Flavon for the win (?)

Too good to be true

CRC TRR 257

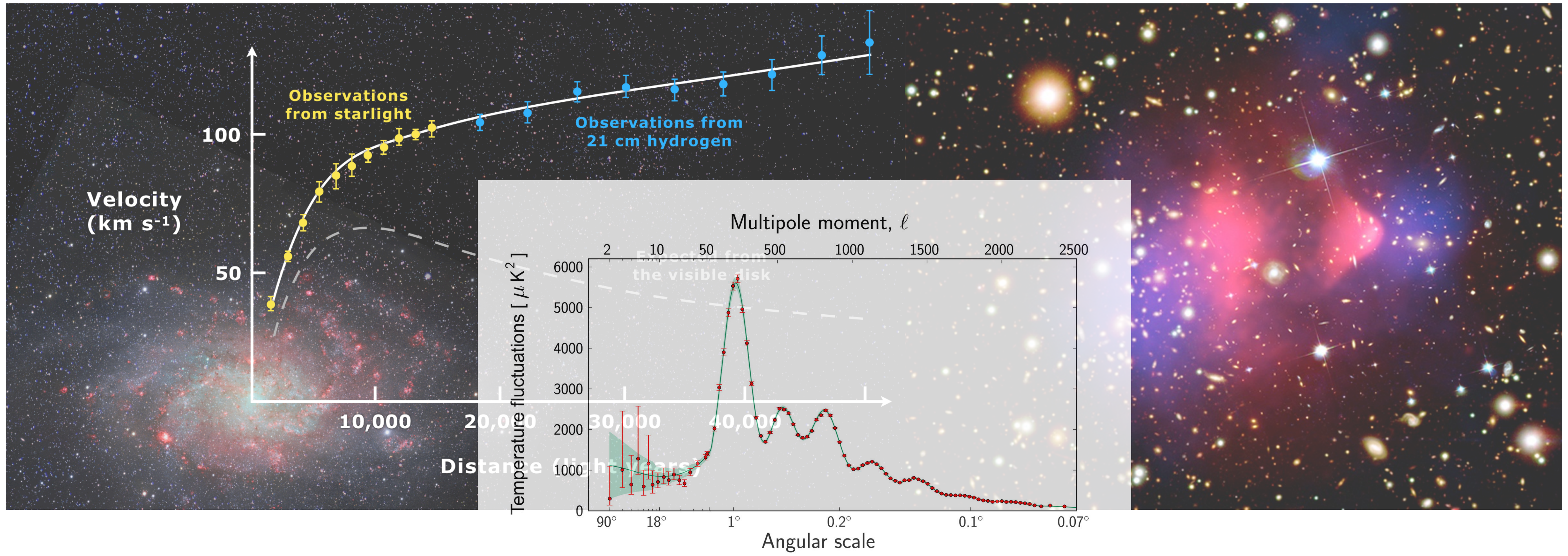
Tom Tong

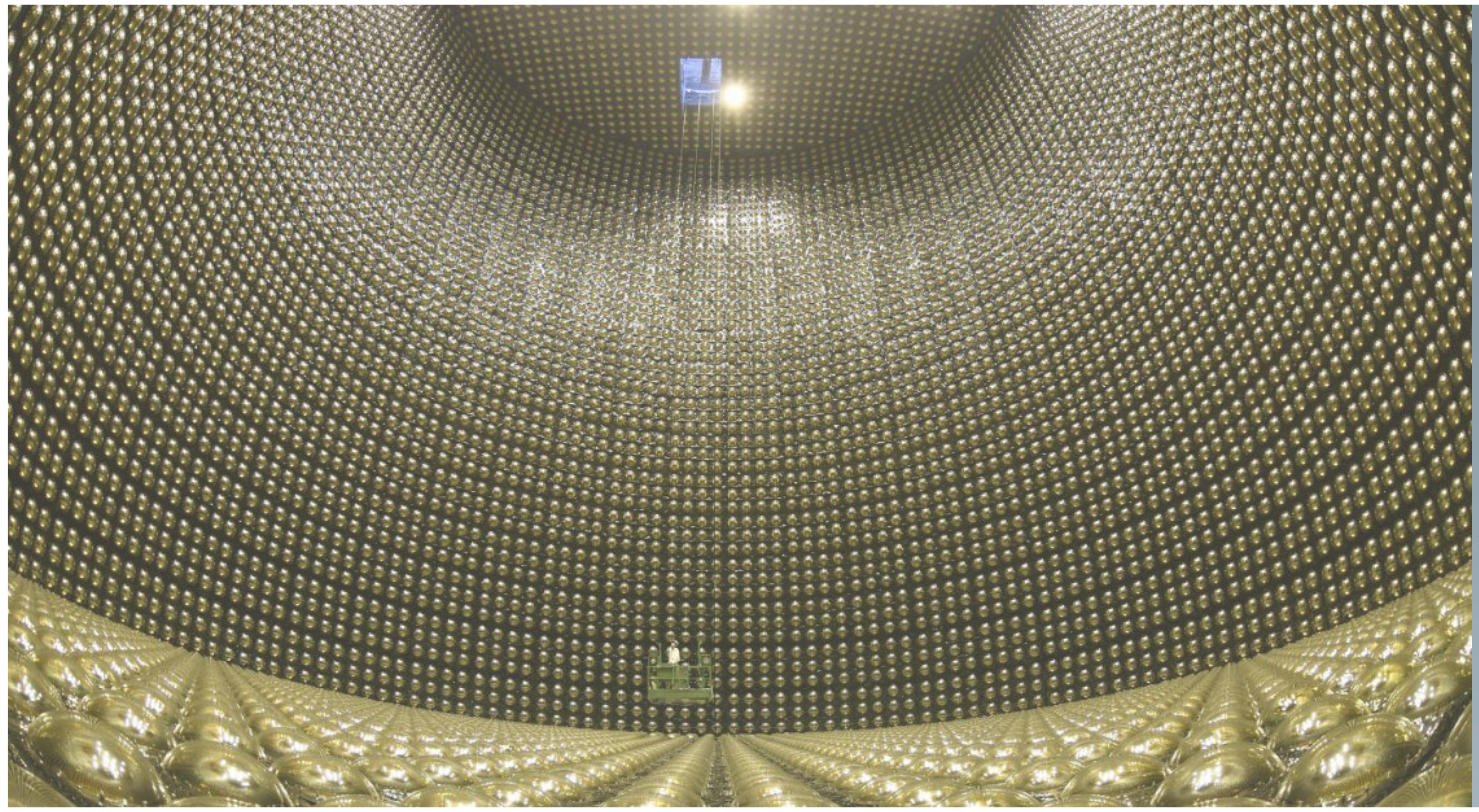
with Rusa Mandal

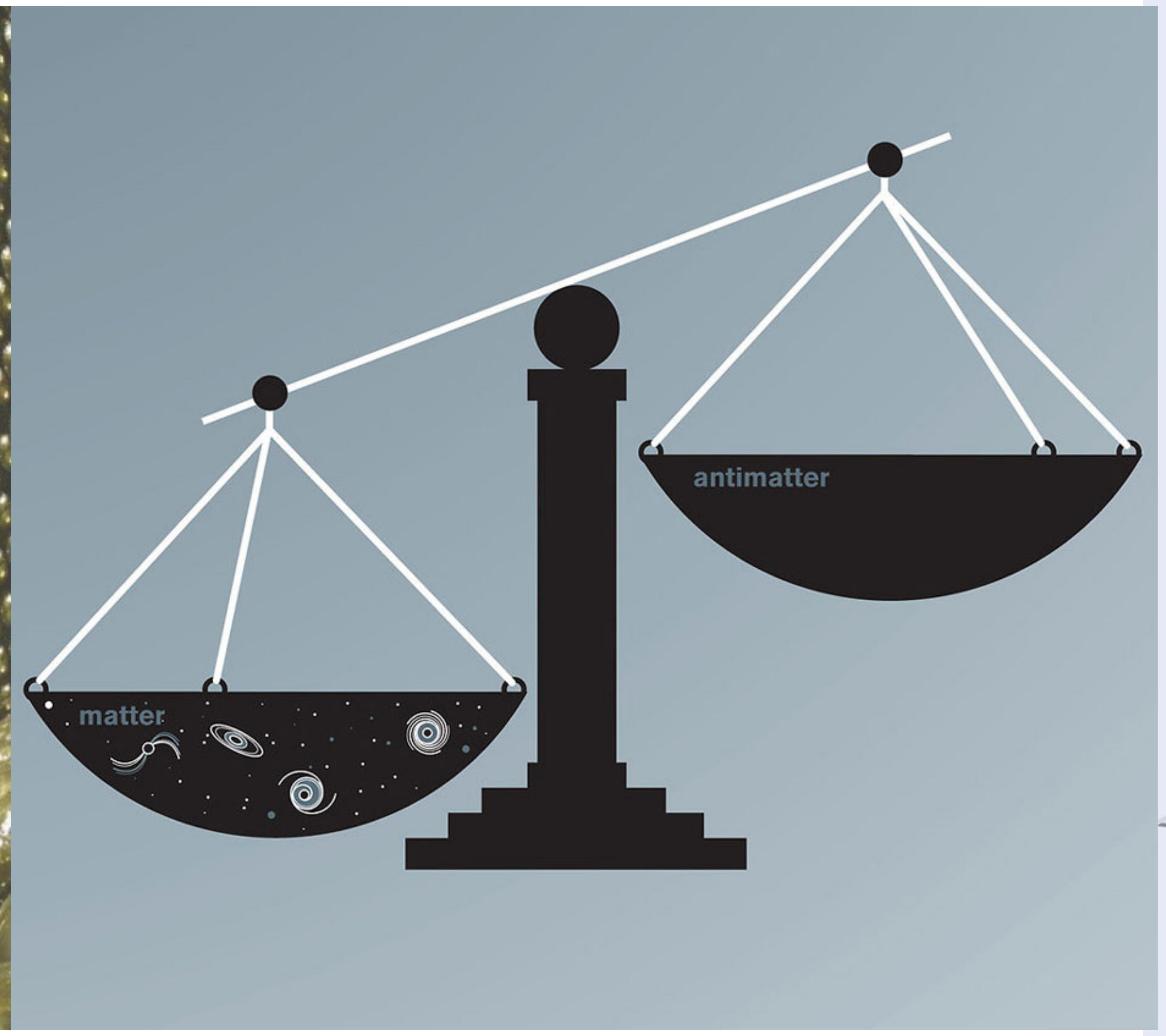
2311.00021 *JCAP* 11 (2023) 074

Universität Siegen / TP1 Theoretical Particle Physics
CPPS Center for Particle Physics Siegen

Evidence of new physics

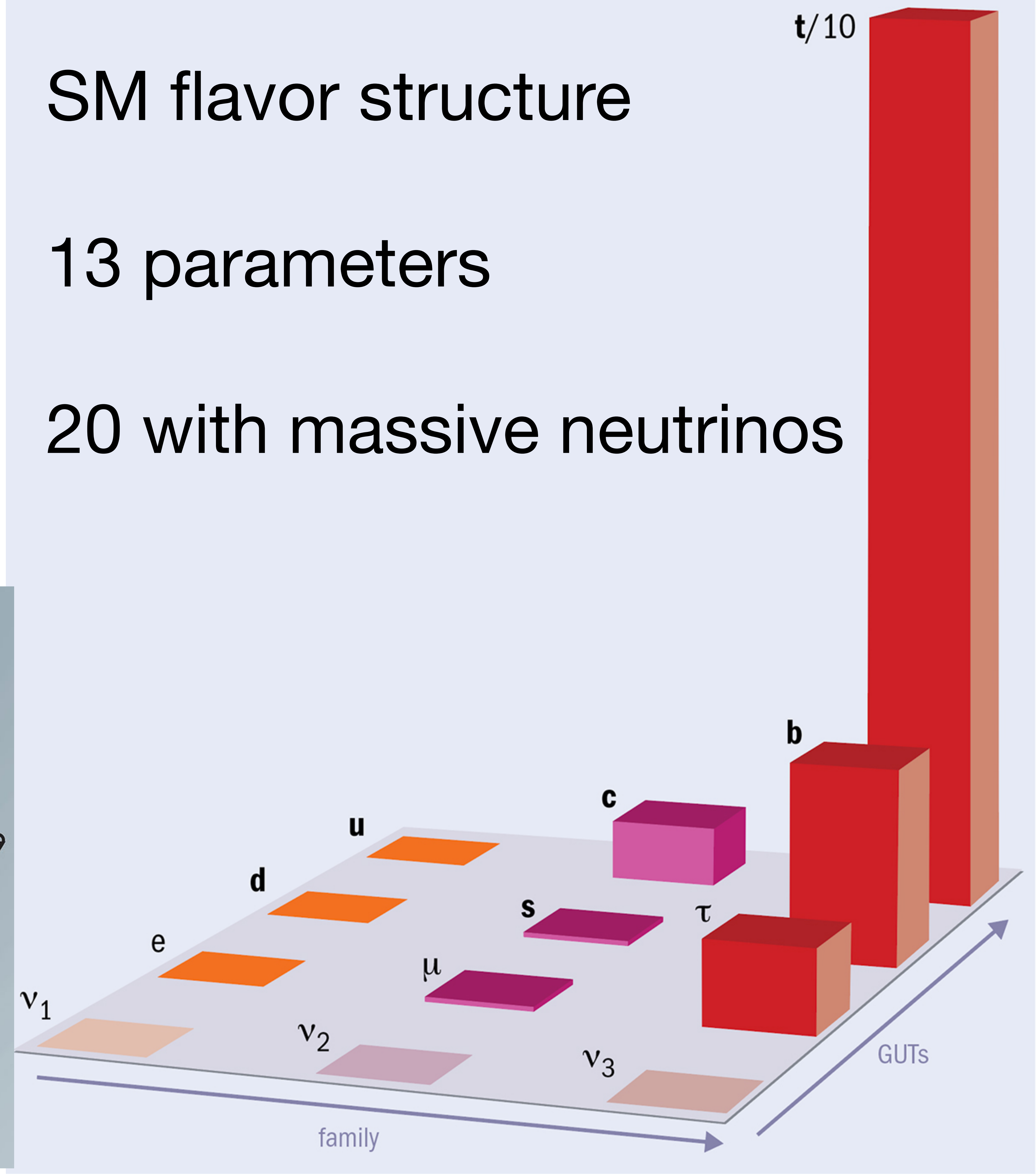




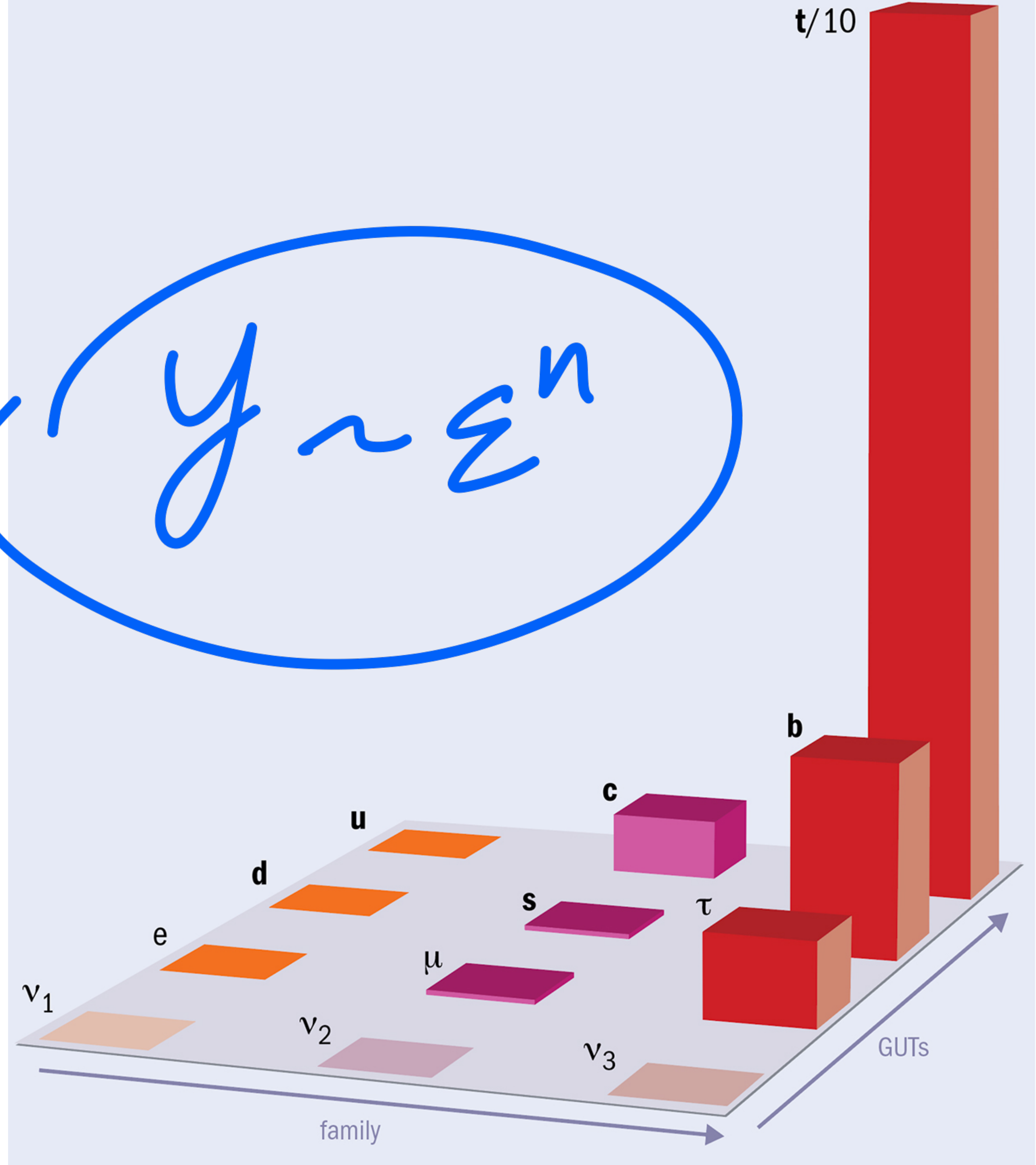


Mystery of flavor

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



Hierarchy in the fermion mass

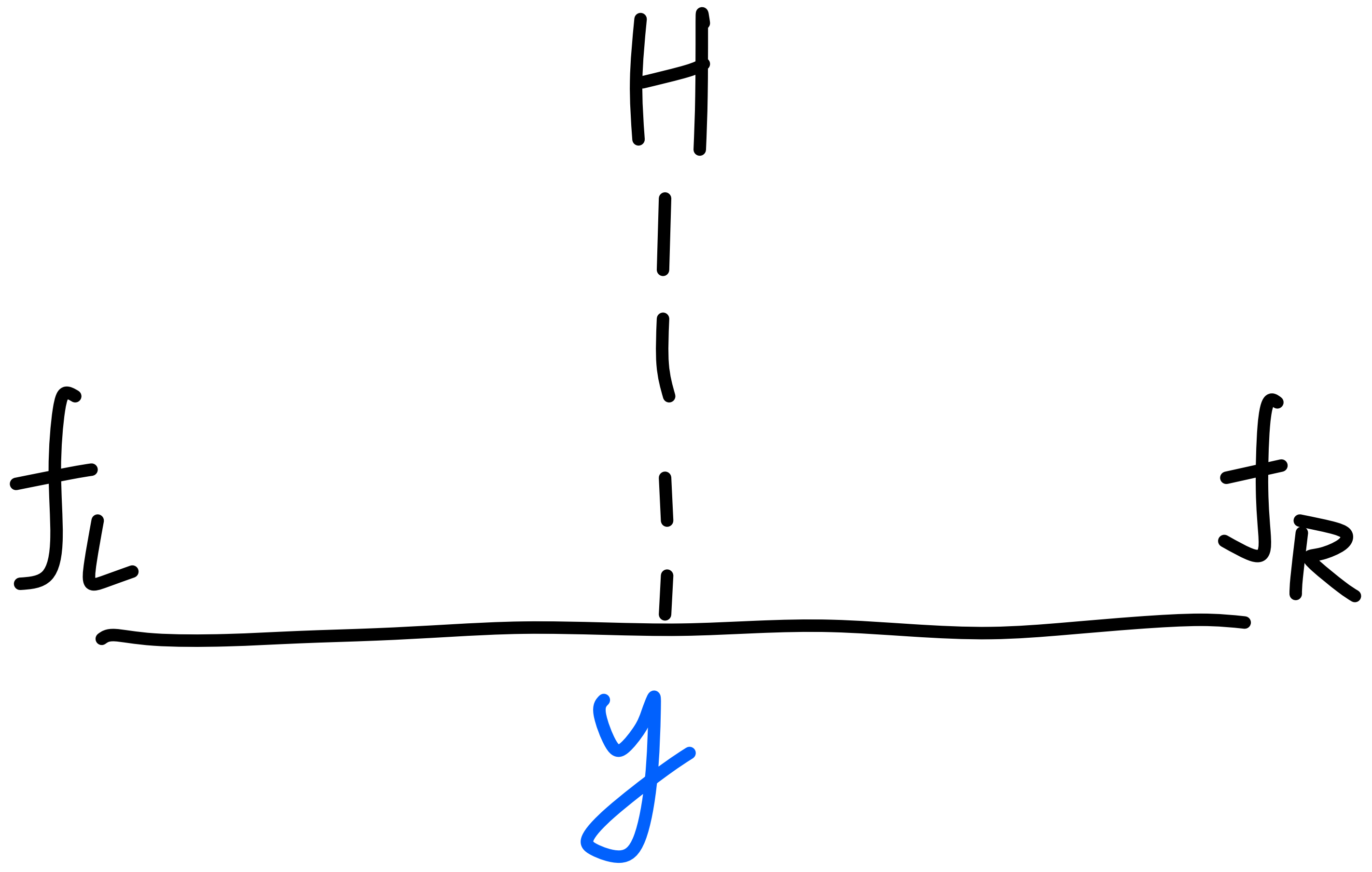


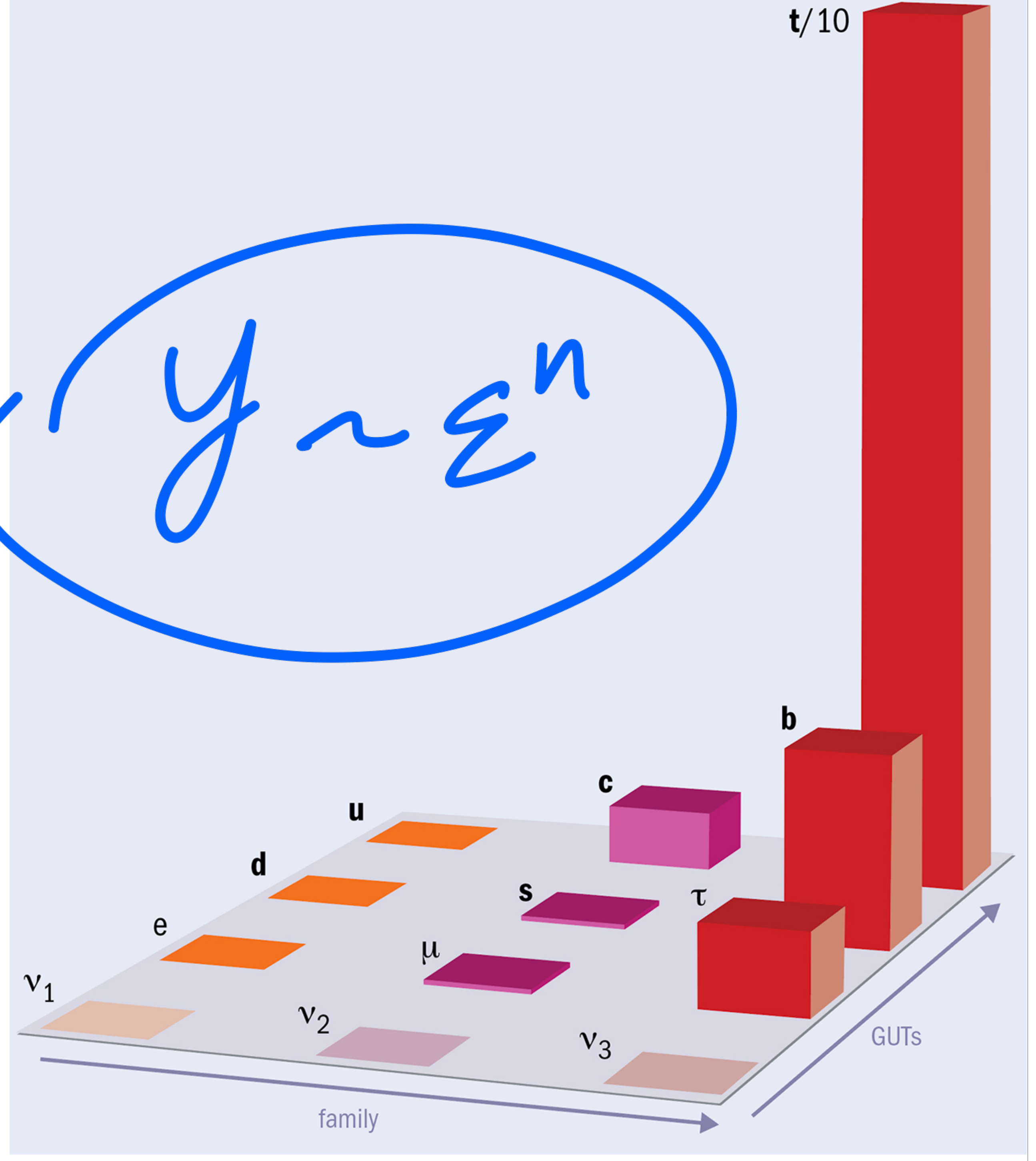
$y \sim \varepsilon^n$

$$\frac{m_e}{m_t} \approx 3\times 10^{-6} \qquad \text{Top Yukawa } y_t \approx 1$$

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

Global U(1) Froggatt-Nielsen

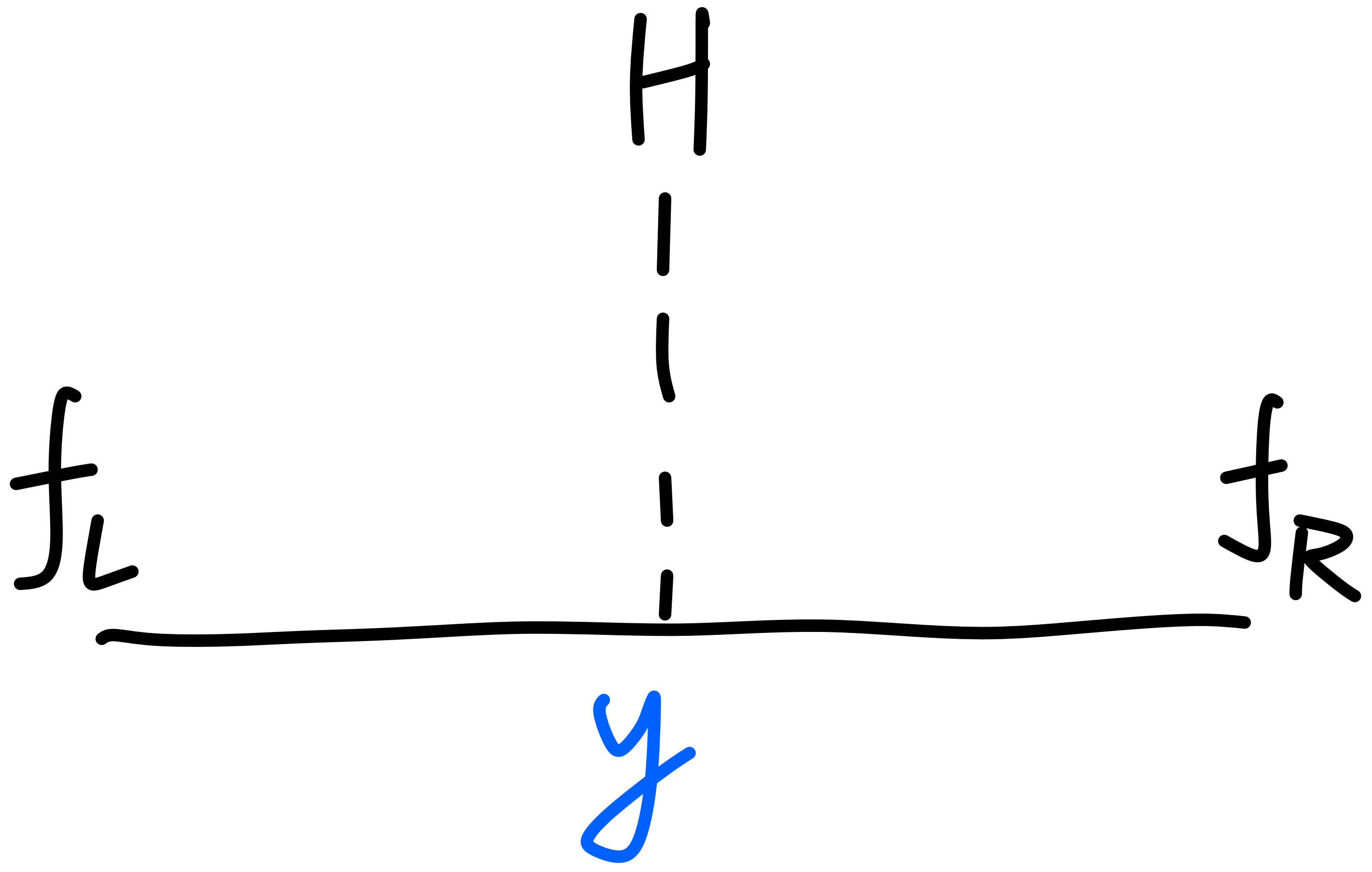




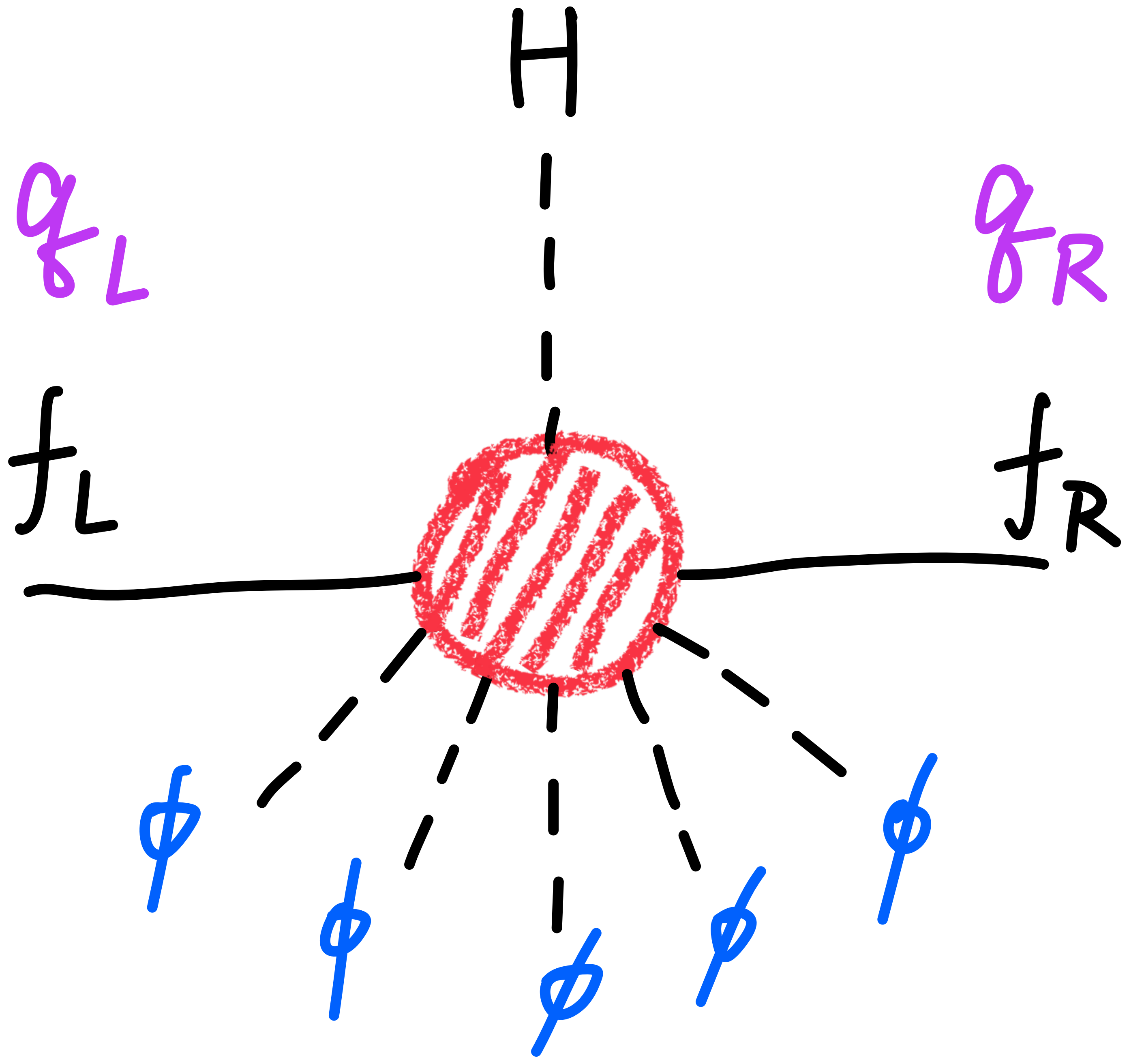
$y \sim \varepsilon^n$

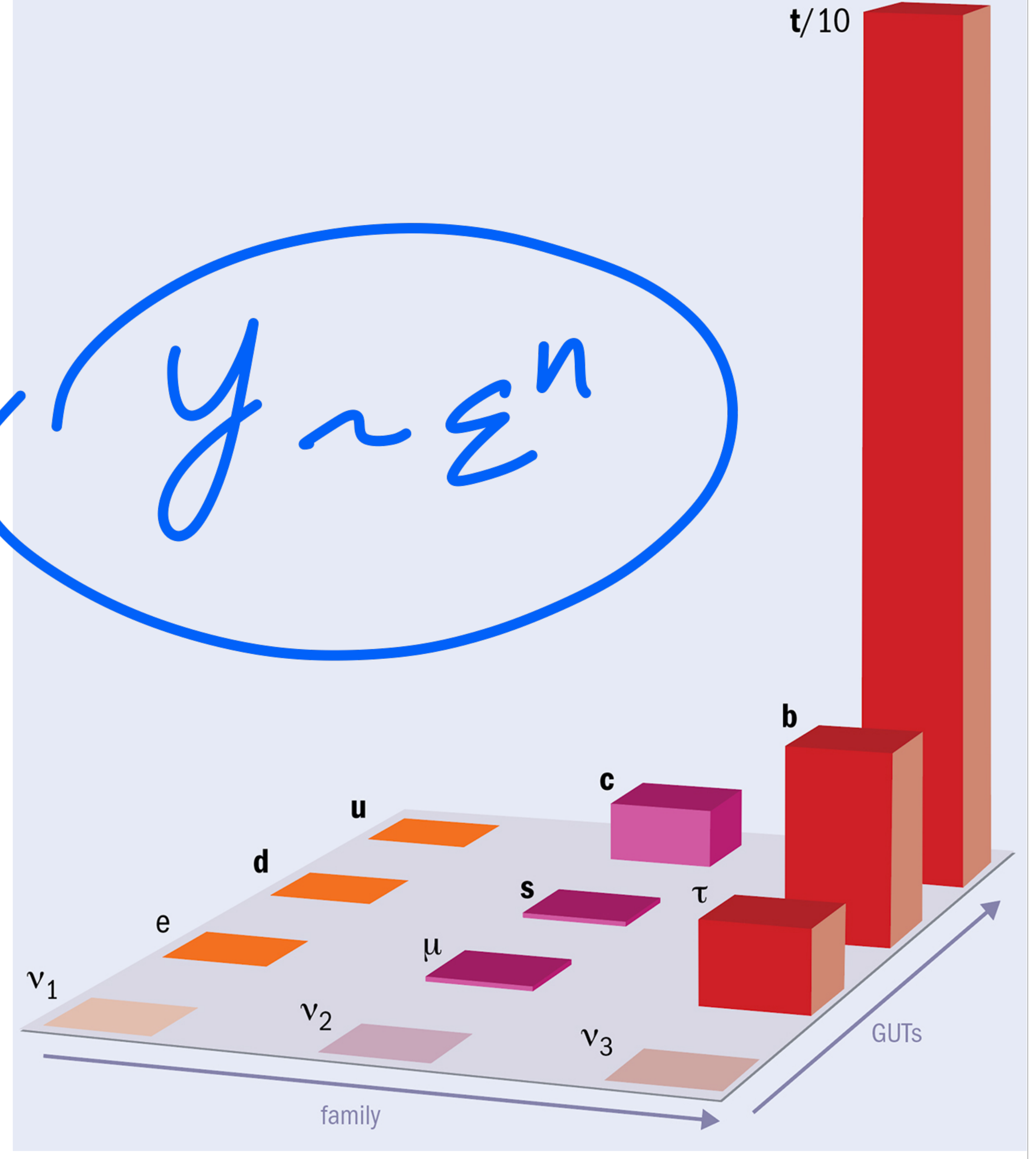
$$y \bar{f}_L H f_R$$

Global U(1) Froggatt-Nielsen



$\Longrightarrow$



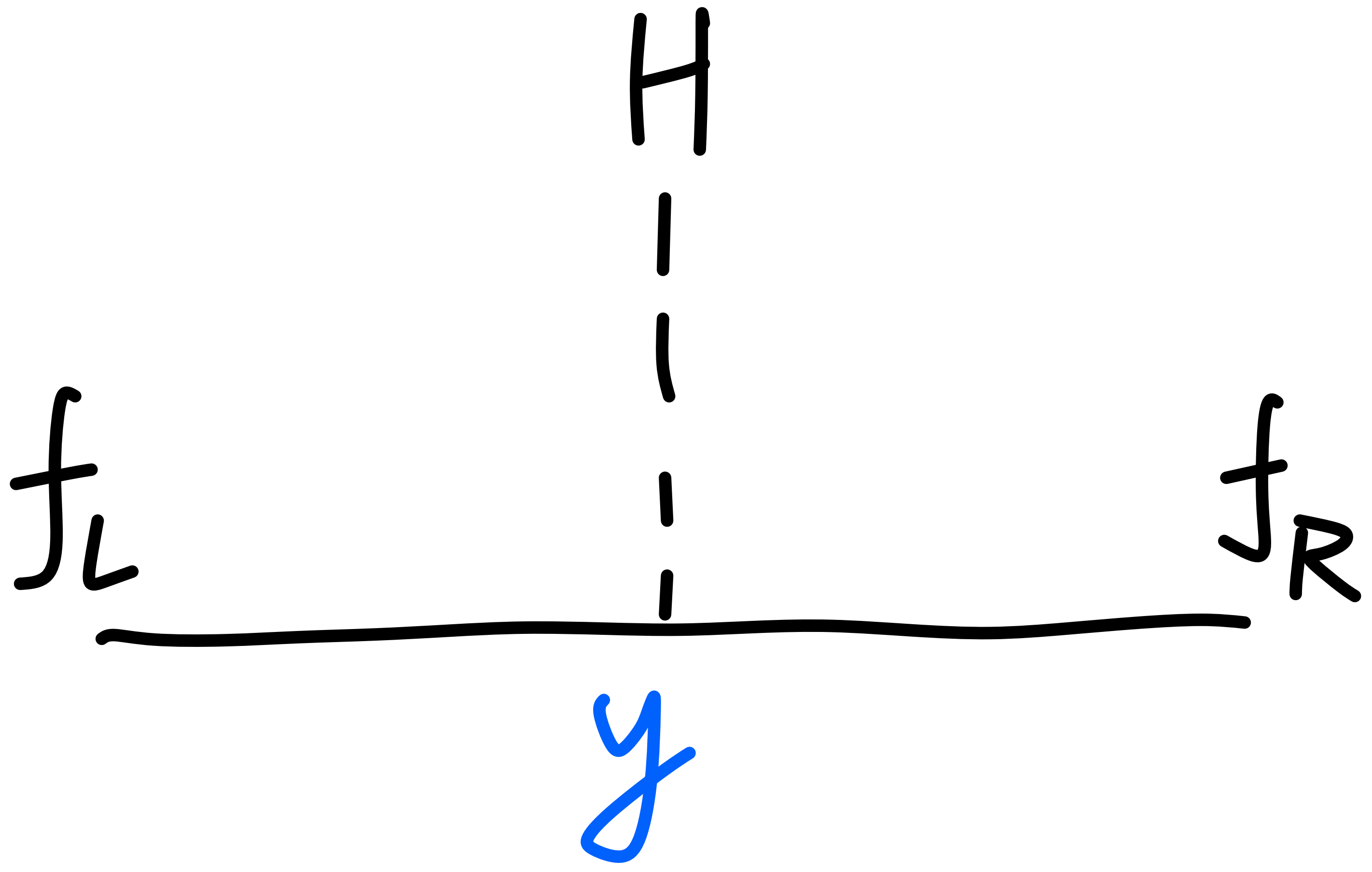


$$y \sim \varepsilon^n$$

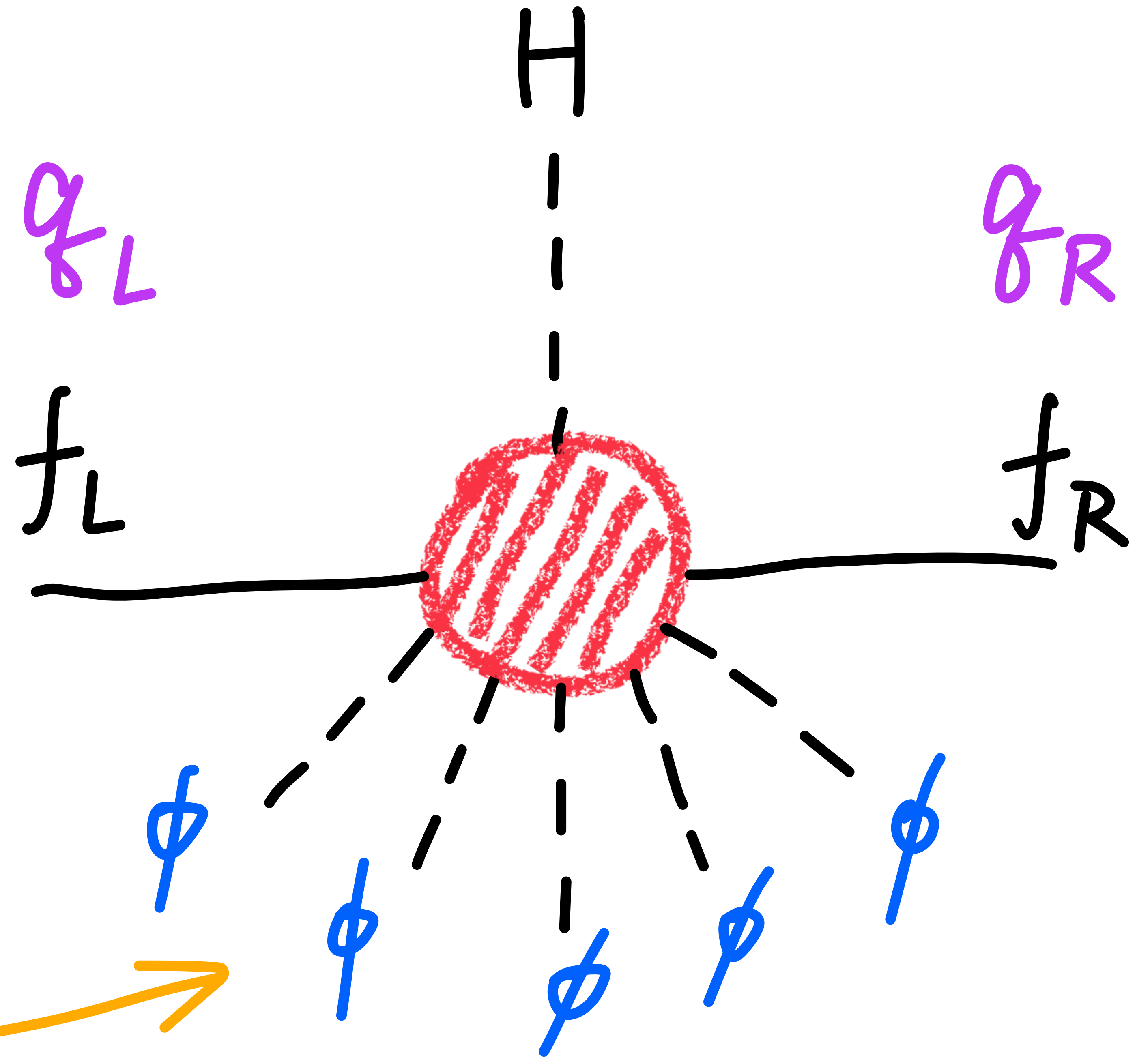
$$y\,\bar{f}_L H f_R \Longrightarrow c\left(\frac{\phi}{M}\right)^n \bar{f}_L H f_R$$

$$\begin{cases} c \sim \mathcal{O}(1) \\ \dfrac{\phi \to v_\phi}{M} = \varepsilon \\ q_L - q_R = n \end{cases}$$

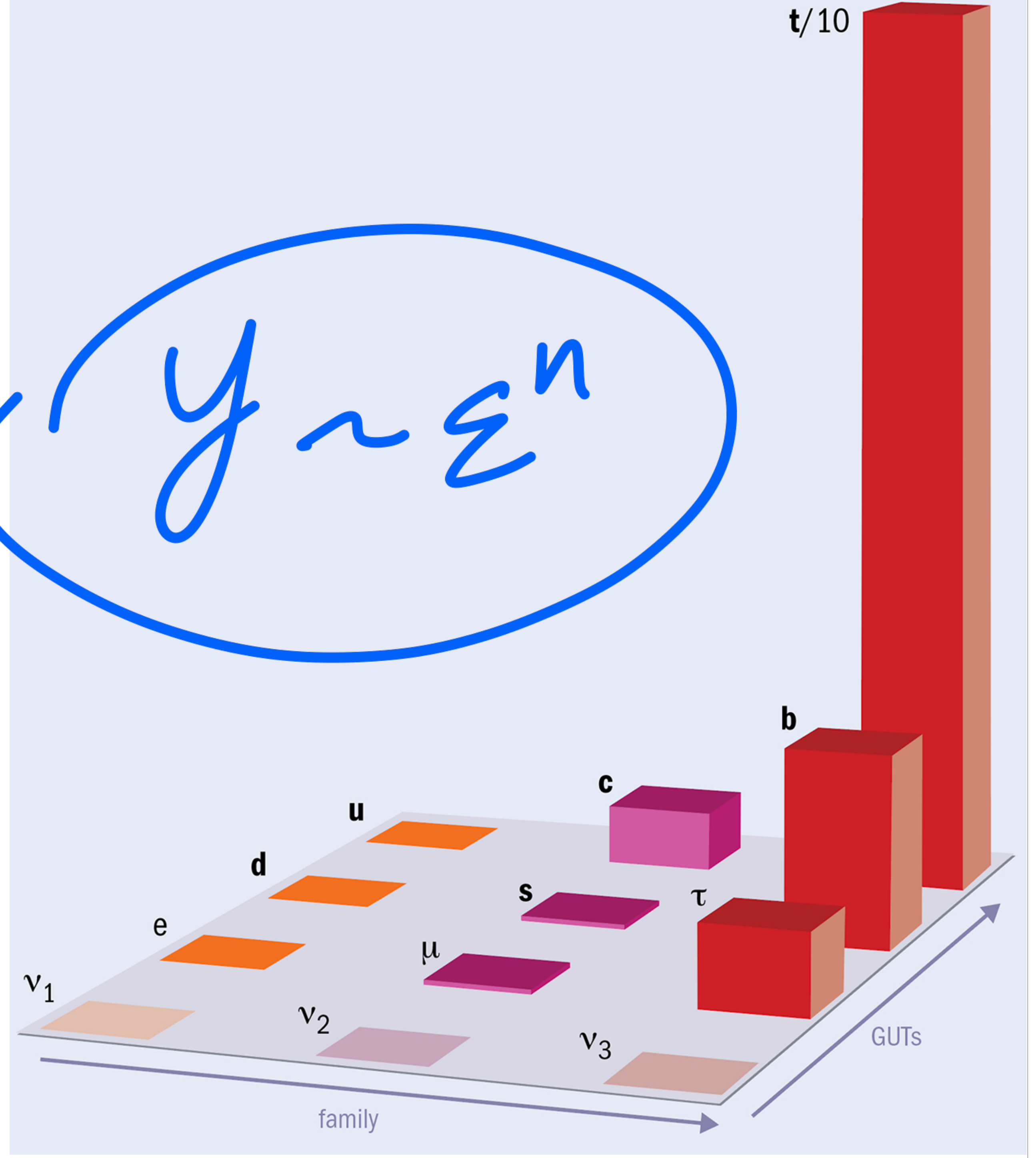
Global U(1) Froggatt-Nielsen



$\Rightarrow$



Flavon



$y \sim \varepsilon^n$

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

$$\begin{cases} c \sim \mathcal{O}(1) \\ \dfrac{\phi \to v_\phi}{M} = \varepsilon \\ q_L - q_R = n \end{cases}$$

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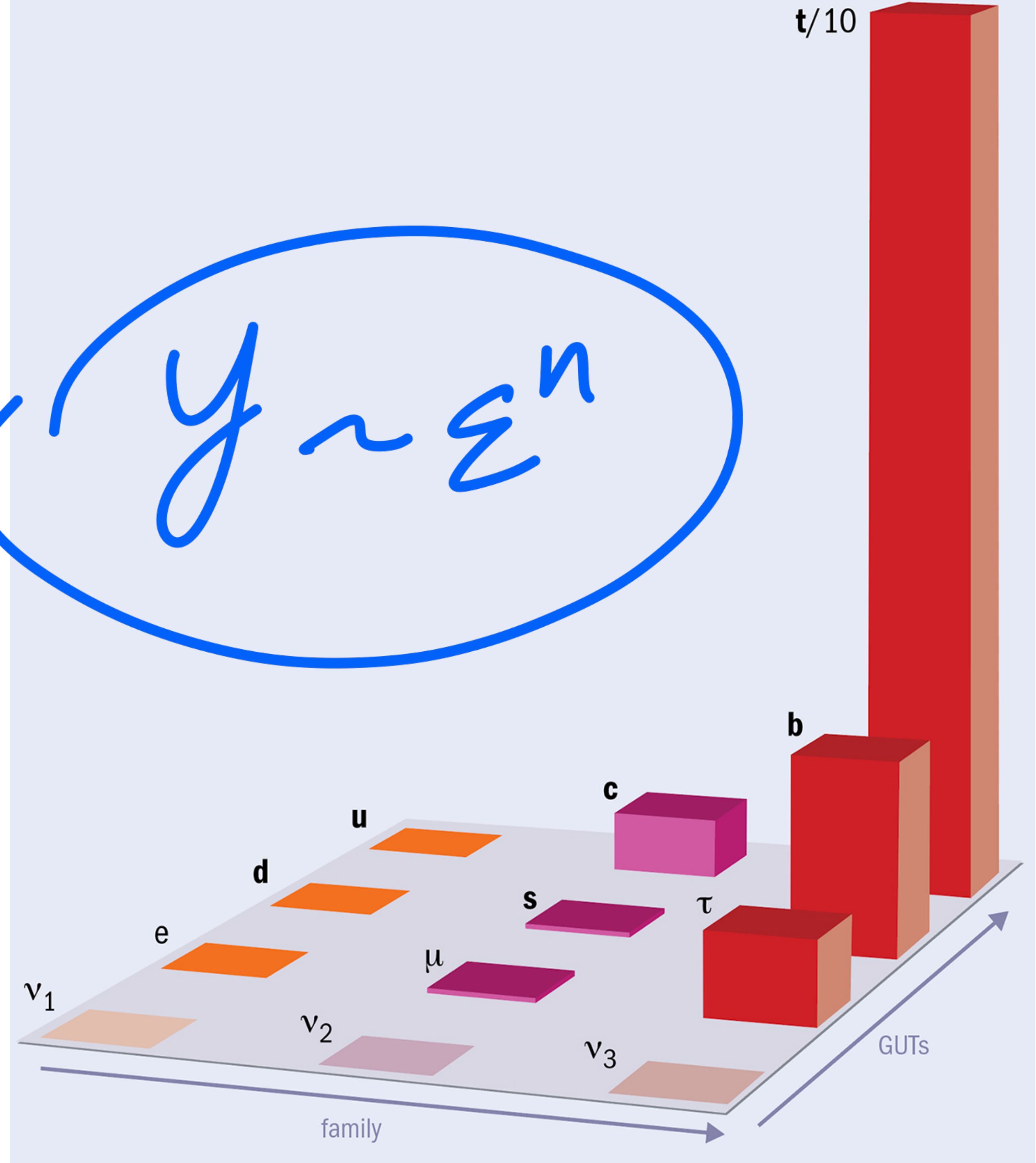
Froggatt-Nielsen charges

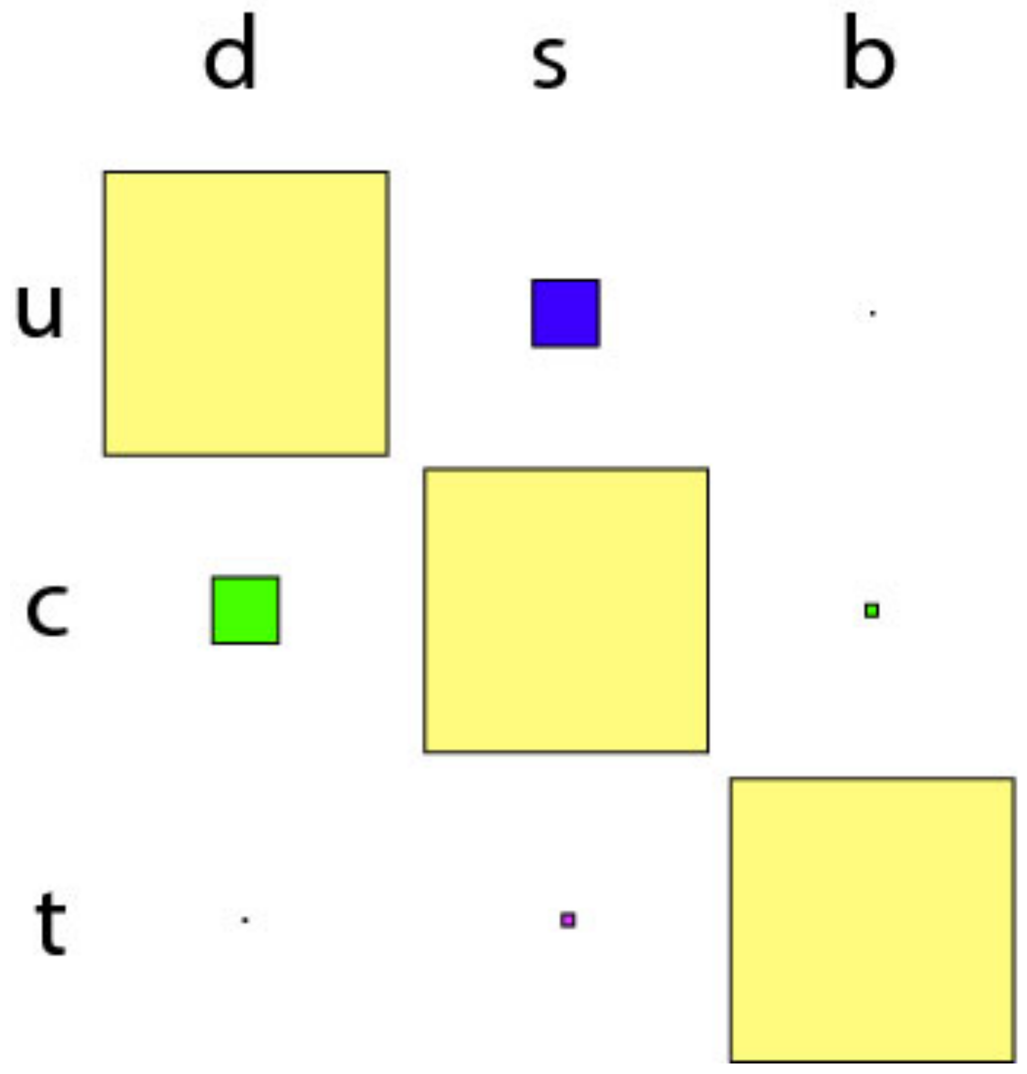
$$\varepsilon = \frac{V_\phi}{M} \approx V_{us} \approx 0.23$$



$$y \sim \varepsilon^n$$

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

CKM



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

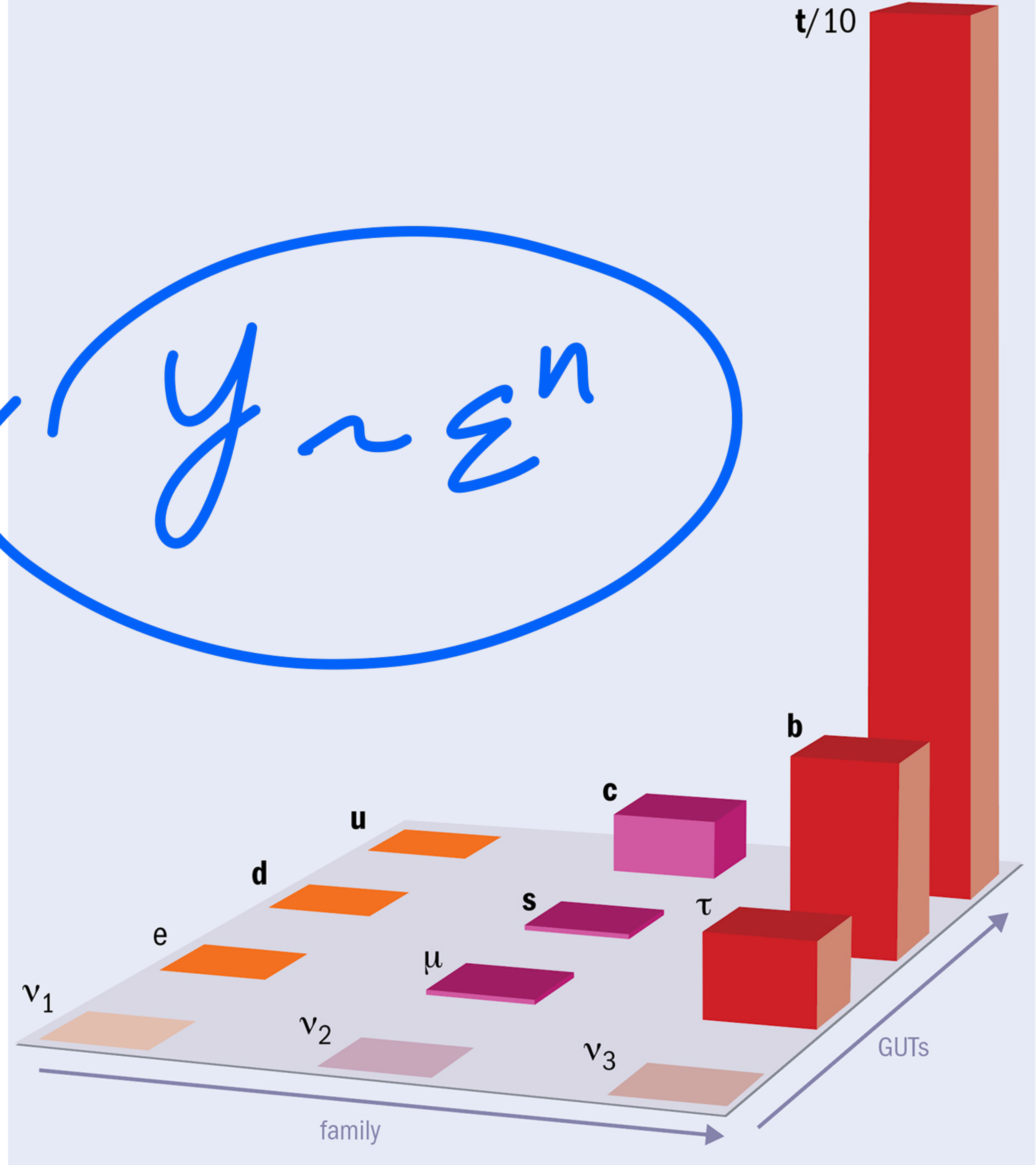
q_L $\qquad$ q_R

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

$$\left\{ \begin{array}{l} c \sim \mathcal{O}(1) \\ \dfrac{\phi \to V_\phi}{M} = \varepsilon \\ q_L - q_R = n \end{array} \right.$$

Froggatt-Nielsen charges

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



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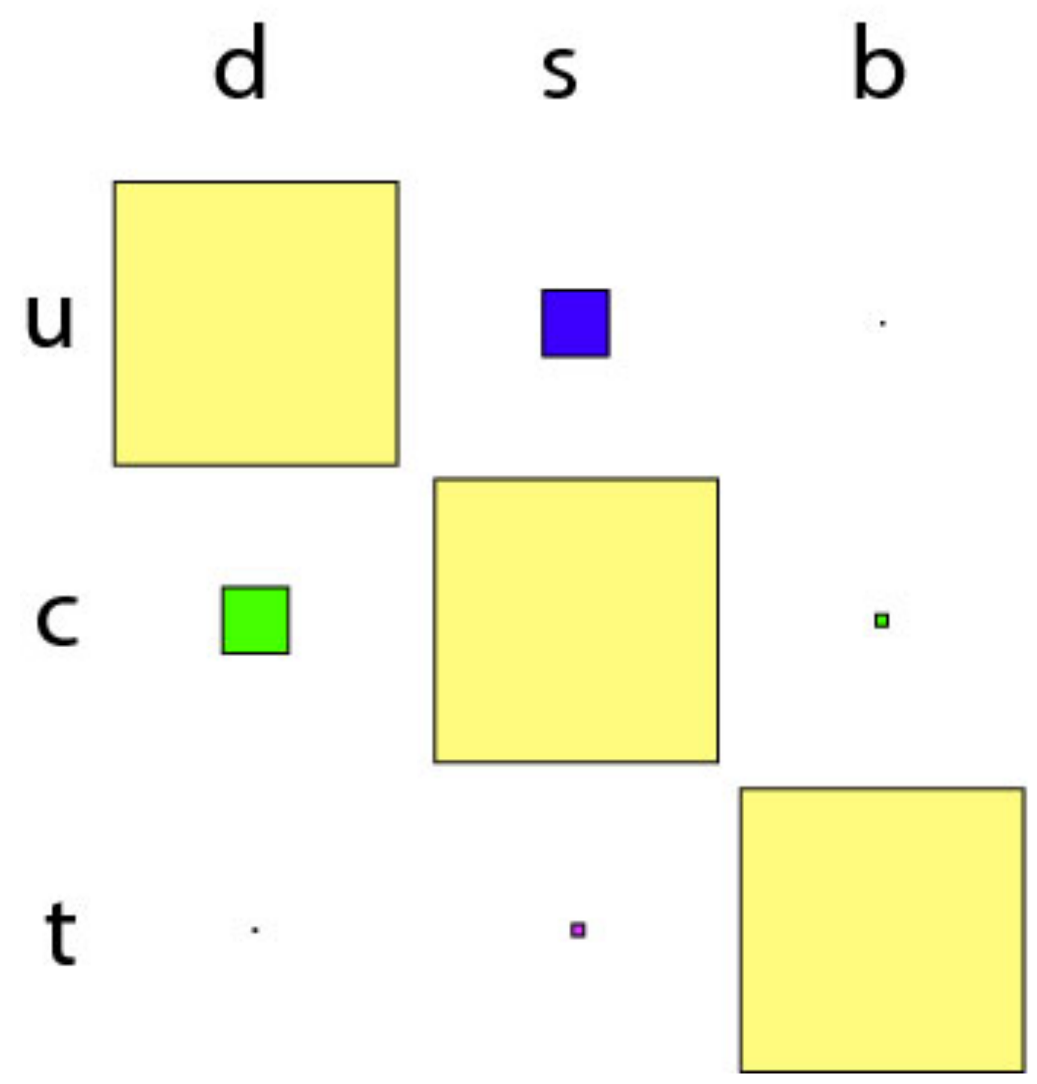
CKM



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

q_L q_R

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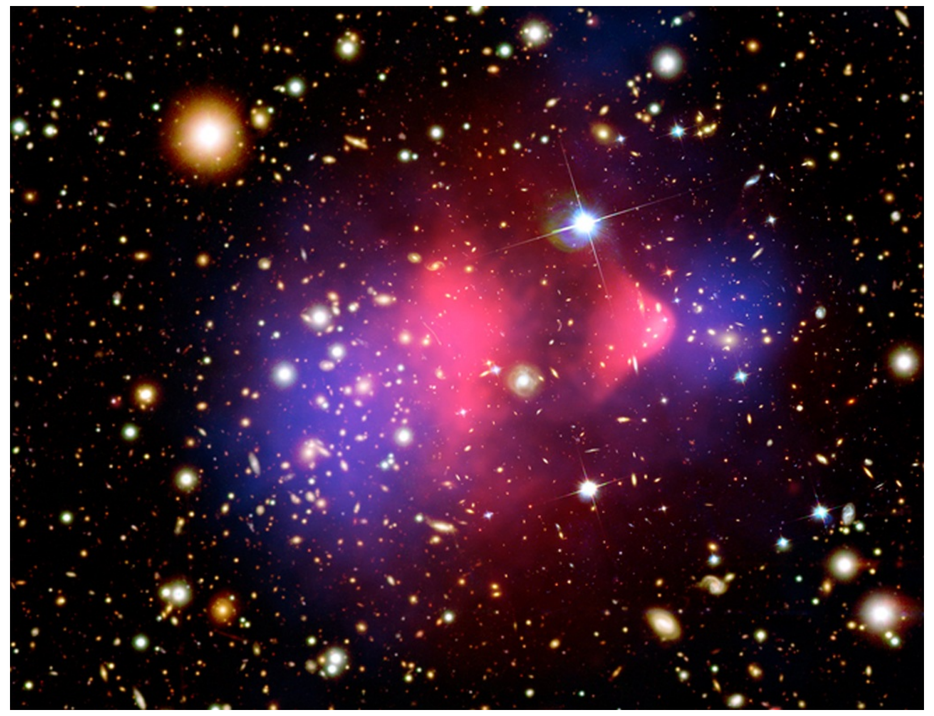
$$(\quad q_\nu \quad) = ?$$

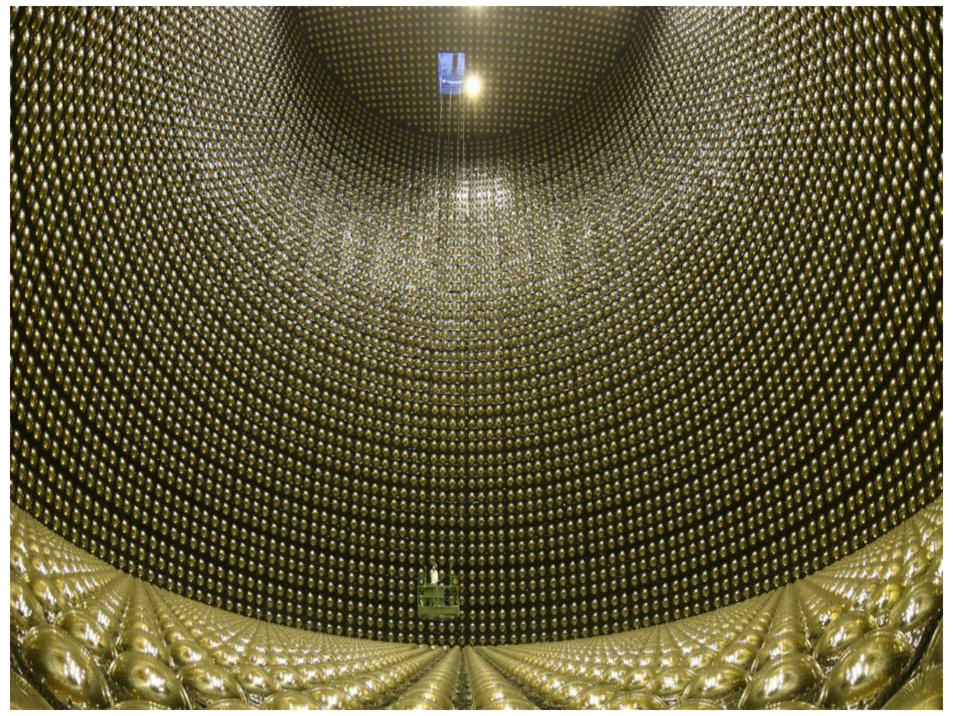
$$\begin{cases} c \sim \mathcal{O}(1) \\ \dfrac{\phi \to v_\phi}{M} = \varepsilon \\ q_L - q_R = n \end{cases}$$

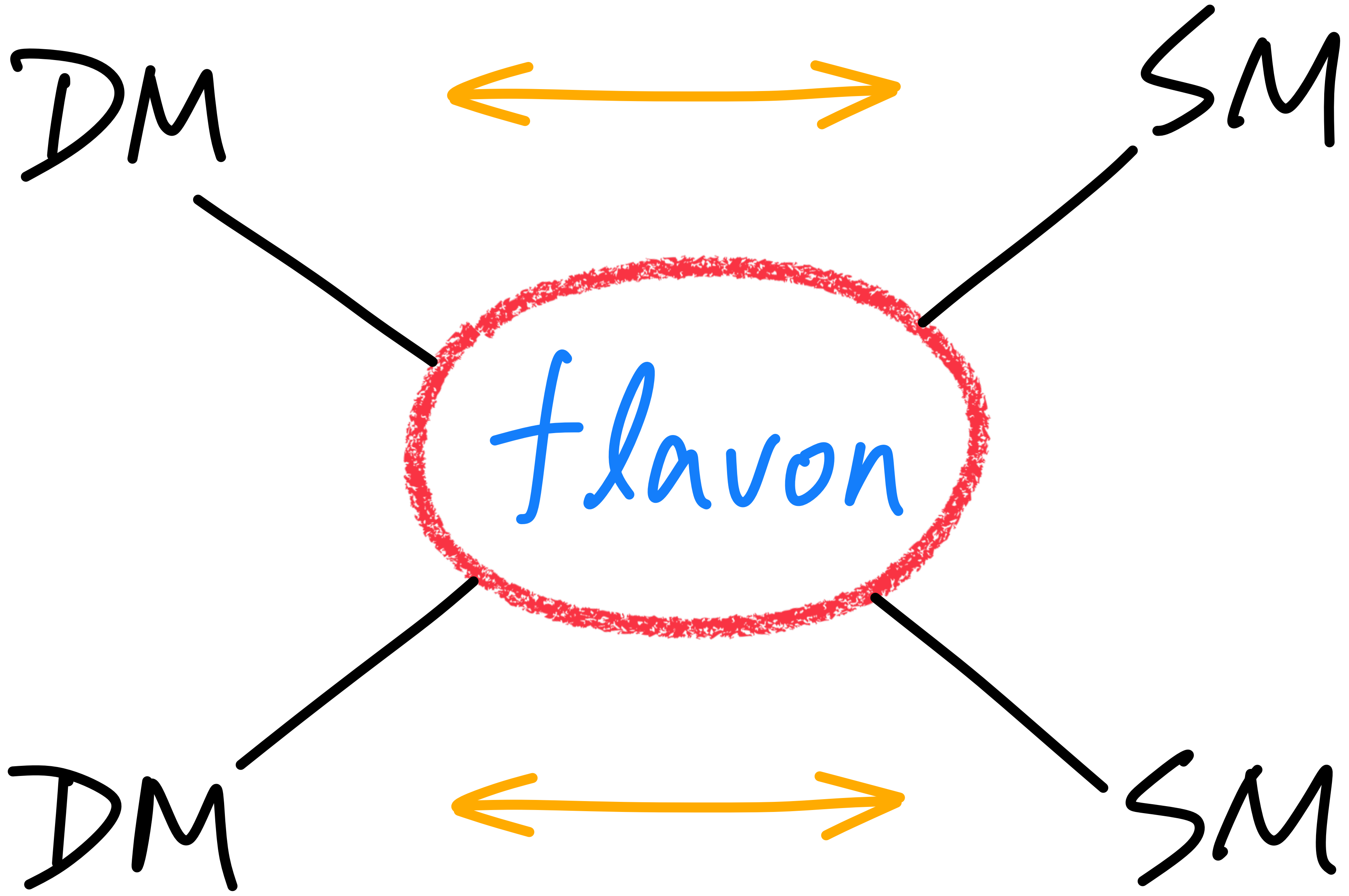
Right-handed neutrino and DM

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

Z_2 symmetry $\Downarrow$ Seesaw $\Downarrow$





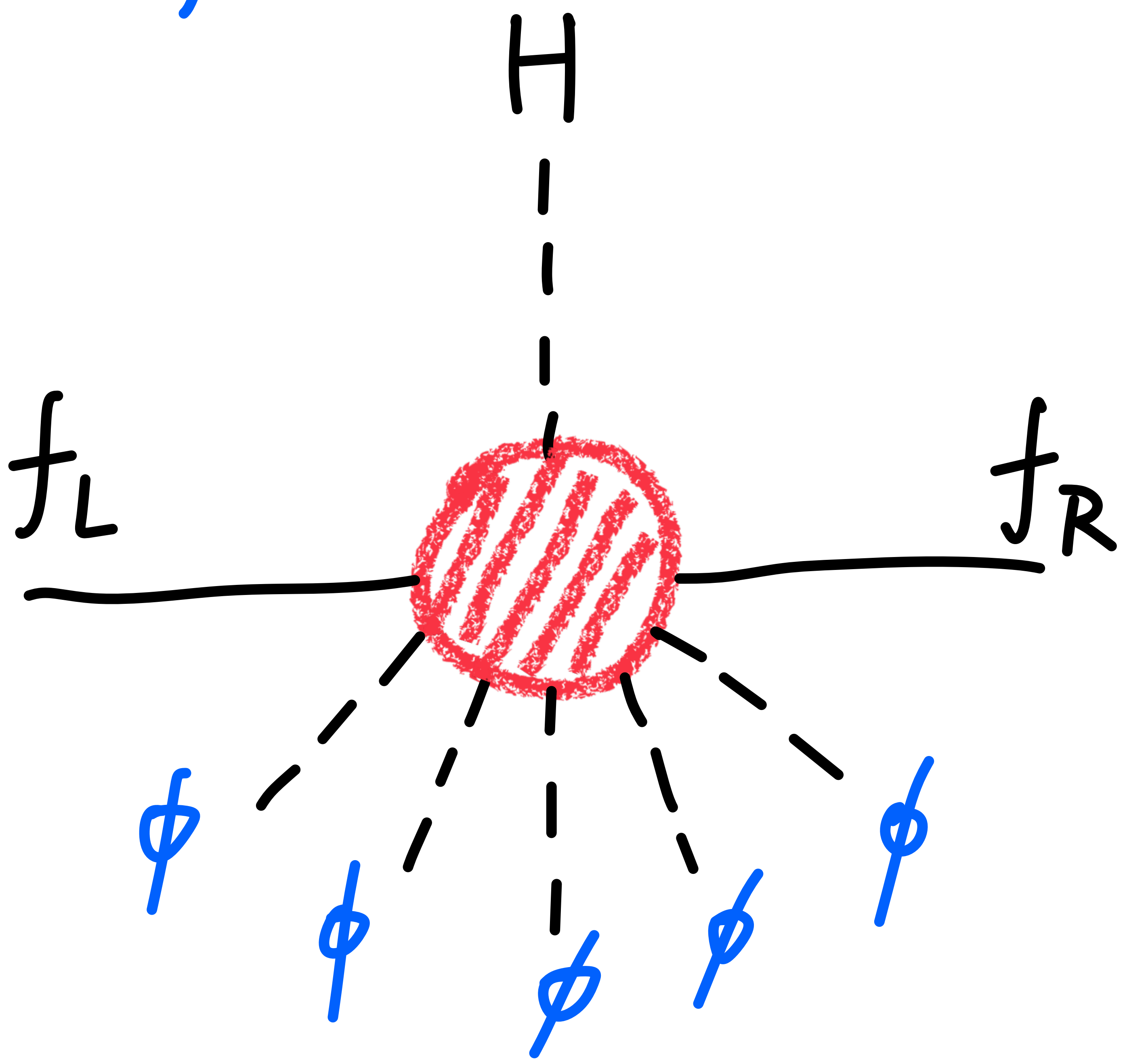


$\Longrightarrow$ $\boxed{\text{Lightest } \nu \text{ is massless!}}$

EFT flavon couplings

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

$$\phi \to v_\phi + \frac{1}{\sqrt{2}}(s + ia)$$



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EFT flavon couplings

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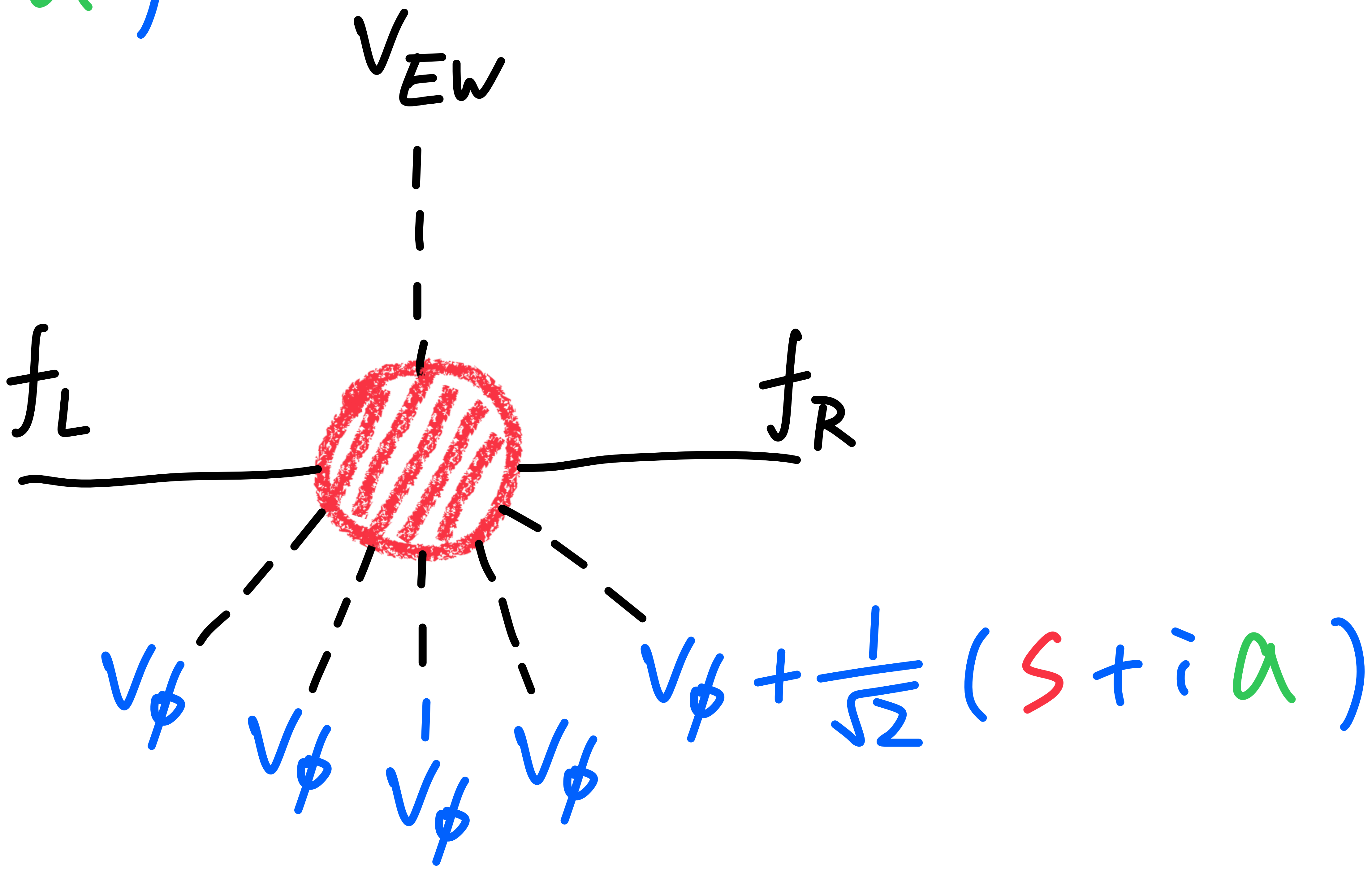

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EFT flavon couplings

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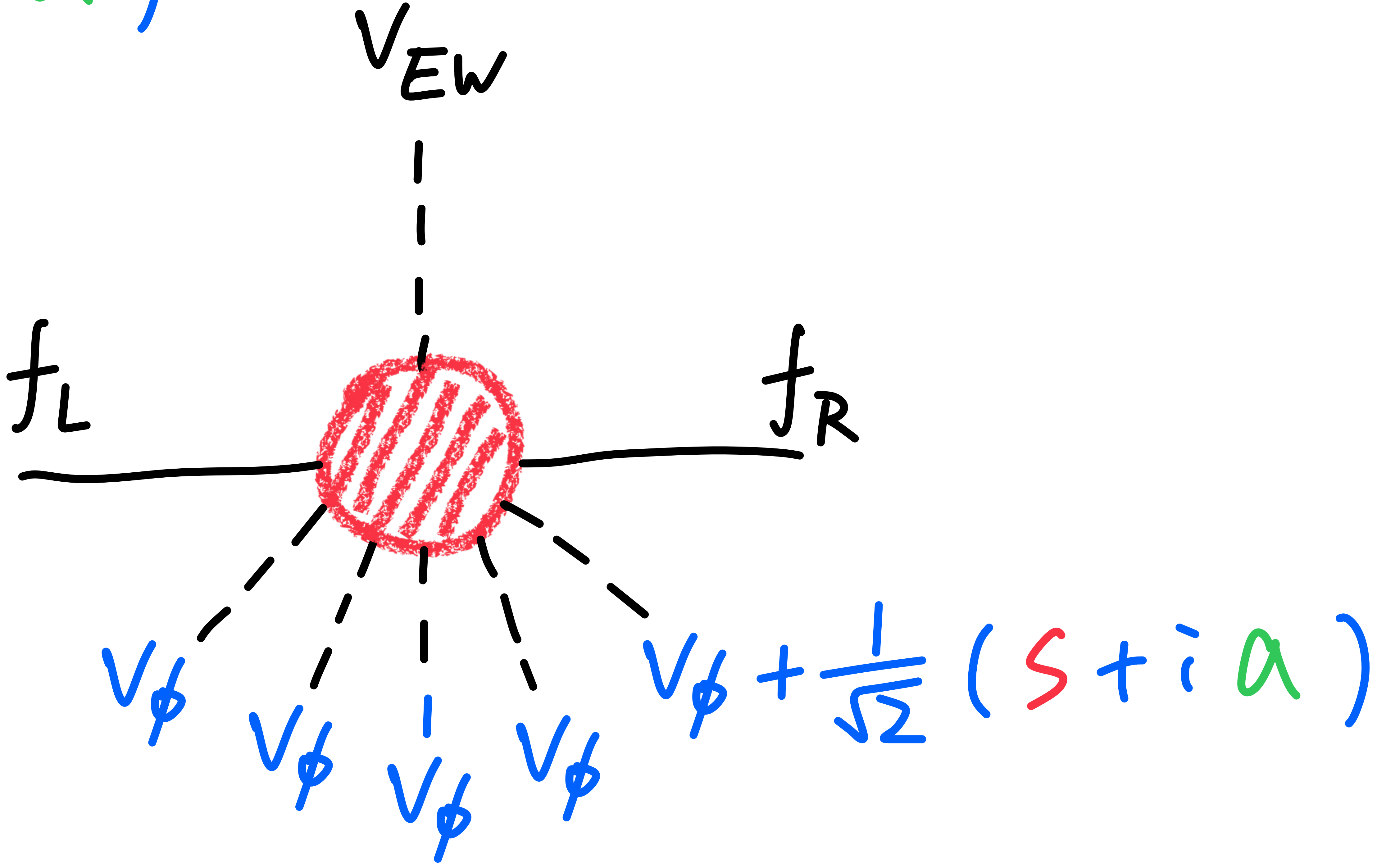
$$\begin{cases} m_s \sim v_\phi \\ 10\,\text{GeV} \leqslant m_a \ll m_s \end{cases}$$



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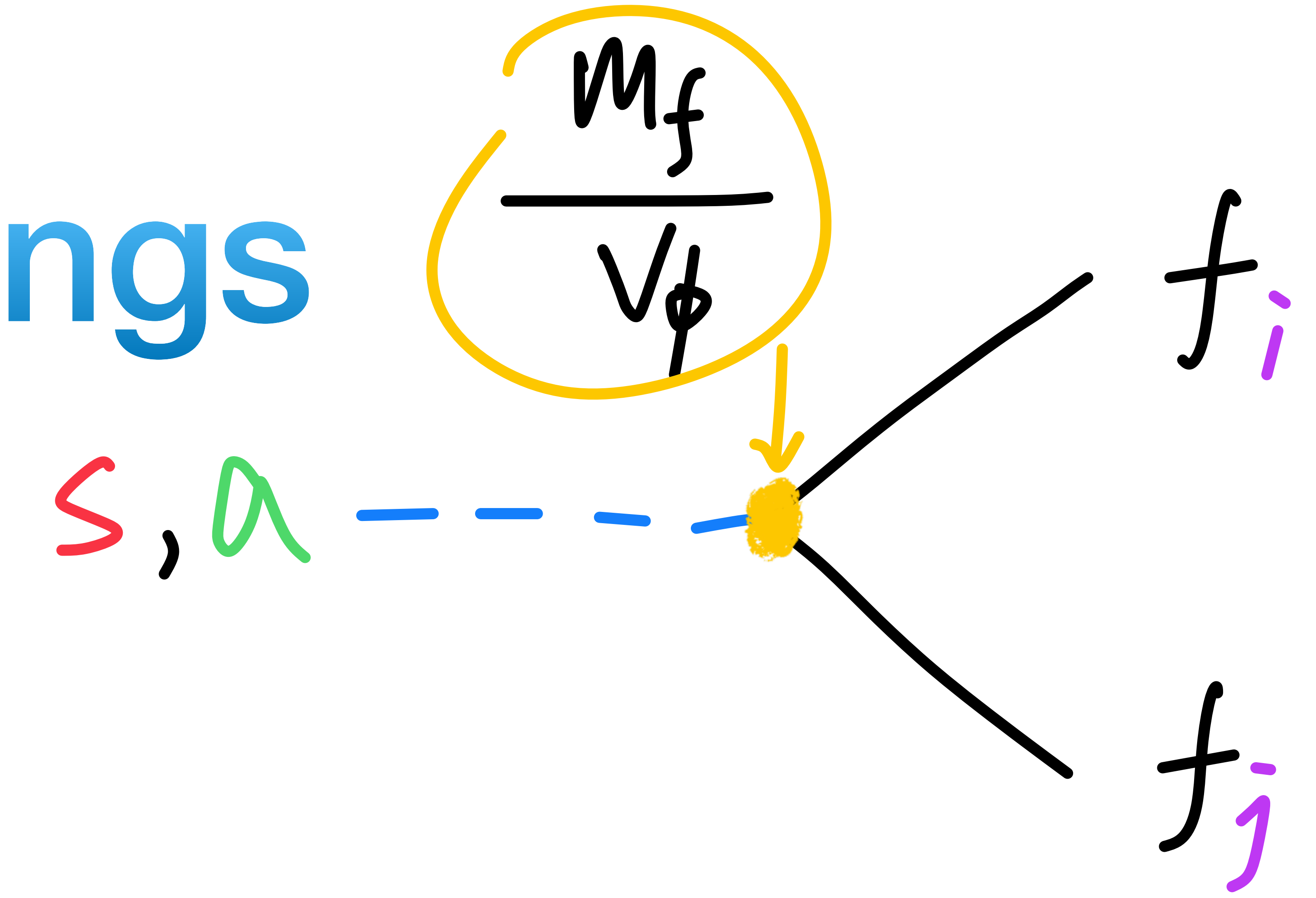

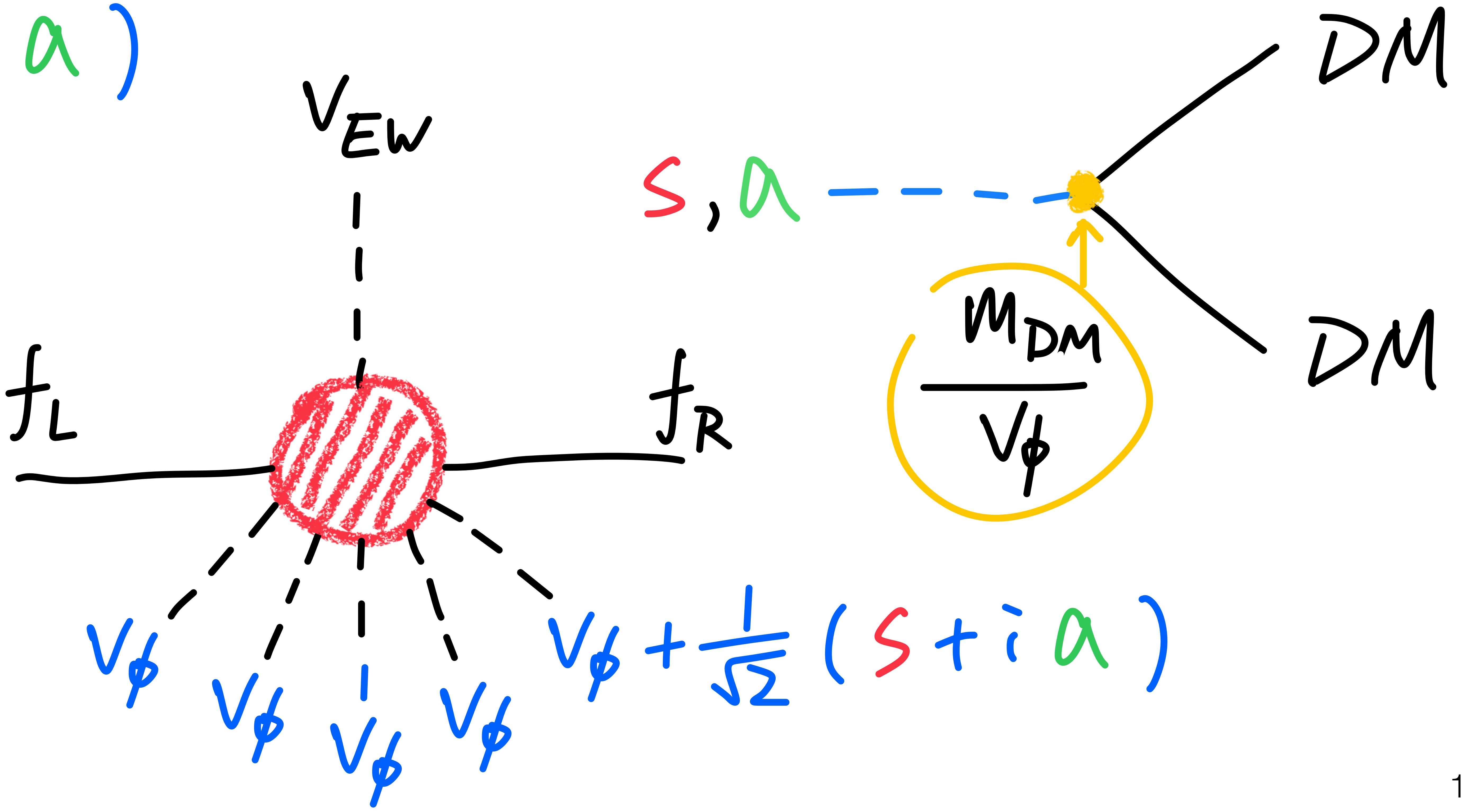

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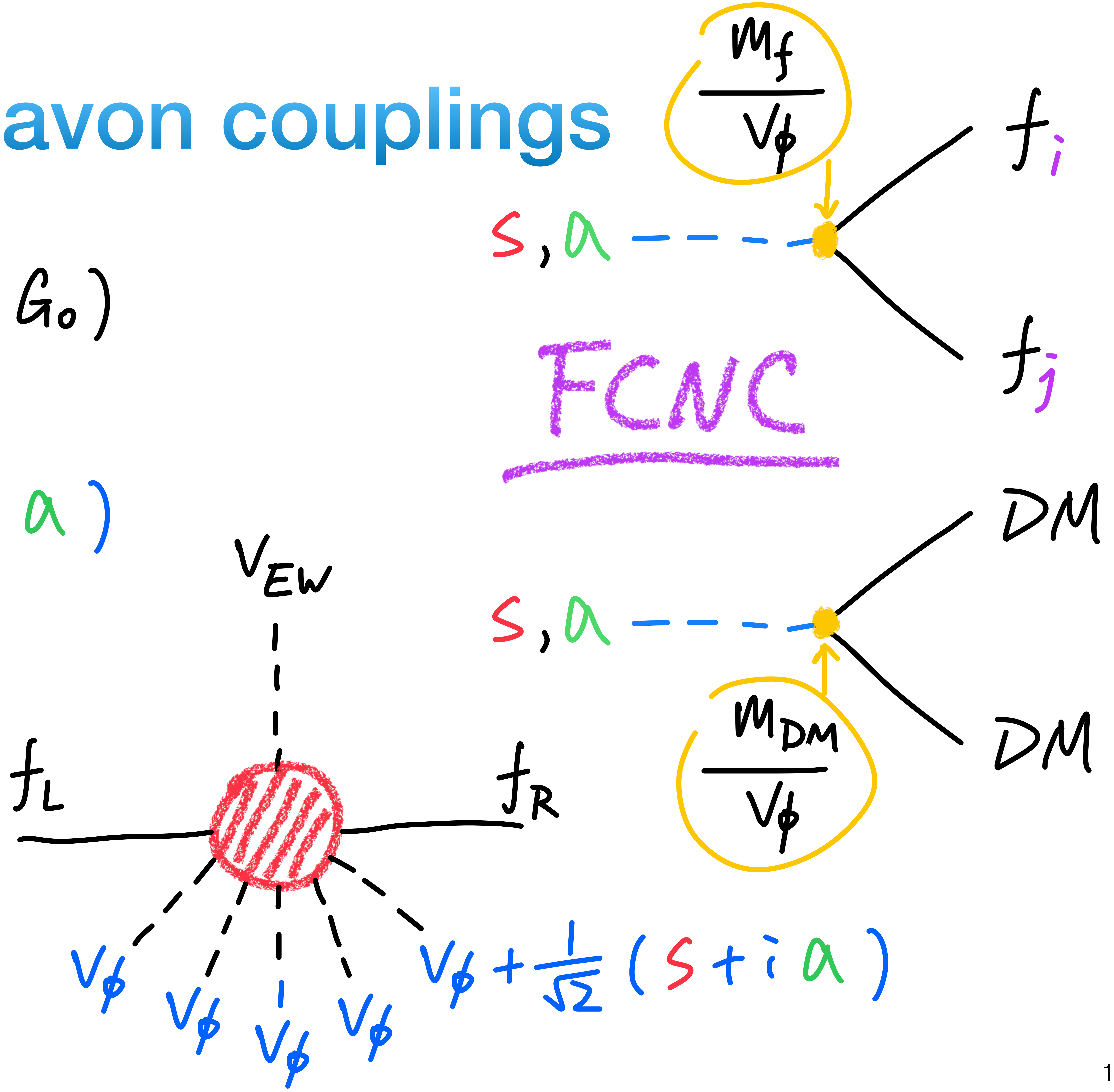
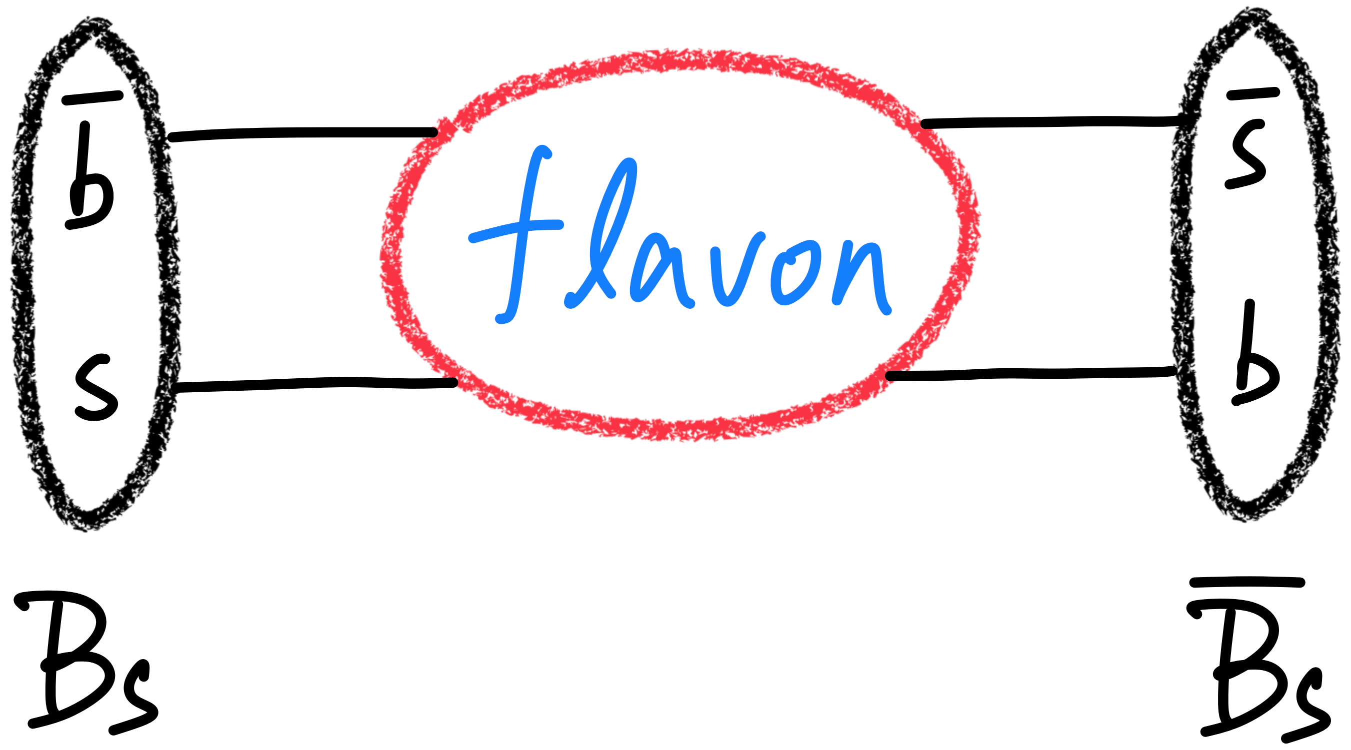


Experimental constraints

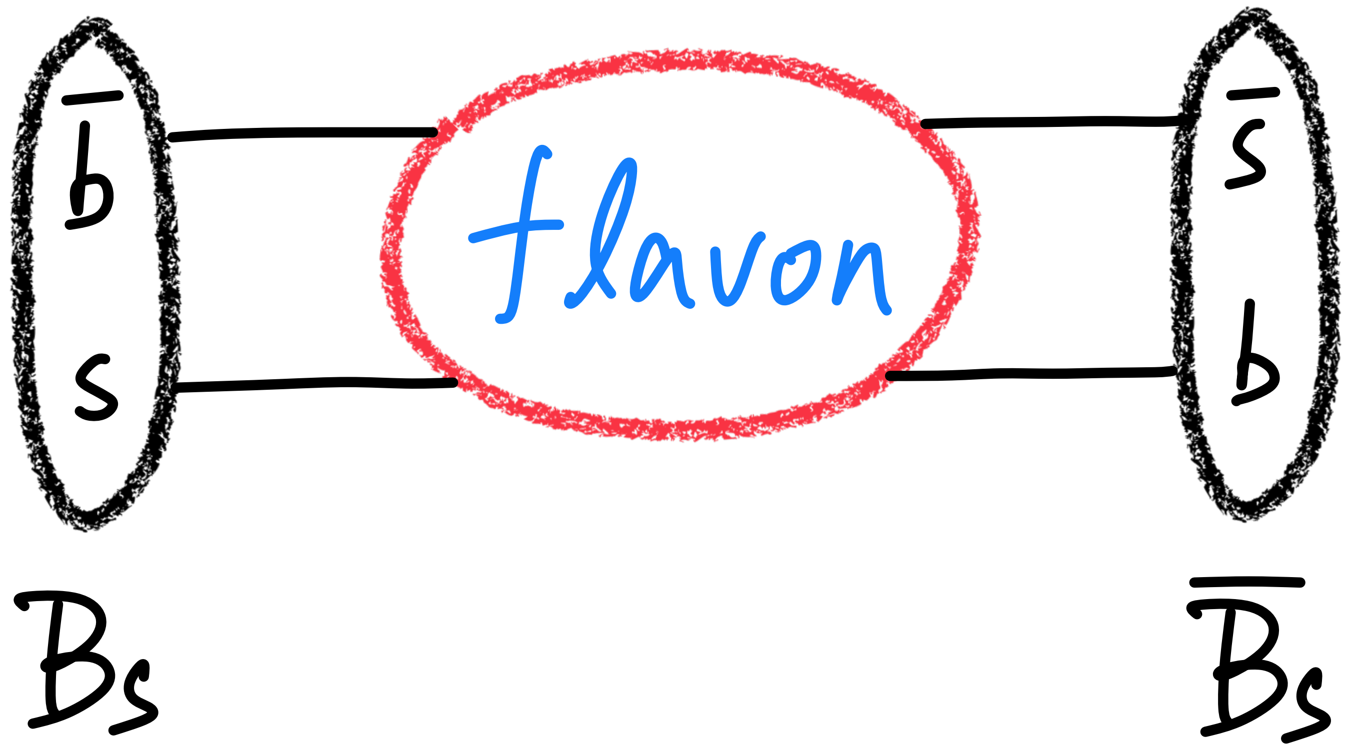
B-meson mixing



$$\left(\frac{m_a}{100\,\mathrm{GeV}}\right)\times\left(\frac{v_\phi}{\mathrm{TeV}}\right) > 1.8$$

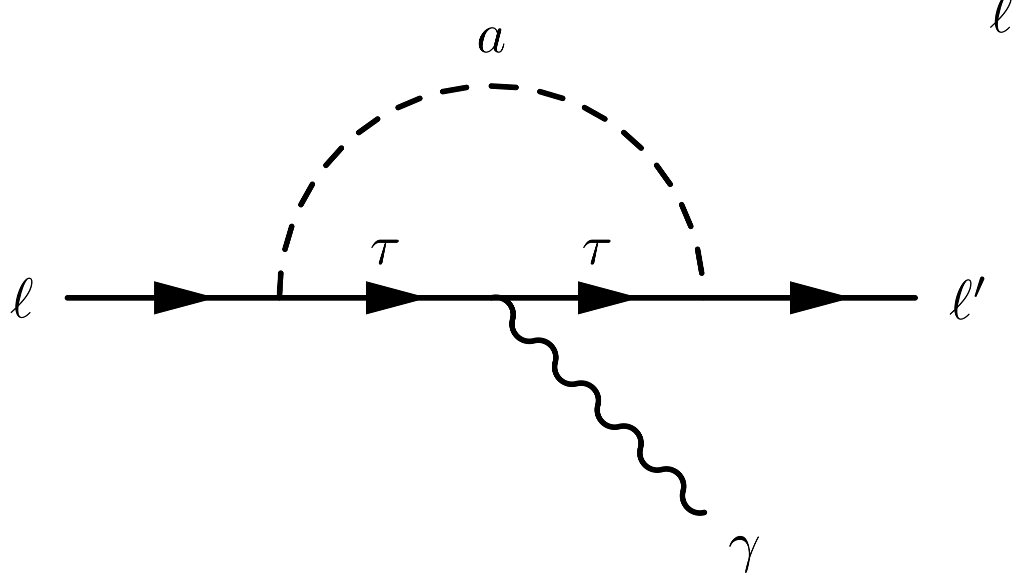
Experimental constraints

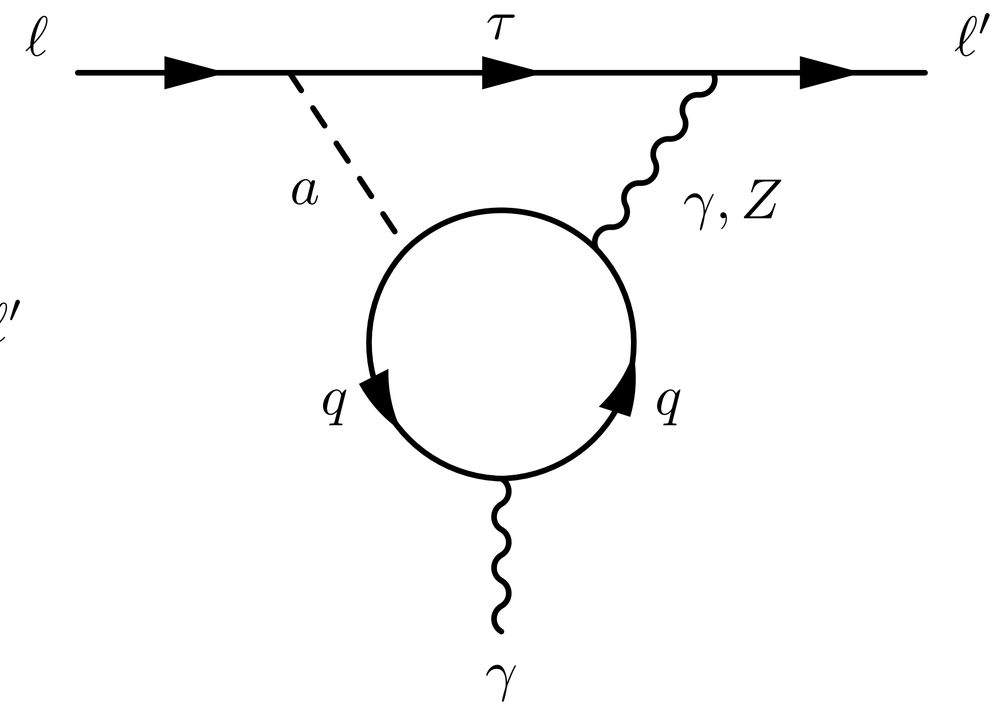
B-meson mixing



$$\left(\frac{m_a}{100\,\text{GeV}}\right) \times \left(\frac{v_\phi}{\text{TeV}}\right) > 1.8$$

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





$$\left(\frac{m_a}{100\,\text{GeV}}\right) \times \left(\frac{v_\phi}{\text{TeV}}\right) > 1.9$$

*For $m_a \lesssim 100$ GeV

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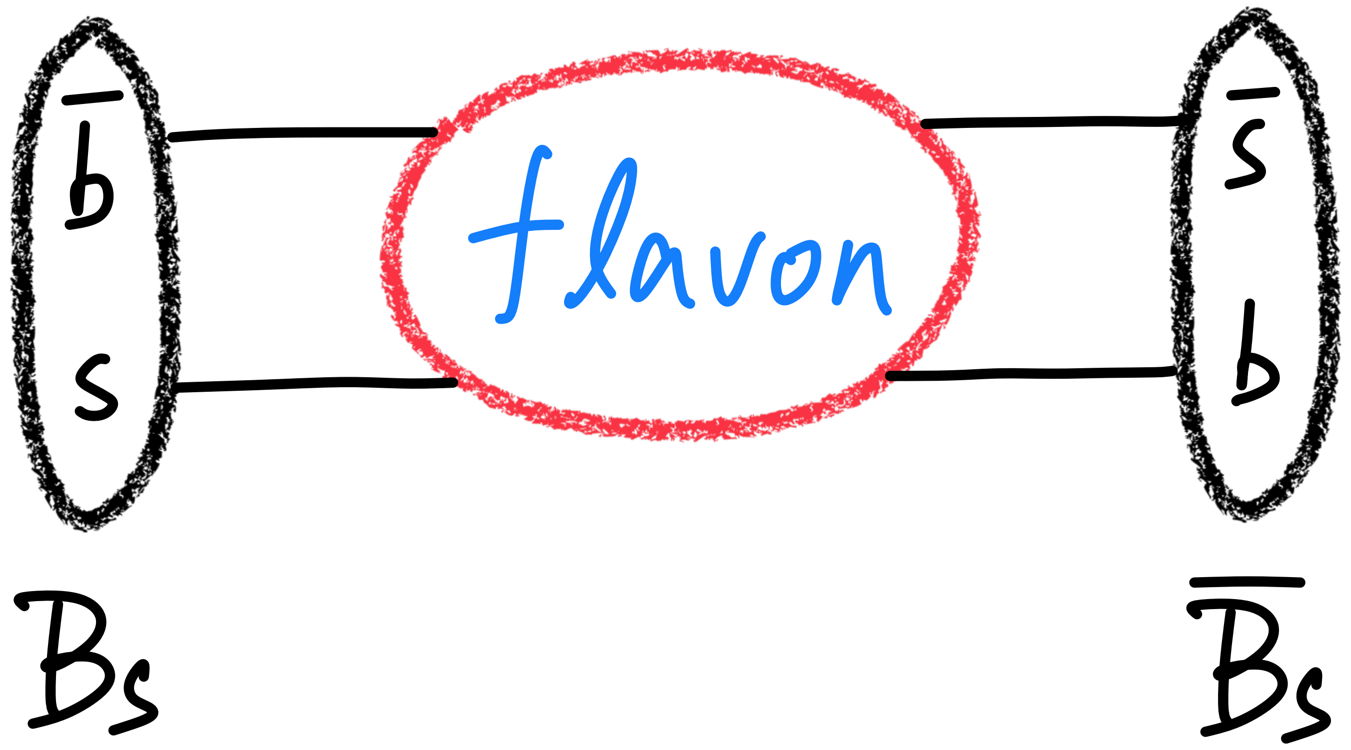
Experimental constraints

B-meson mixing



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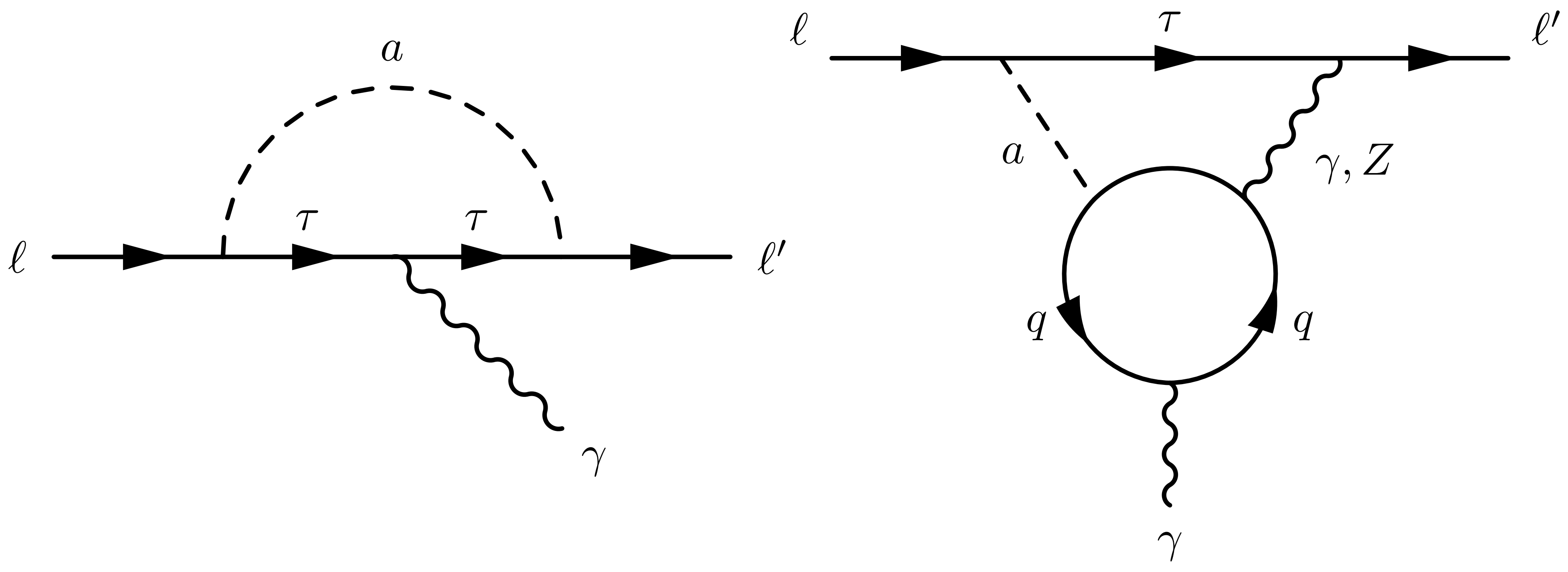
$\mu \to e\gamma$ (MEG)

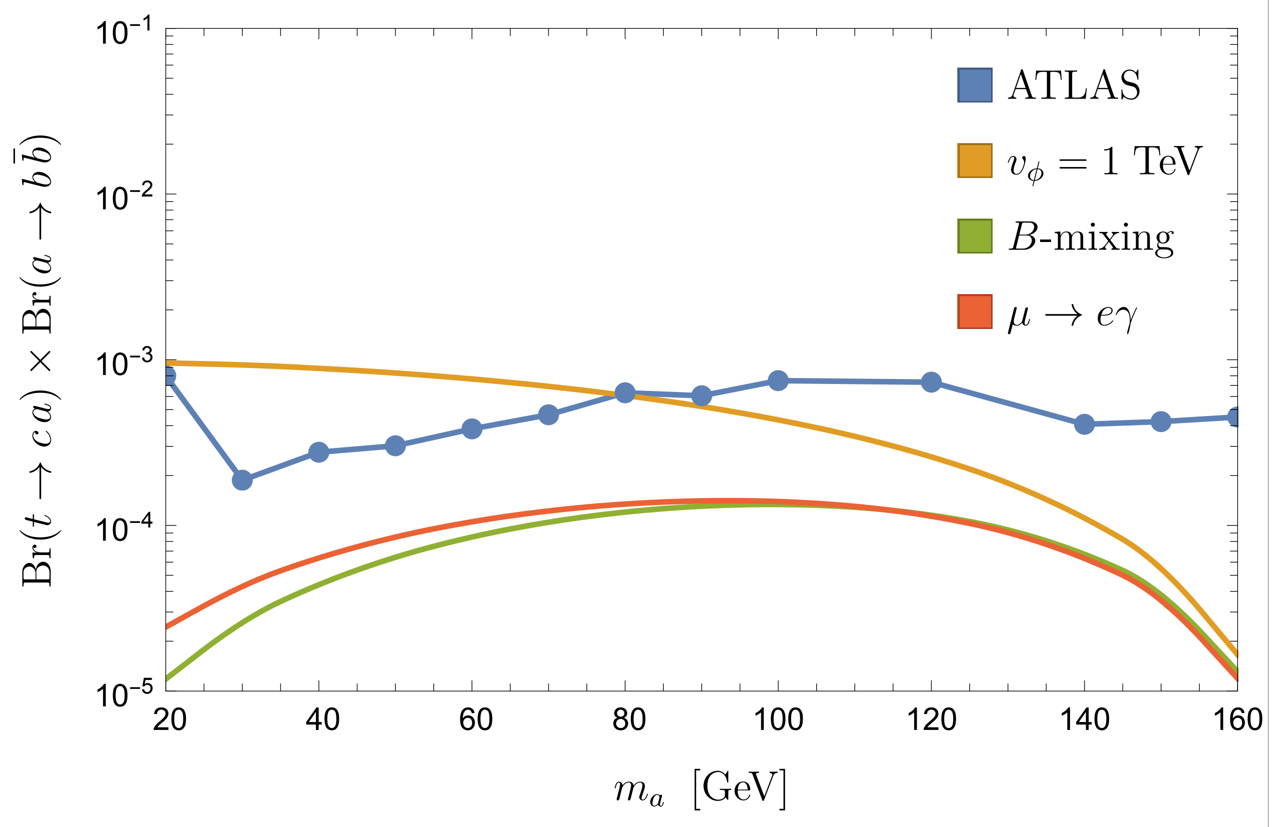


$$\left(\frac{m_a}{100\,\text{GeV}}\right)\times\left(\frac{v_\phi}{\text{TeV}}\right) > 1.9$$

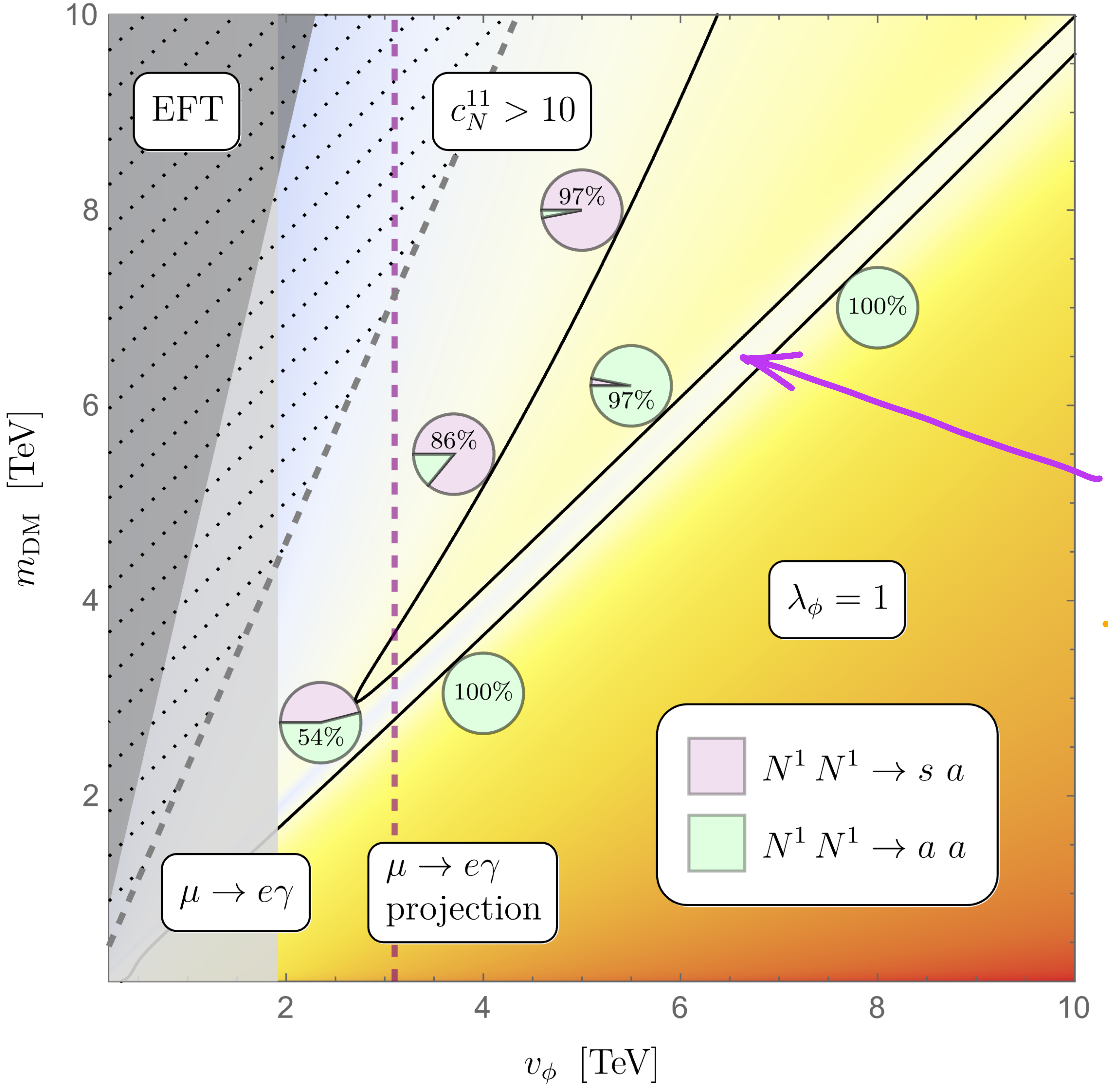
*For $m_a \lesssim 100$ GeV

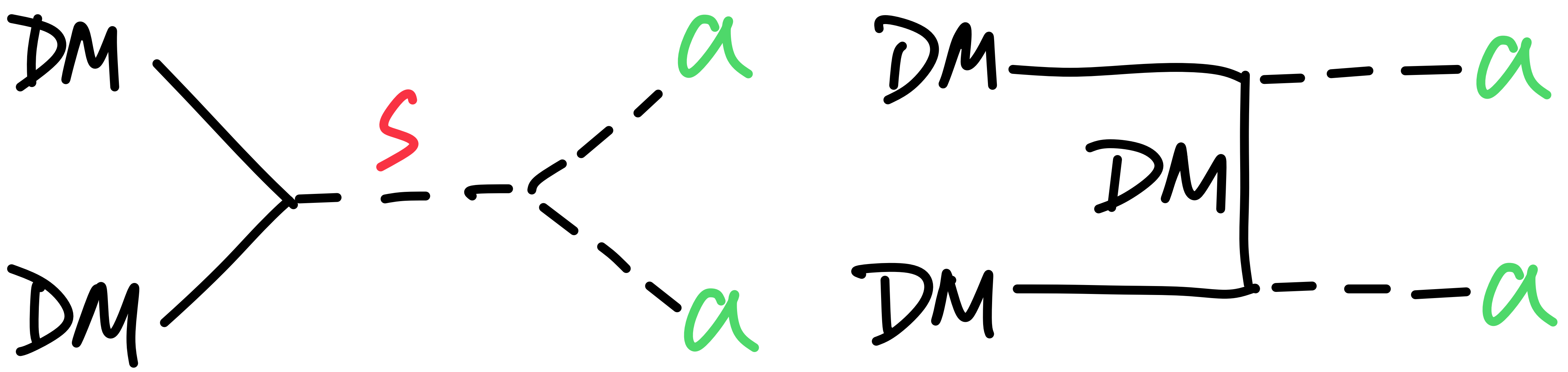
Top decay ATLAS

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

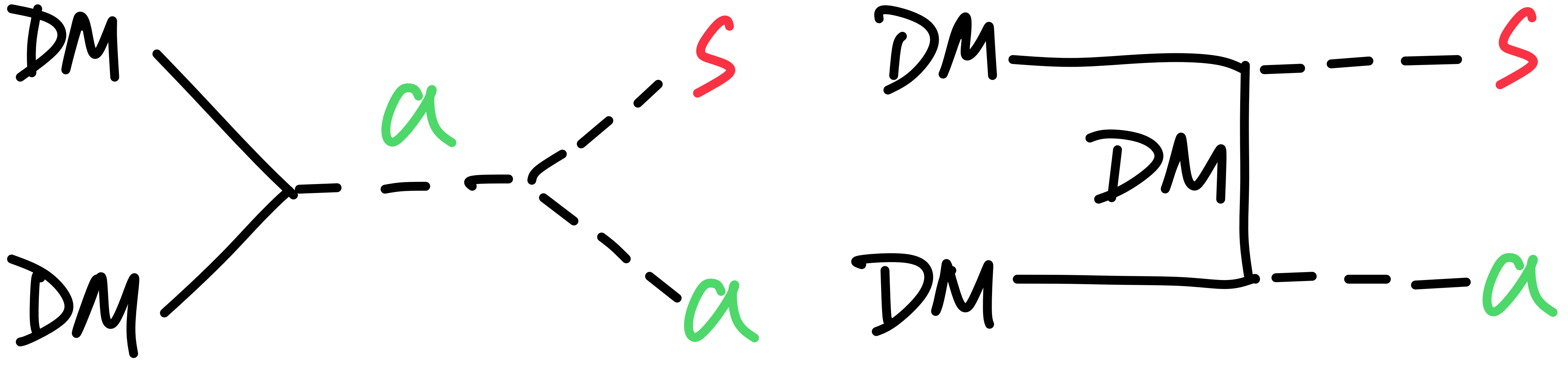


TeV scale: freeze out m_{DM} vs V_ϕ

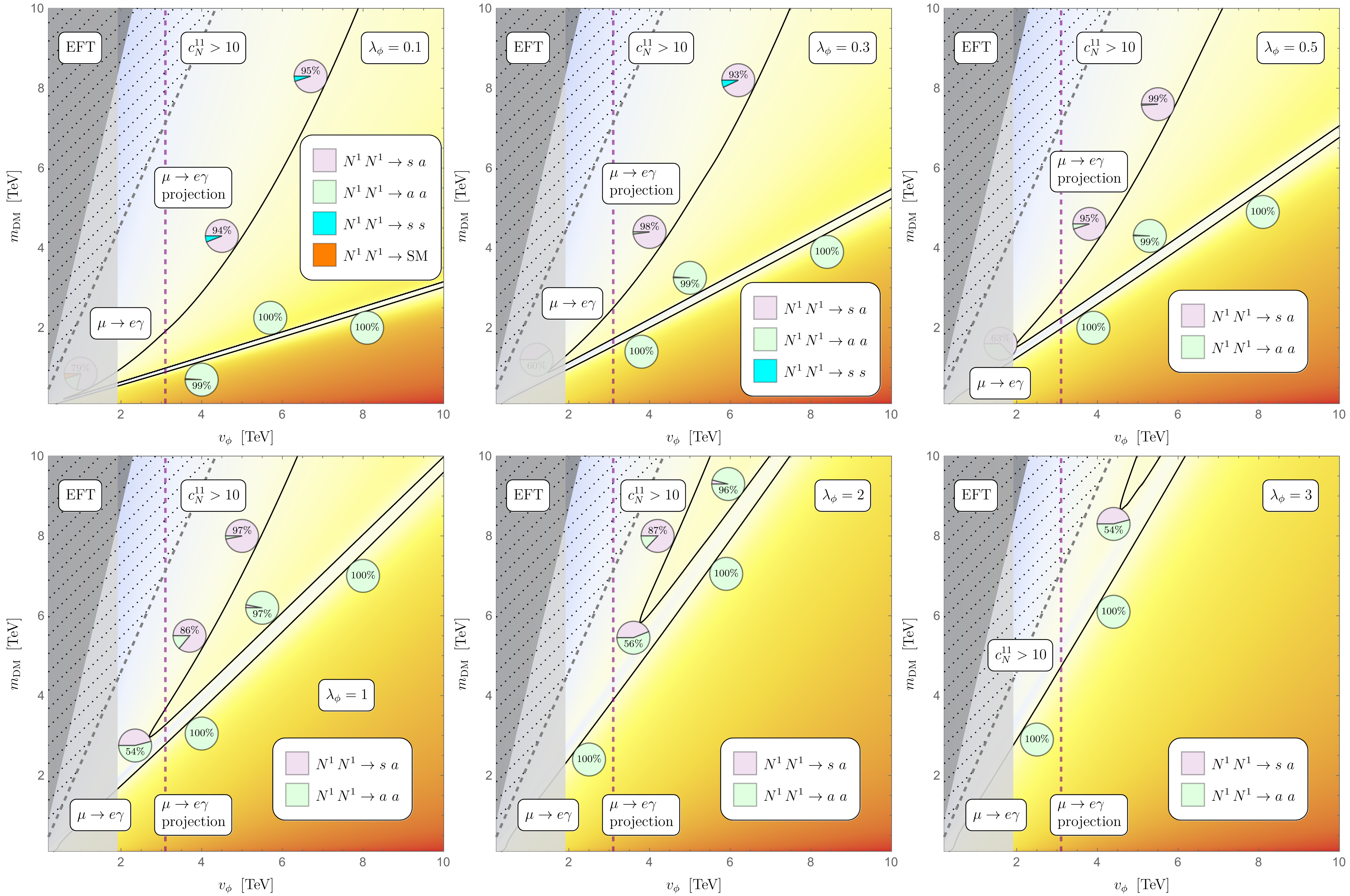




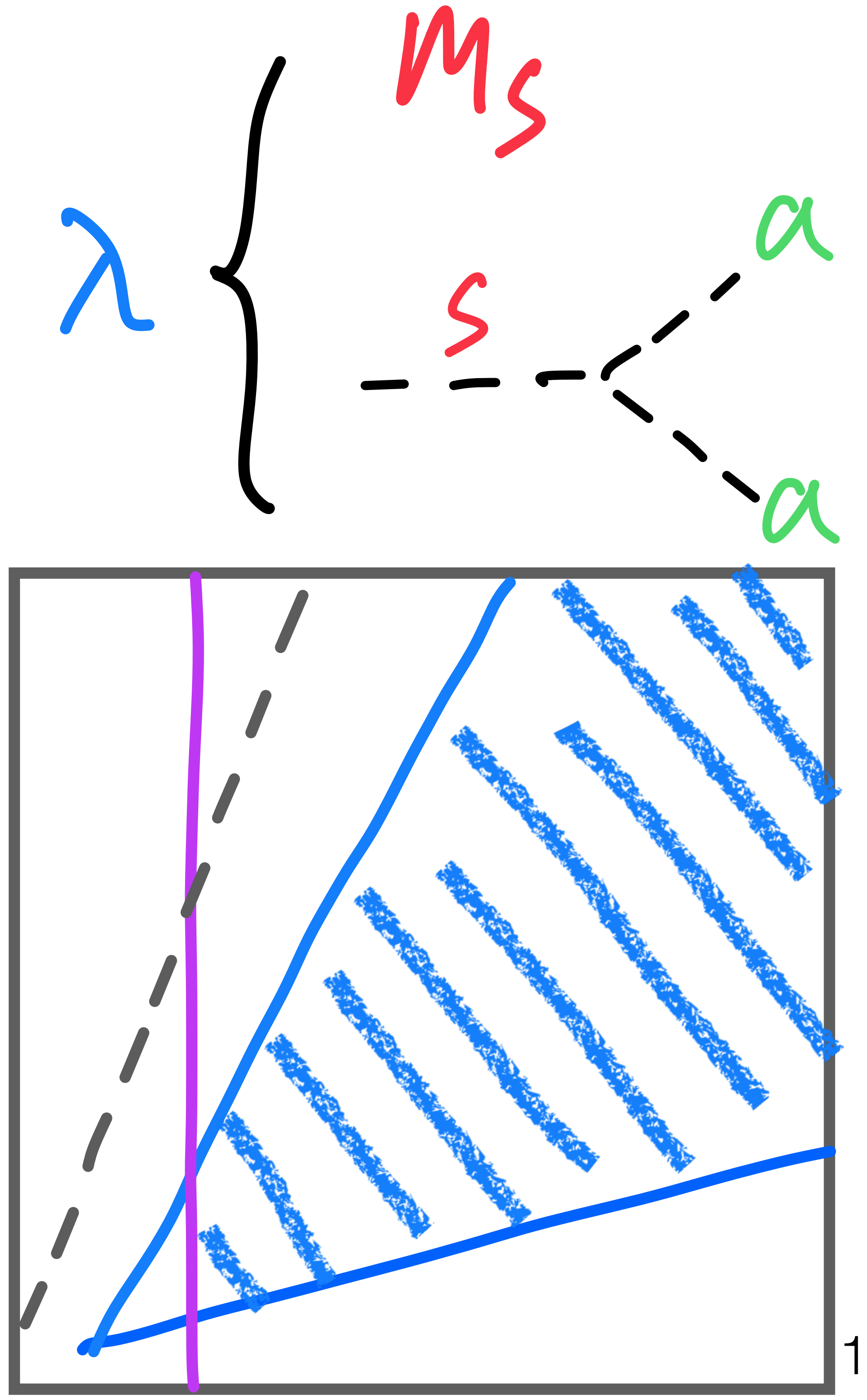
Resonance! $m_s = 2V_\phi$



TeV scale: freeze out with various λ_ϕ



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



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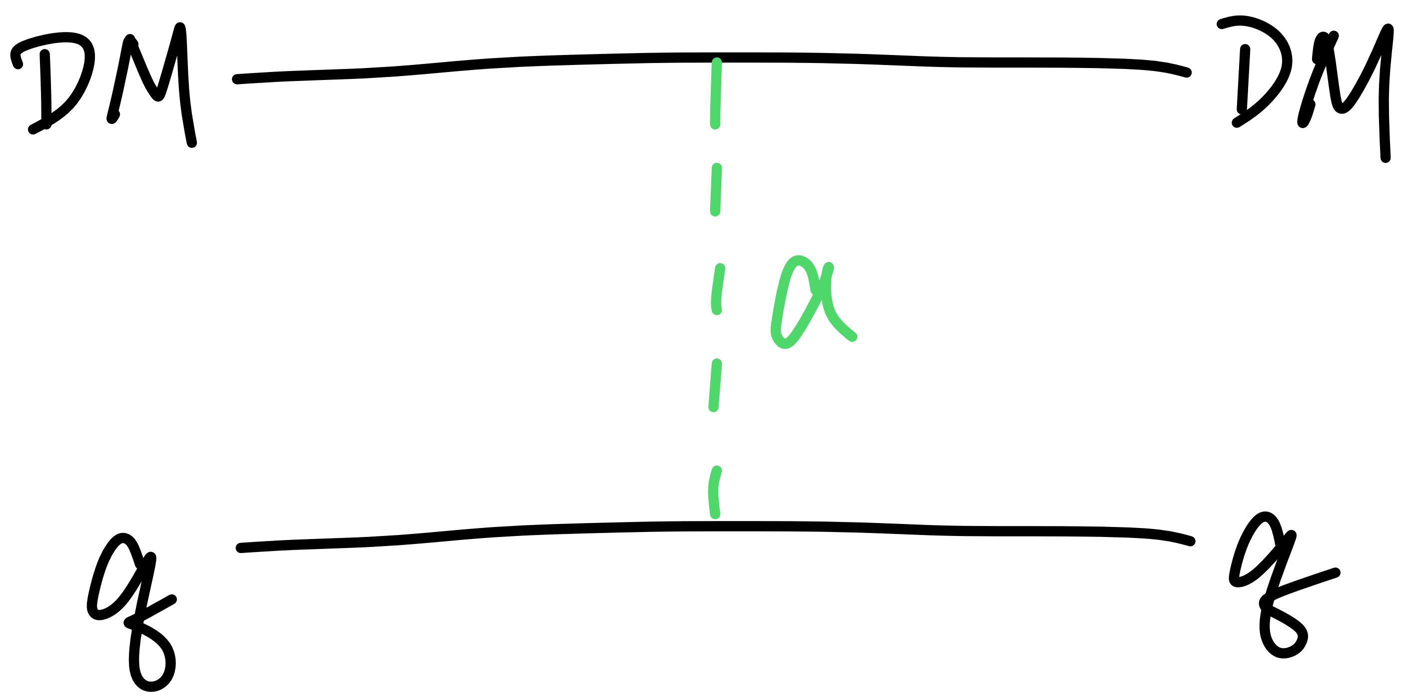
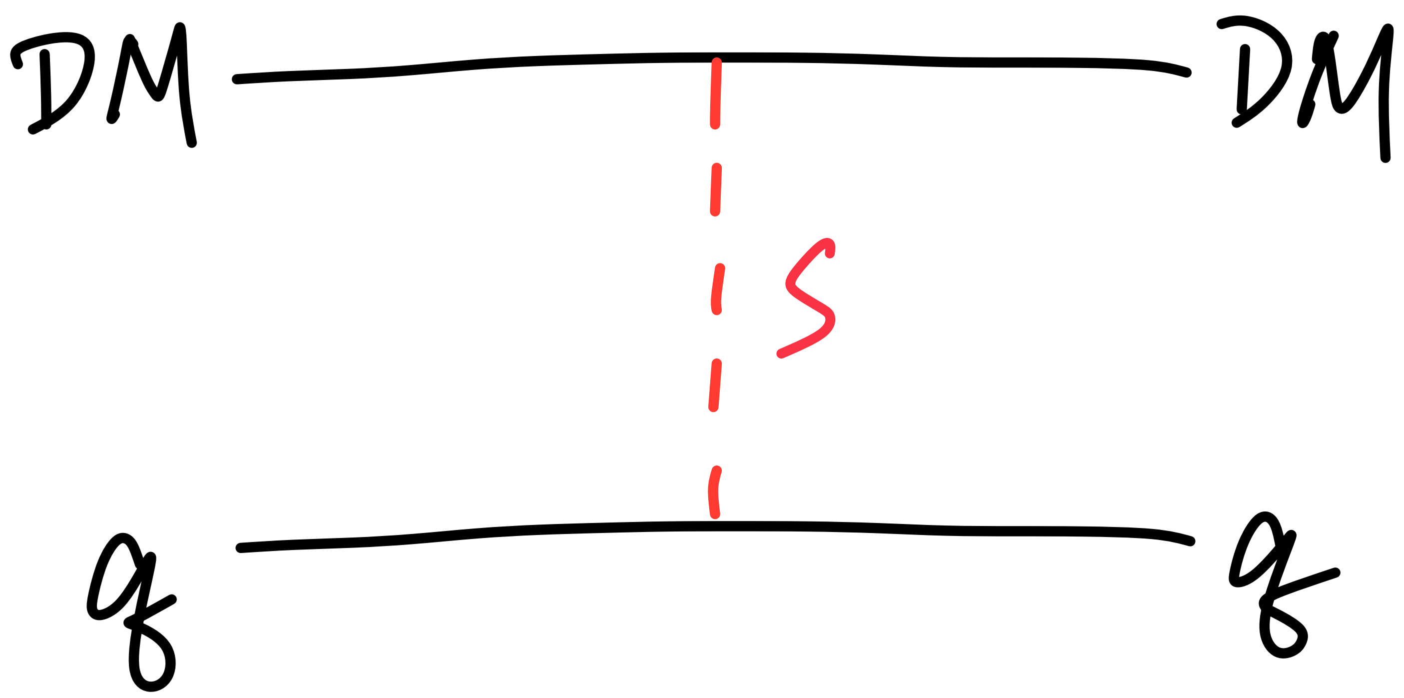
Direct detection

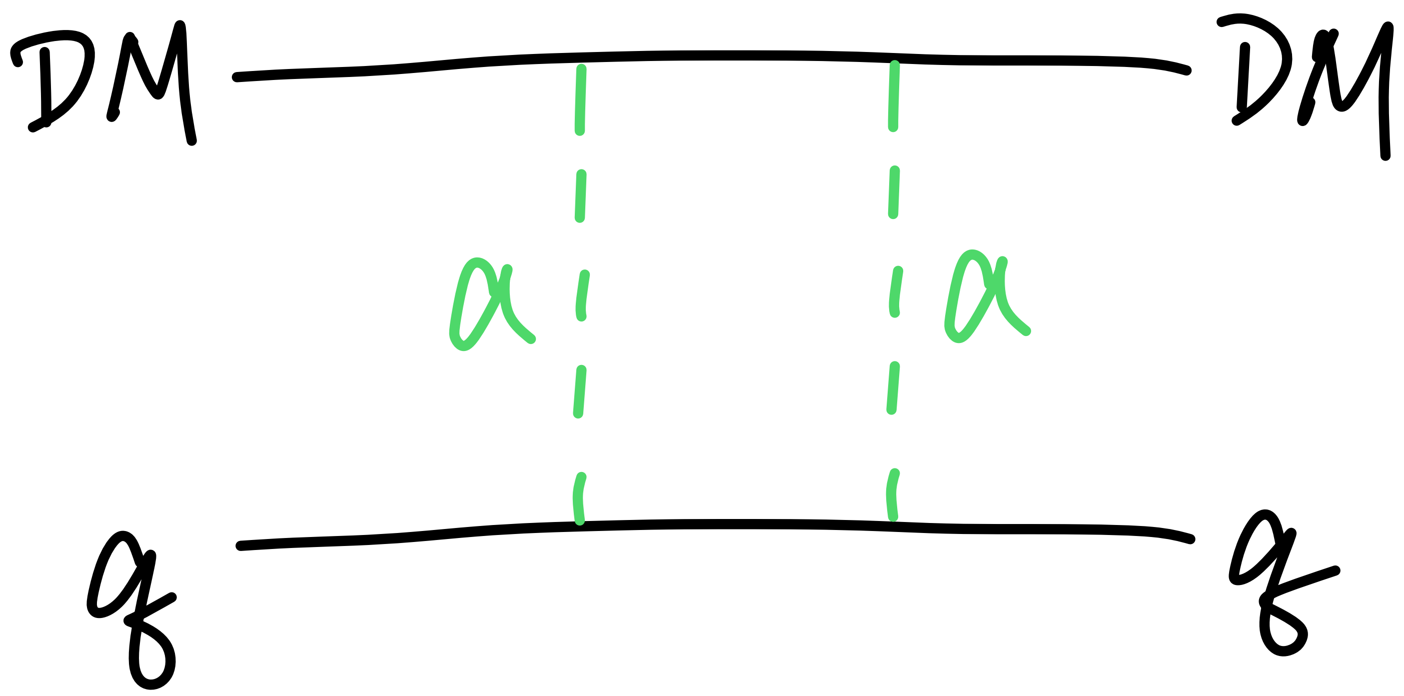


Spin-dependent σ

Momentum suppressed

10^{-5} too small!





Spin-independent σ

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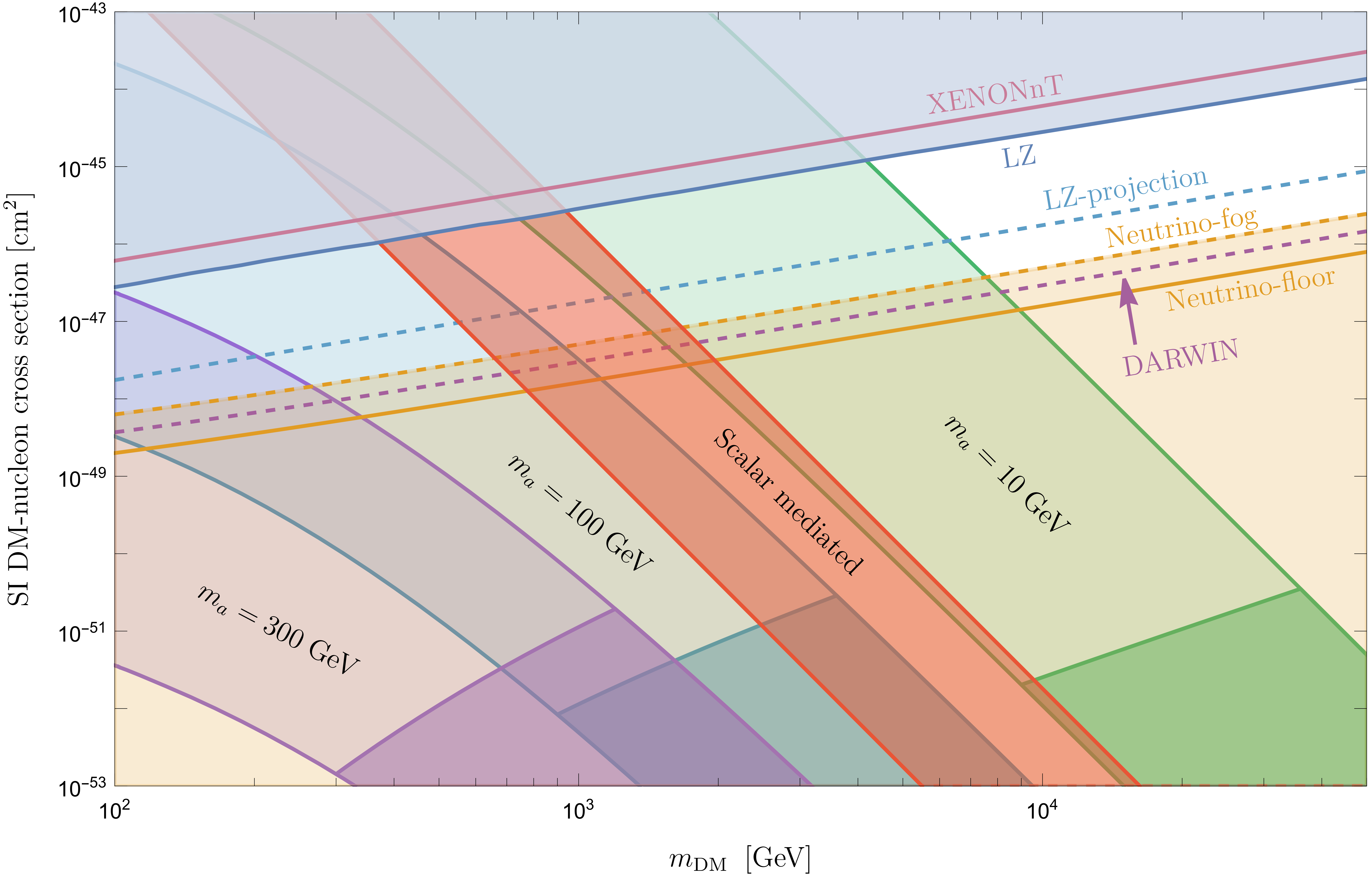
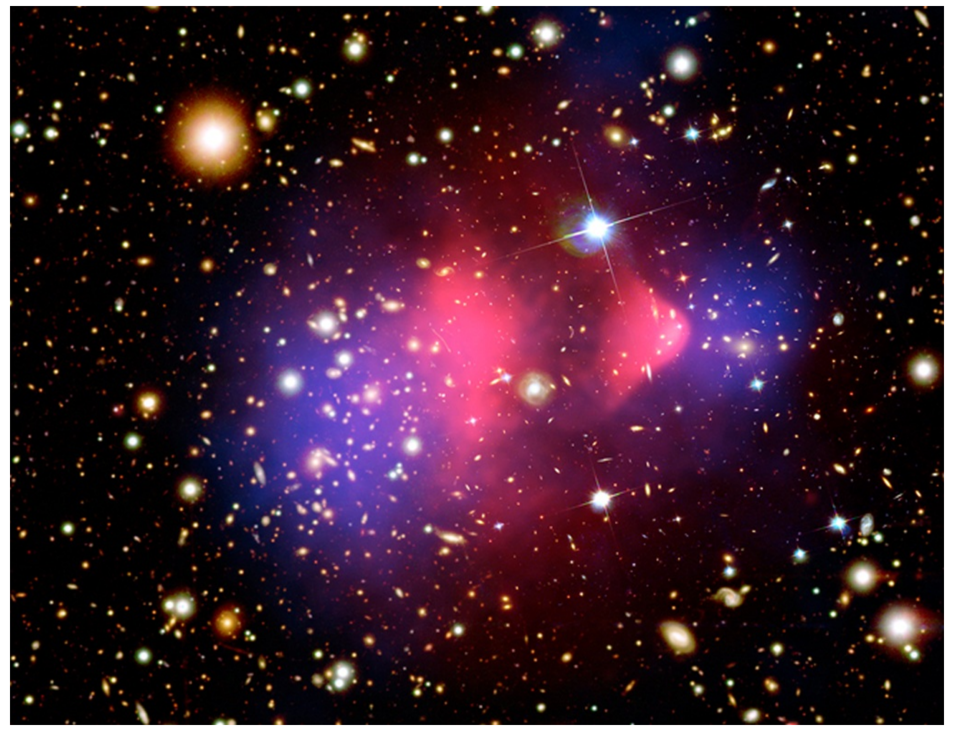


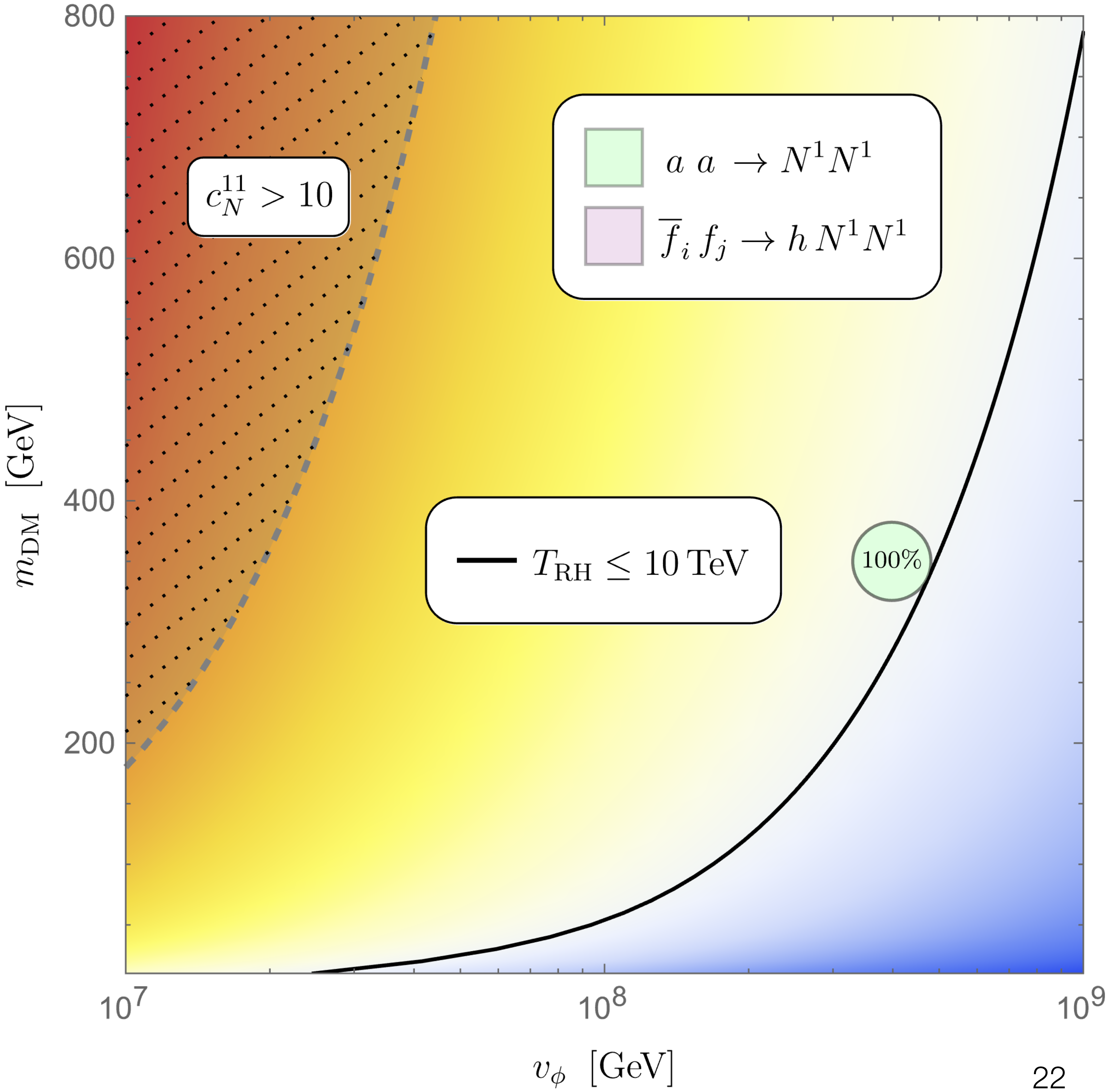
XENONnT
LZ
LZ-projection
Neutrino-fog
Neutrino-floor
DARWIN
$m_a = 10$ GeV
Scalar mediated
$m_a = 100$ GeV
$m_a = 300$ GeV
SI DM-nucleon cross section [cm^2]
$m_{\rm DM}$ [GeV]
10^{-43}
10^{-45}
10^{-47}
10^{-49}
10^{-51}
10^{-53}
10^2
10^3
10^4

21

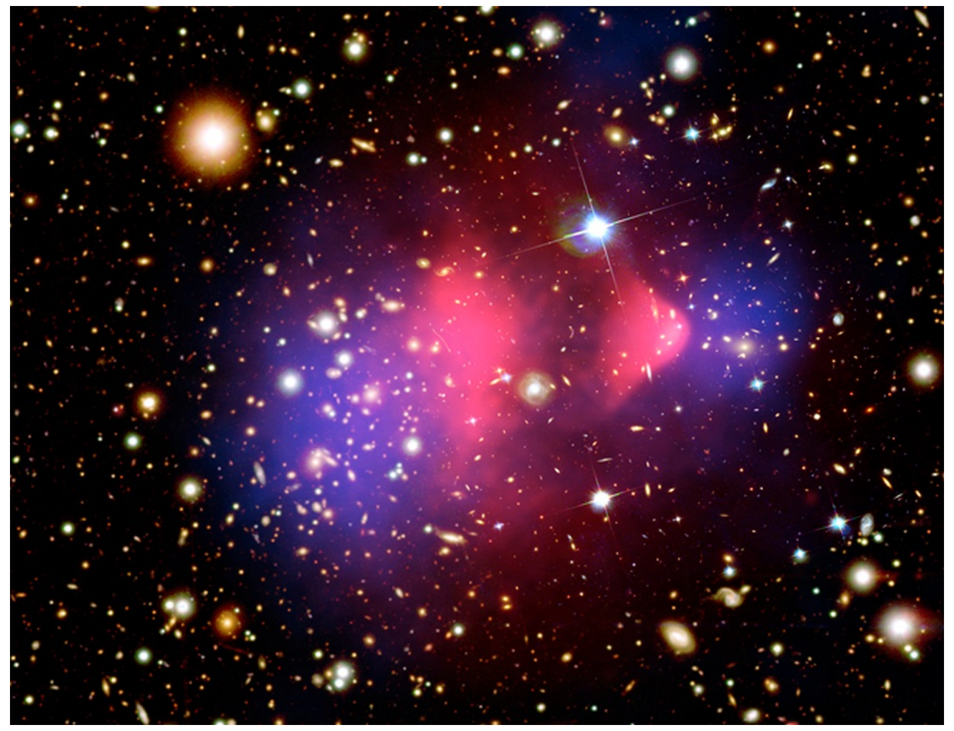
High scale: (IR) freeze in m_{DM} vs V_ϕ

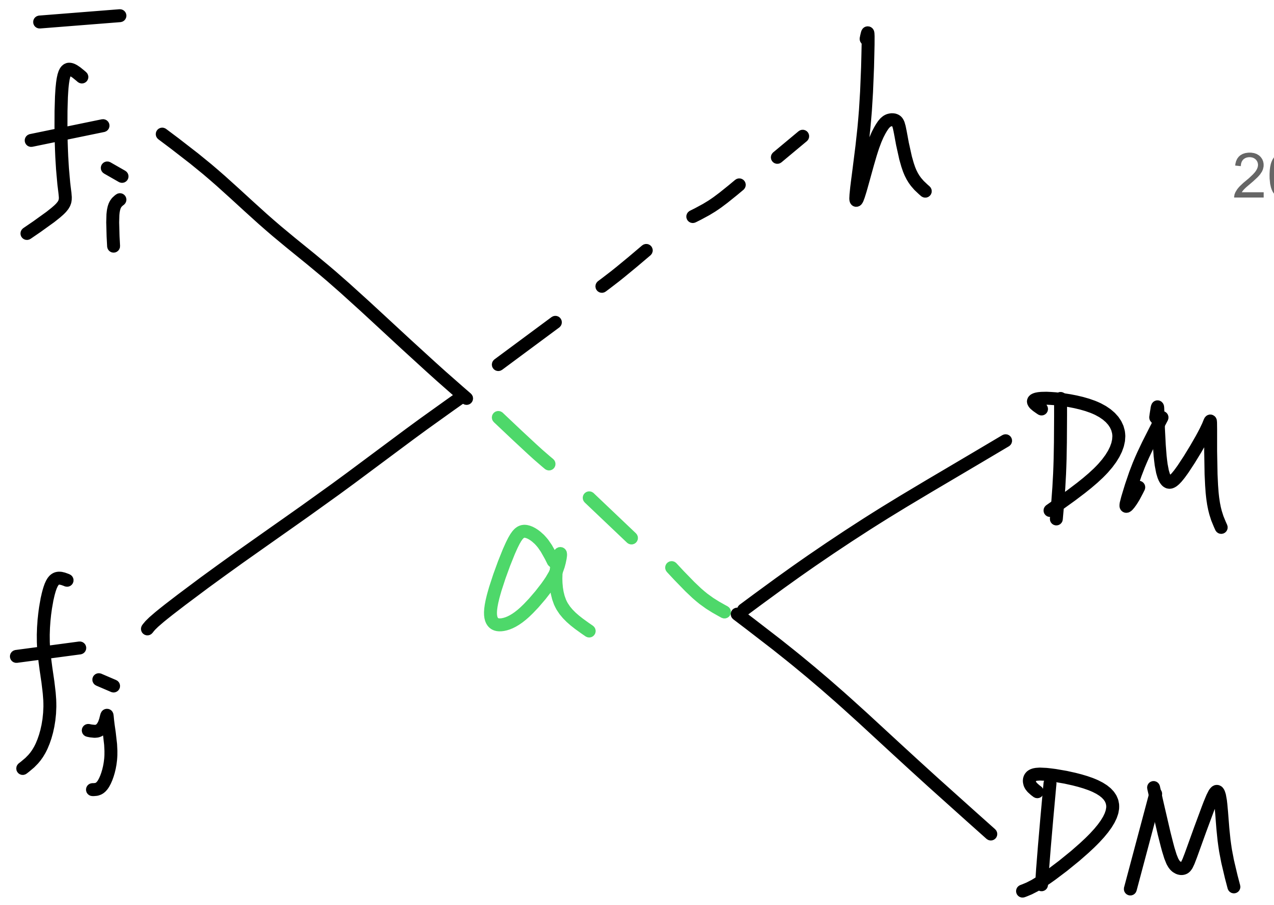


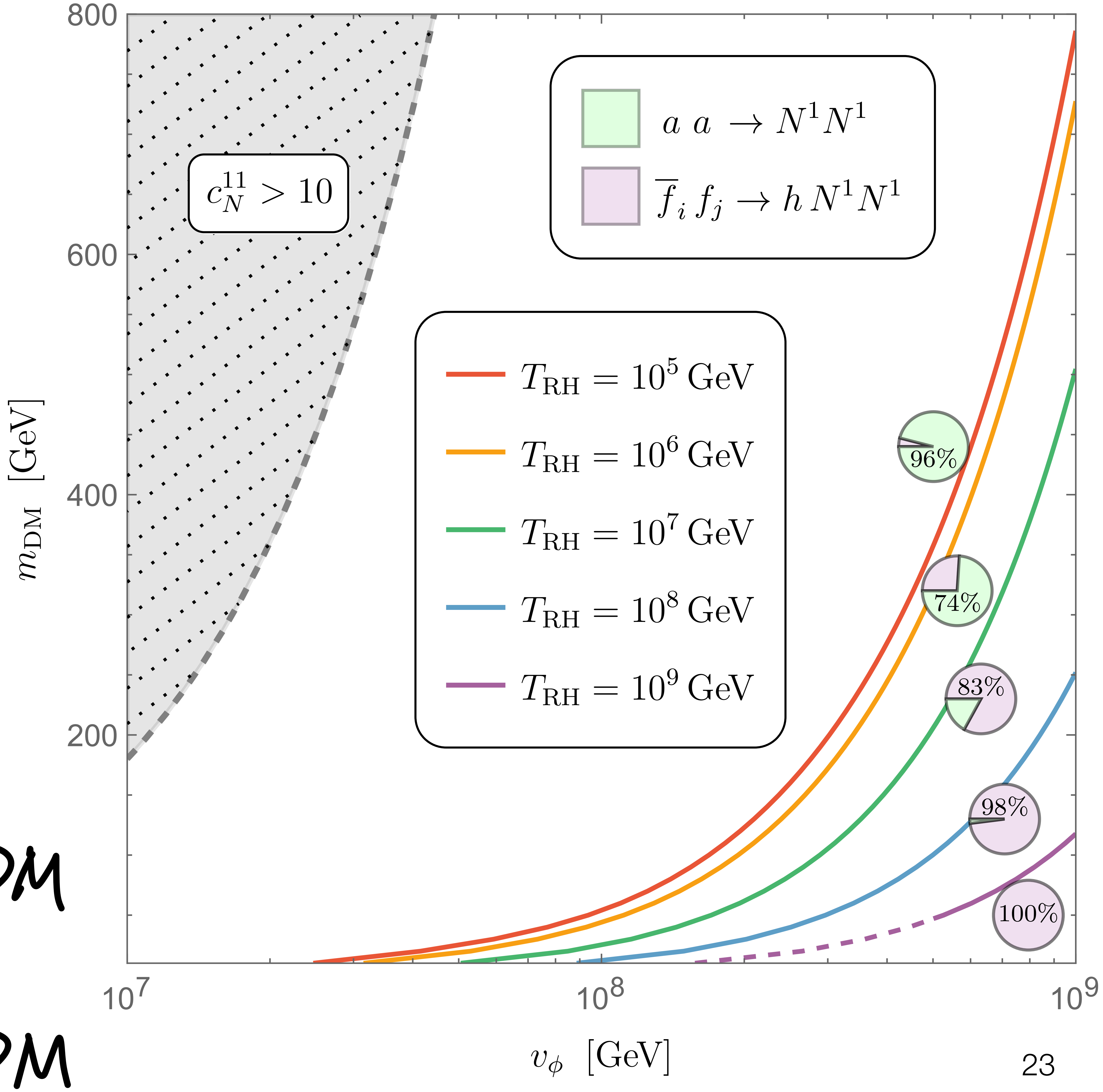
"Low" TRH



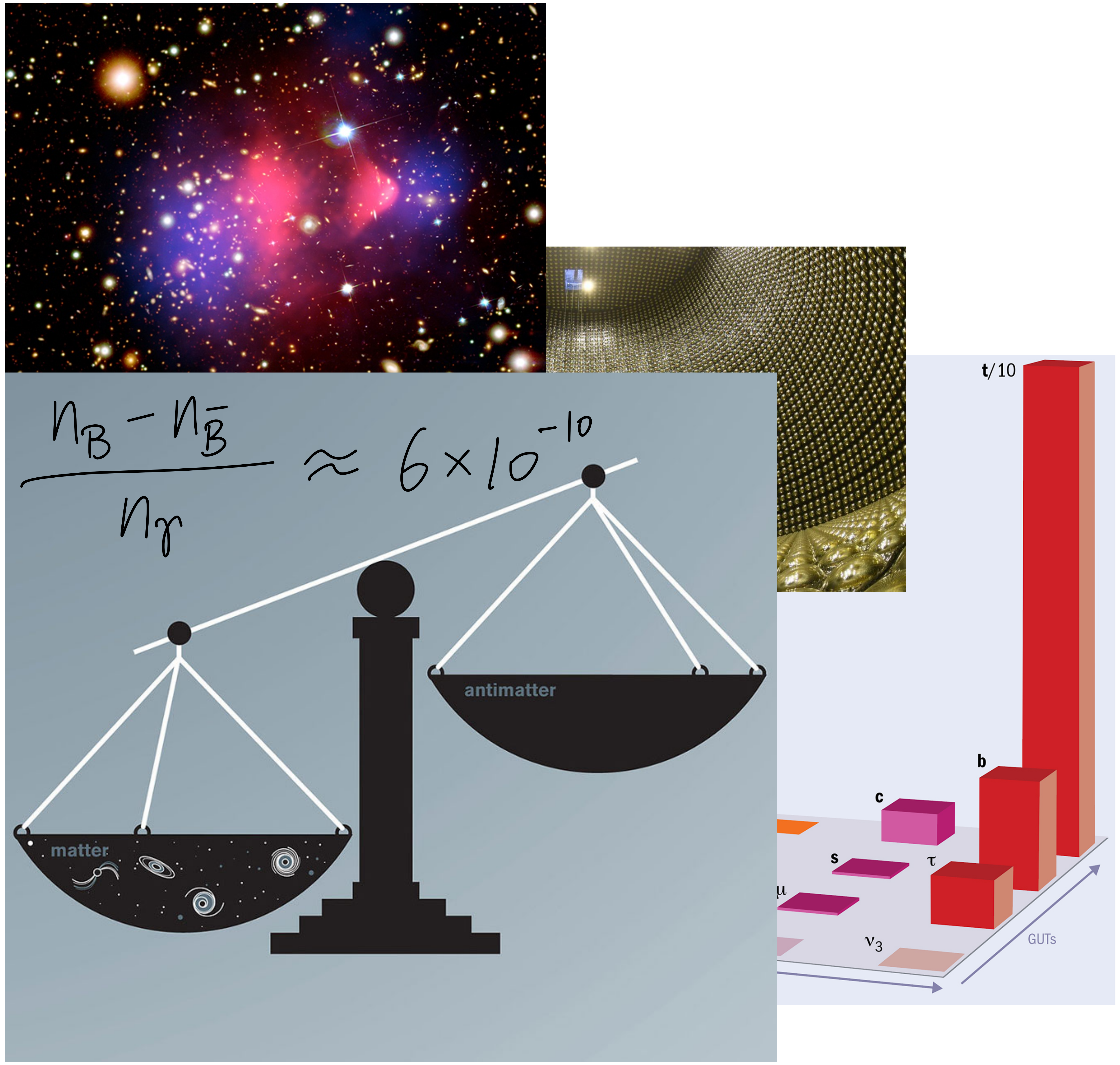
High scale: (UV) freeze in $\quad m_{DM}$ vs V_ϕ

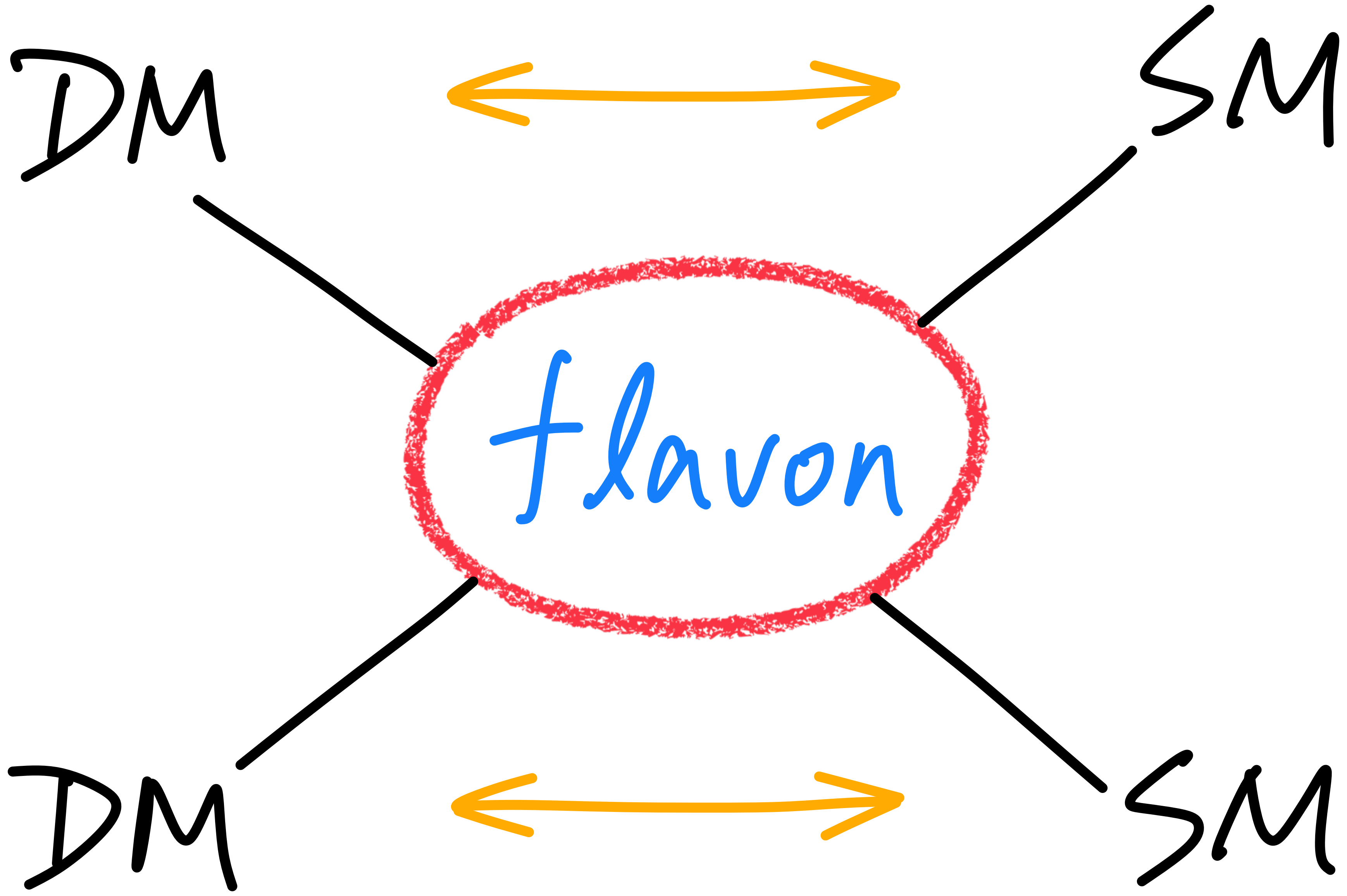






Fake Summary





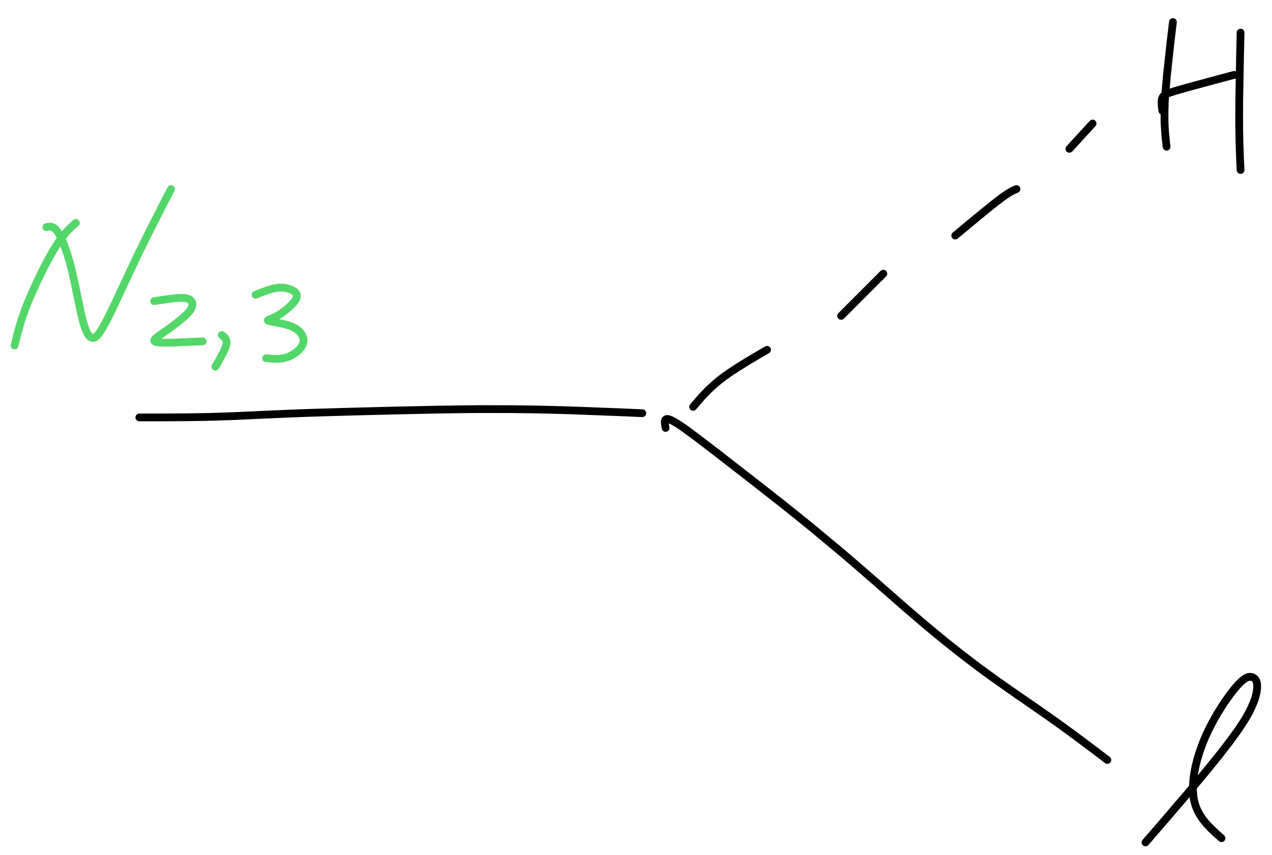
- $V_\phi \sim$ TeV: Freeze-out
- $V_\phi \sim 10^8$ GeV: Freeze-in

Leptogenesis

W.I.P.

with Rusa, Kunal & Cheshta

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



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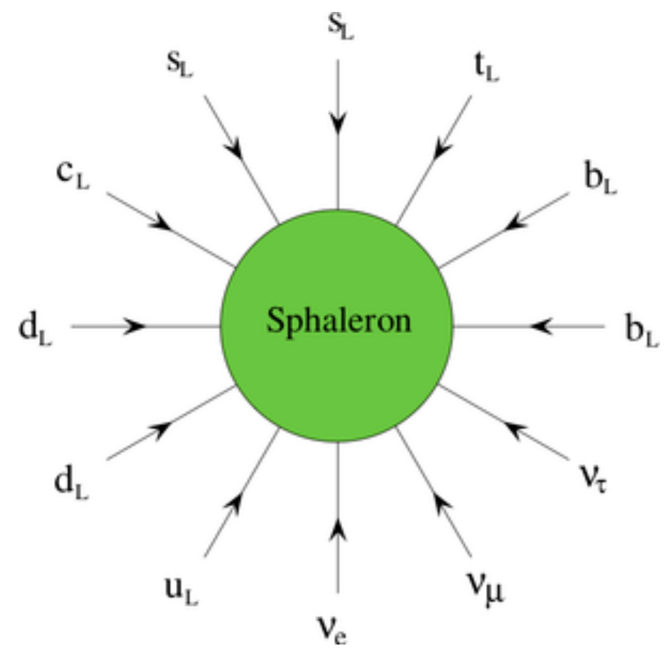
Leptogenesis

W.I.P.

Sakharov conditions

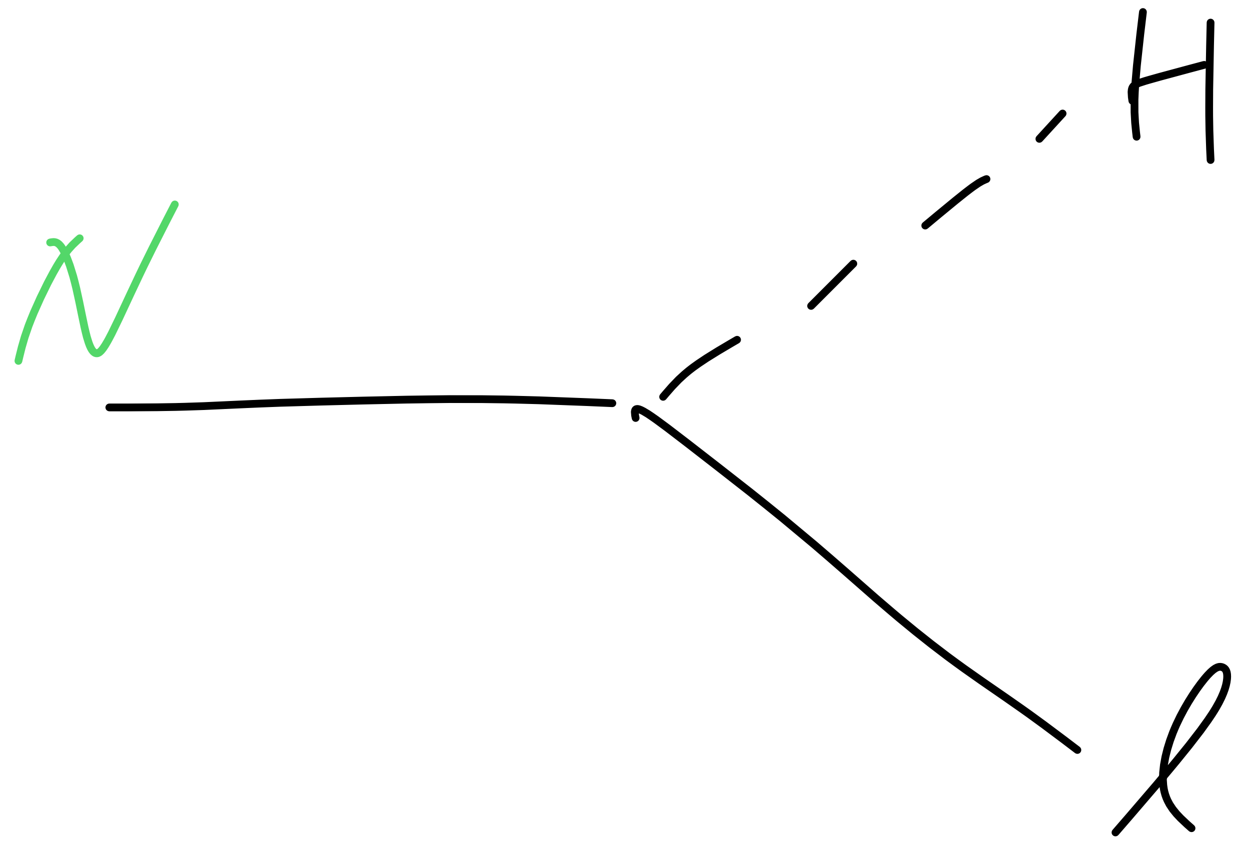
with Rusa, Kunal & Cheshta

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

✓ ① $\cancel{L} \Longrightarrow$ 

$\Longrightarrow \cancel{B}$

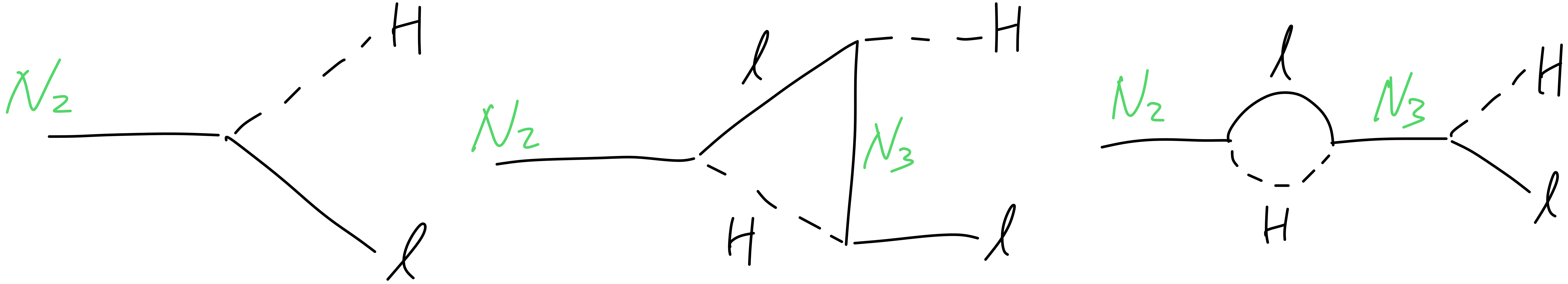
? ② $\cancel{CP}$ How to get enough?



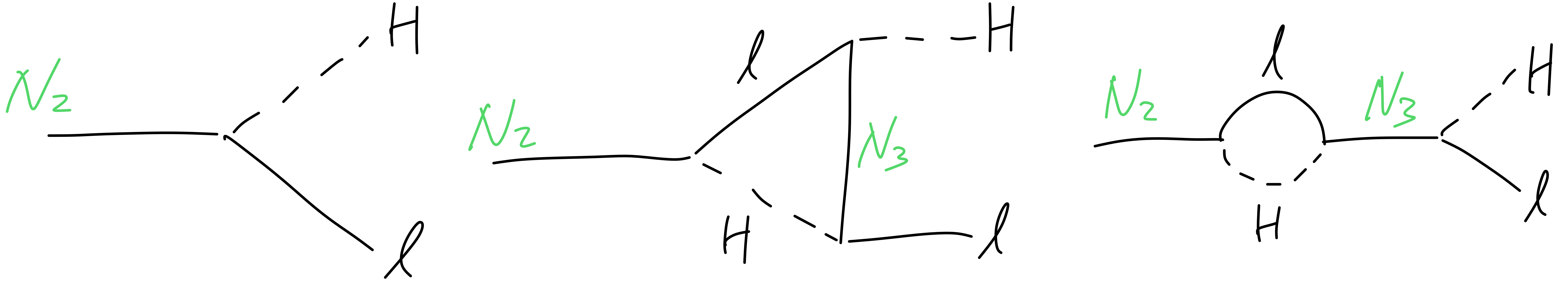
✓ ③ Out of thermal equilibrium

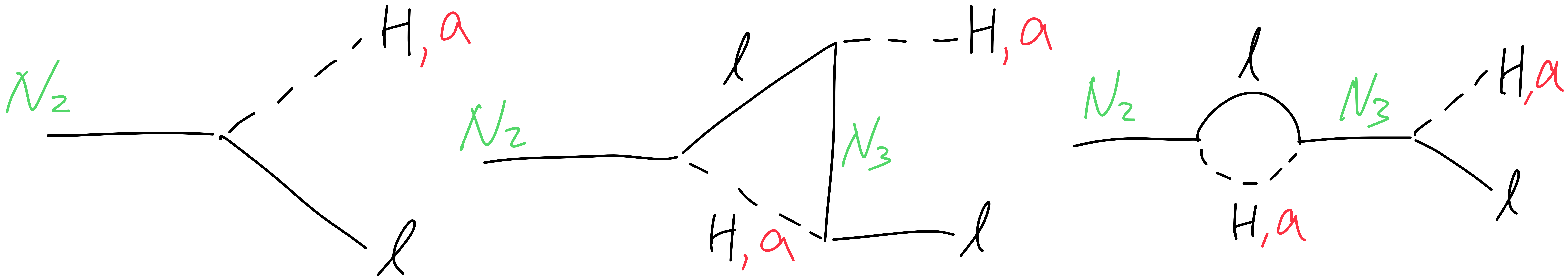
Inverse Decay $\Gamma <$ Hubble

CP-violation from Tree-Loop Interference



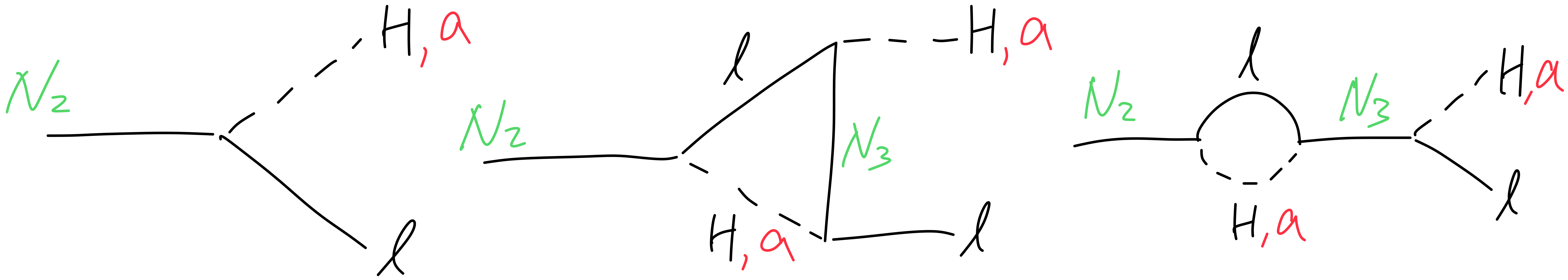
CP-violation from Tree-Loop Interference





CP-violation from Tree-Loop Interference

Approximately 4x enhancement to the amplitudes



Freeze-in $v_\phi \sim 10^8\,\mathrm{GeV}$

$N_{2,3} \sim 10^9\,\mathrm{GeV}$

High-scale Leptogenesis

✓ Works "out of the box"

✗ Hard to test

Freeze-in $v_\phi \sim 10^8\,\mathrm{GeV}$

$N_{2,3} \sim 10^9\,\mathrm{GeV}$

High-scale Leptogenesis

✓ Works "out of the box"

✗ Hard to test

Freeze-Out $v_\phi \sim \mathrm{TeV}$

$N_{2,3} \sim 10\,\mathrm{TeV}$

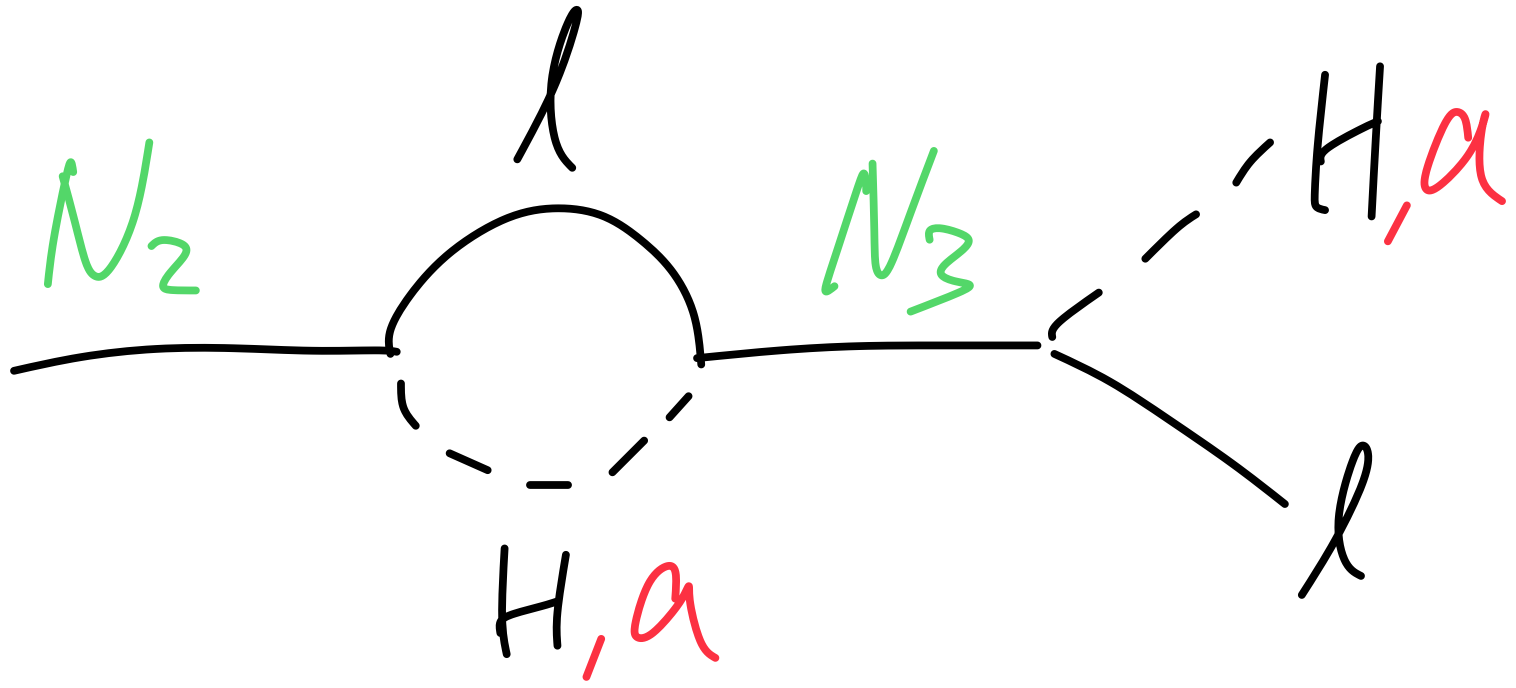
Low-scale Leptogenesis

✗ Baryon # too low by 10^7

✓ "Easy" to test

Resonant Leptogenesis

0309342v3

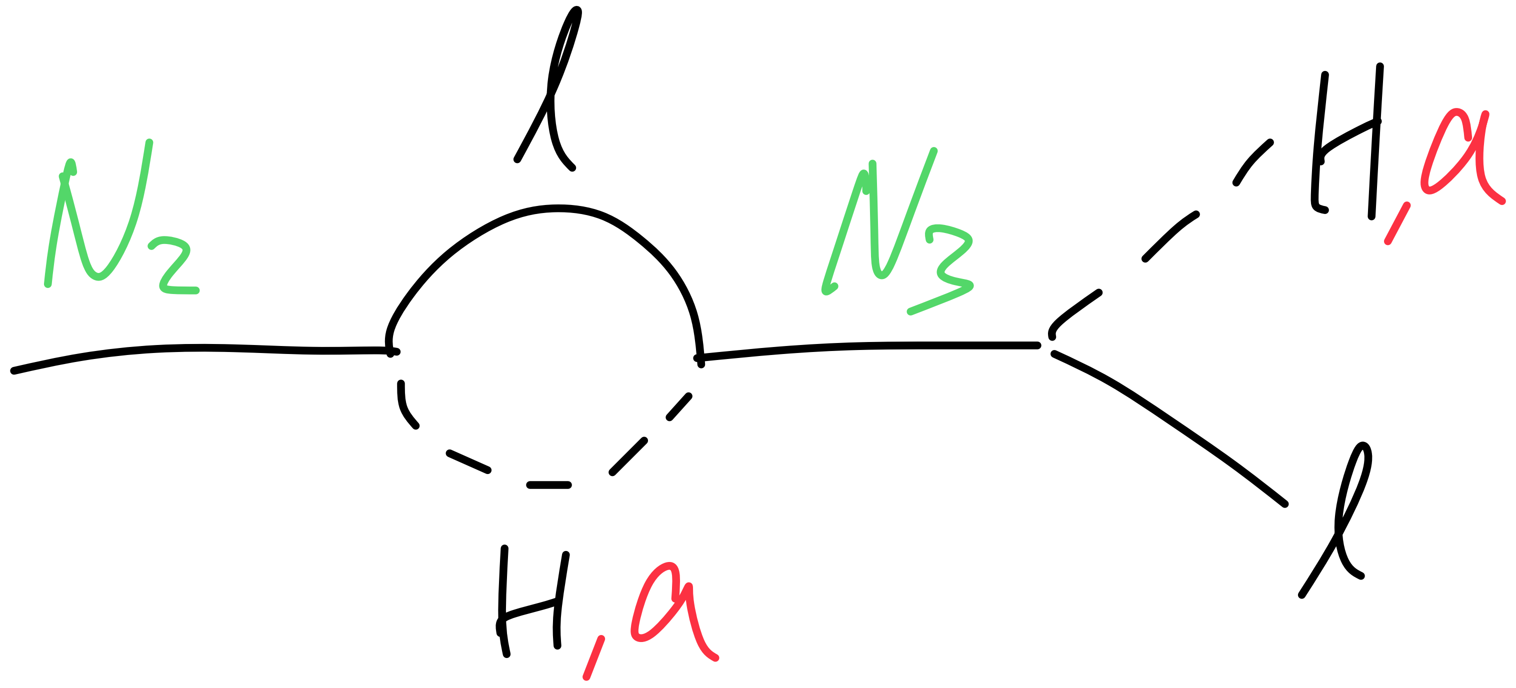


$\cancel{CP}$ enhanced when

$$m_{N_2} \approx m_{N_3}$$

Resonant Leptogenesis

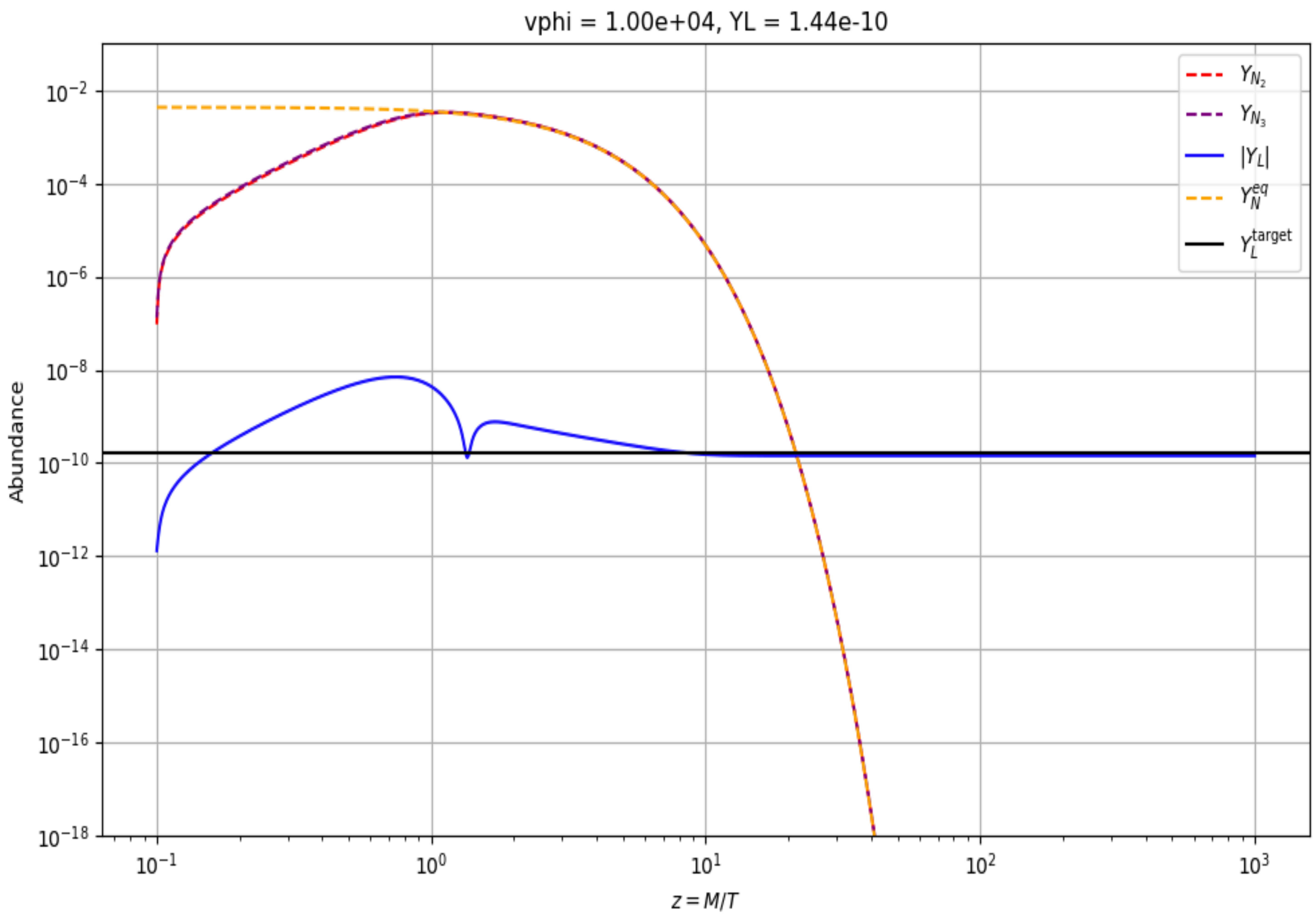
0309342v3



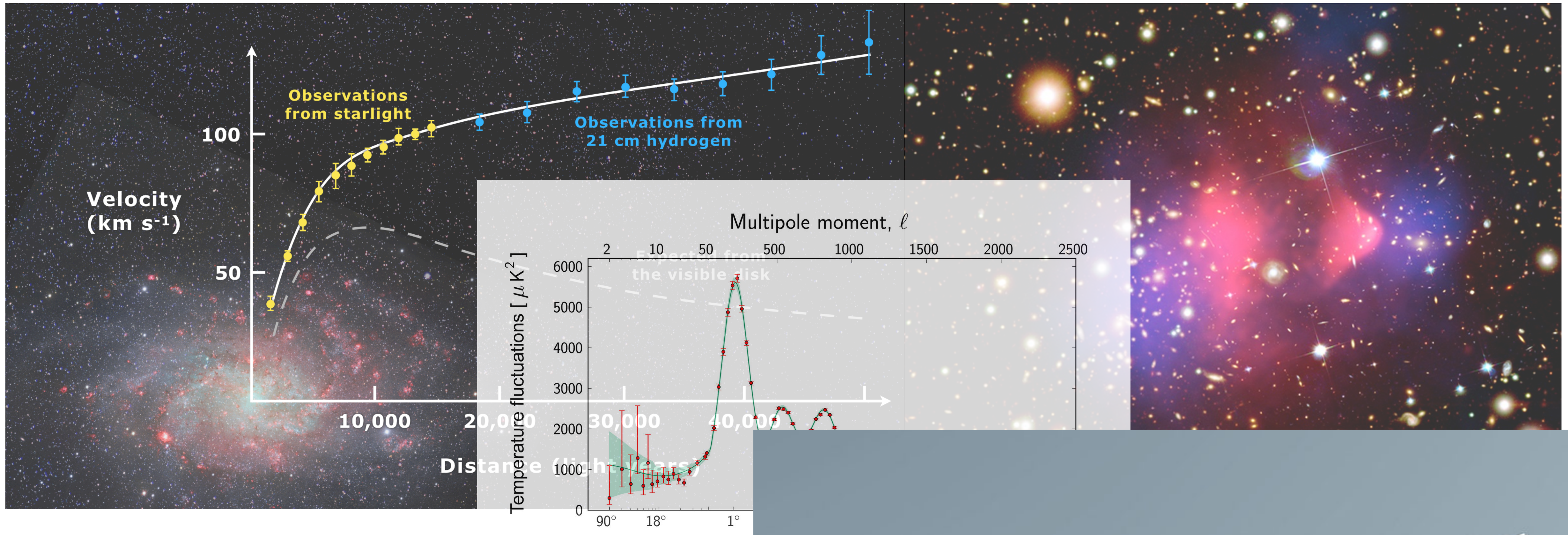
~~CP~~ enhanced when

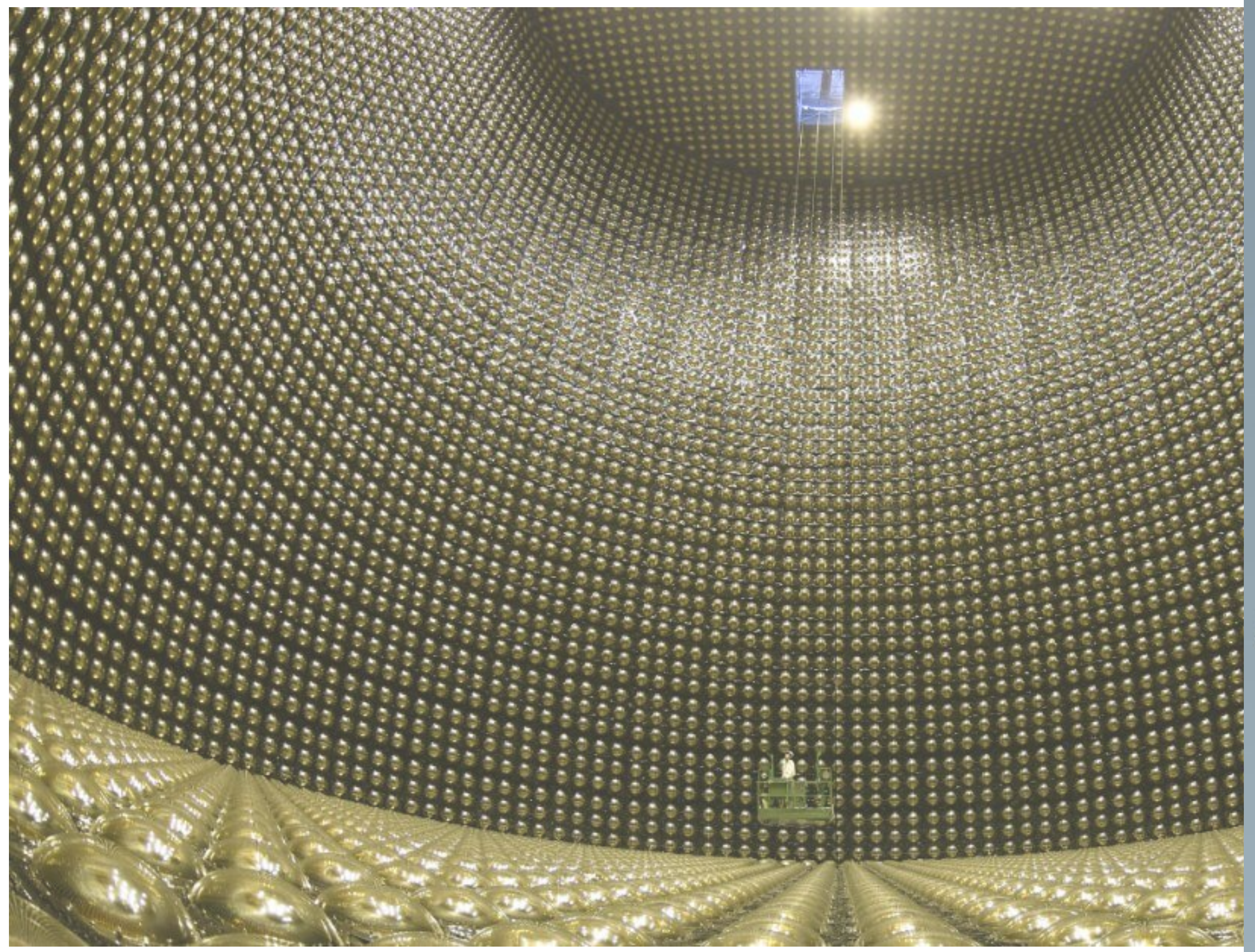
$$m_{N_2} \approx m_{N_3}$$

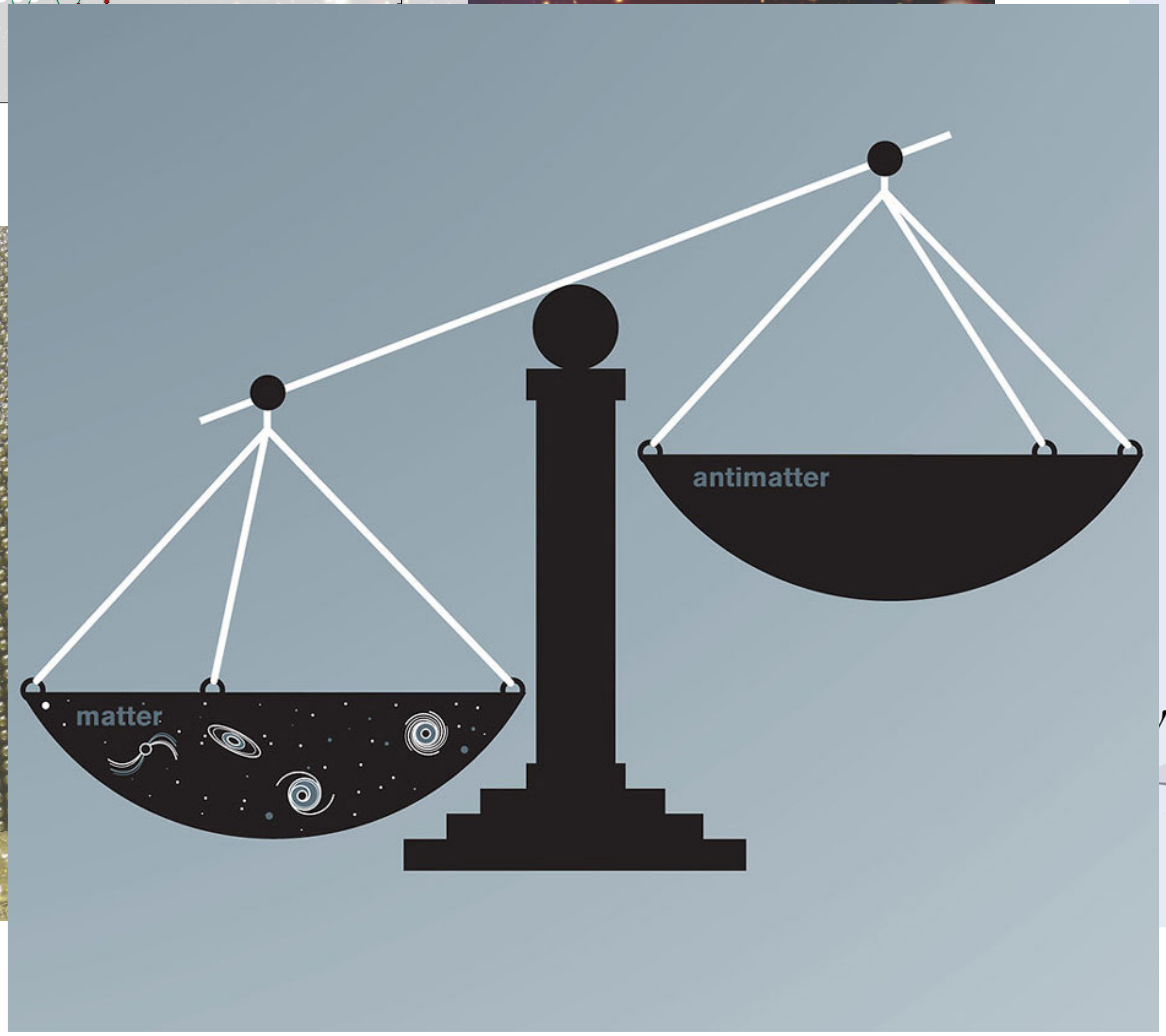
$$\frac{\Delta m}{m_{N_2}} \lesssim 10^{-5}$$



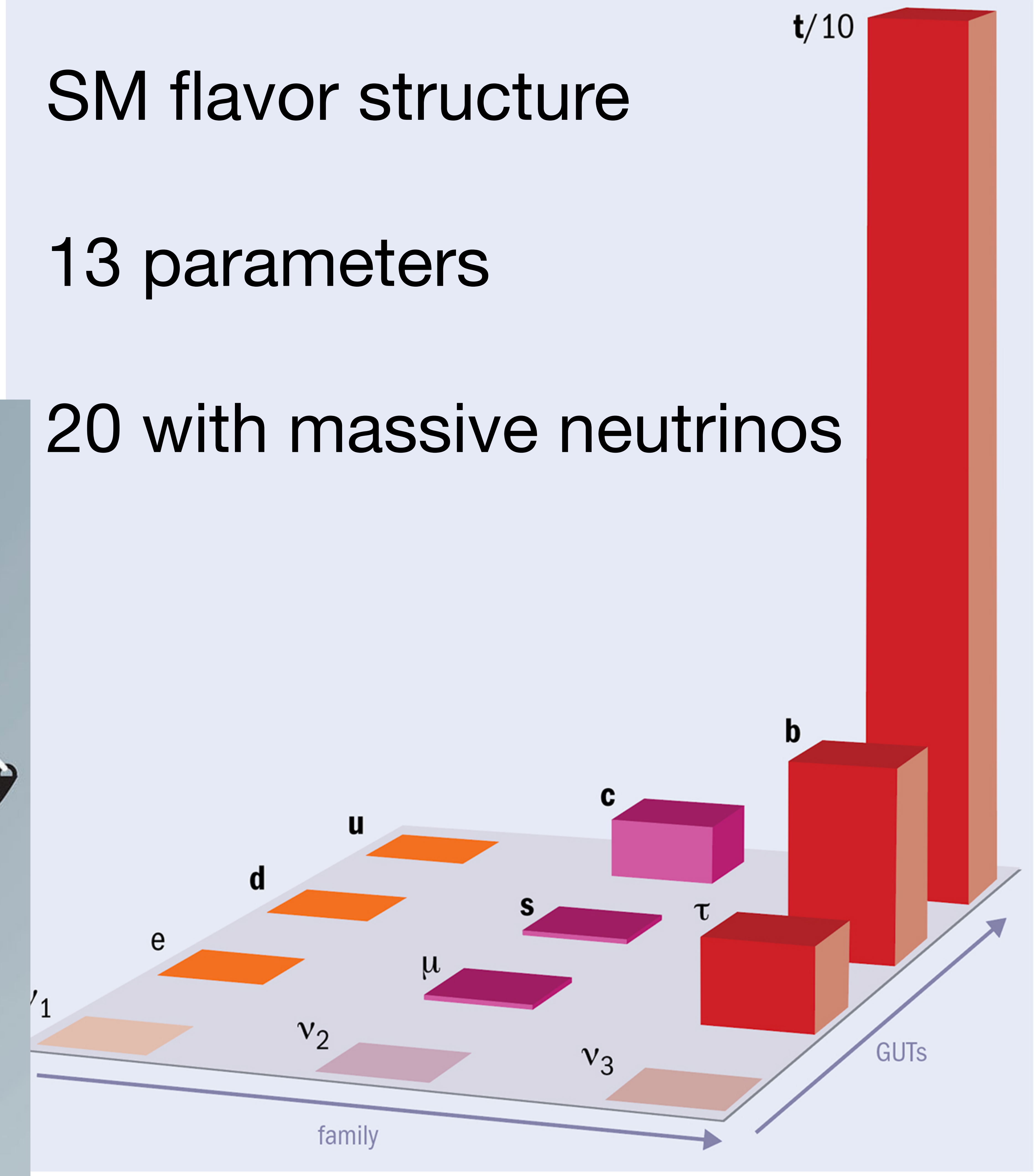
Wir müssen wissen, wir werden wissen







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



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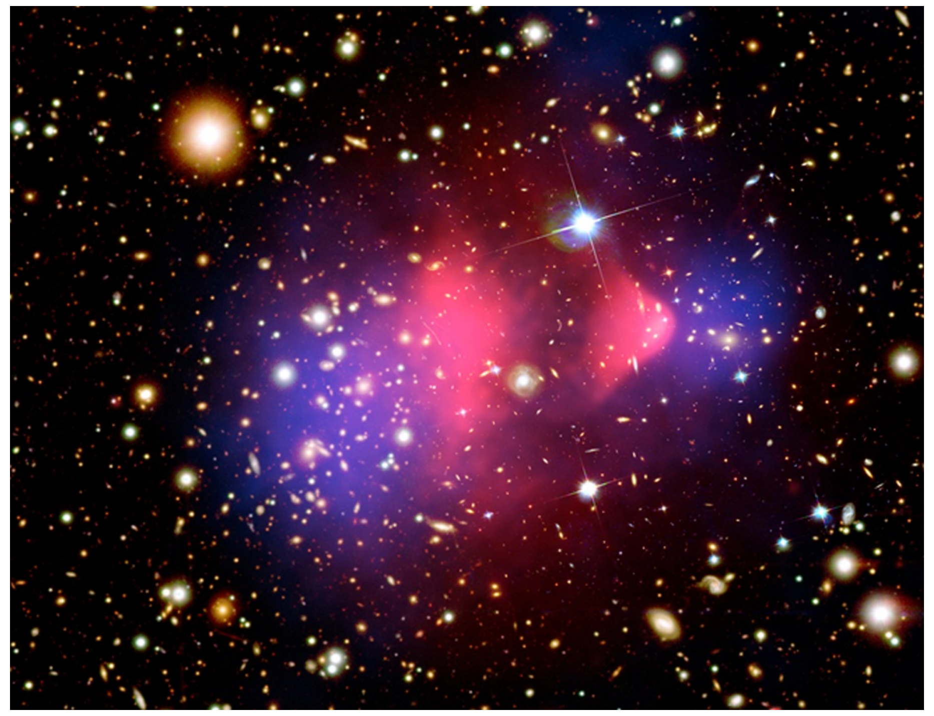
Behind the Scenes

Right-handed neutrino and DM

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

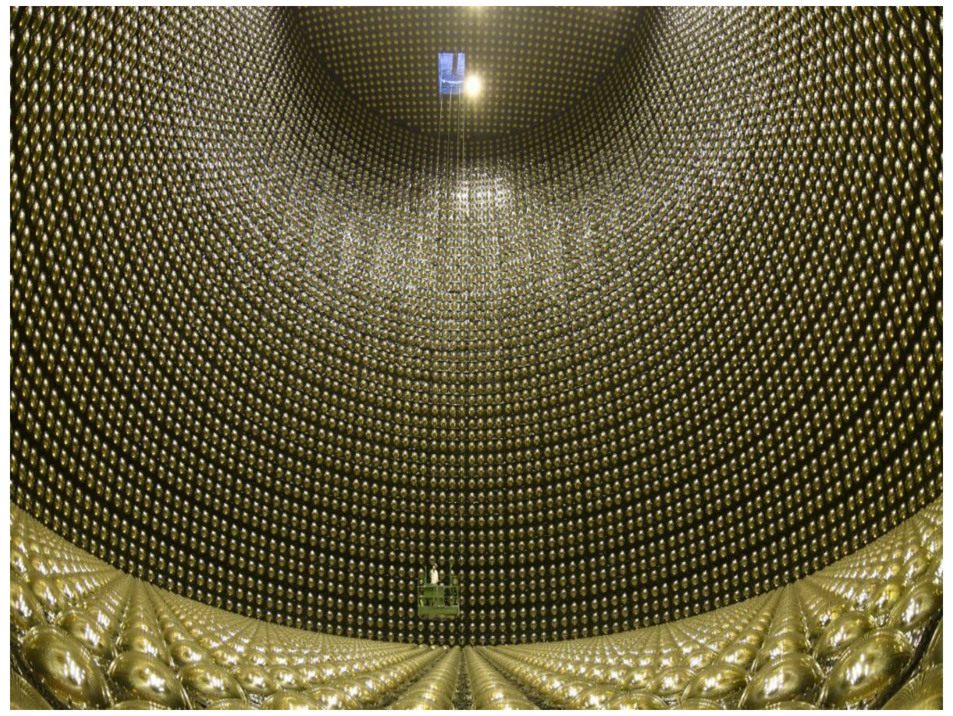
$N_1 \rightarrow$ Z_2 symmetry

$\Downarrow$



$N_2, N_3 \rightarrow$ Heavy

$\Downarrow$



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

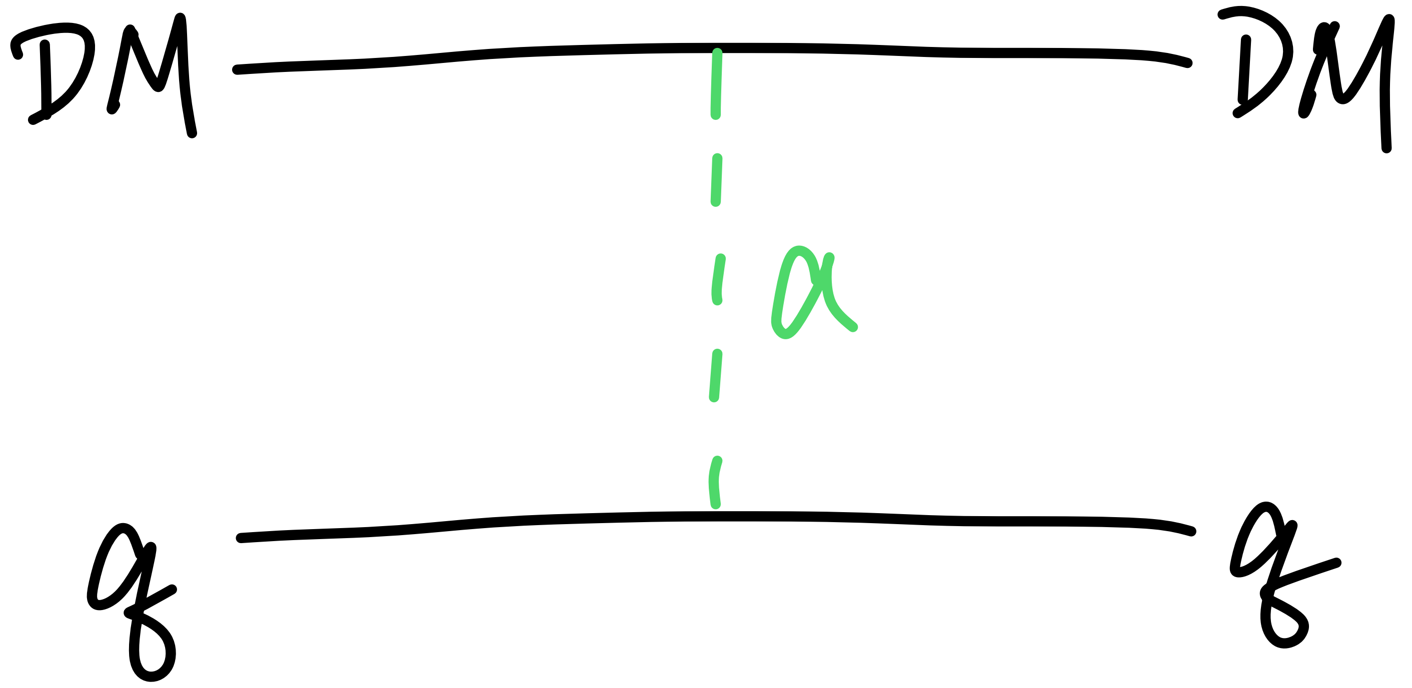
Yukawa: 3×2 matrix $\begin{pmatrix} \times & \times \\ \times & \times \\ \times & \times \end{pmatrix}$

Lightest ν is massless!

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

Majorana: 3×3 matrix $\begin{pmatrix} \times & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix}$

Direct detection



$$\sim \frac{g_{DM}}{M_a^2}\underbrace{\left(g_+^q\, \bar{q}\, \gamma_5 q\right)}\underbrace{\left(\overline{DM}\, \gamma_5\, DM\right)}$$

$$g_n m_n \underbrace{\bar{n} \gamma_5 n}$$

$\downarrow$ NR

$$\frac{|\vec{k}|}{2m_n}\, \bar{n} \gamma^\mu \gamma_5 n$$

NR

$$\frac{|\vec{k}|}{2m_{DM}}\, \overline{DM}\, \gamma^\mu \gamma_5 DM$$

PCAC

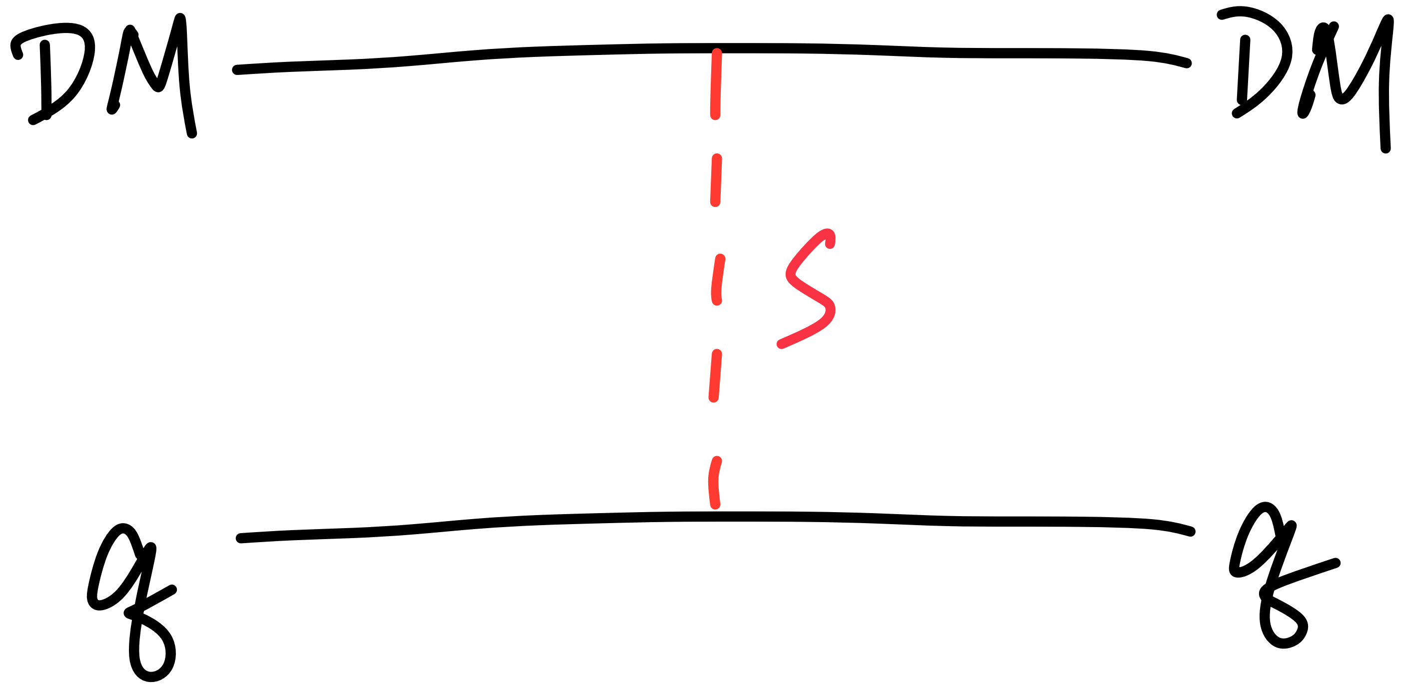
$$g_n = \sum_{q=u,d,s} \left(g_+^q - \bar{m}\,\xi\right) \frac{\Delta_q^n}{m_q},$$

where $\bar{m} = \left(m_u^{-1} + m_d^{-1} + m_s^{-1}\right)^{-1}$ and $\xi = \sum_{q = \text{all quarks}} \frac{g_+^q}{m_q}$.

	Δ_u^n	Δ_d^n	Δ_s^n
Proton	0.80(3)	−0.46(4)	−0.12(8)
Neutron	−0.46(4)	0.80(3)	−0.12(8)

$$|\vec{k}| \sim 100 \text{ MeV}$$

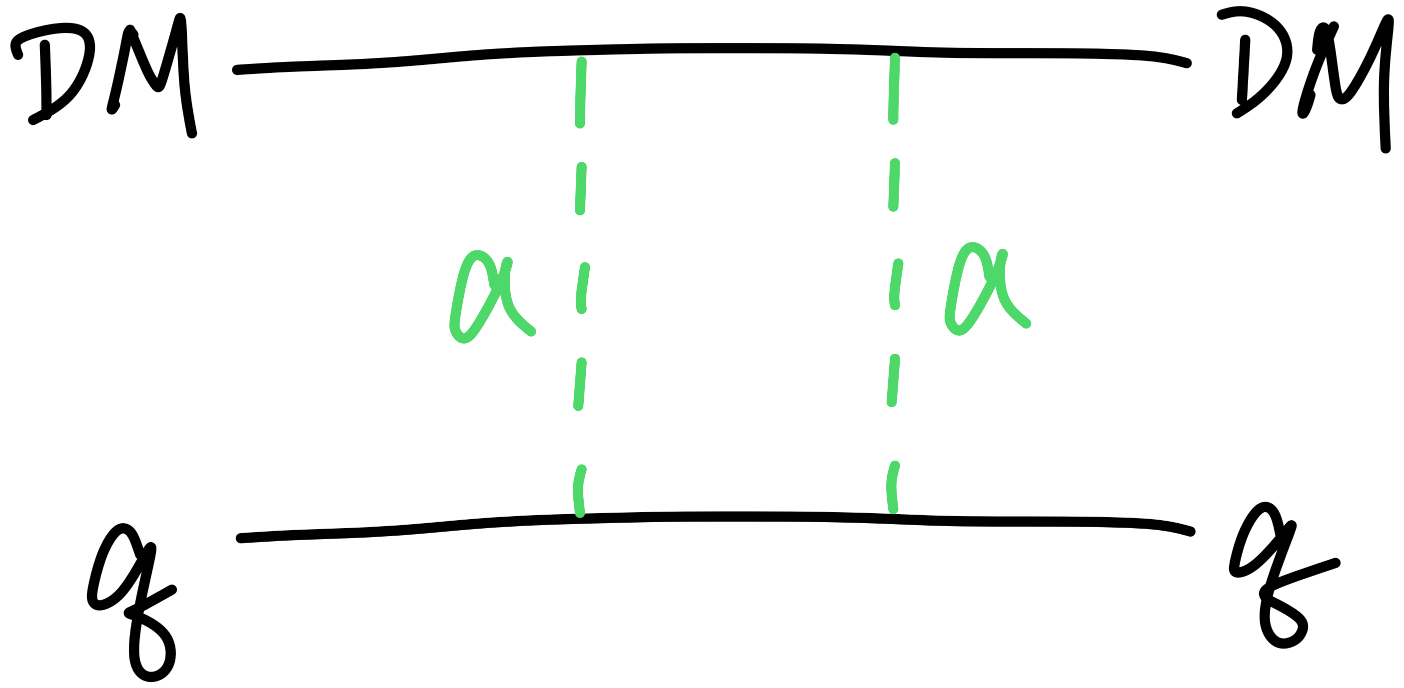
Direct detection



	f^n_{Tu}	f^n_{Td}	f^n_{Ts}	f^n_{TG}
Proton	0.018(5)	0.027(7)	0.037(17)	0.917(19)
Neutron	0.013(3)	0.040(10)	0.037(17)	0.910(20)

$$\frac{g_{DM}}{m_s^2}\left(g_+^q\, \bar{q}\, q\right)\left(\overline{DM}\, DM\right)$$

$$\sigma^{\rm SI}_{\rm scalar} = \frac{4\,\mu_n^2\, m_n^2\, g_{\rm DM}^2}{\pi\, m_s^4}\left|\sum_{q=u,\,d,\,s}\frac{g_+^q}{m_q} f^n_{Tq} + \frac{2}{27} f^n_{TG}\sum_{q=c,\,b,\,t}\frac{g_+^q}{m_q}\right|^2$$



$$\sigma^{\rm SI}_{\rm box} = \frac{4}{\pi}\,\mu_n^2\, m_n^2\, g_{\rm DM}^4\left|\sum_{q=u,d,s}\frac{B_q}{m_q} f^n_{Tq} + \frac{2}{27} f^n_{TG}\sum_{q=c,b,t}\frac{B_q}{m_q}\right|^2$$

$$\text{where } B_q = \sum_{j=1,2,3}\left|(g_+^f)_{ij}\right|^2 C_{S,q^j}(m_{\rm DM},\, m_a,\, m_{q^j})$$

Passarino-Veltman

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