

NNaturalness

In progress with
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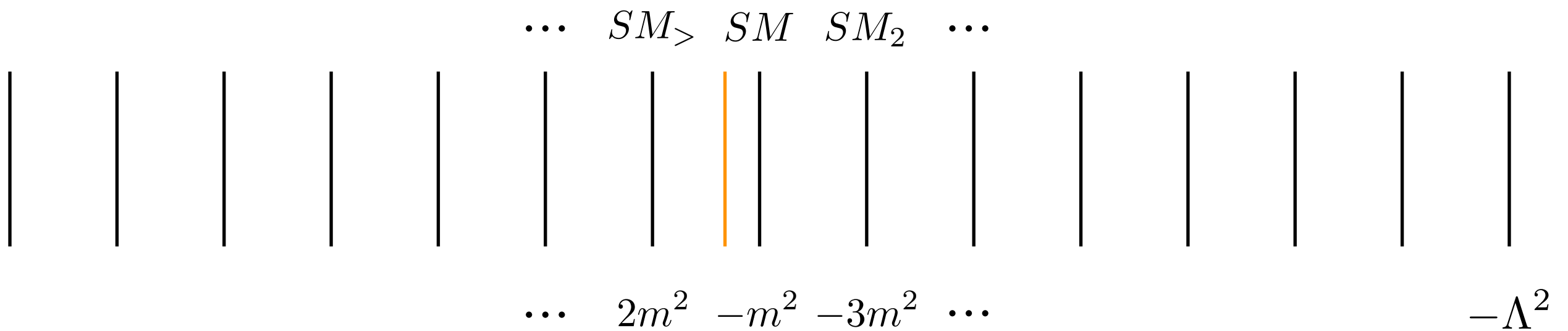
NNATURALNESS

- NO FINE-TUNING OF THE HIGGS MASS
- NO NEW PARTICLES AT THE LHC
- VERY DISTINCT COSMOLOGICAL SIGNATURES

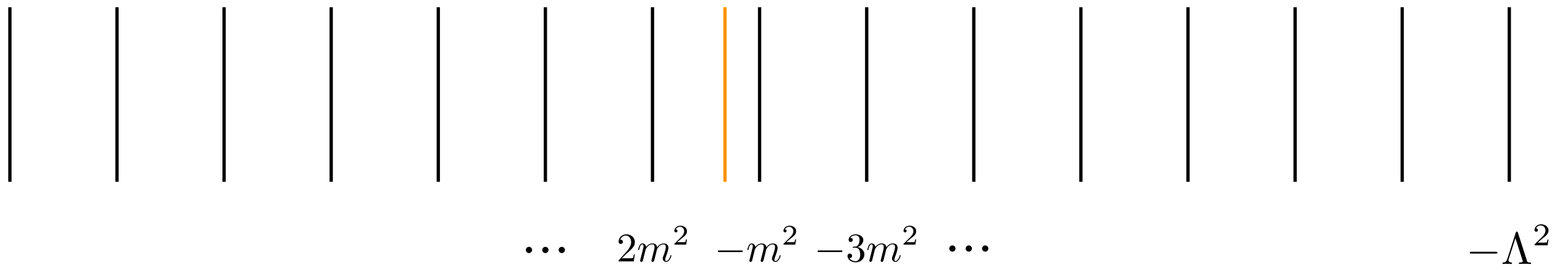
OUTLINE

- THE SOLUTION
- REHEATING
- A MORE COMPREHENSIVE PICTURE
- COMPARISONS AND OUTLOOK

N COPIES

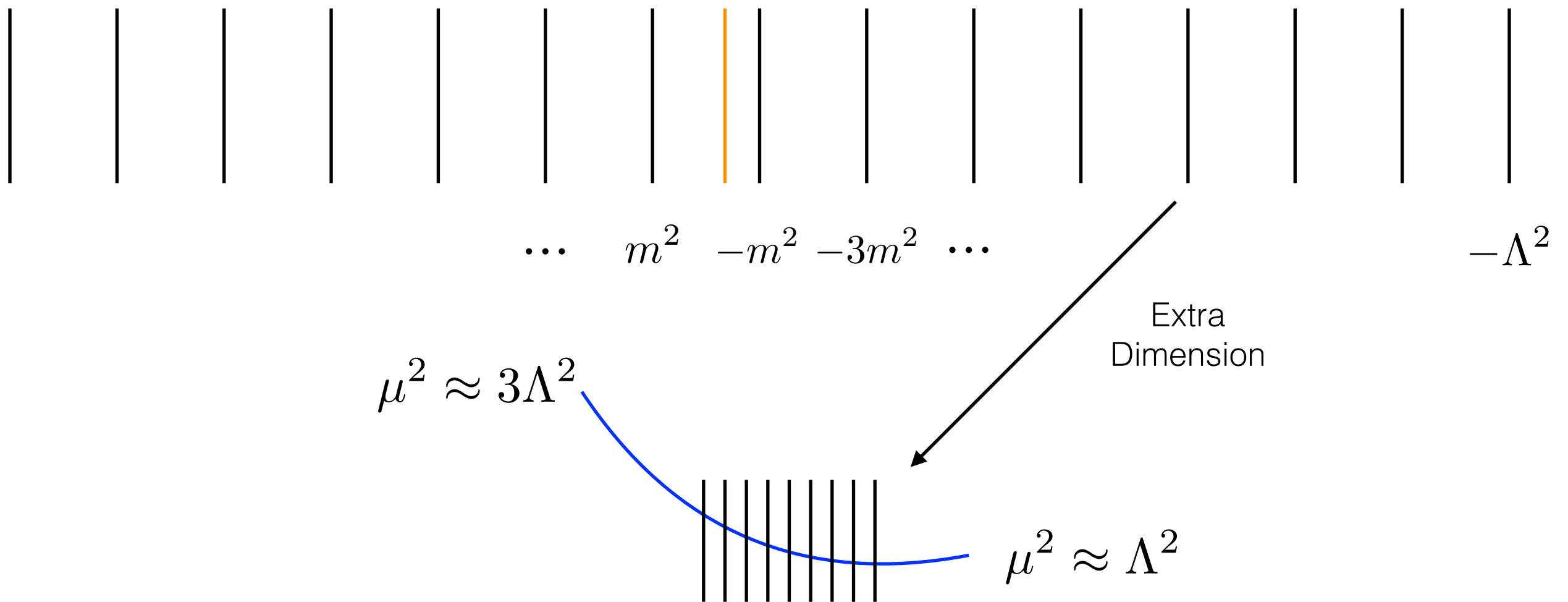


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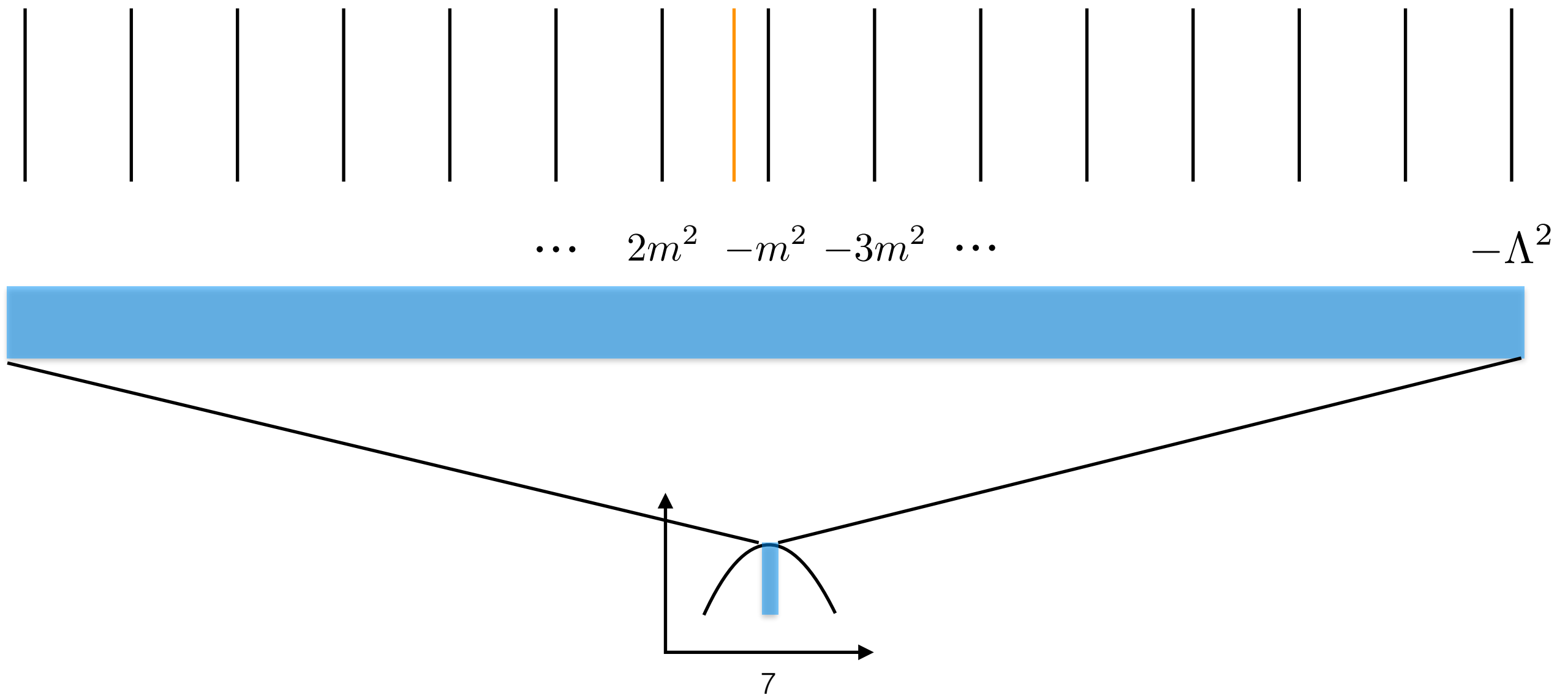


$$\Lambda^2 \sim m^2 N$$

N COPIES



N COPIES



THE SCALES

———— M_{Pl}

———— $\Lambda \sim m_h \sqrt{N}$

———— m_h

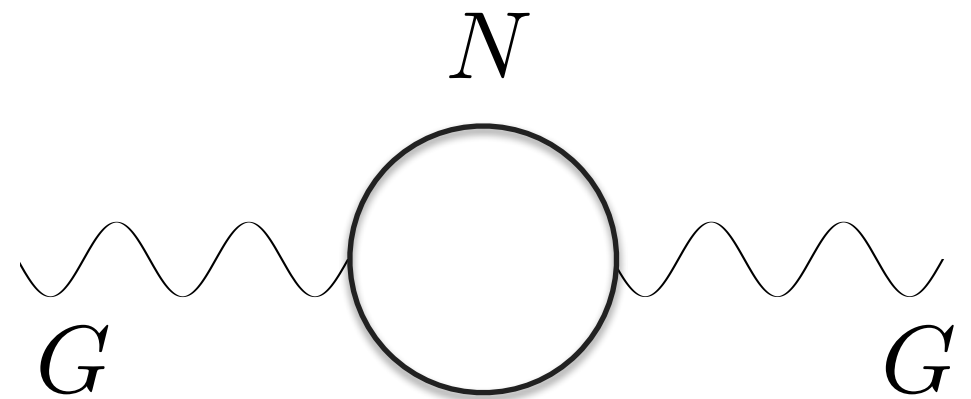
THE SCALES

————— M_{Pl}

————— $\Lambda_G \sim M_{Pl}/\sqrt{N}$

————— $\Lambda \sim m_h \sqrt{N}$

————— m_h



A PARTIAL SOLUTION

————— M_{Pl}

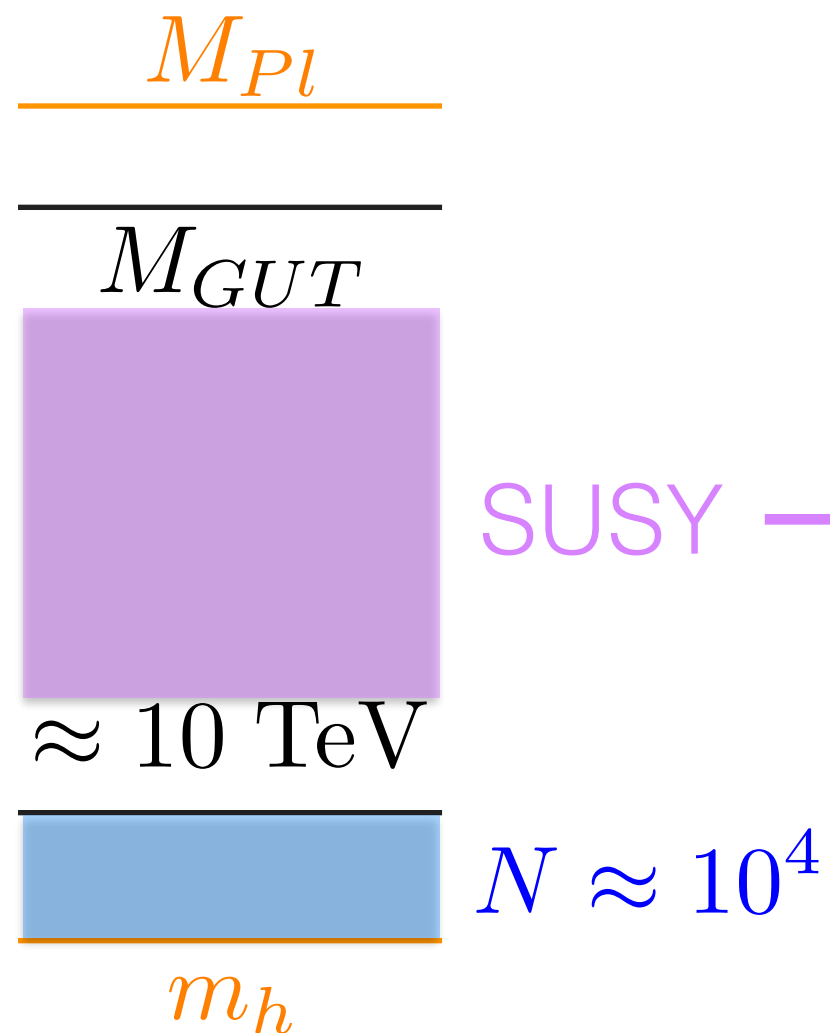
————— $\Lambda_G \sim M_{GUT}$

————— $\Lambda \sim 10 \text{ TeV}$

————— m_h

$$N \approx 10^4$$

SUSY AT FUTURE COLLIDERS



- Unification
- Dark Matter
- Flavor/CP Signals
- Higgs at 125 GeV with no effort (Gauge mediation)

A FULL SOLUTION

———— M_{Pl}

———— $\Lambda_G \approx \Lambda \approx 10^{10} \text{ GeV}$ $N \approx 10^{16}$

———— m_h

N COPIES

ALL THE COPIES ARE IN THE SAME VACUUM.
NOT A MULTIVERSE.

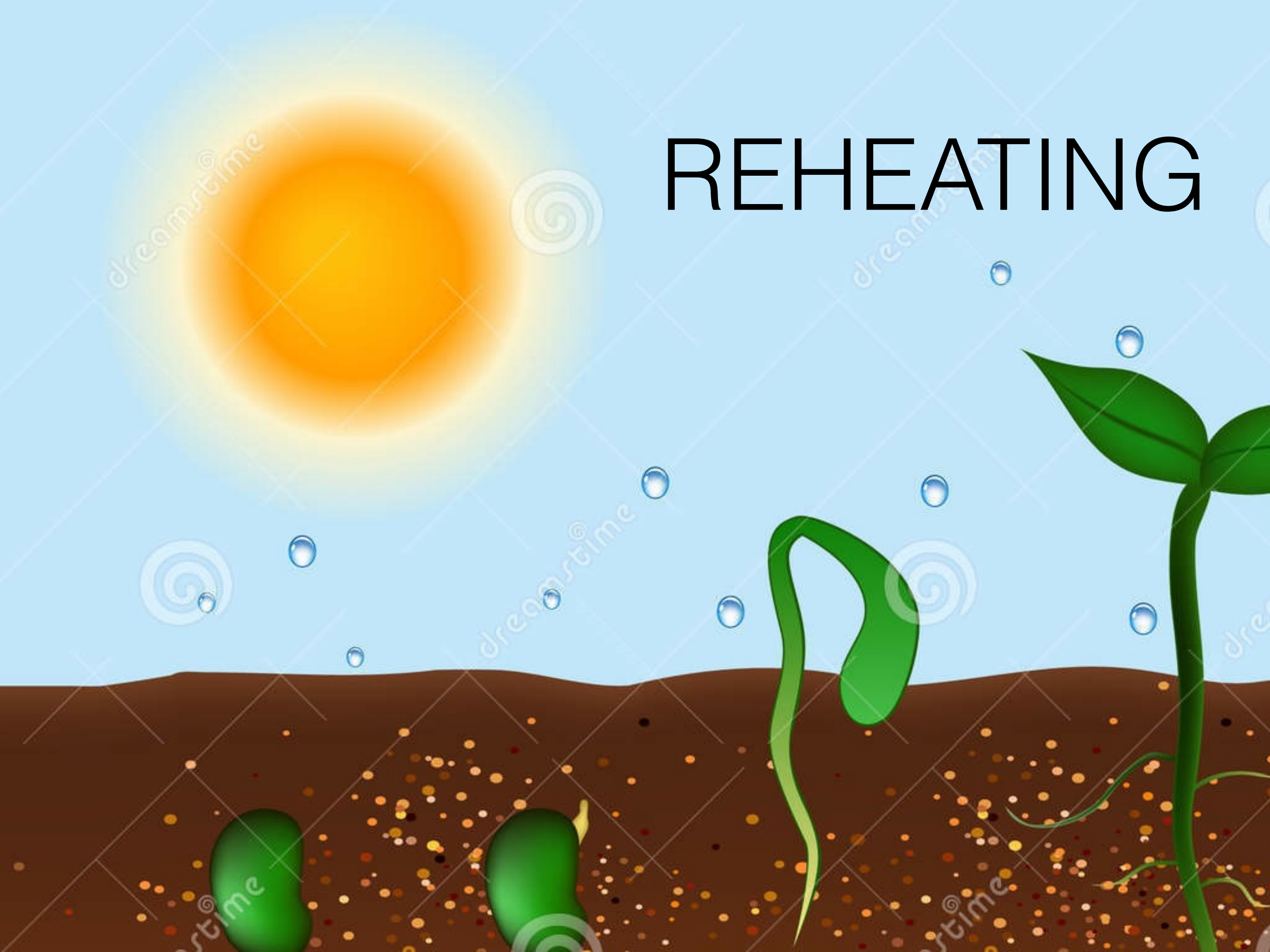
$$m_h^2 < 0$$

- Massless photons
- W, Z and fermion masses scale with v
- Neutrino masses grow as v (Dirac) or v^2 (Majorana)

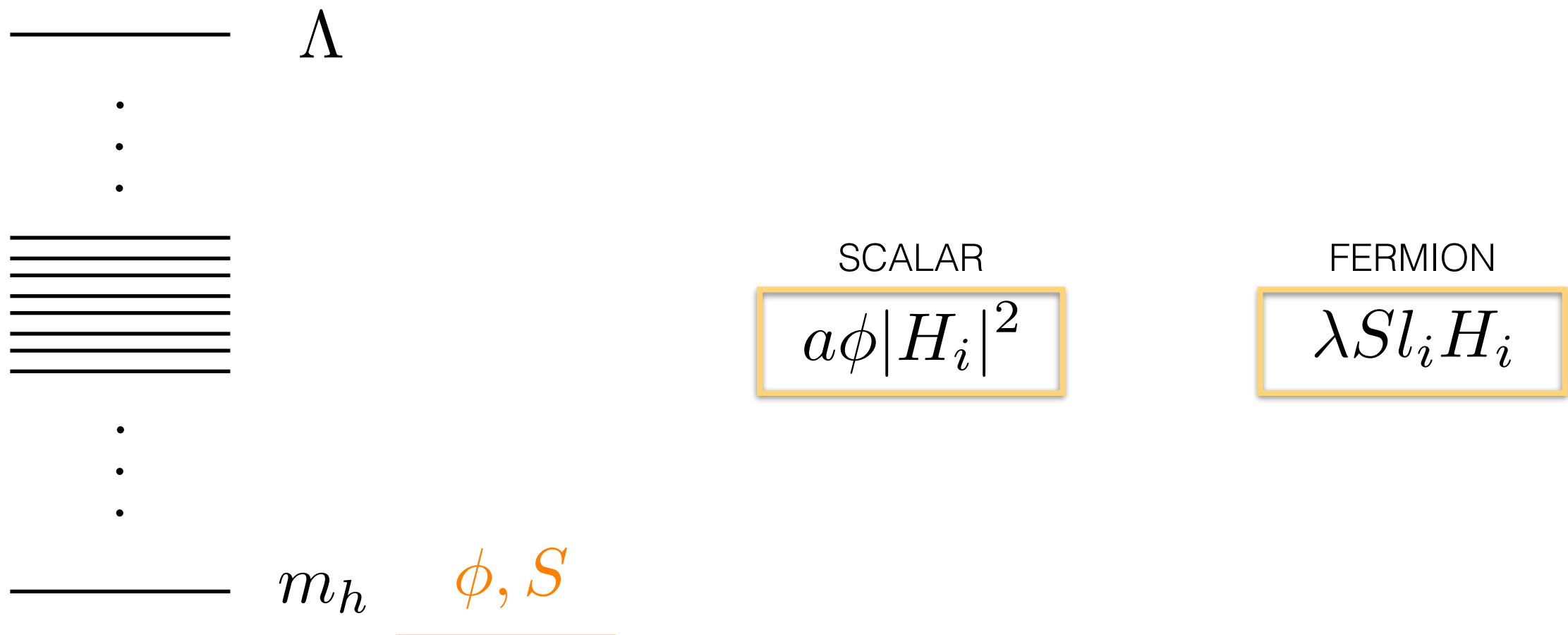
$$m_h^2 > 0$$

- Massless photons
- Nearly massless fermions
- W, Z at the QCD scale
- No baryons

REHEATING



REHEATON

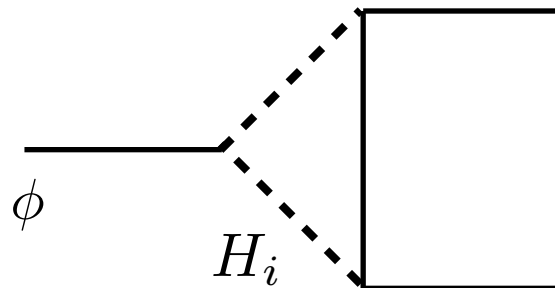


SCALAR REHEATON

SCALAR

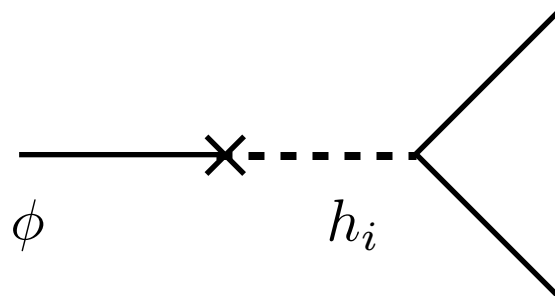
$$a\phi|H_i|^2$$

$$m_h^2 > 0$$



$$\frac{a}{m_{h_i}^2} \phi \bar{\psi} \gamma^\mu \partial_\mu \psi \quad \Gamma \sim \frac{1}{m_{h_i}^4}$$

$$m_h^2 < 0$$



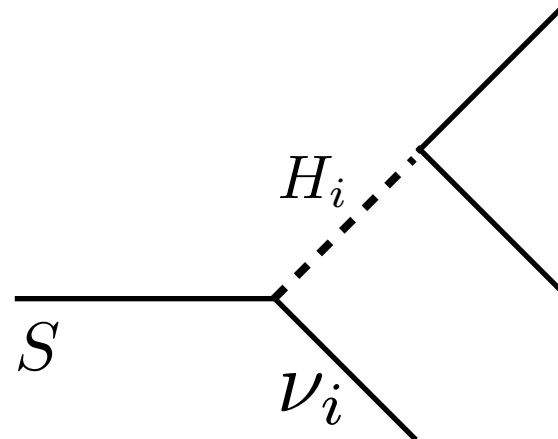
$$\frac{a}{m_{h_i}} \phi \bar{\psi} \psi \quad \Gamma \sim \frac{1}{m_{h_i}^2}$$

FERMIONIC REHEATON

FERMION

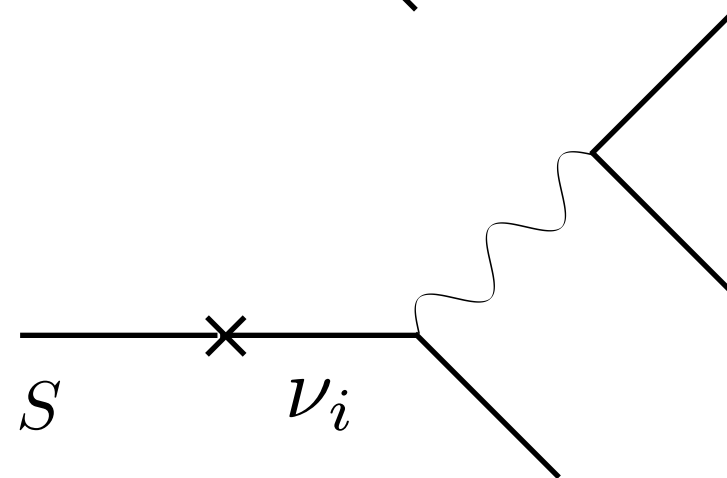
$$\lambda S l_i H_i$$

$$m_h^2 > 0$$



$$\Gamma \sim \frac{1}{m_{h_i}^4}$$

$$m_h^2 < 0$$



$$\Gamma \sim \frac{1}{m_{h_i}^2}$$

L4

In the simple fermionic model: $N \lesssim 10^3$ Neutrino
overclosure, ...

$$\mathcal{L}_{L_4} \supset \mathcal{L}_{\text{mix}} + \mathcal{L}_Y + \mathcal{L}_M ,$$

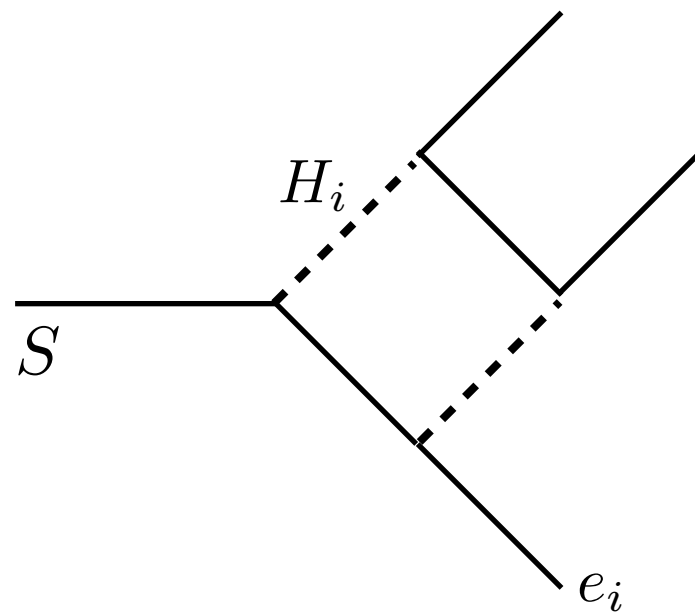
$$\mathcal{L}_{\text{mix}} = -\lambda S^c \sum_i (L_4 H)_i - \mu_E \sum_i (e^c E)_i ,$$

$$\mathcal{L}_Y = - \sum_i \left[Y_E (H^\dagger L_4 E_4^c)_i + Y_E^c (H L_4^c E_4)_i + Y_N (H L_4 N_4^c)_i + Y_N^c (H^\dagger L_4^c N_4)_i \right] ,$$

$$\mathcal{L}_M = - \sum_i \left[M_E (E_4^c E_4)_i + M_L (L_4^c L_4)_i + M_N (N_4^c N_4)_i \right] - m_S S S^c ,$$

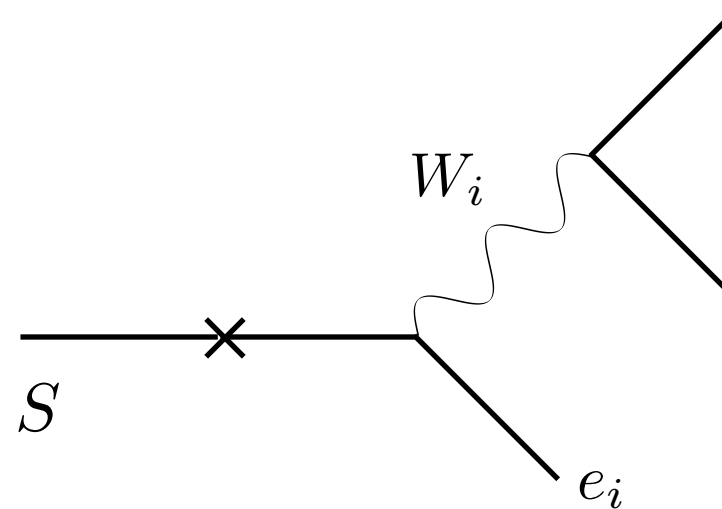
L4

$$m_h^2 > 0$$



$$\Gamma \sim \left(\frac{y_t y_b}{16\pi^2} \right)^2 \frac{1}{m_{h_i}^8}$$

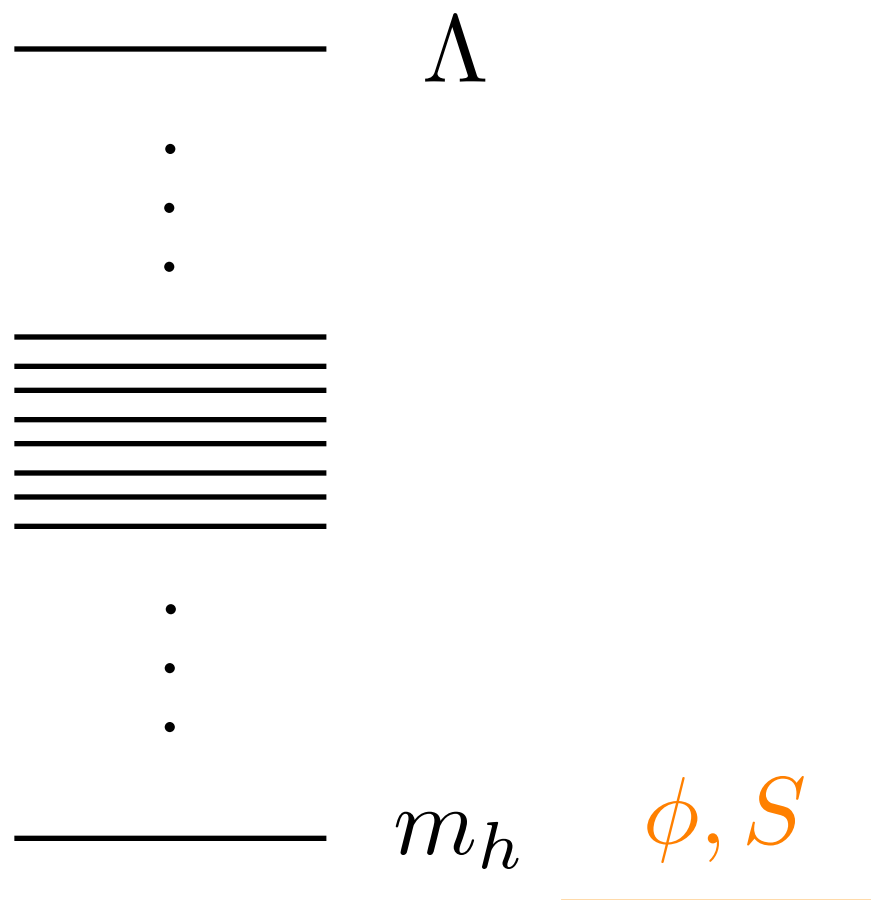
$$m_h^2 < 0$$



$$\Gamma \sim \text{const.} \quad v_i < M_V$$

$$\Gamma \sim \frac{1}{m_{h_i}^8} \quad v_i > M_V$$

OUR MU PROBLEM

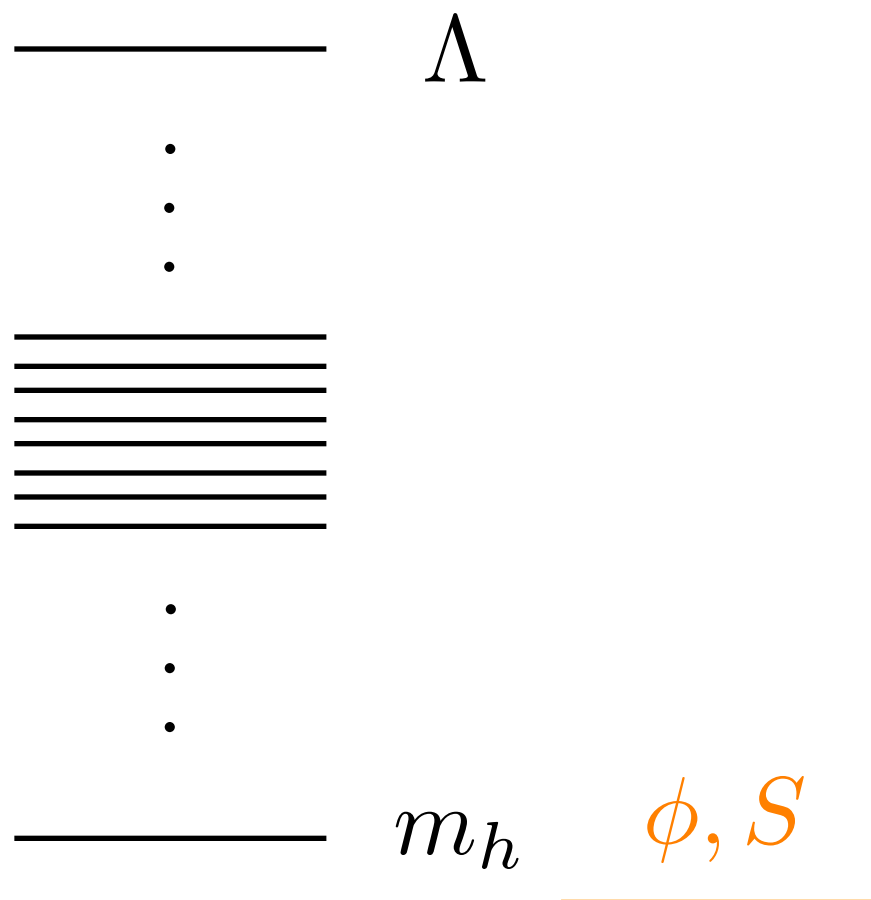


$$(\partial\phi)^2 + \Lambda^4 V\left(\frac{\phi}{\Lambda\sqrt{N}}\right)$$

$$\bar{S}\sigma \cdot \partial S + \frac{\Lambda}{\sqrt{N}} S S^c + \dots$$

- Technically Natural
- Consistent at Large N

OUR MU PROBLEM



$$\phi_1, \dots, \phi_N$$

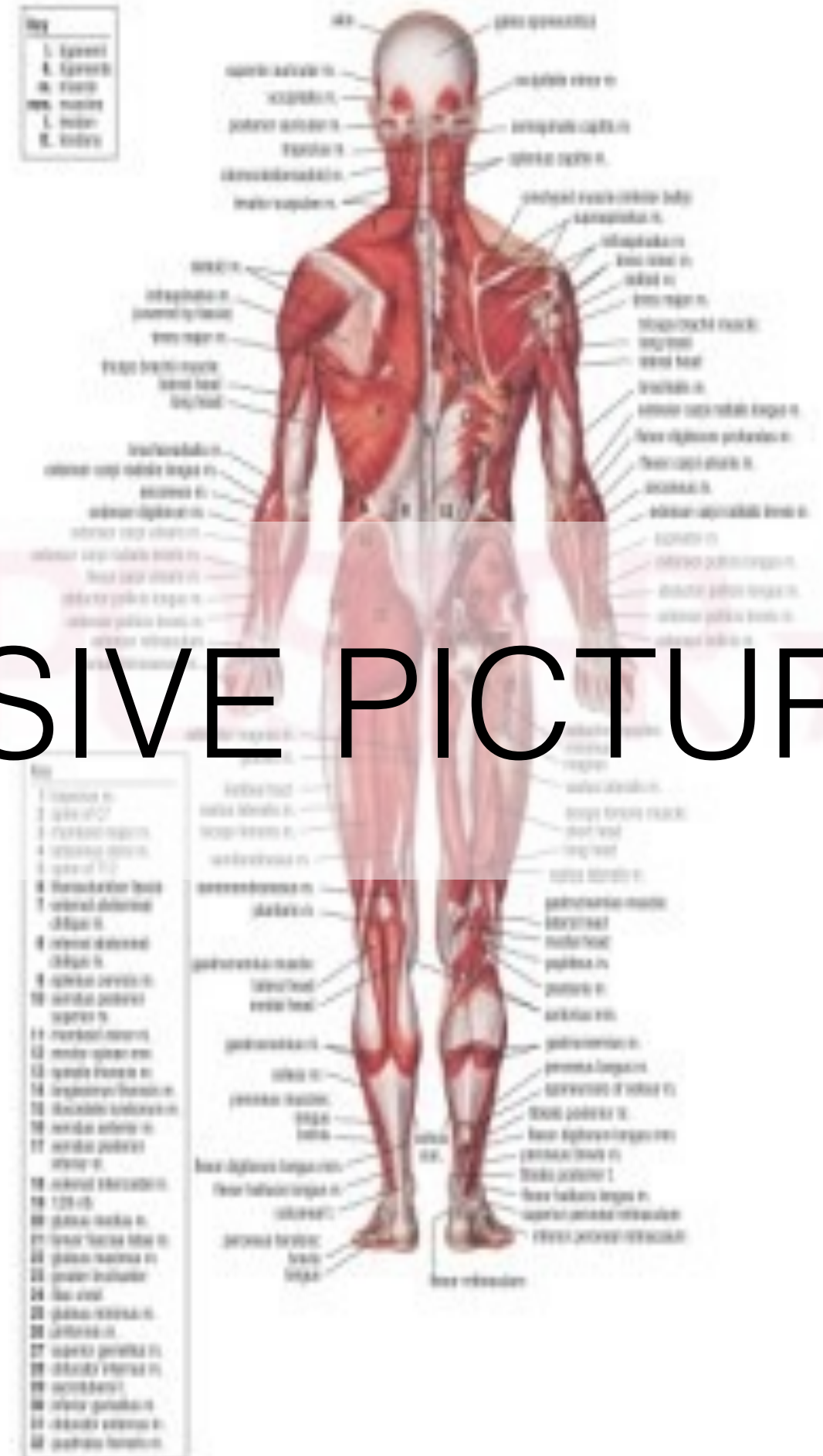
$$\lambda_{ijkl} \phi_i \phi_j \phi_k \phi_l$$

$$\Gamma_{\phi \rightarrow 3\phi} \gtrsim \Gamma_{\phi \rightarrow \text{SM}}$$

MUSCULAR SYSTEM (ANTERIOR VIEW)



MUSCULAR SYSTEM (POSTERIOR VIEW)



A COMPREHENSIVE PICTURE

OUTLINE

- COSMOLOGY
 - Neff
 - RELIC NEUTRINOS
 - BARYOGENESIS
- STRONG CP PROBLEM
- DARK MATTER
- COLLIDERS

COSMOLOGICAL SIGNALS

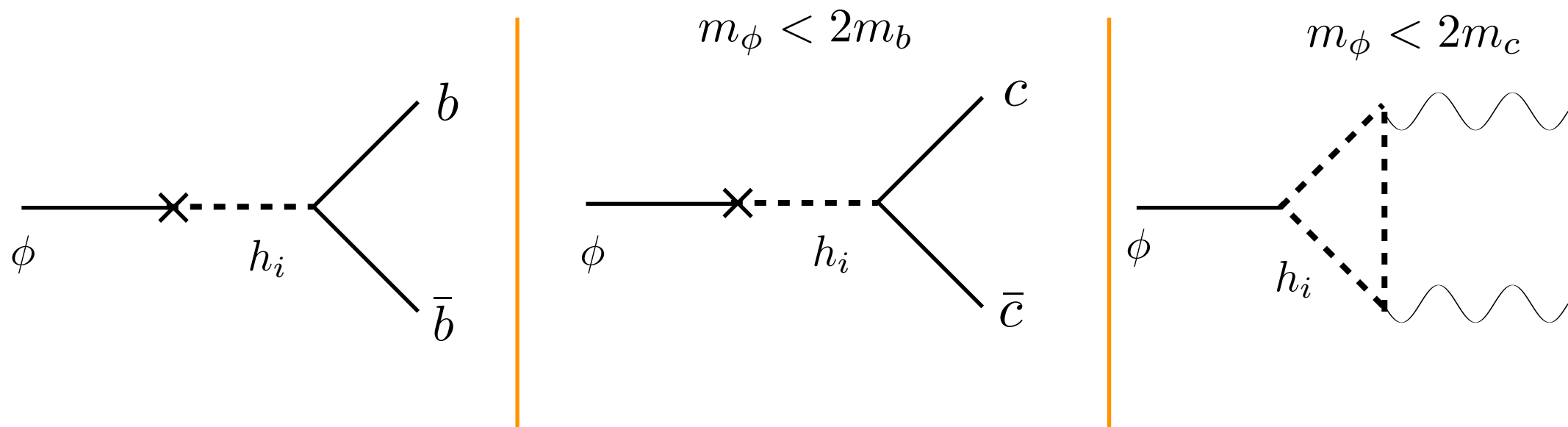
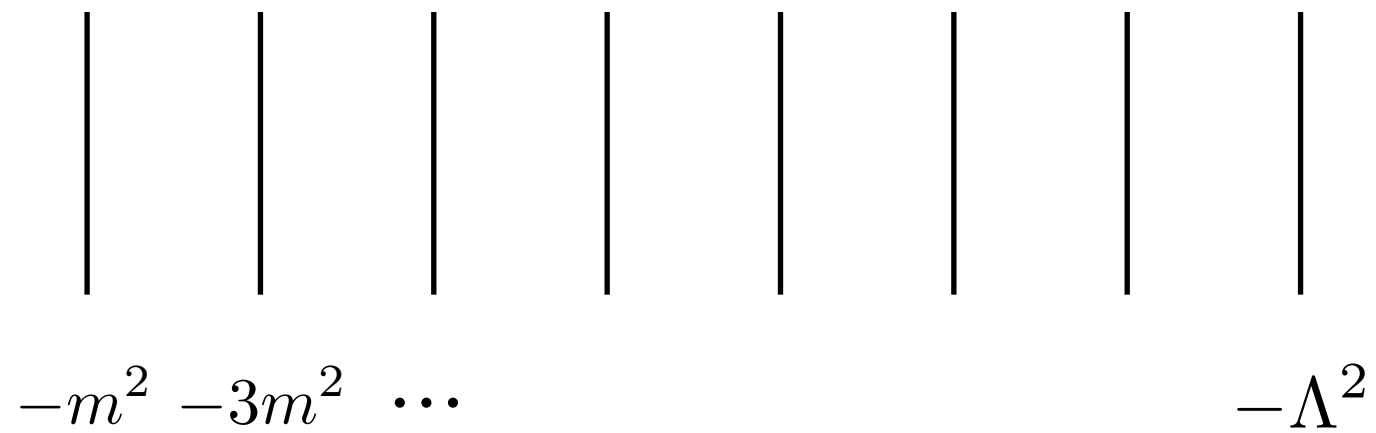
$$\Delta N_{\text{eff}} = \frac{\sum_{i \neq \text{SM}} \rho_i}{\rho_{\nu}^{\text{SM}}} \sim \frac{\sum_{i \neq \text{SM}} \Gamma_i}{\Gamma_{\text{SM}}} \sim \log N$$

$$\Omega_{\nu} h^2 \approx \begin{cases} \frac{\sum_{i \neq \text{SM}} v_i \rho_i^{3/4}}{v \rho_{\text{SM}}^{3/4}} \sim N^{3/4} & \text{Dirac} \\ \frac{\sum_{i \neq \text{SM}} v_i^2 \rho_i^{3/4}}{v^2 \rho_{\text{SM}}^{3/4}} \sim N^{5/4} & \text{Majorana} \end{cases}$$

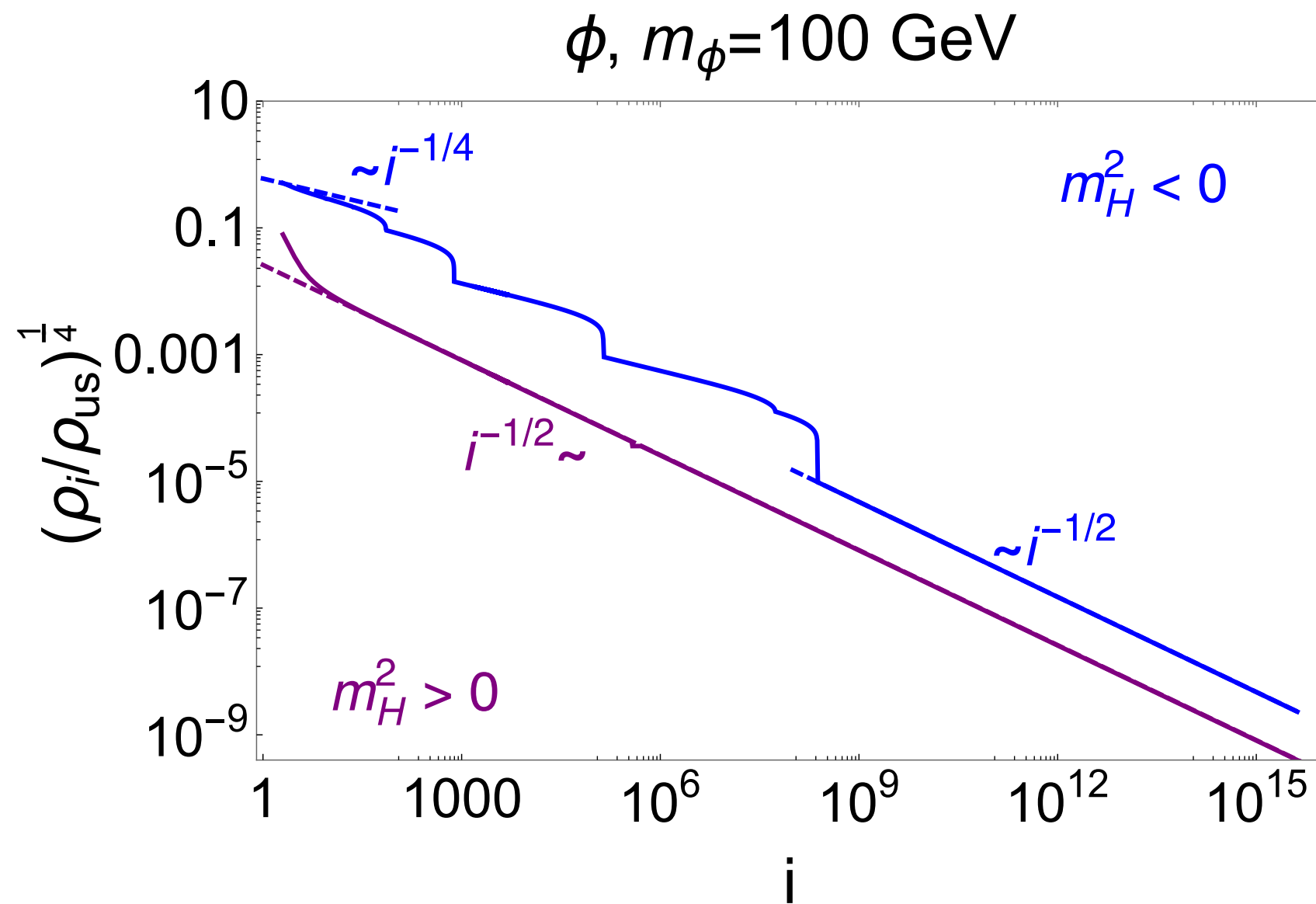
THE FINE STRUCTURE OF THE MODEL

- FROM THE PREVIOUS ESTIMATE WE SEEM TO BE ALREADY IN TENSION WITH EXPERIMENT BUT
 - THRESHOLDS
 - 2 vs 3 BODY DECAYS
 - FINE STRUCTURE AT THE BOTTOM OF THE SPECTRUM

THRESHOLDS

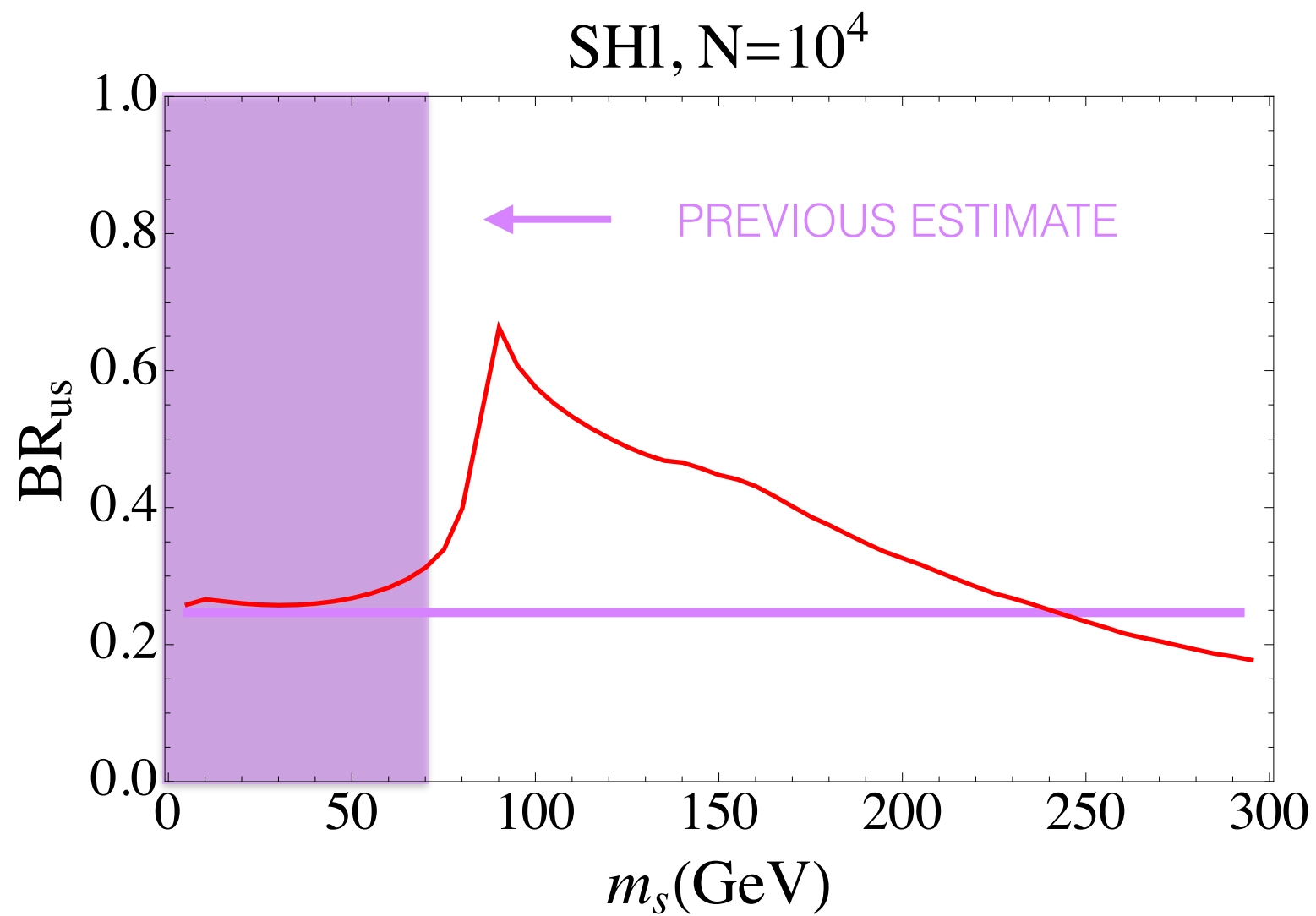


THRESHOLDS

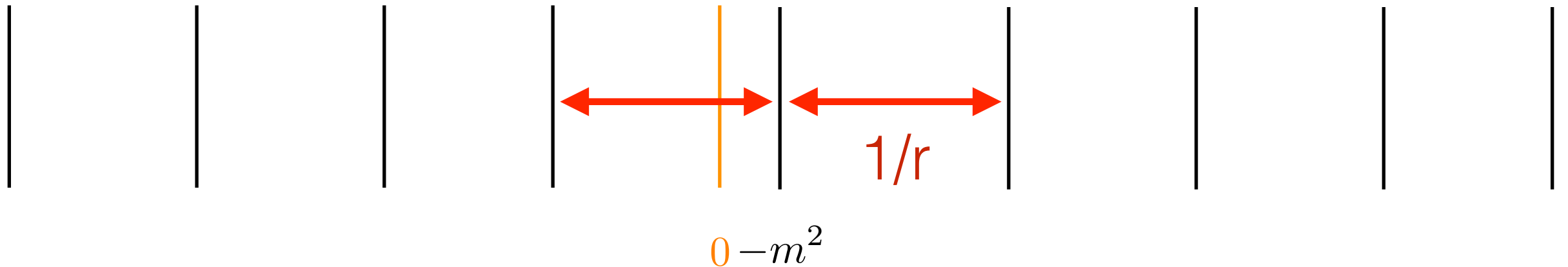
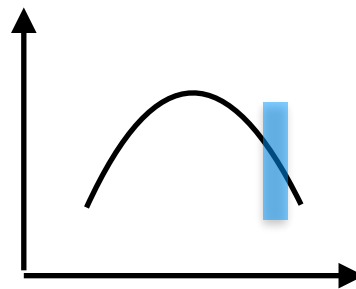


$$i \sim \sqrt{\frac{v_i}{v}}$$

2 vs 3 BODY DECAYS

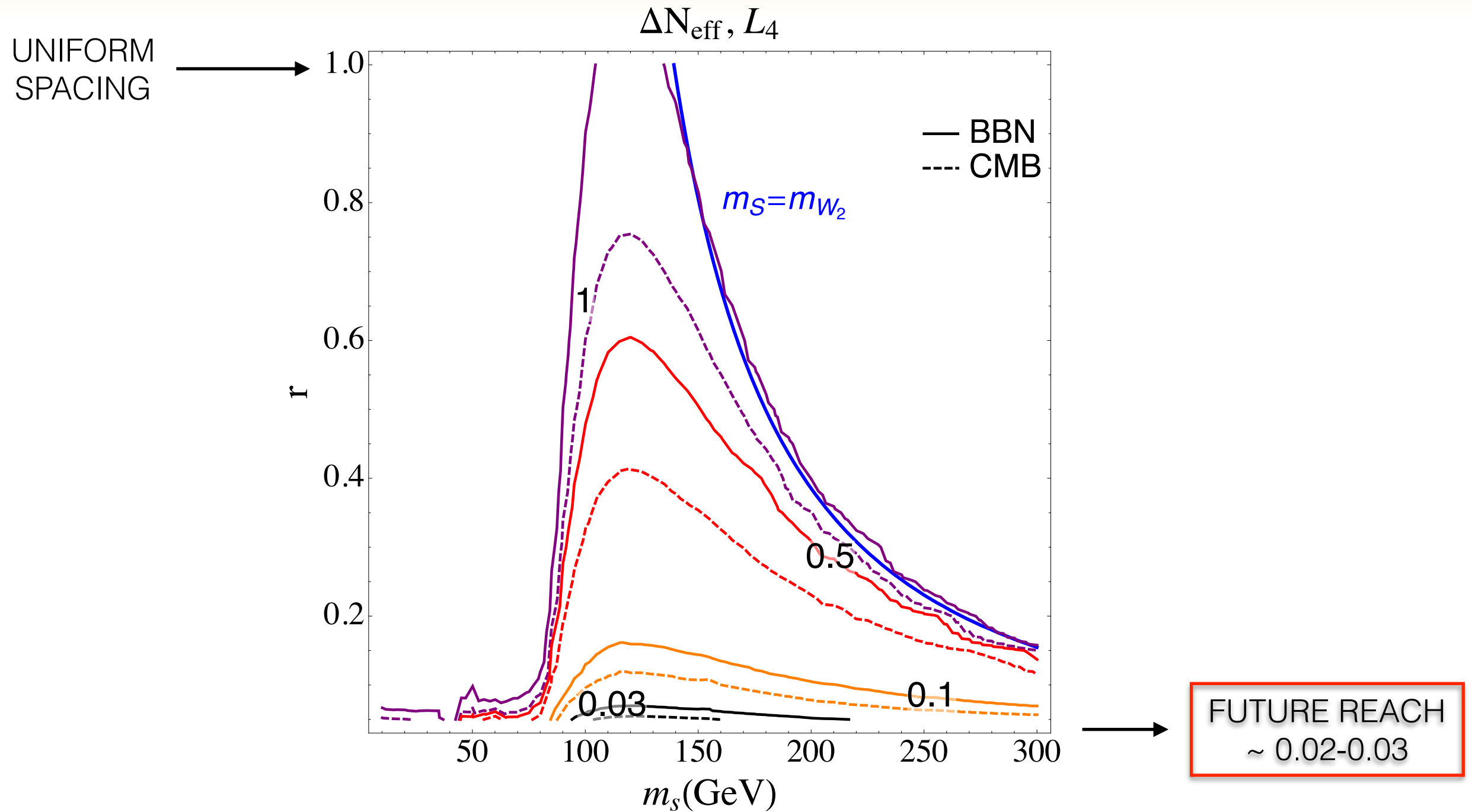


THE BOTTOM OF THE SPECTRUM

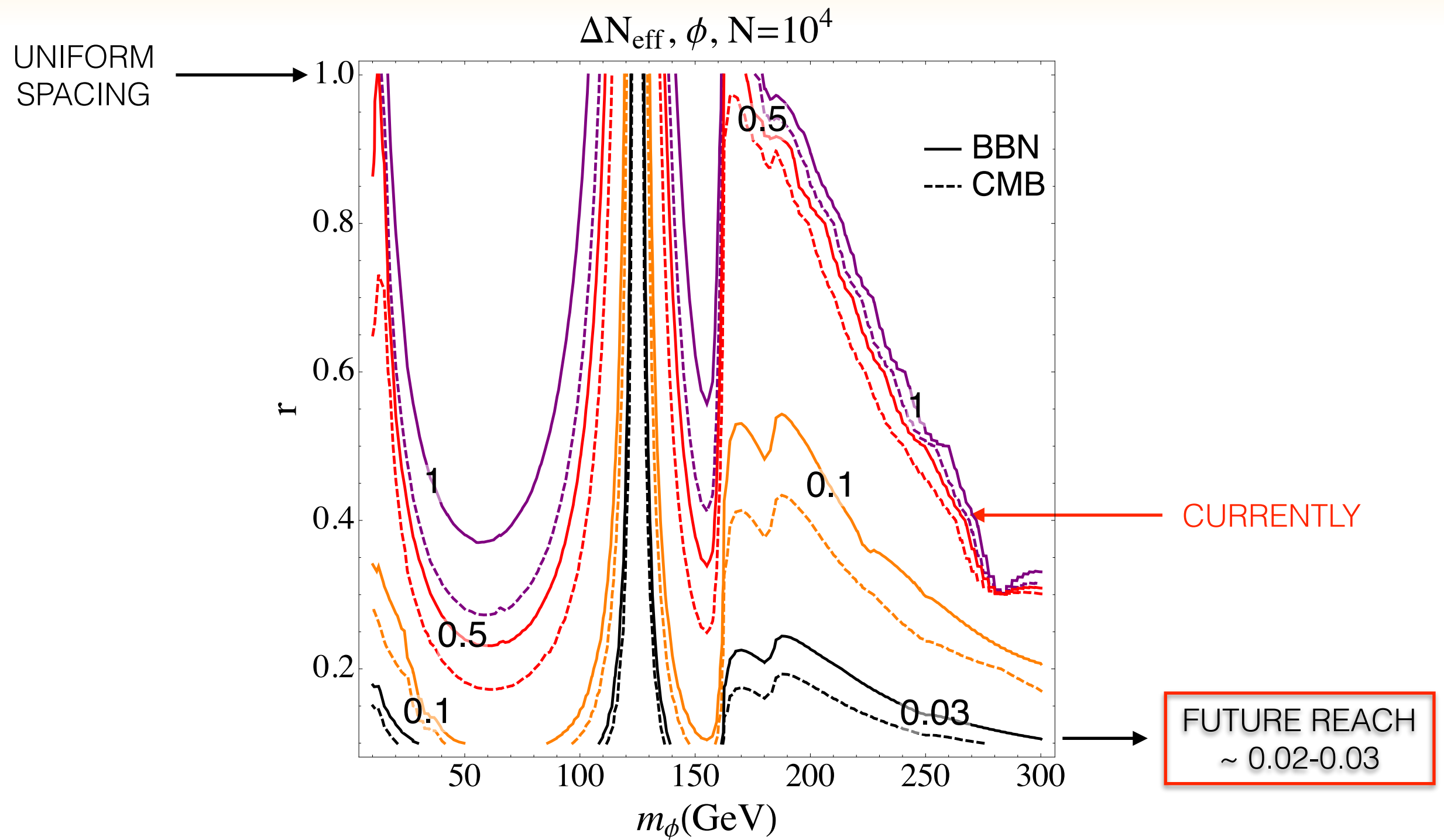


$$r \equiv \frac{2m_h^2}{\Delta m_h^2}$$

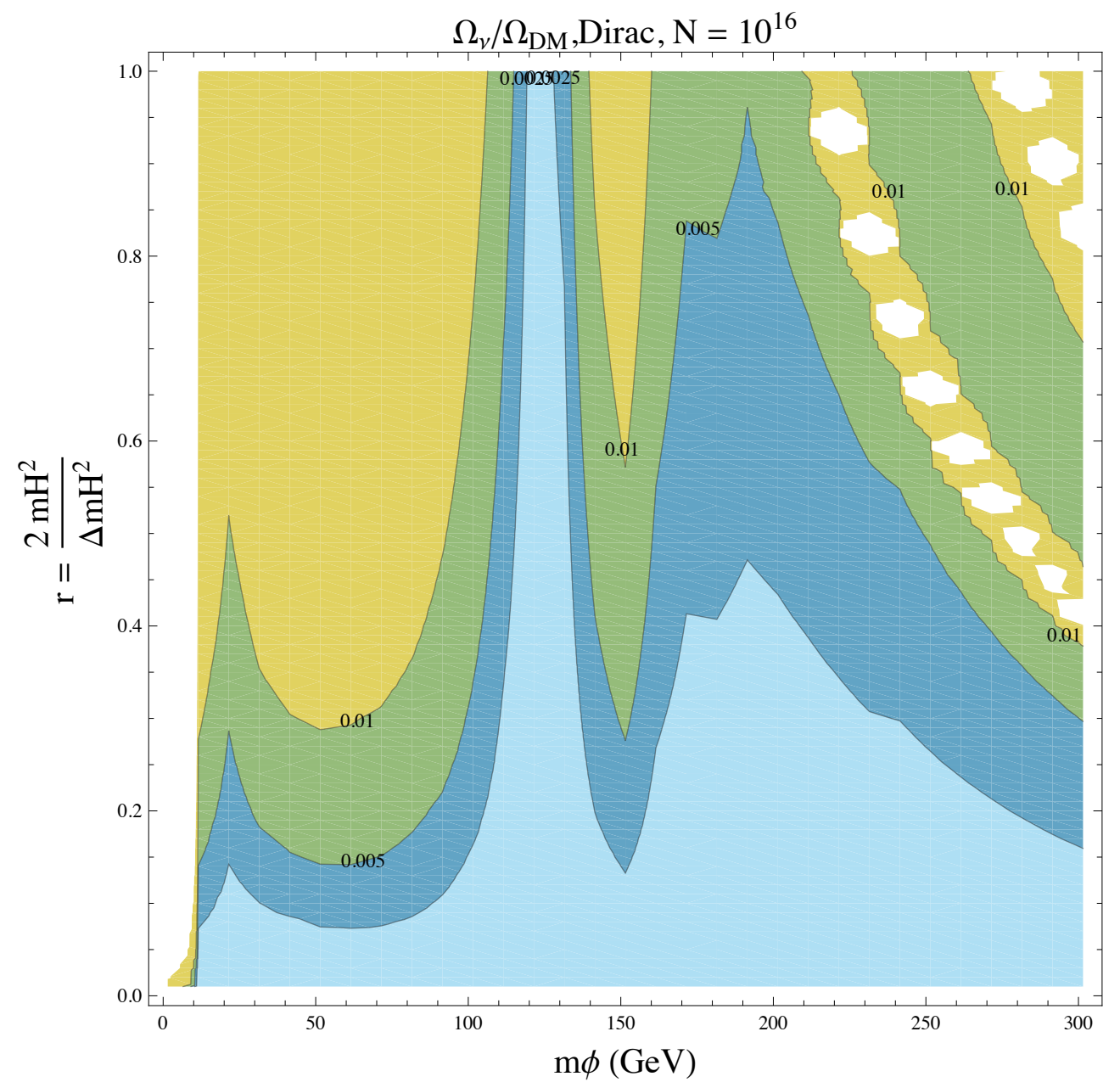
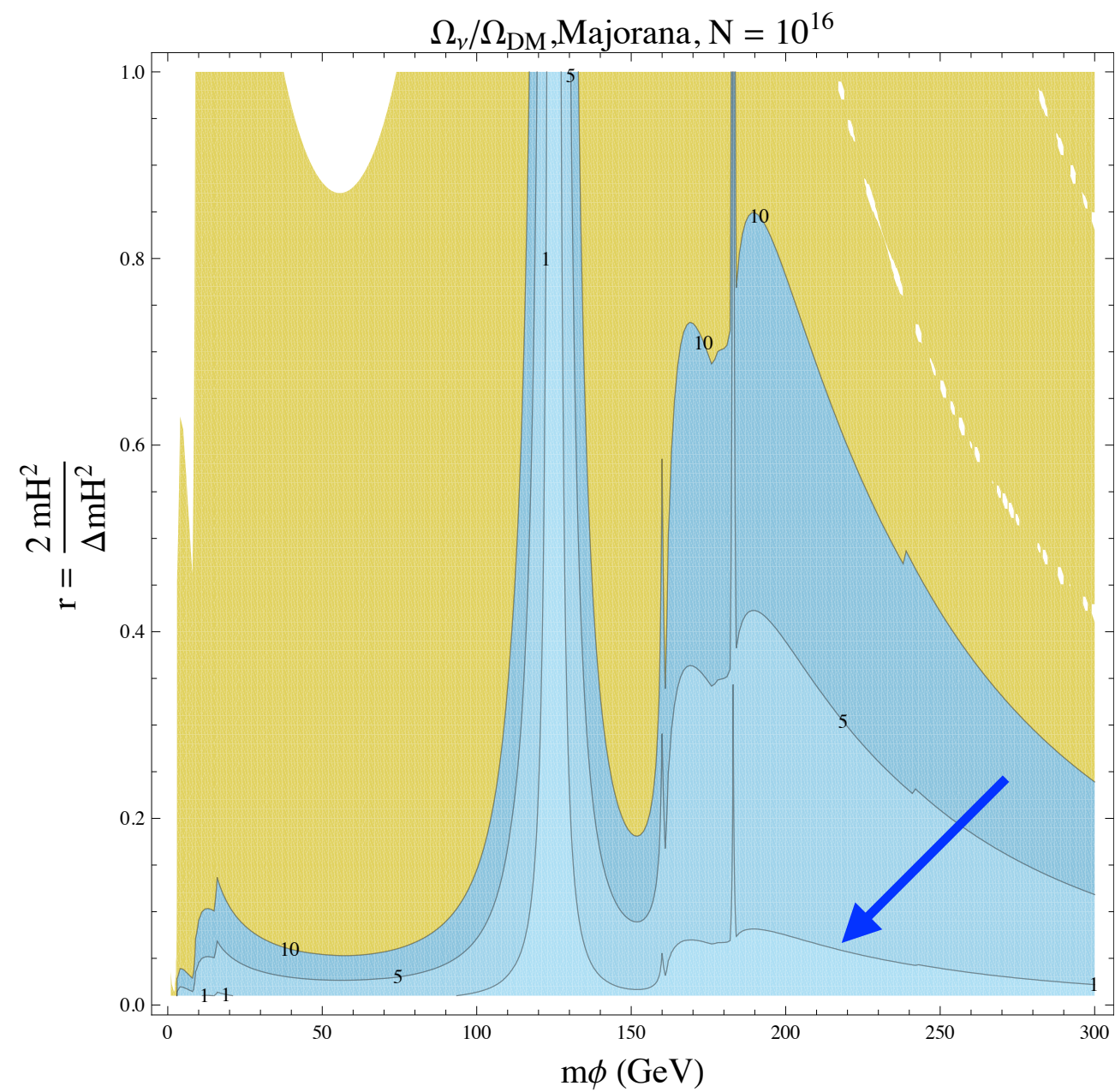
N_{eff}



N_{eff}



NEUTRINO OVERCLOSURE

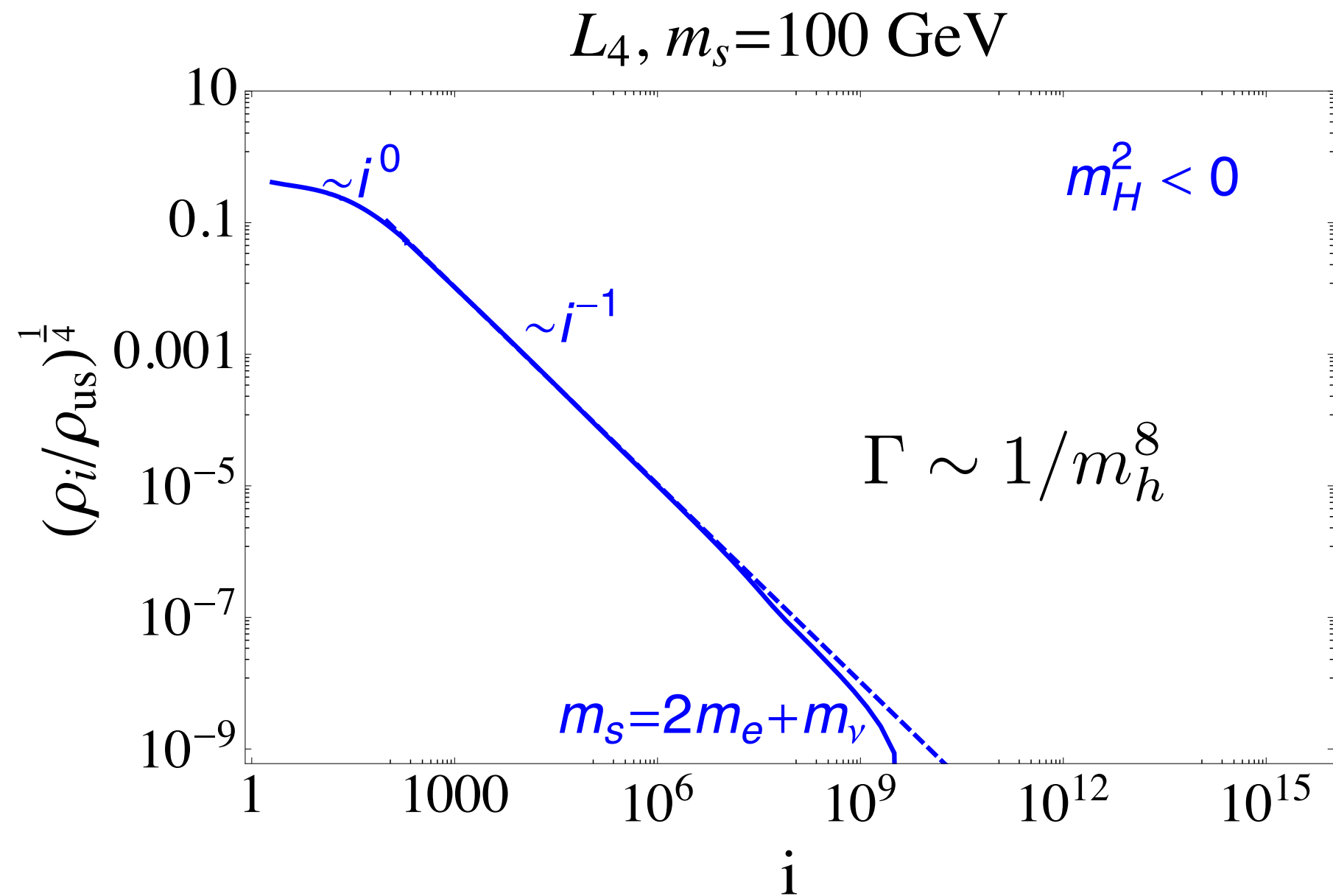


ELECTRON OVERCLOSURE

$$v_i \gg v \quad \longrightarrow \quad \begin{aligned} m_{e_i} &\gg m_e \\ \sigma_{e_i} &\sim \frac{\alpha^2}{m_{e_i}^2} \ll \sigma_e \end{aligned}$$

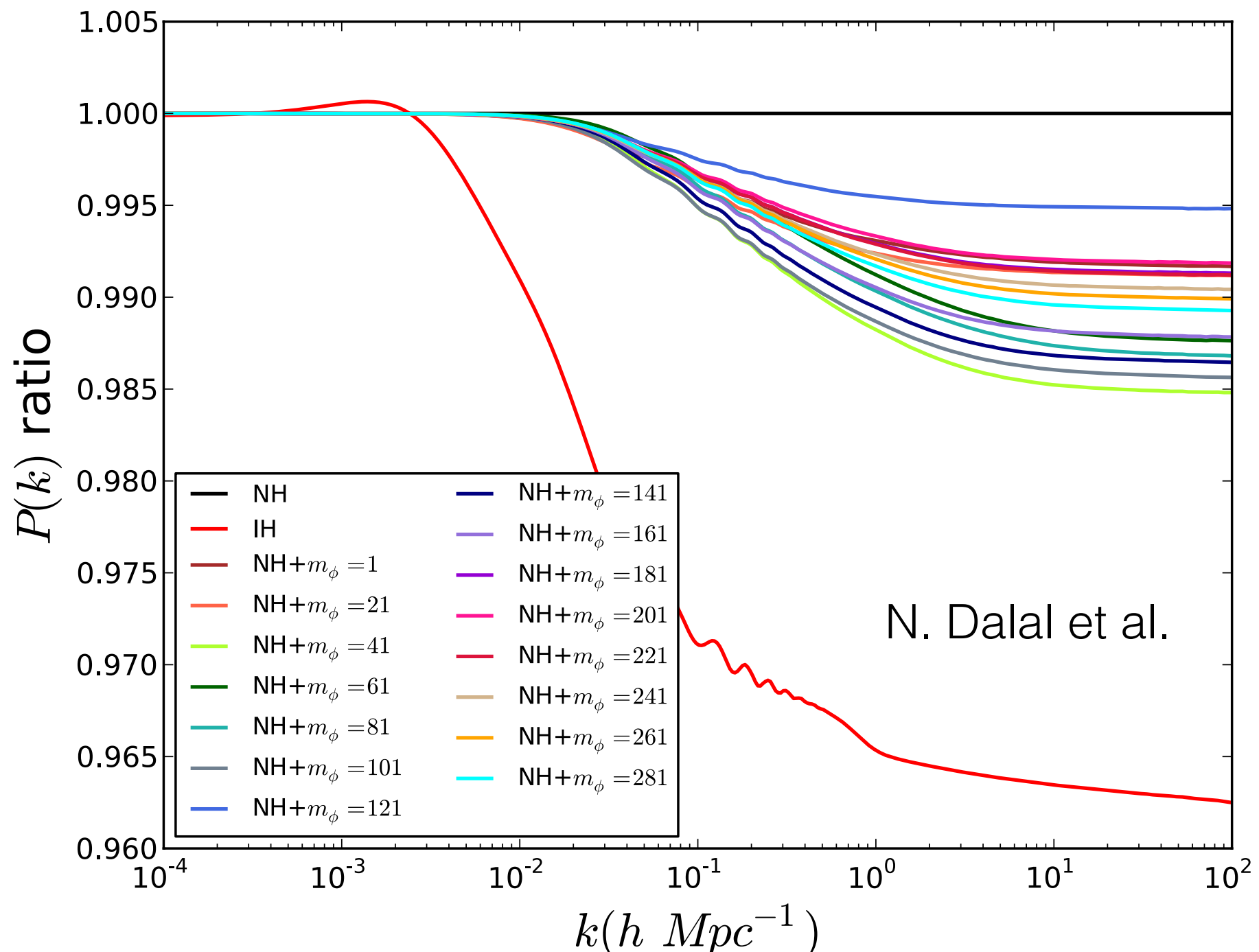
$$N_\phi \lesssim 10^5$$

OVERCLOSURE IN L4



$$N_{L_4} \rightarrow 10^{16}$$

NEUTRINO SIGNAL



ONE AXION

- N COPIES = 1 STRONG CP PHASE
 - WITH SMALL CORRECTIONS FROM THE SOFT BREAKING OF THE Z_N SYMMETRY
- A SINGLE AXION SOLVES ALL CP PROBLEMS

$$m_a = \frac{1}{f} \sum m_{\pi_i} f_{\pi_i} \frac{\sqrt{m_{u_i} m_{d_i}}}{m_{u_i} + m_{d_i}} \sim N^{3/4} \frac{\Lambda_{QCD}^2}{f}$$

DARK MATTER

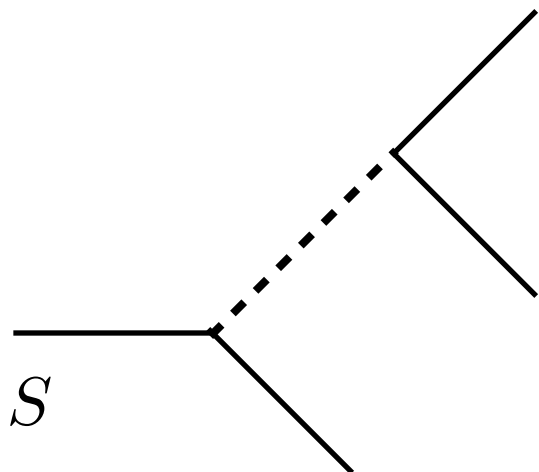
- NEUTRINOS FROM THE OTHER SECTORS
- NEUTRALINOS OF HIGH SCALE SUSY
- SUPERSYMMETRIC PARTNER OF THE REHEATON
- AXION
- ...

BARYOGENESIS

- NOT COMPLETELY TRIVIAL
 - MAXIMAL REHEATING TEMPERATURE
 - OVERCLOSURE FROM PROTONS IN THE OTHER SECTORS

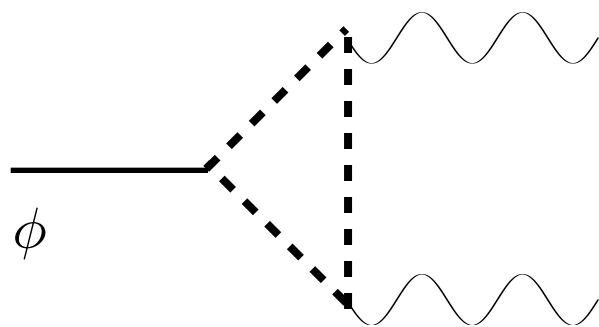
BARYOGENESIS

$$m_h \sim T^2$$



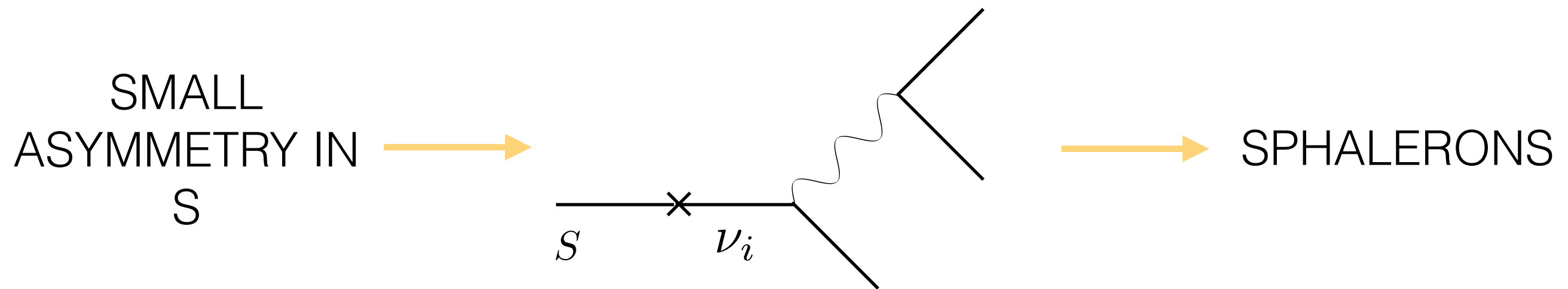
$$\sim \frac{1}{T^4}$$

$$T_{RH} \lesssim m_{h2} \lesssim 200 \text{ GeV}$$



$$\sim \frac{a^2}{T^4}$$

BARYOGENESIS



ONLY A FEW SECTORS GET A
BARYON RELIC ABUNDANCE

NNATURLANESS AT COLLIDERS

- IN PRINCIPLE EXCITING SIGNATURES
 - RARE HIGGS AND Z DECAYS
 - DIRECT PRODUCTION OF THE REHEATON
 - ITS INVISIBLE BR WOULD INCREASE WITH THE CM ENERGY!

NNATURLANESS AT COLLIDERS

$$T_{RH} \lesssim m_{h2} \lesssim 200 \text{ GeV} \longrightarrow \boxed{\lambda, a/m_h \lesssim 10^{-5} - 10^{-6}}$$

- NO SIGNALS AT A 100 TeV pp COLLIDER OR TLEP

LHC RUN II

WHAT IF THE LHC FINDS SUSY?

LHC RUN II

STEP 1



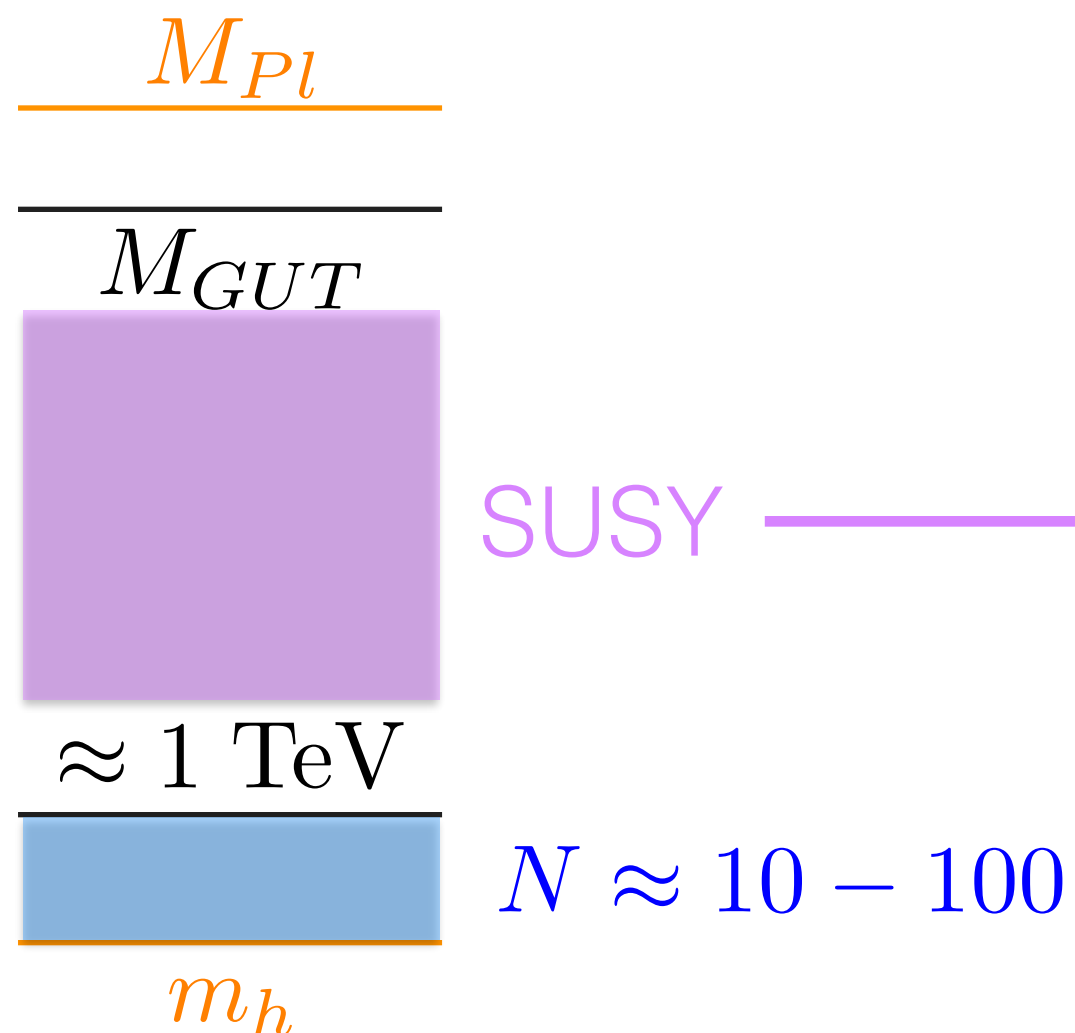
LHC RUN II

STEP 2



IF EWSB IS ESSENTIALLY NATURAL, 1-10% TUNING IS
HARD TO UNDERSTAND

SUSY AT THE LHC



- Unification
- Dark Matter
- Flavor/CP signals

SUMMARY OF SIGNALS

- FUTURE CMB EXPERIMENTS
 - N_{eff}
 - NEUTRINO FRACTION OF DARK MATTER

SUMMARY OF SIGNALS

- FUTURE CMB EXPERIMENTS
 - N_{eff}
 - NEUTRINO FRACTION OF DARK MATTER
- HEAVY AXION
- SUSY AT FUTURE COLLIDERS

THE OTHER KIDS IN THE PLAYGROUND

SUSY

SOFTLY BROKEN
MEDIATED TO US
MU PROBLEM

...

RELAXION

COSMOLOGY

SMOKING
GUN
OBSERVABLES
?

NNATURALNESS

ADD and Dvali-Redi

$N \sim 10^{32}$

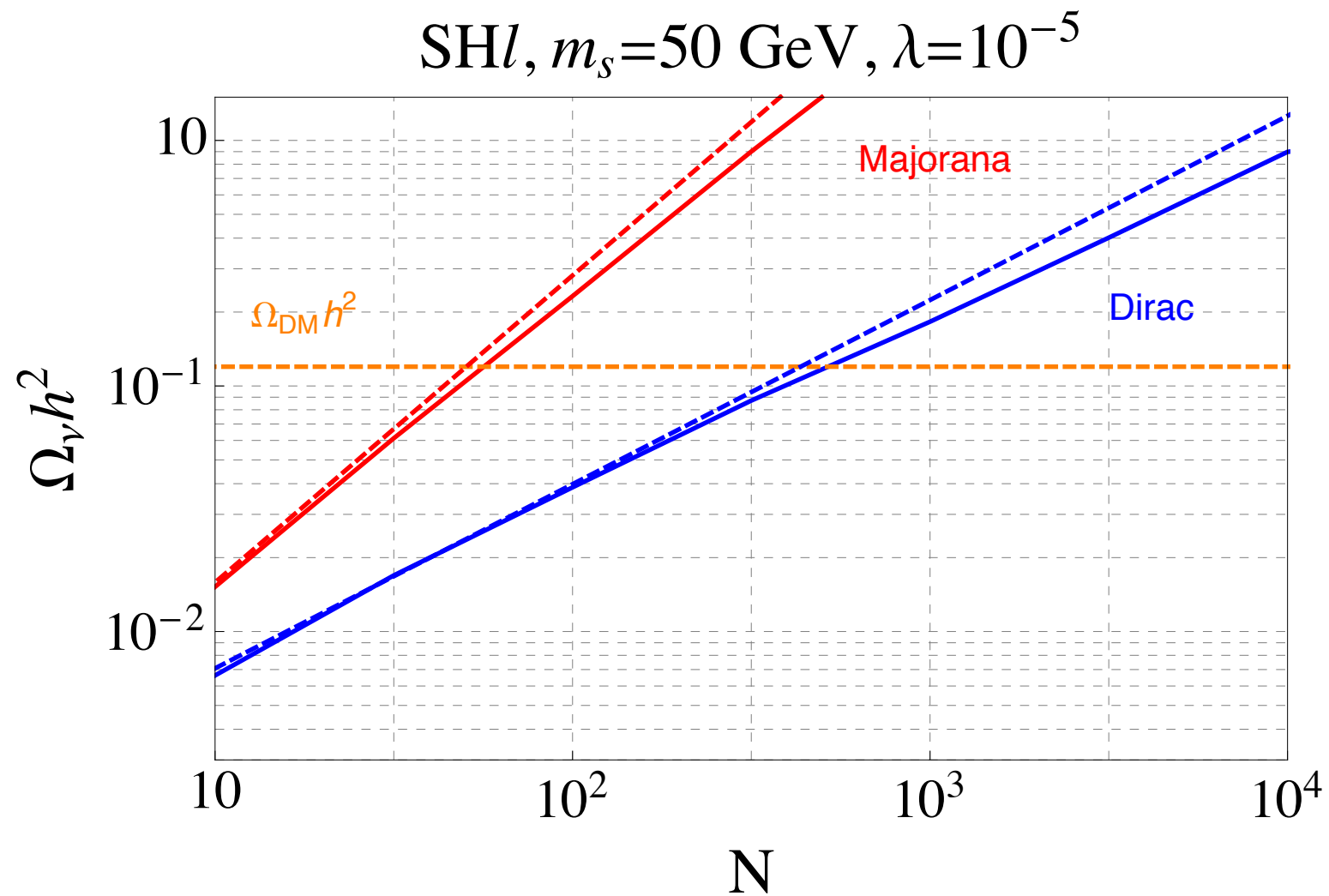
STRONG
GRAVITY
AT
THE LHC

CONCLUSION

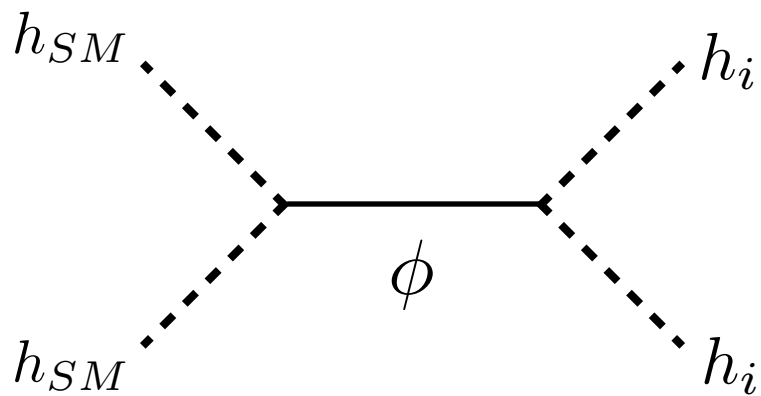
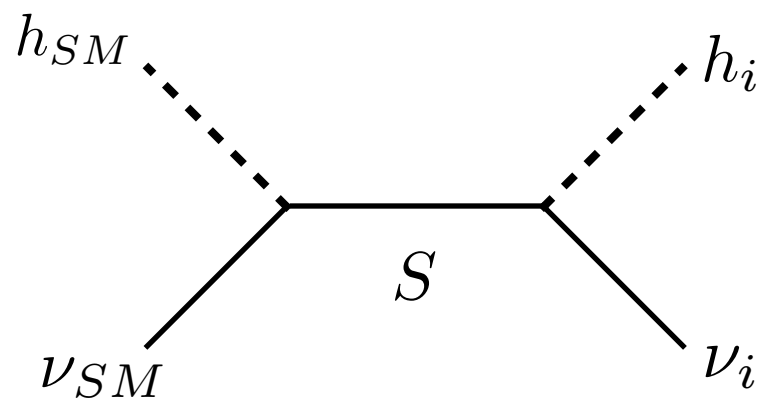
- THE LARGE NUMBER OF COPIES IS HARD TO ACCEPT
- THE MECHANISM WORKS FOR REASONS THAT ARE CLOSELY RELATED TO THE HIERARCHY PROBLEM
- MANY EXPERIMENTS (USUALLY UNRELATED TO THE HIERARCHY PROBLEM) TO LOOK FORWARD TO
- PLENTY OF INTERESTING PHYSICS (STRUCTURE FORMATION, BARYOGENESIS, “MU PROBLEM”, ...) TO THINK ABOUT

BACKUP

NEUTRINO OVERCLOSURE



BOUNDS ON THE REHEAT TEMPERATURES



$$T_{RH} \lesssim 10 \text{ TeV}$$

AXION

