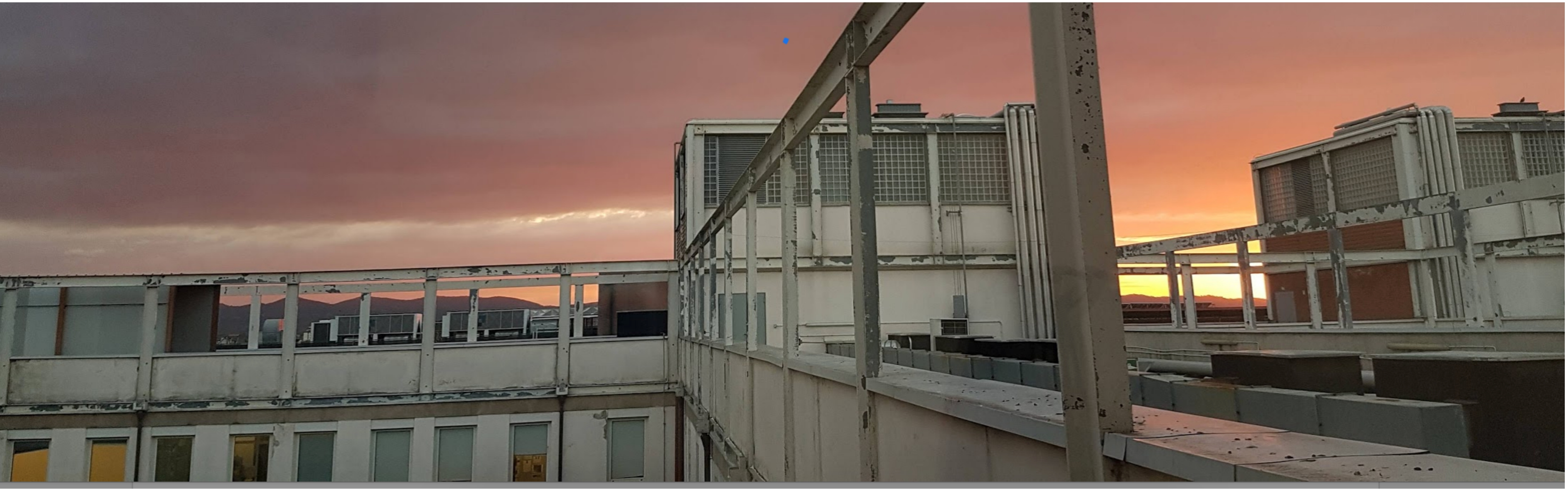
# CATS

Computer Assisted Theoretical physicS

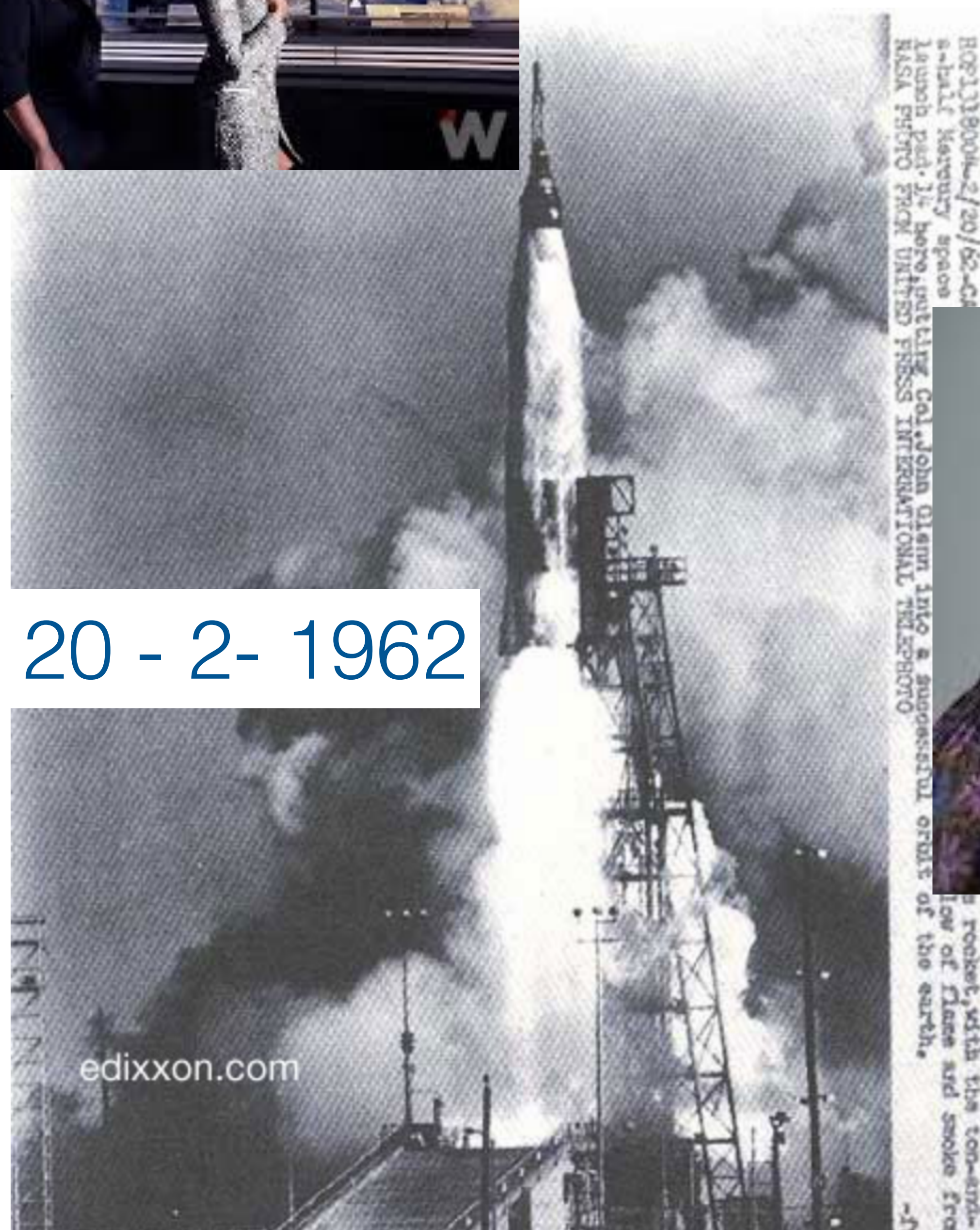


Consiglio di Sezione — Firenze — 5 Dicembre 2018

# Computer Assisted Theoretical physicS
*Qualche applicazione alla Fisica delle Interazioni Forti*

Maria Paola Lombardo
INFN Firenze

*When humans could compete with computers ..*


20 - 2- 1962

# Now .. towards Exascale Era

$10^{18}$ operations/second !

## Top 500 ranking [ edit ]

**Top 10 positions of the 52nd TOP500 in November 2018**[16]

| Rank | Rmax Rpeak (PFLOPS) | Name | Model | Processor | Interconnect | Vendor | Site country, year | Operating system |
|---|---|---|---|---|---|---|---|---|
| 1 — | 143.500 200.795 | Summit | Power System AC922 | POWER9, Tesla V100 | Infiniband EDR | IBM | Oak Ridge National Laboratory United States, 2018 | Linux (RHEL) |
| 2 ▲ | 94.640 125.436 | Sierra | Power System S922LC | POWER9, Tesla V100 | Infiniband EDR | IBM | Lawrence Livermore National Laboratory United States, 2018 | Linux (RHEL) |
| 3 ▼ | 93.015 125.436 | Sunway TaihuLight | Sunway MPP | SW26010 | Sunway[17] | NRCPC | National Supercomputing Center in Wuxi China, 2016[17] | Linux (Raise) |
| 4 ▼ | 61.445 100.679 | Tianhe-2A | TH-IVB-FEP | Xeon E5–2692 v2, Matrix-2000 | TH Express-2 | NUDT | National Supercomputing Center in Guangzhou China, 2013 | Linux (Kylin) |
| 5 ▲ | 21.230 27.154 | Piz Daint | Cray XC50 | Xeon E5-2690 v3, Tesla P100 | Aries | Cray | Swiss National Supercomputing Centre Switzerland, 2016 | Linux (CLE) |
| 6 ▼ | 20.159 41.461 | Trinity | Cray XC40 | Xeon E5–2698 v3, Xeon Phi 7250 | Aries | Cray | Los Alamos National Laboratory United States, 2015 | Linux (CLE) |
| 7 ▼ | 19.880 32.577 | AI Bridging Cloud Infrastructure[18] | PRIMERGY CX2550 M4 | Xeon Gold 6148, Tesla V100 | Infiniband EDR | Fujitsu | National Institute of Advanced Industrial Science and Technology Japan, 2018 | Linux |
| 8 ▲ | 19.477 26.874 | SuperMUC-NG[19] | ThinkSystem SD530 | Xeon Platinum 8174 | Intel Omni-Path | Lenovo | Leibniz Supercomputing Centre Germany, 2018 | Linux (SLES) |

*..somebody is then wondering..*

# ARE YOU LIVING IN A COMPUTER SIMULATION?

**BY NICK BOSTROM**
Faculty of Philosophy, Oxford University
Published in *Philosophical Quarterly* (2003) Vol. 53, No. 211, pp. 243-255.
[www.simulation-argument.com]
pdf-version: [PDF]

## ABSTRACT

This paper argues that *at least one* of the following propositions is true: (1) the human species is very likely to go extinct before reaching a "posthuman" stage; (2) any posthuman civilization is extremely unlikely to run a significant number of simulations of their evolutionary history (or variations thereof); (3) we are almost certainly living in a computer simulation. It follows that the belief that there is a significant chance that we will one day become posthumans who run ancestor-simulations is false, unless we are currently living in a simulation. A number of other consequences of this result are also discussed.

## I. INTRODUCTION

Many works of science fiction as well as some forecasts by serious technologists and futurologists predict that enormous amounts of computing power will be available in the future. Let us suppose for a moment that these predictions are correct. One thing that later generations might do with their super-powerful computers is run detailed simulations of their forebears or of people like their forebears. Because their computers would be so powerful, they could run a great many such simulations. Suppose that these simulated people are conscious (as they would be if the simulations were sufficiently fine-grained and if a certain quite widely accepted position in the philosophy of mind is correct). Then it could be the case that the vast majority of minds like ours do not belong to the original race but rather to people simulated by the advanced descendants of an original race. It is then possible to argue that, if this were the case, we would be rational to think that we are likely among the simulated minds rather than among the original biological ones. Therefore, if we don't think that we are currently living in a computer simulation, we are not entitled to believe that we will have descendants who will run lots of such simulations of their forebears. That is the basic idea. The rest of this paper will spell it out more carefully.

…*leaving this with the philosophers and epistemologists*..

..we anyway confront the fact that computer simulations may bring us VERY far away from everyday world…

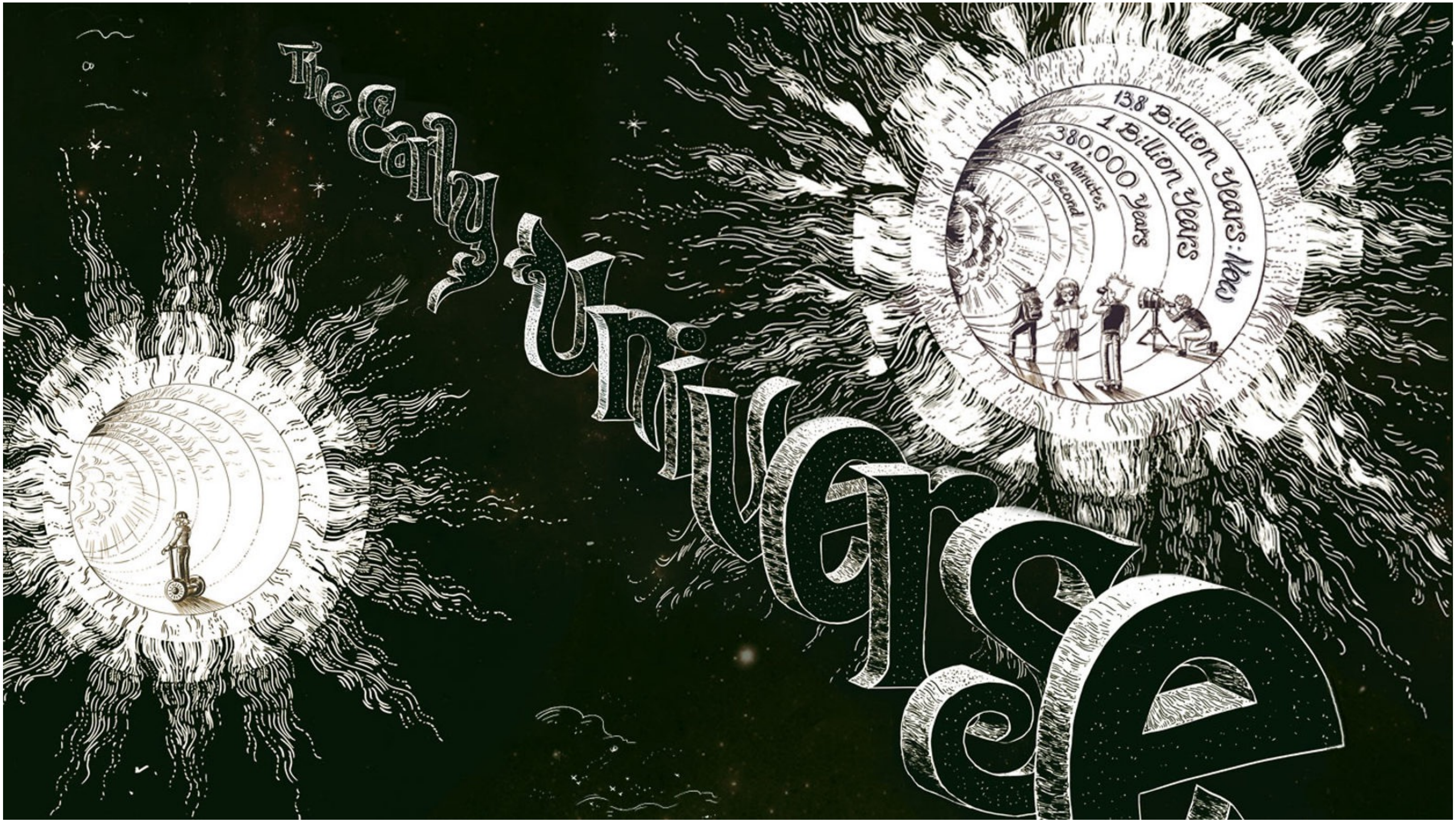
…allowing explorations of unchartered territories, and/or taking us back to the early Universe

…*leaving this with the philosophers and episthemologists..*

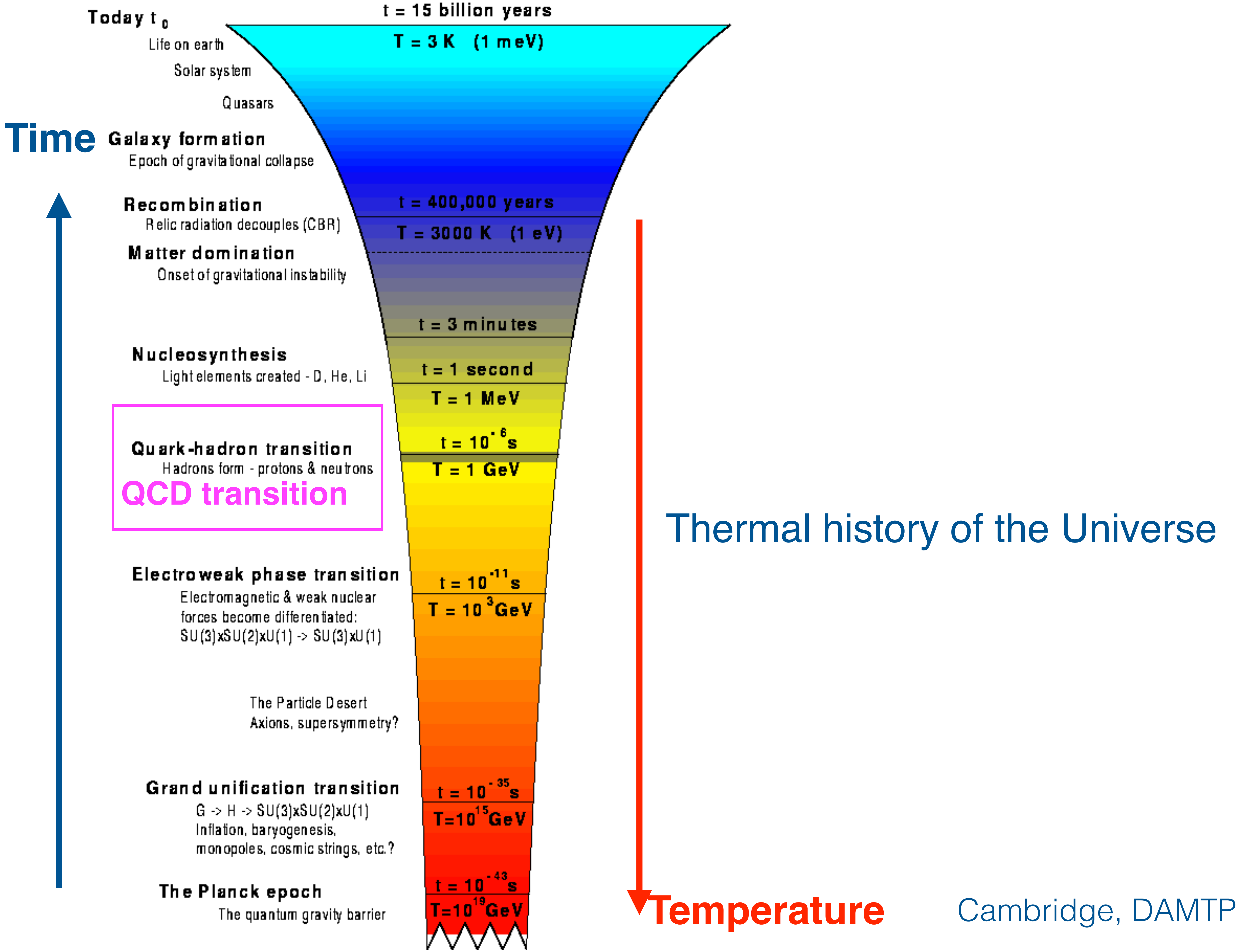
..we anyway confront the fact that computer simulations may bring us VERY far away from everyday world…

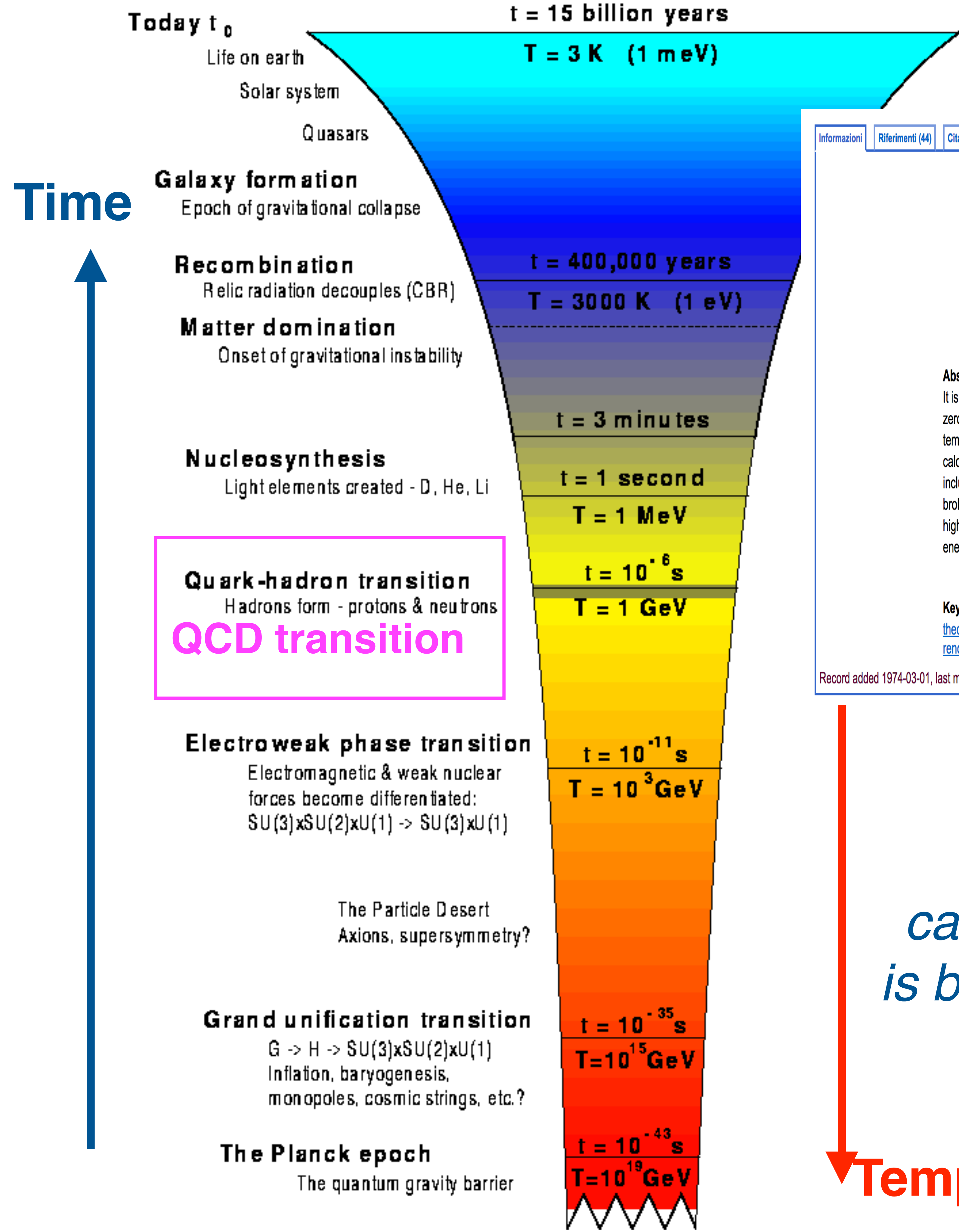
…allowing explorations of unchartered territories, and/or taking us back to the early Universe

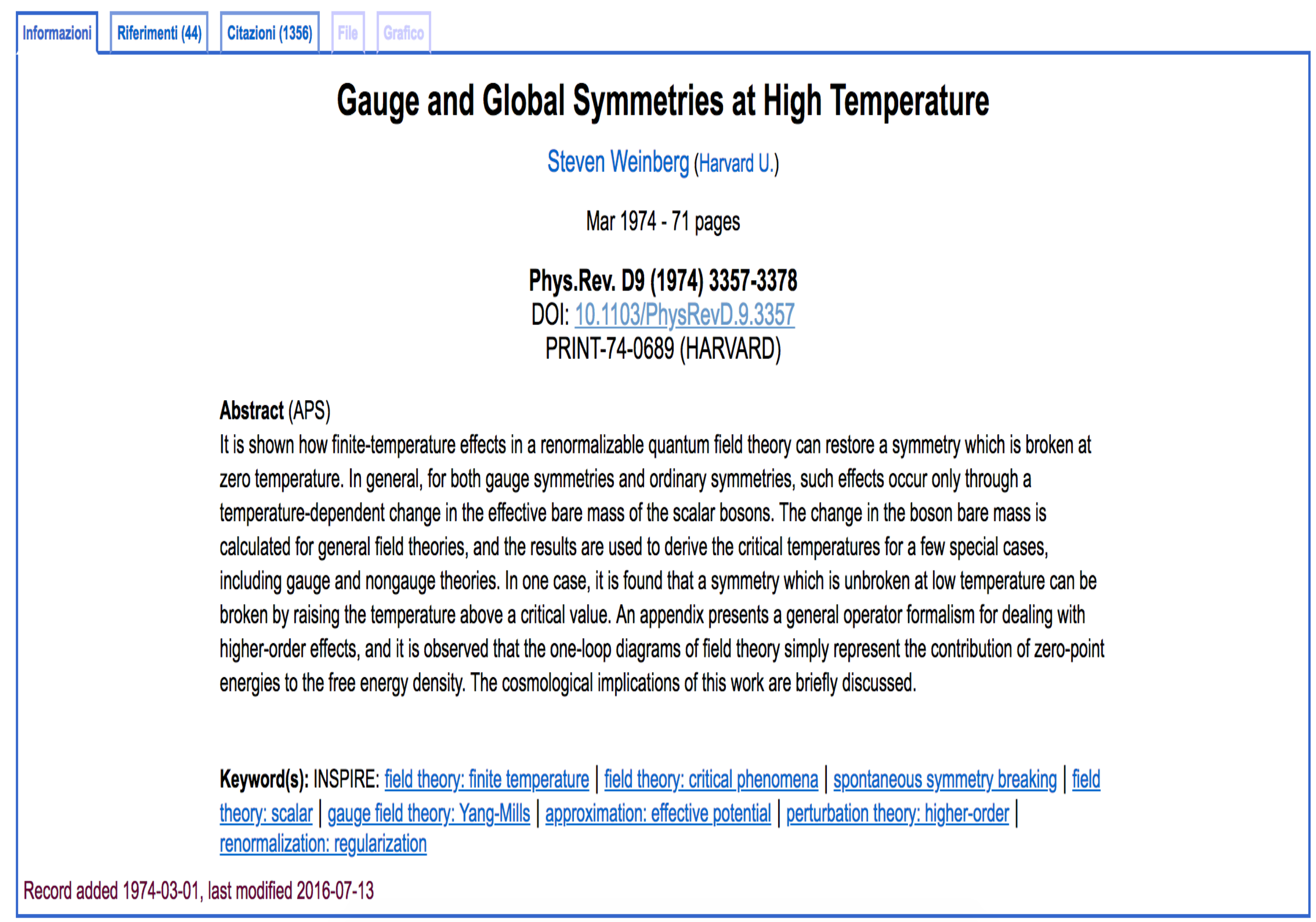
Remarkably, many of these applications rely on
Quantum Chromo Dynamics
QCD




From Symmetry magazine, FNAL/SLAC


Time
Today $t_0$
Life on earth
Solar system
Quasars
Galaxy formation
Epoch of gravitational collapse
Recombination
Relic radiation decouples (CBR)
Matter domination
Onset of gravitational instability
Nucleosynthesis
Light elements created - D, He, Li
Quark-hadron transition
Hadrons form - protons & neutrons
QCD transition
Electroweak phase transition
Electromagnetic & weak nuclear forces become differentiated: SU(3)xSU(2)xU(1) -> SU(3)xU(1)
The Particle Desert
Axions, supersymmetry?
Grand unification transition
G -> H -> SU(3)xSU(2)xU(1)
Inflation, baryogenesis, monopoles, cosmic strings, etc.?
The Planck epoch
The quantum gravity barrier
t = 15 billion years
T = 3 K (1 meV)
t = 400,000 years
T = 3000 K (1 eV)
t = 3 minutes
t = 1 second
T = 1 MeV
$t = 10^{-6}$ s
T = 1 GeV
$t = 10^{-11}$ s
$T = 10^{3}$ GeV
$t = 10^{-35}$ s
$T=10^{15}$ GeV
$t = 10^{-43}$ s
$T=10^{19}$ GeV
Thermal history of the Universe
Temperature
Cambridge, DAMTP



Informazioni | Riferimenti (44) | Citazioni (1356) | File | Grafico

## Gauge and Global Symmetries at High Temperature

Steven Weinberg (Harvard U.)

Mar 1974 - 71 pages

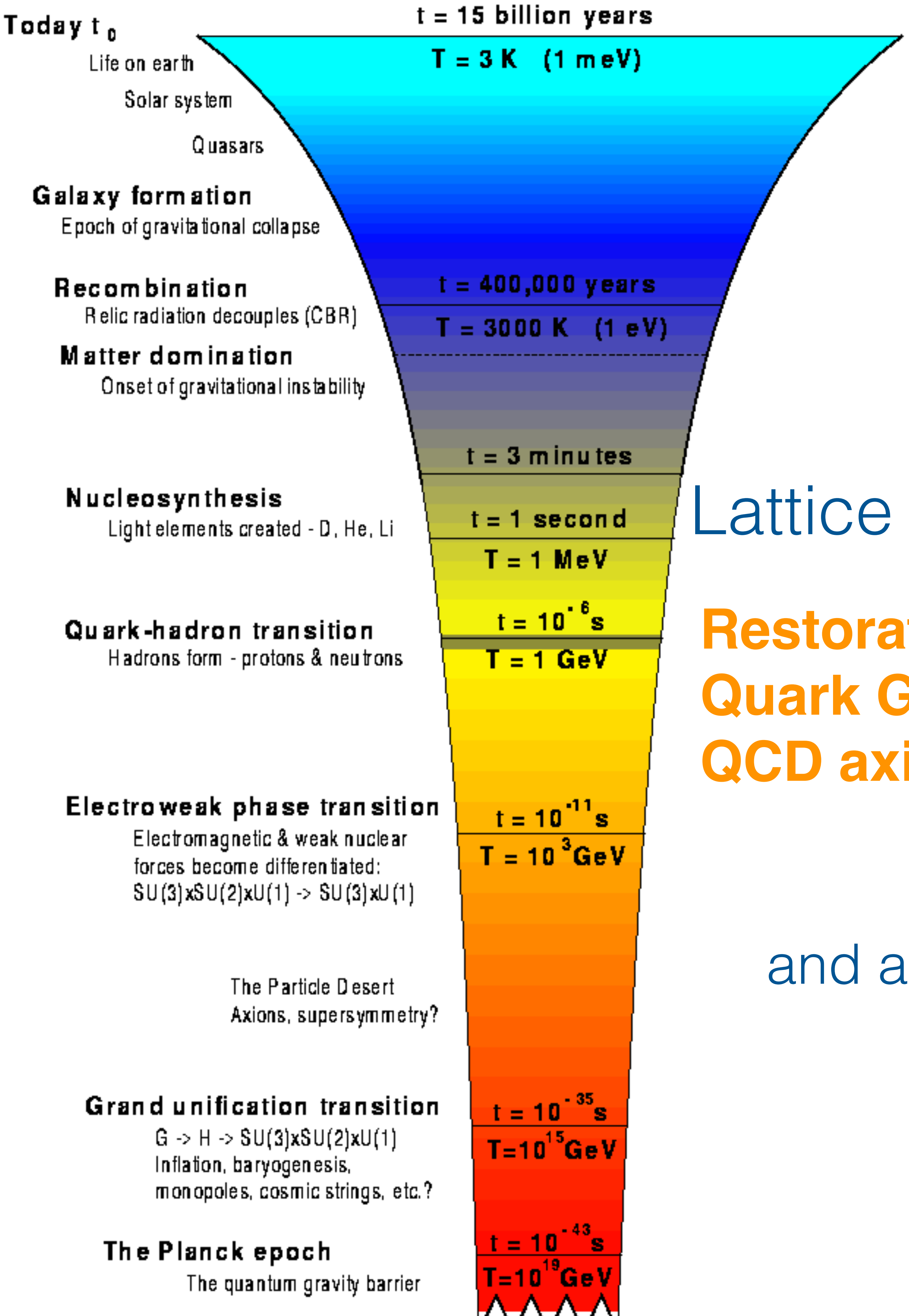
**Phys.Rev. D9 (1974) 3357-3378**
DOI: 10.1103/PhysRevD.9.3357
PRINT-74-0689 (HARVARD)

**Abstract** (APS)
It is shown how finite-temperature effects in a renormalizable quantum field theory can restore a symmetry which is broken at zero temperature. In general, for both gauge symmetries and ordinary symmetries, such effects occur only through a temperature-dependent change in the effective bare mass of the scalar bosons. The change in the boson bare mass is calculated for general field theories, and the results are used to derive the critical temperatures for a few special cases, including gauge and nongauge theories. In one case, it is found that a symmetry which is unbroken at low temperature can be broken by raising the temperature above a critical value. An appendix presents a general operator formalism for dealing with higher-order effects, and it is observed that the one-loop diagrams of field theory simply represent the contribution of zero-point energies to the free energy density. The cosmological implications of this work are briefly discussed.

**Keyword(s):** INSPIRE: field theory: finite temperature | field theory: critical phenomena | spontaneous symmetry breaking | field theory: scalar | gauge field theory: Yang-Mills | approximation: effective potential | perturbation theory: higher-order | renormalization: regularization

Record added 1974-03-01, last modified 2016-07-13

*"..finite temperature*
*in a quantum field theory*
*can restore a symmetry which*
*is broken at zero temperature .."*




Lattice QCD studies:

**Restoration of QCD chiral symmetry**
**Quark Gluon Plasma**
**QCD axions ..**

and also : **QCD based BSM physics**

and much more..

# The experimental side

| Tc | 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 |
|---|---|---|---|---|---|
| ≈200MeV | | | | | |

Quark Gluon Plasma @ Colliders

RECORDS | PRODUCTS | BUSINESS SOLUTIONS | NEWS | ABOUT US

## Highest man-made temperature

Who

**CERN, LARGE HADRON COLLIDER**

What

**5X10^12 DEGREE(S) KELVIN**

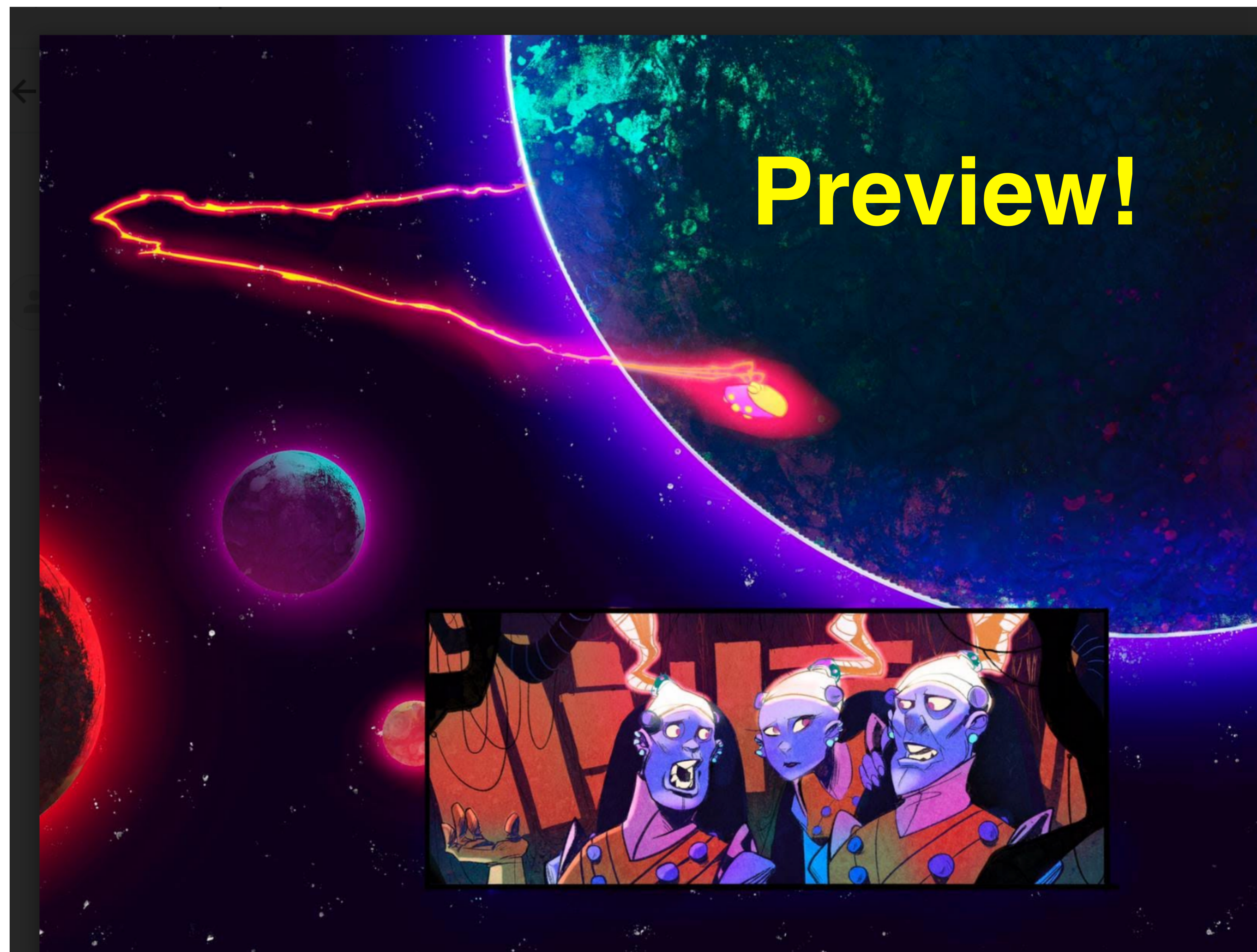
# A joint experimental-theoretical worldwide effort


Preliminary!! Thanks to the INFN communication office !


F. Becattini
and MpL
representing Italy
in the MC

**Thor e il Plasma di Quark :**

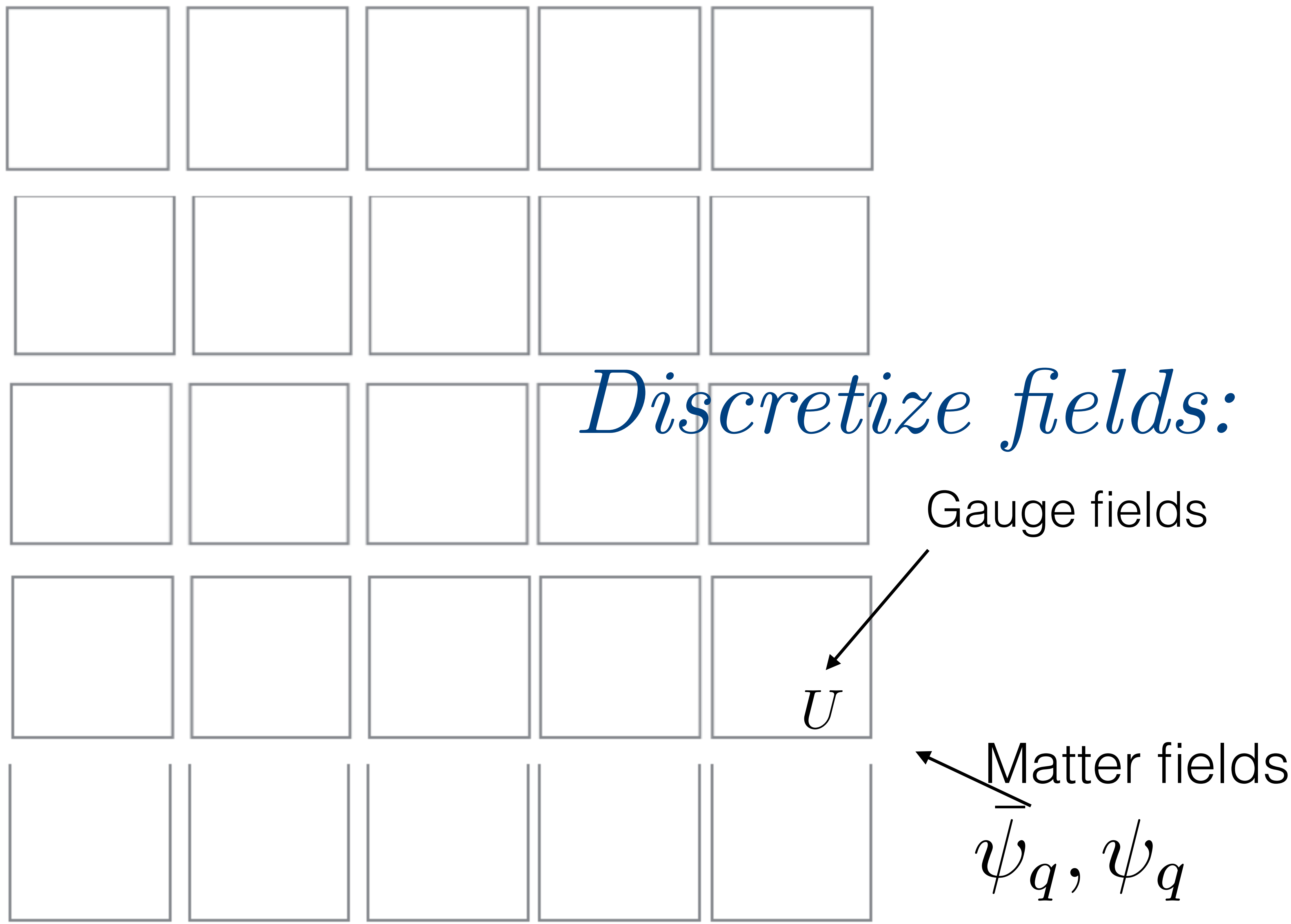
Graphic Novel
by
Simone Gabrielli et al.
Scuola Romana del Fumetto



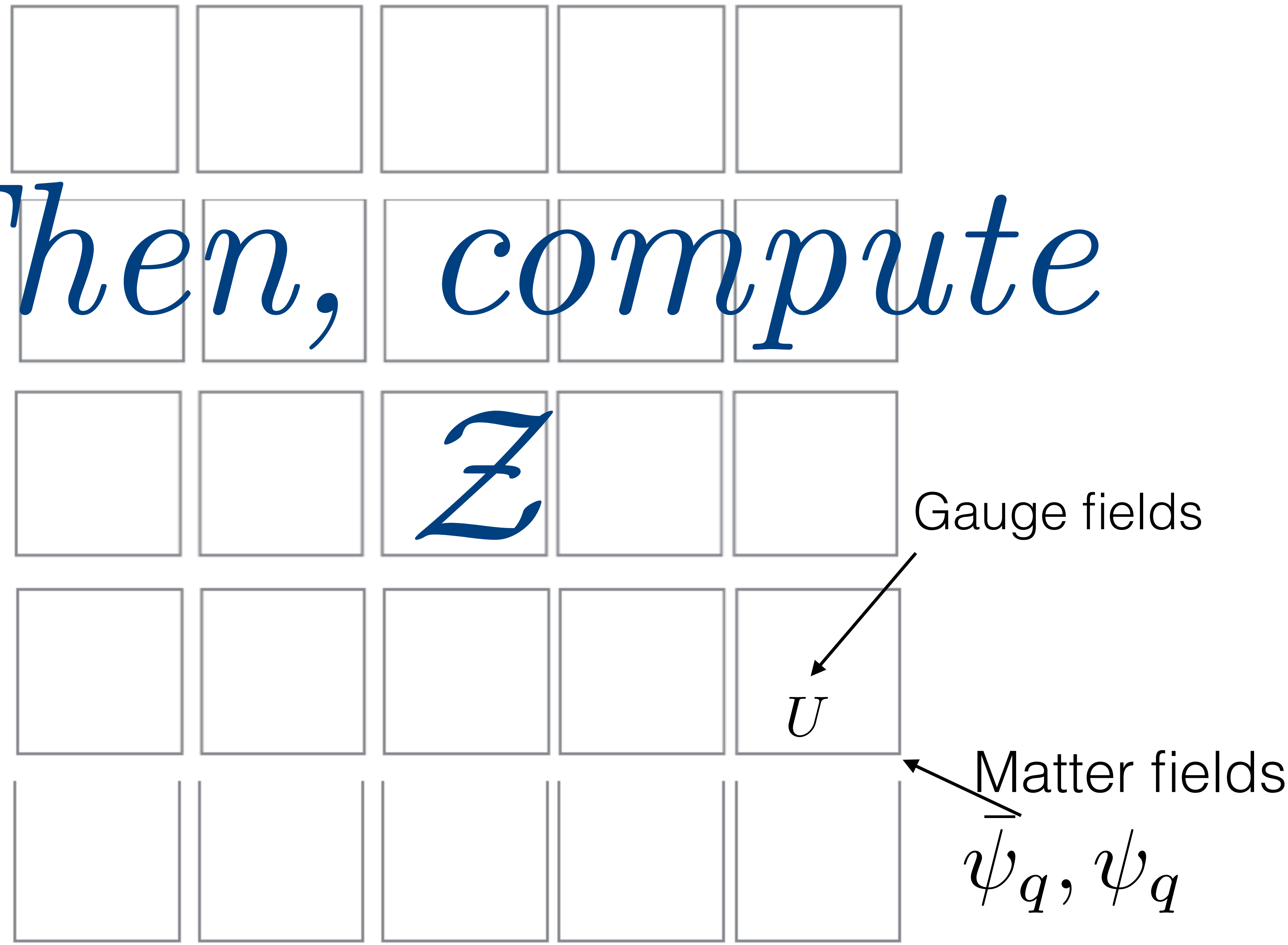
all this stemming from the Lagrangian:

$$\mathcal{L}_{QCD} = \frac{1}{g^2} G_{\mu\nu} G_{\mu\nu} + \sum_q \overline{\psi}_q (i\gamma^\mu D_\mu + m_q) \psi_q$$

# Lattice Gauge Theory



# Lattice Gauge Theory




*Then, compute* $\mathcal{Z}$

# Some selected topics and results

I. QGP in the LHC working region:
bottomonium suppression

II. QGP in the LHC working region:
topology (and $\eta'$ )

III. Axions

IV. Towards neutron stars

V. Strong Interactions BSM

# I. QGP in the LHC working region: bottomonium suppression

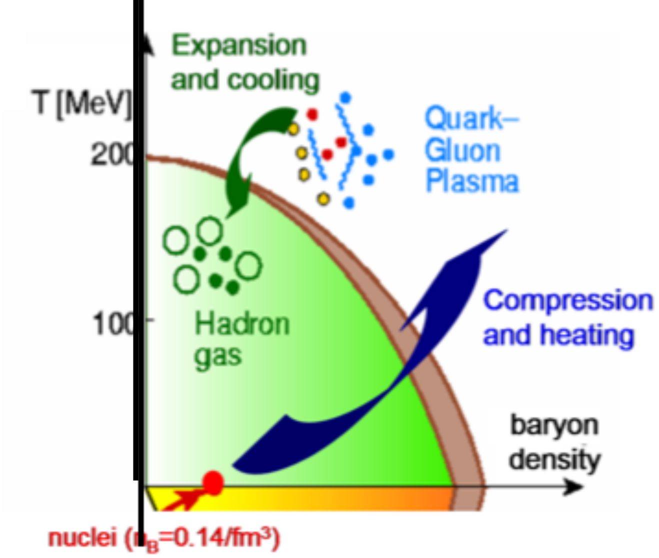
# QGP in the LHC working region: T < 600 MeV

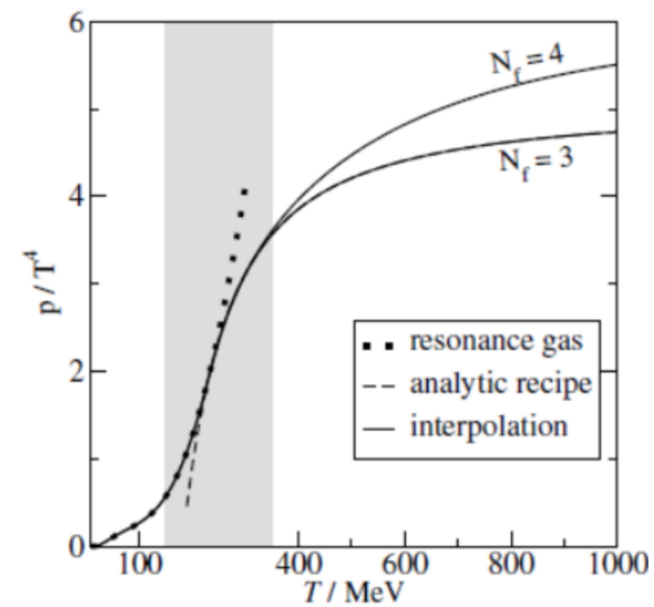
T

? 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

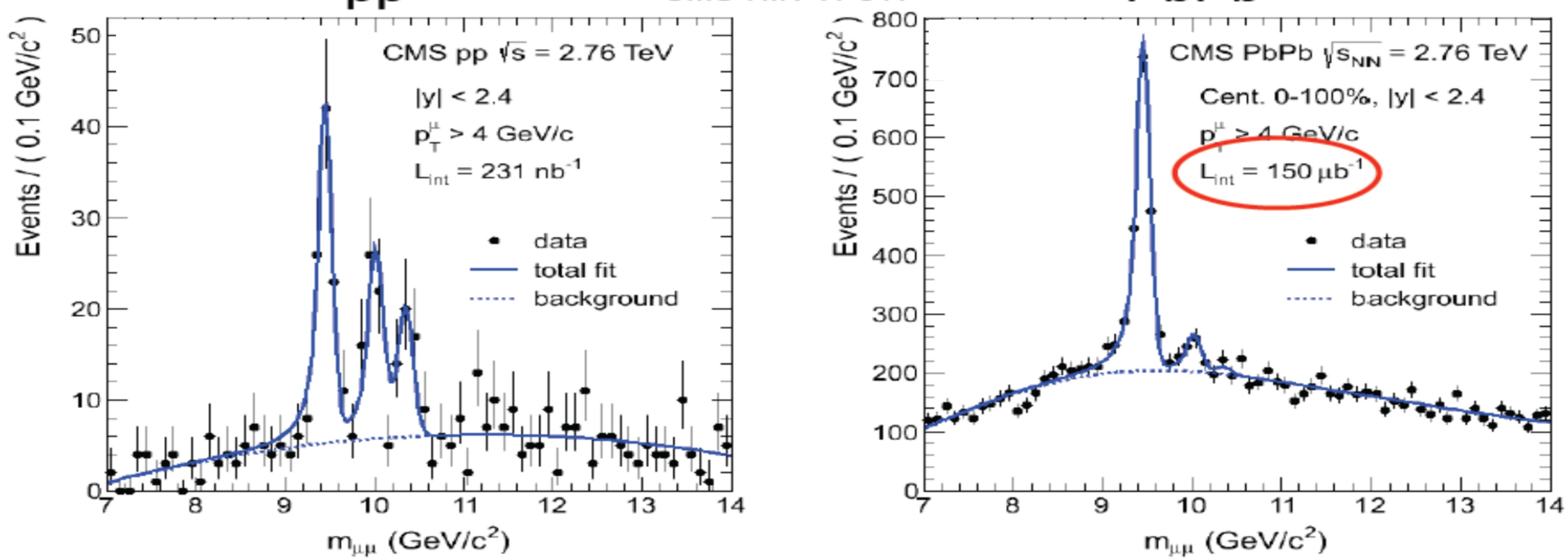
400 MeV charm threshold:

Dynamical charm plays a role

# Bottomonium as a probe of QGP

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

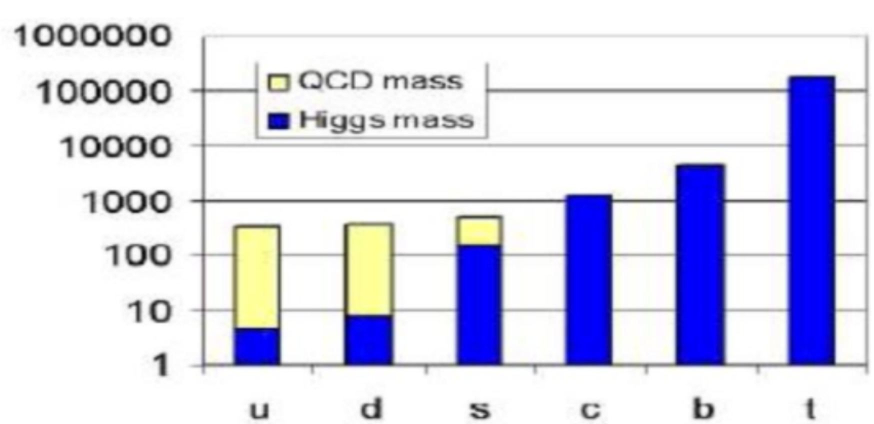
Room temperature **pp** CMS-HIN-11-011 **PbPb** T approx. 500 MeV




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

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

**CMS**




NB: probing complementary aspects wrt to light sector: 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*

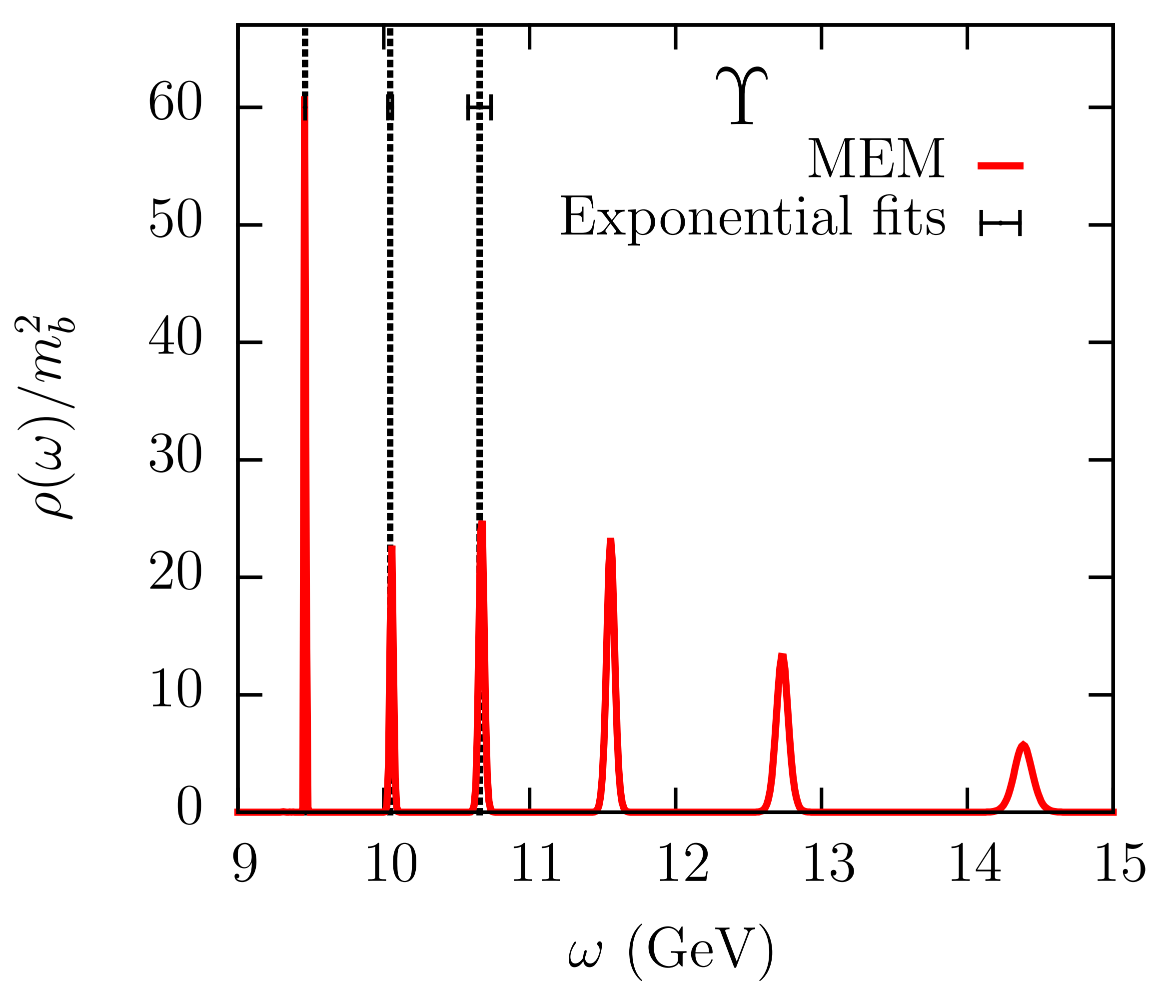
**Mike Peardon, Sinéad Ryan**
*Trinity College, Dublin, Ireland*

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

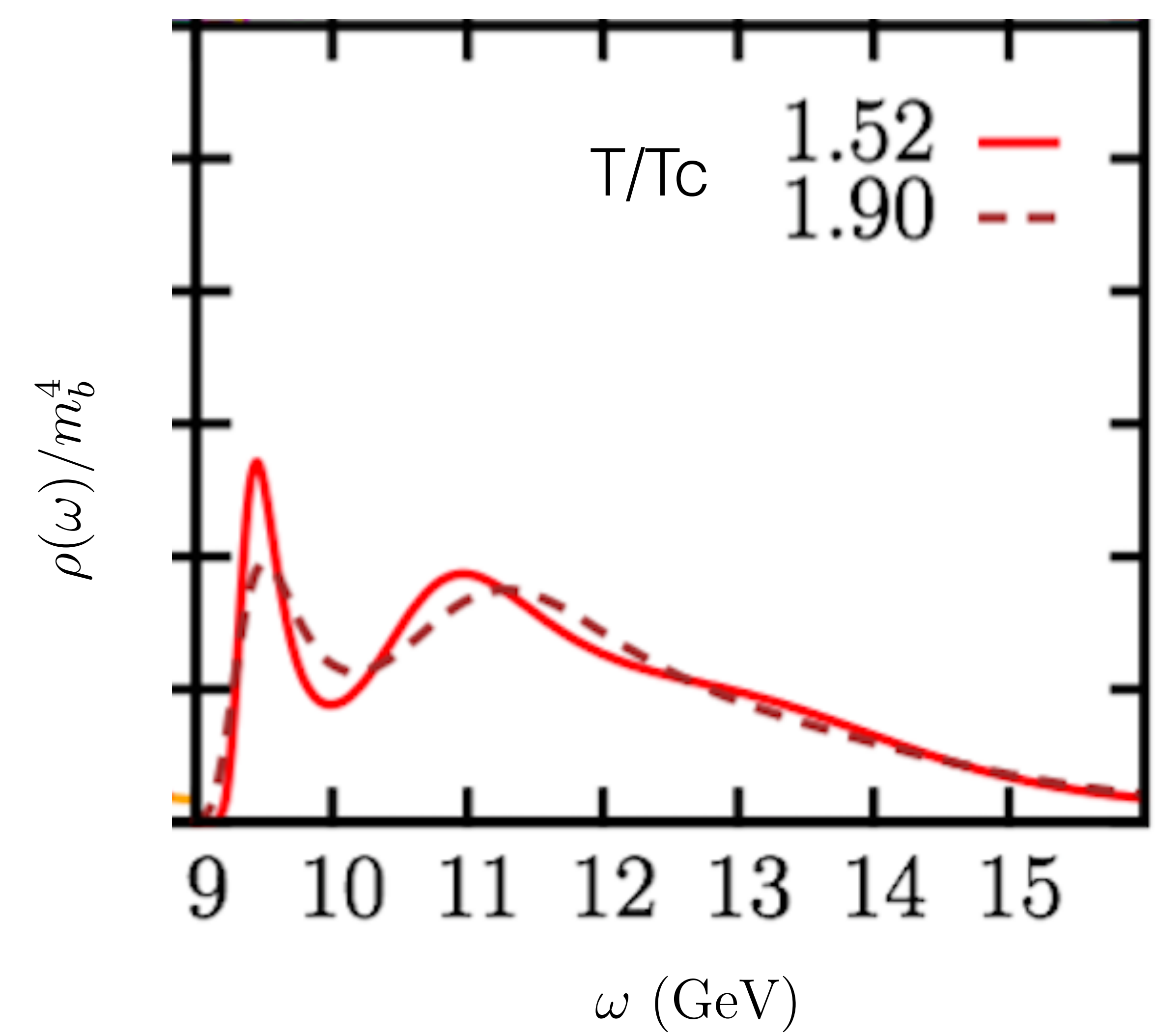
# Bottomonium NRQCD results: spectral functions from MEM

FASTSUM Collaboration

Room temperature




T approx. 400 MeV




Melting of excited states

# NRQCD bottomonium spectral functions at a glance

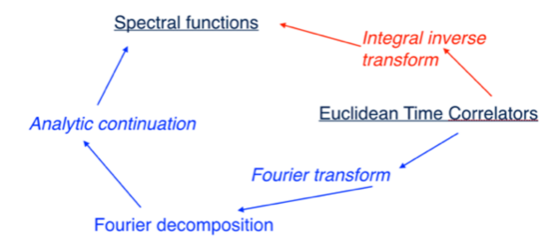
NRQCD appropriate for bottomonium

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.

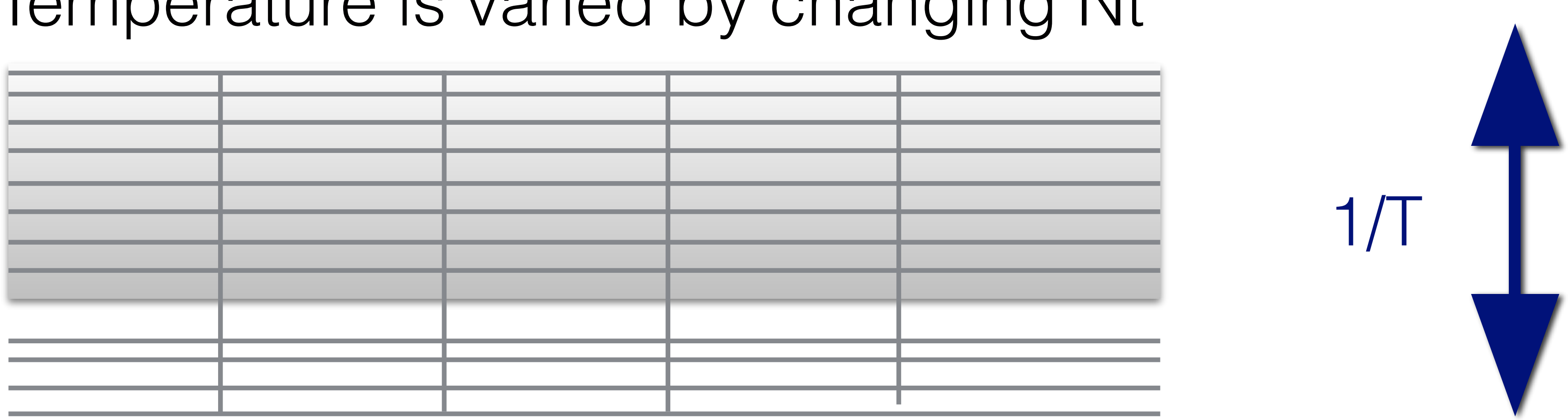
*Disentangle space from time discretization effect.

*Approach to continuum time easier.

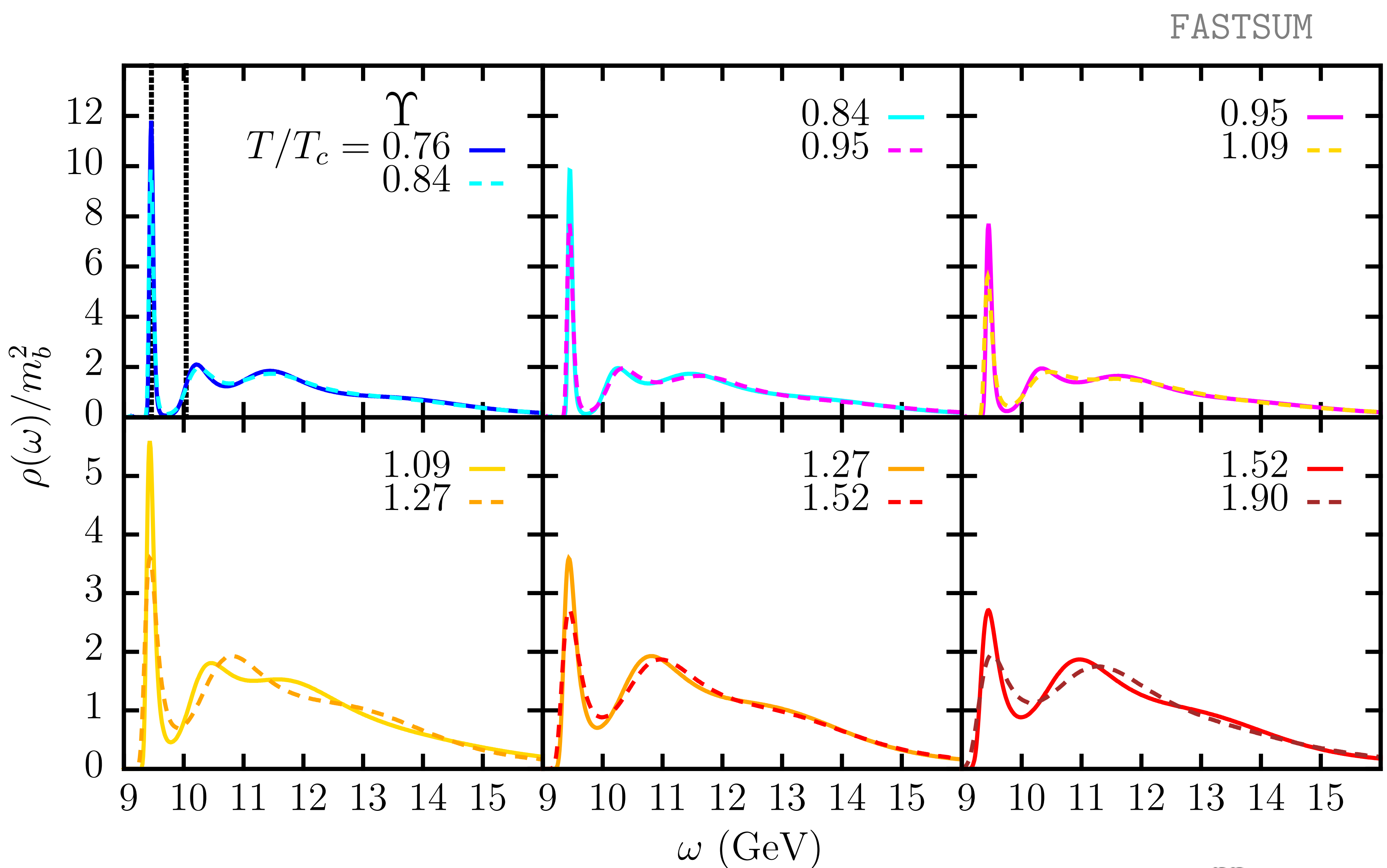
| $M_\pi$ [MeV] | Anisotropy $= a_s/a_t$ | $a_s$ [am] | $a_t$ [am] | |
|---|---|---|---|---|
| 450 | 6 | 167 | 28 | Completed |
| 390 | 3.5 | 123 | 35 | Completed |
| 230 | 3.5 | 113 | 33 | In progress: going to a very fine lattice |
| 390 | 7 | 123 | 18 | In progress: going to a very fine lattice |

Temperature is varied by changing Nt

$0.4\, T_c < T < 2 T_c$



# Bottomonium spectral functions: sequential melting

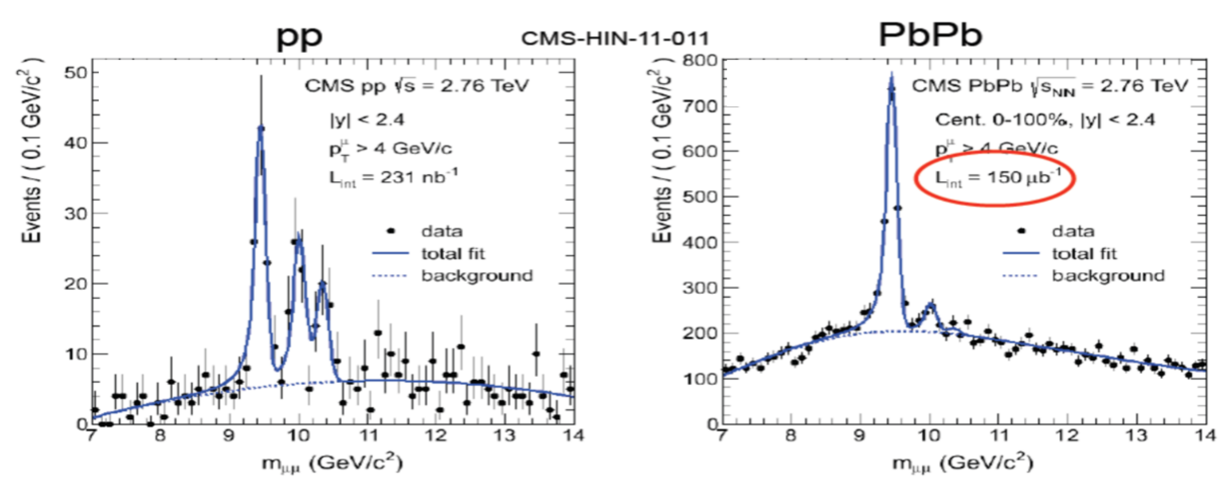



Persistence of the ground state at all temperatures

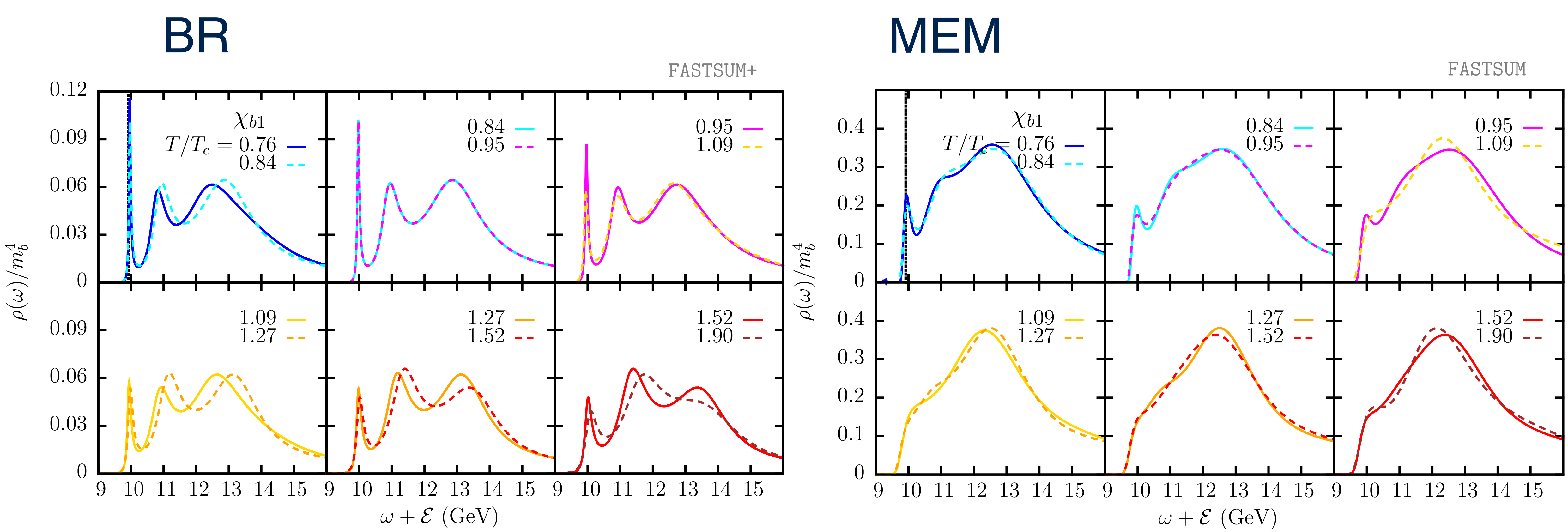
Melting of excited states

Modifications of the ground state

**Pattern reminiscent of experimental observations**



# Bottomonium: Outstanding remaining issue: the (unknown) systematics




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

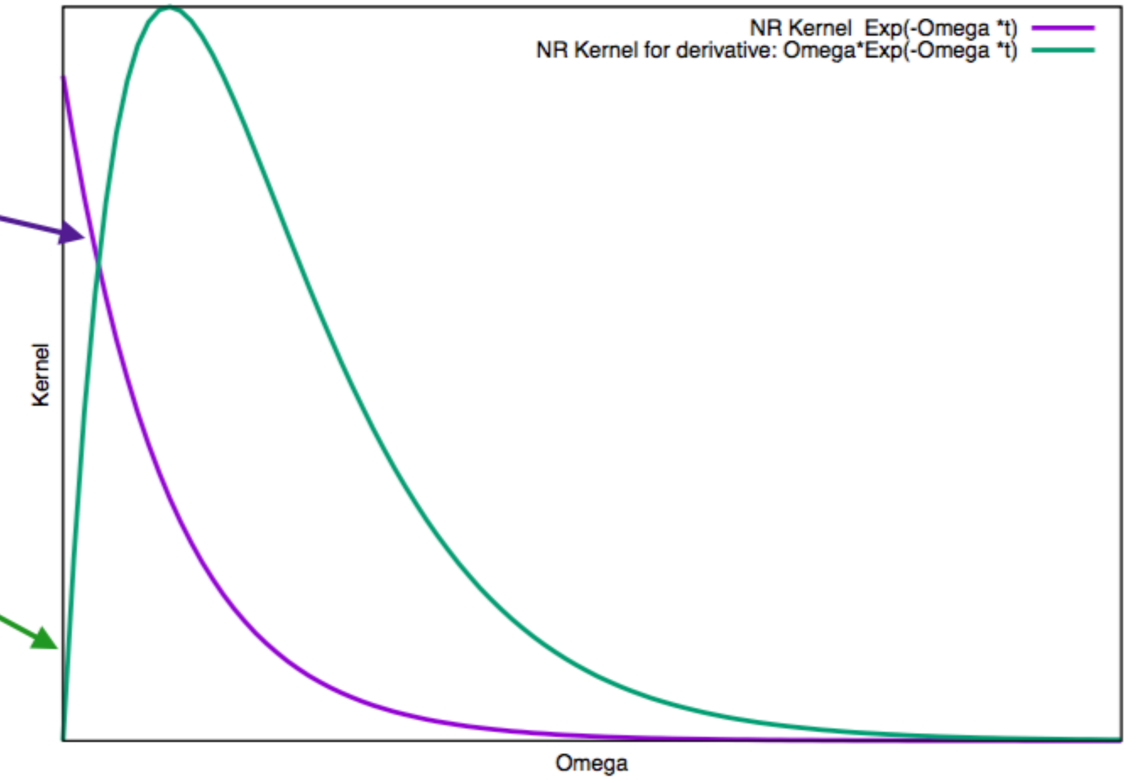
Qualitative differences for the Chi_b: with the BR approach the excited state survives and appears even stronger!

# Weighted spectral functions & Upsilon width

**PRELIMINARY**

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

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




cfr. Sumudu method
by Orlandini, Pederiva, Roggero

$$< \omega >_{S(\omega,t)} = G'(t)/G(t) \equiv m_{eff}(t)$$

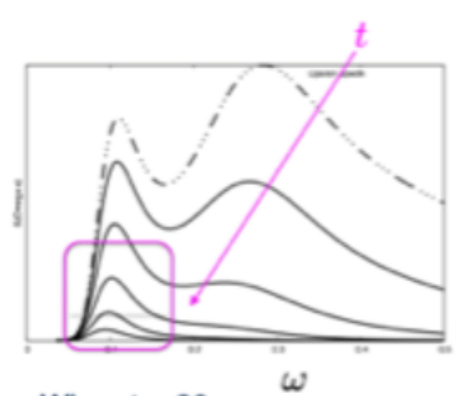
$$< \omega^2 >_{S(\omega,t)} - < \omega >^2_{S(\omega,t)} = -\frac{dm_{eff}(t)}{dt}$$

When t grows large, only the fundamental peak (if any) survives in the weighted spectral function, hence these quantities estimate the central value and the width - otherwise no simple interpretation
(the logic is fairly simple and maybe was tried before, do not know)

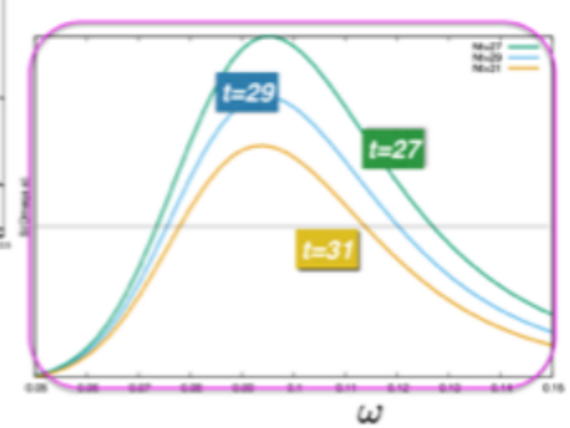
Weighted Spectral Functions

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

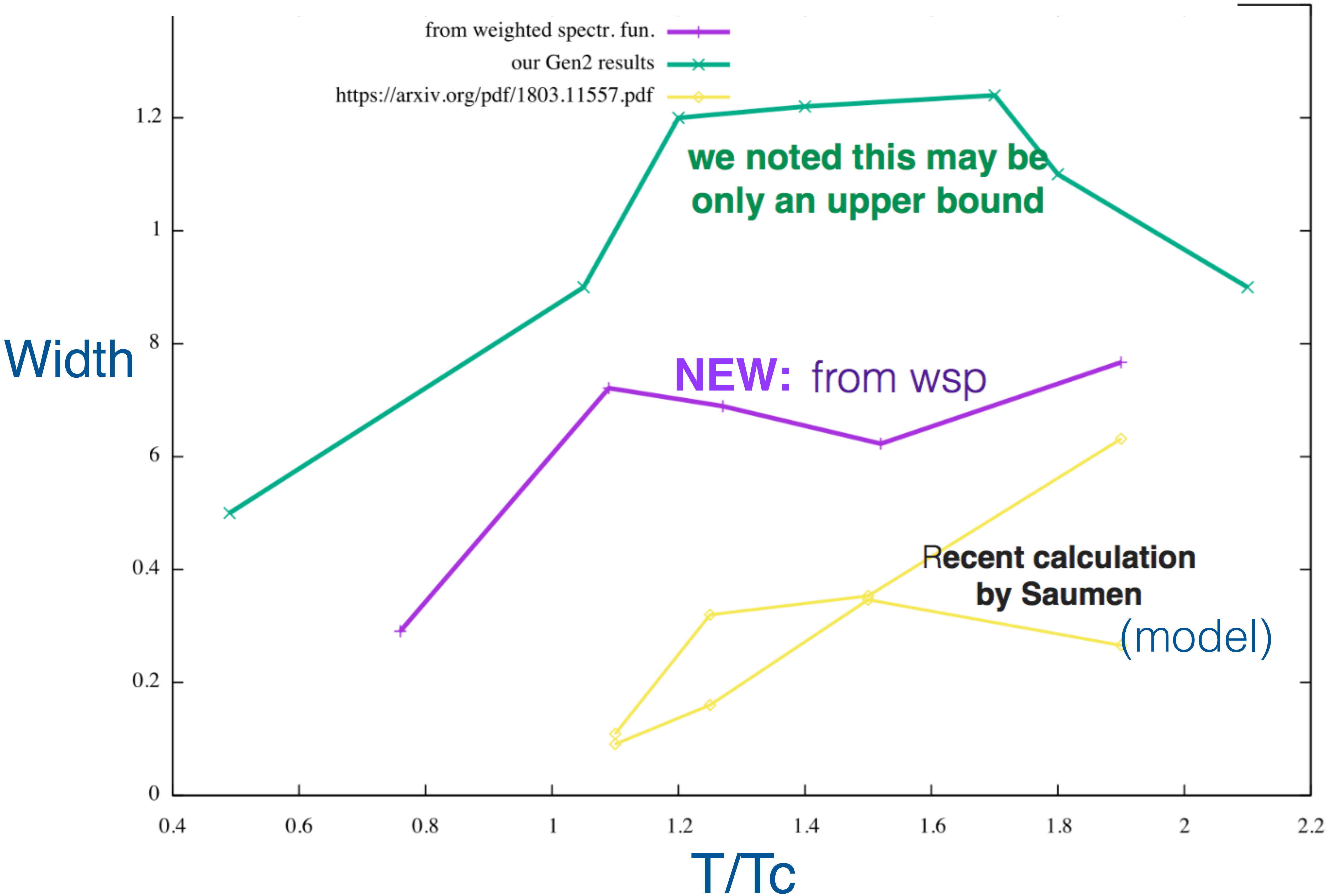
using the Upsilon spectral function




When t > 20
only the fundamental peak is discernable



# PRELIMINARY



# II. QGP in the LHC working region: topology and $\eta'$

# Topology from low to high Temperature

In the hadronic phase topology solves the $\eta'$ 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

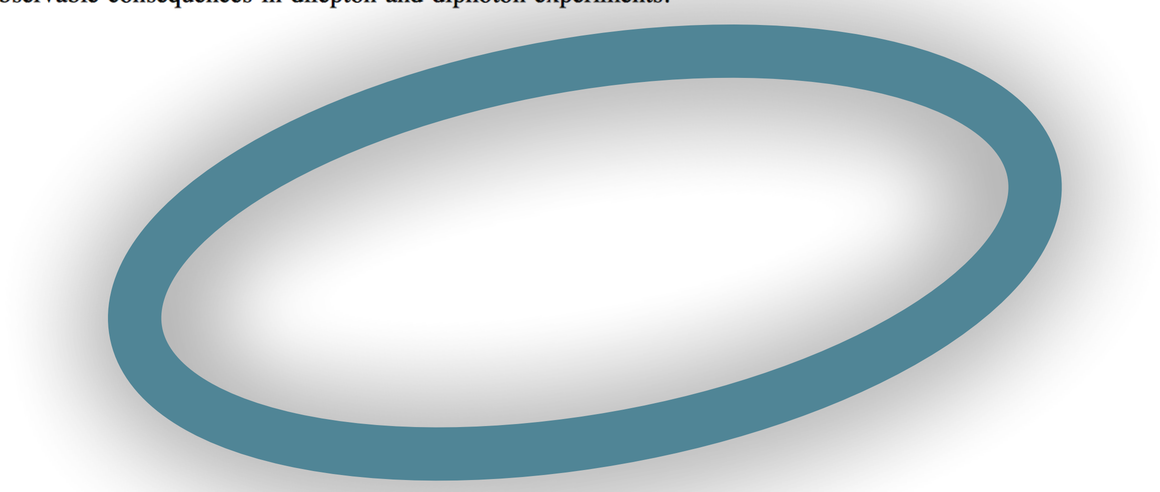
**Return of the prodigal Goldstone boson**

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 $\eta'$ 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 $\eta'$ excitation in hot and dense matter should be small, and, therefore, that the $\eta'$ production cross section should be much increased relative to that for $pp$ collisions. This may have observable consequences in dilepton and diphoton experiments.



# Work on Topology and Axions is

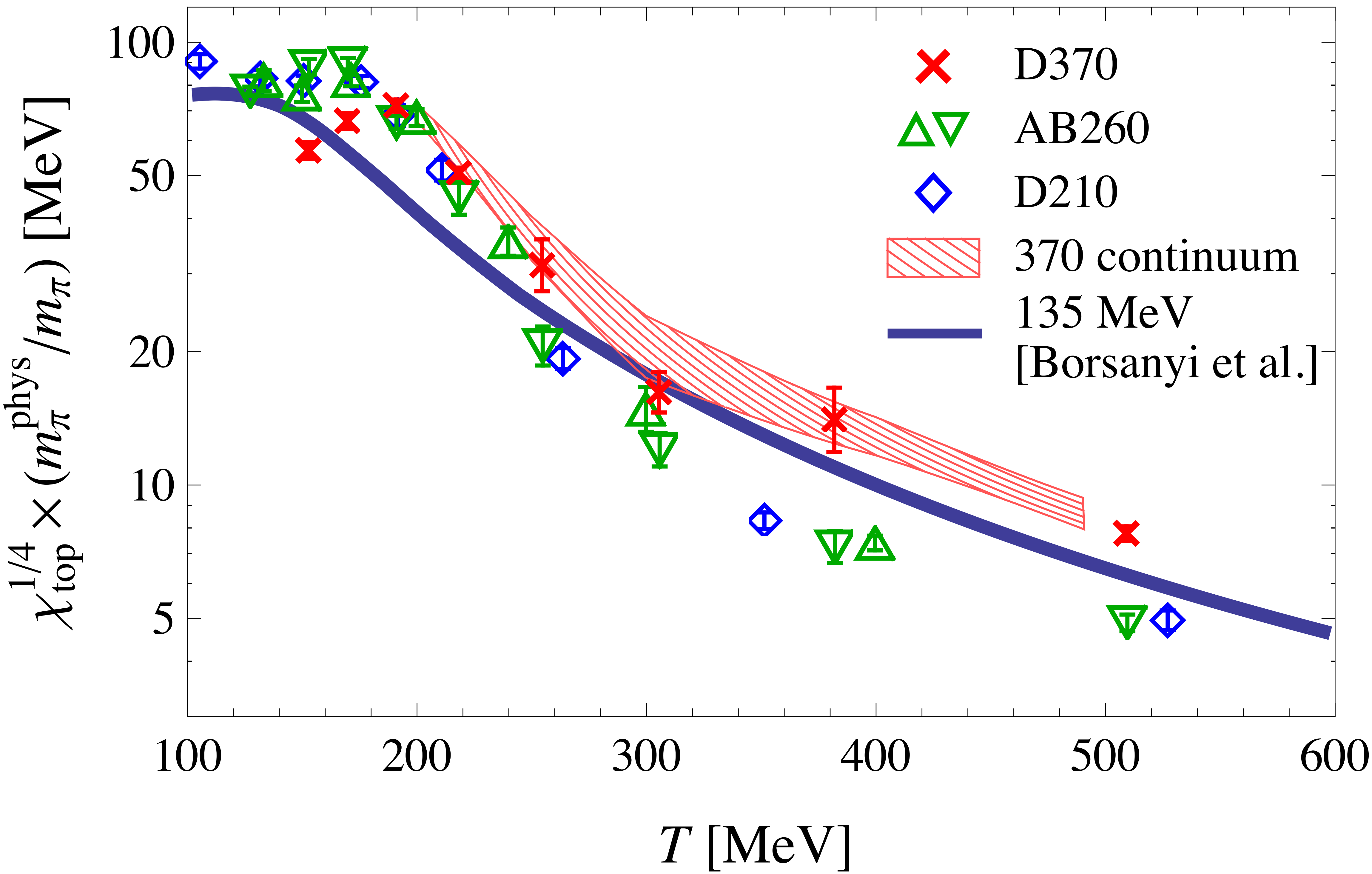
with Anton Trunin, E.-Michael Ilgenfritz and Florian Burger

*with thanks to the ETMC collaboration*

# Topological susceptibility

Rescaled according to

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



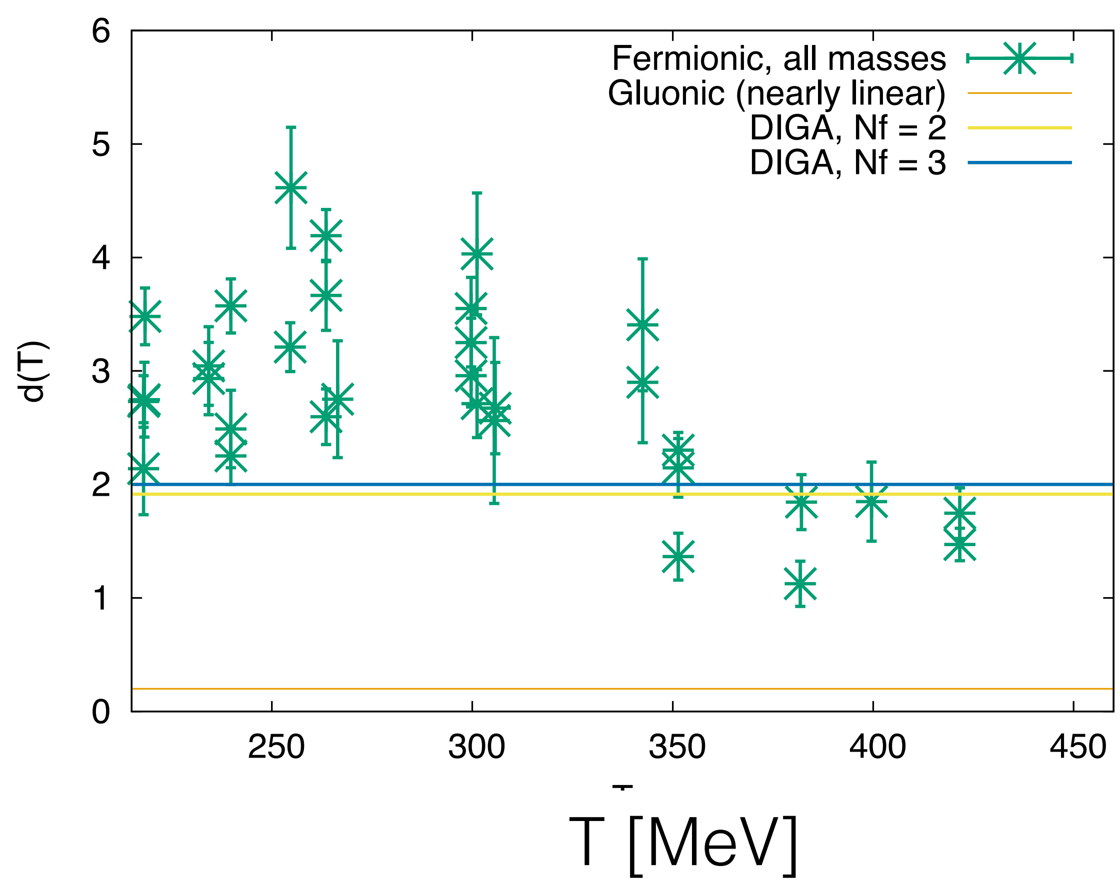
# Parametrizing $\chi_{top}$ temperature dependence

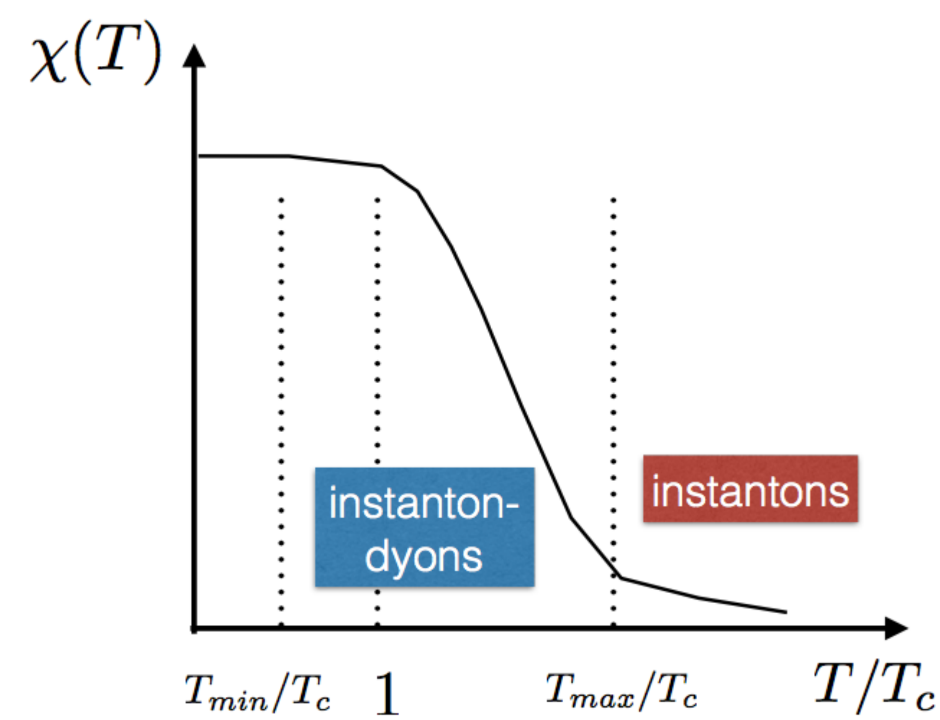
For instanton gas

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

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

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




Faster decrease before DIGA sets in

Possibly consistent with instant -dyon?

Shuryak 2017

# Topology, $\eta'$ 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 $\eta'$ 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

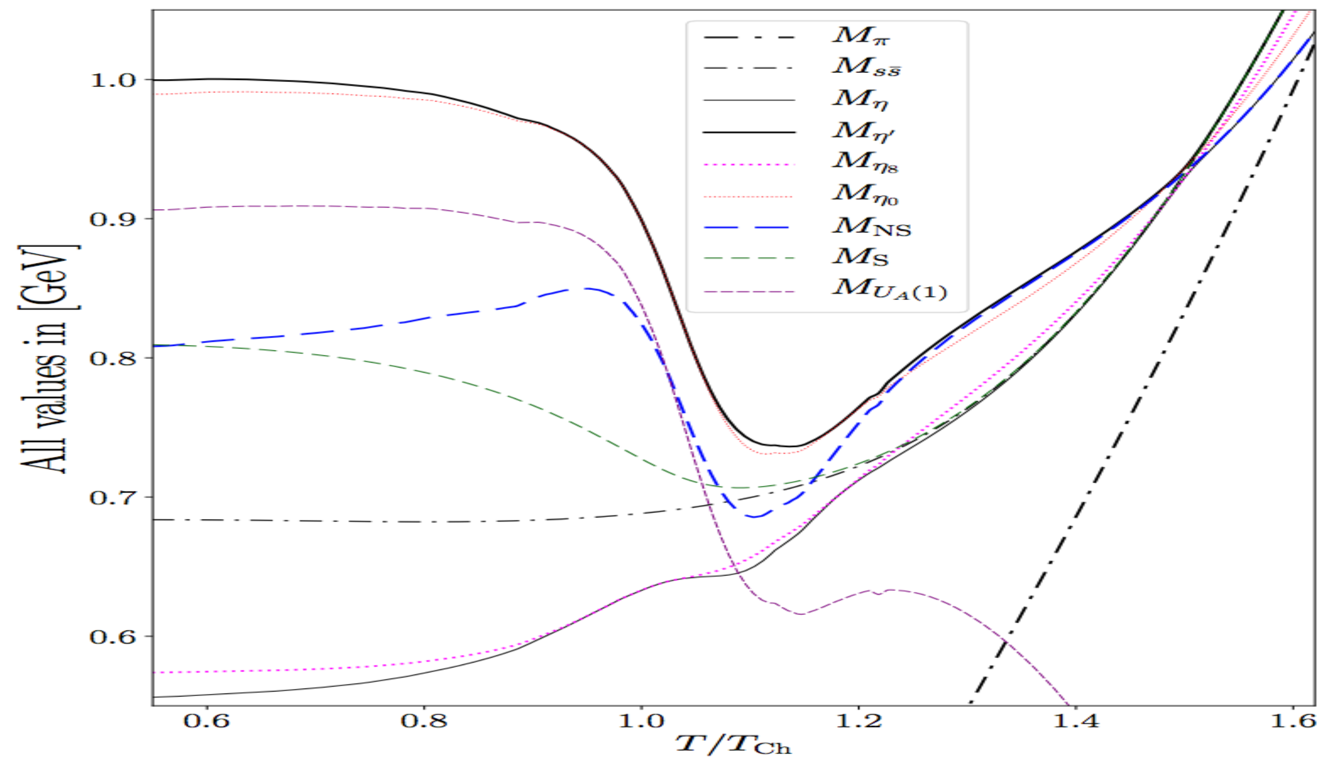
$$m_{\eta'}^2 = \frac{2N_f}{F_\pi^2}\chi_t^{\mathrm{qu}}$$

Successful at T=0

# $\eta'$ in the QGP

So far, only results from model's studies

Horvatic et al. 2018



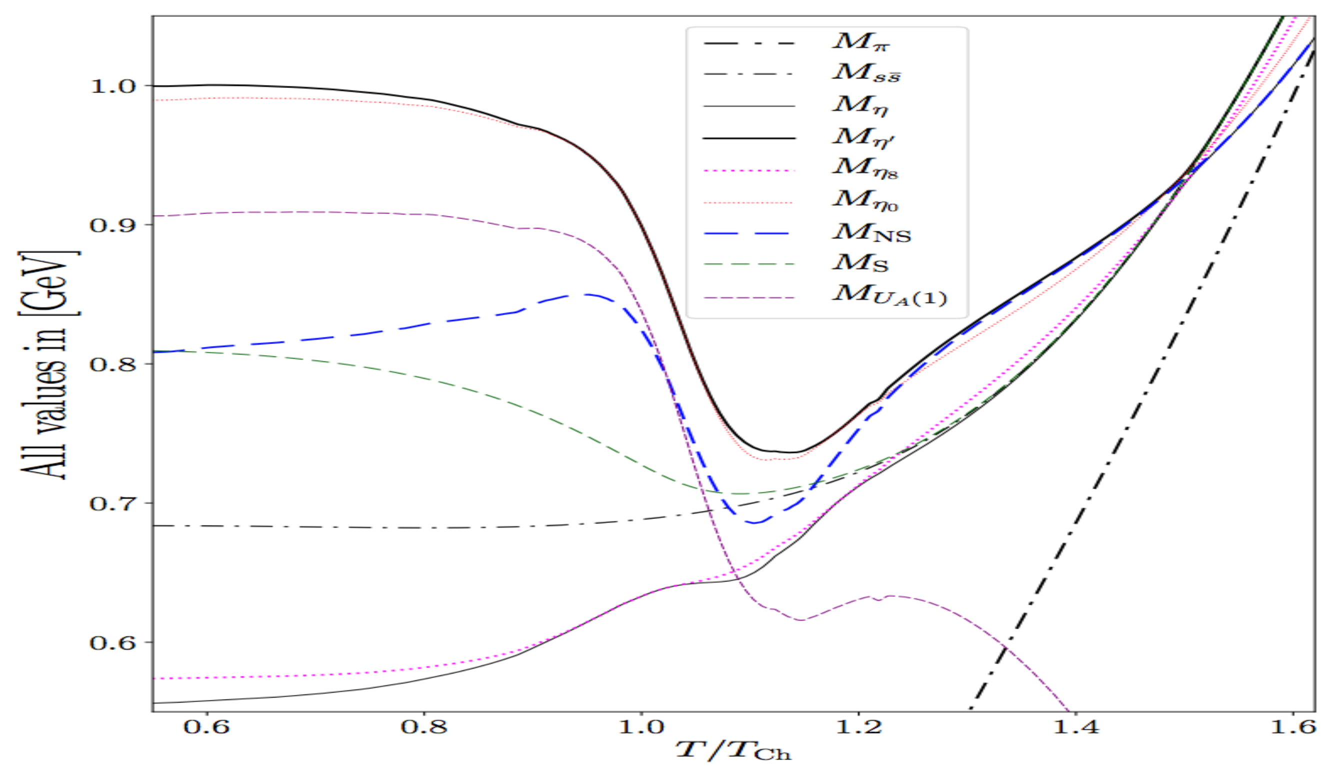

Lattice analysis in progress with A. Kotov and A. Trunin

No strong temperature dependence across Tc

# $\eta'$ in the QGP

So far, only results from model's studies

Horvatic et al. 2018




Lattice analysis in progress with A. Kotov and A. Trunin

No strong temperature dependence across Tc

Preliminary!

# III. Axions

The two faces of QCD topology

Window to Axions

Property of Quark Gluon Plasma

# The QCD axion: ideal Dark Matter candidate

Time from Big Bang

Temperature

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

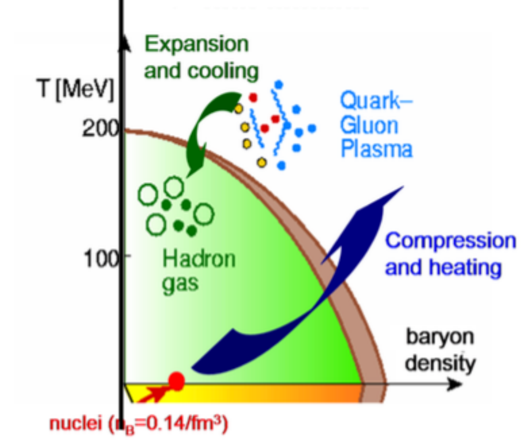
Axions's freezout

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

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

**Axions' mass and density today**

**Quark Gluon Plasma: Topology**



Time from Big Bang

Temperature

Hubble parameter

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

Axions's freezout

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

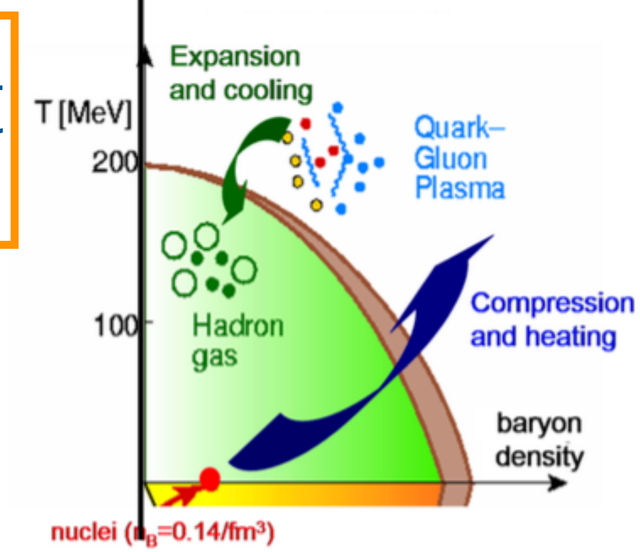
$$m_a(T) = \sqrt{\chi(T)}/f_a$$

**Quark Gluon Plasma: Topology**

**Axions' mass and density today**

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

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




Wantz, Shellard 2010

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

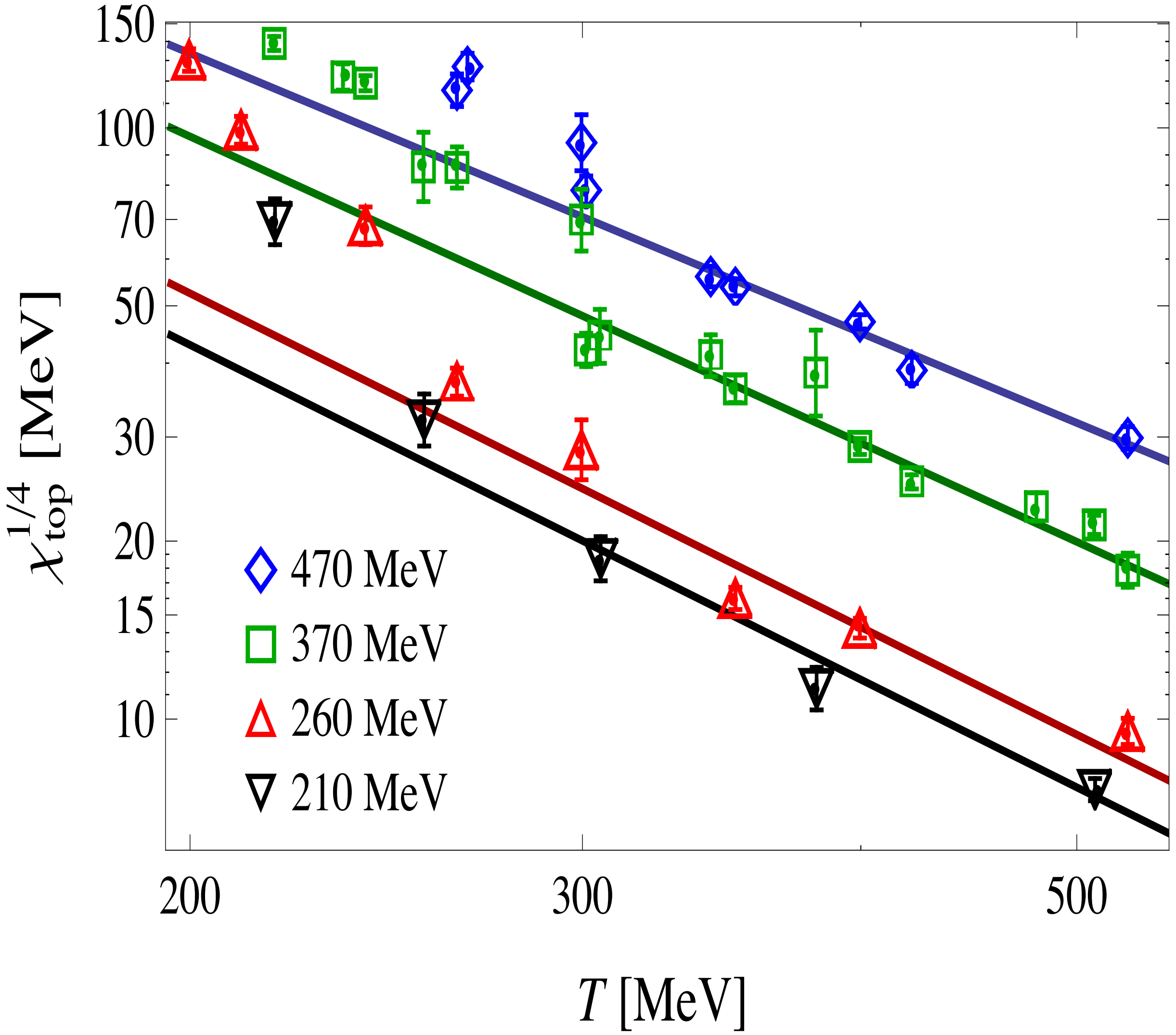
$$d = (6.26, 6.88, 7.52, 7.48)$$

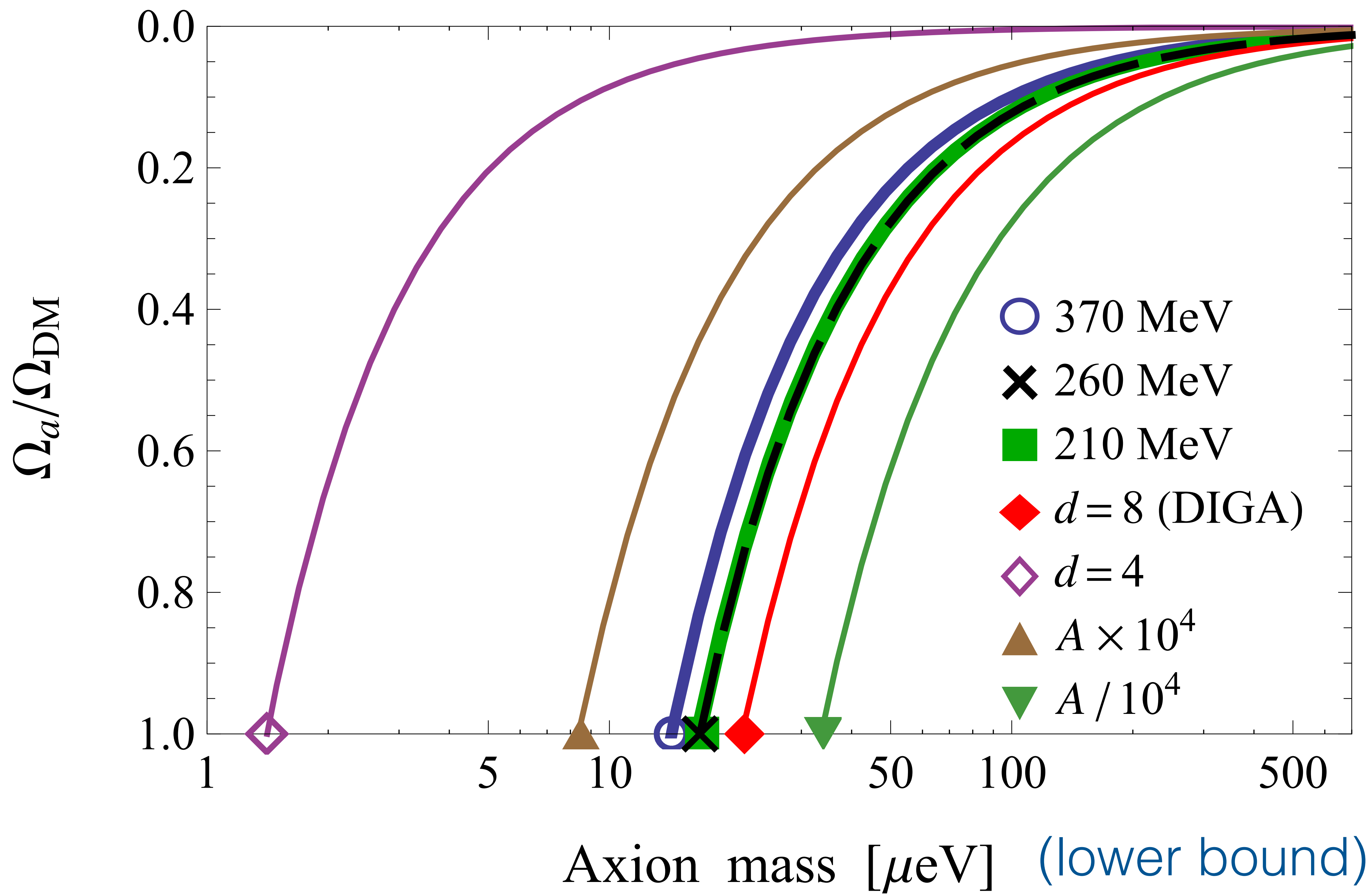
$$m_\pi = (470, 370, 260, 210)\ \mathrm{MeV}$$

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

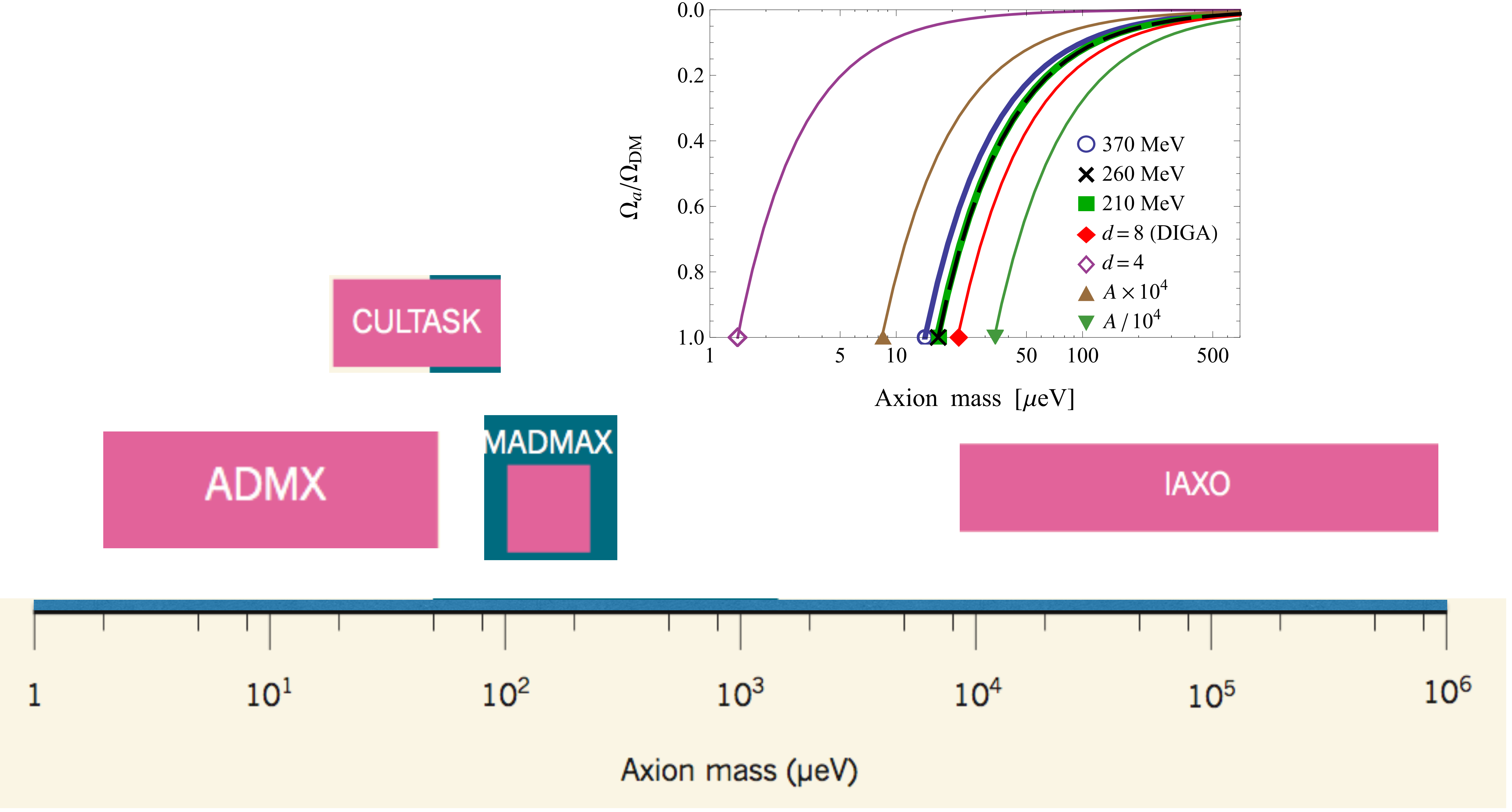
$$m_a = \sqrt{\chi(T)}/f_a$$

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





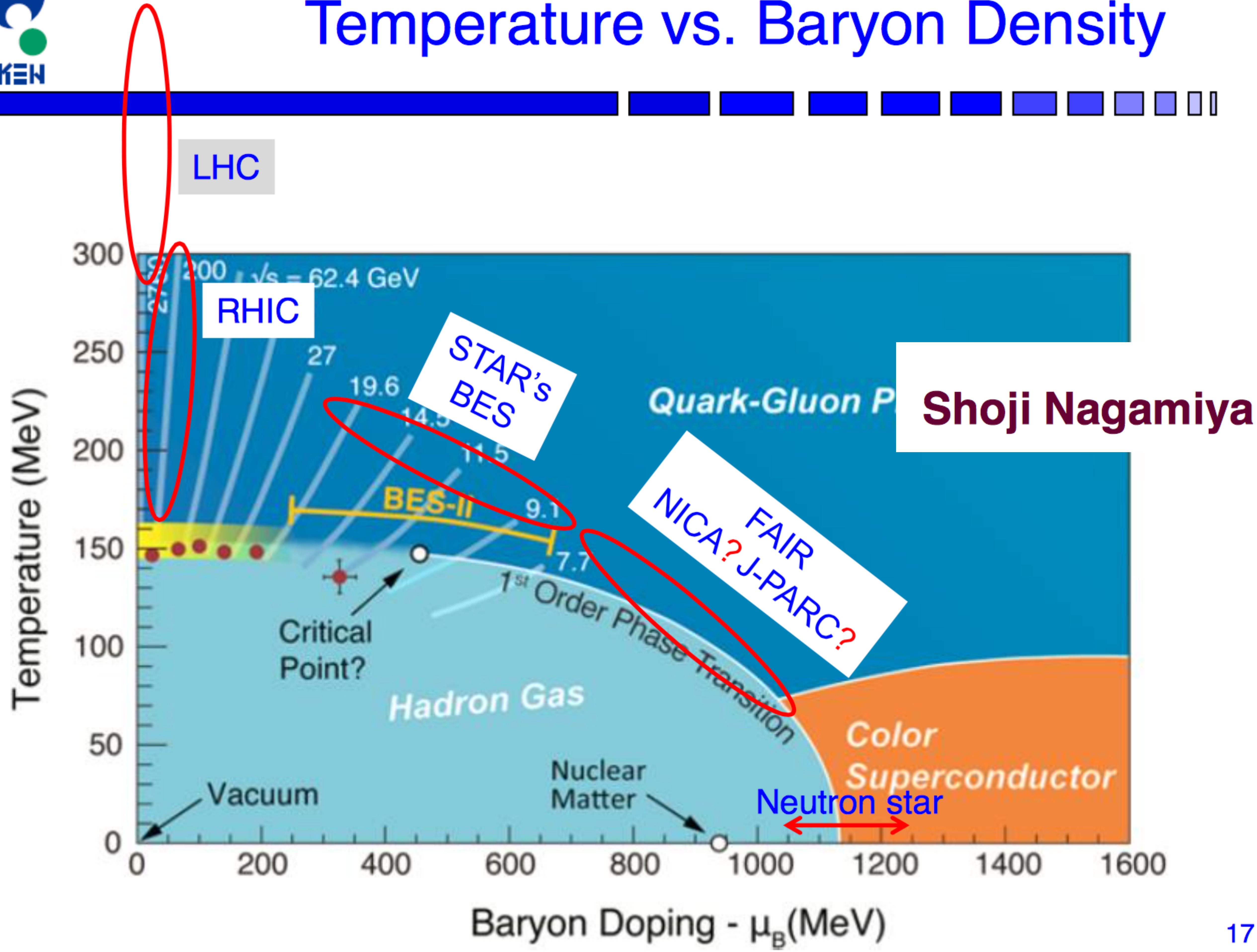

$$\rho_a(m_a) \propto m_a^{-\frac{3.053+d/2}{2.027+d/2}}$$



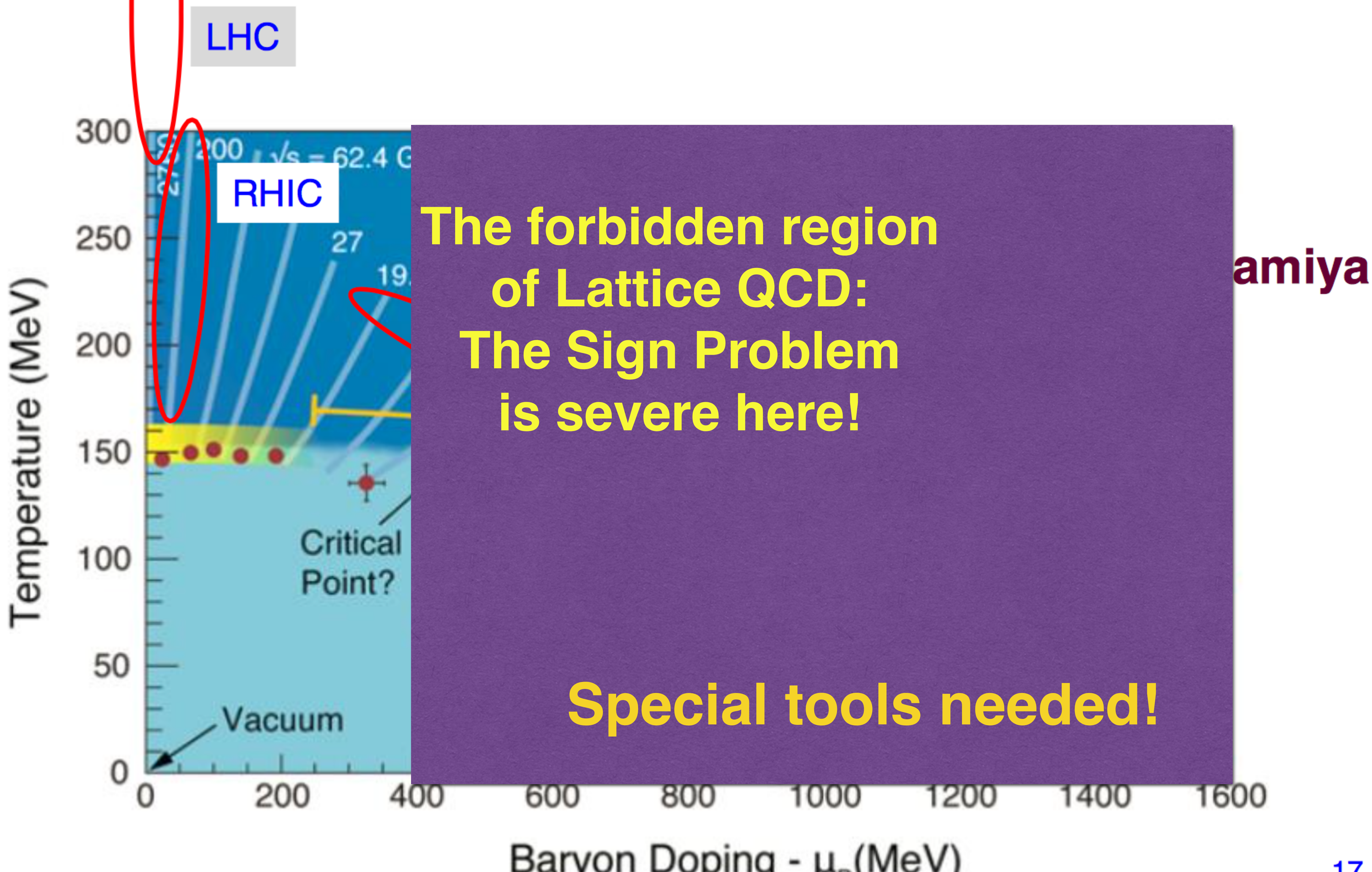
0.0
0.2
0.4
0.6
0.8
1.0
$\Omega_a/\Omega_{DM}$
1
5
10
50
100
500
Axion mass [$\mu$eV]
370 MeV
260 MeV
210 MeV
$d = 8$ (DIGA)
$d = 4$
$A \times 10^4$
$A / 10^4$
CULTASK
ADMX
MADMAX
IAXO
1
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$
$10^6$
Axion mass (μeV)

# IV. Towards neutron stars

# Temperature vs. Baryon Density



# Temperature vs. Baryon Density




**The forbidden region of Lattice QCD: The Sign Problem is severe here!**

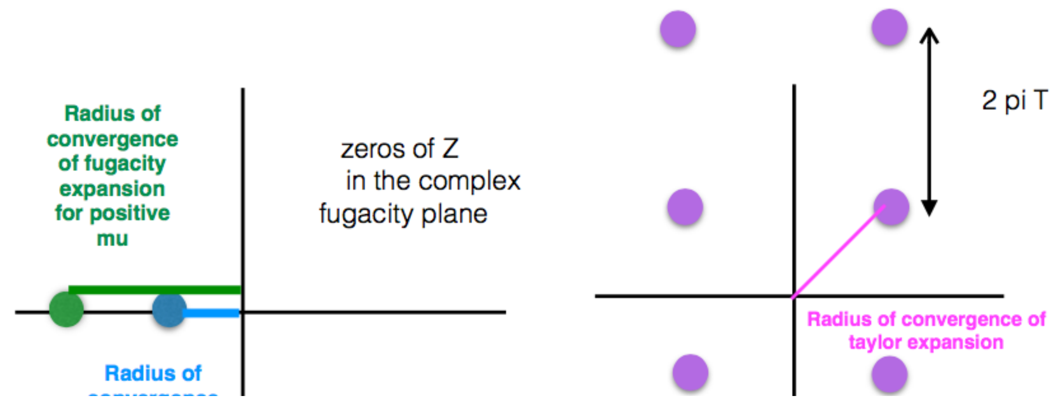
**Special tools needed!**

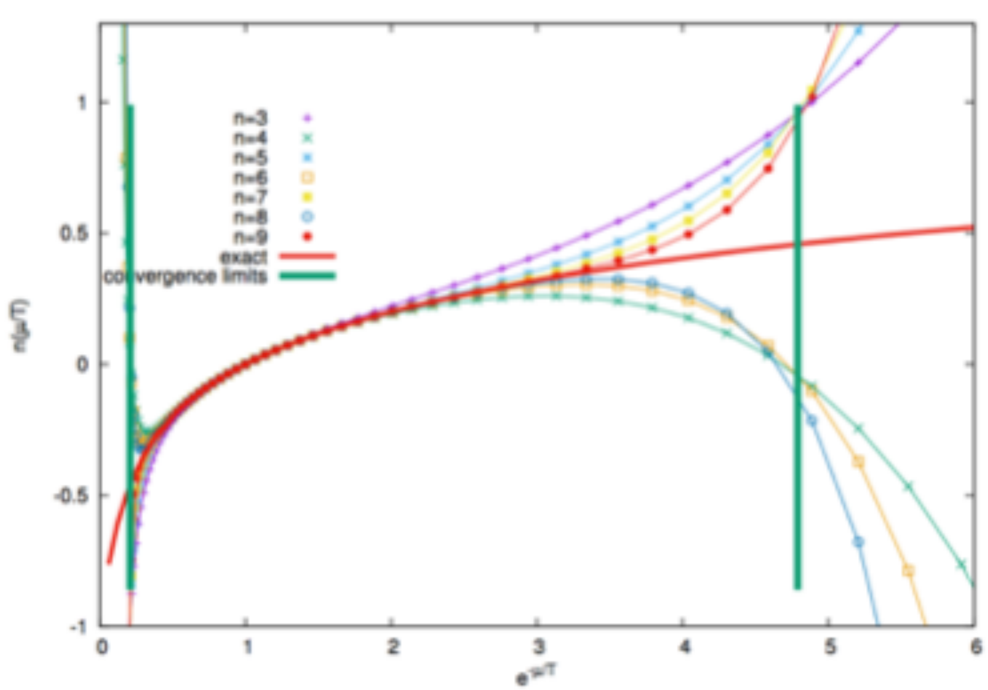
# QCD and dense matter: work in progress

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

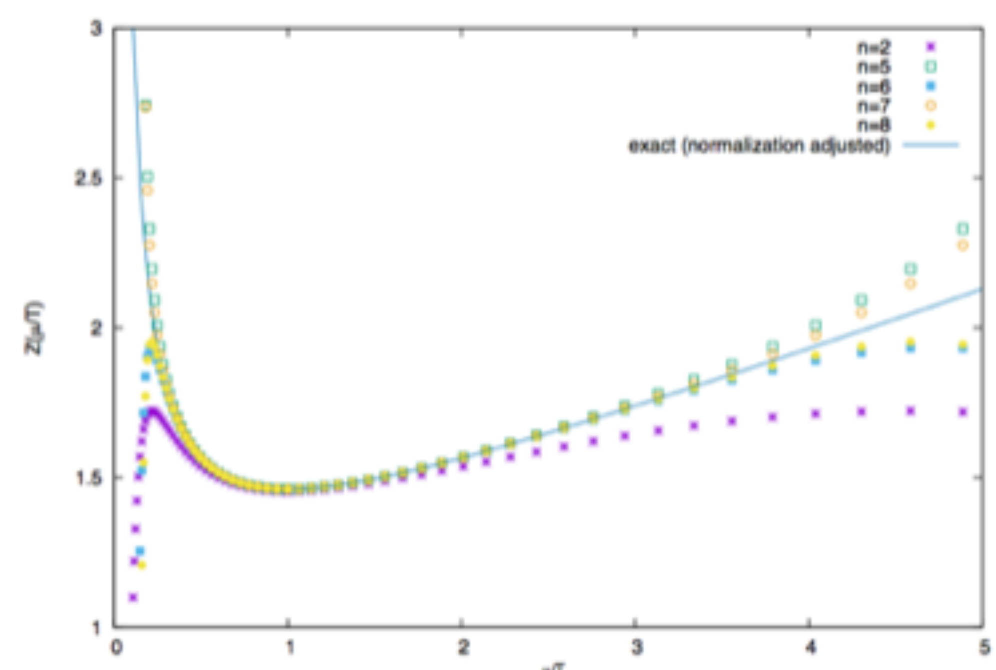
A strategy for the search of the QCD critical point based on joint analysis of

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




limited convergence
of the viral expansion



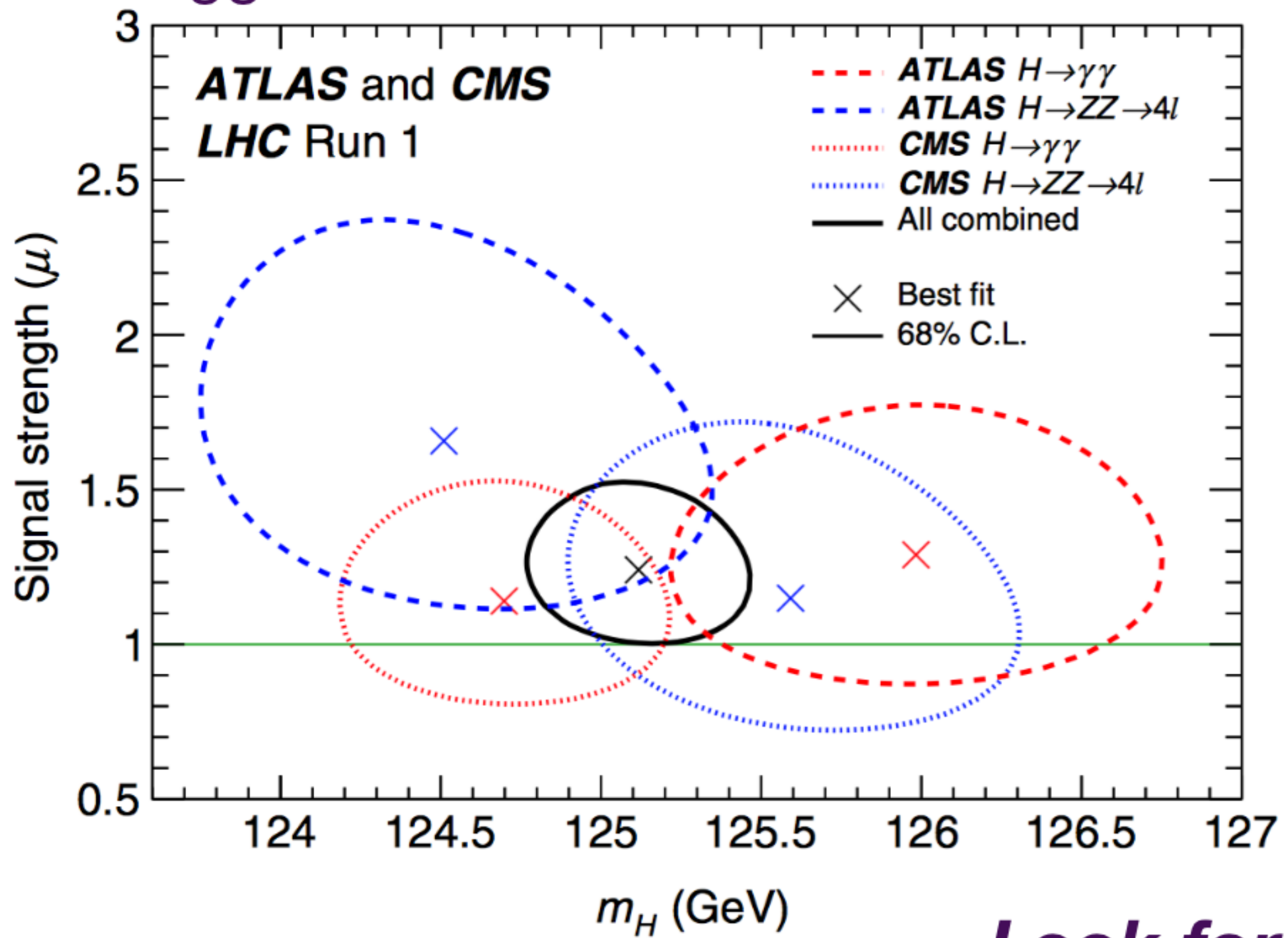

convergence of the canonical
expansion

# V. Strong Interactions BSM

# 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***

# Adding flavours to strong interactions

Nf

grows

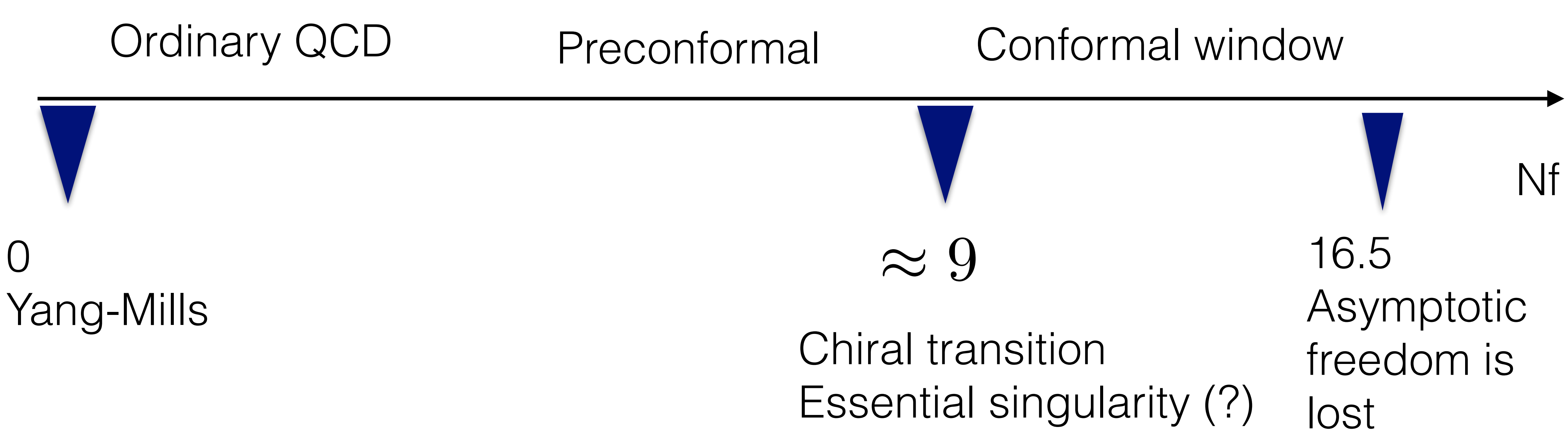
large

# Work on phases of QCD
# at large Nf

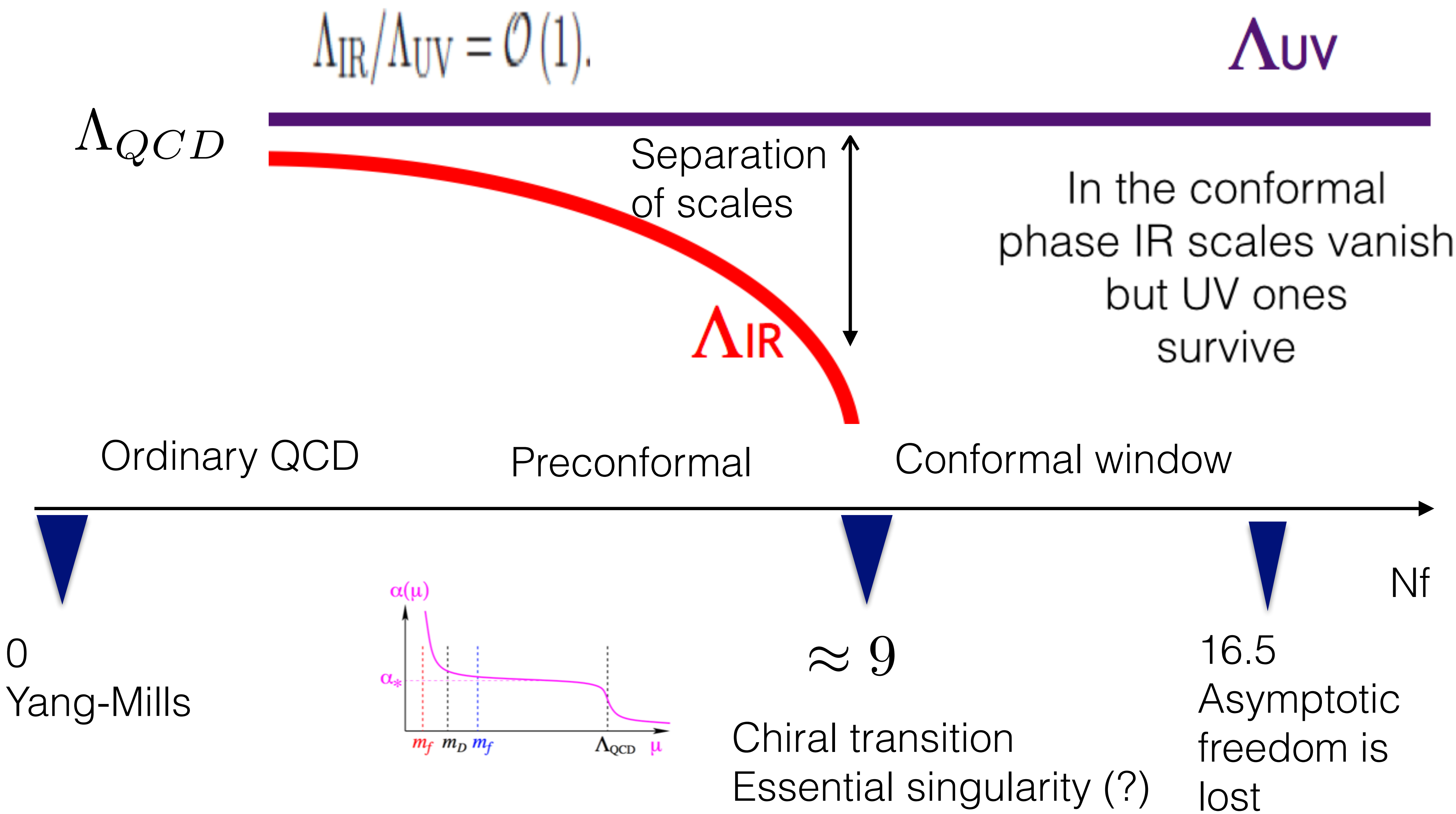
is with

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

# Phases of QCD as a function of Nf

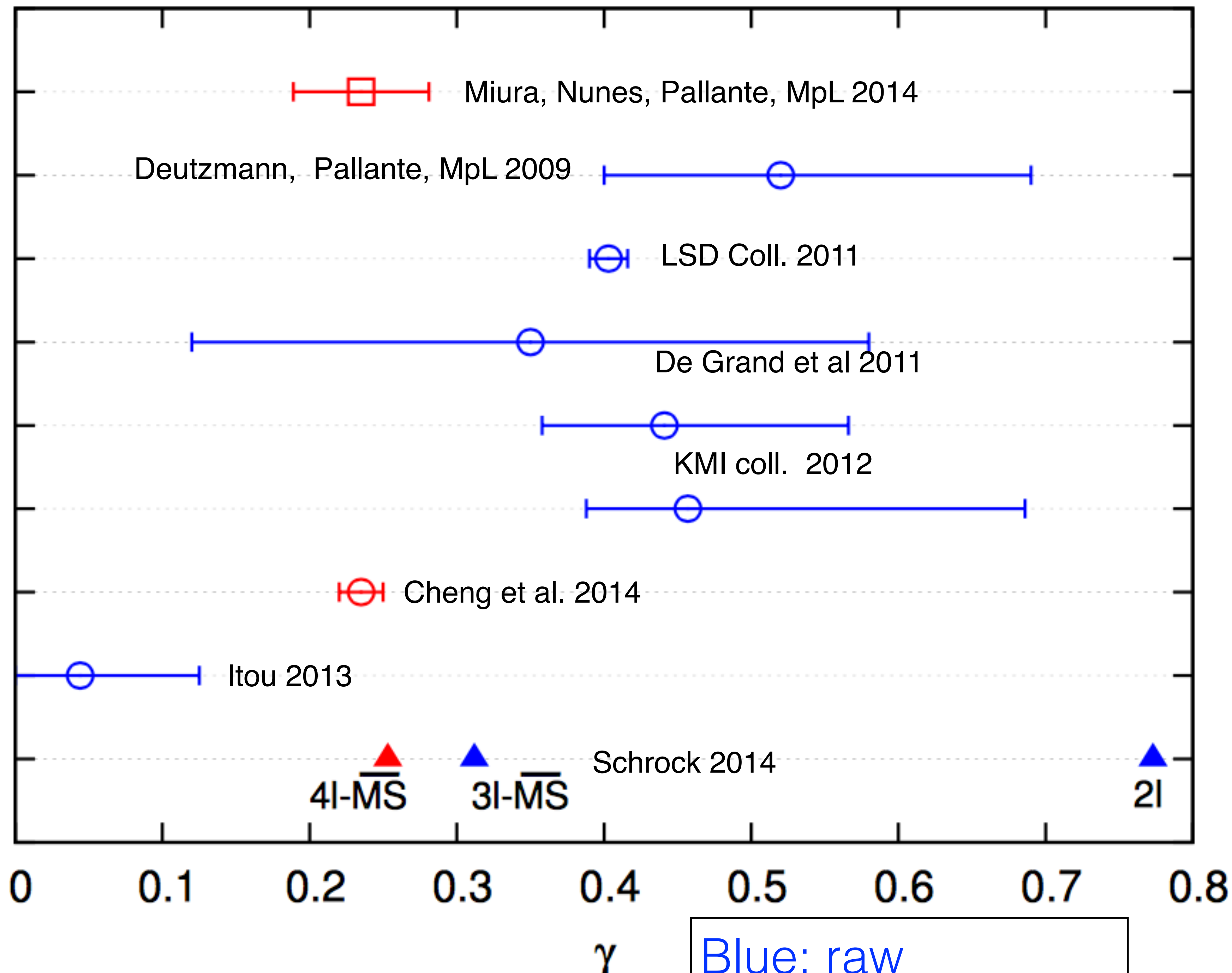


# Phases of QCD as a function of Nf



# Is conformality realized? Yes!  Anomalous dimension Nf=12

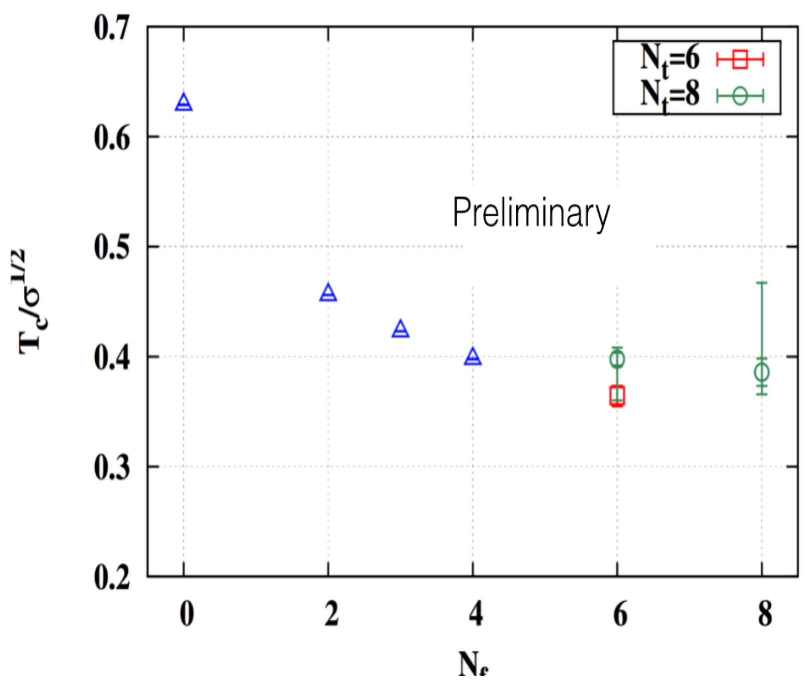
$$M_H = c_H m^{1/y_h}$$

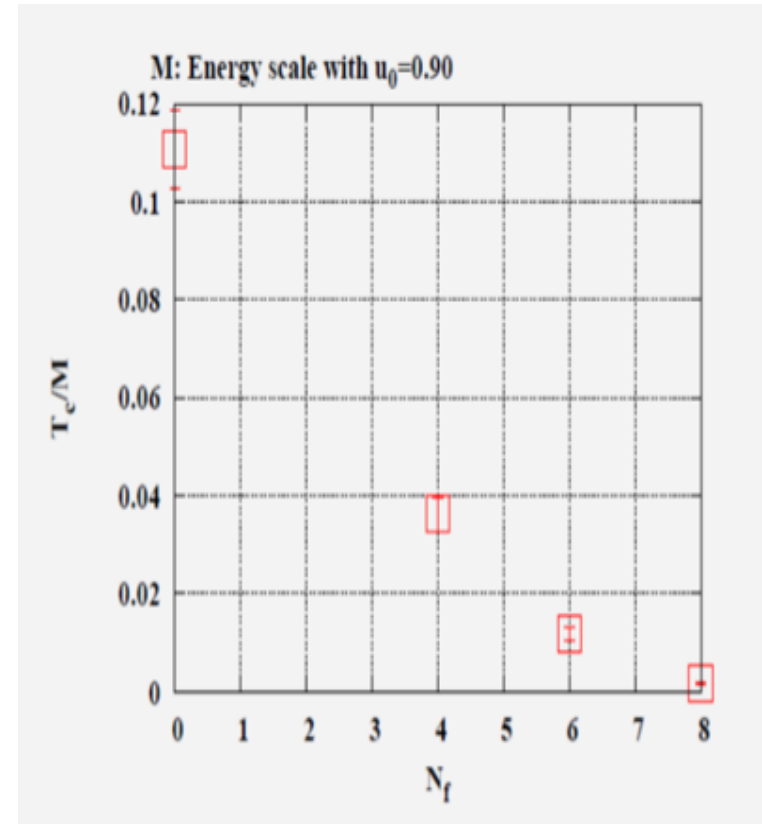



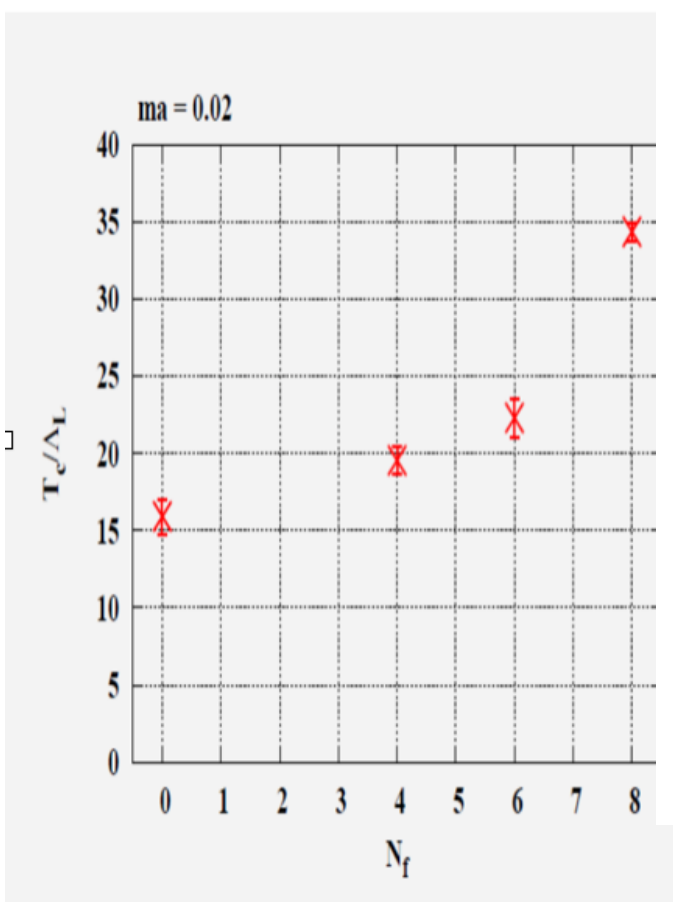

Blue: raw
Red: corrected (scaling violations taken into account)

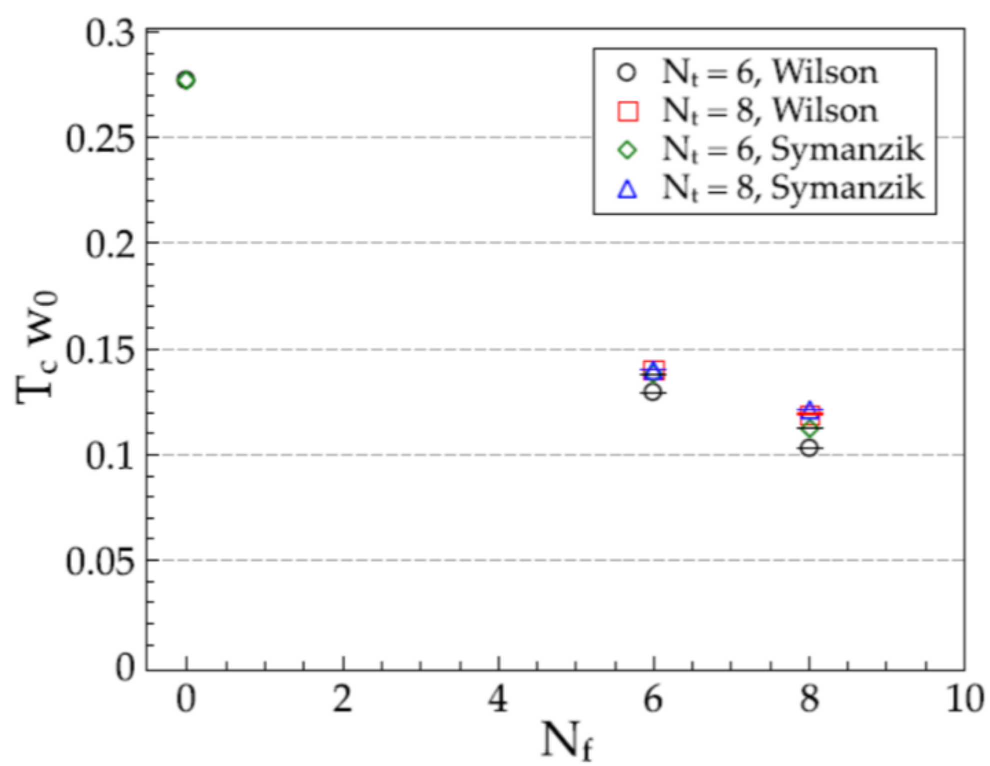
# Hierarchy of scales in the near-conformal phase

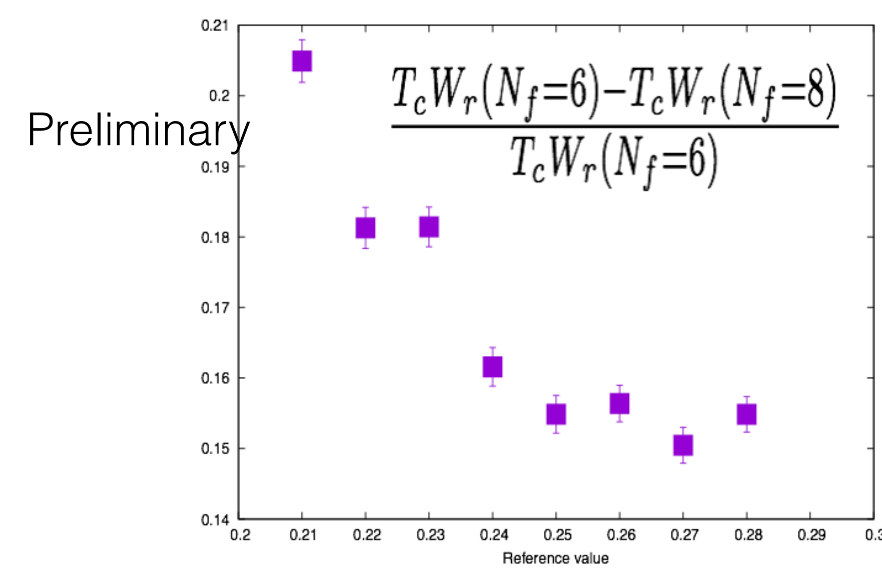
Dimensionless quantities behave differently approaching Nfc



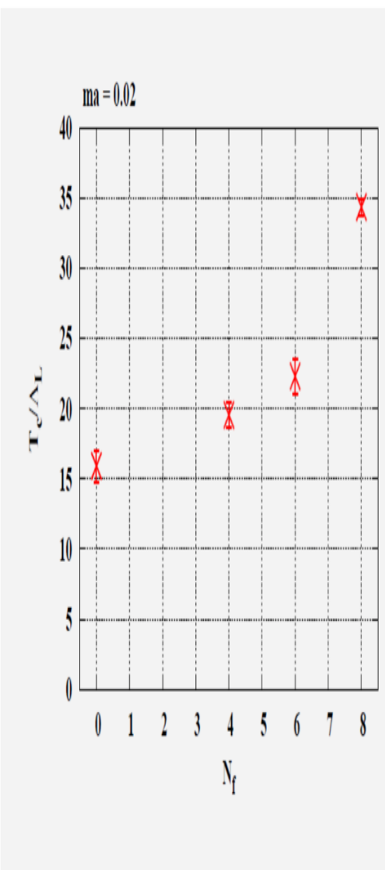




UV

# Comparison with holographic studies

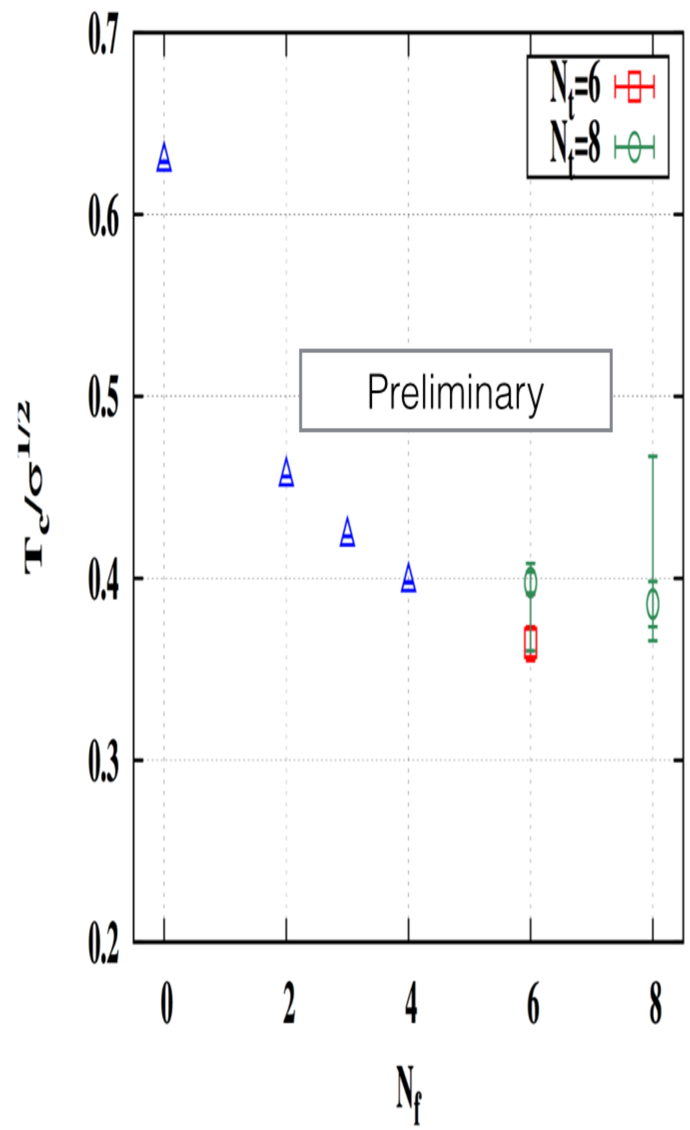
$$\frac{2\pi T_c}{M_{KK}} = 1 - \frac{1}{126\pi^3}\lambda_4^2\frac{N_f}{N_c}\left(1+\frac{12\pi^{3/2}}{\Gamma\left(-\frac{2}{3}\right)\Gamma\left(\frac{1}{6}\right)}\right)$$




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



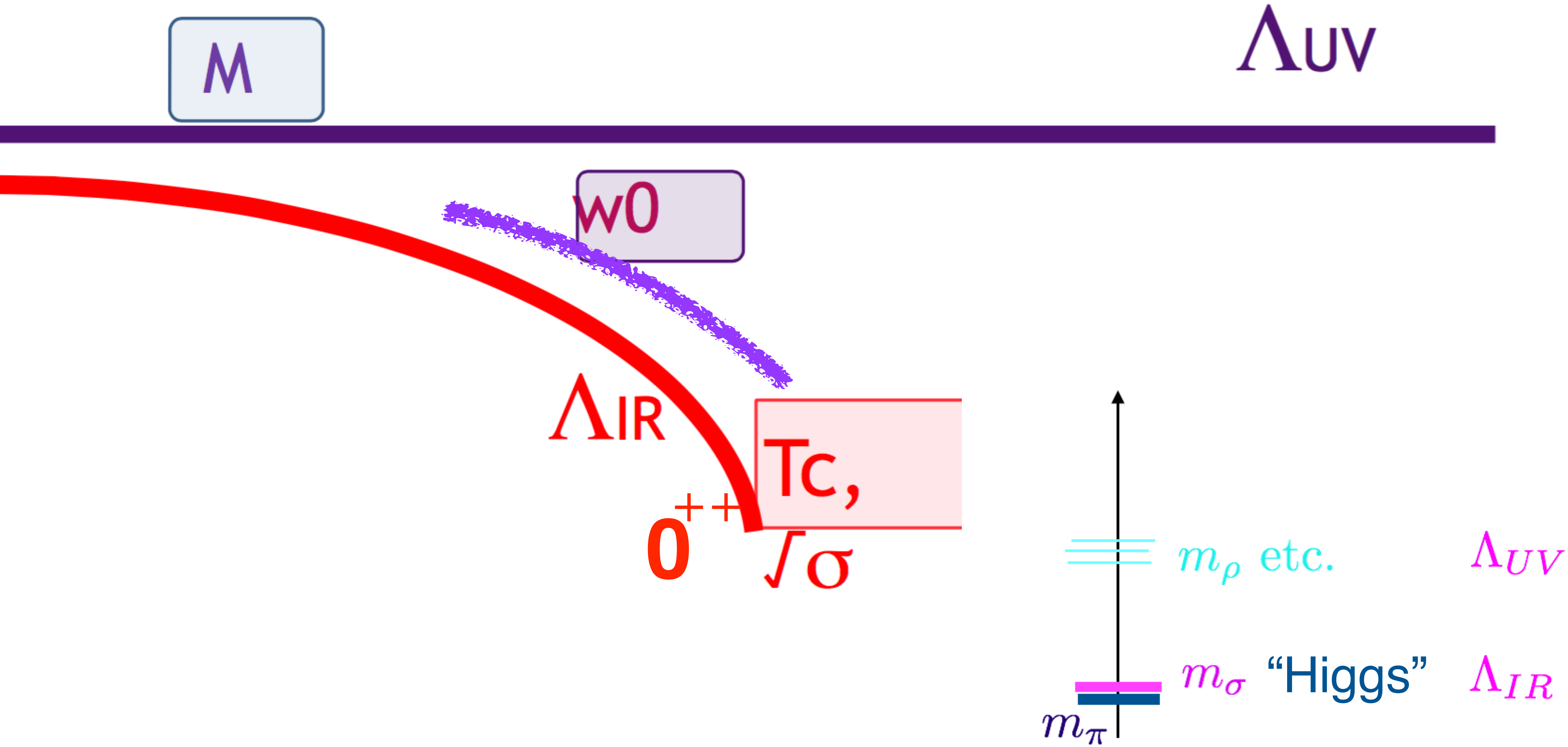

Mild decrease, possibly constant as $N_f \to N_f^c$

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

# Confirmed: hierarchy of scales at Nf=8



*..rather than a summary…*

Numerical simulations of **QCD** hold the key
to the understanding of
many aspects of particle physics,
complementing experiments and
purely analytic approaches

This presentation sketched a few aspects of my own work:
**only a subsample of all**
**the possible studies in lattice QCD!!**

PRACE

# The Scientific Case for Computing in Europe 2018-2026

November 2018

## Particle Physics

Computing plays a similarly critical role in high-energy particle physics … …oring and analysing experimental data, to theoretical predictions of properties of … …eed searches for new physics. At the Large Hadron Collider (LHC), the data requirements are rapidly expanding: In 2017, CERN passed a milestone with 200 petabytes of data permanently archived. The current experiments are producing unprecedented amounts of new data – 73 petabytes in 2016 alone. As these volumes increase, the complexity of storage, access and data analysis must also evolve so that science potential is not limited, and doing so will likely advance the fundamental state-of-the-art in data science too.

One of the largest applications of supercomputing resources in particle physics is quantum chromodynamics (QCD), which is the theoretical framework for the interactions of the fundamental building blocks of all visible matter – called quarks and gluons. These particles are never found free in nature but are inextricably bound inside e.g. protons and neutrons – a process called confinement. This property causes QCD to behave very differently to the

One of the largest applications of supercomputing resources in particle physics is quantum chromodynamics (QCD),