Cosmological implications of the radiative electroweak symmetry breaking theories

Ke-Pan Xie

Beihang University

SM and Beyond 2024 / Gordon Godfrey Workshop

2024.12.12, Sydney, Australia

2408.03649 [PRD], 2304.00908 [PRD], 2206.04691 [JHEP]

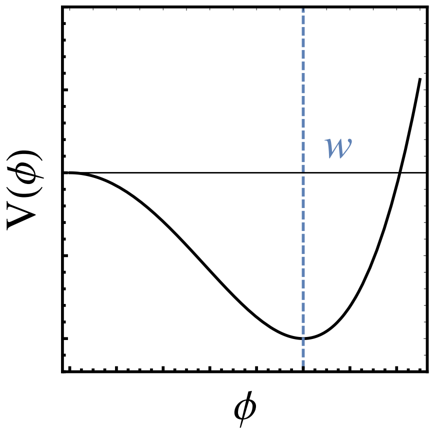
Patterns of spontaneous symmetry breaking

Conventional setup

$$V(\phi) = \frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$

with $\mu^2 < 0$

$\langle\phi\rangle = w = \sqrt{-\mu^2/\lambda}$;



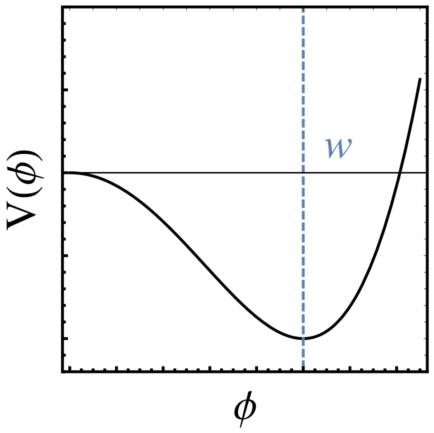
Patterns of spontaneous symmetry breaking

Conventional setup

$$V(\phi) = \frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$

with $\mu^2 < 0$

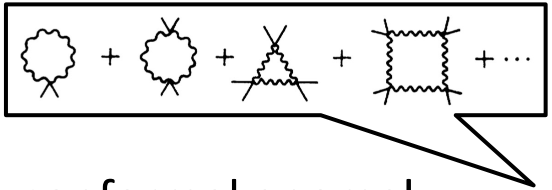
$\langle\phi\rangle = w = \sqrt{-\mu^2/\lambda}$;



Radiative symmetry breaking [this talk]

$V(\phi) = \lambda\phi^4/4$ at tree-level; at one-loop level

$$V_1(\phi) = \frac{B}{4}\phi^4\left(\log\frac{\phi}{w} - \frac{1}{4}\right)$$



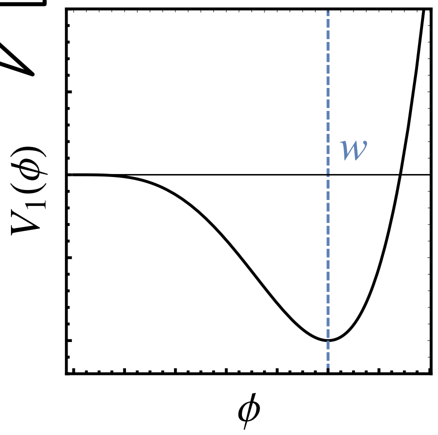
Scale & conformal anomaly

Dimensional transmutation

S. Coleman & E. Weinberg PRD 7 (1973) 1888-1910, citation 5000+

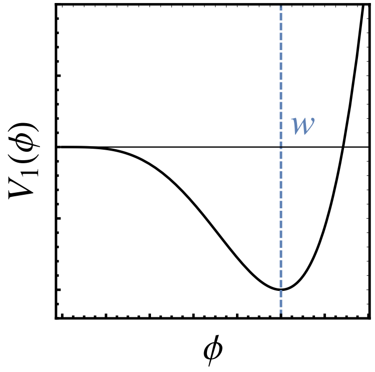
No bare ϕ^2-term, hopefully solving hierarchy problem

Bardeen, FERMILAB-CONF-95-391-T;
Meissner *et al*, PLB 660 (2008) 260-266; etc



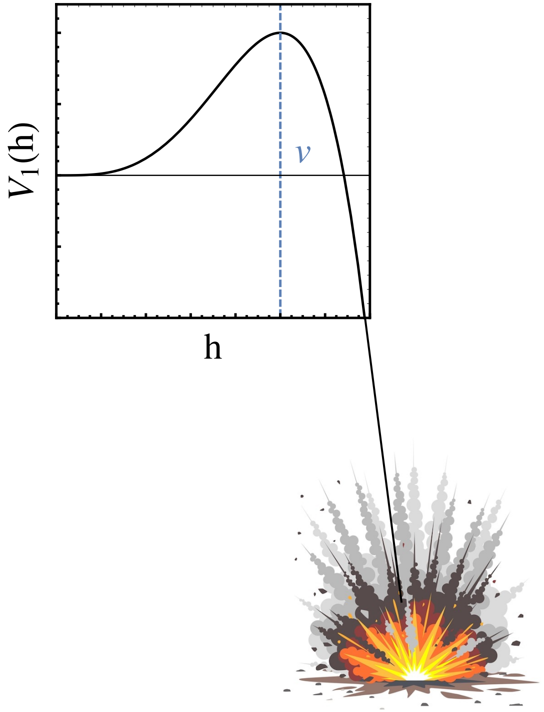
Radiative electroweak symmetry breaking?

However not directly applied to the Standard Model Higgs!



If identifying ϕ as h

$$V_h(h) \sim \frac{B_h}{4} h^4 \left(\log\frac{h}{v} - \frac{1}{4}\right)$$



$$B_h \propto (9g^4 - 48y_t^4) < 0$$

EW bosons top quark

Unstable electroweak vacuum!

Radiative electroweak symmetry breaking!

A realistic framework: new scalar ϕ, tree-level

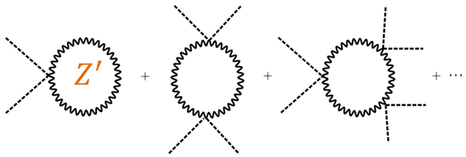
$$V_0(h,\phi) = \frac{\lambda_s}{4}\phi^4 - \frac{\lambda'}{4}\phi^2 h^2 + \frac{\lambda_h}{4}h^4$$

- Classically scale-invariant & conformal

Along the new physics direction

$$V_\phi(\phi) \approx \frac{B}{4}\phi^4\left(\log\frac{\phi}{w} - \frac{1}{4}\right)$$

For example:
- $U(1)_X$ with g_X
- $B = 3g_X^4/8\pi^2$



Then $\phi \to w$, and along the Higgs direction

$$V_h(h) \approx \left(-\frac{\lambda'}{4}\phi^2 h^2 + \frac{\lambda_h}{4}h^4\right) \to \left(\frac{\mu_h^2}{2}h^2 + \frac{\lambda_h}{4}h^4\right)$$

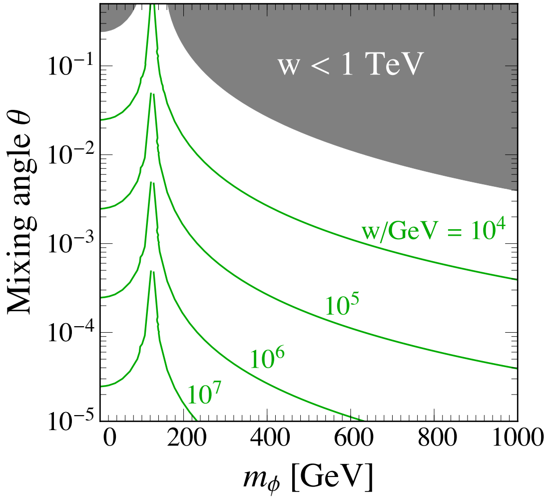
$\mu_h^2 < 0 \to$ EWSB! Hempfling, PLB 379, 153 (1996); Iso *et al*, PLB 676, 81 (2009); Chun *et al*, PLB 725, 158 (2013), etc

Vacuum structure decomposition

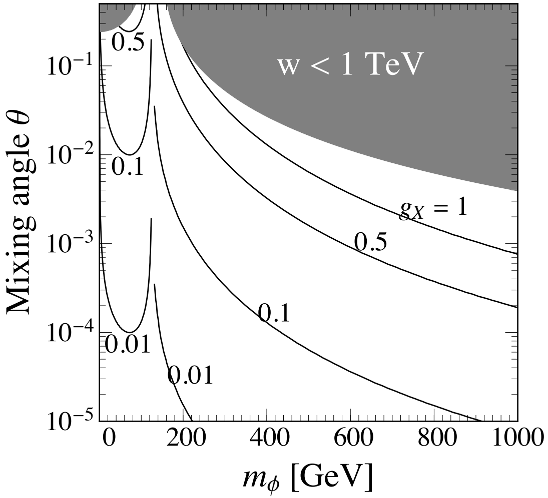
Only 2 free parameters [Liu and **KPX**, PRD 110 (2024) 11, 115001]

- Use (m_ϕ, θ) as input, all other parameters derived **rigorously**

New physics scale w



g_X of the $U(1)_X$

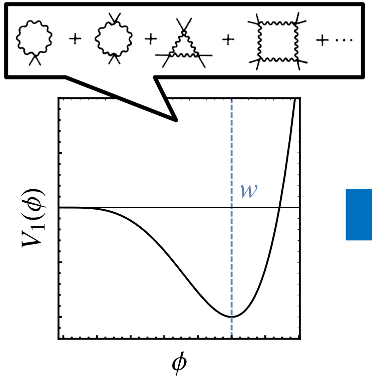


ϕ cannot be degenerate with the Higgs boson, $m_\phi \neq 125$ GeV

$w \gg v_{\rm EW}$ needed for sequential symmetry breaking [Chataignier *et al*, JHEP 08 (2018) 083]

Cosmological implications

If the scale is dynamically generated,
then the early Universe must be *boiling*



Gravitational waves

(*Novel*) dark matter

then more interesting consequences…

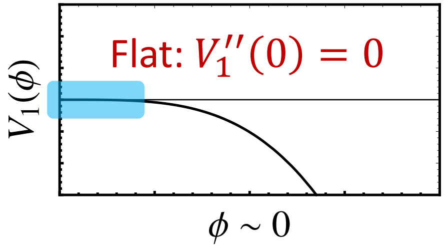
(*Novel*) origin of matter, baryogenesis

Why the Universe was boiling

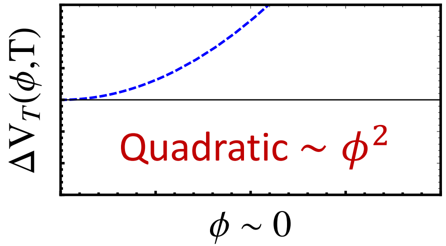
Early Universe → temperature corrections

Near the field origin,

$$V_T \approx \underbrace{\frac{B}{4}\phi^4\left(\log\frac{\phi}{w}-\frac{1}{4}\right)-\frac{\lambda'}{4}h^2\phi^2+\frac{\lambda_h}{4}h^4}+\underbrace{\frac{c_\phi T^2}{2}\phi^2+\frac{c_h T^2}{2}h^2}$$

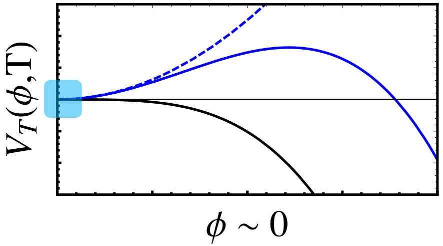


+



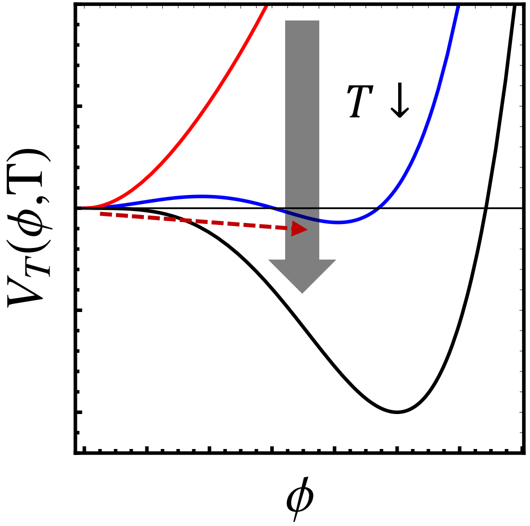
Local minimum exists for $T>0$

The Universe is trapped in the false vacuum!

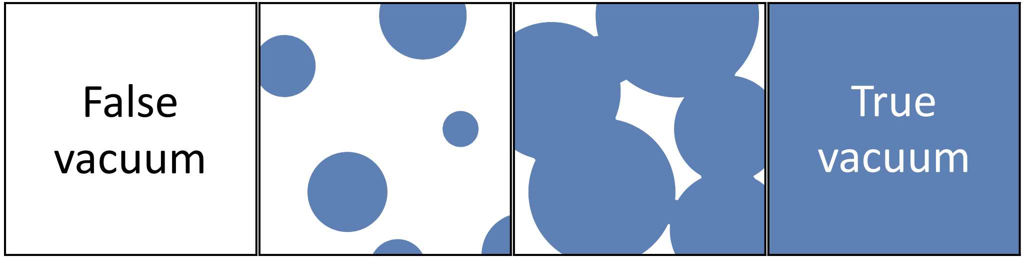


Why the Universe was boiling

Vacuum tunneling

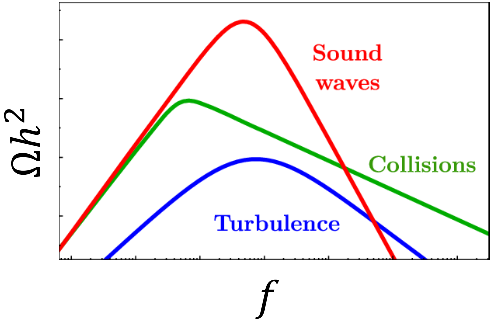


A first-order phase transition



Stochastic GWs:

1. Bubble collisions
2. Sound waves
3. Turbulence



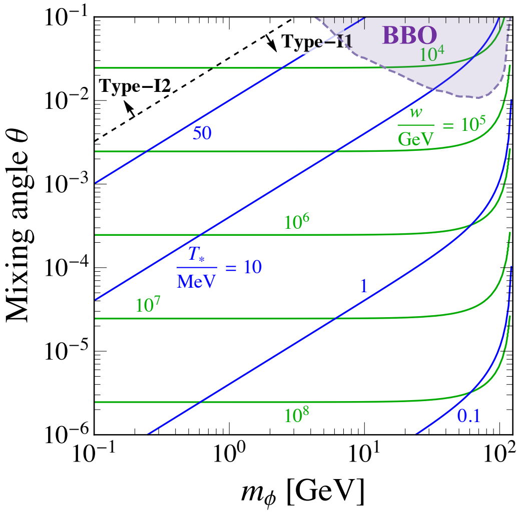
Just for an intuitive explanation; full one-loop calculation included in paper

*See also talks of Huai-Ke Guo, Alan S. Cornell, Tomasz Dutka, Joshua Cesca, and Haipeng An

FOPT and gravitational waves

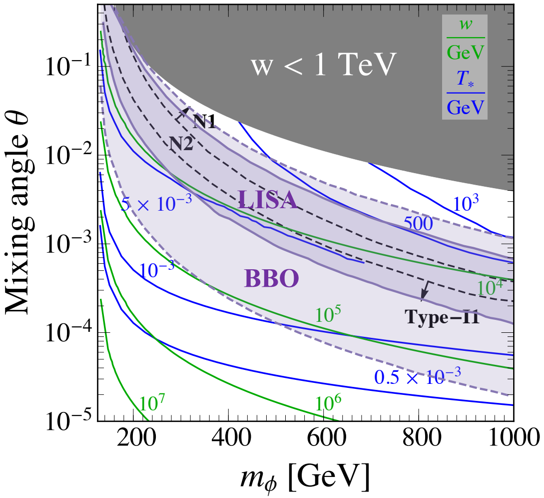
Only two free parameters: new scalar boson mass m_ϕ, mixing angle θ

Fully thermal one-loop calculation [Liu and **KPX**, PRD 110 (2024) 11, 115001]



$\leftarrow m_\phi < 125$ GeV

$m_\phi > 125$ GeV $\rightarrow$



Blue: FOPT temperature T_*

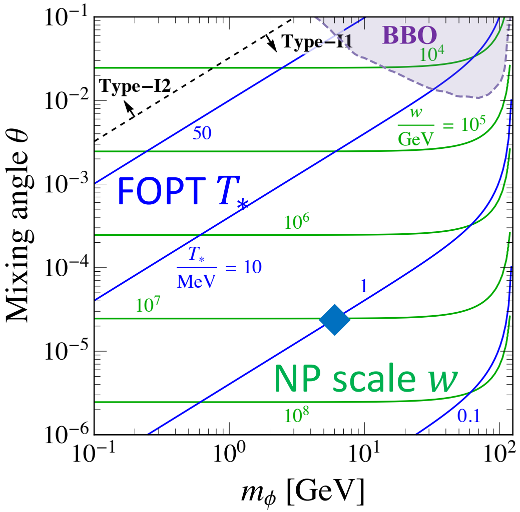
Green: new physics scale w

Purple: LISA (similar for TianQin, Taiji) and BBO gravitational wave detection

FOPT and gravitational waves

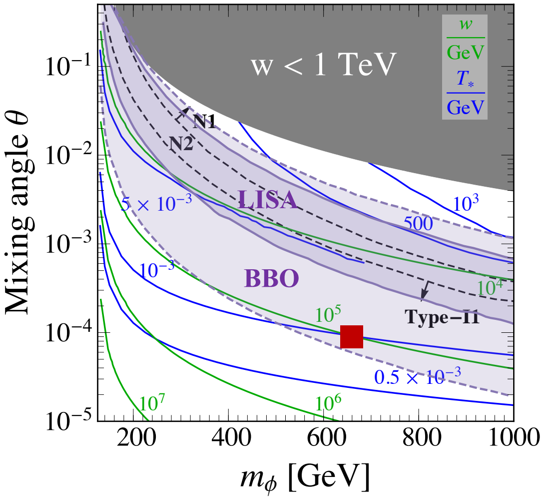
Only two free parameters: new scalar boson mass m_ϕ, mixing angle θ

Fully thermal one-loop calculation [Liu and **KPX**, PRD 110 (2024) 11, 115001]



$T_* \ll w$:

Supercooling!

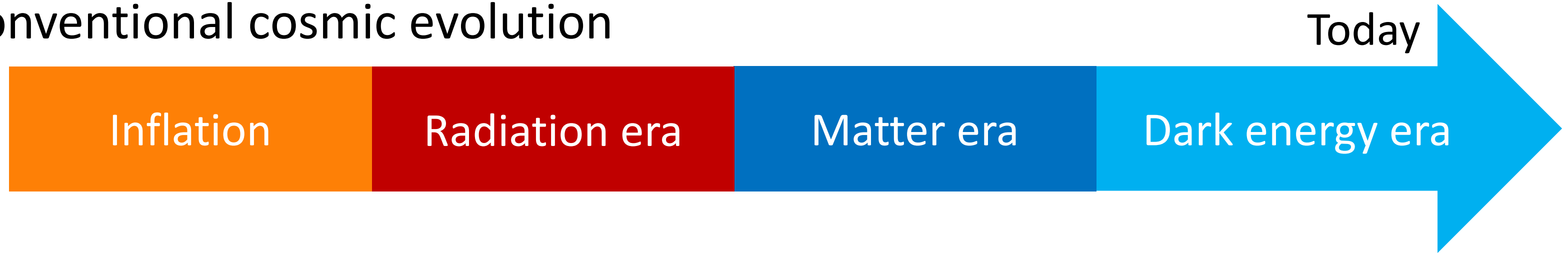


◆ $w = 10^7$ GeV, $T_* = 1$ MeV, $T_{\text{rh}} \sim 1$ TeV

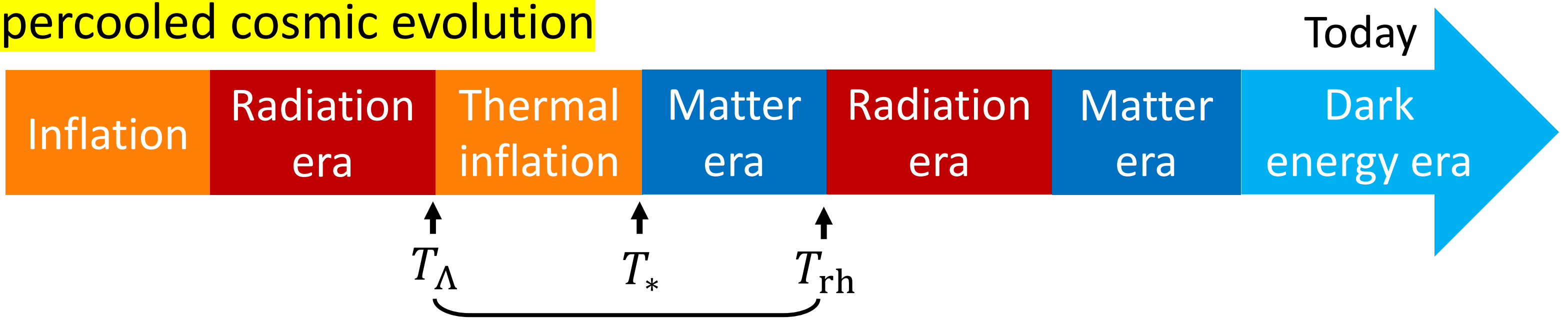
■ $w = 10^5$ GeV, $T_* = 1$ MeV, $T_{\text{rh}} \sim 3$ TeV

Exotic cosmic history

Conventional cosmic evolution



Supercooled cosmic evolution

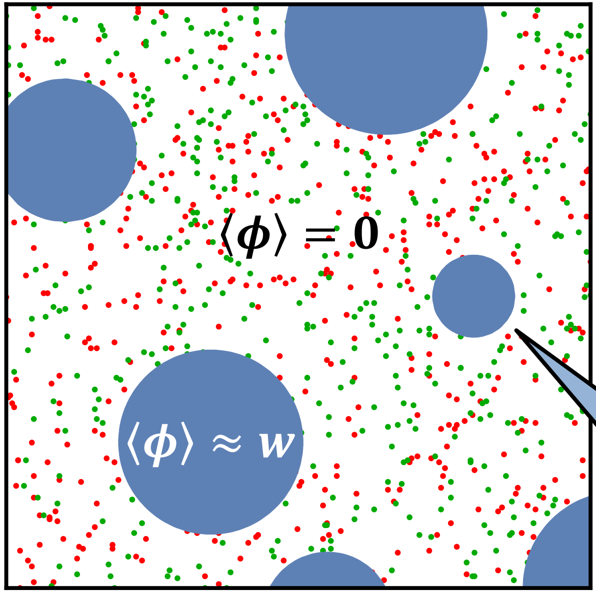


Rich implications on dark matter and baryogenesis mechanisms

Impact on elementary particle physics

Possible interactions (*scale-invariant* at tree-level)

$$\mathcal{L}_{\text{int}} \supset \bar{\chi} i \gamma^\mu \partial_\mu \chi - y_\chi \phi \bar{\chi}\chi + \partial_\mu S^\dagger \partial^\mu S - \frac{\lambda_S}{2}\phi^2 S^\dagger S$$



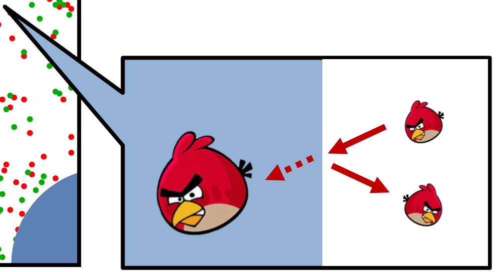
Outside the bubble:

- Particles massless

Mass discontinuity

Inside the bubble:

- $m_\chi \approx y_\chi w$ and $m_S \approx \sqrt{\lambda_S/2}\, w$

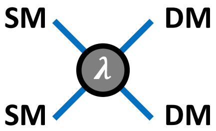


Particles scatter with the bubble wall

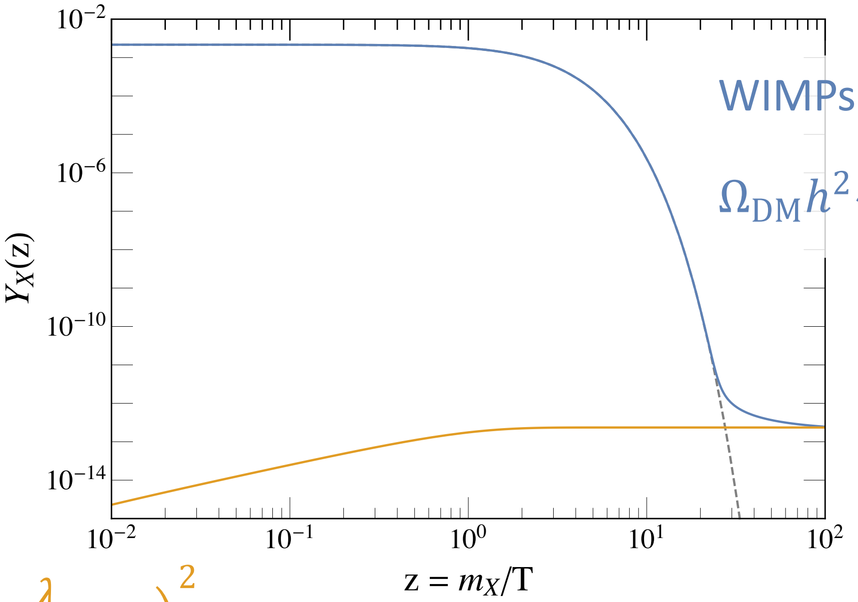
Conventional dark matter scenarios

$2 \to 2$ scattering process between SM & DM

Smooth cosmic evolution



$$\langle \sigma v_{\rm rel} \rangle \sim \frac{\lambda^2}{32\pi m_{\rm DM}^2}$$



WIMPs: **freeze-out**

$$\Omega_{\rm DM} h^2 \sim 0.1 \left(\frac{0.5}{\lambda}\right)^2 \left(\frac{m_X}{\rm TeV}\right)^2$$

FIMPs: **freeze-in**

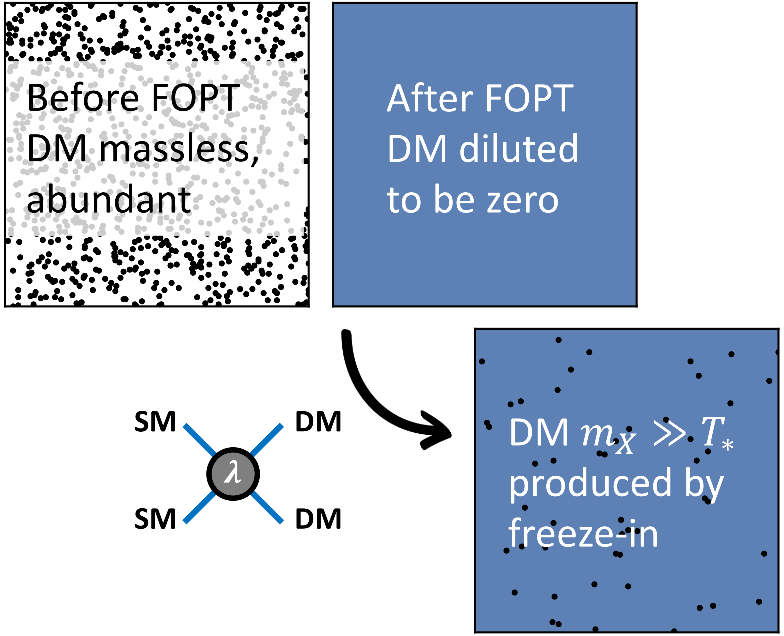
$$\Omega_{\rm DM} h^2 \sim 0.1 \left(\frac{\lambda}{2.5\times 10^{-11}}\right)^2$$

A new possibility arises in a supercooled Universe…

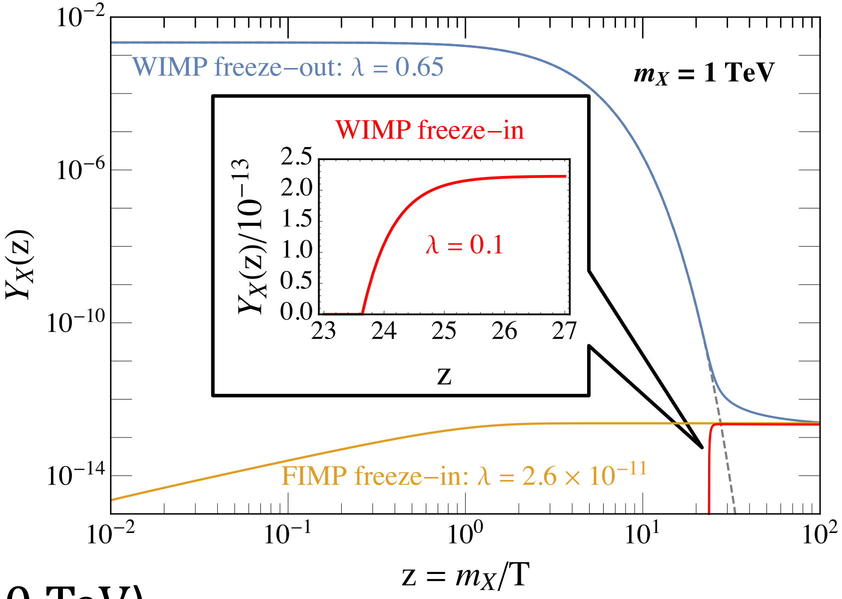
Dark matter in a supercooled Universe

Supercooled **WIMP**: mass changes after the FOPT, and experiences **freeze-in**

Wang and **KPX**, PRD 108 (2023) 5, 055035; Hambye *et al*, JHEP 08 (2018) 188; etc



$$\Omega_{\rm DM}h^2 \sim 0.1(1+2z_2)\left(\frac{\lambda e^{-z_2}}{3.5\times10^{-11}}\right)^2$$

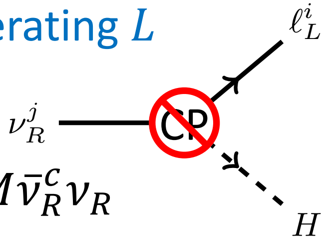


Could go beyond the GK bound ($\sim$ 100 TeV)

Conventional leptogenesis

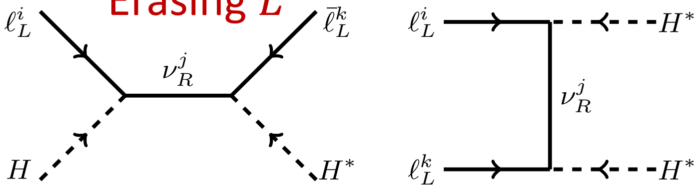
Heavy ν_R decays at $T \lesssim M$, suffers from thermal washout

Generating L

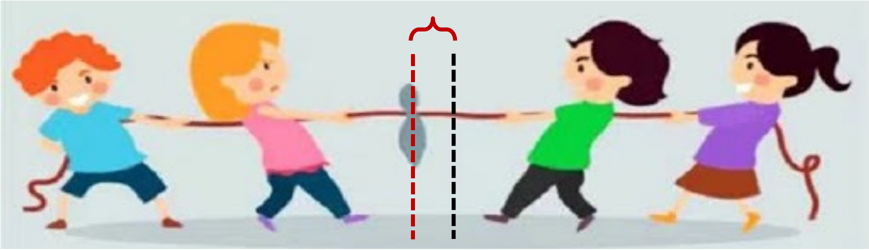


Heavy: $-M\bar{\nu}_R^c\nu_R$

Erasing L



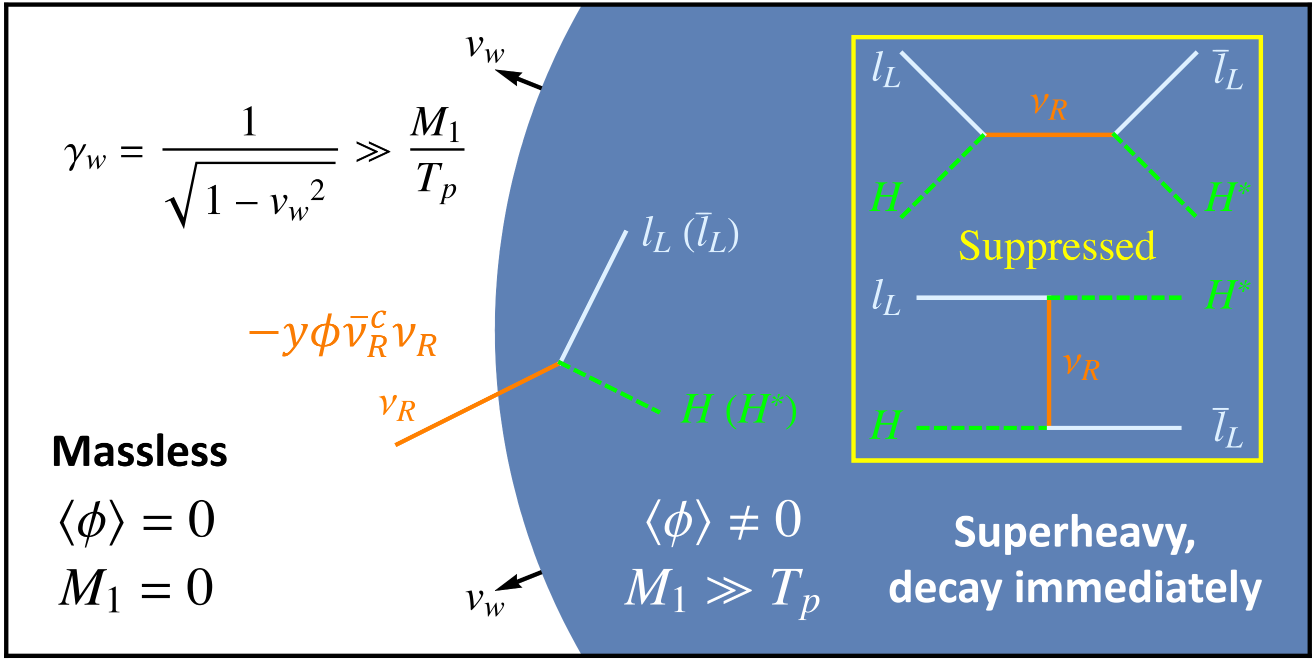
Only 1% survives



A new possibility arises in a supercooled Universe…

Leptogenesis in a supercooled Universe

Supercooled leptogenesis

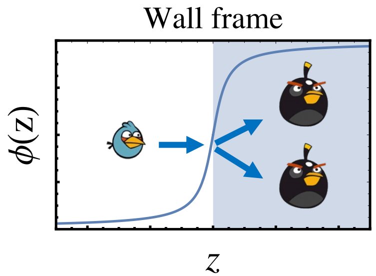


- Leptogenesis without thermal washout

Huang and **KPX**, JHEP 09 (2022) 052; Chun *et al*, JHEP 09 (2023) 164; Baldes *et al*, PRD 104 (2021) 115029; etc

More implications

Heavy particle production on the wall if $\gamma_w T_* \gg m_S \gg T_*$

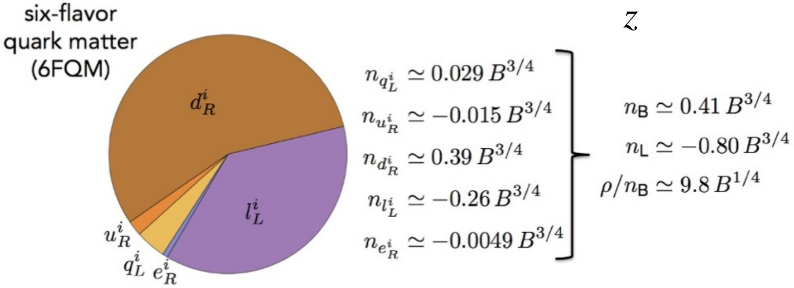


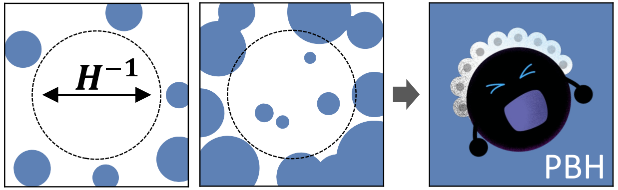
- Dark matter or baryogenesis

Azatov *et al*, JHEP 03 (2021) 288; JHEP 10 (2021) 043;
Baldes *et al*, PRD 104 (2021) 115029; Ai *et al*, 2406.20051; etc

Quark nugget soliton dark matter from a QCD *FOPT* induced by classically conformal theories

Bai *et al*, JHEP 06 (2018) 072; Witten, PRD 30 (1984) 272





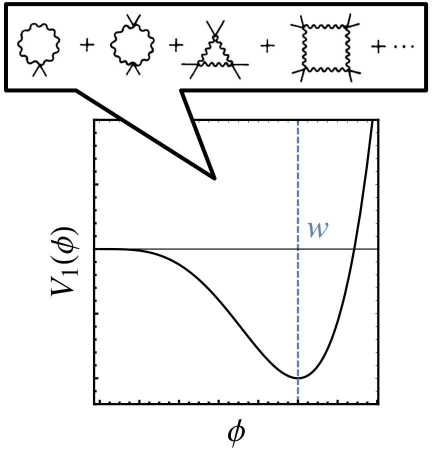
Primordial black holes formation

- Bubble collisions Hawking *et al*, PRD 26 (1982) 2681; Jung *et al*, 2110.04271; etc
- False vacuum "islands" collapse Liu, Bian, Cai, Guo, Wang, PRD 105, L021303; Gouttenoire, PLB 855, 138800 (2024); Ai *et al*, 2409.02175, etc

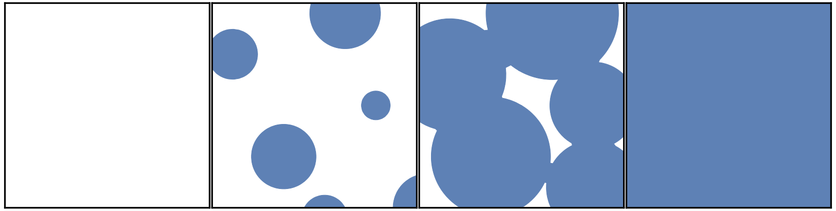
Conclusion & outlook

Simple assumption

Dynamical origin of the scale



Rich cosmological implications



FOPTs + detectable GWs
and maybe impacts on

- Cosmic evolution history
- Dark matter and/or baryogenesis
- Solitons or primordial black holes

A lot of future directions to explore!

Thank you!

Backup: structure of the potential

Why the potential is written as

$$V_1(h,\phi) \approx \frac{B}{4}\phi^4\left(\log\frac{\phi}{w} - \frac{1}{4}\right) - \frac{\lambda'}{4}h^2\phi^2 + \frac{\lambda_h}{4}h^4$$

In principle, both ϕ & h receive Coleman-Weinberg corrections

However if $w \gg v_{\rm EW}$, then sequential SSB [Chataignier *et al*, JHEP 08 (2018) 083]

- ϕ-direction: loop correction dominates,

$$\frac{\lambda_\phi}{4}\phi^4 \sim \frac{B}{4}\phi^4(\log\phi + C)$$

- h-direction: tree-level contribution dominates

$$\frac{\lambda_h}{4}h^4 \gg \frac{B_h}{4}h^4(\log h + C)$$

Therefore, along the ϕ-direction we adopt the log potential while along the h-direction we use the tree-level potential

Backup: thermal history in 2D field space

Normal pattern:

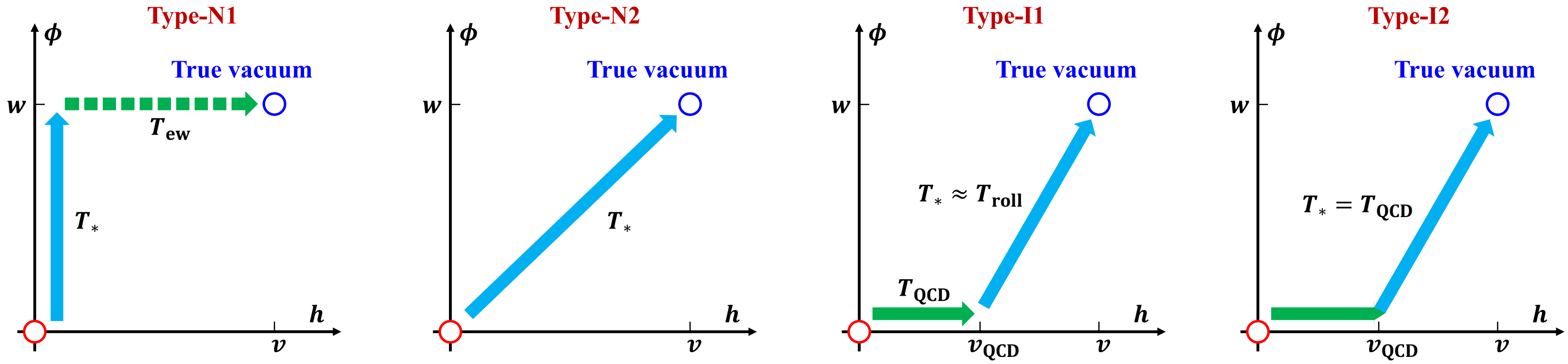
high scale → low scale

- **N1**: ϕ-FOPT → EW crossover
- **N2**: joint ϕ-EW-FOPT

Inverted pattern:

low scale → high scale

- **I1**: QCD-EW-FOPT → ϕ-FOPT
- **I2**: joint QCD-EW-ϕ-FOPT



Detailed classification in Liu and **KPX**, PRD 110 (2024) 11, 115001

- The inverted pattern: QCD-FOPT triggers EWPT $h: 0 \mapsto v_{\rm QCD} \approx 100$ MeV via $-y_t h\langle \bar{t}t\rangle$ Witten, NPB 177, 477 (1981); Iso *et al*, PRL 119 (2017) 14, 141301

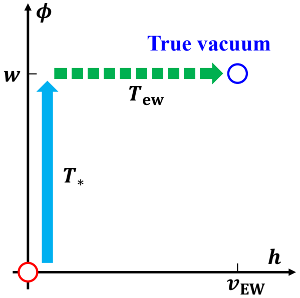
Backup: the normal pattern

ϕ-FOPT: $0 \mapsto w_*$ at T_*, then $V_T \to V_T|_{\phi\approx w} \approx \frac{c_h}{2}(T^2 - T_{\rm ew}^2)h^2 + \frac{\lambda_h}{4}h^4$

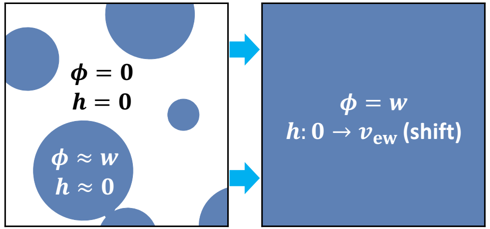
Depending on the sign of $(T_*^2 - T_{\rm ew}^2)$, two sub-types

$$T_{\rm ew} = \frac{m_h}{\sqrt{2c_h}} \sim 140\ {\rm GeV}$$

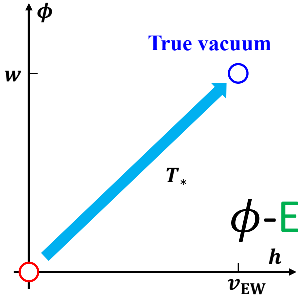
- Type-**N1**: $T_* > T_{\rm ew}$



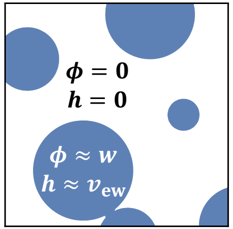
ϕ-FOPT
followed by
EW crossover



- Type-**N2**: $T_* < T_{\rm ew}$



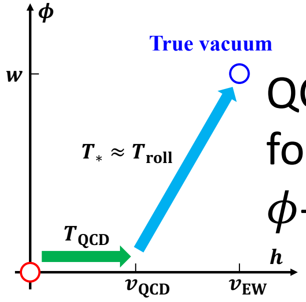
ϕ-EW FOPT



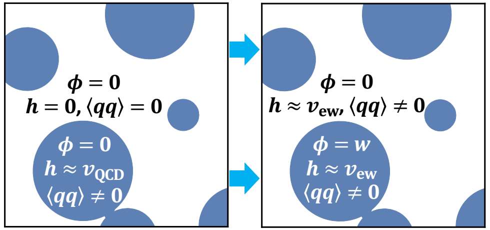
Backup: the inverted pattern

QCD FOPT $\langle\bar{q}q\rangle: 0 \mapsto \mathcal{O}(100\ \mathrm{MeV})$ at $T_{\rm QCD}$, triggering EWPT $h: 0 \mapsto v_{\rm QCD}$ via $-y_t h\langle\bar{t}t\rangle$, $V_T \to V_T|_{h\approx v_{\rm QCD}} \approx \frac{B}{4}\phi^4\left(\log\frac{\phi}{w}-\frac{1}{4}\right)+\frac{c_\phi}{2}\left(T^2-T_{\rm roll}^2\right)\phi^2$

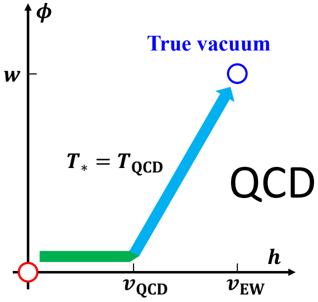
- Type-**I1**: $T_{\rm QCD} > T_{\rm roll}$



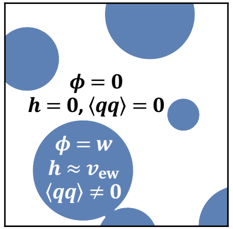
QCD-EW FOPT followed by ϕ- FOPT



- Type-**I2**: $T_{\rm QCD} < T_{\rm roll}$



QCD-EW-ϕ- FOPT



$T_{\rm QCD} \approx 85\ \mathrm{MeV}$

$v_{\rm QCD} \approx 100\ \mathrm{MeV}$

$T_{\rm roll} = \frac{m_h v_{\rm QCD}}{\sqrt{2c_\phi w}}$

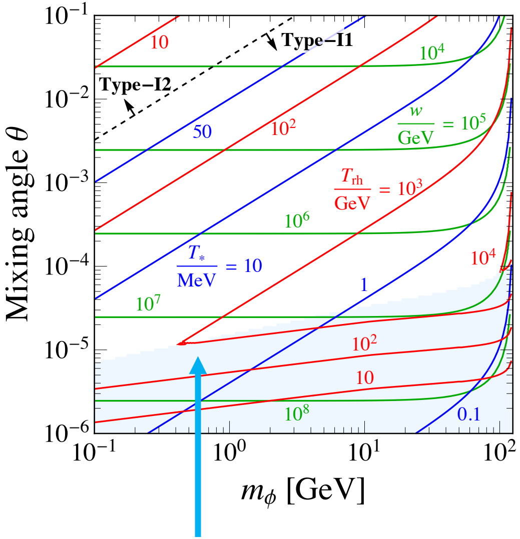
First proposed by Witten

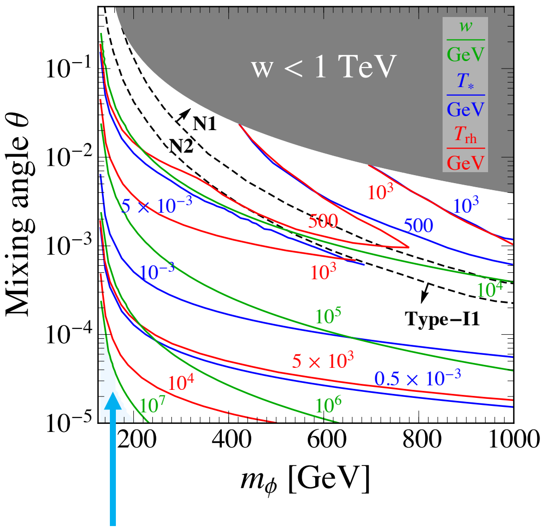
Witten, NPB 177, 477 (1981)

Backup: complete phase diagrams

The Universe is reheated to $T_{\rm rh} \gtrsim T_*$ [Liu and **KPX**, PRD 110 (2024) 11, 115001]

- The EW symmetry might be restored, leading to a second EWPT



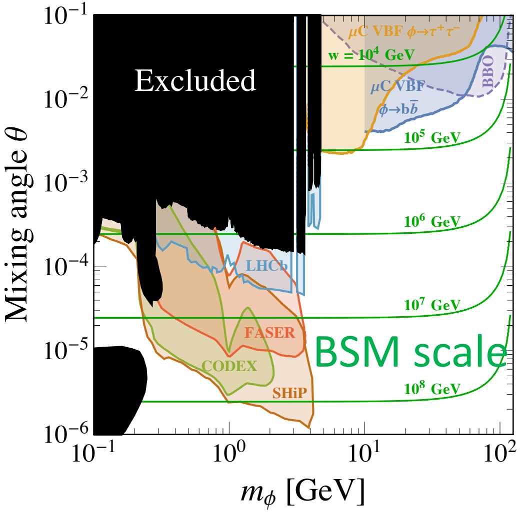


- If the ϕ decay rate is small, reheating is slow: early matter domination
- More detailed phase diagram can be plotted in principle

Backup: phenomenology

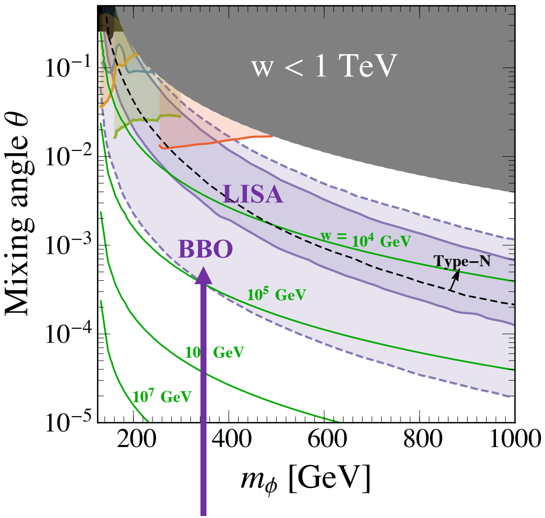
Collider search [Liu and **KPX**, PRD 110 (2024) 11, 115001]

- HL-LHC $\phi \to ZZ$; 10 TeV muon collider VBF $\phi \to b\bar{b}, VV, hh$
- Long-lived particle search



HL-LHC $\phi \to ZZ$

10 TeV MC VBF $\phi \to b\bar{b}, VV, hh$



Gravitational wave search: LISA (also TianQin, Taiji) and BBO