11th LISA CosWG Workshop

A tool for Cosmological Phase Transitions and GWs

Physics Department – University of Porto

2024-06-18

Marco Finetti

Project ID

PRT/BD/154730/2023
Bolsas de Investigação para
Doutoramento FCT-ECIU

Supervisors

António Morais
University of Aveiro | Gr@v

Germano Nardini
University of Stavanger

Contributors

Vedran Brdar (Oklahoma State U.)

Marco Finetti (U. of Aveiro)

Marco Matteini (Jožef Stefan Institute)

António Morais (U. of Aveiro)

Miha Nemevšek (Jožef Stefan Institute)

Universidade de Aveiro
theoria poiesis praxis

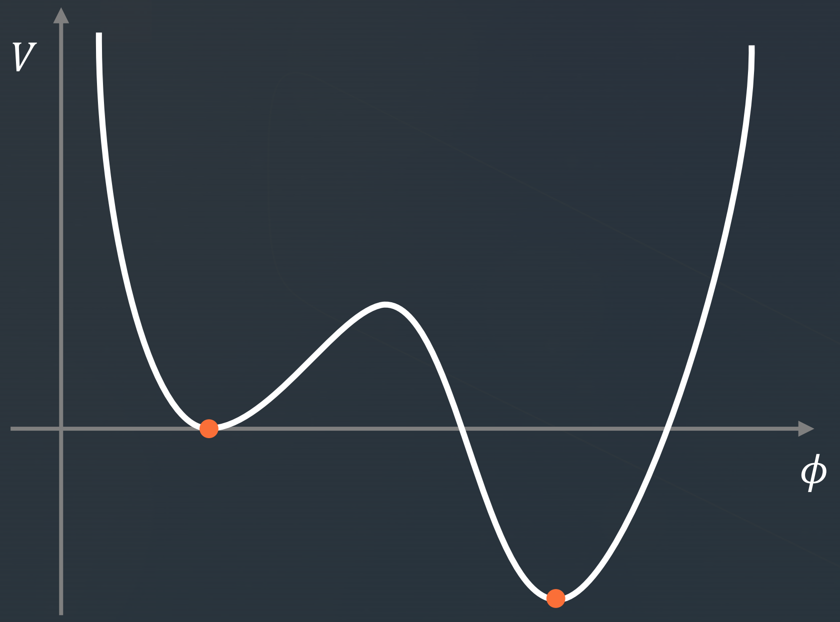
Fundação para a Ciência e a Tecnologia

Cosmological Phase Transitions

& Single-Field Models

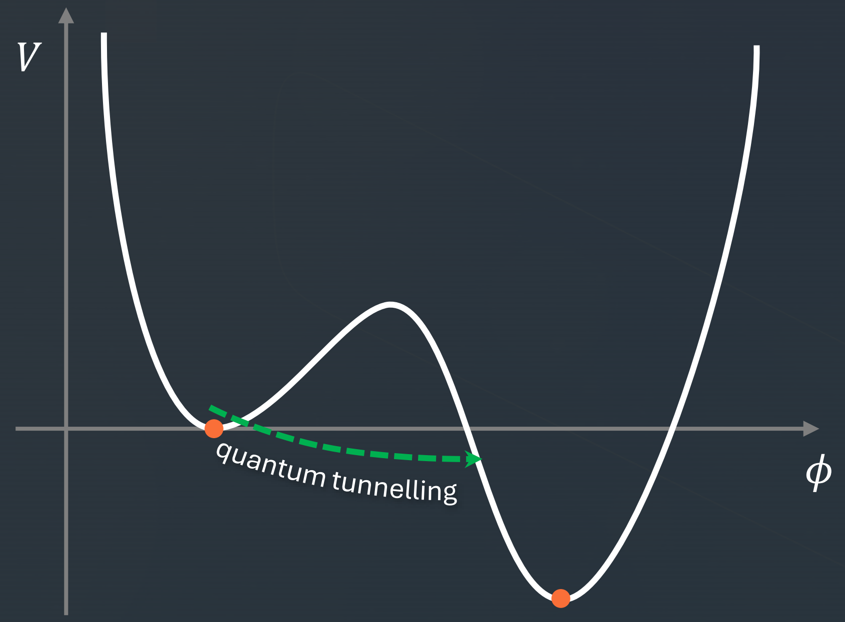
Cosmological Phase Transitions
& Single-Field Models

I order phase transitions (FOPTs)



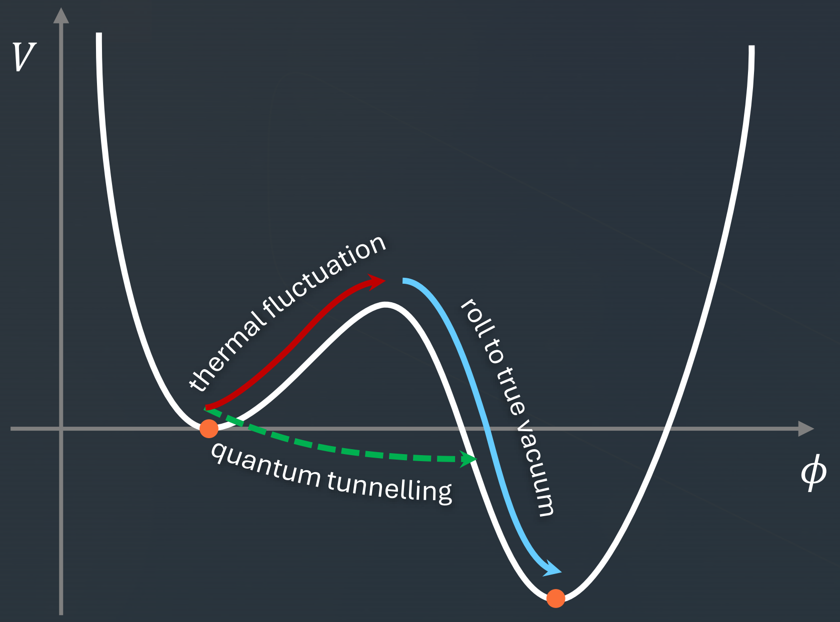
Cosmological Phase Transitions
& Single-Field Models

I order phase transitions (FOPTs)



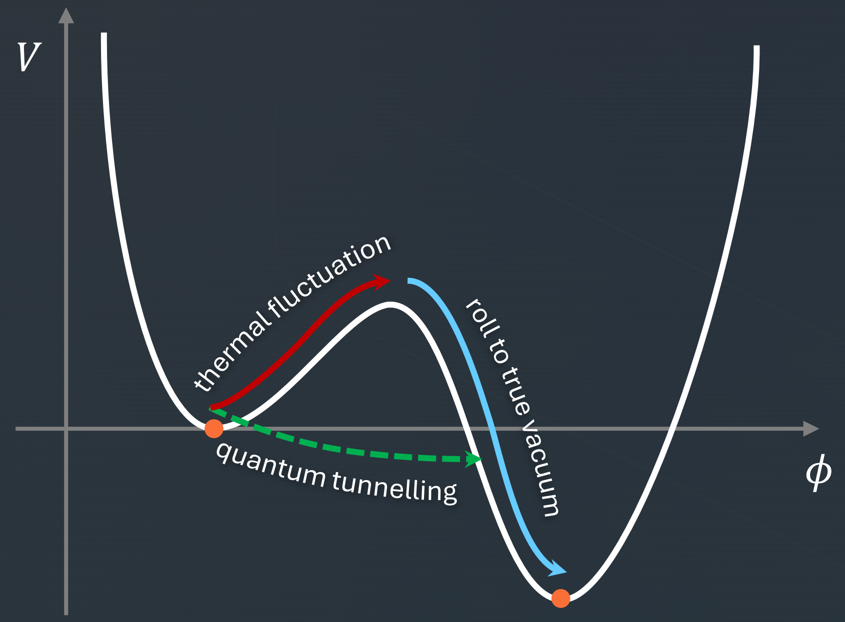
Cosmological Phase Transitions
& Single-Field Models

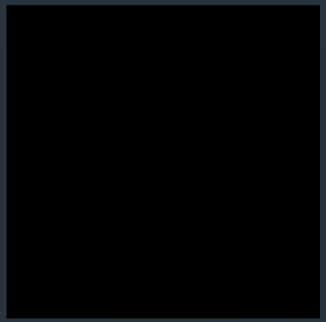
I order phase transitions (FOPTs)



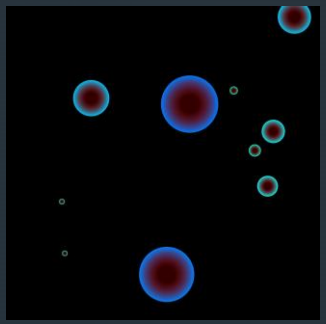
Cosmological Phase Transitions
& Single-Field Models

I order phase transitions (FOPTs)



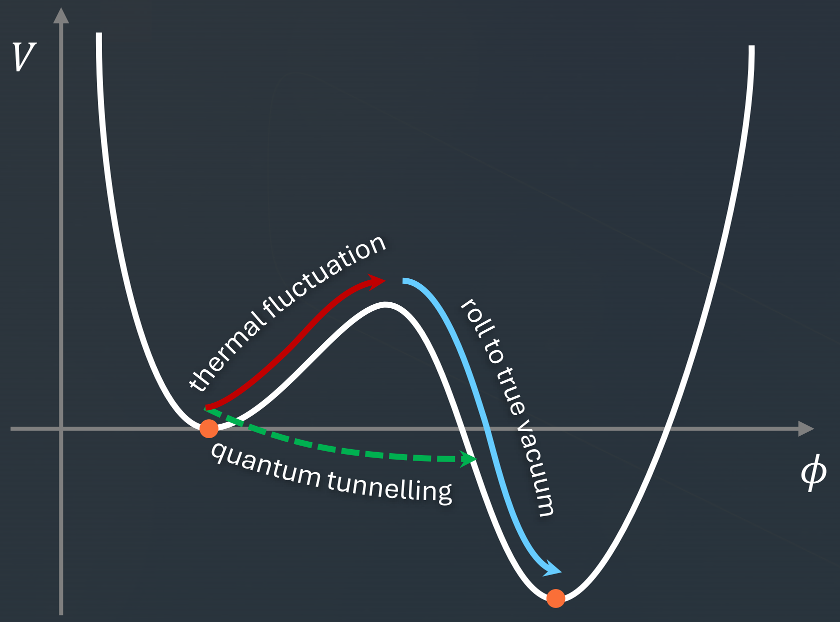


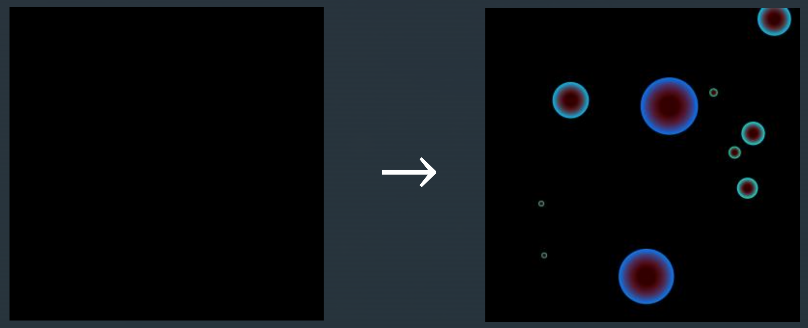
→



Cosmological Phase Transitions
& Single-Field Models

I order phase transitions (FOPTs)

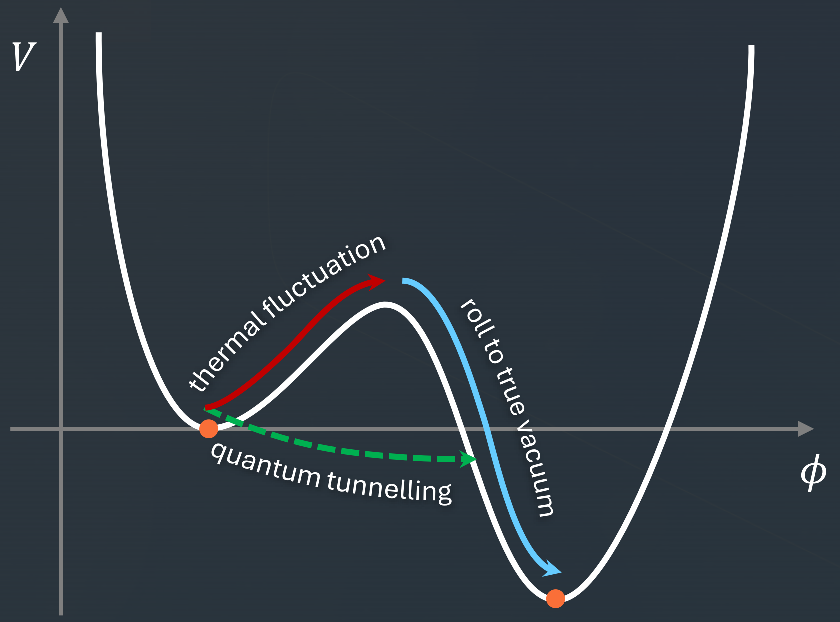


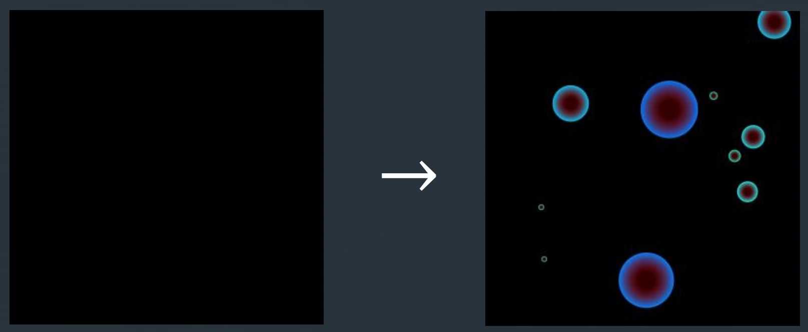


BSM physics

Cosmological Phase Transitions
& Single-Field Models

I order phase transitions (FOPTs)



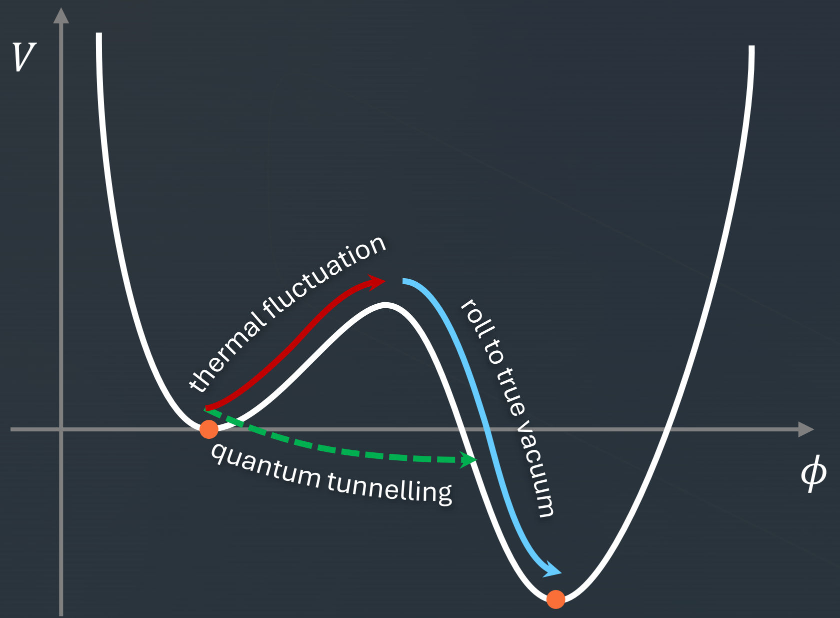


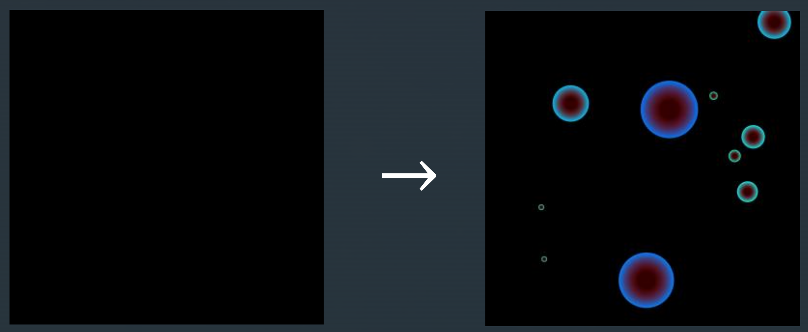
BSM physics

- EW baryogenesis

Cosmological Phase Transitions
& Single-Field Models

I order phase transitions (FOPTs)



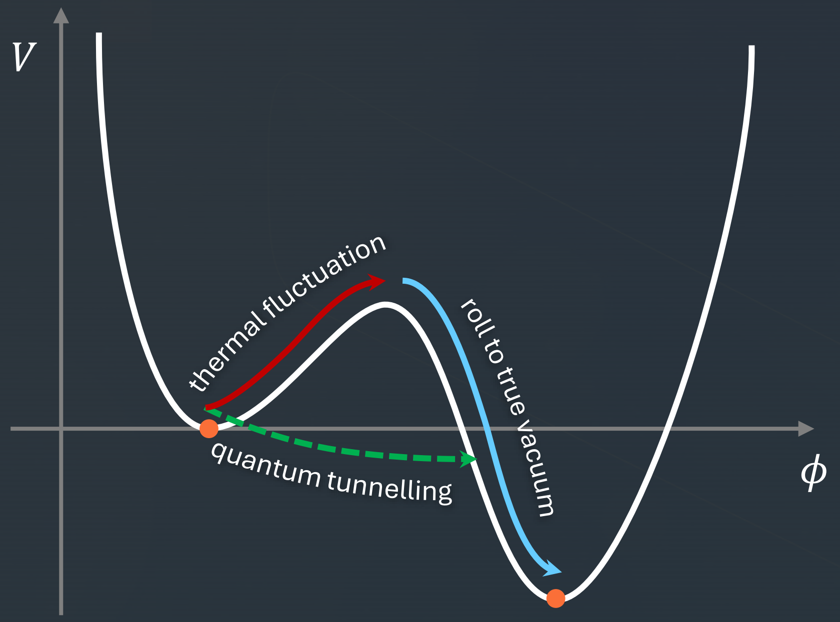


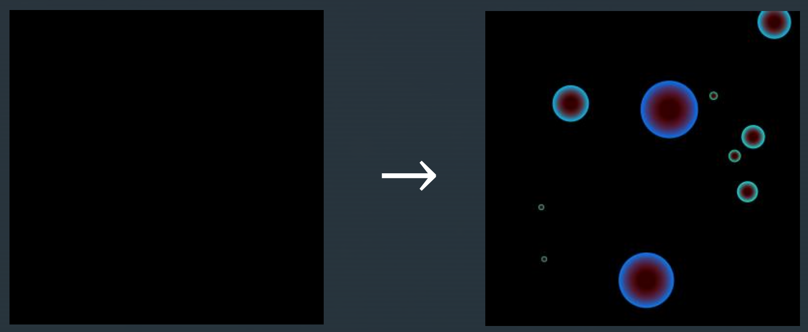
BSM physics

- EW baryogenesis
- Allowing multiple vacuum directions (multi-field models)

Cosmological Phase Transitions
& Single-Field Models

I order phase transitions (FOPTs)





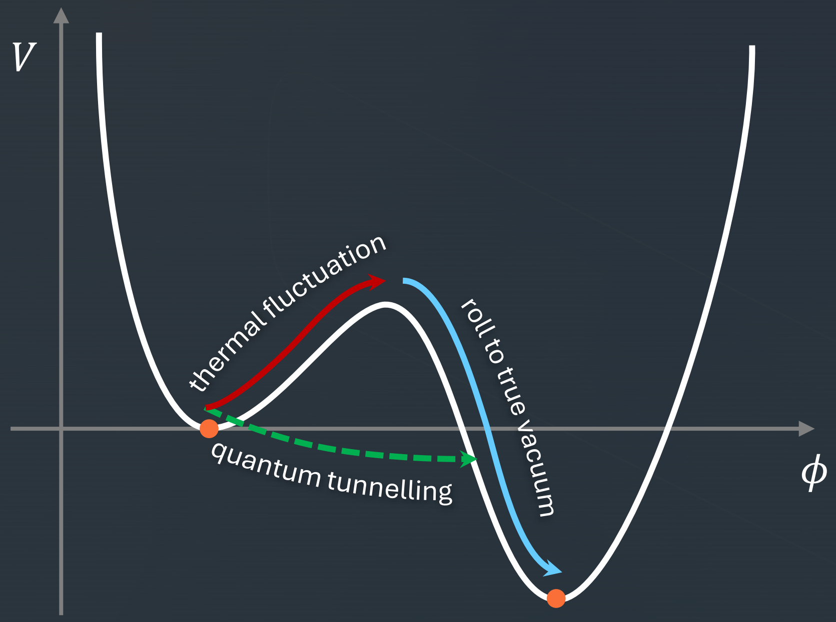
BSM physics

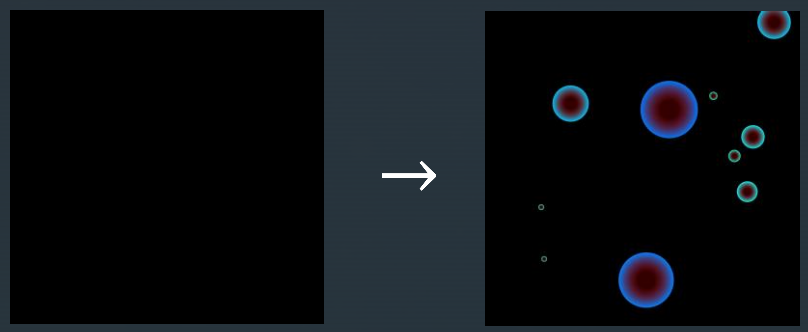
- EW baryogenesis
- Allowing multiple vacuum directions (multi-field models)

➢ Focus on single-field

Cosmological Phase Transitions
& Single-Field Models

I order phase transitions (FOPTs)





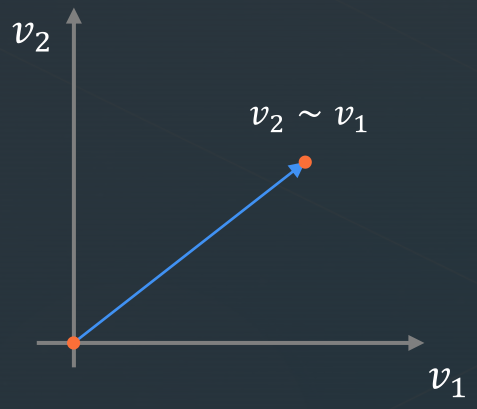
BSM physics

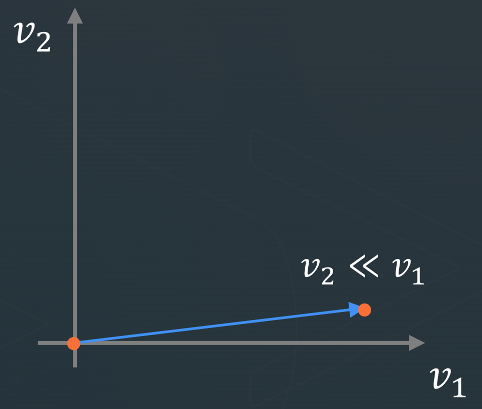
- EW baryogenesis
- Allowing multiple vacuum directions (multi-field models)

➢ Focus on single-field

- strong vev hierarchy

$\Rightarrow$ single-field approximation ✓

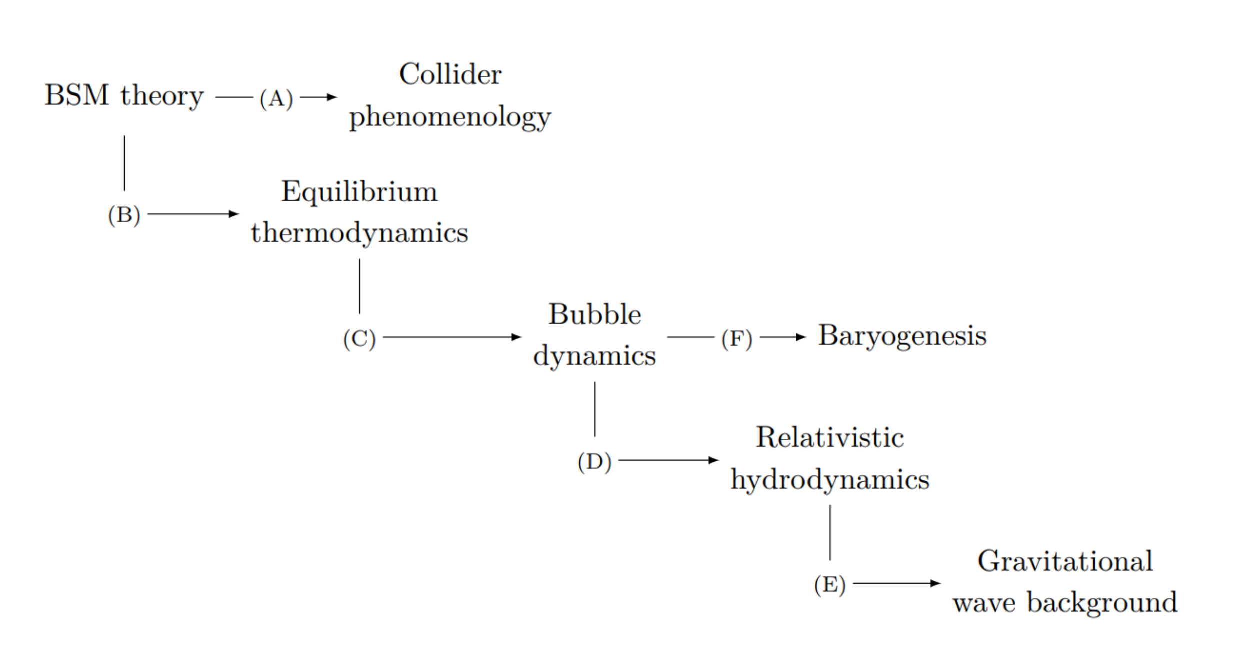




BSM → GW

A pipeline

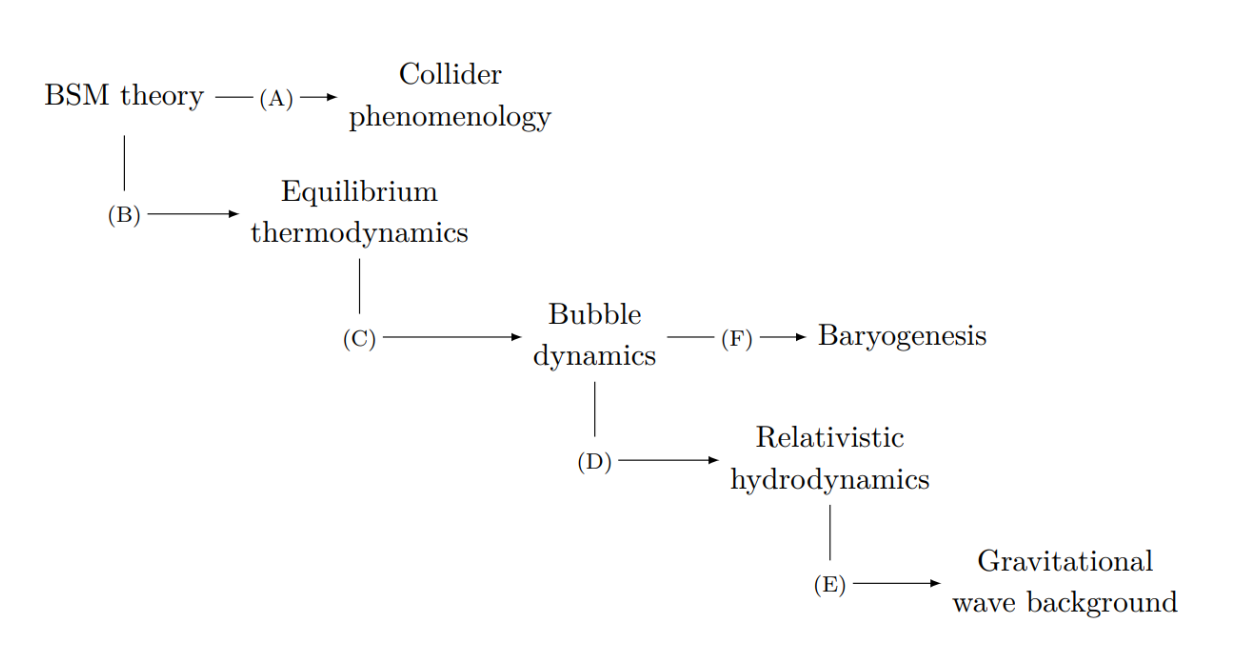
BSM → GW
A pipeline



P.M. Schicho, T.V.I. Tenkanen and J. Östermana (JHEP06(2021)130)

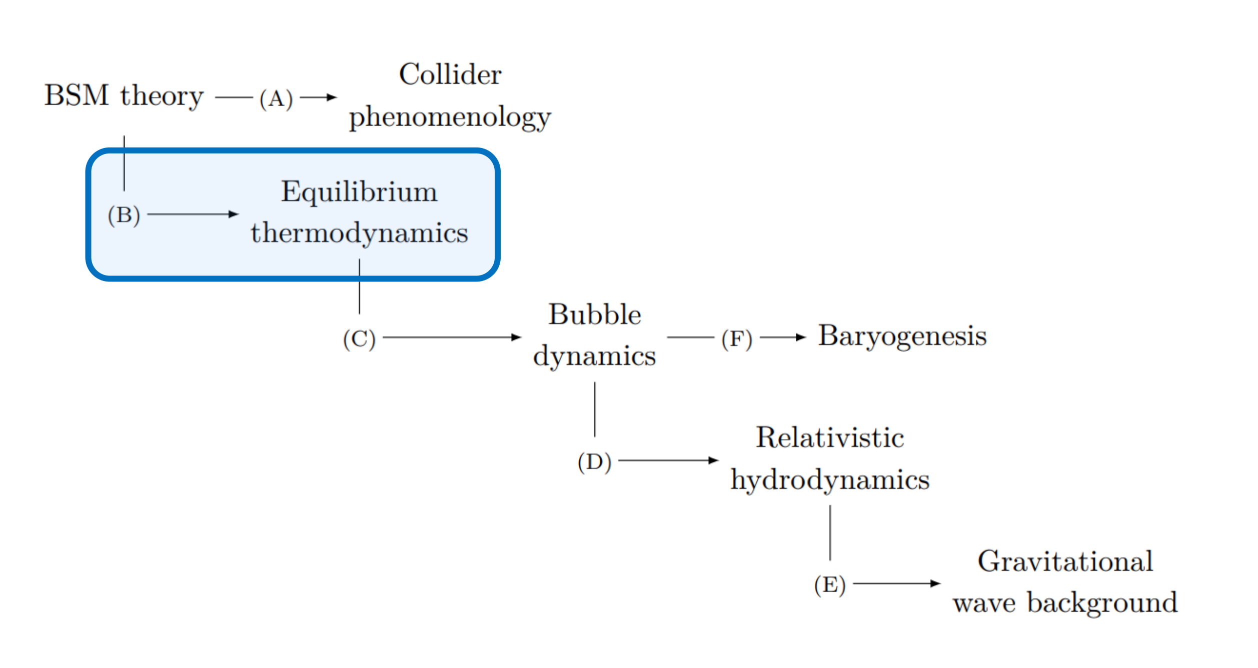
BSM → GW
A pipeline

GWCalc Paclet



P.M. Schicho, T.V.I. Tenkanen and J. Östermana (JHEP06(2021)130)

BSM → GW
A pipeline



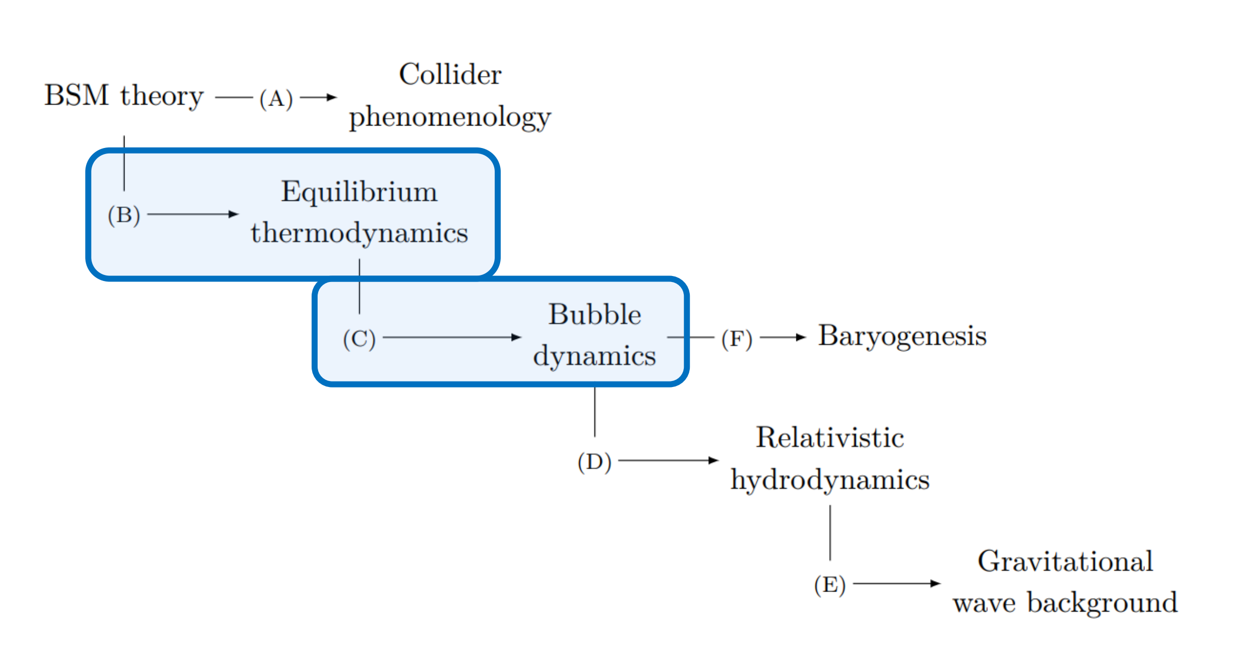
P.M. Schicho, T.V.I. Tenkanen and J. Östermana (JHEP06(2021)130)

GWCalc Paclet

B. Characterize PTs

- critical temperature
- 1st, 2nd order, cross-over

BSM → GW
A pipeline



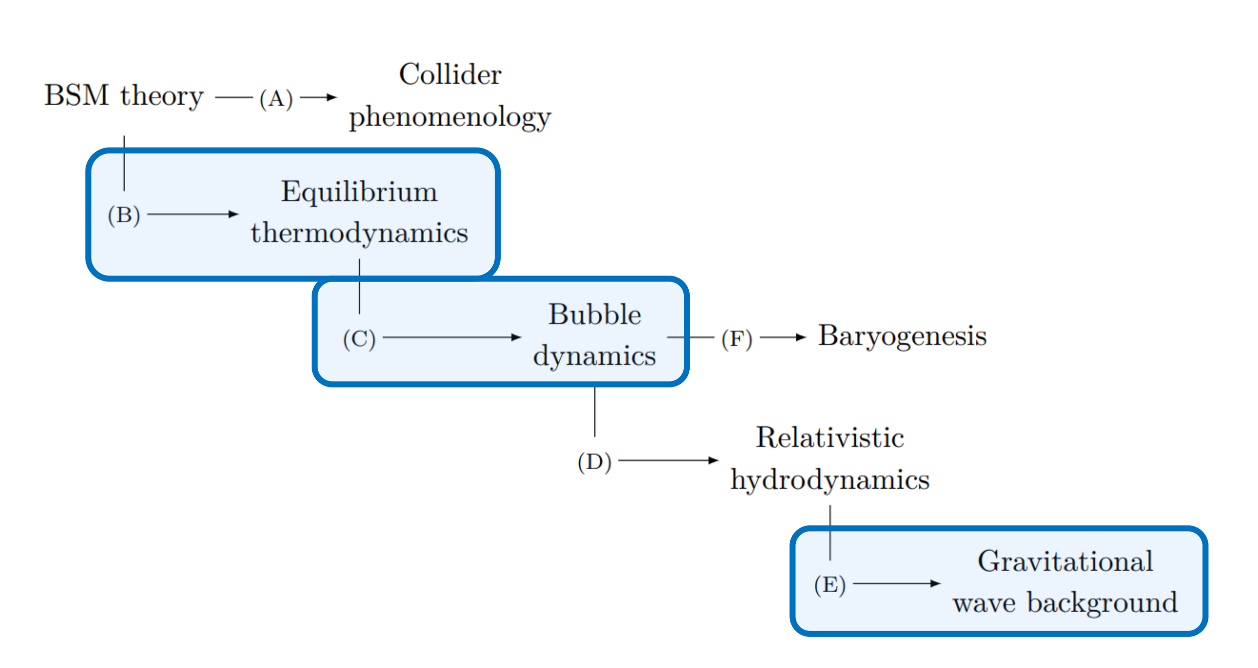
P.M. Schicho, T.V.I. Tenkanen and J. Östermana (JHEP06(2021)130)

GWCalc Paclet

B. Characterize PTs
   - critical temperature
   - 1st, 2nd order, cross-over

C. Bubble dynamics (1st order)
   - T_n, T_p
   - strength α, duration β^{-1}
   - …

BSM → GW
A pipeline



P.M. Schicho, T.V.I. Tenkanen and J. Östermana (JHEP06(2021)130)

GWCalc Paclet

B. Characterize PTs
   - critical temperature
   - 1st, 2nd order, cross-over

C. Bubble dynamics (1st order)
   - T_n, T_p
   - strength α, duration β^{-1}
   - …

D. GWB templates

Paclet

FindBounce + action fit

Paclet

FindBounce + action fit

- Pipeline requires to determine temperatures of

Paclet

FindBounce + action fit

- Pipeline requires to determine temperatures of
  - nucleation $\int_{T_n}^{T_c} dT \, \frac{\Gamma(T)}{T\, H^4(T)} \sim 1$

Paclet
FindBounce + action fit

- Pipeline requires to determine temperatures of
  - nucleation $\int_{T_n}^{T_c} dT \, \frac{\Gamma(T)}{T \, H^4(T)} \sim 1$
  - percolation $I\left(\Gamma, T_p\right) \approx 0.34$

Paclet

FindBounce + action fit

- Pipeline requires to determine temperatures of
  - nucleation $\int_{T_n}^{T_c} dT \, \frac{\Gamma(T)}{T\, H^4(T)} \sim 1$
  - percolation $I\left(\Gamma, T_p\right) \approx 0.34$

$$\Gamma(T) = A\left(\frac{S_3}{T}, T\right) e^{-\frac{S_3}{T}}$$

Paclet

FindBounce + action fit

- Pipeline requires to determine temperatures of
  - nucleation $\int_{T_n}^{T_c} dT \, \frac{\Gamma(T)}{T\, H^4(T)} \sim 1$
  - percolation $I\left(\Gamma, T_p\right) \approx 0.34$

$$\left.\begin{matrix} \\ \\ \end{matrix}\right\} \Gamma(T) = A\left(\frac{S_3}{T}, T\right) e^{-\frac{S_3}{T}}$$

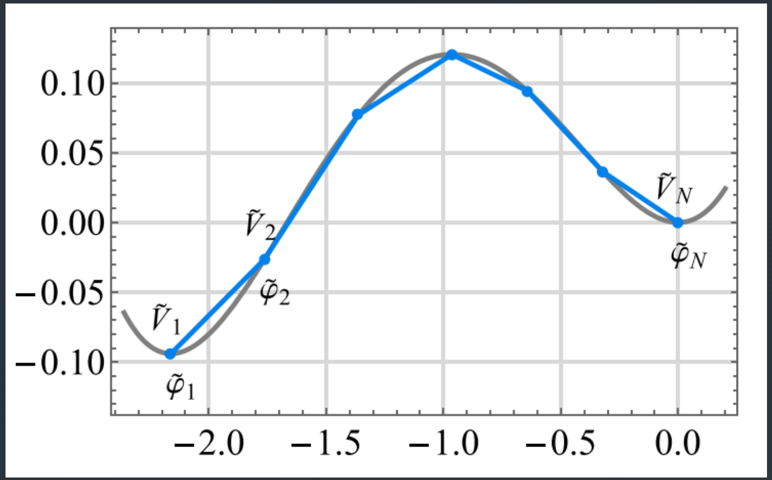
- $\frac{S_3}{T}(T)$ numerical estimation: `FindBounce`

Paclet
FindBounce + action fit

- Pipeline requires to determine temperatures of
  - nucleation $\int_{T_n}^{T_c} dT \frac{\Gamma(T)}{T\,H^4(T)} \sim 1$
  - percolation $I(\Gamma, T_p) \approx 0.34$

$$\Gamma(T) = A\left(\frac{S_3}{T}, T\right) e^{-\frac{S_3}{T}}$$

- $\frac{S_3}{T}(T)$ numerical estimation: `FindBounce`
  - implements *polygonal bounces*



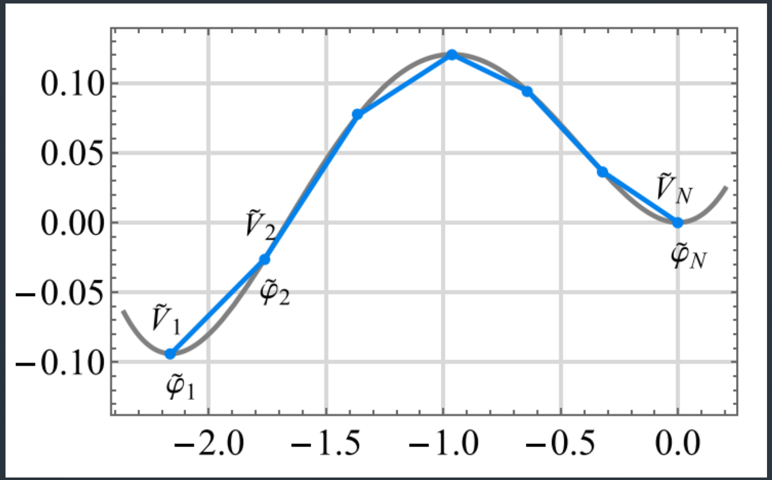
Guada, Nemevšek, Pintar (CPC 256 (2020) 10748)

Paclet
FindBounce + action fit

- Pipeline requires to determine temperatures of
  - nucleation $\int_{T_n}^{T_c} dT \frac{\Gamma(T)}{T\,H^4(T)} \sim 1$
  - percolation $I(\Gamma, T_p) \approx 0.34$

$$\Gamma(T) = A\left(\frac{S_3}{T}, T\right) e^{-\frac{S_3}{T}}$$

- $\frac{S_3}{T}(T)$ numerical estimation: `FindBounce`
  - implements *polygonal bounces*
  - $4d\ (S_4)$ or $3d\ (S_3)$



Guada, Nemevšek, Pintar (CPC 256 (2020) 10748)

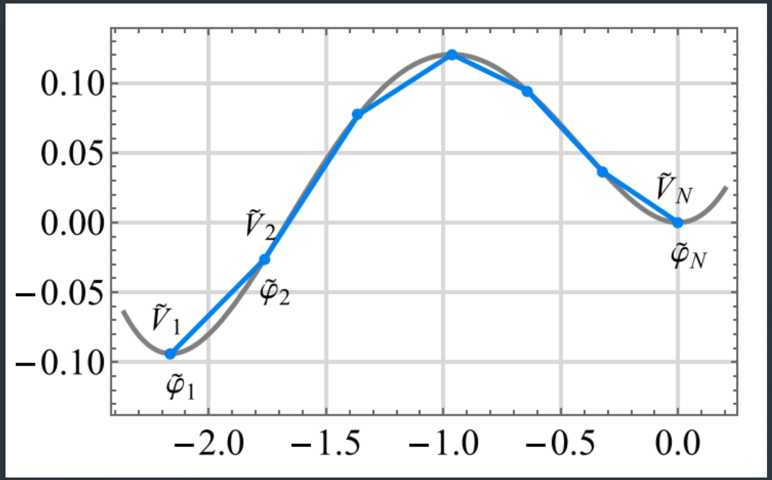
Paclet

FindBounce + action fit

- Pipeline requires to determine temperatures of
  - nucleation $\int_{T_n}^{T_c} dT \frac{\Gamma(T)}{T\, H^4(T)} \sim 1$
  - percolation $I(\Gamma, T_p) \approx 0.34$

$$\Gamma(T) = A\left(\frac{S_3}{T}, T\right) e^{-\frac{S_3}{T}}$$

- $\frac{S_3}{T}(T)$ numerical estimation: `FindBounce`
  - implements *polygonal bounces*
  - $4d\ (S_4)$ or $3d\ (S_3)$
  - ✓ thin-wall regime



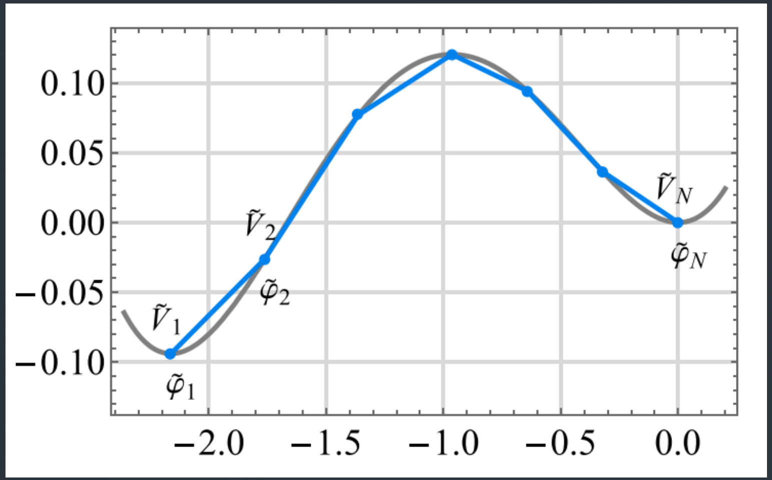
Guada, Nemevšek, Pintar (CPC 256 (2020) 10748)

Paclet
FindBounce + action fit

- Pipeline requires to determine temperatures of
  - nucleation $\int_{T_n}^{T_c} dT \, \frac{\Gamma(T)}{T\, H^4(T)} \sim 1$
  - percolation $I\left(\Gamma, T_p\right) \approx 0.34$

$$\left.\begin{array}{l} \\ \\ \end{array}\right\} \Gamma(T) = A\left(\frac{S_3}{T}, T\right) e^{-\frac{S_3}{T}}$$

- $\frac{S_3}{T}(T)$ numerical estimation: `FindBounce`
  - implements *polygonal bounces*
  - $4d\ (S_4)$ or $3d\ (S_3)$
  - ✓ thin-wall regime
  - efficient: $t \sim O(\#\ \text{fields}), O(\#\ \text{segments})$



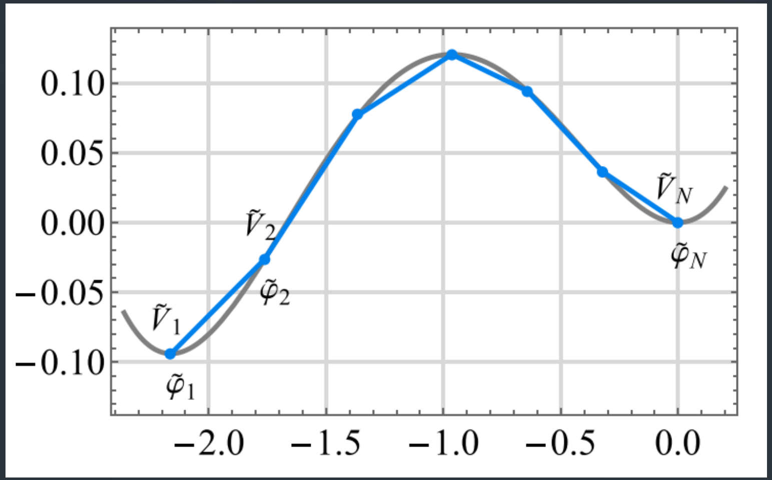
Guada, Nemevšek, Pintar (CPC 256 (2020) 10748)

Paclet

FindBounce + action fit

- Pipeline requires to determine temperatures of
  - nucleation $\int_{T_n}^{T_c} dT \frac{\Gamma(T)}{T\, H^4(T)} \sim 1$
  - percolation $I\left(\Gamma, T_p\right) \approx 0.34$

  $\Big\} \; \Gamma(T) = A\left(\frac{S_3}{T}, T\right) e^{-\frac{S_3}{T}}$
- $\frac{S_3}{T}(T)$ numerical estimation: `FindBounce`
  - implements *polygonal bounces*
  - $4d\ (S_4)$ or $3d\ (S_3)$
  - ✓ thin-wall regime
  - efficient: $t \sim O(\#\ \text{fields}), O(\#\ \text{segments})$
- Method



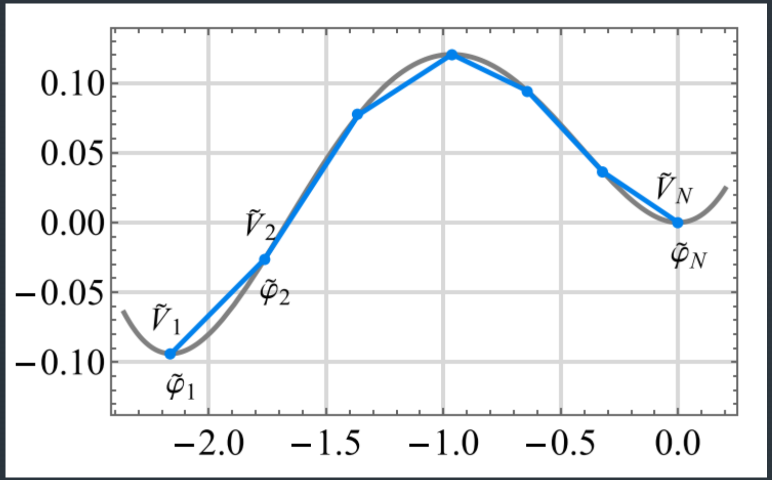
Guada, Nemevšek, Pintar (CPC 256 (2020) 10748)

Paclet
FindBounce + action fit

- Pipeline requires to determine temperatures of
  - nucleation $\int_{T_n}^{T_c} dT \frac{\Gamma(T)}{T\,H^4(T)} \sim 1$
  - percolation $I(\Gamma, T_p) \approx 0.34$

$$\Gamma(T) = A\left(\frac{S_3}{T}, T\right) e^{-\frac{S_3}{T}}$$

- $\frac{S_3}{T}(T)$ numerical estimation: `FindBounce`
  - implements *polygonal bounces*
  - $4d$ (S_4) or $3d$ (S_3)
  - ✓ thin-wall regime
  - efficient: $t \sim O(\#\text{ fields}), O(\#\text{ segments})$
- Method
  1. $\hat{T}_n$ estimate via $\Gamma/H^4 \sim 1$

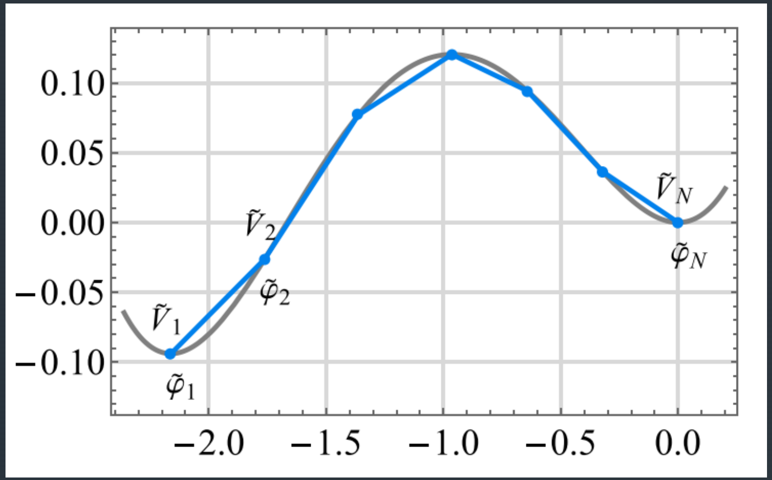


Guada, Nemevšek, Pintar (CPC 256 (2020) 10748)

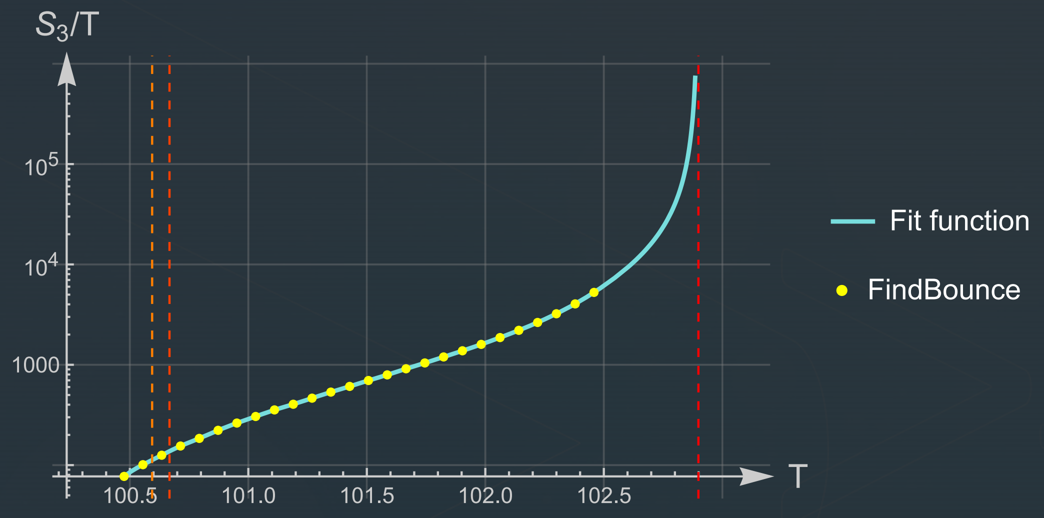
Paclet
FindBounce + action fit

- Pipeline requires to determine temperatures of
  - nucleation $\int_{T_n}^{T_c} dT \frac{\Gamma(T)}{T\, H^4(T)} \sim 1$
  - percolation $I(\Gamma, T_p) \approx 0.34$

  $\Bigg\} \; \Gamma(T) = A\left(\frac{S_3}{T}, T\right) e^{-\frac{S_3}{T}}$
- $\frac{S_3}{T}(T)$ numerical estimation: `FindBounce`
  - implements *polygonal bounces*
  - $4d\ (S_4)$ or $3d\ (S_3)$
  - ✓ thin-wall regime
  - efficient: $t \sim O(\#\text{ fields}), O(\#\text{ segments})$
- Method
  1. $\hat{T}_n$ estimate via $\Gamma/H^4 \sim 1$
  2. S_3/T fit/interpolation about $\left(\sim \hat{T}_n, T_c\right)$



Guada, Nemevšek, Pintar (CPC 256 (2020) 10748)



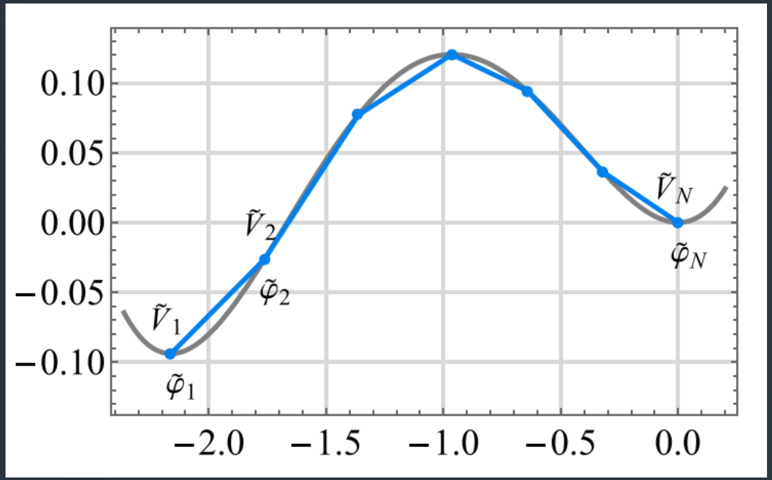
Paclet

FindBounce + action fit

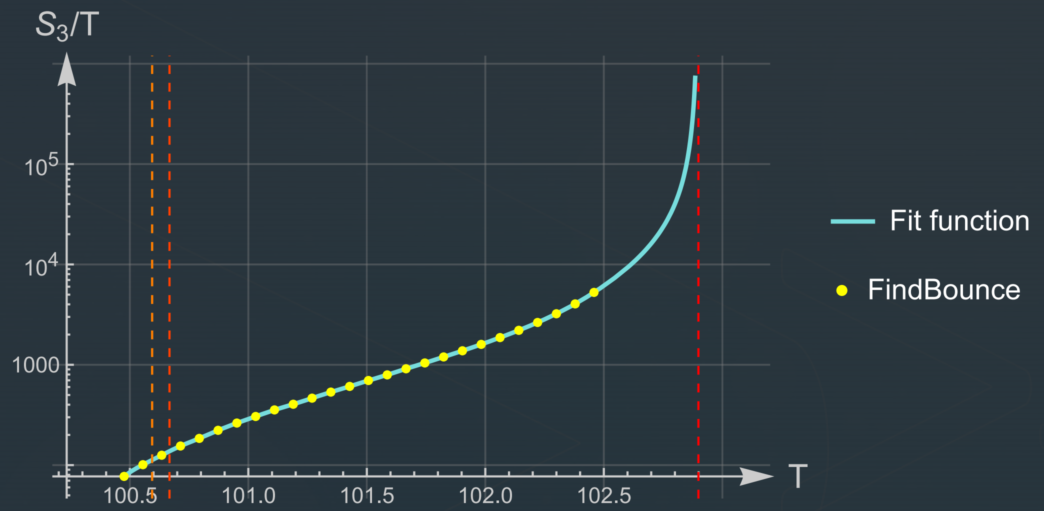
- Pipeline requires to determine temperatures of
  - nucleation $\int_{T_n}^{T_c} dT \frac{\Gamma(T)}{T\,H^4(T)} \sim 1$
  - percolation $I(\Gamma, T_p) \approx 0.34$

$$\Gamma(T) = A\left(\frac{S_3}{T}, T\right) e^{-\frac{S_3}{T}}$$

- $\frac{S_3}{T}(T)$ numerical estimation: `FindBounce`
  - implements *polygonal bounces*
  - $4d\ (S_4)$ or $3d\ (S_3)$
  - ✓ thin-wall regime
  - efficient: $t \sim O(\#\text{ fields}), O(\#\text{ segments})$
- Method
  1. $\hat{T}_n$ estimate via $\Gamma/H^4 \sim 1$
  2. S_3/T fit/interpolation about $\left(\sim \hat{T}_n, T_c\right)$
  3. T_n, T_p via above integrals



Guada, Nemevšek, Pintar (CPC 256 (2020) 10748)



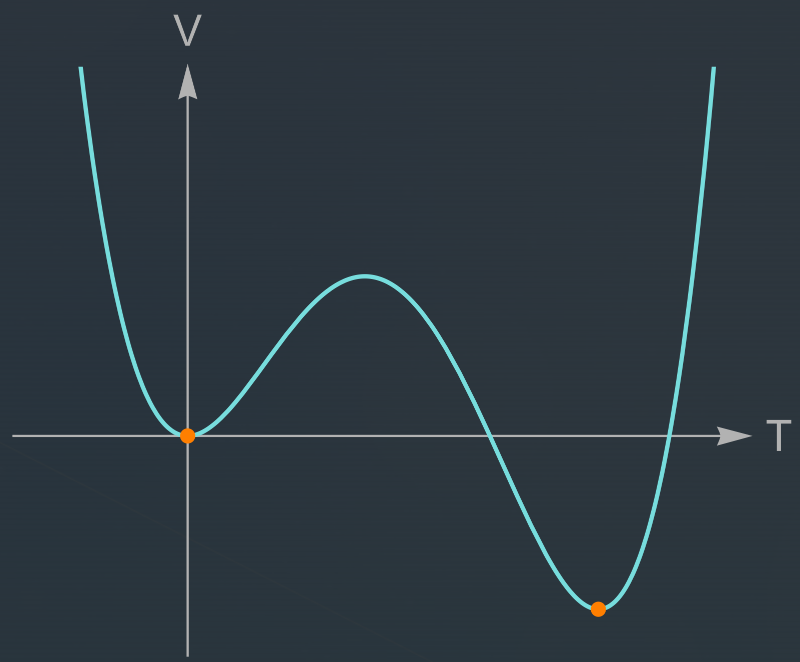
Example I

Fluid-field model

Example I
Fluid-field model

- Scalar potential

$$V(\phi, T) = \frac{c_2}{2}(T^2 - T_0^2)\phi^2 - \frac{c_3}{3}T\phi^3 + \frac{c_4}{4}\phi^4$$



Linde (1983, NPB 216. 2)
Hindmarsh, Huber, Rummukainen, Weir (PRD.92.123009)

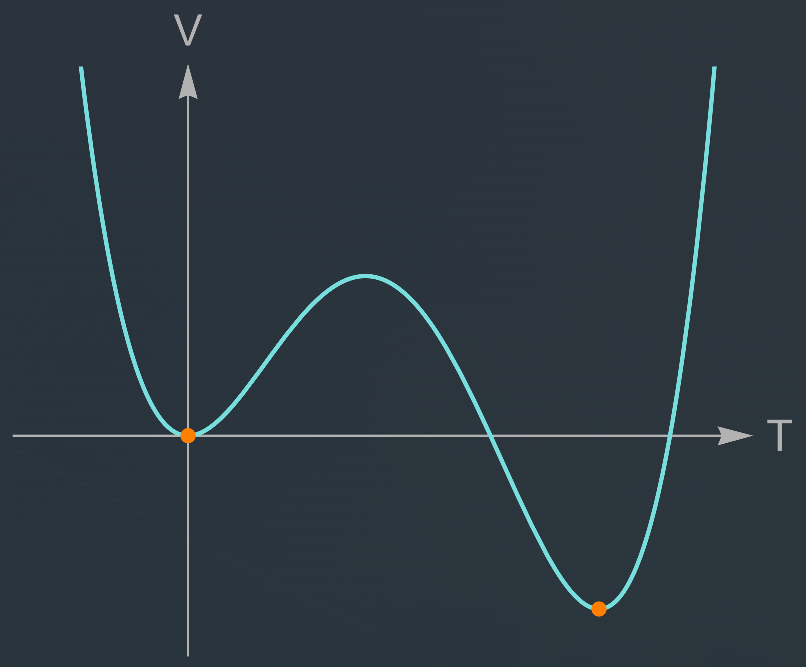
Example I
Fluid-field model

- Scalar potential

$$V(\phi,T) = \frac{c_2}{2}(T^2 - T_0^2)\phi^2 - \frac{c_3}{3}T\phi^3 + \frac{c_4}{4}\phi^4$$

- Analytic derivation of the action
  - in thin/thick wall regimes
  - intermediate interpolation

Matteini, Nemevšek, Shoji, Ubaldi (2024, 2404.17632)



Linde (1983, NPB 216. 2)
Hindmarsh, Huber, Rummukainen, Weir (PRD.92.123009)

Example I
Fluid-field model

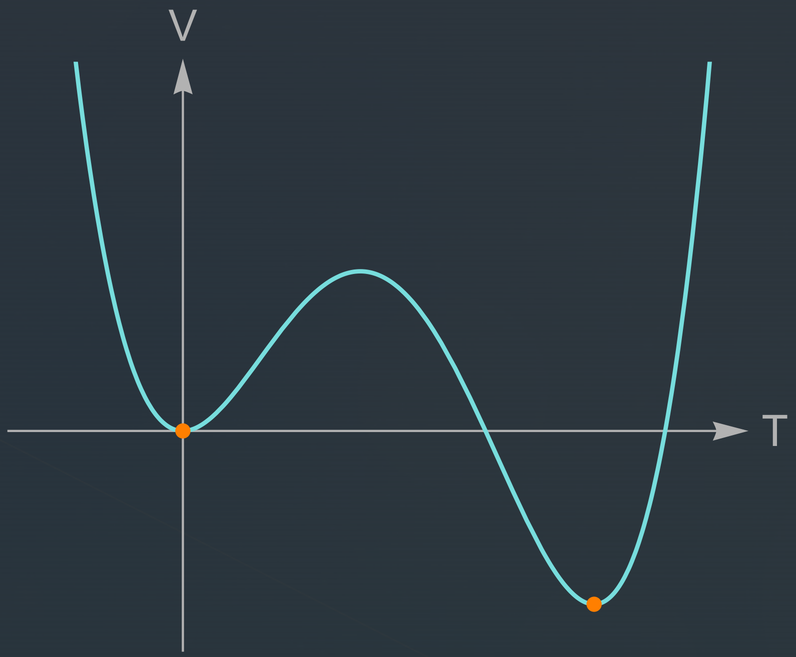
- Scalar potential

$$V(\phi, T) = \frac{c_2}{2}(T^2 - T_0^2)\phi^2 - \frac{c_3}{3}T\phi^3 + \frac{c_4}{4}\phi^4$$

- Analytic derivation of the action
  - in thin/thick wall regimes
  - intermediate interpolation

Matteini, Nemevšek, Shoji, Ubaldi (2024, 2404.17632)

→ Paclet



Linde (1983, NPB 216. 2)
Hindmarsh, Huber, Rummukainen, Weir (PRD.92.123009)

Example I
Fluid-field model

- Scalar potential

$$V(\phi,T)=\frac{c_2}{2}(T^2-T_0^2)\phi^2-\frac{c_3}{3}T\phi^3+\frac{c_4}{4}\phi^4$$

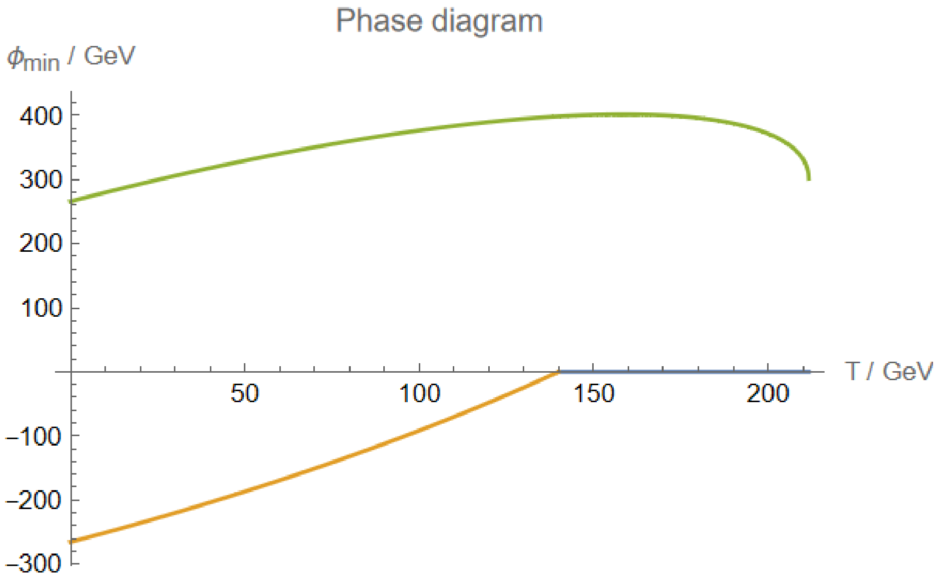
- Analytic derivation of the action
  - in thin/thick wall regimes
  - intermediate interpolation

Matteini, Nemevšek, Shoji, Ubaldi (2024, 2404.17632)

→ Paclet

```
In[71]:= Trs = TBounce[V, vw, "TracingMethod" → NSolve,
   "PlotAction" → True, "PlotGWSpectrum" → True]
```

Determining phase structure



Looping over pairs of phases

Found transition at critical temperature

» $T_c \to$ 197.99

Computing nucleation temperature via $\Gamma/H^4 \approx 1$ criterion and bisection method...

» $T_n^{\text{estimate}} \to$ 170.703 S_3/T = 148.609 Γ/H^4 = 1.00114

Linde (1983, NPB 216. 2)
Hindmarsh, Huber, Rummukainen, Weir (PRD.92.123009)

Example I
Fluid-field model

- Scalar potential

  $$V(\phi,T)=\frac{c_2}{2}(T^2-T_0^2)\phi^2-\frac{c_3}{3}T\phi^3+\frac{c_4}{4}\phi^4$$

- Analytic derivation of the action
  - in thin/thick wall regimes
  - intermediate interpolation

  Matteini, Nemevšek, Shoji, Ubaldi (2024, 2404.17632)

→ Paclet

Fitting action...

» Action function → ActionFunction[Type: PWLaurent Domain: {149., 198.}]

Computing nucleation temperature via $\int dT\, \Gamma/H^4 \approx 1$ criterion and action fit method...

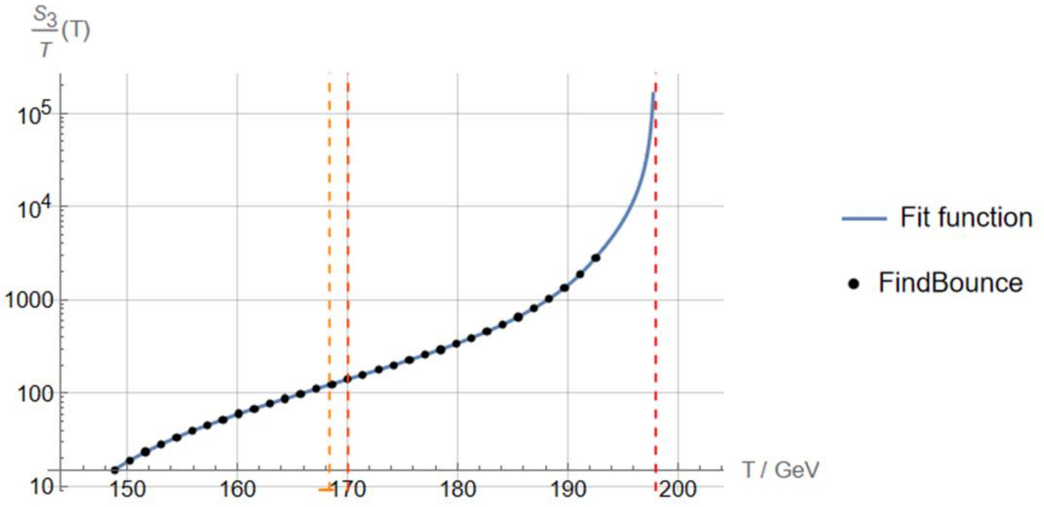
» $T_n \to$ 170.052 S_3/T = 140.957 Γ/H^4 = 1976.88 $\int_{T_n}^{T_c} \frac{dT}{T}\frac{\Gamma}{H^4}$ = 0.999963

Computing phase transition parameters...

Solving $I_{\mathcal{F}}(T_p)$ = 0.34 for Tp

Searching for Tp with FindRoot...

» $T_p \to$ 168.381



Linde (1983, NPB 216. 2)
Hindmarsh, Huber, Rummukainen, Weir (PRD.92.123009)

Example I
Fluid-field model

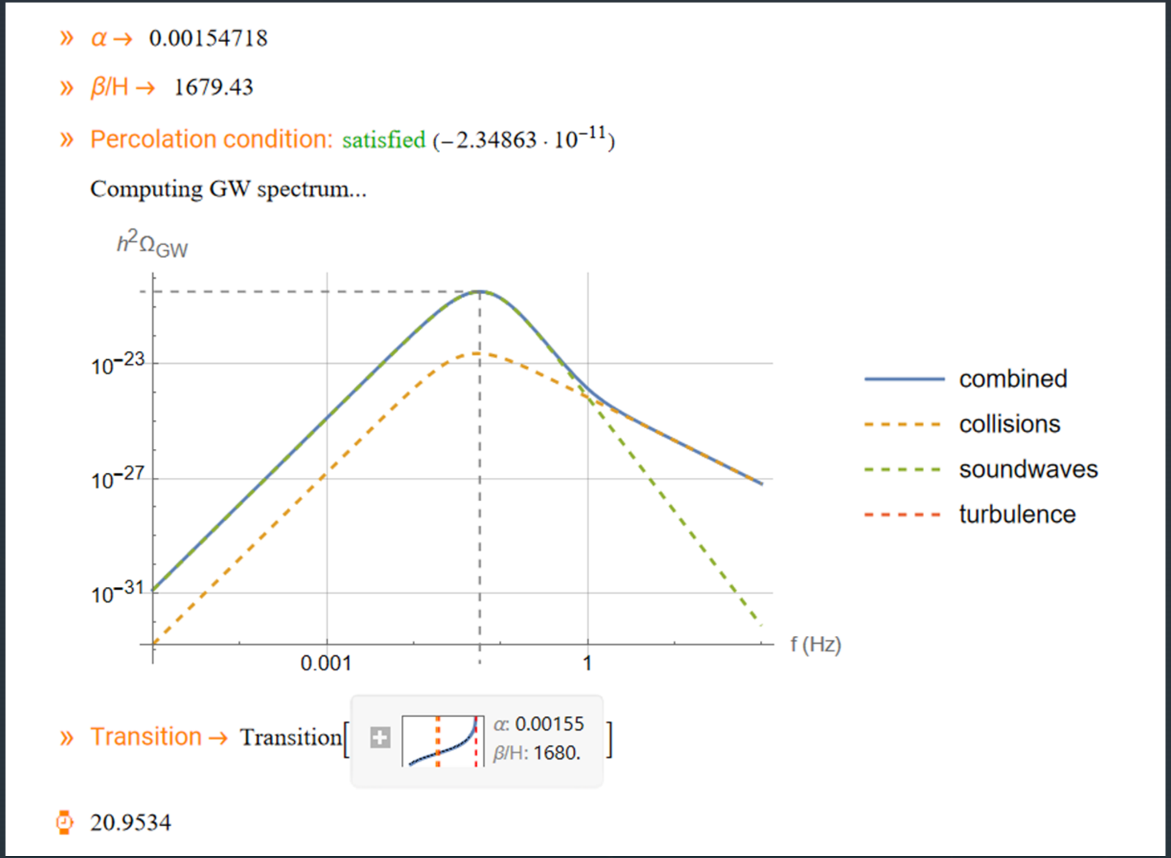
- Scalar potential

$$V(\phi,T) = \frac{c_2}{2}(T^2 - T_0^2)\phi^2 - \frac{c_3}{3}T\phi^3 + \frac{c_4}{4}\phi^4$$

- Analytic derivation of the action
  - in thin/thick wall regimes
  - intermediate interpolation

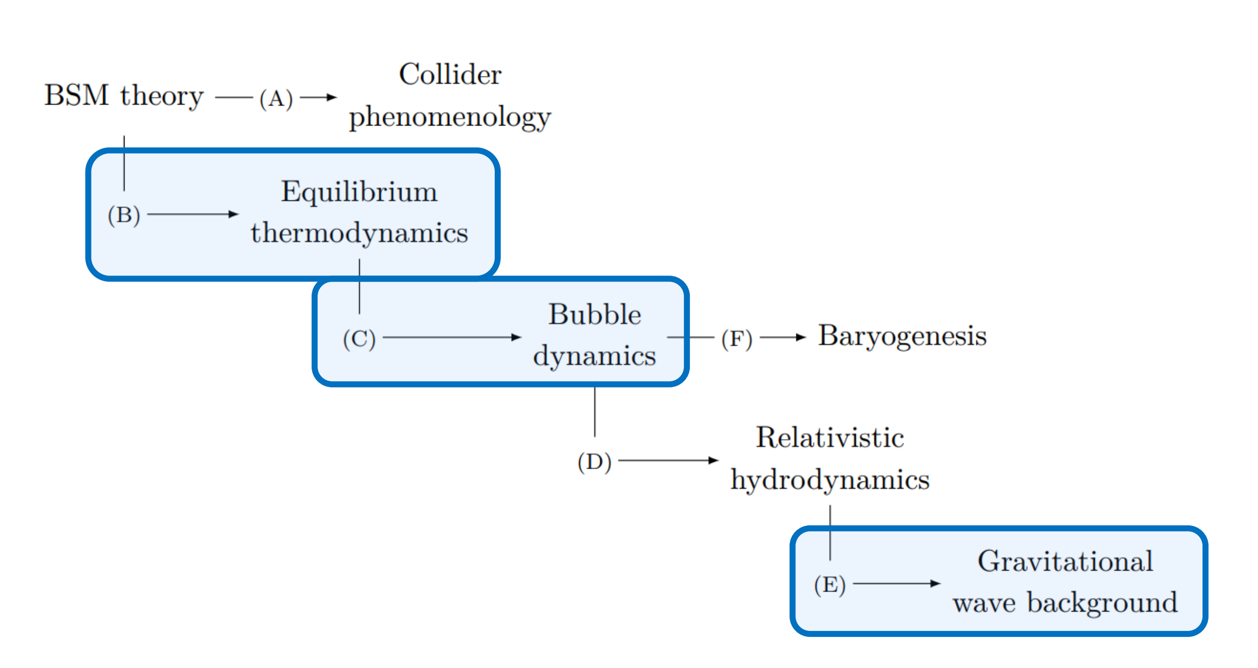
Matteini, Nemevšek, Shoji, Ubaldi (2024, 2404.17632)

$\rightarrow$ Paclet



Linde (1983, NPB 216. 2)
Hindmarsh, Huber, Rummukainen, Weir (PRD.92.123009)

BSM → GW
A pipeline



P.M. Schicho, T.V.I. Tenkanen and J. Östermana (JHEP06(2021)130)

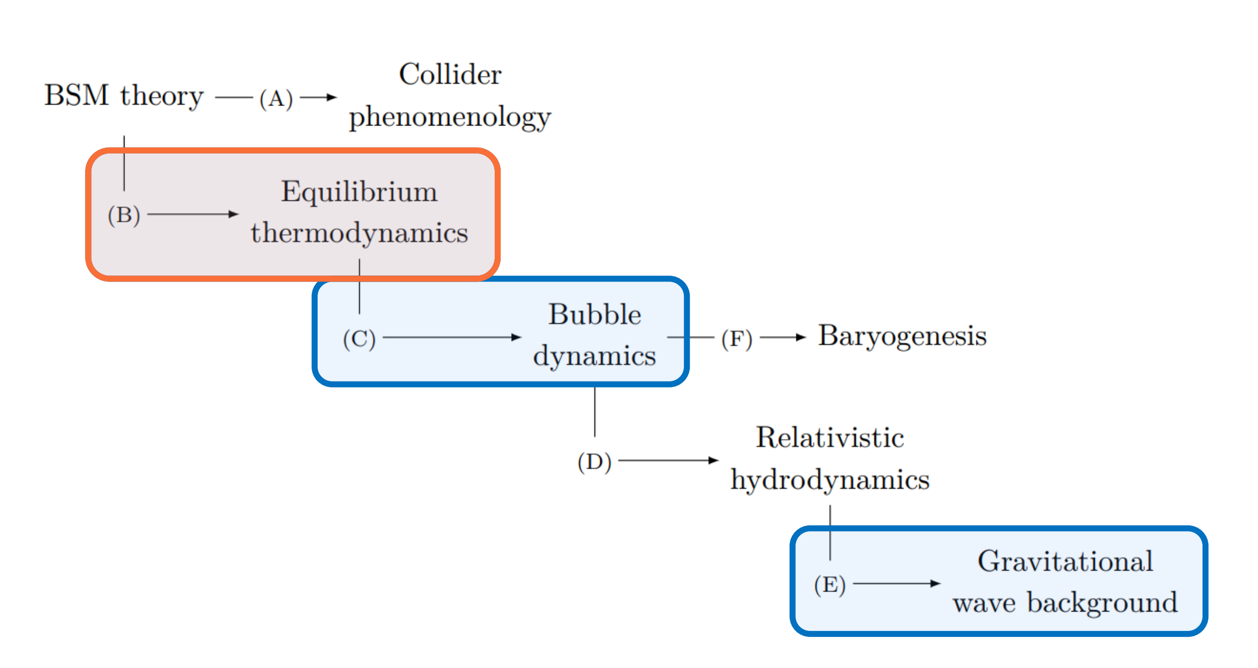
GWCalc Paclet

B. Characterize PTs
   - critical temperature
   - 1st, 2nd order, cross-over

C. Bubble dynamics (1st order)
   - T_n, T_p
   - strength α, duration β^{-1}
   - …

D. GW templates

BSM → GW
A pipeline



P.M. Schicho, T.V.I. Tenkanen and J. Östermana (JHEP06(2021)130)

GWCalc Paclet

B. Characterize PTs
   - critical temperature
   - 1st, 2nd order, cross-over

C. Bubble dynamics (1st order)
   - T_n, T_p
   - strength α, duration β^{-1}
   - …

D. GW templates

B. Dimensional reduction
   - Interface with `DRalgo`

Ekstedt, Schicho, Tenkanen (2205.08815v1)

Dimensional Reduction

An improved recipe for thermal EFTs

Dimensional Reduction

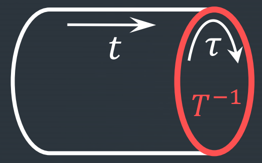
An improved recipe for thermal EFTs

- Dimensional reduction (DR)

Dimensional Reduction
An improved recipe for thermal EFTs

- Dimensional reduction (DR)
  - time → temperature ⇒ high-T approach

$$\boxed{4d \xrightarrow{t\to t+i/T} 3d\ \mathrm{EFT}}$$

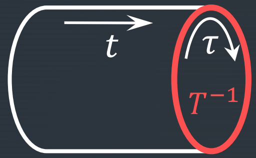


Dimensional Reduction

An improved recipe for thermal EFTs

- Dimensional reduction (DR)
  - time → temperature ⇒ high-T approach
  - include systematically higher-order resummations

$$\boxed{4d \xrightarrow{t\to t+i/T} 3d\ \mathrm{EFT}}$$

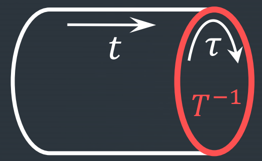


Dimensional Reduction

An improved recipe for thermal EFTs

- Dimensional reduction (DR)
  - time → temperature ⇒ high-T approach
  - include systematically higher-order resummations
- Narrower theoretical uncertainties

$$\boxed{4d \xrightarrow{t\to t+i/T} 3d\ \text{EFT}}$$

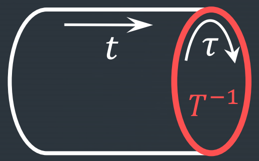


Dimensional Reduction

An improved recipe for thermal EFTs

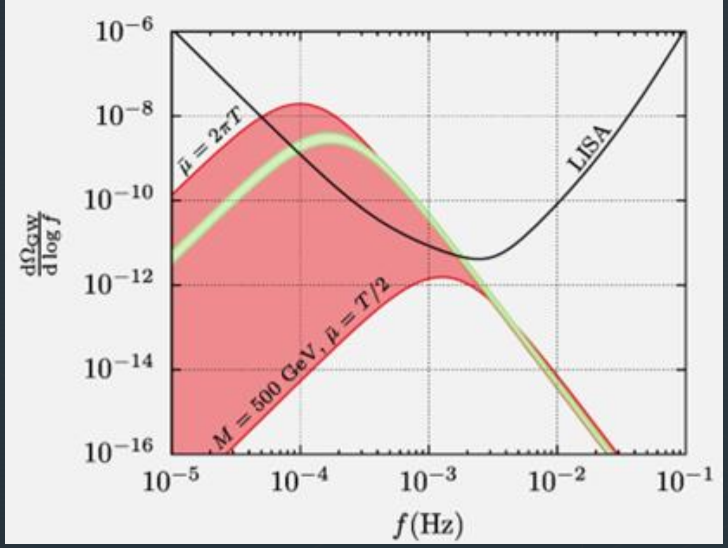
- Dimensional reduction (DR)
  - time → temperature ⇒ high-T approach
  - include systematically higher-order resummations

$$\boxed{4d \xrightarrow{t \to t + i/T} 3d \text{ EFT}}$$



- Narrower theoretical uncertainties

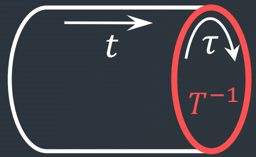
  ⇒ narrower GWB uncertainties



Credit: P. Schicho

Dimensional Reduction
An improved recipe for thermal EFTs

$$\boxed{4d \xrightarrow{t \to t + i/T} 3d \text{ EFT}}$$

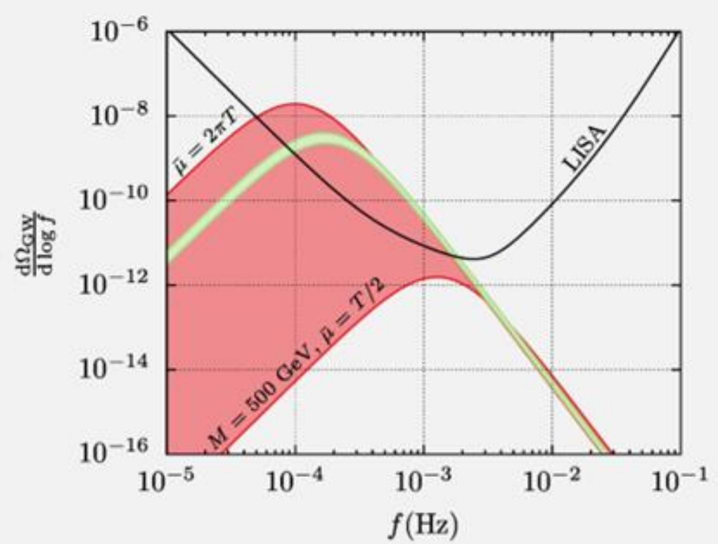


- Dimensional reduction (DR)
  - time → temperature ⇒ high-T approach
  - include systematically higher-order resummations

- Narrower theoretical uncertainties

  ⇒ narrower GWB uncertainties

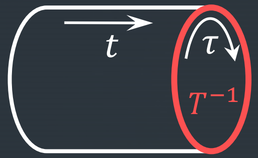
- DR implementation
  Automated extraction `Dralgo` $\to V_{\text{eff}}$,
  including



Credit: P. Schicho

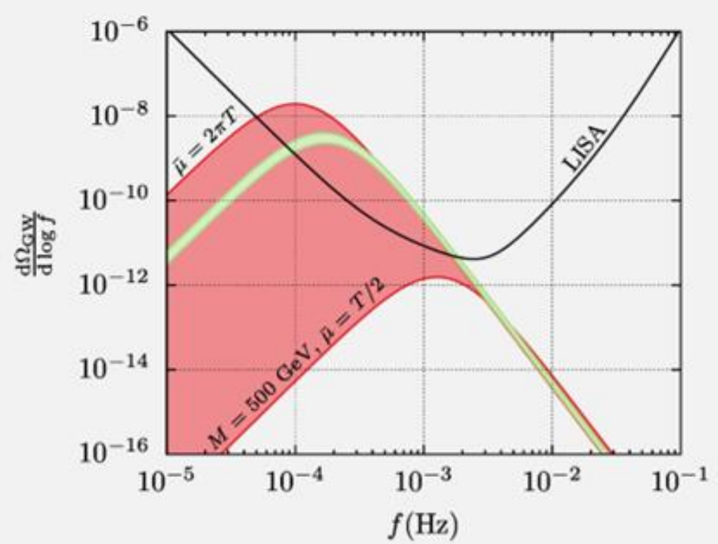
Dimensional Reduction
An improved recipe for thermal EFTs

$$\boxed{4d \xrightarrow{t\to t+i/T} 3d\ \mathrm{EFT}}$$



- Dimensional reduction (DR)
  - time → temperature ⇒ high-T approach
  - include systematically higher-order resummations
- Narrower theoretical uncertainties

  ⇒ narrower GWB uncertainties
- DR implementation
  Automated extraction `Dralgo` → V_{eff} ,
  including
  - export of DR quantities

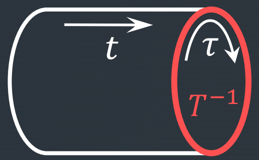


Credit: P. Schicho

Dimensional Reduction
An improved recipe for thermal EFTs

- Dimensional reduction (DR)
  - time → temperature ⇒ high-T approach
  - include systematically higher-order resummations

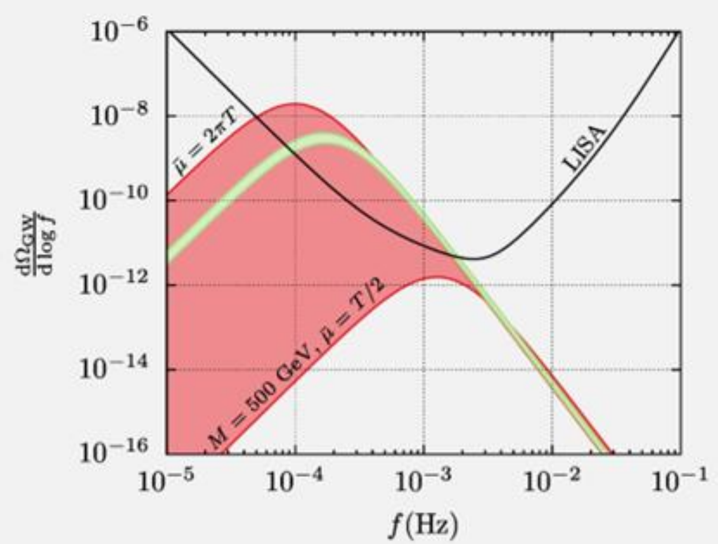
$$\boxed{4d \xrightarrow{t \to t + i/T} 3d \text{ EFT}}$$



- Narrower theoretical uncertainties

  ⇒ narrower GWB uncertainties

- DR implementation
  Automated extraction `Dralgo` $\to V_{\text{eff}}$,
  including
  - export of DR quantities
  - RG resolution



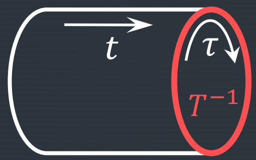
Credit: P. Schicho

Dimensional Reduction

An improved recipe for thermal EFTs

- Dimensional reduction (DR)
  - time → temperature ⇒ high-T approach
  - include systematically higher-order resummations

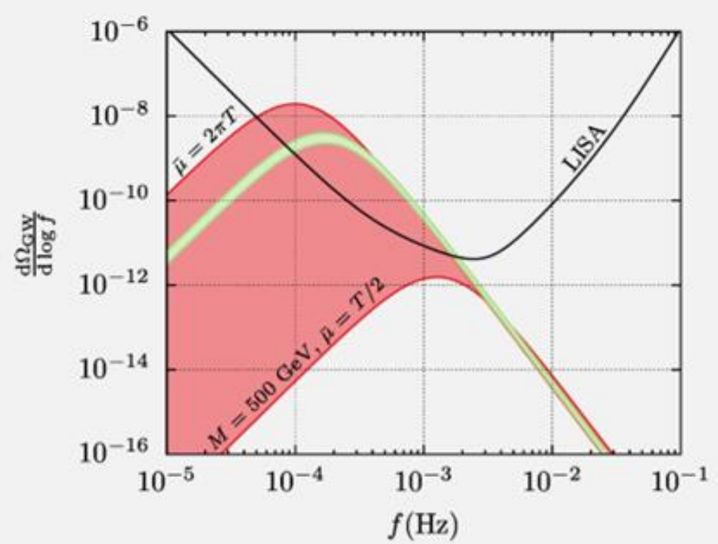
$$\boxed{4d \xrightarrow{t \to t + i/T} 3d\ \mathrm{EFT}}$$



- Narrower theoretical uncertainties

  ⇒ narrower GWB uncertainties

- DR implementation
  Automated extraction `Dralgo` $\to V_{\text{eff}}$,
  including
  - export of DR quantities
  - RG resolution
  - closed-form $V_{\text{eff}}(\phi, T)$



Credit: P. Schicho

Example II

Dark photon model

Example II
Dark photon model

- Dark $U(1)$ gauge sector

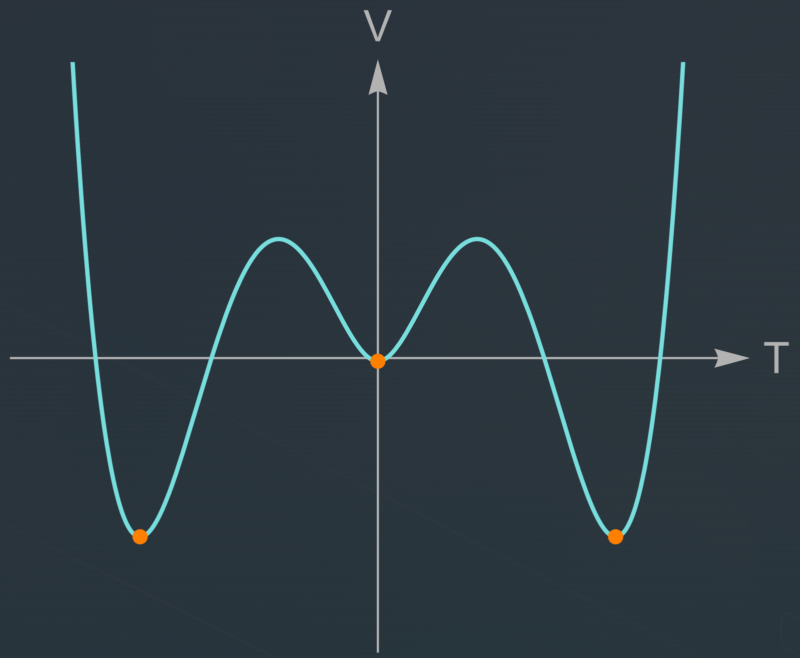
Example II

Dark photon model

- Dark $U(1)$ gauge sector
- Scalar content:

$$V(\phi, T) = \mu^2\phi^2 + \lambda\phi^4$$

+ fermions

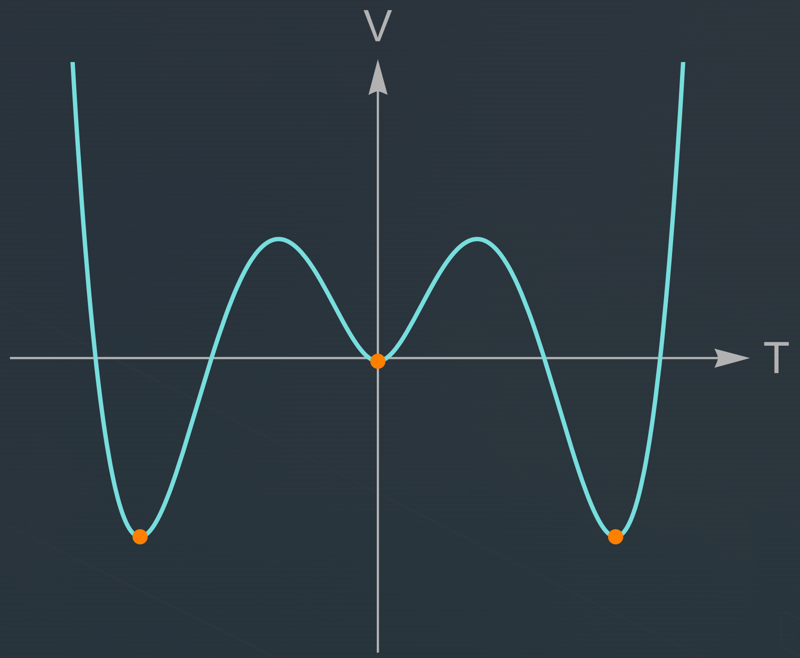


Example II
Dark photon model

- Dark $U(1)$ gauge sector
- Scalar content:

  $V(\phi, T) = \mu^2\phi^2 + \lambda\phi^4$

  $+$ fermions
- V_{eff} @ NLO



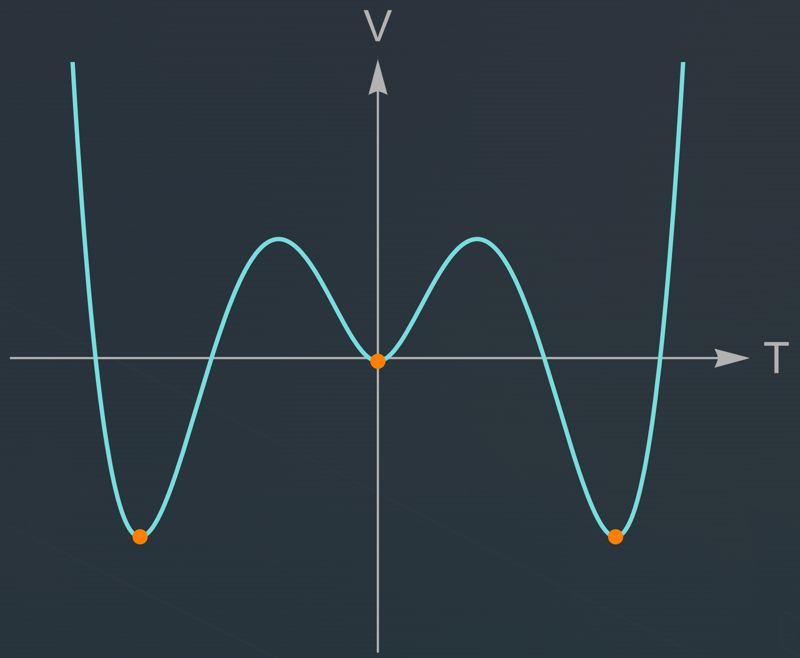
Example II
Dark photon model

- Dark $U(1)$ gauge sector
- Scalar content:

  $V(\phi, T) = \mu^2\phi^2 + \lambda\phi^4$

  \+ fermions
- V_{eff} @ NLO

$\longrightarrow$ Paclet



Example II
Dark photon model

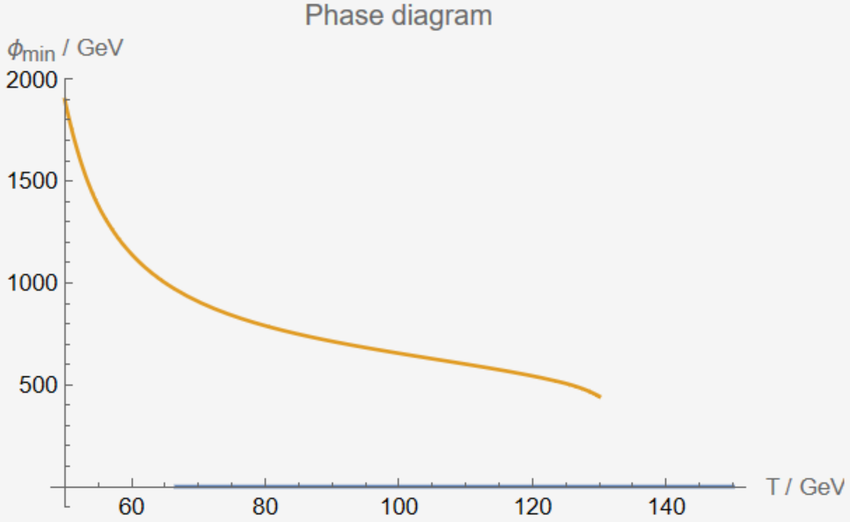
- Dark $U(1)$ gauge sector
- Scalar content:

  $V(\phi, T) = \mu^2\phi^2 + \lambda\phi^4$

  \+ fermions
- V_{eff} @ NLO

$\rightarrow$ Paclet

In[218]:=
```
trs=TBounce[V,vw,
    "TRange"→{μ0/2,1.5μ0},"SymmetricPhaseThreshold"→v/100,
    "PlotAction"→True,"PlotGWSpectrum"→True
    ];//EchoTiming
```



Looping over pairs of phases

Found transition at critical temperature

» $T_c \rightarrow$ 121.823

Computing nucleation temperature via $\Gamma/H^4 \approx 1$ criterion and bisection method...

» $T_n^{\mathrm{estimate}} \rightarrow$ 80.4891 $S_3/T = 151.922$ $\Gamma/H^4 = 0.658416$

Example II
Dark photon model

- Dark $U(1)$ gauge sector
- Scalar content:

  $V(\phi, T) = \mu^2\phi^2 + \lambda\phi^4$

  \+ fermions
- V_{eff} @ NLO

$\rightarrow$ Paclet

Fitting action...

» Action function → ActionFunction[Type: PWLaurent Domain: {75.7, 122.}]

Computing nucleation temperature via $\int \mathrm{dT}\, \Gamma/H^4 \approx 1$ criterion and action fit method...

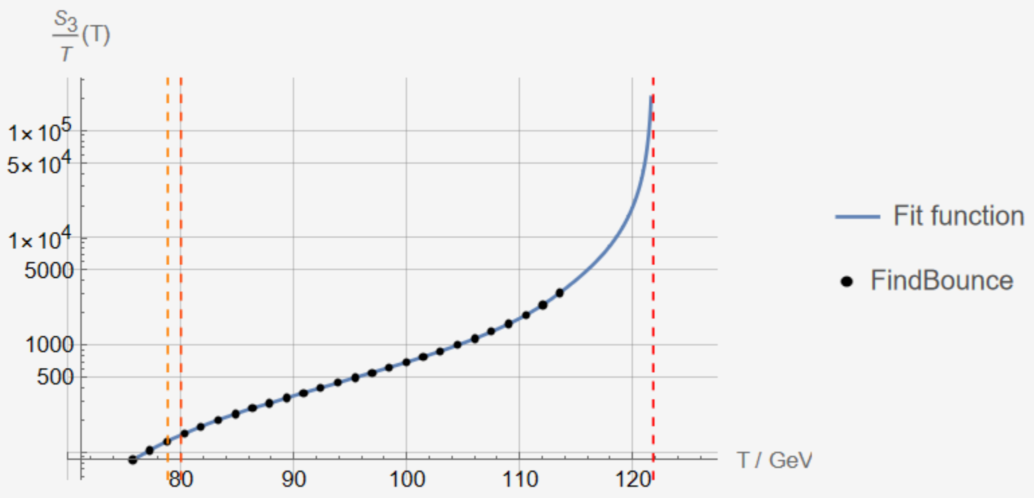
» $T_n \rightarrow$ 80.0018 $\quad S_3/T = 145.741 \quad \Gamma/H^4 = 304.47 \quad \int_{T_n}^{T_c} \frac{\mathrm{dT}}{T}\frac{\Gamma}{H^4} = 1.00087$

Computing phase transition parameters...

Solving $I_{\mathcal{F}}(T_p) = 0.34$ for Tp

Searching for Tp with FindRoot...

» $T_p \rightarrow$ 78.8341



Example II
Dark photon model

- Dark $U(1)$ gauge sector
- Scalar content:

  $V(\phi, T) = \mu^2\phi^2 + \lambda\phi^4$

  + fermions
- V_{eff} @ NLO

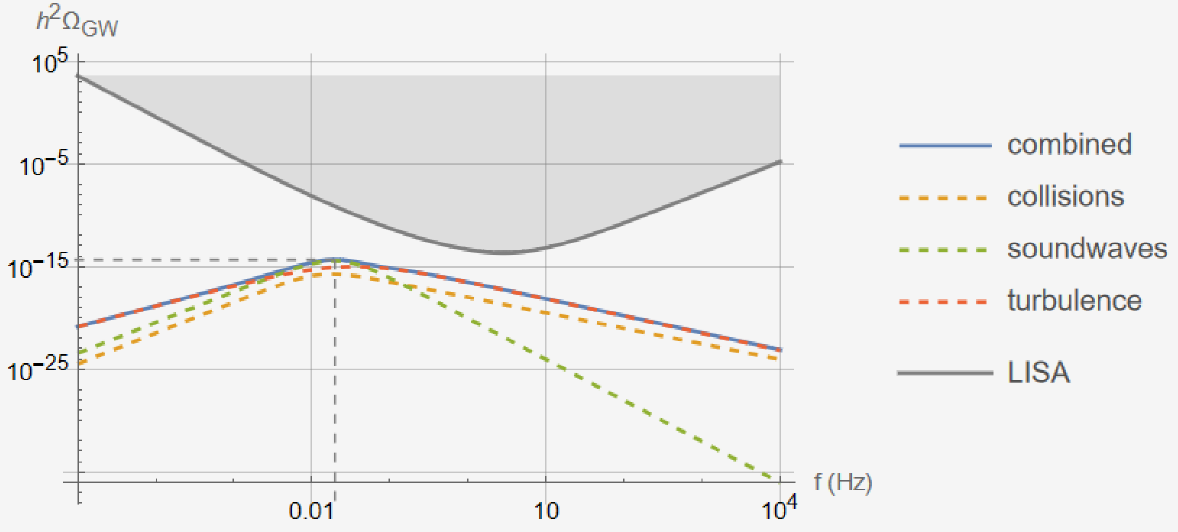
$\longrightarrow$ Paclet

» $\alpha \rightarrow$ 0.162869

» β/H $\rightarrow$ 1144.06

» Percolation condition: satisfied $(-3.46698 \cdot 10^{-12})$

Computing GW spectrum...



» Transition $\rightarrow$ Transition[α: 0.163 β/H: $1.14 \cdot 10^3$]

35.6733

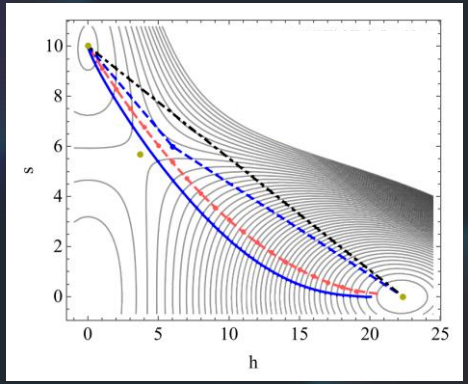
Outcome
& Future Endeavours

Outcome
& Future Endeavours

- Paclet current status
  - ✓ characterize of FOPTs and GWB
    - of single-field models
  - ✓ S_3/T via *polygonal bounce* (`FindBounce`)
  - ✓ optional, user-friendly interface with `DRalgo`
  - ✓ fully `Mathematica`-based

Outcome
& Future Endeavours

- Paclet current status
  - ✓ characterize of FOPTs and GWB
    - of single-field models
  - ✓ S_3/T via *polygonal bounce* (`FindBounce`)
  - ✓ optional, user-friendly interface with `DRalgo`
  - ✓ fully `Mathematica`-based

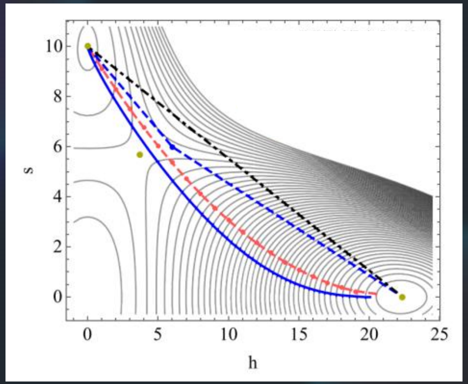


CPC 256 (2020) 10748

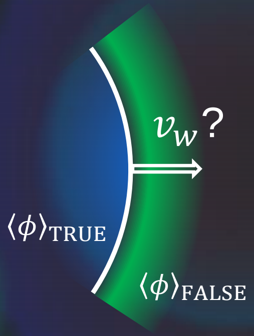
- Upcoming developments
  - ➢ multi-field
  - ➢ improved phase-tracing routine

Outcome
& Future Endeavours

- Paclet current status
  - ✓ characterize of FOPTs and GWB
    - of single-field models
  - ✓ S_3/T via *polygonal bounce* (`FindBounce`)
  - ✓ optional, user-friendly interface with `DRalgo`
  - ✓ fully `Mathematica`-based



CPC 256 (2020) 10748

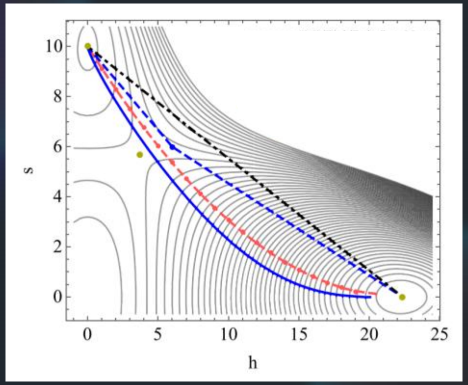


- Upcoming developments
  - ➢ multi-field
  - ➢ improved phase-tracing routine

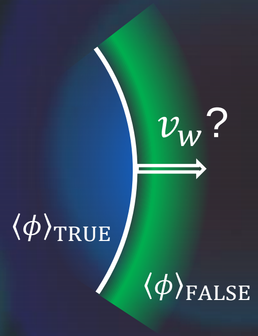
- Potential developments
  - ? v_w estimation in LTE
  - ? Decay rate prefactor $\Gamma = A\, e^{-S_3/T}$

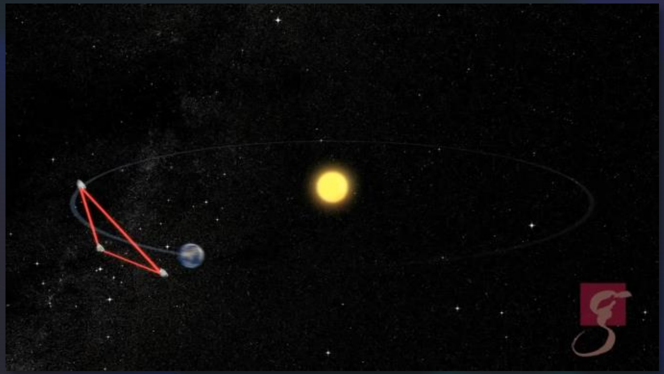
Outcome
& Future Endeavours

- Paclet current status
  - ✓ characterize of FOPTs and GWB
    - of single-field models
  - ✓ S_3/T via *polygonal bounce* (`FindBounce`)
  - ✓ optional, user-friendly interface with `DRalgo`
  - ✓ fully `Mathematica`-based
- Upcoming developments
  - ➢ multi-field
  - ➢ improved phase-tracing routine
- Potential developments
  - ? v_w estimation in LTE
  - ? Decay rate prefactor $\Gamma = A\, e^{-S_3/T}$



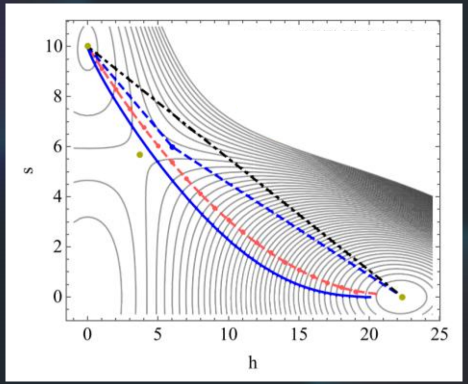
CPC 256 (2020) 10748



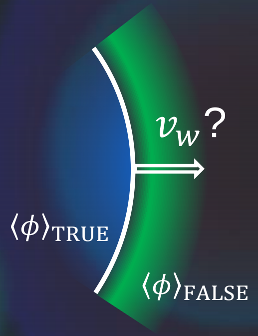


Outcome
& Future Endeavours

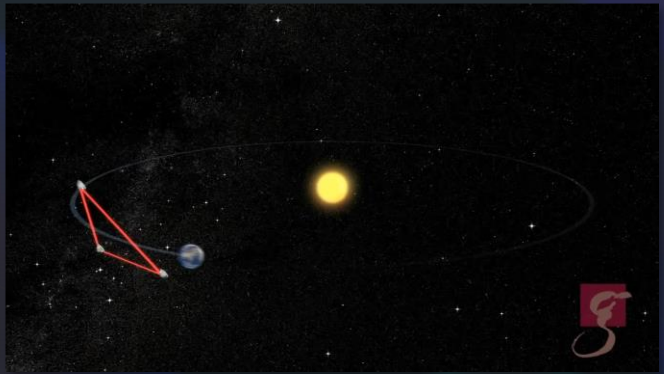
- Paclet current status
  - ✓ characterize of FOPTs and GWB
    - of single-field models
  - ✓ S_3/T via *polygonal bounce* (`FindBounce`)
  - ✓ optional, user-friendly interface with `DRalgo`
  - ✓ fully `Mathematica`-based



CPC 256 (2020) 10748



- Upcoming developments
  - ➢ multi-field
  - ➢ improved phase-tracing routine



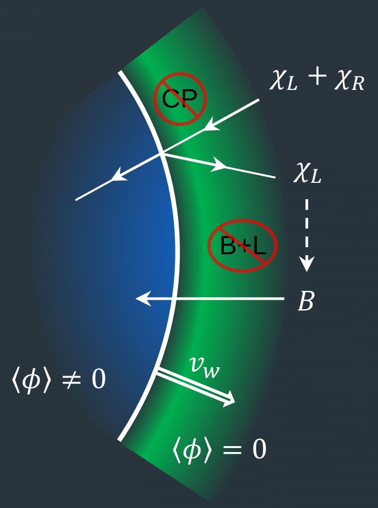
- Potential developments
  - ? v_w estimation in LTE
  - ? Decay rate prefactor $\Gamma = A\, e^{-S_3/T}$

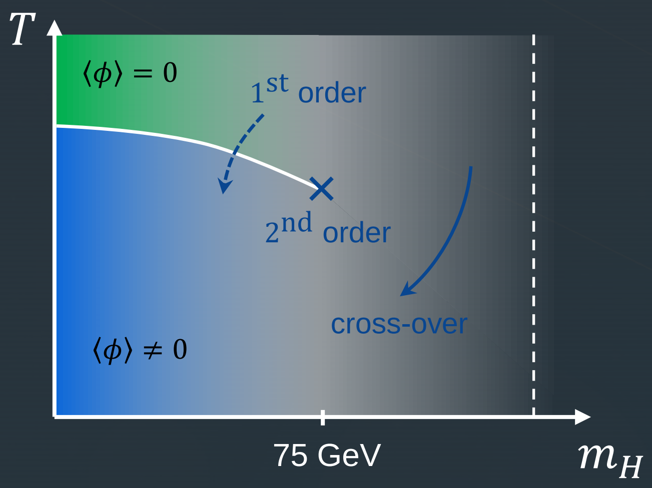
Suggestions are welcome!

EW Baryogenesis
The matter-antimatter problem

- Fundamental problem: baryon asymmetry
- Sakharov conditions (1967)

	SM	LQ Model
1. B-number violation	✓ → non-perturbatively	✓ → LQs acquire vev
2. C & P violation	✓ → weakly	✓ → potential
3. Departure from T-equilibrium	✗ → cross-over	✓ → strong FOPTs





BSM physics required!

Outcome

From Particle Physics to Cosmology

Particle physics model

thermal EFT

PT parameters

T_p, strength α, duration β^{-1},…

Nucleation criterion: $\int_{T_n}^{T_c} dT \, \frac{\Gamma(T)}{T\, H^4(T)} \approx 1$

$$\Gamma(T) = T^4 \left(\frac{S_3}{2\pi T}\right)^{3/2} e^{-S_3/T}$$

percolation criterion: $I(T_p) \approx 0.34$

$$I(T) = \frac{4\pi}{3} v_w^3 \int_T^{T_p} \frac{dT'}{T'^4} \frac{\Gamma(T')}{H^4(T')} \left(\int_T^{T'} \frac{d\tilde{T}}{H(\tilde{T})} \right)^3$$

percolation condition: $\mathcal{V}'_{FV}(t_p) < 0$

$$H(T)(T I'(T) + 3)\Big|_{T_p} < 0$$

- strength $\alpha = \frac{1}{\rho} \Delta \left[V - \frac{T}{4} \partial_T V \right]$
- duration^{-1} $\frac{\beta}{H} = T \frac{d}{dT} \left(\frac{S_3}{T} \right)$

```
In[5]:= SetDirectory[NotebookDirectory[]];
        LoadDRExpressions["ahDRExpressions.m"]

        ComputeEffectivePotential[{gsq0,λ0,msq0},{μ0,μ0/10,100 μ0},
            subRules,"OrderVeff"→"NLO","LoadDRFrom"→"ahDRExpressions.m"]
```

» RG solutions

gsq → InterpolatingFunction[Domain: {10., 1.00·10^4} Output: scalar]

λ → InterpolatingFunction[Domain: {10., 1.00·10^4} Output: scalar]

msq → InterpolatingFunction[Domain: {10., 1.00·10^4} Output: scalar]

```
In[18]:= V[ϕ,μ0]
```

Out[18]=

$$-1.06103\left(\left(53.3507-0.00338267\,\phi^2\right)^{3/2}+\left(53.3507-0.00112756\,\phi^2\right)^{3/2}+0.000265675\,\phi^4-25.1409\,\phi^2+0.118862\left(\phi^2\right)^{3/2}\right)$$

EW Baryogenesis
The matter-antimatter problem