PhaseTracer

-- calculating cosmological phase transition properties

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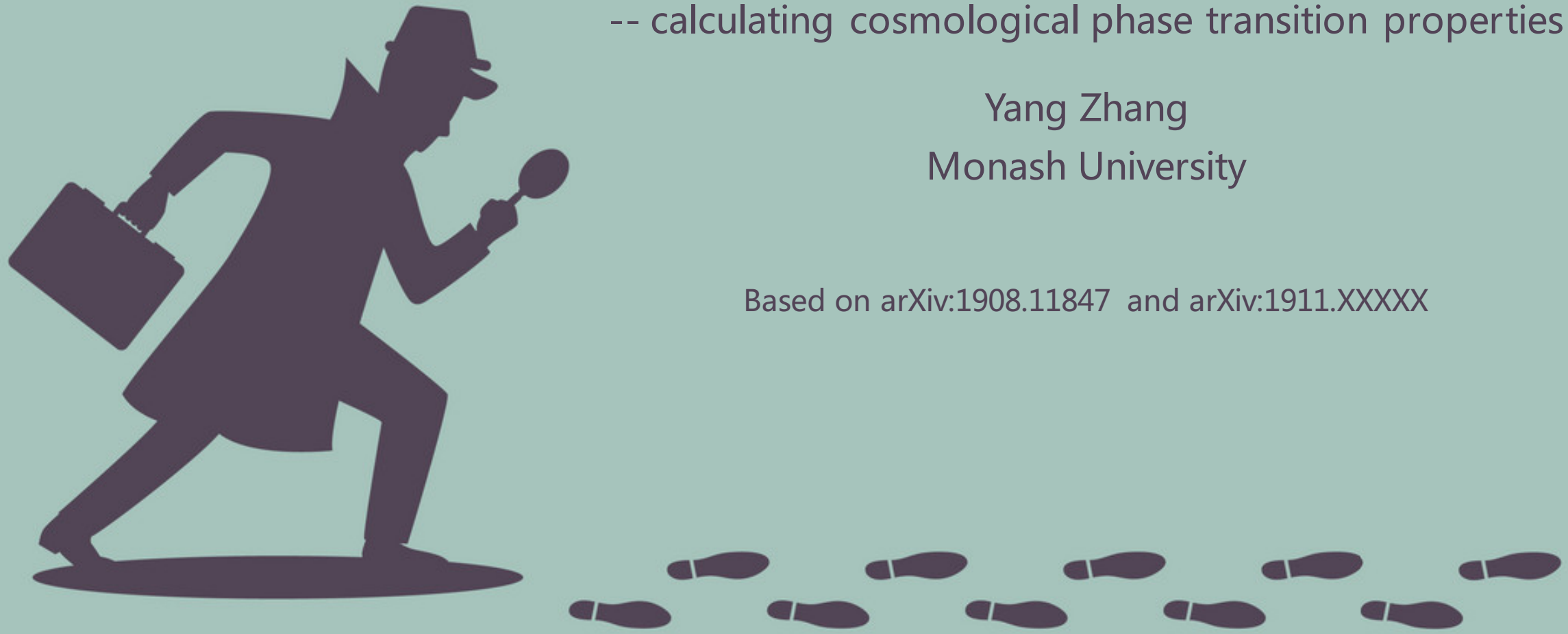
Based on arXiv:1908.11847 and arXiv:1911.XXXXX



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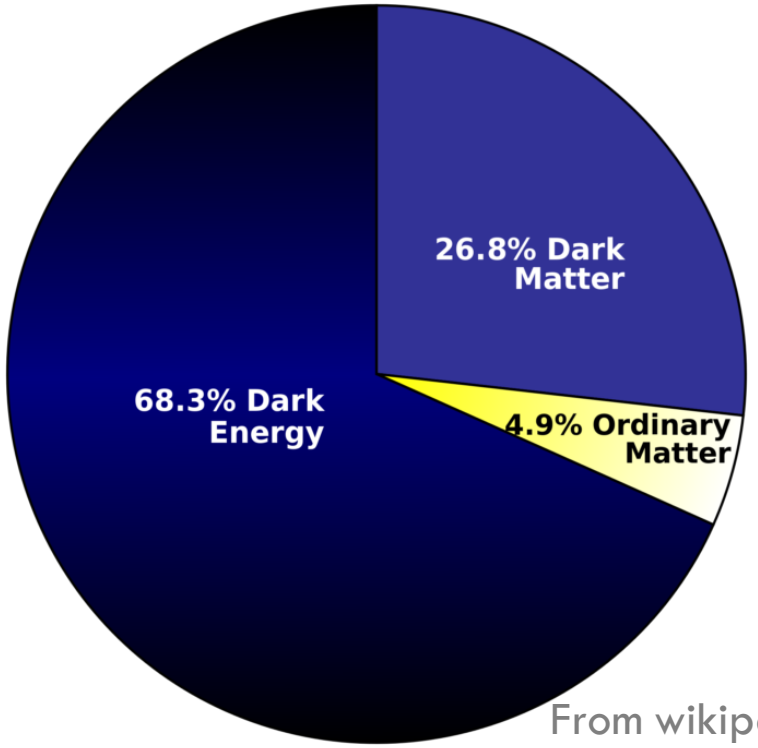
Introduction



From wikipedia

To explain the baryon asymmetry of the Universe (BAU)

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10},$$

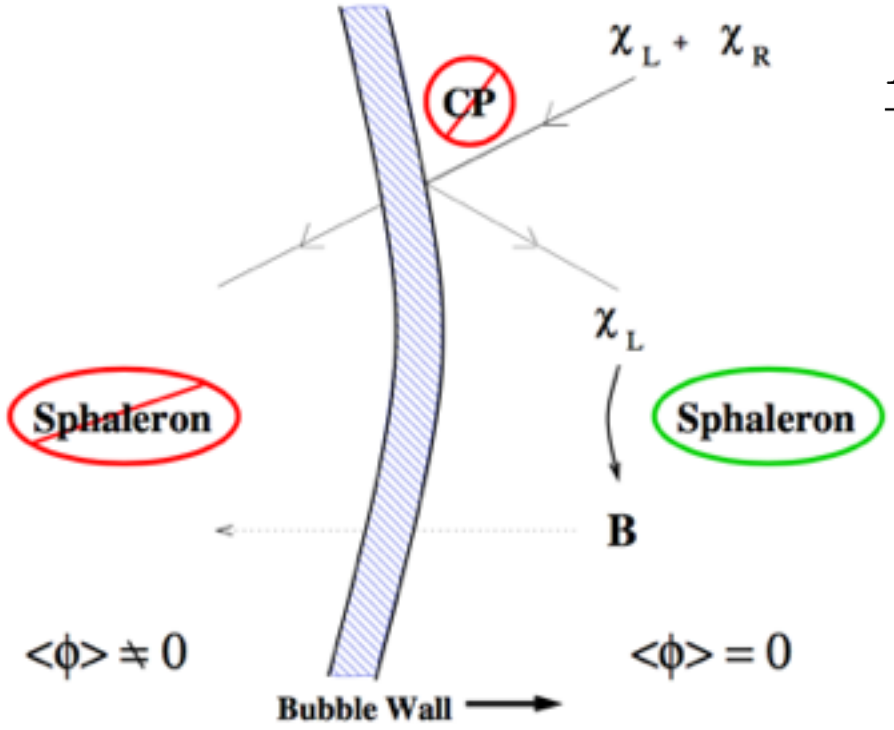
Sakharov Criteria for baryogenesis must be satisfied:

- Baryon number violation,
- C-symmetry and CP-symmetry violation,
- Interactions out of thermal equilibrium.
  - Realized by Electroweak phase transition

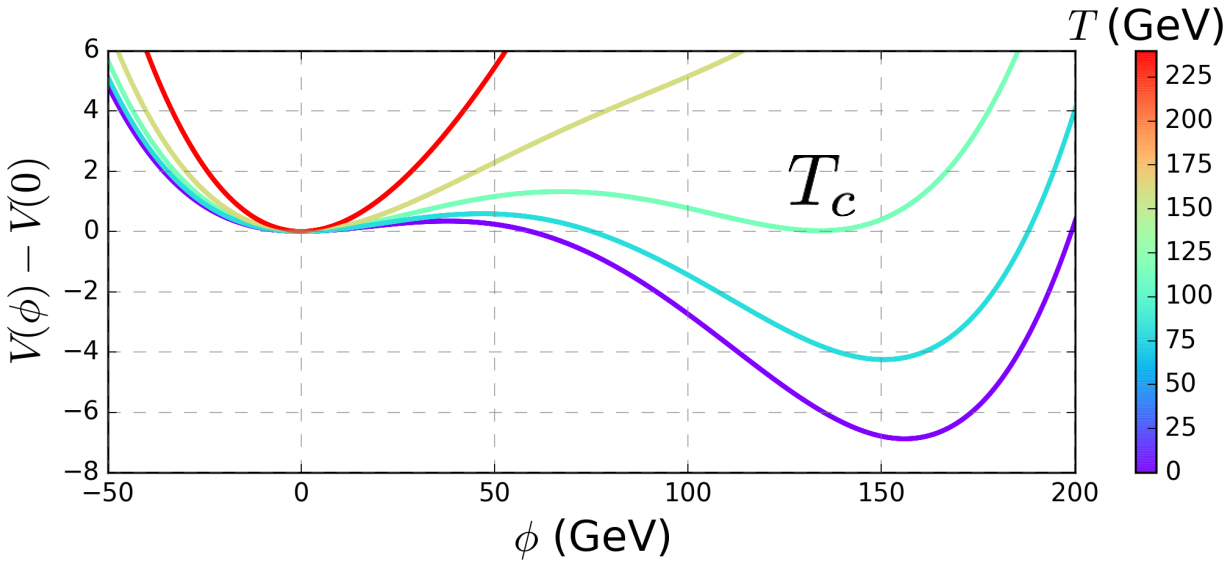
Introduction

In the broken phase, the rate of sphaleron transitions must be strongly suppressed. The bound can be translated into bound on the strength of transition:

$$\frac{E_{\rm sph}(T_c)}{T_c} > 37 \rightarrow \gamma \equiv \frac{\Delta\phi(T_c)}{T_c} \approx \frac{1}{36}\frac{E_{\rm sph}(T_c)}{T_c} > 1.0$$



arXiv:1206.2942



Calculation of transition strength

Method 1

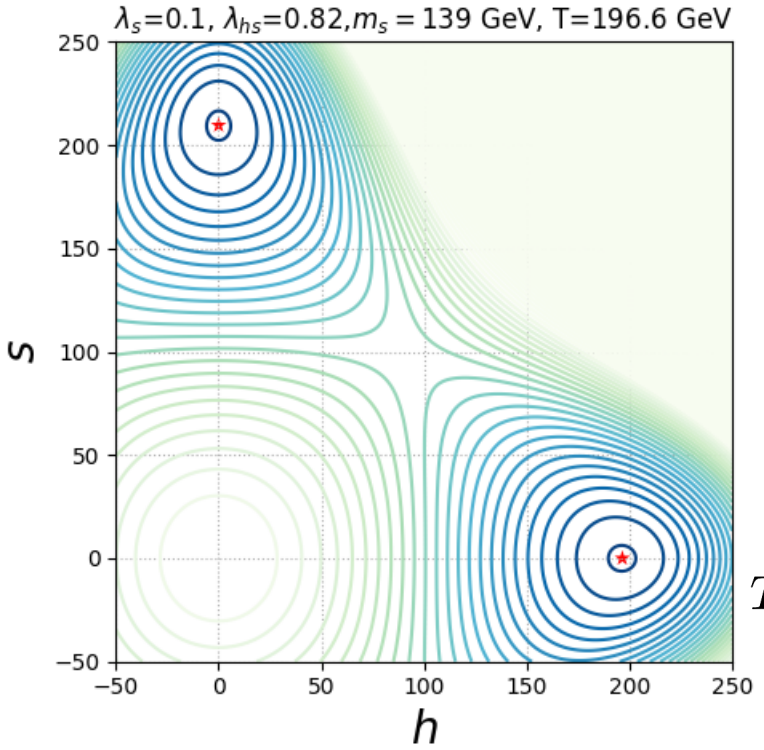
Analytic calculation

Method 2

Method 3

- SM + a Z2 symmetric real scalar singlet (arXiv:1611.02073)

$$V(H,s,T) = (\mu_h^2 + c_h T^2) H^\dagger H + \lambda_h (H^\dagger H)^2 + \frac{\lambda_{hs}}{2}(H^\dagger H) s^2 + \frac{(\mu_s^2 + c_s T^2)}{2} s^2 + \frac{\lambda_s}{4} s^4$$



$$\left.\frac{\partial V}{\partial v}\right|_{v_h, v_s = 0} = \left.\frac{\partial V}{\partial v}\right|_{v_s, v_h = 0} = 0$$

$$v_h = -\frac{\mu_h^2 + c_h T^2}{\lambda_h}, \quad v_s = -\frac{\mu_s^2 + c_s T^2}{\lambda_s}$$

$$V(v_h, 0, T_c) = V(0, v_s, T_c)$$

$$T_c^2 = \frac{\lambda_s c_h \mu_h^2 - \lambda_h c_s \mu_s^2 - \sqrt{\lambda_h \lambda_s} |c_s \mu_h^2 - c_h \mu_s^2|}{\lambda_s c_h^2 - \lambda_h c_s^2}$$

Calculation of transition strength

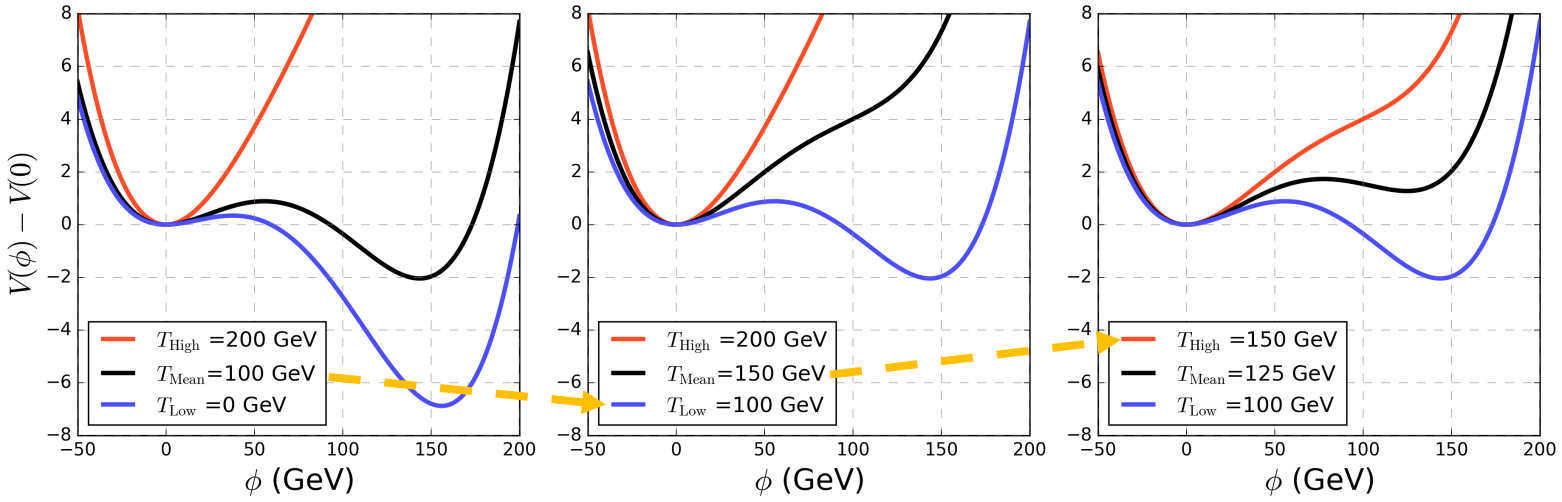
Method 1

Method 2

Bisection

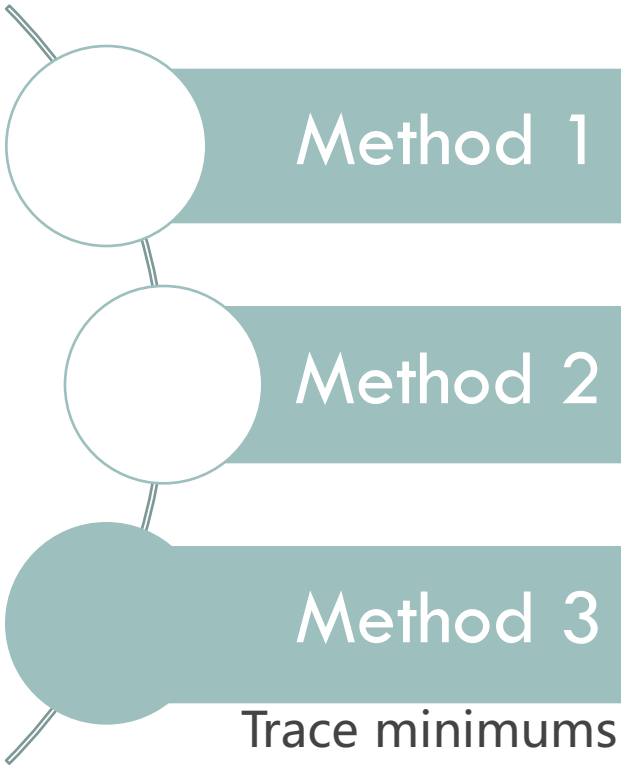
Method 3

Starting with an un-broken phase at high temperature and a broken phase at low temperature, find a temperature that these two phase degenerate using bisection method.

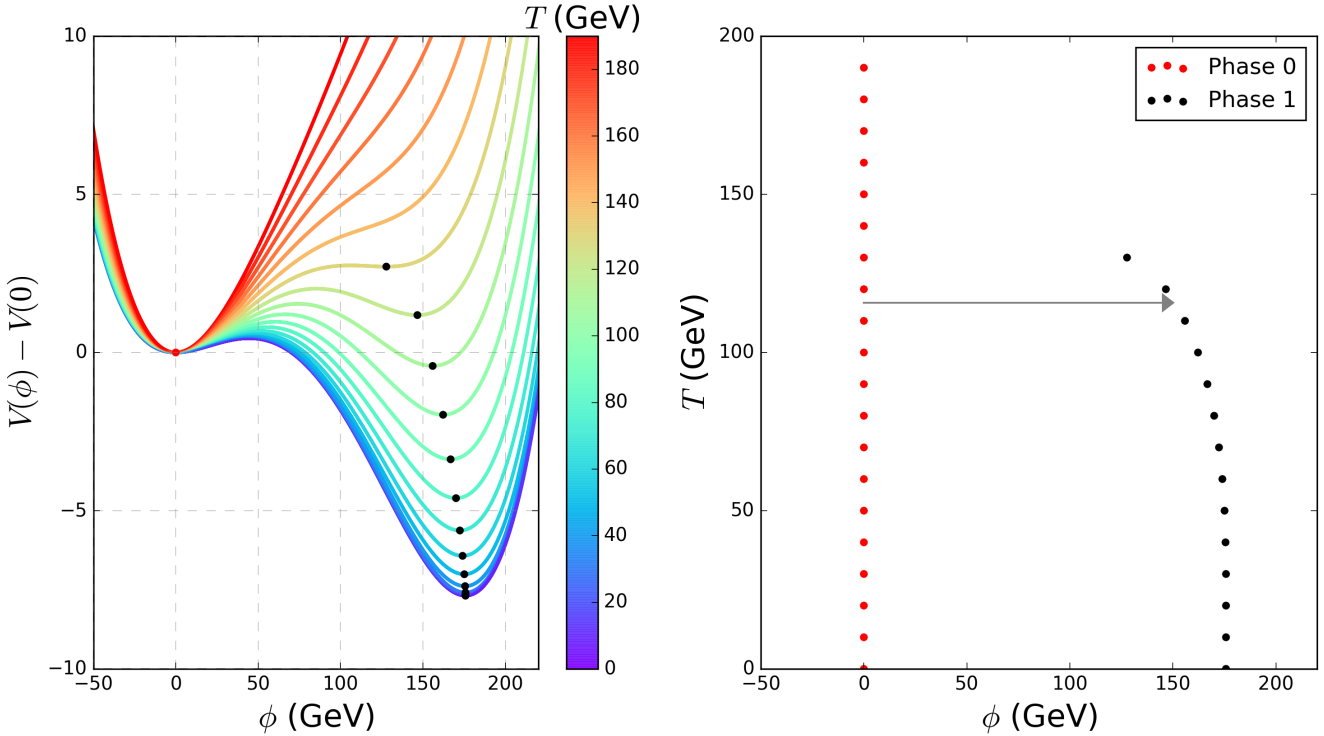


- Used in BSMPT (arXiv: 1803.02846)

Calculation of transition strength



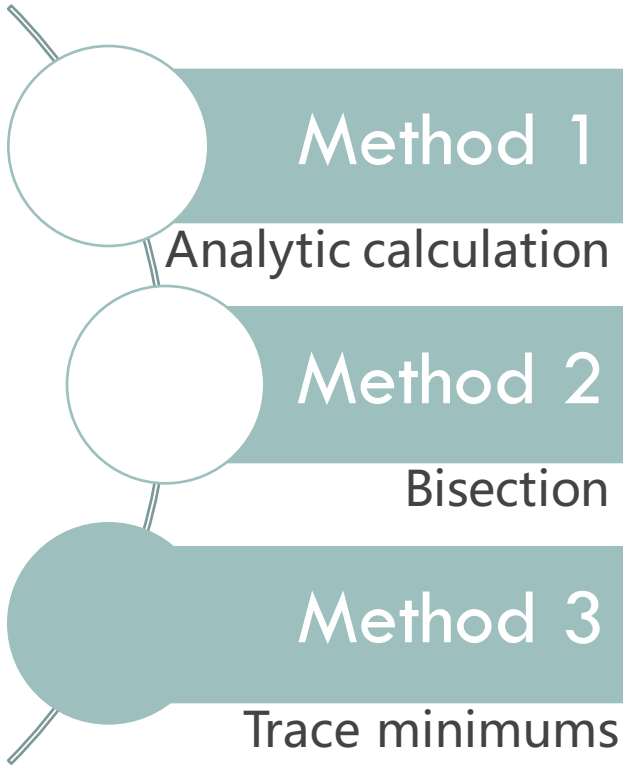
Starting with a minimum at low/high temperature, trace the location of minimum at different temperatures.



- Used in CosmoTransitions (arXiv: 1109.4189)

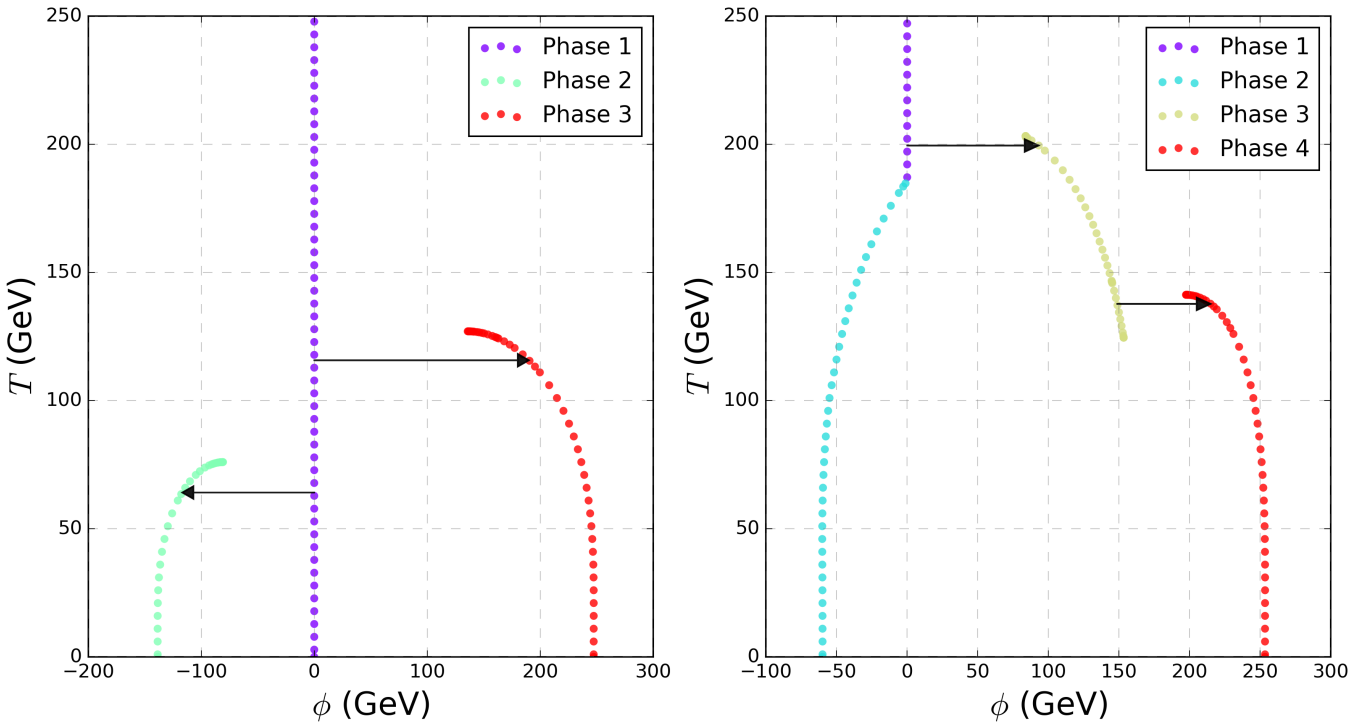
Calculation of transition strength

Fast, Stable, Many assumptions



Slow, Unstable, No assumption

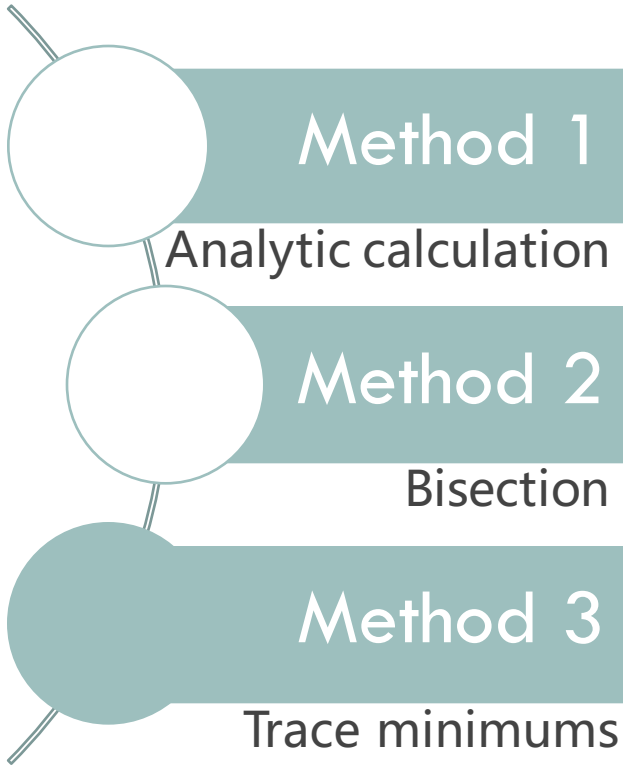
- Find more than one transitions.



- The phase structure can be used to calculate nucleation temperature, the time scale of phase transition …

Calculation of transition strength

Fast, Stable, Many assumptions

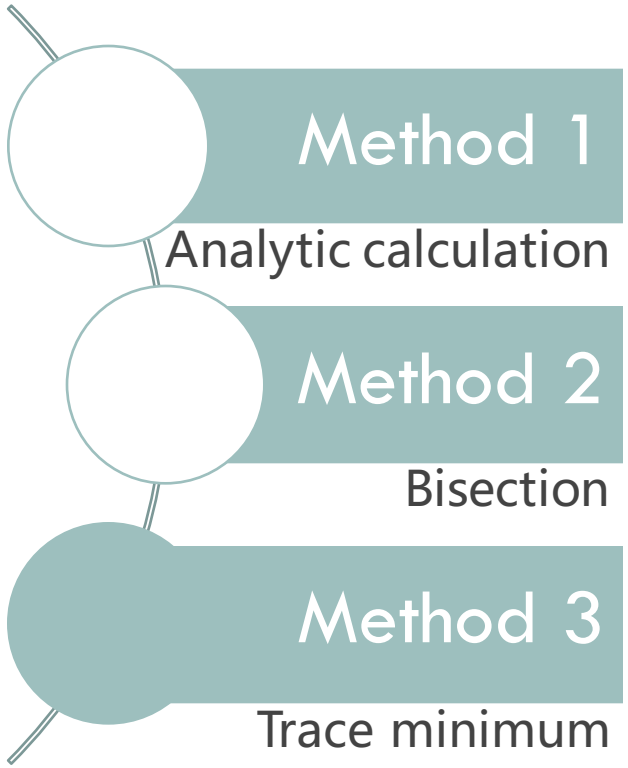


Slow, Unstable, No assumption

	2D simplified potential	NMSSM
CosmoTransitions	4.97 seconds	4 minutes

Calculation of transition strength

Fast, Stable, Many assumptions



Slow, Unstable, No assumptions

Based on method 3, we develop a C++ program, **PhaseTracer**, to map **phase structure** and calculate **transition strength**. Comparing with CosmoTransition（the transition strength calculation part), Phasetracer is optimized for scan:

- Faster

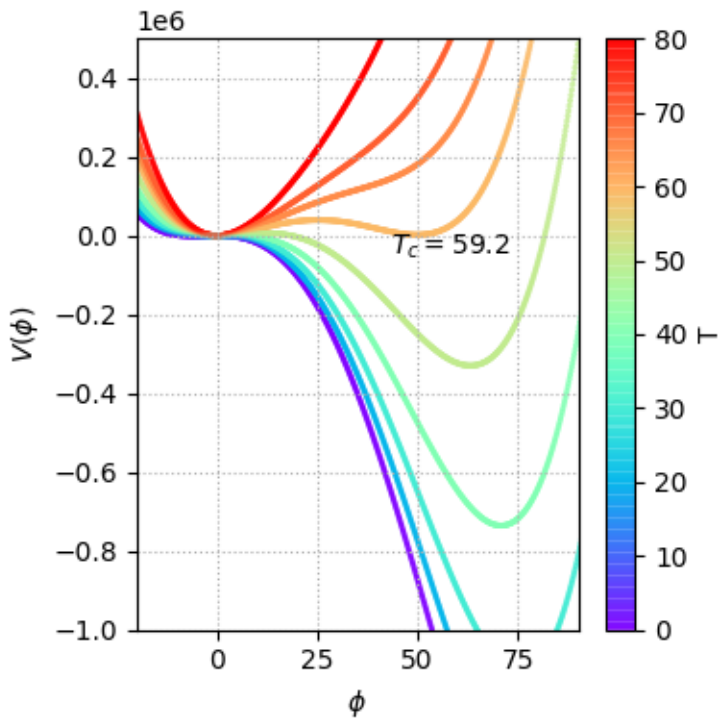
	2D simplified potential	NMSSM
CosmoTransitions	4.97 seconds	4 minutes
PhaseTracer	0.063 second	8.9 seconds

- Relatively stable for complex potential.

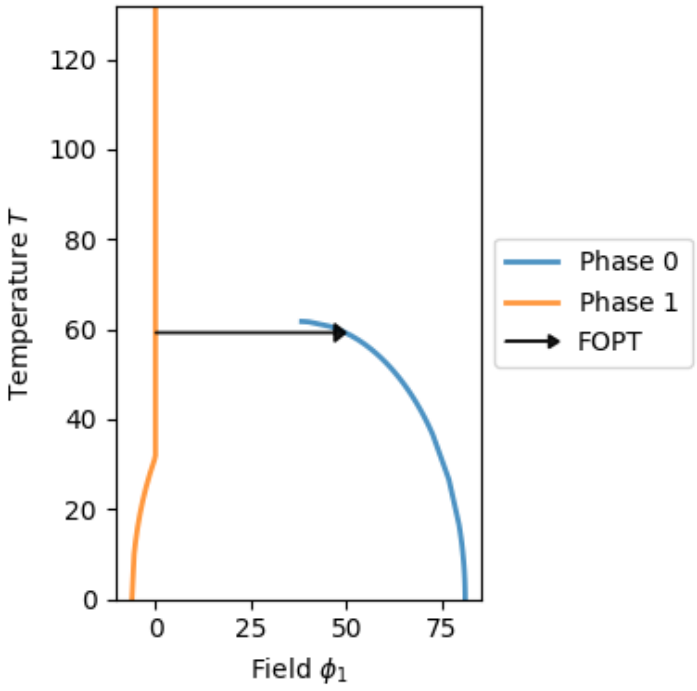
We performed a comprehensive scan for NMSSM with PhaseTracer, and collected more than 3 million valid points .

Example: 1-D test model

$$V(\phi, T) = -100\phi^2 - 10\phi^3 + 0.1\phi^4 + 0.1\phi^2 T^2,$$



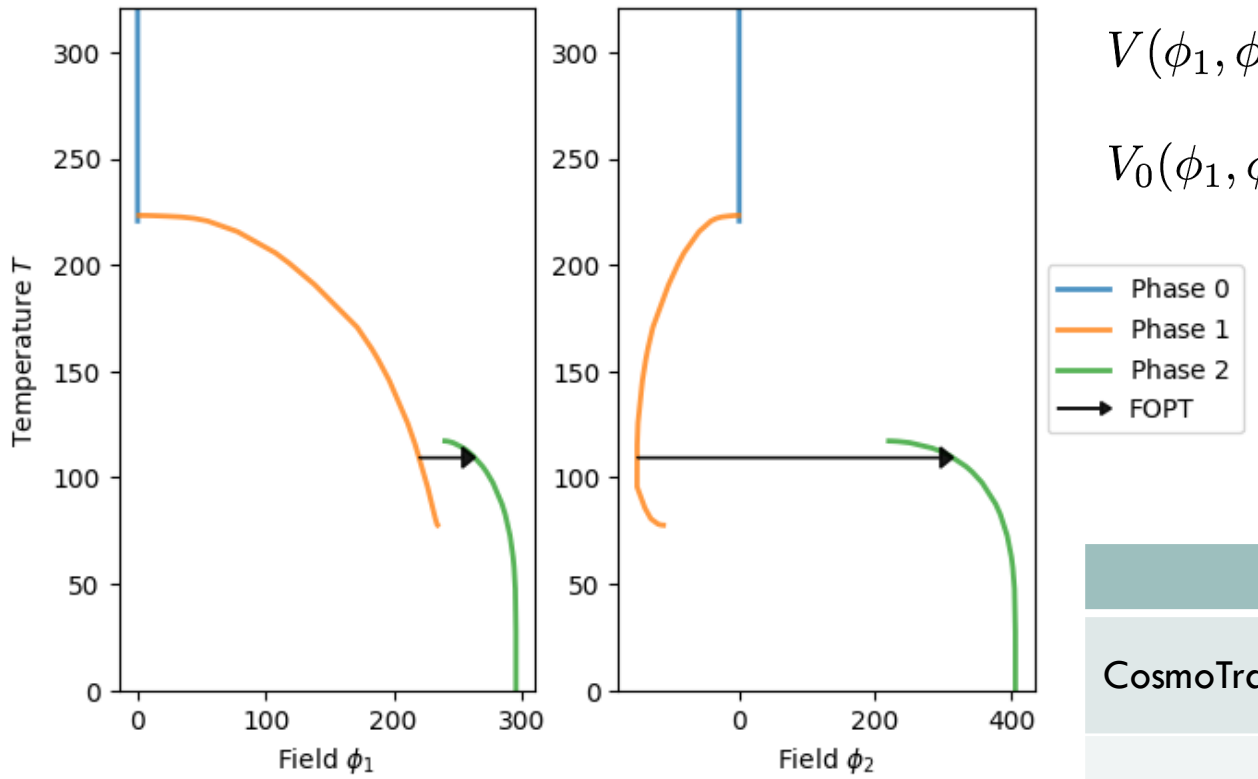
Automatically generated by PhaseTracer




```
$ ./bin/run_1D_test_model
=== phase key = 0 ===
Maximum temperature = 61.7344
Minimum temperature = 0
Field at tmax = [38.3267]
Field at tmin = [81.1602]
Potential at tmax = 65720
Potential at tmin = -1.66587e+06
Ended at tmax = Jump in fields indicated end of phase
Ended at tmin = Reached tstop
=== phase key = 1 ===
Maximum temperature = 1000
Minimum temperature = 0
Field at tmax = [2.0146e-06]
Field at tmin = [-6.16063]
Potential at tmax = 4.05456e-07
Potential at tmin = -1313.12
Ended at tmax = Reached tstop
Ended at tmin = Reached tstop

found 1 transition
=== transition from 2 to 1 ===
true vacuum = [49.8362]
false vacuum = [2.0146e-06]
changed = [true]
TC = 59.2295
gamma = 0.841408
```

Example: 2-D test model



The examples implemented in CosmoTransitions:

$$V(\phi_1, \phi_2, T) = V_0(\phi_1, \phi_2) + V_1(\phi_1, \phi_2) + V_{1T}(\phi_1, \phi_2, T).$$

$$V_0(\phi_1, \phi_2) = \frac{1}{8}\frac{m_1^2}{v^2}(\phi_1^2 - v^2) + \frac{1}{8}\frac{m_2^2}{v^2}(\phi_2^2 - v^2) - \mu^2\phi_1\phi_2$$

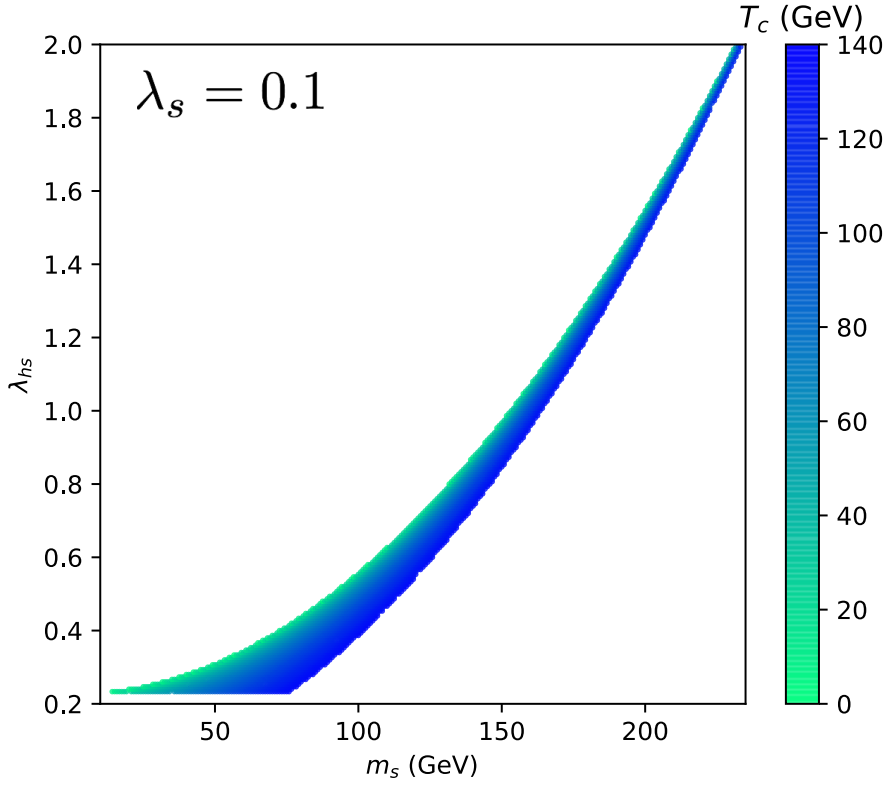
$$V_1(\phi) = \pm\frac{1}{64\pi^2}\sum_i n_i m_i^4(\phi)\left[\log\frac{m_i^2(\phi)}{Q^2} - c_i\right],$$

$$V_{1T}(\phi, T) = \frac{T^4}{2\pi^2}\sum_i n_i J_{\mp}\left(\frac{m_i(\phi)}{T}\right)$$

	Tc(GeV)	False VEV	True VEV	Elapsed time
CosmoTransitions	109.408	(220.0, -150.0)	(263.5, 314.7)	4.97 seconds
PhaseTracer	109.408	(220.0, -150.0)	(263.5, 314.7)	0.07 second

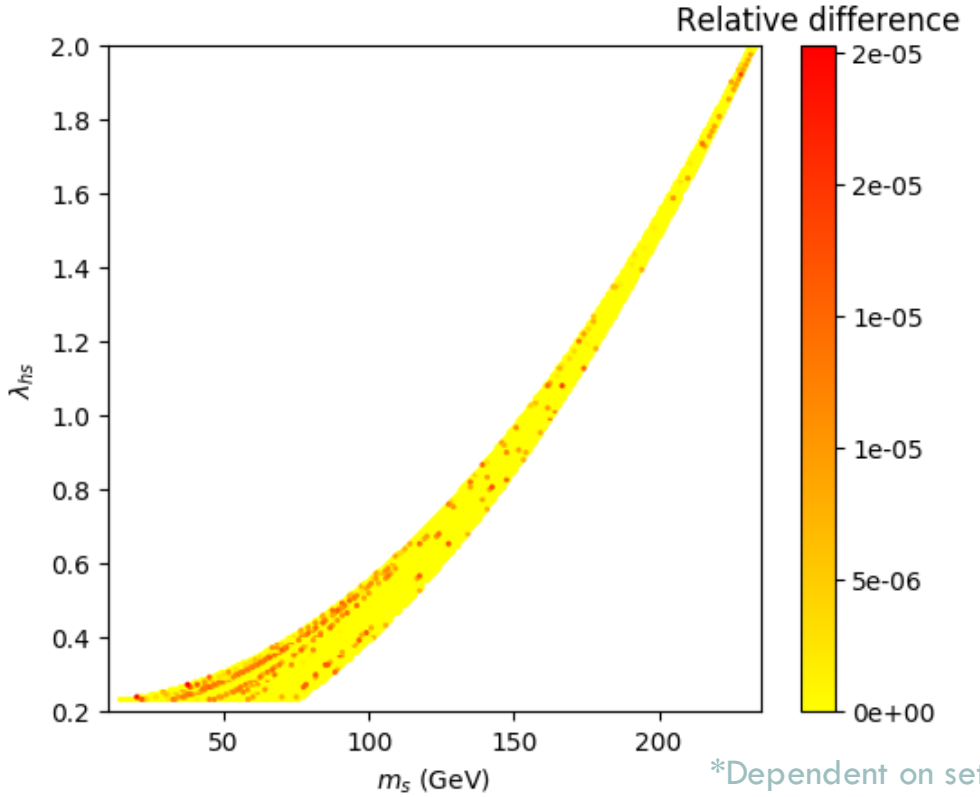
Example: Z2 Scalar Singlet Model

$$V(H,s) = (\mu_h^2 + c_h T^2) H^\dagger H + \lambda_h (H^\dagger H)^2 + \frac{\lambda_{hs}}{2}(H^\dagger H)s^2 + \frac{(\mu_s^2 + c_s T^2)}{2}s^2 + \frac{\lambda_s}{4}s^4$$



Obtained from PhaseTracer

$$T_c^2 = \frac{\lambda_s c_h \mu_h^2 - \lambda_h c_s \mu_s^2 - \sqrt{\lambda_h \lambda_s}|c_s \mu_h^2 - c_h \mu_s^2|}{\lambda_s c_h^2 - \lambda_h c_s^2}$$



*Dependent on setting

Example: NMSSM

Strong first-order phase transitions in the NMSSM - a comprehensive survey (arXiv:1908.11847)
Peter Athron, Csaba Balazs, Andrew Fowlie, Giancarlo Pozzo, Graham White, Yang Zhang

SARAH, FlexibleSUSY
Construct model and calculate the effective potential

↓

Lilith, HiggsBounds
LHC Run I and II measurements of the Higgs boson

↓

PhaseTracer
Calculate transition strength and check phase structure

↓

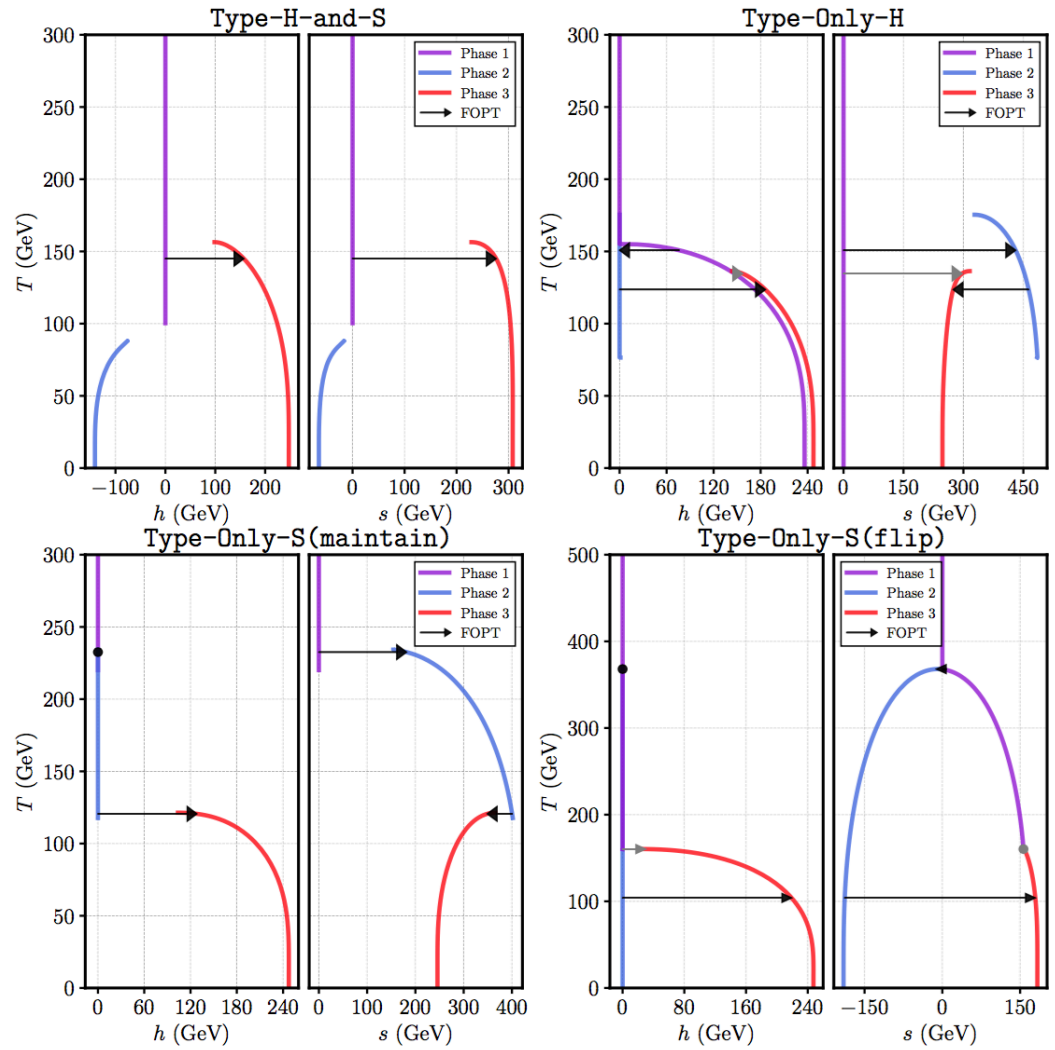
MultiNest
Perform the scan

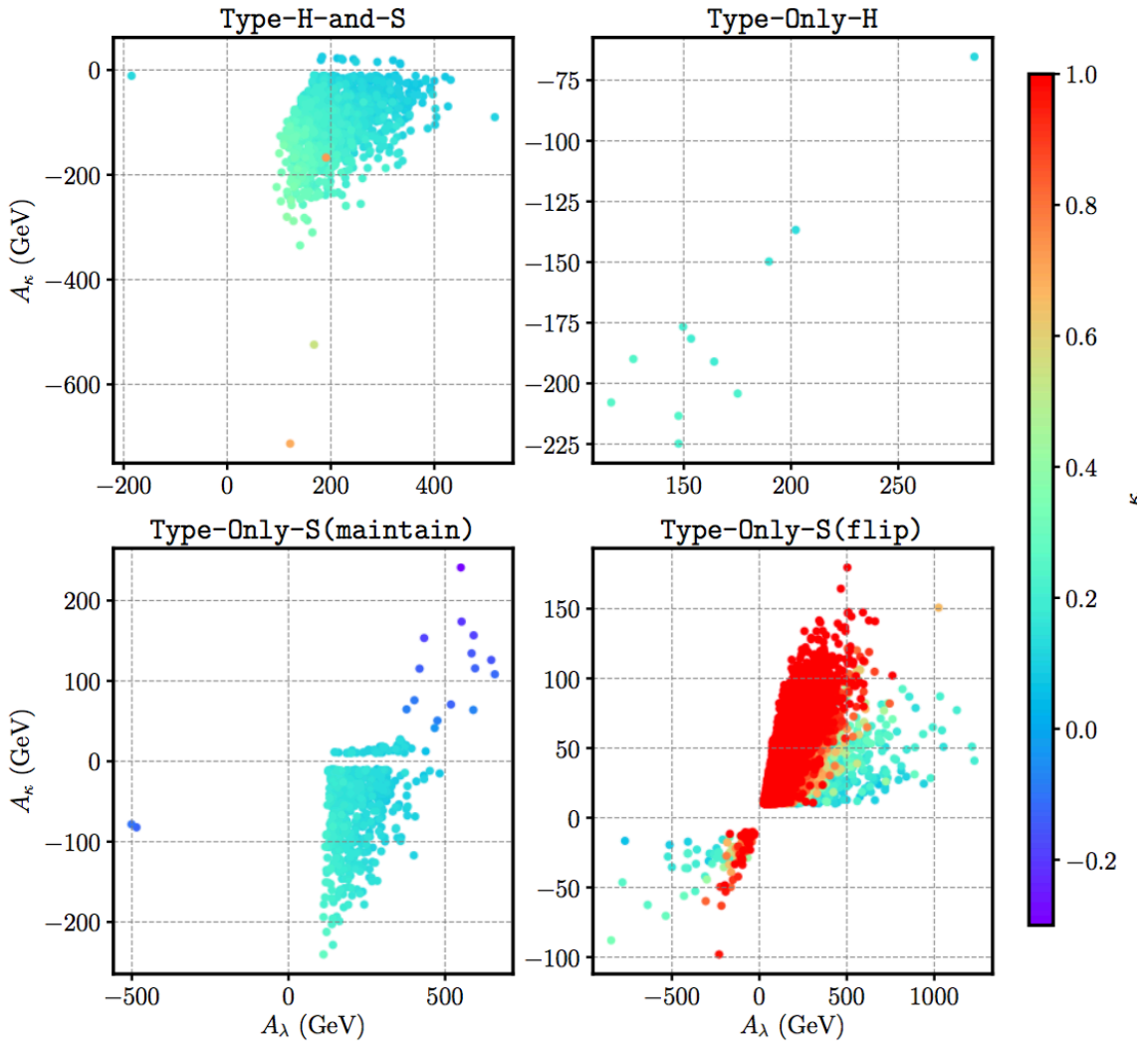
Parameter	Range	Metric
λ	$0,\ \pi/2$	flat
$\lvert\kappa\rvert$	$0,\ \pi/2$	flat
$\lvert A_\lambda\rvert$	$0,\ 10\,\mathrm{TeV}$	hybrid
$\lvert A_\kappa\rvert$	$0,\ 10\,\mathrm{TeV}$	hybrid
$\lvert A_t\rvert$	$0,\ 10\,\mathrm{TeV}$	hybrid
m_{SUSY}	$1,\ 10\,\mathrm{TeV}$	log
$\lvert v_S\rvert$	$0,\ 10\,\mathrm{TeV}$	hybrid
$\tan\beta$	$1,\ 60$	log

$$\chi^2 = \chi^2_{\mathrm{Higgs}} + \chi^2_{\mathrm{SFOPT}} + \chi^2_{\mathrm{LEP}}$$

Example: NMSSM

From arXiv:1908.11847





Summary

PhaseTracer

- Find cosmological phases and calculate transition properties.
- Relatively fast and stable, suitable for scan.
- Easily linked to FlexibleSUSY to obtain field-dependent masses.

Upcoming

- PhaseTracer will link to BubbleProfiler to get actions, and then calculate nucleation temperature and other transition properties.
- The codes will be public soon.