暗黒物質問題を起点に素粒子物理学を考える

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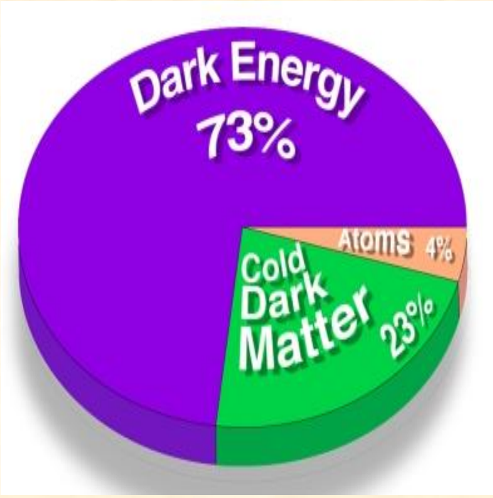
我々の宇宙に暗黒物質が存在するという事実は、とりもなおさず標準模型を超える新物理の存在を明確に示唆する。

- ✓ 暗黒物質について分かっていること、そしてWIMP仮説について。
- ✓ 暗黒物質問題と電弱対称性の破れ。幾つかのシナリオの紹介。
- ✓ 暗黒物質の正体解明を系統的に行う為に。暗黒物質の分類。

Cosmic dark matter problem



Recent cosmological observations reveal that the most of energy in our universe is mainly stored by unknown sources (dark matter & dark energy).

Dark energy: Unknown source with a exotic EOS.

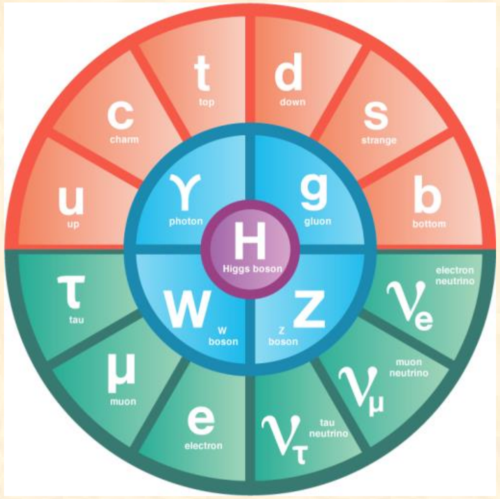
Dark matter: Unknown source with a normal EOS.

Usual matter: Known source with a normal EOS.

The dark matter is required to be enough stable, dark and small interacting, otherwise it must have been detected by the recent observations.

However

Particle physics experiments reveal that neither elementary particles found so far nor matters composed of them can be the dark matter!!!!!



Elementary particles

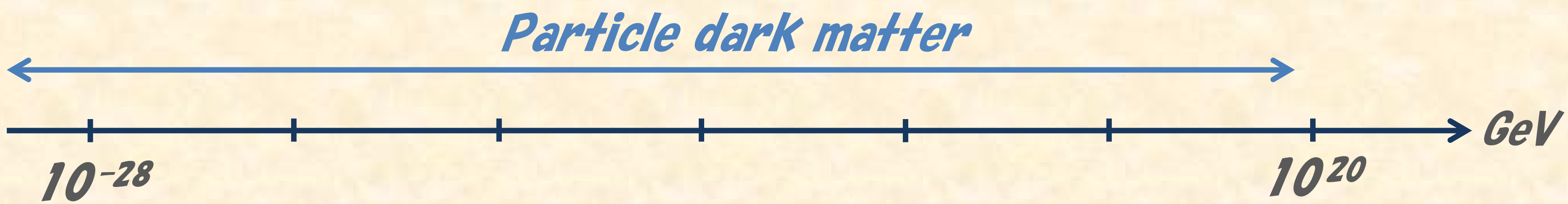
What is dark matter? … It mast be a new elementary particle.

What we know about dark matter

- **What we know about DM**

Observations → ✓ Massive ✓ Stable ✓ Neutral ✓ Cold ✓ Abundant

- **Mass range of a 'particle' DM**



de Broglie length < dSph size
($\lambda = 2\pi/mv$)

Compton length > Schwarzschild radius
($\lambda = 2\pi/m$) ($r = 2m/M_{pl}^2$)

- **Symmetry behind the DM stability?**

Stable SM particles → $e^{\pm}$ ($U(1)_{EM}$ symmetry), p (B symmetry), etc.

Symmetry for DM? → Accidental symmetry, Gauge symmetry, etc.

WIMP hypothesis

Dark matter is a massive, stable and electrically neutral particle, and has a small (and non-gravitational) interaction with ordinal matters.

↓

The reason why WIMP hypothesis attracts attention is because dark matter candidates satisfying the hypothesis explain the dark matter abundance (averaged mass density of the universe) very naturally.

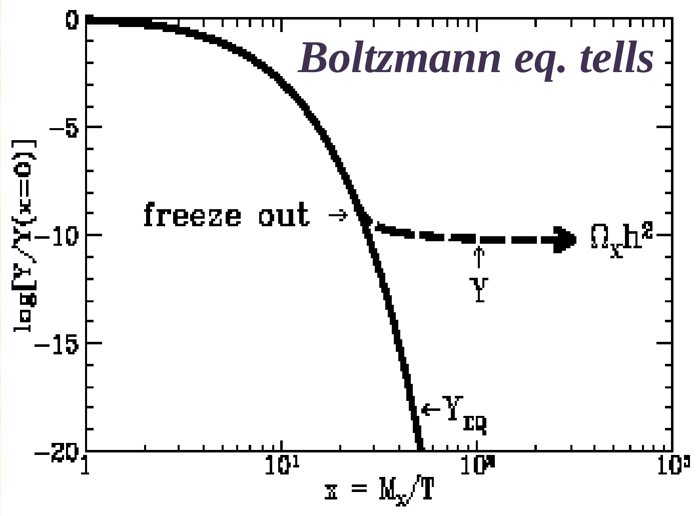
↓

Let us see how the particle (satisfying WIMP hypothesis) behaves in the early epoch of the universe, namely the time-development of the ratio between the dark matter density and the entropy density.

Dark matter is in the chemical equilibrium with usual matters due to the interaction.

Due to the expansion of the universe, the dark matter stops keeping the equilibrium.

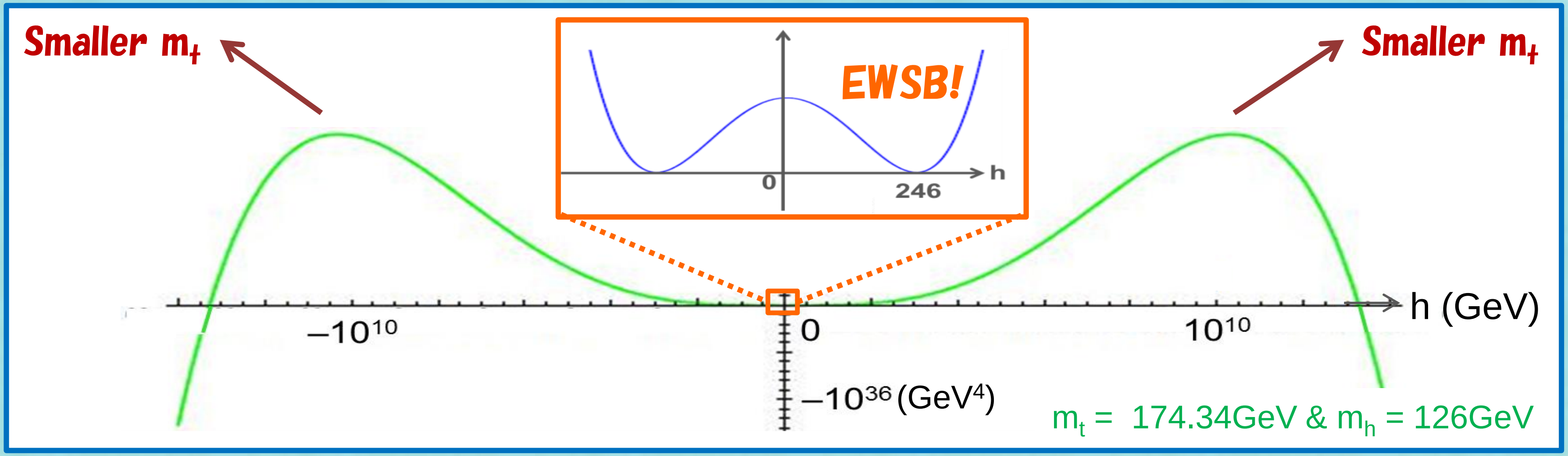
The net dark matter number is then fixed, giving the abundance today. It is matched w/ observation when m_{DM} is 10-1000GeV.



Electroweak symmetry breaking

Why electroweak symmetry is broken at O(100)GeV?

The breaking is simply assumed in the standard model through the negative $|H|^2$ term, so that it can not answer to the above question.



Since the Planck scale (about 10^{19}GeV) is regarded as a fundamental energy scale in the quantum field theory, the electroweak symmetry breaking (the non-zero vacuum expectation value of the Higgs field) seems to be caused by some small breaking effect(s). In other words, the symmetry is not broken at the 0^{th} order approximation. In fact, this philosophy is adopted in the baryon asymmetry of the universe.

Electroweak symmetry breaking

Why electroweak symmetry is broken at O(100)GeV?

There was the very similar problem in the condensed matter physics, which is the so-called superconductor problem, and is already solved.

Ginzburg-Landau theory → BCS theory ('Higgs' = :ee:)

The important point is that the scale of new physics responsible for the electroweak symmetry breaking is not necessarily to be around 100GeV, and it can be much higher than the electroweak scale.

Applying the simple analogy to the BCS theory (technicolor scenario, one of the composite Higgs scenarios) unfortunately does not work.

SUSY scenario

SUSY is broken at some high some high energy scale and it causes the EW symmetry breaking.

MPP scenario

EW symmetry is broken because of some special boundary condition for the Higgs potential.

DS scenario

The EW scale is caused because of the classical conformal symmetry breaking at DS sector.

It is worth remembering that both the EW scale and the mass of WIMP are around 100GeV, so that the both seem to have the same origin!!

Supersymmetry (SUSY)

Invariance under the replacement between boson(s) and fermion(s).

Superstring theory predicts it.

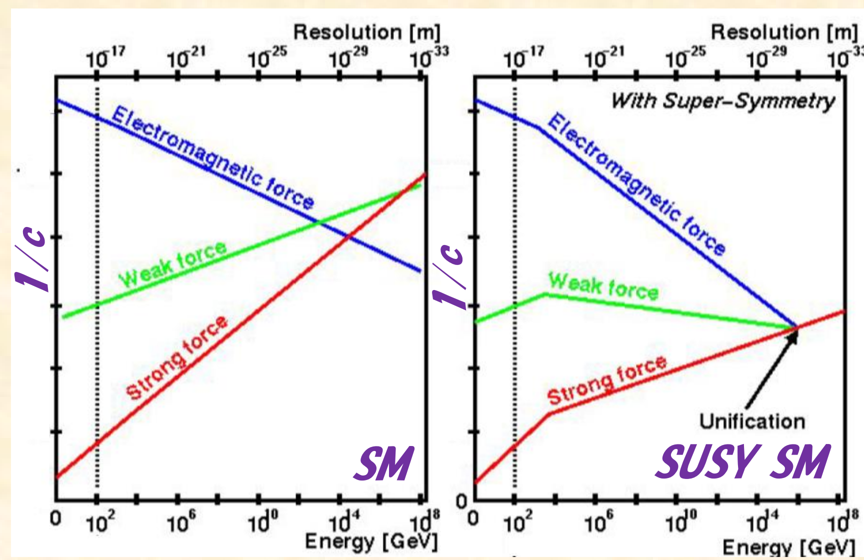
SUSY allows us to explain why EW symmetry is broken (at 100GeV).

SUSY allows us to explain why EW symmetry is broken (at 100GeV).

$F = c(r) \times (\mathrm{charge})^2 / r^2$

All interactions interactions lead to the coulomb's-like force when two particles are close each other.

QM gives the r-dependence of 'c'.



WIMP is predicted to be the lightest supersymmetric particle, say LSP!

'Natural' SUSY scenario

SUSY breaking→ EWSB (negative m^2),

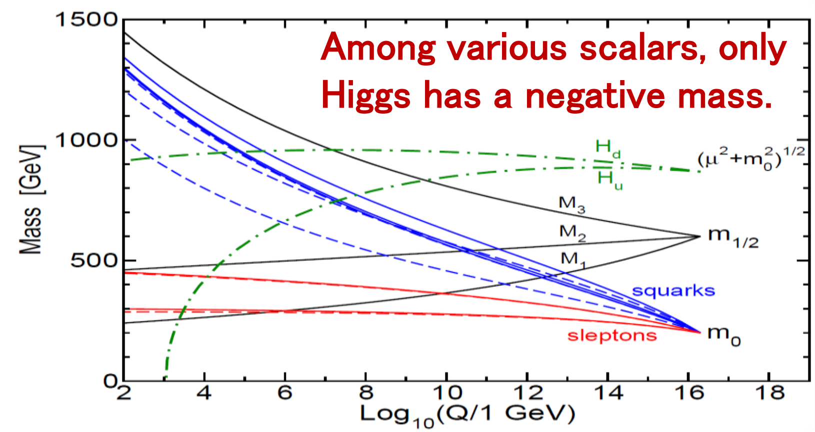
$$V = m^2|H|^2 + \lambda|H|^4$$

which is called the radiative breaking.

[K. Inoue, et. al, PTP,1982]

$\lesssim 10^{10}$GeV

~~SUSY~~ is expected to be dynamical one.



Why m^2 is O(100)GeV?

$$m^2 = |\mu|^2 + m_{H_u}^2 + \delta m_{H_u}^2|_{\text{stop}} + \delta m_{H_u}^2|_{\text{gluino}} + \cdots$$

Higgsino mass | Heavy Higgs mass | Squark (Stop) mass | Gluino mass

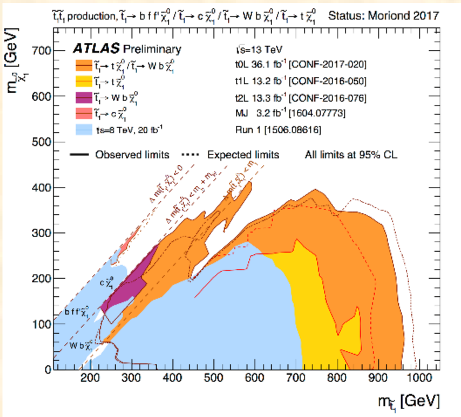
No fine-tuning | Small fine-tuning | Large fine-tuning?

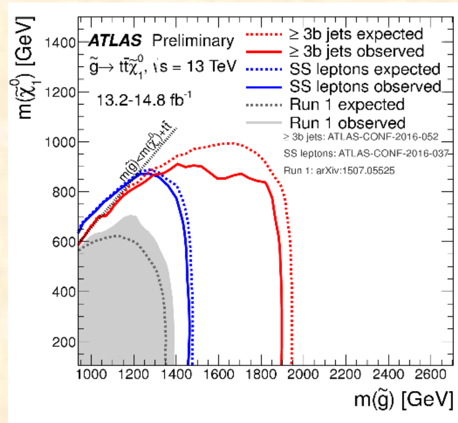
M_{SUSY} ~ O(0.1)TeV? | M_{SUSY} ~ 1TeV? | M_{SUSY} >> 1TeV?

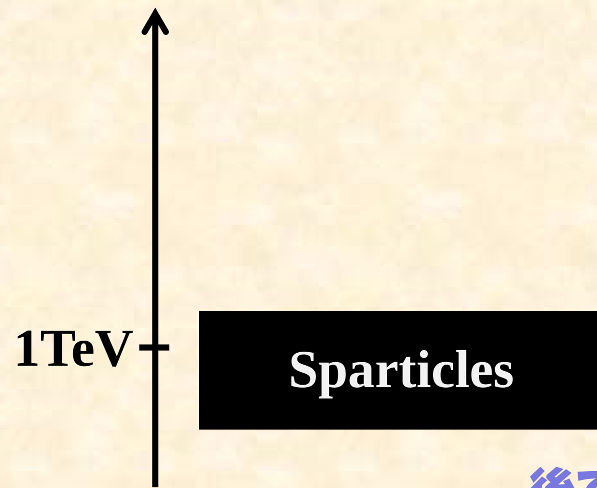
0.1TeV — 1TeV — Mass

'Natural' SUSY scenario

Traditional Natural SUSY scenario







後で

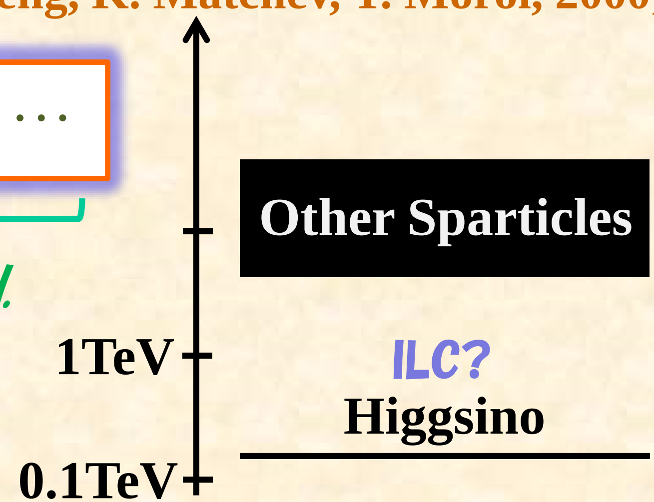
LHC is ruling out the scenario. Some difficulty exist in MSSM due to m_h

Focus point SUSY scenario

[J. Feng, K. Matchev, T. Moroi, 2000]

$$m^2 = |\mu|^2 + m_{H_u}^2 + \delta m_{H_u}^2|_{\rm stop} + \delta m_{H_u}^2|_{\rm gluino} + \cdots$$

∃ *Correlation → O(100)GeV in total.*



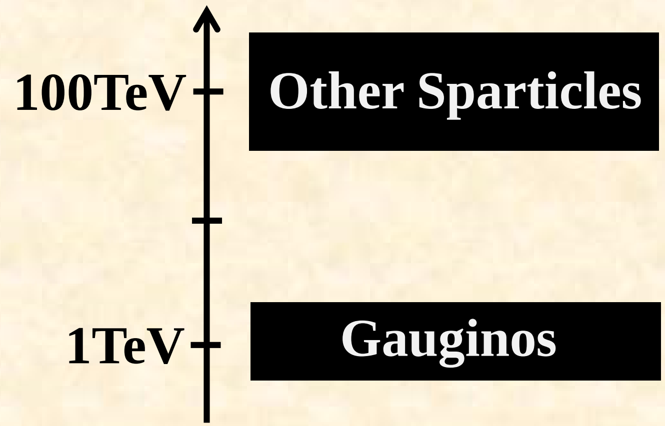
- ✓ *M is the supersymmetric mass term.*
- ✓ *Other mass terms are from SUSY.*
- ✓ *LSP is predicted to be the Higgsino!*

High-scale SUSY scenario

Pure gravity mediation model [M. Ibe, T. Yanagida, T. Moroi, S. M., 2006, 2012]

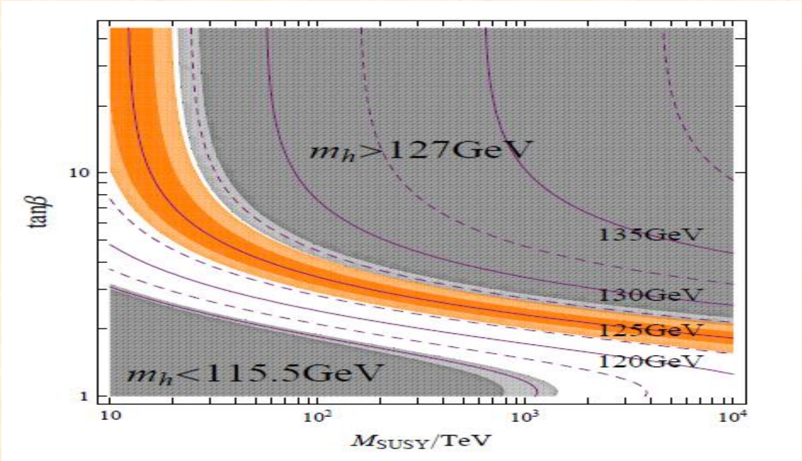
Motivation:

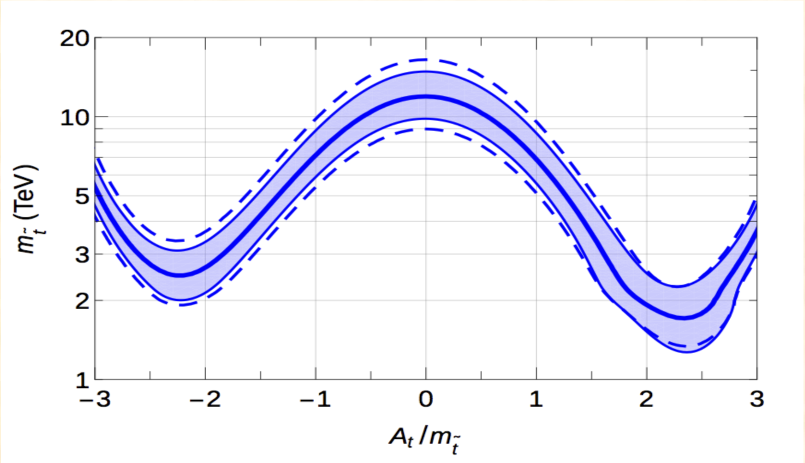
- ✓ *Simplest SUSY breaking framework.*
- ✓ *Suppressed Flavor-changing processes.*
- ✓ *Consistent with the simplest cosmology.*
- ✓ *Consistent with the ground unification.*
- ✓ *LSP (WIMP) is predicted to be the wino!*



The scenario predicts the Higgs mass to be what we observed at LHC!

Higgs mass vs. SUSY breaking mass 前々ページ参照





If SUSY is considered, Higgs mass observed at LHC tells us something…

High-scale SUSY scenario

$\lesssim 10^{11}$GeV

How the EW scale is obtained? It is usually expected to be O(100)TeV.

↓

Paradigm shift is required for the naturalness problem. E.g. Multiverse.

[Y. Nomura, 2011; Y. Nomura, S. Shirai, 2014; M. Ibe, et al, 2015 in SUSY framework]

Taking the fact that a bias exists for (some of) physical observables.

① We are living in one of the universes.

② Each has different physical constants.

③ We can live in the universe where the EW symmetry is broken at O(100)GeV.

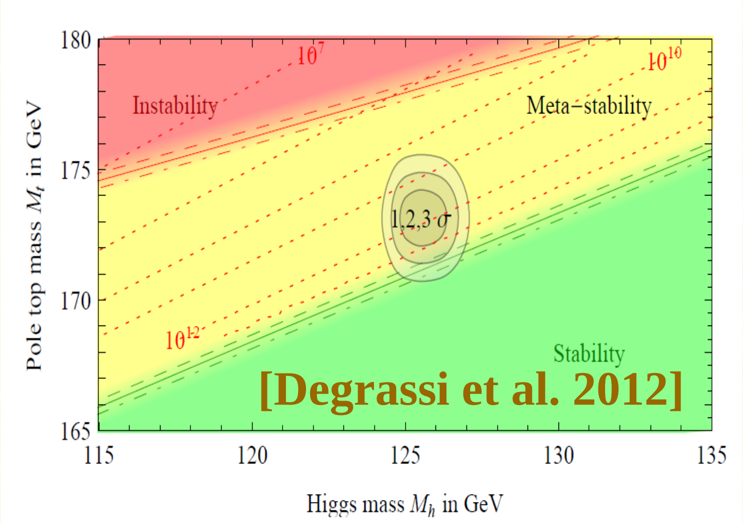
This idea is recently supported by String theory & Eternal inflation.

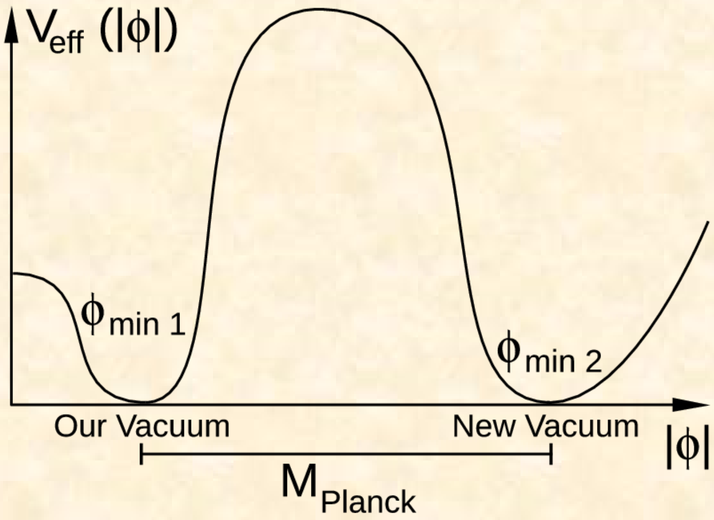
Let's calculate the conditional probability of M_{SUSY} w/ the condition ③.

- ✓ Since SUSY is dynamically broken, $P(M_{SUSY})\, dM_{SUSY} \propto dM_{SUSY}/M_{SUSY}$.
- ✓ Since μ is a complex-valued SUSY invariant mass, $P(|\mu|)\, d|\mu| \propto |\mu|\, d|\mu|$.
- ✓ Hence, $P_c(M_{SUSY}) = \int P(M_{SUSY})\, P(|\mu|)\, \delta(|\mu|^2 - (M_{SUSY})^2)\, d|\mu| \sim 1/M_{SUSY}$.
- ✓ M_{SUSY} is can be everywhere, being consistent with O(100)TeV SUSY!

Multiple point principle (MPP) scenario

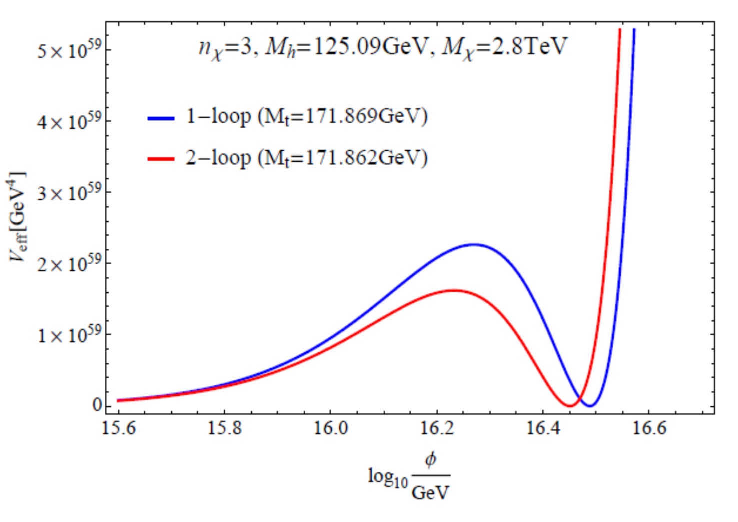
[C. Froggatt, H. Nielsen, 1996; H. Kawai, et. al. for recent studies]





$\lesssim 10^{18}$GeV

- ✓ The EW scale is fixed by MPP, which gives a non-trivial relation among the EW scale, Higgs and top masses.
- ✓ With fixing (m_t, v) = (172, 246)GeV, m_h = 129GeV is predicted in the SM.
- ✓ If the contribution from the WIMP (triplet Majorana) is added, above prediction becomes m_h = 129GeV.



[Y. Hamada, K. Kawana, 2015]

Multiple point principle (MPP) scenario

What Kind of Physics can be behind the MPP?

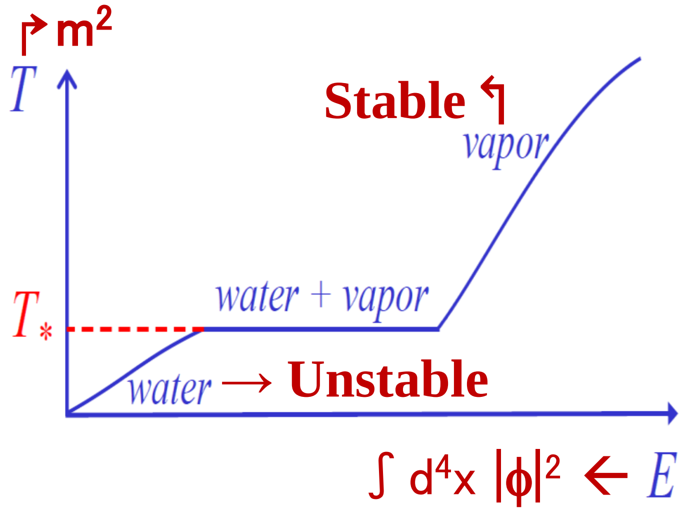
◎ **Canonical**

$$\int [d\varphi]\, e^{-\beta H[\varphi]}$$

↑

◎ **Micro-canonical**

$$\int [d\varphi]\, \delta(H[\varphi] - E)$$



◎ **Field theory (SM)**

$$Z = \int [d\varphi]\, e^{iS[\varphi]}$$

↑

◎ **More fundamental**

???????????

- ✓ *There may be a more fundamental description of particle physics than quantum field theory, corresponding to the micro-canonical description (rather than canonical one) in statistical mechanics.*
- ✓ *Degenerate vacuua describes the co-existence of multiple phases.*
- ✓ *From the quantum field theory viewpoint (intensive variable), co-existence requires fine-tuning, while does not require the tuning from this more-fundamental description (extensive variable).*

Dark sector (DS) scenario

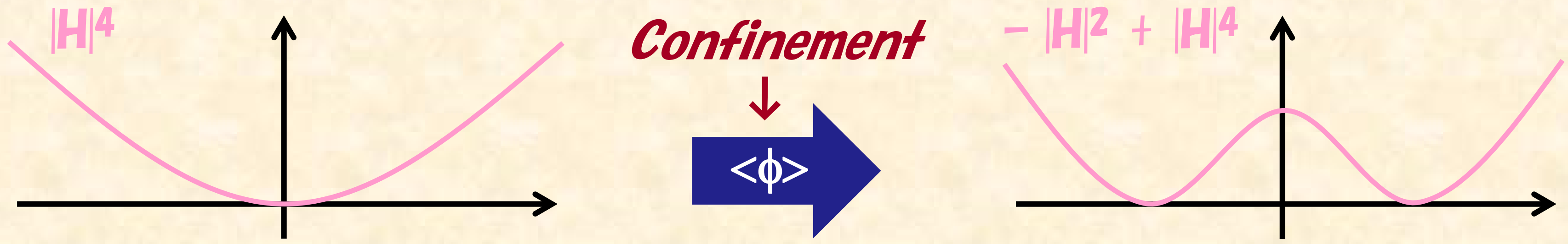
DS = The sector of articles not charged under SM gauge interactions.

$\lesssim 10^2$GeV

Standard model — E.g. $\phi^2|H|^2$ — Dark sector

QCD-like dynamics

- ✓ Considering a classical conformal field theory (the theory does not have any dimension-full parameters), let us assume that it has a dark sector involving a QCD-like (strongly interacting) dynamics.
- ✓ QCD-like dynamics generates a mass dimension, giving the vev of the scalar field ϕ, and it leads to the Higgs quadratic coupling!



- ✓ WIMP candidate is also provided, which is e.g. a baryon in the hidden sector. Universal prediction in such a DS scenario is that the WIMP is always predicted to be a singlet under the SM gauge interactions.