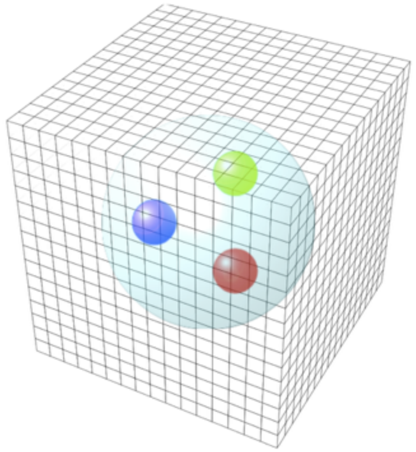
Conformal to non-conformal transition via holography: Light scalars & cosmology

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



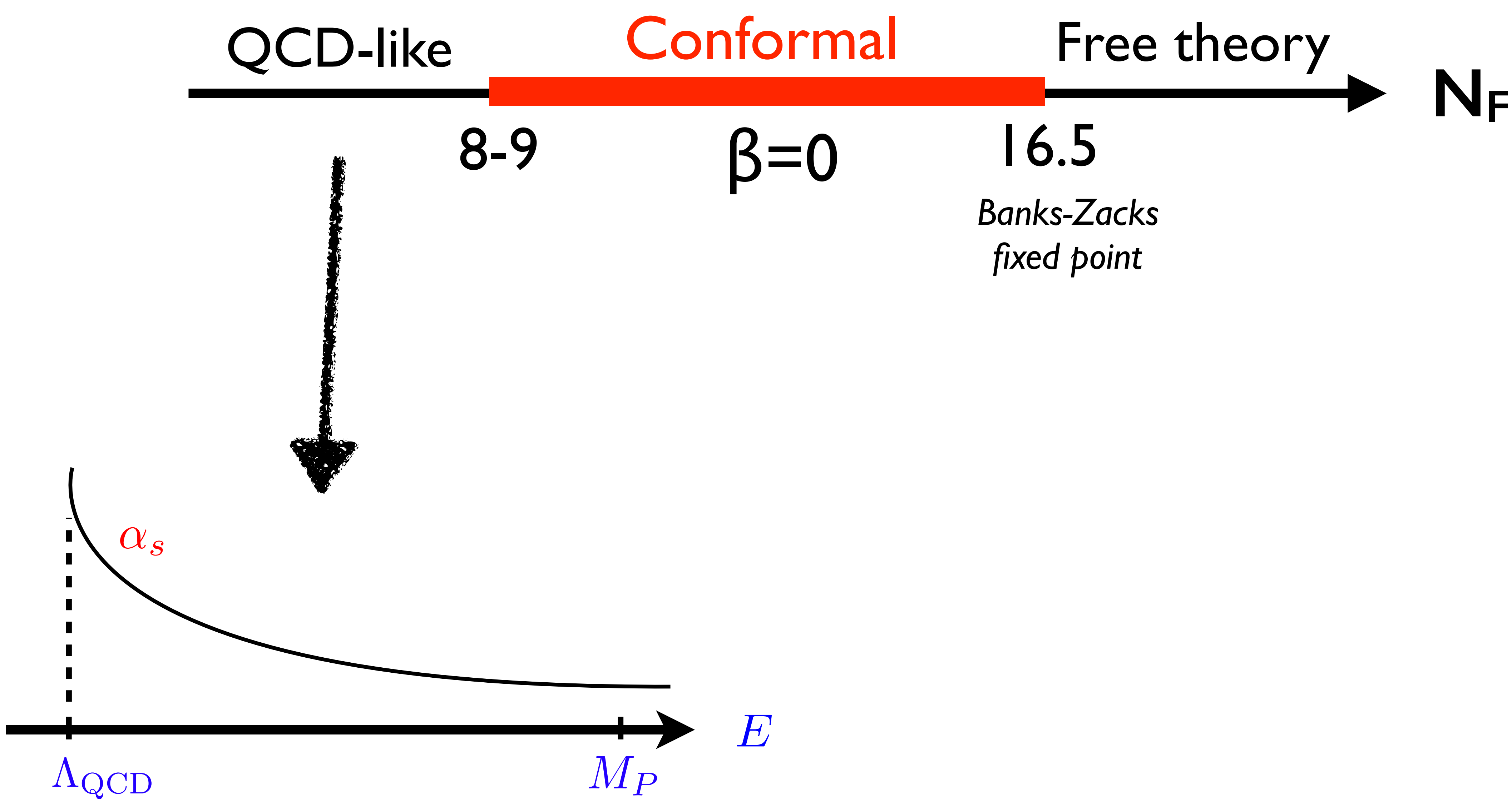
- Important for the hierarchy problem:

  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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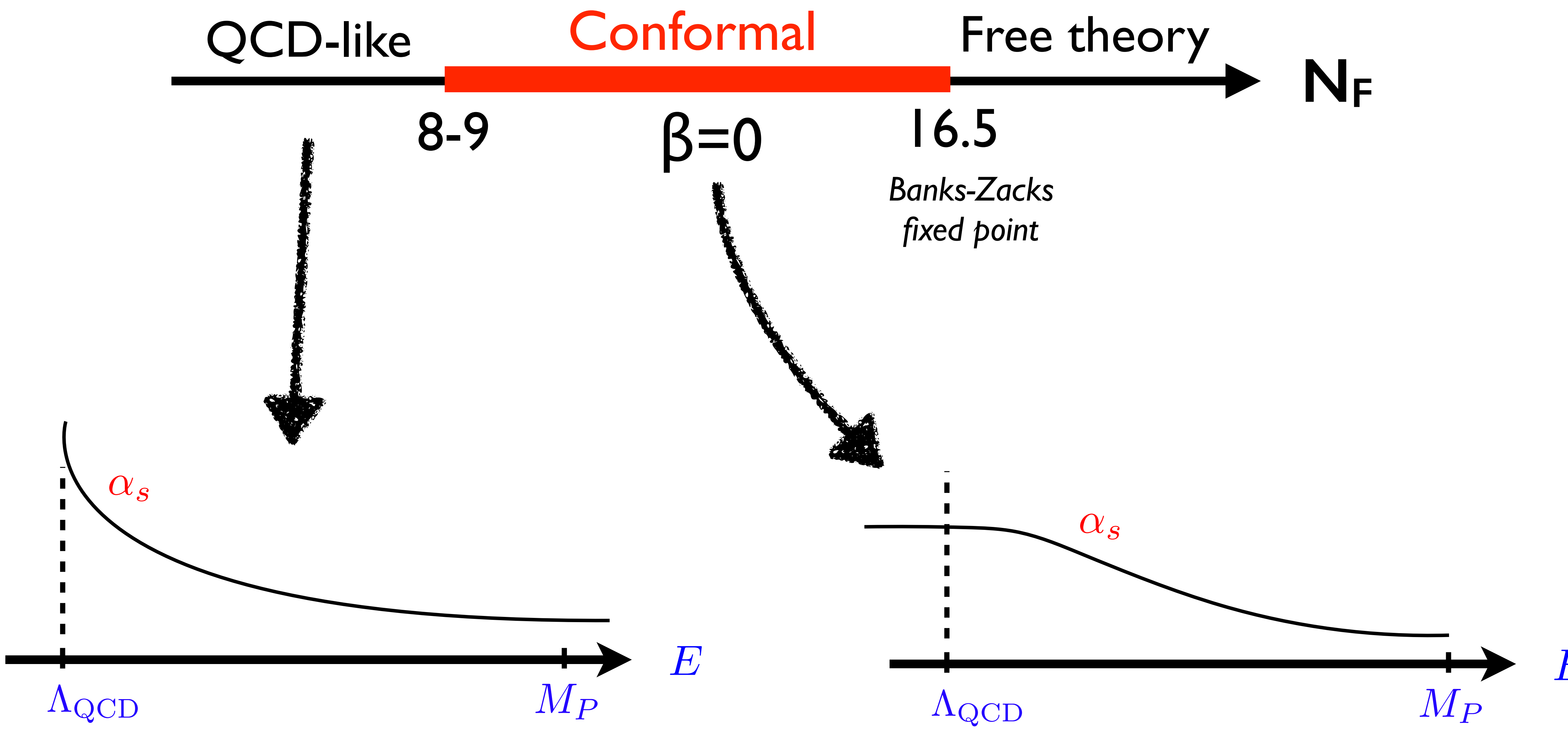

Mass gap ~ Λ_{QCD}

Chiral-symmetry breaking

No mass gap ~ Λ_{QCD}

No chiral-symmetry breaking

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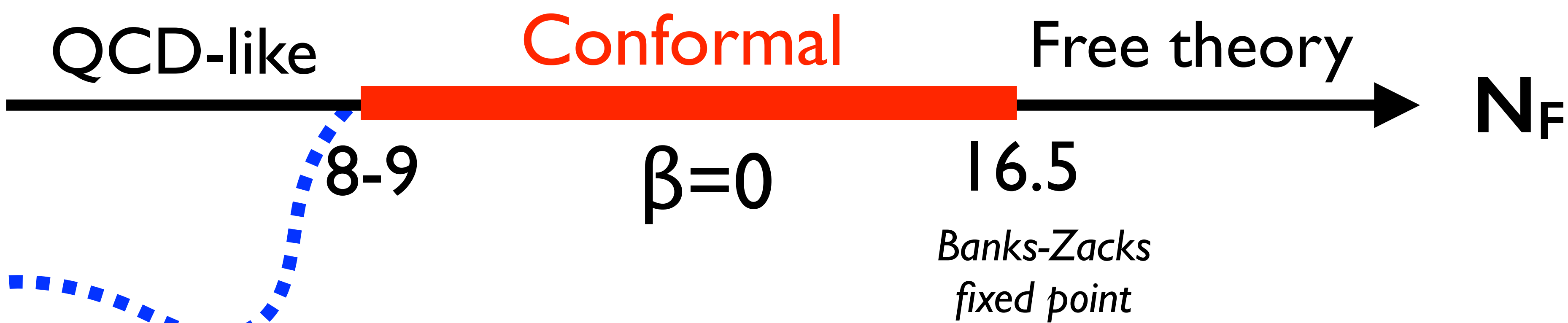
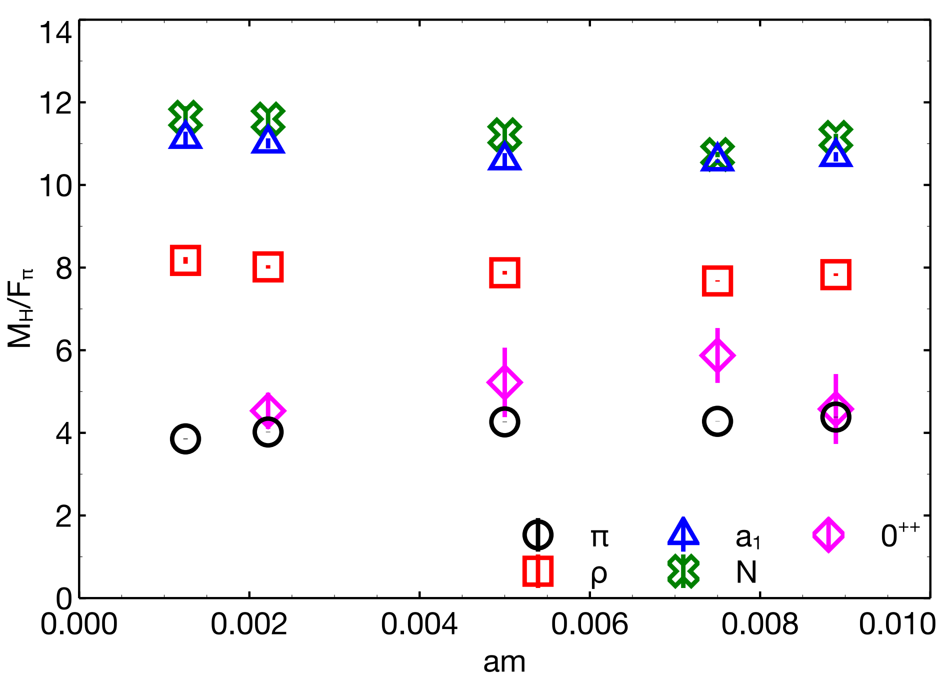
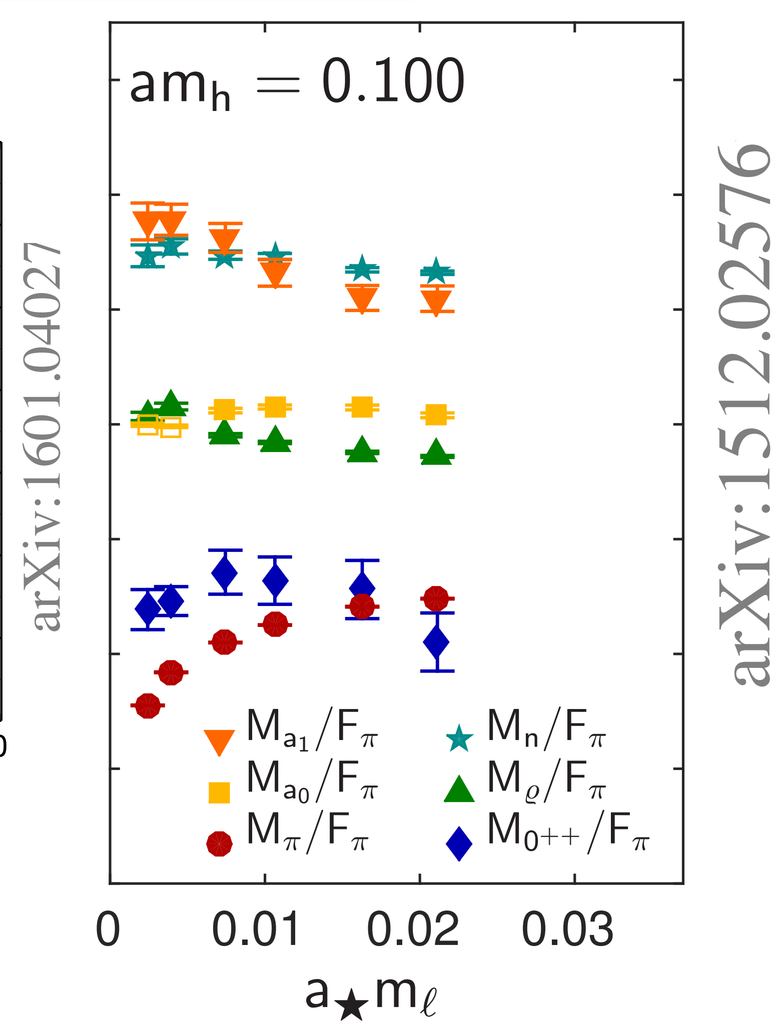


Lattice results:

N_F=8





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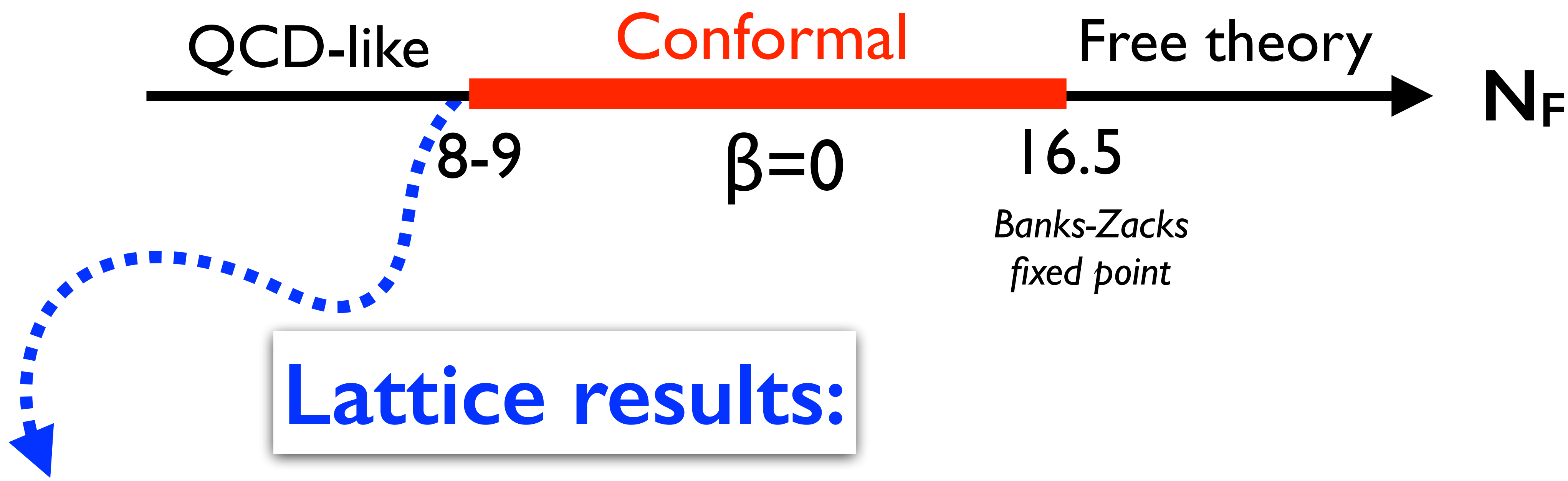

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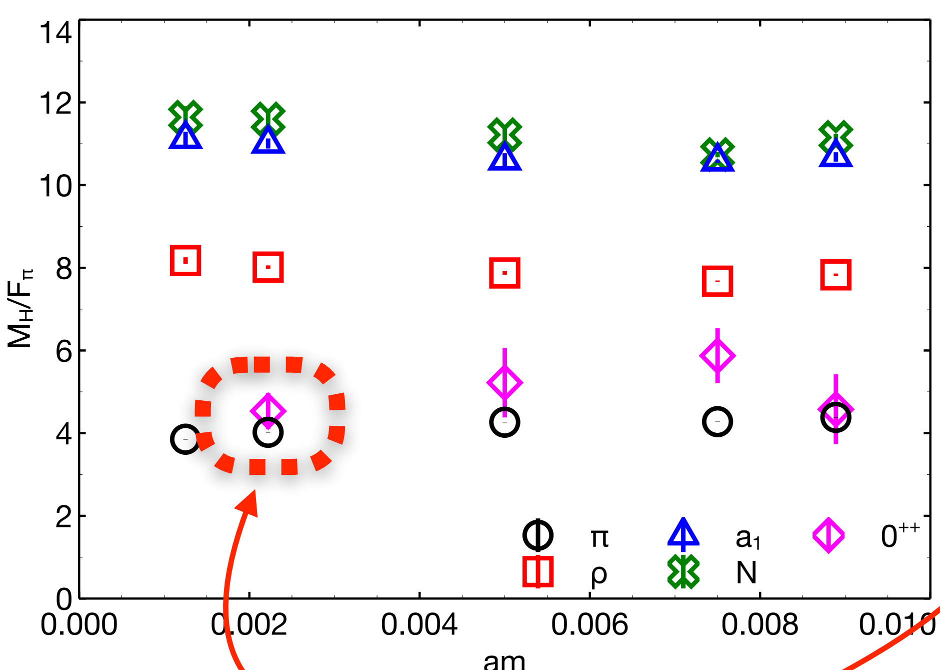
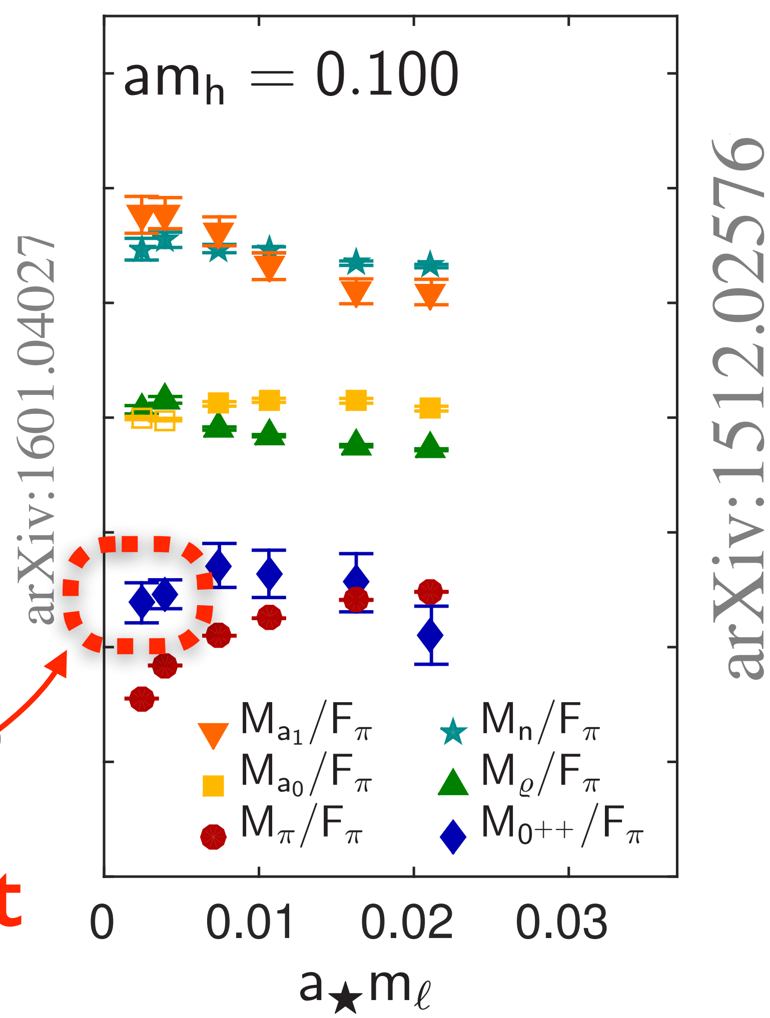
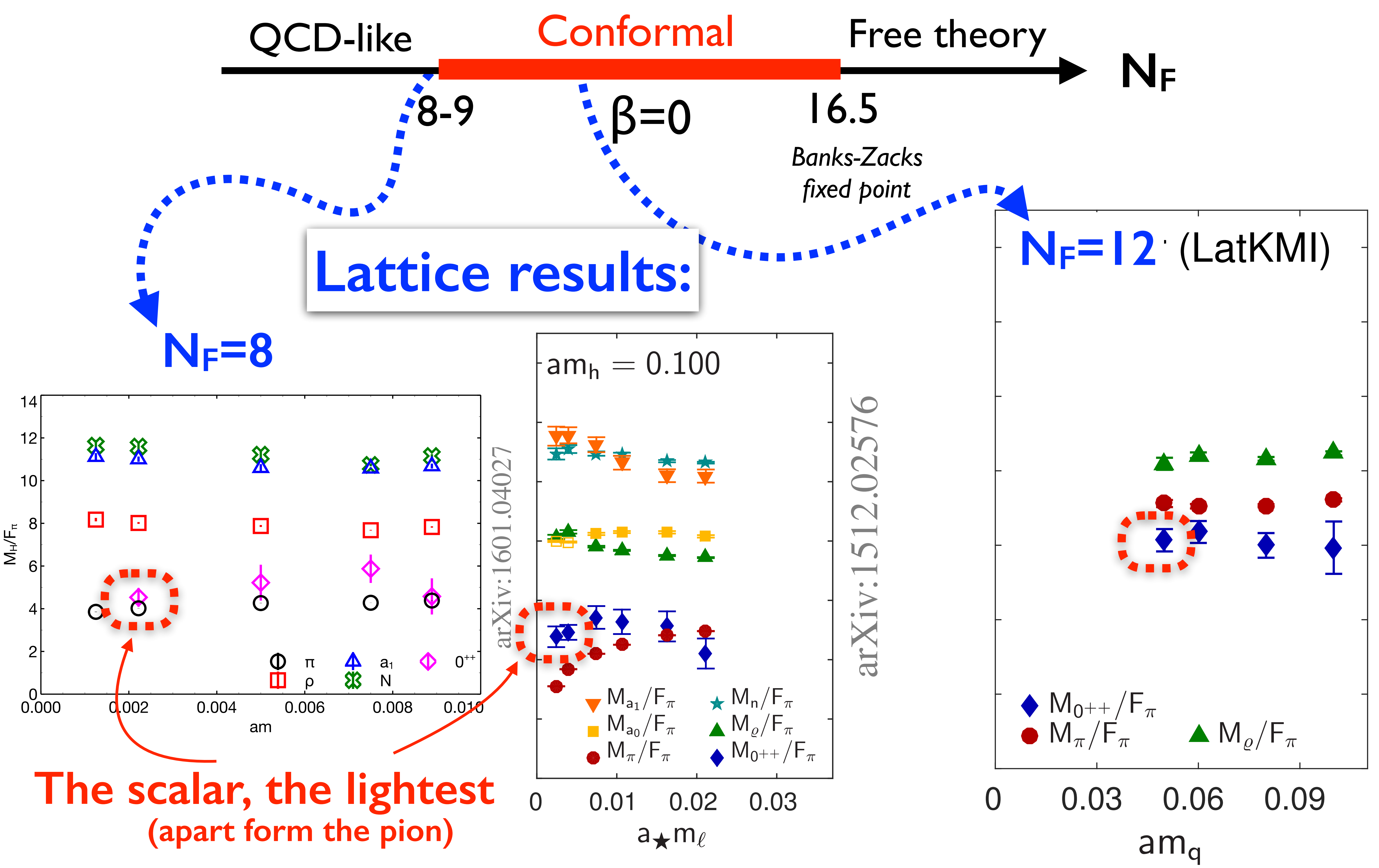




The scalar, the lightest
(apart form the pion)

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



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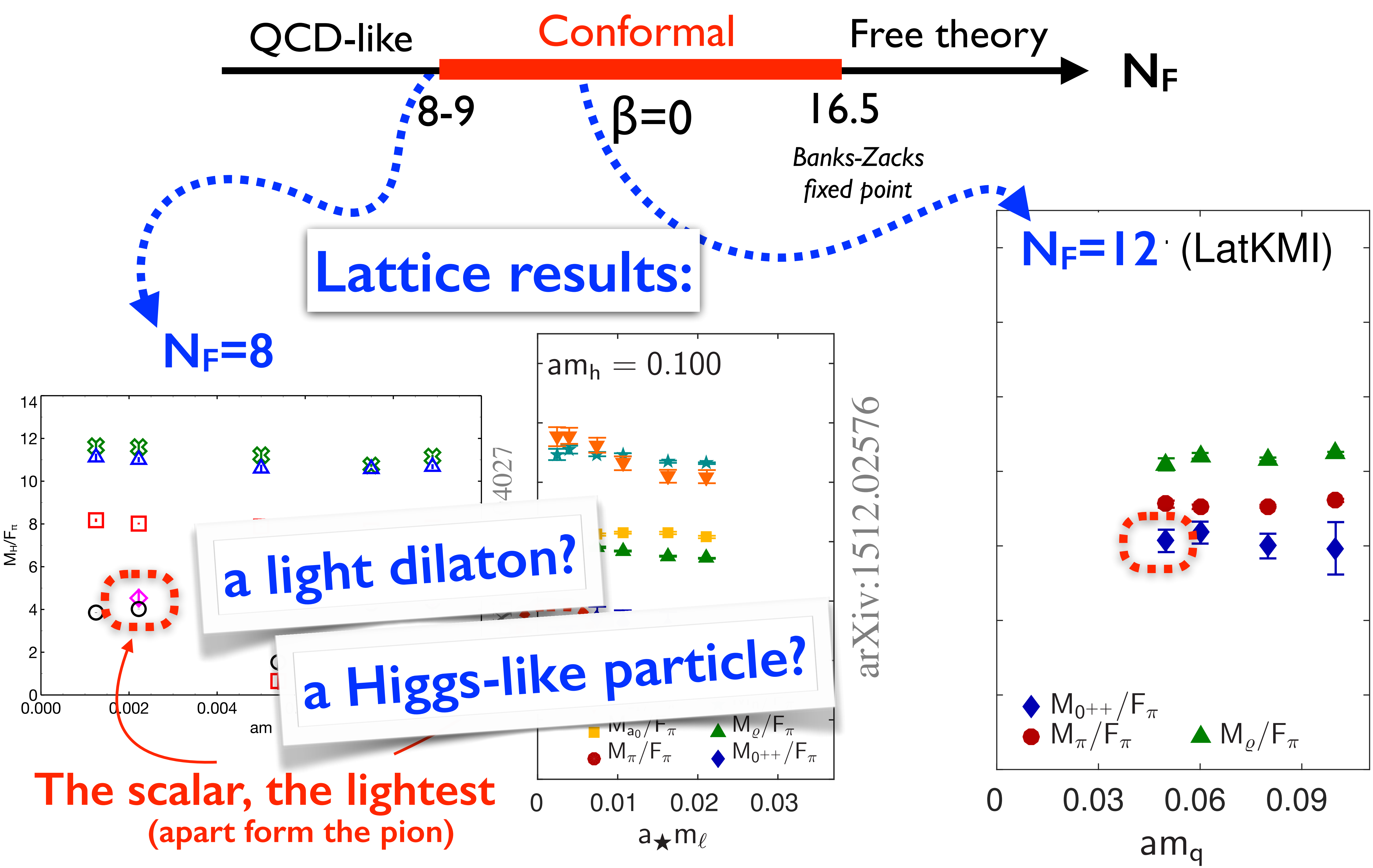

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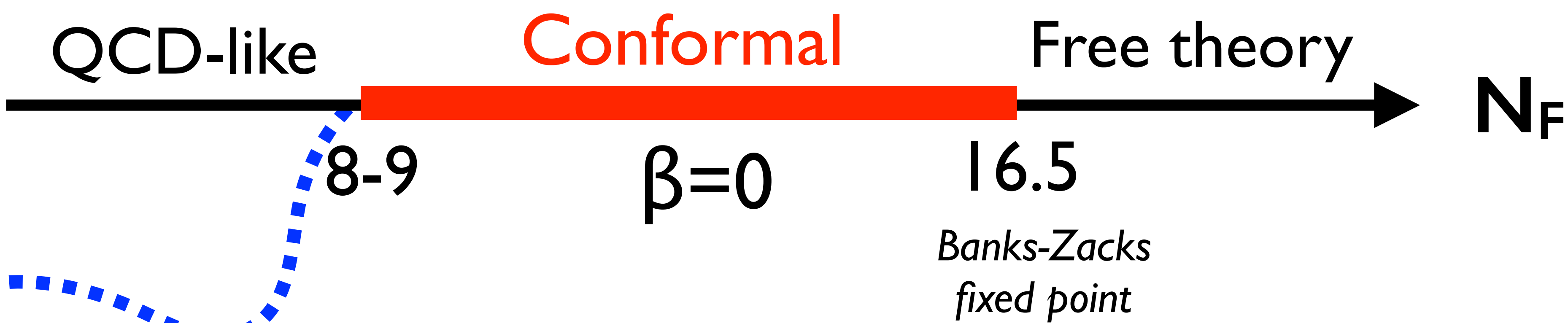

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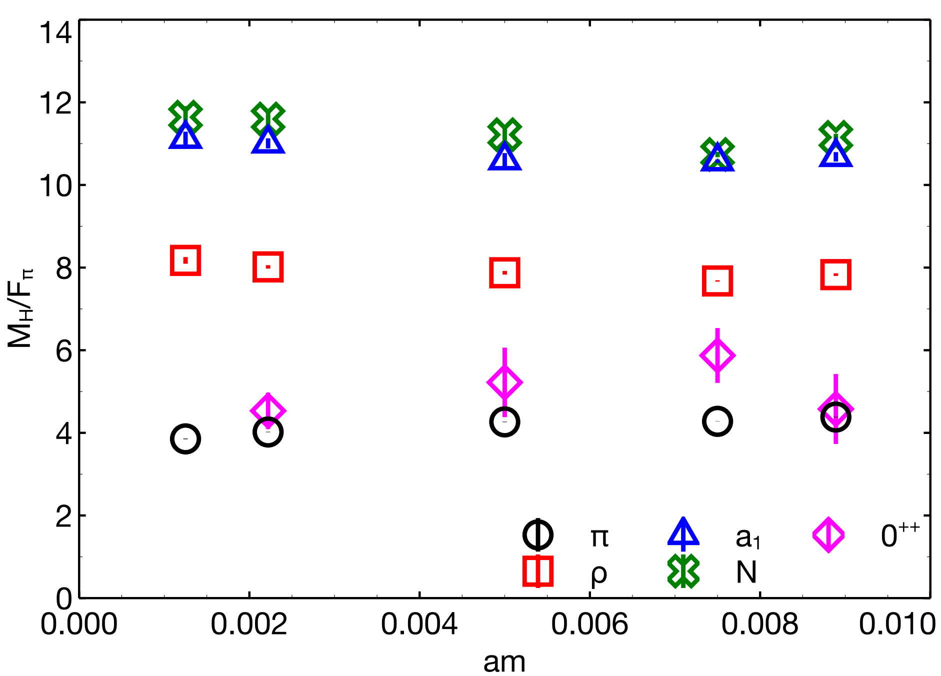
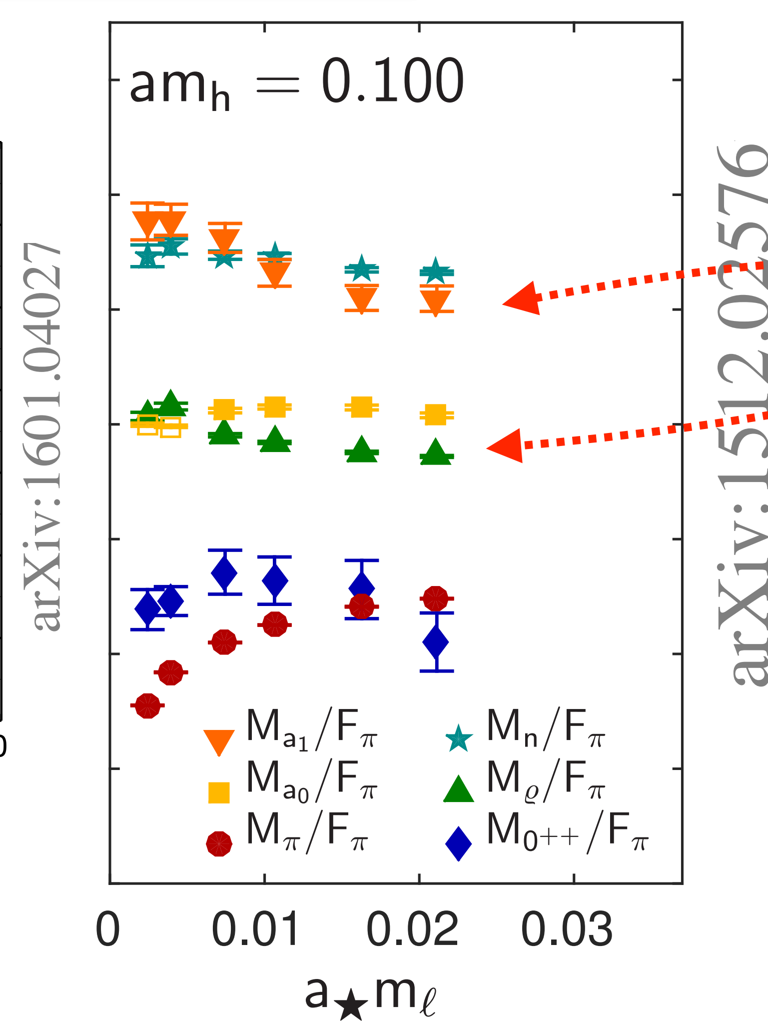




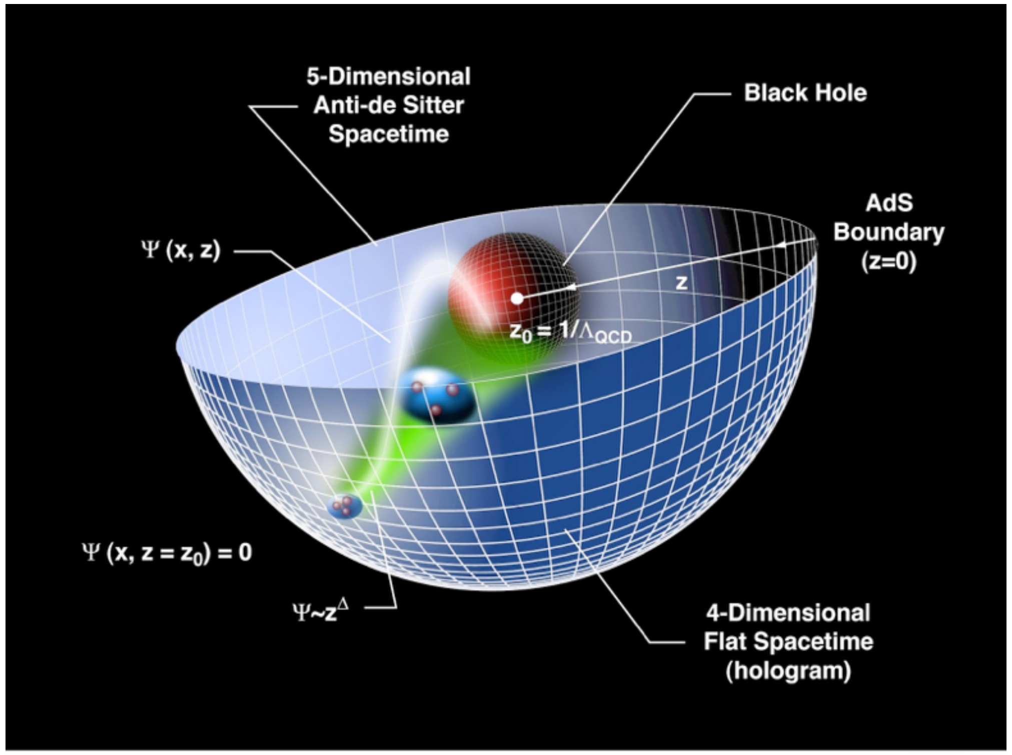
Smaller mass-splitting

$m_\rho - m_{a_1}$

from chiral breaking

(as compared with QCD)

What could we say from holography?



in collaboration with O.Pujolas & L.Salas

PRELIMINARY

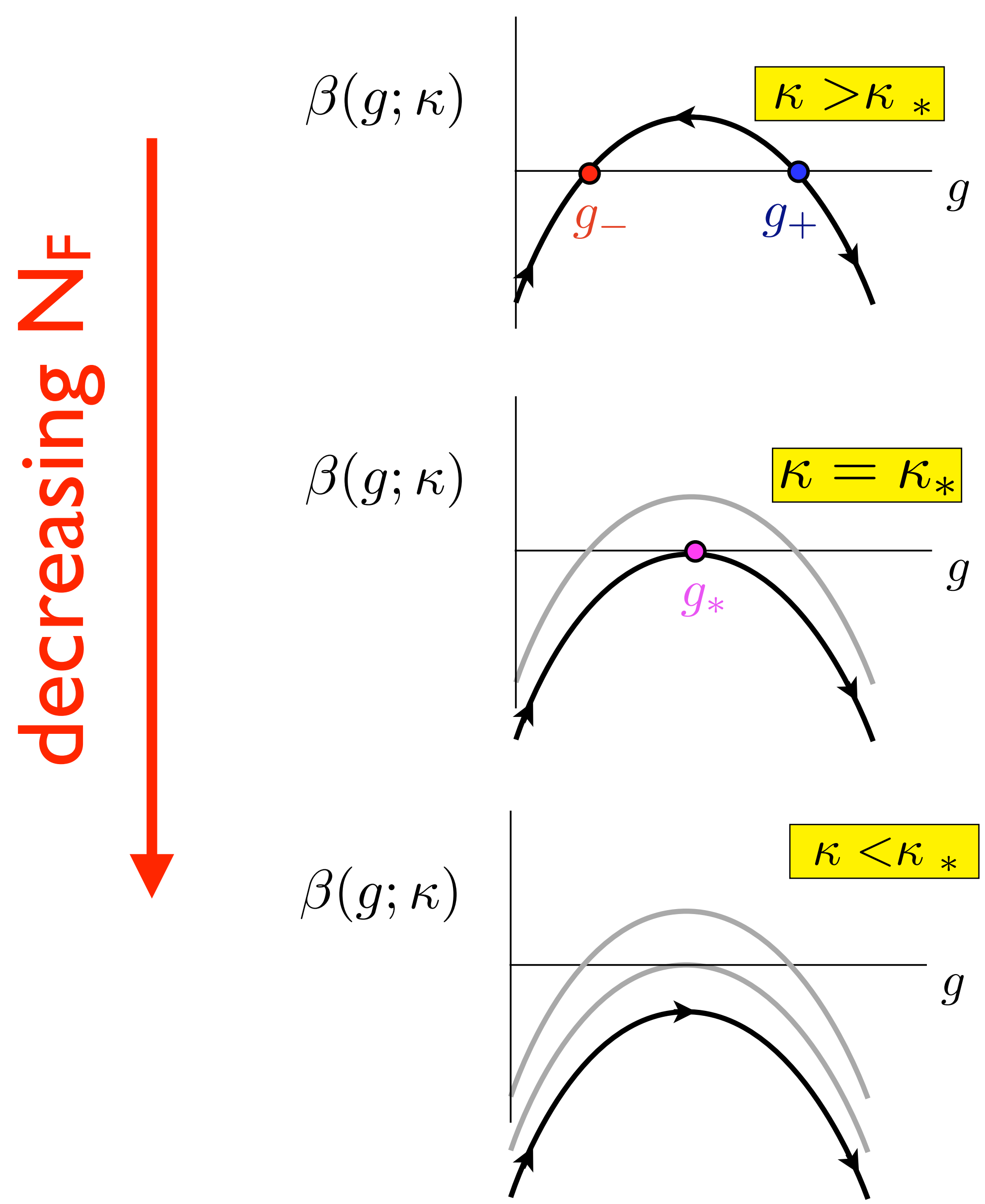
see also previous works:

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

Conformal breaking as N_F decreases

How the fixed point could disappear?

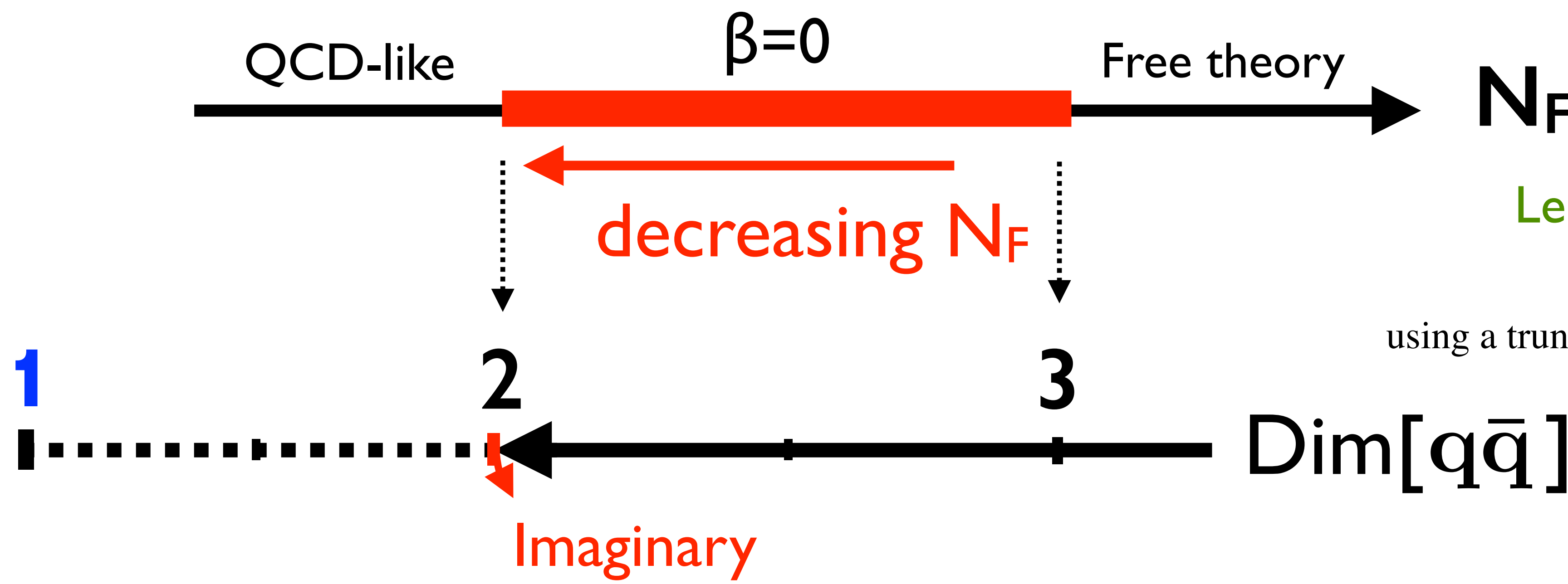
Lee,Son,Stephanov,Kaplan
arXiv:0905.4752
using a truncation of the Schwinger-Dyson eqs.



IR & UV fixed-point annihilation

D.B.Kaplan

Conformal breaking as N_F decreases



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Triggered by $\langle q\bar{q}\rangle \neq 0$ after its dimension becomes imaginary

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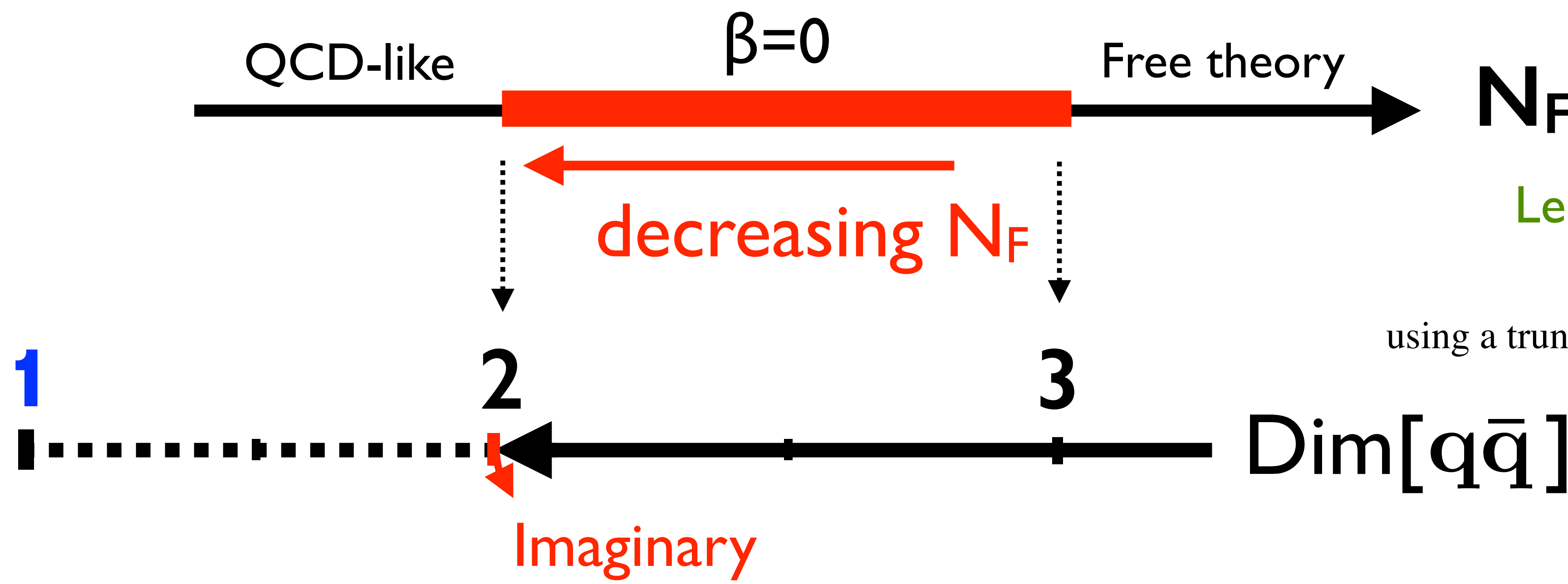

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Using AdS/CFT:

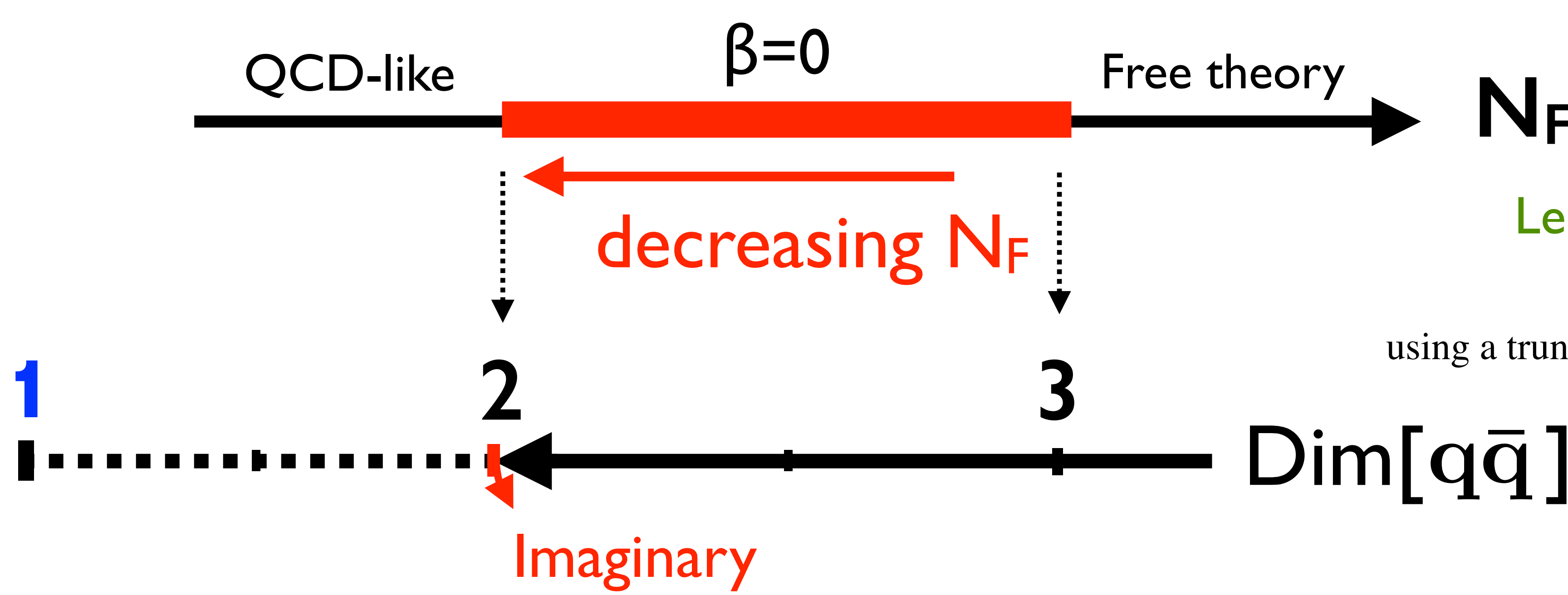
DICTIONARY

$\mathrm{CFT}_4 \longrightarrow \mathrm{AdS}_5$

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

Strongly-coupled → Weakly-coupled

Conformal breaking as N_F decreases



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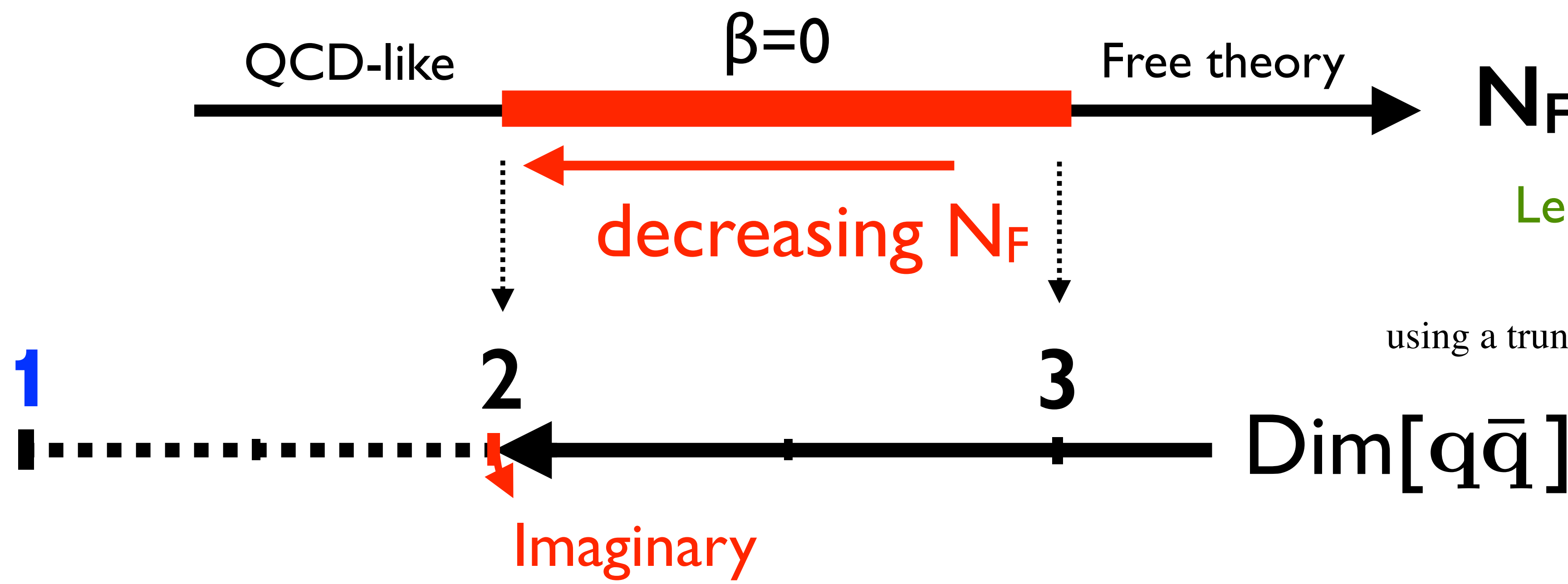

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$$\bar{q}q \longrightarrow \Phi$$

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

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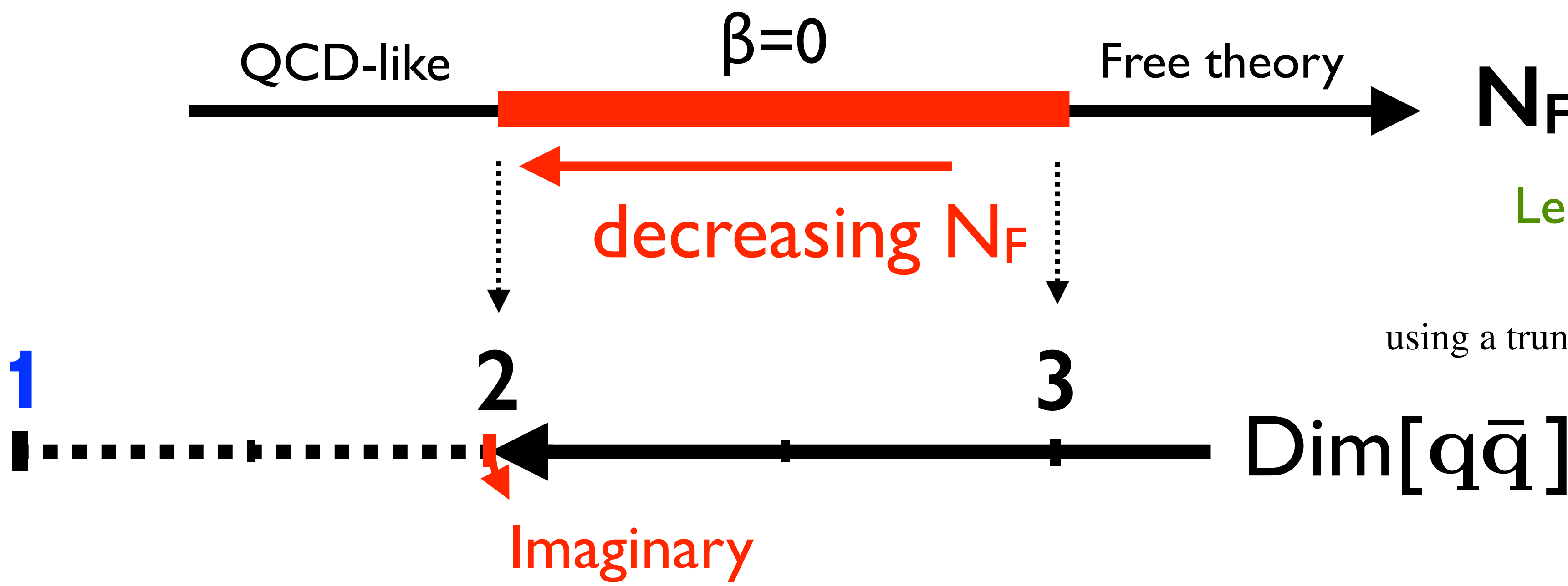

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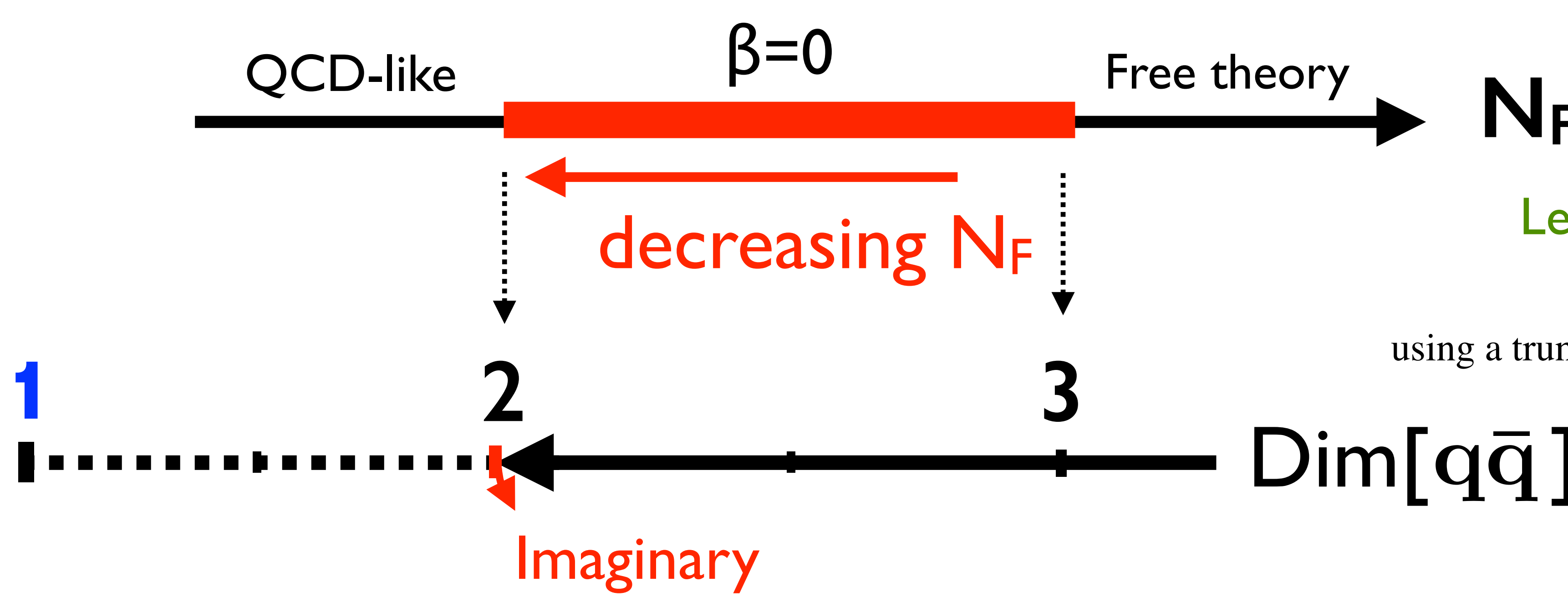

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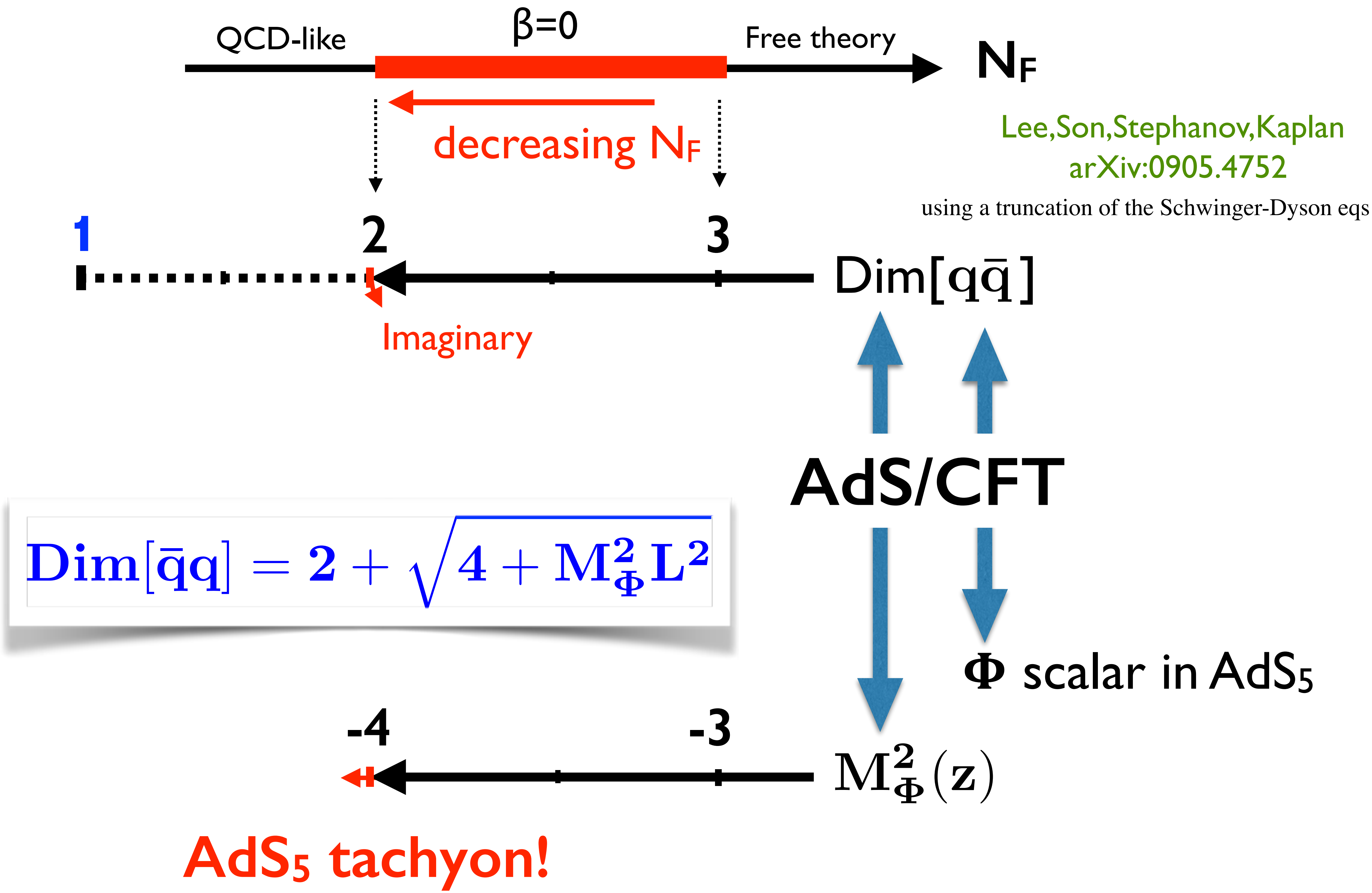
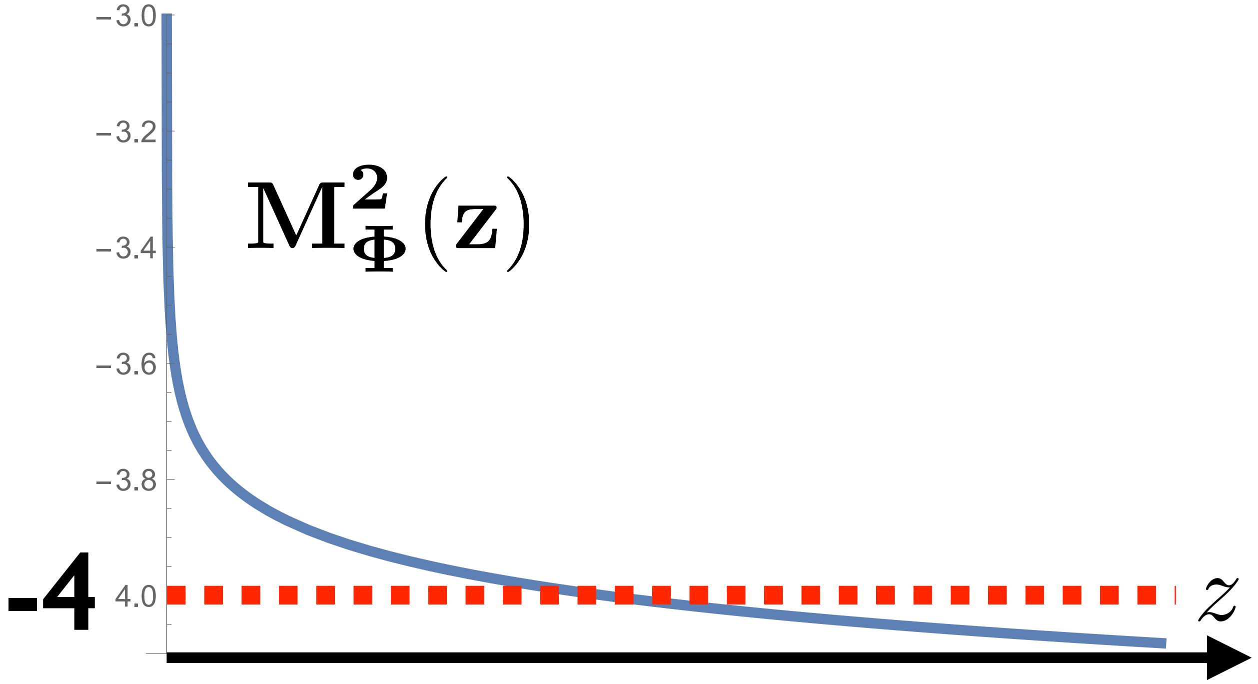
Imaginary when M_Φ goes below the BF bound ($M_\Phi^2 = -4/L^2$)

☛ AdS tachyon!

Conformal breaking as N_F decreases



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



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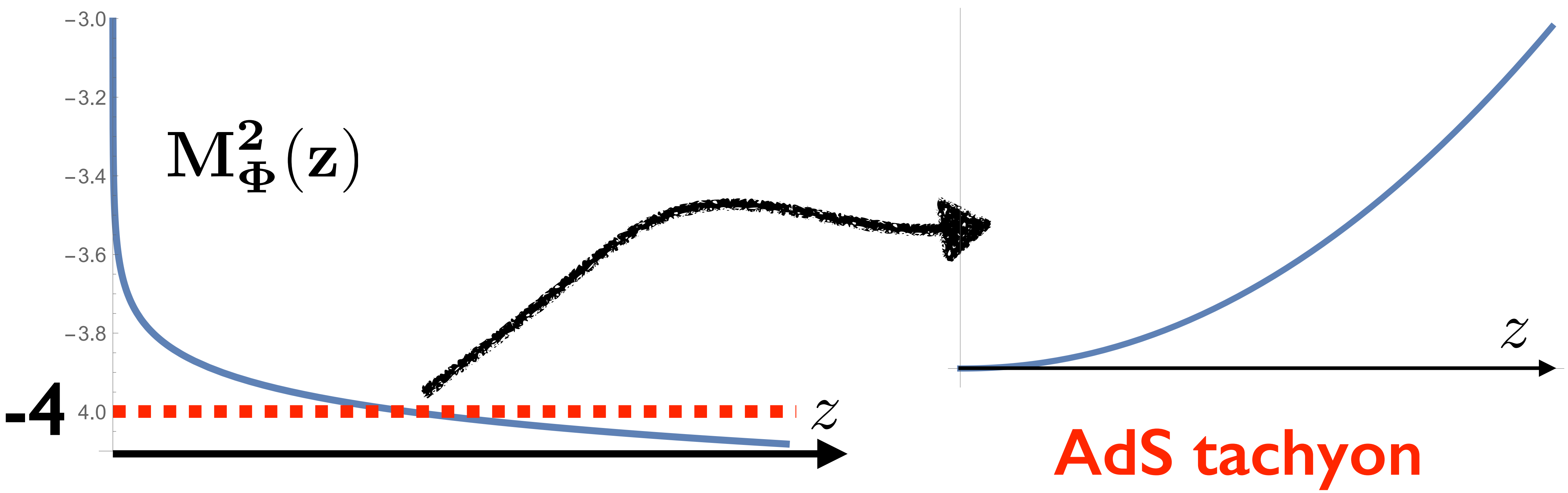

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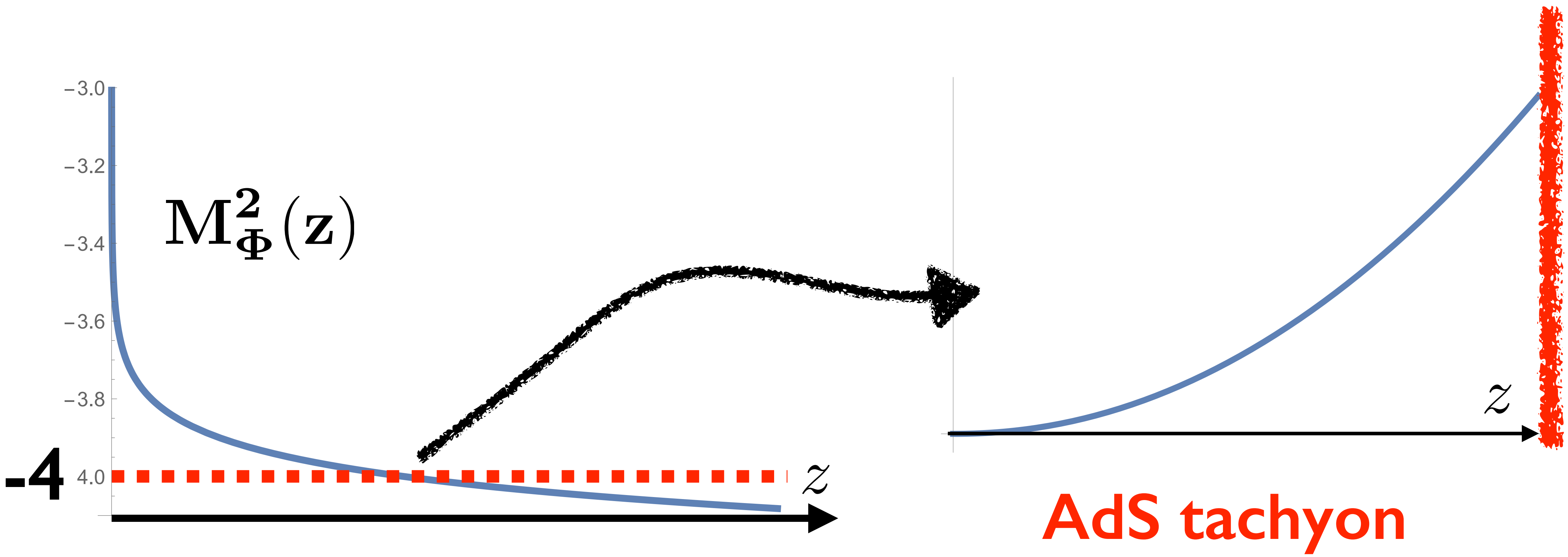


- We **regularize the IR with a brane**, and include the metric back-reaction from the tachyon:
  - ☛ Necessary to understand the dilaton/radion mass

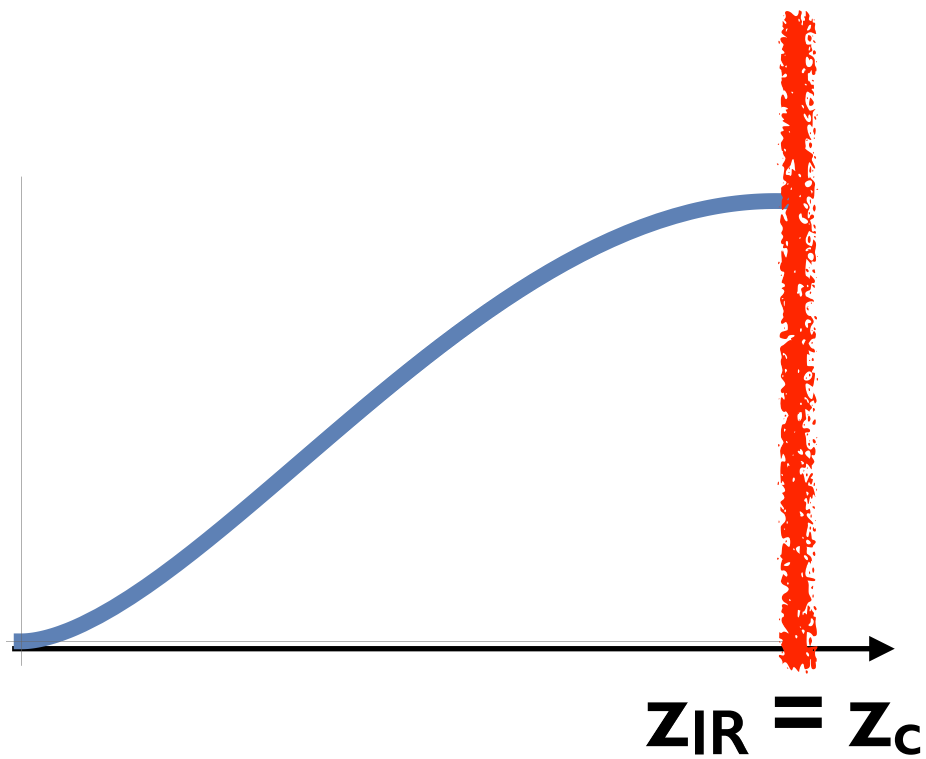
The position of the brane is dynamical: Indeed a minimum exits!

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 $\mathbf{z_{IR}=z_c}$:



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

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

(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**

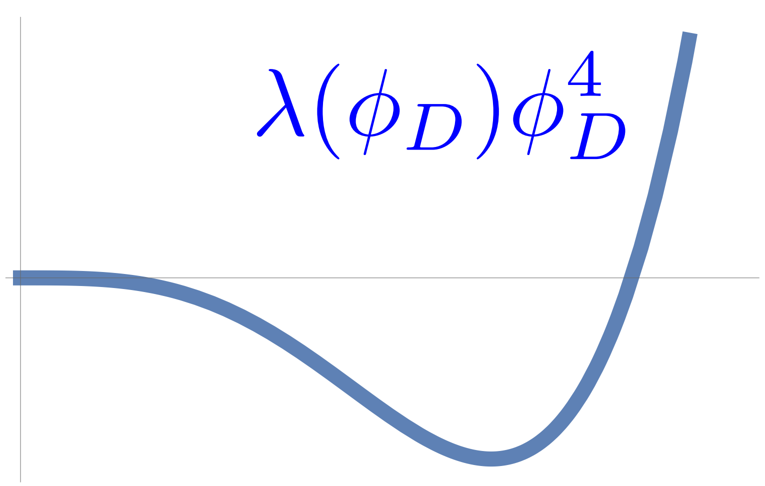
$$V_{\rm eff}(\phi) = -\frac{1}{2} m^2(\phi_D)\phi^2\phi_D^2 + \frac{1}{4}\lambda_\phi \phi^4 + \frac{1}{4}\lambda_D \phi_D^4$$

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

boundary mass

Integrating out the tachyon

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

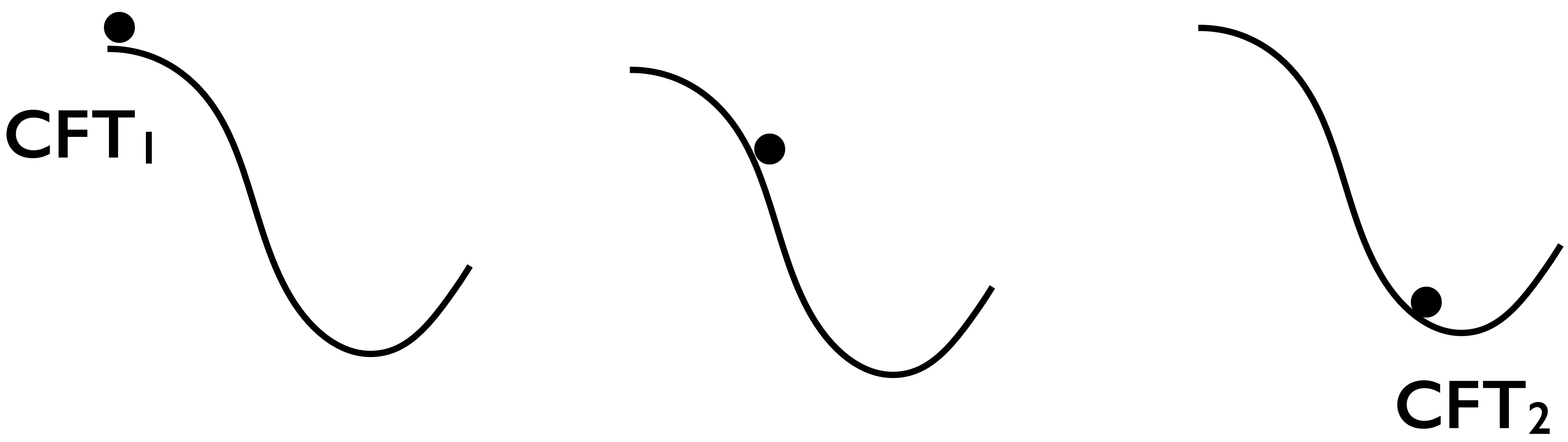


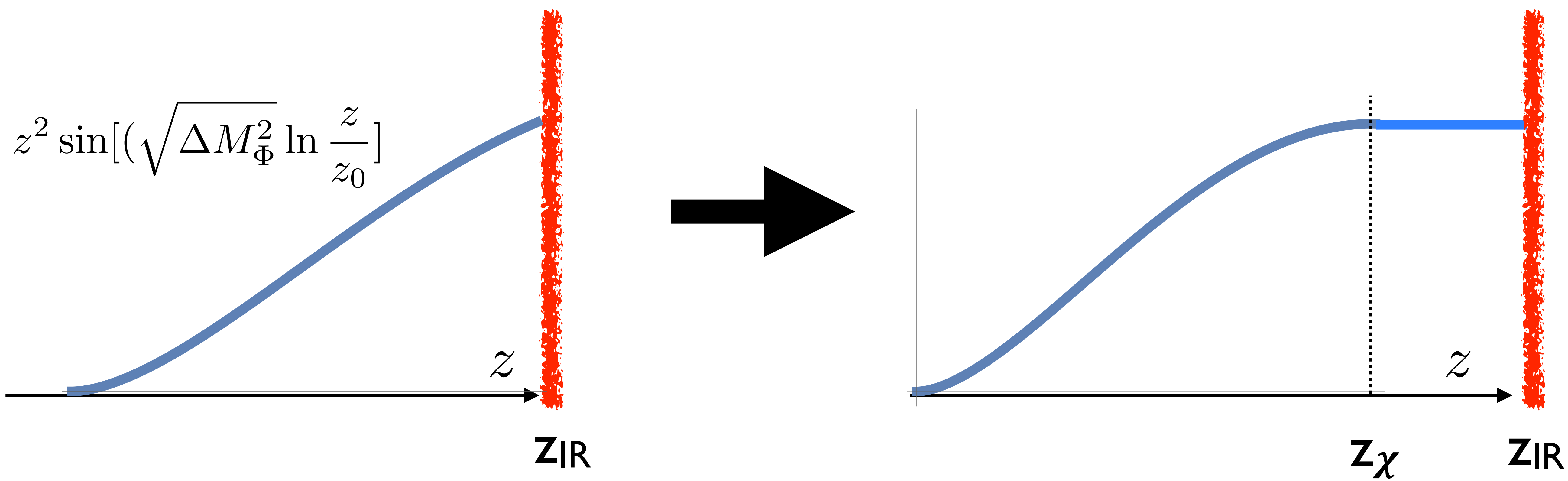
$$m_{\phi_D}^2 \sim \beta < 4$$

tachyon VEV ≳ dilaton VEV

(not supporting arXiv:1804.00004)

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





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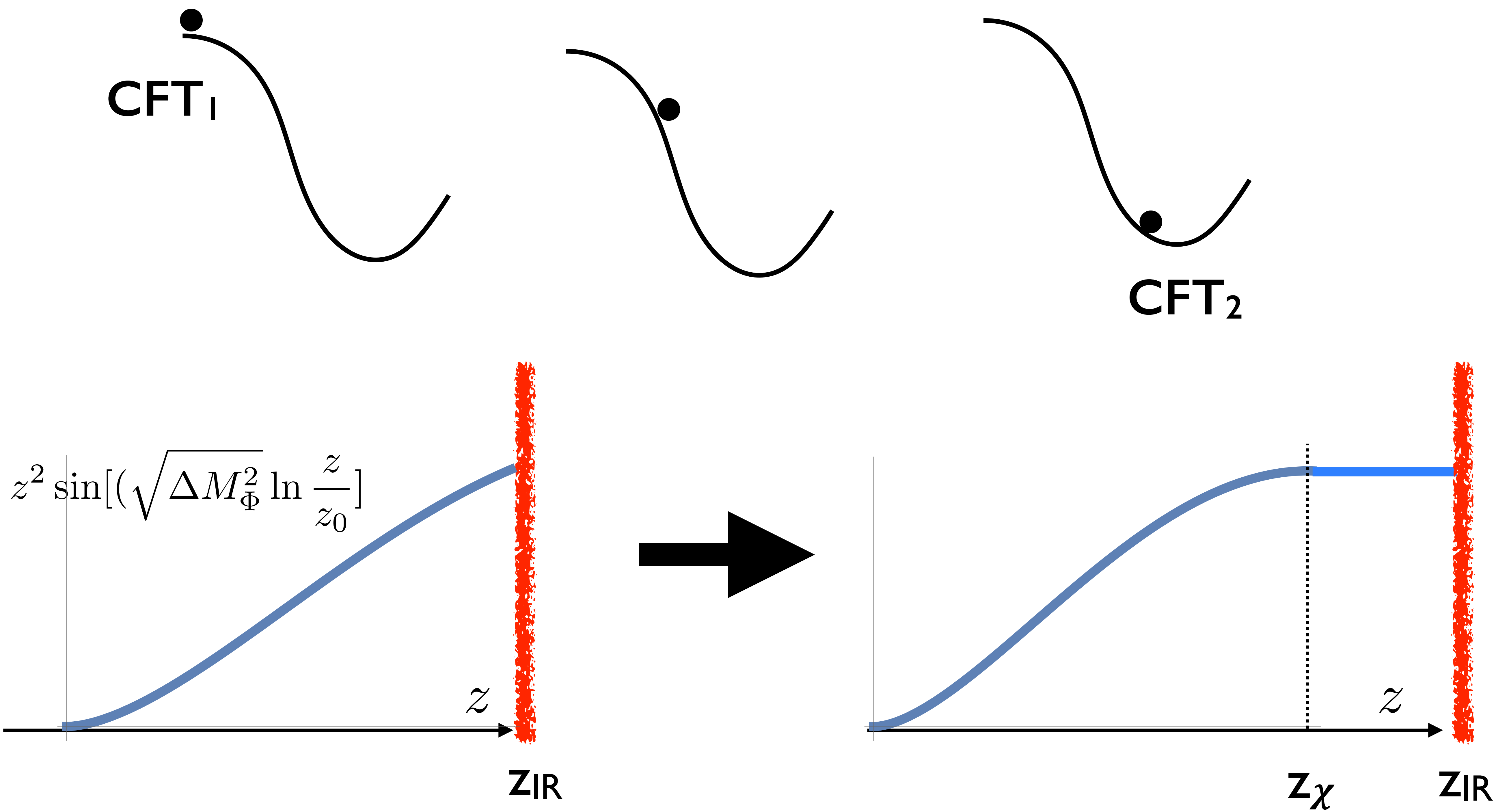

chiral breaking scale >> confinement scale

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

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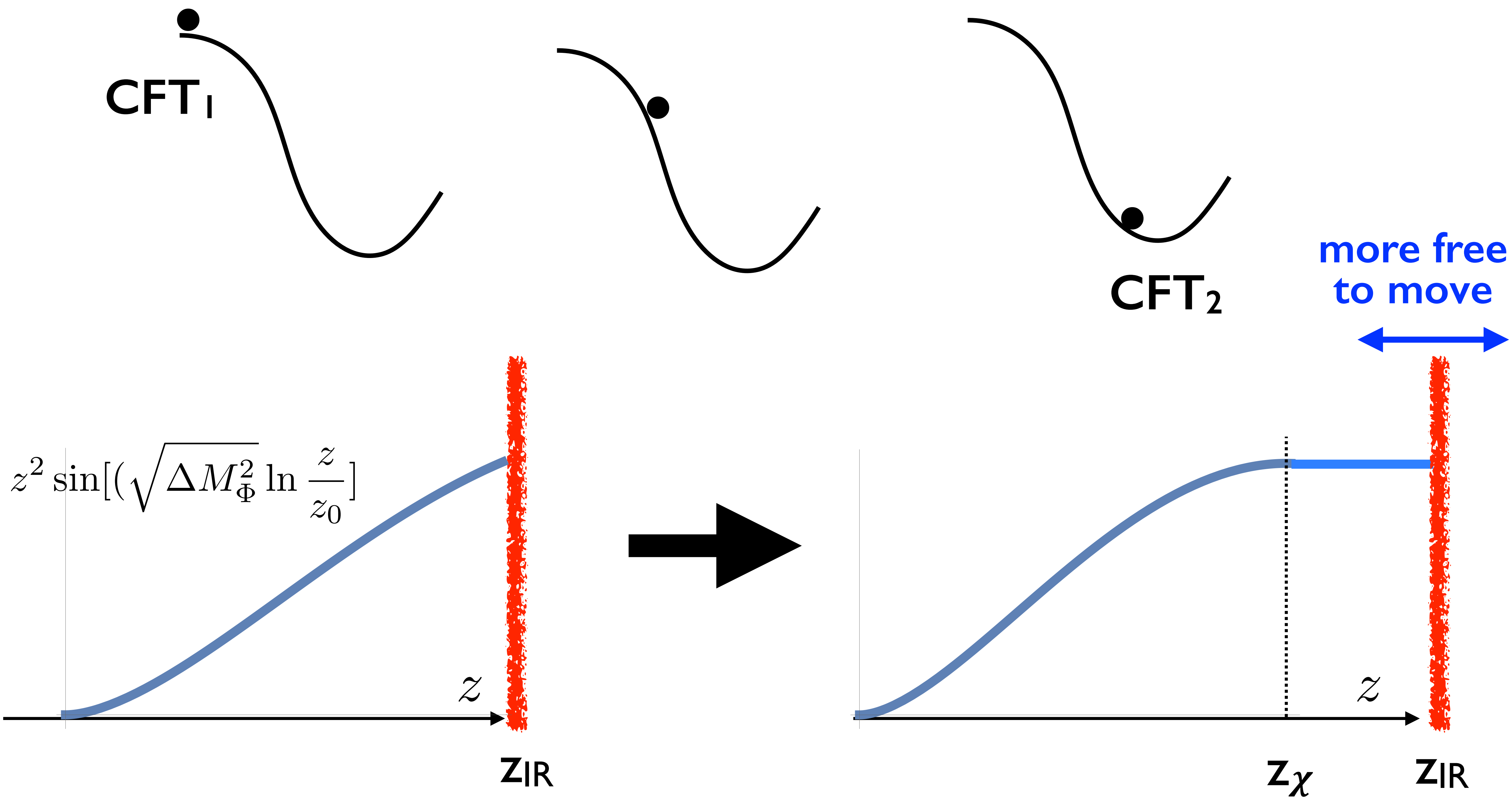

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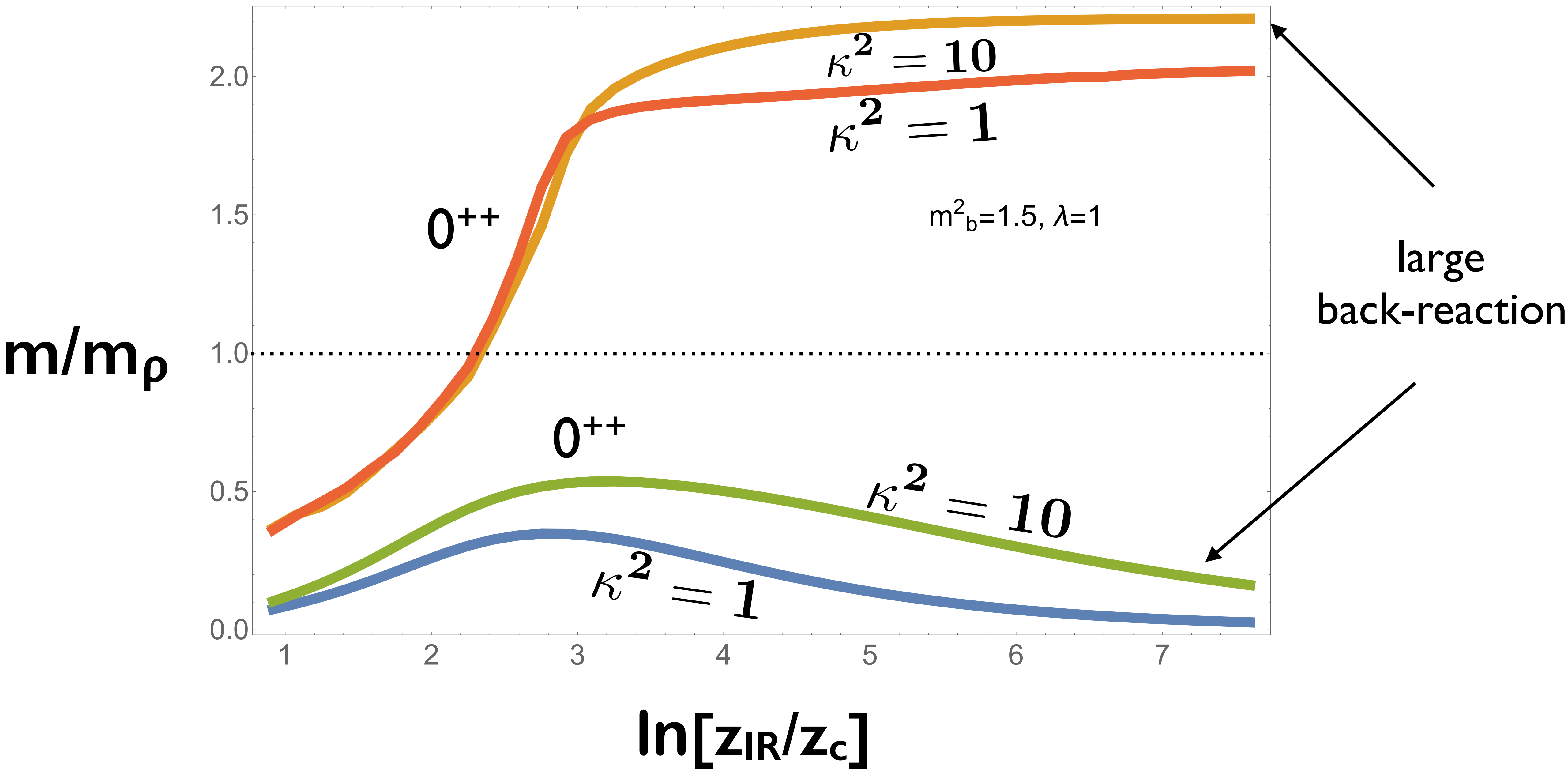


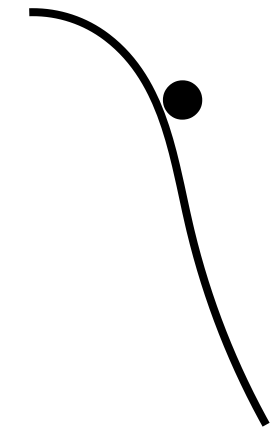
m/mρ
ln[zIR/zc]
0++
κ² = 10
κ² = 1
m²b=1.5, λ=1
large
back-reaction
0++
κ² = 10
κ² = 1
2.0
1.5
1.0
0.5
0.0
1
2
3
4
5
6
7

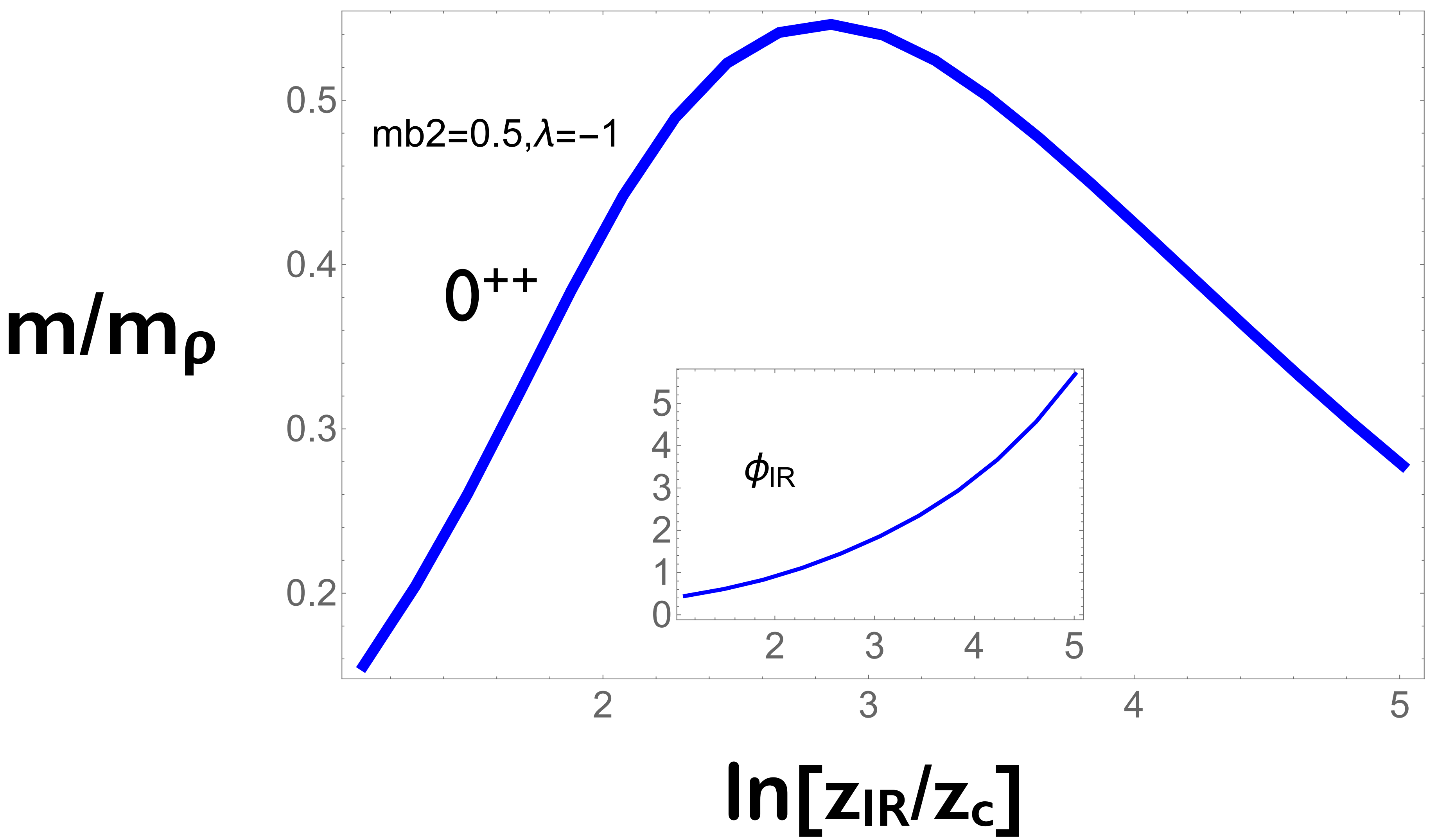
In proper coordinates:

$$ds^2 = e^{-2A}dx^2 - dy^2$$

$$\begin{cases} m^2_{\phi_D} \simeq -\dfrac{\kappa^2}{3}\left(\dfrac{m_b^4\phi^2 - \phi\partial_\phi V}{2\dot{A}} + 2m_b^2\phi^2\right)\Bigg|_{\mathrm{IR}} \dfrac{\partial_{y_{\mathrm{IR}}}\phi_{\mathrm{IR}}}{\phi_{\mathrm{IR}}} \\[2em] m^2_\rho \simeq \left(\dfrac{3\pi}{4}\,\dot{A}|_{\mathrm{IR}}\right)^2 \qquad \dot{A} = \sqrt{1 + \dfrac{\kappa^2}{12}\Big(\dfrac{\dot{\phi}^2}{2} - V(\phi)\Big)} \end{cases}$$

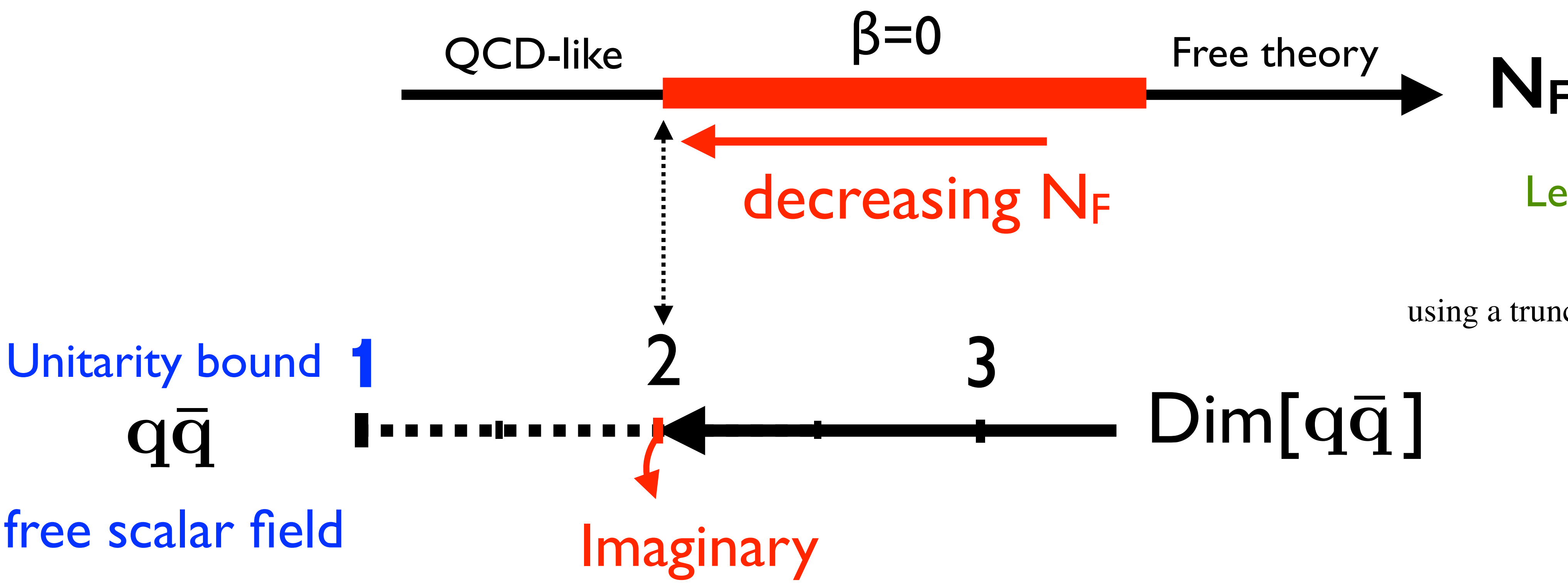
The potential do not need to have a minimum (λ<0), if strong back-reaction, but this always leads to a **lighter dilaton**





☛ Always a light scalar (mostly dilaton) !

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



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arXiv:0905.4752

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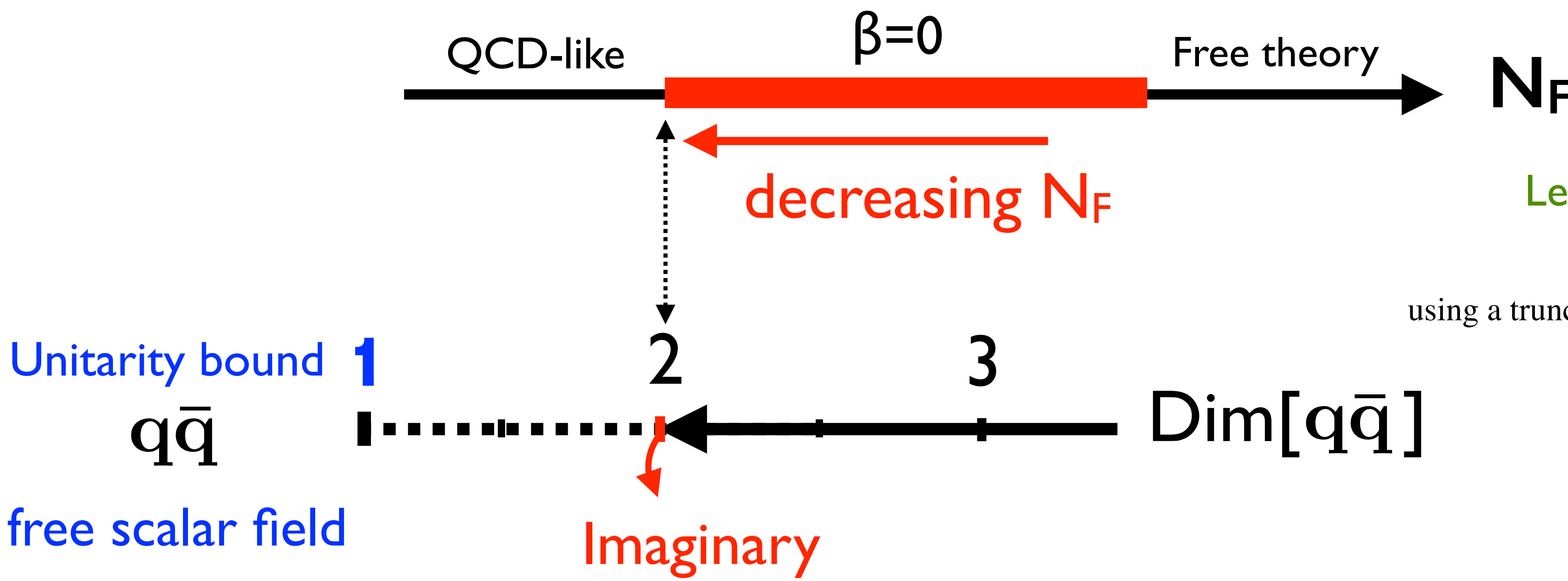

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Closest point to a free scalar!

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

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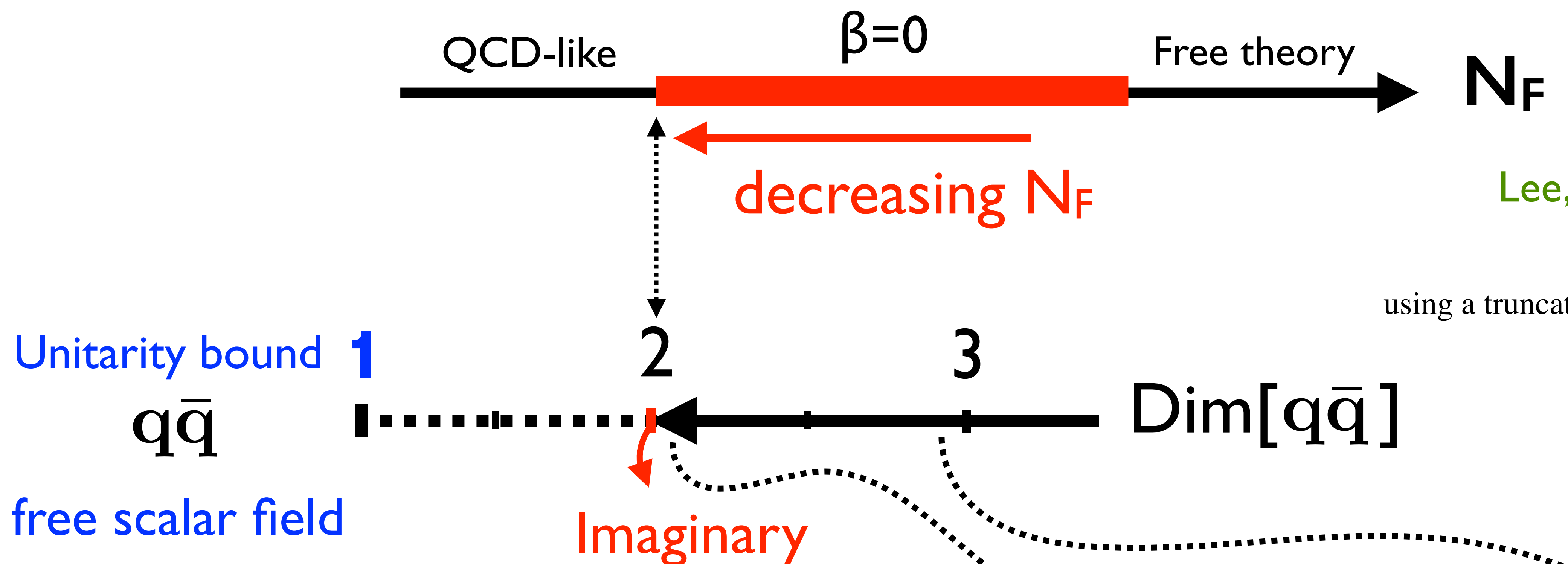

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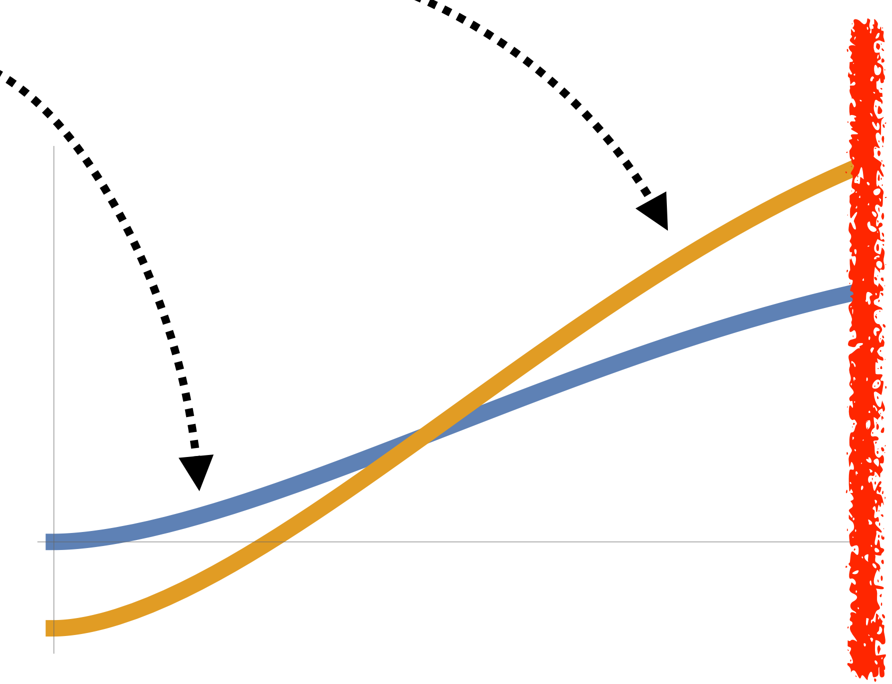
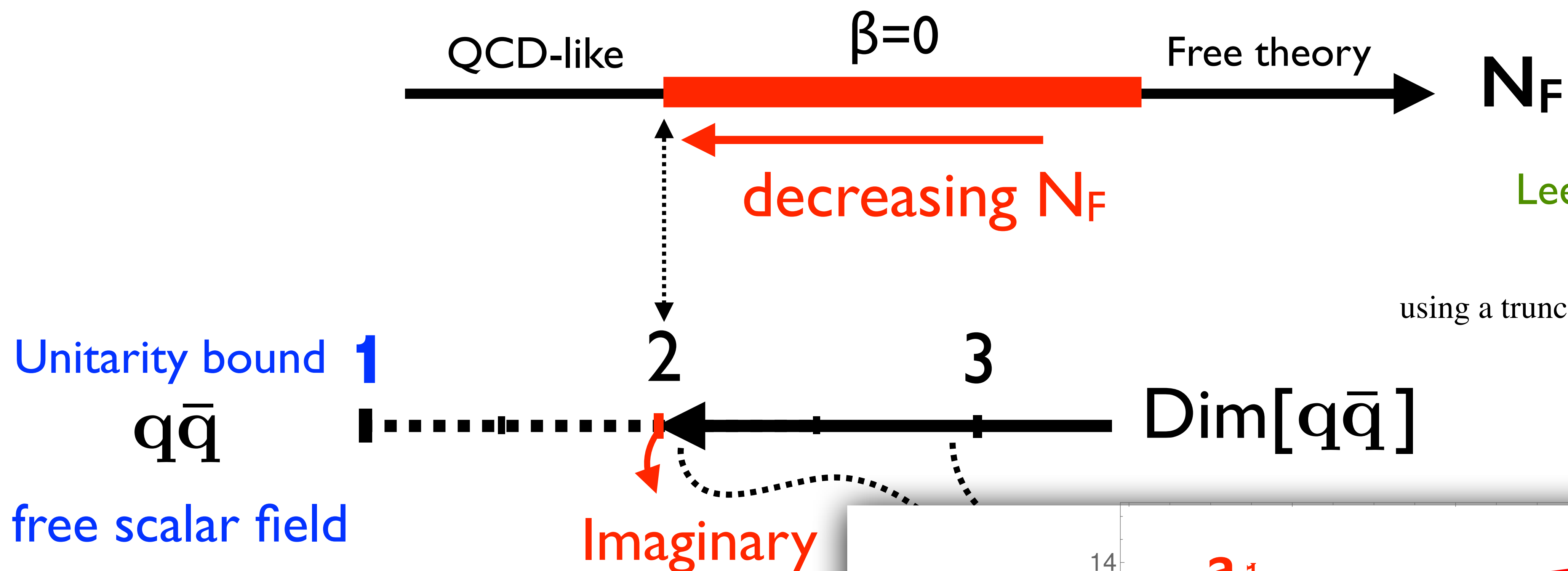


Geometrical interpretation

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



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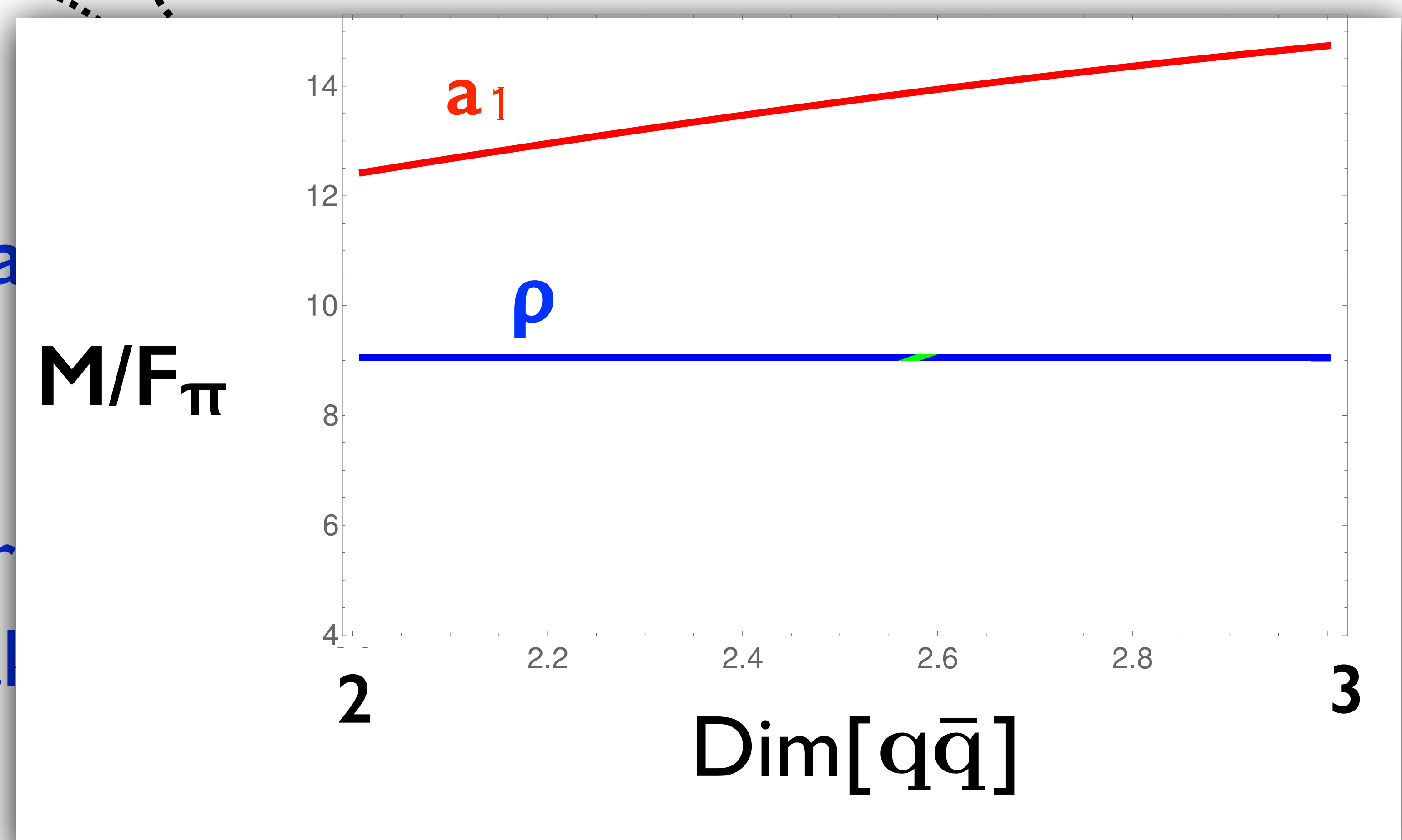


More AdS$_5$ predictions

Splitting Adj & singlet in the scalar sector:

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

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

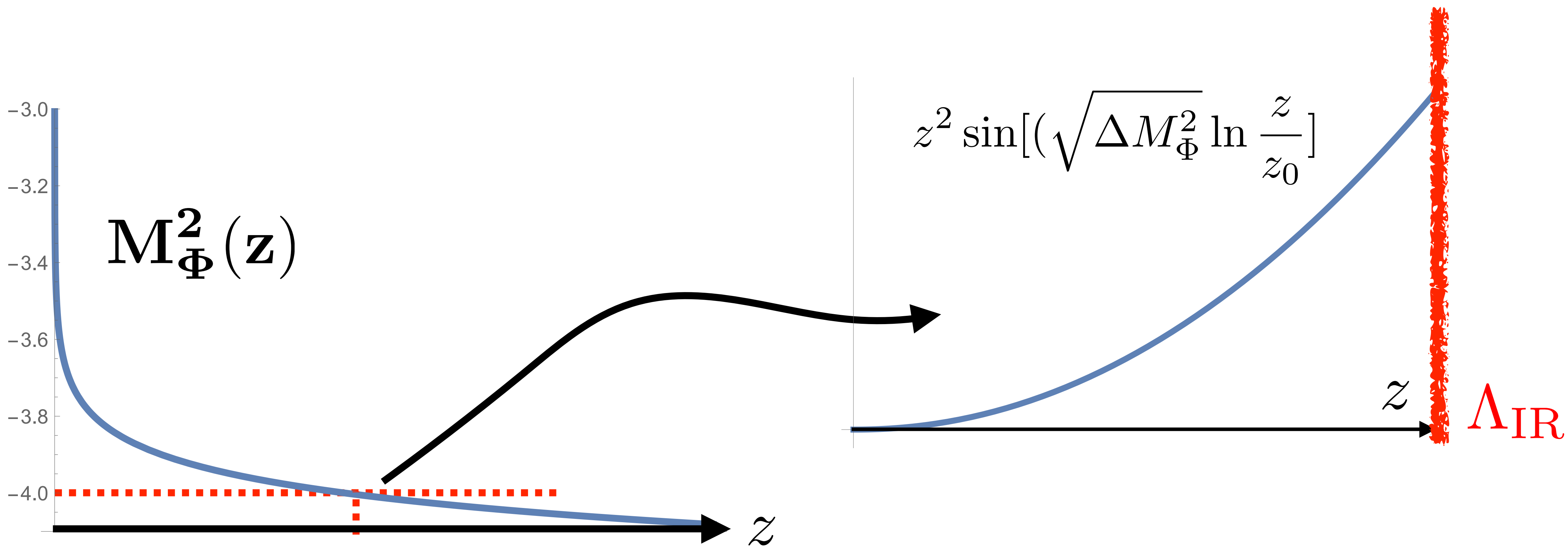
$$m_\rho \simeq m_\omega \quad \& \quad m_{a_1} \simeq m_{f_1}$$

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

Implications for the hierarchy problem

Nice scenarios to solve the hierarchy problem:

Tachyon in AdS puts you out from a CFT



Hierarchy controlled
by the "slow-rolling" of $\mathbf{M_\Phi}$
(stable under radiative corrections)

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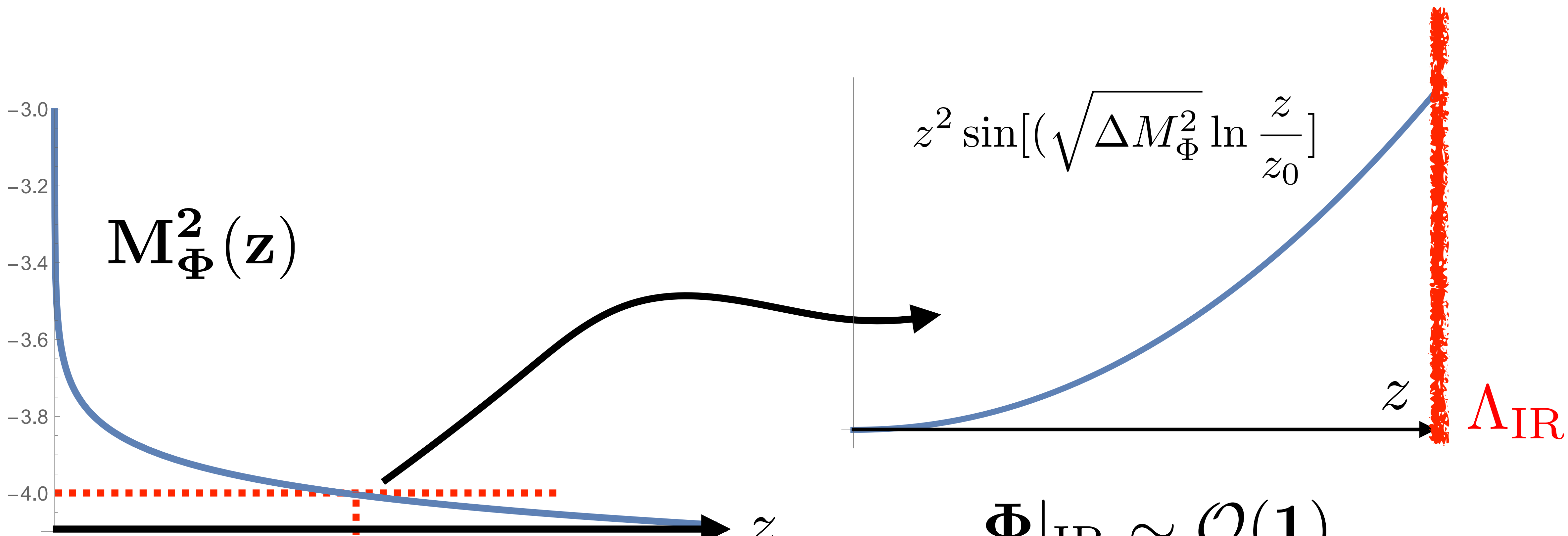

$$\mathbf{\Phi}|_{\rm IR} \sim \mathcal{O}(\mathbf{1})$$

$$\Delta M^2_\phi \equiv -4 - M^2_\phi$$

$$\boxed{\mathbf{\Lambda_{\rm IR} \sim \Lambda_{\rm UV}\, e^{-\pi/\sqrt{\Delta M^2_\phi}}}}$$

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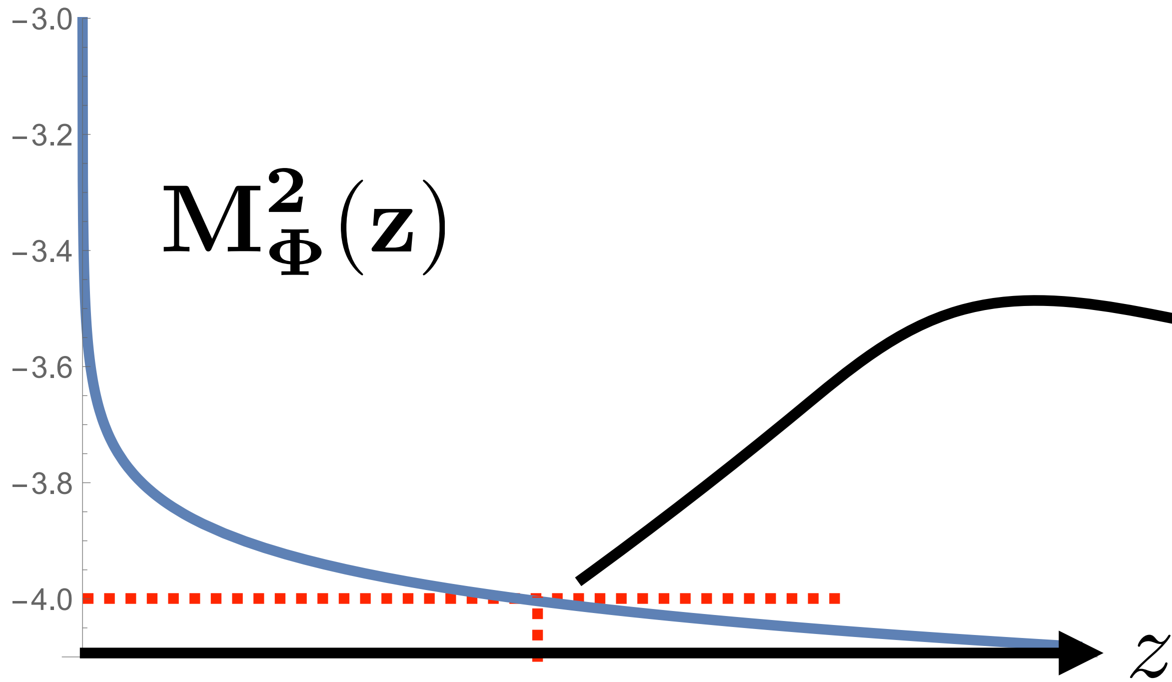

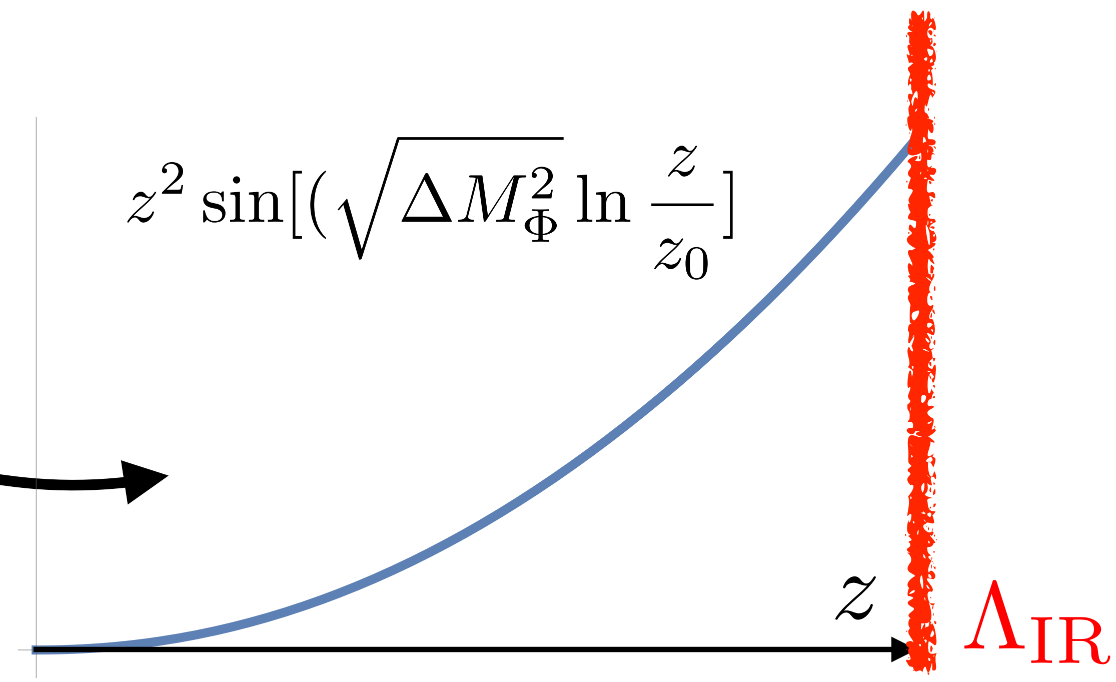

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BKT transition

Could this lighter scalar be the Higgs? Resurrecting Technicolor?

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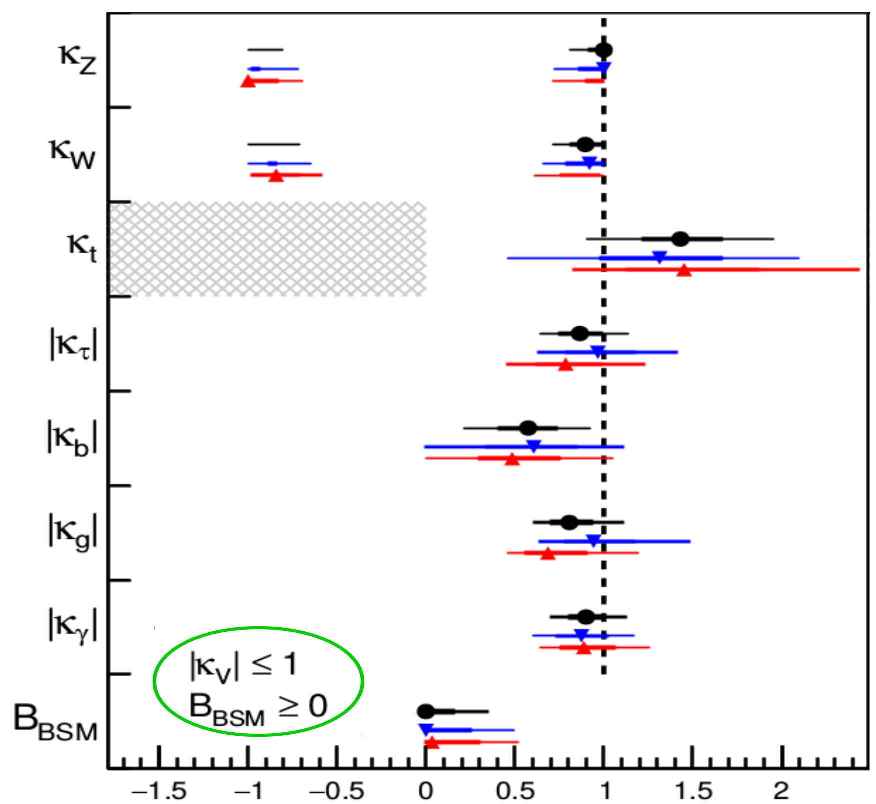
Mass? Not light enough

For $M_{TC\text{-}\rho} \sim 3$ TeV,
we need a reduction, in squared masses, of ~ 0.002

Higgs-like coupling? Hardly compatible with present measurements

$$\kappa_i = \frac{g_{Hii}}{g_{Hii}^{\rm SM}}$$



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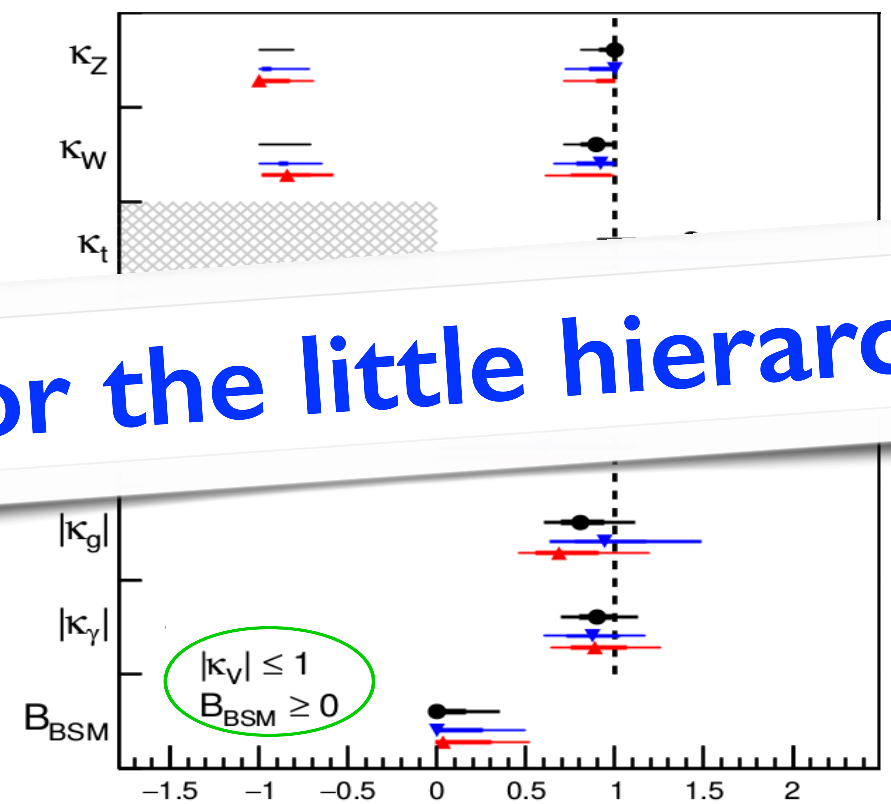
Mass? Not light enough

For $M_{TC\text{-}\rho} \sim 3$ TeV,
we need a reduction, in squared masses, of ~ 0.002

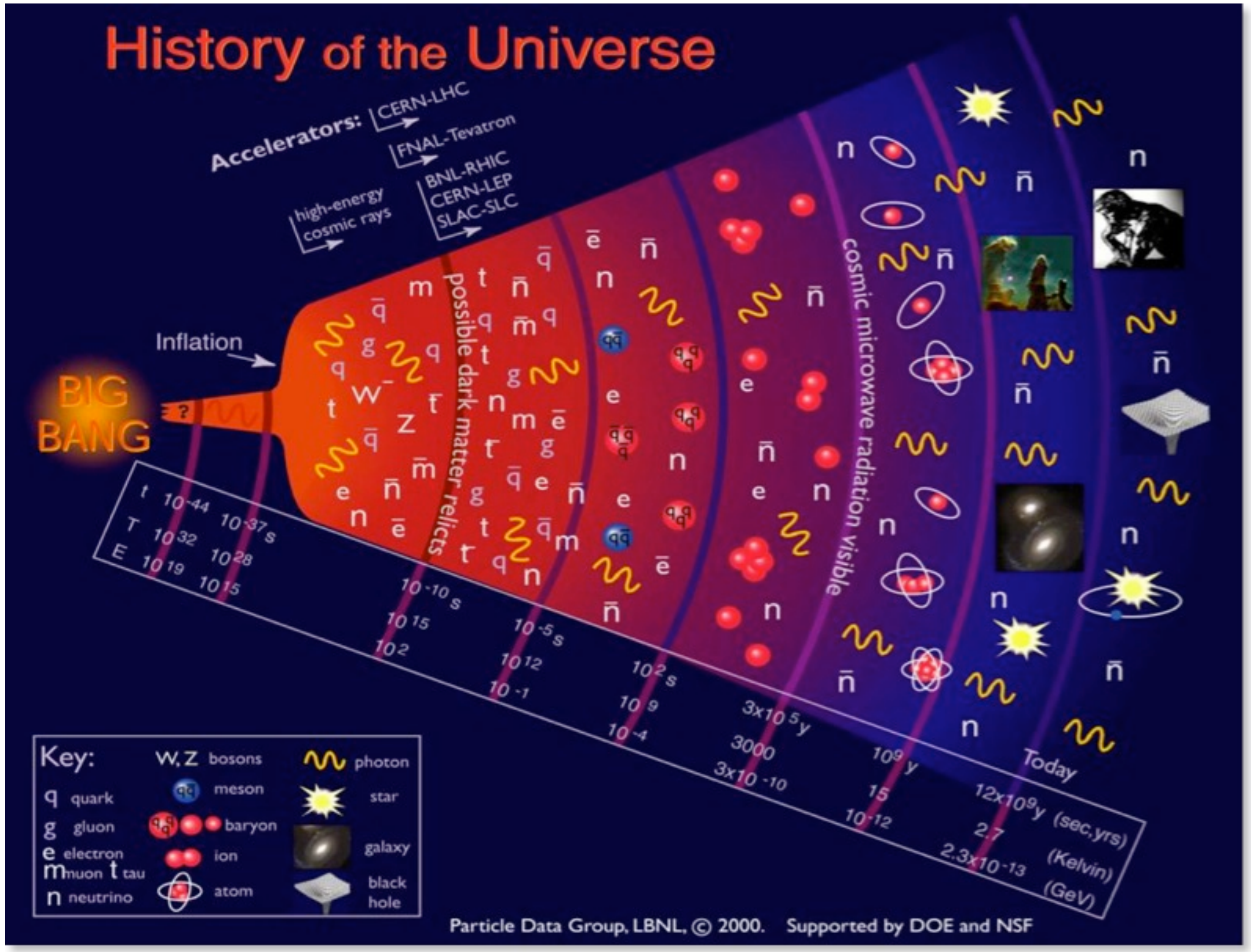
Higgs-like coupling? Hardly compatible with present measurements

$$\kappa_i = \frac{g_{Hii}}{g_{Hii}^{\rm SM}}$$



but relevant for the little hierarchy problem?

Implications in the cosmological history

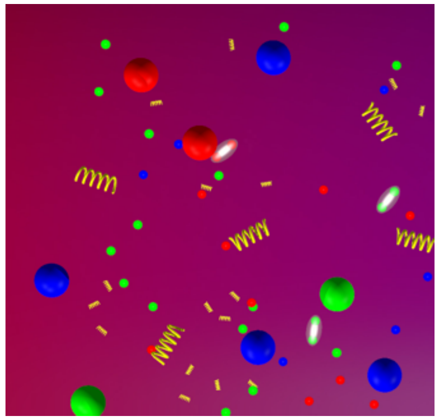


preliminary work with P.Baratella and F. Rompineve

After inflation, reheating, …, big bang

T

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



"quark-gluon" plasma

TeV

After inflation, reheating, …, big bang

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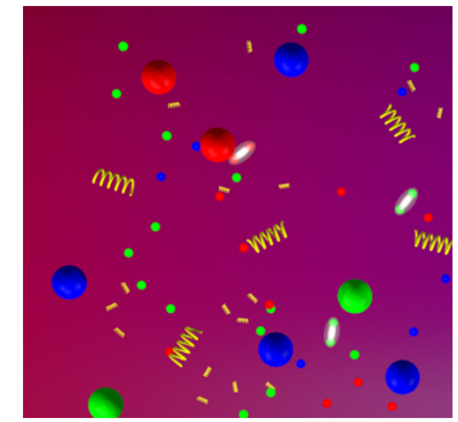
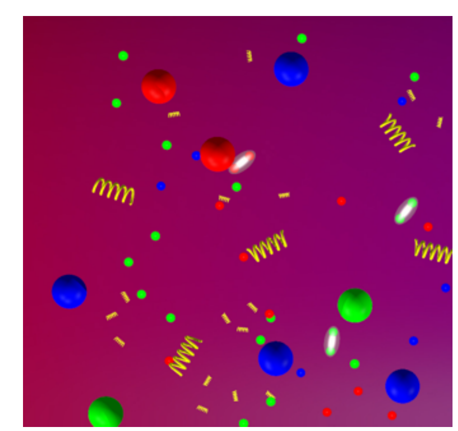


TeV

Confined phase of the new strong sector ?

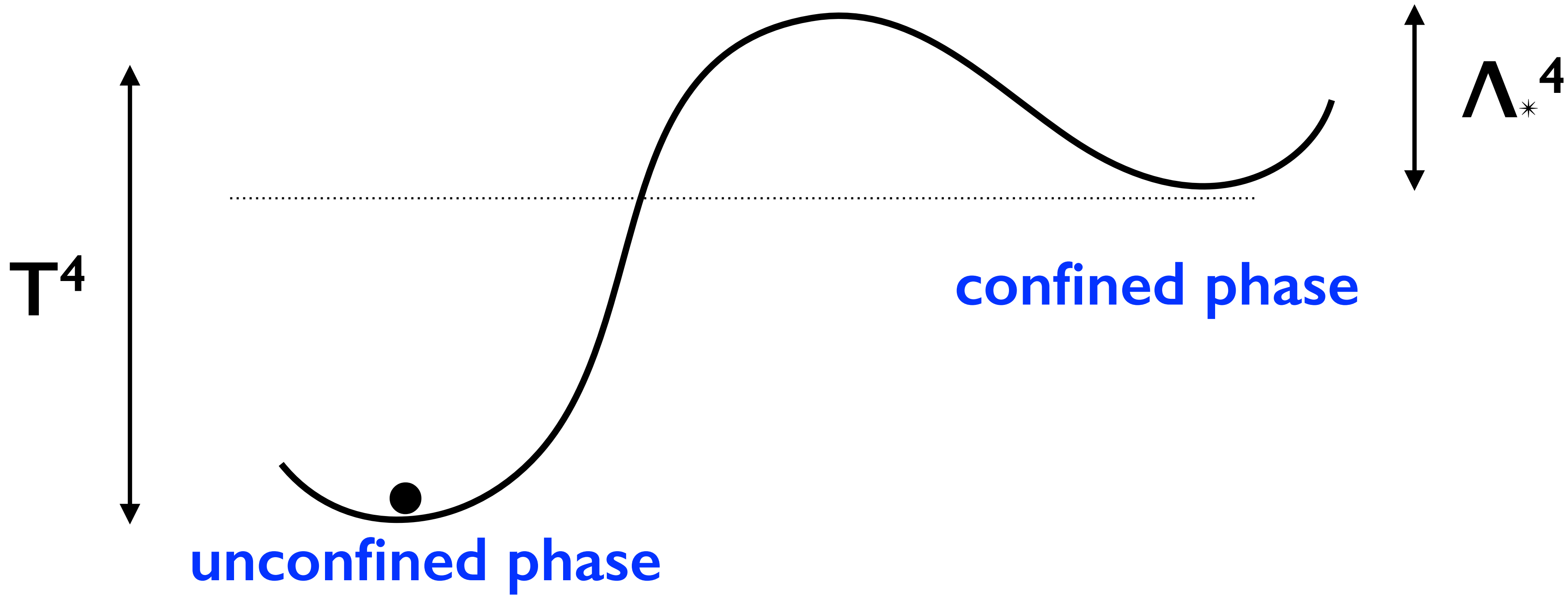
No, for large N_c theories

Supercooling



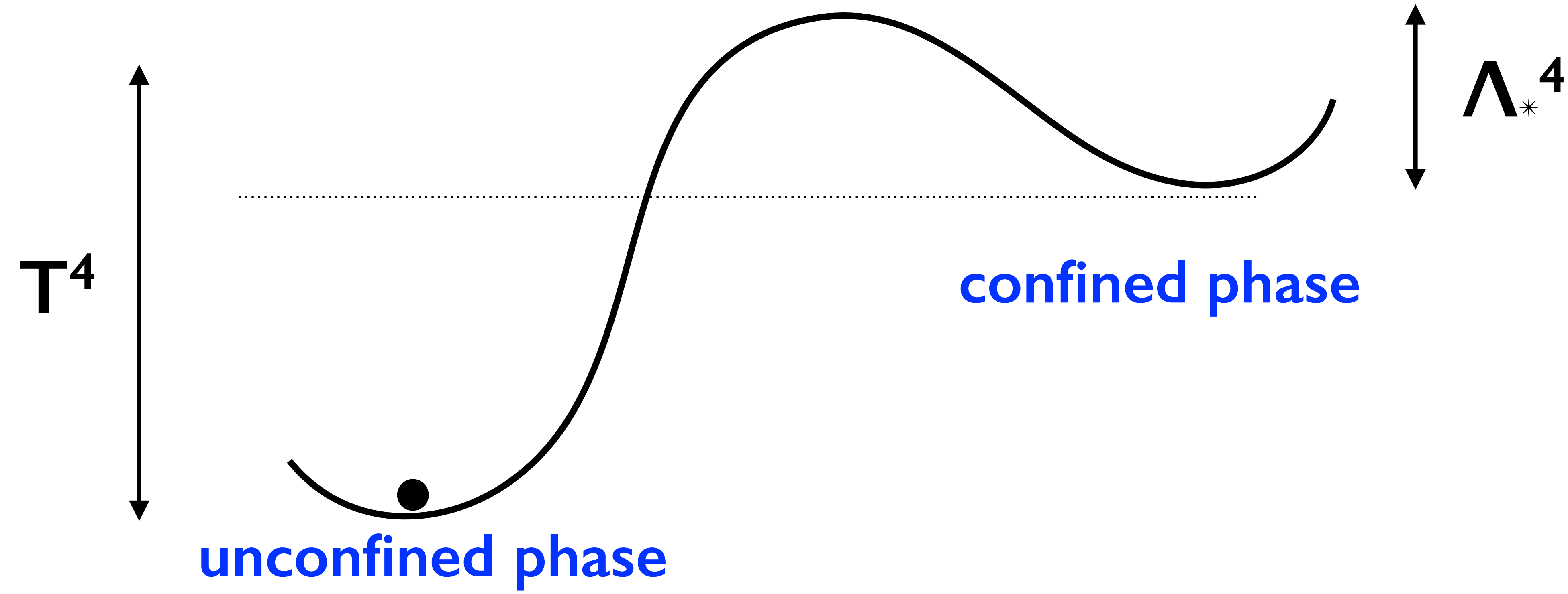
$$\mathbf{F = E - S\,T}$$

I) High T:

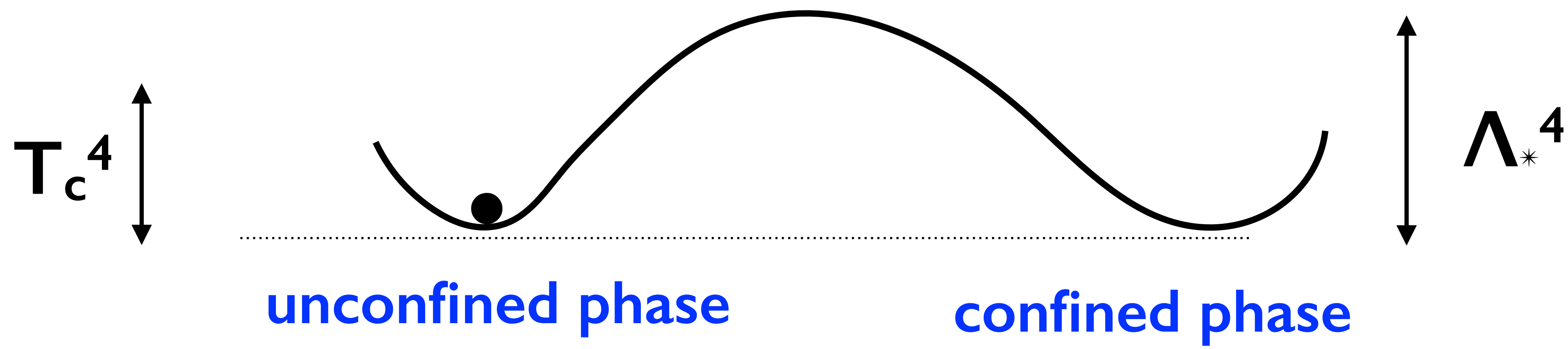


$$\mathbf{F = E - S\,T}$$

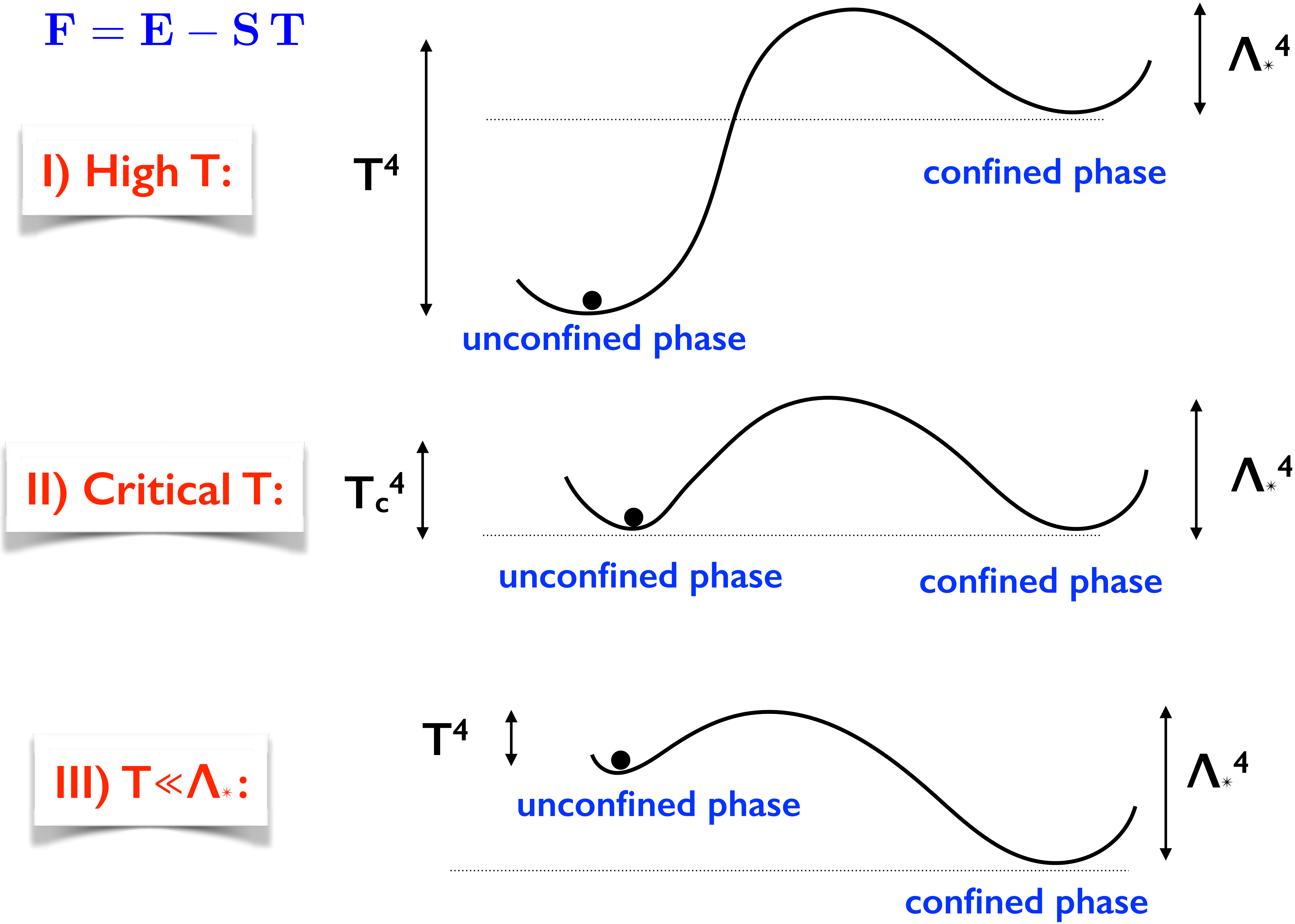
I) High T:

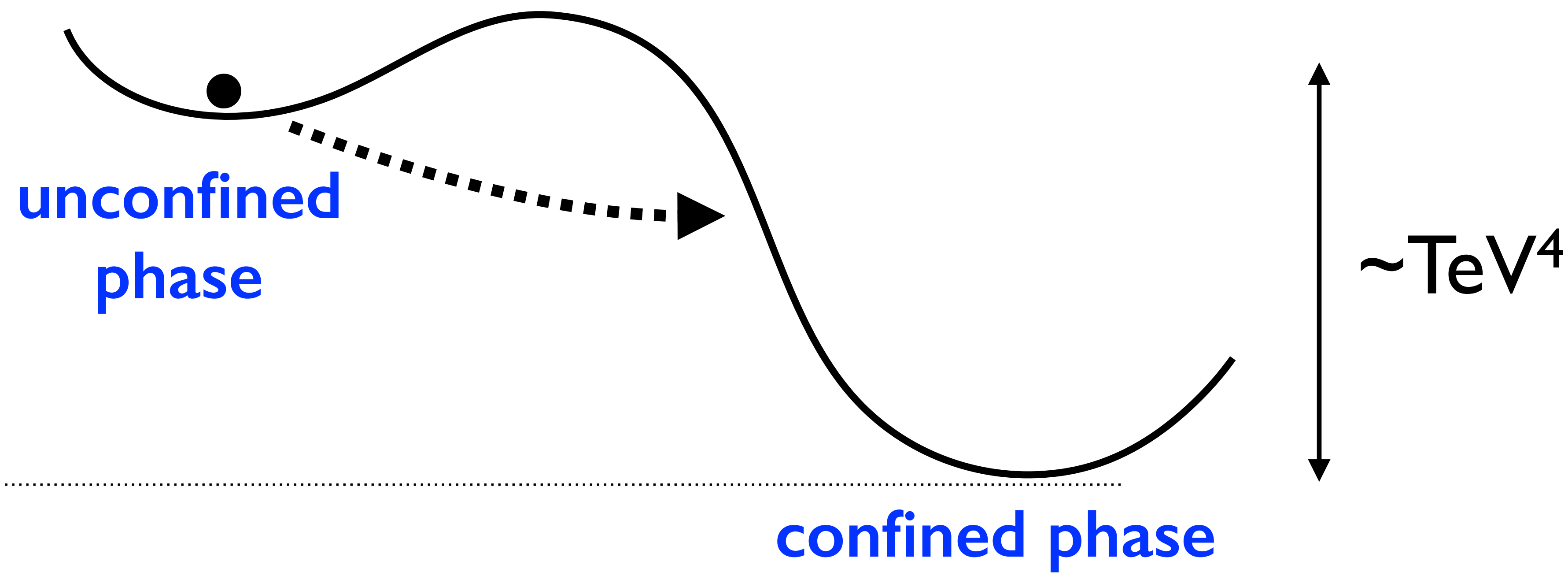


II) Critical T:



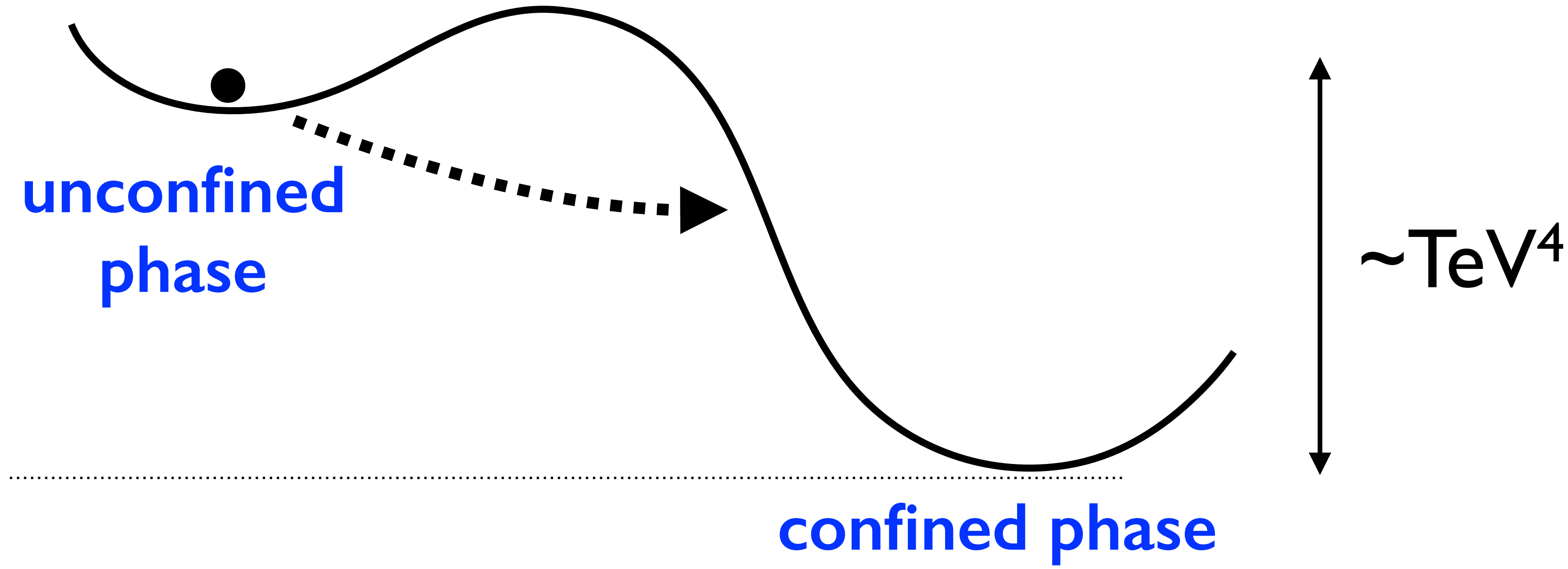
$$\mathbf{F = E - S\,T}$$


I) High T:
T^4
Λ_*^4
confined phase
unconfined phase
II) Critical T:
T_c^4
Λ_*^4
unconfined phase
confined phase
III) $T \ll \Lambda_*$:
T^4
Λ_*^4
unconfined phase
confined phase



Tunneling rate:

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

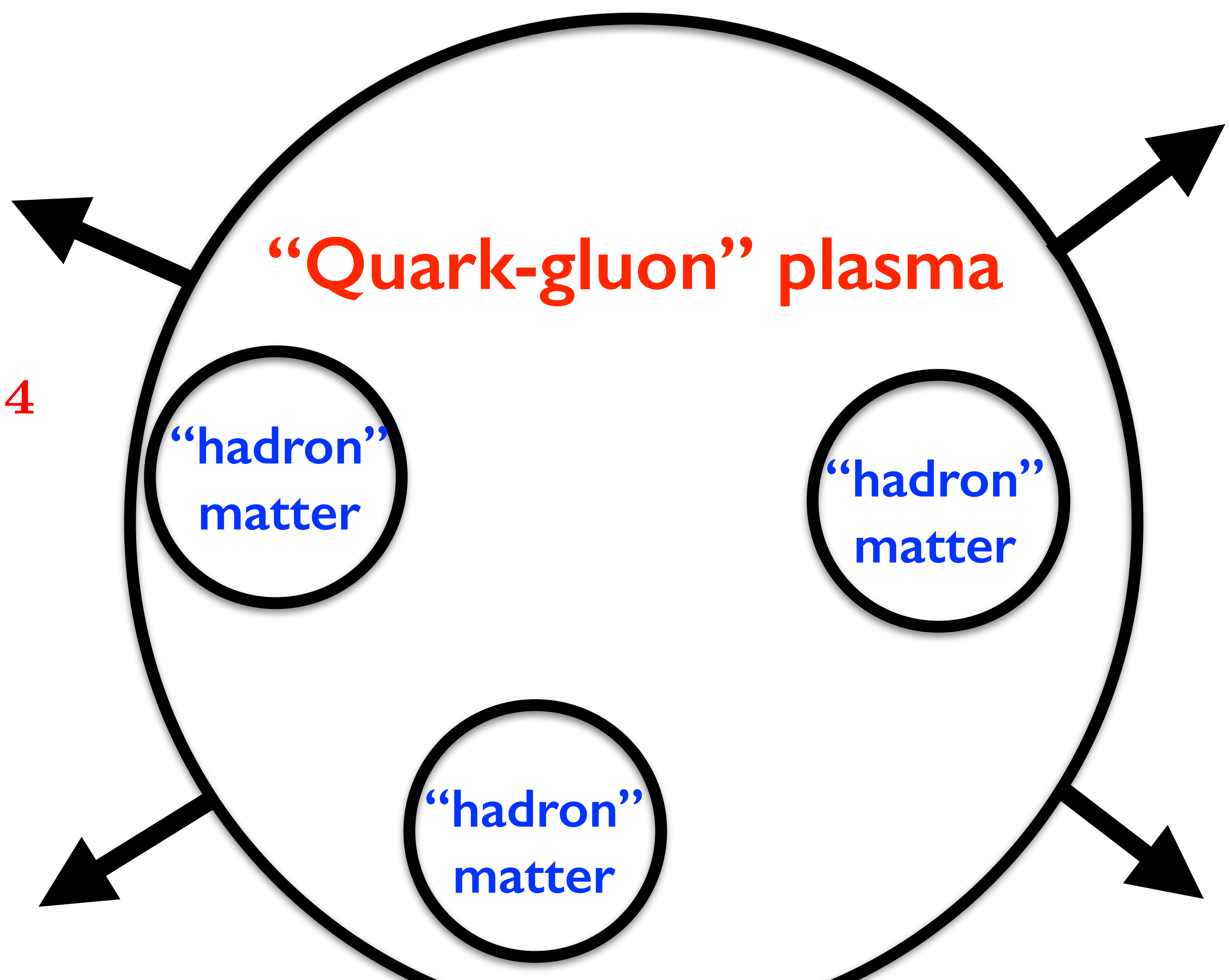


Tunneling rate:

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

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

No percolation!

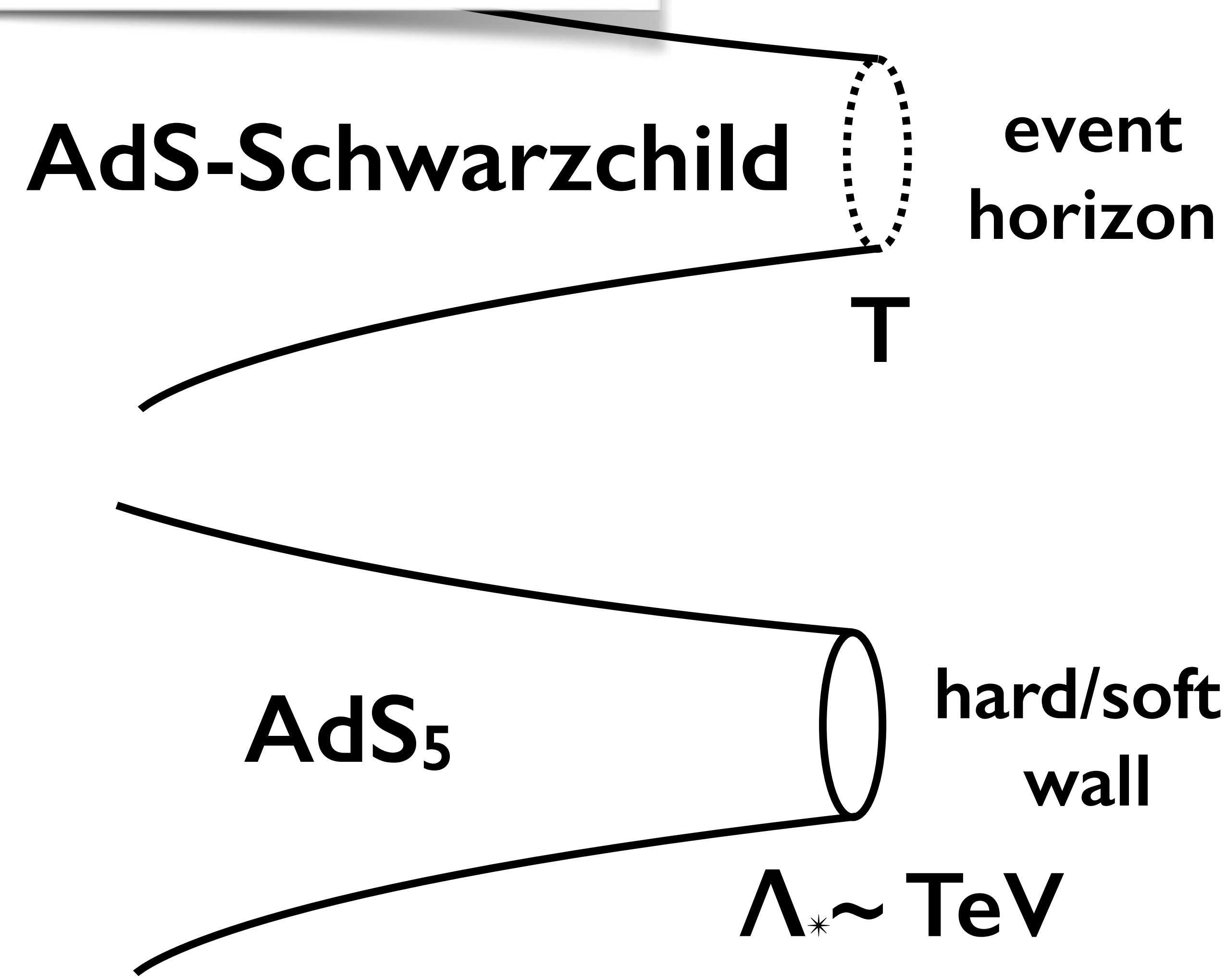


From holography: At finite-T, two solutions:

DeConfined phase:

Hawking-Page transition

Confined phase:

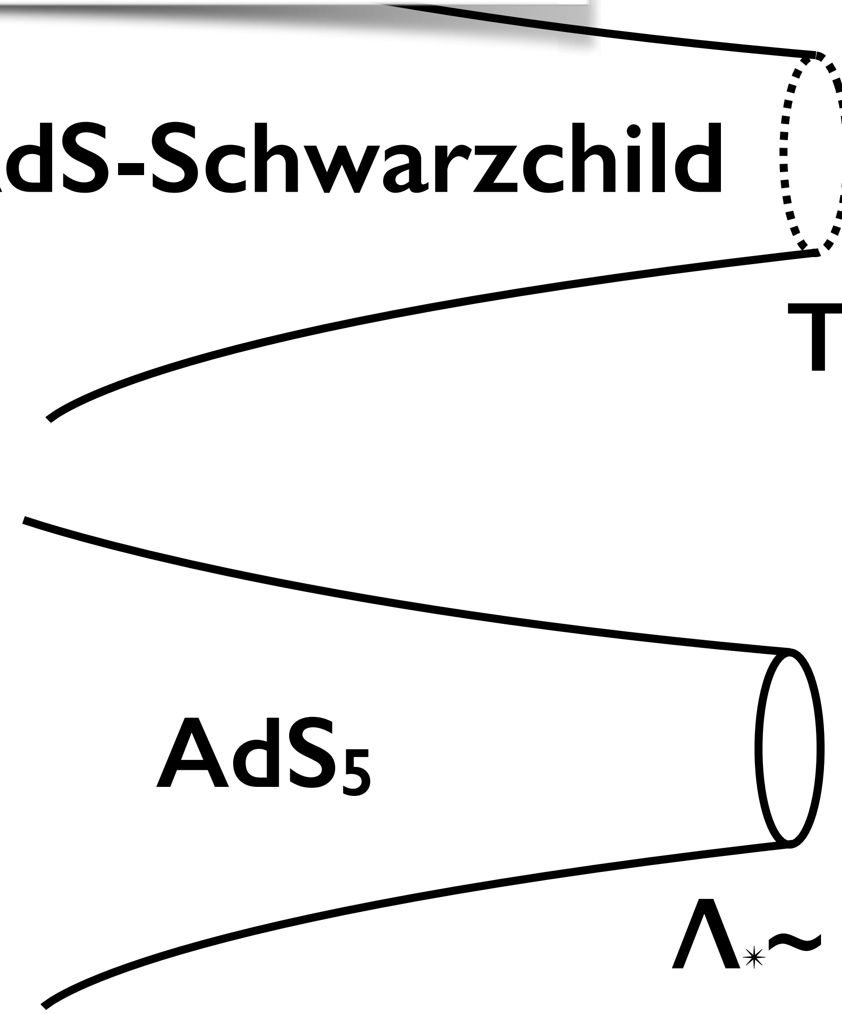


From holography: At finite-T, two solutions:

DeConfined phase: AdS-Schwarzchild

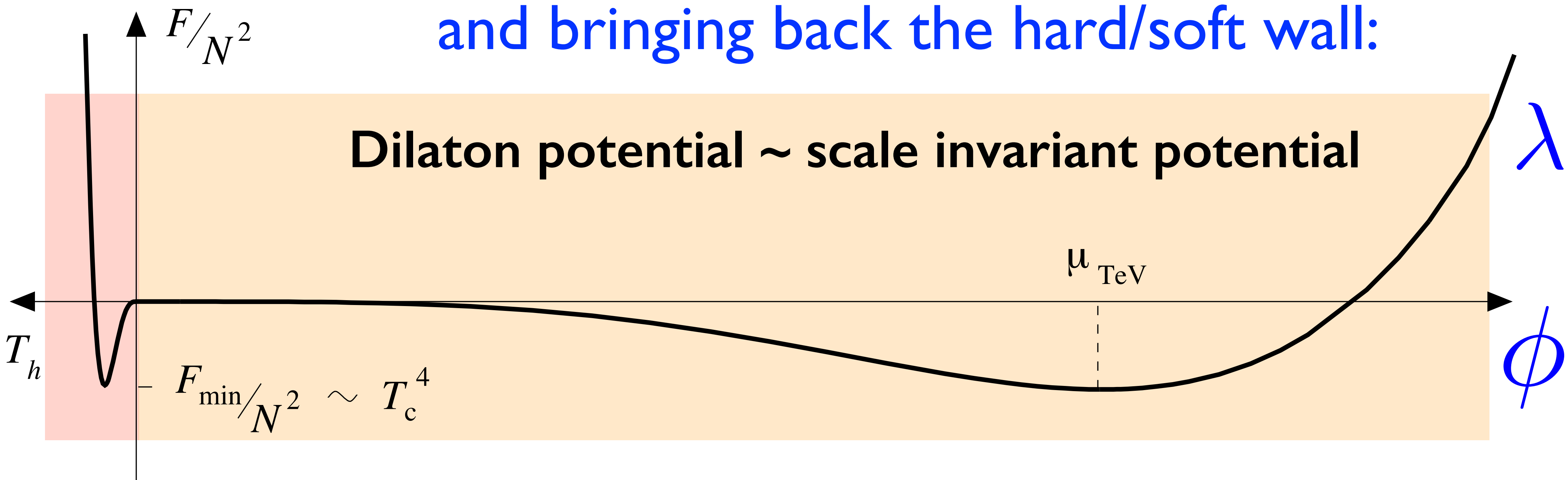
Hawking-Page transition

Confined phase: AdS_5

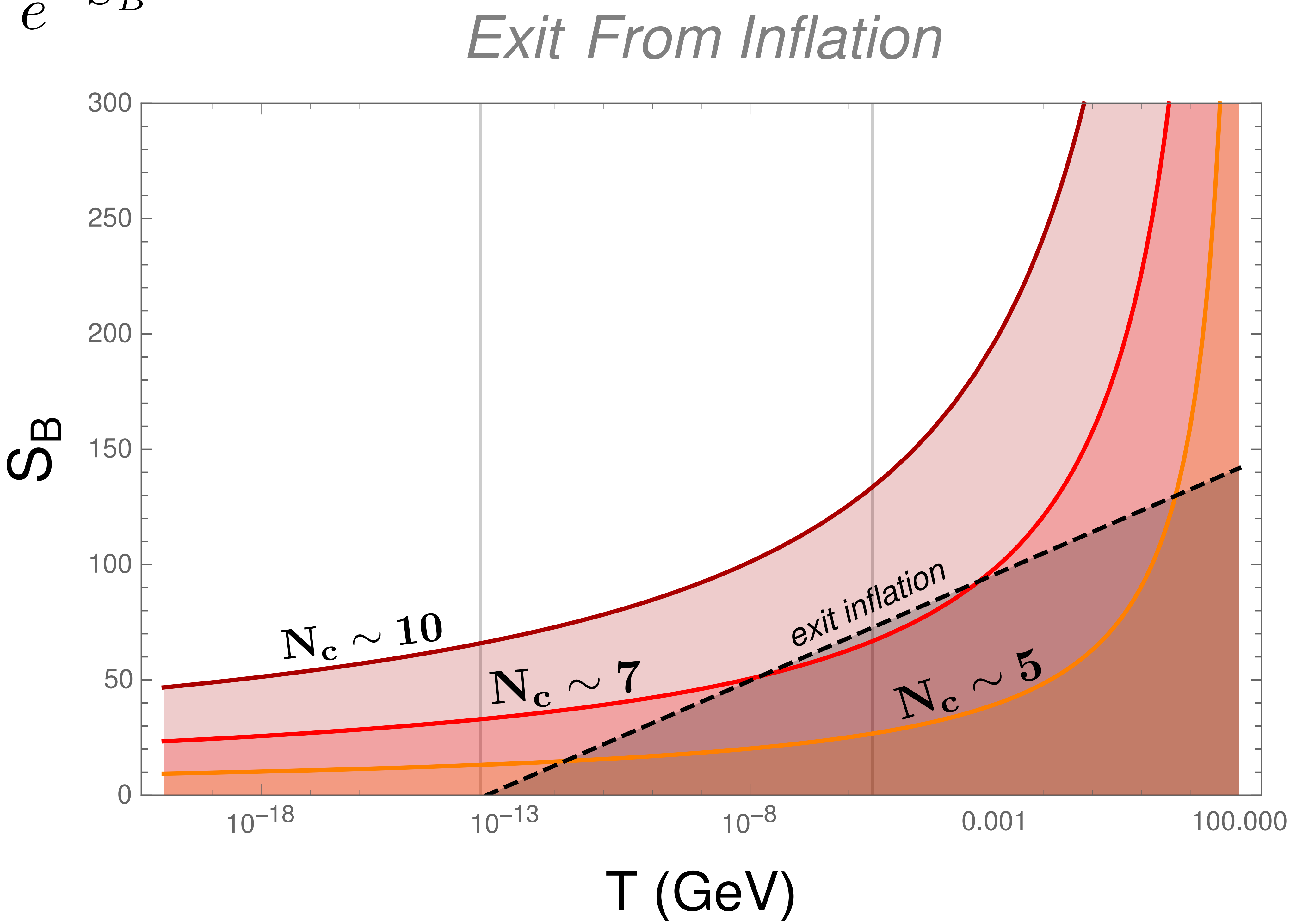


Tunneling path: moving the BH horizon to infinity and bringing back the hard/soft wall:

Creminelli etal, hep-th 0107141



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



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

After inflation, reheating, …, big bang

T

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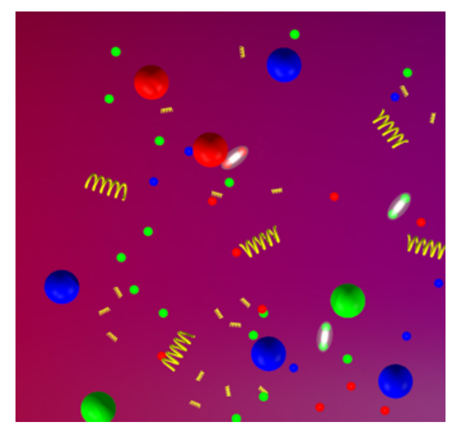
“quark-gluon” plasma

TeV



GeV

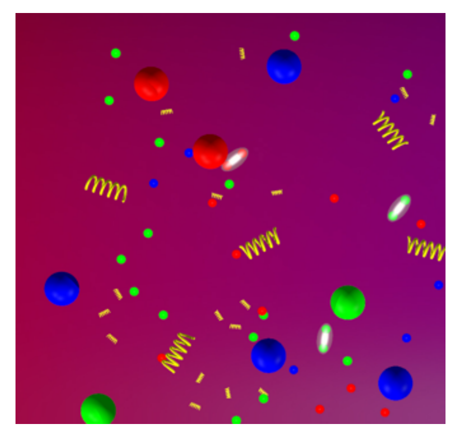
After inflation, reheating, …, big bang

T

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

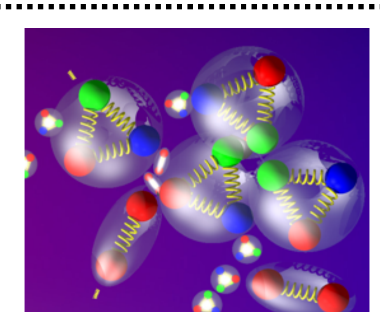
“quark-gluon” plasma

TeV



GeV

QCD confinement

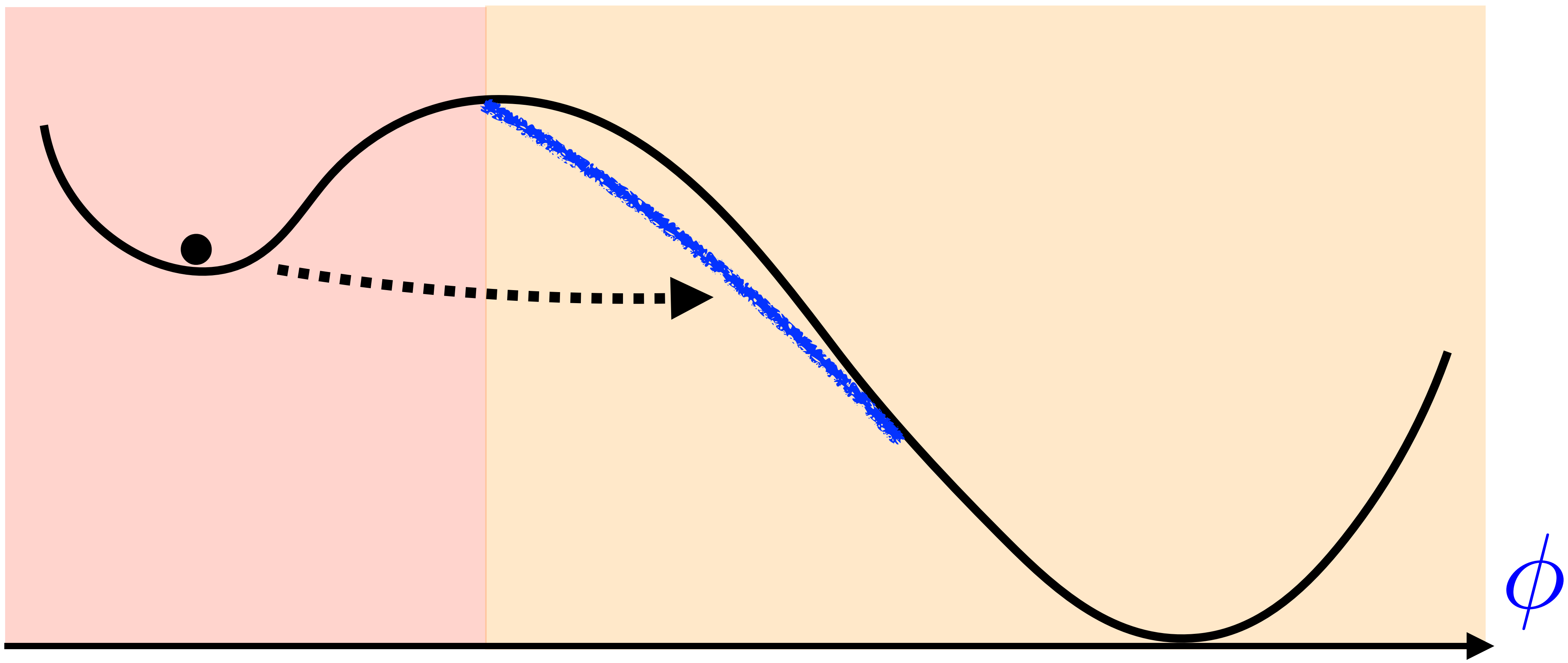


Studied by Witten, Nucl.Phys.B177(1981)477, for a Coleman-Weinberg potential

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

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

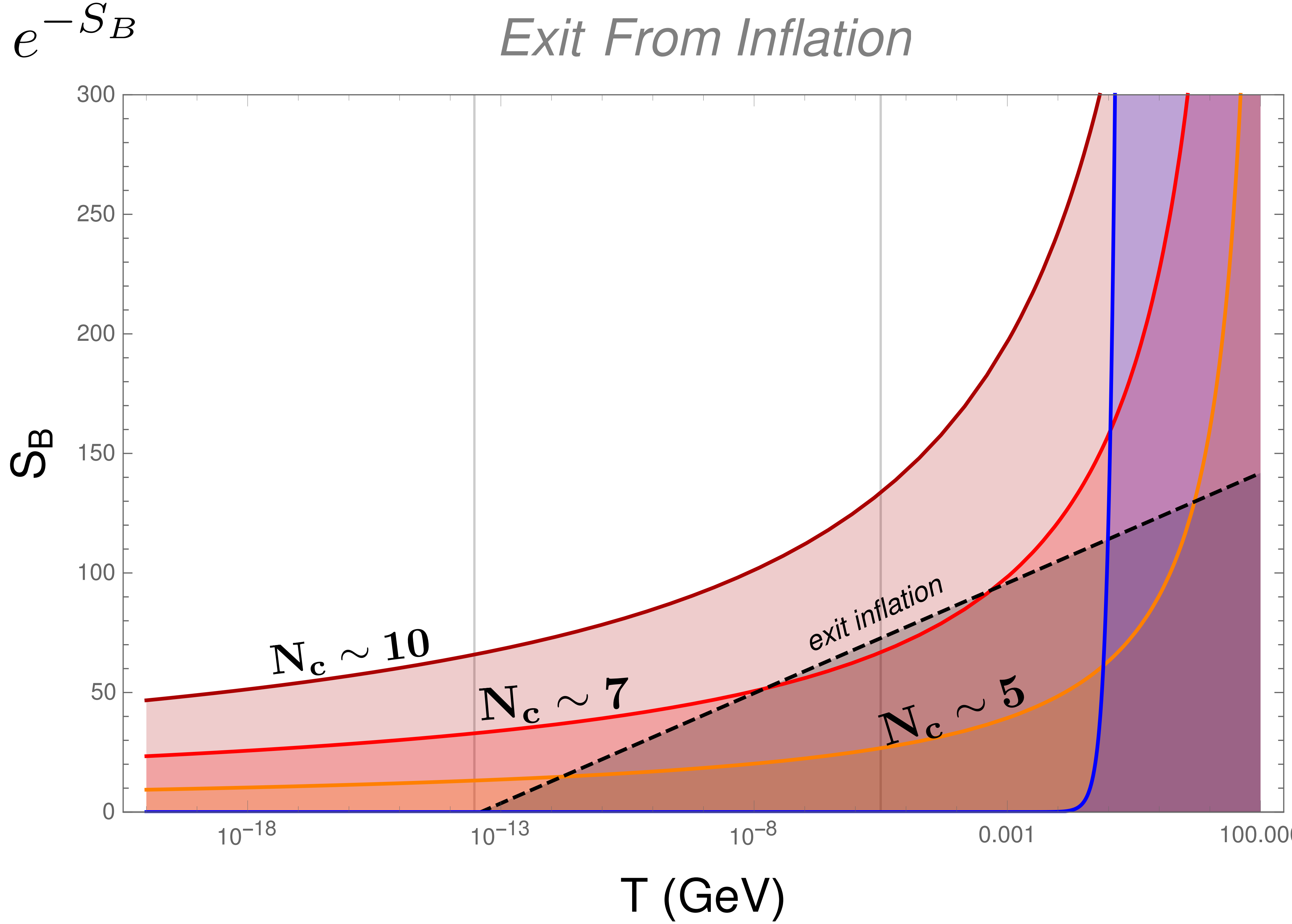
as masses arises from
the TeV strong dynamics



Exit from the supercooling phase at $\lesssim\Lambda_{QCD}$:

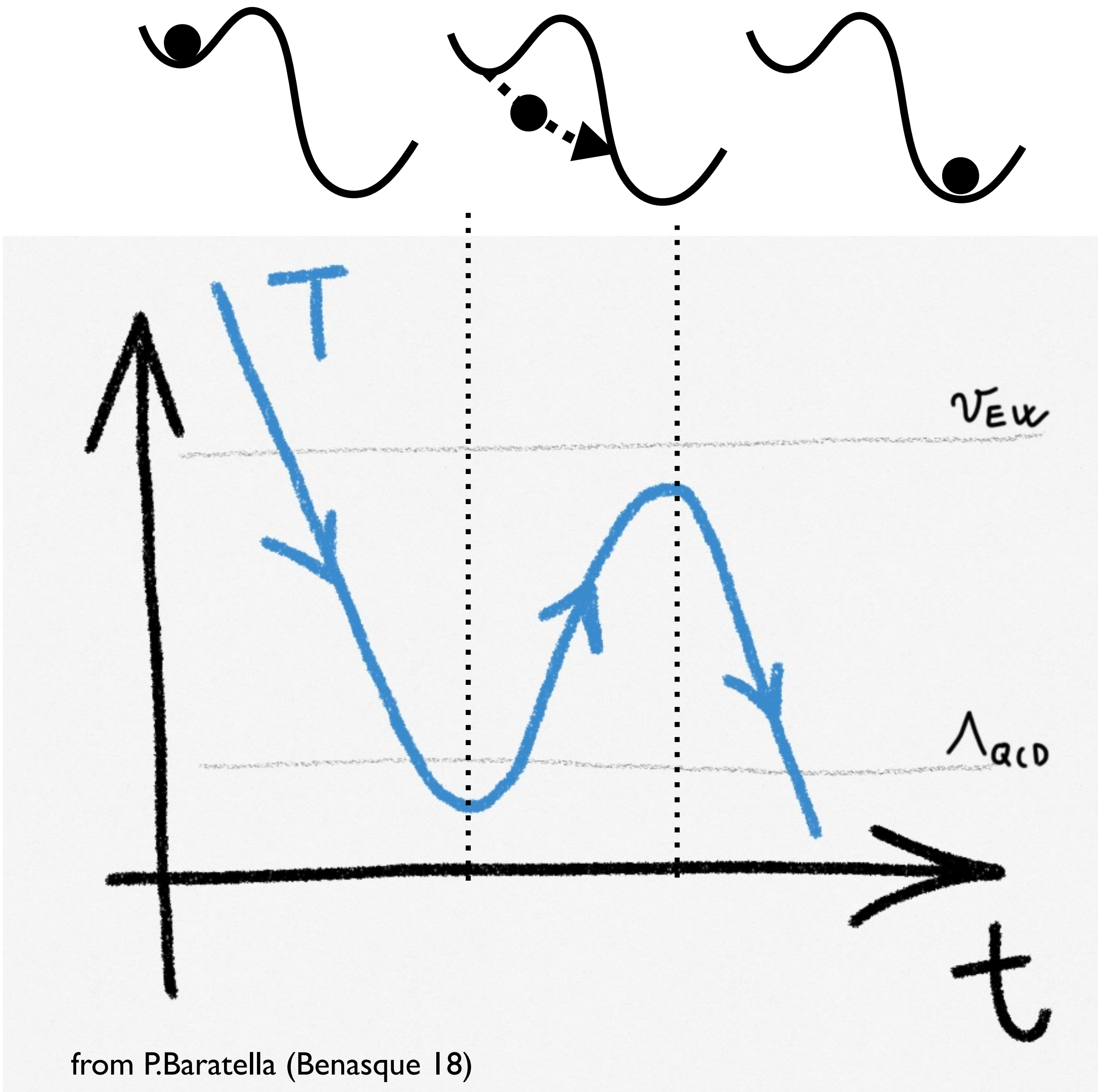
$$T_{exit} \sim \frac{Y_q^{1/3}}{N_c^{4/3}}\Lambda_{\rm QCD}$$

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



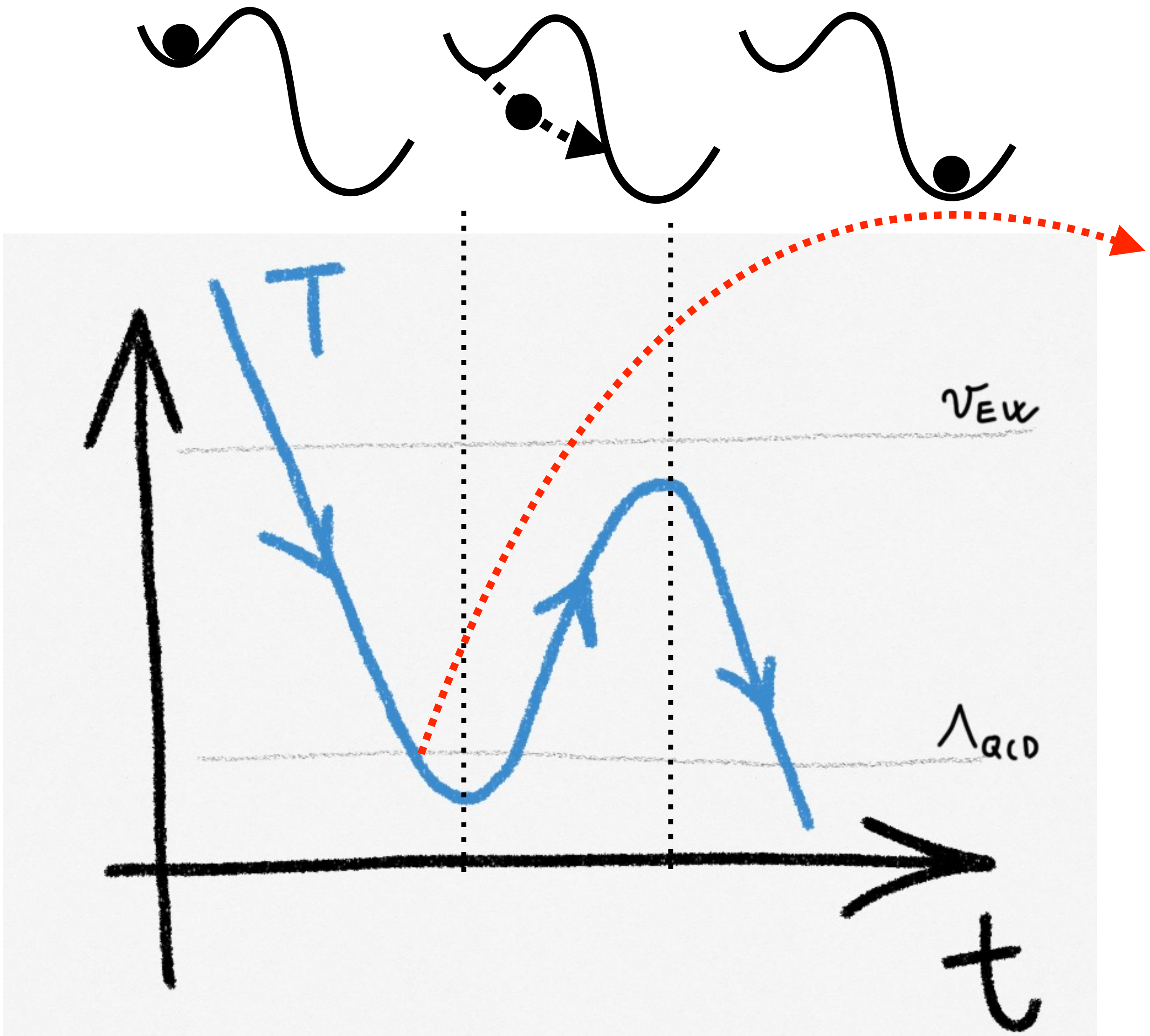
$$\frac{\Lambda_{\mathrm{QCD}}}{Y_q^{1/3} N_c^{4/3}} \sim 20 \text{ MeV}$$

Possible implications of this cosmological phase of supercooling



from P.Baratella (Benasque 18)

Possible implications of this cosmological phase of supercooling



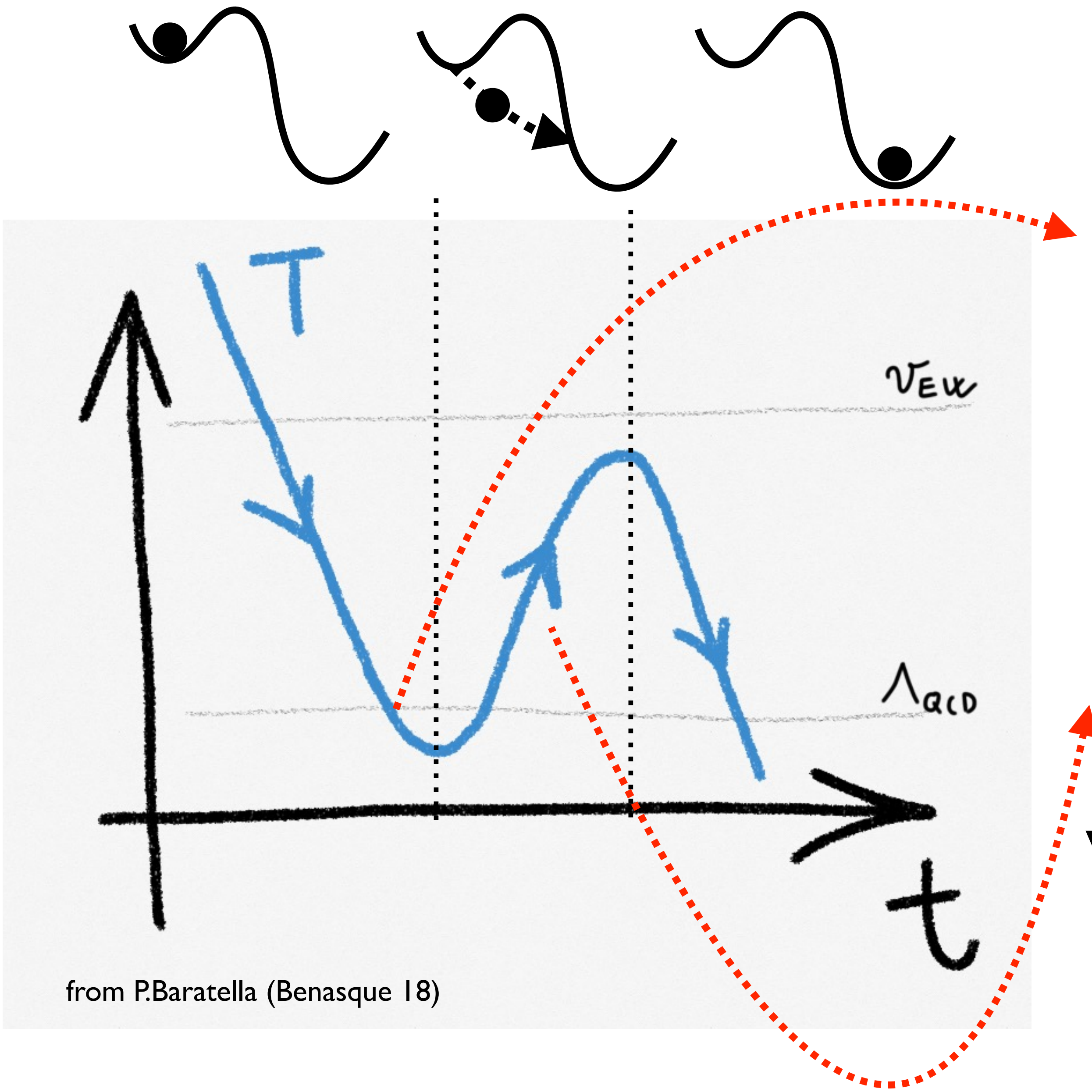
from P.Baratella (Benasque 18)

- **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



from P.Baratella (Benasque 18)

• 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:

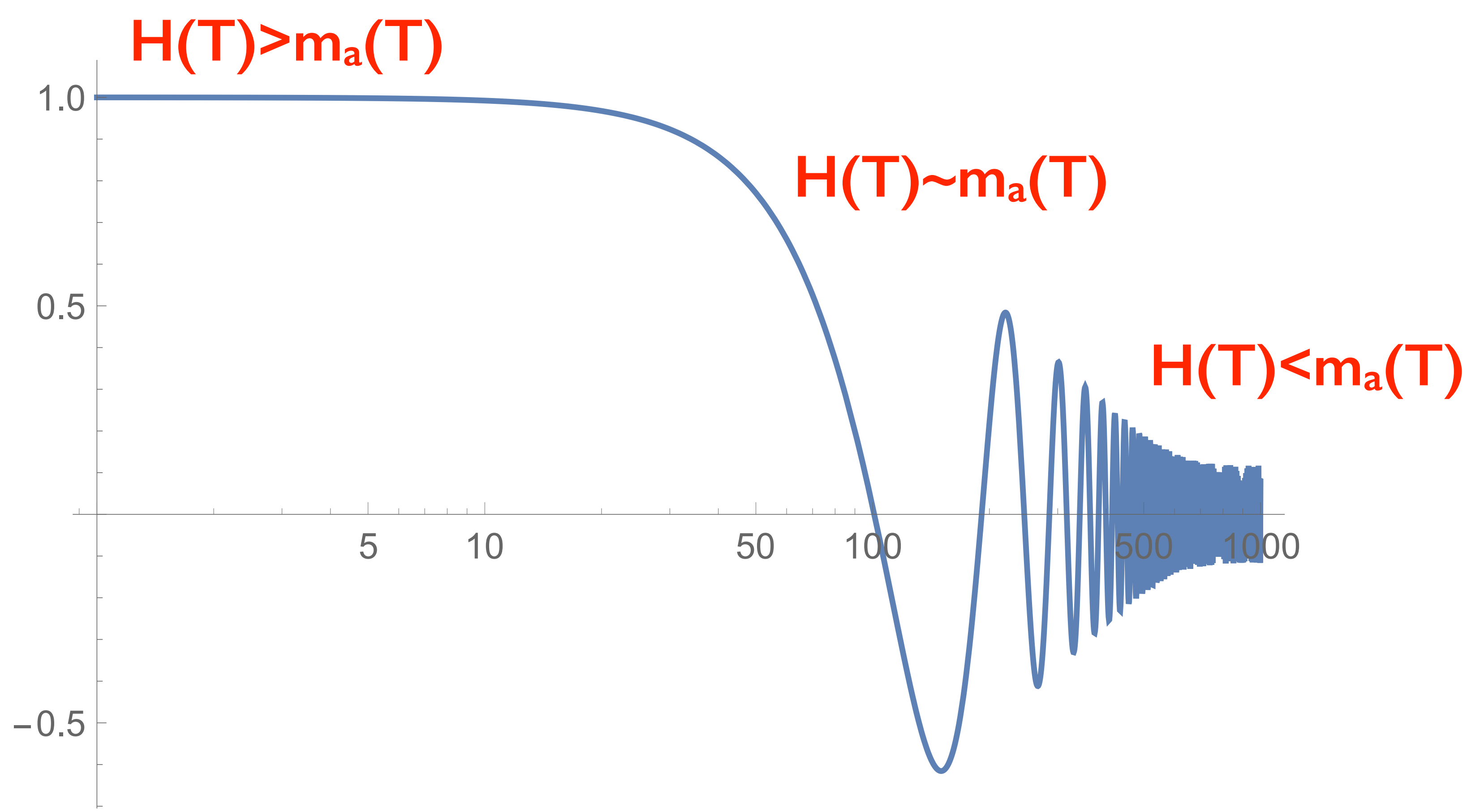
  $1 / n_\gamma \sim (\Lambda_{QCD}/\mathrm{TeV})^3 \sim 10^{-9}$

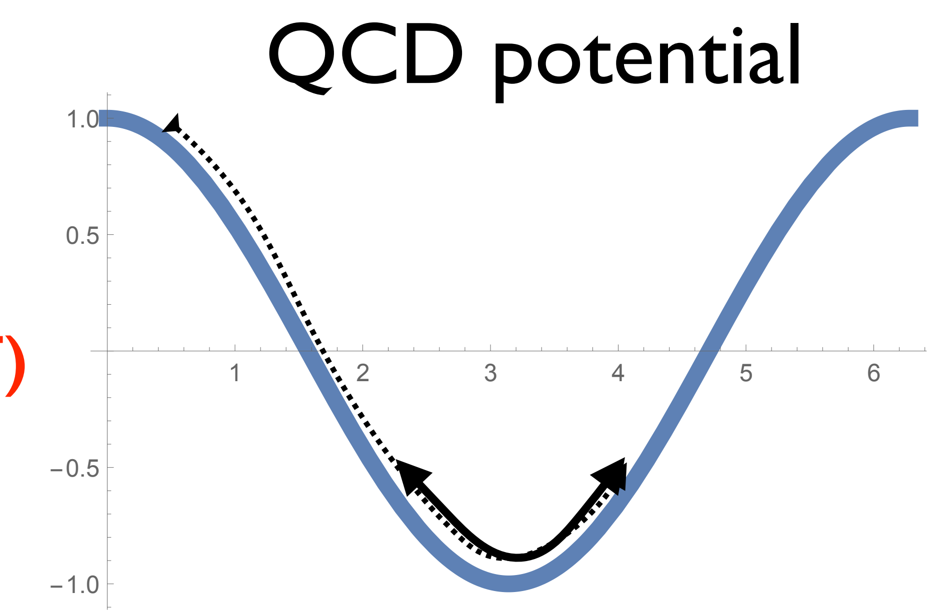
- “Electroweak” baryogenesis
  if no reheating over the EW scale
- Gravitational waves

Axion relic abundance

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

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

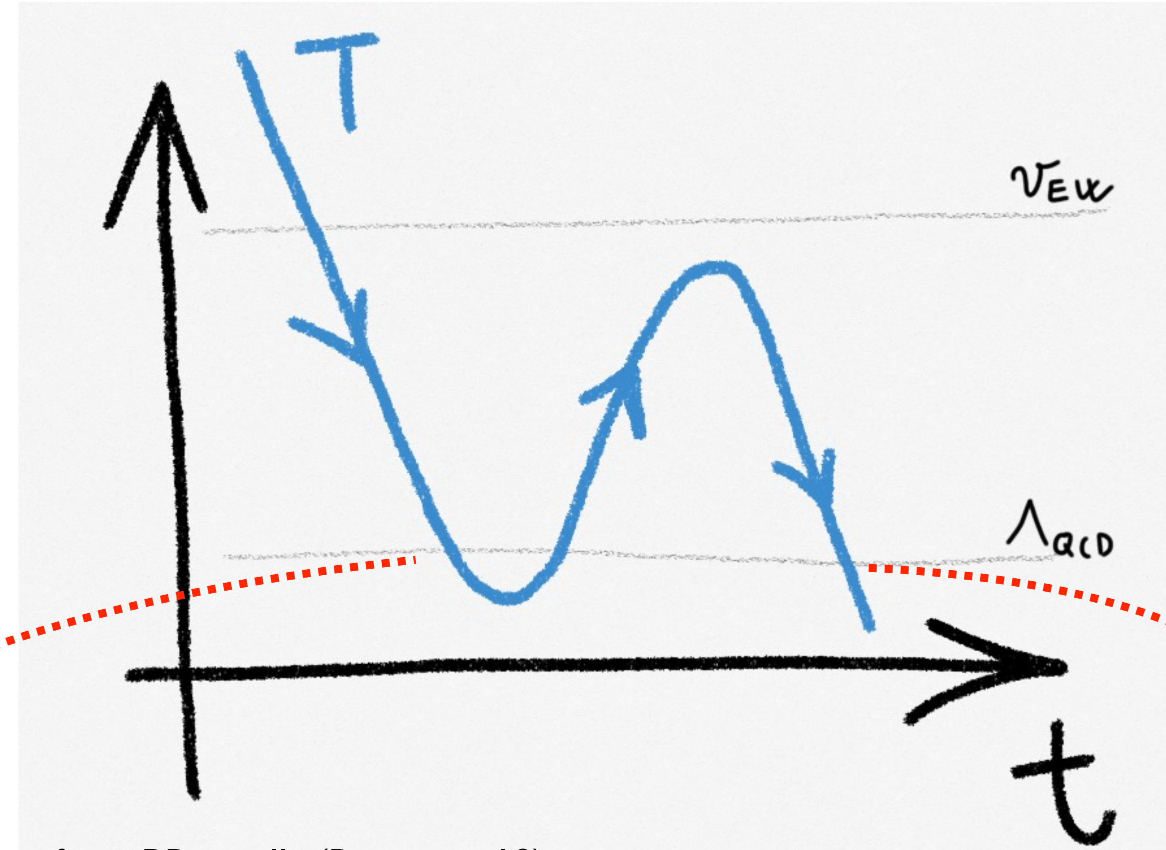




PQ breaking after inflation:

Right DM abundances for $f_a \sim 10^{12}$ GeV

If supercooling:



from P.Baratella (Benasque 18)

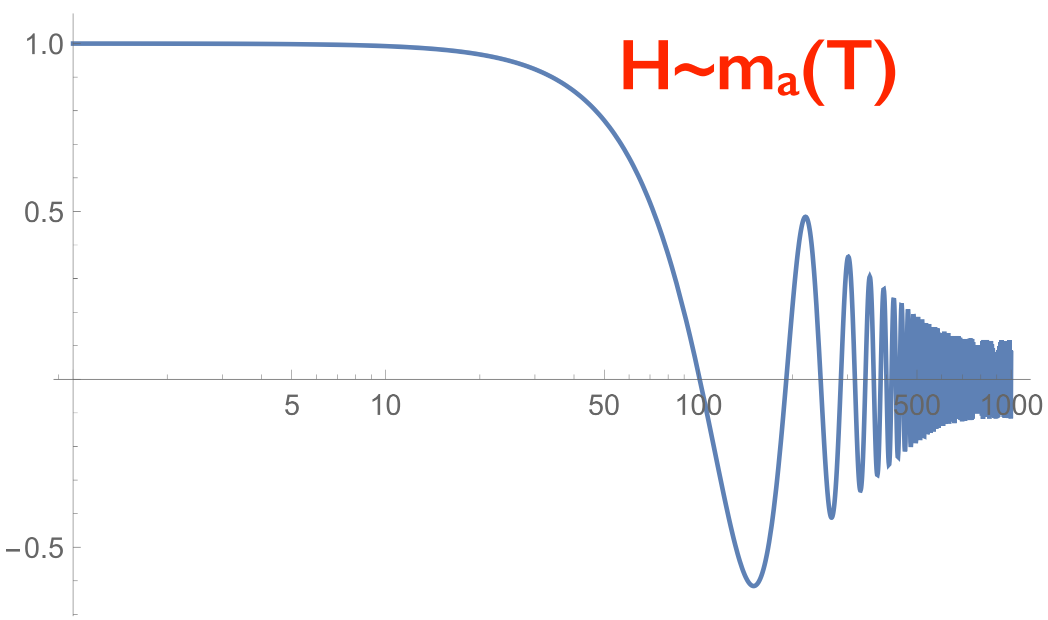
Additional QCD phase transition

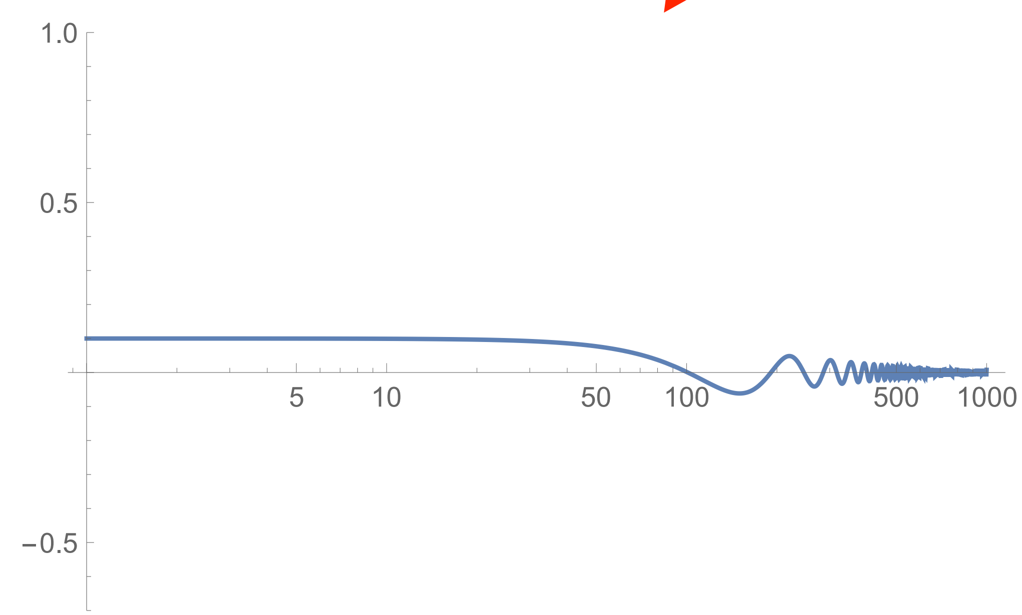
($H \sim TeV^2/M_P$)

Ordinary QCD phase transition

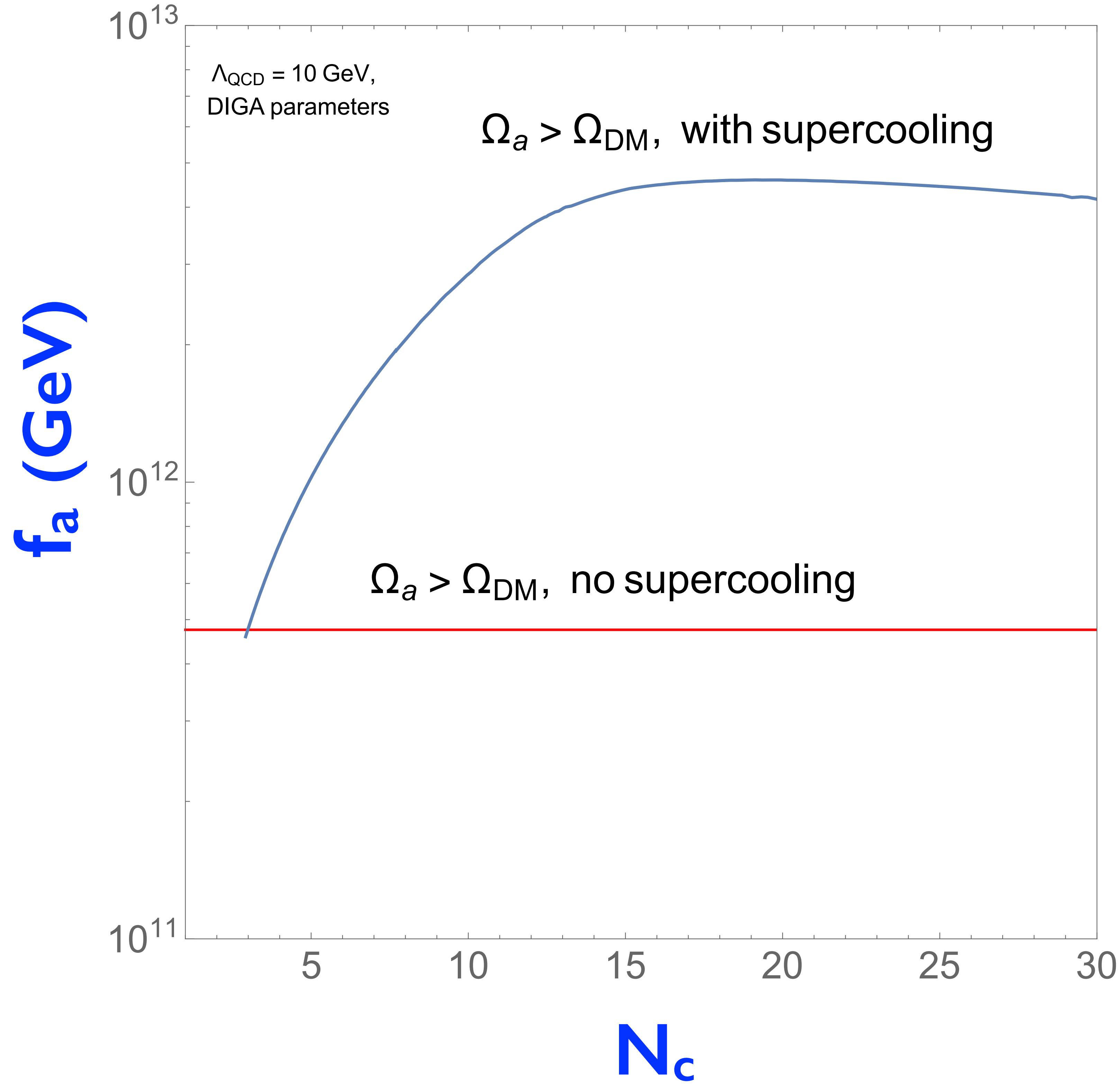
($H \sim T^2/M_P$)

$H \sim m_a(T)$





Right DM abundances for larger f_a :



Conclusions

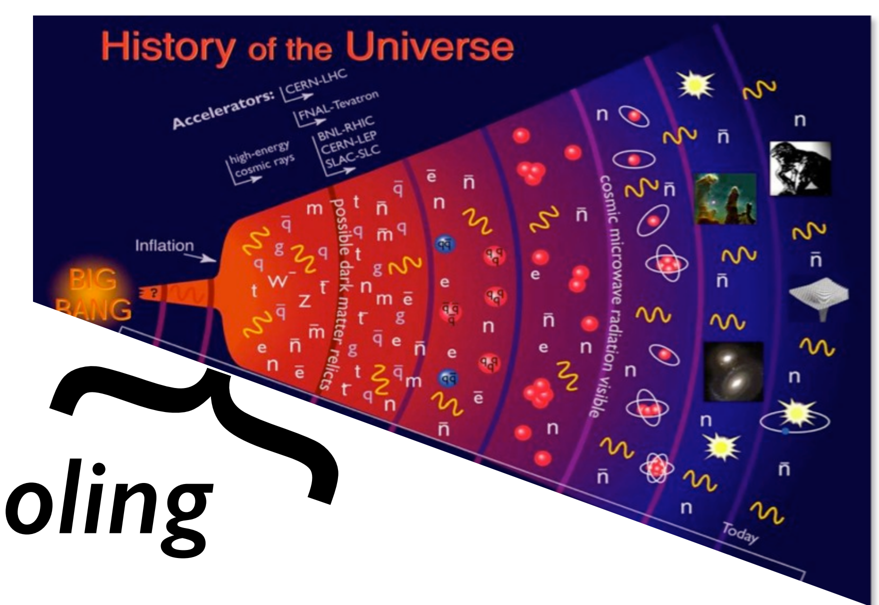
- **Conformal to non-conformal transition** are important in physics

- 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:



Supercooling

- Additional QCD phase transition ☛ triggers 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!