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The Phenomenology of Vacuum decay with Vevacious:

A companion to BSM collider constraints

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Vacuum Stability

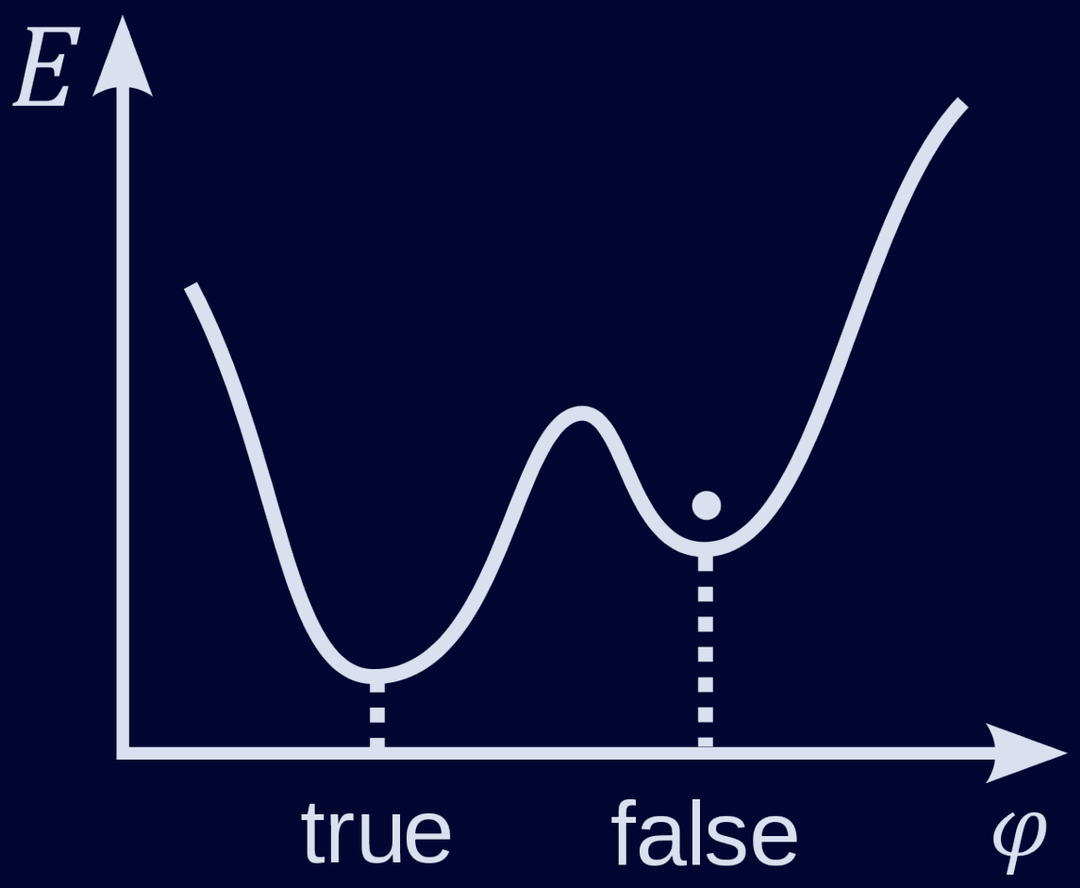
- Any QFT prediction is calculated around a **minimum** of the scalar **potential**.

- It is possible to have a **transition** from one minimum to a **deeper** one.

- This is something we can calculate, both due to **quantum tunneling** but also **thermal** fluctuations.

- A given minimum also tells us the **symmetries** of the ground state.

Vacuum Stability

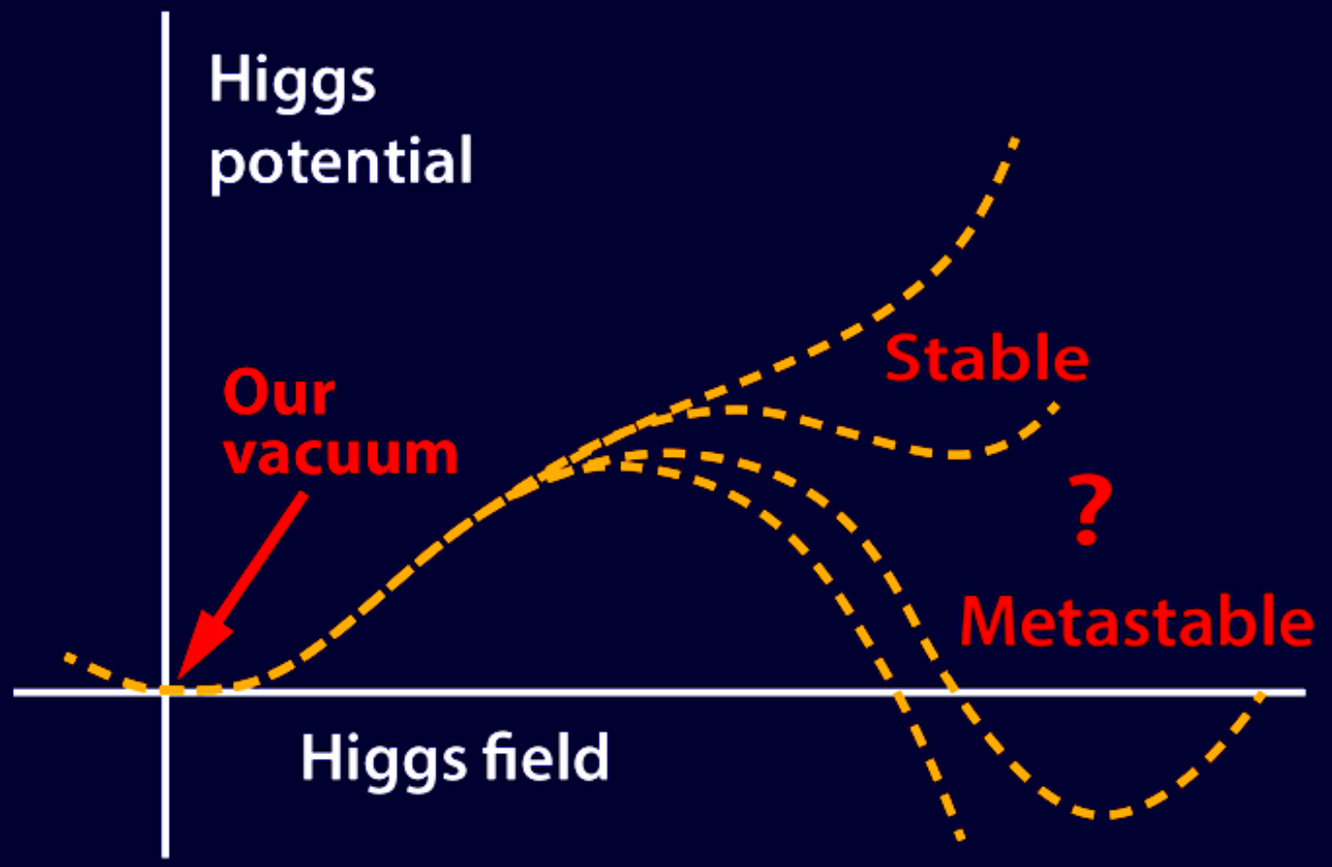


- The minimum corresponding to observed phenomena can be the false vacuum.
- It is possible to calculate decay with per unit volume by minimizing the “bounce” action.
- Solutions are 4 (3) dimensional instantons at zero (non-zero) T
- The calculation is relatively straightforward

Same same, but different

- In the SM (with only one scalar) at high energies a new minimum develops.

- In theories with many scalars, even at lower energies, there can be charge- and color- breaking minima.



YOU CAN NOT CHOOSE WHICH FIELDS HAVE VEVS
We need to understand the scalar potential very well!

Typical approach

- You have a great **BSM model**, with a perfect DM candidate, **evades all collider searches** while giving great search opportunities for next week, fits in a SO(10) GUT…

- With the **right** VEV assignment, you break symmetries to the SM or $U(1)_{EM}$, get right **gauge boson masses** … **You have a “good” minimum**

- You implement whatever **TL conditions** you find in the literature, some parameter regions get excluded.

- **Done.**

What can happen?

- Solving the minimization conditions even at TL is very difficult. Analytical conditions are almost surely **wrong**:
  There will be regions with deeper minima that you'll miss.

  Points you think are good are excluded.

- Excluding some points with **maybe** deeper minima is not very useful:
  There will be regions with deeper minima that are fine.

  Points you think are excluded are good.

What to do?

Given a BSM model with many scalars:

- Find dangerous minima for a given parameter point.

- If there are deeper minima, then calculate the bounce action. Get the probability that a critical bubble was nucleated in the past light-cone.

- Is the point still fine (large lifetime of the “good vacuum”) or not (the theory predicts we would be in a deeper vacuum already)?

levels of sophistication

Potential Function:
Which scalars get VEVs?
Tree-level or N-loop?

Potential Minimization:
Numerical minimization?
Do we get all minima?
Take into account RG running?

Bounce Action calculation:
Straight tunneling path?
Path deformation?
How to find the optimal path?

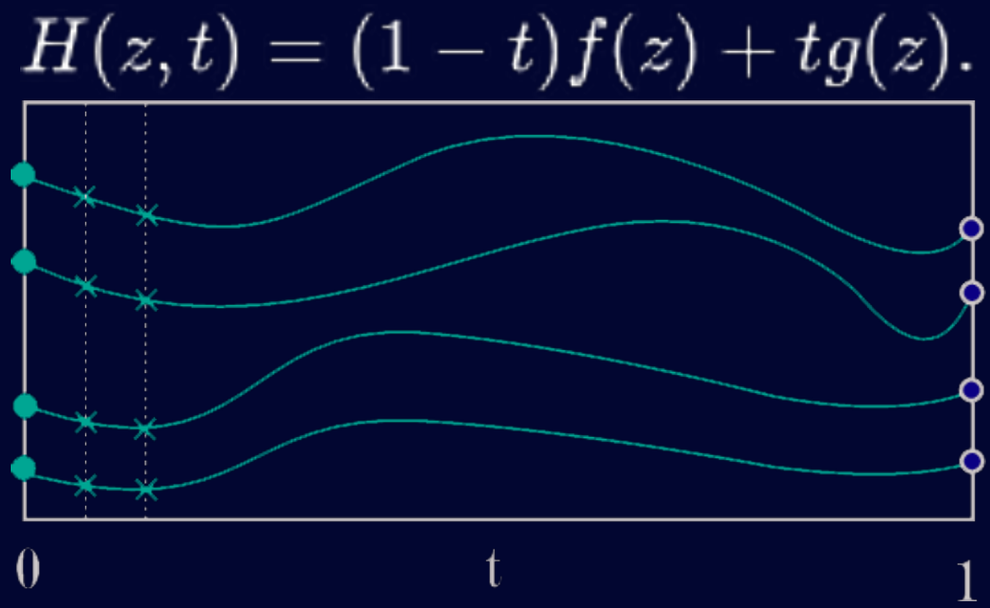
Which level is best depends on your particular problem!!
Often TL + straight path is OK
Sometimes it is not!

vevacious

JECM,O'Leary, Porod, Staub.
arXiv:1307.1477 | Eur. Phys. J. C73 http://vevacious.hepforge.org/

C++ code that writes specific Python code for a given model and parameter point.

- Finds all the tree level potential minima using the **homotopy continuation** ALL tree-level solutions are found



- Uses them as starting points for numerically minimizing the one-loop effective potential, it calculates finite T corrections.
- Calculates tunneling times between DSB minimum and most dangerous minima.
- **Classifies your minimum as short-lived, long-lived or stable.**

vevacious

JECM,O'Leary, Porod, Staub.
arXiv:1307.1477 | Eur. Phys. J. C73 http://vevacious.hepforge.org/

Model implementation at Lagrangian level with SARAH*.

Automatic calculation of one-loop effective potential

Homotopy Continuation uses HOM4PS

One-loop minima found numerically

No RG running

CosmoTransitions** is used for bounce action calculation

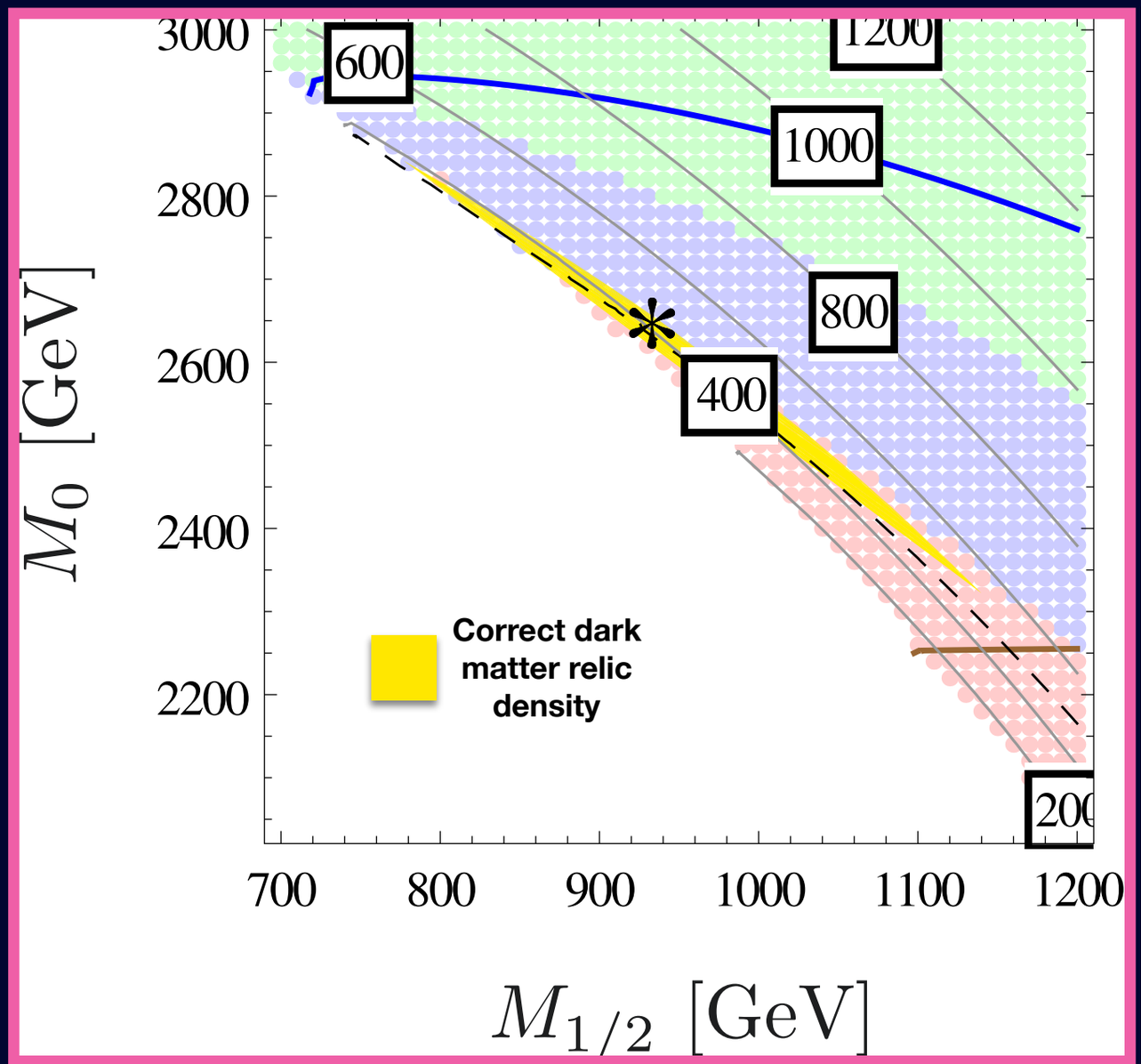
In principle you can change settings if you dive into the code.

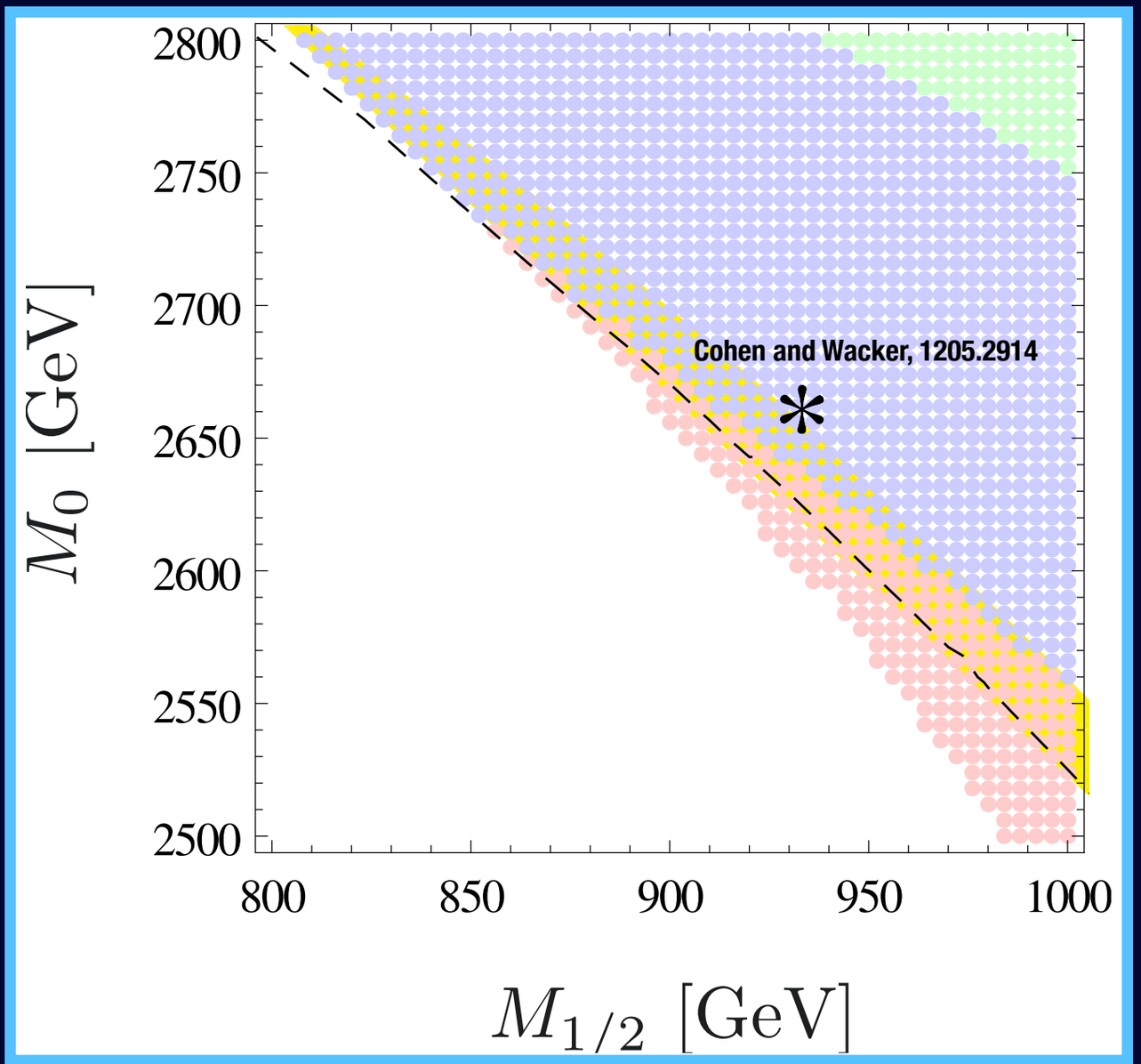
* [Staub, sarah.hepforge.org] **[Wainwright, clwainwright.github.io/CosmoTransitions/]

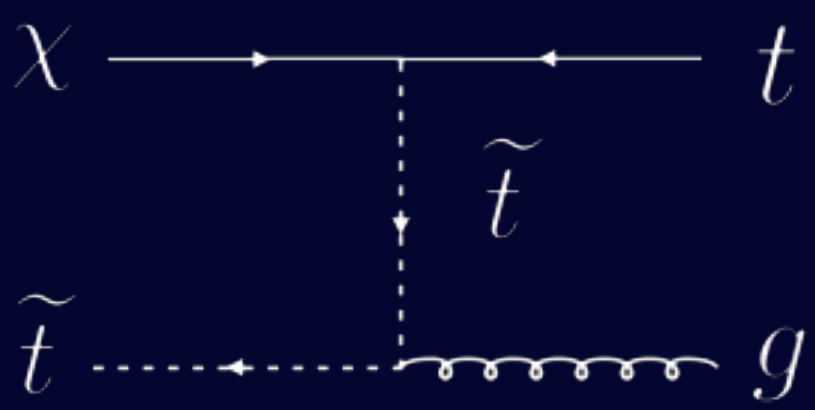
Stability of the CMSSM against sfermion VEVs

JECM,O'Leary, Porod, Staub.

arXiv:1309.7212 | JHEP 1312, 103







$$A_0 = -6444 \text{ GeV}, \mu < 0$$

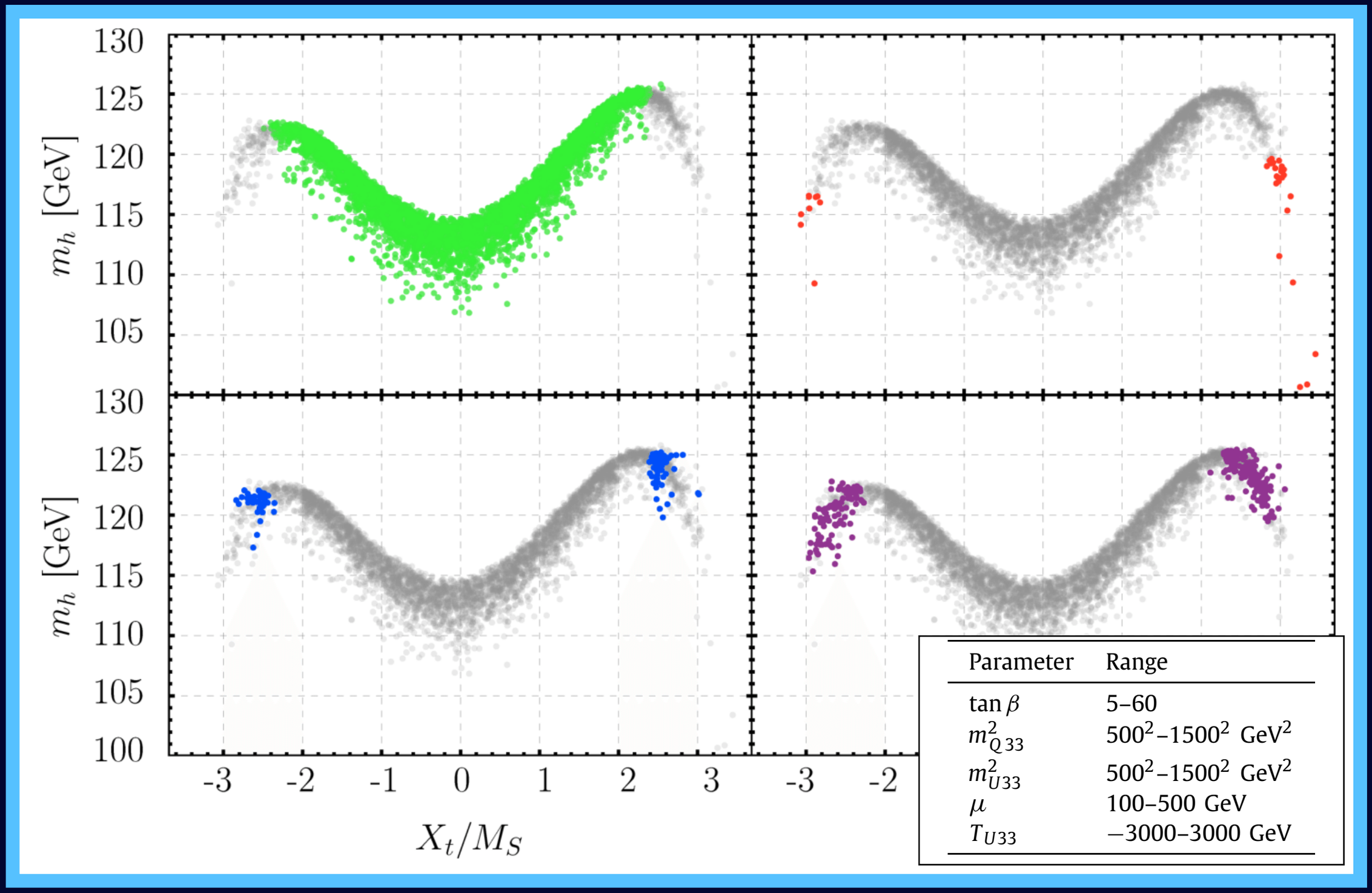
$$\tan\beta = 8.52$$

- Stable DSB minimum
- Short-lived (τ<3Gyrs)
- Long-lived (τ>3Gyrs)

Constraining the Natural MSSM through tunneling to color-breaking vacua at zero and non-zero temperature

JECM, O'Leary, Garbrecht, Porod, Staub.

arXiv:1405.7376 | Phys. Lett. B



Parameter	Range
$\tan\beta$	5–60
$m^2_{Q\,33}$	500^2–1500^2 GeV^2
m^2_{U33}	500^2–1500^2 GeV^2
μ	100–500 GeV
T_{U33}	−3000–3000 GeV

Higgs mass and thermal tunneling

$$X_t = A_t - \mu\cot(\beta)$$

No CCB minimum deeper than the DSB

Long-lived

Short-lived due to Quantum

Short-lived due to Thermal

Disfavouring Electroweak Baryogenesis and a hidden Higgs in a CP-violating Two-Higgs-Doublet Model

1611.05757

Anders Haarr,[a] **Anders Kvellestad,**[b] **Troels C. Petersen**[c]

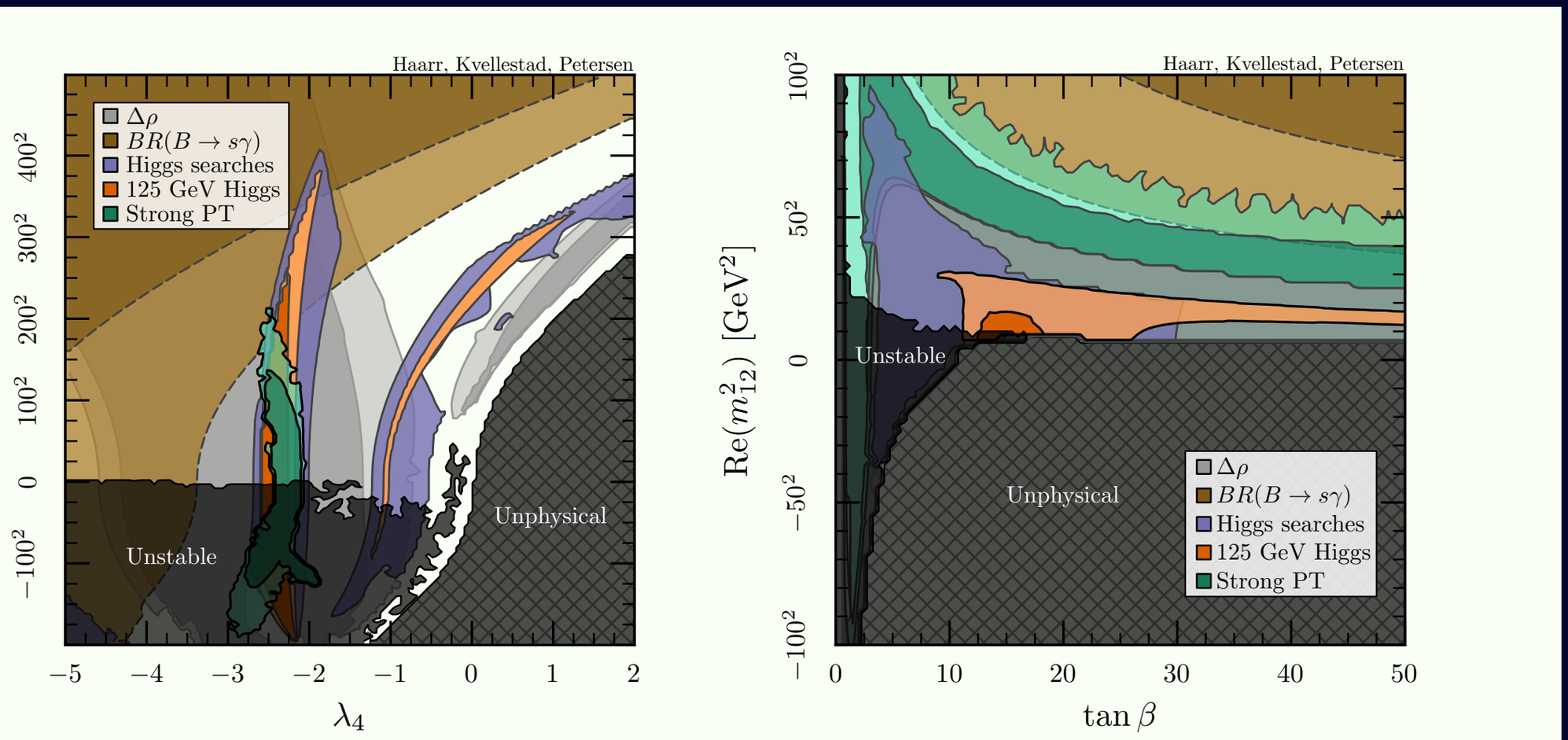
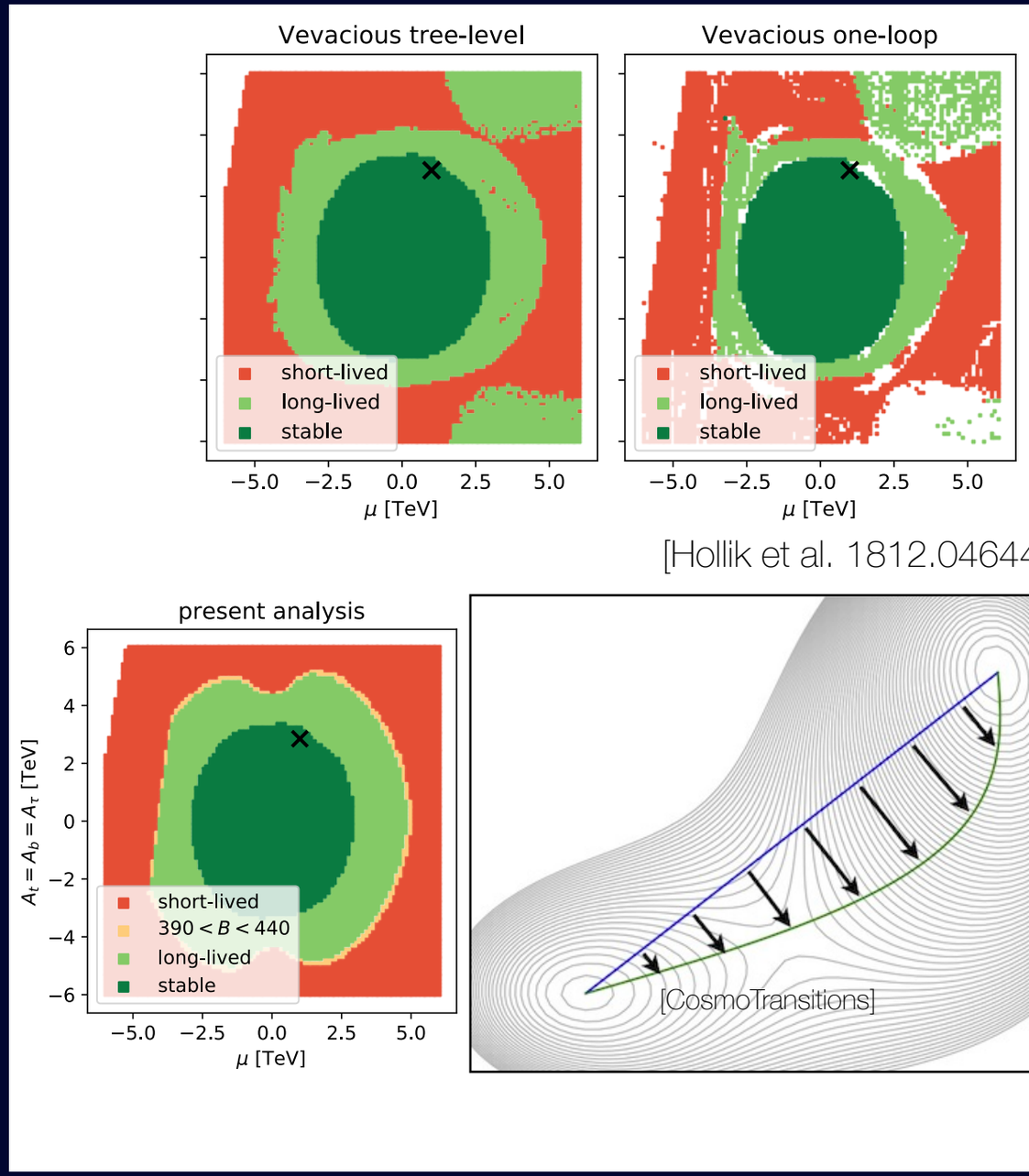


Figure 12. Lower-dimensional grid scans exhibiting regions of strong electroweak phase transition. *Left:* The plane of λ_4 vs $\mathrm{Re}(m_{12}^2)$, with the remaining parameters chosen according to the "standard scenario" in Table 6. *Right:* The plane of $\tan\beta$ vs $\mathrm{Re}(m_{12}^2)$, with the other parameters set to the hidden-Higgs scenario in Table 6. Dark regions marked "unstable" and "unphysical" fail the stability condition and have negative squared masses, respectively. The other coloured regions depict the following: *Teal (cyan):* Phase transition strength satisfying $\xi_c > 1$ ($\xi_c > 0.5$). *Dark (light) orange:* Within 2σ (3σ) of the best-fit point for the 125 GeV Higgs data. *Purple:* Allowed at the 95% CL by collider searches for additional Higgs bosons. *Dark (light) brown:* Predicted $BR(b \to s\gamma)$ within 2σ (3σ) of the observed value. *Dark (light) grey:* Predicted $\Delta\rho$ within 2σ (3σ) of the observed value.

It’s all about the minima

In principle the problem is straightforward

- Get the potential of your theory
- Is TL OK? Or do I need loop corrections? **[Hollik et al. 1812.04644]** Is it OK to set some parameters to zero?
- If the minimum you want is not the global one, identify the dangerous ones
- How to find the minima? Did I find them all? Which one is the most dangerous?
- Find the minimum of the bounce action for all tunneling processes
- Recent developments: **[Athron et al. 1901.03714]** **[Espinosa, Konstandin, 1811.09185]** **[Guada, Maiezza, Nemevšek, 1803.02227]**
- Use the calculated decay width to determine the lifetime of the minimum you want



vevacious PlusPlus

Ben O'Leary, JECM

Modular framework for vacuum stability calculations written in C++.
Easy to use and install, interface through dynamic library.

Model implementation at Lagrangian level with SARAH.

Automatic calculation of one-loop effective potential

Homotopy Continuation interfaces (HOM4PS2 and PHC included)

One-loop minima found numerically

RG running coming soon

Bounce action calculation done natively.
Interface to CosmoTransitions is included as well.
More bounce action calculation methods coming soon

Everything can be turned on/off by XML input options
Loop corrections
Finite temperature
Path deformation
....

2.0b Out now!*

github.com/JoseEliel/VevaciousPlusPlus

Super Quick start guide

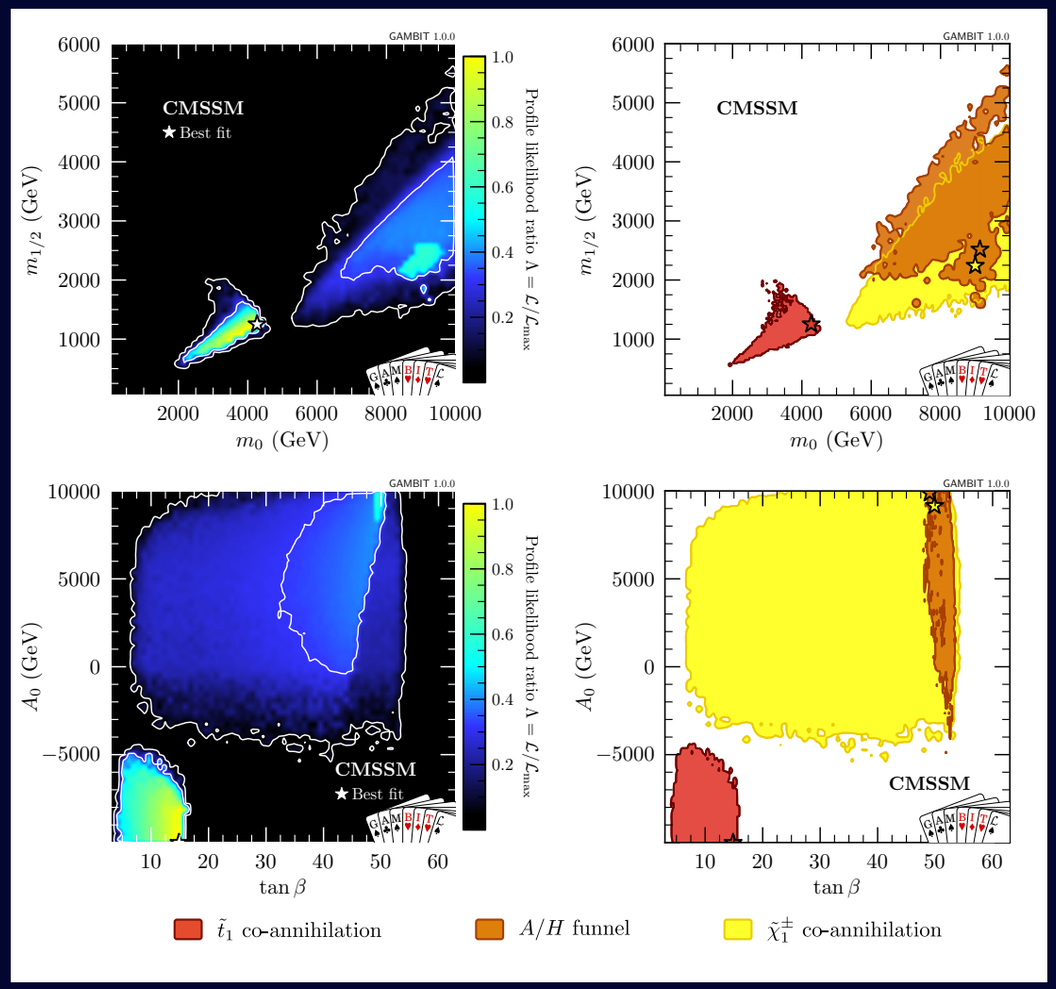
- Get Eigen and Boost if you don’t have it.
- Clone/Download repo.
- CMake will take care of the rest.
- Implement your model in SARAH and do:
  `MakeVevacious[Version -> ”++”]`
- Copy Model files into respective folders.
- Prepare LHA files and input files for your favorite parameter points.
- Included MSSM and 2HDM type I
  (More models to come soon, let me know what you would like!)

*Detailed manual and documentation in preparation

vevacious in global fits

- Previous VS studies are done in slices of parameter spaces together with some experimental constraints.
- It is computationally expensive, but feasible!
- Perfect candidate for a global fit.
  In the (C)MSSM, indications of tension with measured Higgs mass and DM relic density

vevacious in global fits



GAMBIT is a global fitting code for generic Beyond the Standard Model theories, designed to allow fast and easy definition of new models, observables, likelihoods, scanners and backend physics codes.

Global fits of GUT-scale SUSY models with GAMBIT

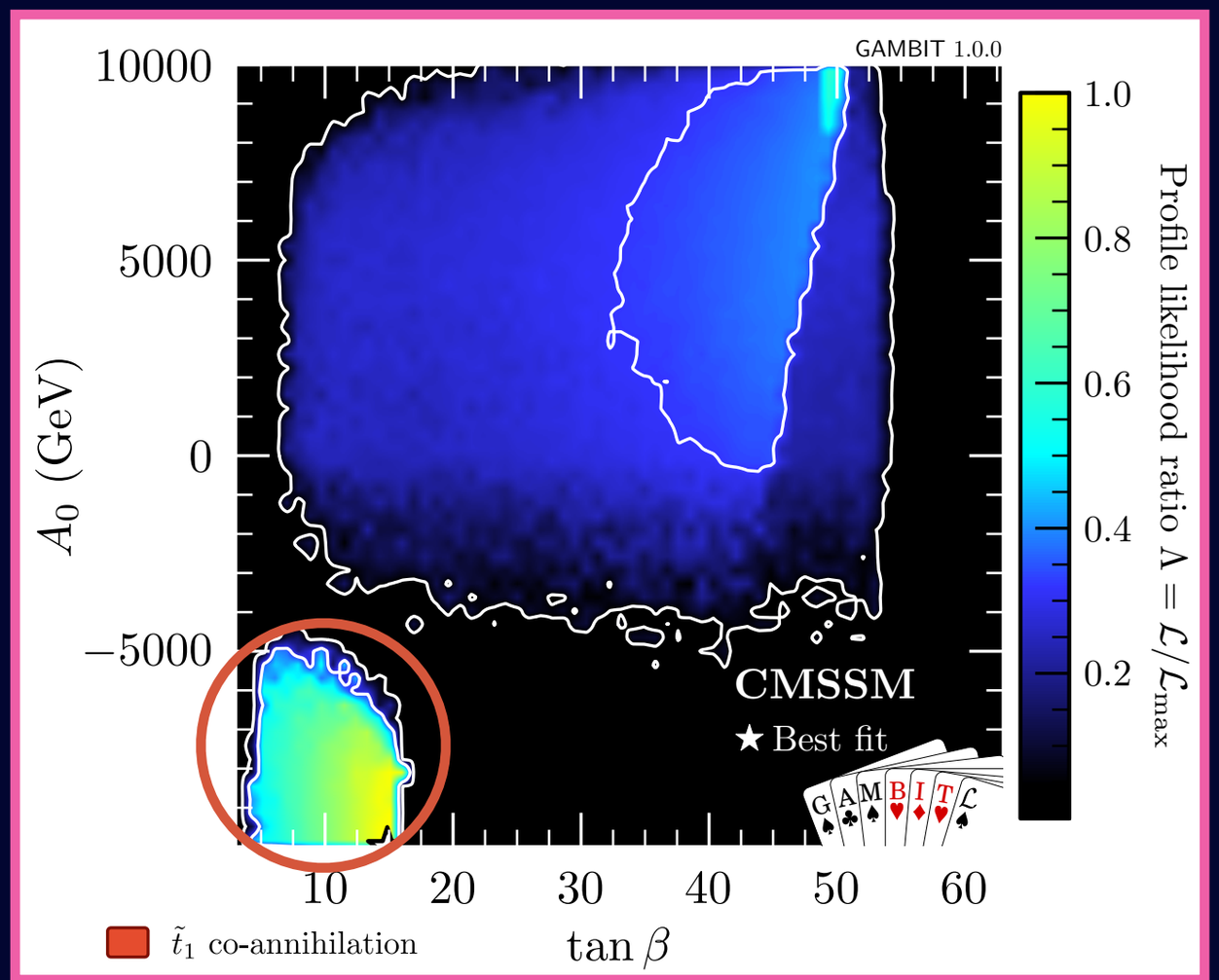
The GAMBIT Collaboration: Peter Athron[1,2,a], Csaba Balázs[1,2], Torsten Bringmann[3], Andy Buckley[4], Marcin Chrząszcz[5,6], Jan Conrad[7,8], Jonathan M. Cornell[9], Lars A. Dal[3], Joakim Edsjö[7,8], Ben Farmer[7,8,b], Paul Jackson[10,2], Abram Krislock[3], Anders Kvellestad[11,c], Farvah Mahmoudi[12,13,*], Gregory D. Martinez[14], Antje Putze[15], Are Raklev[3], Christopher Rogan[16], Roberto Ruiz de Austri[17], Aldo Saavedra[18,2], Christopher Savage[11], Pat Scott[19,d], Nicola Serra[5], Christoph Weniger[20], Martin White[10,2,e]

> “We found that whilst some points in this region do violate one or more of these conditions, removing all points that do so neither modifies the shapes of the likelihood contours in our plots, nor the fact that the best-fit occurs in the stop co-annihilation region. This question could in principle be investigated further by calculating the tunnelling probability for each point, e.g. using Vevacious [316]. However, it is not possible to do this in a reasonable amount of time with the large number of points in our scans. Even though the conditions above are not definitive, being neither necessary nor sufficient to establish that the vacuum of the theory breaks gauge invariance, neither is studying stability with tools such as Vevacious, due to the large number of scalar fields in the MSSM and the resulting difficulty of finding all relevant minima of the potential. We therefore leave”

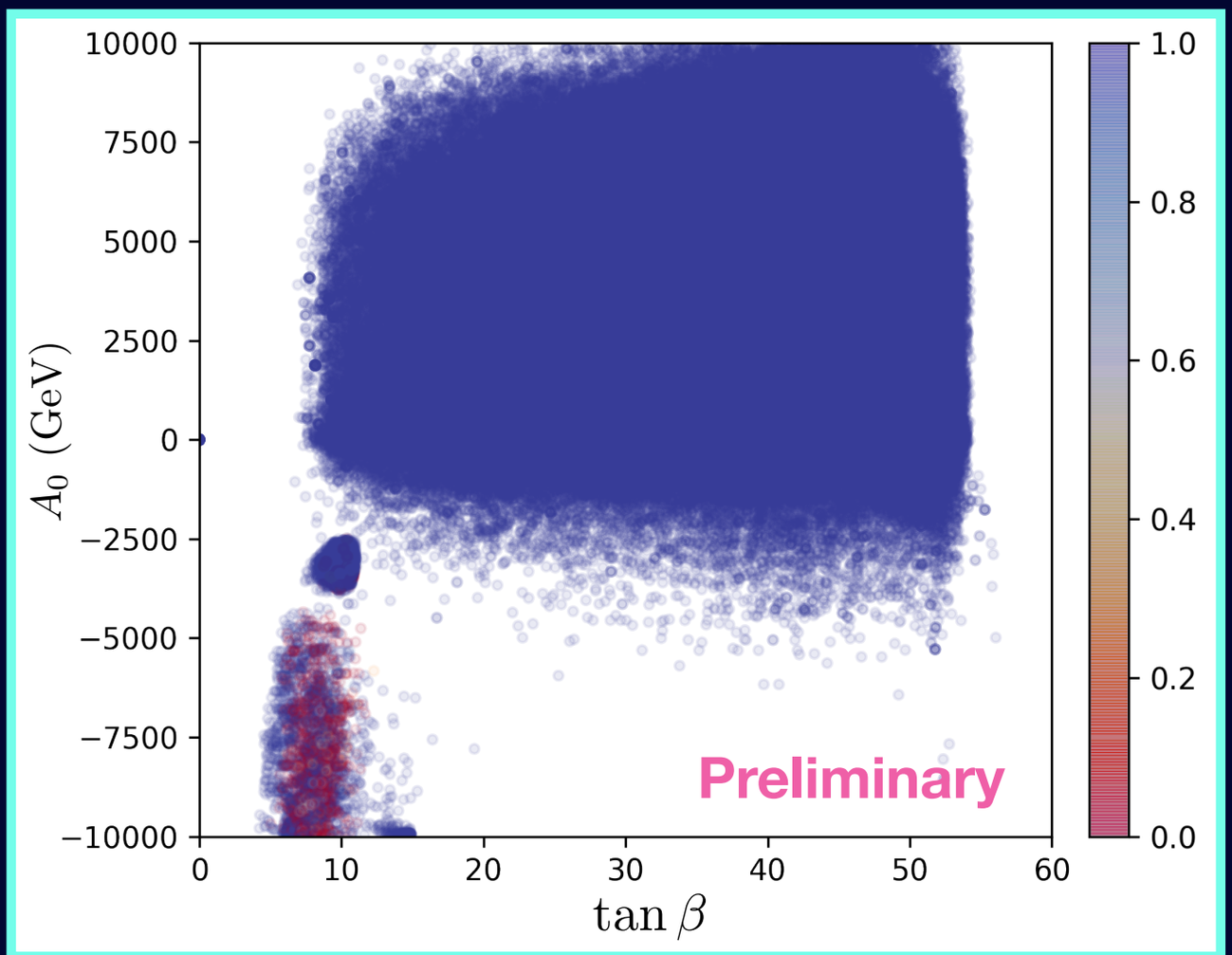
vevacious in global fits

- Vevacious will be a default backend in **GAMBIT**, starting with the MSSM and related models.
- Together we are working on post-processing the points of their CMSSM global fit and adding vacuum stability Likelihood.

vevacious in global fits



GAMBIT current global fit



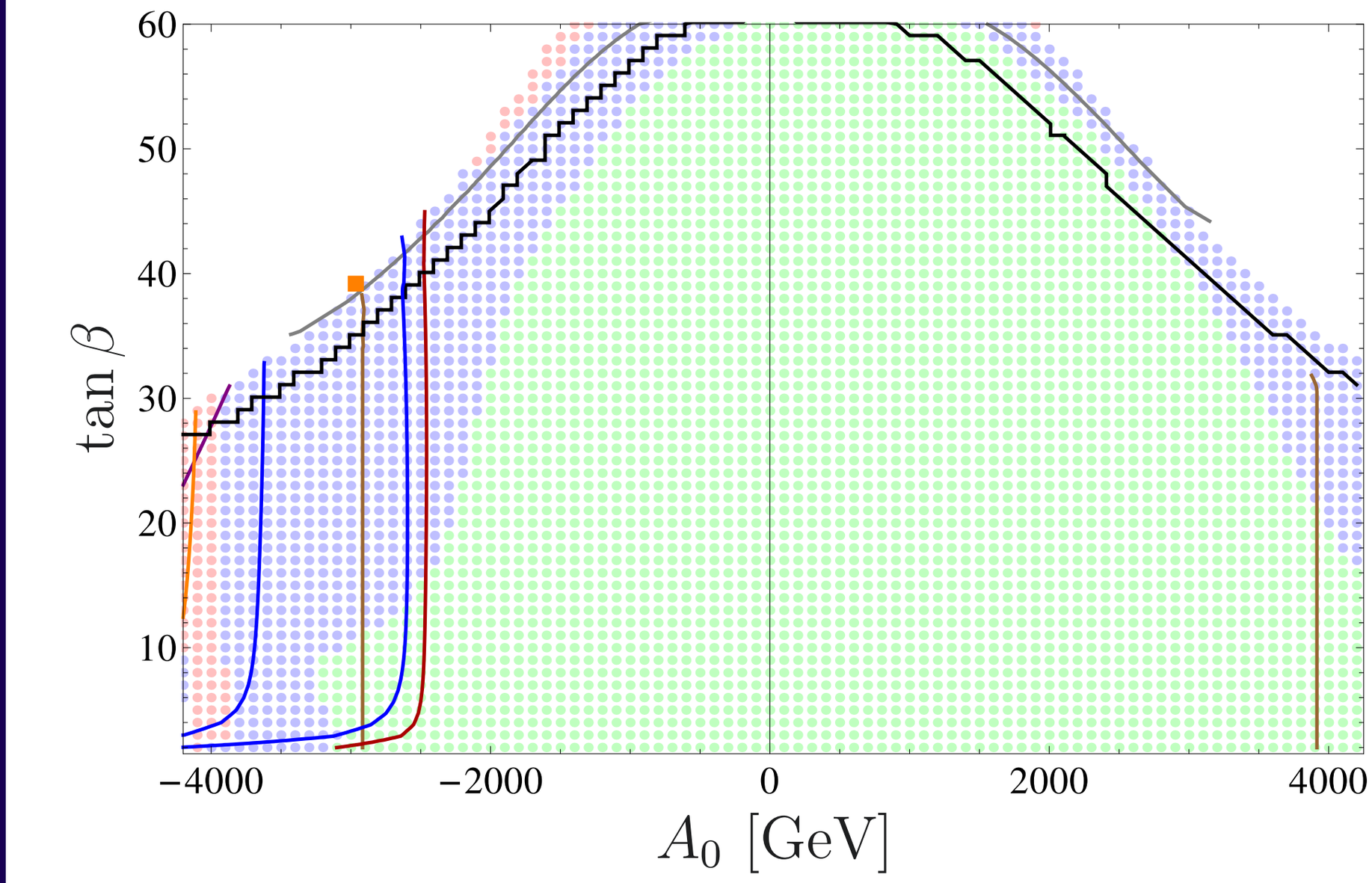
Vacuum Stability Likelihood alone
Including finite temperature
and one-loop corrections

Conclusions

- Parameter points of BSM models can pass all experimental constraints but one: We are here today!
- **YOU CAN NOT CHOOSE WHICH FIELDS HAVE VEVS**
- Symmetry breaking minima can provide complementary constraints, sometimes even in tension with other observables.

- Calculation is straightforward but there are subtleties.
- Vevacious is a platform to address that, open to extension, interfacing and customization.
- Available now to try. Talk to me if you are interested in a particular model to be added (though you can add your own easily).
- Ongoing studies together with GAMBIT.

Thank you


60
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tan β
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2000
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A_0 [GeV]

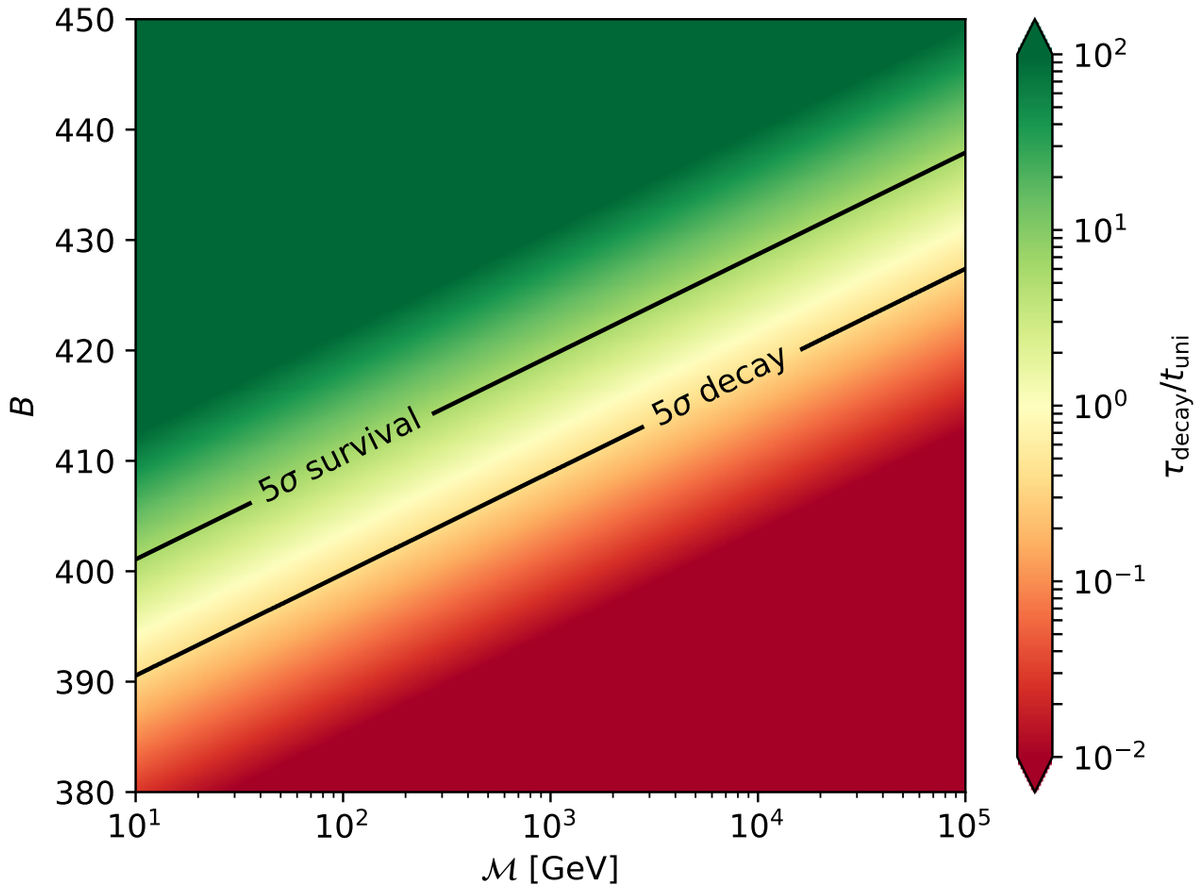
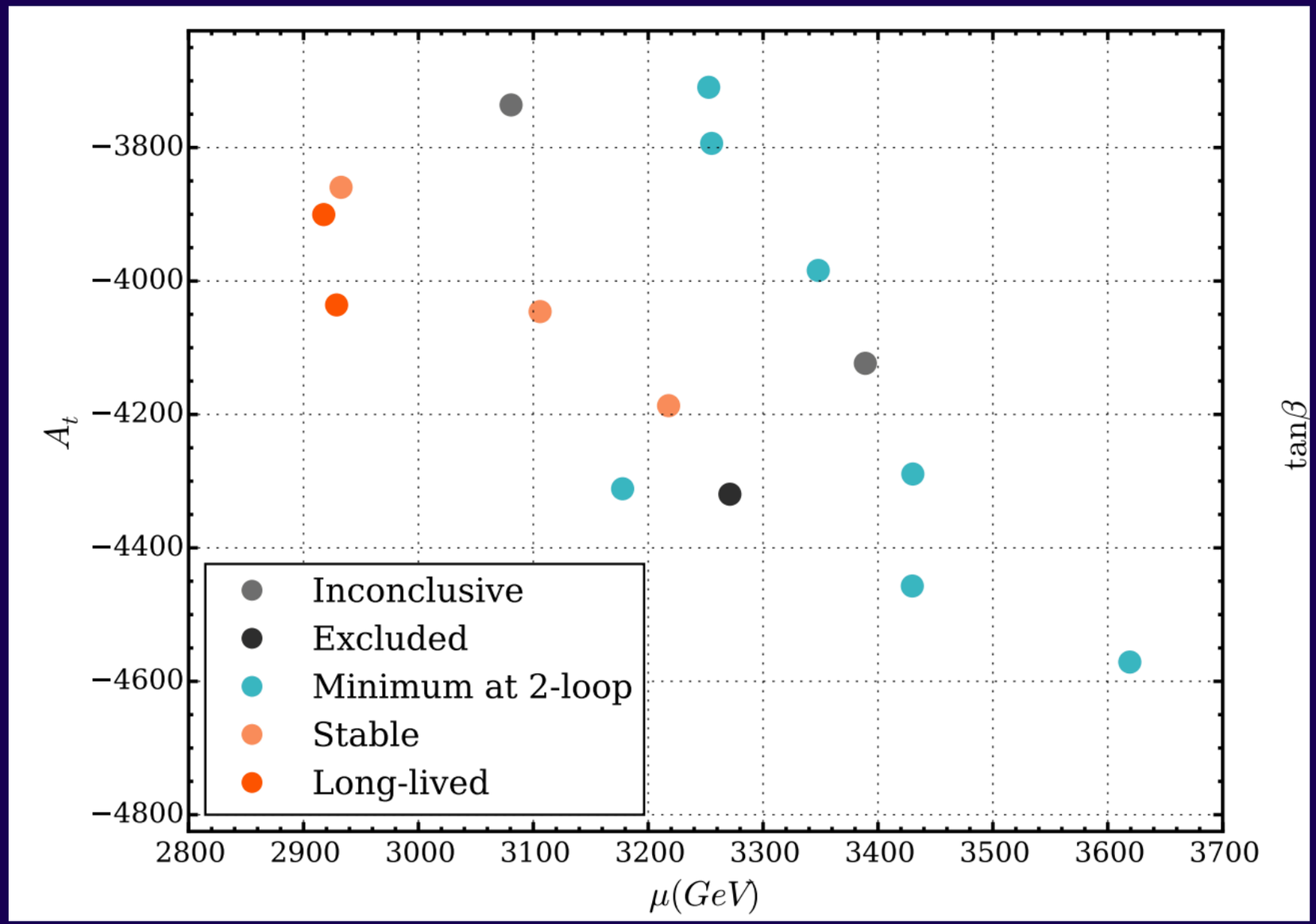


Figure 2. The lifetime of the metastable vacuum $\tau_{\rm decay}$ relative to the age of the universe $t_{\rm uni}$ is given in the plane of the scale $\mathcal{M}$ and the bounce action B. The contour lines denote a 5σ probability for decay and survival, respectively.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3700
$\mu(GeV)$
Inconclusive
Excluded
Minimum at 2-loop
Stable
Long-lived
tanβ