

Probing quantum gravity at all scales

“Causal Fermion Systems”, Regensburg

October 9, 2025

Astrid Eichhorn

Heidelberg University



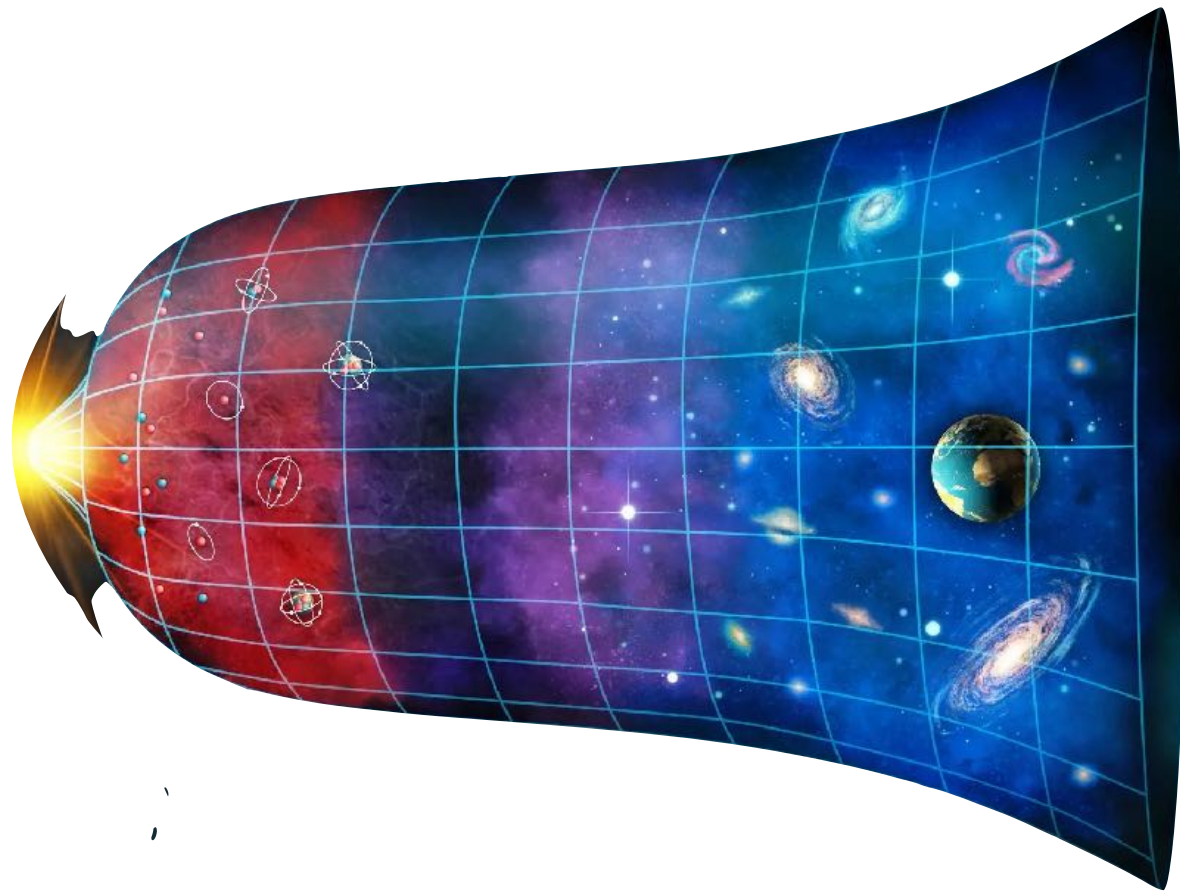
European Research Council



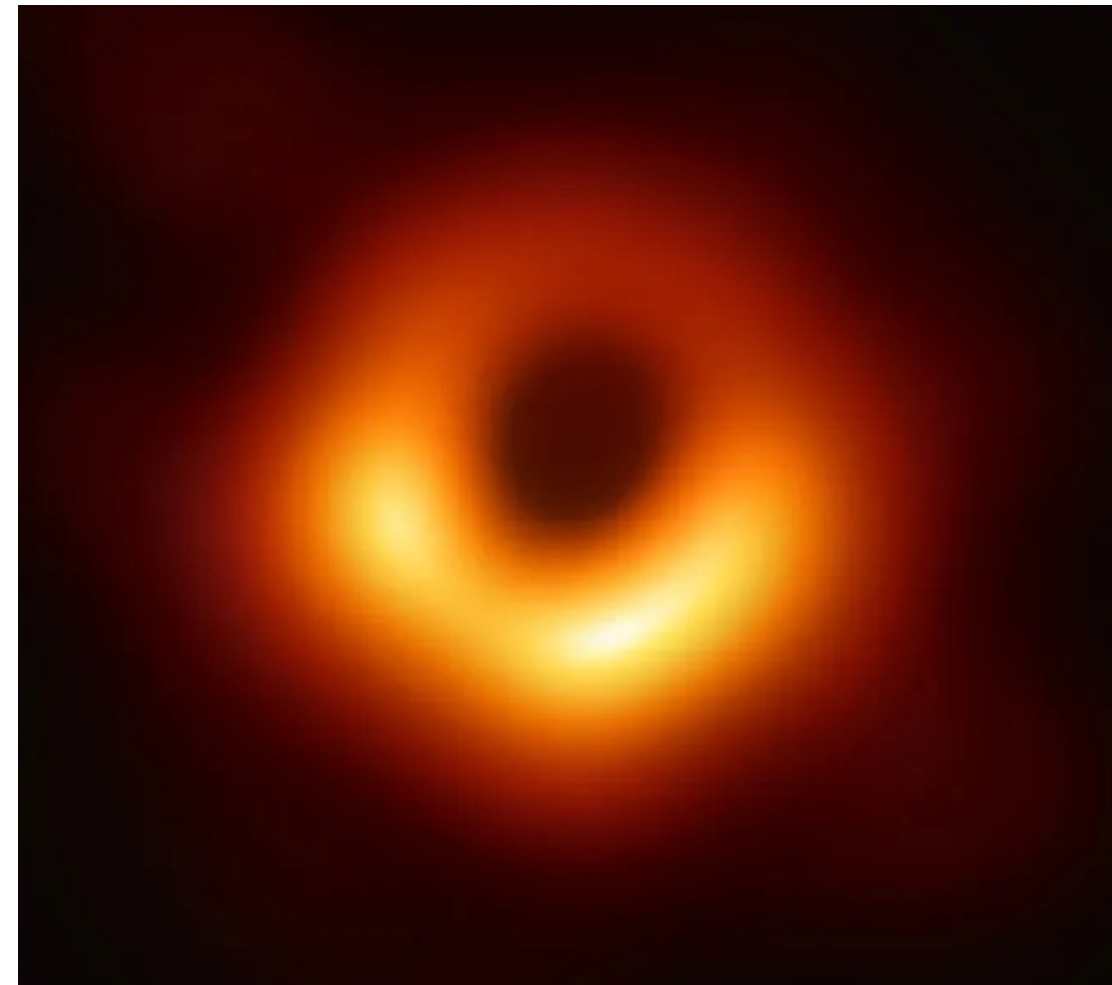
**UNIVERSITÄT
HEIDELBERG**
ZUKUNFT
SEIT 1386

Motivation

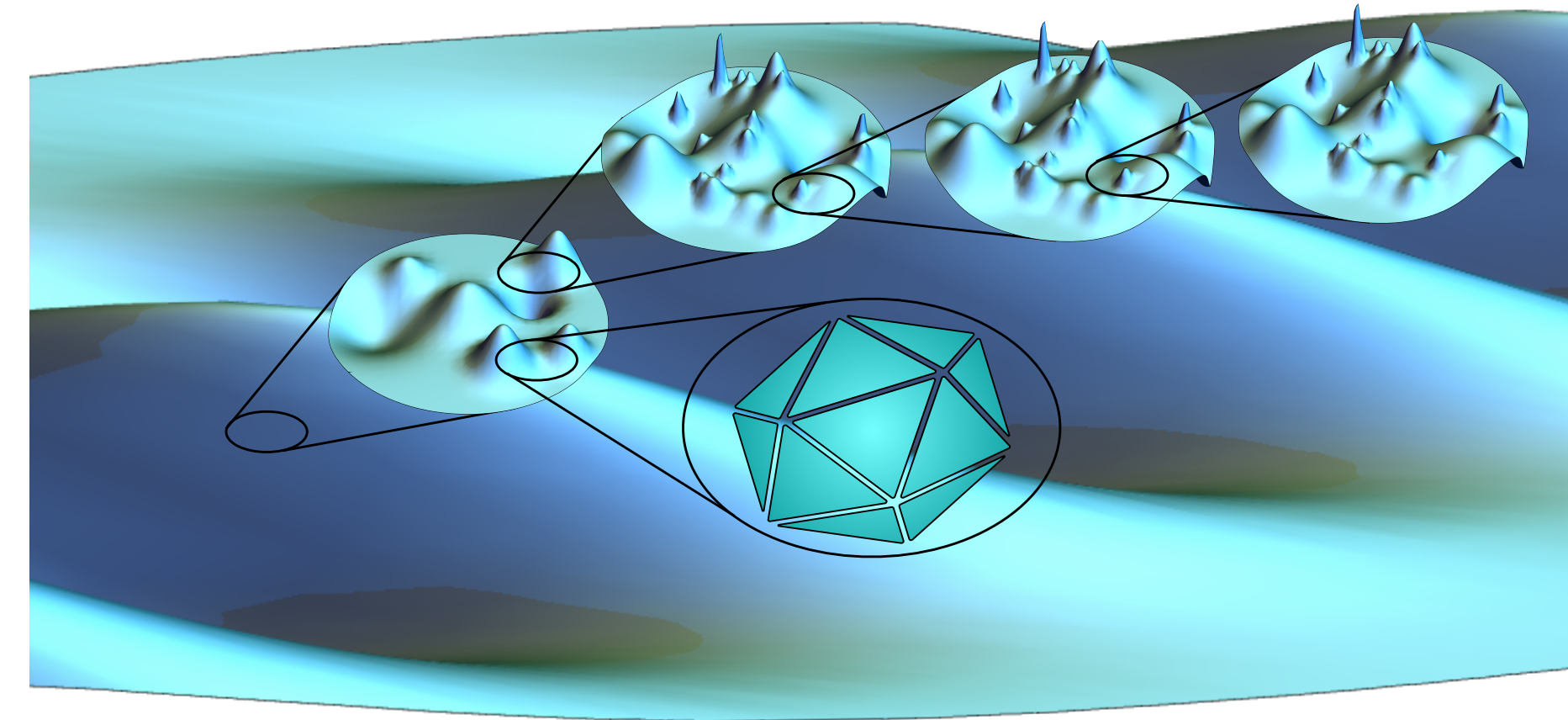
- Quantum gravity is necessary to answer profound questions about our universe



What is the origin of the universe?



What is the true nature of black holes?



What is the quantum structure of spacetime?

Motivation

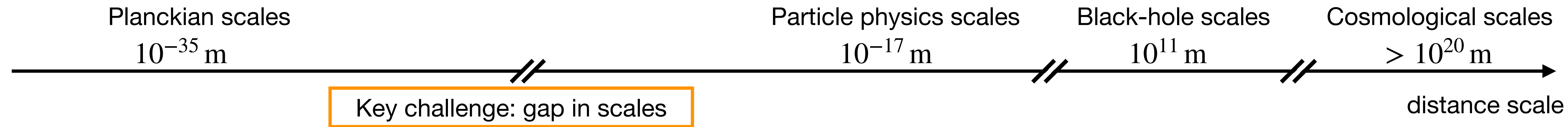
- Quantum gravity is necessary to answer profound questions about our universe
- Candidate quantum gravity theories exist (asymptotic safety, Loop Quantum Gravity, String Theory...)

Motivation

- Quantum gravity is necessary to answer profound questions about our universe
- Challenging to test proposed answers: expected scale of quantum gravity is Planck scale

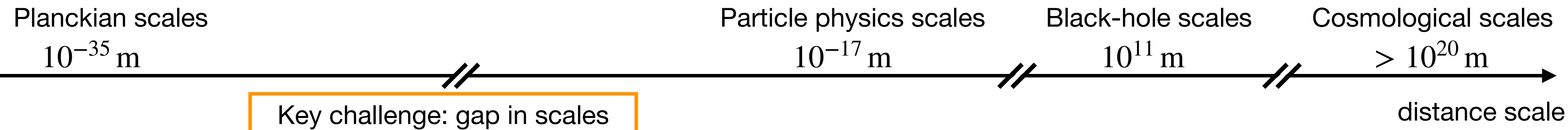
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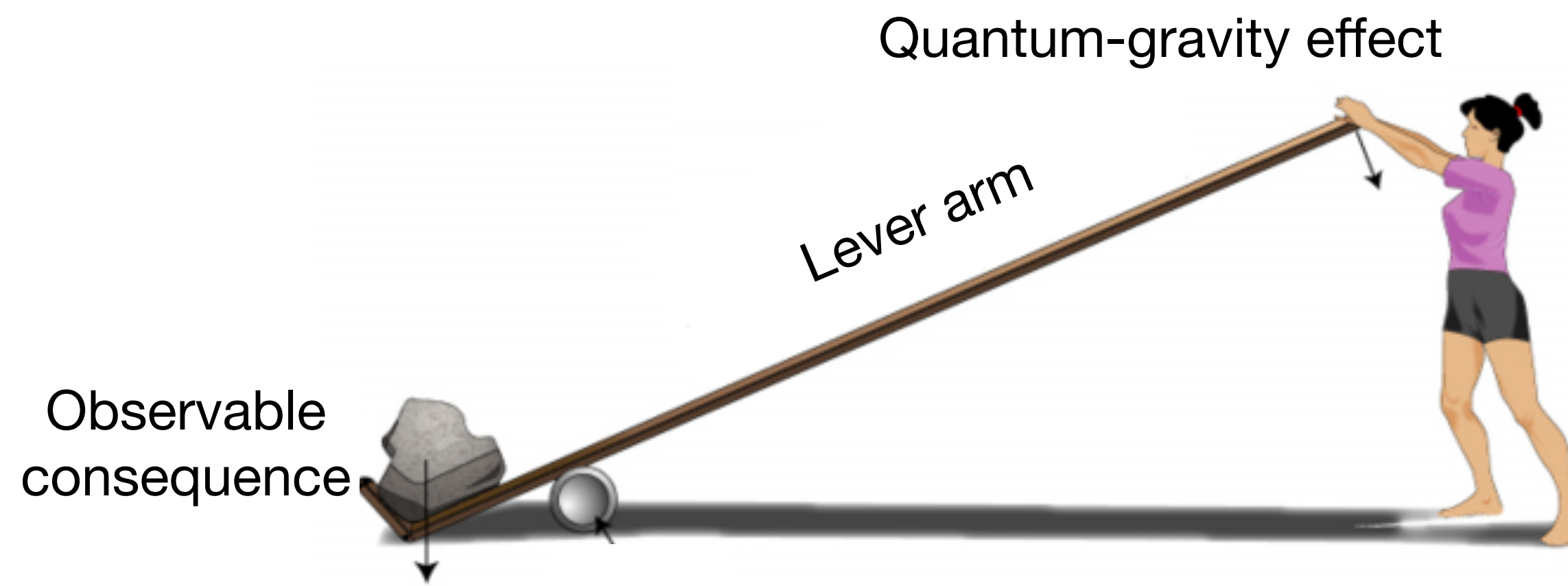


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- Quantum gravity is necessary to answer profound questions about our universe
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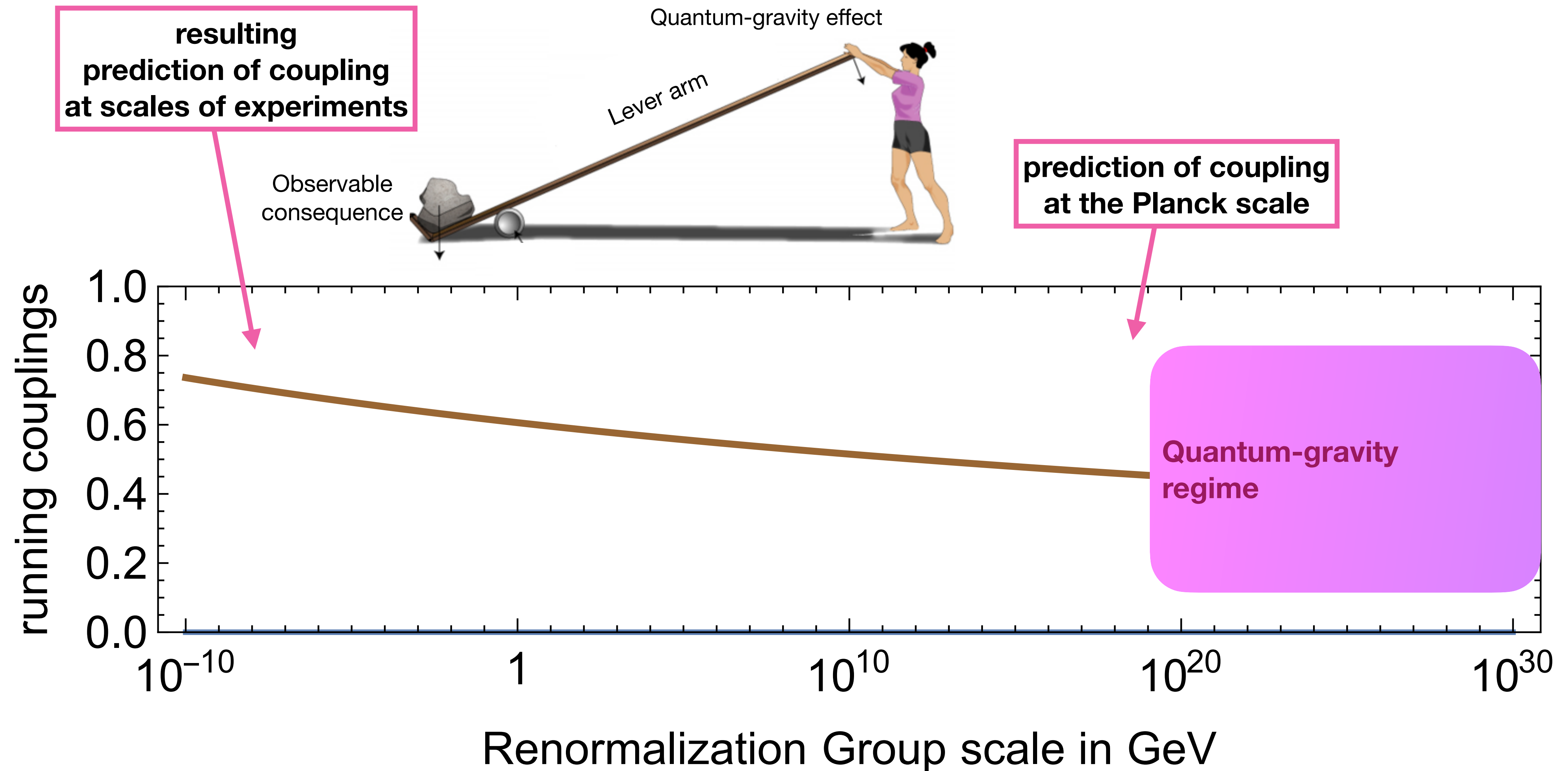
- Solution:
Lever arm translates effect at Planck scale into effect at observationally accessible scale



Examples:

- Accumulation of Lorentz-Invariance-Violation over astrophysical distances of photons from short Gamma-Ray-Bursts
[Amelino-Camelia, Ellis, Mavromatos Nanopoulos, Sakar '97]
- Large extra dimensions
[Arkani-Hamed, Dimopoulos, Dvali '98]
- this talk: Renormalization Group flow of couplings

Renormalization Group flow as a lever arm



Quantum-gravity approaches with predictions for values of the couplings at the Planck scale

- String theory (see also stringy swampland conjectures)

[Vafa, Valenzuela, Montero, Ooguri, Palti, Heidenreich, McNamara, Rudelius, Shiu...]

[swampland conjectures in asymptotic safety: [de Alwis, AE, Held, Pawłowski, Schiffer, Versteegen '19; Basile, Platania '21; Knorr, Platania '24; AE, Hebecker, Pawłowski, Walcher '24]]

- Asymptotically safe gravity

[AE, de Brito, Held, Pawłowski, Percacci, Reichert, Saueressig, Shaposhnikov, Schiffer, Wetterich, Yamada...]

review: AE, Schiffer '22

- Causal sets: constraint on quartic coupling in scalar field theory

[de Brito, AE, Fausten '23]

- ...an opportunity for other quantum-gravity approaches!

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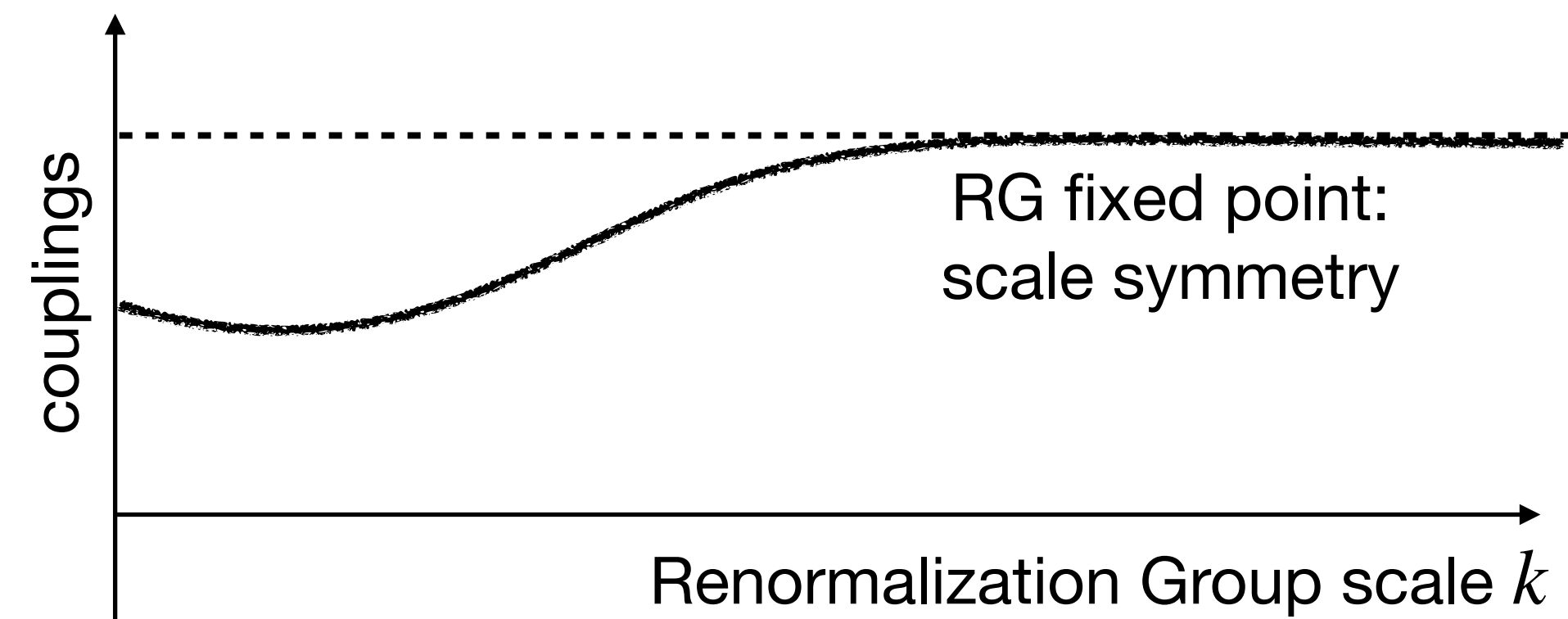
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Key idea of asymptotic safety

Asymptotic safety = quantum scale symmetry

scale symmetry realized in transplanckian regime

signature: Renormalization Group fixed point



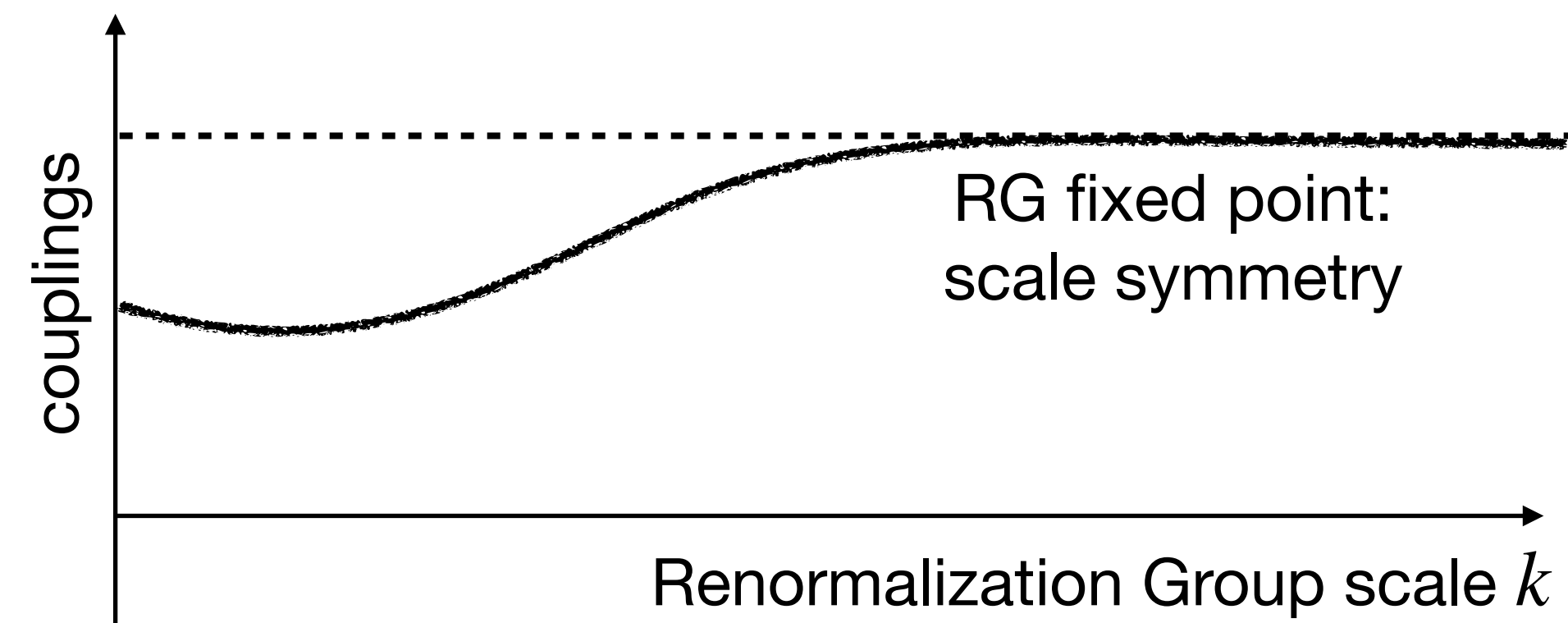
scale symmetry = deep principle of nature

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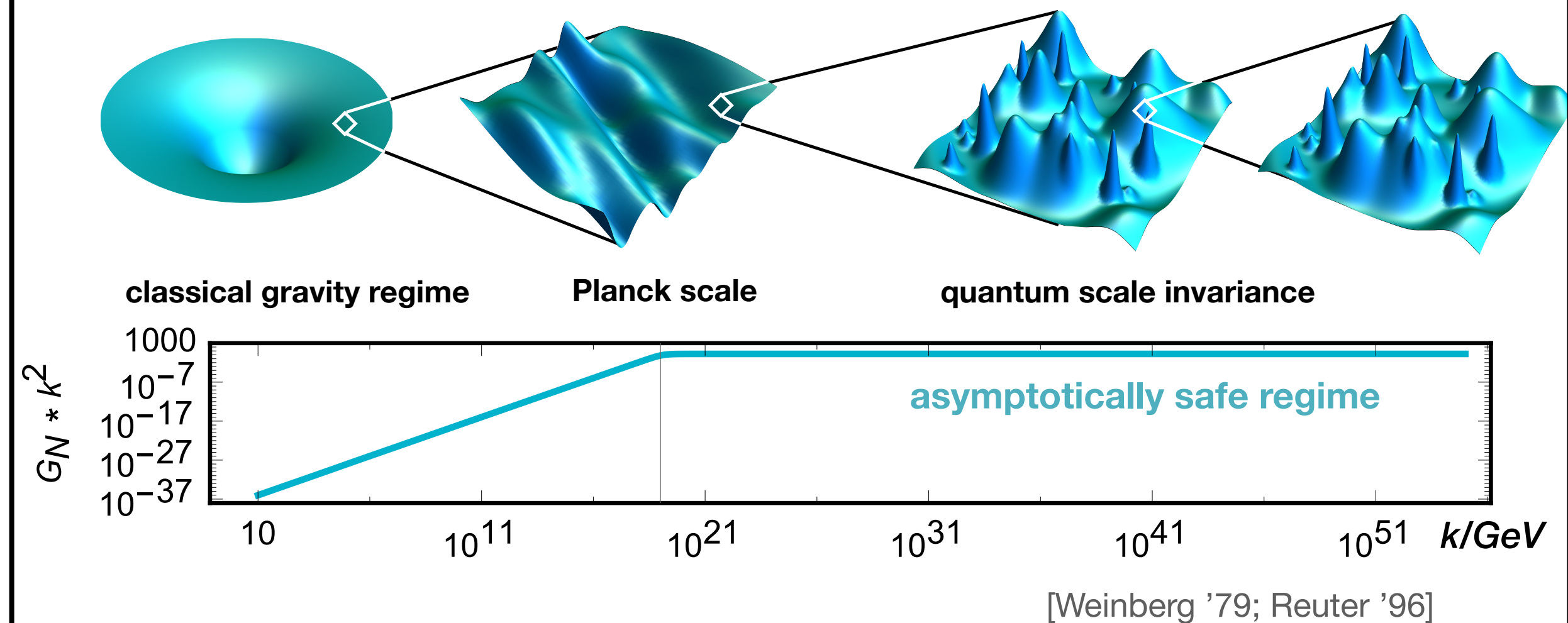
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scale symmetry = deep principle of nature

Asymptotic safety in gravity:

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

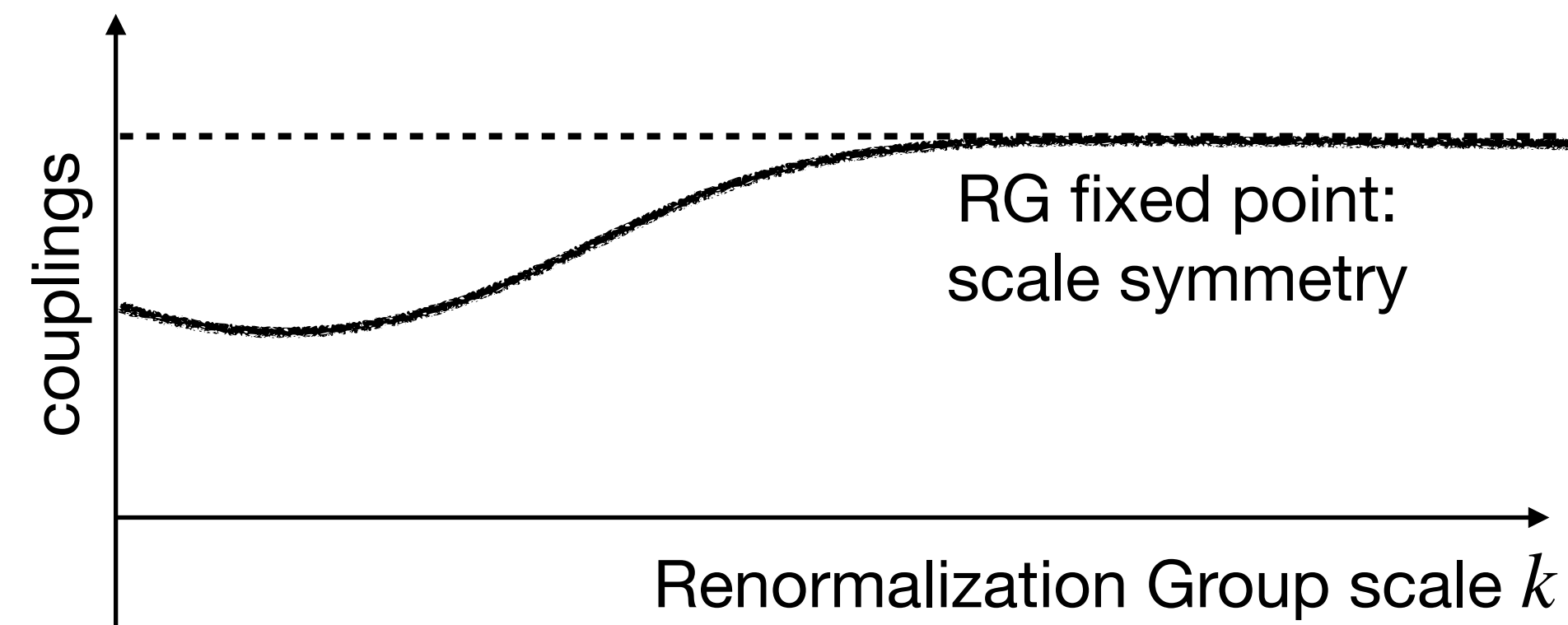


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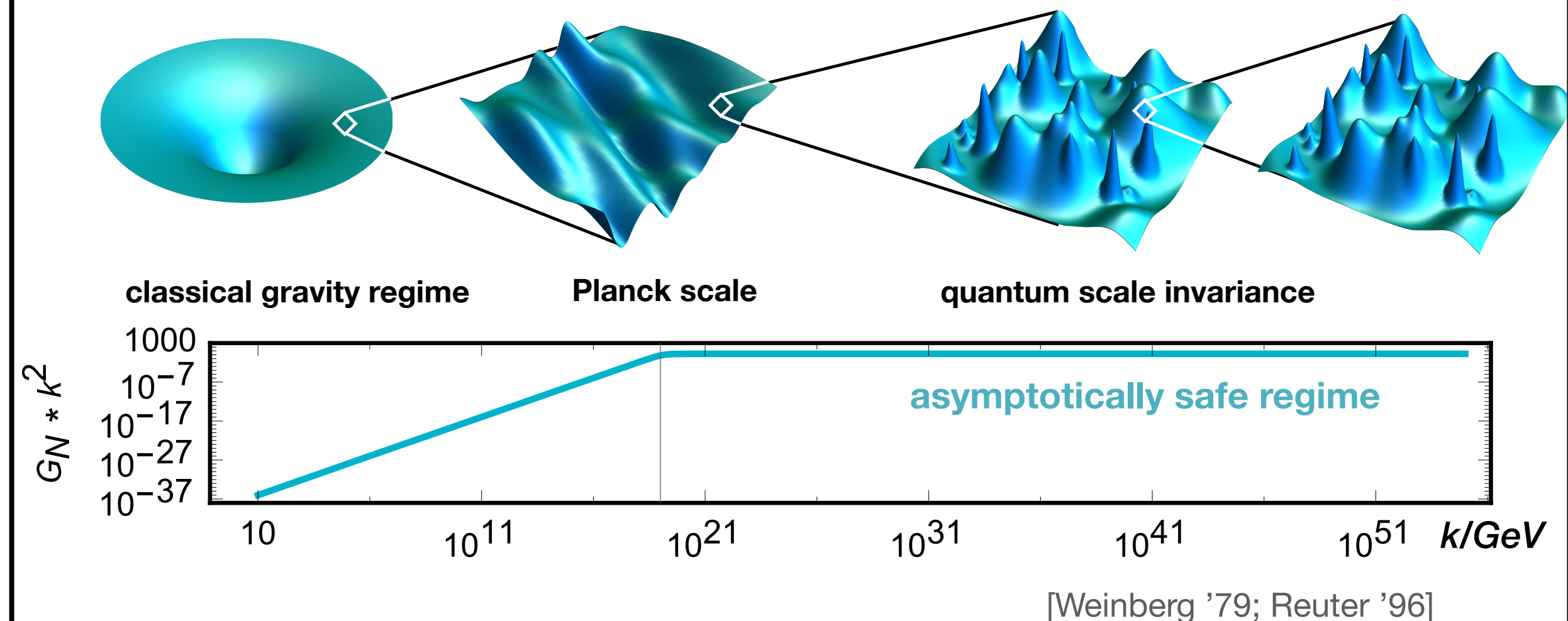
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Compelling theoretical evidence for asymptotic safety in Euclidean gravity:

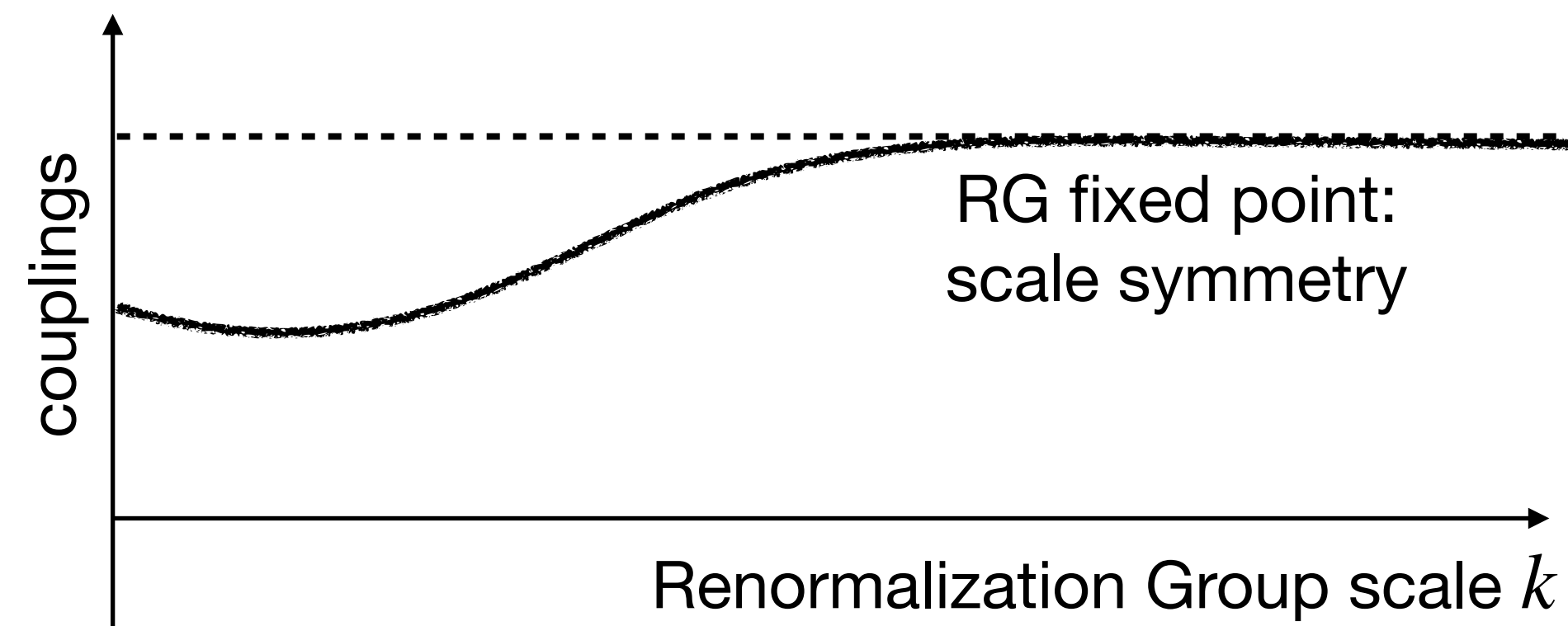
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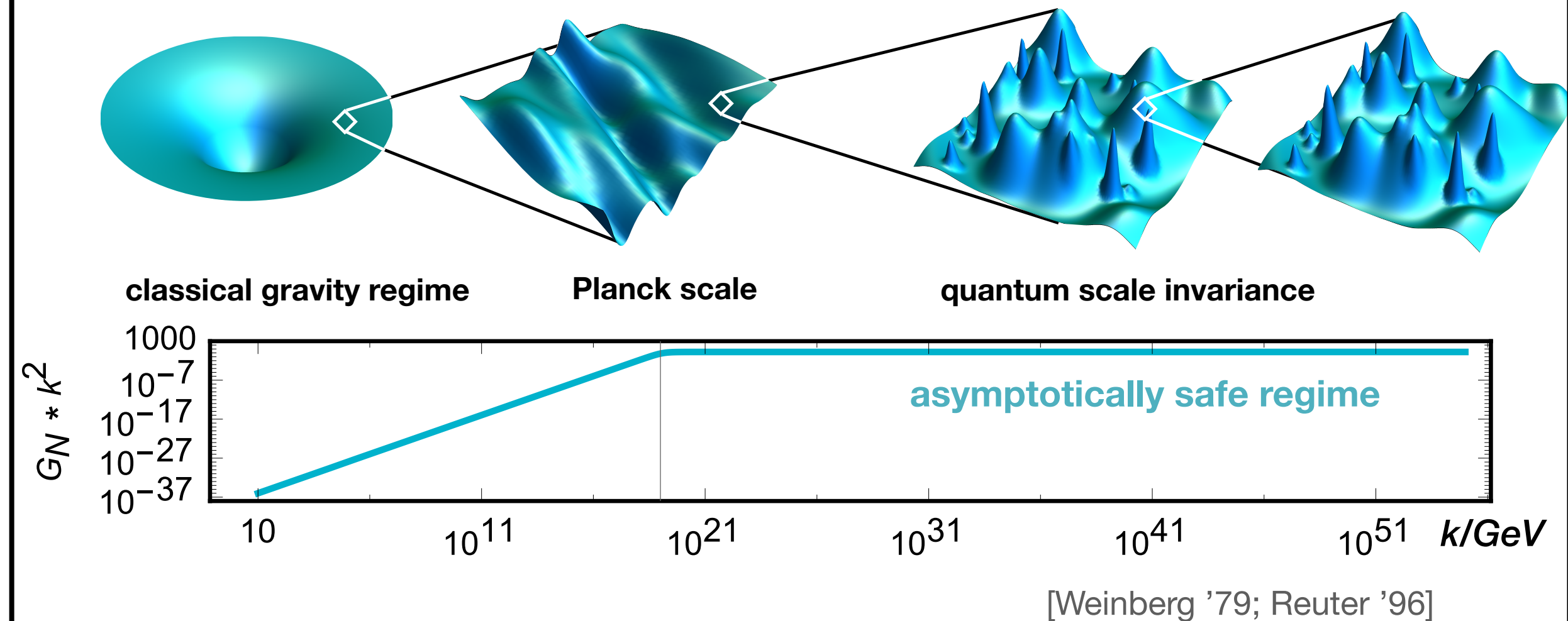
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Open questions: Lorentzian signature, unitarity under investigation

[e.g., Fehre, Litim, Pawłowski, Reichert '21; Platania '22; Saueressig, Wang '23; d'Angelo '23; Pastor-Gutierrez, Pawłowski, Reichert, Ruisi '24; D'Angelo, Ferrero, Fröb '25; Pawłowski, Reichert, Wessely '25]

Predictive power in asymptotic safety

Origin of predictions at the Planck scale

Quantum fluctuations

screen or antiscreen interactions, e.g.,

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

→ $e(k)$ decreases as k is lowered

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

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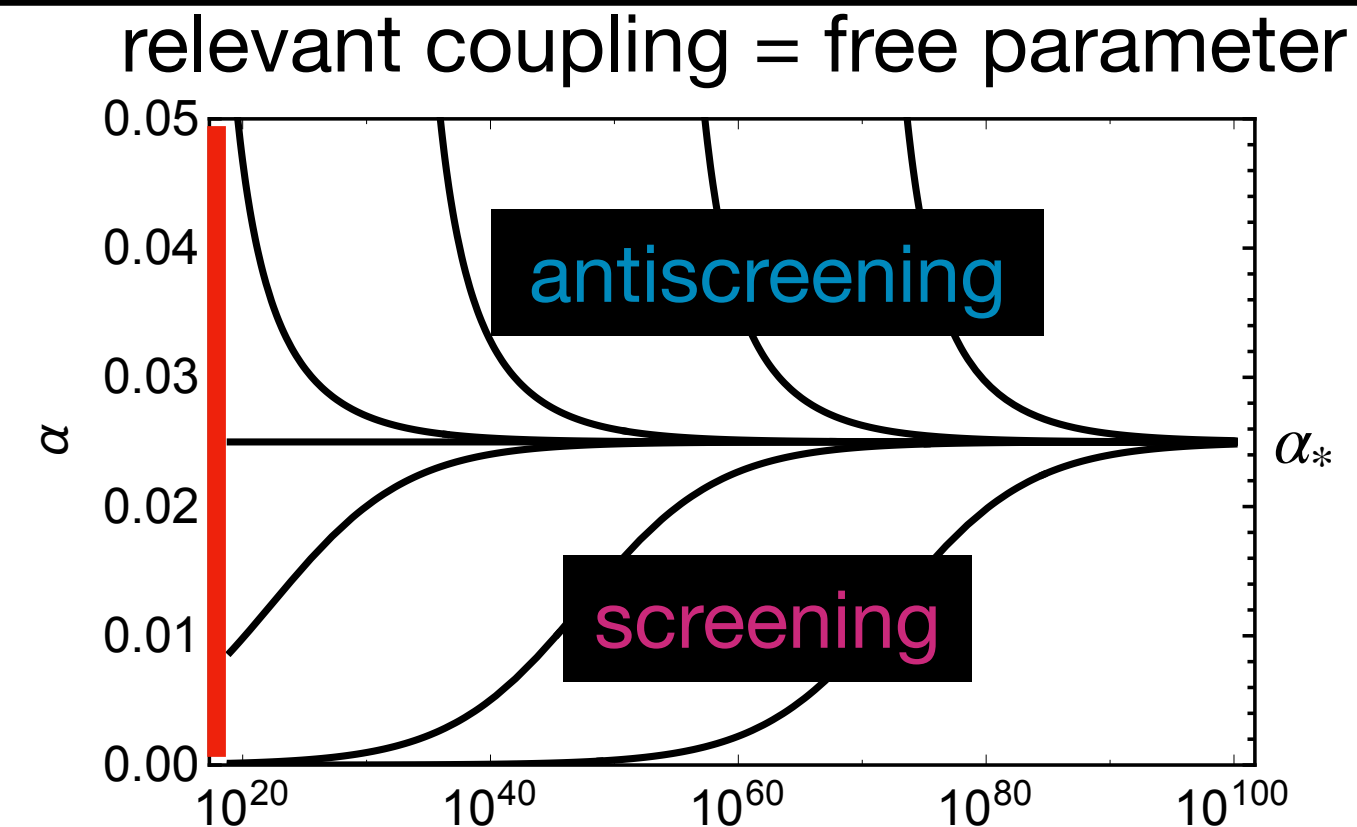
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$$\beta_\alpha = \alpha \left(\alpha_*^k - \alpha \right)$$

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

→ a range of coupling values
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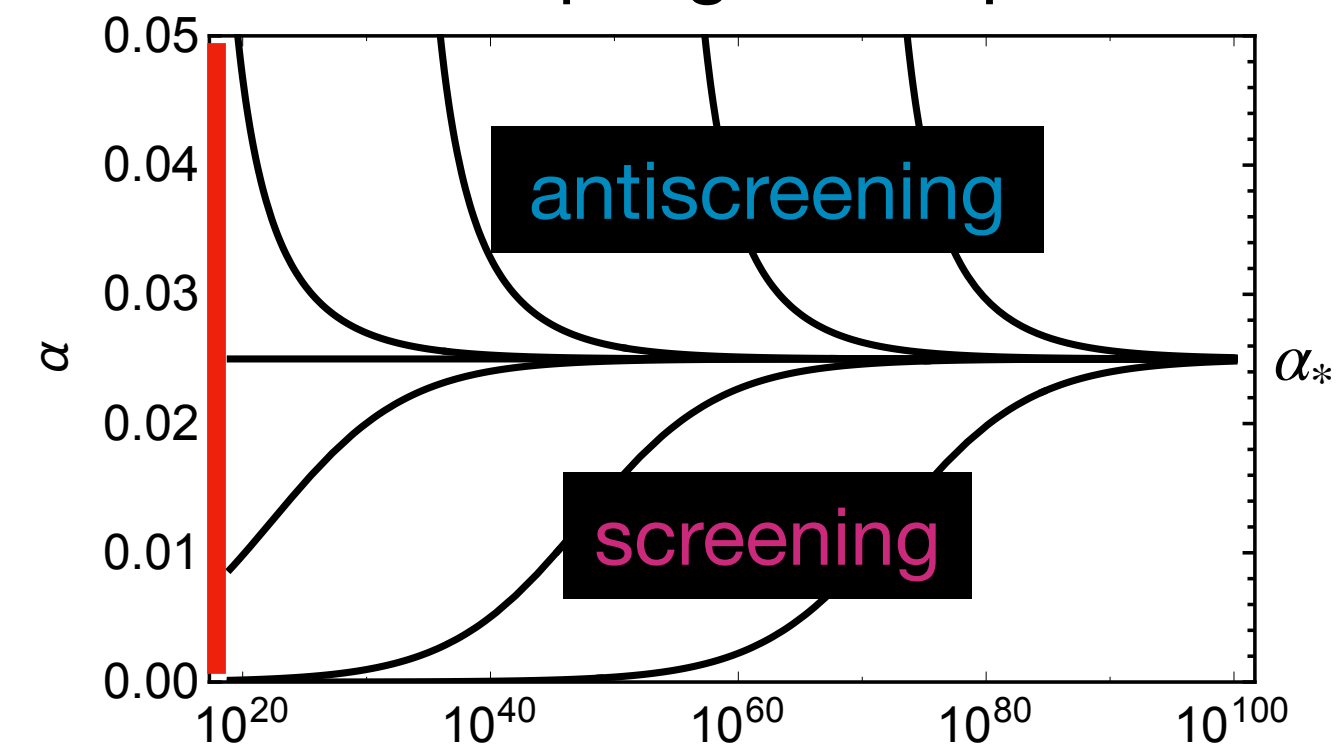
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relevant coupling = free parameter

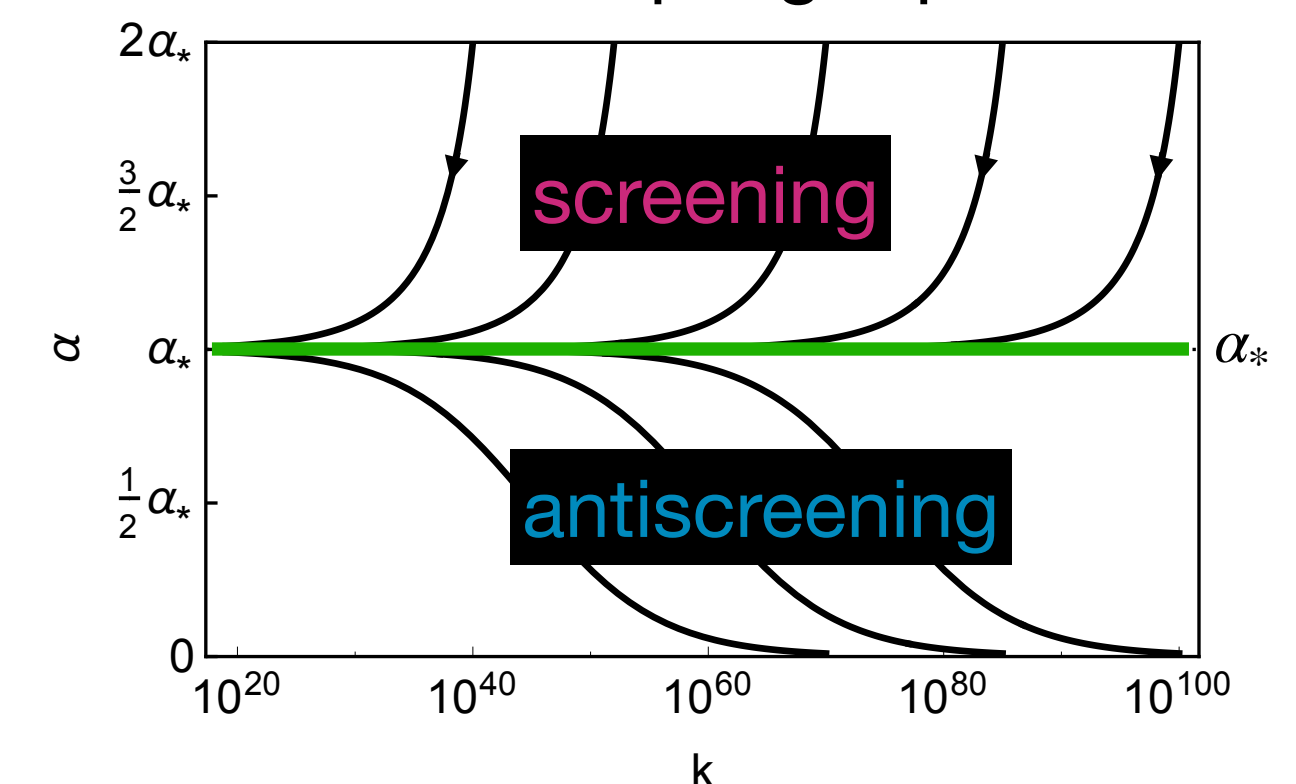


$$\beta_\alpha = \alpha \left(\alpha_* - \alpha \right)$$

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

→ a range of coupling values achievable at the Planck scale

irrelevant coupling = prediction



$$\beta_\alpha = \alpha \left(-\alpha_* + \alpha \right)$$

quantum fluctuations drive coupling **towards** scale symmetry

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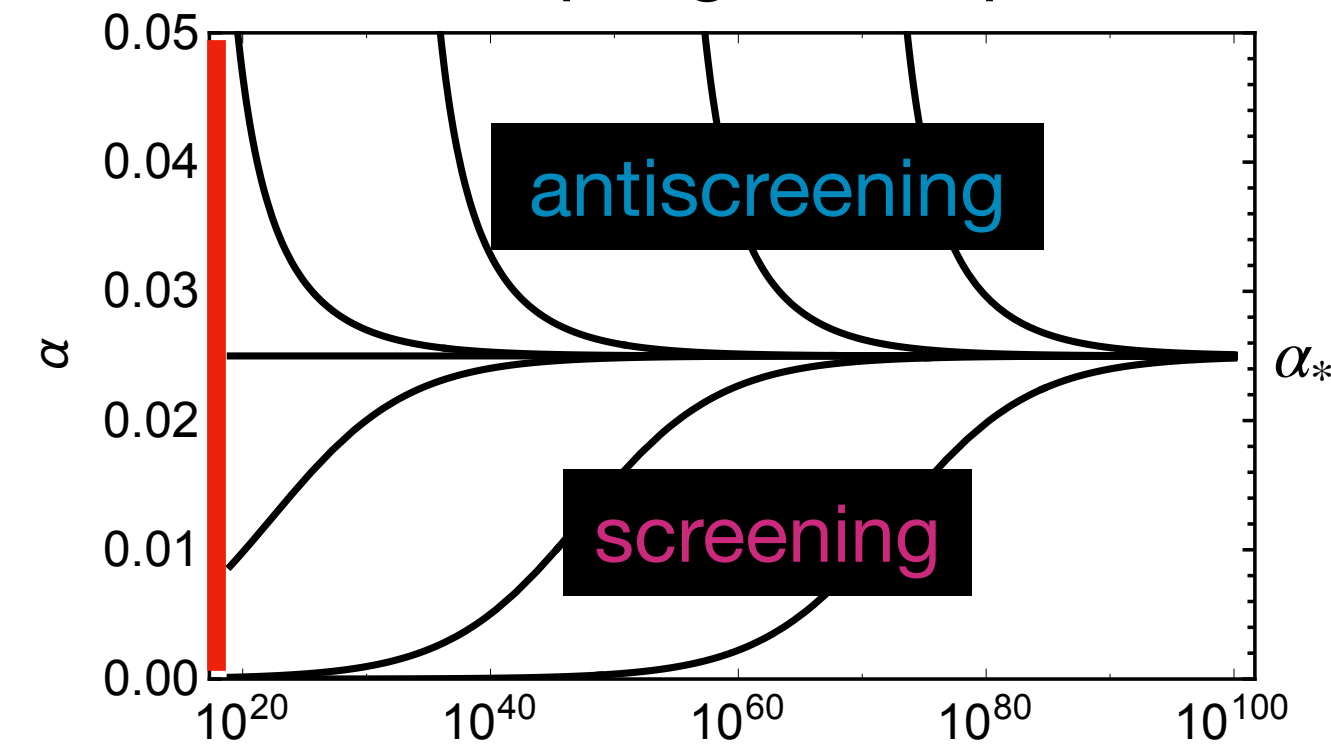
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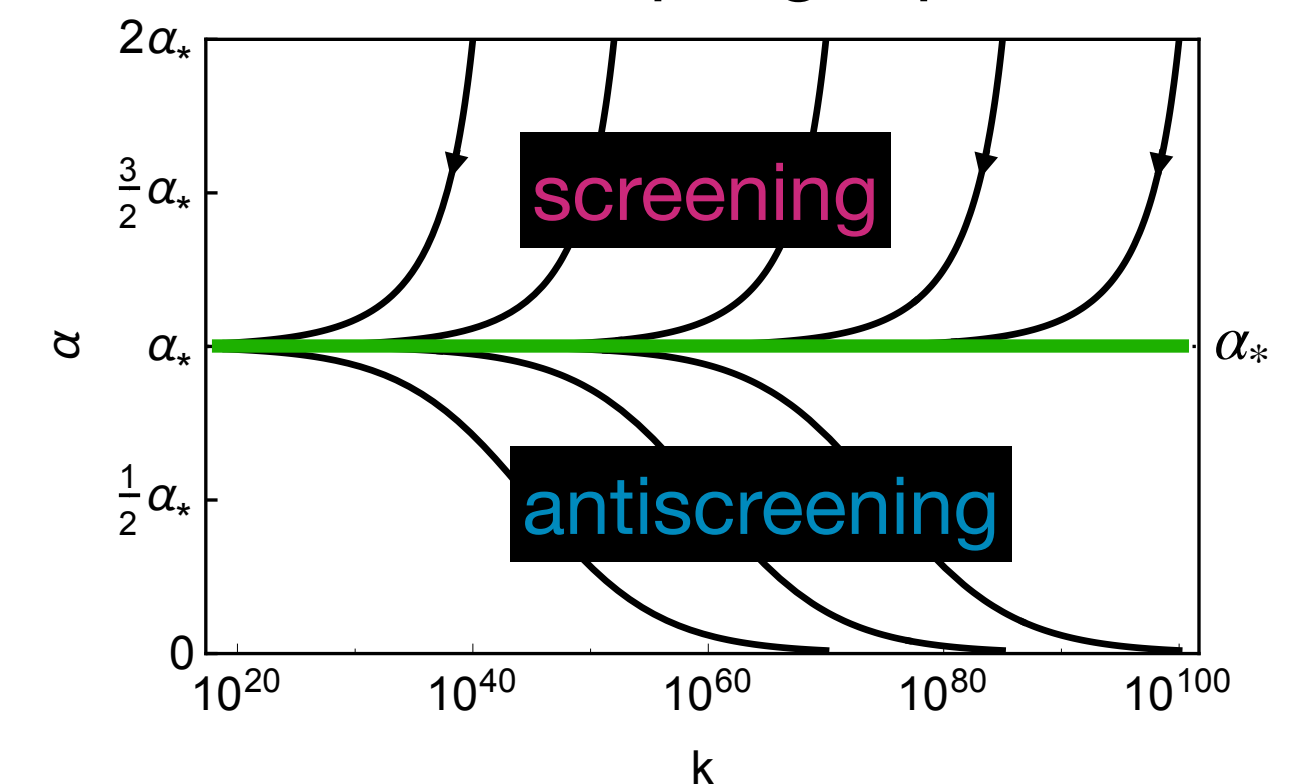


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[Benedetti, Machado, Saueressig '09; Falls, Litim, et al. '13, '14; Denz, Pawłowski, Reichert '16;
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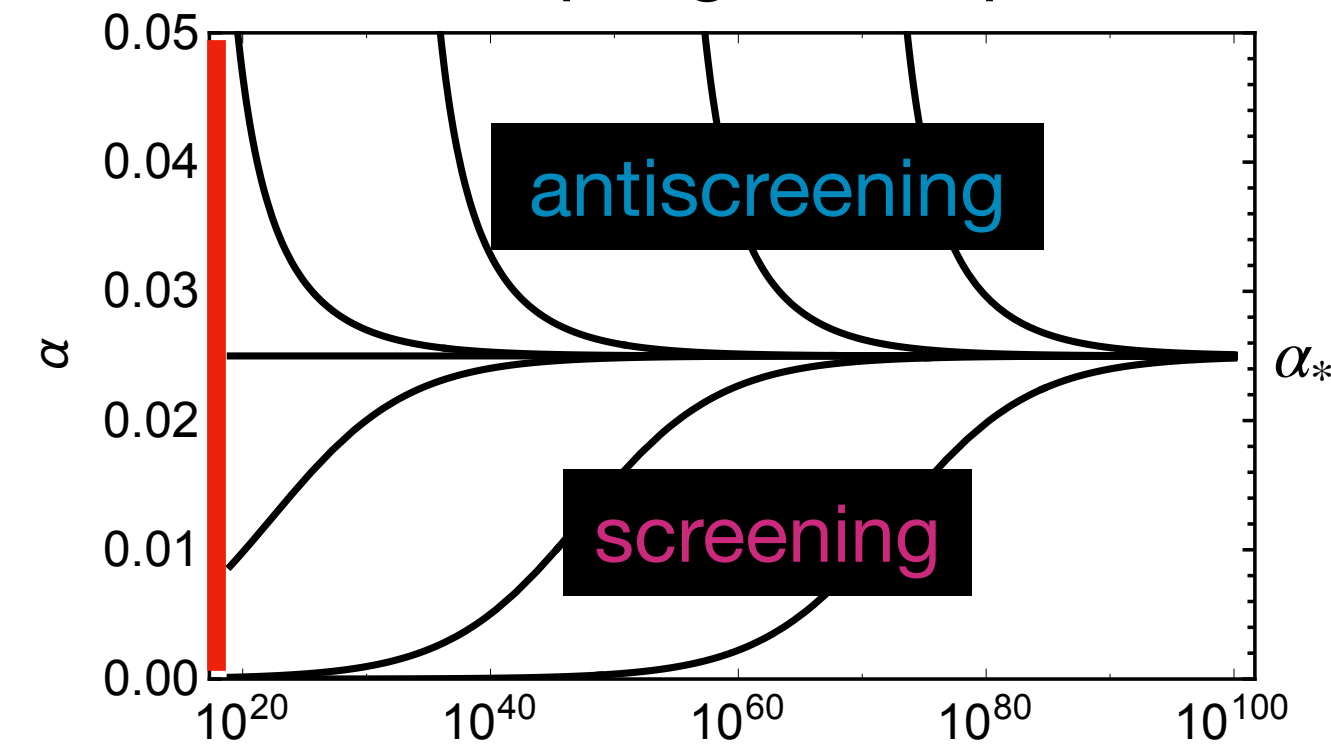
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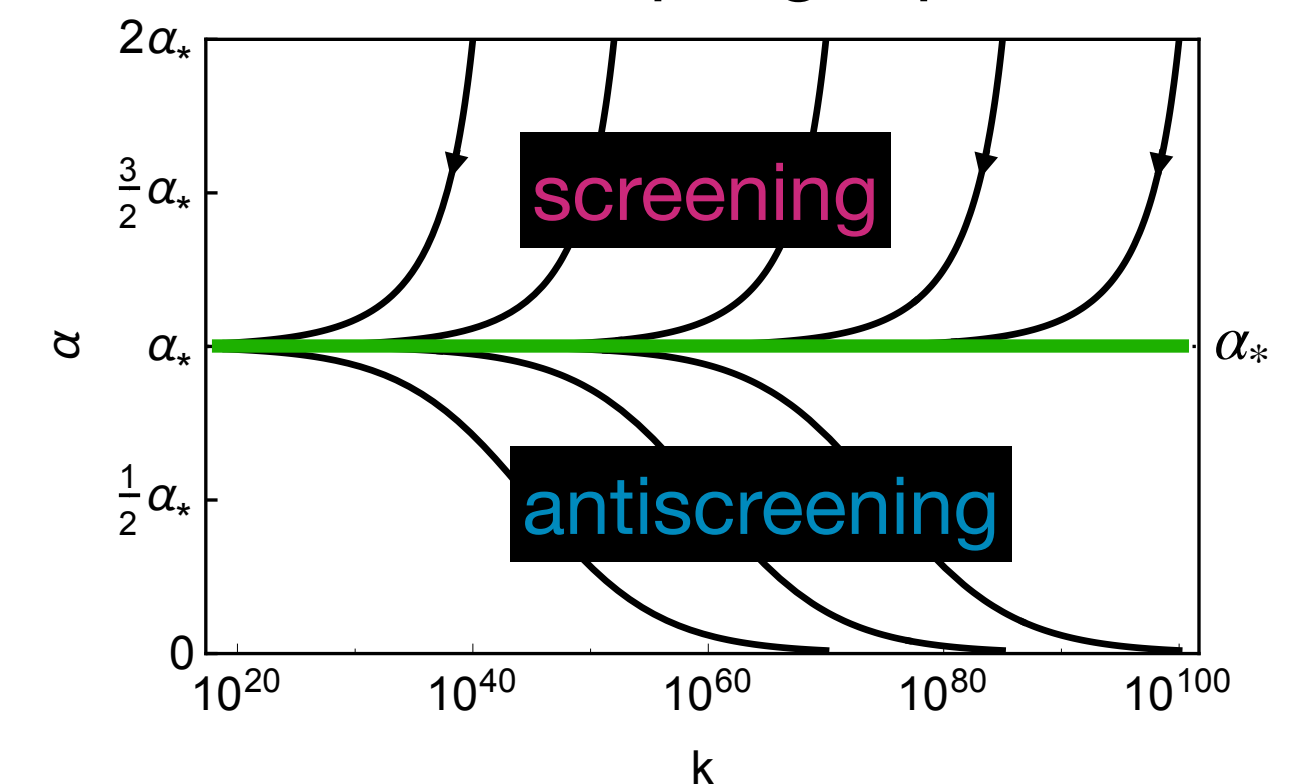


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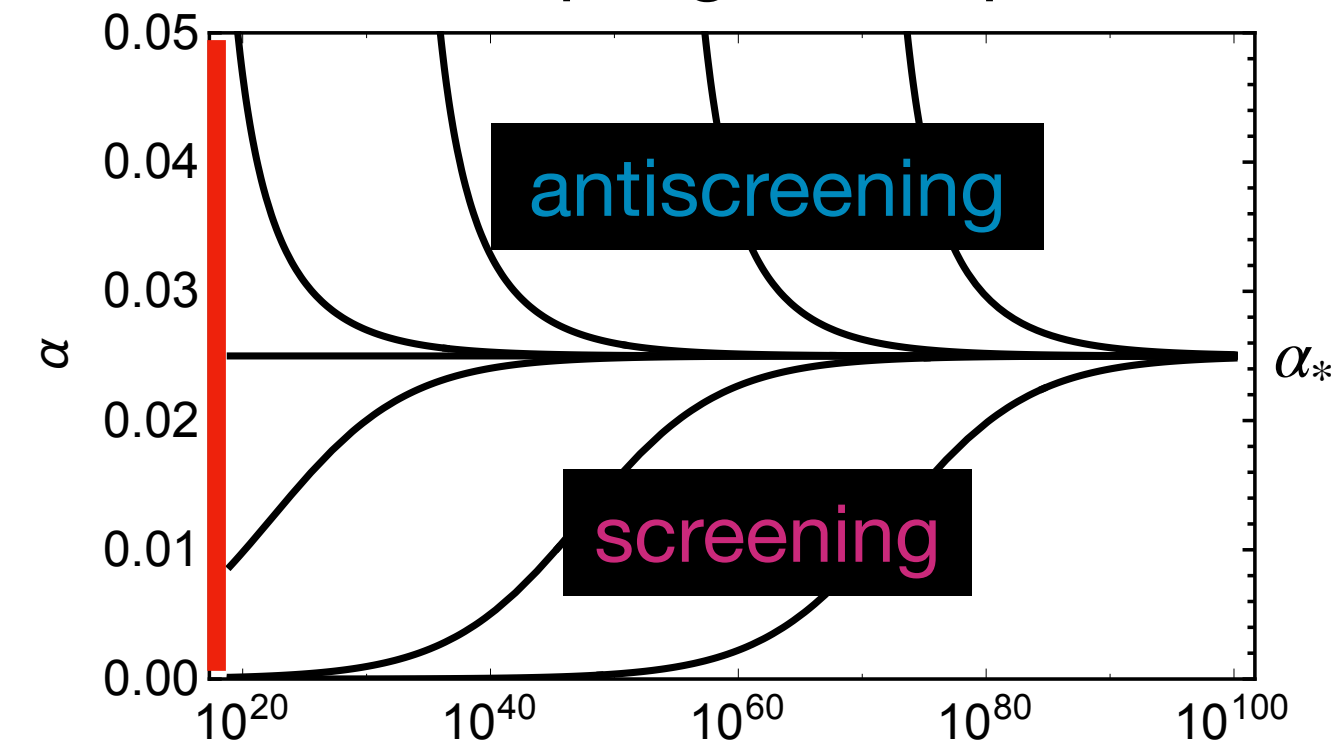
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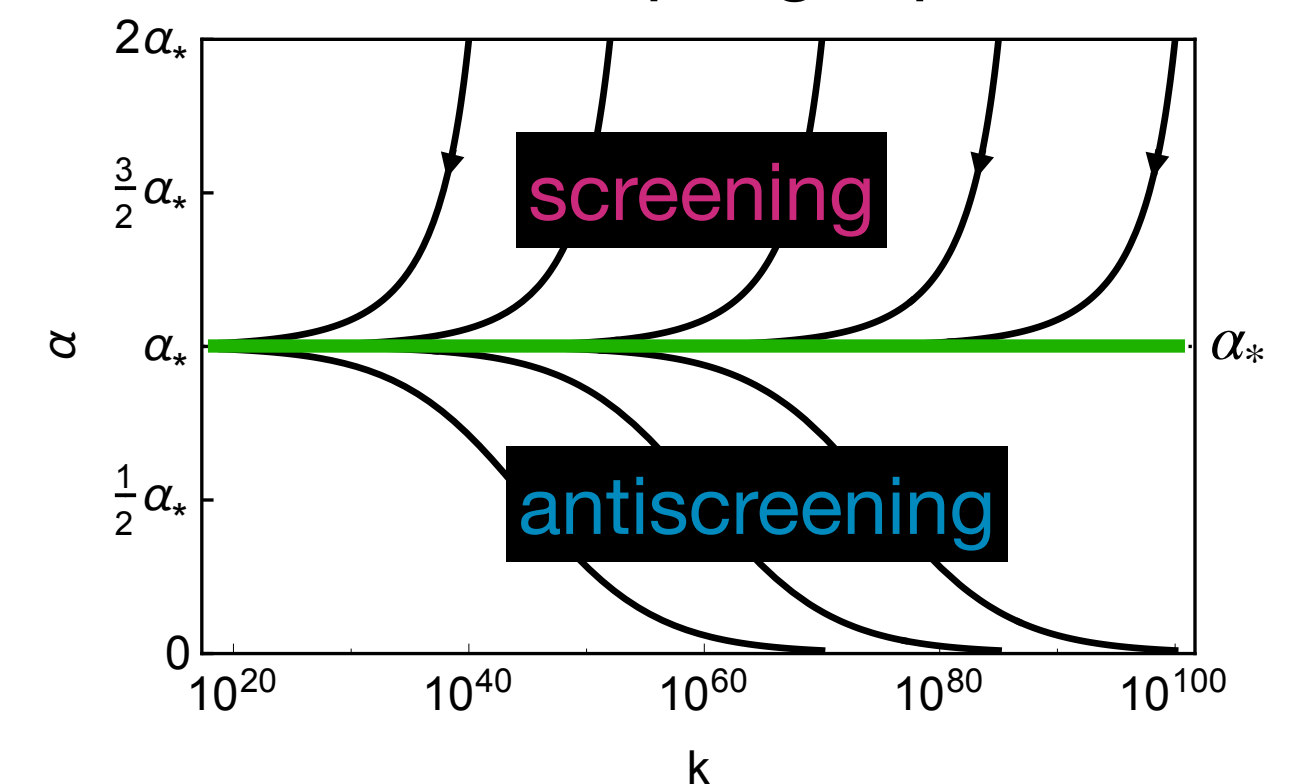


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for matter:

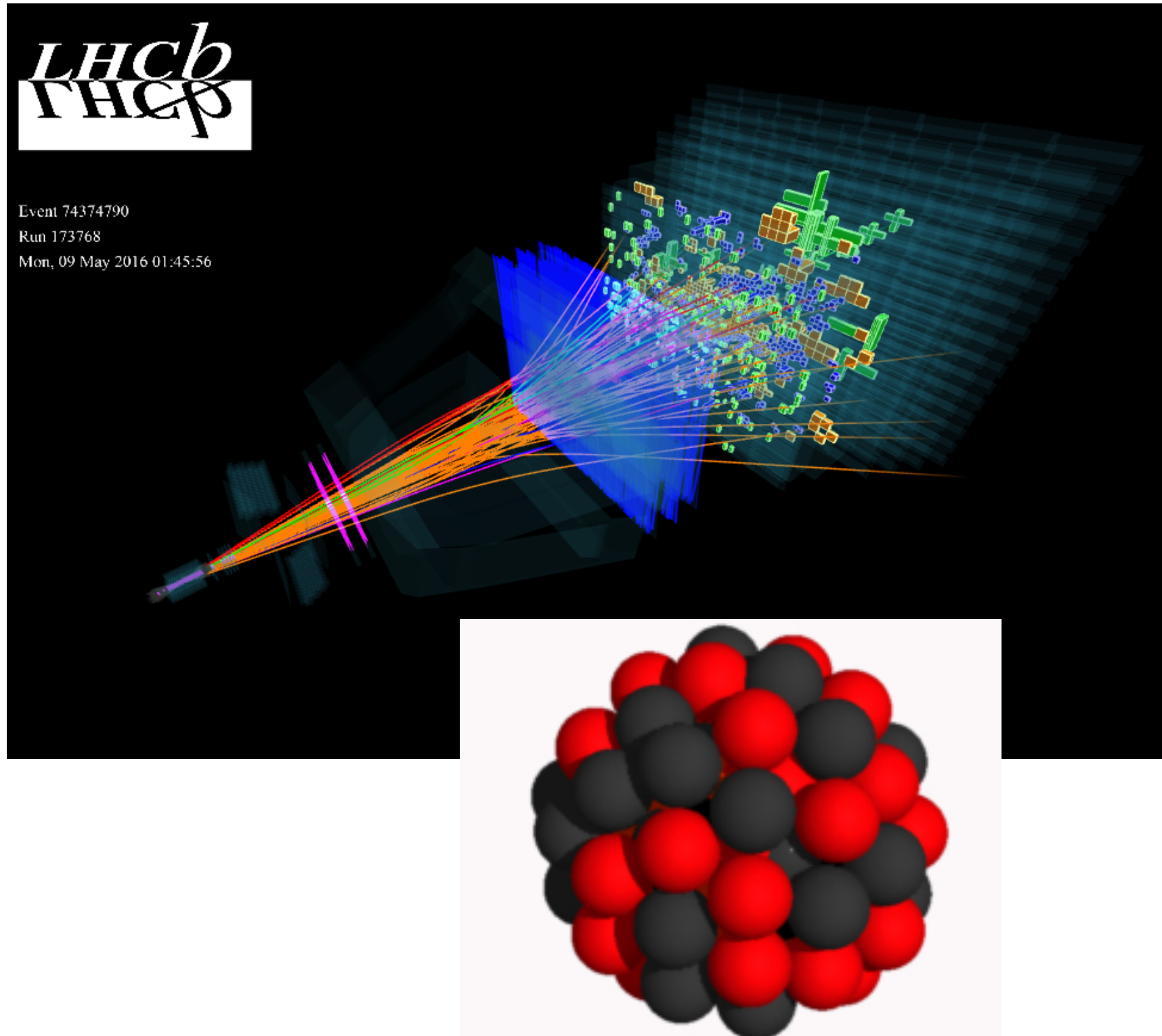
rest of this talk!

Predictive power of asymptotic safety for matter

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Quantum gravity at particle-physics scales?!

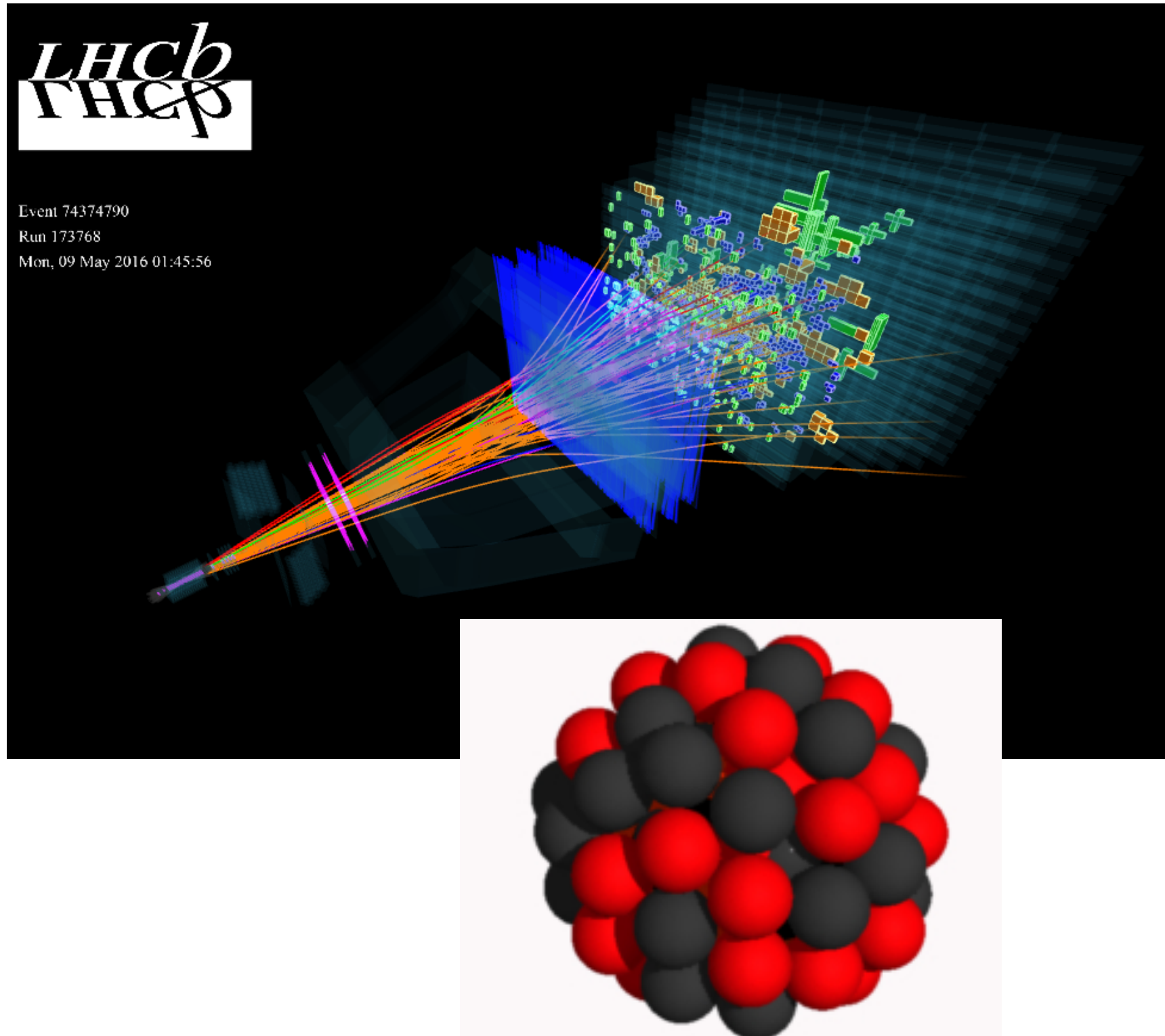
ratio of electric to gravitational force
between two protons: 10^{36}



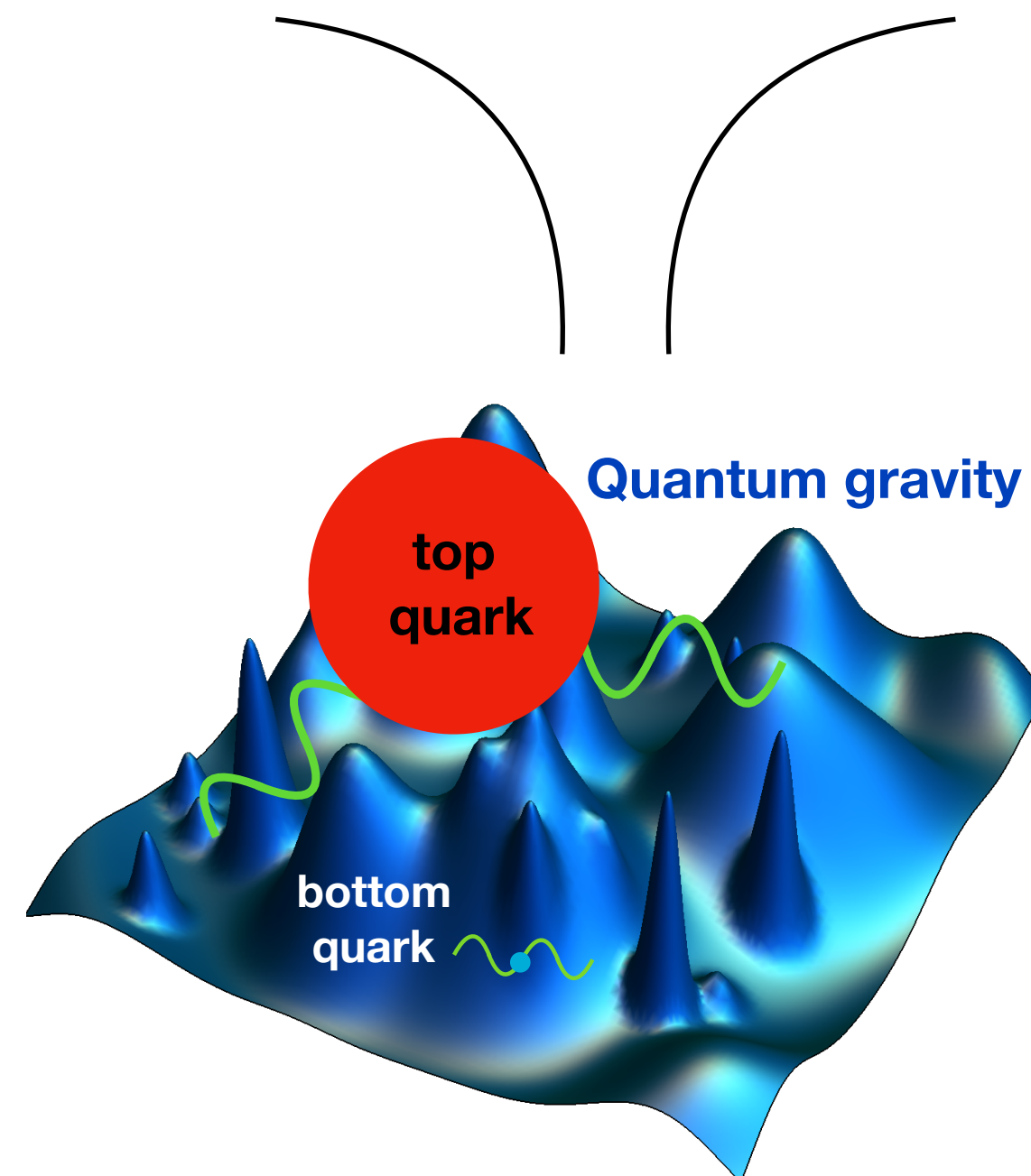
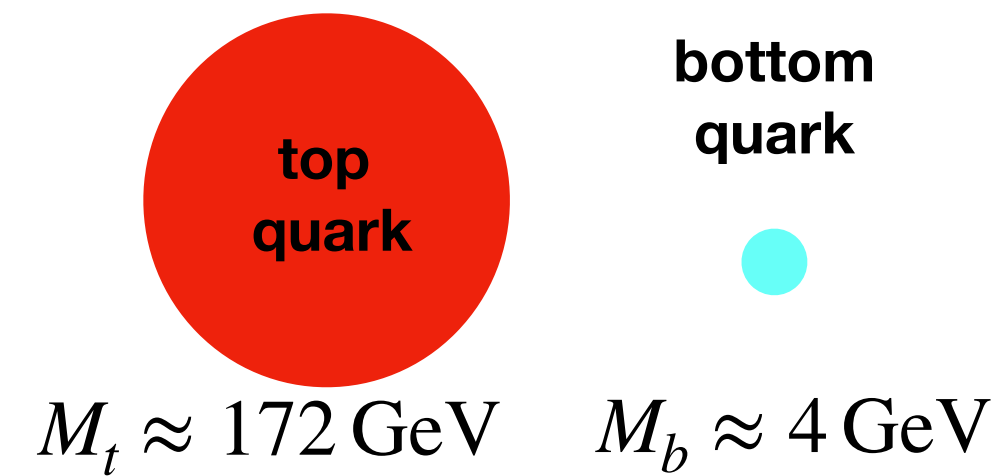
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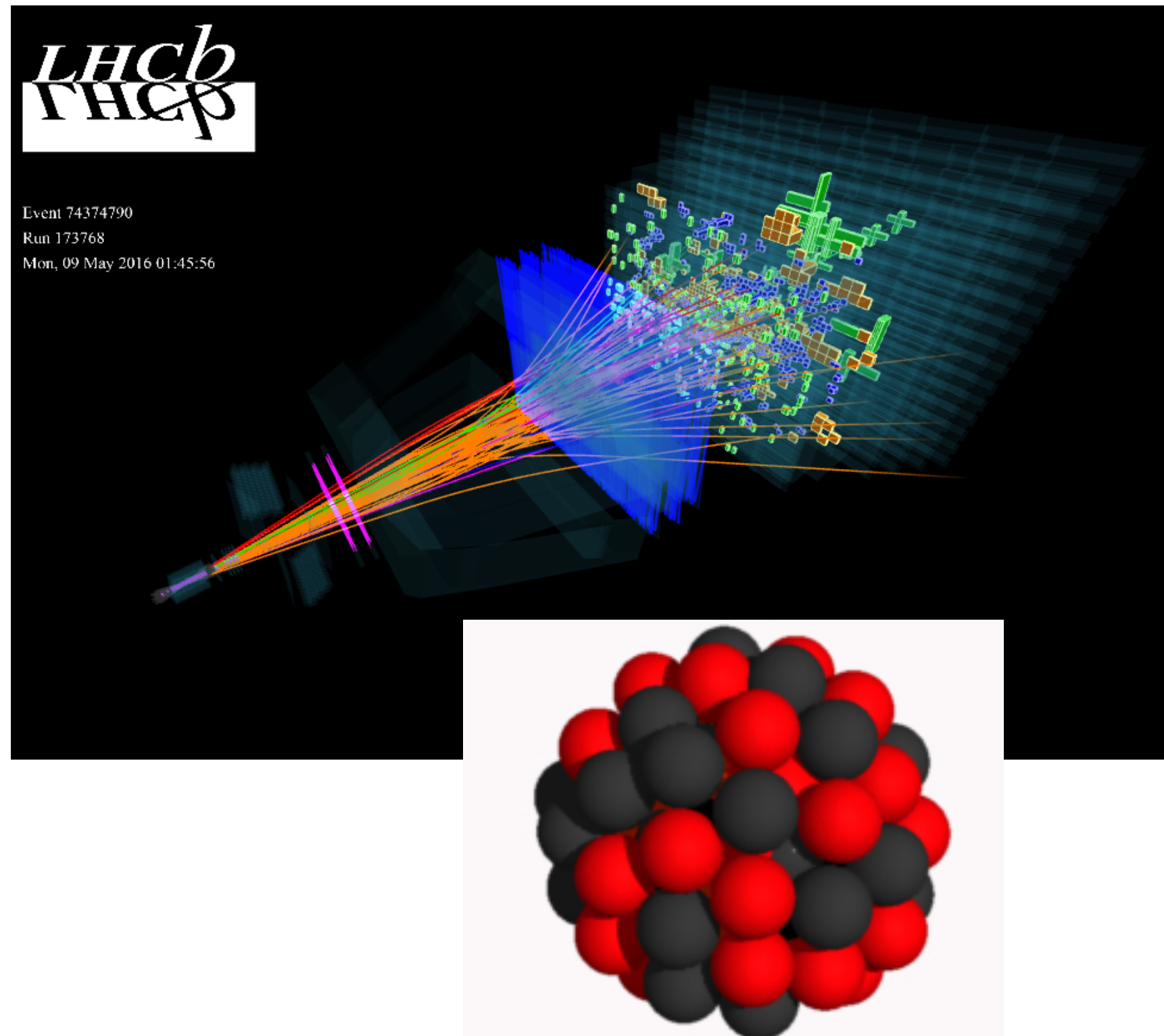
Idea: microphysics
determines properties
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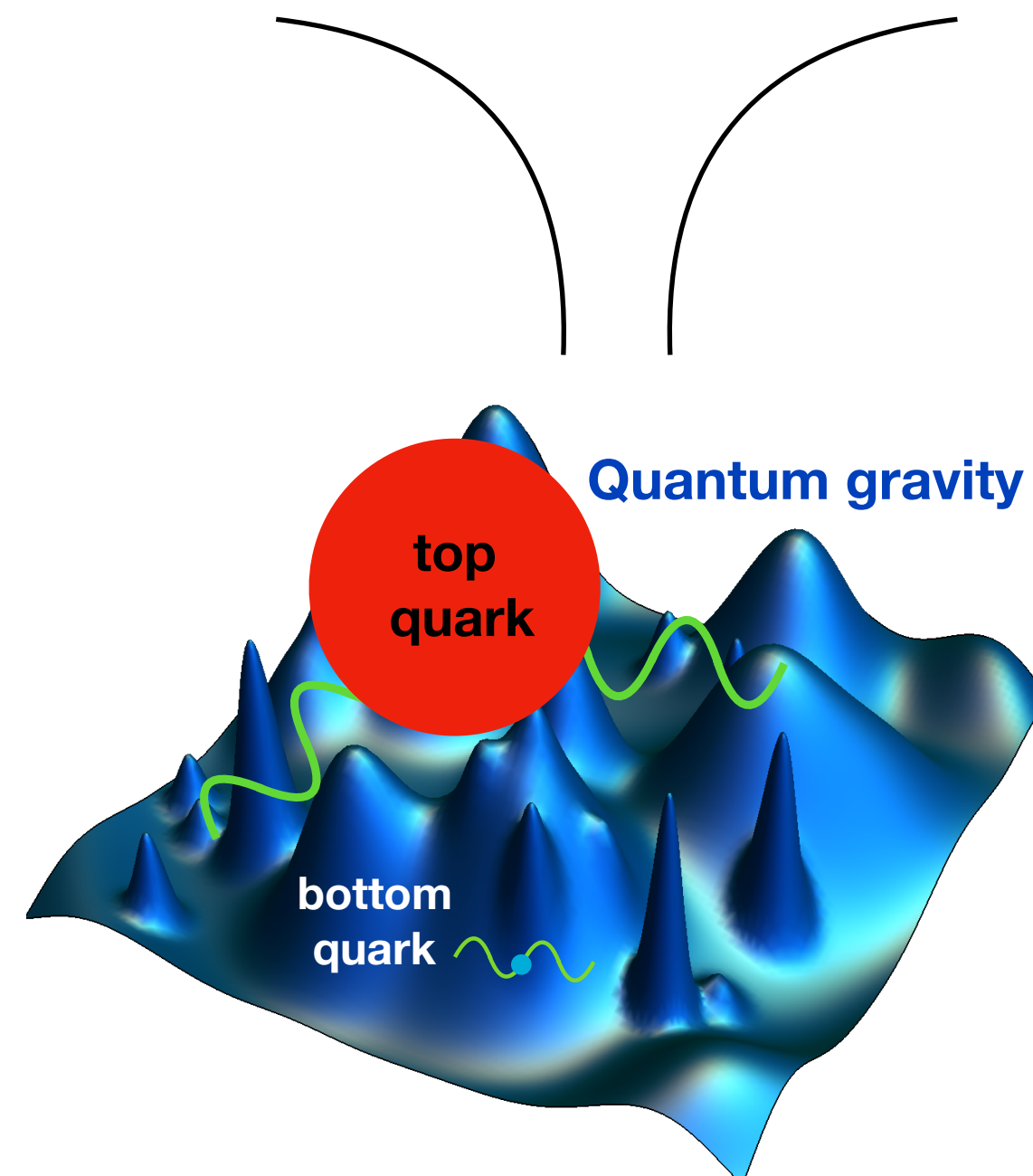
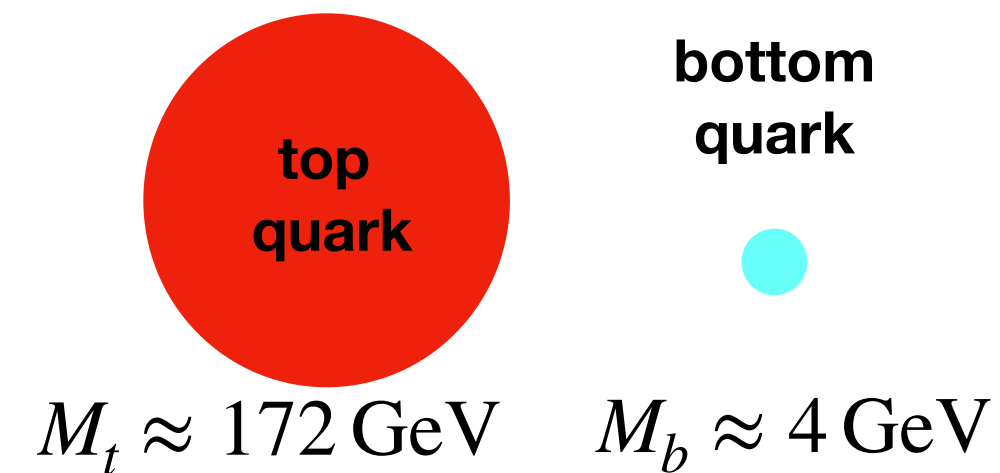
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Predictive power:

From microphysics that is scale symmetric
only a subset of effective field theories can
emerge:

Space of all EFTs

EFTs that
emerge from
asymptotic
safety

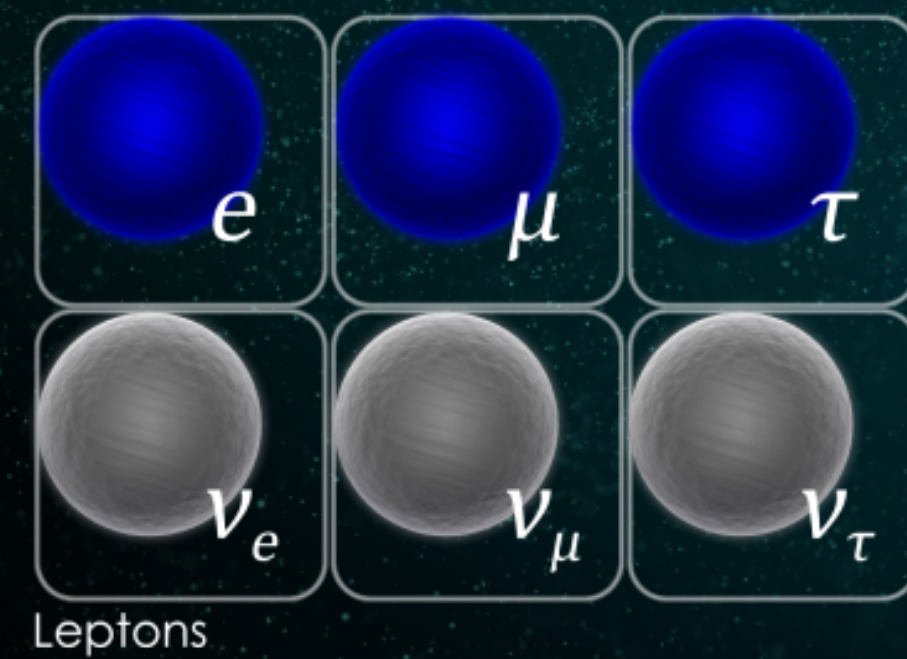
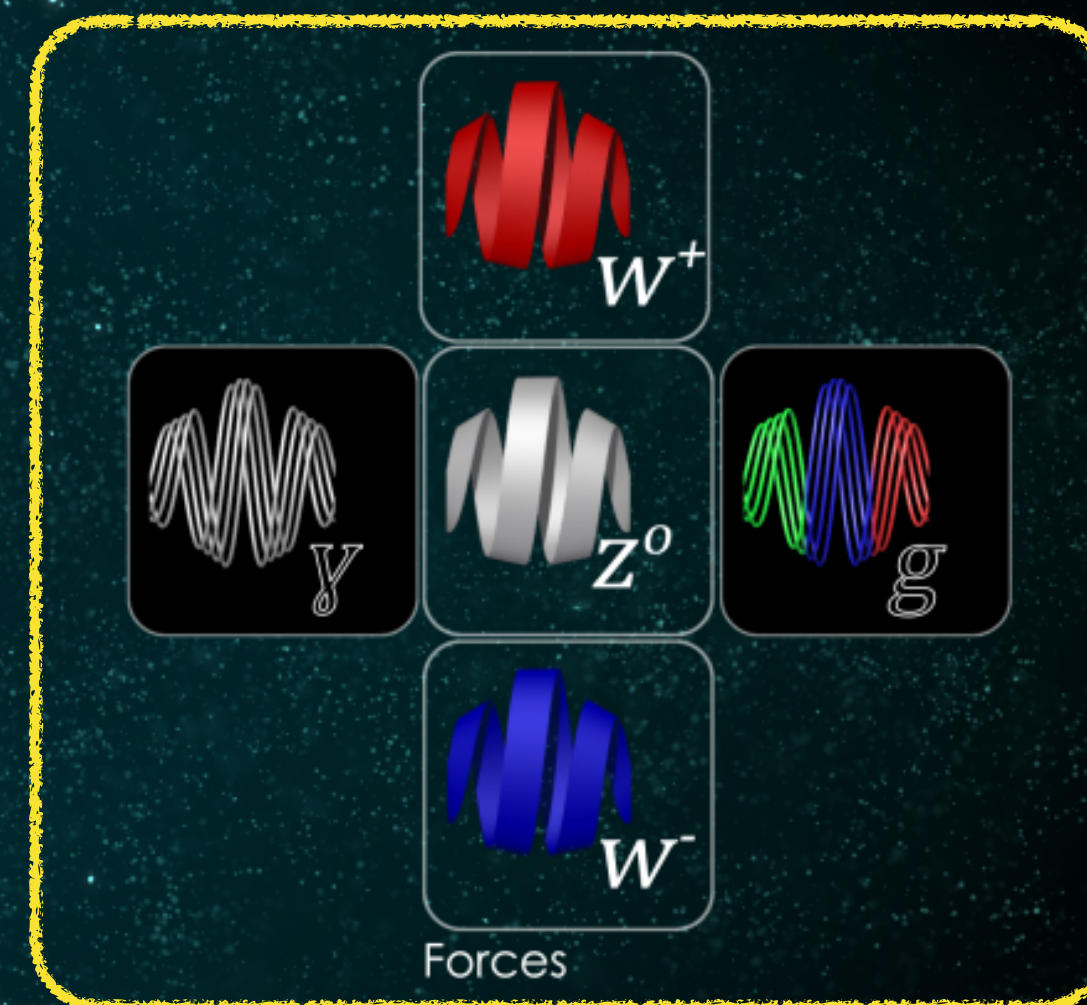
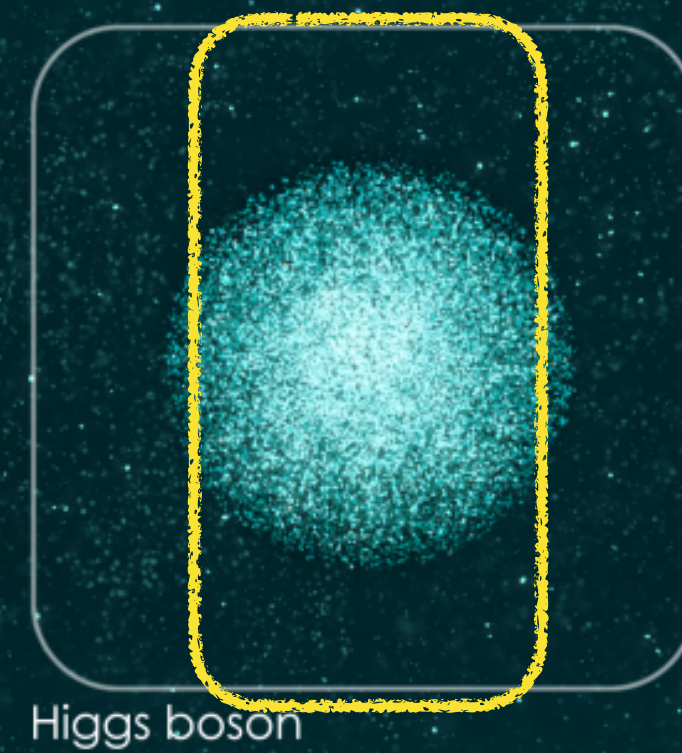
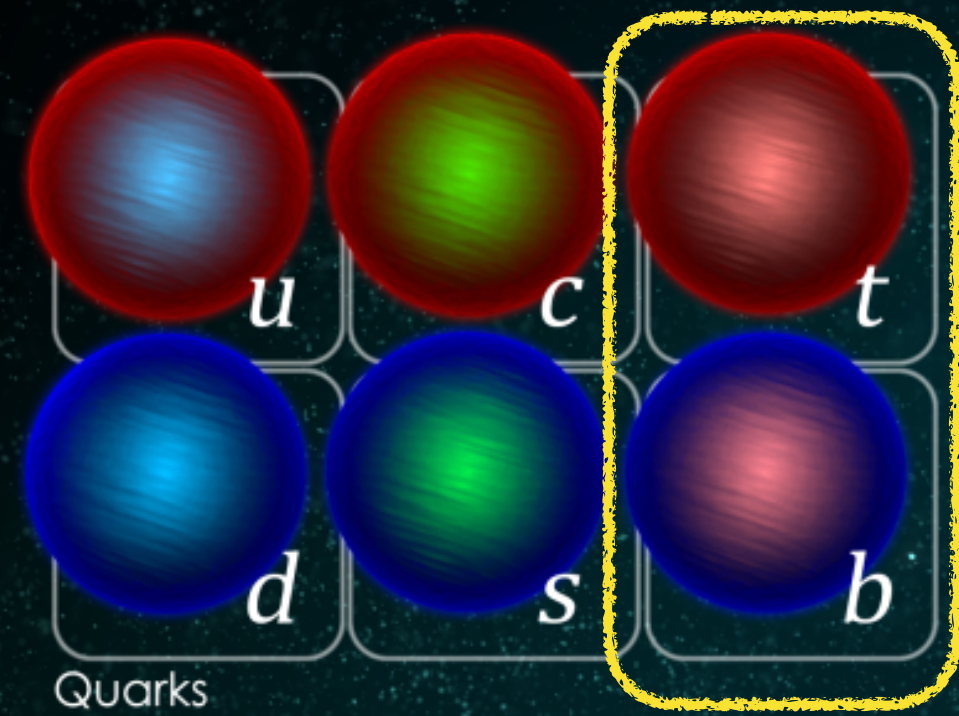
relative swampland
of asymptotic safety

relative vs absolute swamplands:
AE, Hebecker, Pawłowski, Walcher '24

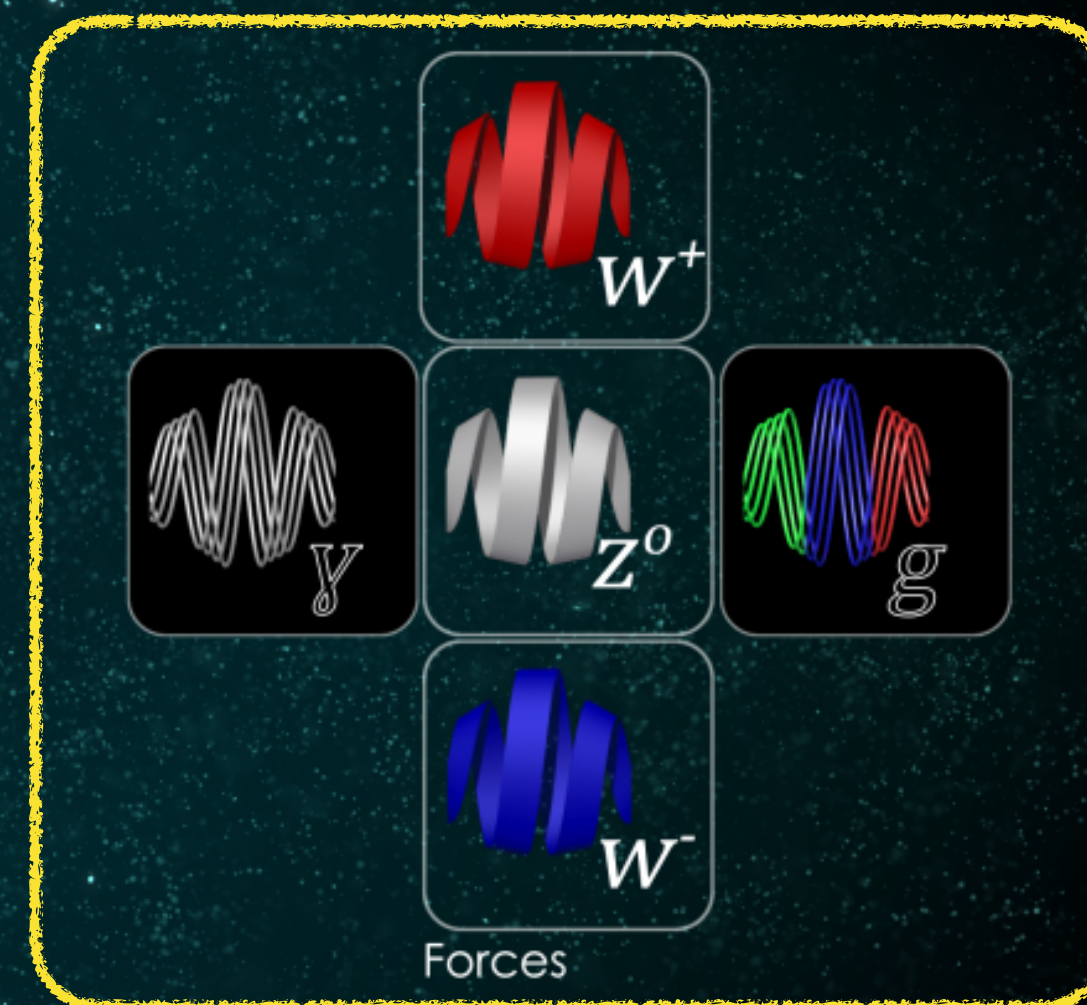
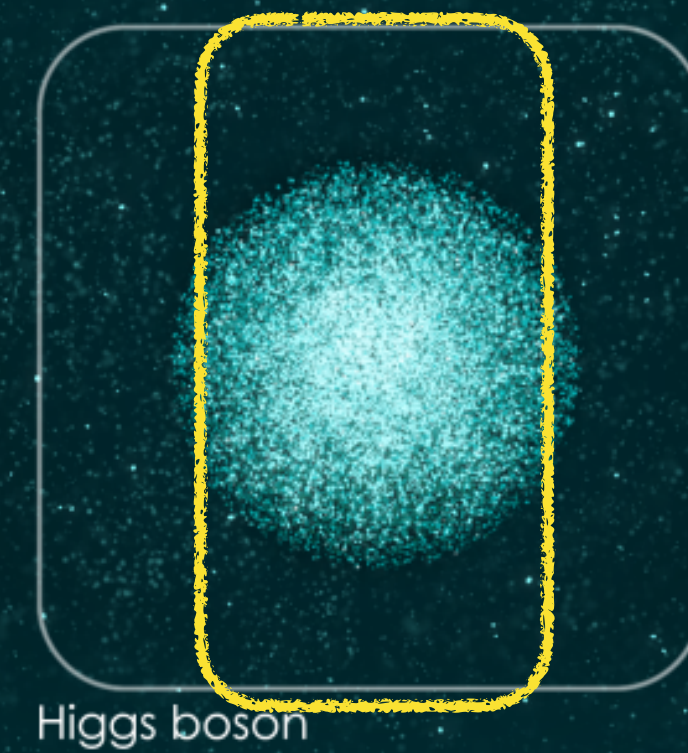
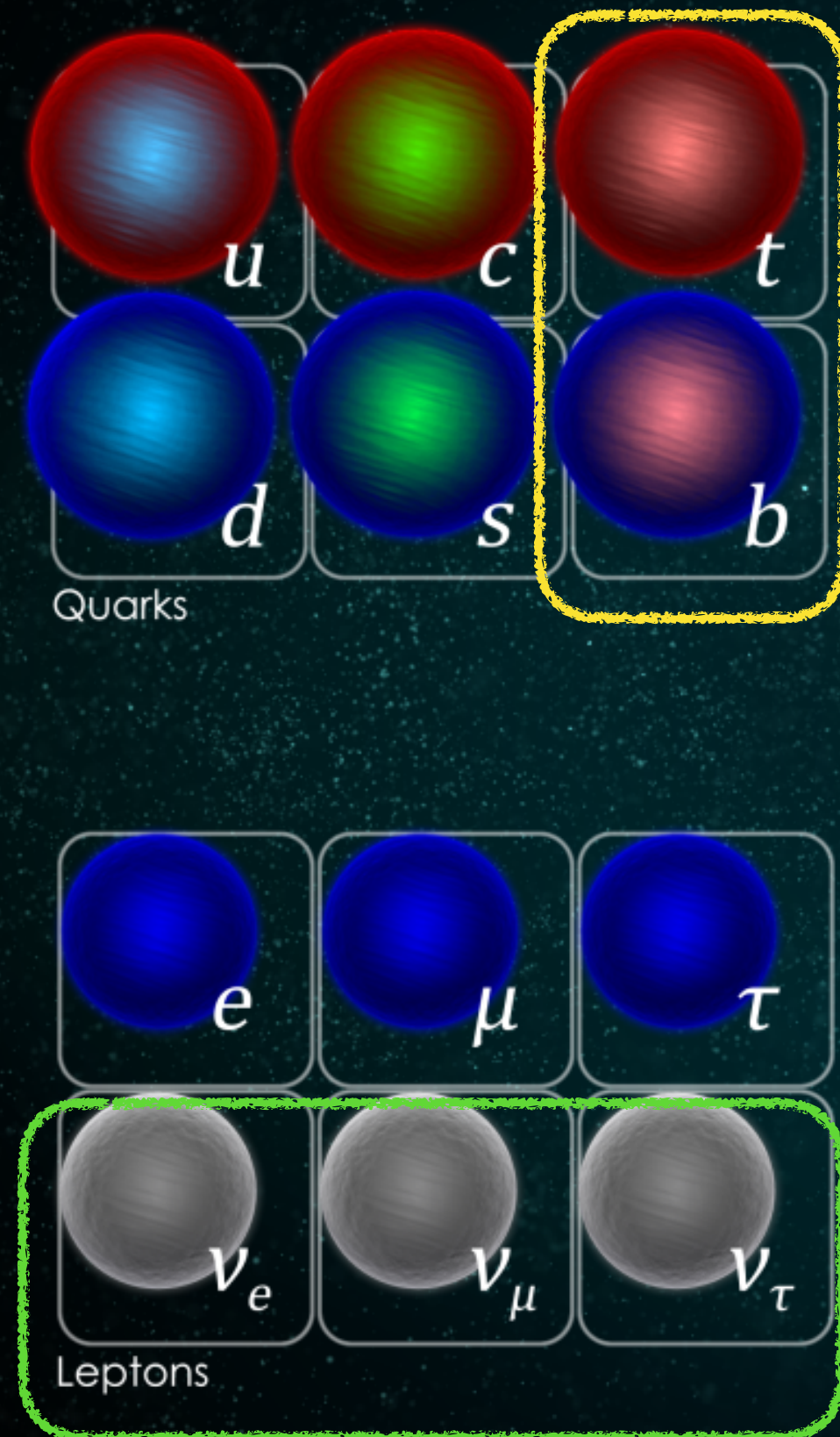
Standard Model couplings

ingredient 1: “heavy” Standard Model

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



Standard Model couplings



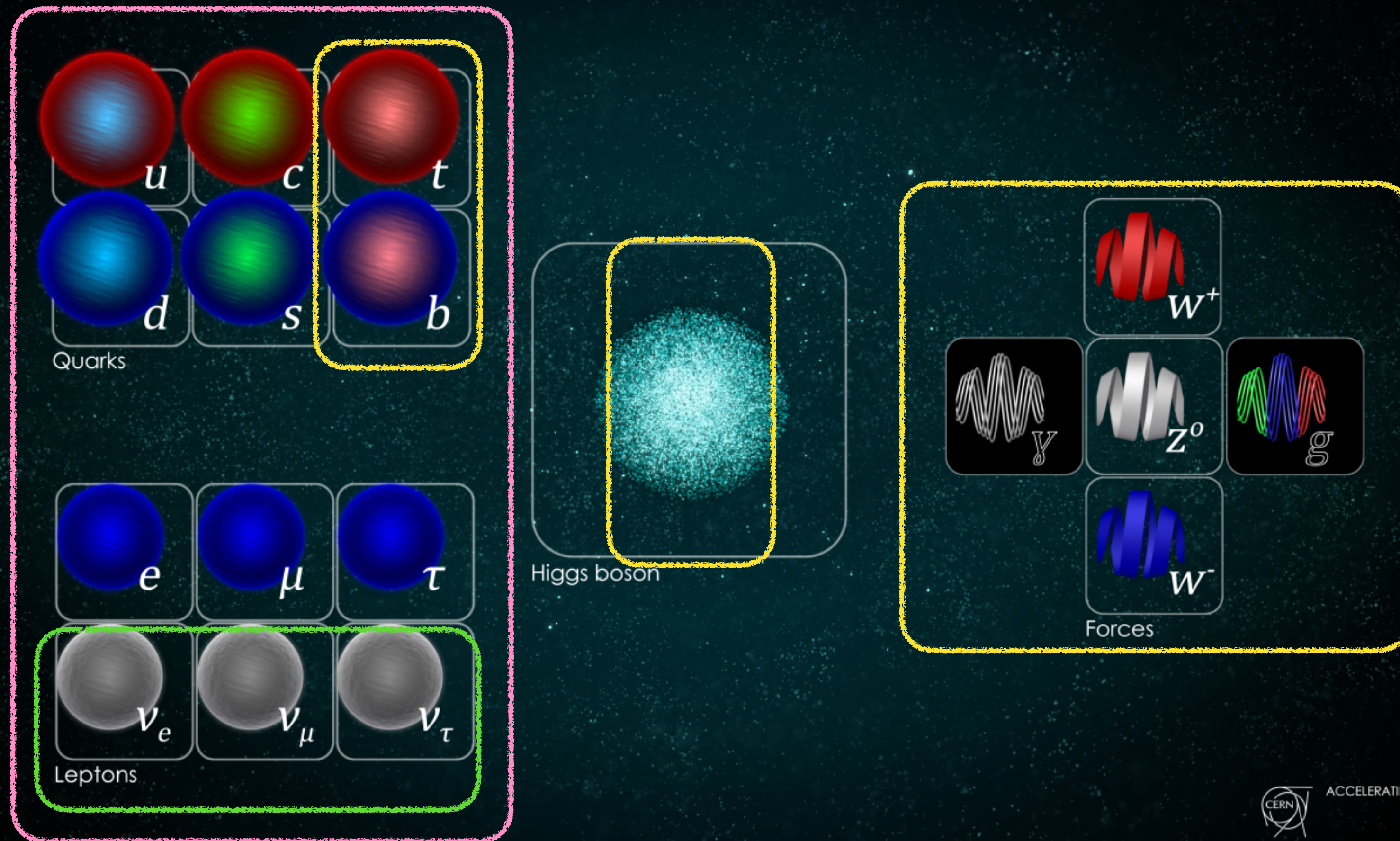
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[Held, PhD thesis '19;
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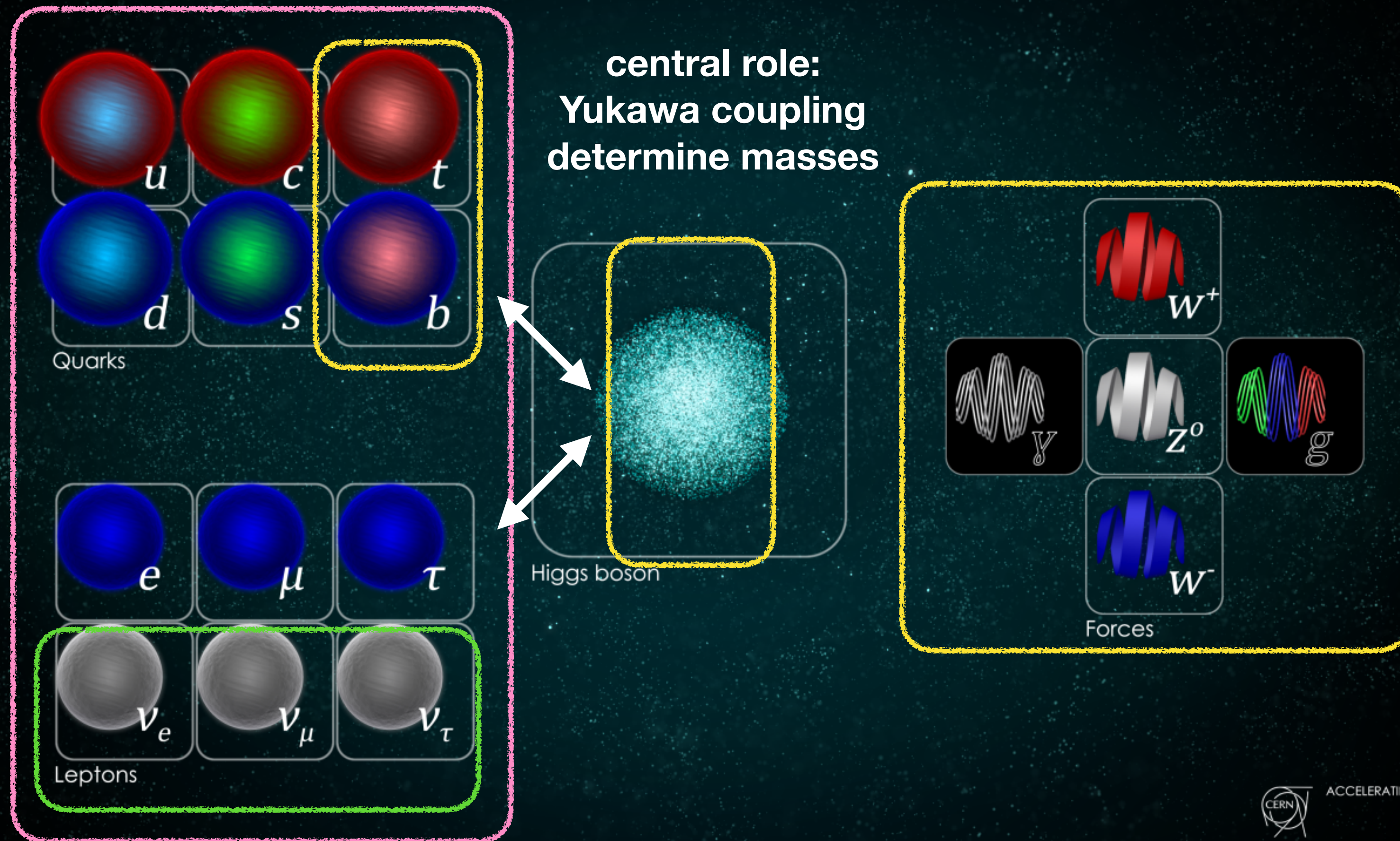
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Result: mixing of mass eigenstates (CKM and PMNS)

[Alkofer, AE, Held, Nieto, Percacci, Schröfl '20; Kowalska, Sessolo, Yamamoto '20; AE, Gyftopolous, Held '25]

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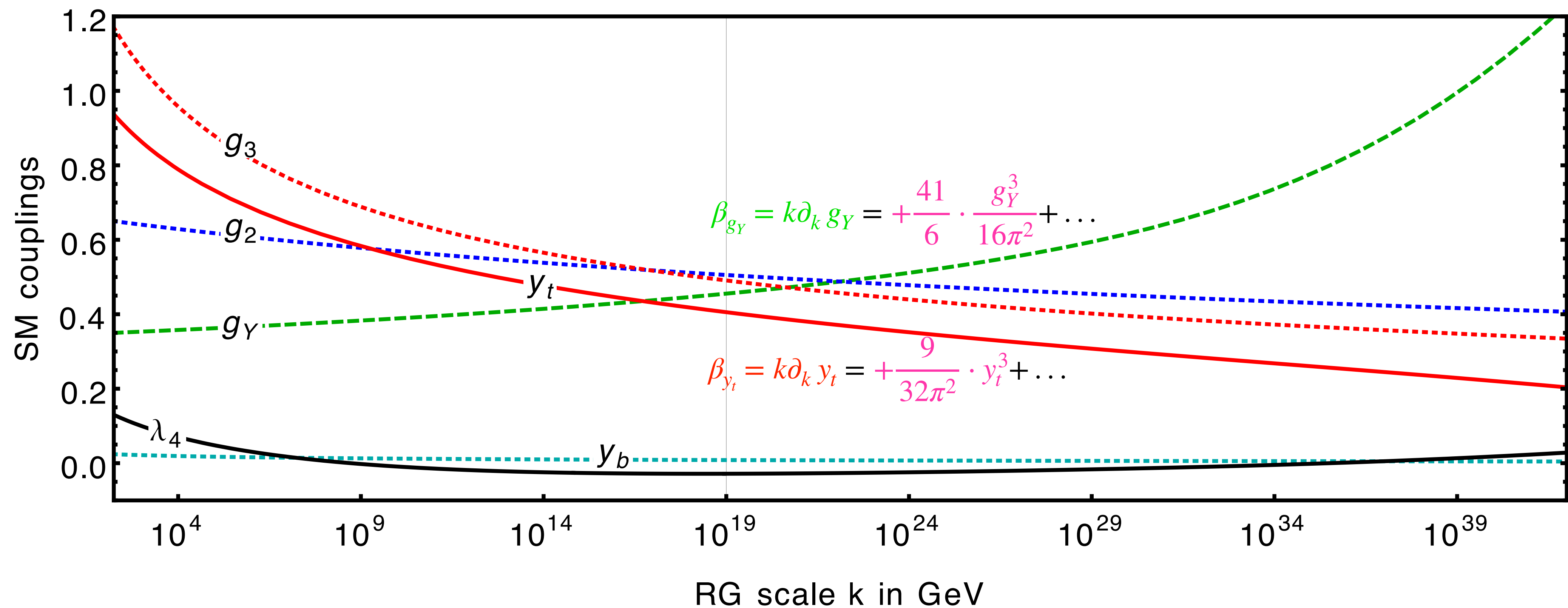
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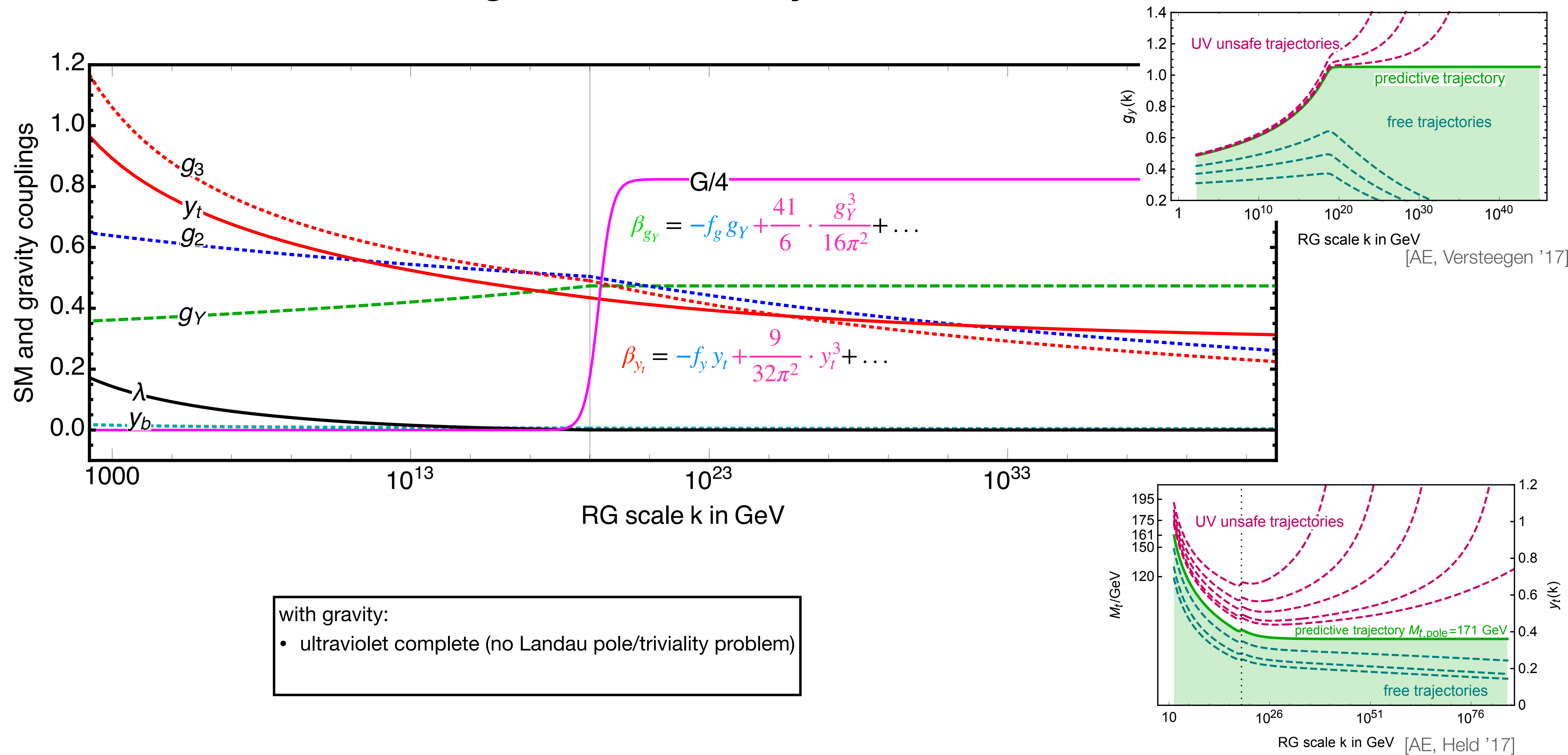
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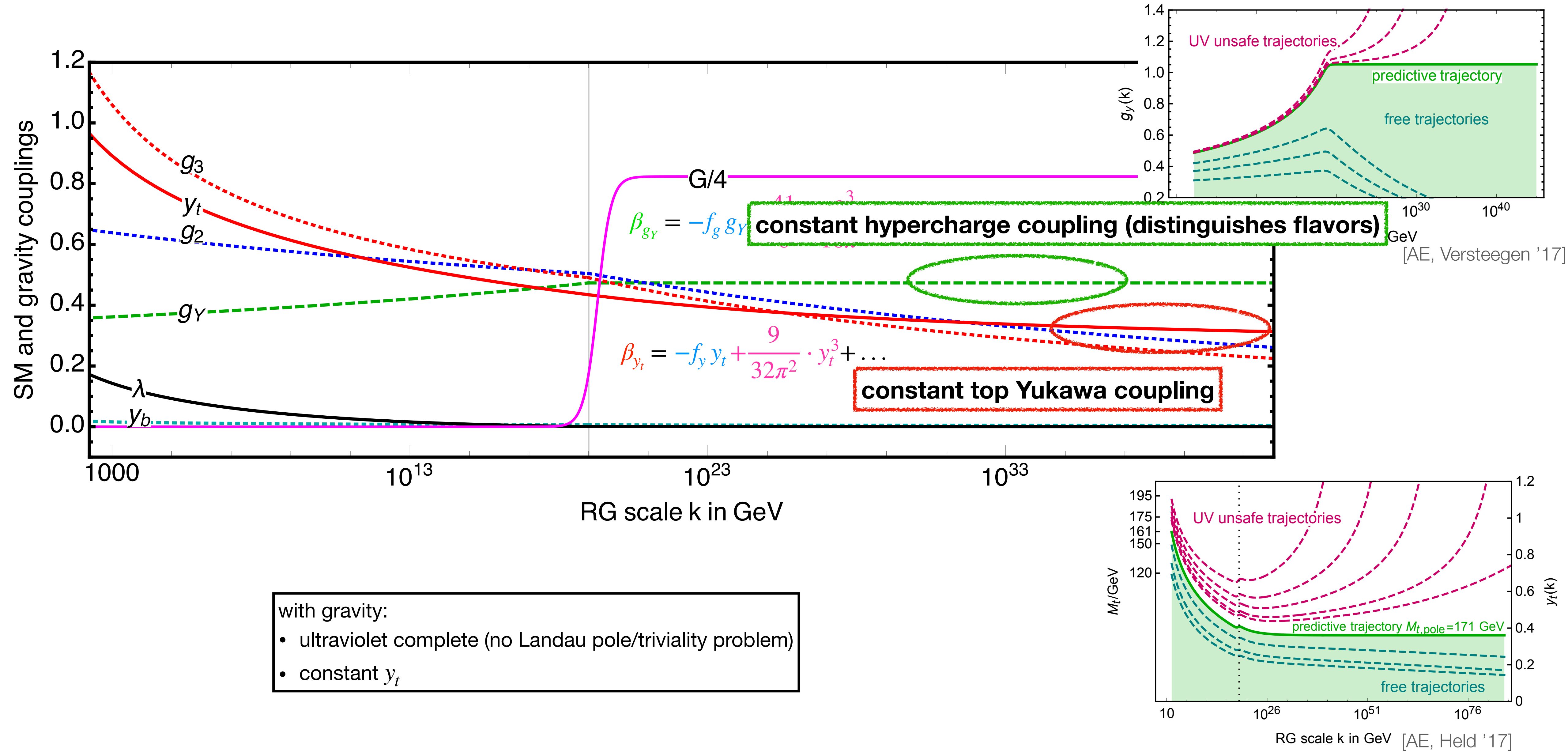
without gravity:

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

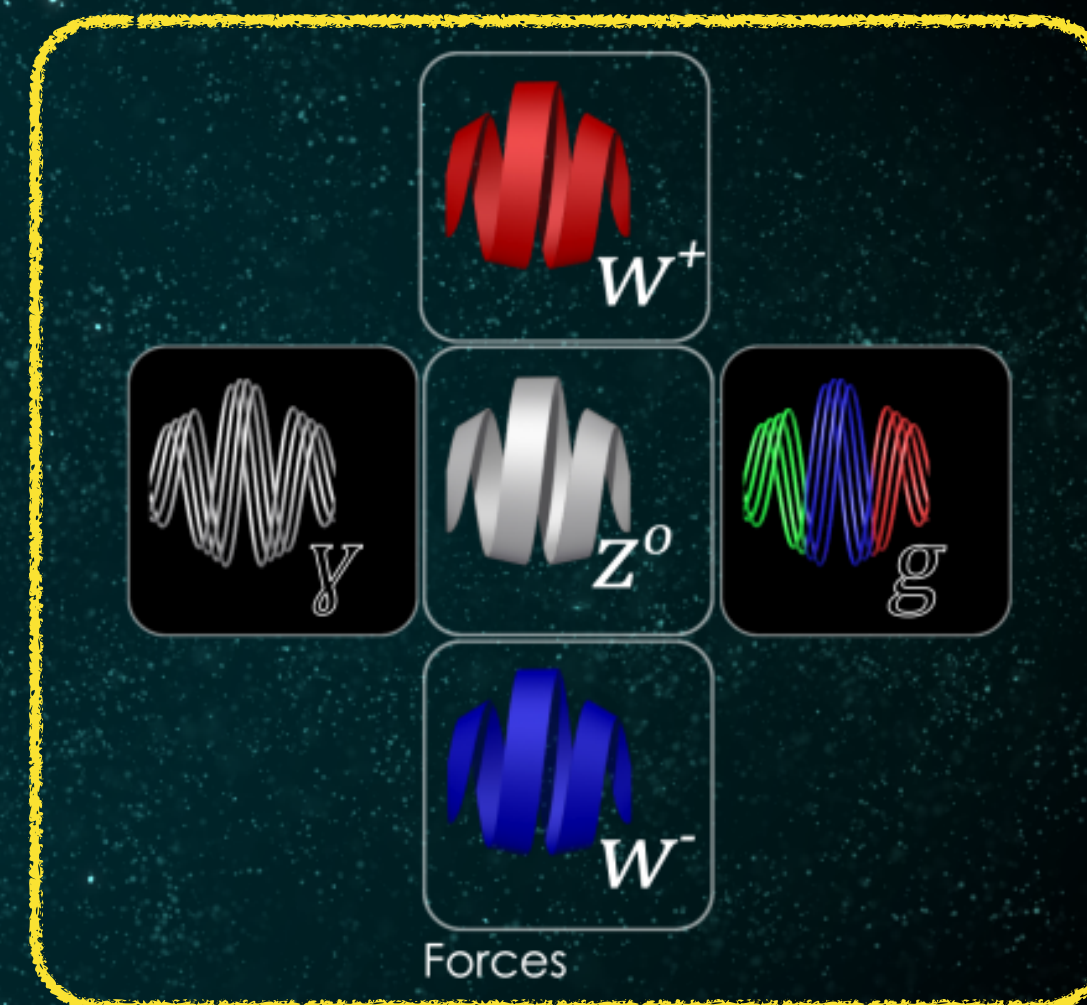
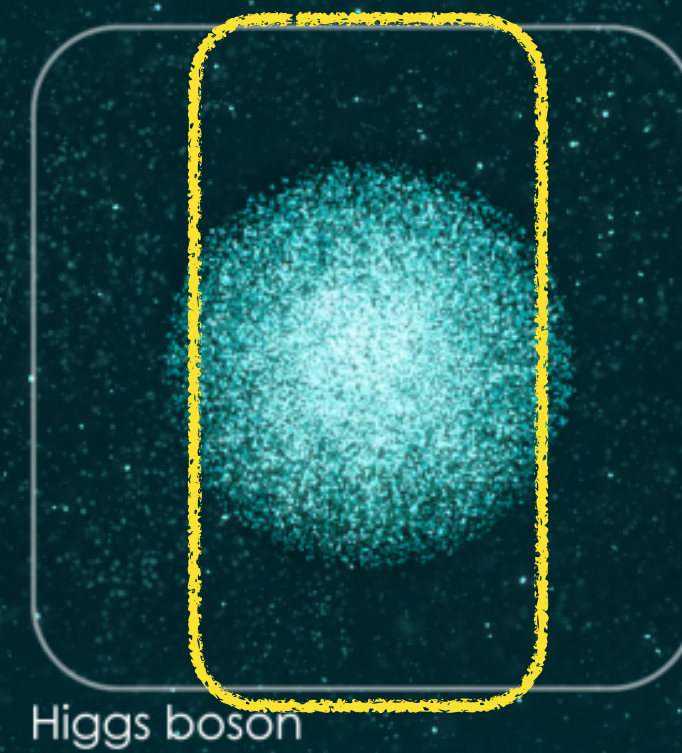
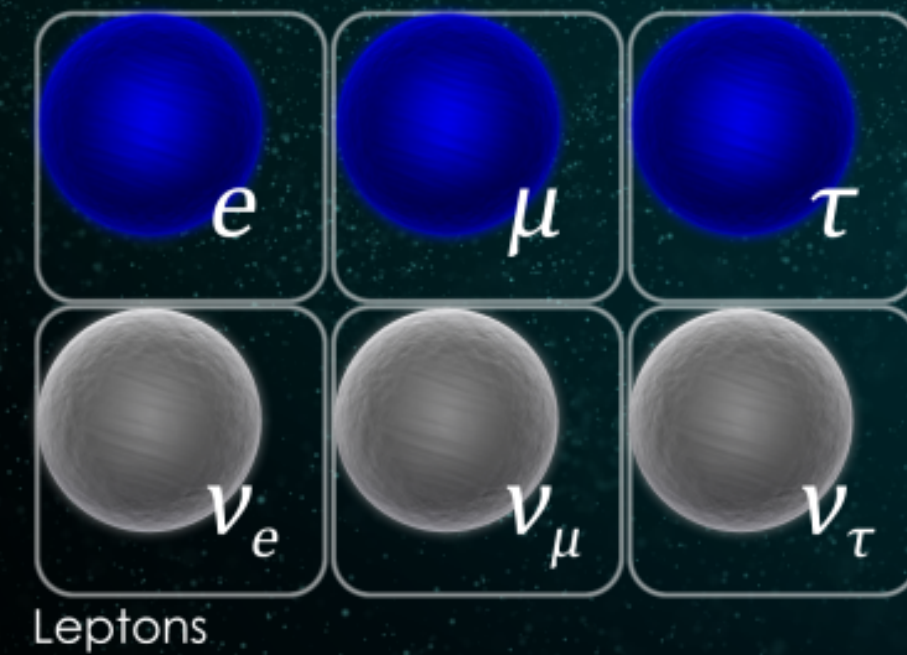
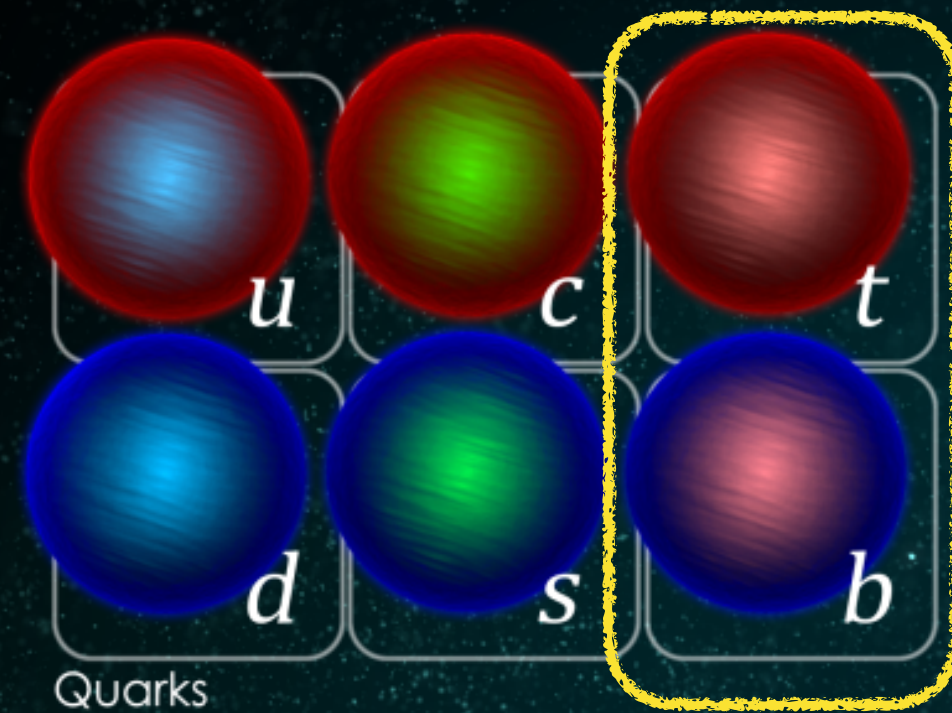
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Ingredient 1: Heavy Standard Model



Standard Model couplings



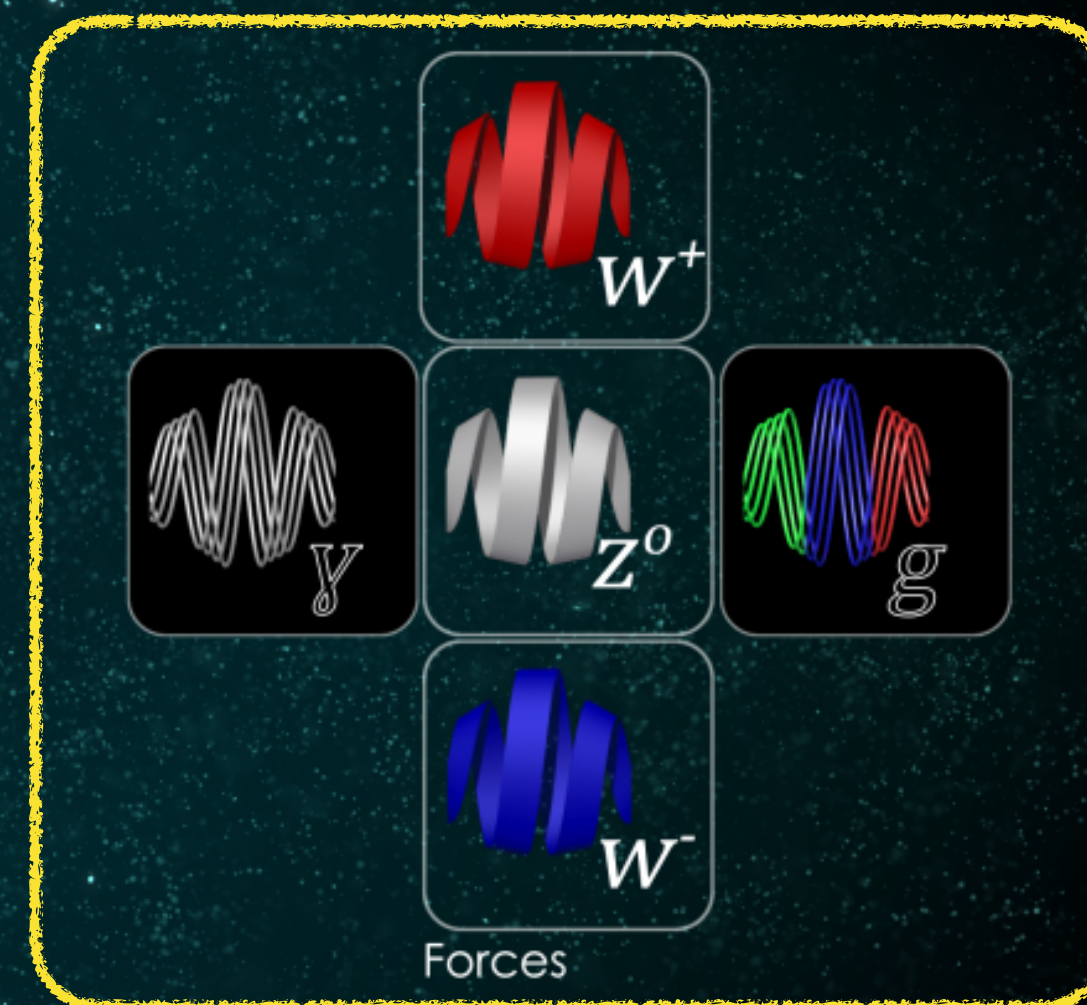
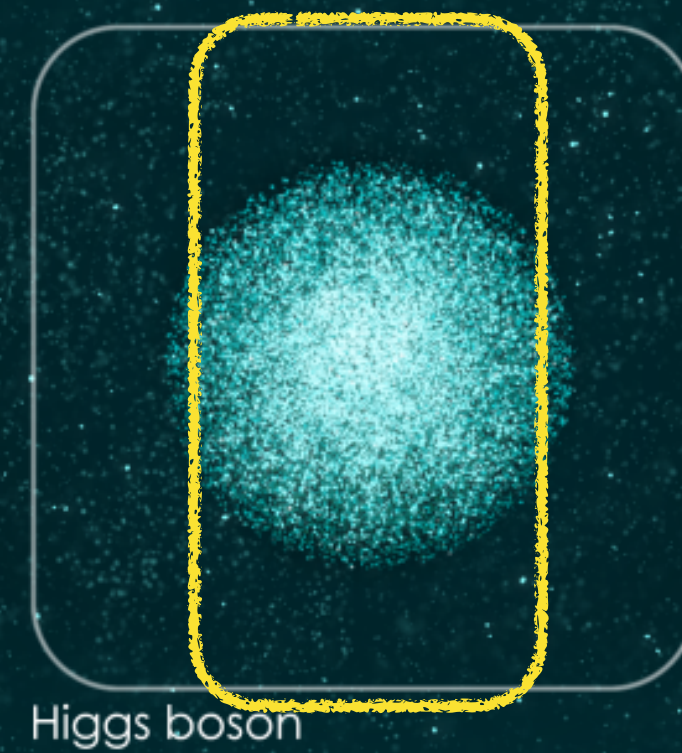
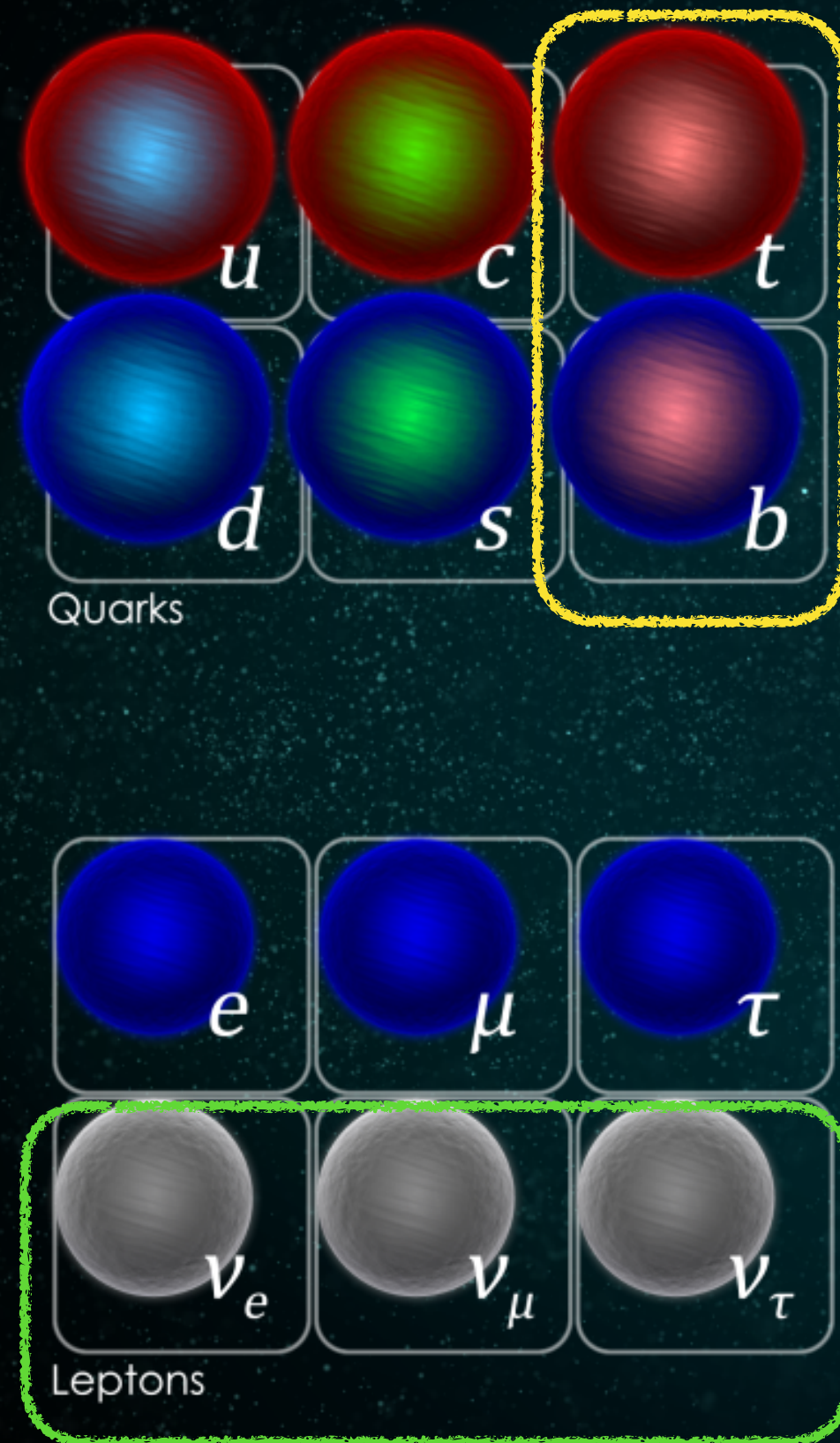
ingredient 1: “heavy” Standard Model

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

ingredient 2: the lightest fermions: neutrinos

[Held, PhD thesis '19;
Kowalska, Pramanick, Sessolo '22; AE, Held '22;
de Brito, AE, Pereira, Yamada '25;
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Standard Model couplings



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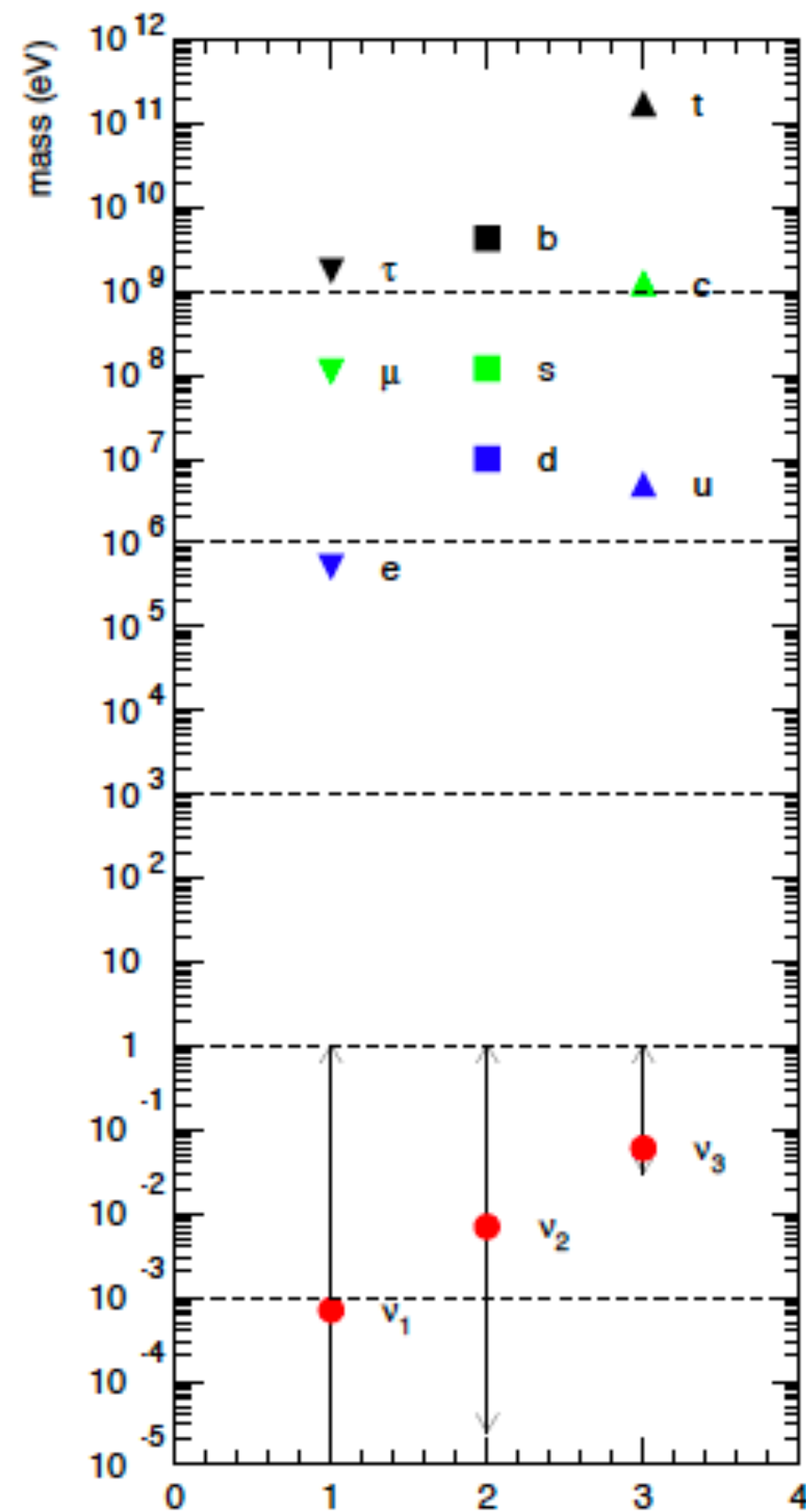
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Ingredient 2: neutrino masses

Standard Model fermion masses



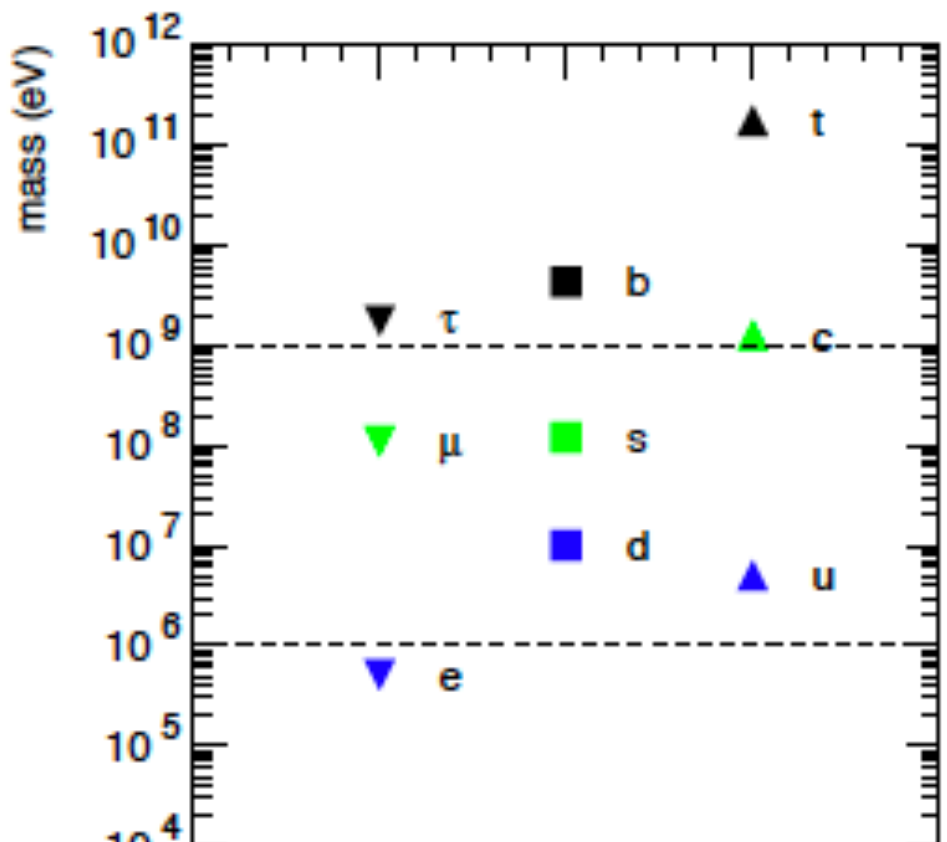
Right-handed neutrinos with Yukawa couplings: Higgs mechanism generates neutrino masses

standard perspective: not a convincing explanation, because Yukawa couplings for neutrinos

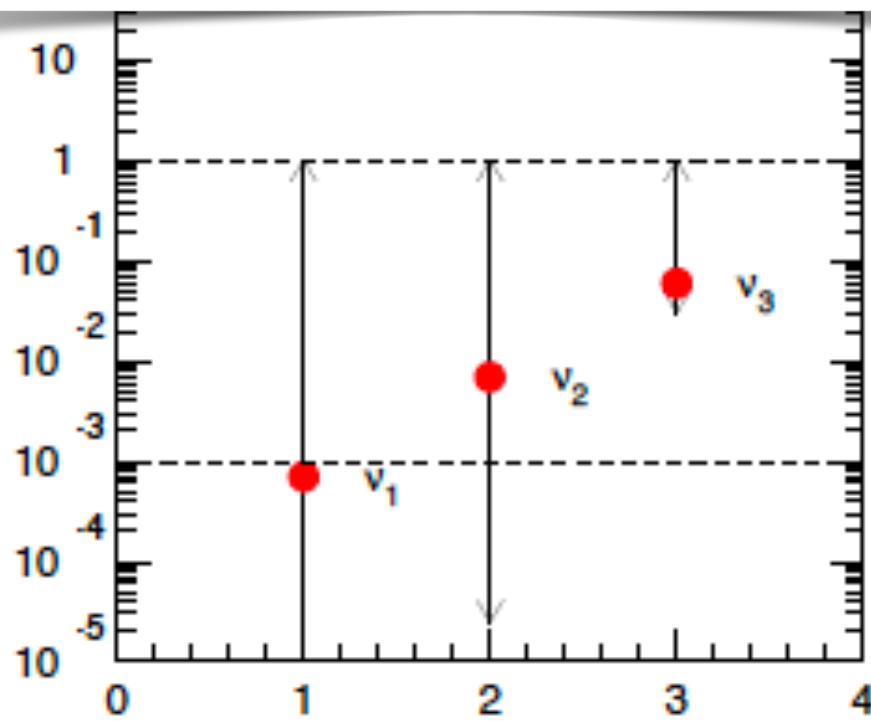
$y_\nu \sim 10^{-13}$ without explanation for this small number

Ingredient 2: neutrino masses

Standard Model fermion masses



mass gap generic
exact values: free parameters



Right-handed neutrinos with Yukawa couplings: Higgs mechanism generates neutrino masses

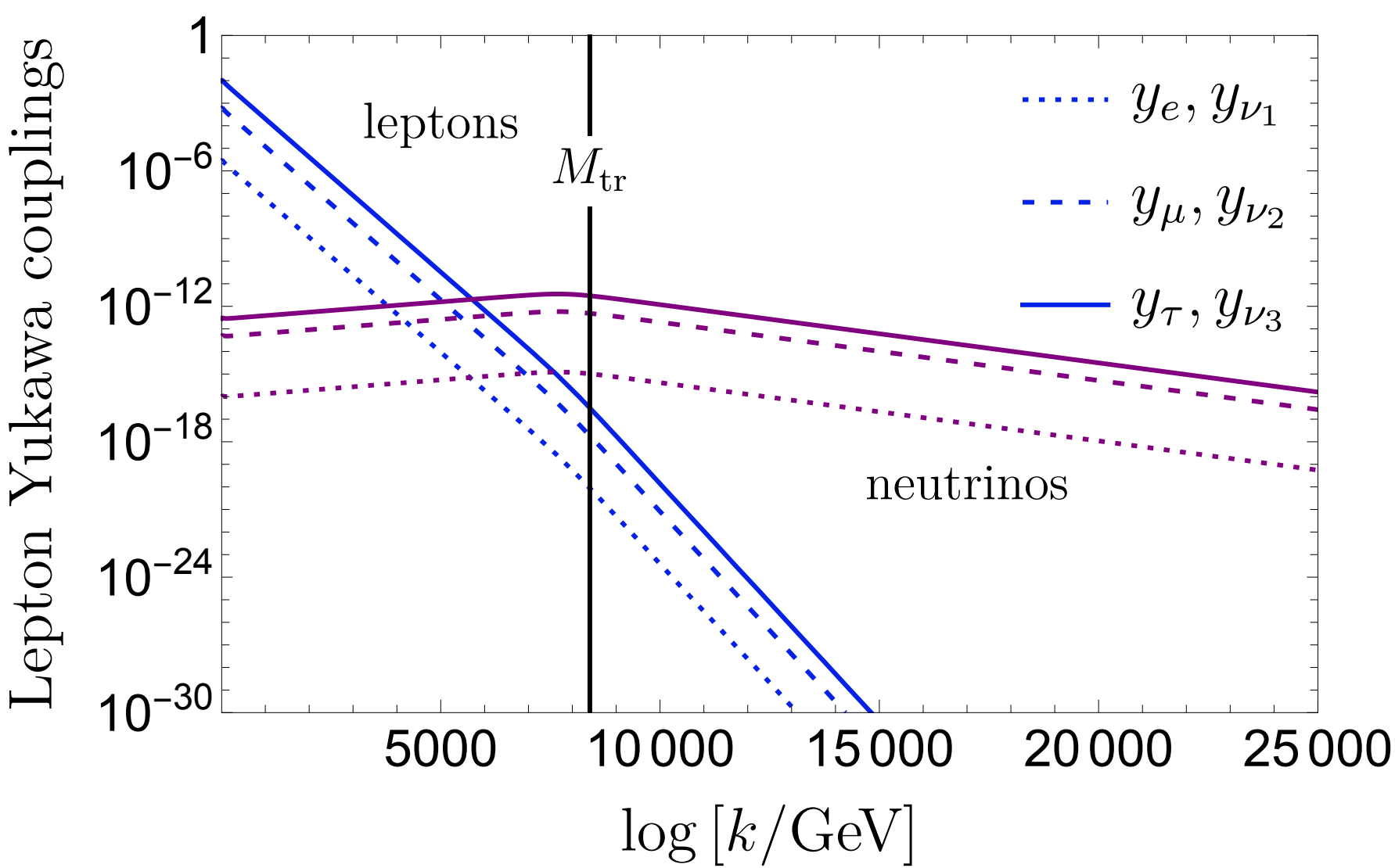
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asymptotically safe perspective:

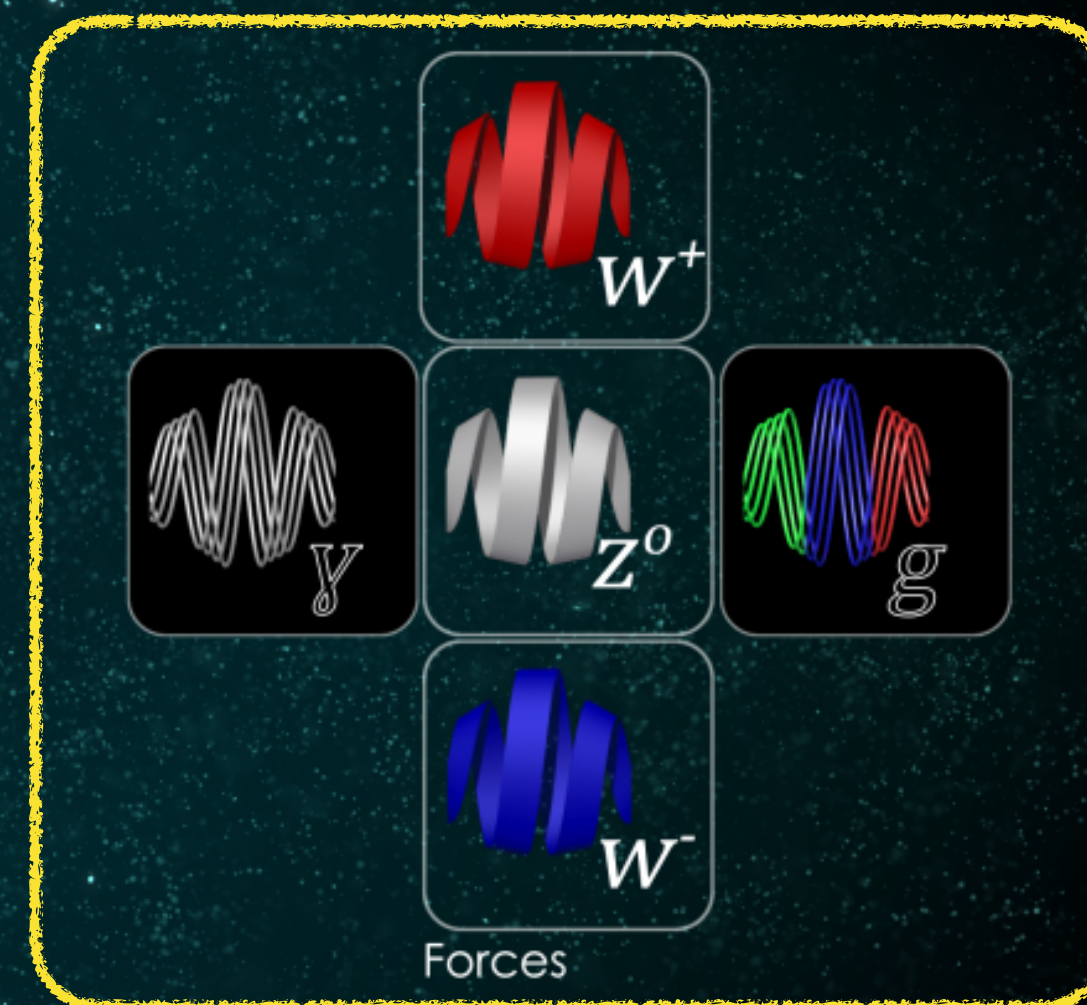
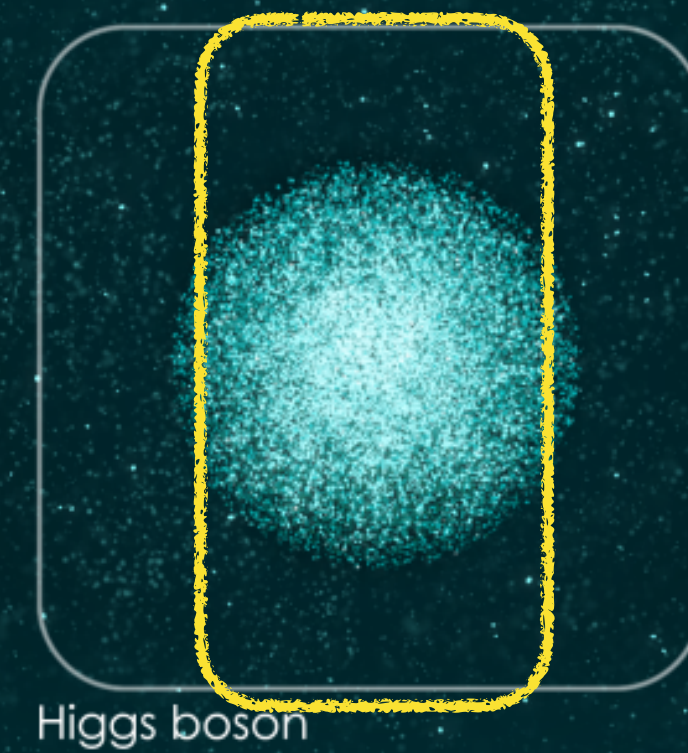
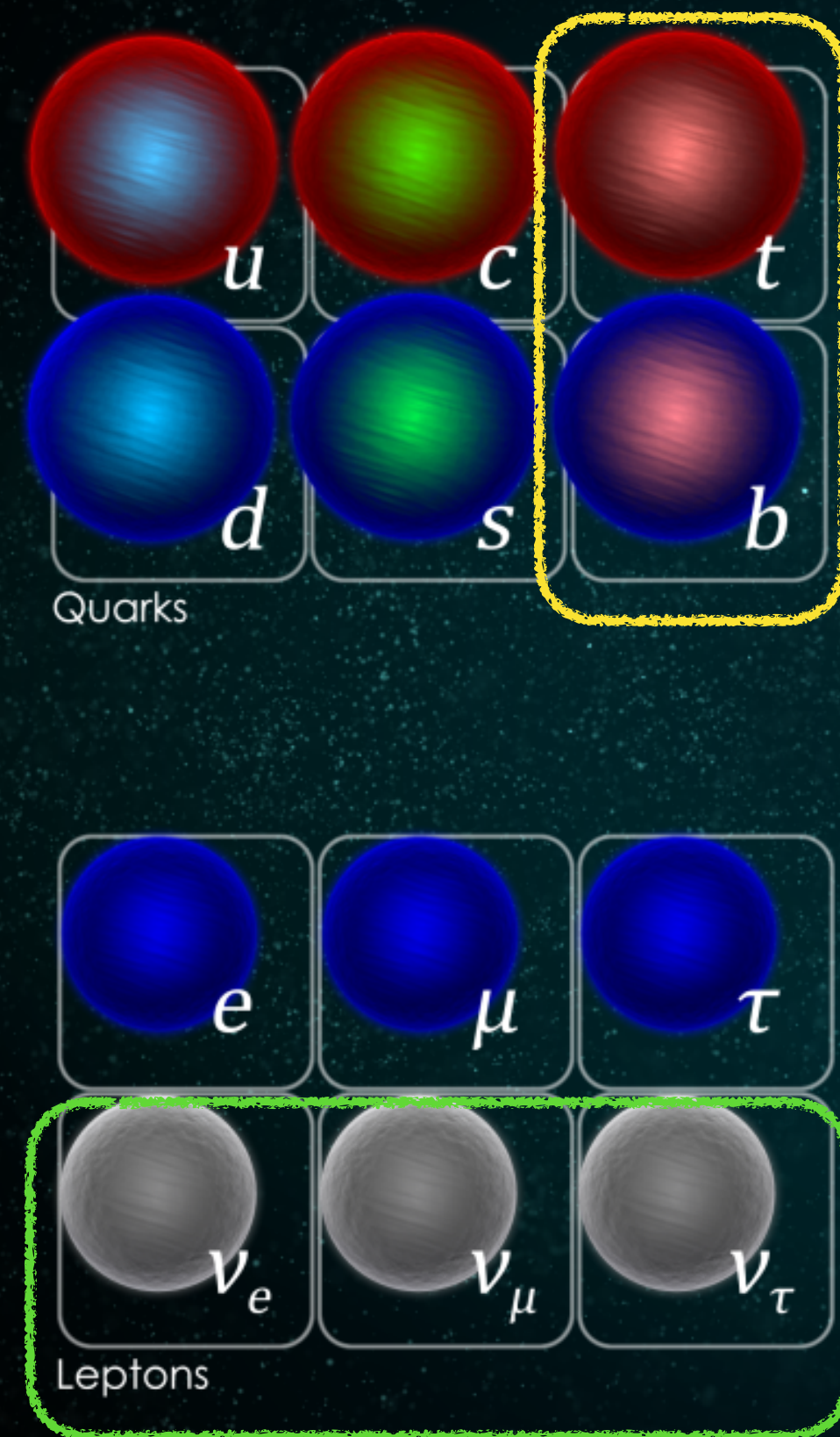
neutrino Yukawas are dynamically kept small

[Held, PhD thesis '19;
Kowalska, Sessolo '22; AE, Held '22]



[AE, Gyftopoulos, Held '25]

Standard Model couplings



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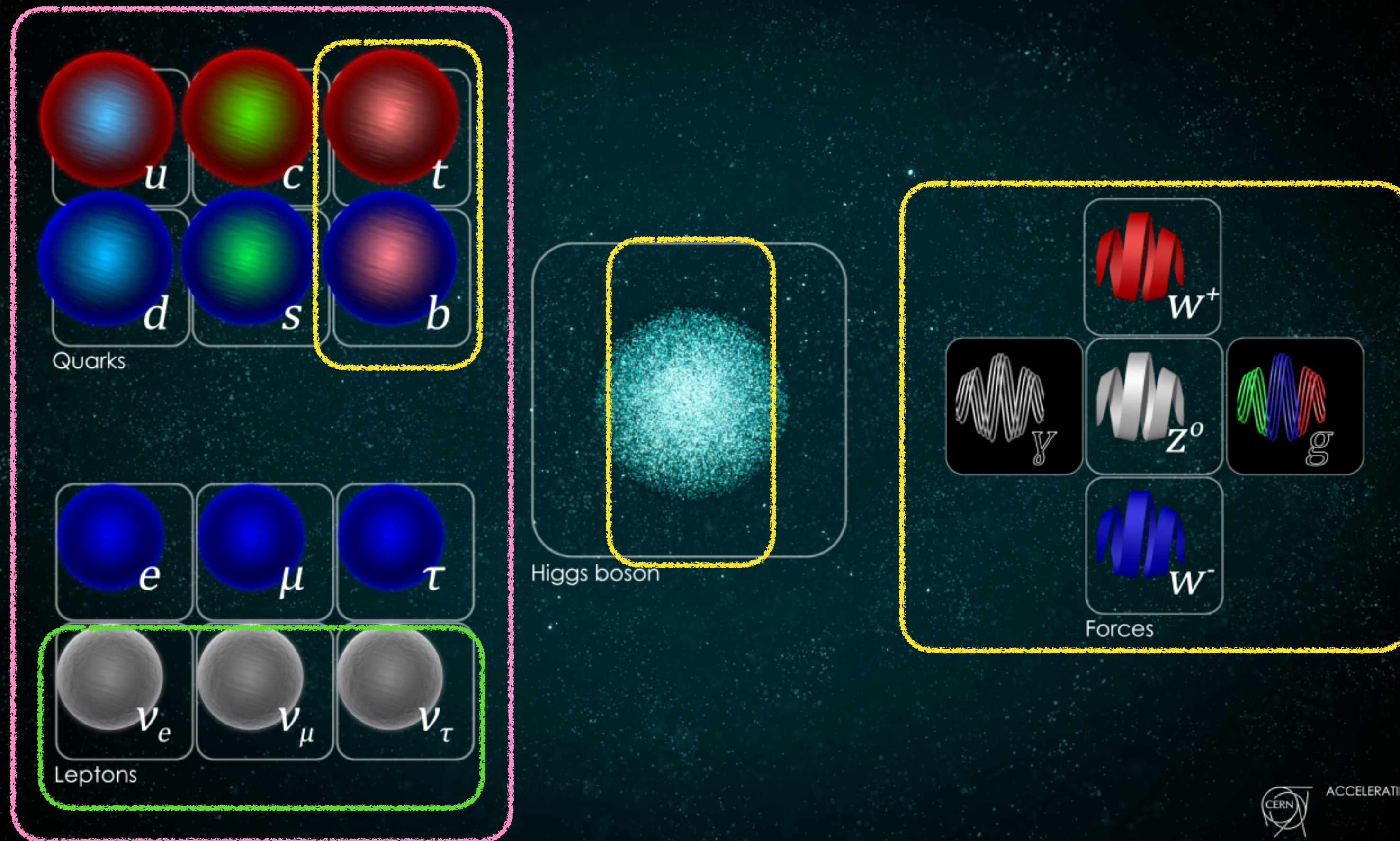
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Result: mixing of mass eigenstates (CKM and PMNS)

[Alkofer, AE, Held, Nieto, Percacci, Schröfl '20;
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Standard Model couplings



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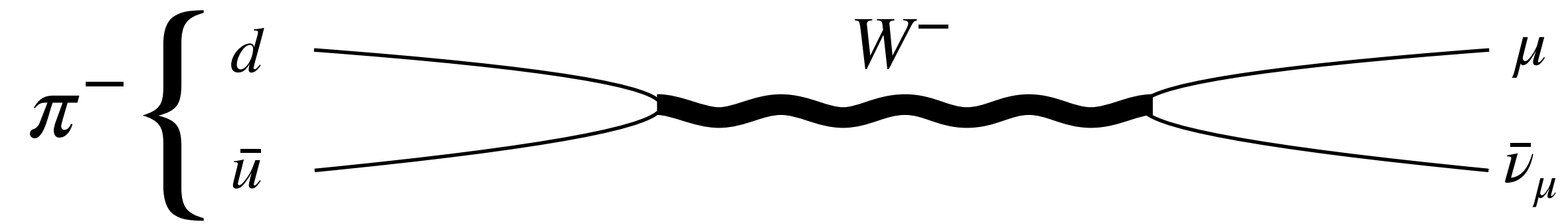
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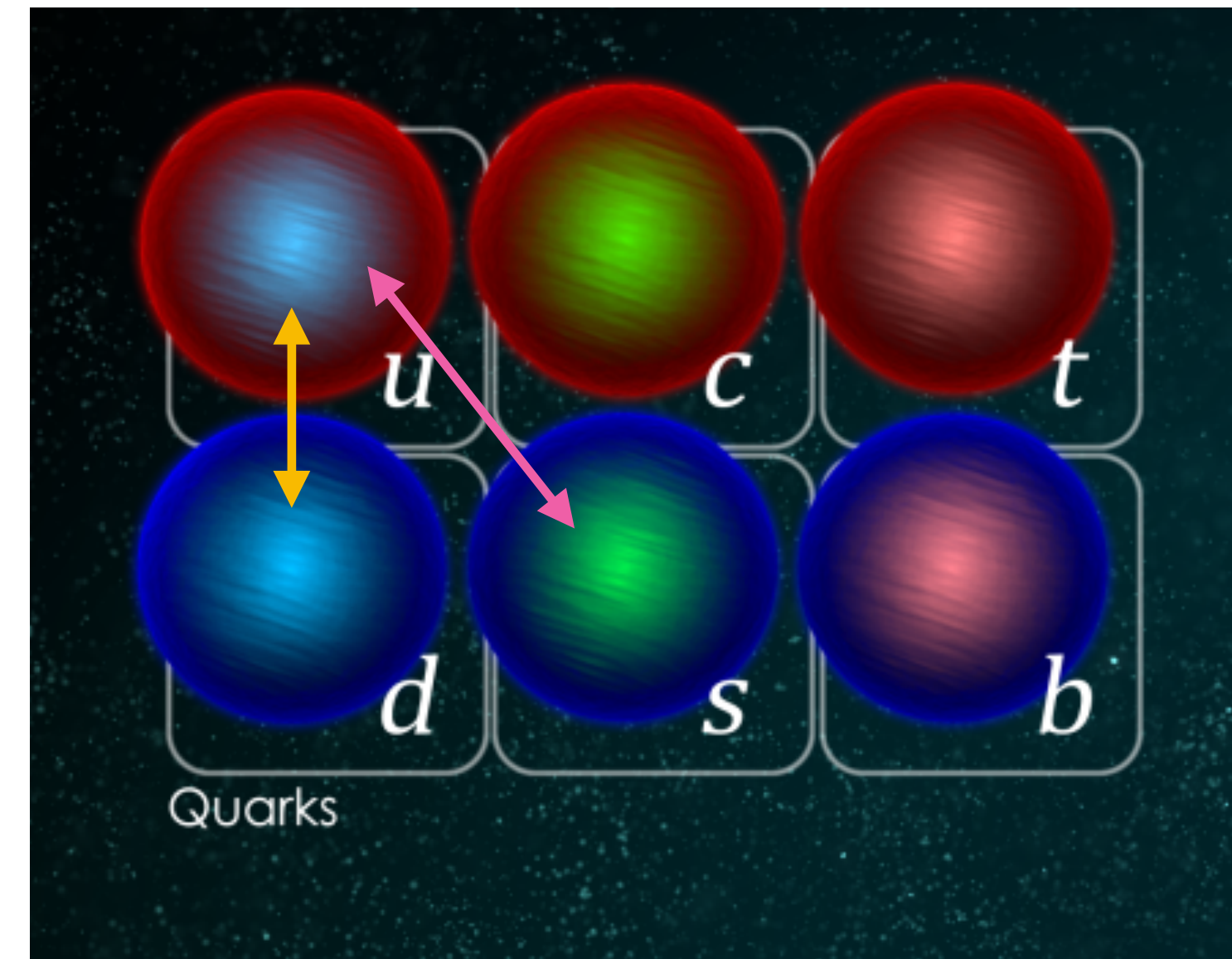
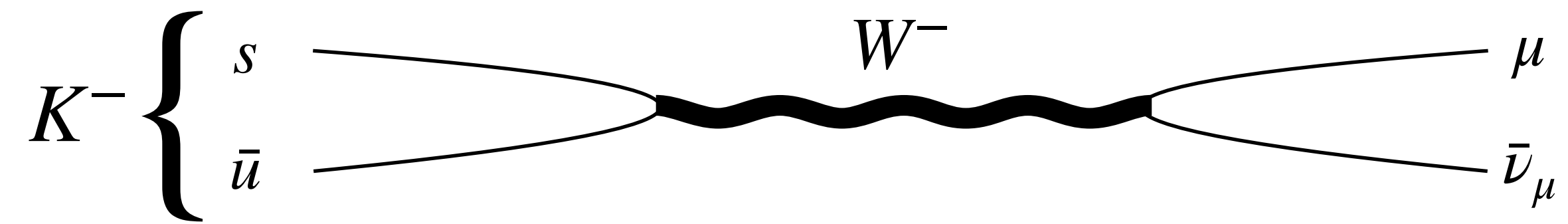
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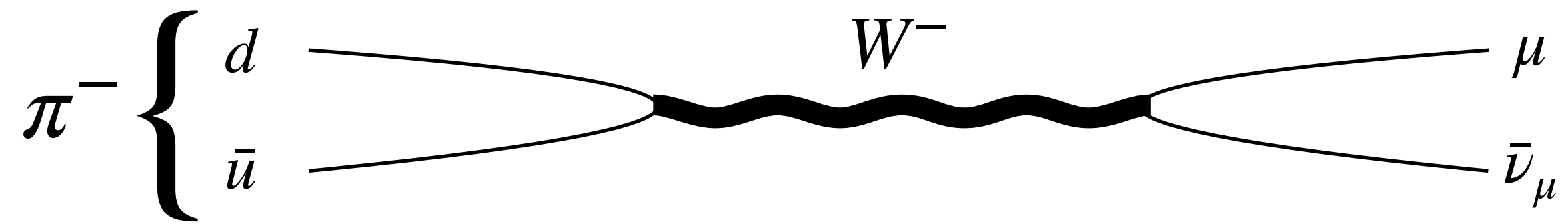


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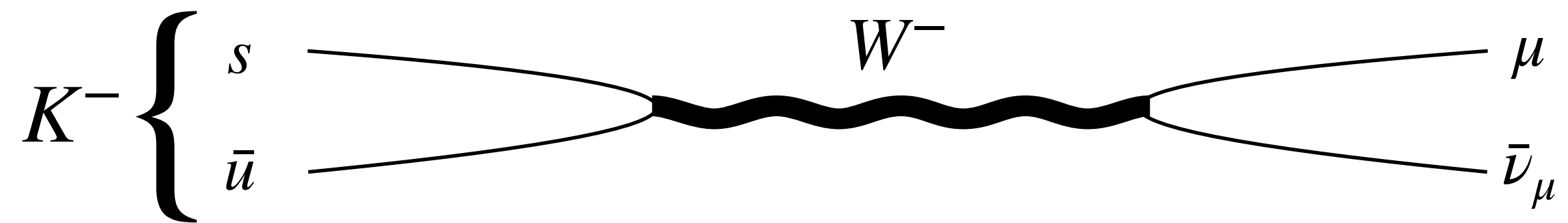


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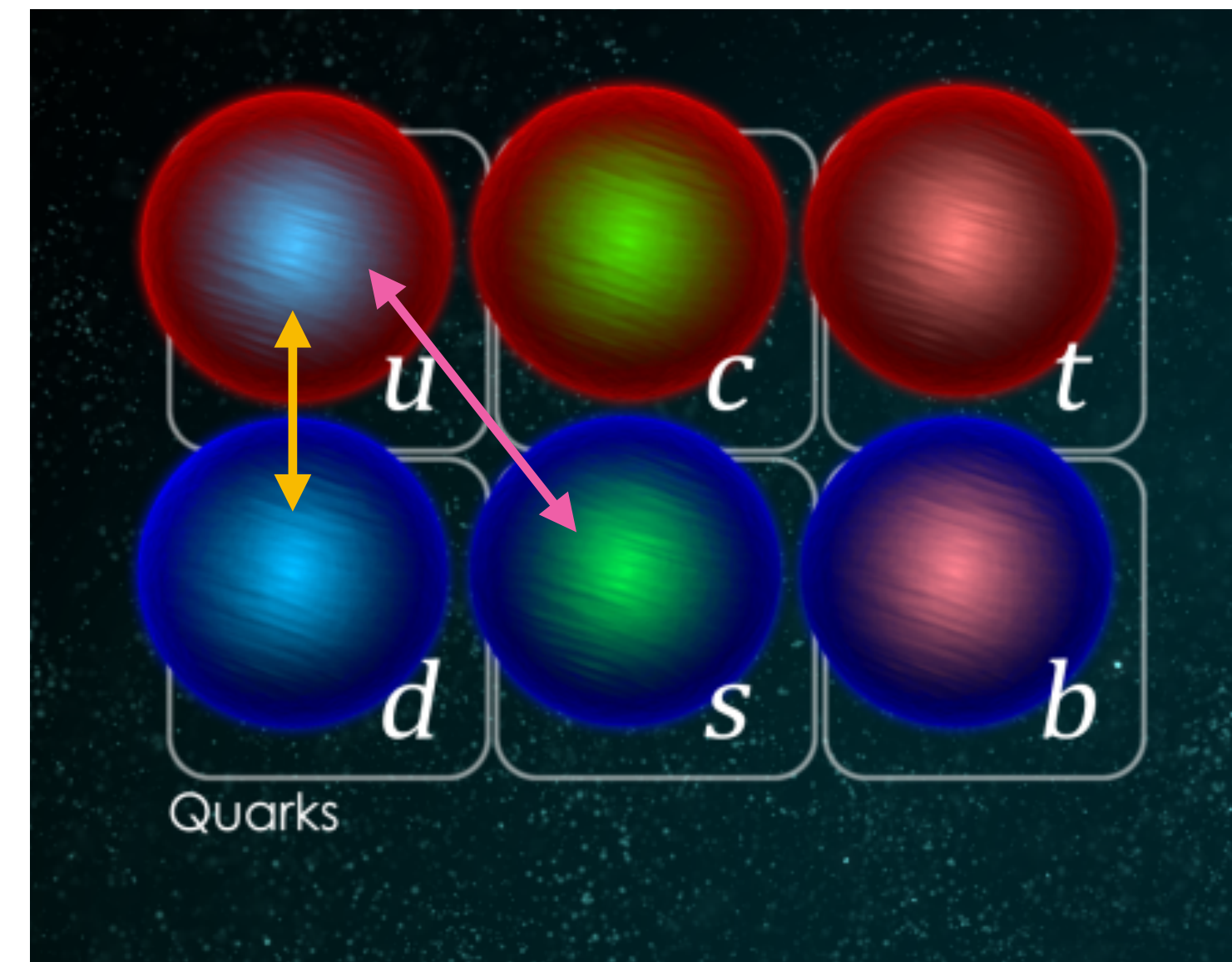
without mixing



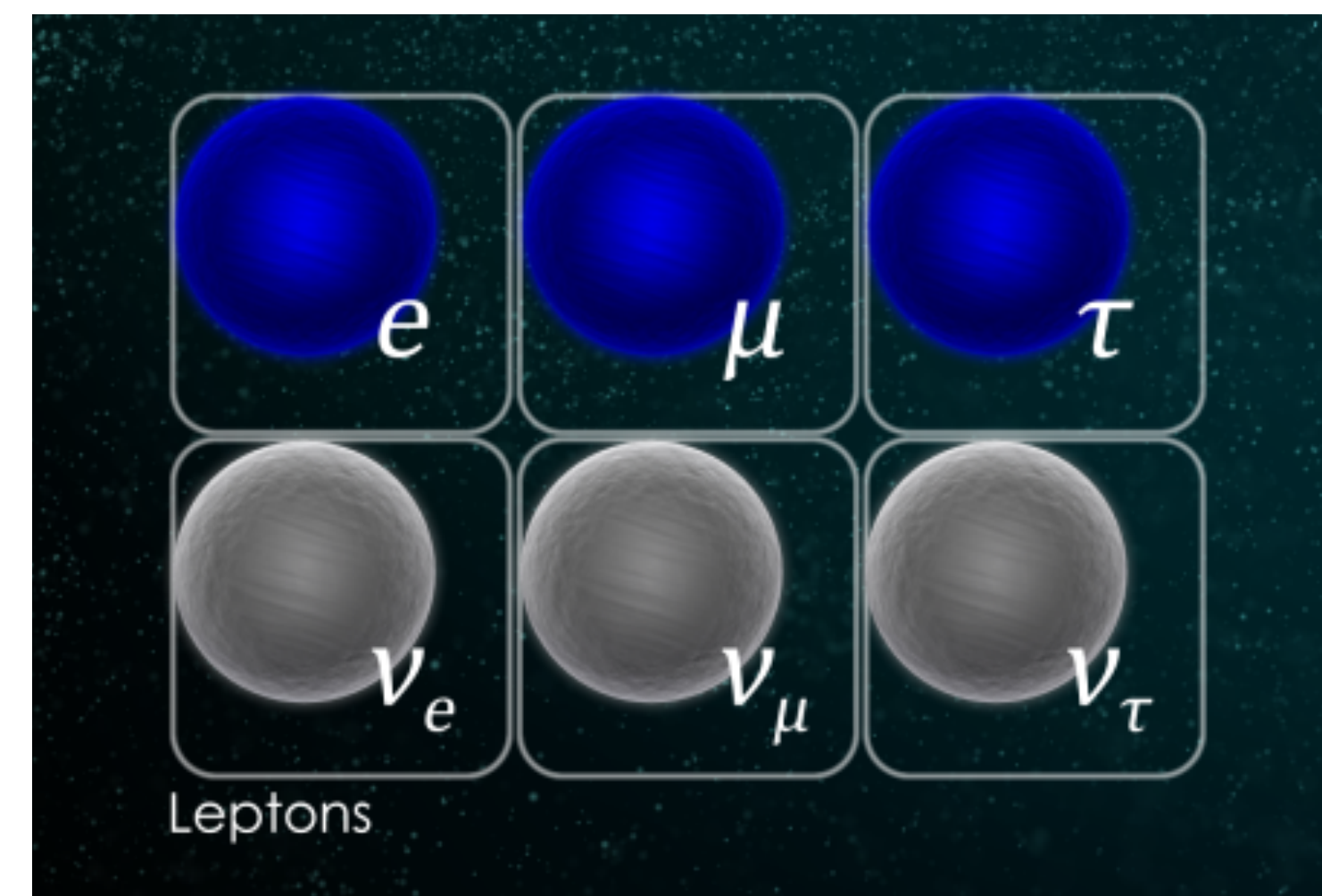
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CKM

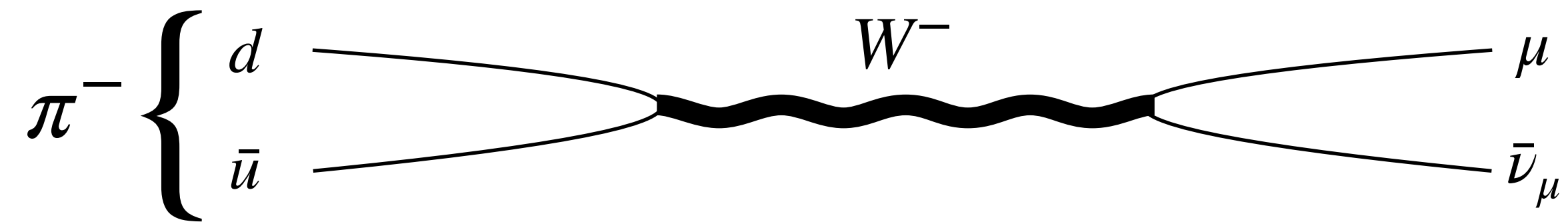


PMNS

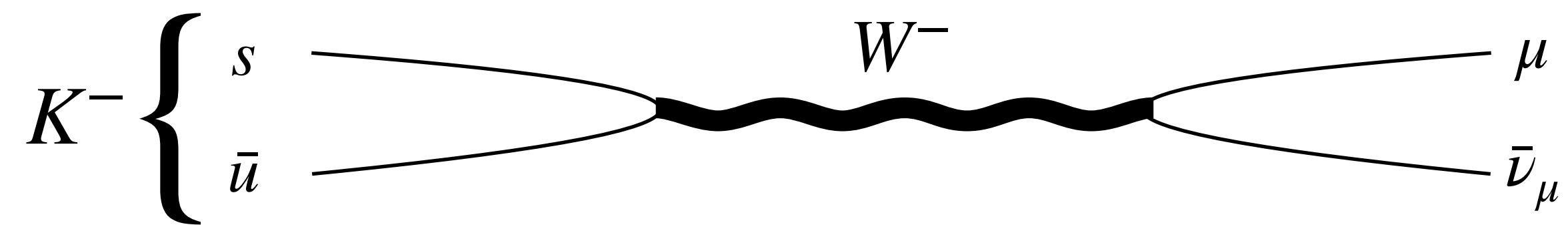


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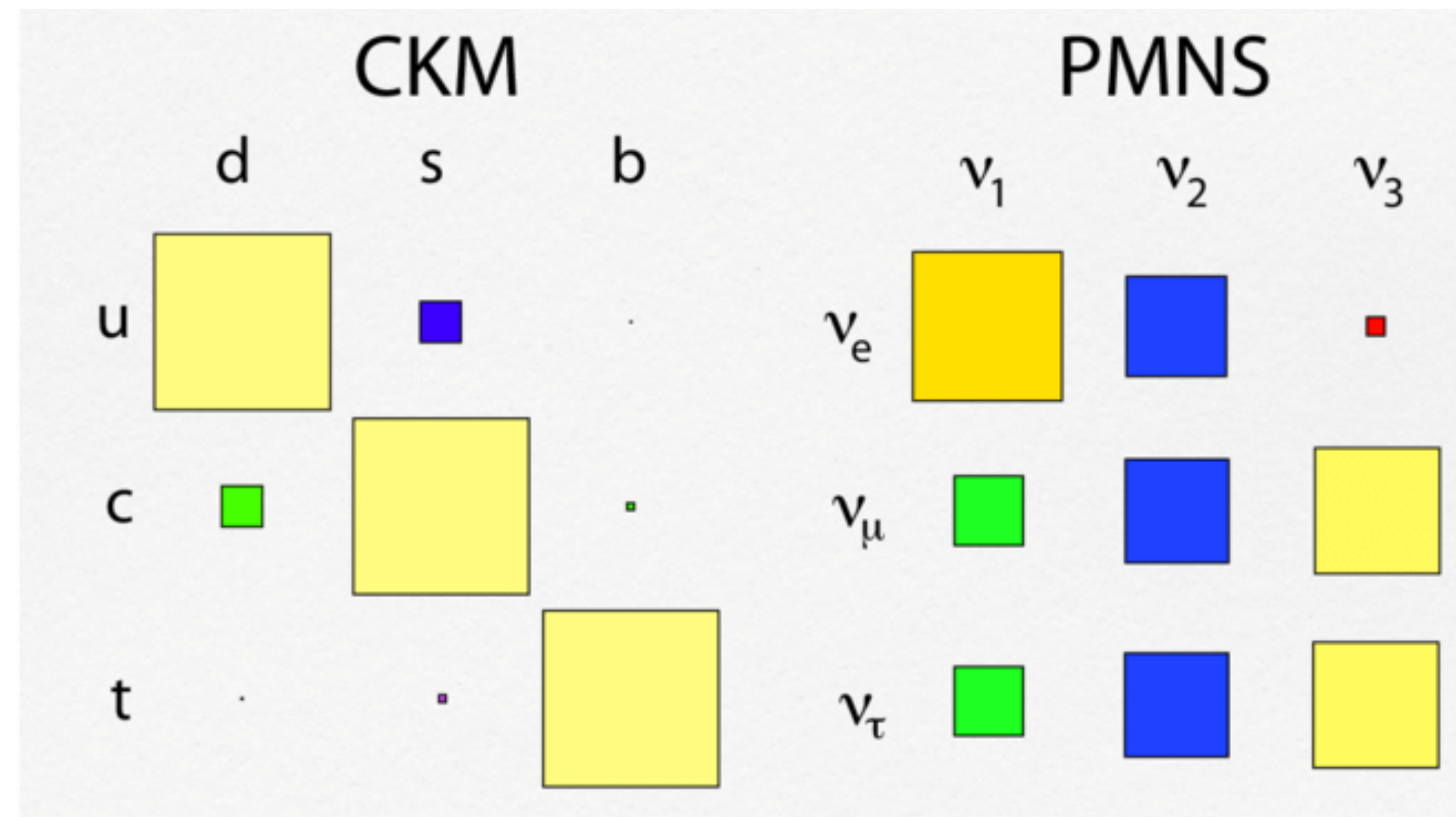
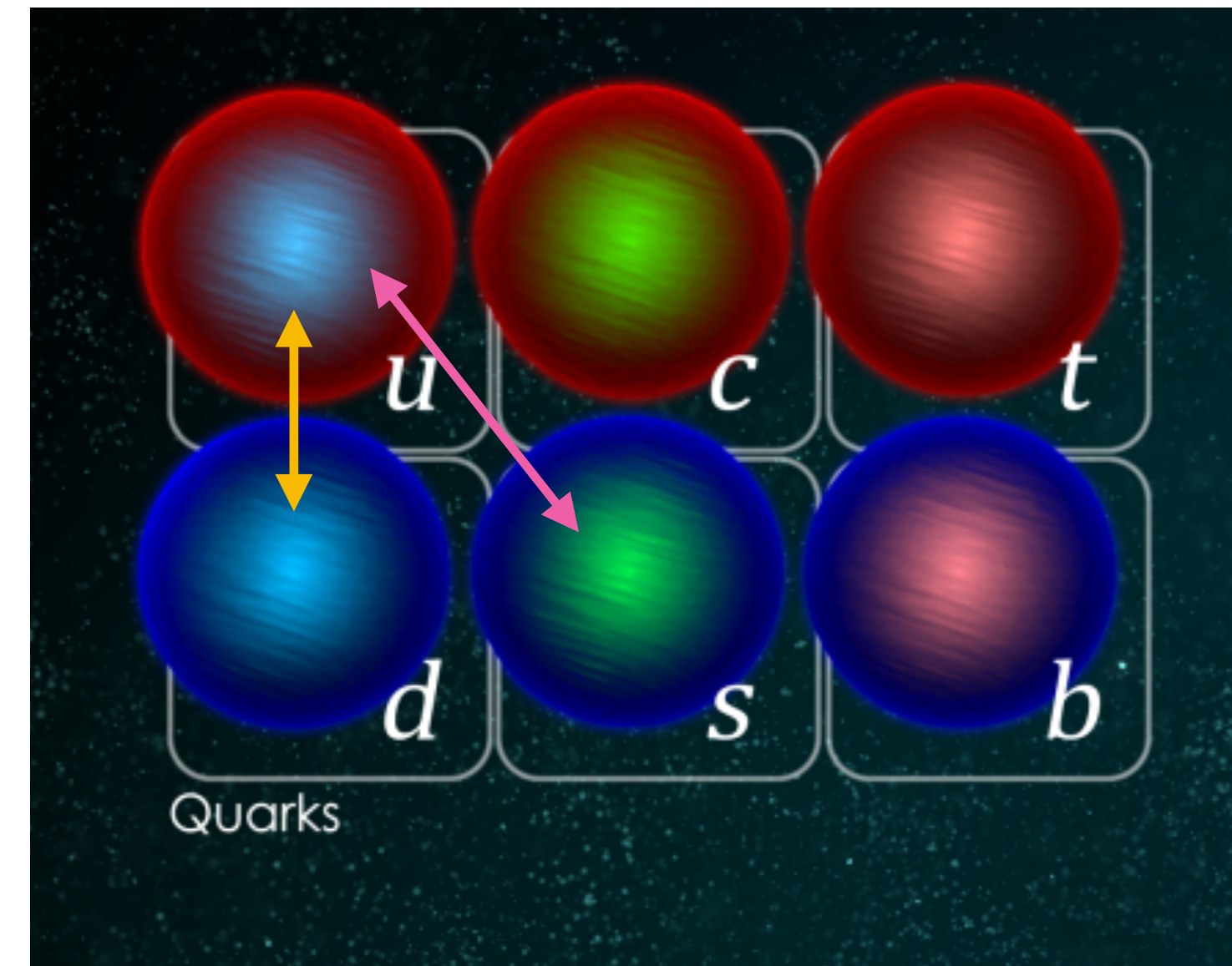
without mixing



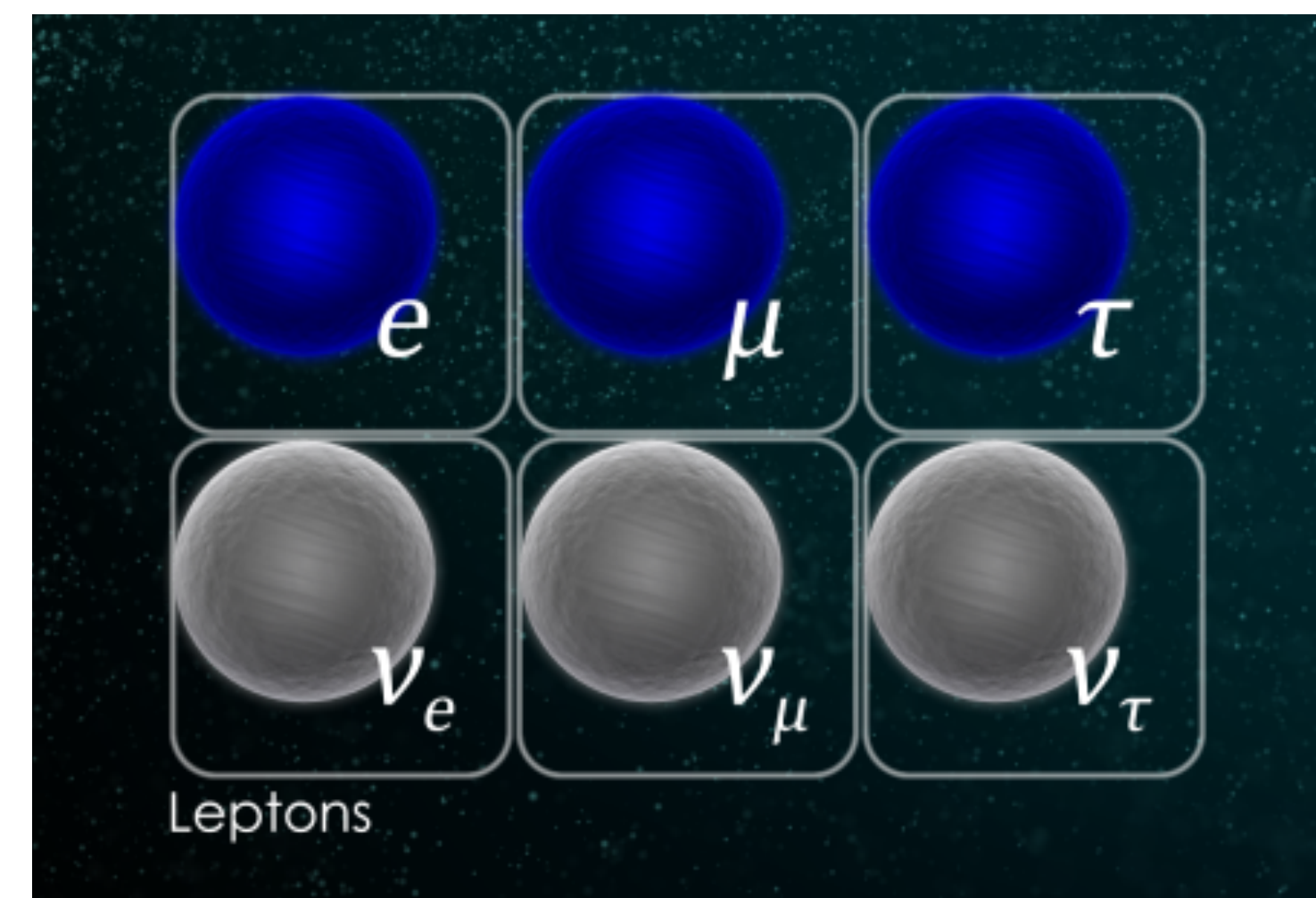
with mixing



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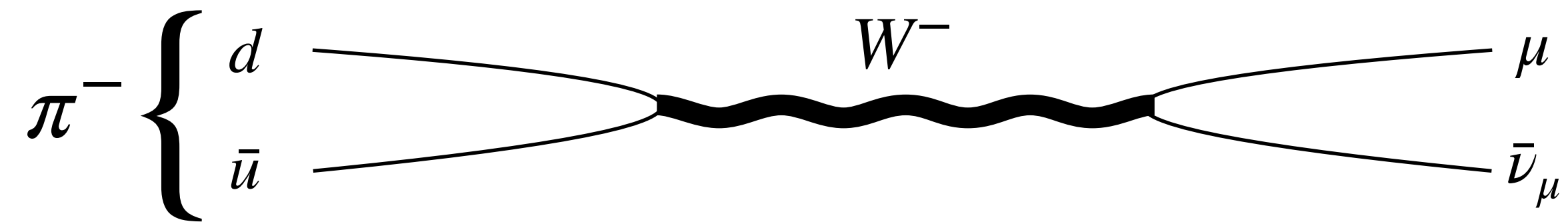


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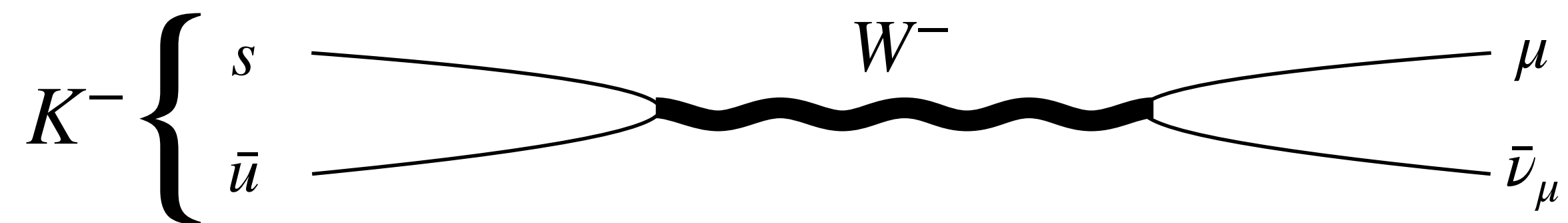


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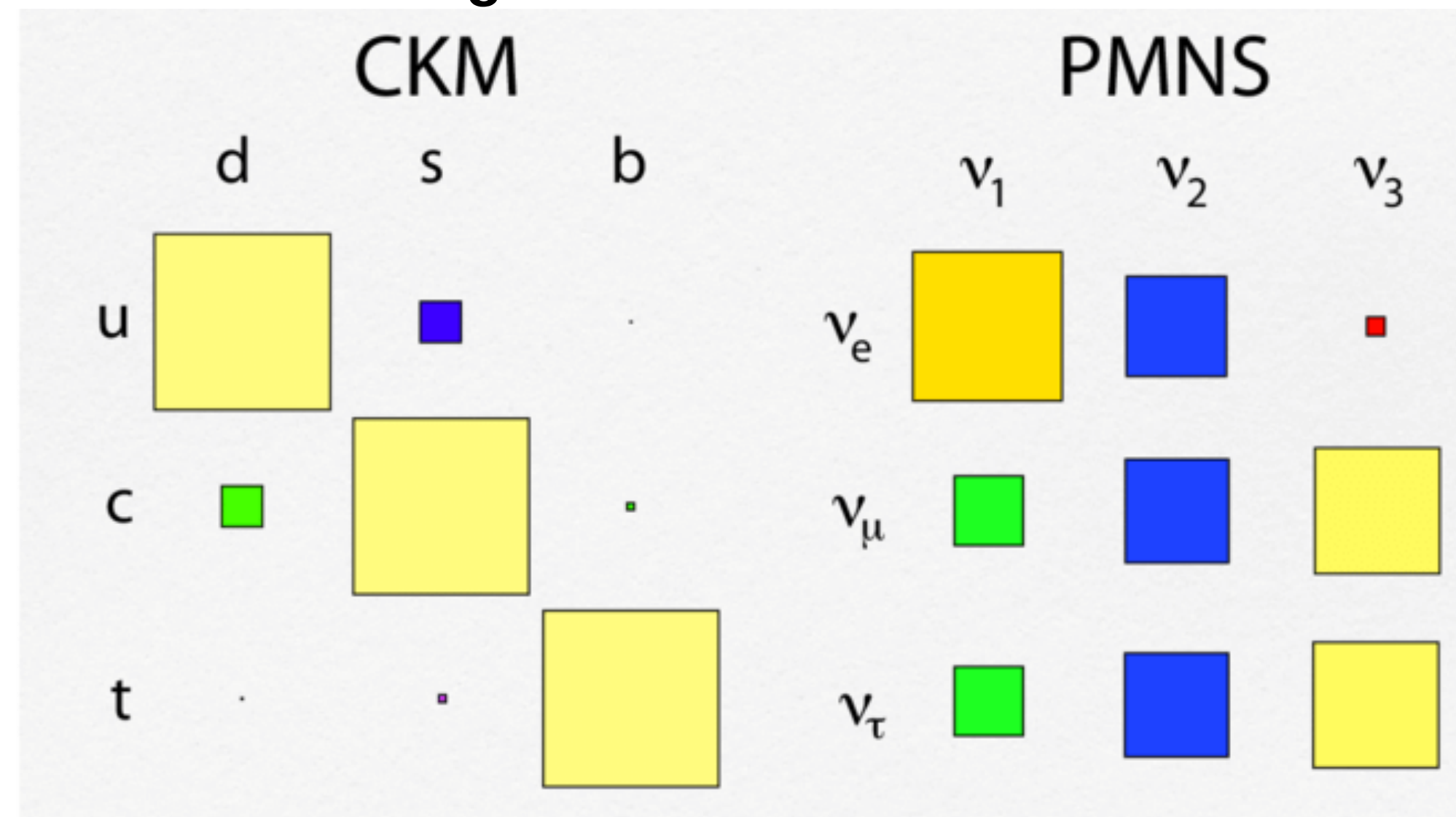
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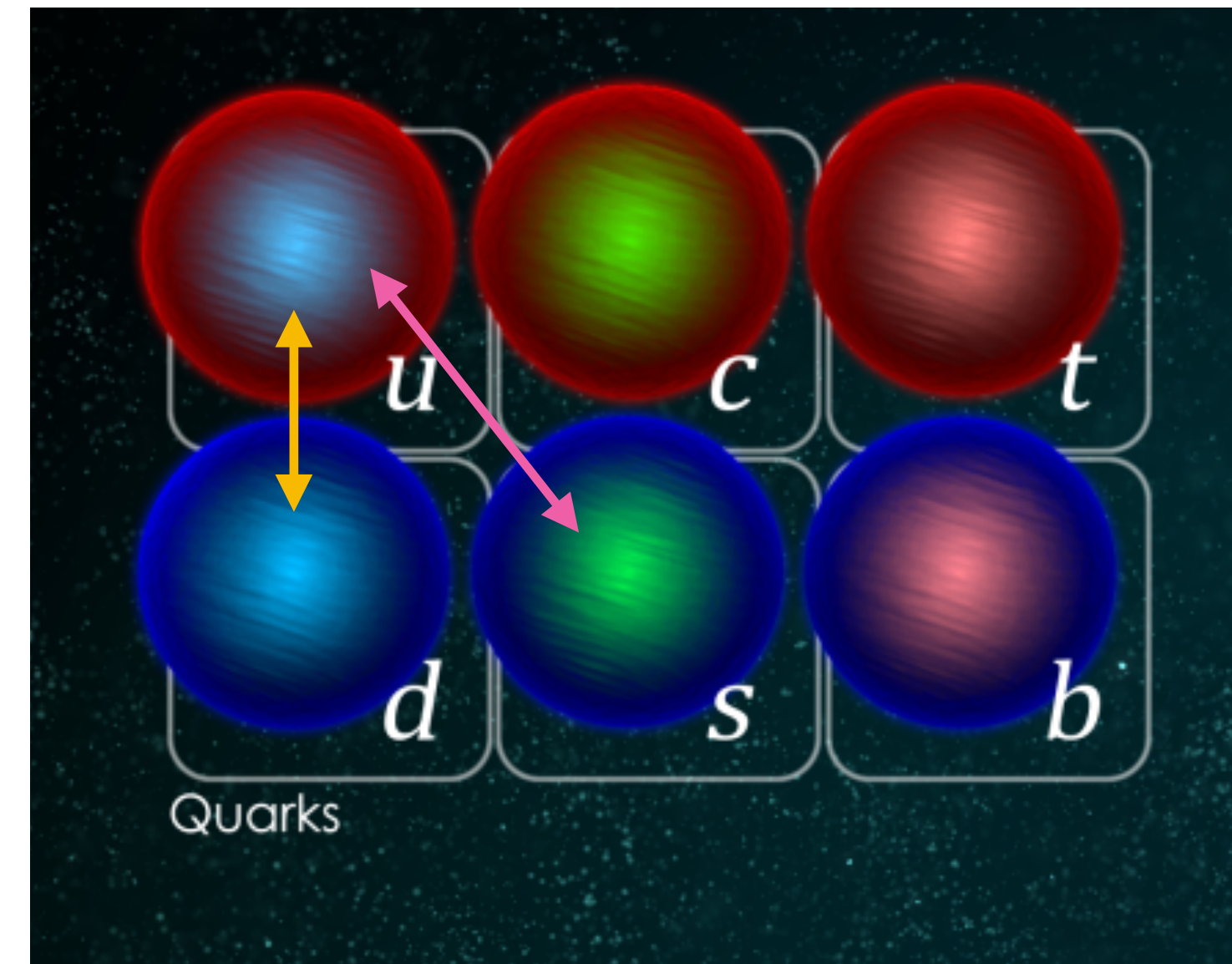
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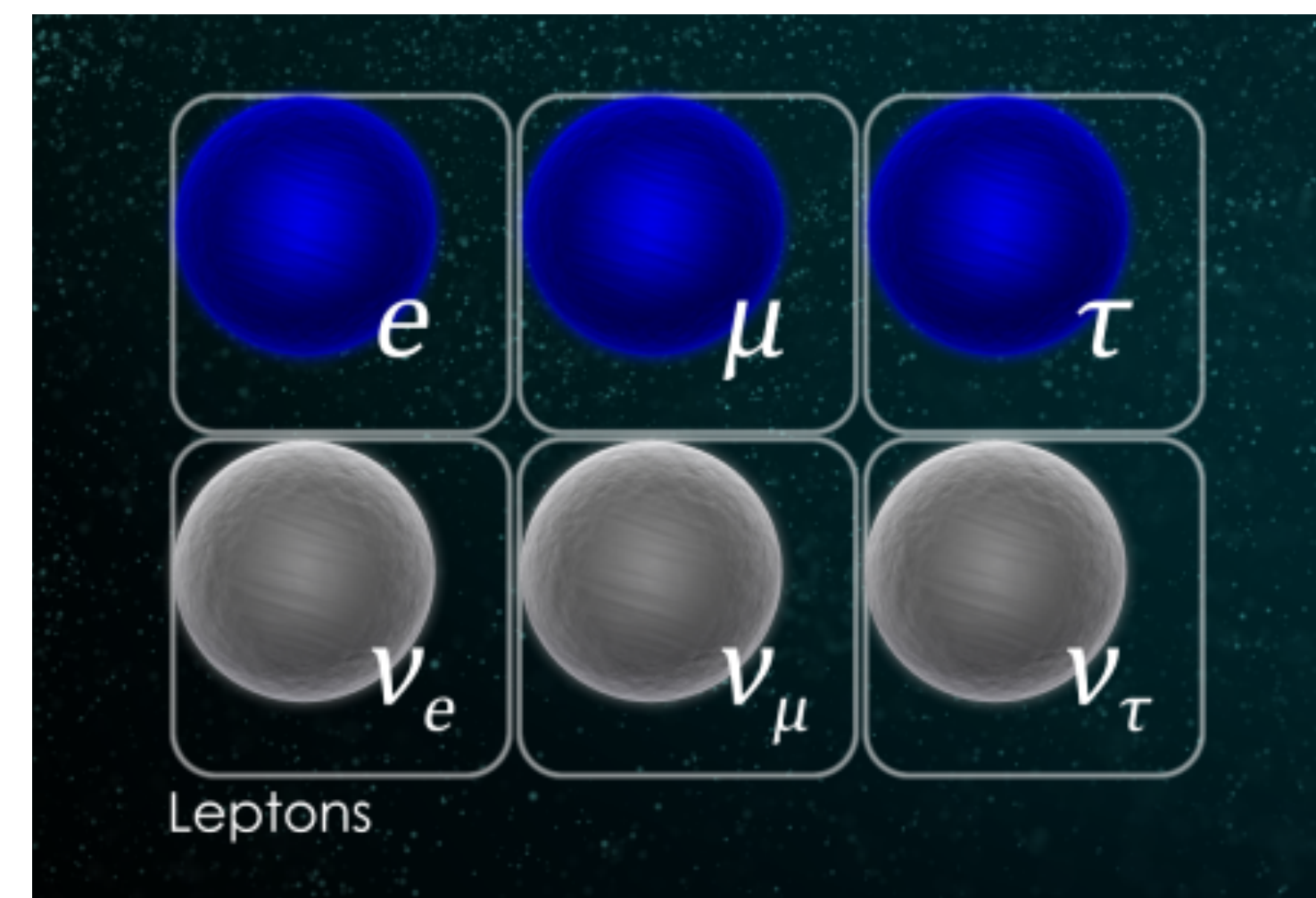
What generates these structures?



CKM

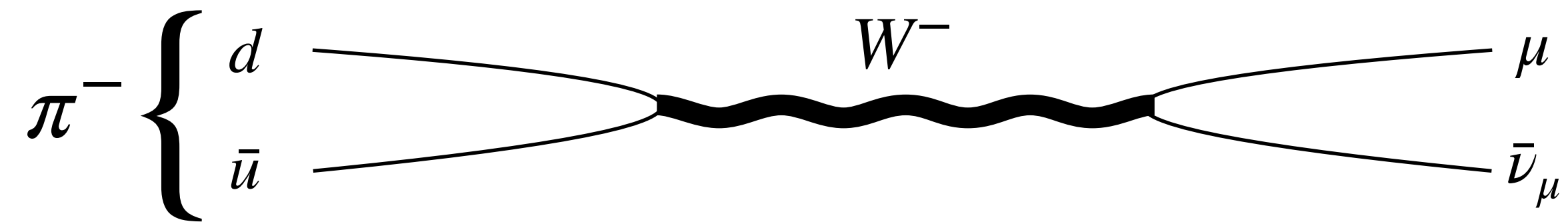


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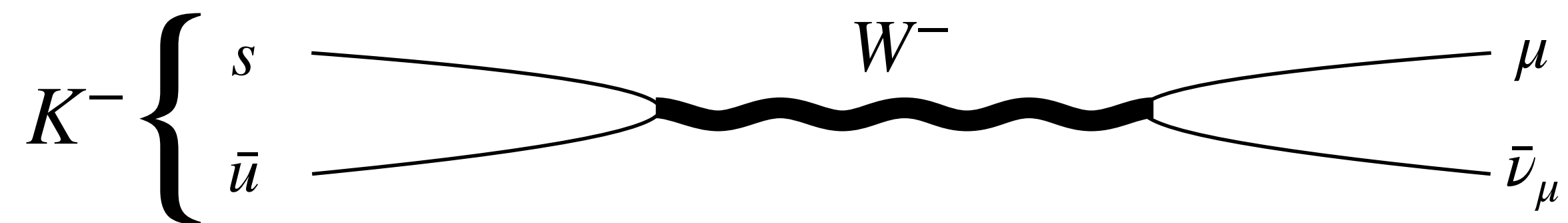


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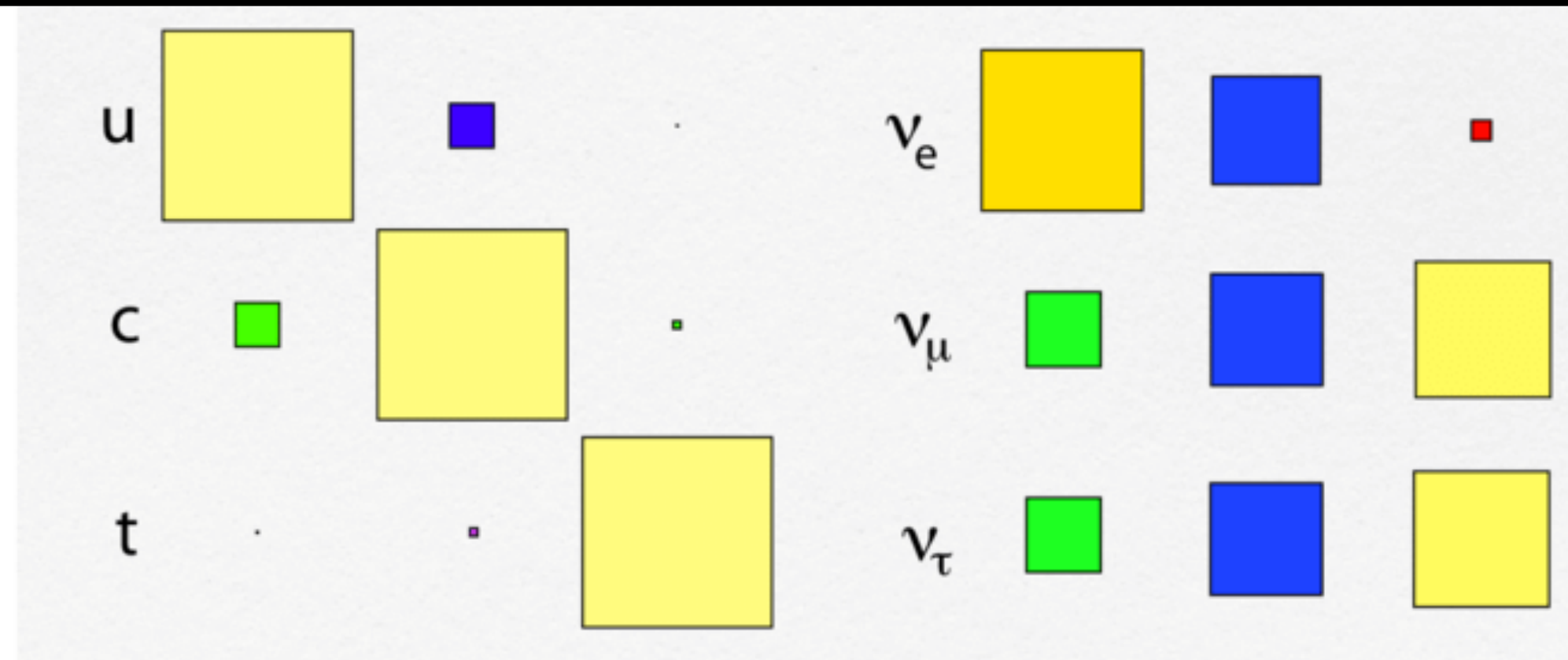
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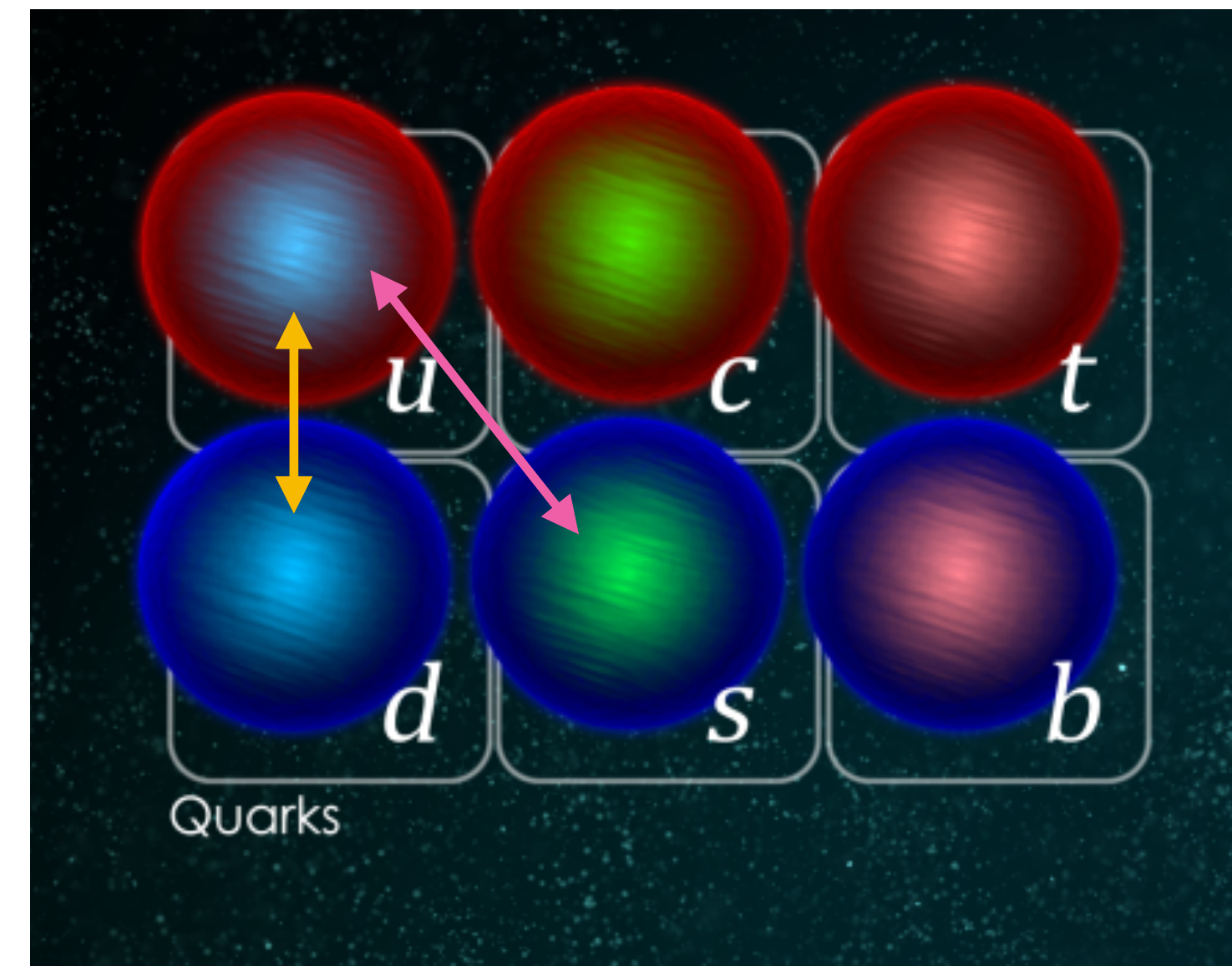
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Proposed answer:

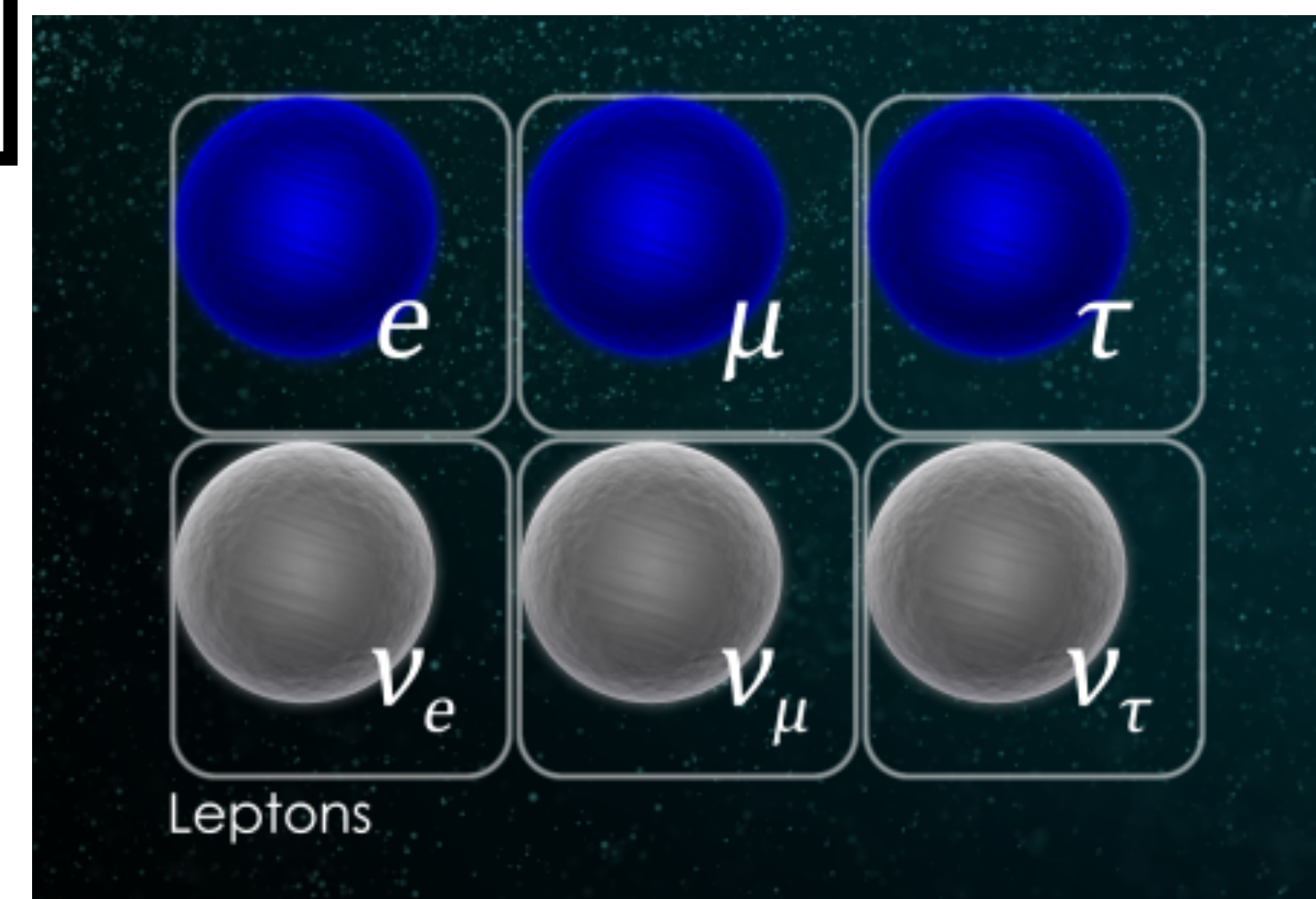
These structures are partially emergent from regime with quantum gravity



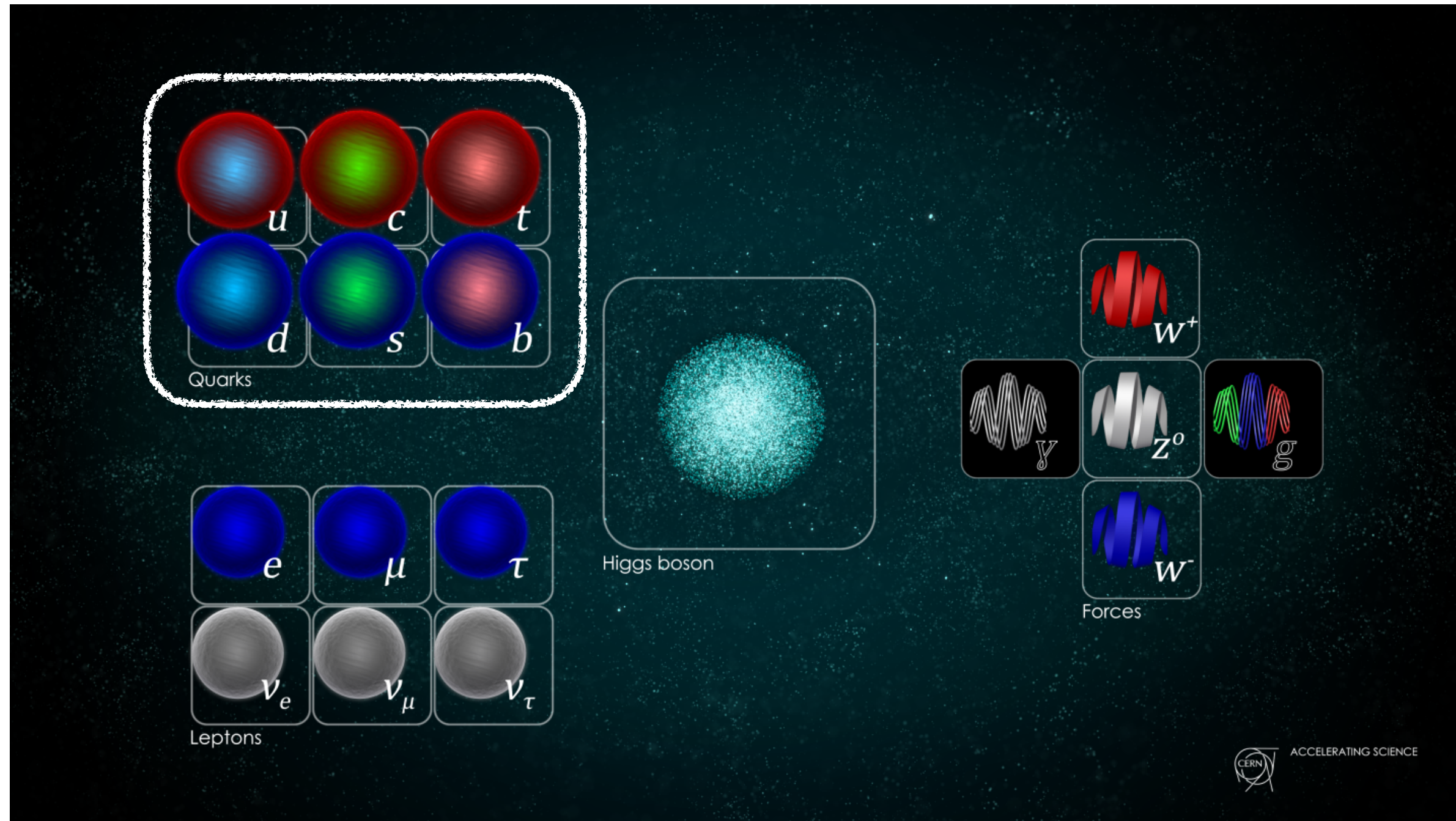
CKM



PMNS



Result: mixing matrices



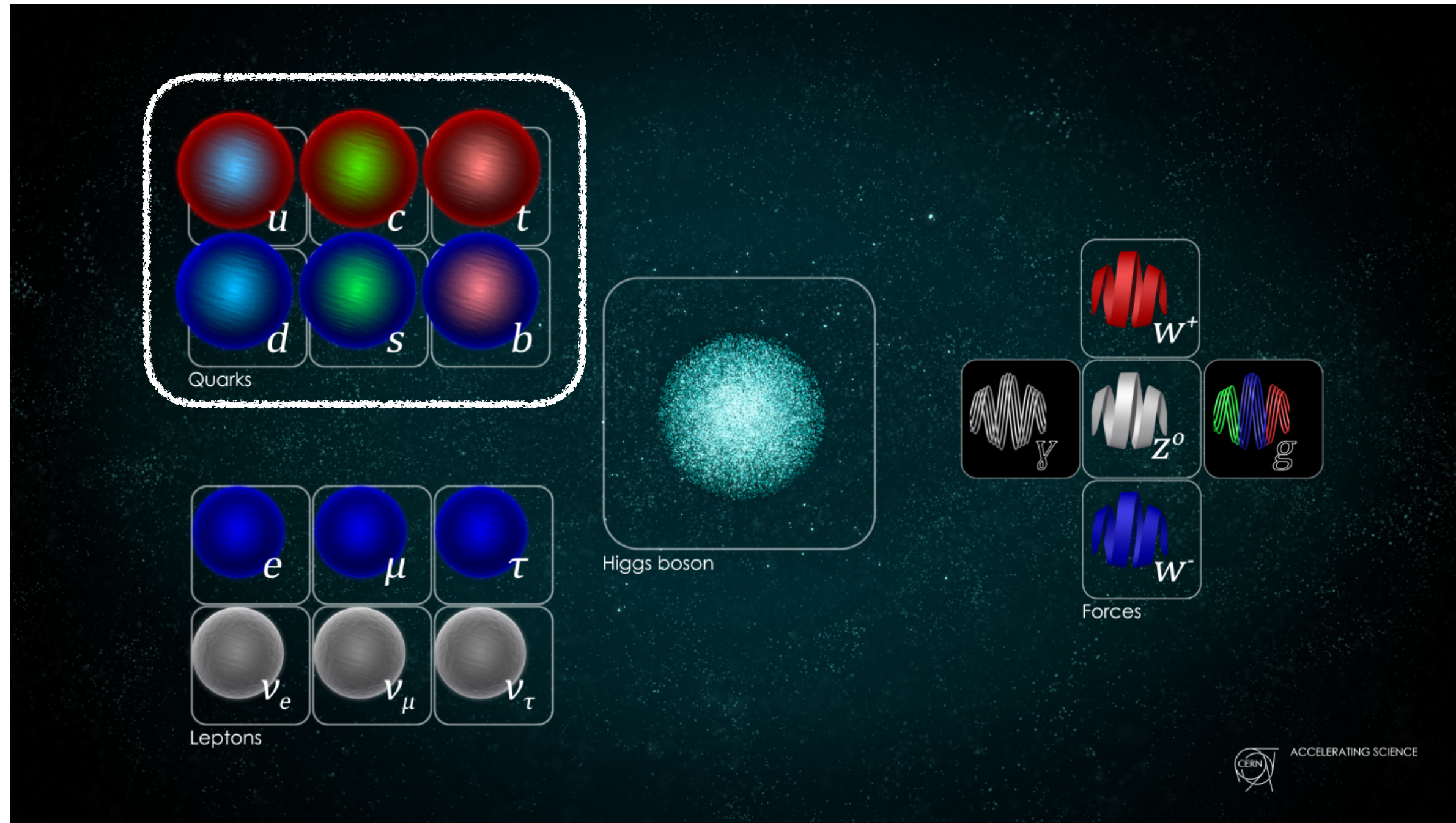
- Yukawa couplings (determine quark masses)
- CKM mixing matrix (determines mixing of flavors in weak interactions)

$$|V|_{\text{CKM}}^2 = \begin{pmatrix} |V_{ud}|^2 & |V_{us}|^2 & |V_{ub}|^2 \\ |V_{cd}|^2 & |V_{cs}|^2 & |V_{cb}|^2 \\ |V_{td}|^2 & |V_{ts}|^2 & |V_{tb}|^2 \end{pmatrix}.$$

$$|V_{ud}|^2 = 0.94936 \pm 0.00031, \quad |V_{us}|^2 = 0.05063 \pm 0.00031$$

$$|V_{cd}|^2 = 0.05057 \pm 0.00031, \quad |V_{cs}|^2 = 0.94768 \pm 0.00031$$

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observation: $|V_{ud}|^2 + |V_{us}|^2 = 0.99999 \pm 0.00044, \quad |V_{cd}|^2 + |V_{cs}|^2 = 0.99825 \pm 0.00044.$

approximately satisfies: $|V_{ud}|^2 + |V_{us}|^2 = 1, \quad |V_{cd}|^2 + |V_{cs}|^2 = 1.$

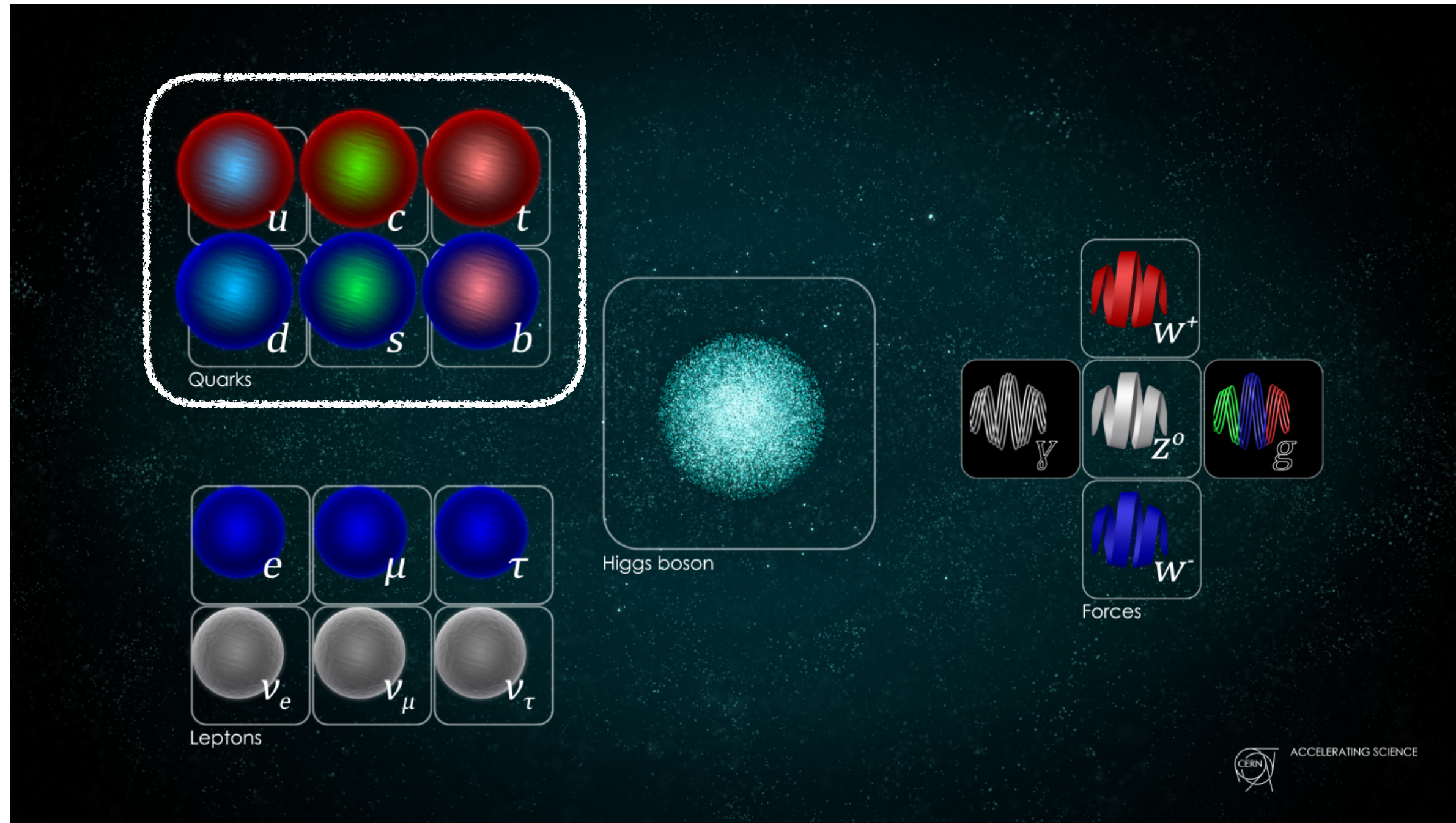
fact: [Alkofer, AE, Held, Nieto, Percacci, Schröfl '19]

this relation is emergent (an infrared attractive fixed line of the RG flow),

if there is long regime (highly transplanckian)

during which $y_t \gg y_{b,c,s,u,d}$ **and** $y_t = \text{const}$

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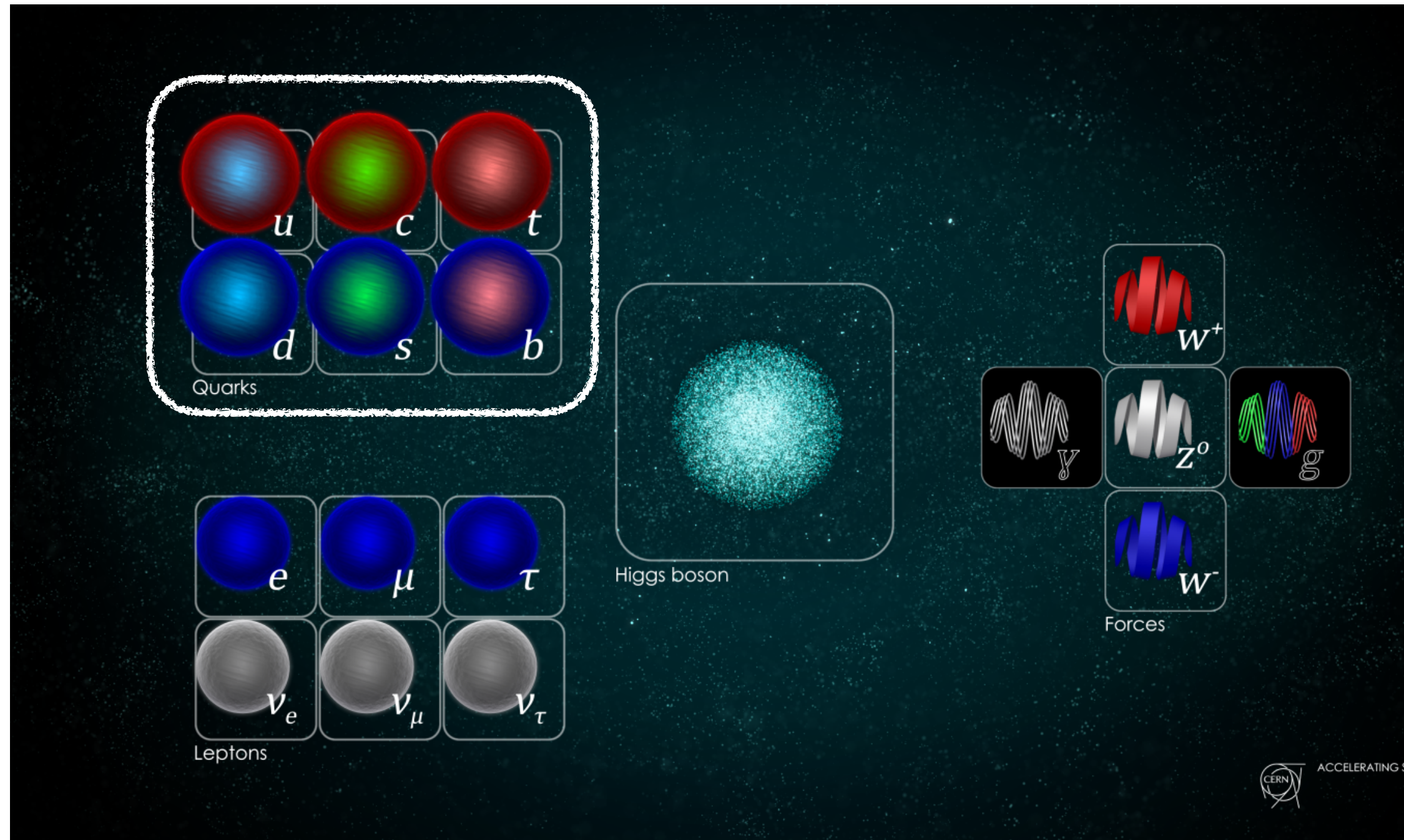
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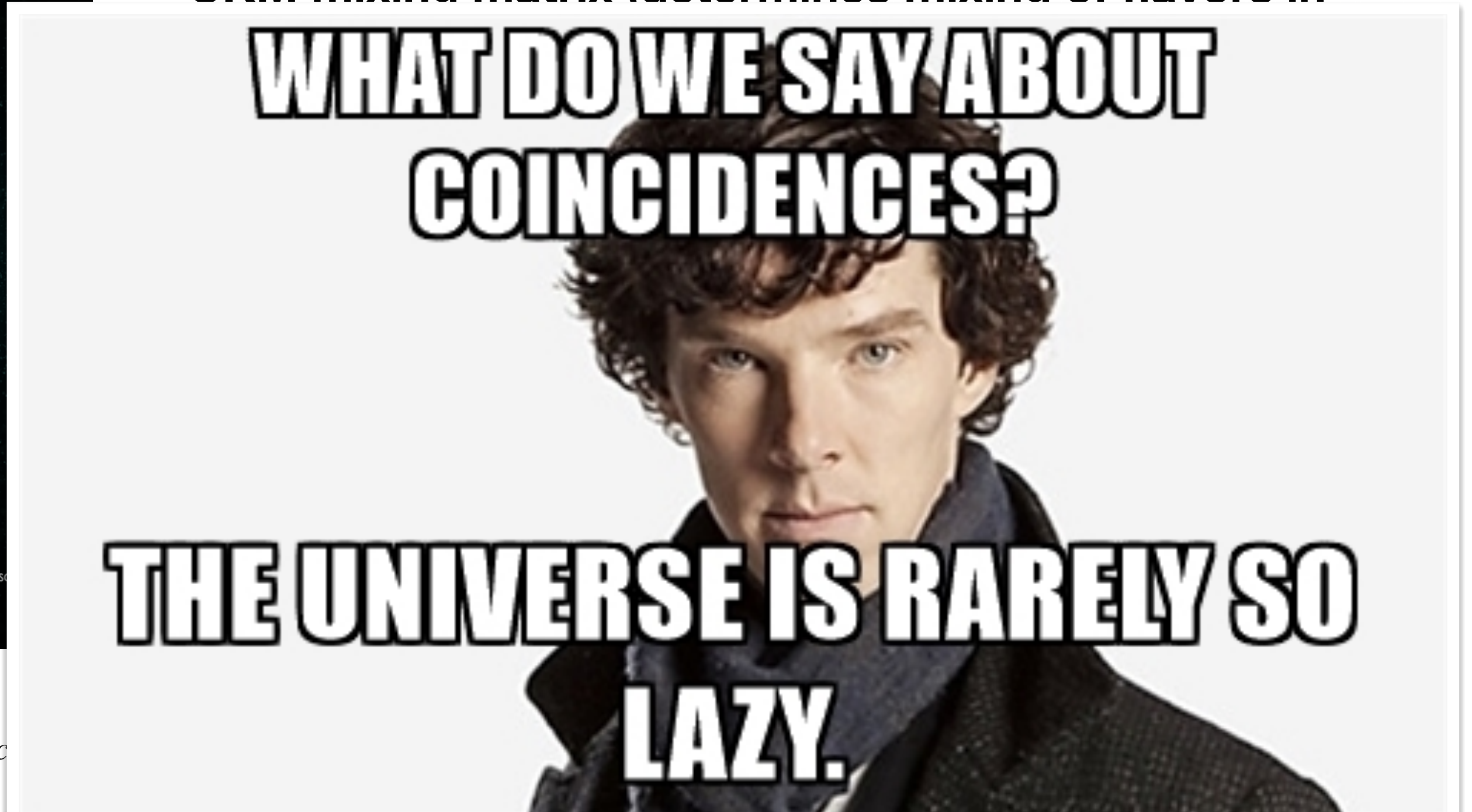
**Option 1): QFT has a cut-off at the Planck scale,
and the fact is just pure coincidence**

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Result: mixing matrices



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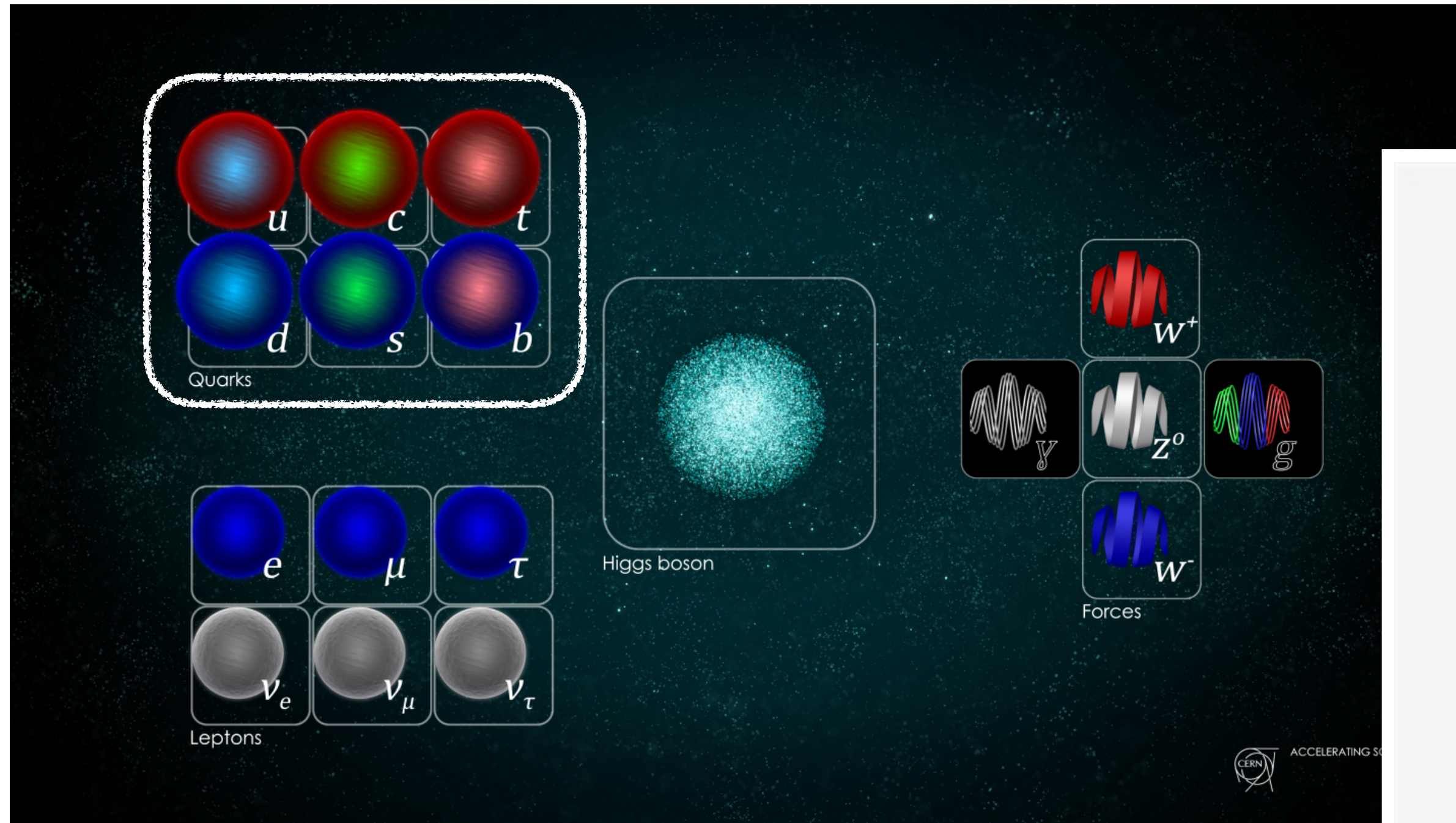
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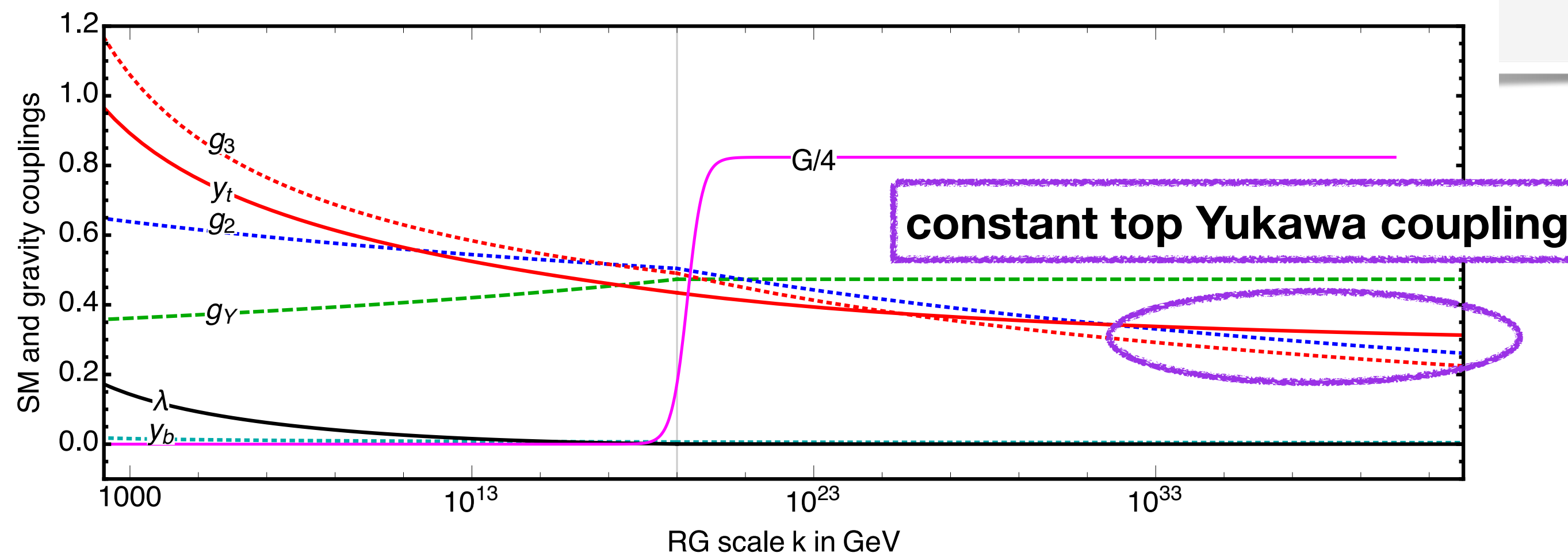
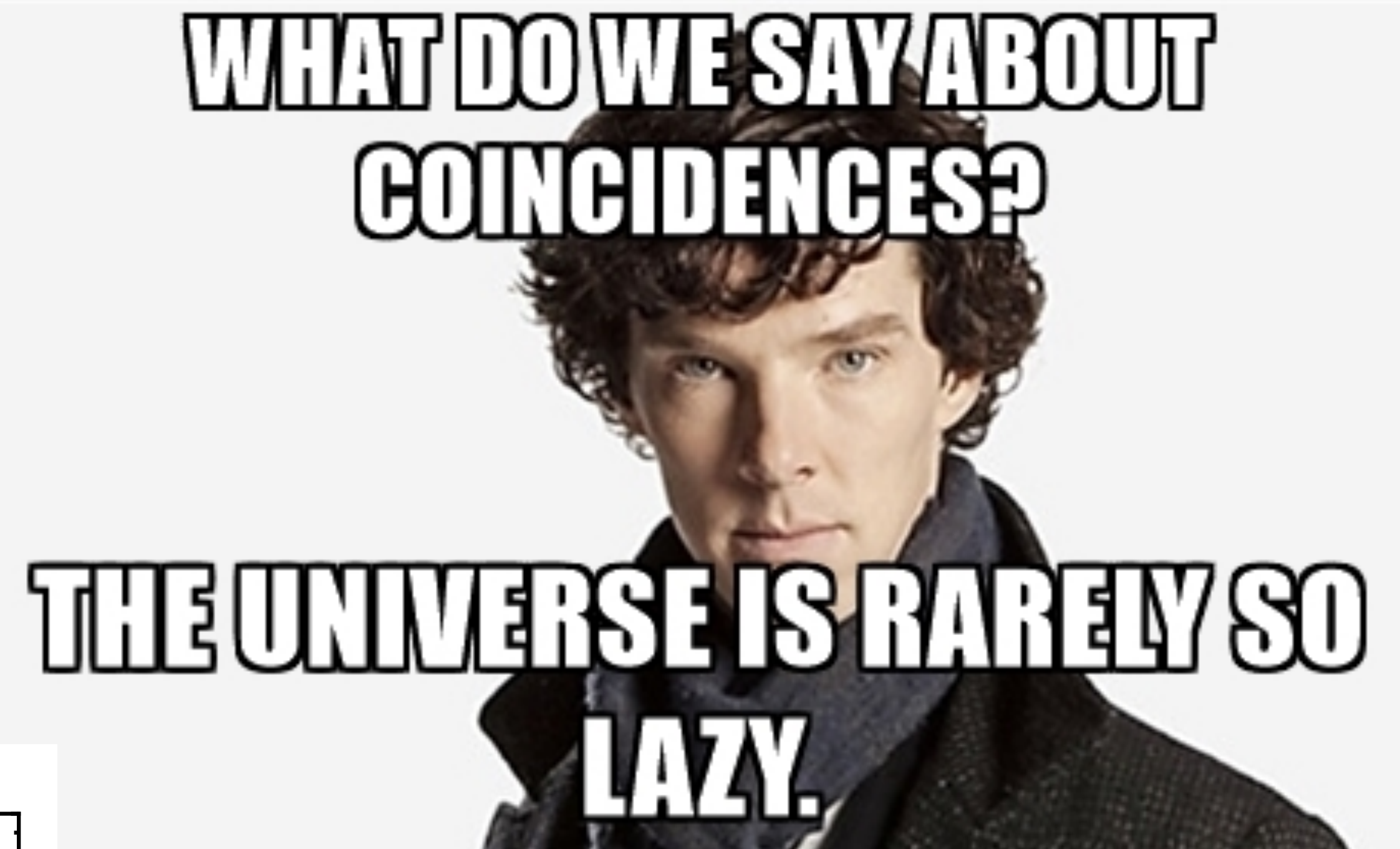
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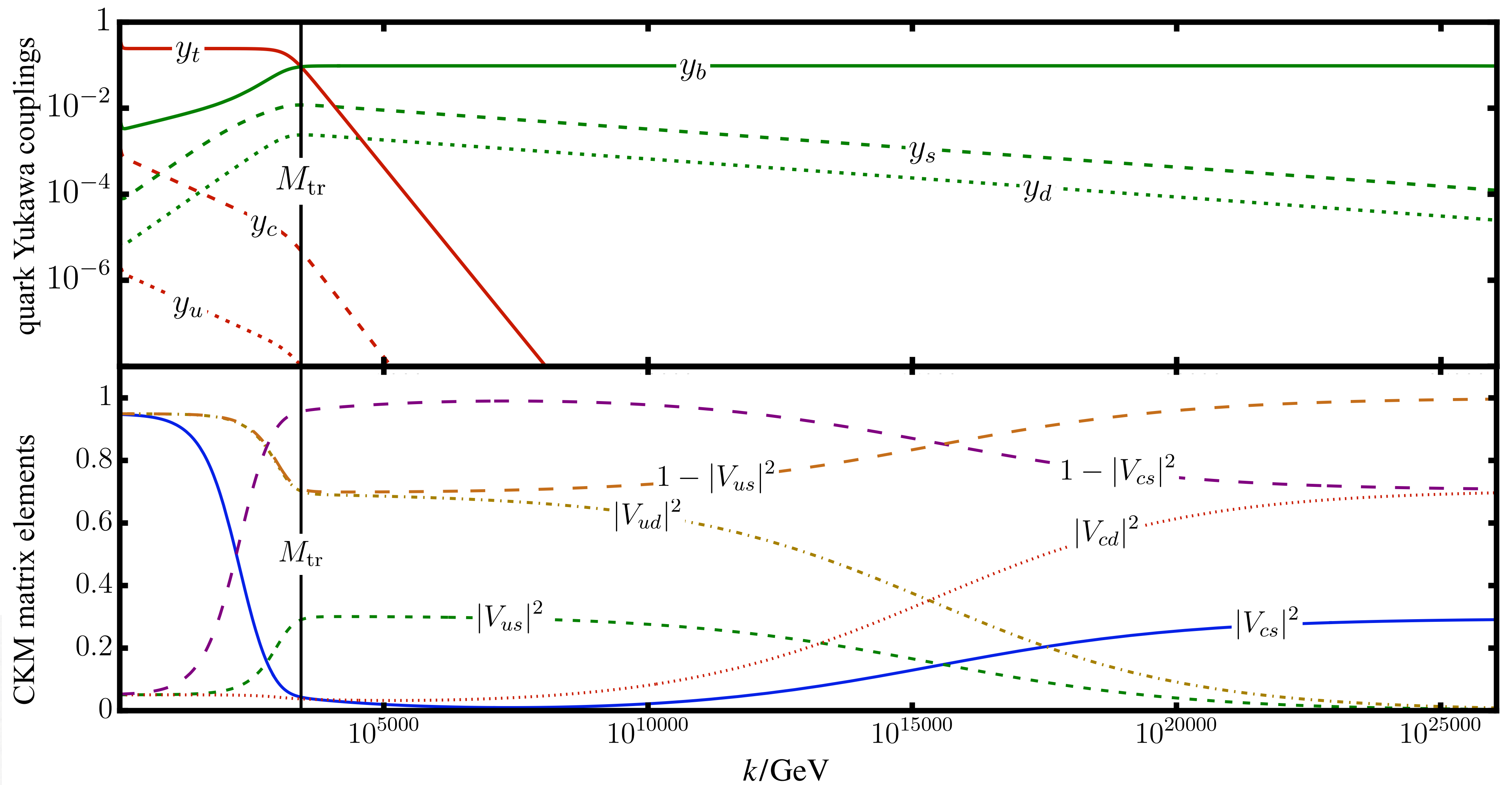
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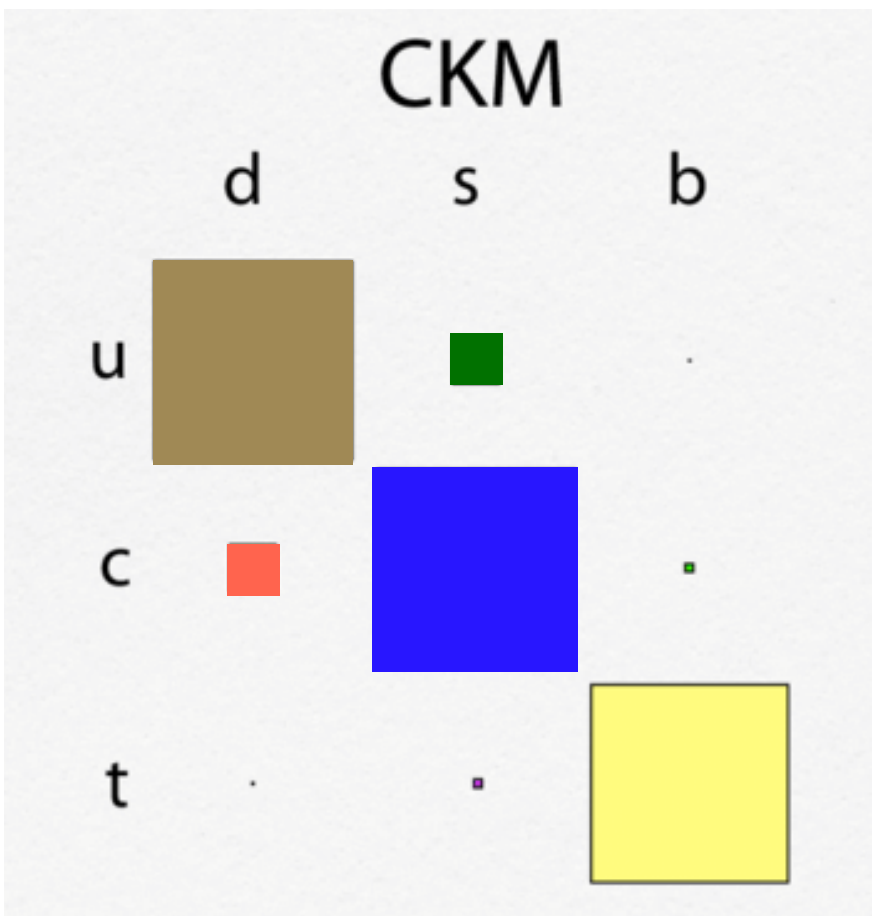
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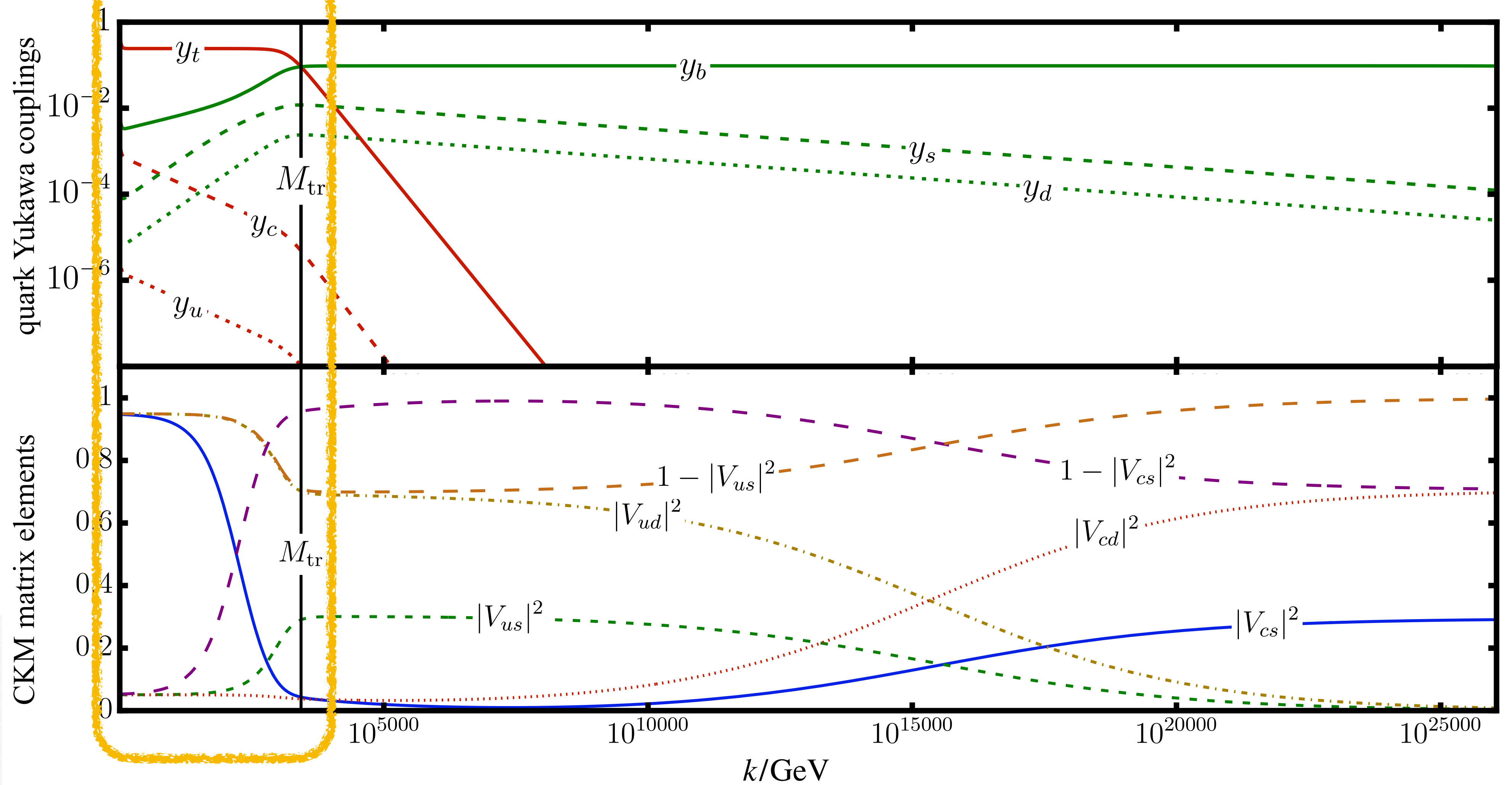
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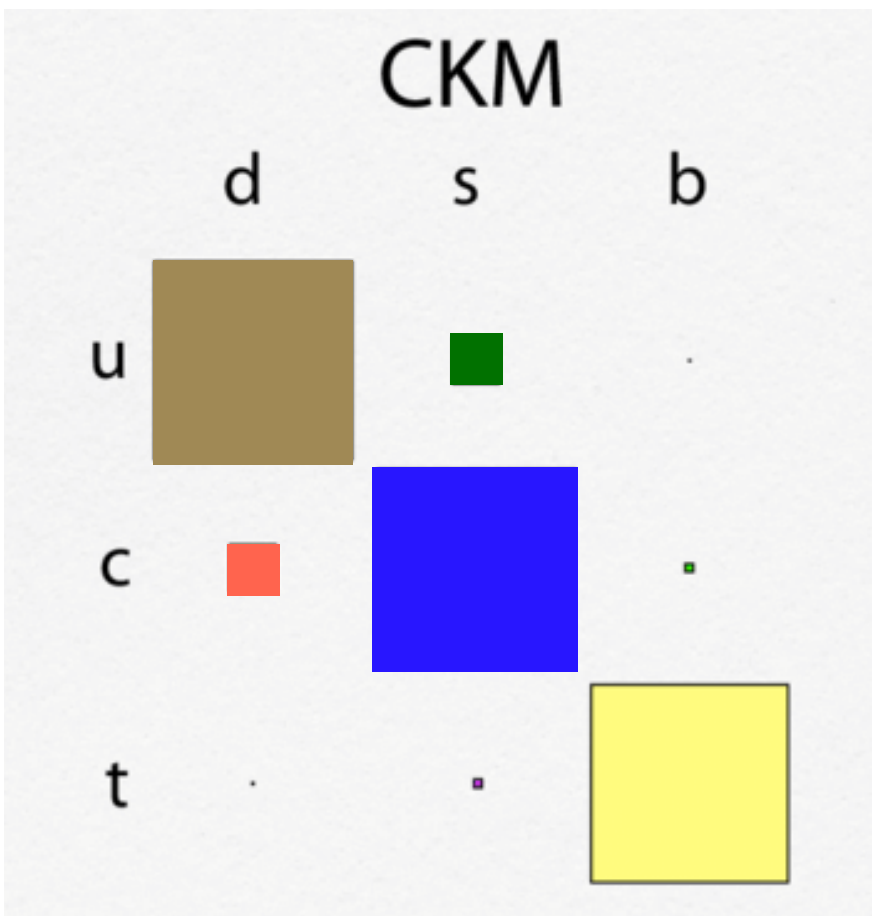
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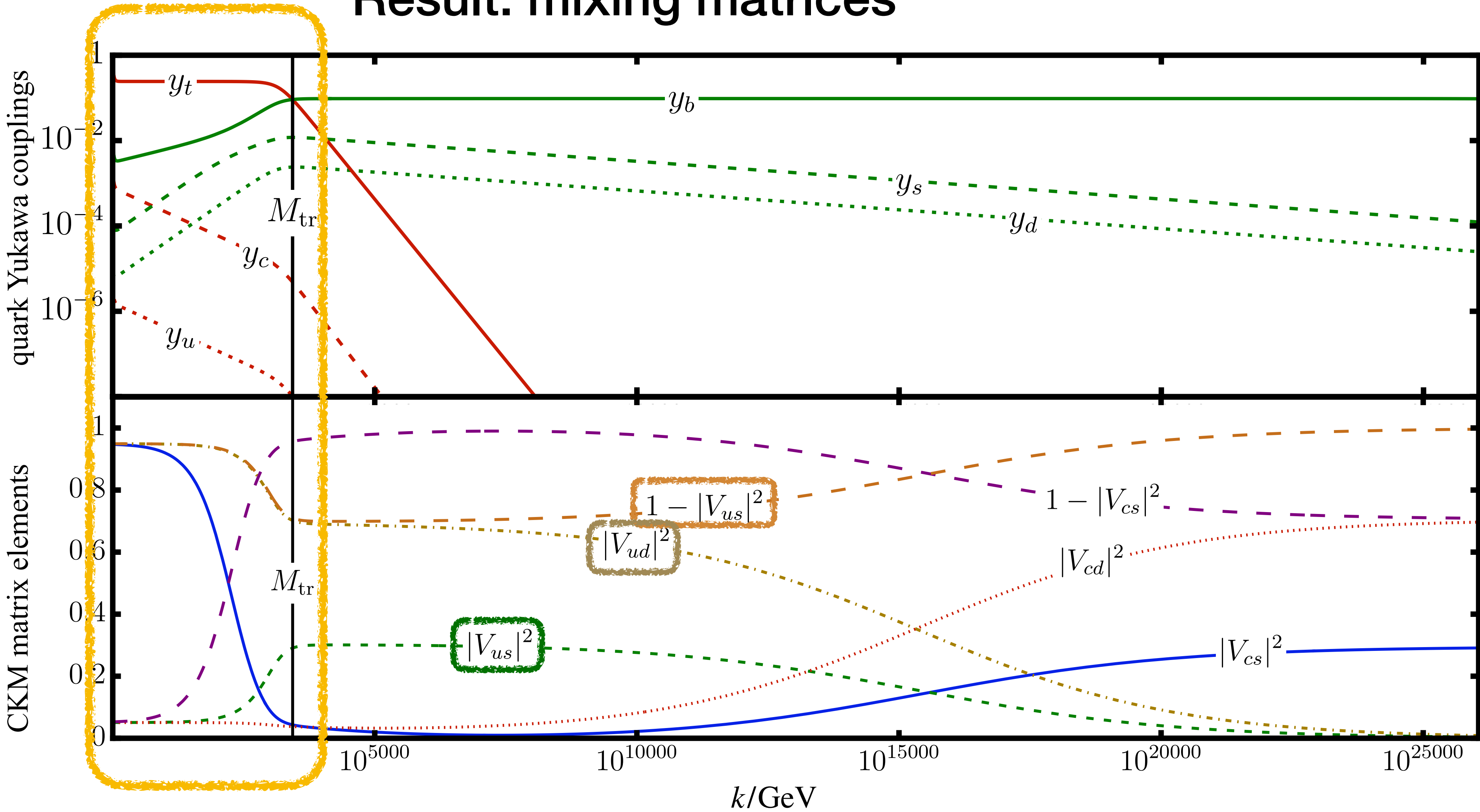
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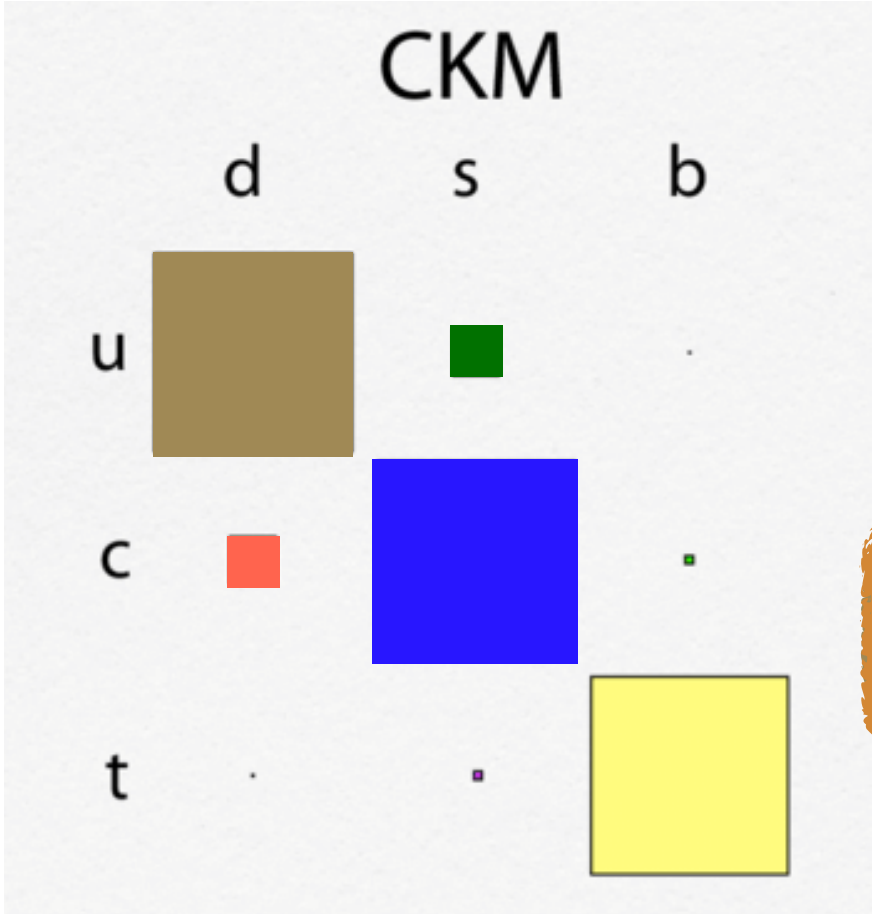


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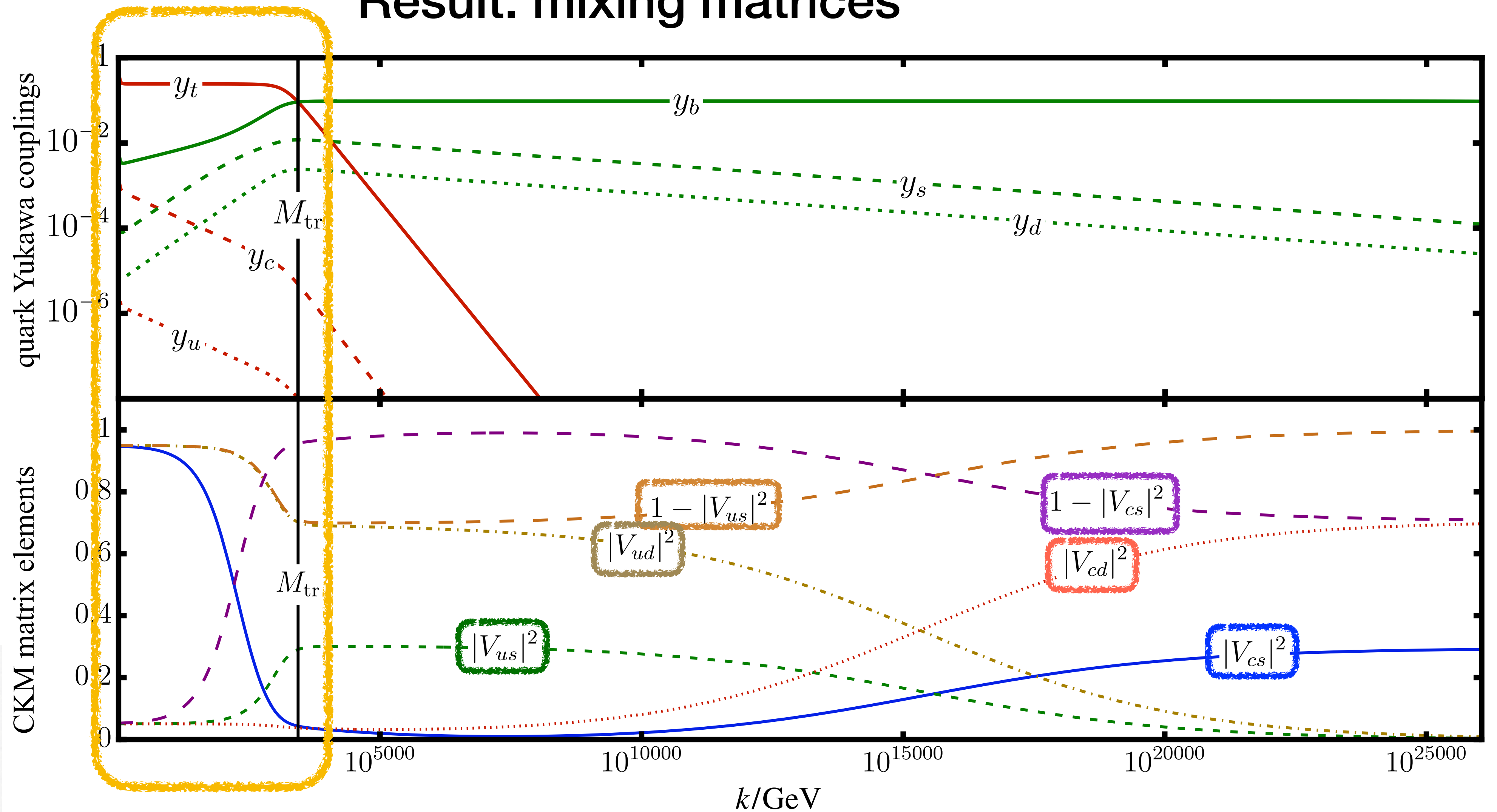


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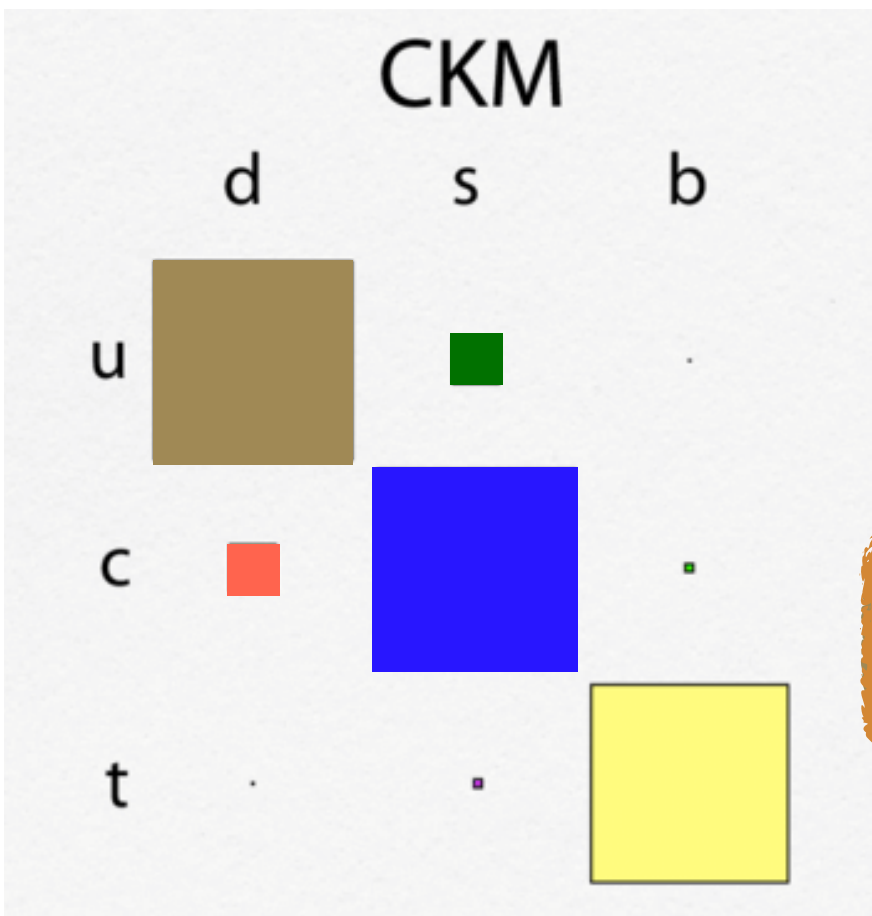


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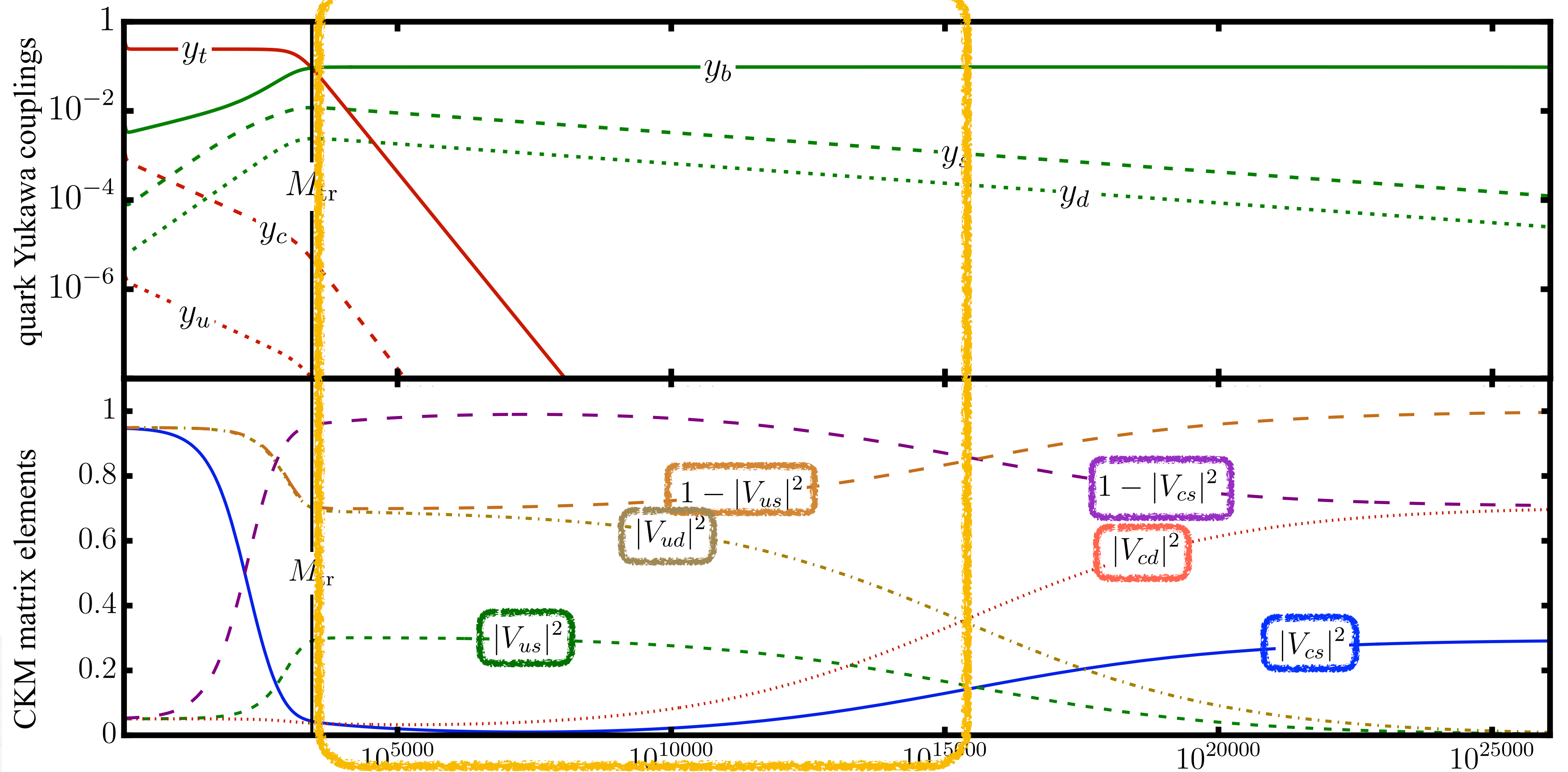


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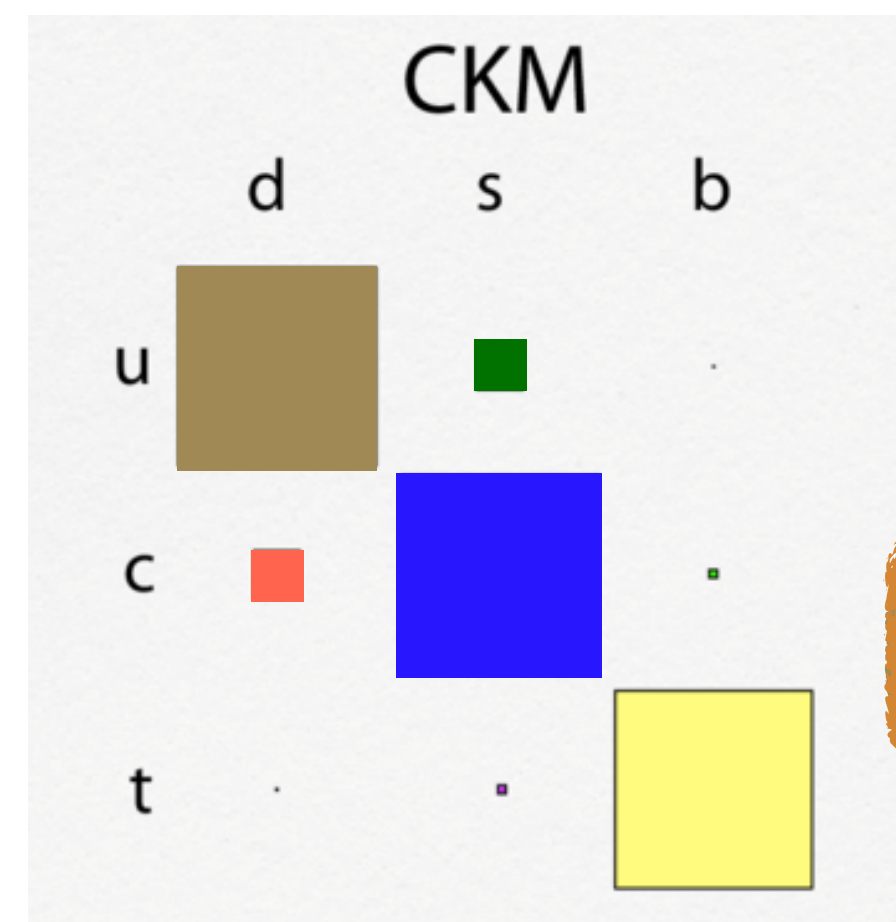
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emergent relations: earlier emergence $\Rightarrow$ higher accuracy

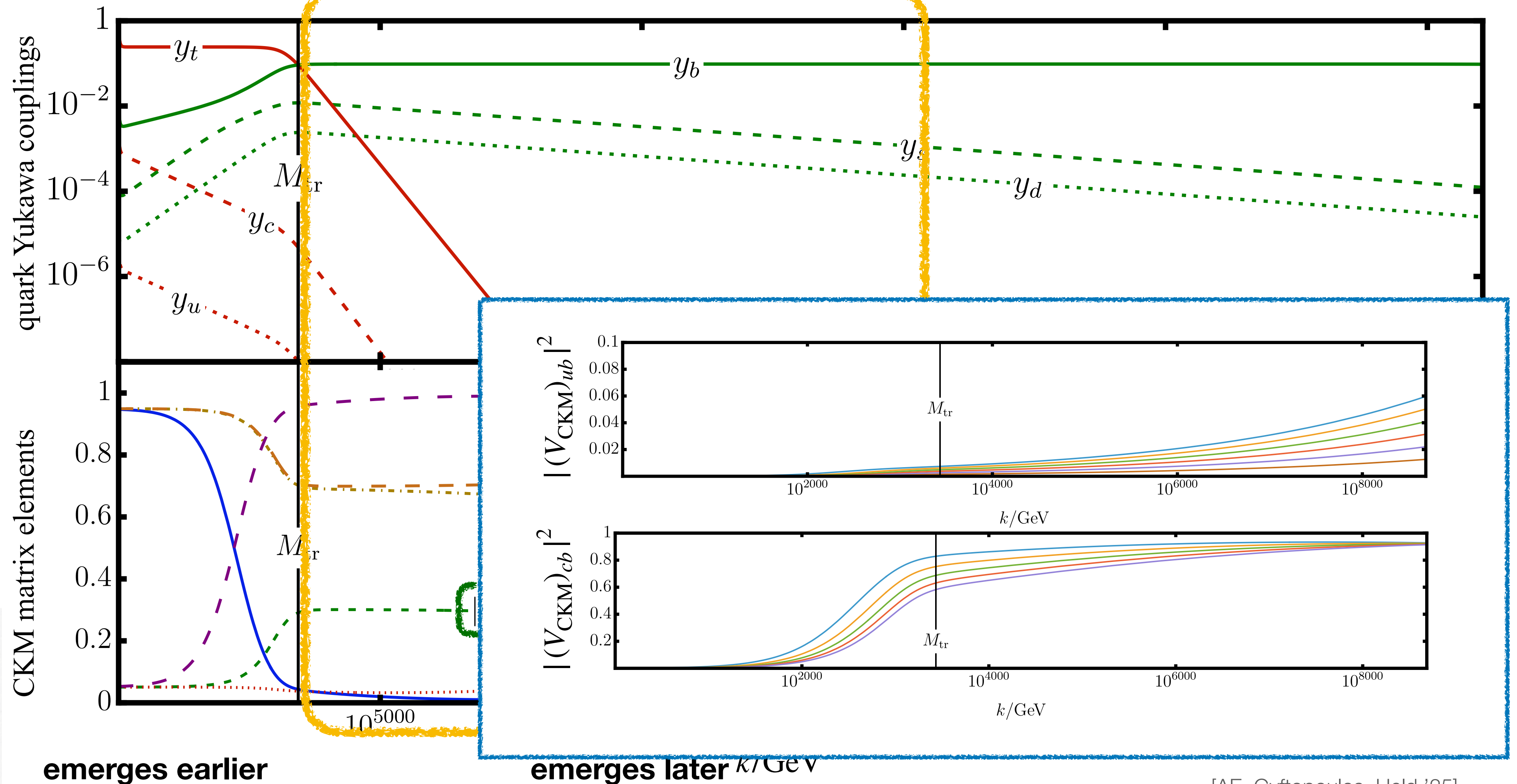
$$\Rightarrow |V_{ub}|^2 \ll |V_{cb}|^2$$

experimental data:

$|V_{ub}|^2 > |V_{cb}|^2$ ruled out at 29σ



Result: mixing matrices



emerges earlier

emerges later

[AE, Gyftopoulos, Held '25]

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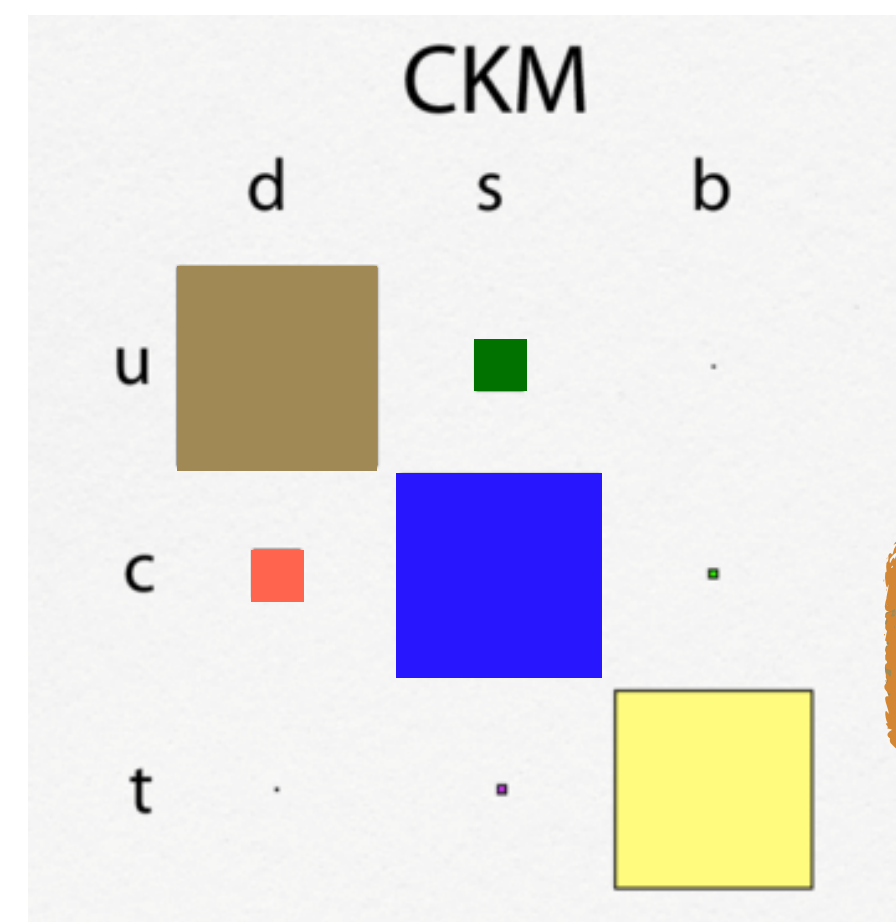
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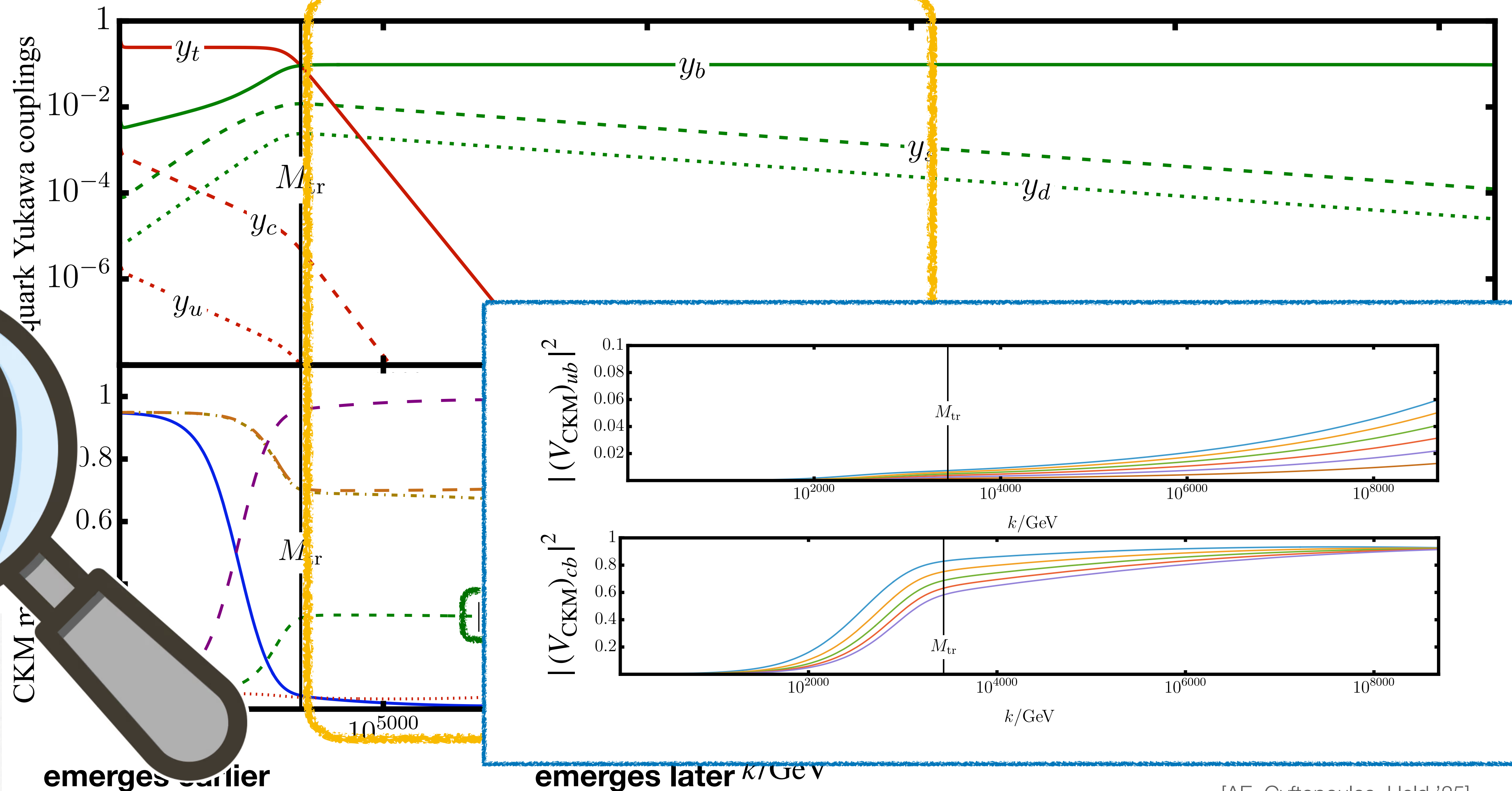
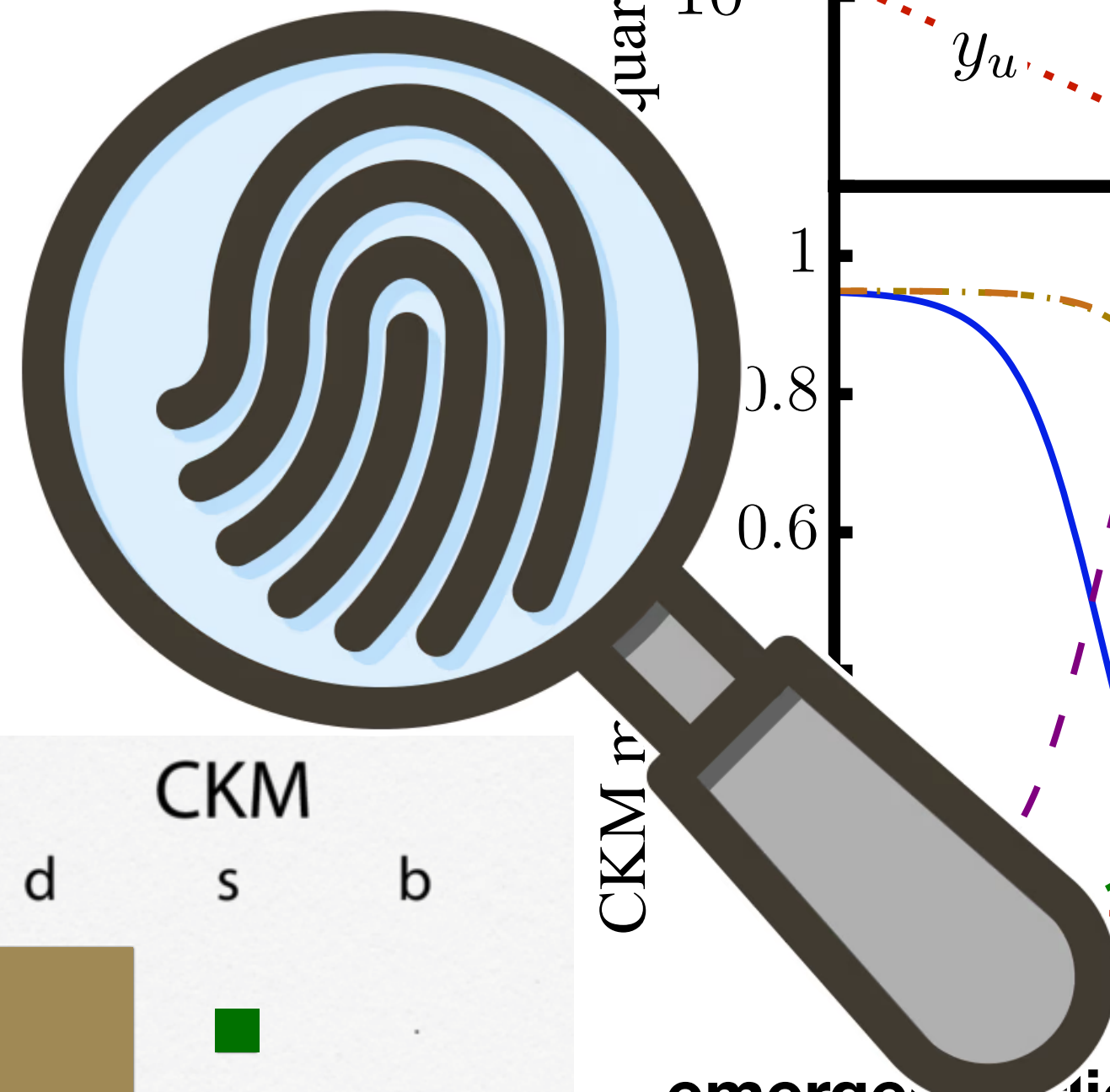
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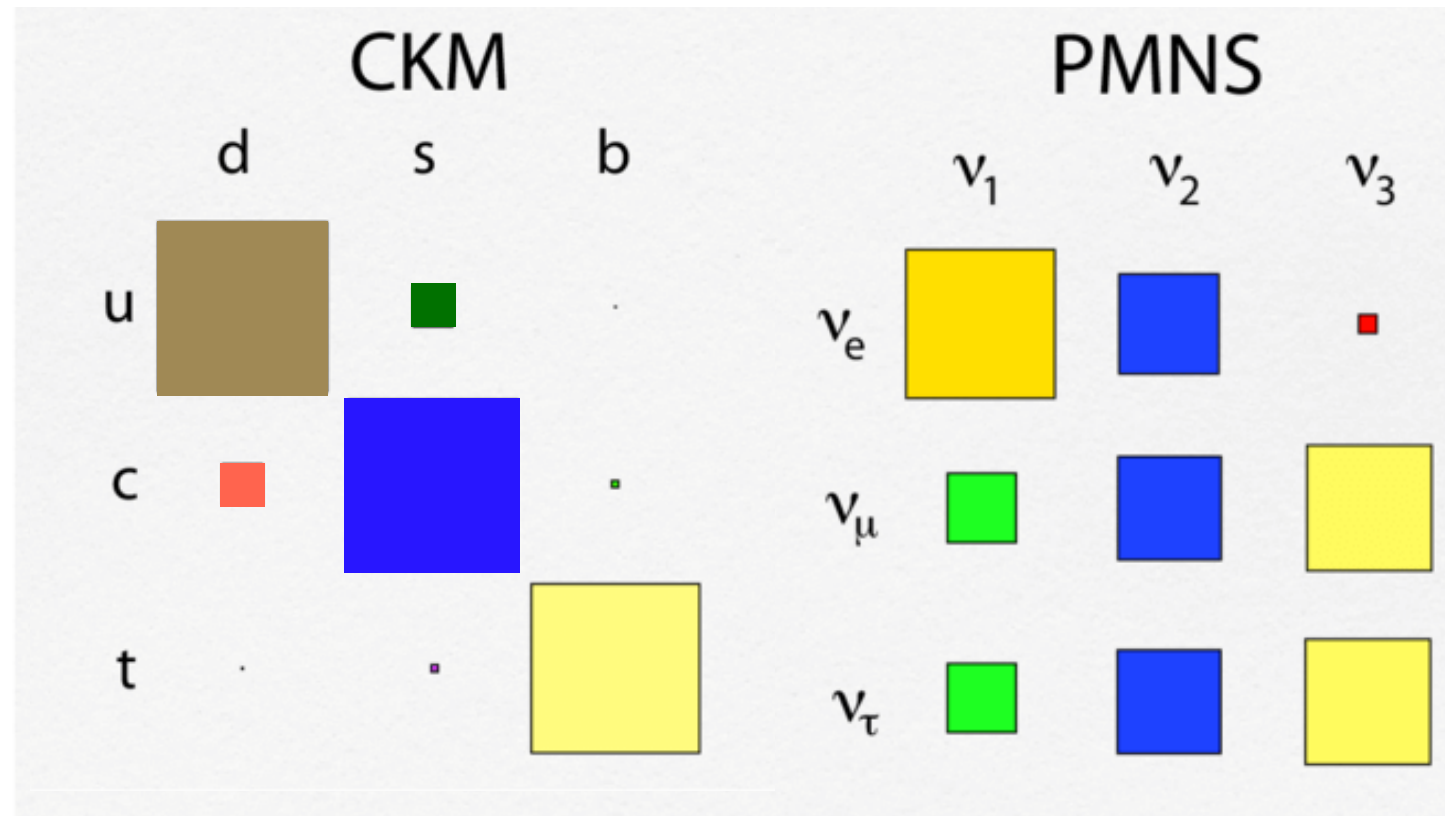
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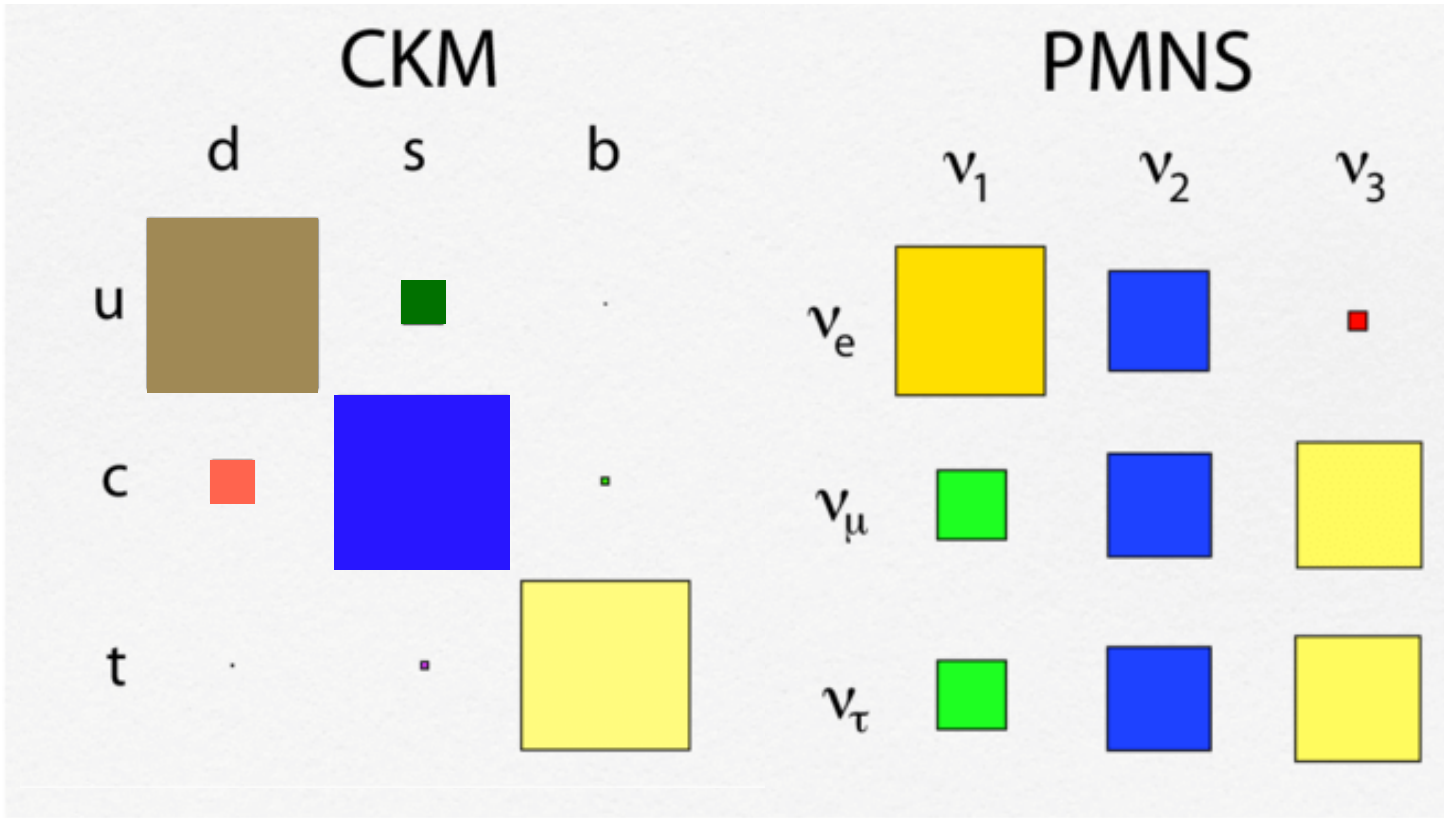
BUT: the scale dependence of the PMNS mixing matrix is fully analogous to the CKM mixing matrix, under the exchange of quarks and leptons



Does this scenario produce the wrong PMNS matrix?

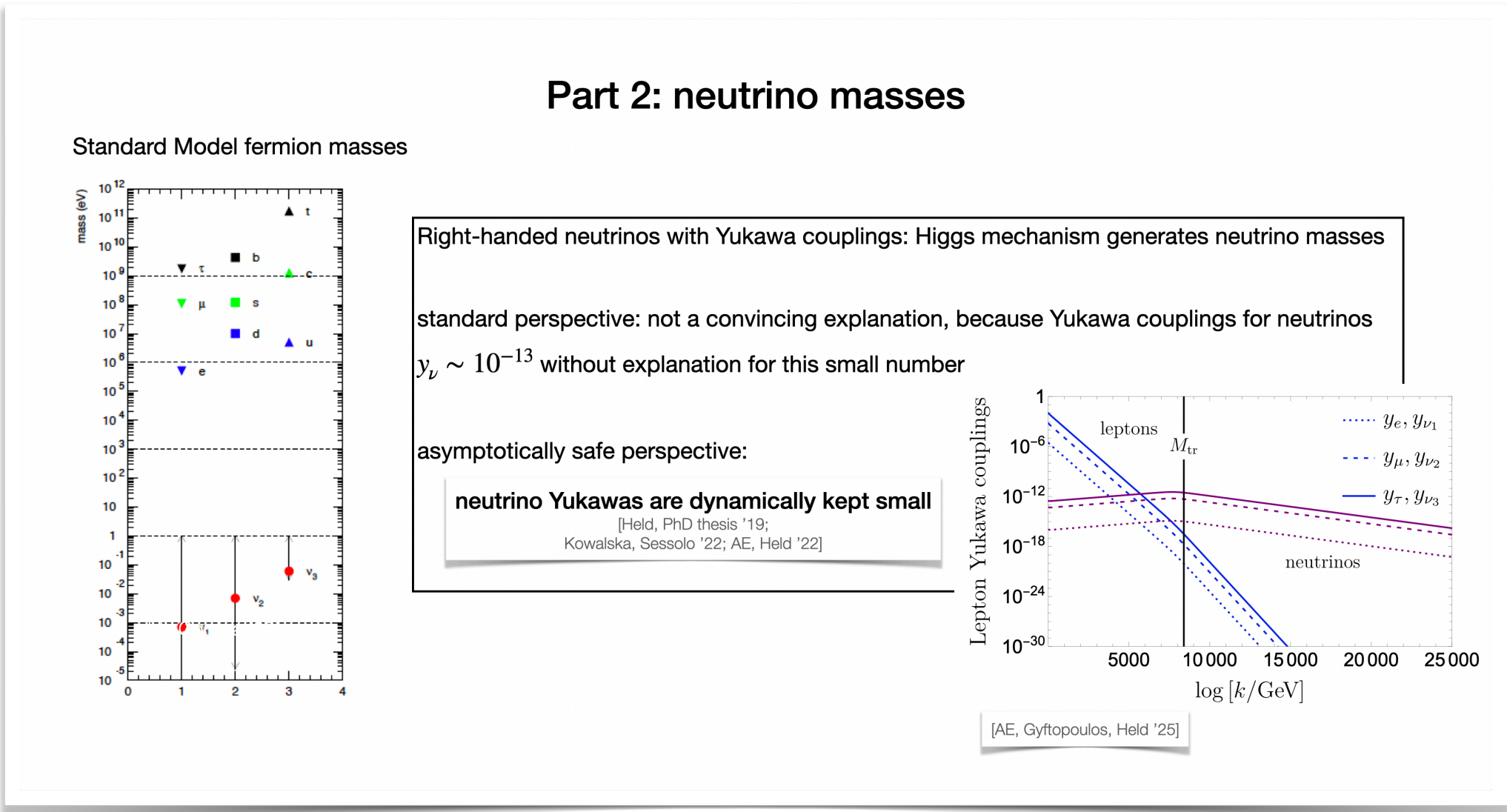
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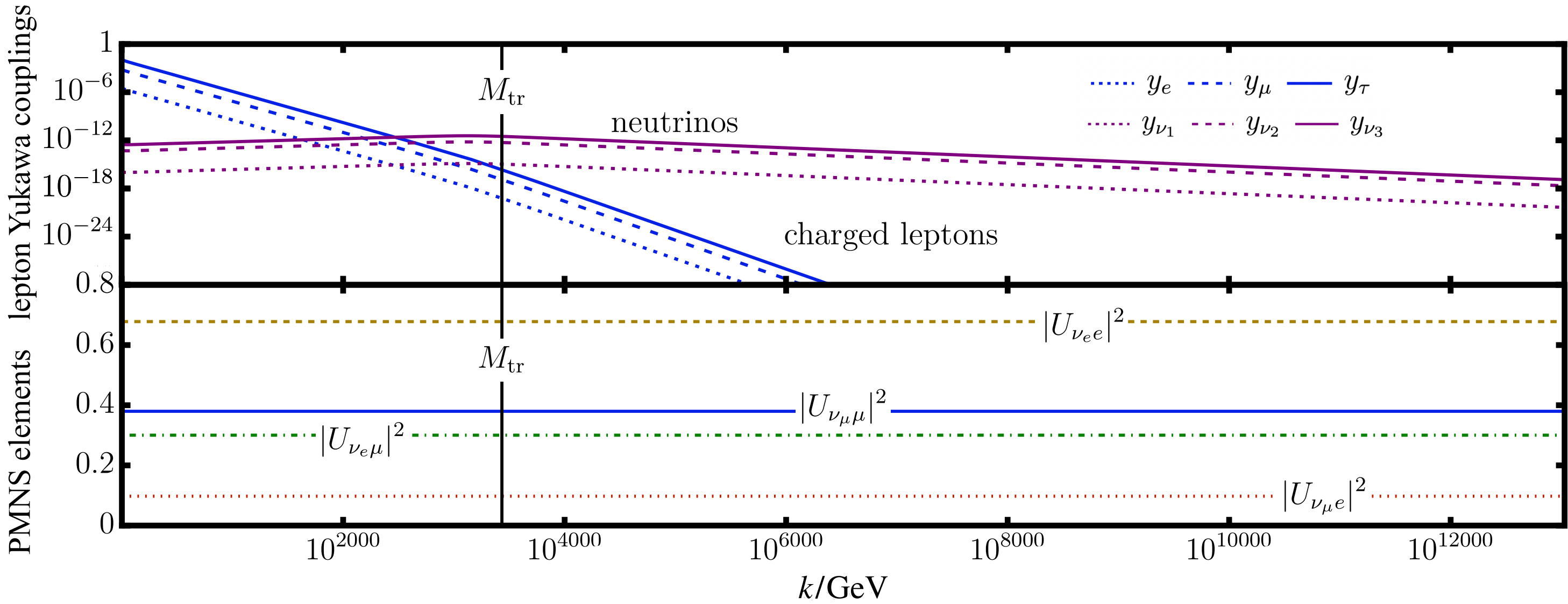
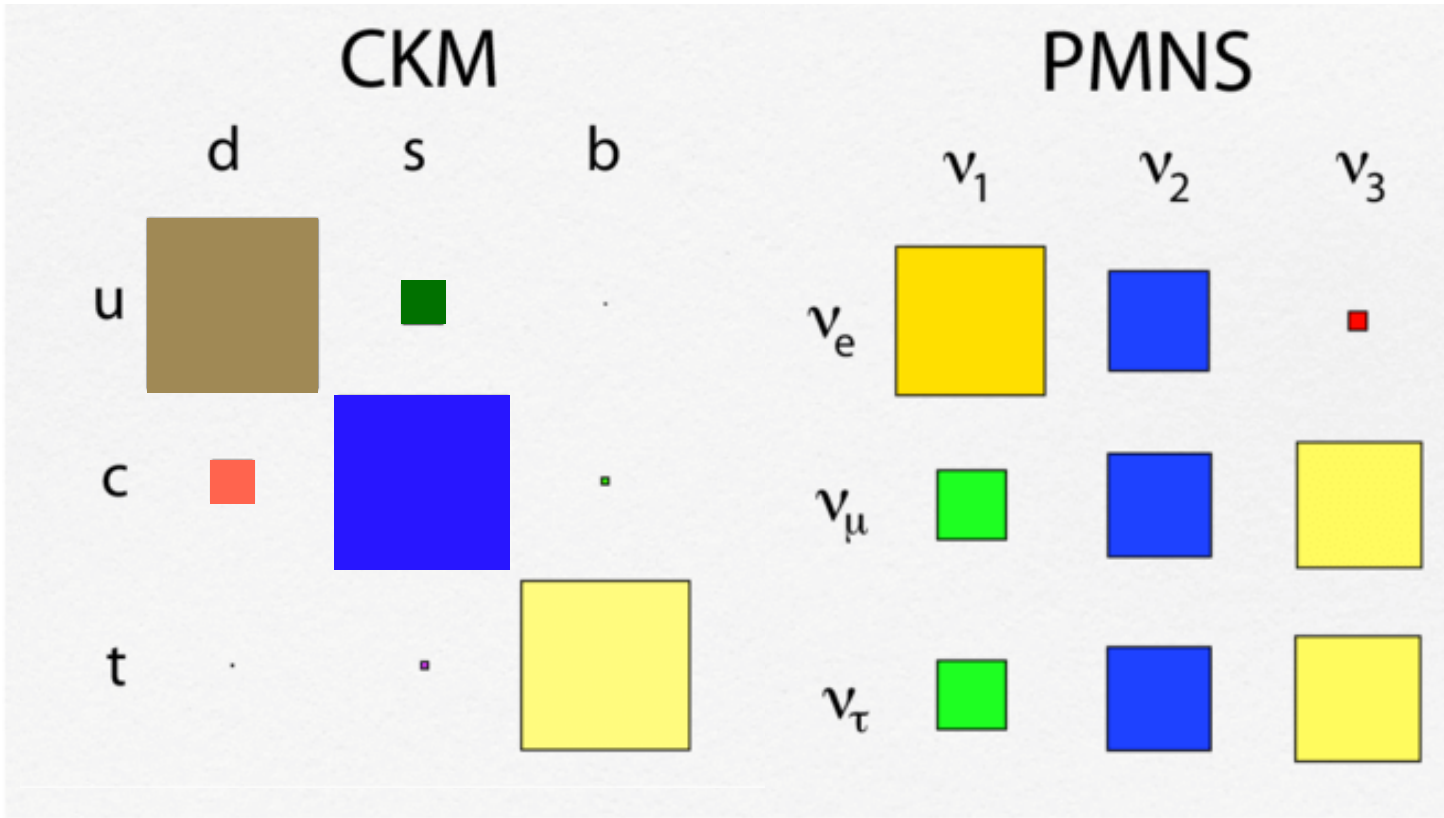
Does this scenario produce the wrong PMNS matrix?

No, because neutrino Yukawa couplings behave differently!



Result: mixing matrices

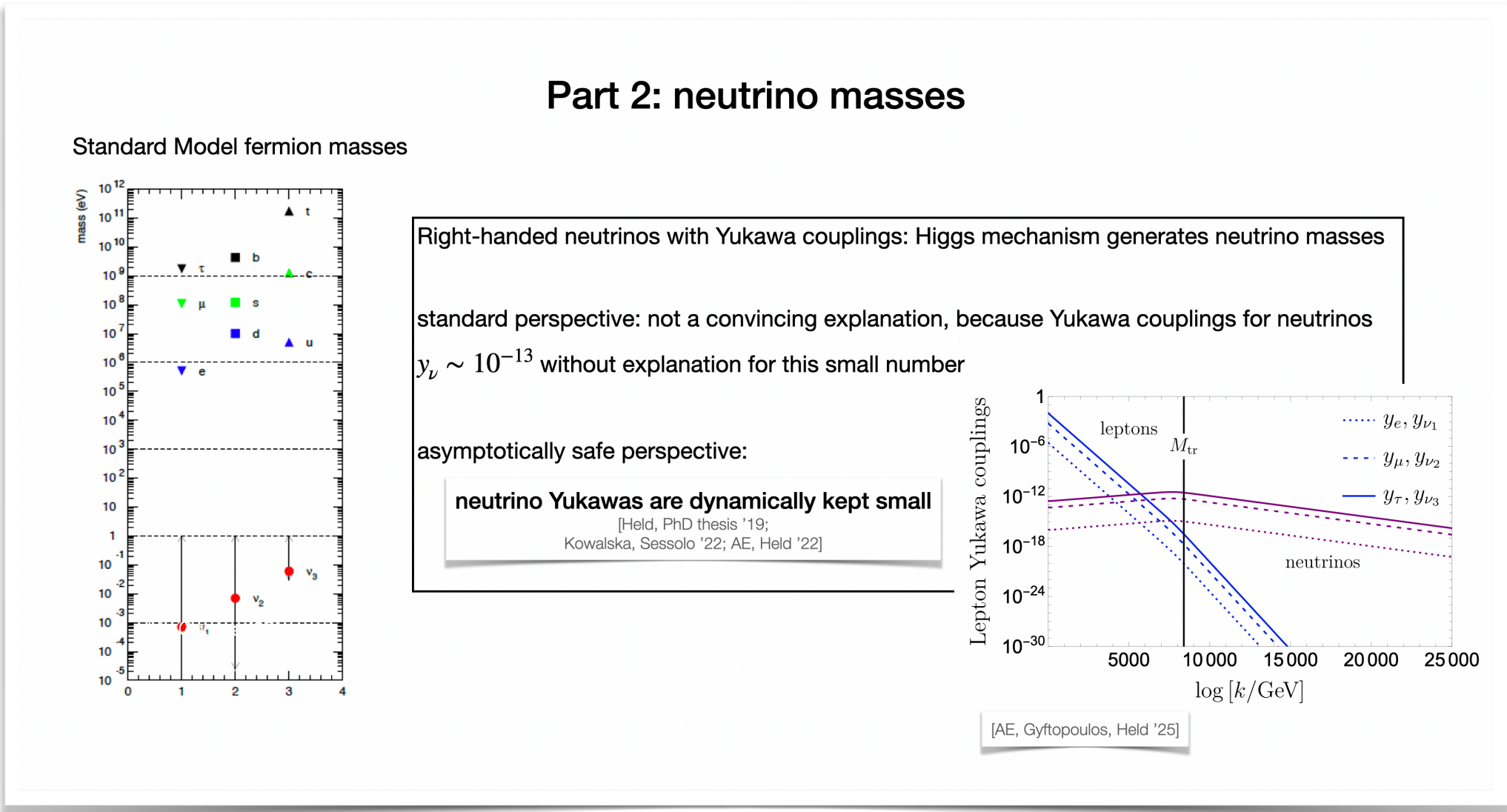
BUT: the scale dependence of the PMNS mixing matrix is fully analogous to the CKM mixing matrix, under the exchange of quarks and leptons



Does this scenario produce the wrong PMNS matrix?

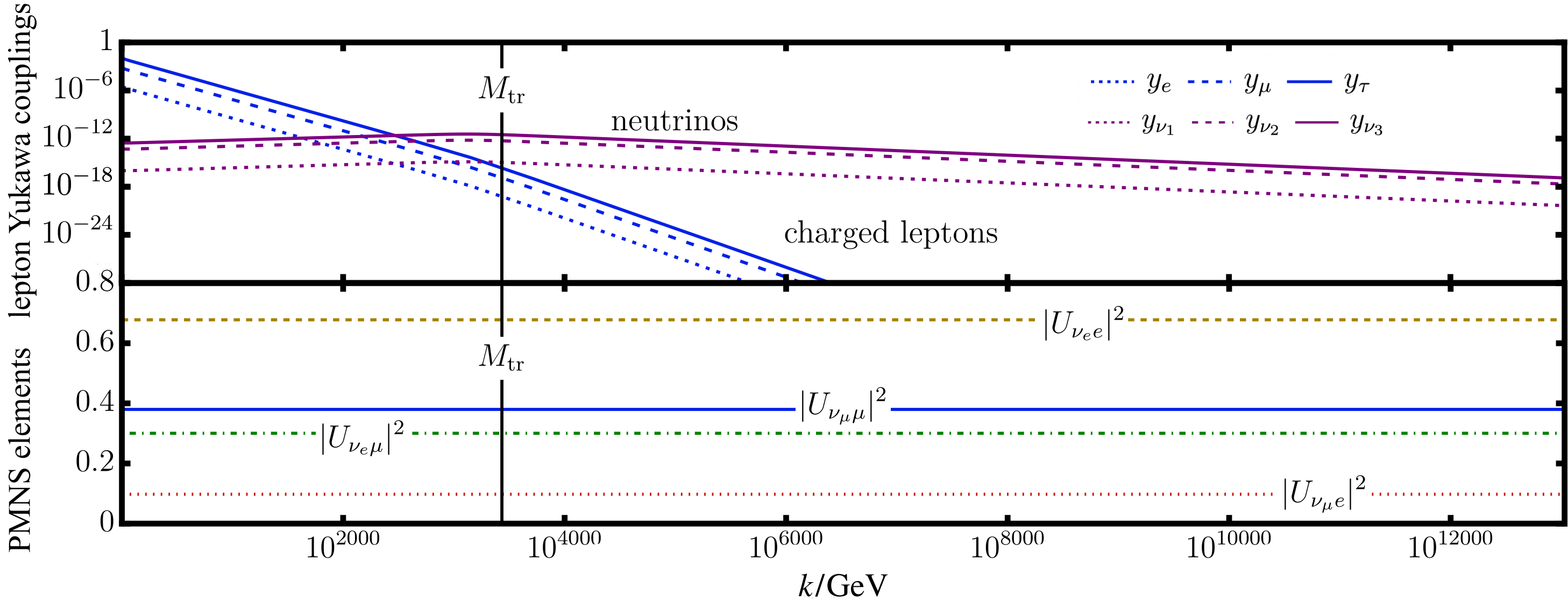
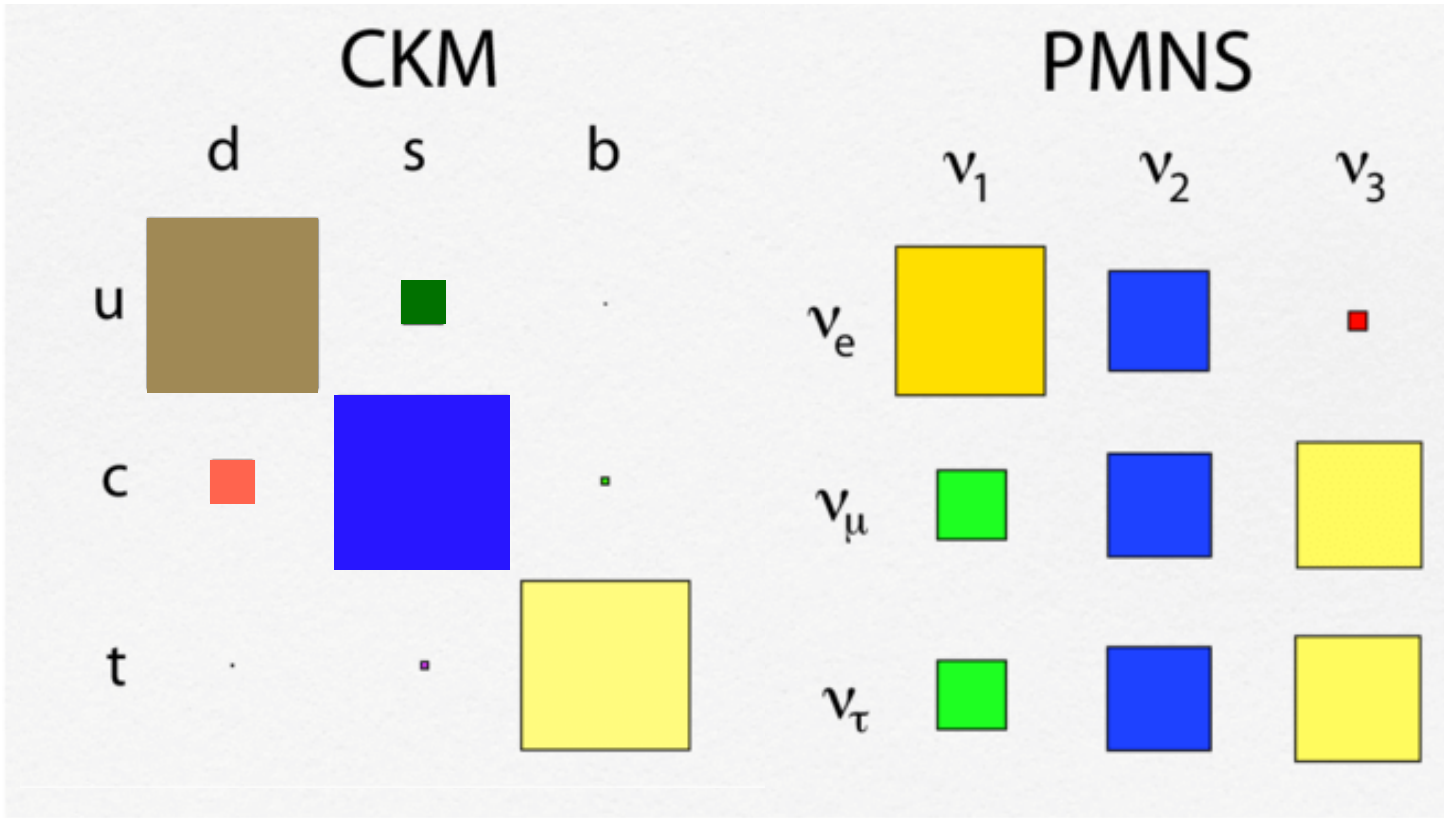
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[AE, Gyftopoulos, Held '25]



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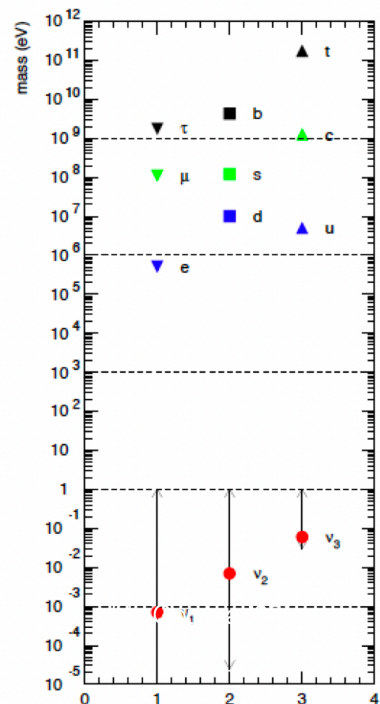
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[AE, Gyftopoulos, Held '25]

Part 2: neutrino masses

Standard Model fermion masses



Right-handed neutrinos with Yukawa couplings: Higgs mechanism generates neutrino masses

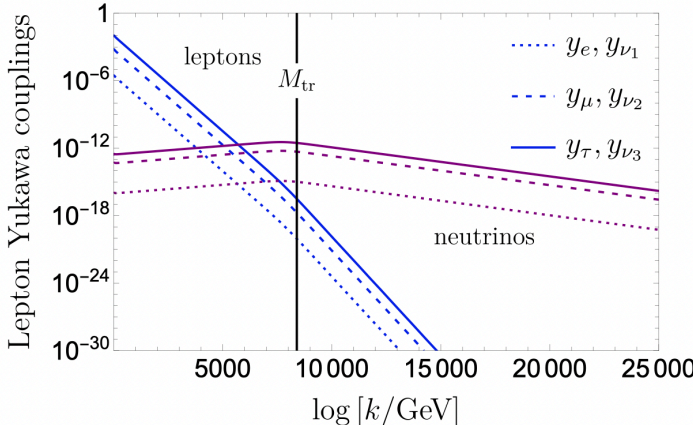
standard perspective: not a convincing explanation, because Yukawa couplings for neutrinos

$y_\nu \sim 10^{-13}$ without explanation for this small number

asymptotically safe perspective:

neutrino Yukawas are dynamically kept small

[Held, PhD thesis '19;
Kowalska, Sessolo '22; AE, Held '22]

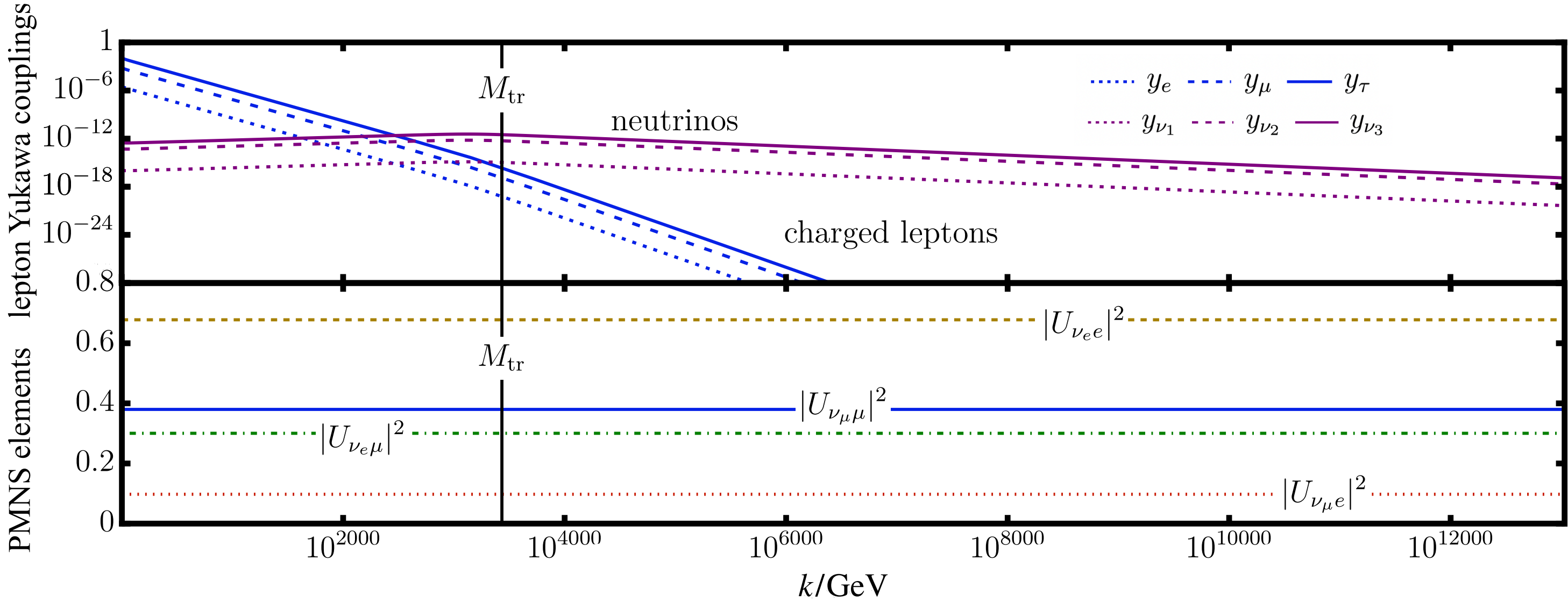
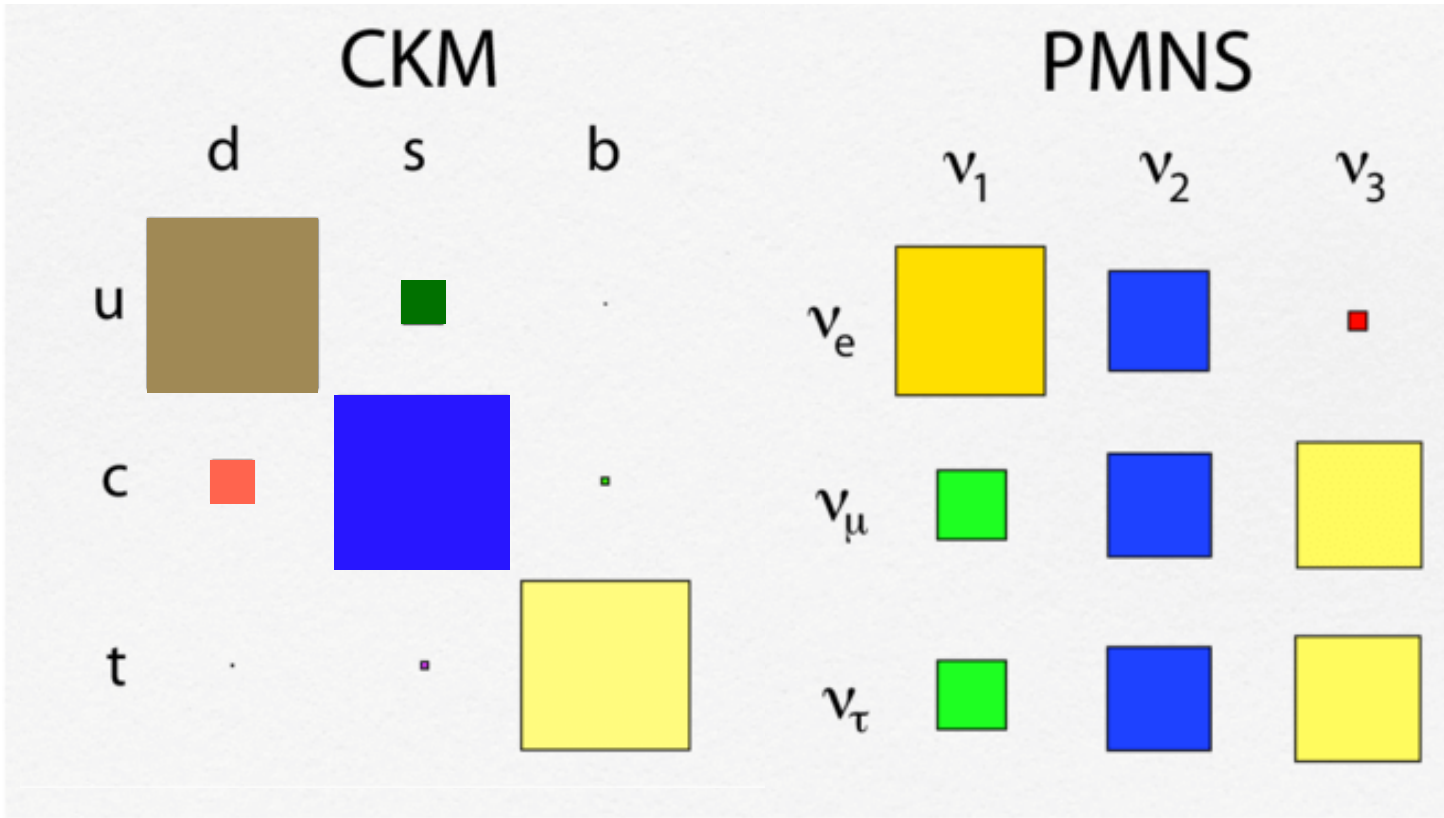


[AE, Gyftopoulos, Held '25]

Neutrino oscillations (neutrino mixing) are large, **because** neutrinos are so light.

Result: mixing matrices

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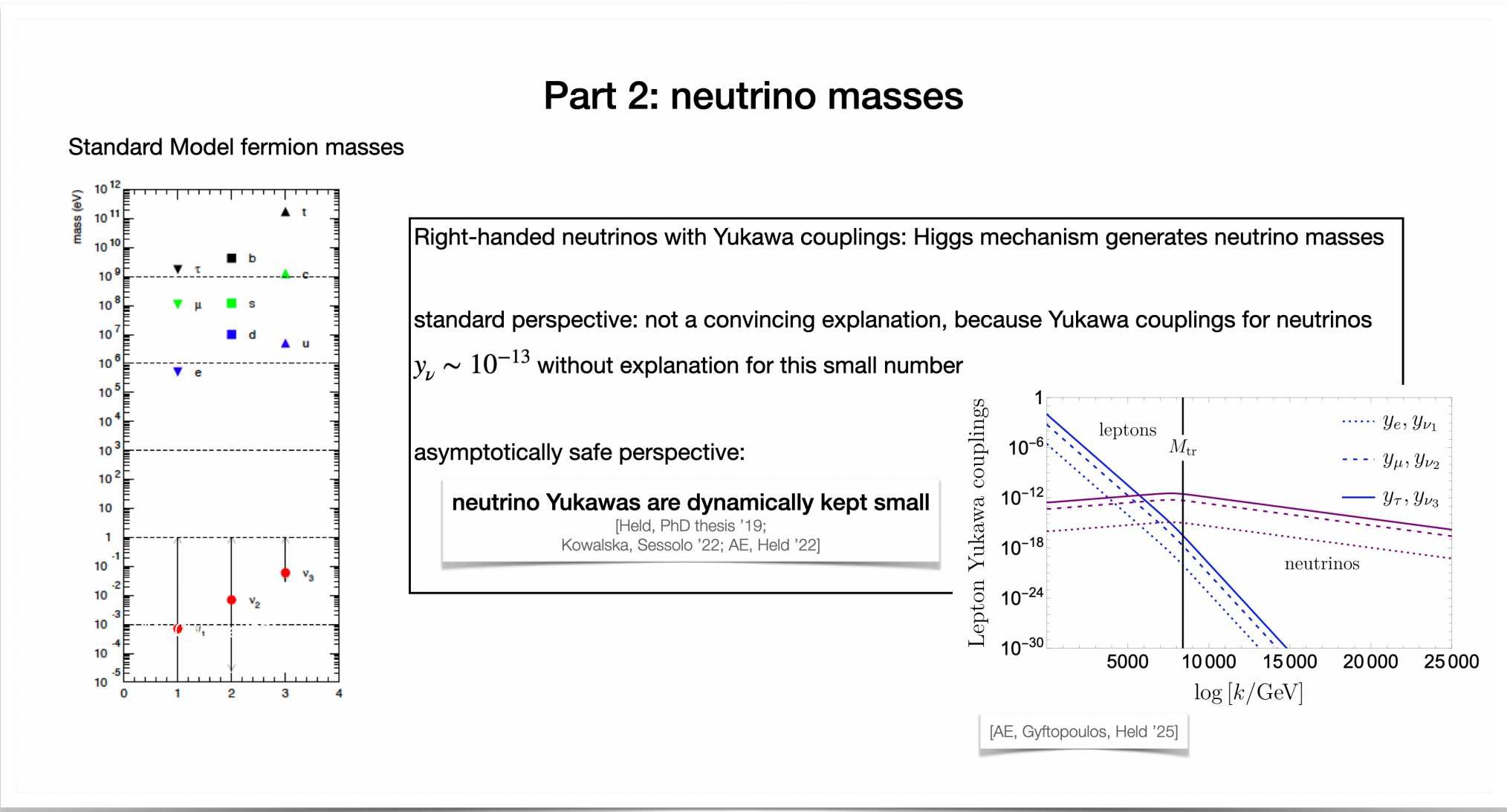
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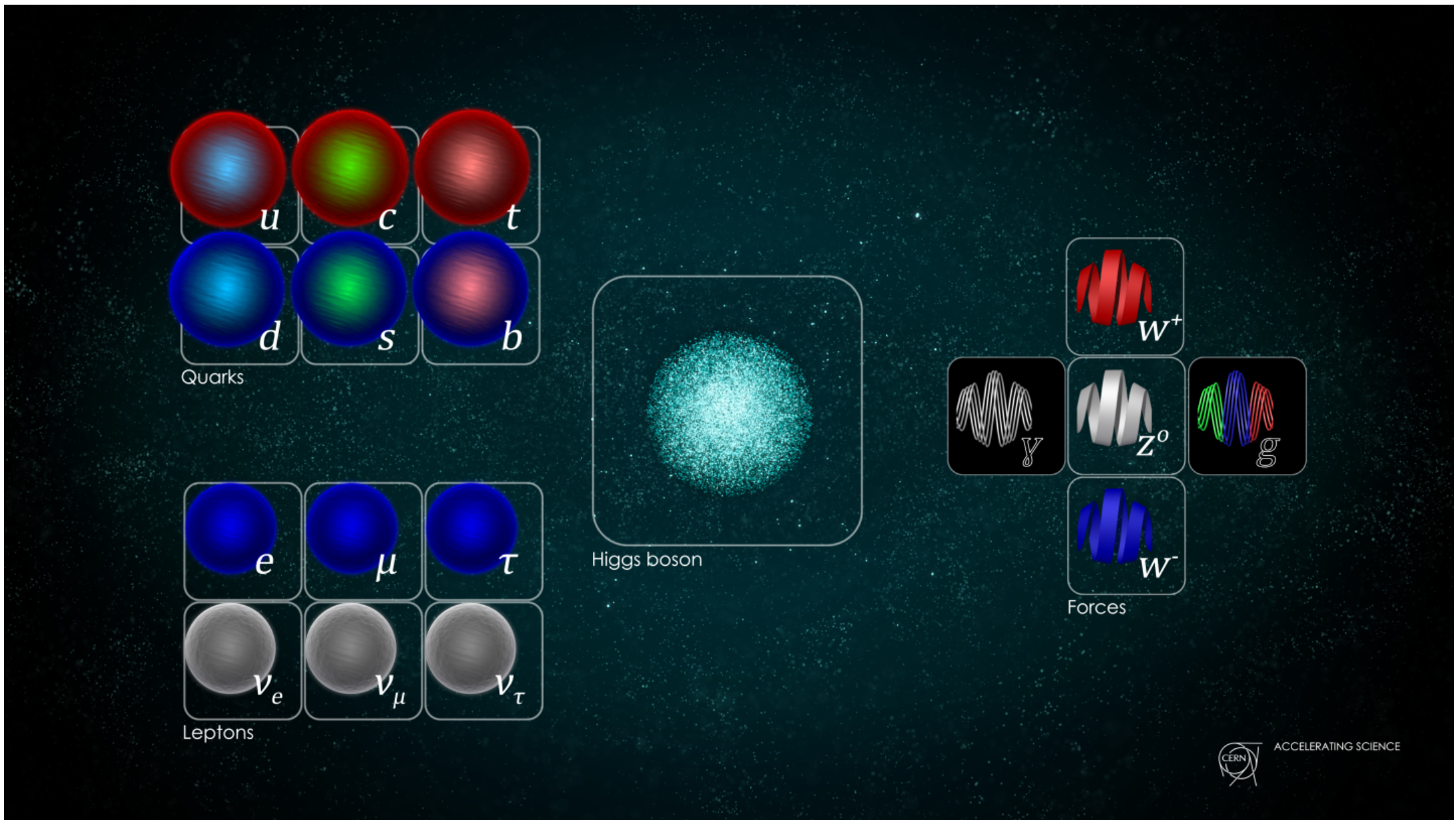
[AE, Gyftopoulos, Held '25]

Neutrino oscillations (neutrino mixing) are large, **because** neutrinos are so light.

structural connection between two properties of neutrinos
that is due to quantum gravity

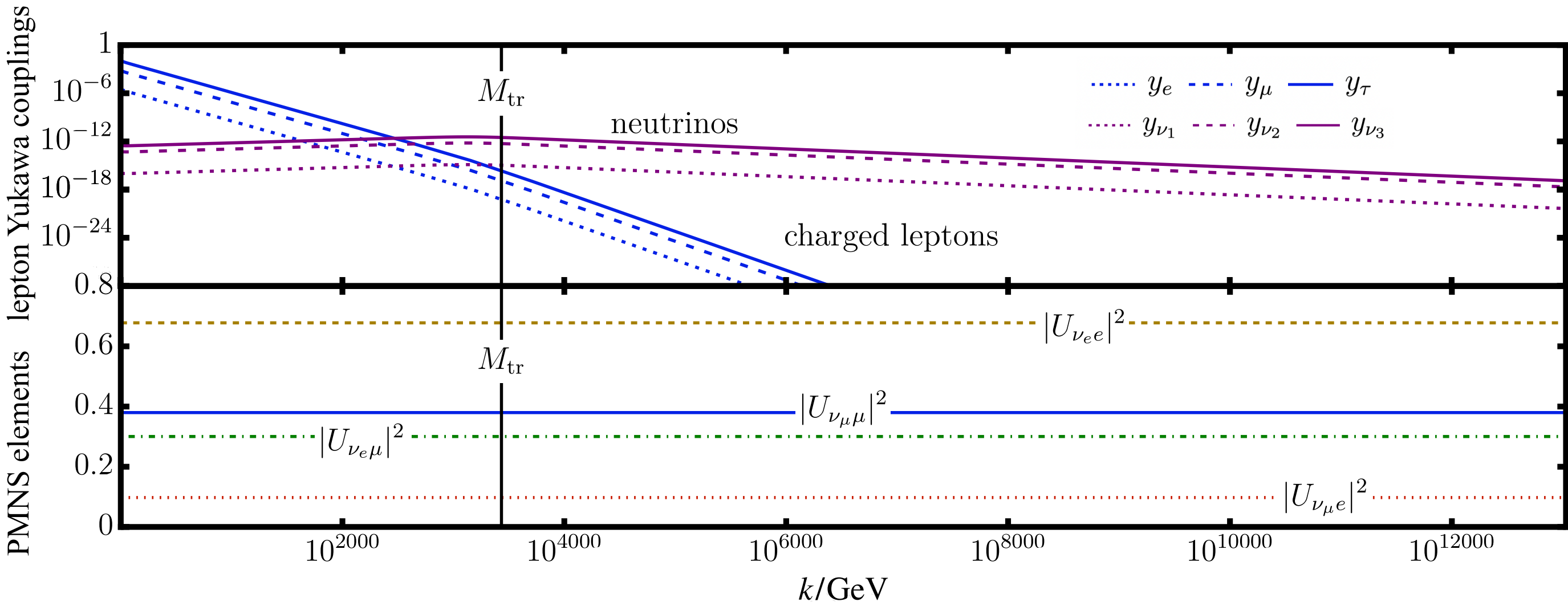
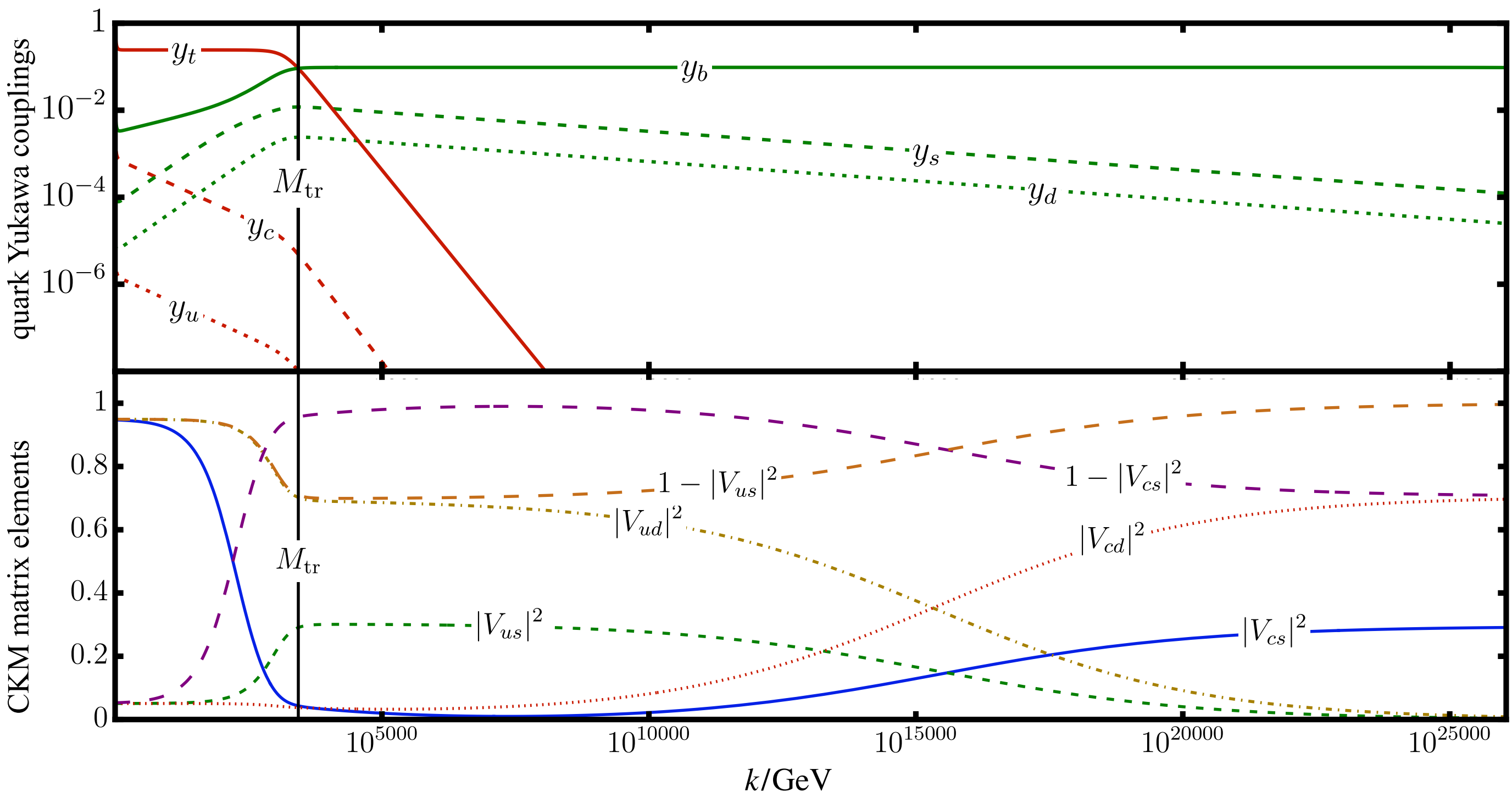


Standard Model

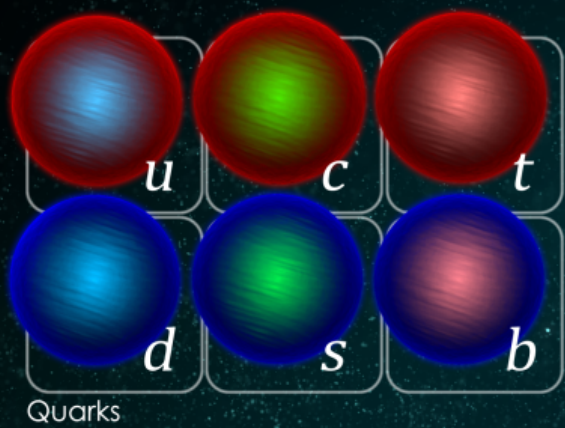


some structures in the Standard Model emerge
from a transplanckian regime with quantum gravity
that is governed by scale symmetry

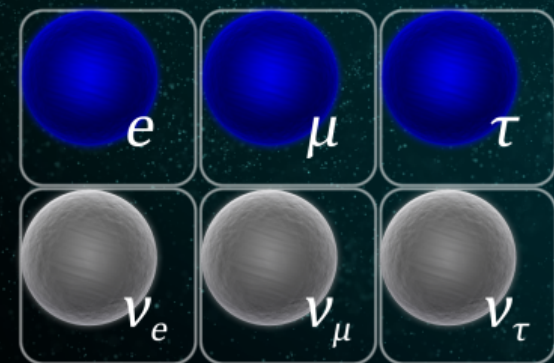
observable physics explained by quantum gravity
 $\leftrightarrow$
quantum gravity testable by observable physics



Standard Model



Quarks



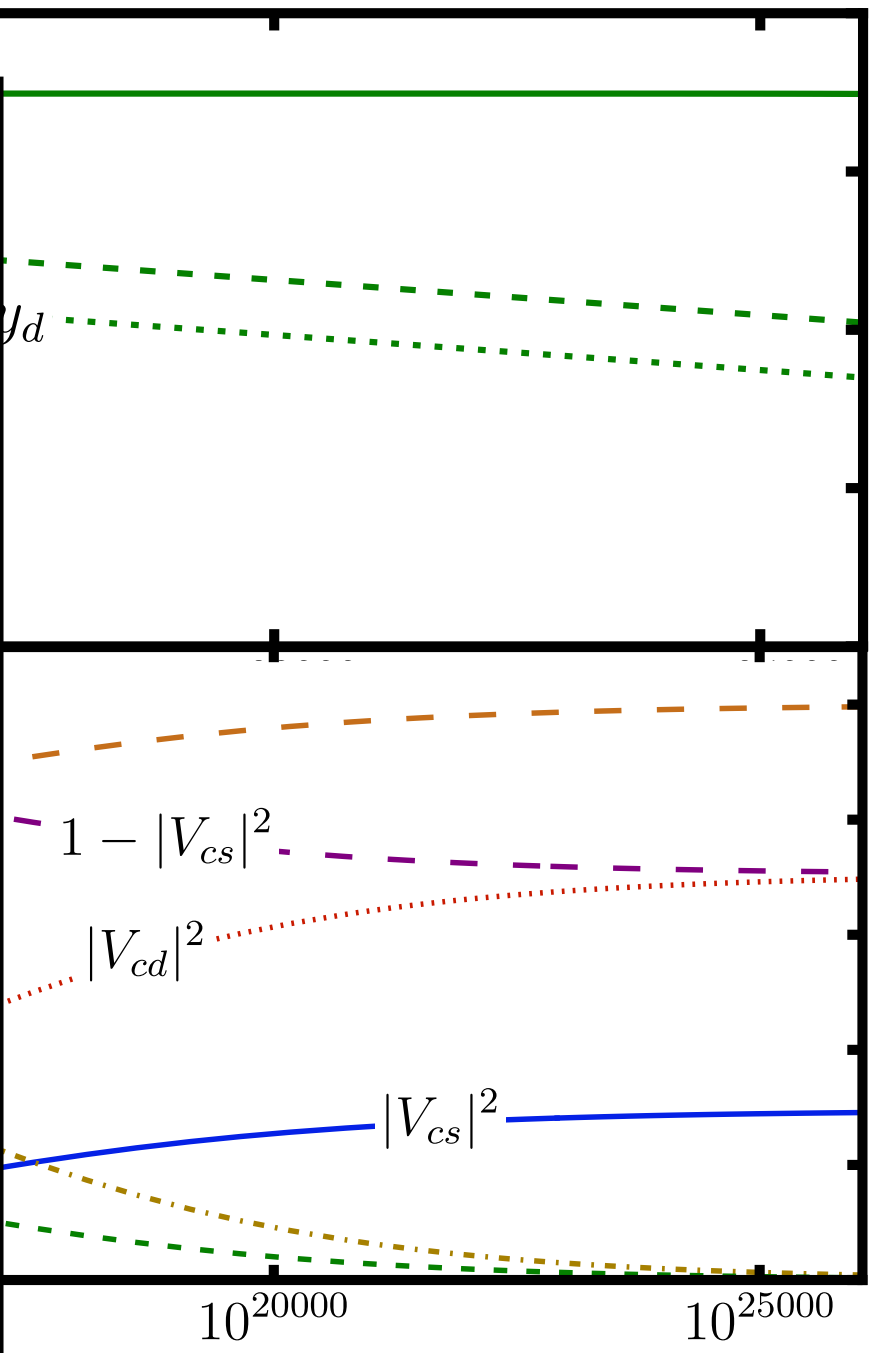
Leptons

Higgs

new paradigm for new physics beyond the Standard Model

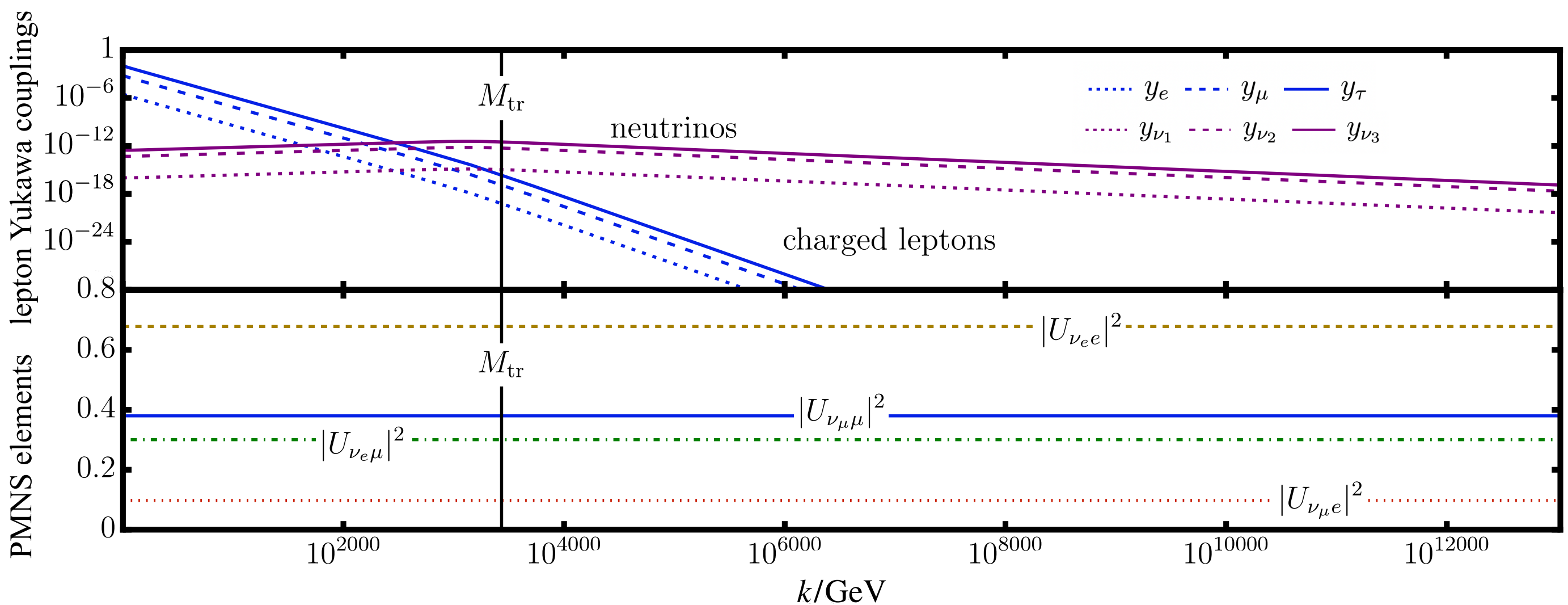
it seems that there is a theoretically viable possibility that there is no new physics over huge range of scales

→ but what about dark matter...?

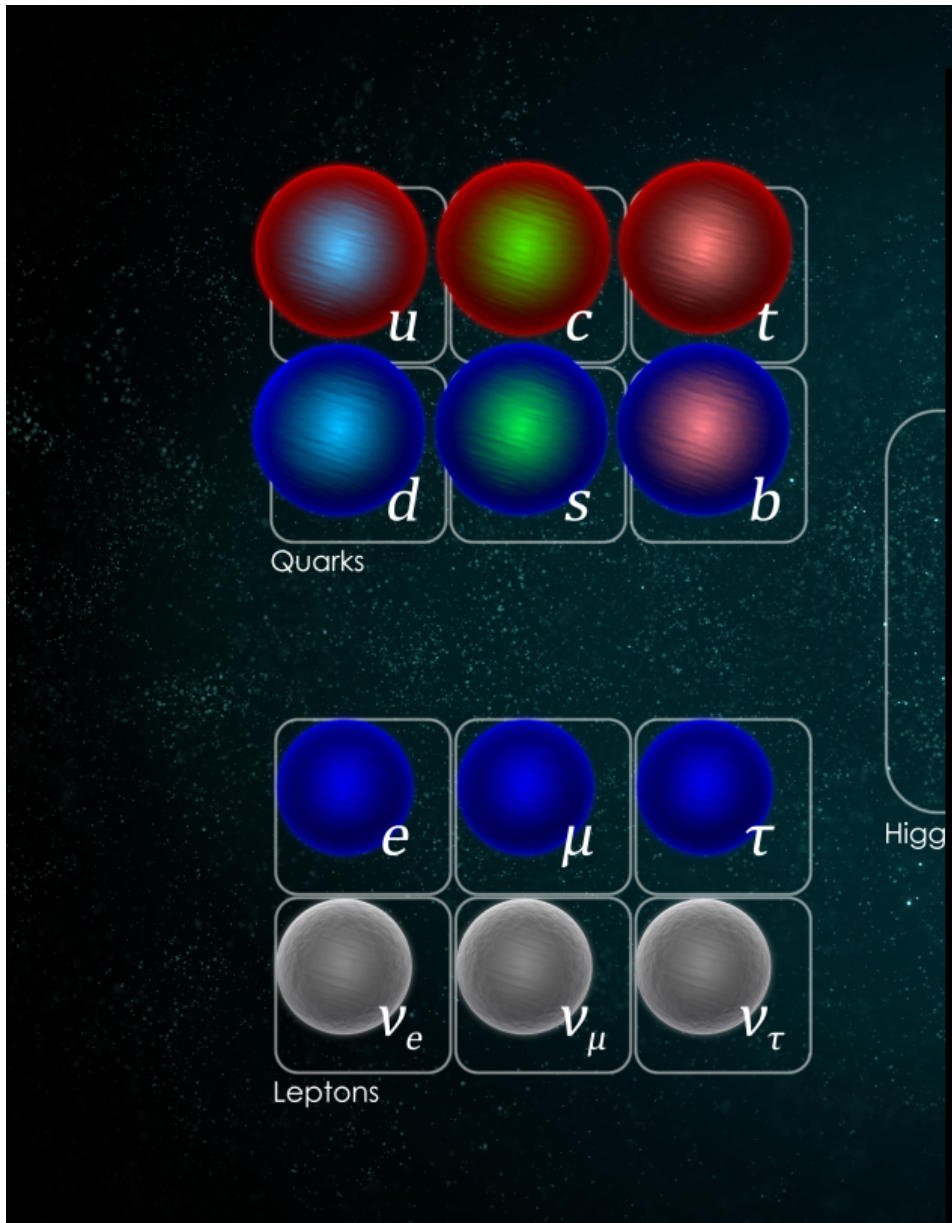


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observable physics explained by quantum gravity ↔ quantum gravity testable by observable physics



Standard Model



new paradigm for new physics beyond the Standard Model

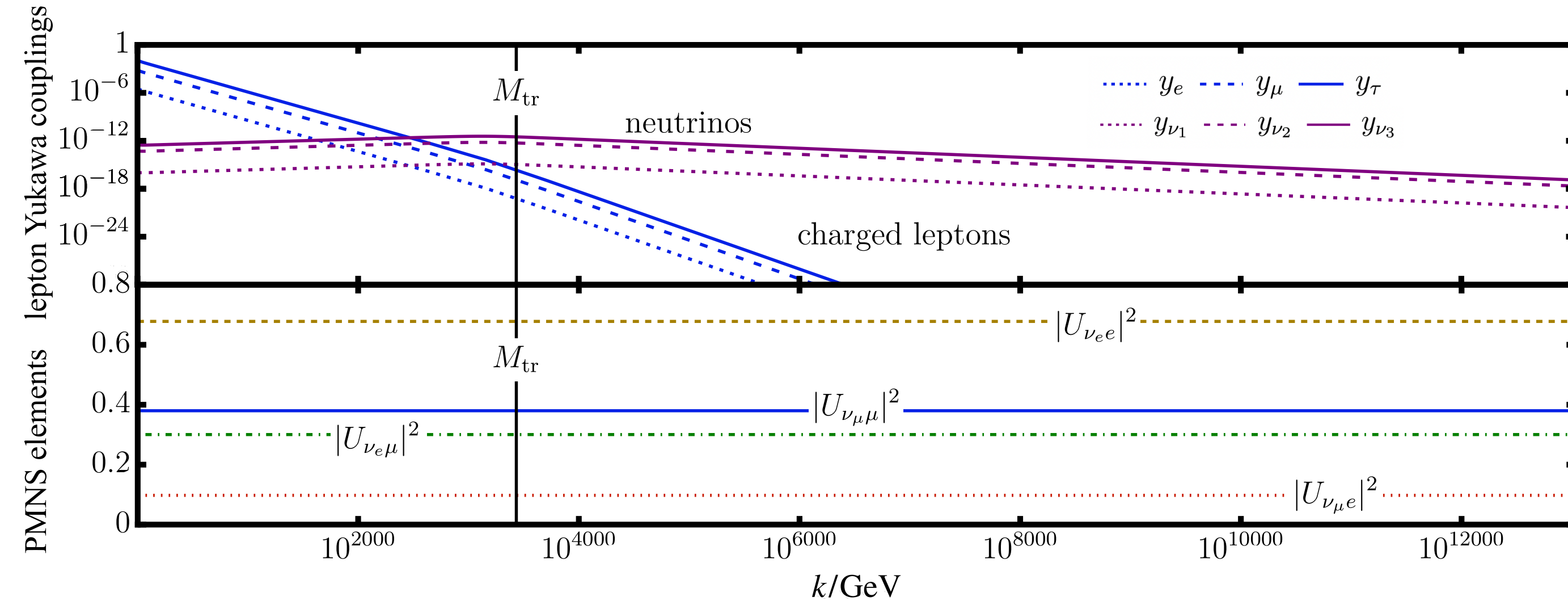
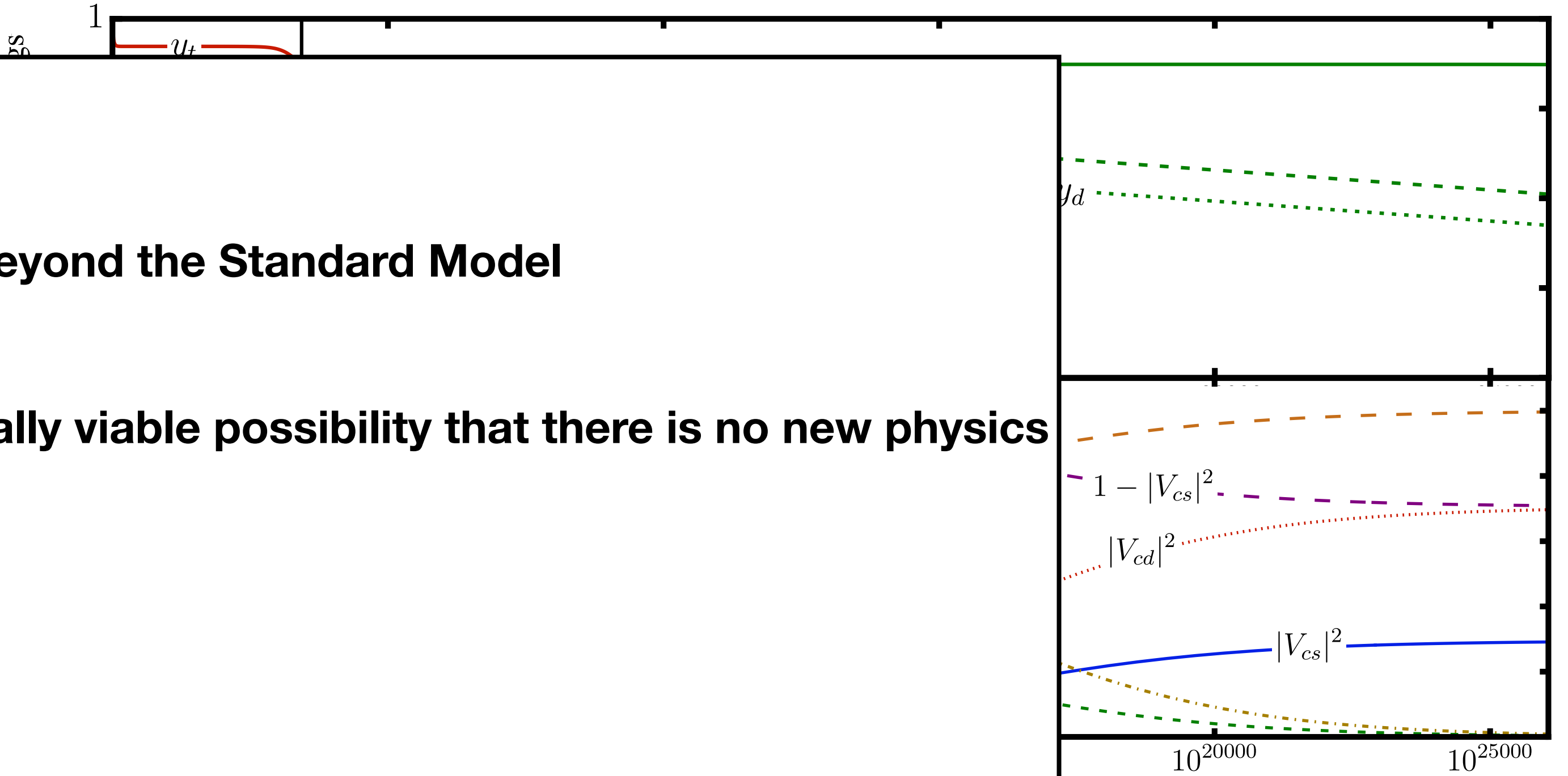
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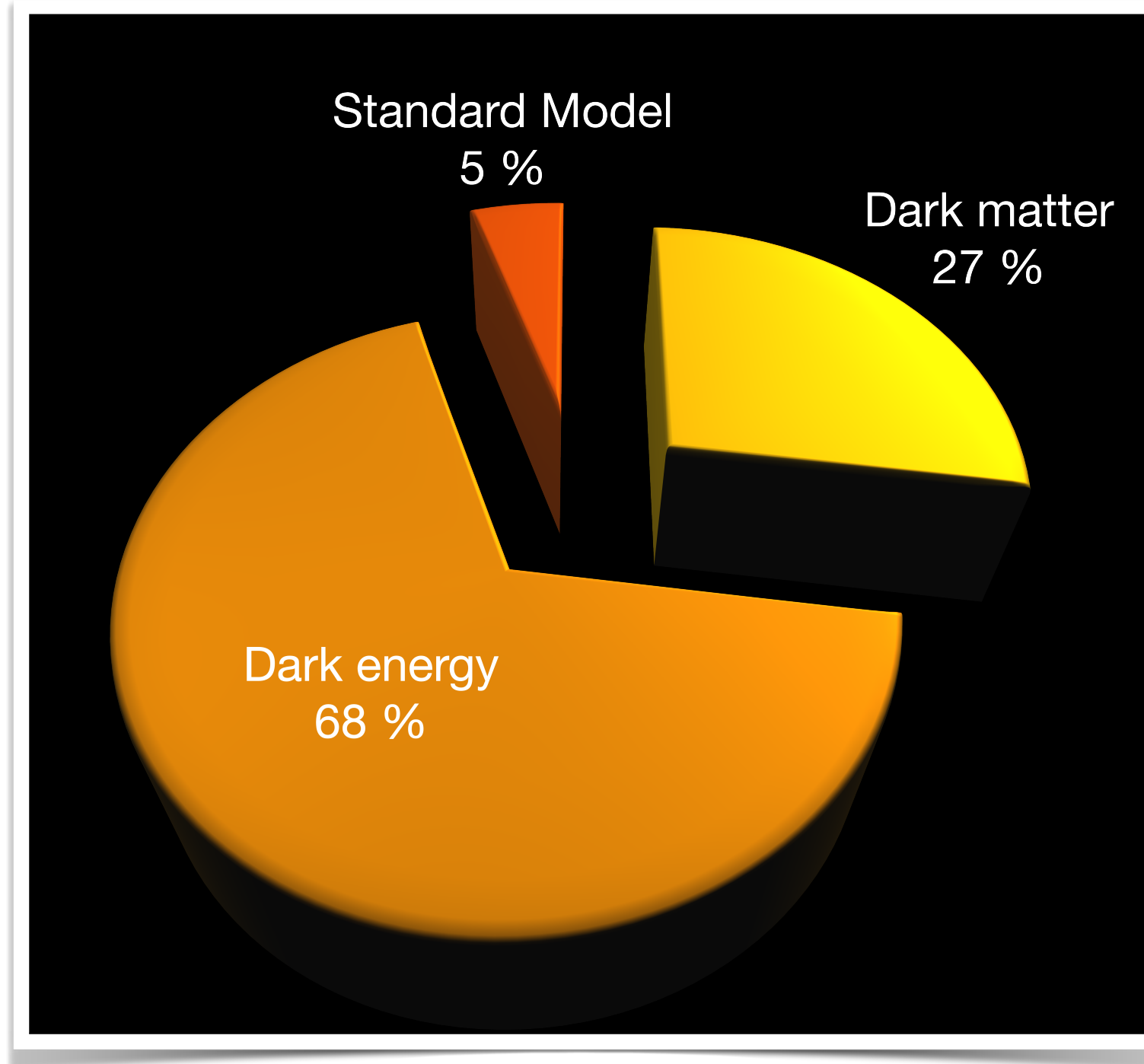
observable physics explained by quantum gravity



quantum gravity testable by observable physics



Asymptotic safety and the dark universe

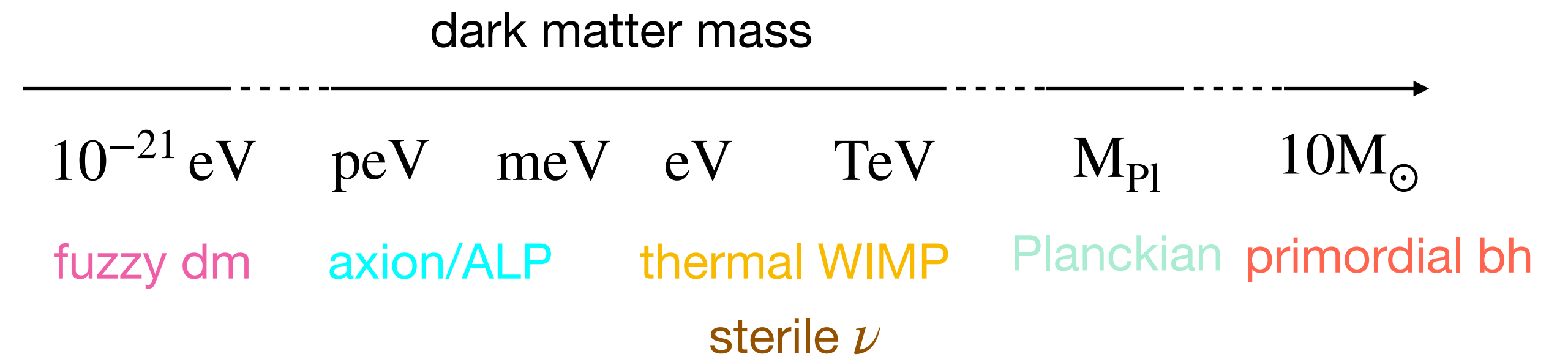
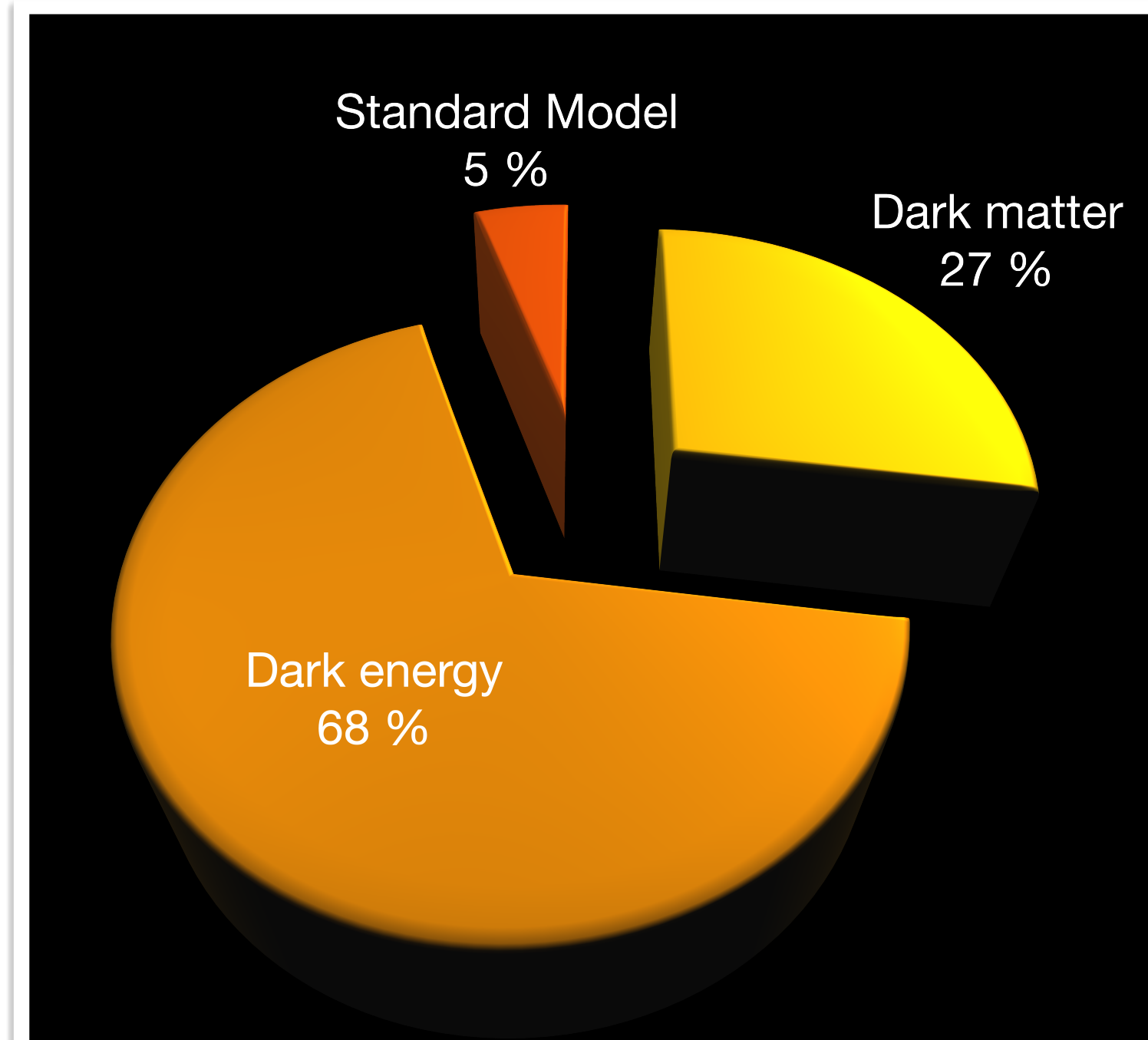


General idea: Use predictive power of asymptotic safety to constrain models of the dark sector

→ to make quantum gravity testable

→ to make dark sector predictive

Asymptotic safety and the dark universe

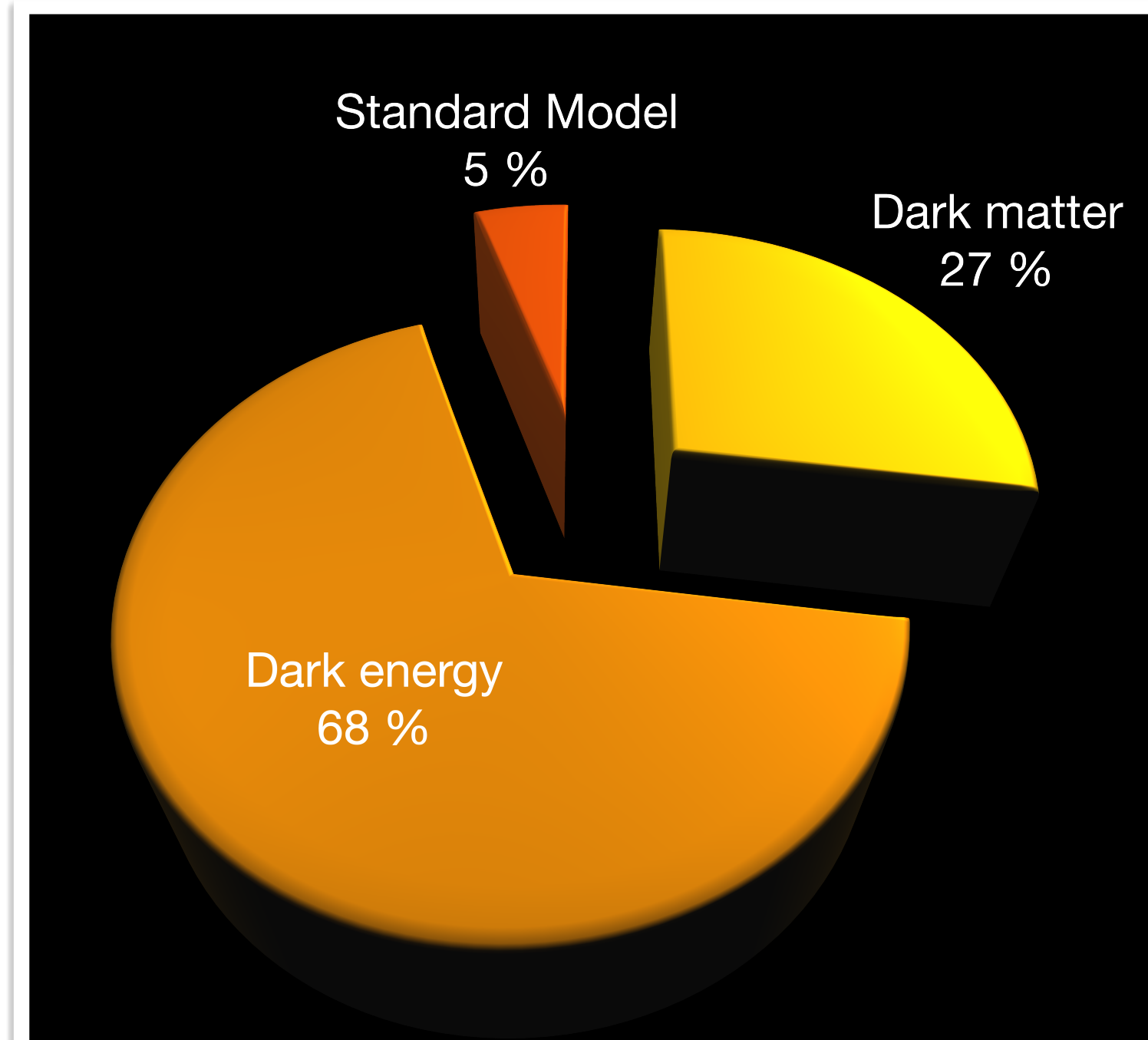


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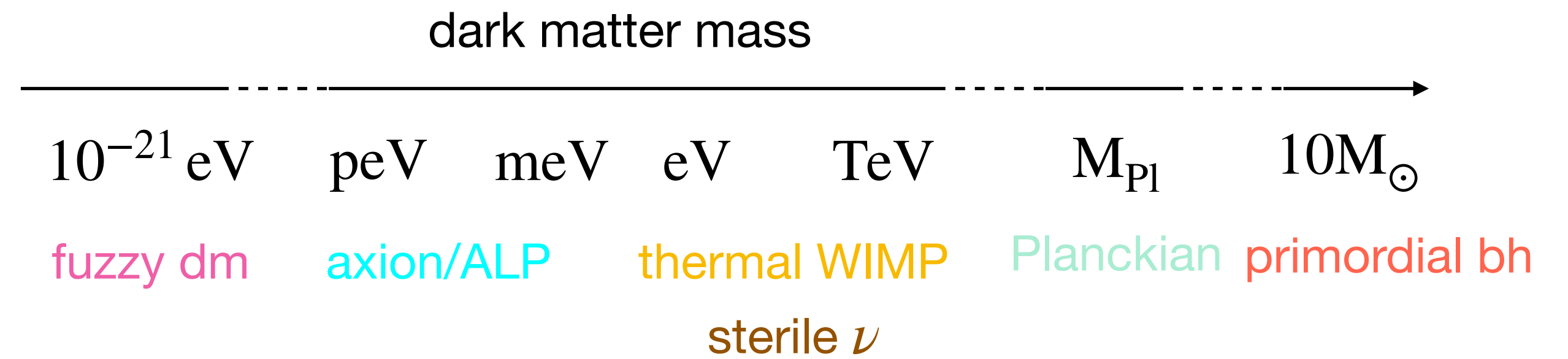
Asymptotic safety and the dark universe



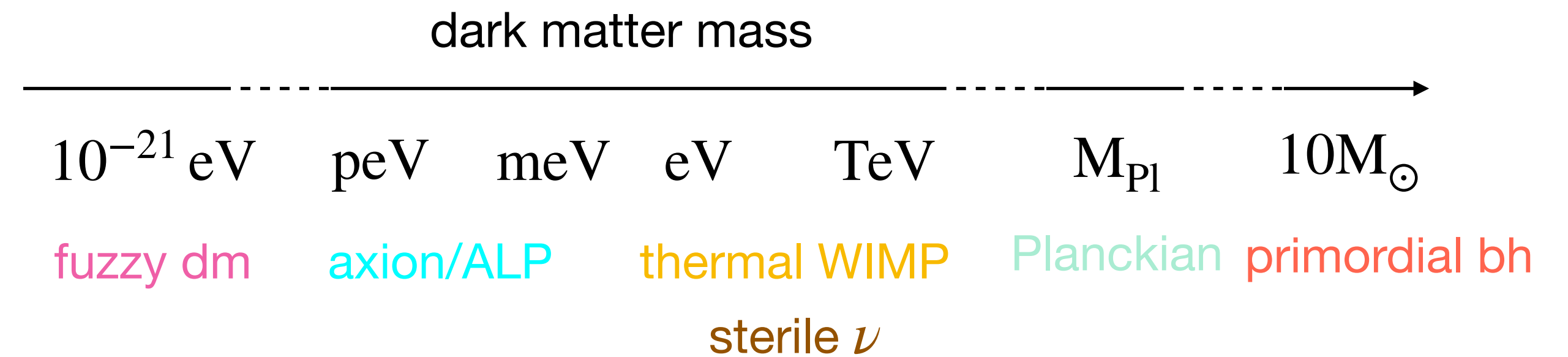
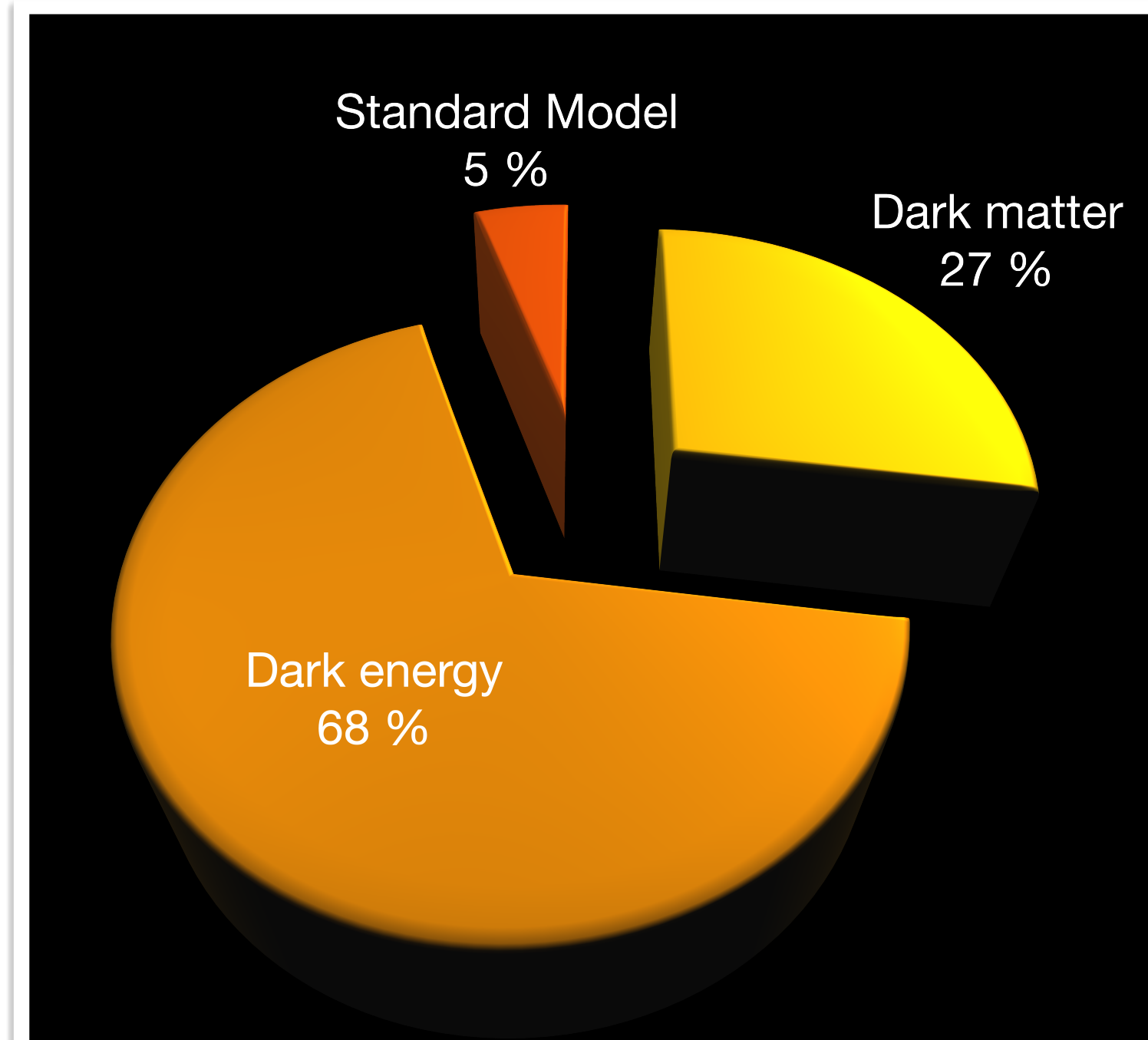
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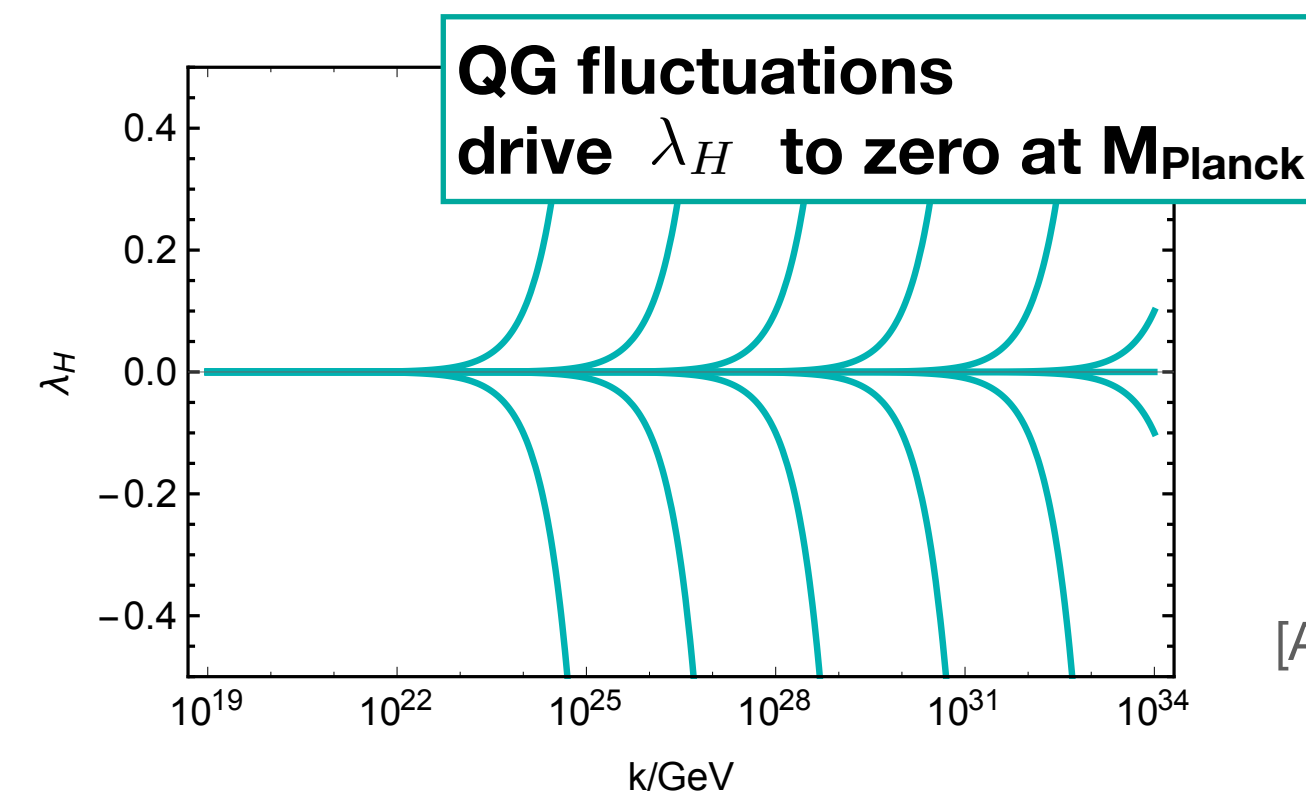


Asymptotic safety and the dark universe



Thermal WIMP:

- Dark scalar with Higgs portal $\lambda_H H^\dagger H \phi^2$



[AE, Hamada, Lumma, Yamada '17]

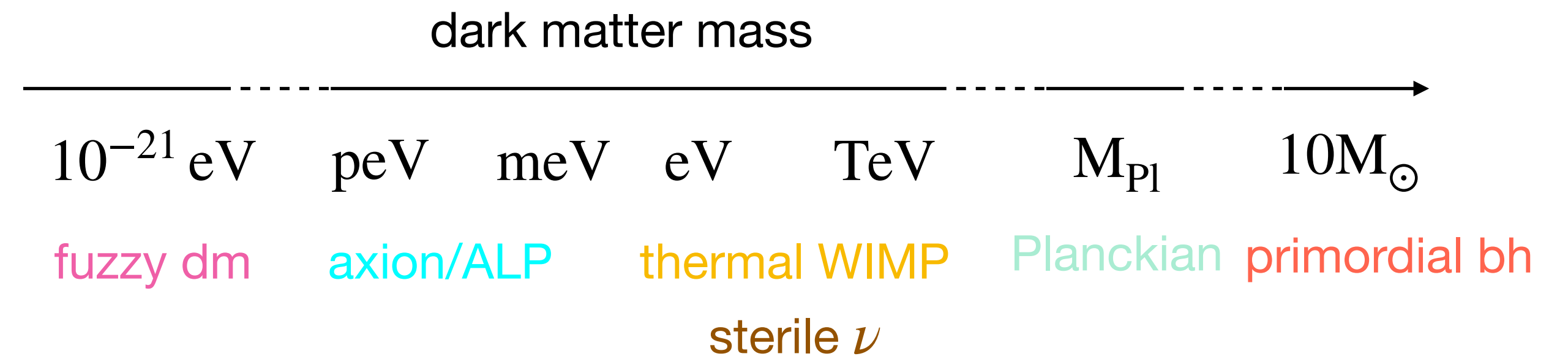
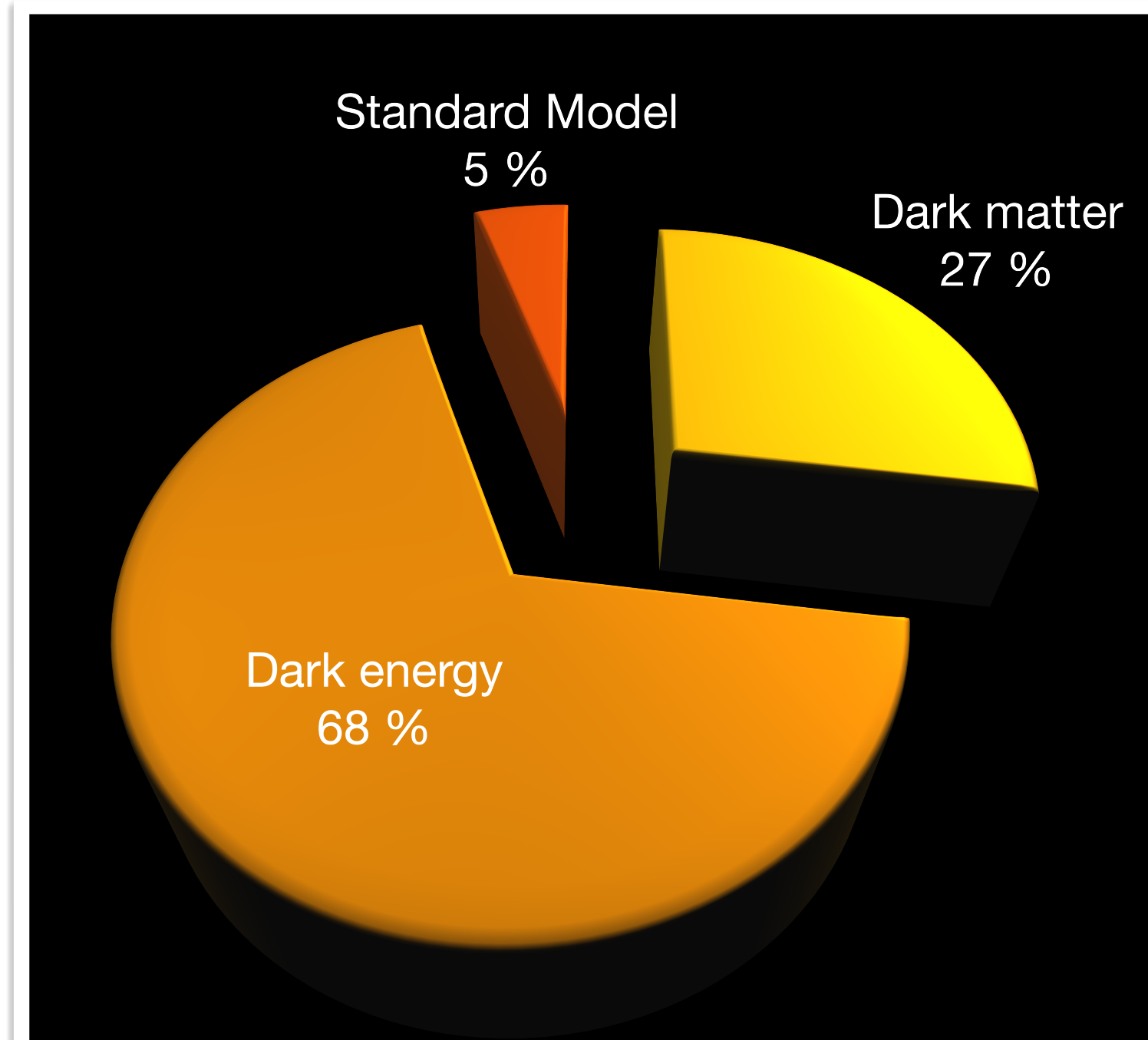
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→ single dark scalar decouples in asymptotic safety

Asymptotic safety and the dark universe



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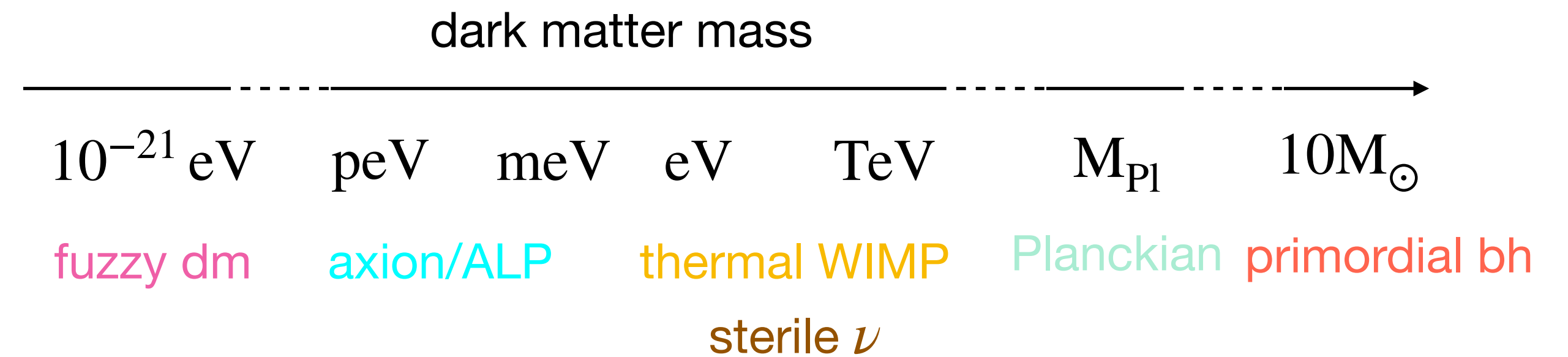
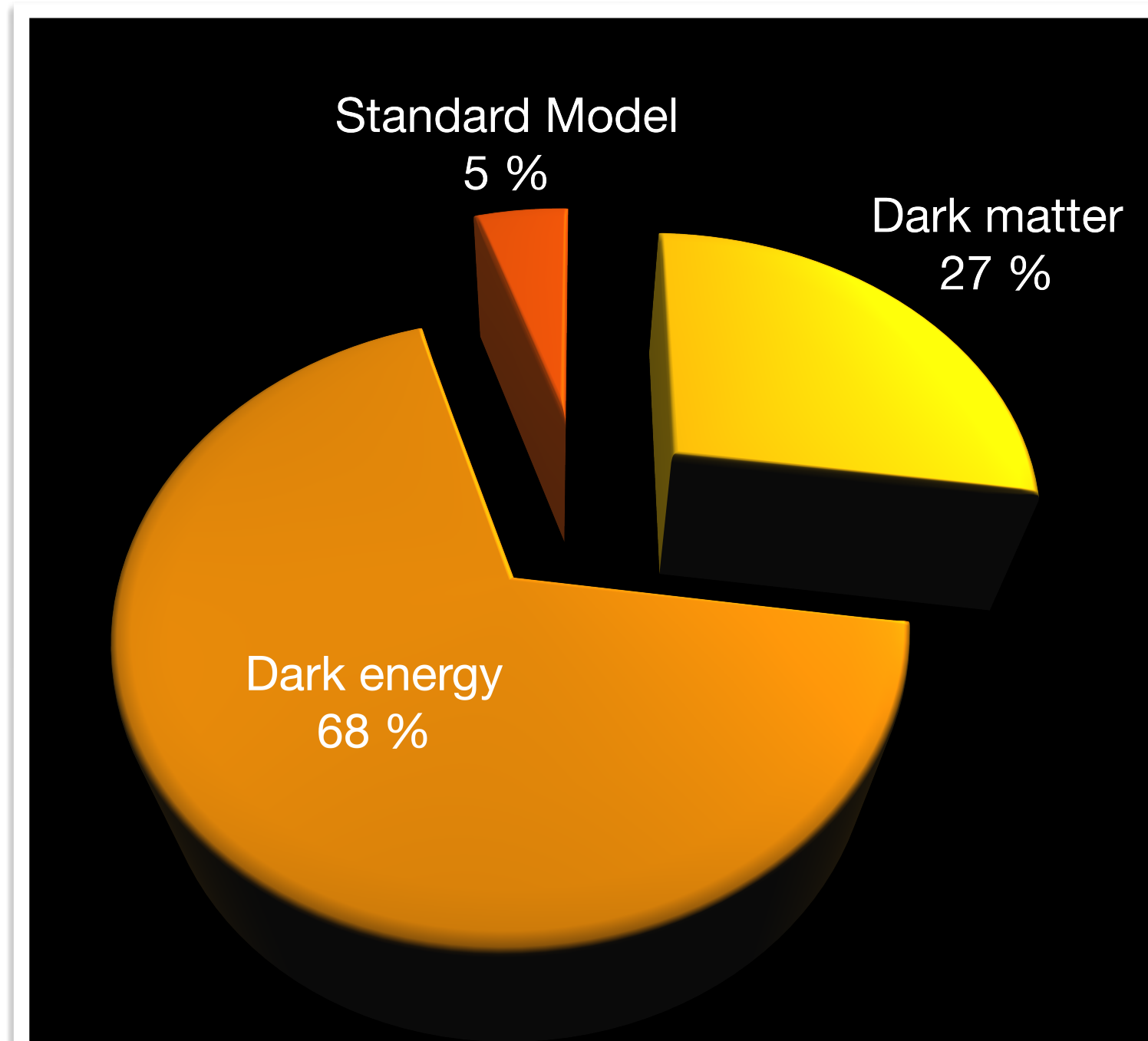
- Dark scalar with Higgs portal ~~$\lambda_H H^\dagger H \phi^2$~~ [AE, Hamada, Lumma, Yamada '17]

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Asymptotic safety and the dark universe



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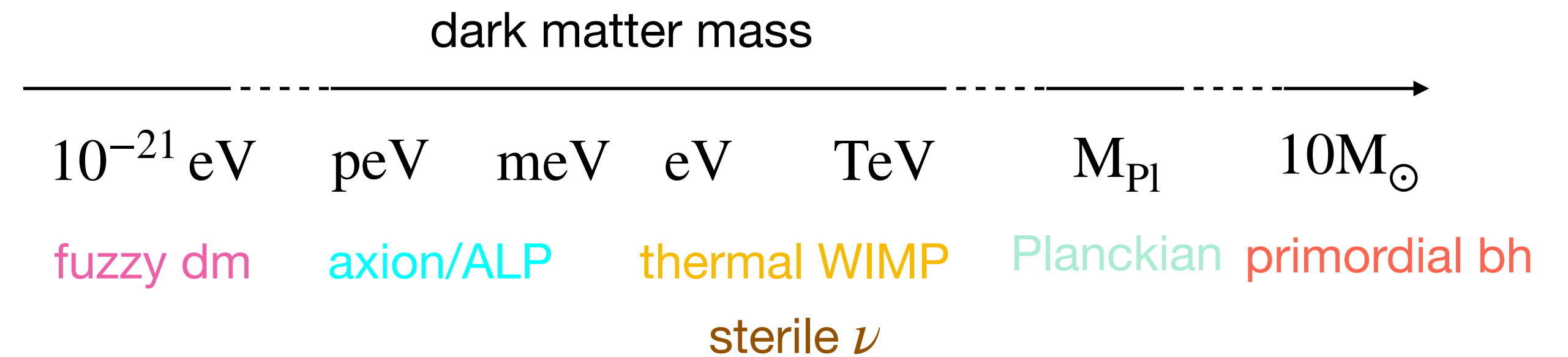
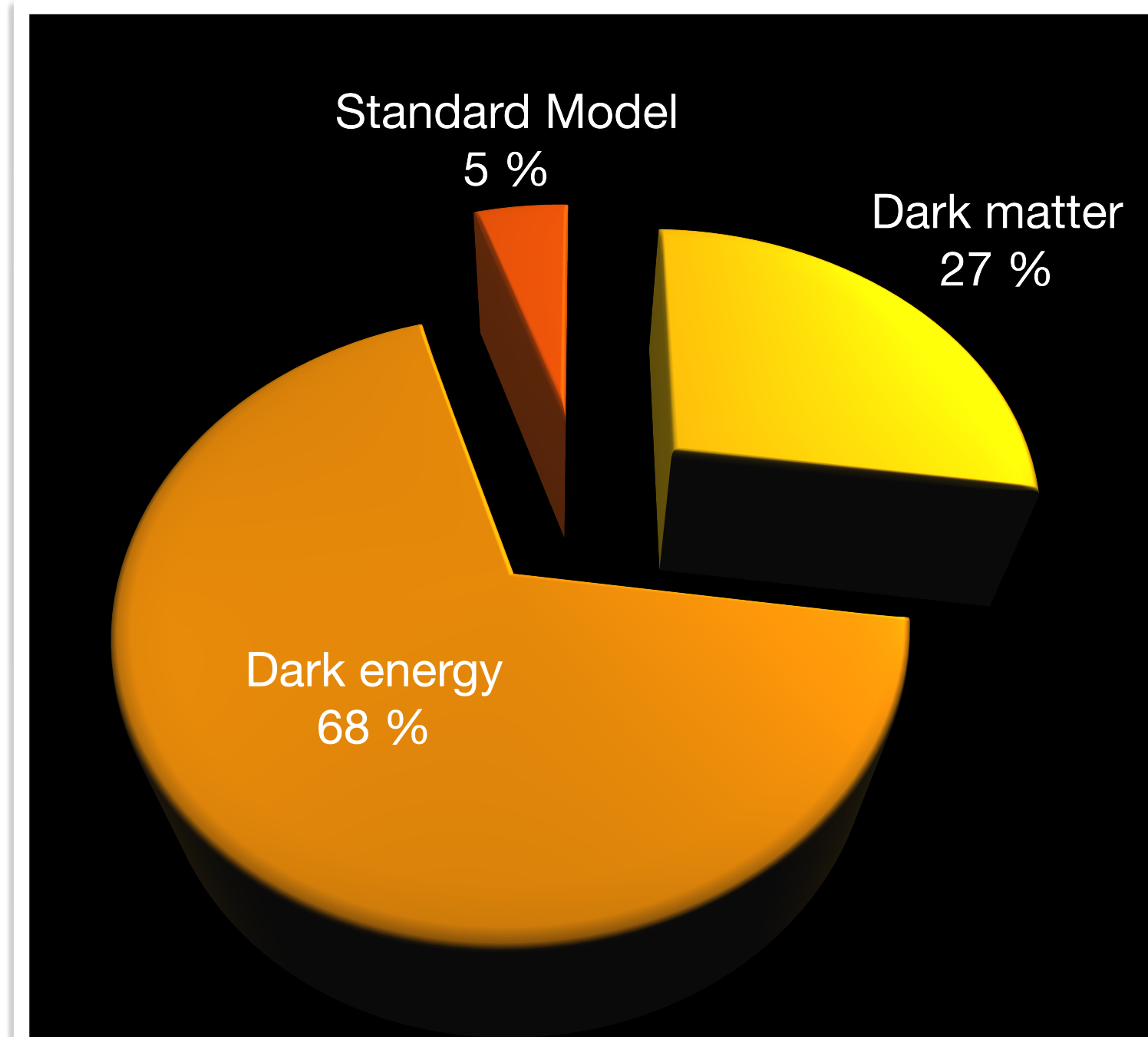
- **Dark scalar with Higgs portal** ~~$\lambda_H H^\dagger H \phi^2$~~ [AE, Hamada, Lumma, Yamada '17]
- **Several dark-sector fields: constrained** [Reichert, Smirnov '19; Hamada, Yamada '20; AE, Pauly '21; de Brito, AE, Frandsen et al. '23]

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Axion-like particles (ALPS):

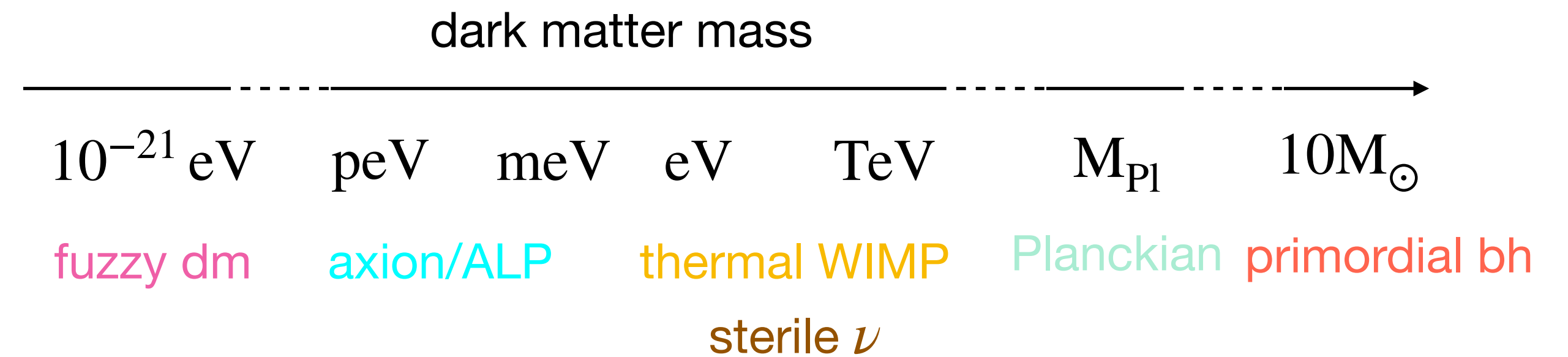
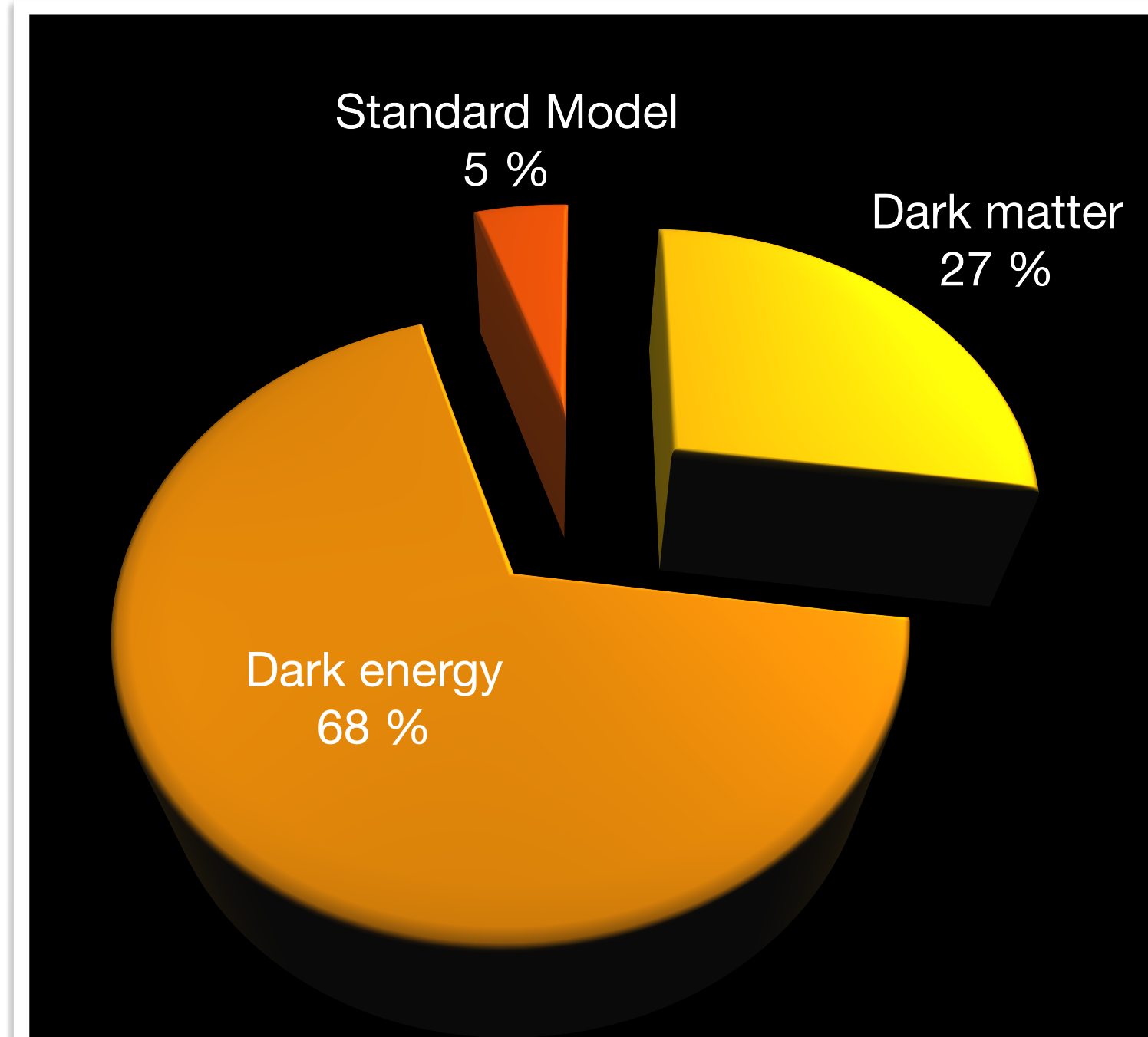
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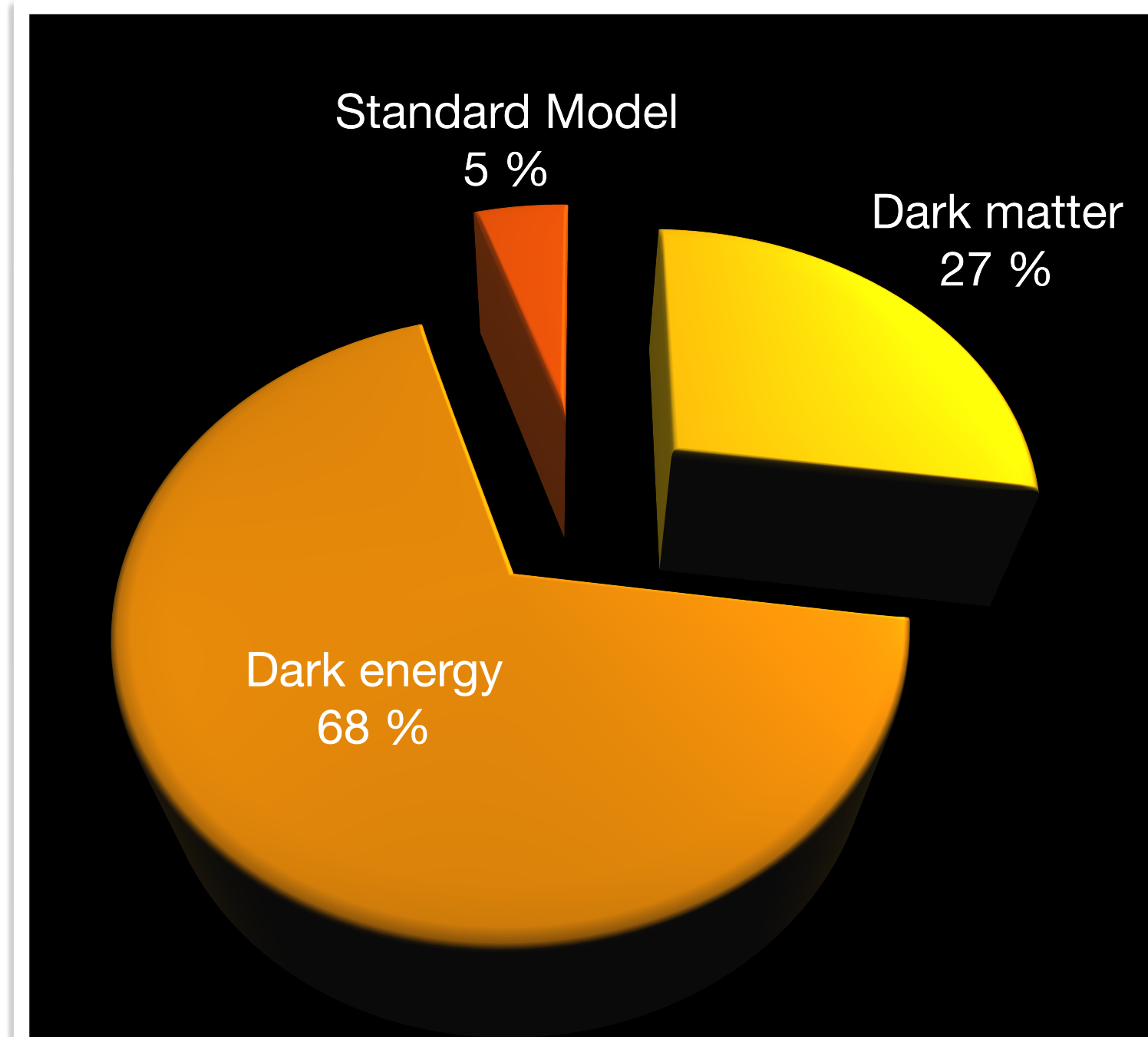
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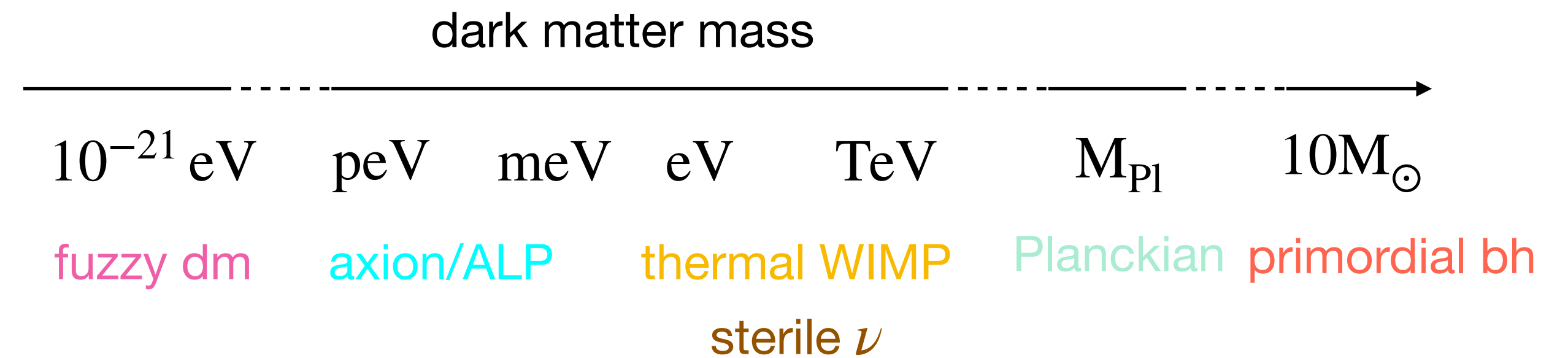
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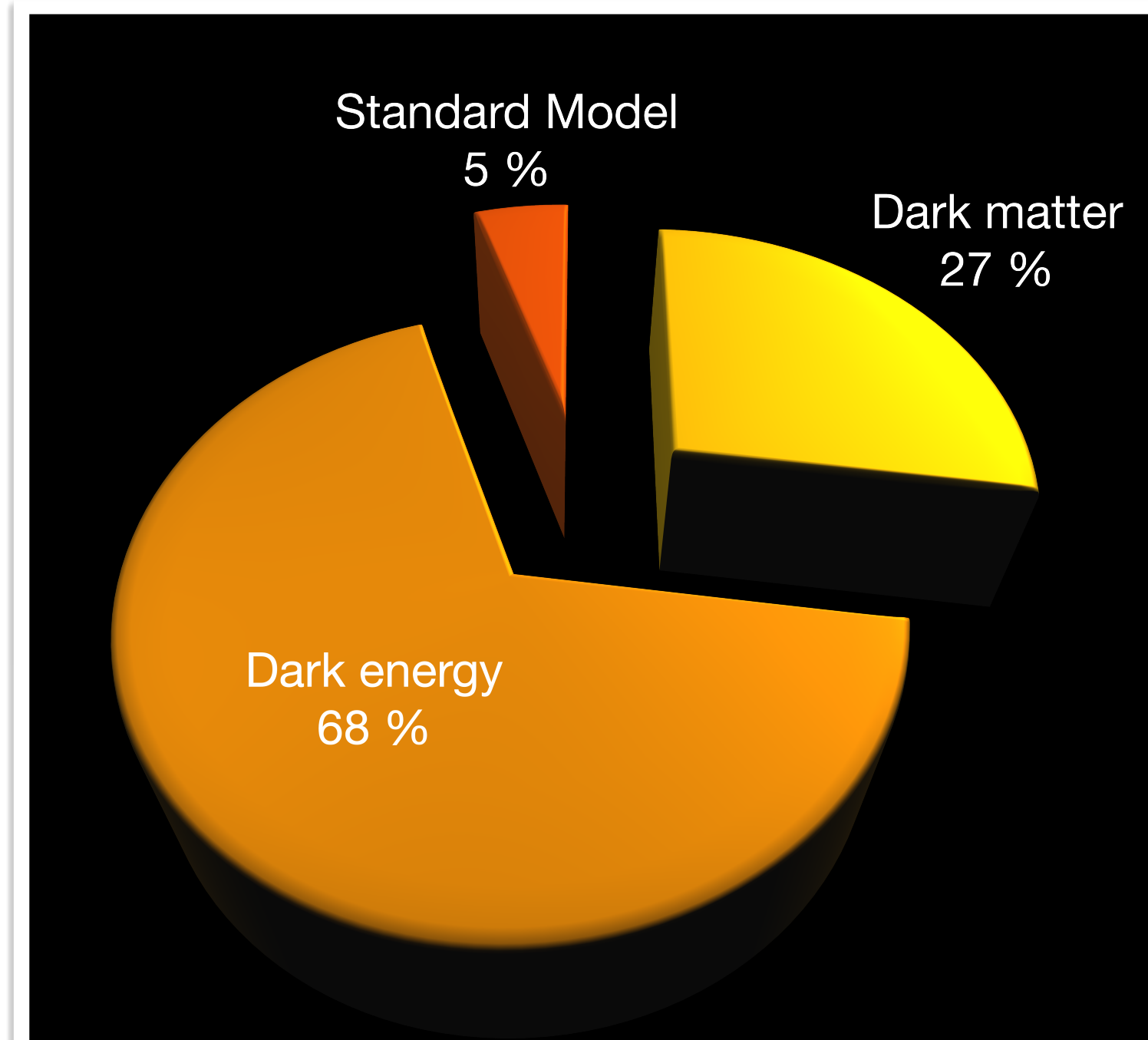
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Ultralight scalar dark matter:

- **Scalar-photon interaction** $\zeta \phi F_{\mu\nu} \widetilde{F}^{\mu\nu}$ [to appear; Assant, AE, Knorr]

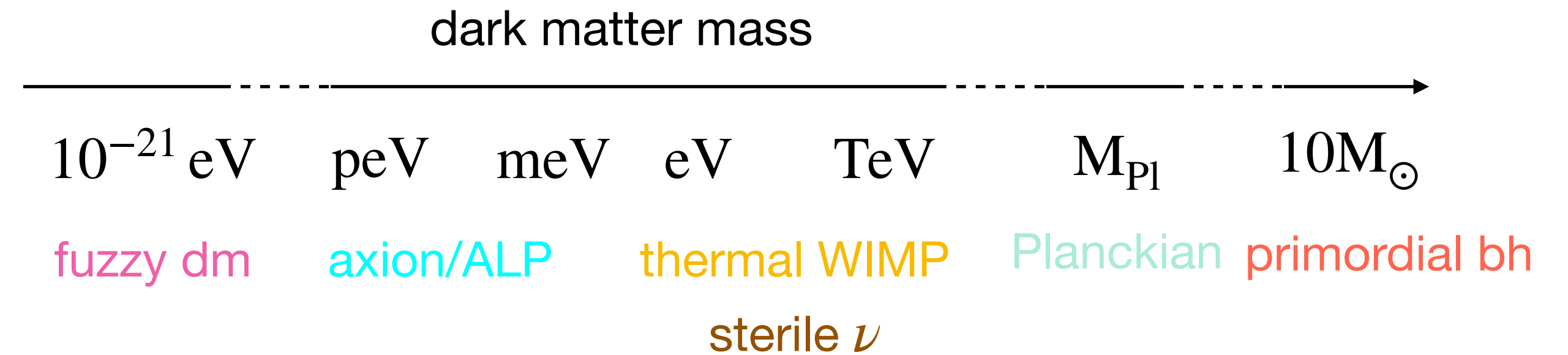
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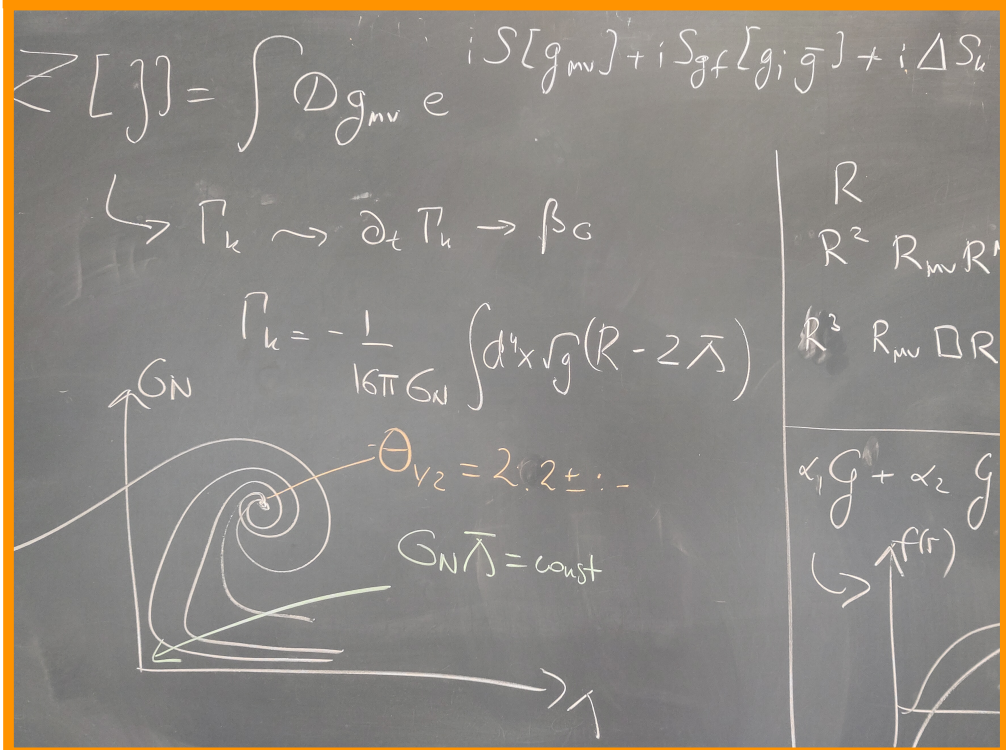
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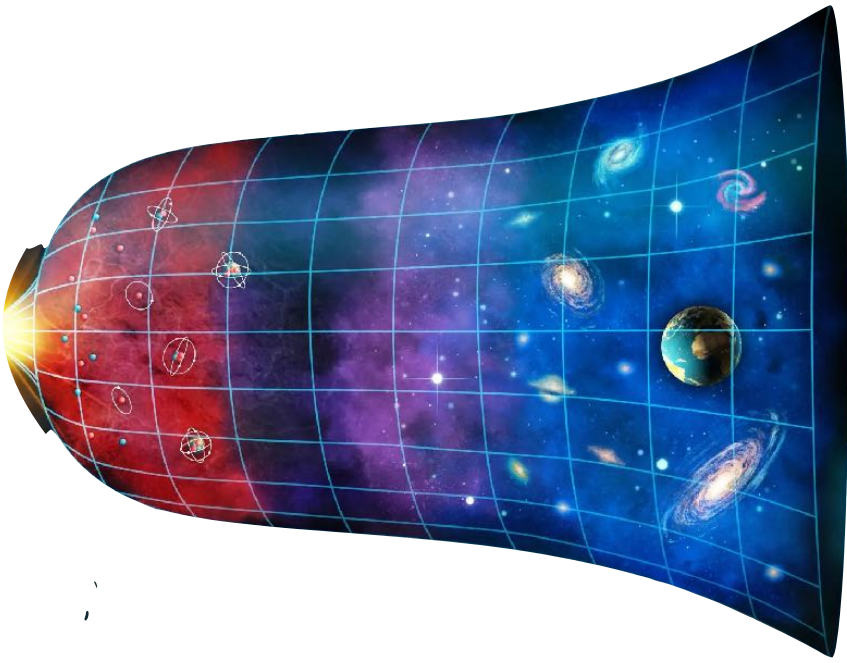
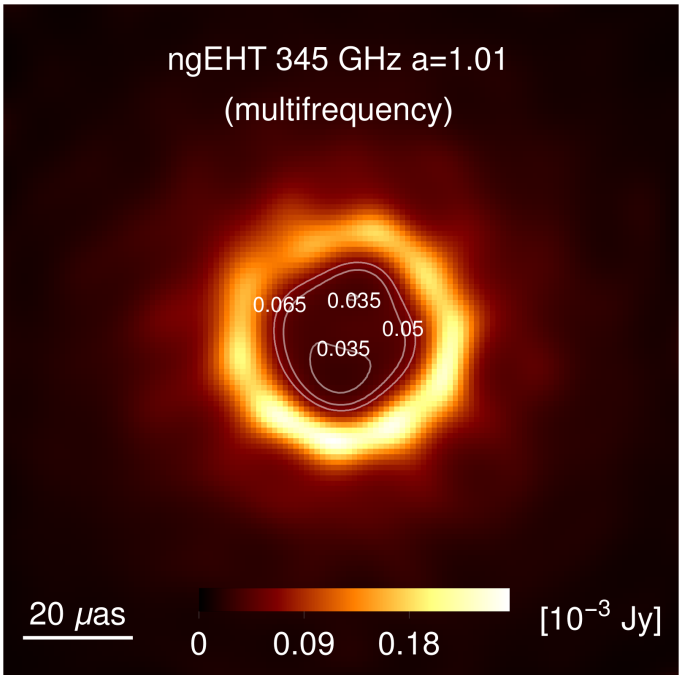
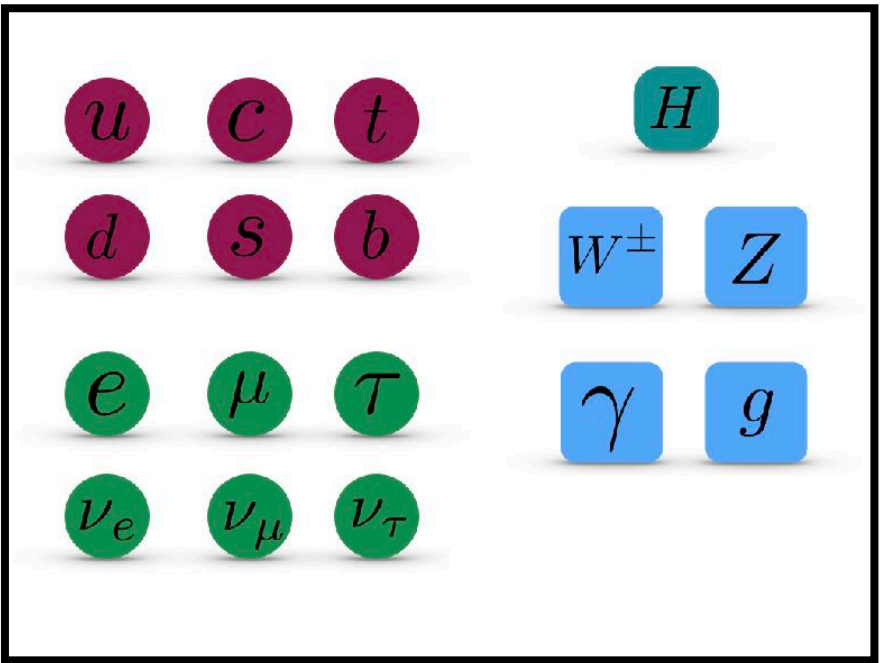
Summary

Theory of quantum gravity



!

Observational tests of quantum gravity



Planckian scales

Particle physics scales

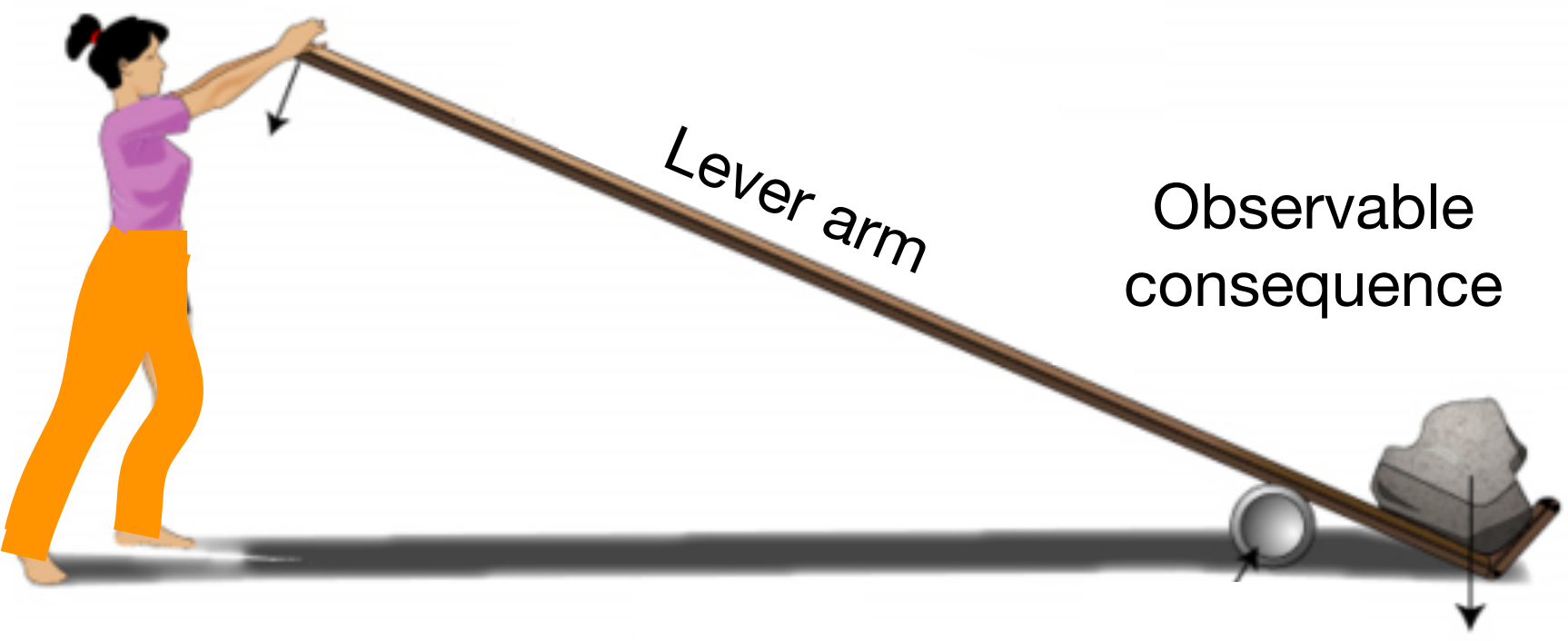
Black-hole scales

Cosmological scales

Key challenge: gap in scales

Key idea: lever arms

Quantum-gravity effect



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:



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Fluminense Federal U., São Paulo State U., Brazil
Brazil



Gustavo P. de Brito,
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São Paulo State U., Brazil



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



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

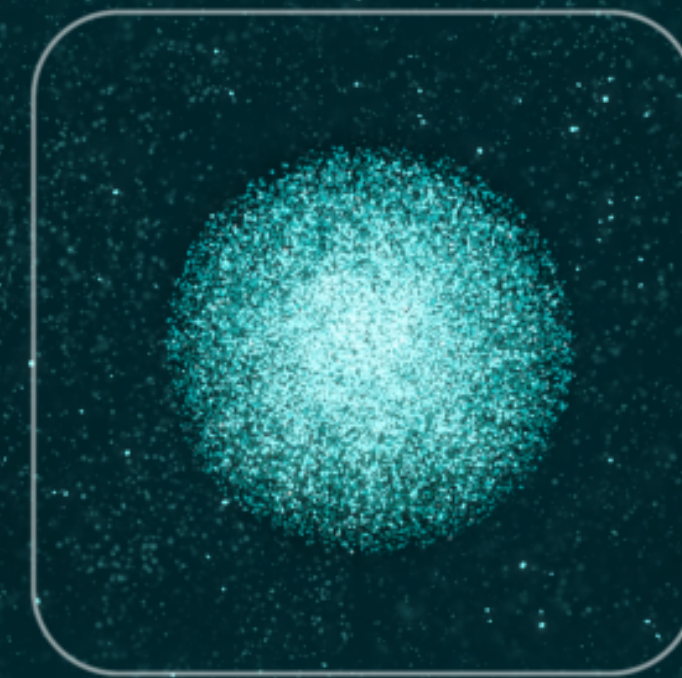
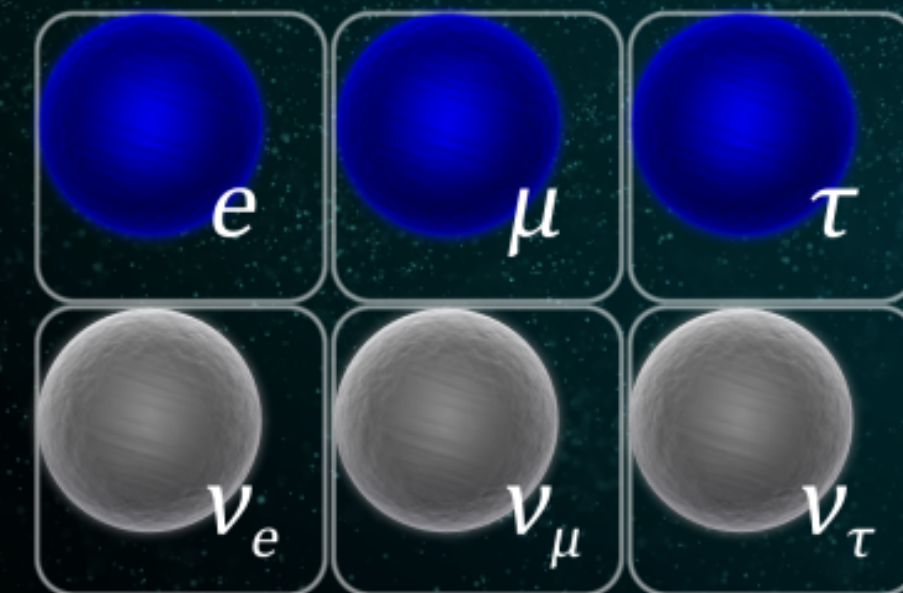
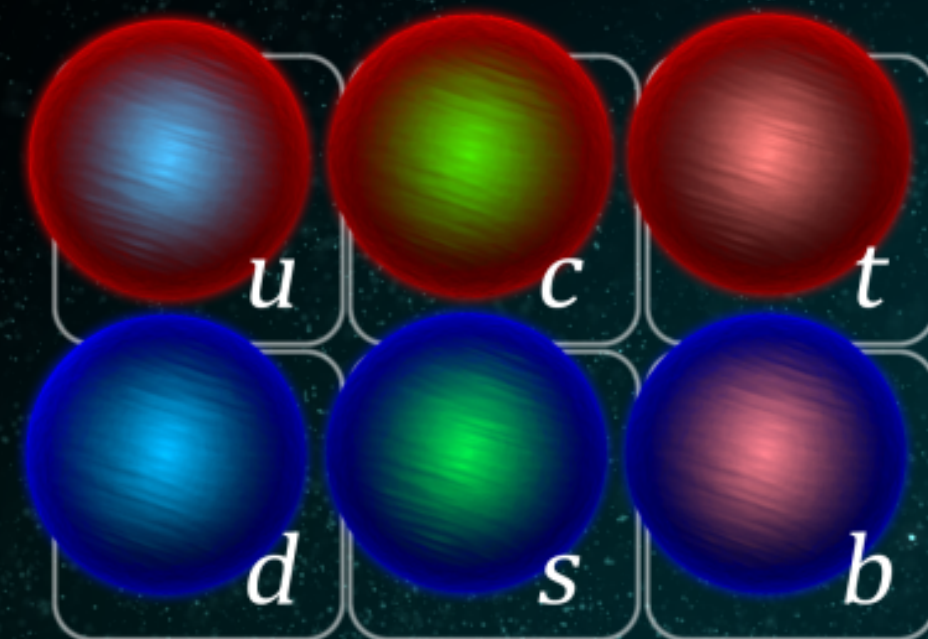


Shouryya Ray
assist. prof.
at U. of Faroe Islands

current group members:

Zois Gyftopoulos (PhD student)
Vanessa Hollmeier (master student)
Tim Eckert (master student)
Sylvester Danos (master student)
Pedro Fernandes (postdoc)
Nawder Stokes (master student)
Moritz Gessner (master/PhD student)
Lukas Bauer (master student)
Lidia Marino (PhD student)
Fabian Willaschek (master student)
Fabian Wagner (postdoc)
Daniele Berruti (master student)
Benjamin Knorr (postdoc)
Alicia Castro (postdoc)

Standard Model couplings



Higgs boson



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

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[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](#)