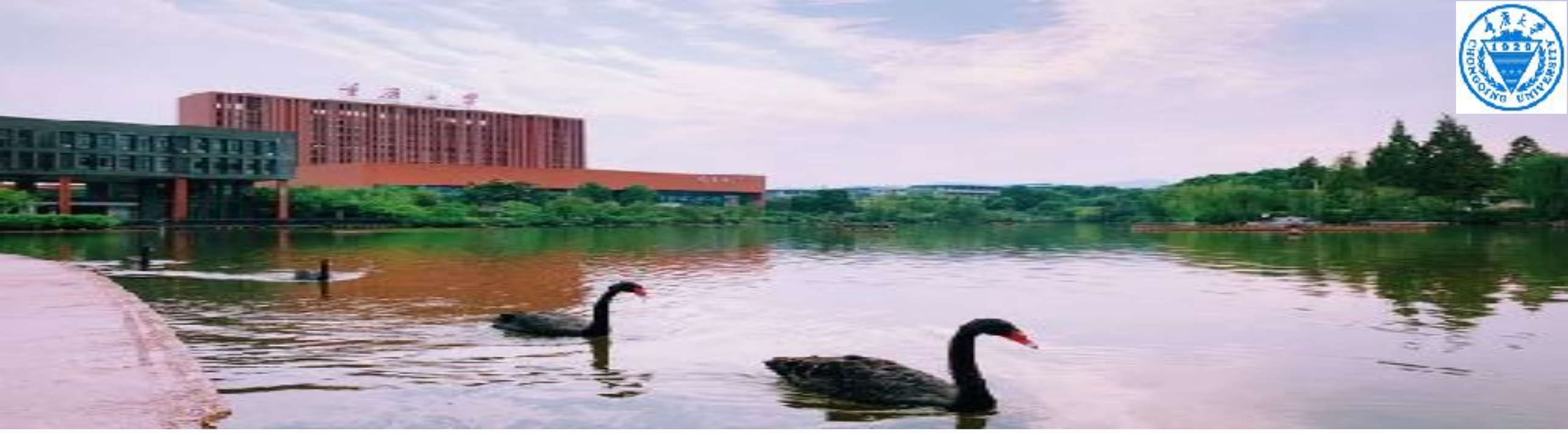

Probing EWSB in the early Universe with GWs and colliders

Ligong Bian(边立功)

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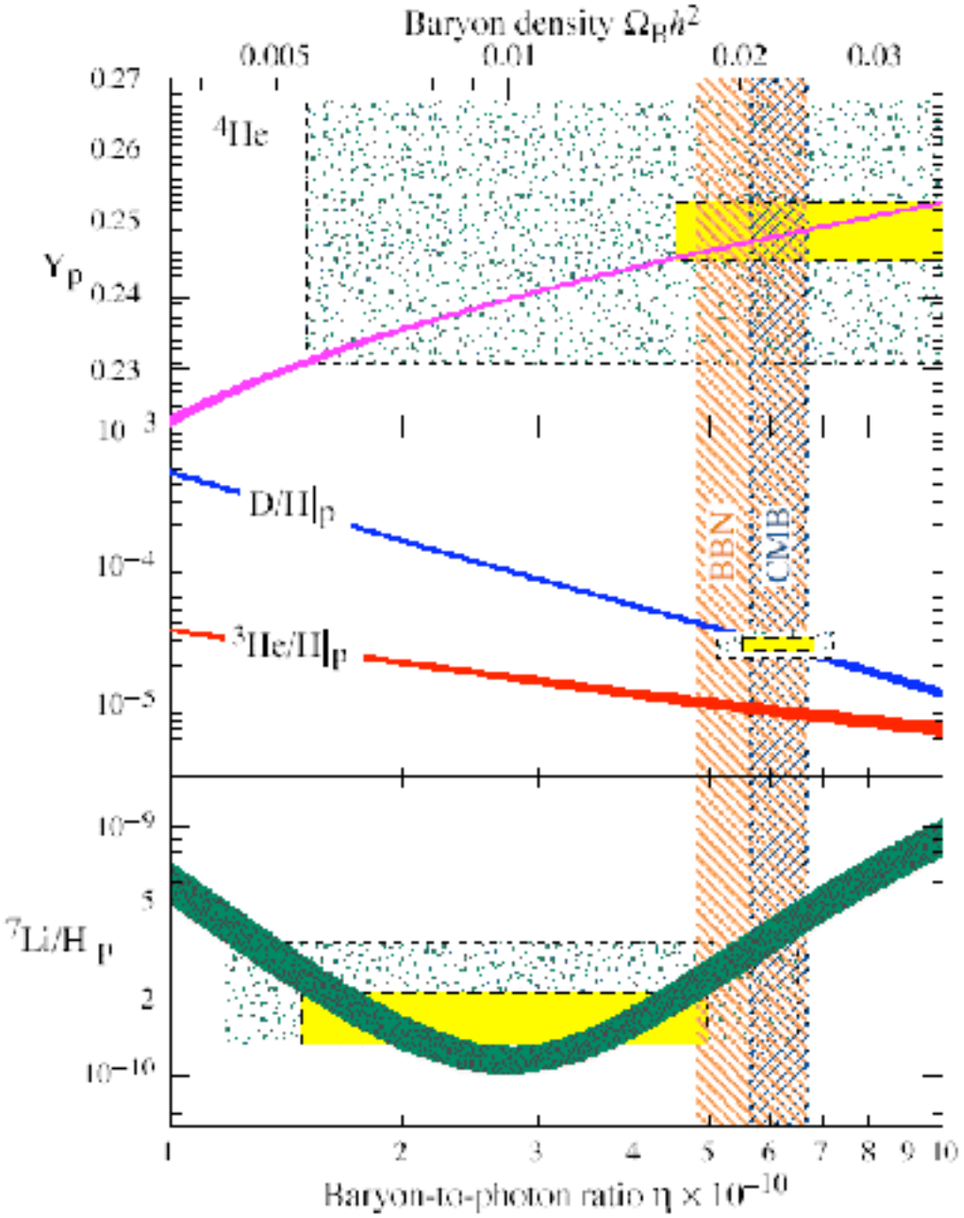
Joint Workshop of the CEPC Physics, Software and New Detector Concept in 2022

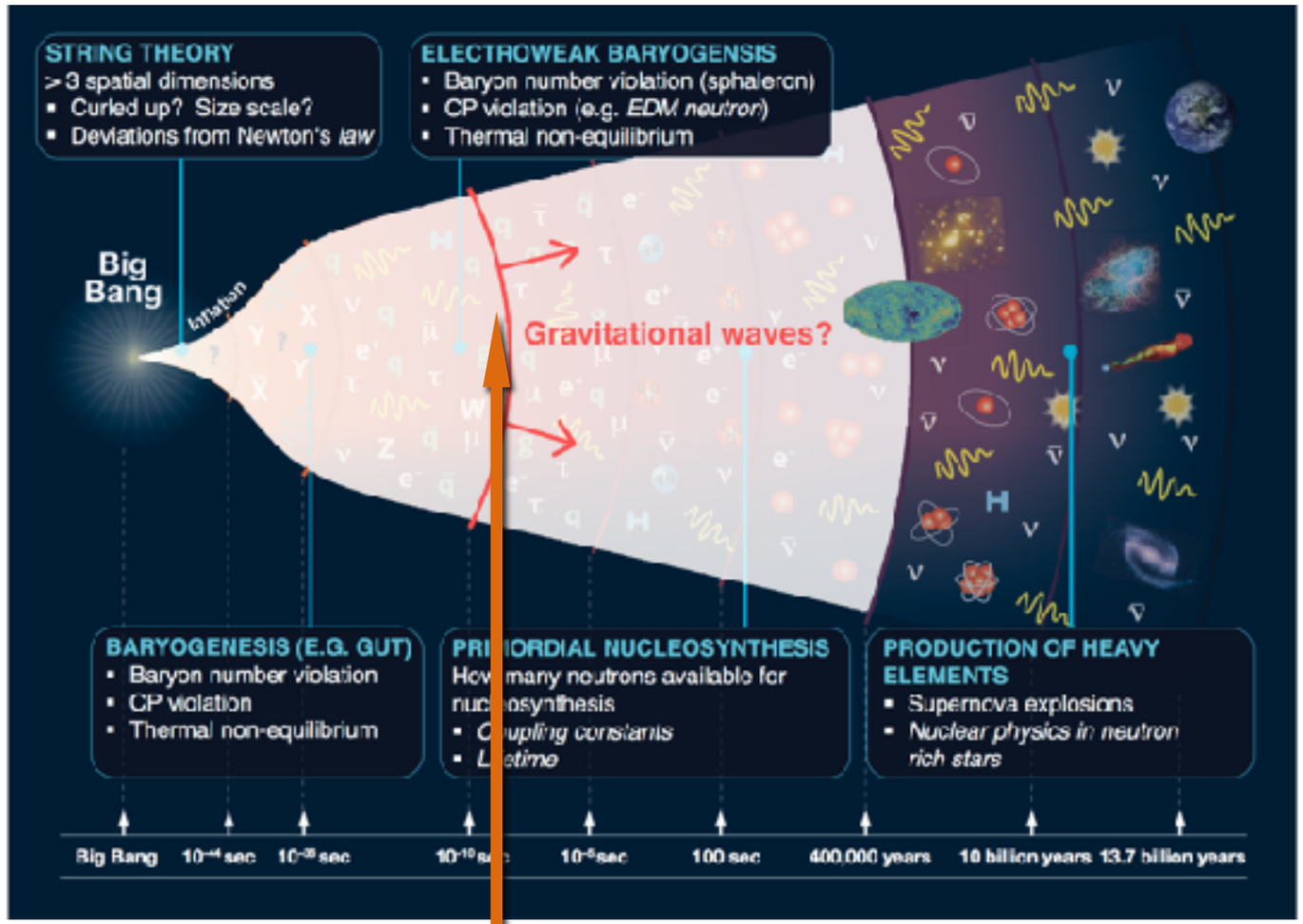
2022/05/25

Contents

- Motivation
- One-step FOPT
- Two-step FOPT
- Summary

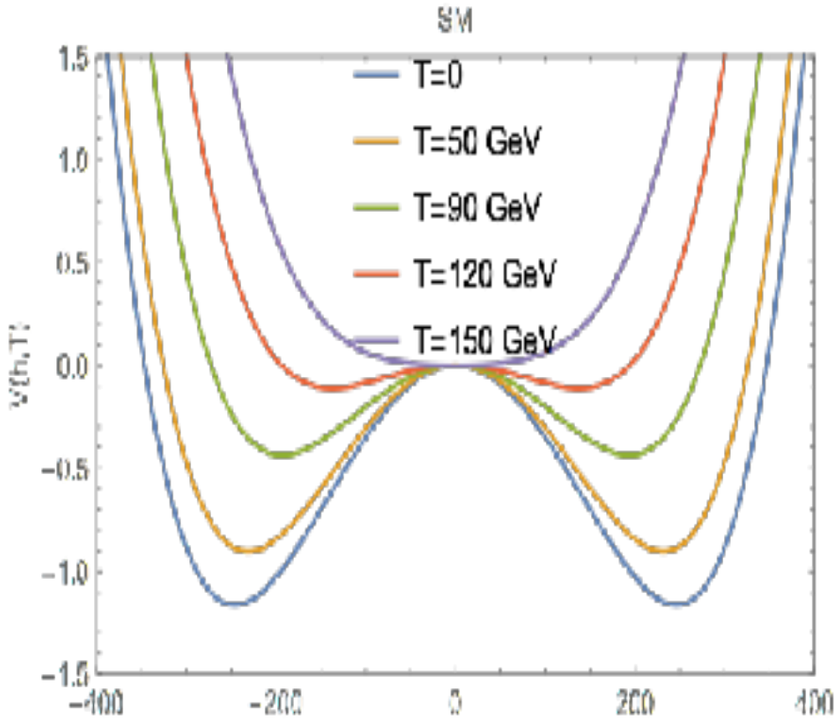
SFOEWPT&BAU&GW



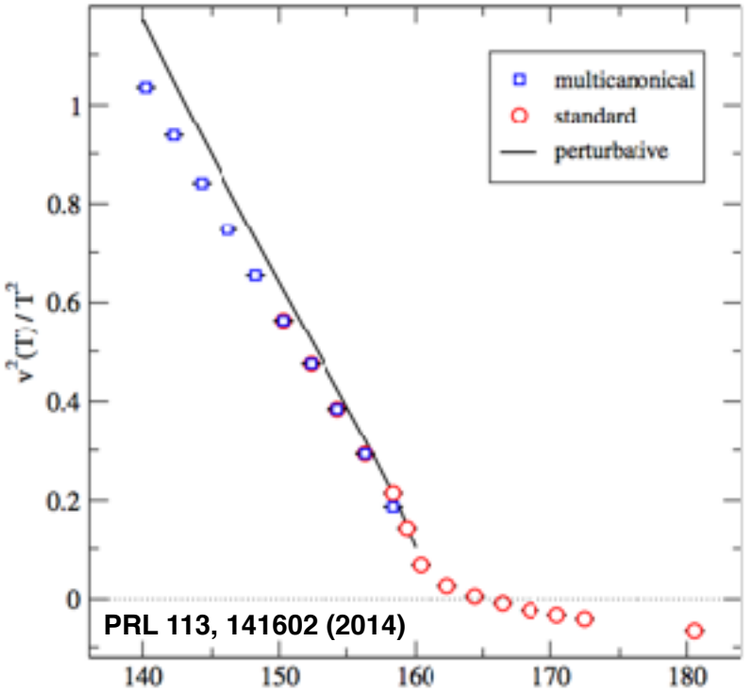


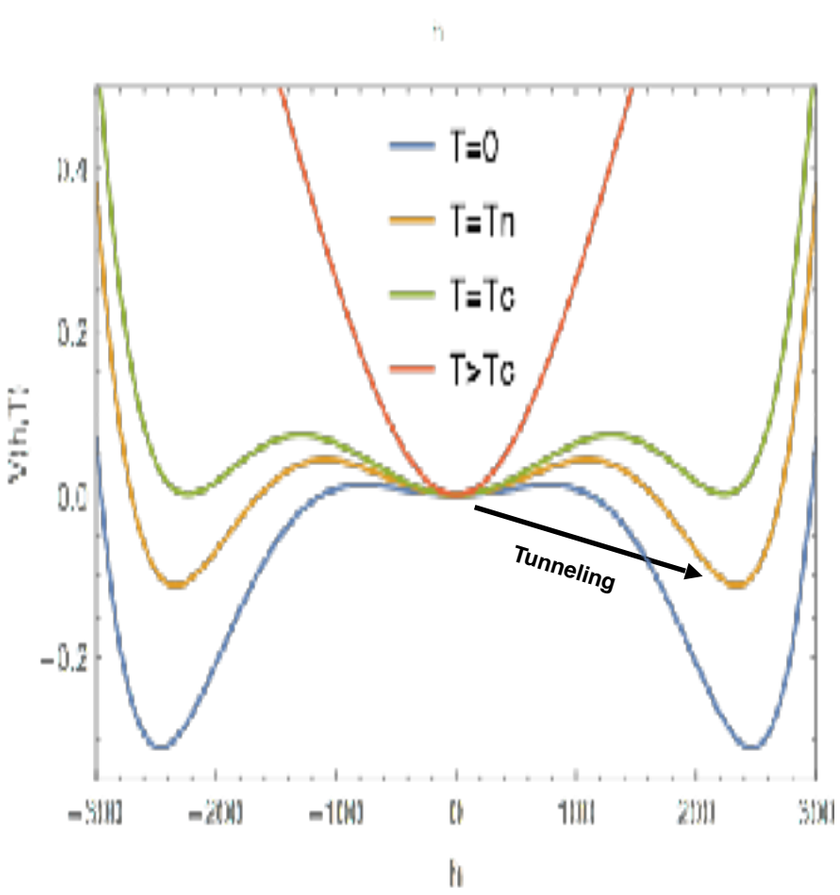
EWBG + SGWB

FOEWPT&Higgs physics

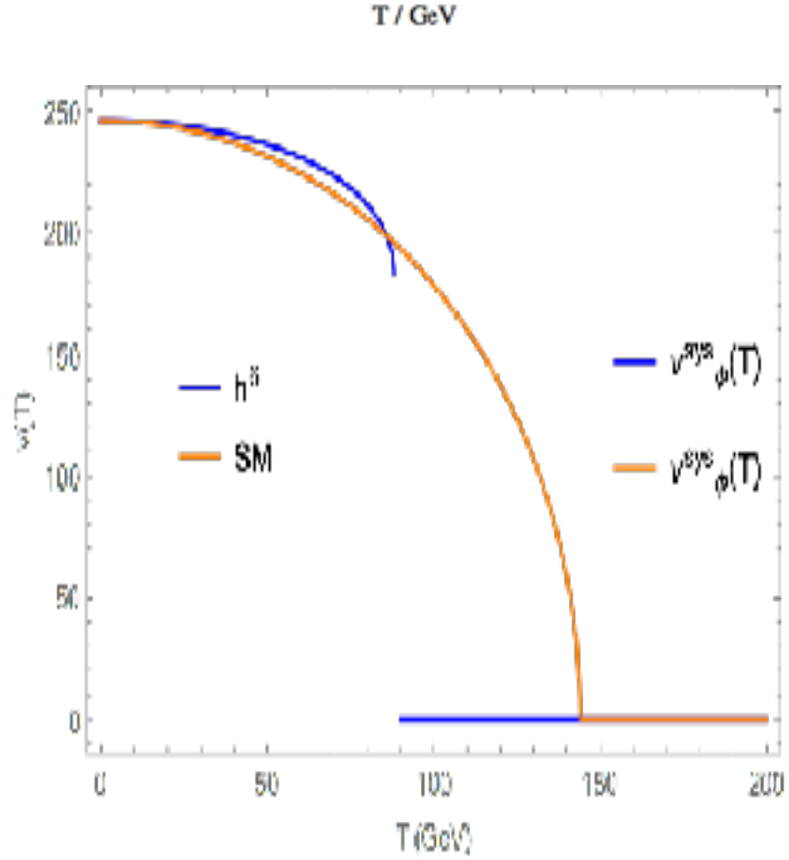



Higgs announcement seminar on 4 July 2012

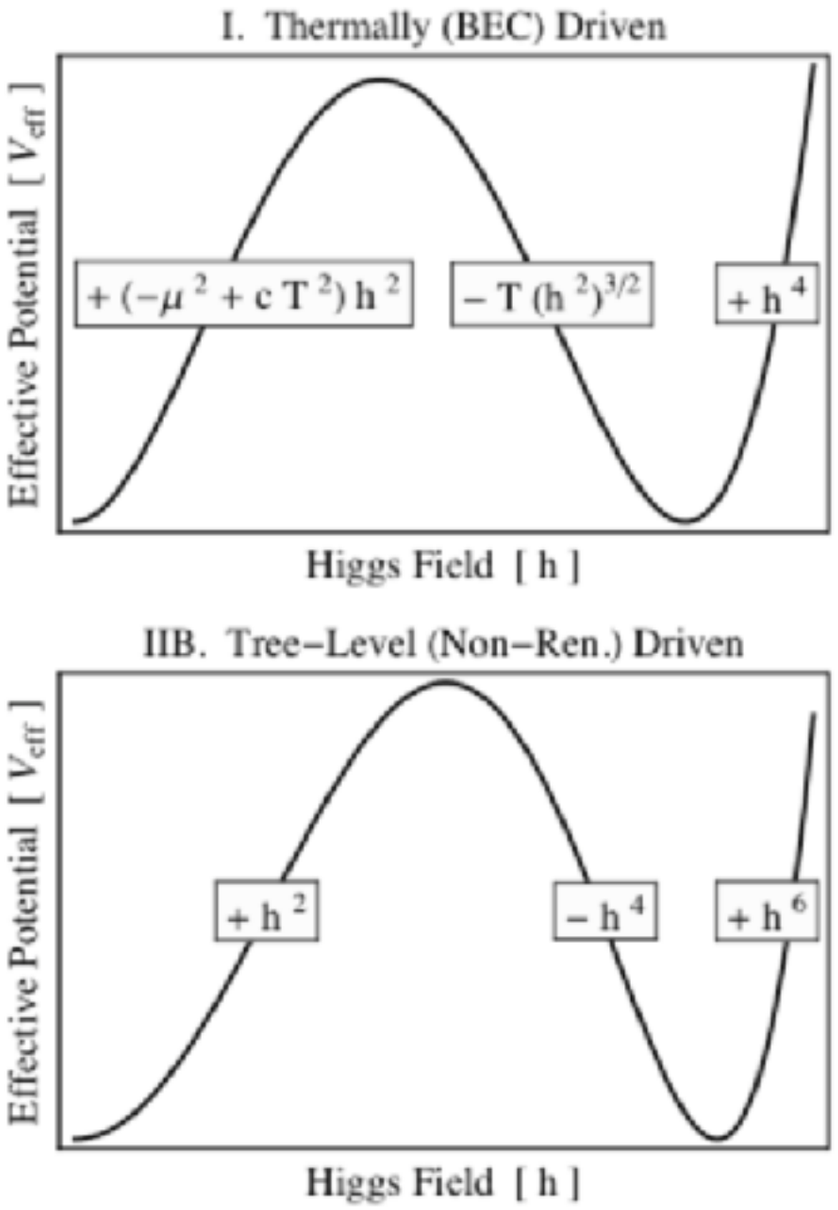


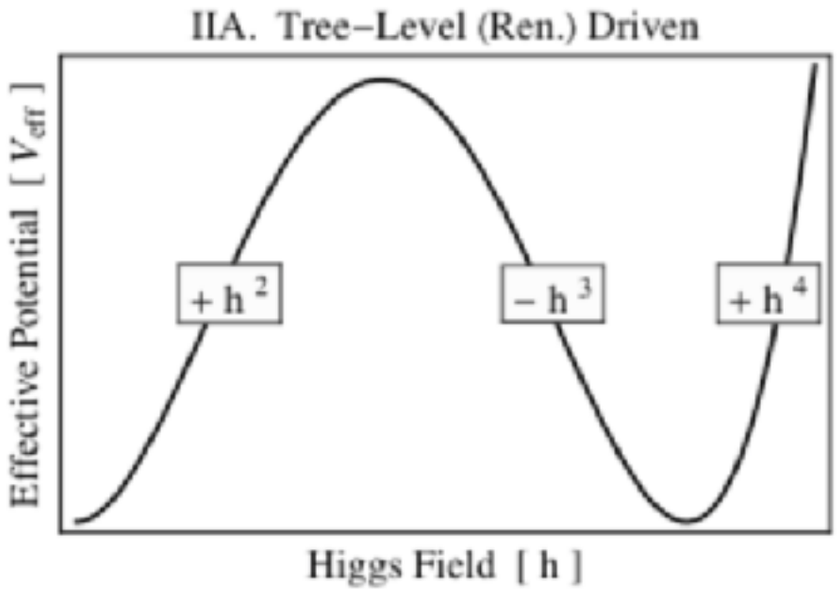


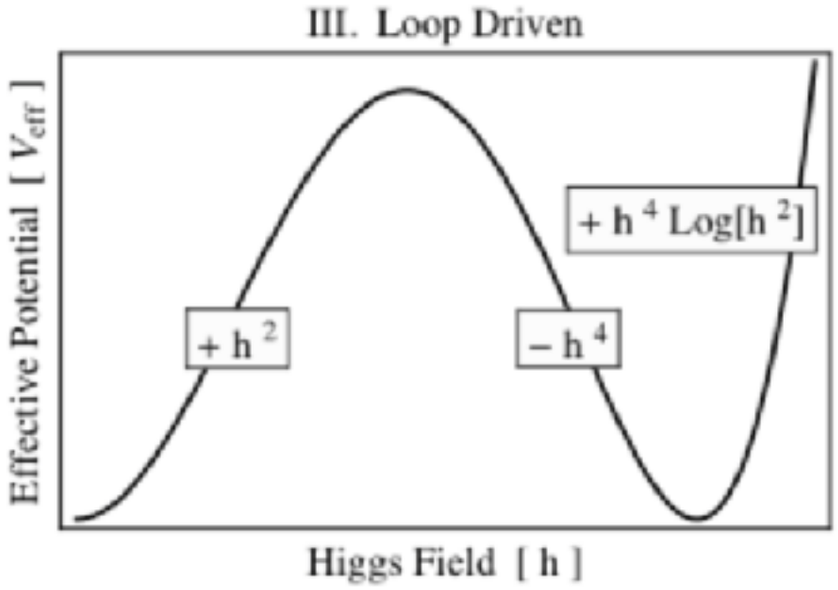
Grojean, Servant, Wells 05, Huang, Jokelar, Li, Wagner 15, Cao, Huang, Xie, & Zhang 17, Zhou, Bian, Guo 19



Model classes for one-step FOPT



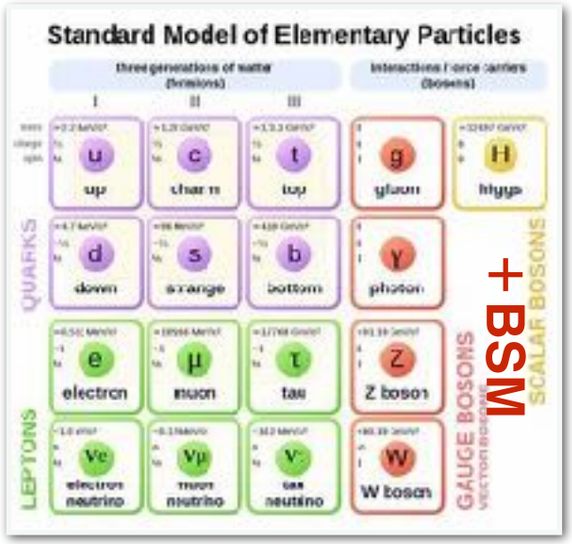




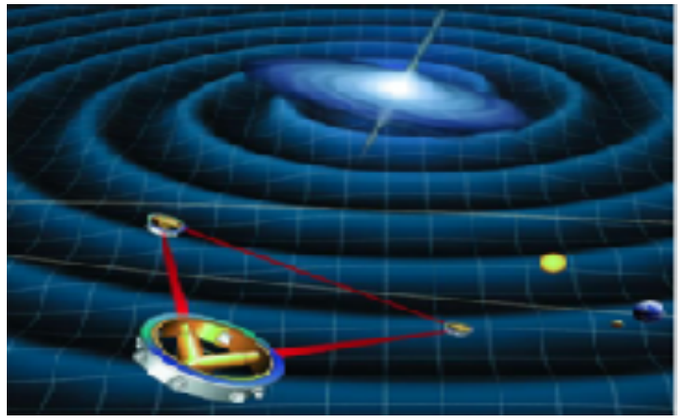
Chung, Long, Wang, Phys.Rev.D 87 (2013) 2, 023509

BSM for FOPT GW

Particle physics model



PTA,LIGO,LISA,TianQin,Taiji,…



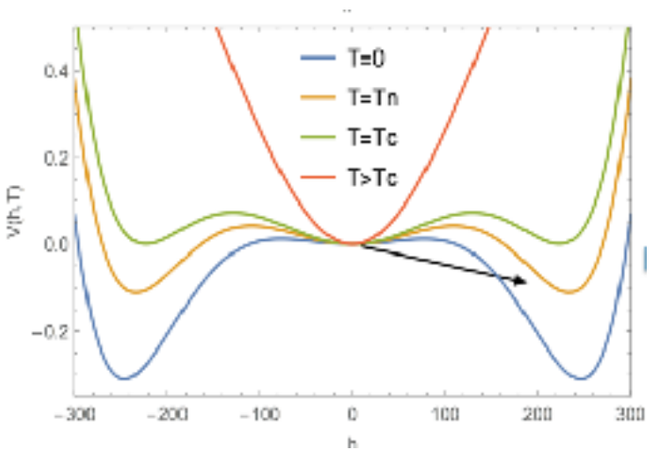
PT parameters

Effective action → β, H_*

Energy budget → α, $\kappa(\alpha, v_w)$

Bubble wall dynamics → v_w

Thermal field theory



GW power spectrum

Numerical simulations →
$h^2\Omega_{GW}(f; H_*, \alpha, \beta, v_w)$

Lattice simulation

LISA sensitivity

Configuration + noise level →
$h^2\Omega_{sens}(f)$

Signal-to-noise ratio

SNR

Chiara Caprini *et al* JCAP03(2020)024

One-step FOPT

PHYSICAL REVIEW LETTERS 126, 251102 (2021)

Magnetic Field and Gravitational Waves from the First-Order Phase Transition

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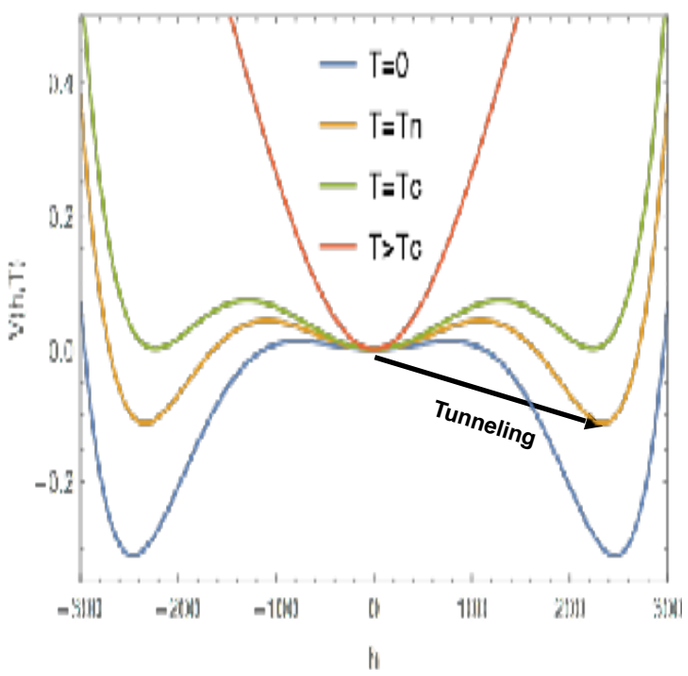
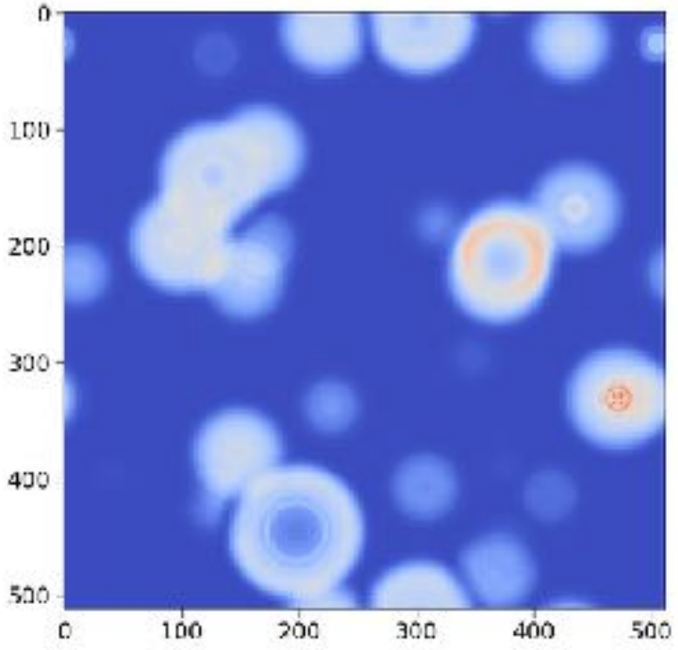
and School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China

Finite-T Veff

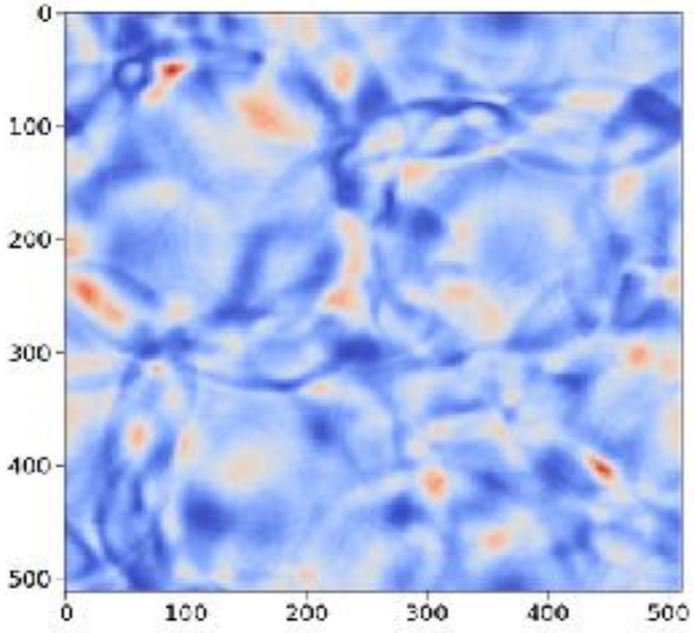


PT temperature (T_*)
duration (β)
strength (α)

Nucleation



Expansion&Percolation



Finite-T calculation

Lattice Simulation

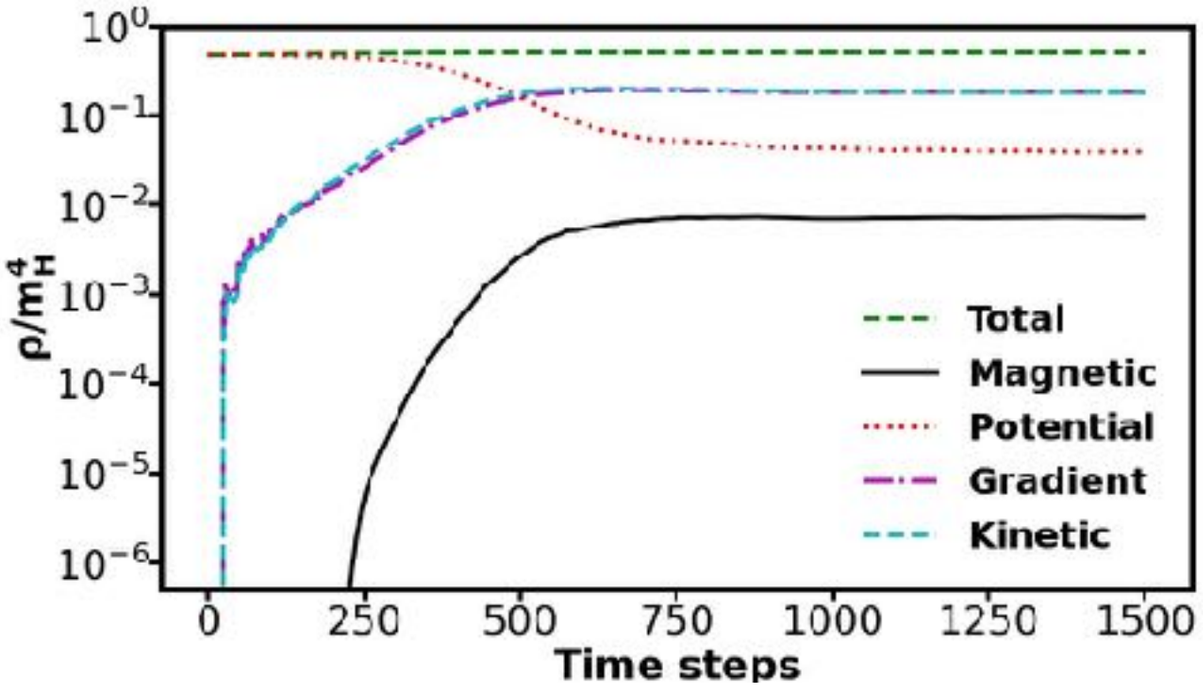
GW from Bubble collisions

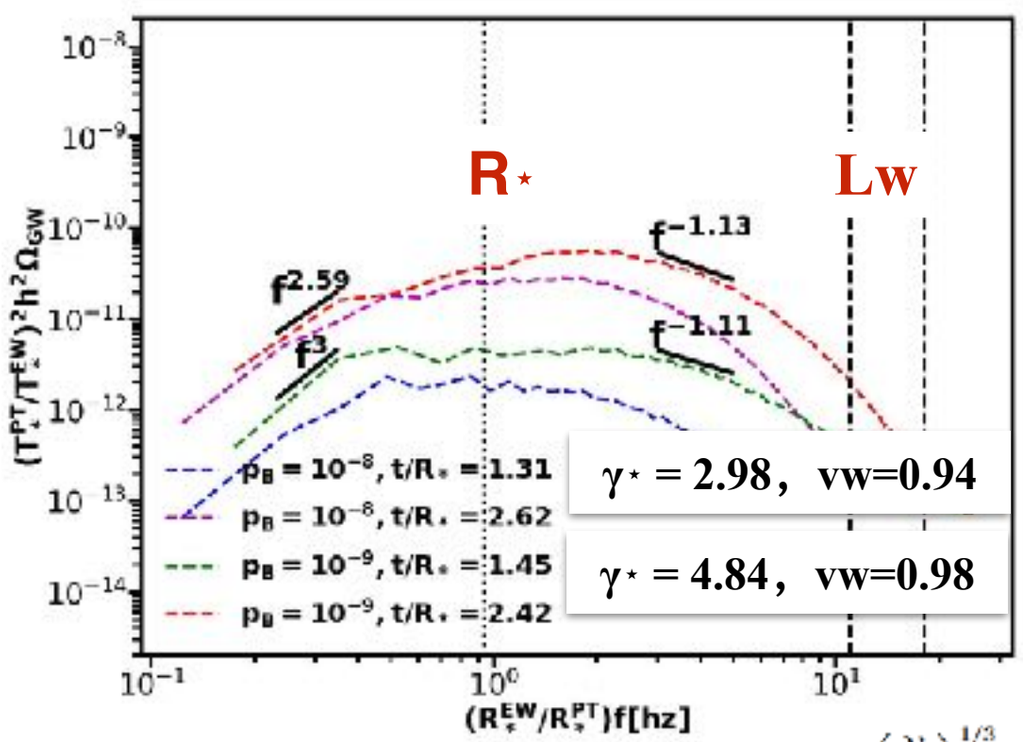
$$\ddot{h}_{ij} - \nabla^2 h_{ij} = 16\pi G T^{\mathrm{TT}}_{ij}$$

$$T_{\mu\nu} = \partial_\mu \Phi^\dagger \partial_\nu \Phi - g_{\mu\nu} \frac{1}{2} \mathrm{Re}[(\partial_i \Phi^\dagger \partial^i \Phi)^2]$$

$$\langle \dot{h}^{TT}_{ij}(\mathbf{k}, t) \dot{h}^{TT}_{ij}(\mathbf{k}', t) \rangle = P_h(\mathbf{k}, t)(2\pi)^3 \delta(\mathbf{k} + \mathbf{k}')$$

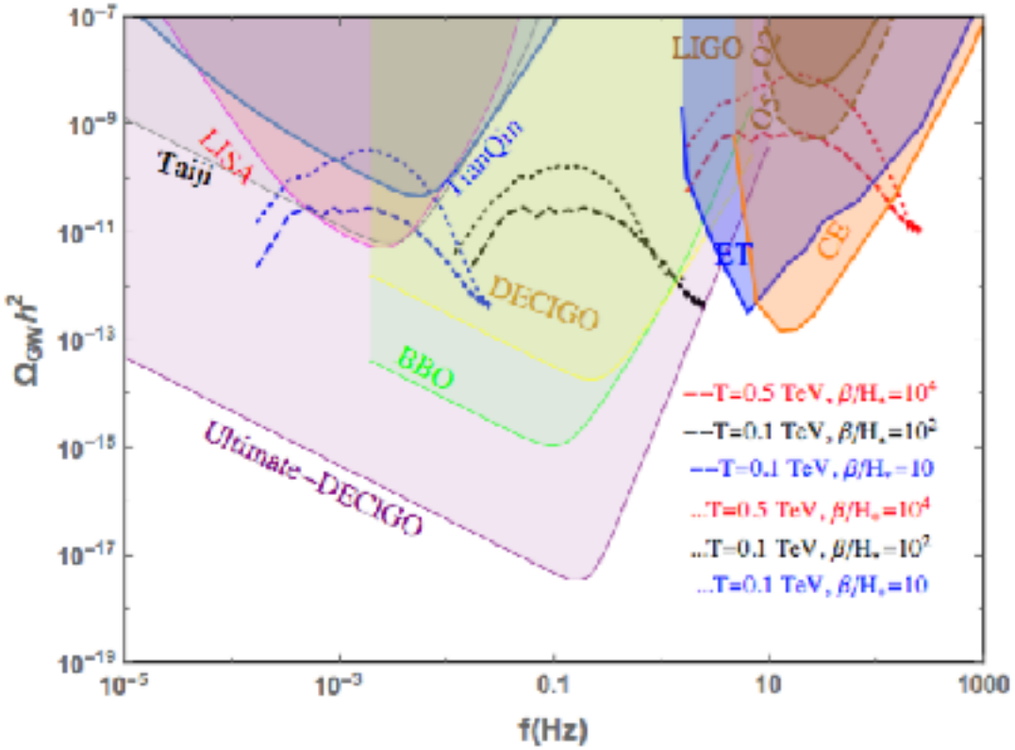
$$\frac{d\Omega_{\mathrm{gw}}}{d\ln(k)} = \frac{1}{32\pi G \rho_c} \frac{k^3}{2\pi^2} P_h(\mathbf{k}, t)$$





$\gamma_\star = R_\star / (2Rc)$

$$R_* = \left(\frac{\nu}{N_b}\right)^{1/3}$$

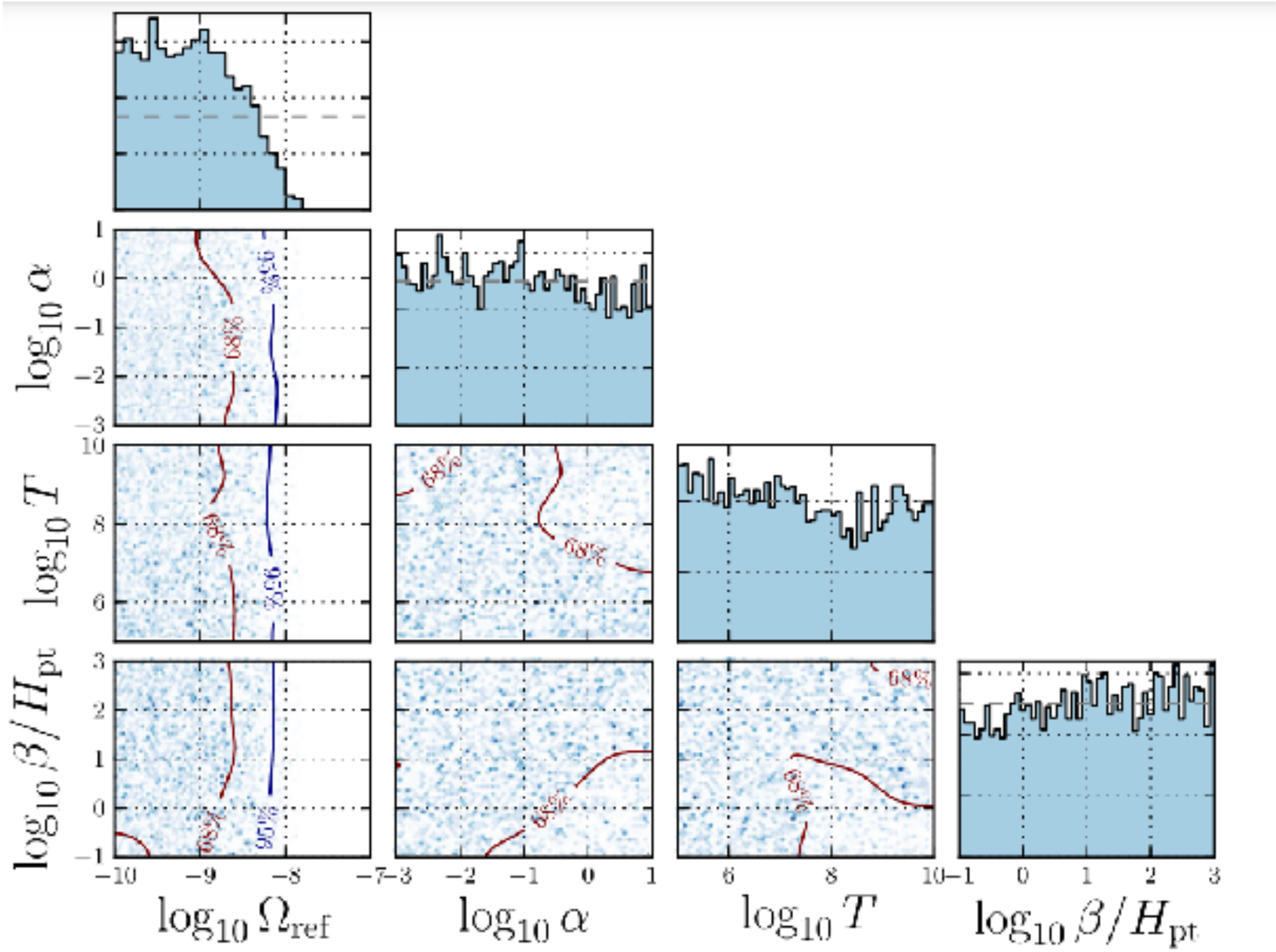


Di, Wang, Zhou, **Bian***, Cai*,Liu*, Phys.Rev.Lett. 126 (2021) 251102

LIGO-Virgo search for FOPT

High-scale PT Romero, Martinovic,Callister, Guo, et al., Phys.Rev.Lett. 126 (2021) 15, 151301

LIGO-Virgo O3



PPTA search for FOPT

- **PPTA DR2 dataset constrain low-scale phase transition，dark sector and QCD scale FOPT**

PHYSICAL REVIEW LETTERS **127,** 251303 (2021)

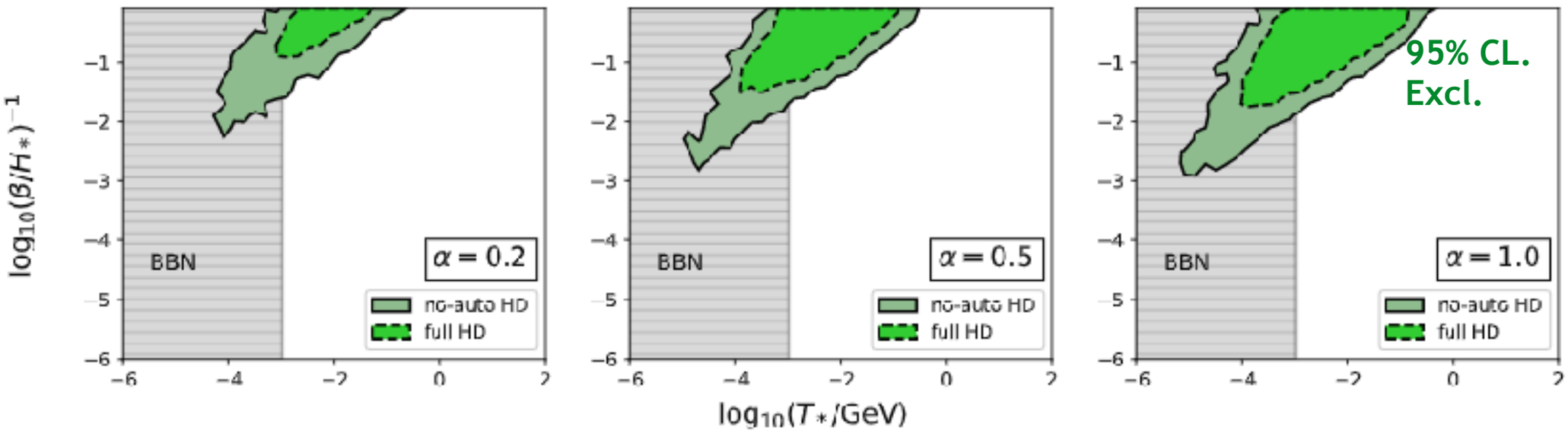
Editors' Suggestion | Featured in Physics

Constraining Cosmological Phase Transitions with the Parkes Pulsar Timing Array

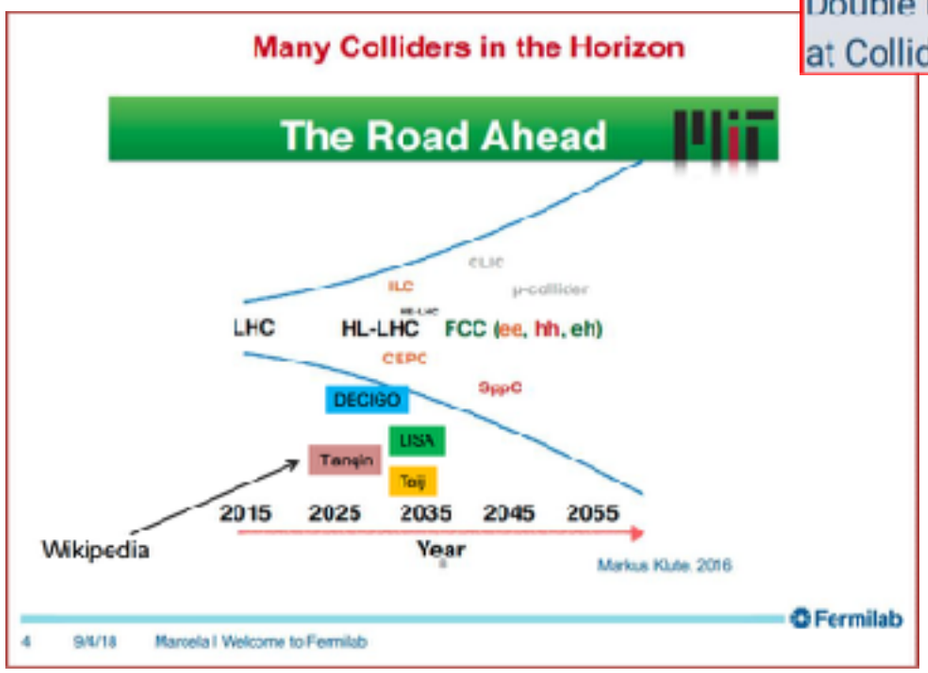
Xiao Xue,[1,2,3] Ligong Bian,[4,5,*] Jing Shu,[1,2,6,7,8,†] Qiang Yuan,[9,10,7,‡] Xingjiang Zhu,[11,12,13,§] N. D. Ramesh Bhat,[14] Shi Dai,[15] Yi Feng,[16] Boris Goncharov,[11,12] George Hobbs,[17] Eric Howard,[17,18] Richard N. Manchester,[17] Christopher J. Russell,[19] Daniel J. Reardon,[12,20] Ryan M. Shannon,[12,20] Renée Spiewak,[21,20] Nithyanandan Thyagarajan,[22] and Jingbo Wang[23]

TABLE I: Description of hypotheses tested in this work and the Bayes factors between them.

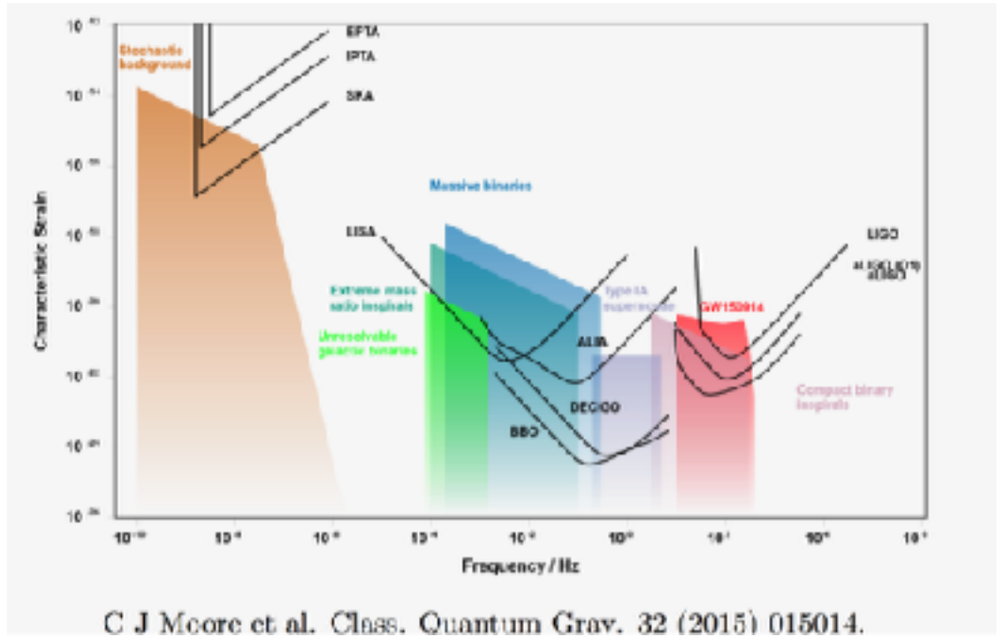
Hypothesis	Pulsar noise	Common red process	HD process FOPT spectrum	Bayes Factors	Parameter Estimation (median and 1-σ interval)	
					T_*/MeV, $\alpha \times 10^3$, β/H_*	$A_{\rm comred}$, $\gamma_{\rm comred}$
H0:Pulsar Noise	yes	no	no			
H1:Common Red	yes	yes	no	$10^{3.5}$ (against H0)		$-14.45^{+0.62}_{-0.64}$, $3.31^{+1.36}_{-1.53}$
H2:FOPT	yes	no	yes (full HD)	$10^{1.8}$ (against H0)	$7.4^{+11.9}_{-4.7}$, 271^{+165}_{-92}, $9.9^{+11.4}_{-5.4}$	
H3:FOPT1	yes	yes	yes (full HD)	1.04 (against H1)	$9.6^{+232.2}_{-9.2}$, $3.8^{+27.9}_{-3.4}$, 854^{+9622}_{-782}	$-14.51^{+0.64}_{-0.68}$, $3.36^{+1.39}_{-1.54}$
H4:FOPT2	yes	yes	yes (no-auto HD)	0.96 (against H1)	$10.9^{+290.5}_{-10.6}$, $3.2^{+19.9}_{-2.8}$, 1053^{+11256}_{-962}	$-14.45^{+0.62}_{-0.64}$, $3.27^{+1.37}_{-1.54}$



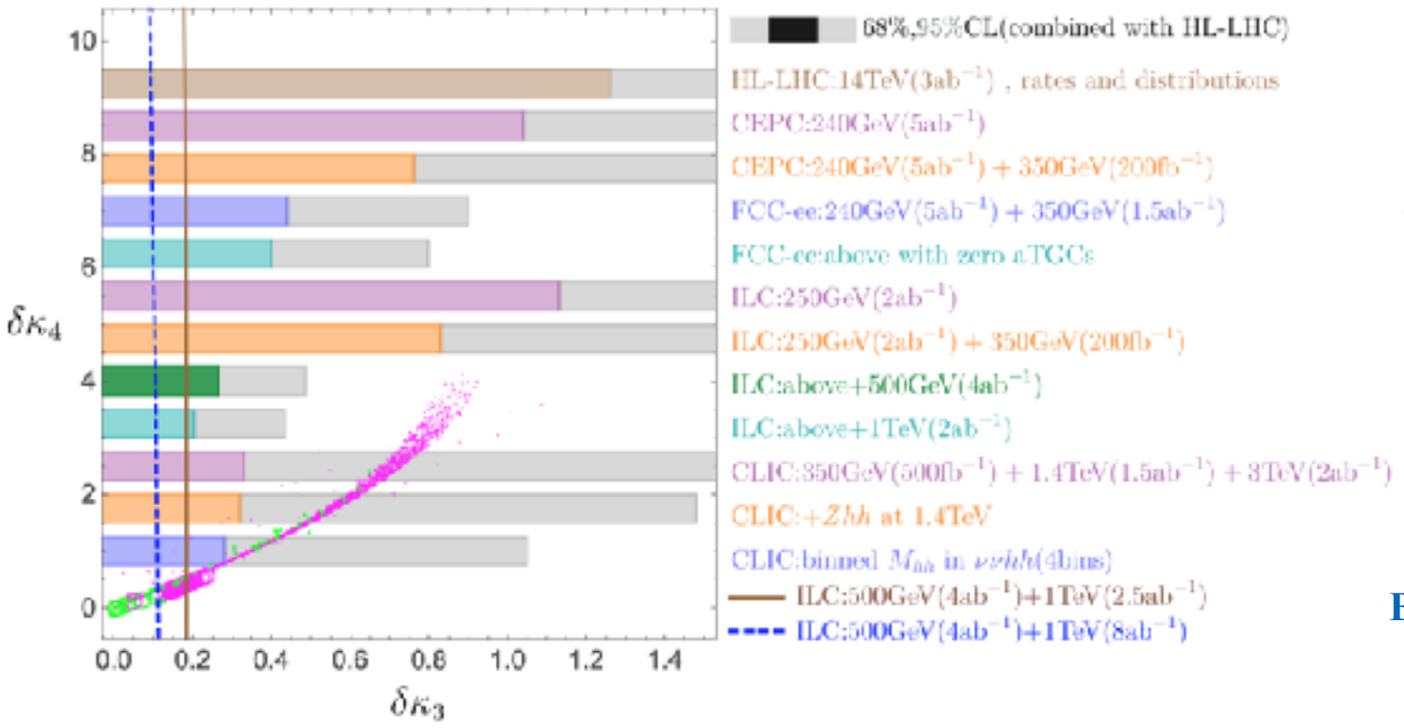
PTGW and collider search



Double Higgs Production at Colliders Workshop



C J Moore et al. Class. Quantum Grav. 32 (2015) 015014.



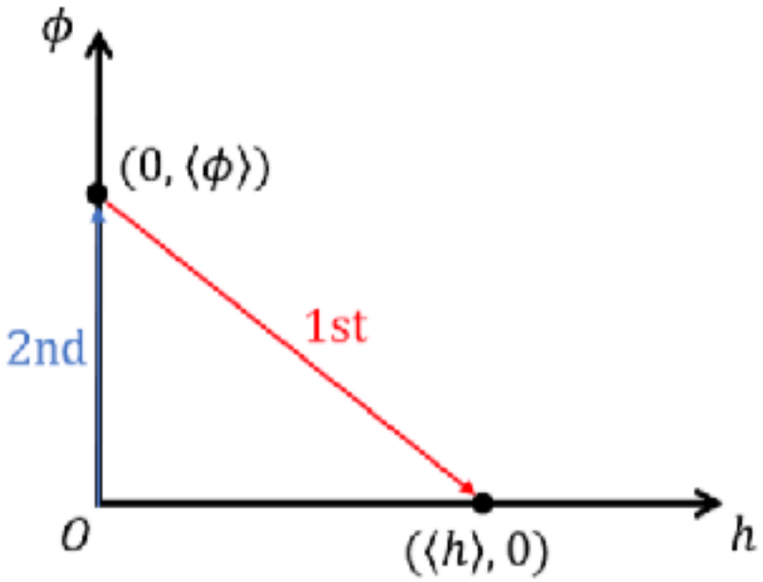
$$\Delta\mathscr{L} = -\frac{1}{2}\frac{m_h^2}{v}(1+\delta\kappa_3)h^3 - \frac{1}{8}\frac{m_h^2}{v^2}(1+\delta\kappa_4)h^4$$

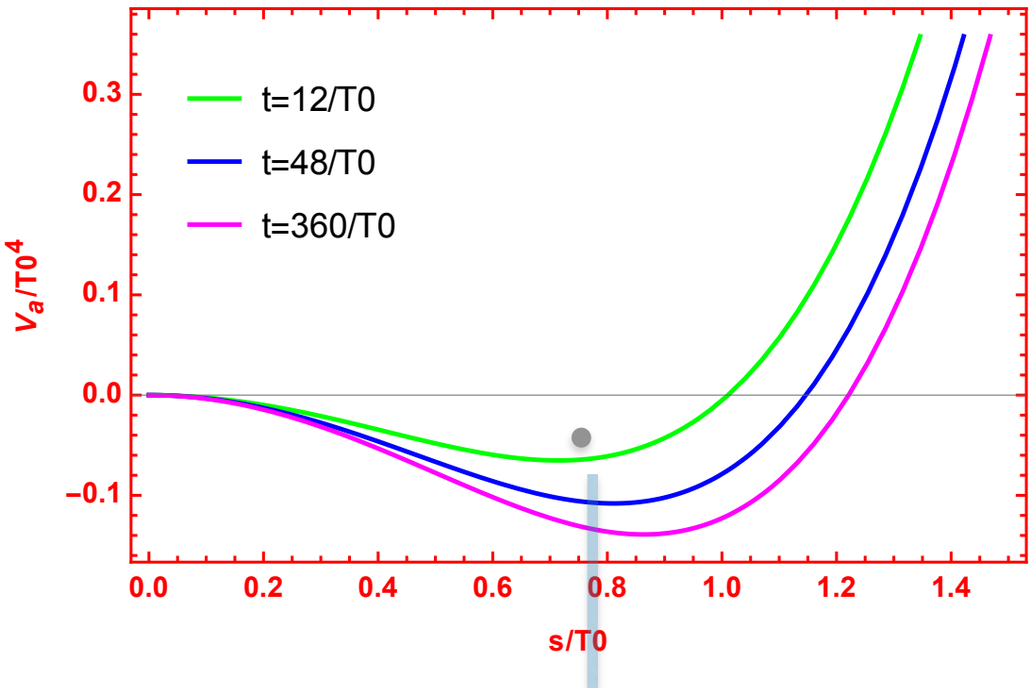
SNR > 10 for two-step and one-step SFOEWPT

Bian, Guo, Wu, Zhou, Phys.Rev.D 101 (2020) 3, 035011

Two-step FOPT

Type-a

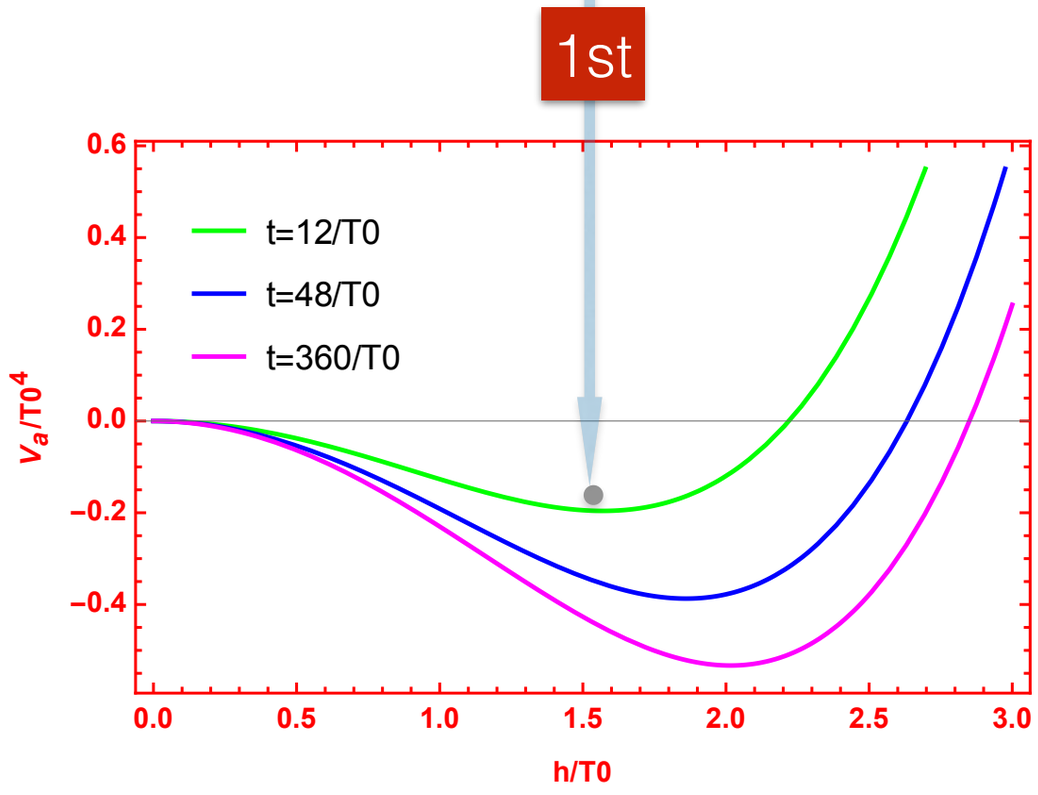




$$V_a(\phi, h, T) = \frac{1}{2}(\mu_\phi^2 + c_\phi T^2)\phi^2 + \frac{1}{2}\lambda_{h\phi}h^2\phi^2 + \frac{1}{4}\lambda_\phi\phi^4 + \frac{1}{2}(-\mu_h^2 + c_h T^2)h^2 + \frac{1}{4}\lambda_h h^4$$

$$c_\phi = \lambda_\phi/4 + \lambda_{h\phi}/3$$

$$c_h = (2m_W^2 + m_Z^2 + 2m_t^2)/(4v^2) + \lambda_h/2 + \lambda_{h\phi}/12$$



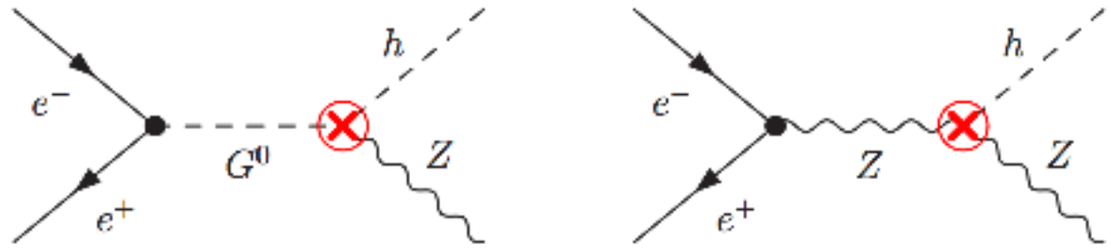
Motivated for DM&EWBG, see:1804.06813,1702.06124,1609.07143, 1605.08663, 1605.08663,etc

Collider search for FOPT

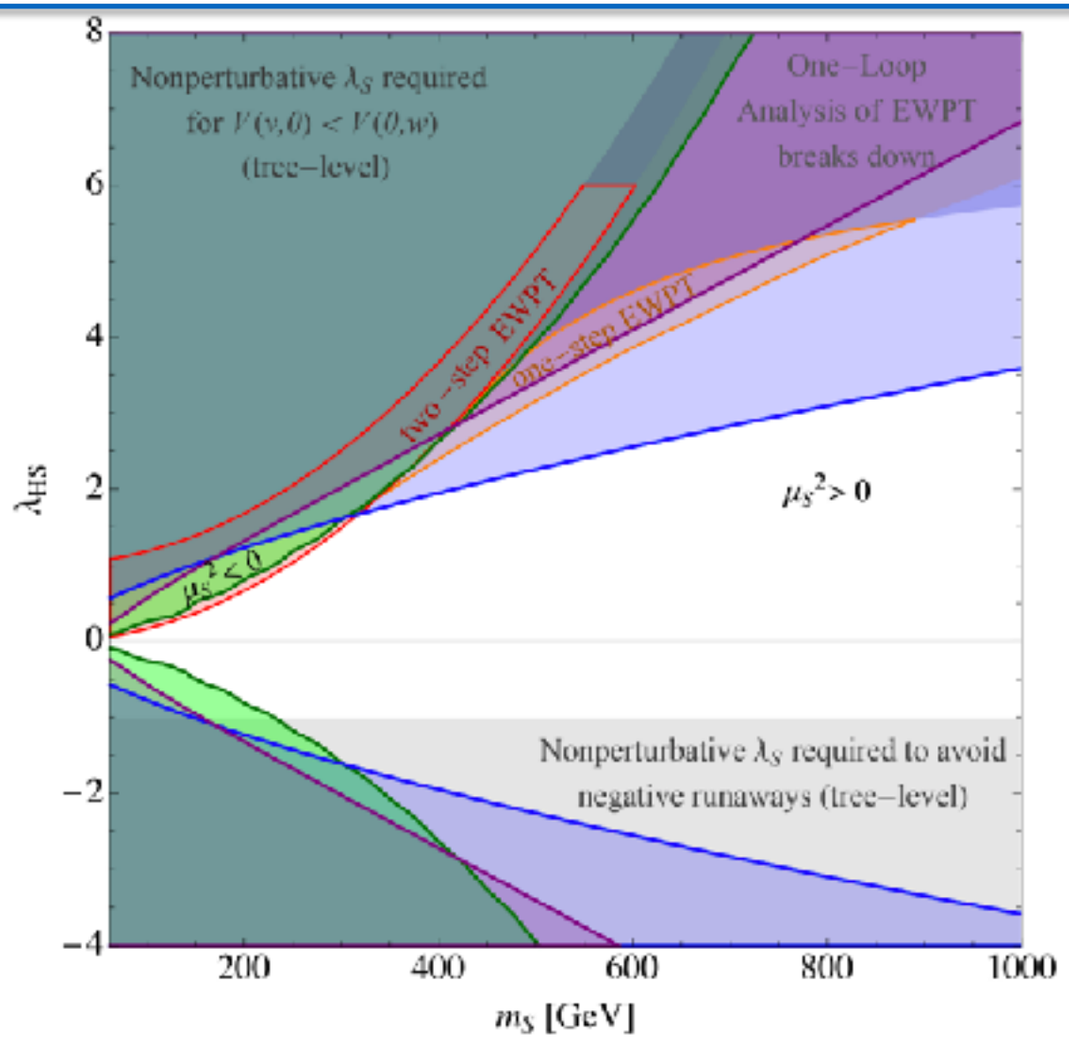
Zh@ILC/CEPC

$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4$$

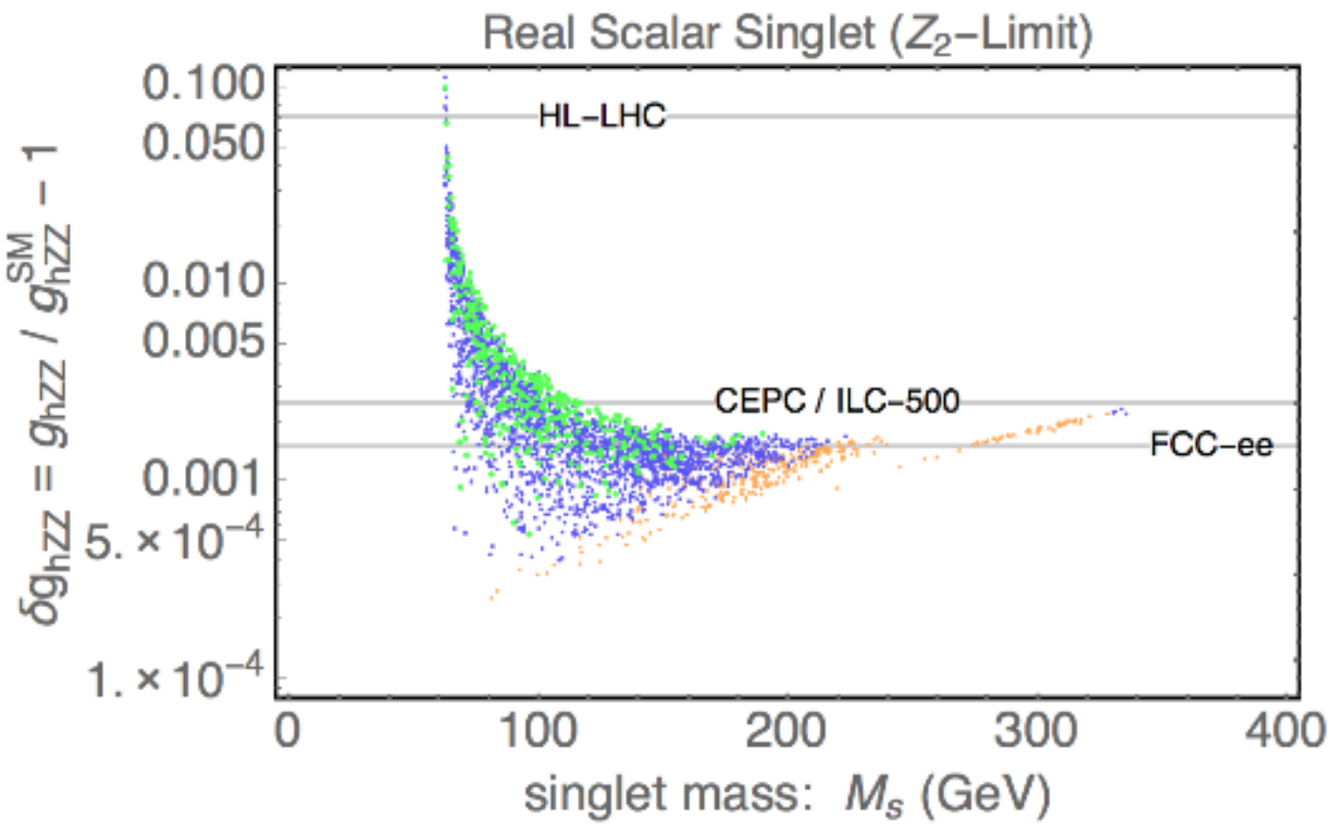
$$V_{\rm eff}(h,T) = V_0(h) + V_0^{CW}(h) + V_T(h,T) + V_r(h,T)$$



Craig,Englert, and McCullough,1305.5251



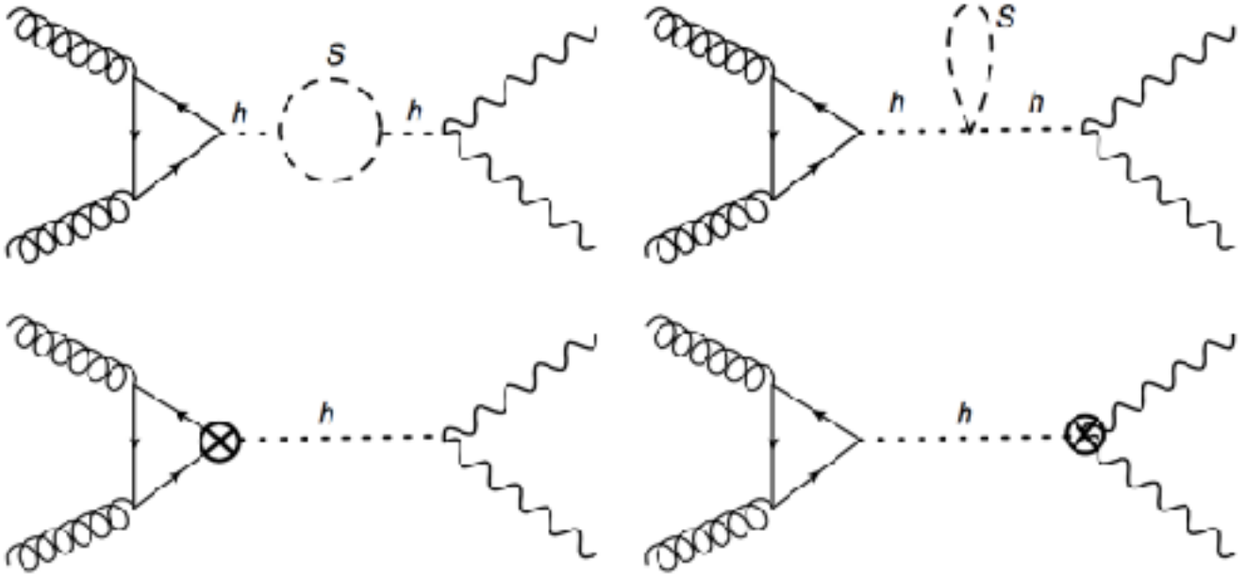
Curtin, Meade, Yu,1409.0005

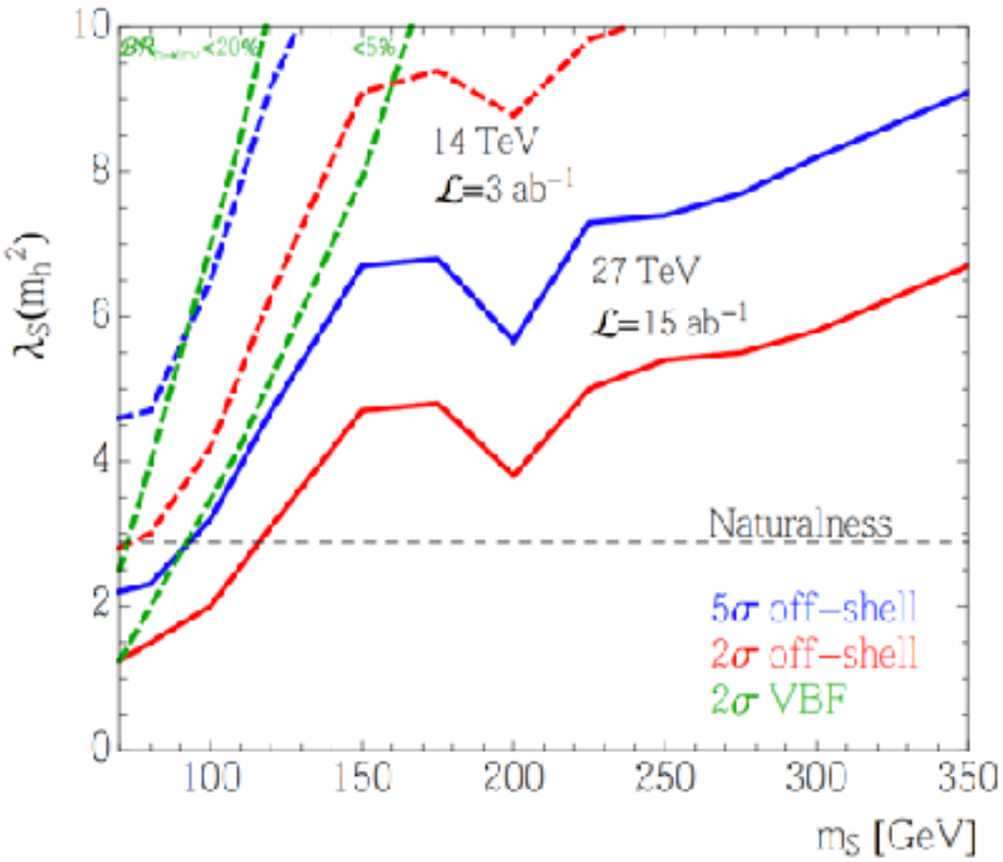


Huang, Long, and Wang,1608.06619

Collider search for FOPT

Off-shell Higgs@LHC



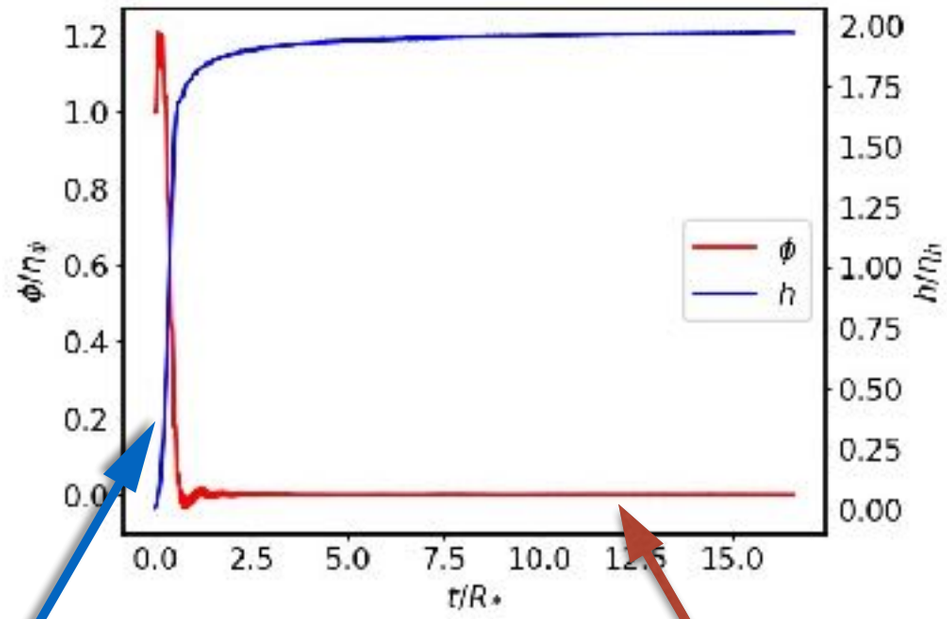


Goncalves,Han,and Mukhopadhyay, 1710.02149

See also: Lee, Park,and Qian, 1812.02679

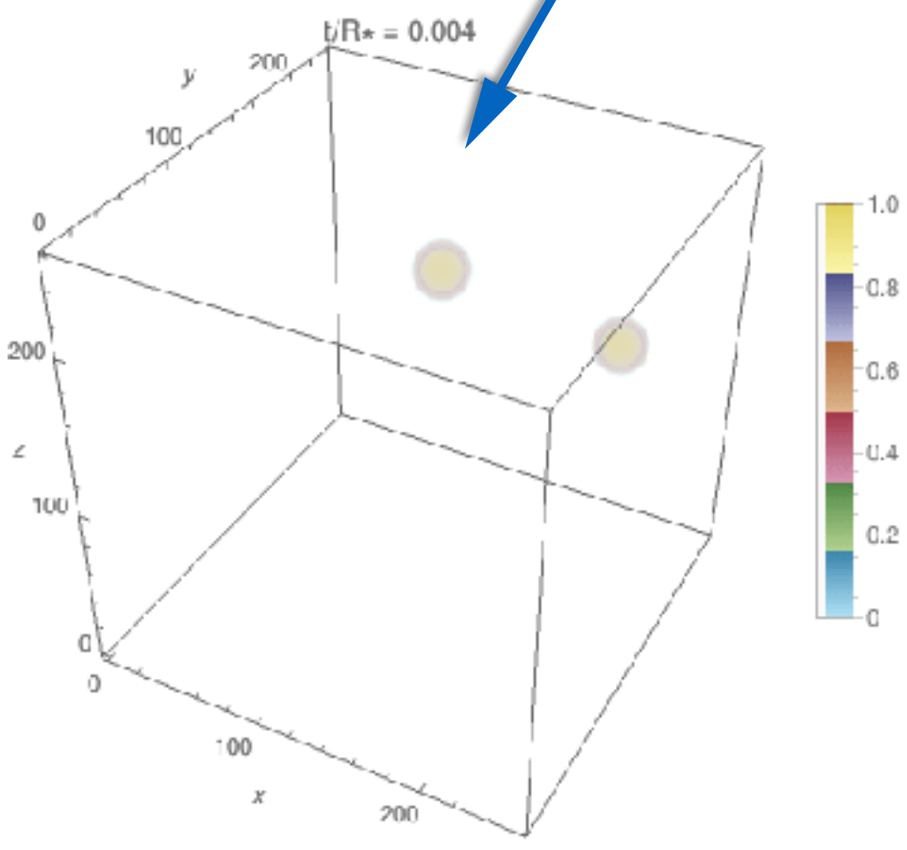
Two-step PT with the second-step being FOPT

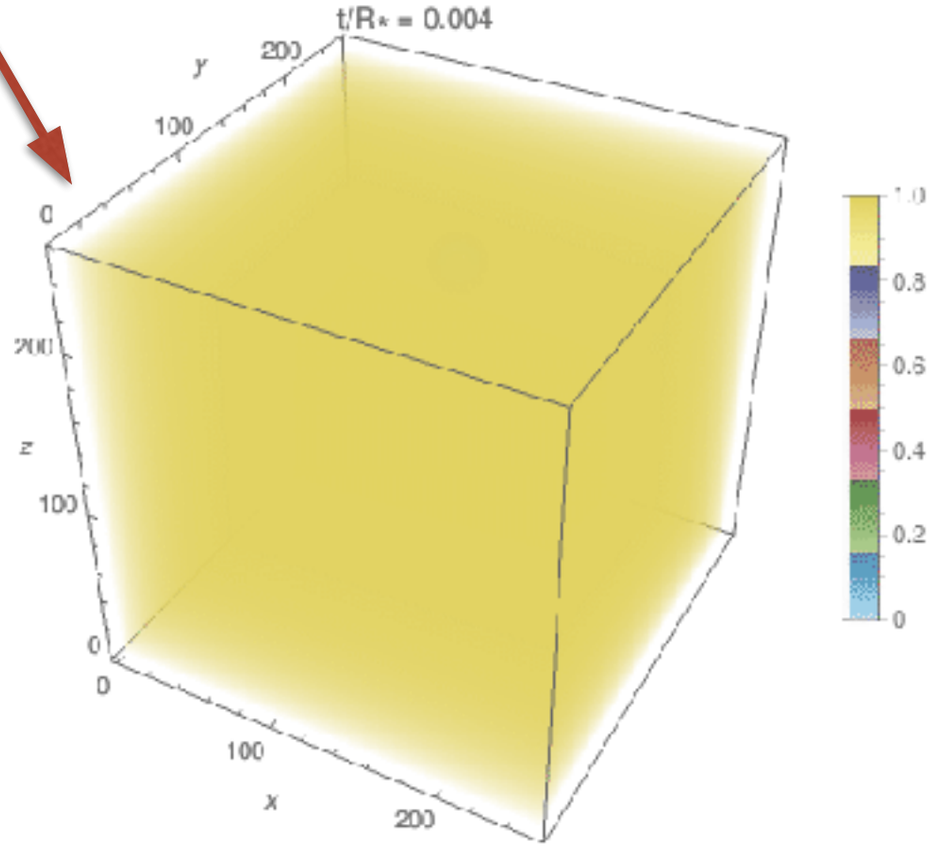
Type-a



$$h(t=0,r) = \eta_h/2\left[1-\tanh\left(\frac{r-R_0}{L_w}\right)\right]$$

$$\phi(t=0,r) = \eta_\phi/2\left[1+\tanh\left(\frac{r-R_0}{L_w}\right)\right]$$

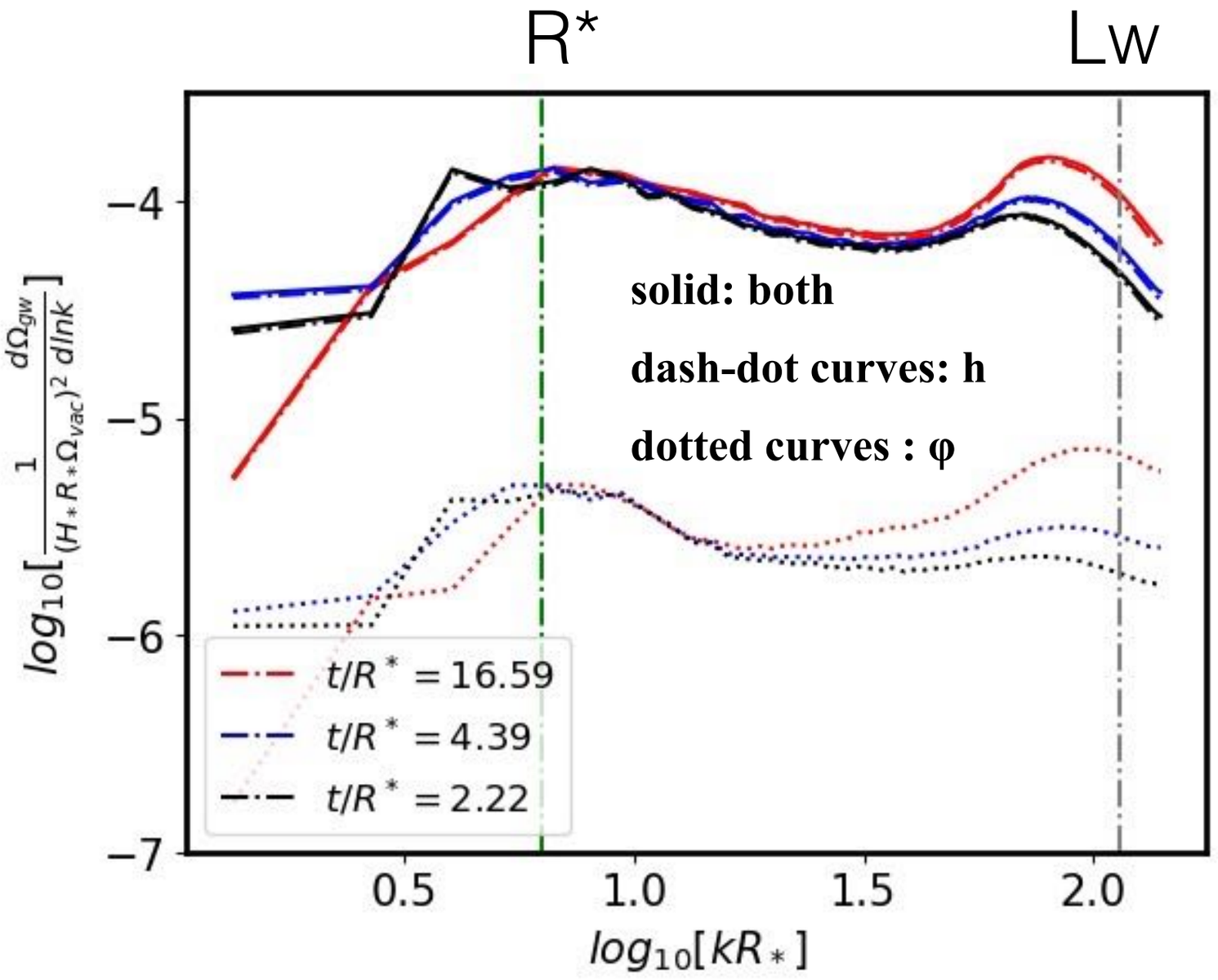




Zhao, Di, **Bian**, Cai,2204.04427

▸ Two-step PT with the second-step being FOPT

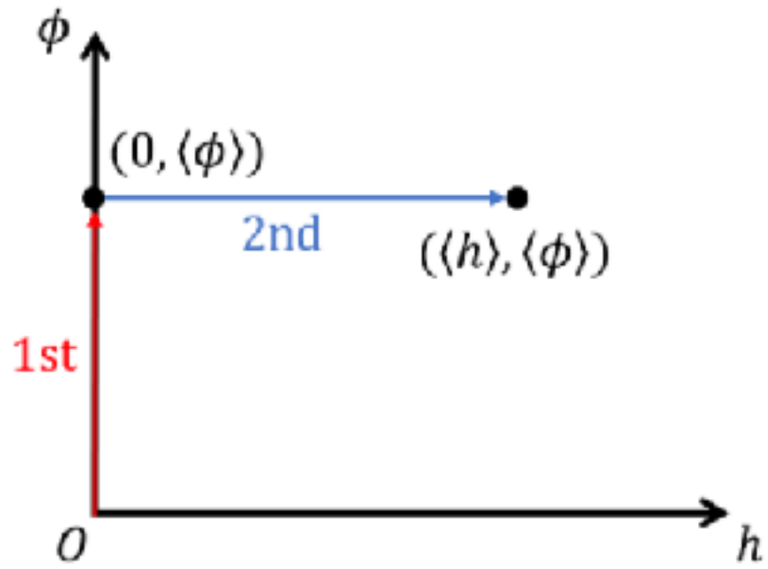
Type-a



Zhao, Di, **Bian**, Cai,2204.04427

Two-step PT with first-step being FOPT

Type-b Without Global U(1)



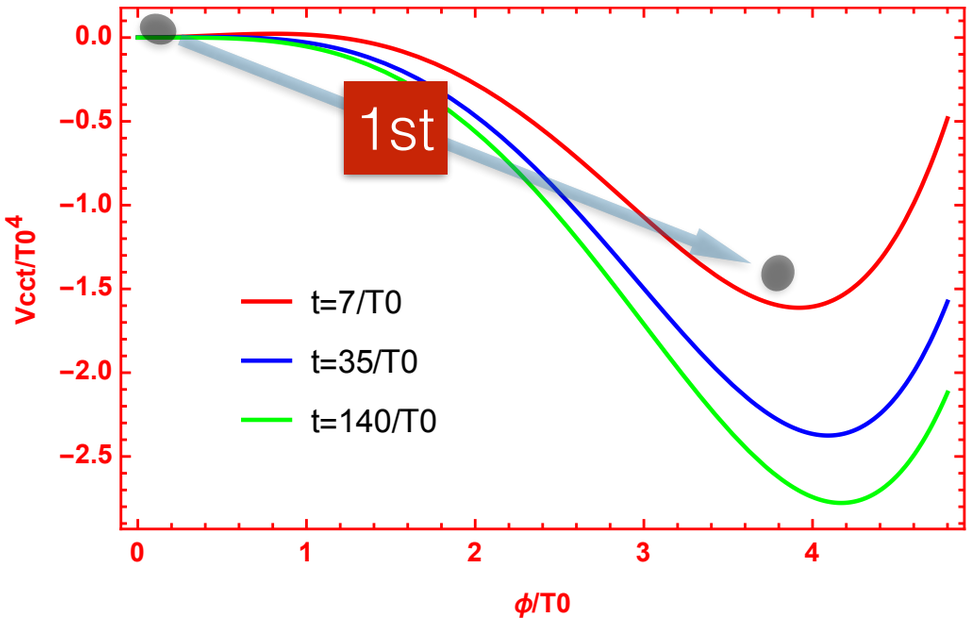
$$V_{cct}(\phi,T)=a\phi^4(\log[|\phi|^2/v_\phi^2]-1/4)+bT^2|\phi|^2$$

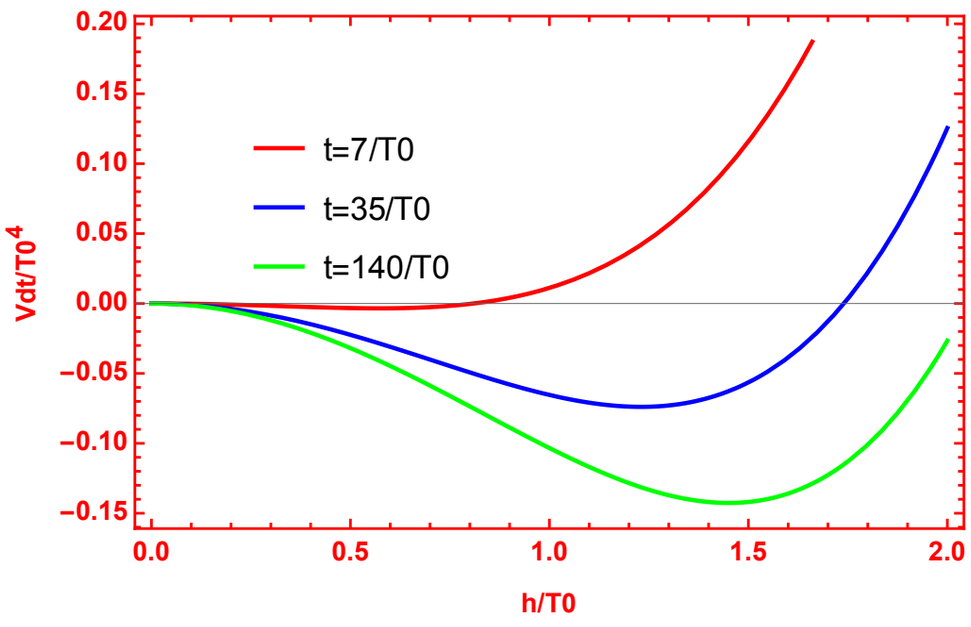
$$V_{da}(\phi,h,T)=\frac{1}{2}c_h'T^2h^2+\frac{1}{4}\lambda_h h^4-\frac{\lambda_p}{4}h^2\phi^2$$

$$c_h'=(2m_W^2+m_Z^2+2m_t^2)/(4v^2)+\lambda_h/2+\lambda_p/24$$

$$\langle h\rangle=\sqrt{(\lambda_p\eta^2-2c_h'T^2)/(2\lambda_h)}$$

Classical conformal + Dimensional transmutation



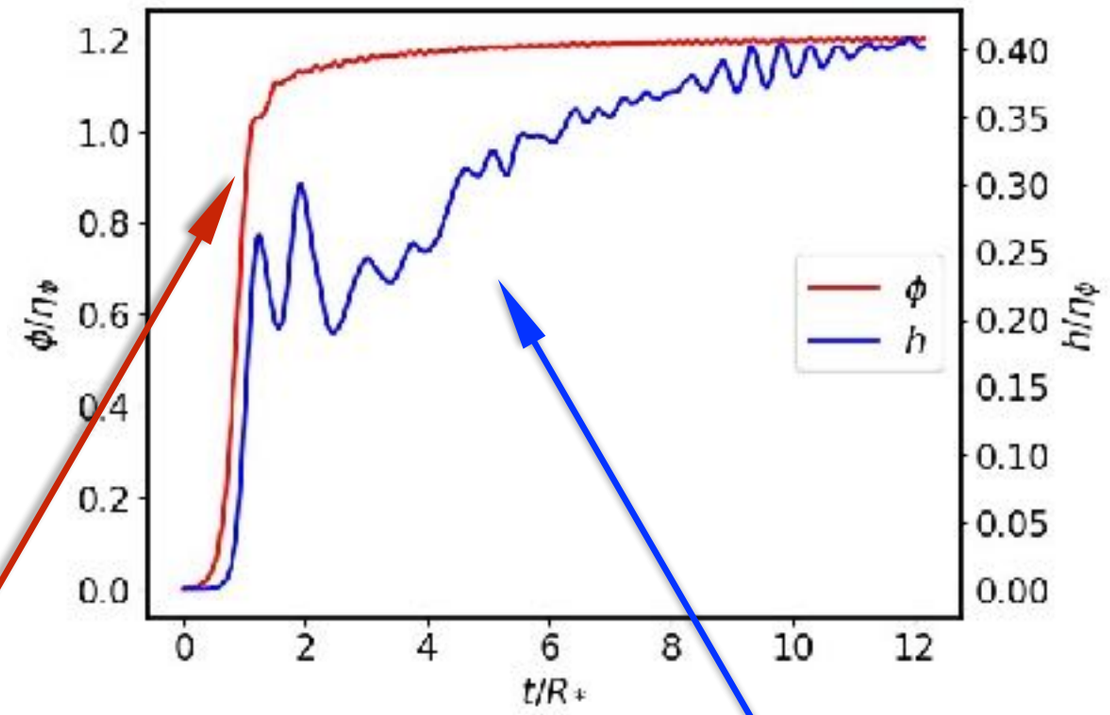


Zhao, Di, **Bian**, Cai,2204.04427

Two-step PT with first-step being FOPT

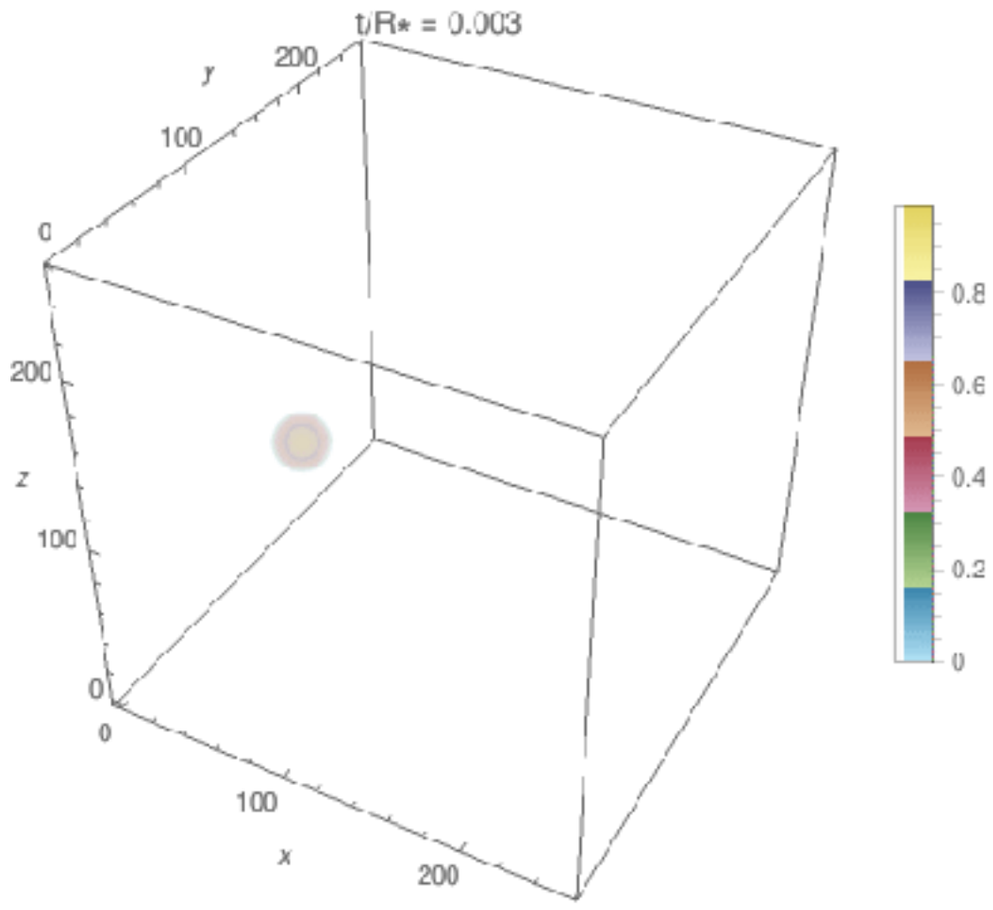
Type-b

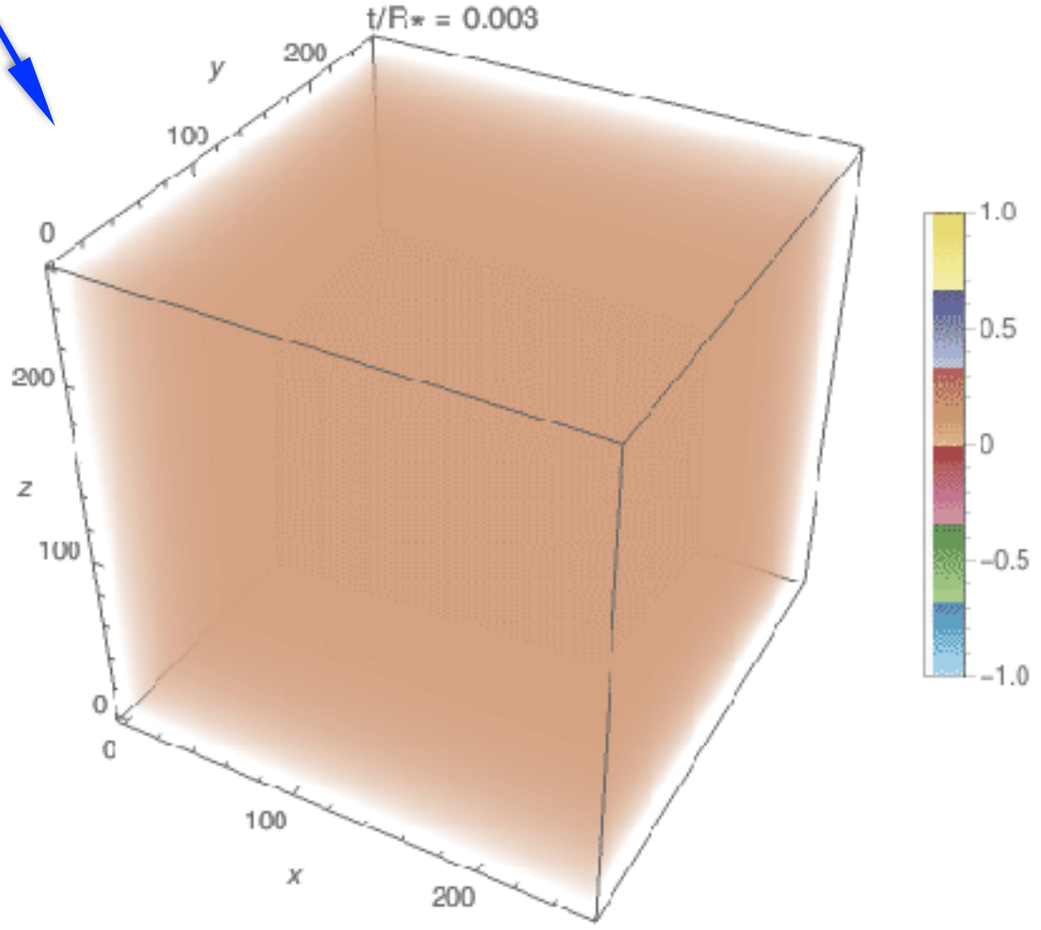
Without Global U(1)



$$\phi(t=0,r) = \eta_\phi/2\left[1-\tanh\left(\frac{r-R_0}{L_w}\right)\right]$$

$$\langle h\rangle = \sqrt{(\lambda_p\eta^2 - 2c_h'T^2)/(2\lambda_h)}$$





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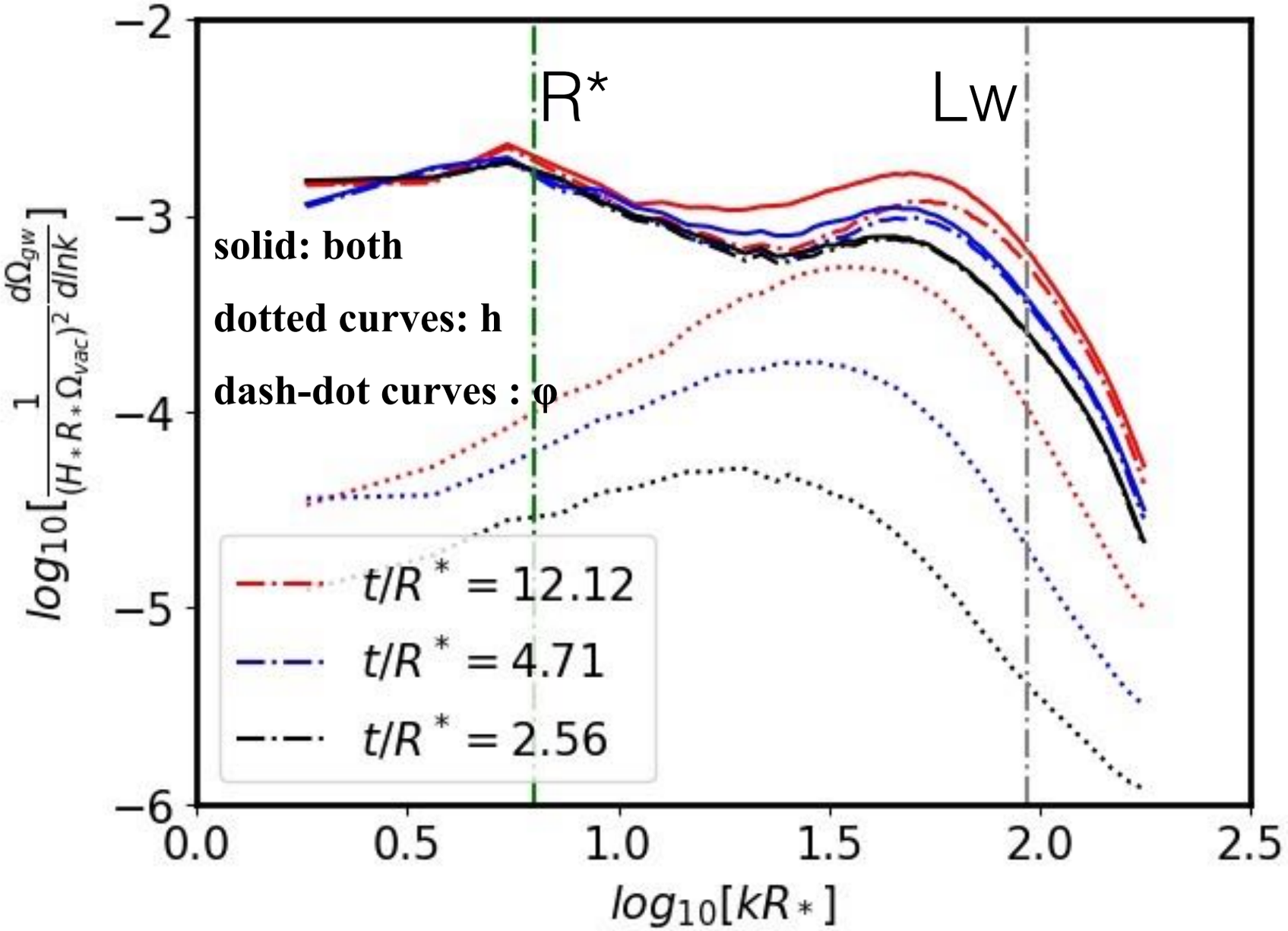
Two-step PT with first-step being FOPT

Type-b

Without Global U(1)



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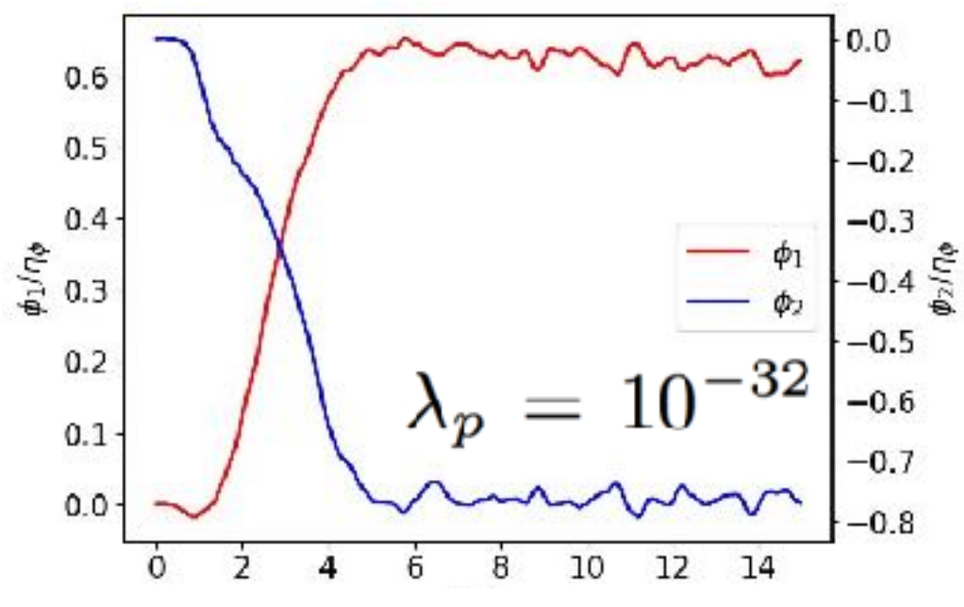
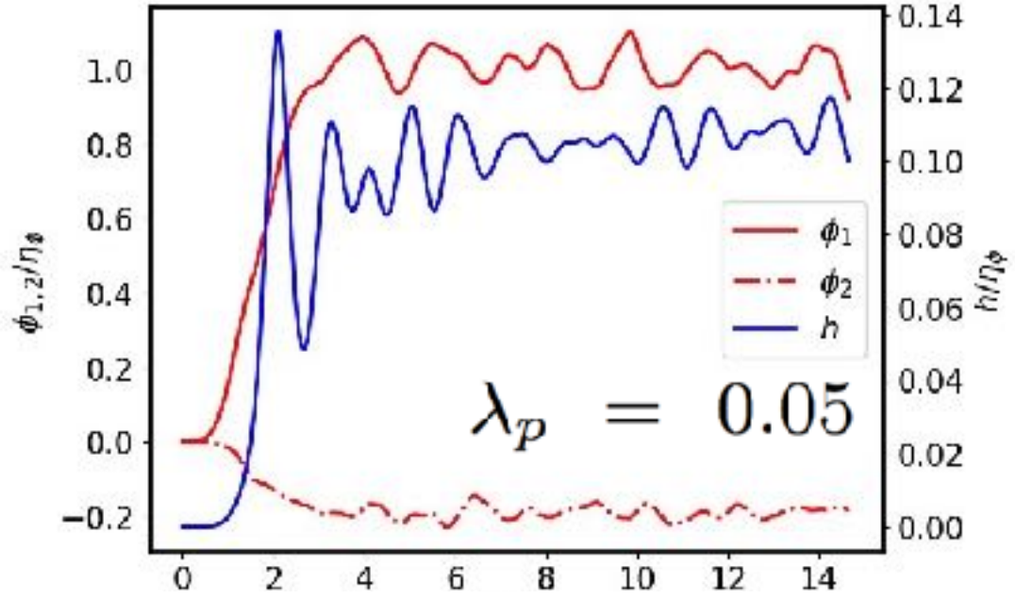
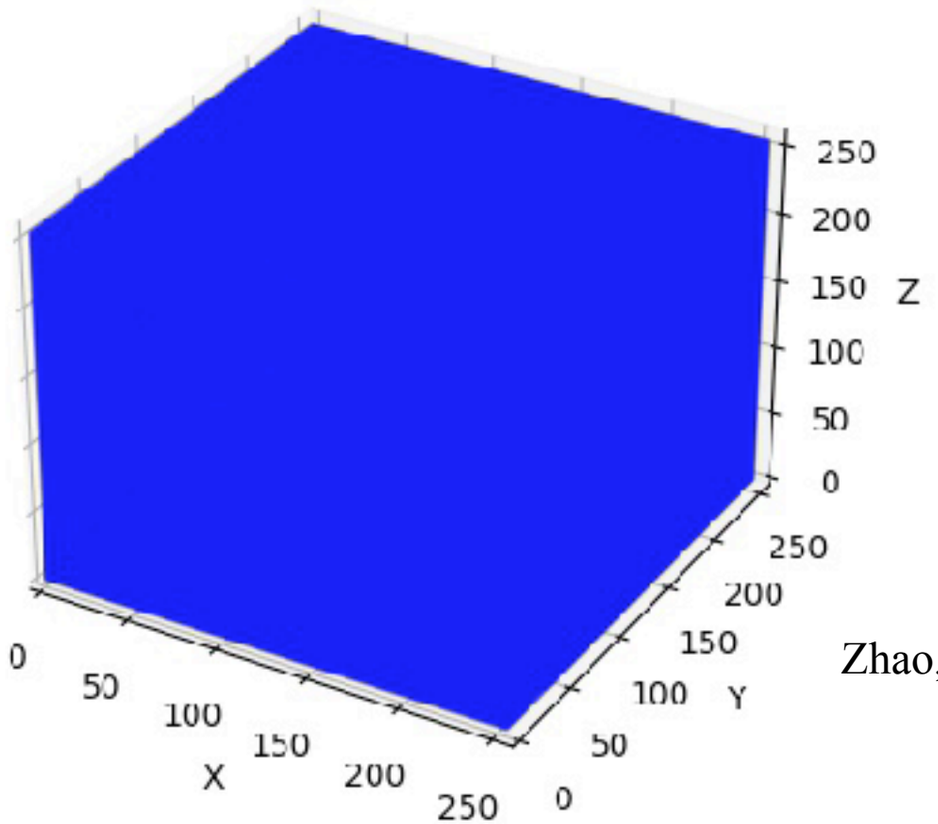
Two-step FOPT with global U(1)

Type-b **With Global U(1)** Motivated for strong CP and axion DM

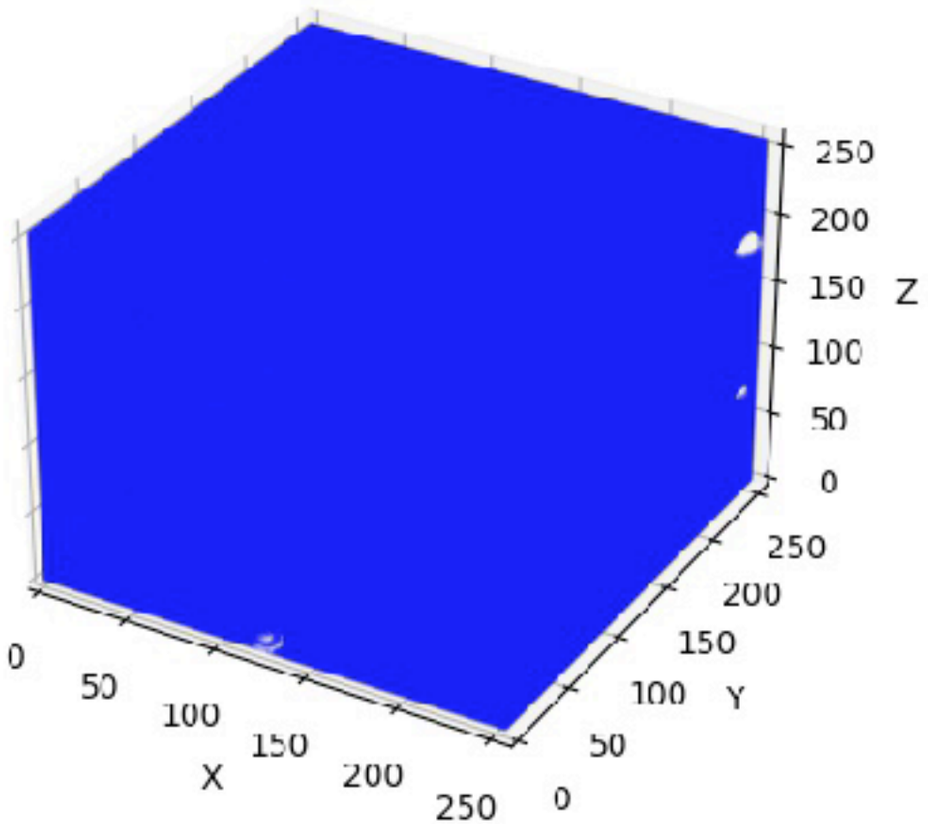




$t/R^* = 0.43$



$t/R^* = 0.45$



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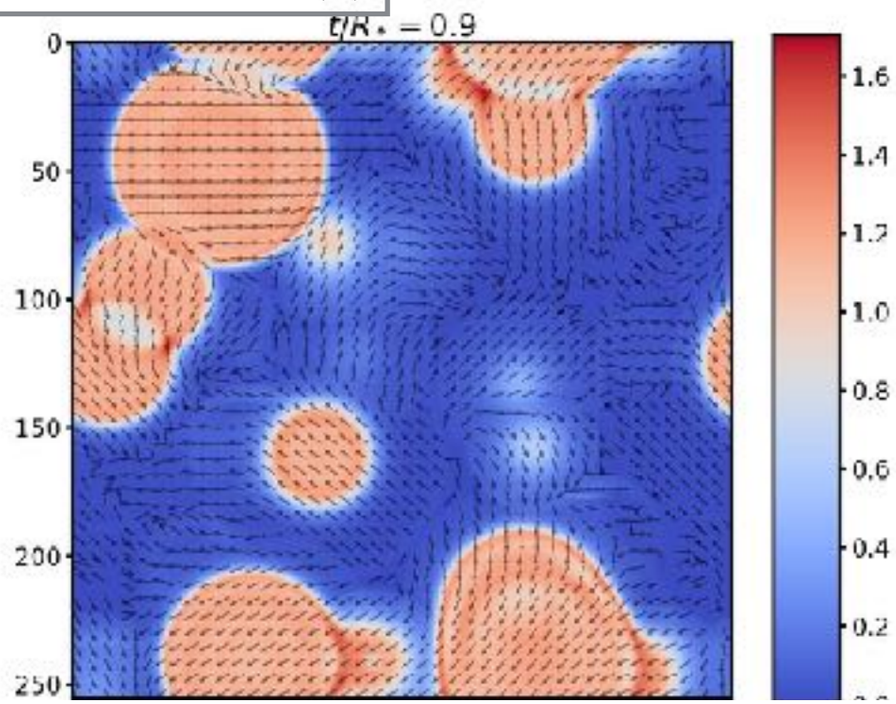
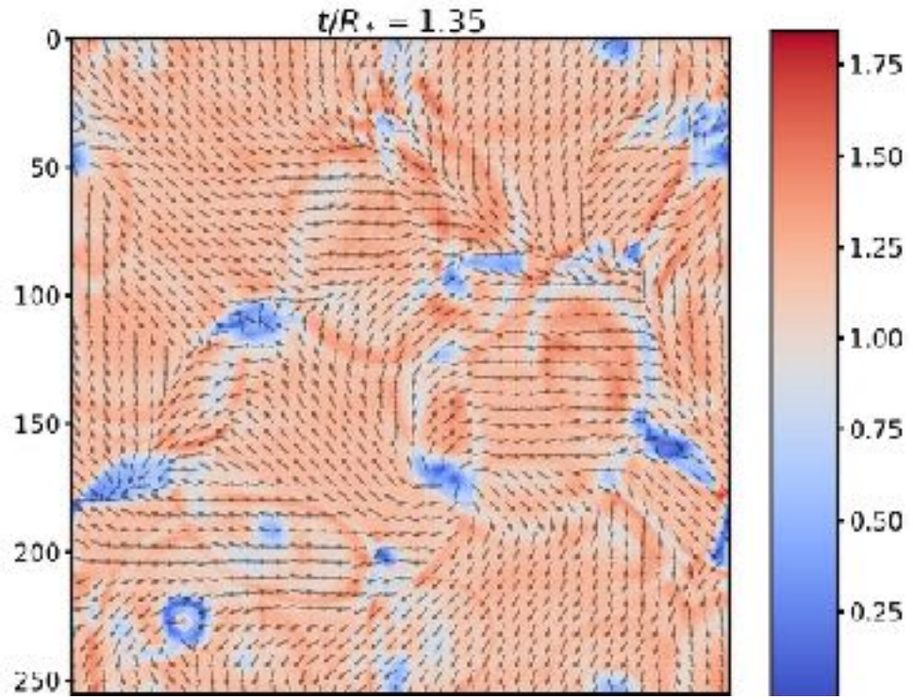
Bubbles and vortex&anti-vortex

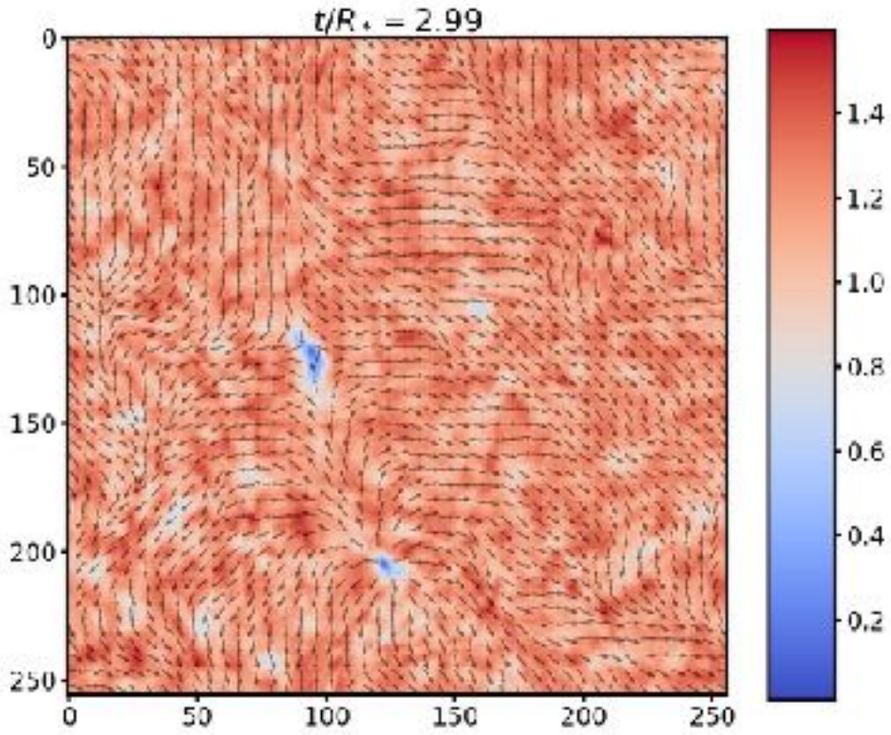
Type-b

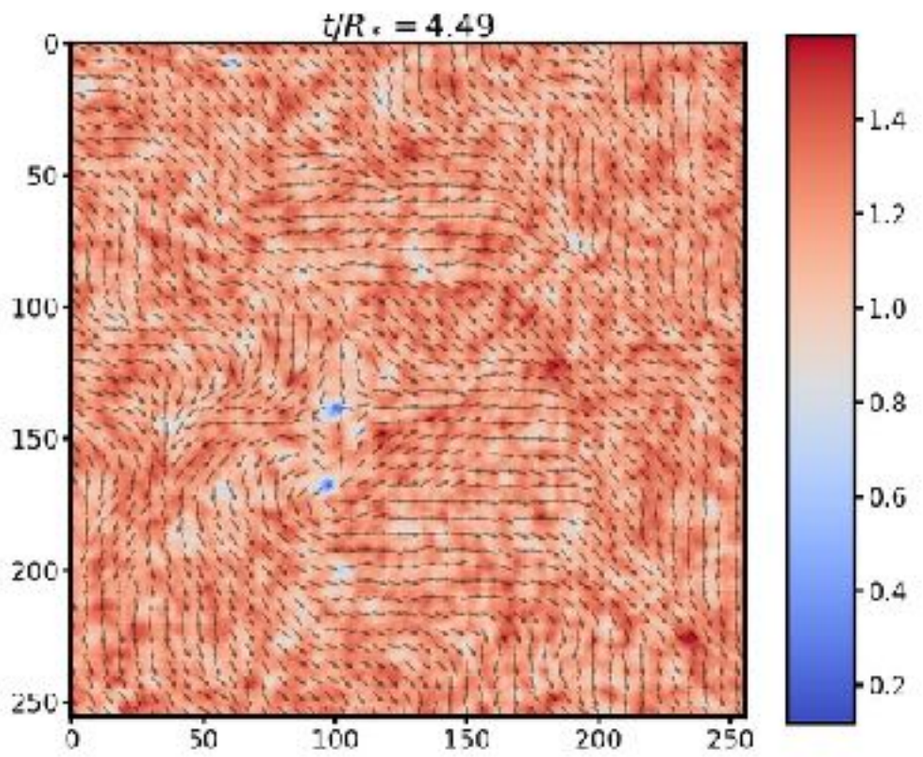
With Global U(1)





Arrows: phase distribution





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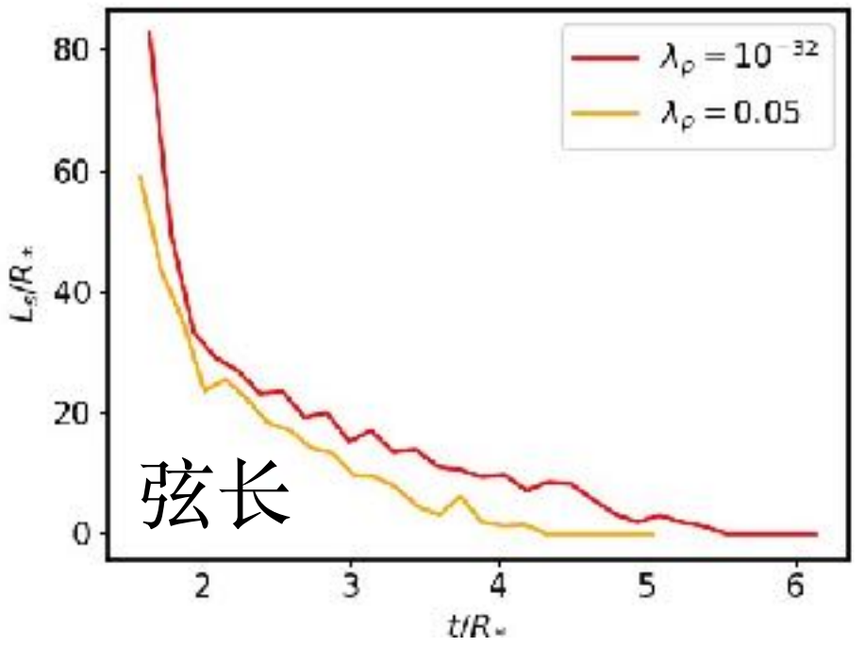
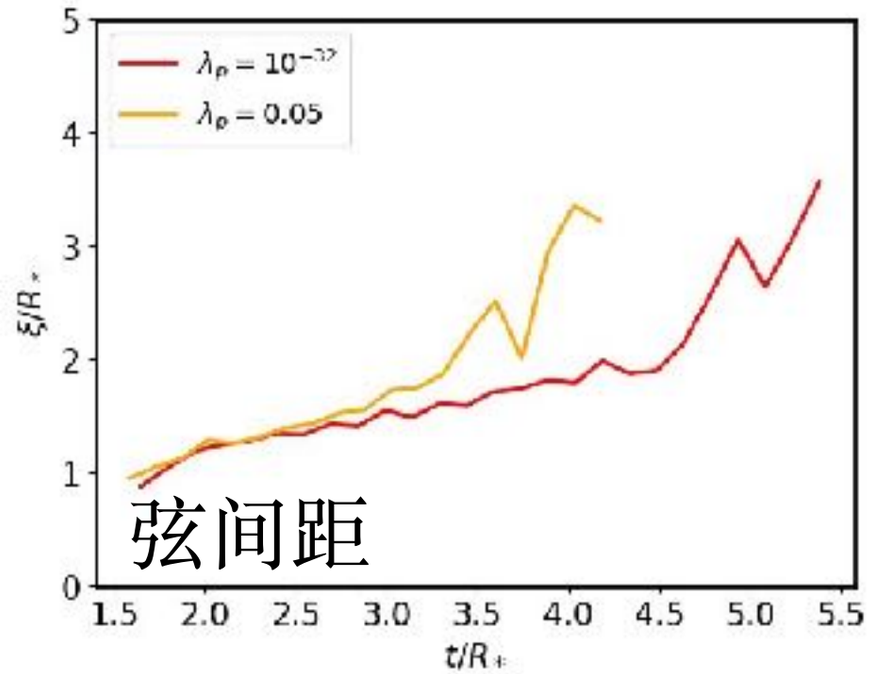
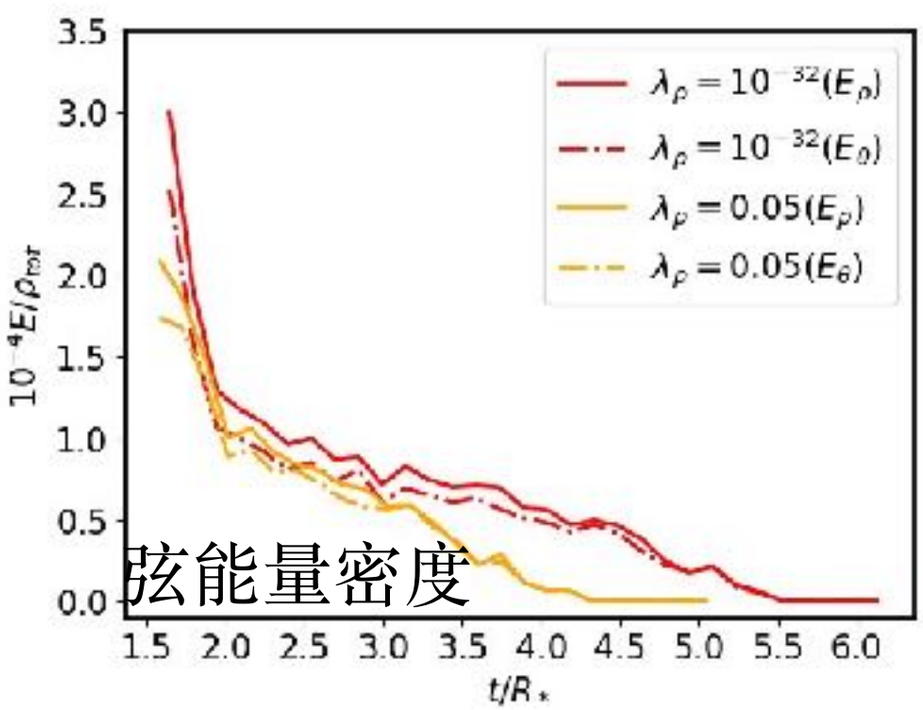
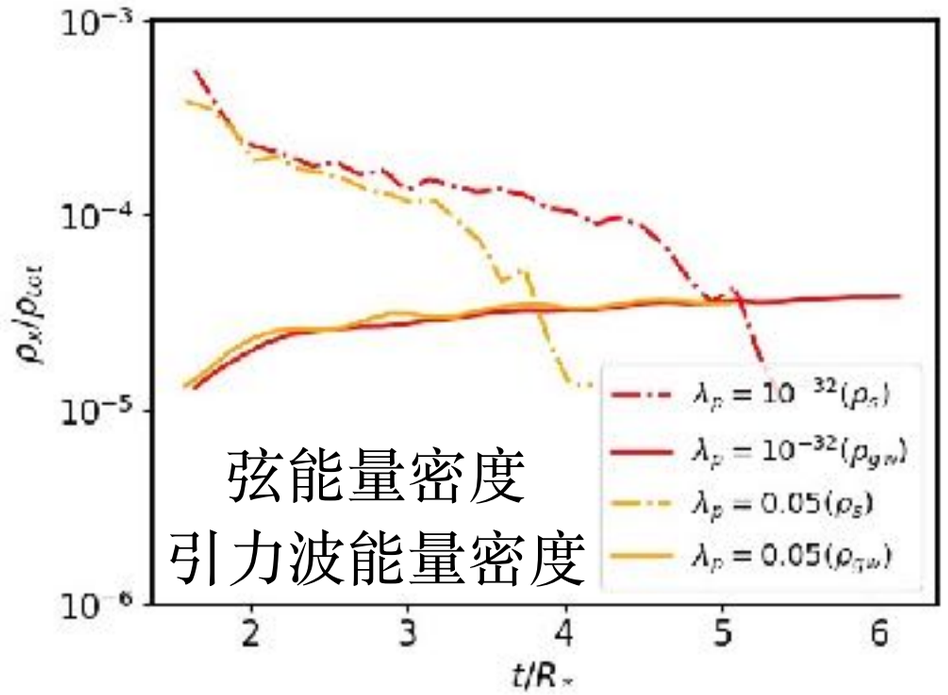
Global string from FOPT

Type-b | **With Global U(1)**









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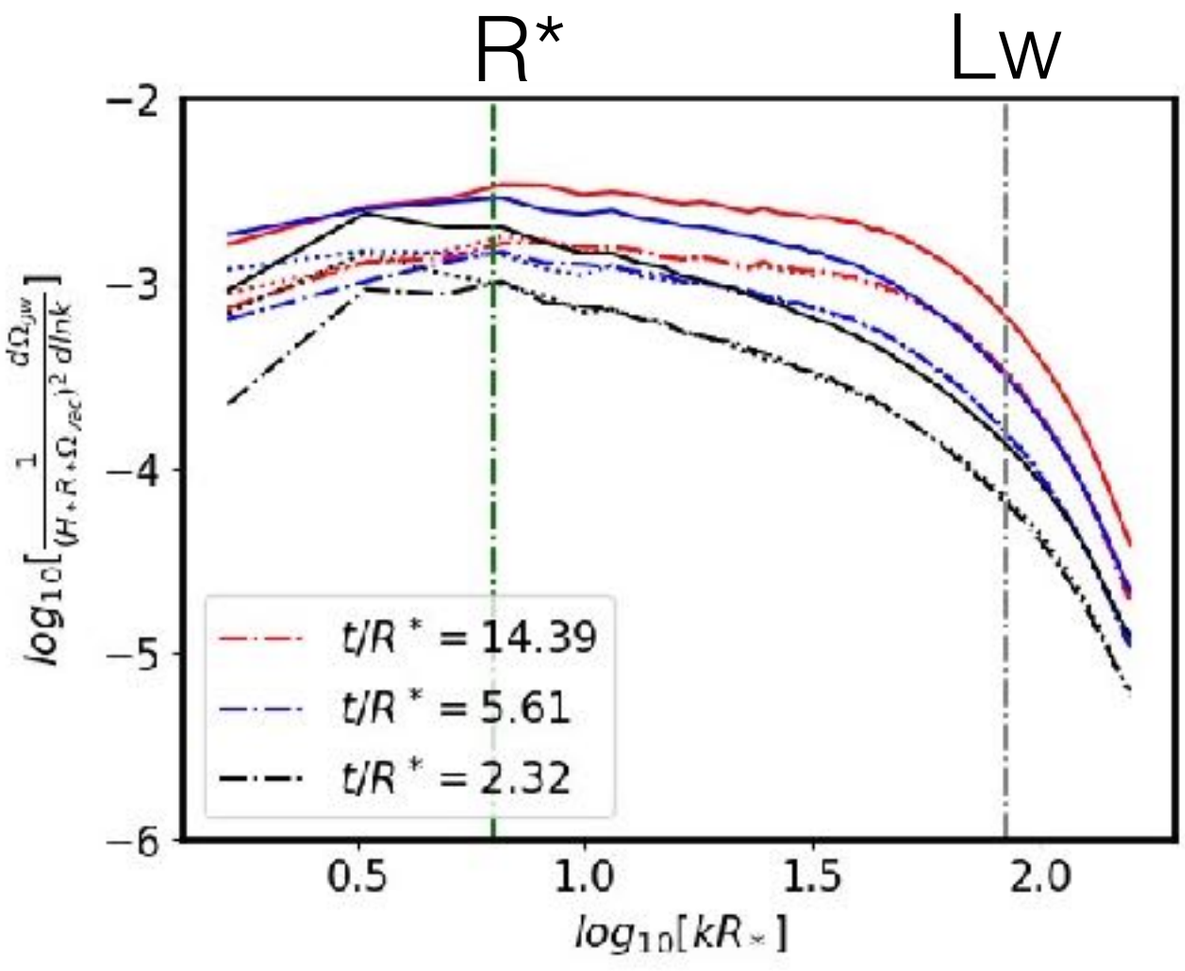
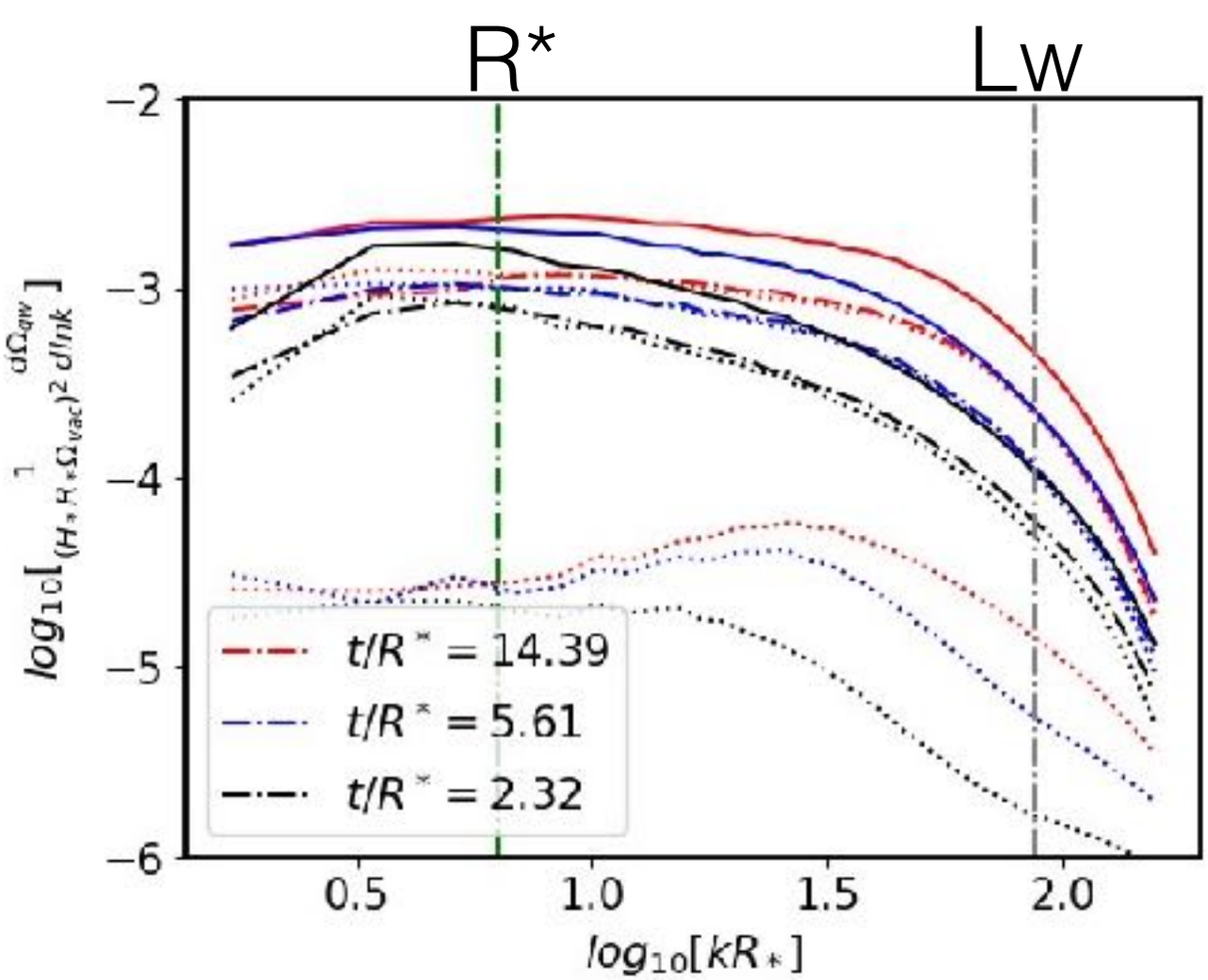
Global string from FOPT

Type-b | **With Global U(1)**

$\lambda_p = 10^{-32}$



$\lambda_p = 0.05$



solid: all dotted curves: h dash-dot curves : φ1 dash curves : φ2

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Summary

1. EWSB and GW from FOPT

- **Probing the Higgs Potential shape and EWPT patterns with GW production and Colliders complementarily**

2. BAU and GW from FOPT

- **Sphaleron process, bubble velocity**

3. DM and GW from FOPT

- **DM and high/low-scale PT, DM out-of-equilibrium & FOPT, PBH DM&FOPT**

4. Topological defects from FOPT

- **Magnetic monopoles, cosmic strings, domain walls**

Thanks!