QFT  HEP

on the lattice

M.P. Lombardo
INFN-LNF

Plan

Quark Gluon Plasma in the LHC working region

- Topology
- Bottomonium spectral functions

Beyond the Standard Model

- Topology at very high T and axions
- Composite Higgs

Next steps

- Bottomonium on veryfine lattices&new methods
- Finite density and search for the QCD critical point
- Topology with overlap operator

Summary

Common threads

Exotic phases and phase transitions in QFT

Phenomenological implications

QFT____HEP

on the lattice

I. QGP in the LHC working region

Topology

Bottomonium spectral functions

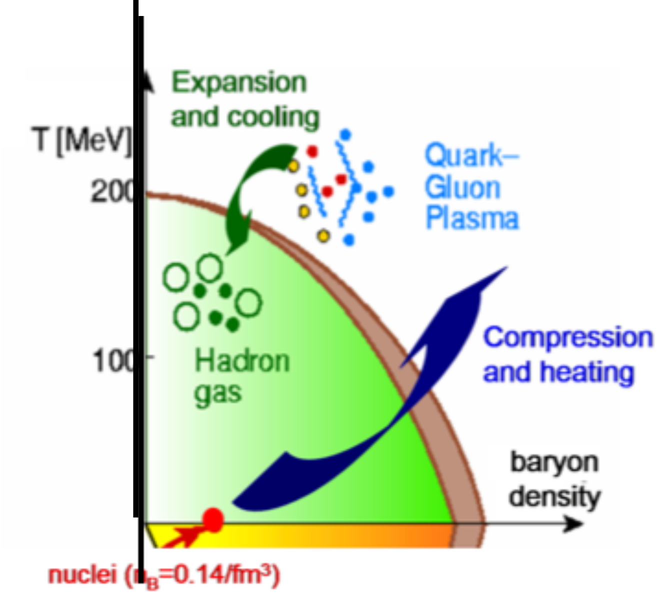
QGP in the LHC working region: T < 600 MeV

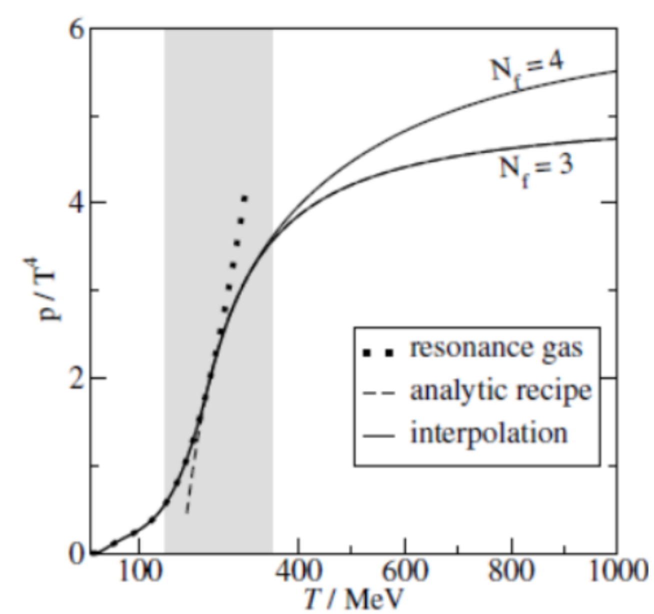
T

? 5.12 TeV analysis in progress

600-700 MeV 2.76 TeV (-hottest spots 2015 - current)

420-480 MeV 2.76 TeV (2012 - breaking RHIC record)





Laine Schroeder 2006

400 MeV charm threshold:

Dynamical charm plays a role

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

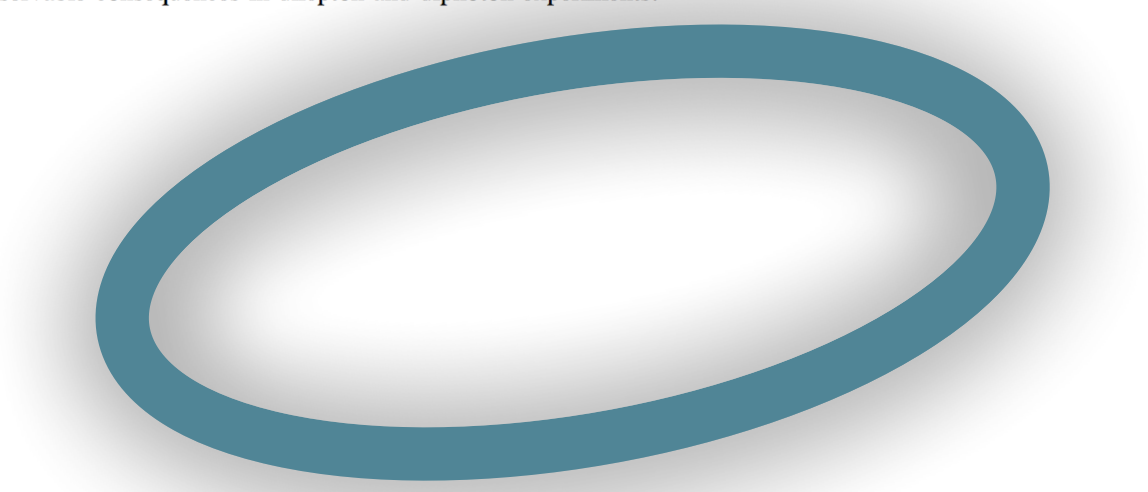
Return of the prodigal Goldstone boson

J. Kapusta
School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455

D. Kharzeev
Theory Division, CERN, Geneva, Switzerland
and Fakultät für Physik, Universtät Bielefeld, Bielefeld, Germany

L. McLerran
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.



Topology

with Anton Trunin, E.-Michael Ilgenfritz and Florian Burger

The Hot Twisted Mass project

Topology (and axion's properties) from lattice QCD with a dynamical charm
A. Trunin, F. Burger, E. M. Ilgenfritz, M. P. Lombardo and M. Müller-Preussker.
Nucl.Phys. **A967** (2017) 880-883

Finite temperature gluon spectral functions from $N_f = 2+1+1$ lattice QCD
E.M.Ilgenfritz, J.M.Pawlowski, A. Rothkopf,A.Trunin, arXiv:1701:08610

Topological susceptibility from $N_f = 2+1+1$ lattice QCD at nonzero temperature
A. Trunin, F. Burger, E. M. Ilgenfritz, M. P. Lombardo and M. Müller-Preussker.
J. Phys. Conf. Ser. **668**, no. 1, 012123 (2016)

Towards the quark–gluon plasma Equation of State with dynamical strange and charm quarks
F. Burger, E. M. Ilgenfritz, M. P. Lombardo, M. Müller-Preussker and A. Trunin.
J. Phys. Conf. Ser. **668**, no. 1, 012092 (2016)

Equation of state of quark-gluon matter from lattice QCD with two flavors of twisted mass Wilson fermions
F. Burger *et al.* [tmfT Collaboration].
Phys. Rev. D **91**, no. 7, 074504 (2015)

Towards thermodynamics with $N_f = 2+1+1$ twisted mass quarks
F. Burger, G. Hotzel, M. Müller-Preussker, E. M. Ilgenfritz and M. P. Lombardo.
PoS Lattice **2013**, 153 (2013)

Thermal QCD transition with two flavors of twisted mass fermions
F. Burger *et al.* [tmfT Collaboration].
Phys. Rev. D **87**, no. 7, 074508 (2013)

Phase structure of thermal lattice QCD with $N_f = 2$ twisted mass Wilson fermions
E.-M. Ilgenfritz, K. Jansen, M. P. Lombardo, M. Müller-Preussker, M. Petschlies, O. Philipsen and L. Zeidlewicz.
Phys. Rev. D **80**, 094502 (2009)

with thanks to the ETMC collaboration

Topological susceptibility
from disconnected chiral susceptibility

How to measure topological charge :

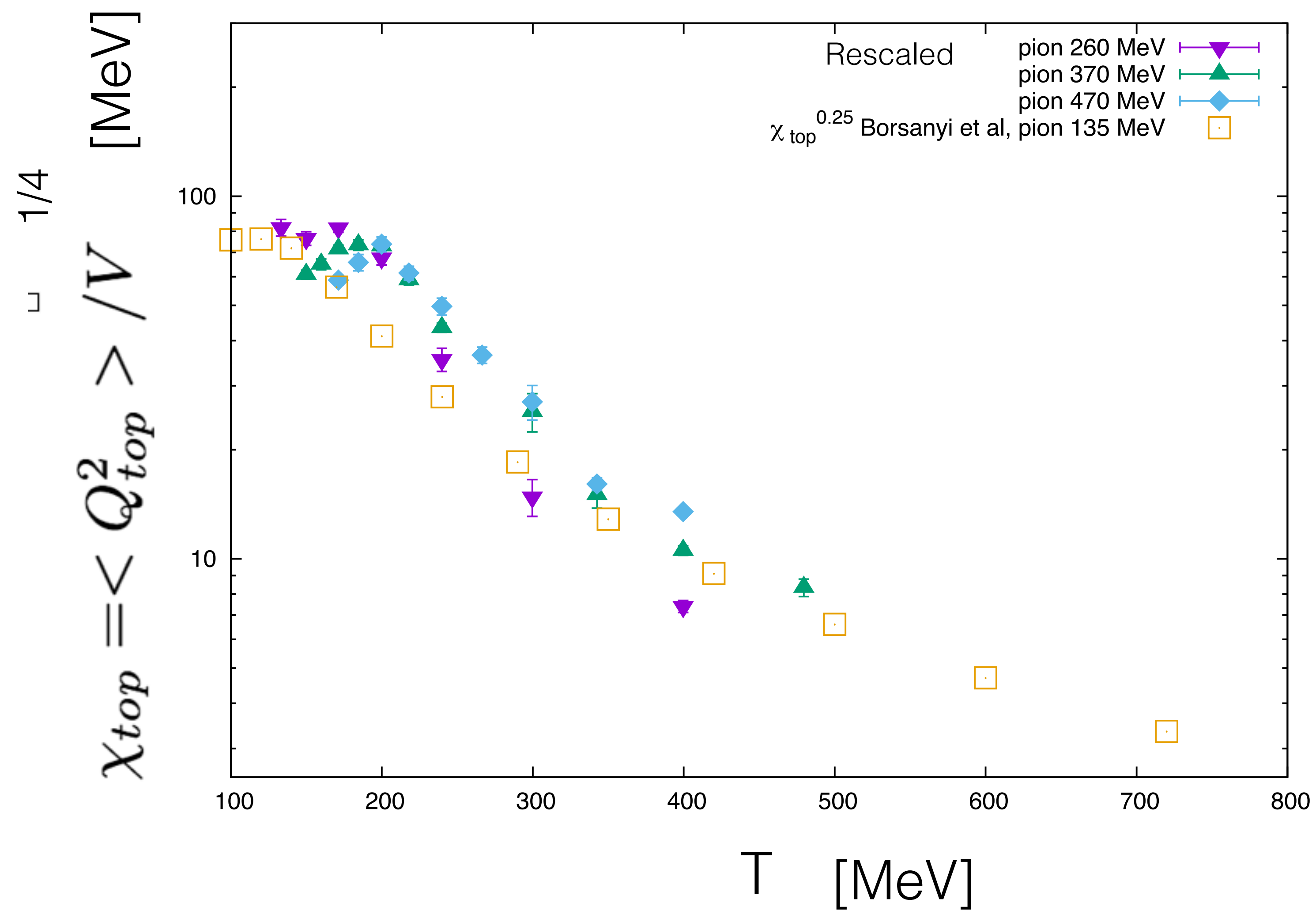
1 $\frac{1}{32\pi^2}\int d^4x F\tilde{F} = Q$

2 $Q = n_+ - n_-$

3 $\chi_{top} = m_l^2 \chi_5$

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

$$T > T_{U(1)_A} \simeq T_c$$



$$\chi_5 = \chi_{disc} \quad T > T_{U(1)_A}$$

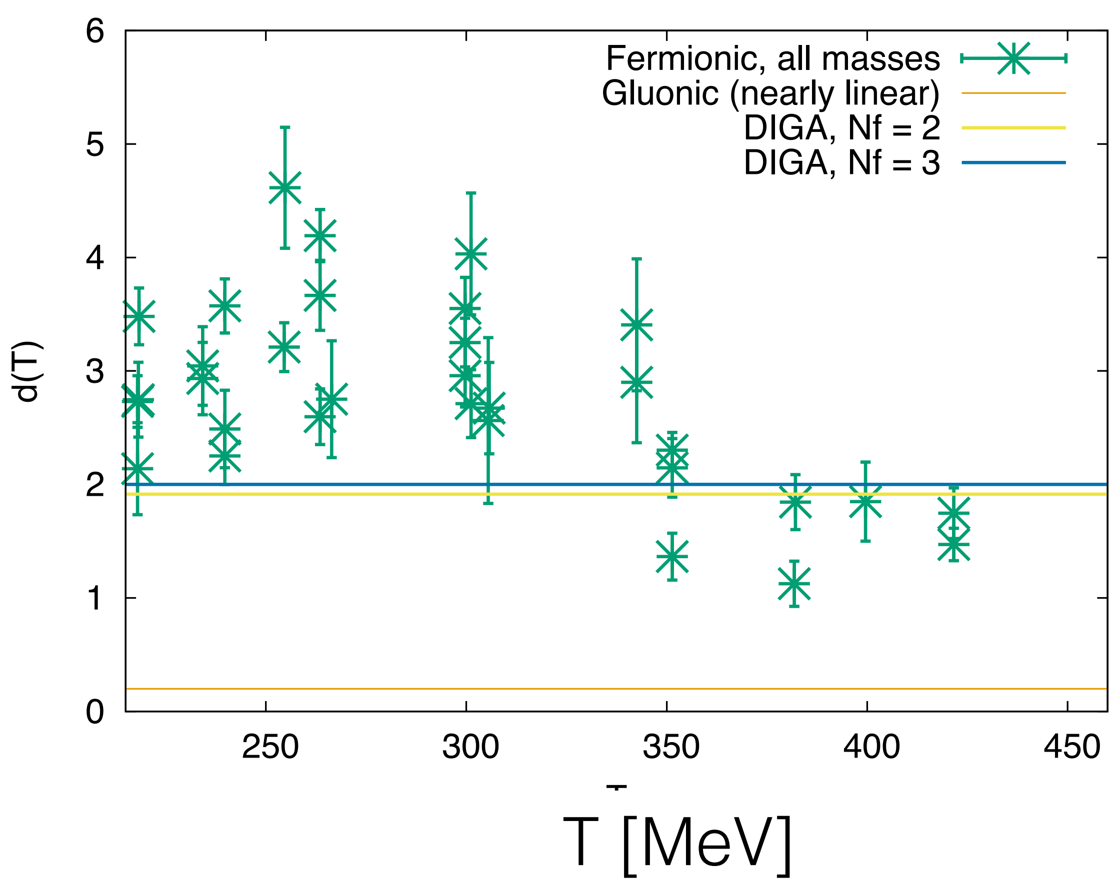
Parametrizing χ_{top} temperature dependence

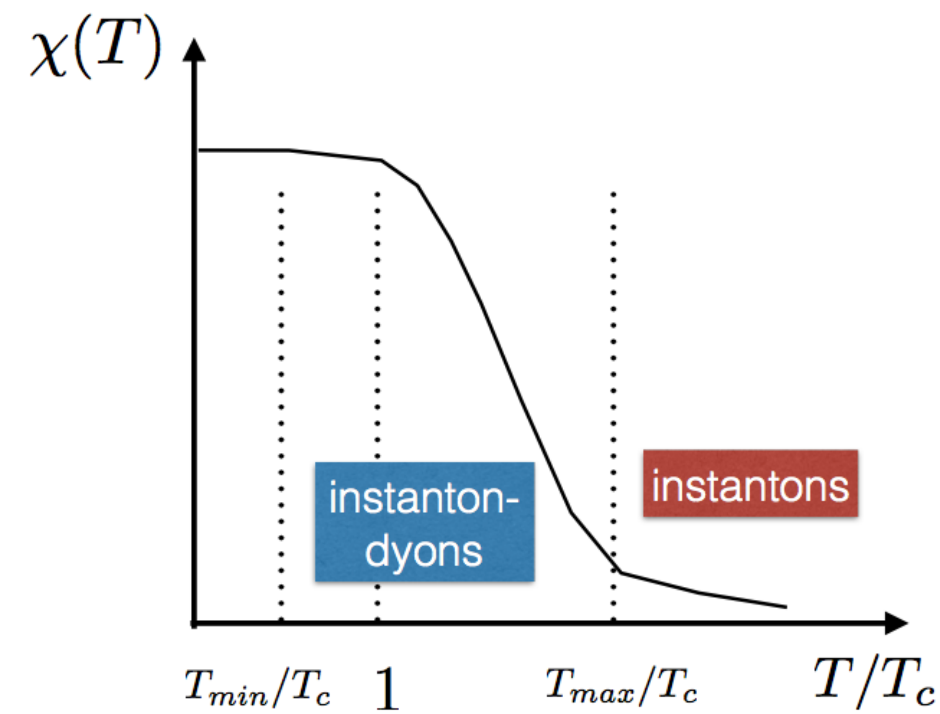
$$\chi^{0.25}(T) = aT^{-d(T)}$$

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

For instanton gas

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





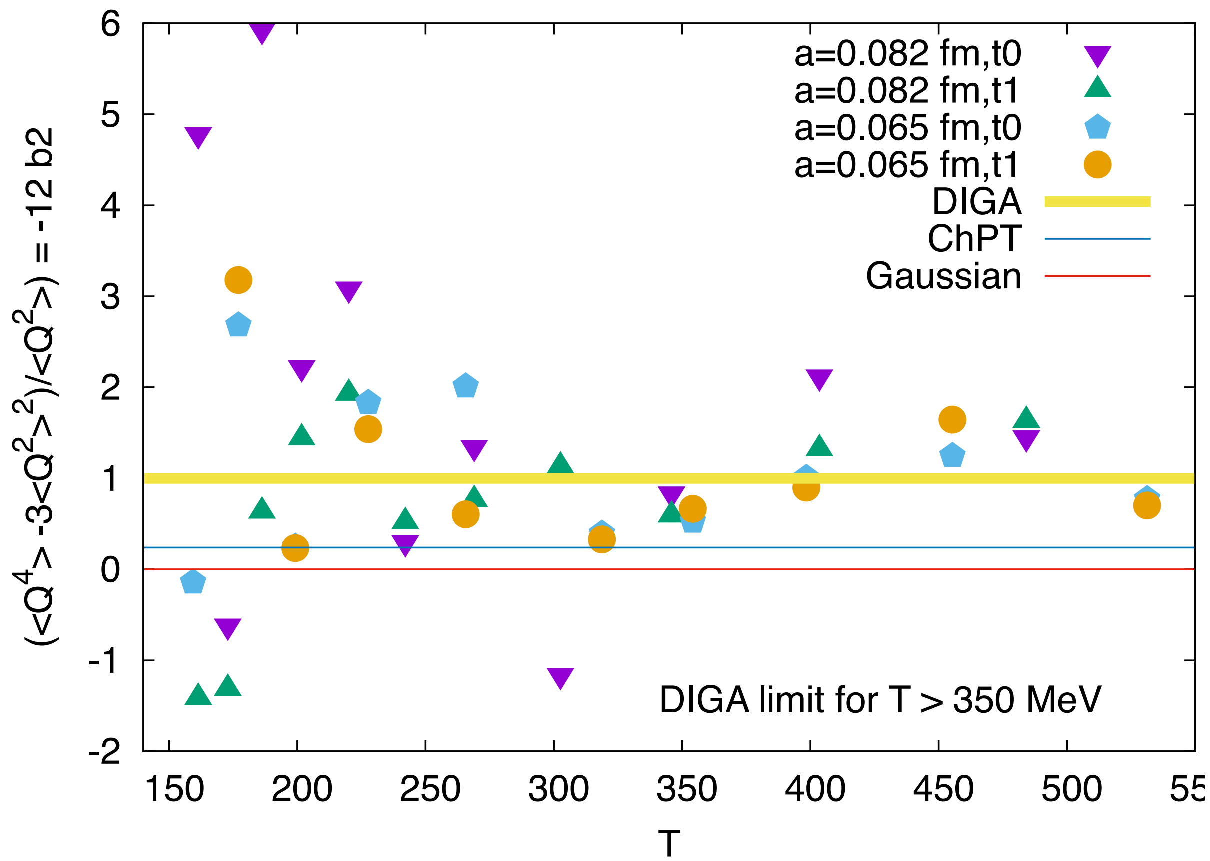
Faster decrease before DIGA sets in

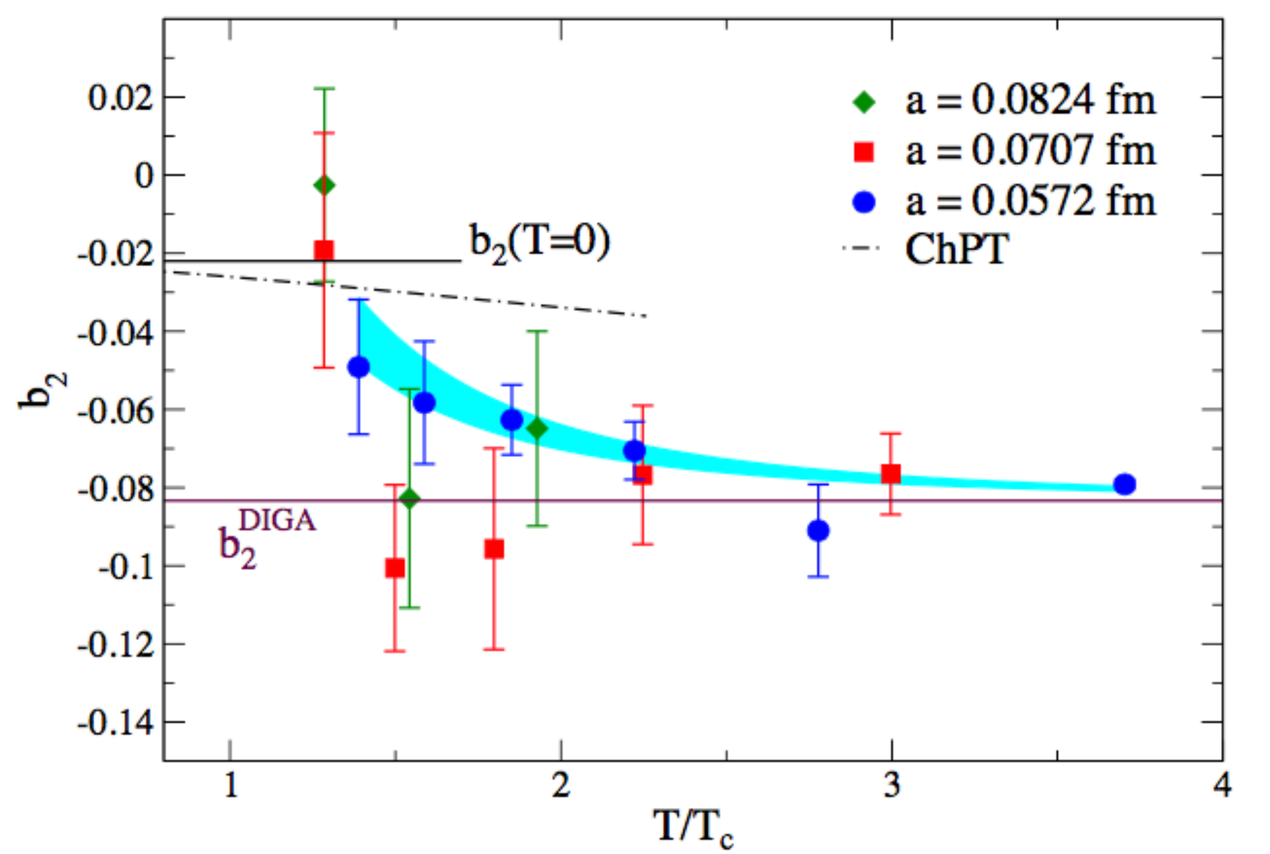
Possibly consistent with instant -dyon?
Shuryak 2017

Topology beyond topological susceptibility

$$\mathcal{L}_{QCD}(\theta) = \mathcal{L}_{QCD} + \theta Q \qquad Z_{QCD}(\theta, T) = e^{-VF(\theta,T)}$$

$$F(\theta,T) = \sum_{n=1}^{\infty}(-1)^{n+1}\frac{\theta^{2n}}{(2n)!}C_n(T) \qquad C_n(T) =< Q^{2n} >_{conn}$$



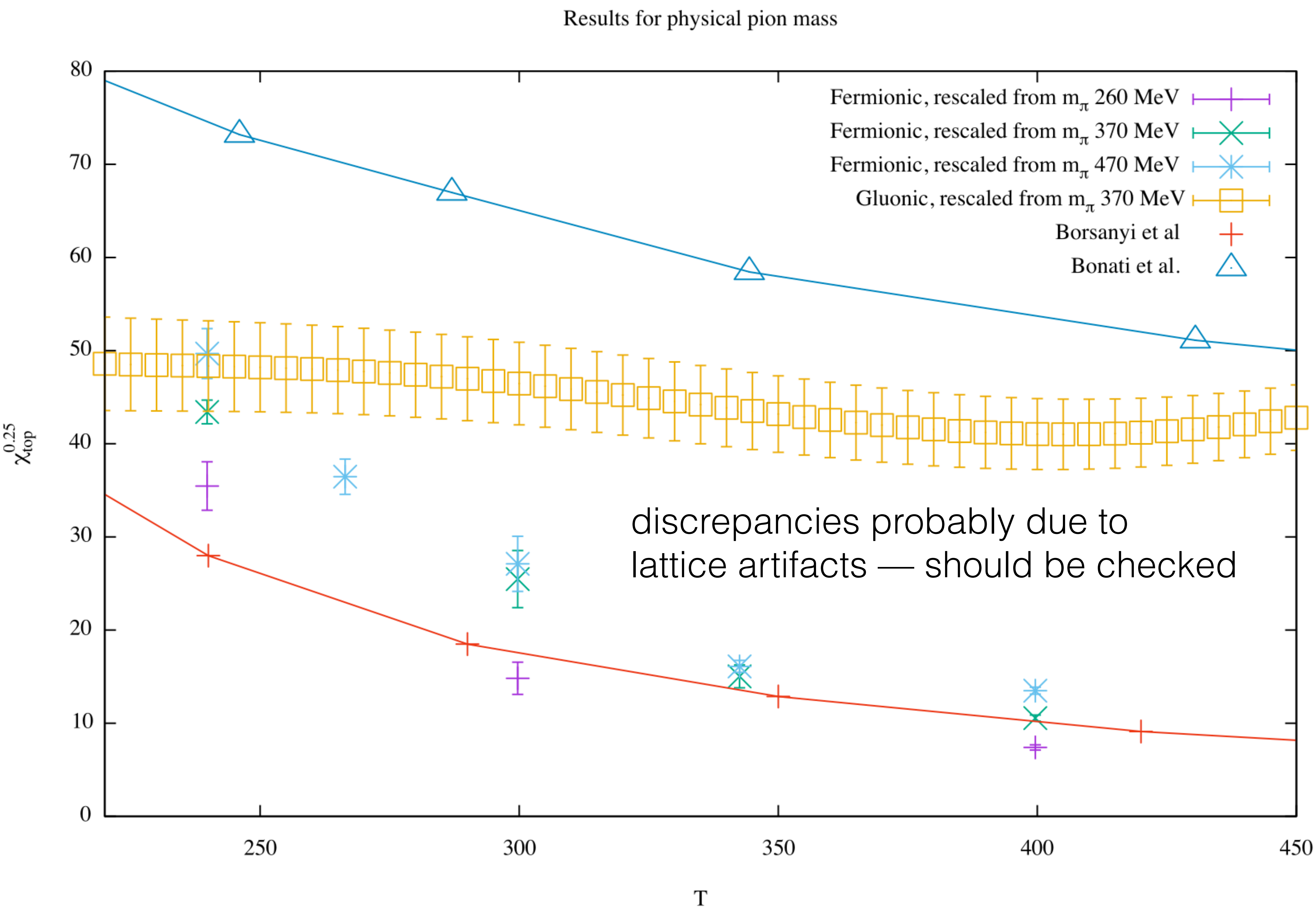


DIGA predicts

$$F(\theta,T) - F(0,T) = \chi(T)(1 - cos(\theta)) \longrightarrow b_2 = -1/12$$

Consistent with Bonati et al.

Topology: Outstanding remaining issue

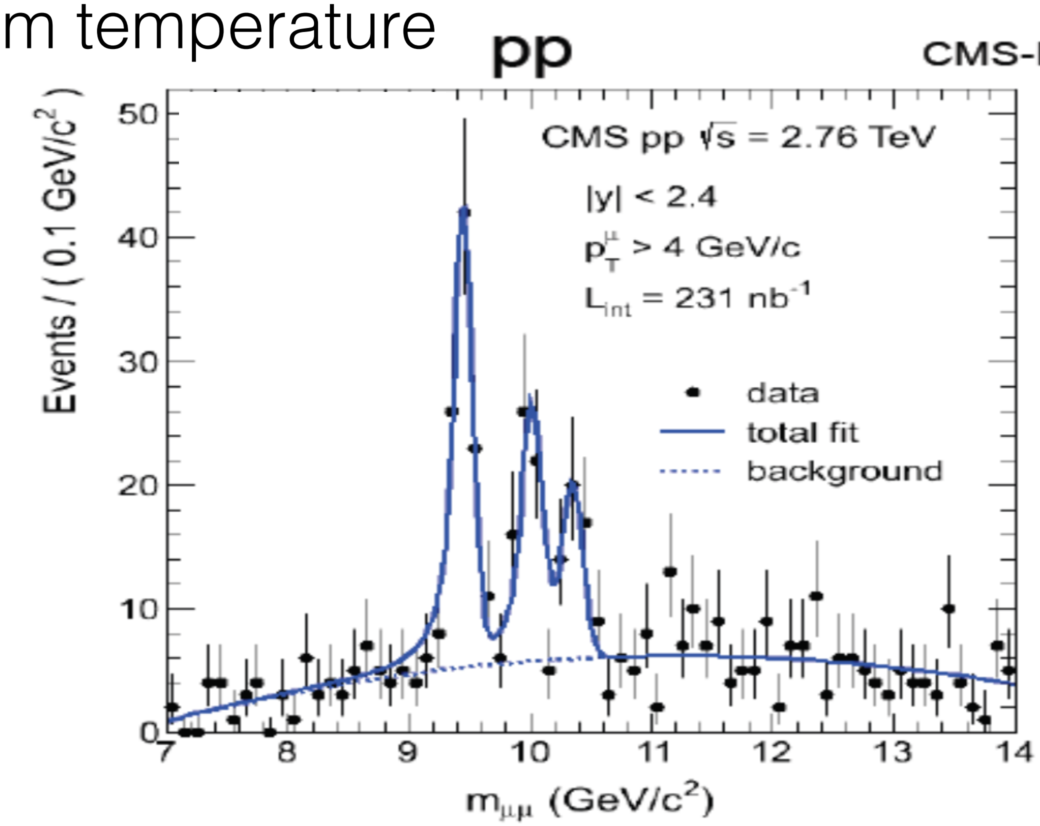


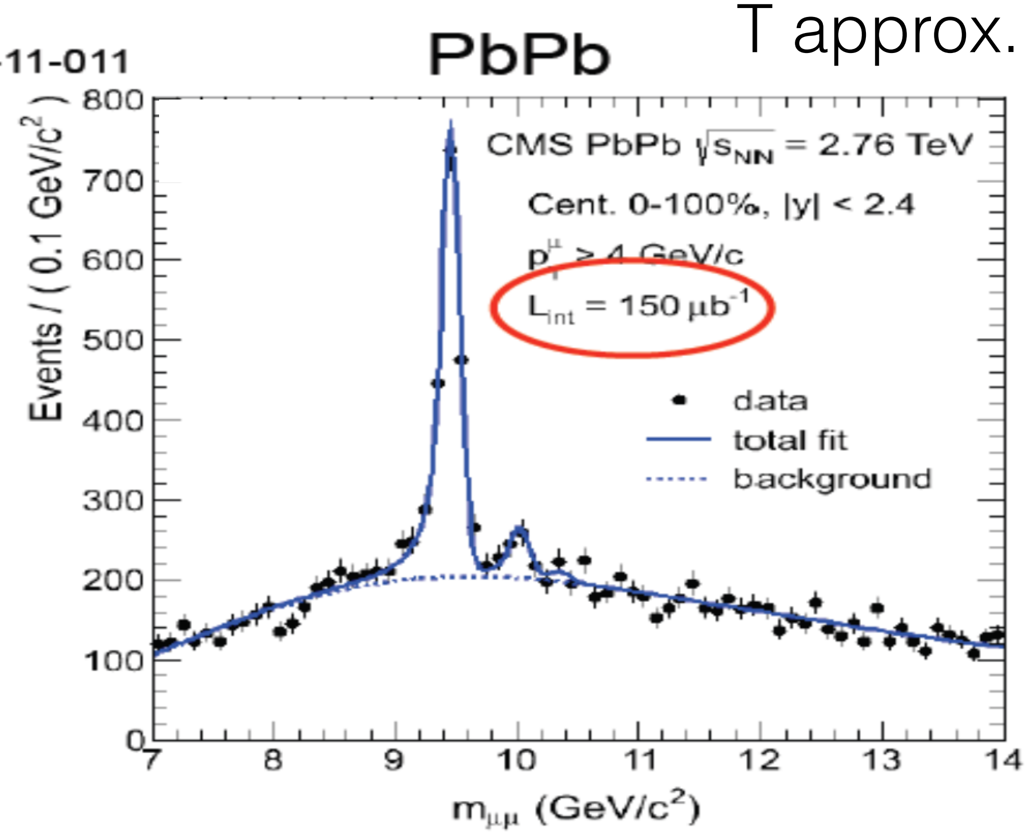
Bottomonium as a probe of QGP

Eur.Phys.J. C76 (2016) no.3, 107

Room temperature

T approx. 500 MeV

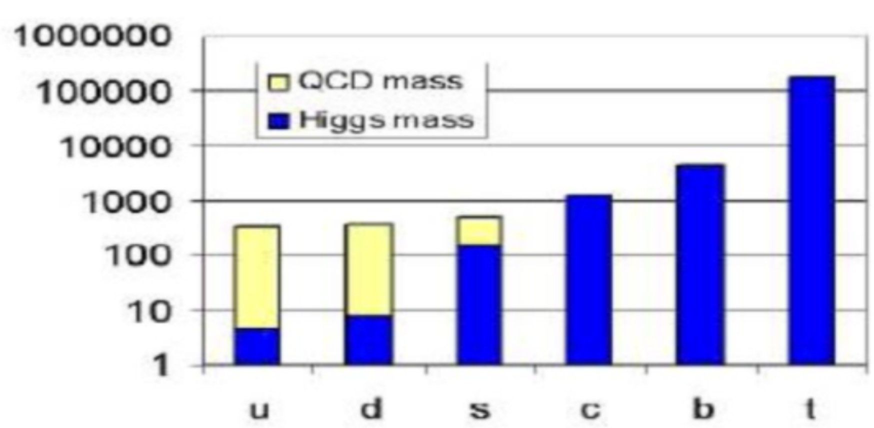




$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$$
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.21 \pm 0.11 \pm 0.02$$

$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.01$$
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb} < 0.07$$

CMS



NB: probing complementary aspects wrt to topology: no sensitivity to chiral physics here!

Bottomonium work is with the FASTSUM collaboration

Gert Aarts, Chris Allton, Jonas Glesaaen, Simon Hands,
Swansea University, U.K.

Benjamin Jäger
University of Southern Denmark, Odense, Denmark

Seyong Kim
Sejong University, Seoul, South Korea

Maria Paola Lombardo
INFN, Frascati, Italy

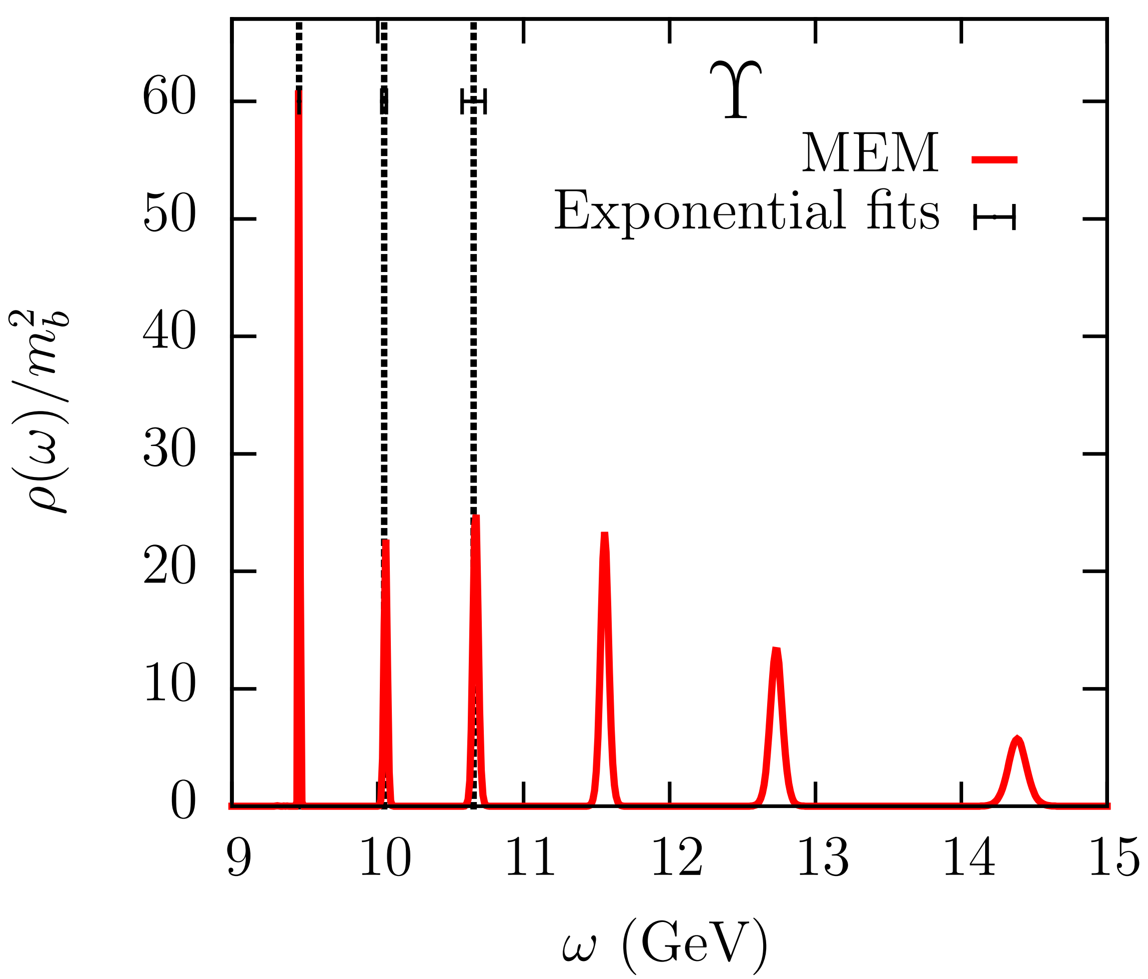
Mike Peardon, Sinéad Ryan
Trinity College, Dublin, Ireland

Jon-Ivar Skullerud
National University of Ireland, Maynooth, Ireland

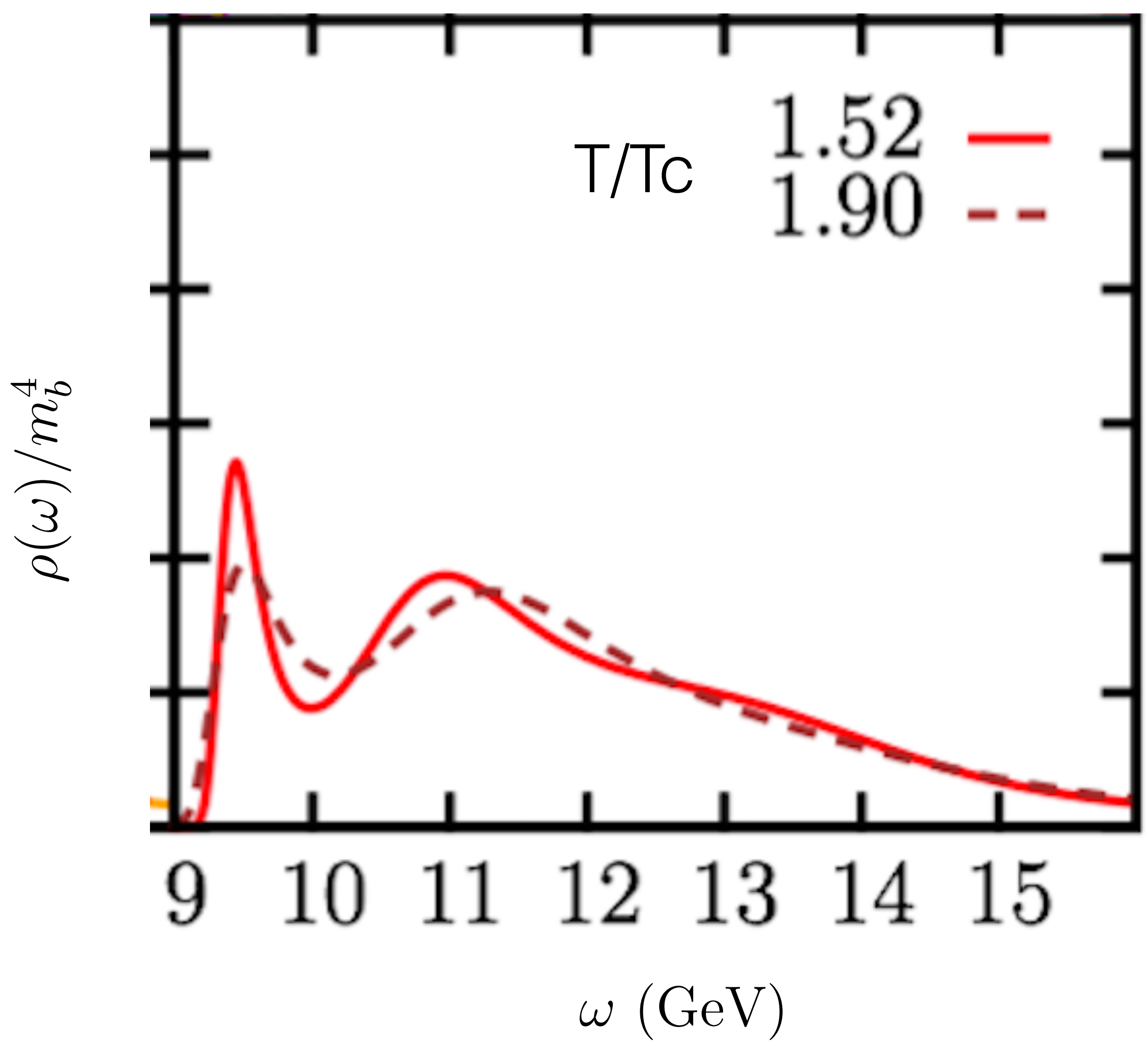
Bottomonium NRQCD results: spectral functions from MEM

FASTSUM Collaboration

Room temperature



T approx. 400 MeV



Melting of excited states

NRQCD bottomonium spectral functions at a glance

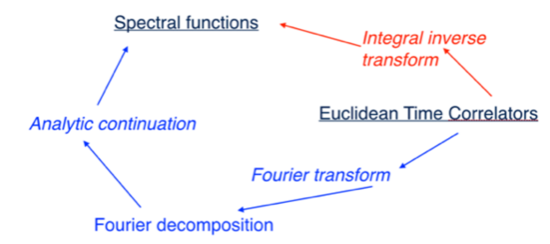
NRQCD appropriate for bottomonium

easier inversion

easier to compute propagators

Relativistic

$$D(\tau) = \int_0^\infty \frac{e^{-\tau\omega} + e^{-(\beta-\tau)\omega}}{1 - e^{-\beta\omega}} S(\omega) d\omega$$



Non-relativistic

$$D(\tau) = \int_{-M_0}^\infty e^{-\tau\omega} S(\omega) d\omega$$

Inverse Laplace: makes life easier..

Interesting application: bottomonium

Anisotropic lattices:

*Many points in time direction.

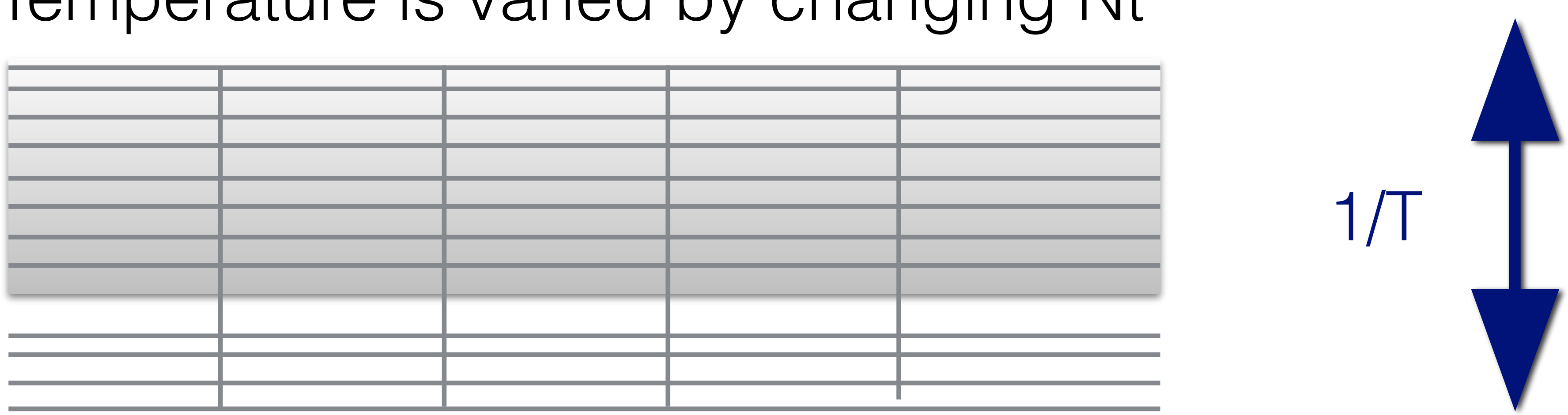
*Disentangle space from time discretization effect.

*Approach to continuum time easier.

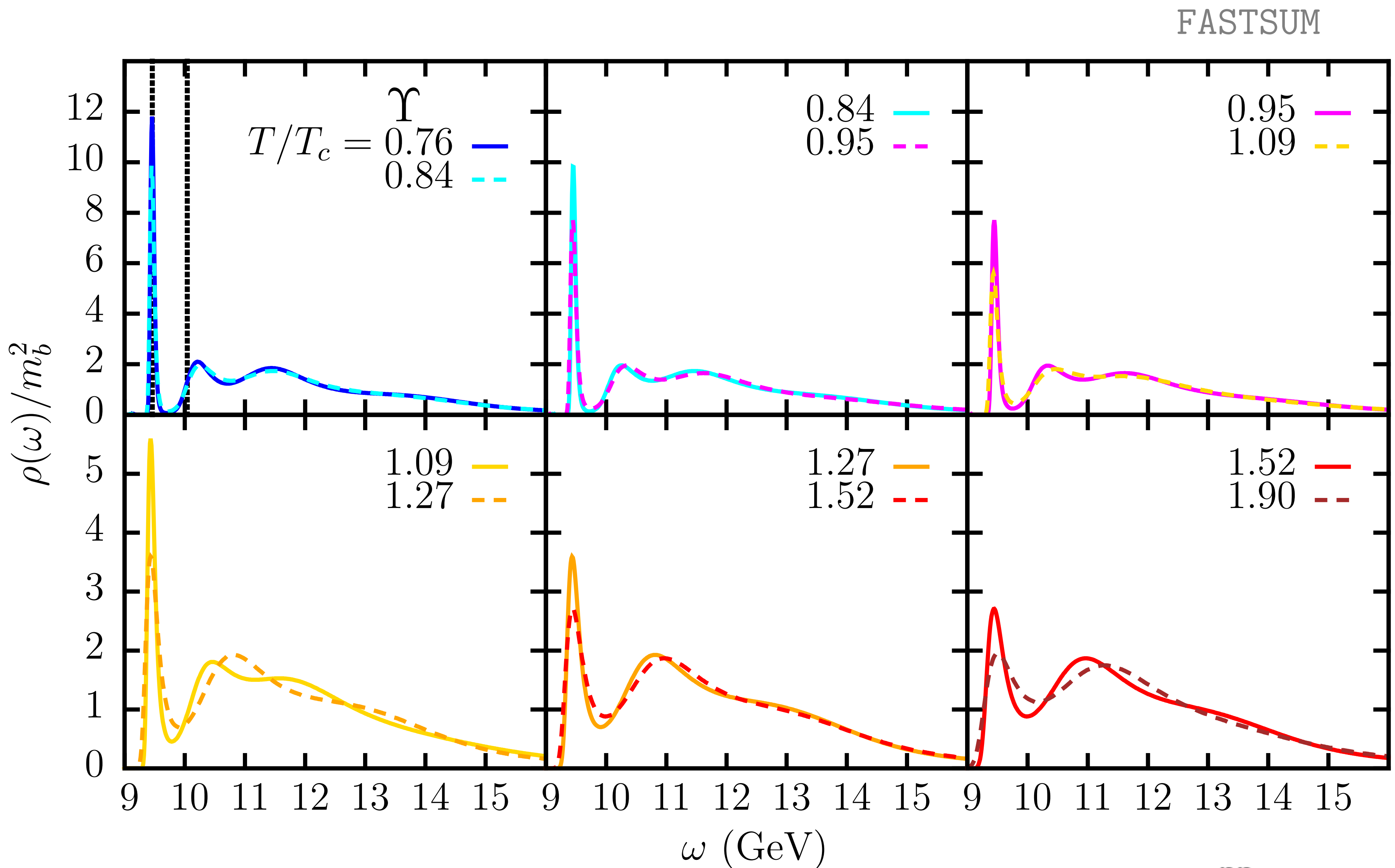
M_π [MeV]	Anisotropy $= a_s/a_t$	a_s [am]	a_t [am]	
450	6	167	28	Completed
390	3.5	123	35	Completed
230	3.5	113	33	In progress: going to a very fine lattice
390	7	123	18	In progress: going to a very fine lattice

0.4 Tc < T < 2Tc

Temperature is varied by changing Nt



Bottomonium spectral functions: sequential melting

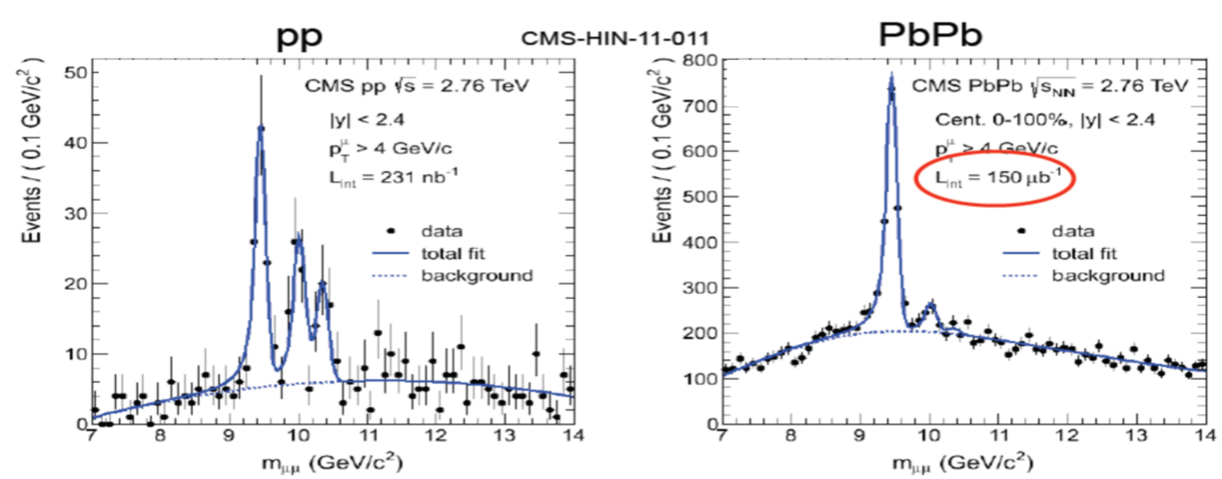


Persistence of the ground state at all temperatures

Melting of excited states

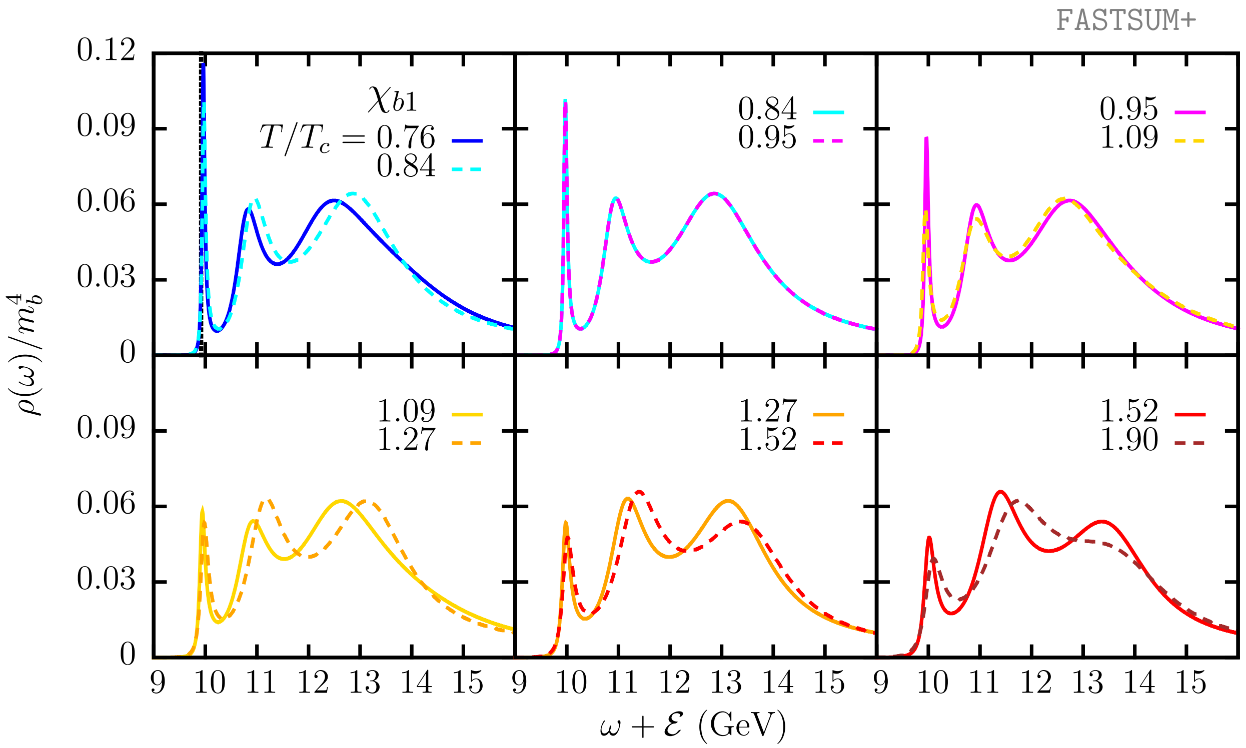
Modifications of the ground state

Pattern reminiscent of experimental observations

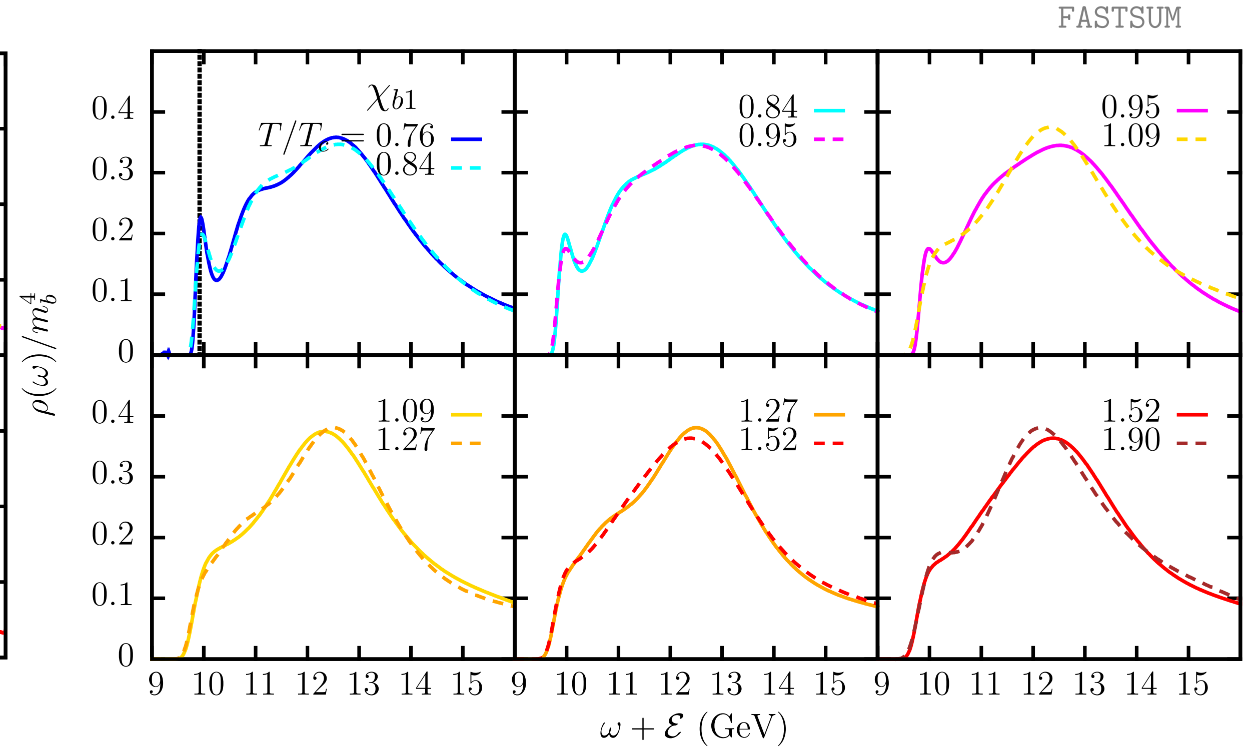


Bottomonium: Outstanding remaining issue: the (unknown) systematics

BR



MEM



FASTSUM +
Y. Burnier and
A. Rothkopf
AIP Conf.Proc. 1701 (2016) 060018

Qualitative differences for the Chi_b: with the BR approach the excited state survives and appears even stronger!

II. Beyond the standard model

Axions
Composite Higgs

The QCD axion: ideal Dark Matter candidate

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 $\theta < 10^{-9}$

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

Postulate axions, coupled to Q:

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

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

Axion potential

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

$f_A \gtrsim 4 \times 10^8$ GeV

weakly coupled

The QCD axion: ideal Dark Matter candidate

Temperature

Time from Big Bang

Hubble parameter

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

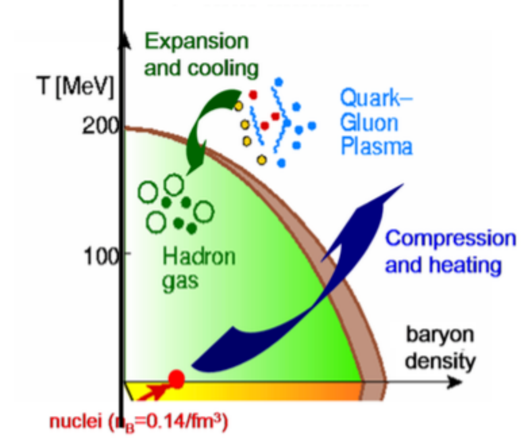
Axions's freezout

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

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

Quark Gluon Plasma: Topology

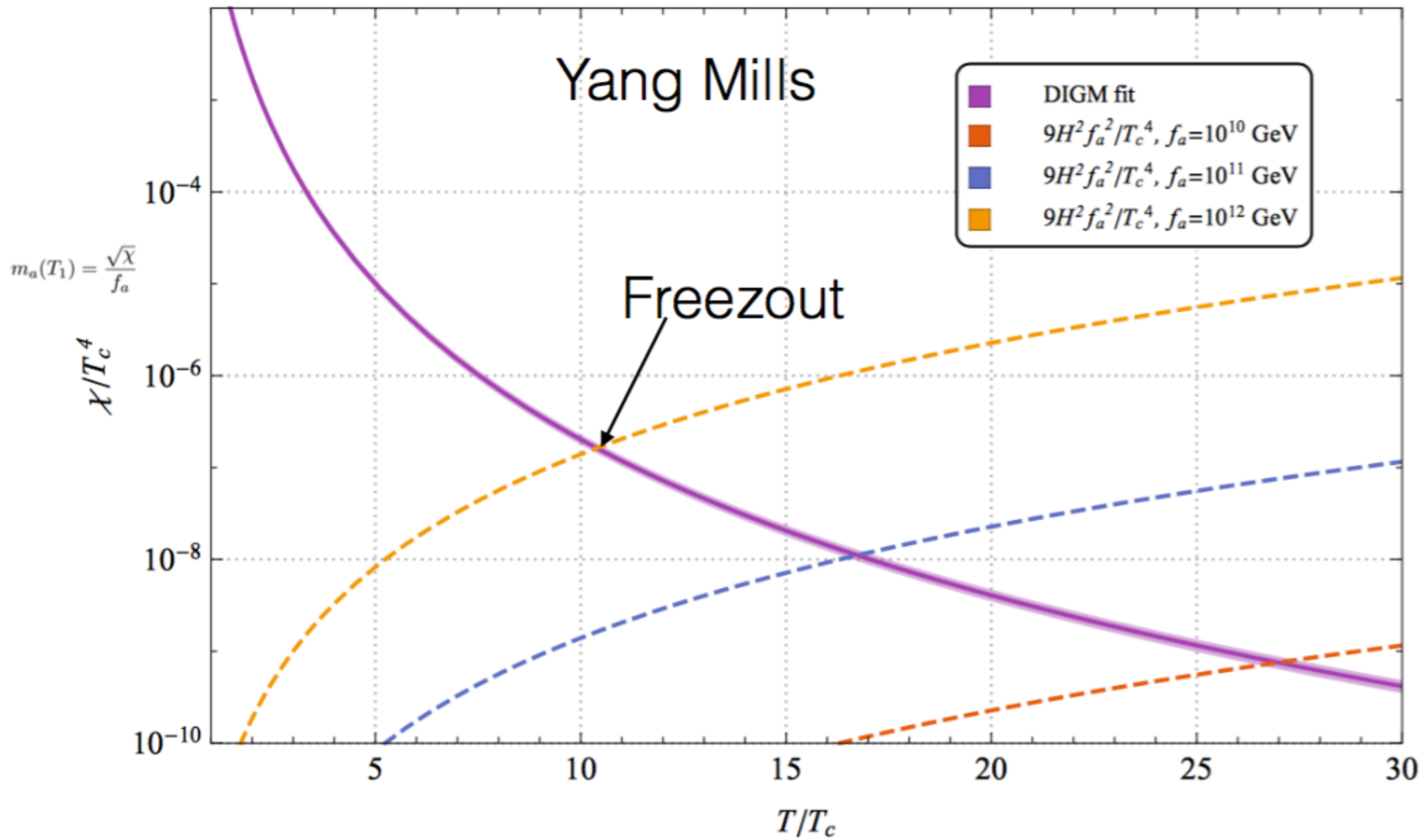
Axions' mass and density today



Axion freezout from lattice results

Axion freezout : 3H(T) = m_a(T) = $\sqrt{\chi(T)}/f_a$

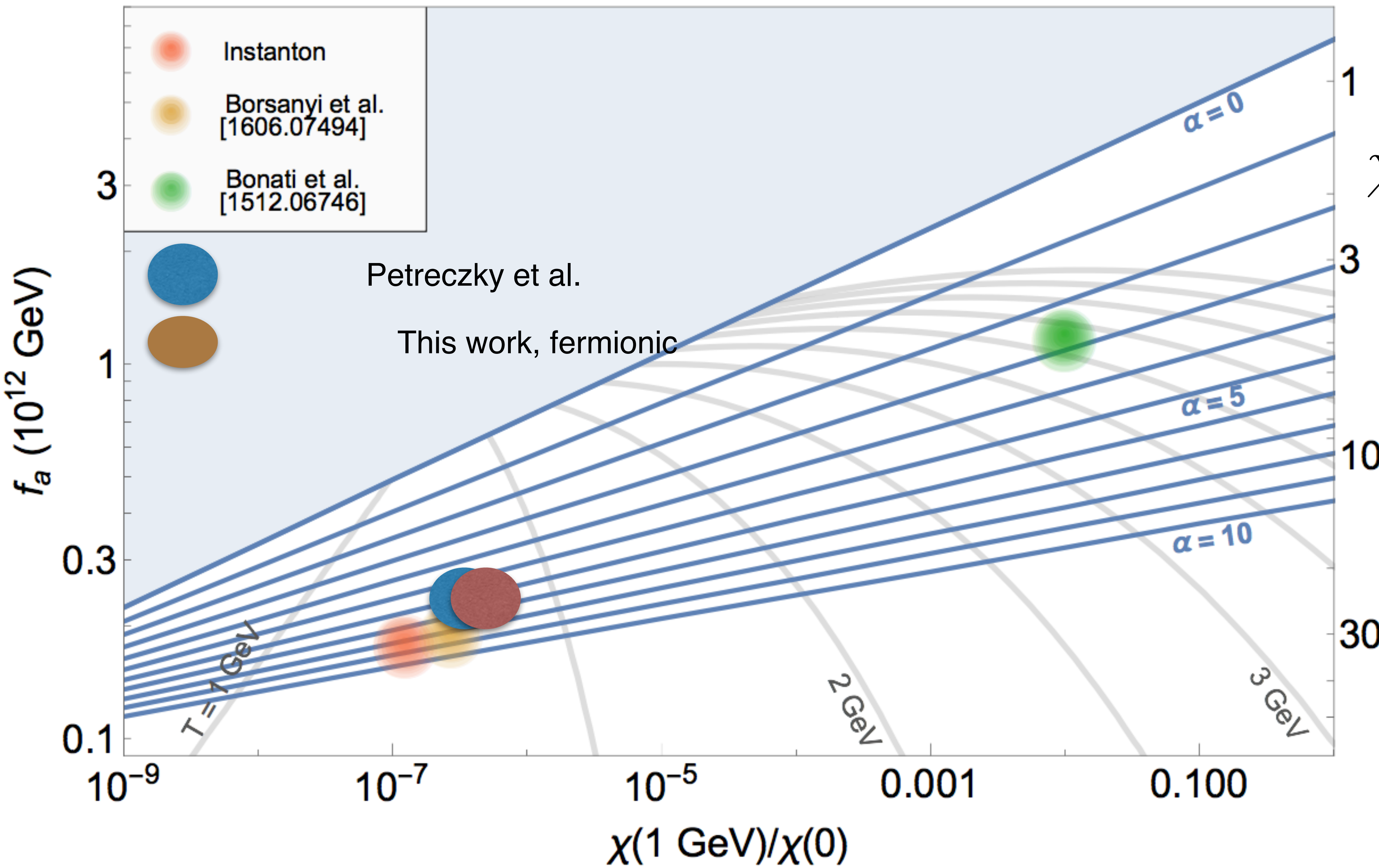
Berkowitz Buchoff Rinaldi 2015



Axion density at freezout controls axion density today

Needed assumption on fraction of DM made of axions

Assume: Axions make all of Dark Matter



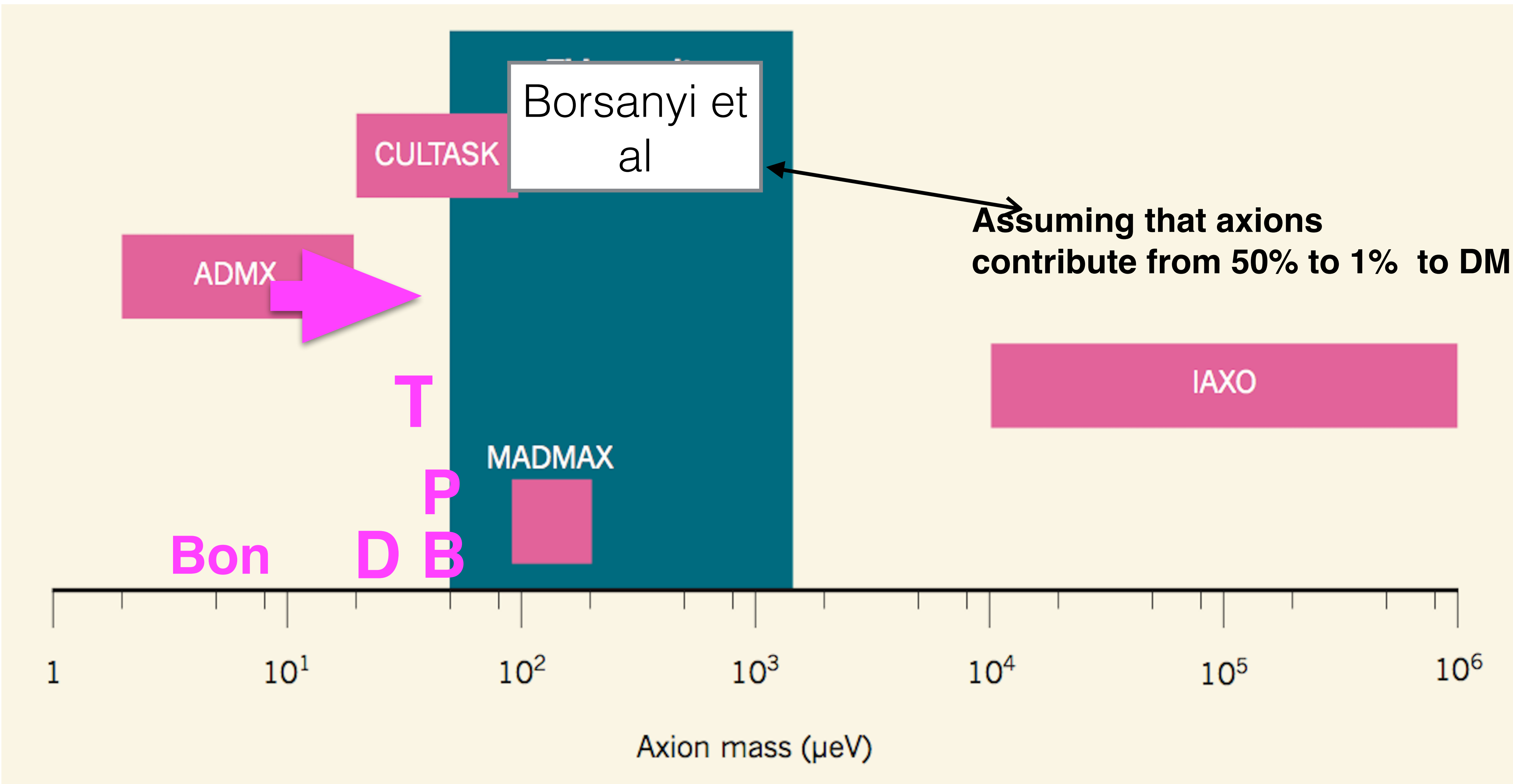
$$\chi(T) \propto 1/T^{\alpha}$$

$$T > 1\ \mathrm{GeV}$$

PhD Thesis, G. Grilli di Cortona, Sissa 2016
(advisor G. Villadoro)

Lower limits on the axion mass assuming that axions make 100% of DM:

Bon: Bonati et al.; D: DIGA, B: Borsanyi et al.,
P: Petreczky et al., T: this work, fermionic

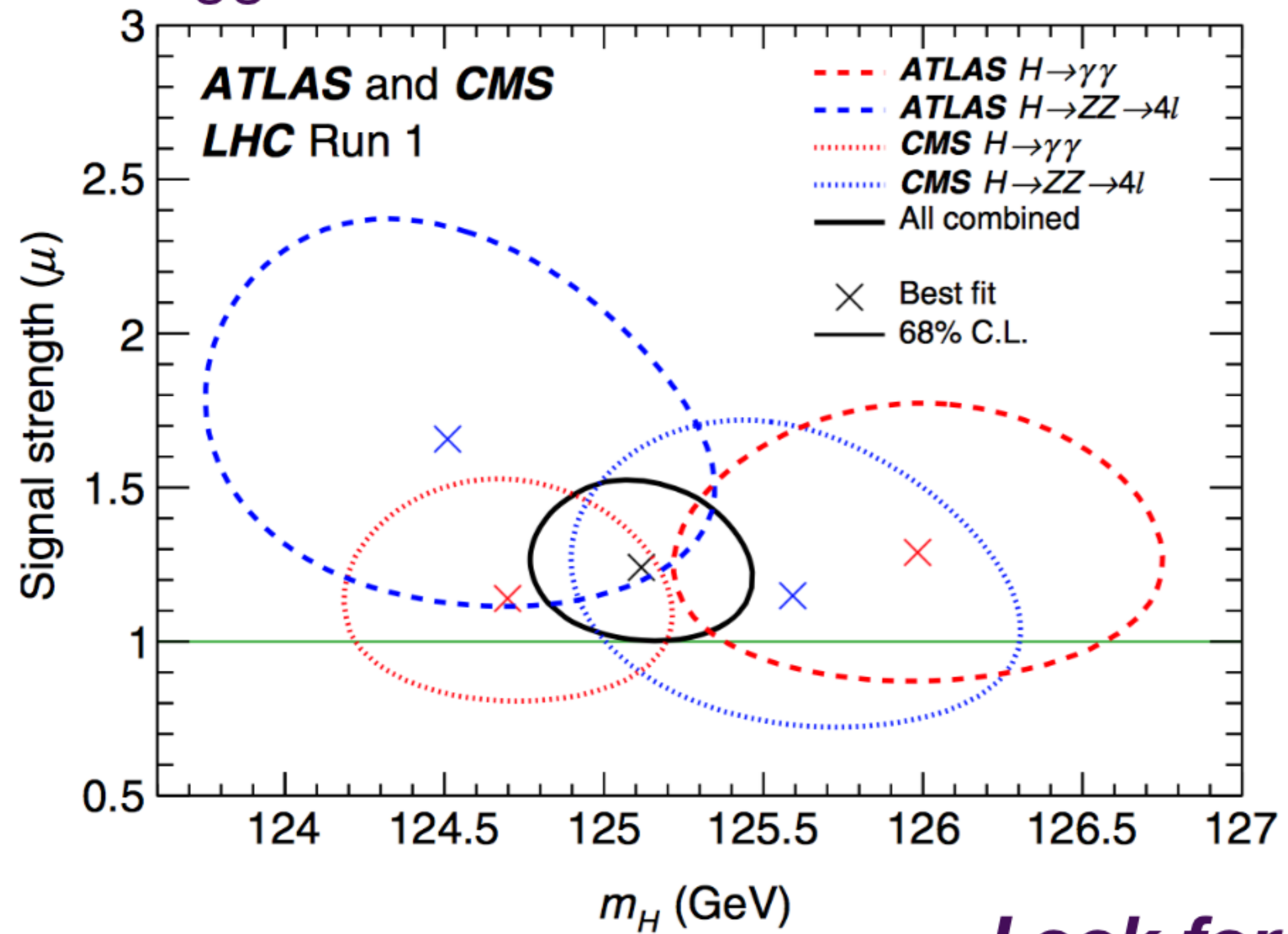


Updated from MpL Nature N&V 2017

Composite Higgs

Beyond the Standard Model:

Can we find a theory which produces a narrow Higgs-like status?



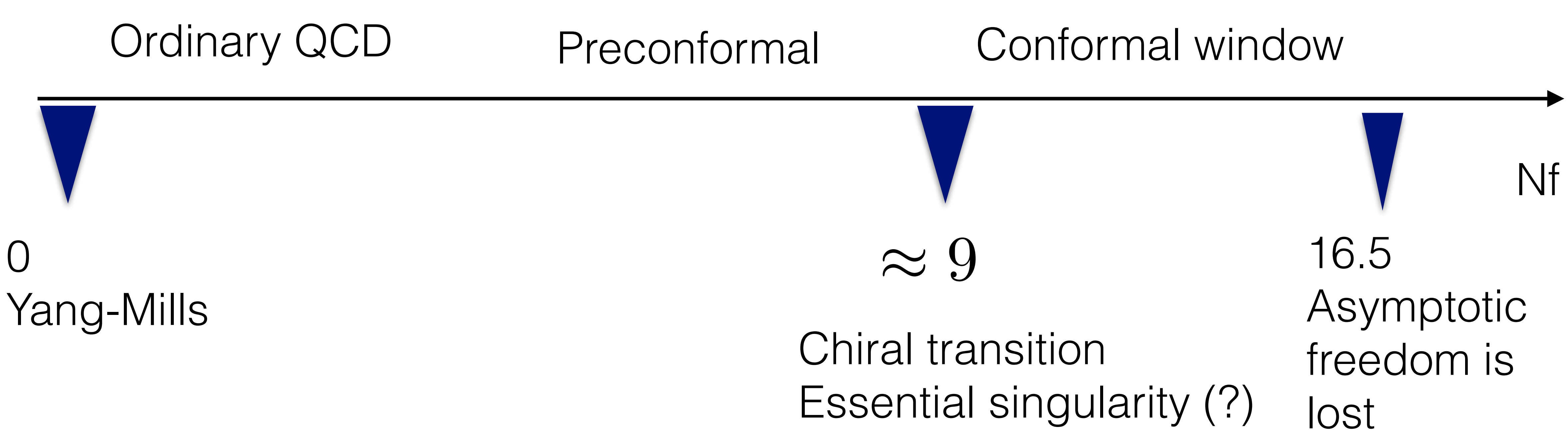
Maybe in the preconformal region?

It should be a composite scalar particle, lighter then so-far unobserved composite vector states

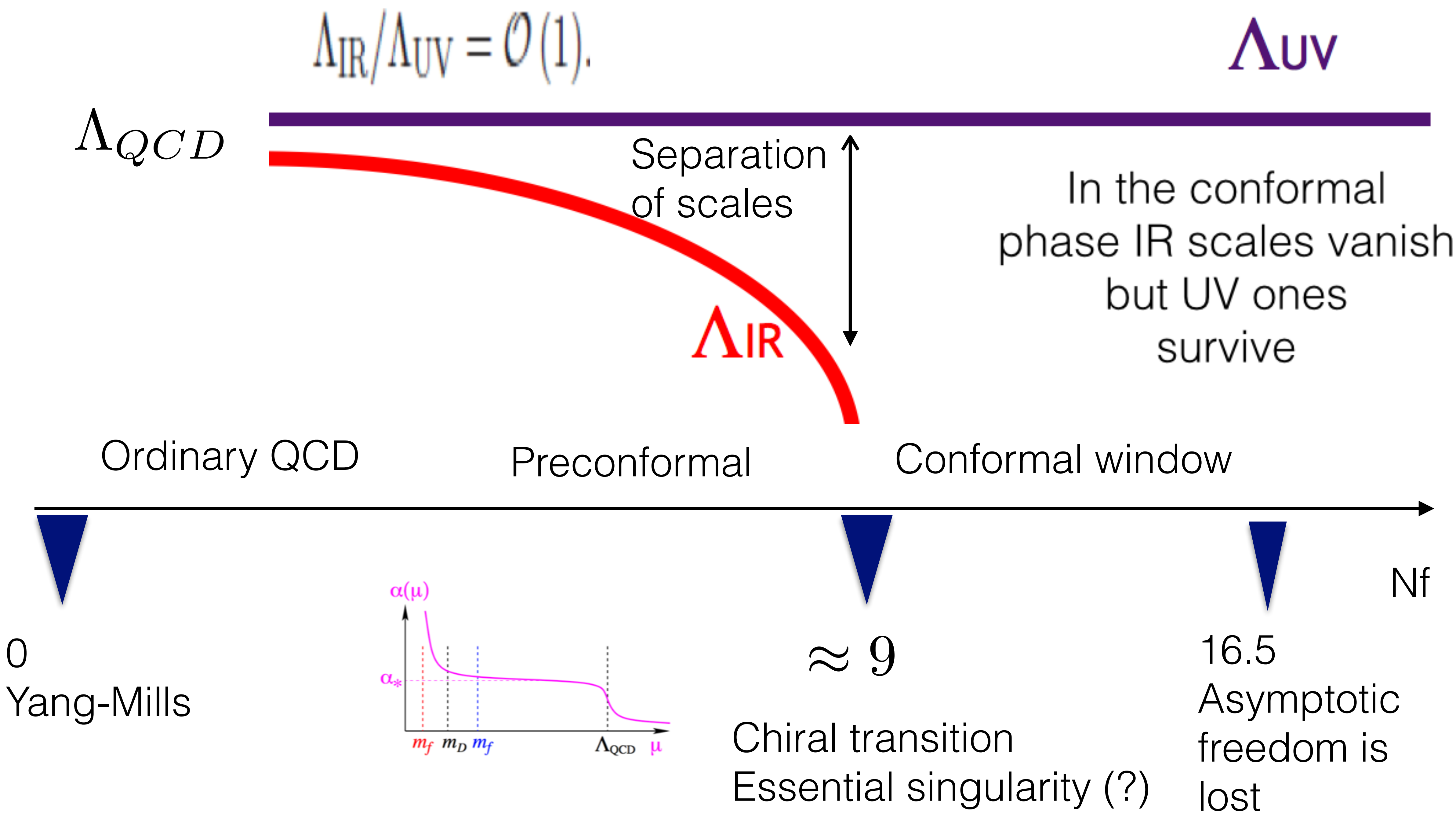
Look for theories with scale separation

..as possible BSM candidates

Phases of QCD as a function of Nf



Phases of QCD as a function of Nf



Work on phases of QCD at large Nf

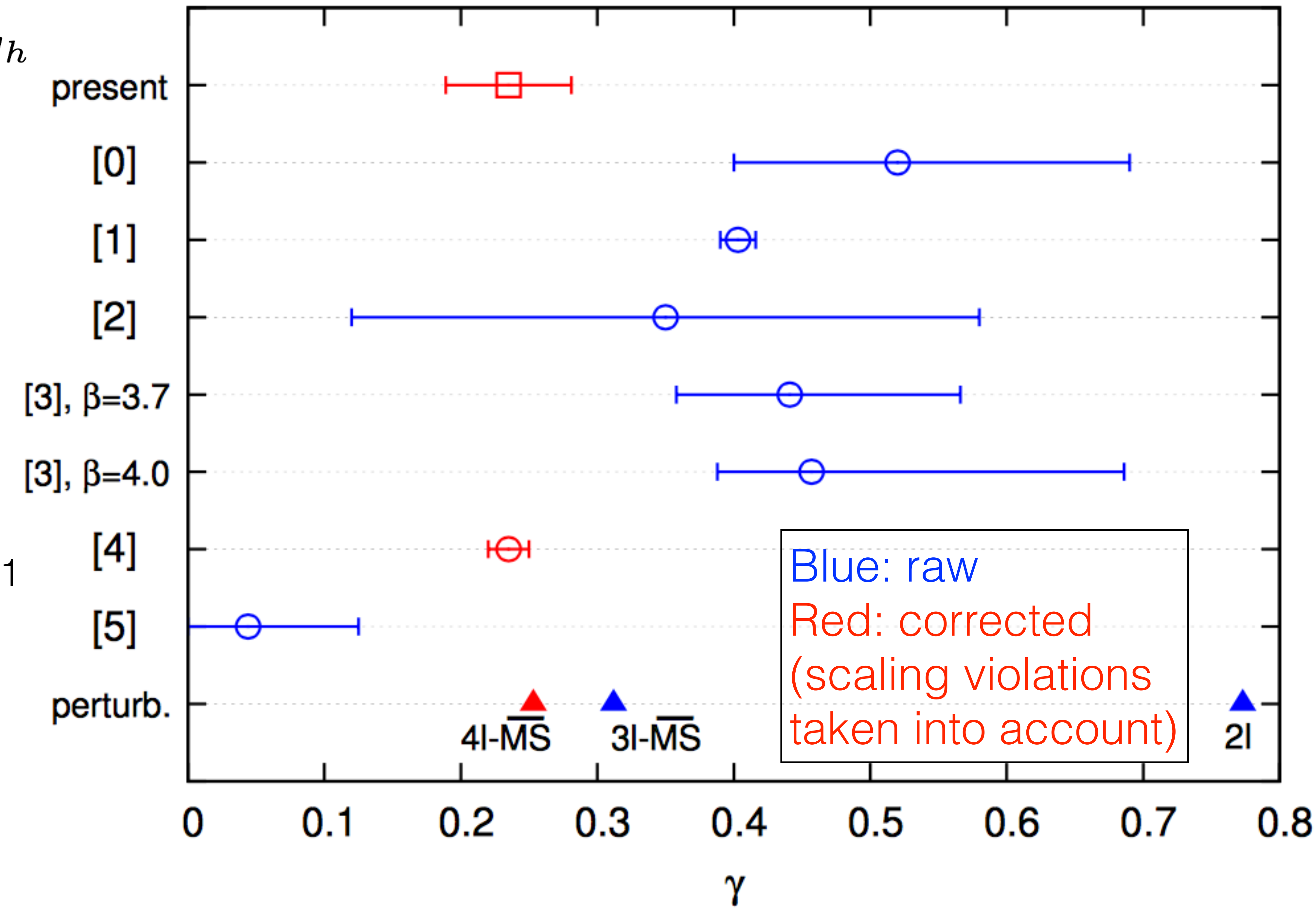
is with

Elisabetta Pallante (Groningen),
Kohtaroh Miura(Marseille),
Tiago Nunes da Silva (Sao Paulo)

Compilation of results for the anomalous dimension in the conformal phase for Nf=12

$$M_H = c_H m^{1/y_h}$$

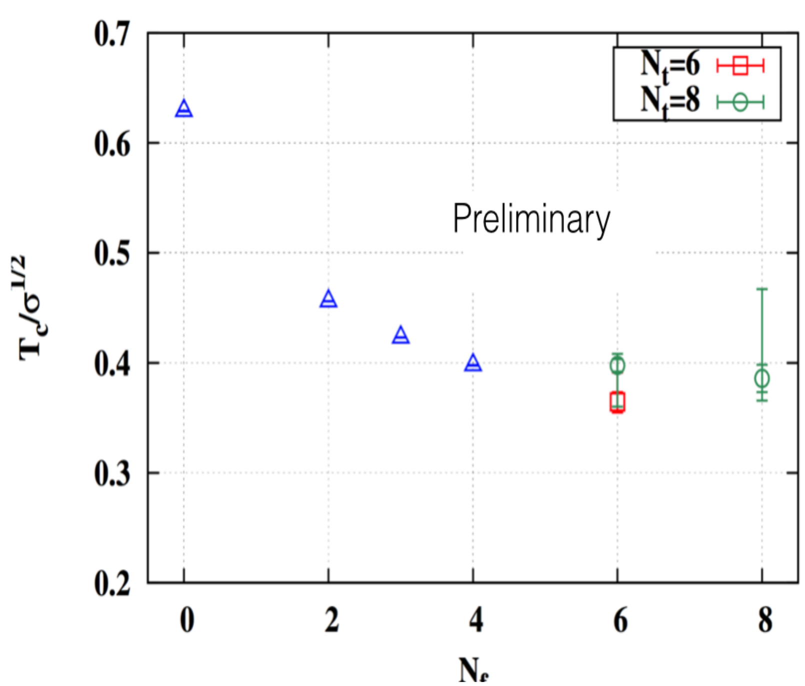
[0] DPL, 2009
[1] LSD coll. 2011
[2] De Grand et al.2011
[3] KMI coll. 2012
[4] Cheng et al. 2014
[5] Itou 2013

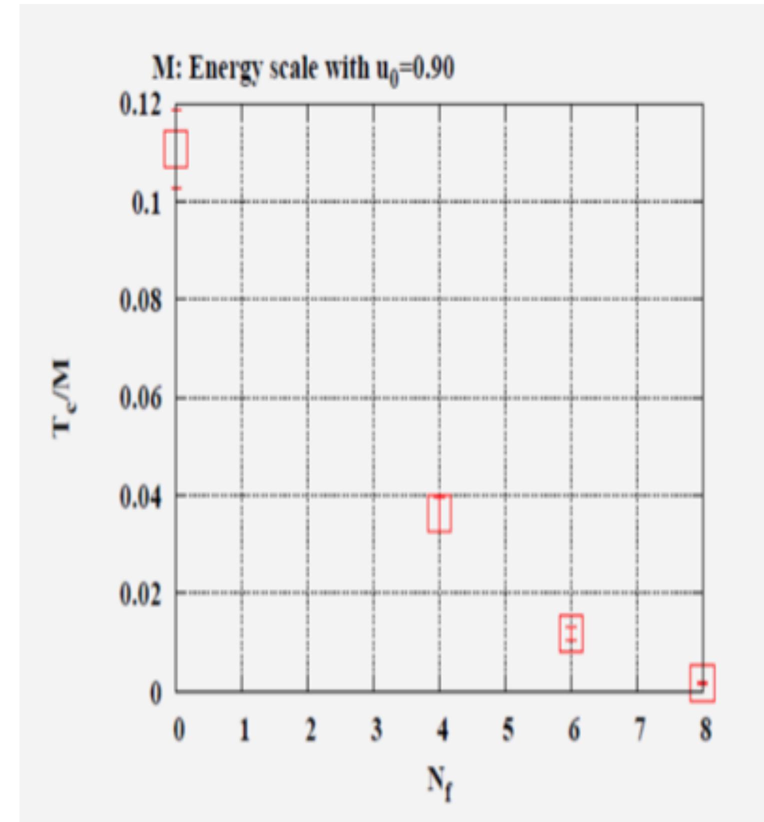


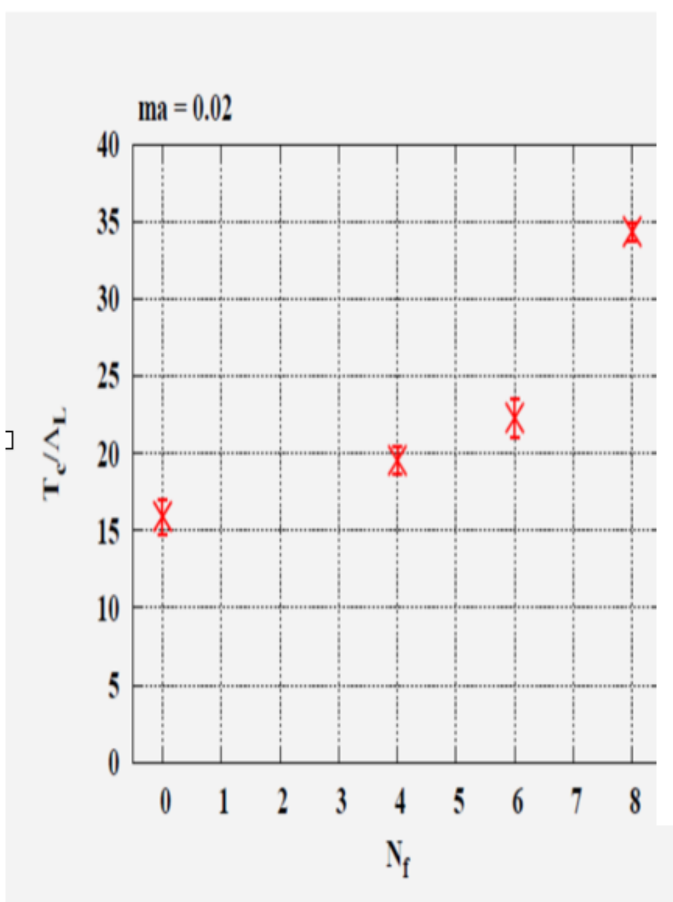
MpL, Miura, Nunes da Silva, Pallante 2014

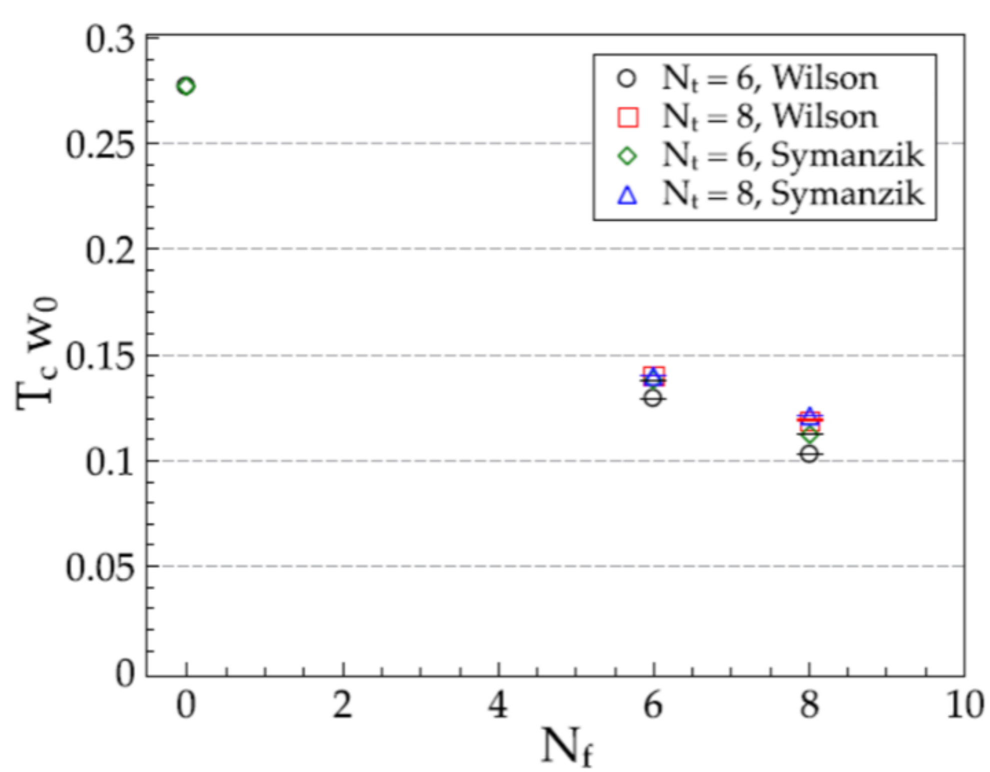
Hierarchy of scales in the near-conformal phase

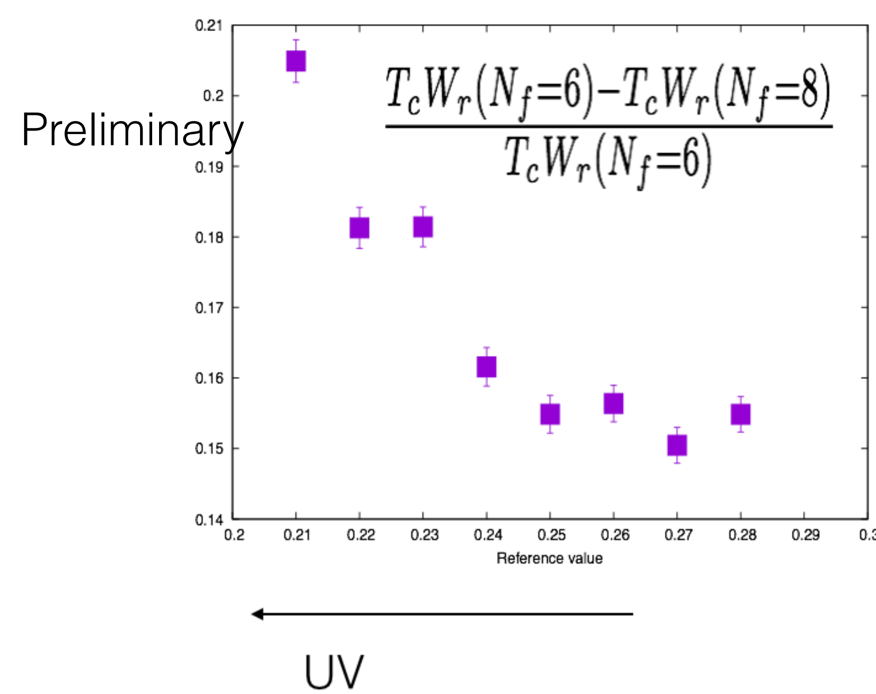
Dimensionless quantities behave differently approaching Nfc





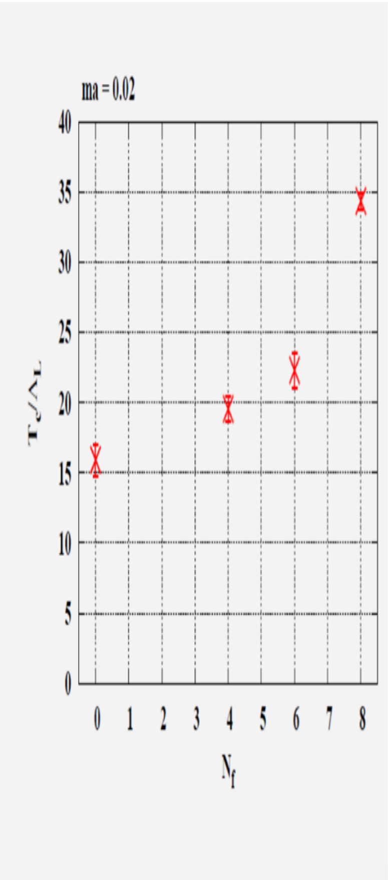






Comparison with holographic studies

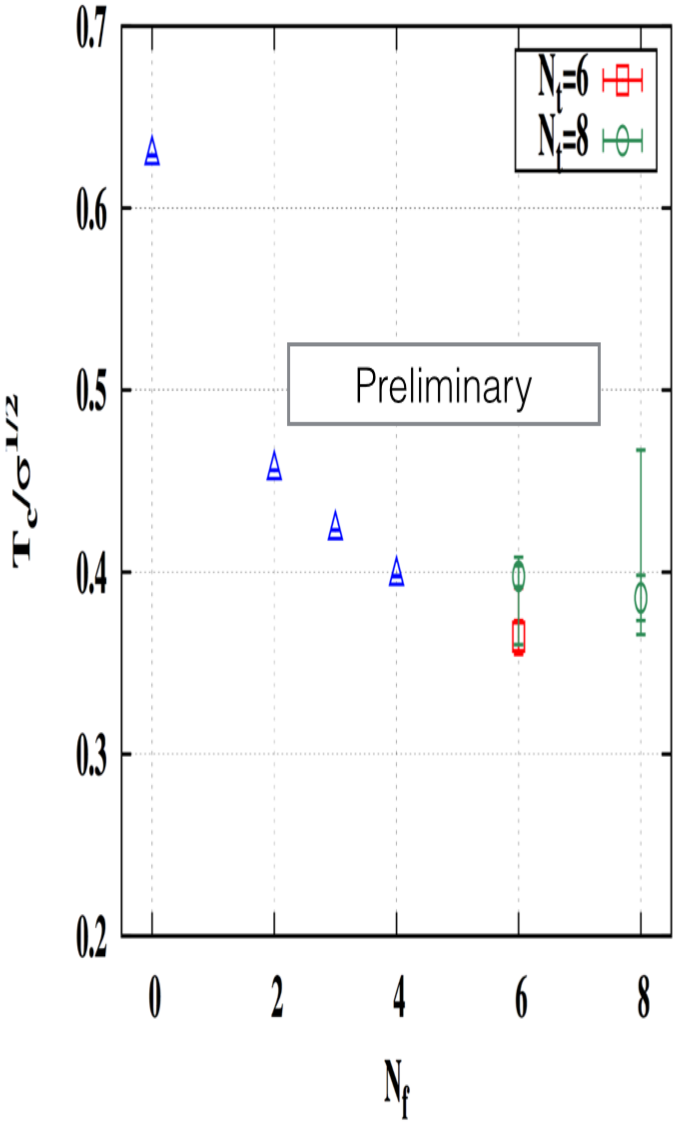
$$\frac{2\pi T_c}{M_{KK}} = 1 - \frac{1}{126\pi^3}\lambda_4^2\frac{N_f}{N_c}\left(1+\frac{12\pi^{3/2}}{\Gamma\left(-\frac{2}{3}\right)\Gamma\left(\frac{1}{6}\right)}\right)$$



Bigazzi and Cotrone, JHEP 2015

$$\left(1+\frac{12\pi^{3/2}}{\Gamma\left(-\frac{2}{3}\right)\Gamma\left(\frac{1}{6}\right)}\right) \approx -1.987$$

T increases with Nf on the scales used in these two studies



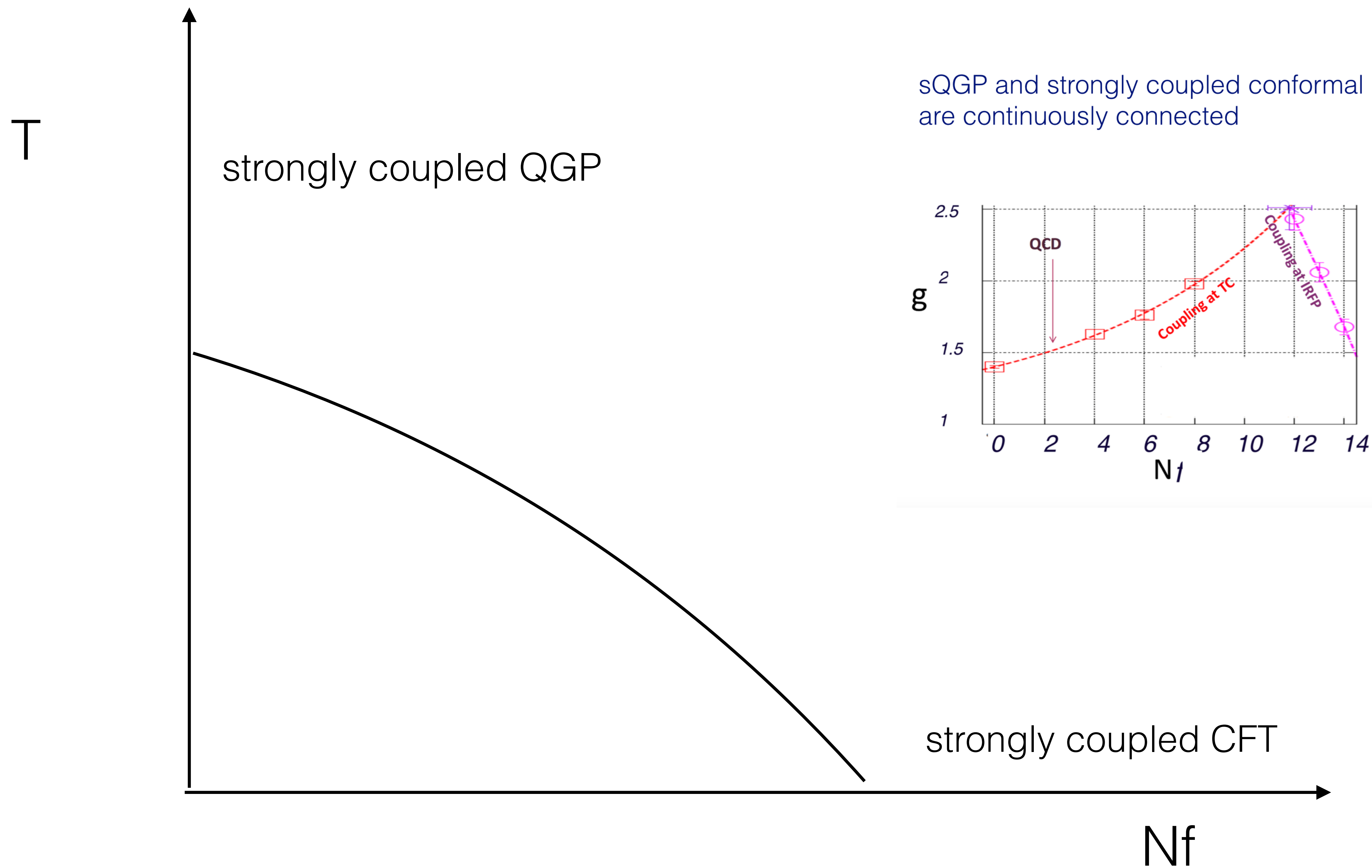
Mild decrease, possibly constant as $N_f \to N_f^c$

Again similar to the prediction of the WSS model:

$$\frac{T_c}{\sqrt{\sigma}} \propto (1-\epsilon N_f/N_c)$$

communicated by F. Bigazzi

Phases of QCD in the T, Nf plane



sQGP and strongly coupled conformal QCD are continuously connected

The strenght of the coupling increases with Nf

Miura, MpL 2013

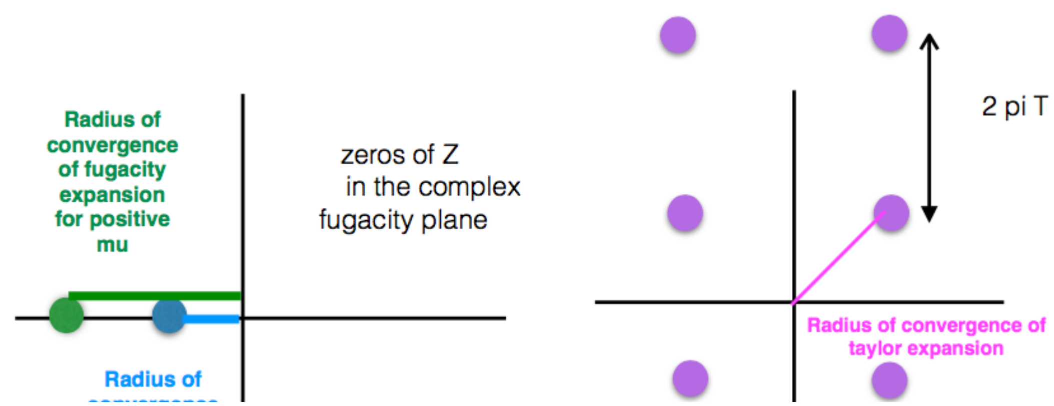
Next steps

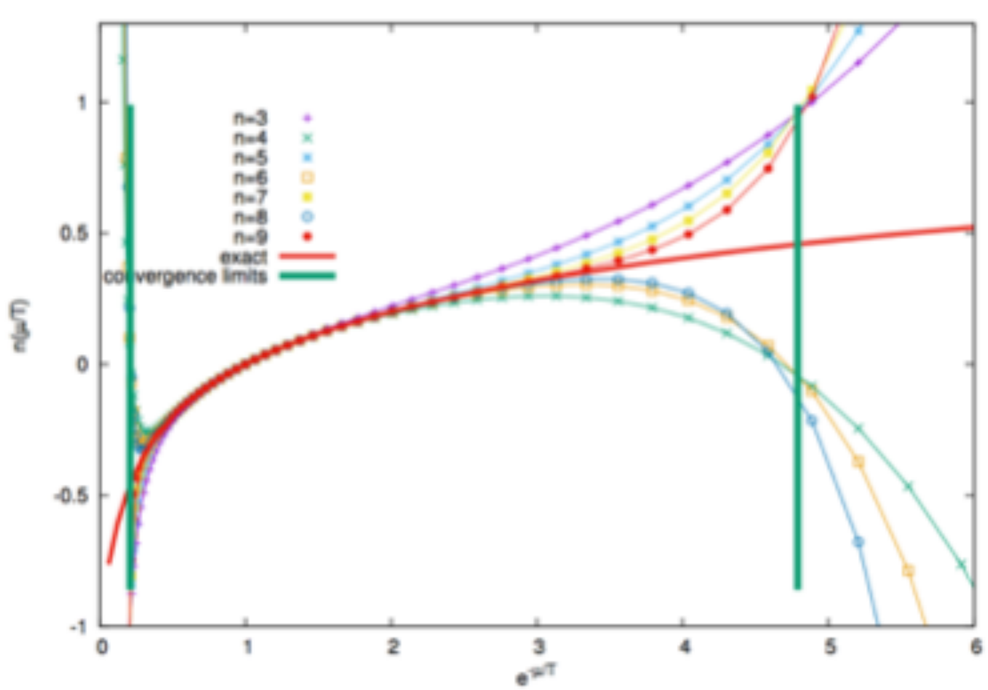
QCD and dense matter

with V. Bornyakov (Protvino), A.Goy(Vladivostok), A.Nakamura(Vladivostok&RIKEN)

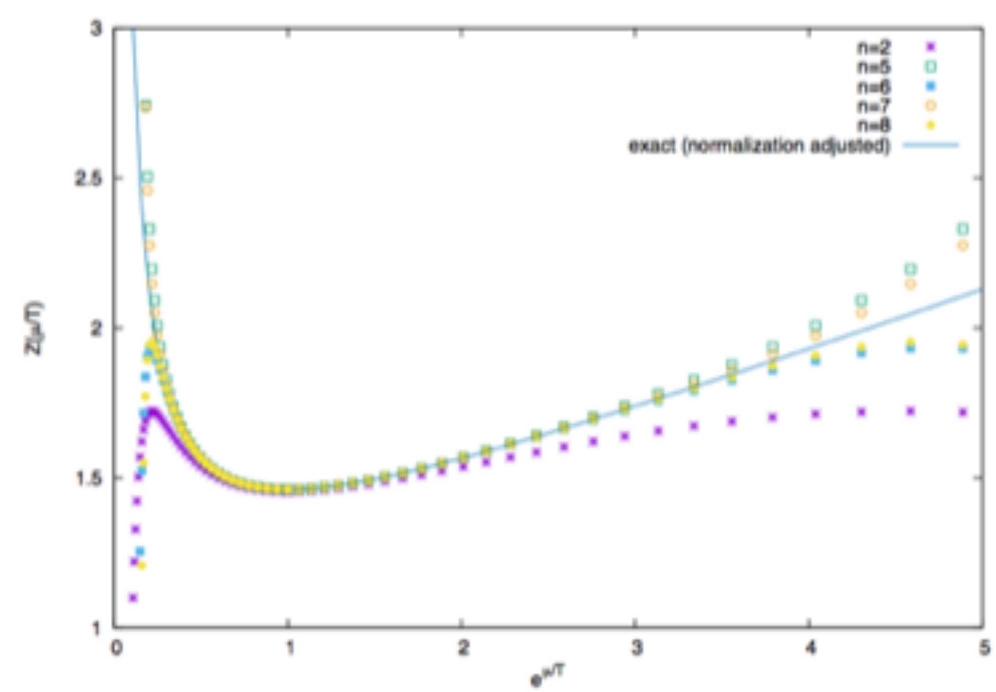
A strategy for the search of the QCD critical point based on joint analysis of

*Virial expansion,
*Taylor expansion ,
*Canonical expansion
using
*Cluster Model as a baseline





limited convergence
of the viral expansion

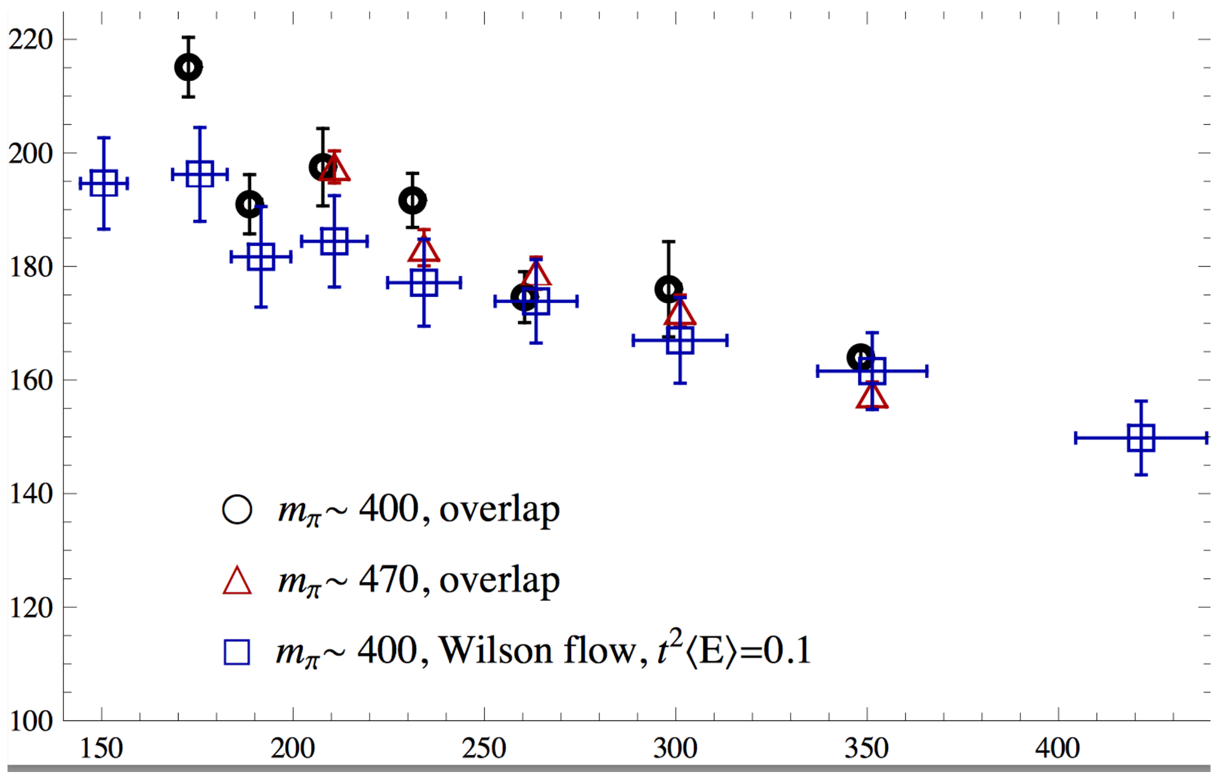


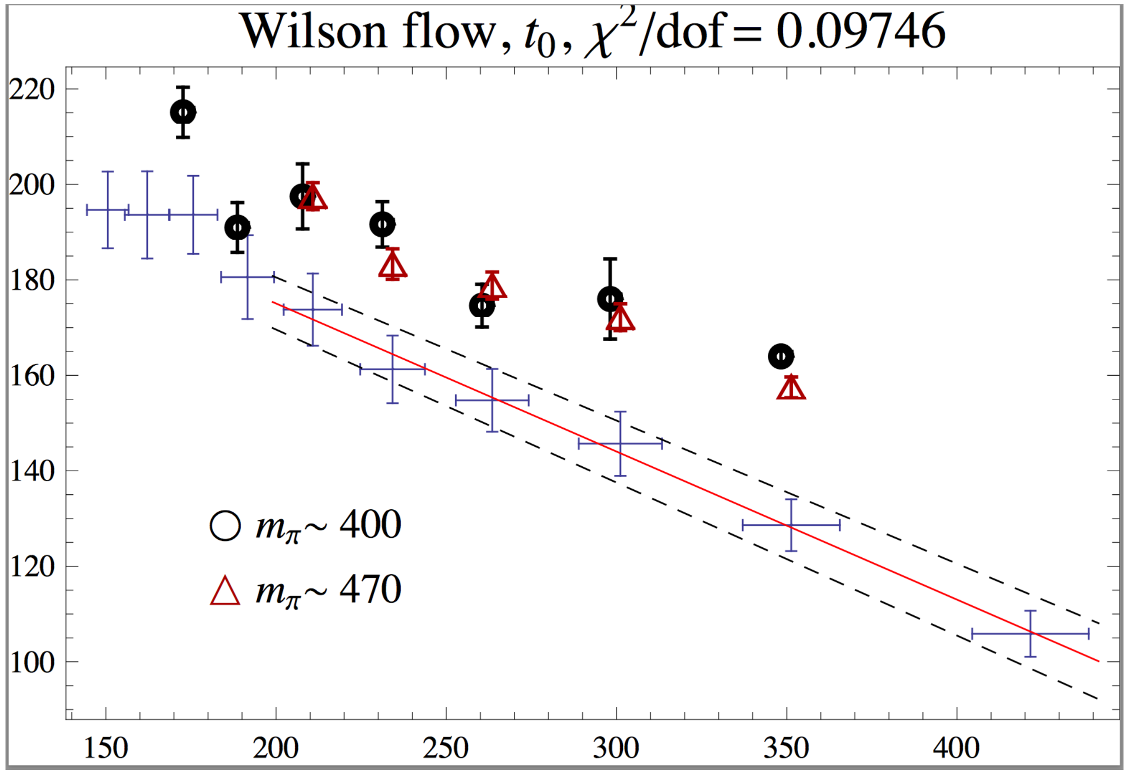
convergence of the canonical
expansion

Topology

with F. Burger, E.-Michael Ilgenfritz, Anton Trunin - and L. Hollik , L. von Smekal

*Preliminary results with overlap operator obtained on Marconi:





*For this project we would like to rely mostly on CINECA-INFN 2018 allocation

*Also very important 15Tbyte $DRES

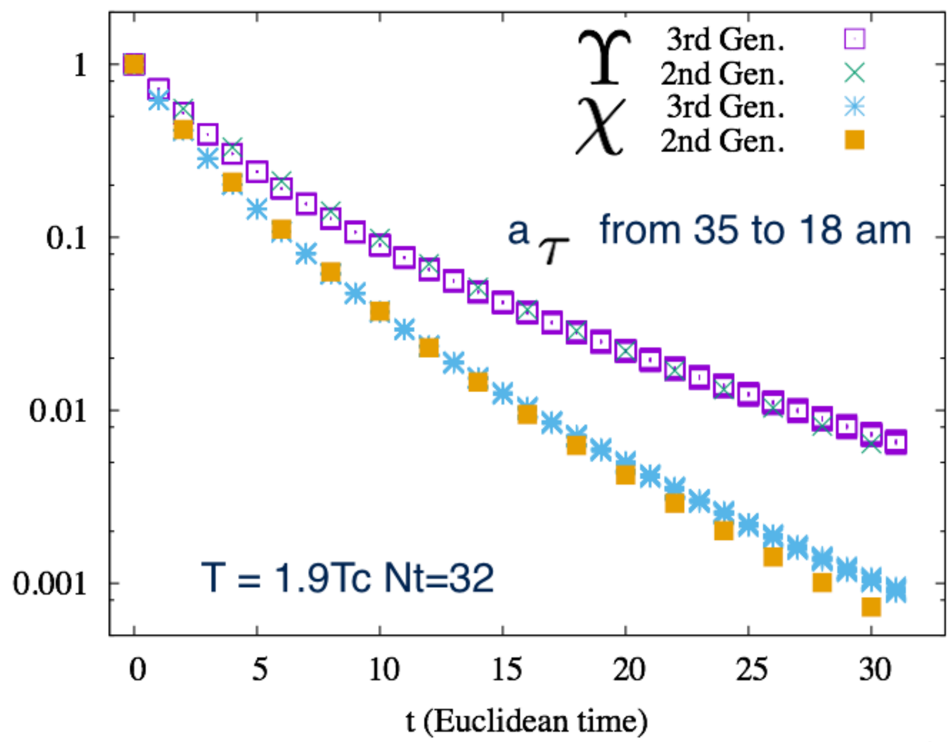
*Under debate whether to join effort with Anderson localization study (more demand on storage and CPU in that case)

Bottomonium

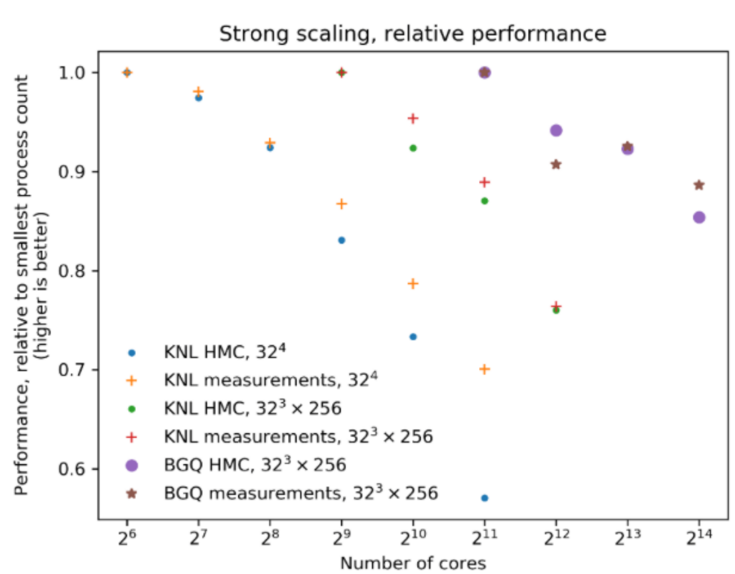
with FASTSUM coll.

Work in progress:

*Preliminary results on fine lattices



*OpenQCD for FASTSUM



Already secured resources:

*135.6M core-hours on Edinburgh BG/Q under DIRAC (all FASTSUM)

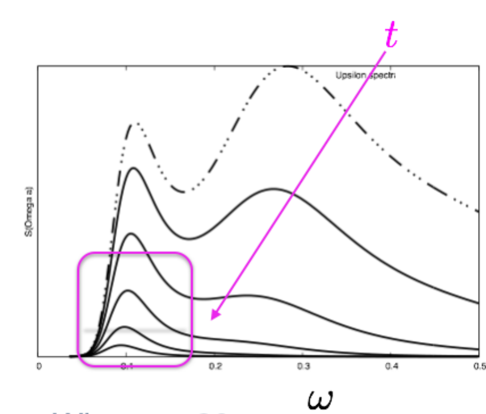
*10M core-hours on Marconi KNL under PRACE (all FASTSUM)

*Developed new analysis based on weighted spectral functions

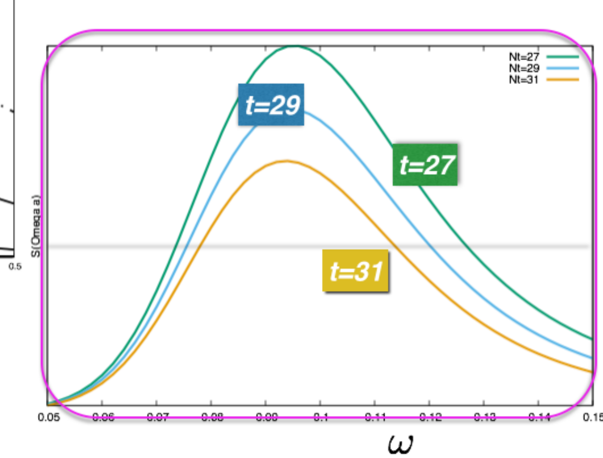
Weighted Spectral Functions

$$e^{-\omega t} S(\omega)$$

using the Upsilon spectral function



When t > 20
only the fundamental
peak is discernable



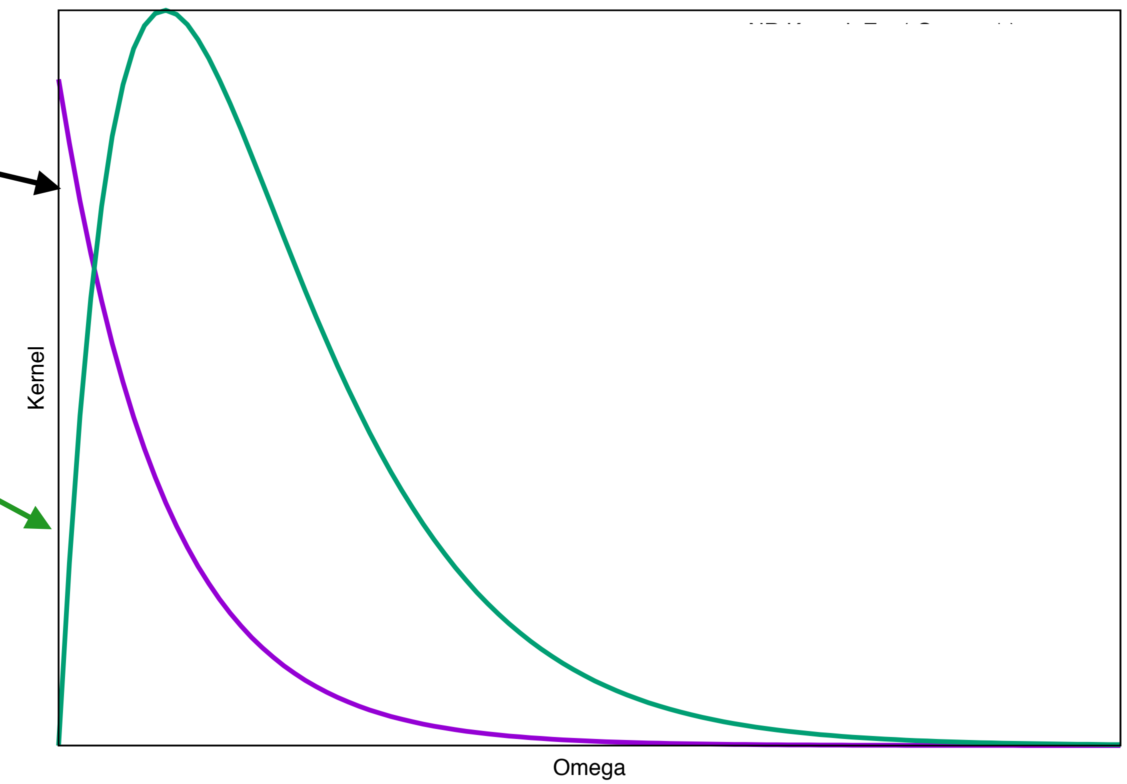
Weighted spectral functions

$$G(t) = \int e^{-\omega t} S(\omega) \frac{d\omega}{2\pi}$$

$$K(\omega, t) = e^{-\omega t}$$

$$\frac{dG(t)}{dt} = \int \omega e^{-\omega t} S(\omega) \frac{d\omega}{2\pi}$$

$$K_{der}(\omega, t) = \omega e^{-\omega t}$$



cfr. Sumudu
method
by Orlandini, Pederiva, Roggero

The smoothness of the correlators allows the determination of the numerical derivative

Summary

QFT_HEP lattice activities explore
aspects of phases of gauge theories in the
Temperature, Flavors, (Chemical potential) space

These projects involve several collaborations.
Computing resources are provided either via European grants and/or national agencies.

In particular CINECA-INFN allocation will be most important for
- Generation of configurations on finer lattice for bottomonium
- New computation of topological charge with overlap operator

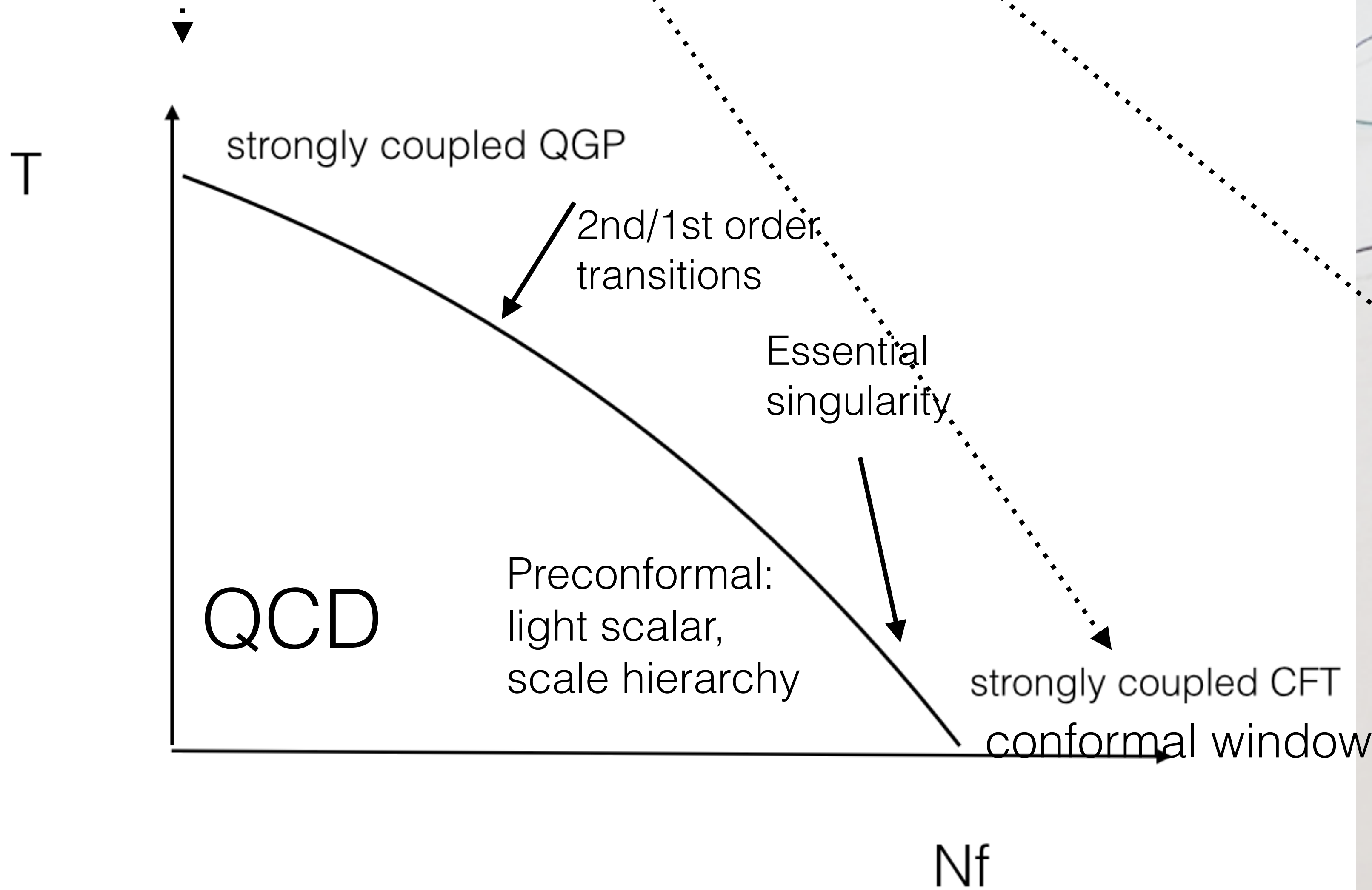
$DRES storage has also been extremely useful

Threads in the QCD phase diagram

Strongly coupled, yet symmetric

Conformality ubiquitous

Varieties of critical behaviors



Approach to the free field

Bulk viscosity set to zero

AdS/CFT methods

Speed of sound close to 0.3

Coupling slowly running :

Hints of conformality also at Strong coupling