ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

RMT in sub-atomic physics and beyond

5 August 2019

Maria Paola Lombardo

Celebrating Jac Verbaarschot's birthday

Crossing paths with Jac..

The Fluctuations of the Quark Number and of the Chiral Condensate

M.P. Lombardo,[1] K. Splittorff,[2] and J.J.M. Verbaarschot[3]

..collaborating..

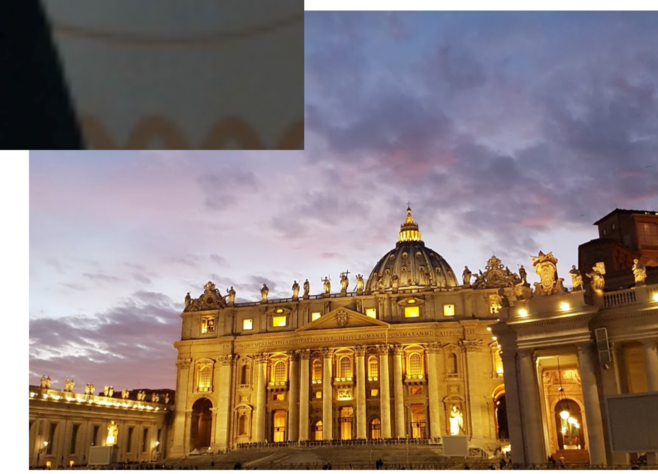
A Mesoscopic Approach to the QCD Phase Diagram

Maria Paola LOMBARDO,[1] K. SPLITTORFF[2] and Jacobus J. M. VERBAARSCHOT[3]

NY

Rome

..mutual visits ..



…by sheer chance! ..

..at many workshops…

Crossing paths with Jac.. ..always a pleasure !

A Very Happy Birthday to You!

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RMT in sub-atomic physics and beyond

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Symmetries and Topology of strong interactions, between the QCD and the EW transition.

Maria Paola Lombardo

INFN Firenze

Florian Burger, Ernst-Michael Ilgenfritz, MpL and Anton Trunin Phys. Rev. D 98, 094501 (2018)
Andrey Kotov, MpL, Anton Trunin, Phys.Lett. B794 (2019)

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE

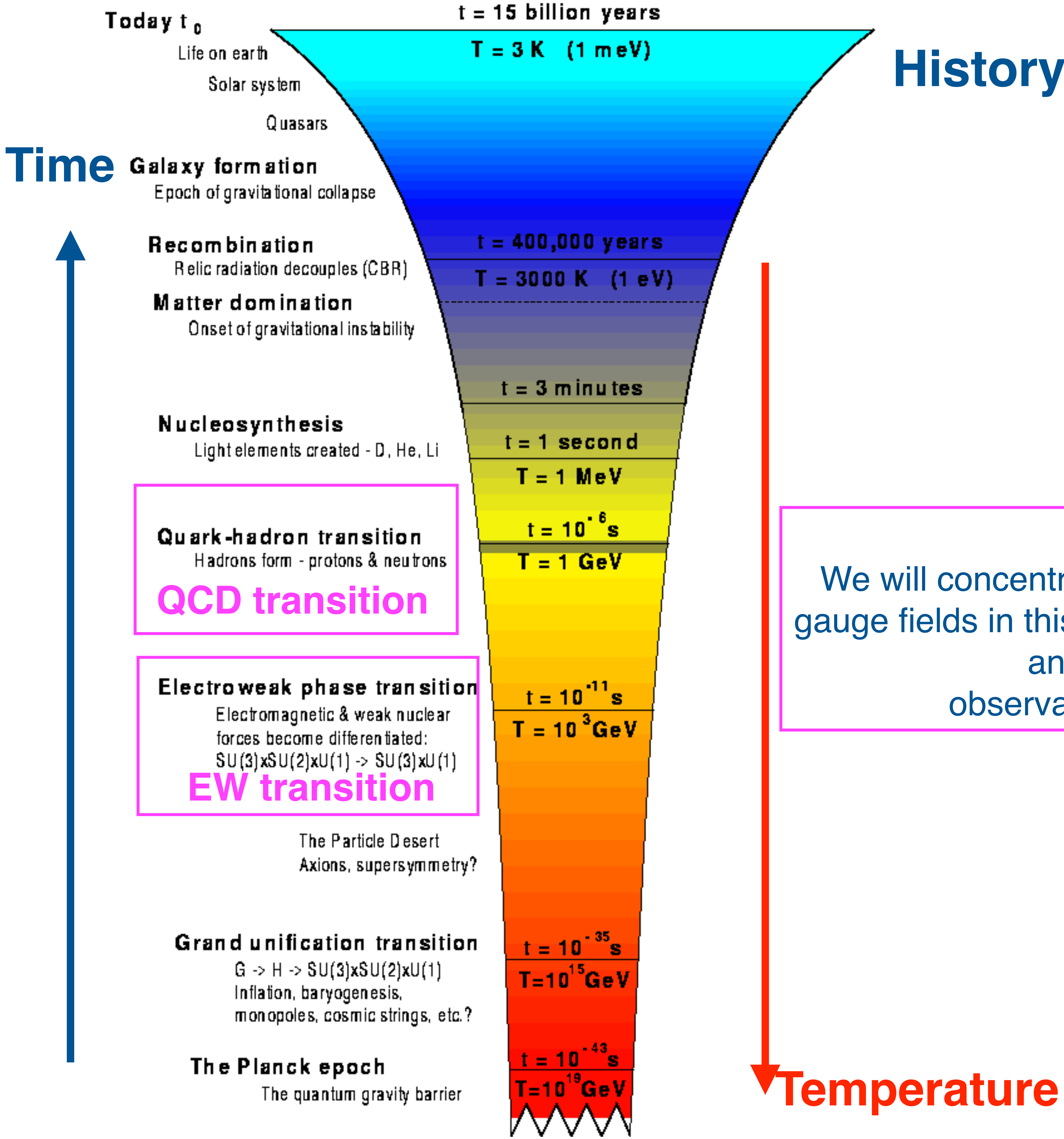
cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

The two faces of QCD topology

Window to Dark Matter

Strong interactions dynamics

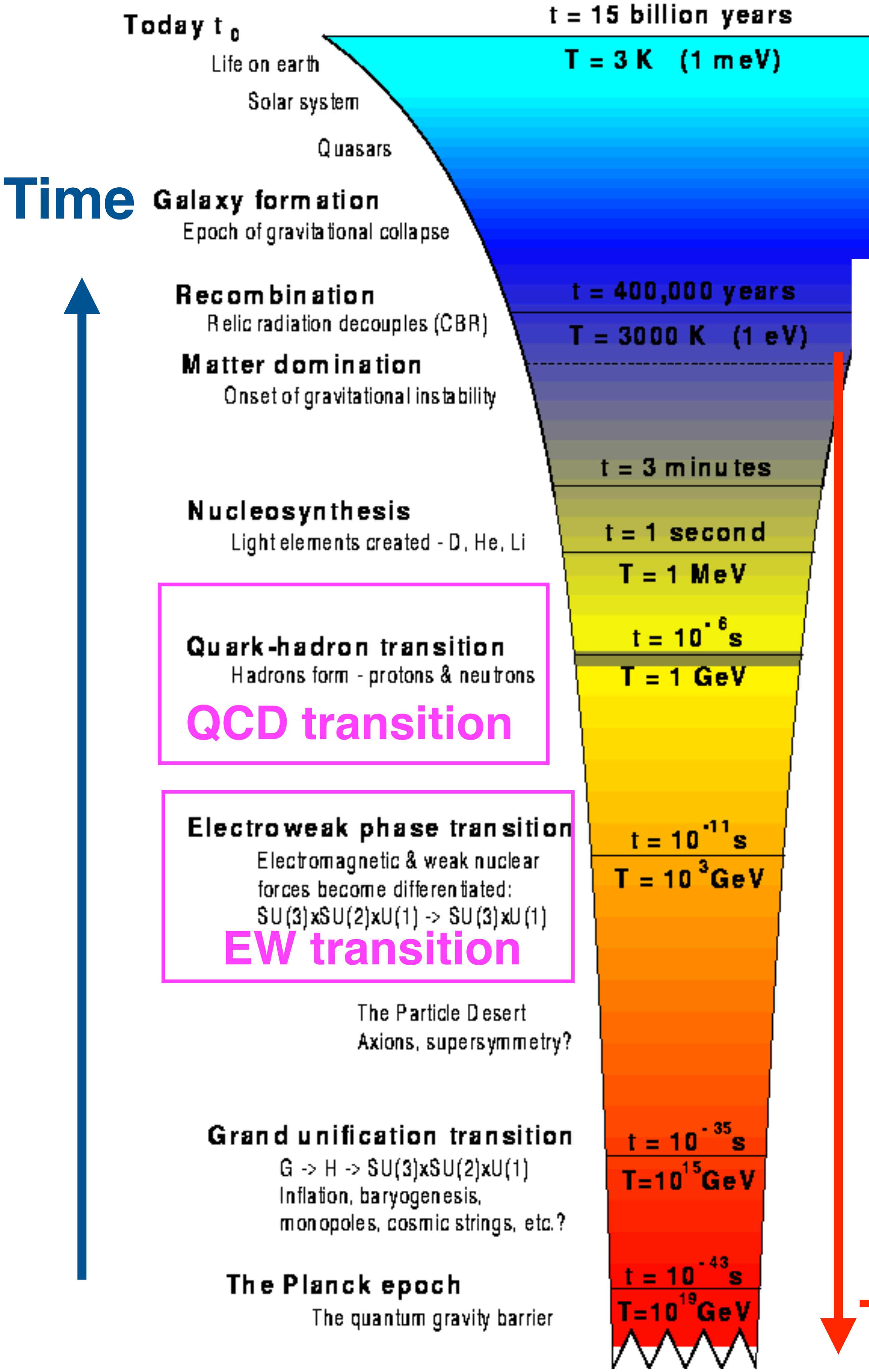
History of the Universe

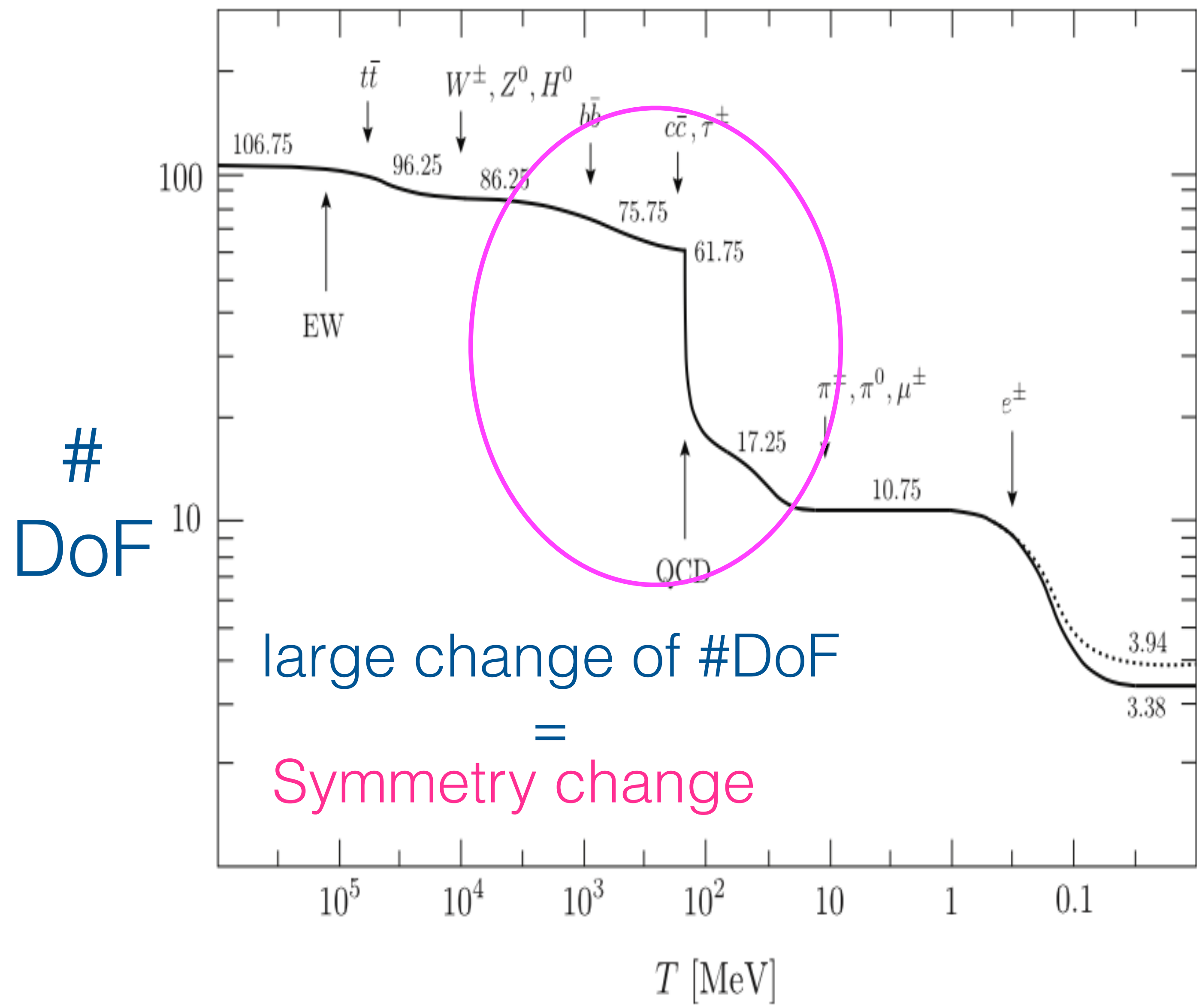


We will concentrate on the topology of gauge fields in this range of temperatures, and on their observable properties

Cambridge, DAMTP

History of the Universe





Cambridge, DAMTP

QCD Lagrangian symmetries:

Always exact

$$SU(N_f)_L \times SU(N_f)_R \times U(1)_A \times U(1)_B.$$

Breaking/restoration
at Tc
studied a lot
on the lattice

Always broken if topological charge
fluctuates!

DOES IT?

BUT:
the 'amount' of breaking,
may
depend on temperature!

HOW ARE THESE RELATED??

IMPLICATIONS?

Plan

Axions
Topology in QCD

Results:

Topological Susceptibility
Bounds on the QCD axion's mass
The η' and its fate in the plasma

Axion:

theoretically well motivated

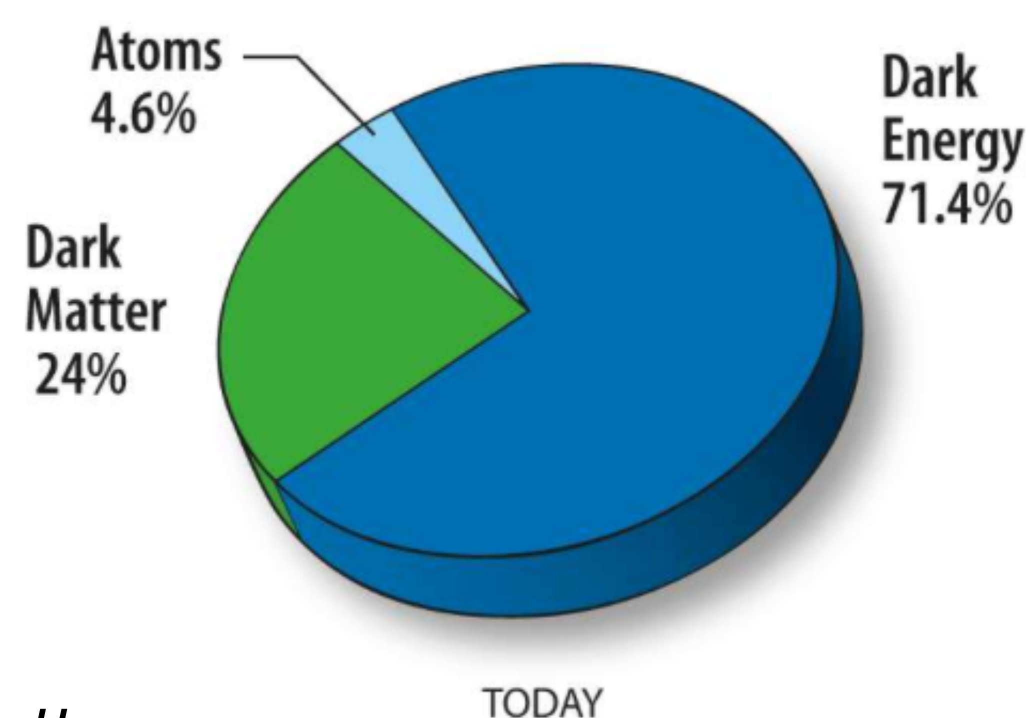
searched and not found in experiments ->weakly coupled

-> Dark Matter Candidate

Rough estimate for axion contribution to DM

$$\frac{\rho_{\text{axion}}}{\rho_{DM}} \sim \left(\frac{f_a}{10^{11}\text{GeV}}\right)^{\frac{3}{2}}$$

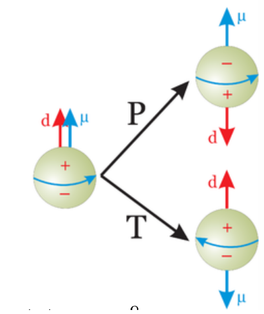
from ‘almost’ 1 till ‘very small



Axions 'must' be there: solution to the strong CP problem

$$\mathcal{L}_{QCD}(\theta) = \mathcal{L}_{QCD} + \frac{g^2\theta}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}F^a_{\mu\nu}F^a_{\rho\sigma}.$$

Ammitted but $\theta < 10^{-9}$



$$Q = \int d^4x \, \frac{g^2}{32\pi^2}\mathrm{tr}F\tilde{F}$$

Top. charge

Postulate axions, coupled to Q:

$$\mathcal{L}_{\mathrm{axions}} = \frac{1}{2}(\partial_\mu a)^2 + \left(\frac{a}{f_a} + \theta\right)\frac{1}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}$$

$$Z_{QCD}(\theta, T) = \int [dA][d\psi][d\bar{\psi}] \exp\left(-T\sum_t d^3x\, \mathcal{L}_{QCD}(\theta)\right) = \exp[-VF(\theta, T)]$$

$$m_a^2(T)f_a^2 = \left.\frac{\partial^2 F(\theta, T)}{\partial\theta^2}\right|_{\theta=0} \equiv \chi(T),$$

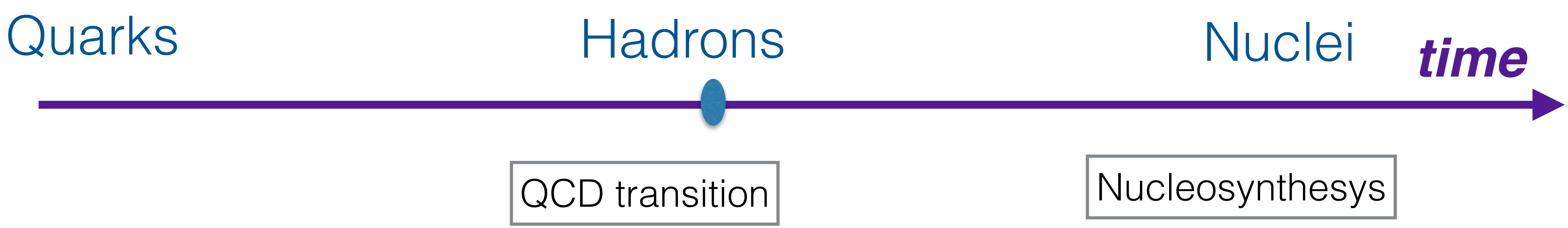
Top. Susceptibility

QCD topology and phenomenology

Hadron cosmology:

Origin of mass

Almost all hadrons can be described taking into account chiral symmetry breaking and confining potential



Chiral symm. breaking
Confinement:

Chiral perturbation theory +
Potential models
=
Hadron spectrum

Hadron cosmology:

Origin of mass

Almost all hadrons can be described taking into account chiral symmetry breaking and confining potential

With an important exception

Quarks — Hadrons — Nuclei → ***time***

QCD transition

Nucleosynthesys

Chiral symm. breaking
Confinement:

Chiral perturbation theory +
Potential models
=
Hadron spectrum

Pseudoscalar light spectrum: eight pseudoGoldstones

$$SU(3)_L X SU(3)_R \rightarrow SU(3)_V$$

χPT predicts

$$m_\pi^2 \propto (m_u + m_d)\Lambda_{QCD}$$
$$m_K^2 \propto (m_s + m_{u,d})\Lambda_{QCD}$$
$$m_\eta^2 \propto \frac{1}{3}(m_u + m_d + 4m_s)\Lambda_{QCD} \ ,$$

Particle name	Particle symbol	Antiparticle symbol	Quark content	Rest mass (MeV/c^2)
Pion[6]	π^+	π^-	$u\bar{d}$	139.570 18 ±0.000 35
Pion[7]	π^0	Self	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$ [a]	134.9766 ±0.0006
Eta meson[8]	η	Self	$\frac{u\bar{u}+d\bar{d}-2s\bar{s}}{\sqrt{6}}$ [a]	547.862 ±0.018
Eta prime meson[9]	η'(958)	Self	$\frac{u\bar{u}+d\bar{d}+s\bar{s}}{\sqrt{3}}$ [a]	957.78 ±0.06
Kaon[12]	K^+	K^-	$u\bar{s}$	493.677 ±0.016
Kaon[13]	K^0	$\bar{K}^0$	$d\bar{s}$	497.614 ±0.024

$U(1)_A$

should be broken as well producing a 9th Goldstone BUT:

Exception!

η' is too heavy

Topology, η' and the $U_A(1)$ problem:

The $U_A(1)$ symmetry $q \to e^{i\alpha\gamma_5} q$

would be broken by the (spontaneously generated) $\bar{q}q$:

the candidate Goldstone is the η'

too heavy!! (900 MeV)

Particle name	Particle symbol	Antiparticle symbol	Quark content	Rest mass (MeV/c²)
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BUT:
the divergence of the current $j_5^\mu = \bar{q}\gamma_5\gamma_\mu q,$

contains a mass independent term ↓

$$\partial_\mu j_5^\mu = m\bar{q}\gamma_5 q + \frac{1}{32\pi^2} F\tilde{F}.$$

IF $\frac{1}{32\pi^2}\int d^4x F\tilde{F} \neq 0$

The $U_A(1)$ symmetry is **explicitly** broken

Topology, η' and the $U_A(1)$ problem:

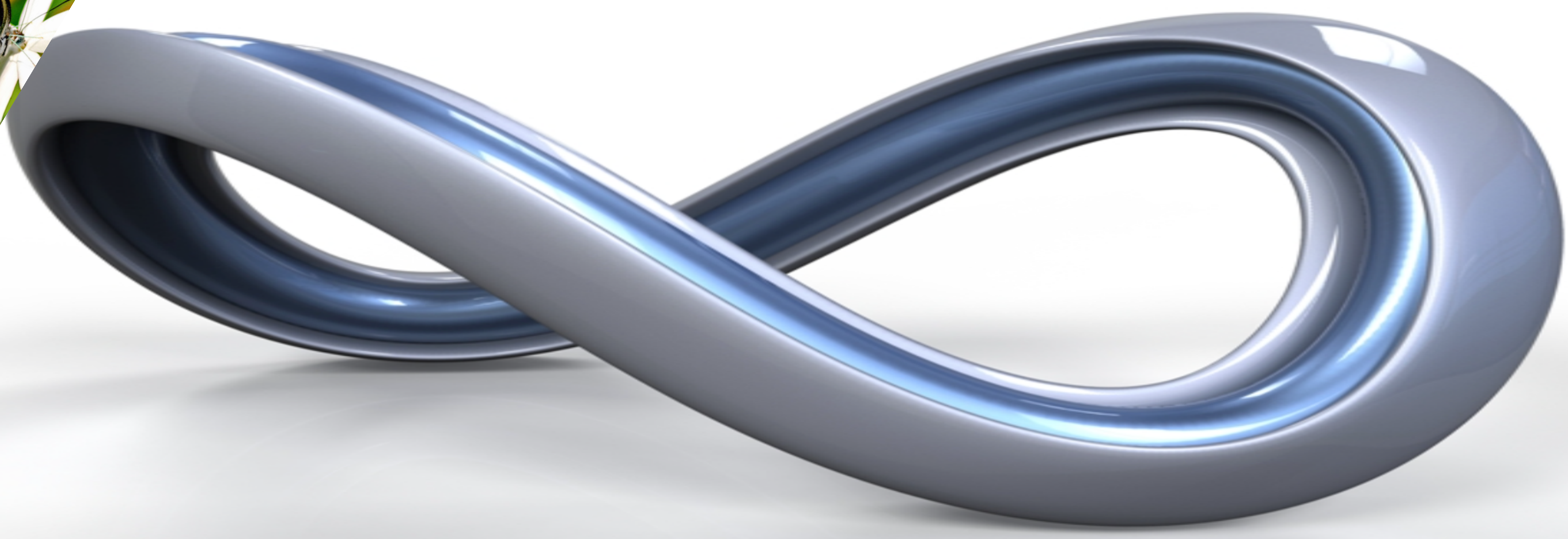
It can be proven that

$$\frac{1}{32\pi^2}\int d^4x F\tilde{F} = Q$$ **Gluonic definition**

and

$$Q = n_+ - n_-$$ **Fermionic definition**

$$F\tilde{F}$$



Topology, η' and the $U_A(1)$ problem:

It can be proven that

$$\frac{1}{32\pi^2}\int d^4x F\tilde{F} = Q$$

Gluonic definition

and

$$Q = n_+ - n_-$$

Fermionic definition

The η' mass may now be computed from the decay of the correlation

$$\langle \partial_\mu j_5^\mu(x) \partial_\mu j_5^\mu(y) \rangle \propto \frac{1}{N^2} \langle F(x)\tilde{F}(x)F(y)\tilde{F}(y) \rangle$$

which at leading order gives the Witten-Veneziano formula

$$m_{\eta'}^2 = \frac{2N_f}{F_\pi^2}\chi_t^{\mathrm{qu}}$$

Topology, η' and the $U_A(1)$ problem:

It can be proven that

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The η' mass may now be computed from the decay of the correlation

Q(x) Q(y)

$$\langle \partial_\mu j_5^\mu(x)\partial_\mu j_5^\mu(y)\rangle \propto \frac{1}{N^2}\langle F(x)\tilde{F}(x)F(y)\tilde{F}(y)\rangle$$

which at leading order gives the Witten-Veneziano formula

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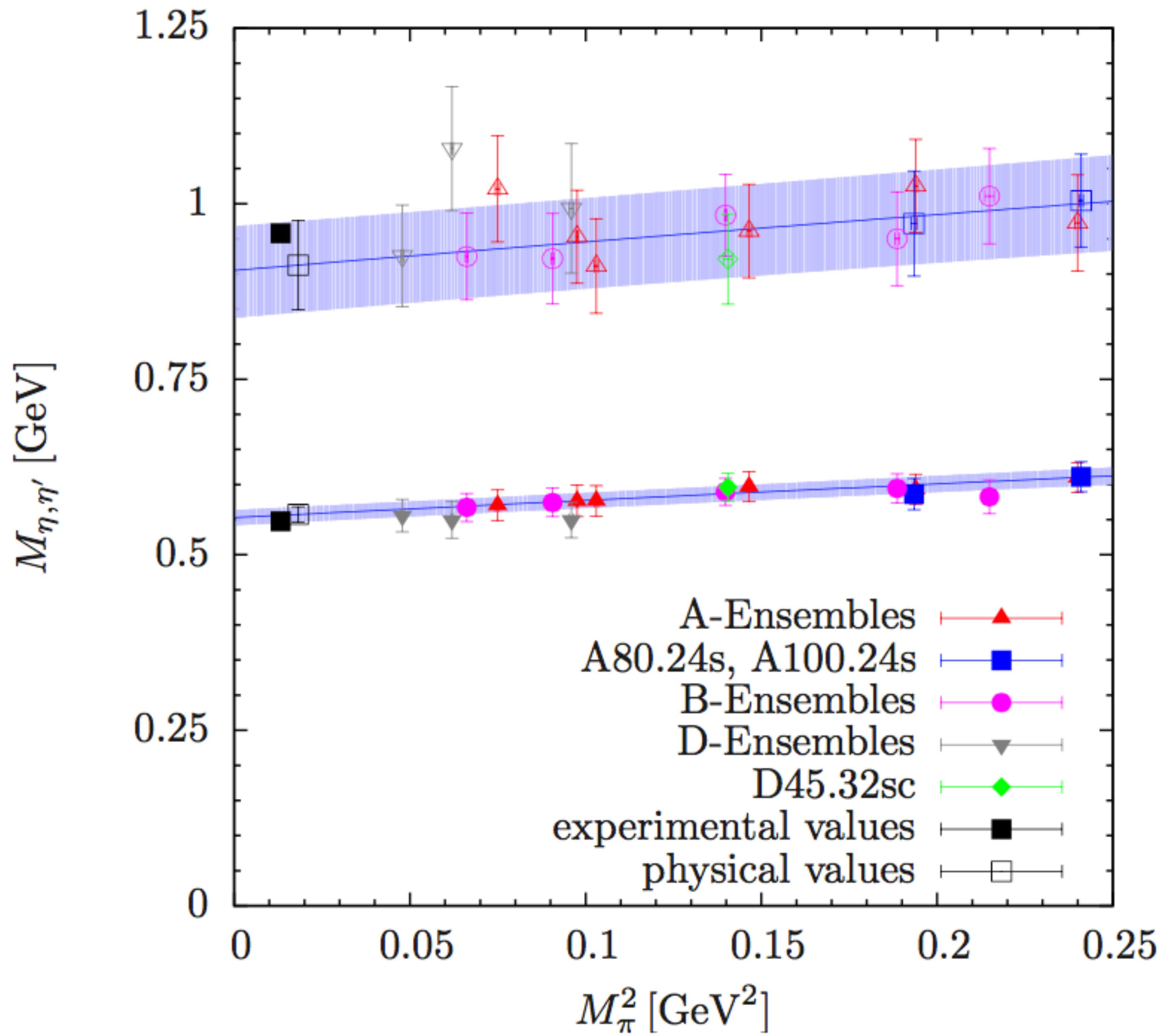
Successful at T=0

Topology, η' and the $U_A(1)$ ~~problem~~ solution



ETMC 2017

Results

Twisted mass Wilson Fermions, Nf=2+1+1

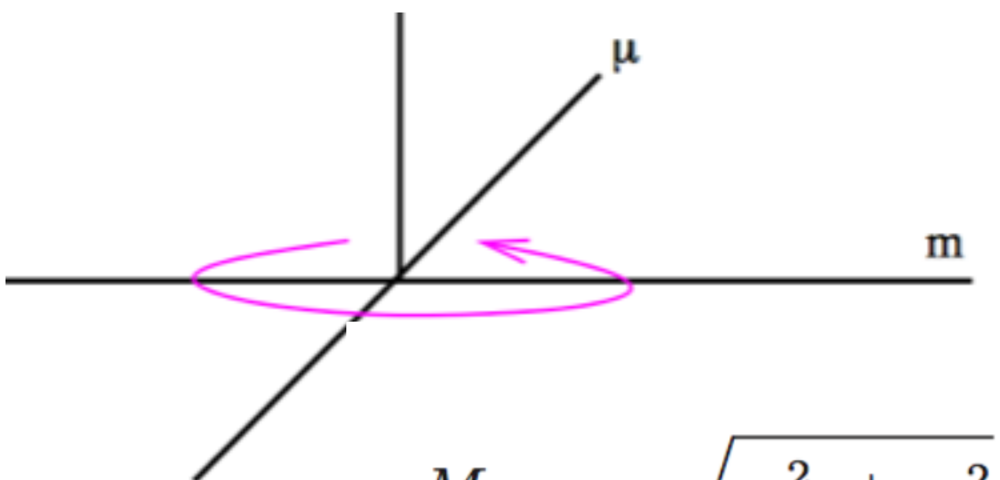
Wilson fermions with a twisted mass term

Frezzotti Rossi 2003

A twisted mass term in flavor space:

$i\mu\tau_3\gamma_5$ for two degenerate light flavors

is added to the standard mass term in the Wilson Lagrangian



$$M_{\rm inv} = \sqrt{m_0^2 + \mu_q^2}$$

Consequences:

- -simplified renormalization prop
- -automatic O(a) improvement
- -control on unphysical zero modes

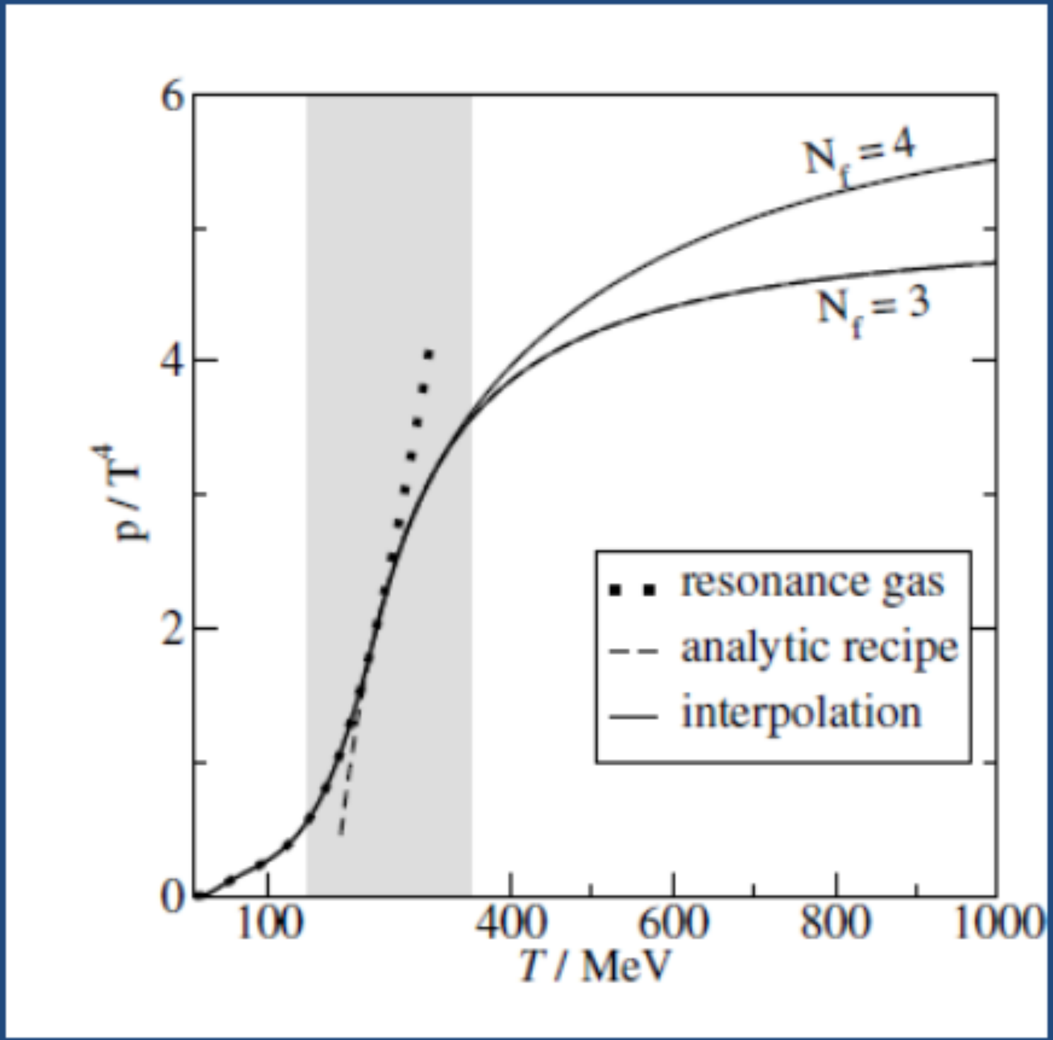
Successful phenomenology at T=0

ETMC collaboration 2003—

Why Nf = 2 +1 +1 ?

Tc ≈200MeV

340 –380 MeV RHIC AuAu 200 GeV	420-480 MeV LHC 2.76 TeV	500- 600MeV LHC hot spots 2.76 TeV	→	1 GeV LHC 7 TeV



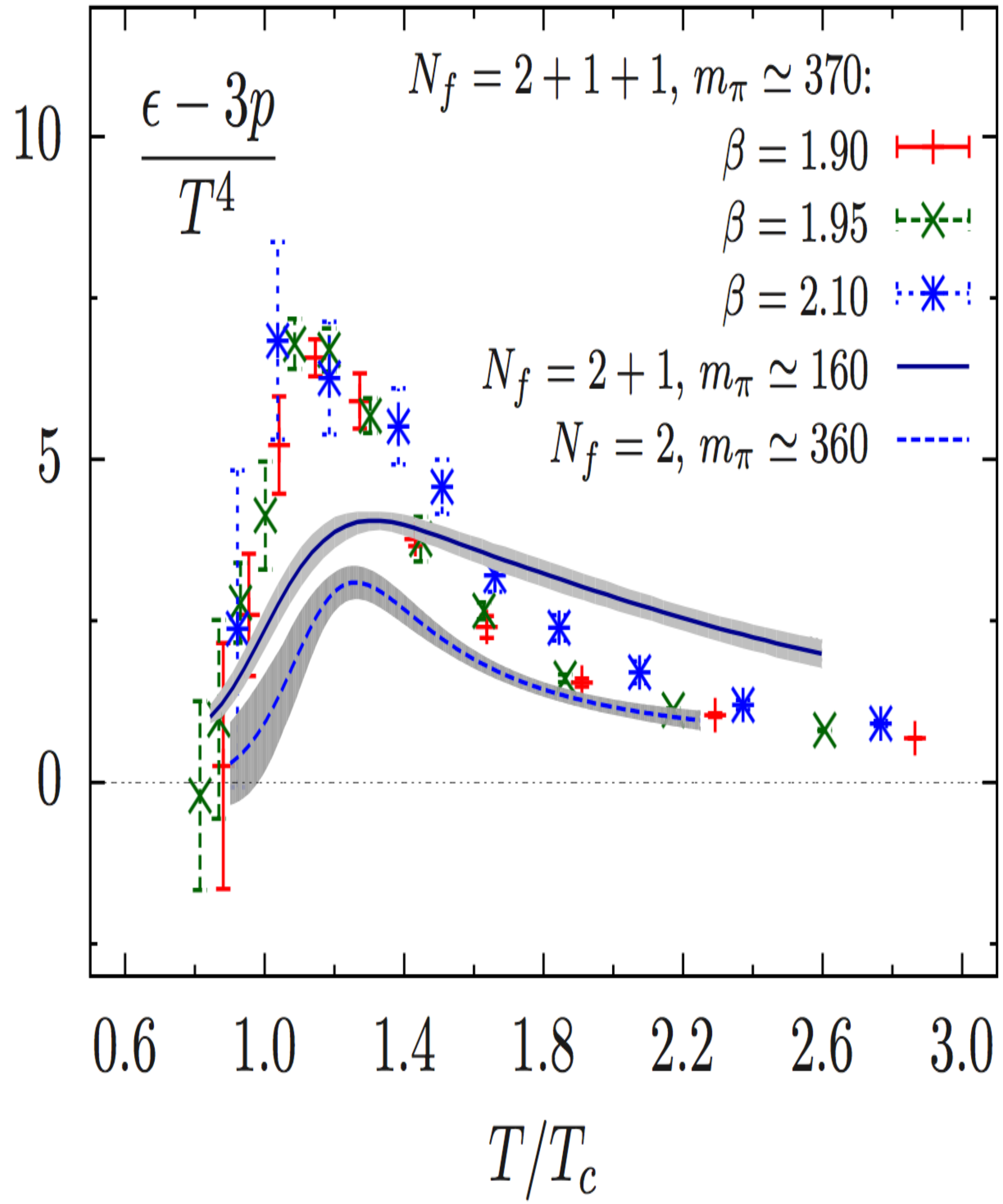
Quark Gluon Plasma @ Colliders

Analytic studies suggest that a dynamical charm becomes relevant above 400 MeV, well within the reach of LHC

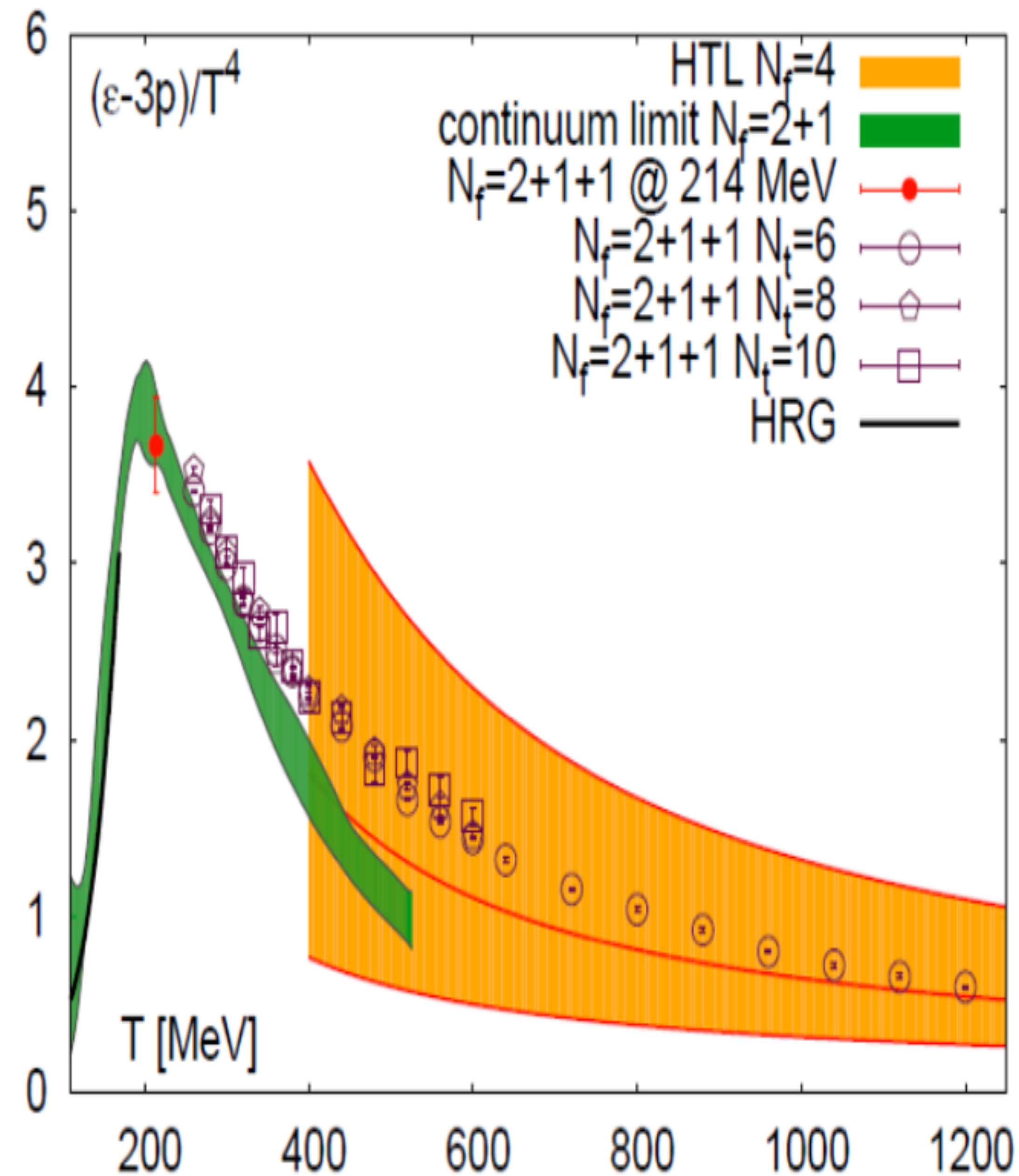
Laine Schroeder 2006

Trace anomaly: effects of a dynamical charm

Tmft



Wuppertal-Budapest



Staggered

Nf = 2 +1+1 Setup

Fixed varying scale

For each lattice spacing we explore a range of temperatures 150MeV — 500 MeV by varying Nt

We repeat this for three different lattice spacings following ETMC T=0 simulations.

Four pion masses

Number of flavours	$m_{\pi^\pm}$
$N_f = 2+1+1$	210 260 370 470
$N_f = 2$	360 430

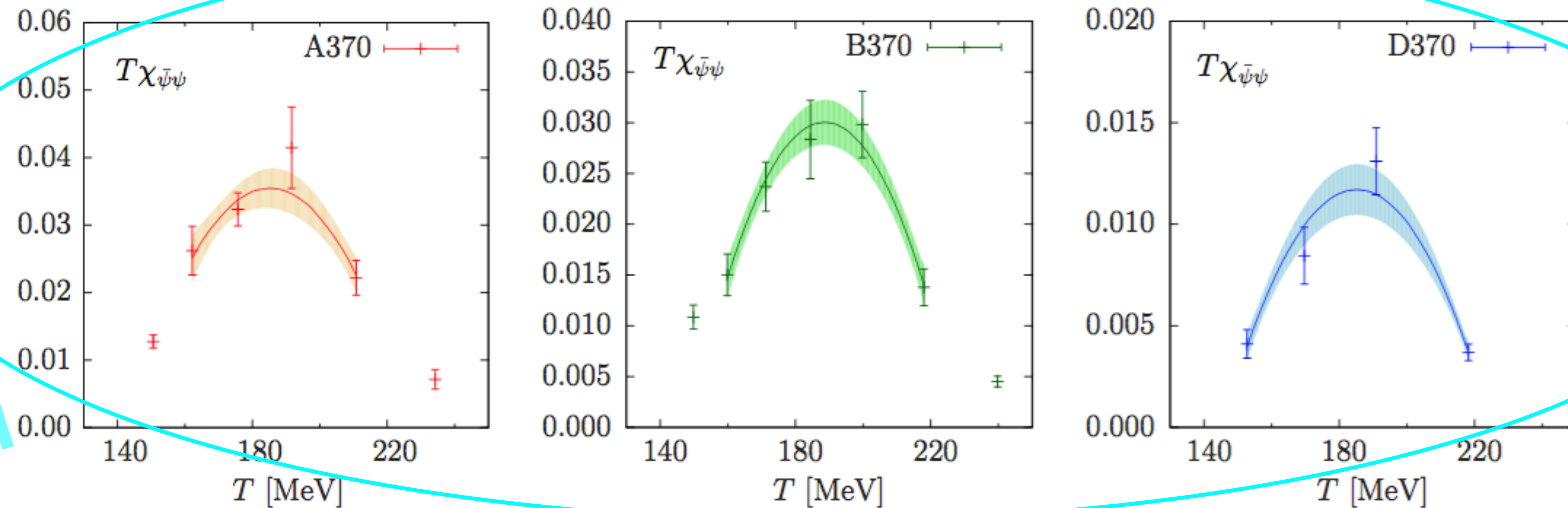
Advantages: we rely on the setup of ETMC T=0 simulations. Scale is set once for all.

Disadvantages: mismatch of temperatures - need interpolation before taking the continuum limit

$T=0$ (ETMC) nomenclature	β	a [fm] [6]	N_σ^3	N_τ	T [MeV]	# confs.
A60.24	1.90	0.0936(38)	24^3	5	422(17)	585
				6	351(14)	1370
				7	301(12)	341
				8	263(11)	970
				9	234(10)	577
				10	211(9)	525
				11	192(8)	227
				12	176(7)	1052
			32^3	13	162(7)	294
				14	151(6)	1988
B55.32	1.95	0.0823(37)	32^3	5	479(22)	595
				6	400(18)	345
				7	342(15)	327
				8	300(13)	233
				9	266(12)	453
				10	240(11)	295
				11	218(10)	667
				12	200(9)	1102
				13	184(8)	308
				14	171(8)	1304
				15	160(7)	456
				16	150(7)	823
D45.32	2.10	0.0646(26)	32^3	6	509(20)	403
				7	436(18)	412
				8	382(15)	416
				10	305(12)	420
				12	255(10)	380
				14	218(9)	793
				16	191(8)	626
			40^3	18	170(7)	599
			48^3	20	153(6)	582

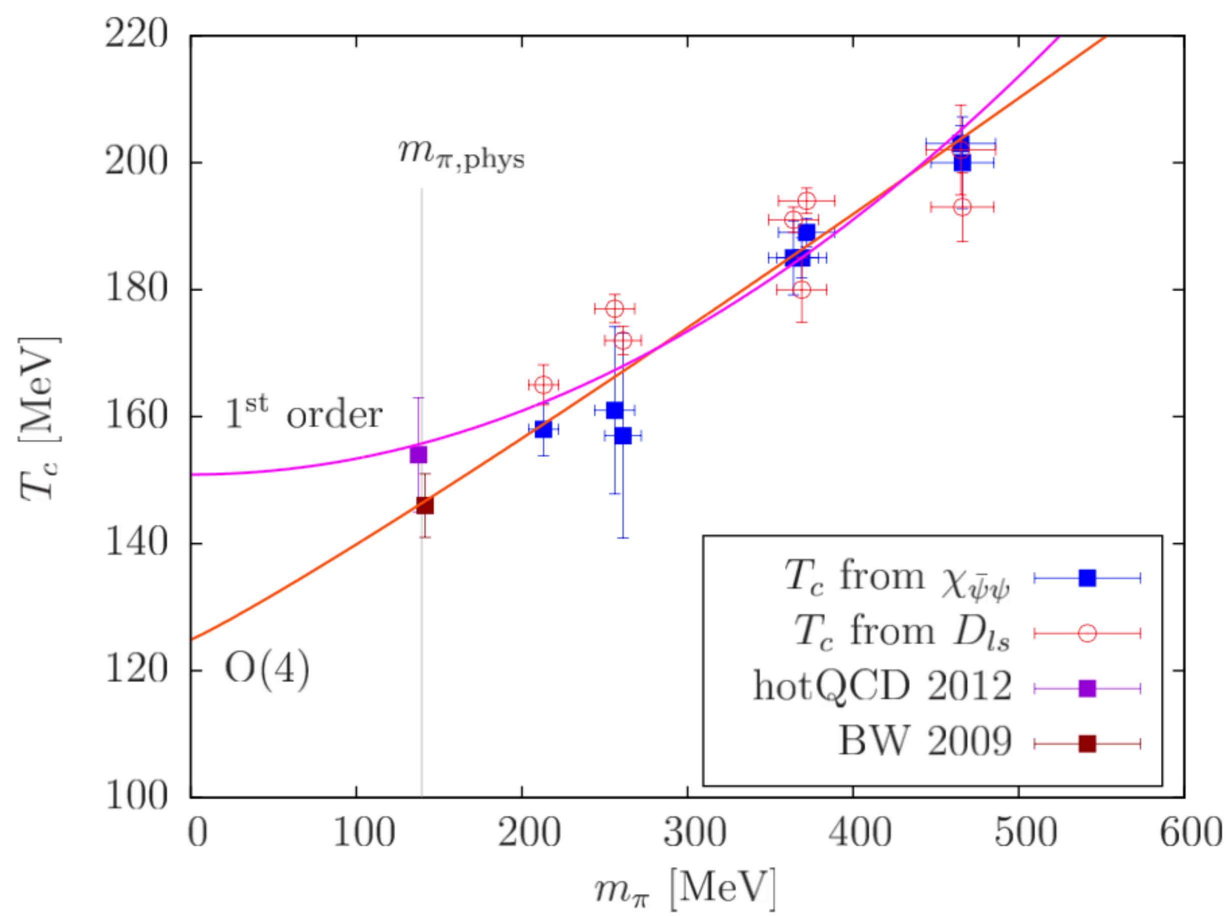
Overview of Chiral observables
Nf 2 + 1 +1

Outcome: twisted mass ok; and the results confirm that a dynamical charm does not contribute around Tc



a [fm]	m_π [MeV]	T_χ [MeV]	T_Δ [MeV]	$T_{\rm deconf}$ [MeV]
0.065	213	158(1)(4)	165(3)(1)	176(8)(8)
0.094	261	157(8)(14)	172(2)(1)	188(6)(1)
0.082	256	161(13)(2)	177(2)(1)	192(9)(2)
0.094	364	185(5)(3)	191(2)(0)	202(3)(0)
0.082	372	189(2)(1)	194(2)(0)	201(6)(0)
0.065	369	185(1)(3)	180(5)(1)	193(13)(2)
0.094	466	200(4)(6)	193(5)(2)	205(4)(2)
0.082	465	203(2)(2)	202(7)(1)	212(6)(1)

spacing effects below statistical errors



Topology

Topological and chiral susceptibility

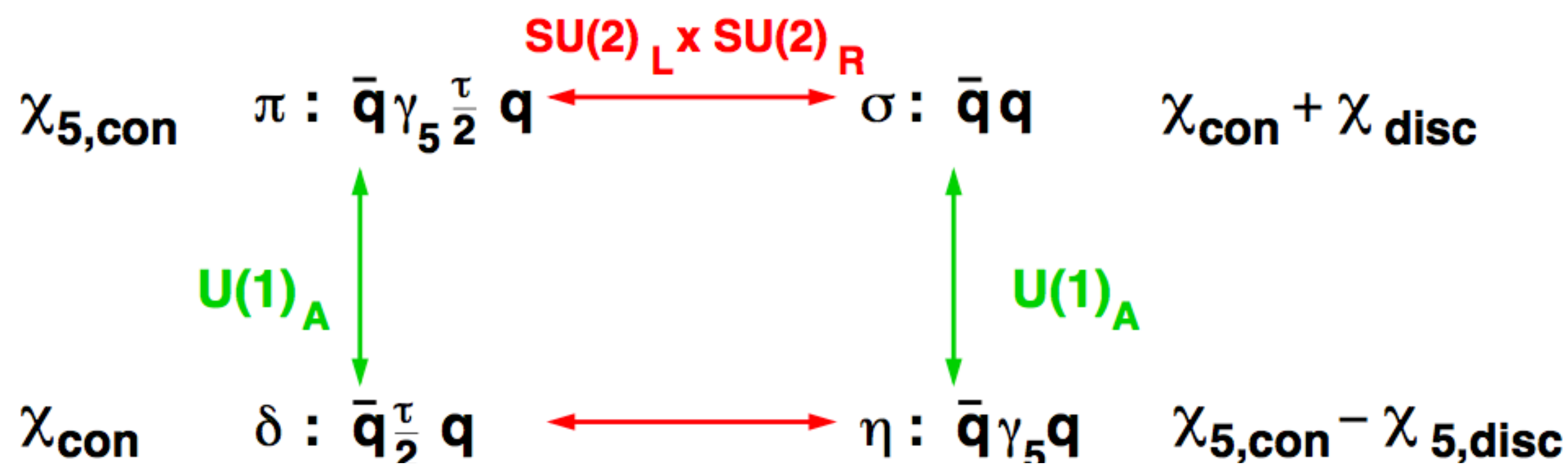
Kogut, Lagae, Sinclair 1999

HotQCD, 2012

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

From:

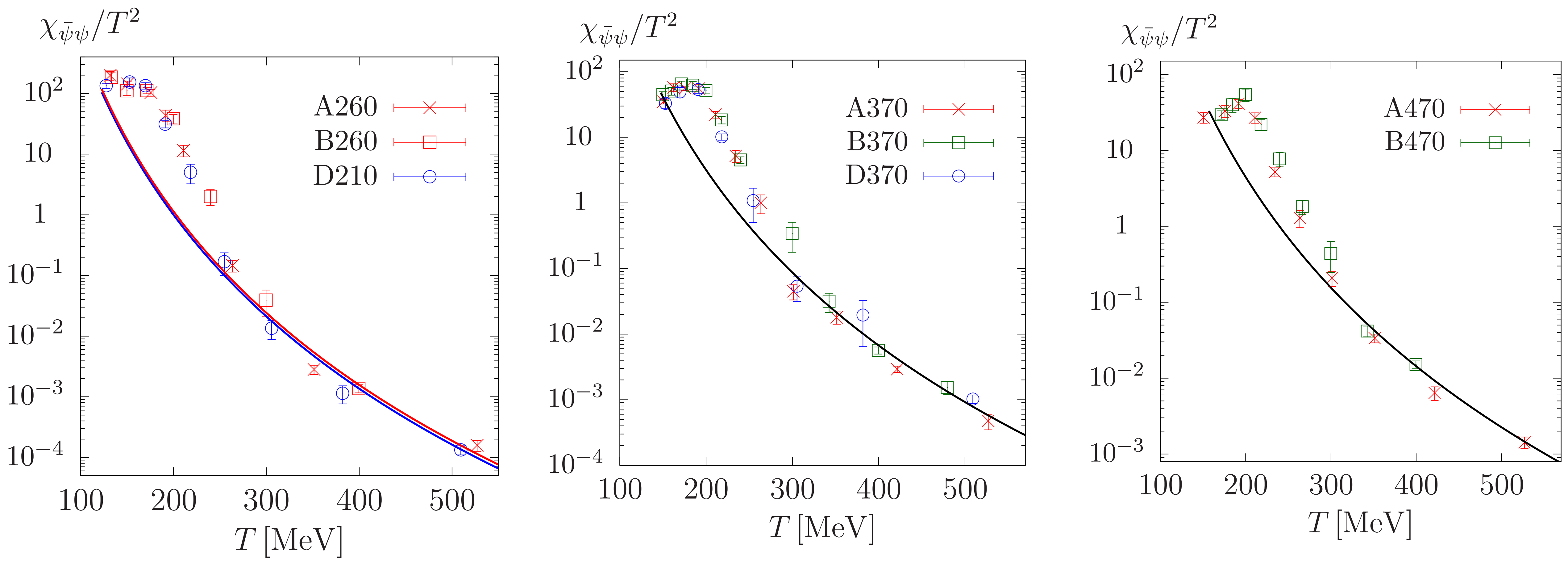
$$m \int d^4x \bar{\psi}\gamma_5\psi = Q_{top}$$



$$\chi_\pi - \chi_\delta = \chi_{\rm disc} = \chi_{5,\rm disc} \,, \qquad \text{for} \quad T \geq T_c \,, \; m_l \to 0$$

$$\chi_{top} = < Q_{top}^2 > /V = m_l^2 \chi_{disc}$$

Chiral susceptibility

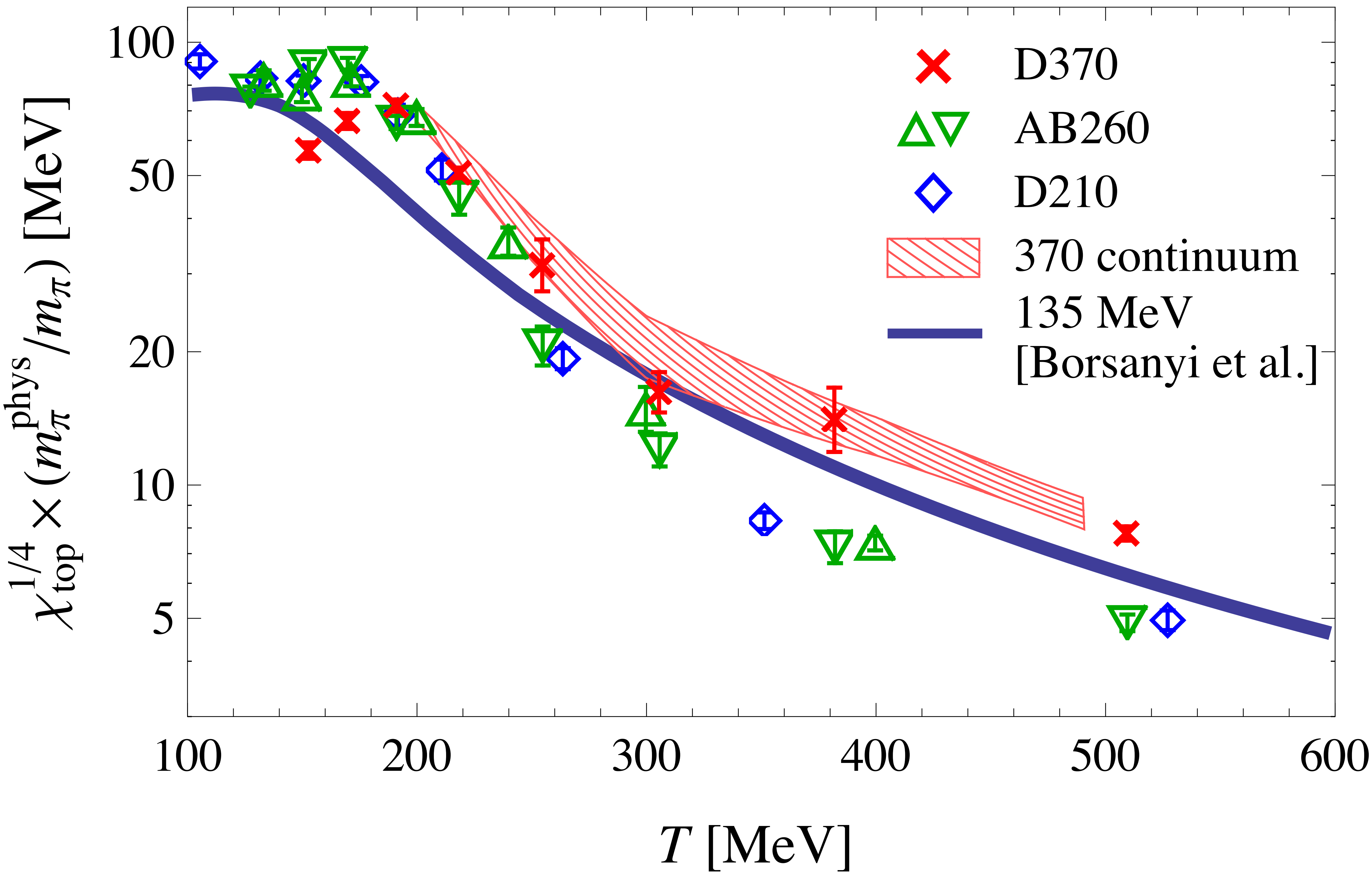


Within errors, no discernable spacing dependence

Results for physical pion mass

Rescaled according to

$$\chi_{\mathrm{top}} = m_l^2 \chi_{\bar{\psi}\psi}^{\mathrm{disc}} = \sum_{n=0} a_n m_\pi^{4(n+1)}.$$

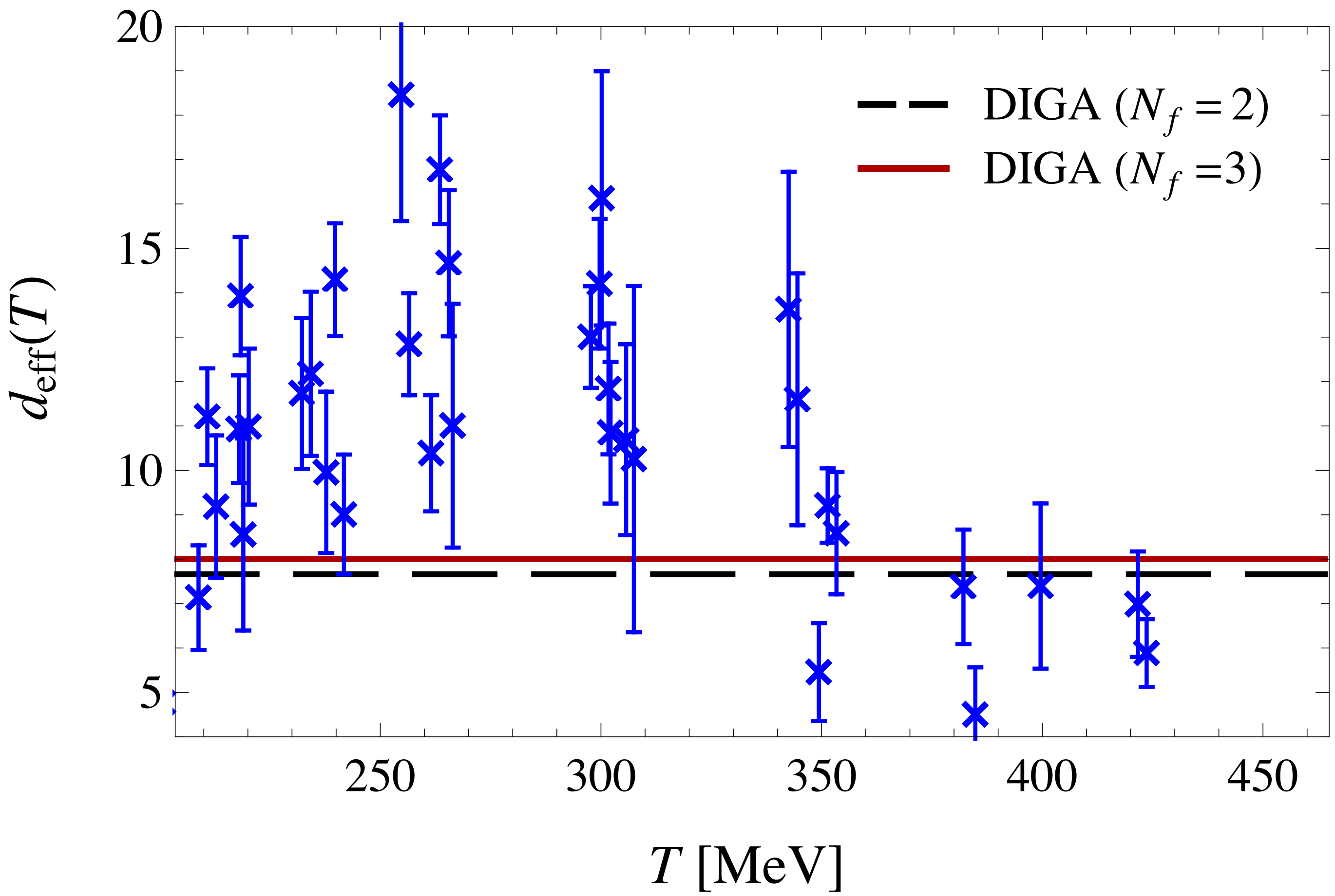


Power-law decay?

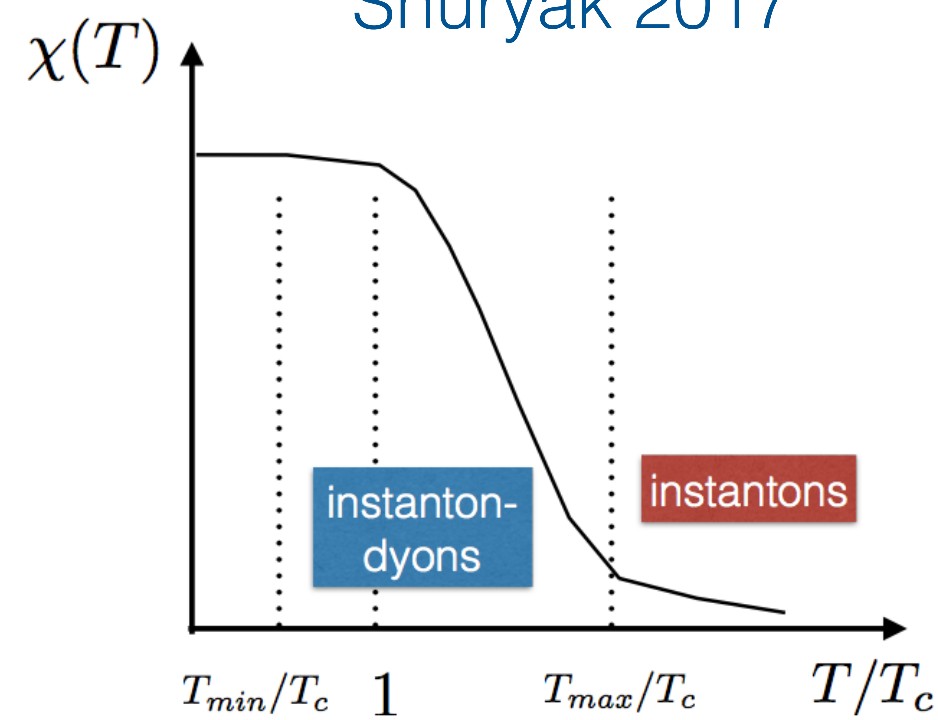
$$\chi^{0.25}(T) = aT^{-d(T)}$$

For instanton gas $\quad d(T) \equiv const \simeq (7 + \frac{N_f}{3})$

$$d(T) = -T\frac{d}{dT}\ln\chi^{0.25}(T)$$



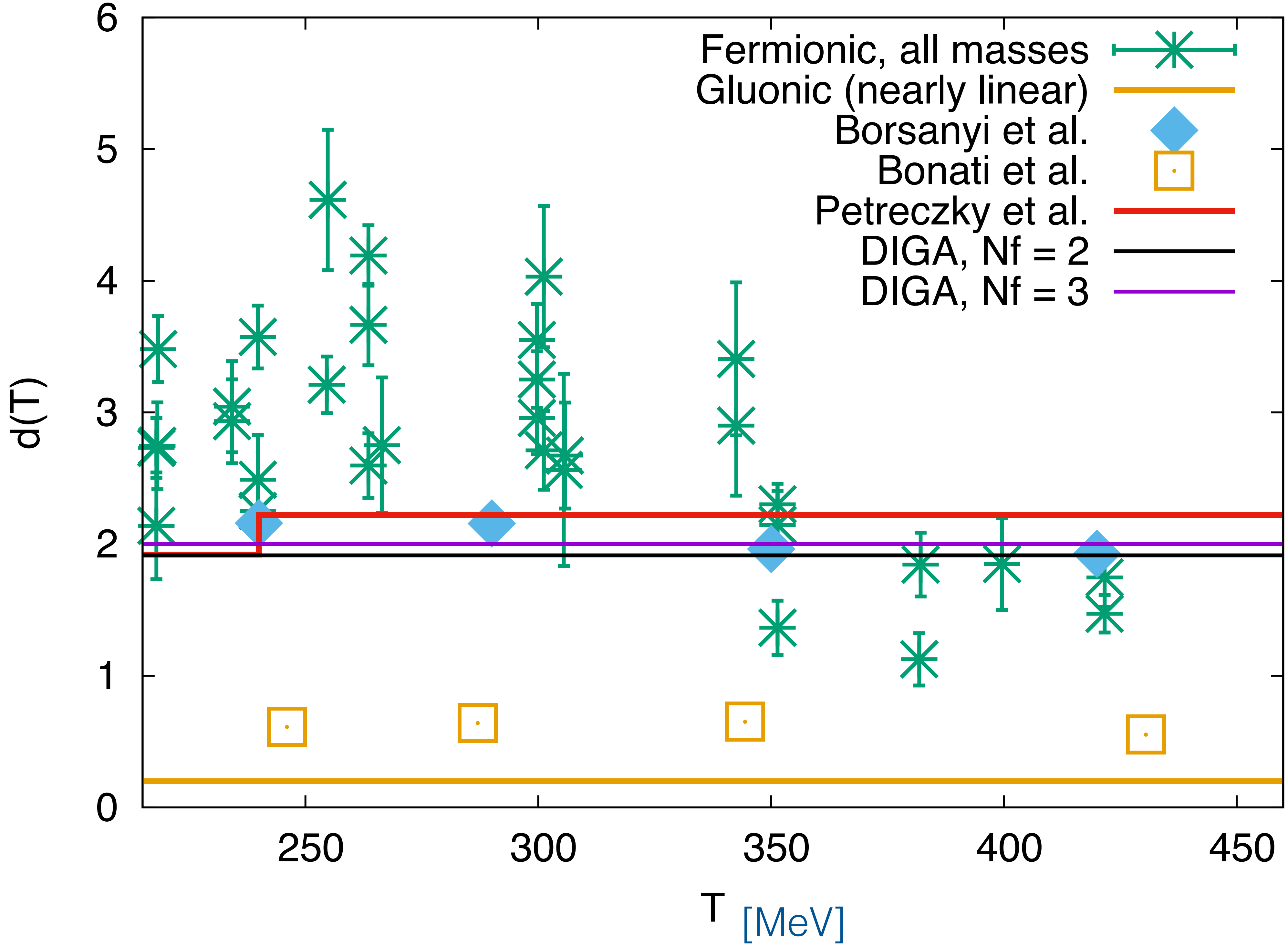
Possibly consistent with instant -dyon? Shuryak 2017



Faster decrease before DIGA sets in

Effective exponent d(T):

$$\chi_{top}^{1/4} = aT^{-d(T)}$$



<- Revised?

QCD axion

From exponent *d* to axion mass in three steps

$$\chi_{\rm top} \simeq A\, T^{-d}$$

Time from Big Bang

Temperature

Hubble parameter
$H(T) \simeq T^2/M_P$

$$d = (6.26, 6.88, 7.52, 7.48)$$

Axions's freezout

$3H(T) = m_a(T)$

$m_a(T) = \sqrt{\chi(T)}/f_a$

$$m_\pi = (470, 370, 260, 210)\ \text{MeV}$$

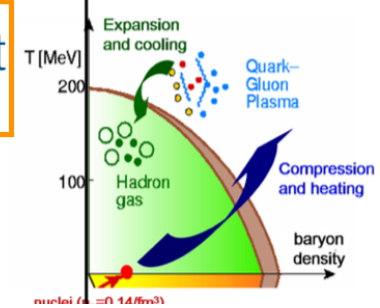
1.

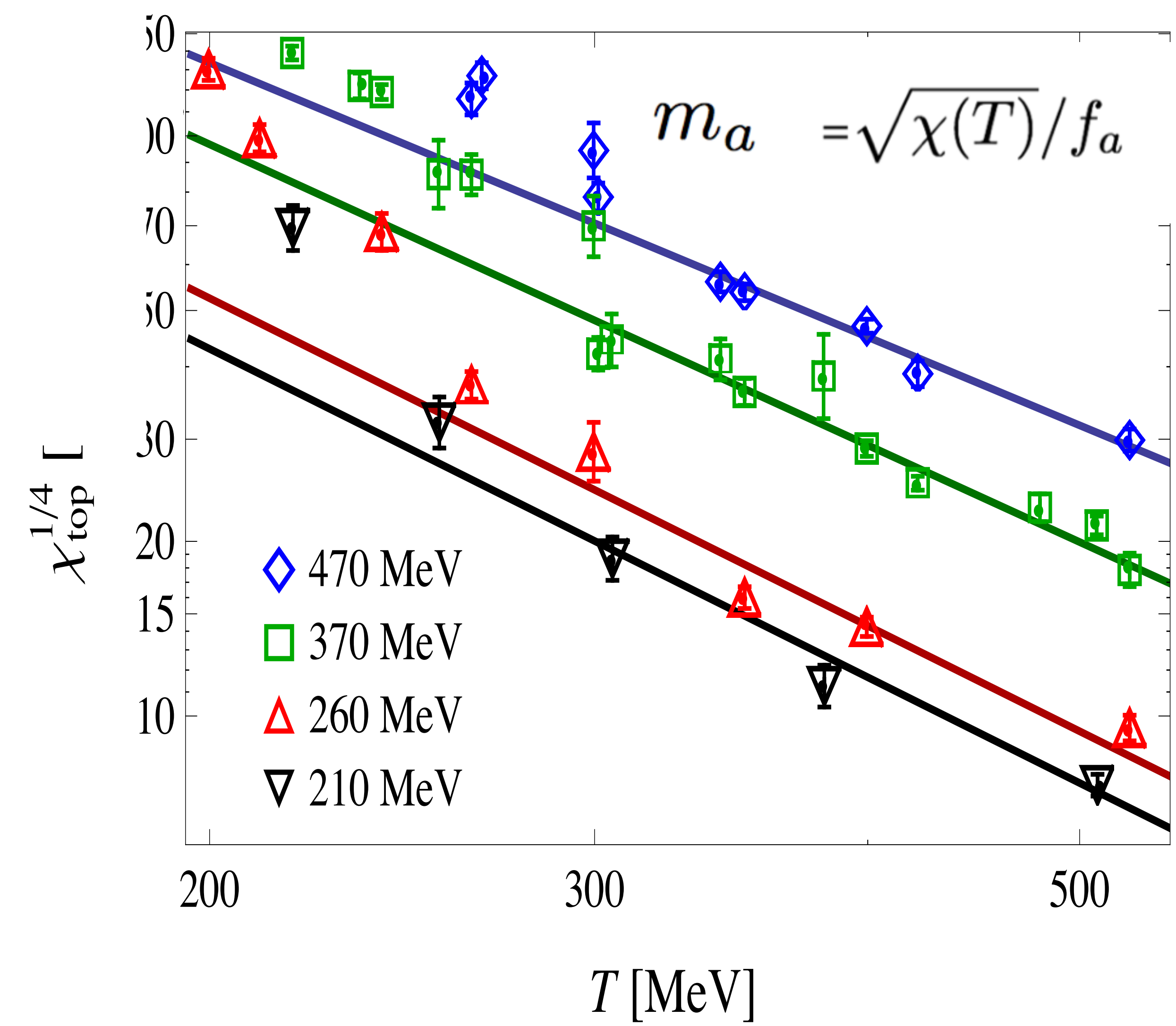
Quark Gluon Plasma: Topology

Axions' mass and density today

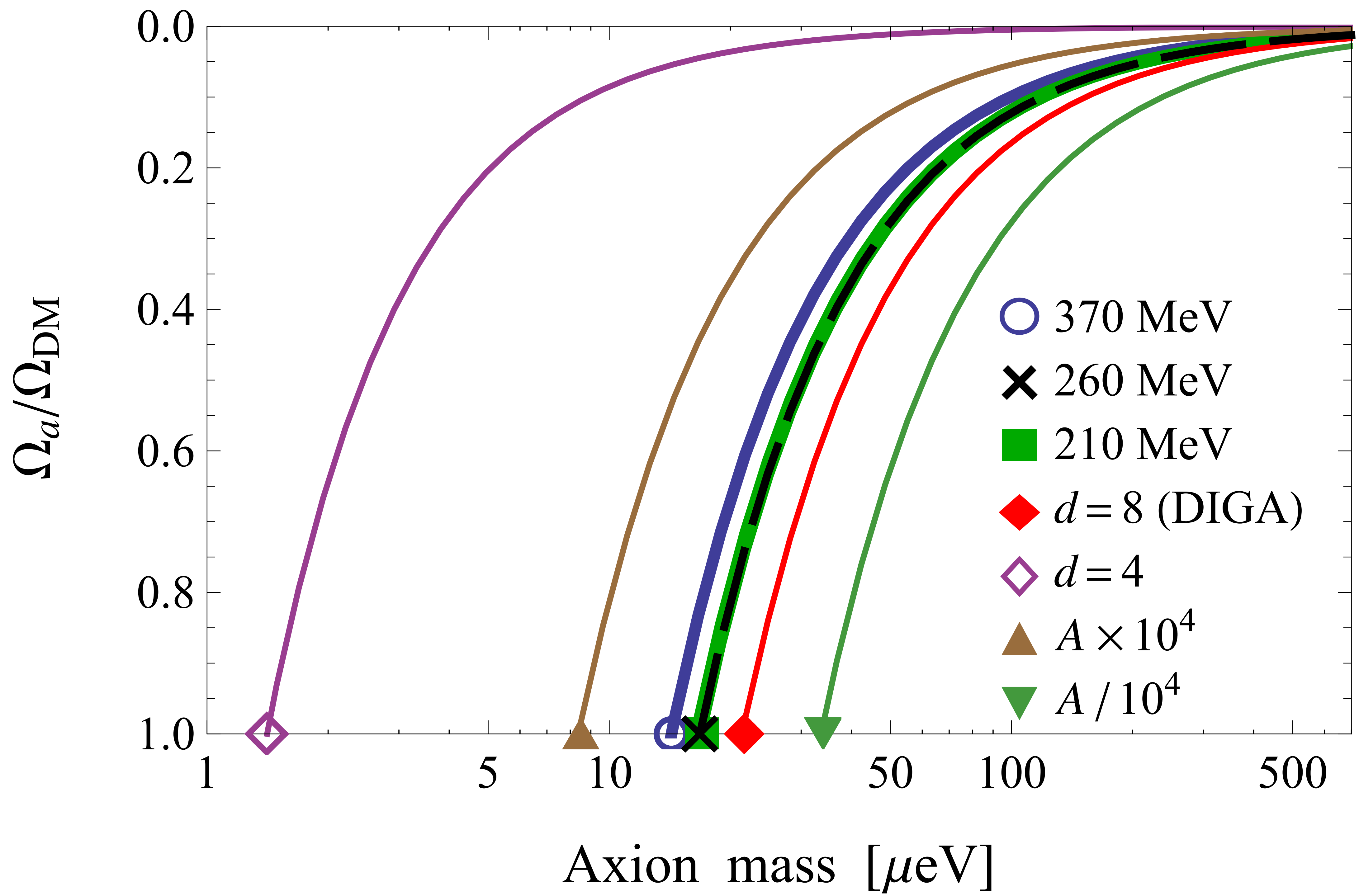
2. After freezout $\frac{n_a}{s}$ constant

3. $\rho_{a,0} = \frac{n_a}{s} m_a s_0$

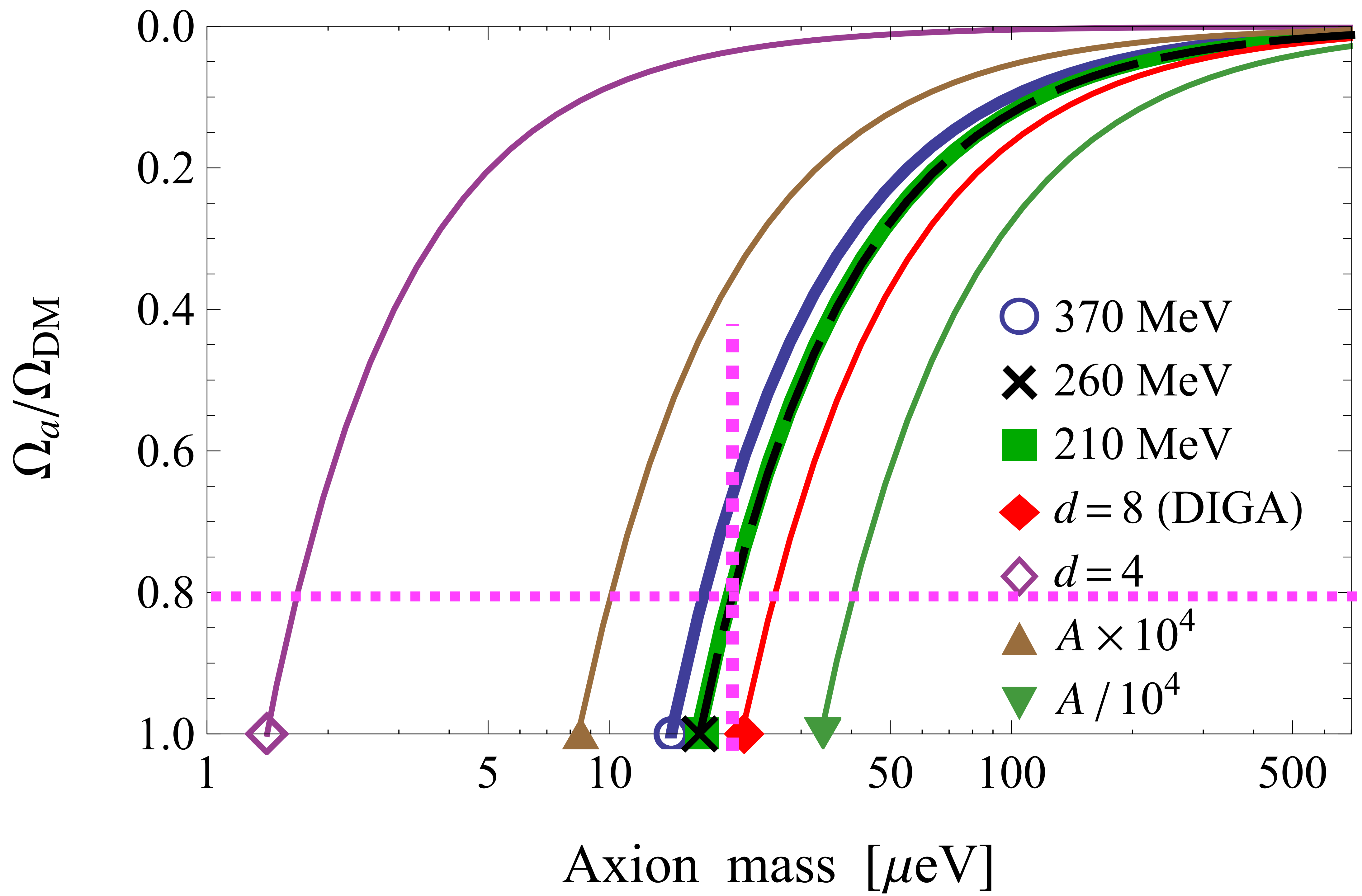




$$\rho_a(m_a) \propto m_a^{-\frac{3.053+d/2}{2.027+d/2}}$$

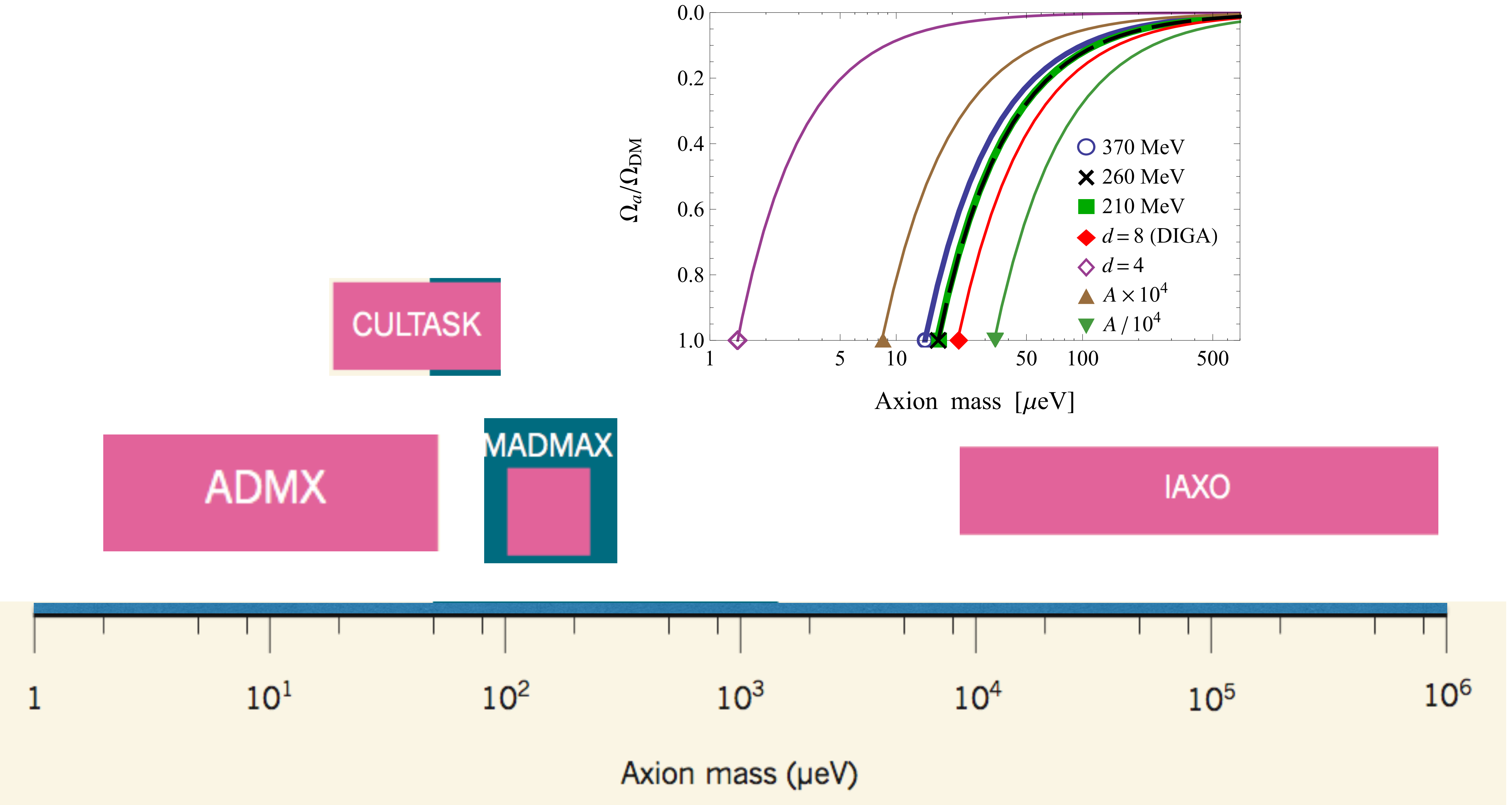


$$\Omega_a = \frac{\rho_{a,0}}{\rho_c},$$



$$\Omega_a = \frac{\rho_{a,0}}{\rho_c},$$

Example: if axions constitute 80% DM, our results give a lower bound for the axion mass of $\simeq 30\mu\mathrm{eV}$



Adapted from MpL, Nature N&V 2016

η'

Topology from low to high Temperature

In the hadronic phase topology solves the η' puzzle by explicit breaking $U(1)_A$

What happens to topology in the Quark Gluon Plasma?

PHYSICAL REVIEW D VOLUME 53, NUMBER 9 1 MAY 1996

Return of the prodigal Goldstone boson

J. Kapusta
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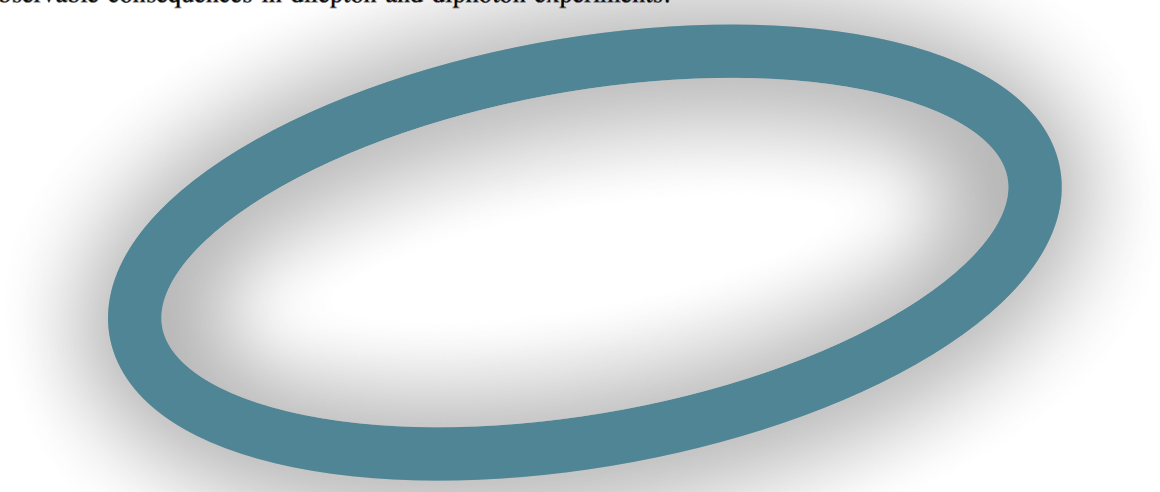
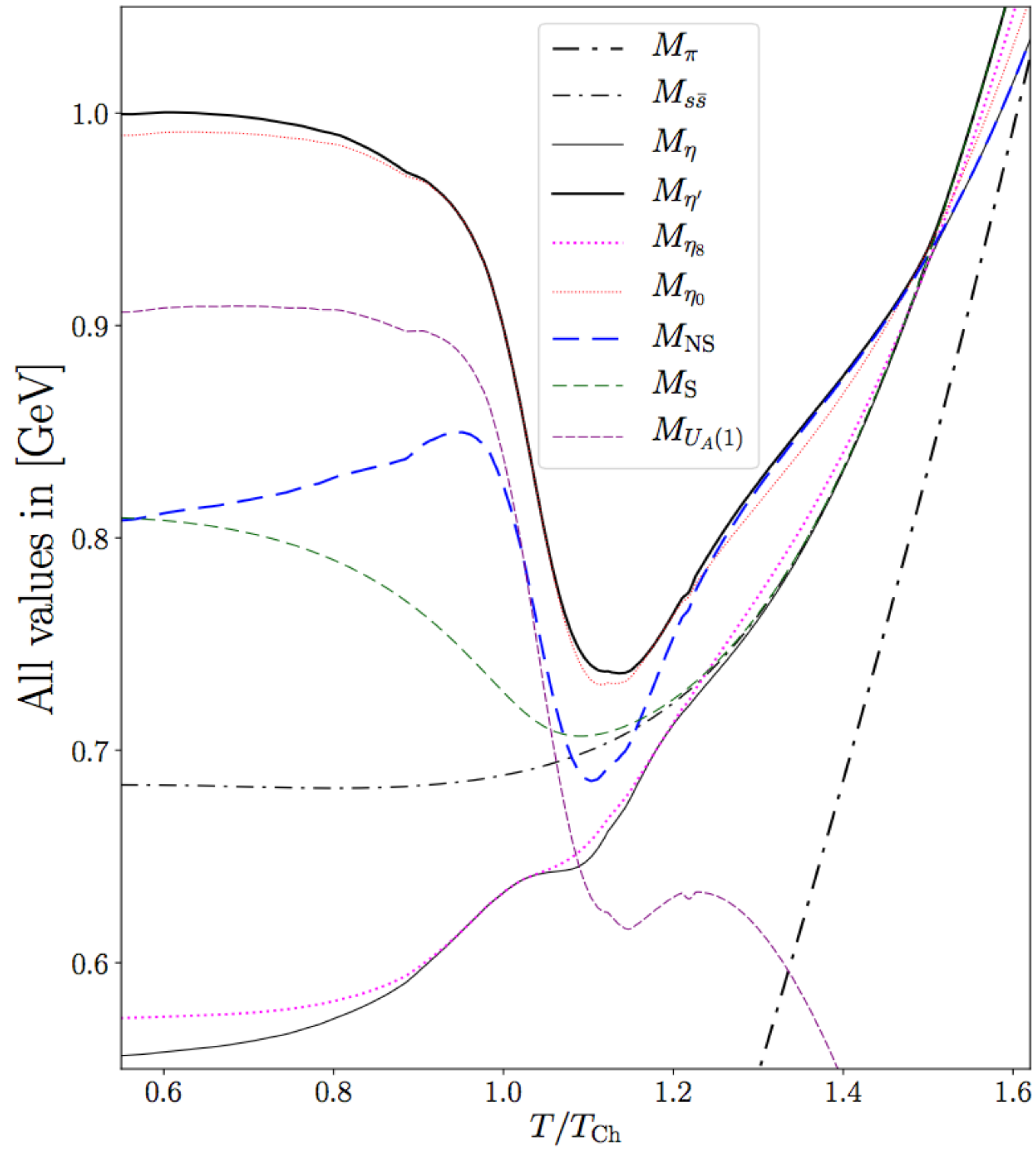
School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455
(Received 14 July 1995)

We propose that the mass of the η' meson is a particularly sensitive probe of the properties of finite energy density hadronic matter and quark-gluon plasma. We argue that the mass of the η' excitation in hot and dense matter should be small, and, therefore, that the η' production cross section should be much increased relative to that for pp collisions. This may have observable consequences in dilepton and diphoton experiments.



η' in the QGP

So far, only results from model's studies



Horvatic et al. 2018

Different mechanisms leading to η' (900 MeV) mass reduction

Adopting the basis

$$I \equiv \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$$

$$S \equiv s\bar{s}$$

$$m_A^2 = 2\frac{N_f}{f_0^2}\chi^2$$

The mass matrix of the η complex is:

$$\begin{pmatrix} m_\pi^2 + m_A^2 & m_A^2/\sqrt{2} \\ m_A^2/\sqrt{2} & 2m_K^2 - m_\pi^2 + m_A^2/2 \end{pmatrix}$$

Veneziano, 1981

Non anomalous: $\eta' \simeq 700\ \mathrm{MeV}$ (strange only)

However: also sensitive to SU(2)XSU(2)

Indication of topology suppression in PHENIX

NICA?

Effects of chain decays, radial flow and $U_A(1)$ restoration on the low-mass dilepton enhancement in $\sqrt{s_{NN}}$=200 GeV Au+Au reactions

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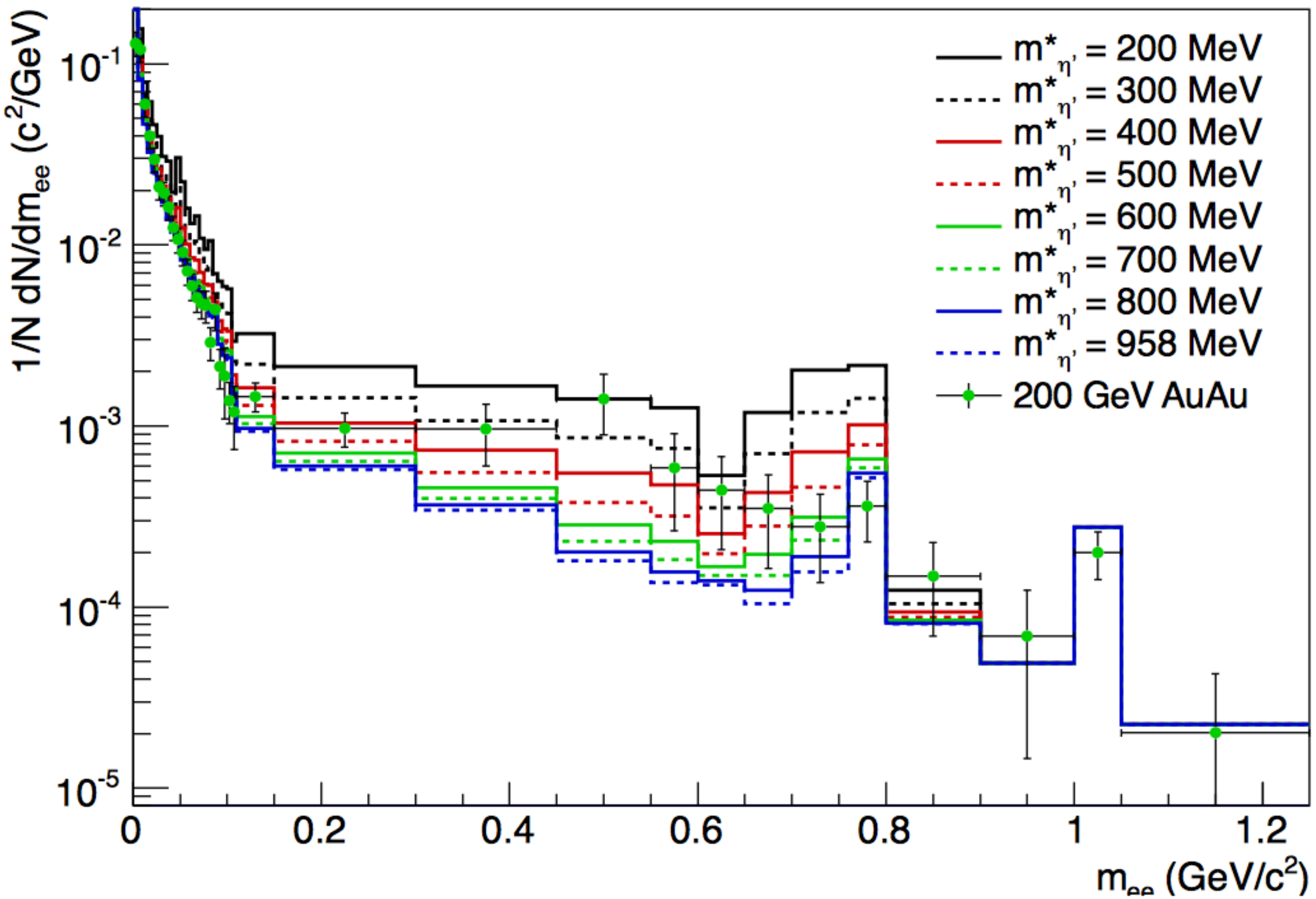
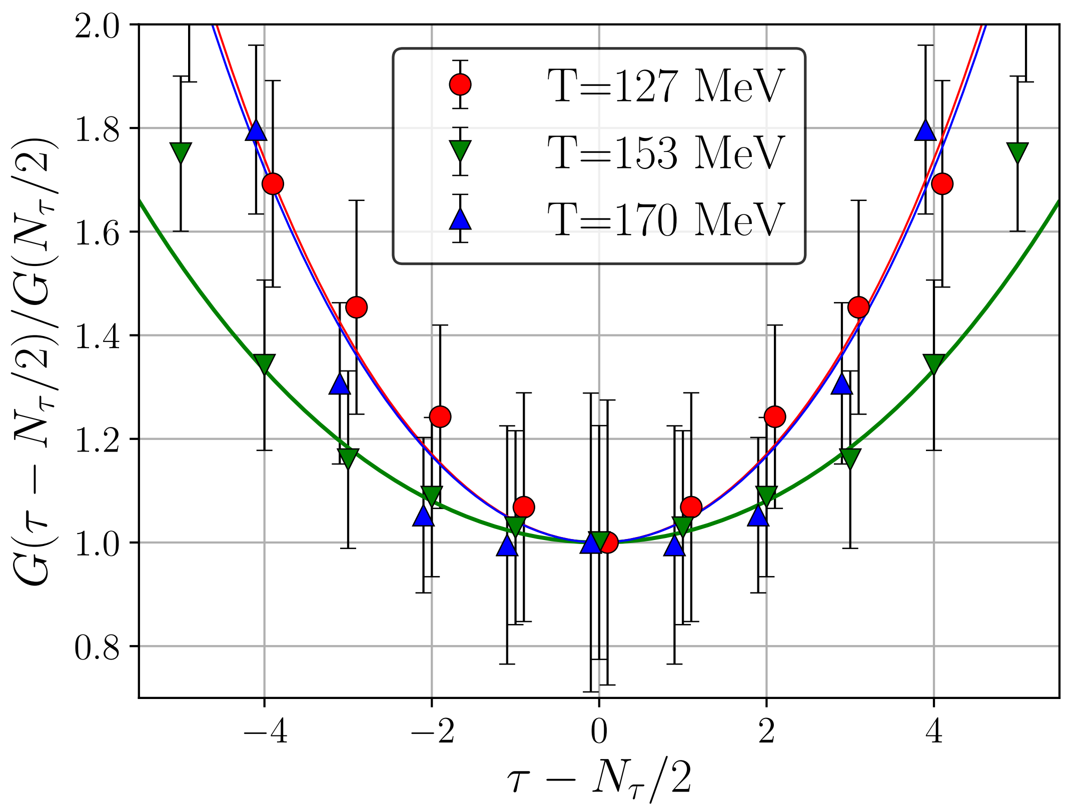


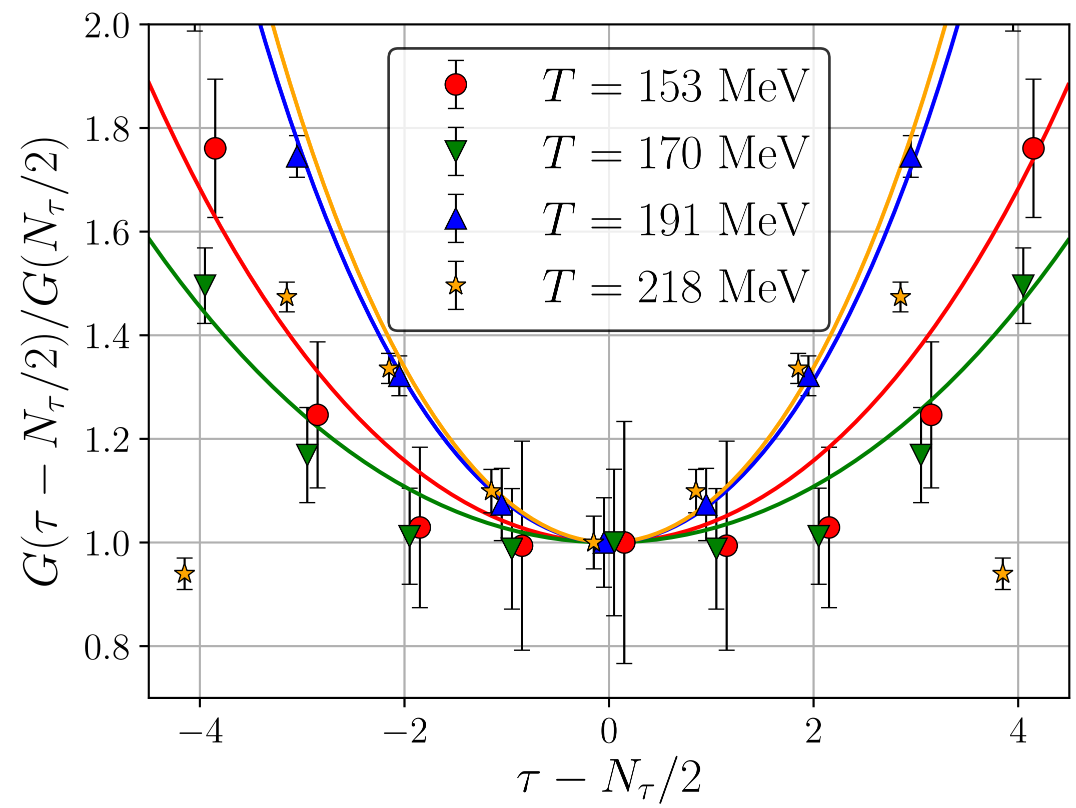
This is at finite density!

η' mass from topological charge correlators

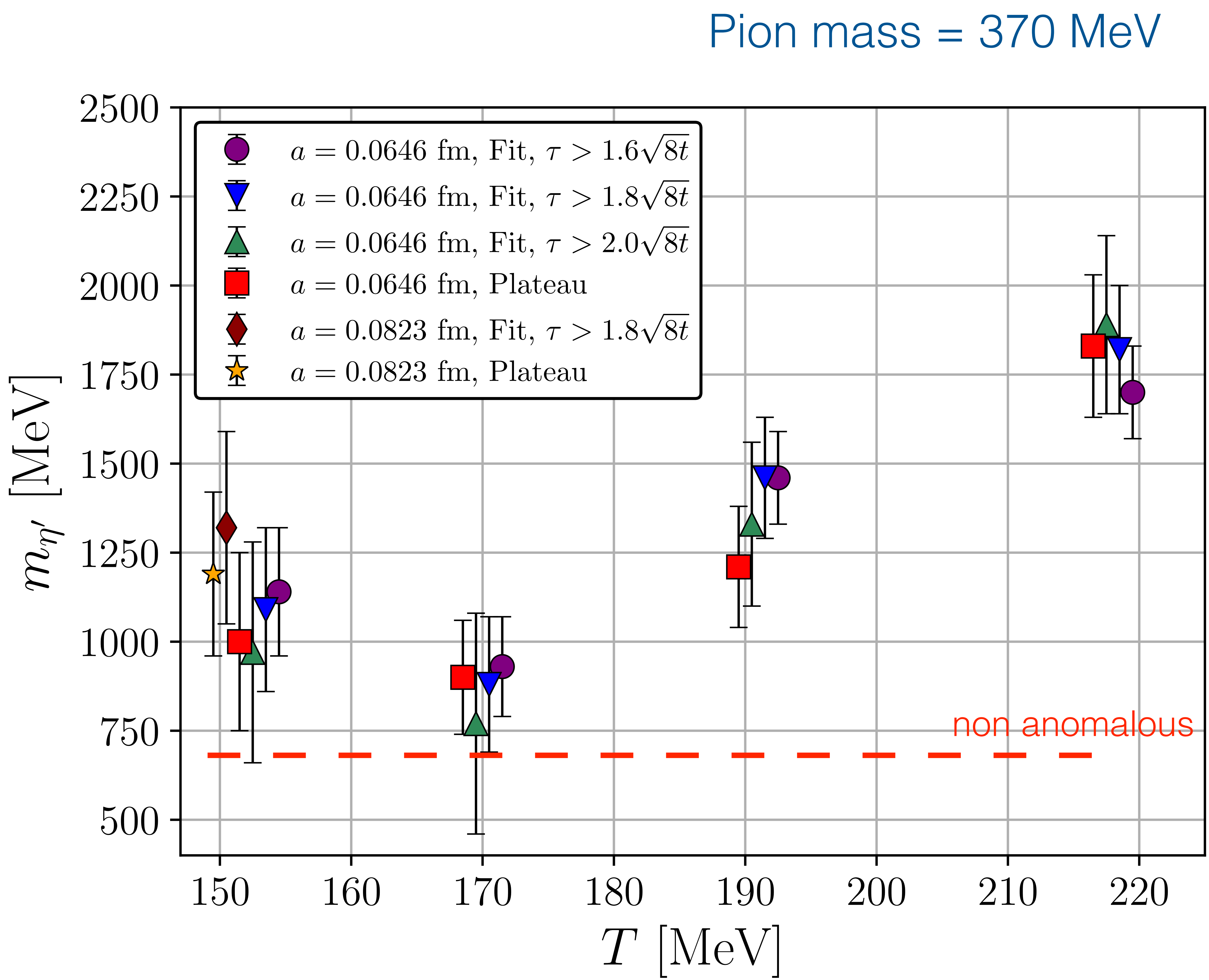
$$G(\tau) = \int d^3\bar{x}\, q(0) q(\tau,\bar{x}) = \int d^3\bar{x} \frac{1}{32\pi^2} F_{\mu\nu}\tilde{F}_{\mu\nu}(0) \times$$
$$\times \frac{1}{32\pi^2} F_{\mu\nu}\tilde{F}_{\mu\nu}(\tau,\bar{x}) \simeq e^{-m_{\eta'}\tau}$$



Pion mass 210 MeV

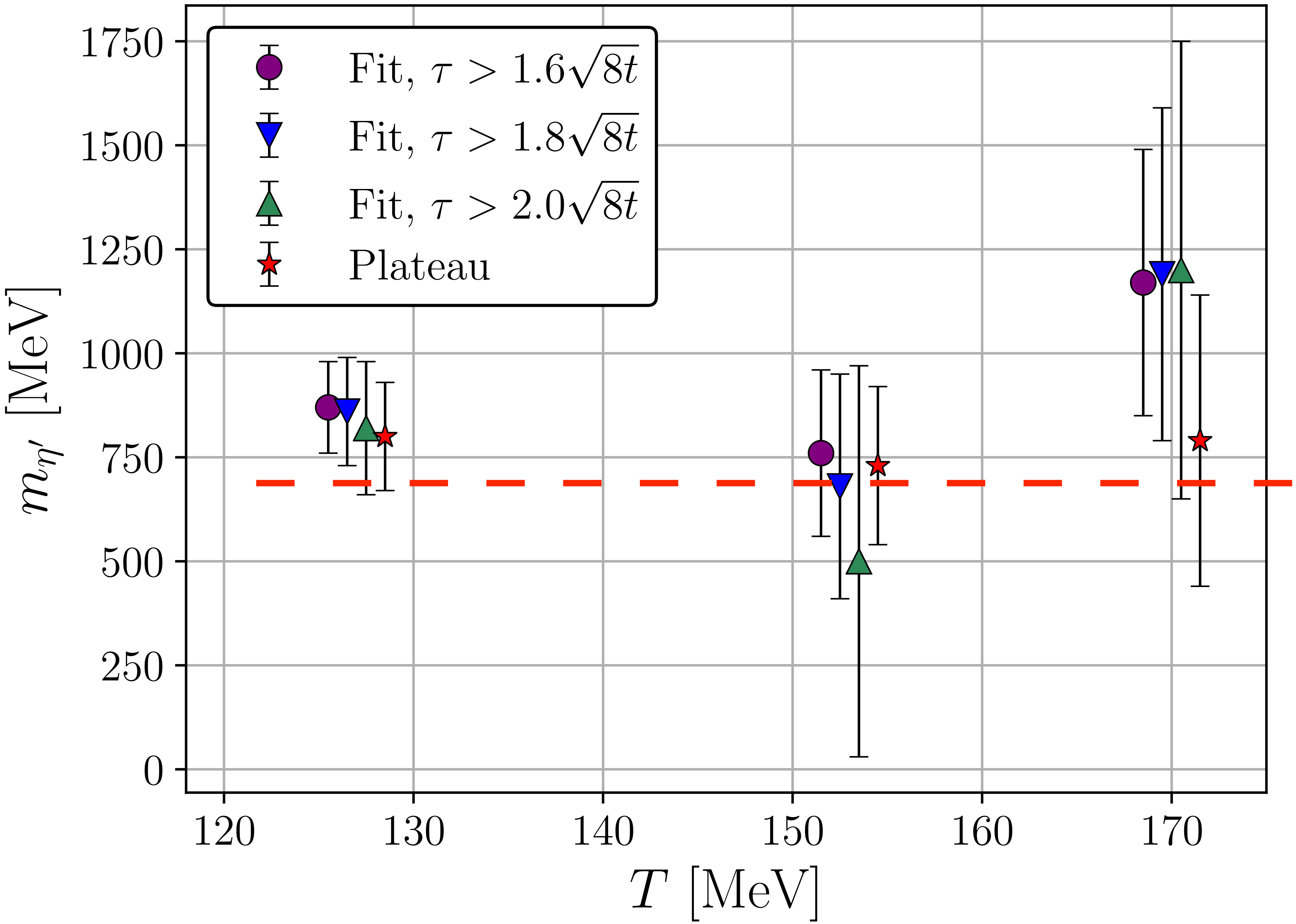


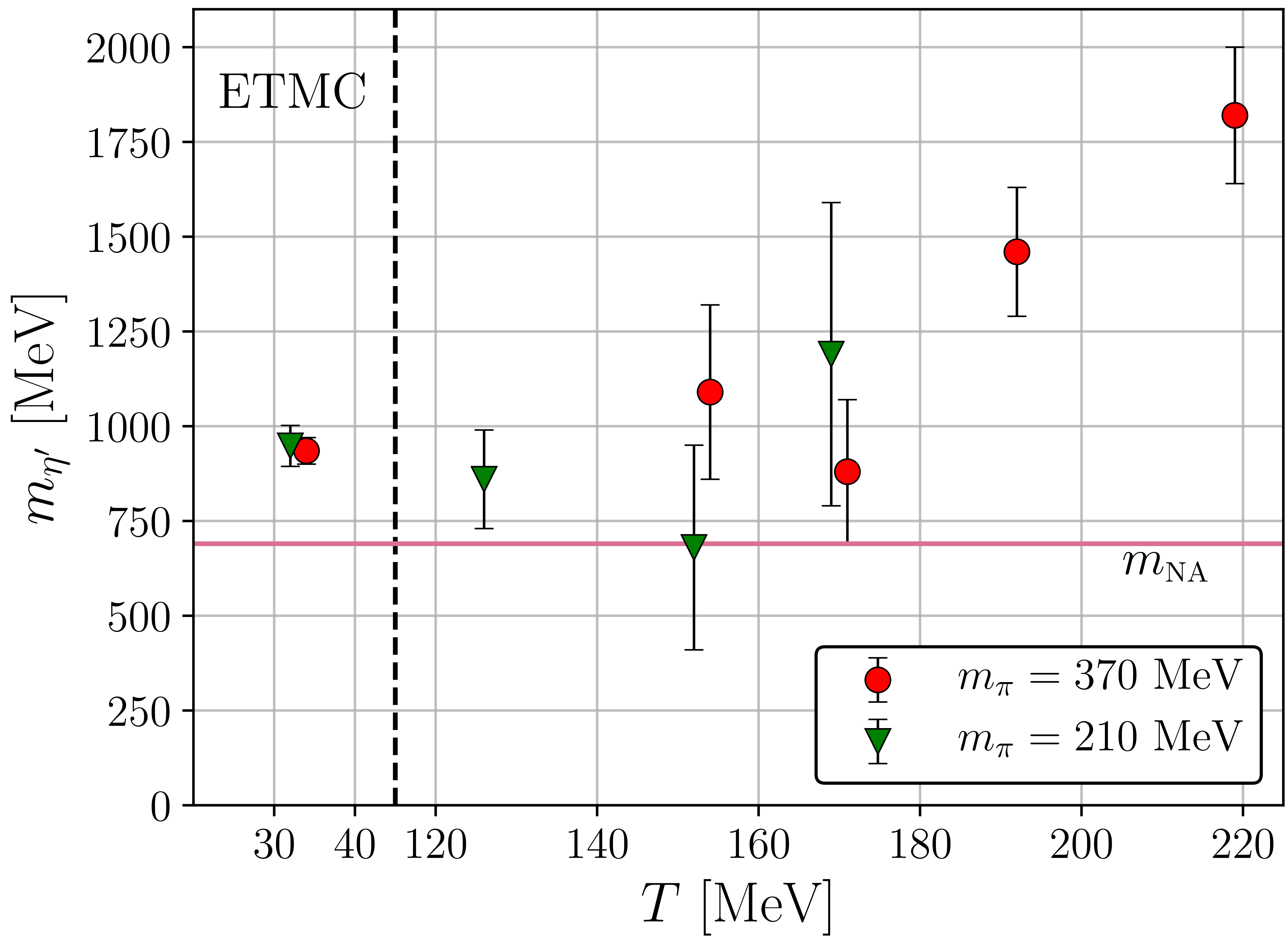
Pion mass 370 MeV



Pion mass = 370 MeV
$a = 0.0646$ fm, Fit, $\tau > 1.6\sqrt{8t}$
$a = 0.0646$ fm, Fit, $\tau > 1.8\sqrt{8t}$
$a = 0.0646$ fm, Fit, $\tau > 2.0\sqrt{8t}$
$a = 0.0646$ fm, Plateau
$a = 0.0823$ fm, Fit, $\tau > 1.8\sqrt{8t}$
$a = 0.0823$ fm, Plateau
$m_{\eta'}$ [MeV]
2500
2250
2000
1750
1500
1250
1000
750
500
non anomalous
150
160
170
180
190
200
210
220
T [MeV]

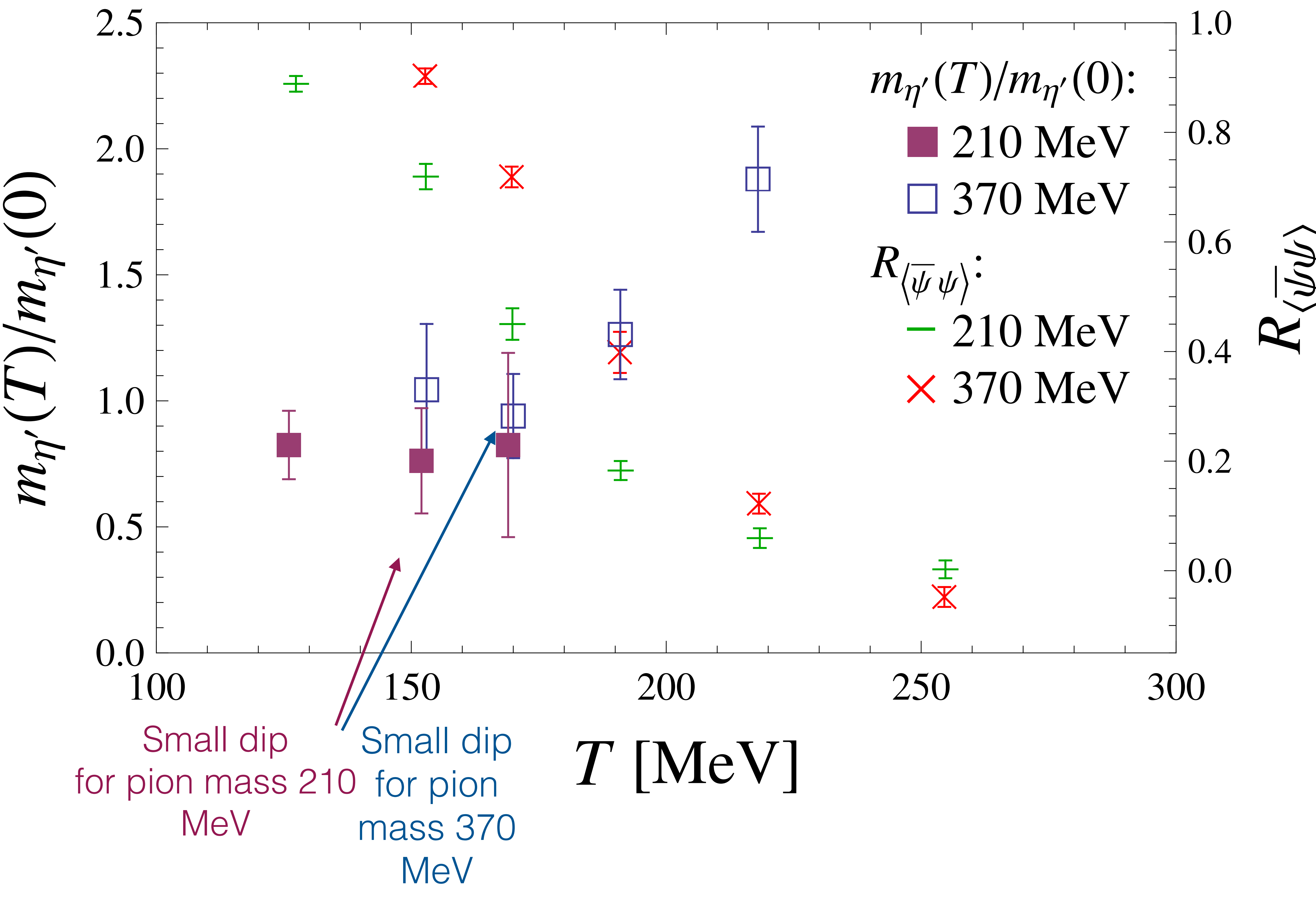
Pion mass 210 MeV





ETMC
$m_{\eta'}$ [MeV]
2000
1750
1500
1250
1000
750
500
250
0
30
40
120
140
160
180
200
220
T [MeV]
$m_{\rm NA}$
$m_\pi = 370$ MeV
$m_\pi = 210$ MeV

Correlations?



Minimum of the η'

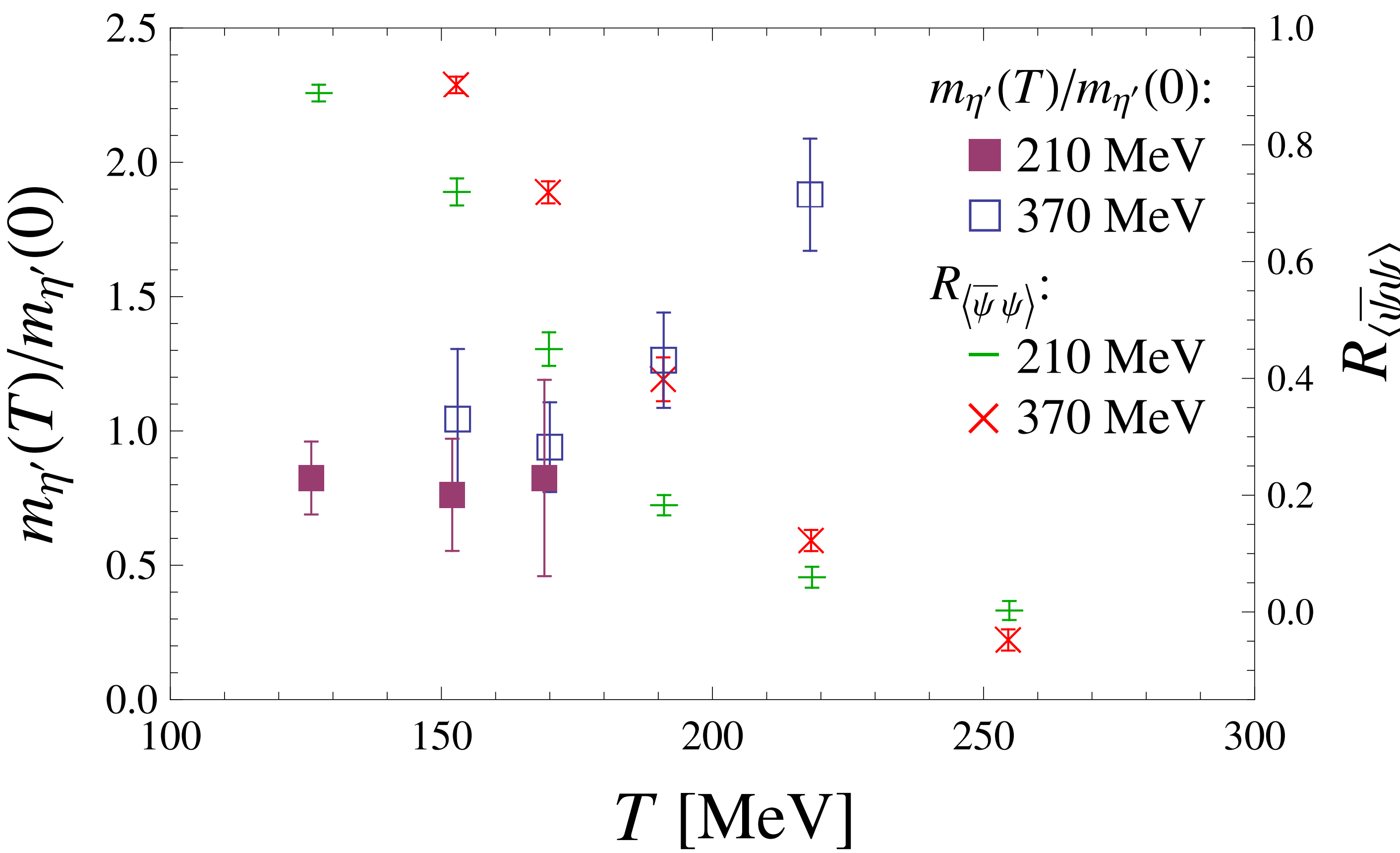
Approx. correlated with T_χ

Ensemble	a [fm]	m_π [MeV]	T_χ [MeV]
D210	0.065	213	158(1)(4)
A260	0.094	261	157(8)(14)
B260	0.082	256	161(13)(2)
A370	0.094	364	185(5)(3)
B370	0.082	372	189(2)(1)
D370	0.065	369	185(1)(3)
A470	0.094	466	200(4)(6)
B470	0.082	465	203(2)(2)

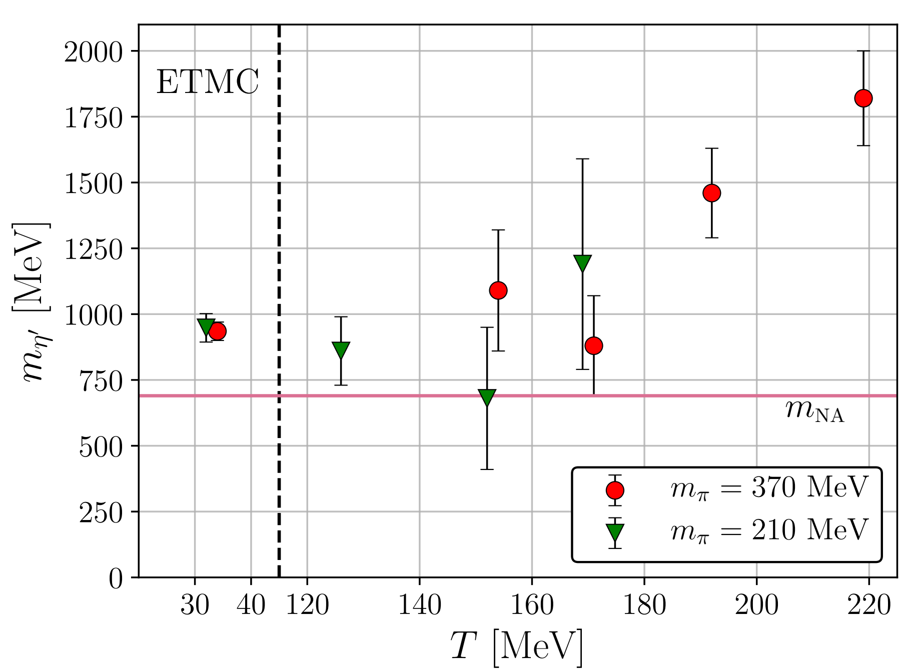
$T_{\eta'}$ [MeV]

$\simeq 150$

$\simeq 170$



Consistent with suppression of the anomalous contribution



Summary

Axions are attractive dark matter candidates

The QCD topological susceptibility at high temperature gives a strict lower bound on the axion mass.
Some of the planned experiments do not seem to be able to explore this region.

The η' meson is an important probe of axial symmetry and of its interplay, or lack thereof, with chiral symmetry.

The correlators of the QCD topological charge afford an estimate of the η' mass, which appears to be correlated with signals of chiral symmetry restoration.

Thank You!