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

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

Lattice 2026

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Introduction

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

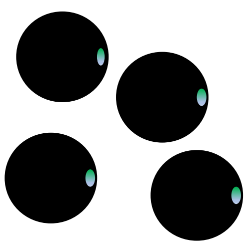
  ⇒ *Possibility that DM is composite?*

- Hyper Stealth Dark Matter **Fleming, Kribs, Neil, Schaich, Vranas PRD 2025**

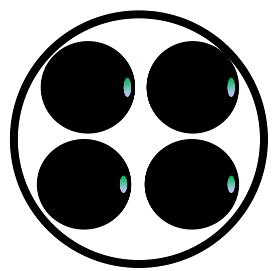
  Pushing forward the Stealth Dark Matter: **Appelquist et al. [LSD Collaboration] PRD 2015**

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

- Chiral anomaly -> No light meson

review: Creutz 2001, 2007

- 1^{st} order transition at large mass

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

Columbia, PRL 65 (1990) 2491

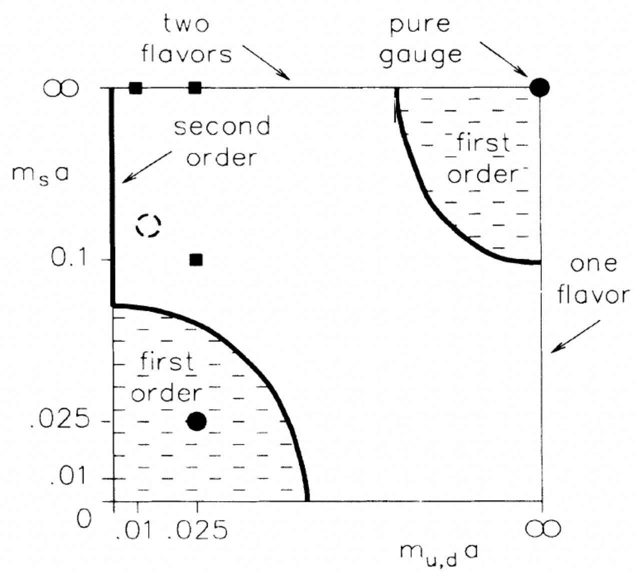


FIG. 1. Presence and absence of the finite-temperature QCD phase transition as a function of $m_{u,d}a$ and $m_s a$. Mass values for which the transition is and is not seen on a $16^3 \times 4$ lattice are denoted respectively by solid circles and squares. The physical point, indicated roughly by the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

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

Gunn et al. 1978
Kolb-Turner

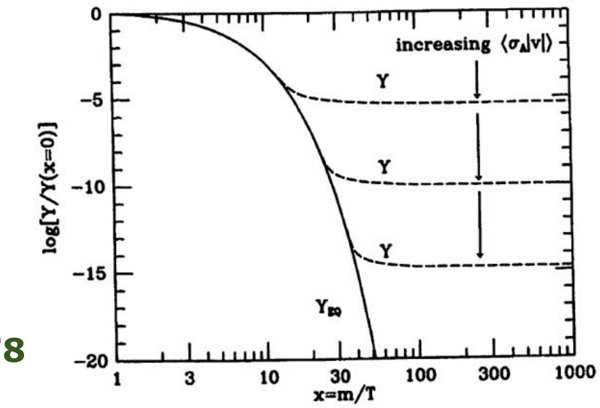
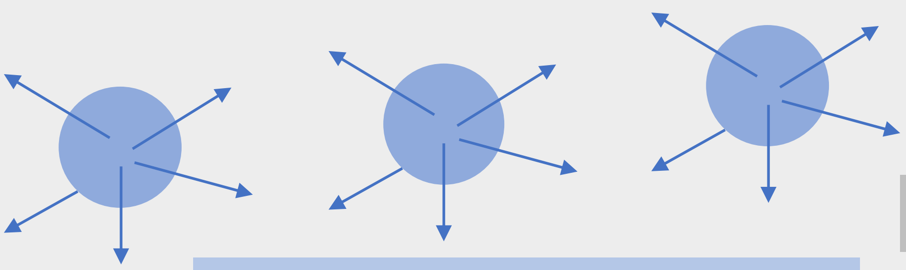


Fig. 5.1: The freeze out of a massive particle species. The dashed line is the actua abundance, and the solid line is the equilibrium abundance.

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

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



deconfined phase (false vac)

confined phase (true vac)

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

$N_s = 16, 24, 32$

$N_\tau = 8$

(cutoff effect subdominant, ignored)

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

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

Lawrence Livermore National Laboratory

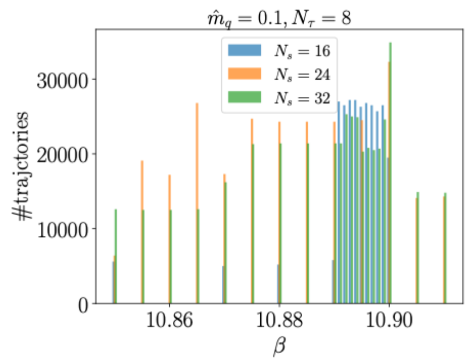
- Zero temp. w/ $N_s = 24$ for scale setting

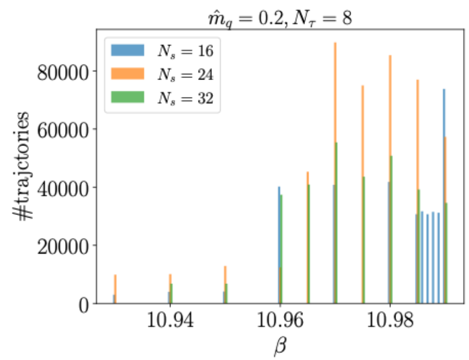
- Exact one-flavor HMC under Grid
  Chen, Chiu ‘14 **Boyle, Yamaguchi, Cossu, Portelli '15**

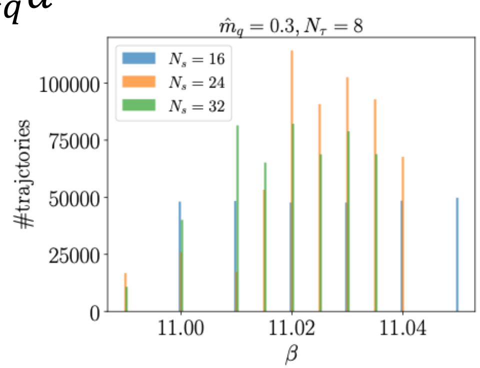
- $O(10^4 - 10^5)$ configs/ensemble;
  $O(10)$ ensembles around β_c for each $m_q a$

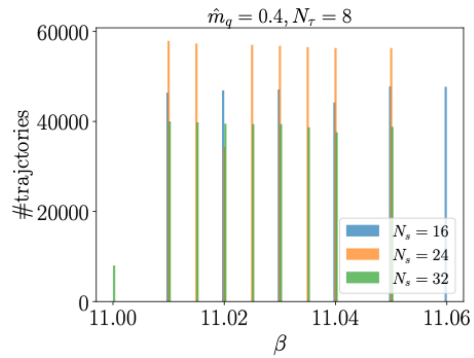
- Multipoint reweighting to vary β
  Ferrenberg, Swendsen ‘88, ‘89

  cf. Saito, Ejiri, Aoki, Kanaya, Nakagawa, Ohno, Okuno, Umeda [WHOT-QCD] ‘13
  Iwami, Ejiri, Kanaya, Nakagawa, Yamamoto, Umeda [WHOT-QCD] ‘15







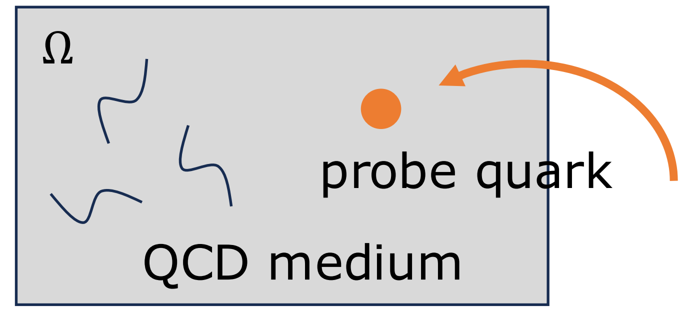


Polyakov loop effective potential

relative free energy to put a probe quark

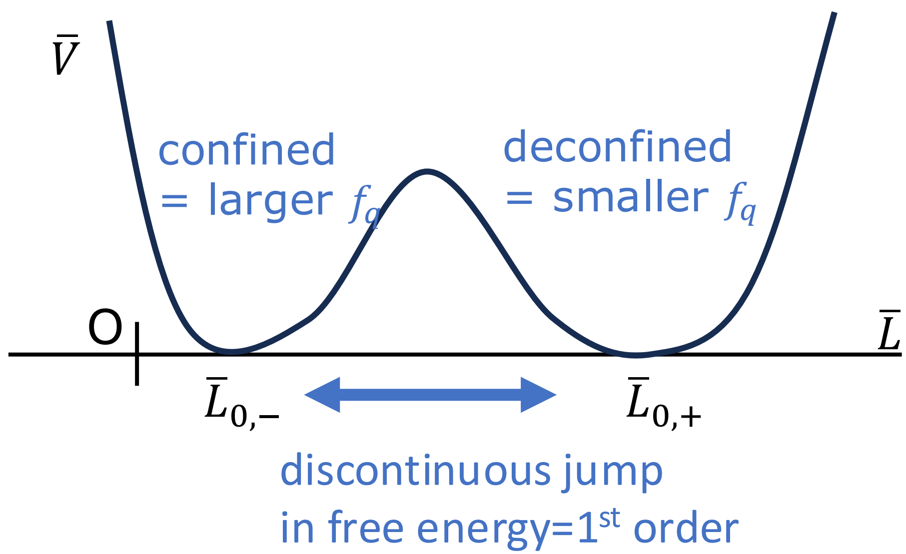
Polyakov 1979

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



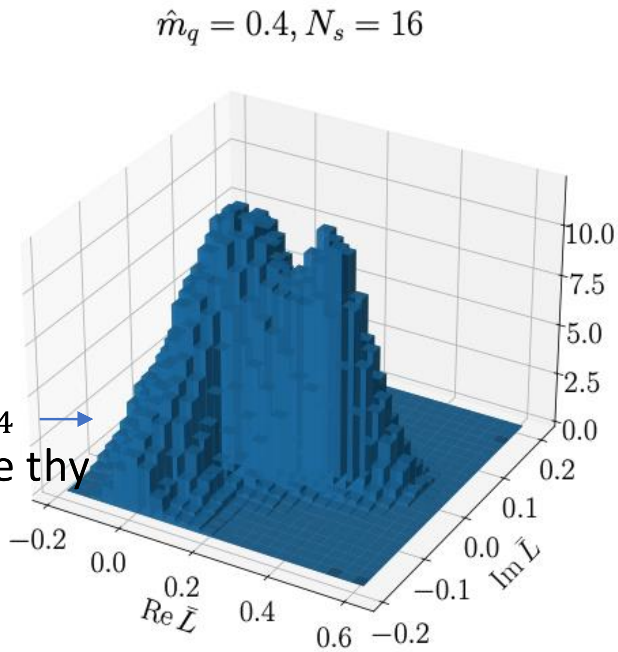
- Constrained effective potential $\bar{V}(L)$

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

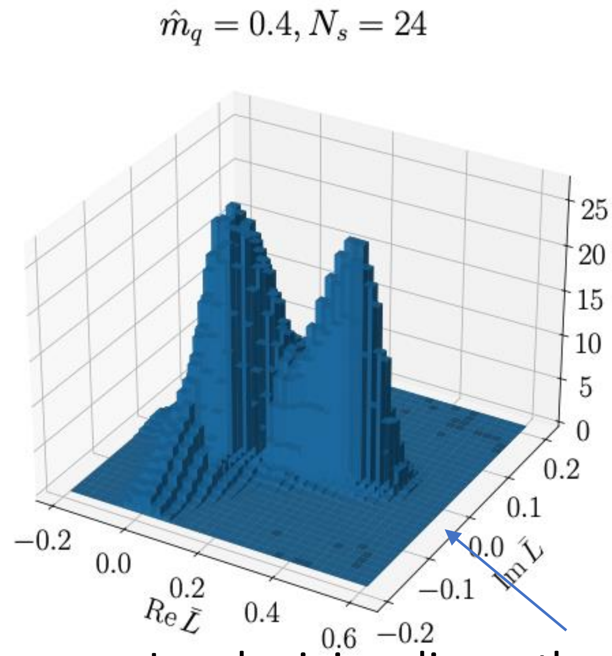


$$e^{-\frac{\Omega}{T}\bar{V}(\bar{L})} \equiv \left\langle \delta^2\left(\bar{L} - \frac{1}{\Omega}\int d^3\mathbf{x}\; L(\mathbf{x})\right)\right\rangle$$

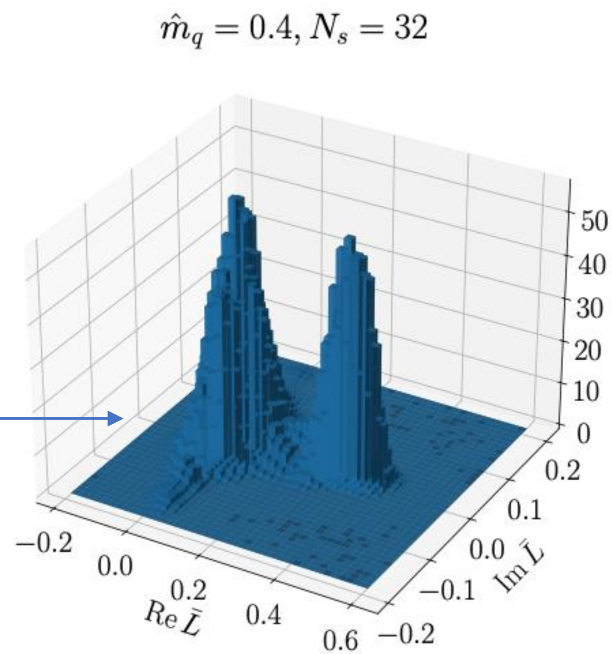
- In the thermodynamic limit, saddle pt analysis is exact; minimum=expec value



Remnant Z_4 of pure glue thy

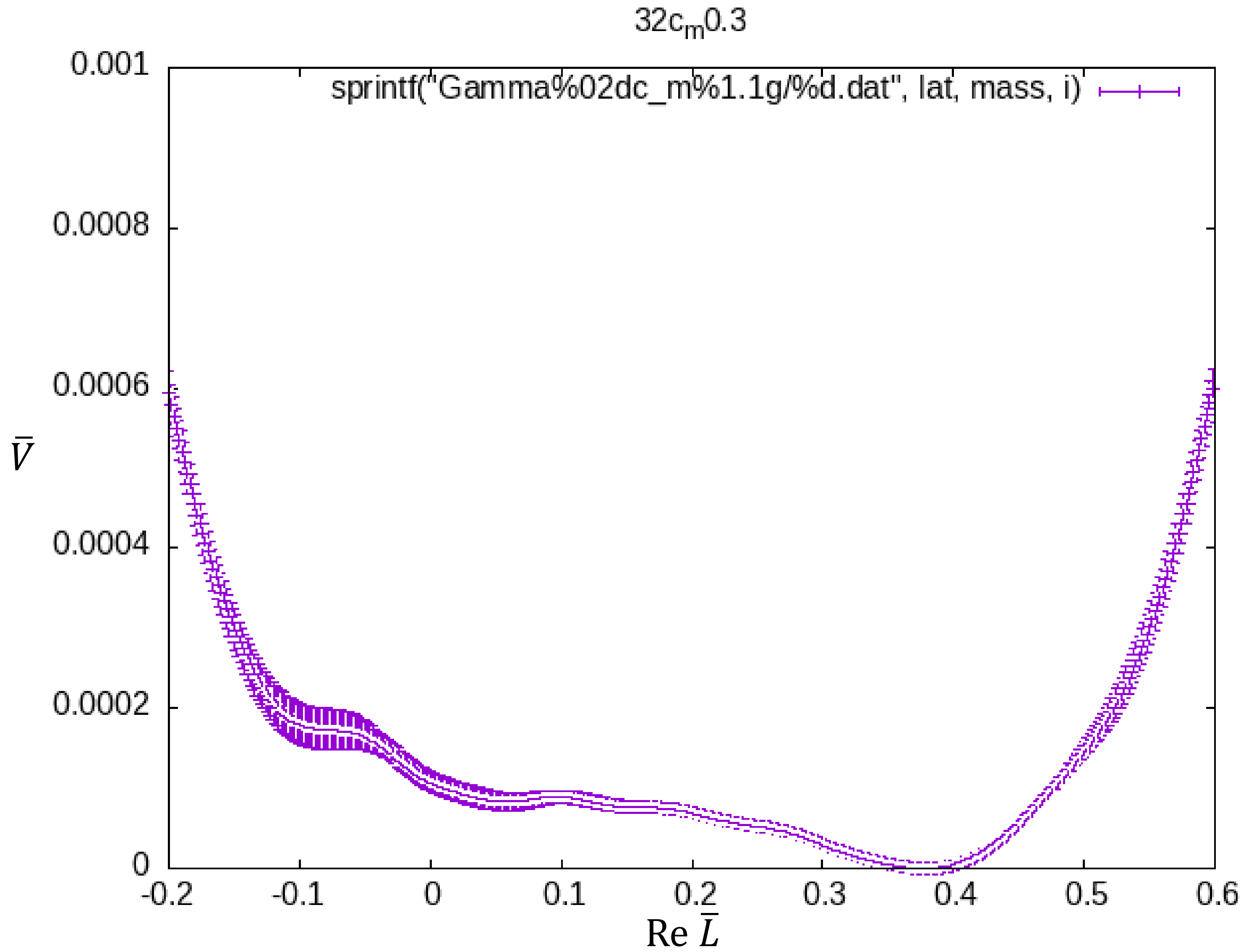


Local minima lie on the real axis

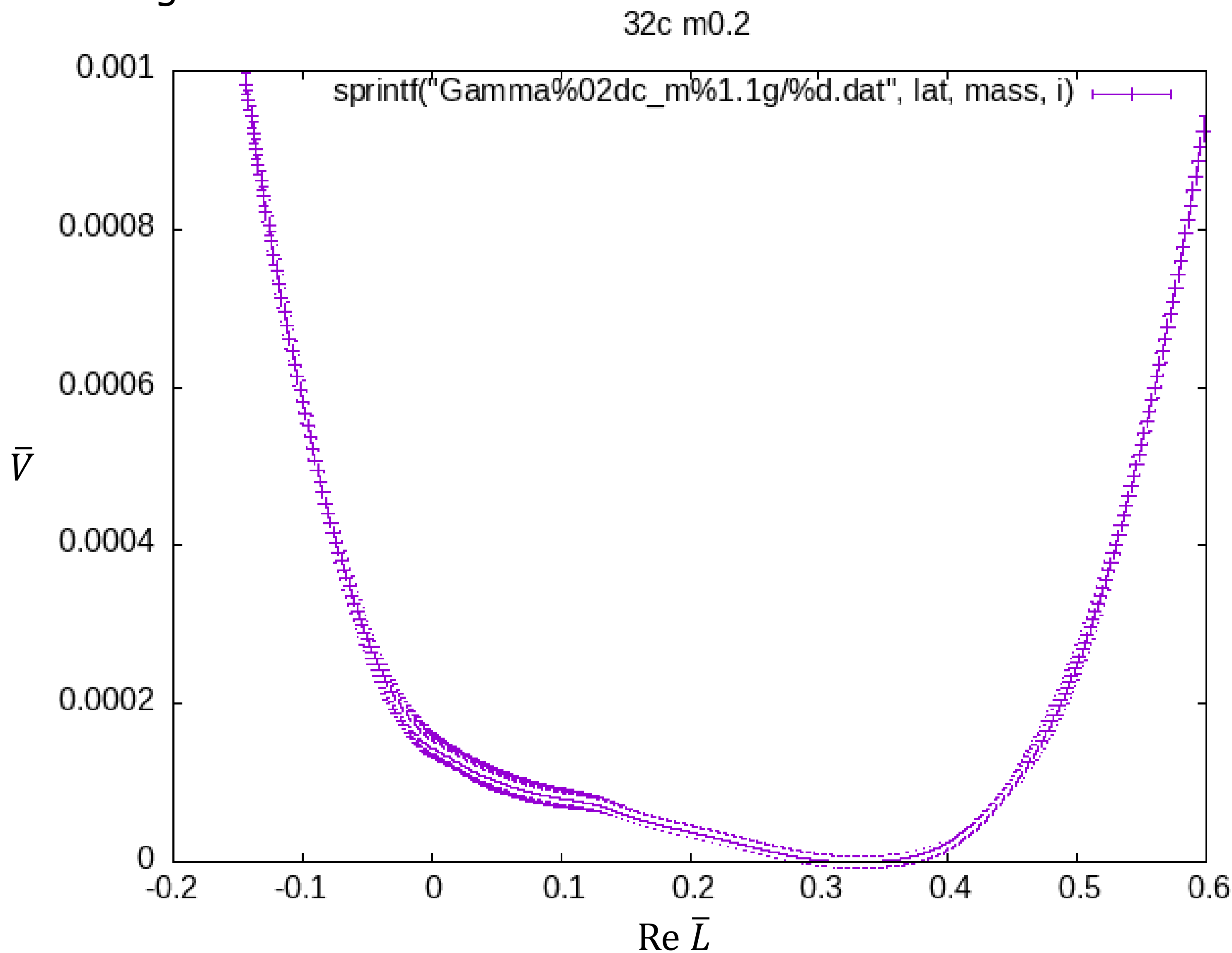


Soft breaking of Z_4 by fermion BC more manifest in larger volumes

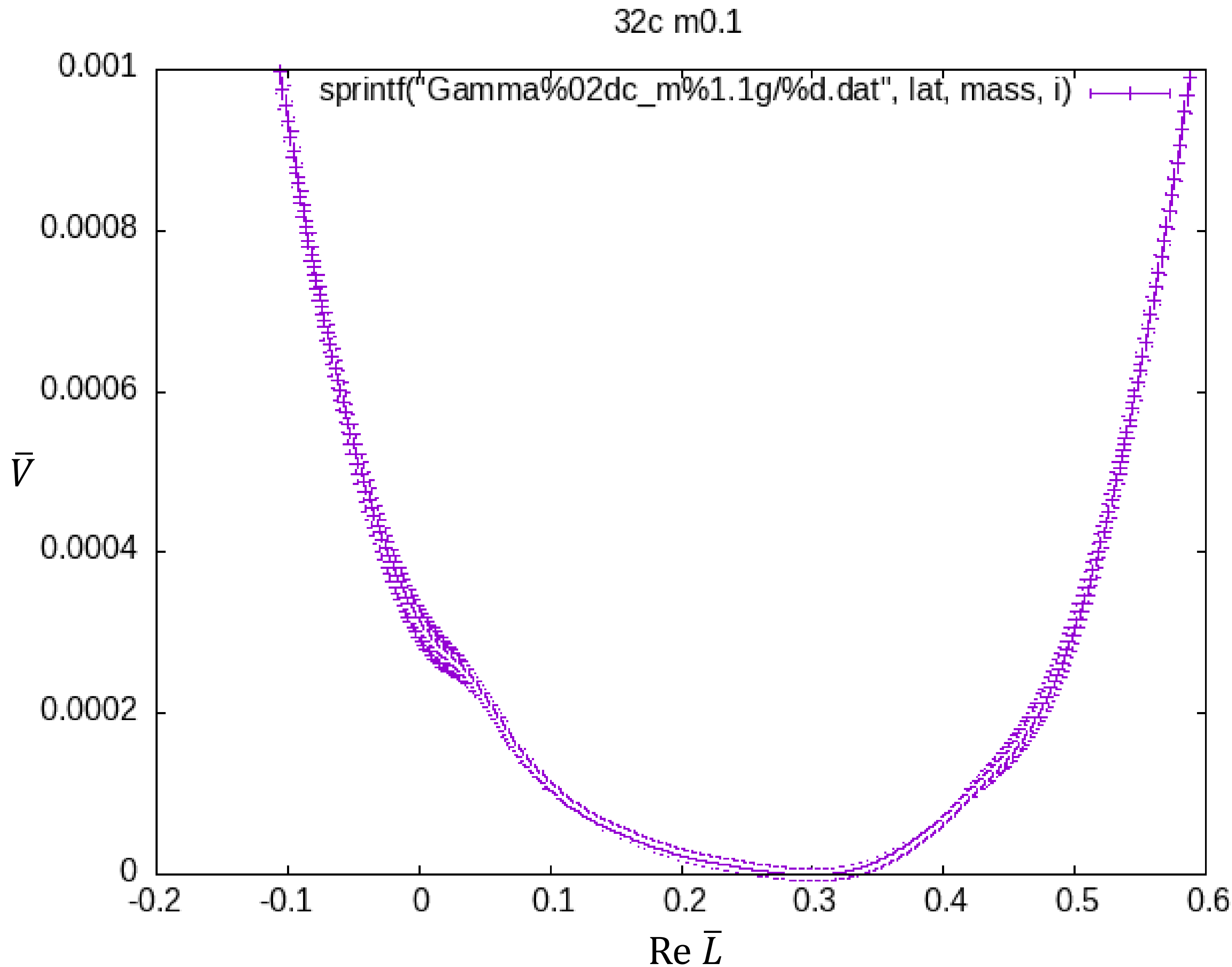
1st order regime



1[st] order regime



Crossover


32c m0.1
sprintf("Gamma%02dc_m%1.1g/%d.dat", lat, mass, i)
0.001
0.0008
0.0006
0.0004
0.0002
0
$\bar{V}$
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
Re $\bar{L}$

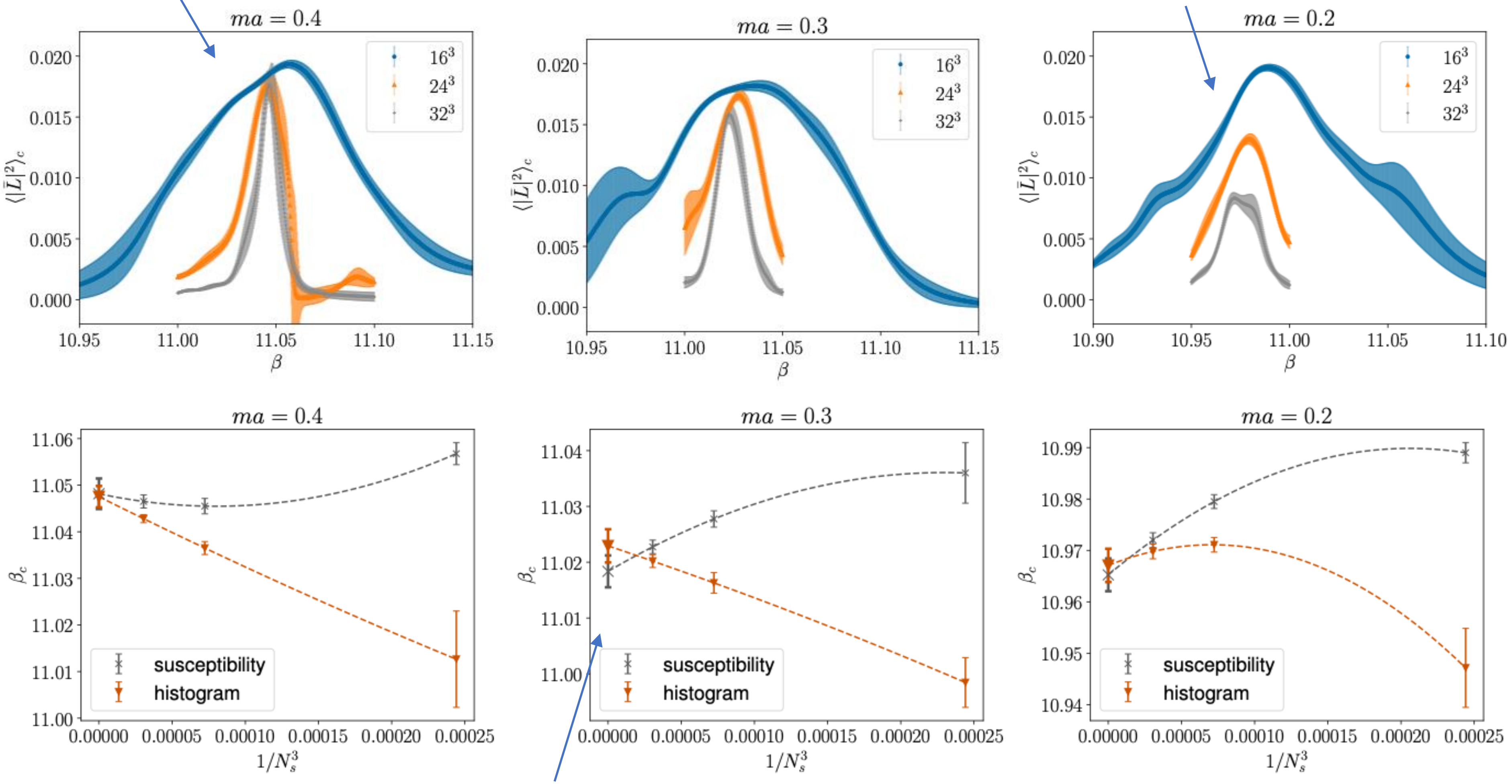
Consistency check

$|\bar{L}|$ 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

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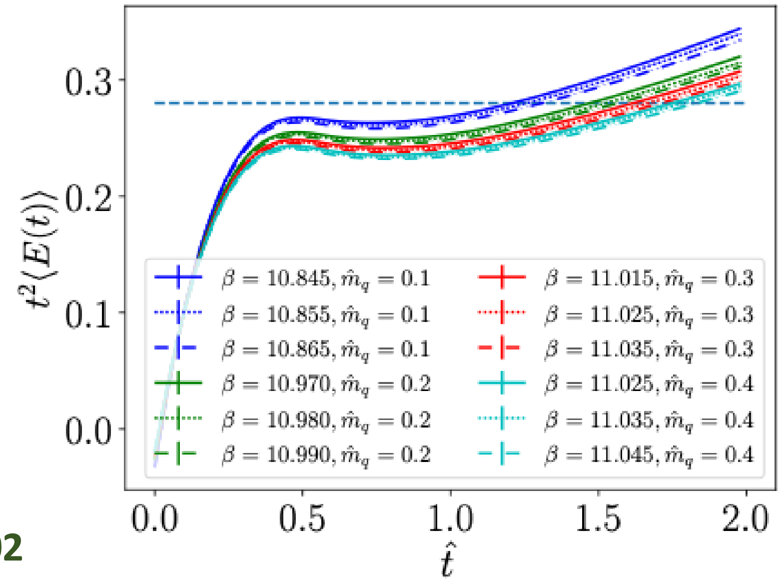
- Theory scale by Wilson flow **Lüscher '10**

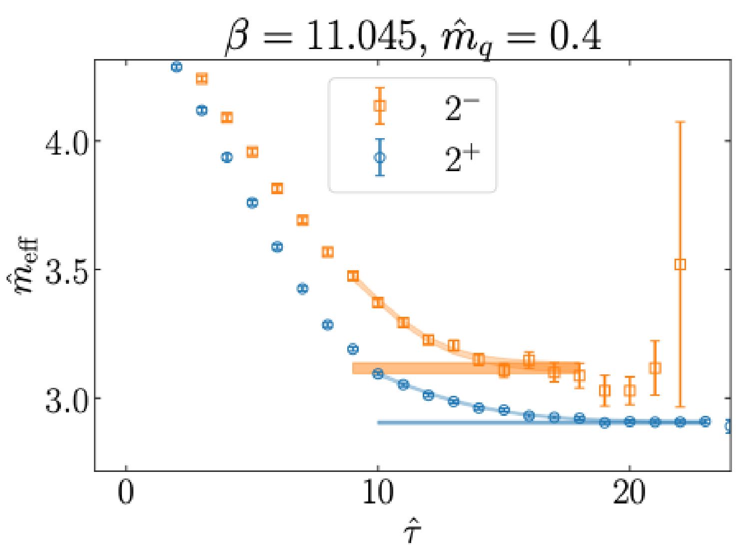
$$t^2 \langle E(t) \rangle|_{t=t_0} = 0.28,$$

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^+)



Interface tension

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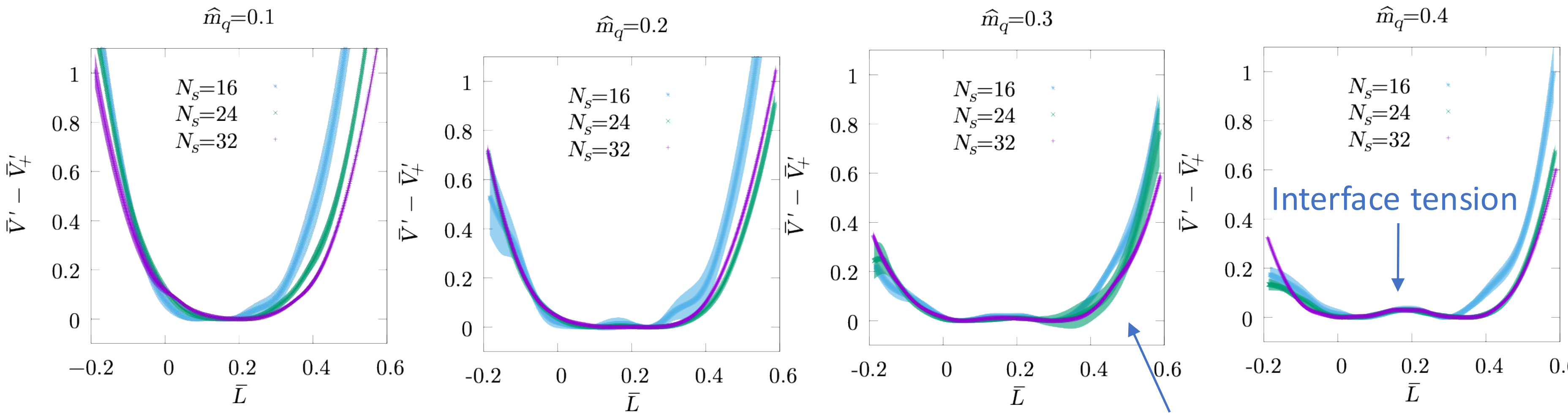


1/Ω convergence in the tail (after renorm.)

NB Double-well shape is a finite-volume effect

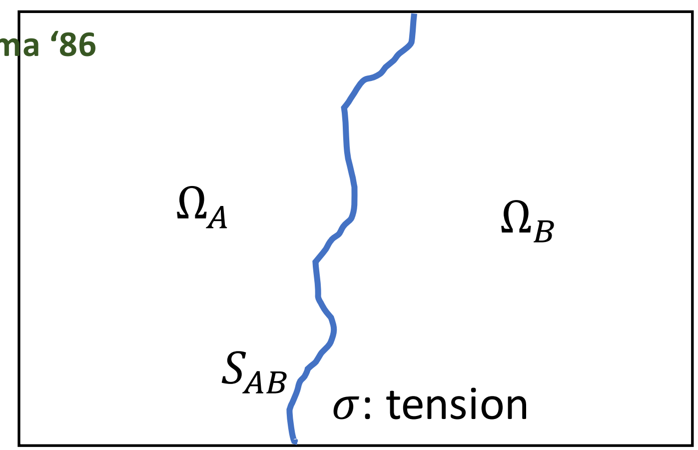
Heller-Seiberg ’83
O’Raifeartaigh, Wipf, Yoneyama ‘86

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

Negligible in the thermodynamic limit

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

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

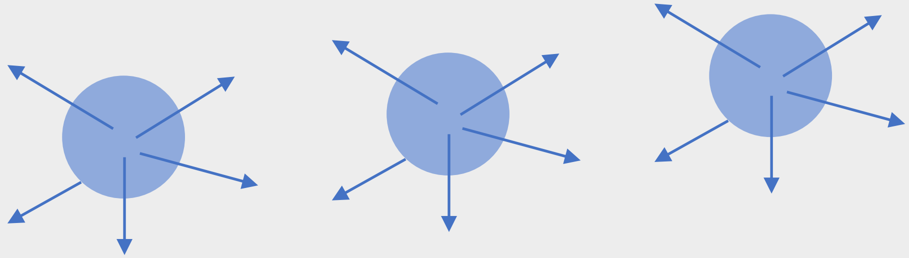


- In practice, the disappearance of the barrier is slow

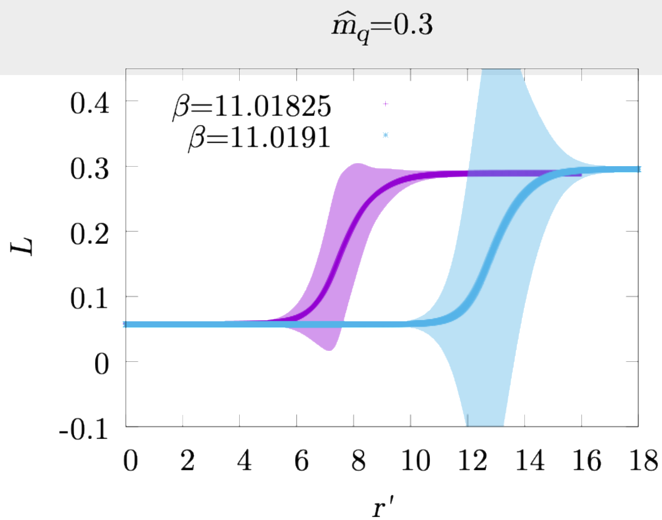
➡ Use $N_s = 24{,}32$ result as the classical potential V in the Polyakov loop eff theory

Elllis, Lewicki, No ‘18

Bubbles nucleation=supercooling



➡ sound waves



- Decay rate in the units of Hubble H

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

$$\tilde{\beta} = \frac{d}{d\log T}\frac{S_3(T)}{T}$$

Bounce: Coleman ‘77, Callan Coleman ‘77

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

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

bubble volume

Total volume of nucleated bubbles

v_w: wall velocity

T ~time^-1

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

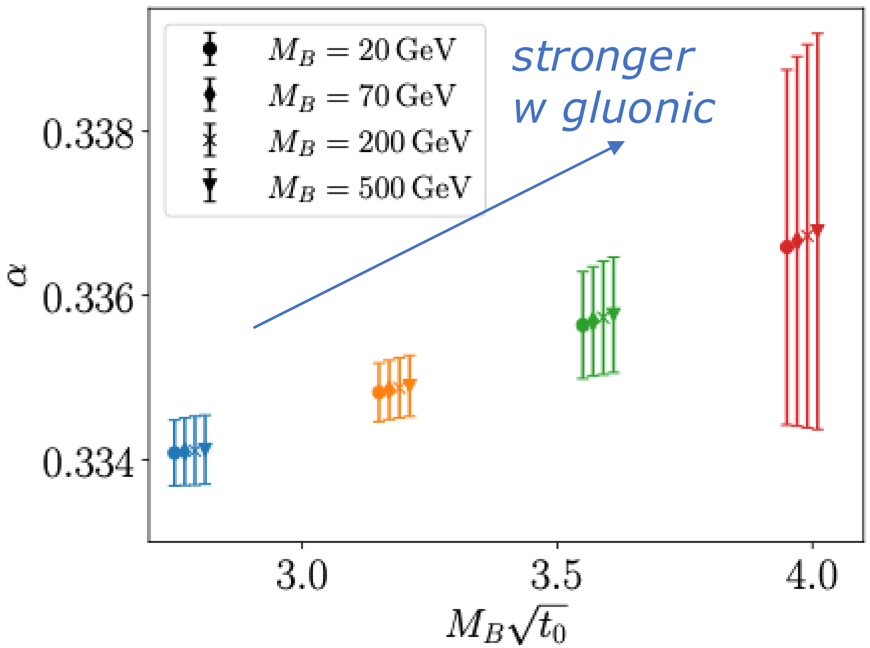
W.-C. Huang, M. Reichert, F. Sannino, Z.-W. Wang PRD 2021
R. Pasechnik, M. Reichert, F. Sannino, Z.-W. Wang JHEP 2024

- Strength of phase transition α

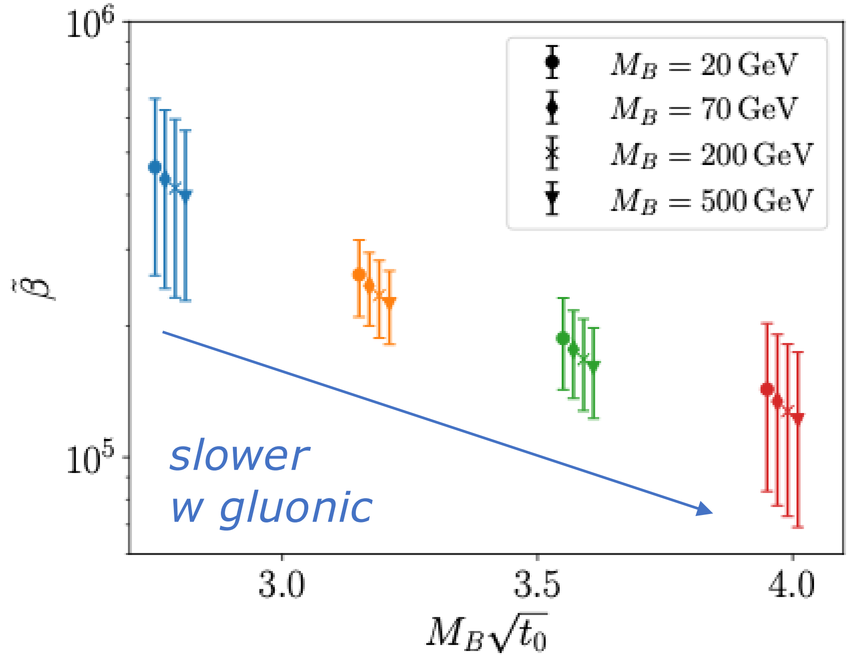
  =interaction measure/latent heat per DOF

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

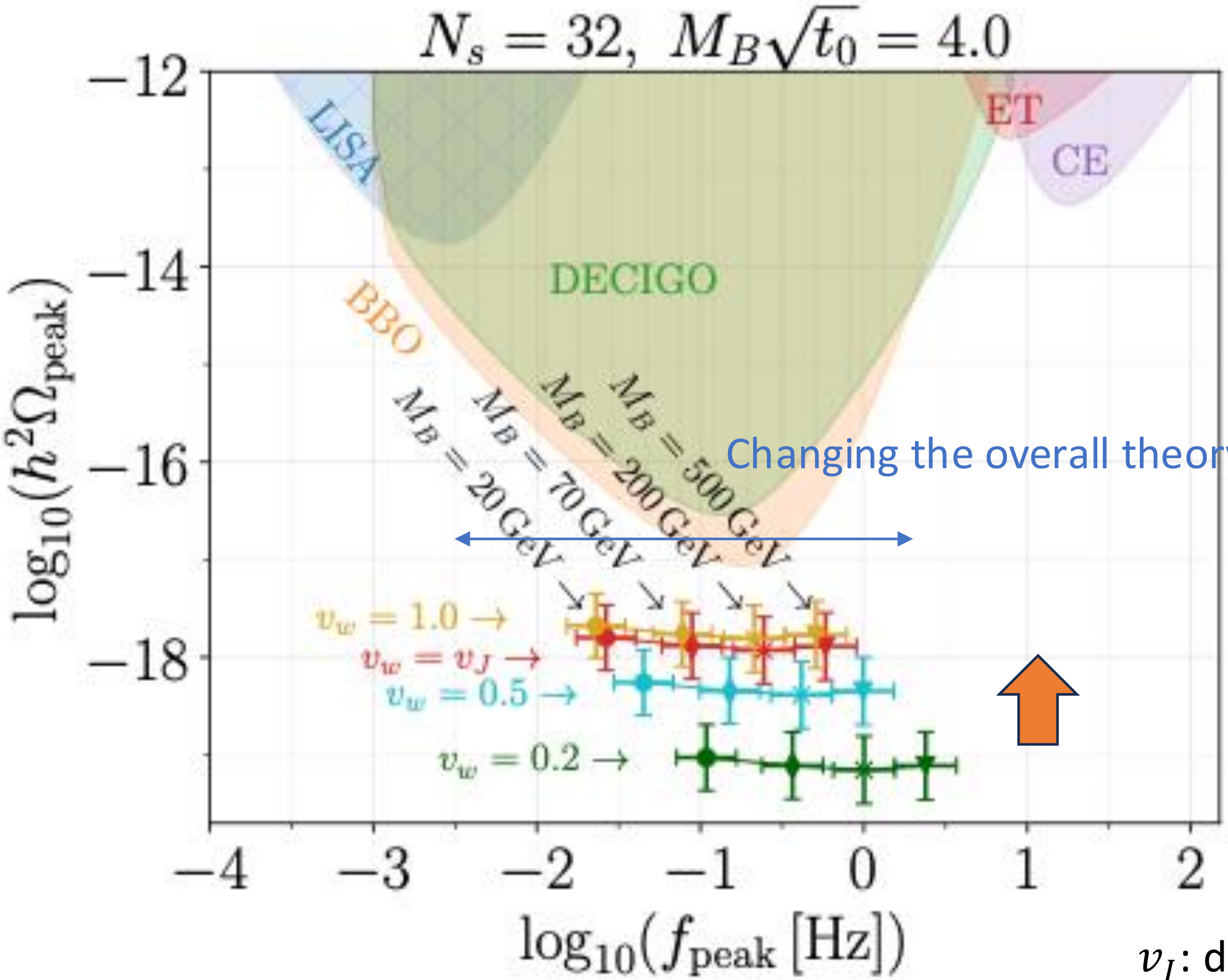
minor assumptions on universal scalar eff DOF



~quark mass



Sensitivity curves from Schmitz '21



Changing the overall theory scale $1/\sqrt{t_0}$ [GeV]

Faster wall
→ larger kinetic energy
→ larger signal

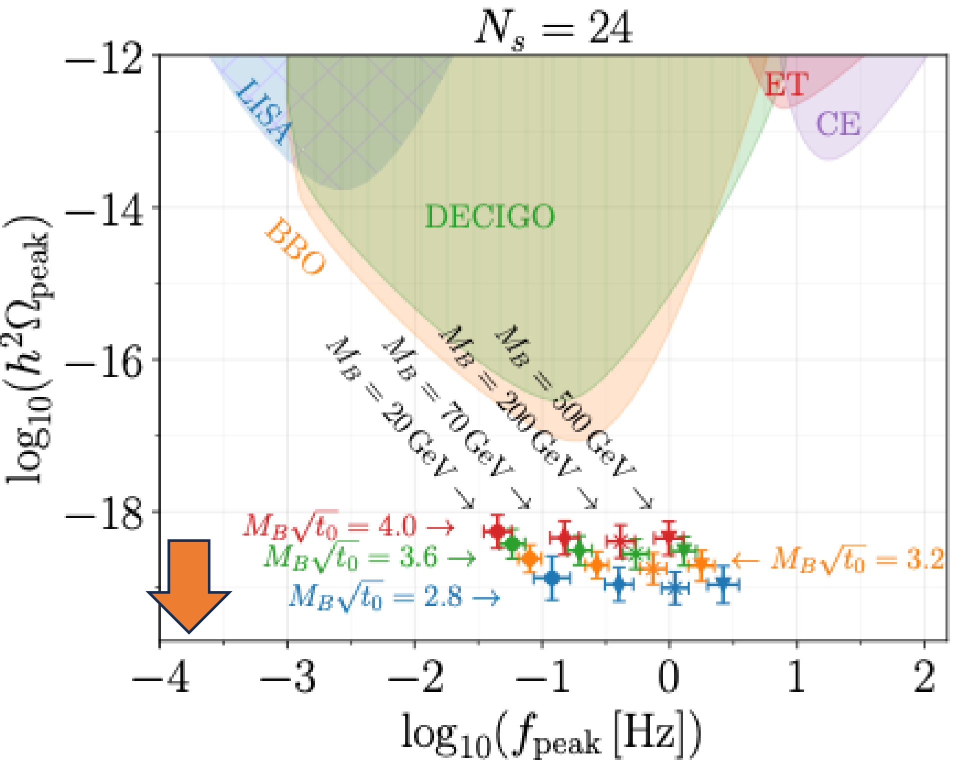
v_J: detonation velocity
P. J. Steinhardt, PRD 1982

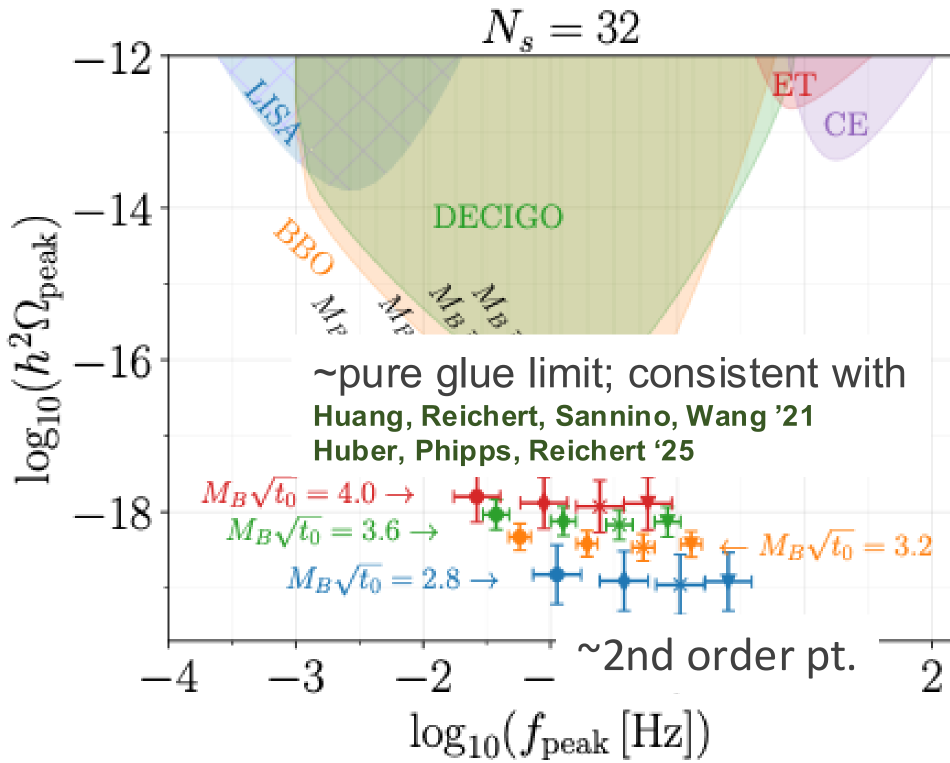
optimistic choice in the thermal transition ($v_J < 1$)
Espinosa Konstandin No Servant JCAP 2010

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

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

$v_w = v_J$





~pure glue limit; consistent with

Huang, Reichert, Sannino, Wang '21

Huber, Phipps, Reichert '25

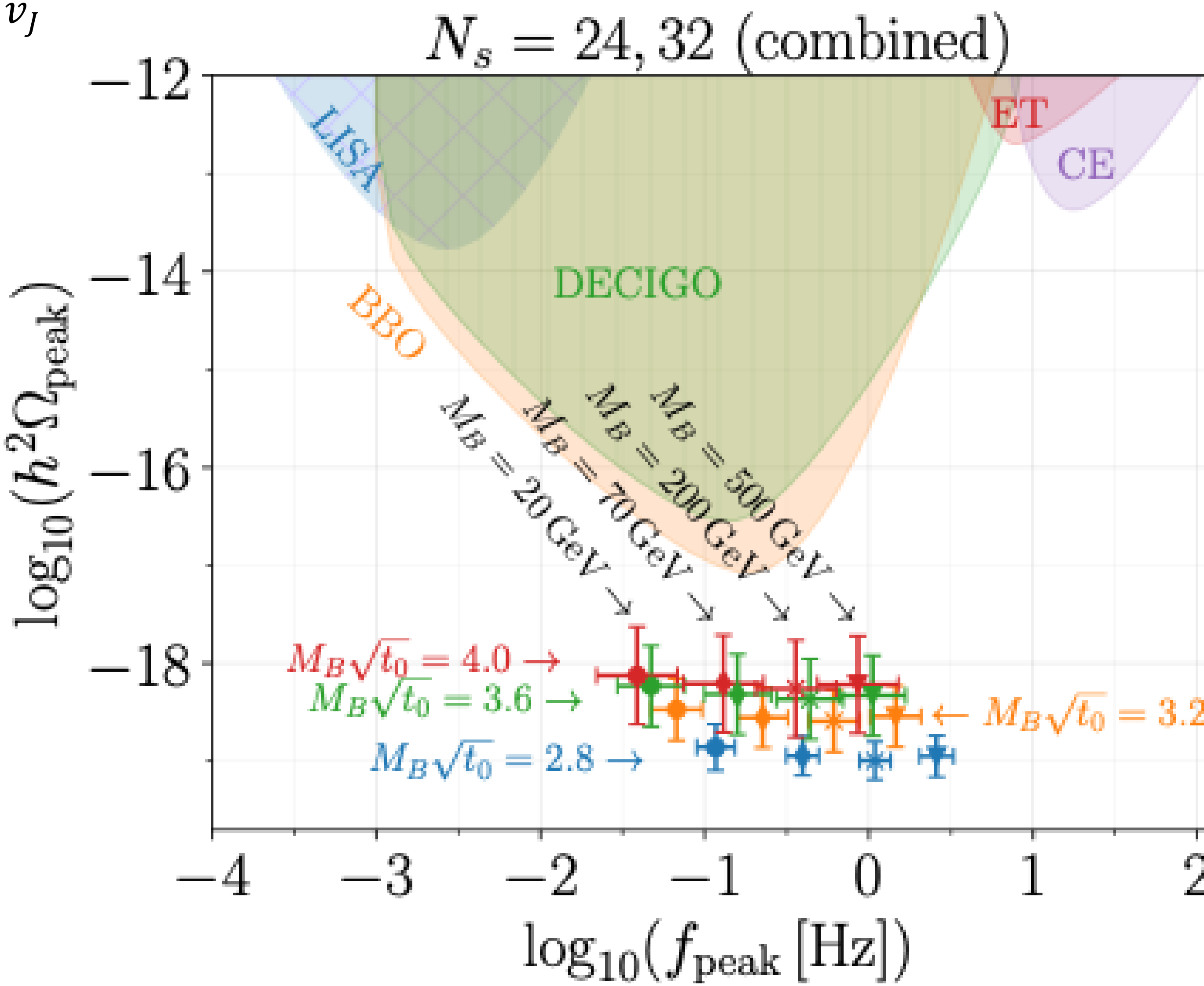
~2nd order pt.

smaller quark mass

→ smaller interface tension/shallower potential

→ 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 chaging the gauge group

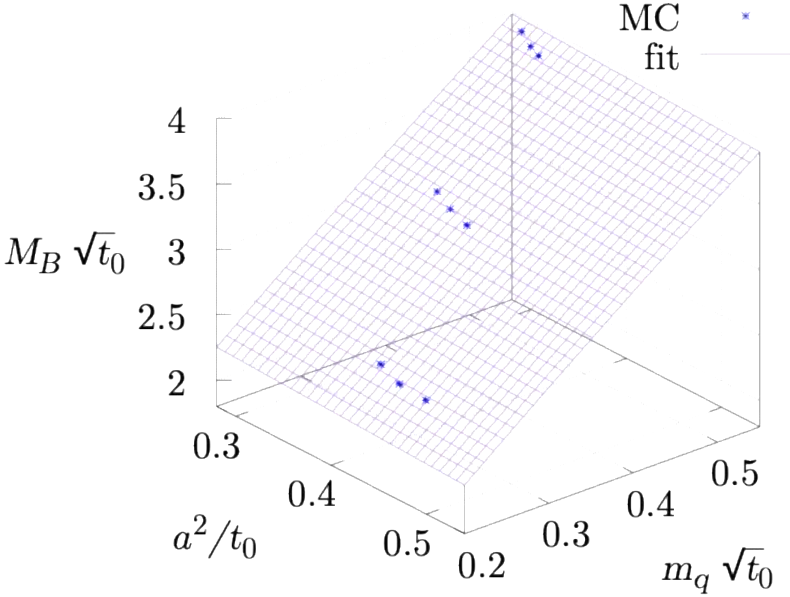
    Sp(N): *Alexis's talk on Tue*
    See also: Bruno, Forzano, Panero, Smecca '24
    Bennett, Lucini, Mason, Piai, Rinaldi, Vadacchino '24
    Bennett, Lucini, Mason, Piai, Rinaldi, Vadacchino, Zierler (TELOS) '25

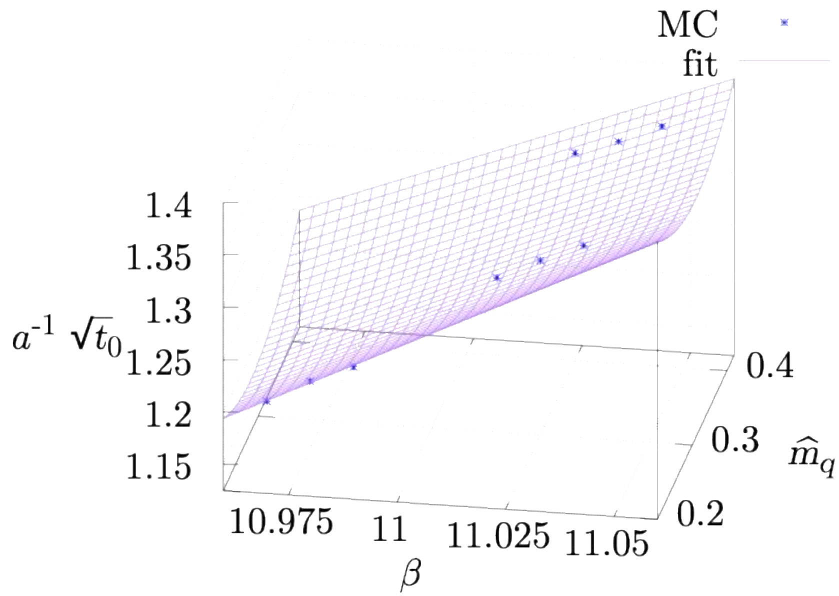
  - Fermion decreases the tension, whereas scalar fields increase it
    Explicit confirmation in this work

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

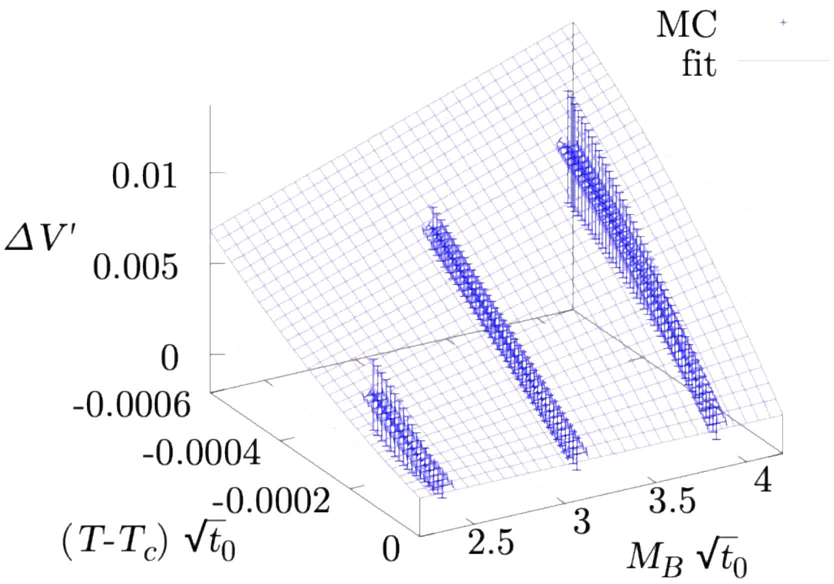
- Brush up the methodology
  - Accurate wall velocity from first-principles
    holographic models: **Bea et al. PRD '21, Bigazzi et al. JHEP '21, Janik et al. PRL '22, Chen et al. JHEP '23**
  - α and $\tilde{\beta}$ w/o the eff. potential **Shen Draper El-Khadra '22, Jin Swaim '25**

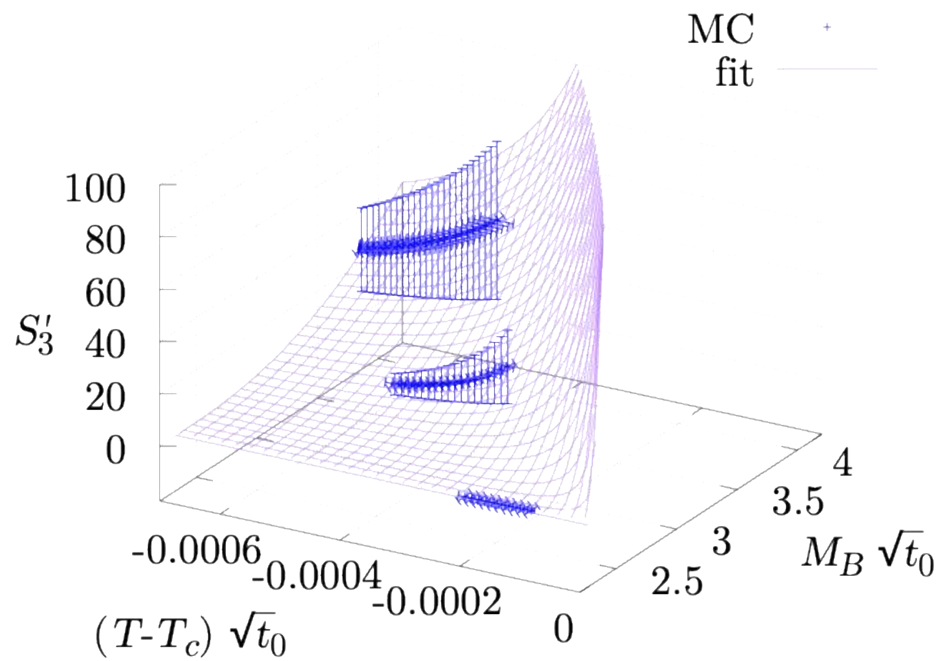
Thank you!


MC
fit
4
3.5
3
2.5
2
$M_B \sqrt{t_0}$
0.3
0.4
0.5
a^2/t_0
0.2
0.3
0.4
0.5
$m_q \sqrt{t_0}$

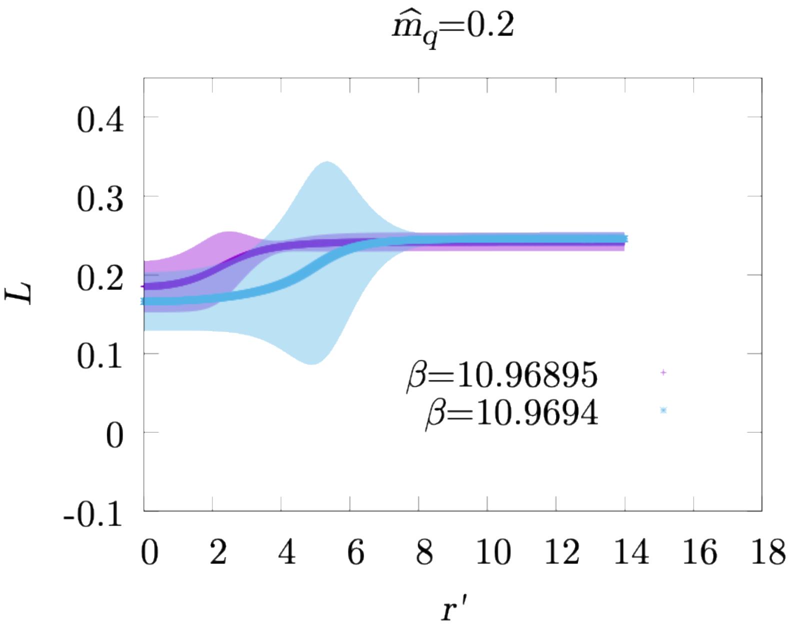

MC
fit
1.4
1.35
1.3
1.25
1.2
1.15
$a^{-1} \sqrt{t_0}$
10.975
11
11.025
11.05
β
0.2
0.3
0.4
$\widehat{m}_q$

Global fit 2/2

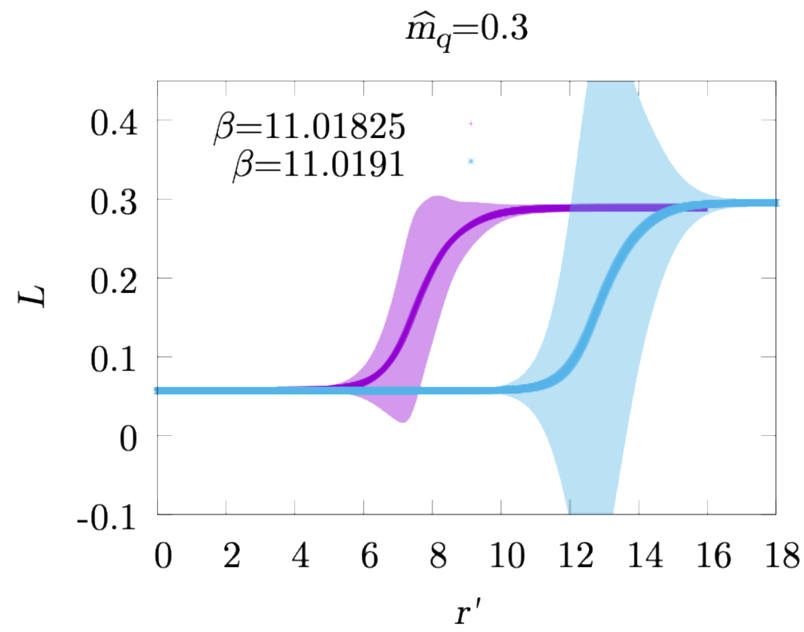




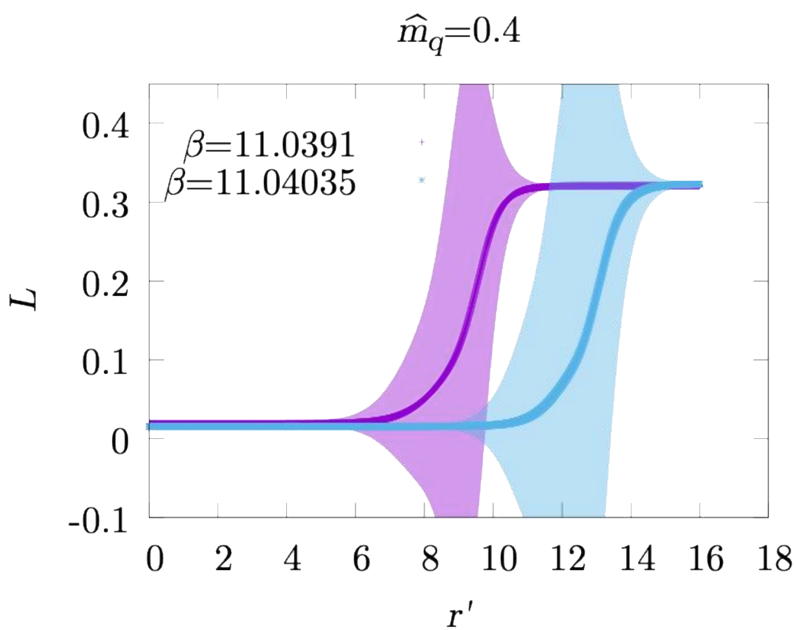
Bounce



$\widehat{m}_q$=0.2
β=10.96895
β=10.9694
L
r'
0.4
0.3
0.2
0.1
0
-0.1
0 2 4 6 8 10 12 14 16 18



$\widehat{m}_q$=0.3
β=11.01825
β=11.0191
L
r'
0.4
0.3
0.2
0.1
0
-0.1
0 2 4 6 8 10 12 14 16 18



$\widehat{m}_q$=0.4
β=11.0391
β=11.04035
L
r'
0.4
0.3
0.2
0.1
0
-0.1
0 2 4 6 8 10 12 14 16 18

$$\kappa \equiv \sqrt{\tau_{\rm sw}}\kappa_v. \tag{A.13}$$

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

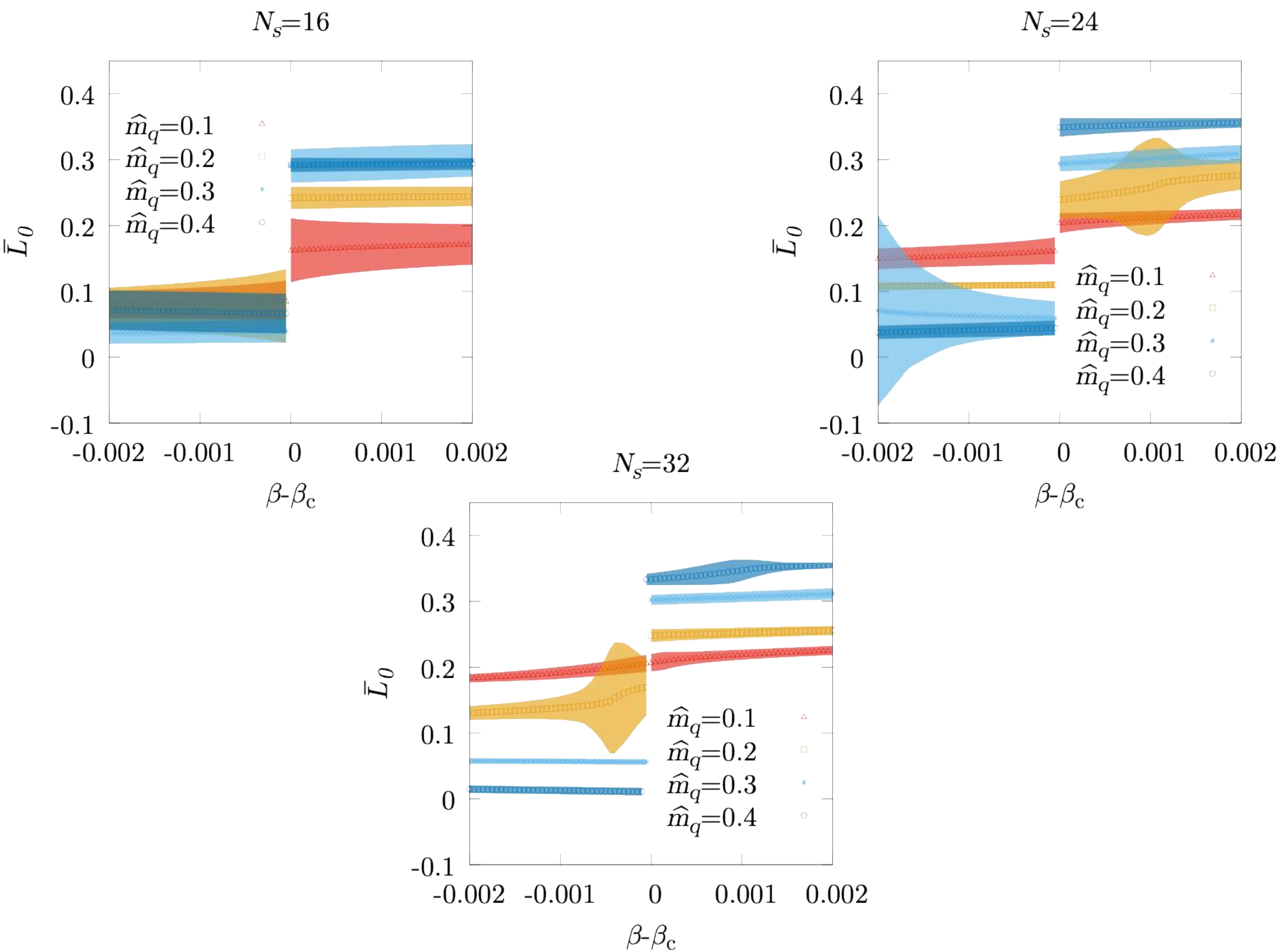
$$\tau_{\rm sw} = 1 - \left[1 + 2\frac{(8\pi)^{\frac{1}{3}} v_w}{\tilde{\beta} U_f}\right]^{-1/2}, \quad U_f^2 = \frac{3}{4}\frac{\alpha}{1+\alpha}\kappa_v, \tag{A.14}$$

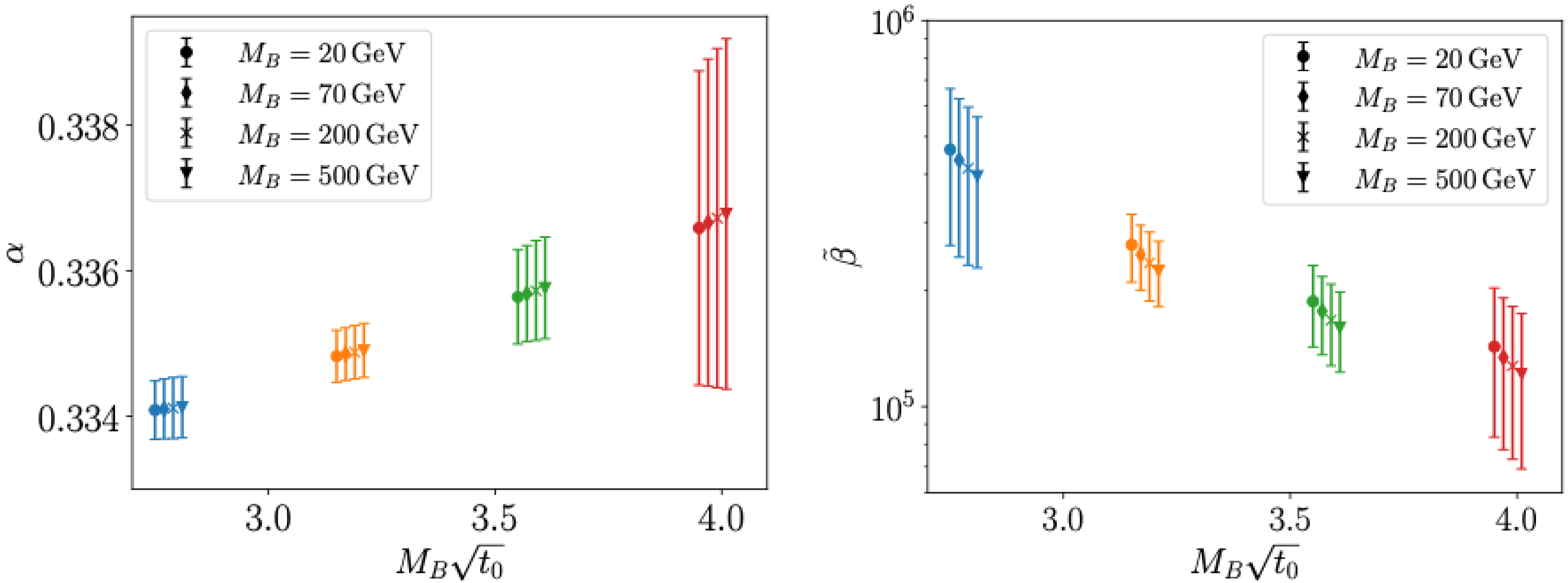
which lowers the amplitude in numerics. κ_v is the factor that is derived from hydrodynamical analysis, and is given for the Jouguet detonation as [52]

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

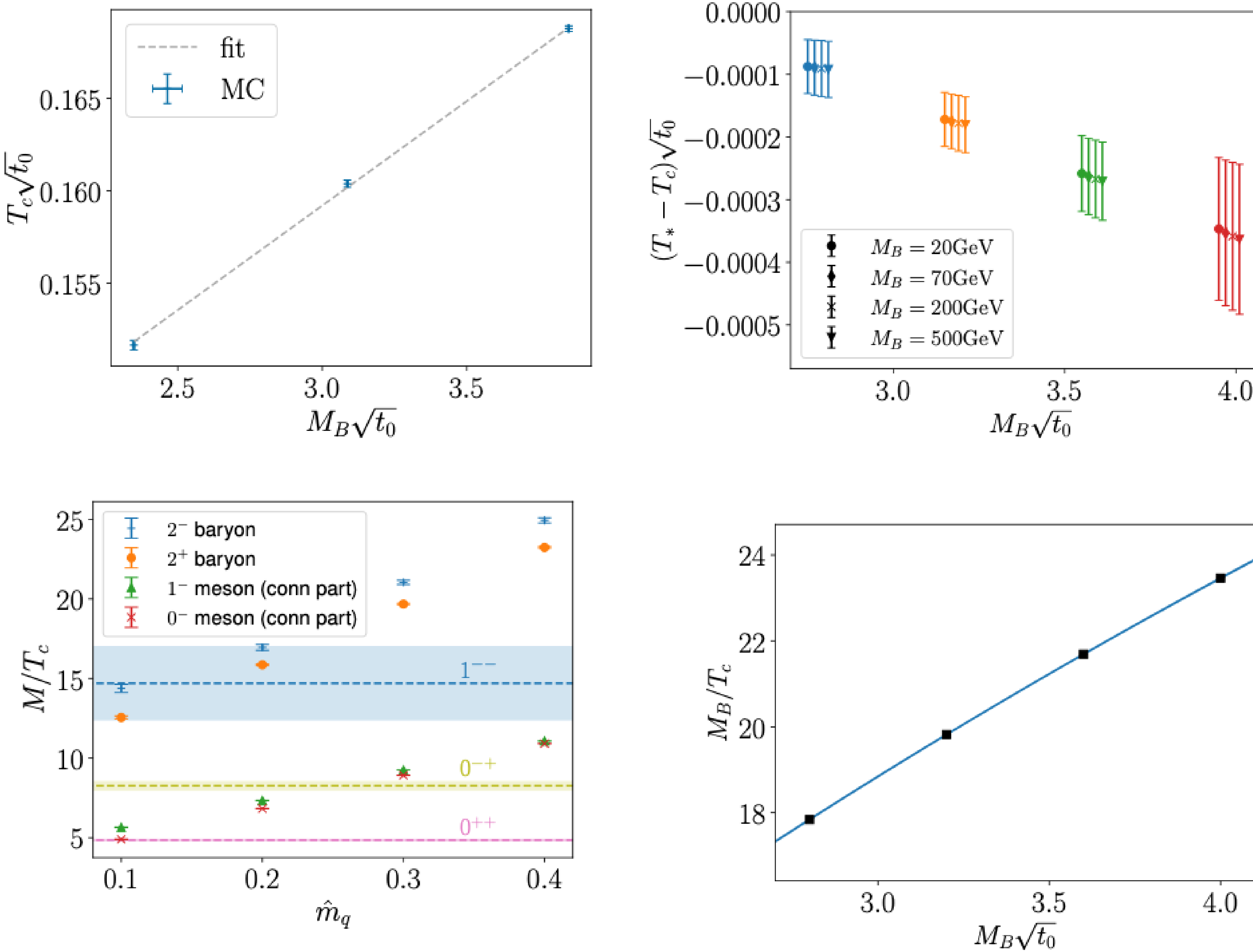
$$I(T) \equiv \int_T^{T_c} \frac{dT_1}{H(T_1)} \frac{\Gamma(T_1)}{T_1^4} \frac{4\pi}{3} \left[\int_T^{T_1} \frac{dT_2}{H(T_2)} v_w(T_2)\right]^3,$$

Discontinuity





α
0.334
0.336
0.338
3.0
3.5
4.0
$M_B\sqrt{t_0}$
$M_B = 20\,\mathrm{GeV}$
$M_B = 70\,\mathrm{GeV}$
$M_B = 200\,\mathrm{GeV}$
$M_B = 500\,\mathrm{GeV}$
$\tilde{\beta}$
10^5
10^6
3.0
3.5
4.0
$M_B\sqrt{t_0}$
$M_B = 20\,\mathrm{GeV}$
$M_B = 70\,\mathrm{GeV}$
$M_B = 200\,\mathrm{GeV}$
$M_B = 500\,\mathrm{GeV}$



fit
MC
$T_c\sqrt{t_0}$
0.155
0.160
0.165
2.5
3.0
3.5
$M_B\sqrt{t_0}$
$(T_* - T_c)\sqrt{t_0}$
0.0000
−0.0001
−0.0002
−0.0003
−0.0004
−0.0005
$M_B = 20$GeV
$M_B = 70$GeV
$M_B = 200$GeV
$M_B = 500$GeV
3.0
3.5
4.0
$M_B\sqrt{t_0}$
2^- baryon
2^+ baryon
1^- meson (conn part)
0^- meson (conn part)
M/T_c
5
10
15
20
25
1^{--}
0^{-+}
0^{++}
0.1
0.2
0.3
0.4
$\hat{m}_q$
M_B/T_c
18
20
22
24
3.0
3.5
4.0
$M_B\sqrt{t_0}$