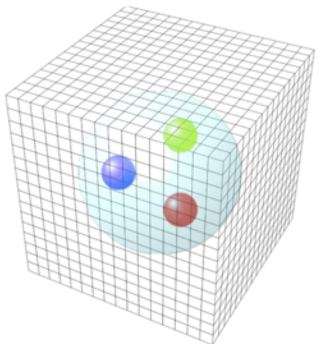
Conformal to non-conformal transition, supercooling & axions

(via holography)

Alex Pomarol   UAB & IFAE (Barcelona)

Interest in the conformal to non-conformal transition:

- Being explored in the lattice (QCD with large number of fermions):
  - ☛ Light scalar found
  - ☛ Smaller splittings from chiral breaking



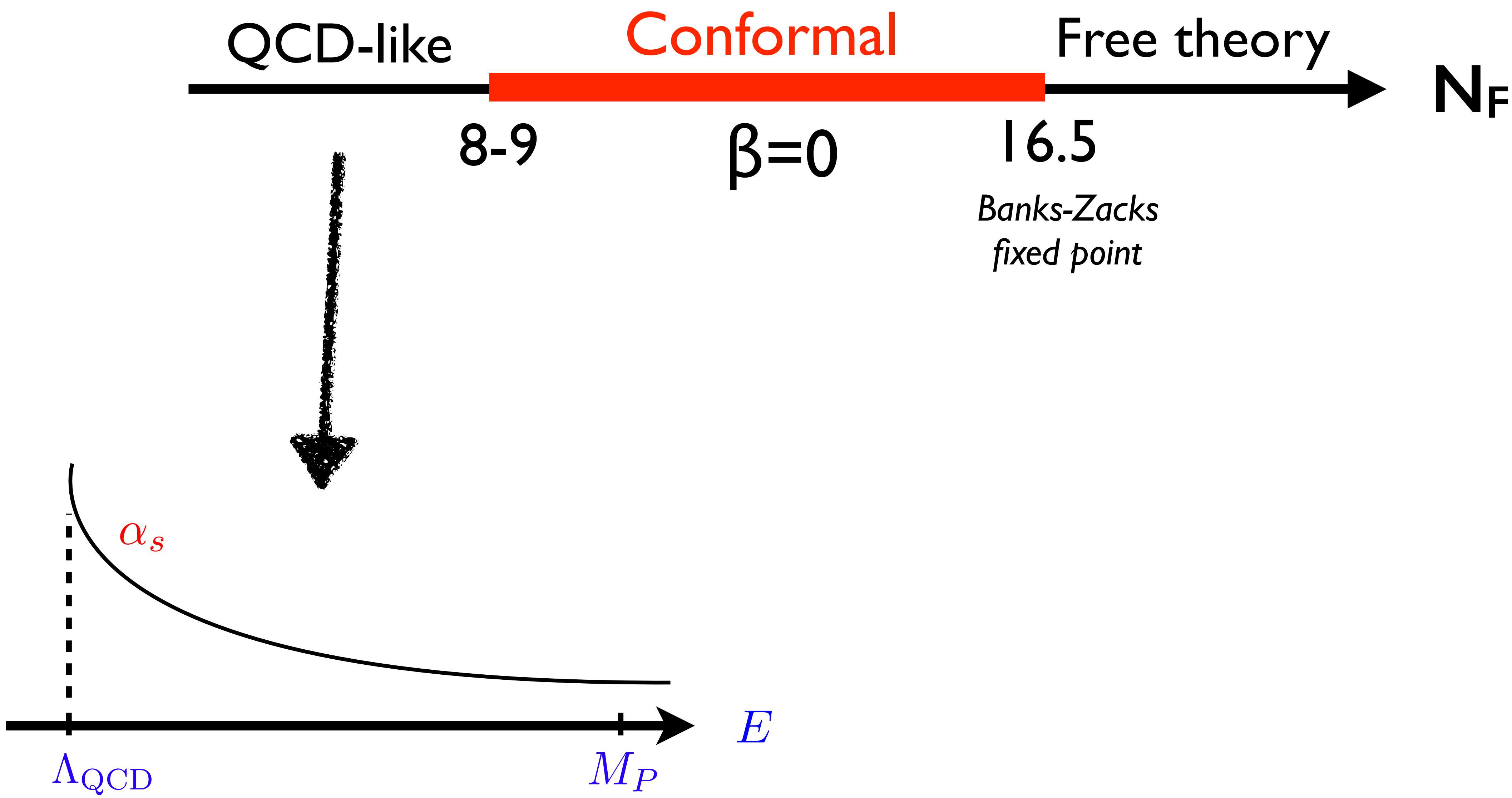
- Important for the hierarchy problem:

  SM emerging from a near-conformal theory

- Impact in cosmology:

  Supercooling and impact on axion abundance

Conformal window in SU(3) with large number of fermions (N_F)



Mass gap ~ $\Lambda_{\rm QCD}$

Chiral-symmetry breaking

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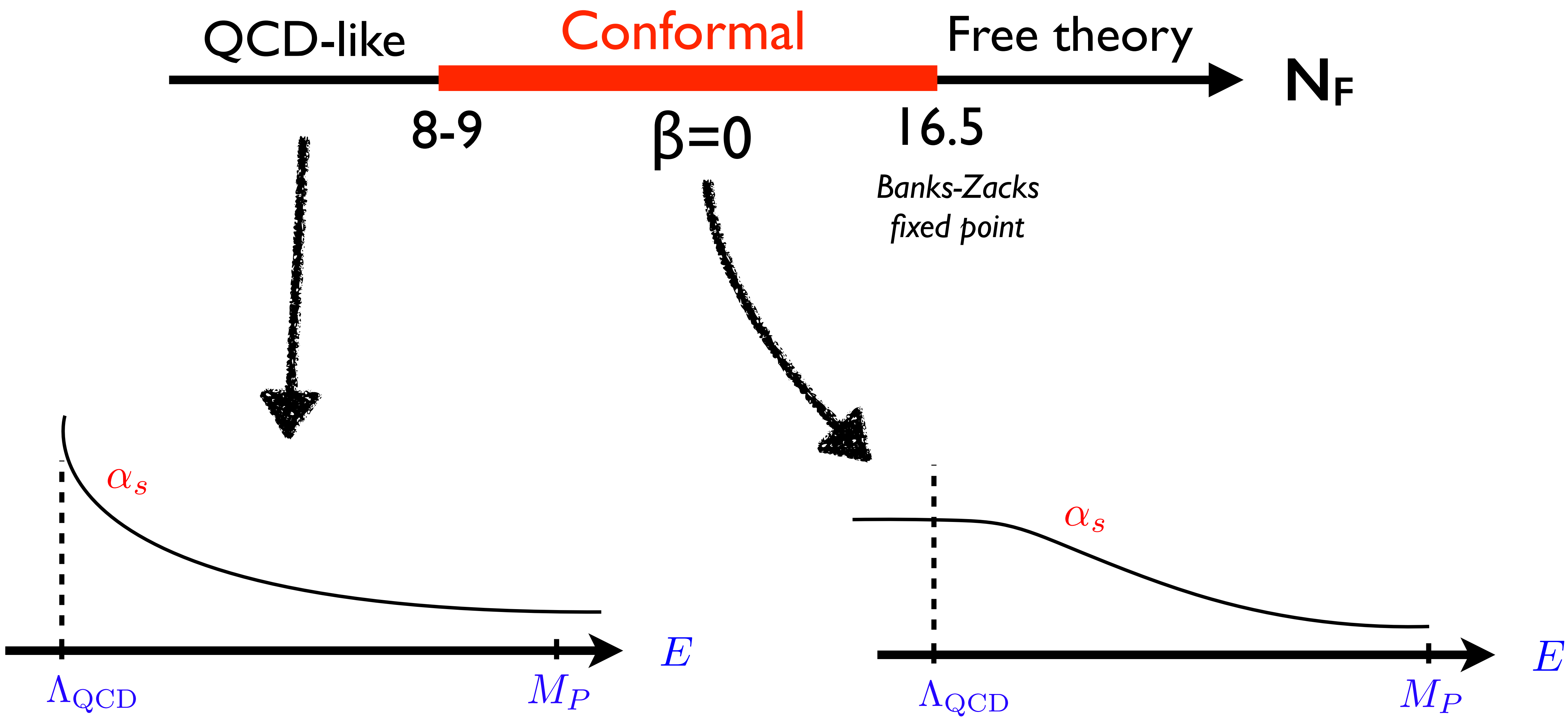


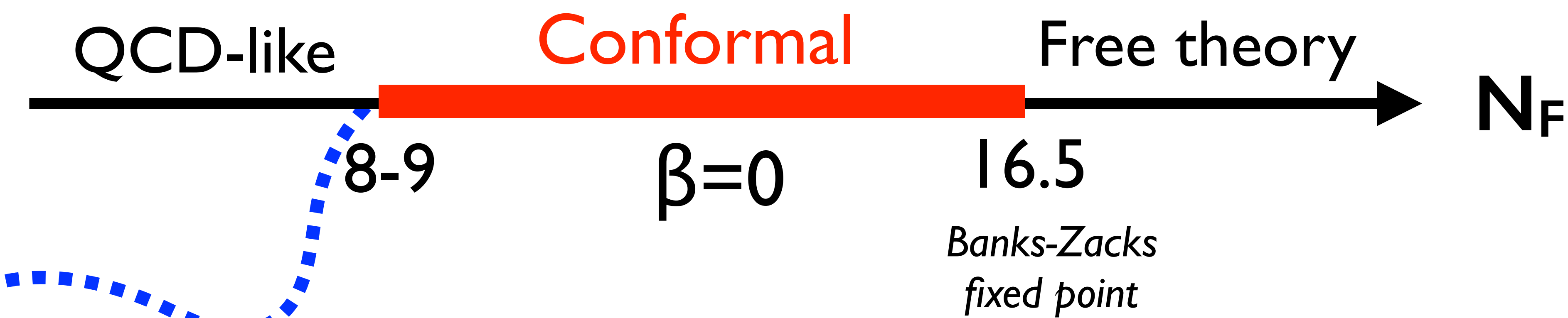
Mass gap ~ Λ_{QCD}

Chiral-symmetry breaking

No mass gap ~ Λ_{QCD}

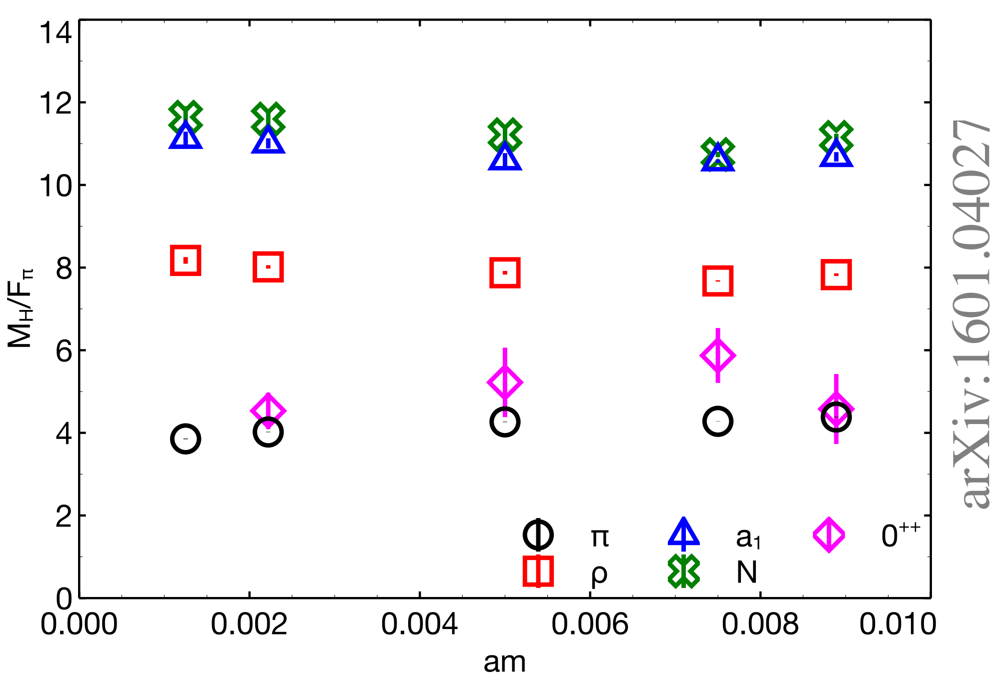
No chiral-symmetry breaking

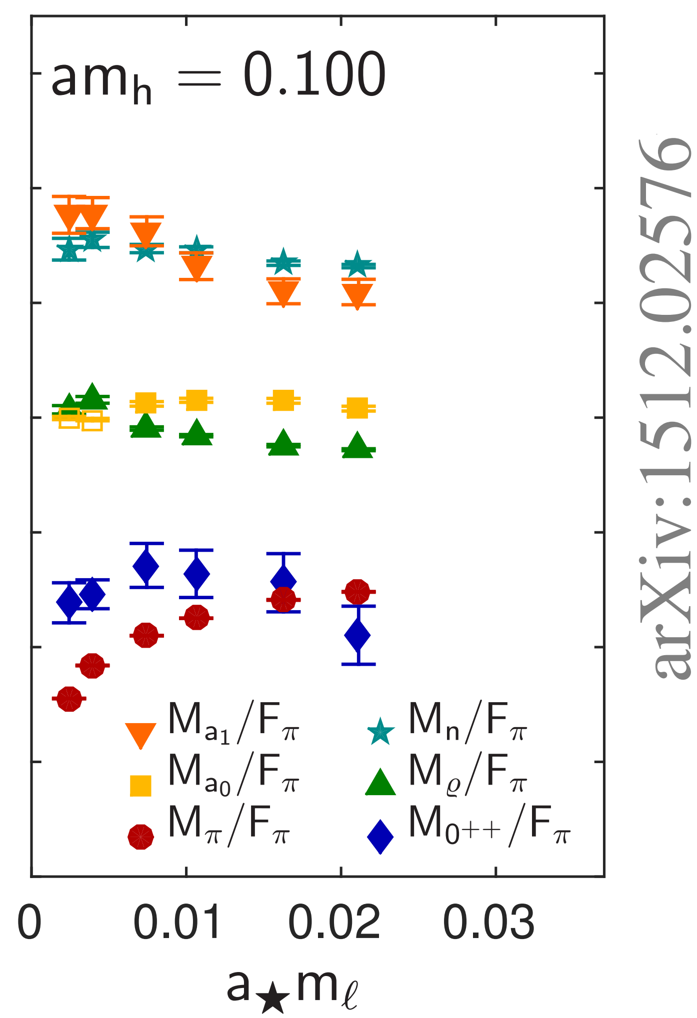
Conformal window in SU(3) with large number of fermions (N_F)

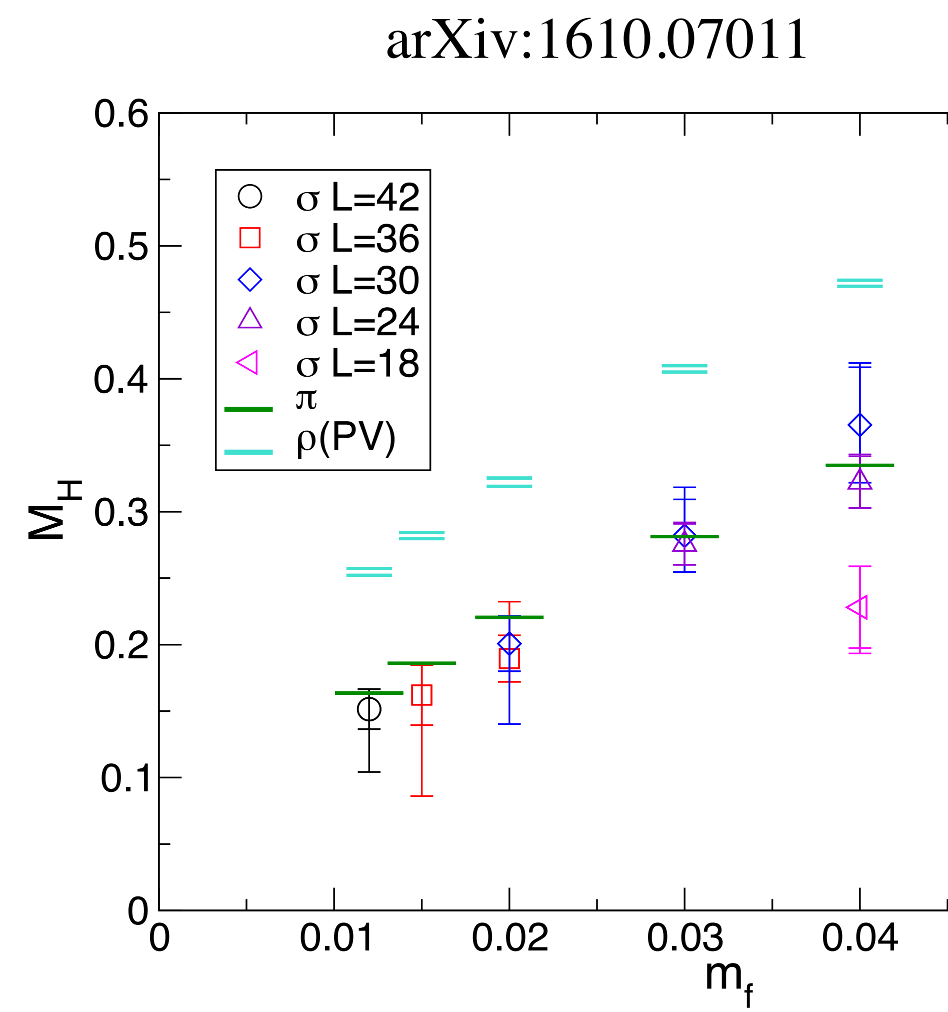


Lattice results:

N_F=8







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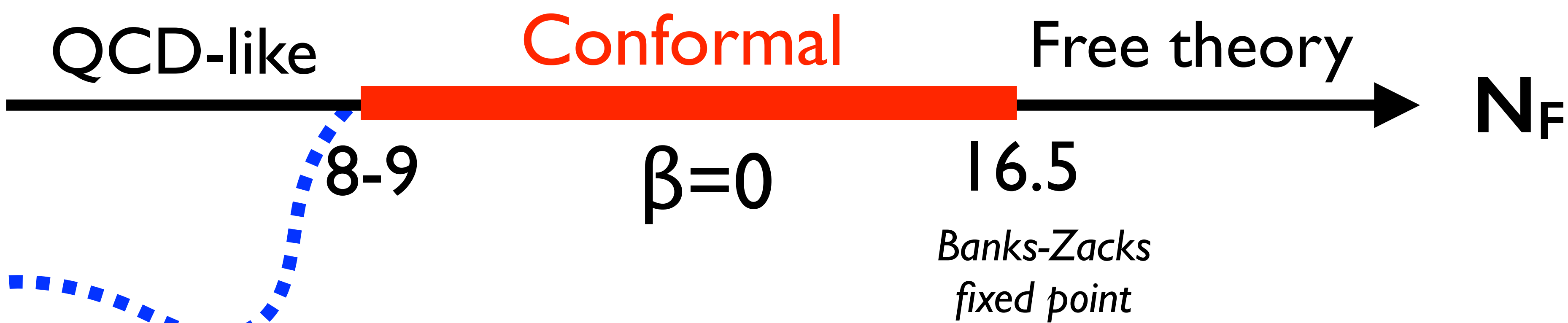

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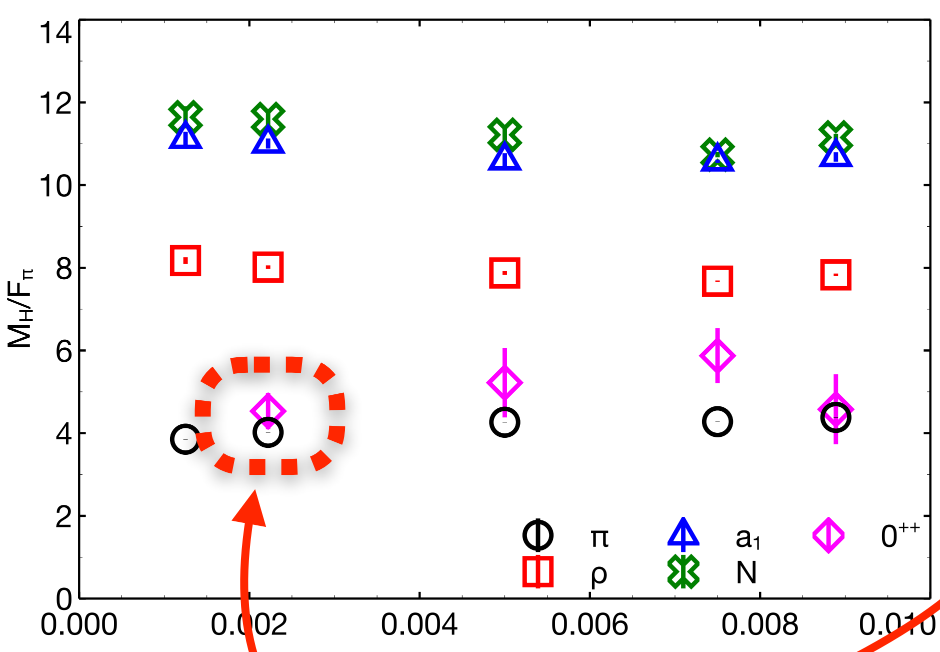
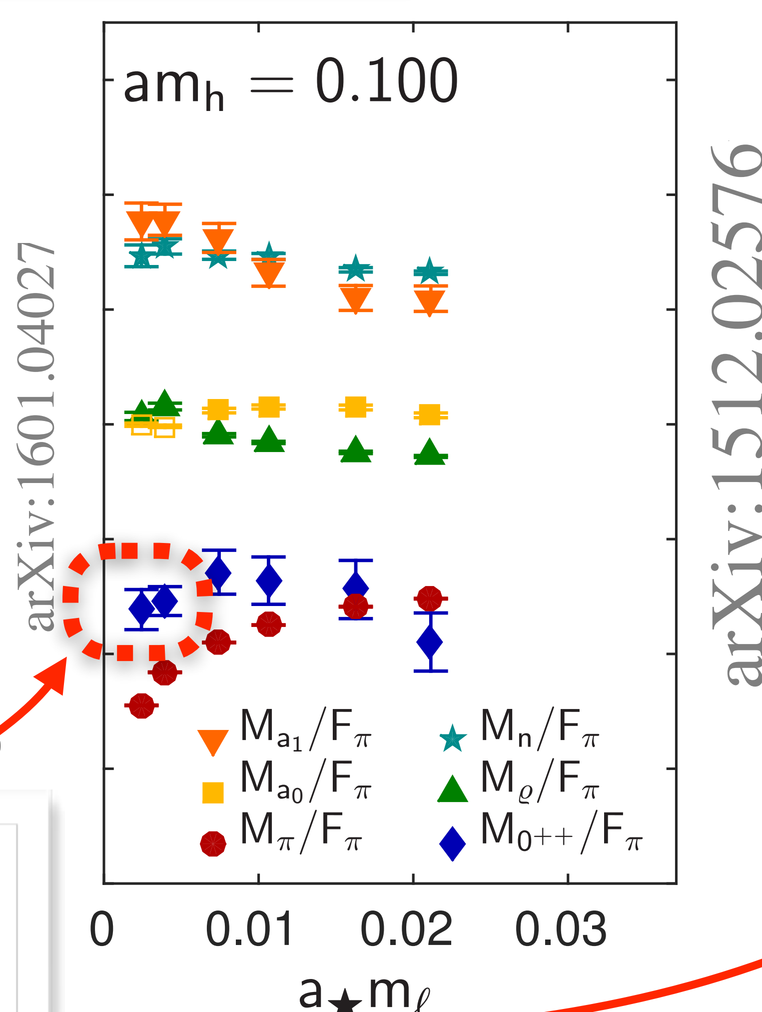
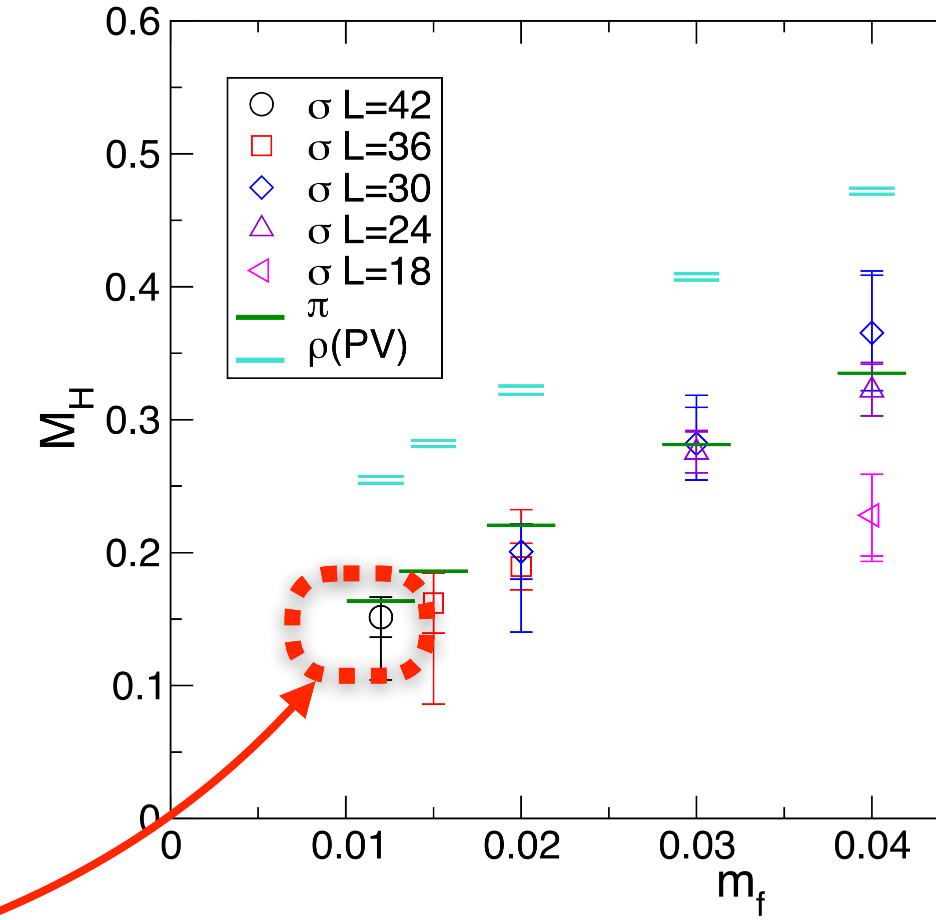


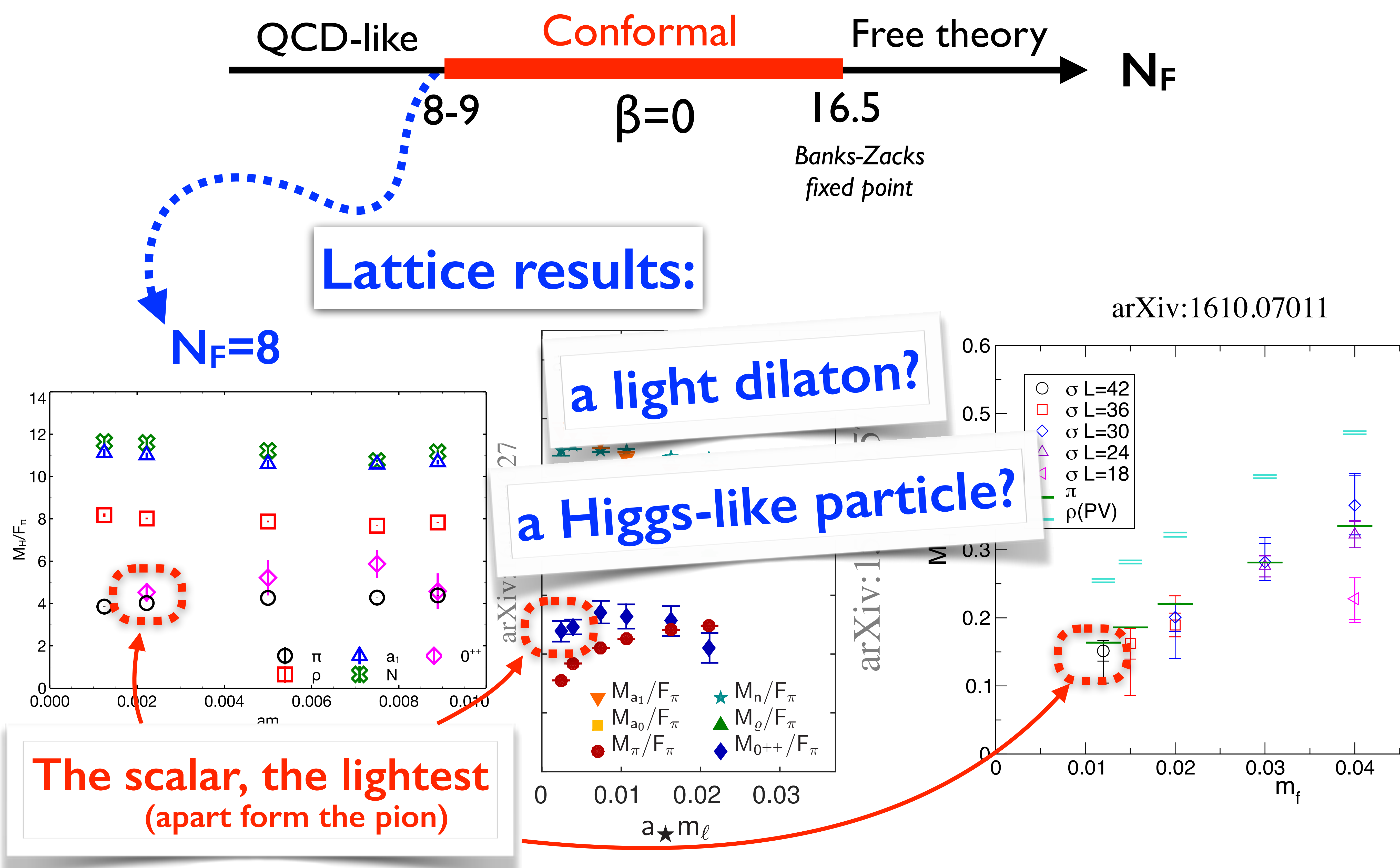


arXiv:1610.07011



The scalar, the lightest
(apart form the pion)

Conformal window in SU(3) with large number of fermions (N_F)



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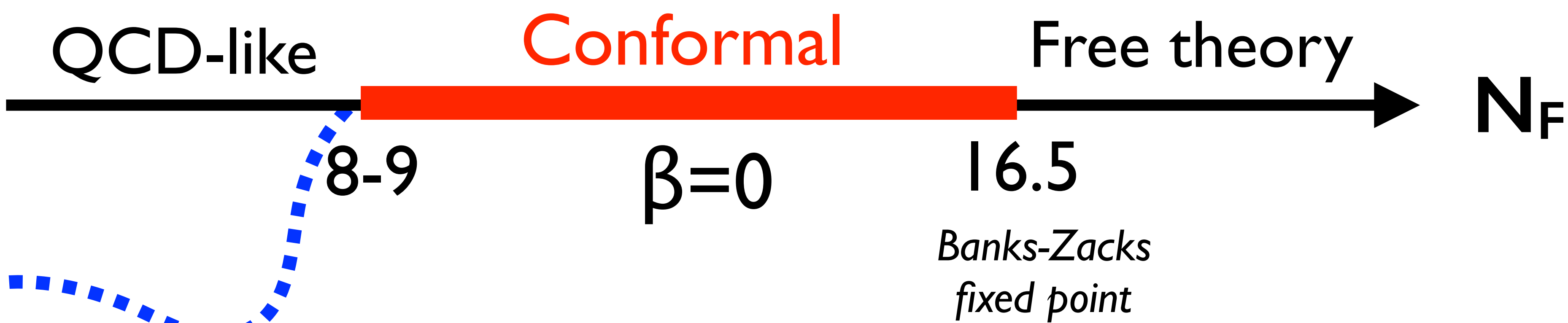

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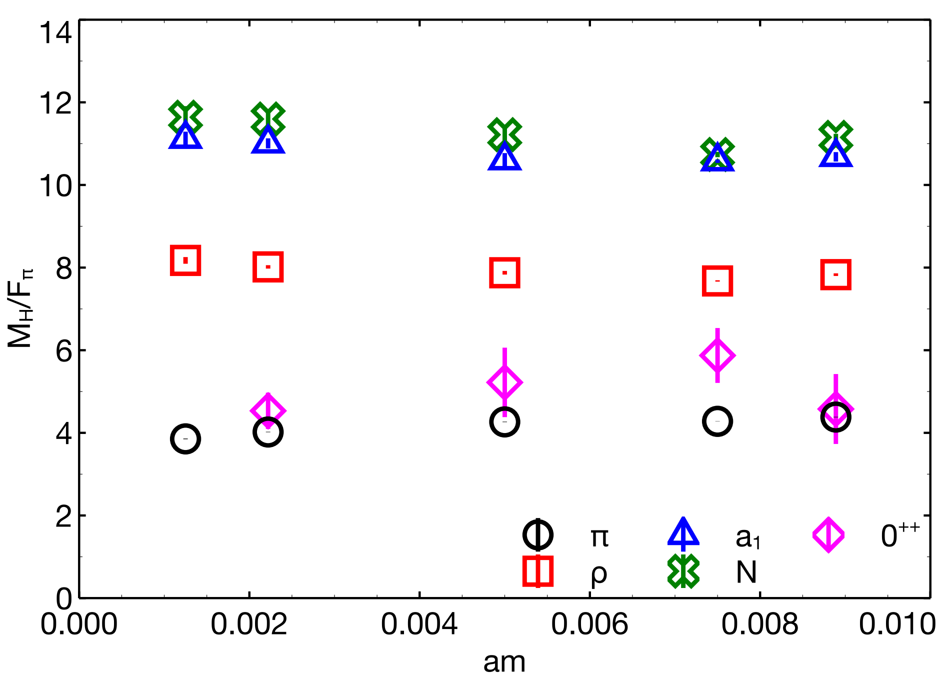
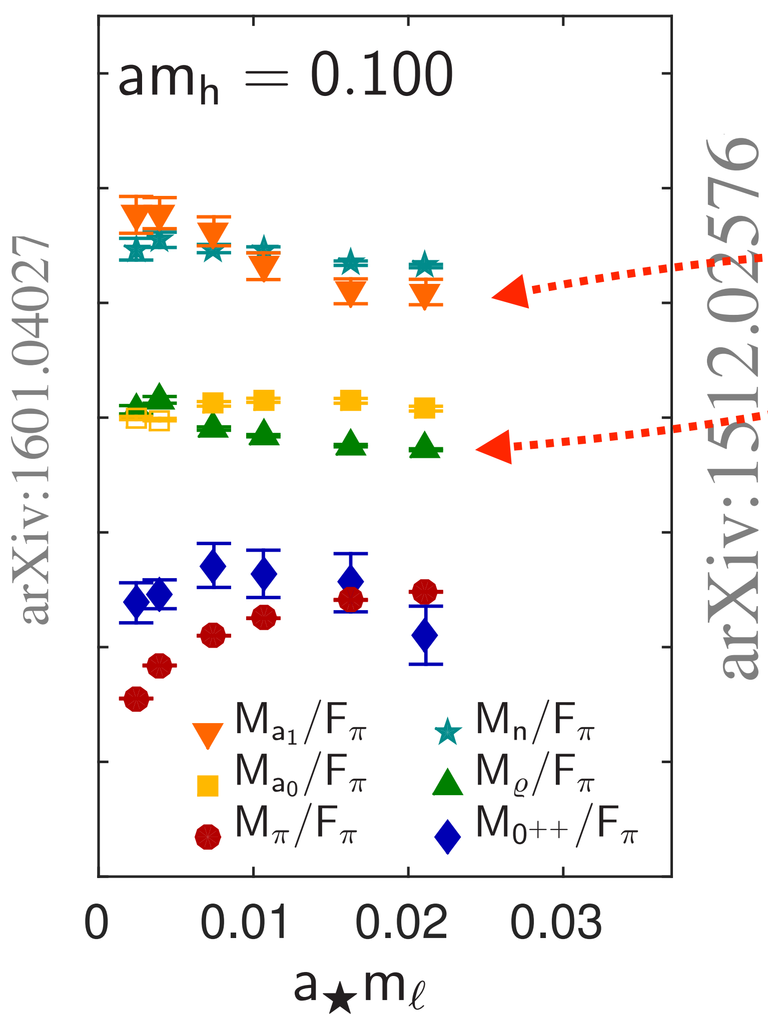




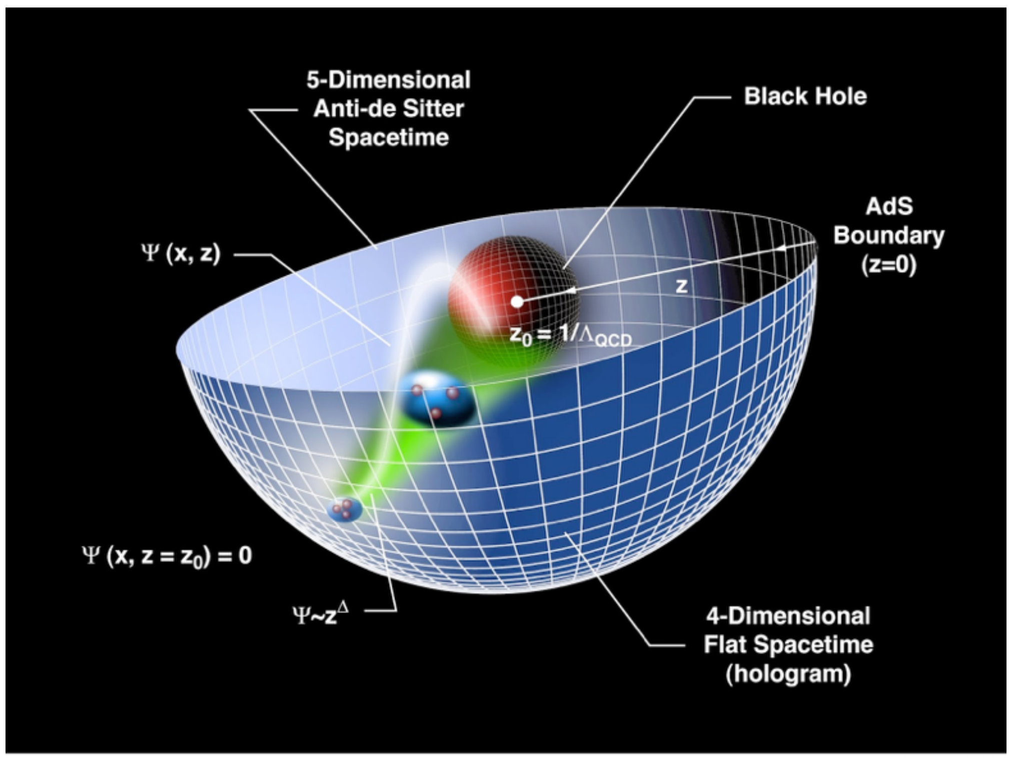
Smaller mass-splitting

$m_\rho - m_{a_1}$

from chiral breaking

(as compared with QCD)

What could we say from holography?



in collaboration with O.Pujolas & L.Salas

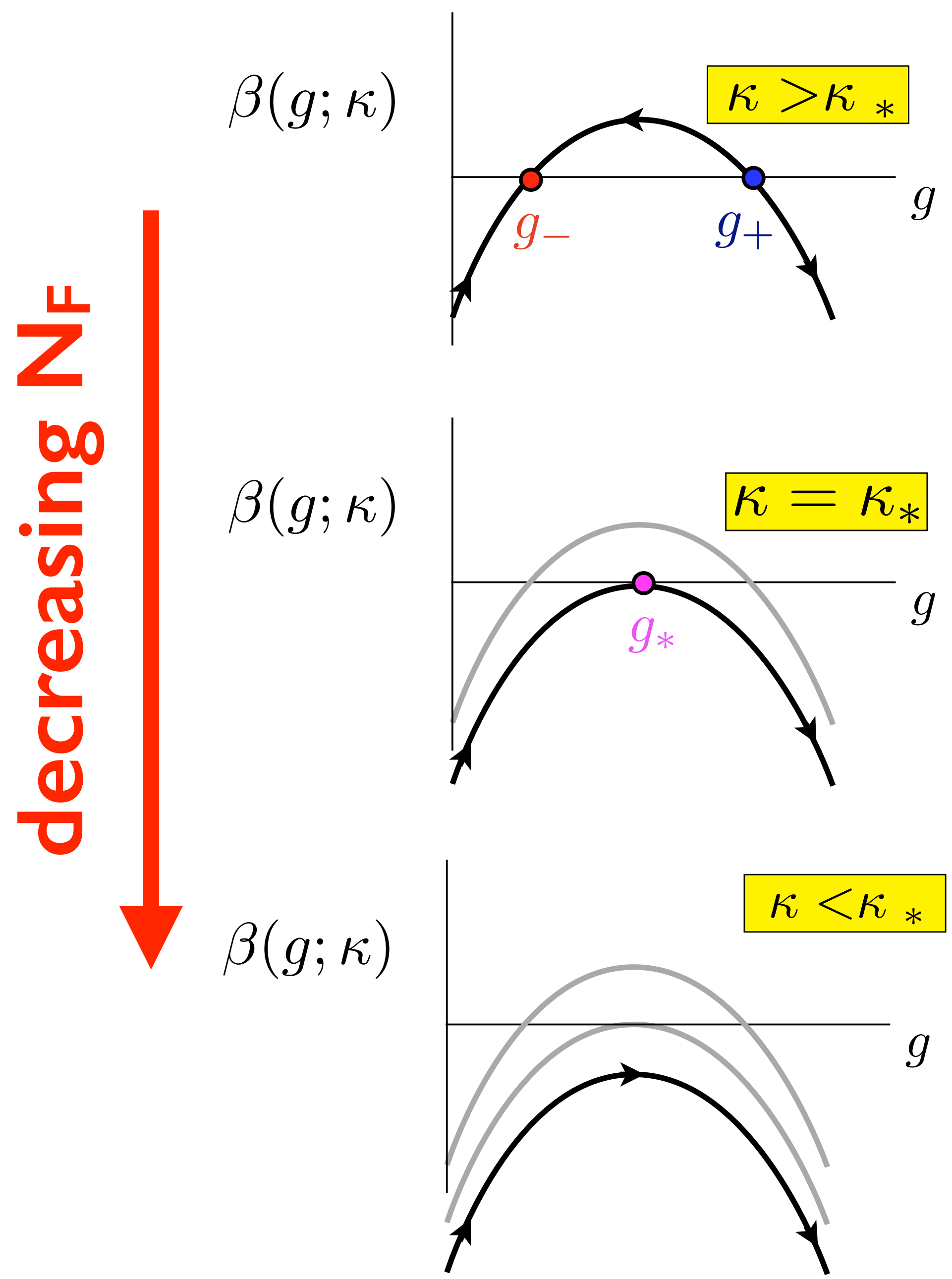
PRELIMINARY

see also previous works:

Kutasov,Lin,Parnachev 11,
Elander, Piai 11, Jarvinen,Kiritsis 11, …

Conformal breaking as N_F decreases

How the fixed point could disappear?



Lee,Son,Stephanov,Kaplan
arXiv:0905.4752

IR & UV fixed-point annihilation

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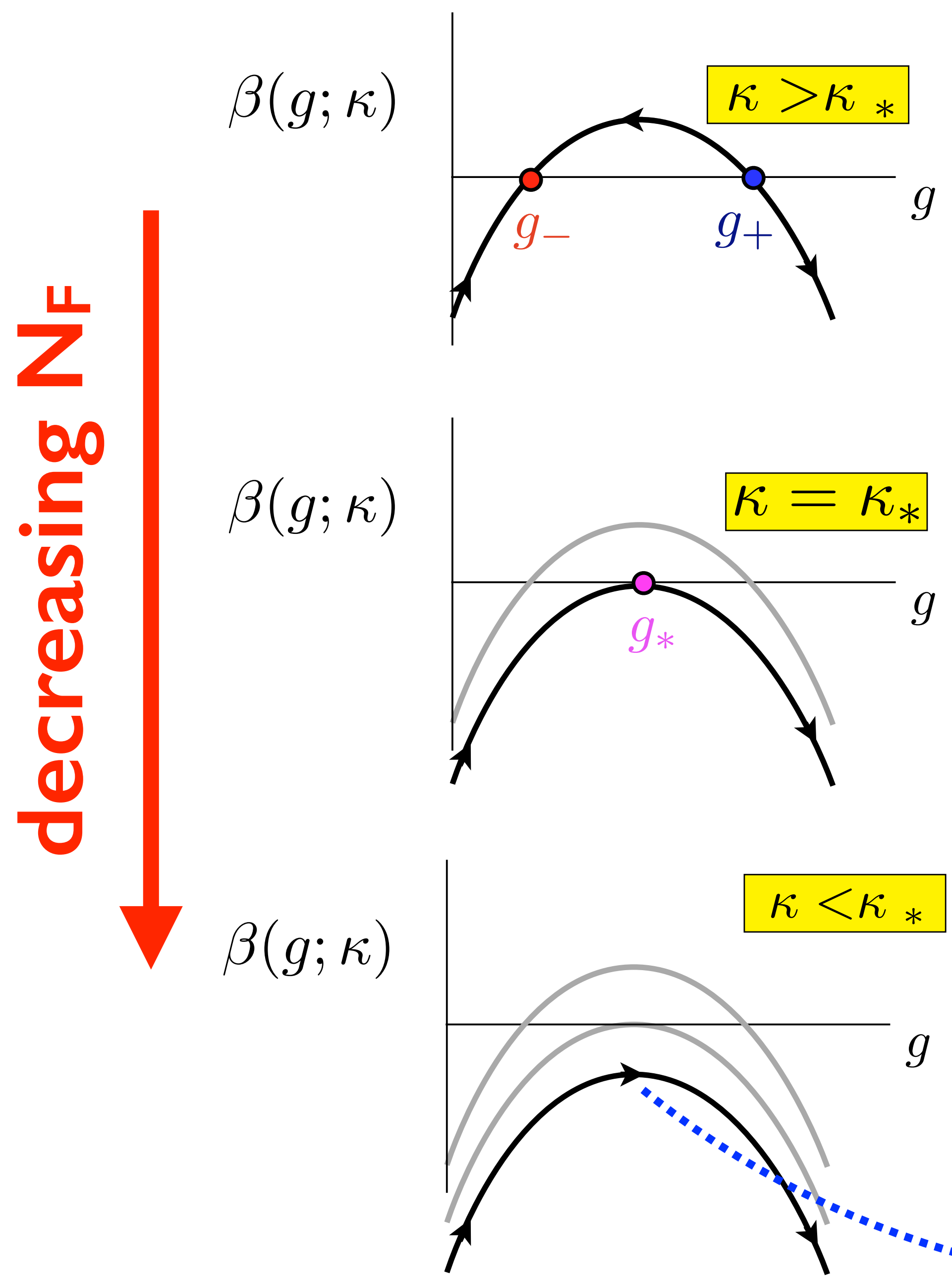


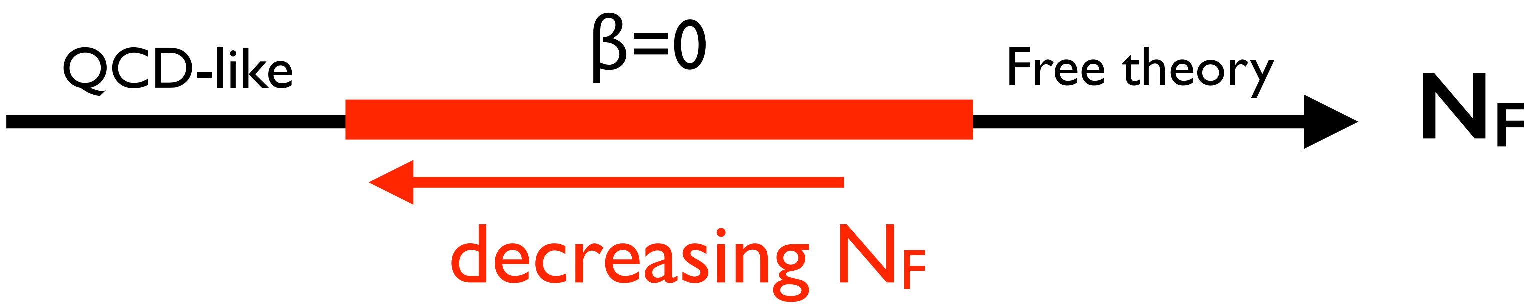
IR & UV fixed-point annihilation

Fixed point in the imaginary plane:

$$g_* = \pm i\epsilon$$

Operator with *imaginary* dimension!

Conformal breaking as N_F decreases



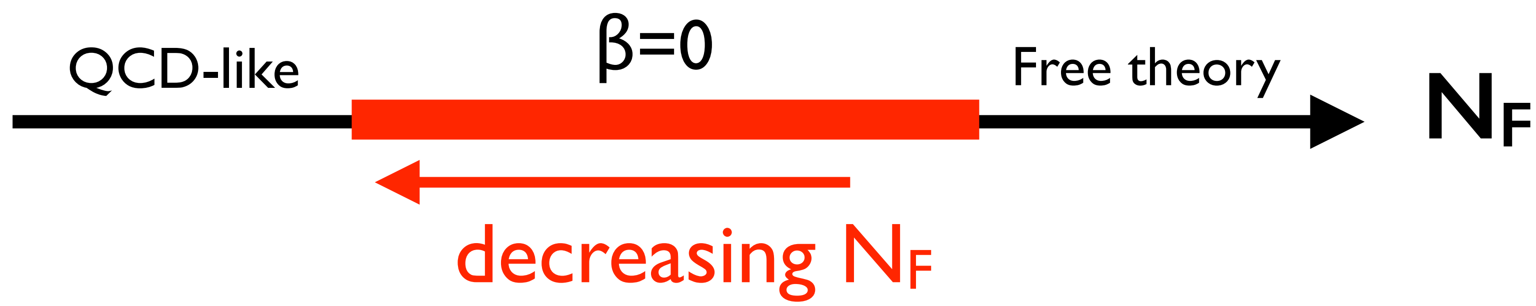
Using AdS/CFT:

DICTIONARY

$CFT_4 \longrightarrow AdS_5$

Strongly-coupled → Weakly-coupled

Conformal breaking as N_F decreases



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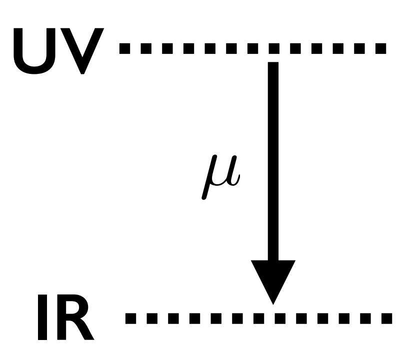
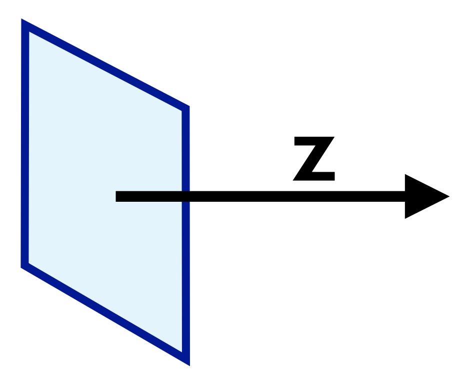
$$\mathrm{RG-scale}\ (\mu) \longrightarrow \mathrm{extra\ dim}\ (\mathrm{z})$$





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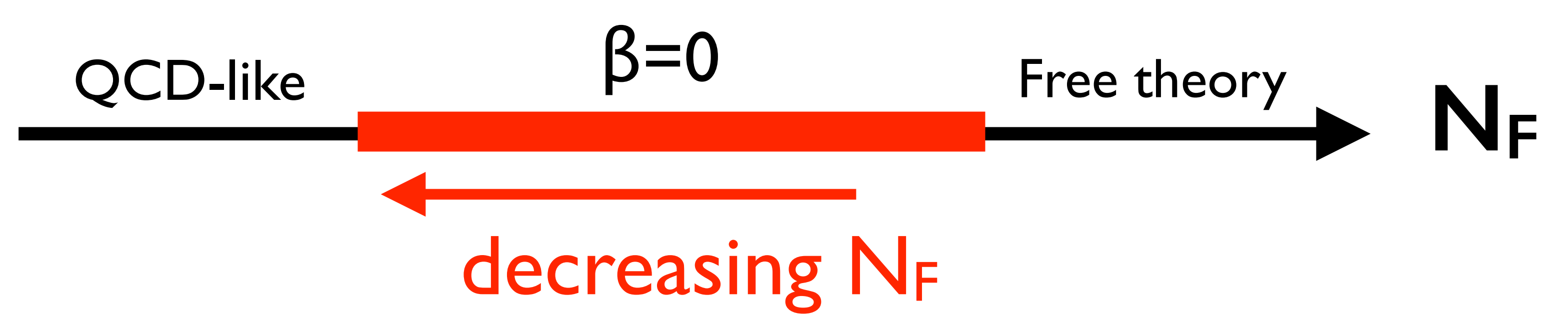

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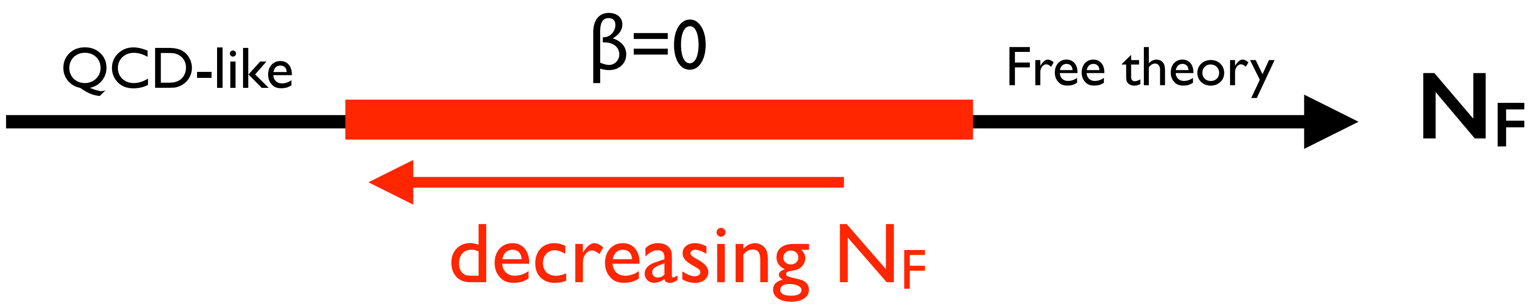

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$$\bar{q}q \longrightarrow \Phi$$

$$\mathrm{Dim}[\bar{q}q] \longrightarrow M_\Phi^2$$

$$\mathrm{Dim}[\bar{q}q] = 2 + \sqrt{4 + M_\Phi^2 L^2}$$

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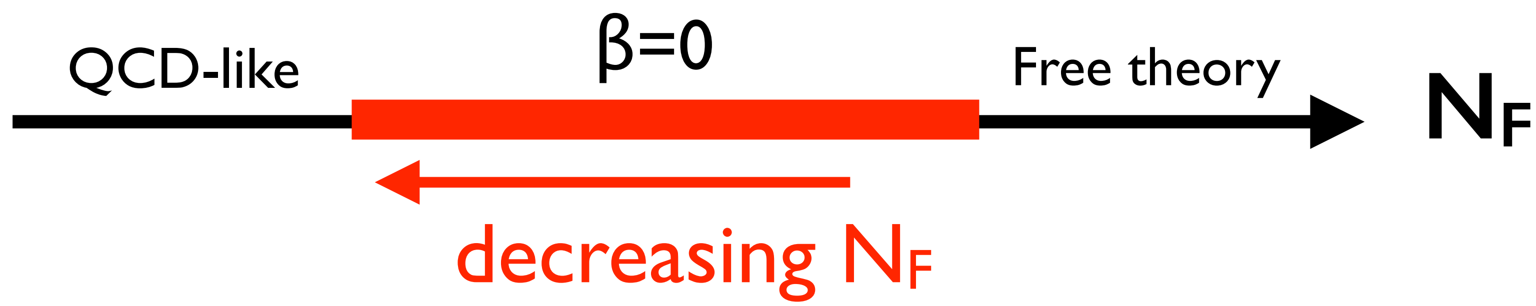

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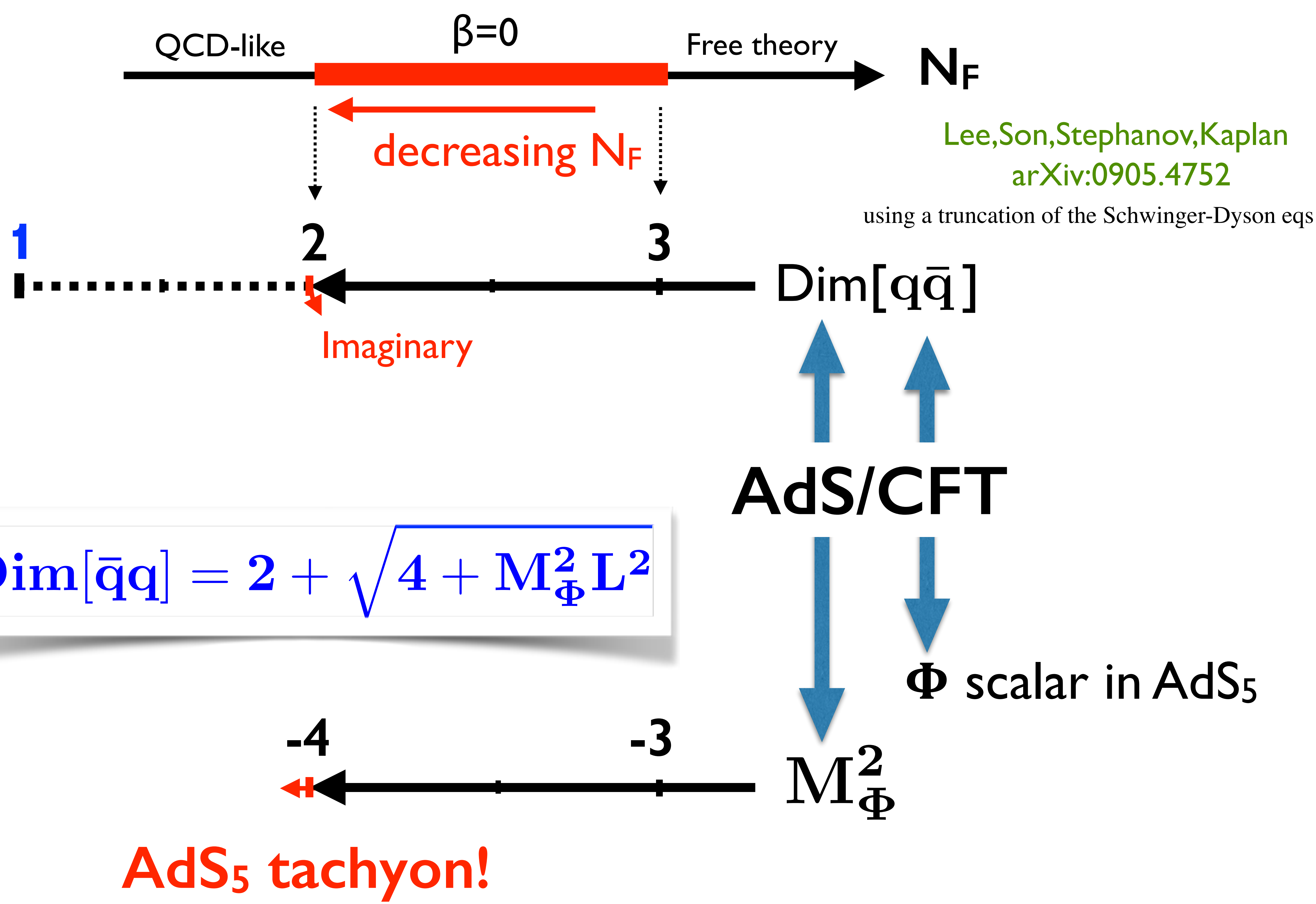
Imaginary when M_Φ goes below the BF bound ($M_\Phi^2 = -4/L^2$)

☛ **AdS tachyon!**

Conformal breaking as N_F decreases



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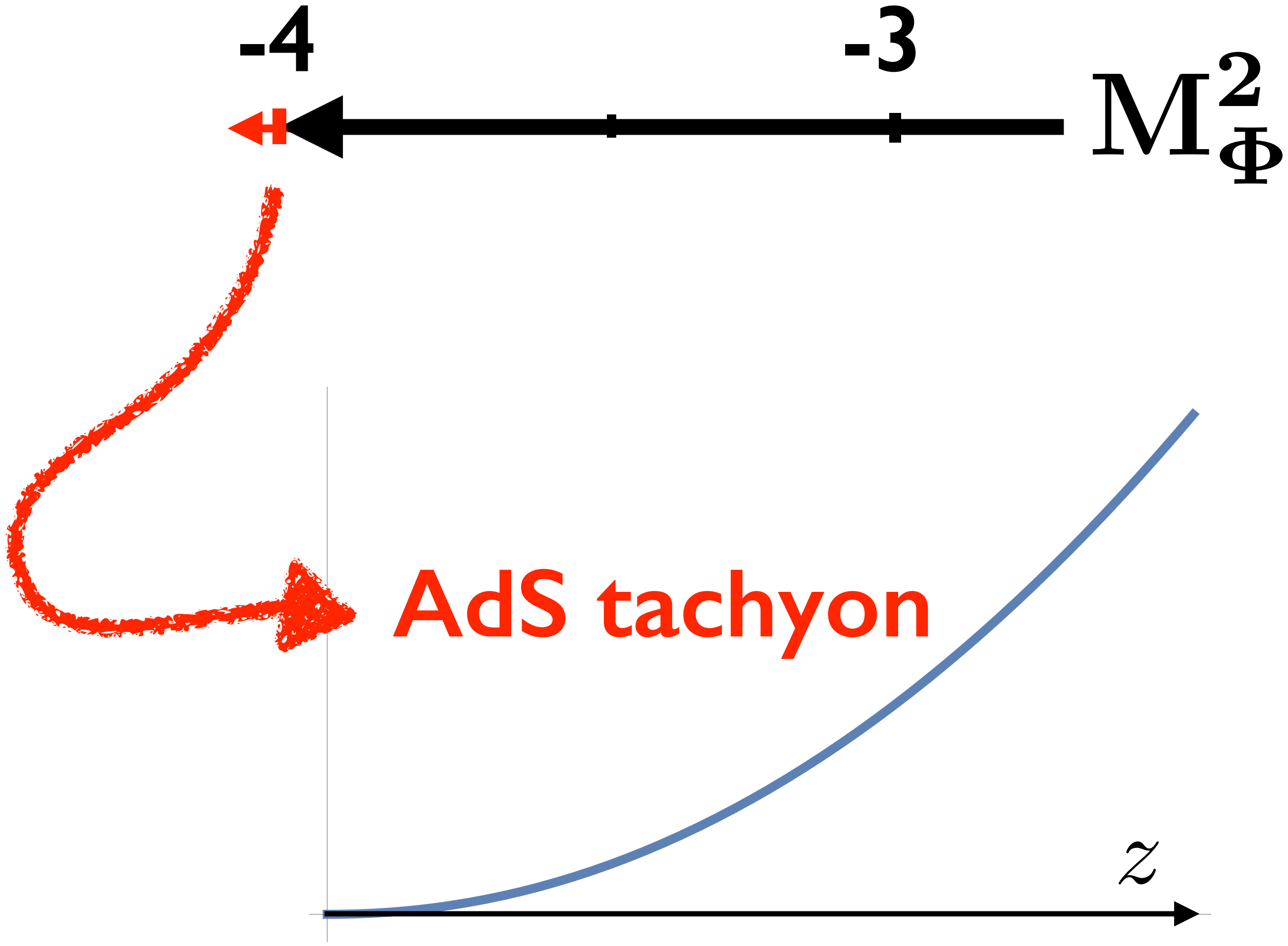
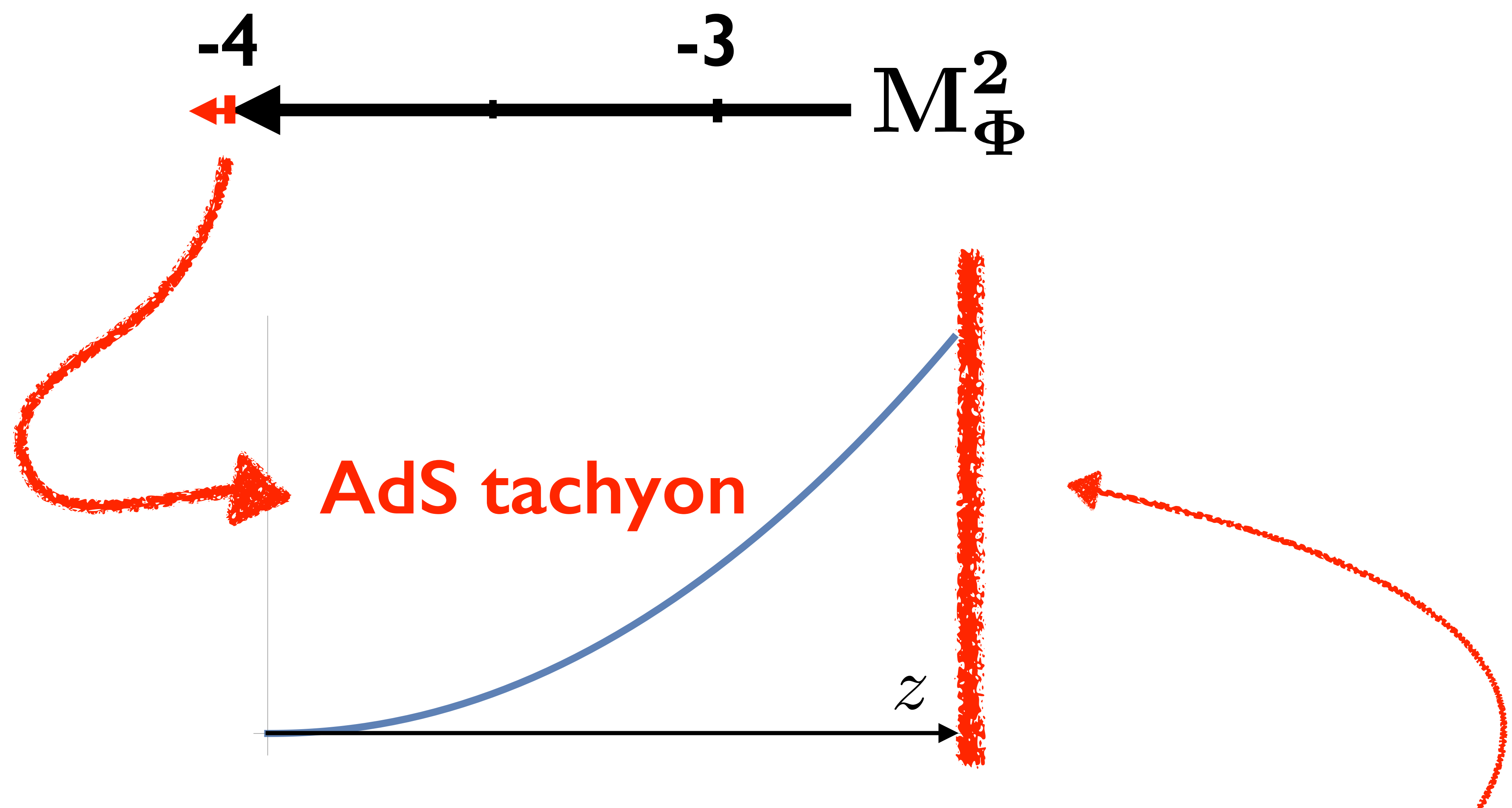
Conformal breaking in AdS$_5$ due to the mass going below the BF bound



Conformal breaking in AdS₅ due to the mass going below the BF bound



- We **regularize the IR with a brane**, and include the metric back-reaction from the tachyon:

  ☛ Necessary to understand the dilaton/radion mass

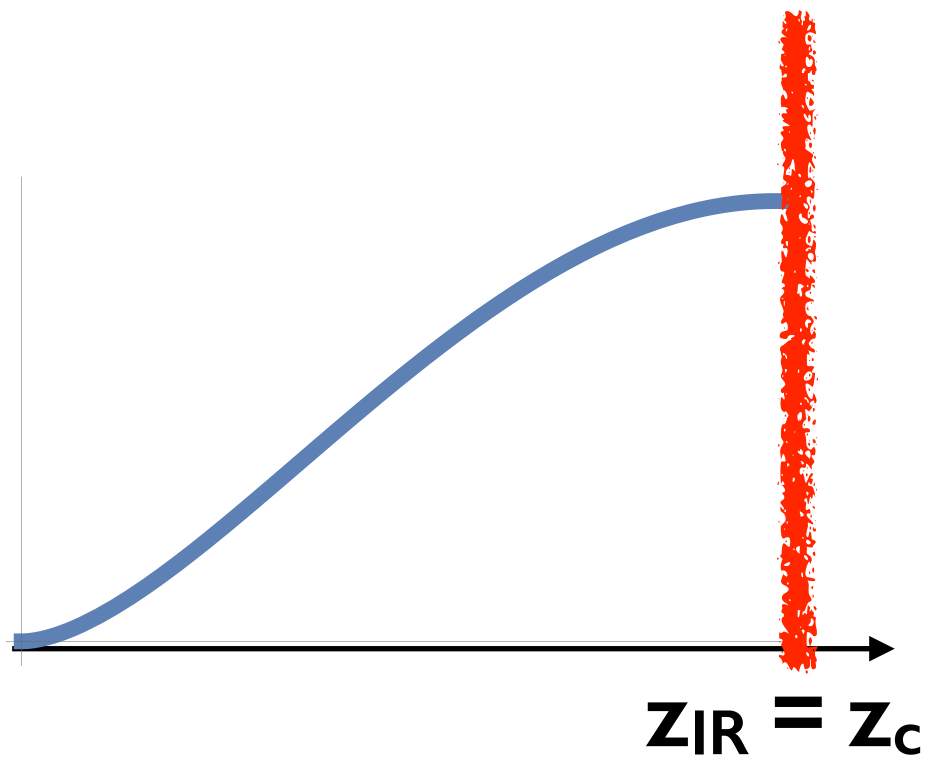
The position of the brane is dynamical: Indeed a minimum exits!

To understand better the model,

lets consider a **5D scalar** just a little bit **below the BF bound**:

$$M^2 = -4-\epsilon \quad \& \quad \epsilon \to 0$$

4D Massless mode for a critical position of the brane $z_{IR}=z_c$:



$$\phi(z) = A\, z^2 \sin\left(\sqrt{\epsilon}\ln\frac{z}{z_{\rm UV}}\right)$$

$$\sqrt{\epsilon}\ln\frac{z_c}{z_{\rm UV}} = n\pi \quad \begin{cases} n=1 & \text{ground state} \\ n=2,3,\ldots & \text{Efimov states} \end{cases}$$

(the model has a discrete scale invariance)

☛ Tachyon mode for $z_{IR}>z_c$

For $z_{IR} \simeq z_c$: *A Tale of two 4D scalars:* **tachyon & dilaton**

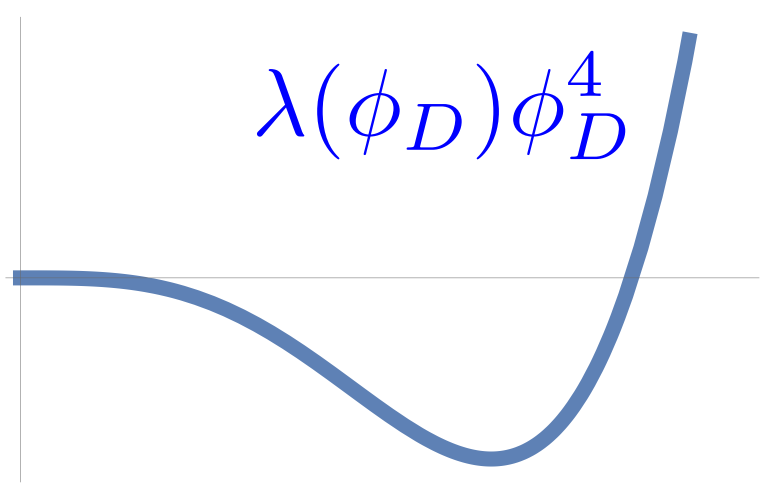
$$V_{\rm eff}(\phi) = -\frac{1}{2} m^2(\phi_D)\phi^2\phi_D^2 + \frac{1}{4}\lambda_\phi \phi^4 + \frac{1}{4}\lambda_D \phi_D^4$$

$$m^2(\phi_D) = \beta \ln \frac{\phi_D}{1/z_c}\,, \qquad \beta = \frac{4(m_b^2+2)^2}{m_b^4 + 6m_b^2 + 10}\,,$$

boundary mass

Integrating out the tachyon

☛ *Coleman-Weinberg-like* potential for the dilaton

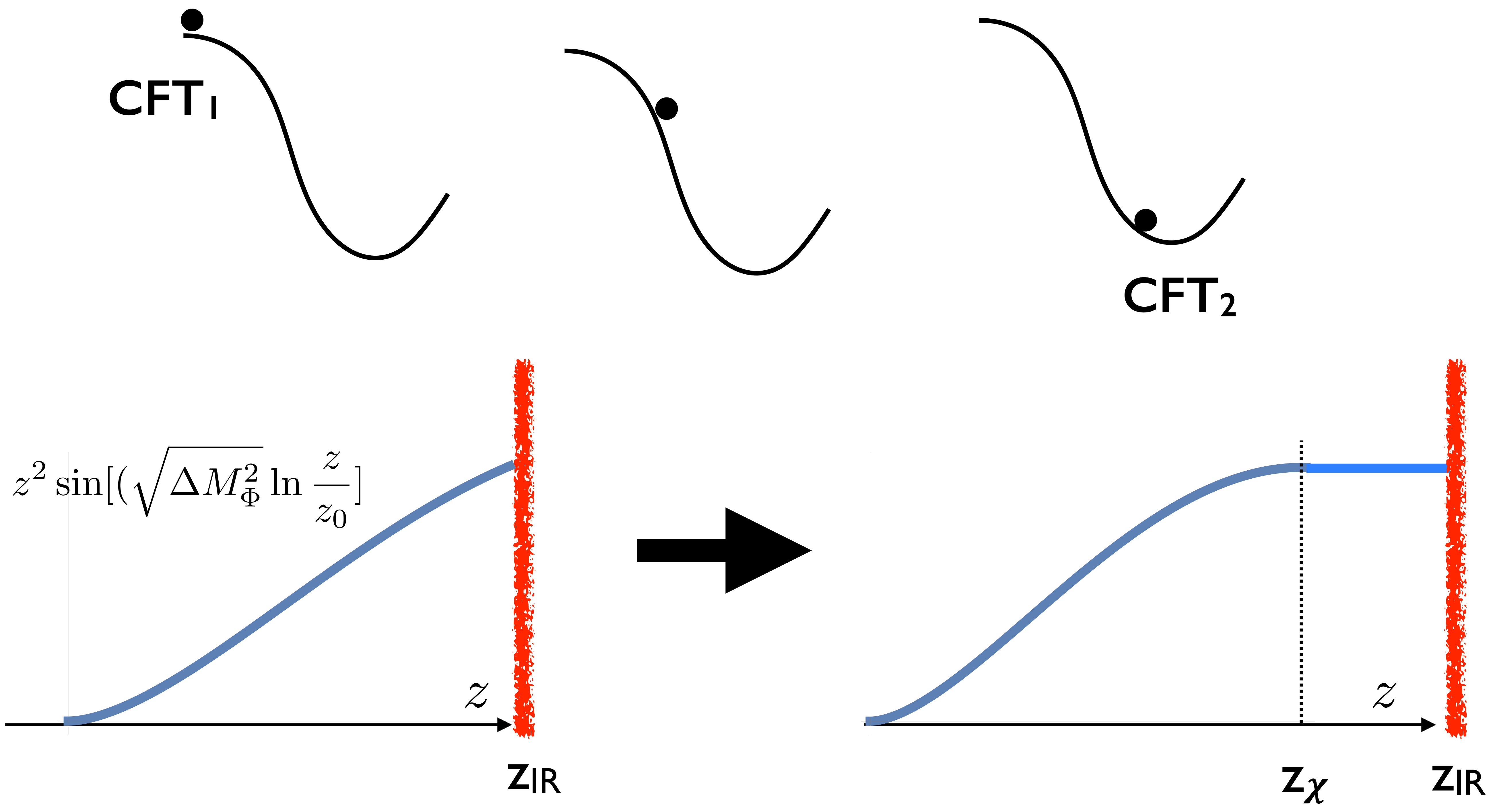


$$m^2_{\phi_D} \sim \beta < 4$$

tachyon VEV ≳ dilaton VEV

(see however arXiv:1804.00004)

For $z_{IR} \gg z_c$, we need to solve the full 5D theory:



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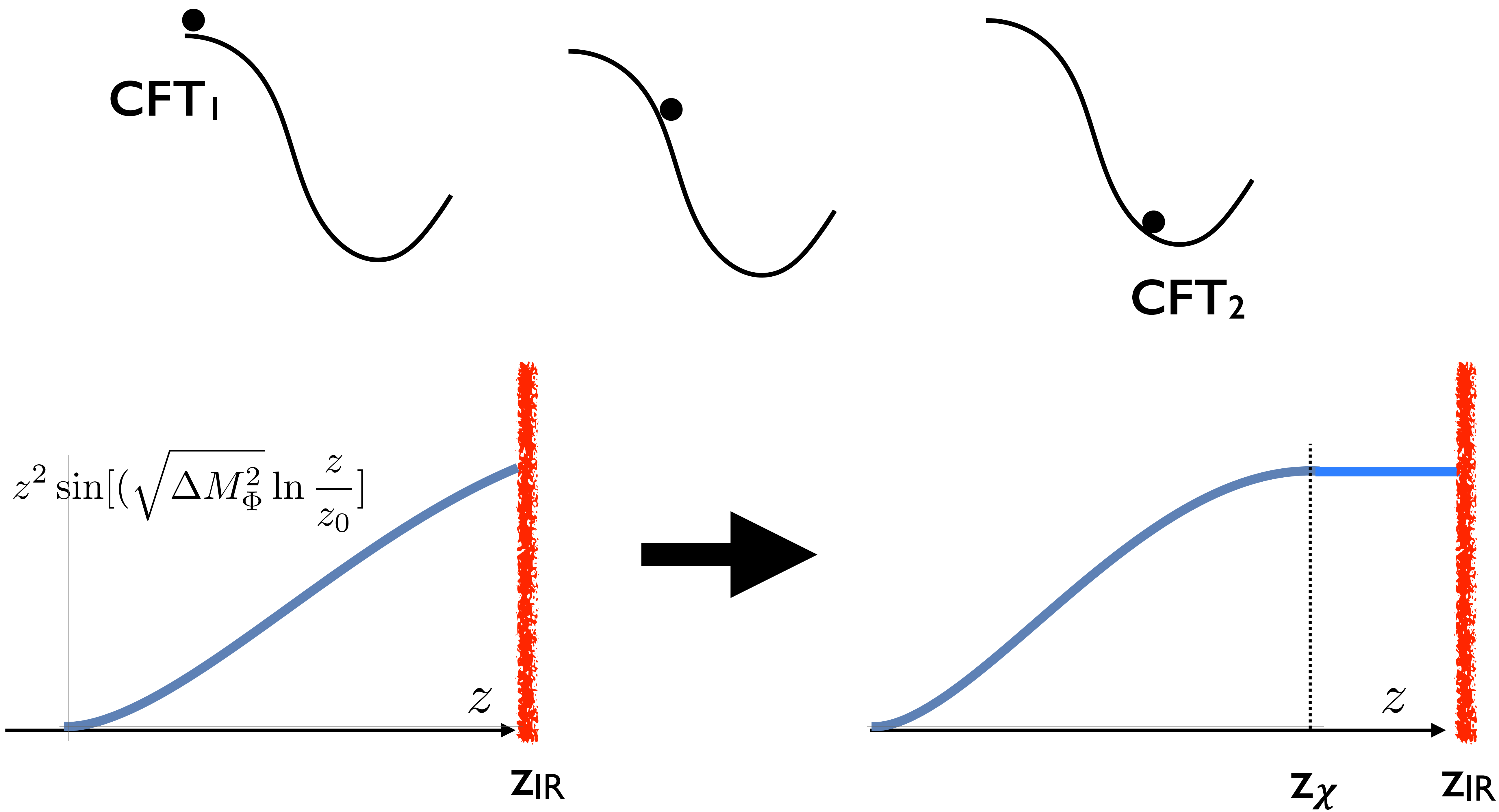
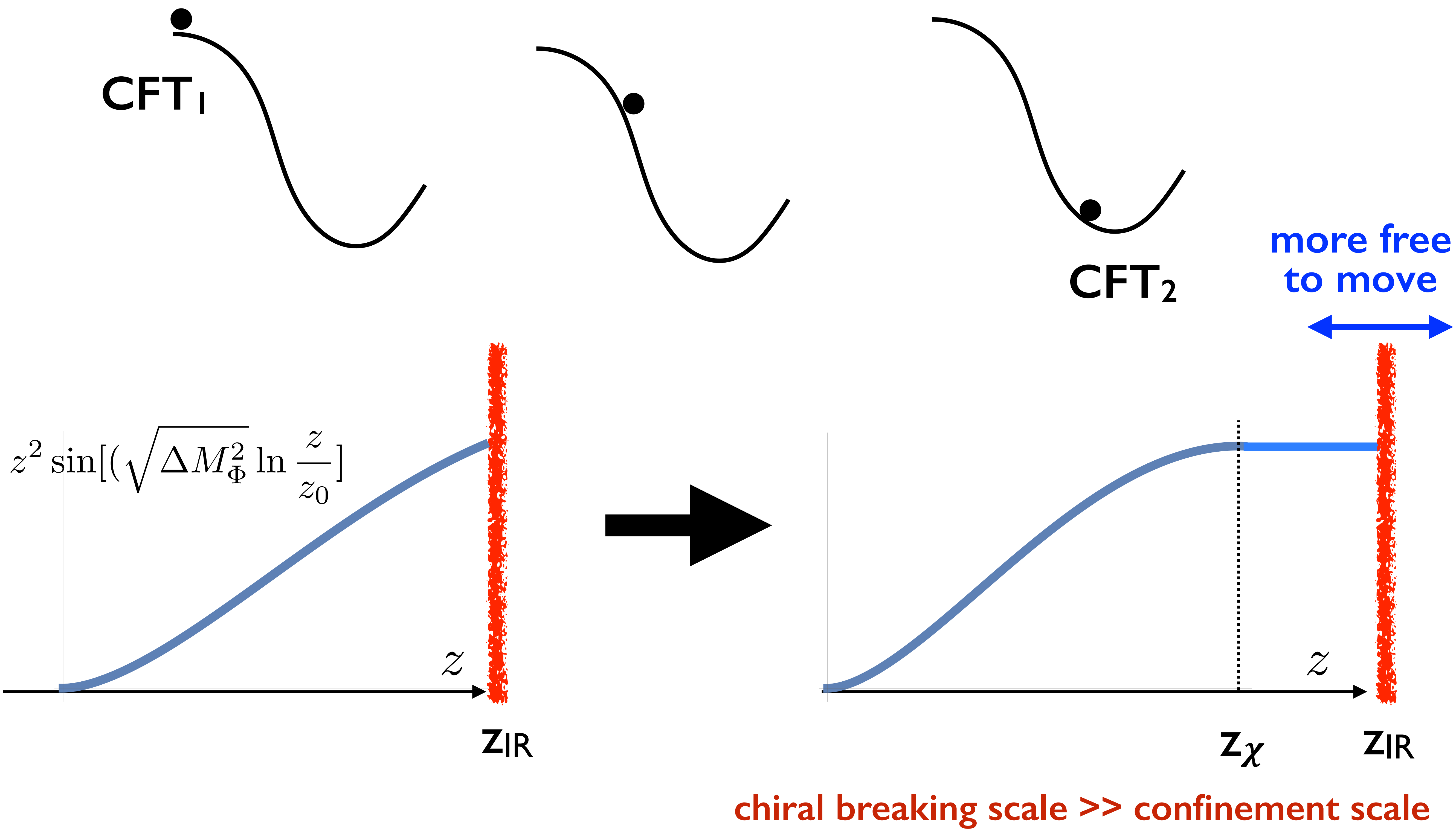


chiral breaking scale >> confinement scale

Expected minimum for $z_\chi \sim z_{IR}$ (but enough parameters to be anywhere)

For $z_{IR} \gg z_c$, we need to solve the full 5D theory:



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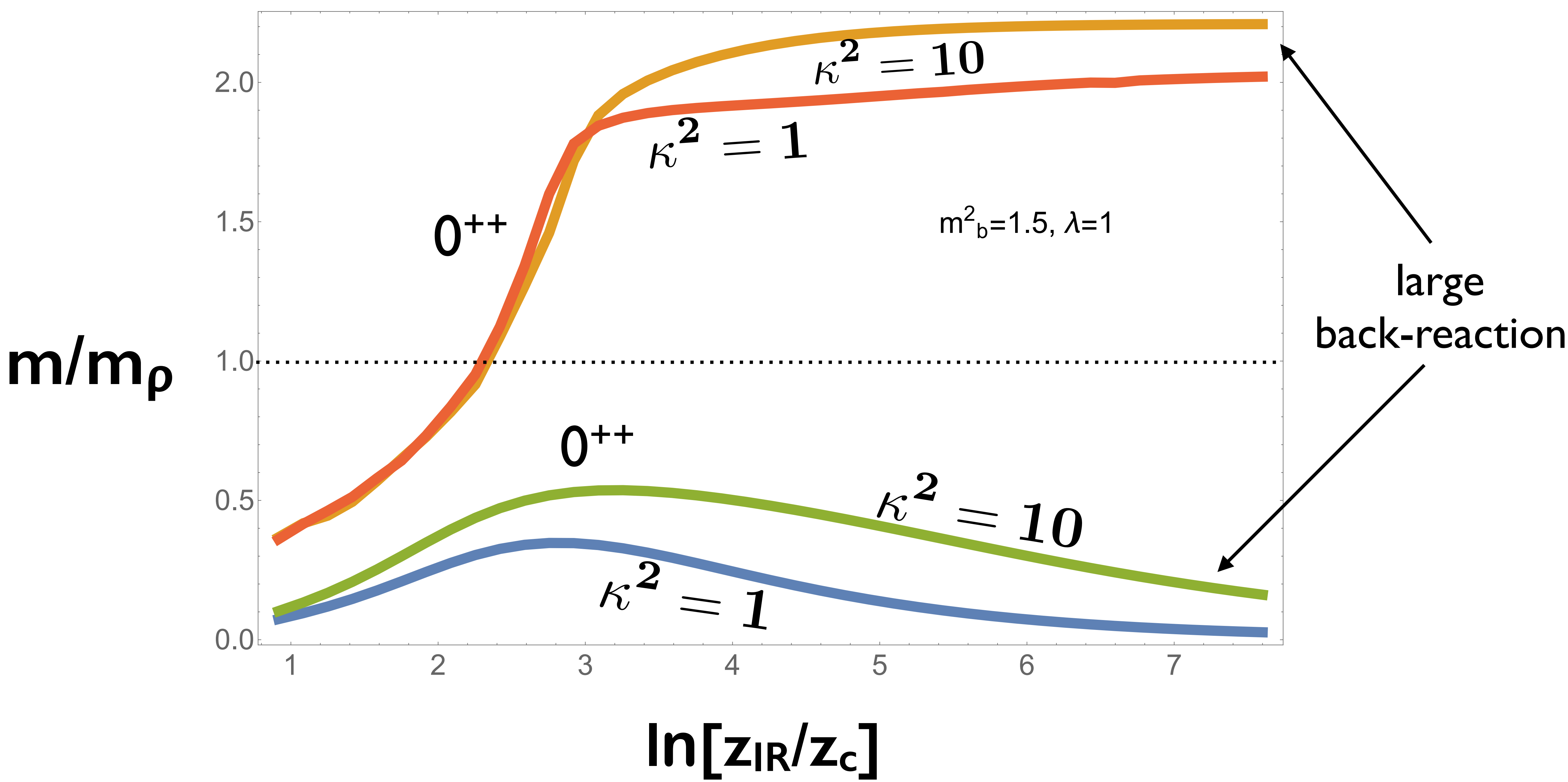
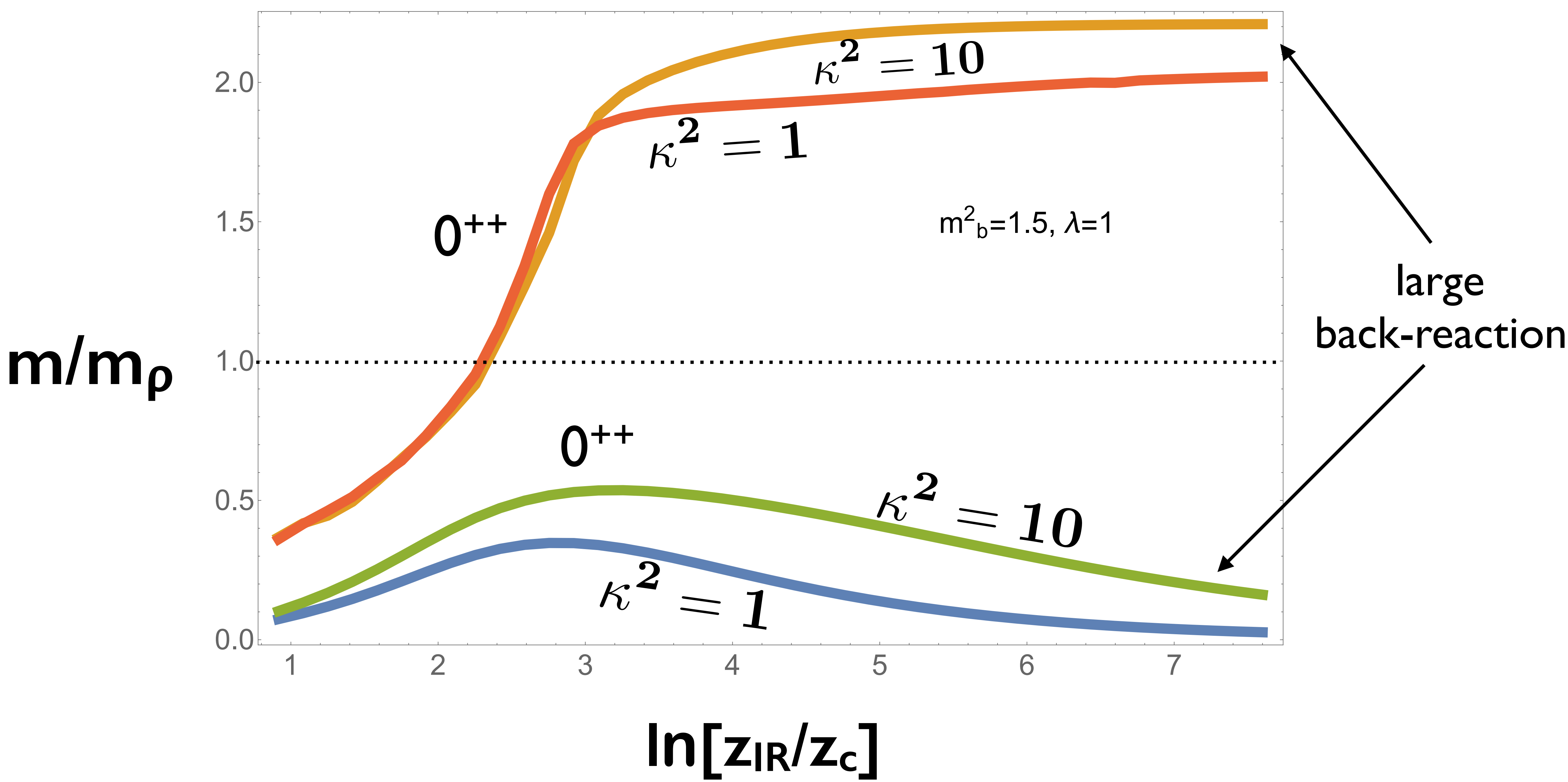
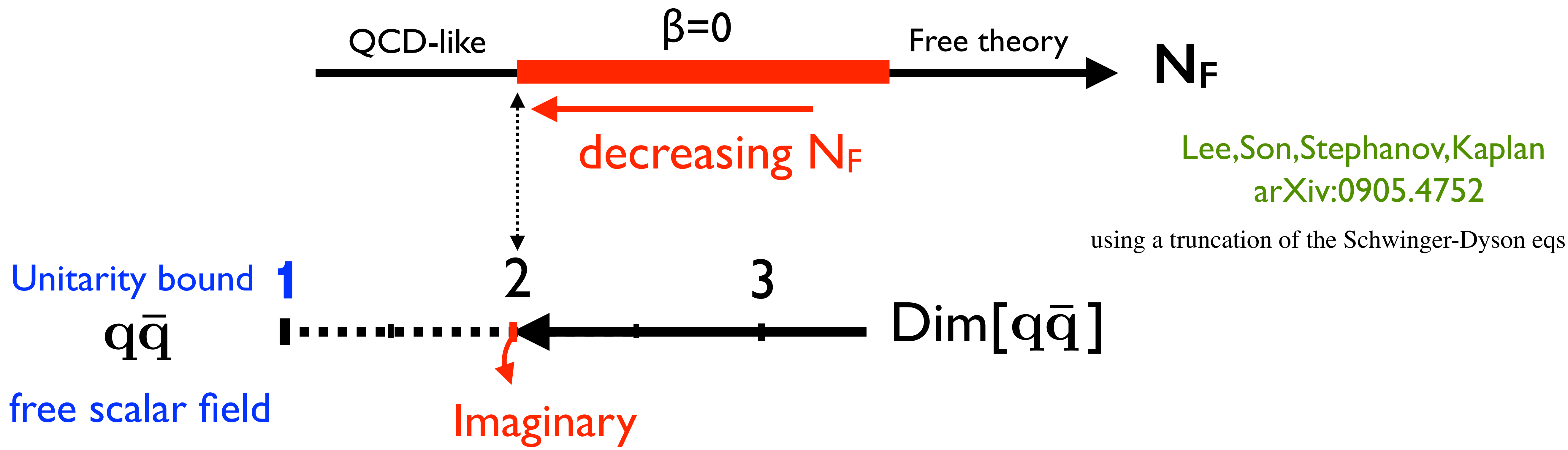


m/m$_\rho$
ln[z$_{IR}$/z$_c$]
0^{++}
$\kappa^2 = 10$
$\kappa^2 = 1$
0^{++}
$\kappa^2 = 10$
$\kappa^2 = 1$
m^2_b=1.5, λ=1
large
back-reaction
0.0
0.5
1.0
1.5
2.0
1
2
3
4
5
6
7

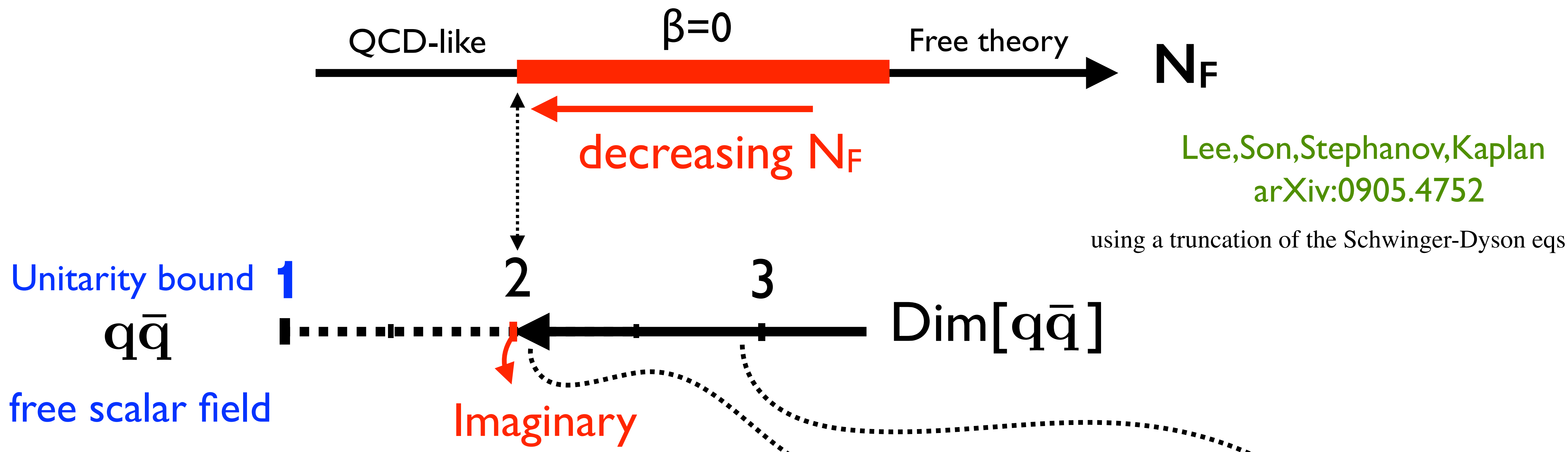


☛ **Always a light scalar (mostly dilaton) !**

As N_F decreases, $q\bar{q}$ approaches the free scalar limit

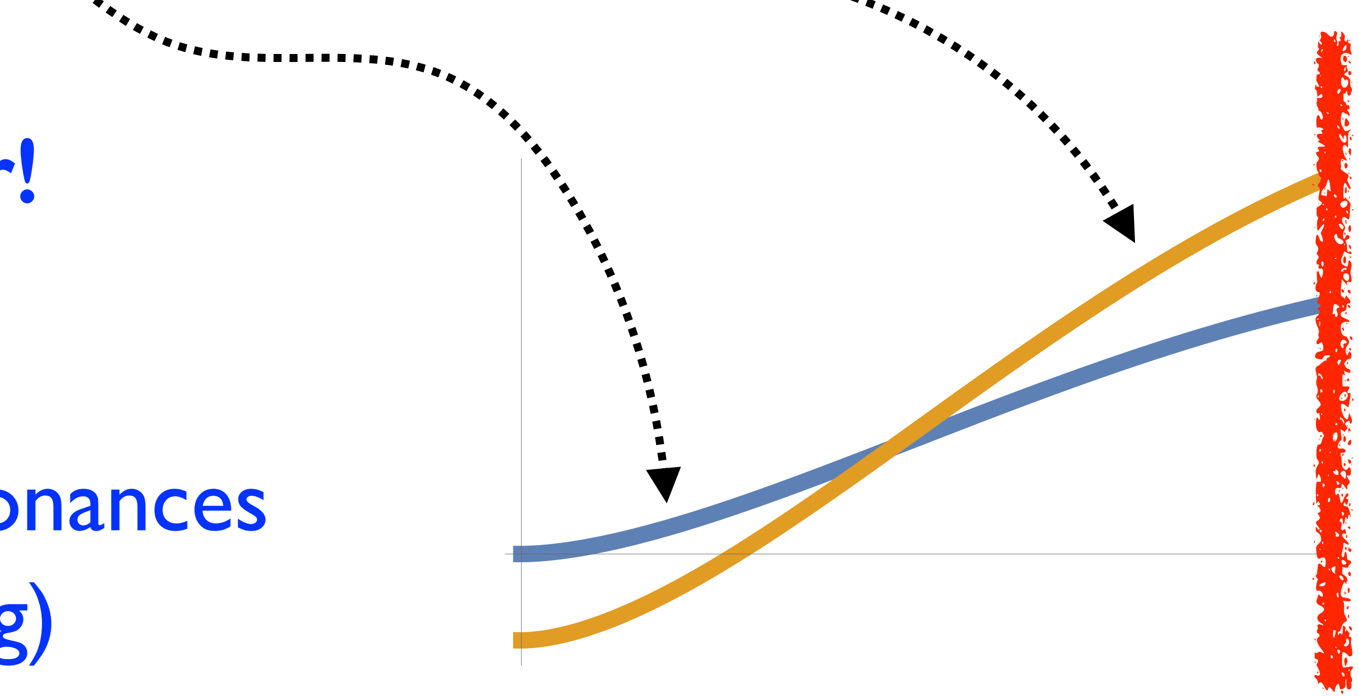


As N_F decreases, $q\bar{q}$ approaches the free scalar limit



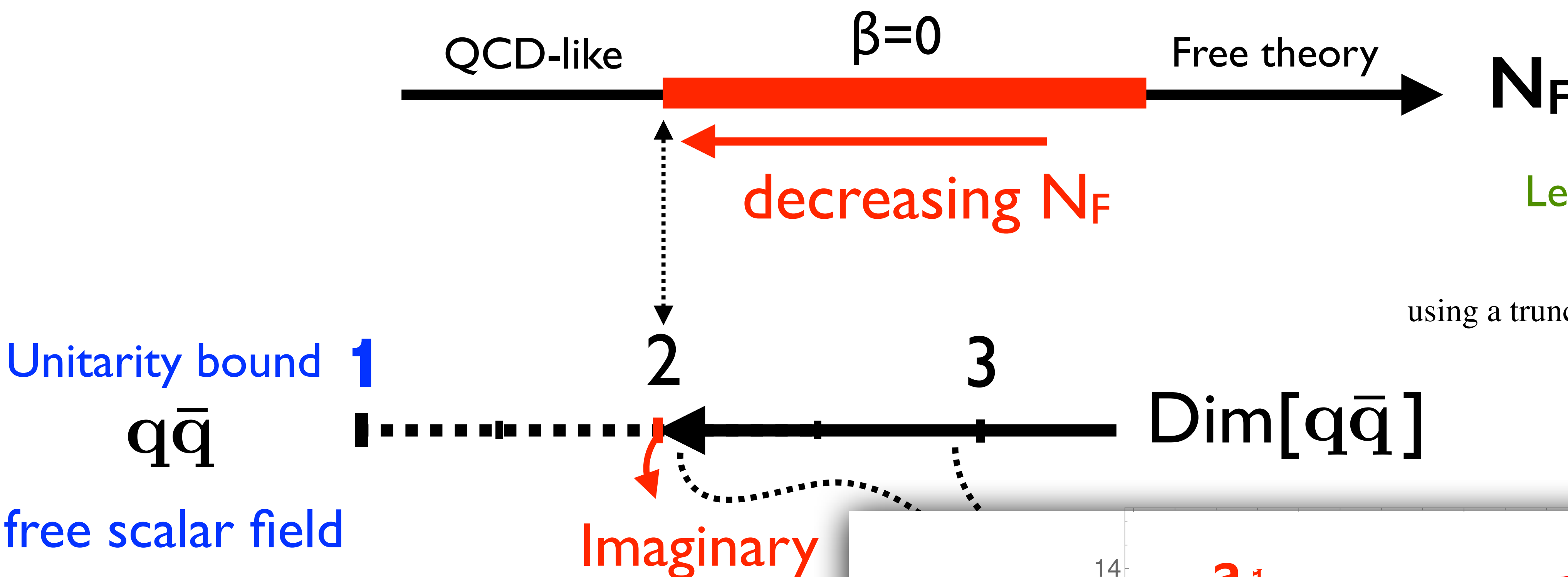
Closest point to a free scalar!

☛ Smaller contribution
to the mass splitting of resonances
(from chiral breaking)



Geometrical interpretation

As N_F decreases, $q\bar{q}$ approaches the <u>free scalar limit</u>



Lee,Son,Stephanov,Kaplan
arXiv:0905.4752

using a truncation of the Schwinger-Dyson eqs.

Closest point to a free sca

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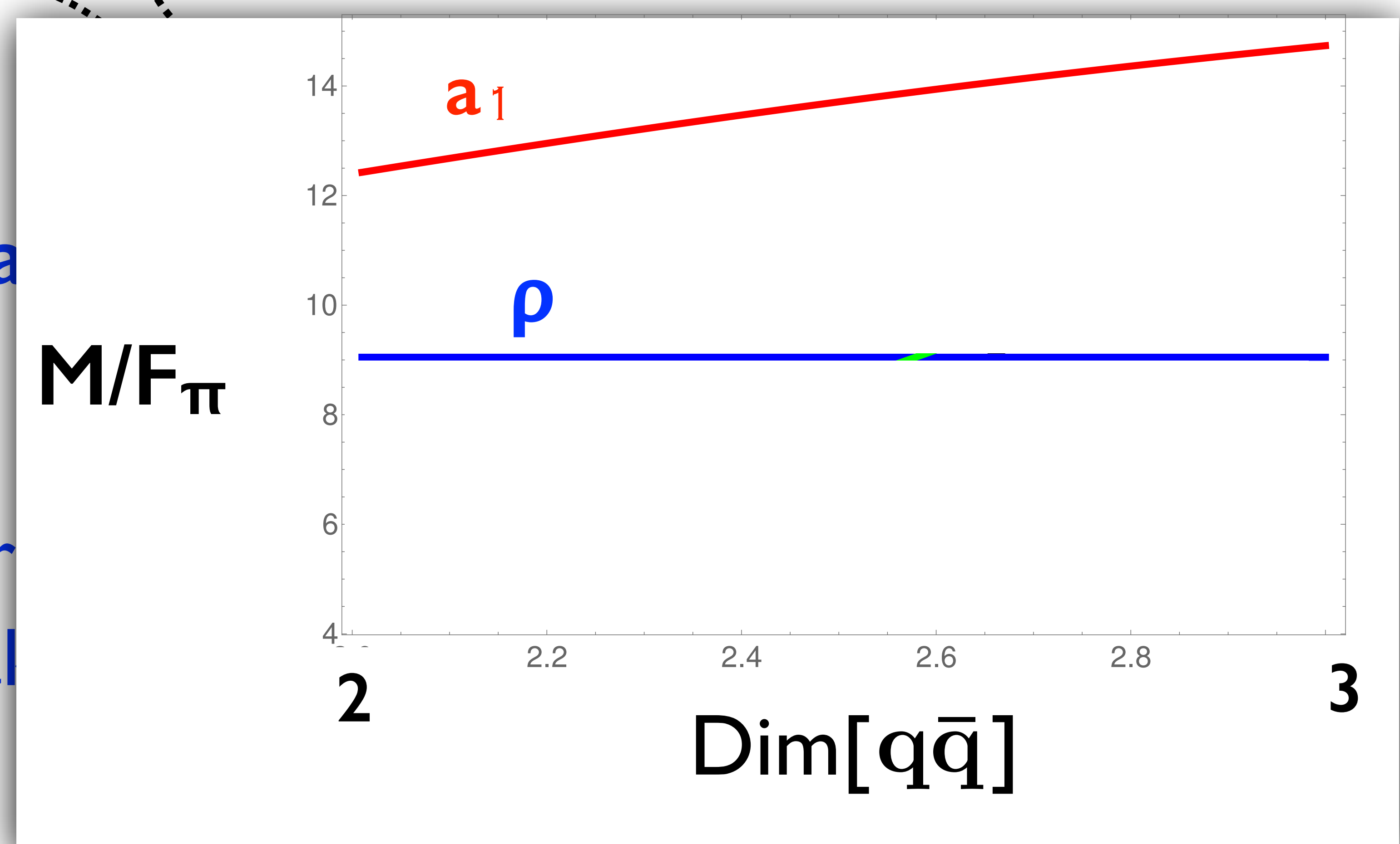
(from chiral breal



More AdS_5 predictions

Splitting Adj & singlet in the scalar sector:

$$\mathbf{m_{f_0} \ll m_{a_0}}$$

but no splitting Adj & singlet in the spin-1 sector:

$$\mathbf{m_\rho \simeq m_\omega \quad \& \quad m_{a_1} \simeq m_{f_1}}$$

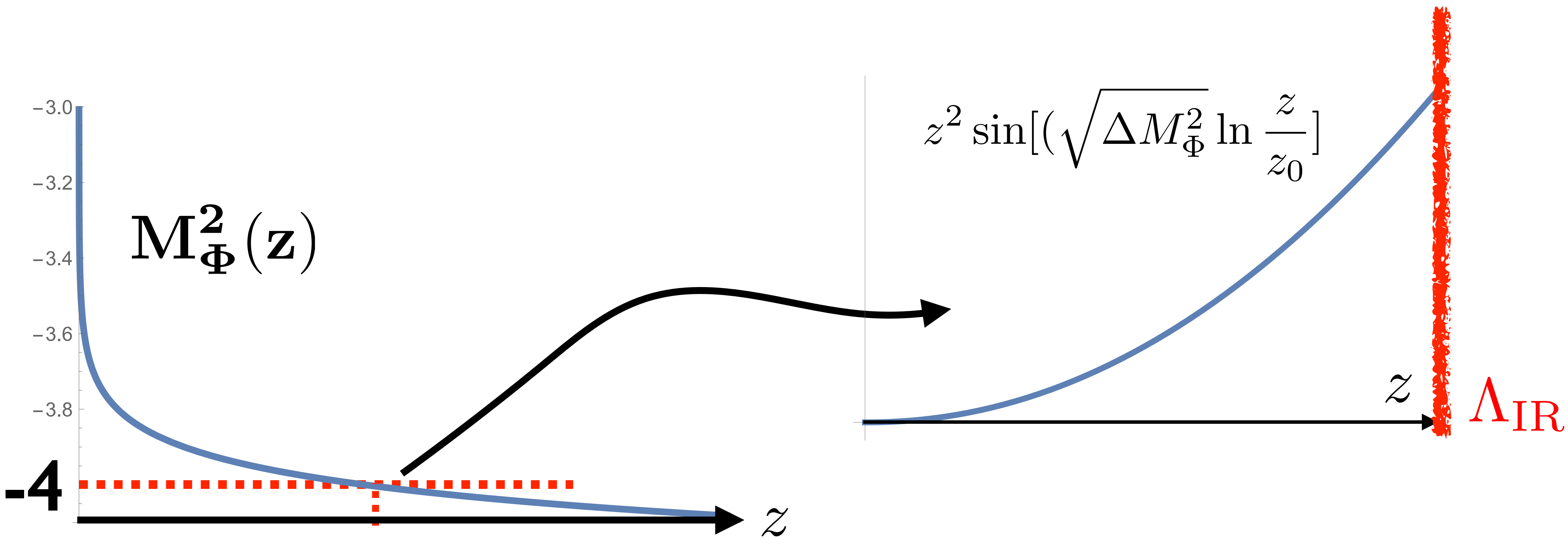
↳ Since no 5D double trace operators for vectors, but possible for scalars!

Use for the hierarchy problem?

If somebody still cares…

Use for the hierarchy problem?

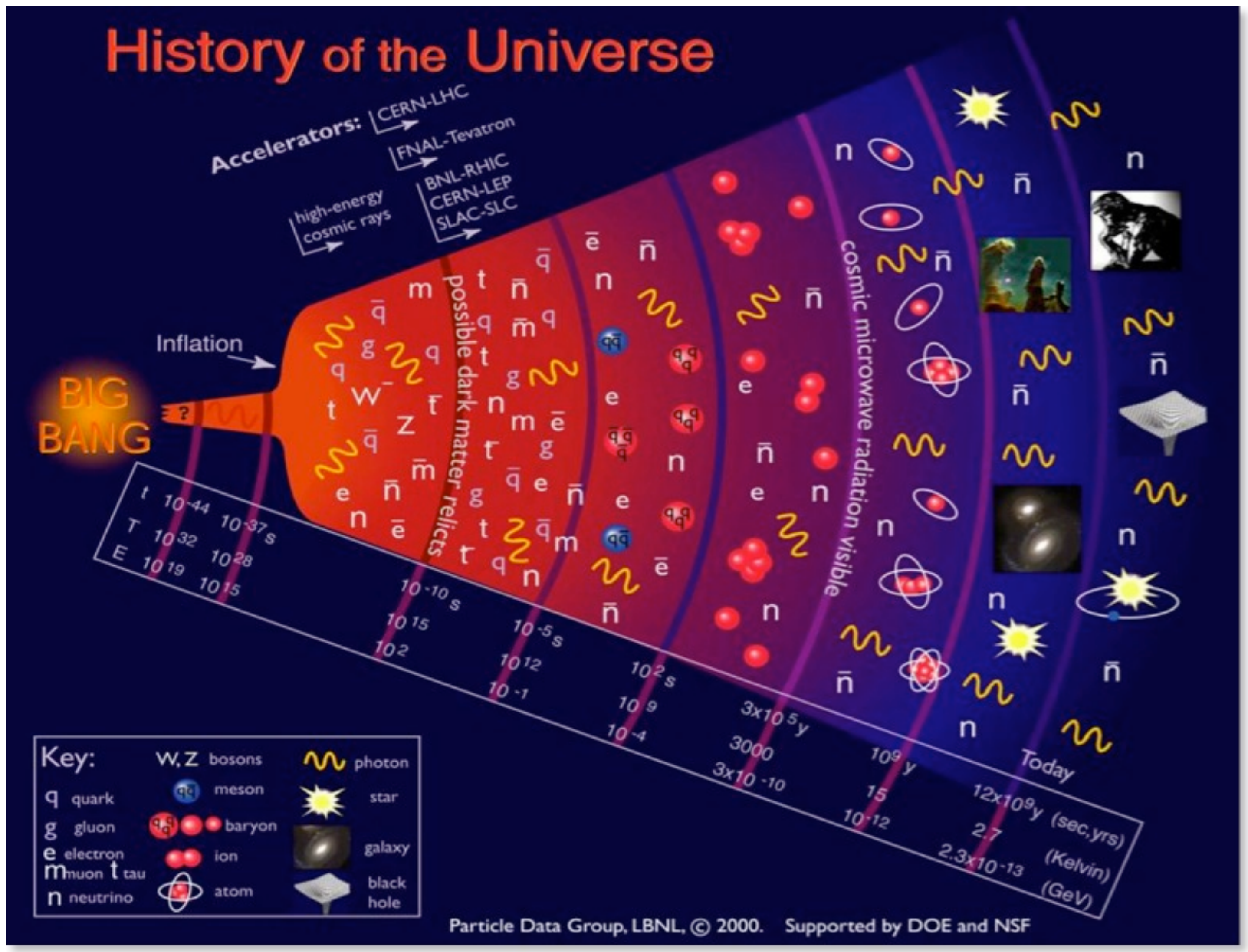
Tachyon in AdS puts you out from a CFT



$M_\Phi{}^2$ slowly evolves towards -4

e.g. from a *Relaxion* in AdS

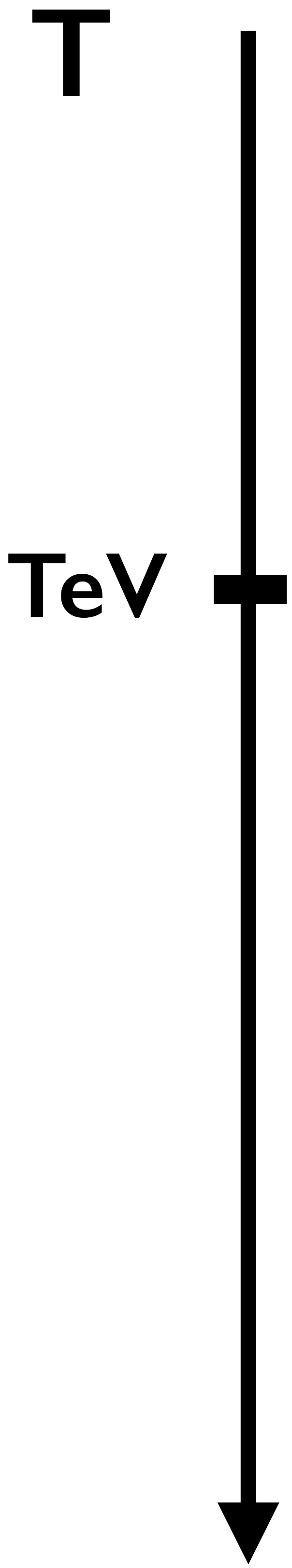
Implications in the cosmological history



preliminary work with P.Baratella and F. Rompineve

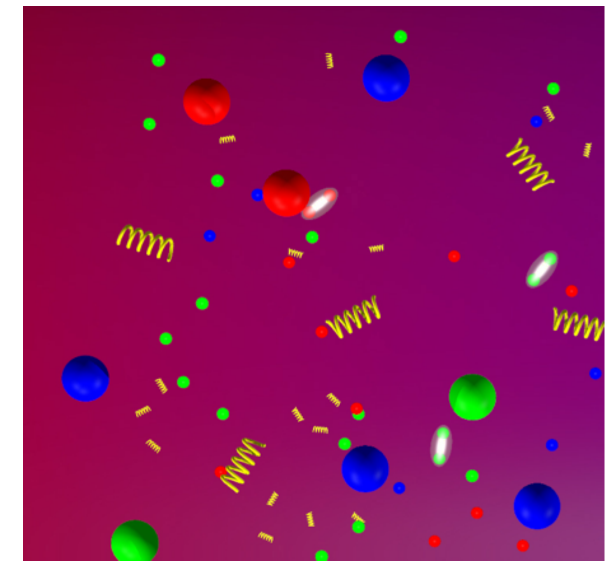
***see also G. Servant's talk** (or 1711.11554 & 1407.0030)*

After inflation, reheating, …, big bang



QCD & new TeV strong-sector
in the **deconfined** phase

"quark-gluon" plasma



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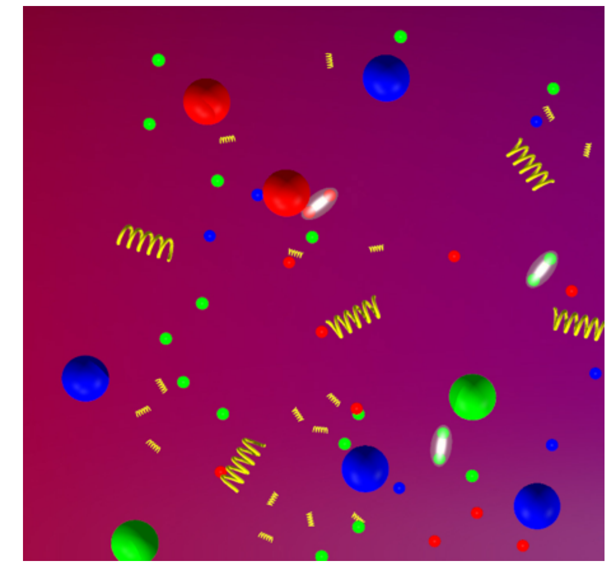

TeV

Confined phase of the new strong sector **?**

After inflation, reheating, …, big bang

T

QCD & new TeV strong-sector
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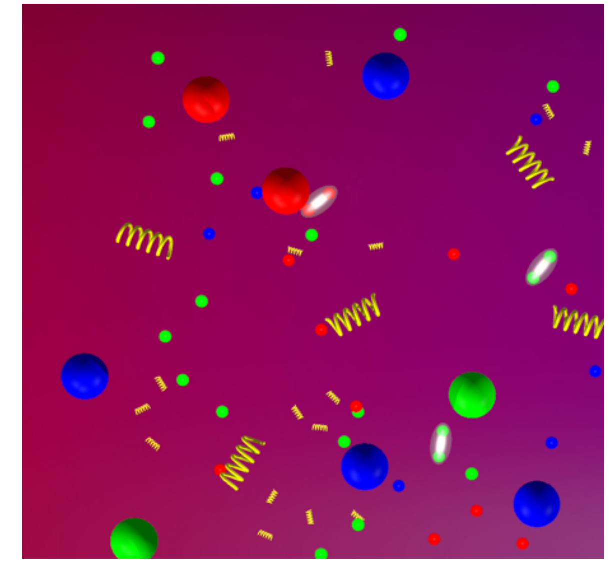
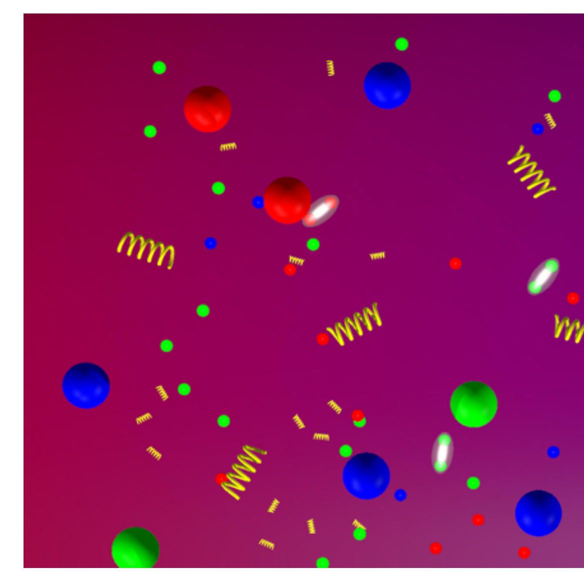


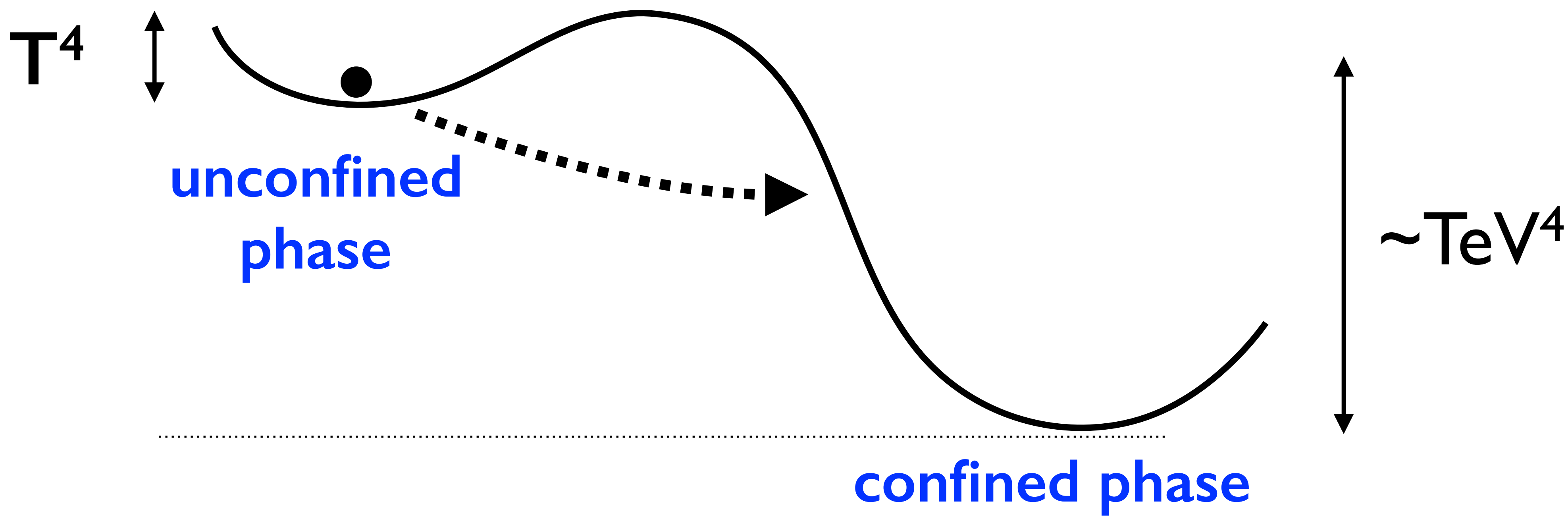
TeV

Confined phase of the new strong sector ?

No, for large N_c theories

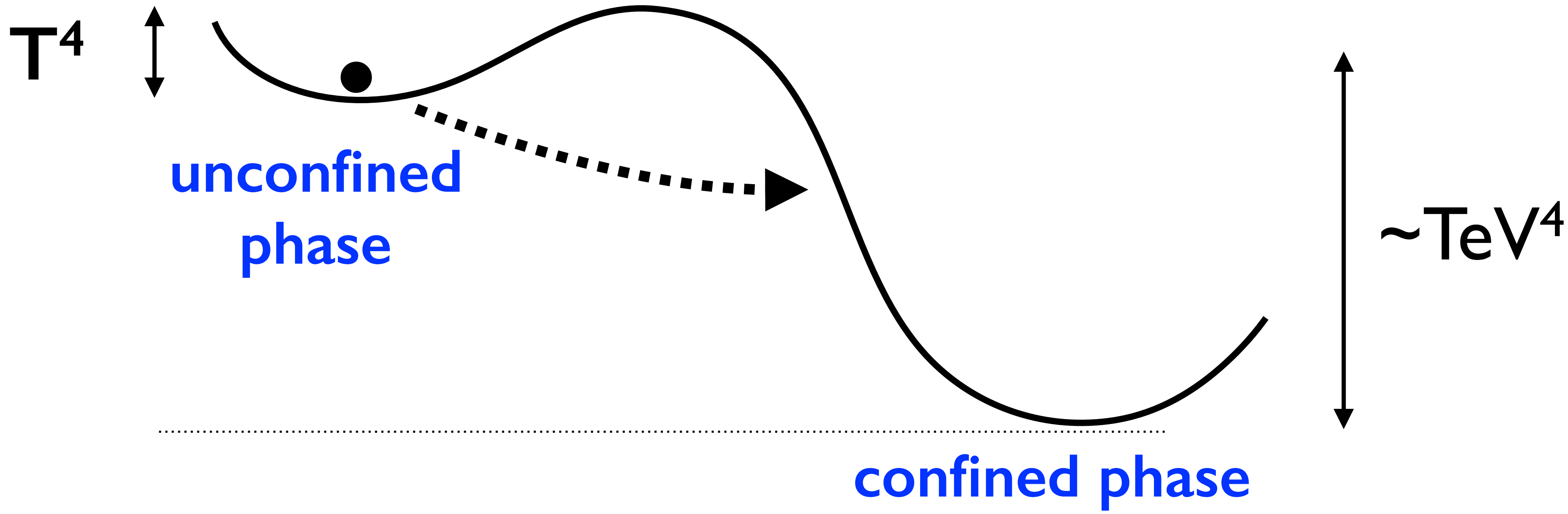
Supercooling





Tunneling rate:

$$\Gamma \sim e^{-S_E} \sim e^{-1/g_*^2} \sim e^{-N_c^2}$$



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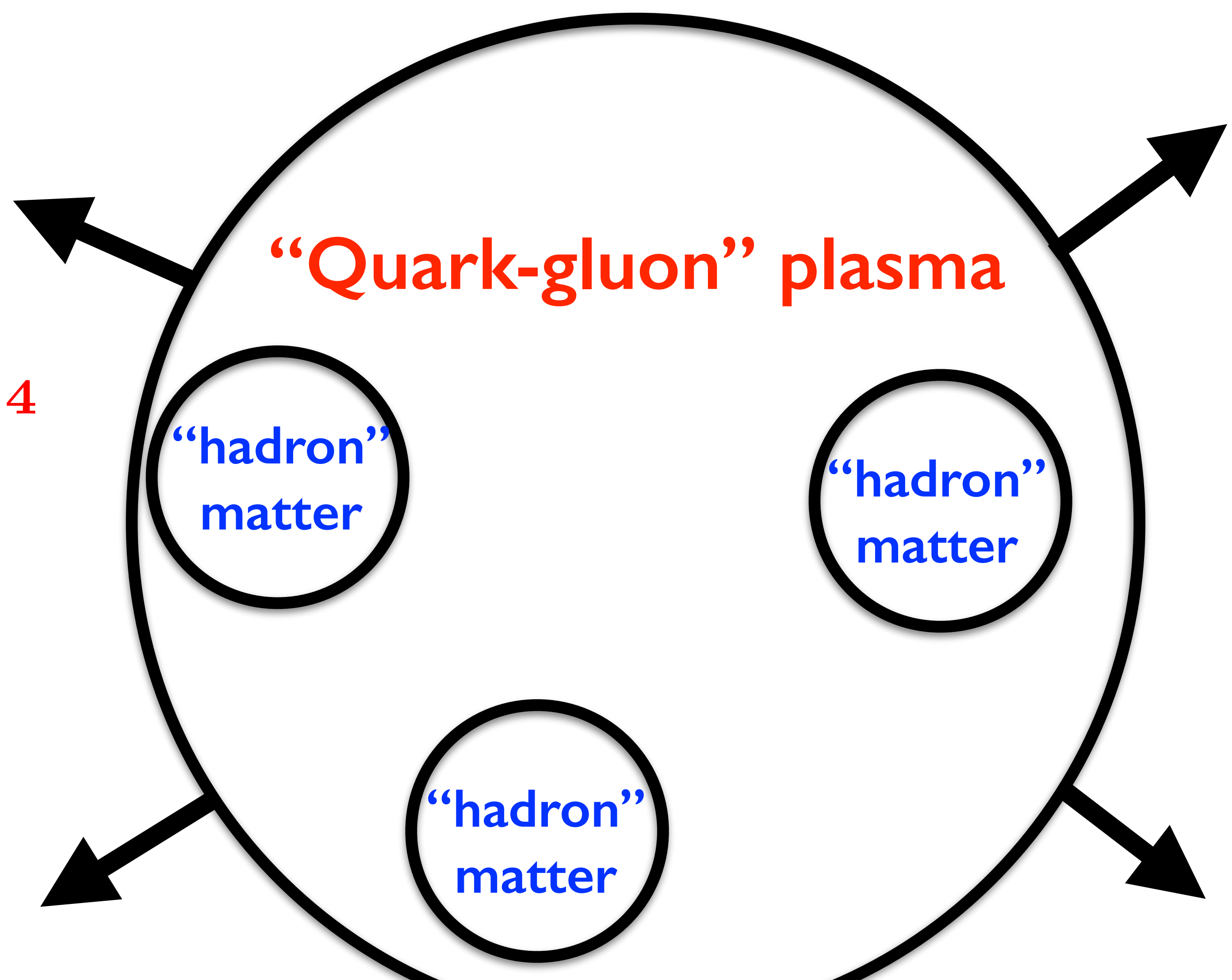


$$\Gamma \ll H^4 \sim \left(\frac{TeV^2}{M_P}\right)^4$$

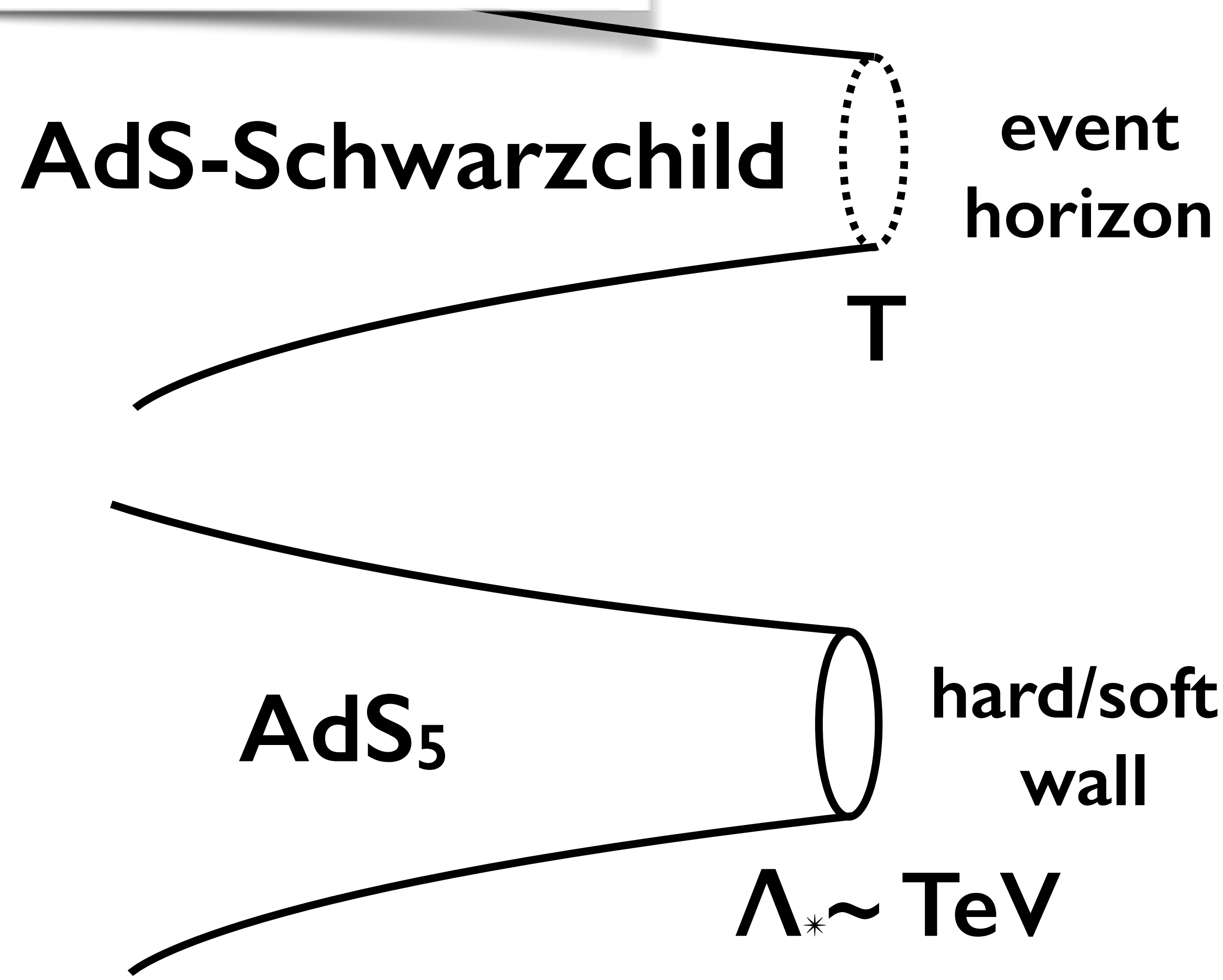
No percolation!

From holography: At finite-T, two solutions:

DeConfined phase:

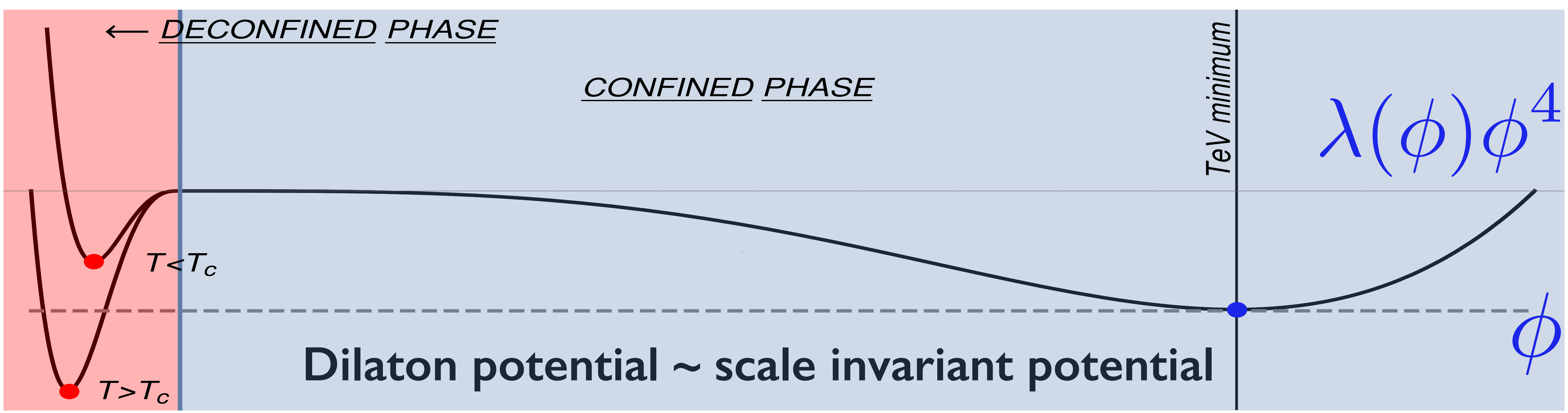
Hawking-Page transition

Confined phase:

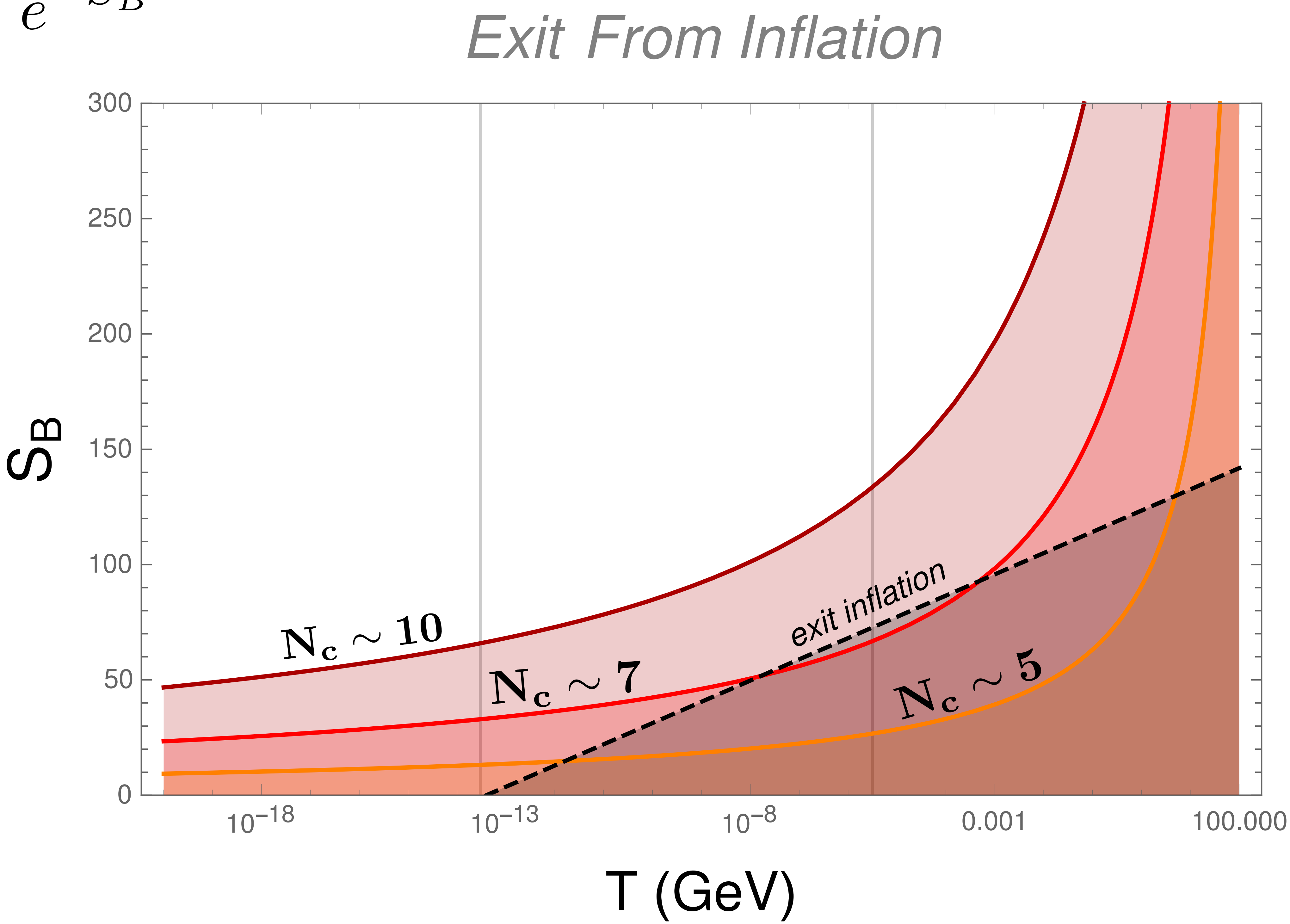


Creminelli etal, hep-th 0107141

Tunneling path: moving the BH horizon to infinity & bringing back the hard/soft wall:



$$\Gamma_{tunnel} \sim e^{-S_B}$$



We never exit inflation, unless $N_c \lesssim 7$!

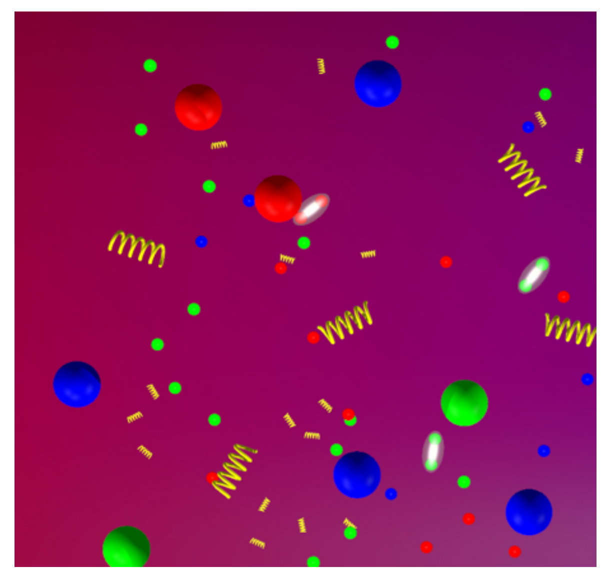
After inflation, reheating, …, big bang

T

QCD & new strong sector
in the **deconfined** phase

"quark-gluon" plasma

TeV



GeV

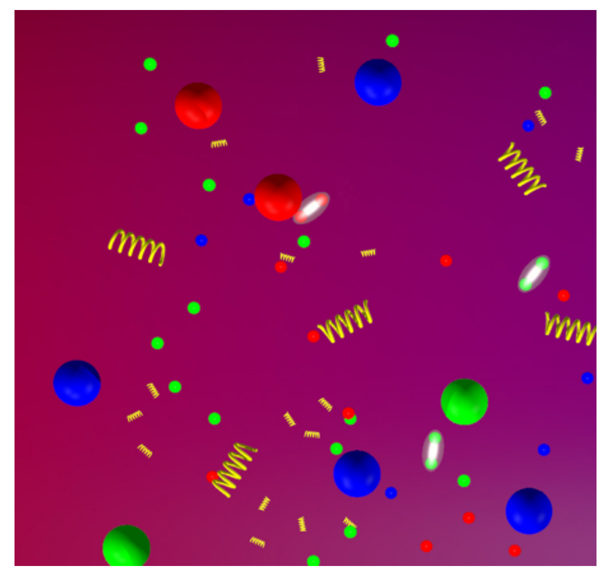
After inflation, reheating, …, big bang

T

QCD & new strong sector
in the **deconfined** phase

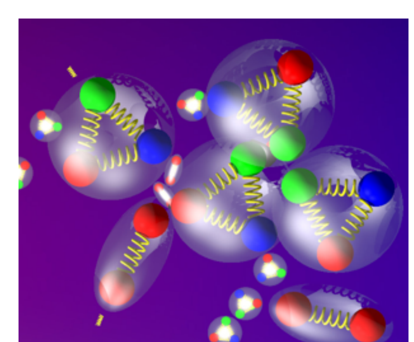
"quark-gluon" plasma

TeV



GeV

QCD confinement

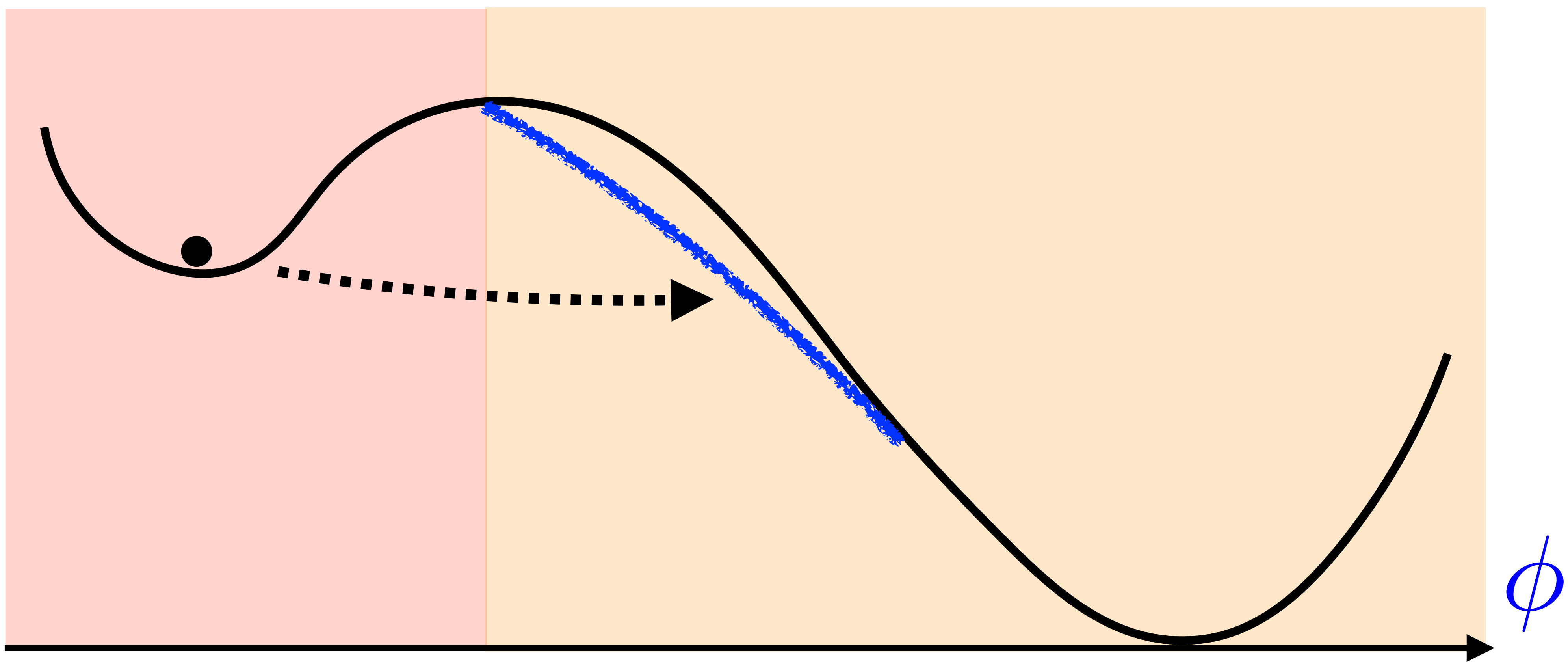


Studied by Witten, Nucl.Phys.B177(1981)477, for a Coleman-Weinberg potential

New scale (Λ_{QCD}) into the dilaton potential:

$$\mathbf{\Delta V}(\phi) \sim \mathbf{Y_q}\phi\langle\mathbf{q\bar{q}}\rangle$$

as masses arises from
the TeV strong dynamics



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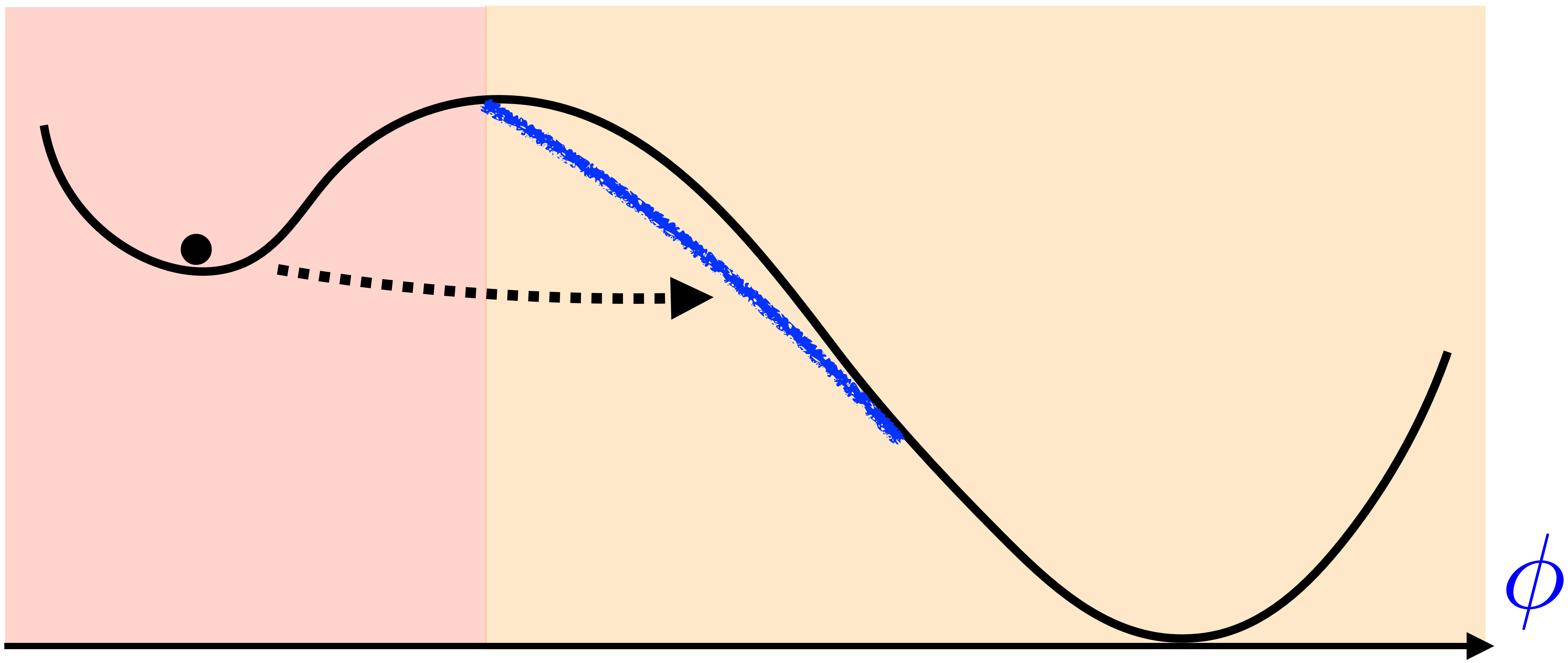
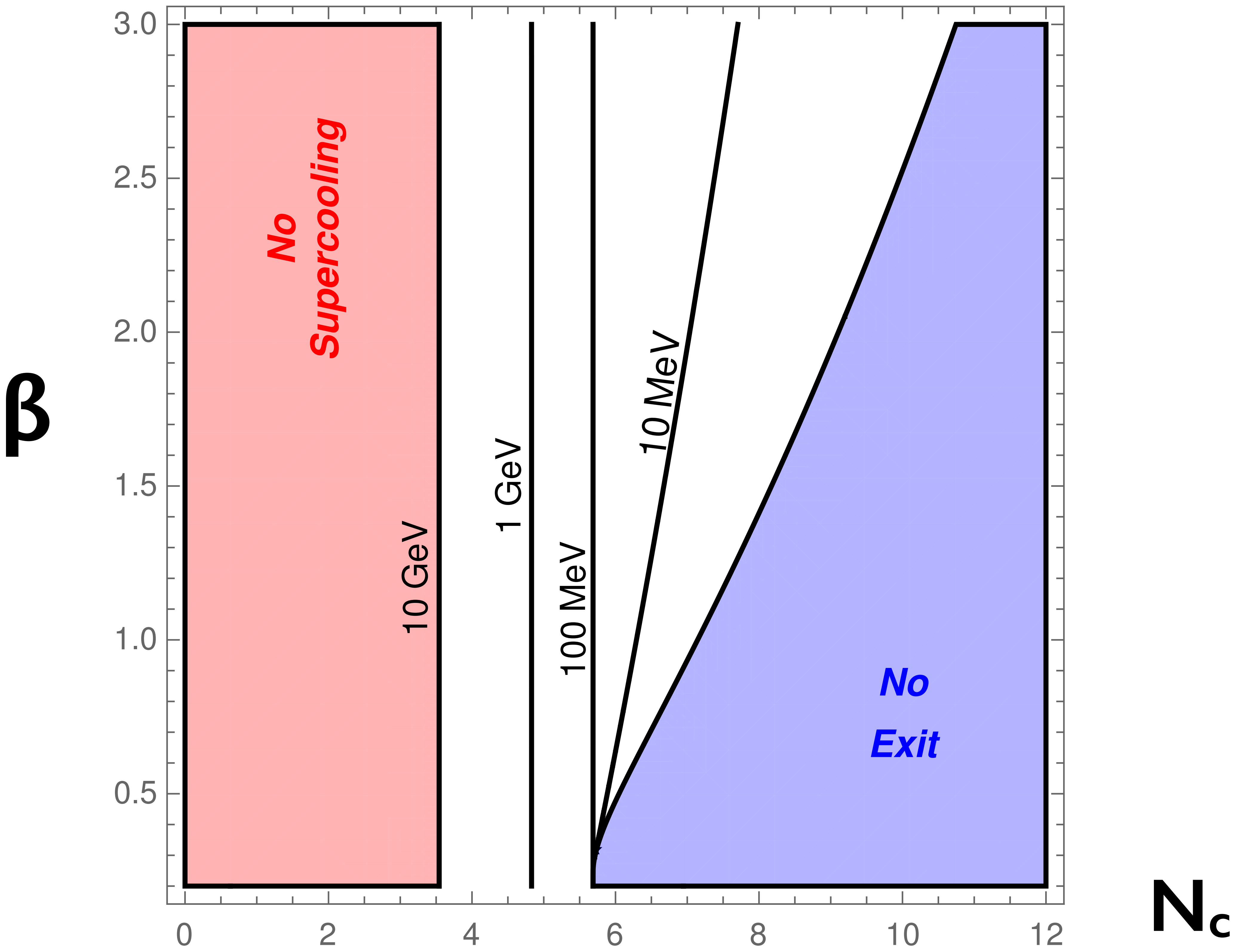


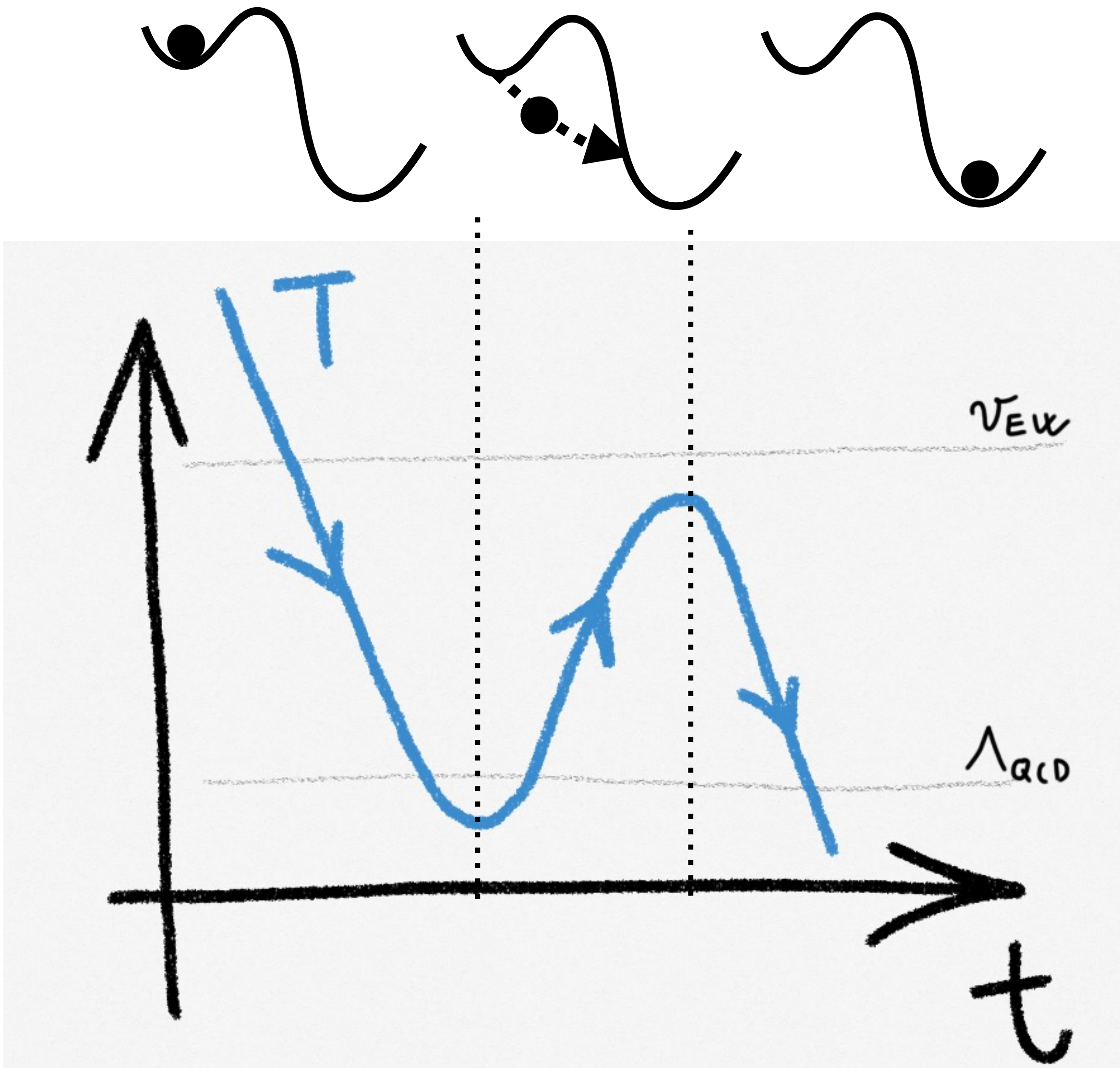
It can allow to **exit** from the supercooling phase at $\lesssim \Lambda_{QCD}$

see also G. Servant's talk & 1711.11554

If QCD impact $\Delta V \sim \beta\, \phi^4 \log \phi$

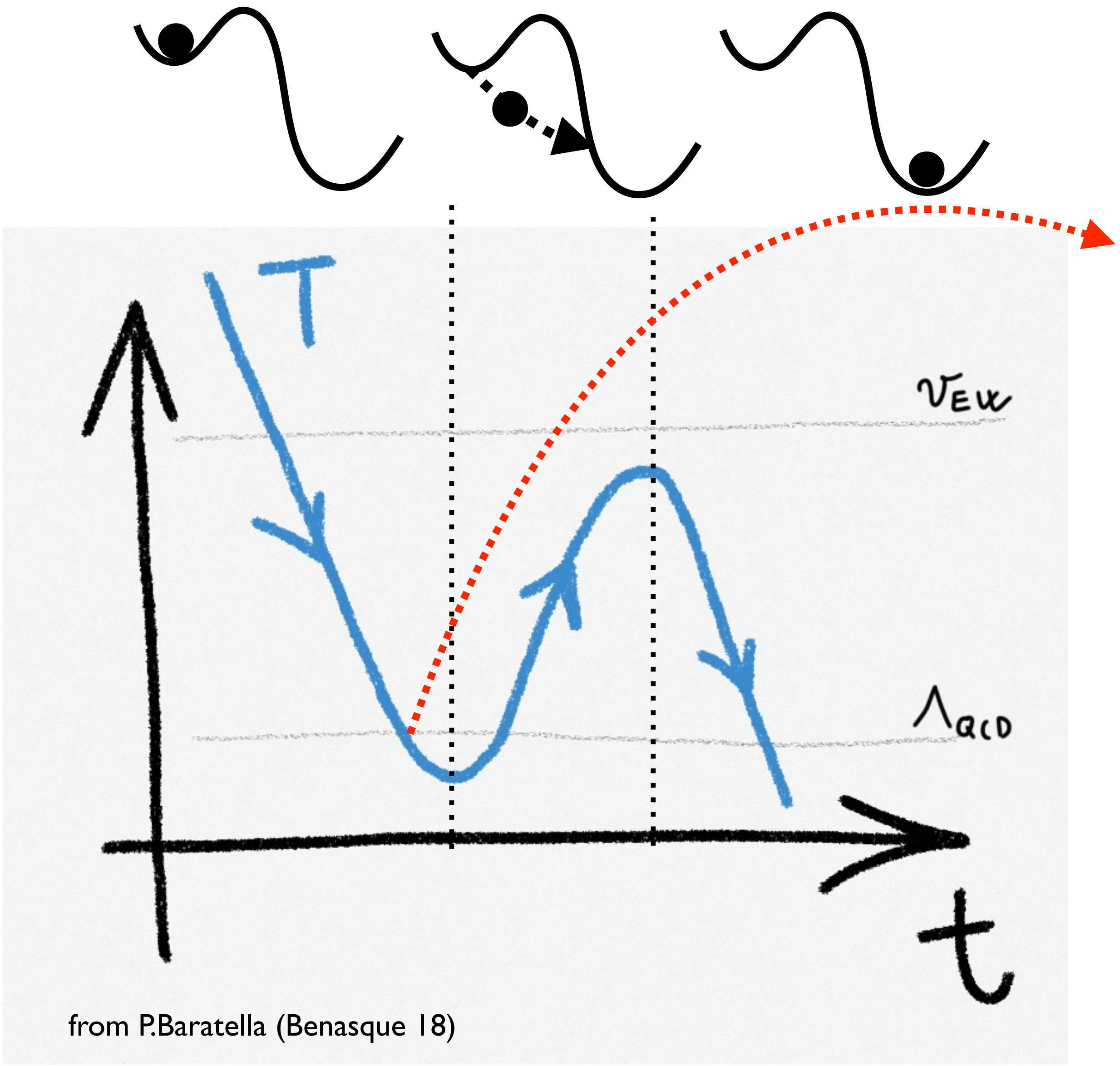


Possible implications of this cosmological phase of supercooling



from P.Baratella (Benasque 18)

Possible implications of this cosmological phase of supercooling

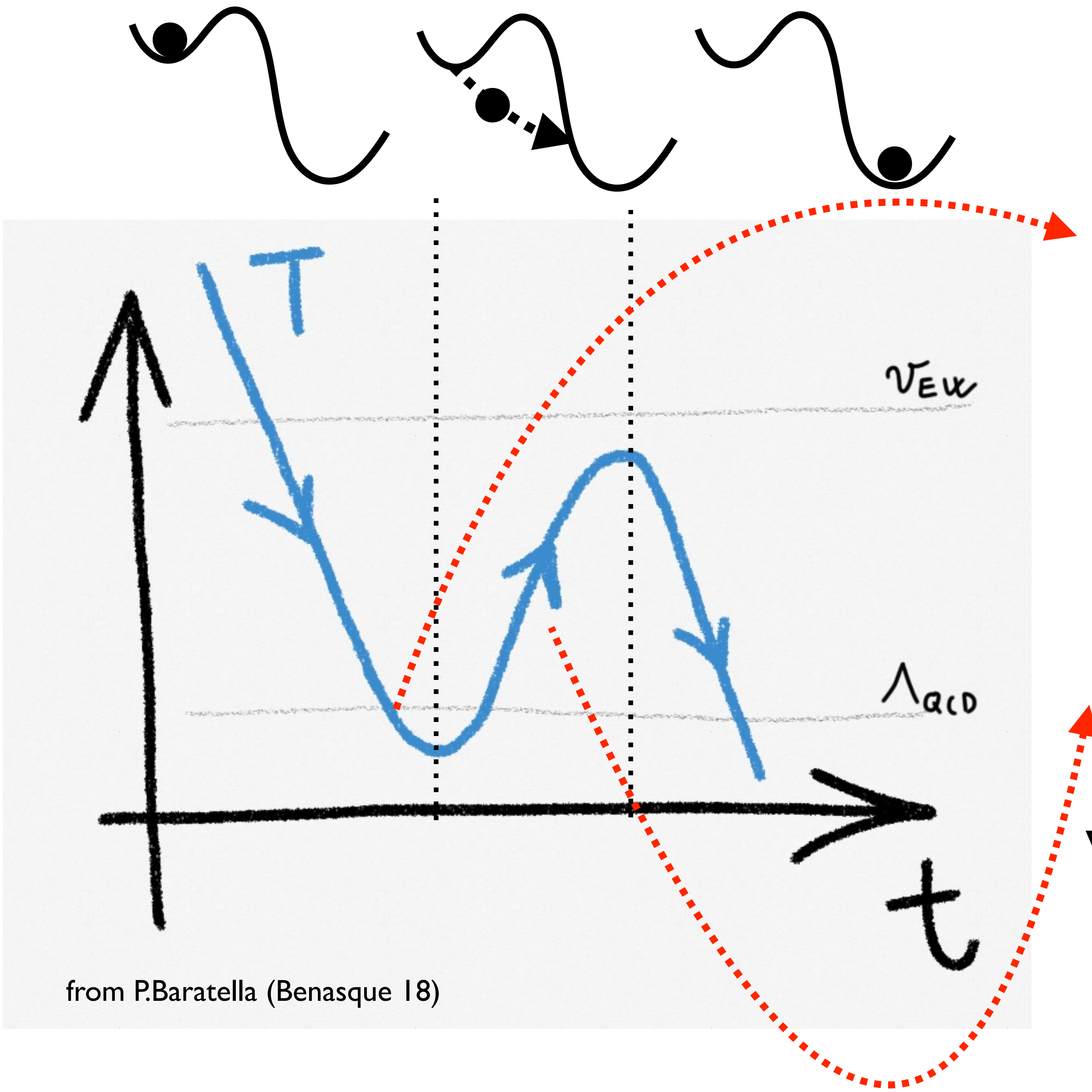


- **Additional QCD phase transition**

Possibility to be 1st order (extra light states)!

Implications? **Impact on axion abundance**

Possible implications of this cosmological phase of supercooling



- **Additional QCD phase transition**

Possibility to be 1st order (extra light states)!

Implications? **Impact on axion abundance**

- **Exit of supercooling:**

  ☛ **1st order phase transition**

Vacuum energy released into thermal energy

- DM and baryon number diluted:

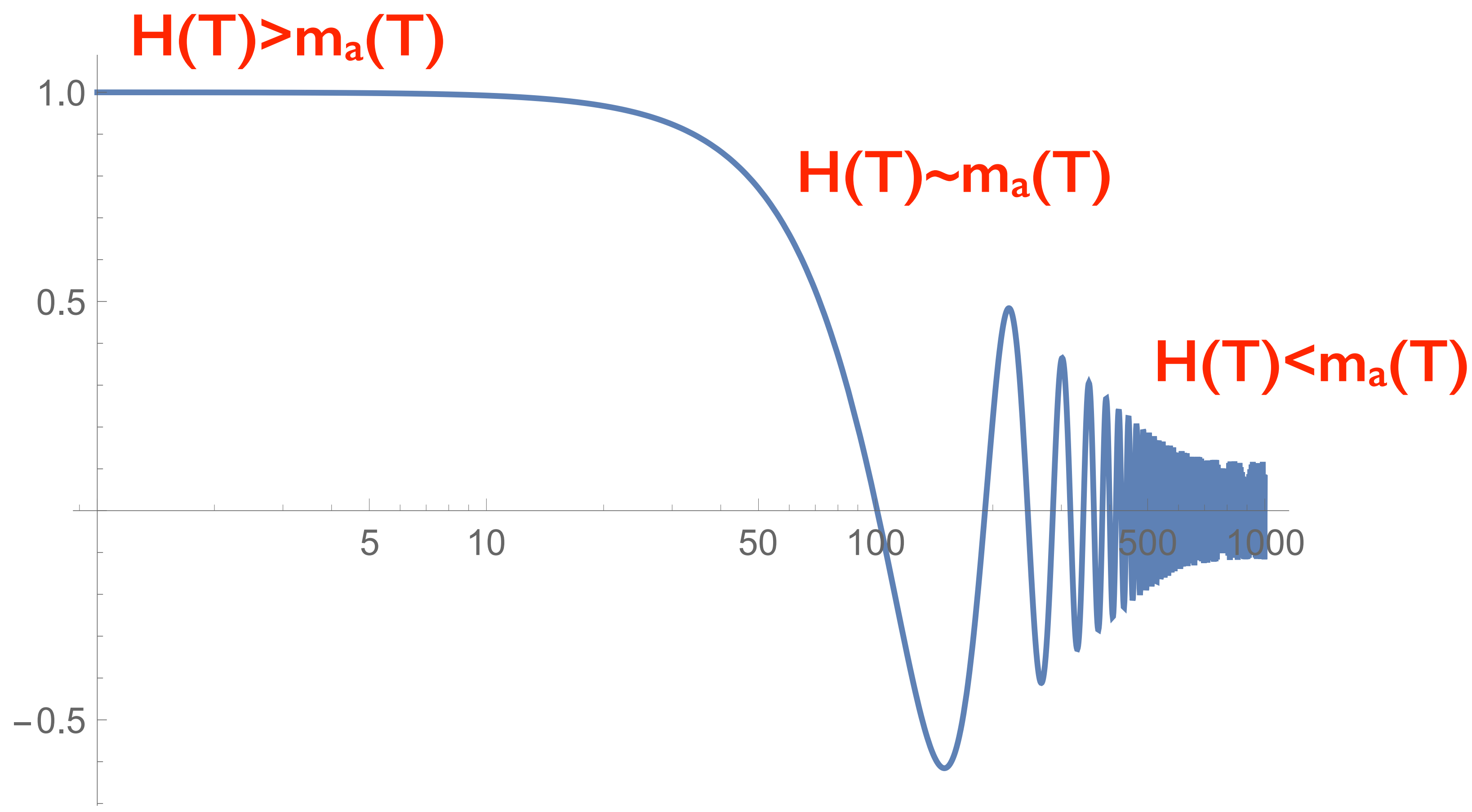
  $1 / n_\gamma \sim (\Lambda_{QCD}/\mathrm{TeV})^3 \sim 10^{-9}$

- "Electroweak" baryogenesis
  if no reheating over the EW scale
- Gravitational waves

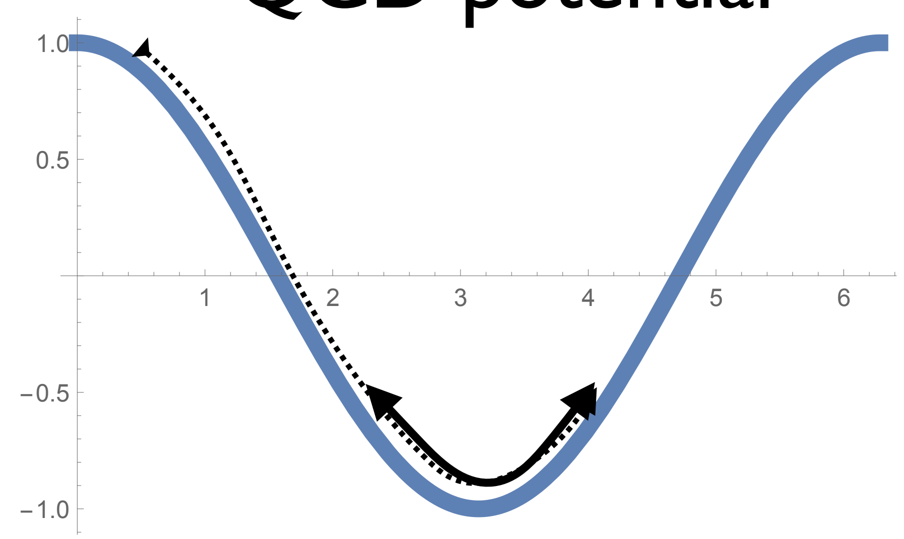
Axion relic abundance

$$\rho_a = m_a^2 a^2$$

$$\ddot{a} + 3H\dot{a} + m_a^2(T)\, f_a \sin\left(\frac{a}{f_a}\right) = 0$$



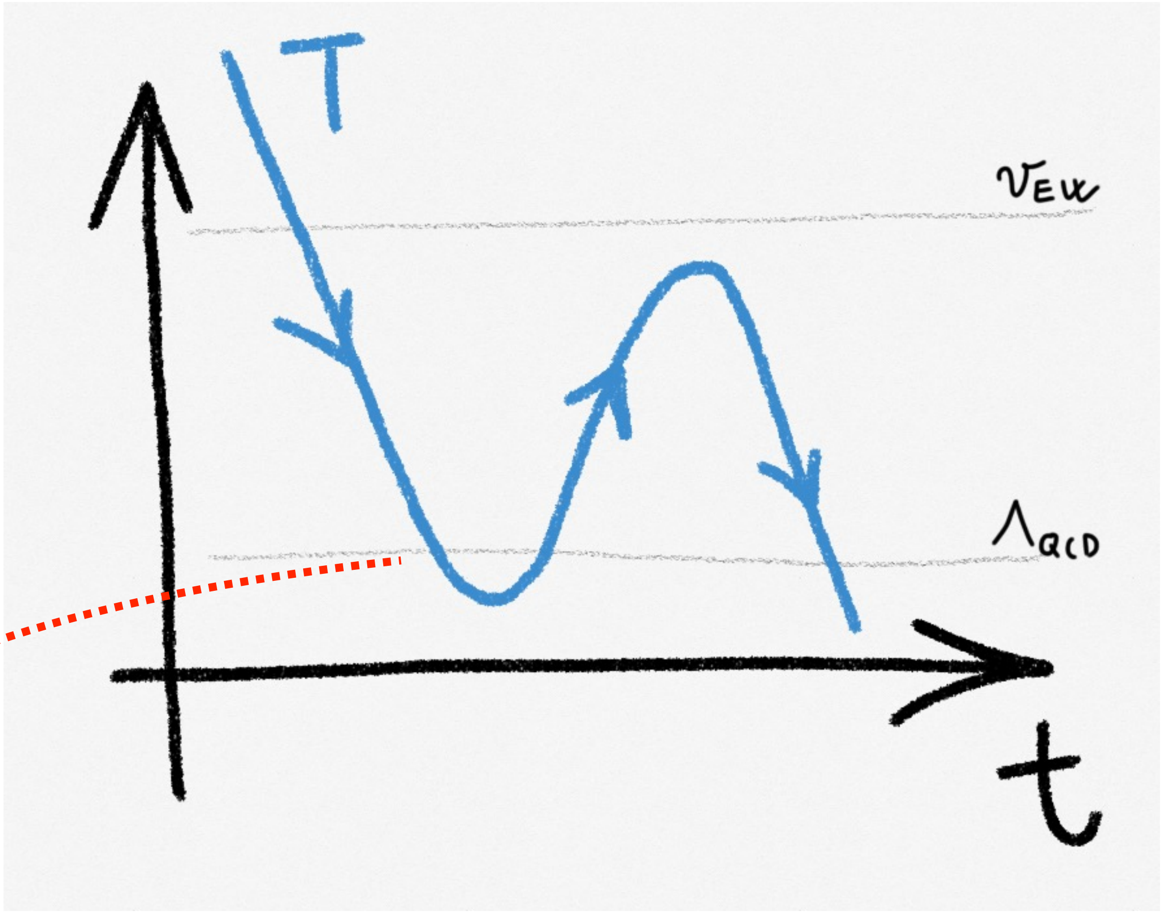
QCD potential



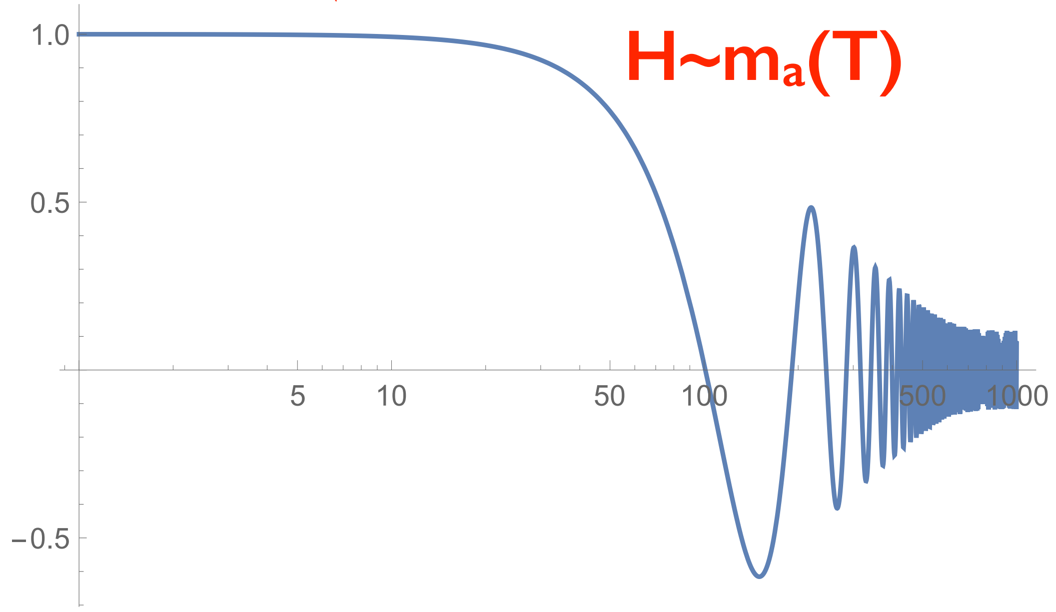
If PQ breaking after inflation:

Right DM abundances for $f_a \sim 10^{11}$ GeV

If supercooling:



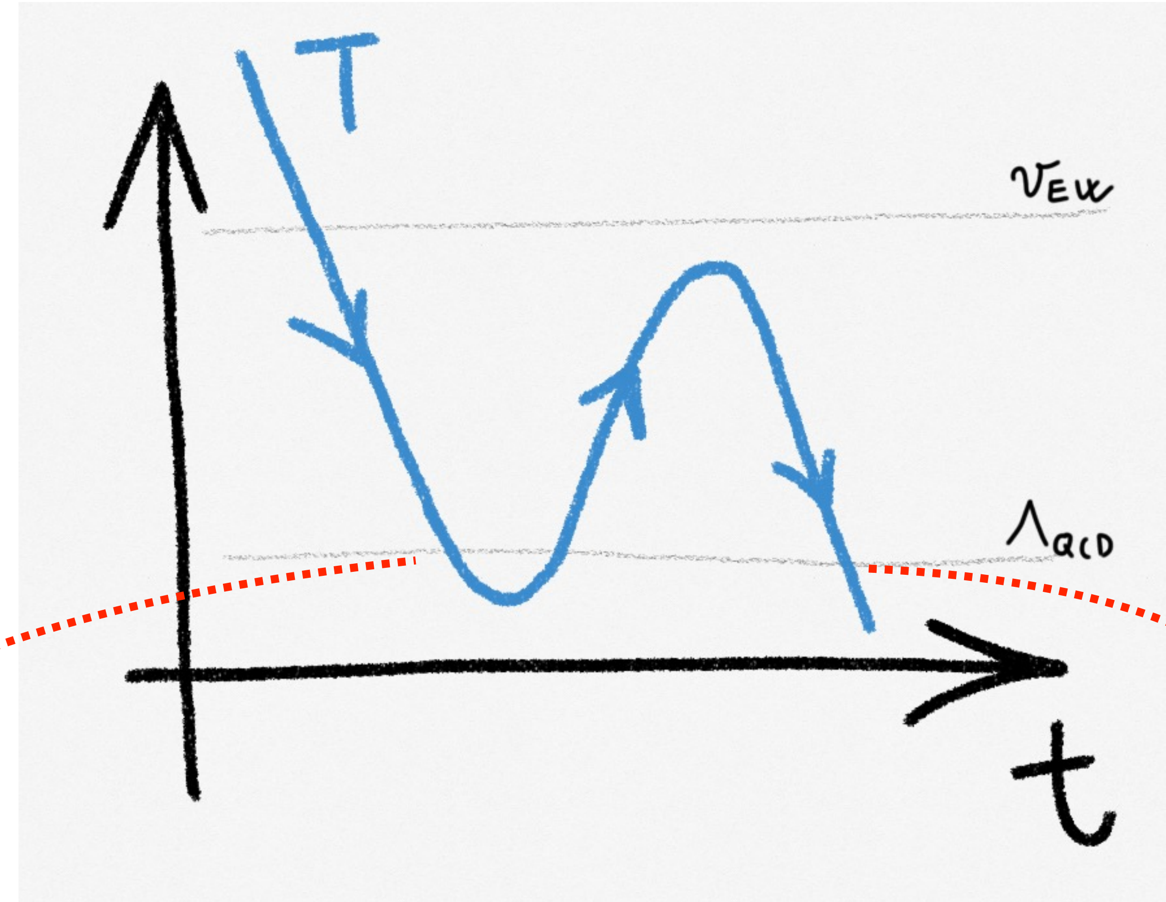
Additional QCD phase transition



$H \sim m_{dil}$ TeV/M_P & $m_a \sim (m_u \Lambda_{QCD}^3)^{1/2}/f_a$

in the deconfined phase

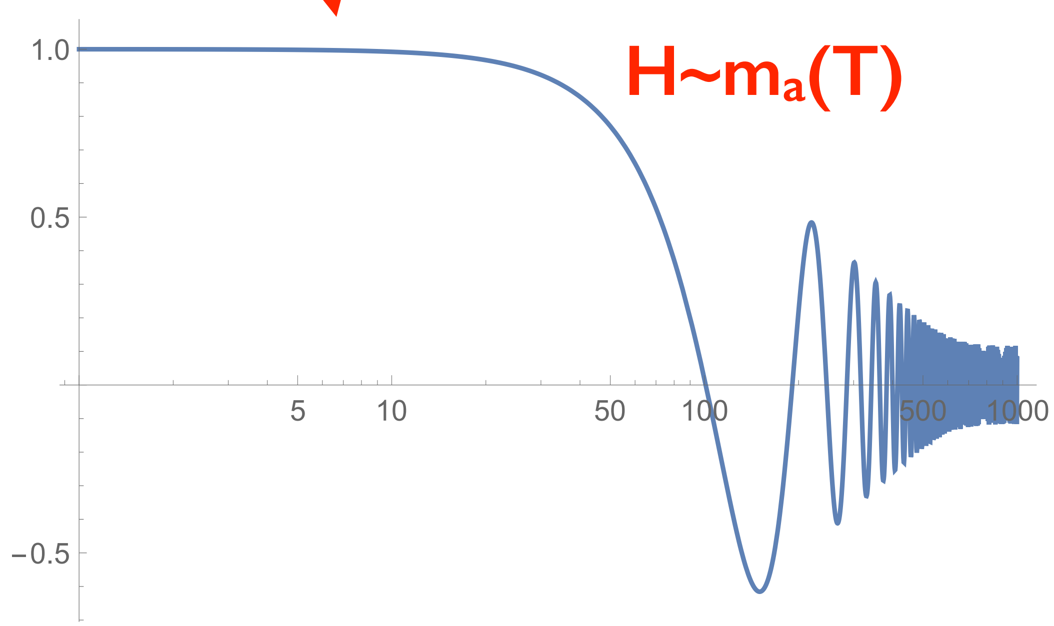
If supercooling:

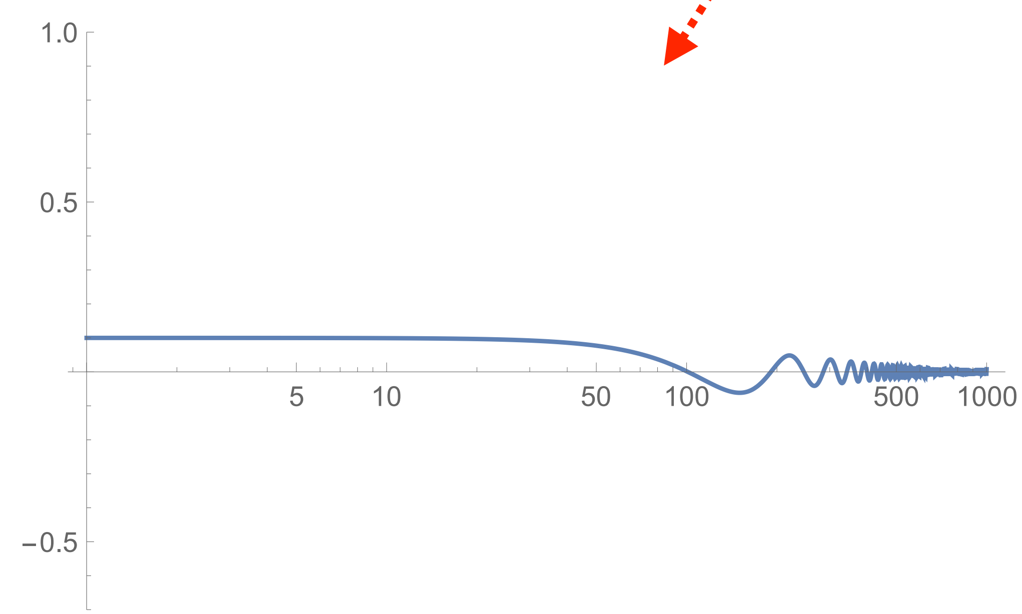


Additional QCD phase transition

Ordinary QCD phase transition

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

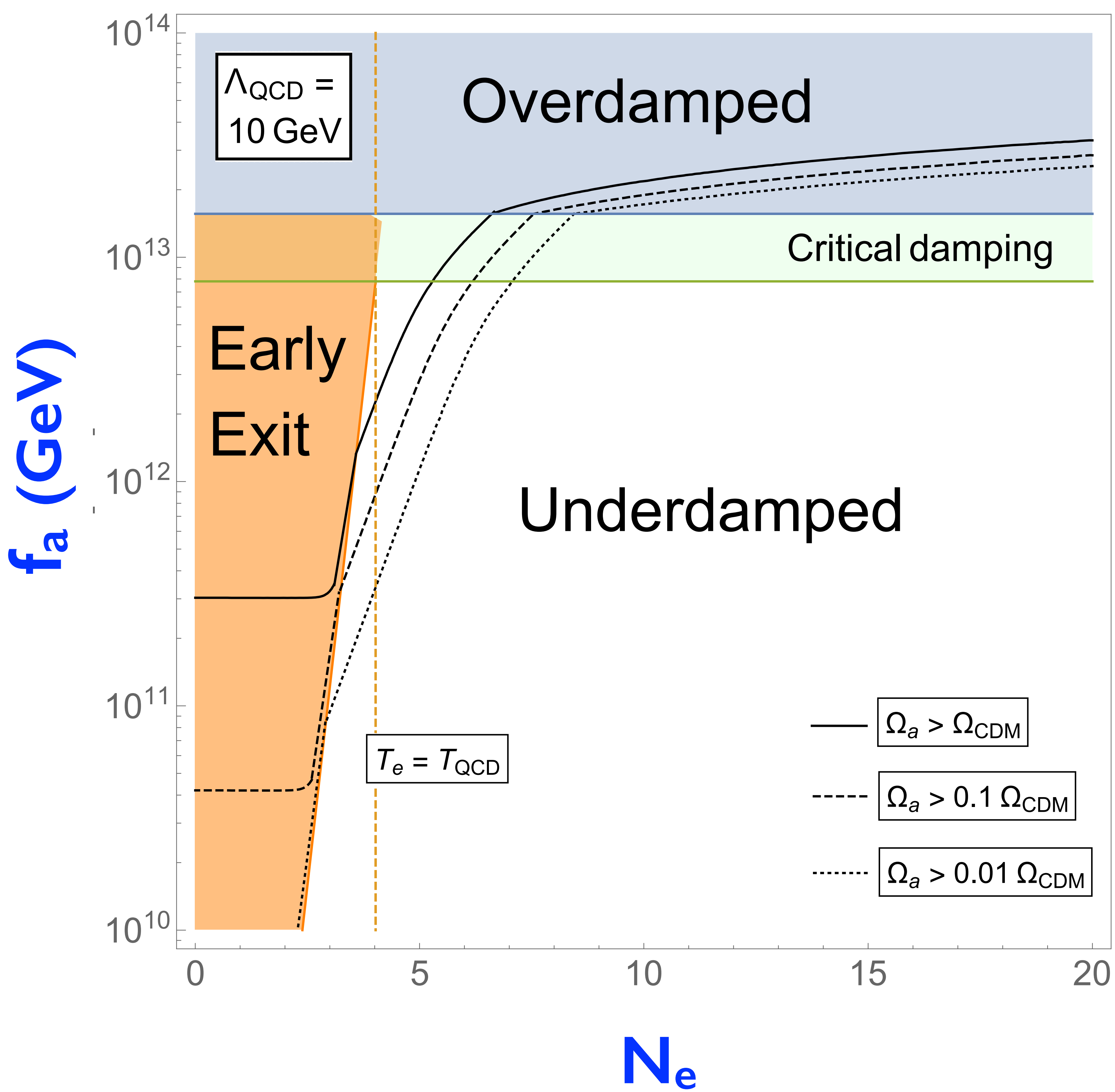




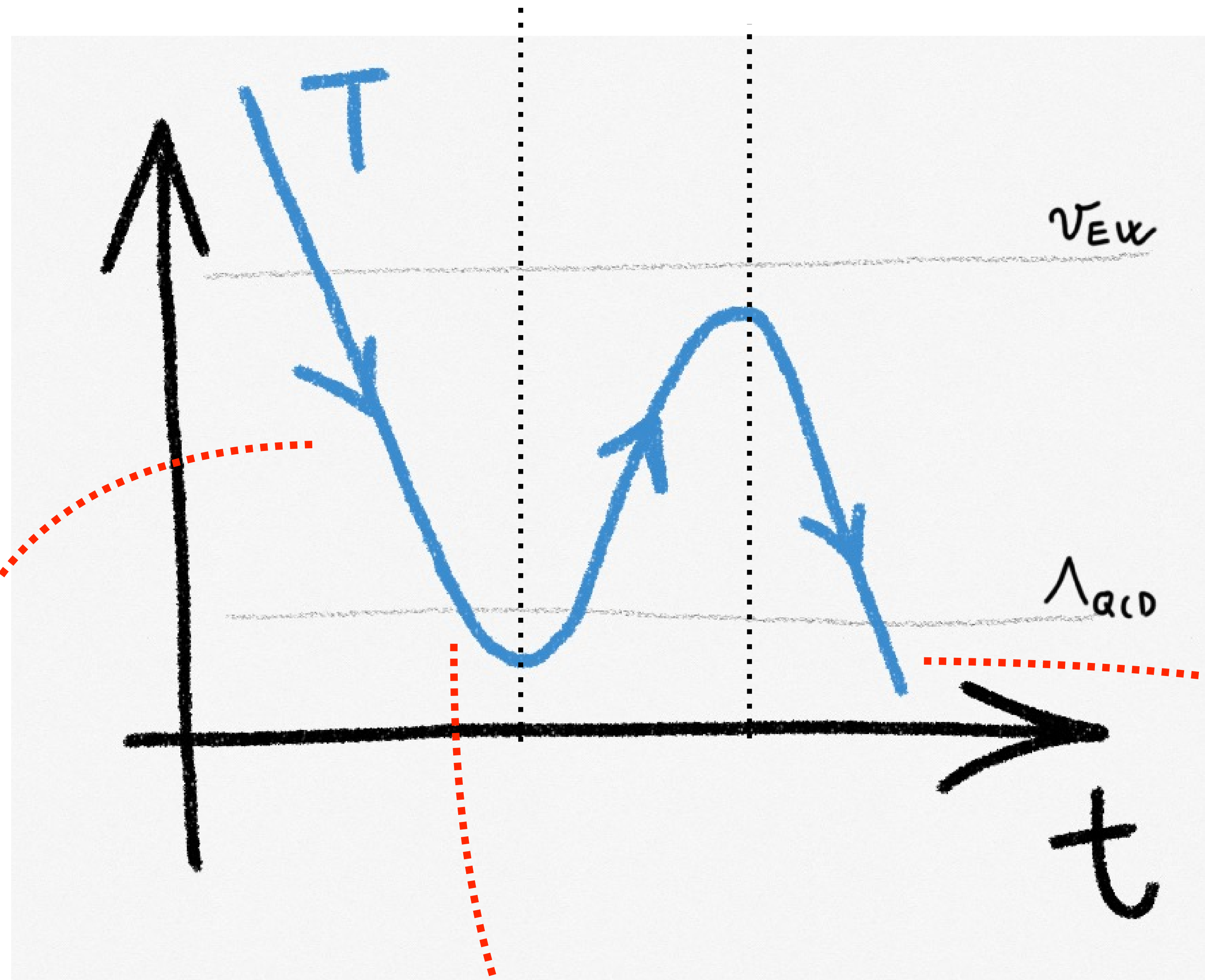
$H \sim m_{dil}$ TeV/M_P & $m_a \sim (m_u \Lambda_{QCD}^3)^{1/2}/f_a$

in the deconfined phase

Right DM abundances for larger f_a :



Cosmic strings and domain walls



strings reenter!

String stretched
beyond the horizon

domain walls
cannot annihilate them

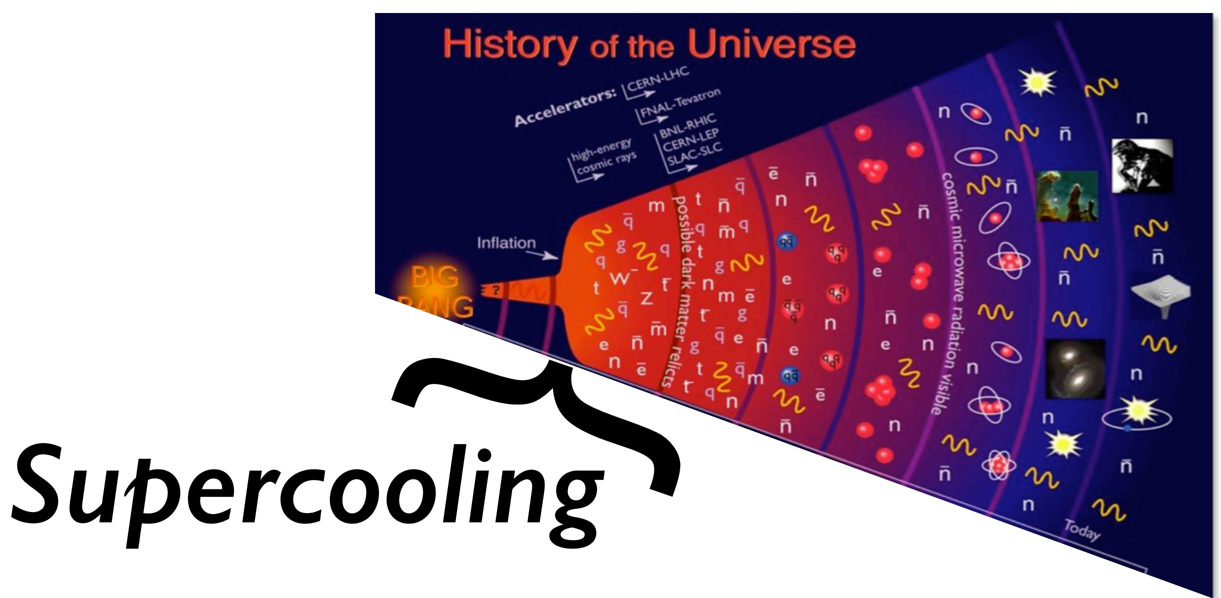
Conclusions

- **Conformal to non-conformal transition** are important in physics
- Lattice "sees" a **light scalar** close to the **QCD conformal transition**

From **holography a light scalar always emerge:**

☛ **Not parametrically lighter than other resonances**

- **Impact** in the cosmological history:



- Additional QCD phase transition ☛ can trigger the exit of supercooling
- Release of latent heat ☛ impact in DM and baryogenesis
- Changes in the axion relic abundance ☛ f_a larger could be possible!