

Freeze out Freeze in and the Flavon

One model working at two scales

Dedicated to 2023



Theory Workshop



Tom Tong



arXiv: 2307.14972

Co-directed by Rusa Mandal

50th ANNIVERSARY EDITION

CLINT EASTWOOD



**THE
GOOD**

**THE
BAD**

**and THE
UGLY**

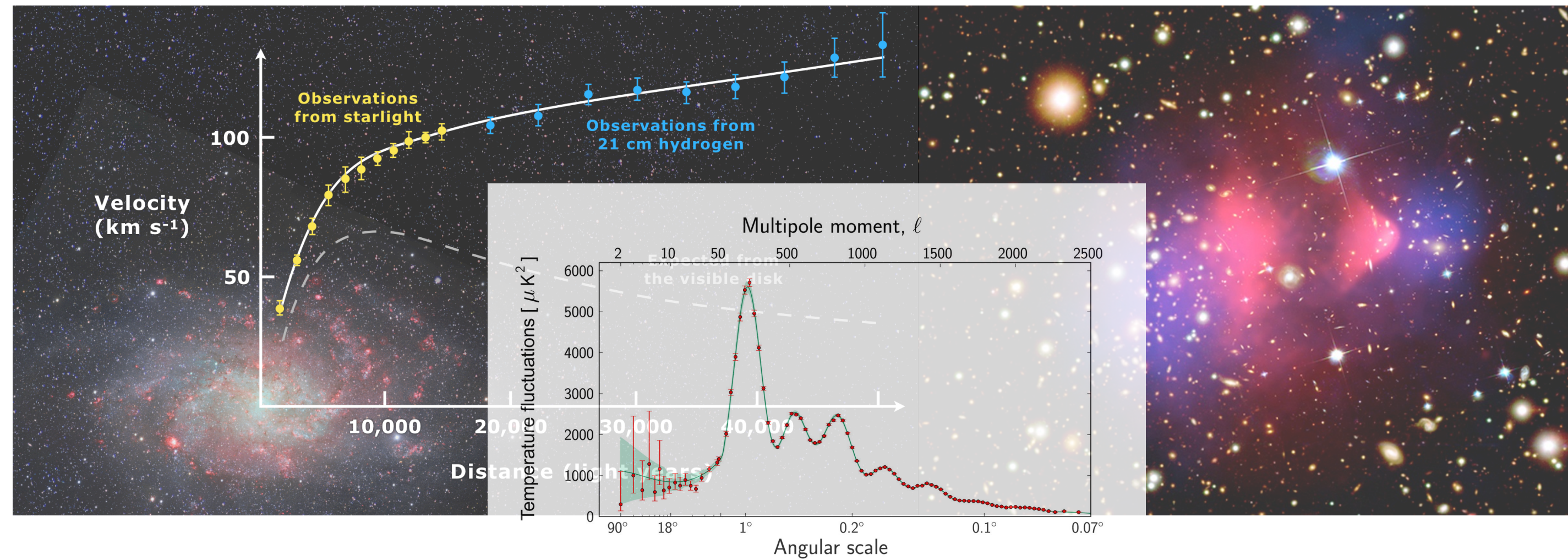
co-starring
LEE VAN CLEEF

also starring
ELI WALLACH
in the role of TUCO

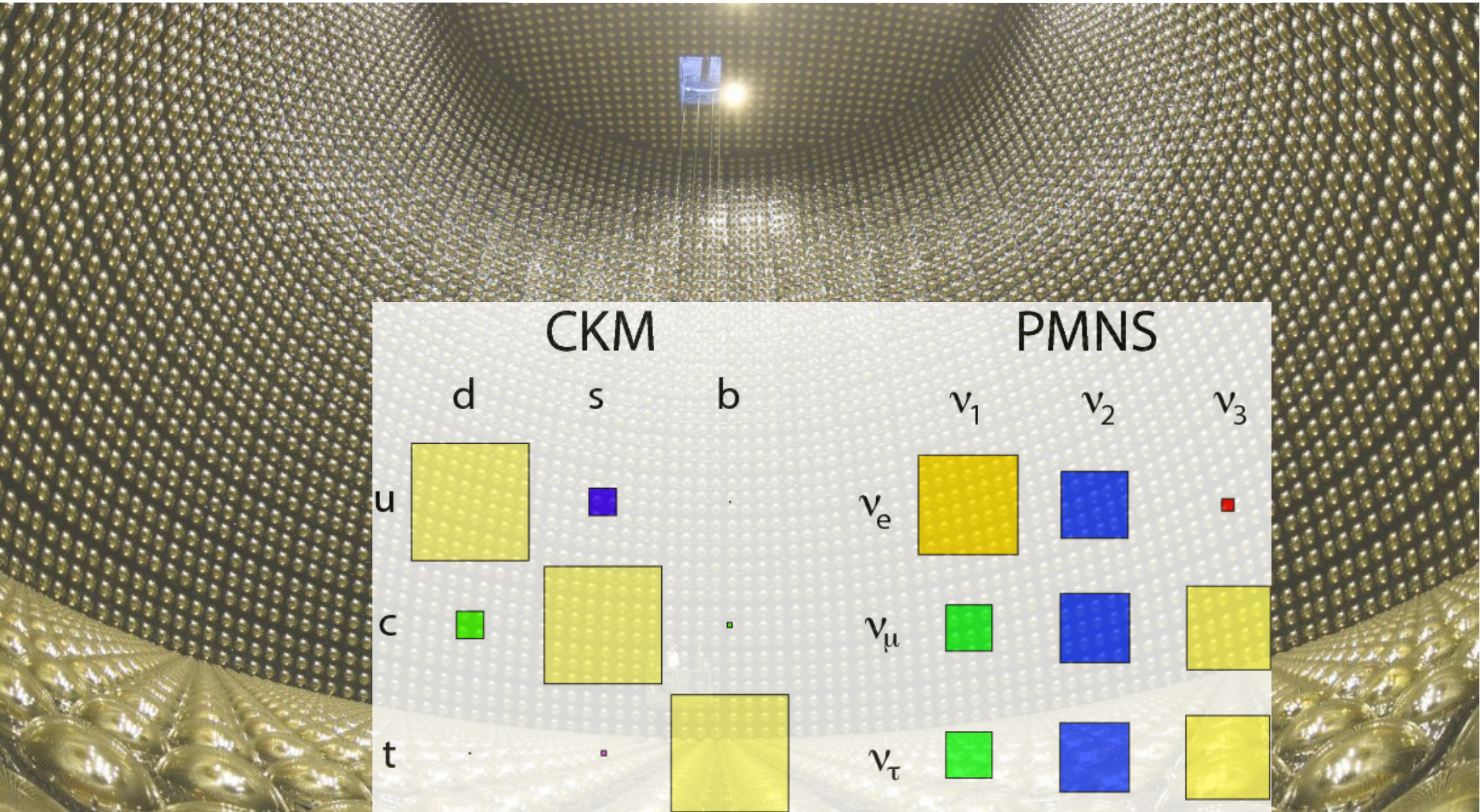
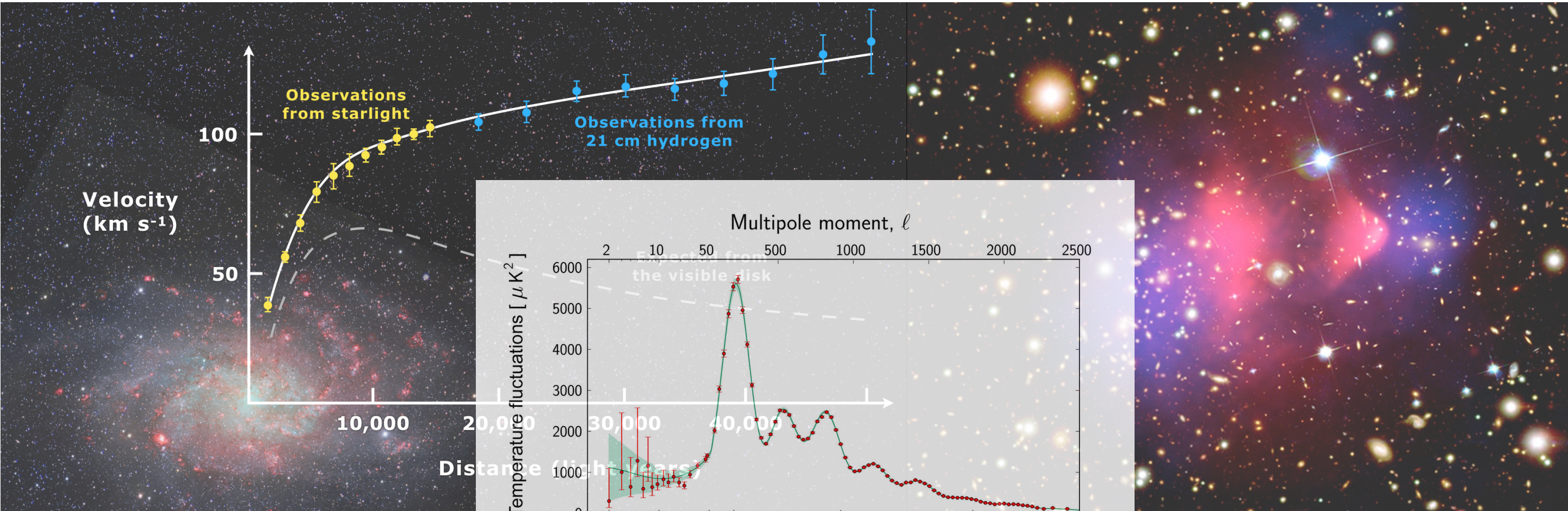
directed by
SERGIO LEONE

Evidence of new physics

Evidence of new physics

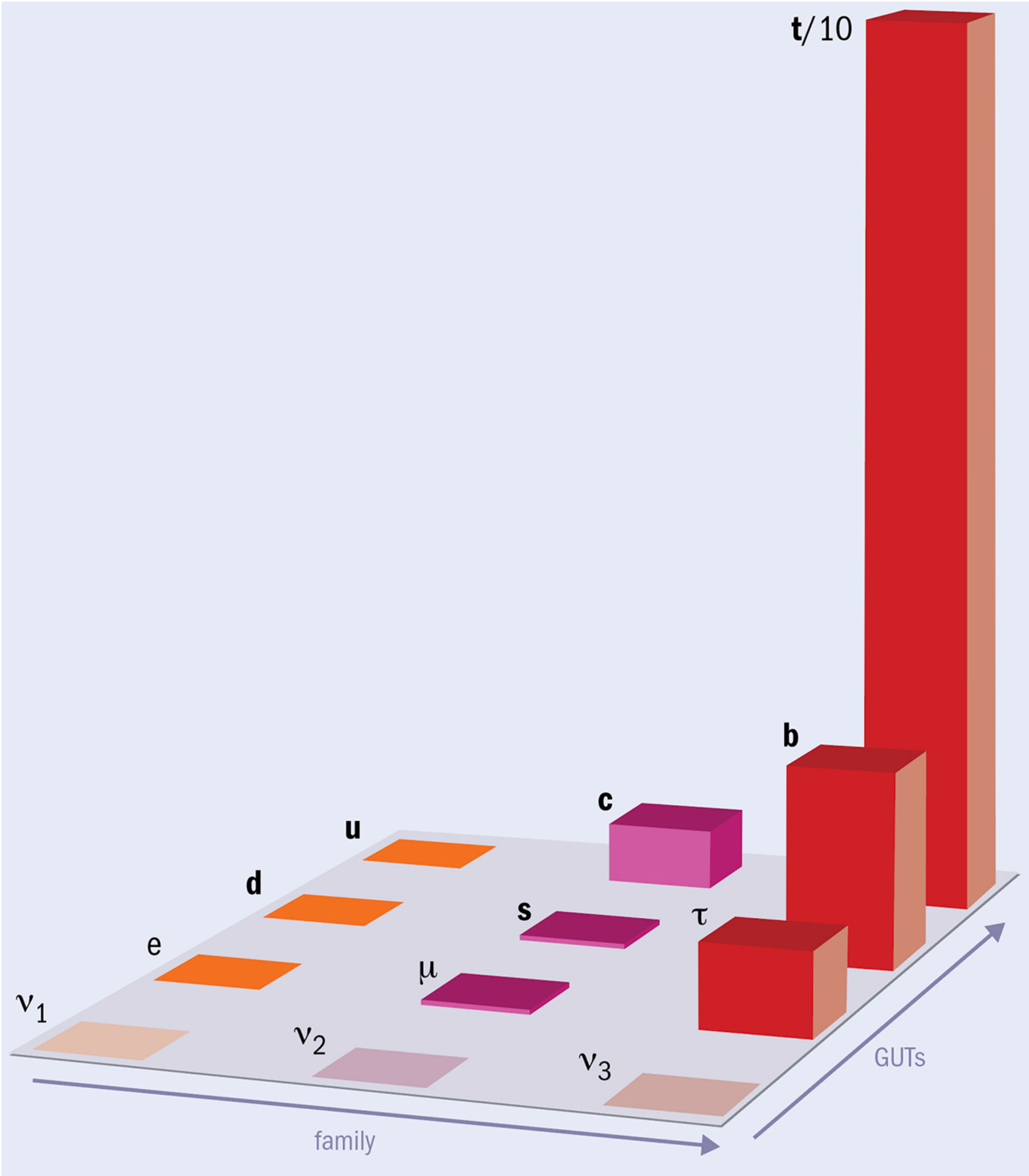
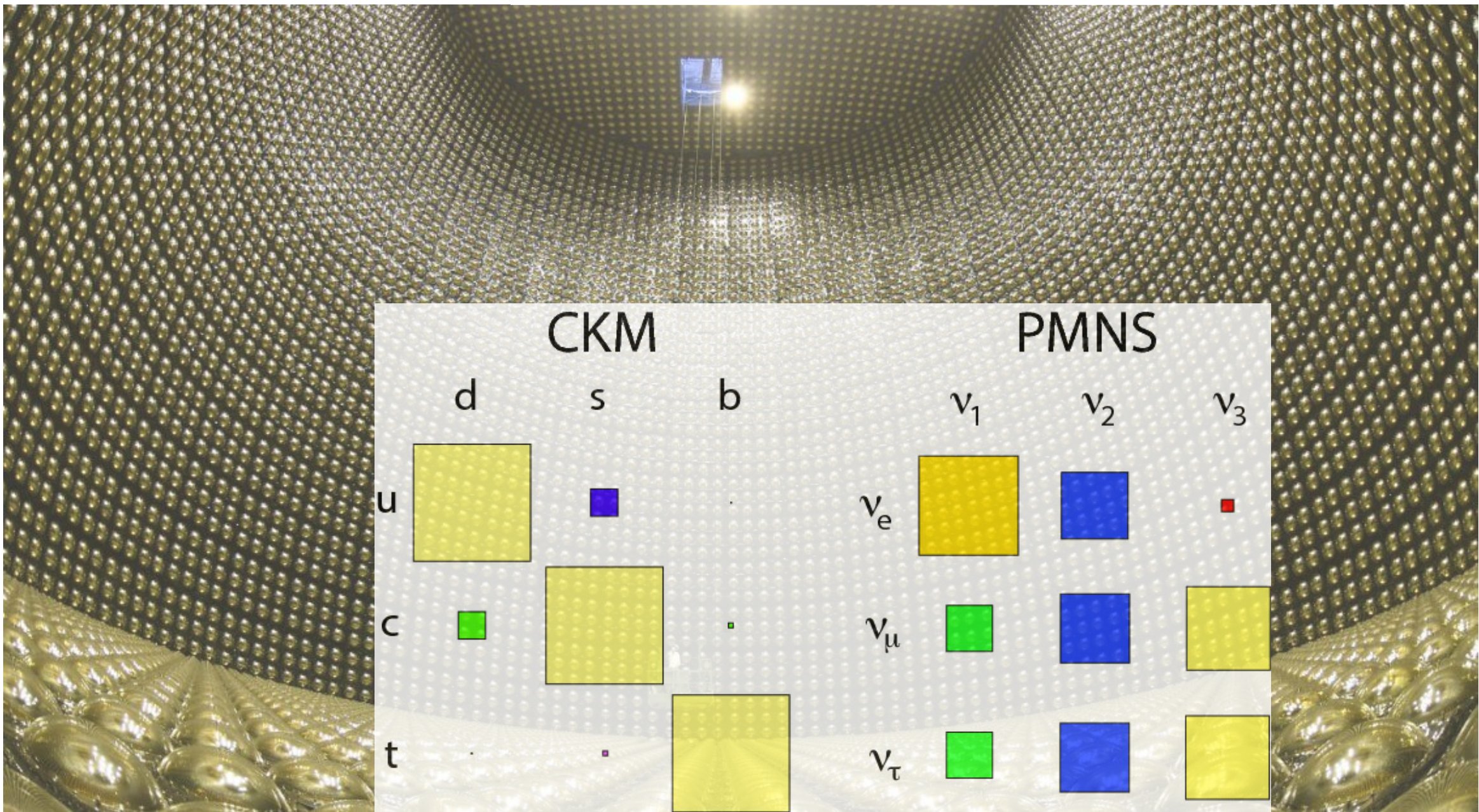
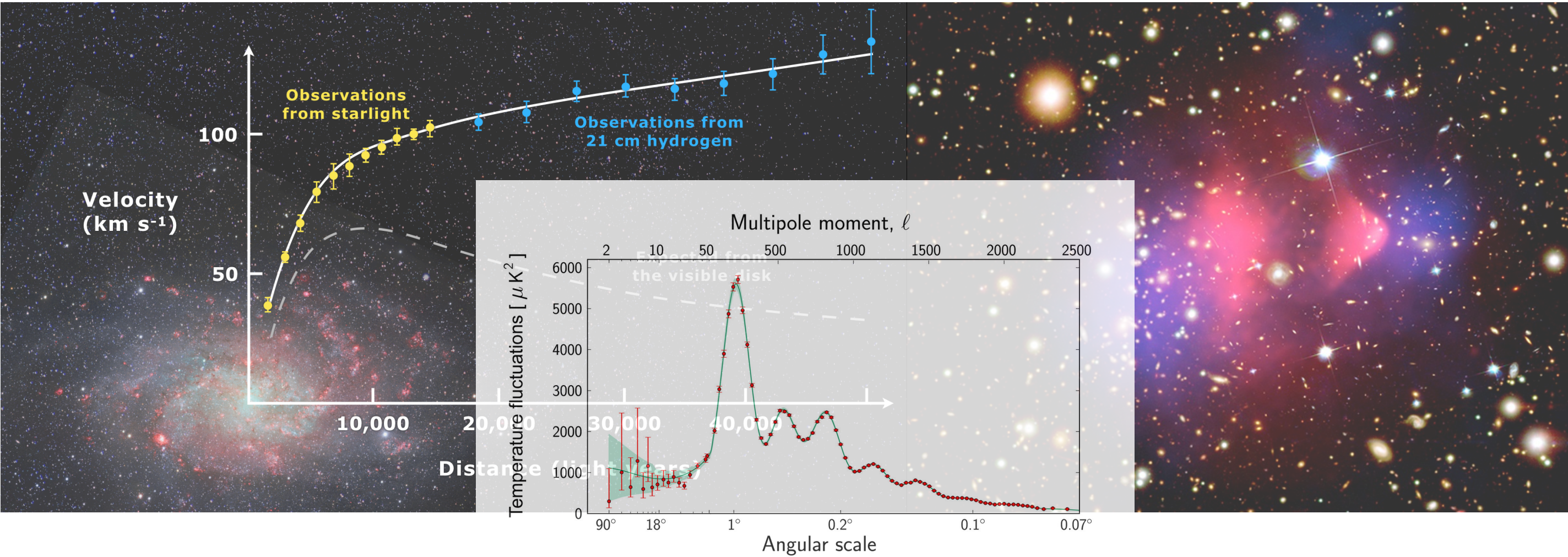


Evidence of new physics

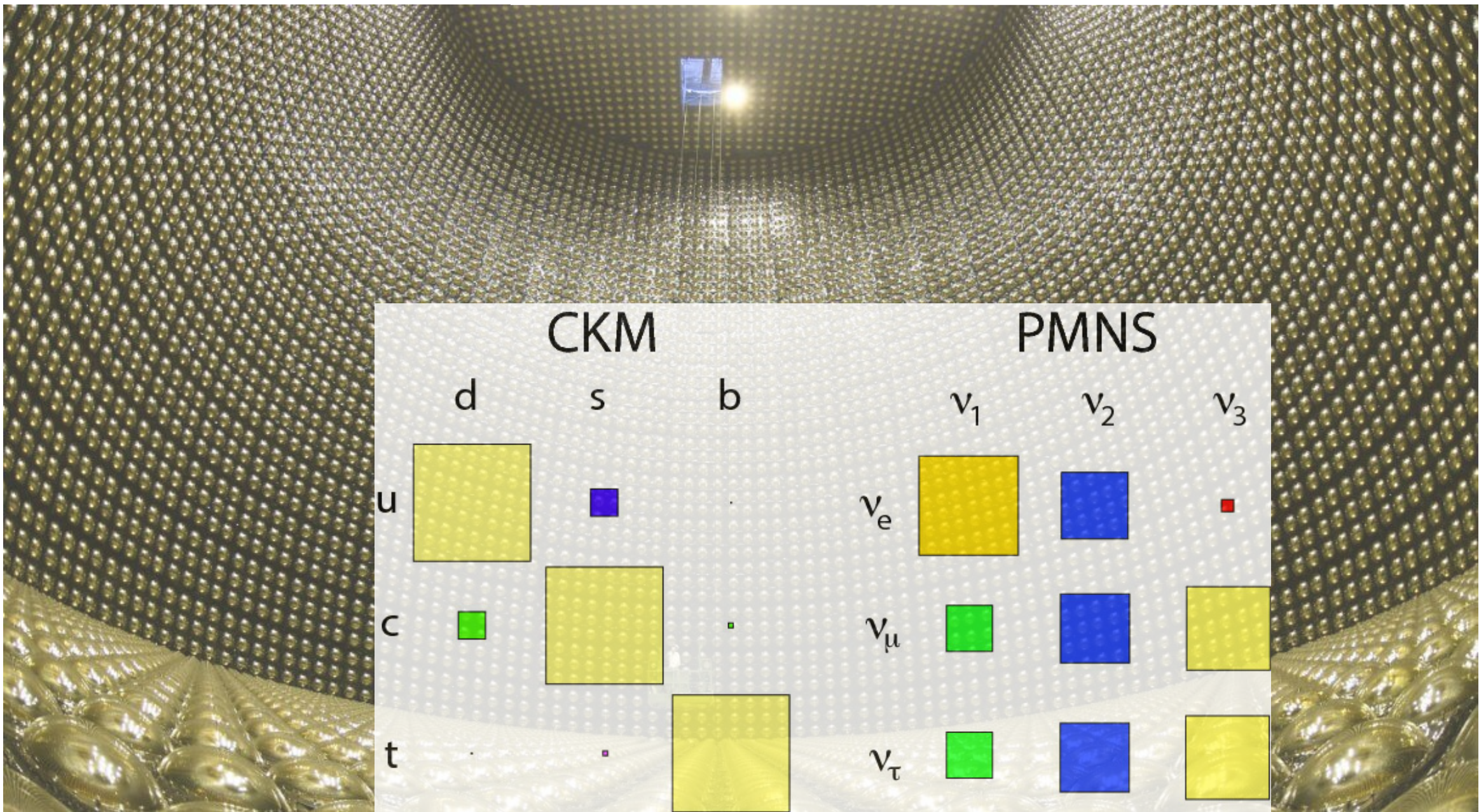
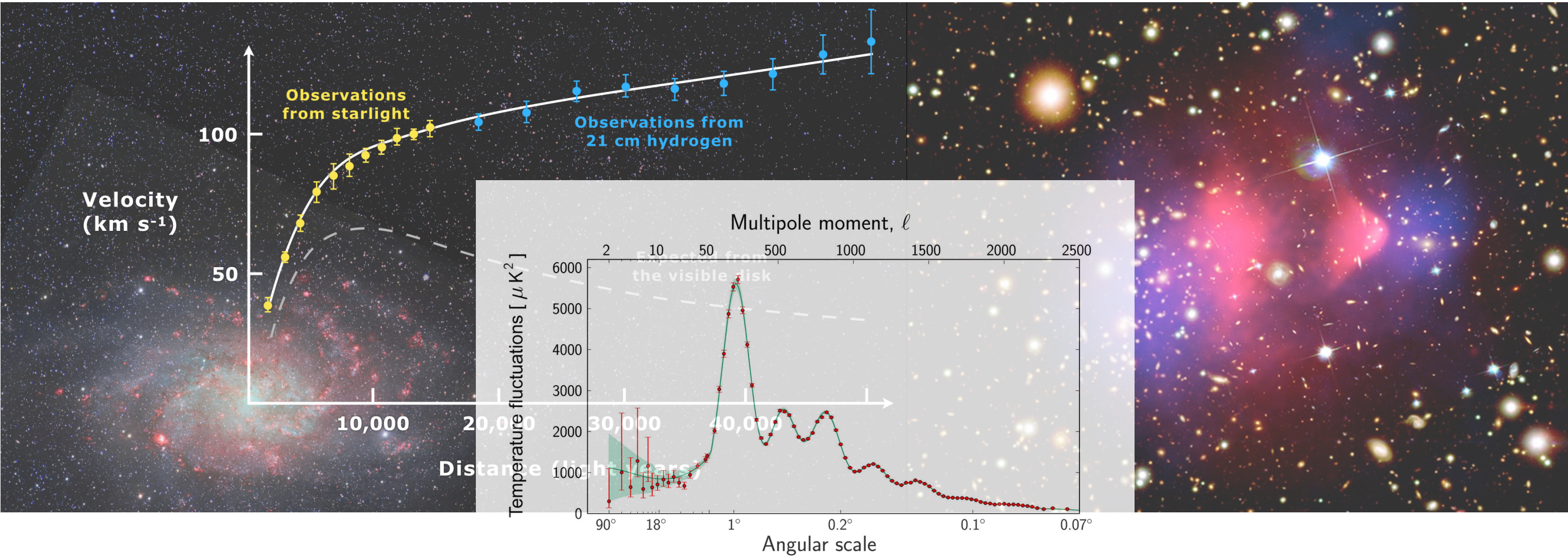


Evidence of new physics

Mystery of flavor

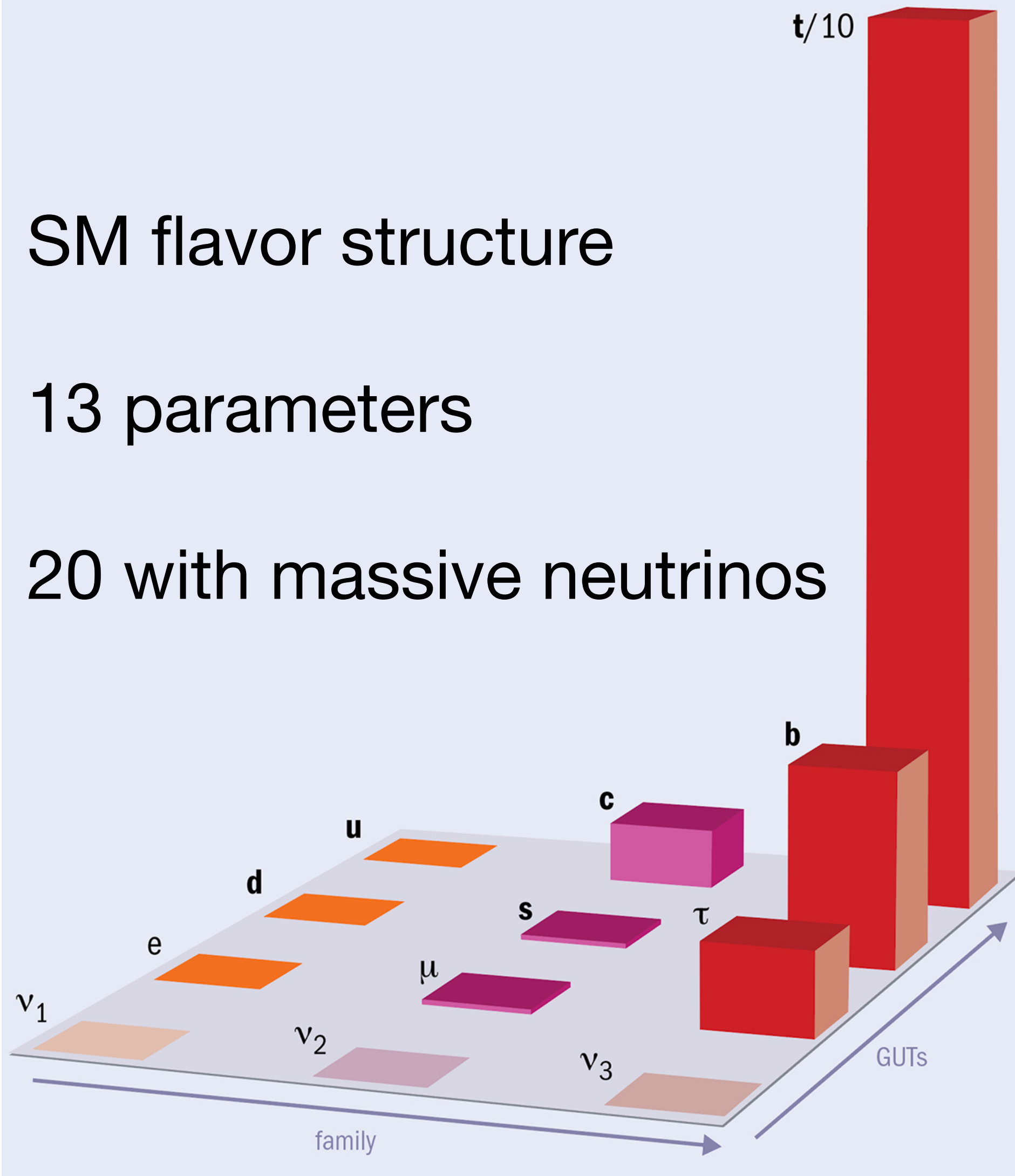


Evidence of new physics



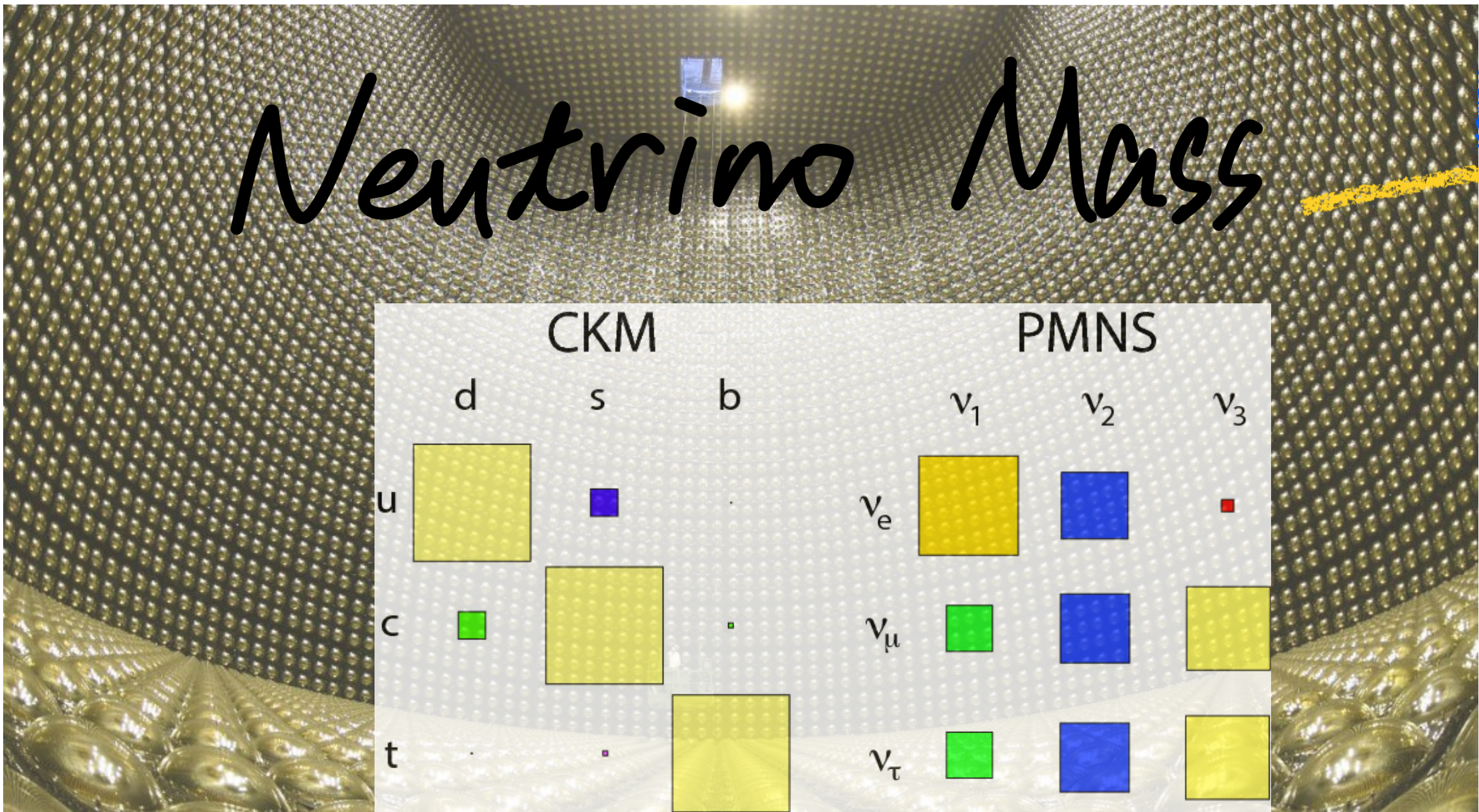
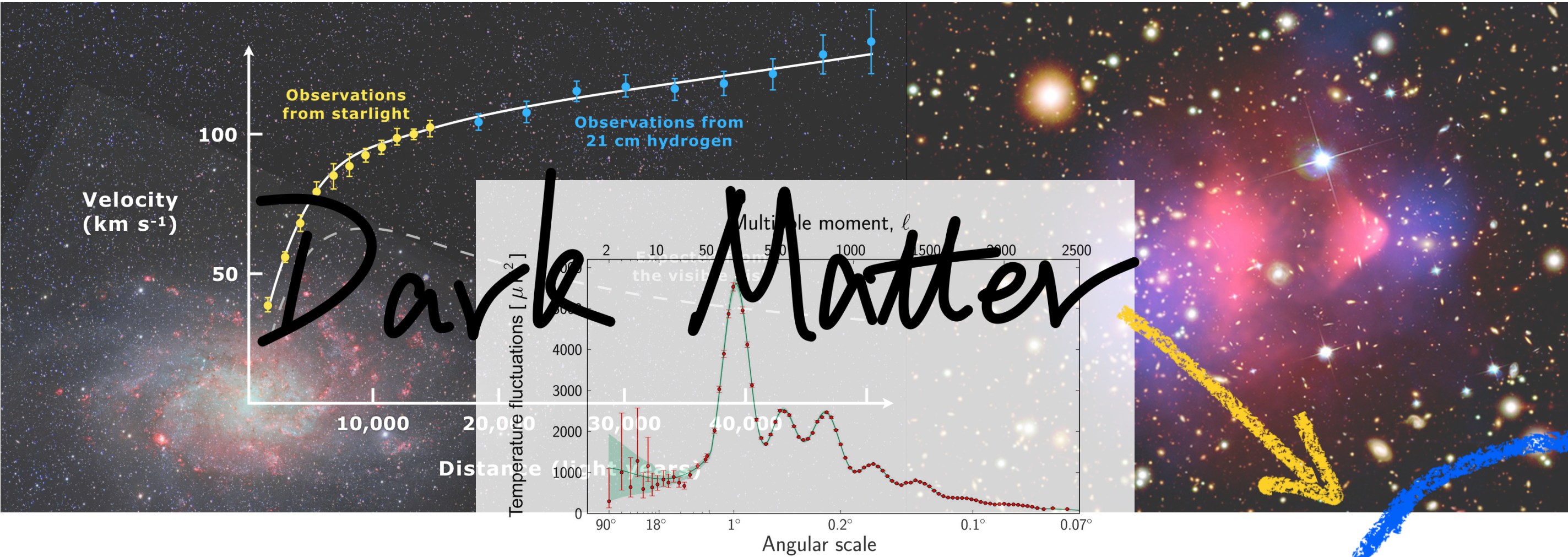
Mystery of flavor

- SM flavor structure
- 13 parameters
- 20 with massive neutrinos

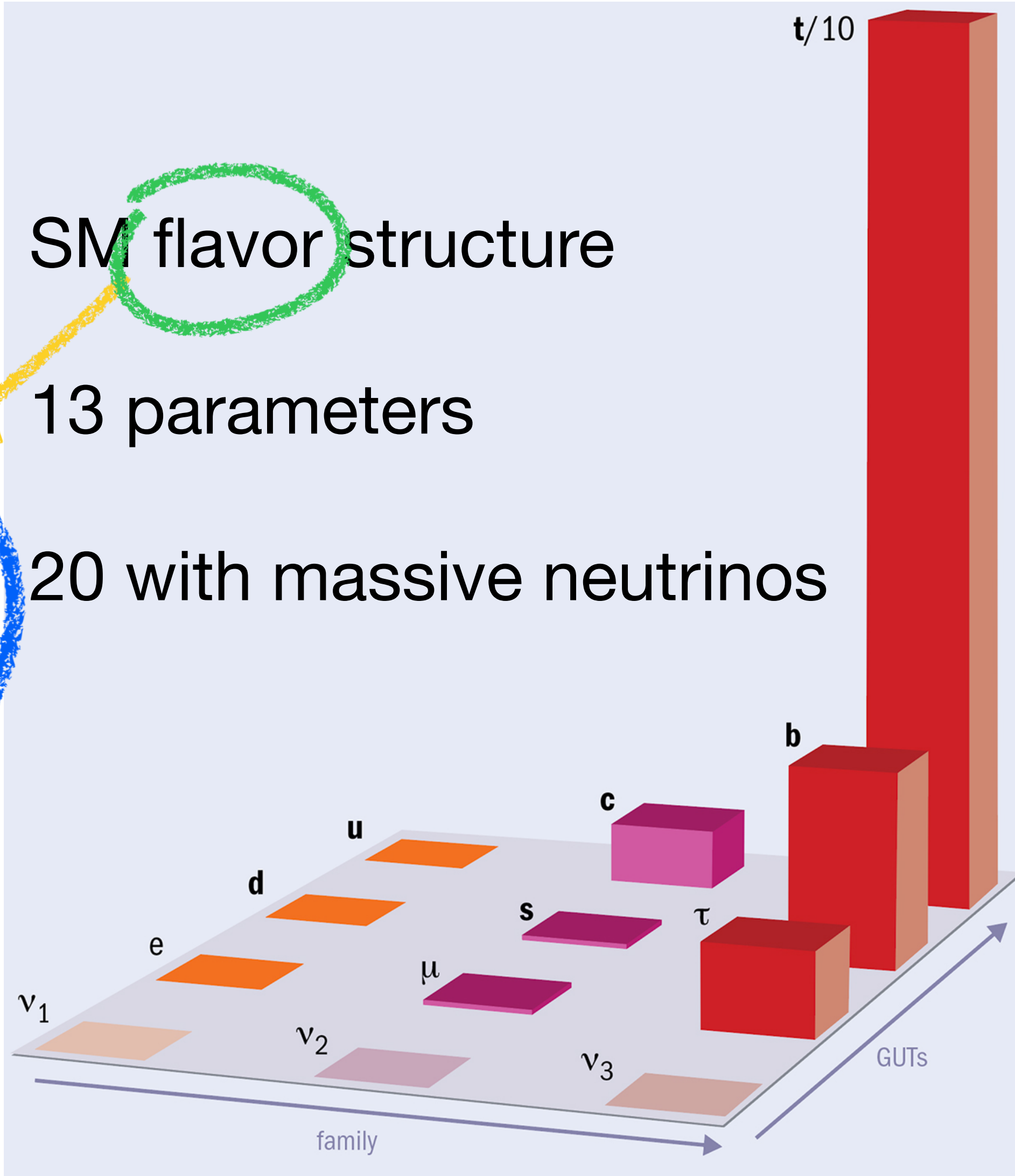


Evidence of new physics

Mystery of flavor



- SM flavor structure
- 13 parameters
- 20 with massive neutrinos



Summary for the impatient



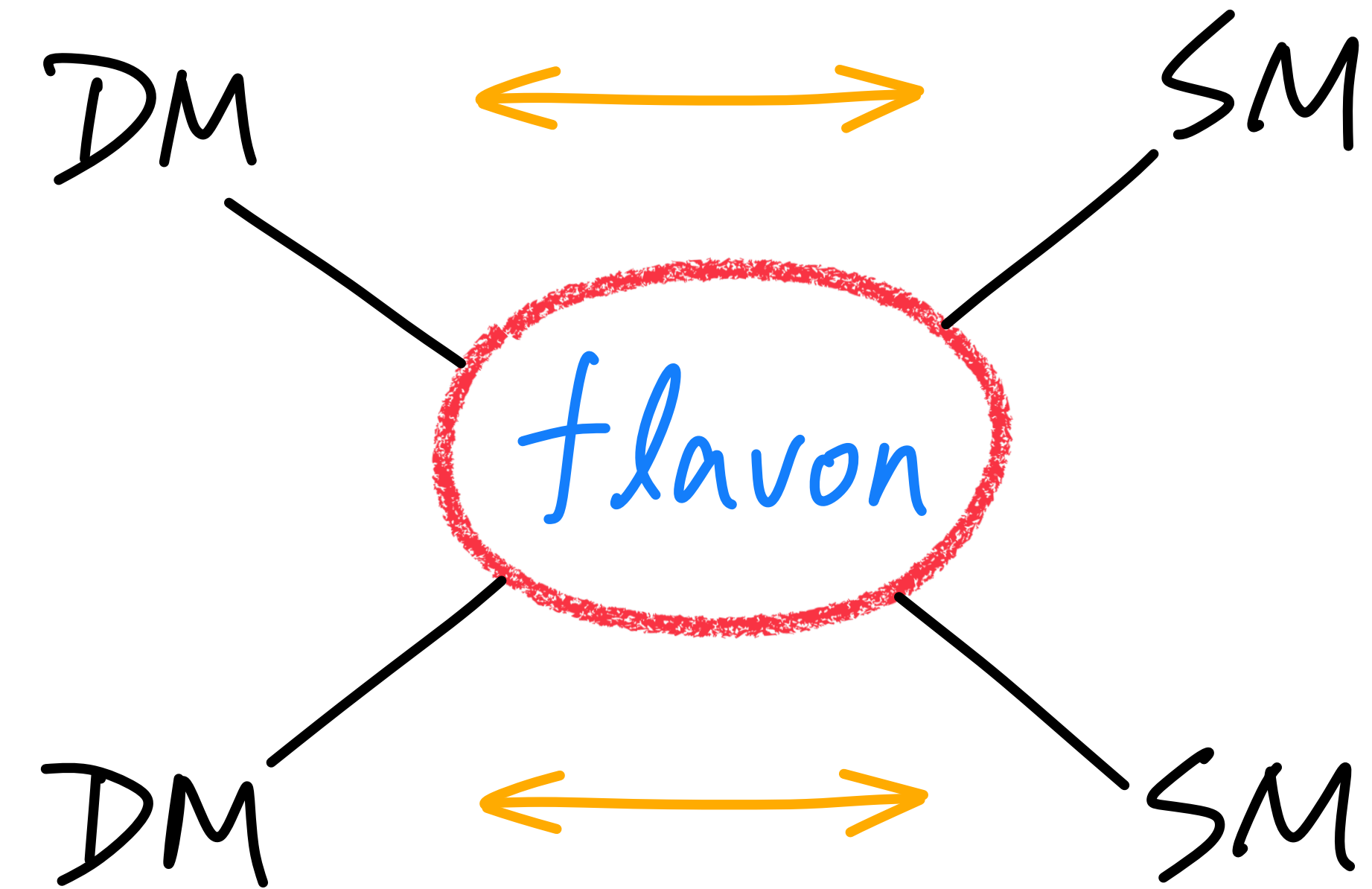
RESOURCEFULSELLING.COM

"THAT'S THE END OF MY PRESENTATION. ANY QUESTIONS?"

Summary for the impatient



"THAT'S THE END OF MY PRESENTATION. ANY QUESTIONS?"

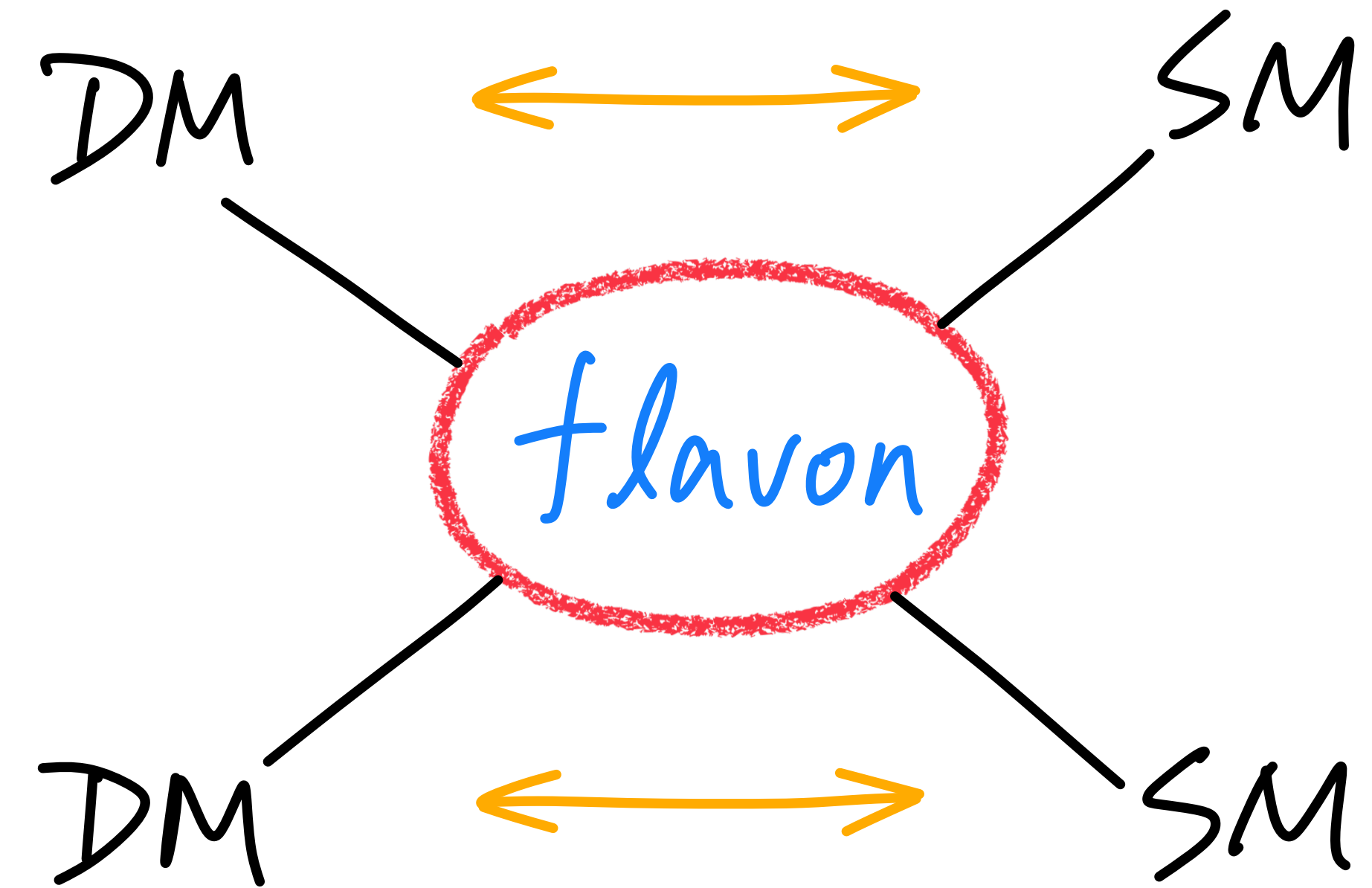


Summary for the impatient



"THAT'S THE END OF MY PRESENTATION. ANY QUESTIONS?"

Thanks for watching!



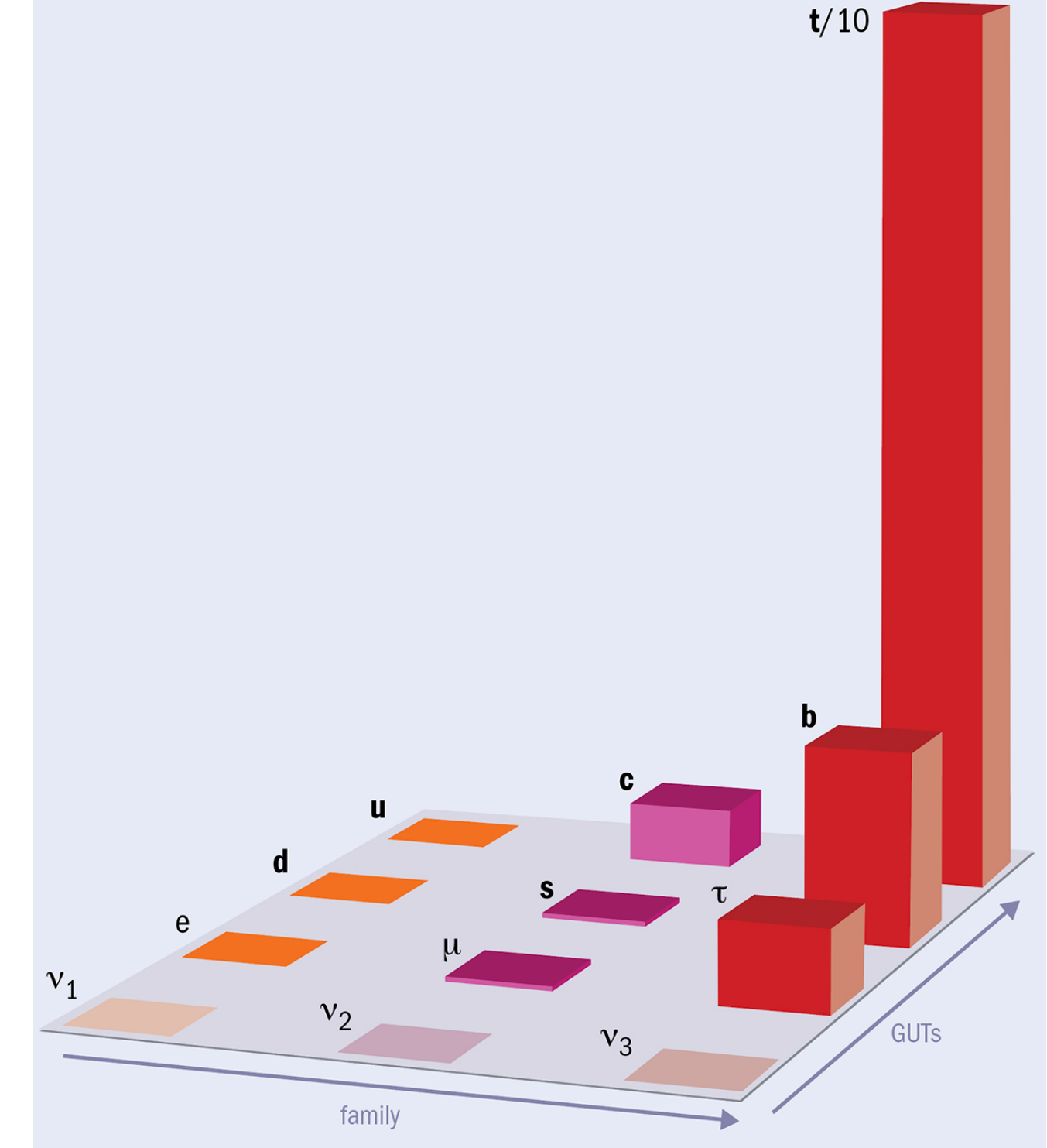
✓ • Freeze-out WIMP

✓ • Freeze-in FIMP

Hierarchy in the fermion mass

$$\frac{m_e}{m_t} \approx 3 \times 10^{-6}$$

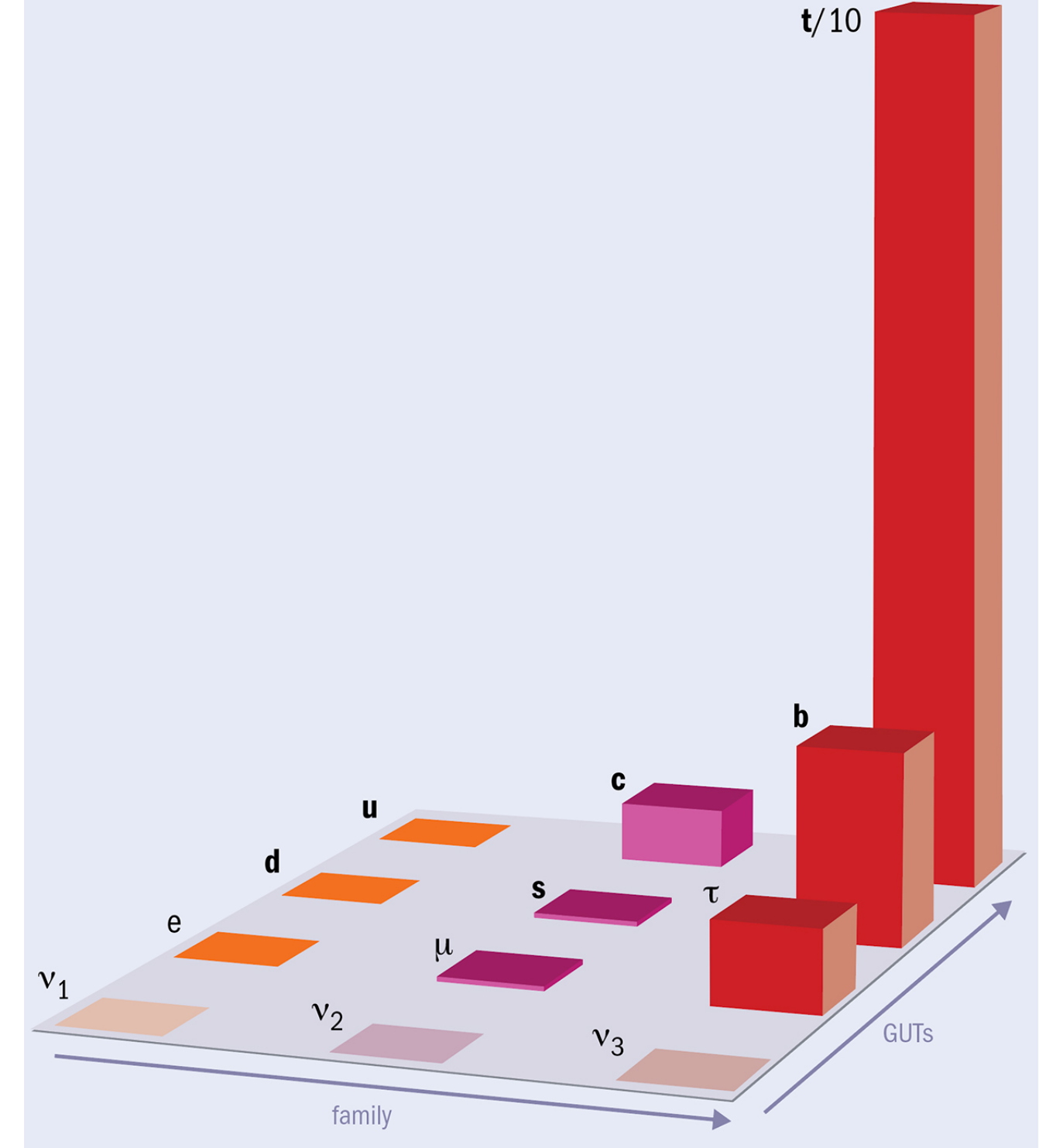
Top Yukawa $y_t \approx 1$



Hierarchy in the fermion mass

$$\frac{m_e}{m_t} \approx 3 \times 10^{-6}$$

Top Yukawa $y_t \approx 1$

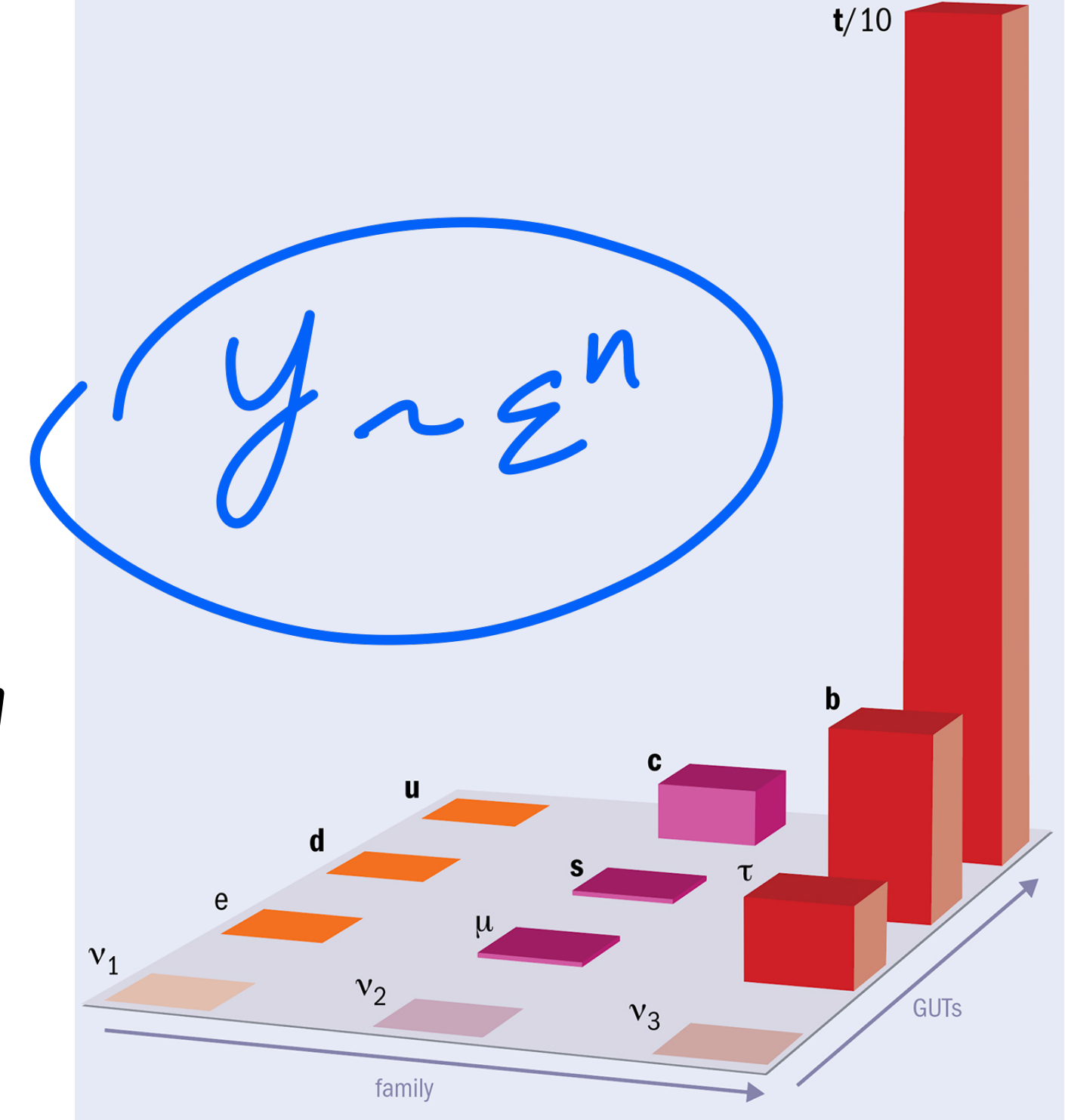


$$\text{Log}_{10} \left(\frac{\text{Mass} \begin{pmatrix} e & u & \tau \\ d & s & b \\ u & c & t \end{pmatrix}}{m_t} \right) \approx - \begin{pmatrix} 5.5 & 3.2 & 2 \\ 4.5 & 3.2 & 1.6 \\ 4.8 & 2.1 & 0 \end{pmatrix}$$

Hierarchy in the fermion mass

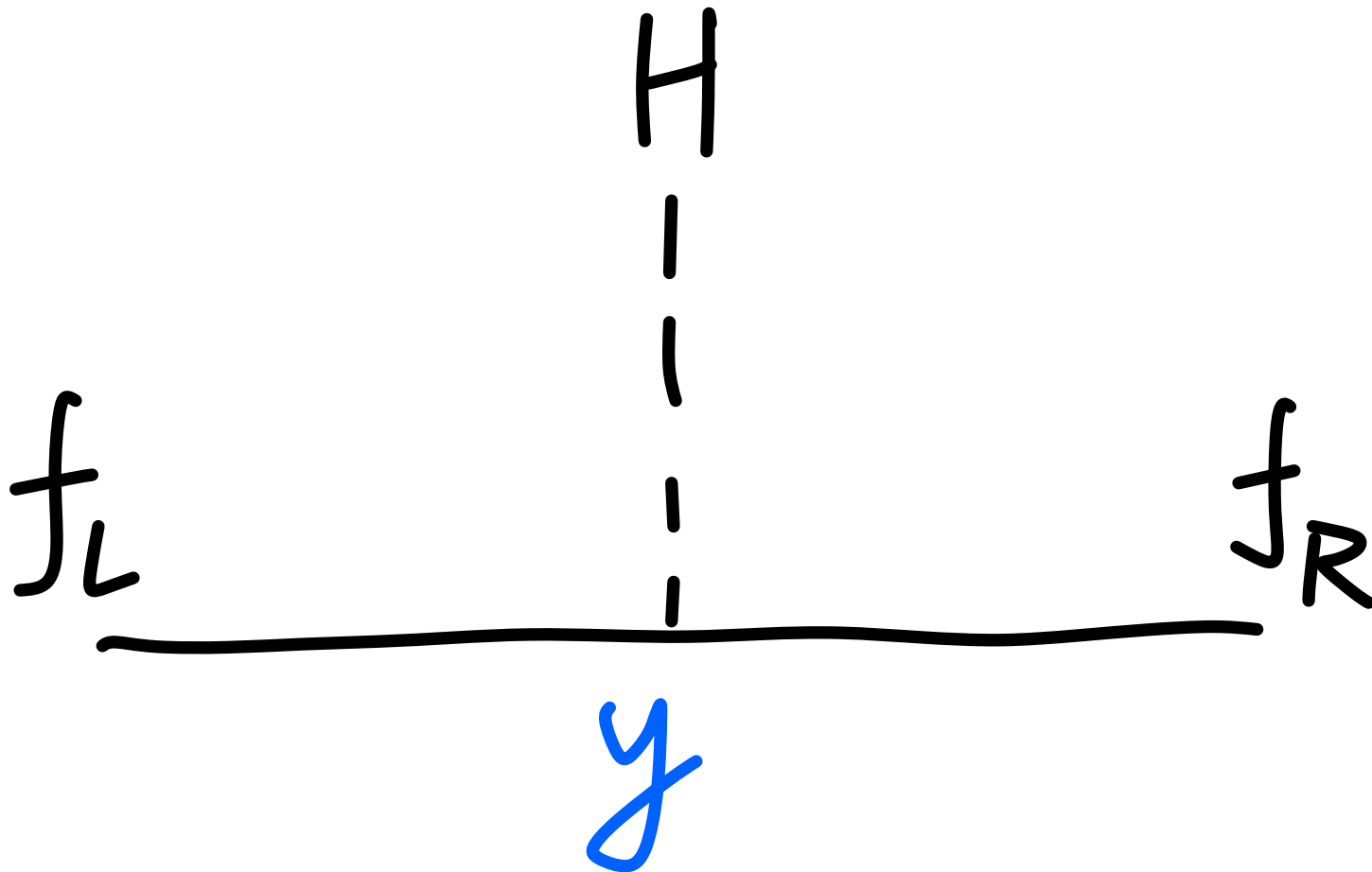
$$\frac{m_e}{m_t} \approx 3 \times 10^{-6}$$

Top Yukawa $y_t \approx 1$

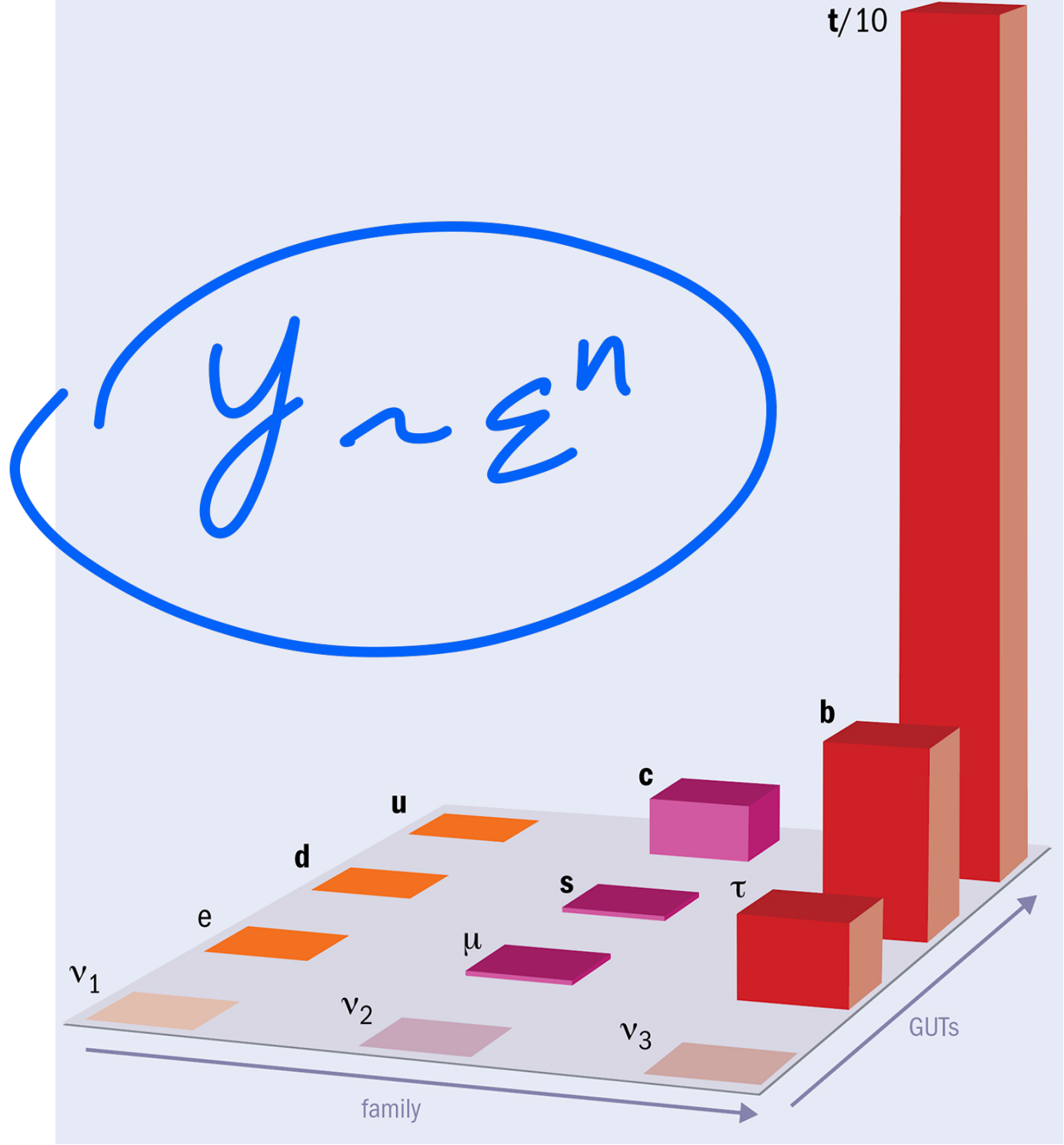


$$\text{Log}_{10} \left(\frac{\text{Mass} \begin{pmatrix} e & u & \tau \\ d & s & b \\ u & c & t \end{pmatrix}}{m_t} \right) \approx - \begin{pmatrix} 5.5 & 3.2 & 2 \\ 4.5 & 3.2 & 1.6 \\ 4.8 & 2.1 & 0 \end{pmatrix}$$

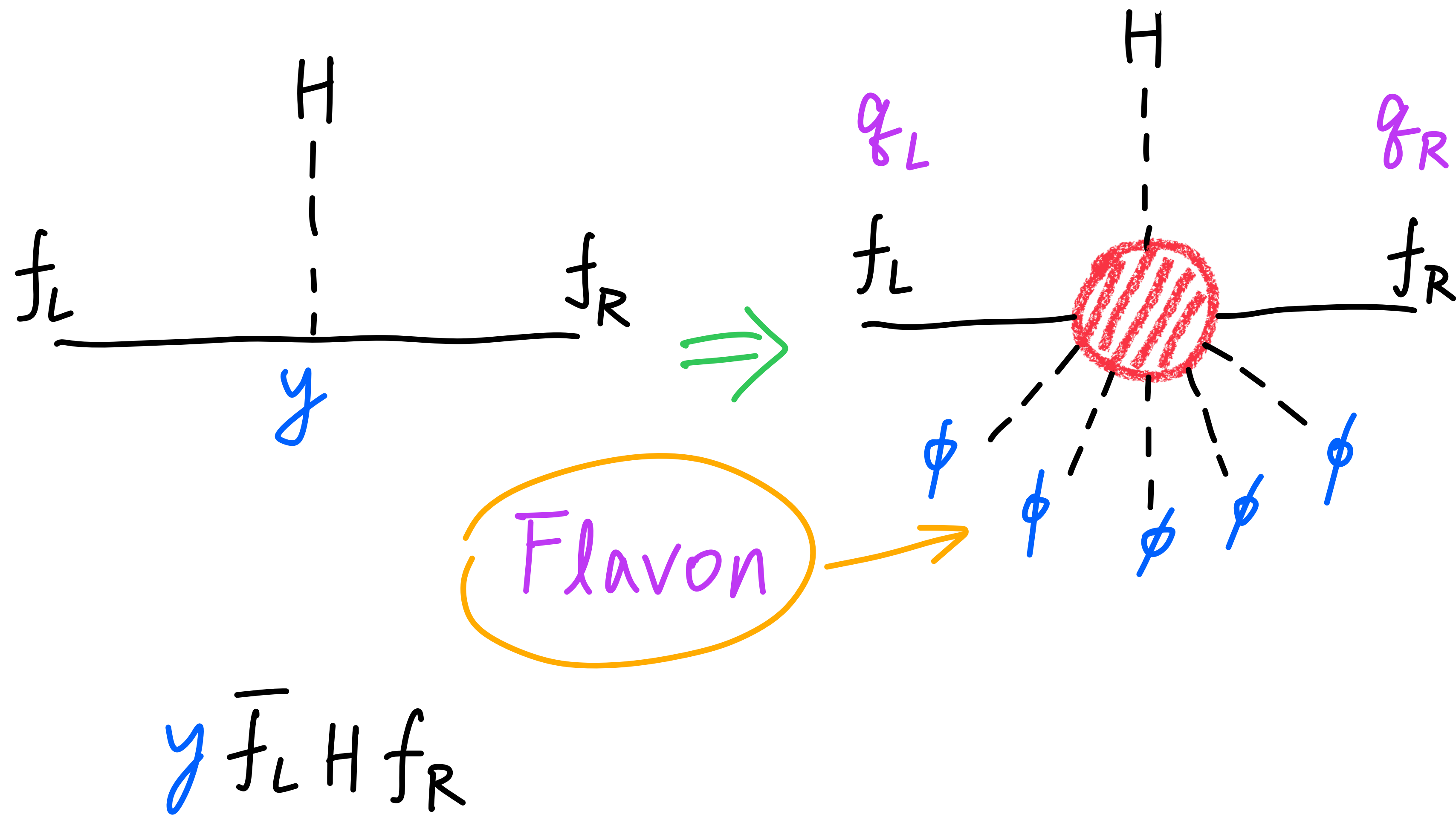
Global U(1) Froggatt-Nielsen symmetry



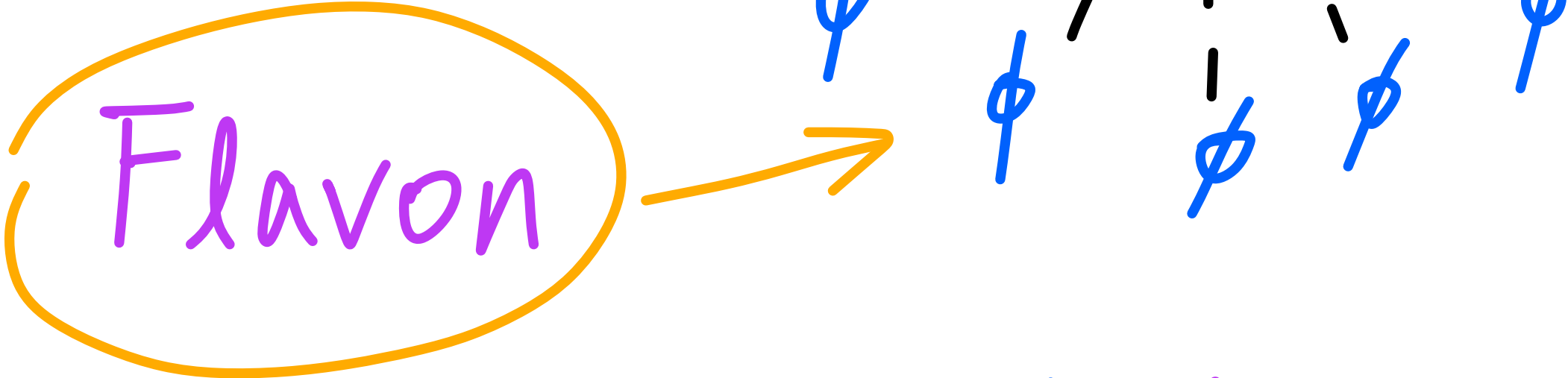
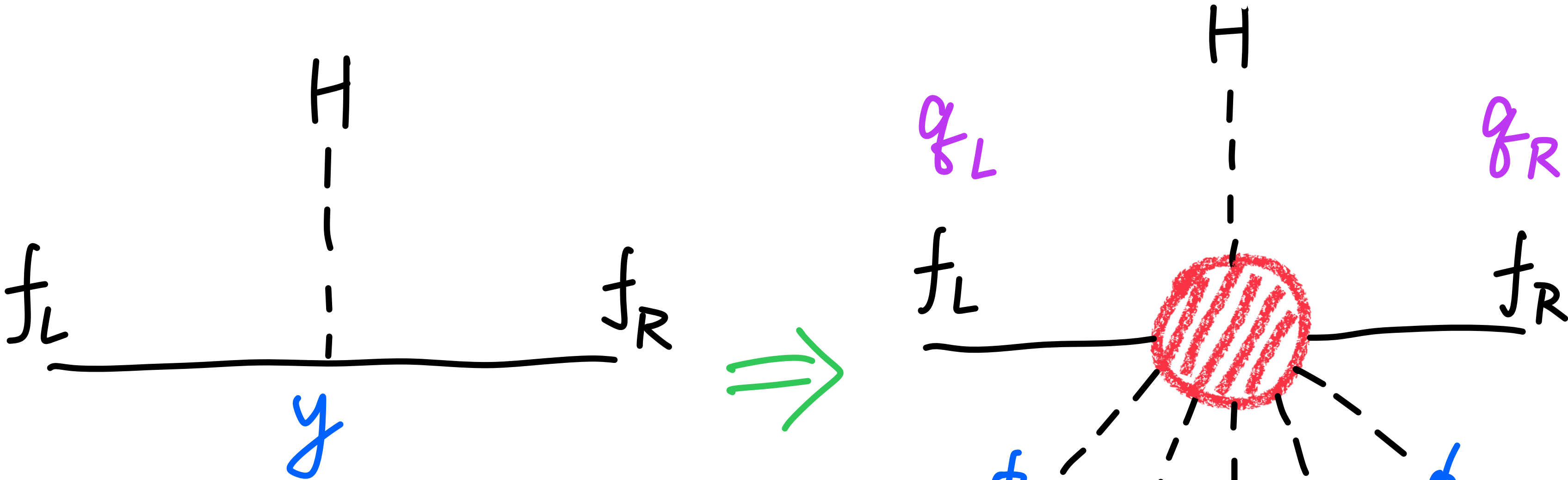
$$y \bar{f}_L H f_R$$



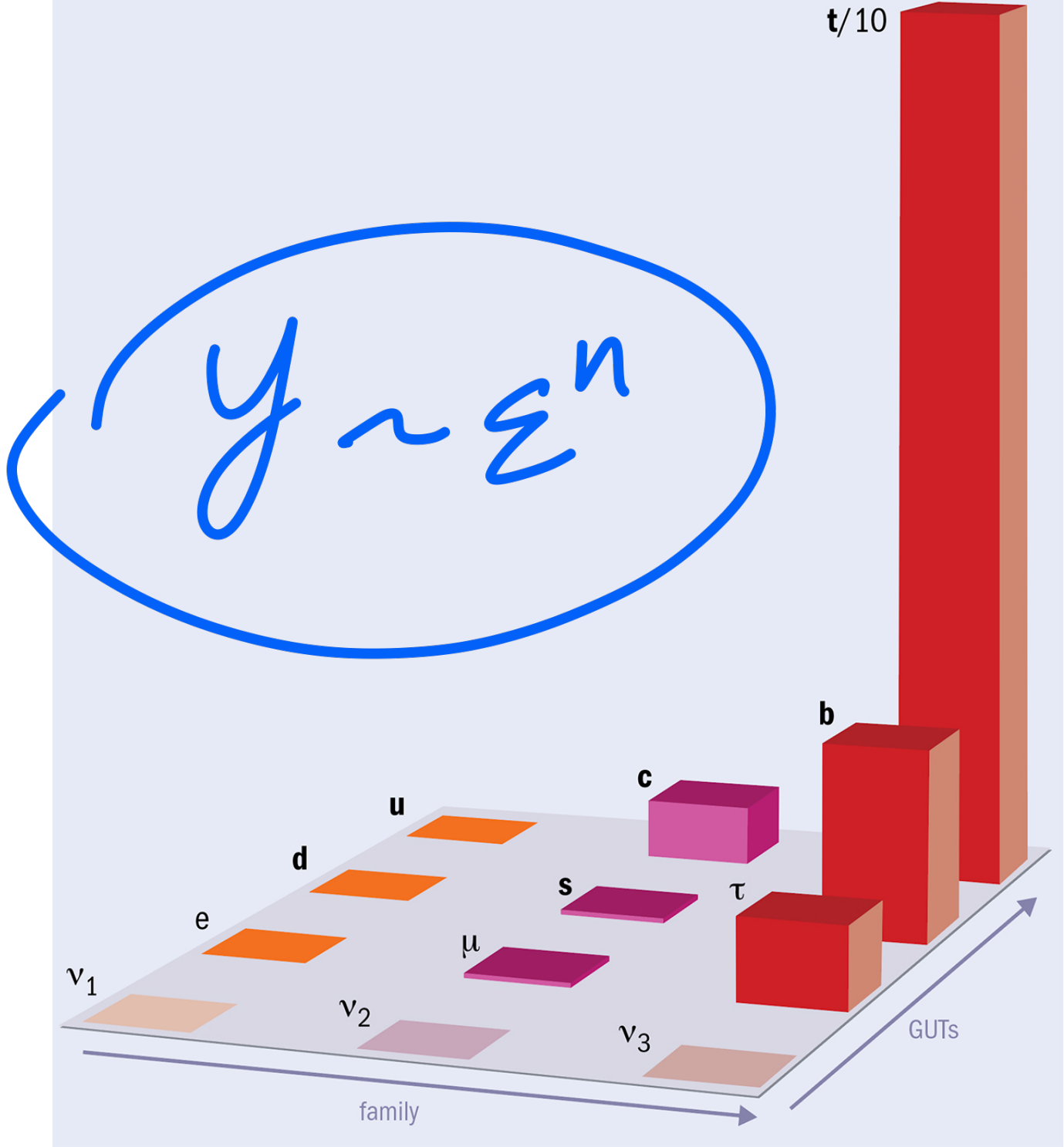
Global U(1) Froggatt-Nielsen symmetry



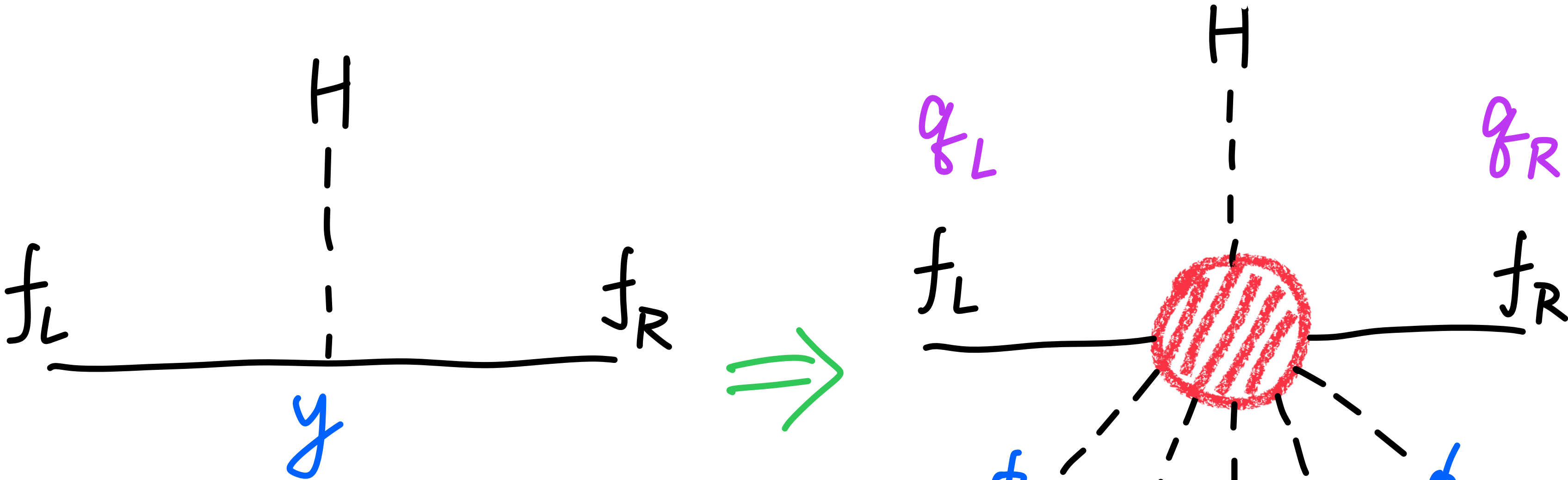
Global U(1) Froggatt-Nielsen symmetry



$y \bar{f}_L H f_R \Rightarrow C \left(\frac{\phi}{M}\right)^n \bar{f}_L H f_R$

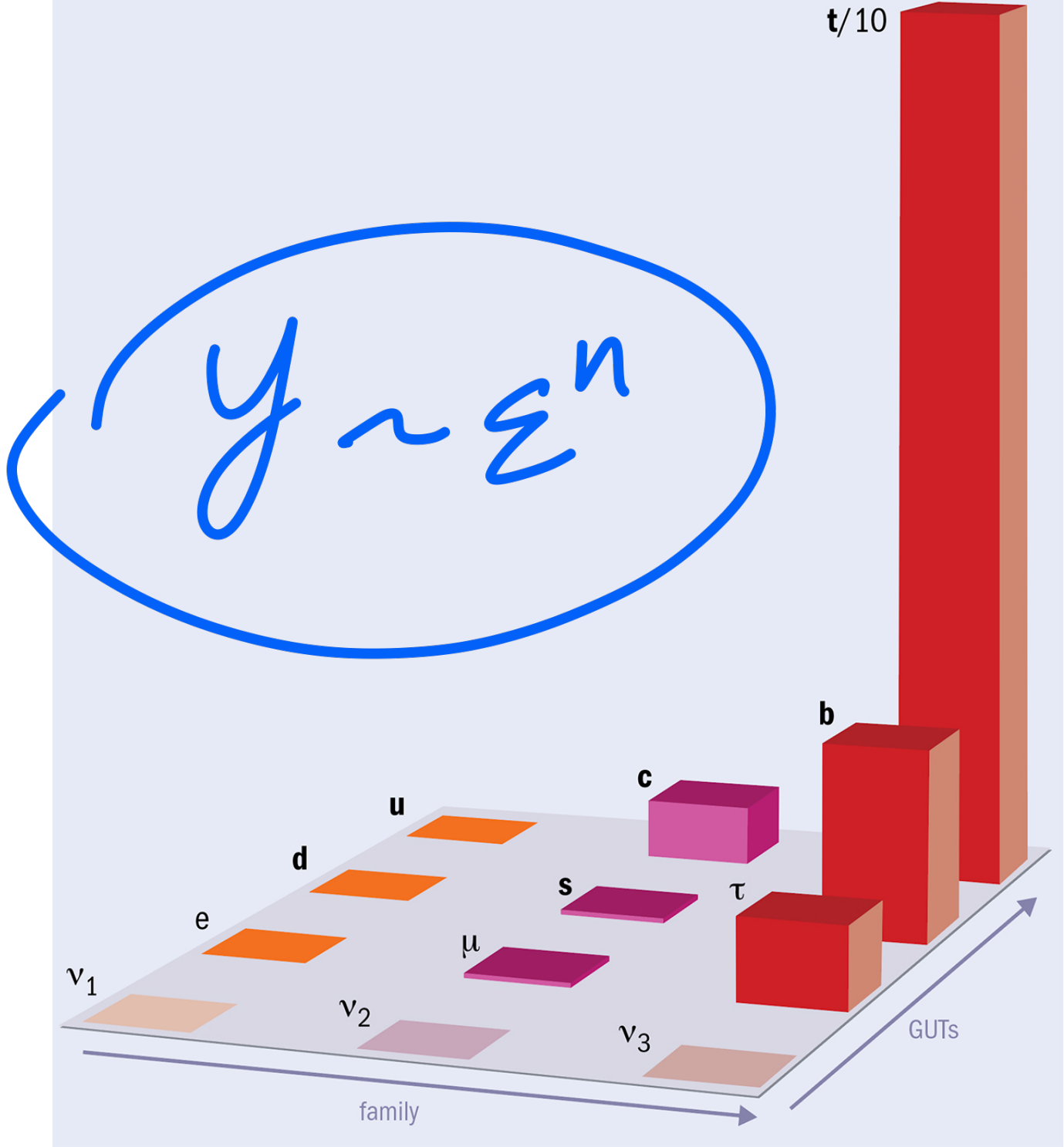


Global U(1) Froggatt-Nielsen symmetry



Flavon

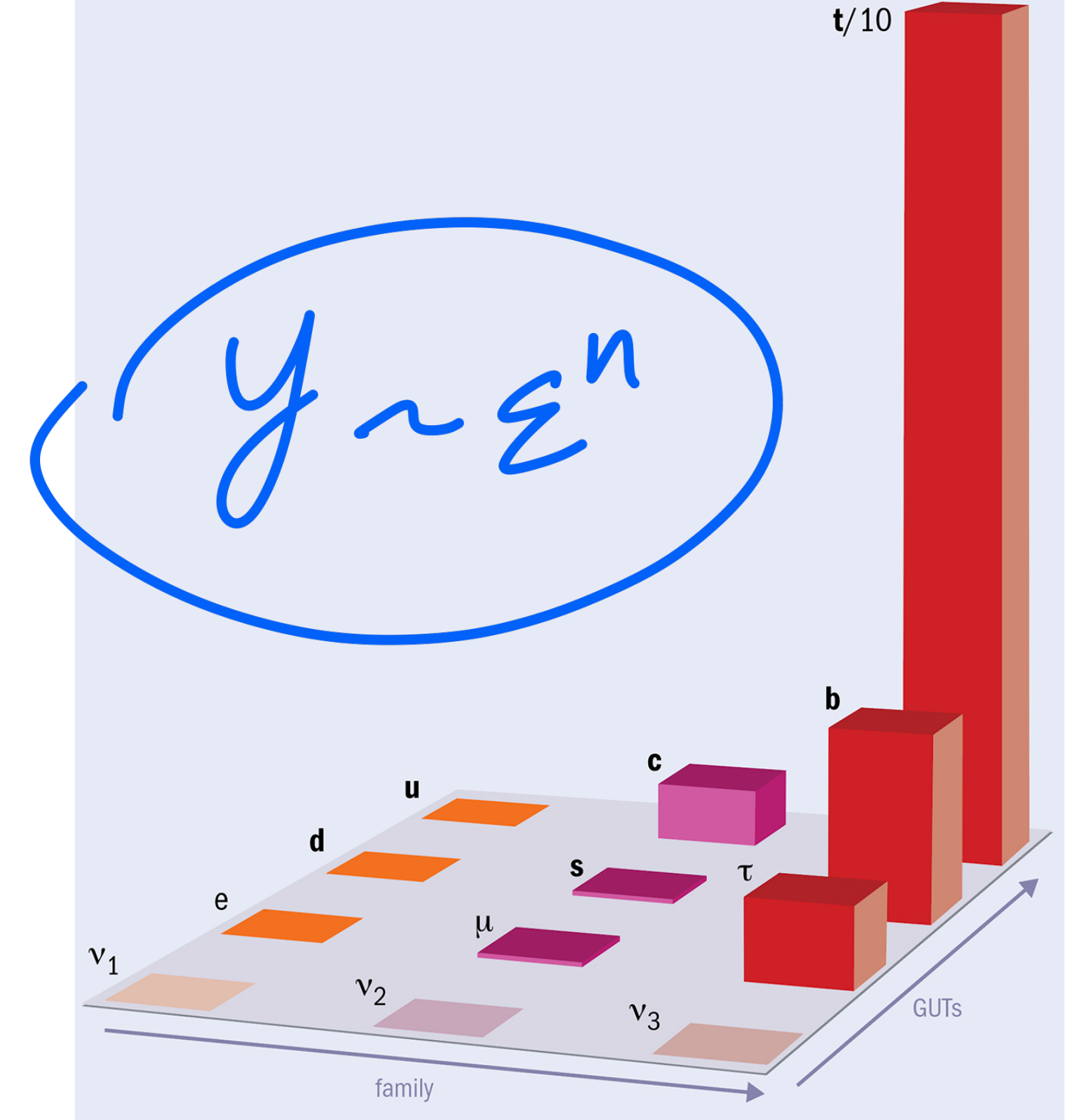
$$y \bar{f}_L H f_R \Rightarrow C \left(\frac{\phi}{M} \right)^n \bar{f}_L H f_R$$



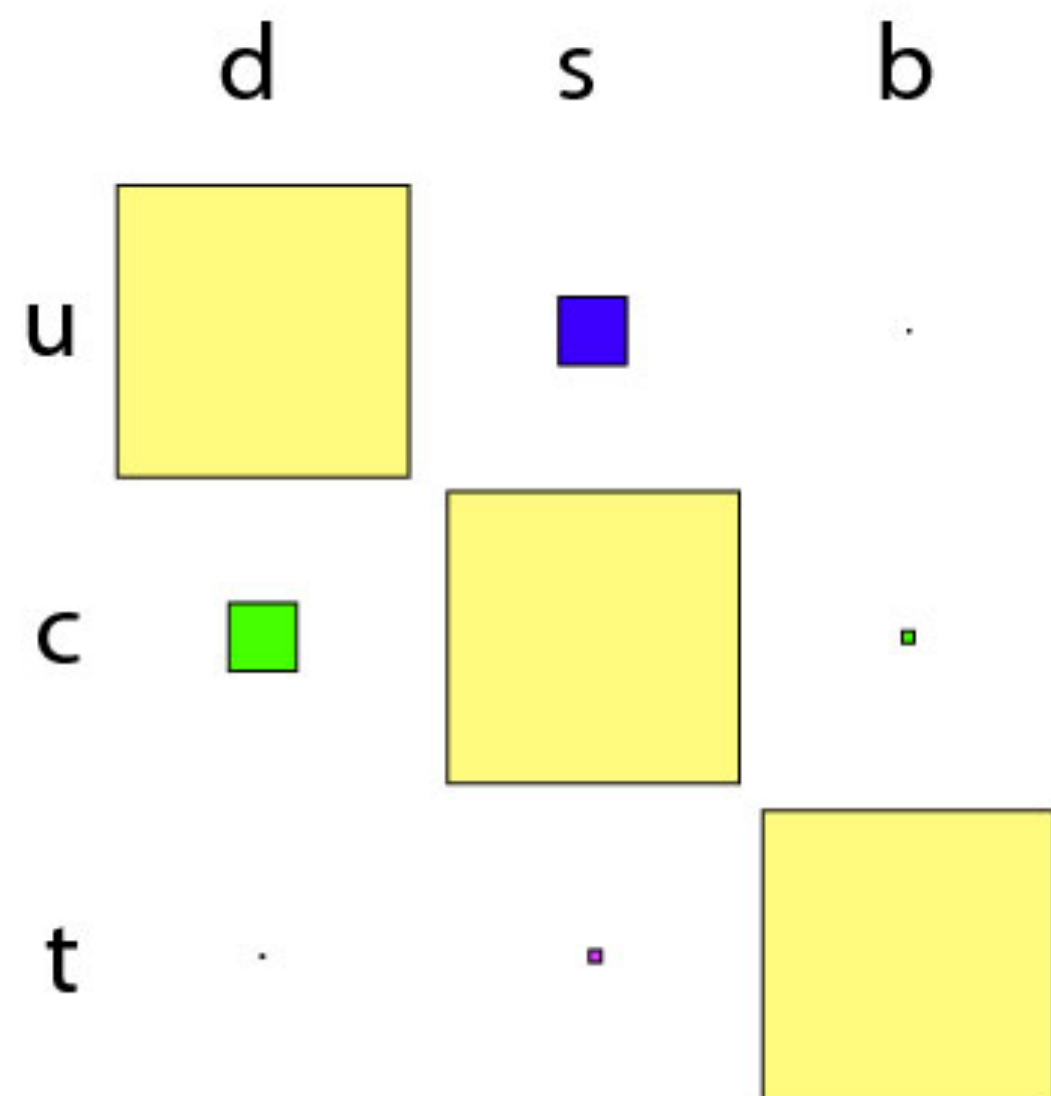
$$\left\{ \begin{array}{l} C \sim \mathcal{O}(1) \\ \frac{\phi \rightarrow v_\phi}{M} = \epsilon \\ q_L - q_R = n \end{array} \right.$$

Froggatt-Nielsen charges

$$\xi = \frac{V_\phi}{M} \approx V_{us} \approx 0.23$$



CKM



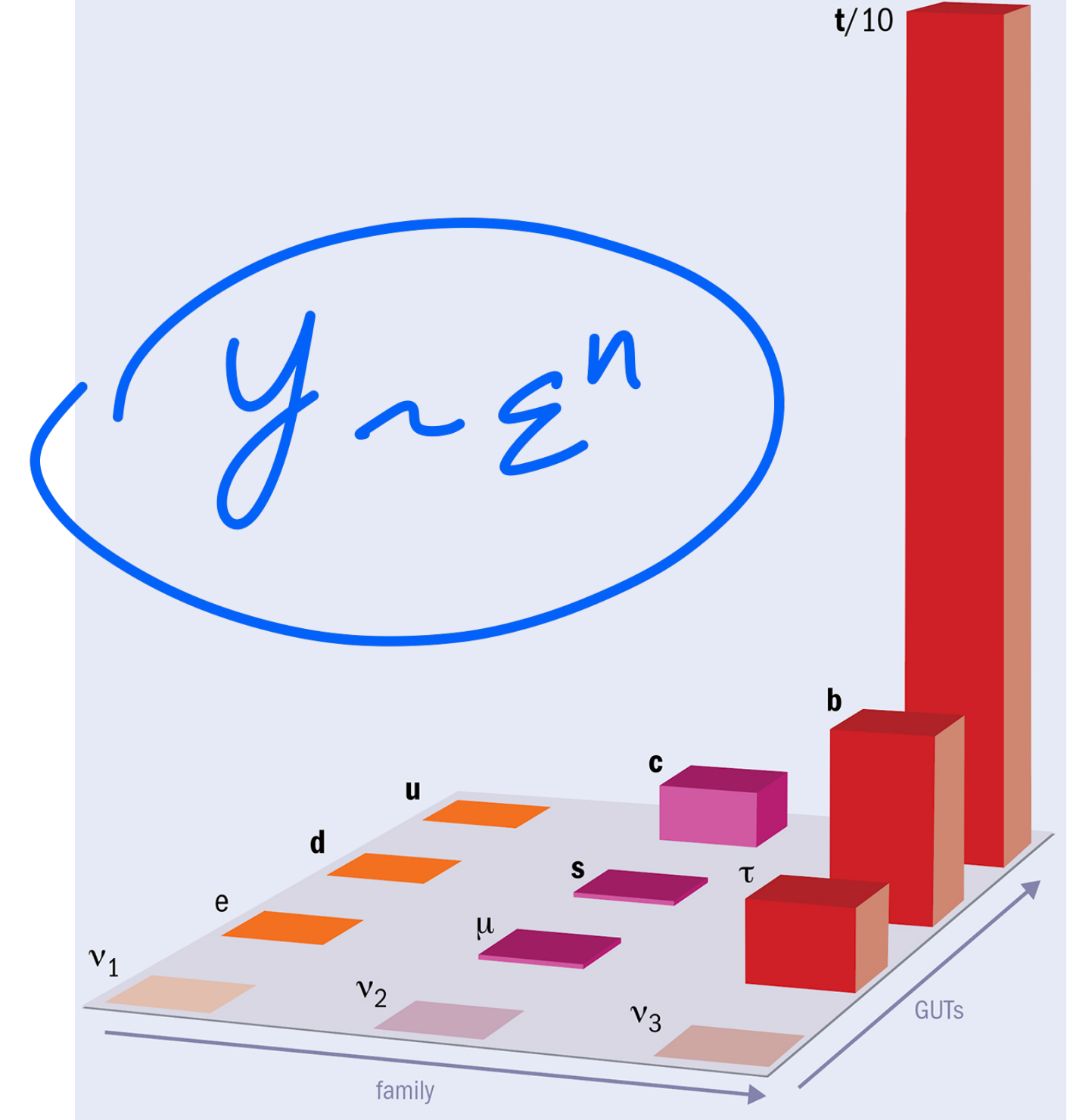
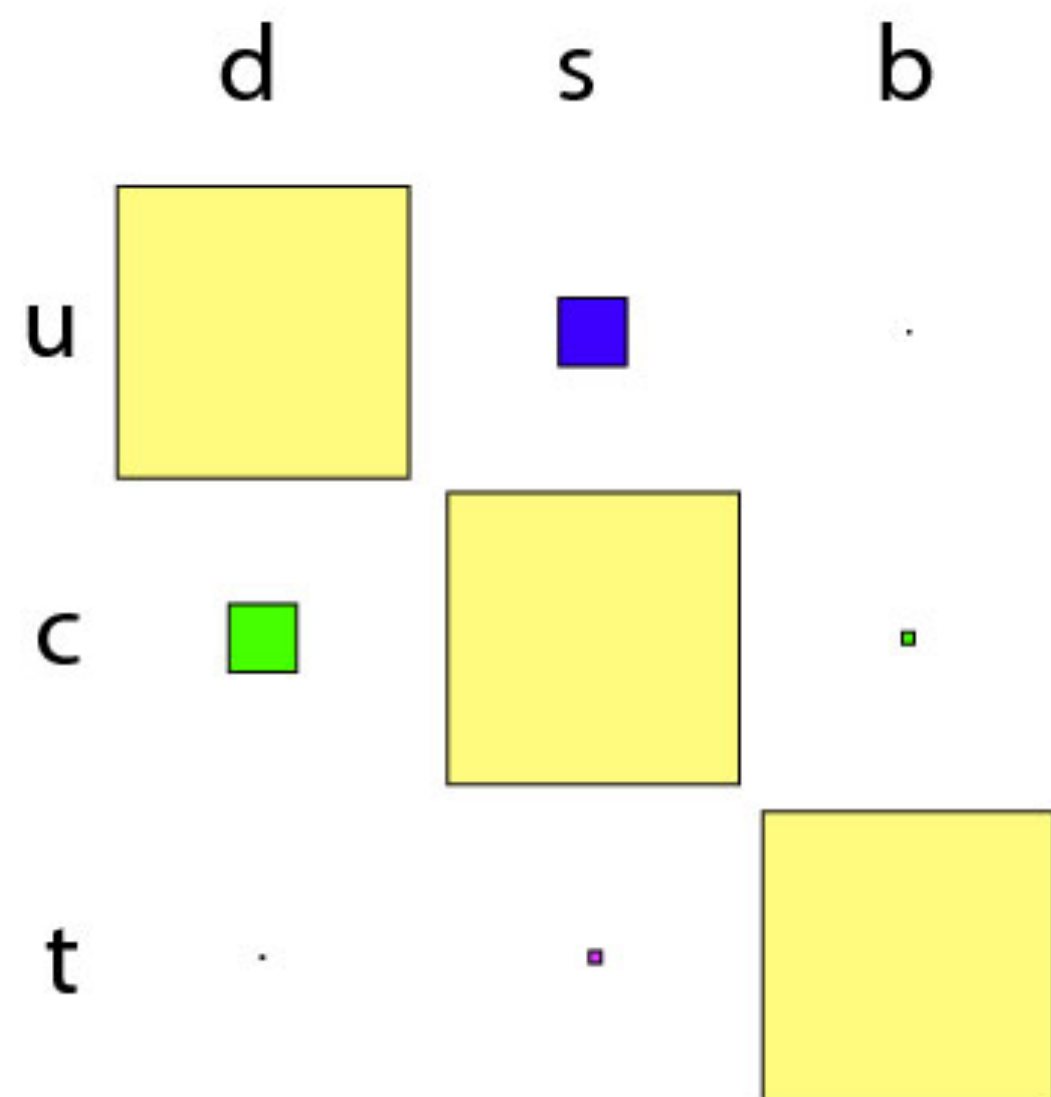
$$\left\{ \begin{array}{l} C \sim O(1) \\ \frac{\phi \rightarrow V_\phi}{M} = \xi \\ g_L - g_R = n \end{array} \right.$$

Froggatt-Nielsen charges

$$\varepsilon = \frac{V_\phi}{M} \approx V_{us} \approx 0.23$$

$$n_u^{ij} = \begin{pmatrix} 8 & 4 & 3 \\ 7 & 3 & 2 \\ 5 & 1 & 0 \end{pmatrix}, \quad n_d^{ij} = \begin{pmatrix} 7 & 6 & 6 \\ 6 & 5 & 5 \\ 4 & 3 & 3 \end{pmatrix}, \quad n_e^{ij} = \begin{pmatrix} 9 & 6 & 4 \\ 8 & 5 & 3 \\ 8 & 5 & 3 \end{pmatrix}$$

CKM



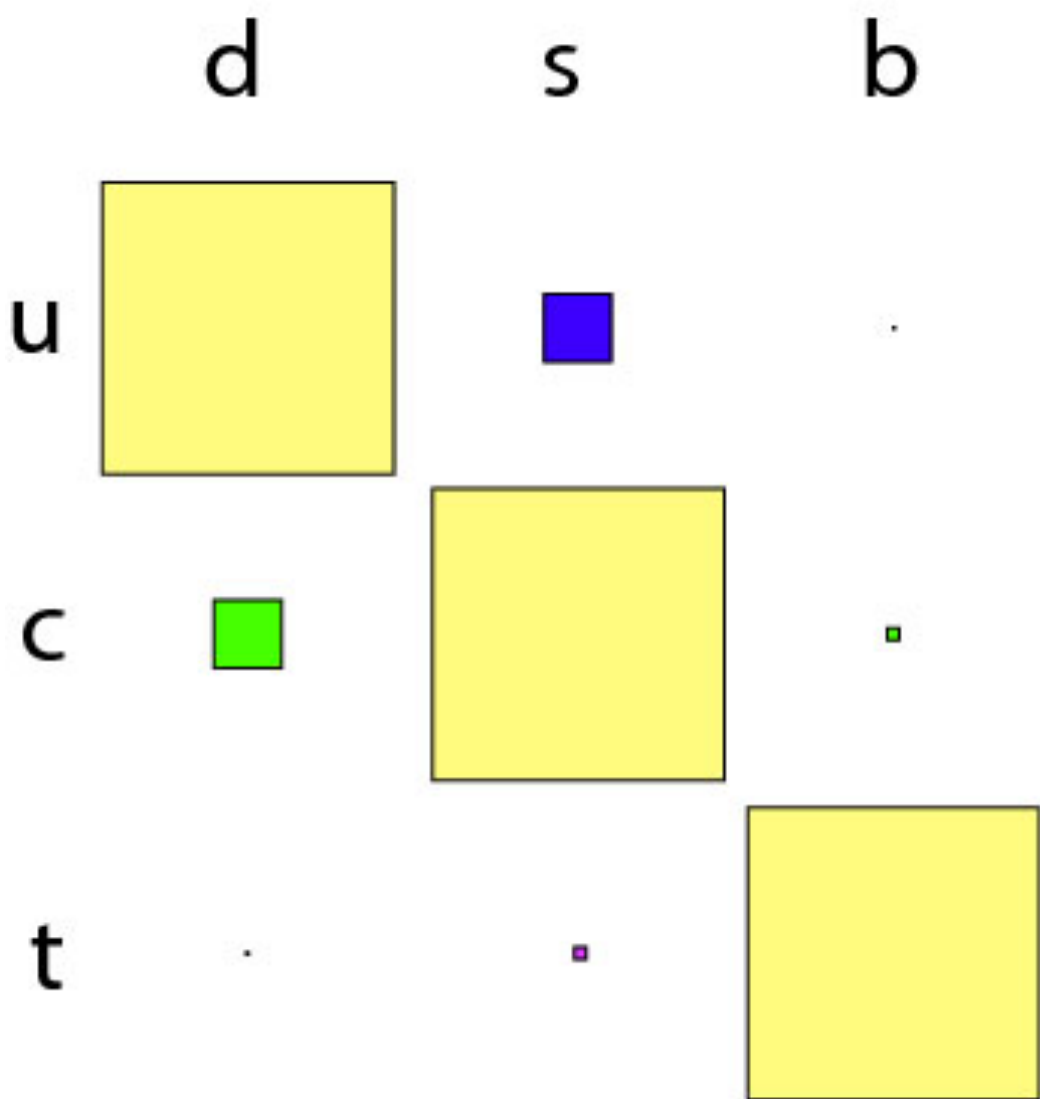
$$\left\{ \begin{array}{l} C \sim O(1) \\ \frac{\phi \rightarrow V_\phi}{M} = \varepsilon \\ g_L - g_R = n \end{array} \right.$$

Froggatt-Nielsen charges

$$\varepsilon = \frac{V_\phi}{M} \approx V_{us} \approx 0.23$$

$$n_u^{ij} = \begin{pmatrix} 8 & 4 & 3 \\ 7 & 3 & 2 \\ 5 & 1 & 0 \end{pmatrix}, \quad n_d^{ij} = \begin{pmatrix} 7 & 6 & 6 \\ 6 & 5 & 5 \\ 4 & 3 & 3 \end{pmatrix}, \quad n_e^{ij} = \begin{pmatrix} 9 & 6 & 4 \\ 8 & 5 & 3 \\ 8 & 5 & 3 \end{pmatrix}$$

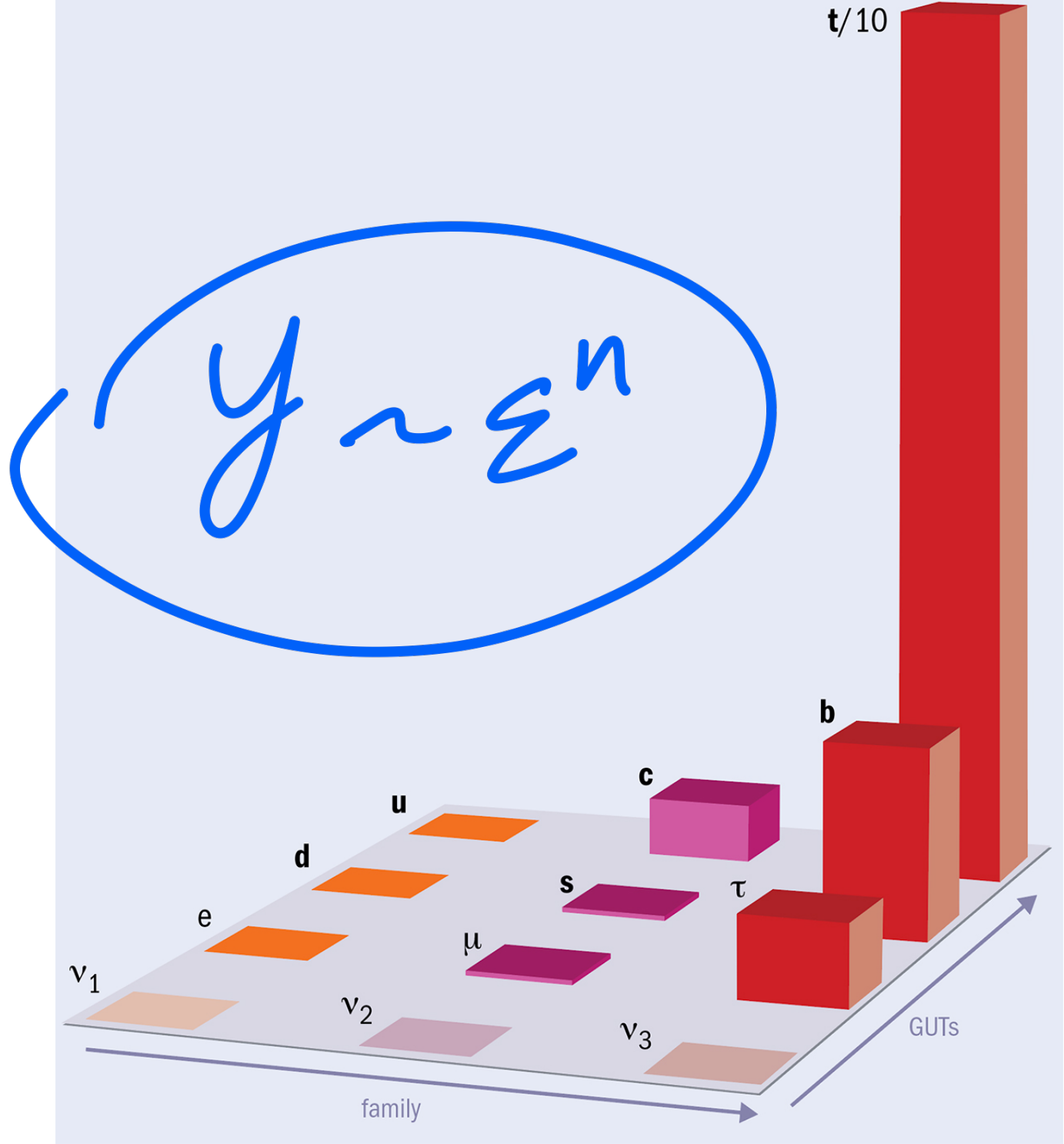
CKM



$$\begin{pmatrix} q_{Q_1} & q_{Q_2} & q_{Q_3} \\ q_u & q_c & q_t \\ q_d & q_s & q_b \end{pmatrix} = \begin{pmatrix} 3 & 2 & 0 \\ -5 & -1 & 0 \\ -4 & -3 & -3 \end{pmatrix}$$

q_L points to the first two matrices.

$$\begin{pmatrix} q_{L_1} & q_{L_2} & q_{L_3} \\ q_e & q_\mu & q_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ -8 & -5 & -3 \end{pmatrix}$$



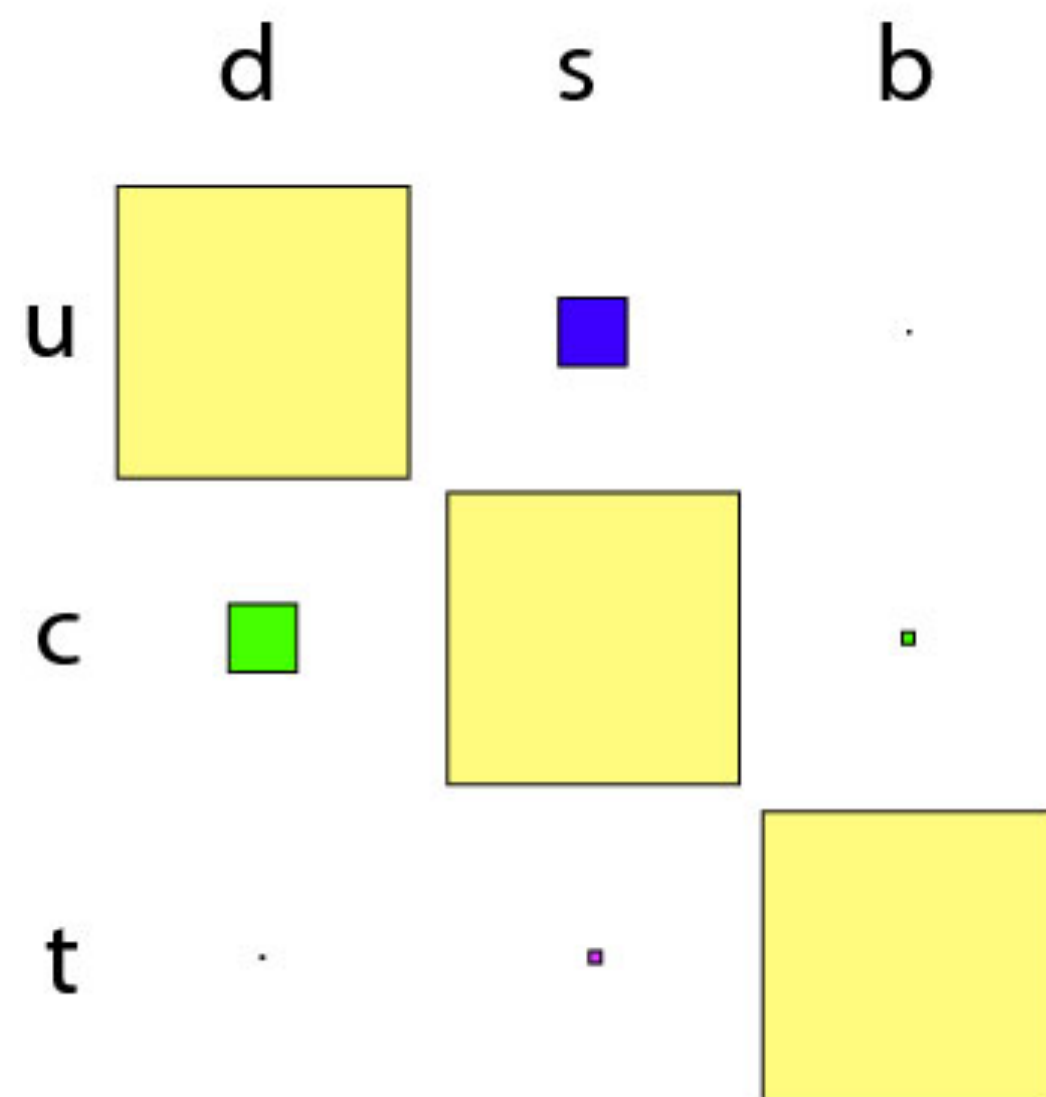
$$\begin{cases} C \sim \mathcal{O}(1) \\ \frac{\phi \rightarrow V_\phi}{M} = \varepsilon \\ q_L - q_R = n \end{cases}$$

Froggatt-Nielsen charges

$$\varepsilon = \frac{V_\phi}{M} \approx V_{us} \approx 0.23$$

$$n_u^{ij} = \begin{pmatrix} 8 & 4 & 3 \\ 7 & 3 & 2 \\ 5 & 1 & 0 \end{pmatrix}, \quad n_d^{ij} = \begin{pmatrix} 7 & 6 & 6 \\ 6 & 5 & 5 \\ 4 & 3 & 3 \end{pmatrix}, \quad n_e^{ij} = \begin{pmatrix} 9 & 6 & 4 \\ 8 & 5 & 3 \\ 8 & 5 & 3 \end{pmatrix}$$

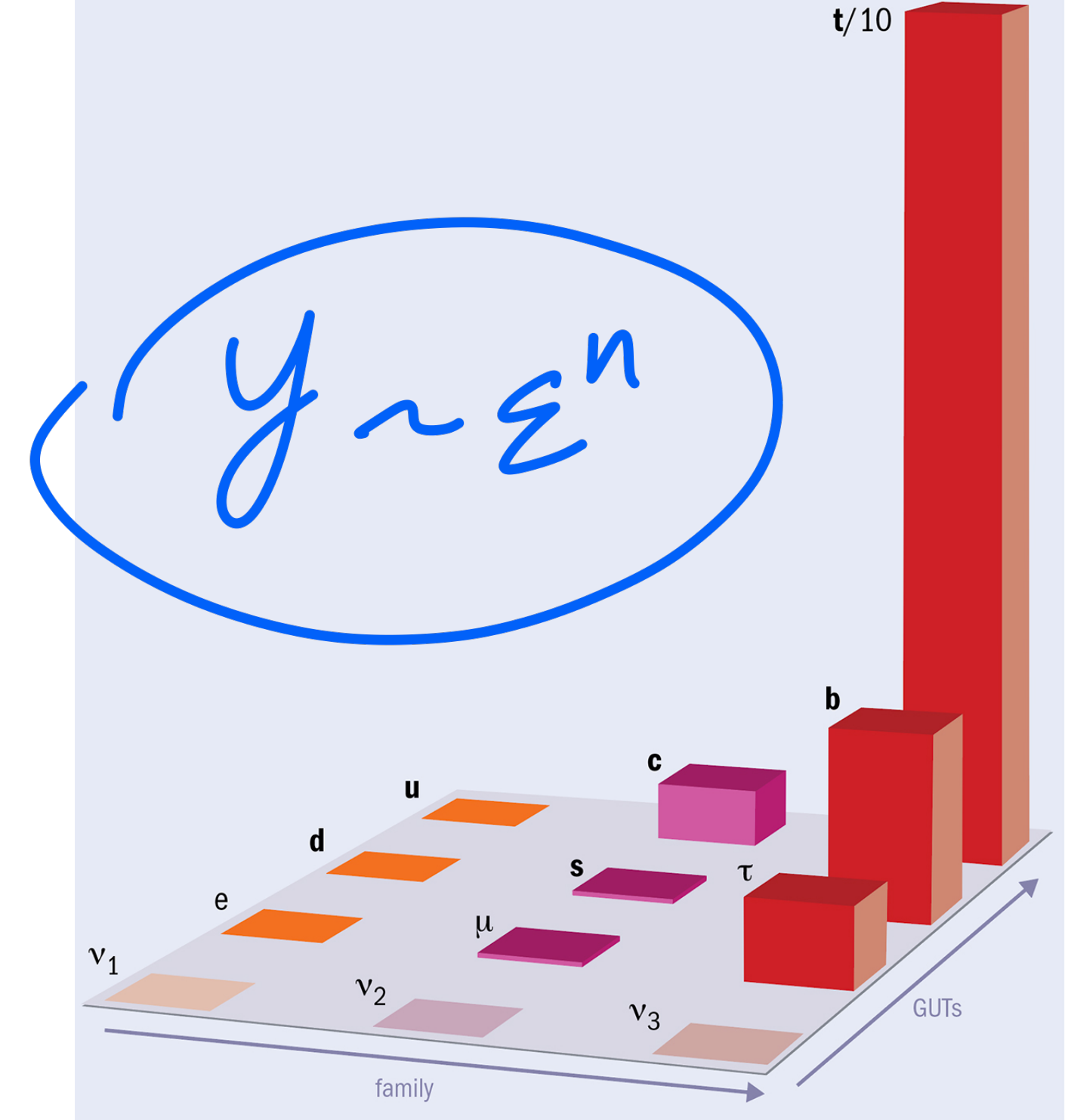
CKM



$$\begin{pmatrix} q_{Q_1} & q_{Q_2} & q_{Q_3} \\ q_u & q_c & q_t \\ q_d & q_s & q_b \end{pmatrix} = \begin{pmatrix} 3 & 2 & 0 \\ -5 & -1 & 0 \\ -4 & -3 & -3 \end{pmatrix}$$

$$\begin{pmatrix} q_{L_1} & q_{L_2} & q_{L_3} \\ q_e & q_\mu & q_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ -8 & -5 & -3 \end{pmatrix}$$

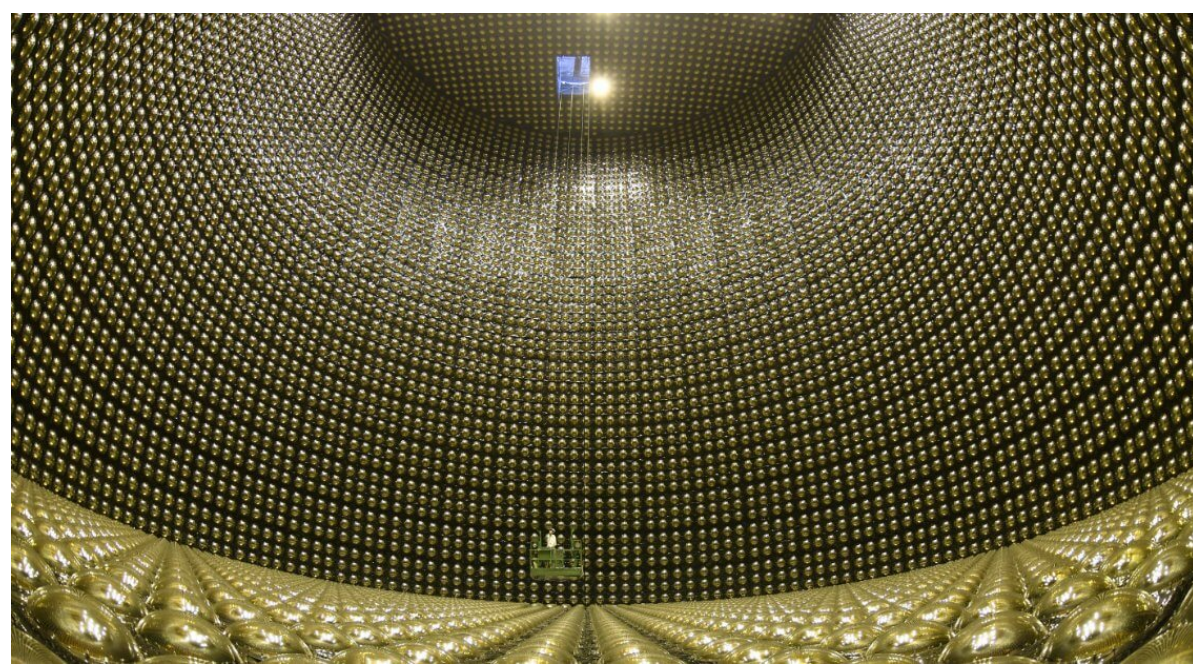
q_L (orange arrow) and q_R (green arrow) are indicated.



$$C \sim O(1)$$

$$\frac{\phi \rightarrow V_\phi}{M} = \varepsilon$$

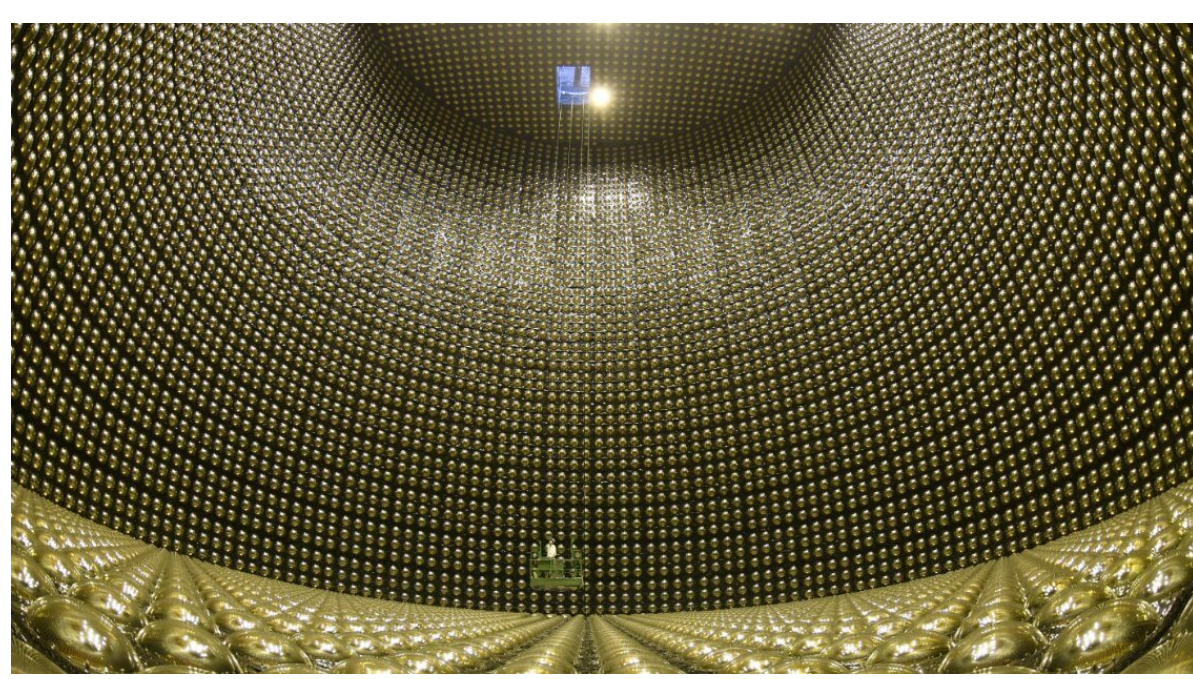
$$q_L - q_R = n$$



Right-handed neutrino and DM

$$\{ N_1 \quad N_2 \quad N_3 \}$$

Heavy



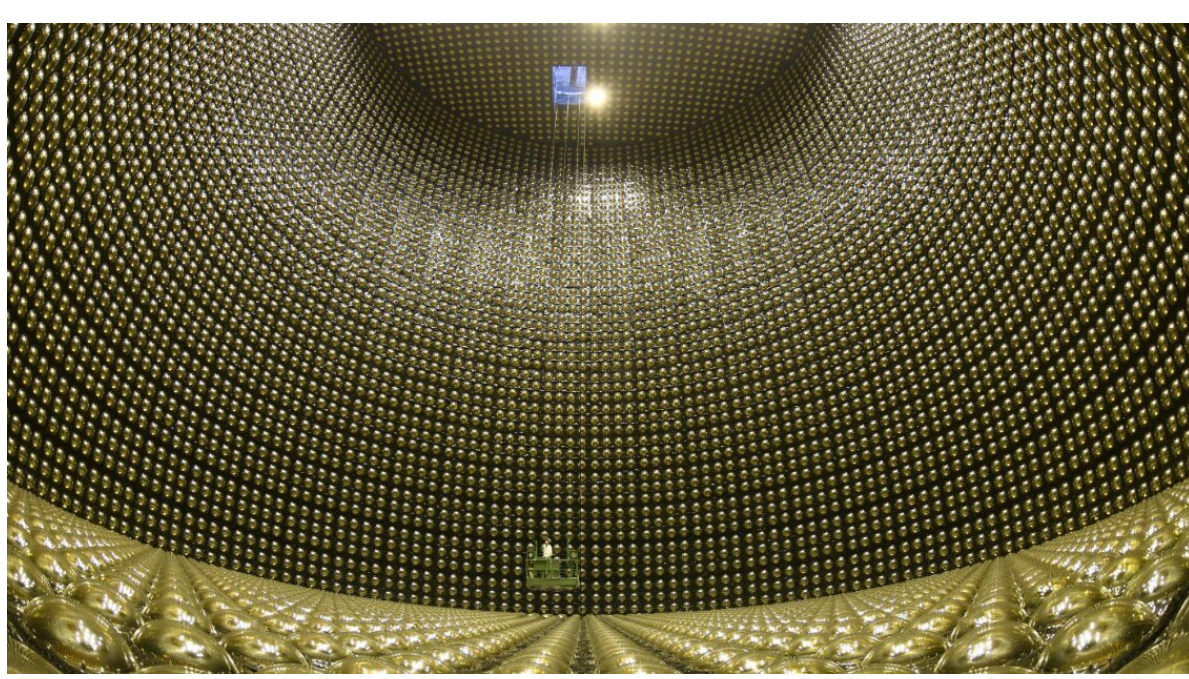
Right-handed neutrino and DM

$$\left\{ N_1 \quad \underbrace{N_2 \quad N_3}_{\text{Heavy}} \right\}$$

$$C_\nu \left(\frac{\phi}{M} \right)^{n_\nu} \bar{L} \tilde{H} N_{2,3}$$

Yukawa = 3 x 2 matrix

$$\begin{pmatrix} \times & \times \\ \times & \times \\ \times & \times \end{pmatrix}$$



Right-handed neutrino and DM

$$\{ N_1 \quad N_2 \quad N_3 \}$$

Heavy

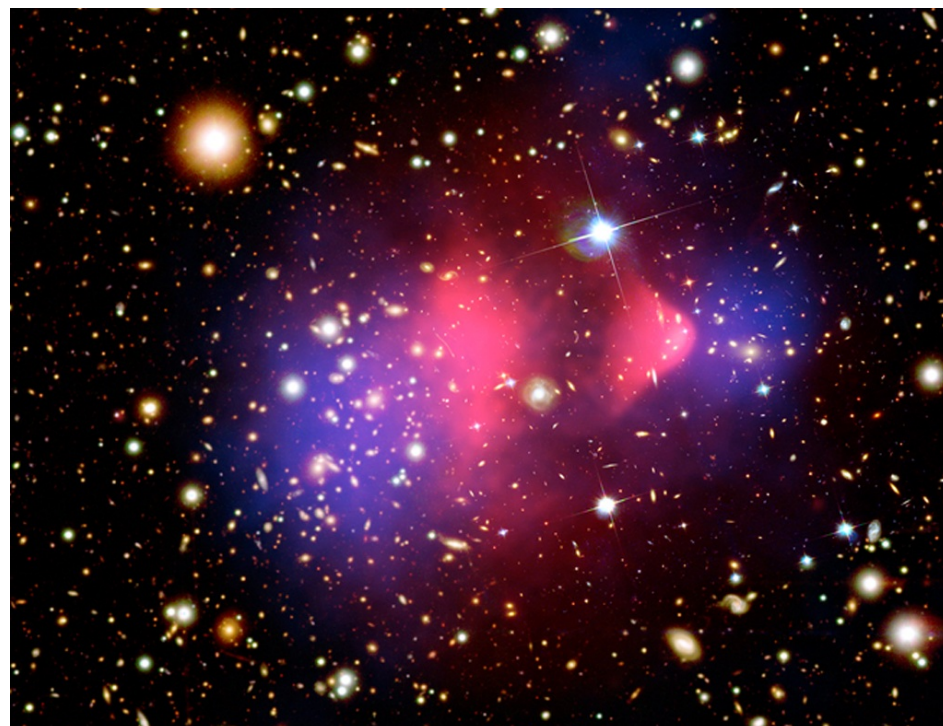
Z_2 symmetry

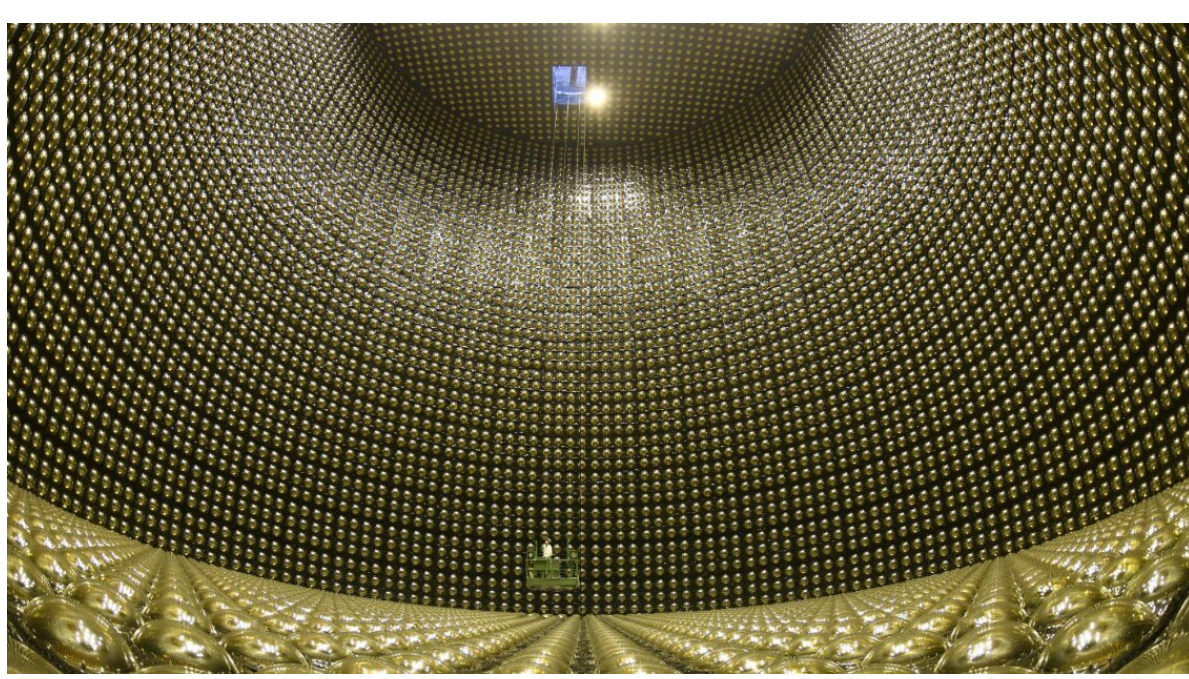
$$C_\nu \left(\frac{\phi}{M} \right)^{n_\nu} \bar{L} \tilde{H} N_{2,3}$$

Yukawa = 3 x 2 matrix

$$\begin{pmatrix} \times & \times \\ \times & \times \\ \times & \times \end{pmatrix}$$

DM





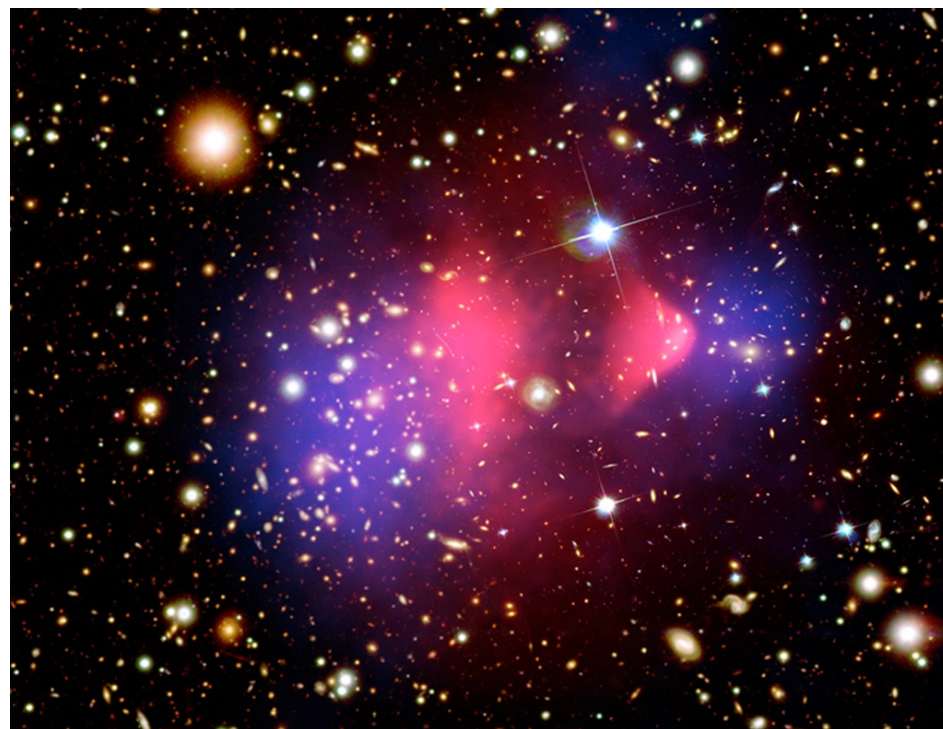
Right-handed neutrino and DM

$\{ N_1 \quad N_2 \quad N_3 \}$

Heavy

Z_2 symmetry

DM



$$C_\nu \left(\frac{\phi}{M} \right)^{n_\nu} \bar{L} \tilde{H} N_{2,3}$$

Yukawa = 3 x 2 matrix

$$\begin{pmatrix} x & x \\ x & x \\ x & x \end{pmatrix}$$

$$\frac{1}{2} C_N \left(\frac{\phi}{M} \right)^{n_N} M \bar{N} N$$

Majorana = 3 x 3 matrix

$$\begin{pmatrix} x & 0 & 0 \\ 0 & x & x \\ 0 & x & x \end{pmatrix}$$

Flavon couplings

$$H \rightarrow v_{EW} + \frac{1}{\sqrt{2}} (h + iG_0)$$

Flavon couplings

$$H \rightarrow v_{EW} + \frac{1}{\sqrt{2}} (h + i G_0)$$

$$\phi \rightarrow v_\phi + \frac{1}{\sqrt{2}} (s + i a)$$

Flavon couplings

$$H \rightarrow v_{EW} + \frac{1}{\sqrt{2}} (h + iG_0)$$

$$\phi \rightarrow v_\phi + \frac{1}{\sqrt{2}} (s + i a)$$

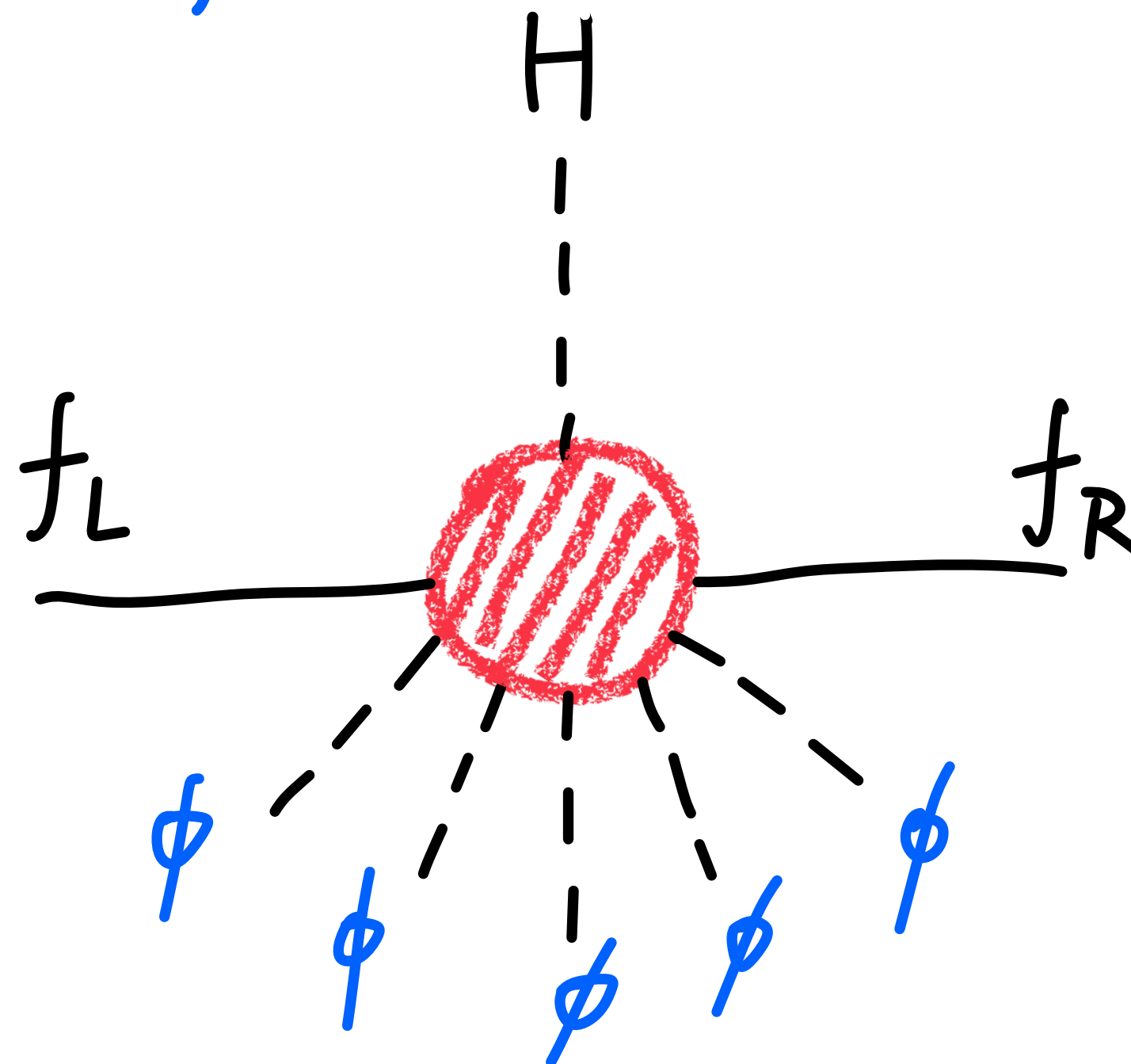
$$\left\{ \begin{array}{l} M_s \sim v_\phi \\ 10 \text{ GeV} \leq m_a \ll M_s \end{array} \right.$$

Flavon couplings

$$H \rightarrow v_{EW} + \frac{1}{\sqrt{2}} (h + iG_0)$$

$$\phi \rightarrow v_\phi + \frac{1}{\sqrt{2}} (s + i a)$$

$$\left\{ \begin{array}{l} M_S \sim v_\phi \\ 10 \text{ GeV} \leq M_a \ll M_S \end{array} \right.$$

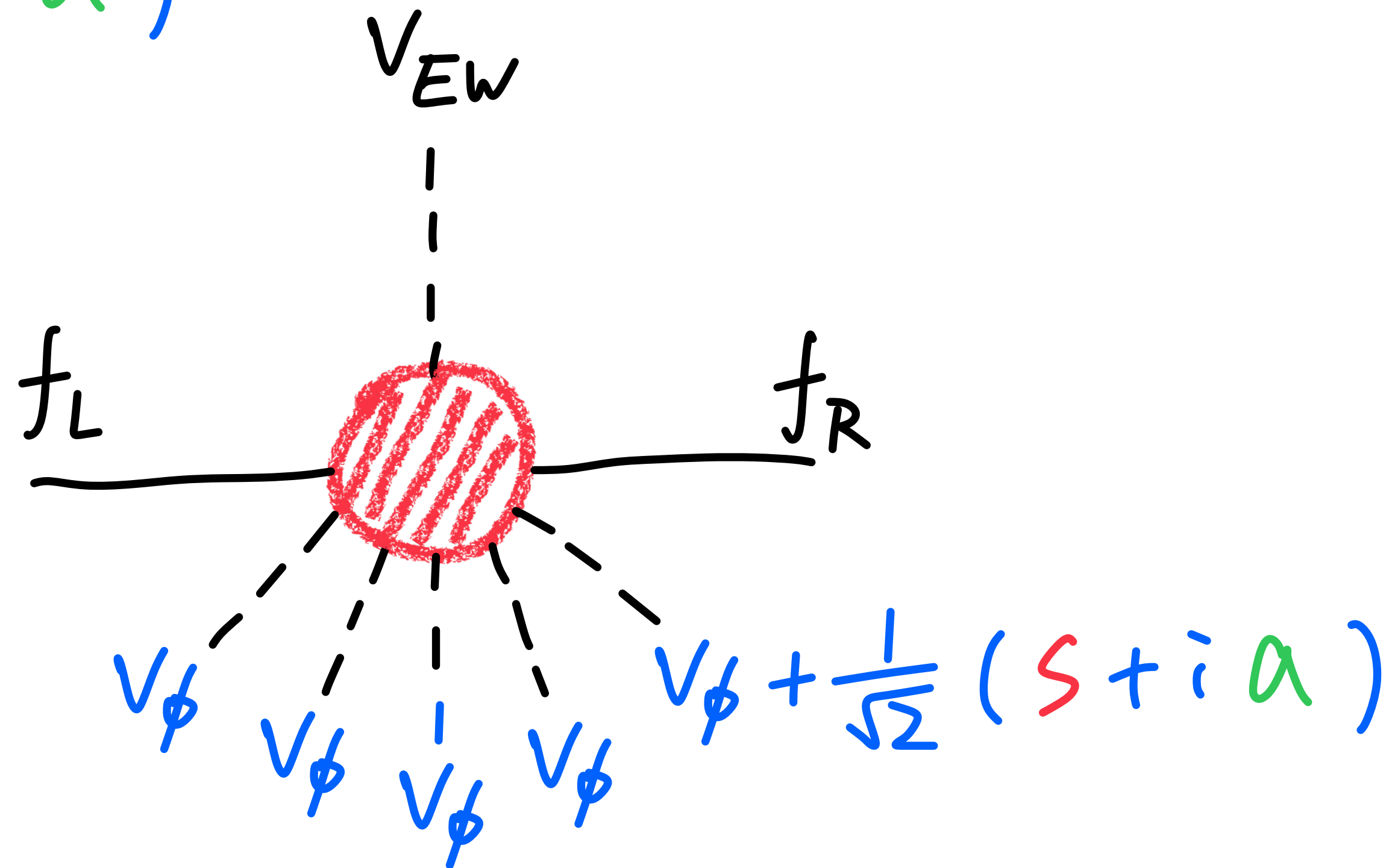


Flavon couplings

$$H \rightarrow V_{EW} + \frac{1}{\sqrt{2}} (h + iG_0)$$

$$\phi \rightarrow V_\phi + \frac{1}{\sqrt{2}} (S + iA)$$

$$\left\{ \begin{array}{l} M_S \sim V_\phi \\ 10 \text{ GeV} \leq M_A \ll M_S \end{array} \right.$$

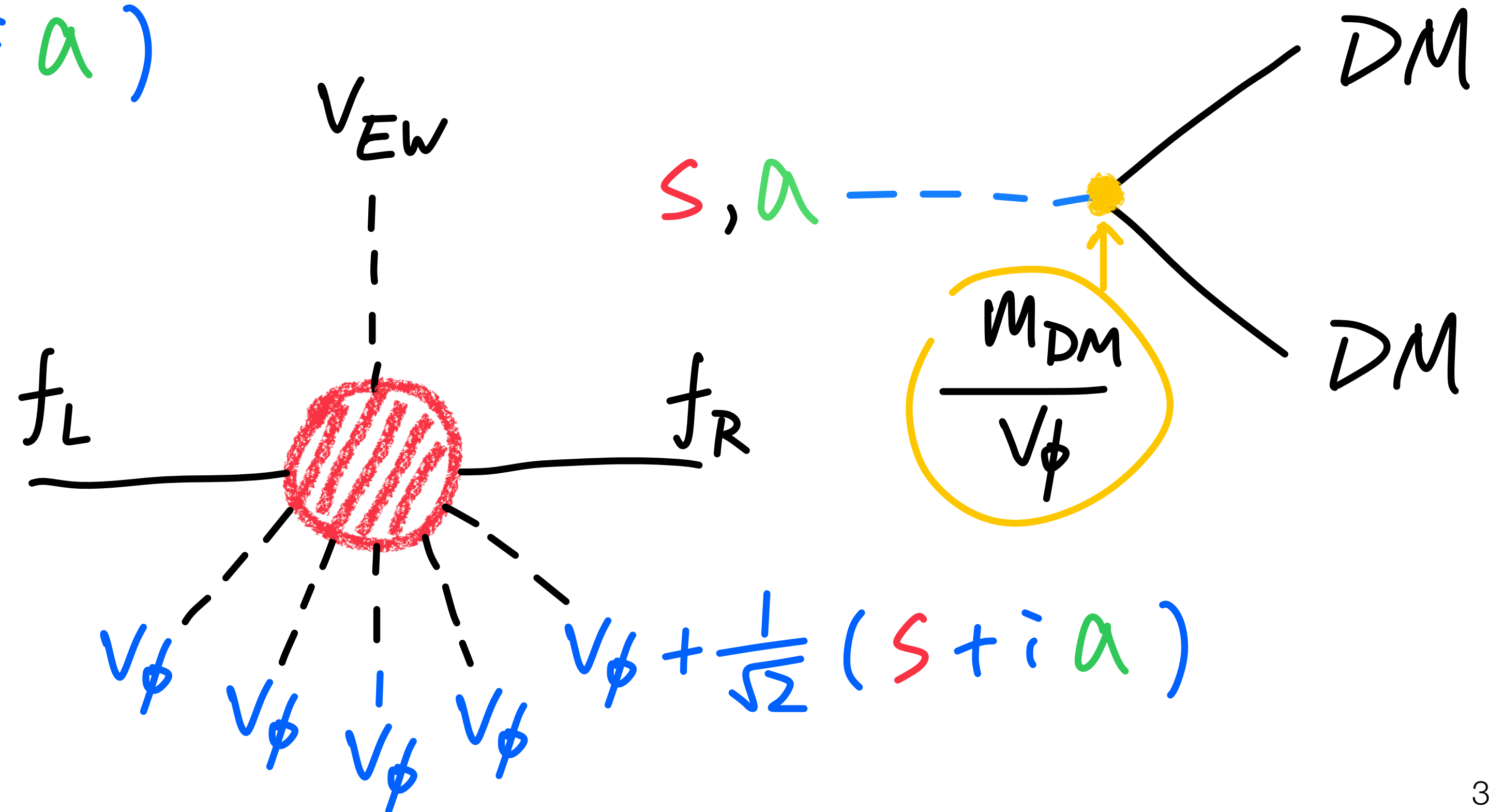


Flavon couplings

$$H \rightarrow V_{EW} + \frac{1}{\sqrt{2}} (h + iG_0)$$

$$\phi \rightarrow V_\phi + \frac{1}{\sqrt{2}} (S + iA)$$

$$\left\{ \begin{array}{l} M_S \sim V_\phi \\ 10 \text{ GeV} \leq M_A \ll M_S \end{array} \right.$$

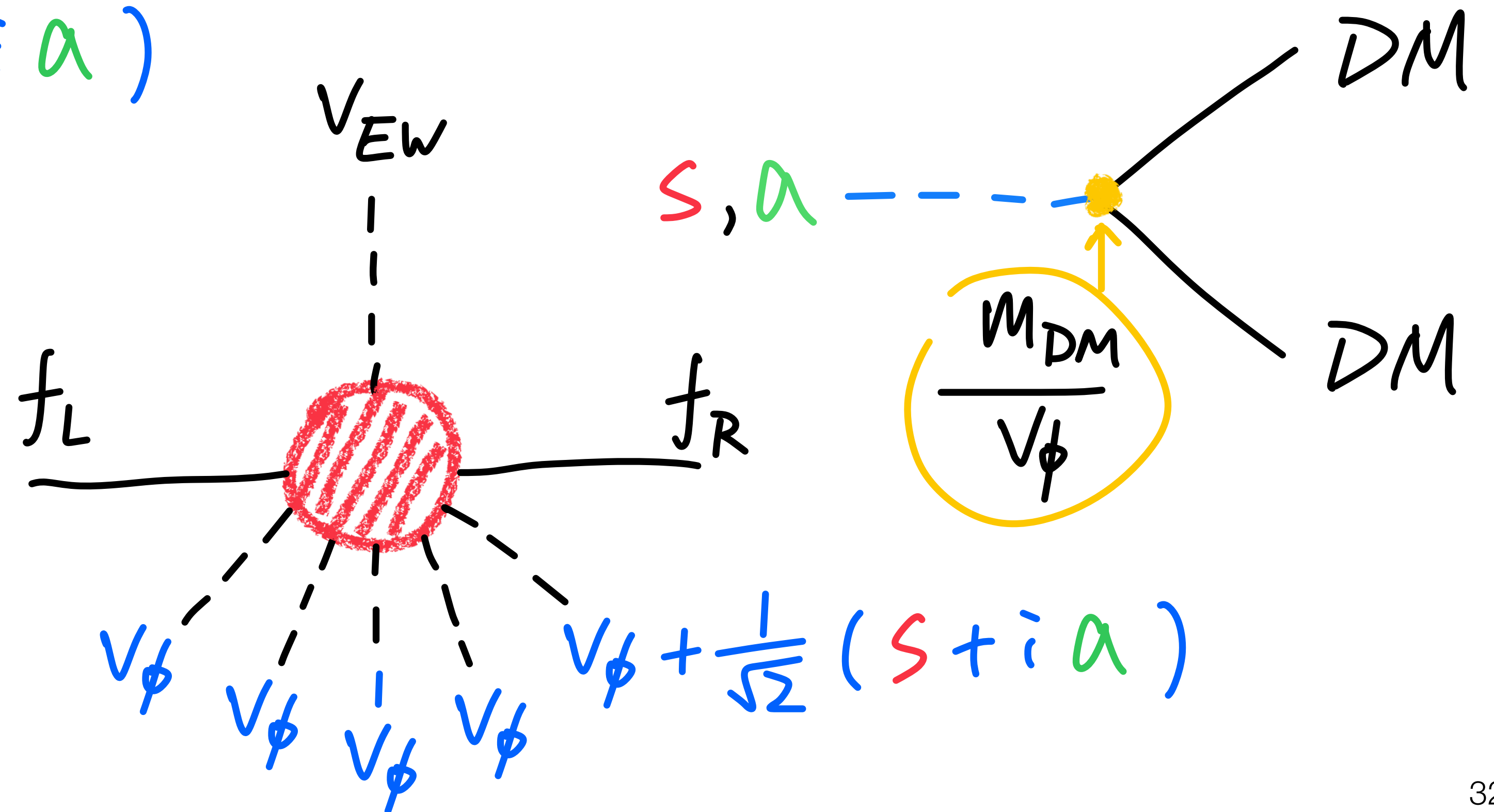
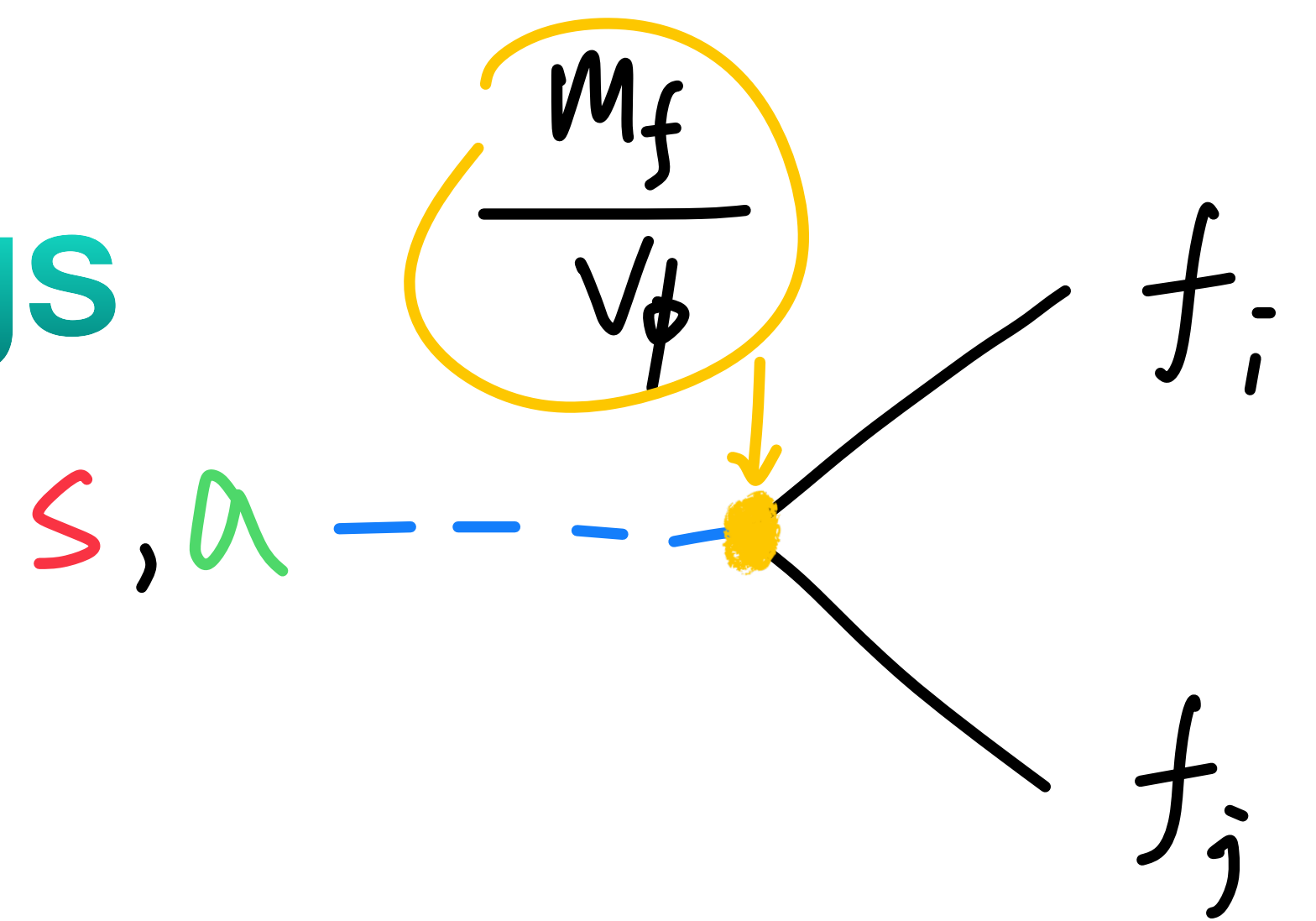


Flavon couplings

$$H \rightarrow V_{EW} + \frac{1}{\sqrt{2}} (h + iG_0)$$

$$\phi \rightarrow V_\phi + \frac{1}{\sqrt{2}} (S + iA)$$

$$\left\{ \begin{array}{l} M_S \sim V_\phi \\ 10 \text{ GeV} \leq M_A \ll M_S \end{array} \right.$$

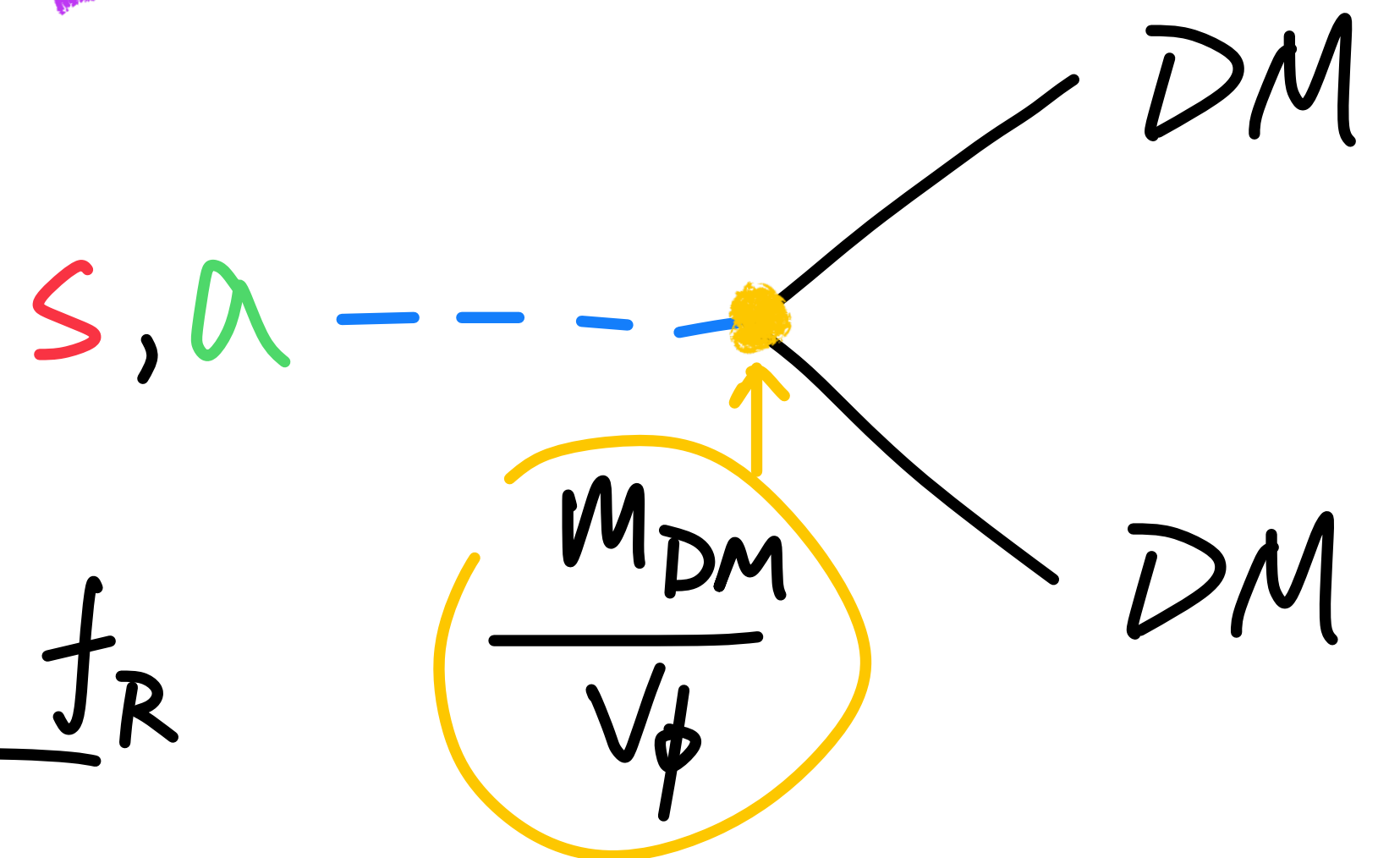
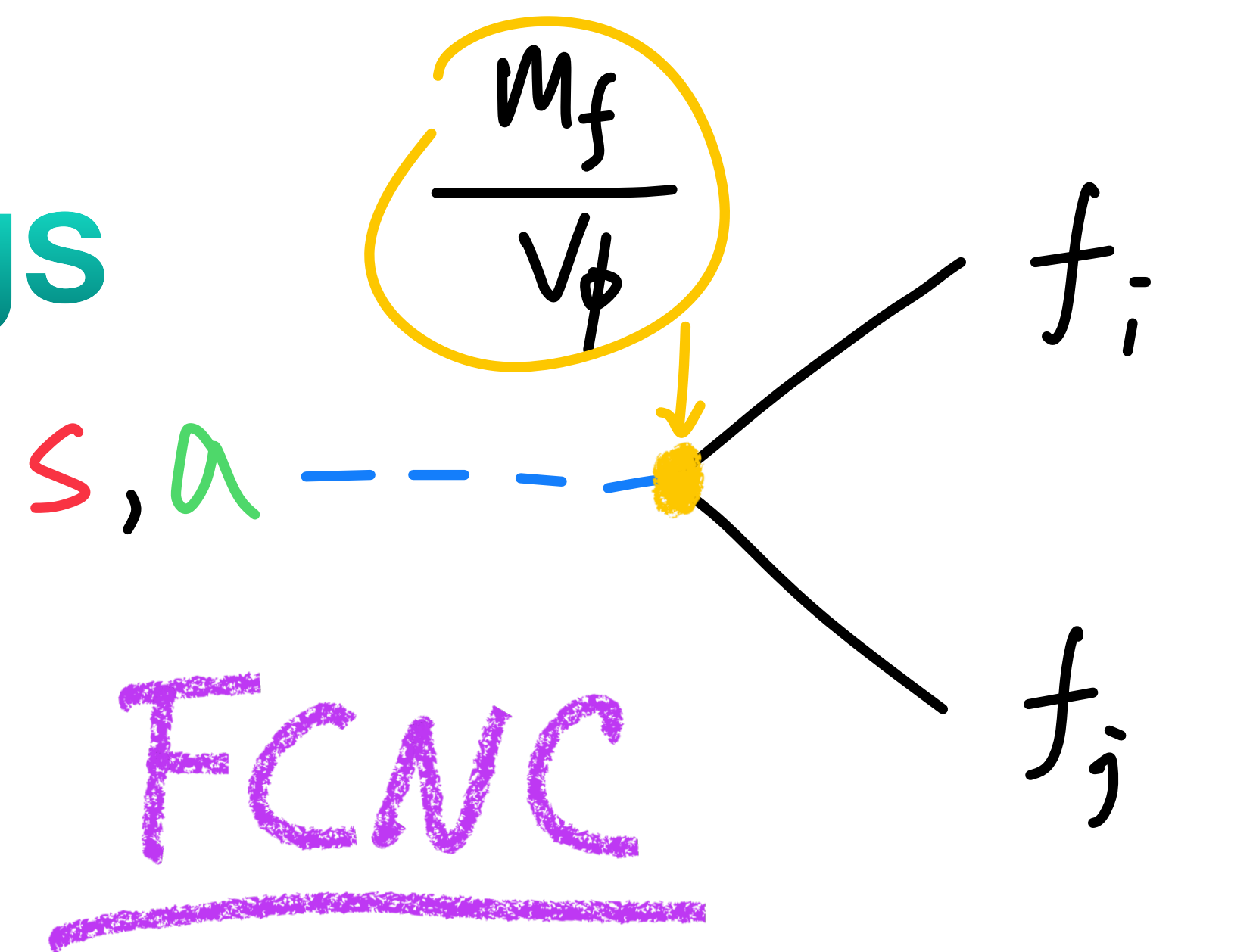
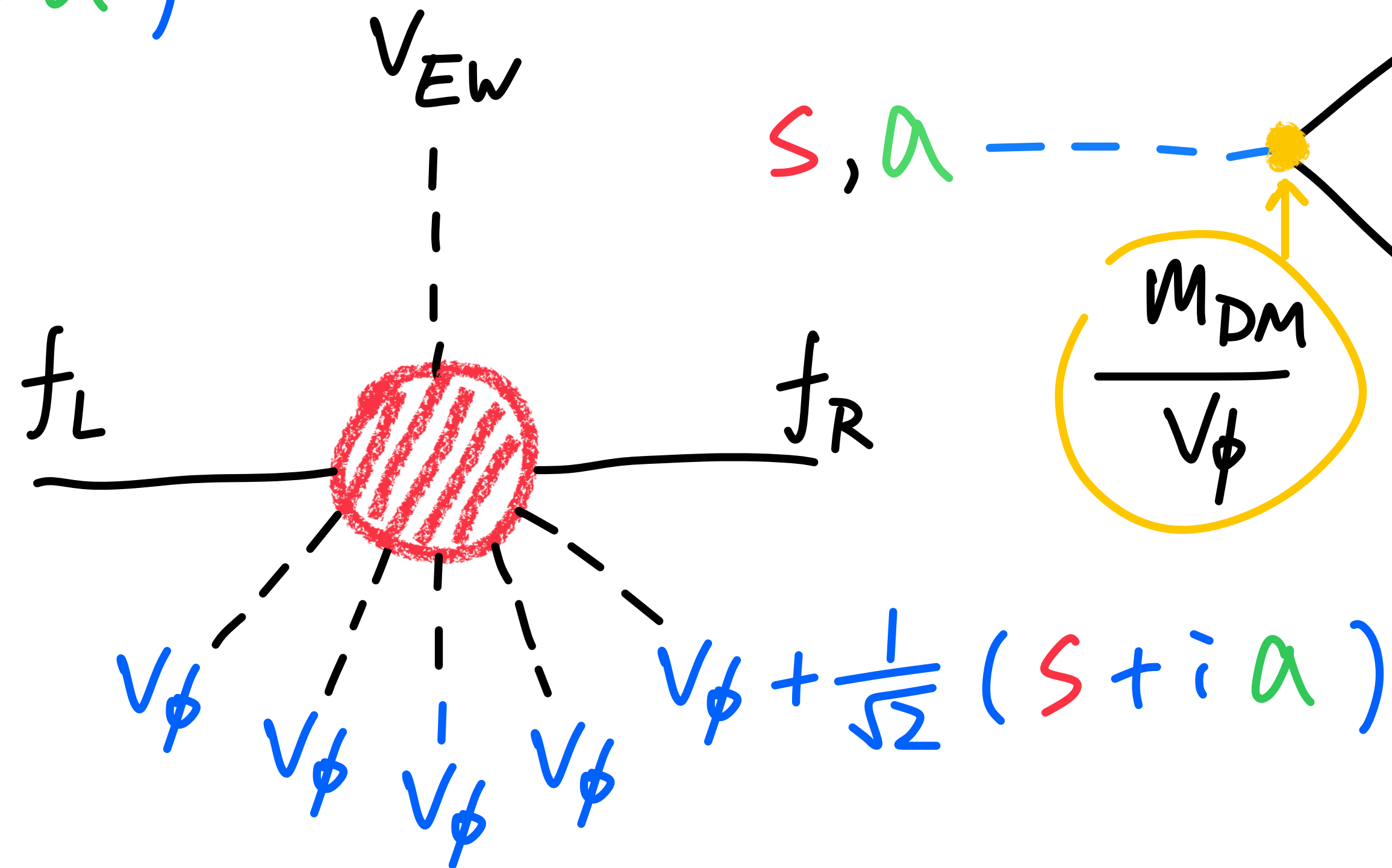


Flavon couplings

$$H \rightarrow V_{EW} + \frac{1}{\sqrt{2}} (h + iG_0)$$

$$\phi \rightarrow V_\phi + \frac{1}{\sqrt{2}} (S + iA)$$

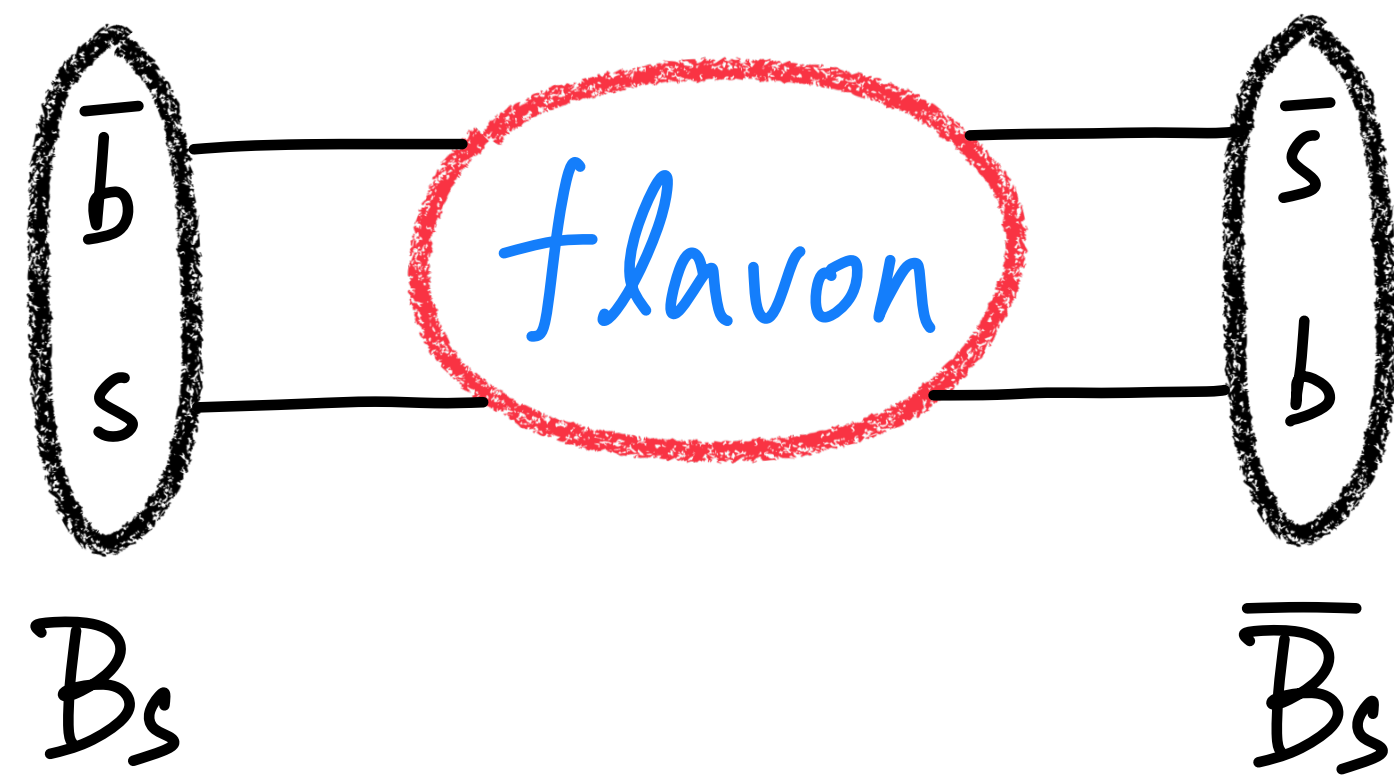
$$\left\{ \begin{array}{l} M_S \sim V_\phi \\ 10 \text{ GeV} \leq M_A \ll M_S \end{array} \right.$$



Experimental constraints

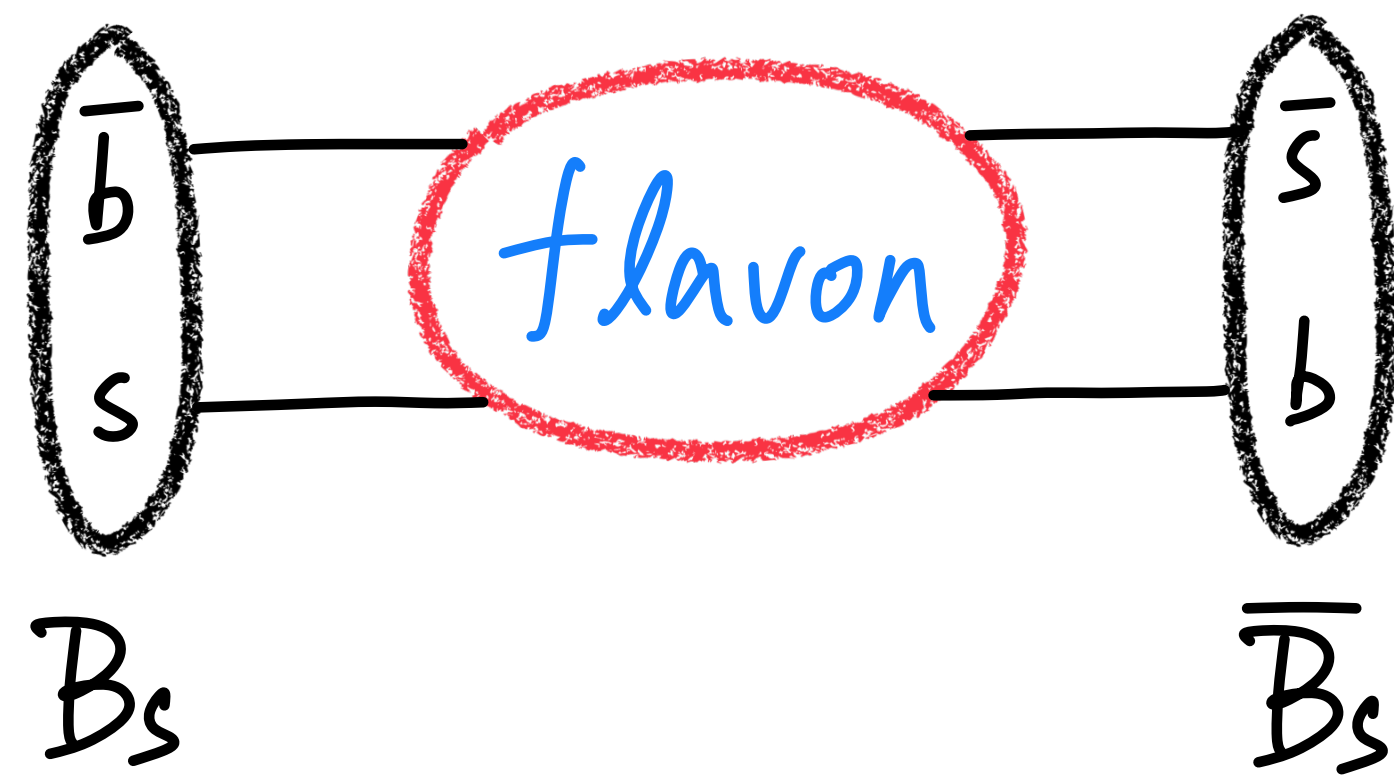
Experimental constraints

B-meson mixing



Experimental constraints

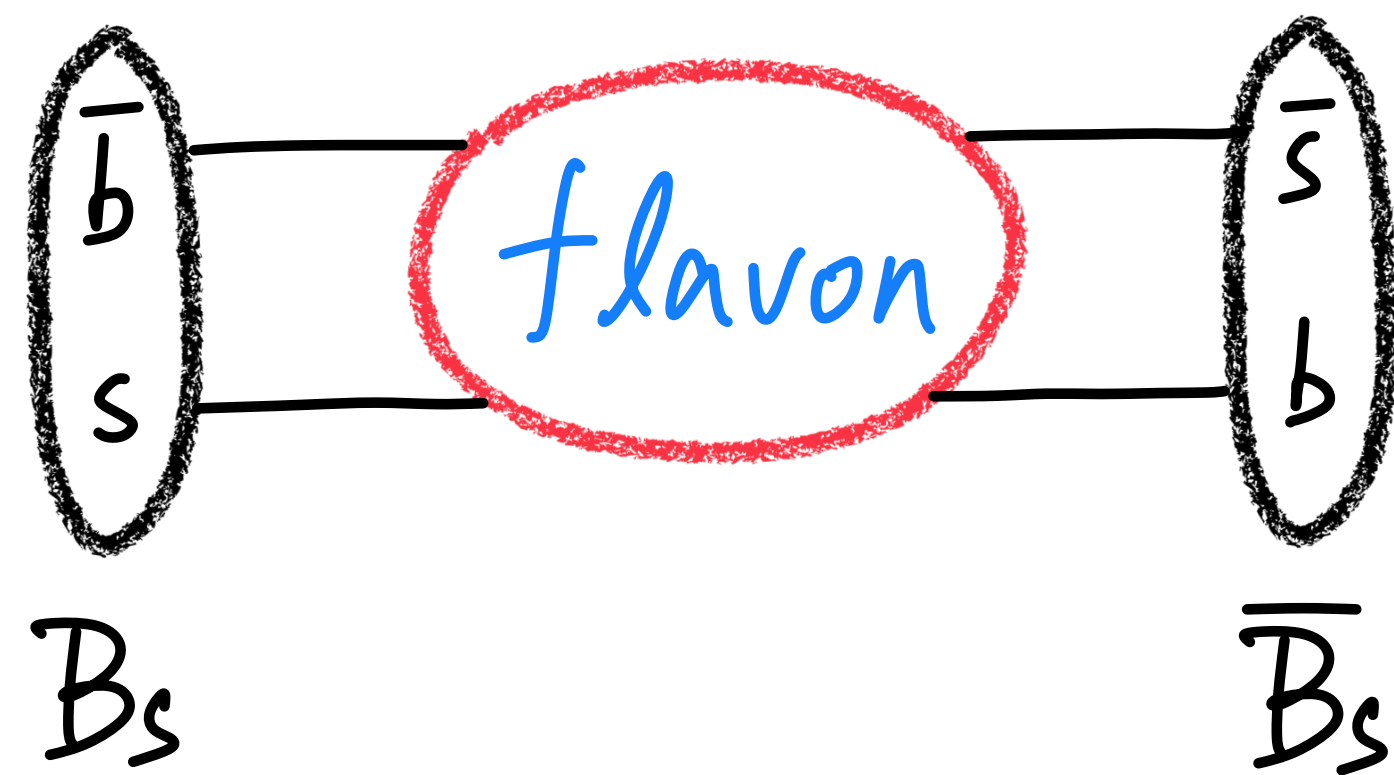
B-meson mixing



$$\left(\frac{M_\alpha}{\text{GeV}} \right) \times \left(\frac{V_\phi}{\text{TeV}} \right) \geq 180$$

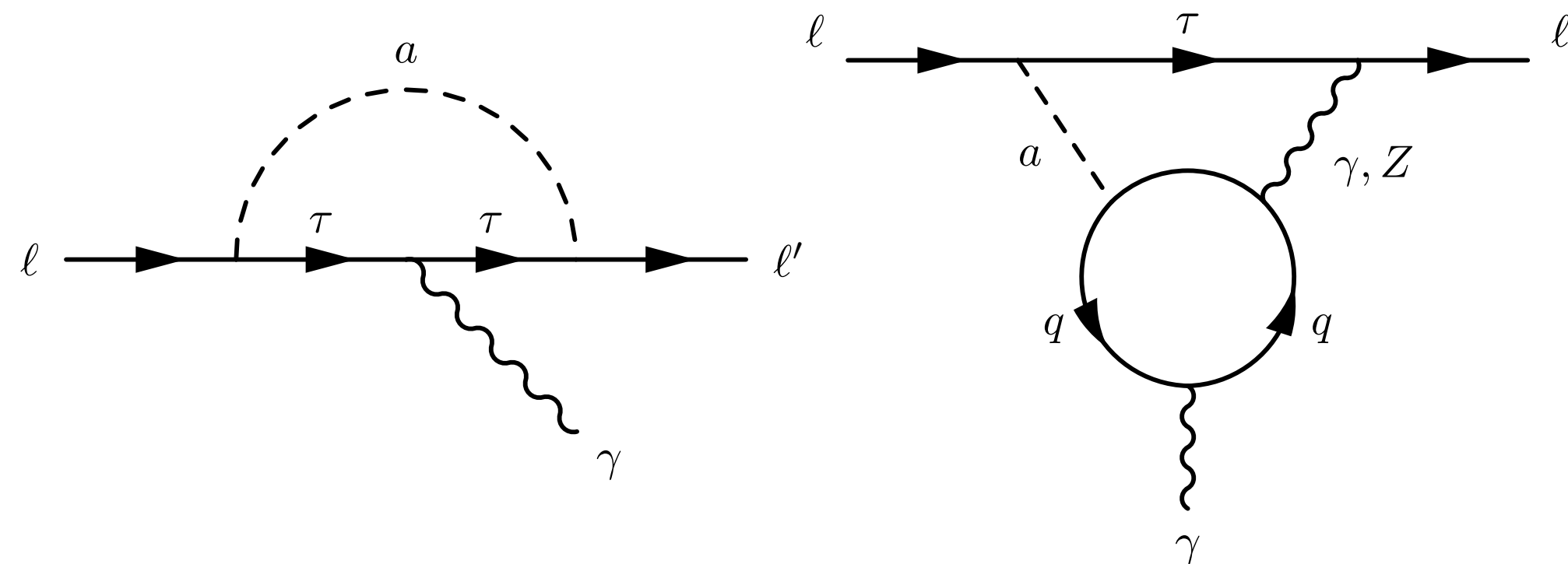
Experimental constraints

B-meson mixing



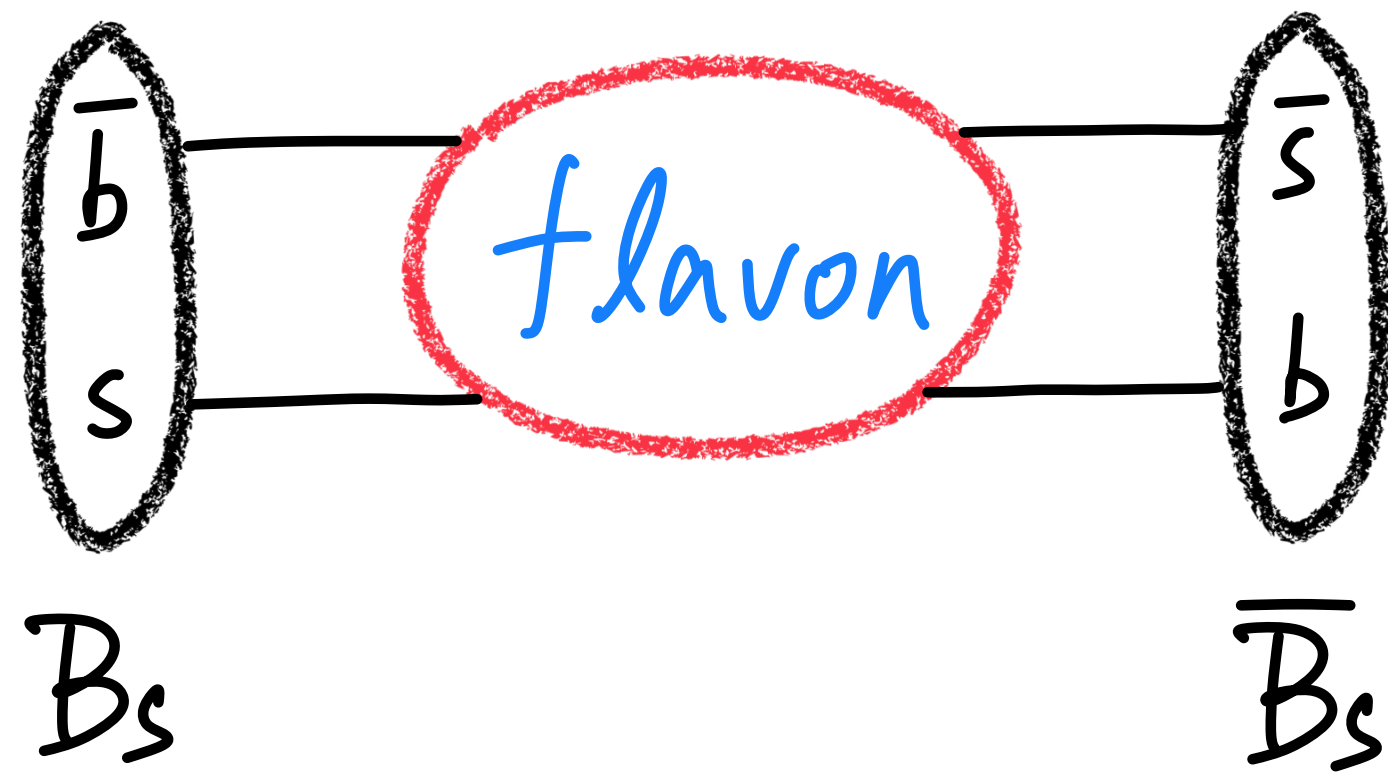
$$\left(\frac{M_\alpha}{\text{GeV}} \right) \times \left(\frac{V_\phi}{\text{TeV}} \right) \geq 180$$

$\mu \rightarrow e \gamma$ (MEG)



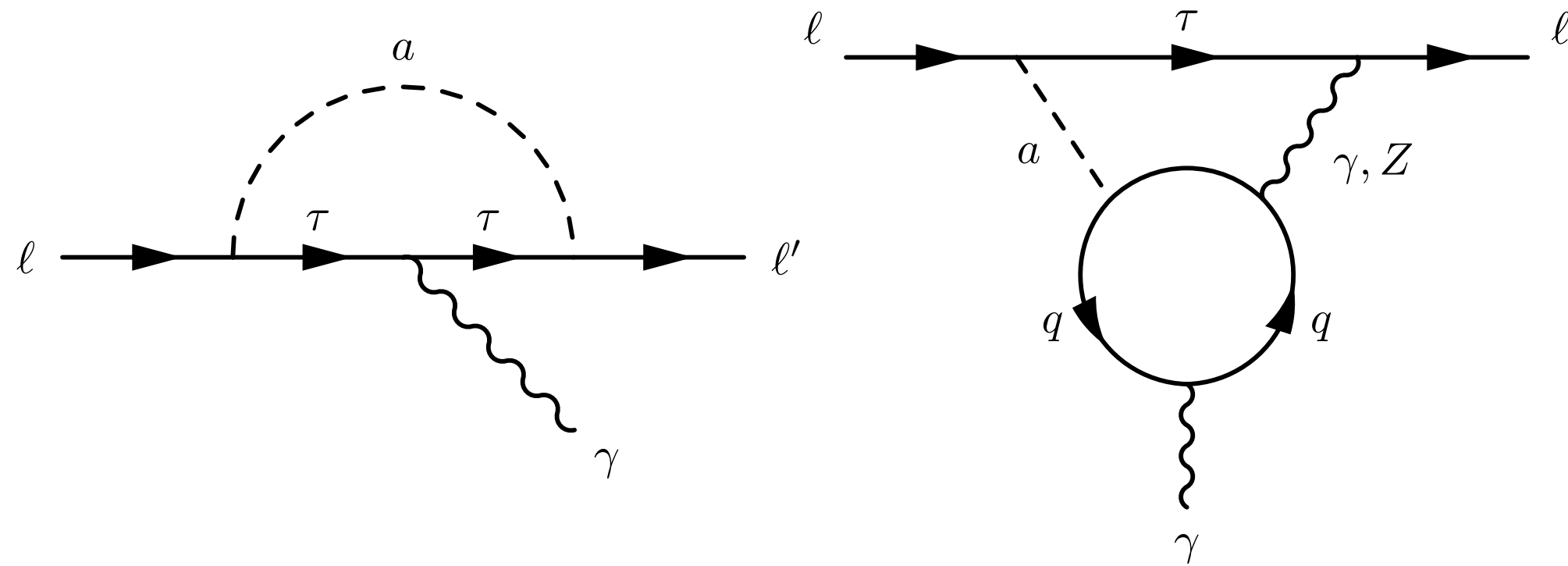
Experimental constraints

B-meson mixing



$$\left(\frac{M_\alpha}{\text{GeV}} \right) \times \left(\frac{V_\phi}{\text{TeV}} \right) \geq 180$$

$\mu \rightarrow e \gamma$ (MEG)

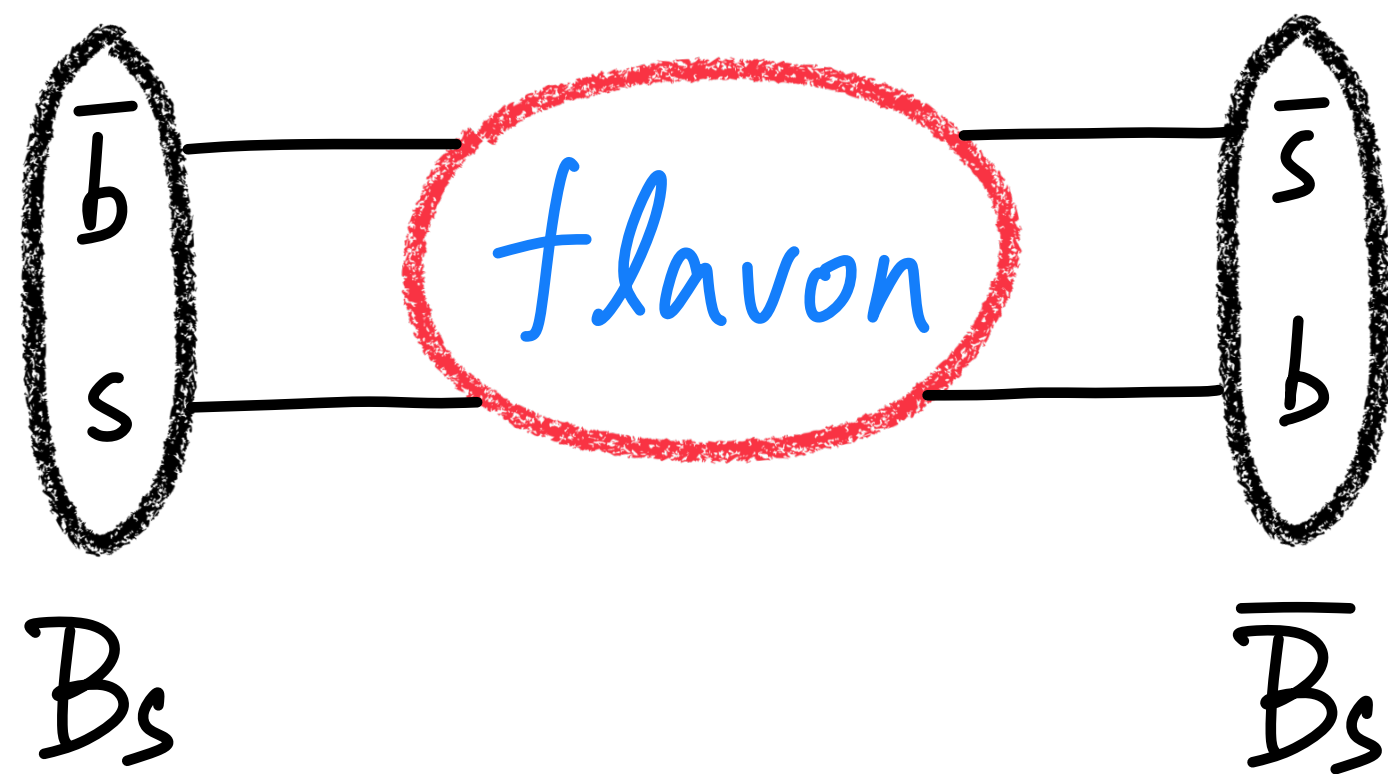


$$\left(\frac{M_\alpha}{\text{GeV}} \right) \times \left(\frac{V_\phi}{\text{TeV}} \right) \geq 190^*$$

* For $M_\alpha \lesssim 100 \text{ GeV}$

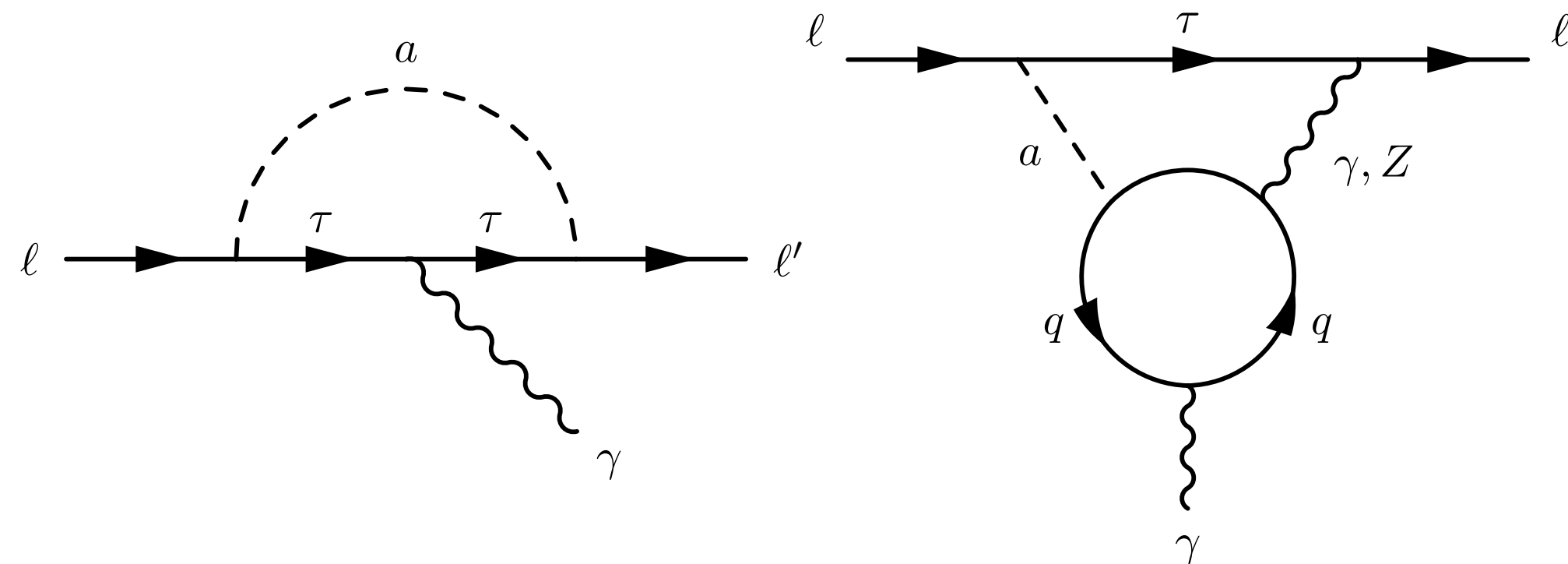
Experimental constraints

B-meson mixing



$$\left(\frac{M_\alpha}{\text{GeV}} \right) \times \left(\frac{V_\phi}{\text{TeV}} \right) \geq 180$$

$\mu \rightarrow e \gamma$ (MEG)



$$\left(\frac{M_\alpha}{\text{GeV}} \right) \times \left(\frac{V_\phi}{\text{TeV}} \right) \geq 190^*$$

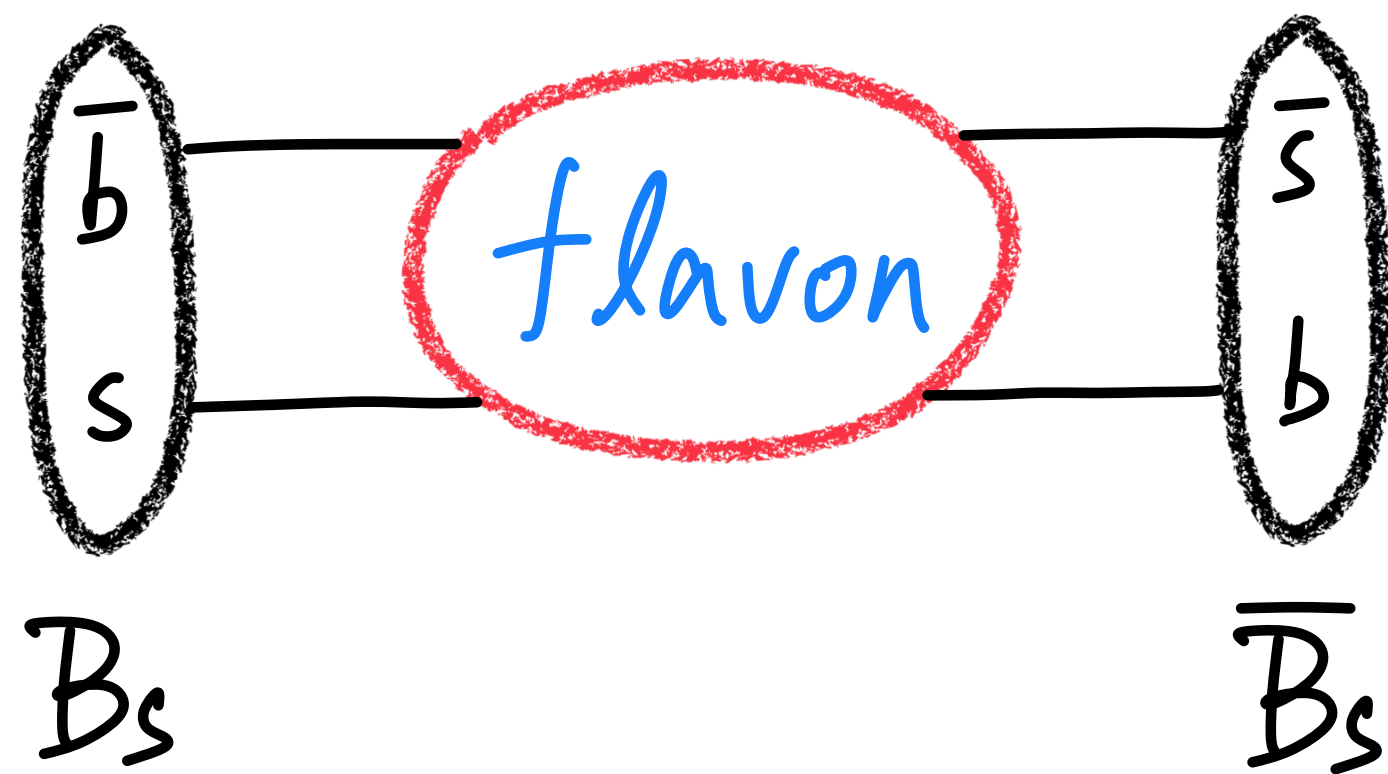
* For $M_\alpha \lesssim 100 \text{ GeV}$

Top decay
ATLAS

$$\text{Br}(t \rightarrow c a) \times \text{Br}(a \rightarrow b \bar{b})$$

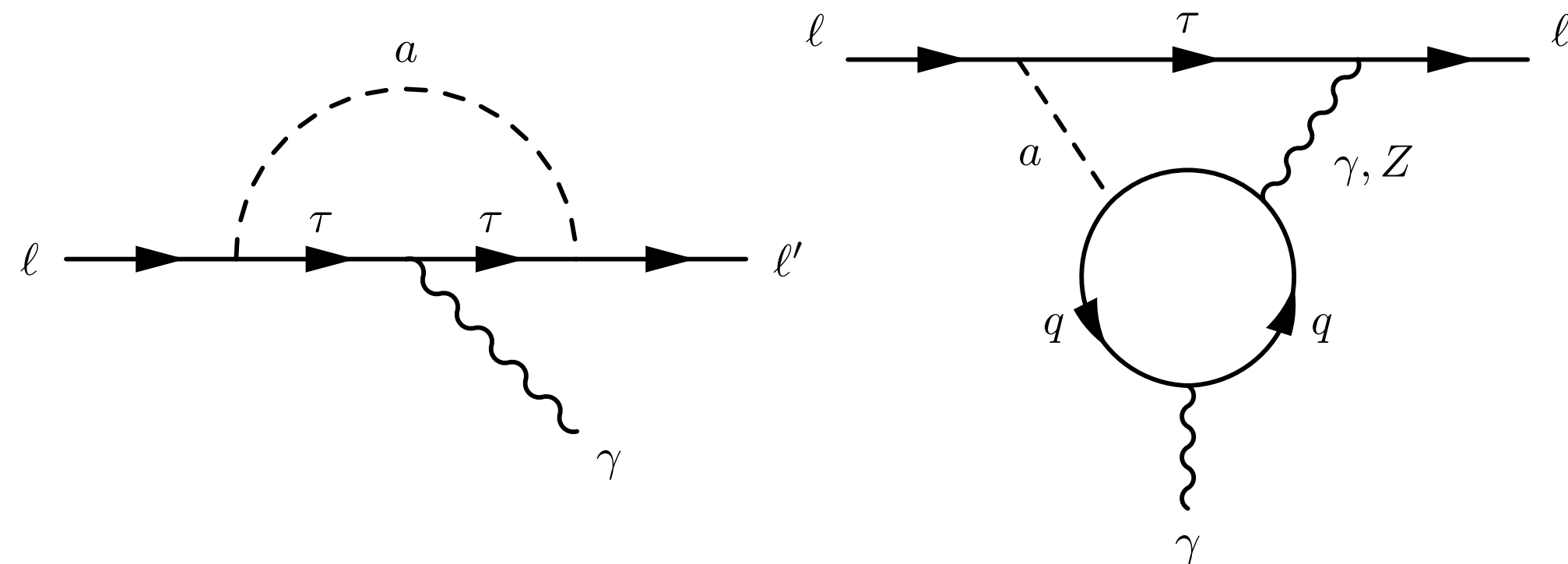
Experimental constraints

B-meson mixing



$$\left(\frac{M_a}{\text{GeV}} \right) \times \left(\frac{V_\phi}{\text{TeV}} \right) \geq 180$$

$\mu \rightarrow e \gamma$ (MEG)

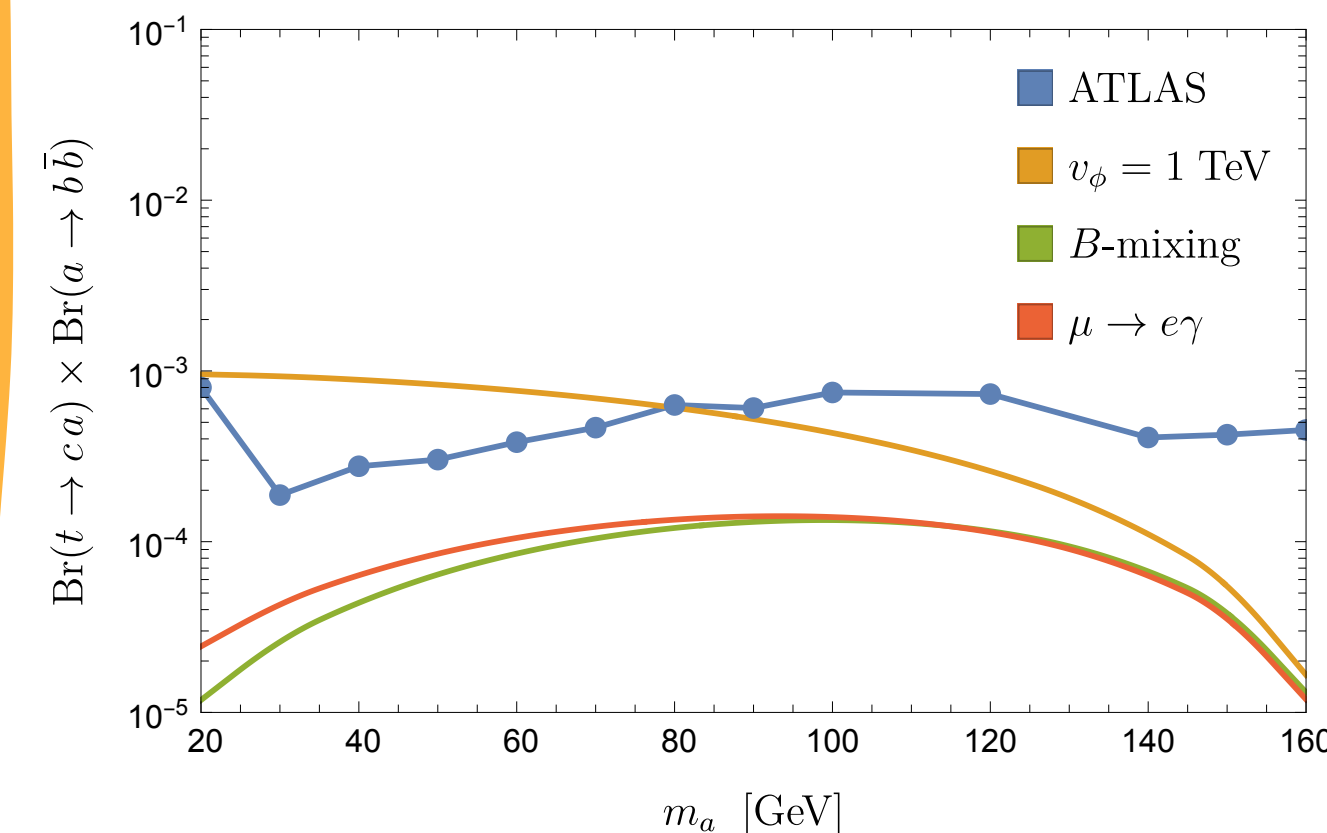


$$\left(\frac{M_a}{\text{GeV}} \right) \times \left(\frac{V_\phi}{\text{TeV}} \right) \geq 190^*$$

* For $M_a \lesssim 100 \text{ GeV}$

Top decay
ATLAS

$$\text{Br}(t \rightarrow c a) \times \text{Br}(a \rightarrow b \bar{b})$$



EFT... at what scale? $V_\phi = ?$

EFT... at what scale? $V_\phi = ?$

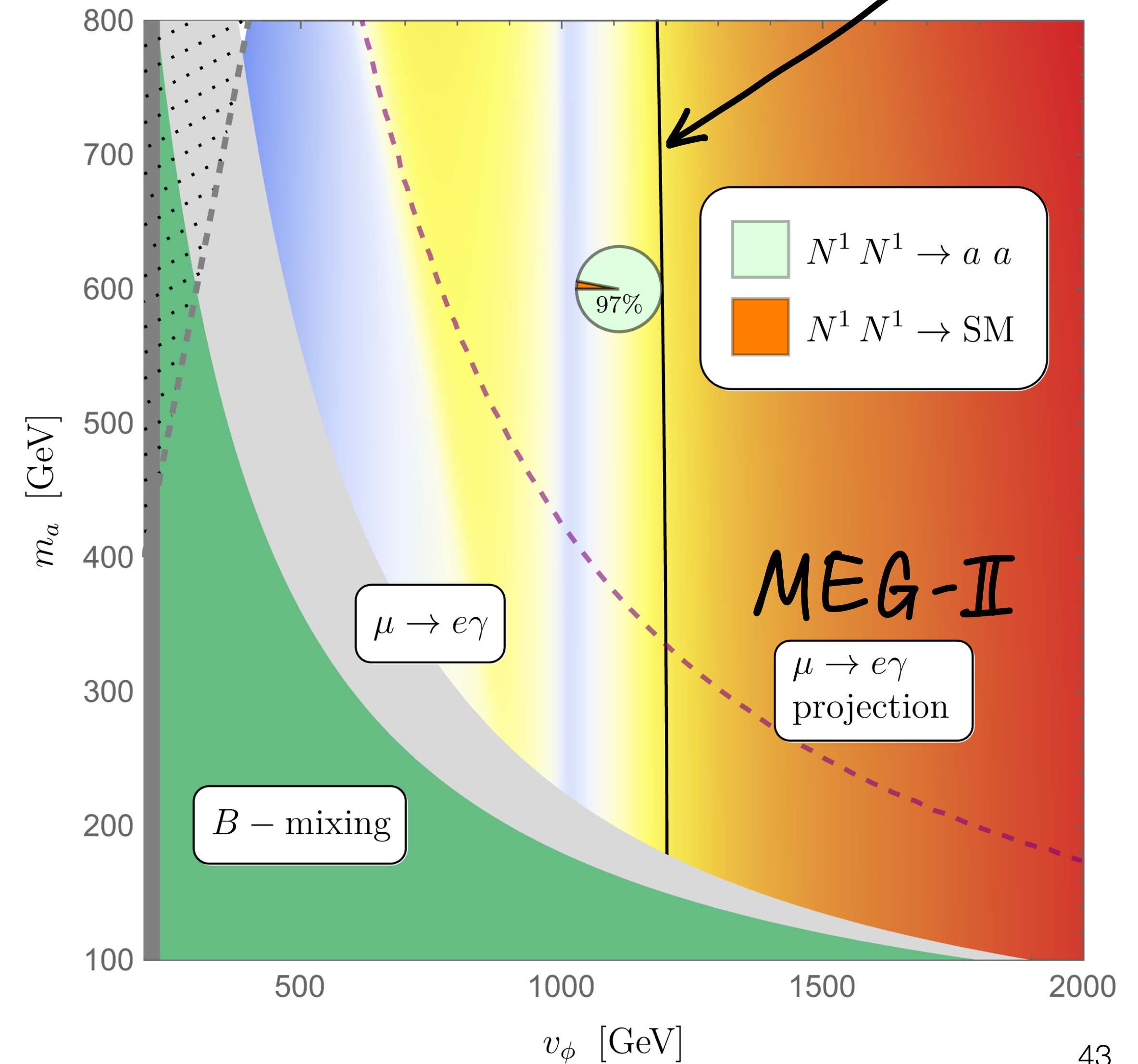
Freeze out
Freeze in
and the Flavon

One model working at two scales

TeV scale: freeze out

m_a vs V_ϕ

$$\Omega h^2 = 0.12$$

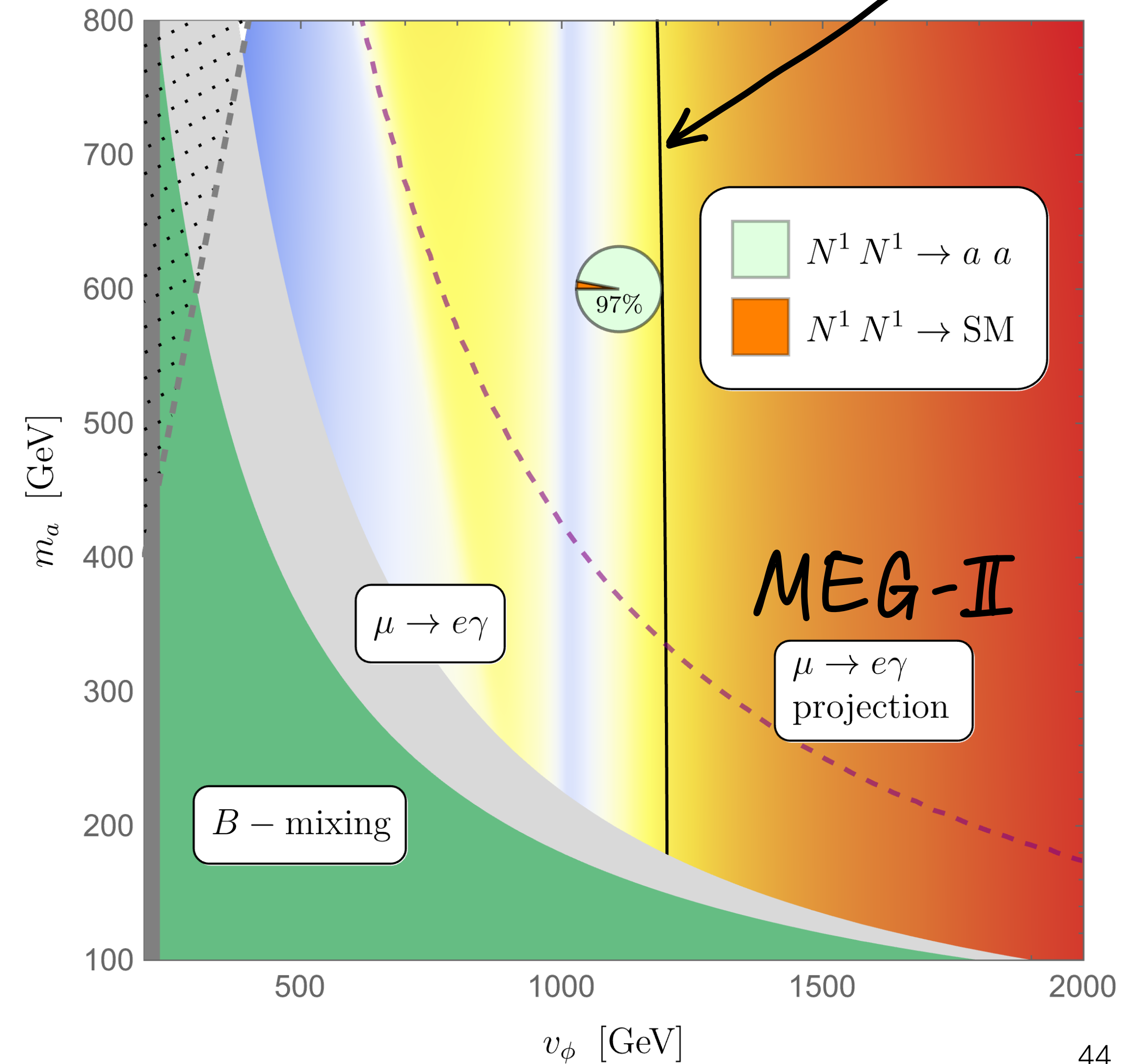


TeV scale: freeze out

m_a vs V_ϕ

$$\Omega h^2 = 0.12$$

$$\left(\frac{m_a}{\text{GeV}} \right) \times \left(\frac{V_\phi}{\text{TeV}} \right) \geq \begin{cases} 180 & B_s \\ 190^* & u \rightarrow e\gamma \end{cases}$$

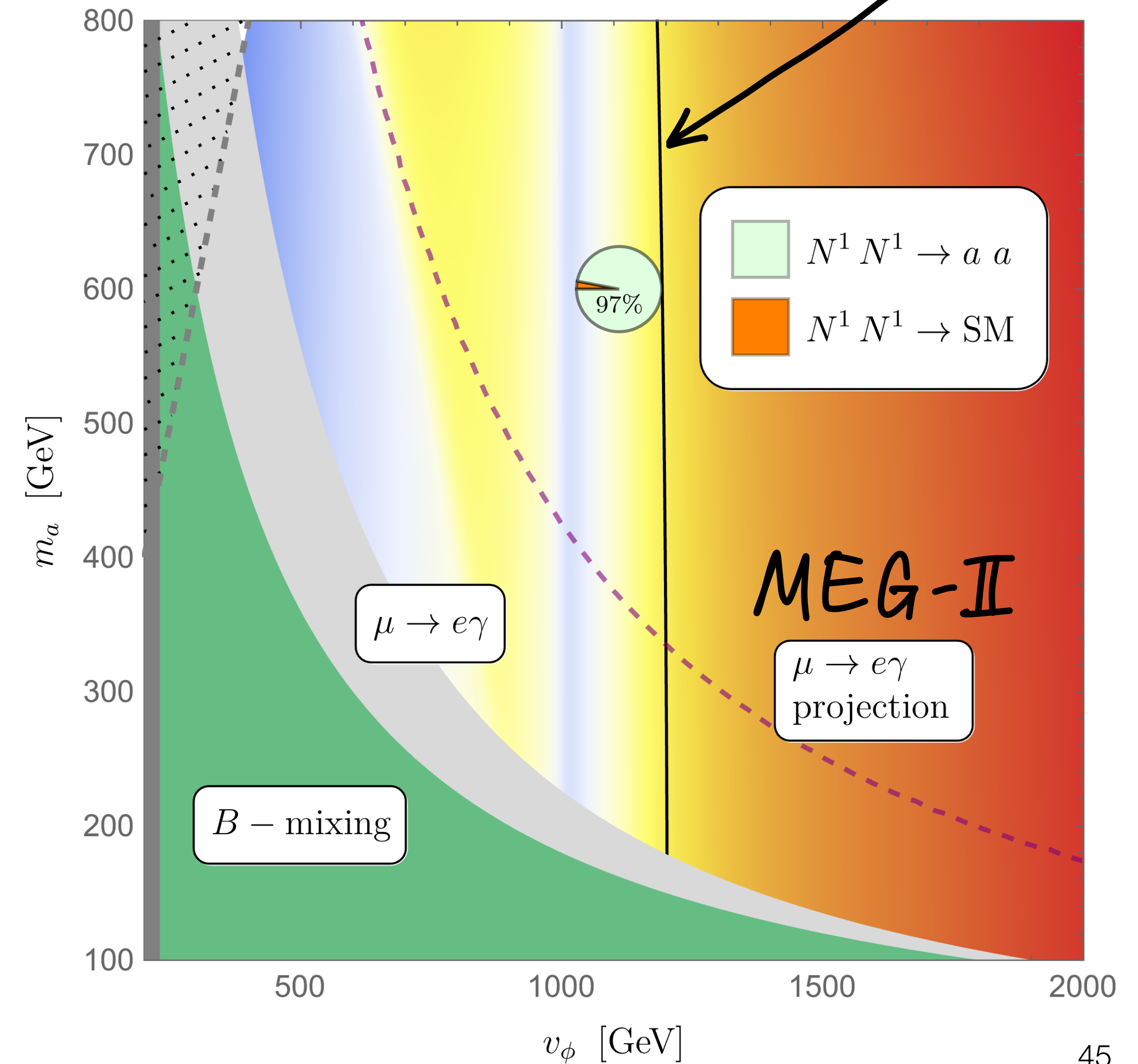
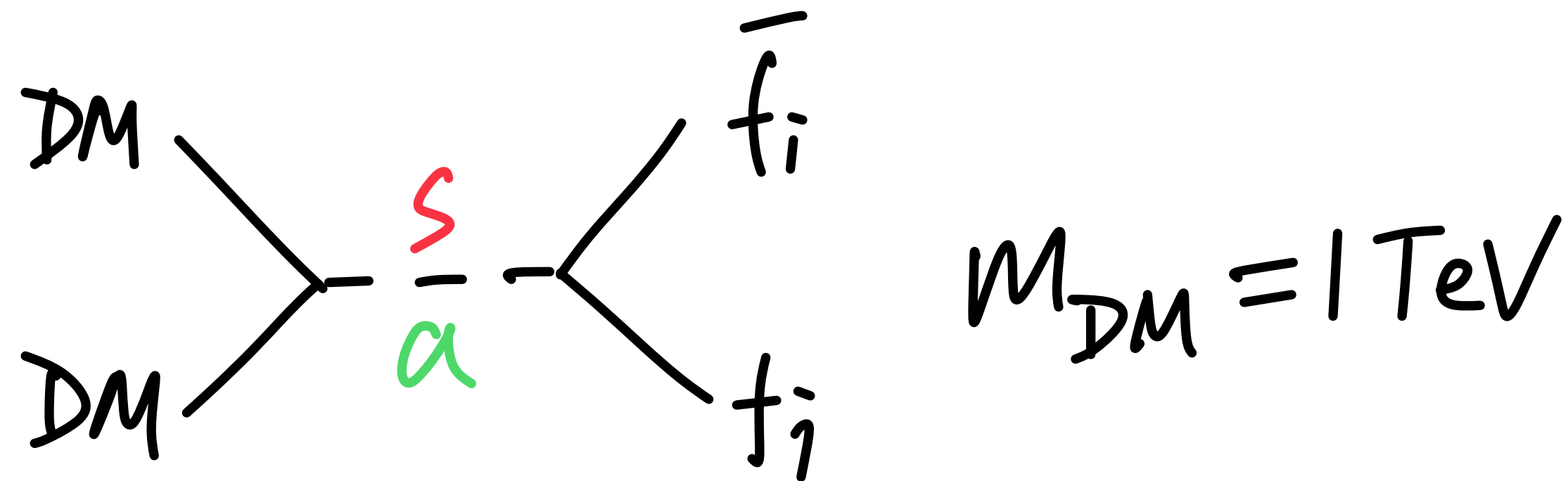


TeV scale: freeze out

m_a vs V_ϕ

$$\Omega h^2 = 0.12$$

$$\left(\frac{m_a}{\text{GeV}} \right) \times \left(\frac{V_\phi}{\text{TeV}} \right) \geq \begin{cases} 180 & B_s \\ 190^* & u \rightarrow e\gamma \end{cases}$$

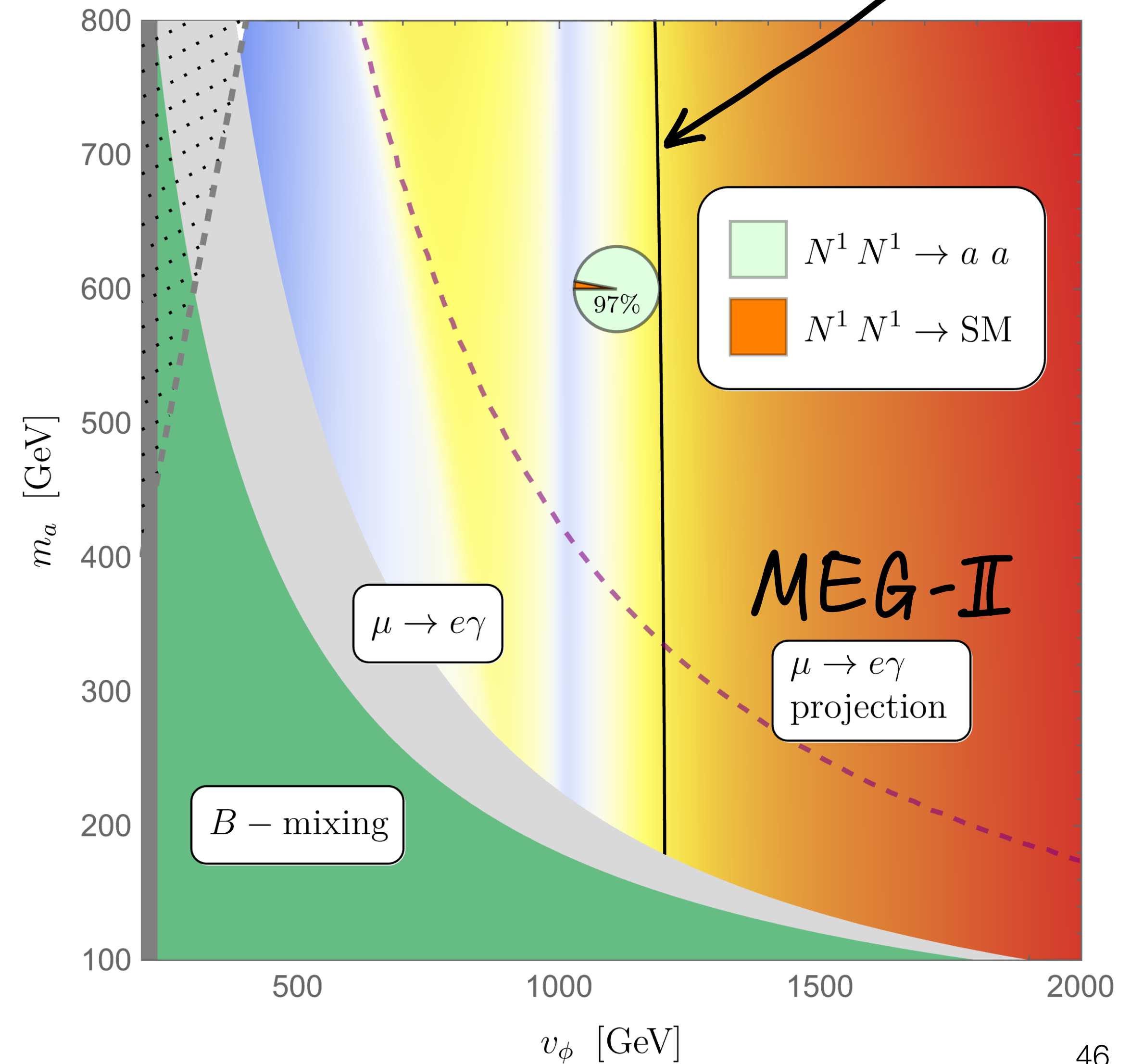
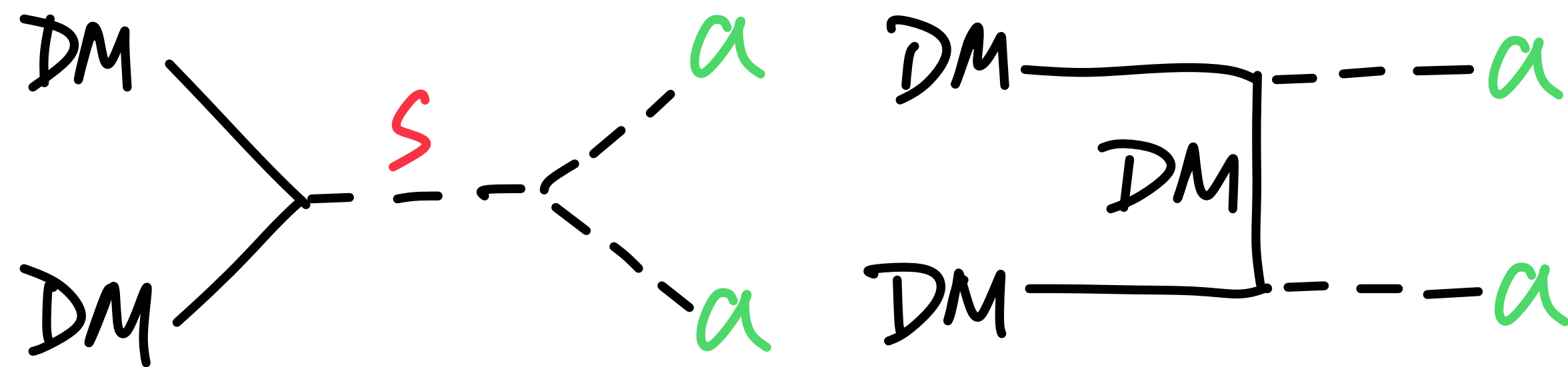
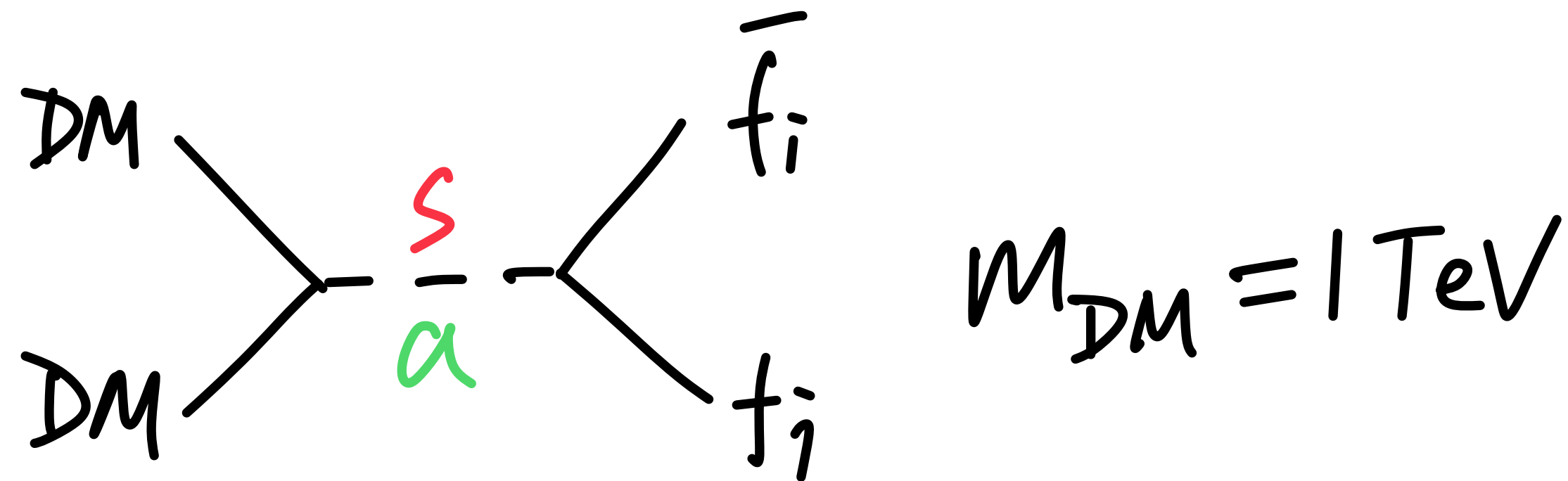


TeV scale: freeze out

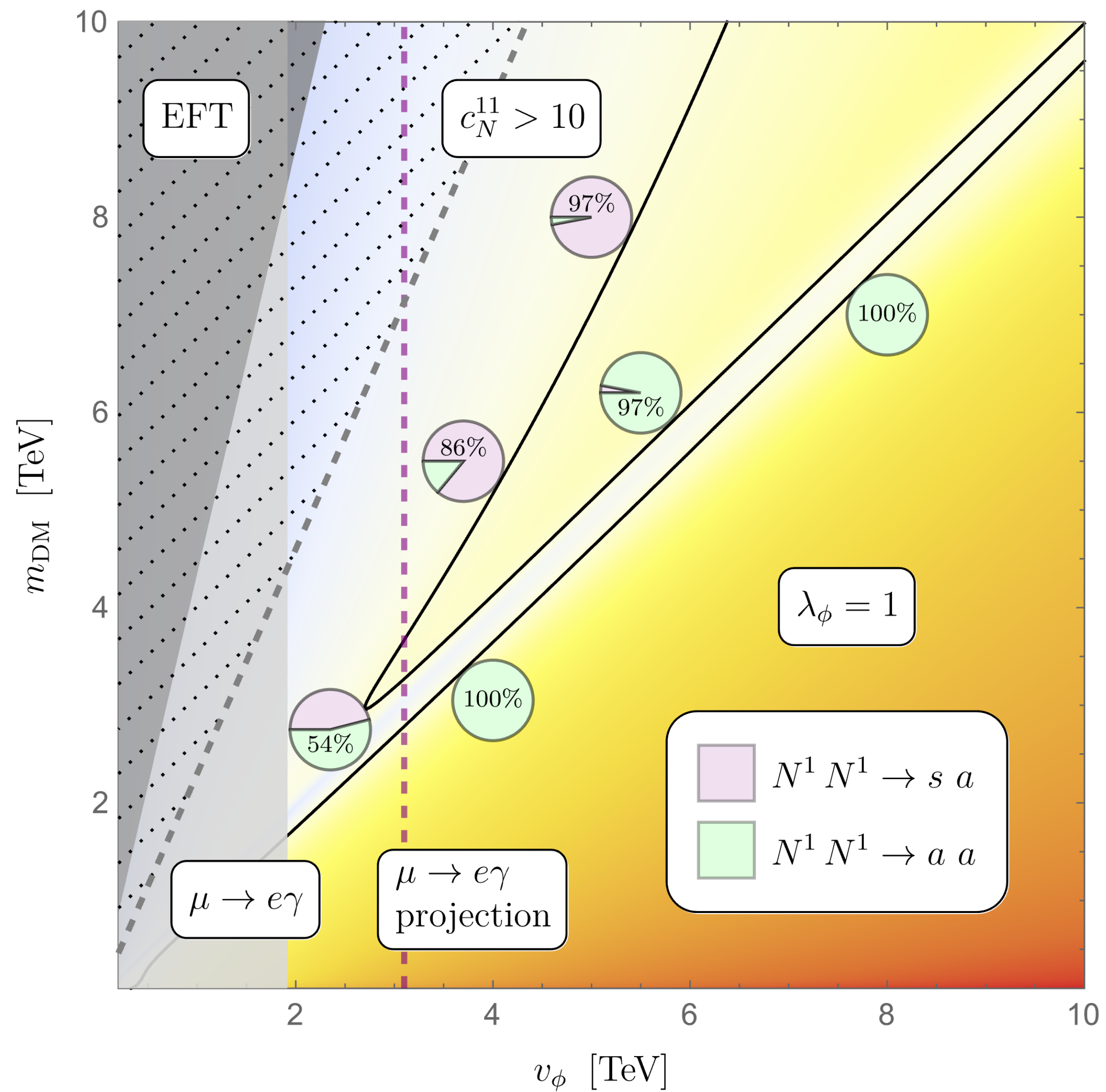
m_a vs V_ϕ

$$\Omega h^2 = 0.12$$

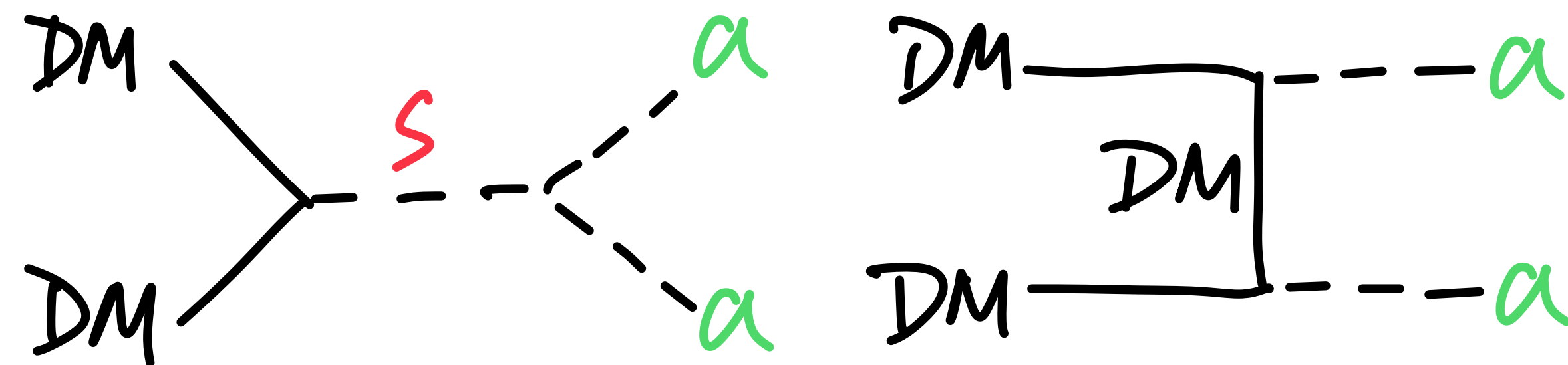
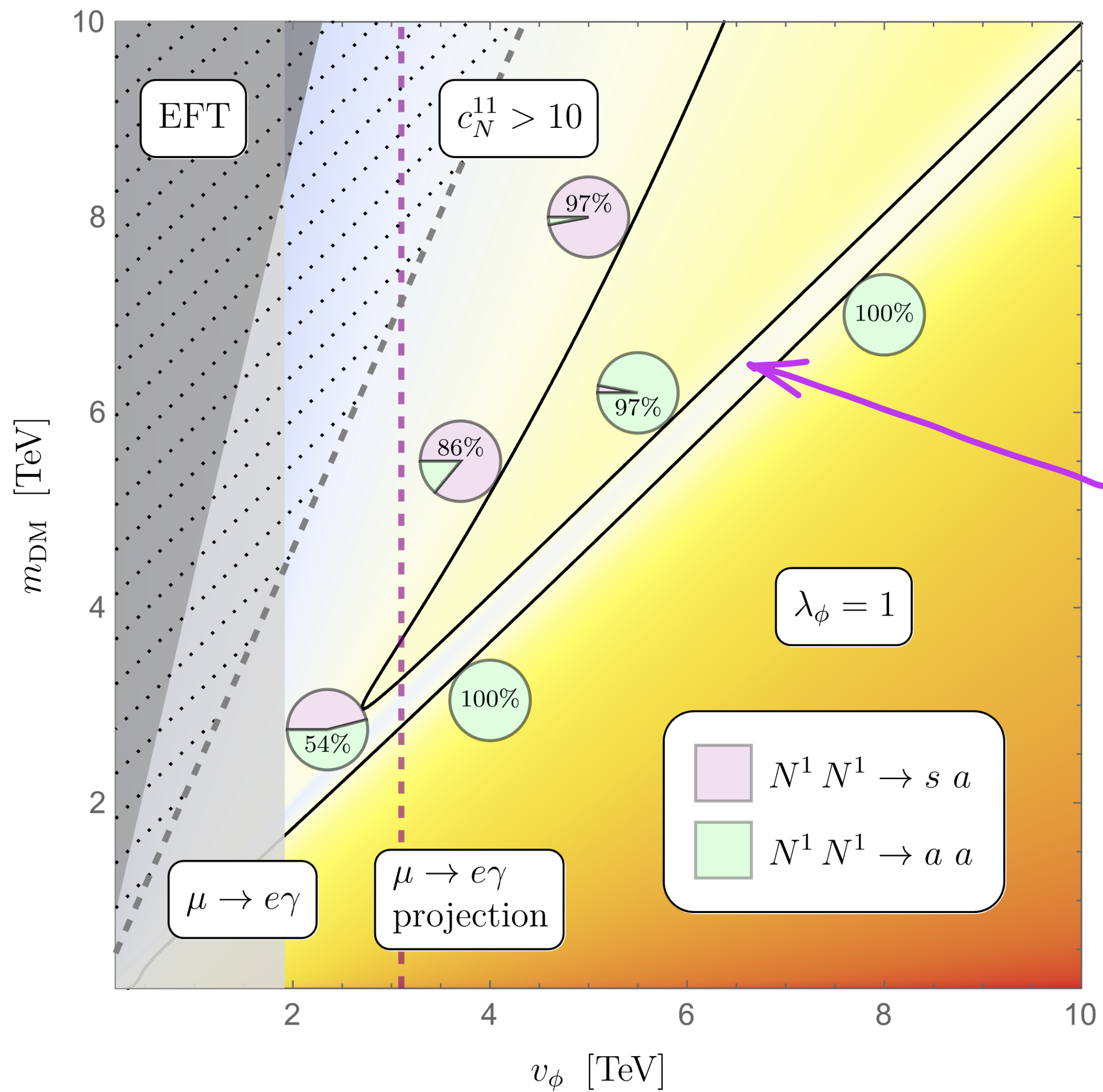
$$\left(\frac{m_a}{\text{GeV}} \right) \times \left(\frac{V_\phi}{\text{TeV}} \right) \geq \begin{cases} 180 & B_s \\ 190^* & u \rightarrow e\gamma \end{cases}$$



TeV scale: freeze out m_{DM} vs V_ϕ

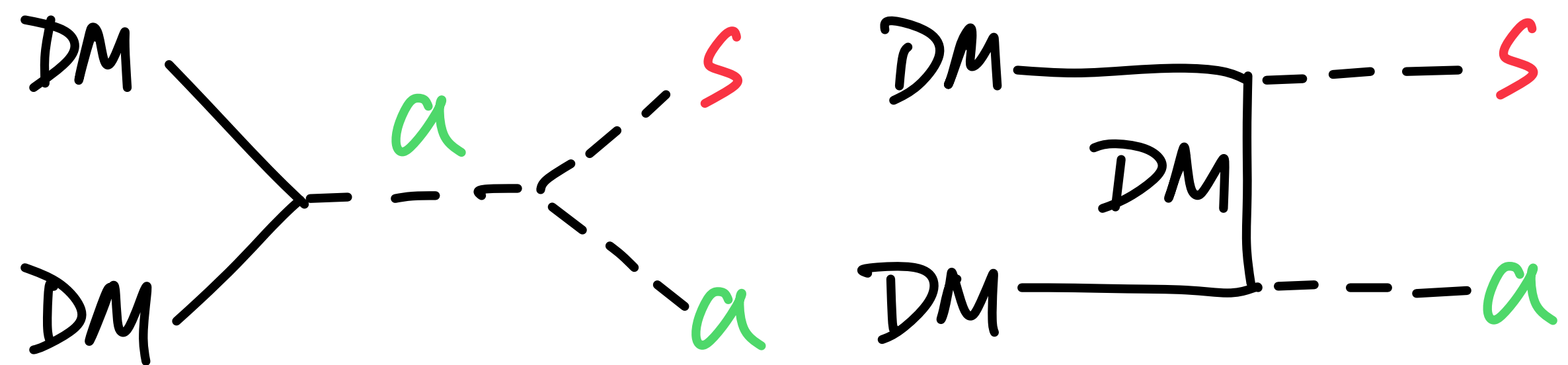
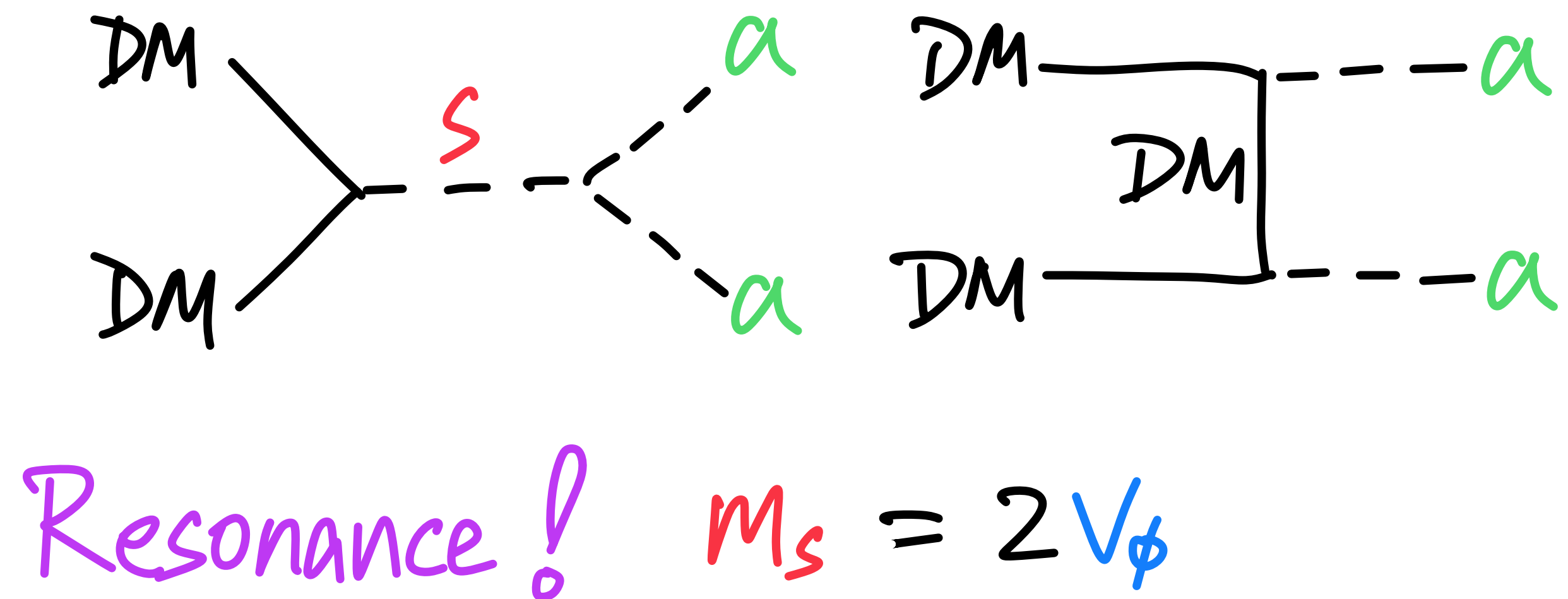
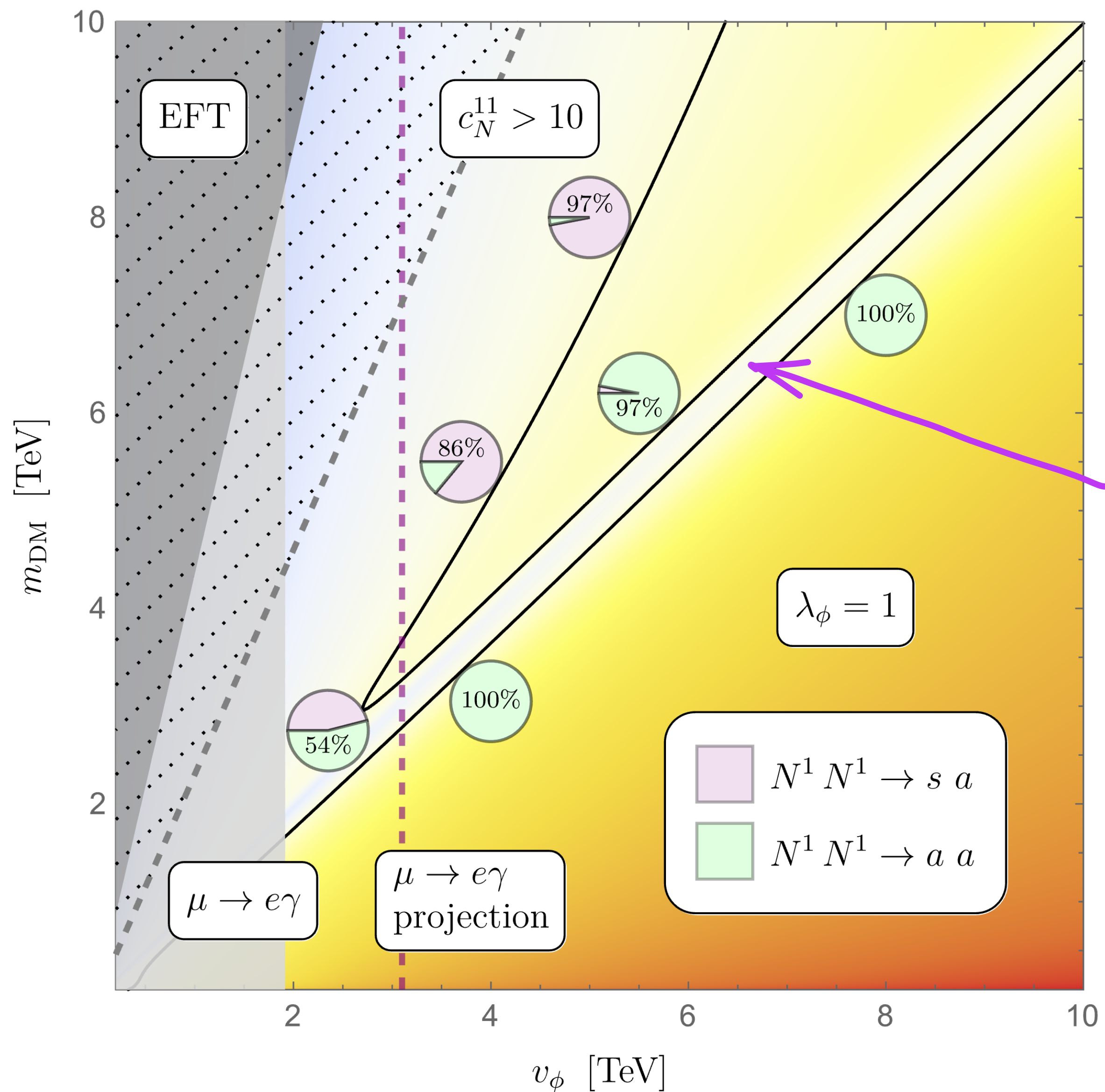


TeV scale: freeze out m_{DM} vs V_ϕ

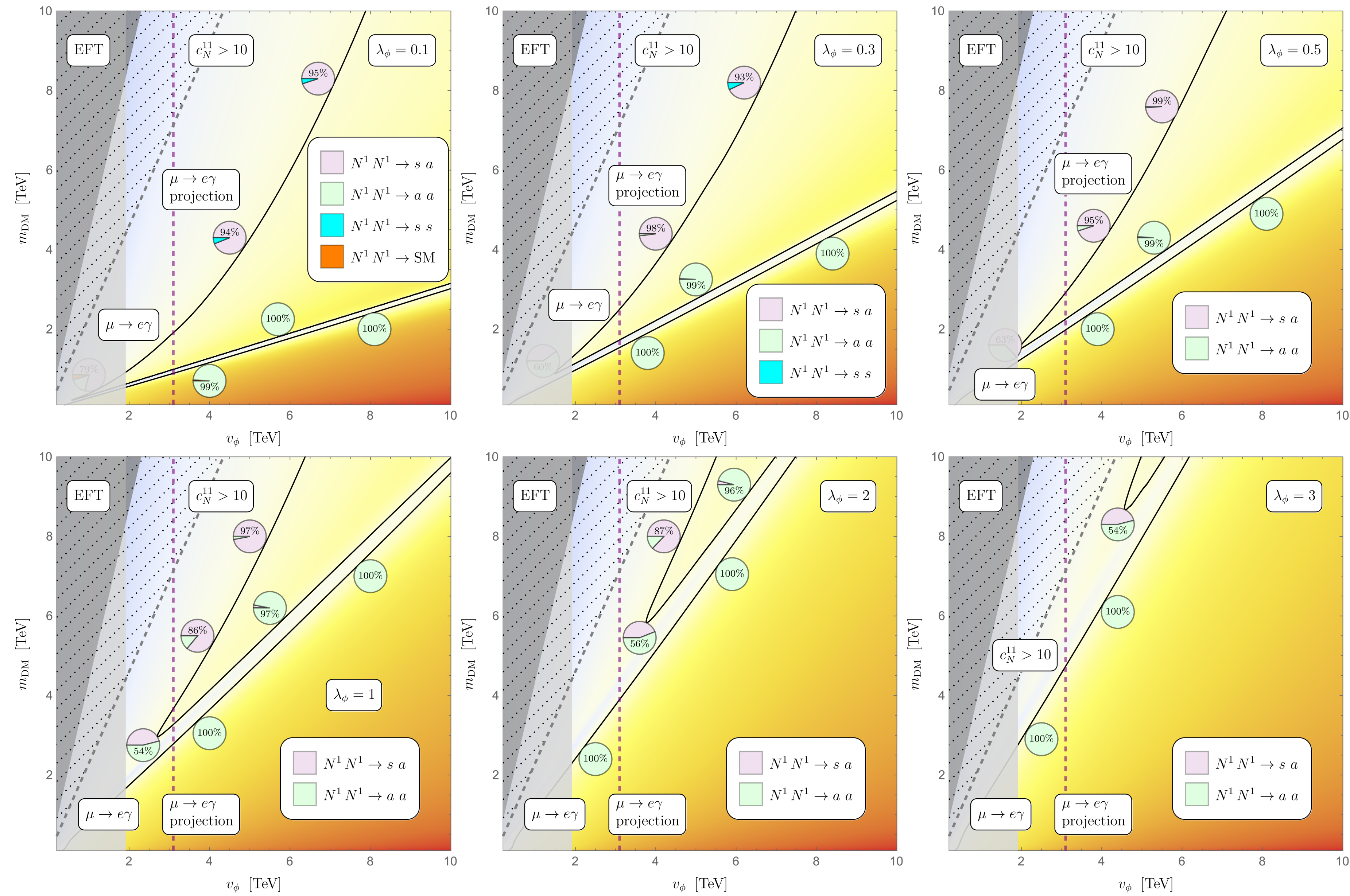


Resonance! $m_s = 2V_\phi$

TeV scale: freeze out m_{DM} vs V_ϕ

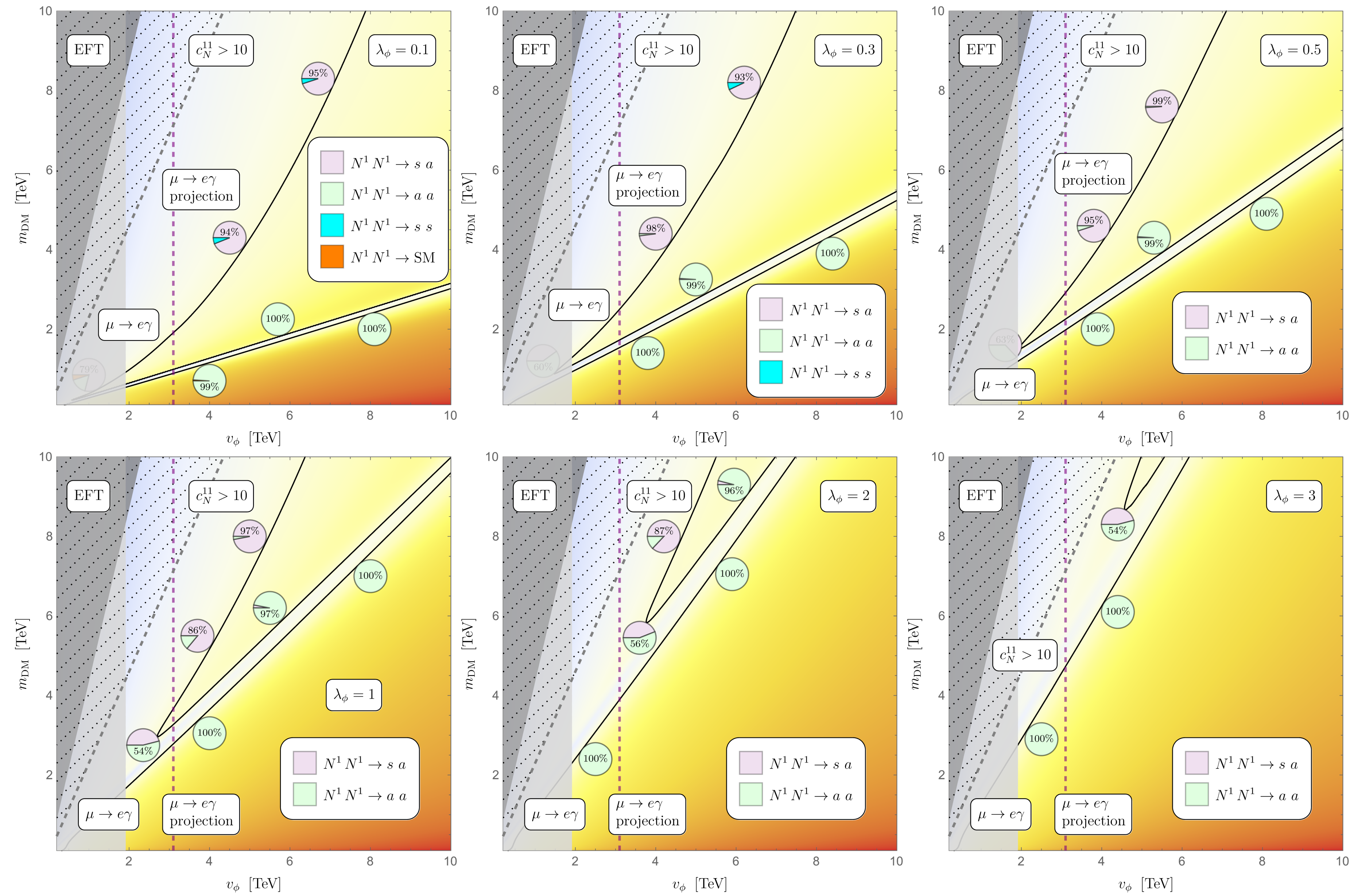


TeV scale: freeze out with various λ_ϕ

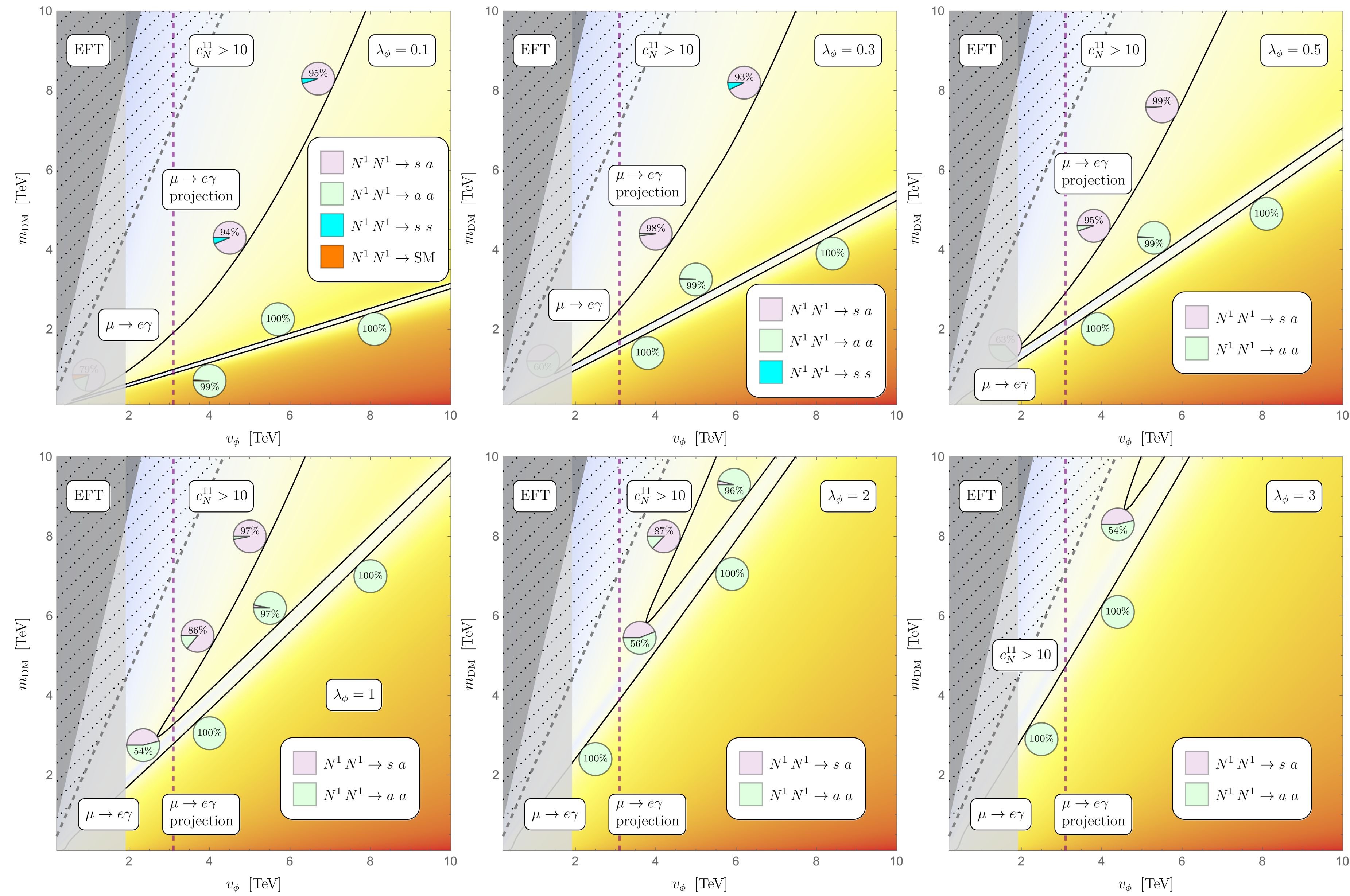


TeV scale: freeze out with various λ_ϕ

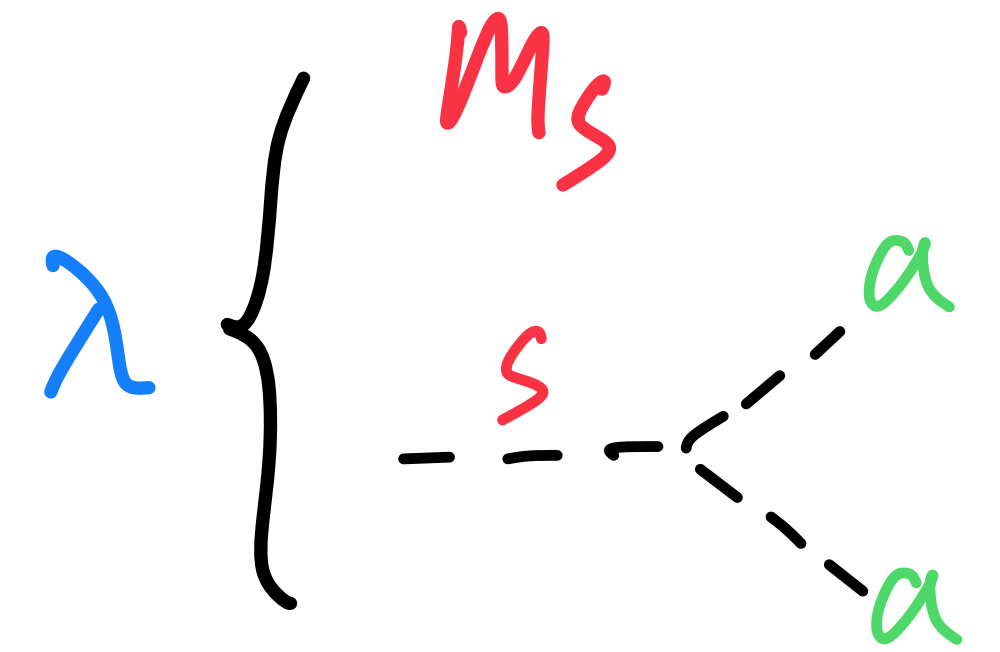
$\lambda\phi^4$ term in
flavon potential



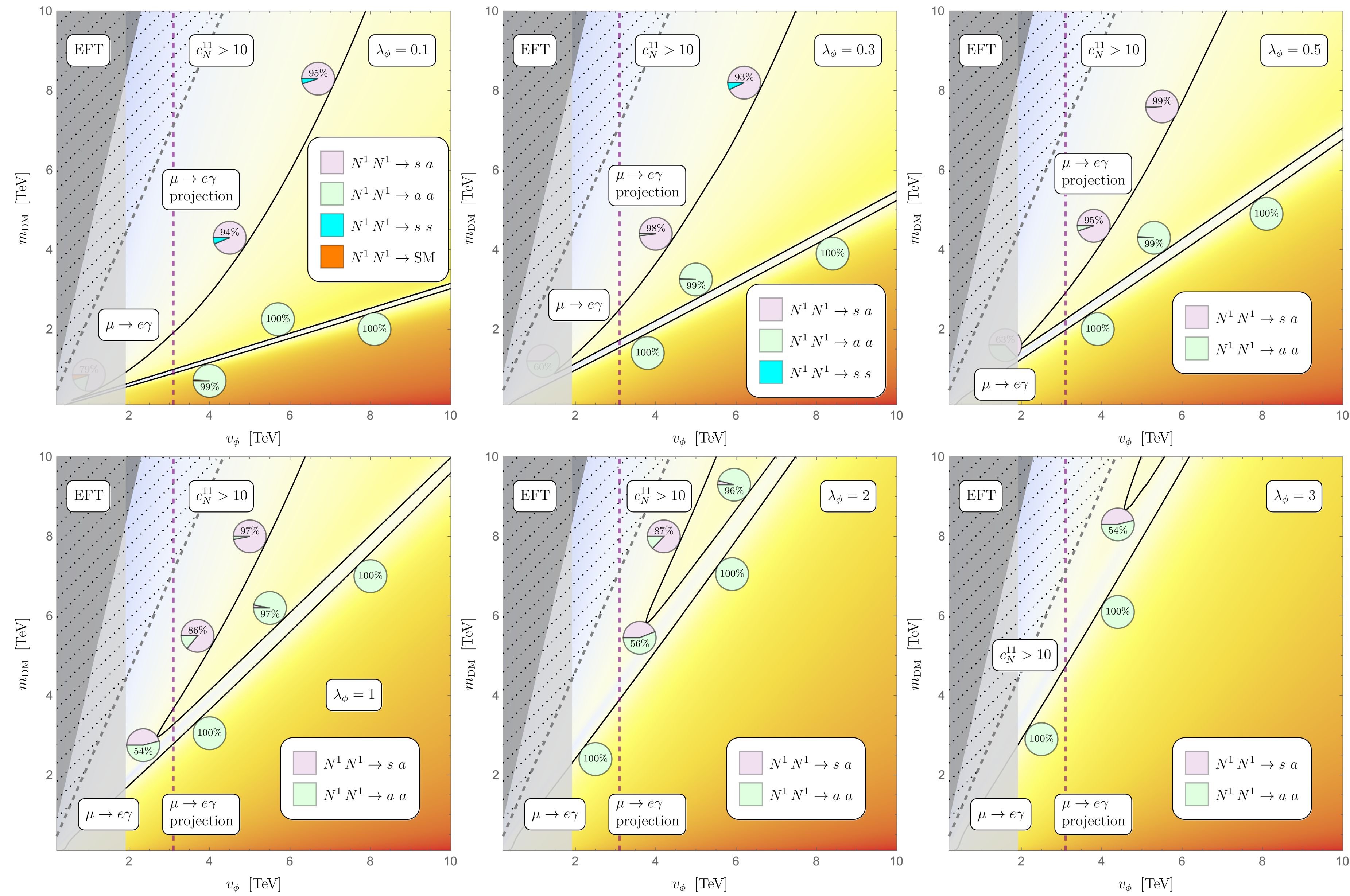
TeV scale: freeze out with various λ_ϕ



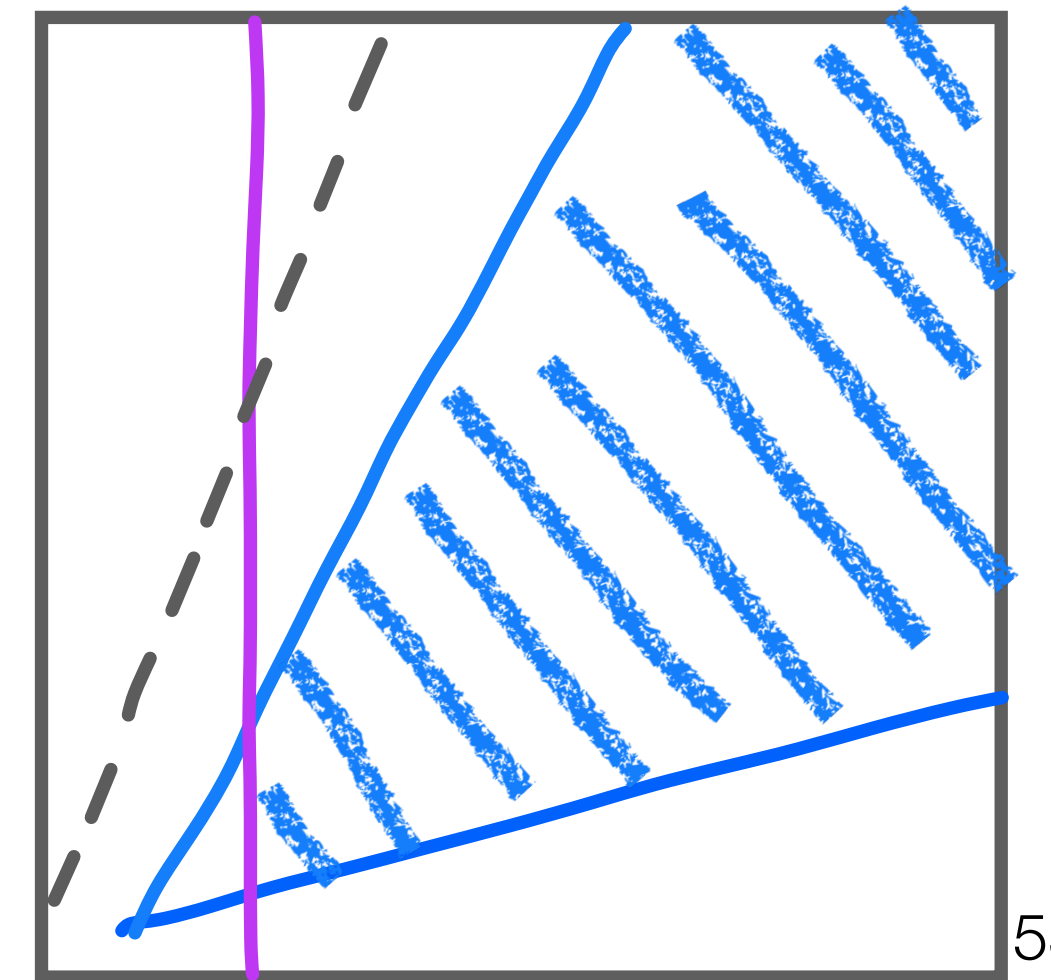
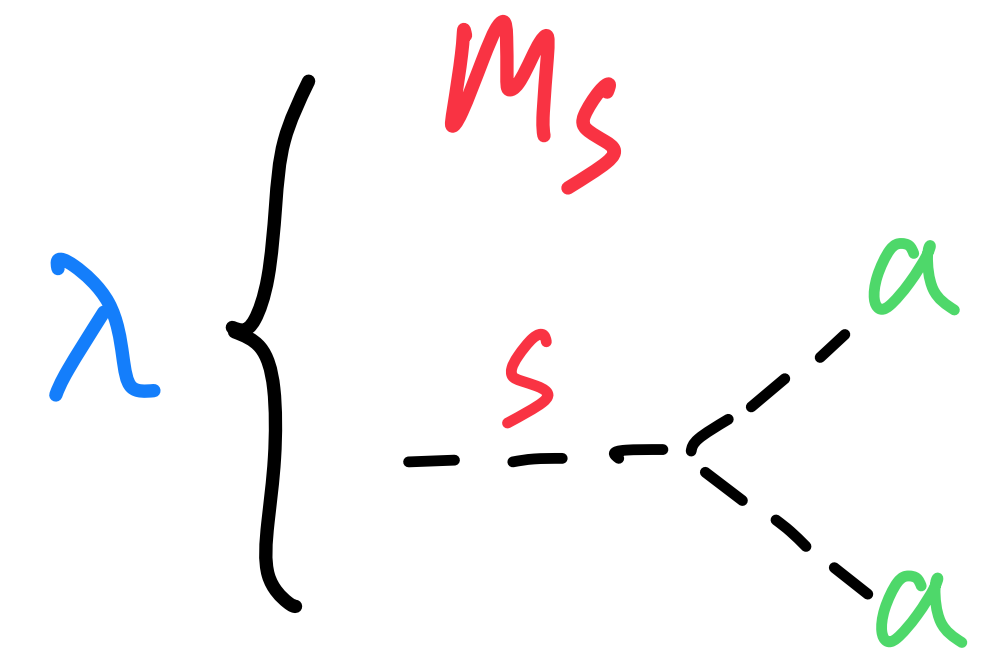
$\lambda \phi^4$ term in flavon potential



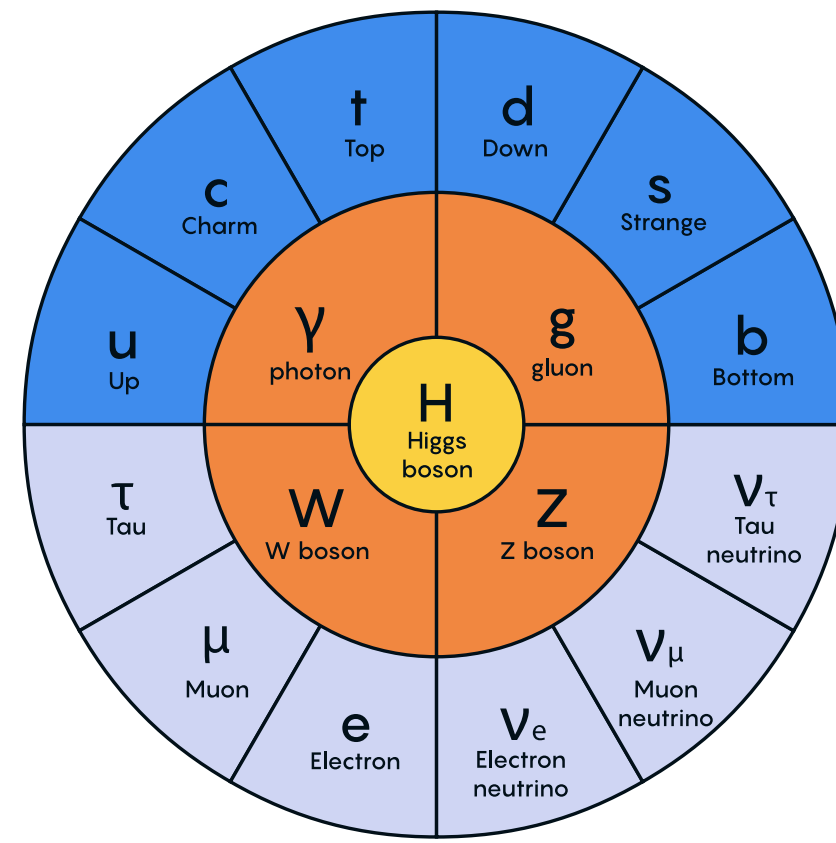
TeV scale: freeze out with various λ_ϕ



$\lambda\phi^4$ term in flavon potential



High scale: (IR) freeze in m_{DM} vs V_ϕ



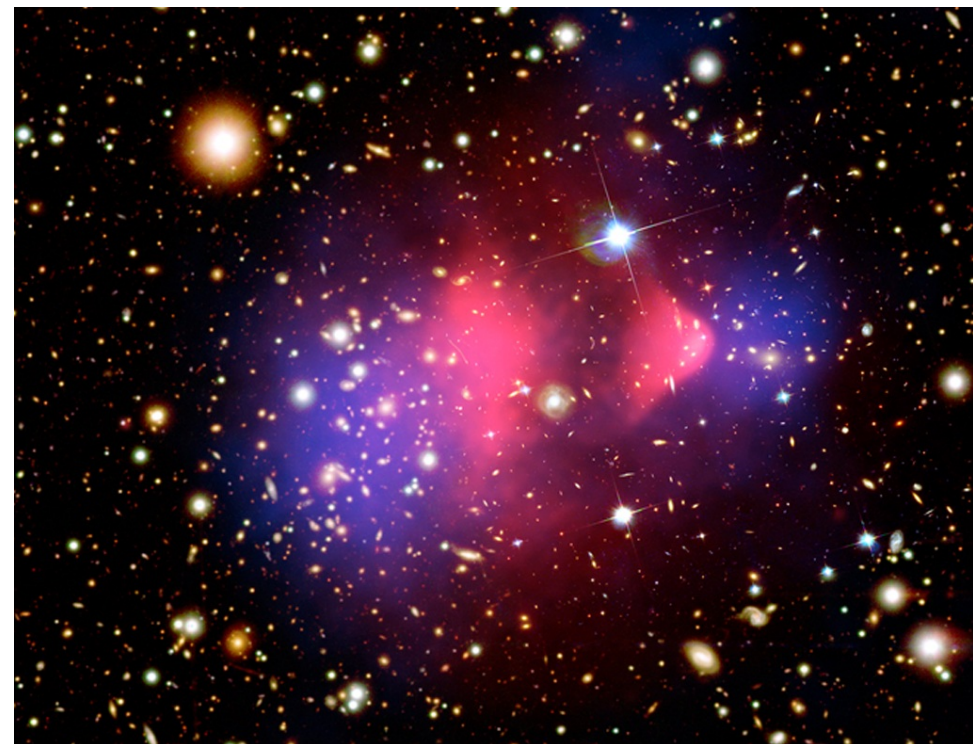
High scale: (IR) freeze in

m_{DM} vs V_ϕ

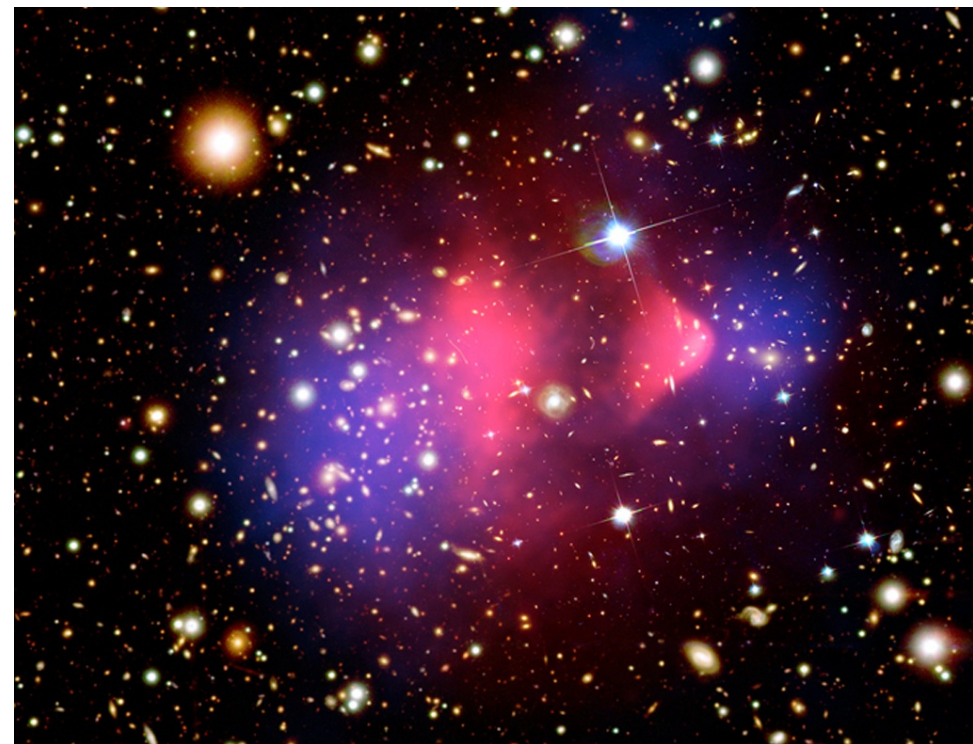


High scale: (IR) freeze in

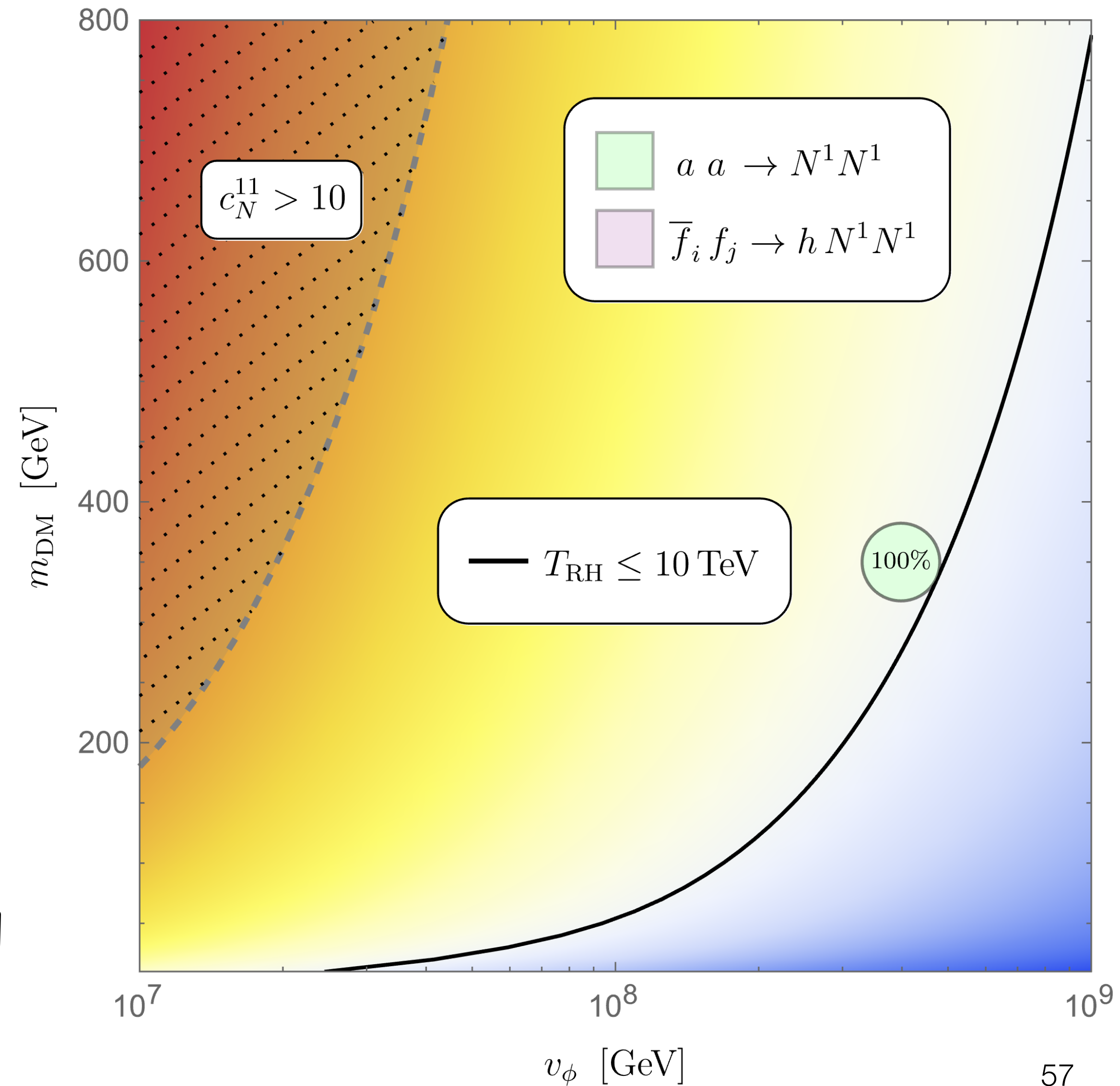
m_{DM} vs V_ϕ



High scale: (IR) freeze in m_{DM} vs V_ϕ

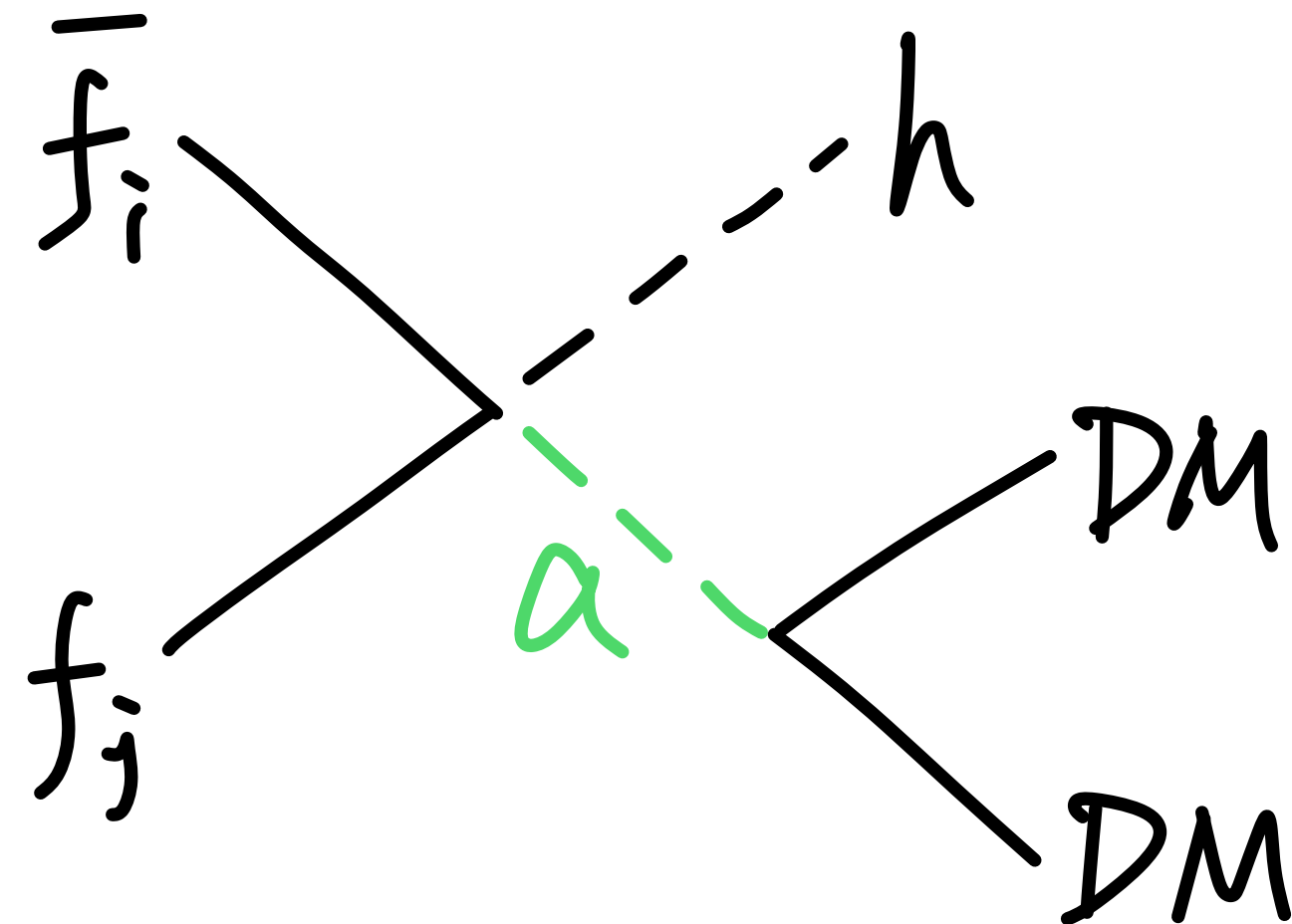
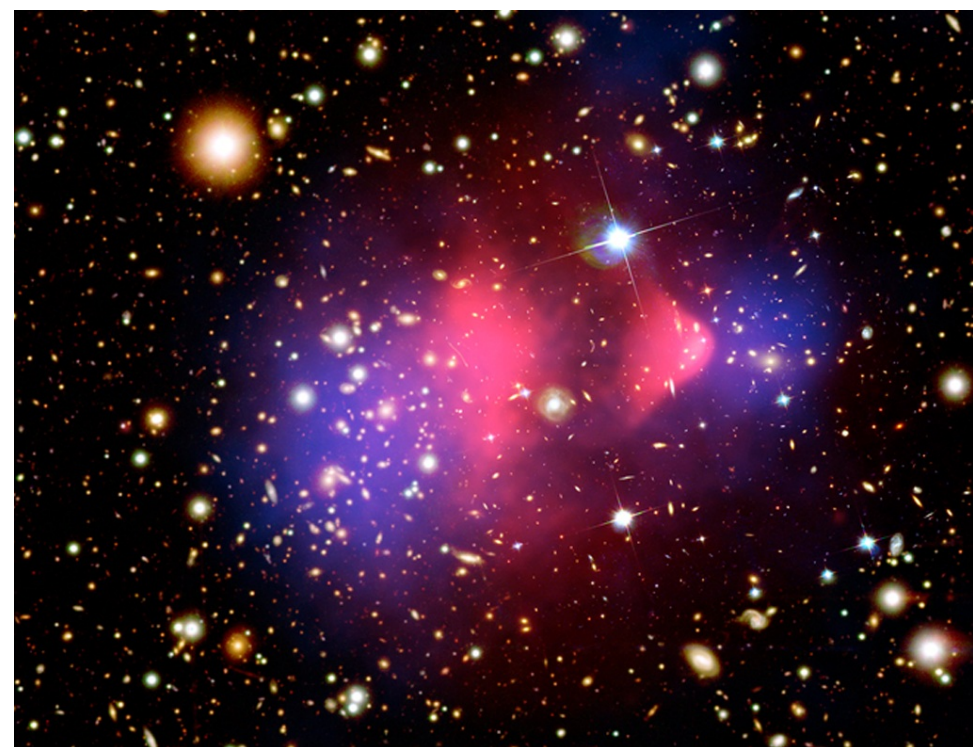
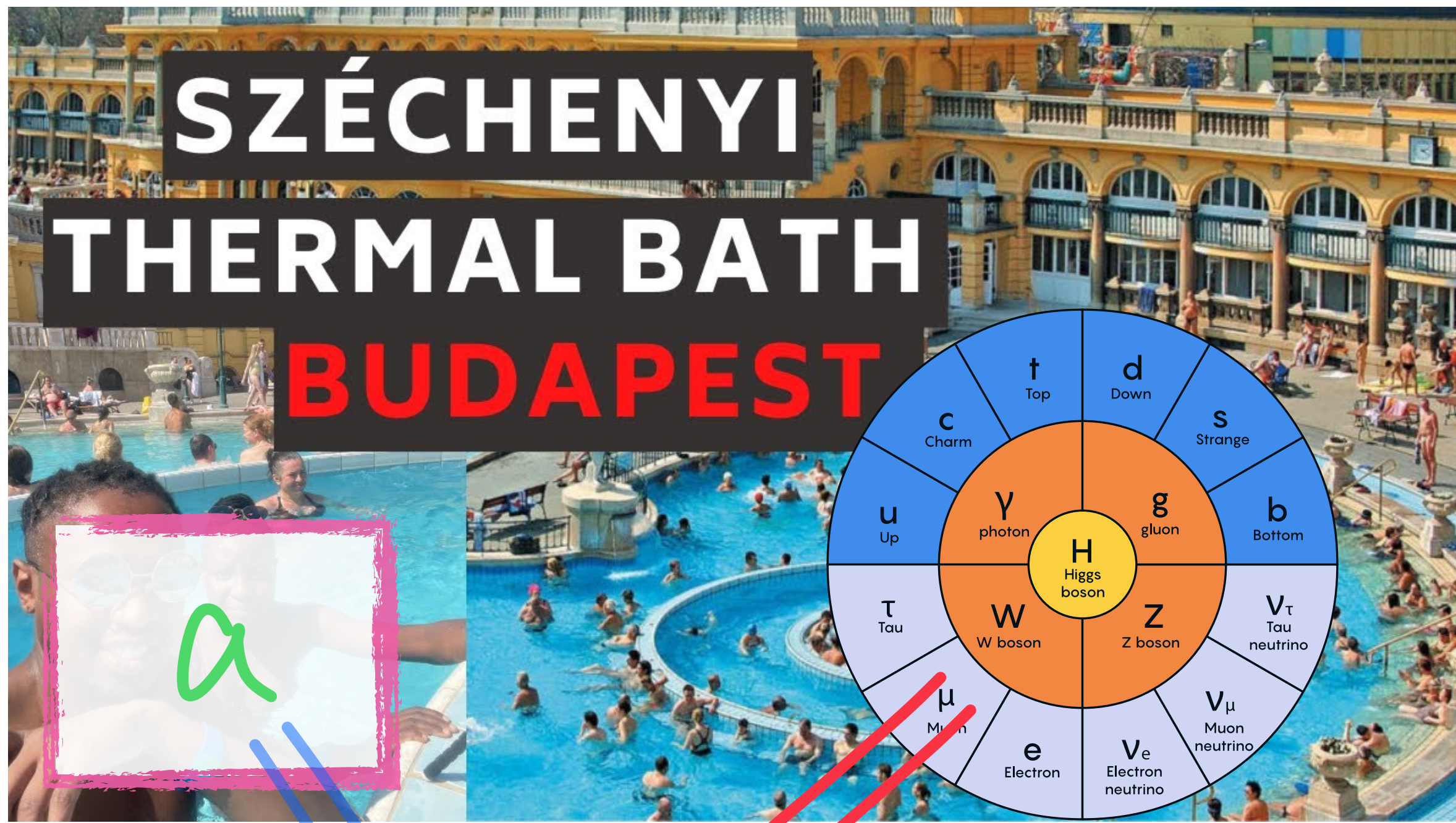


"Low" T_{RH}

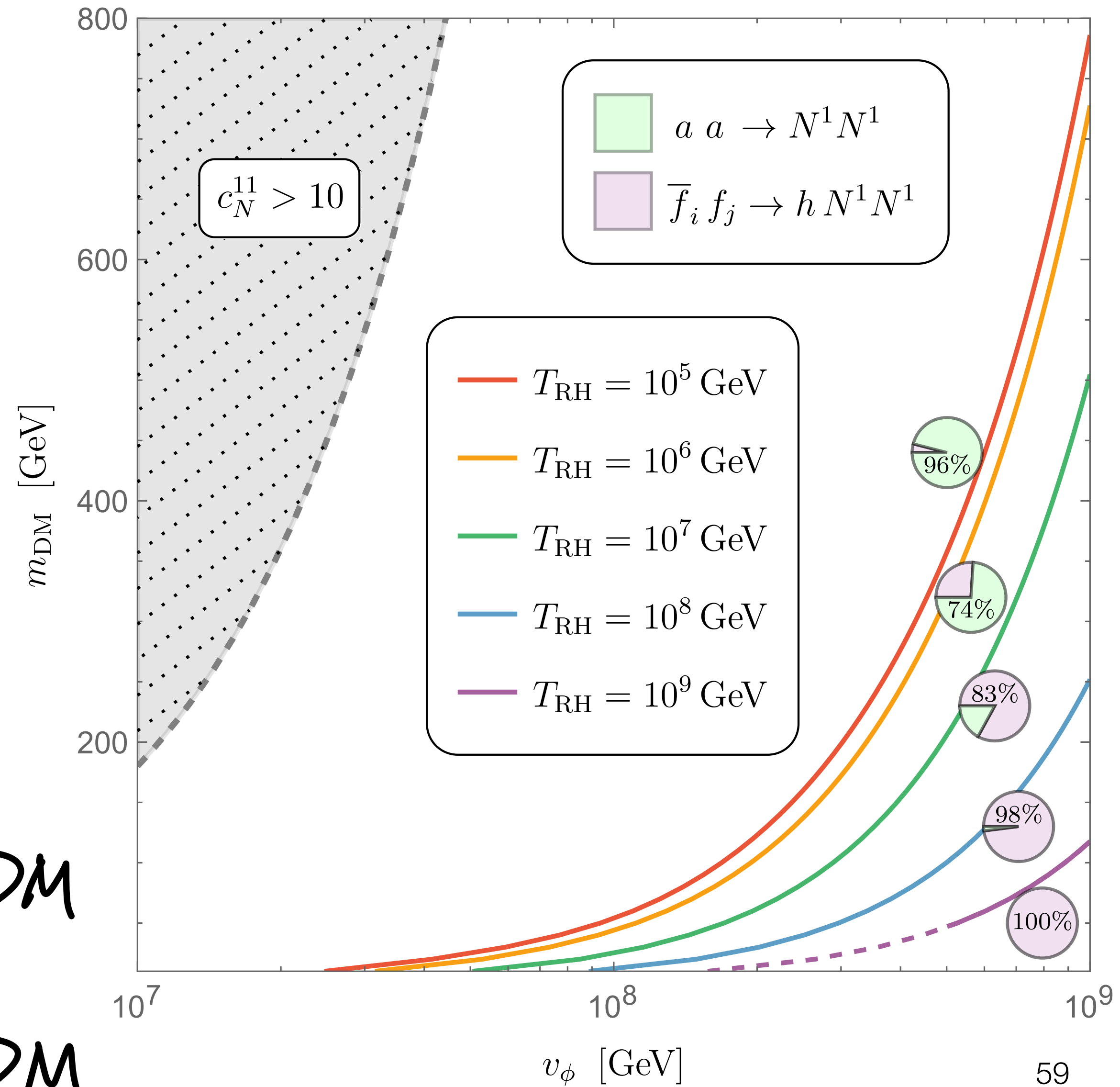
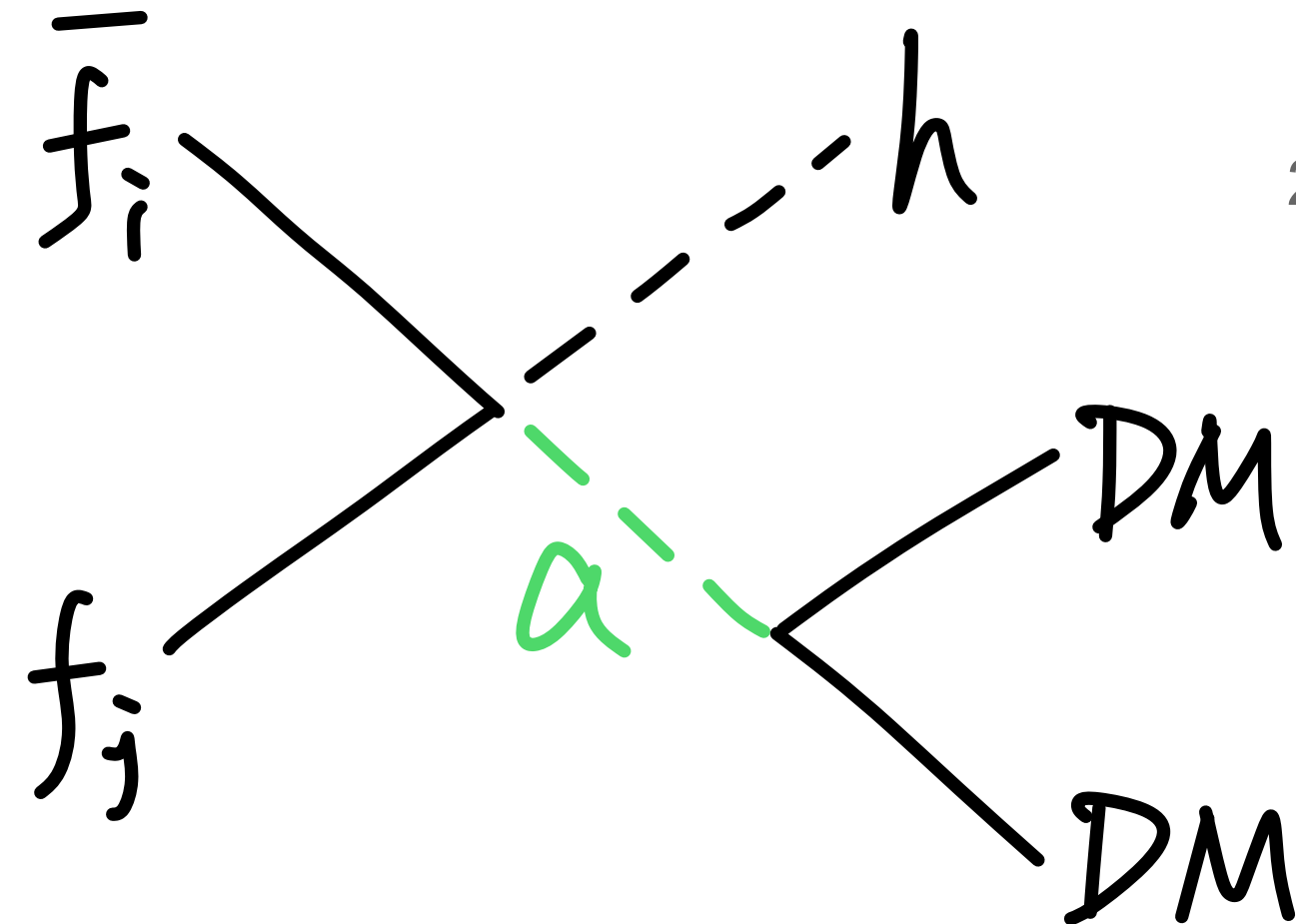
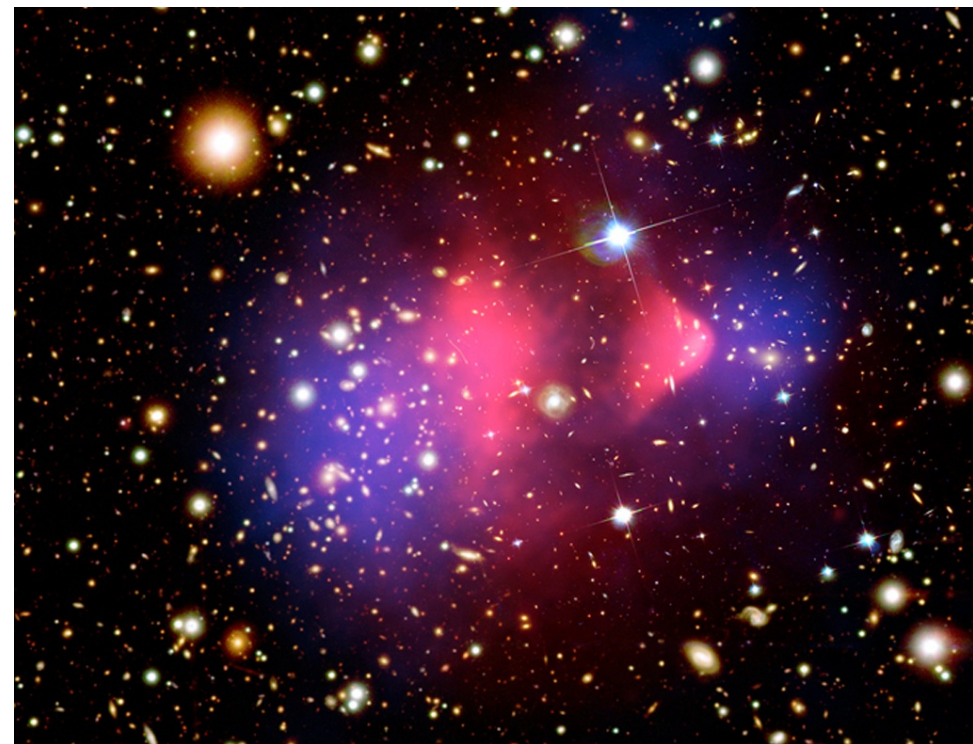
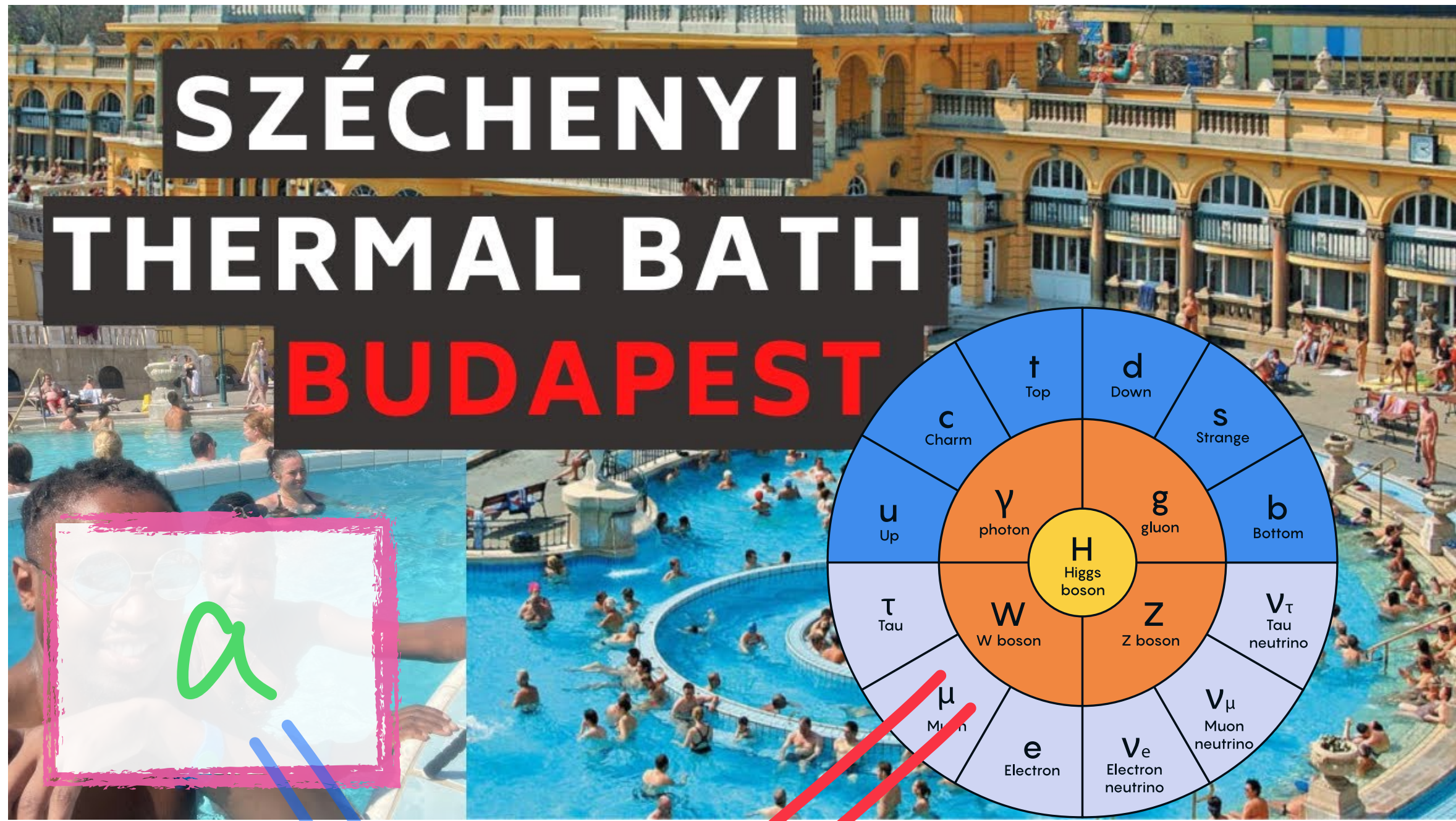


High scale: (UV) freeze in

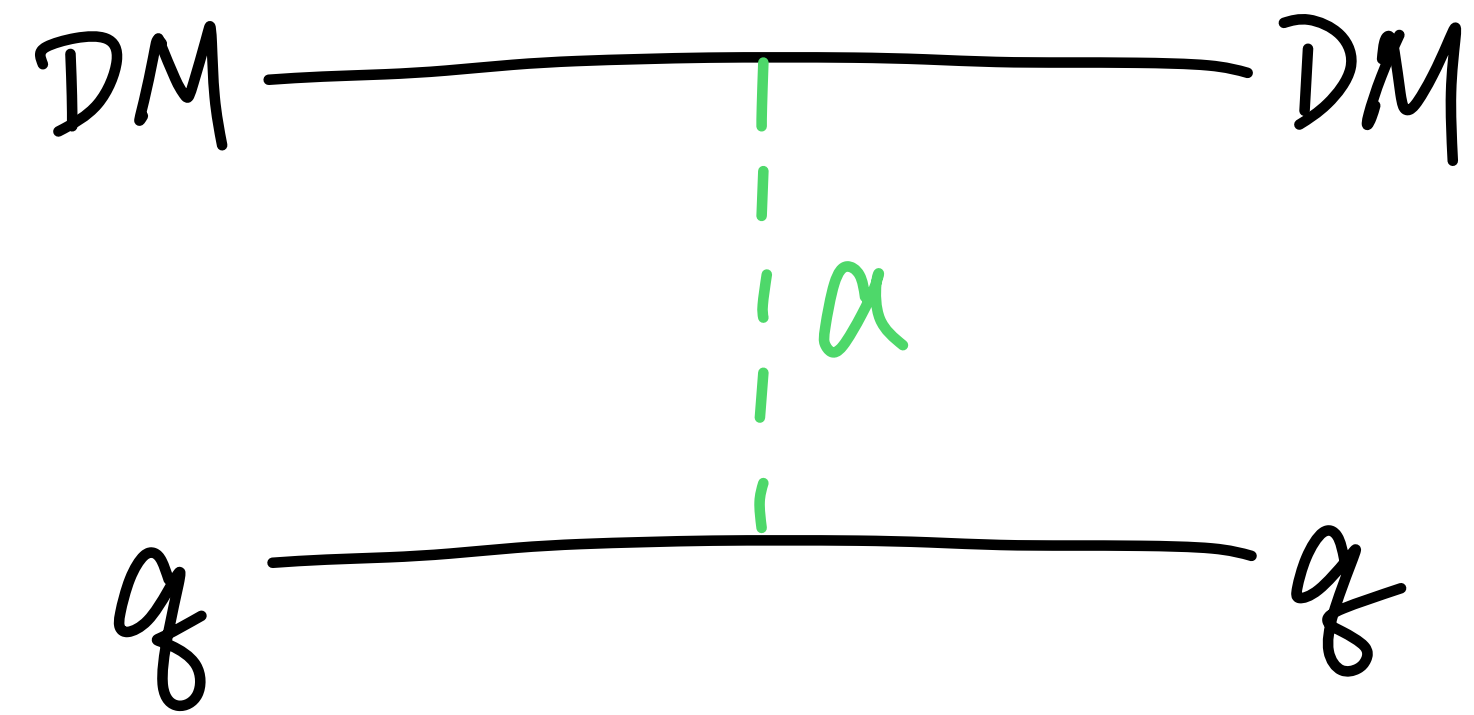
m_{DM} vs V_ϕ



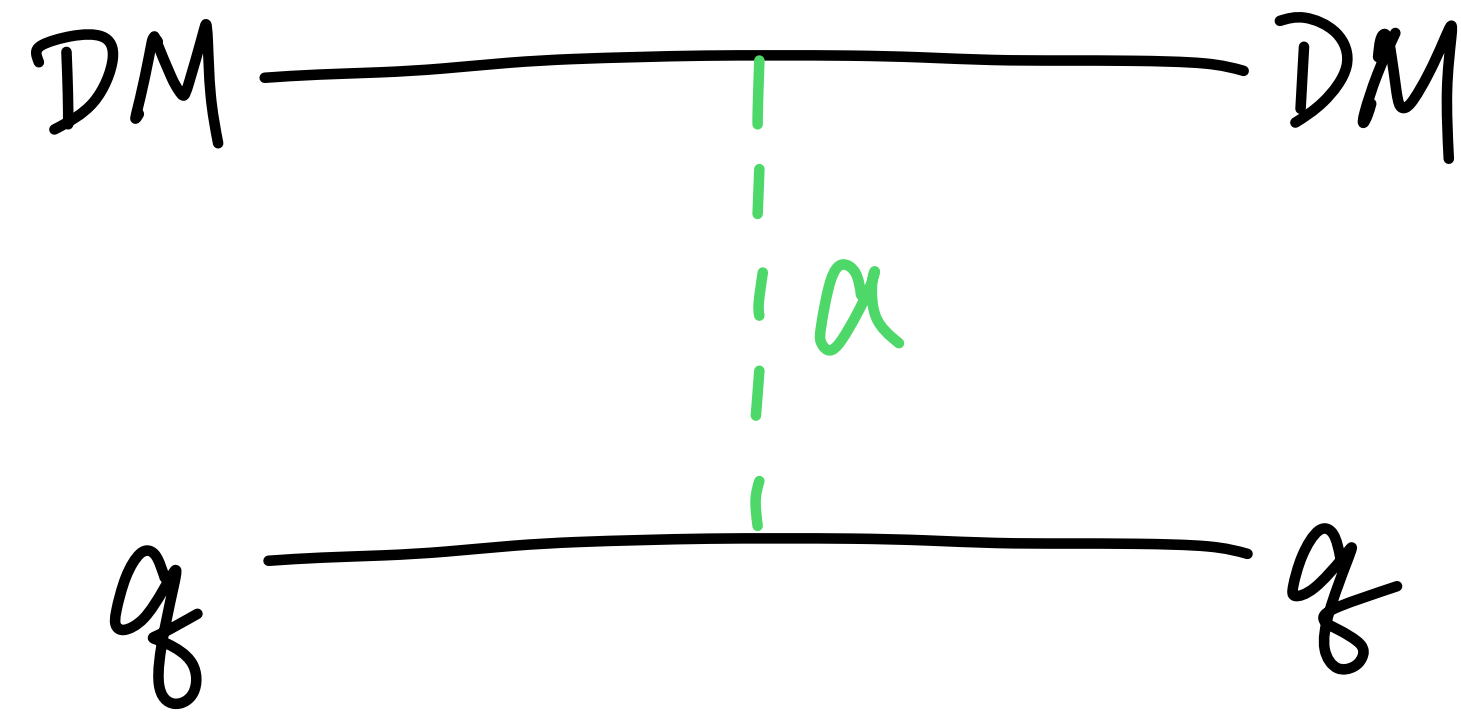
High scale: (UV) freeze in m_{DM} vs V_ϕ



Direct detection



Direct detection

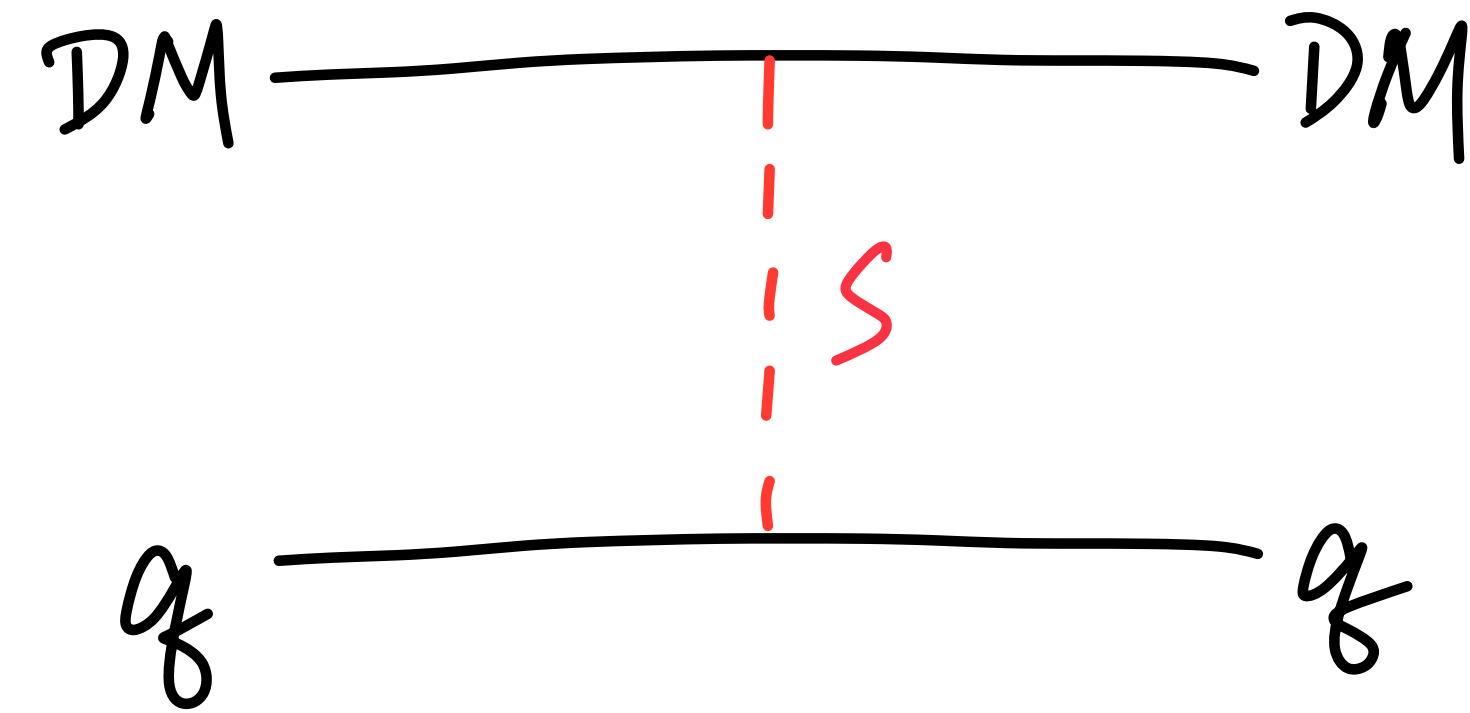
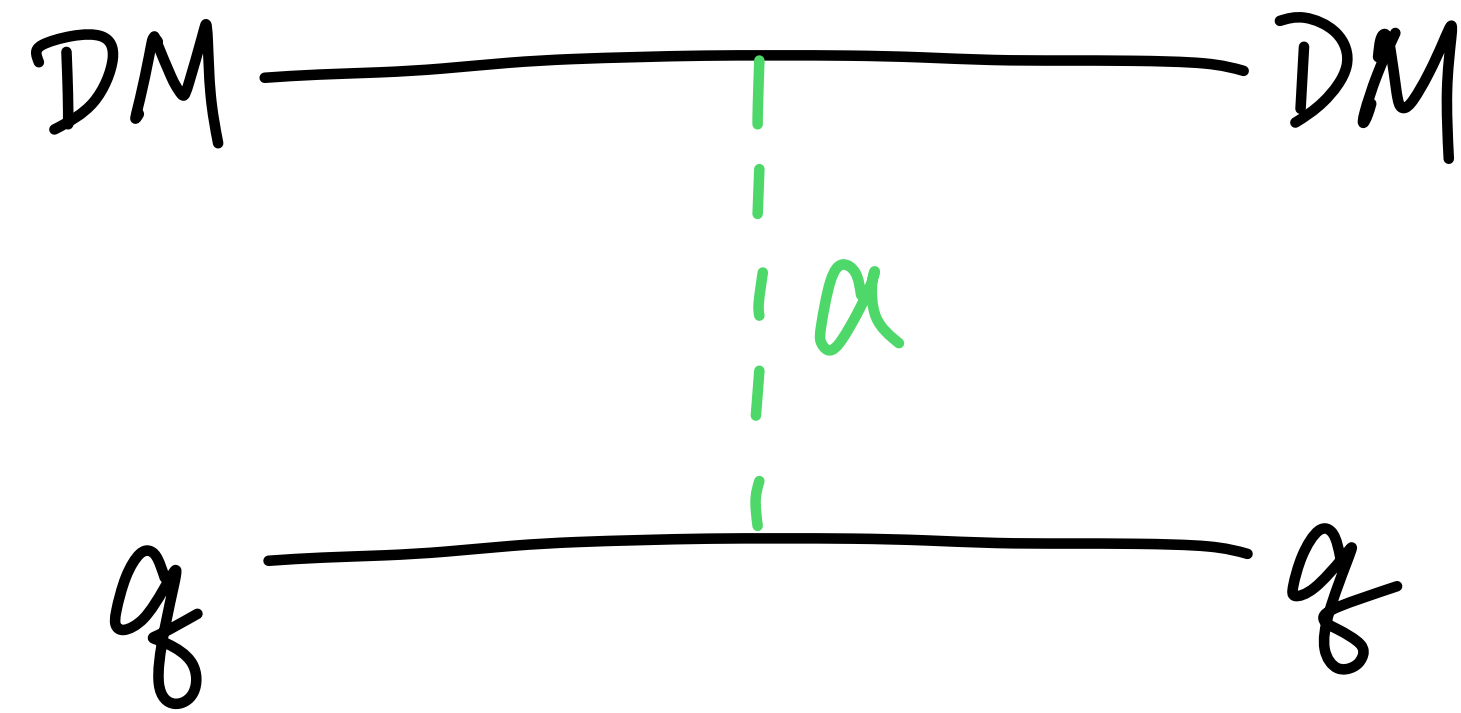


Spin-dependent σ

Momentum suppressed

10^{-5} too small!

Direct detection

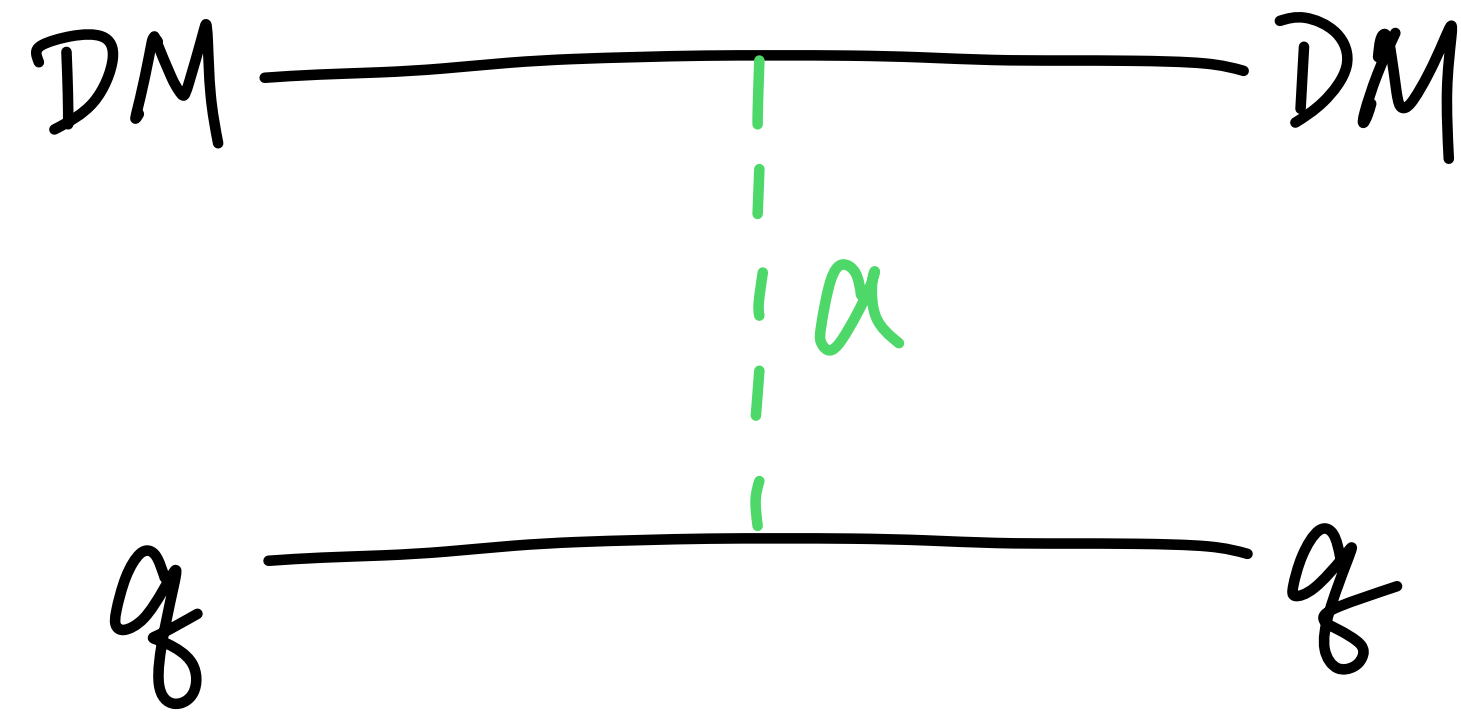


Spin-independent σ

Momentum suppressed

10^{-5} too small!

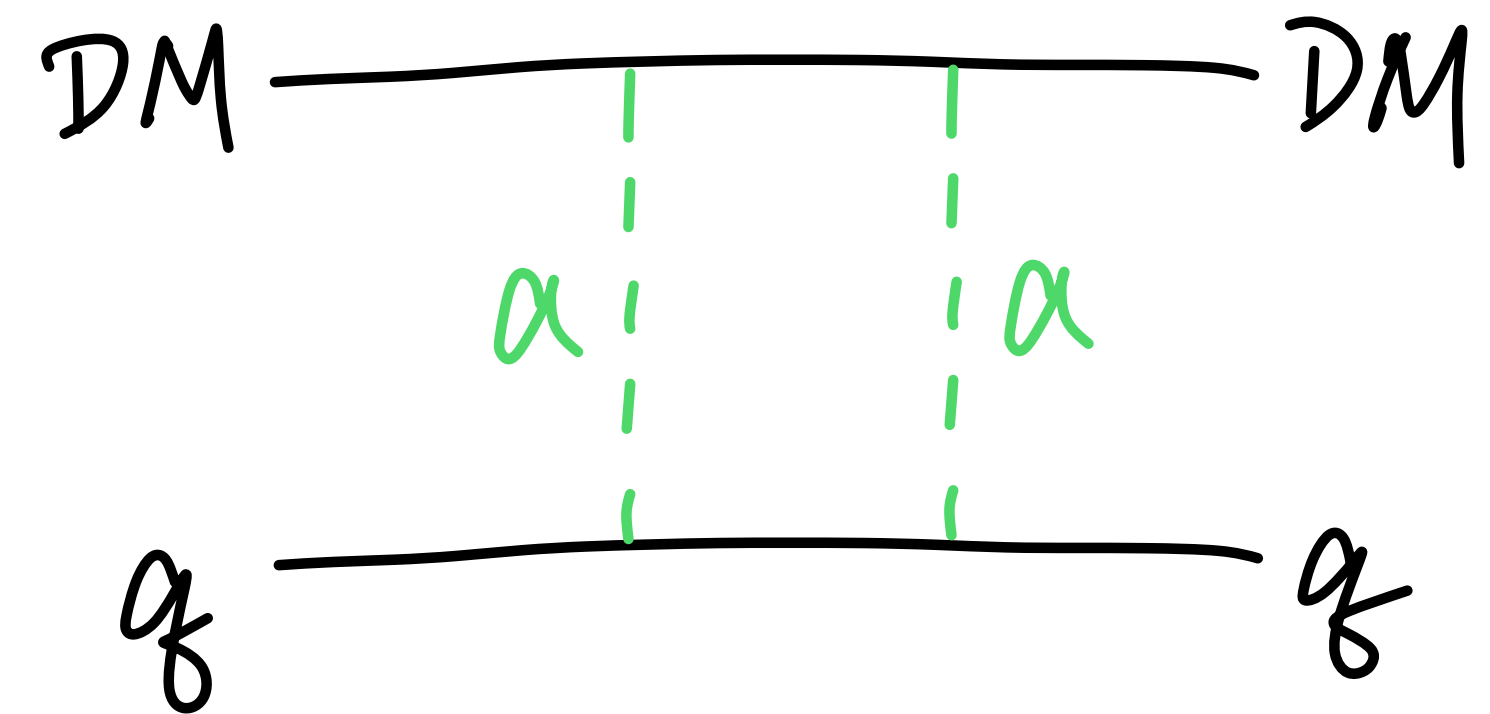
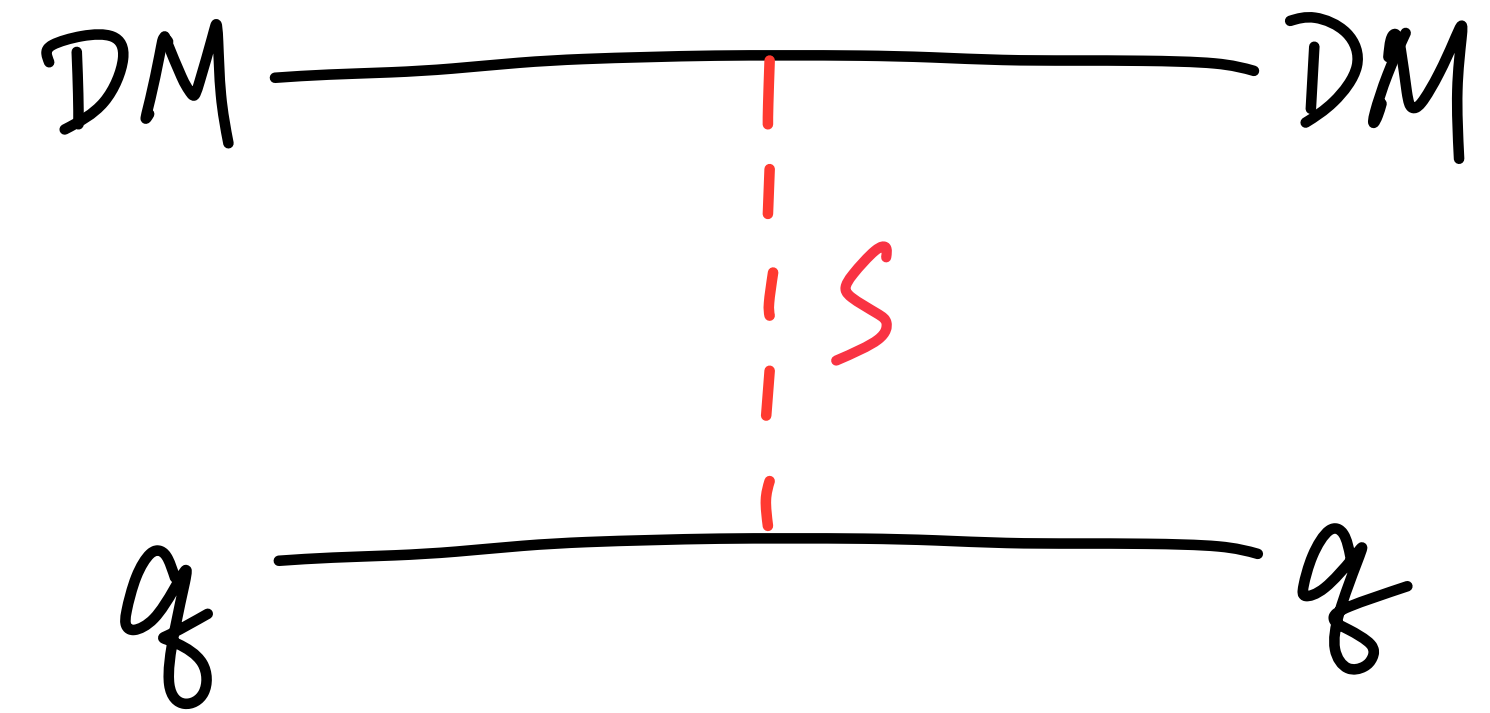
Direct detection



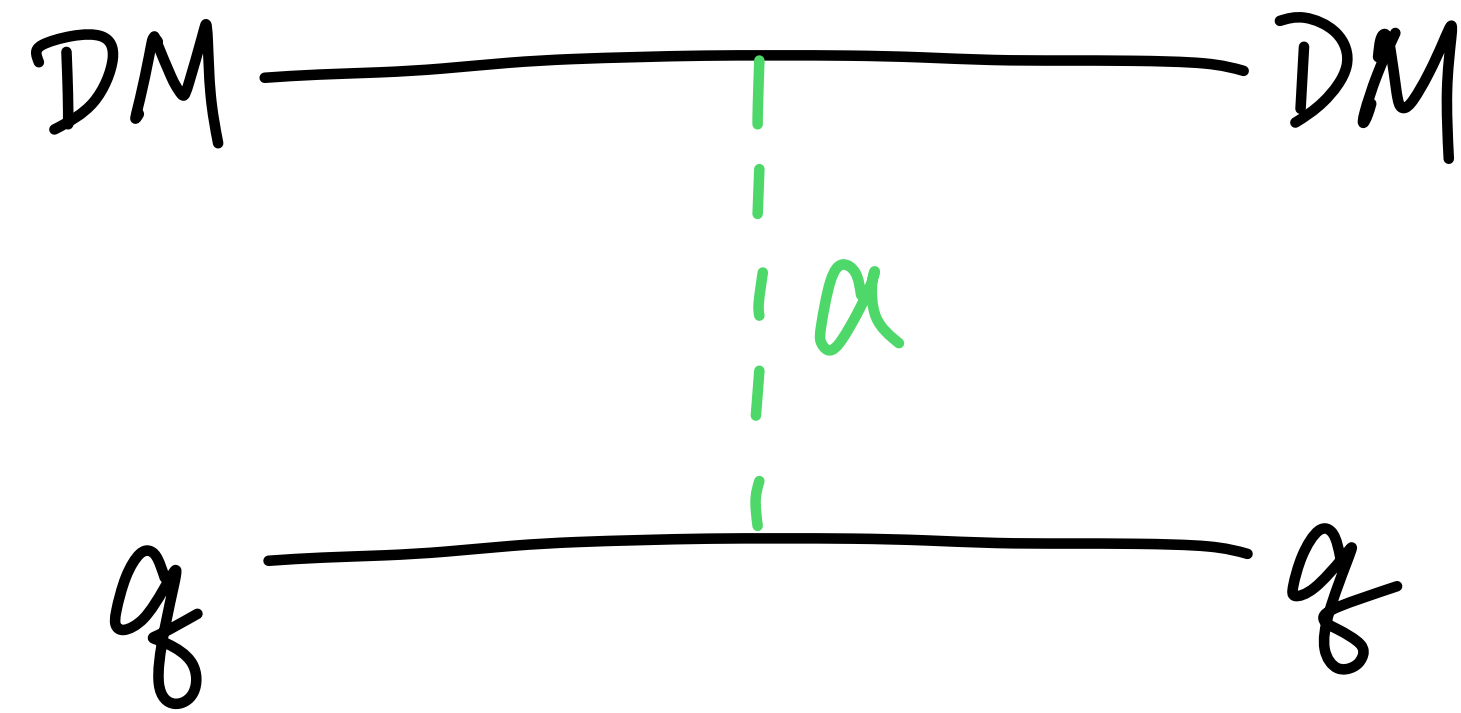
Spin-independent σ

Momentum suppressed

10^{-5} too small!



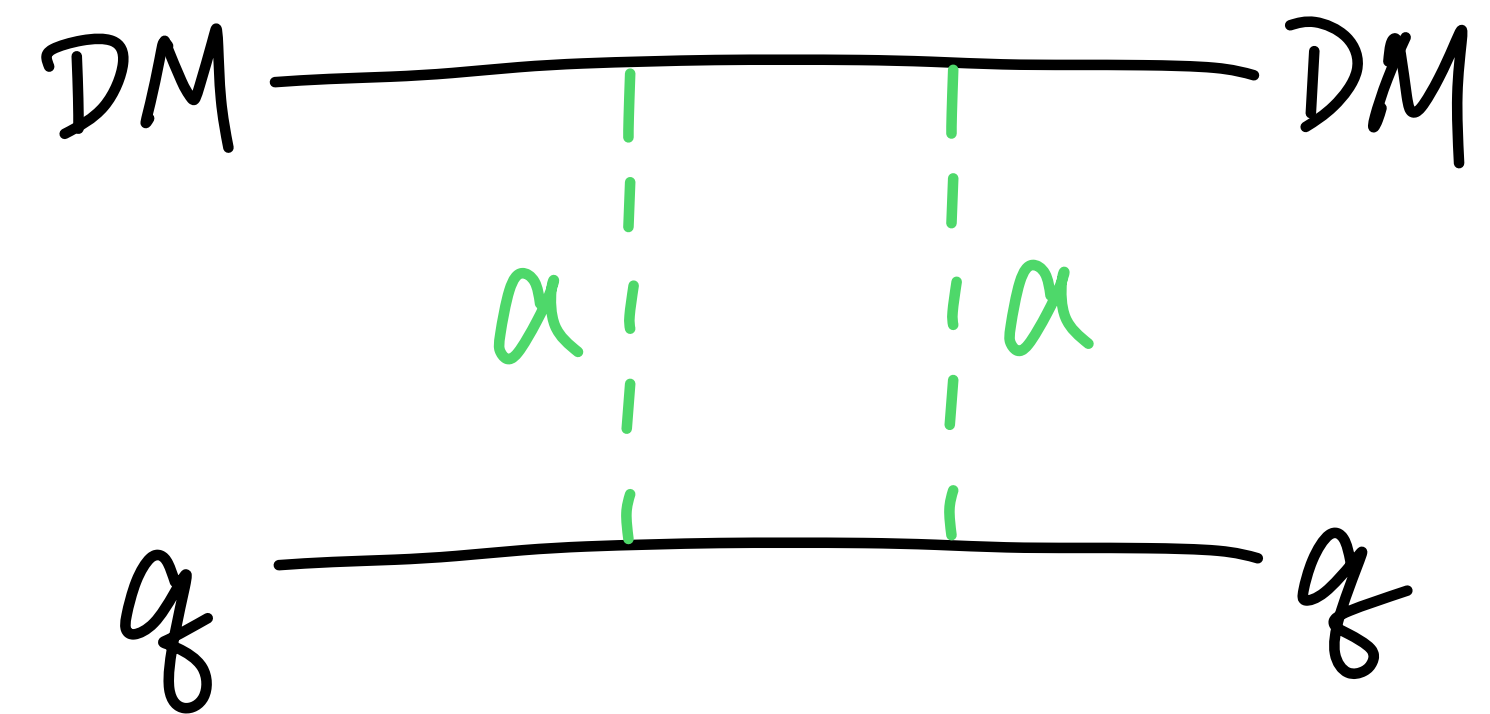
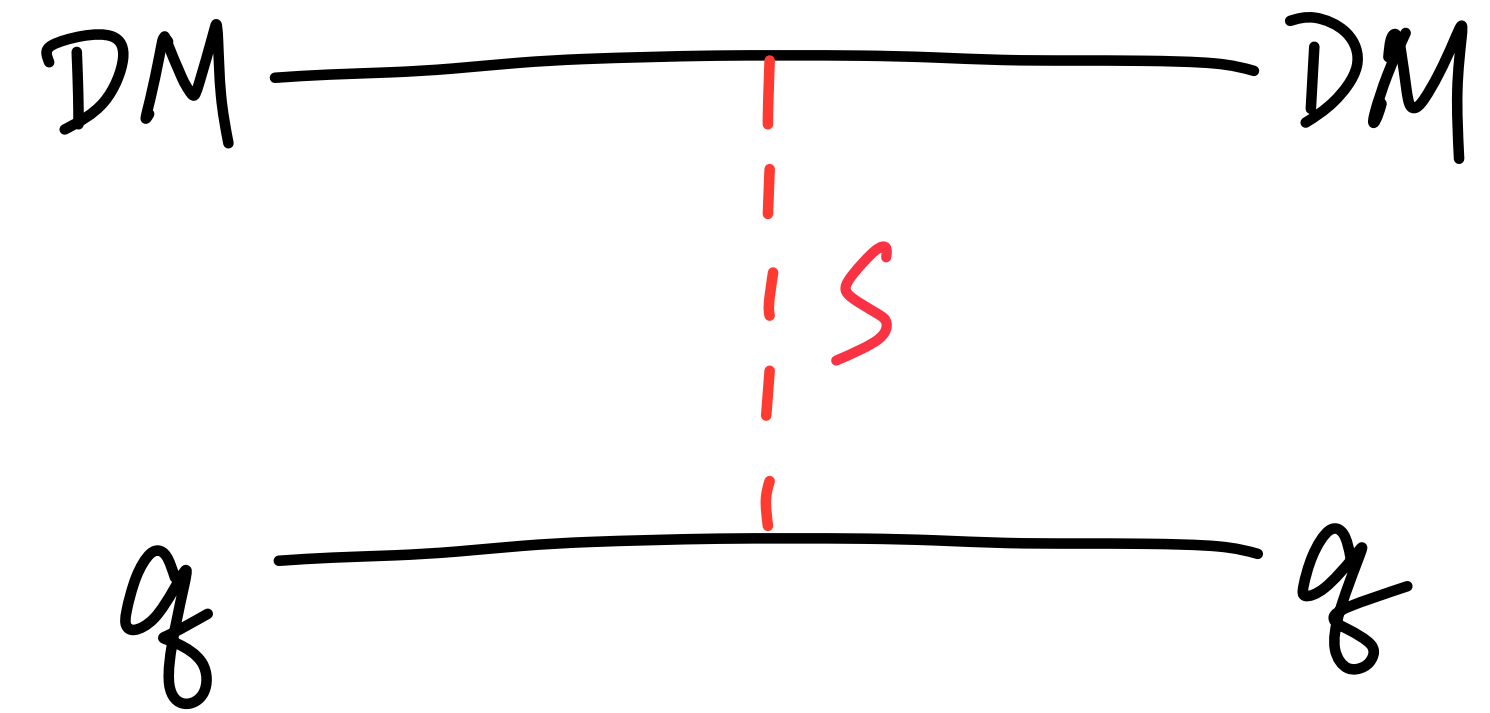
Direct detection



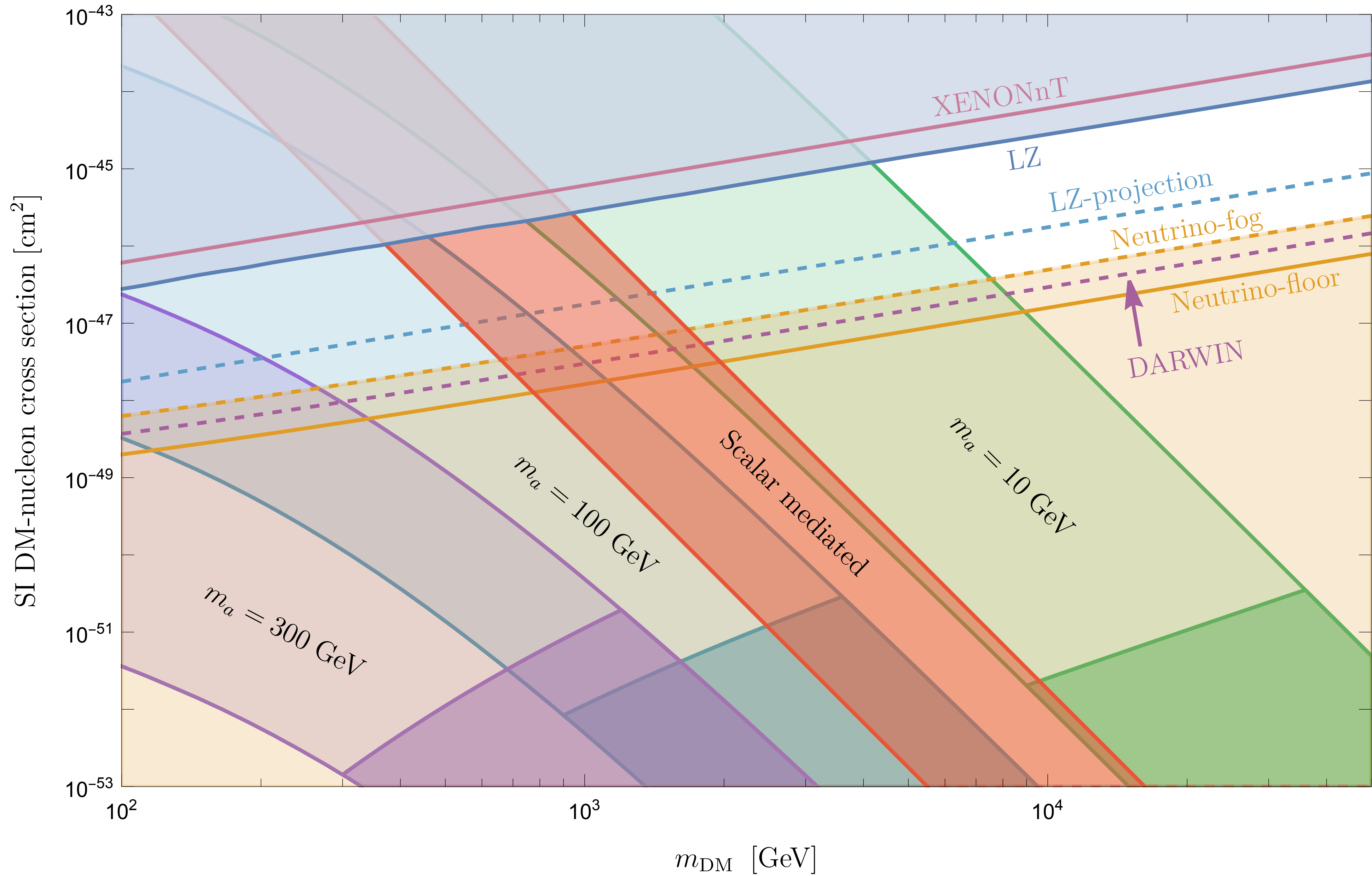
Spin-dependent σ

Momentum suppressed

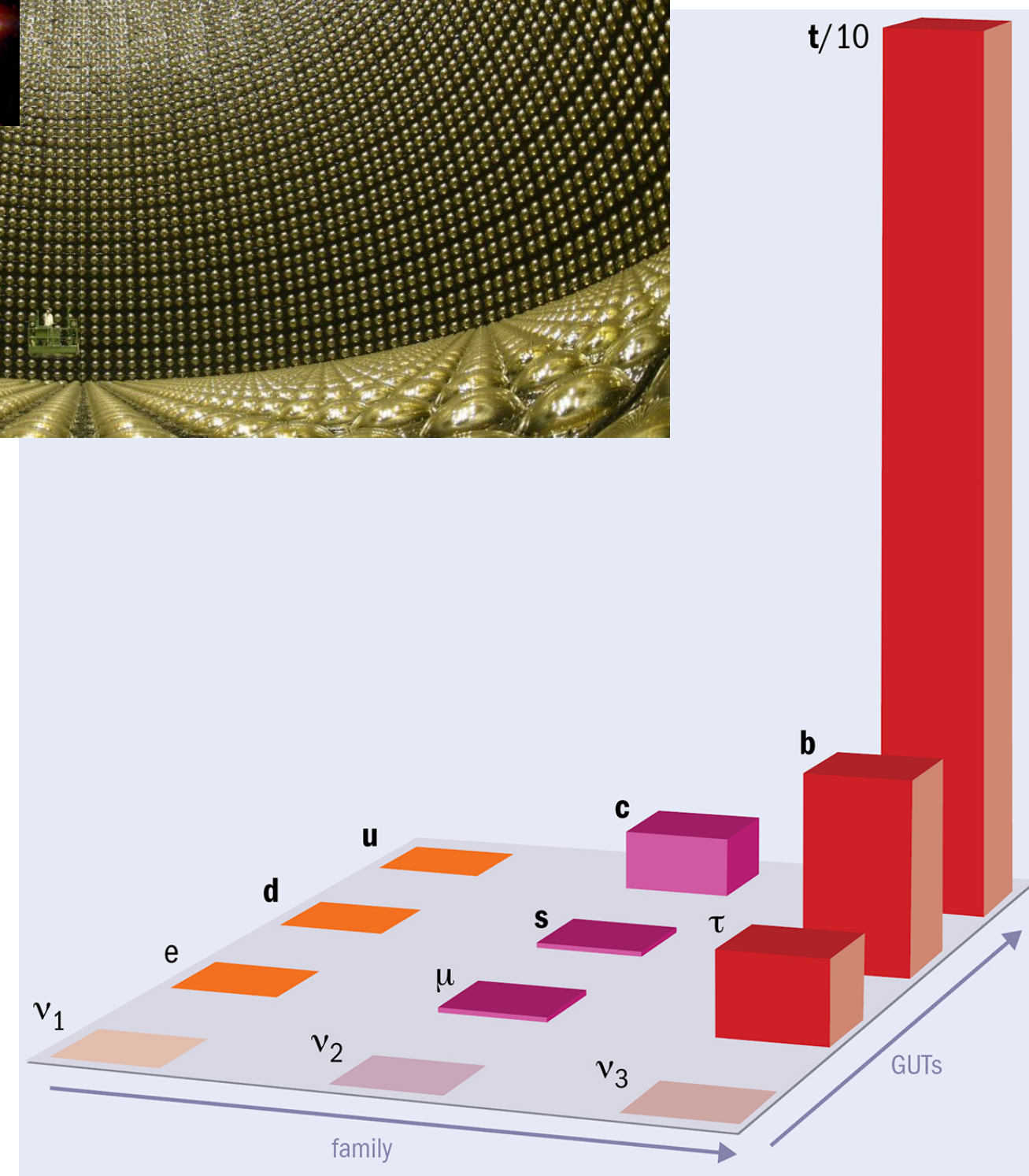
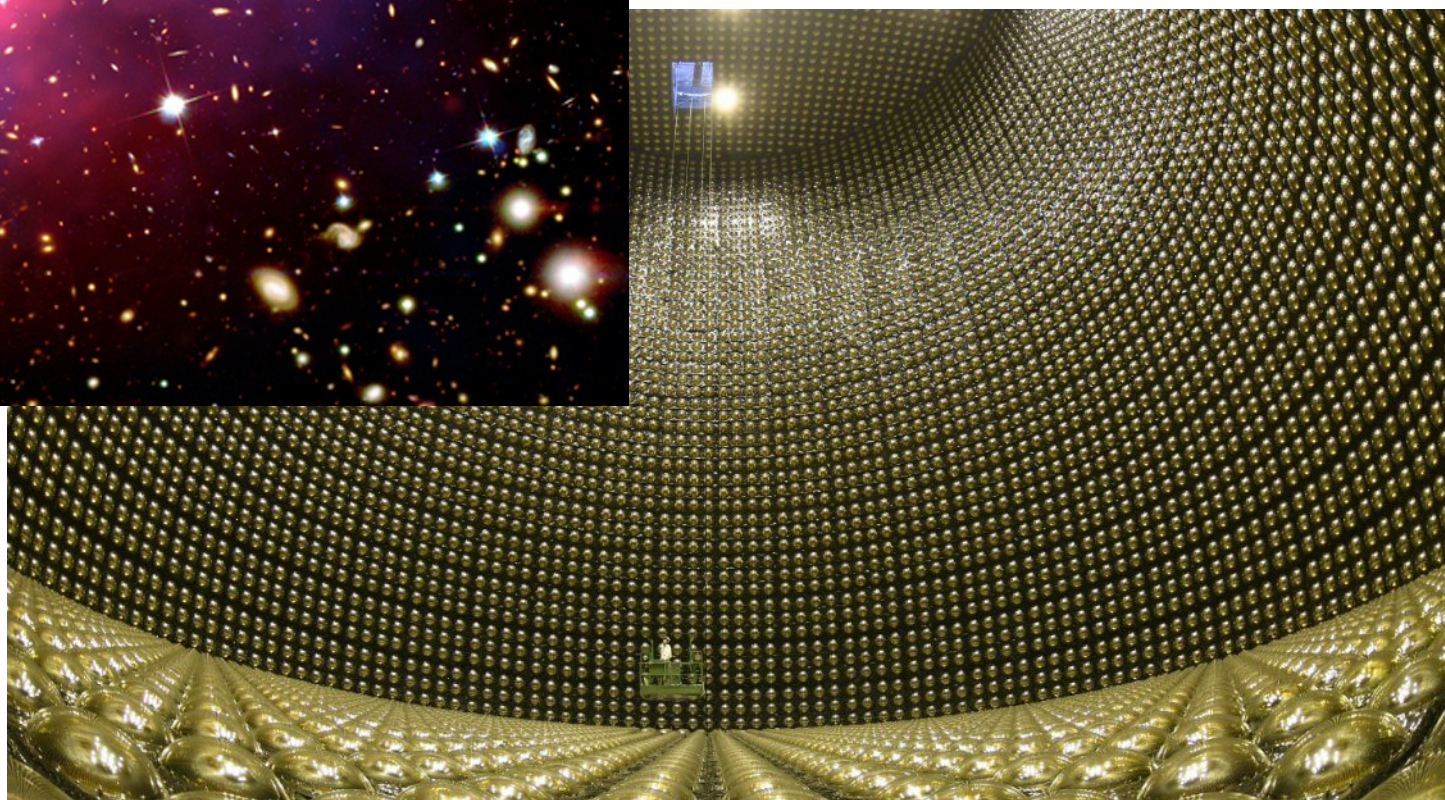
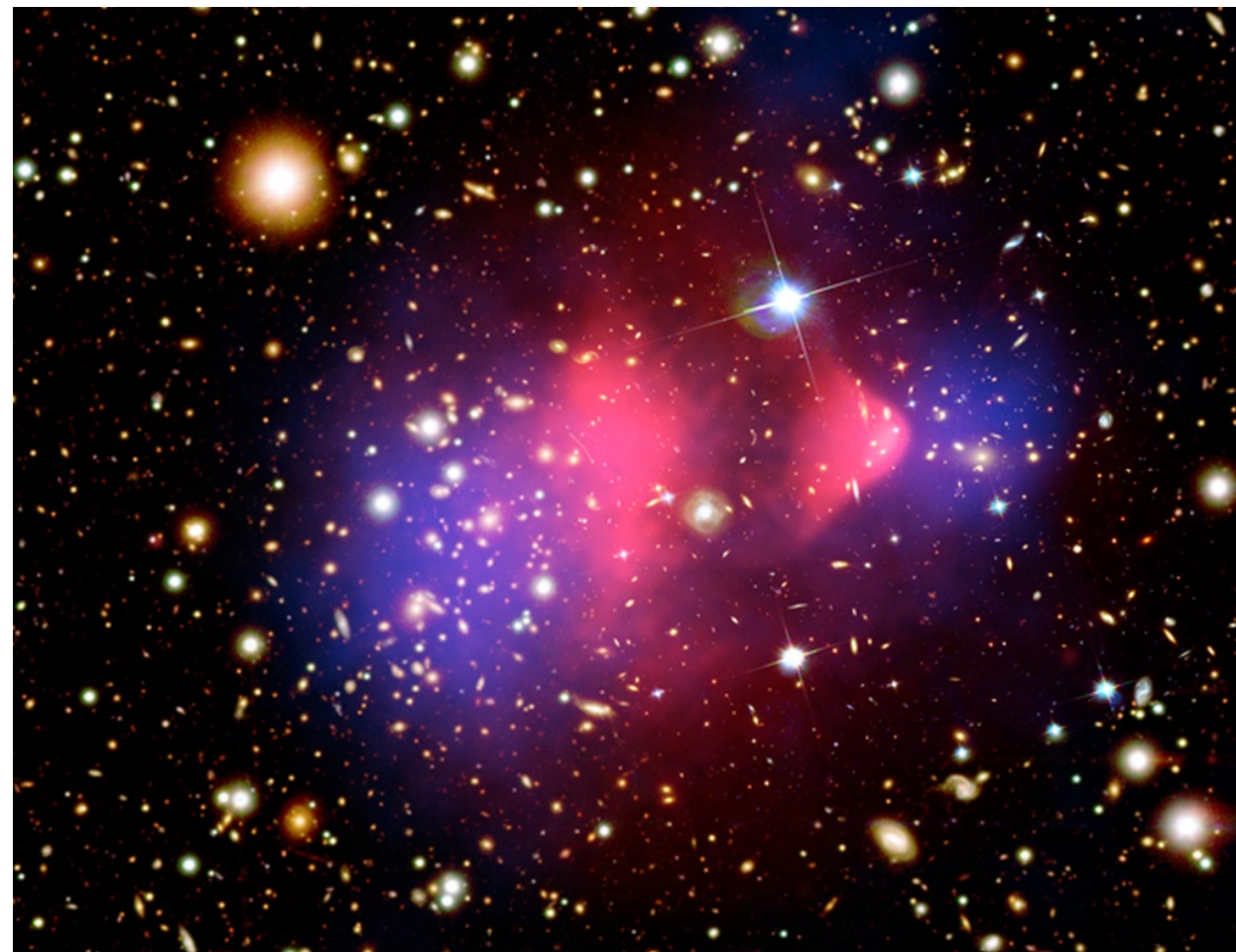
10^{-5} too small!



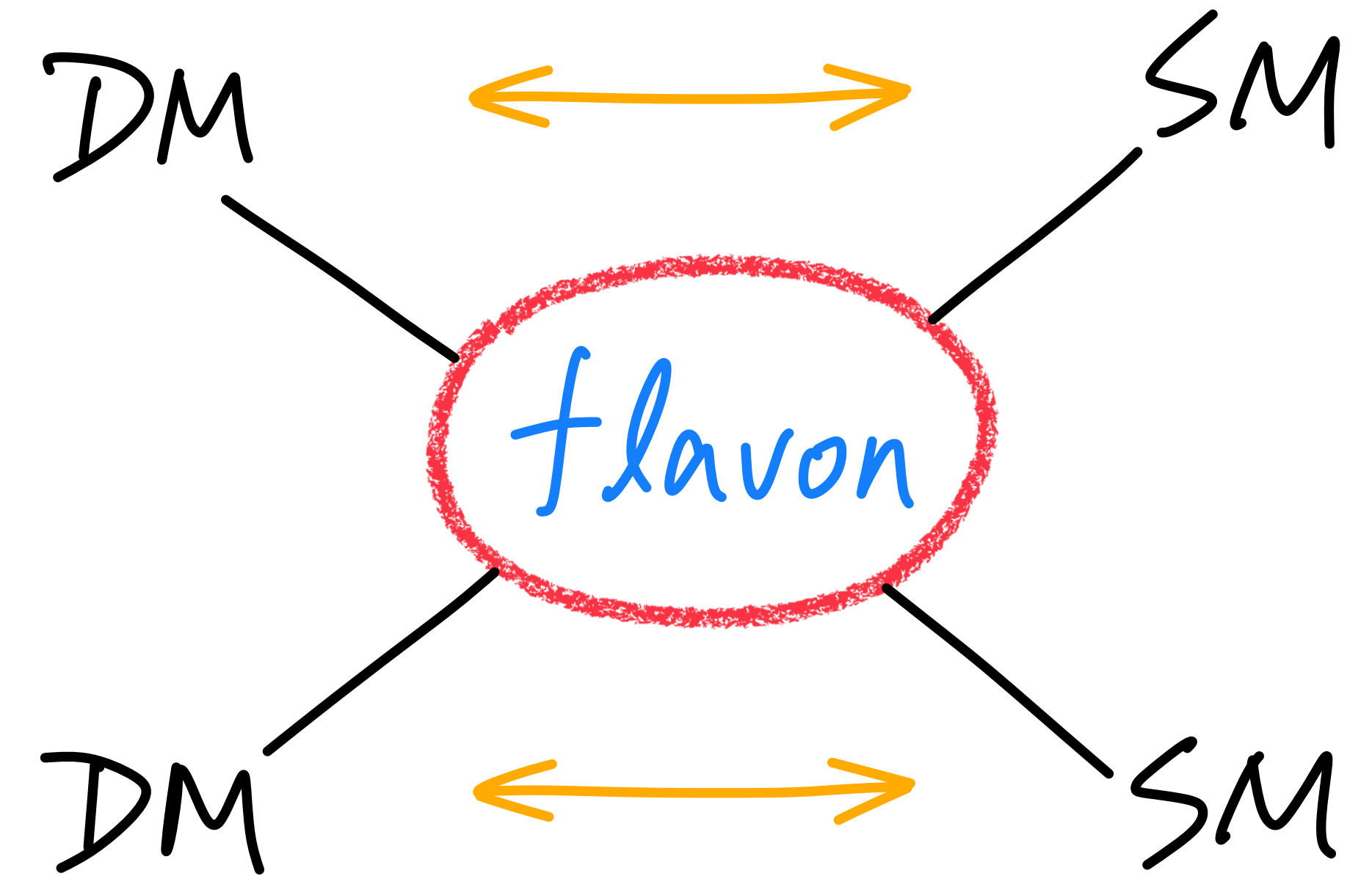
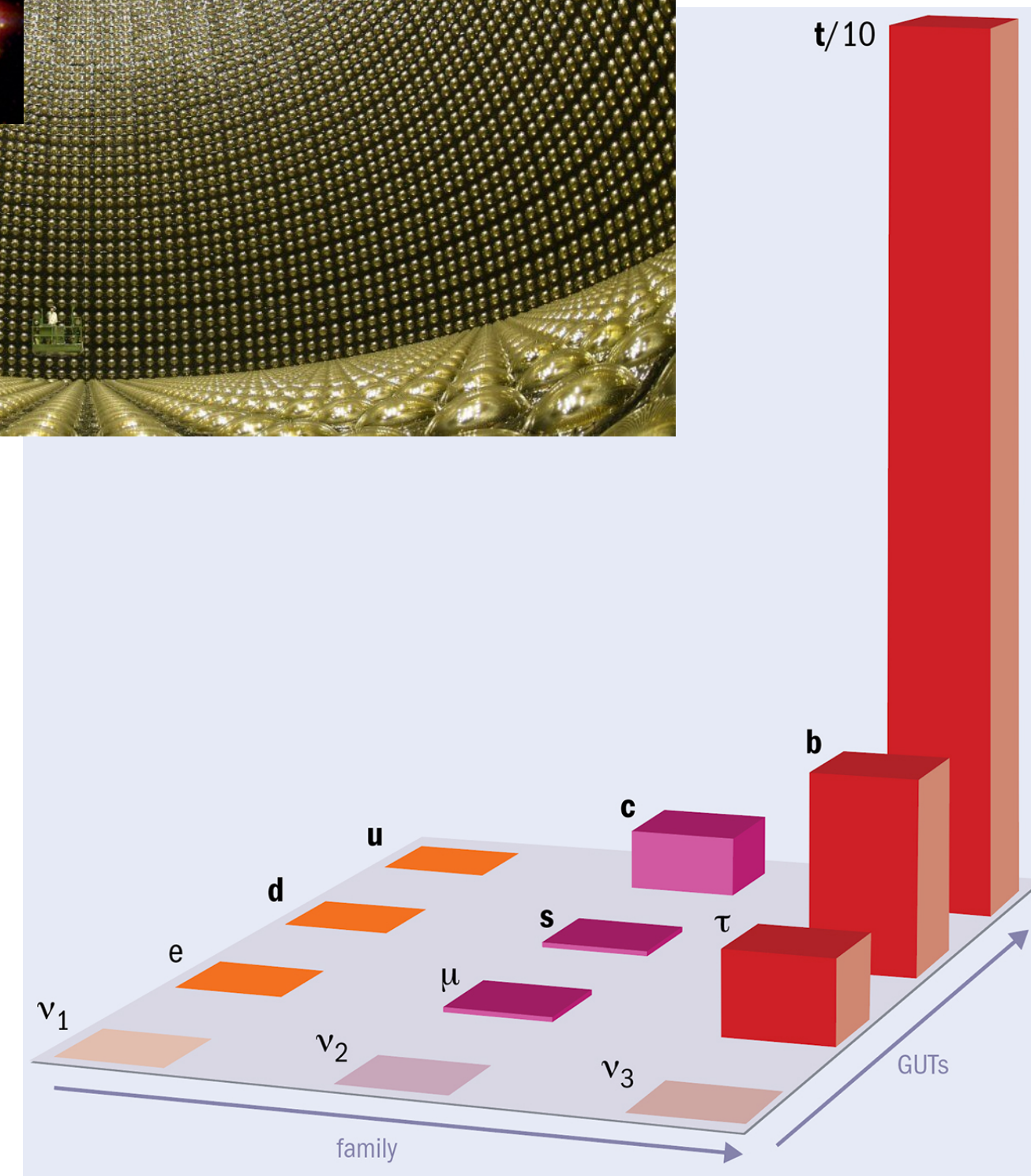
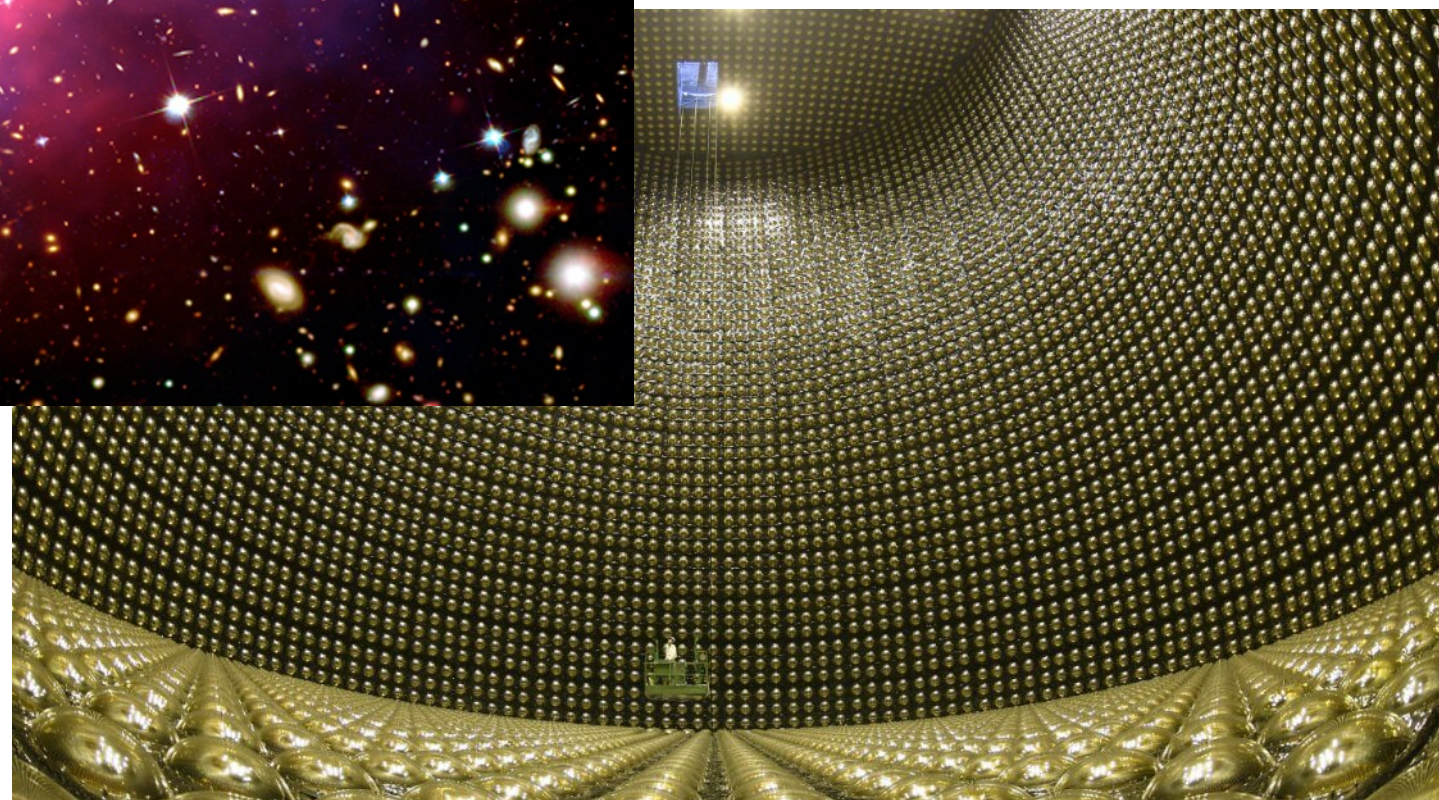
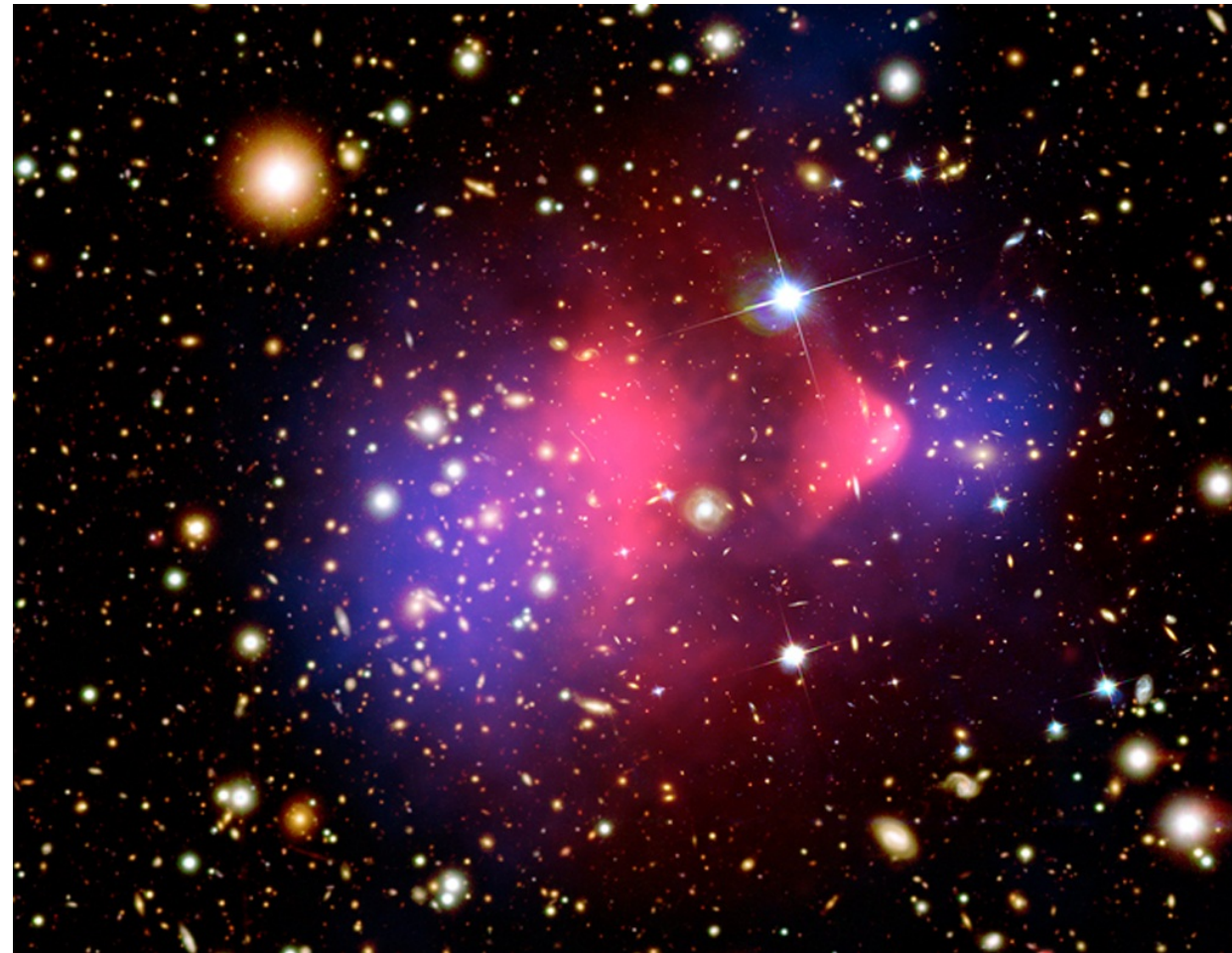
Spin-independent σ



Summary for the impatient

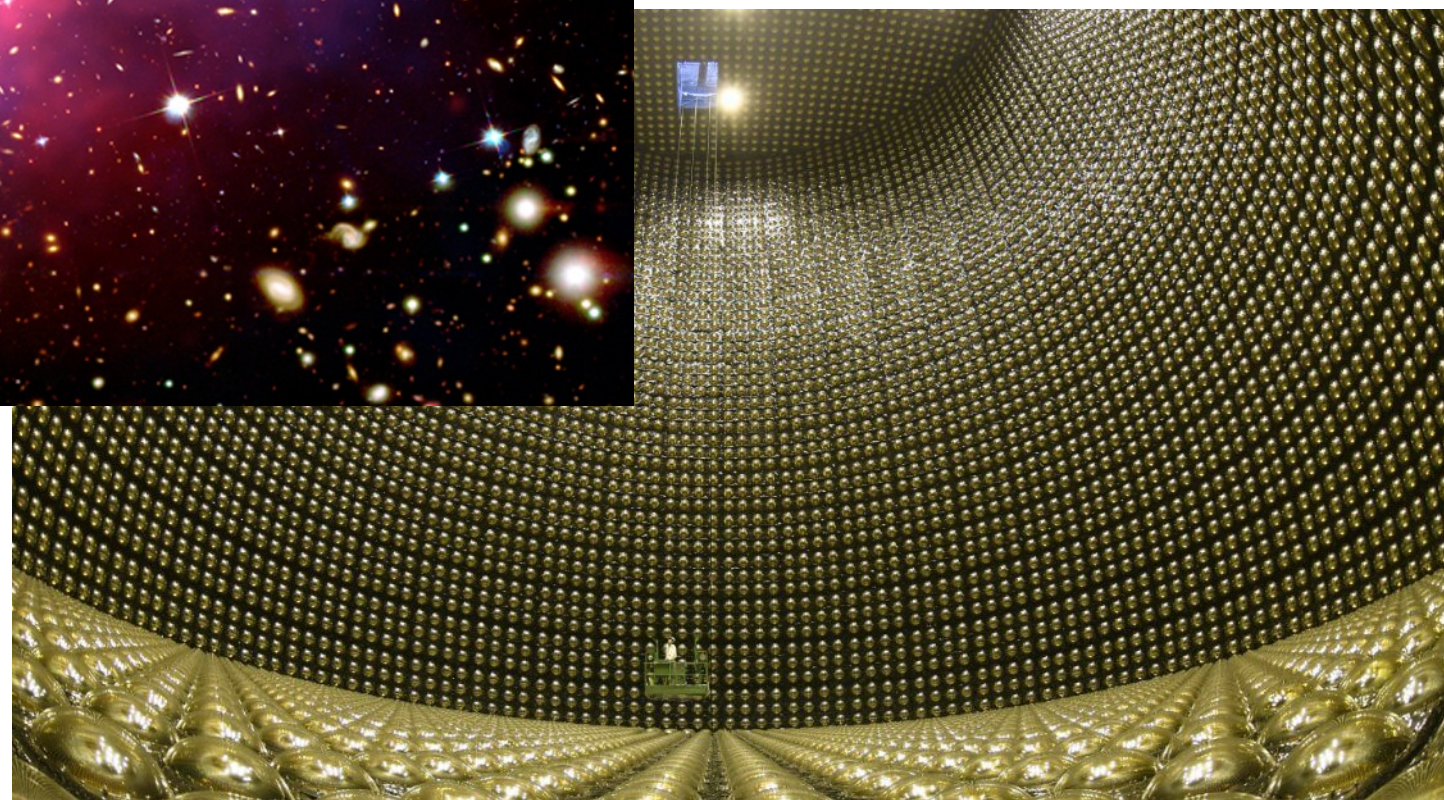
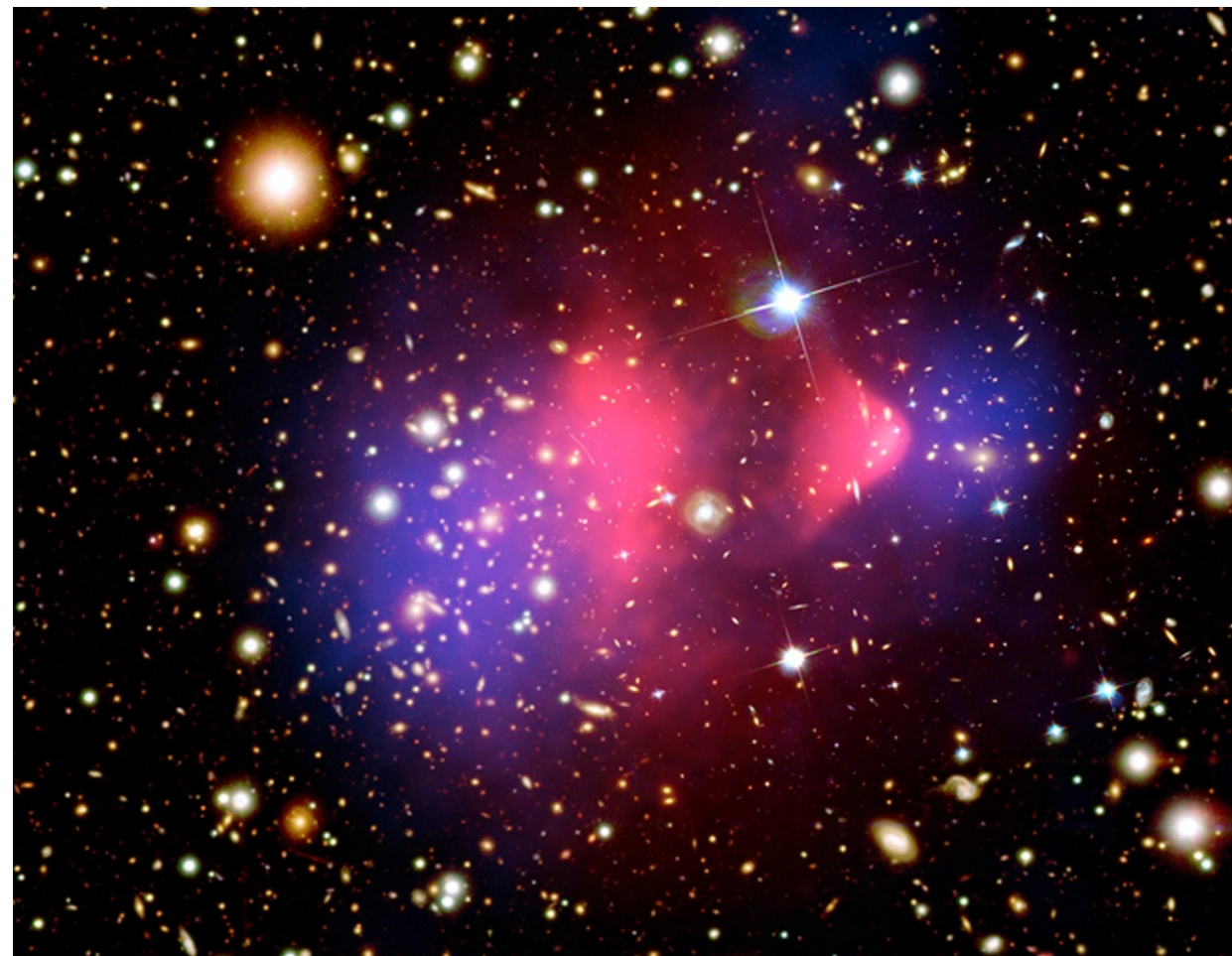


Summary for the impatient

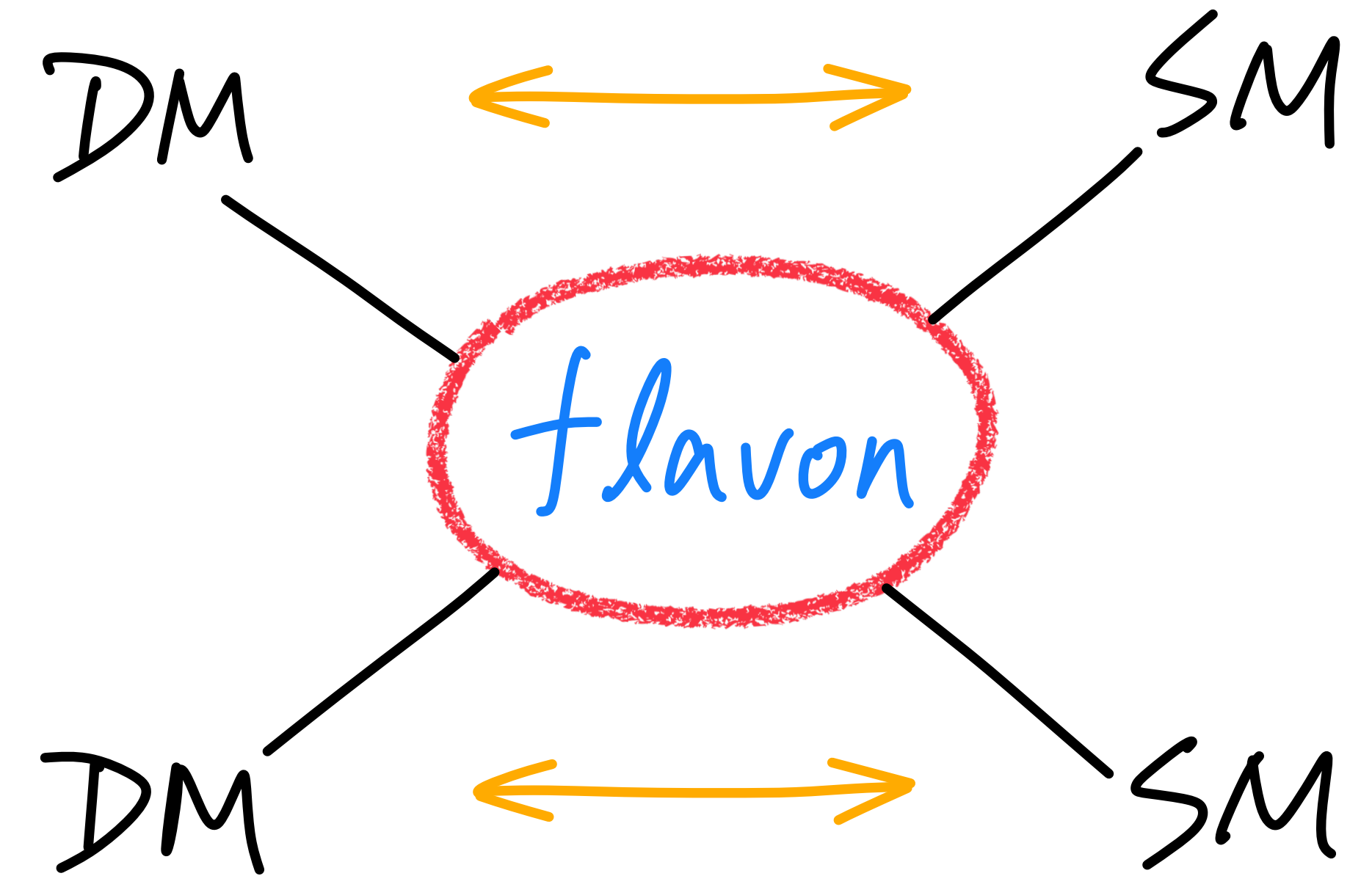
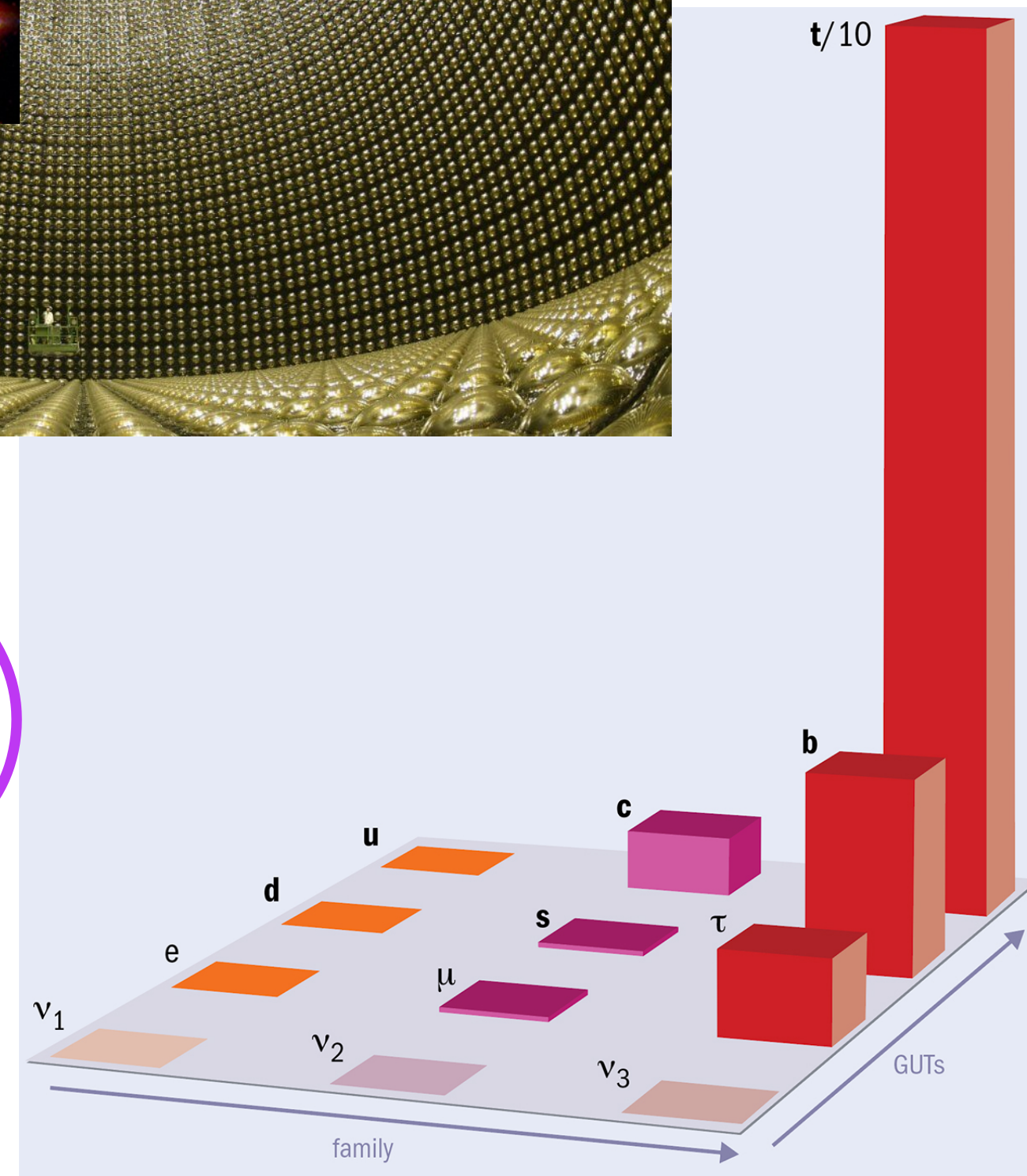


- ✓ • Freeze-out WIMP
- ✓ • Freeze-in FIMP

Summary for the impatient



Next = 
Baryogenesis



- ✓ • Freeze-out WIMP
- ✓ • Freeze-in FIMP