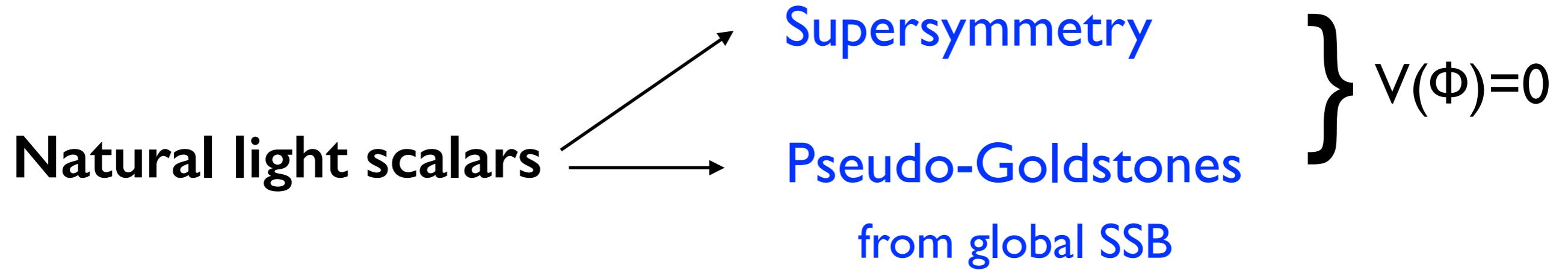
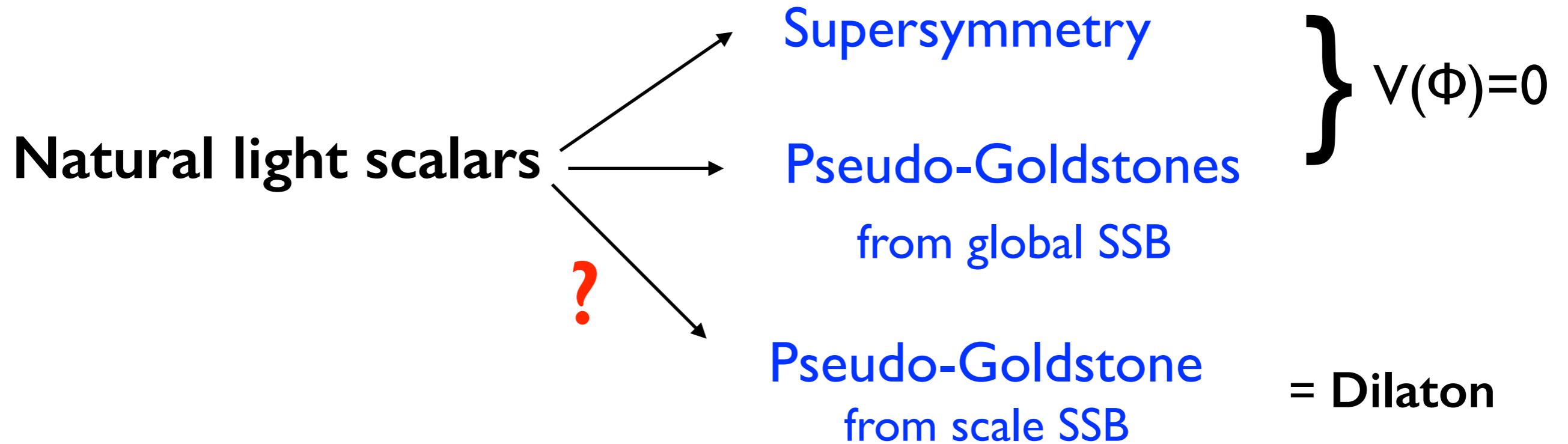


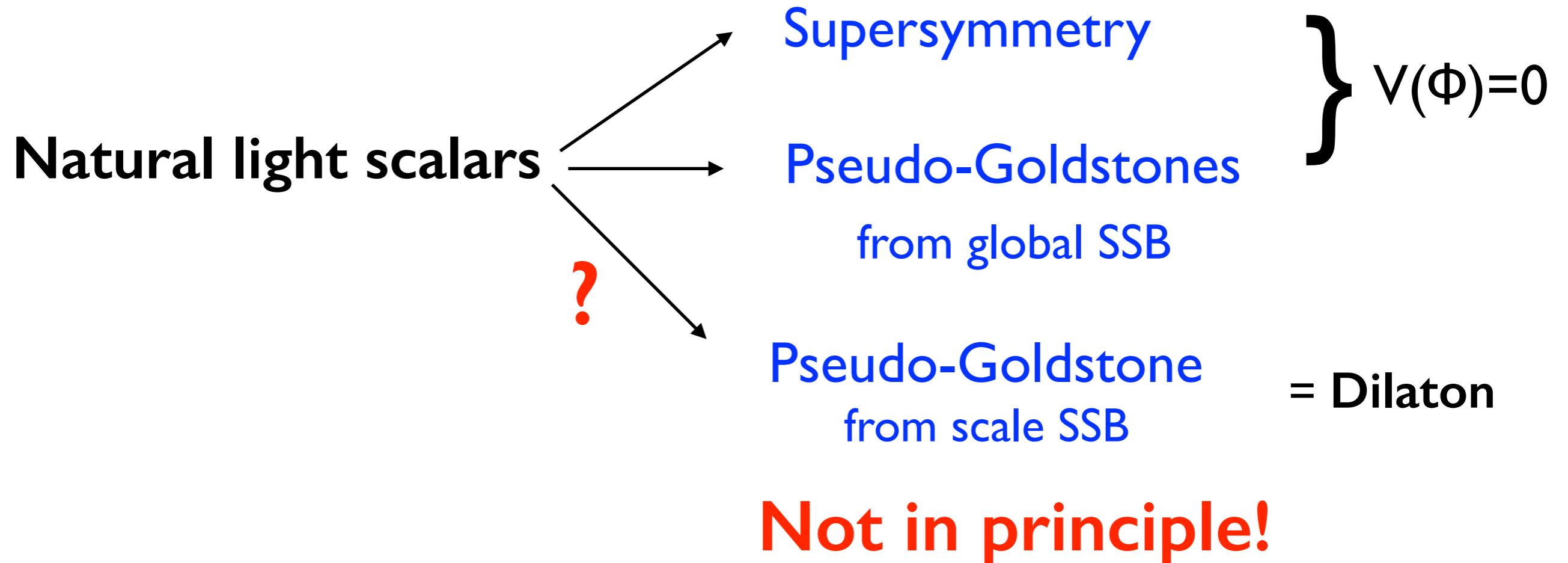
(Naturally) Light Dilaton

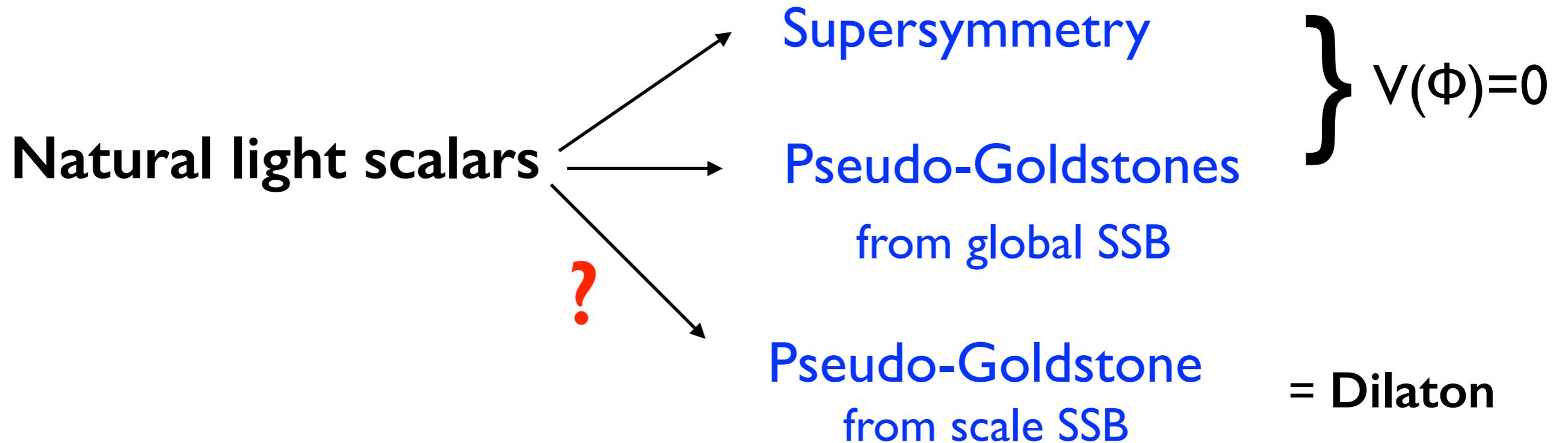
Alex Pomarol UAB & IFAE (Barcelona)

- ◆ Short overview
- ◆ Conformal transitions (in view of lattice results)
- ◆ Phenomenological consequences





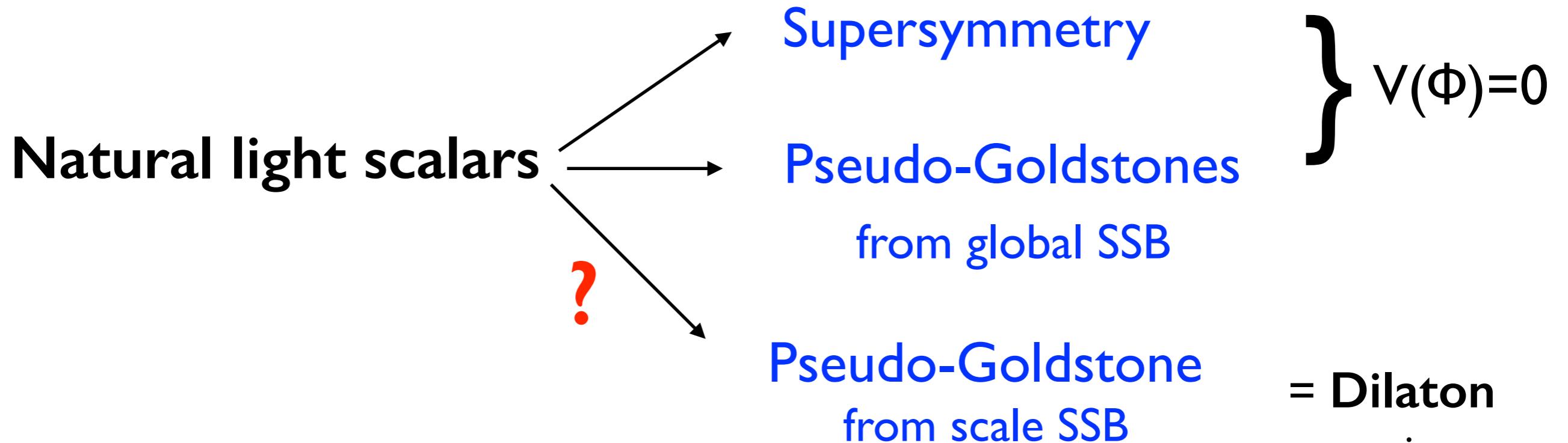




Under **phase** transformations:

$$\Phi(x) \rightarrow e^{i\theta} \Phi(x) \quad \Phi = e^{i\pi}$$

No potential is allowed by $\pi \rightarrow \pi + \theta$



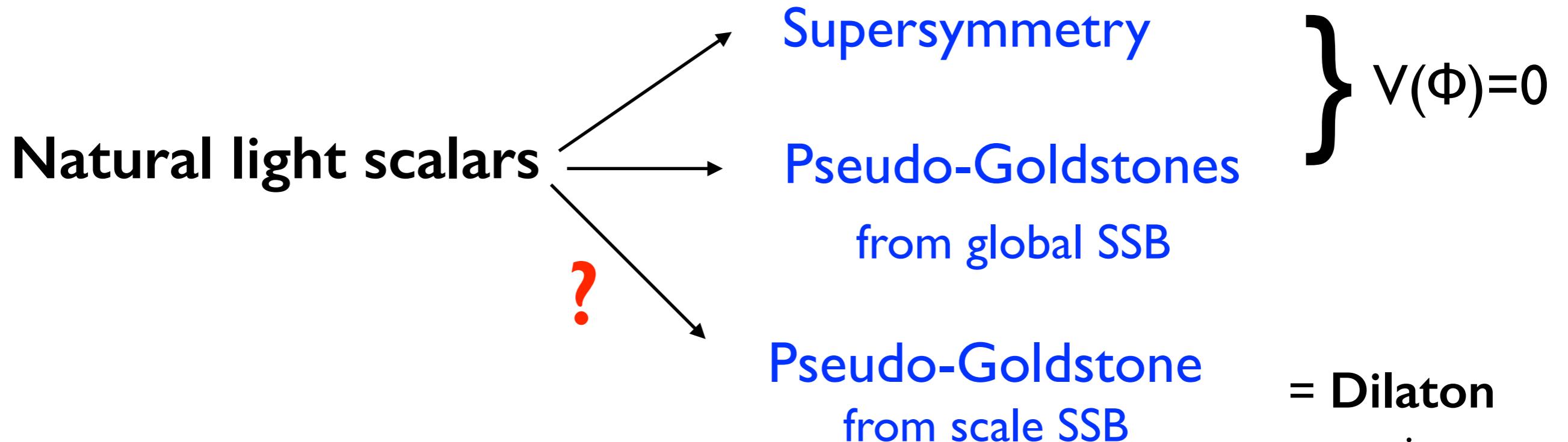
Under **scale** transformations:

$$\Phi(x) \rightarrow e^k \Phi(e^k x)$$

$$\Phi = e^{\phi_d} \downarrow \dots$$

A potential is allowed:

$$\int d^4x V(\Phi) = \int d^4x \lambda \Phi^4$$



Under **scale** transformations:

$$\Phi(x) \rightarrow e^k \Phi(e^k x)$$

$$\Phi = e^{\phi_d} \downarrow \dots$$

A potential is allowed:

$$\int d^4x V(\Phi) = \int d^4x \lambda \Phi^4$$

SSB: $\langle \Phi \rangle = \text{const} \neq 0$ only if $\lambda = 0$ (tuning!)

Fubini 76

As the cosmological problem: Why $V(\Phi)=0$?

Light dilaton \leftrightarrow Small vacuum energy

*Important
for phase transitions*

(Only) way out: Add explicit breaking of scale inv.:

$$\Delta\mathcal{L}_{\text{def}} = g\mathcal{O}_g$$

Almost marginal coupling

$$\beta_g \approx \epsilon \ll 1$$

$$V(\phi) = \lambda(g(\phi))\phi^4$$

Coleman-Weinberg-like

$$\beta_\lambda \sim \beta_g \approx \epsilon \ll 1$$

(Only) way out: Add explicit breaking of scale inv.:

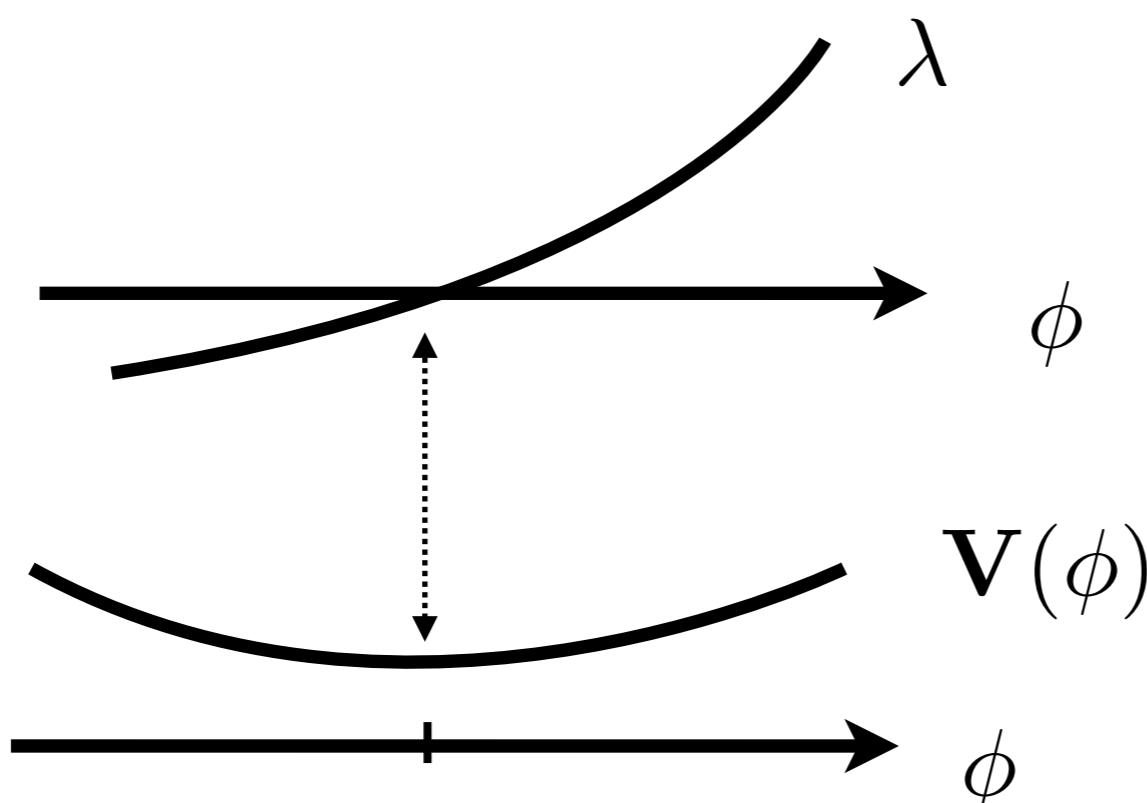
$$\Delta\mathcal{L}_{\text{def}} = g\mathcal{O}_g$$

Almost marginal coupling

$$\beta_g \approx \epsilon \ll 1$$

∇

$$V(\phi) = \lambda(g(\phi))\phi^4$$



slow running of λ

↓
flattish potential

↓
small dilaton mass

$$m_{\text{dil}}^2 \sim \beta_\lambda \sim \epsilon$$

- **Weakly-coupled theories (elementary dilaton):**

$$\cancel{m^2 \phi^2} + \lambda \phi^4$$

→ **why it is not there?** (hierarchy problem)

Also: $\beta_\lambda \sim \frac{g^2}{16\pi^2} \rightarrow \text{light} \sim \text{decoupled}$

- **Weakly-coupled theories (elementary dilaton):**

$$\cancel{m^2 \phi^2} + \lambda \phi^4$$

→ **why it is not there?** (hierarchy problem)

Also: $\beta_\lambda \sim \frac{g^2}{16\pi^2} \rightarrow \text{light} \sim \text{decoupled}$

- **Strongly-coupled theories (composite dilaton):**

QCD-like theories: Difficult to keep $\beta_\lambda \ll 1$ at the Λ_{QCD}

→ **heavy dilaton**

- **Weakly-coupled theories (elementary dilaton):**

$$\cancel{m^2 \phi^2} + \lambda \phi^4$$

→ **why it is not there?** (hierarchy problem)

Also: $\beta_\lambda \sim \frac{g^2}{16\pi^2} \rightarrow \text{light} \sim \text{decoupled}$

- **Strongly-coupled theories (composite dilaton):**

QCD-like theories: Difficult to keep $\beta_\lambda \ll 1$ at the Λ_{QCD}

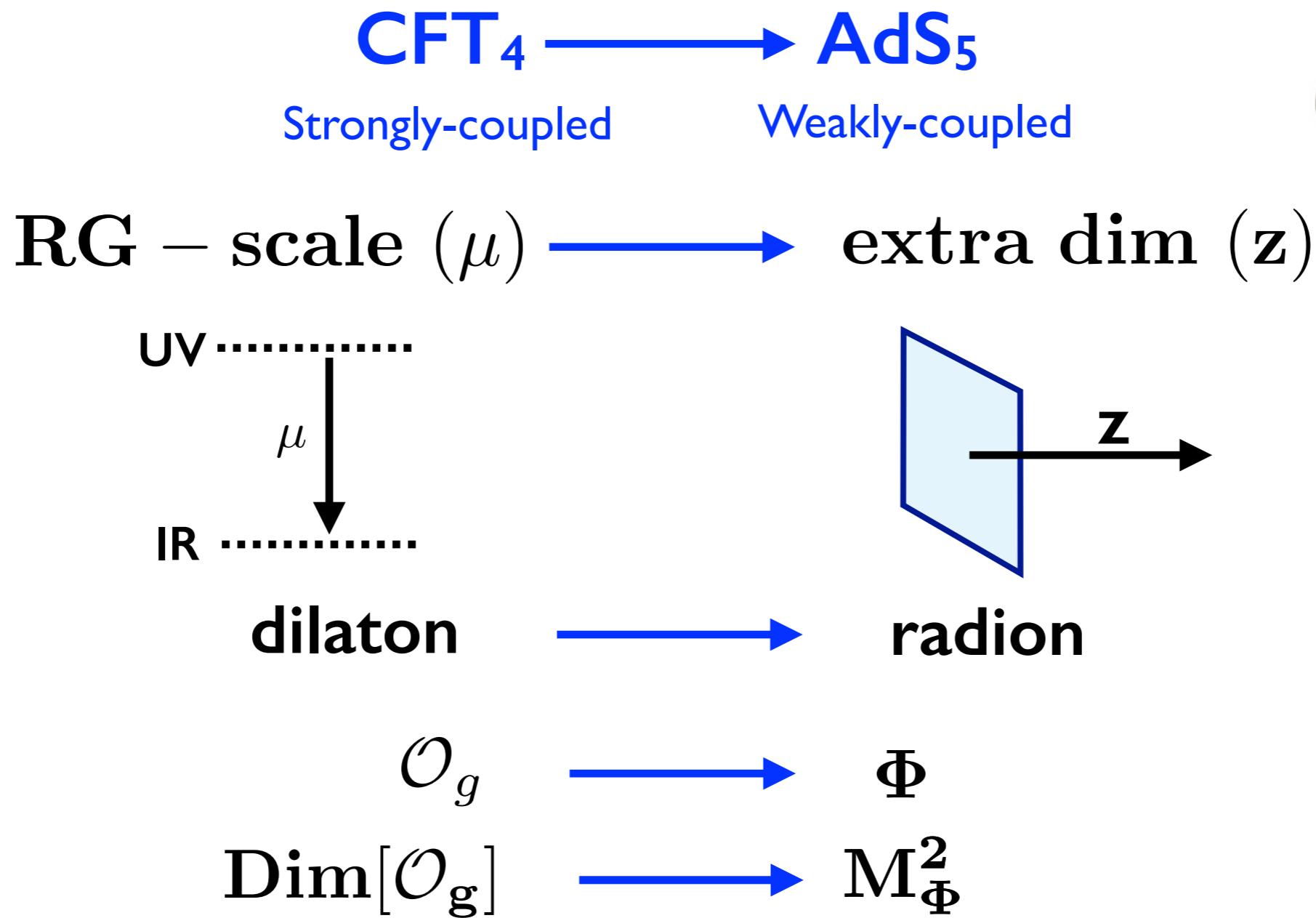
→ **heavy dilaton**

Only option:

→ **Holography (extra-dimensional models)**

Using AdS/CFT:

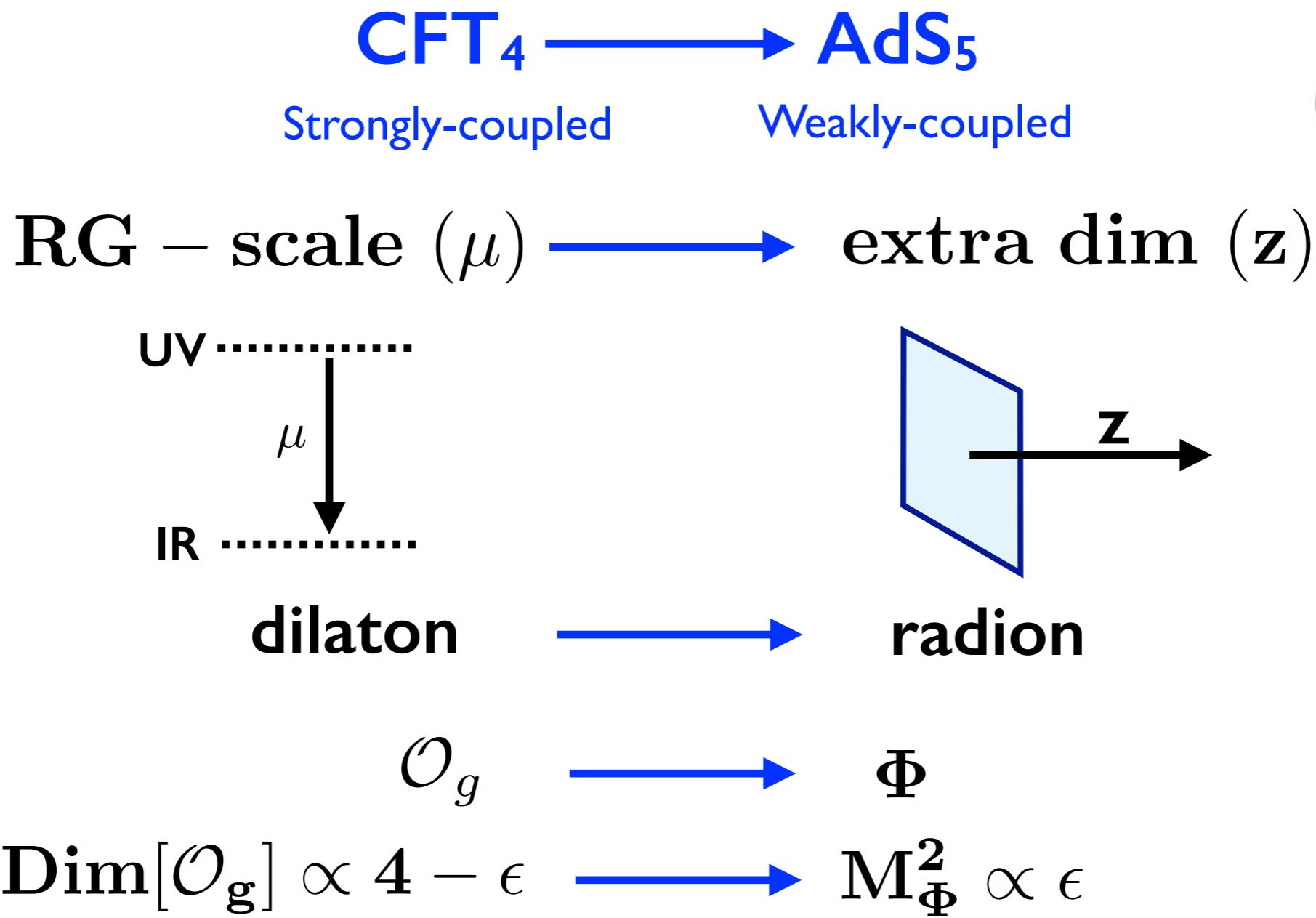
DICTIONARY



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

Using AdS/CFT:

DICTIONARY



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



Using AdS/CFT:

DICTIONARY

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

Strongly-coupled Weakly-coupled

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



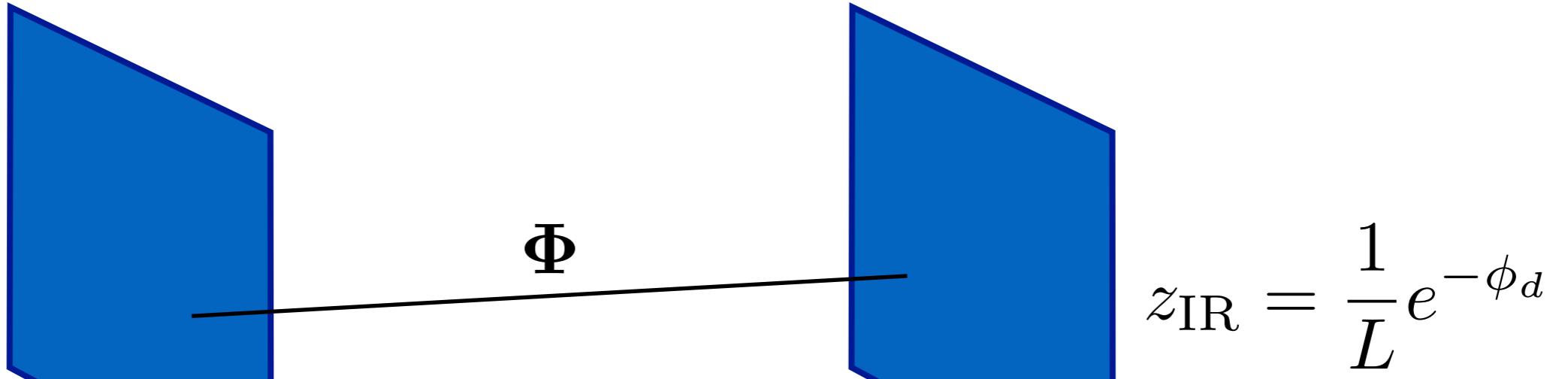
$$\text{dilaton} \longrightarrow \text{radion}$$

$$\mathcal{O}_g \longrightarrow \Phi$$
$$\text{Dim}[\mathcal{O}_g] \propto 4 - \epsilon \longrightarrow M_\Phi^2 \propto \epsilon$$

PGB in 5D!

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

5D theory of a light radion/dilaton



$$z_{\text{IR}} = \frac{1}{L} e^{-\phi_d}$$

$$V(z_{\text{IR}}) \simeq \frac{\lambda(z_{\text{IR}})}{z_{\text{IR}}^4}$$

$$m_{\text{rad}}^2 \propto \frac{\partial_{z_{\text{IR}}} \Phi}{\Phi} \propto \epsilon$$

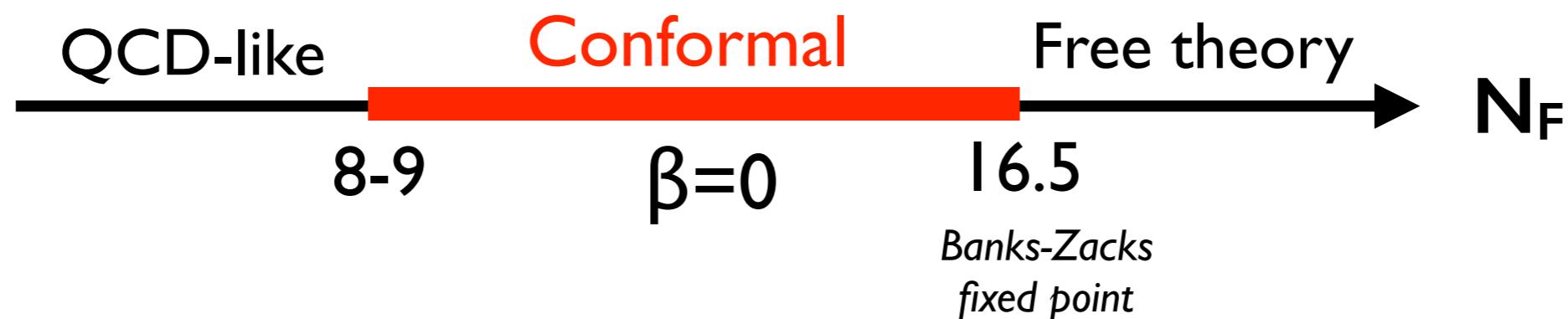
see e.g. B. Bellazzini et al (arXiv:1305.3919)

F. Coradeschi et al (arXiv:1306.4601)

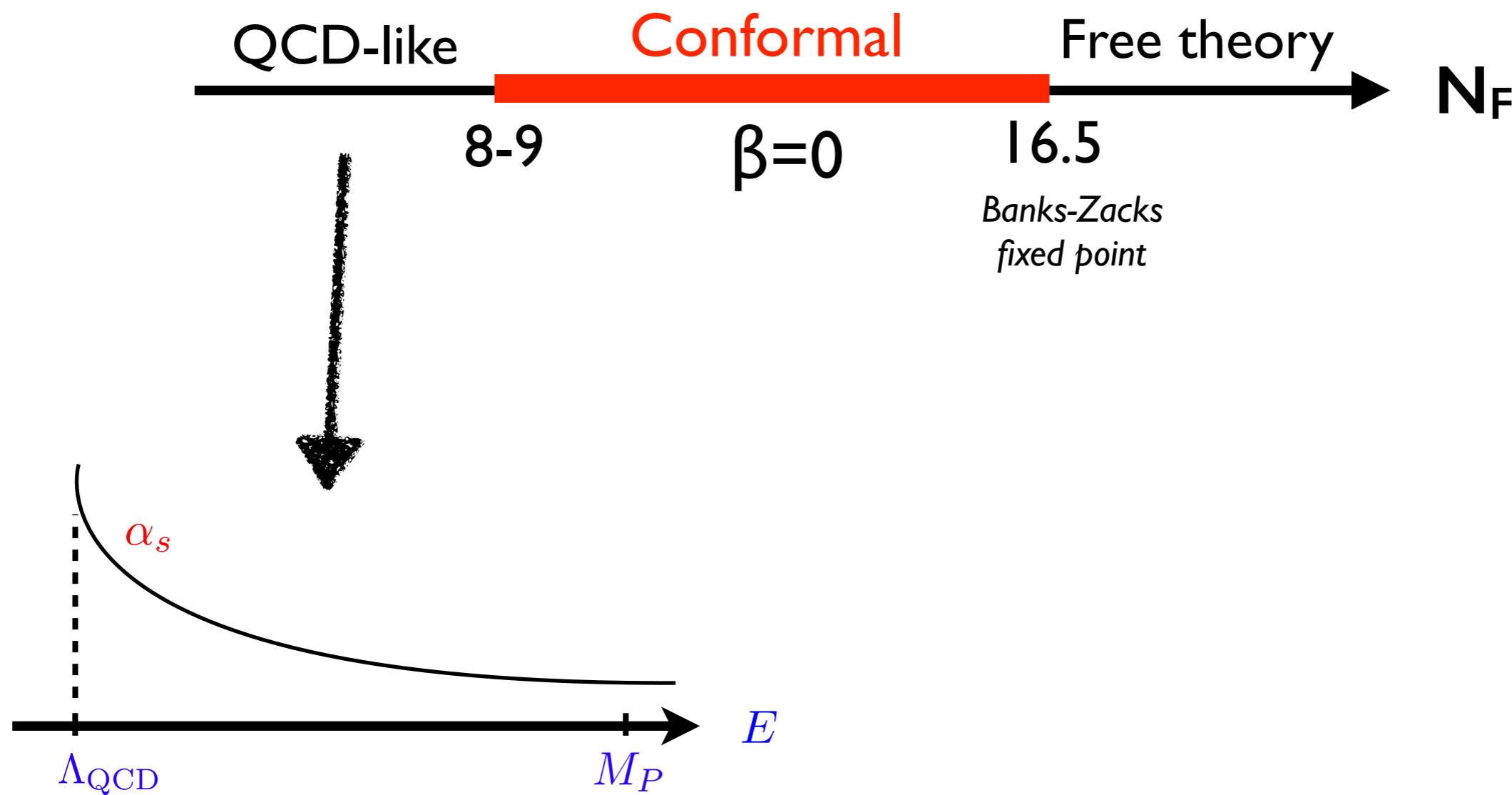
Megias, Pujolas (arXiv:1401.4998)

Recent inside from Lattice
on light dilatons
in the QCD conformal transition

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



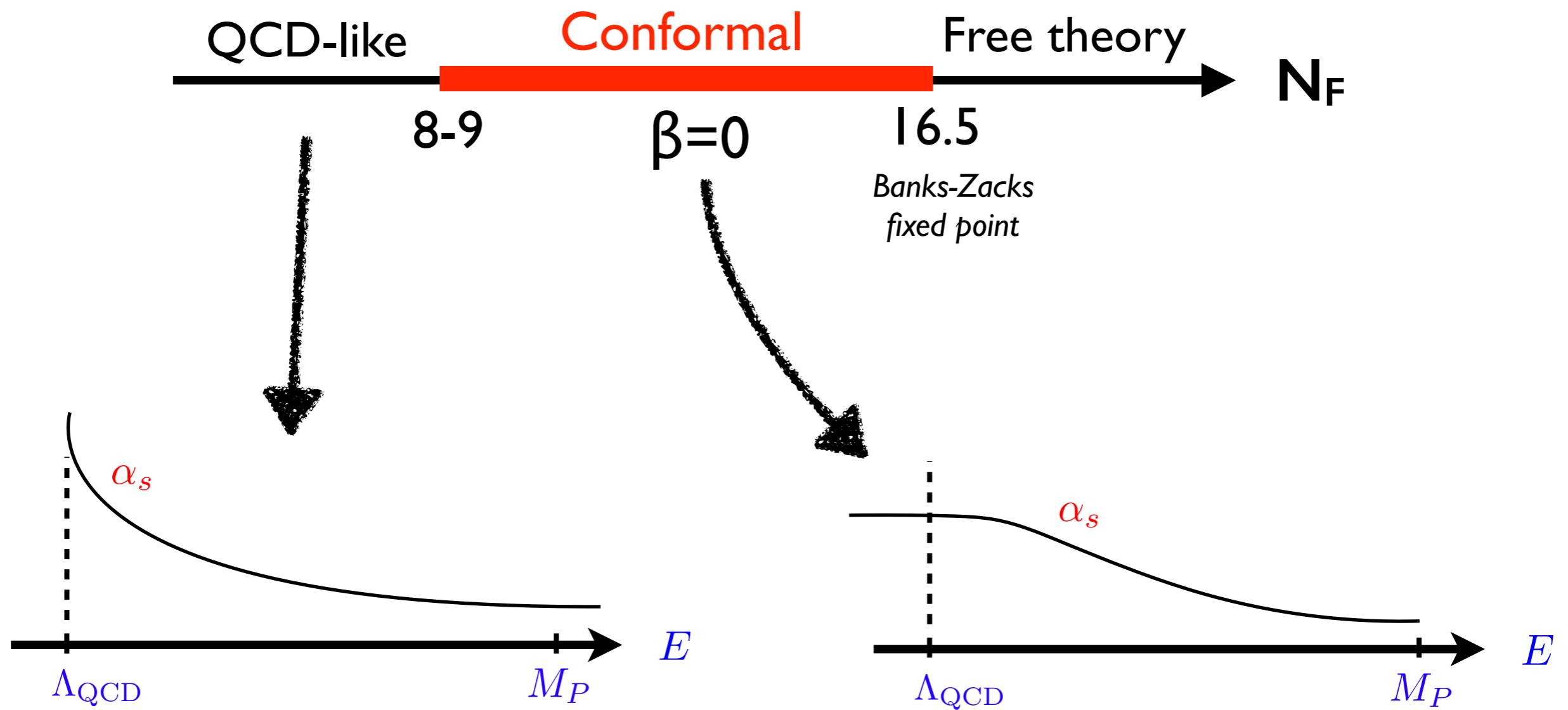
Conformal window in SU(3) with large number of fermions (N_F)



Mass gap $\sim \Lambda_{QCD}$

Chiral-symmetry breaking

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



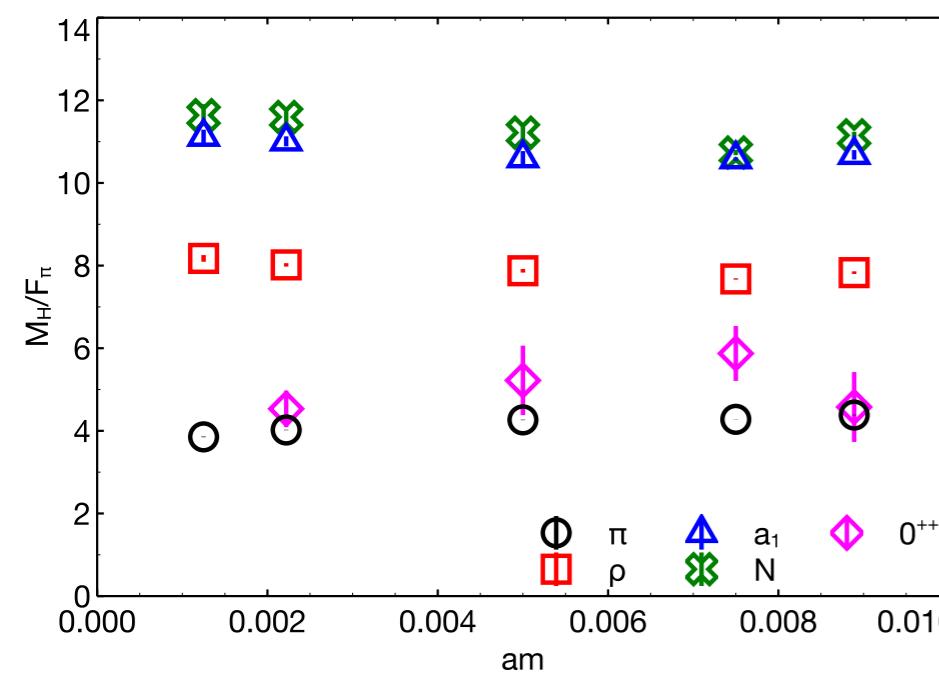
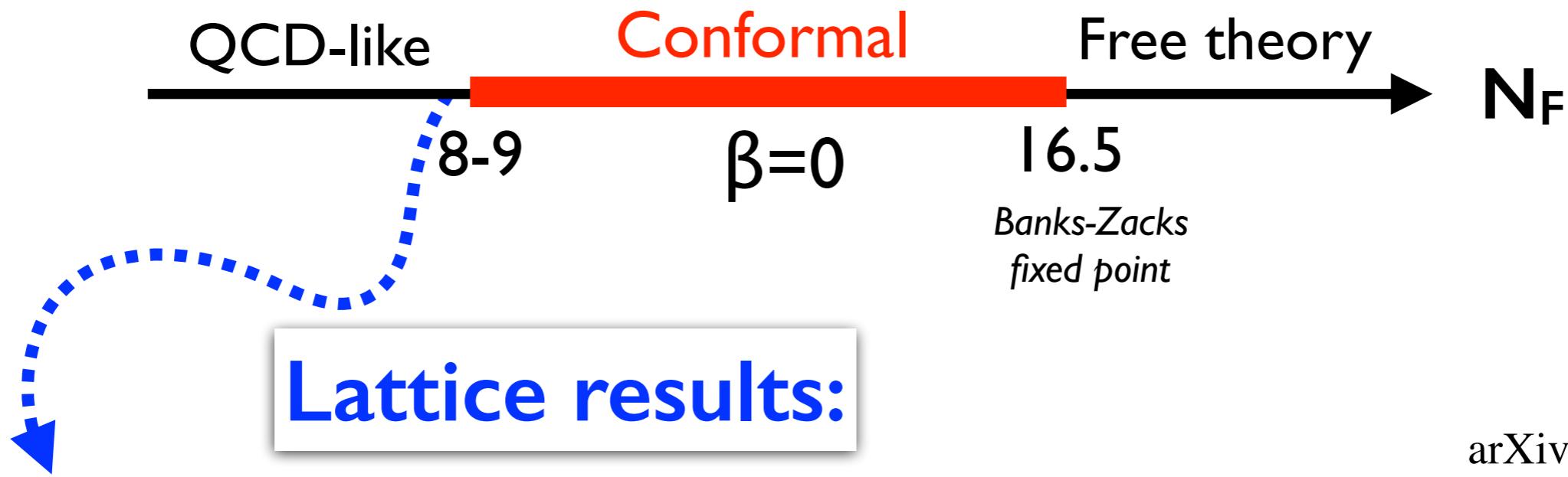
Mass gap $\sim \Lambda_{QCD}$

Chiral-symmetry breaking

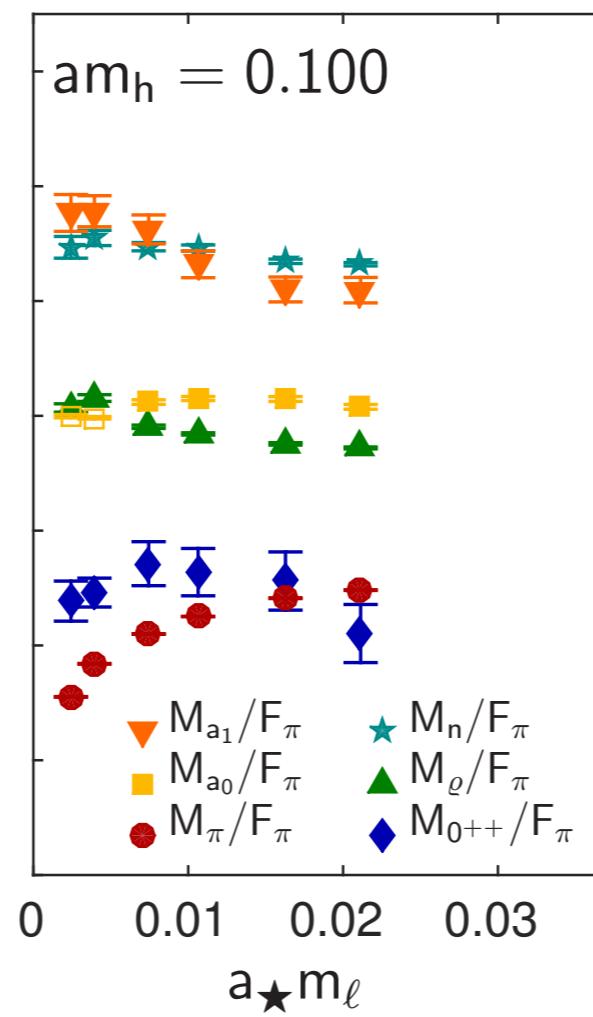
No mass gap $\sim \Lambda_{QCD}$

No chiral-symmetry breaking

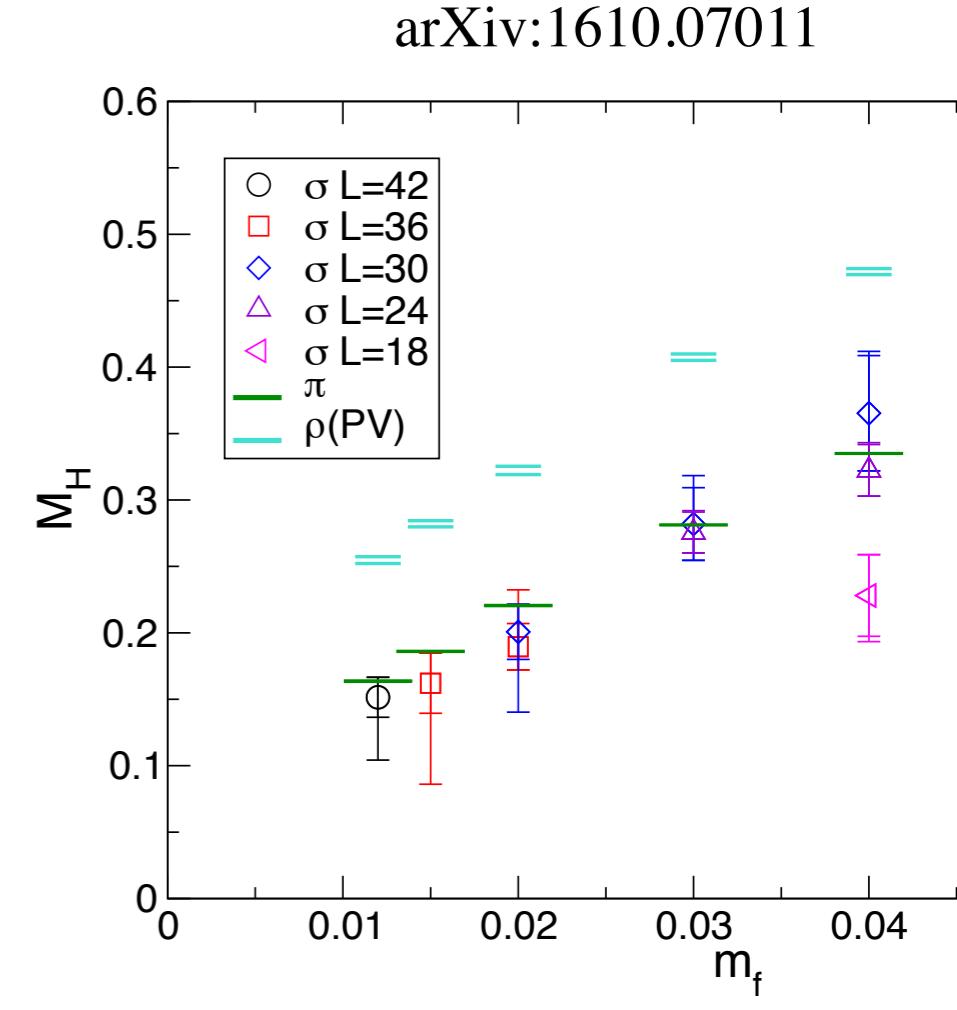
Conformal window in SU(3) with large number of fermions (N_F)



arXiv:1601.04027

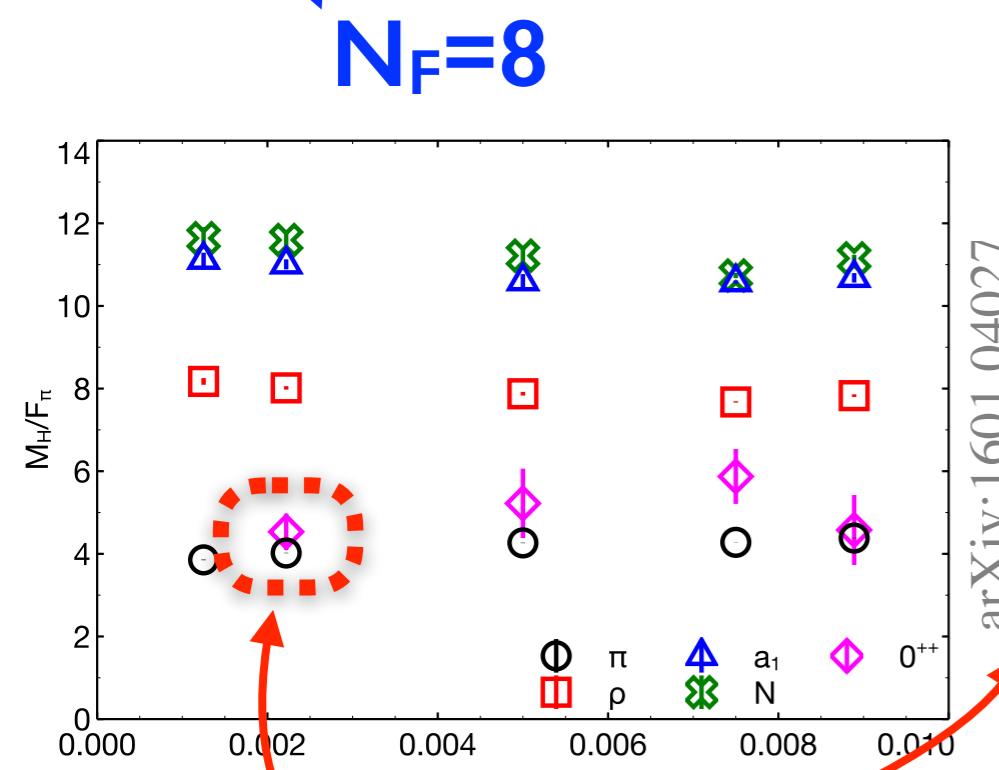
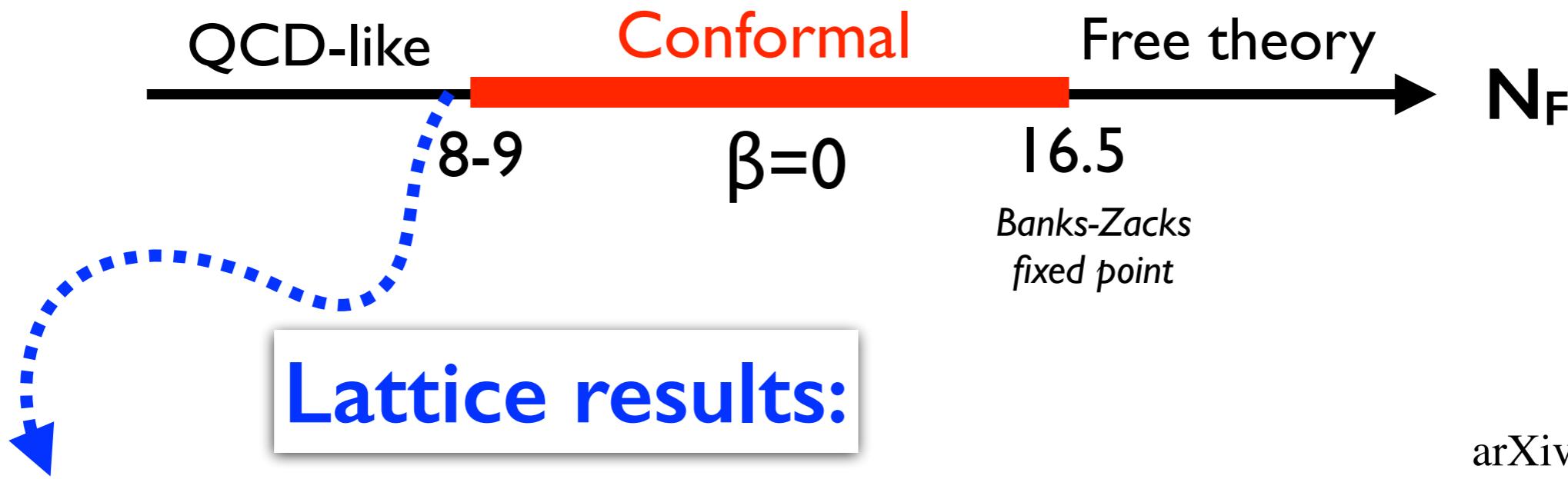


arXiv:1512.02576

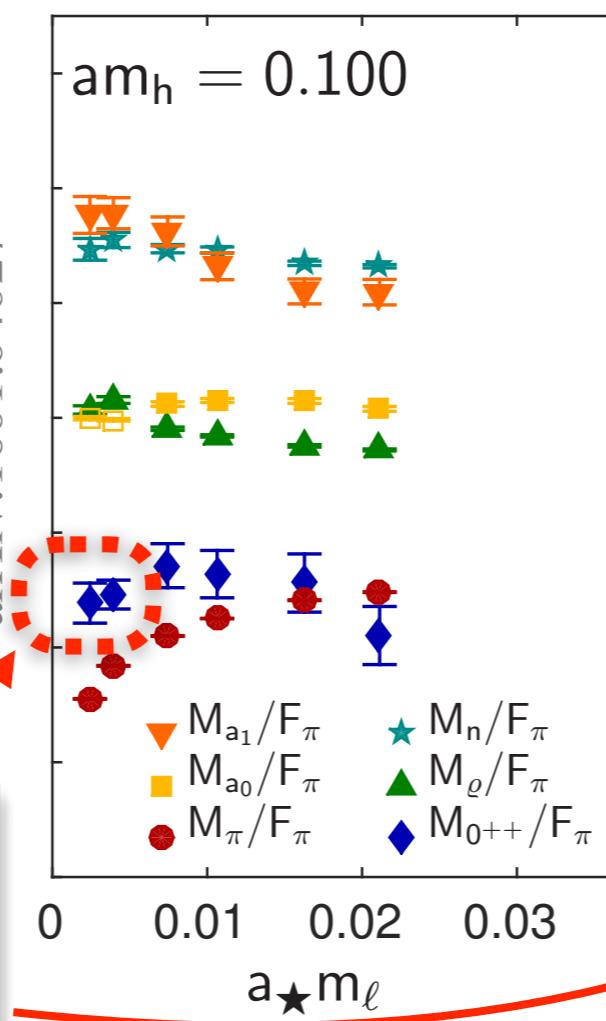


arXiv:1610.07011

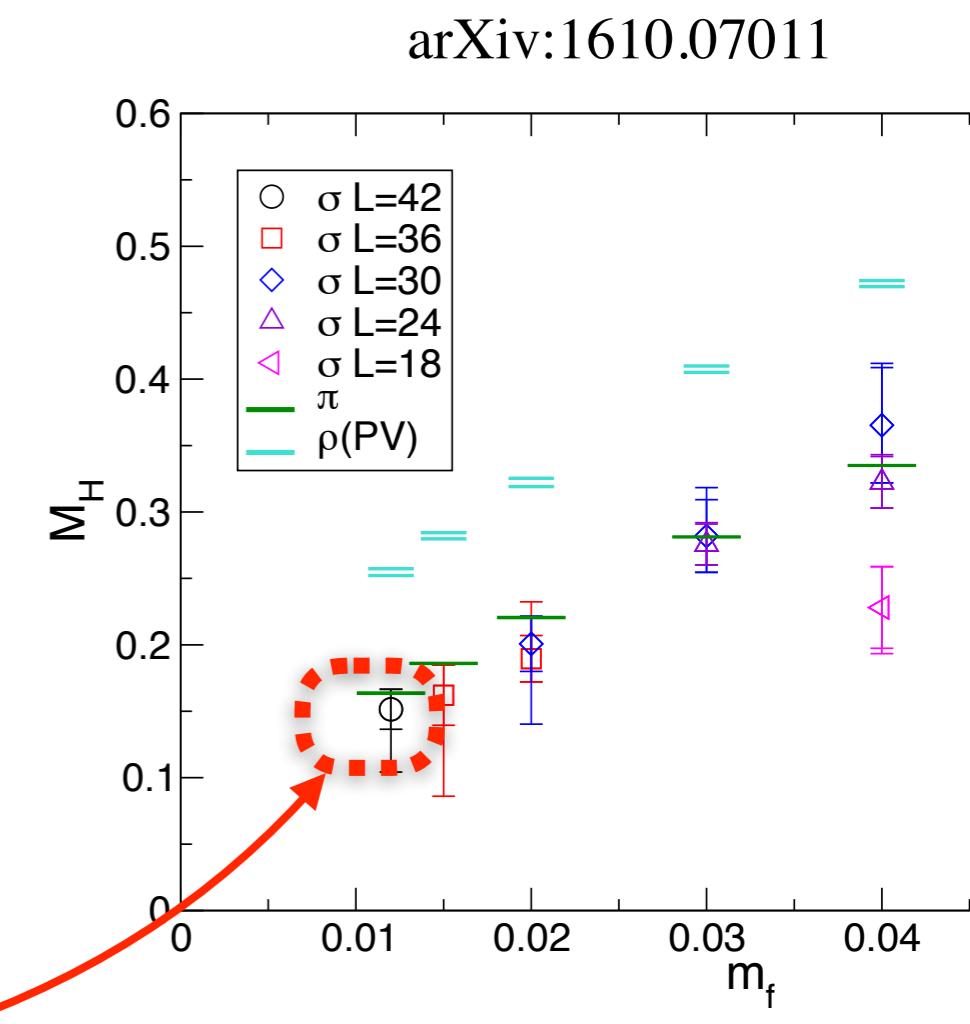
Conformal window in SU(3) with large number of fermions (N_F)



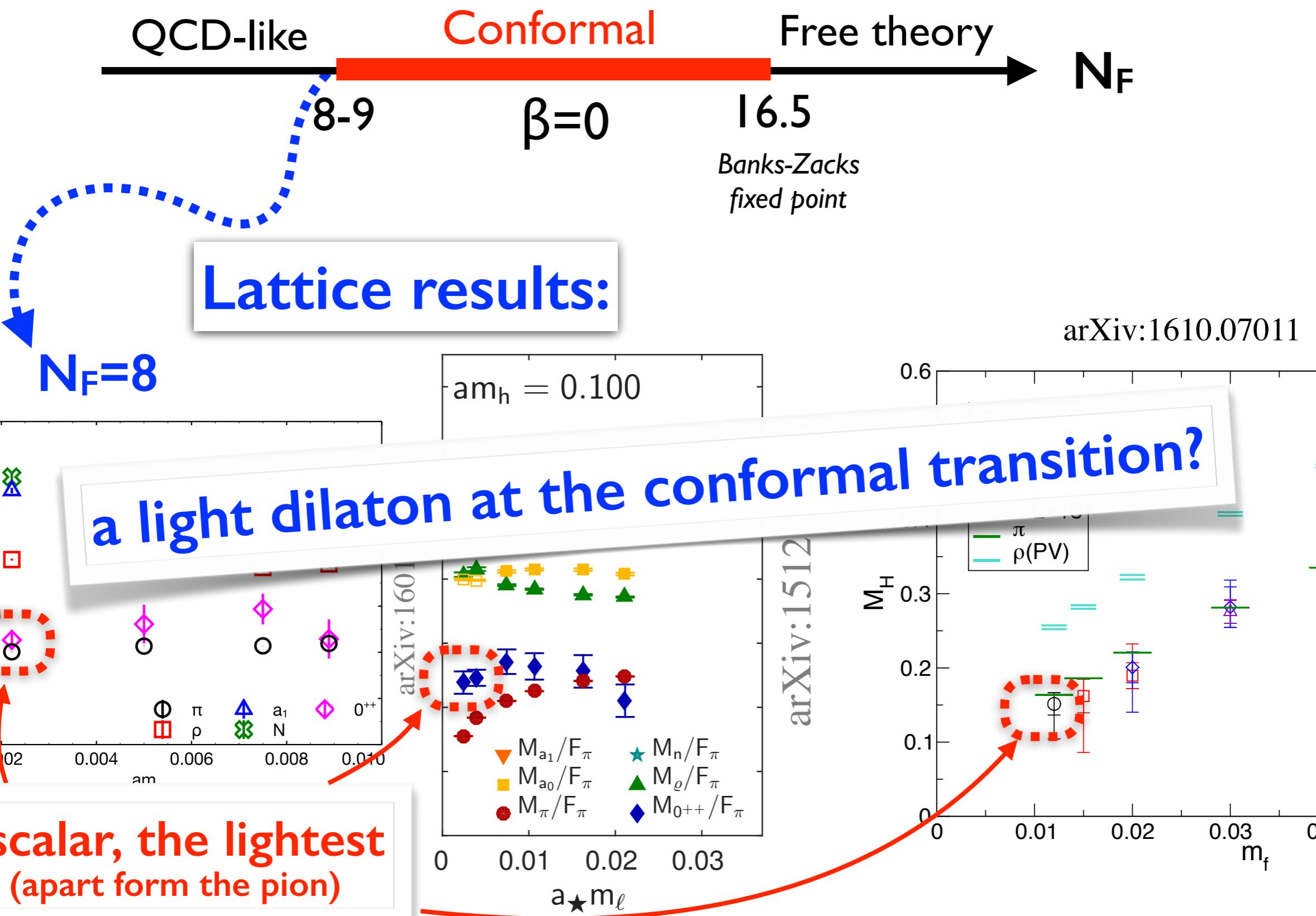
**The scalar, the lightest
(apart from the pion)**



arXiv:1512.02576



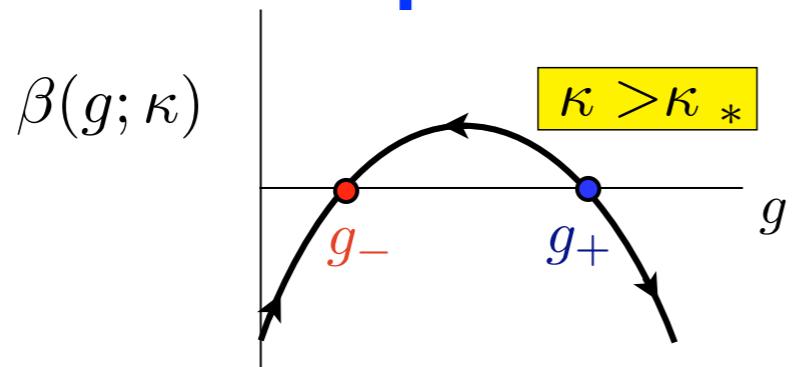
Conformal window in SU(3) with large number of fermions (N_F)



Conformal breaking as N_F decreases



How the fixed point could disappear?

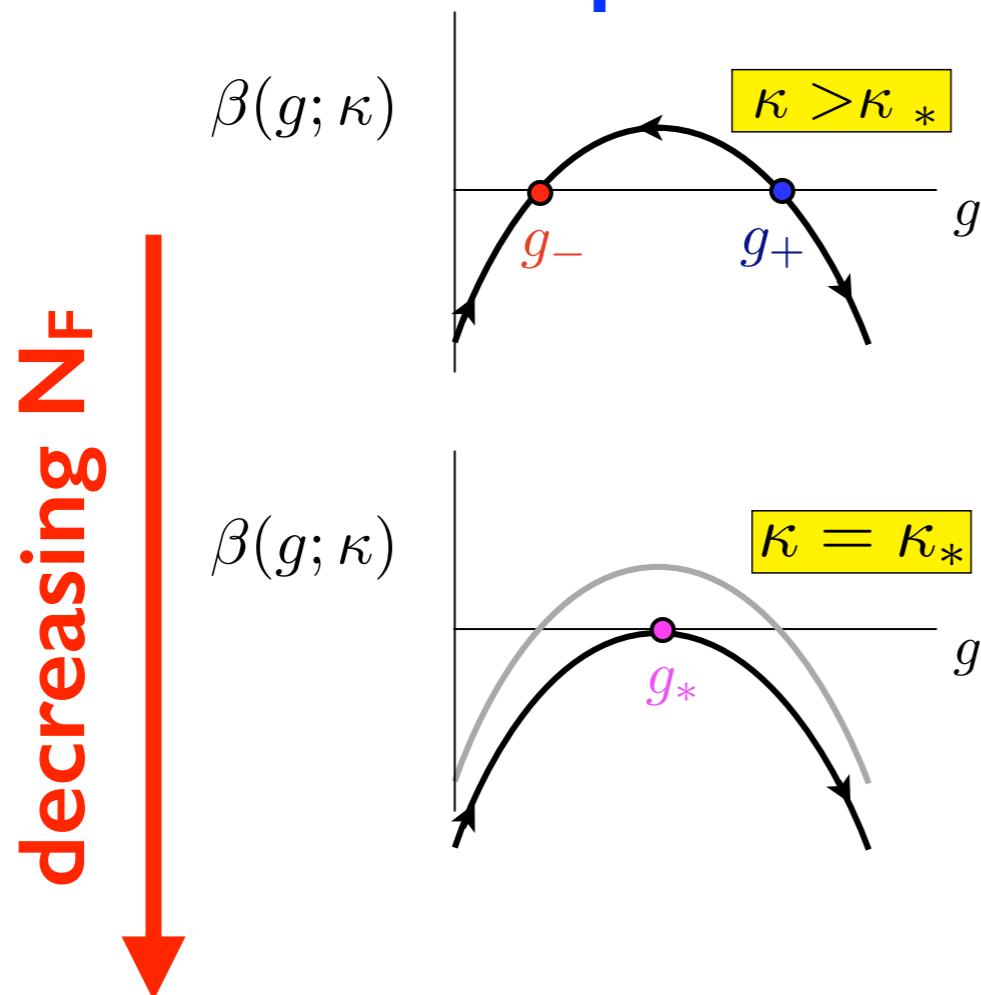


Lee,Son,Stephanov,Kaplan
arXiv:0905.4752

Conformal breaking as N_F decreases



How the fixed point could disappear?



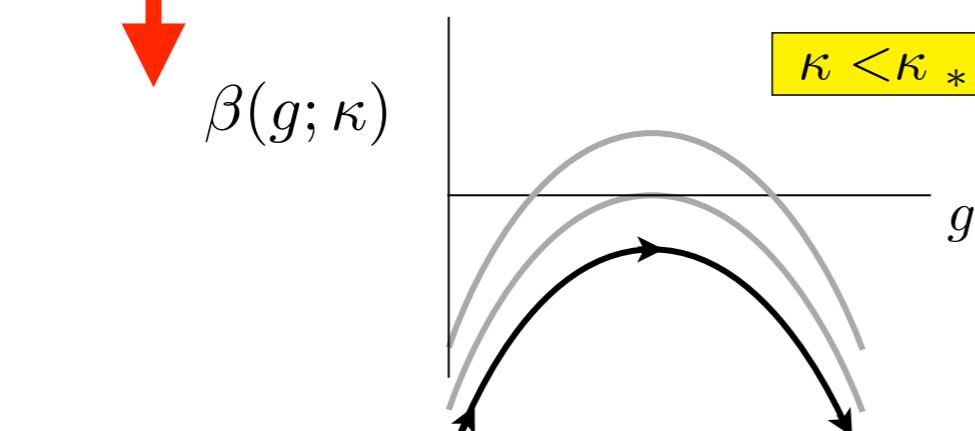
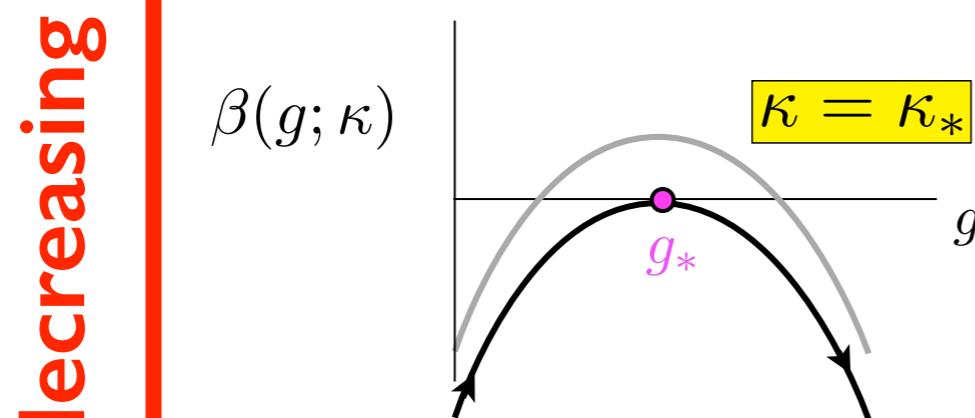
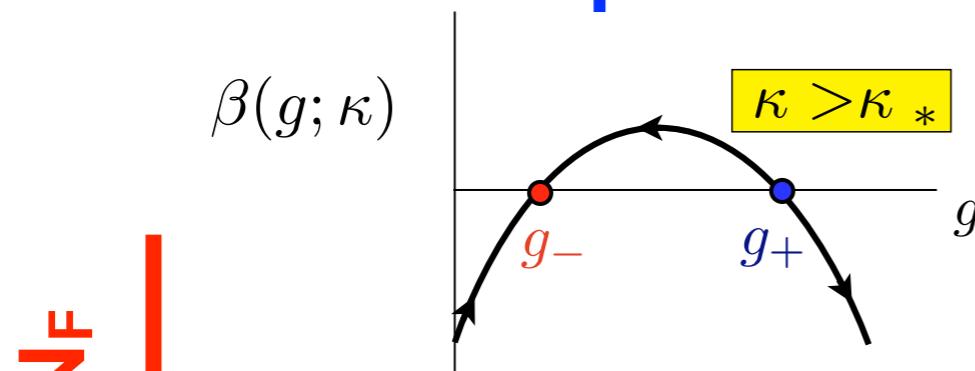
Lee,Son,Stephanov,Kaplan
arXiv:0905.4752

IR & UV fixed-point annihilation

Conformal breaking as N_F decreases



→ How the fixed point could disappear?



Lee,Son,Stephanov,Kaplan
arXiv:0905.4752

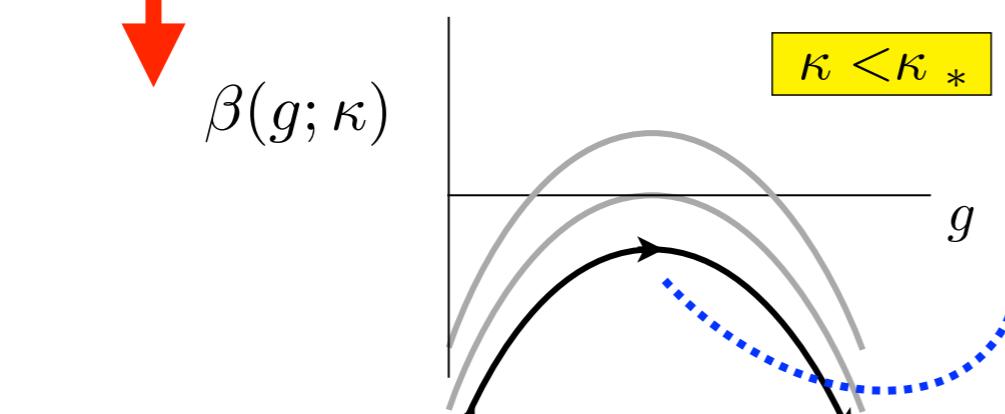
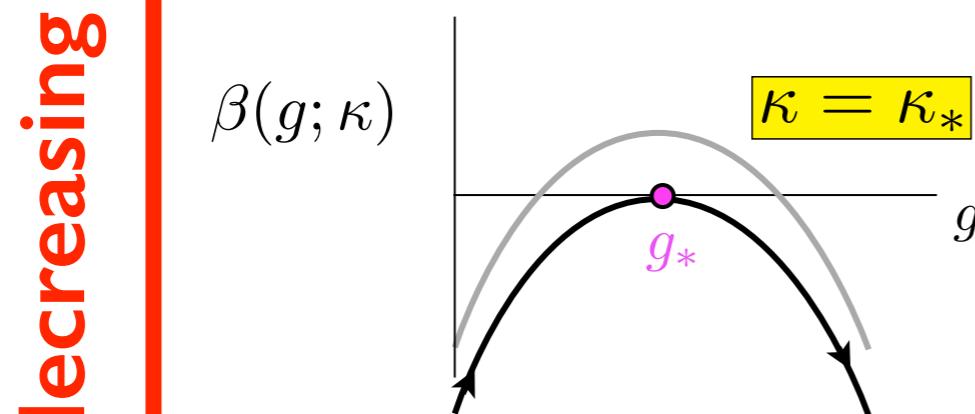
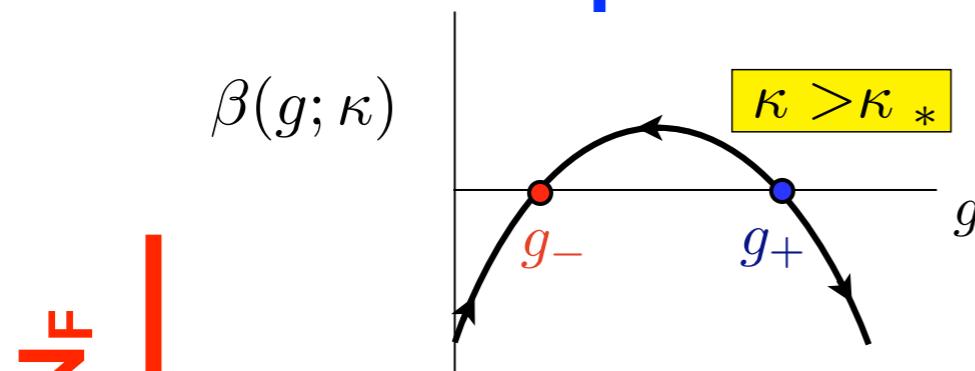
IR & UV fixed-point annihilation

decreasing N_F

Conformal breaking as N_F decreases



→ How the fixed point could disappear?



Lee,Son,Stephanov,Kaplan
arXiv:0905.4752

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



CFT₄ → **AdS₅**

Strongly-coupled

Weakly-coupled

RG – scale (μ) → extra dim (z)

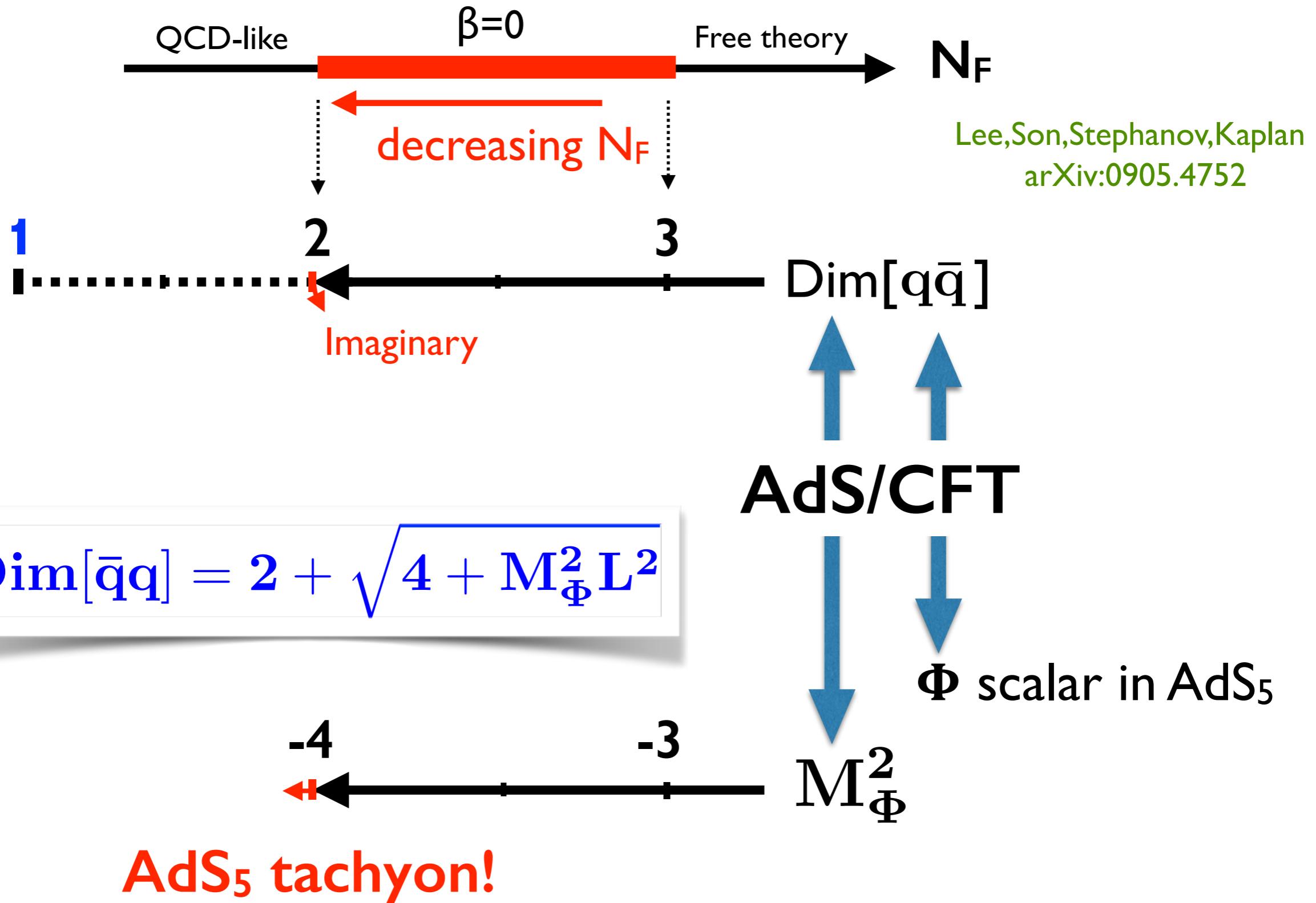
\mathcal{O} → Φ

$$\text{Dim}[\mathcal{O}] = 2 + \sqrt{4 + M_\Phi^2 L^2}$$

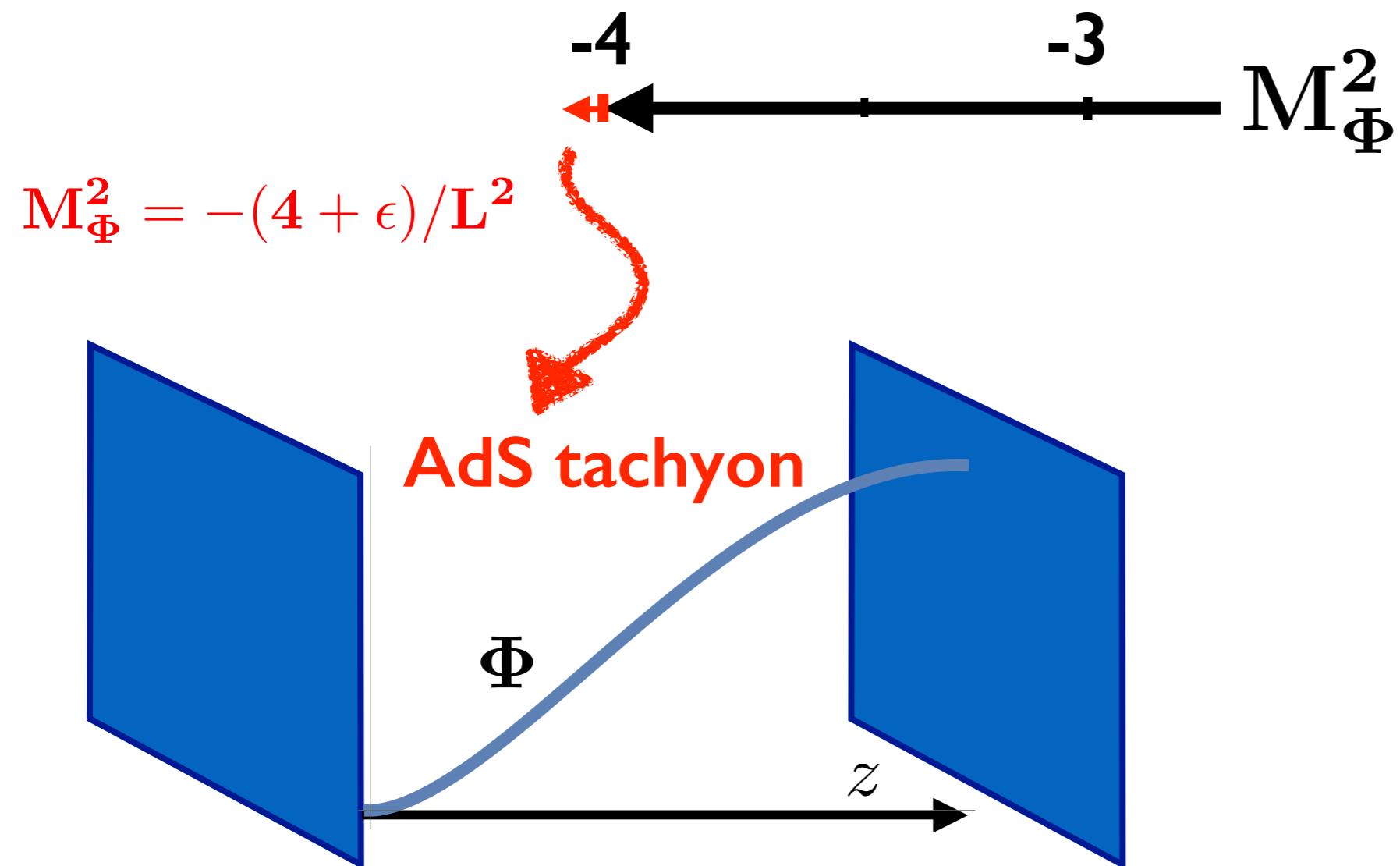
👉 AdS tachyon!

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

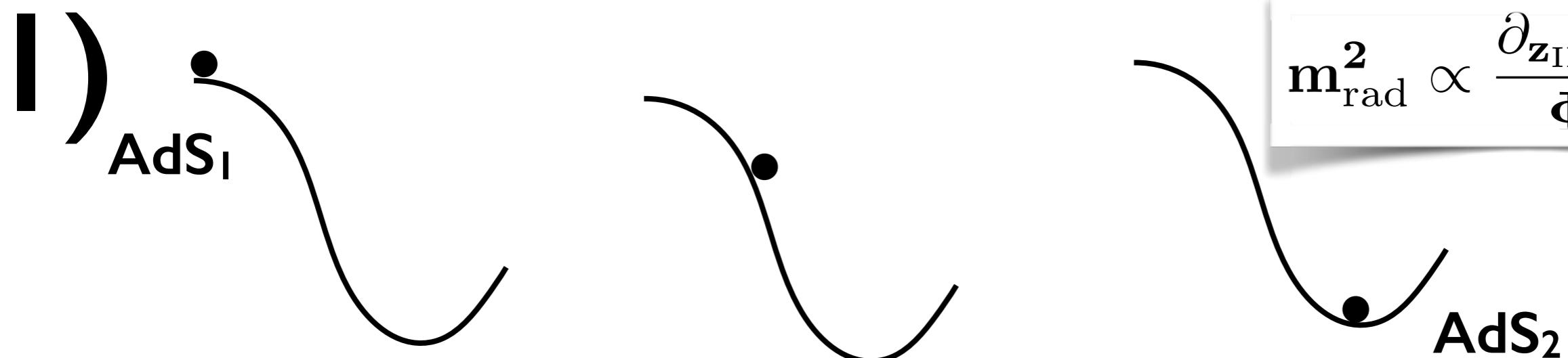
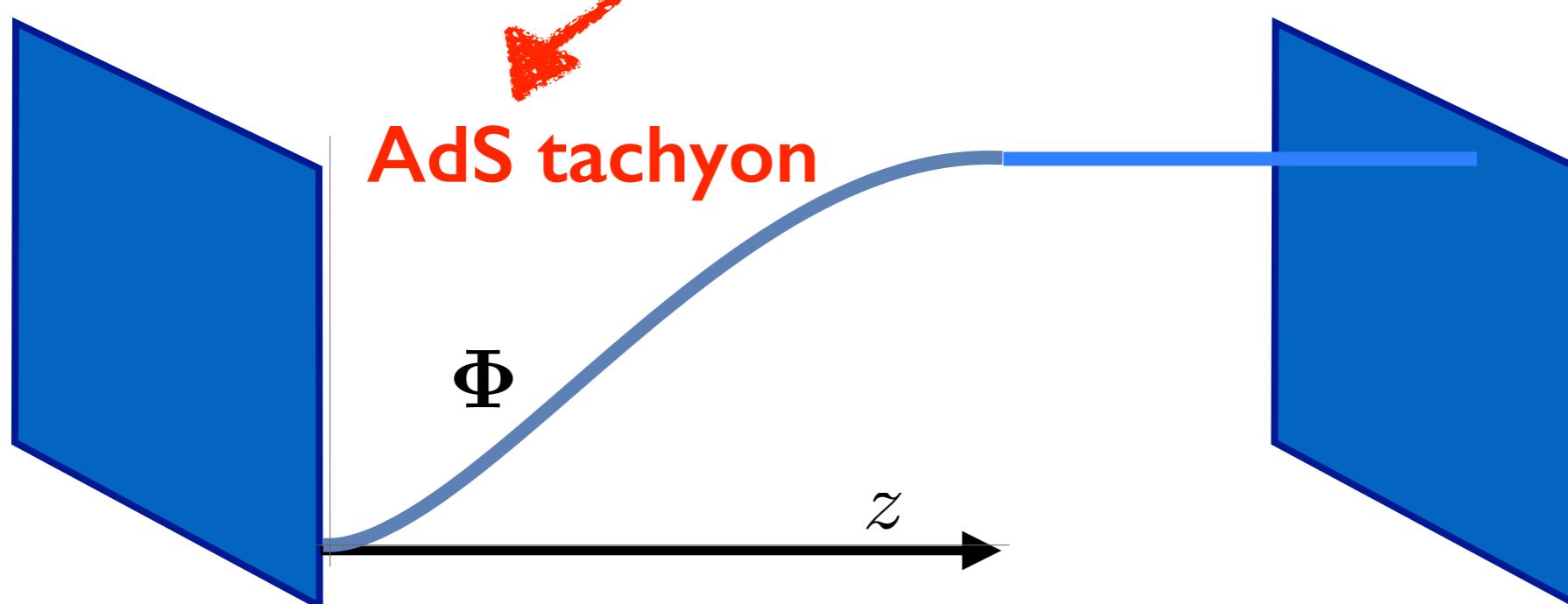
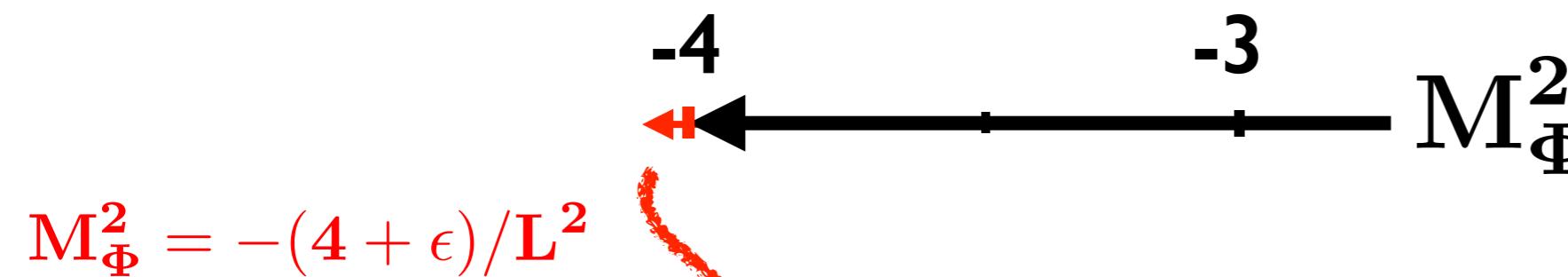
Conformal breaking as N_F decreases



Conformal breaking in AdS_5 due to the mass going below the BF bound

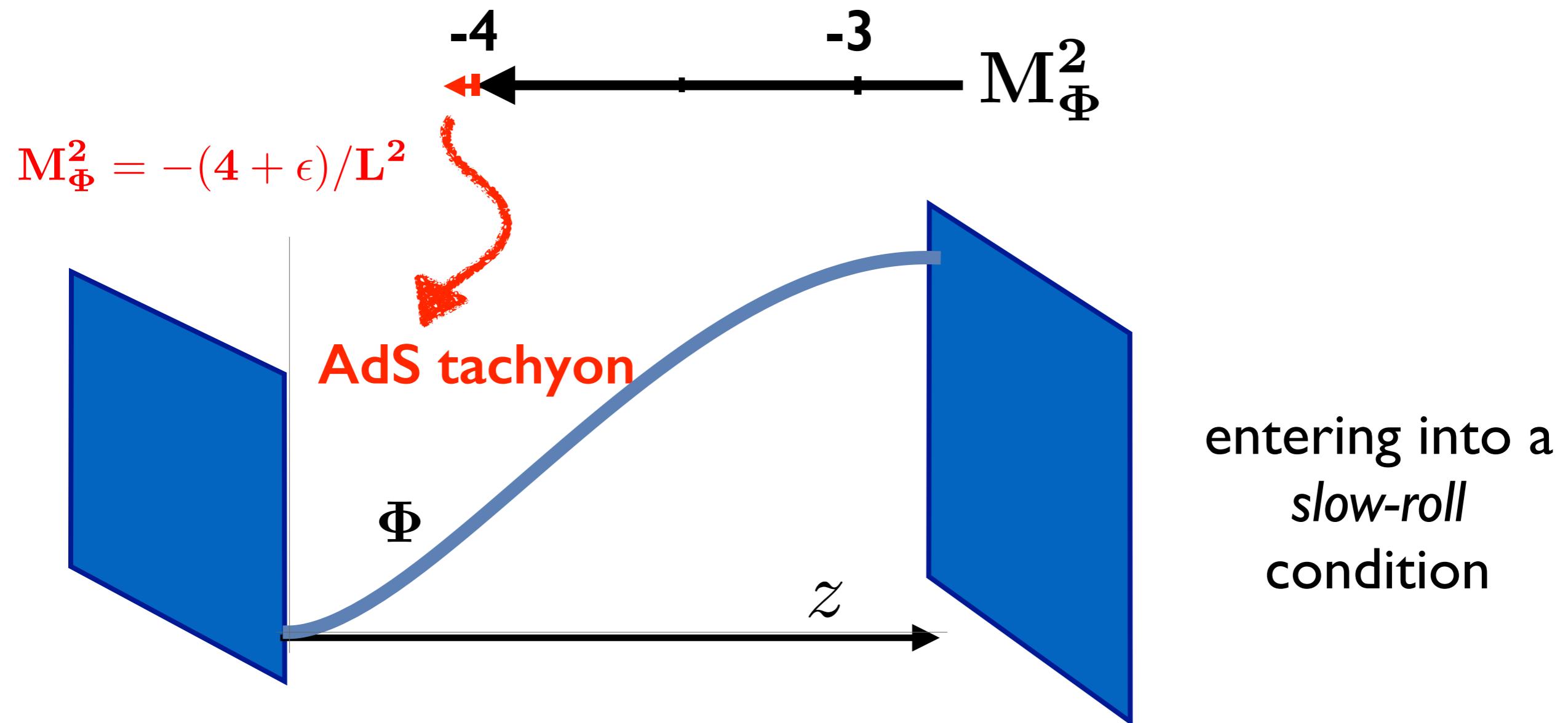


Conformal breaking in AdS_5 due to the mass going below the BF bound



$$m_{\text{rad}}^2 \propto \frac{\partial_{z_{\text{IR}}} \Phi}{\Phi} \rightarrow 0$$

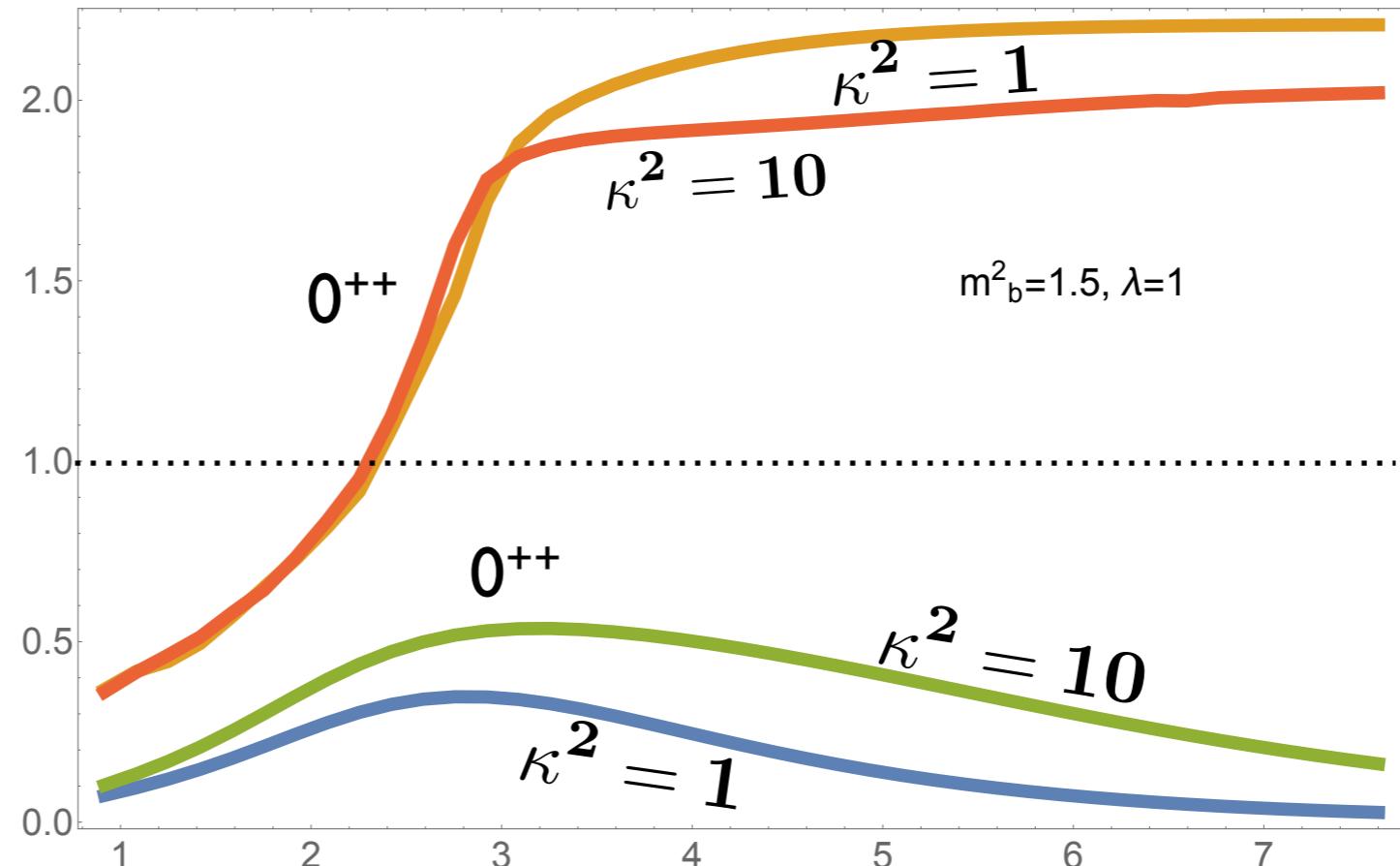
Conformal breaking in AdS_5 due to the mass going below the BF bound



$$m_{\text{rad}}^2 \propto \frac{\partial_{z_{\text{IR}}} \Phi}{\Phi} \rightarrow 0$$

I)

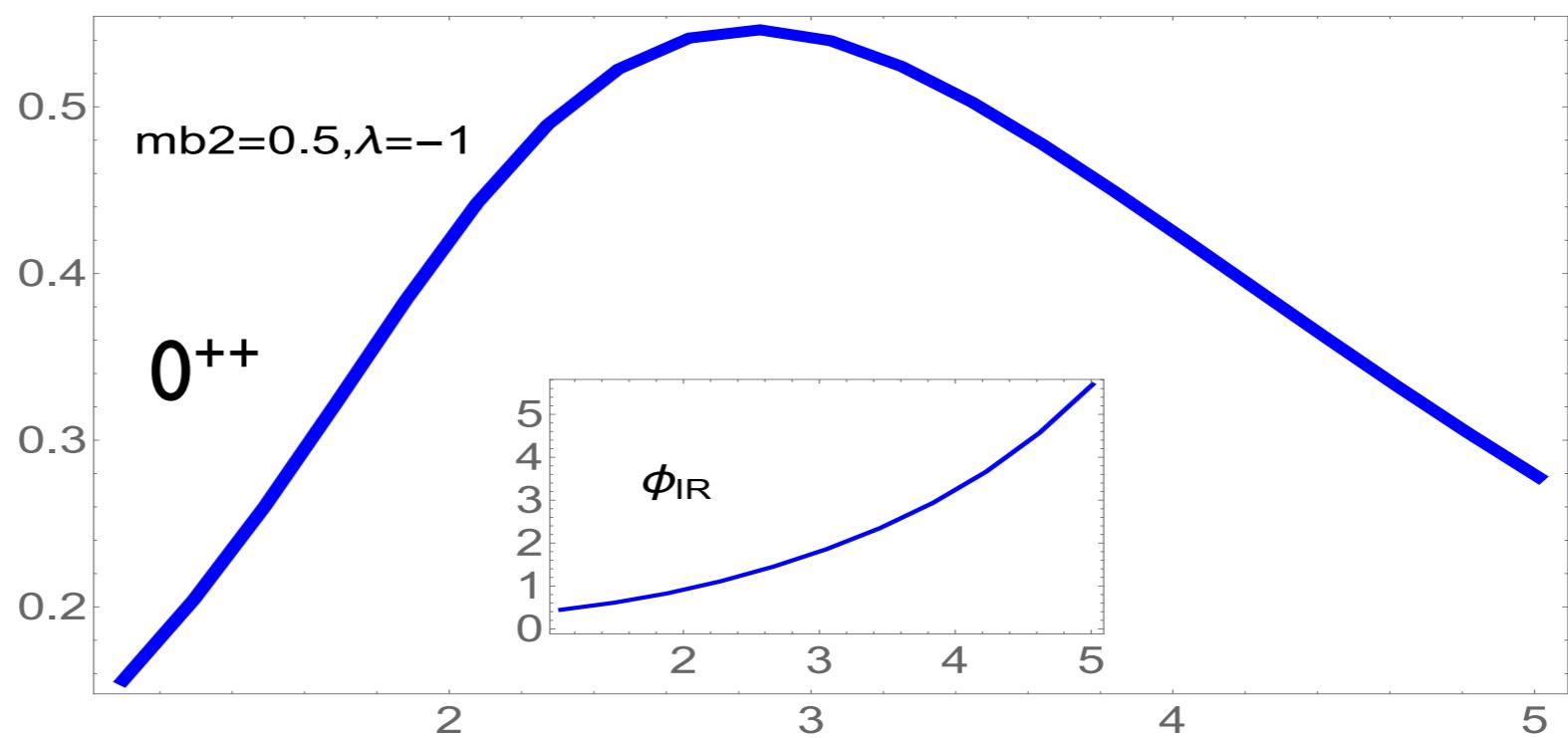
$$\frac{m_S}{m_\rho}$$

 $\ln[z_{\text{IR}}]$

AP, O.Pujolas, L.Salas 19

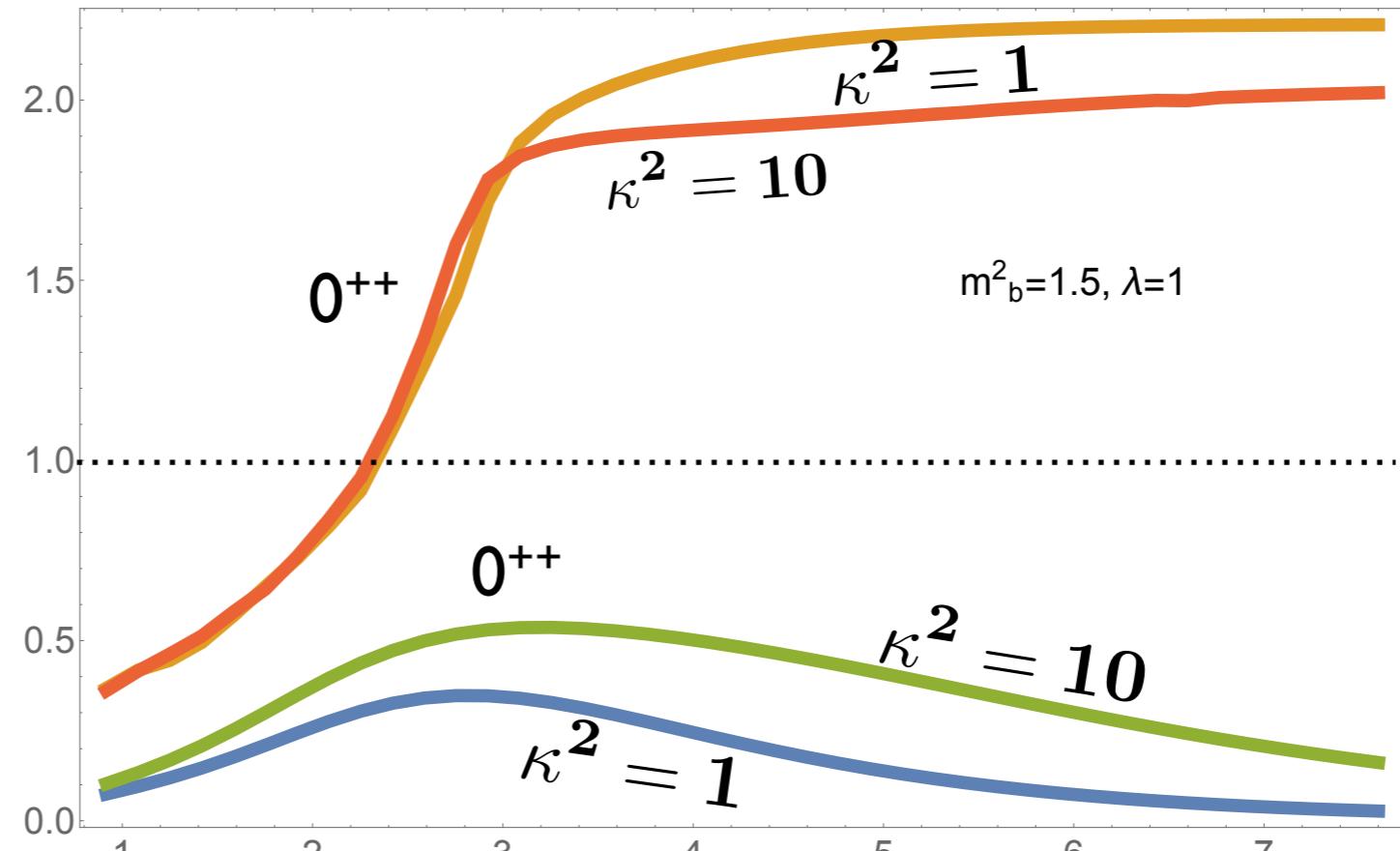
II)

$$\frac{m_S}{m_\rho}$$

 $\ln[z_{\text{IR}}]$ $mb2=0.5, \lambda=-1$ ϕ_{IR}

I)

$$\frac{m_S}{m_\rho}$$

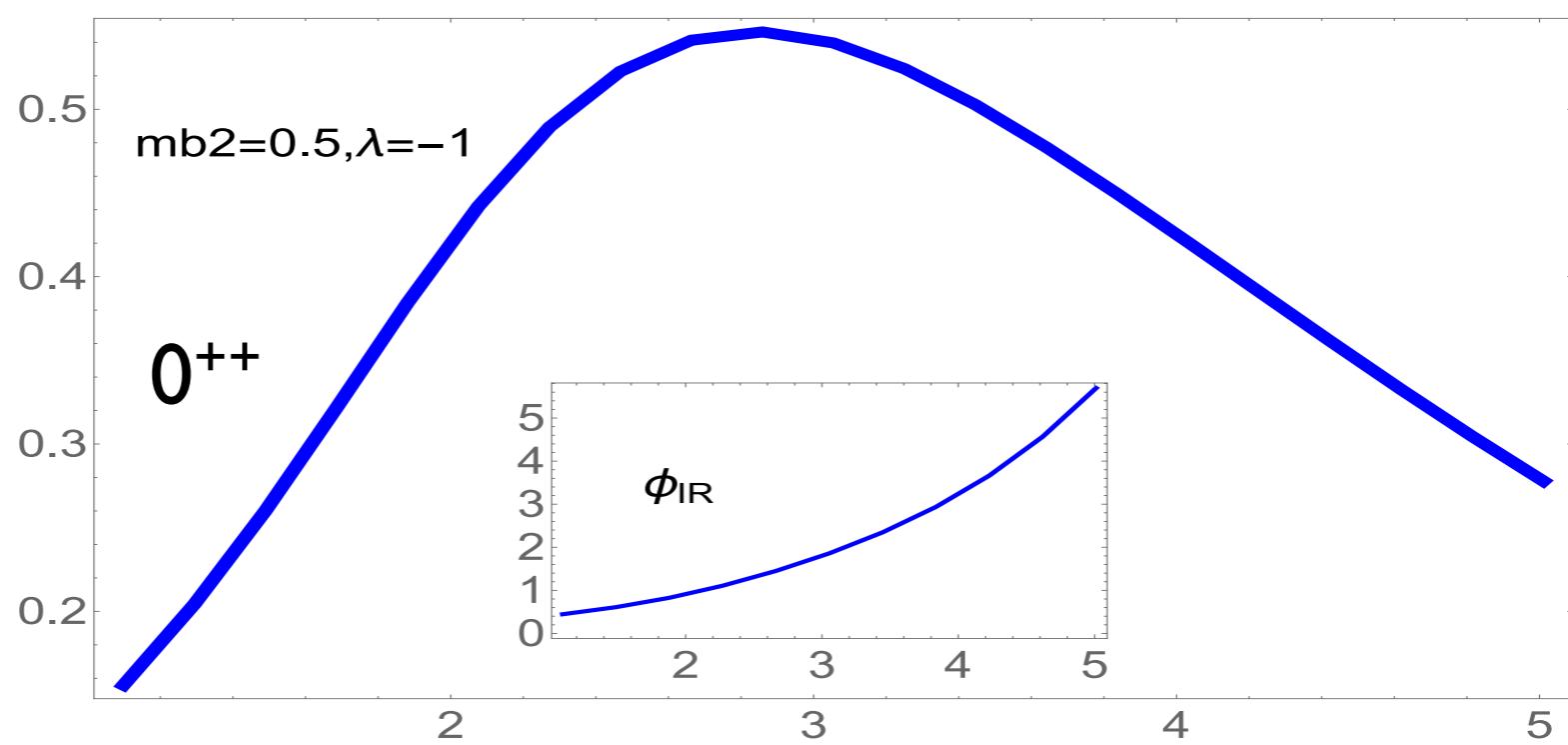


$\ln[z_{\text{IR}}]$

AP, O.Pujolas, L.Salas 19

II)

$$\frac{m_S}{m_\rho}$$



$\ln[z_{\text{IR}}]$

Always a light scalar (mostly dilaton) but not parametrically light!

Always possible to stabilize the brane by the 4D tachyon:

$$\sqrt{\epsilon} \ln \frac{z_{\text{IR}}}{z_{\text{UV}}} \simeq n\pi , \quad n = 1, 2, \dots ,$$

{ n=1 ground state
n=2,3,... Efimov states

(the model has a discrete scale invariance)

Some pheno implications

(for strongly-coupled TeV sector with light dilatons)

Could this lighter scalar be the Higgs? Resurrecting Technicolor?

- Mass? Not light enough

For $M_{\text{vector reso.}} > 3 \text{ TeV}$,
we need a reduction, in squared masses, of < 0.002

Could this lighter scalar be the Higgs? Resurrecting Technicolor?

- Mass? Not light enough

For $M_{\text{vector reso.}} > 3 \text{ TeV}$,
we need a reduction, in squared masses, of < 0.002

- Higgs-like couplings?

$$\mathcal{L} = \frac{M_V^2}{2} V_\mu^2 \left(1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} \right) - m_f \bar{\psi}_L \psi_R \left(1 + c \frac{h}{v} \right) + \dots$$

SM Higgs: $a = b = c = 1$

Dilaton: $a = \sqrt{b} = c = \frac{v}{f_D} \sim \mathcal{O}(1)$

Could this lighter scalar be the Higgs? Resurrecting Technicolor?

- Mass? Not light enough

For $M_{\text{vector reso.}} > 3 \text{ TeV}$,
we need a reduction, in squared masses, of < 0.002

- Higgs-like couplings?

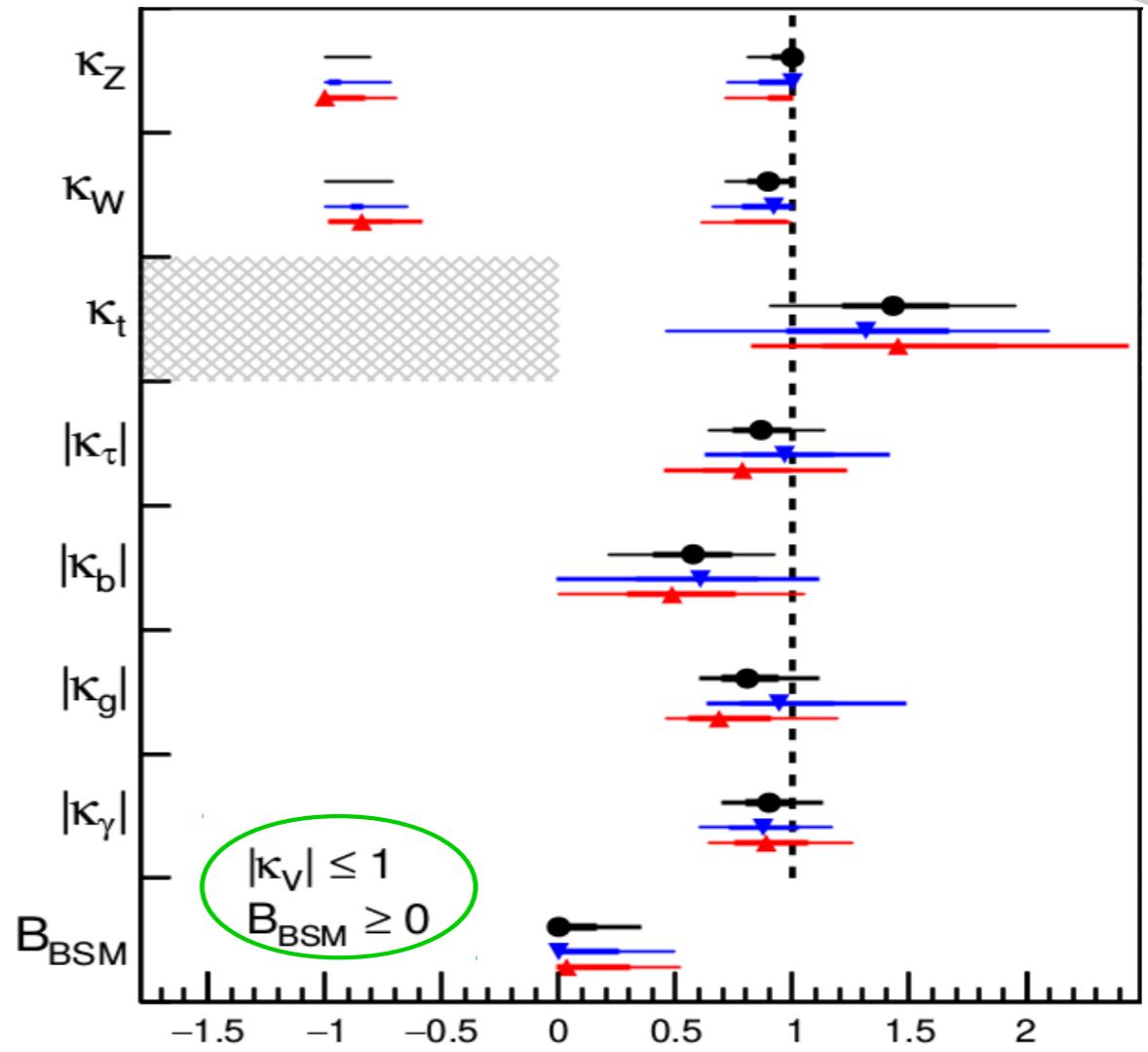
$$\mathcal{L} = \frac{M_V^2}{2} V_\mu^2 \left(1 - \right)$$

SM Higgs:

Dilaton:

Hardly consistent
with present measurements

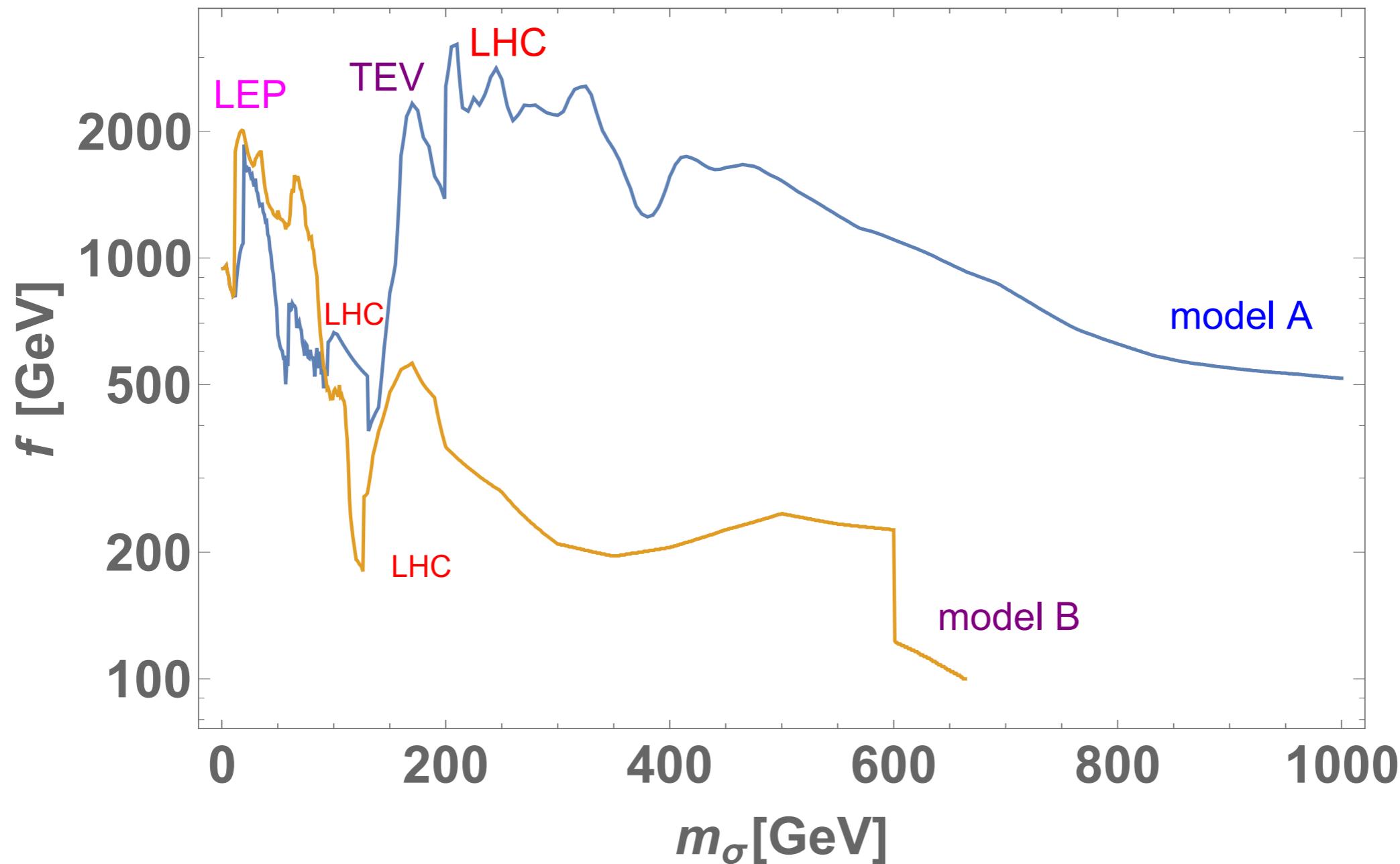
$$\kappa_i = \frac{g_{Hii}}{g_{Hii}^{\text{SM}}}$$



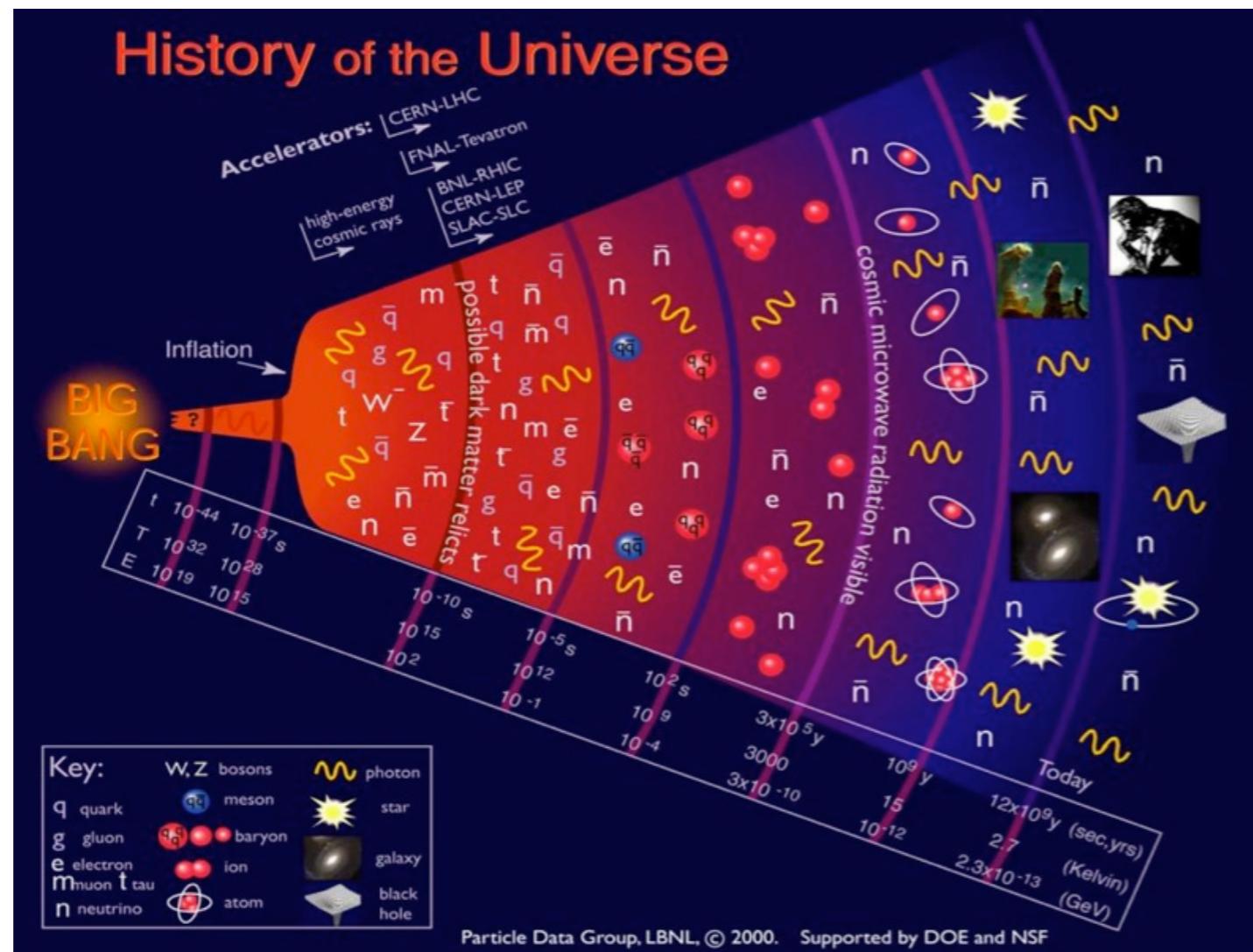
If not the Higgs, it could be the lightest resonance

Experimental bounds

arXiv:1410.1873



Implications in the cosmological history

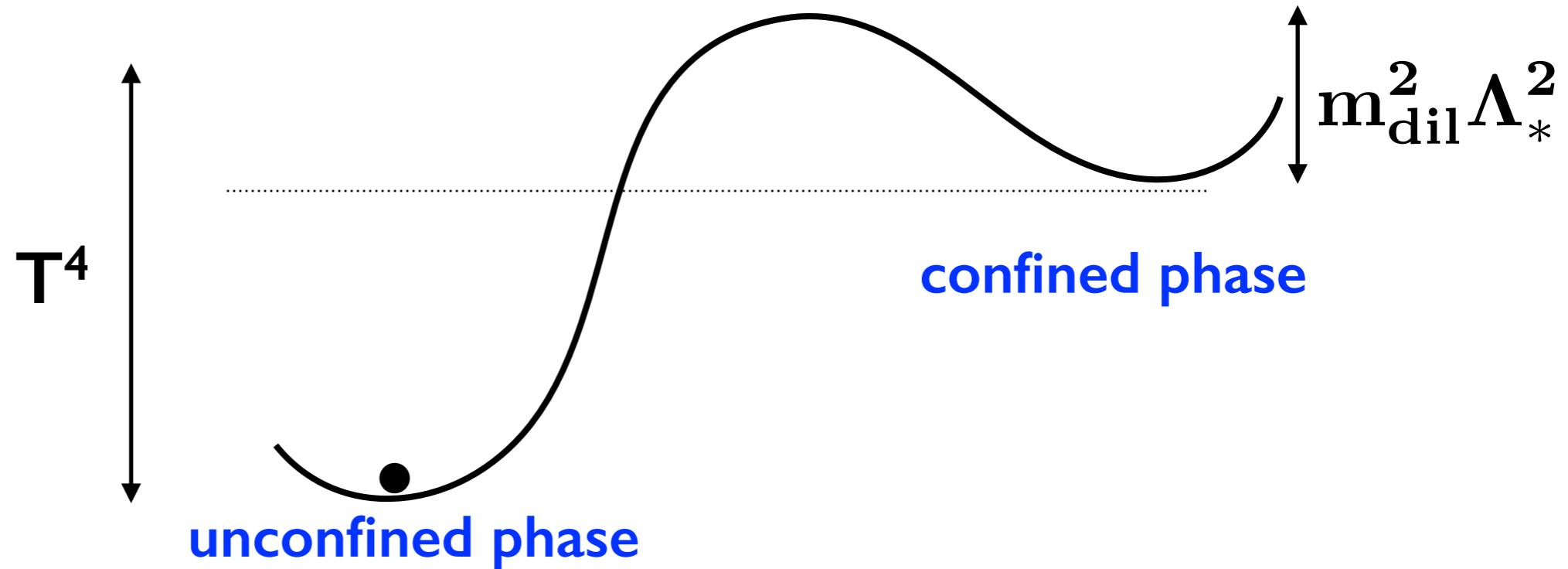


P.Baratella, AP, F.Rompineve arXiv:1812.06996

(see also 1711.11554 & 1407.0030)

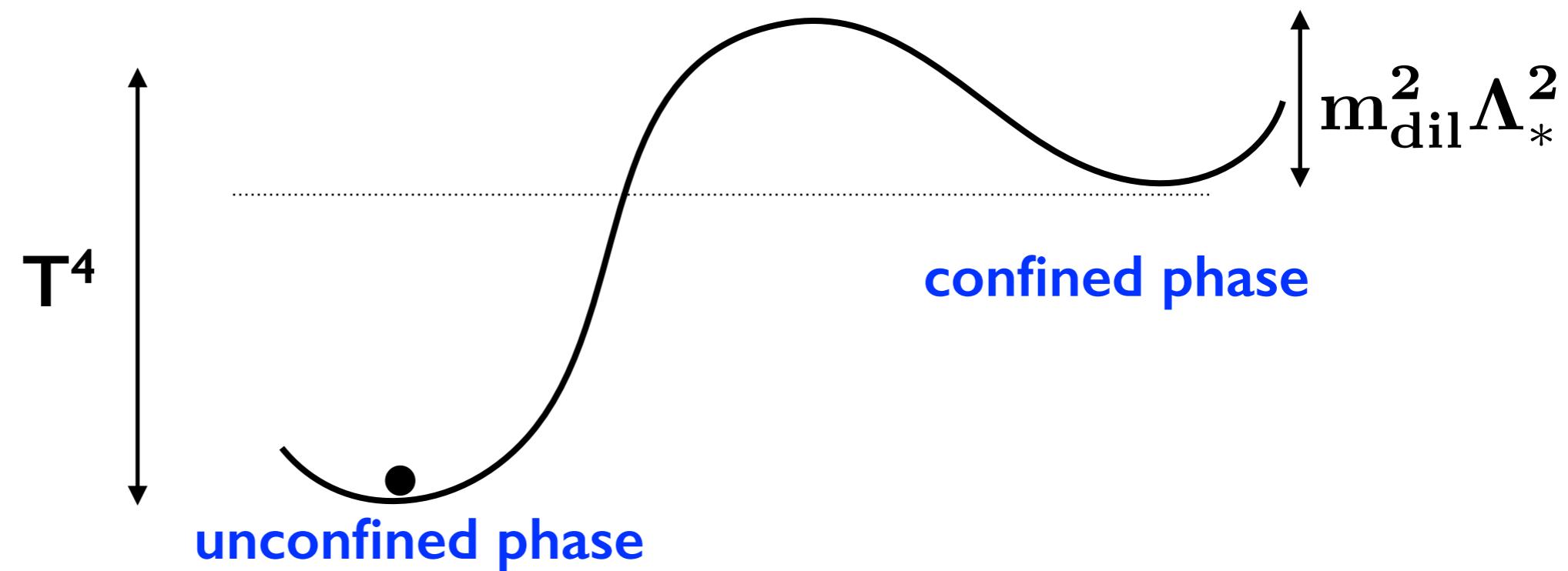
$$F = E - S T$$

I) High T:

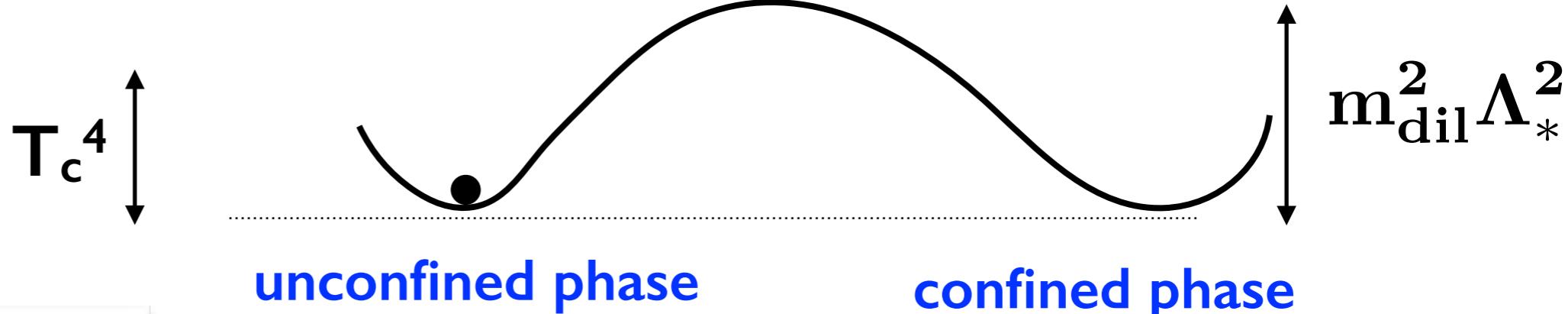


$$F = E - S T$$

I) High T:



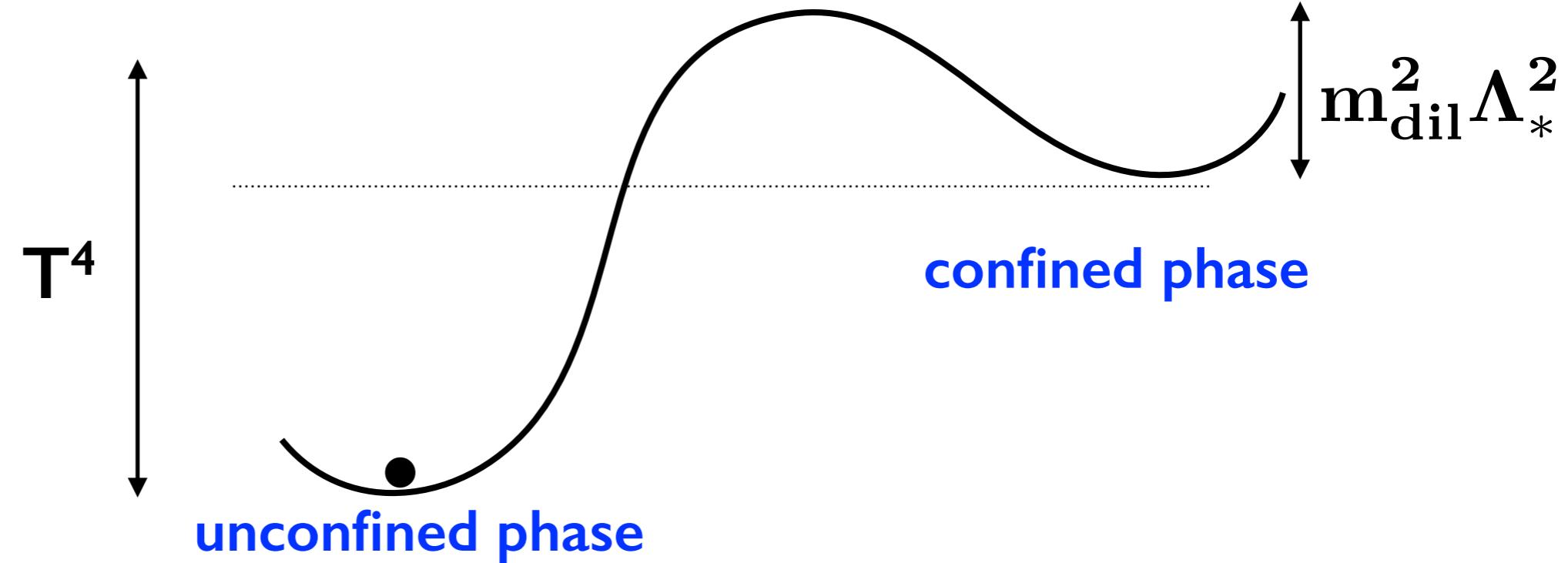
II) Critical T:



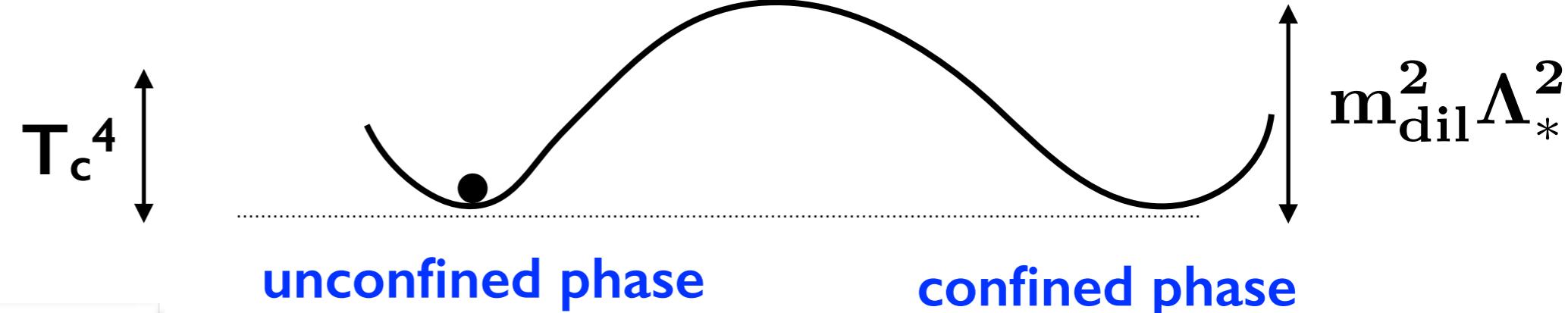
$$T_c \simeq \sqrt{m_{\text{dil}} \Lambda_*}$$

$$F = E - S T$$

I) High T:

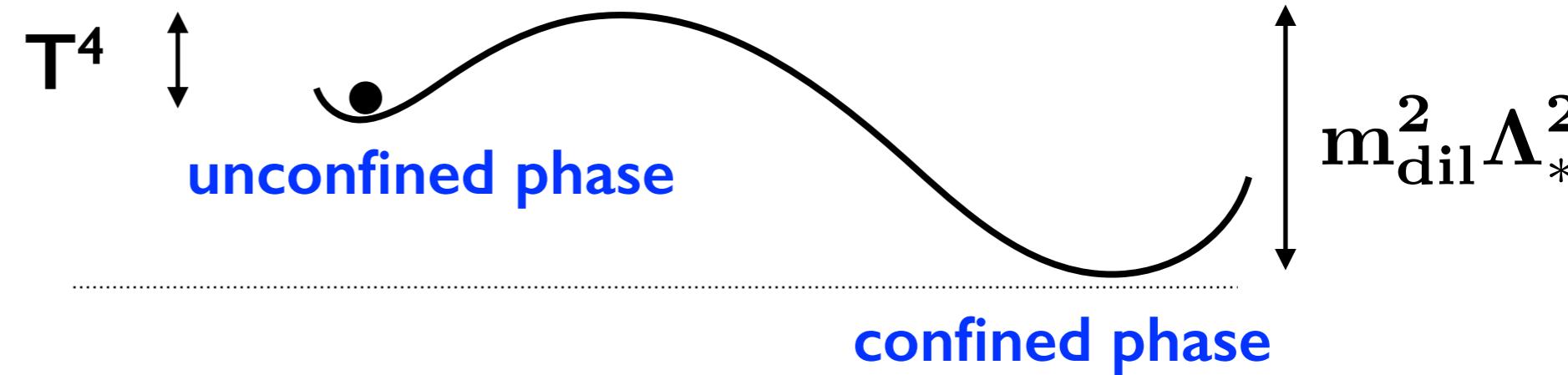


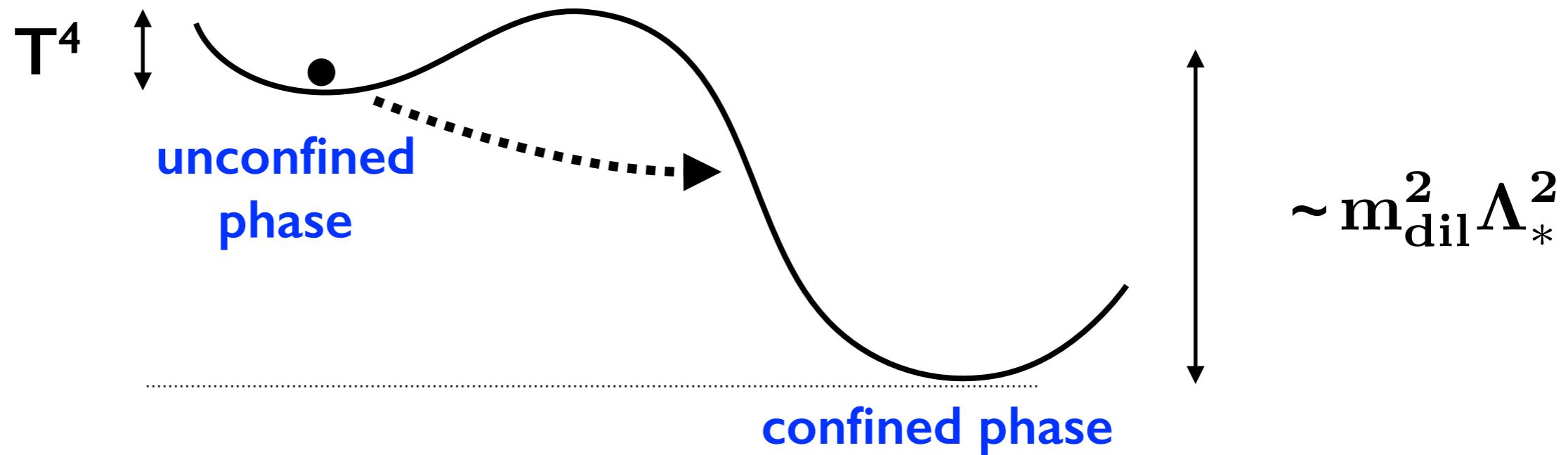
II) Critical T:



$$T_c \simeq \sqrt{m_{\text{dil}} \Lambda_*}$$

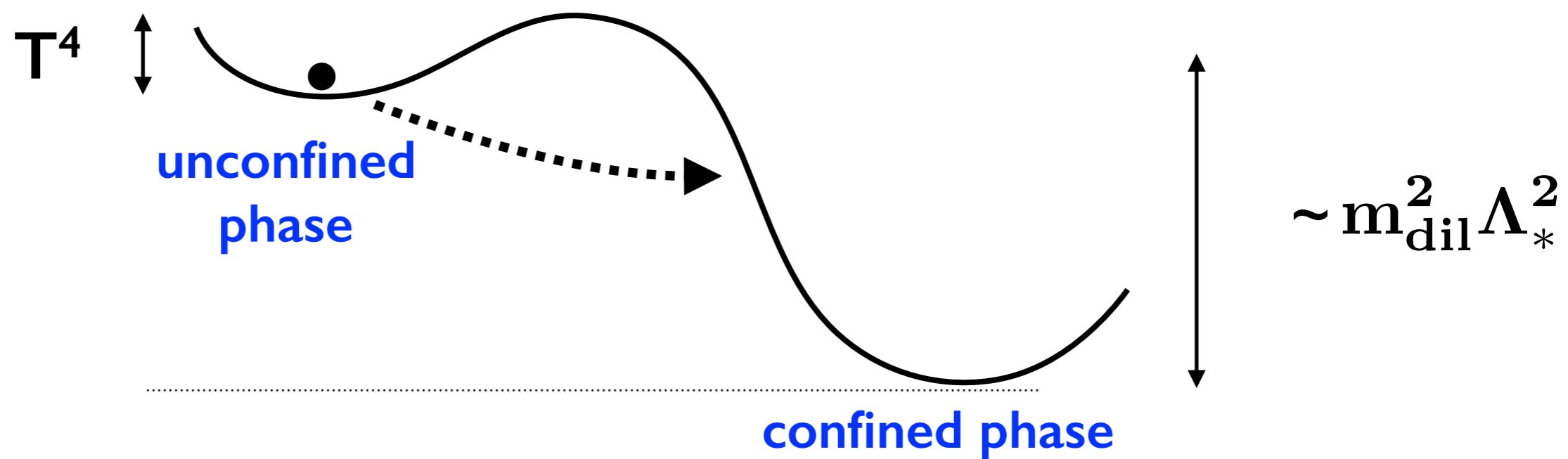
III) $T \ll \Lambda_*$:





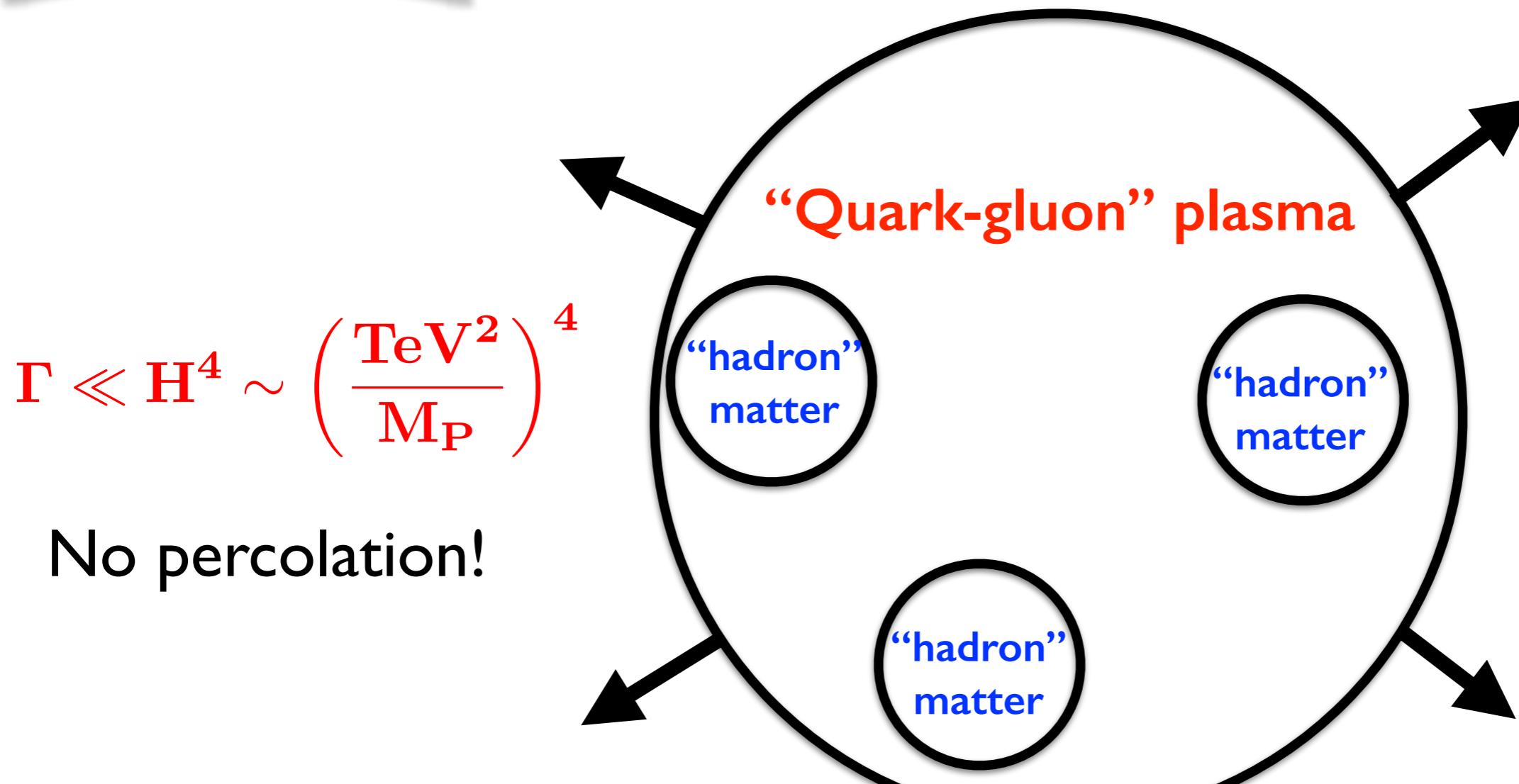
Tunneling rate:

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

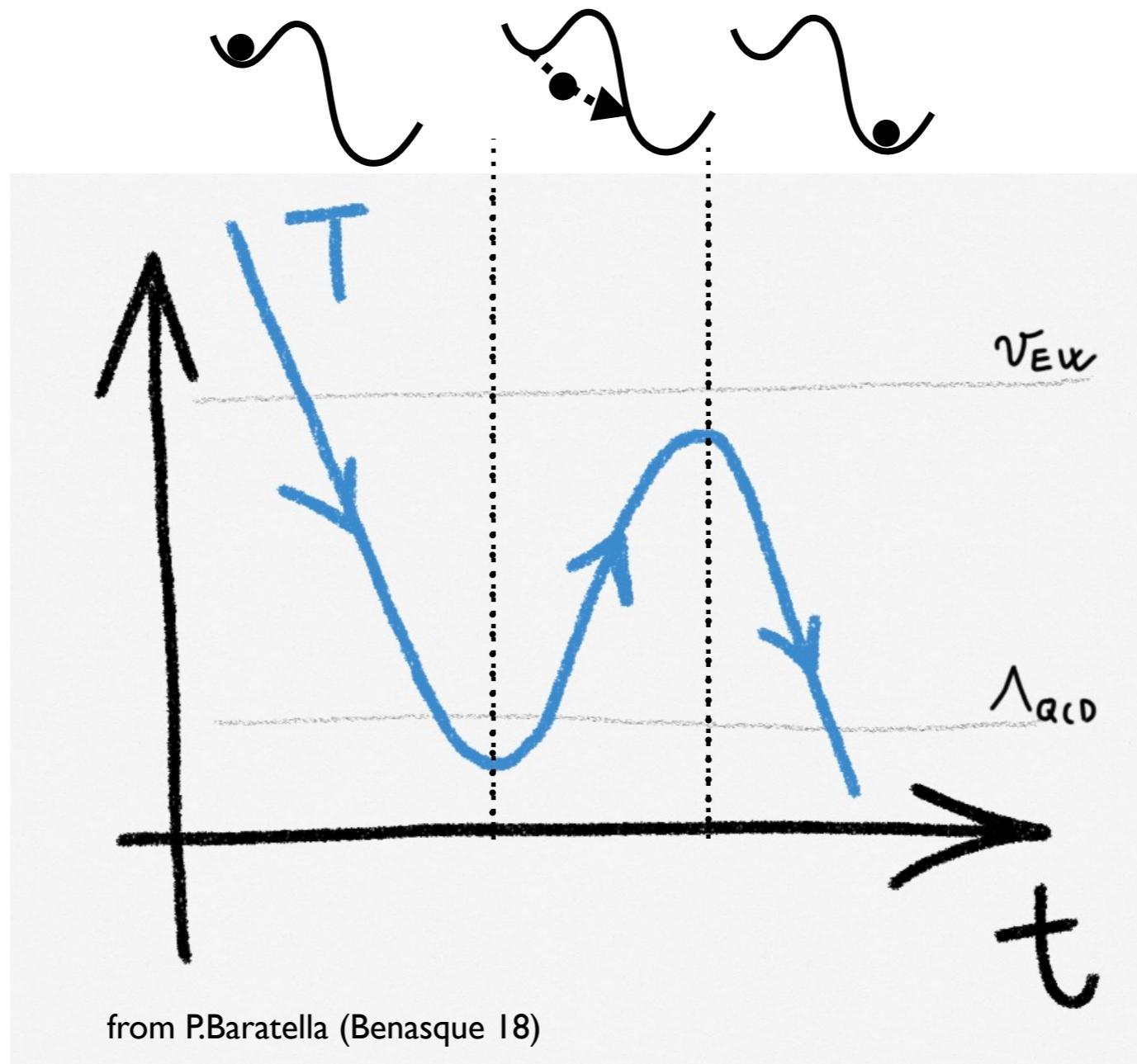


Tunneling rate:

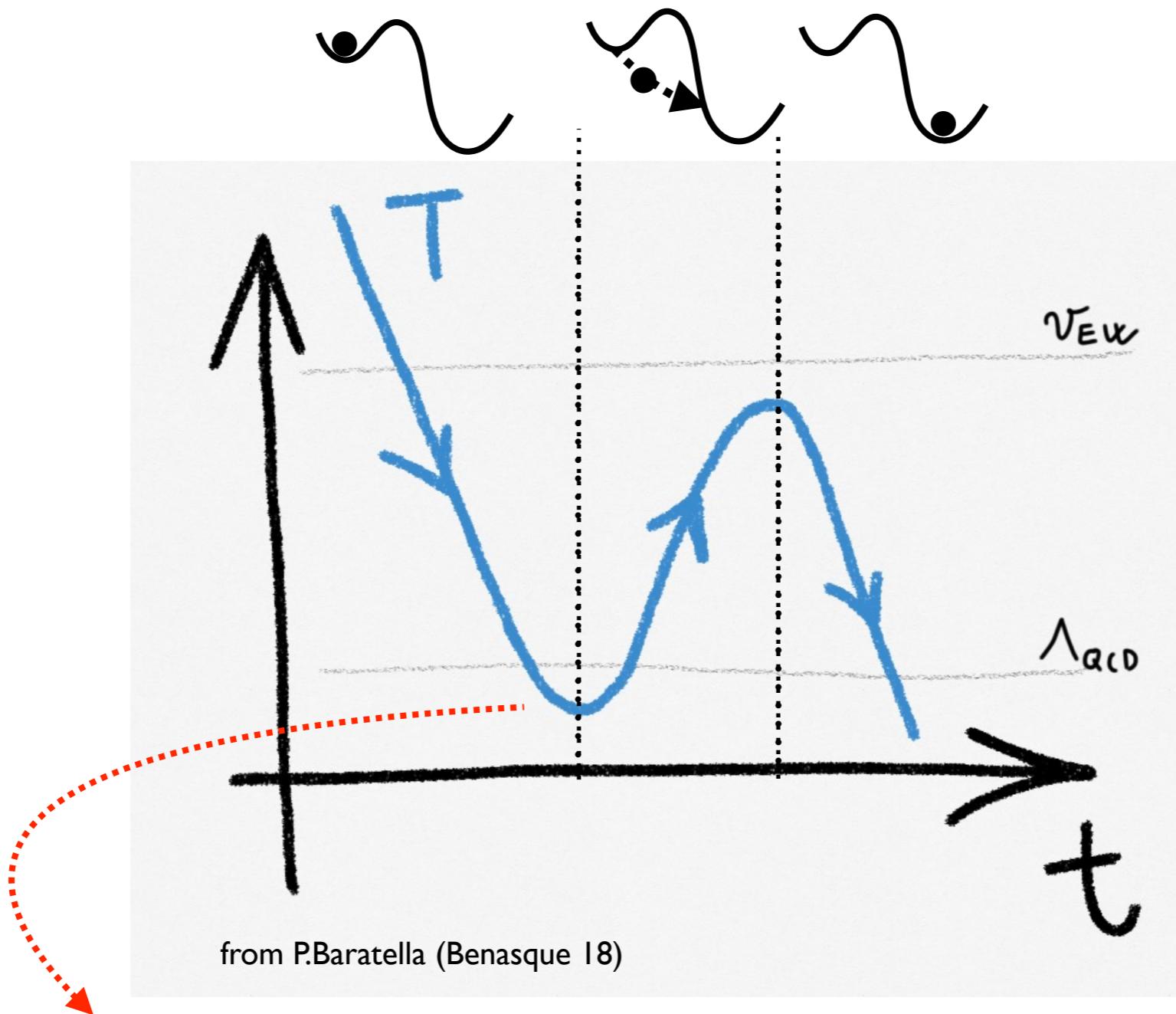
$$\Gamma \sim e^{-S_E} \sim e^{-1/g_*^2} \sim e^{-N_c^2}$$



Additional supercooling epoch



Additional supercooling epoch

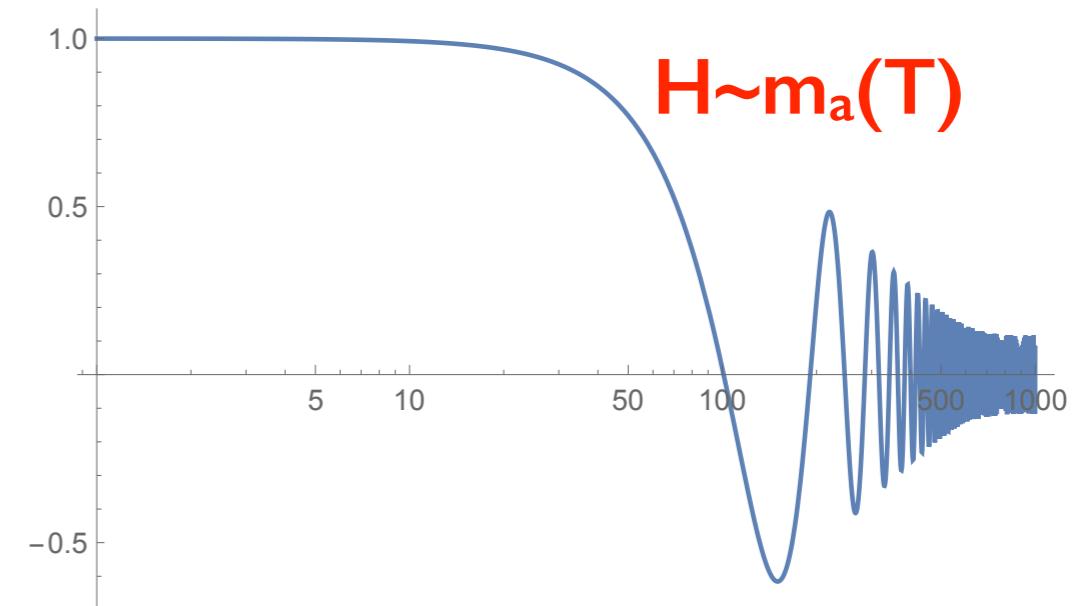
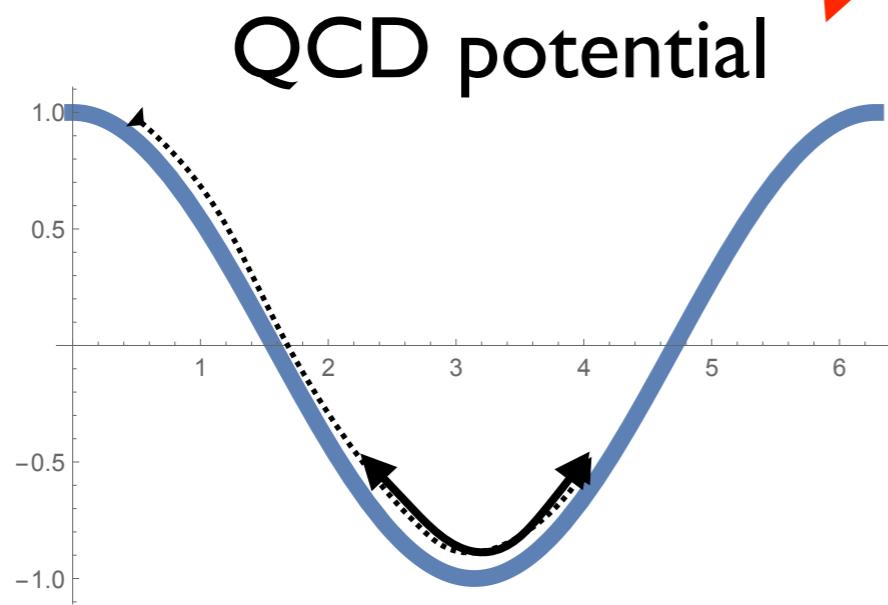
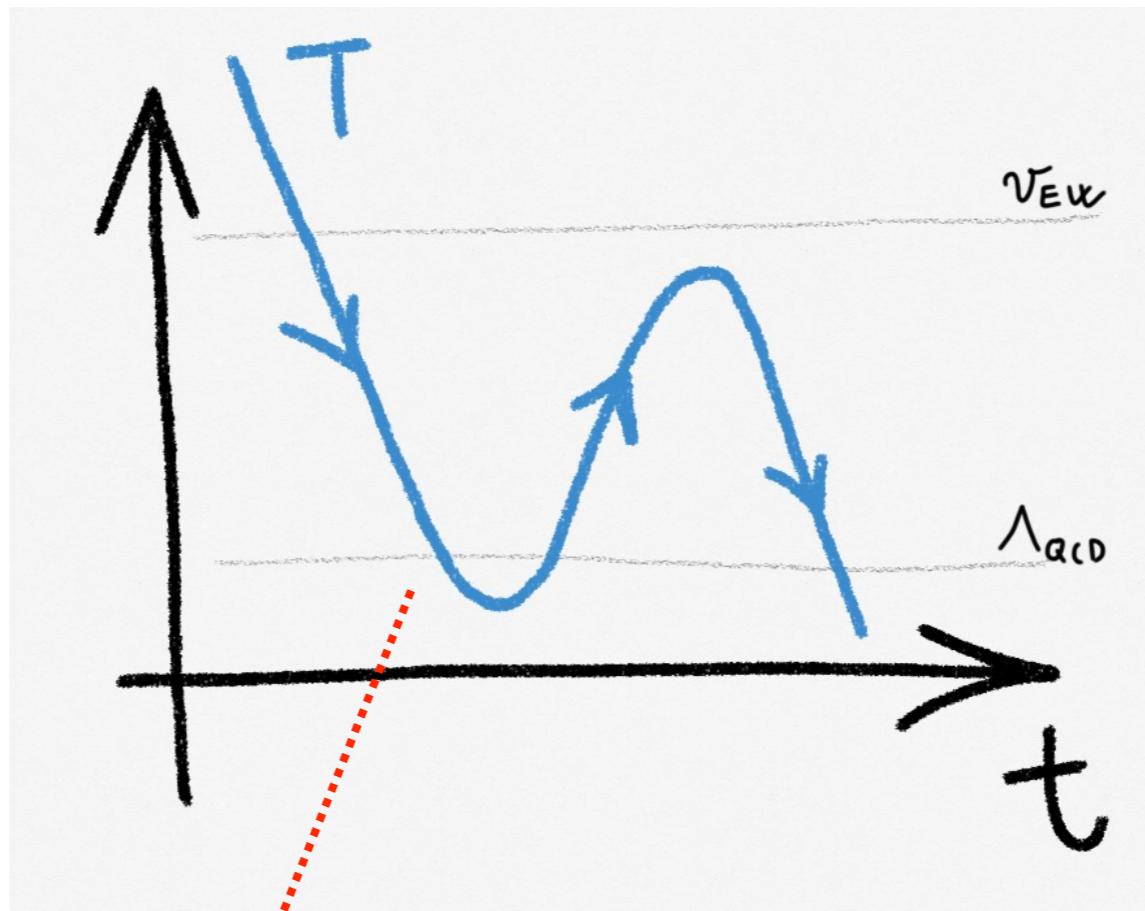


Additional QCD phase transition

Implications? Impact on axion abundance

If supercooling:

Additional QCD phase transition

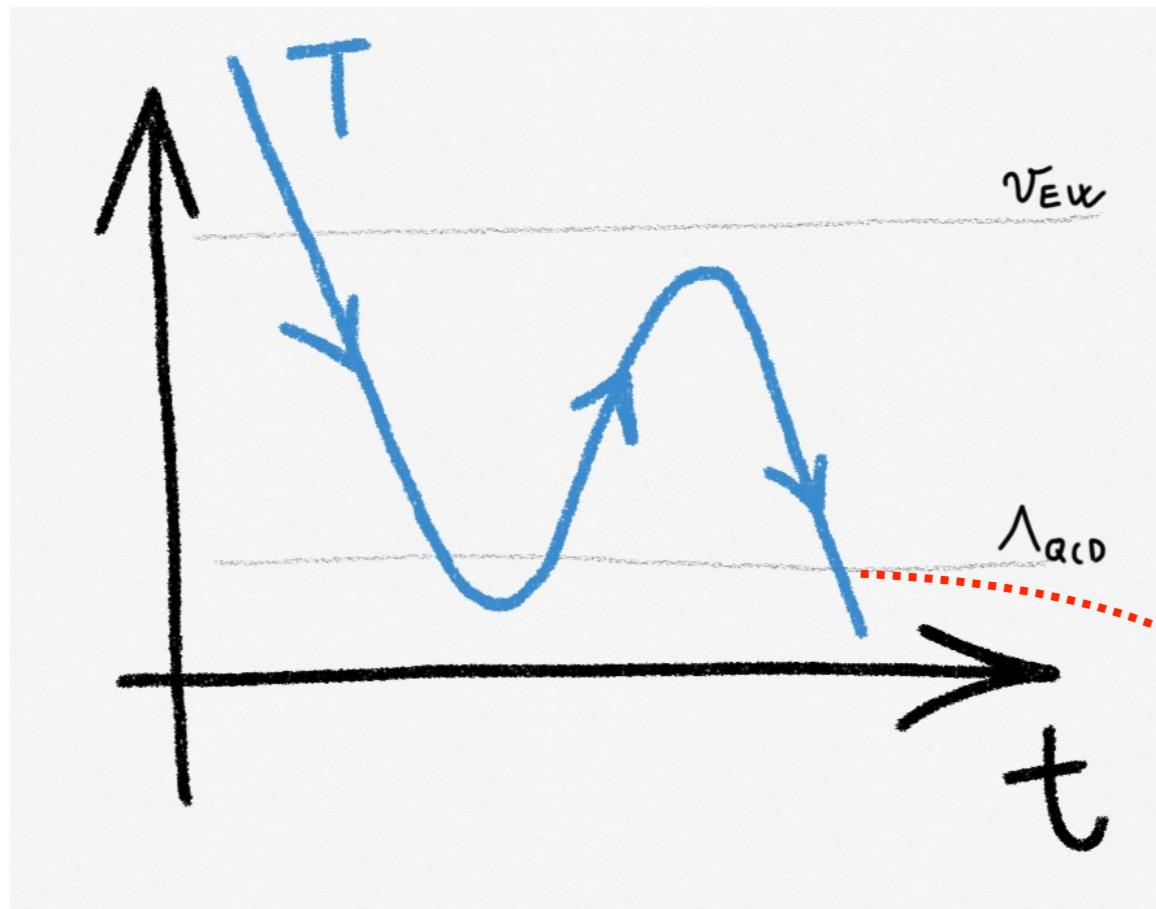


$$H \sim \frac{m_{\text{dil}} \Lambda_*}{M_P} \sim m_a \sim \frac{\Lambda_{\text{QCD}}^{3/2}}{F_a}$$

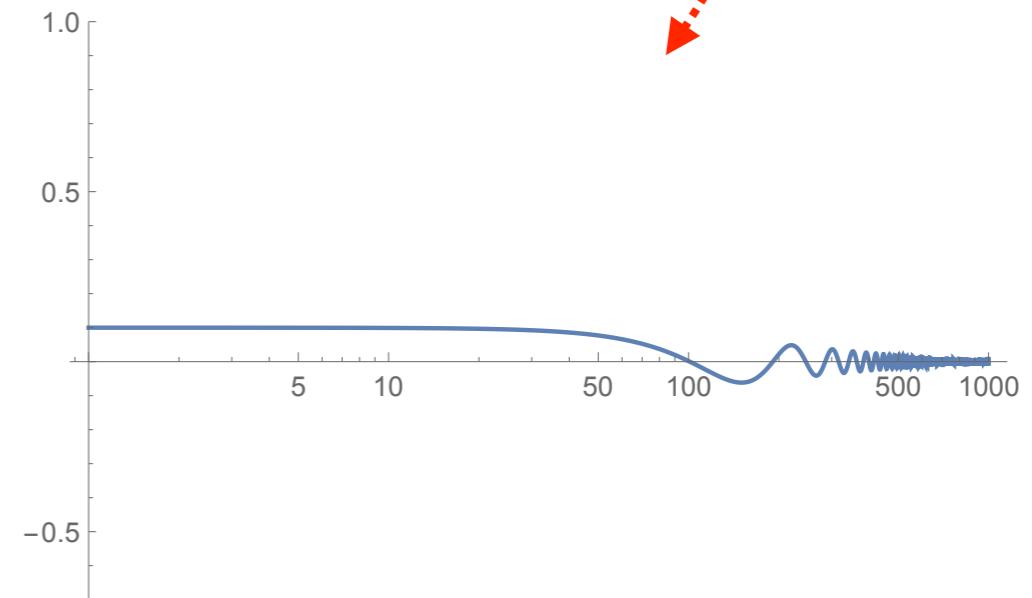
\sim

in the deconfined phase

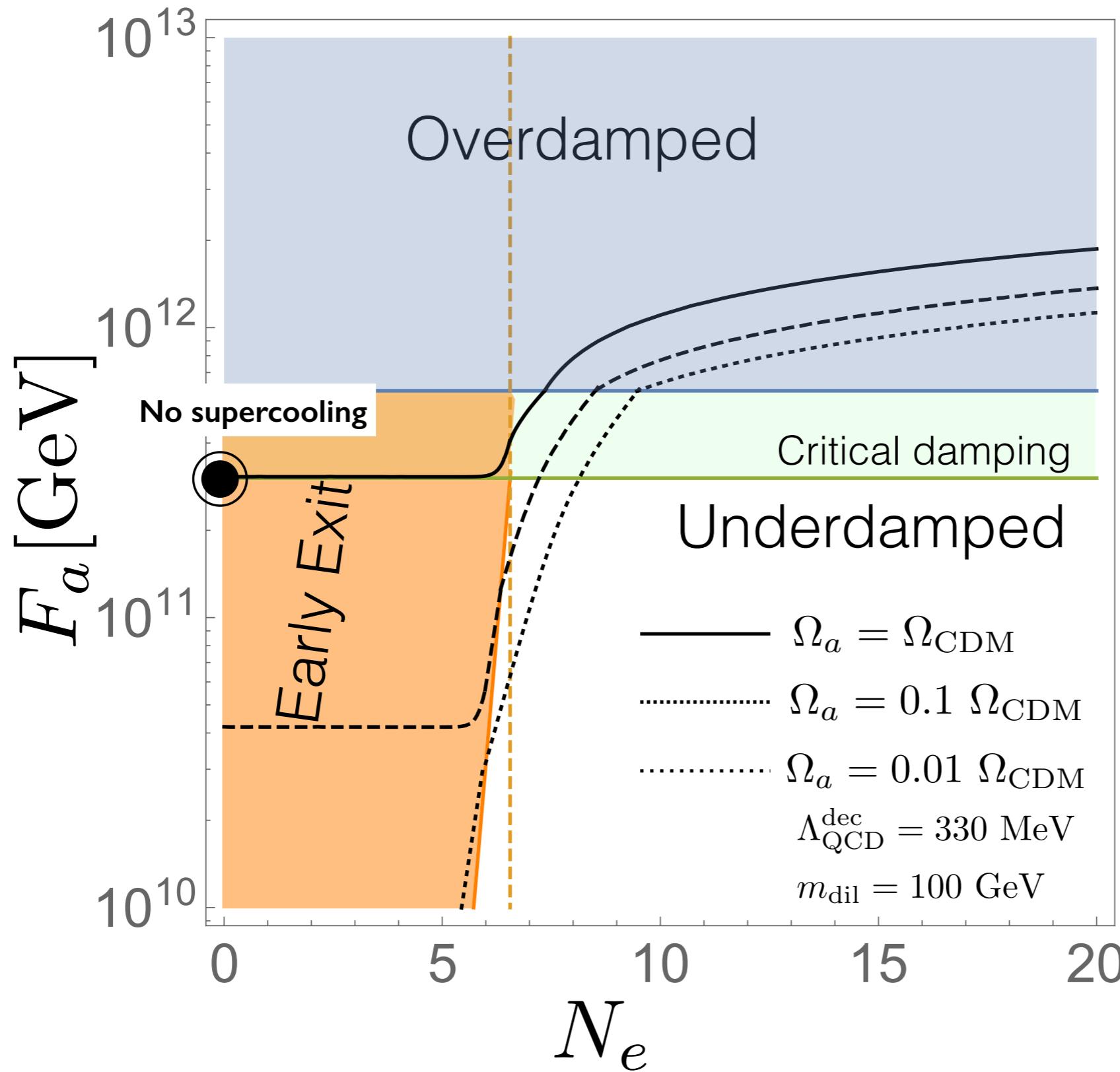
If supercooling:



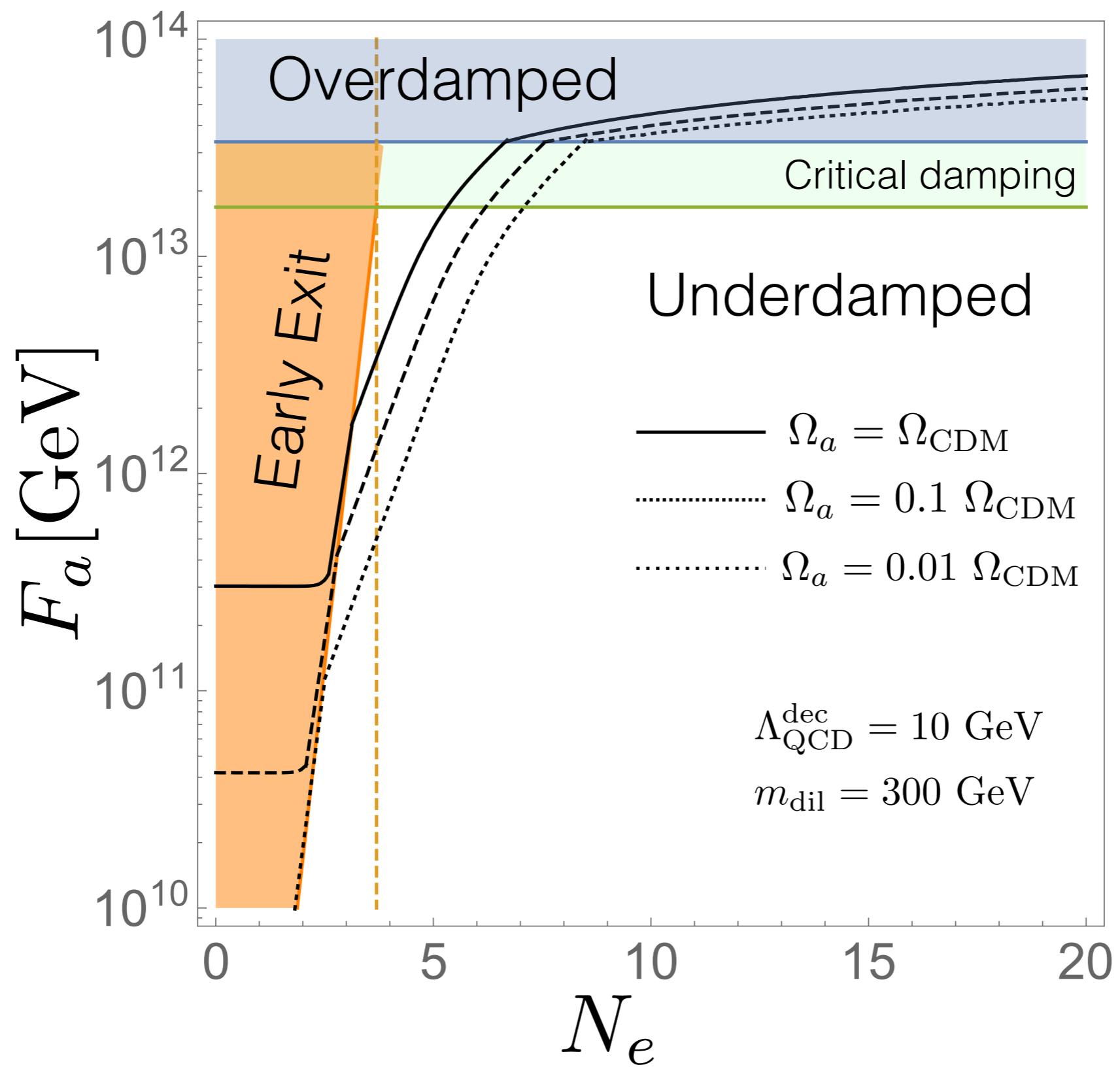
Ordinary QCD
phase transition
 $(H \sim T^2/M_P)$



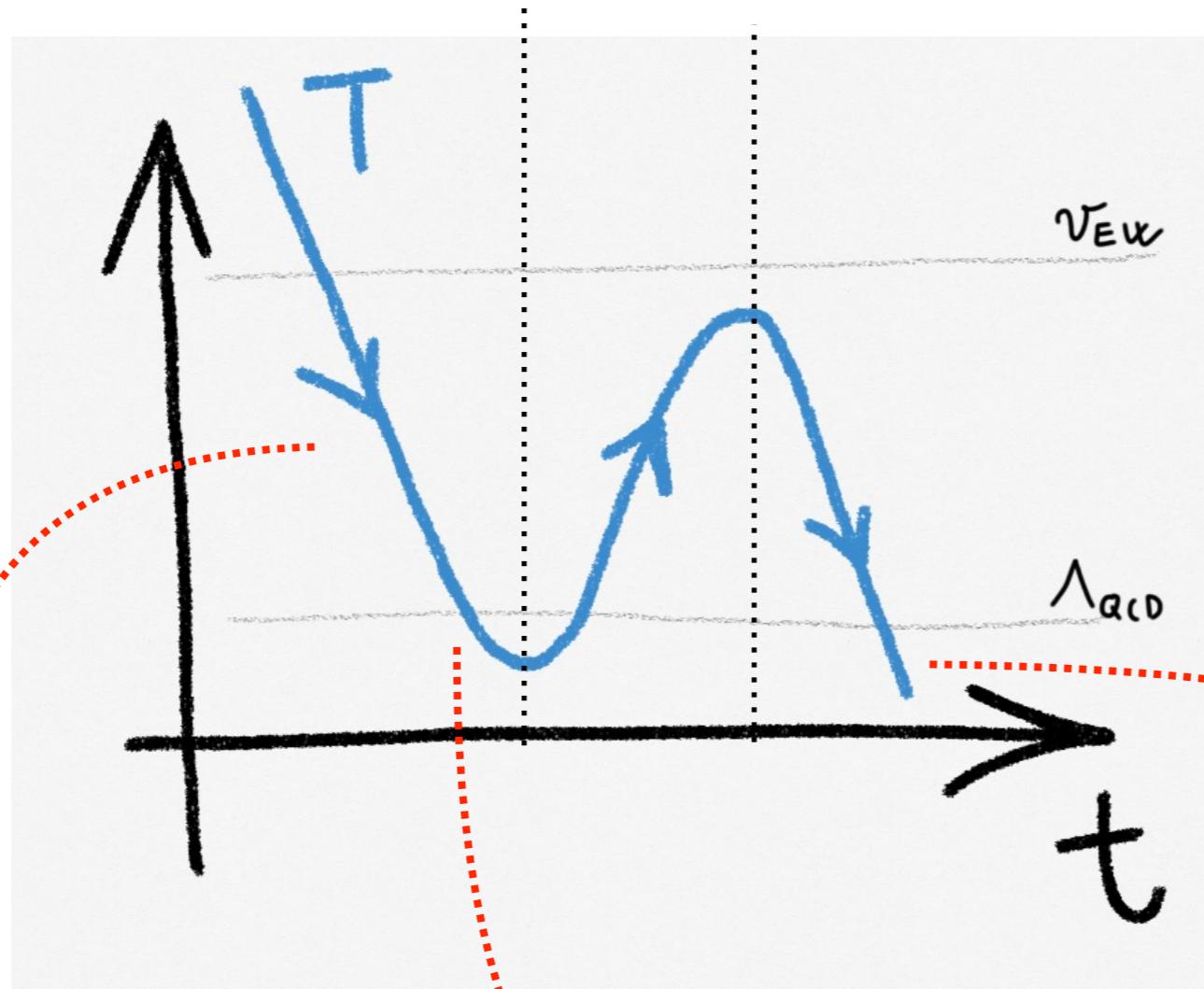
Right axion DM abundances for larger F_a :



implications
for axion searches
less axions!



Cosmic strings and domain walls

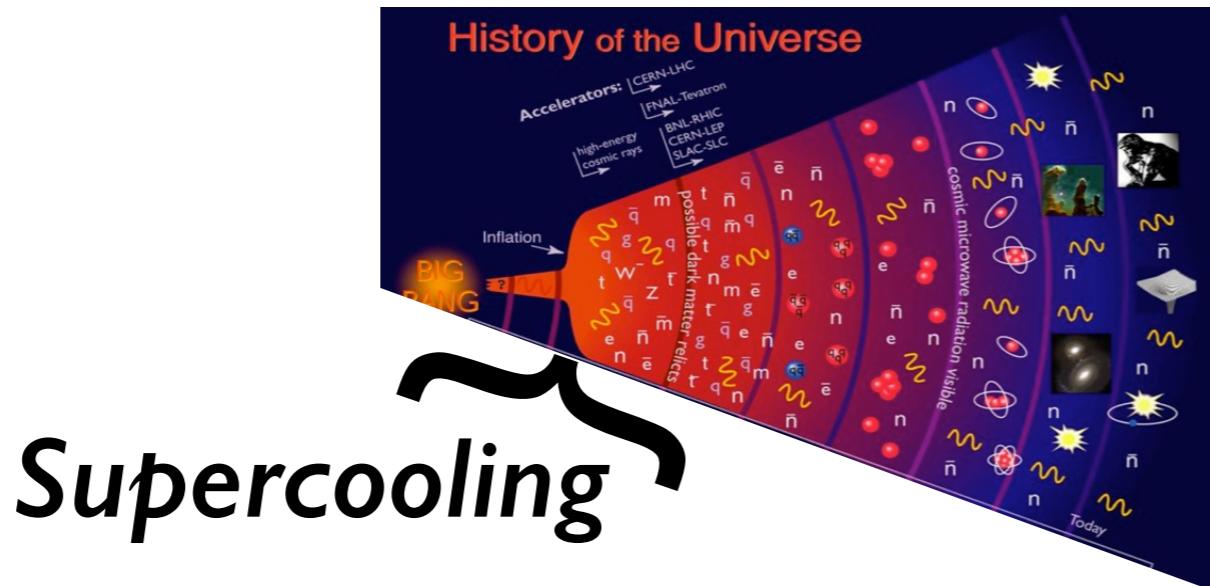


String stretched
beyond the horizon

domain walls
cannot annihilate them

Conclusions

- Light dilatons not easy but possible
- Could emerge from a **conformal to non-conformal transition** as seen by Lattice (but not parametrically light)
- **Important to search for them at the LHC**
- **Impact in the cosmological history:**



High-energy physics can affect low-energy physics

- Changes in the axion relic abundance → F_a larger can be possible!