相变过程中FIMP 暗物质的产生

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arXiv: 2312.15752

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Outline

- Freeze in mechanism: Feebly Interacting Massive Particle
- A two-step Phase Transition pattern
- Evolution of the FIMP DM
- Summary

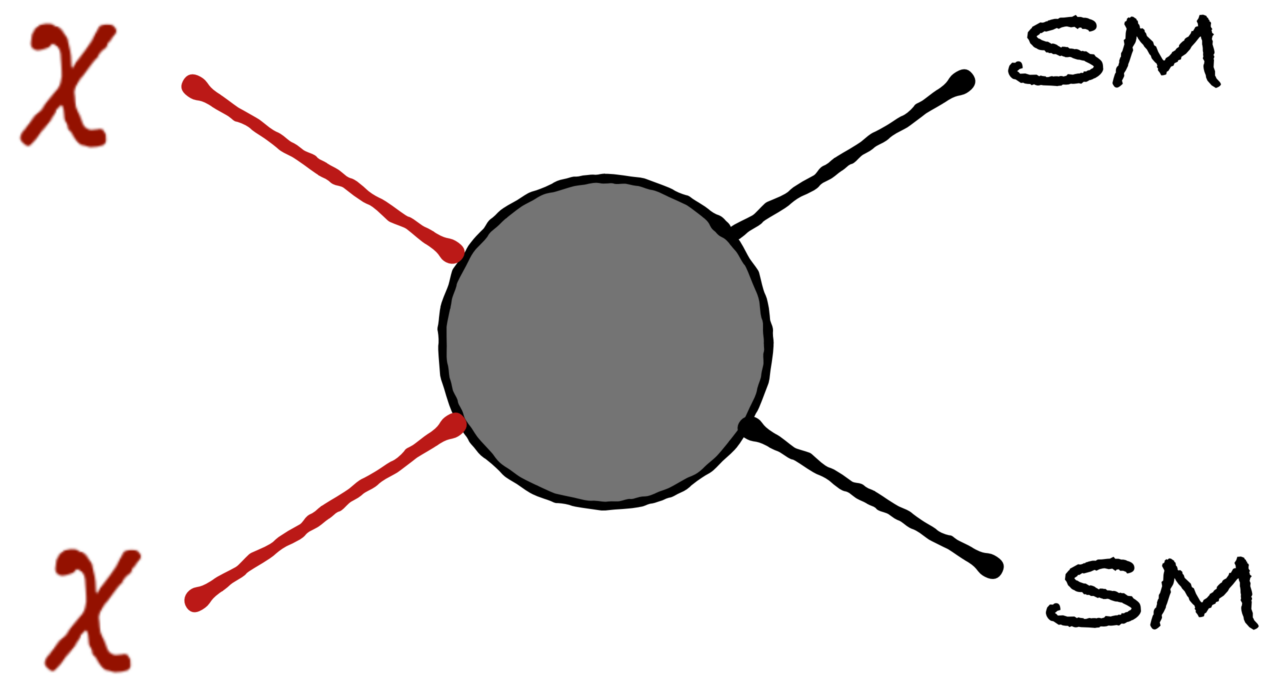
1 Freeze in mechanism

Boltzmann Equation

$$E(\frac{\partial}{\partial t} - H\overrightarrow{p} \cdot \frac{\partial}{\partial \overrightarrow{p}})\, f_\chi = C\ [f_\chi]$$

- Evolution of Phase space density f_χ
- Liouville Operator: Change in spacetime of the DM f_χ
- C [f_χ] : Collision term, interactions between DM and other particles (including itself) that may alter f_χ
- With some assumptions, turn it into BE of number density

Boltzmann Equation: WIMP



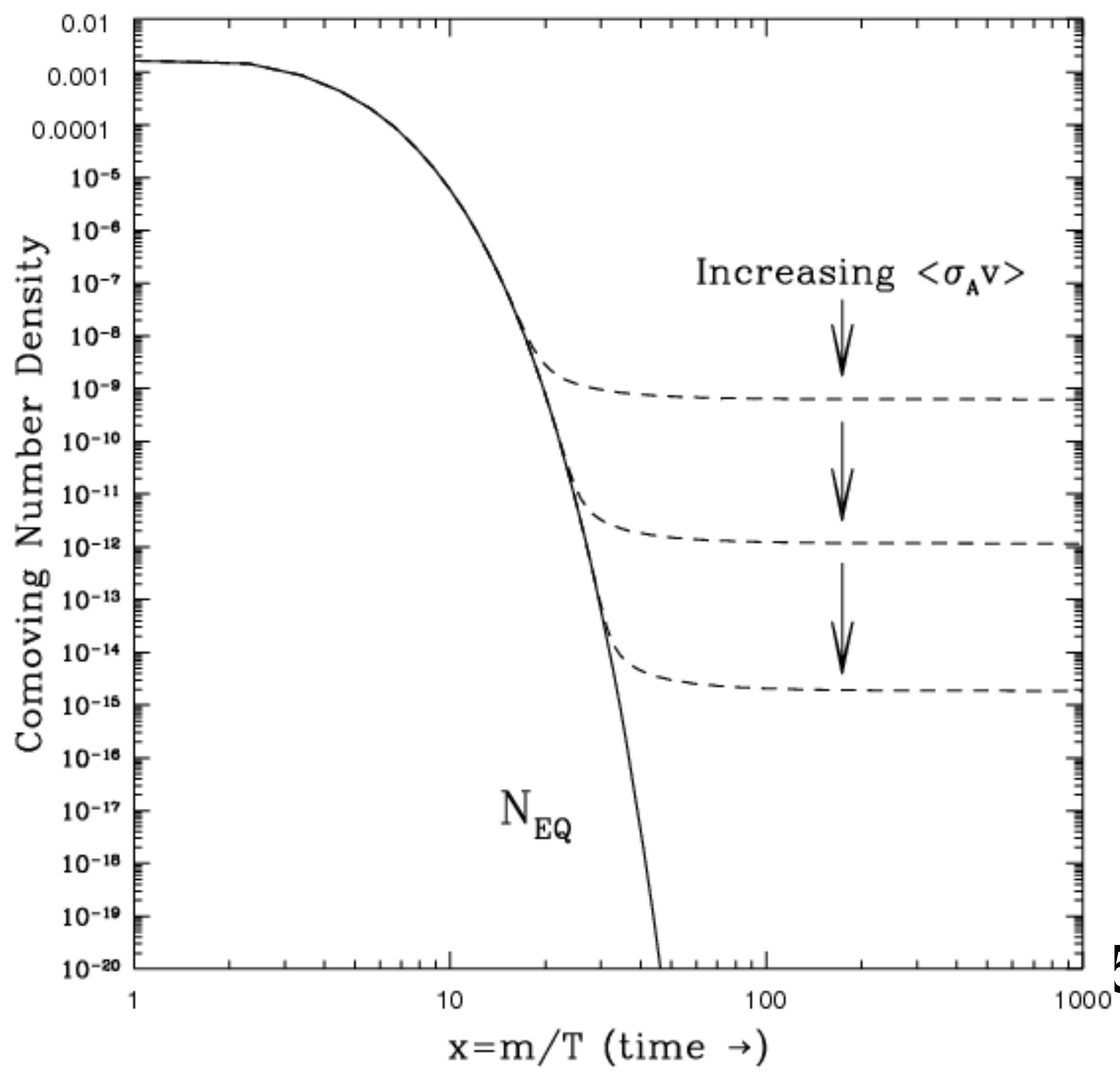
- Freeze-out mechanism: WIMPs

- Gondolo, Gelmini, Nucl.Phys.B 360 (1991) 145-179

- $C[f_\chi] = C_{\text{ann.}}$, DM annihilation process

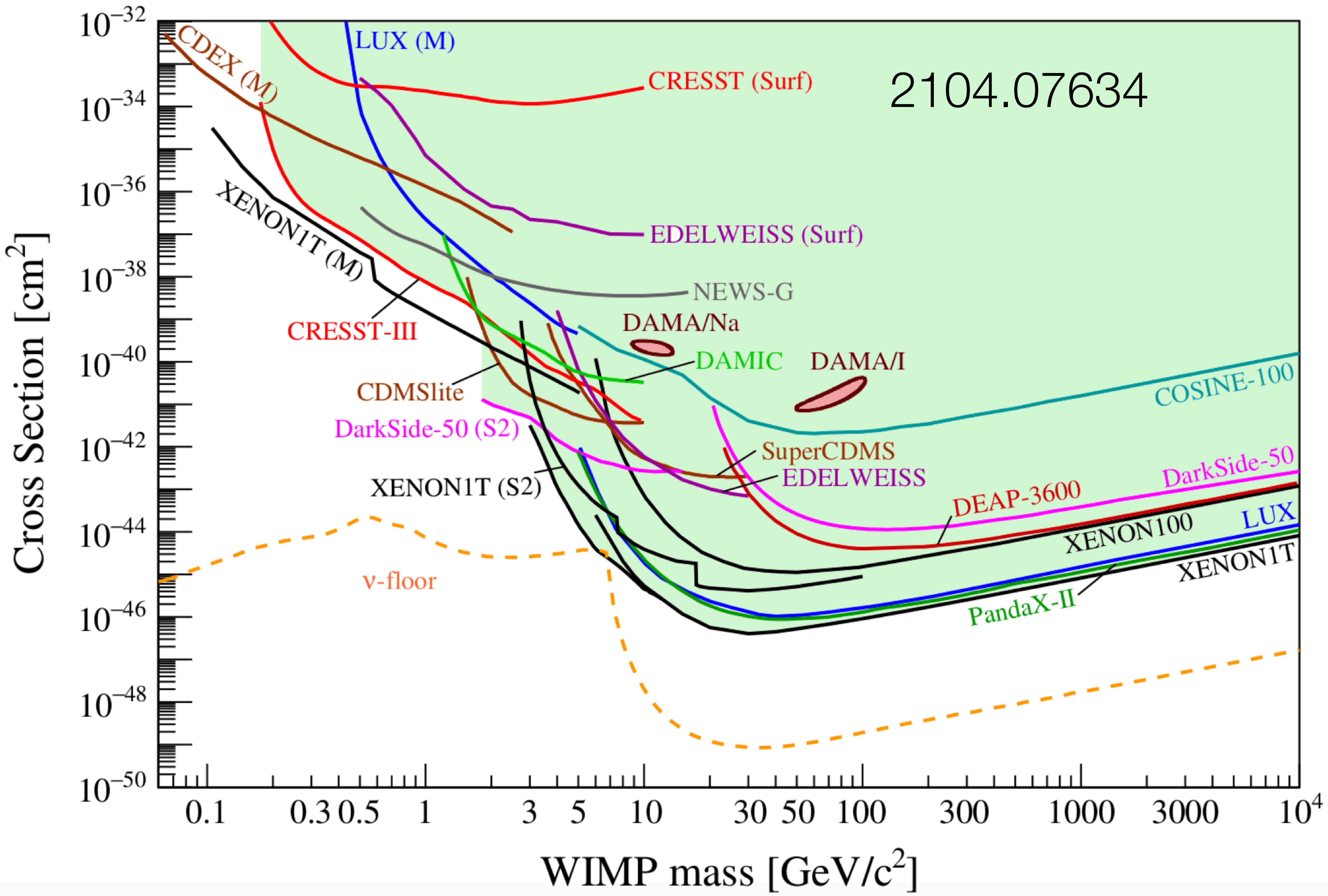
- Transfer phase-space density f_χ to number density n_χ

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \langle \sigma v \rangle_{\text{ann}} (n_{\text{eq}}^2 - n_\chi^2)$$



No WIMP signal: alternative mechanism

- Freeze-in mechanism
- Tiny couplings $\sim 10^{-10}$
- Feebly Interacting Massive Particle



Boltzmann Equation: freeze-in mechanism

- Initial FIMP abundance was zero/negligible

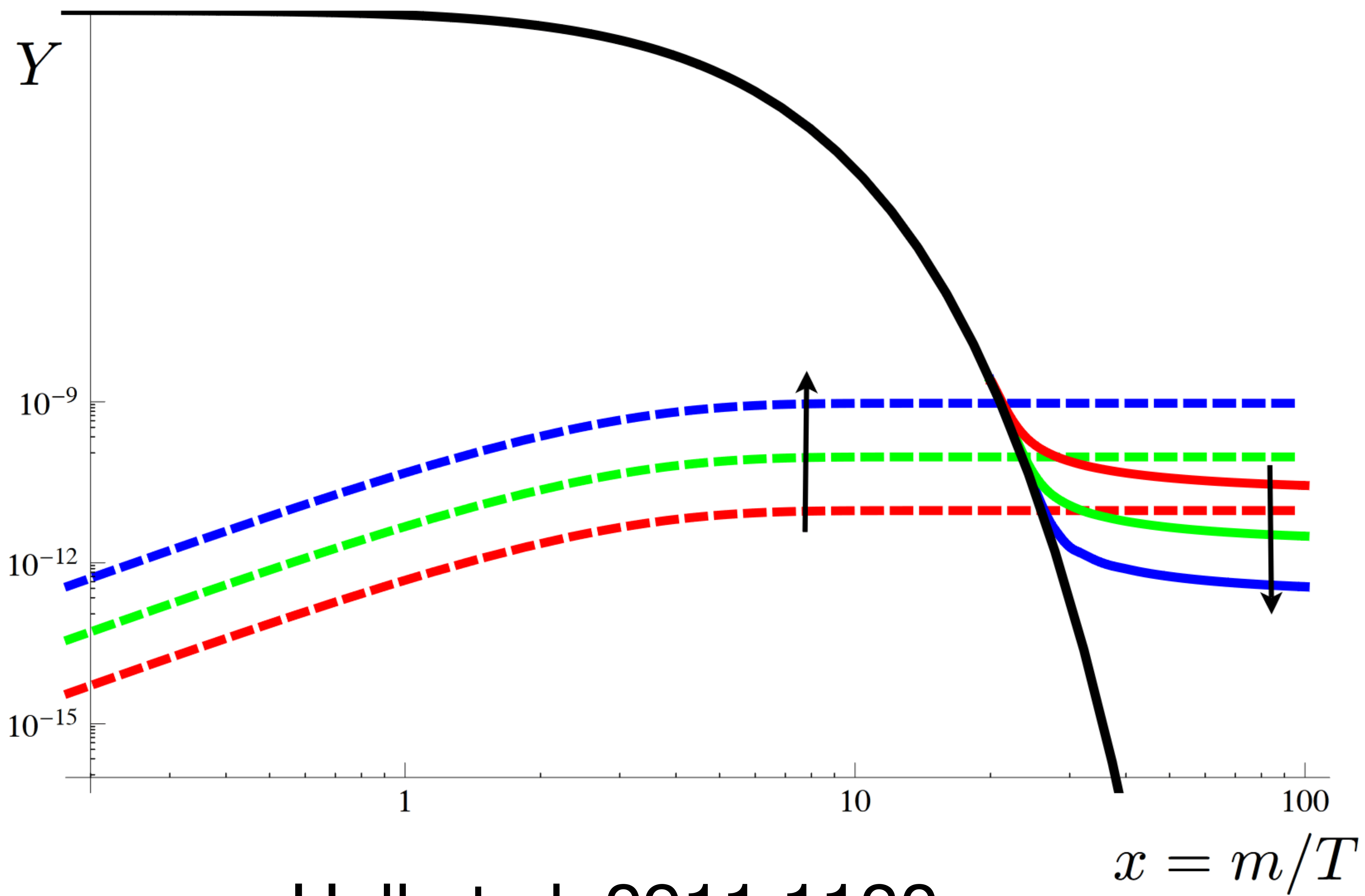
- Production from different channels:

  Decay of thermal bath particle

  Annihilations (scattering) of thermal bath particles

- Freeze at when $\Gamma < H$

- Never reach thermal equilibrium with thermal plasma

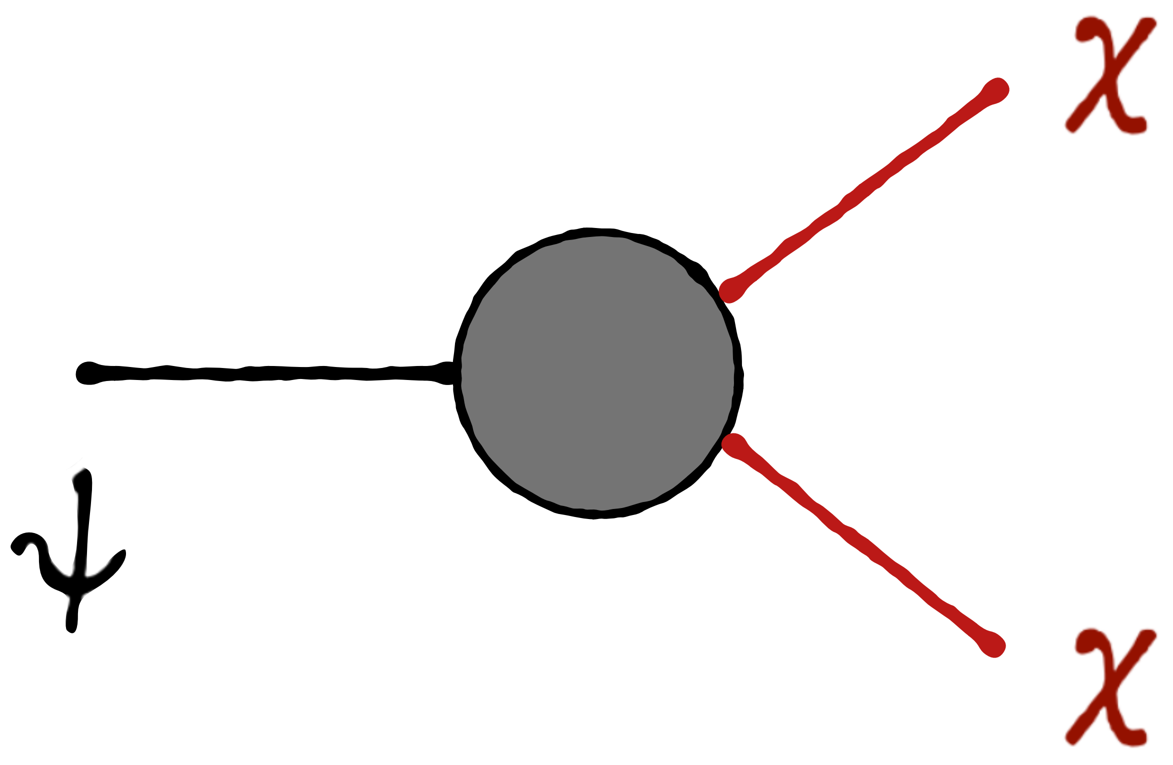


Hall et al. 0911.1120

Boltzmann Equation: decay and annihilations

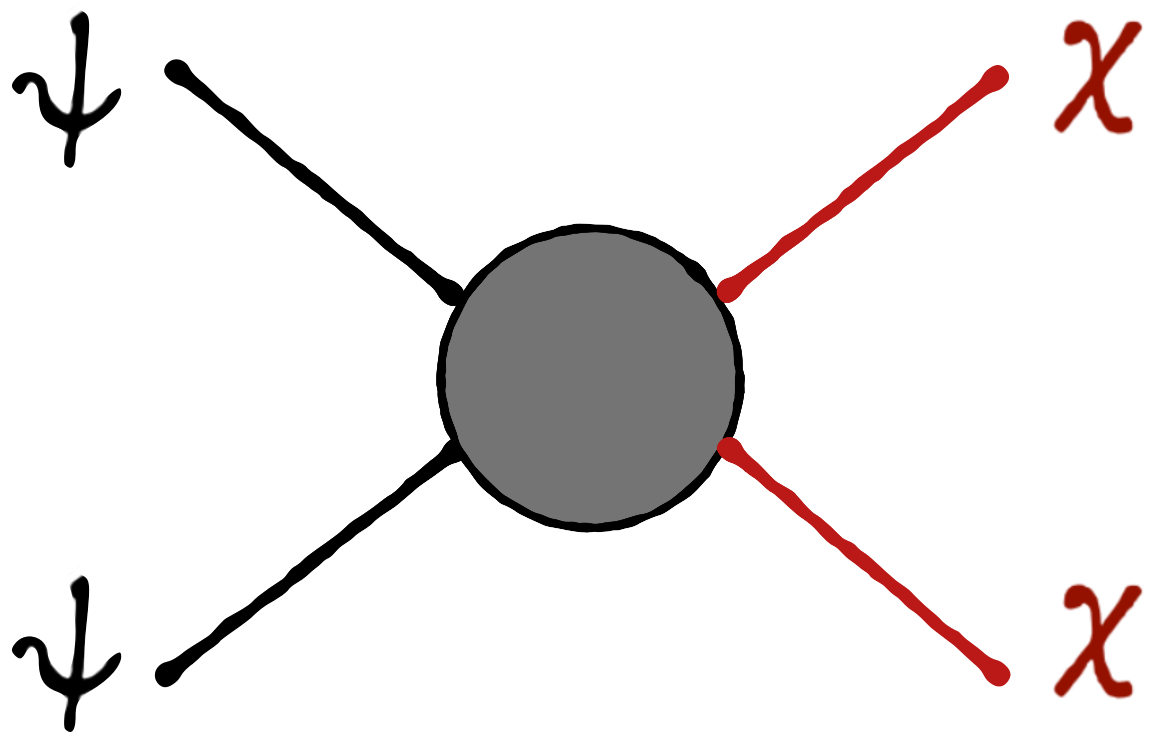
Depending on Collision term:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \mathcal{C}_\alpha$$



$$\mathcal{C}_{B_1 \to B_2 \chi} = n_{B_1}^{\text{eq}} \, \Gamma_{B_1 \to B_2 \chi} \frac{K_1[m_{B_1}/T]}{K_2[m_{B_1}/T]}$$

$$\mathcal{C}^{(a)}_{B_1 B_2 \to \chi\chi} = \langle \sigma_{B_1 B_2 \to \chi\chi} v \rangle \, n_{B_1}^{\text{eq}} n_{B_2}^{\text{eq}}$$



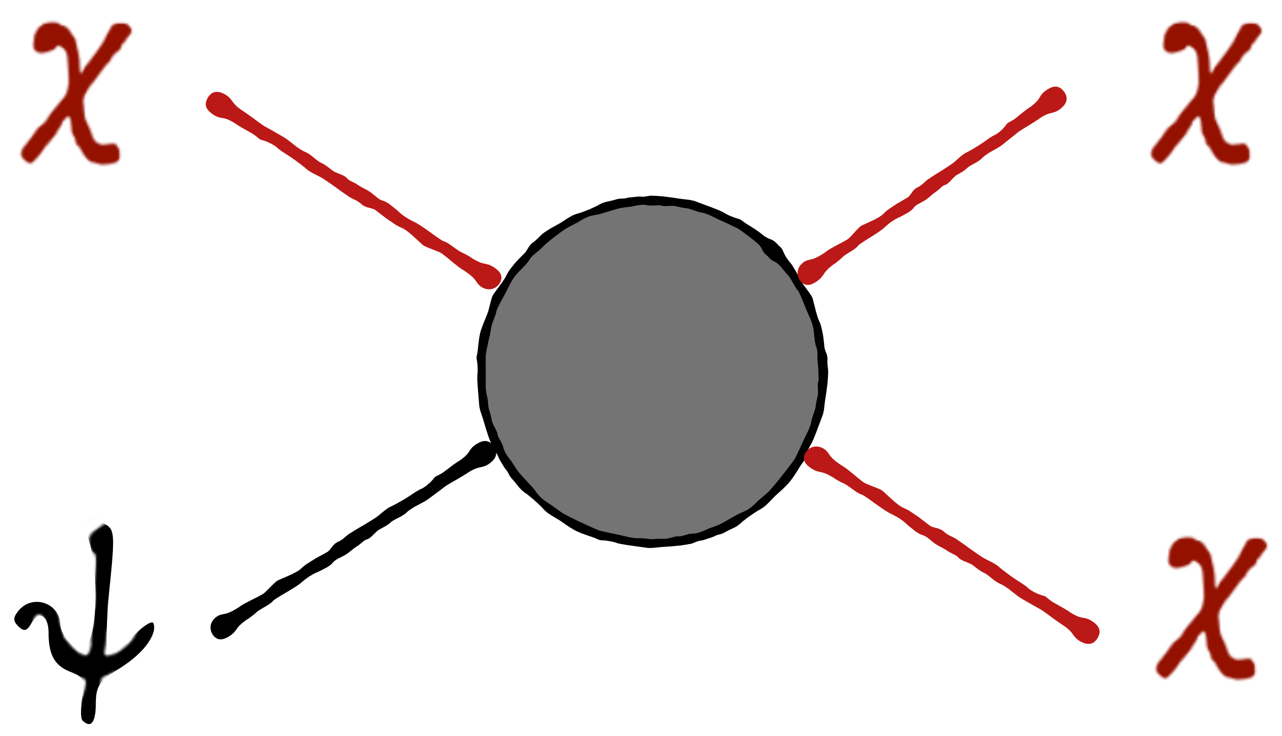
- Notice: Maxwell-Boltzmann distribution functions of Bath Particle

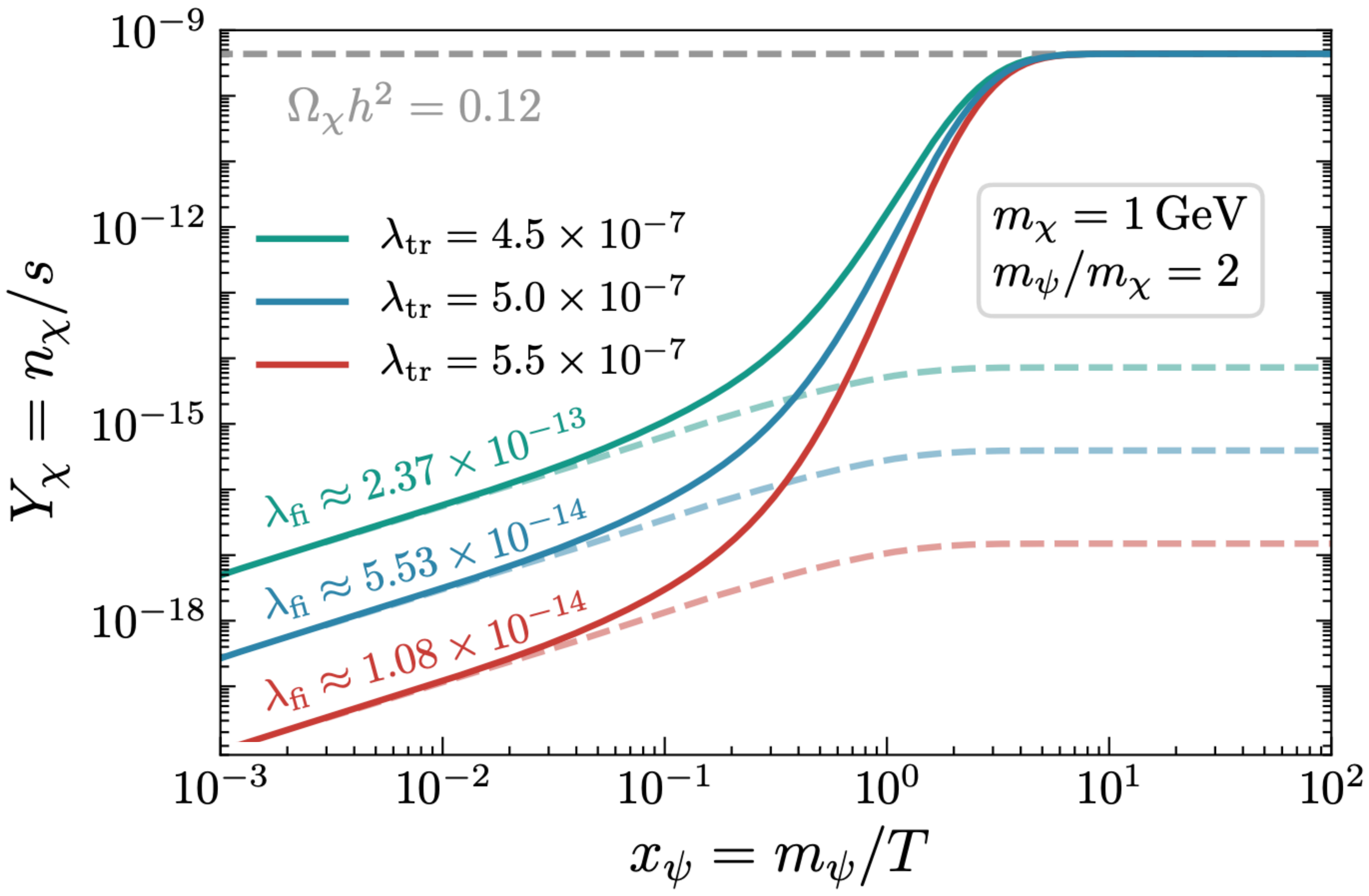
Boltzmann Equation: FIMP-semi production

Exponential growth process, Bringmann et al. (2103.16572)

$$\dot{n}_S + 3Hn_S \simeq \langle\sigma v\rangle_{\text{semi}}\, n_S\, n_\Phi^{\text{eq}}$$

$$Y_S = Y_S^{\text{initial}} \exp\left[\int_{x_{\text{init}}}^{x} dx\, \frac{h_{\text{eff}}(x)\langle\sigma v\rangle_{\text{semi}} n_\Phi^{\text{eq}}}{xH(x)}\right]$$





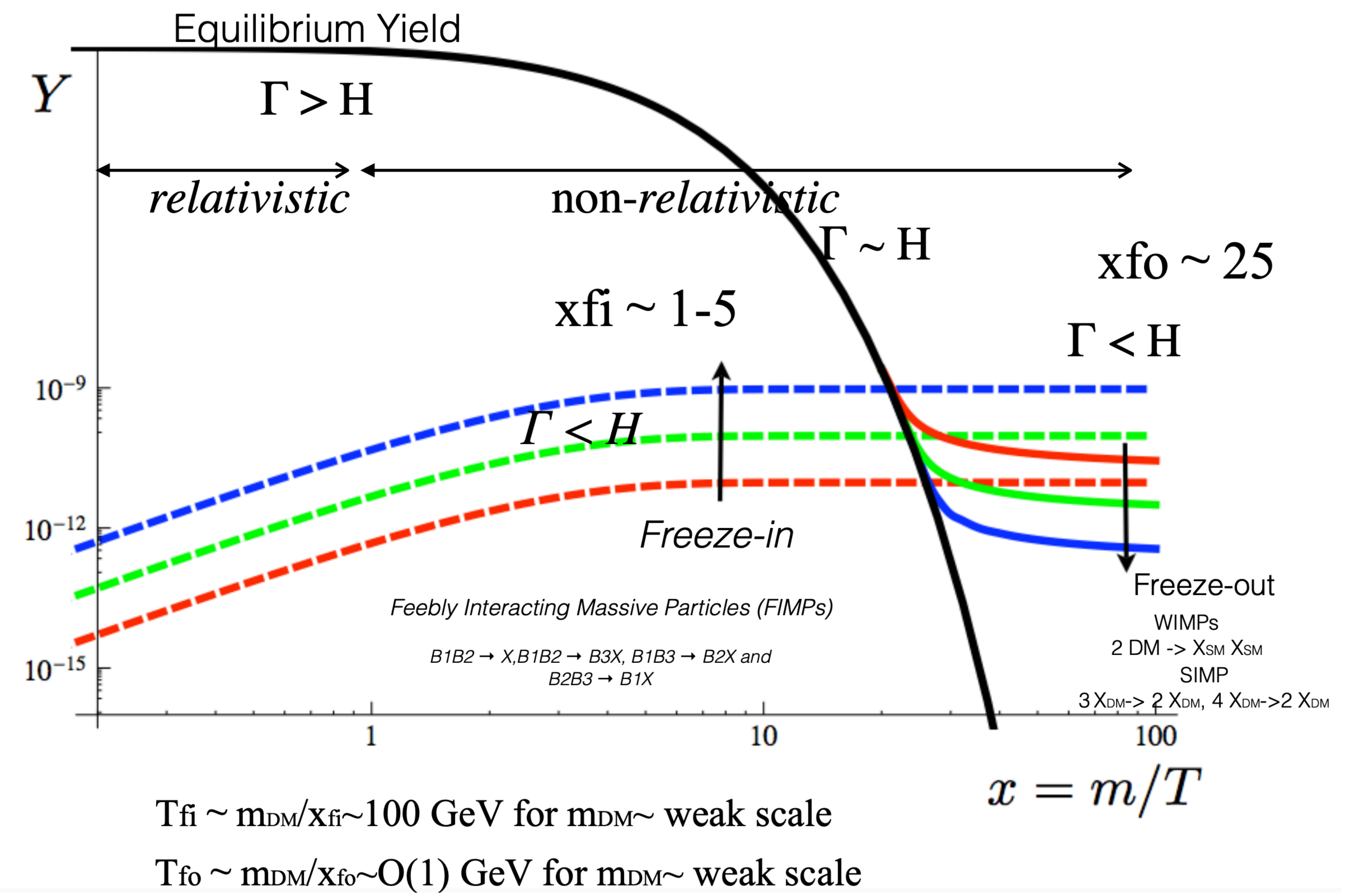
Phys. Rev. Lett. 127, 191802 (2021), 2103.16572
Phys. Rev. Lett. 128, 069901(E) (2022)

Temperature is important

- Electroweak phase transitions:
  thermal corrections

- Literature:
  1712.03962, 1810.03172, 1811.03279,2012.15174, 2111.10608, etc

- Our focus is on the semi-production & 3-body decay processes



2 A Two-step Phase Transition Pattern

Model: A well studied PT model

Introducing two scalars

$$-\mathcal{L} \supset \mu_H^2|H|^2 + \mu_\Phi^2\Phi^2 + \lambda_H|H|^4 + \lambda_\Phi\Phi^4 + \lambda_{H\Phi}|H|^2\Phi^2$$
$$+ \lambda_S S^4 + \lambda_{SH}S^2|H|^2 + \mu_S^2 S^2$$
$$+ \lambda_{S\Phi}S^2\Phi^2 + \lambda_1\Phi S^3 + \lambda_2\Phi^3 S$$

SM+singlet PT model

- Scalar S: FIMP DM
- Scalar Φ: Bath particle
- Symmetry: Z2, odd for S and Φ
- Take $\lambda_{SH} = 0$
- $\lambda_{1,2,S\Phi}$ is tiny
- $\Phi S \to SS$
- $\Phi \to SSS$
- $\Phi\Phi \to SS, \quad \Phi\Phi \to \Phi S$

Finite temperature effective potential

- High-temperature expansion approach

$$V_T(h,\Phi,T) = \frac{\mu_H^2 + c_h(T)}{2}h^2 + \frac{\lambda_H}{4}h^4 + \frac{\lambda_{H\Phi}}{2}h^2\Phi^2 + \frac{2\mu_\Phi^2 + c_\Phi(T)}{2}\Phi^2 + \lambda_\Phi\Phi^4,$$

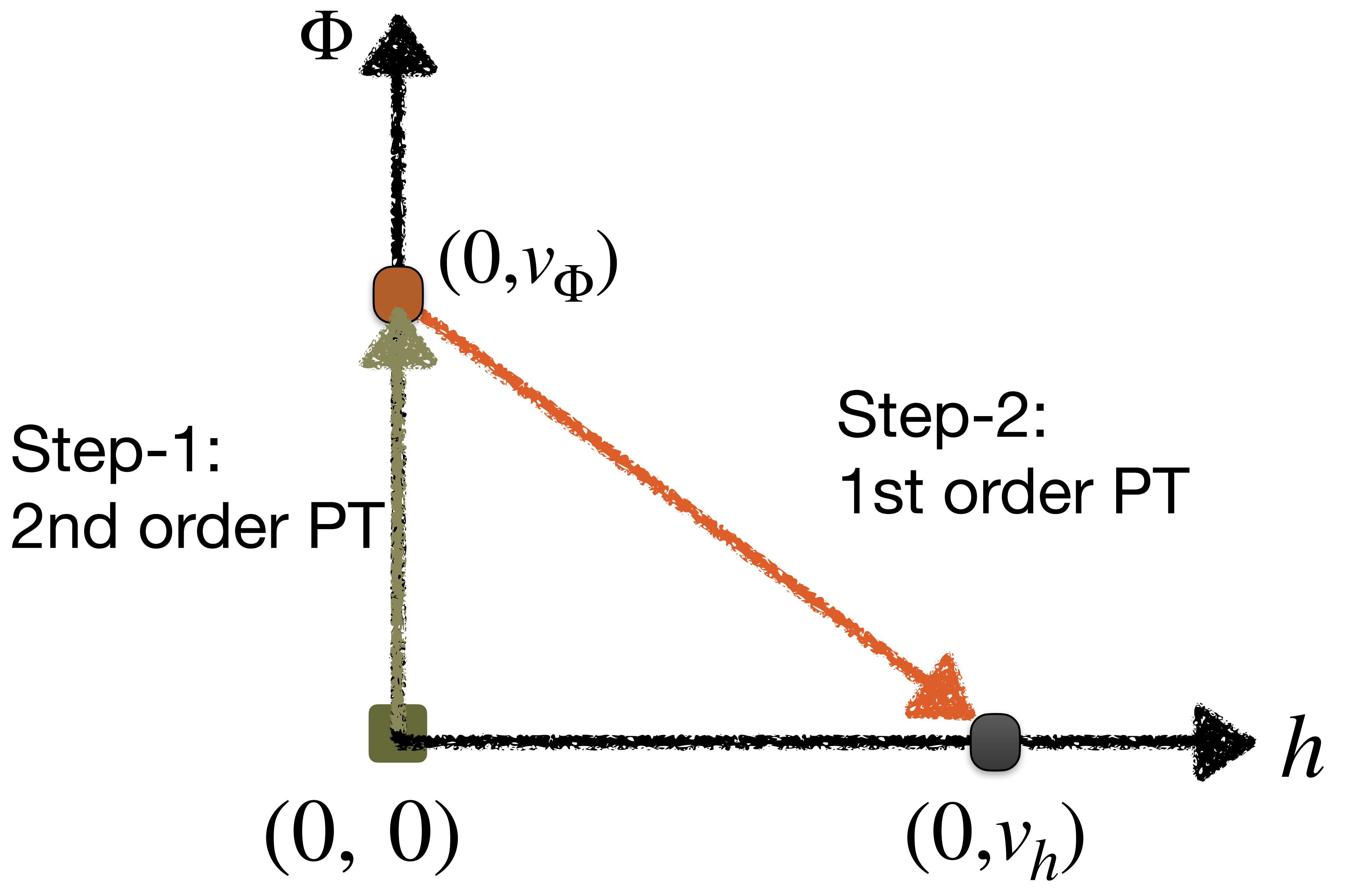
- Thermal corrections:

$$c_h(T) = \frac{1}{48}(9g^2 + 3g'^2 + 12y_t^2 + 24\lambda_H + 4\lambda_{H\Phi})T^2$$

$$c_\Phi(T) = \frac{1}{6}(2\lambda_{H\Phi} + \lambda_{S\Phi} + 6\lambda_\Phi)T^2.$$

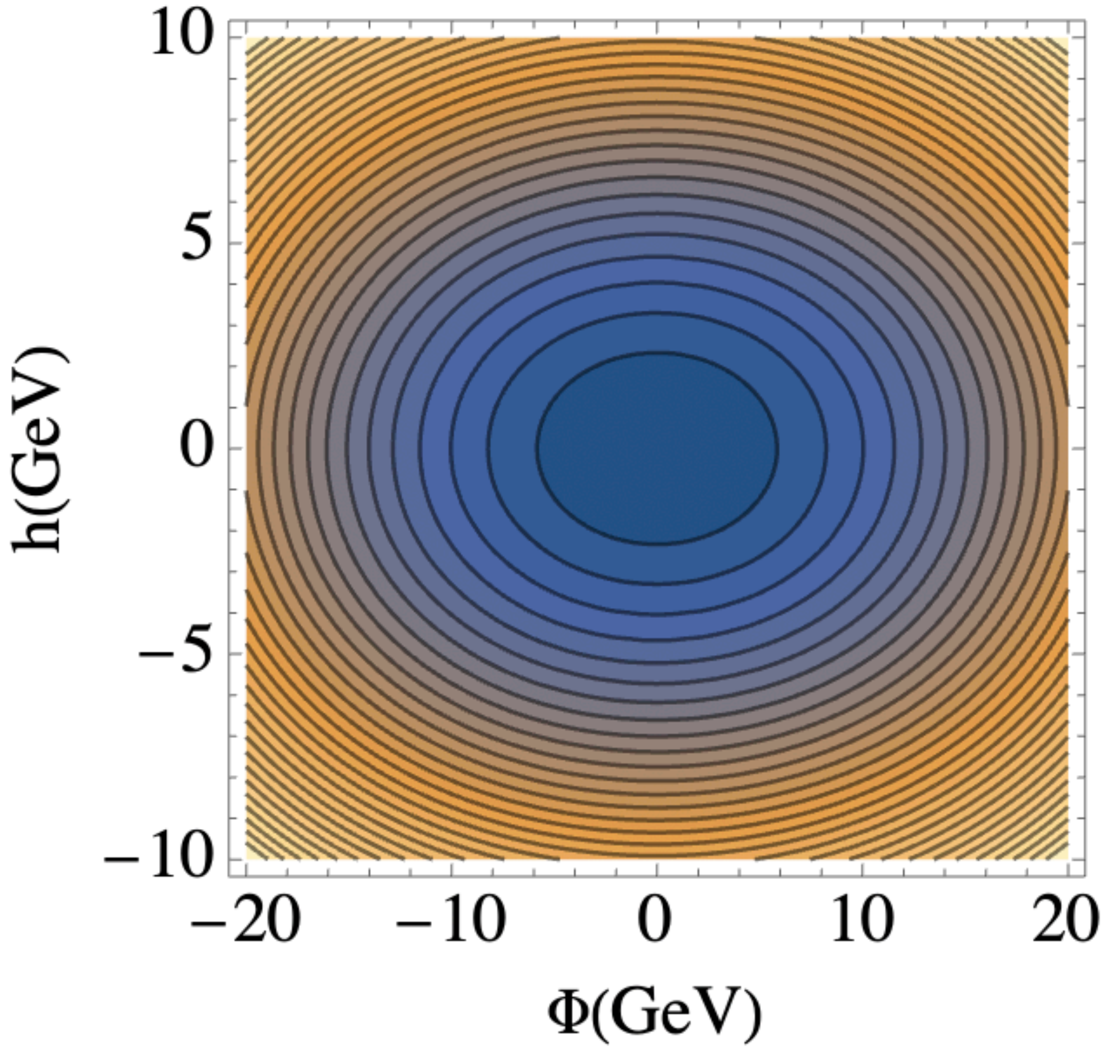
Chao,Guo,Shu,1702.02698

Huang, Qian, Zhang,1804.06813, ………..

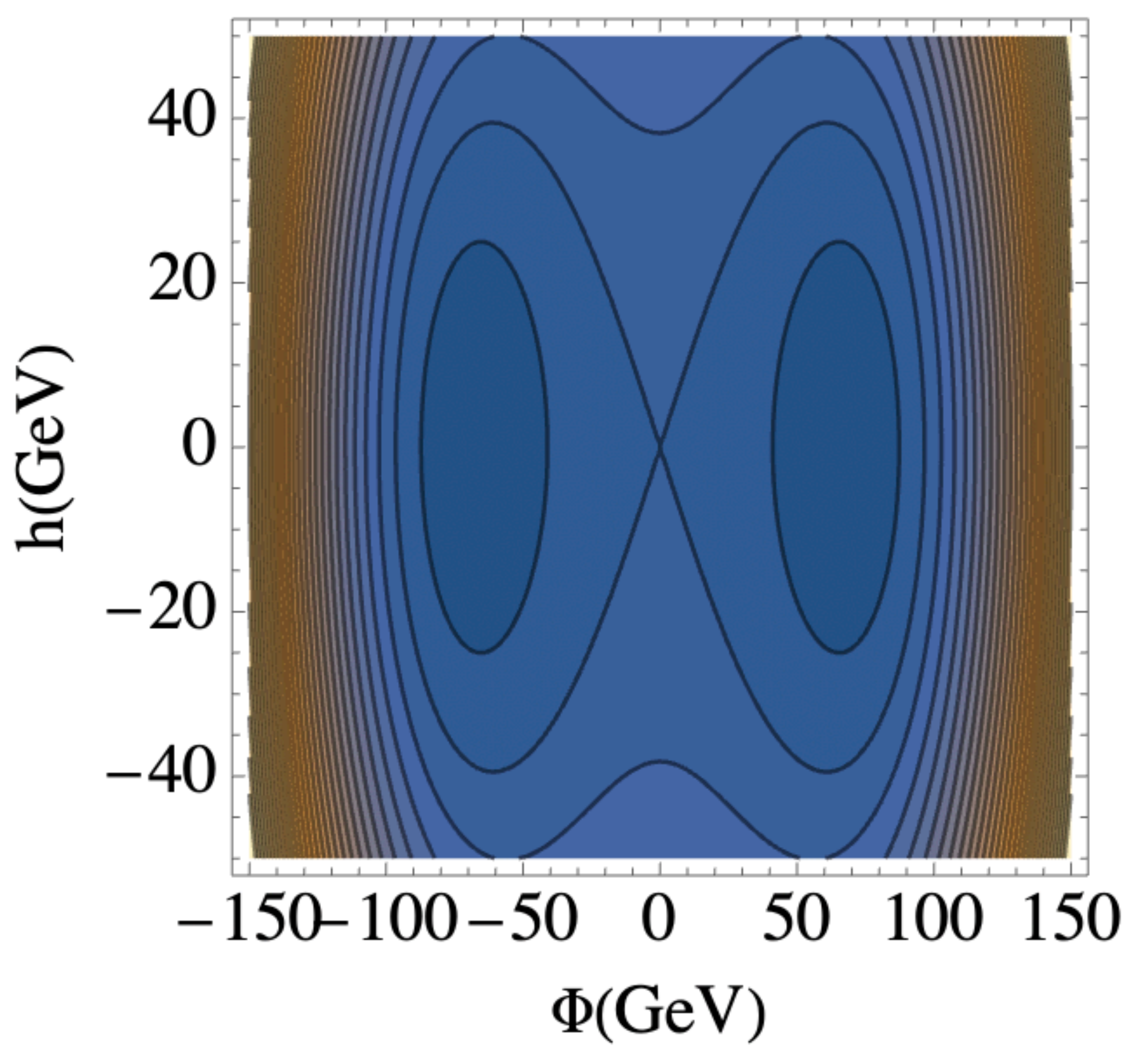


Broken pattern

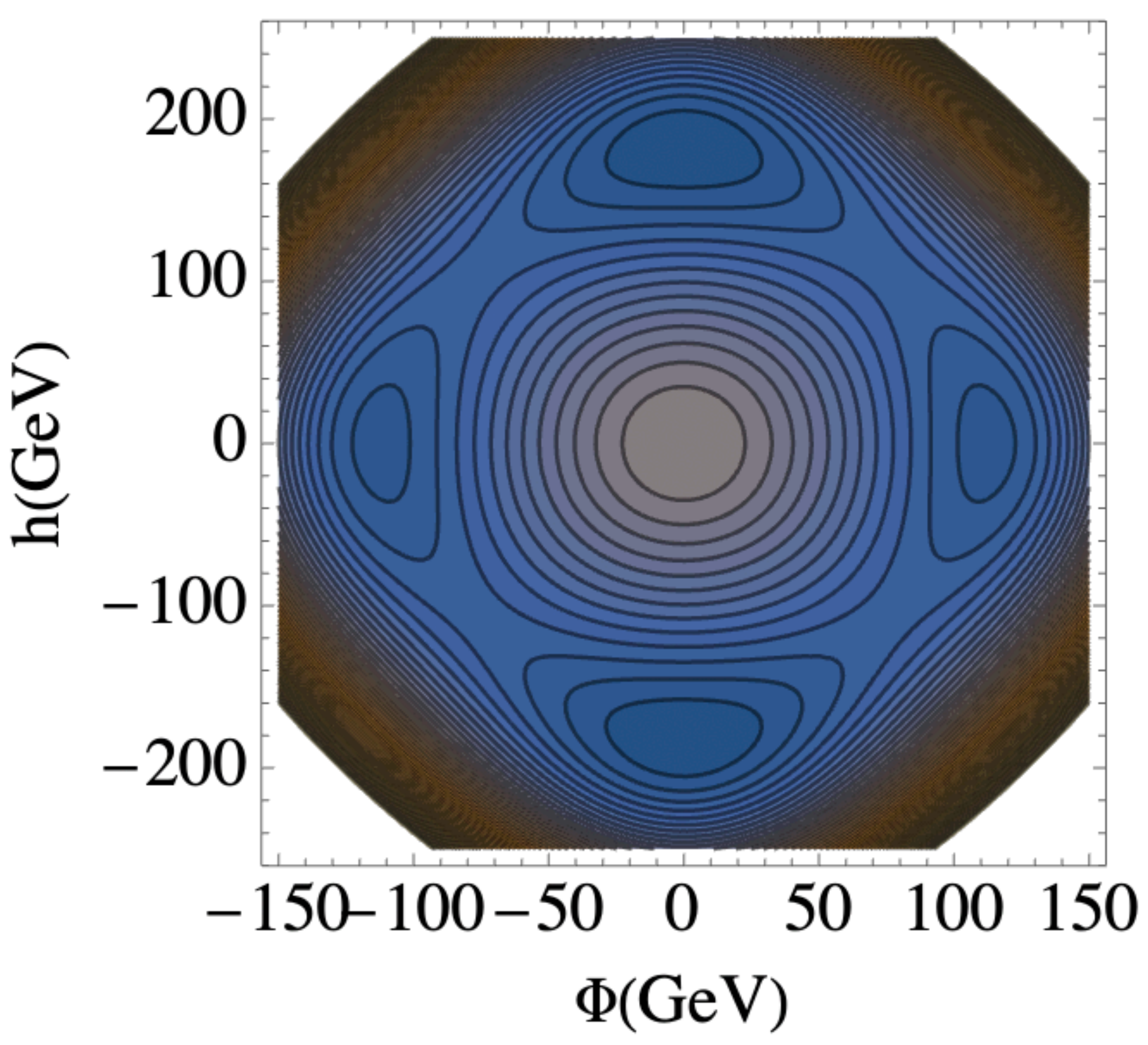
A 2-step PT pattern: Evolution of Potential Minimum



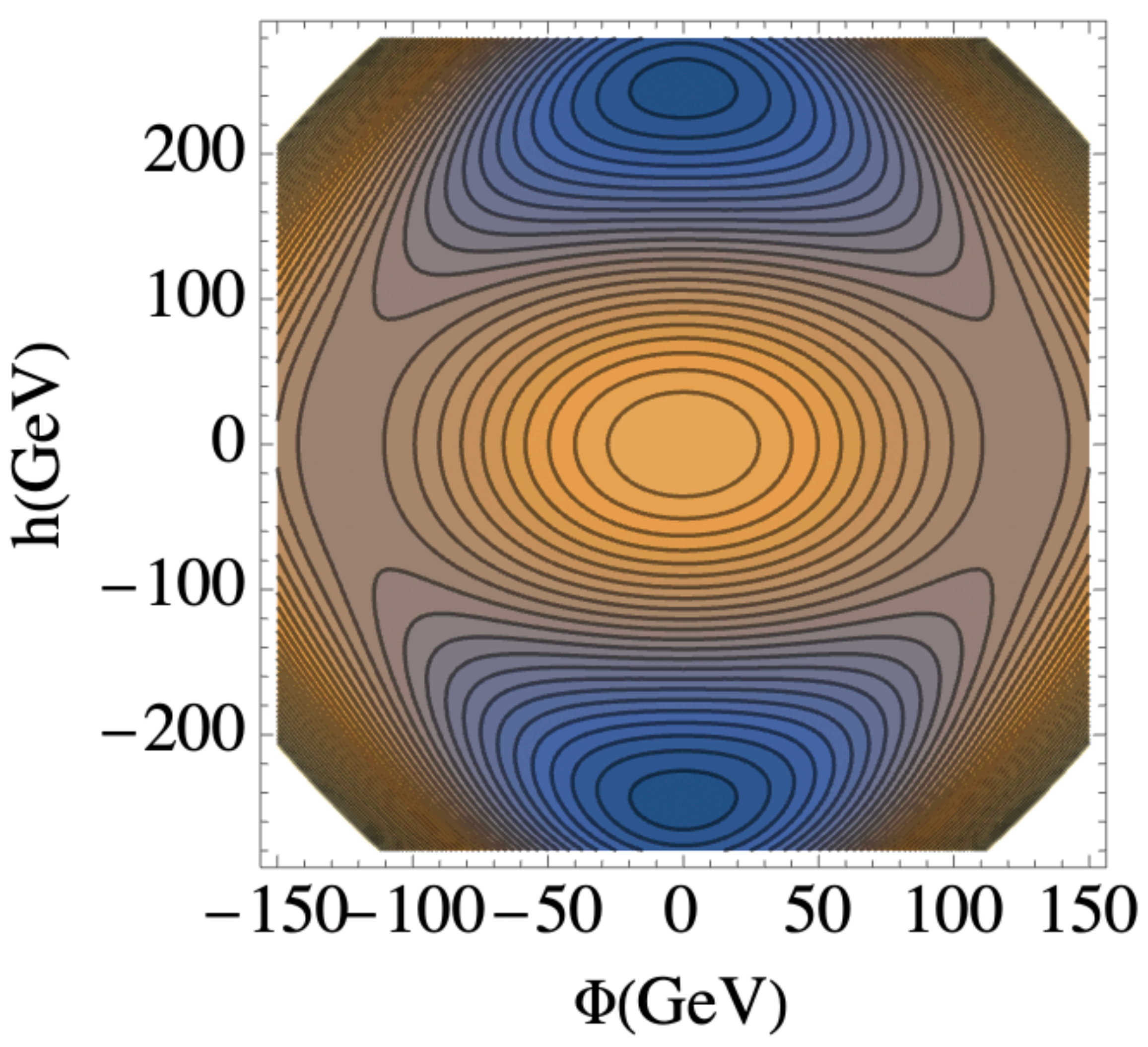
T=200 GeV



T=160 GeV



T=89 GeV



T=0

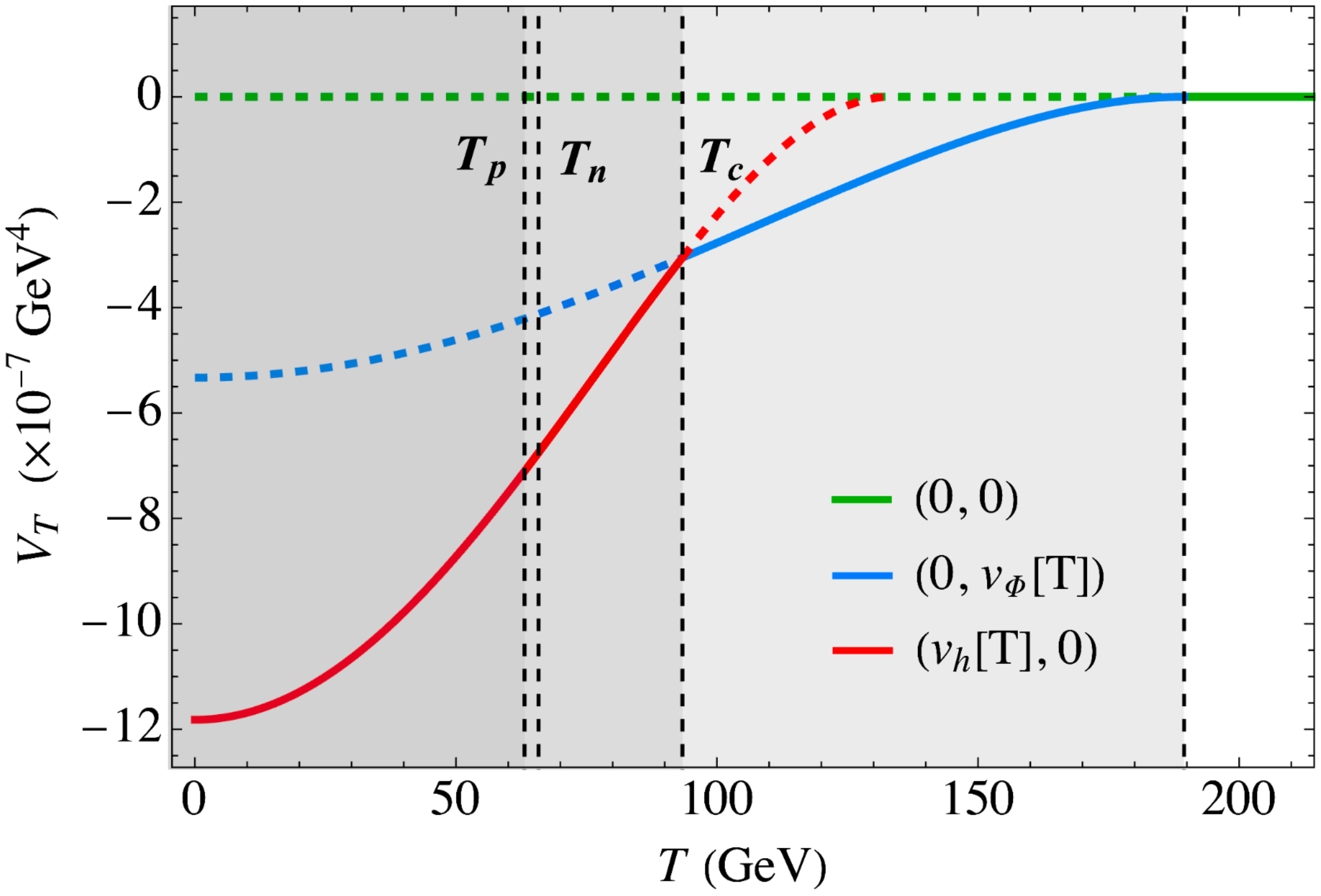
A 2-step PT pattern: Evolution of Potential Minimum

Thermal VEVs:

$$v_h(T) = \pm\sqrt{\frac{-\mu_H^2 - c_h(T)}{\lambda_H}}$$

$$v_\Phi(T) = \pm\sqrt{\frac{-2\mu_\Phi^2 - c_\Phi(T)}{4\lambda_\Phi}}$$

m_Φ^0(GeV)	$\lambda_{H\Phi}$	λ_Φ	T_p(GeV)	$\frac{v_h(T_p)}{T_p}$	α	$\frac{\beta}{H_*}$
128.8	0.491	0.202	63.1	3.431	0.17	282.2



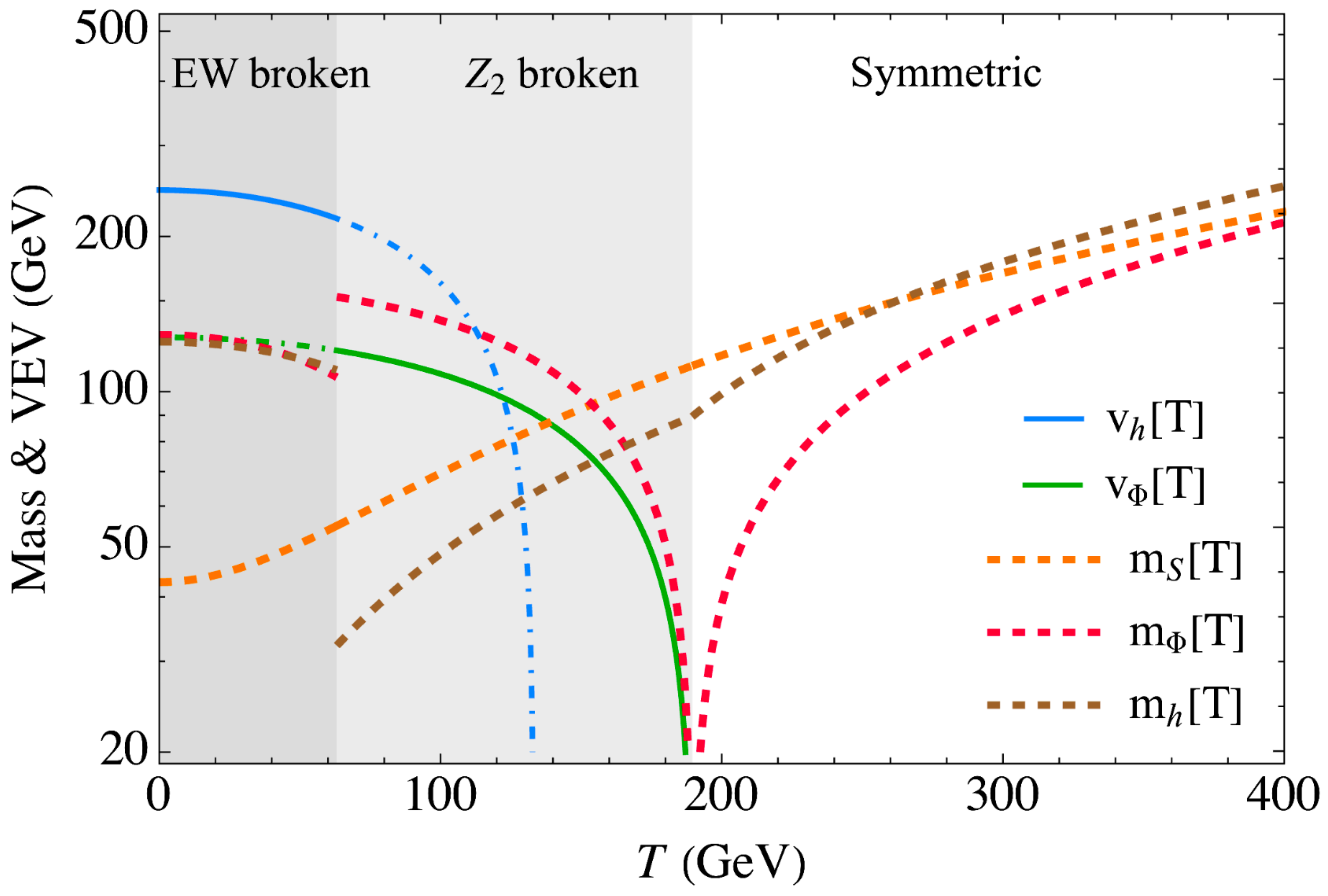
Thermal masses

Masses:

$$m_S^2 = 2\mu_S^2 + 2\lambda_{S\Phi} v_\Phi(T)^2 + \frac{1}{6}T^2(6\lambda_S + \lambda_{S\Phi})$$

$$m_\Phi^2 = 2\mu_\Phi^2 + \lambda_{H\Phi} v_h(T)^2 + 12\lambda_\Phi v_\Phi(T)^2 + c_\Phi(T)$$

$$m_h^2 = \mu_H^2 + 3\lambda_H v_h(T)^2 + \lambda_{H\Phi} v_\Phi(T)^2 + c_h(T)$$



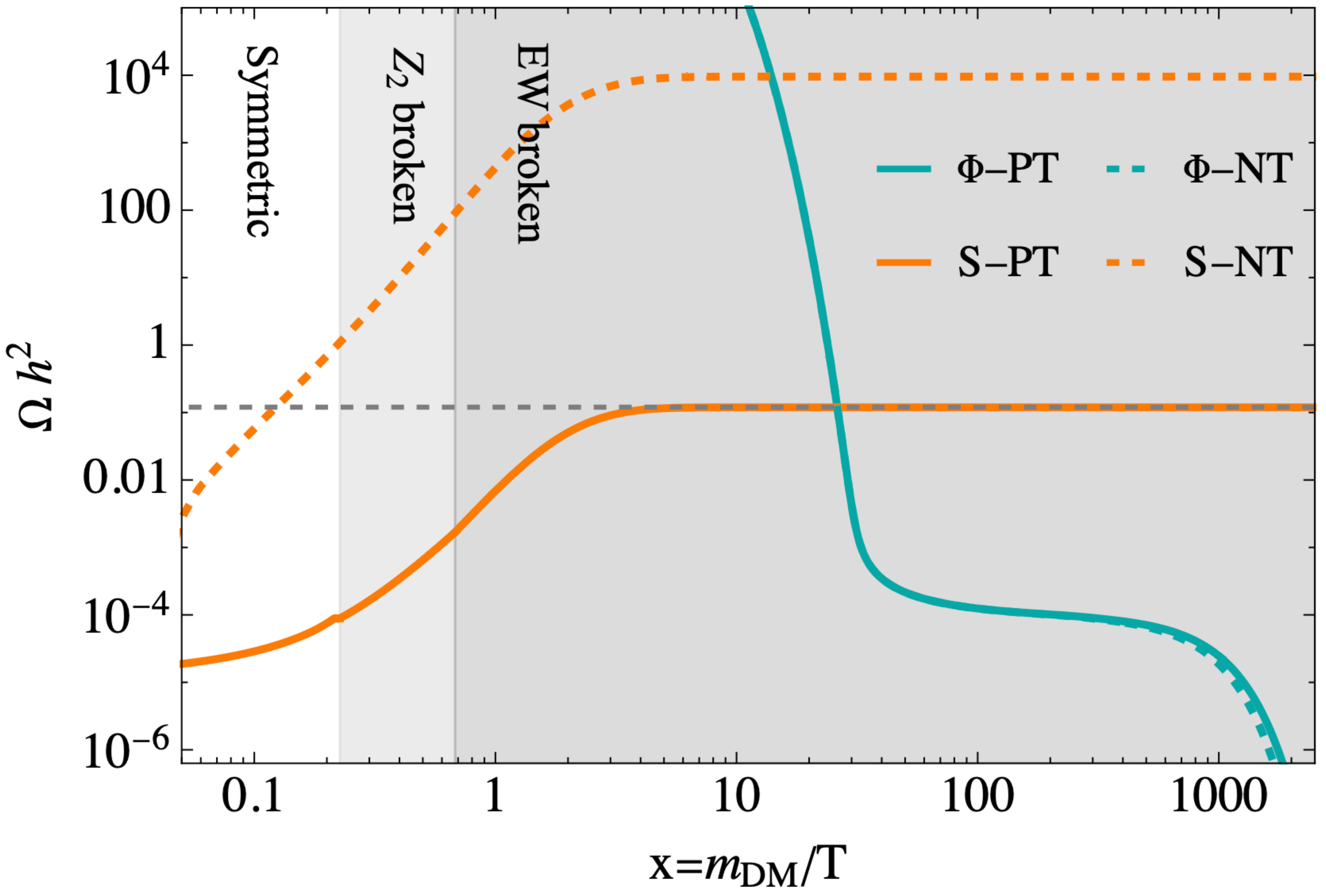
3 Dark Matter Evolution

Semi production

- All phases: $\Phi S \to SS$
- Dashed: Without thermal correction

  with $\Phi \to SSS$

- Cyan: bath particle Φ
- **5 orders of magnitude deviation**



Three body decay

- Without thermal effect:

  typical freeze-in feature

- Symmetric phase:

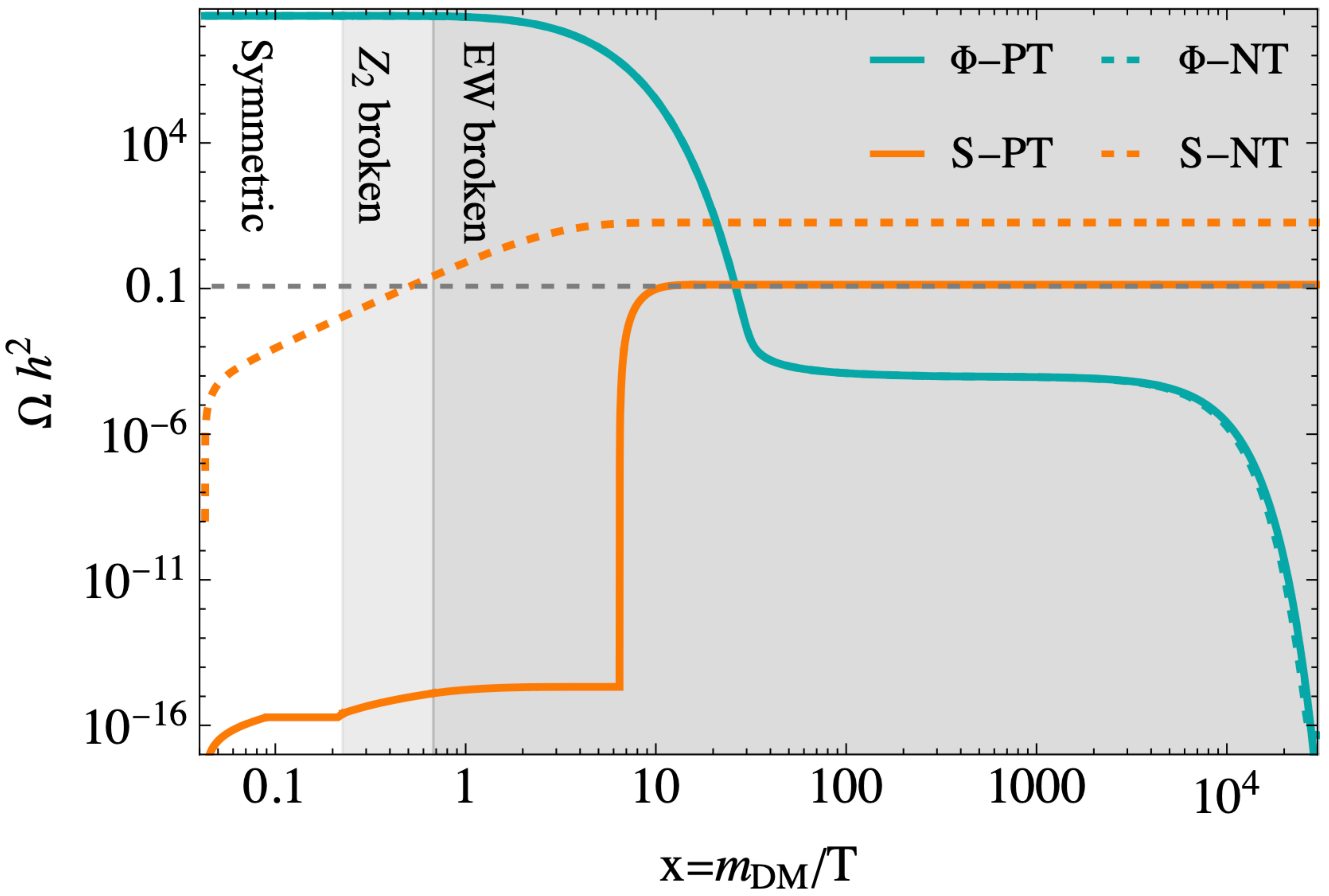
$$\Phi\Phi \to SS, \quad \Phi\Phi \to \Phi S$$

- Z2 broken phase:

$$\Phi\Phi \to SS, \quad \Phi\Phi \to \Phi S$$

- EW broken phase: $\Phi \to SSS$

- **2 orders of magnitude deviation**

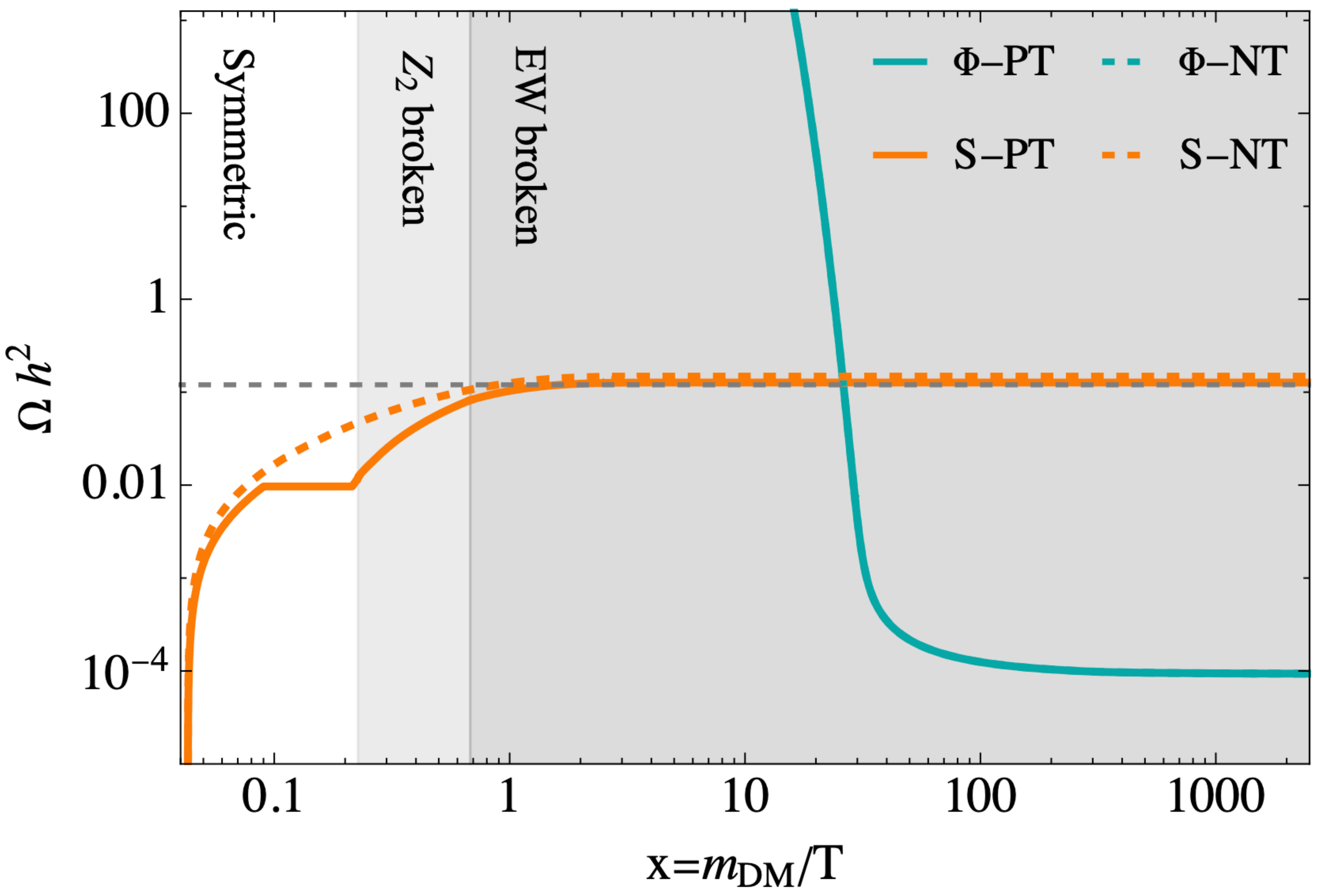


Pair annihilation

- Three phases:

$$\Phi\Phi \to SS, \quad \Phi\Phi \to \Phi S$$

- **Similar result, but different trajectory**



4 Gravitational Wave Signals

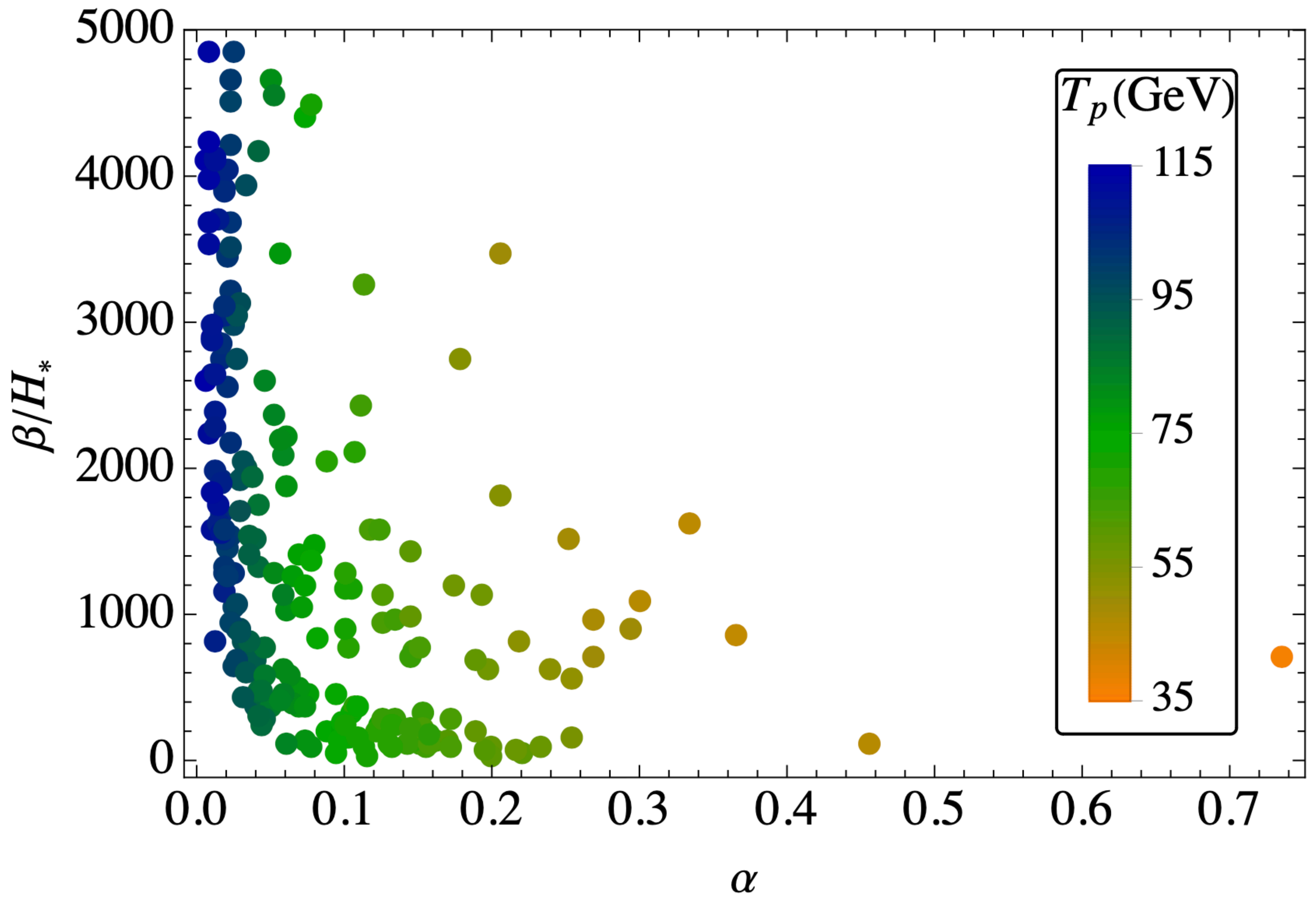
Gravitational Waves

- Key parameters of PT v.s. Tp

- PT strength $\alpha = \frac{\Delta\rho}{\rho_R}$

- PT inverse duration

$$\frac{\beta}{H_*} = T\frac{d(S_3/T)}{dT}|_{T=T_*}$$



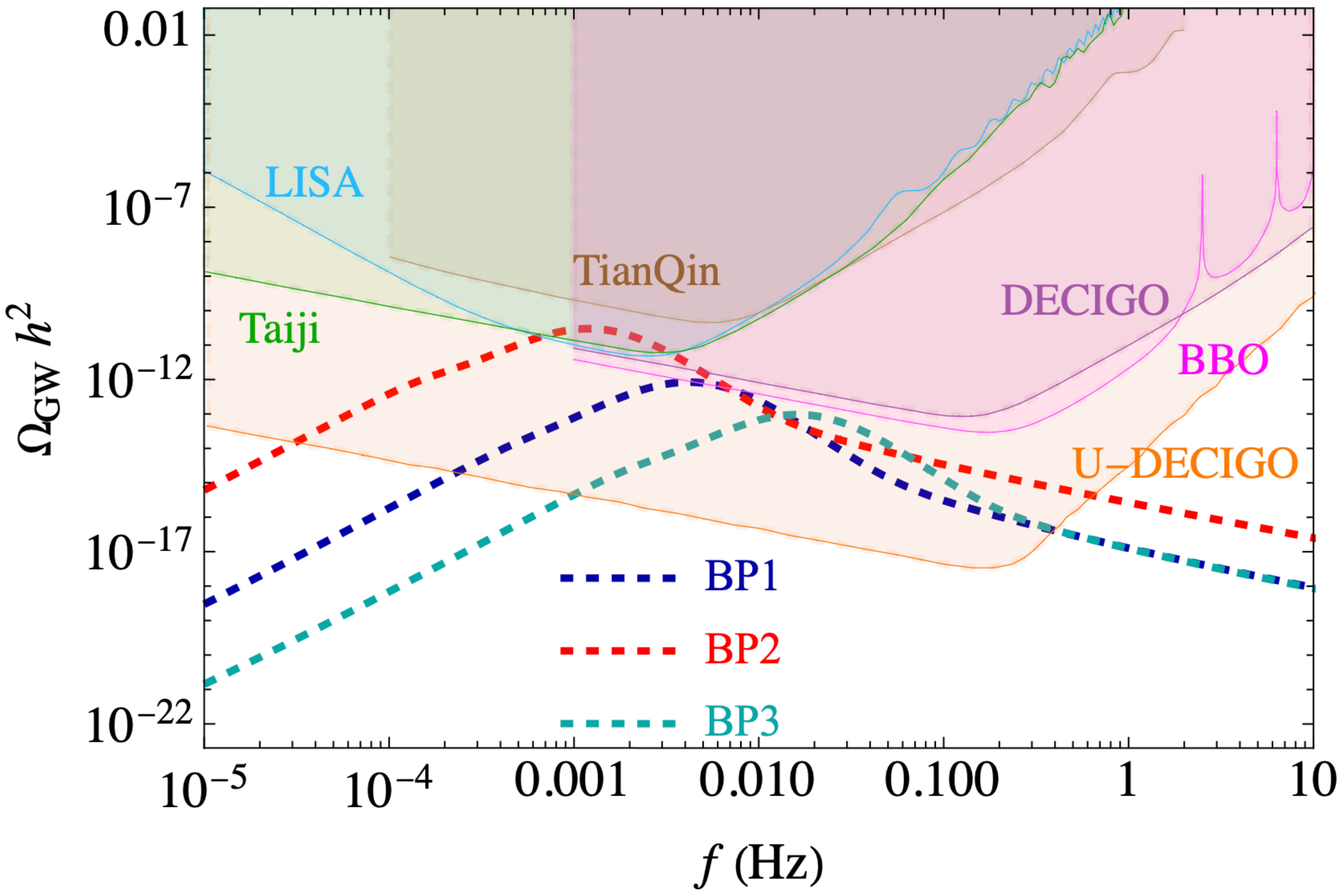
Gravitational Waves

- GWs from Bechmarks

BP	m^0_Φ(GeV)	$\lambda_{H\Phi}$	λ_Φ	T_p(GeV)	$\frac{v_h(T_p)}{T_p}$	α	$\frac{\beta}{H_*}$
BP1	128.8	0.491	0.202	63.1	3.431	0.17	282.2
BP2	131.3	0.663	0.482	45.8	5.034	0.46	121.6
BP3	80.0	0.502	0.410	45.1	5.134	0.33	1620.1

- Be tested in sensitivities of LISA, Taiji, TianQin…

- Complementary search



5 Summary

Summary

- We study three different production processes for FIMP production.
- Effects from phase transition is crucial, leading to distinctive evolution trajectories of the FIMP
- However, beside the phase transition, in-meadium effects and relativistic distribution functions of bath particles should be taken into account.
- Notice: this is an **ad-hoc correction**. Requiring a full quantum-field-theoretical approach at finite-temperature [M. Becker et al. 2312.17246].

Thanks

BACKUP SLIDES

Benchmarks

Scenario	m_S^0(GeV)	$\lambda_{S\Phi}$	λ_1	λ_2
Semi-production	42.9	10^{-19}	10^{-7}	10^{-19}
3-body decay	42.7	10^{-19}	10^{-9}	10^{-19}
Pair-annihilation	42.9	6×10^{-13}	10^{-19}	6×10^{-13}