

Gravitational waves from the confinement transition in the one-flavor SU(4) Hyper Stealth Dark Matter

Nobuyuki Matsumoto (Boston U)

Ayyar, NM, et al. [LSD Collaboration] 2602.23002

Lattice 2026



RIKEN BNL
Research Center



U.S. DEPARTMENT OF
ENERGY

Office of Science
Scidac5

Lattice Strong Dynamics Collaboration



X.-Y. Jin
J. Osborn



J. Kiskis
(deceased)



G. Fleming



C. Peterson



E. Rinaldi



A. Gasbarro*



A. Hasenfratz
E. Neil



S. Park
P. Vranas



E. Weinberg



O. Witzel



V. Ayyar*
R. Brower
N. Matsumoto
E. Owen*
C. Rebbi



J. Ingoldby



C. Culver*
D. Schaich



G. Kribs



T. Appelquist
K. Cushman*



Introduction

- Dark Matter (DM): convincing signal of beyond-Standard-Model physics
- Perturbative DM models, e.g., WIMP, becoming highly constrained

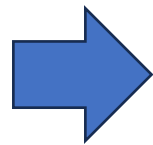
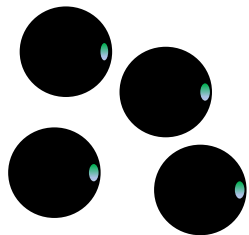
➡ *Possibility that DM is composite?*

- Hyper Stealth Dark Matter **Fleming, Kribs, Neil, Schaich, Vranas PRD 2025**
Pushing forward the Stealth Dark Matter: **Appelquist et al. [LSD Collaboration] PRD 2015**

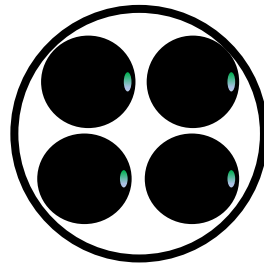
Dark SU(4) gluons + 1f quark; full electroweak coupling at UV (equilibration sector)

@Hot universe

dark quarks & gluons



confinement
phase transition
at finite temperature T



@ Cold universe

dark baryon = *dark matter candidate*

bosonic statistics;
electrically neutral,
magnetically suppressed

1f SU(4) theory

- Chiral anomaly -> No light meson

review: Creutz 2001, 2007

- 1st order transition at large mass

Columbia, PRL 65 (1990) 2491

Fukugita, Ohta, Ukawa '88, Fukugita, Ukawa '88,
Alexandrou et al. PRD '98,
Shoji, Takaishi '04, Takaishi, Nakamura '07

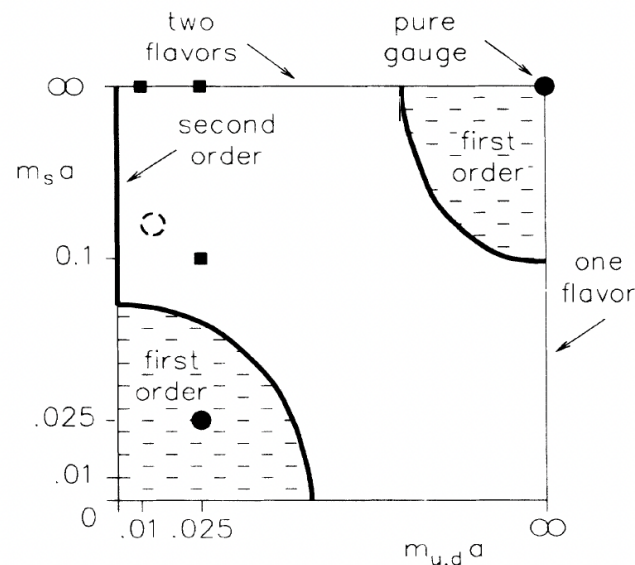


FIG. 1. Presence and absence of the finite-temperature QCD phase transition as a function of $m_{u,d}a$ and $m_s a$. Mass values for which the transition is and is not seen on a $16^3 \times 4$ lattice are denoted respectively by solid circles and squares. The physical point, indicated roughly by the dashed circle, lies in the region of no transition.

More motivation

- Non-adiabatic change in the effective DOF
- ➔ Non-conventional thermal history (baryogenesis?)

Gunn et al. 1978
Kolb-Turner

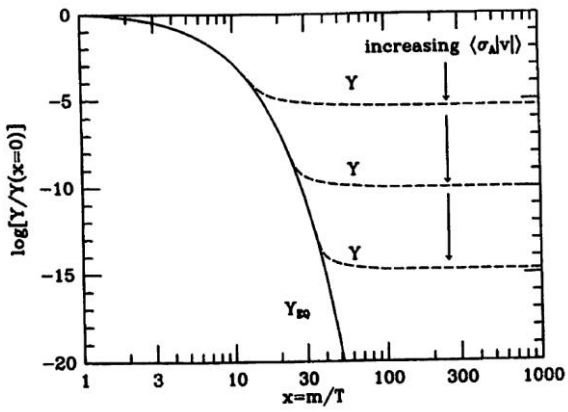
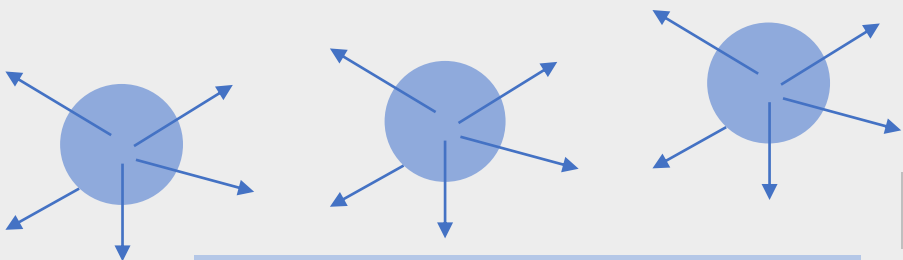


Fig. 5.1: The freeze out of a massive particle species. The dashed line is the actual abundance, and the solid line is the equilibrium abundance.

- Create gravitational waves (GW) in the transition 1st regime

Bubbles expand and collide in a supercooling process @ $T_* < T_c$



➔ sound waves

confined phase (true vac)

deconfined phase (false vac)

- Möbius Domain-wall fermions + Wilson gauge
Brower, Neff, Orginos '12

$$N_s = 16, 24, 32$$

$$N_\tau = 8$$

(cutoff effect subdominant, ignored)

$$m_q a = 0.1, 0.2, 0.3, 0.4$$

$$L_s = 8, m_{\text{res}} = O(10^{-4})$$

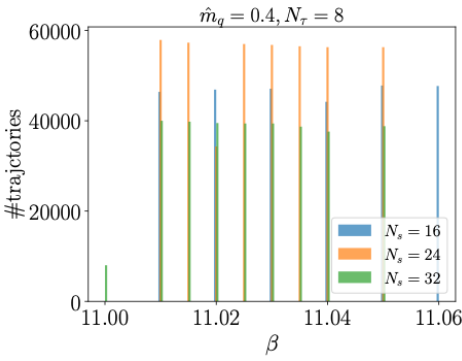
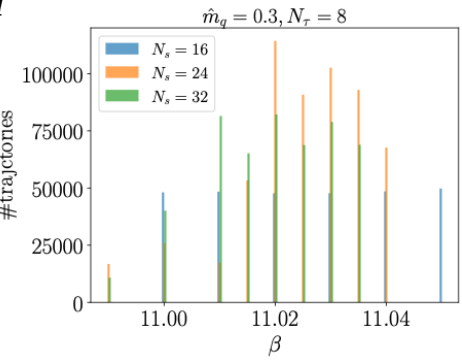
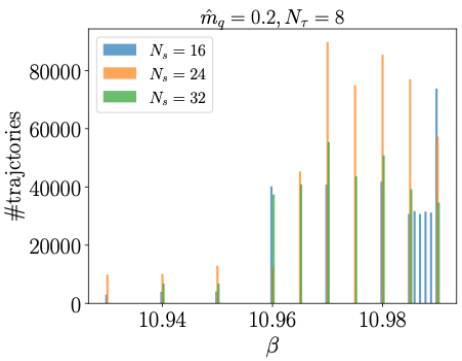
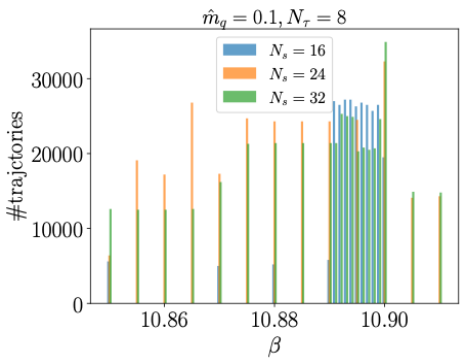


- Zero temp. w/ $N_s = 24$ for scale setting

- Exact one-flavor HMC under Grid
Chen, Chiu '14
Boyle, Yamaguchi,
Cossu, Portelli '15

- $O(10^4 - 10^5)$ configs/ensemble;
 $O(10)$ ensembles around β_c for each $m_q a$

- Multipoint reweighting to vary β
Ferrenberg, Swendsen '88, '89
cf. Saito, Ejiri, Aoki, Kanaya, Nakagawa, Ohno,
Okuno, Umeda [WHOT-QCD] '13
Iwami, Ejiri, Kanaya, Nakagawa,
Yamamoto, Umeda [WHOT-QCD] '15

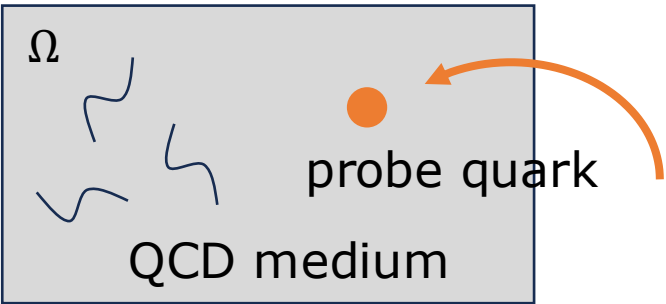


Polyakov loop effective potential

relative free energy to put a probe quark

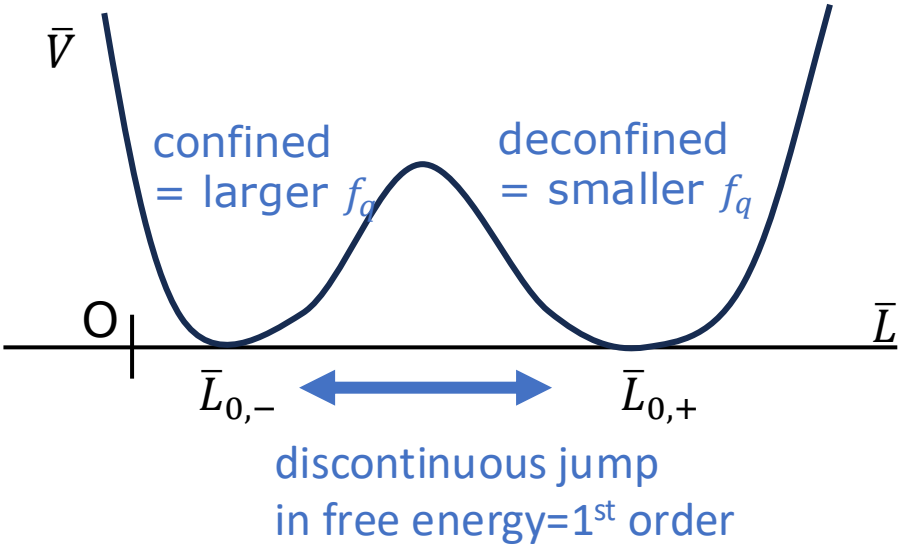
Polyakov 1979

$$\langle L(\mathbf{x}) \rangle \equiv e^{-\frac{\Omega}{T}(f_q - f)}, \qquad Z \equiv e^{-\frac{\Omega}{T} f}$$



- Constrained effective potential $\bar{V}(L)$

cf. Bhattacharya, Gocksch, Altes, Pisarski NPB 1992
Altes NPB 1994

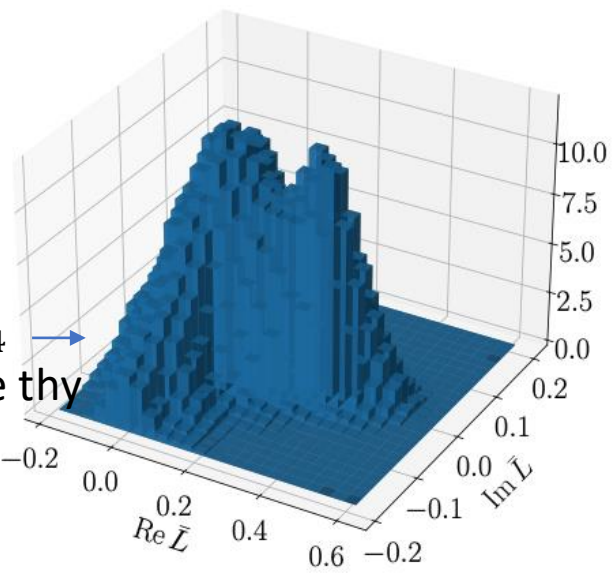


$$e^{-\frac{\Omega}{T} \bar{V}(\bar{L})} \equiv \left\langle \delta^2 \left(\bar{L} - \frac{1}{\Omega} \int d^3\mathbf{x} L(\mathbf{x}) \right) \right\rangle$$

- In the thermodynamic limit, saddle pt analysis is exact; minimum=expec value

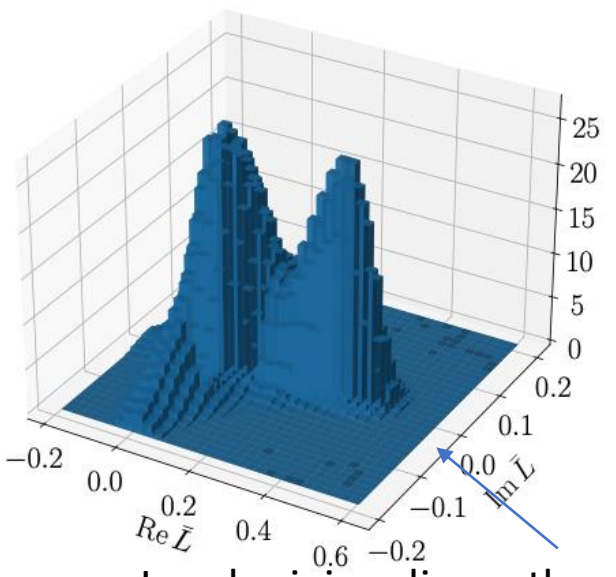
$\hat{m}_q = 0.4, N_s = 16$

Remnant Z_4
of pure glue th



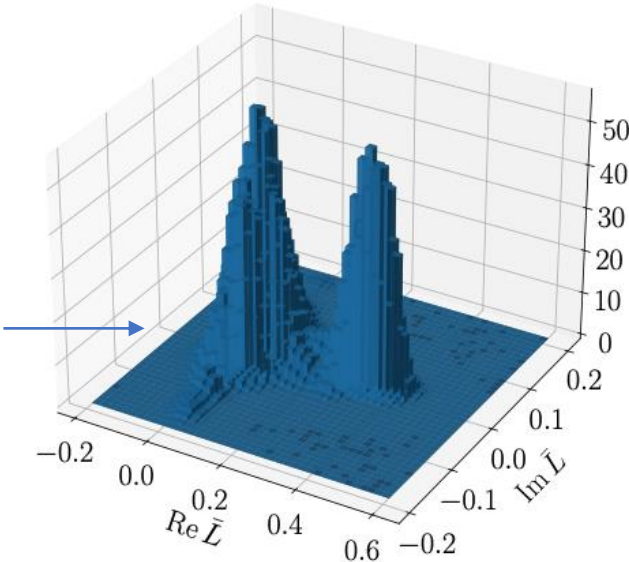
$\hat{m}_q = 0.4, N_s = 24$

Local minima lie on the real axis



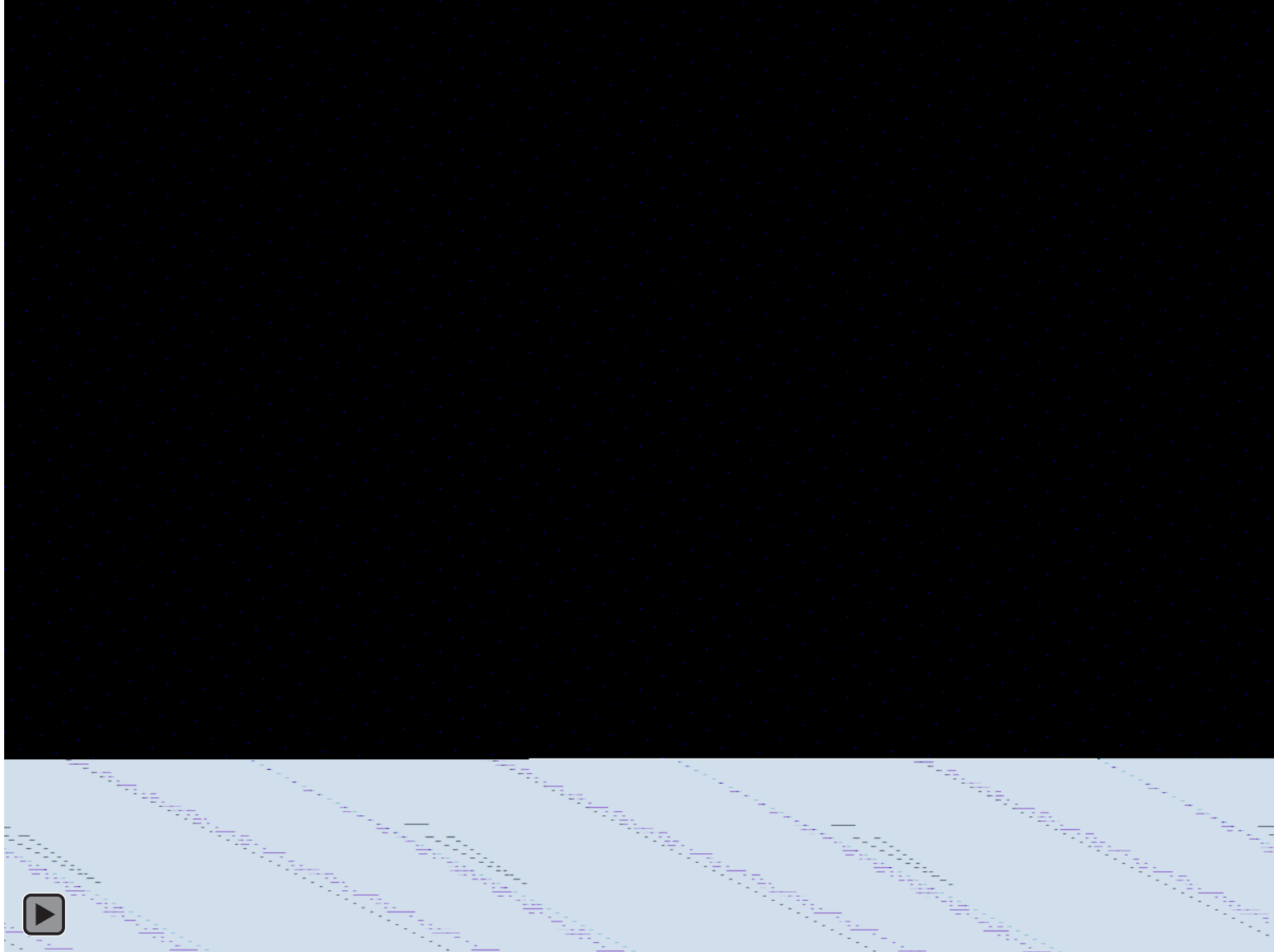
$\hat{m}_q = 0.4, N_s = 32$

Soft breaking of Z_4
by fermion BC
more manifest
in larger volumes

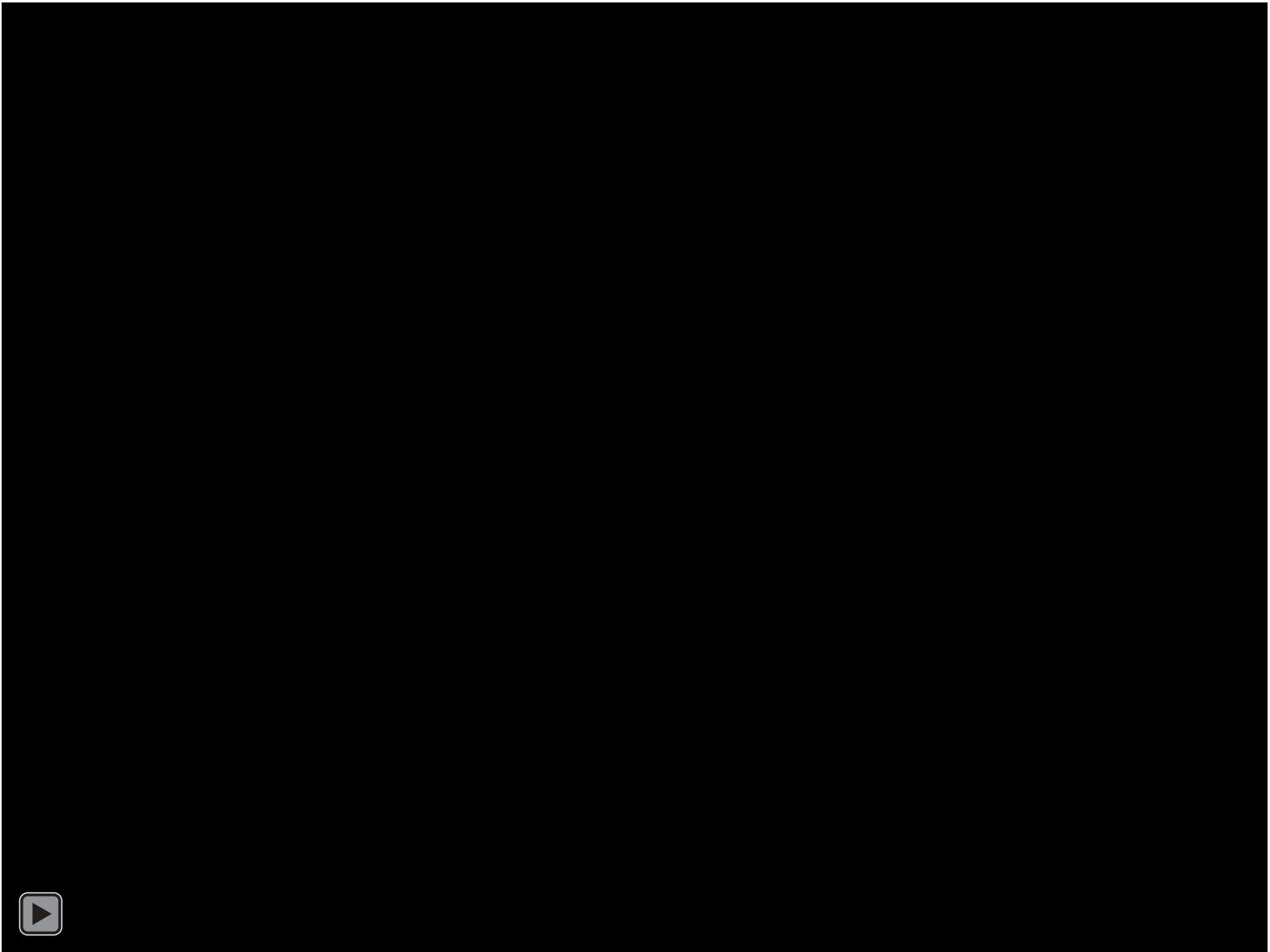


$$m_q a = 0.3$$

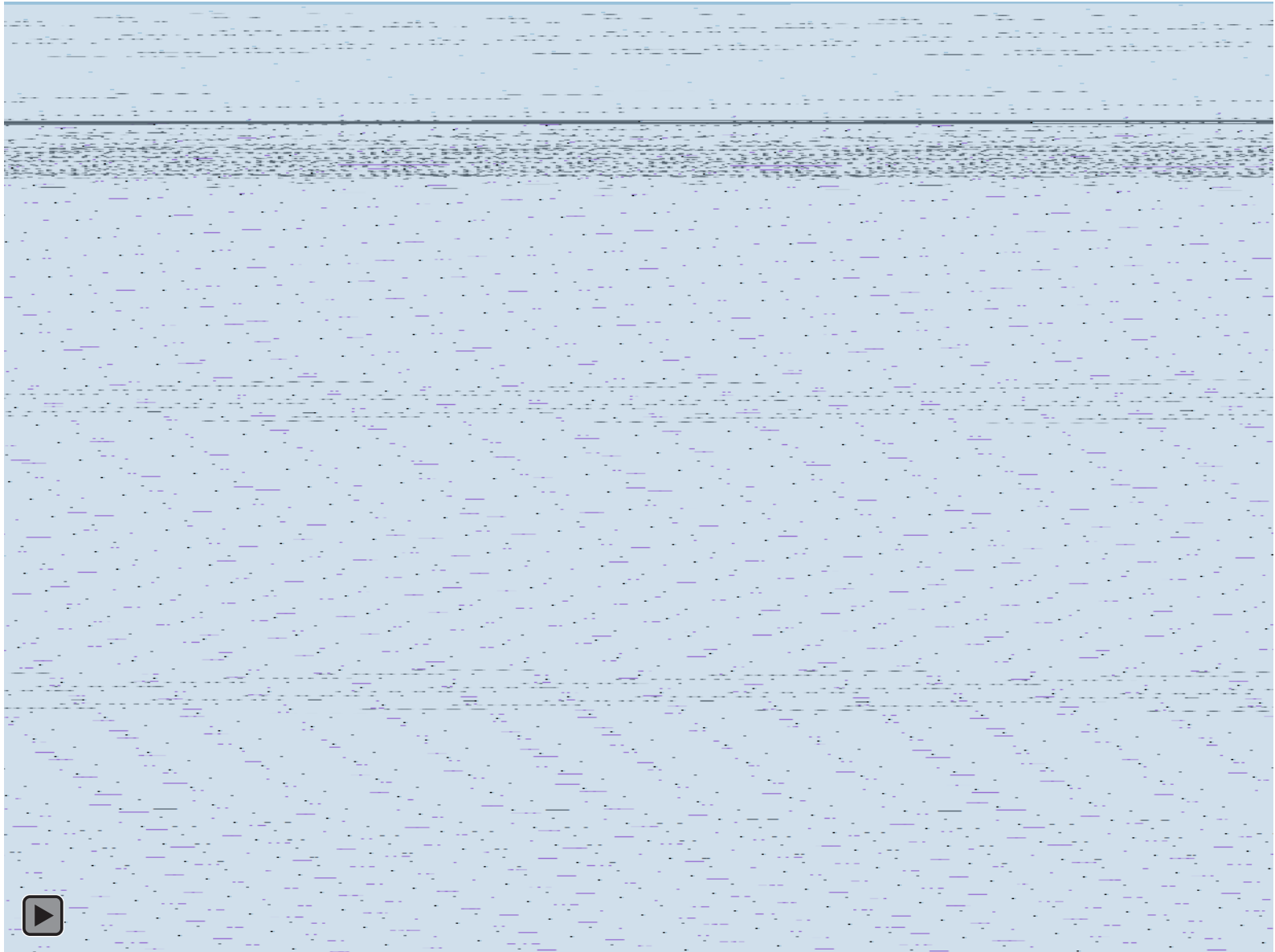
1st order regime



1st order regime



Crossover



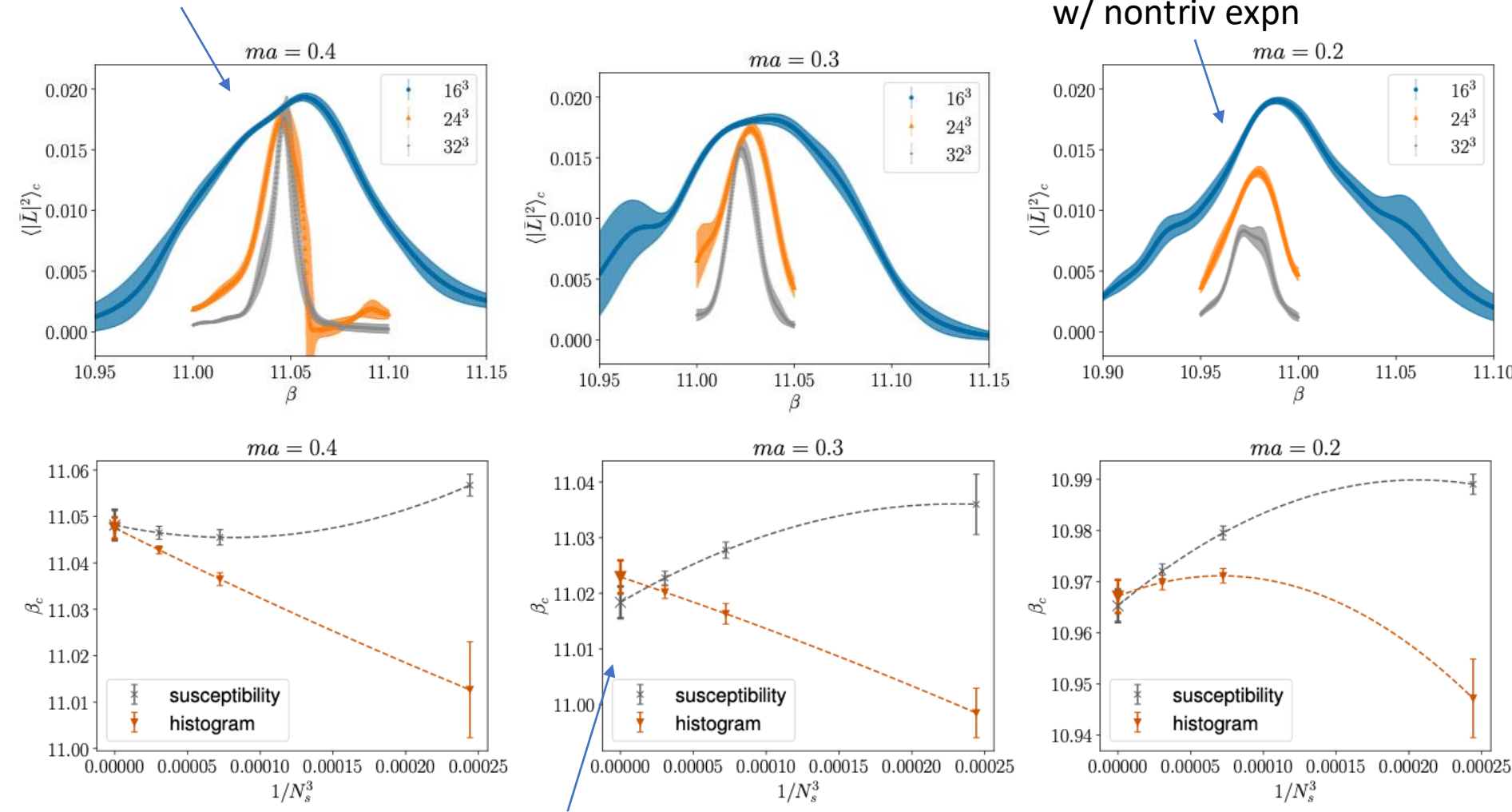
Consistency check

$|\bar{L}|$ susceptibility / Ω ($\bar{L}$: unrenormalized)

cf. Fukugita, Okawa, Ukawa PRL 1989

Volume scaling of 1st order

Governed by the 2nd order pt w/ nontriv expn



Same thermodynamic lim

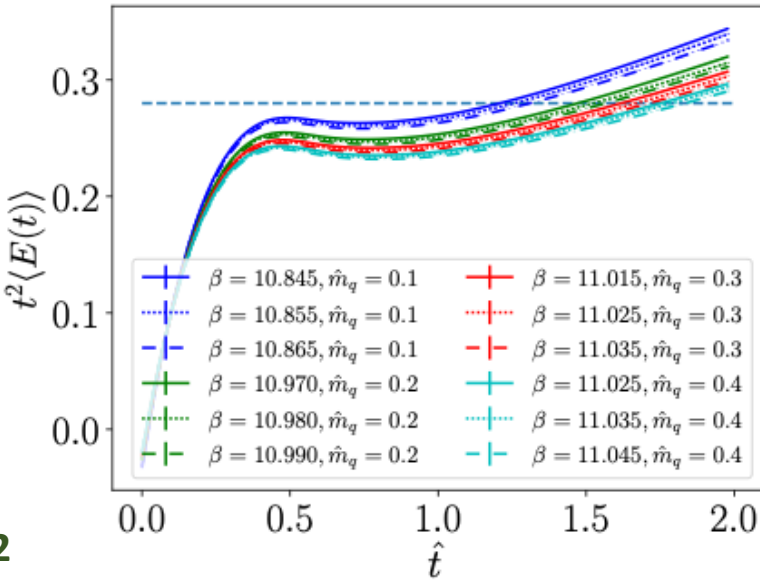
- Theory scale by Wilson flow **Lüscher '10**

$$t^2 \langle E(t) \rangle|_{t=t_0} = 0.28,$$

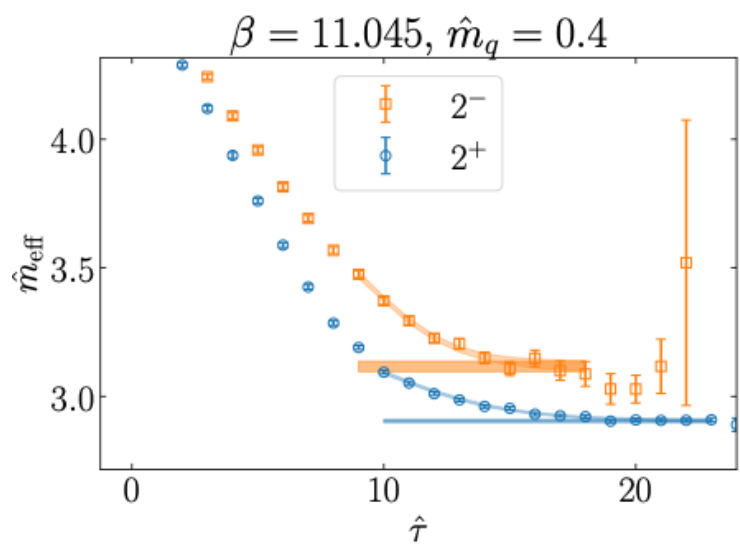
Polyakov loop renormalized at t_0

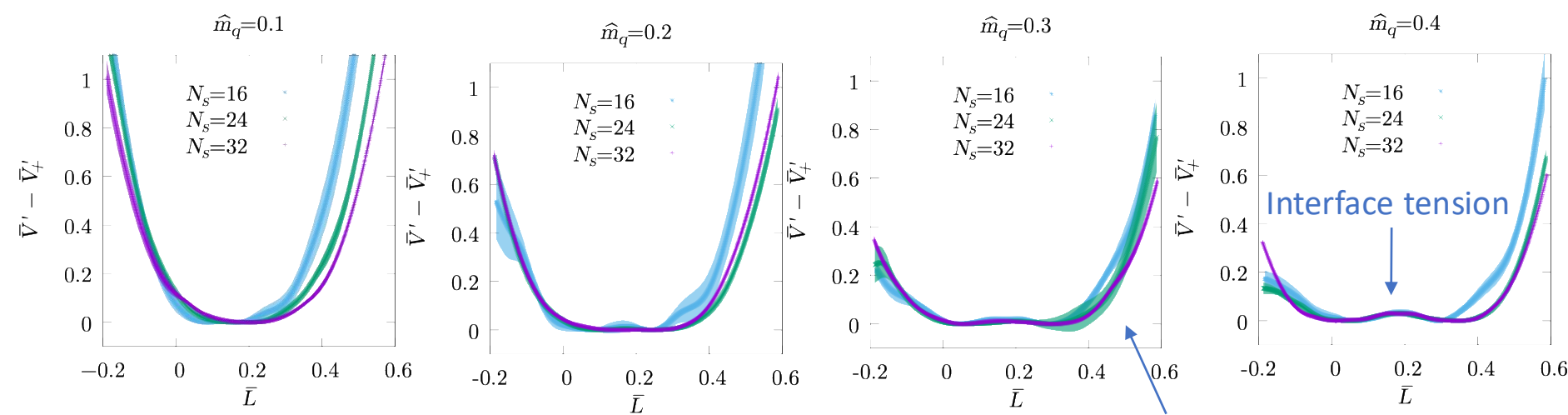
Petreczky, Schadler '15

See also **Kaczmarek, Karsch, Petreczky, Zantow '02**



- Define the line of const physics by the mass M_B of the lightest baron (2^+)





1/Ω convergence in the tail (after renorm.)

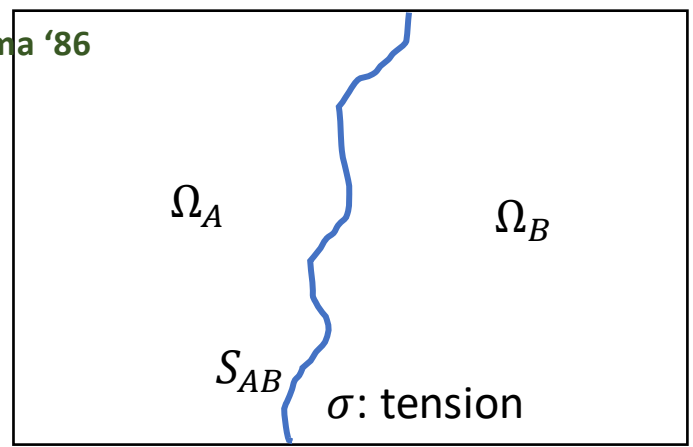
NB Double-well shape is a finite-volume effect

Heller-Seiberg '83
O'Raifeartaigh, Wipf, Yoneyama '86

$$f \bar{V} \sim f_A V_A + f_B V_B + \sigma S_{AB}$$

Negligible in the thermodynamic limit

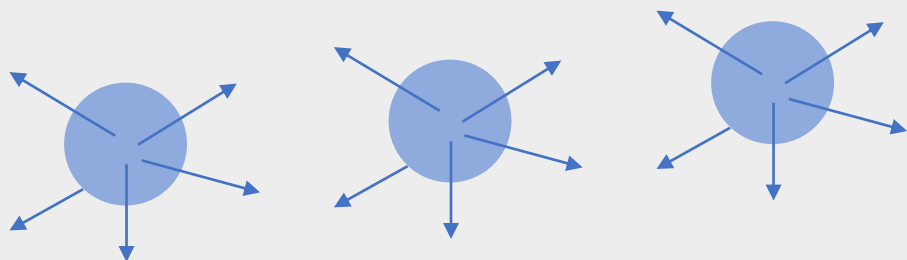
$$\text{For } \bar{L} = r\bar{L}_A + (1-r)\bar{L}_B,$$
$$\bar{V}(\bar{L}) \sim r\bar{V}(\bar{L}_A) + (1-r)\bar{V}(\bar{L}_B)$$



- In practice, the disappearance of the barrier is slow

➡ Use $N_s = 24, 32$ result as the classical potential V in the Polyakov loop eff theory

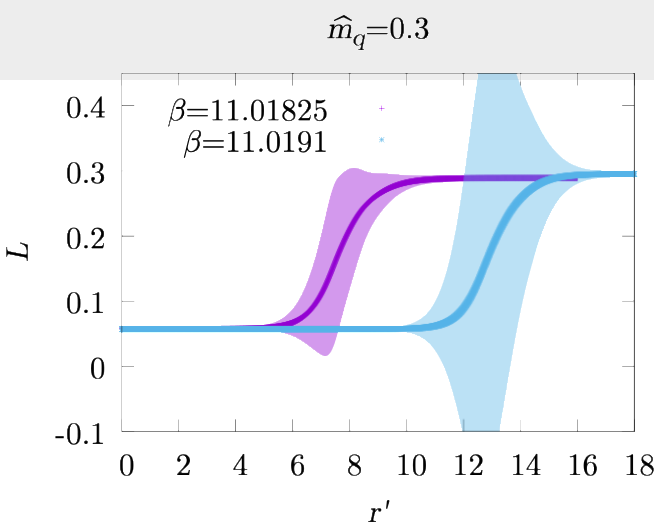
Bubbles nucleation=supercooling



➡ sound waves

- Decay rate in the units of Hubble H

$$\Gamma = \left(\frac{S_3}{2\pi T}\right)^{3/2} e^{-S_3/T} \sim e^{-\tilde{\beta} \cdot Ht}$$
$$\tilde{\beta} = \frac{d}{d \log T} \frac{S_3(T)}{T}$$



- $T_*(< T_c)$: percolation temperature

$$I(T) \equiv \underbrace{\int_T^{T_c} \frac{dT_1}{H(T_1)} \frac{\Gamma(T_1)}{T_1^4} \cdot \frac{4\pi}{3} \left[\int_T^{T_1} \frac{dT_2}{H(T_2)} v_w \right]}_{\text{Total volume of nucleated bubbles}}^3$$

Bounce: Coleman '77, Callan Coleman '77

v_w : wall velocity
 $T \sim \text{time}^{-1}$

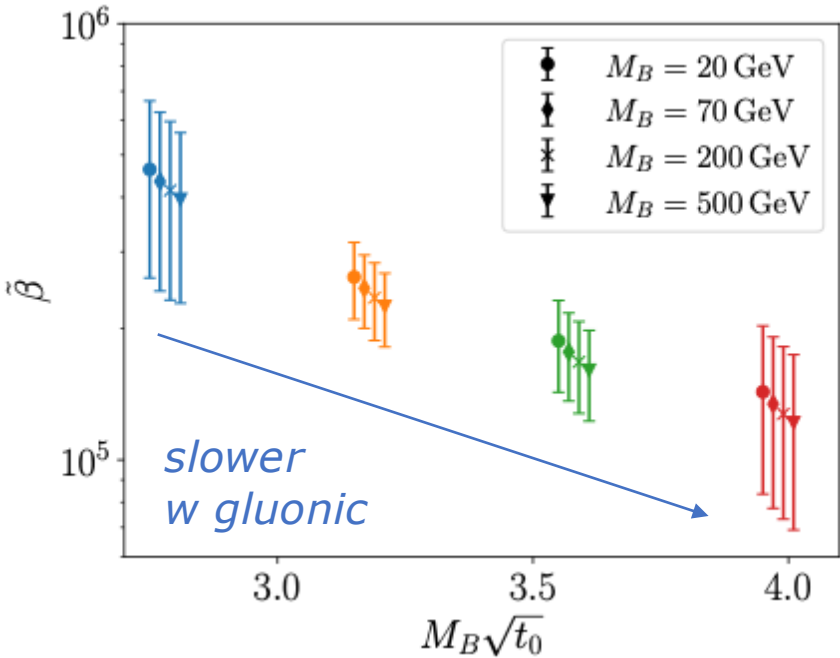
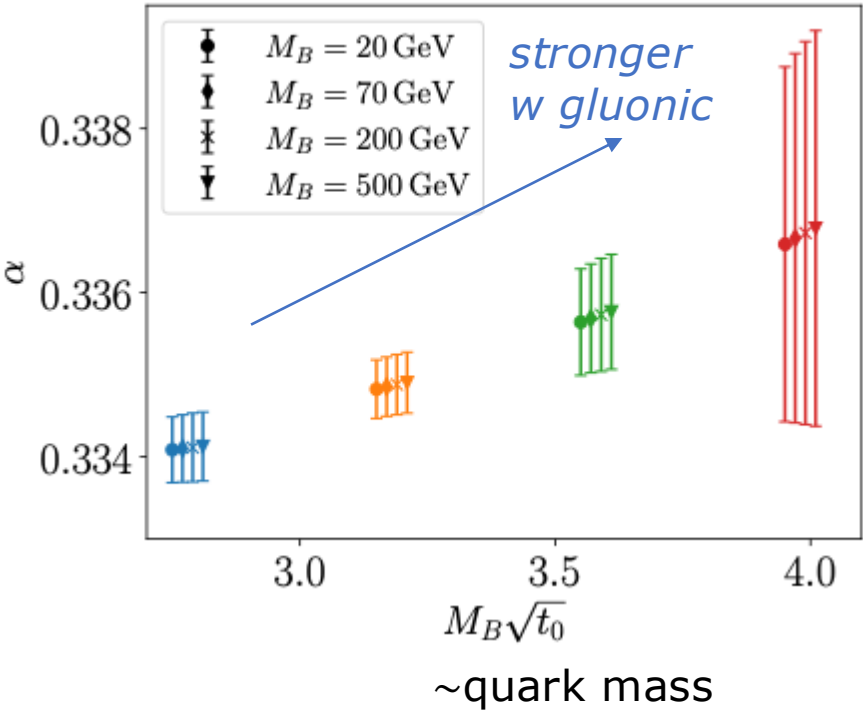
- Three scale system: Glue= $1/\sqrt{t_0}$, Baryon= M_B , Cosmology= $H \sim \sqrt{g_{\text{eff}}} \cdot T^2/M_{\text{pl}}$

- Strength of phase transition α
=interaction measure/latent heat per DOF

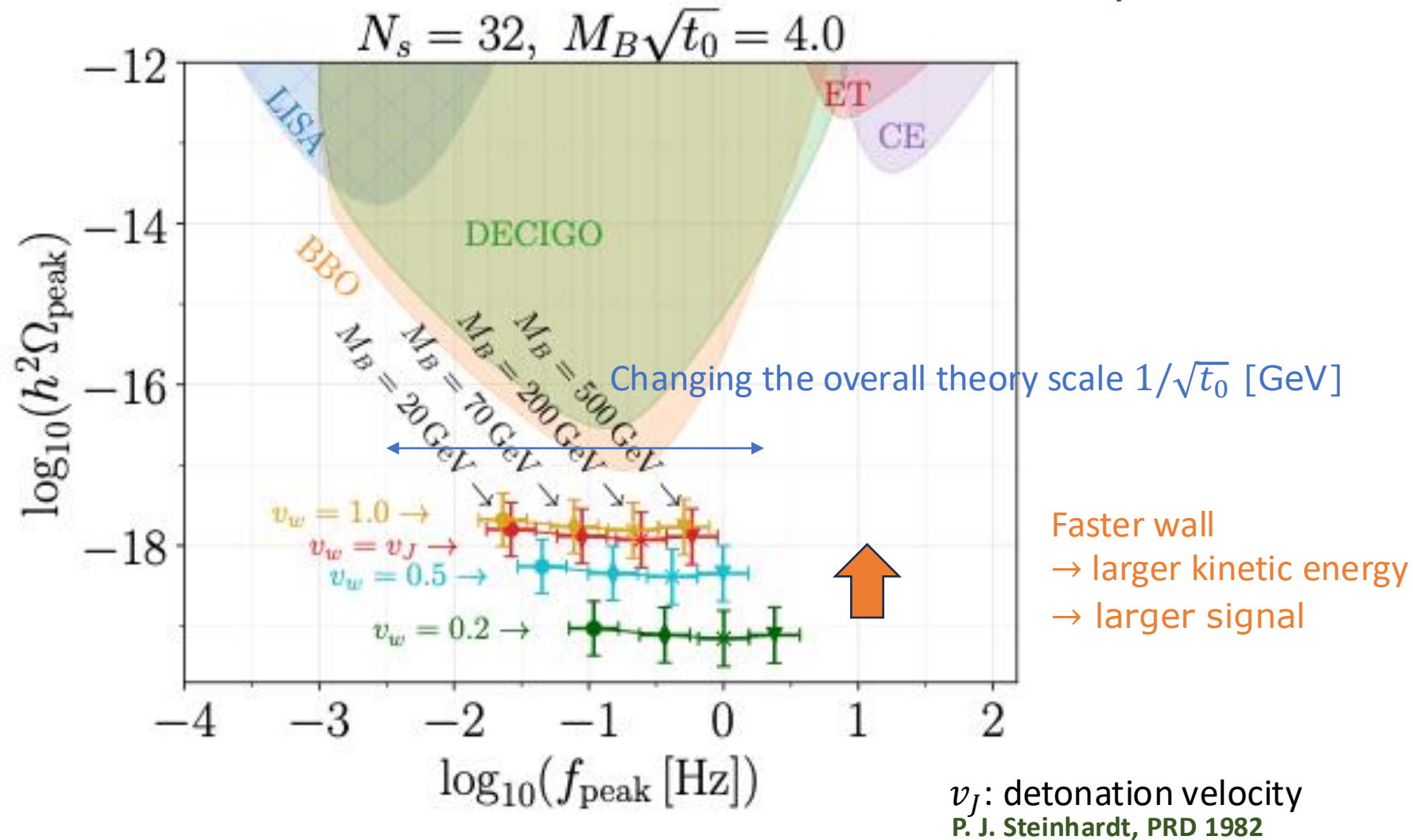
$$\alpha \equiv \frac{(1/4)\Delta T_\mu^\mu}{\text{DOF}} = \frac{1}{3} \frac{4\Delta V - \frac{d\Delta V}{d\log T}}{-\frac{d\Delta V}{d\log T}}$$

↑

minor assumptions on
universal scalar eff DOF



Sensitivity curves from Schmitz '21



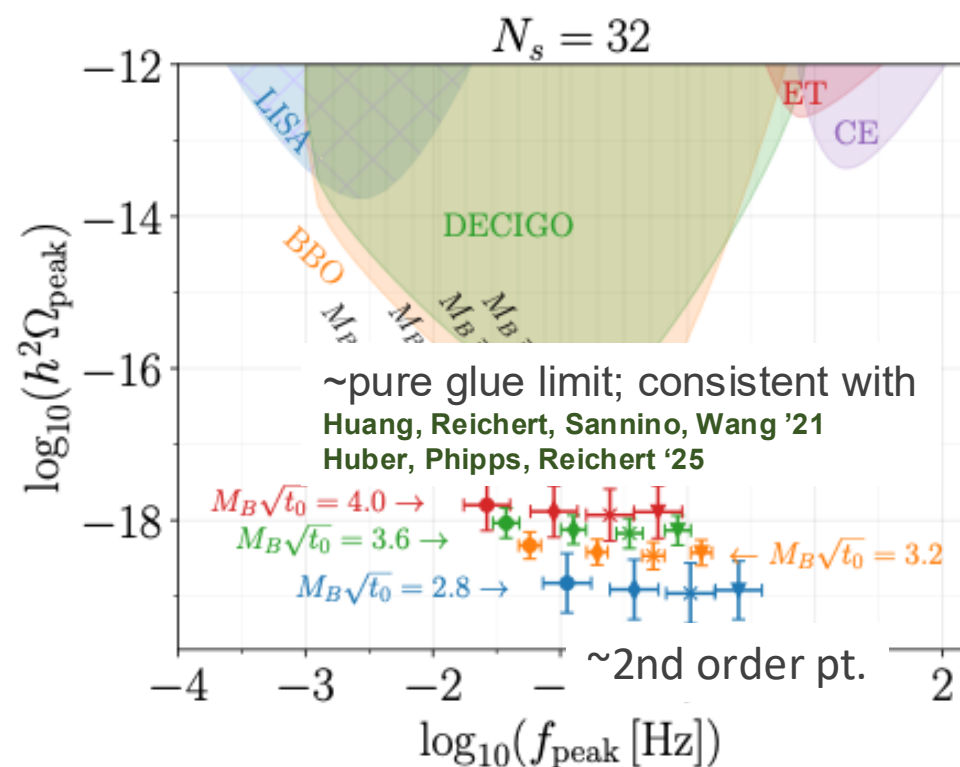
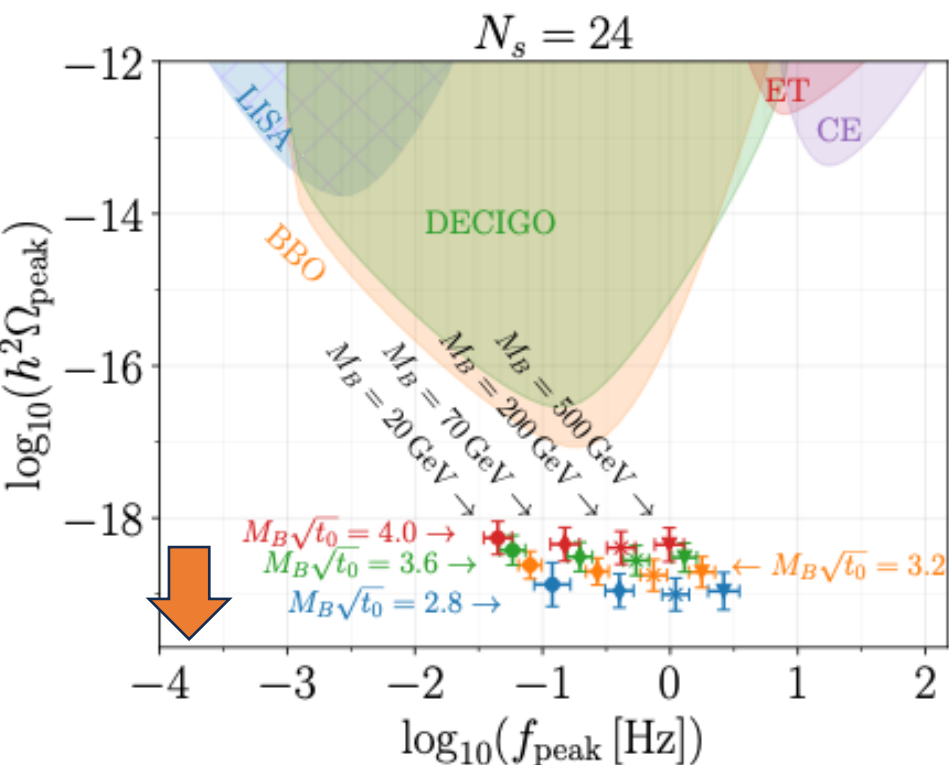
v_J : detonation velocity
P. J. Steinhardt, PRD 1982

Consistent w/ W.-C. Huang, M. Reichert,
F. Sannino, Z.-W. Wang PRD 2021

optimistic choice in the
thermal transition ($v_J < 1$)

Espinosa Konstandin No Servant JCAP 2010
14/17

$$v_w = v_J$$

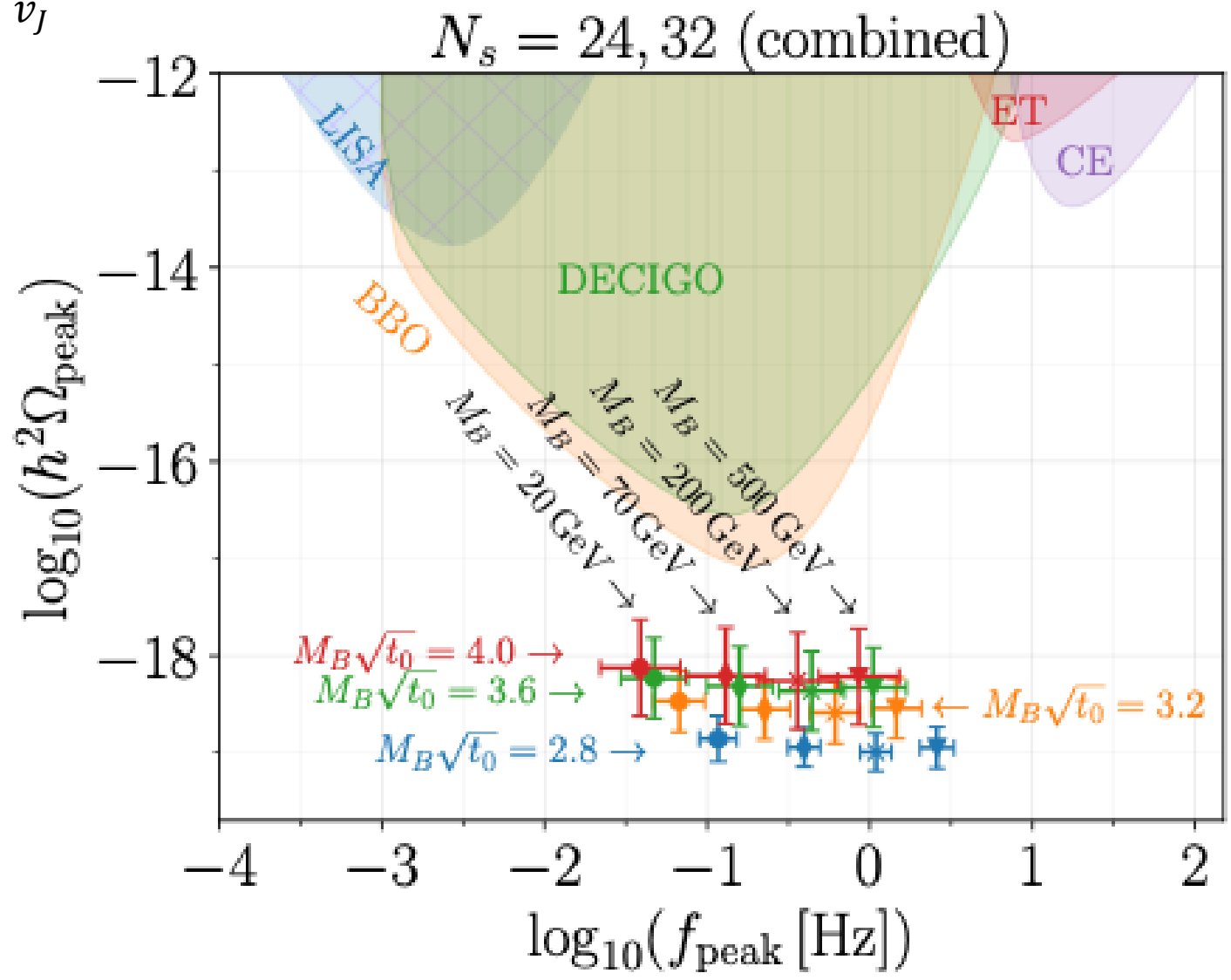


smaller quark mass

$\rightarrow$ smaller interface tension/shallower potential

$\rightarrow$ smaller amplitude

$v_w = v_J$



- Statistical error from the weighted average
- Generous systematic error from the $N_s = 24, 32$ difference

- Exploring various models: both interesting and important **Schwaller '15**

- Signals may be amplified by varying N_c or changing the gauge group

Sp(N): Alexis's talk on Tue

See also: Bruno, Forzano, Panero, Smecca '24

Bennett, Lucini, Mason, Piai, Rinaldi, Vadamchino '24

Bennett, Lucini, Mason, Piai, Rinaldi, Vadamchino, Zierler (TELOS) '25

- Fermion decreases the tension, whereas scalar fields increase it

Explicit confirmation in this work

- GW from a crossover transition? (even QCD w/ nanograv?) **Escrivà, Inui, Tada, Yoo '24**
H. Davoudiasl private comm

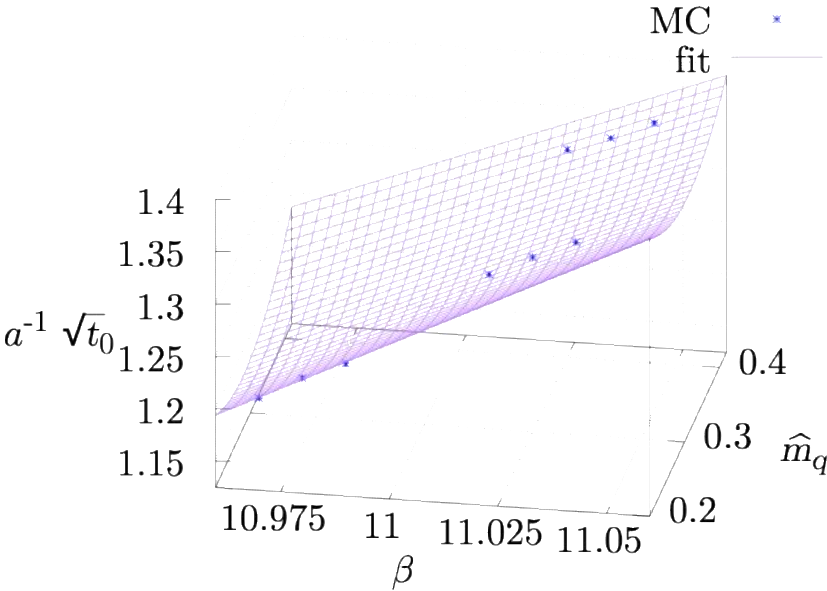
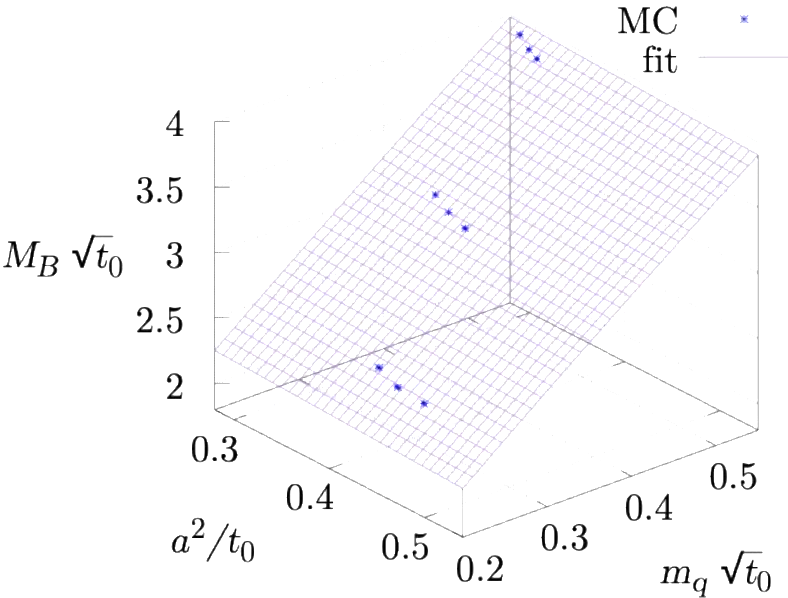
- Brush up the methodology

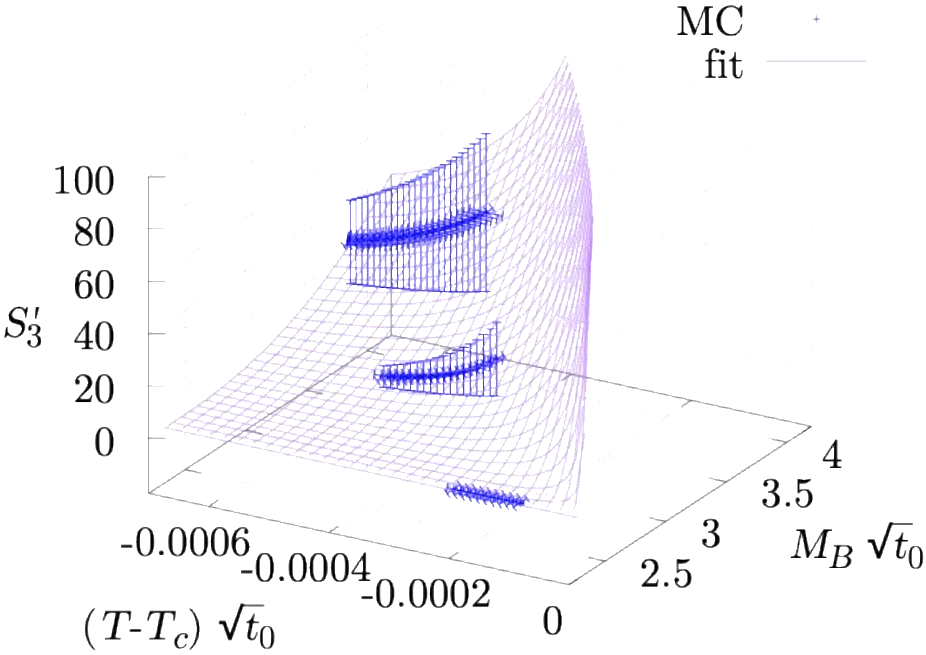
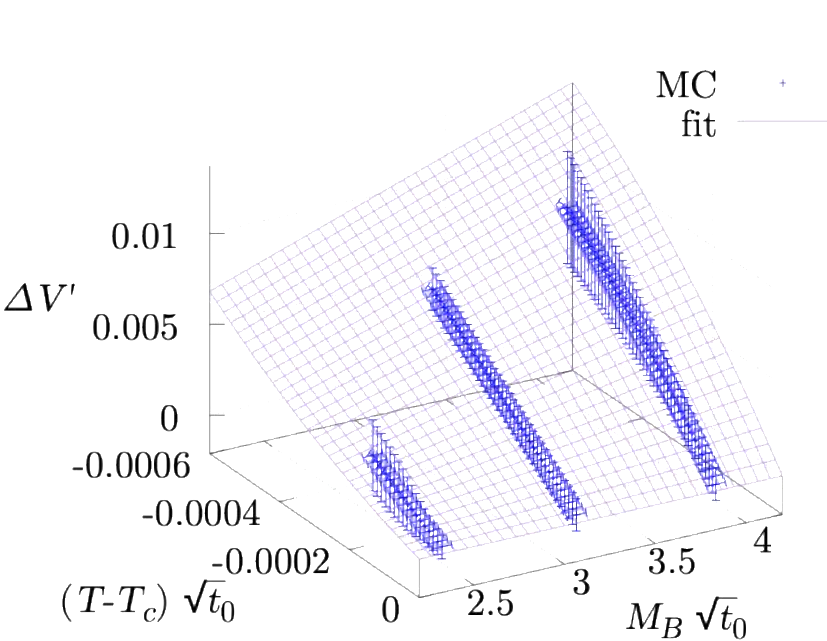
- Accurate wall velocity from first-principles

holographic models: **Bea et al. PRD '21, Bigazzi et al. JHEP '21,**
Janik et al. PRL '22, Chen et al. JHEP '23

- α and $\tilde{\beta}$ w/o the eff. potential **Shen Draper El-Khadra '22, Jin Swaim '25**

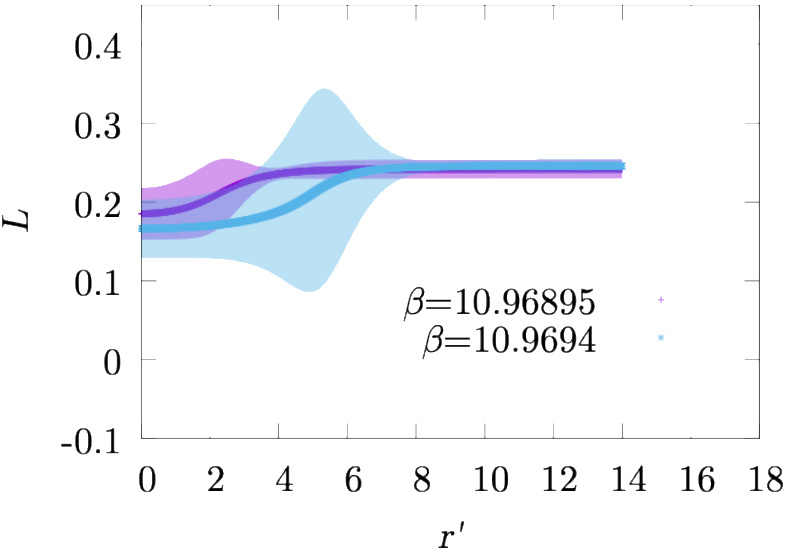
Thank you!



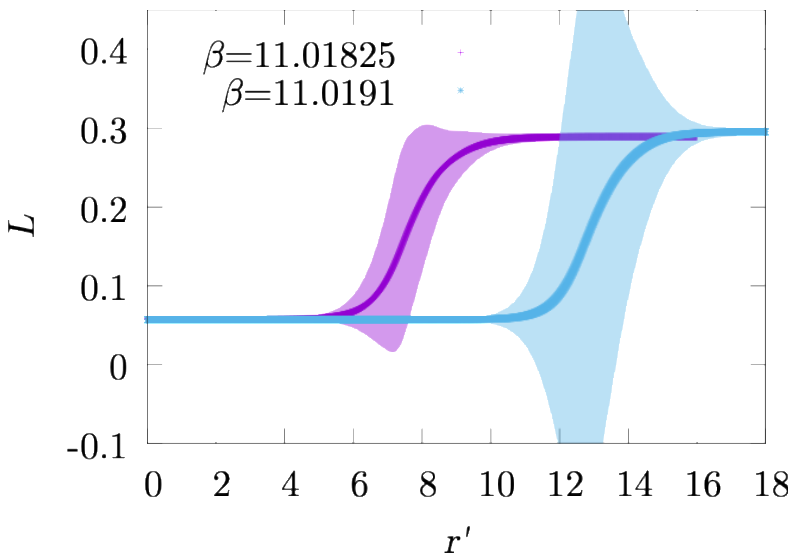


Bounce

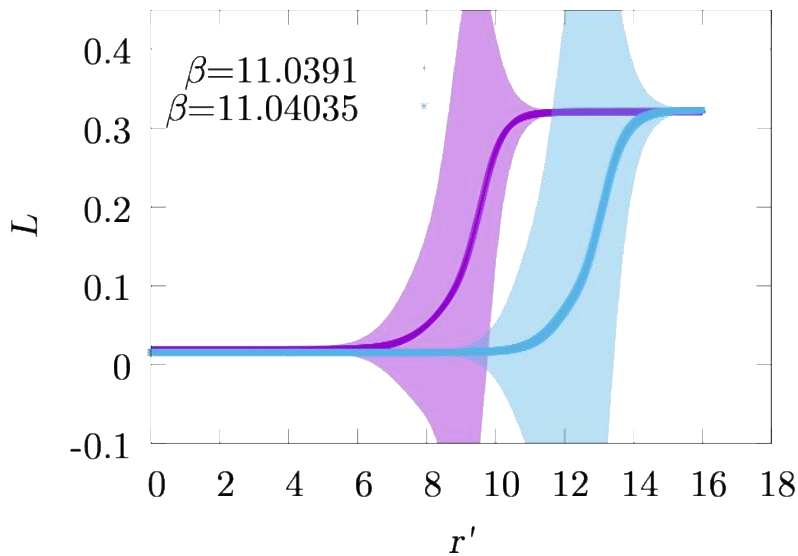
$\hat{m}_q=0.2$



$\hat{m}_q=0.3$



$\hat{m}_q=0.4$



$$\kappa \equiv \sqrt{\tau_{\text{sw}}} \kappa_v. \quad (\text{A.13})$$

The factor $\sqrt{\tau_{\text{sw}}}$ takes into account the lifetime of the sound-wave source [94, 95]:

$$\tau_{\text{sw}} = 1 - \left[1 + 2 \frac{(8\pi)^{\frac{1}{3}} v_w}{\tilde{\beta} U_f} \right]^{-1/2}, \quad U_f^2 = \frac{3}{4} \frac{\alpha}{1 + \alpha} \kappa_v, \quad (\text{A.14})$$

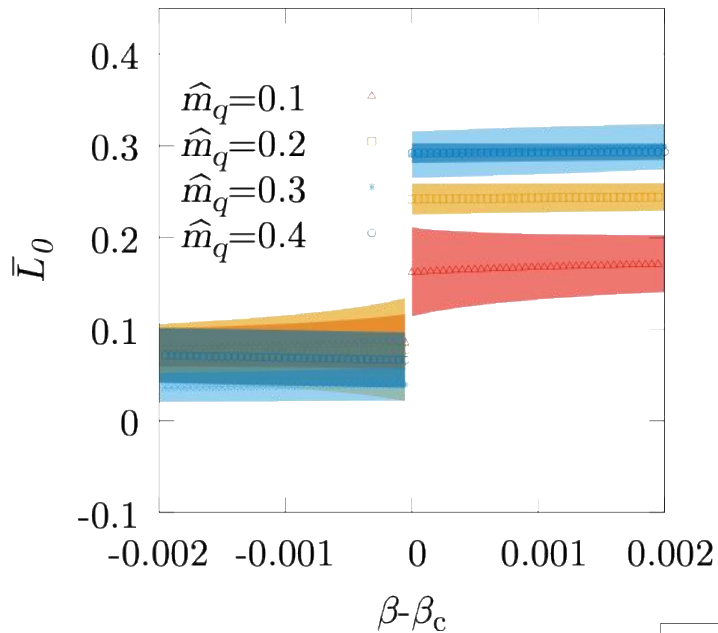
which lowers the amplitude in numerics. κ_v is the factor that is derived from hydrodynamical analysis, and is given for the Jouguet detonation as [52]

$$\kappa_v(v_w = v_J) = \frac{\sqrt{\alpha}}{0.135 + \sqrt{0.98 + \alpha}}. \quad (\text{A.15})$$

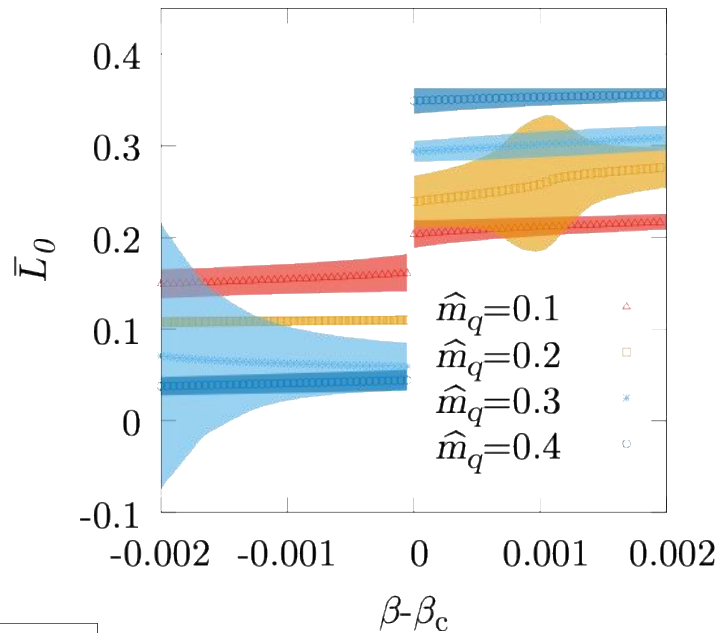
$$I(T) \equiv \int_T^{T_c} \frac{dT_1}{H(T_1)} \frac{\Gamma(T_1)}{T_1^4} \frac{4\pi}{3} \left[\int_T^{T_1} \frac{dT_2}{H(T_2)} v_w(T_2) \right]^3,$$

Discontinuity

$N_s=16$



$N_s=24$



$N_s=32$

