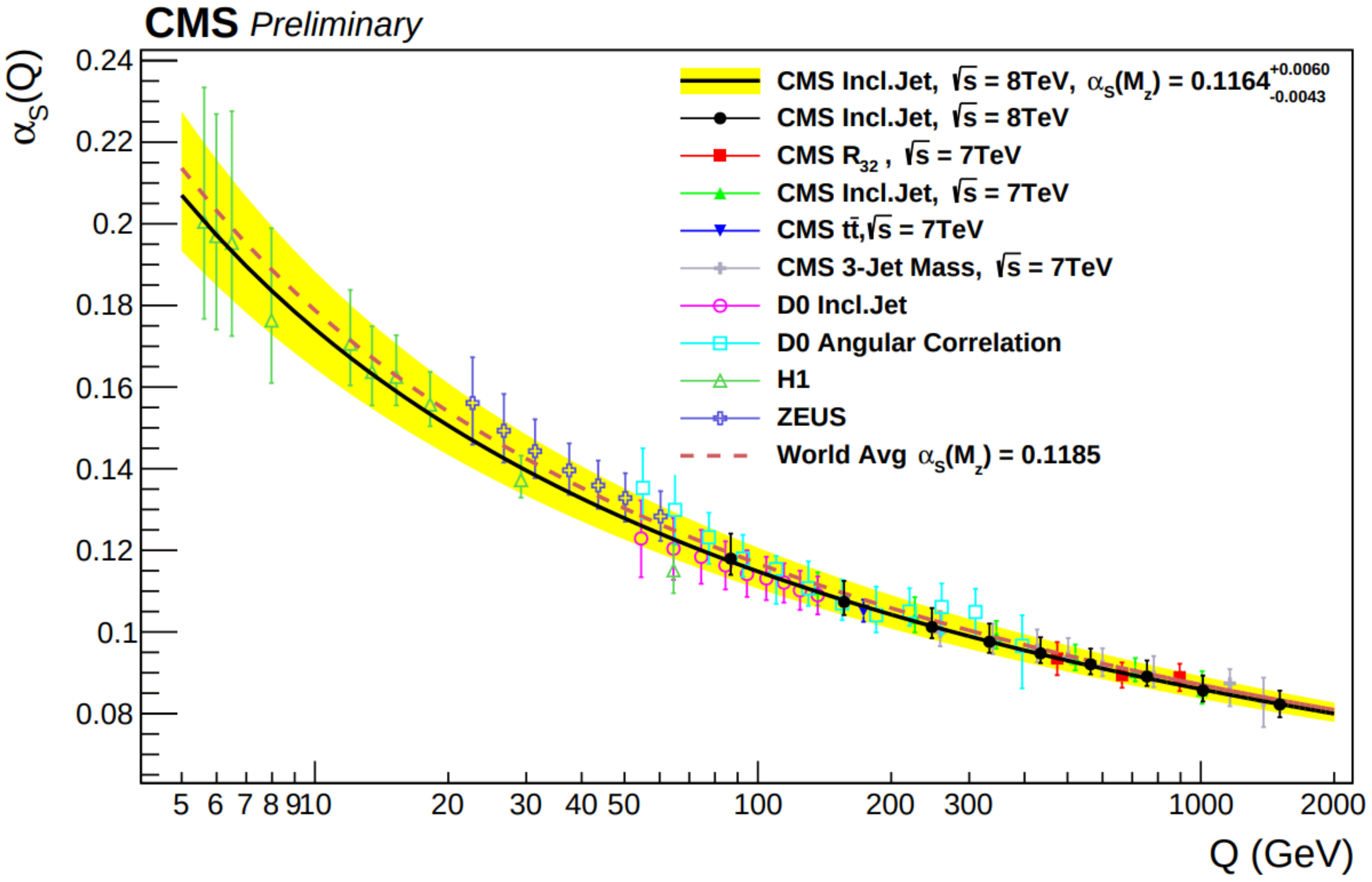
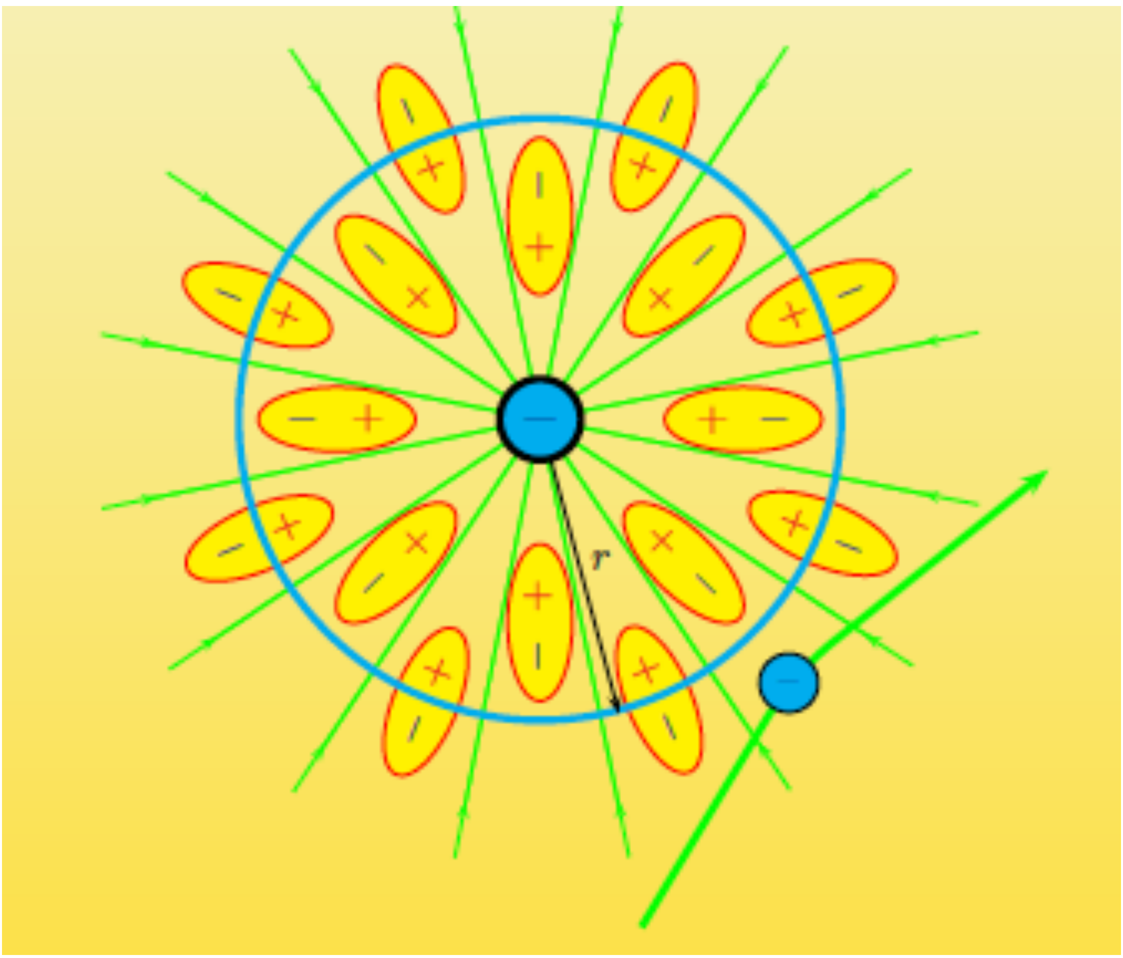


Quantum fluctuations screen or antiscreen interactions



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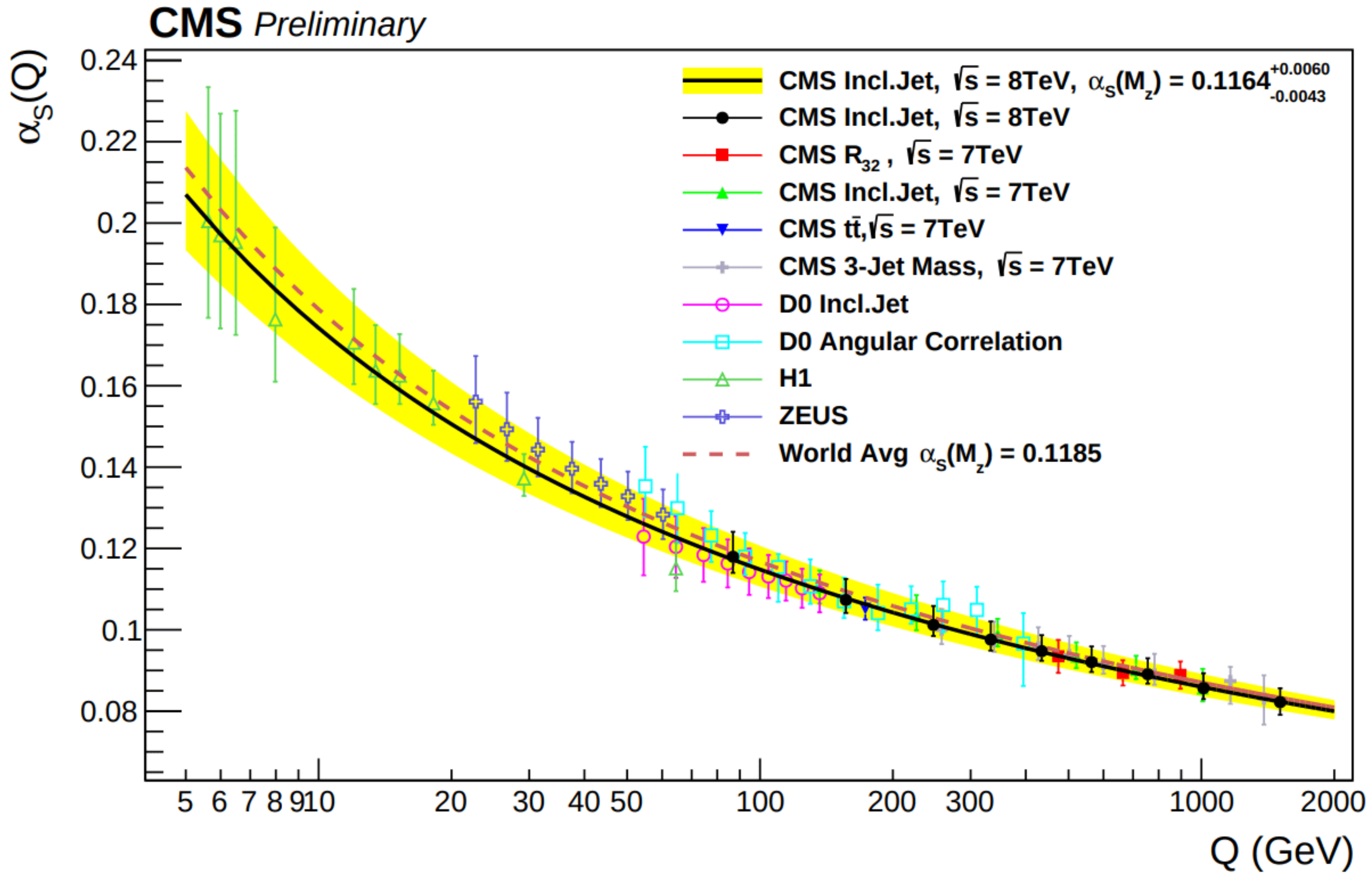

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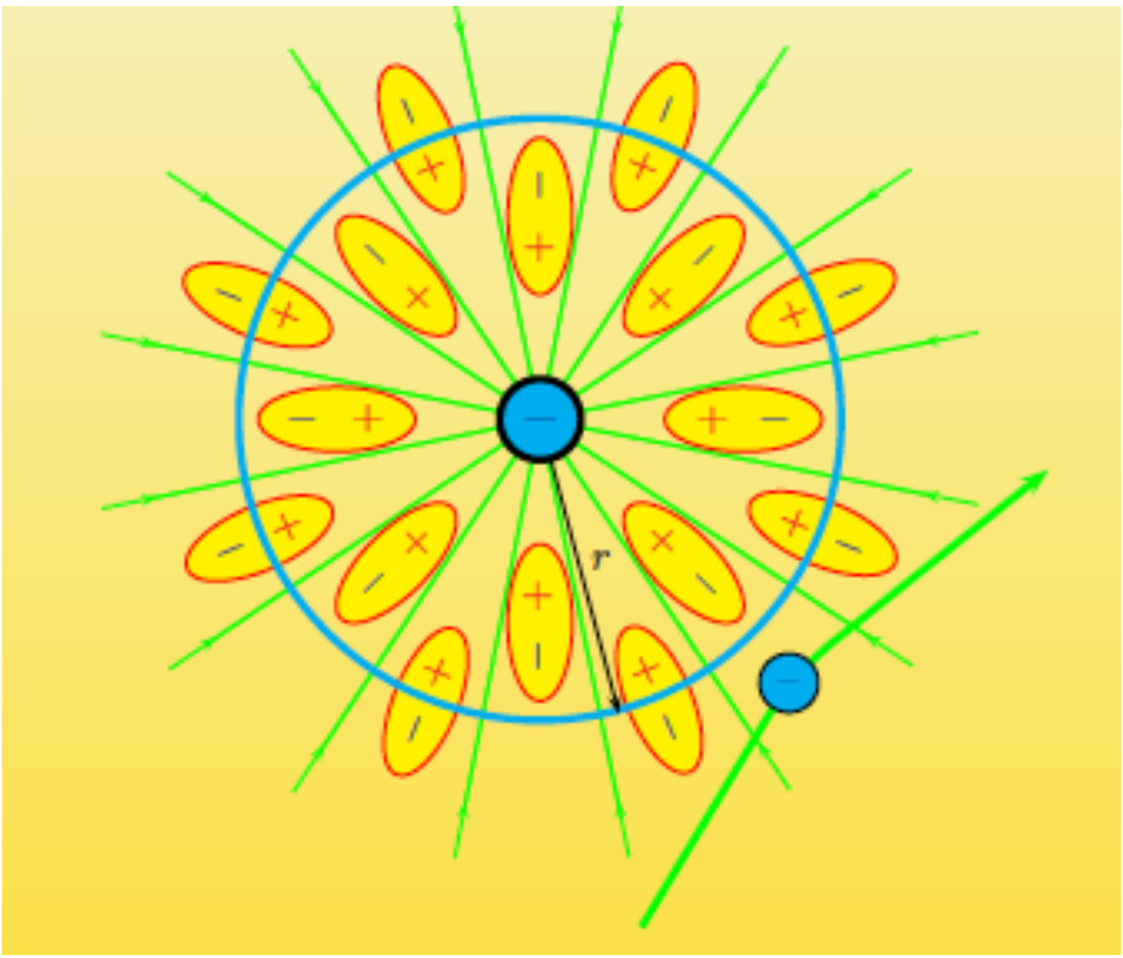
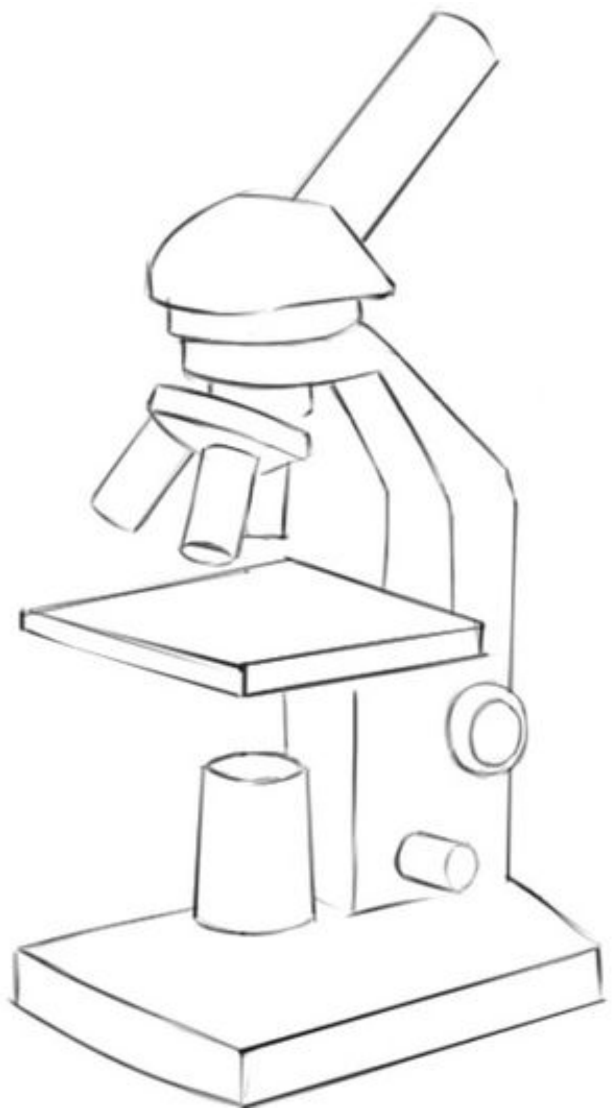
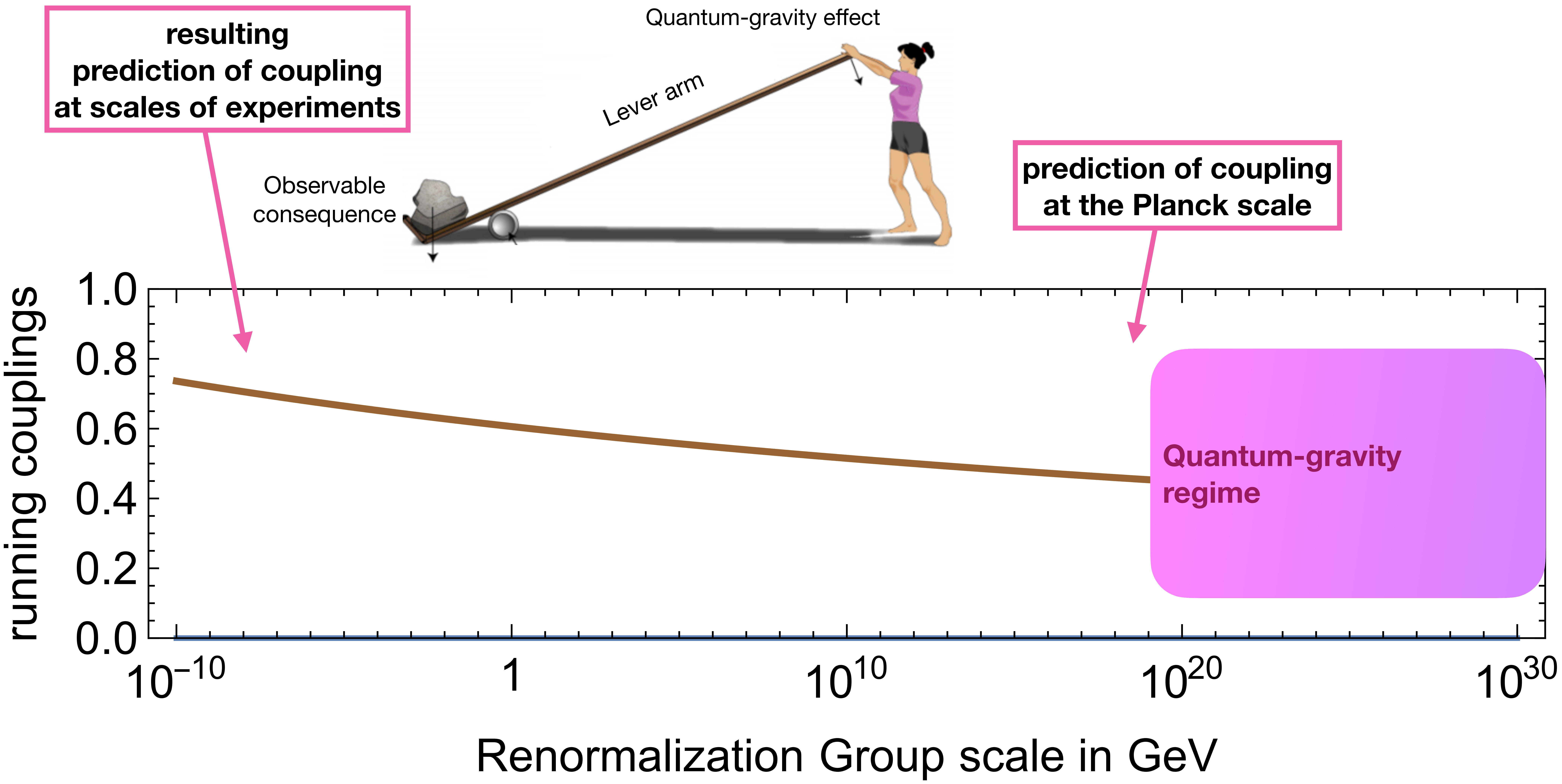




Renormalization Group flow
= ``microscope” for the theory

⇒ can calculate how couplings change as function of scale

Renormalization Group flow as a lever arm

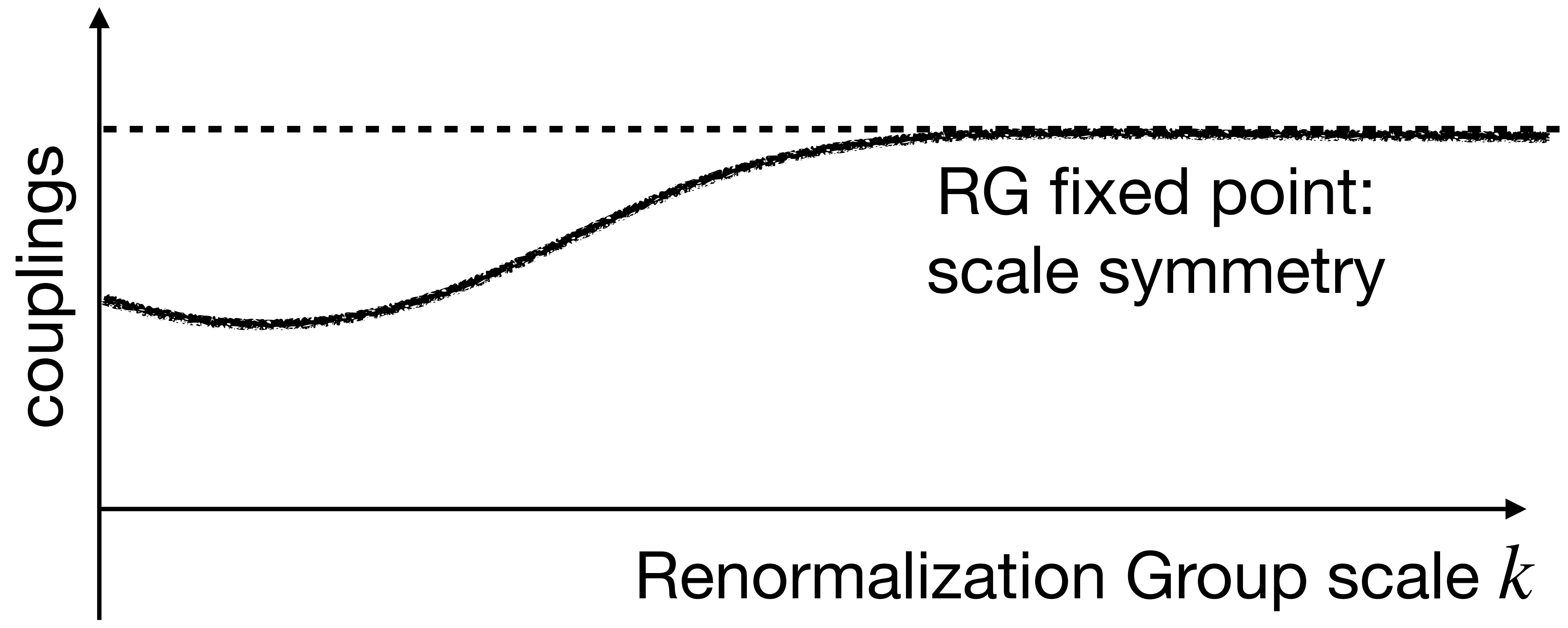


Key idea of asymptotic safety

Asymptotic safety = quantum scale symmetry

scale symmetry realized in transplanckian regime

signature: Renormalization Group fixed point



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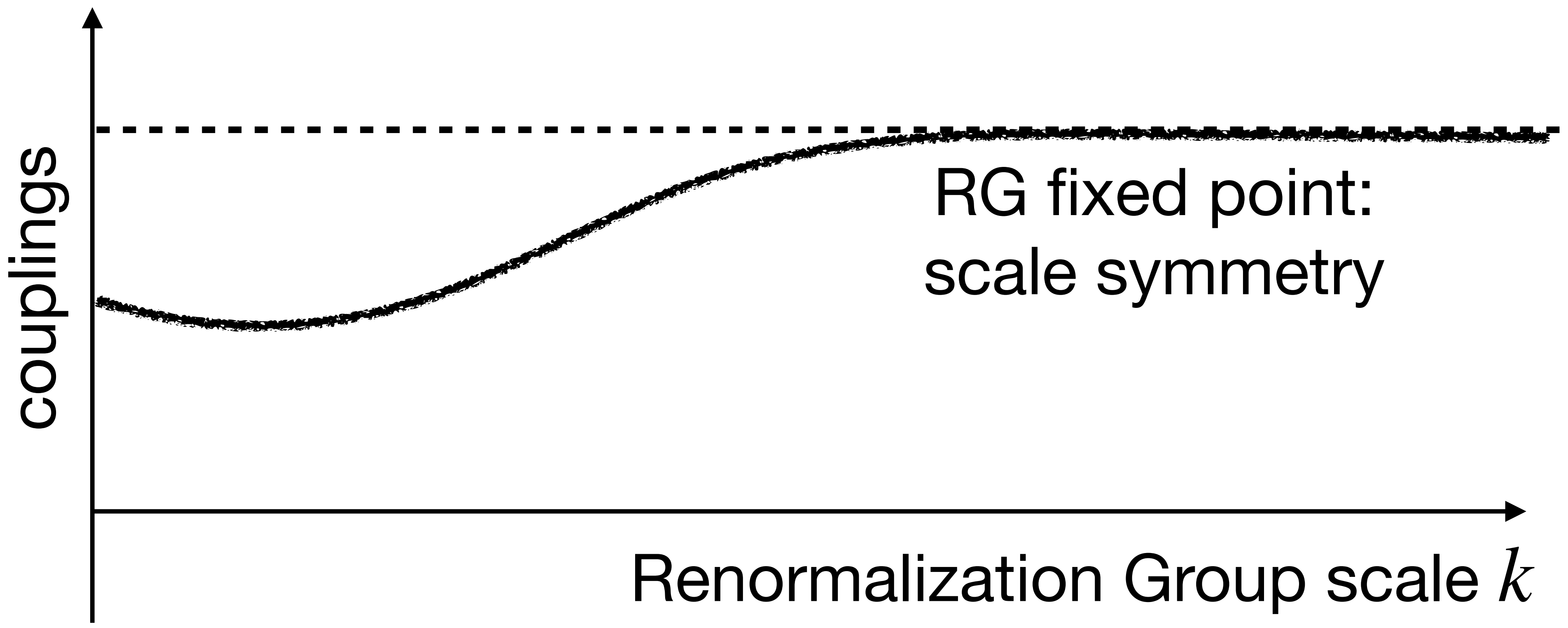
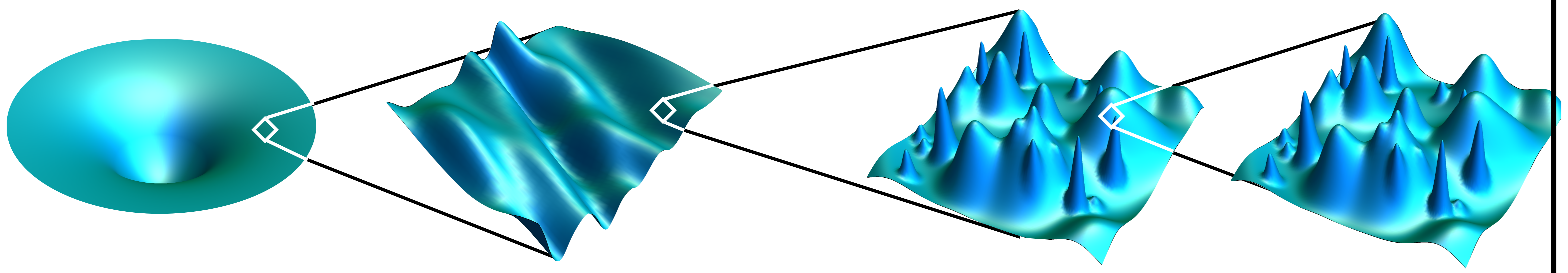
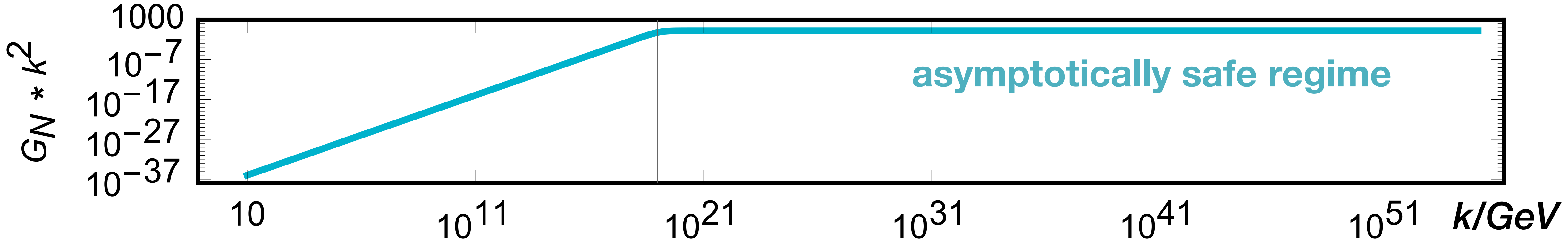


scale symmetry = deep principle of nature

Asymptotic safety in gravity: [Weinberg '79; Reuter '96]

$$S = \int d^4x \sqrt{-g} \left(\Lambda(k) + \frac{1}{16\pi G_N(k)} R + a(k) R^2 + b(k) R_{\mu\nu} R^{\mu\nu} + \ldots \right)$$





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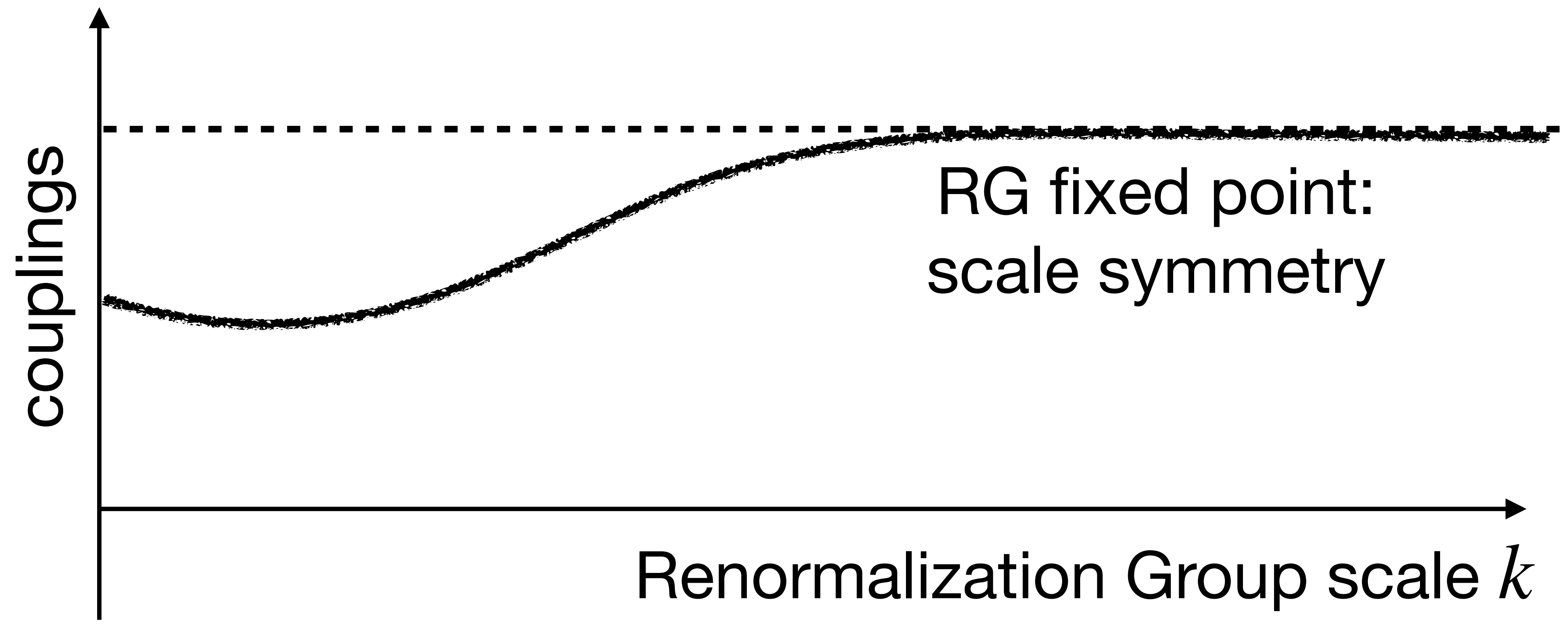

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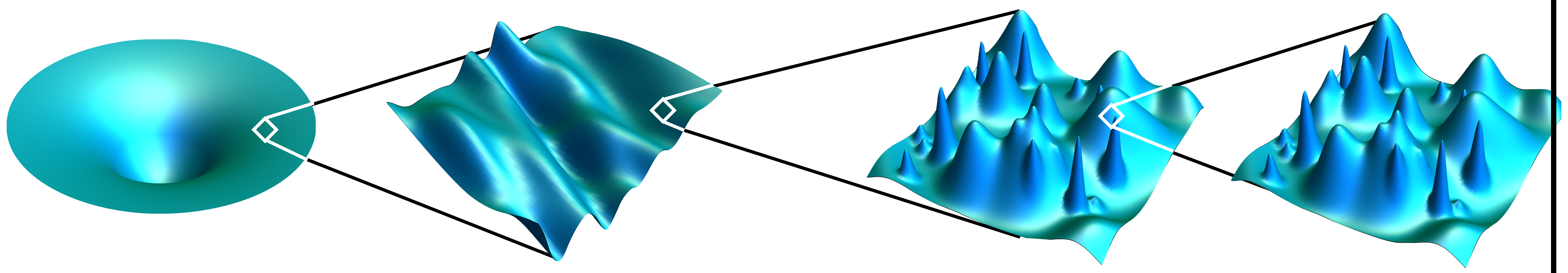

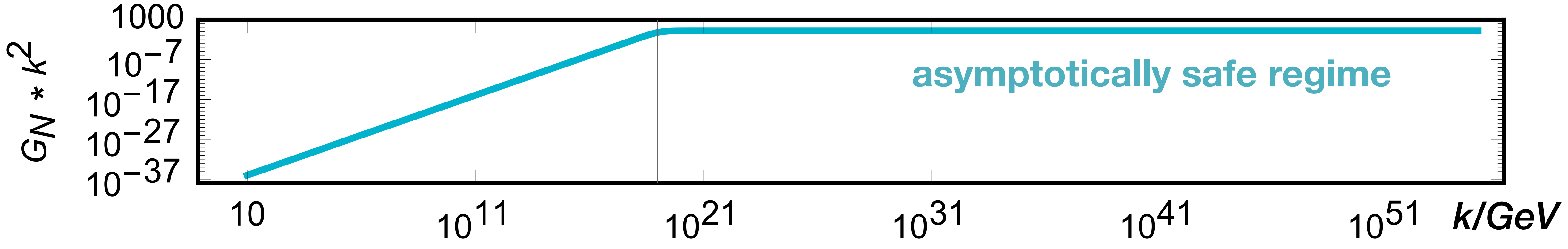

Theoretical evidence for asymptotic safety in gravity:
Fixed point regarded as established (hundreds of papers)

Benedetti, Bonanno, Codello, de Brito, AE, Falls, Ferrero, Gies, Held, Kluth, Knorr, Litim, Ohta, Pawlowski, Percacci, Pereira, Platania, Reichert, Reuter, Saueressig, Schiffer, Wetterich, Yamada, Zanusso…

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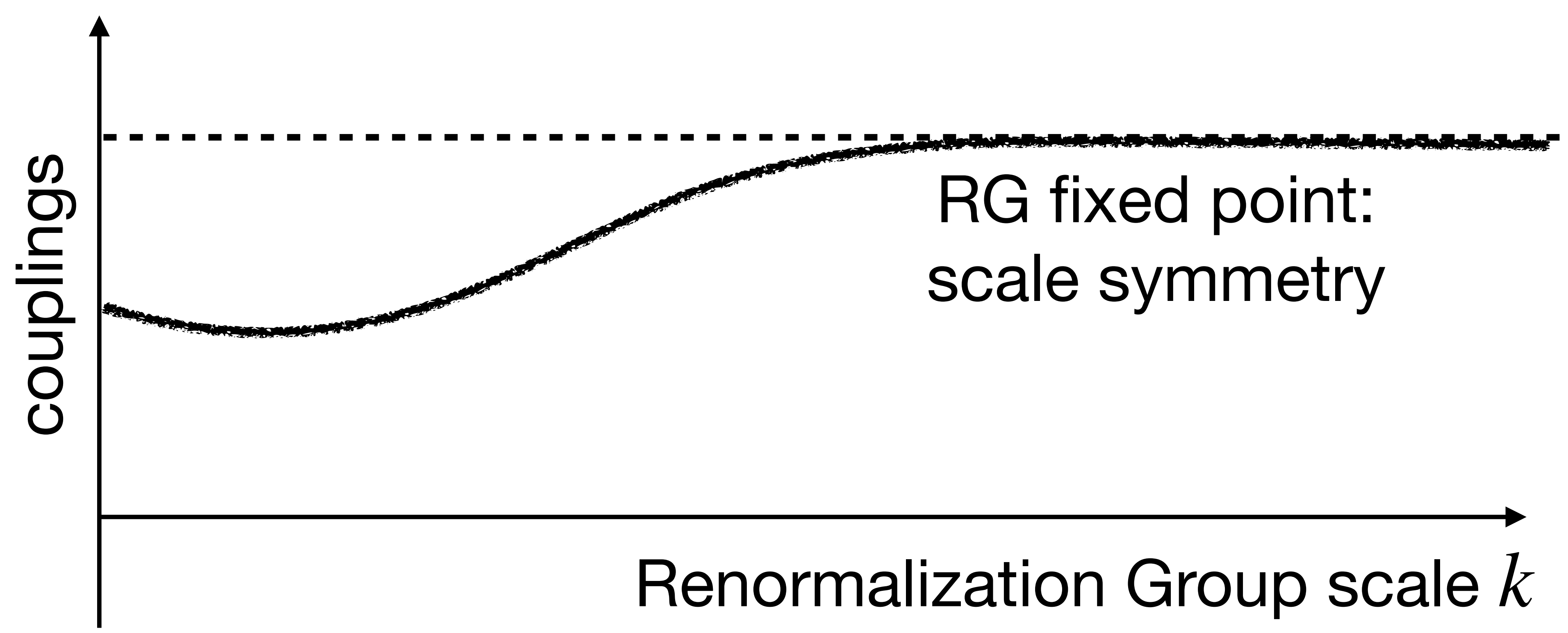

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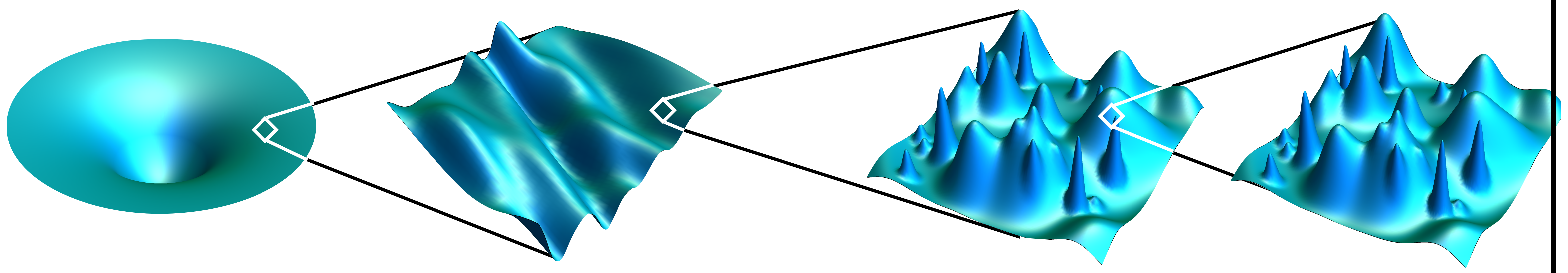

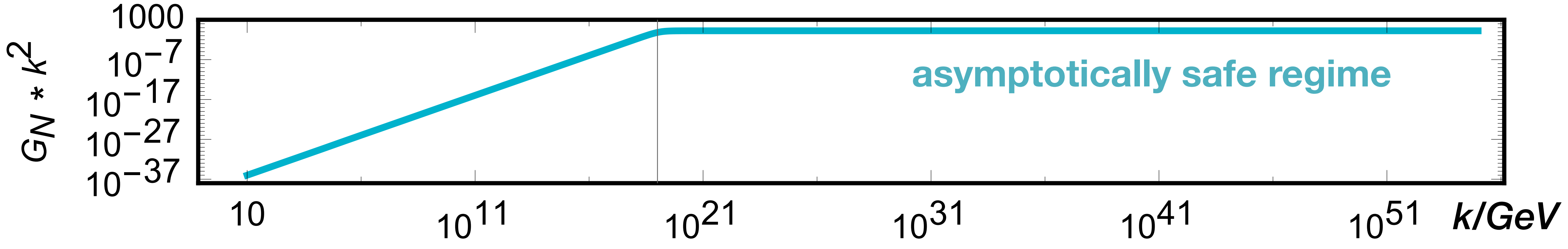

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Open questions: Lorentzian signature, unitarity under investigation
[e.g., Fehre, Litim, Pawlowski, Reichert ’21; Platania ’22; Saueressig, Wang ’23; d’Angelo ’23; Pastor-Guiterrez, Pawlowski, Reichert, Risi ’24; d’Angelo, Ferrero, Fröb ’25]

Predictive power in asymptotic safety

Origin of predictions at the Planck scale

Quantum fluctuations
screen or antiscreen interactions, e.g.,

QED: $\beta_e = k\,\partial_k\,e(k) = \frac{1}{12\pi^2}e^3 + \ldots$

$\rightarrow e(k)$ decreases as k is lowered

QCD: $\beta_g = k\,\partial_k\,g(k) = -\frac{7}{16\pi^2}g^3 + \ldots$

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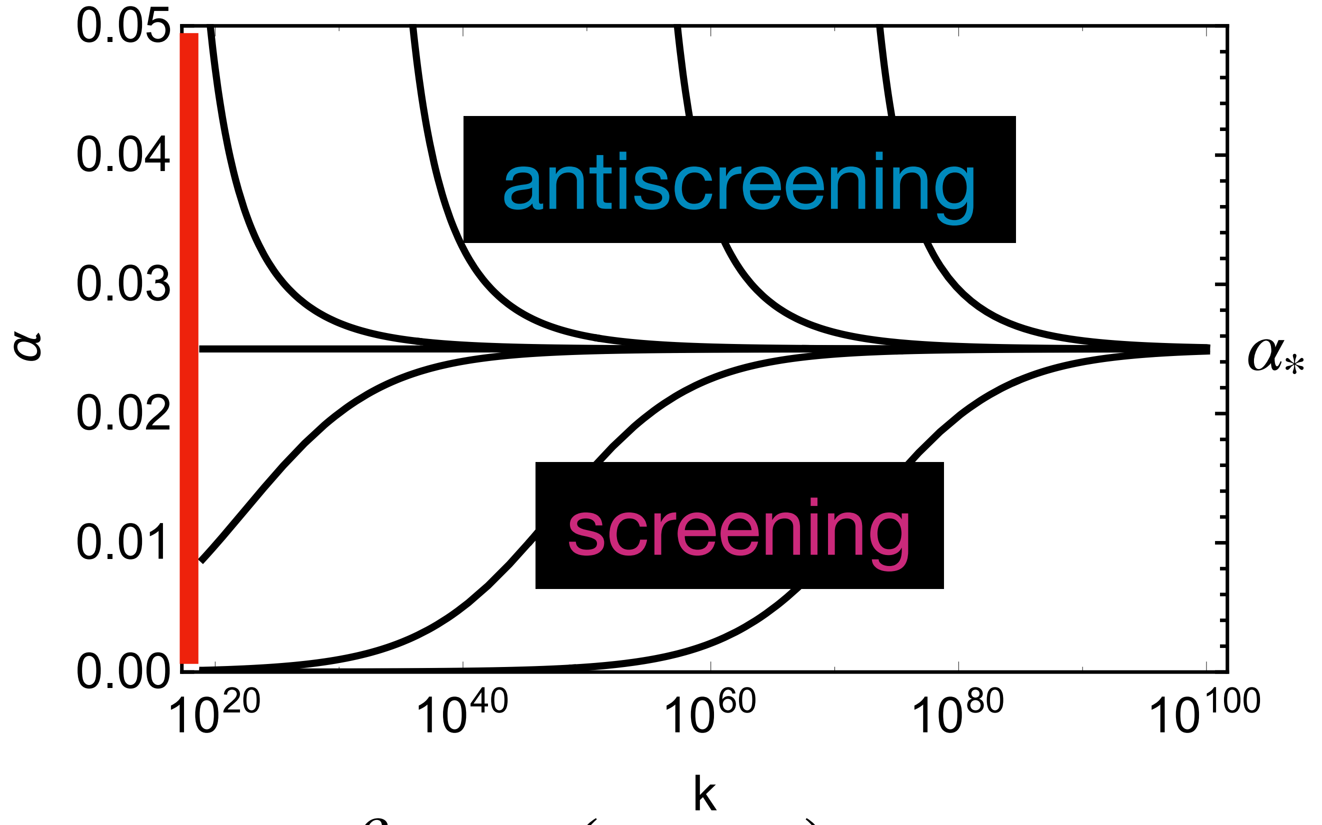

$\beta_\alpha = \alpha\,(\alpha_* - \alpha)$

quantum fluctuations drive coupling **away from** scale symmetry

→ a range of coupling values achievable at the Planck scale

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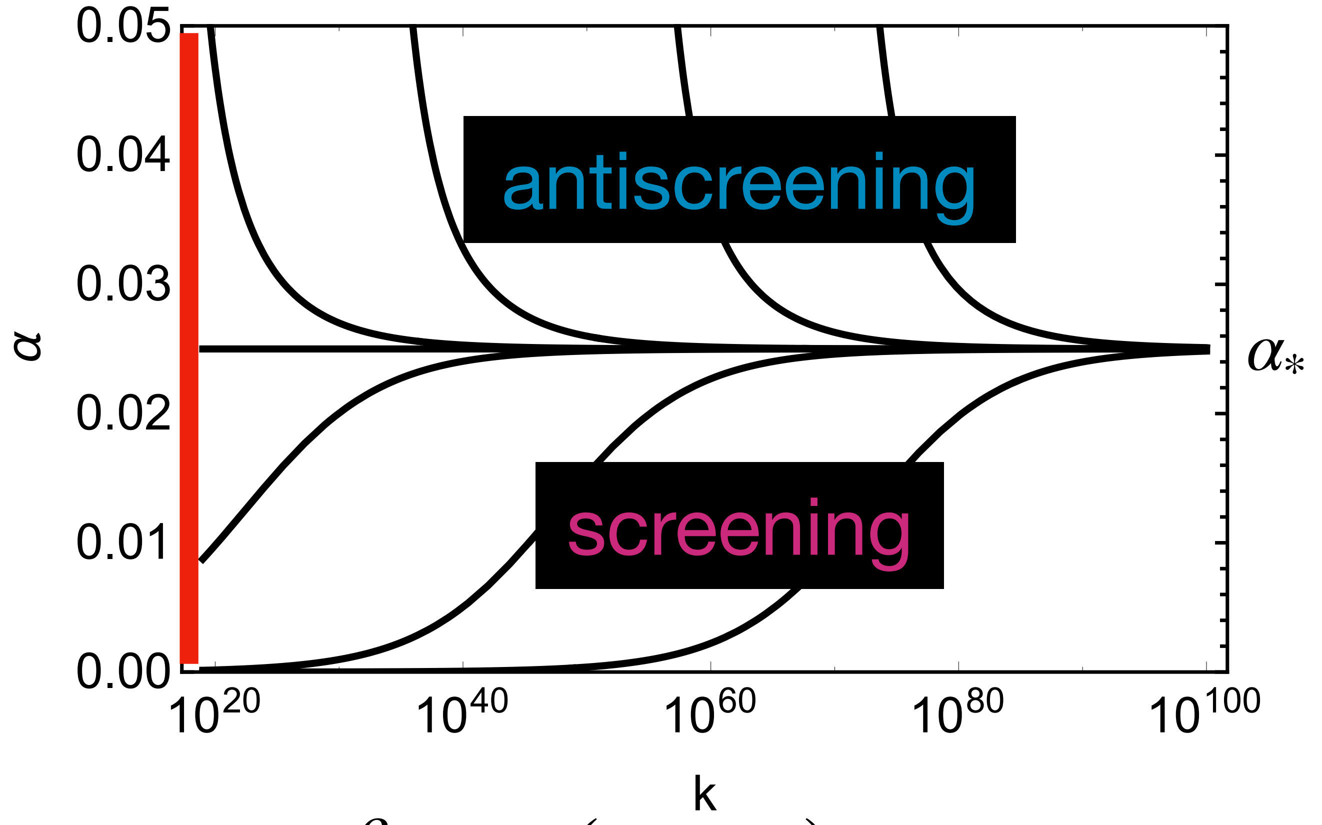

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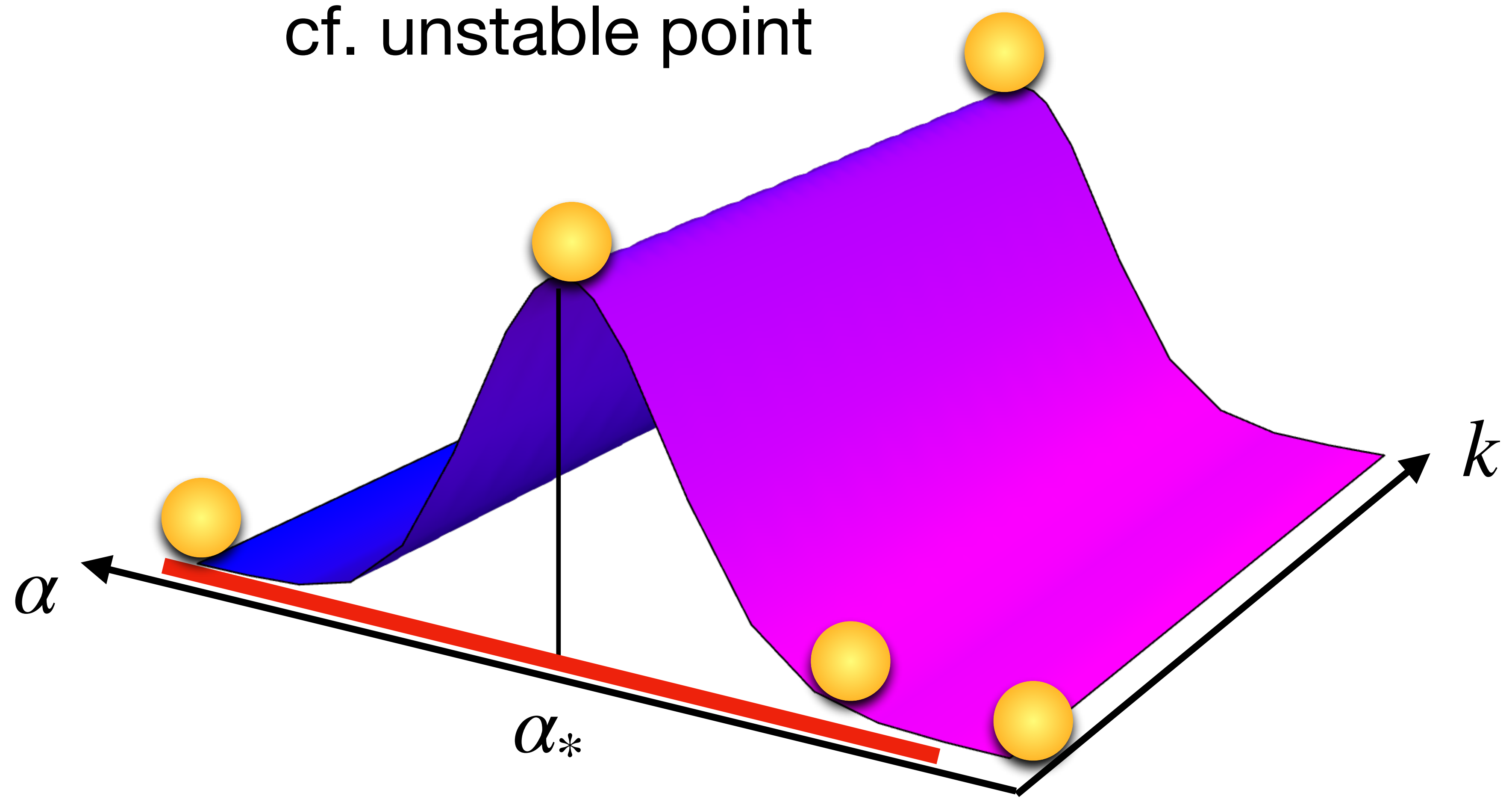

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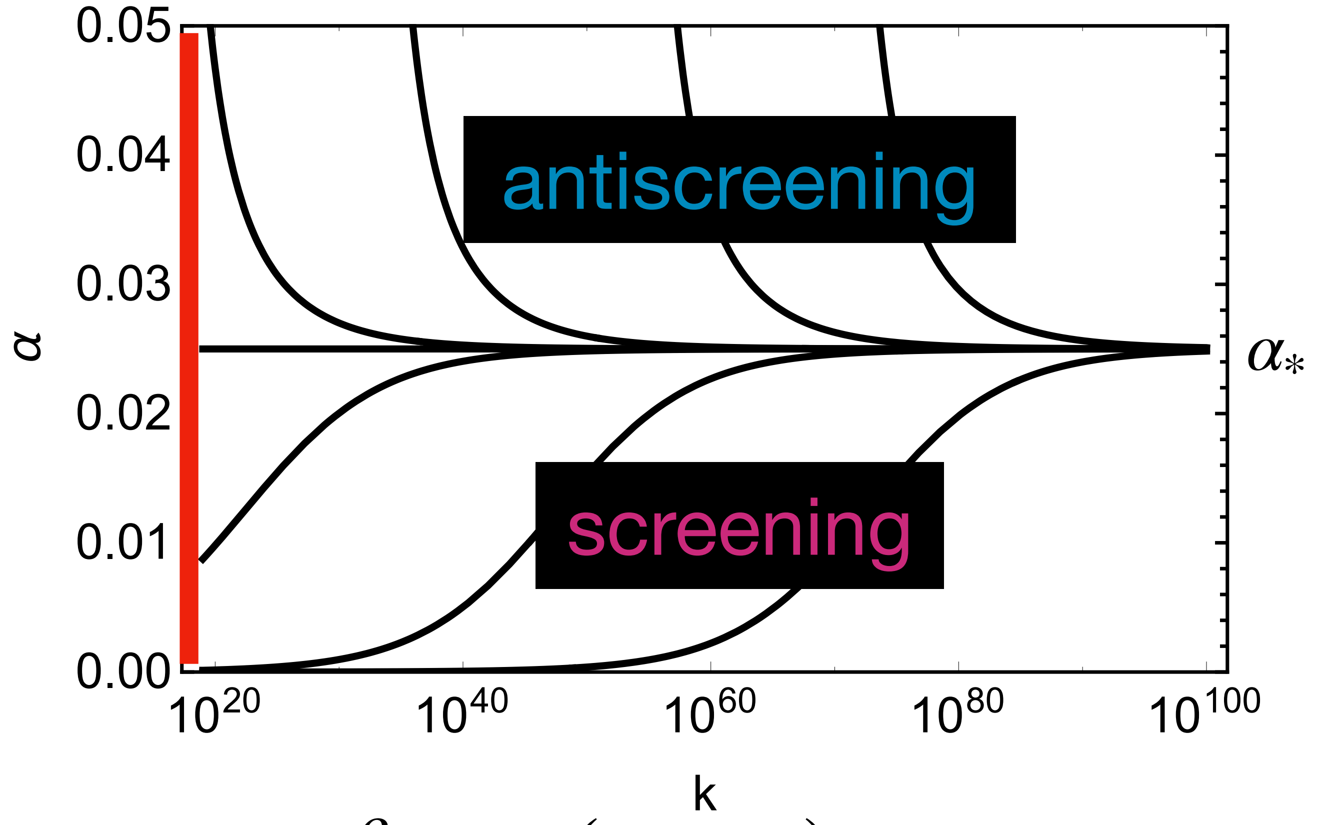

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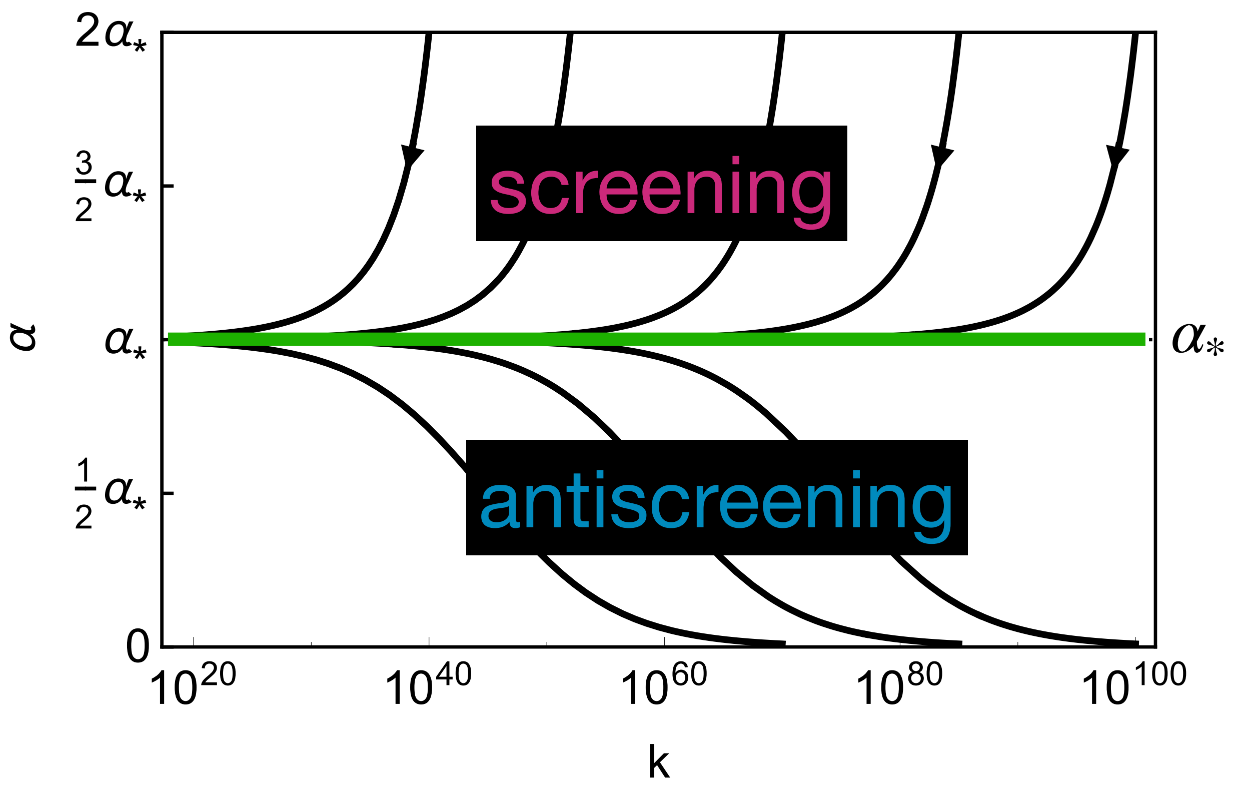

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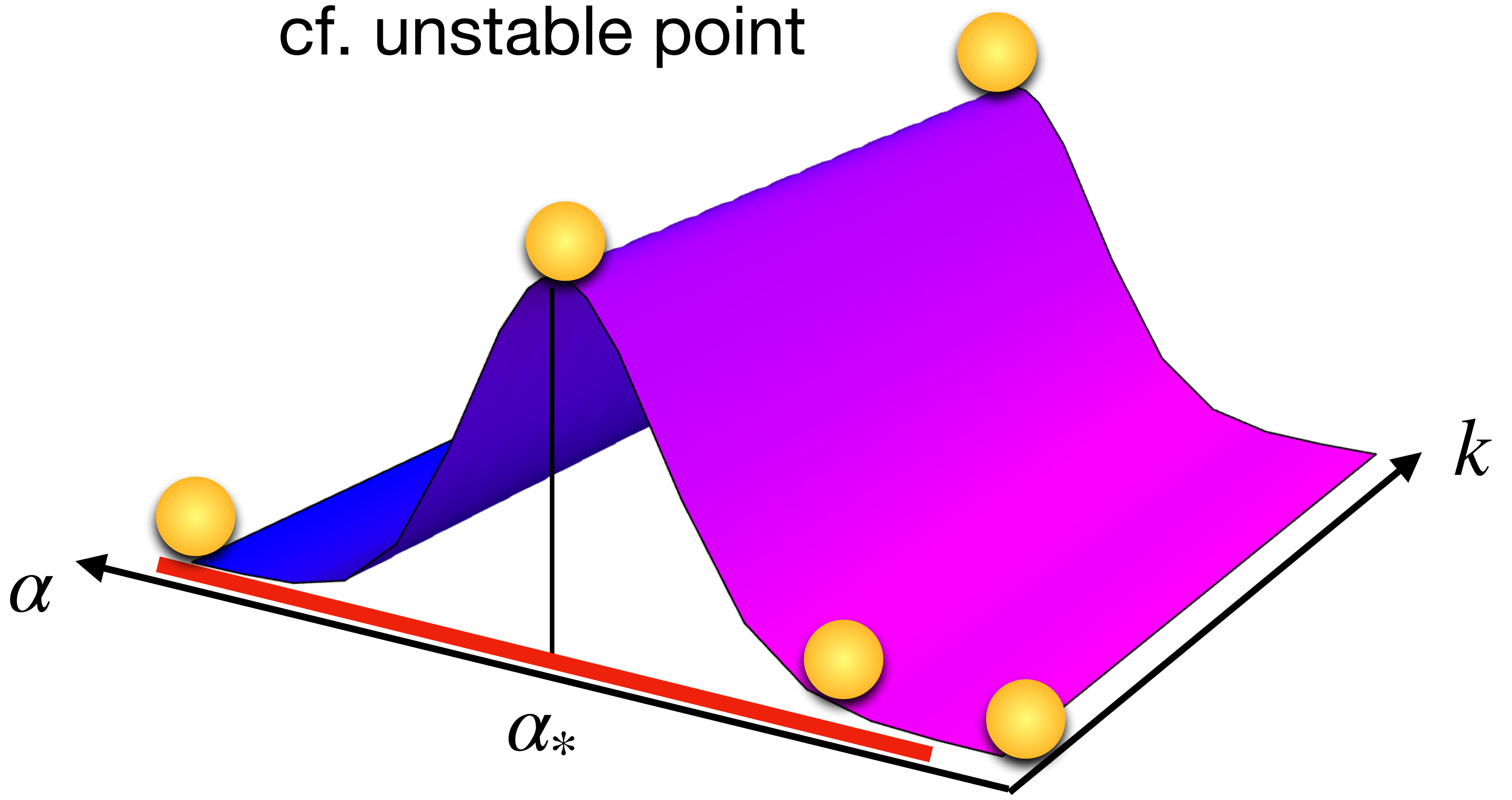

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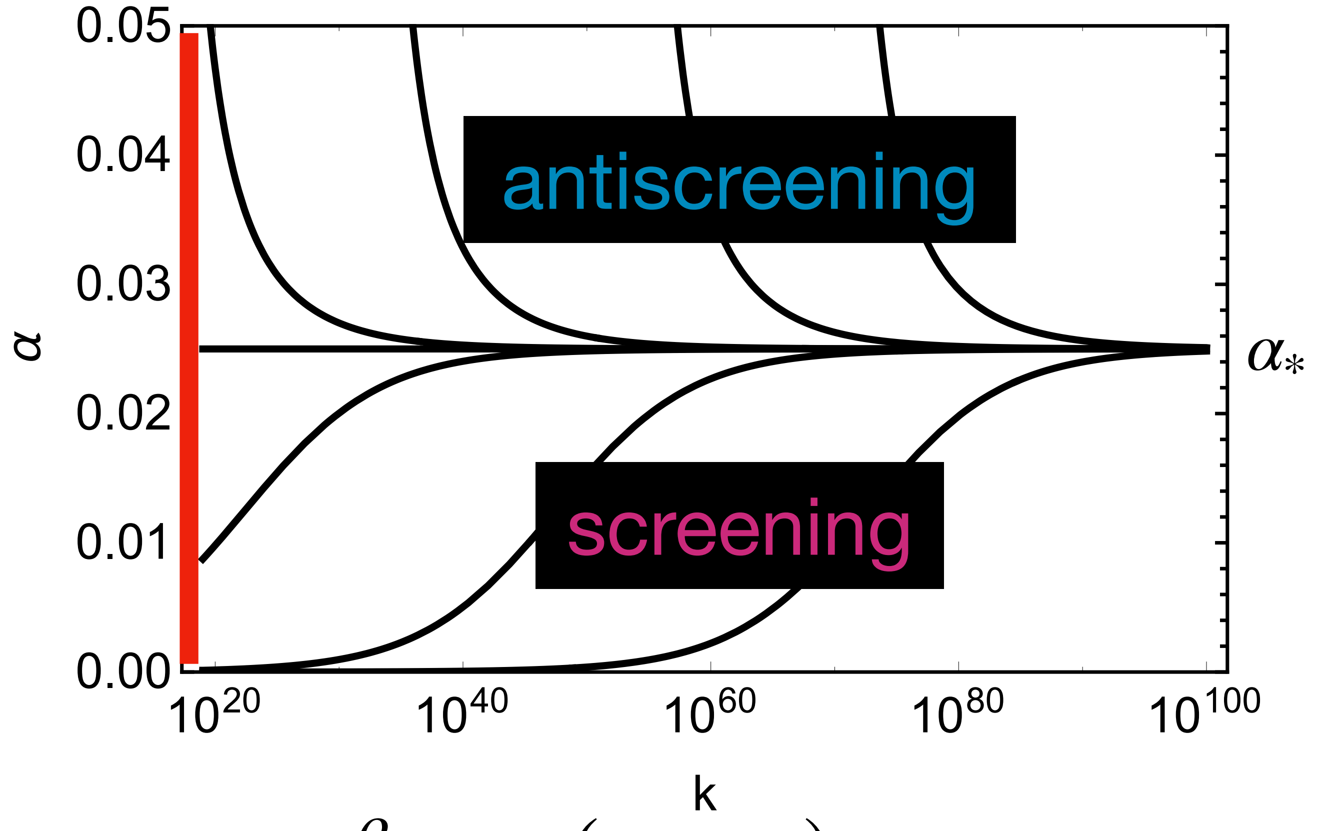

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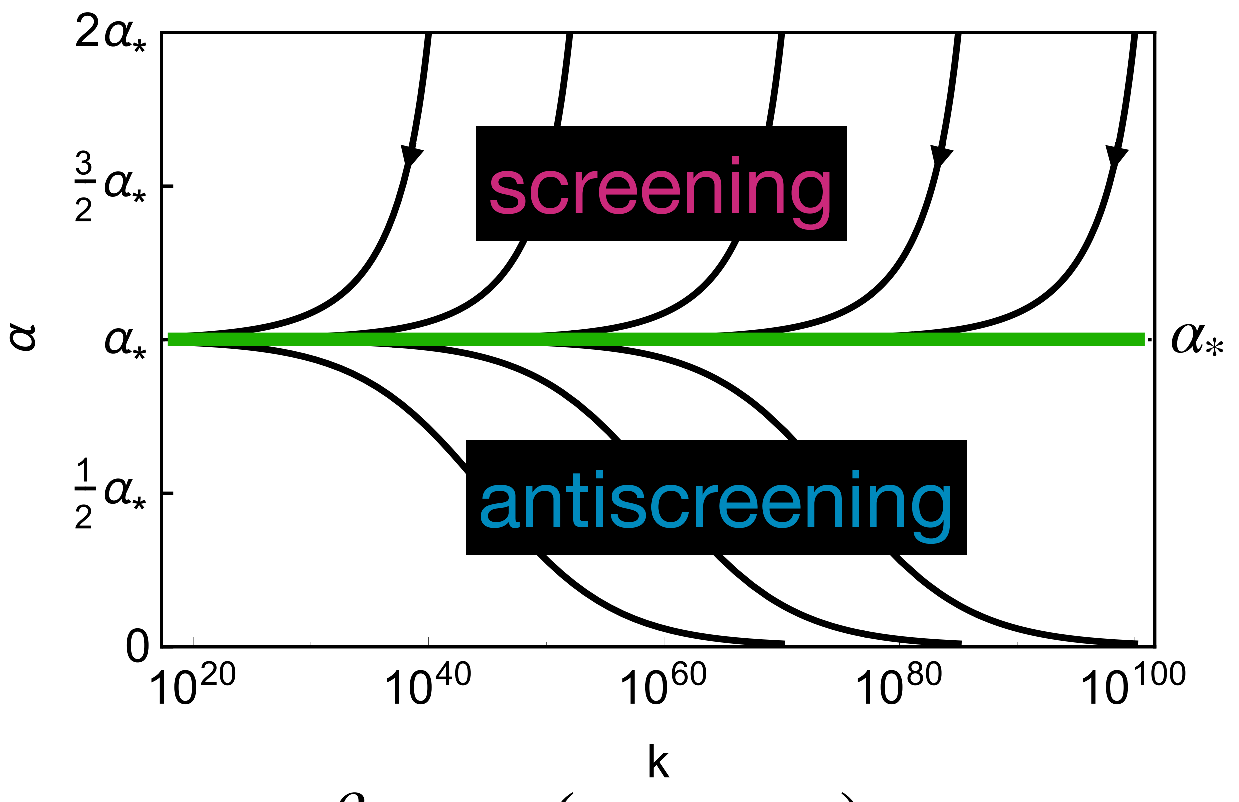

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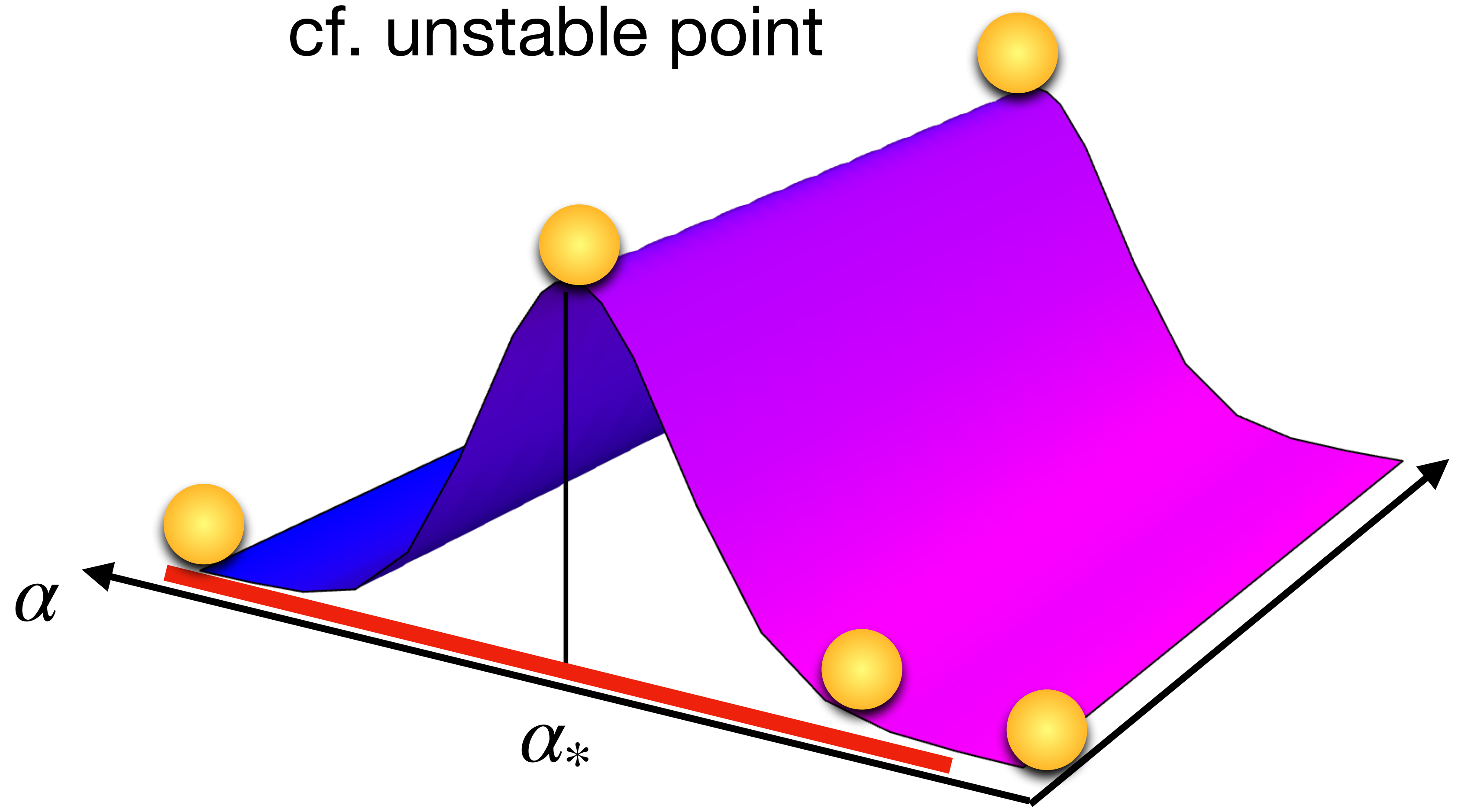

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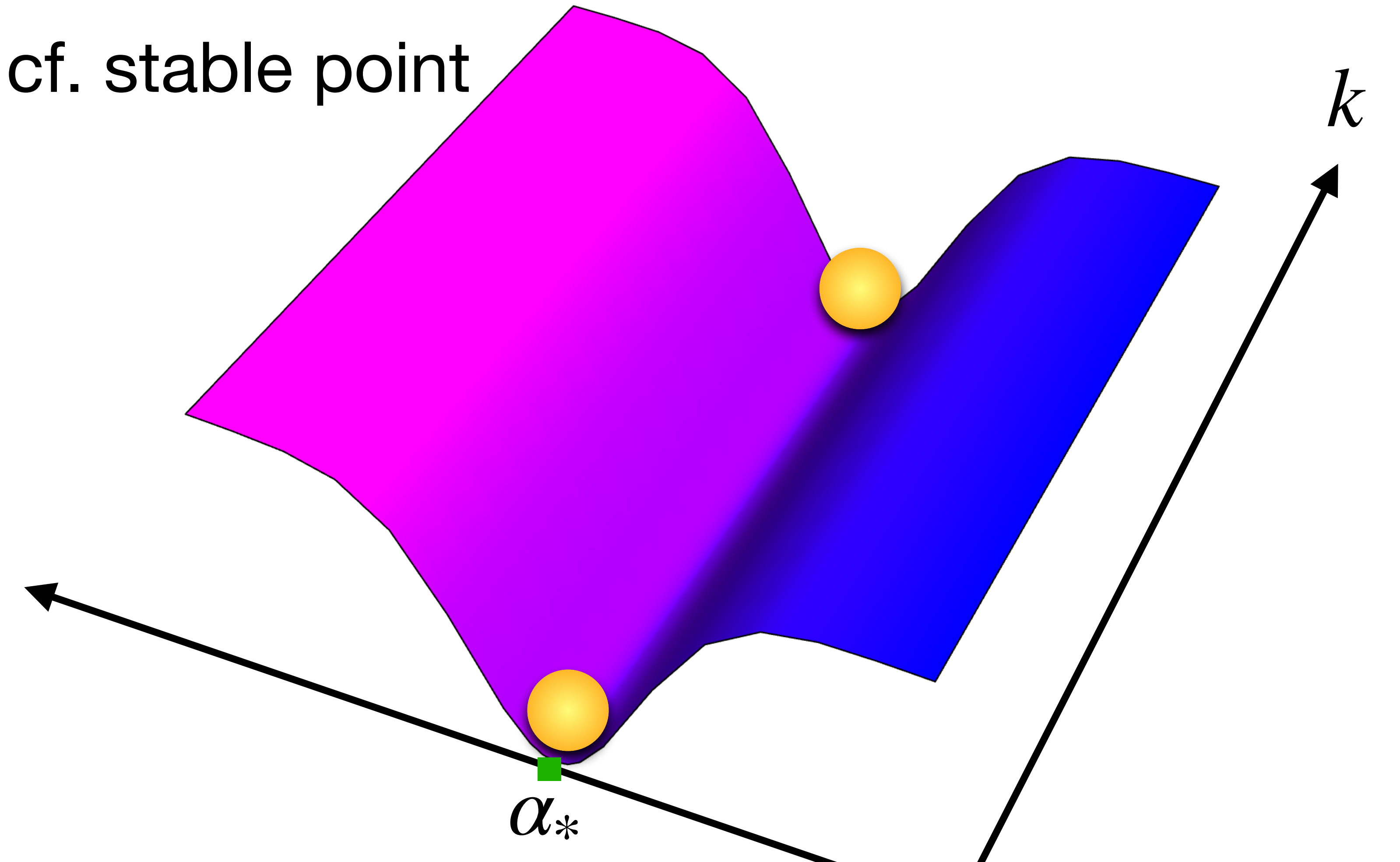

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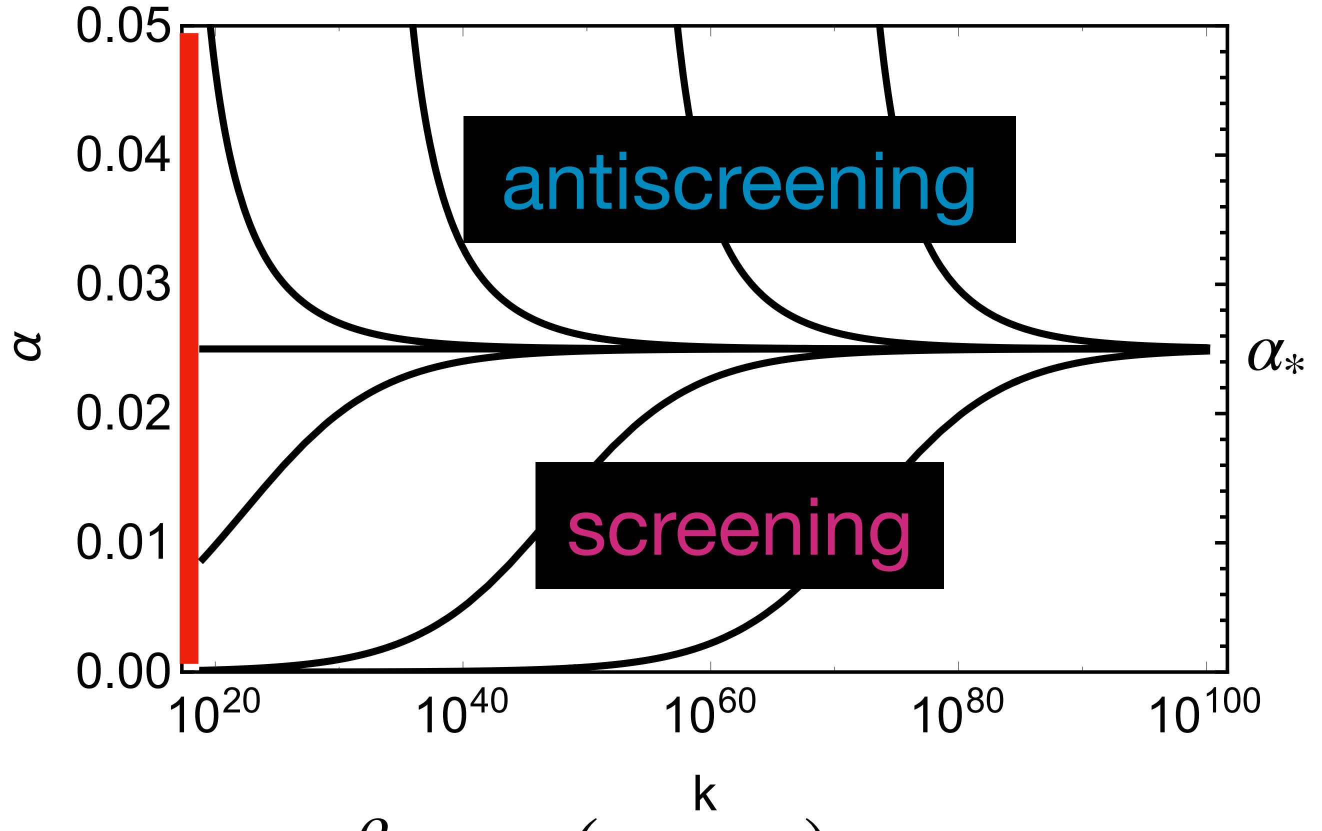

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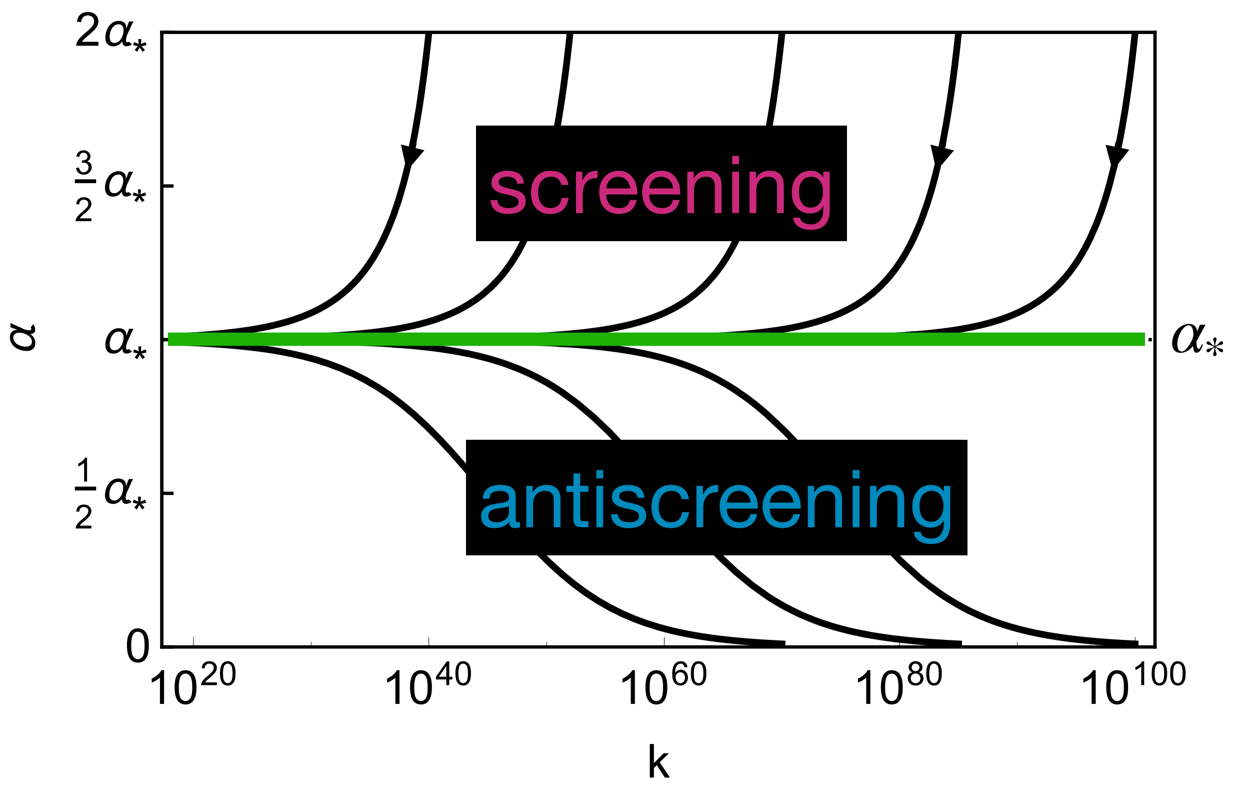

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[Benedetti, Machado, Saueressig ’09; Falls, Litim, et al. ’13, ’14; Denz, Pawlowski, Reichert ’16; Falls, Ohta, Percacci ’20]

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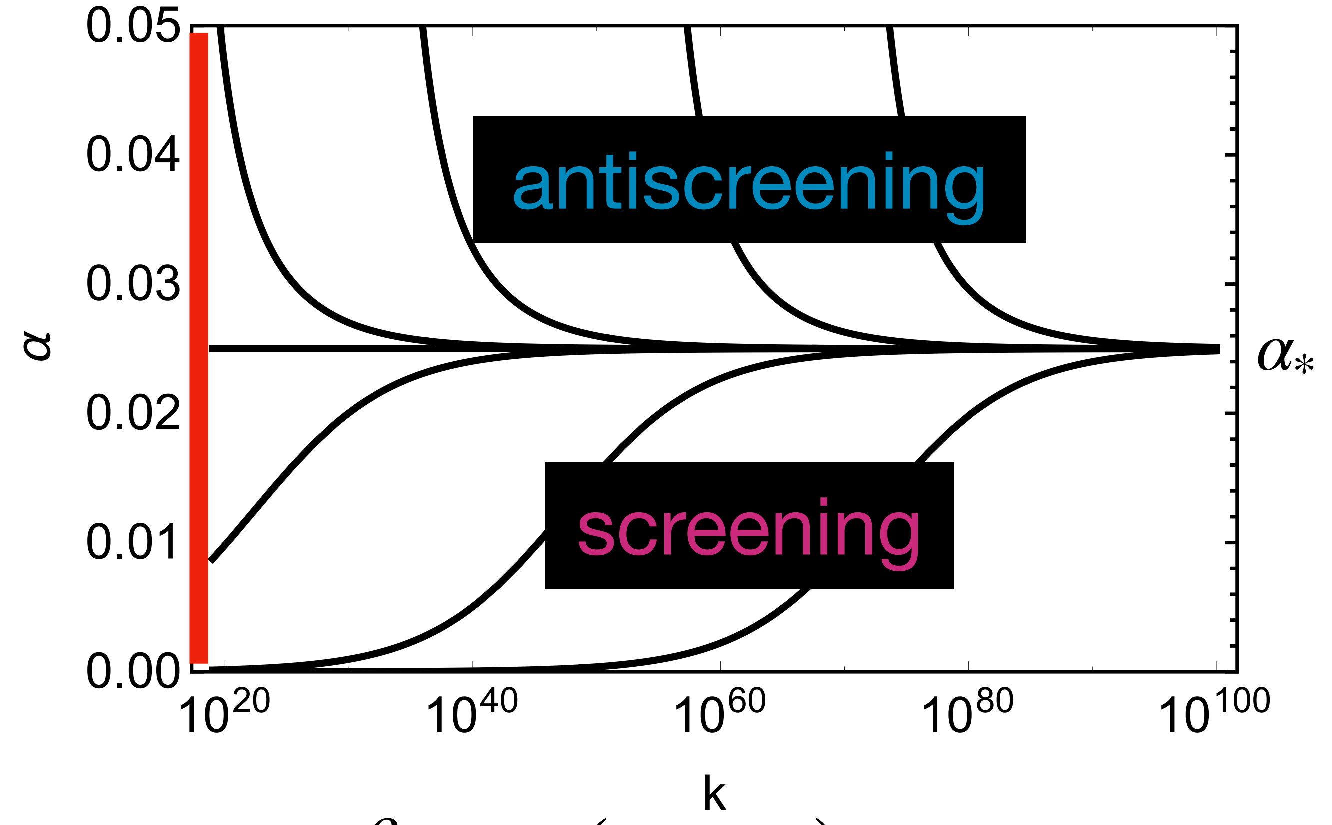

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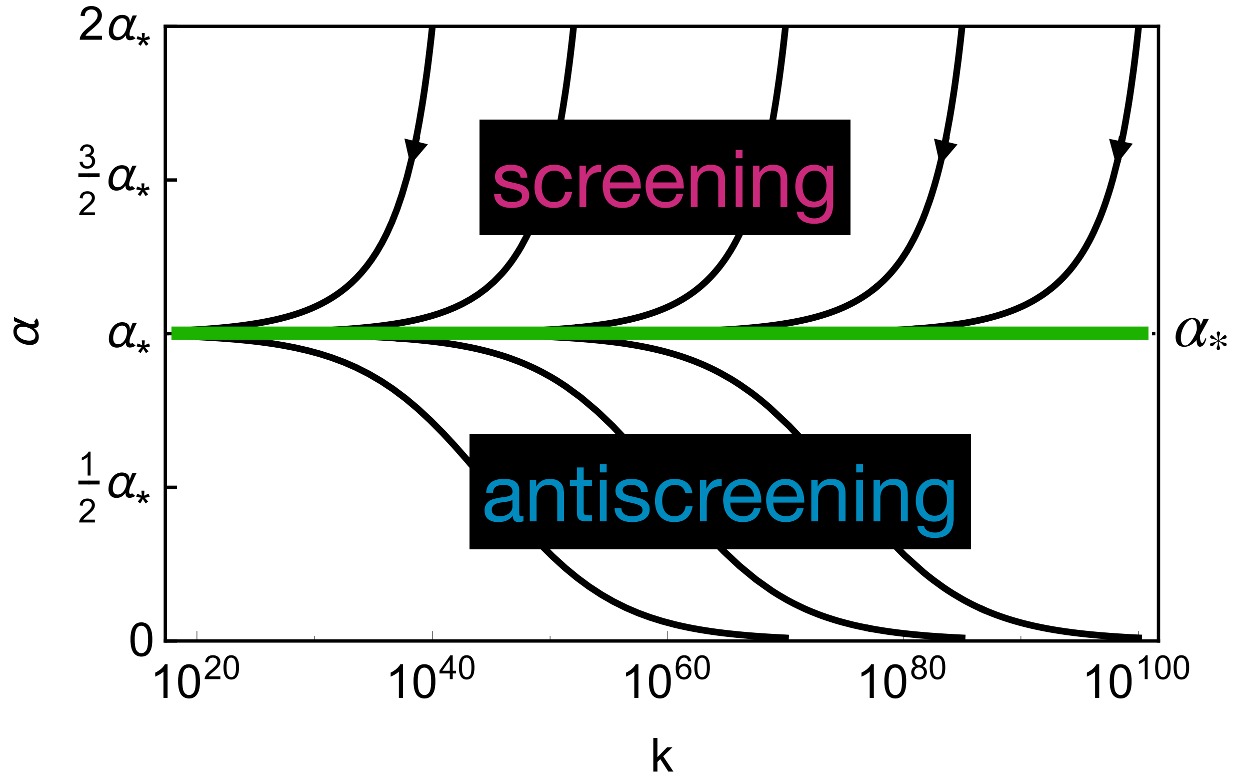

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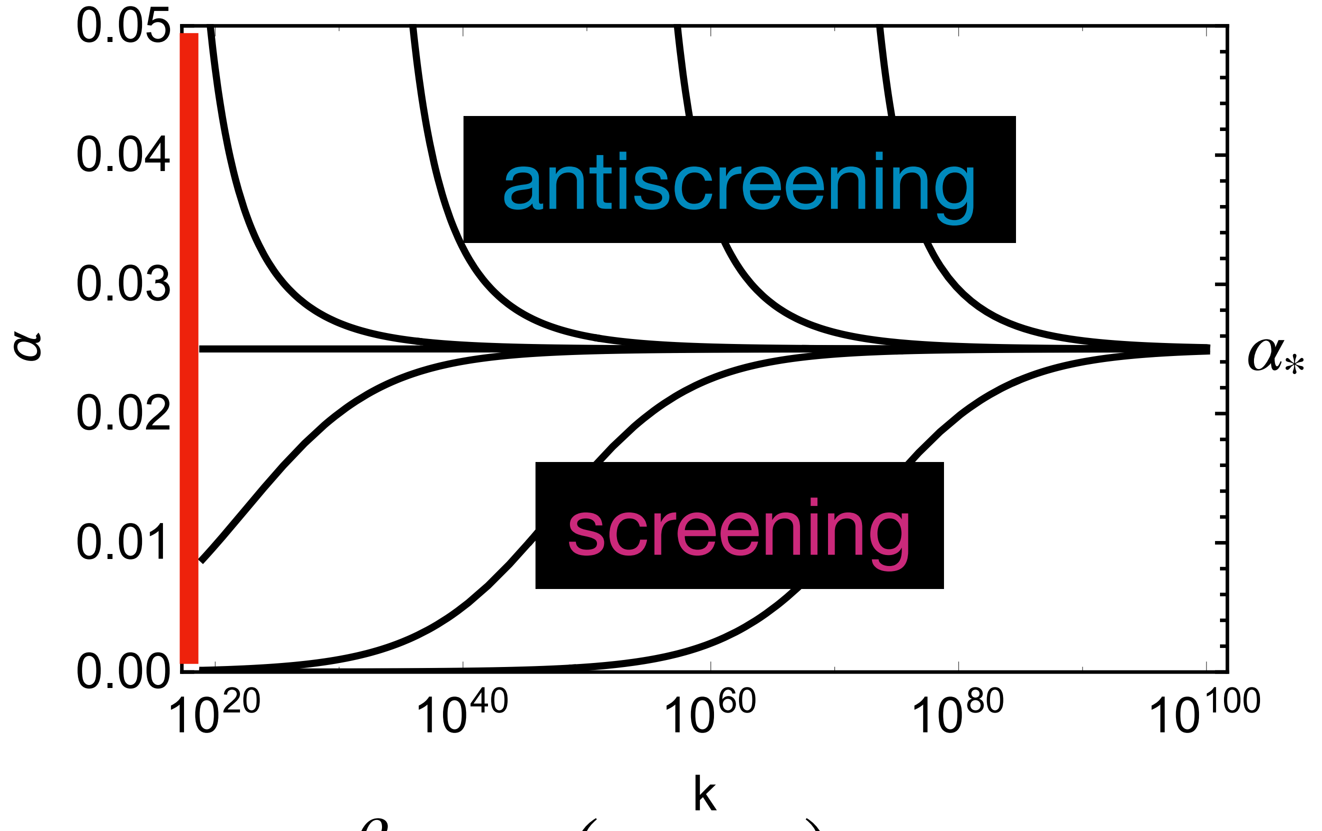

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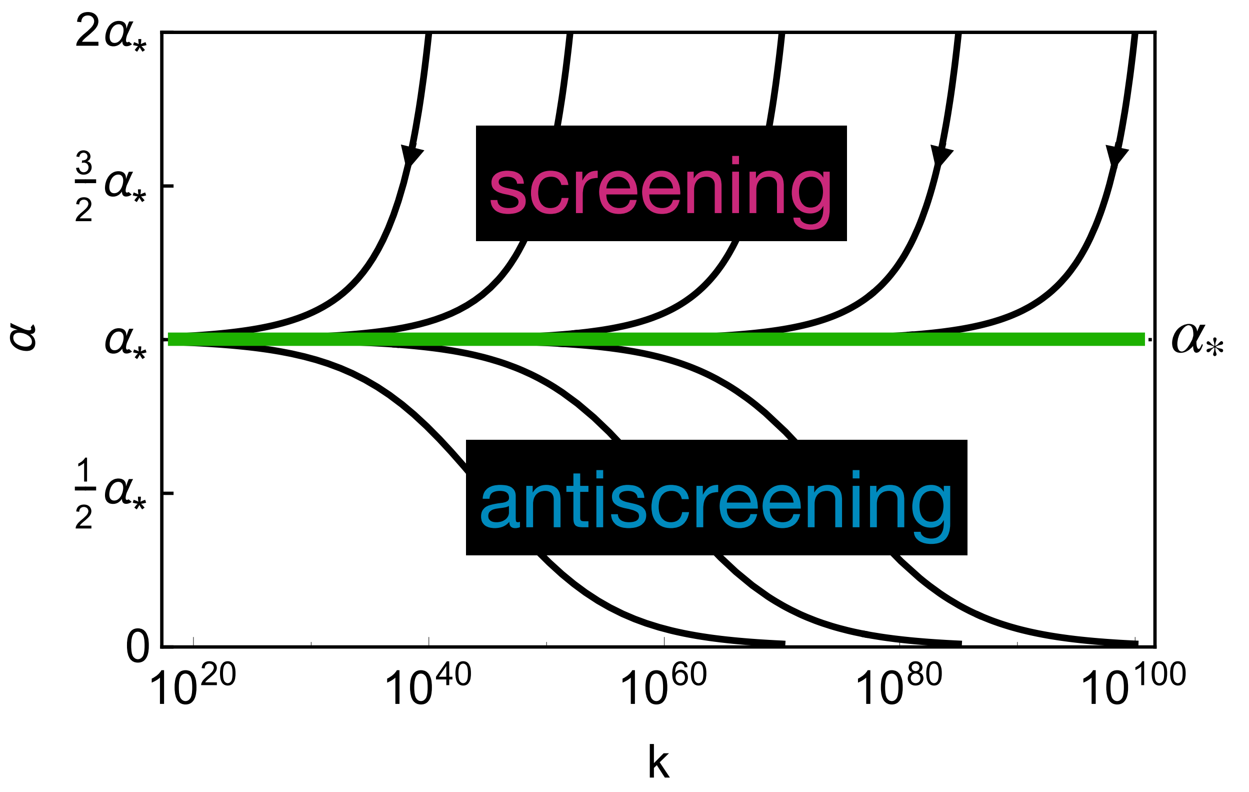


$\beta_\alpha = \alpha\,(-\alpha_* + \alpha)$

quantum fluctuations drive coupling **towards** scale symmetry

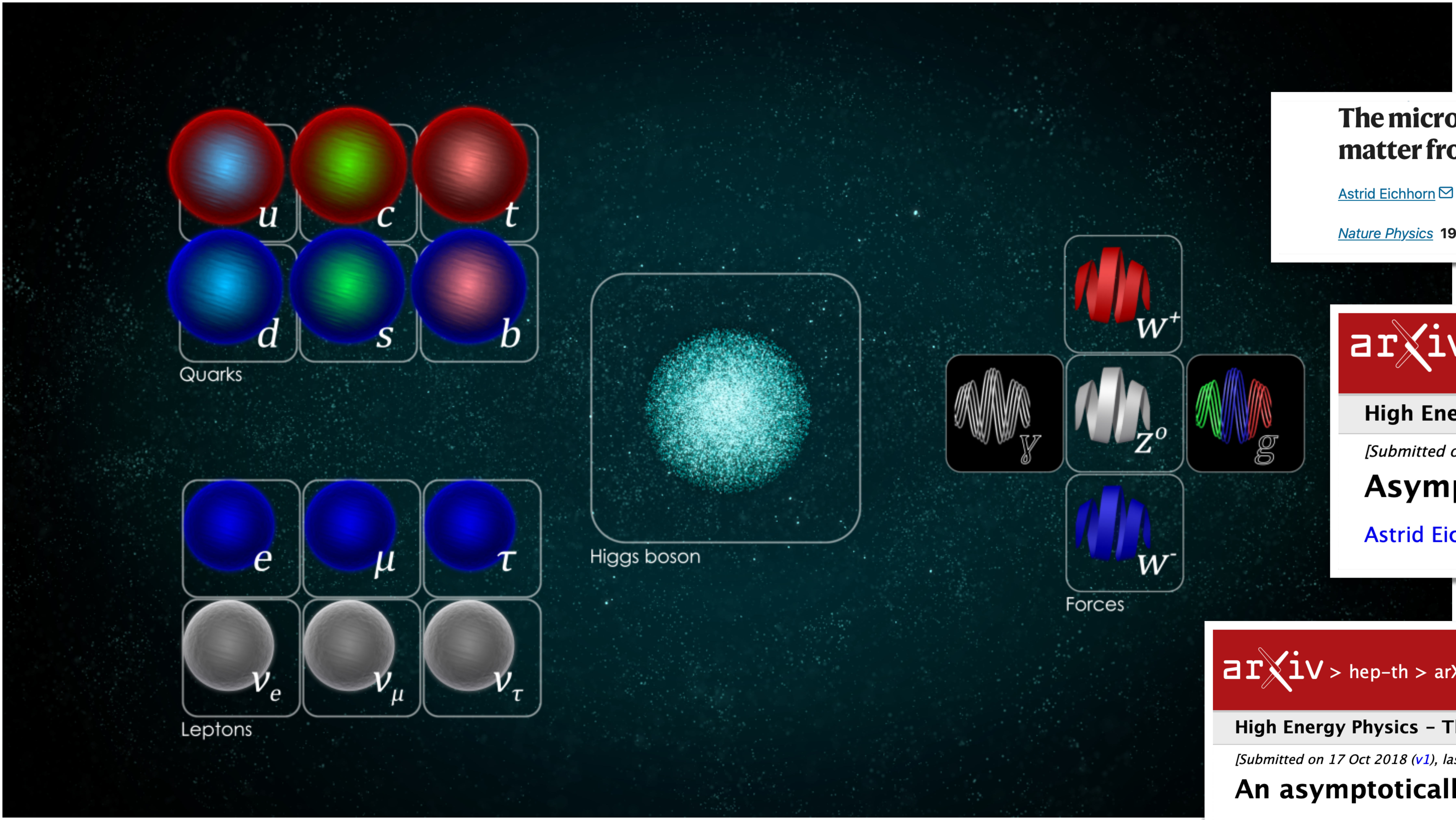
$\rightarrow$ a unique coupling value predicted at the Planck scale

for gravity: $\sqrt{-g}\,\Lambda,\ \sqrt{-g}\,R\,\frac{1}{16\pi G_N},\ \sqrt{-g}\,(R^2 + \#R_{\mu\nu}R^{\mu\nu})\,a$ all other couplings

[Benedetti, Machado, Saueressig ’09; Falls, Litim, et al. ’13, ’14; Denz, Pawlowski, Reichert ’16; Falls, Ohta, Percacci ’20]

for matter: rest of this talk!

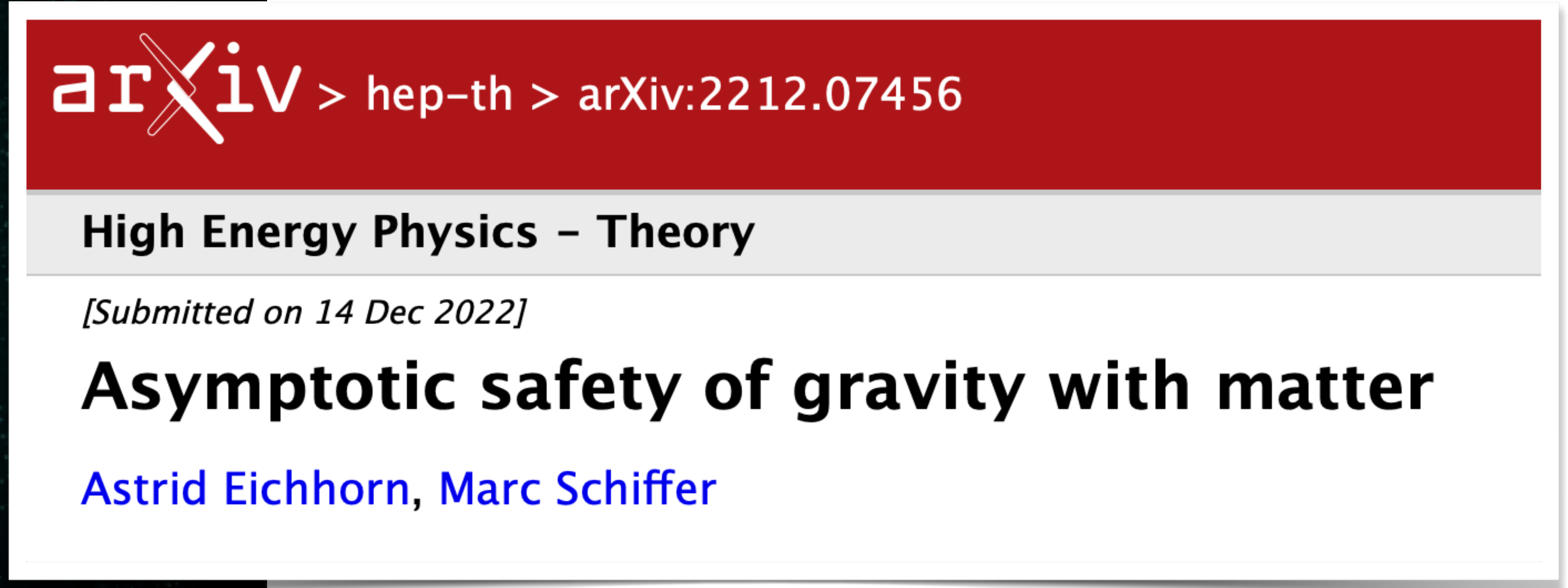
Standard Model couplings



The microscopic structure of quantum space-time and matter from a renormalization group perspective

Astrid Eichhorn

Nature Physics **19**, 1527–1529 (2023) | Cite this article



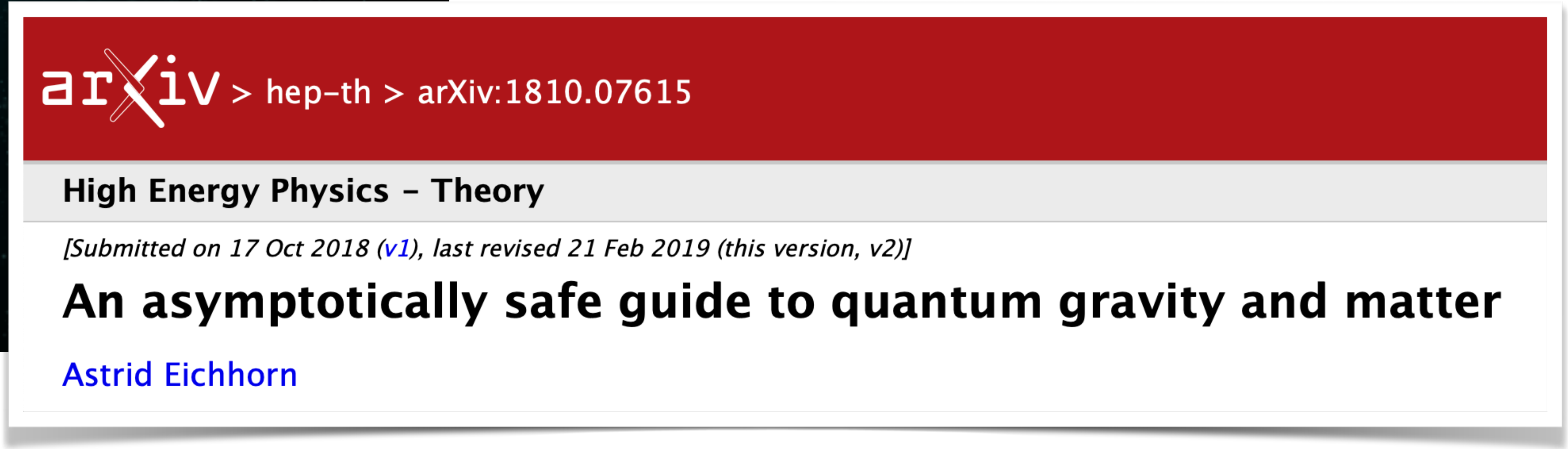
arXiv > hep-th > arXiv:2212.07456

High Energy Physics – Theory

[Submitted on 14 Dec 2022]

Asymptotic safety of gravity with matter

Astrid Eichhorn, Marc Schiffer



arXiv > hep-th > arXiv:1810.07615

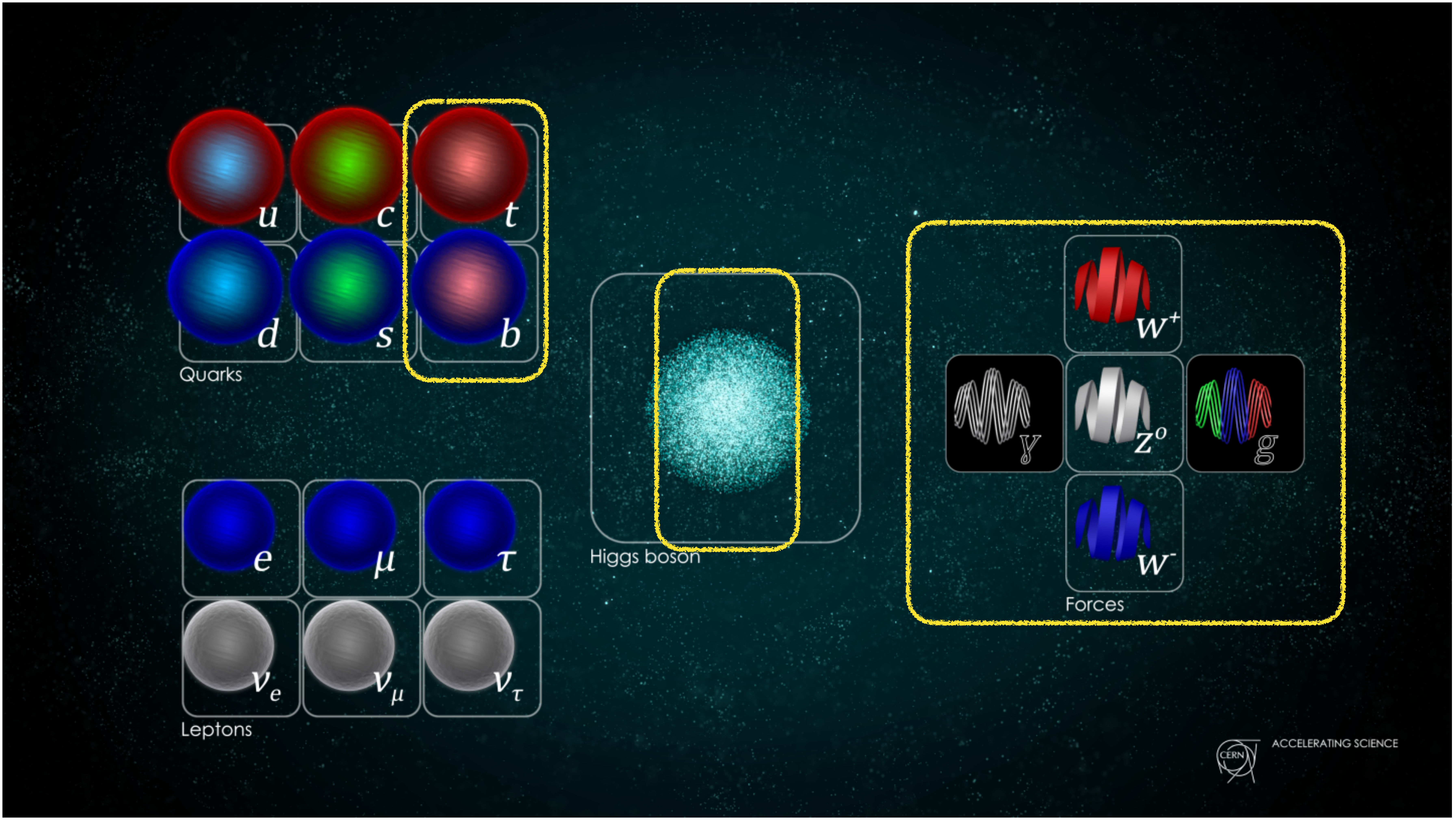
High Energy Physics – Theory

[Submitted on 17 Oct 2018 (v1), last revised 21 Feb 2019 (this version, v2)]

An asymptotically safe guide to quantum gravity and matter

Astrid Eichhorn

Standard Model couplings



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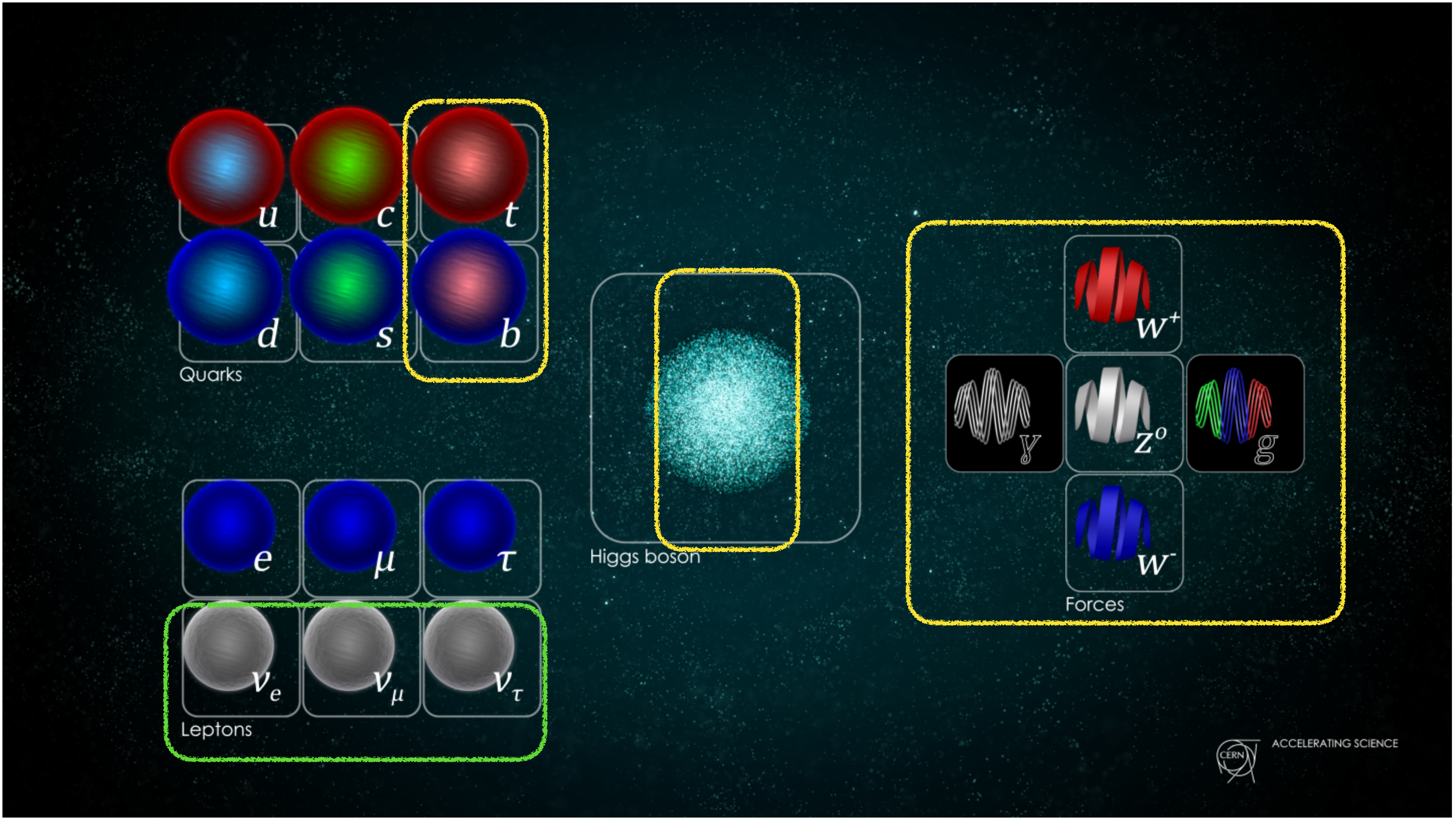
“heavy” Standard Model

[Harst, Reuter ’11; Shaposhnikov, Wetterich ’09, AE, Held ’17, ‘18, AE, Versteegen ’17]

Standard Model couplings



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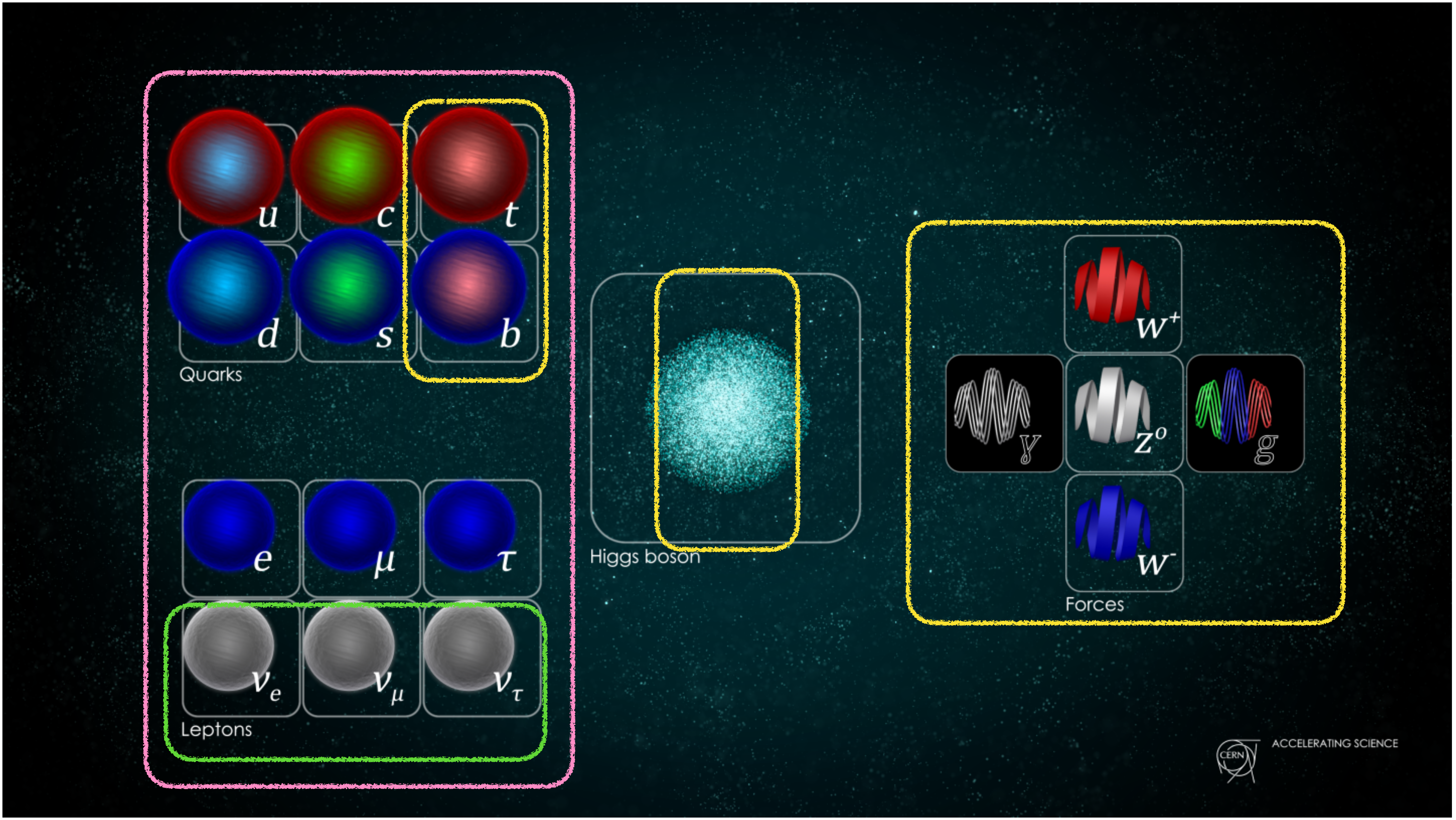

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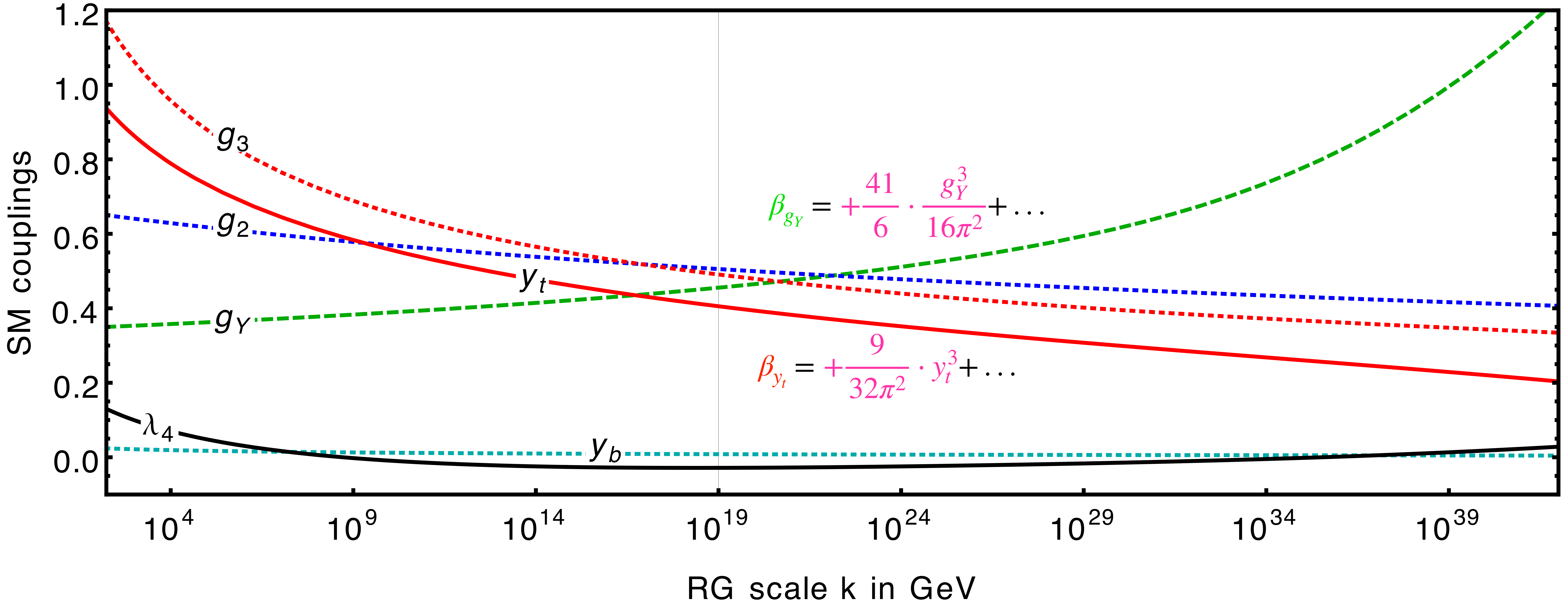

without gravity:

- not ultraviolet complete (Landau pole/triviality problem)
- measured values are free parameters

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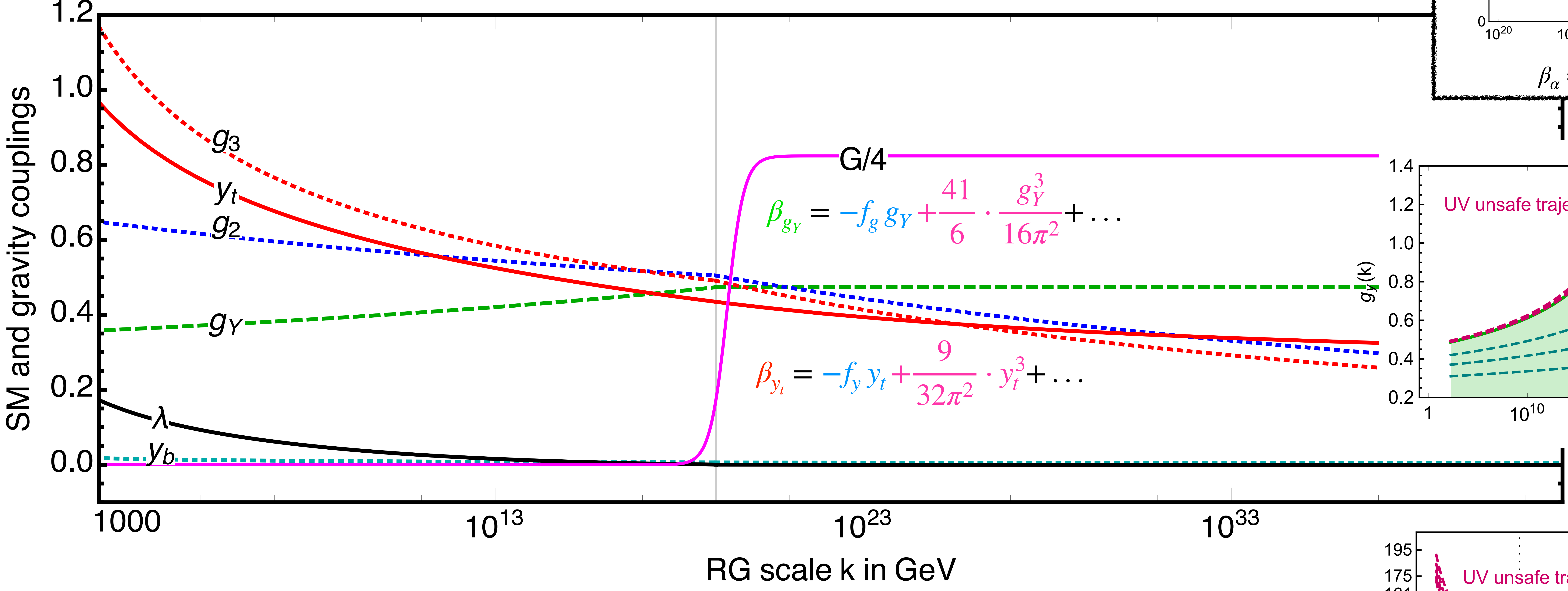
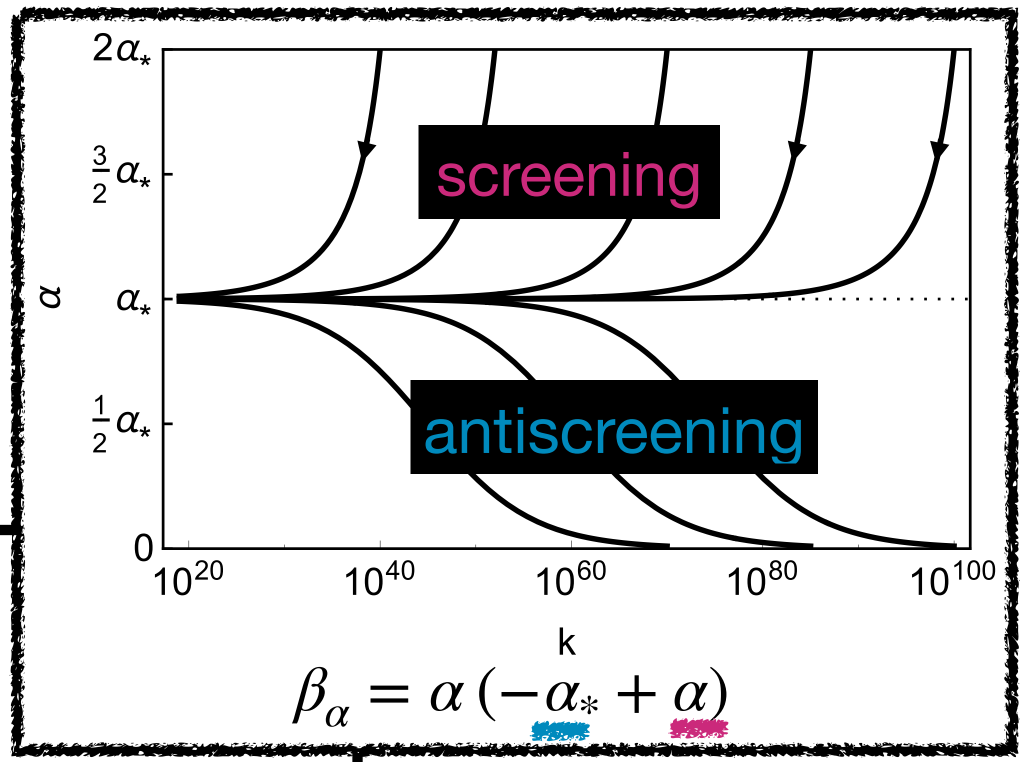
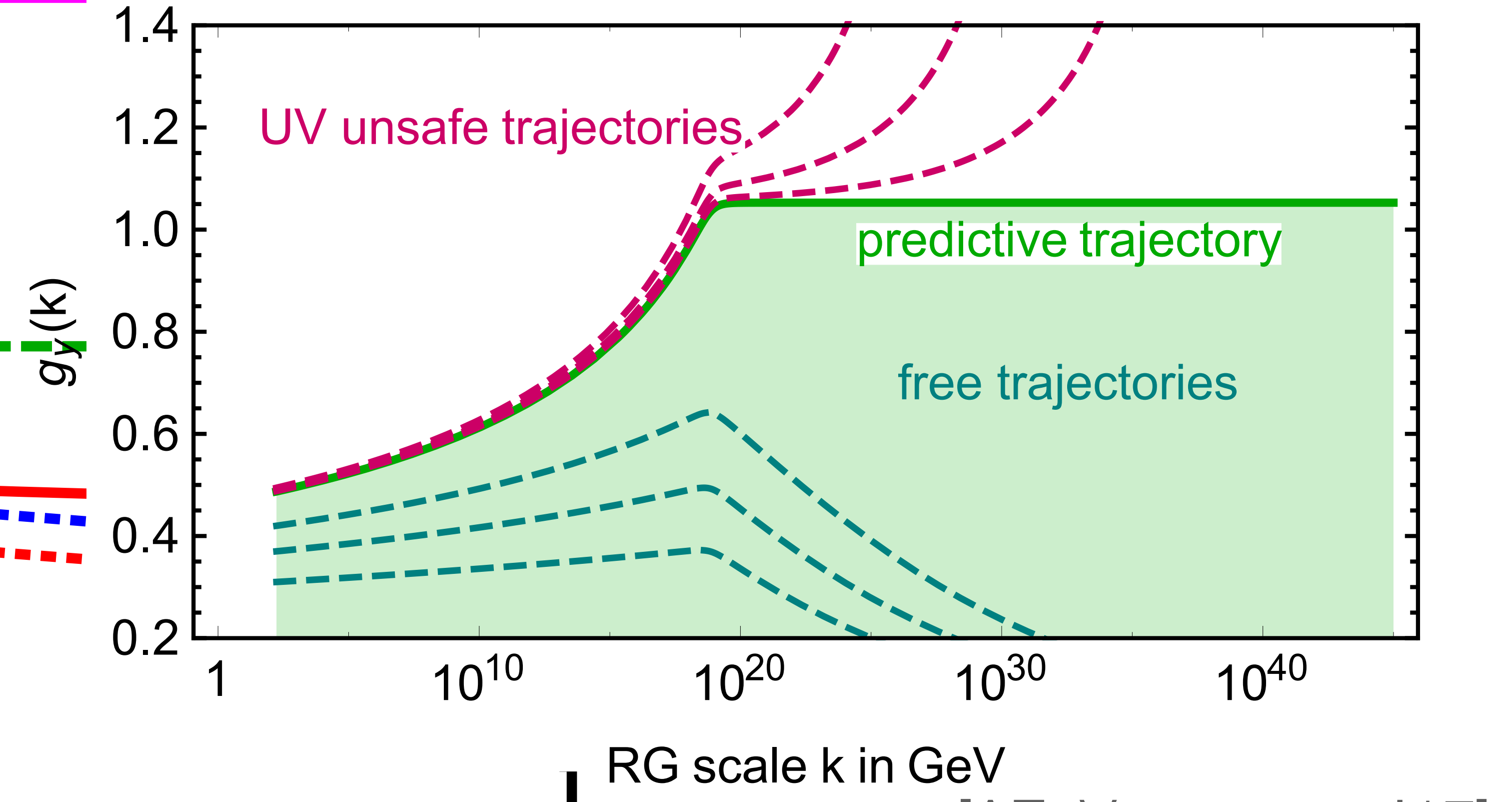
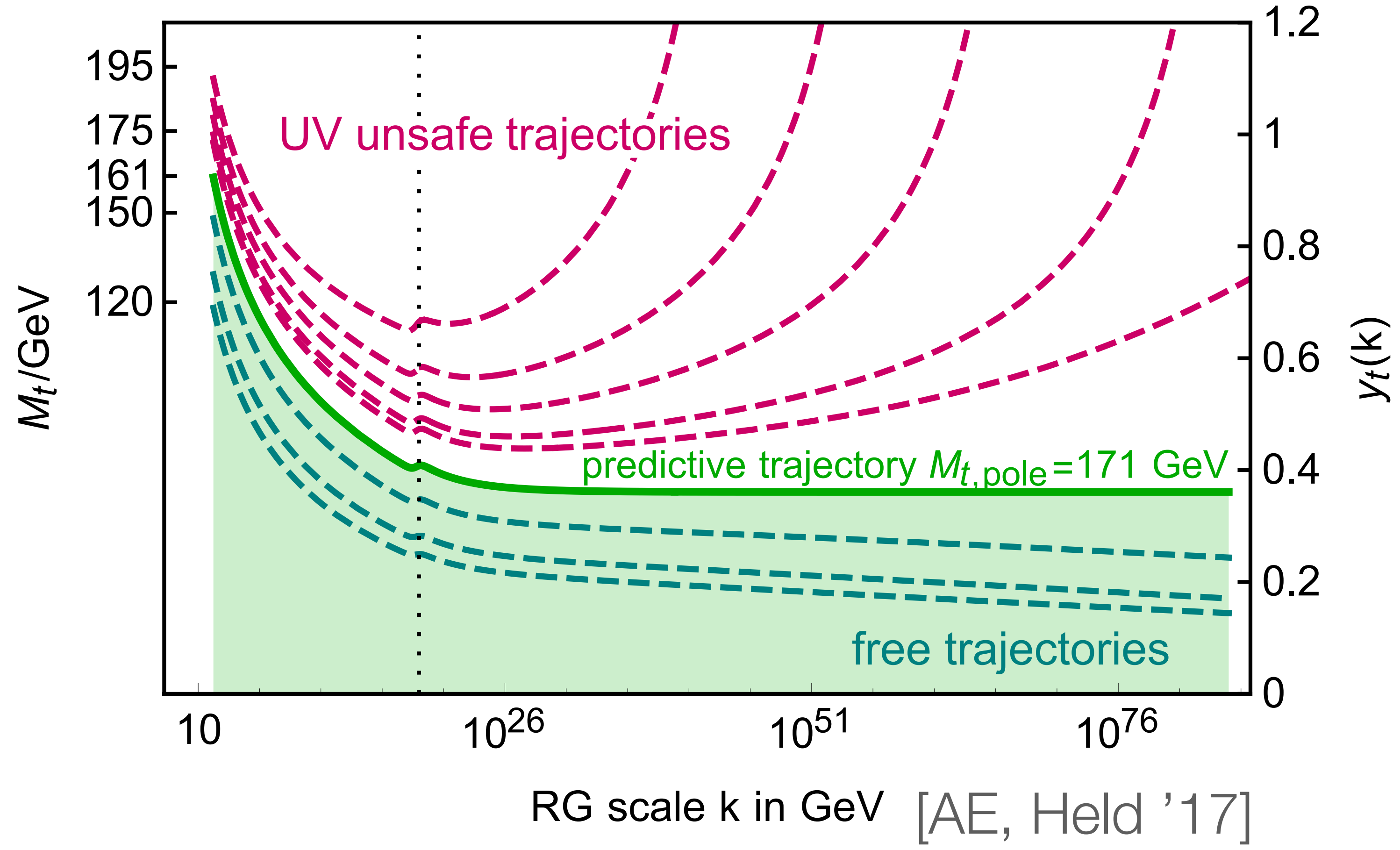






[AE, Versteegen '17]



[AE, Held '17]

with gravity:

- ultraviolet complete (no Landau pole/triviality problem)
- y_t and g_Y are bounded from above

& can be constant above Planck scale for appropriate f_g, f_y

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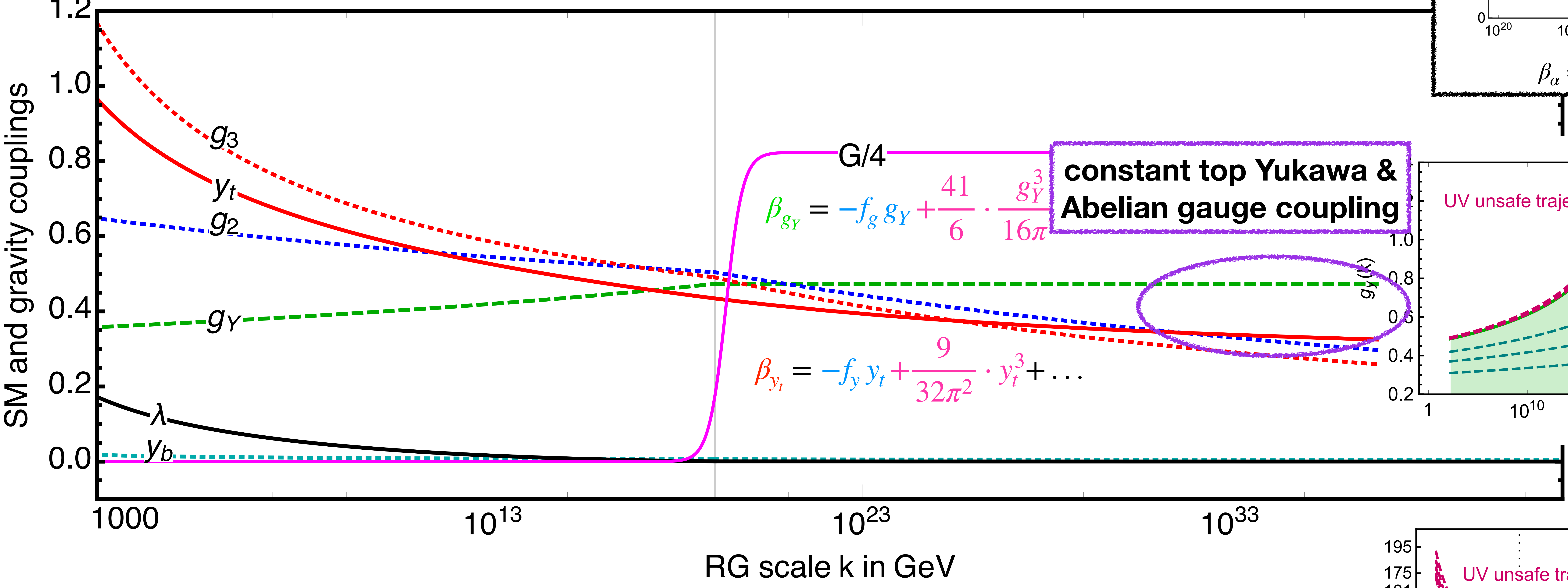

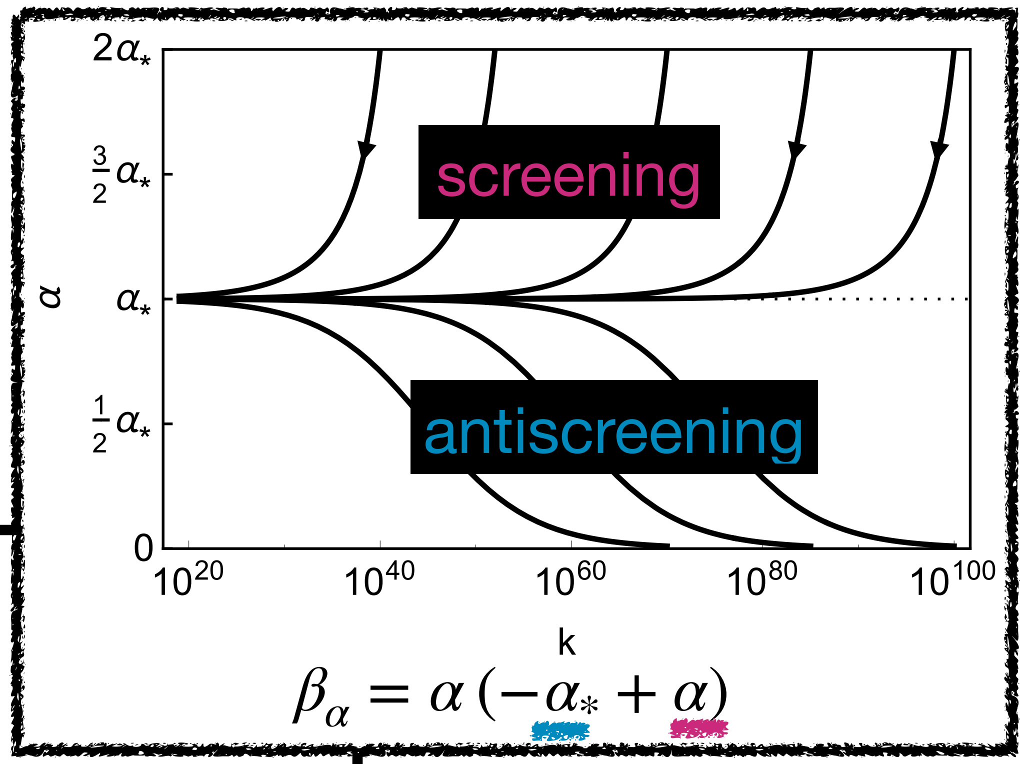

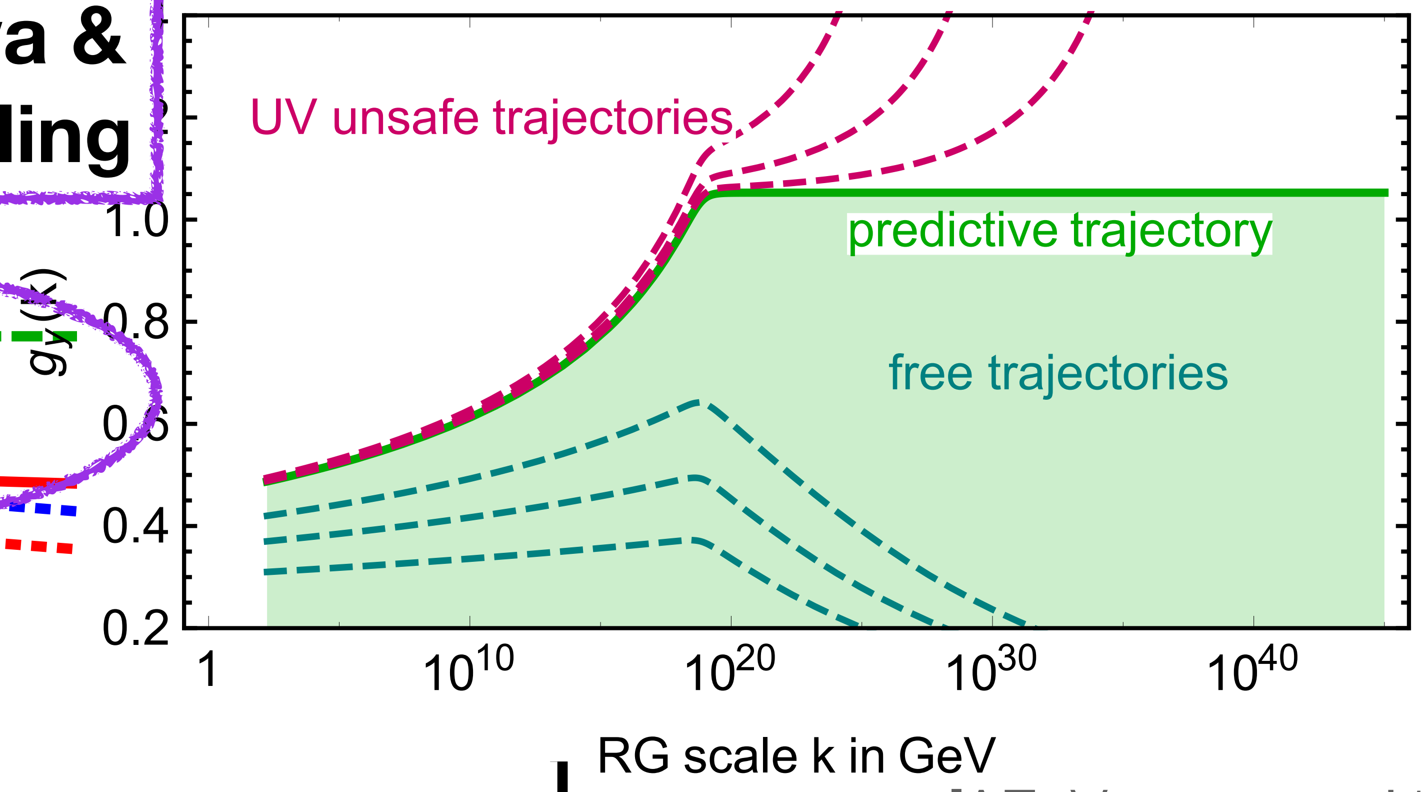

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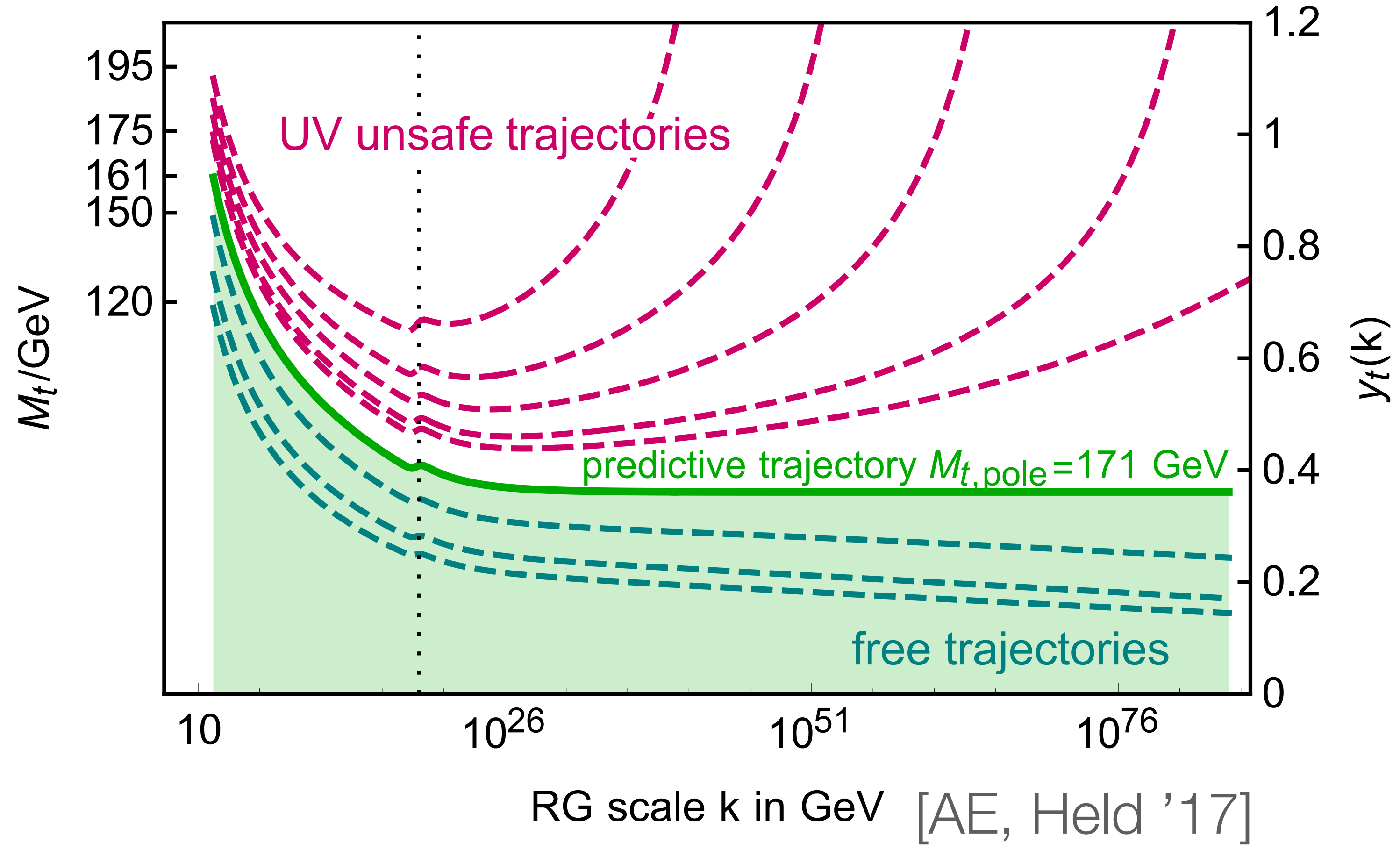

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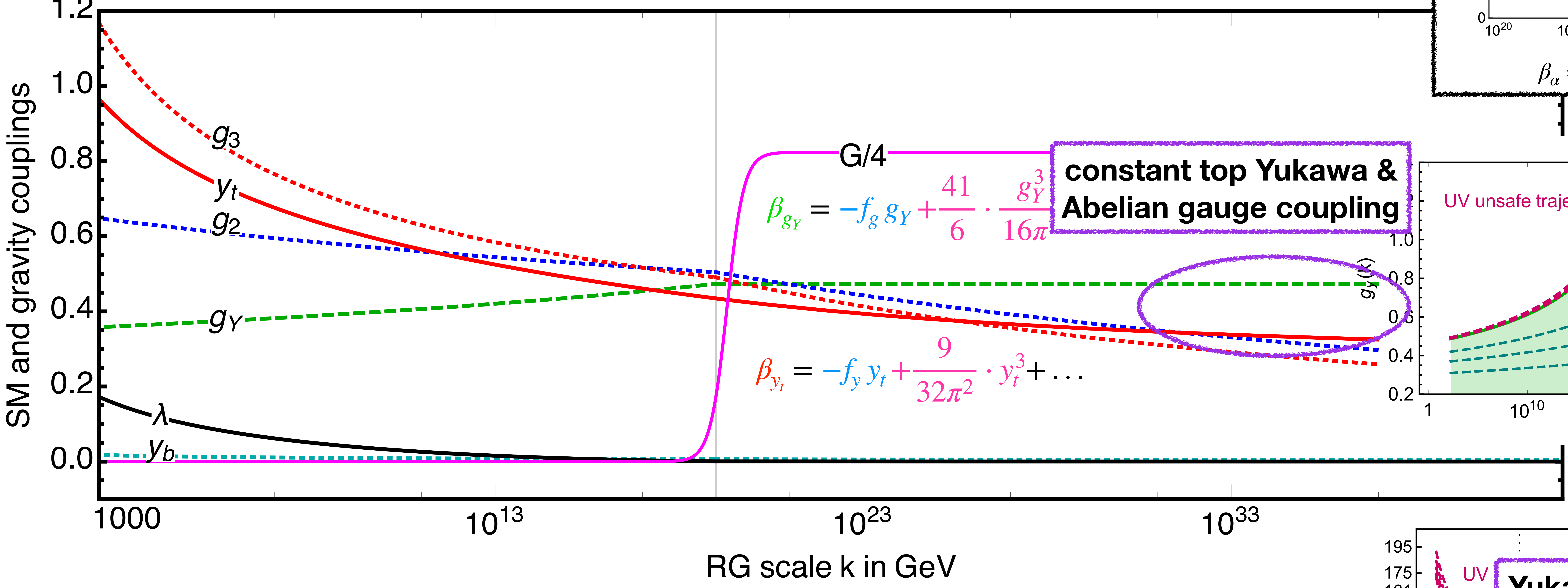

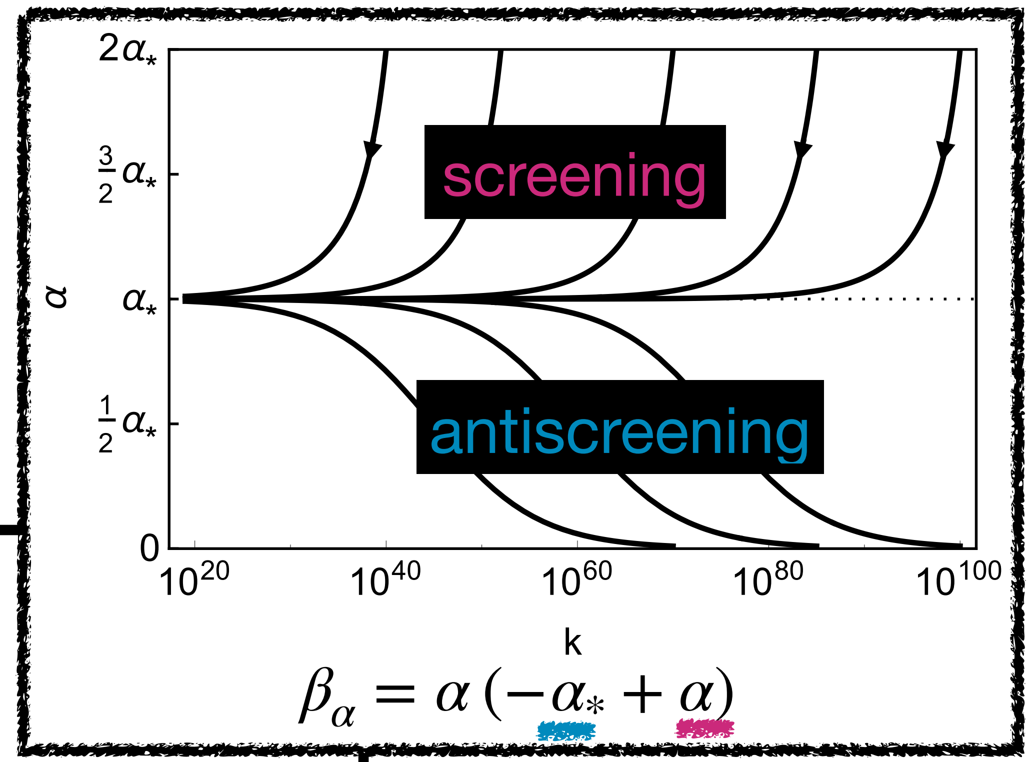

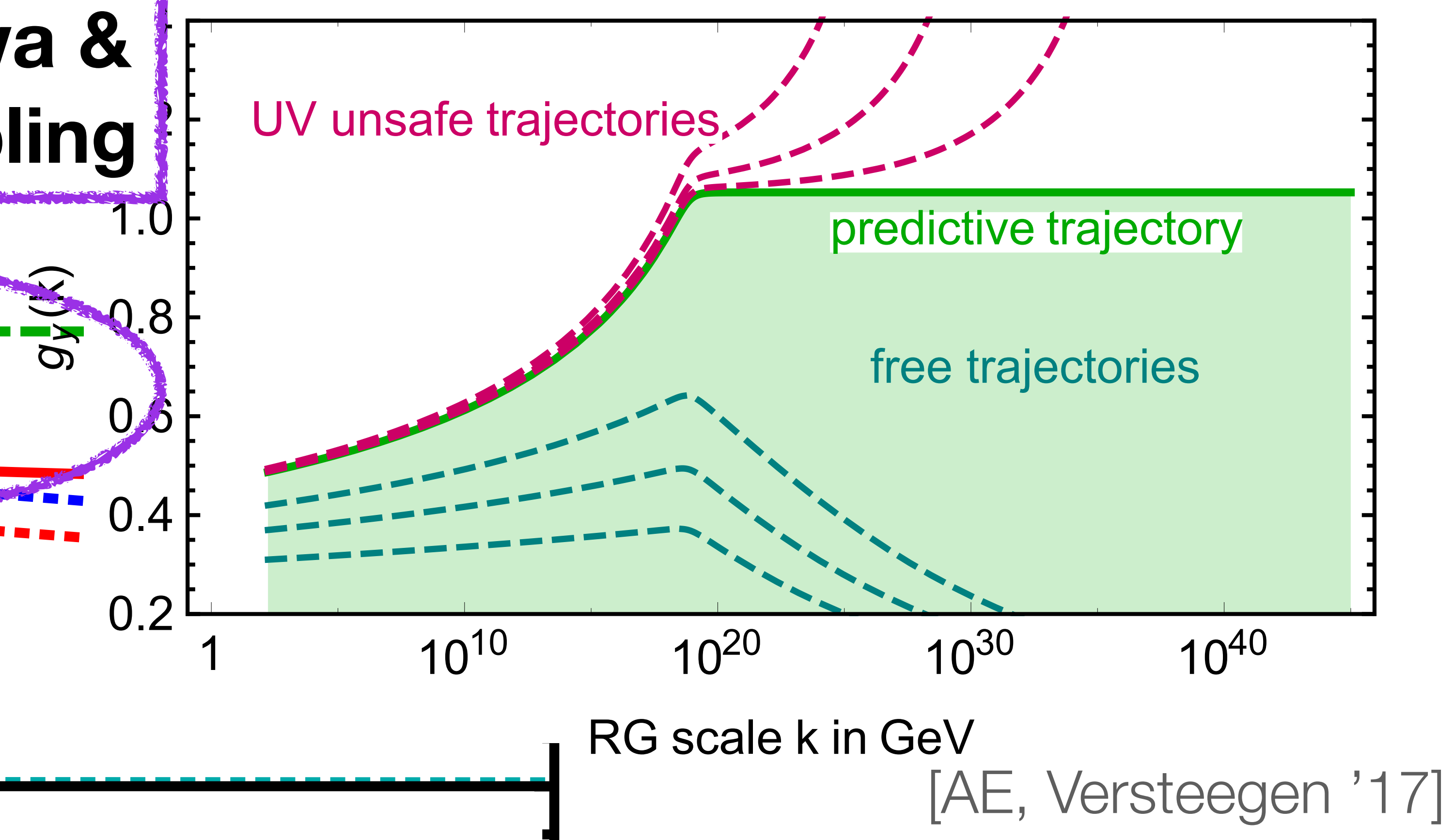

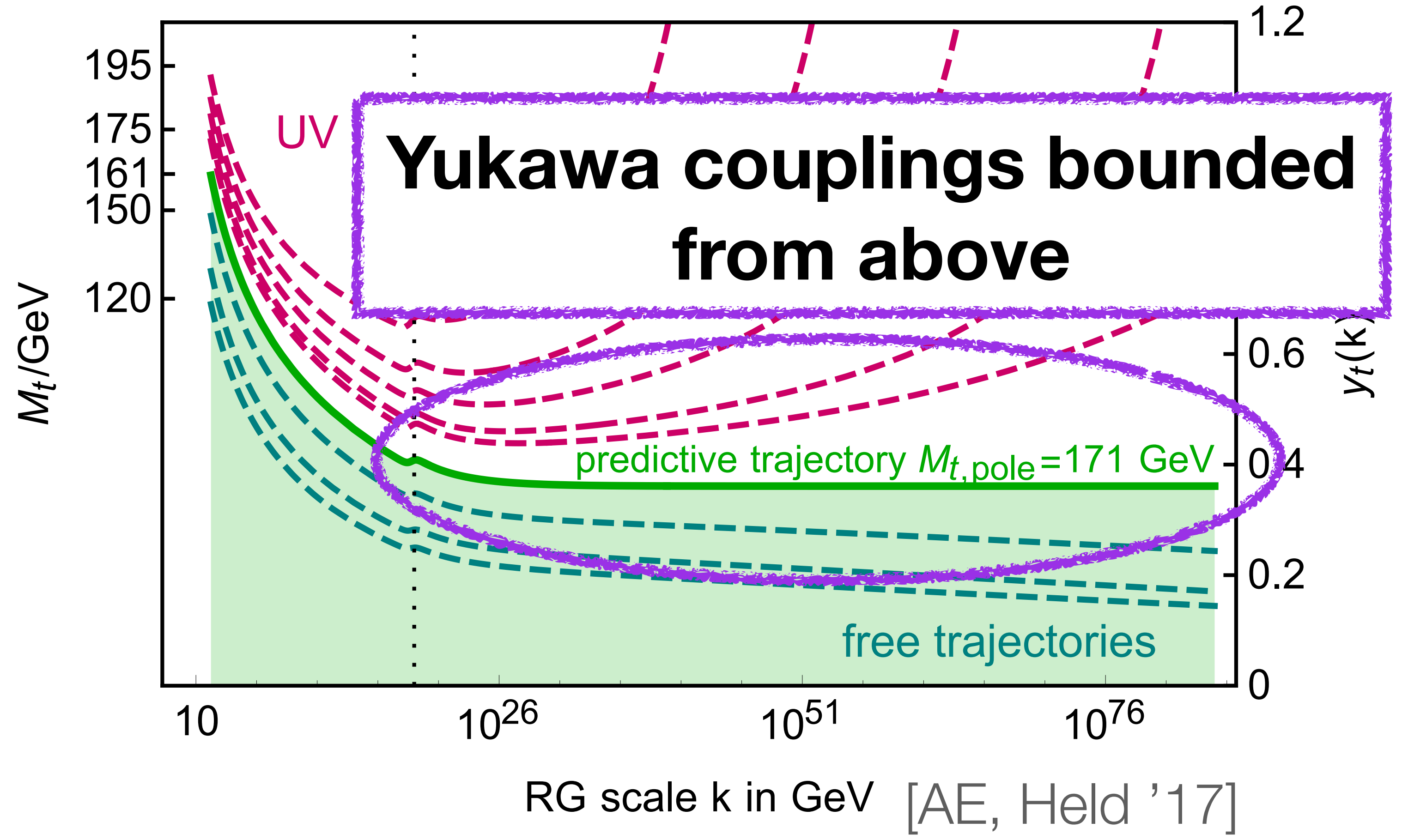

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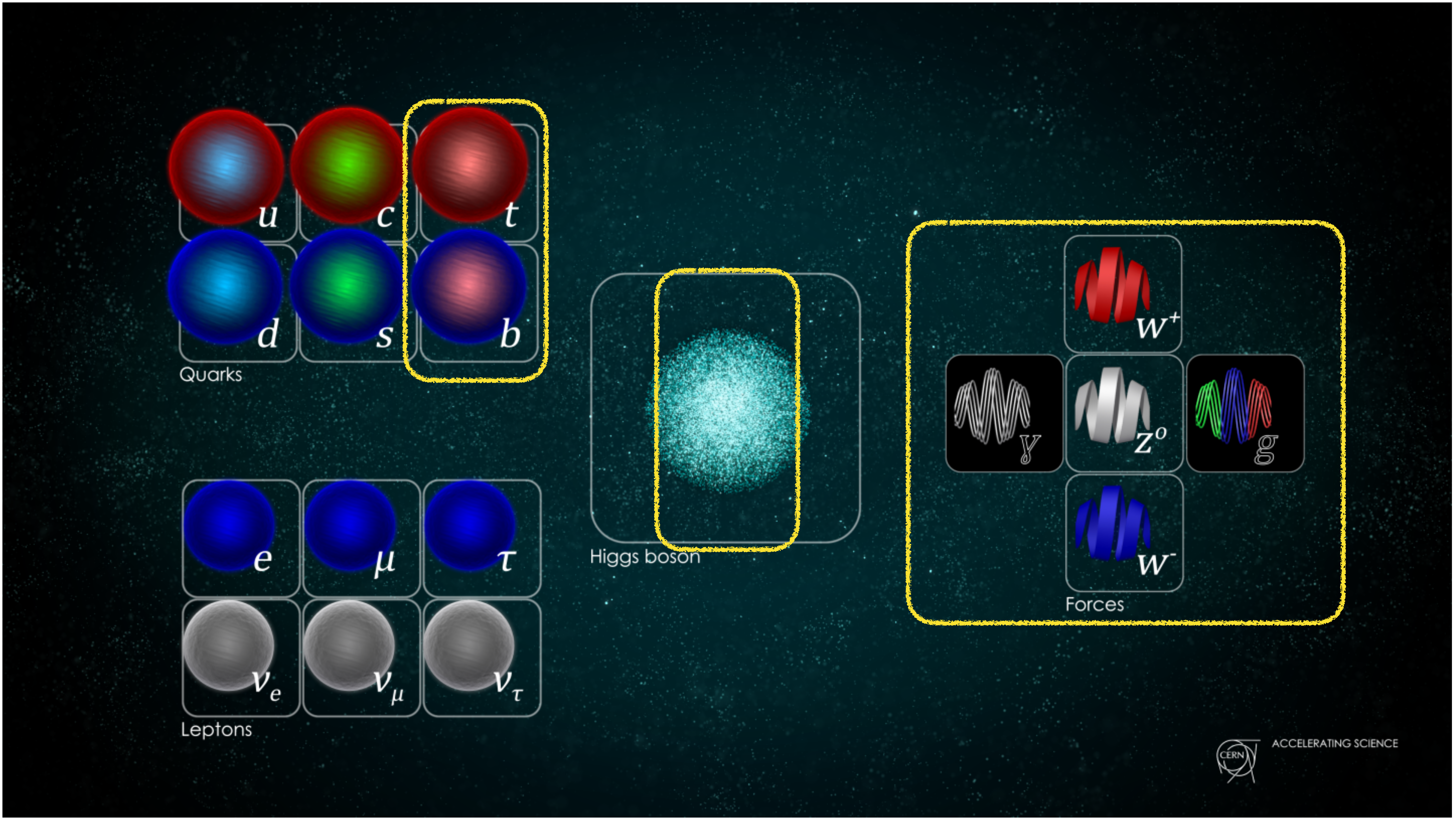

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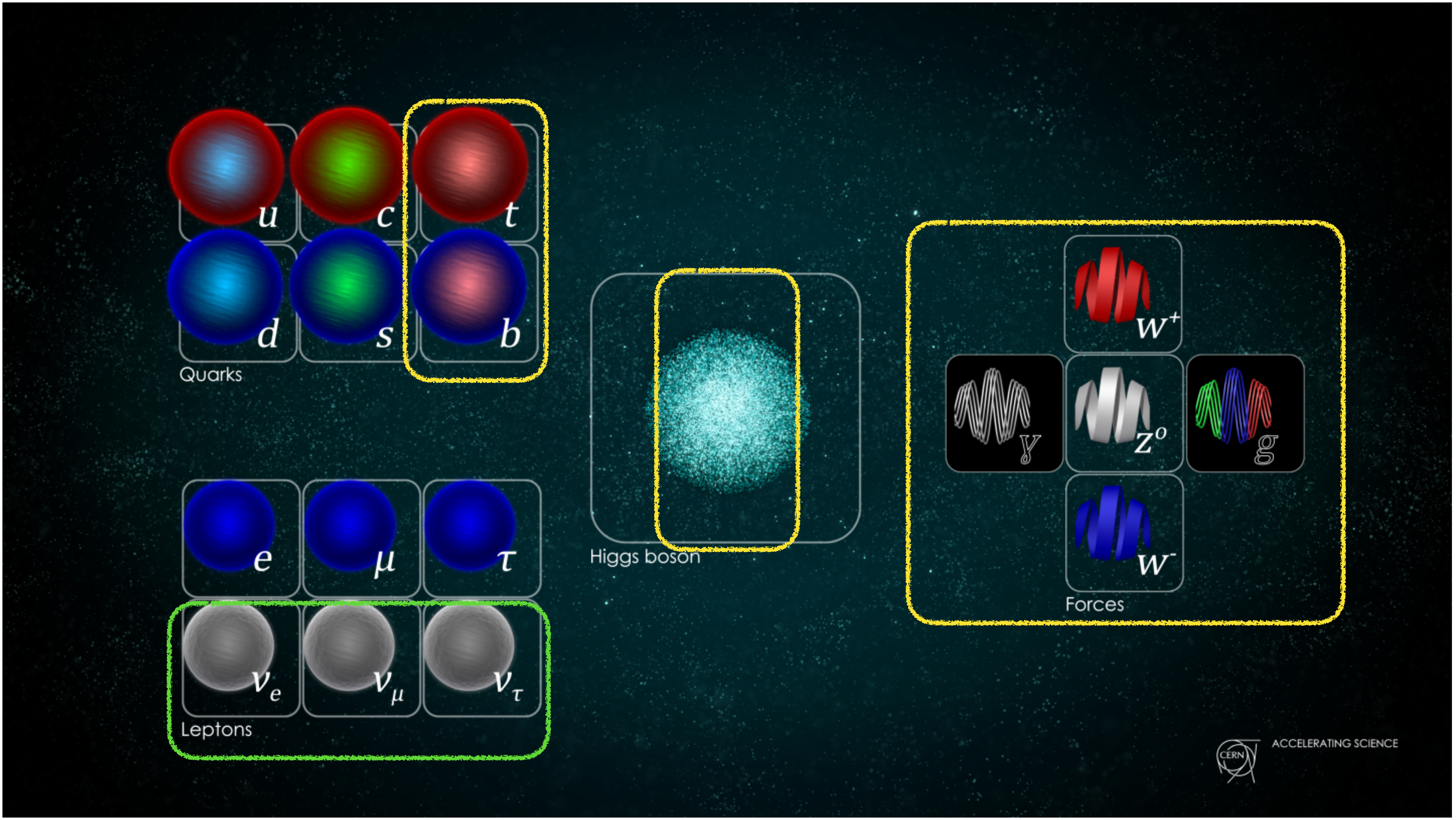

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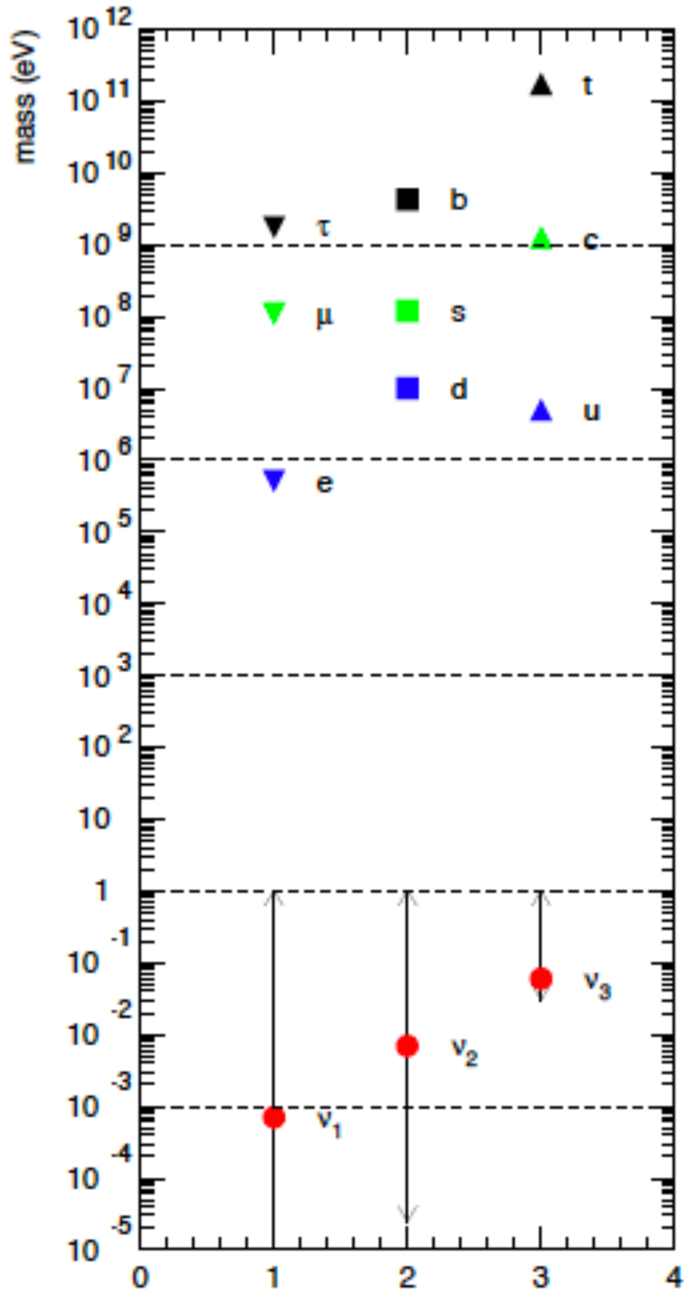

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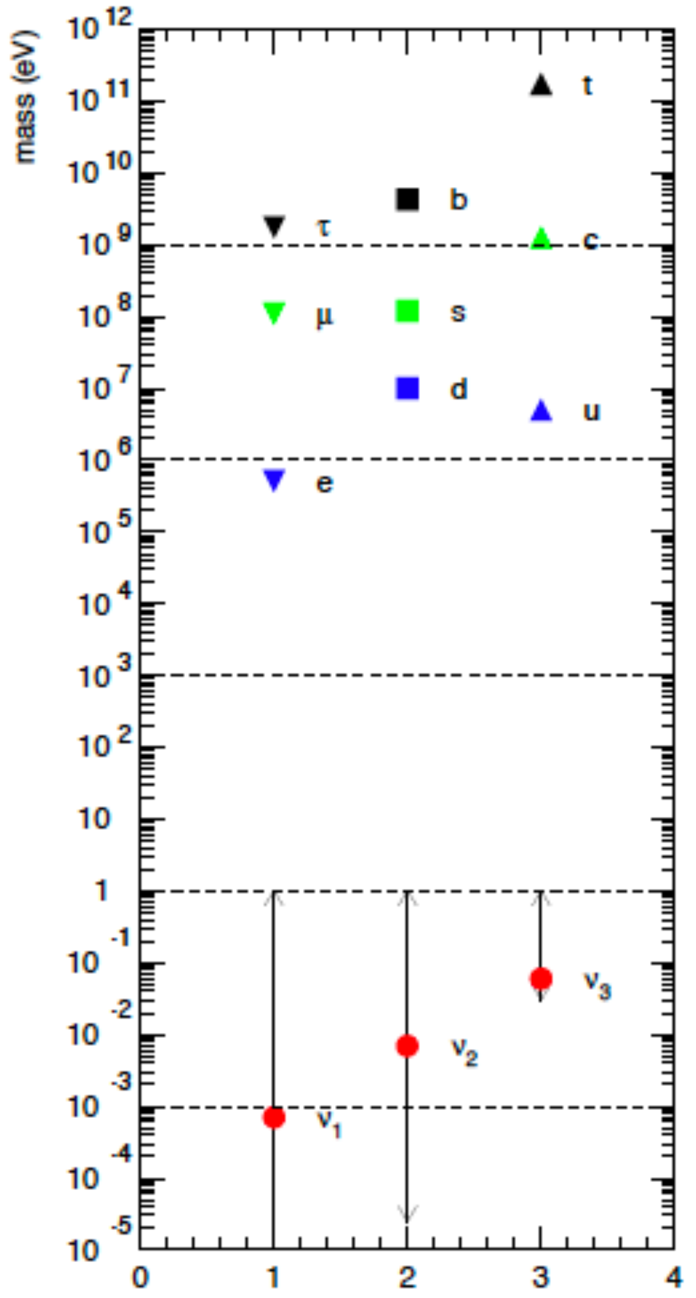

- Option 1: no new degrees of freedom, just Weinberg operator

$$\mathscr{L}_{\text{Weinberg}} = \frac{\zeta}{k}\left((\bar{L}\sigma_2 H^*)(H^\dagger \sigma_2 L^C) + \text{h.c.} \right)$$

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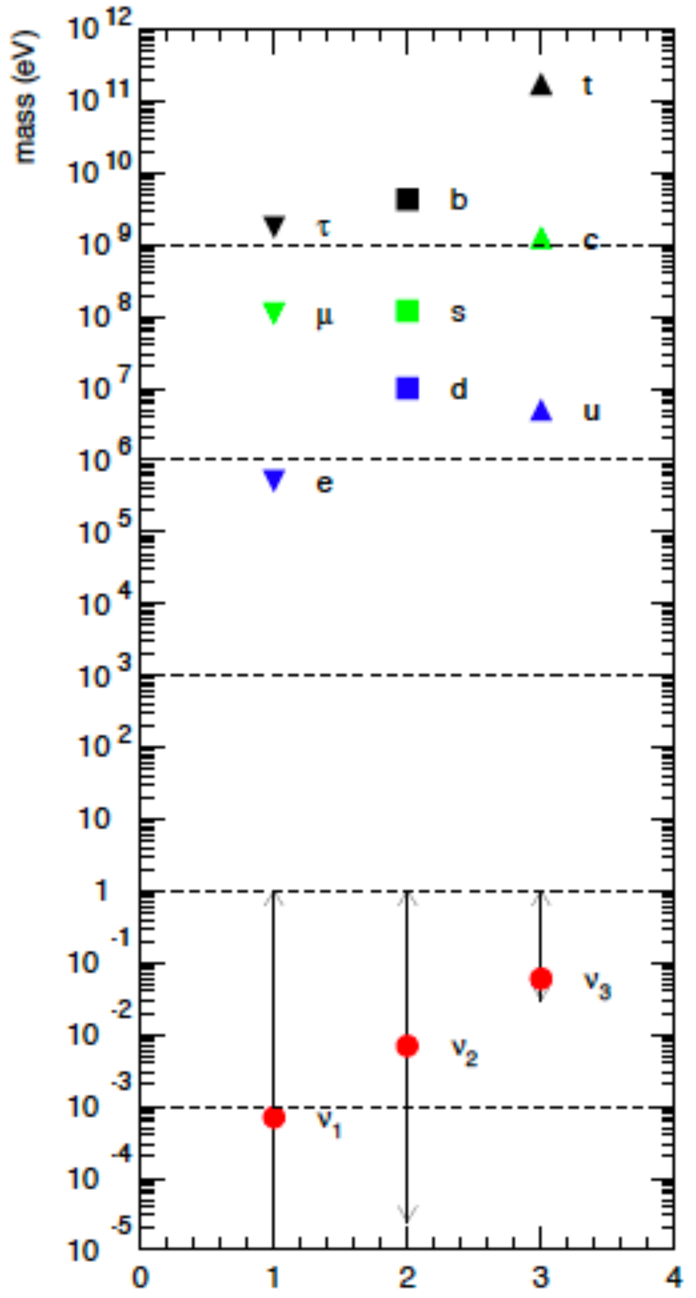

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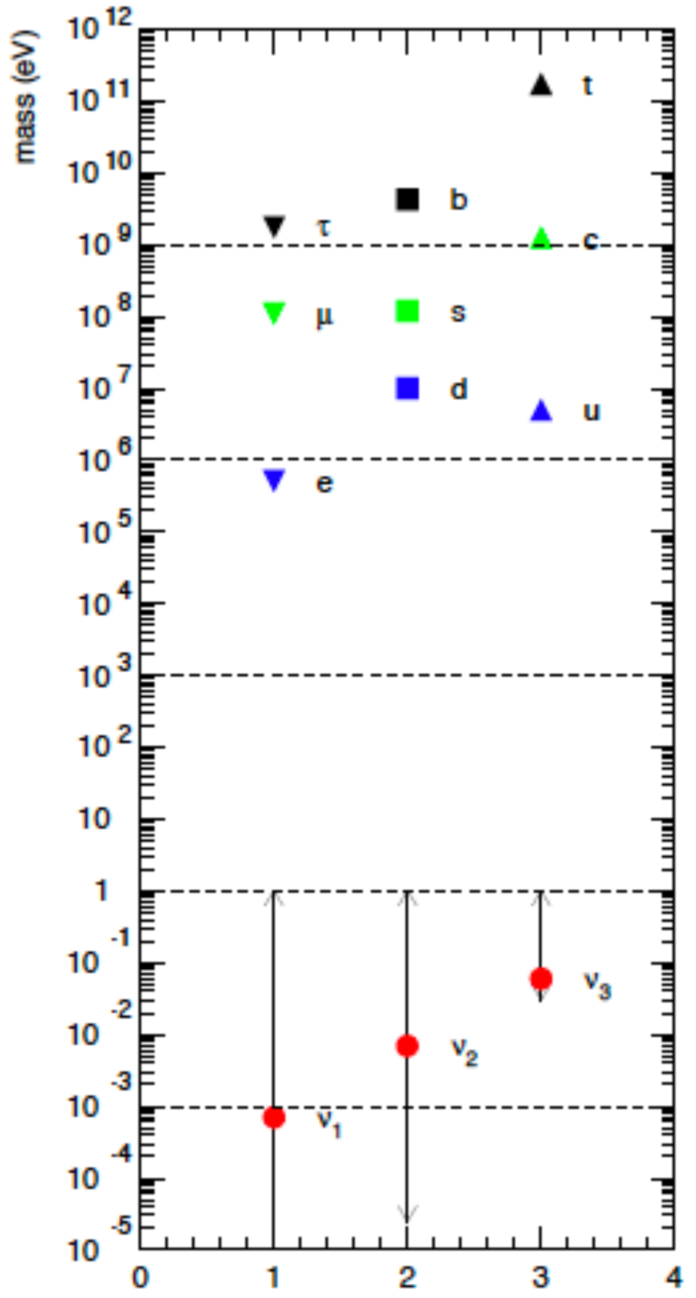

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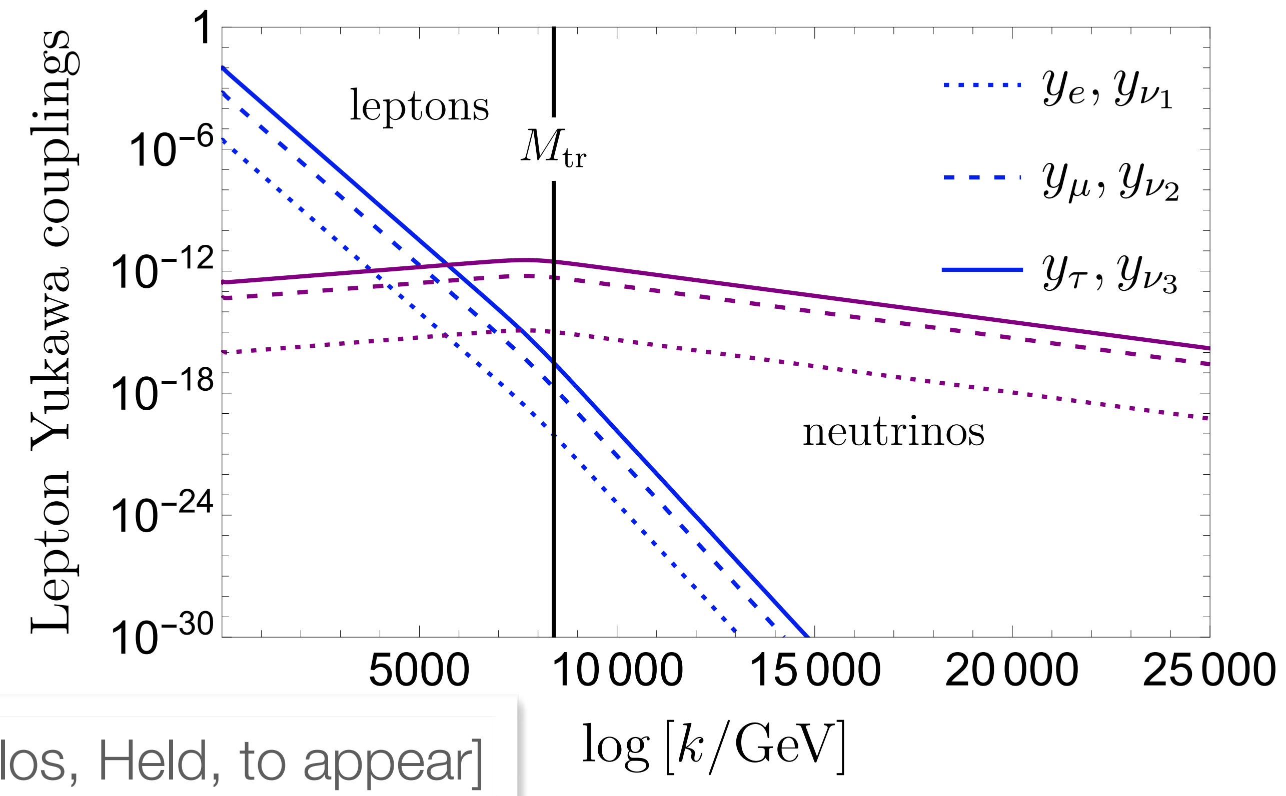

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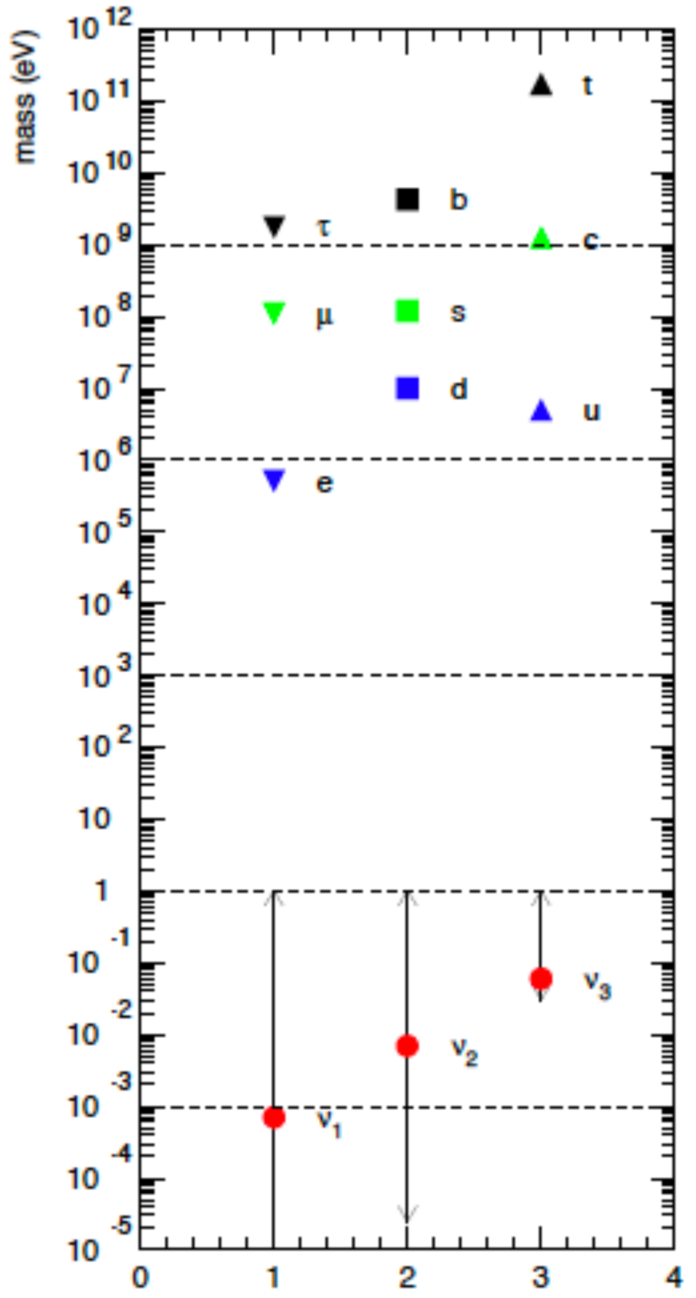

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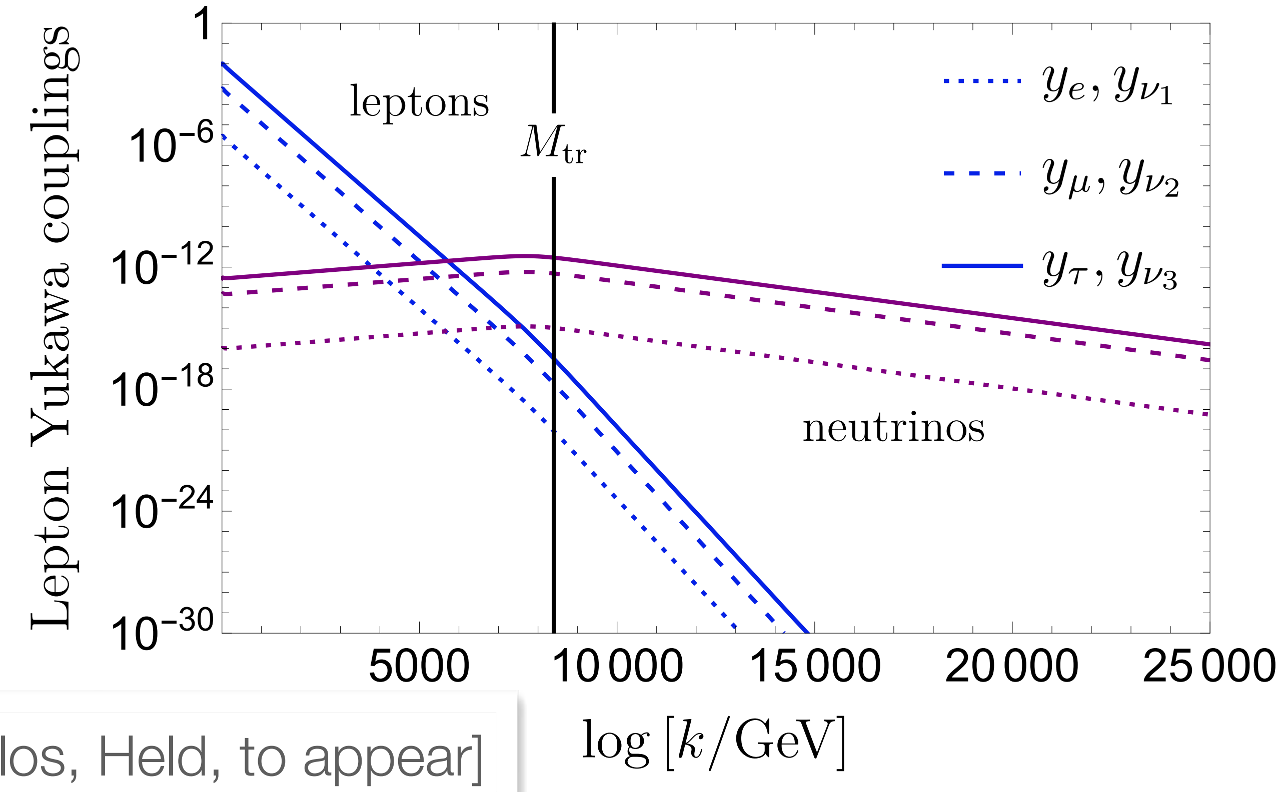

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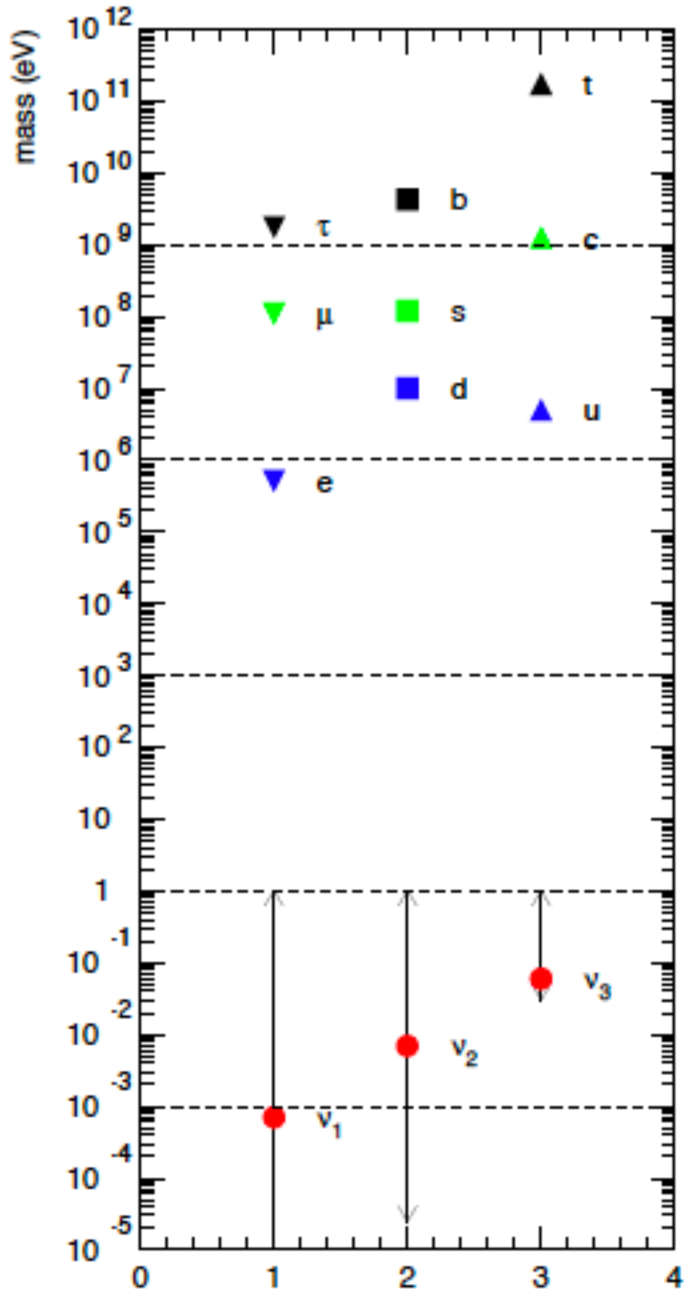
Part 2: neutrino masses

Standard Model fermion masses



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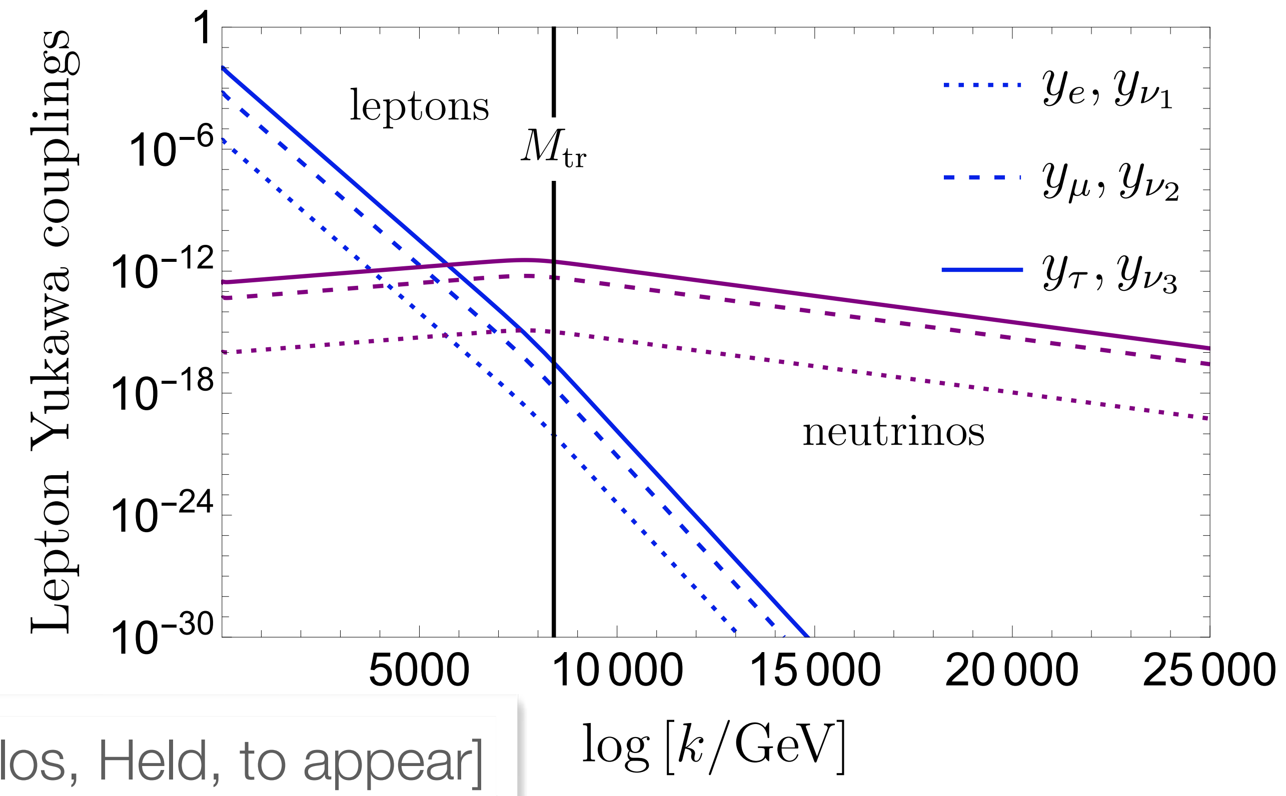

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Majorana mass bounded from above

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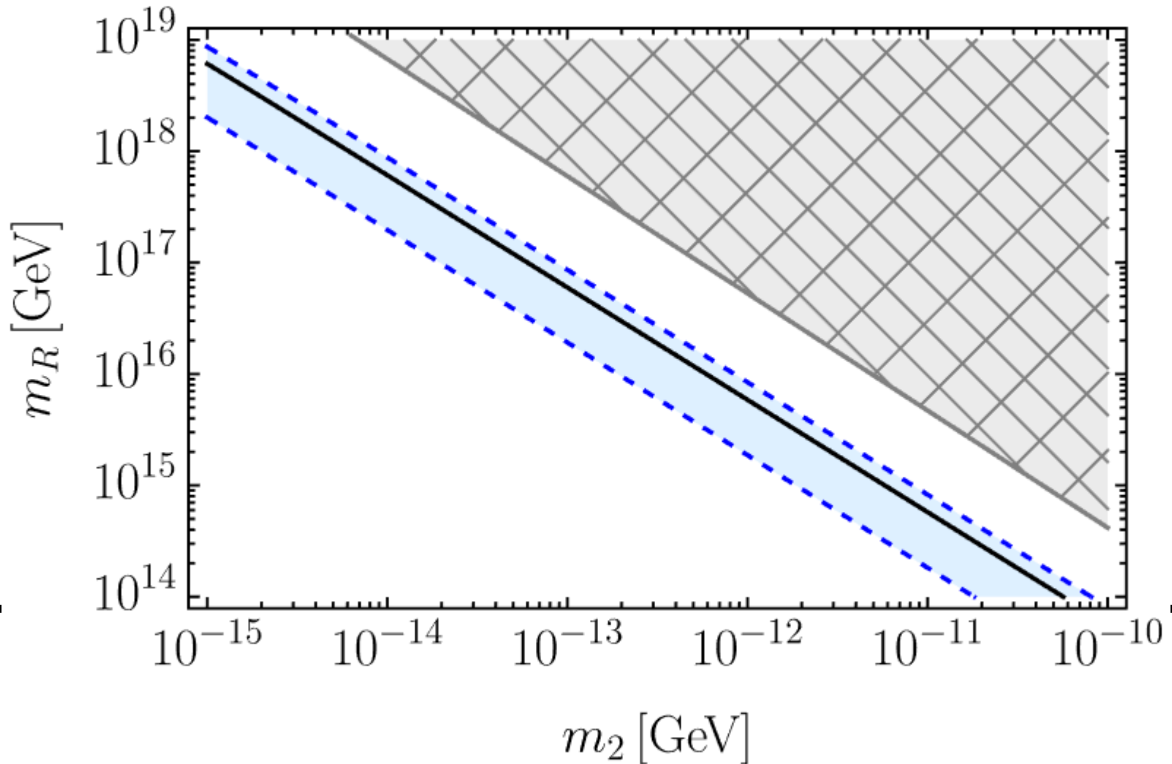
[de Brito, AE, Pereira, Yamada '25]



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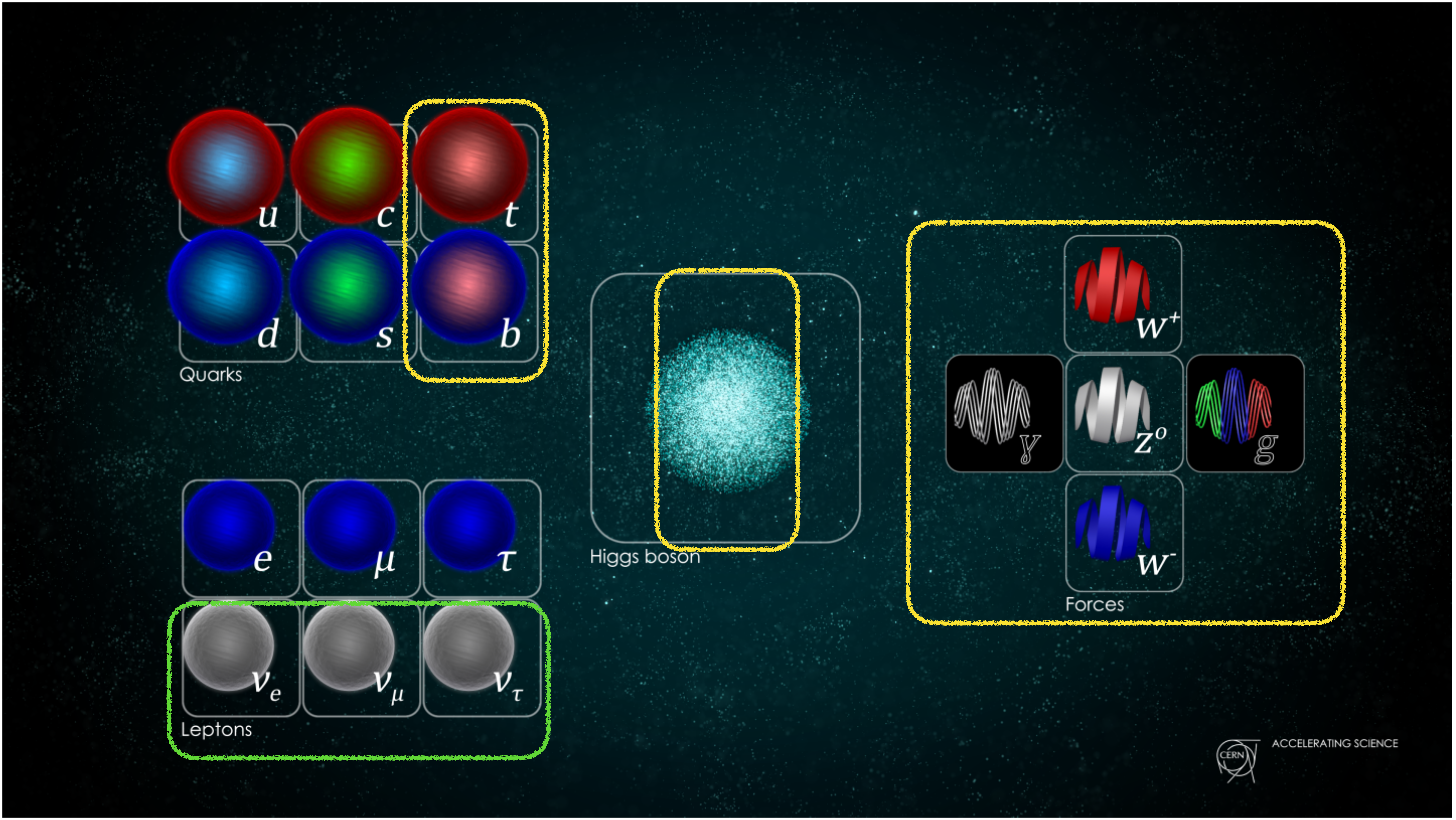

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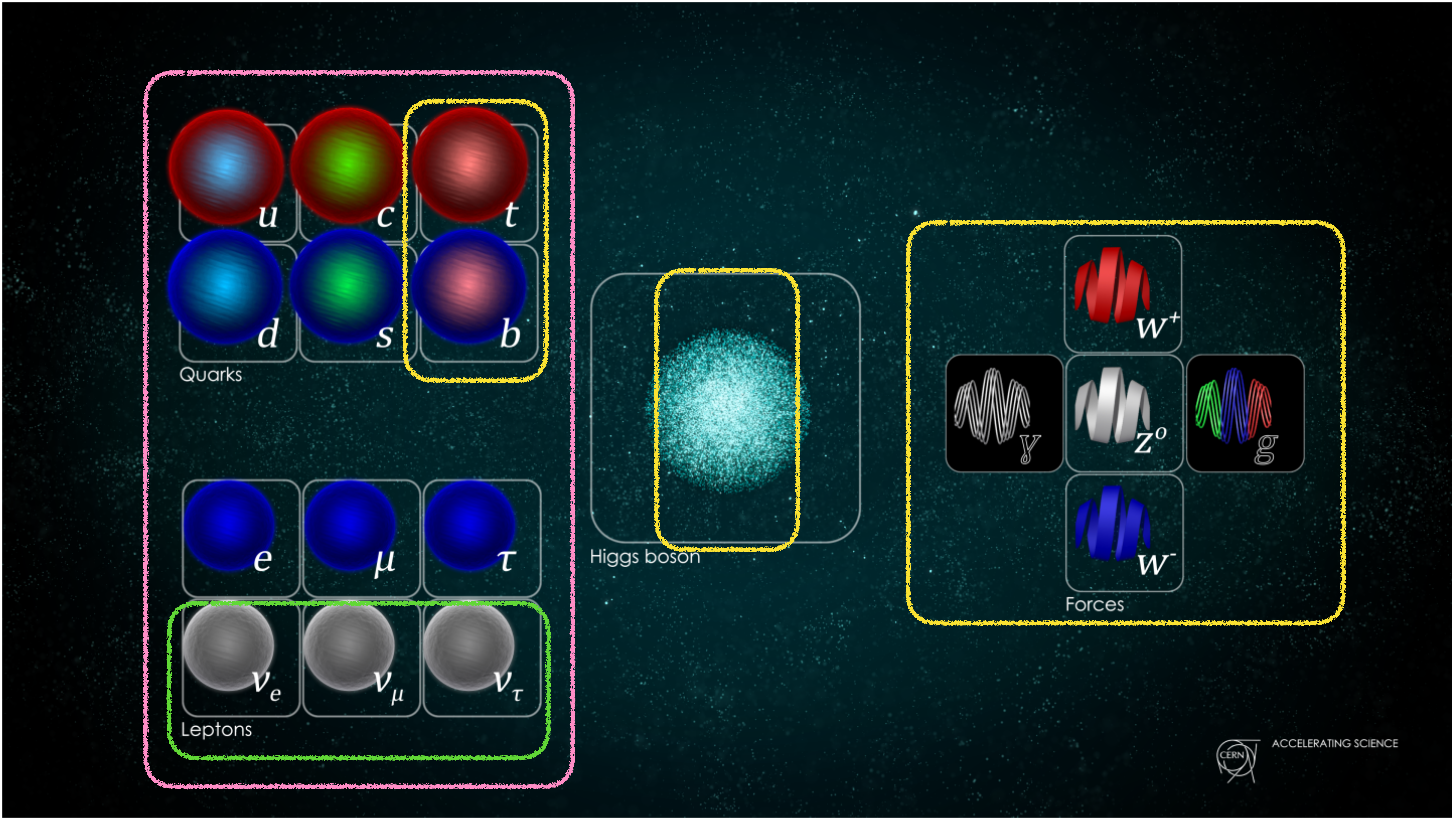

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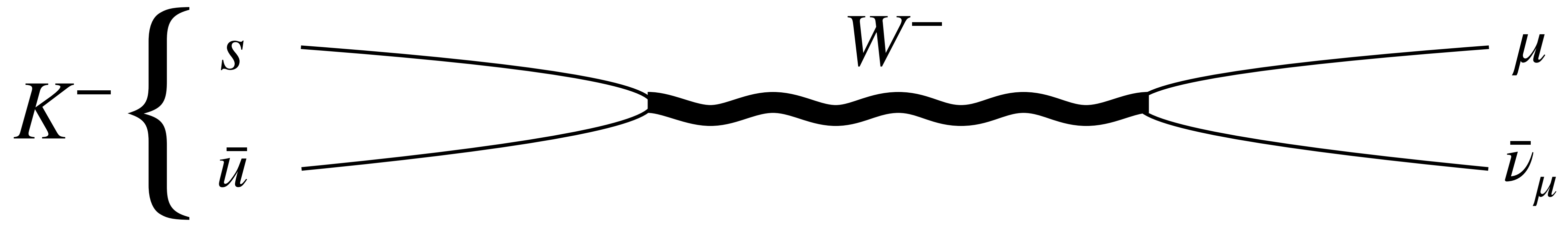
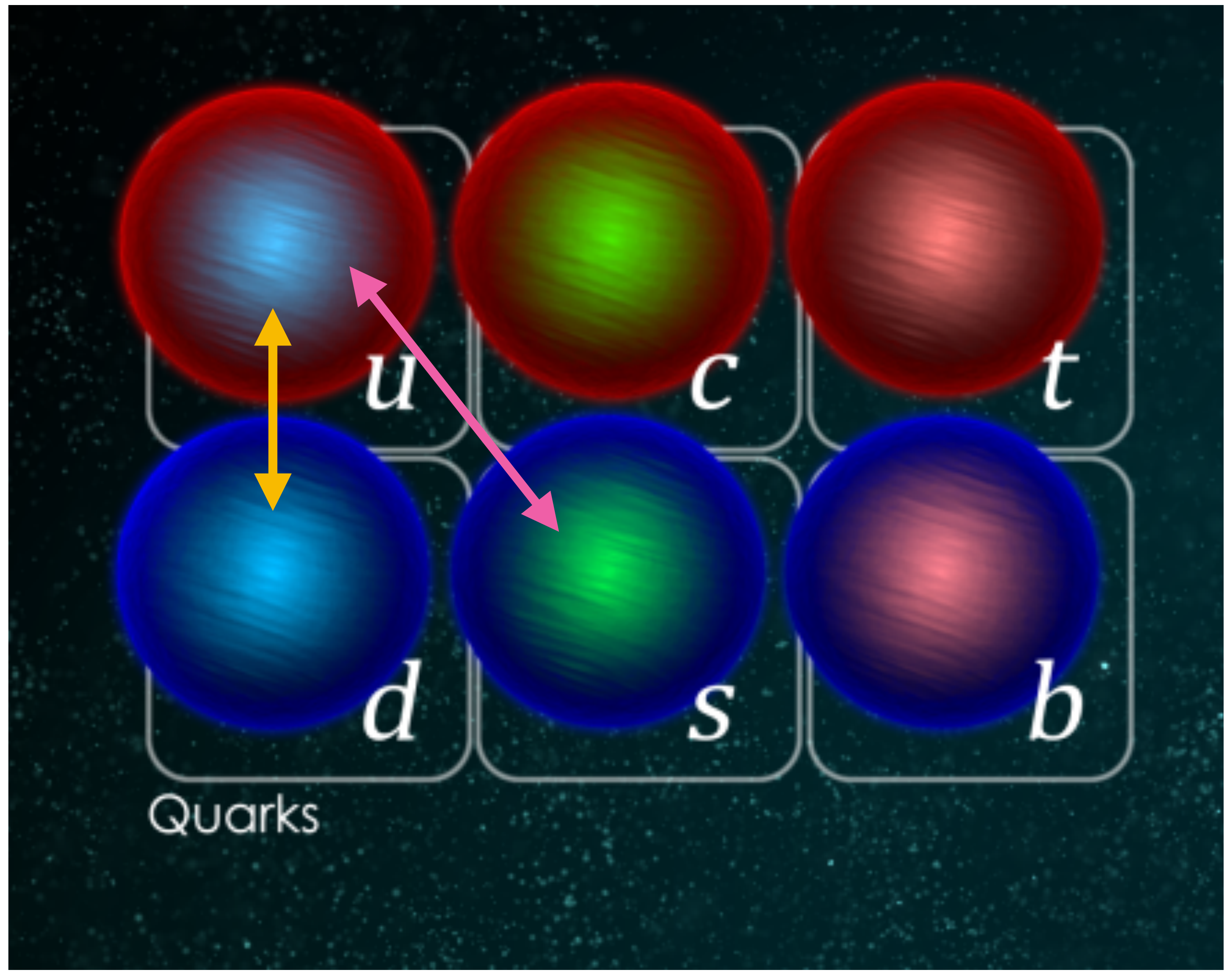
Part 3: mixing matrices

without mixing

with mixing





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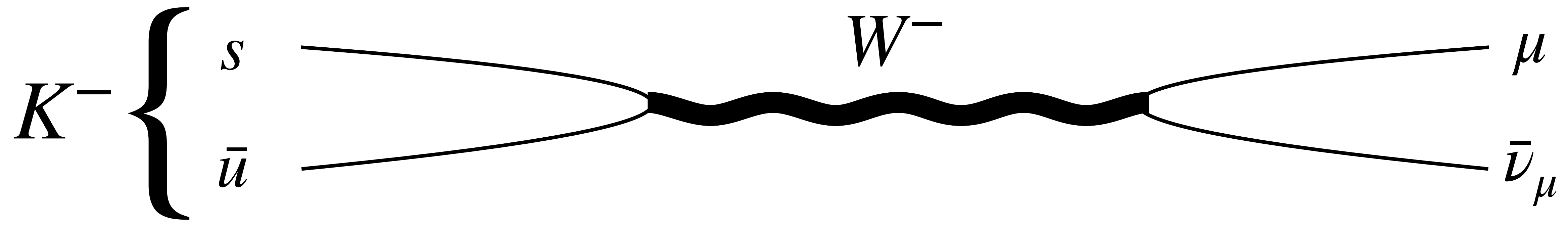
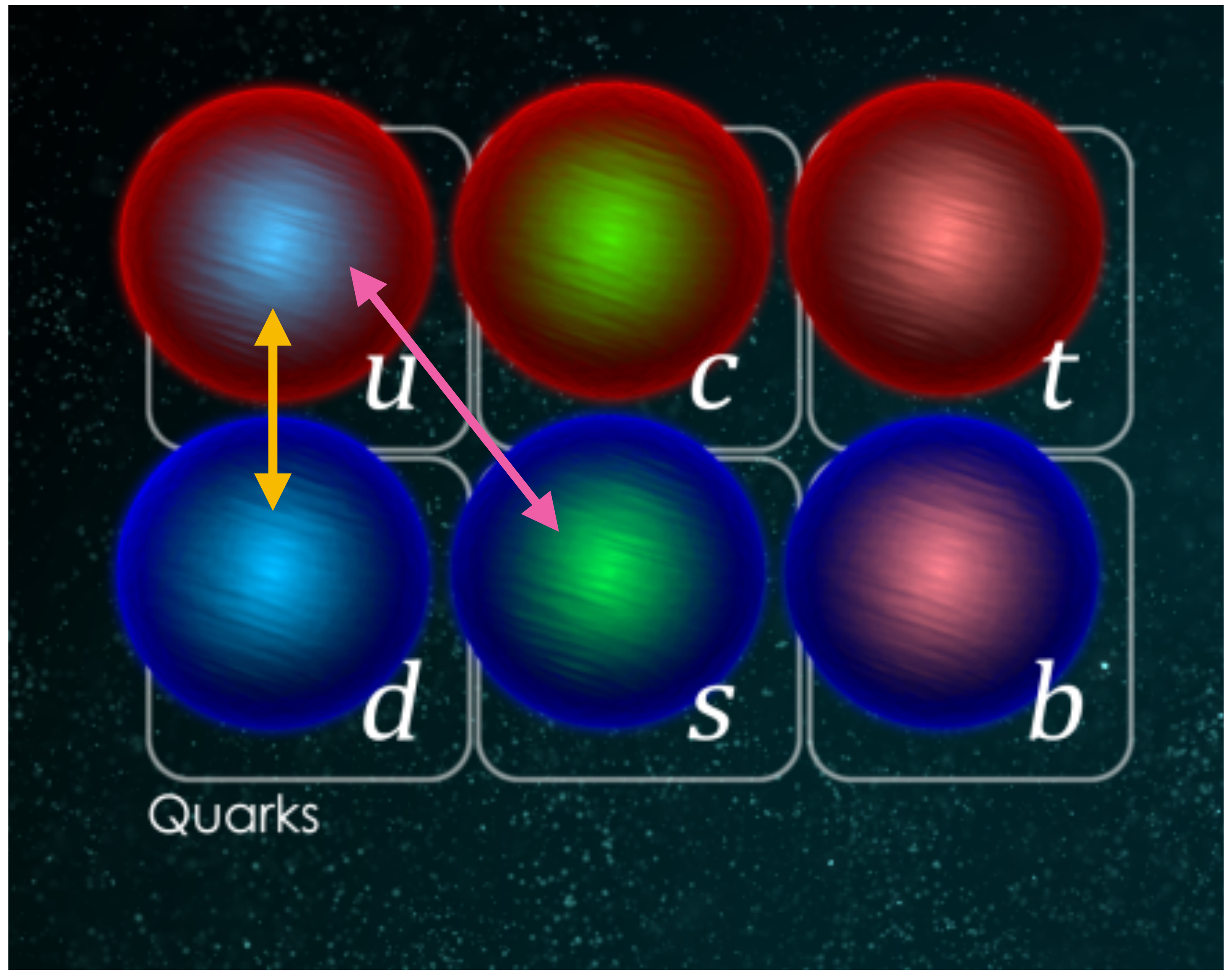
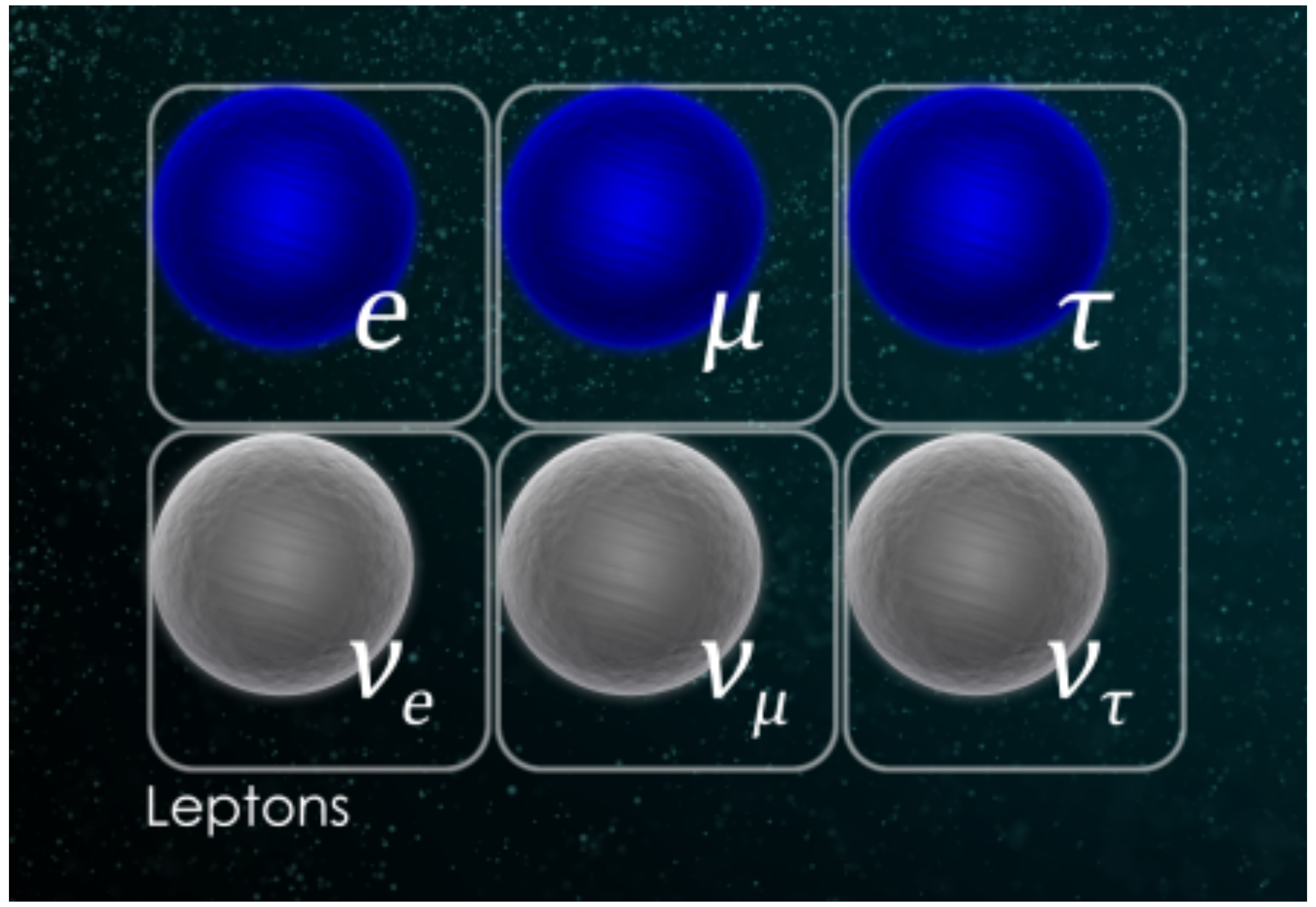


CKM



PMNS



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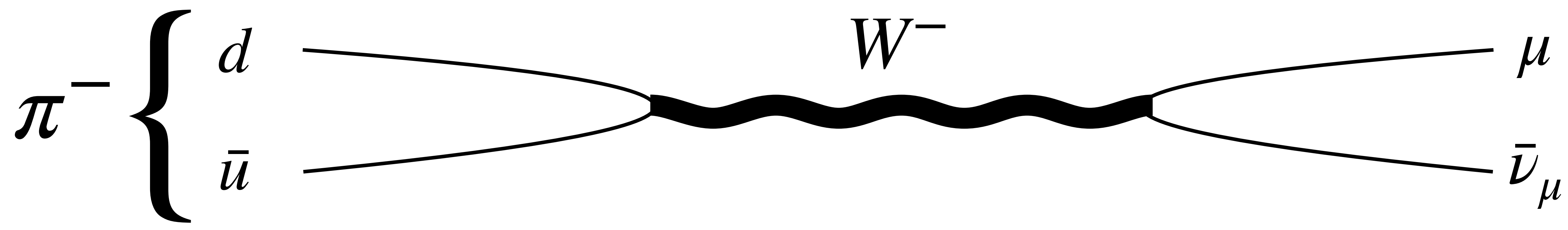
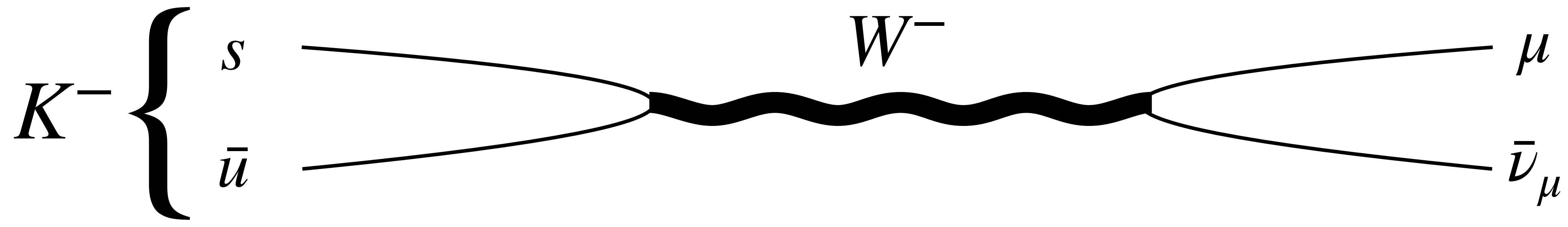
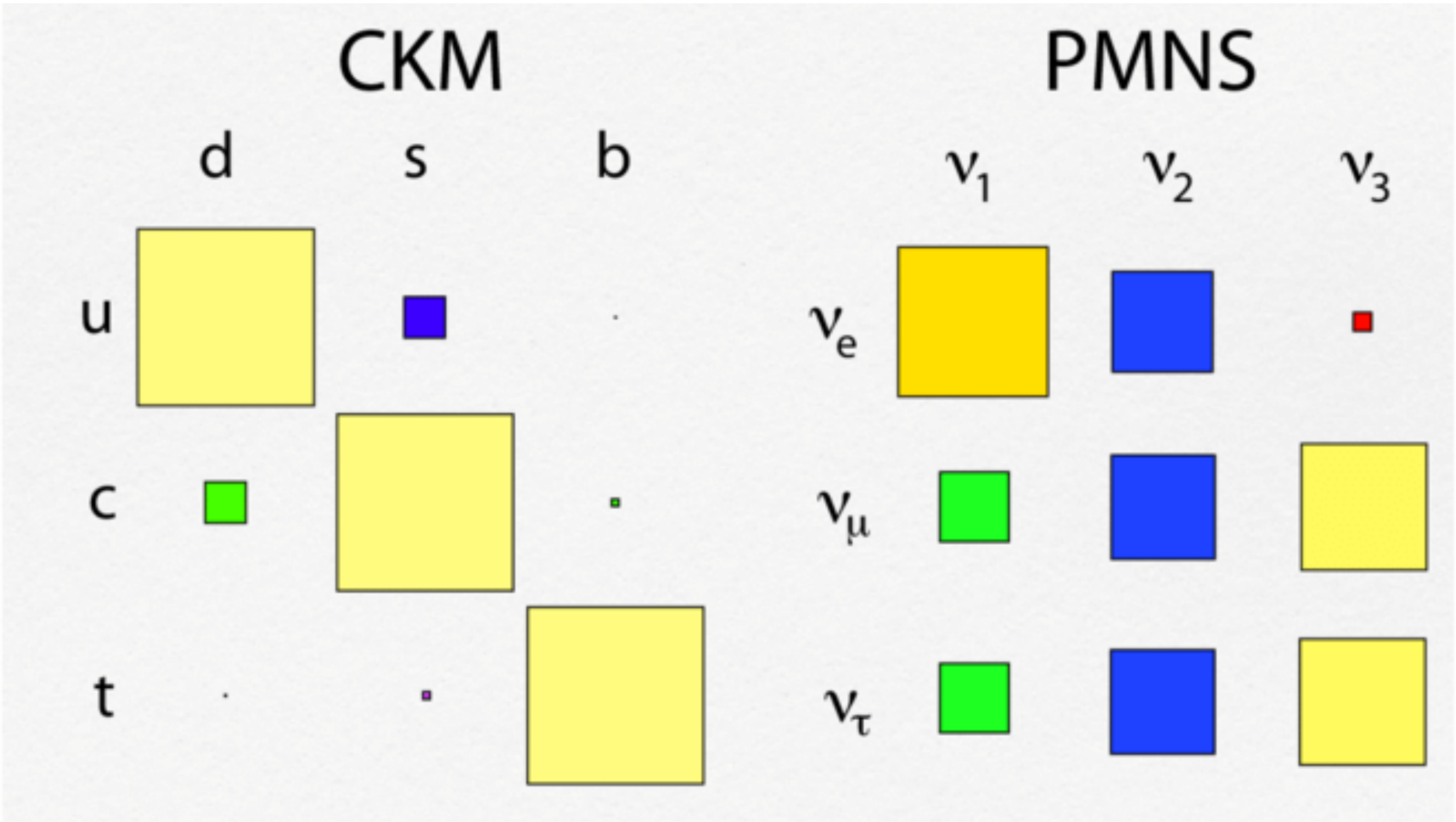
without mixing



with mixing





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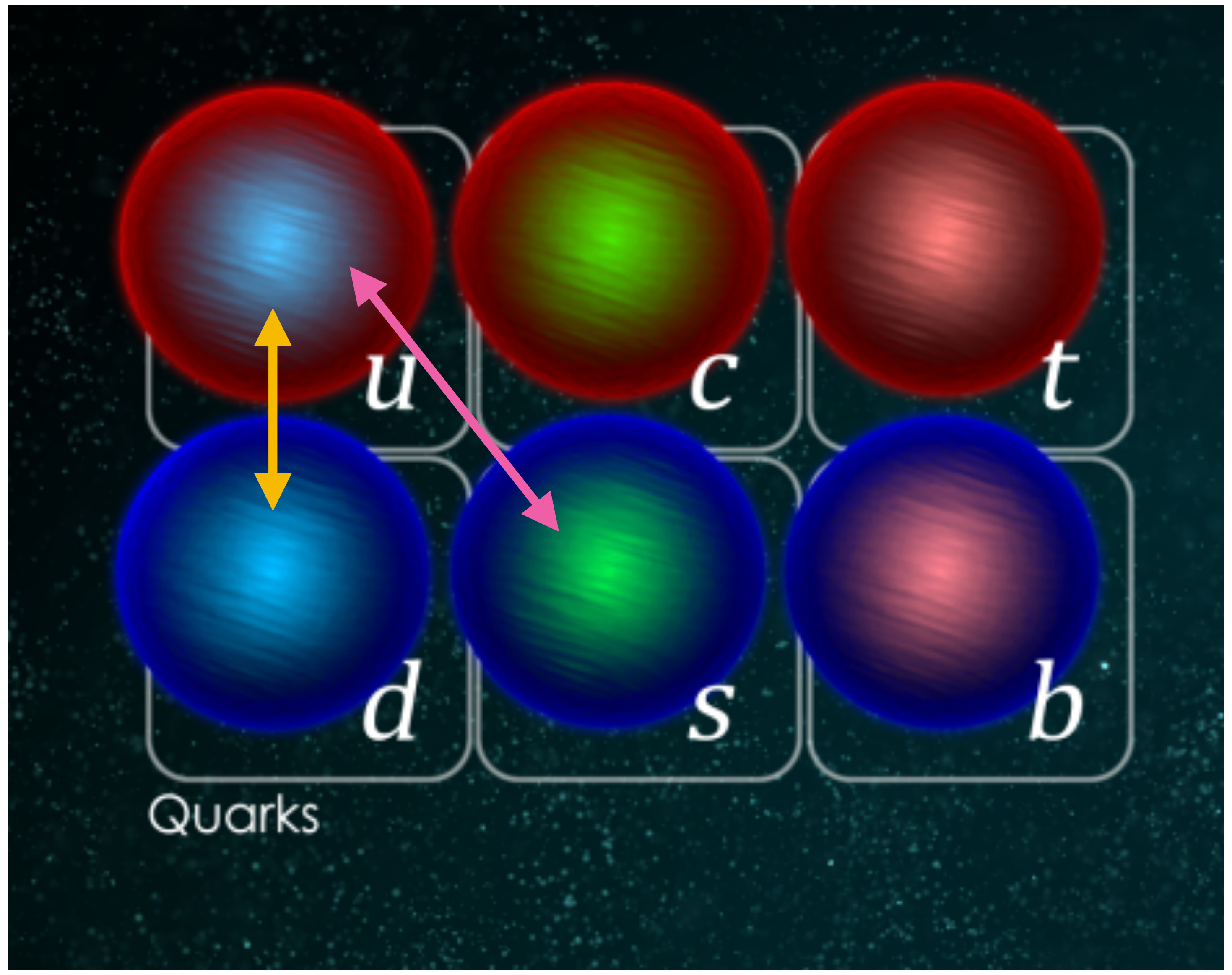

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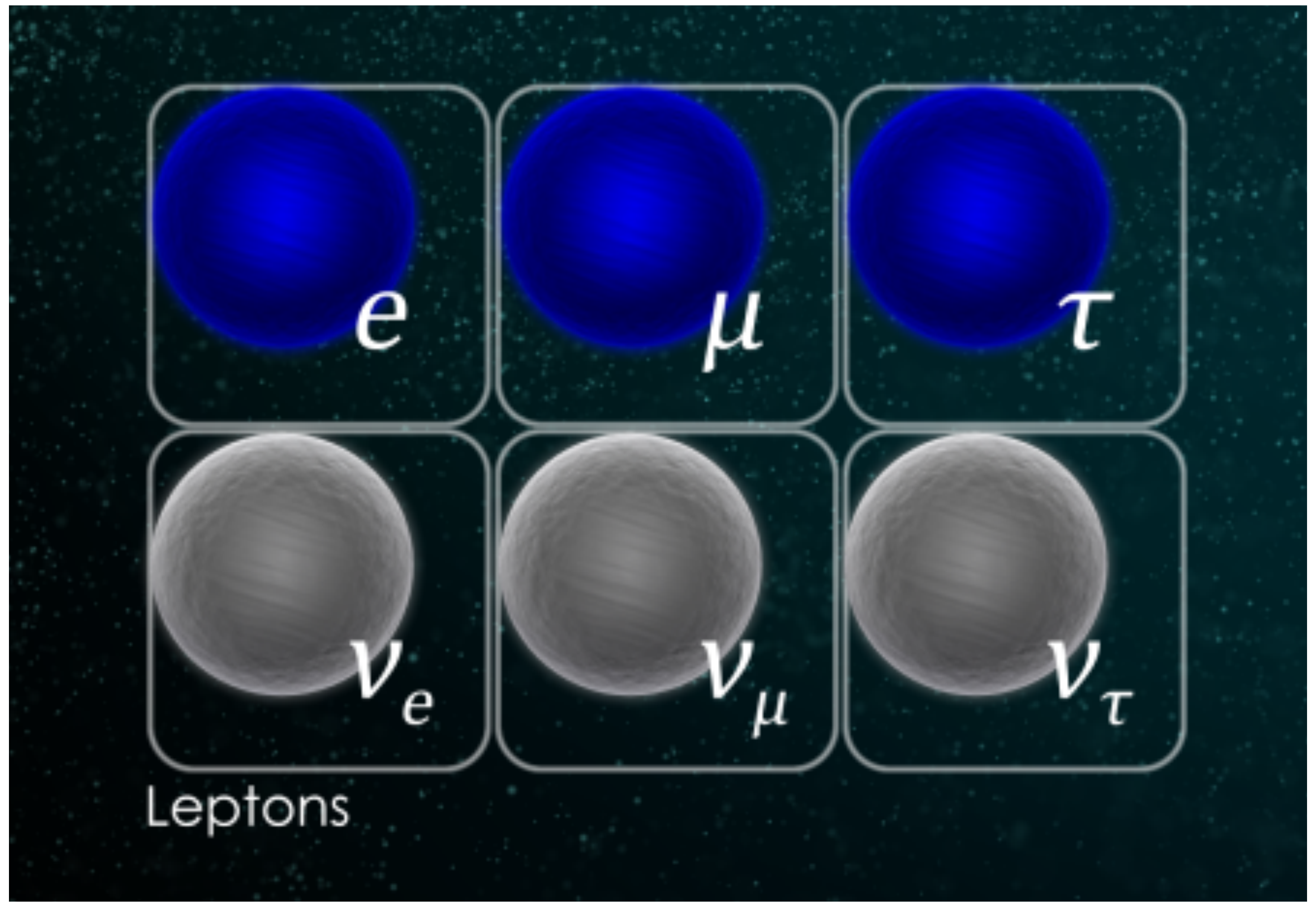

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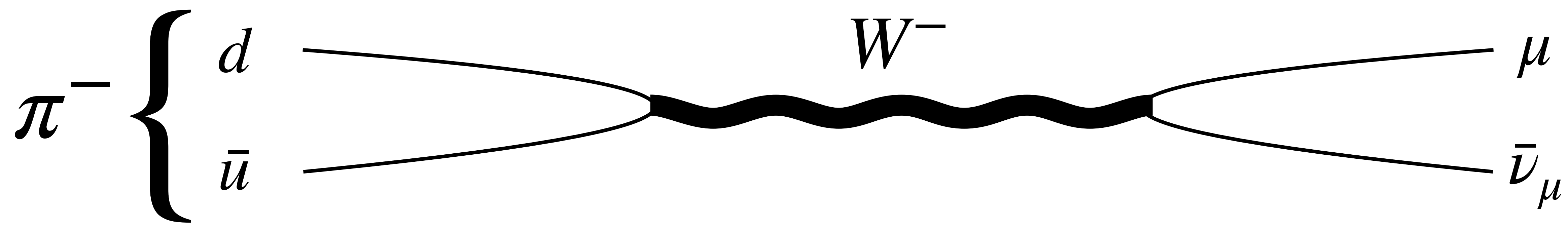

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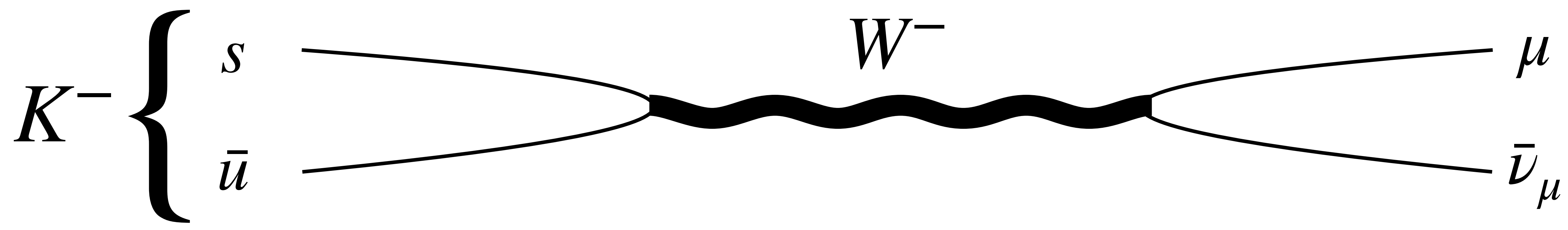
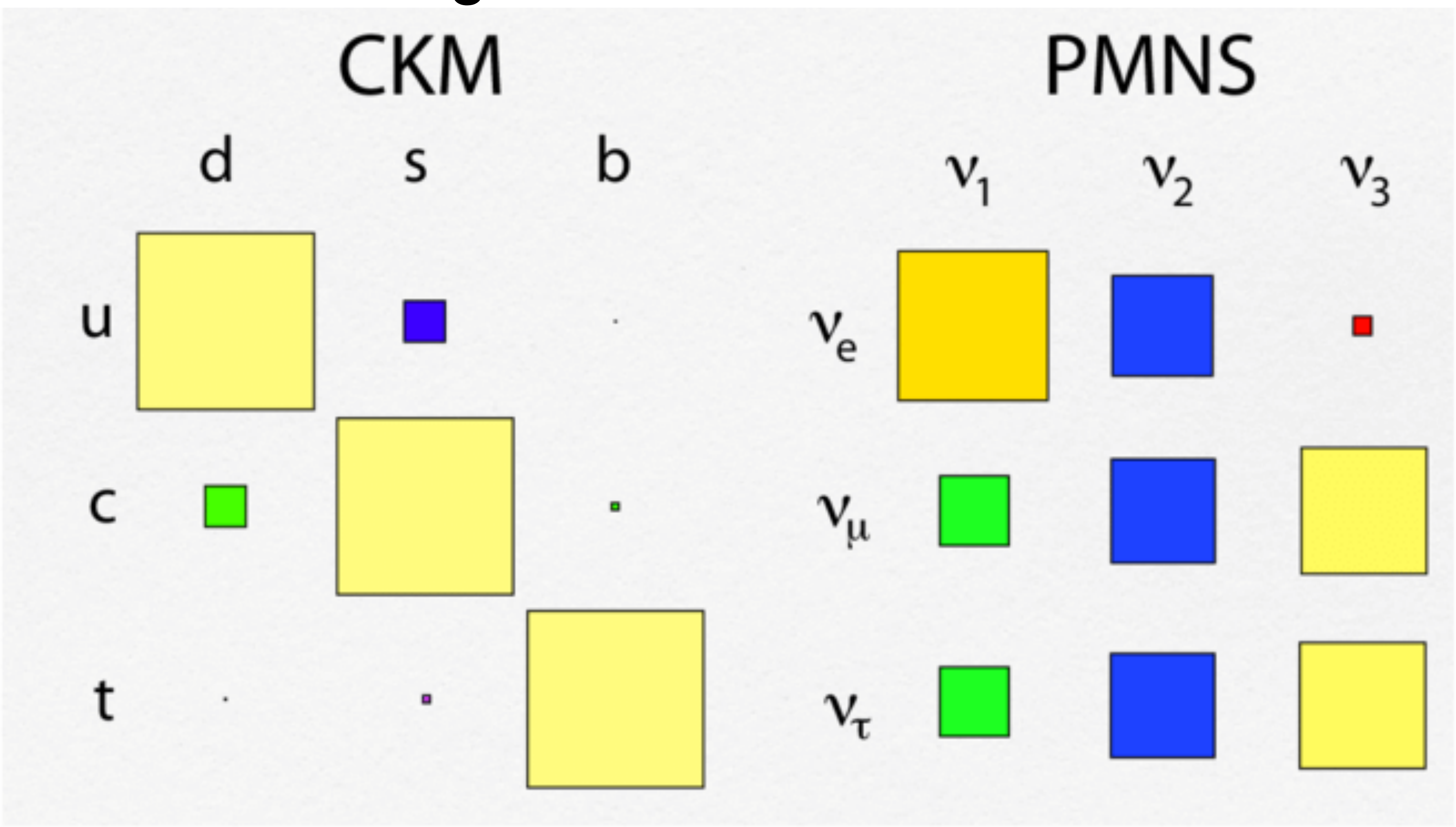


What generates these structures?



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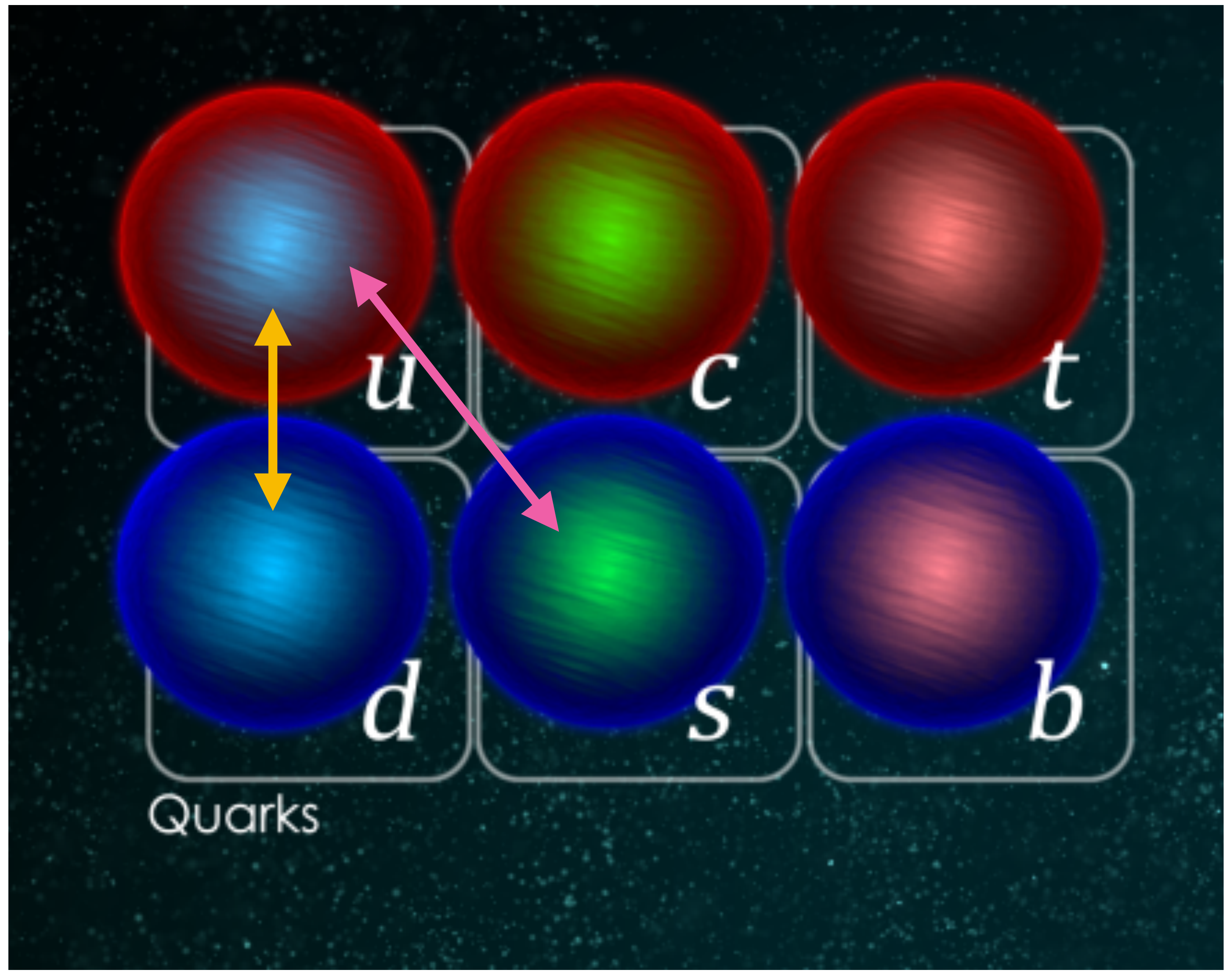

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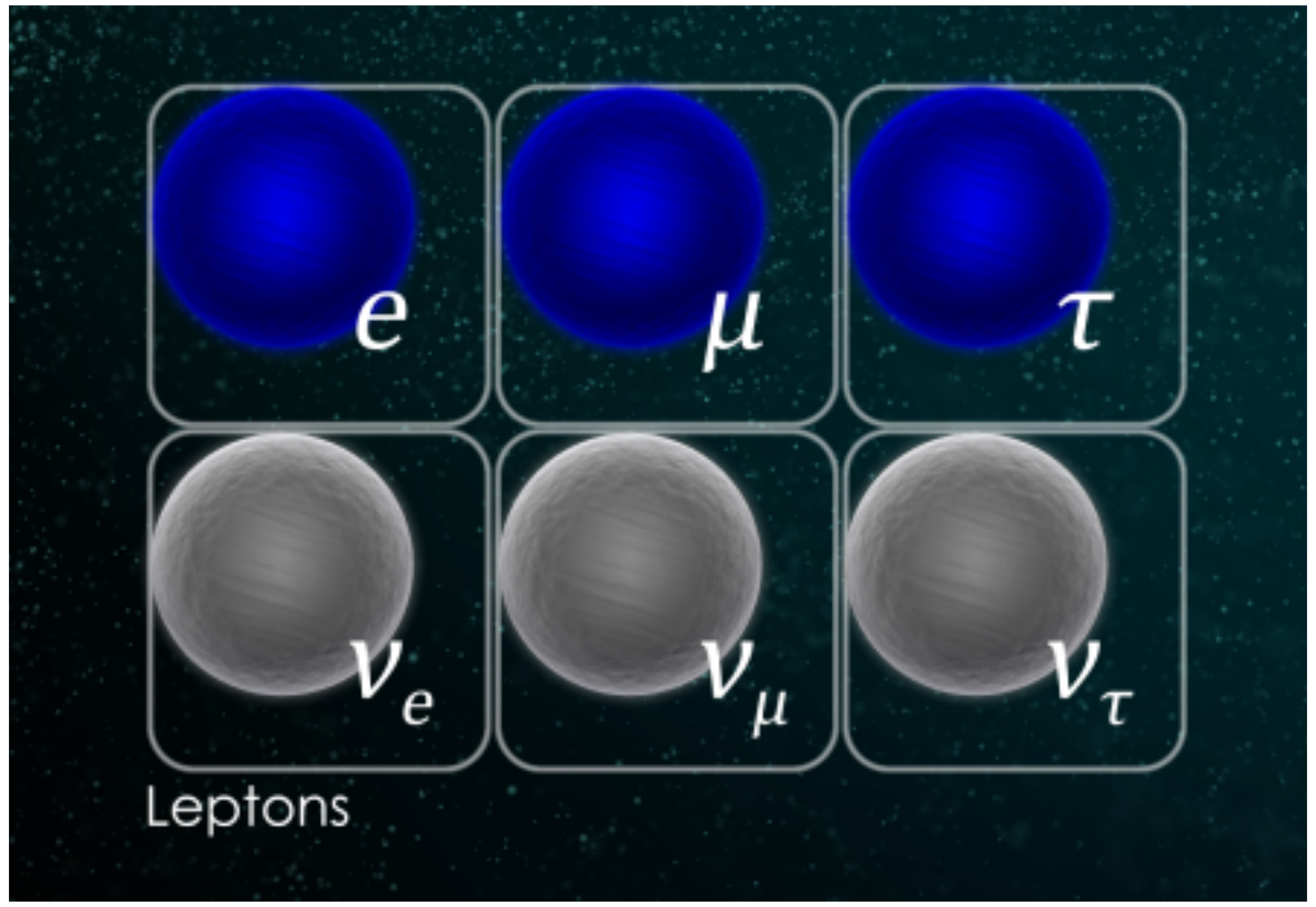

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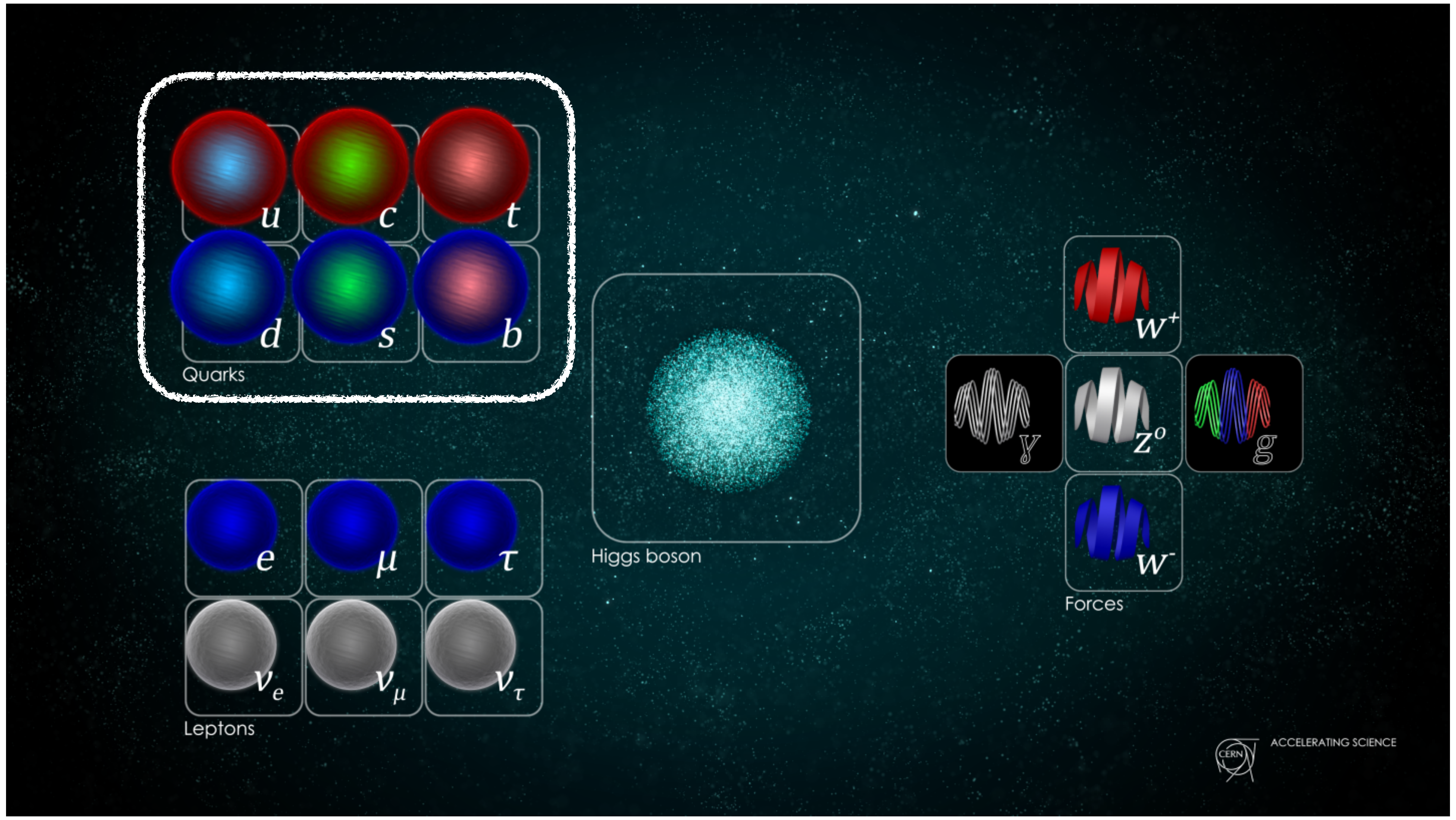


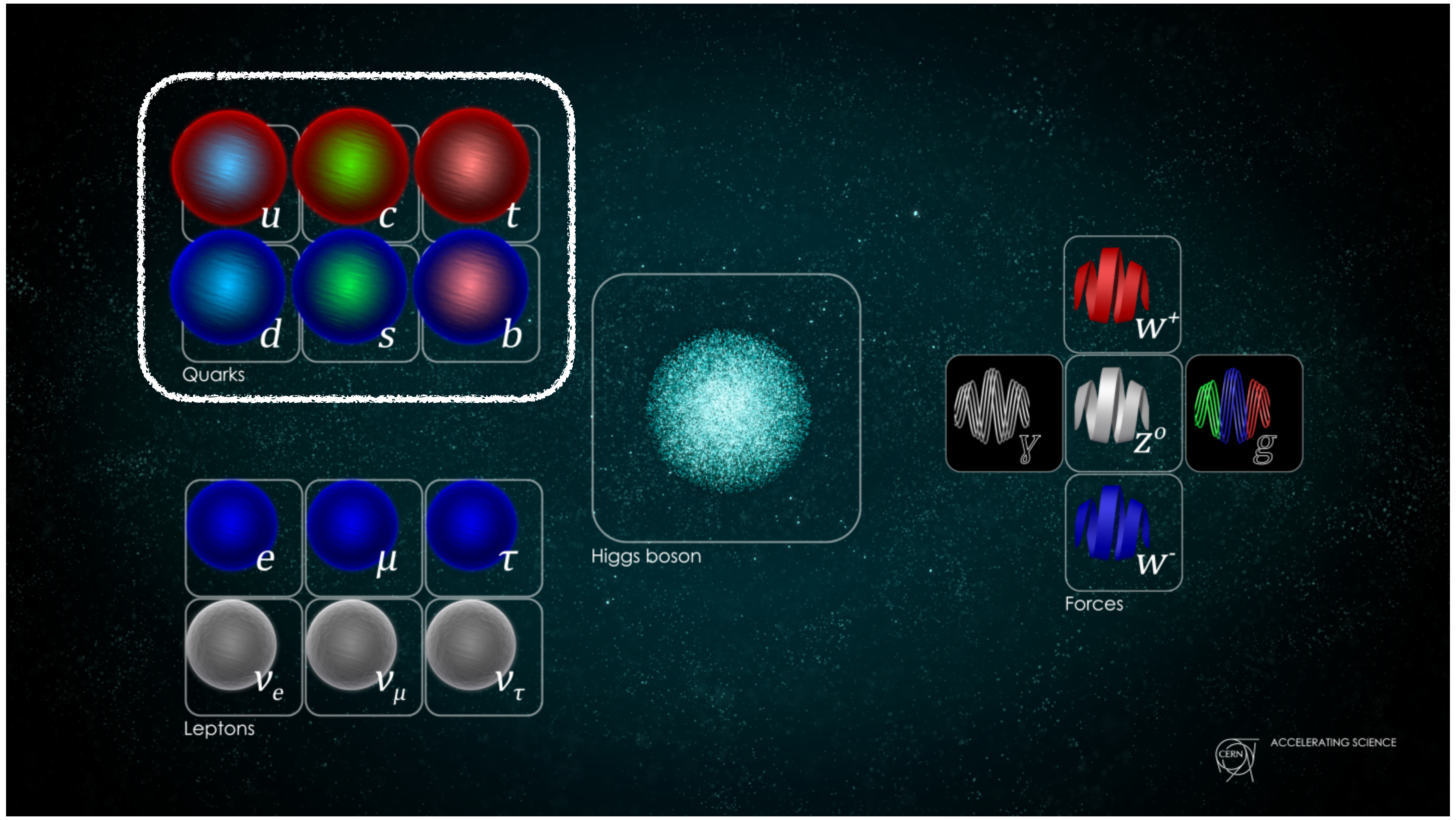
- **Yukawa couplings (determine quark masses)**
- **CKM mixing matrix (determines mixing of flavors in weak interactions)**

$$|V|^2 = \begin{pmatrix} X & Y & 1-X-Y \\ Z & W & 1-Z-W \\ 1-X-Z & 1-Y-W & X+Y+Z+W-1 \end{pmatrix}$$

$$X = 0.94936 \pm 0.00031 \quad , \quad Y = 0.05063 \pm 0.00031$$

$$Z = 0.05057 \pm 0.00031 \quad , \quad W = 0.94768 \pm 0.00031,$$

Part 3: mixing matrices



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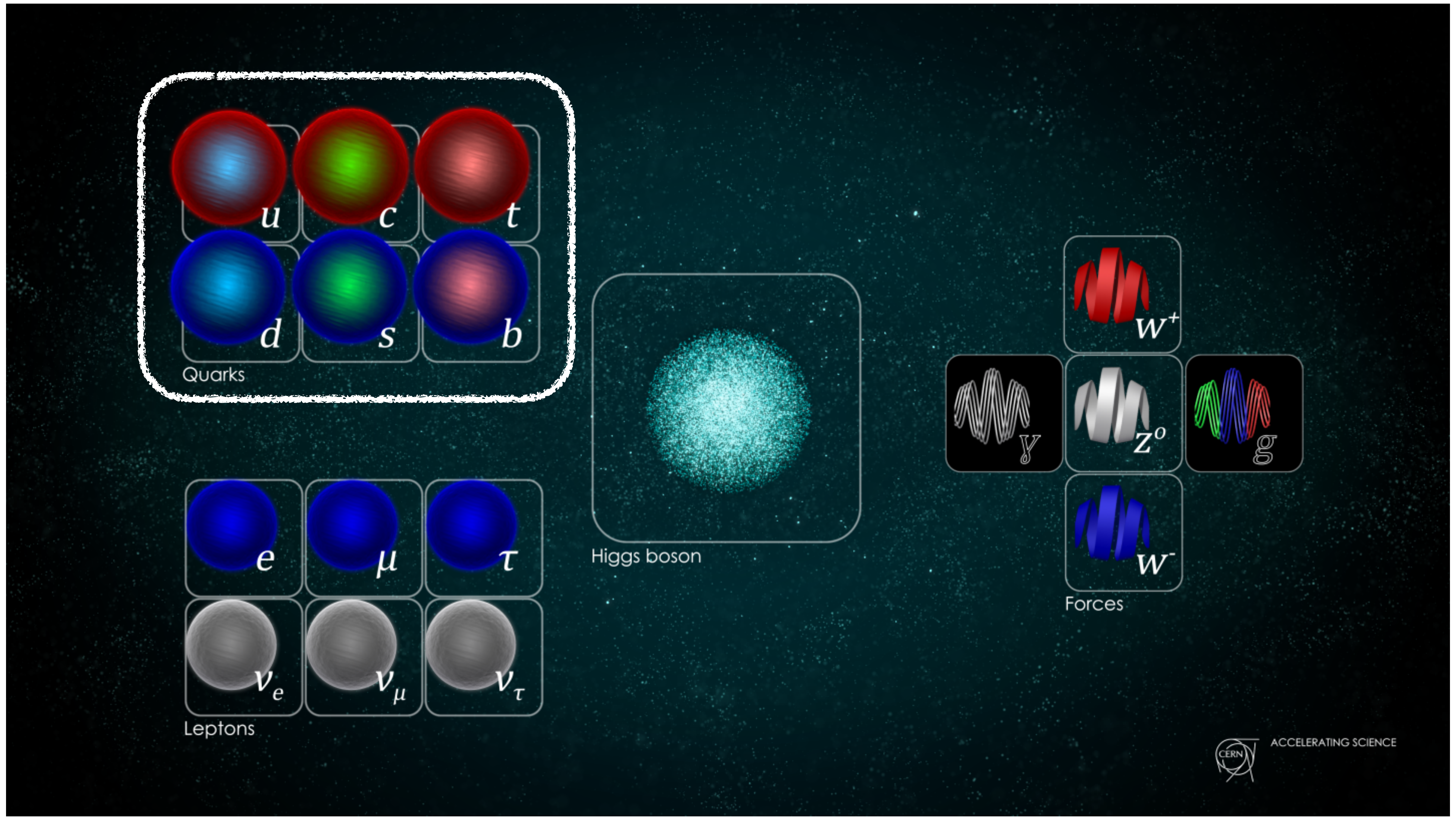

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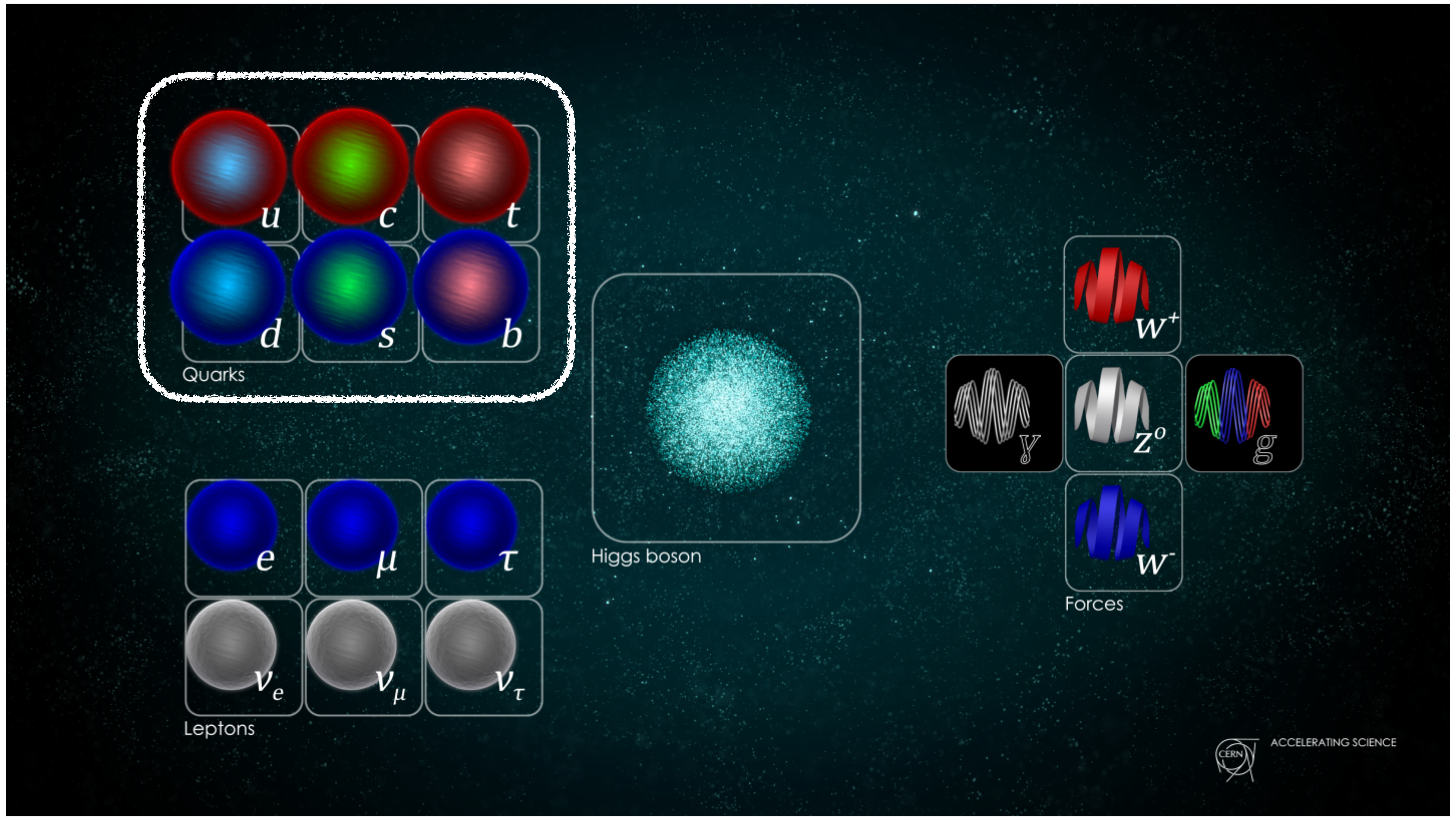

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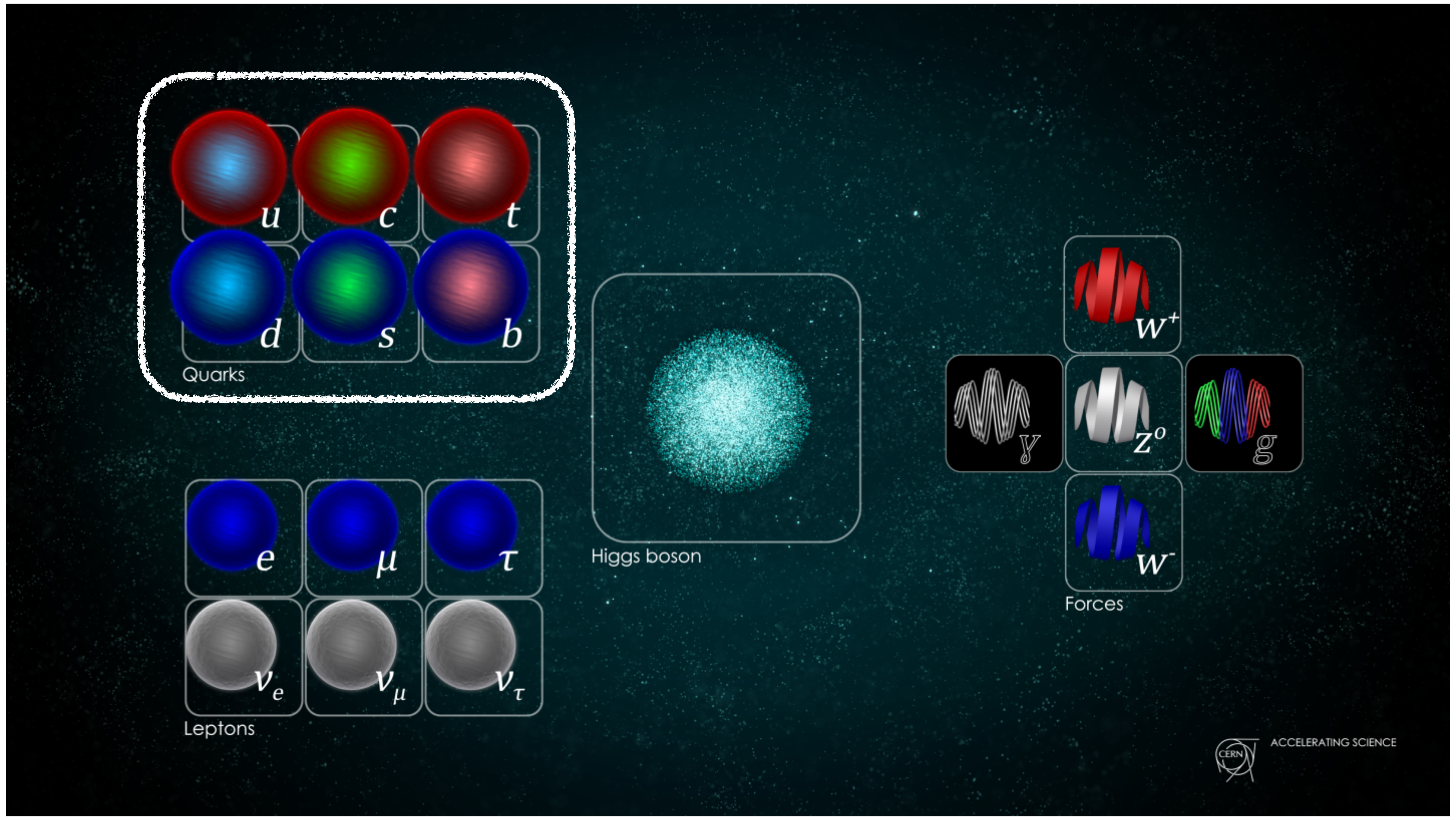

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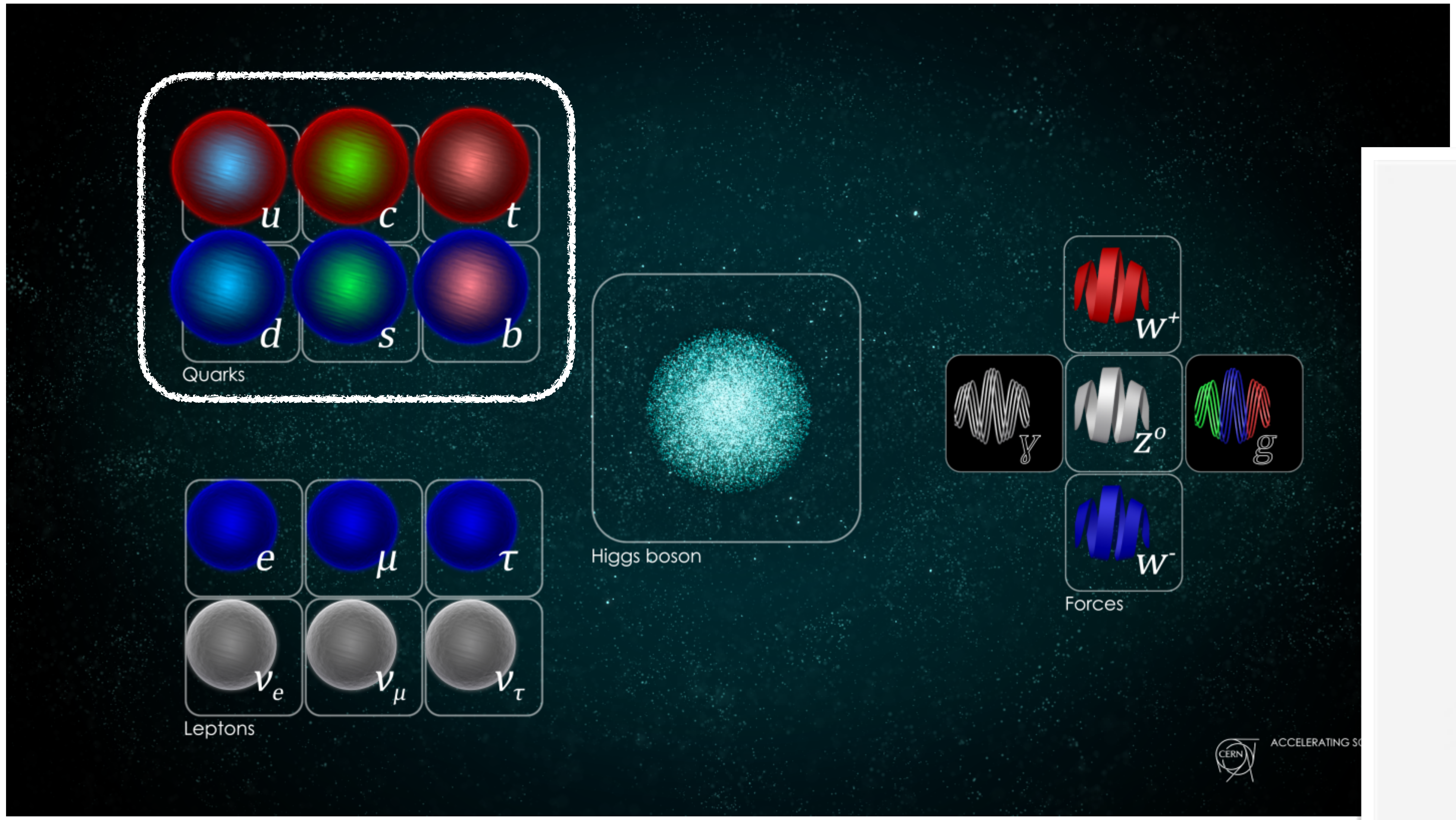

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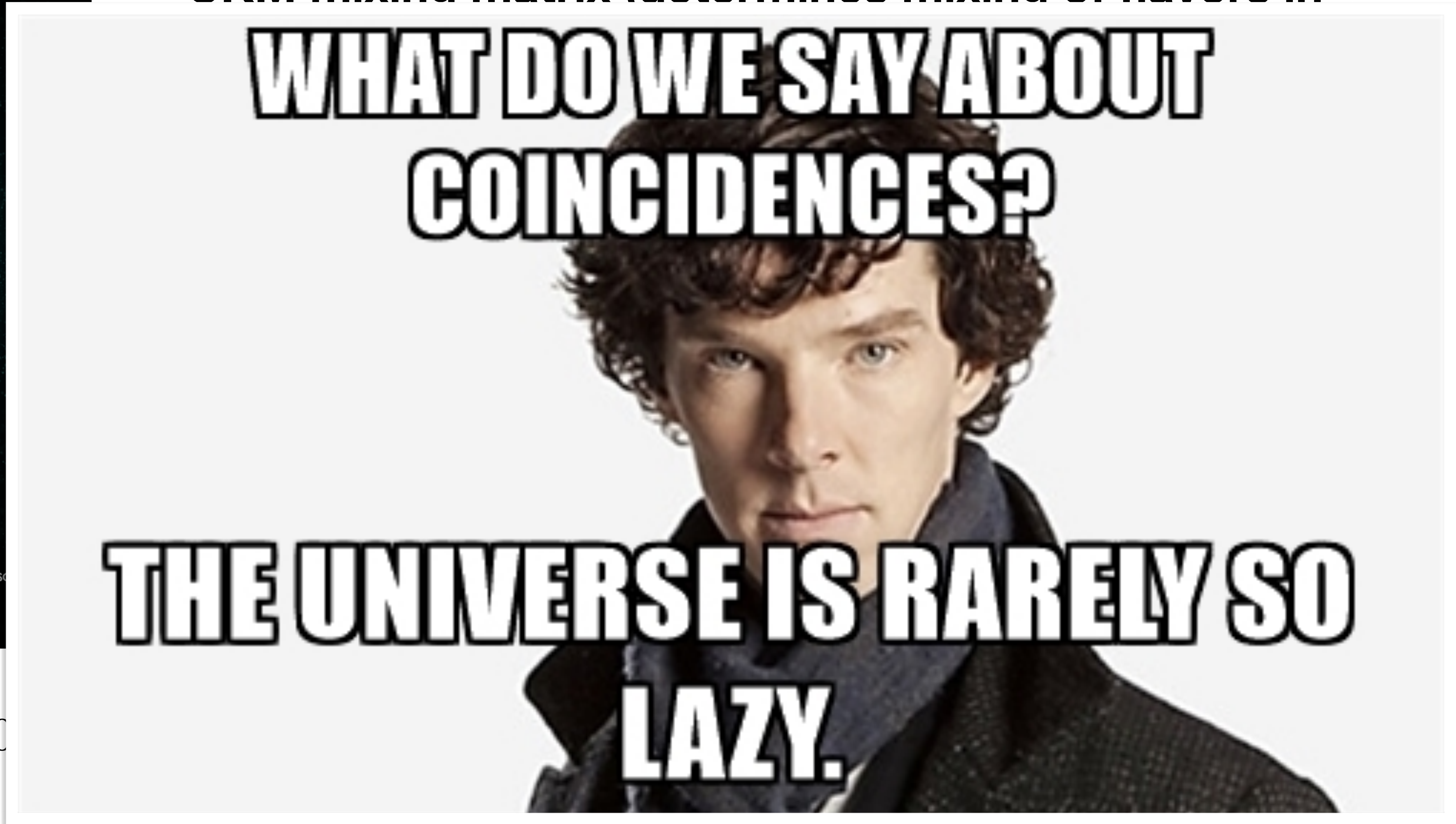

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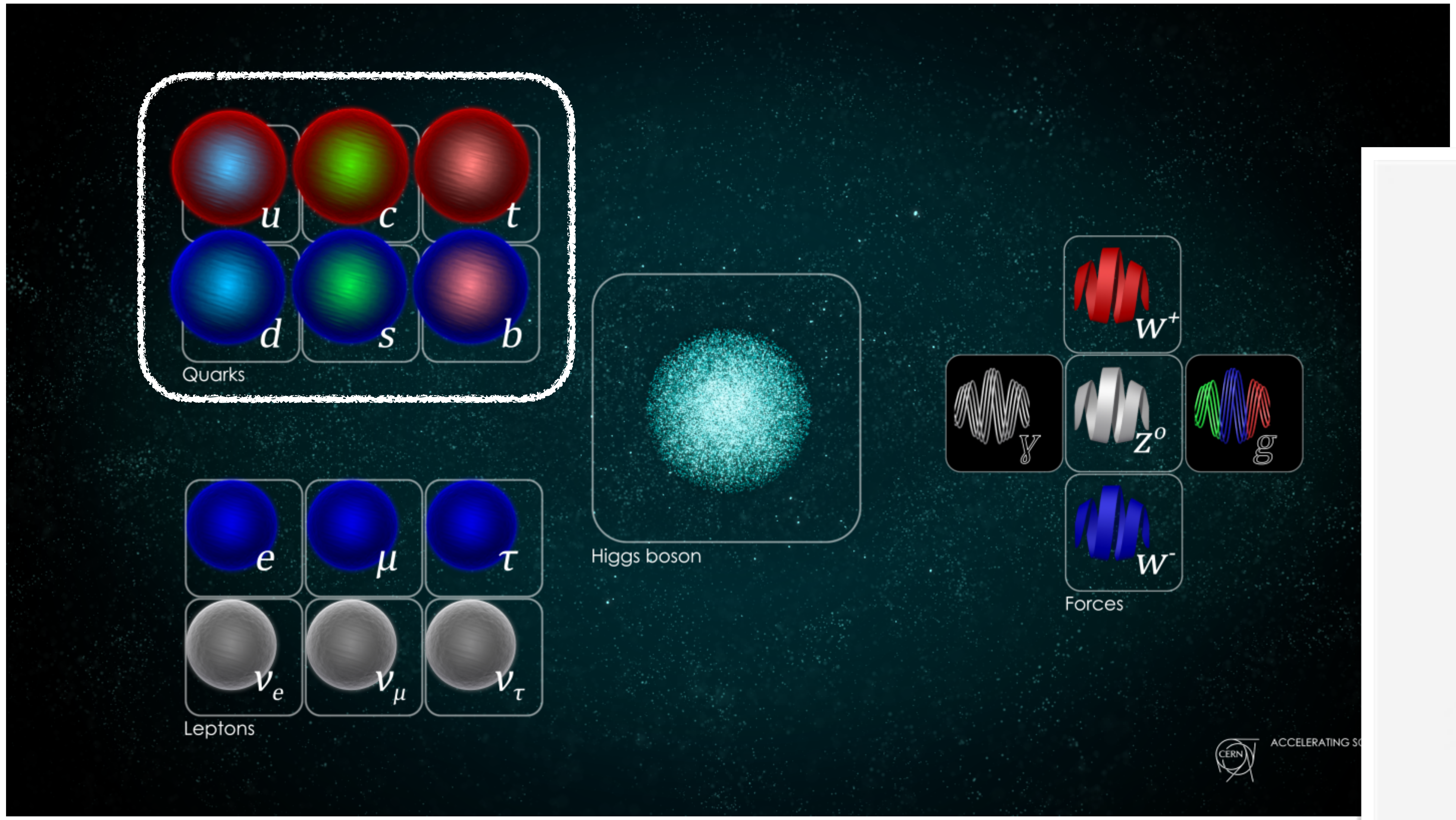

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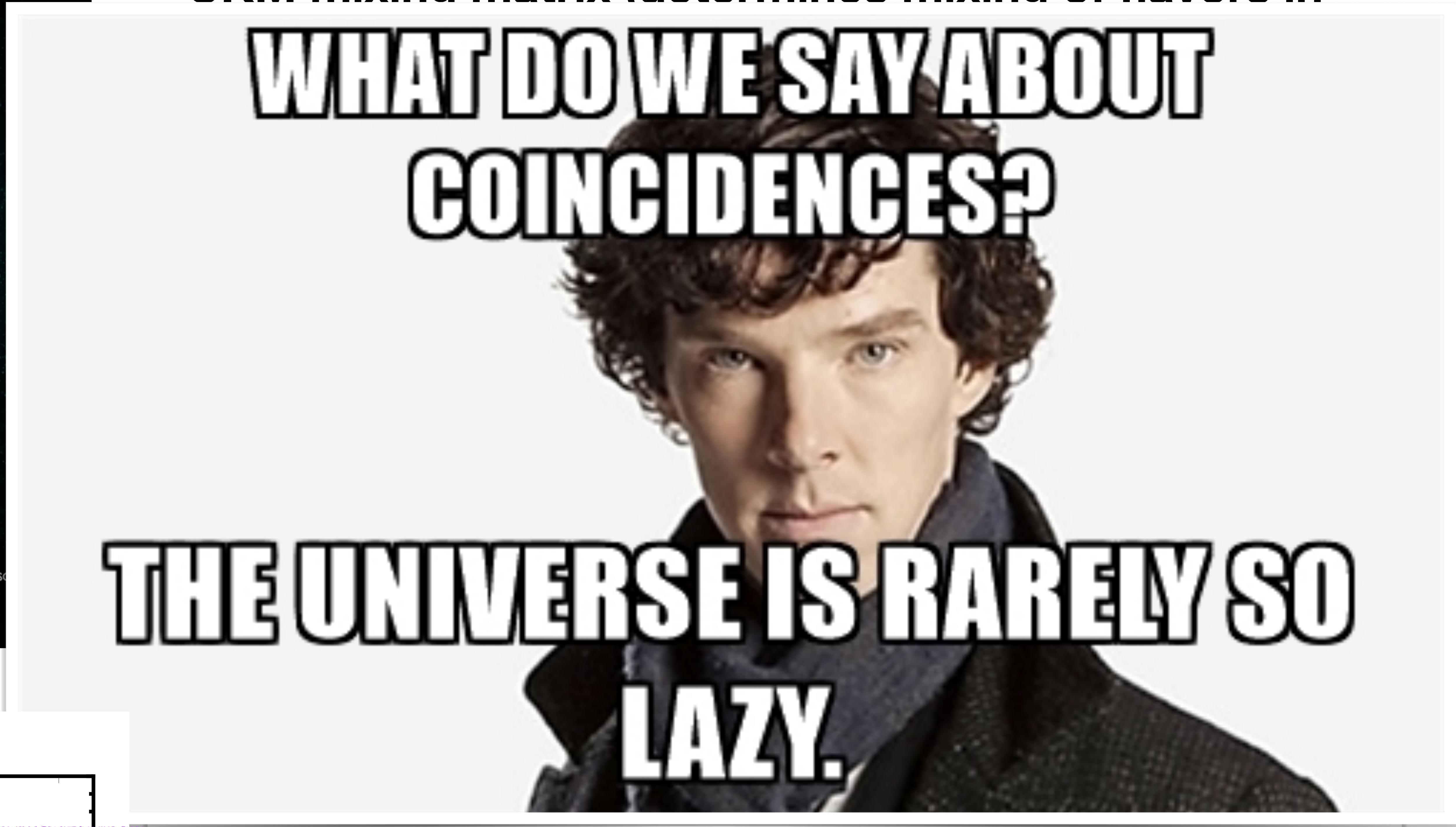

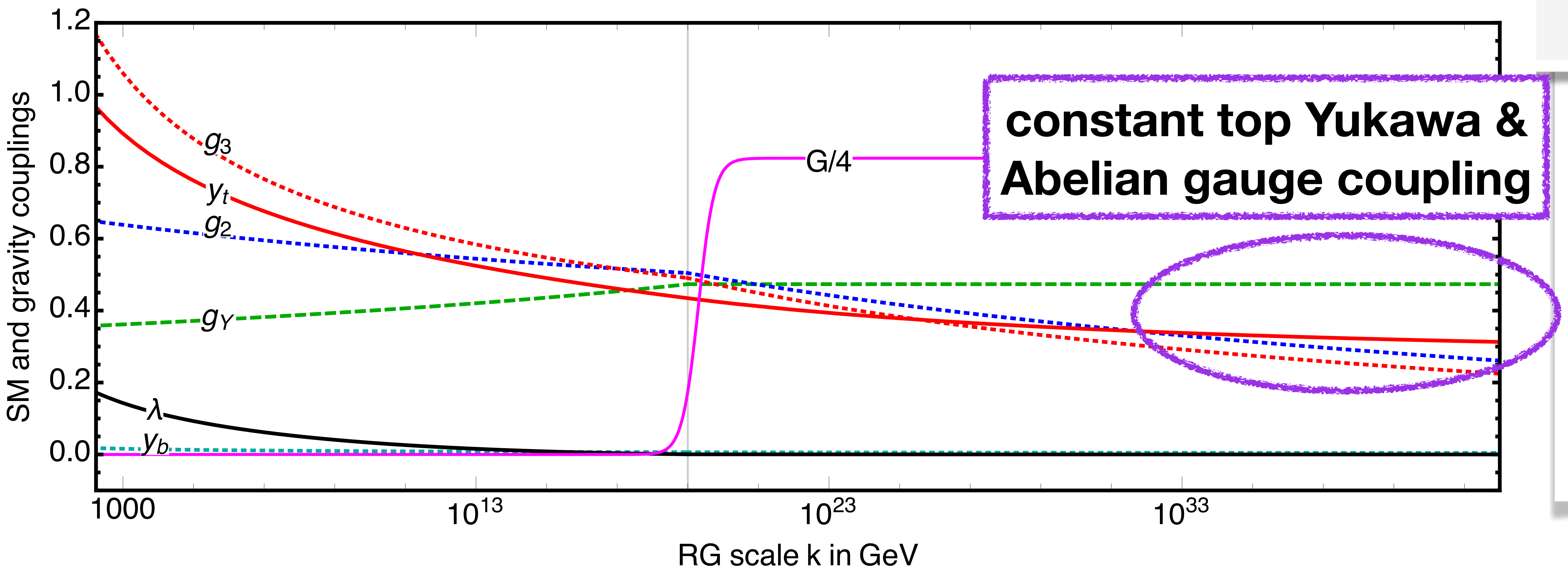

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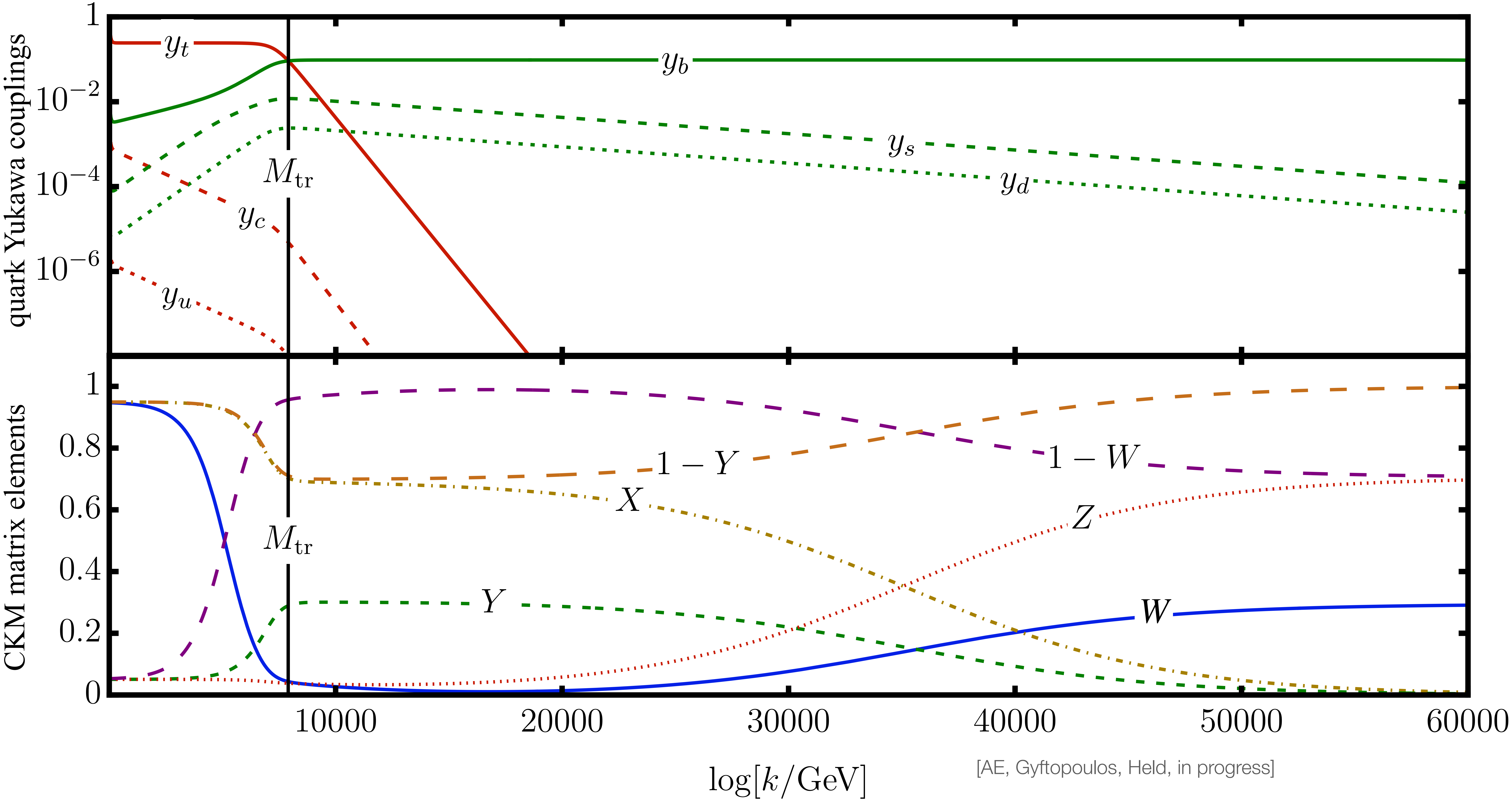

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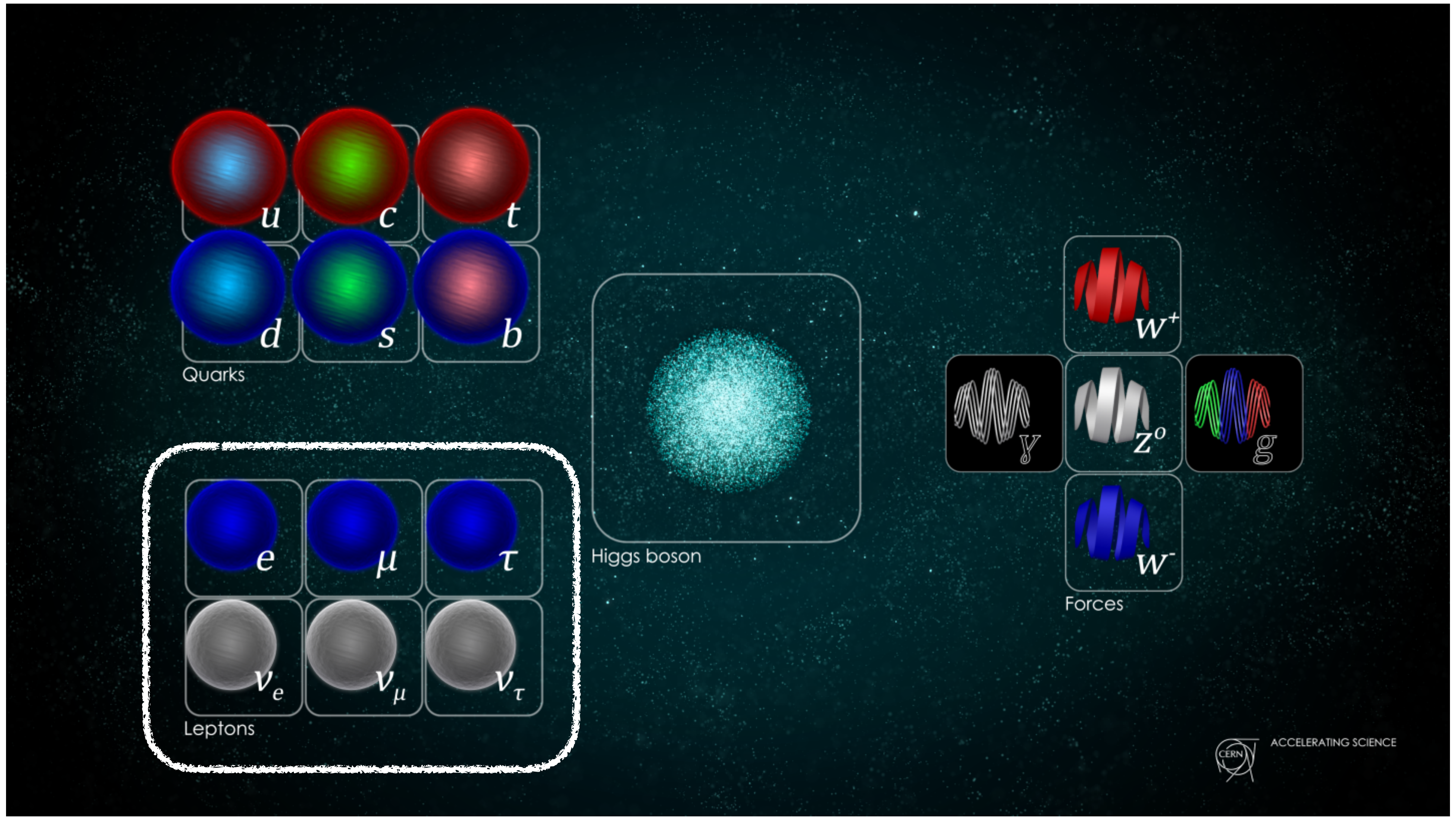

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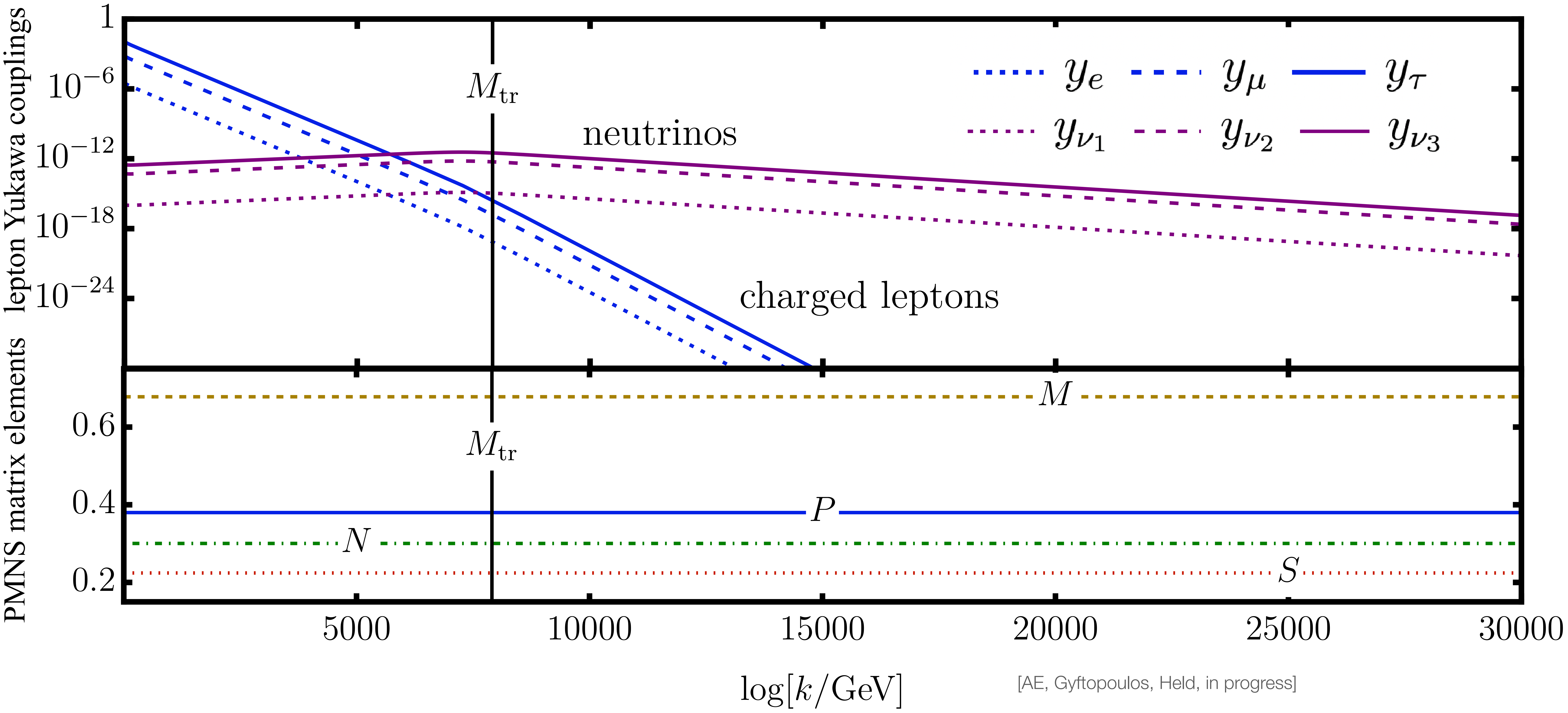

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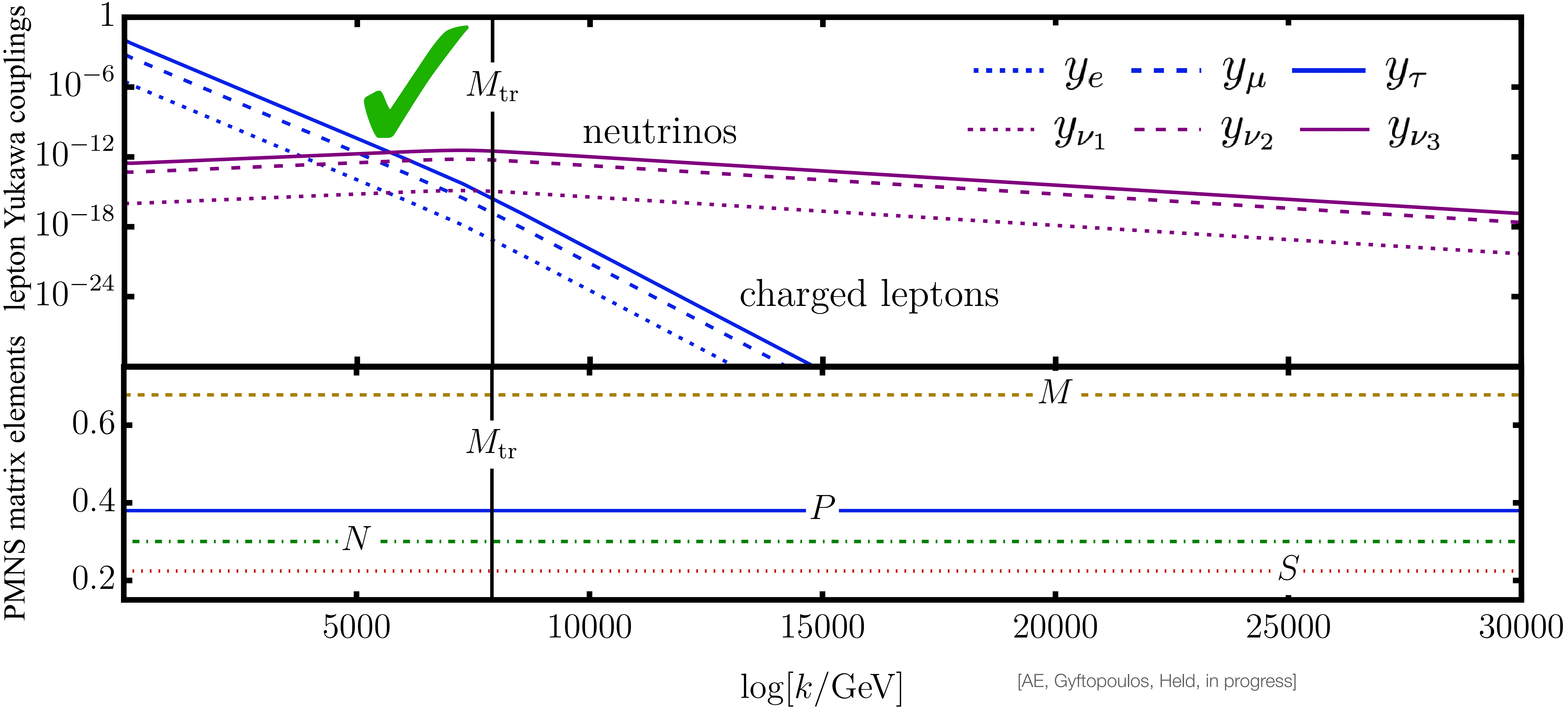

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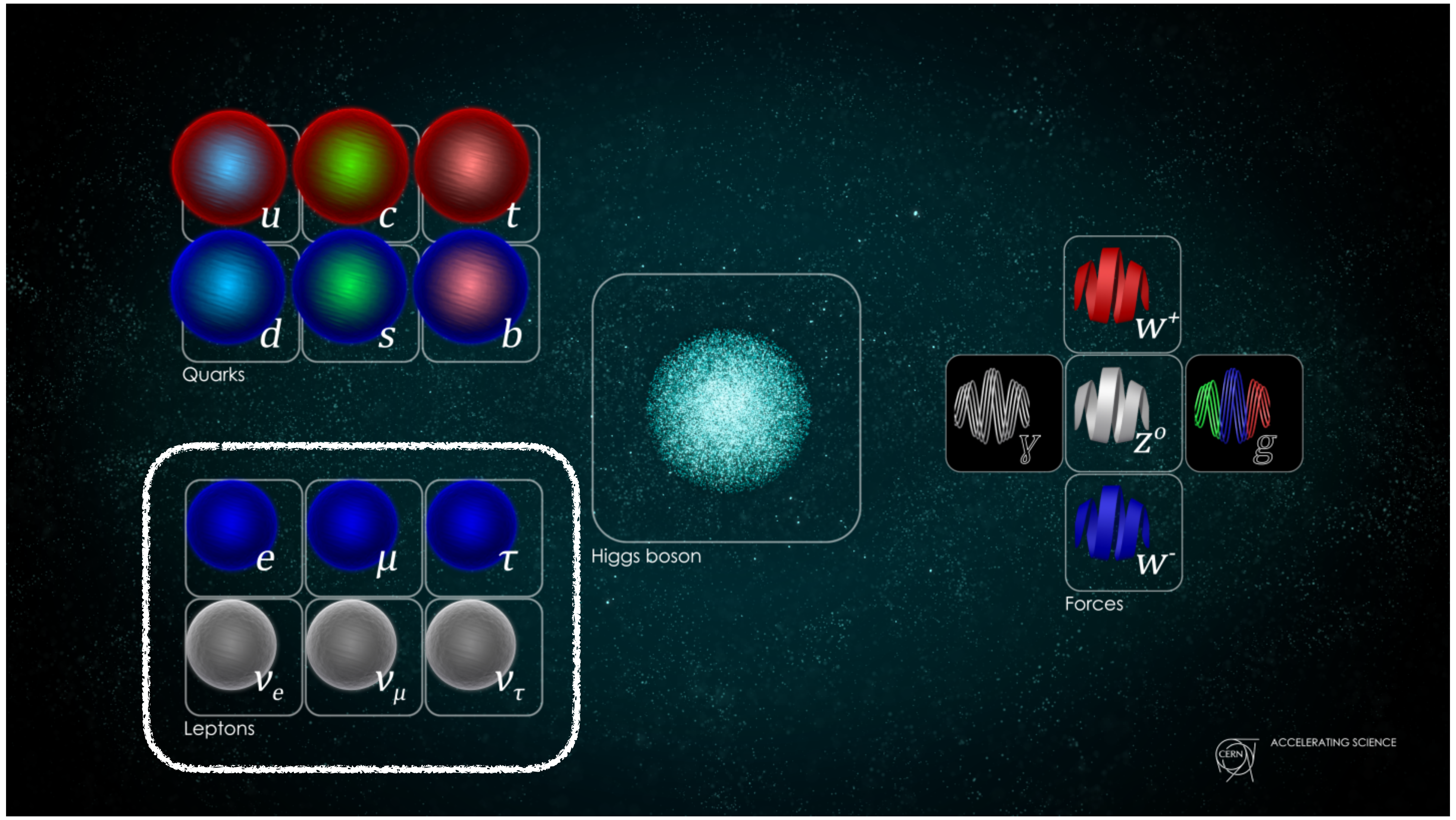

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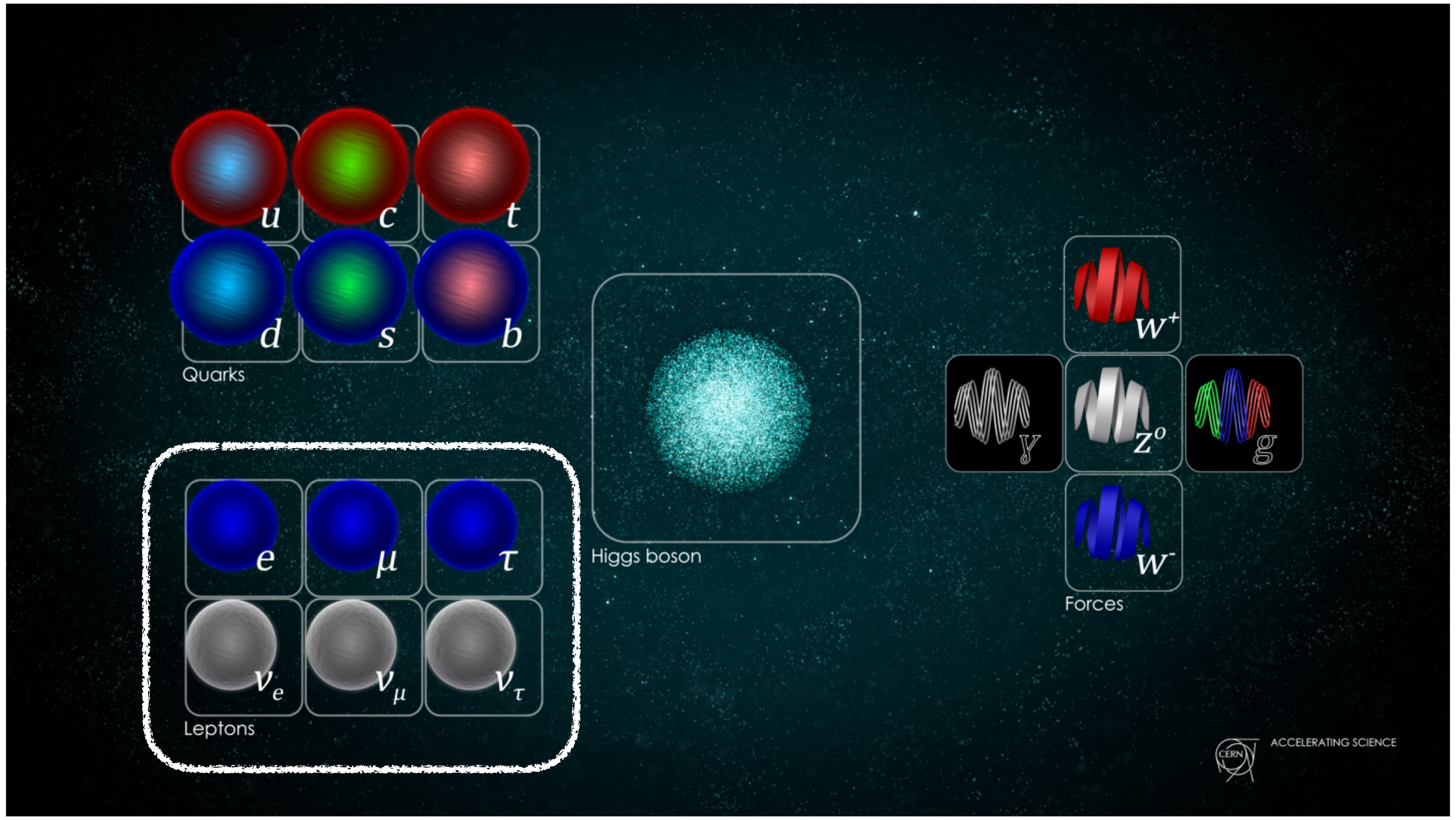

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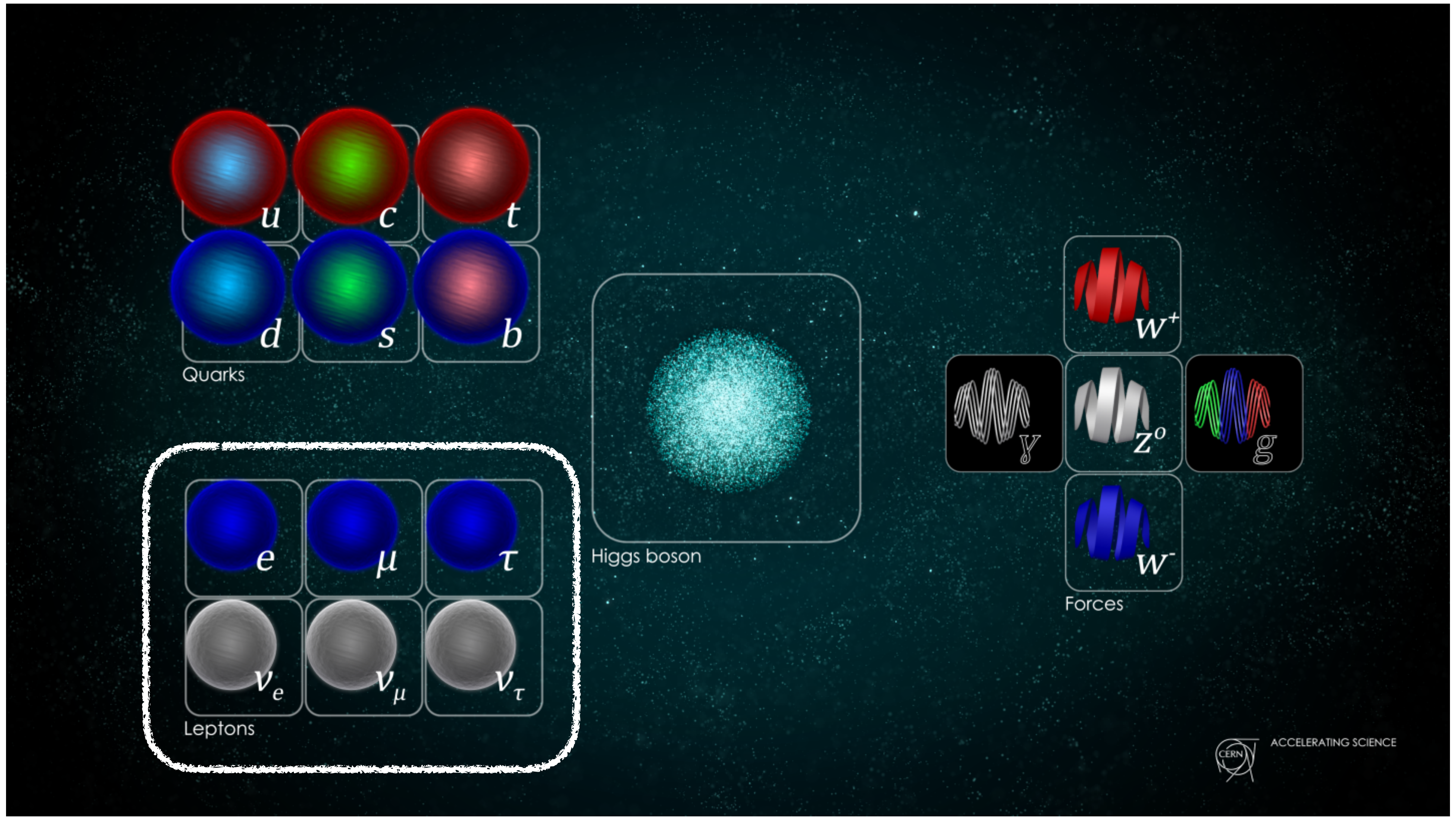

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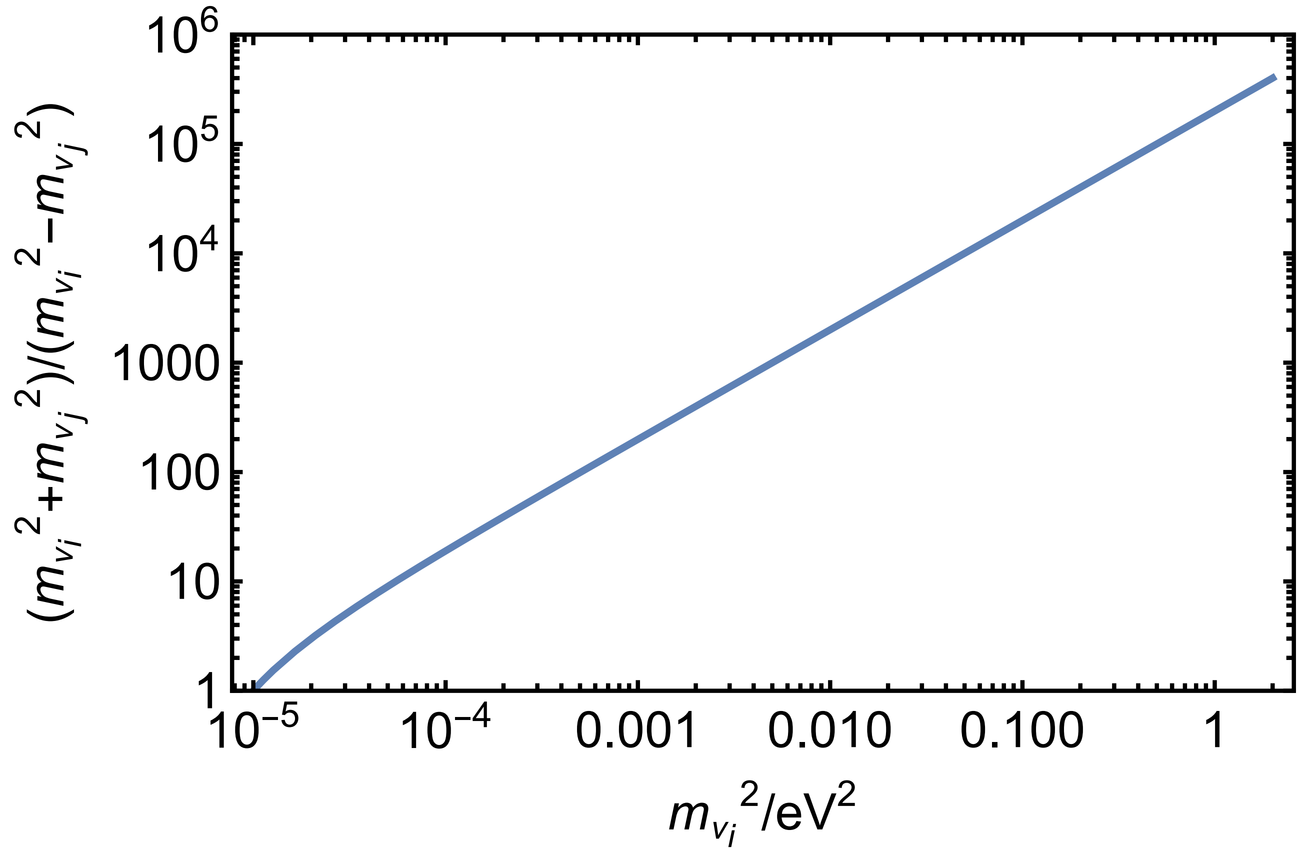

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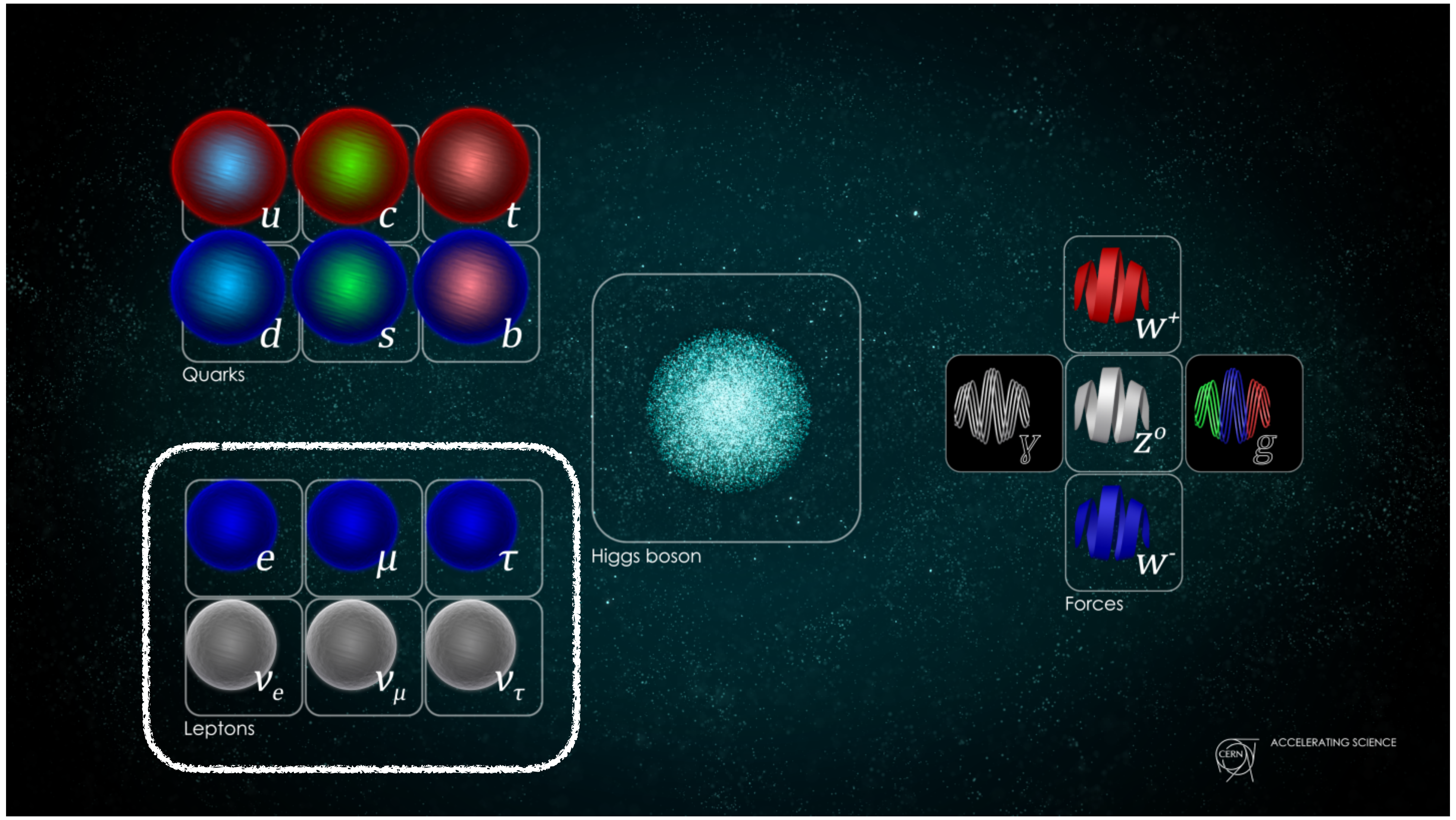

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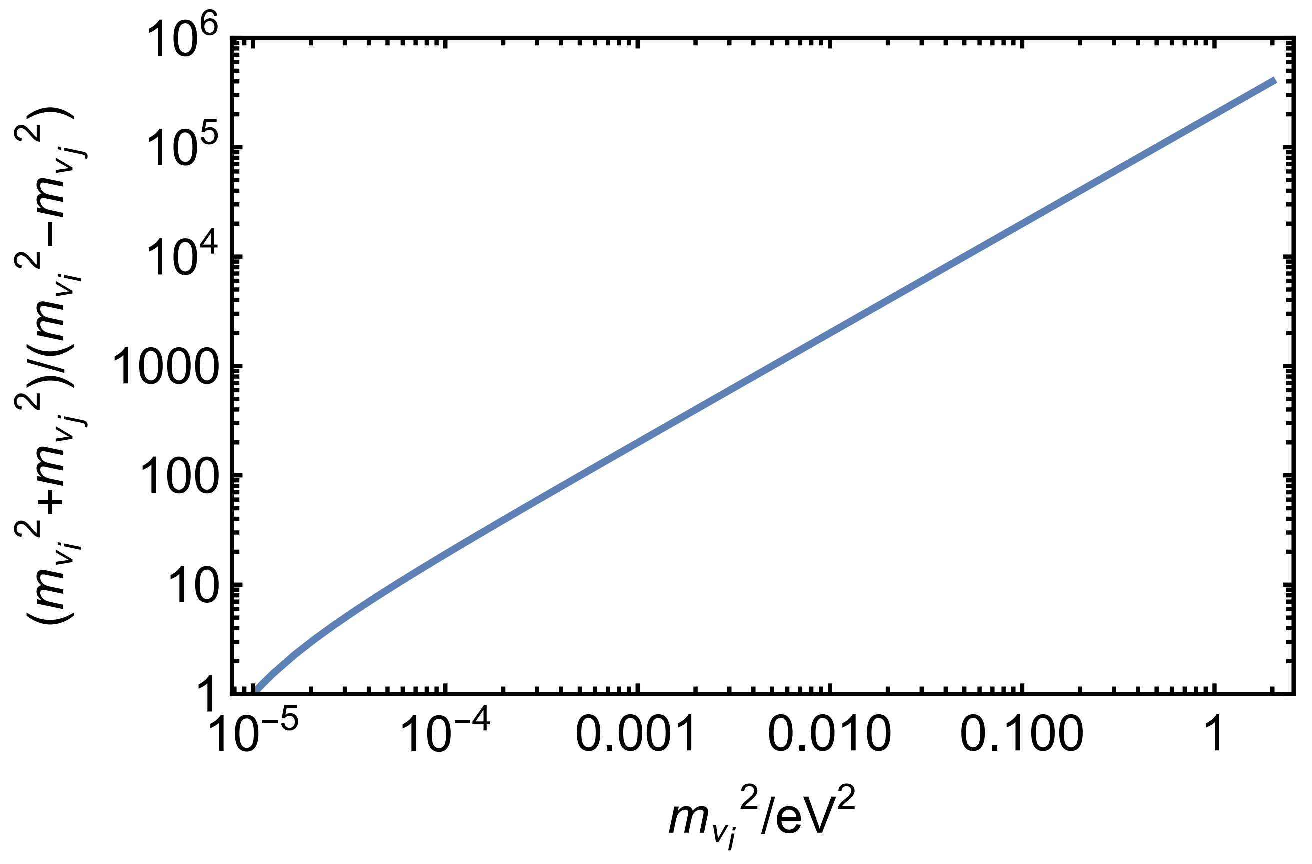

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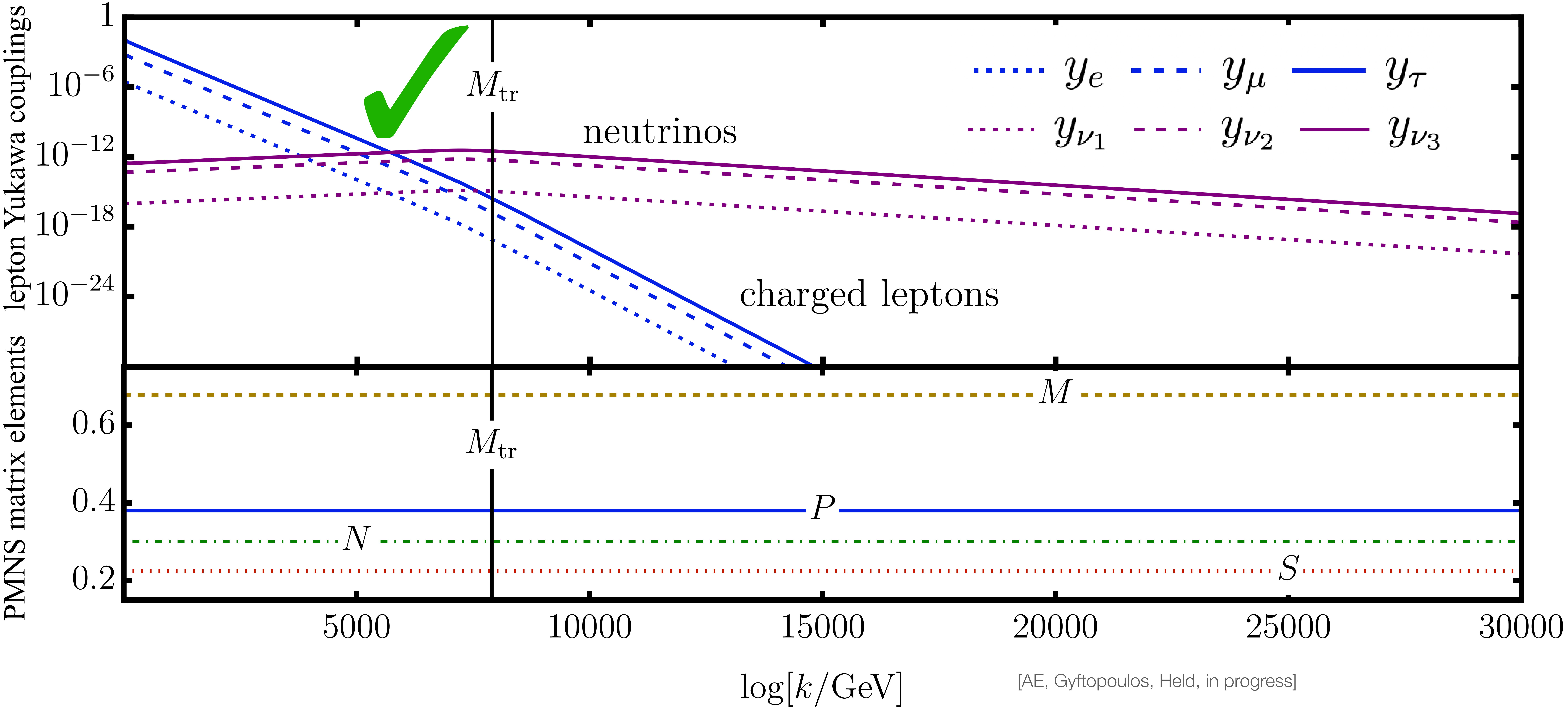

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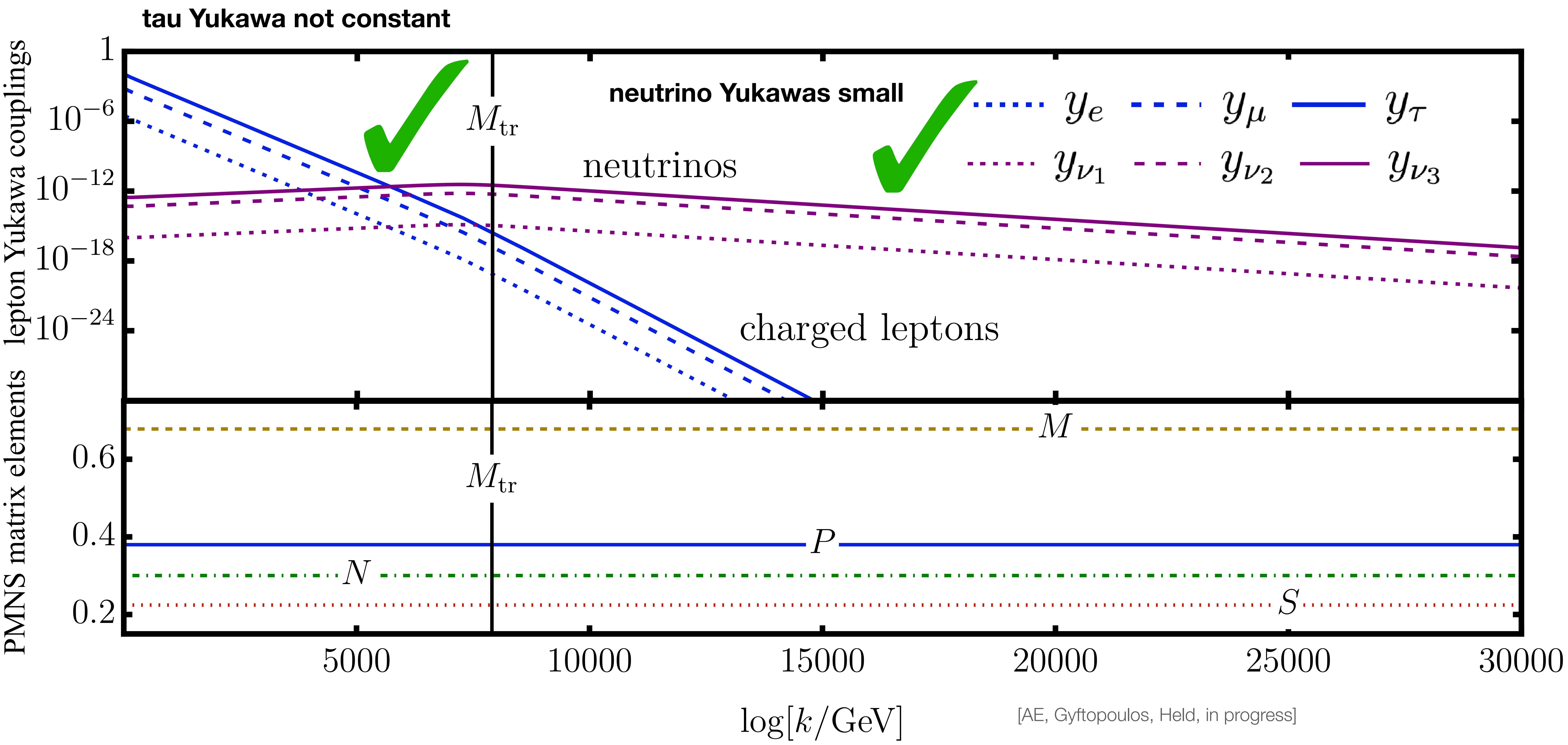

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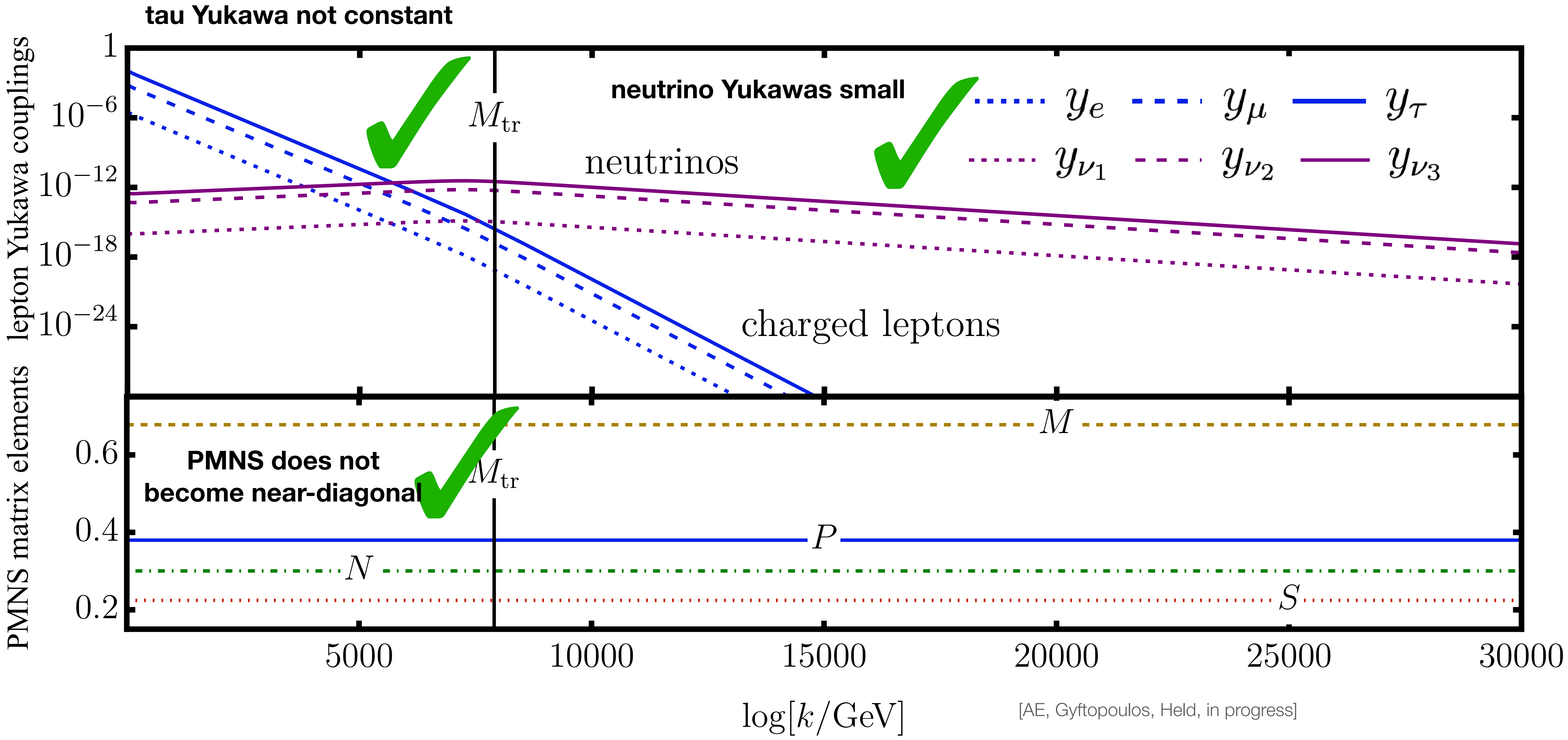

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Mixing matrix summary

Mechanism for mixing matrices to approach near-diagonal configuration, if:

heaviest fermion dominates the RG flow over long range of scales,
or relative differences between fermion Yukawa couplings become tiny.

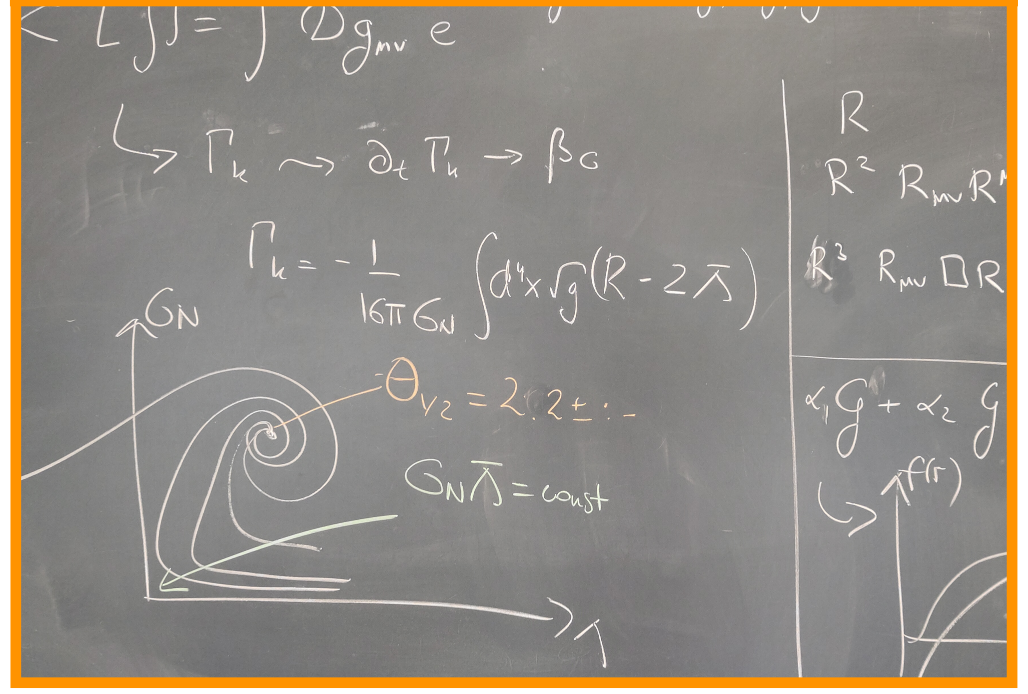
Asymptotically safe Standard Model:

- **realizes this mechanism for CKM, because top Yukawa coupling is constant and large over huge range in scales**
- **avoids this mechanism for PMNS, because tau Yukawa coupling is non-constant and overall neutrino mass scale is kept low, so relative differences do not become tiny**

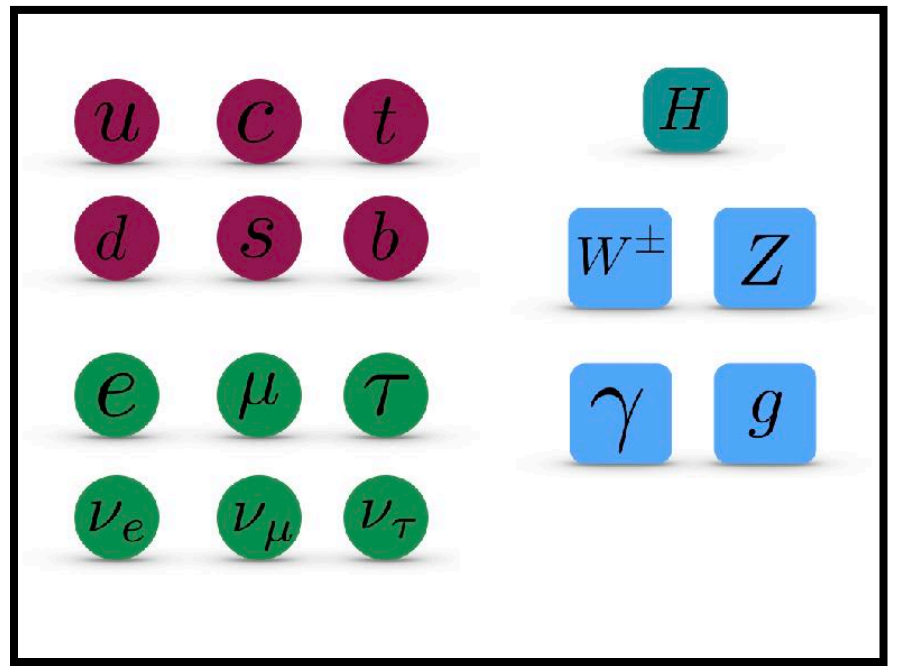
Consequence: RG flows over huge ranges of scales are suggested by observed patterns in mixing matrices

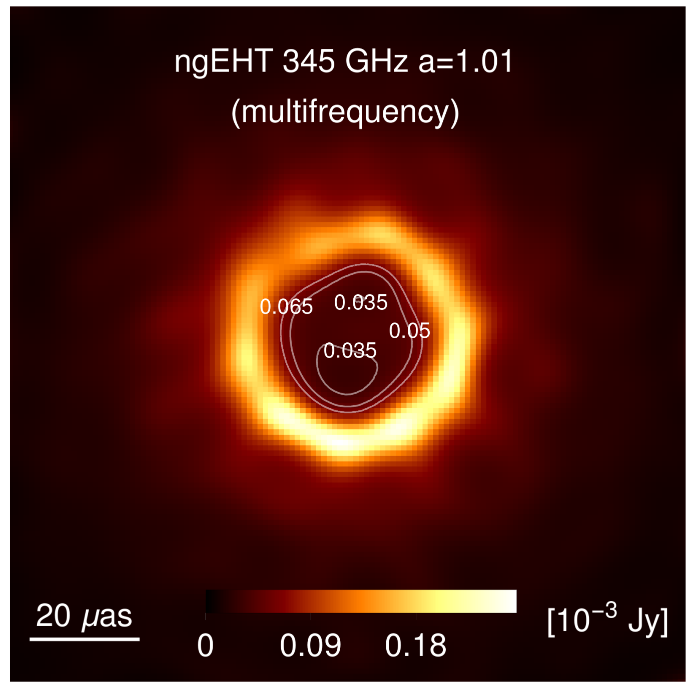
Motivation: How to test proposed theories of quantum gravity?

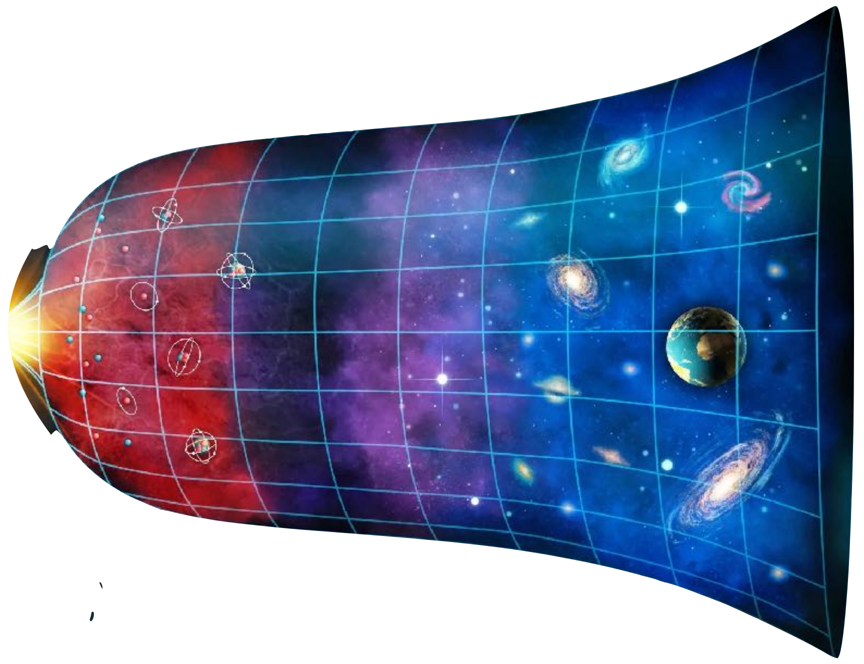
Theory of quantum gravity



Key challenge: gap in scales

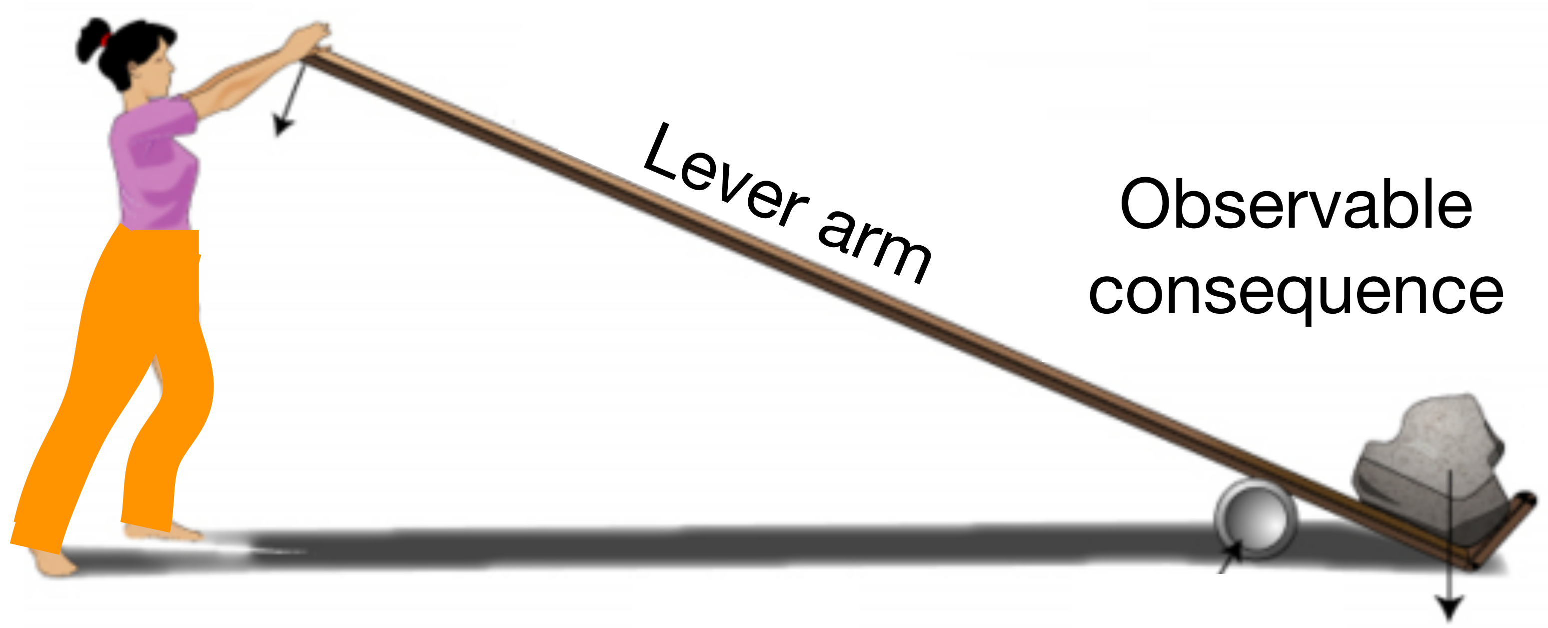






Planckian scales	Particle physics scales	Black-hole scales	Cosmological scales
10^{-35} m	10^{-17} m	10^{11} m	$> 10^{20}$ m

distance scale



Examples:

- Accumulation of Lorentz-Invariance-Violation over astrophysical distances of photons from short Gamma-Ray-Bursts
  [Amelino-Camelia, Ellis, Mavromatos Nanopoulos, Sakar '97]
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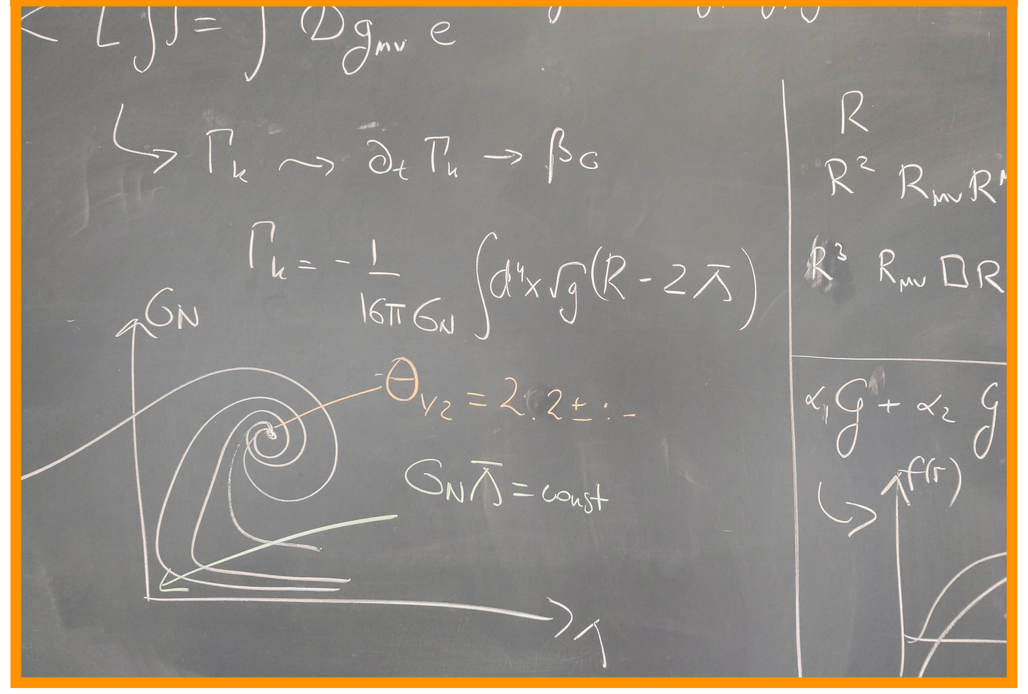

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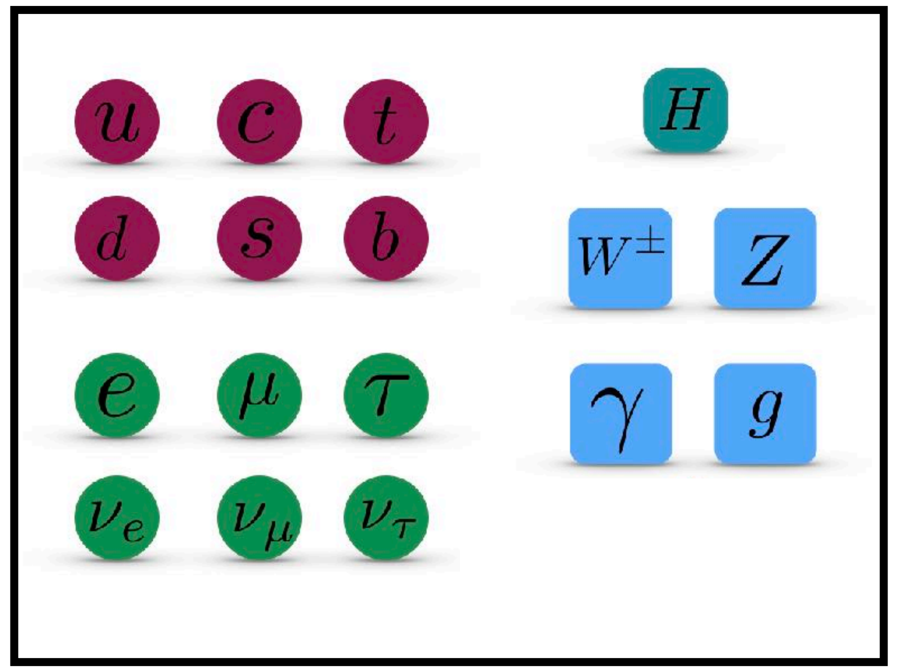

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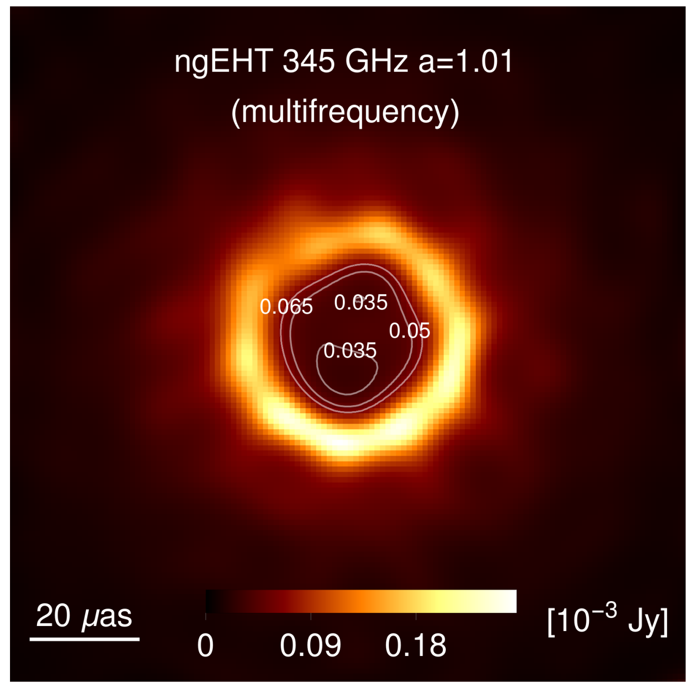

Black-hole scales

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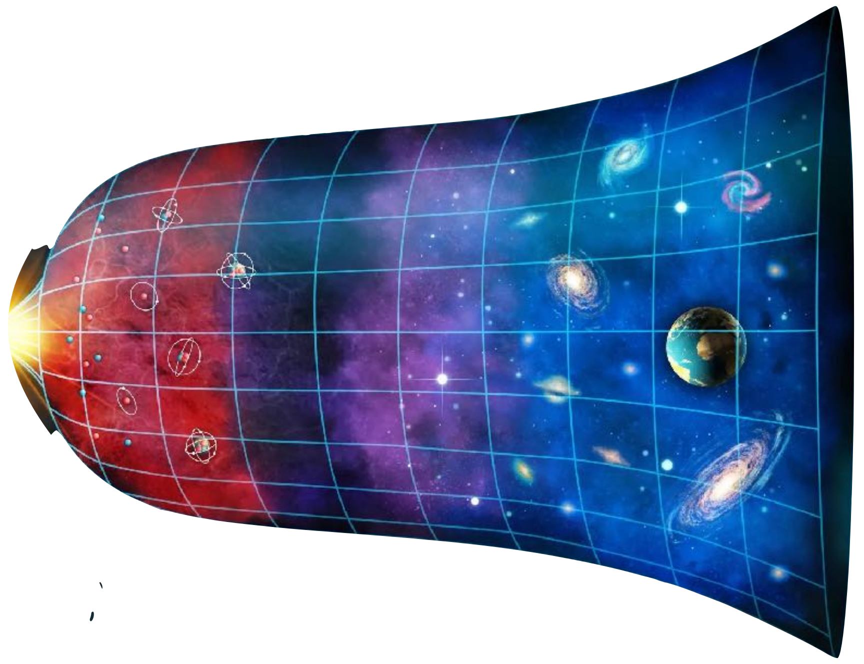
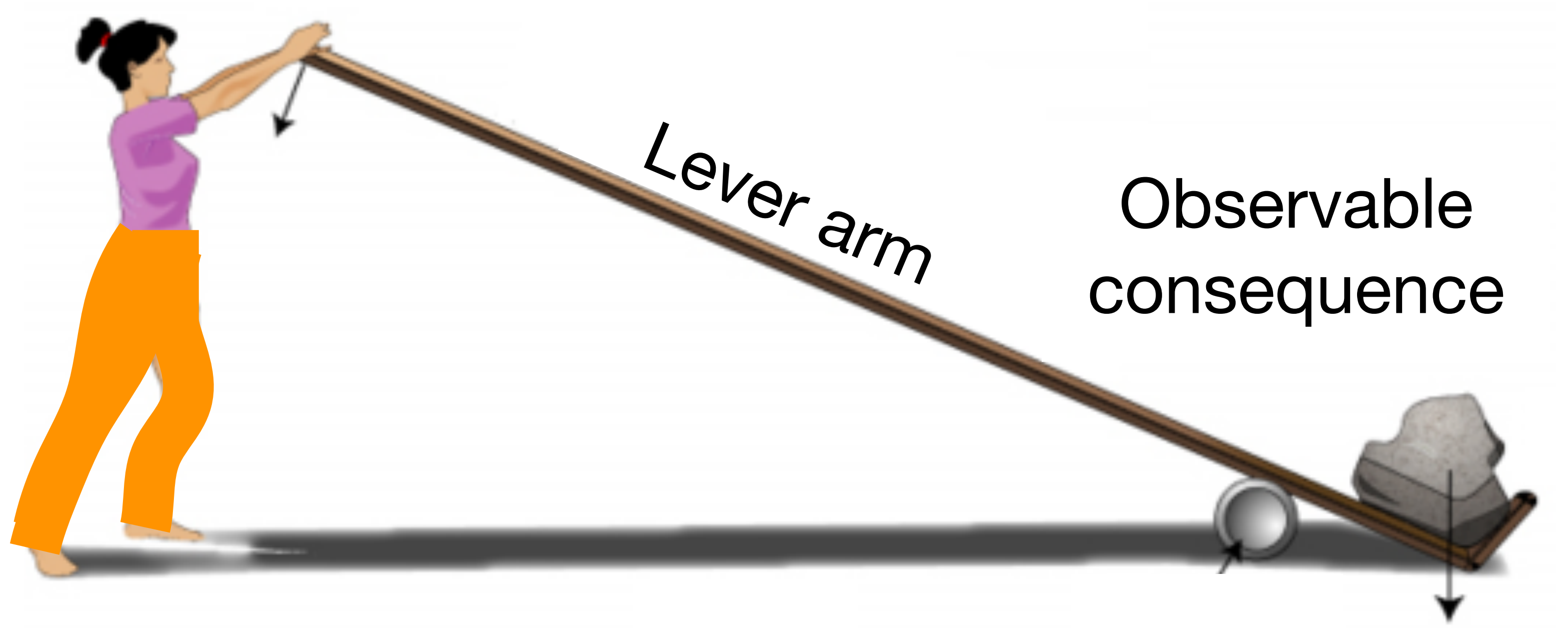


Cosmological scales

$> 10^{20}$ m

distance scale



What about the Renormalization Group perspective on Lorentz-invariance-violations and CPT violation?

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CPT & Lorentz violation and Renormalization Group flows

[AE, Schiffer ’25]

$$S_{\text{scalar}}^{\text{CPT-odd}} = i\, g_\phi \int d^4x \sqrt{g}\, n_\mu \left(\phi^* \partial^\mu \phi - \phi \partial^\mu \phi^* \right) .$$

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Experimental status: numerous constraints,

some examples: (see Kostelecky)

[Submitted on 1 Jan 2008 (v1), last revised 13 Jan 2025 (this version, v18)]

Data Tables for Lorentz and CPT Violation

Alan Kostelecky, Neil Russell

This work tabulates measured and derived values of coefficients for Lorentz and CPT violation in the Standard-Model Extension. Summary tables are extracted listing maximal attained sensitivities in the matter, photon, neutrino, and gravity sectors. Tables presenting definitions and properties are also compiled.

Comments: 160 pages, 2025 edition

$g_\gamma n_\mu < 10^{-43}\,\text{GeV}$ **(CMB)**

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$$g_i(k) = g_i(\Lambda_{\mathrm{UV}}) \cdot \left(\frac{k}{\Lambda_{\mathrm{UV}}} \right)^{f_i}$$

anomalous dimension from quantum-gravity fluctuations

- **if $f_i < 0$, $g_i(k)$ generically large**
- **if $f_i > 0$, $g_i(k)$ generically small**

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Experimental status: numerous constraints,

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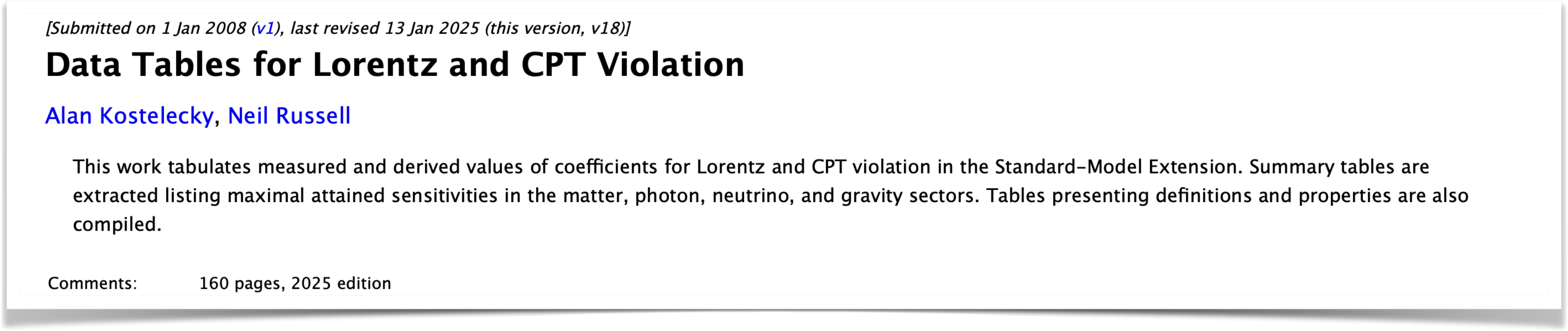
[Submitted on 1 Jan 2008 (v1), last revised 13 Jan 2025 (this version, v18)]

Data Tables for Lorentz and CPT Violation

Alan Kostelecky, Neil Russell

This work tabulates measured and derived values of coefficients for Lorentz and CPT violation in the Standard-Model Extension. Summary tables are extracted listing maximal attained sensitivities in the matter, photon, neutrino, and gravity sectors. Tables presenting definitions and properties are also compiled.

Comments: 160 pages, 2025 edition

$g_\gamma n_\mu < 10^{-43}\,\mathrm{GeV}$ **(CMB)**

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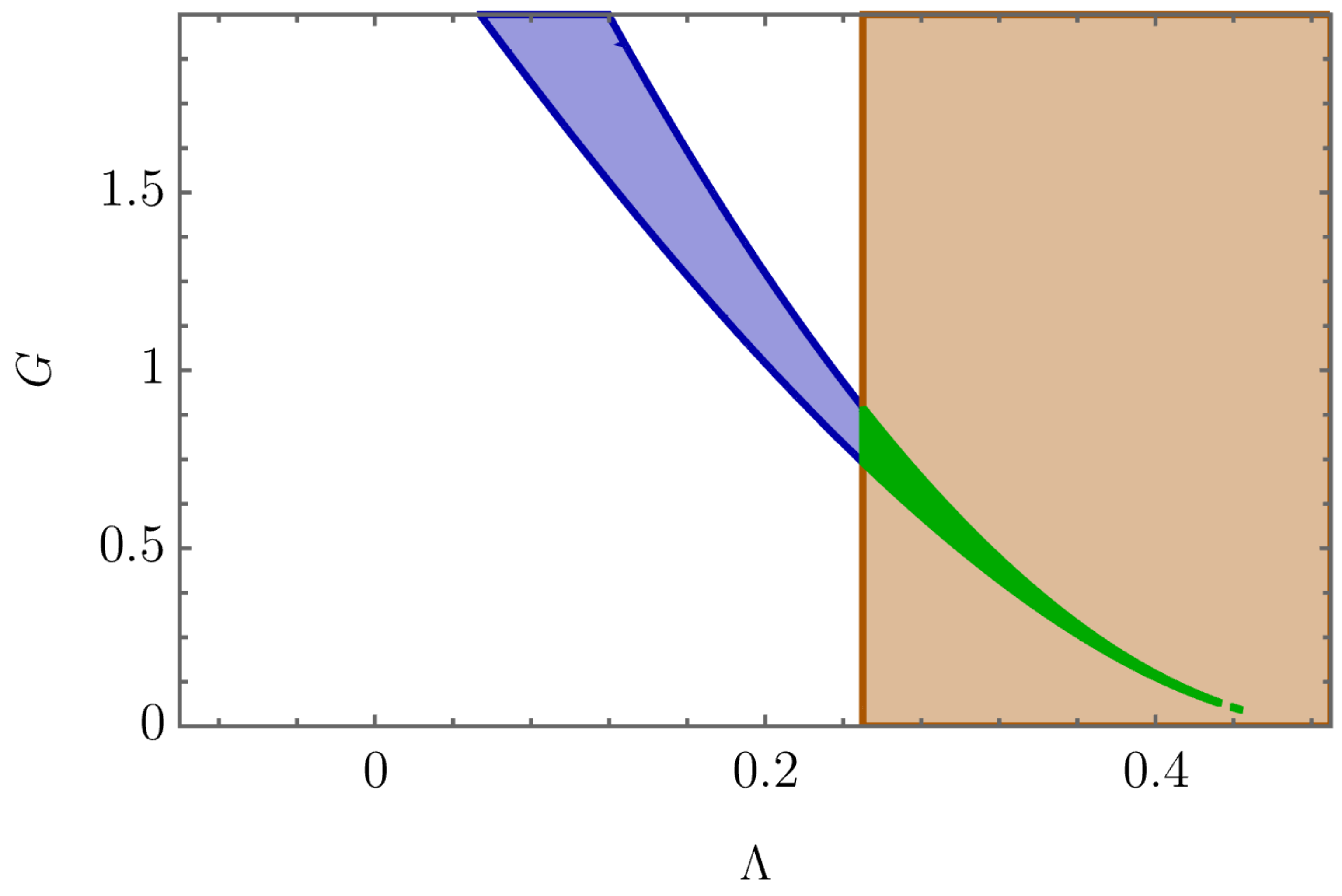

$f_\phi > 0$

$f_\gamma > 0$

$f_\gamma > 0 \;\&\; f_\phi > 0$

$f_\psi < 0$ **everywhere**

CPT & Lorentz violation and Renormalization Group flows

[AE, Schiffer '25]

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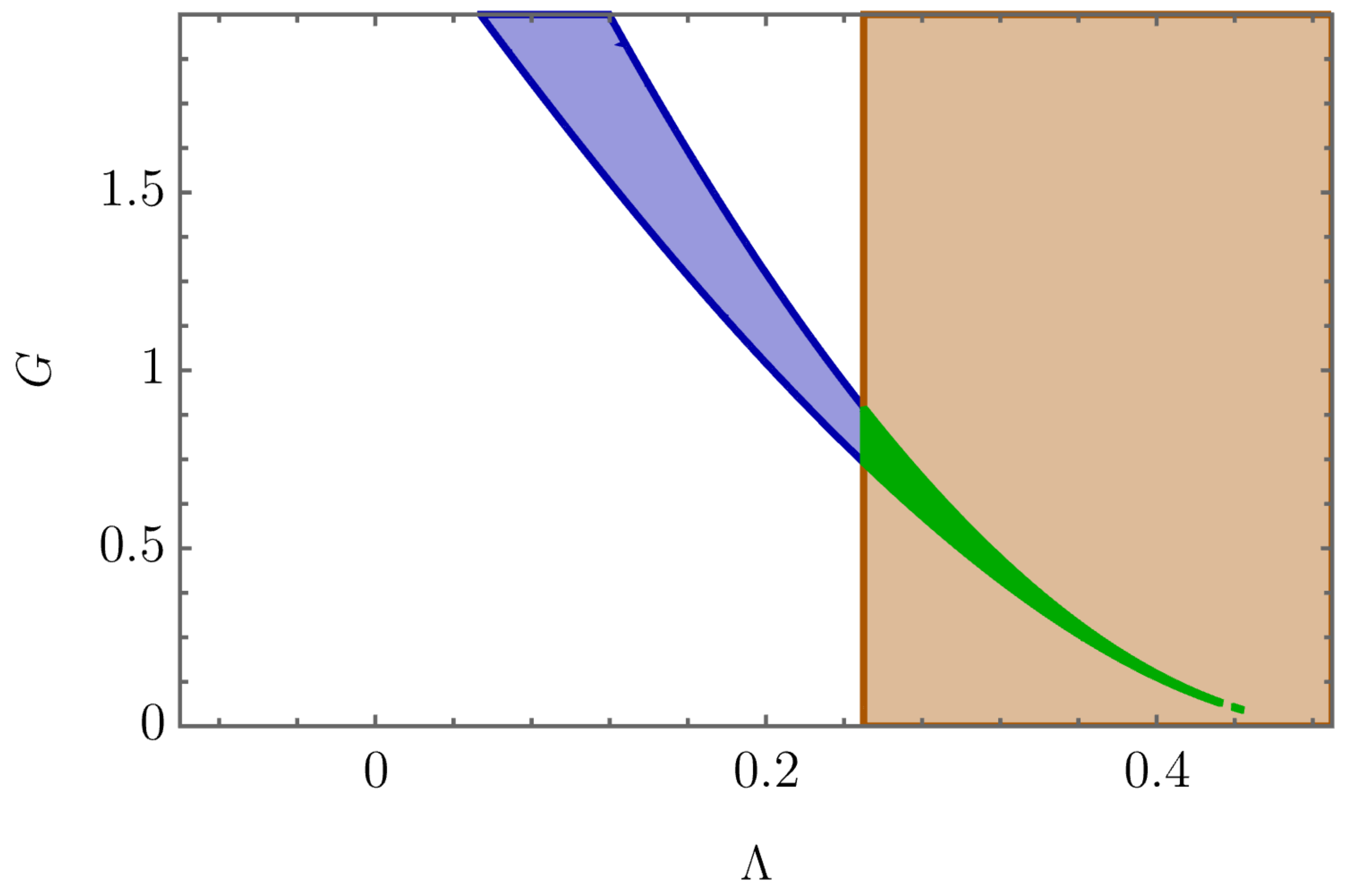

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$\Rightarrow$ **quantum-gravity theories need a mechanism to ensure** $g_i(\Lambda_{\mathrm{UV}}) = 0$

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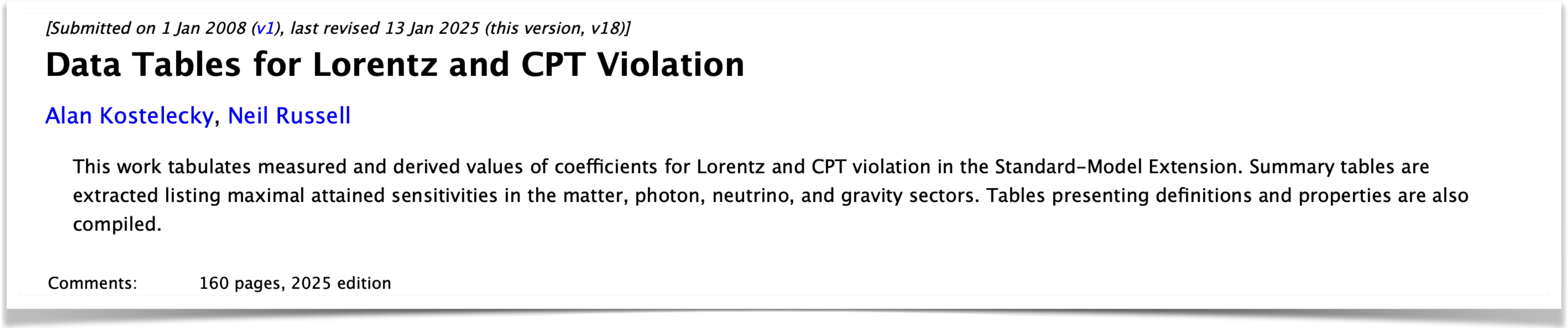
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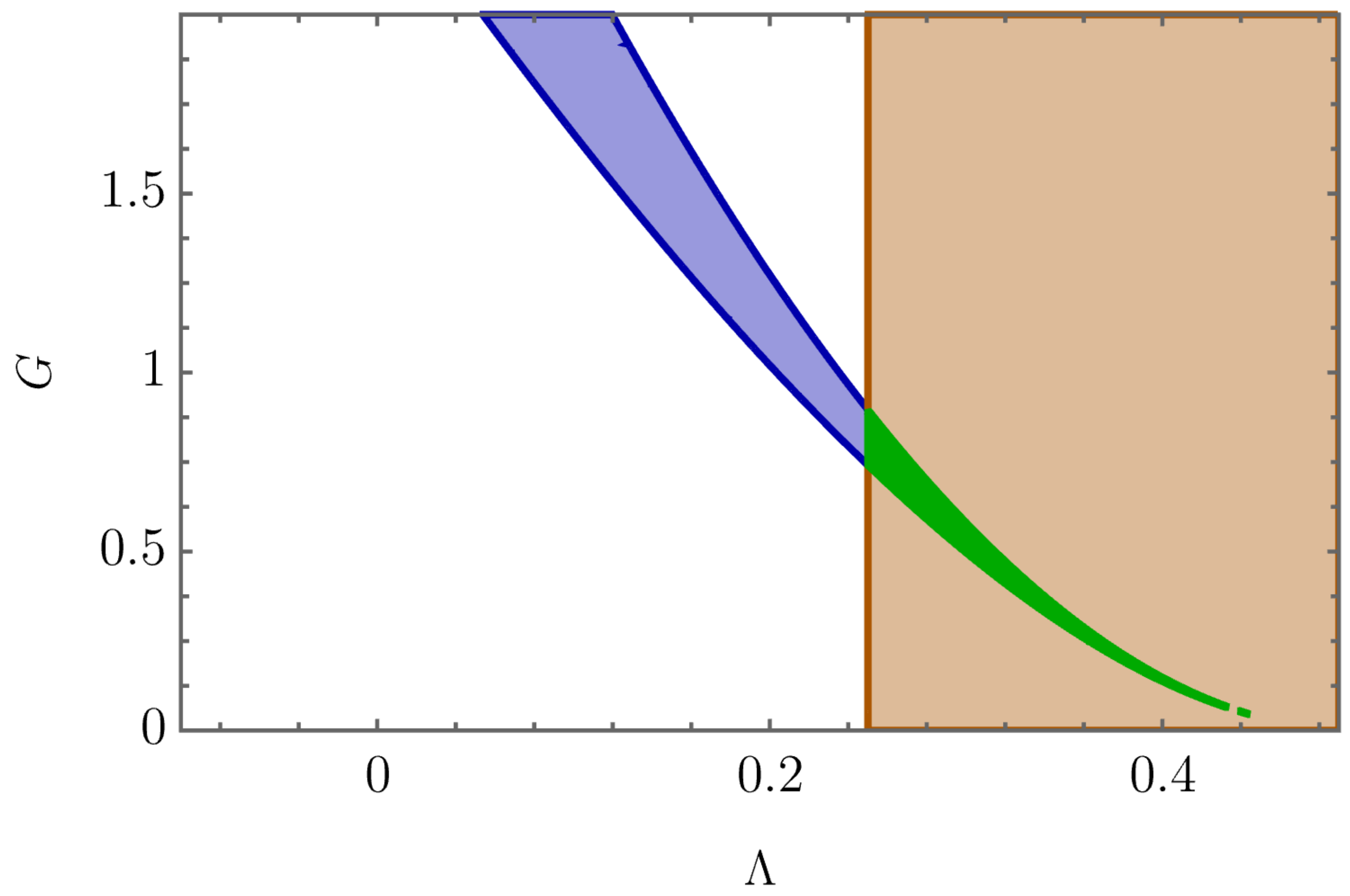

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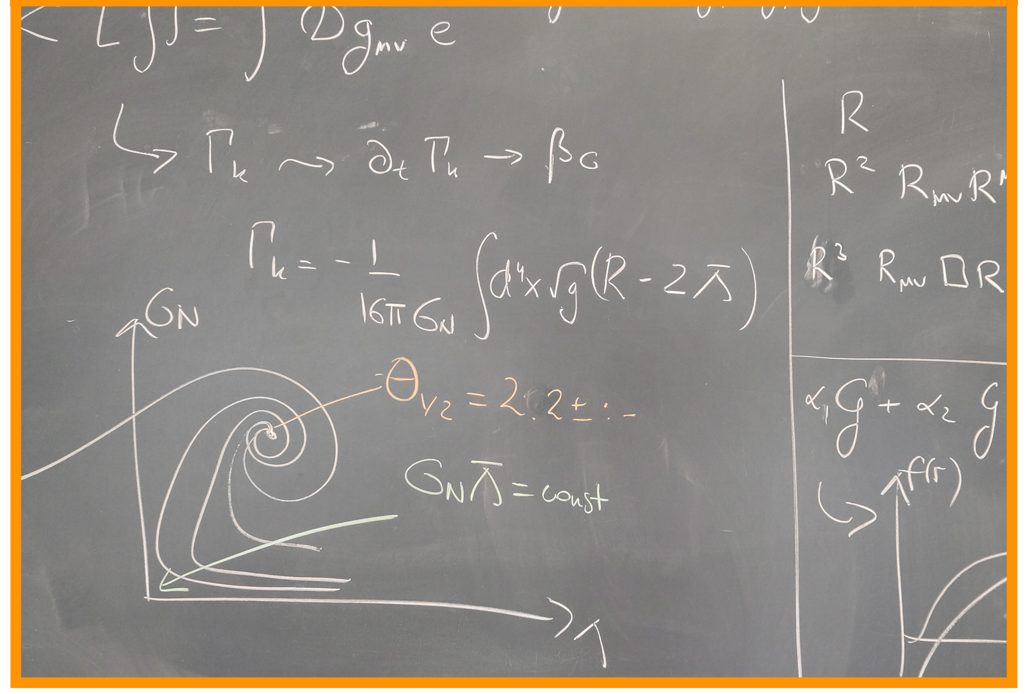
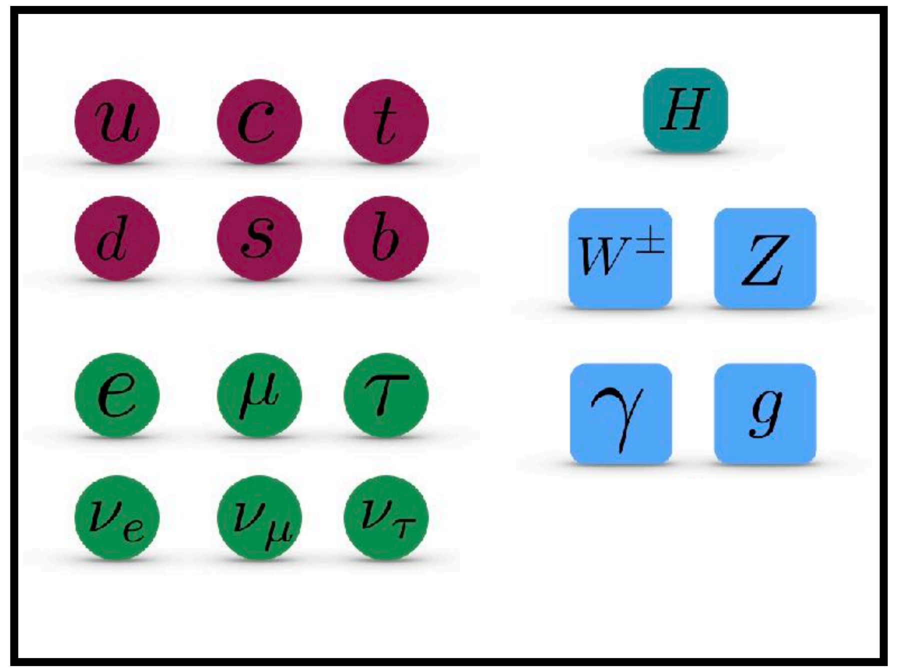
Two examples: string theory (all symmetries are gauged), asymptotic safety (global symmetries can be imposed)

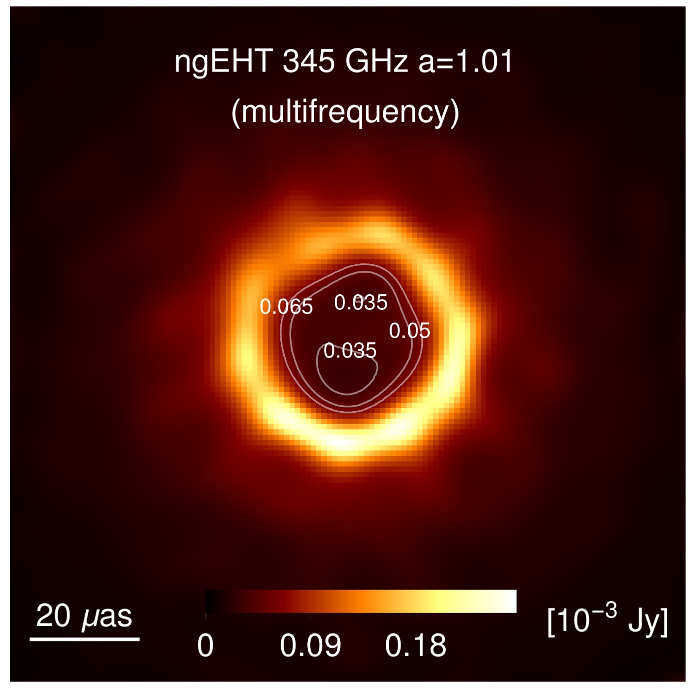
Motivation: How to test proposed theories of quantum gravity?

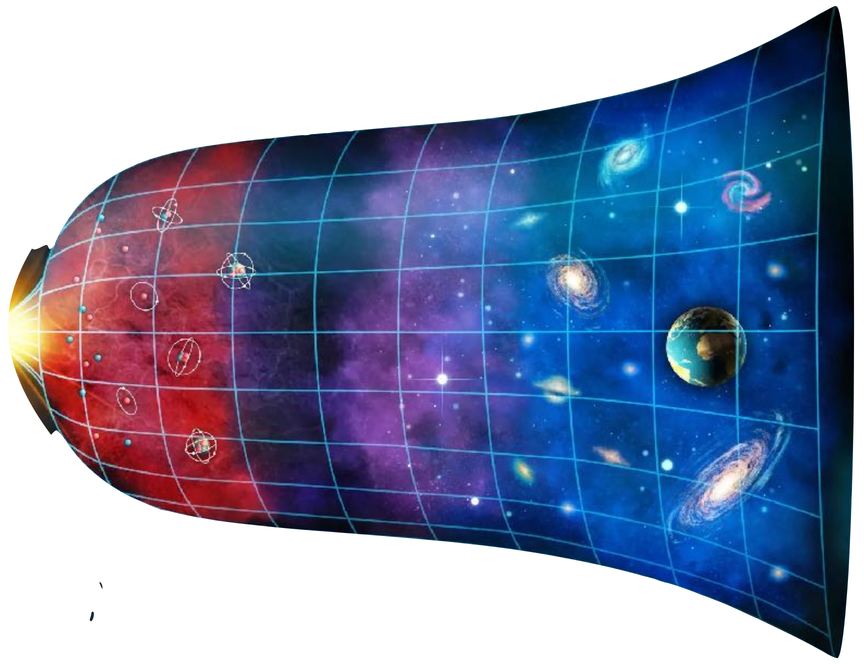
Theory of quantum gravity



Key challenge: gap in scales







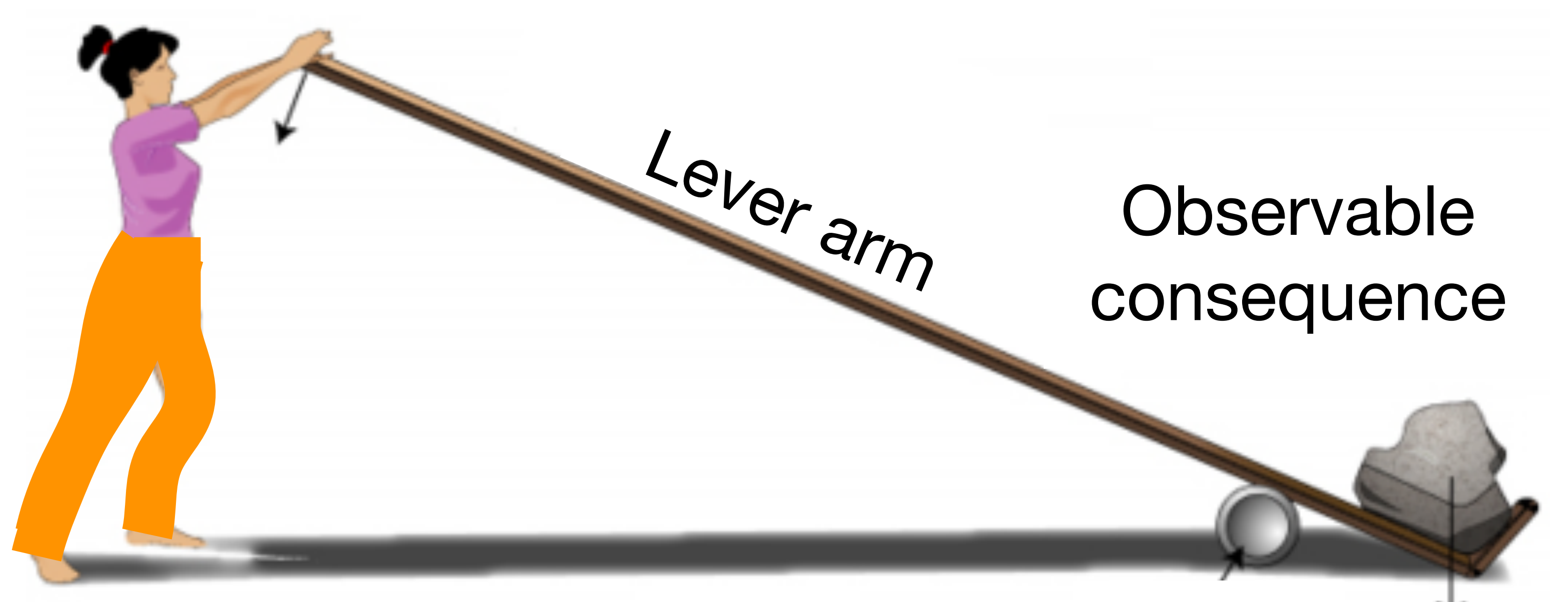
Planckian scales $10^{-35}\,\mathrm{m}$

Particle physics scales $10^{-17}\,\mathrm{m}$

Black-hole scales $10^{11}\,\mathrm{m}$

Cosmological scales $> 10^{20}\,\mathrm{m}$

distance scale



Renormalization Group flow of couplings can be powerful lever arm for Bridging high & low energies

Examples:

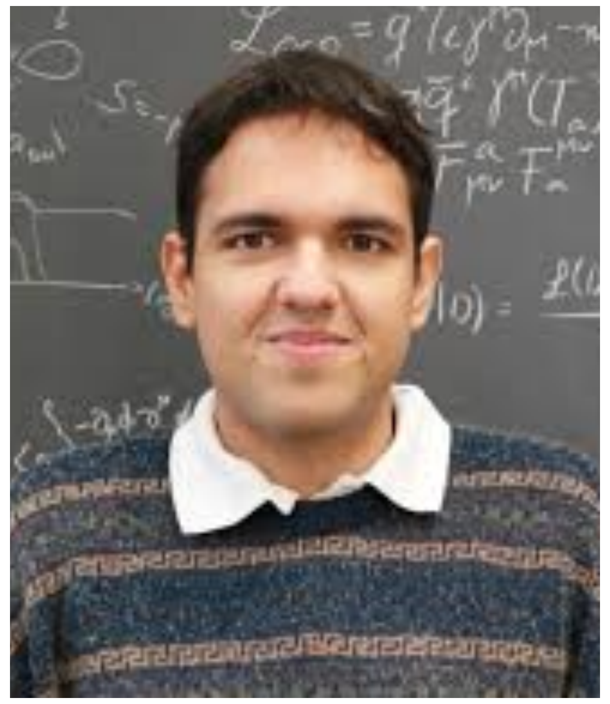
- Accumulation of Lorentz-Invariance-Violation over astrophysical distances of photons from short Gamma-Ray-Bursts
  [Amelino-Camelia, Ellis, Mavromatos Nanopoulos, Sakar '97]
- High sensitivity in probes of CPT symmetry breaking in the Standard Model
  [Colladay, Kostelecky '96]
- Renormalization Group flow of couplings

Thanks to current and former group members!

Former PhD students:

Aaron Held,
now ENS Paris

Marc Schiffer,
now Radboud U.



Rafael R. Lino dos Santos,
now Warsaw U.

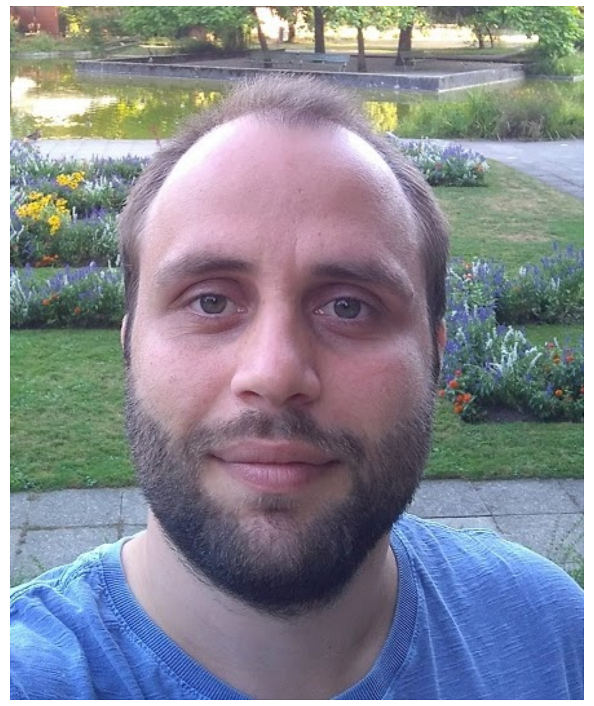
Johannes Lumma,
now Oxford U.

Fleur Versteegen,
now ASML

Martin Pauly,
now exnaton

Héloïse Delaporte,
now U. of Faroe Islands

Former postdocs:



Antonio Pereira,
assist. prof. at
Fluminense Federal U.,
Brazil

Gustavo P. de Brito,
assist. prof. at
São Paolo State U.

Alessia Platania,
assist. prof.
at Niels-Bohr-
Institute,
soon prof. at U. Graz

Raúl Carballo-Rubio
associate prof.
at U of Granada, Spain

Shouryya Ray
assist. prof.
at U. of Faroe Islands

Near-perturbative nature of asymptotic safety

How non-perturbative is the fixed point?

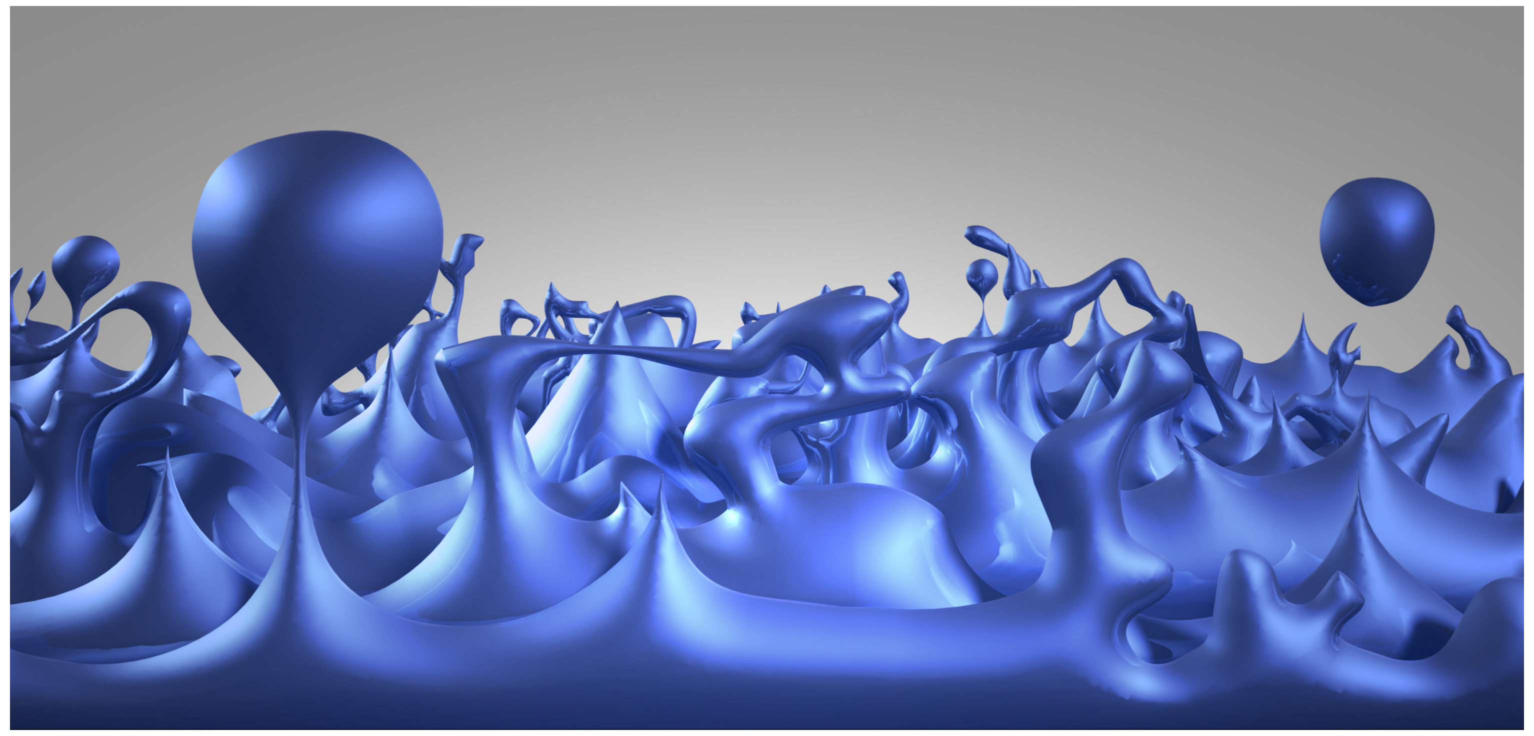
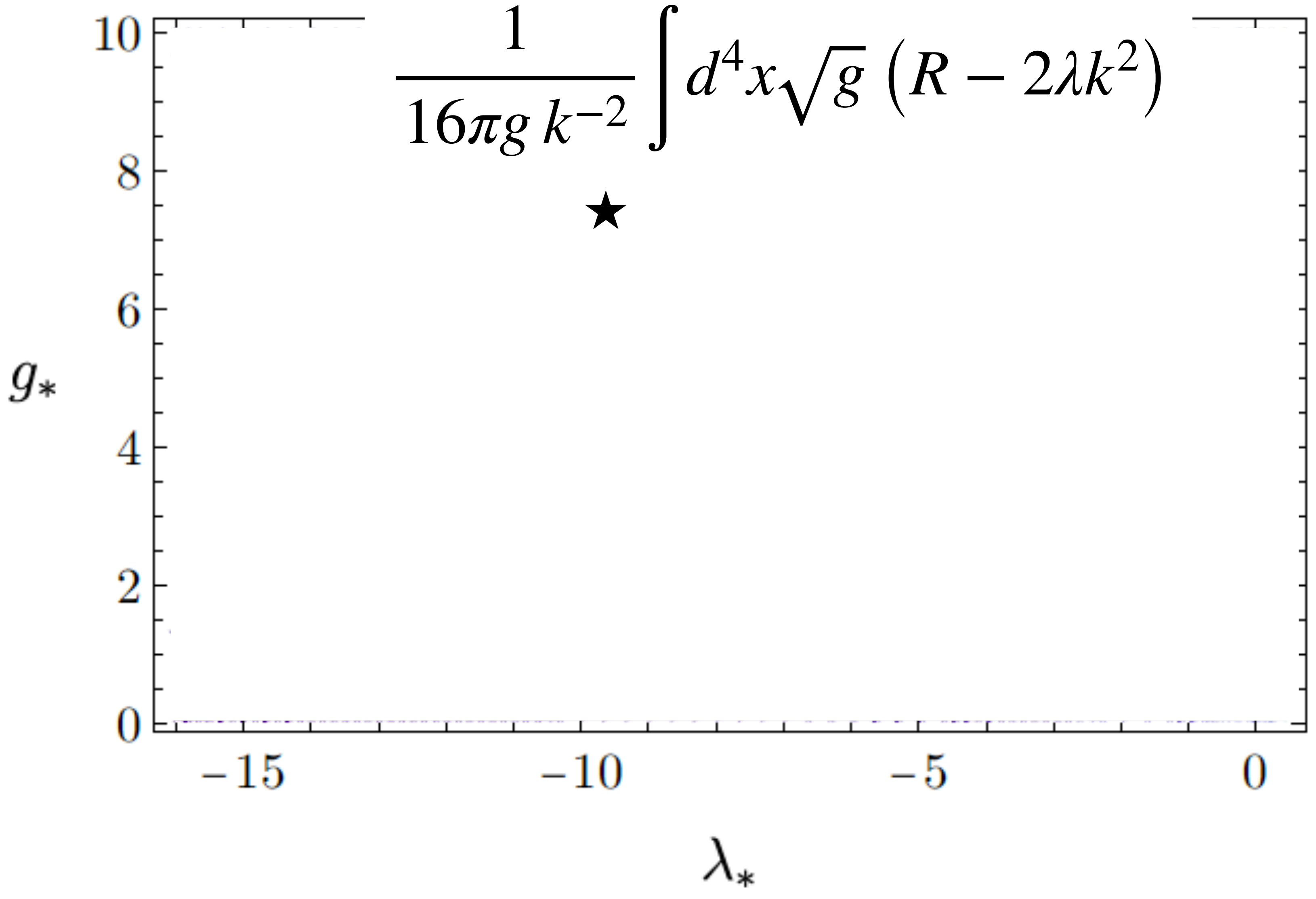


Image Credit: NASA/CXC/M.Weiss

or

?



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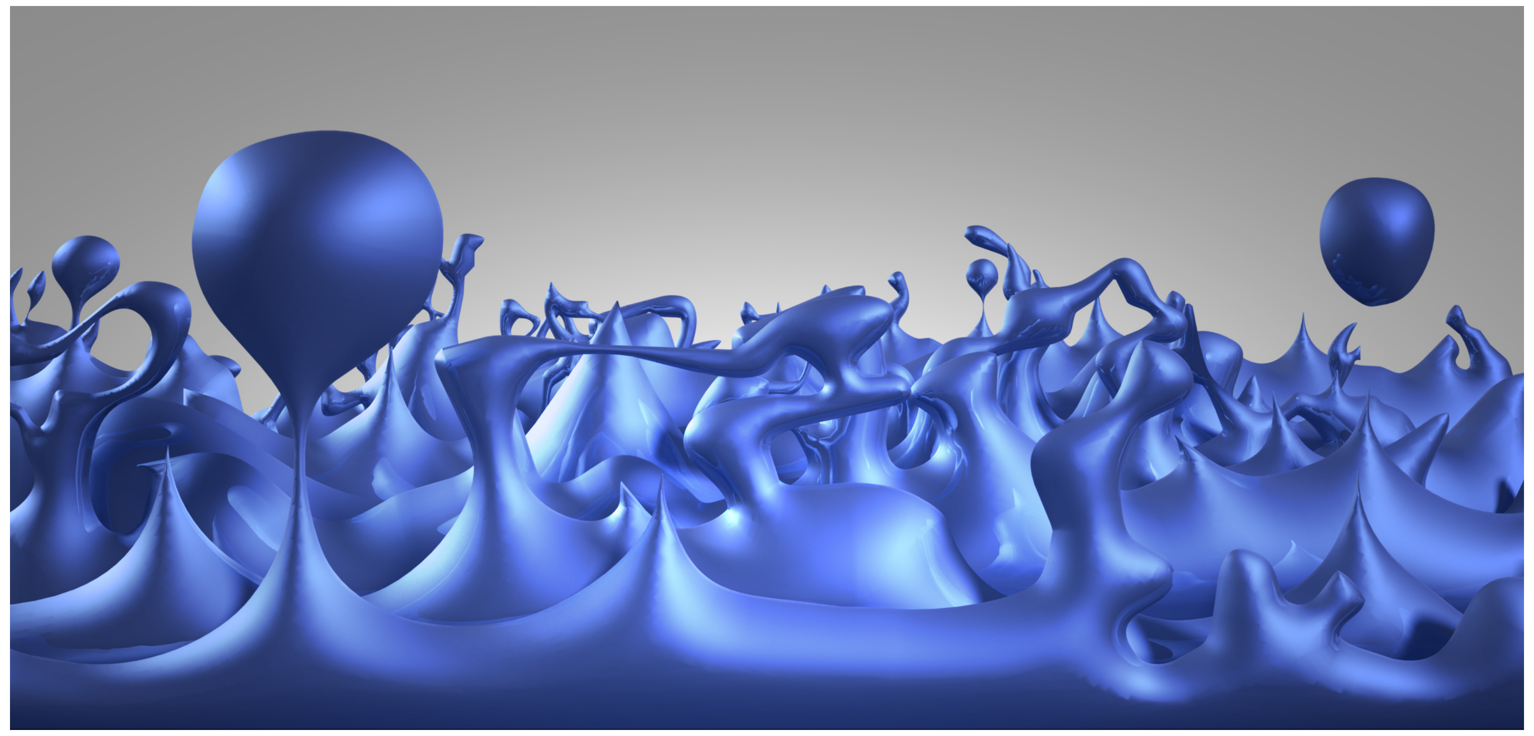

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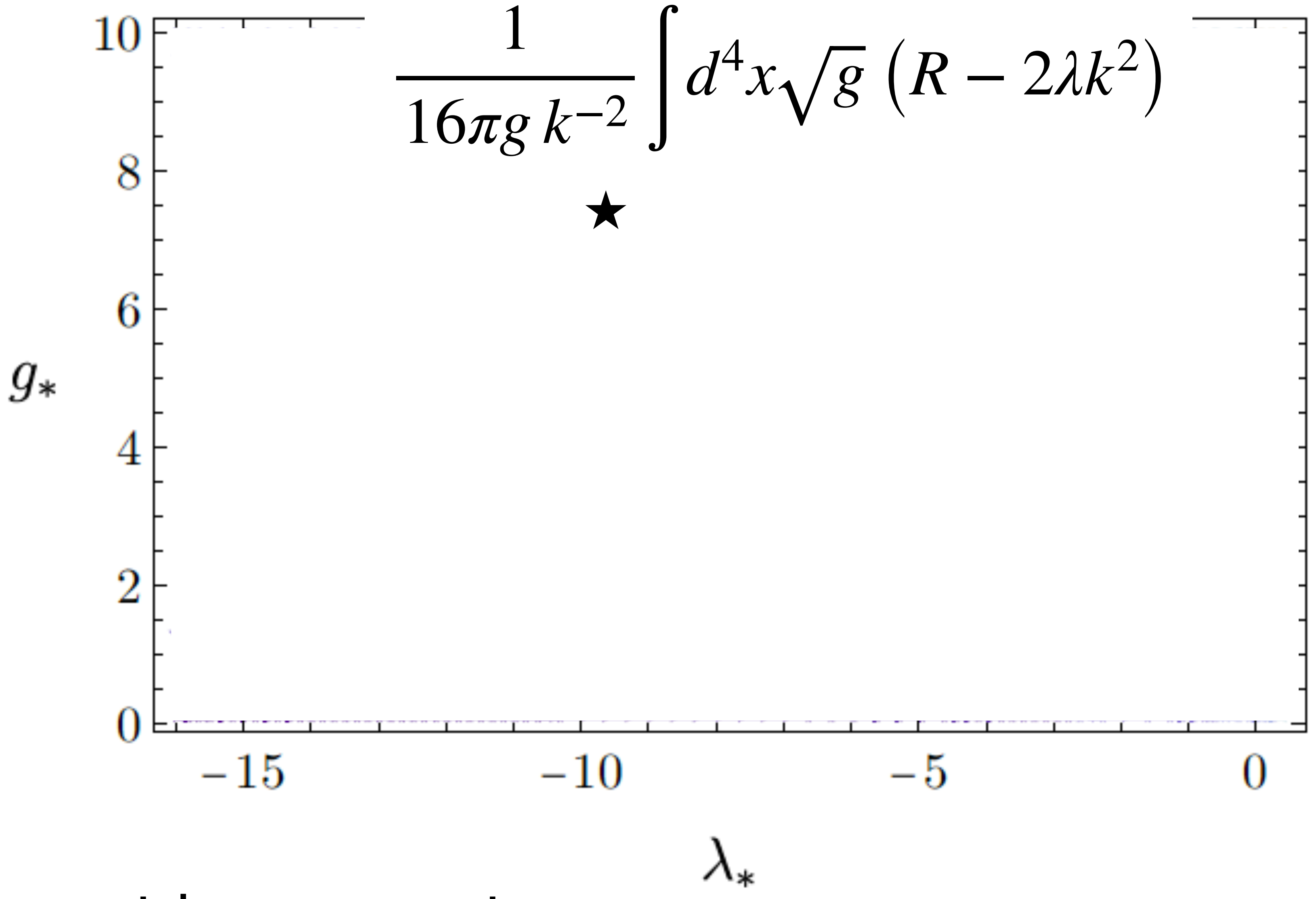

$$\frac{1}{16\pi g\, k^{-2}} \int d^4x \sqrt{g}\, \left(R - 2\lambda k^2\right)$$

metric propagator:

$$\frac{g_*}{1 - 2\lambda_* + \ldots}$$

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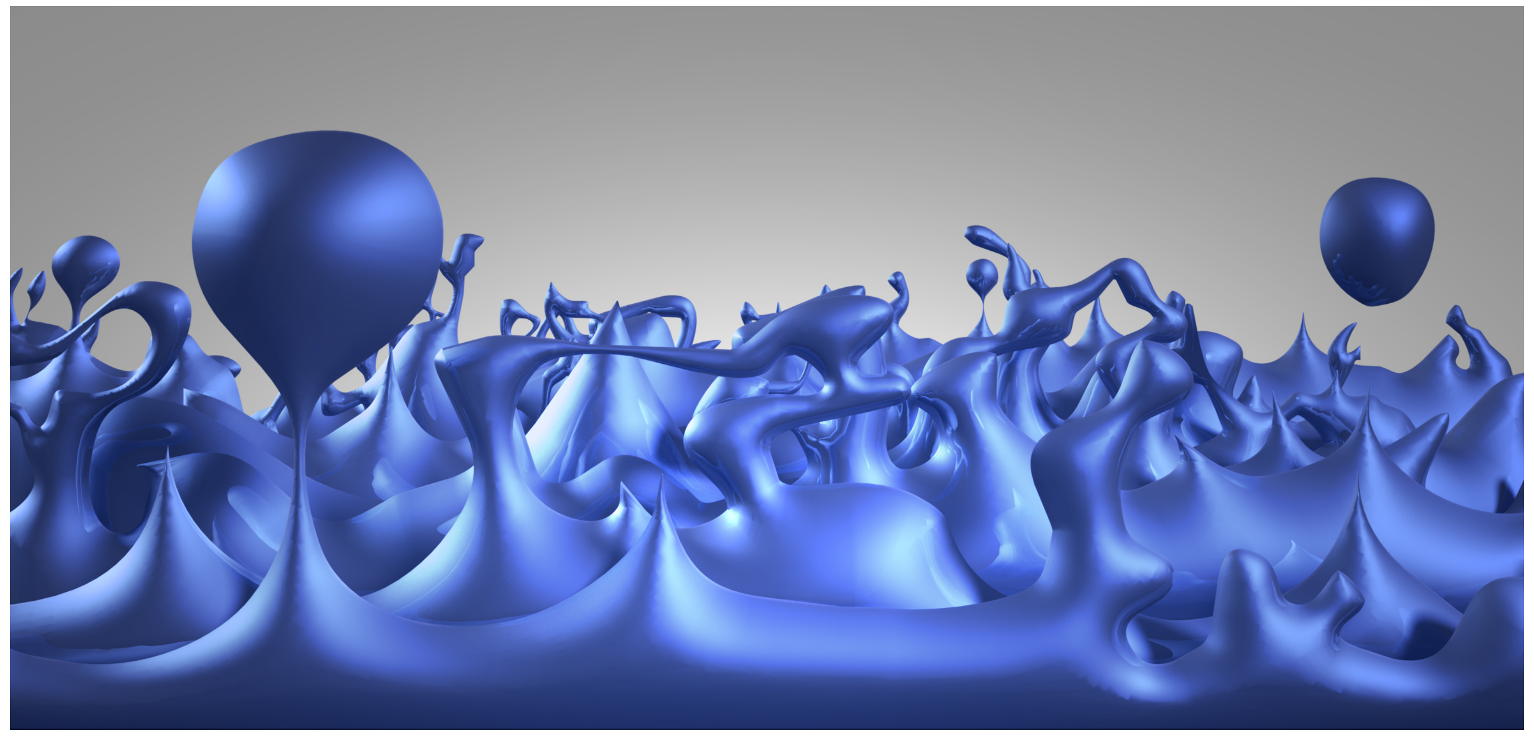

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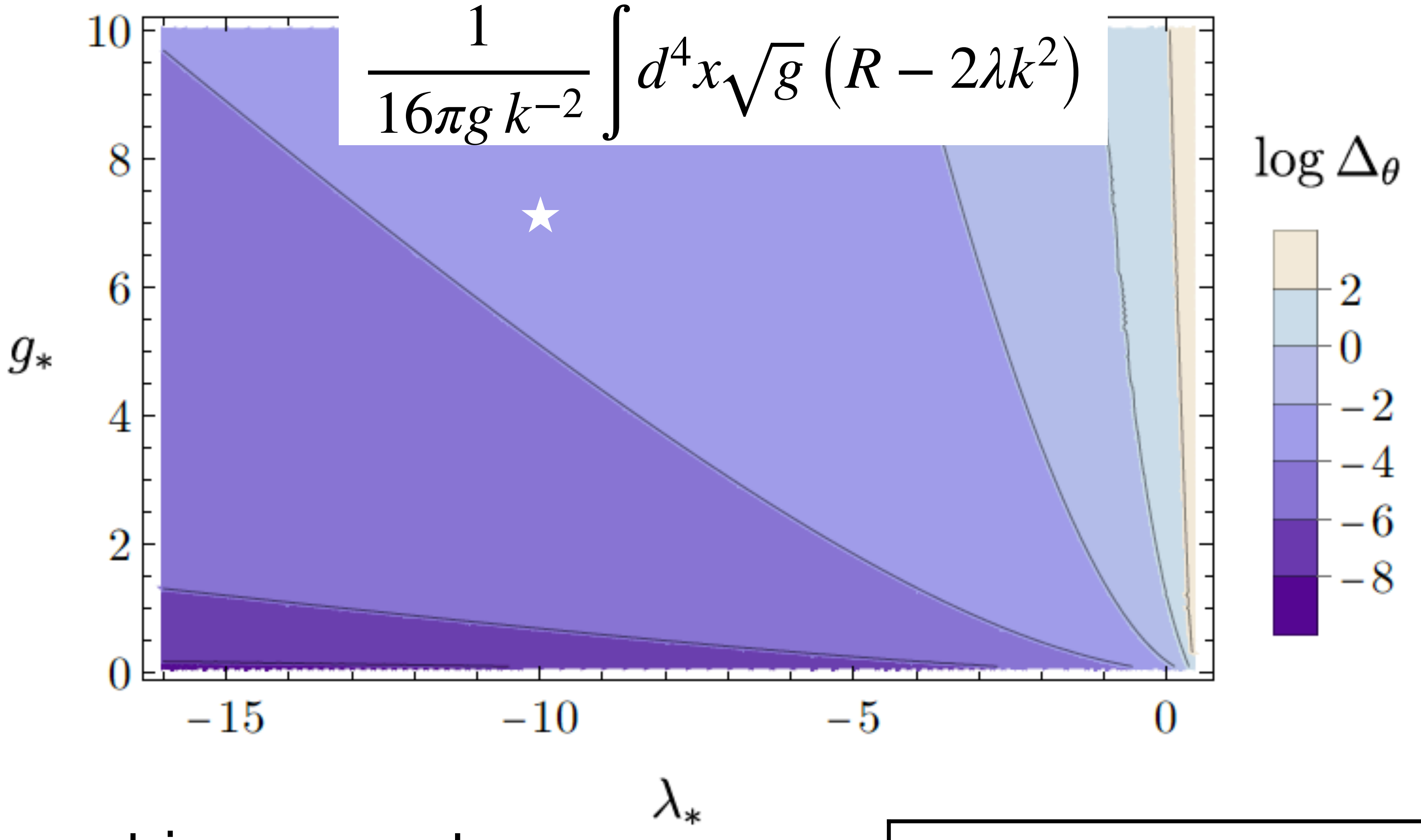
Key property: near-perturbative

- free parameters $\simeq$ dimension-4-interactions
- similar set as free parameters at perturbative (Gaussian) fixed point

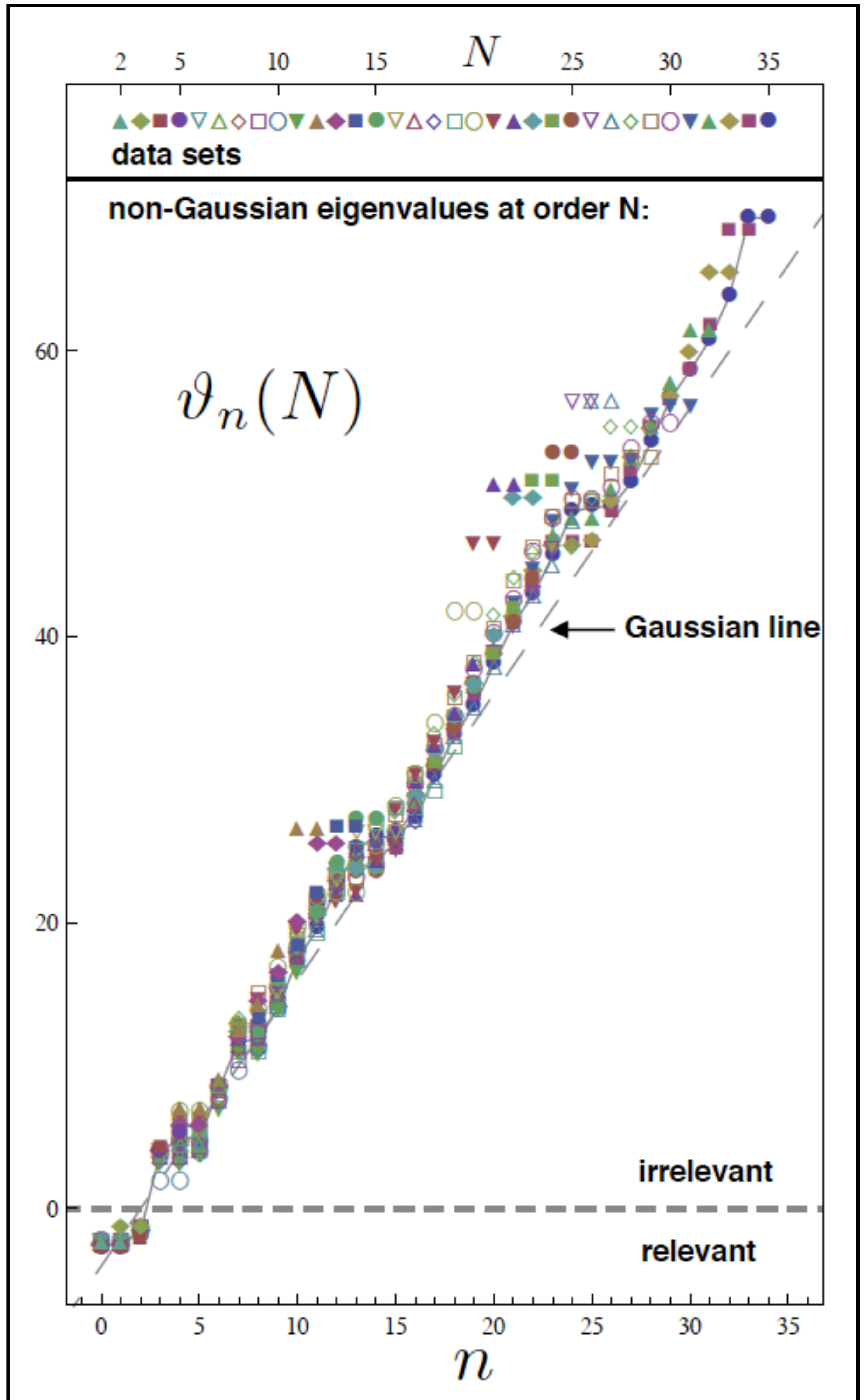


metric propagator:

$$\frac{g_*}{1-2\lambda_*+\dots}$$

$$\Delta_\theta=\sqrt{\frac{\sum_i\left(\mathrm{Re}(\theta^{(i)})-\theta_{\mathrm{Gauss}}\right)^2}{\sum_i}}$$

[AE, Pauly '18]



[Falls, Litim et al. '13]

Method & key assumptions

Functional Renormalization Group: based on Euclidean path integral

Γ_k: analog of classical action, but with quantum fluctuations above k included

$$k\,\partial_k\,\Gamma_k = \frac{1}{2}\mathrm{Tr}\left[\left(\Gamma_k^{(2)} + R_k\right)^{-1} k\,\partial_k R_k\right] \qquad \to \beta_g = k\partial_k\, g(k)$$

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Quantitative precision achievable

Example: Fixed point in the Ising model, derivative expansion

derivative expansion	ν	η
$s = 0$ (LPA)	0.651(1)	0
$s = 2$	0.6278(3)	0.0449 (6)
$s = 4$	0.63039(18)	0.0343(7)
$s = 6$	0.63012(5)	0.0361 (3)
$s \to \infty$	0.6300(2)	0.0358(6)
conformal bootstrap	0.629971(4)	0.0362978(20)

[Balog, Chaté, Delamotte, Marohnić, Wschebor '19]

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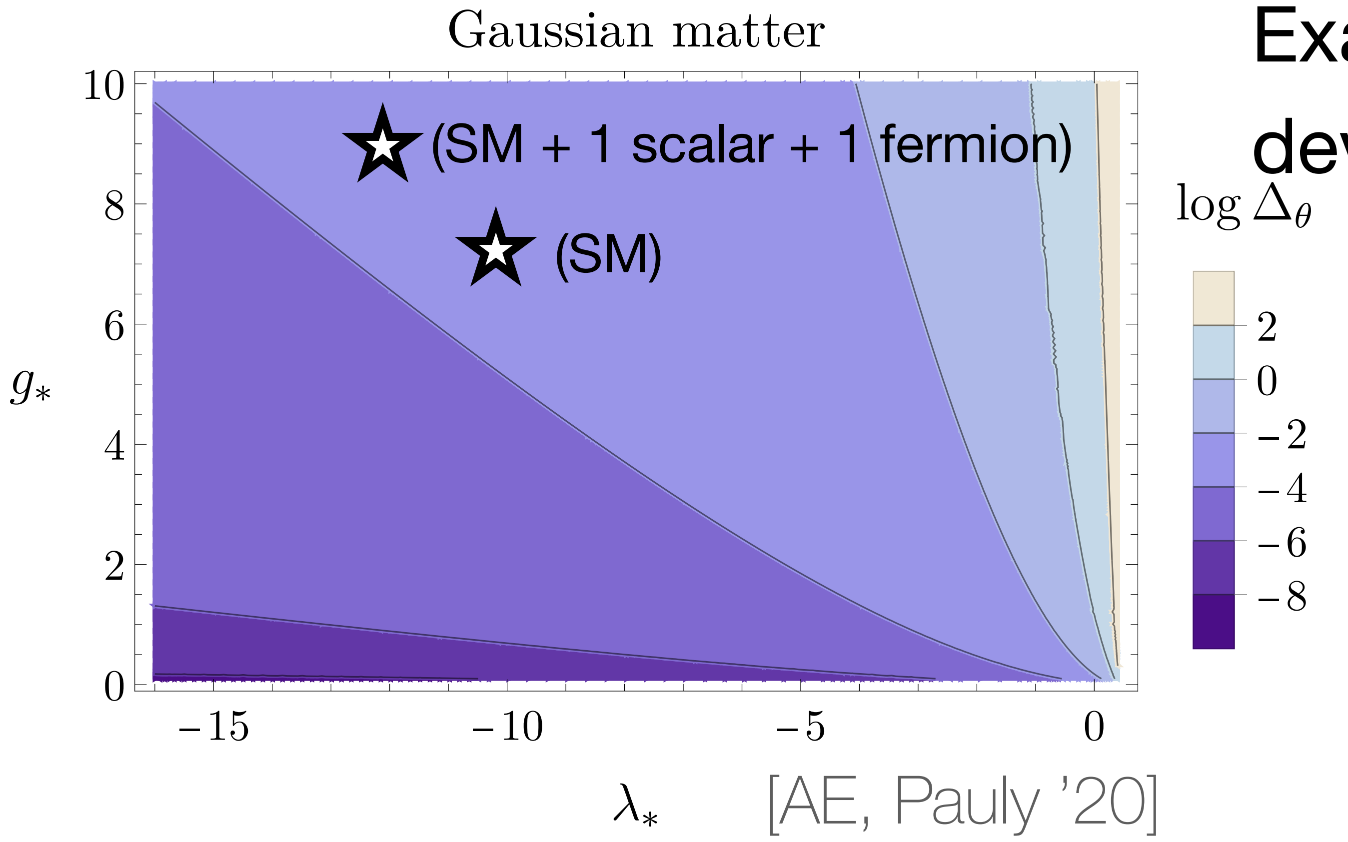
Truncation scheme for matter-gravity: near-perturbativity as a bootstrap

- assume near-perturbativity:
  quantum corrections are subleading compared to canonical scaling
- use canonical power-counting to set up truncations
- check that near-perturbativity holds at fixed point in truncation



[AE, Pauly '20]

Example (SM & BSM Yukawa sector):
deviation from perturbative scaling:

$$\Delta_\theta = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\left(\theta_i - d_{\bar{g}_i}\right)^2}$$

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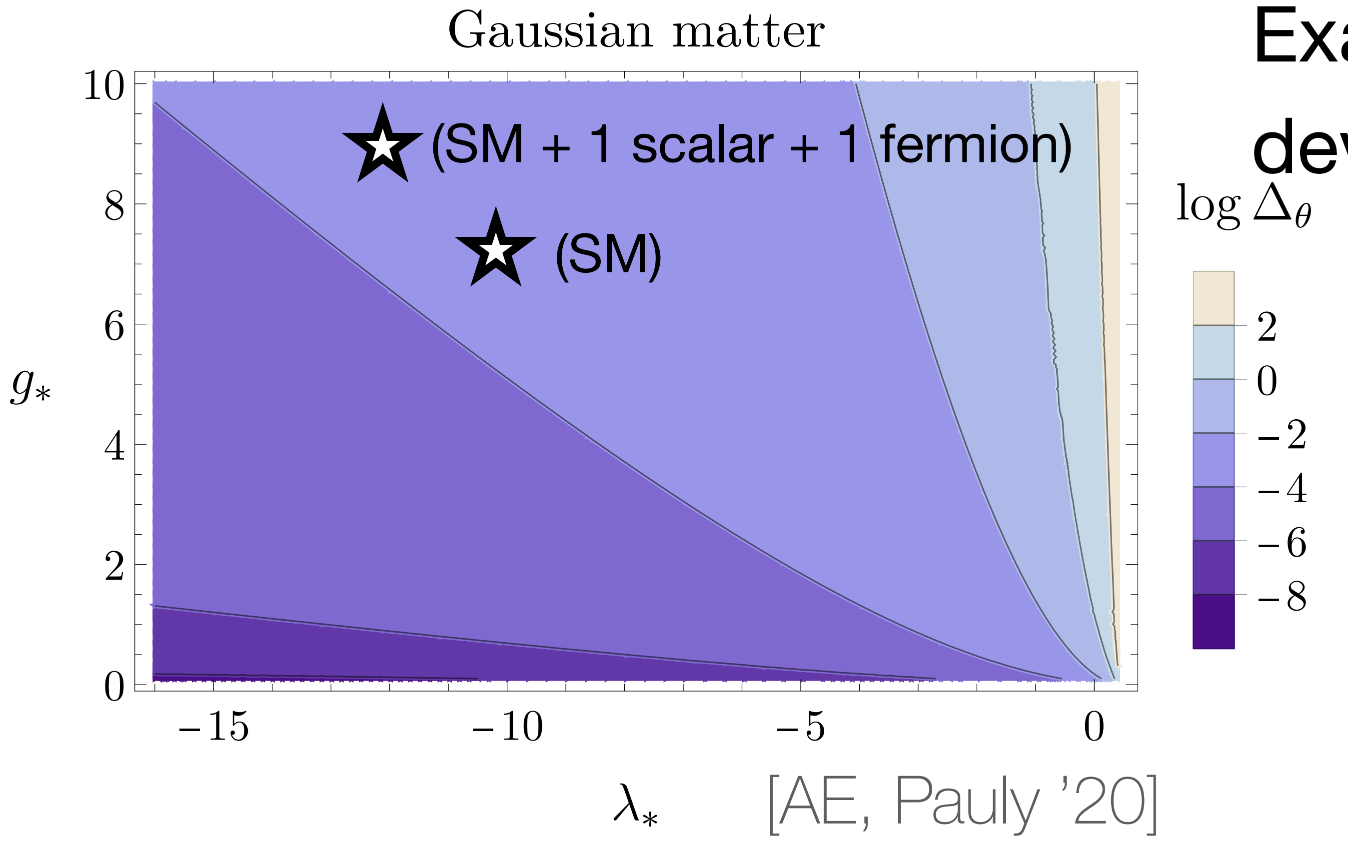

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[Balog, Chaté, Delamotte, Marohnić, Wschebor '19]

Key assumption: Euclidean vs. Lorentzian signature

First hints of Lorentzian asymptotic safety

- impact of foliation on fixed-point structure small
  [Biemans, Platania, Saueressig '16 '17; Saueressig, Wang '23]
- calculation in Einstein-Hilbert truncation in Lorentzian signature yields fixed point
  [Fehre, Litim, Pawlowski, Reichert '21]