Thermal QCD phases by TWEXT collaboration

A. Yu. Kotov

JÜLICH Forschungszentrum

[AYuK, M.P. Lombardo, A. Trunin, Phys.Lett.B 823, 2021]
[AYuK, M.P. Lombardo, A. Trunin, Symmetry 13, 2021]
[AYuK, M.P. Lombardo, A. Trunin, PoS Lattice 2021]
[AYuK, M.P. Lombardo, A. Trunin, in progress]

New trends in Thermal Phases of QCD, Prague, 2023

TWEXT (Twisted Wilson @ EXTreme) Collaboration

- Andrey Yu. Kotov
- Maria Paola Lombardo
- Anton Trunin

TWEXT (Twisted Wilson @ EXTreme) Collaboration

Lattice details

- 2+1+1 Wilson twisted mass fermions at maximal twist

  automatically $O(a)$ improved

  [R. Frezzotti, G. Rossi, 2004]

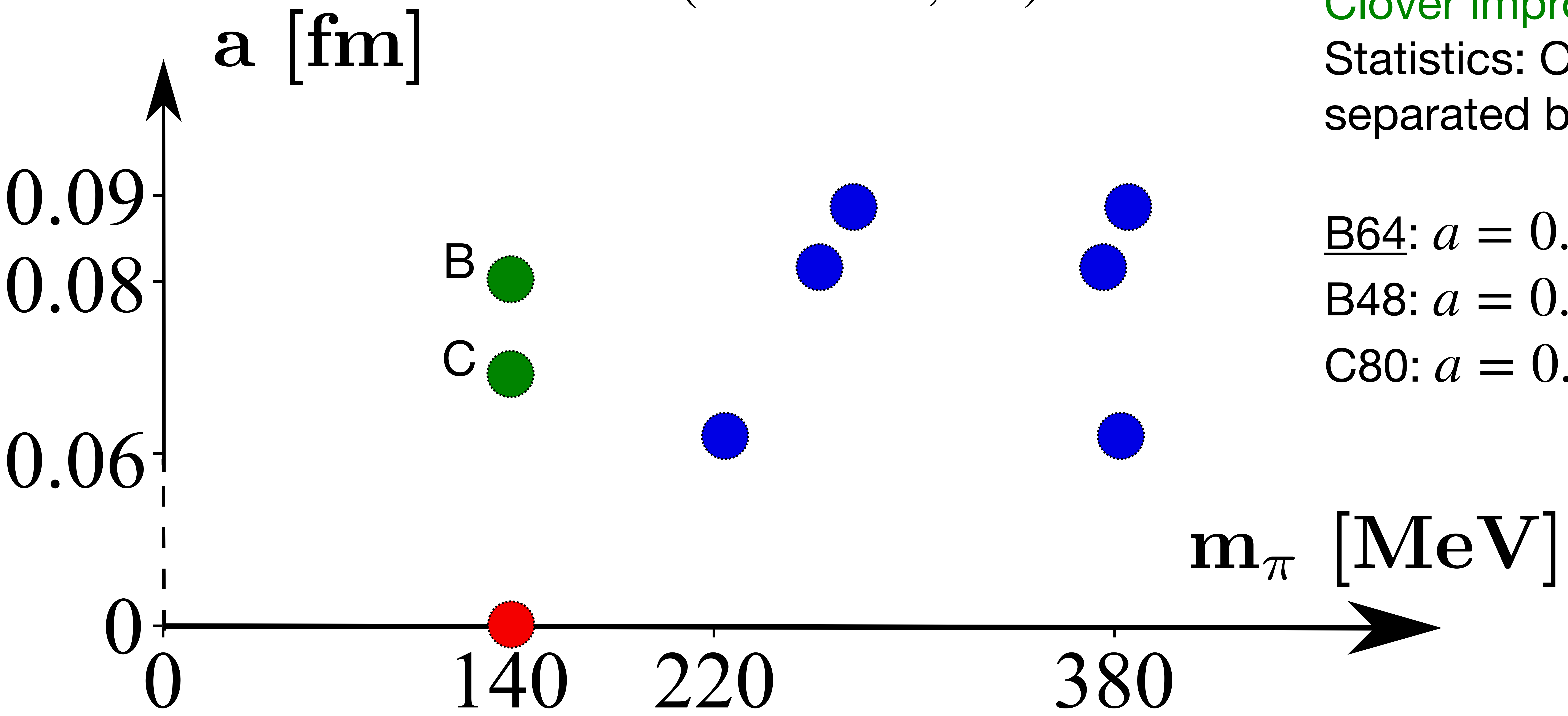
- Iwasaki gauge action
- Heavy quarks (c, s): close to the physical values
- $m_\pi \in [135,\ 370]$ MeV
- Fixed scale approach: $a =$ fixed, $T \leftrightarrow N_t$ (even for technical reasons)
- Based on ETMC $T = 0$ parameters & tmLQCD code

  [C. Alexandrou et al.,2018][C. Alexandrou et al.,2021]

TWEXT (Twisted Wilson @ EXTreme) Collaboration

Ensemble summary

$T \in (120 - 600{,}800)$ MeV



New ensembles @ $m_\pi = m_\pi^{\text{phys}}$:
Clover improved
Statistics: O(300) config's, separated by several MC traj's

<u>B64</u>: $a = 0.080$ fm, $L = 64a \approx 5.1$ fm
B48: $a = 0.080$ fm, $L = 48a \approx 3.8$ fm
C80: $a = 0.069$ fm, $L = 80a \approx 5.5$ fm

Chiral phase transition & novel order parameter

Novel order parameter

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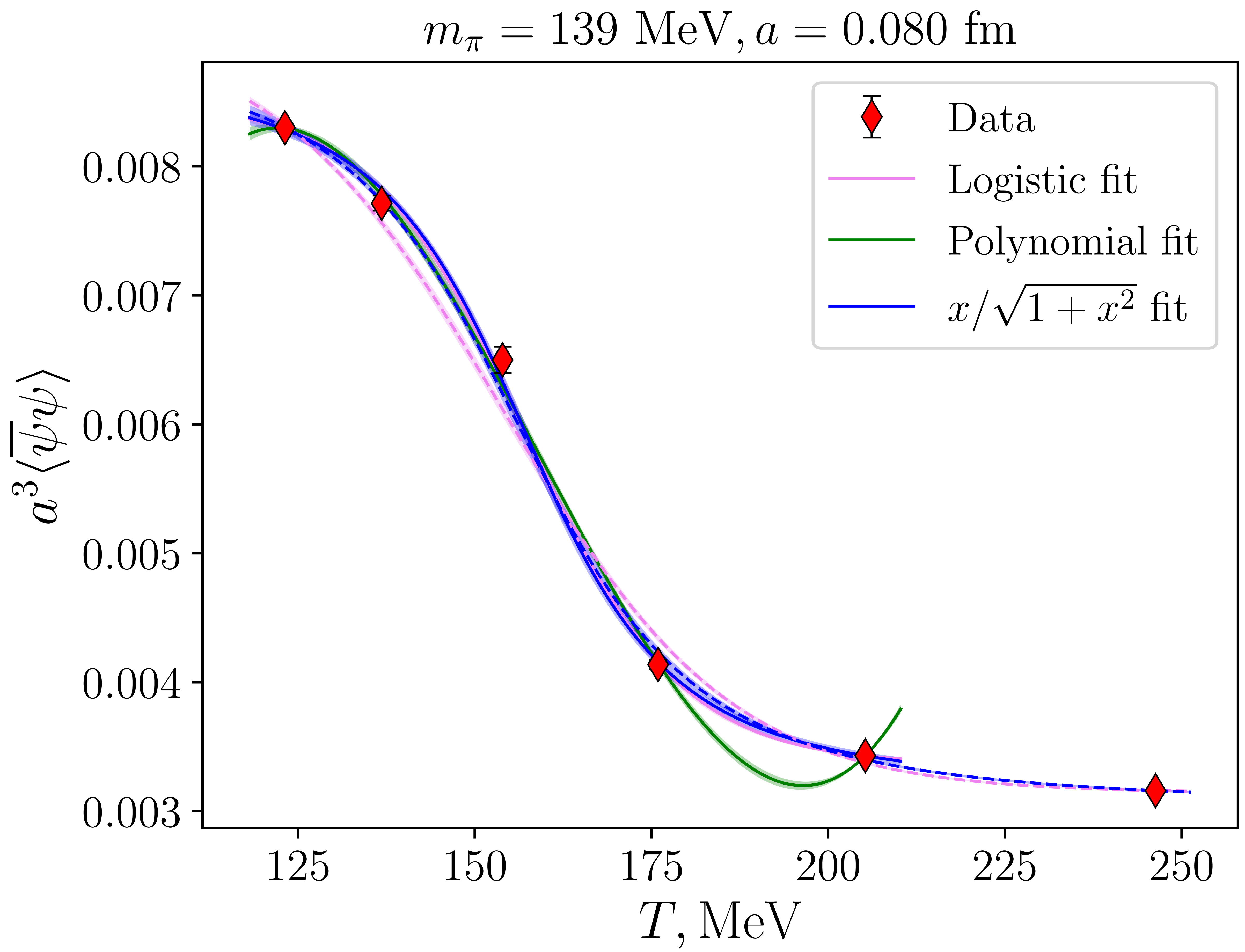
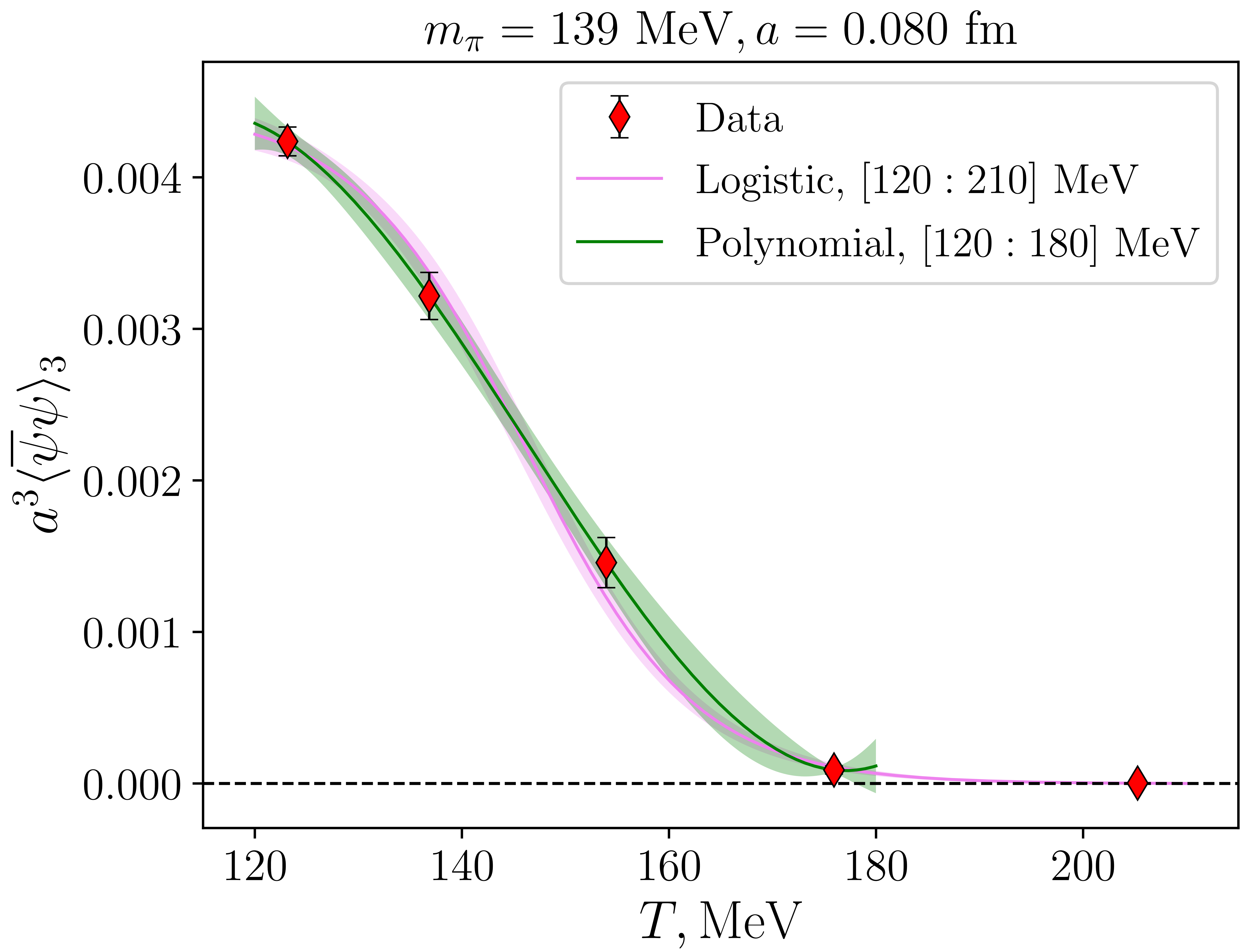
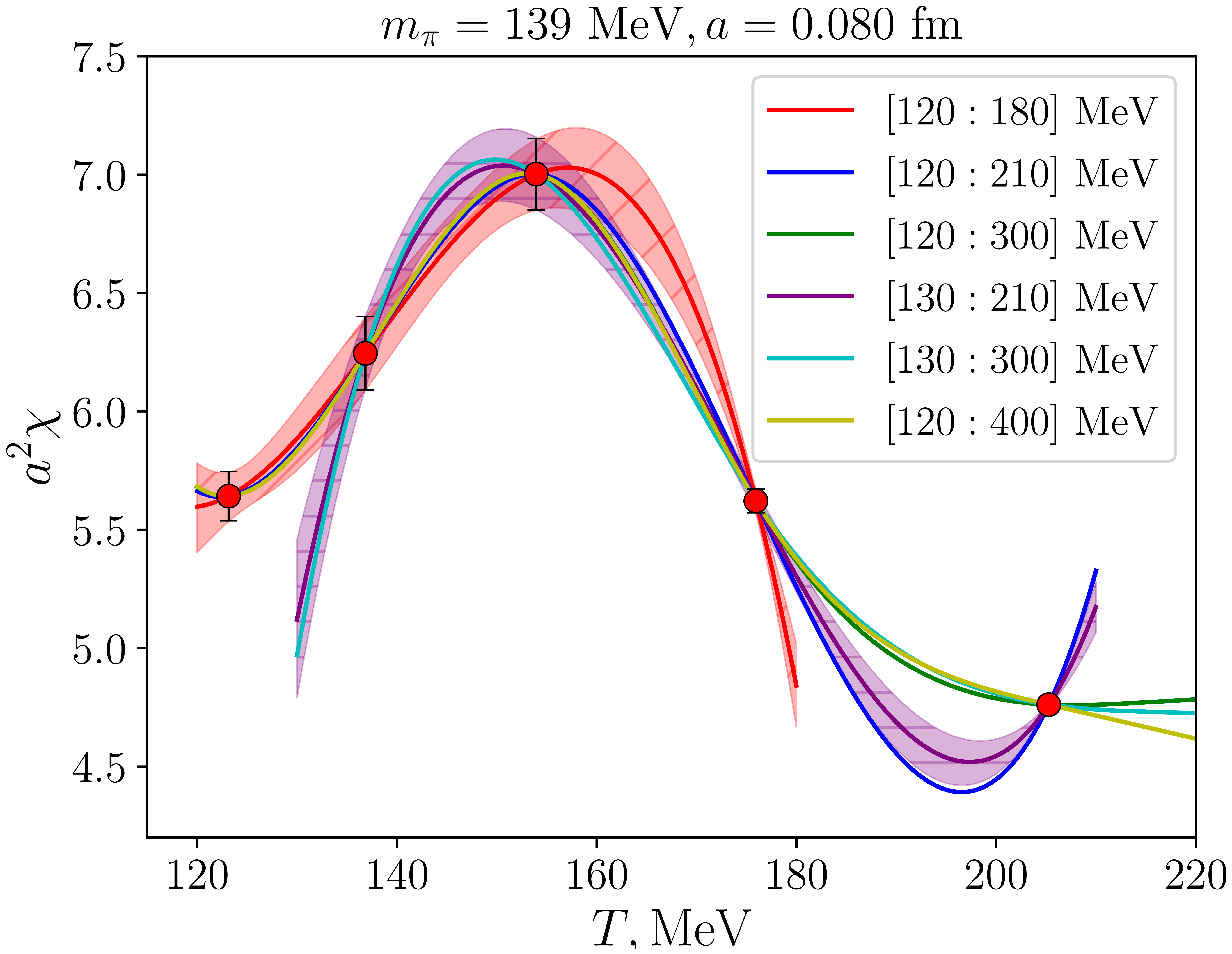
  - Although not important in the fixed scale approach
- Chiral susceptibility $\chi = \partial\langle\bar{\psi}\psi\rangle/\partial m$
- Novel order parameter: $\langle\bar{\psi}\psi\rangle_3 = \langle\bar{\psi}\psi\rangle - m\chi$
  - $1/a^2$ divergences cancel
  - ~m^3 (symmetric phase, large T)



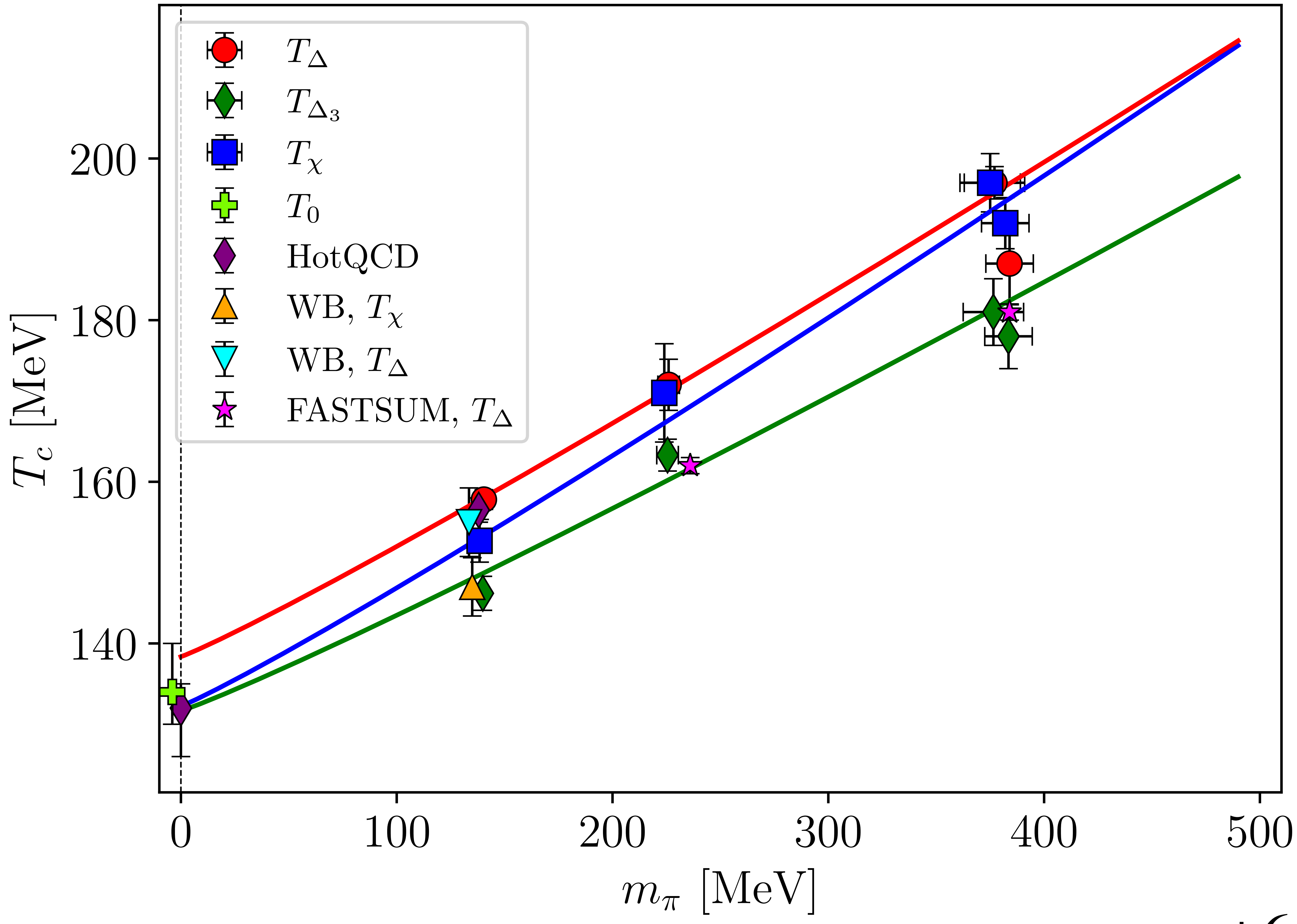
$m_\pi = 139$ MeV, $a = 0.080$ fm
Data
Logistic fit
Polynomial fit
$x/\sqrt{1+x^2}$ fit
$a^3\langle\overline{\psi}\psi\rangle$
0.008
0.007
0.006
0.005
0.004
0.003
125
150
175
200
225
250
T, MeV



$m_\pi = 139$ MeV, $a = 0.080$ fm
Data
Logistic, [120 : 210] MeV
Polynomial, [120 : 180] MeV
$a^3\langle\overline{\psi}\psi\rangle_3$
0.004
0.003
0.002
0.001
0.000
120
140
160
180
200
T, MeV


$m_\pi = 139$ MeV, $a = 0.080$ fm
$a^2\chi$
7.5
7.0
6.5
6.0
5.5
5.0
4.5
120
140
160
180
200
220
T, MeV
[120 : 180] MeV
[120 : 210] MeV
[120 : 300] MeV
[130 : 210] MeV
[130 : 300] MeV
[120 : 400] MeV

Critical temperature and the chiral limit



	$T(m_\pi = 139$ MeV) [MeV]	$T(m_\pi = 0)$ [MeV]
$\langle\bar{\psi}\psi\rangle$	157.8(12)	138(2)
χ	153(3)	132(4)
$\langle\bar{\psi}\psi\rangle_3$	146(2)	132(3)

$T_0 = 134^{+6}_{-4}$ MeV

[AYuK, M.P. Lombardo, A. Trunin, 2021]

$T_c = T_c(0) + k_s m_\pi^{2/\beta\delta}, O(4)$

Scaling behaviour

Symmetries of QCD with n quarks

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Global symmetry: $U_L(n) \times U_R(n) \cong \boxed{SU_L(n) \times SU_R(n)} \times U_B(1) \times U_A(1)$

Spontaneously broken → $SU_V(n)$

Baryon number

Anomalously Broken

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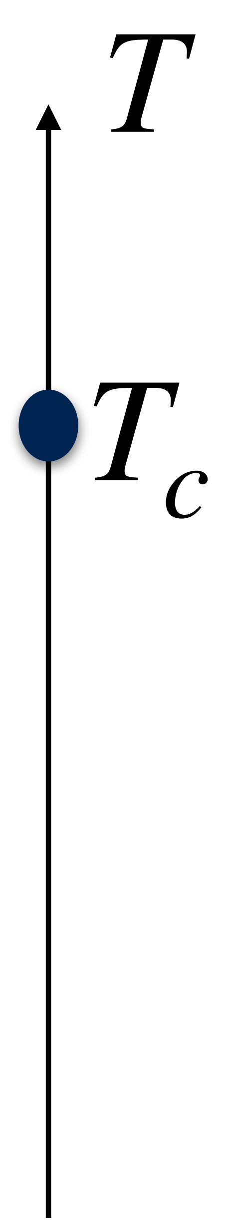

$T > T_c$ $(m = 0)$: (which?) symmetry restoration ⇔ order (universality)

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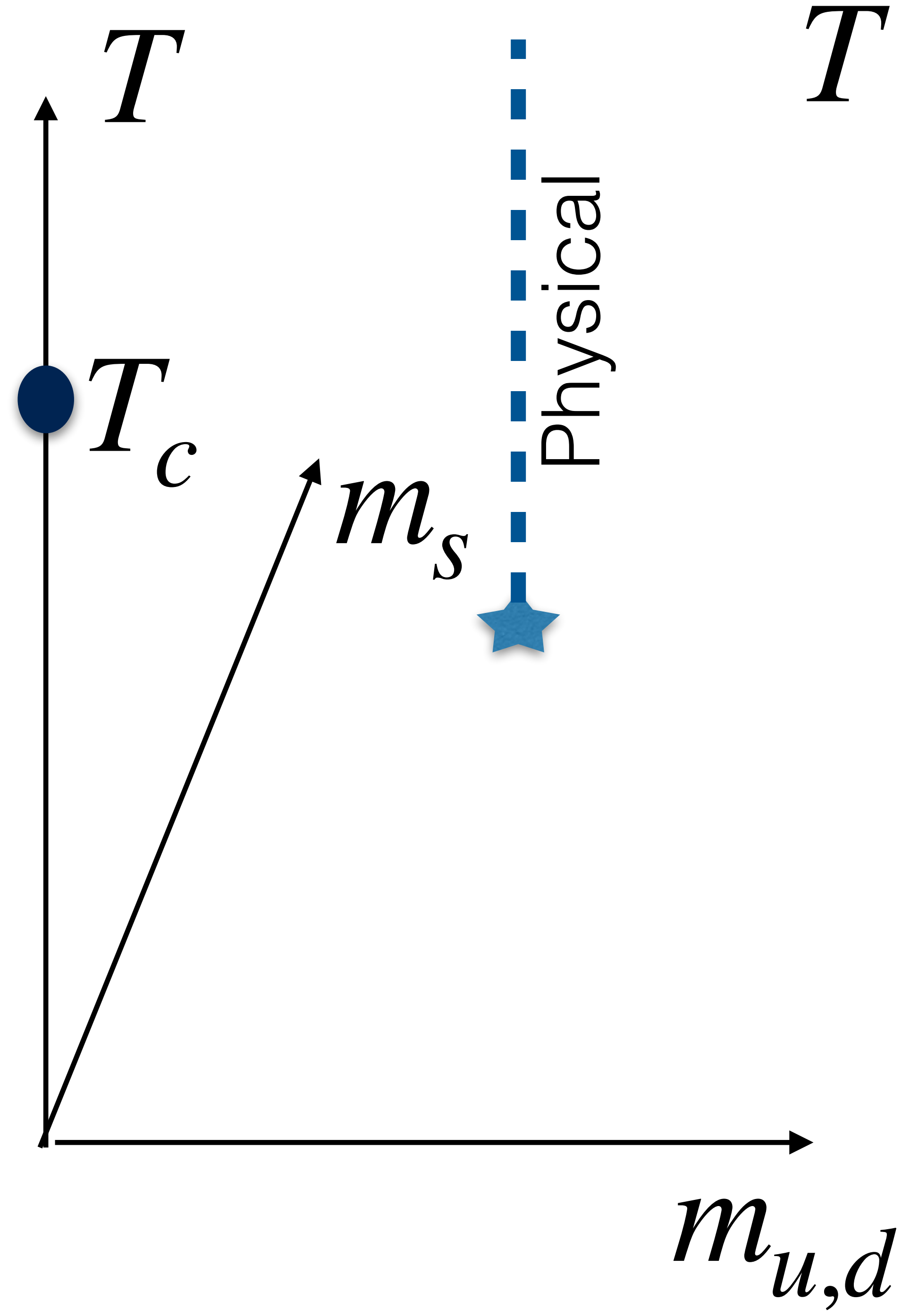
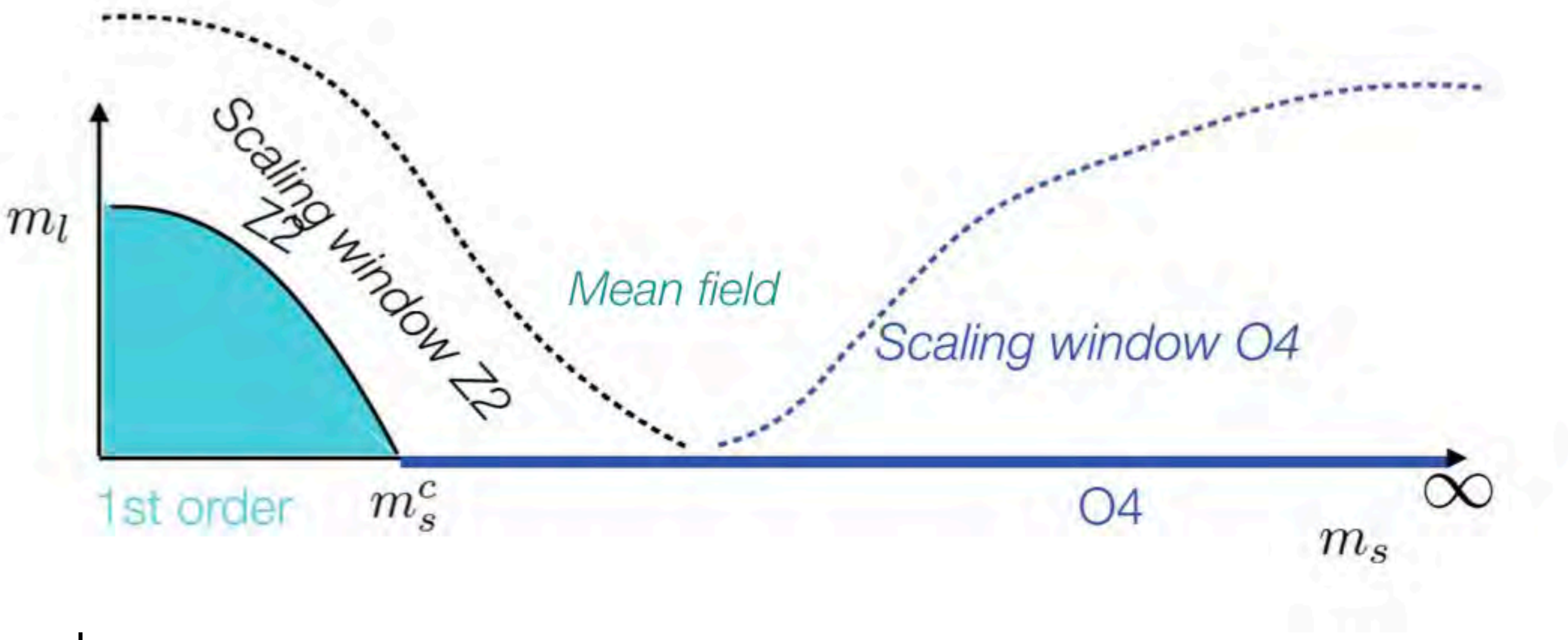
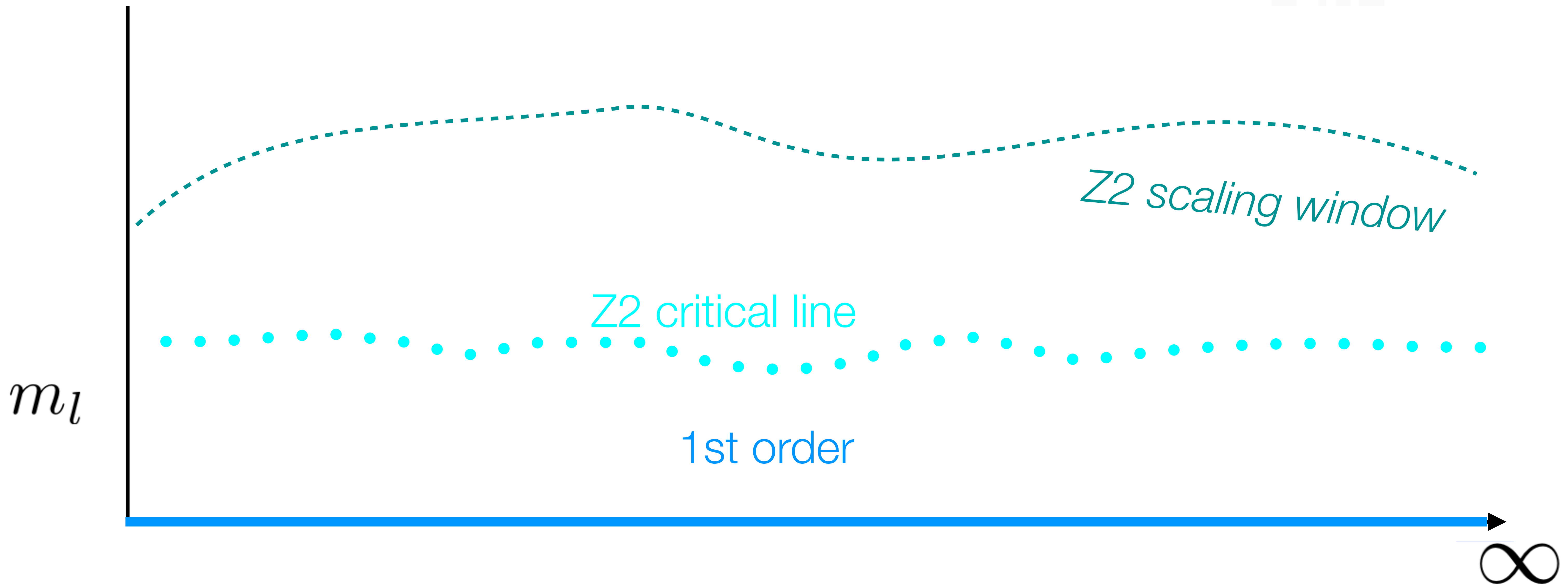


$T > T_c$ ($m = 0$): (which?) symmetry restoration ⇔ order (universality)

$m \neq 0$: explicit symmetry breaking

$m_l \neq 0$, possible scenarios





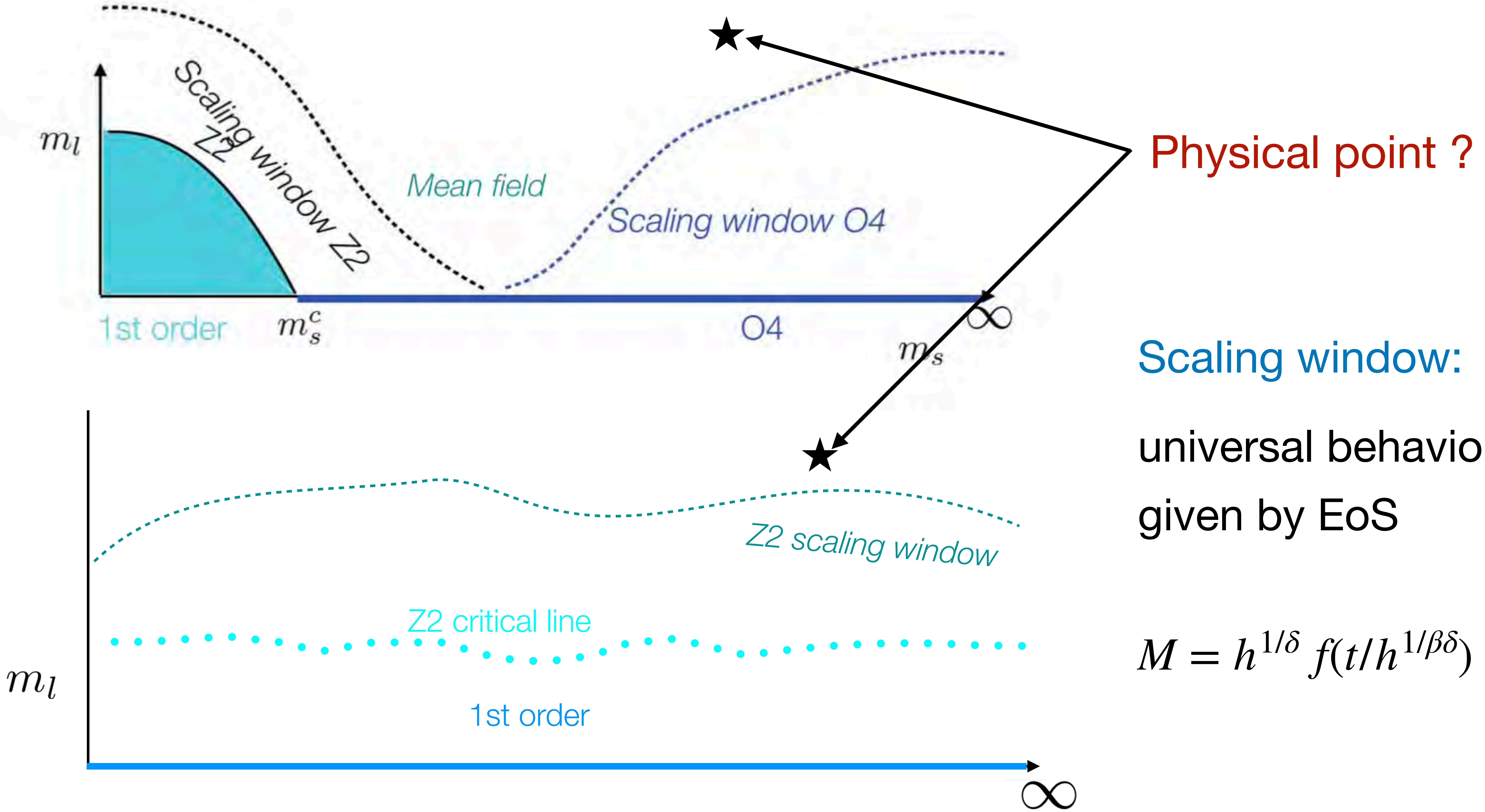
Scaling window:

universal behaviour

given by EoS

$$M = h^{1/\delta} f(t/h^{1/\beta\delta}) + \text{regular terms}$$

$m_l \neq 0$, possible scenarios



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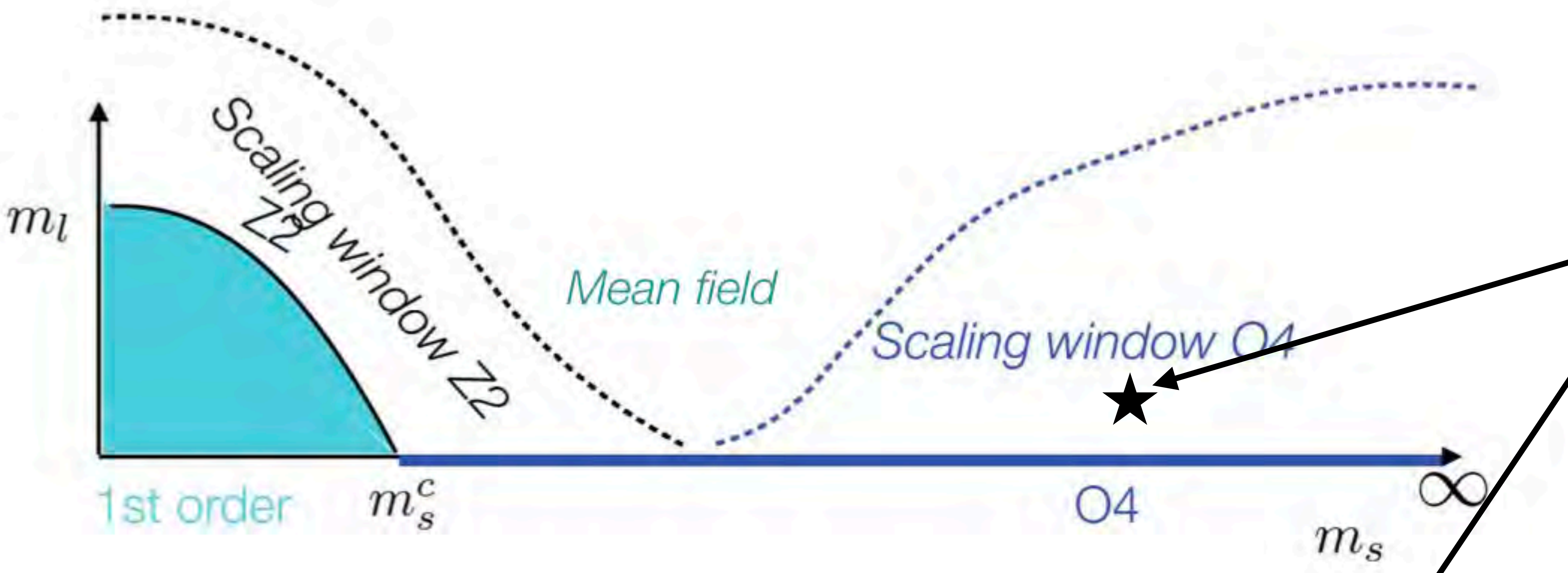

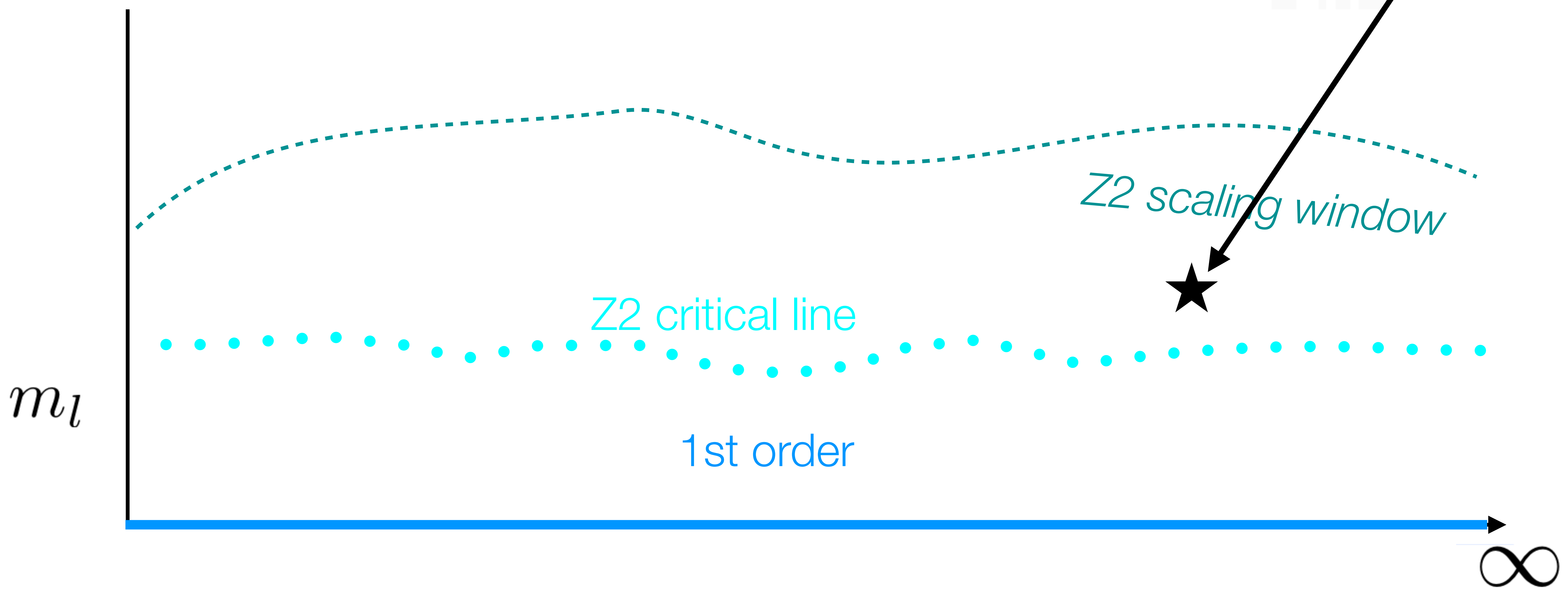

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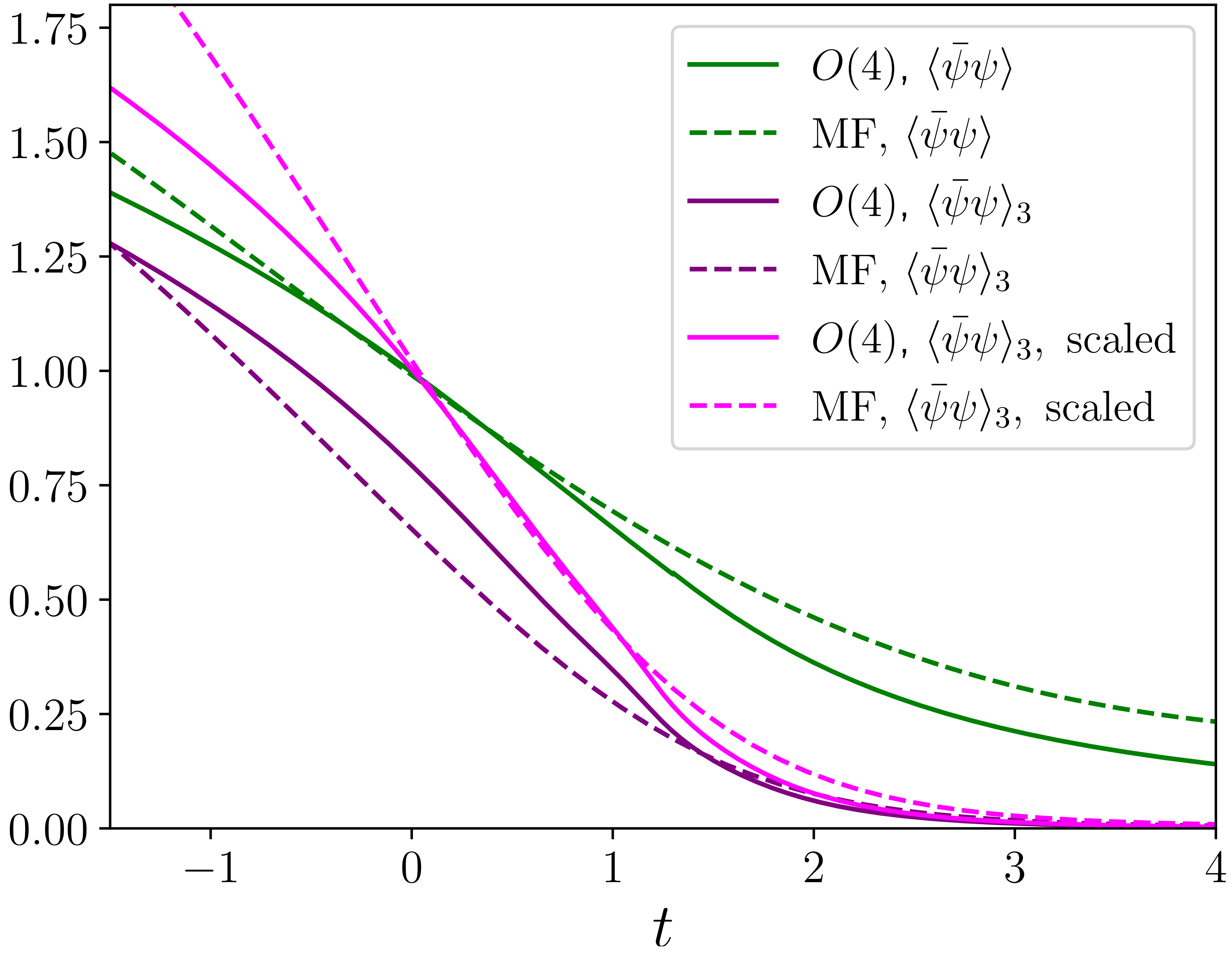
  as $m \to 0$

  - $\langle\bar{\psi}\psi\rangle_3 \sim t^{-\gamma-2\beta\delta}$ as $t \to \infty$
  - $\langle\bar{\psi}\psi\rangle \sim t^{-\gamma}$ as $t \to \infty$



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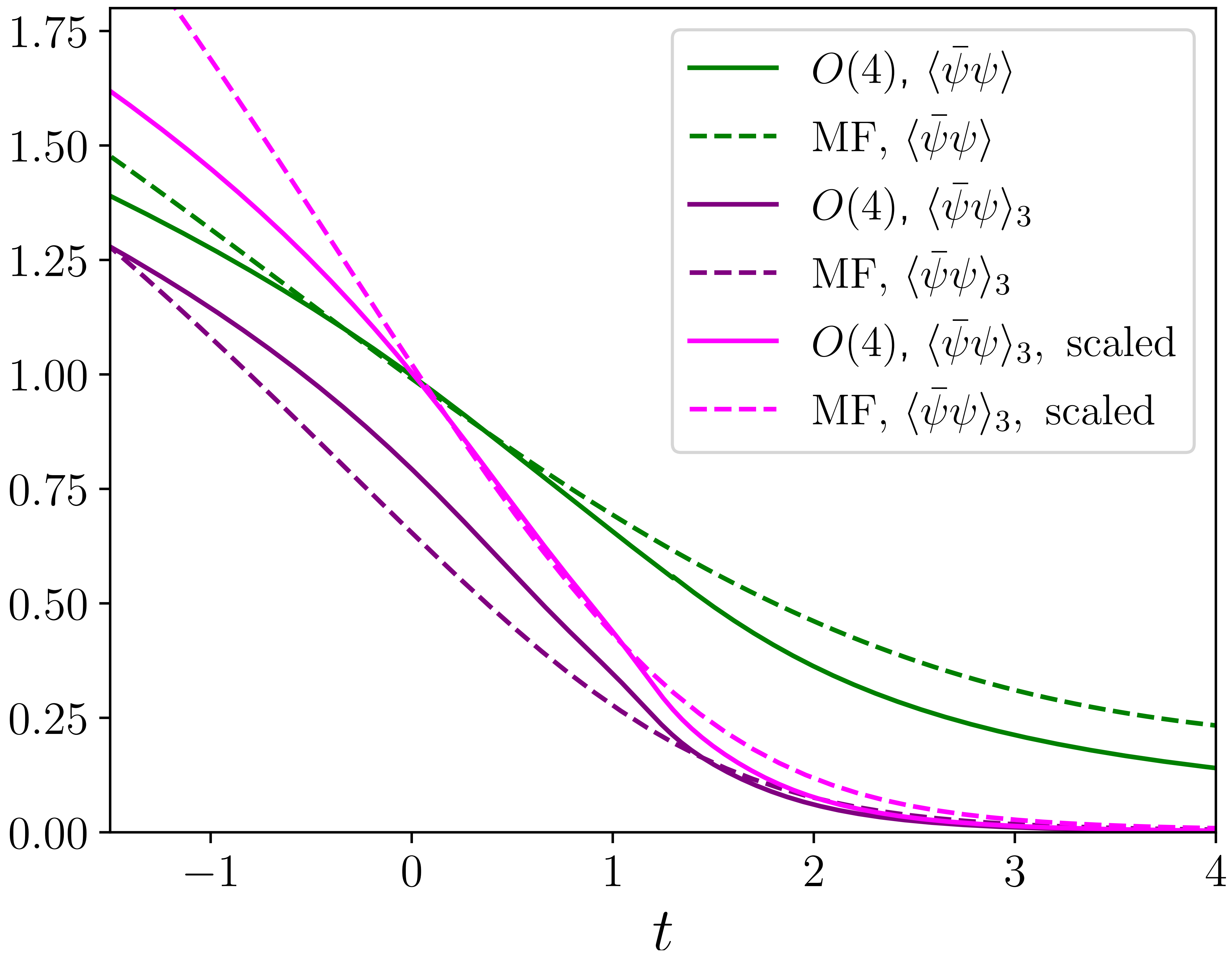
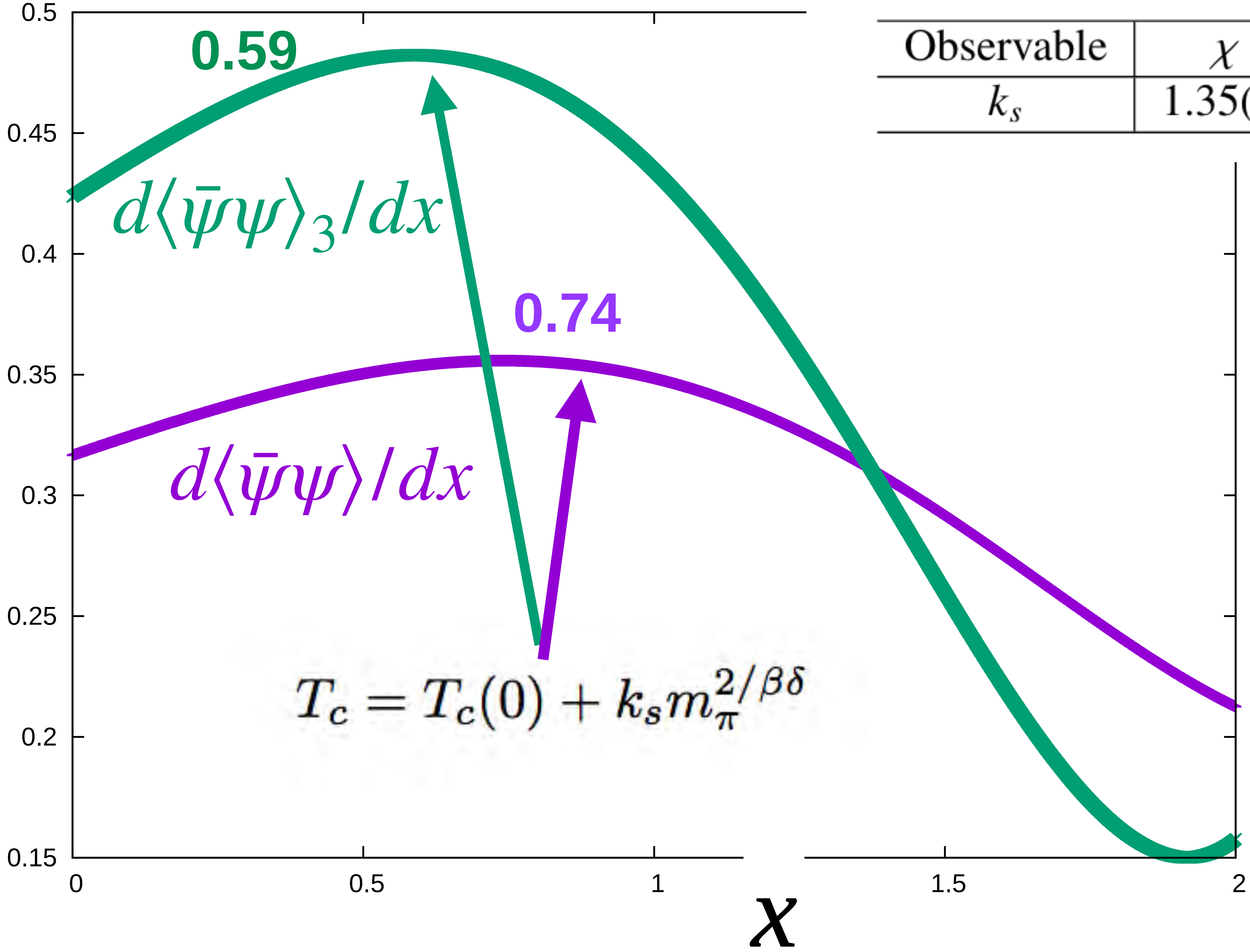
  - $\langle \bar{\psi}\psi \rangle_3 \sim t^{-\gamma-2\beta\delta}$ as $t \to \infty$
  - $\langle \bar{\psi}\psi \rangle \sim t^{-\gamma}$ as $t \to \infty$
- If $\langle \bar{\psi}\psi \rangle_3 < 0$: possibly first order, or closeness to the first order phase transition (Z_2 scenario ?)

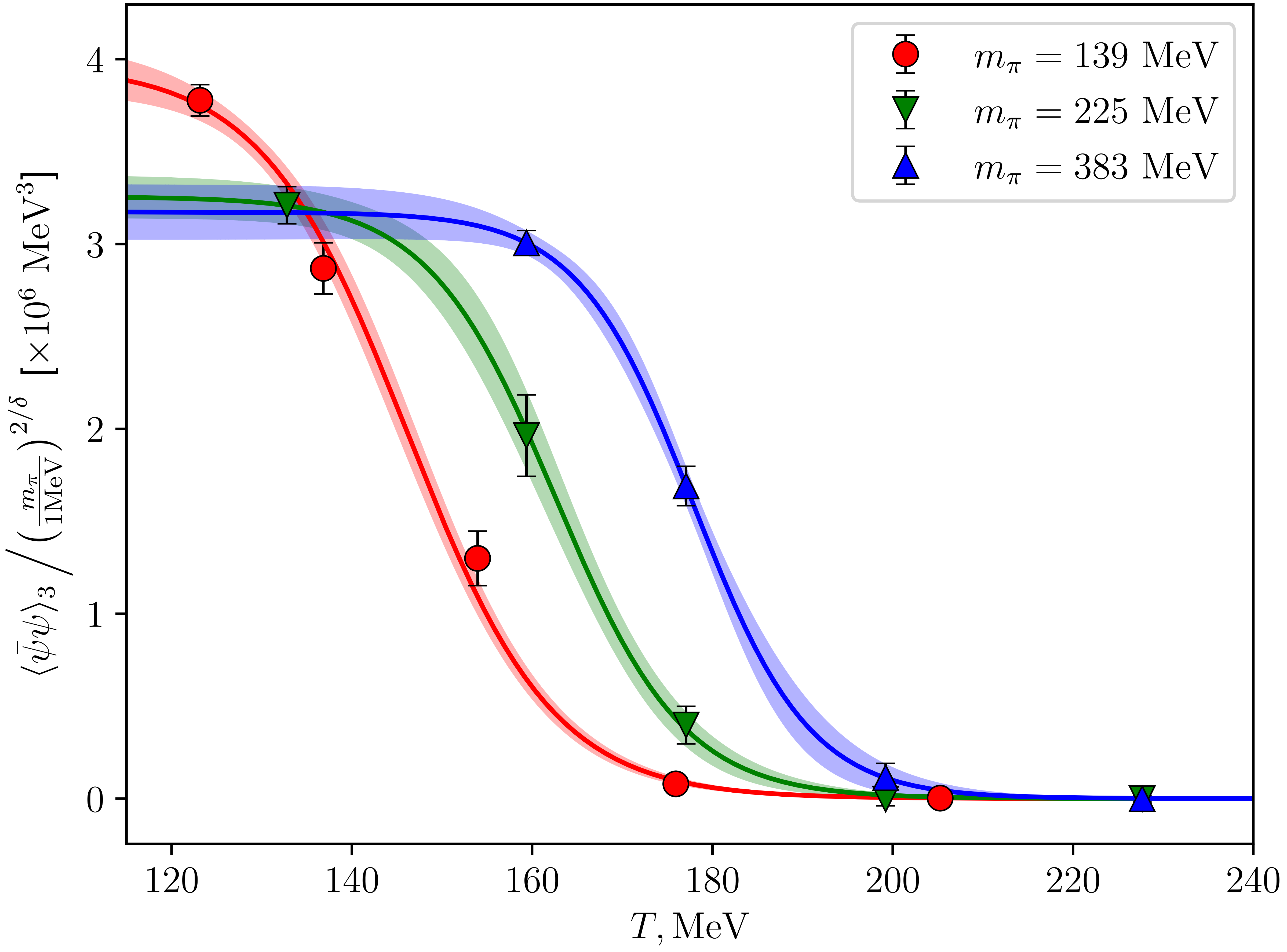


Scaling of T_c with pion mass



Observable	χ	$\bar{\psi}\psi$	Δ_3
k_s	1.35(3)	0.74(4)	0.59(1)

Simple estimation of T_0 from EOS



Prediction of EoS:

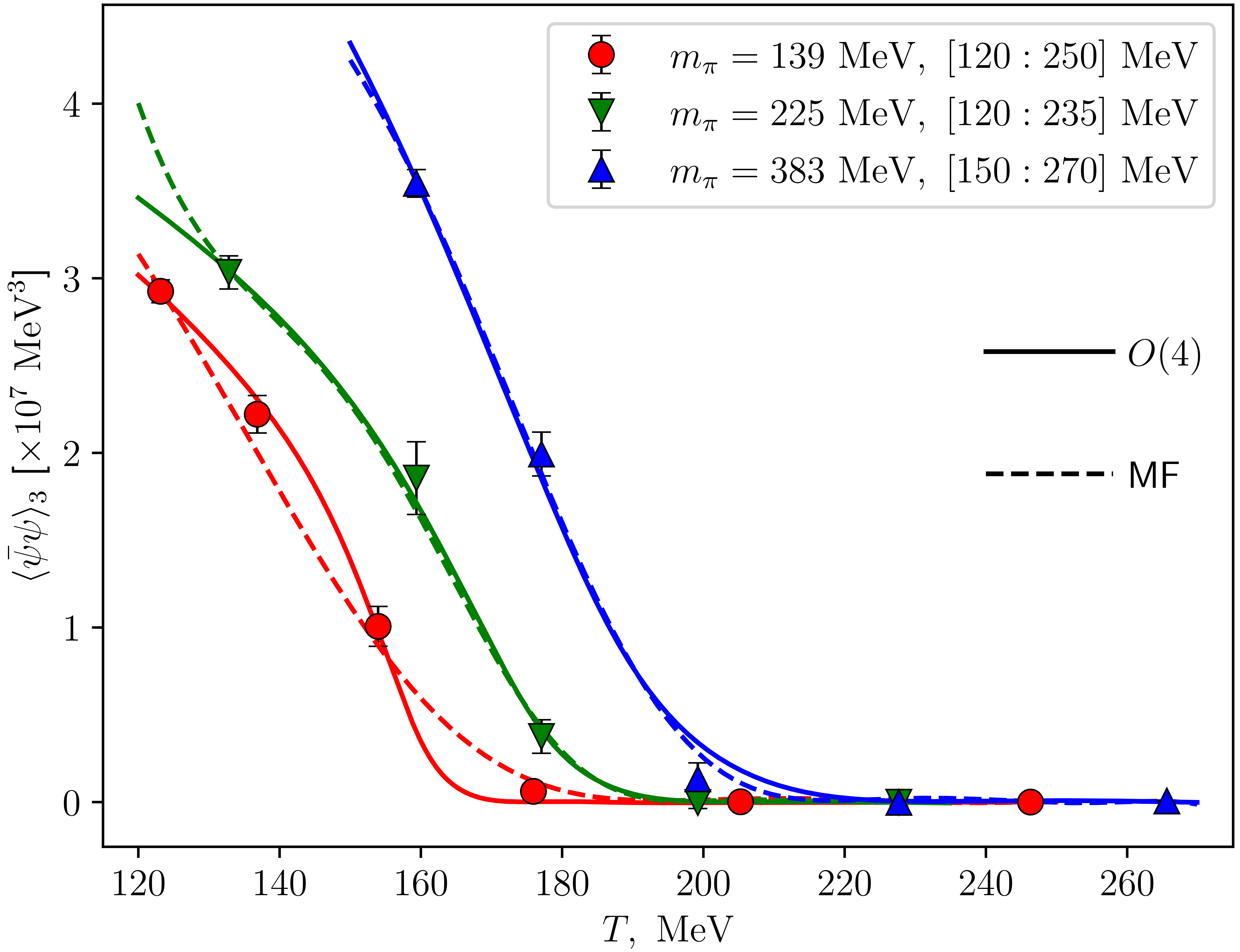
$$\frac{\langle\bar{\psi}\psi\rangle_3}{m^{1/\delta}} \sim \frac{\langle\bar{\psi}\psi\rangle_3}{m_\pi^{2/\delta}} = \text{const}$$

at

$$T = T_0(m_\pi = 0) = 138(2) \text{ MeV}$$

$$M = h^{1/\delta} f(t/h^{1/\beta\delta}) + \text{regular terms}$$

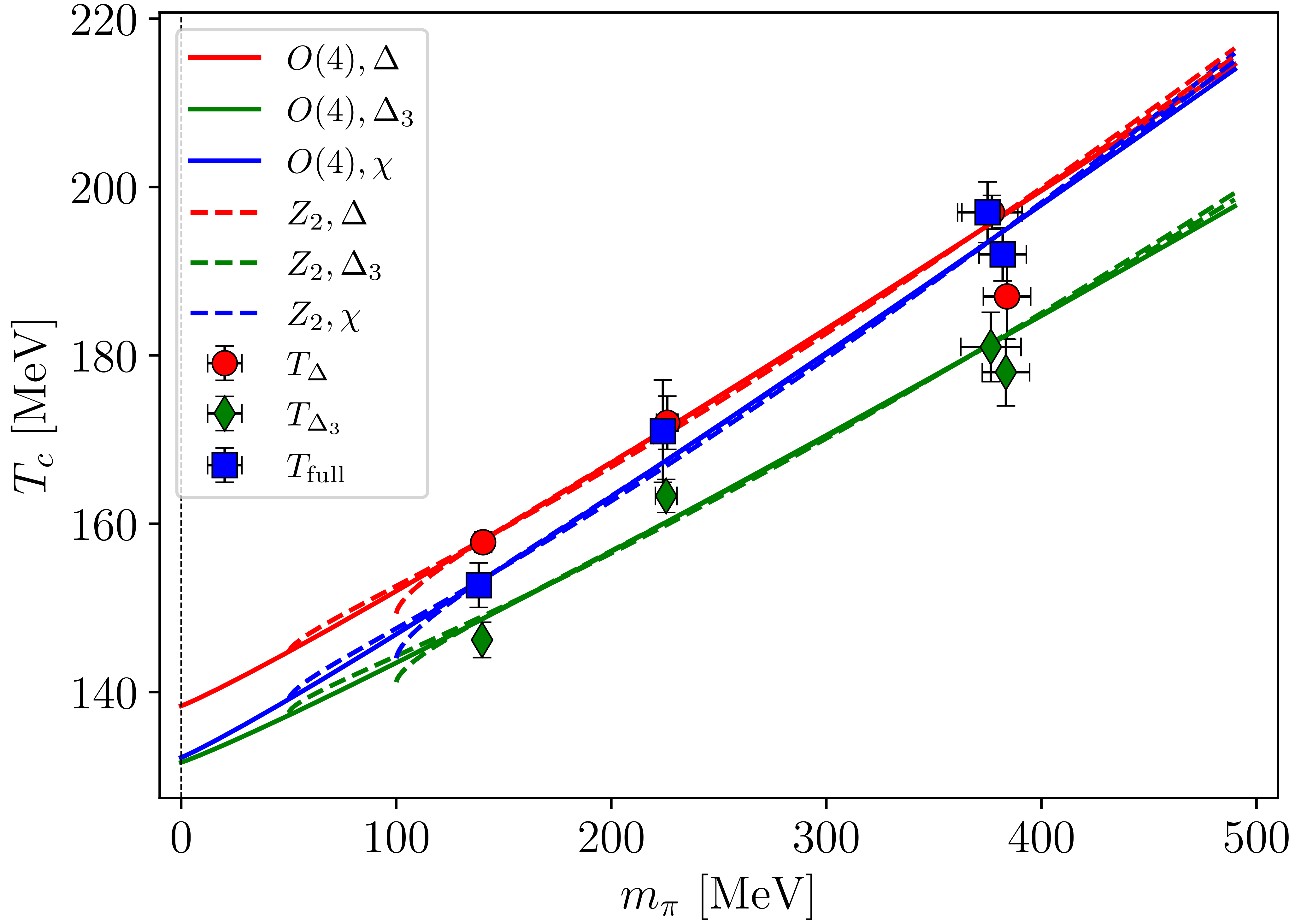
O(4) vs mean field



Mild tension between data and MF for m_π=139 MeV

m_π [MeV]	T_0 [MeV]
139	142(2)
225	159(3)
383	174(2)

Z_2 vs O(4) scaling



$$T_0 = T_c(m_\pi \to 0) = 134^{+6}_{-4} \text{ MeV}$$

O(4) scaling:

Observable	T_0 [MeV]	$z_p/z_{\bar\psi\psi_3}$	$z_p/z_{\bar\psi\psi_3}$ $O(4)$	z_p $O(4)$
χ	132(4)	1.24(17)	2.45(4)	1.35(3)
$\langle\bar\psi\psi\rangle$	138(2)	1.15(24)	1.35(7)	0.74(4)
$\langle\bar\psi\psi\rangle_3$	132(3)	1	1	0.55(1)

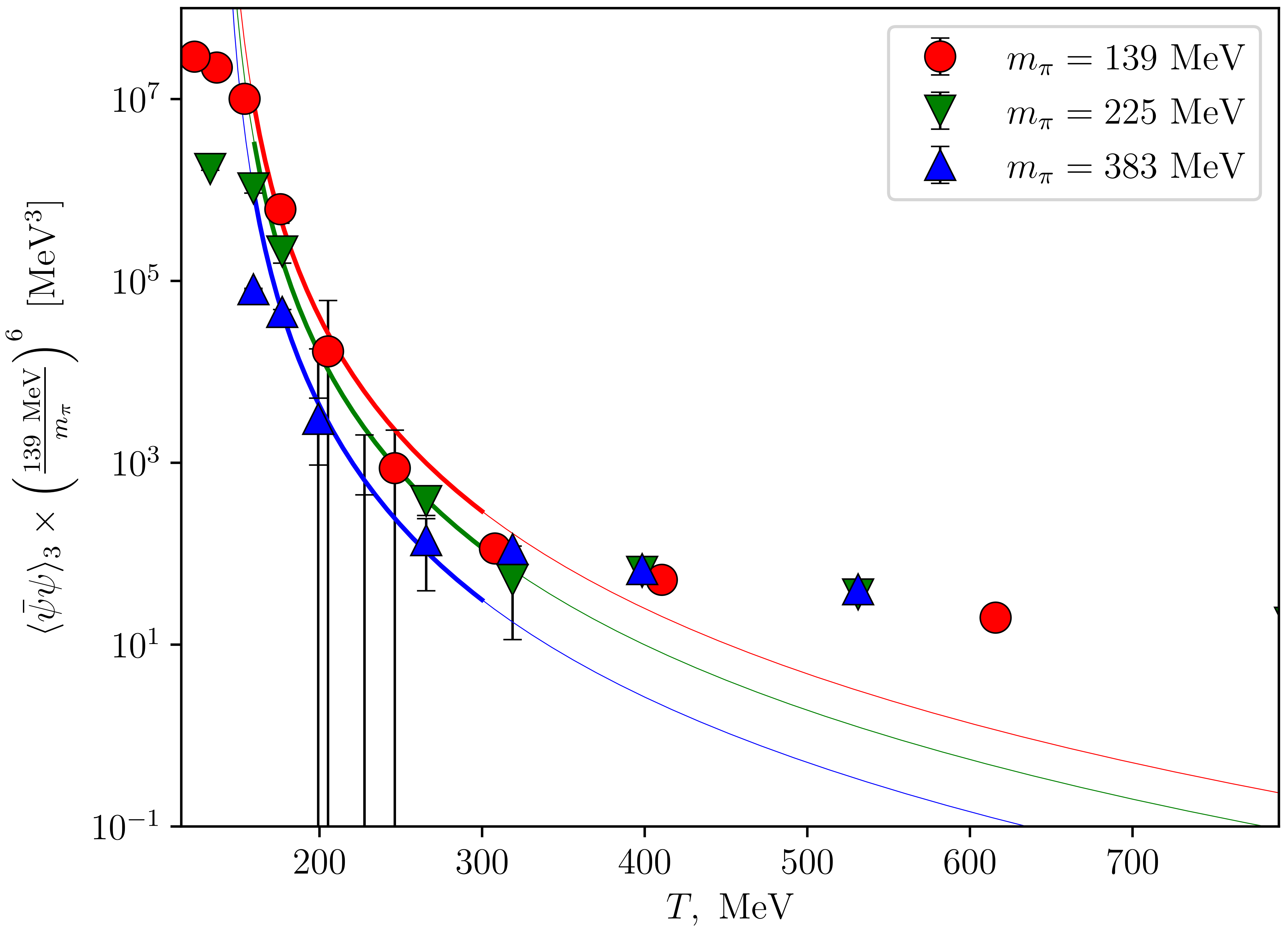
Z_2 scaling:

$m_\pi^c = 100$ MeV is still ok

$m_\pi^c = 0$ MeV is indistinguishable from O(4)

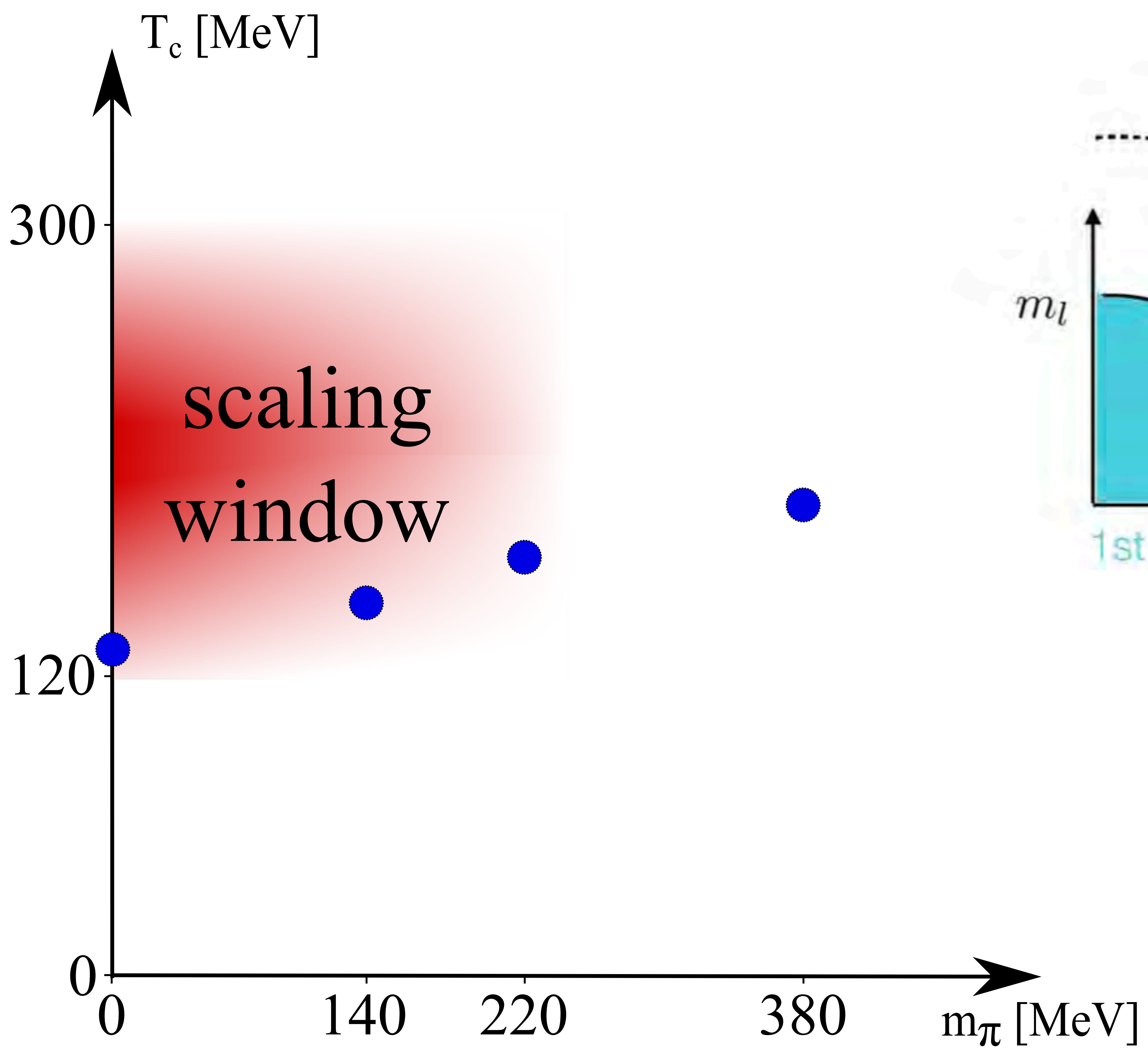
$$T_c = T_c(0) + k_s(m - m_c)^{1/\beta\delta}, m \sim m_\pi^2$$

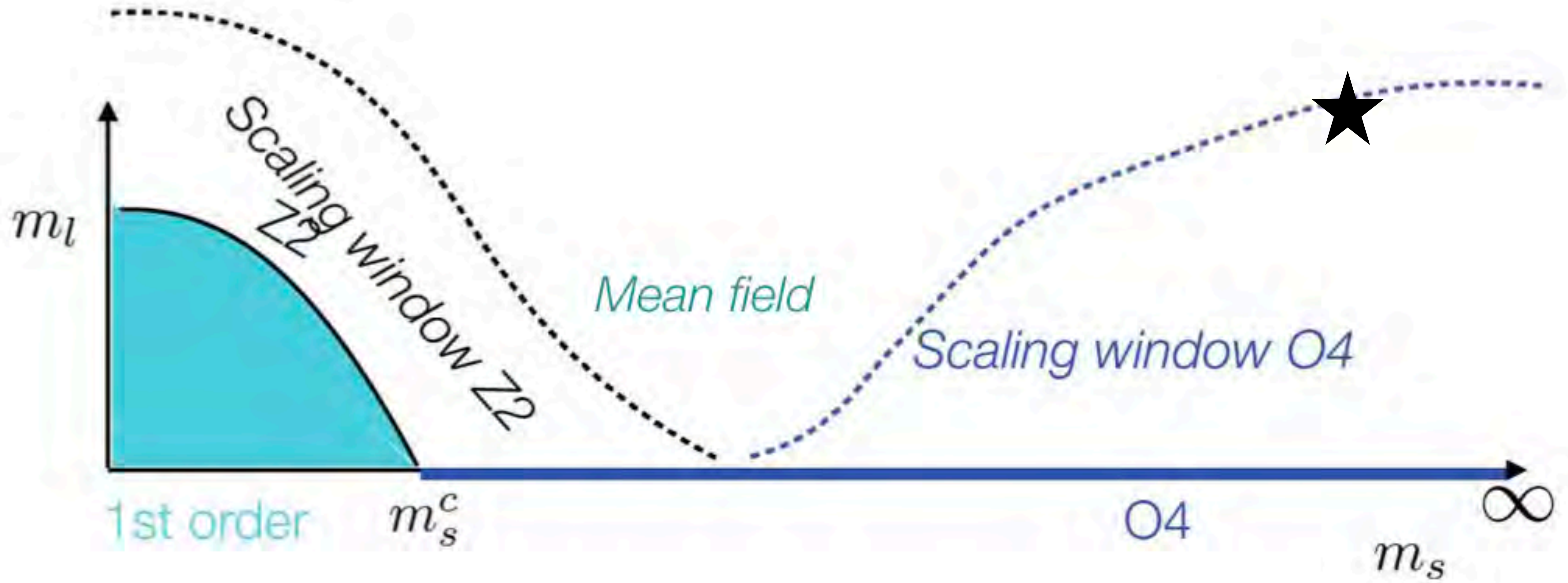
Large temperature behaviour



- O(4): $\langle\bar\psi\psi\rangle_3 \sim t^{-\gamma-2\beta\delta}$
- Griffith analyticity: $\langle\bar\psi\psi\rangle_3 \sim m^3 \sim m_\pi^6$
- $T \sim 300$ MeV

Scaling window





Threshold at $T = 300$ MeV and topology

Method to measure topological susceptibility

QCD and topology, finite temperature

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QCD and topology, finite temperature

$$\chi_{top} = \langle Q_{top} \rangle^2 / V = m_l^2 \chi_{5,disc}$$

$$m \int d^4 x \bar{\psi} \gamma_5 \psi = Q_{top}$$

[Kogut, Lagae, Sinclair, 1998]

$SU_L(2) \times SU_R(2)$

$\chi_{5,con}$ $\quad \pi : \bar{\psi}\gamma_5 \frac{\tau}{2} \psi \longleftrightarrow \sigma : \bar{\psi}\psi \quad \chi_{con} + \chi_{disc}$

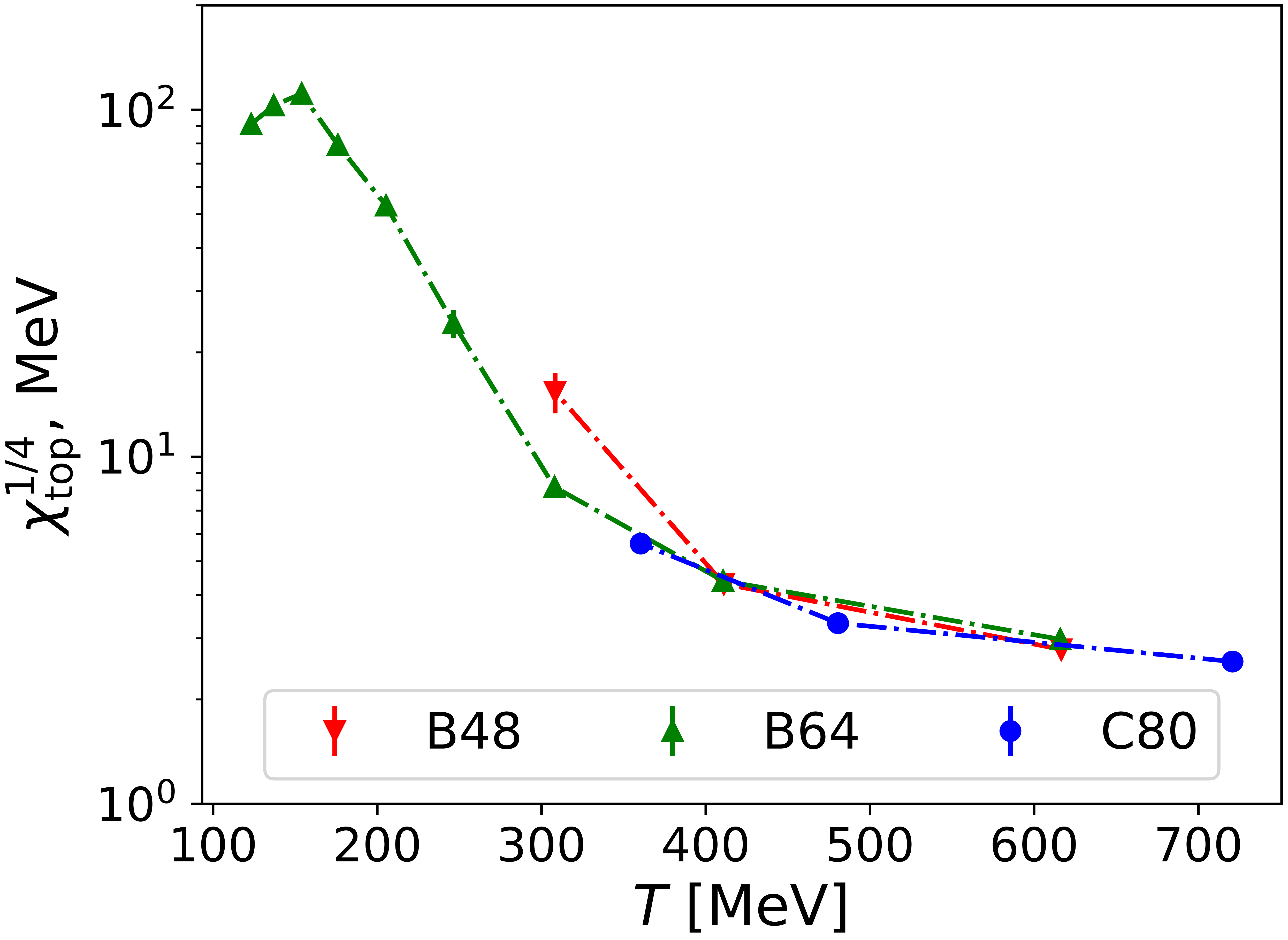
$U_A(1) \updownarrow \qquad\qquad \updownarrow U_A(1)$

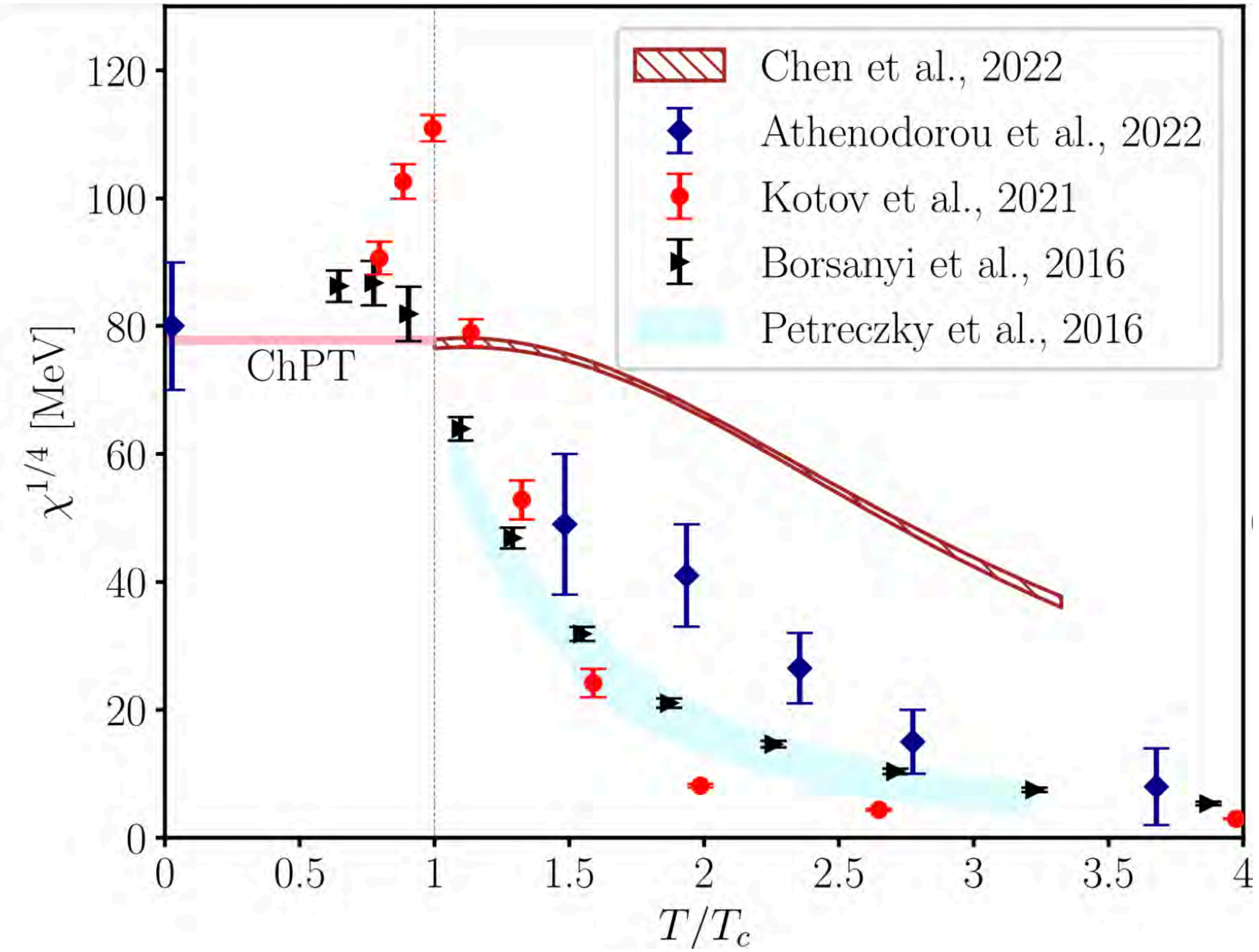
χ_{con} $\quad \delta : \bar{\psi} \frac{\tau}{2} \psi \longleftrightarrow \eta : \bar{\psi}\gamma_5 \psi \quad \chi_{5,con} - \chi_{5,disc}$

$SU_L(2) \times SU_R(2)$

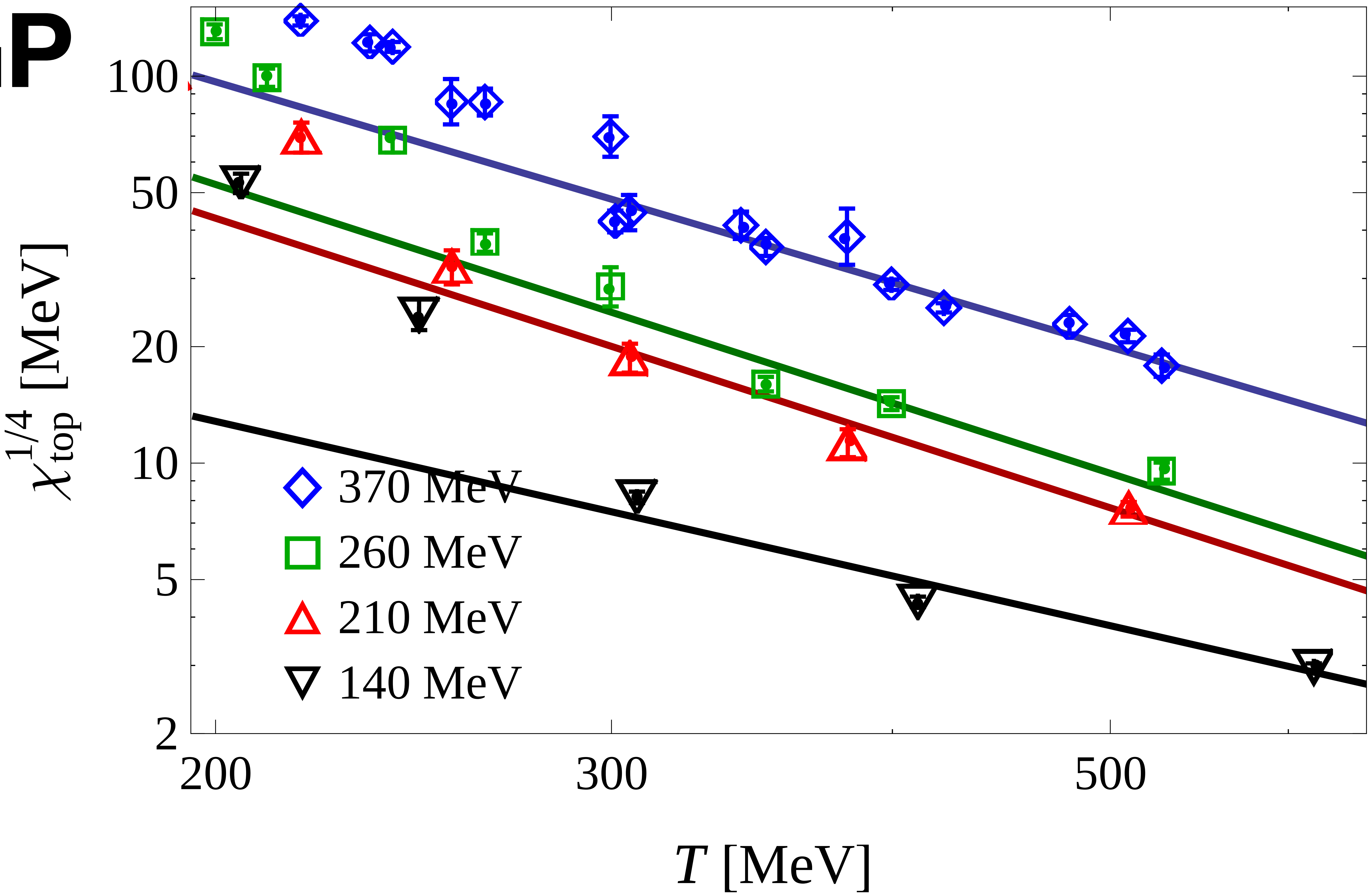
$\chi_\pi - \chi_\delta = \chi_{disc} = \chi_{5,disc}$, for $T \geq T_C, m_l \to 0$ $\Longrightarrow \chi_{top} = \langle Q_{top} \rangle^2 / V = m_l^2 \chi_{disc}$

Plot by C. Bonanno





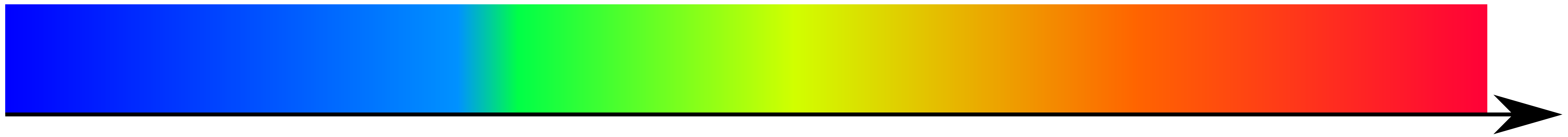
Threshold in QGP



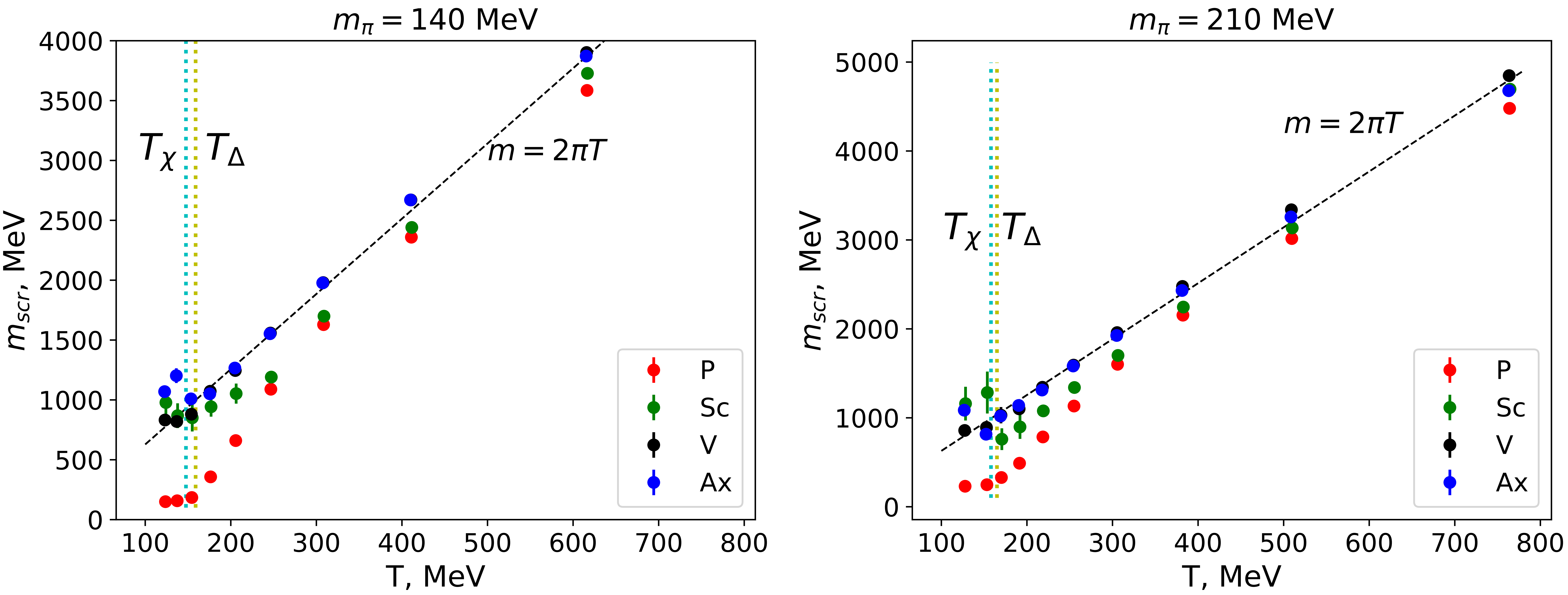
$T \sim 300$ **MeV**

- Onset of DIGA behaviour

$$\chi \sim T^{-d}$$



Screening masses



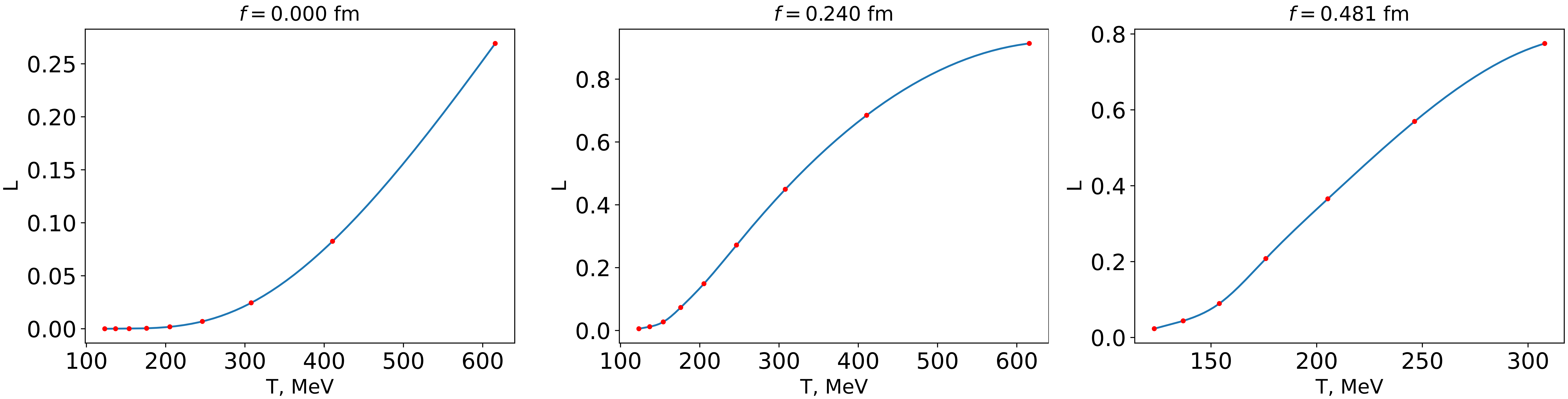
$m_\pi = 140$ MeV
$m_\pi = 210$ MeV
m_{scr}, MeV
T, MeV
T_χ
T_Δ
$m = 2\pi T$
P
Sc
V
Ax

Polyakov loop

- Polyakov loop $|\langle P \rangle| = e^{-F_Q/T}$: needs renormalisation
- Renormalise with Gradient Flow
- GF evolution: $\partial_\tau A_\mu(\tau, t, x) = -\dfrac{\partial S}{\partial A_\mu}$, smearing over radius $f = \sqrt{8\tau}$
- Different GF times $\Longrightarrow$ different renormalisation schemes: $F_Q(\tau', T) = F_Q(\tau, T) + \delta F_Q(\tau, \tau')$
- Inflection point of Polyakov loop is ambiguously defined

[TUMQCD, 2016]

- Use $F_Q(T)$ or $S_Q(T) = -\partial F_Q(T)/\partial T$



$f = 0.000$ fm
$f = 0.240$ fm
$f = 0.481$ fm
L
T, MeV
0.00
0.05
0.10
0.15
0.20
0.25
0.0
0.2
0.4
0.6
0.8
100
150
200
250
300
400
500
600

Consistent with chiral pseudo-critical temperature

Conclusions

- Thermal QCD phases by TWEXT collaboration
- $\langle\bar{\psi}\psi\rangle_3 = \langle\bar{\psi}\psi\rangle - m\chi$ for critical/scaling phenomena
- $T_0 = 134^{+6}_{-4}$ MeV in the chiral limit $m \to 0$
- Consistent with $O(4)$ scaling for $m_\pi \lesssim 140$ MeV, $T \in [120,\ 300]$ MeV
- $T \sim 300$ MeV: indications of threshold in QGP