Big questions in particle physics

KFCC brainstorming workshop

Jeonghyeon Song, 2021. 11. 13.

Questions
that made our hearts pounding

1. **Dark matter**
2. **Baryogenesis & Strong EW phase transition**
3. **Neutrino mass**
4. **Flavor physics**
5. **Stability of the Higgs vacuum**

1. Dark Matter

Too familiar: WIMP

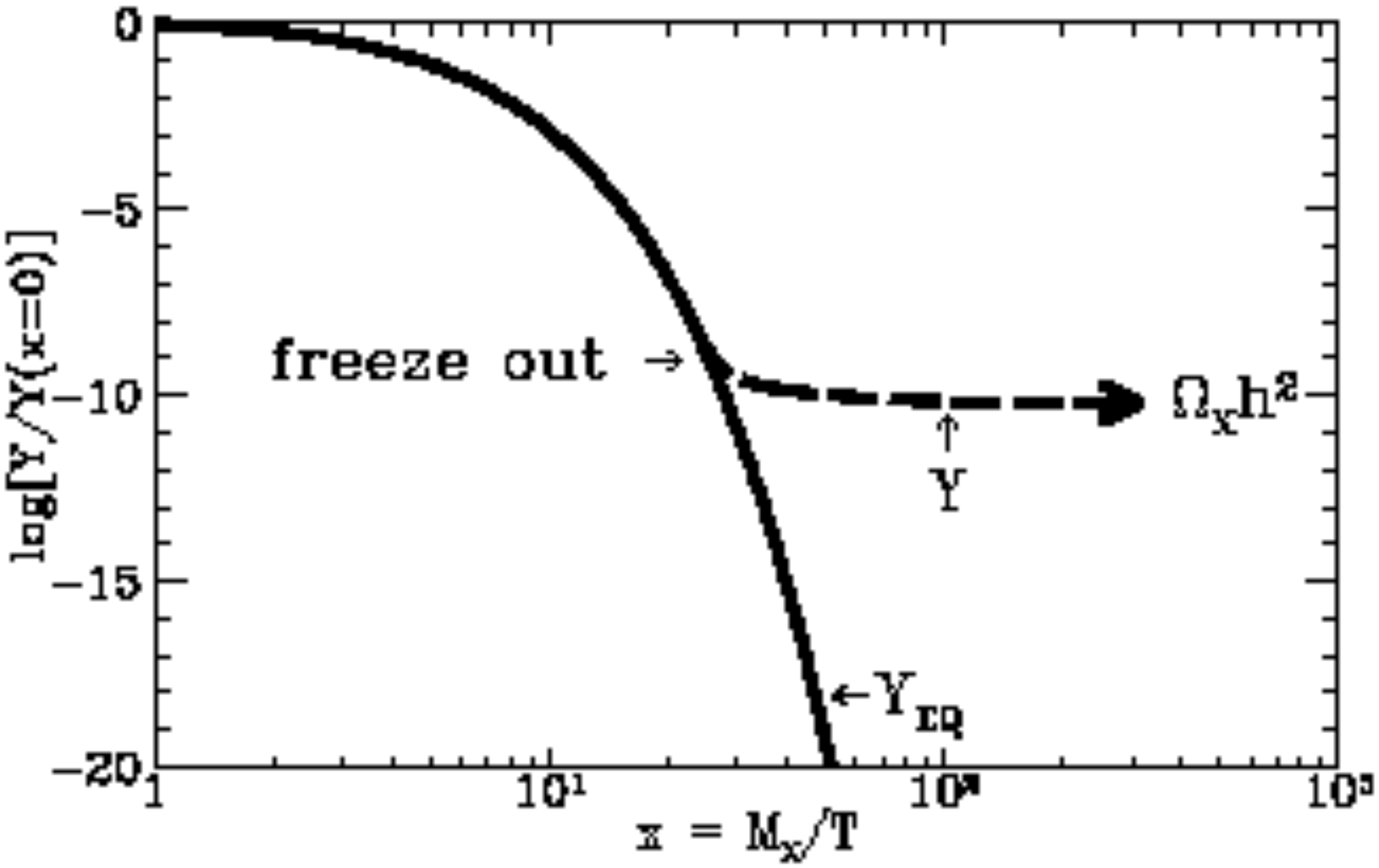
- The CMB observations by the Planck satellite

$$\Omega_{\rm DM}h^2 = 0.120 \pm 0.001,$$

- DM χ in thermal equilibrium with the SM particles at high T
- As the Universe cools down, χ's are decoupled.
- To avoid overclose, the relic must be cold, i.e., heavy with respect to the temperature where the decoupling occurs.
- The freeze-out genesis of χ's

1. Dark Matter

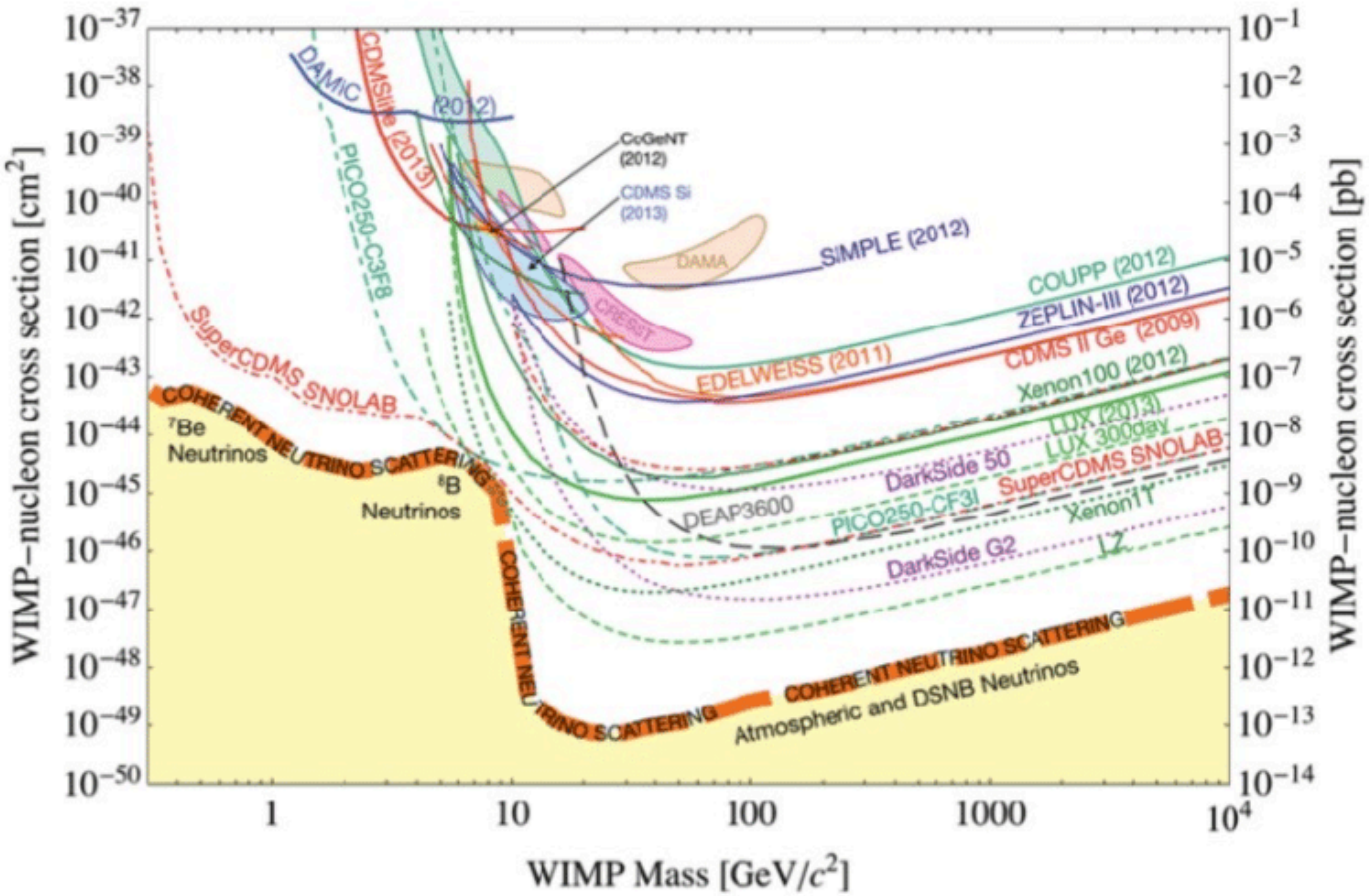
WIMP: initially populated



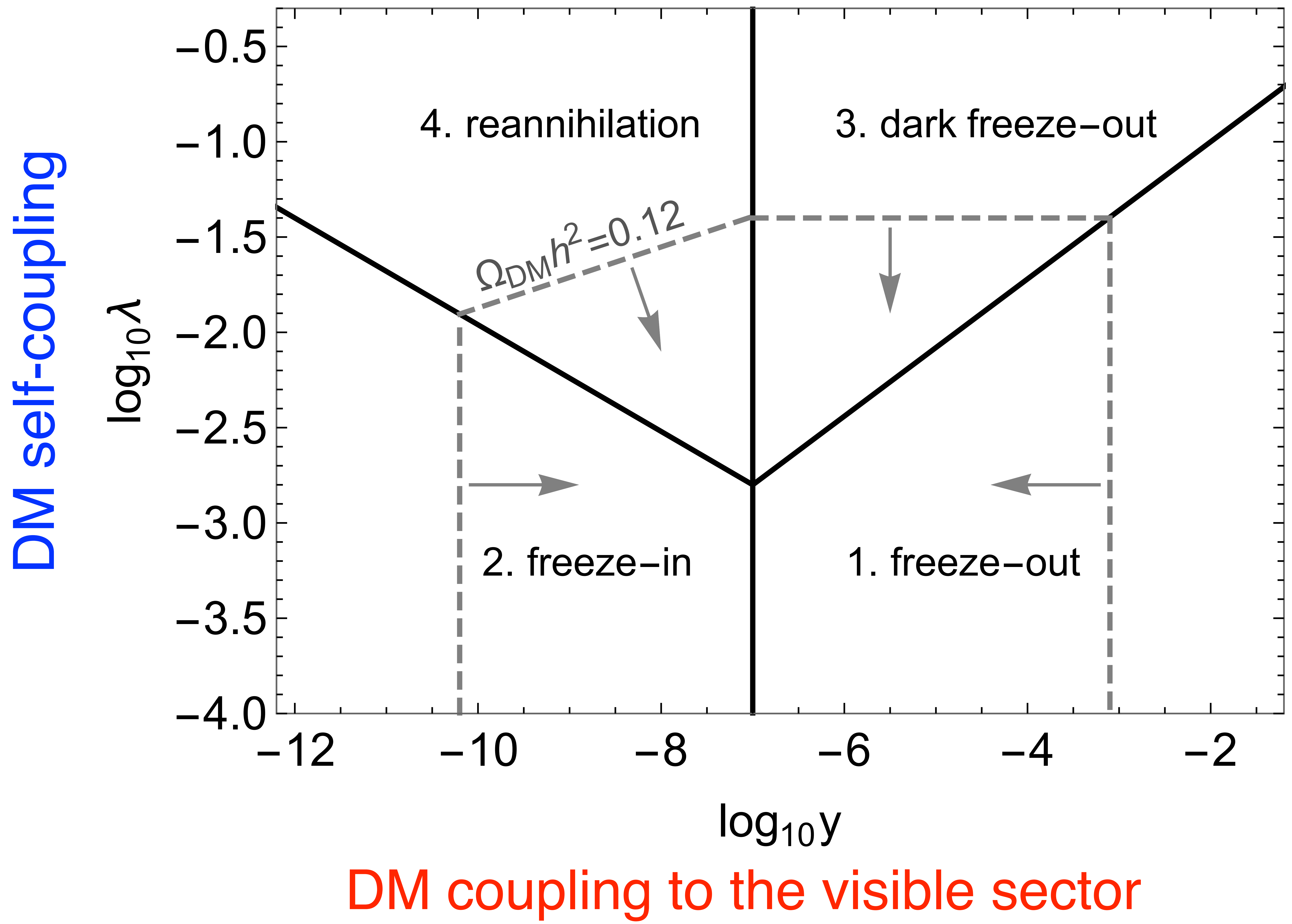
WIMP miracle

$$g^2 \sim \frac{m}{10\,\mathrm{TeV}}$$

Dedicated searches for WIMP, but in vain



Other Dark Matter Genesis



Freeze-in genesis of Dark matter:
Feebly Interacting Massive Particles

- DM interacts with the SM so weakly that it cannot come into equilibrium
  ⇒ Feebly interaction
  ⇒ g below 10^(-7)
- The population of χ is initially zero, but can be produced by the decays of the heat bath particles

FIMP models

- Moduli with weak scale supersymmetry
- Higgs portal model
- Additional U(1) with kinetic mixing

Simplest FIMP: Higgs portal

- Boltzmann equation for the DM number density

$$\frac{dn_\chi}{dt} + 3Hn_\chi = 2\Gamma_{h\to\chi\chi}\frac{K_1(x)}{K_2(x)}n_h^{\rm eq},$$

- Higgs decay rate into DM's

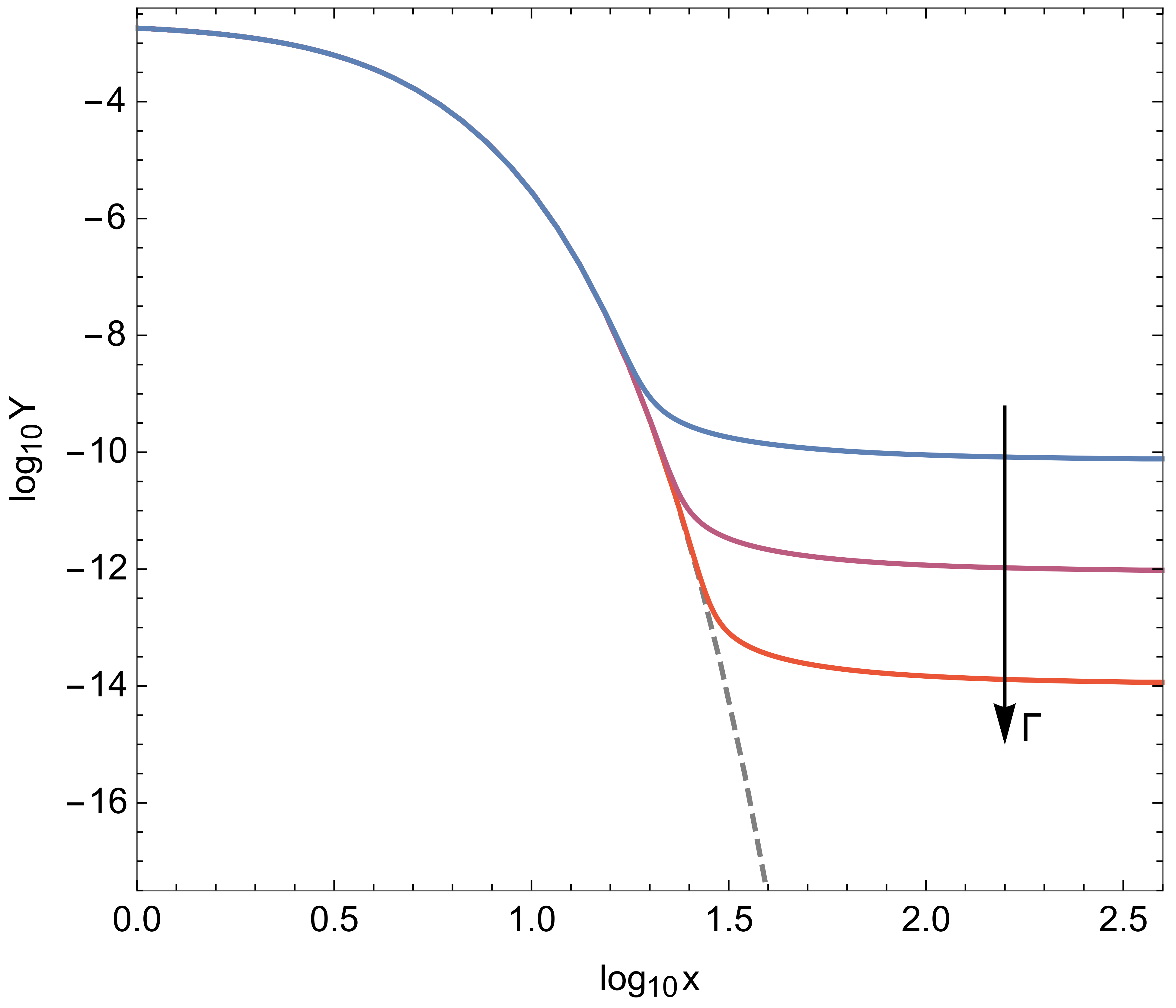
$$\Gamma_{h\to\chi\chi} \simeq y^2 m_h/(8\pi).$$

- Required Higgs coupling

$$y \simeq 10^{-12}\left(\frac{\Omega_\chi h^2}{0.12}\right)^{1/2}\left(\frac{g_*}{100}\right)^{3/4}\left(\frac{m_h}{m_\chi}\right)^{1/2}.$$

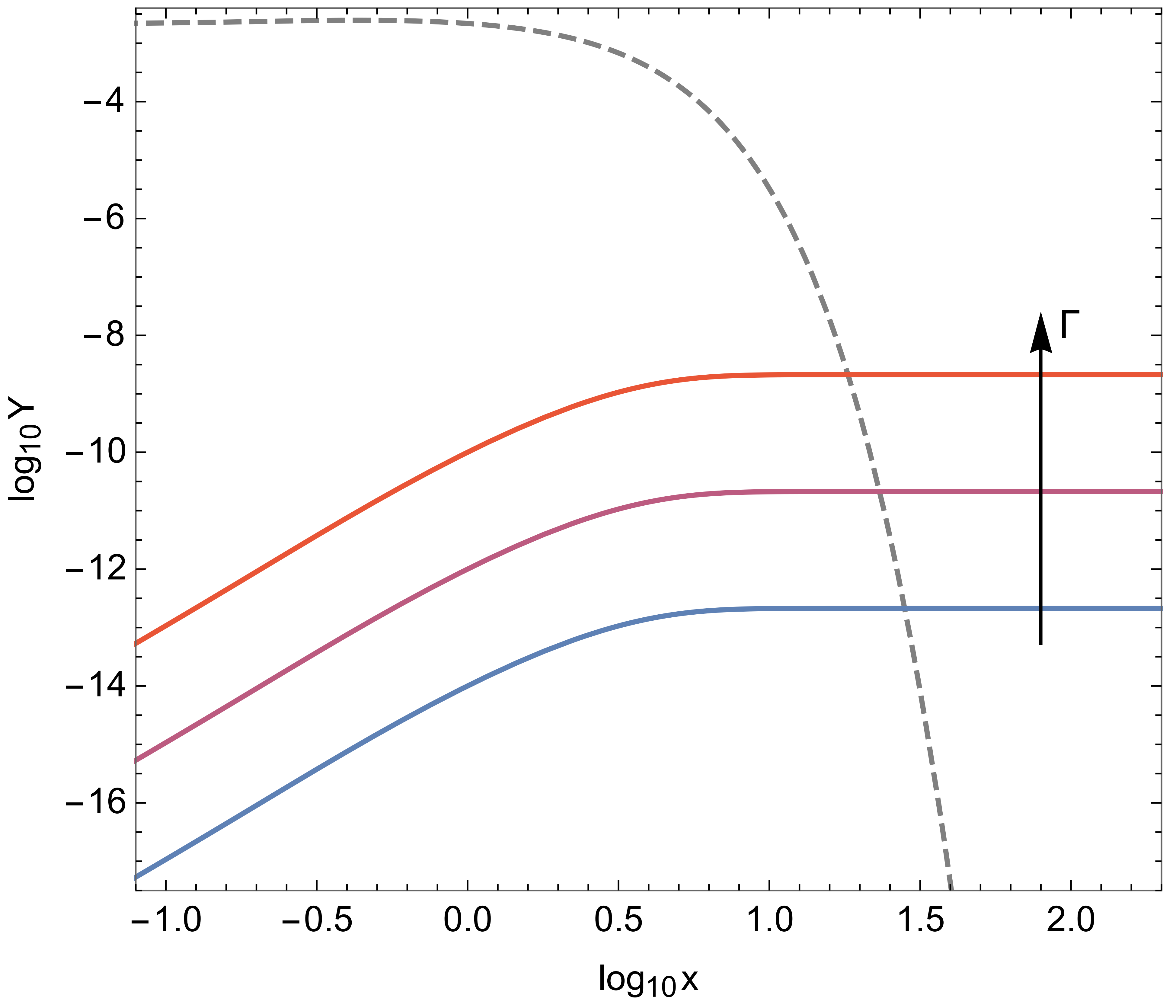
1. Dark Matter

Freeze-out



x=mDM/T

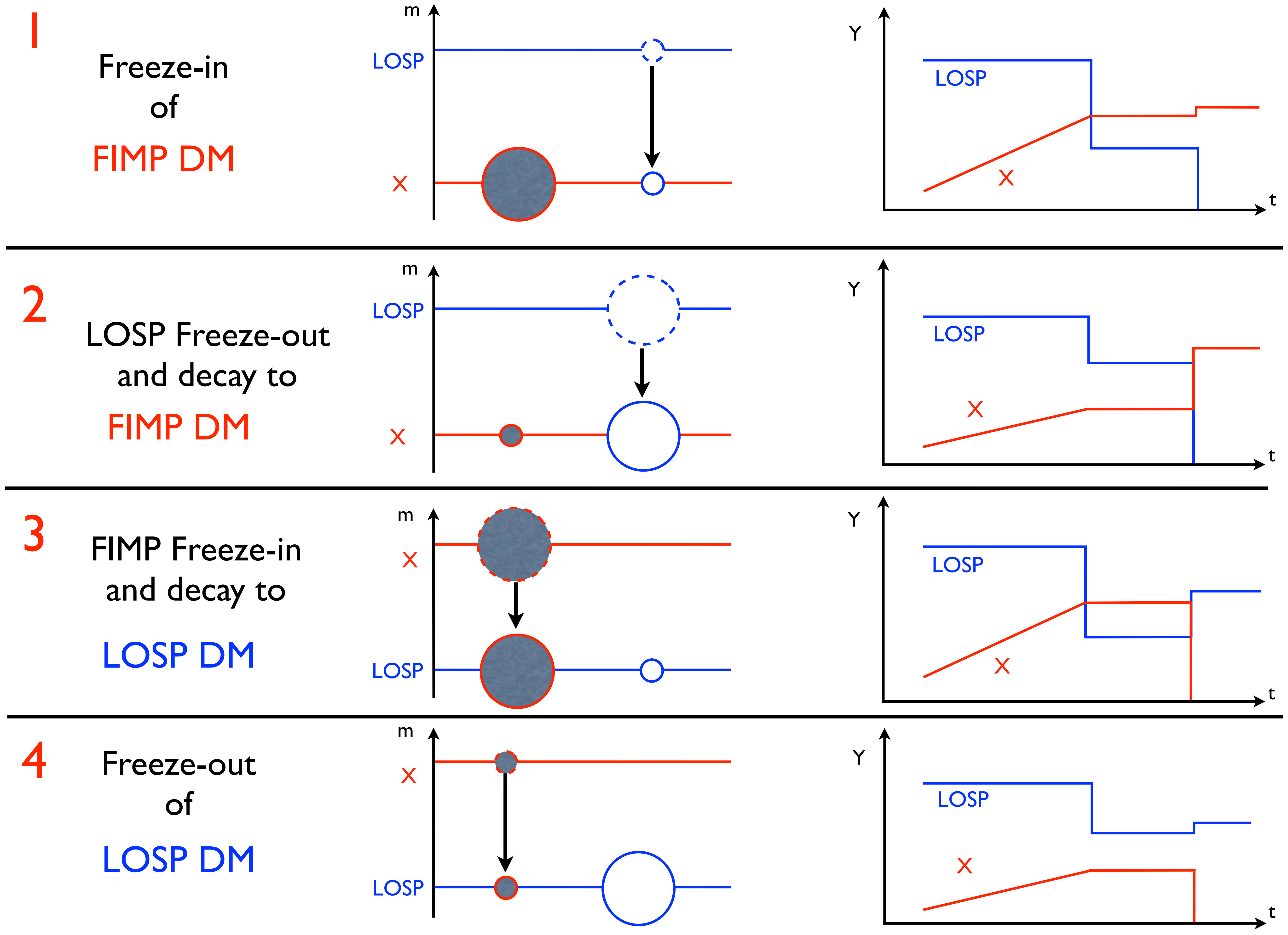
Freeze-in



x=mH/T

Y=n(DM)/s

Variety of FIMP scenarios & relic density



LHC Signatures of Freeze-In & FIMP

- Invisible Higgs decay
- If there exists LOSP heavier than FIMP, long-lived particles

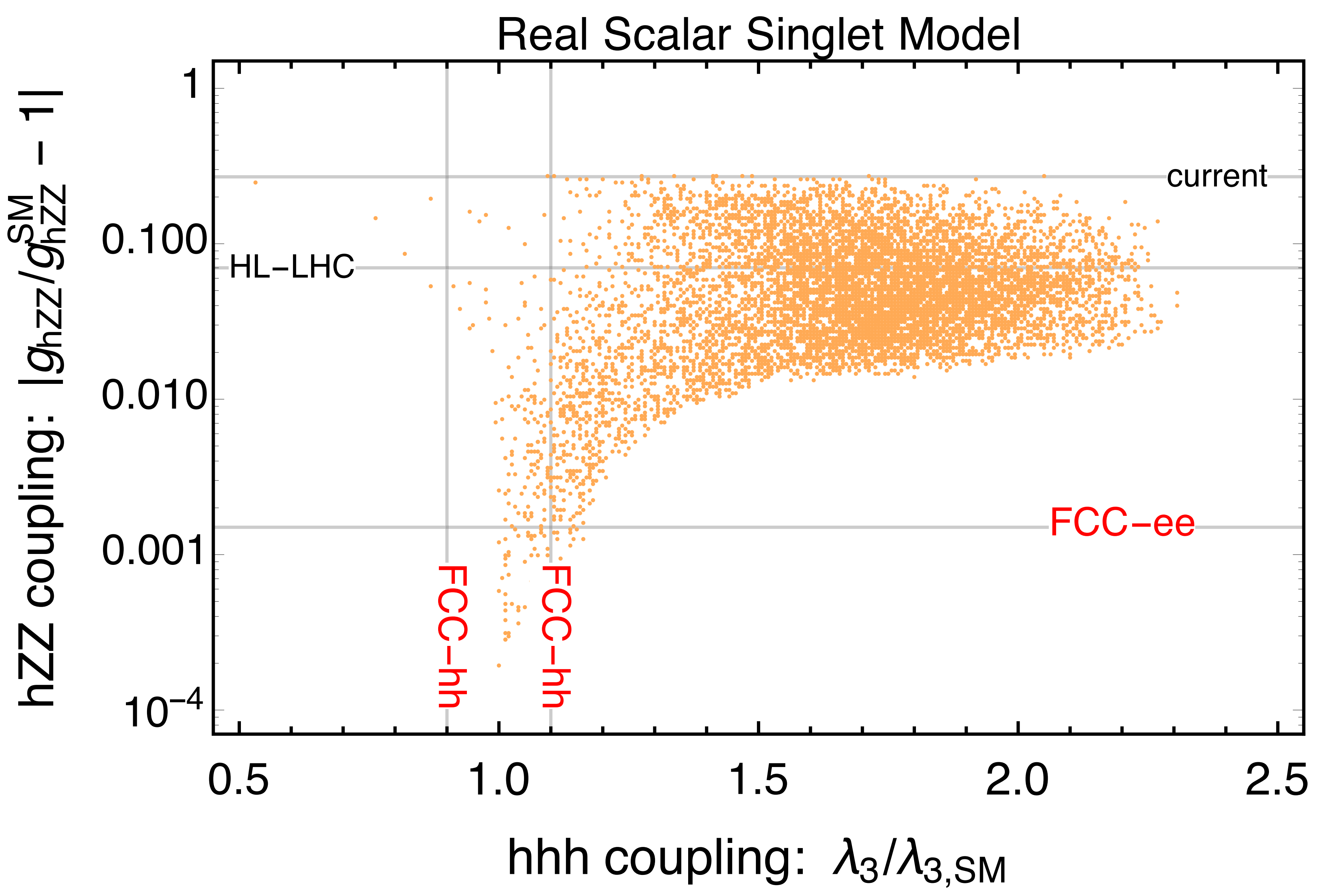
2. Baryogenesis
&
Strong EW phase transition

Baryogengesis $\Rightarrow$ strong EW phase transition

- Explaining the origin of the cosmic matter-antimatter asymmetry
- Very probably, it is connected with EWSB
- 2 key ingredients that the SM cannot offer:
    - a sufficiently violent transition to the broken-symmetry phase: strong EW phase transition
    - adequate sources of CP-violation

Strong EW phase transition

- New particles with masses typically below one TeV.
- Interactions with the Higgs boson that modify the Higgs potential energy in the early universe.



3. Neutrino mass generation
&
Lepton Flavor Violation

Neutrino mass generation

- Various NP modes to explain the neutrino masses and mixing angles

Parameter	best-fit
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)
$\sin^2\theta_{12}$	0.297
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216
δ/π	1.38 (1.31)

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How to discriminate the models?

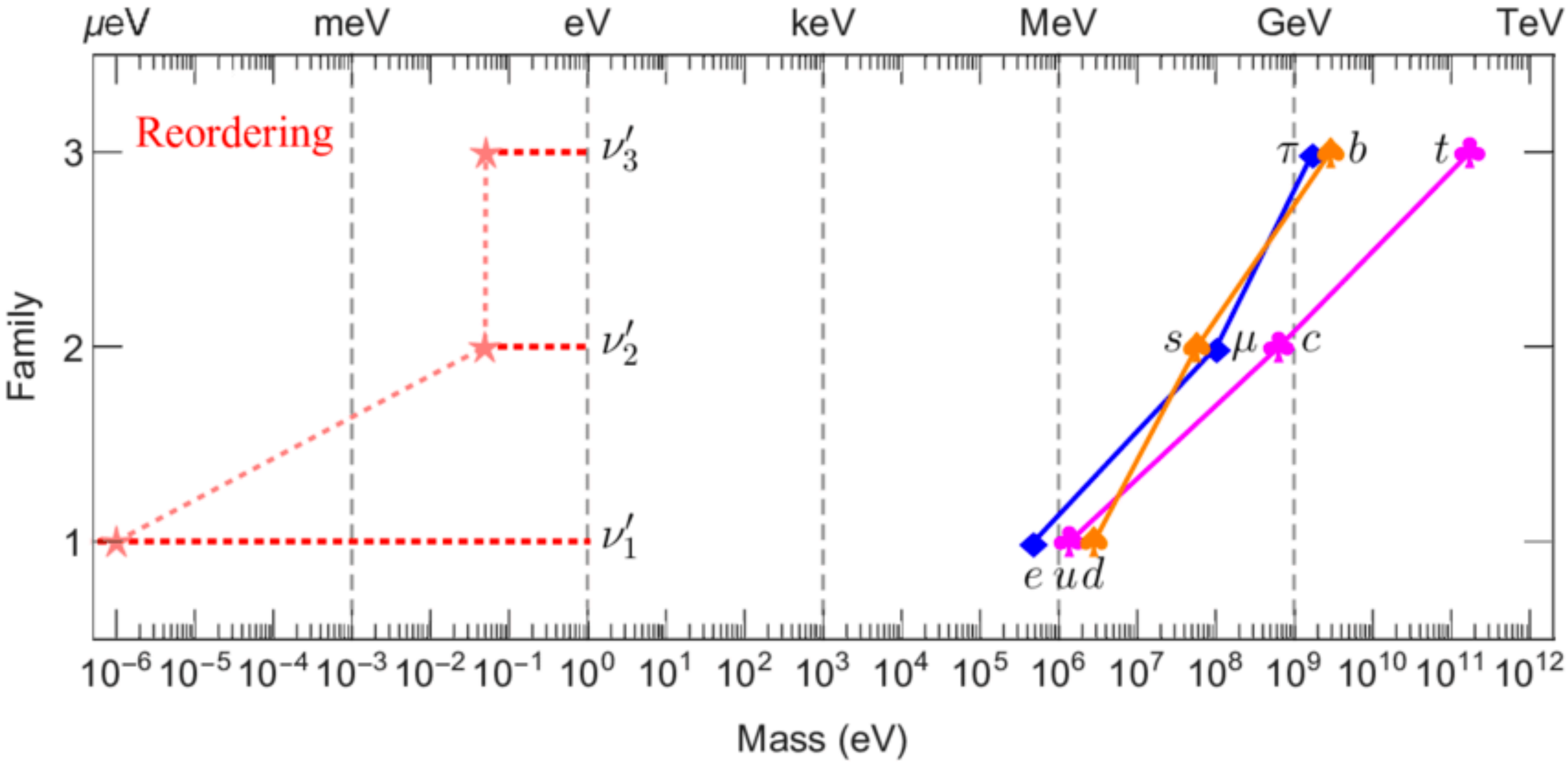
Neutrino mass generation ⇒ LFV

- How to discriminate several types of neutrino-mass generation models?
- Each model predicts different LFV.
- FCC-ee ⇒ giga-Z project

$$Z \to \tau\mu/e, \ \tau \to 3\mu, \ e\gamma \text{ or } \mu\gamma$$

4. Flavor Puzzle

Flavor puzzles



Flavor puzzles

- How to explain the structure (smallness and hierarchy) in the charged fermion masses and the CKM mixing angles?
- Why no structure (no hierarchy, degeneracy, or smallness) in the neutrino-related flavor parameters?
- Measure new flavor parameters beyond CKM, especially in the Higgs sector

Higgs is a key

Model	$\dfrac{y_\tau}{\sqrt{2}m_\tau/v}$	$\dfrac{y_\mu/y_\tau}{m_\mu/m_\tau}$	$\dfrac{BR(h\to\mu\tau)}{BR(h\to\tau\tau)}$
SM	1	1	0
NFC	$V^*_{hl}v/v_l$	1	0
MSSM	$\sin\alpha/\cos\beta$	1	0
MFV	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(m_\tau^2/\Lambda^2)$	0
FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\lvert U_{23}\rvert^2 v^4/\Lambda^4)$
GL	3	5/3	$\mathcal{O}[(25/9)(m_\mu^2/m_\tau^2)]$

	SM	2HDM	MSSM
$t\to hc$	3×10^{-15}	2×10^{-3}	$\leqslant 10^{-5}$
$t\to hu$	2×10^{-17}	6×10^{-6}	$\leqslant 10^{-5}$

5. Stability of the Higgs vacuum

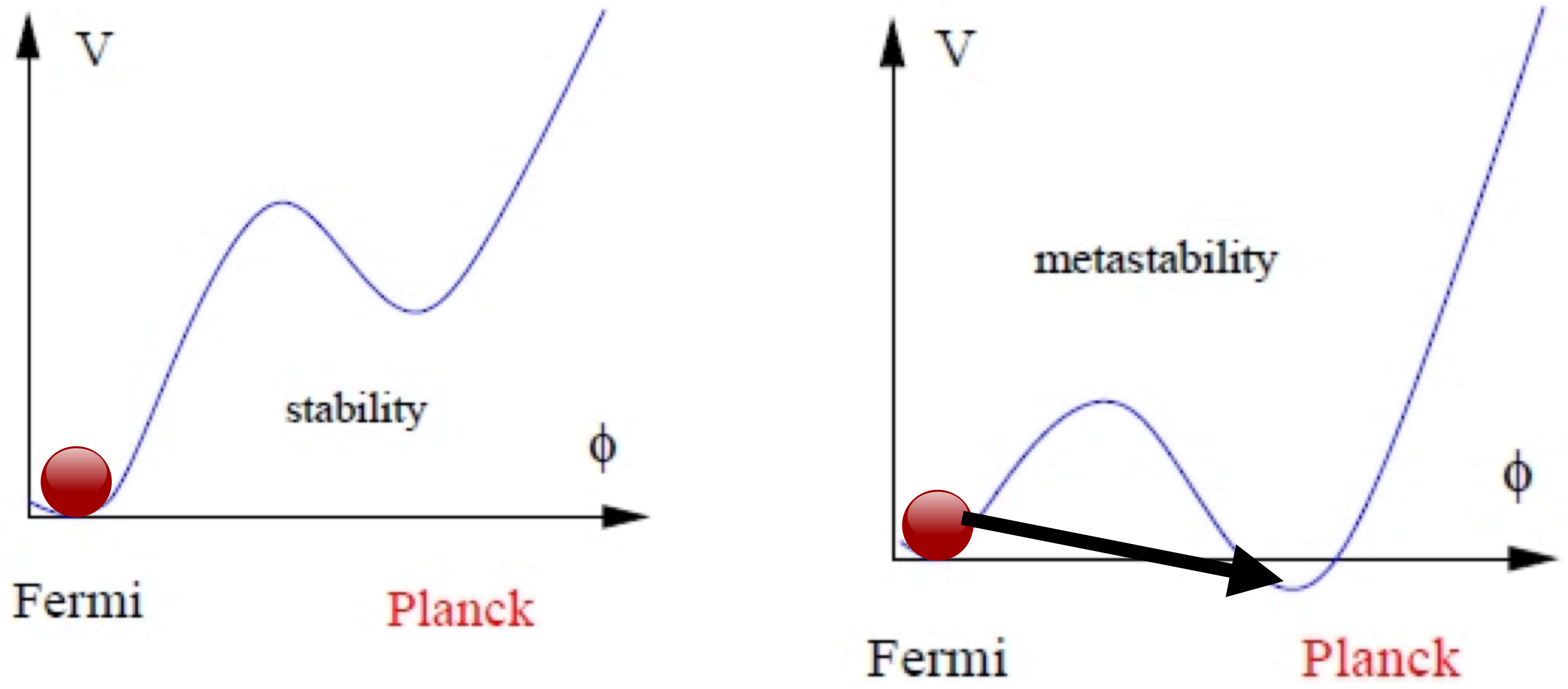
Stability of the Higgs vaccum

- The most quick, clean, and efficient way of wiping out the Universe: meta-stable vacuum
- The Higgs potential determines whether the Universe is in a true vacuum, or a false vacuum.
- In the SM, the measurements of the Higgs boson mass seem to indicate the vacuum is metastable.

What would happen if the vacuum did decay?

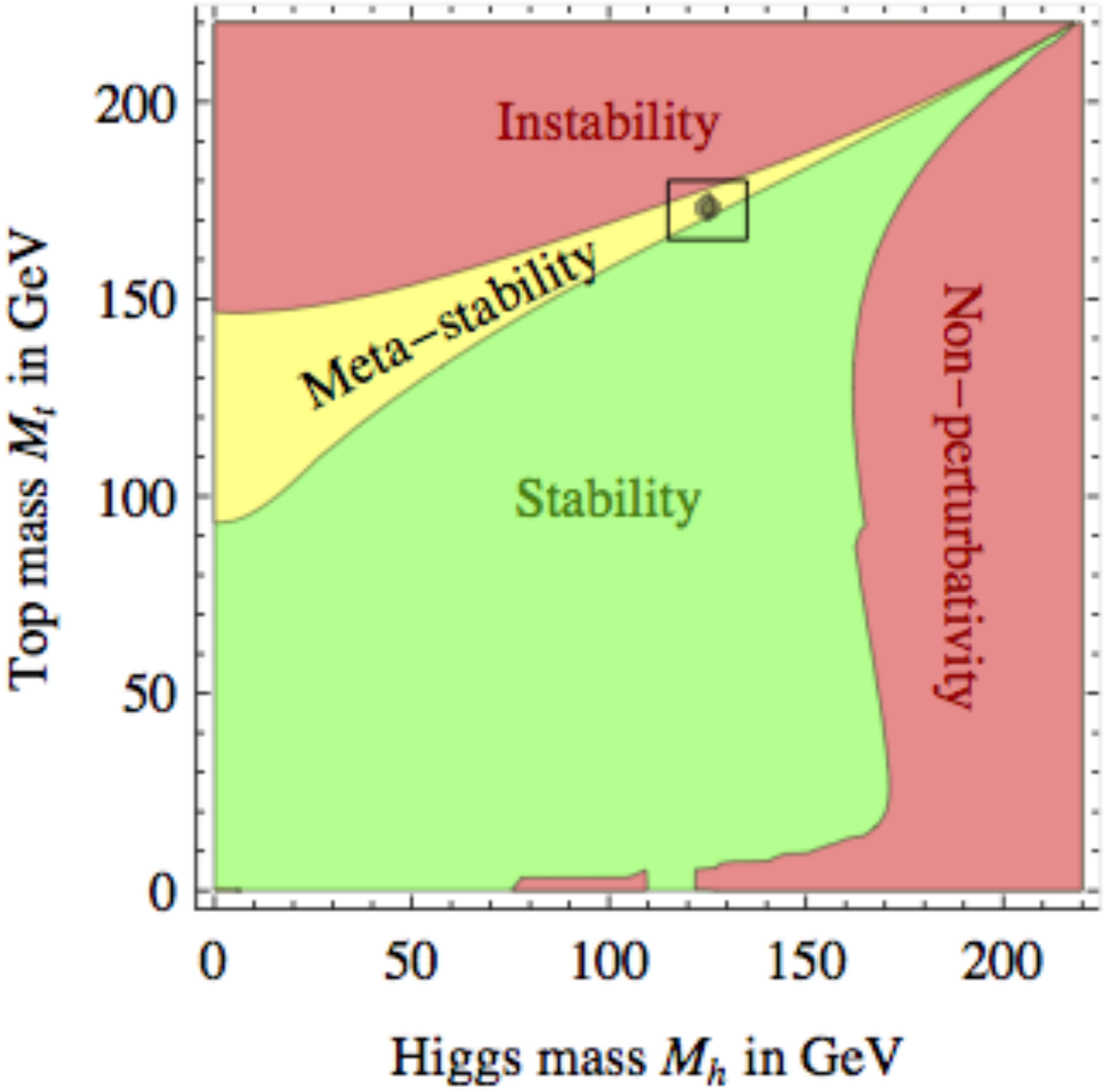
- The walls of the true vacuum bubble would expand in all directions at the speed of light.
- The walls can contain a huge amount of energy, so you might be incinerated as the bubble wall ploughed through you.
- Coleman & De Luccia in 1980: any bubble of true vacuum would immediately suffer total gravitational collapse.

Effective potential of the Higgs field at finite T

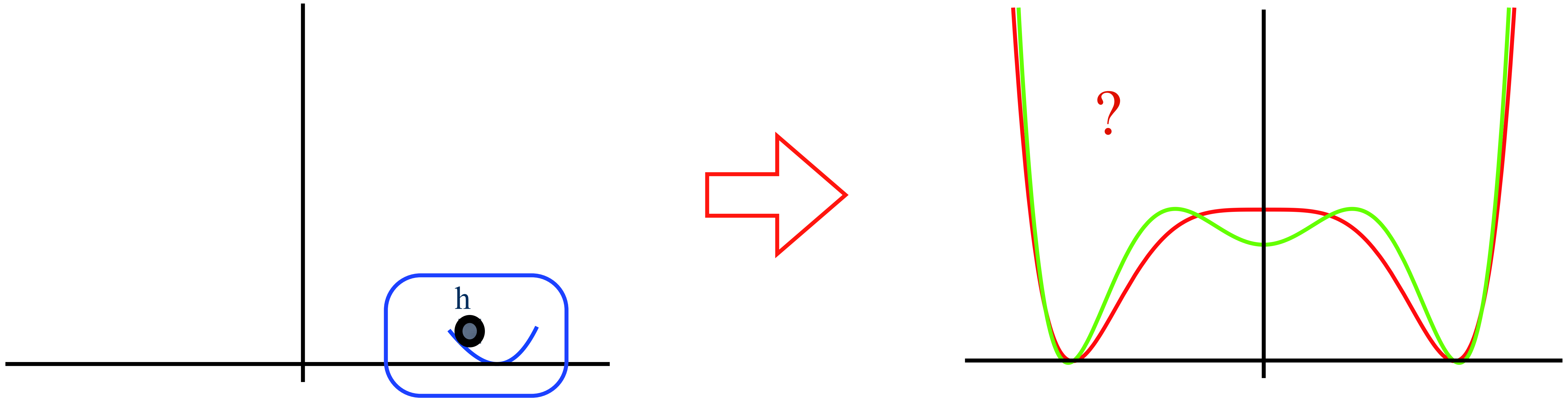


Lifetime > Universe age

5. Stability


Instability
Meta–stability
Stability
Non–perturbativity
Top mass M_t in GeV
Higgs mass M_h in GeV
0
50
100
150
200
0
50
100
150
200

Global shape of the Higgs potential



Our current knowledge of the Higgs potential

the SM Mexican Hat potential ?

- Being the third derivative,
  it carries more information about the global shape of the Higgs potential than the mass