A CC Miracle
(in a Corona-infected world)
Dynamical Emergence of a Small Λ

March 2020

Tomer Volansky
Tel-Aviv University

With: Itay Bloch, Csaba Csaki, Michael Geller

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The CC Miracle

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What's the Problem?

- Three problems:

  1. Why is $\Lambda_{\rm obs}^4$ so small? $(\Lambda_{\rm obs} \sim \text{meV})$

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$$\frac{1}{2}\int^{\Lambda_{\mathrm{UV}}} d^3k \left[\sum_{\mathrm{bosons}} \sqrt{k^2+m_B^2} - \sum_{\mathrm{fermions}} \sqrt{k^2+m_F^2}\right] \simeq (g_B - g_F)\Lambda_{\mathrm{UV}}^4 + \ldots$$

$$\Lambda_{\mathrm{UV}} = M_{\mathrm{pl}} \qquad \Longrightarrow \qquad \left(\frac{\Lambda_{\mathrm{obs}}}{M_{\mathrm{Pl}}}\right)^4 \sim 10^{-120}$$

$$\Lambda_{\mathrm{UV}} = \Lambda_{\mathrm{QCD}} \qquad \Longrightarrow \qquad \left(\frac{\Lambda_{\mathrm{obs}}}{\Lambda_{\mathrm{QCD}}}\right)^4 \sim 10^{-44}$$

The CC Problem

What's the Problem?

- Three problems:

1. Why is Λ_{obs}^4 so small? $(\Lambda_{\text{obs}} \sim \text{meV})$

2. Why is $\underbrace{\Omega_{\Lambda,0}}_{0.7} \simeq 2\,\underbrace{\Omega_{m,0}}_{0.3}$?

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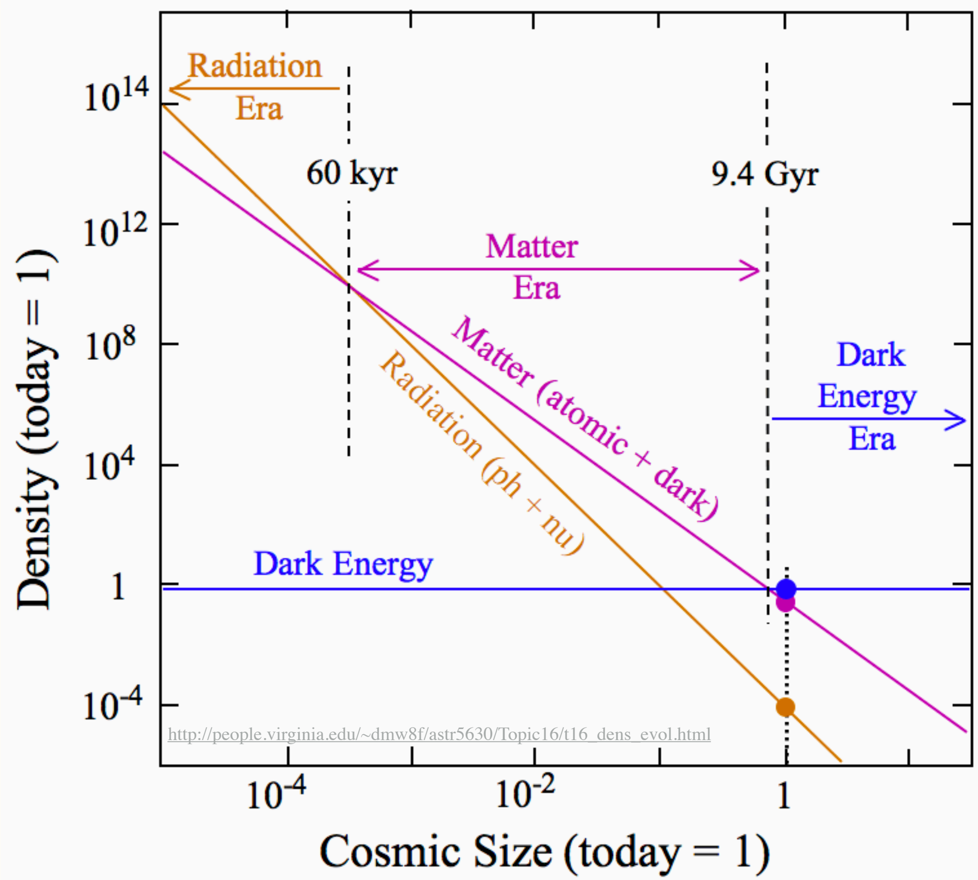
  2. Why is $\Omega_{\Lambda,0} \simeq 2\,\Omega_{m,0}$?

     $\Omega_{\Lambda,0}$: 0.7 $\quad$ $\Omega_{m,0}$: 0.3

Coincidence Problem

"Why Now?" Problem



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2. Why is $\Omega_{\Lambda,0} \simeq 2\,\Omega_{m,0}$?

3. Numerology

$$\Lambda_{\rm obs} \sim \frac{\mathrm{TeV}^2}{M_{\rm Pl}}$$

Is the CC related to the weak scale?

Miracles at the Weak Scale

$$\frac{1}{2}\int^{\Lambda_{\mathrm{UV}}} d^3k \left[\sum_{\mathrm{bosons}} \sqrt{k^2 + m_B^2} - \sum_{\mathrm{fermions}} \sqrt{k^2 + m_F^2} \right] \simeq (g_B - g_F)\Lambda_{\mathrm{UV}}^4 + (m_B^2 - m_F^2)\Lambda_{\mathrm{UV}}^2 + \ldots$$

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$$\simeq (g_B - g_F)\Lambda_{\rm UV}^4 + h^2\Lambda_{\rm UV}^2 + \ldots$$

$$\Longrightarrow \qquad m_h^2 \sim \Lambda_{\rm UV}^2$$

Why is $m_h^2 \ll \Lambda_{\rm UV}^2$?

The Hierarchy Problem

Miracles at the Weak Scale

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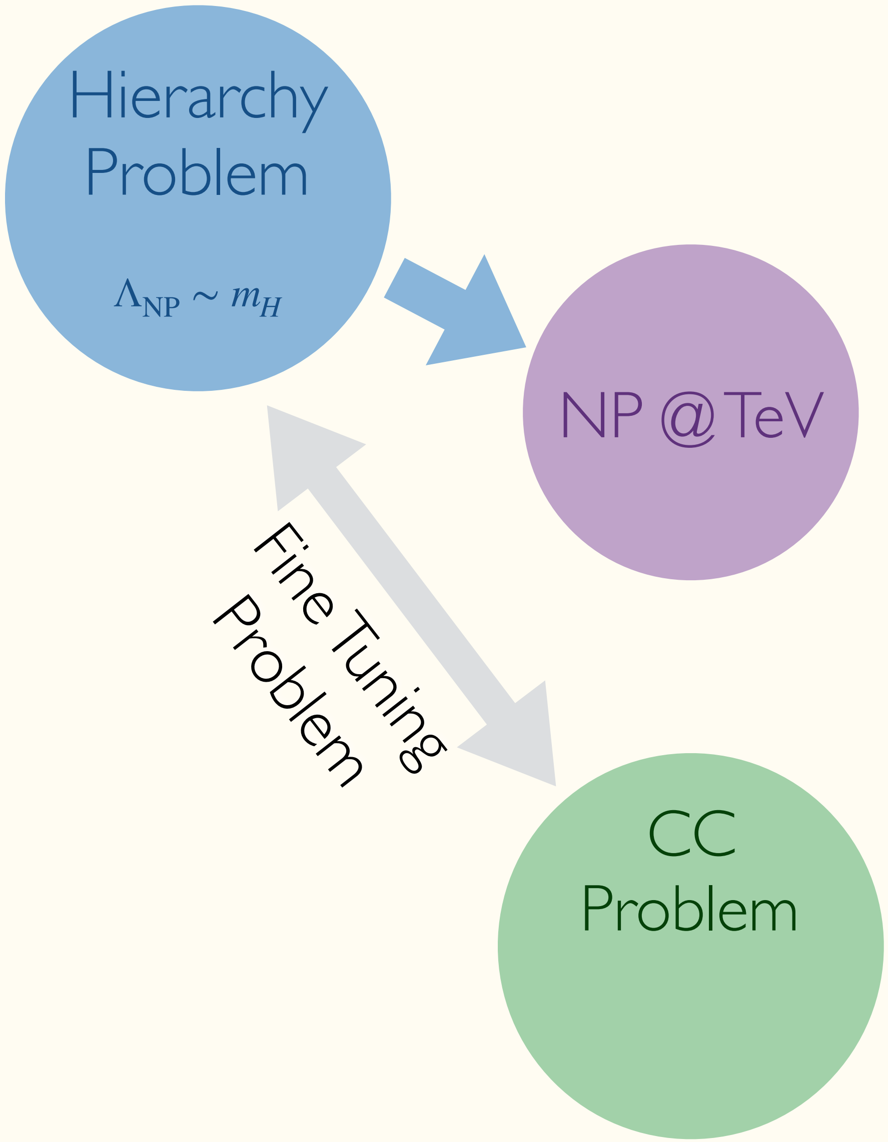
The Hierarchy Problem

Most solutions predict NP at the weak scale

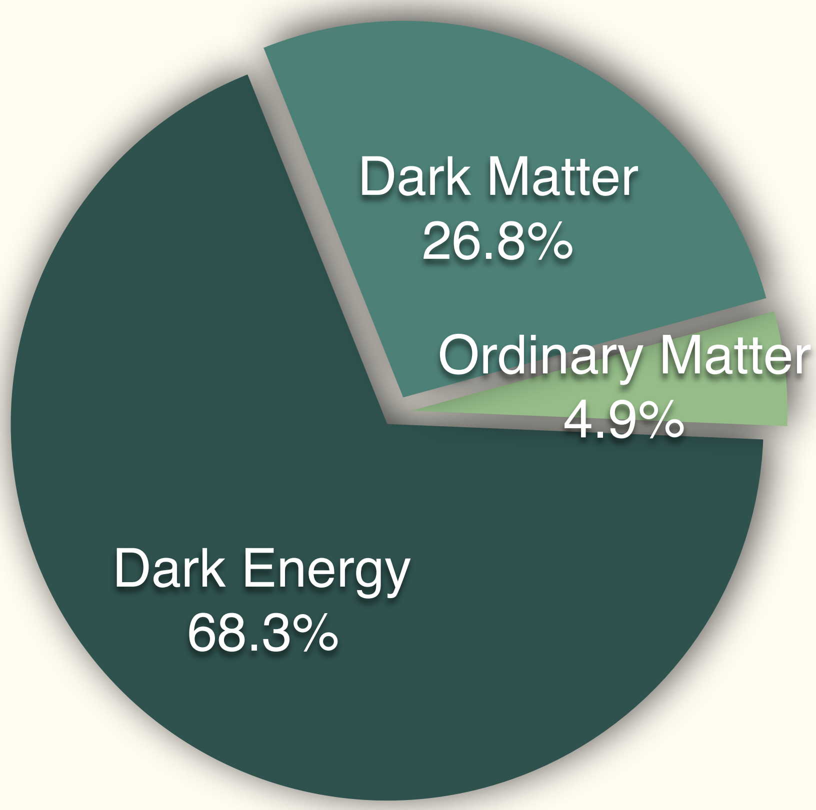
Miracles at the Weak Scale



Miracles at the Weak Scale

Some dark matter candidates also point to the TeV scale.

WIMPs are produced in the early universe through freeze-out mechanism



Miracles at the Weak Scale

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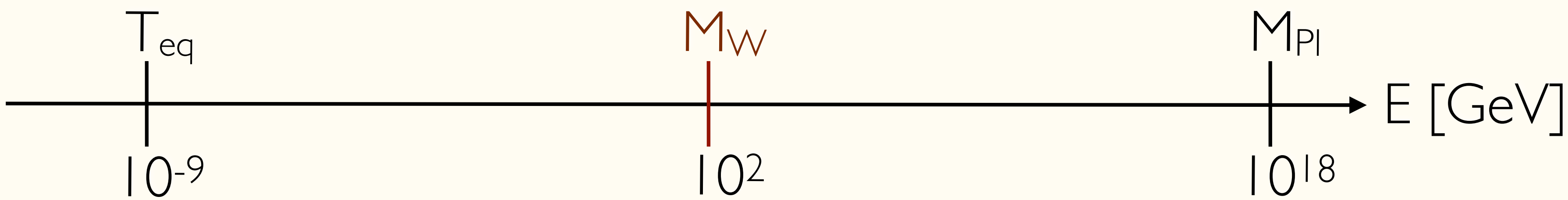
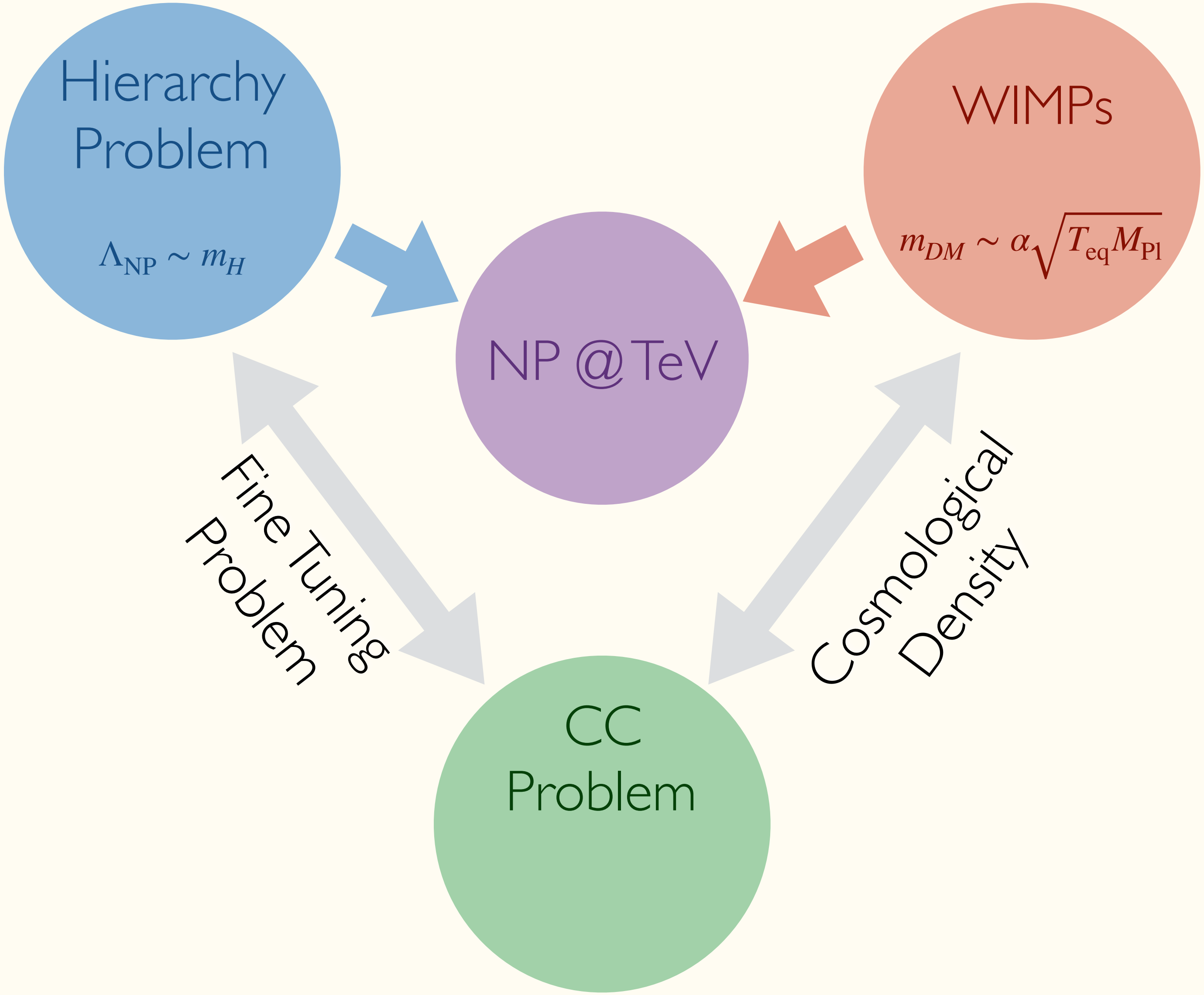
$$m_{\mathrm{DM}} \simeq \alpha_{\mathrm{eff}} \sqrt{T_{\mathrm{eq}} M_{\mathrm{Pl}}} \sim \mathbf{TeV}$$



The WIMP Miracle

Miracles at the Weak Scale



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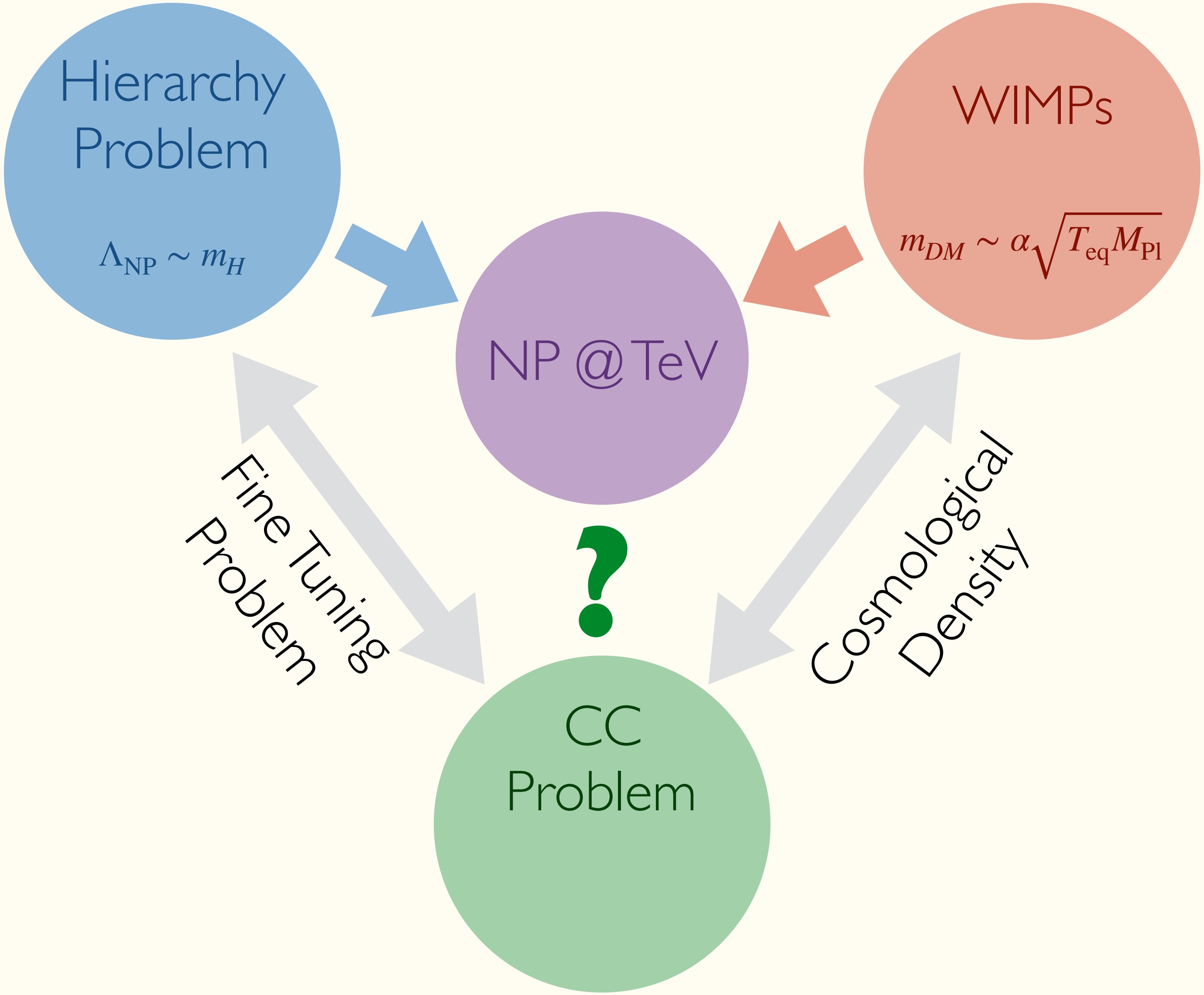


Is the CC related to the TeV Scale?

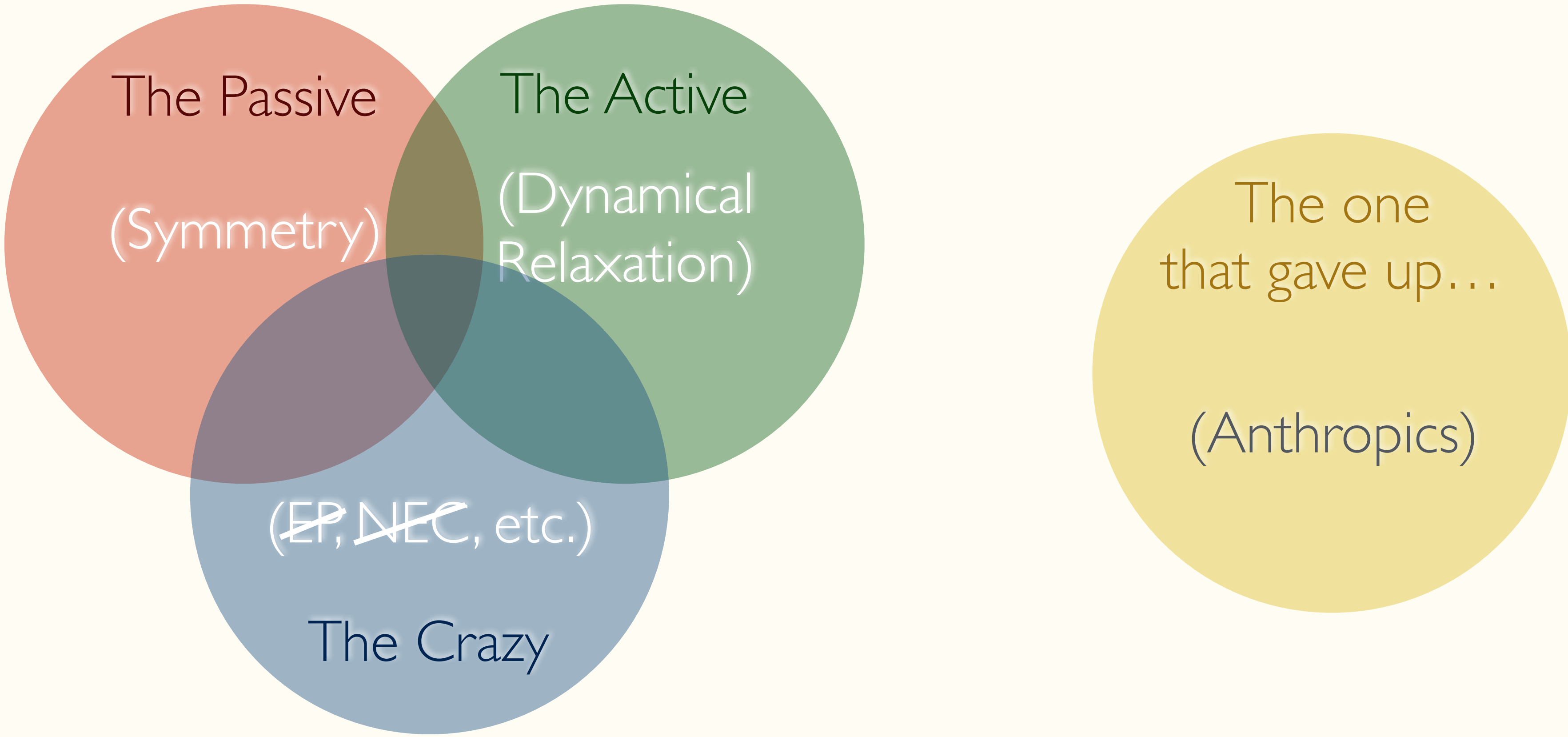
Outline

- The Idea
- The Crunching Sector
    - A Model
    - The Phase Transition
- Results
- Phenomenological Implications
- Discussion

A New Approach

Approaches for Solving the CC Problem

Over the years, numerous proposals to solve the CC problem



Approaches for Solving the CC Problem

- The anthropic solution assumes that our universe is filled with many domains each with a different value of the CC (the multiverse).

- Anthropic principle: Living observers should only exist in a universe which allows for structure to form and life to develop. [Weinberg, 1987]

- Two main requirements:
  - Theory that enables scanning of CC.
  - Dynamics that populates regions with different CC.

The one that gave up…

(Anthropics)

Approaches for Solving the CC Problem

- Implication: Eternal inflation $\Longrightarrow$ Universe is infinitely large.
- Significant shortcoming: The Measure Problem
  - An eternally inflating universe presents a predictivity crisis.
  - How do we regulate the infinities?
  - Choices of different measures have vastly different predictions.

Can we evade eternal inflation?

The one
that gave up…

(Anthropics)

Basic Idea

- This talk: a hybrid approach.

Many domains with different CC values.

Dynamics act to crunch regions with large CC

Basic Idea

- This talk: a hybrid approach.

Many domains with different CC values.

Dynamics act to crunch regions with large CC

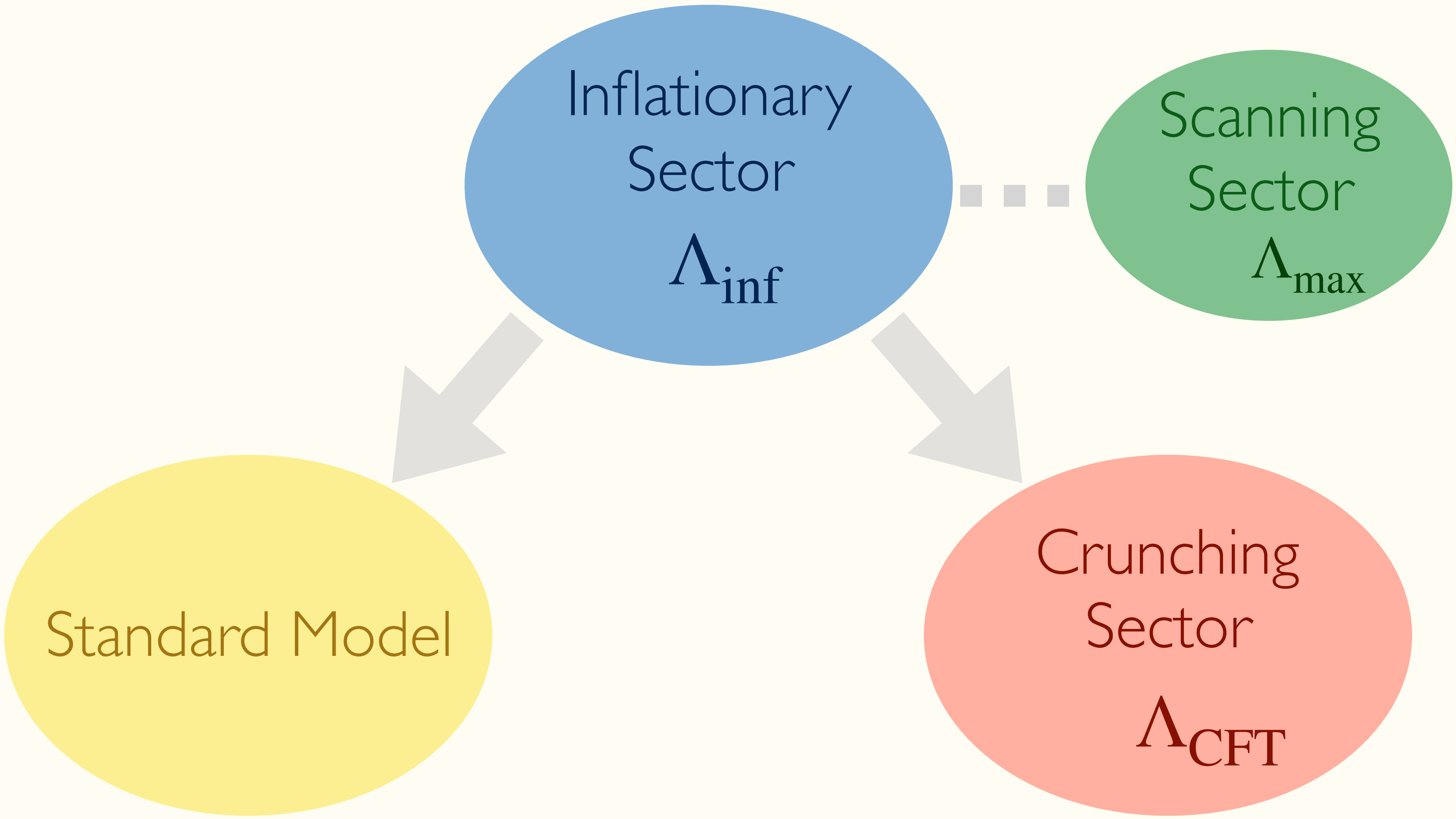
Only regions with small CC survive till today

No need for eternal inflation

Observational consequences!

Basic Idea

3 New Sectors

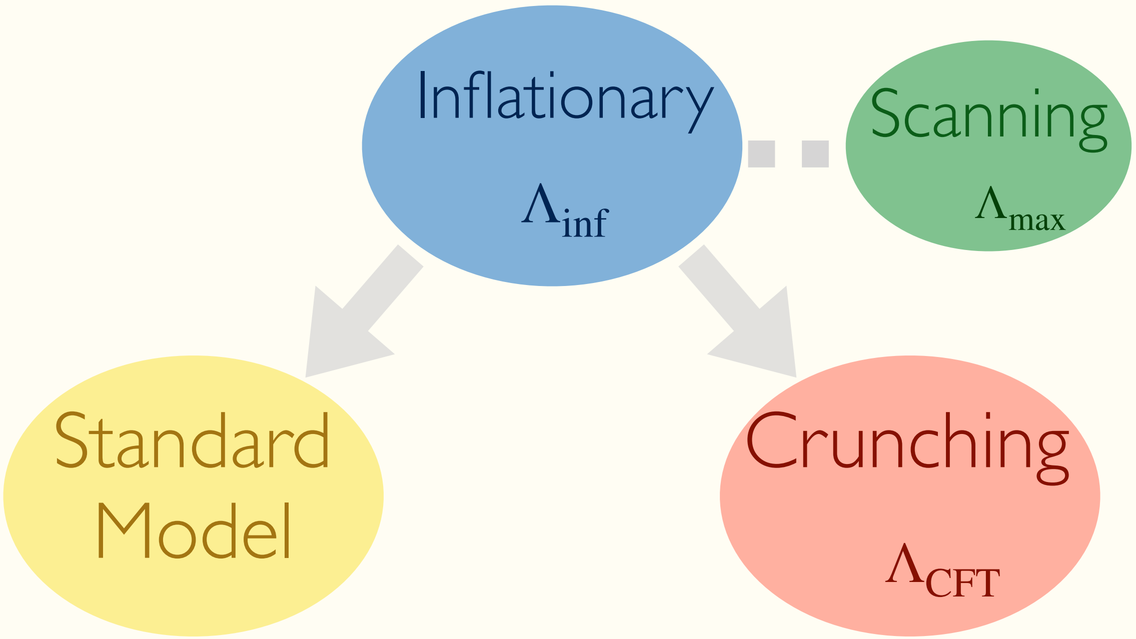


Scales

3 Scales: Λ_{max} , Λ_{CFT} , Λ_{inf}

Inflaton dominates during inflation: $\Lambda_{\text{CFT}} \lesssim \Lambda_{\text{inf}}$

Crunching occurs after phase transition: $\Lambda_{\text{max}} \lesssim \Lambda_{\text{CFT}}$



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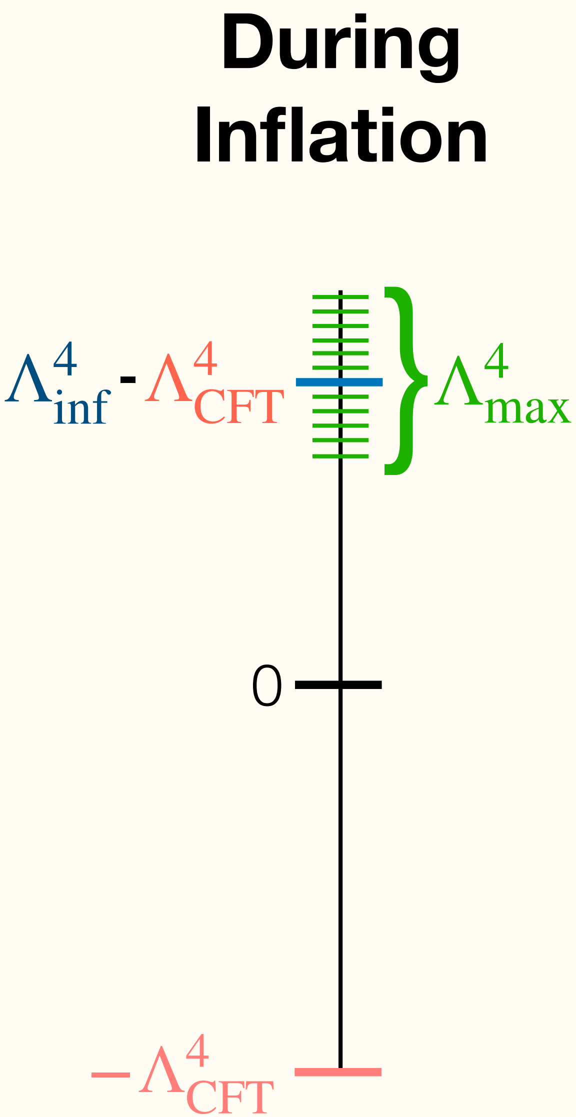
$$\Lambda_{\rm max} \lesssim \Lambda_{\rm CFT} \lesssim \Lambda_{\rm inf}$$

A successful model: $\mathbf{TeV} \lesssim \Lambda_{\rm max}$

Scales



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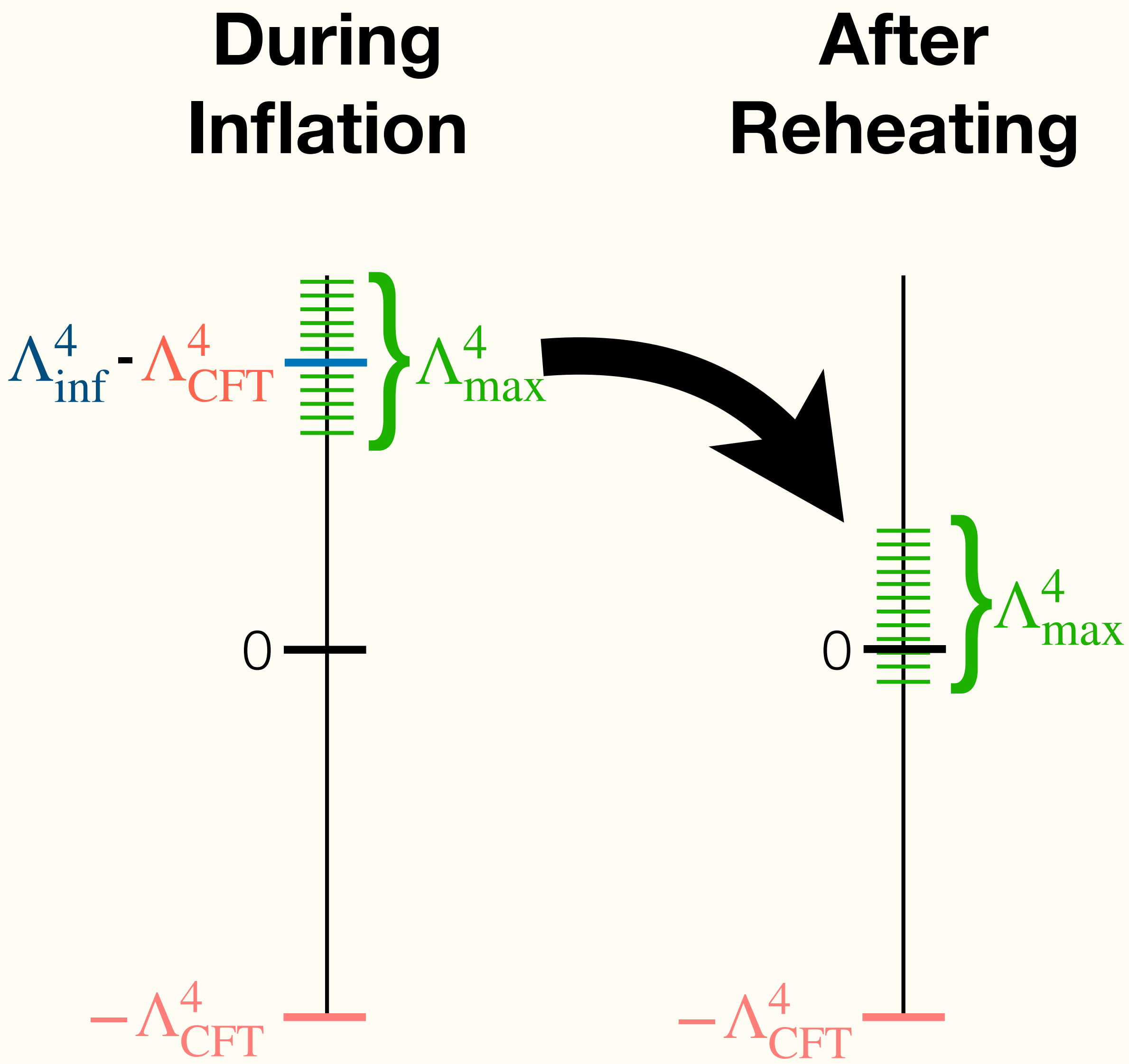

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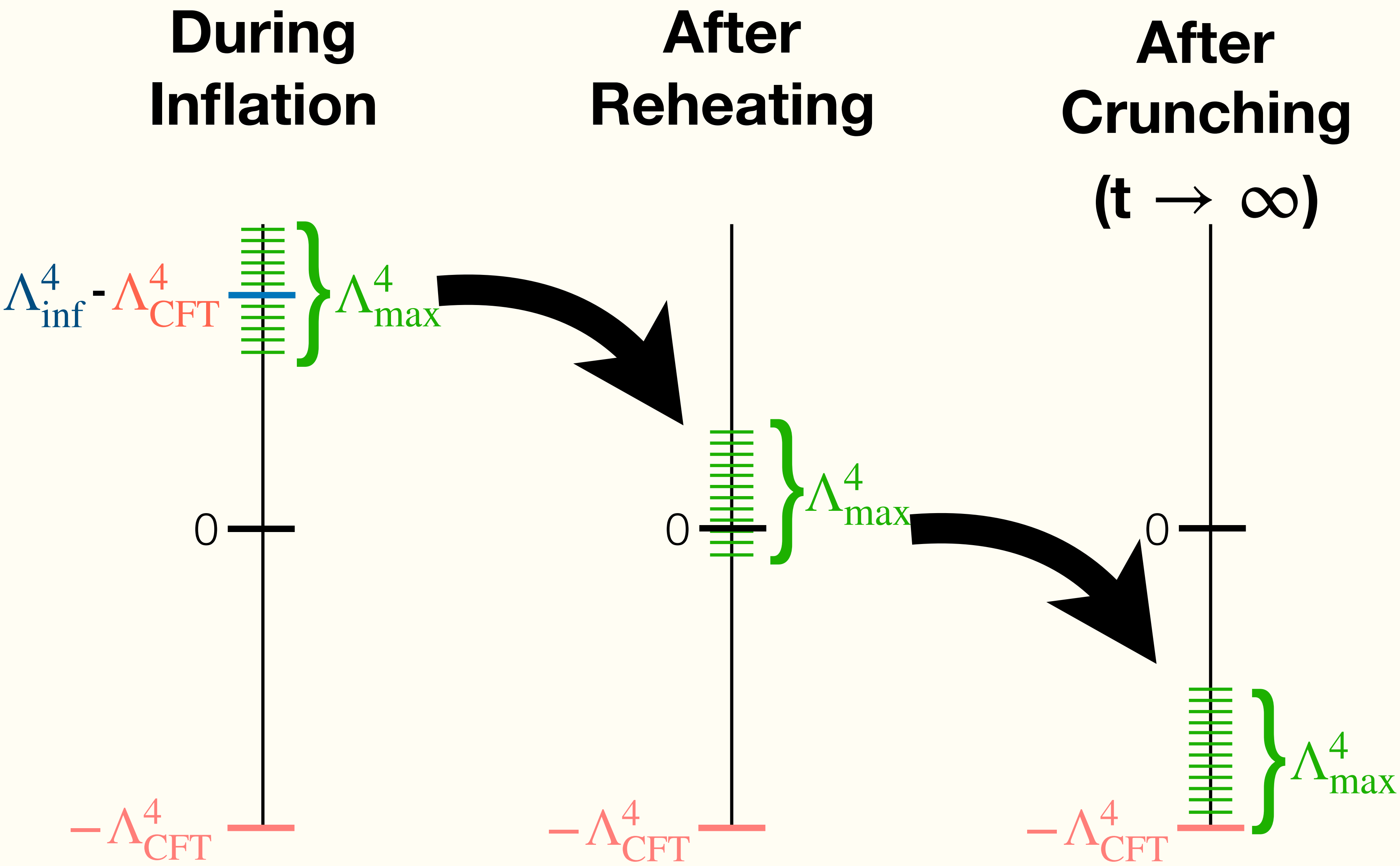

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Crunching Dynamics?

- What kind of crunching sector can drive a universe to crunch?
- Within a given region of the universe, it must react to the (local) value of the CC. Two options:

    1. CC-dependent potential for a field that drives it negative.
    2. CC-dependent cosmological evolution (secondary phase of inflation).

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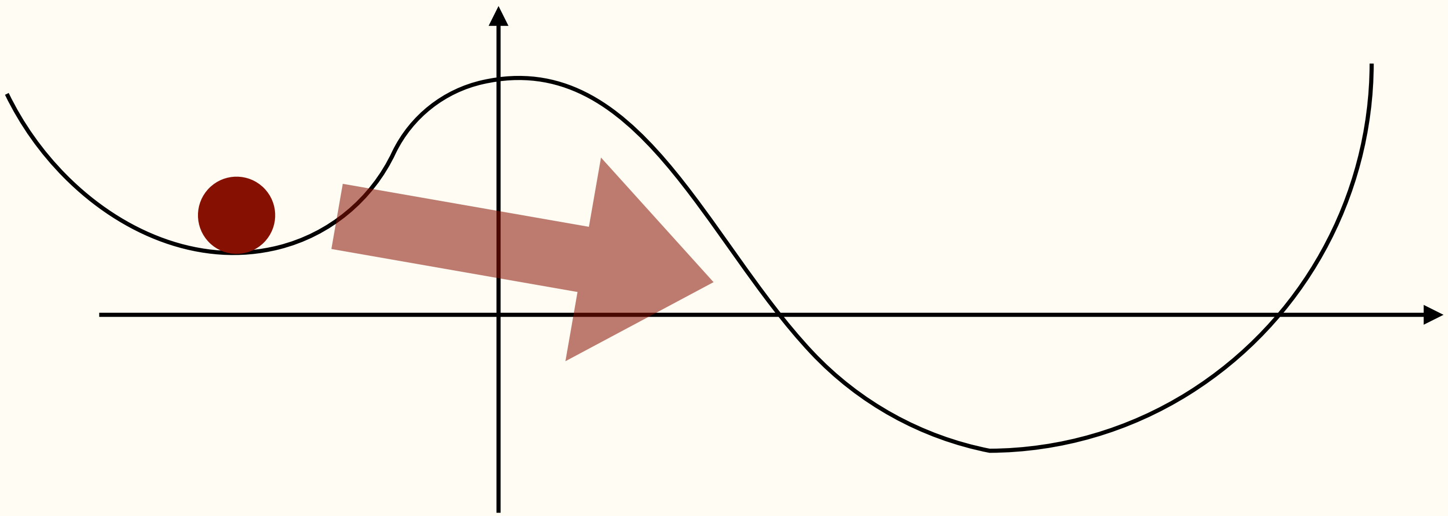
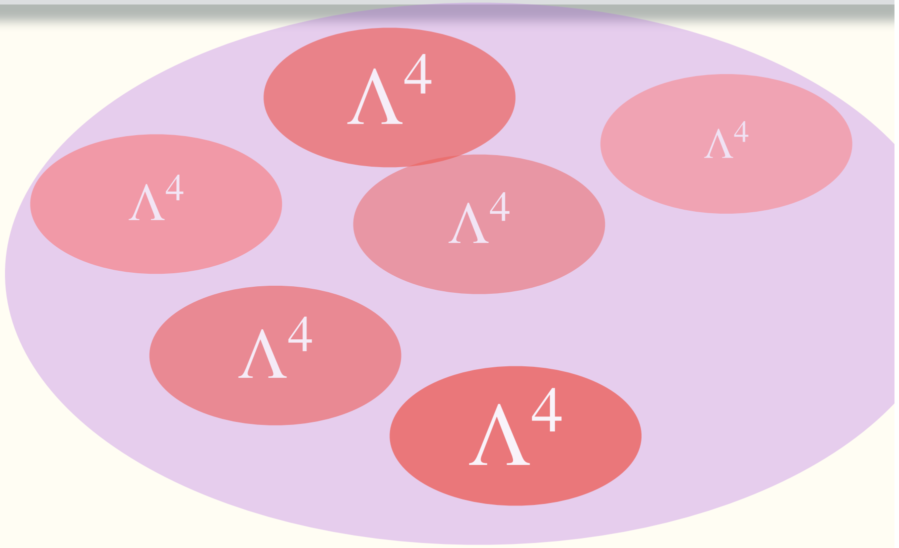
  2. CC-dependent cosmological evolution (secondary phase of inflation).

- In this talk: simply allow secondary phase of inflation to drive a phase transition which triggers the crunching of the patch.



Cosmic History



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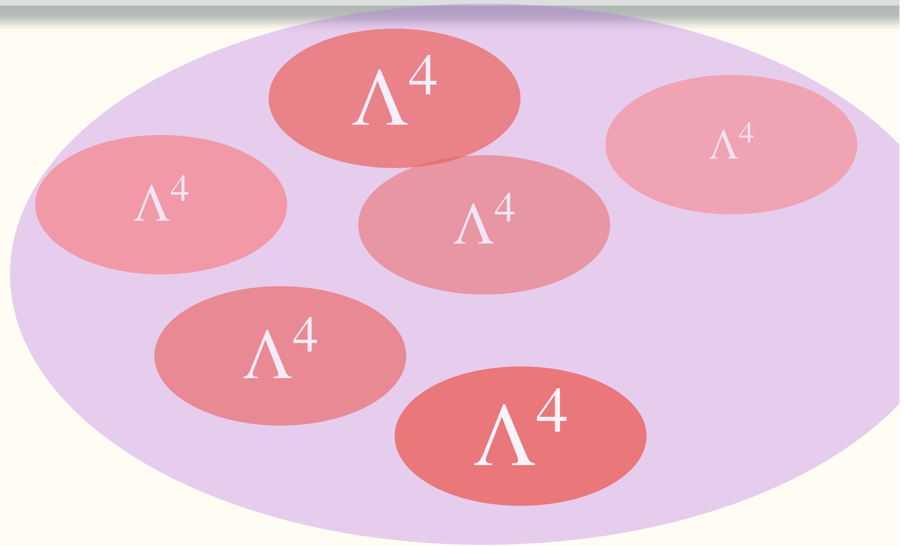


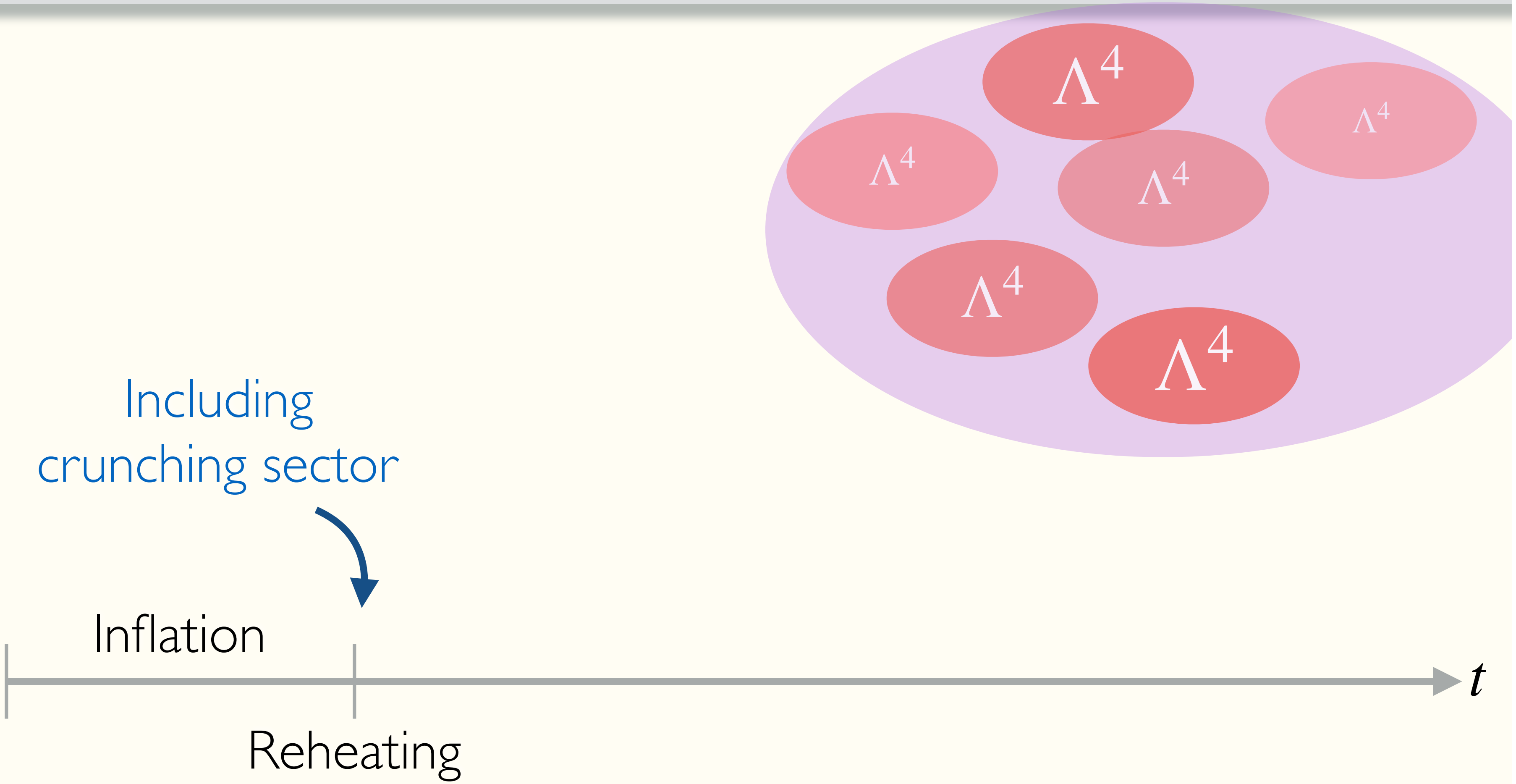
$\Lambda = \mathrm{GeV}$

Inflation

t

Cosmic History

$\Lambda = \mathrm{GeV}$



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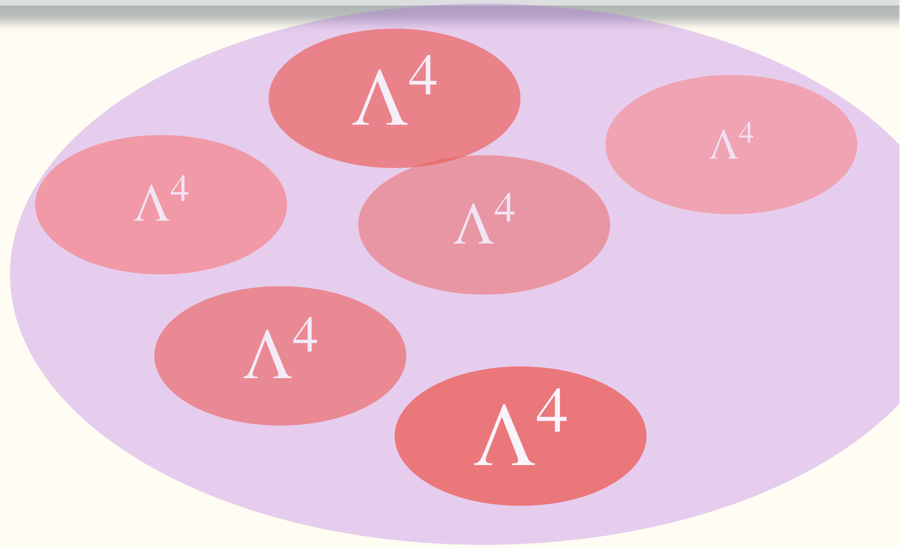

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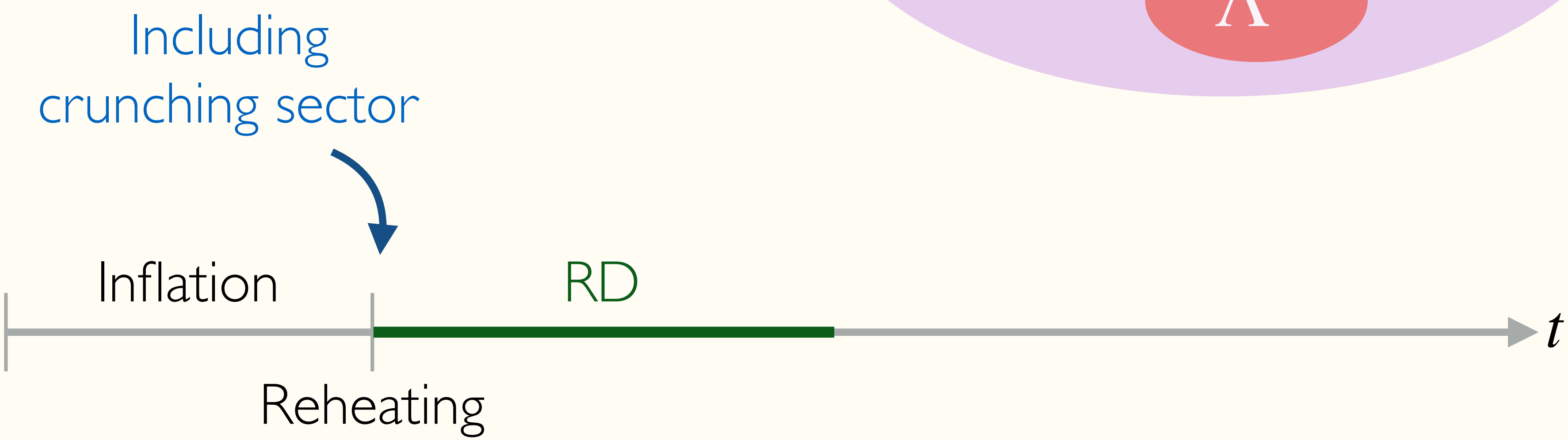

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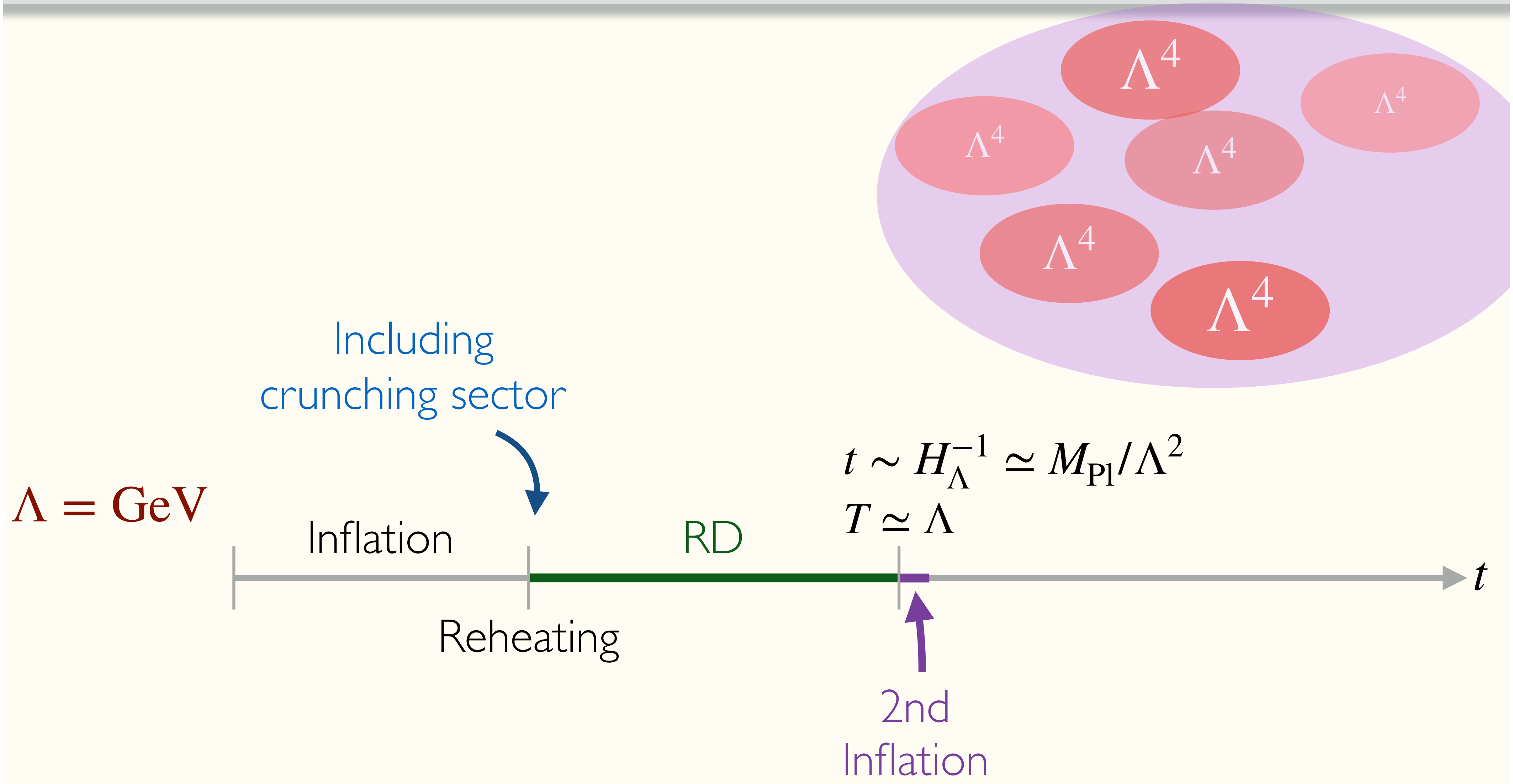

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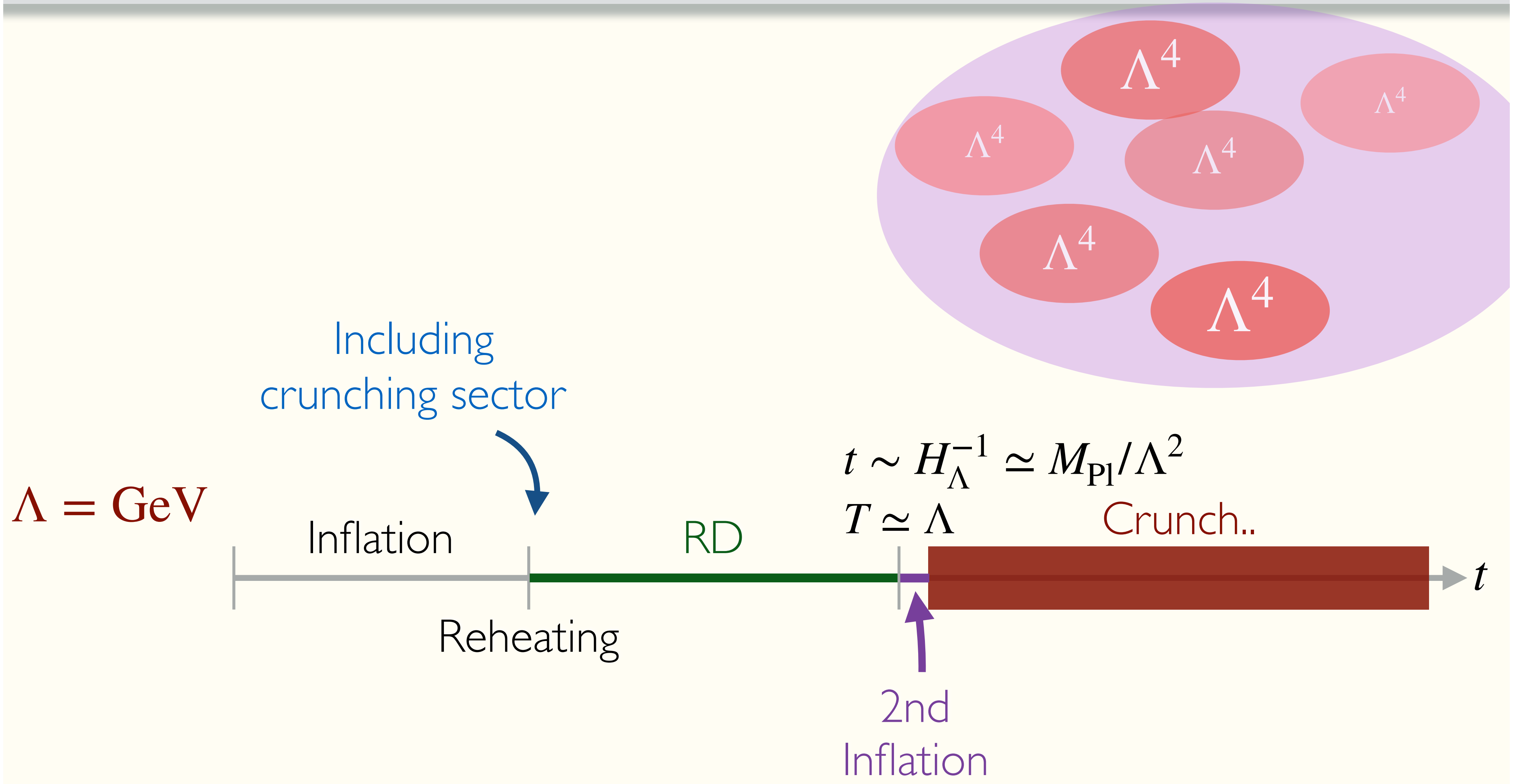

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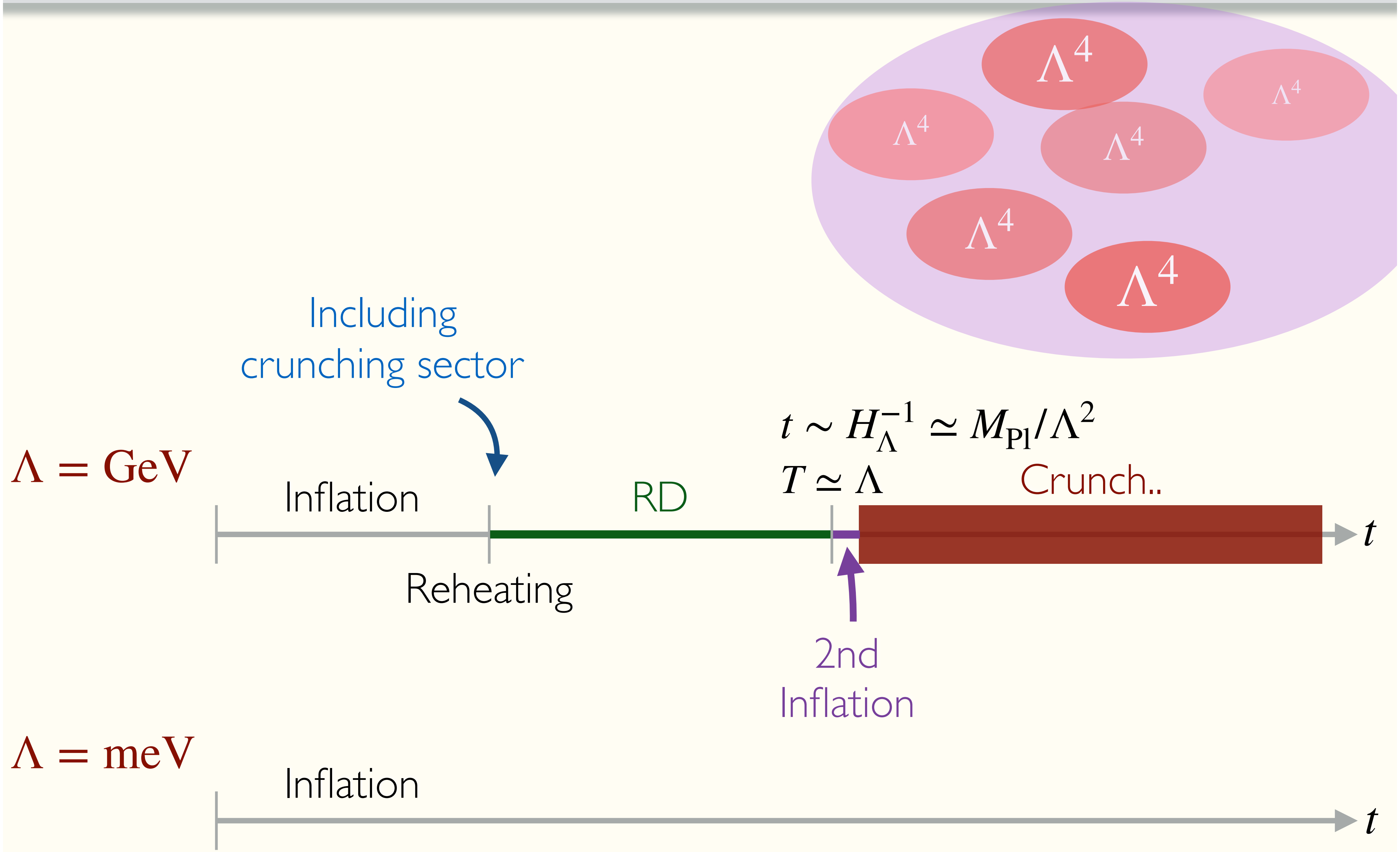

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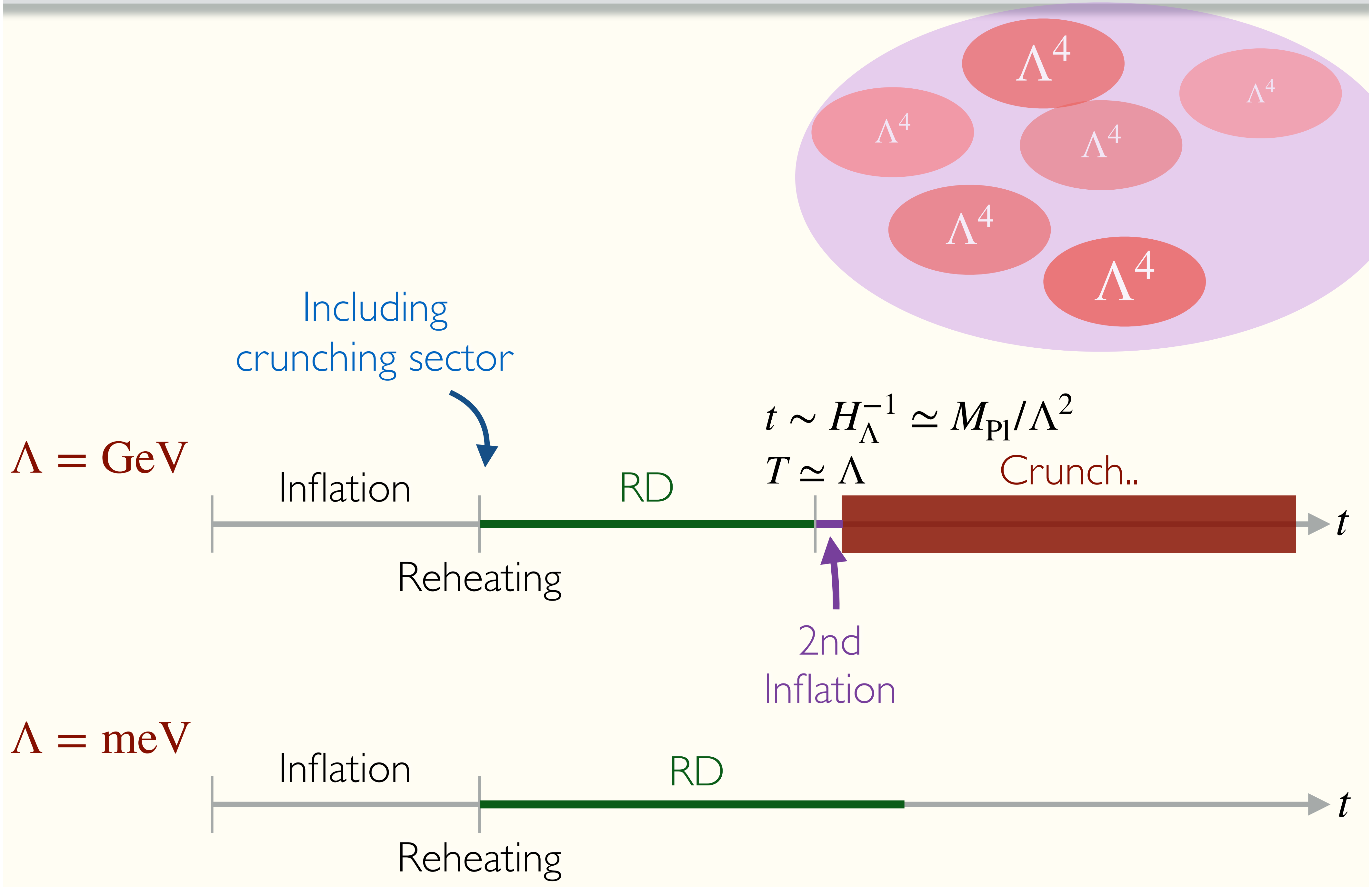

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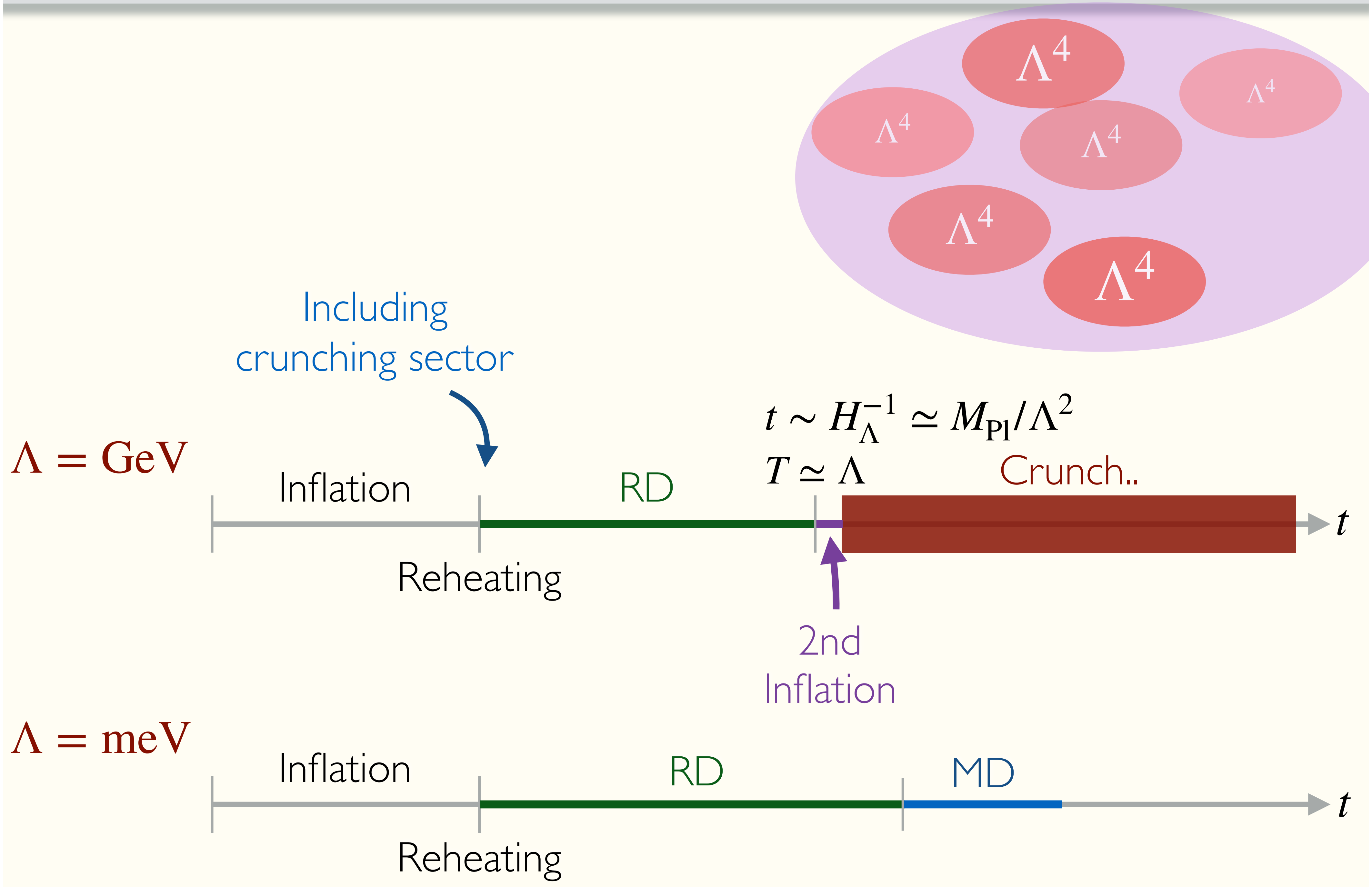

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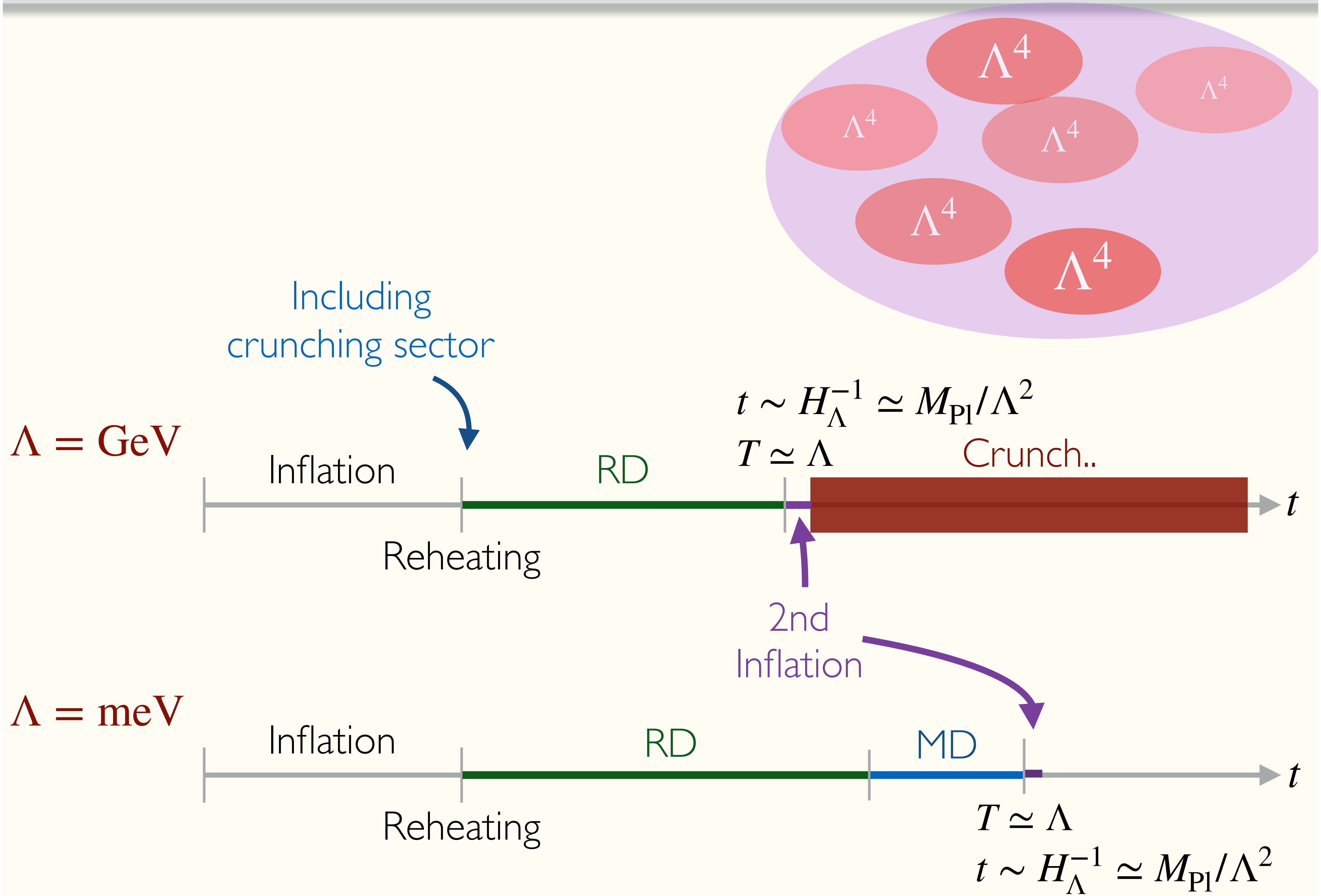

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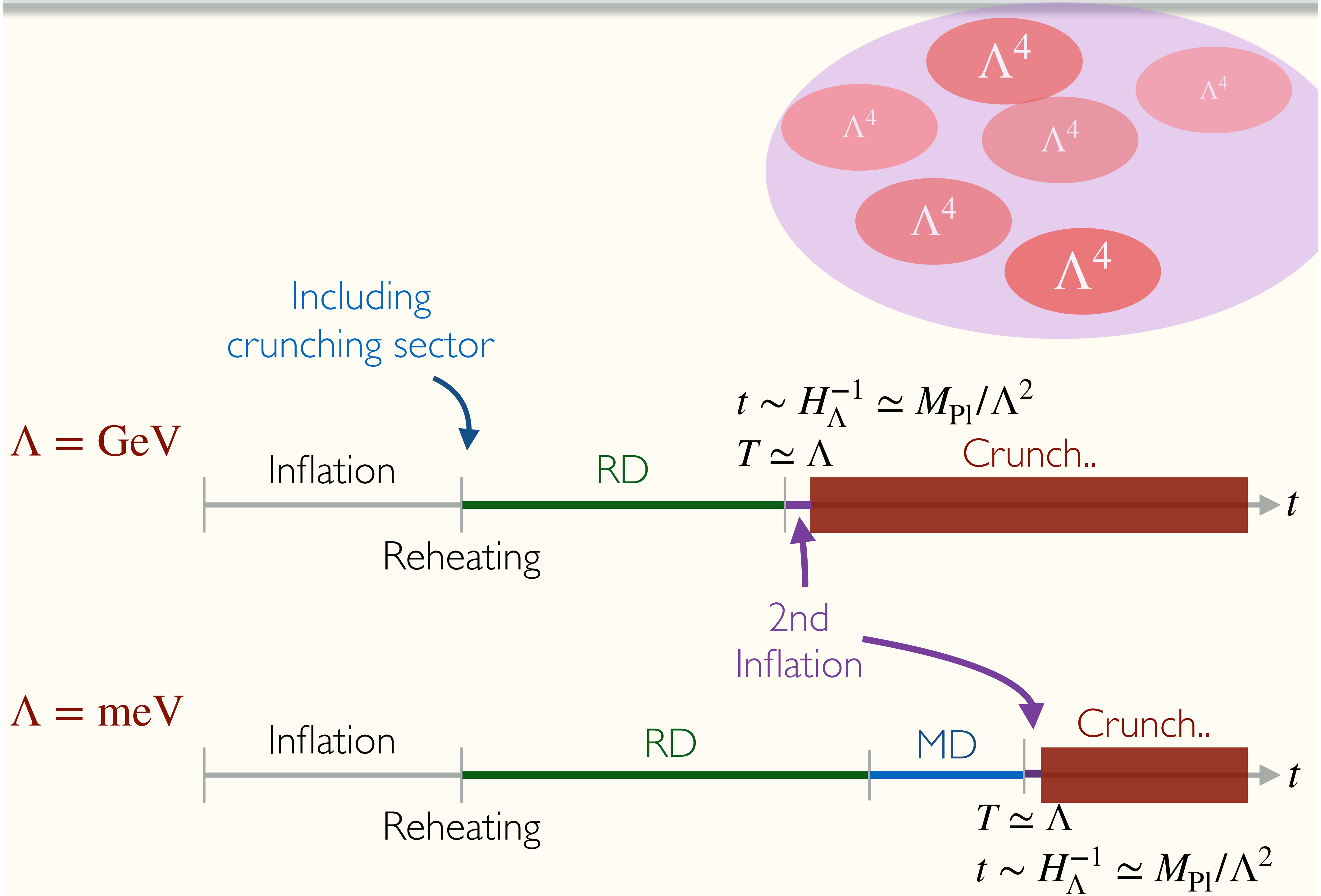

Solution?

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Only small CC survives till today.

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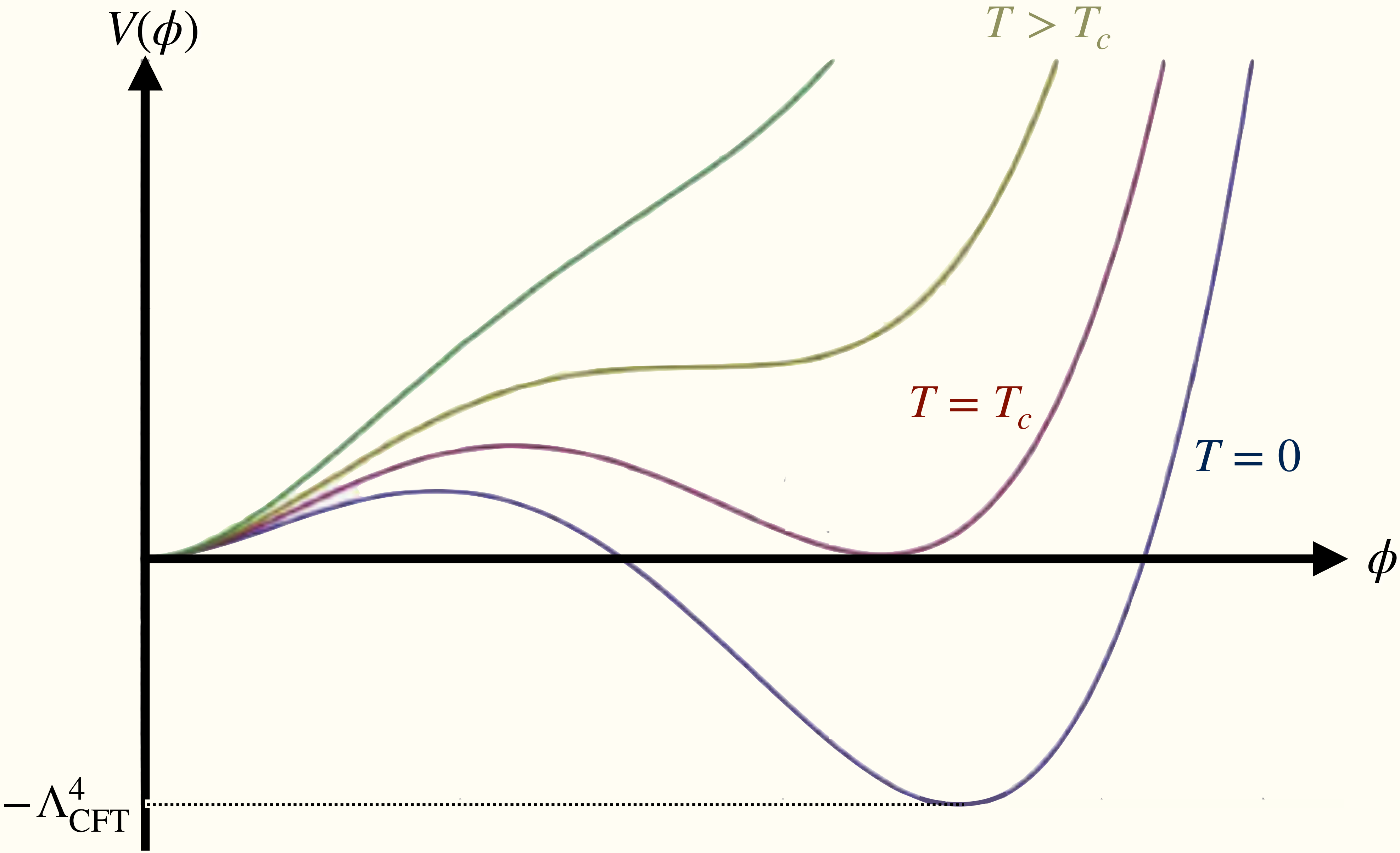
$$\Downarrow$$

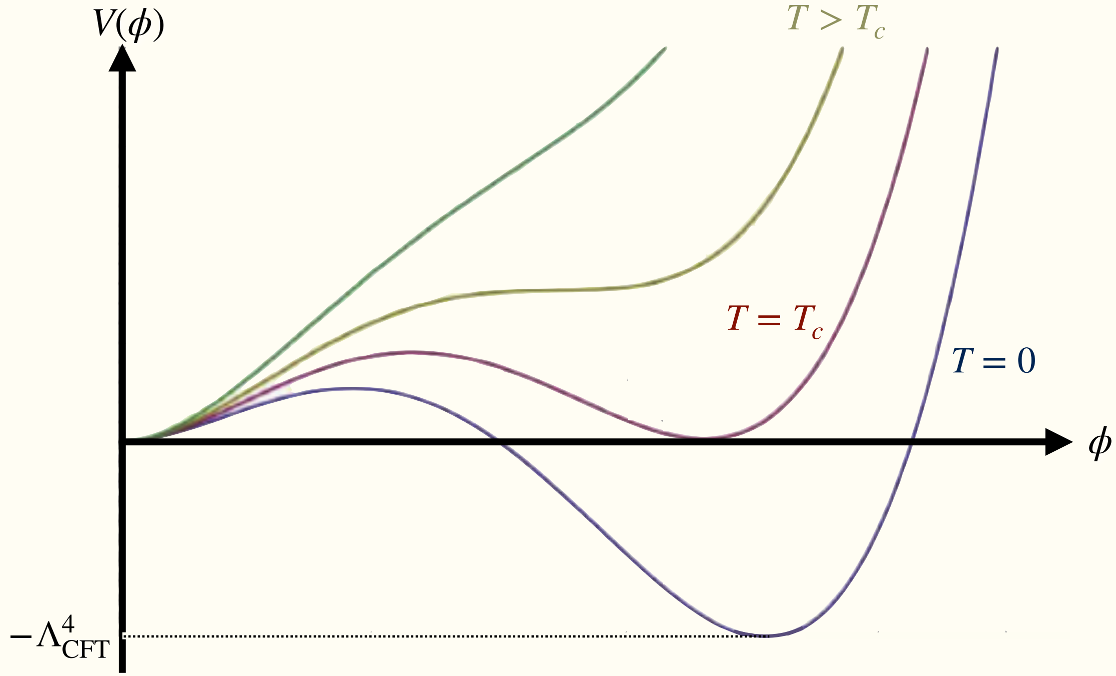
$$\Lambda < \sqrt{T_0 M_{\rm Pl}} \sim \text{TeV}$$

The Crunching Sector

A Supercooled Sector

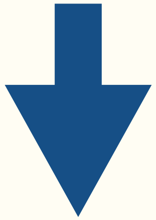


A Supercooled Sector



$\Lambda_{\rm CFT} \gtrsim \mathbf{TeV} \implies$ Energy difference between vacua are large

Nucleation temperature $< T_0 \simeq \mathbf{meV} \ll \mathbf{TeV}$



Supercooled Crunching Sector

A Supercooled Sector

- It is believed that a spontaneously broken CFT (should one truly exist) exhibits a supercooled phase transition.

- In the unbroken phase, the CFT does not contribute to the CC. In the broken phase it contributes a large and negative CC, triggering the crunching.

- A dual description of such (large-N, non-supersymmetric) theories is described by RS.

Randall-Sundrum

[Randall,Sundrum, 1999]

- A slice of AdS:

$z = 1/k$ $\qquad\qquad\qquad\qquad$ $z = z_{\rm IR}$

SM here

$$ds^2 = \frac{1}{k^2 z^2}\left(dx_\mu dx^\mu - dz^2\right)$$

UV $\qquad\qquad\qquad\qquad$ IR

- This theory is dual to a large-N CFT.

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[Randall,Sundrum, 1999]

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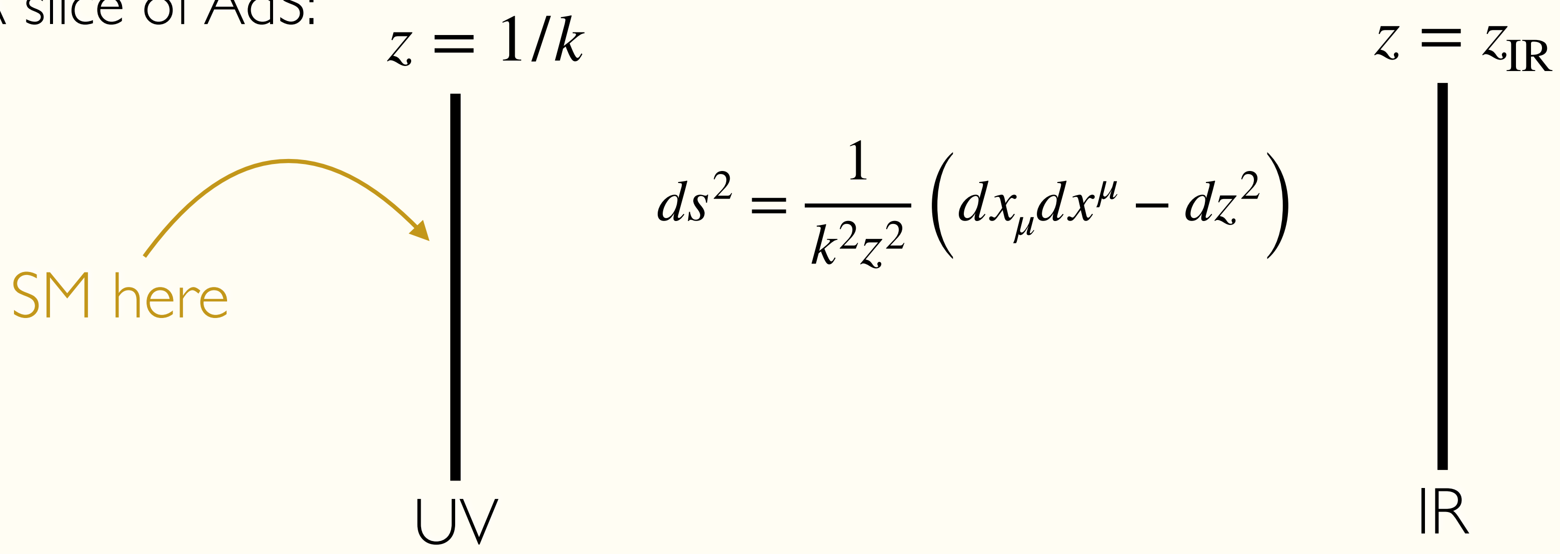

$$ds^2 = \frac{1}{k^2 z^2}\left(dx_\mu dx^\mu - dz^2\right)$$

- This theory is dual to a large-N CFT.

- IR brane represents spontaneous breaking of CFT.
  The dilaton is the location of the IR brane:

$$\chi \equiv \frac{1}{z_{\rm IR}}$$

- In the absence of stabilization, the dilaton has a $V(\chi) = \lambda\chi^4$, driving the IR brane to infinity or to the UV brane.

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[Randall,Sundrum, 1999]

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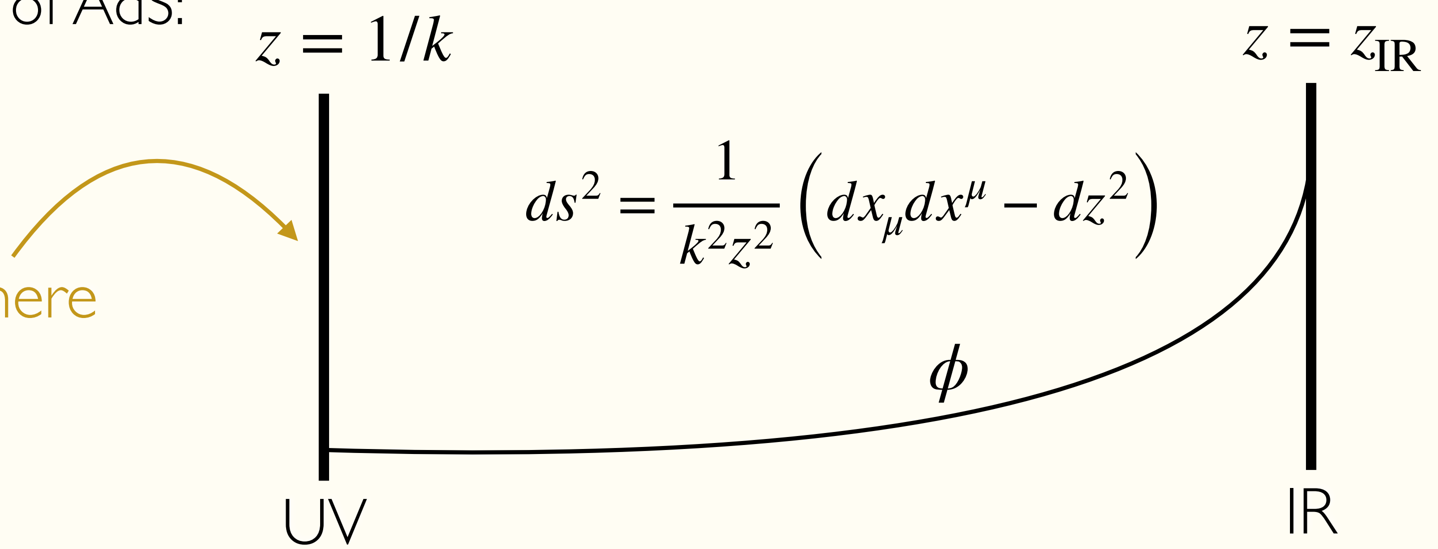


$$ds^2 = \frac{1}{k^2 z^2}\left(dx_\mu dx^\mu - dz^2\right)$$

- Stabilization is added via Goldberger-Wise mechanism:

[Goldberger,Wise, 1999]

$$S = \int d^4x dz \sqrt{g}\,\left(g^{MN}\partial_M\phi\partial_N\phi + \Lambda^5_{\rm bulk} - m^2_{\rm bulk}\phi^2\right) - \int_{\rm UV} d^4x\sqrt{g_{\rm ind}}\,V_{\rm UV}(\phi) - \int_{\rm IR} d^4x\sqrt{g_{\rm ind}}\,V_{\rm IR}(\phi)$$

- The solution to the ϕ EOM:

$$\phi(z) \sim k^{3/2}(kz)^{4+\epsilon} + k^{3/2}(kz)^{-\epsilon}\,, \qquad \epsilon = \sqrt{4 + m_\phi^2/k^2} - 2$$

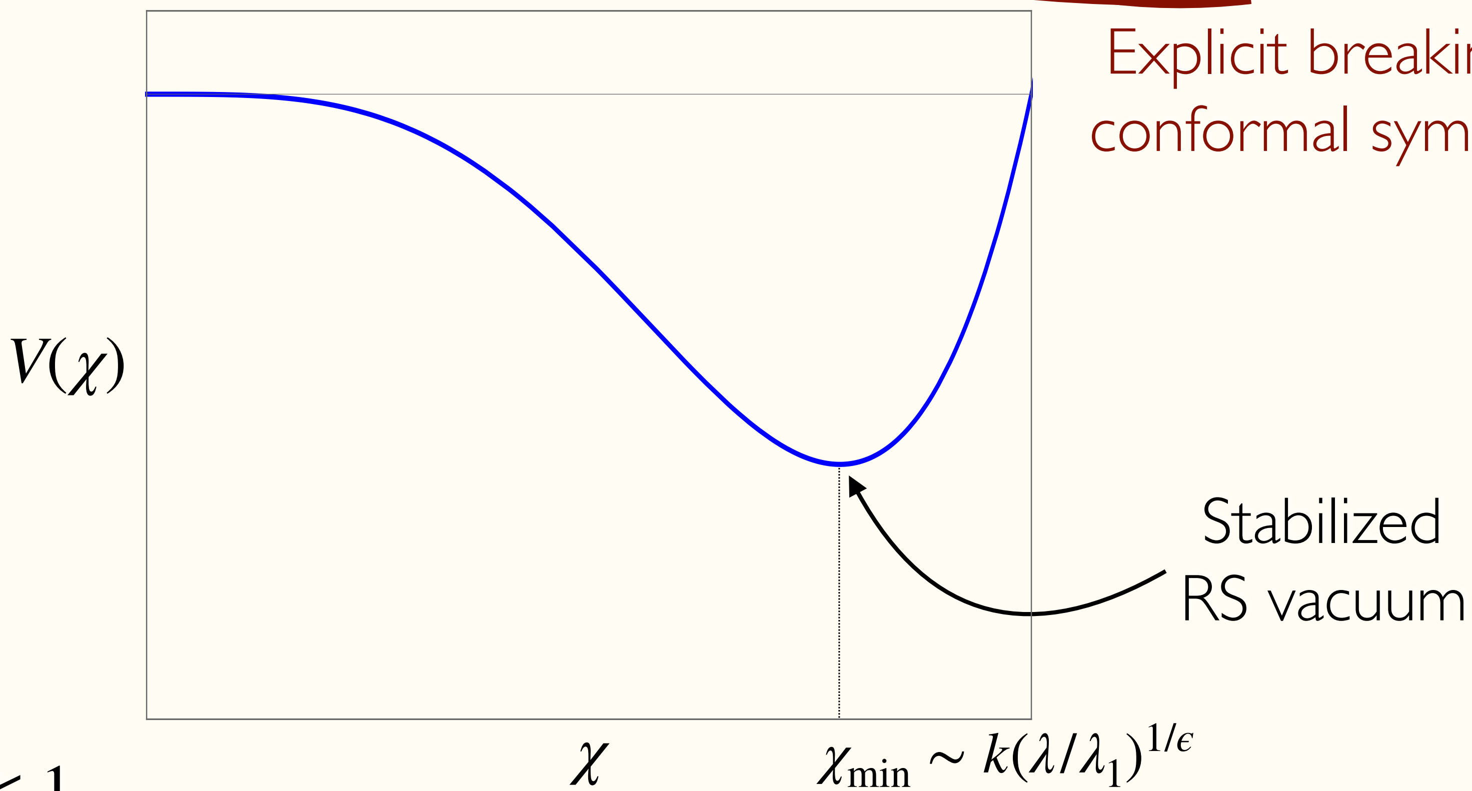
Randall-Sundrum

[Randall,Sundrum, 1999]

- Using the solution we find:

$$V(\chi) = -\lambda\chi^4 + \frac{\lambda_1}{k^\epsilon}\chi^{4+\epsilon} + \frac{\lambda_2}{k^{2\epsilon}}\chi^{4+2\epsilon}$$

Explicit breaking of conformal symmetry



- Typically $\epsilon \ll 1$.

AdS-Schwarzschild

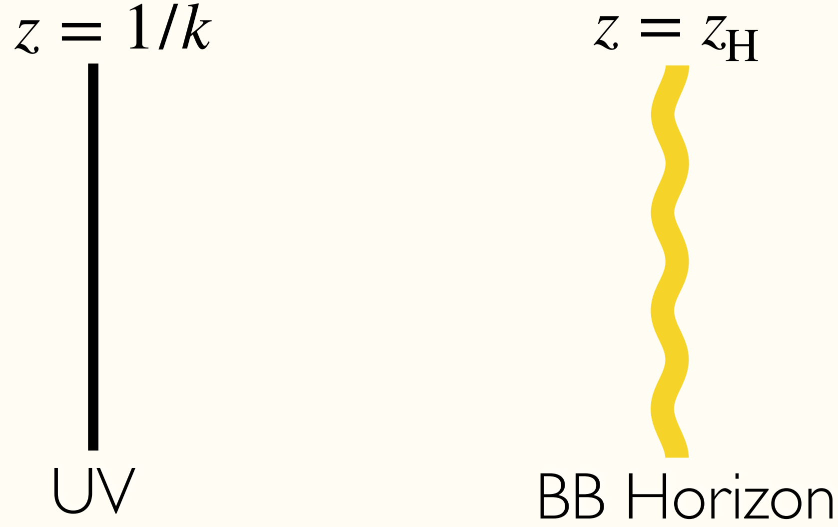
- The thermal phase of the CFT is argued to be described by the canonical ensemble of AdS: AdS-Schwarzschild.

- Black brane horizon (z_H) replaces IR brane:

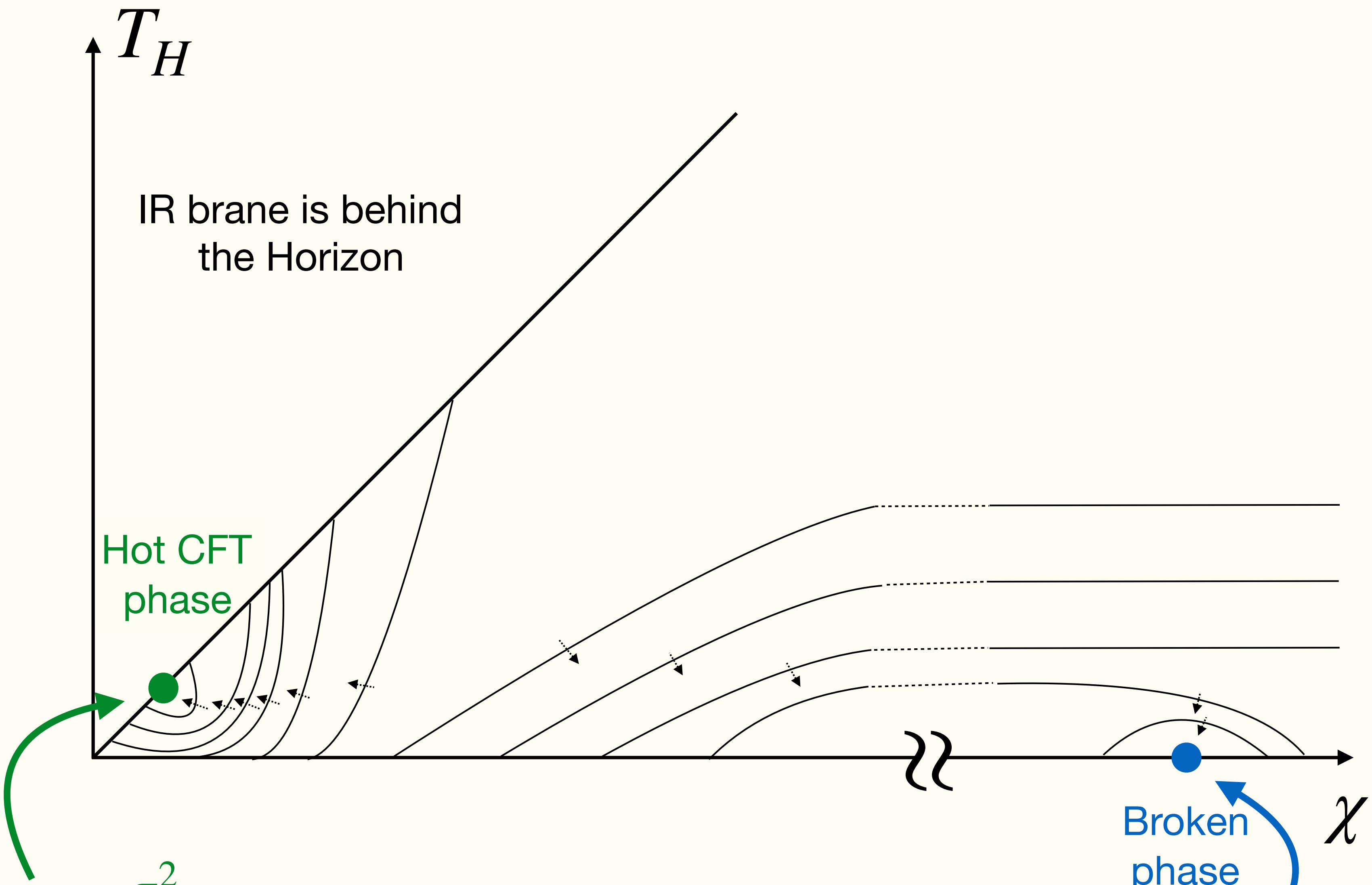
$$ds^2 = \left(\frac{1}{k^2z^2} - \frac{z^2}{k^2z_H^4}\right)dt^2 + \left(\frac{1}{k^2z^2} - \frac{z^2}{k^2z_H^4}\right)^{-1}\frac{dz^2}{k^4z^4} + \frac{dx_i^2}{k^2z^2}$$

- Hawking temperature: $T_H = 1/\pi\, z_H$

- At $z_H \to \infty$ we get back AdS metric.



Two Phases

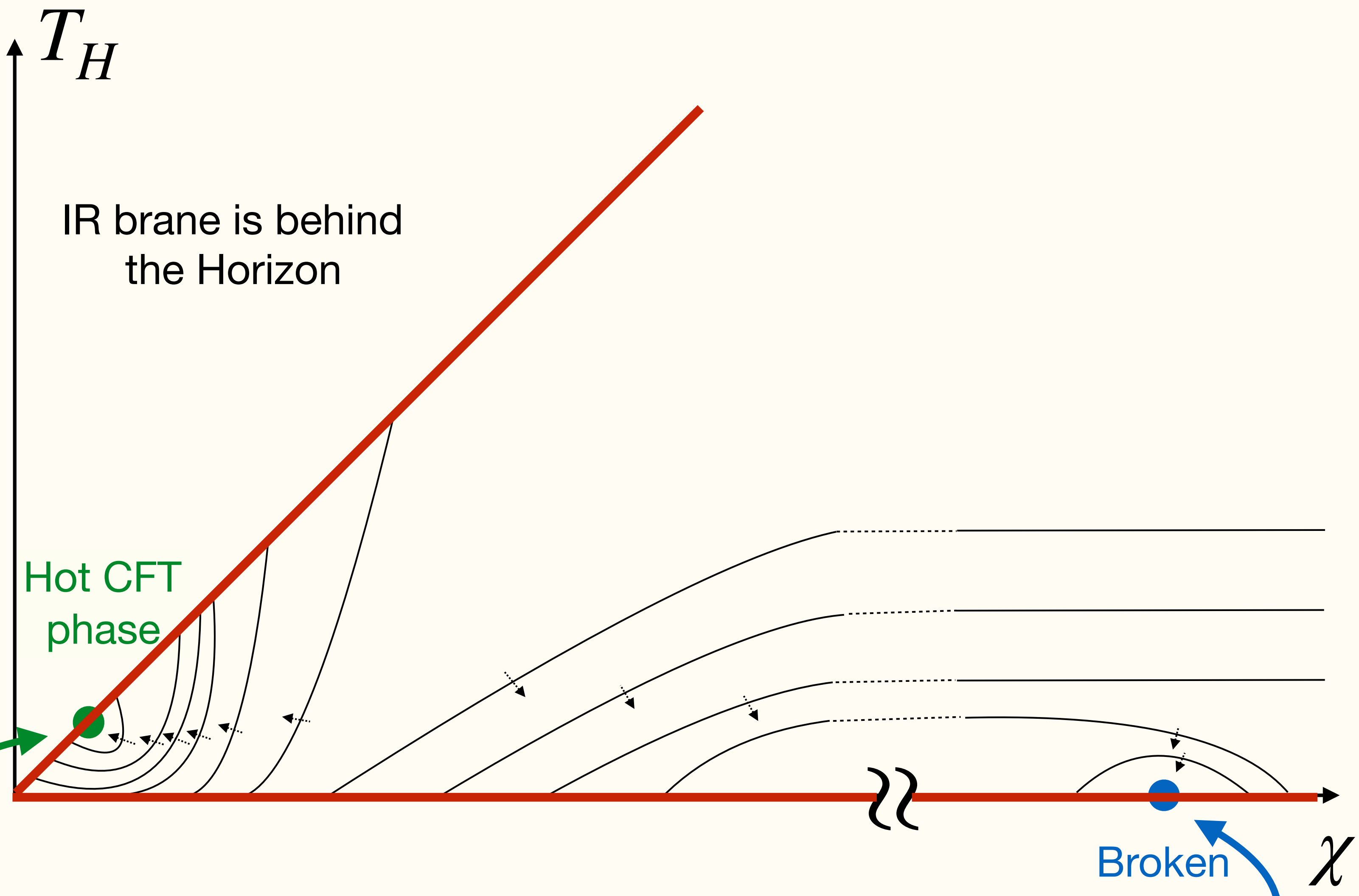


$$F_{\mathrm{CFT}} = -\frac{\pi^2}{8} N^2 T^4$$

$$N^2 = 16\pi^2 (M_*/k)^3 + 1$$

$$F_{\mathrm{broken}}(\chi, T) \simeq V(\chi)\,,$$

Two Phases



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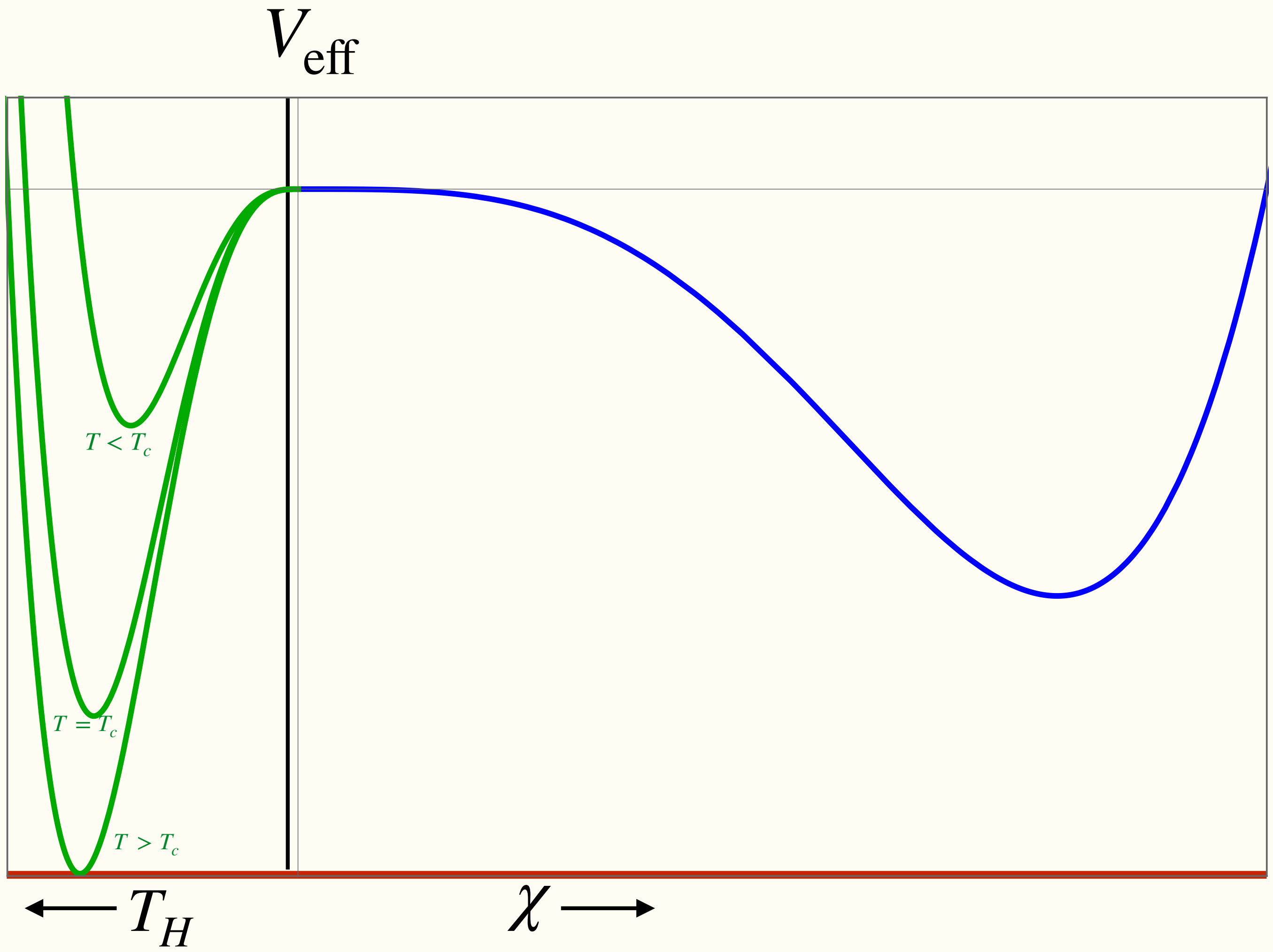

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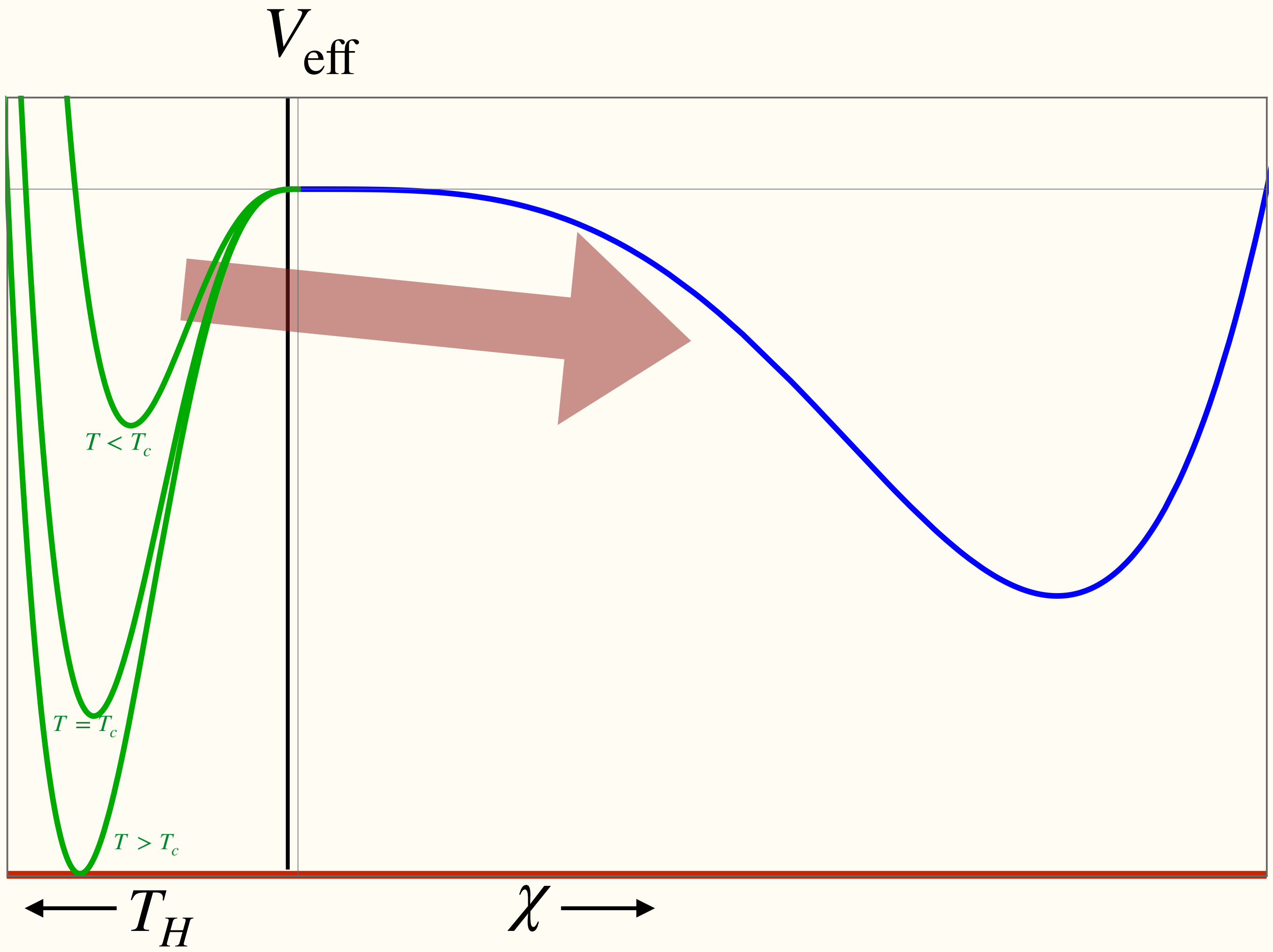

Crunching transition is known as
the Hawking-Page phase transition

Randall-Sundrum

- Two problems:

  1. Small ϵ would imply a very slowly varying tunneling rate as T drops. To improve, consider more generally:

$$V(\chi) = -\lambda\chi^4 + \frac{\lambda_1}{k^{\epsilon}}\chi^{4+\epsilon_1} - \frac{\lambda_2}{k^{2\epsilon}}\chi^{4-\epsilon_2}$$

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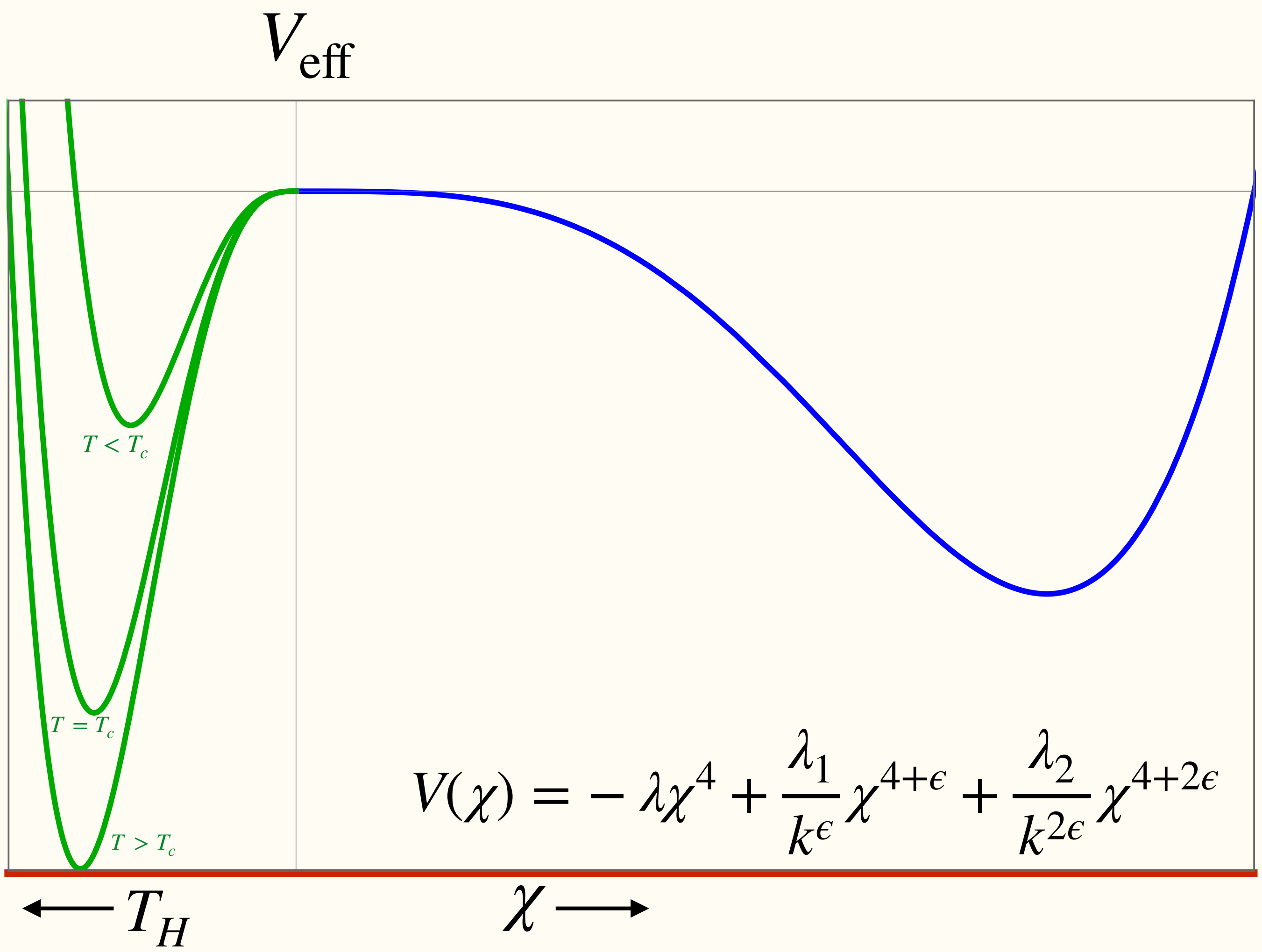
2. Effective theory breaks down when explicit conformal breaking becomes order one:

$$m_\chi(\chi_*) < \chi_* \;\; = \text{IR scale}$$

$$\Downarrow$$

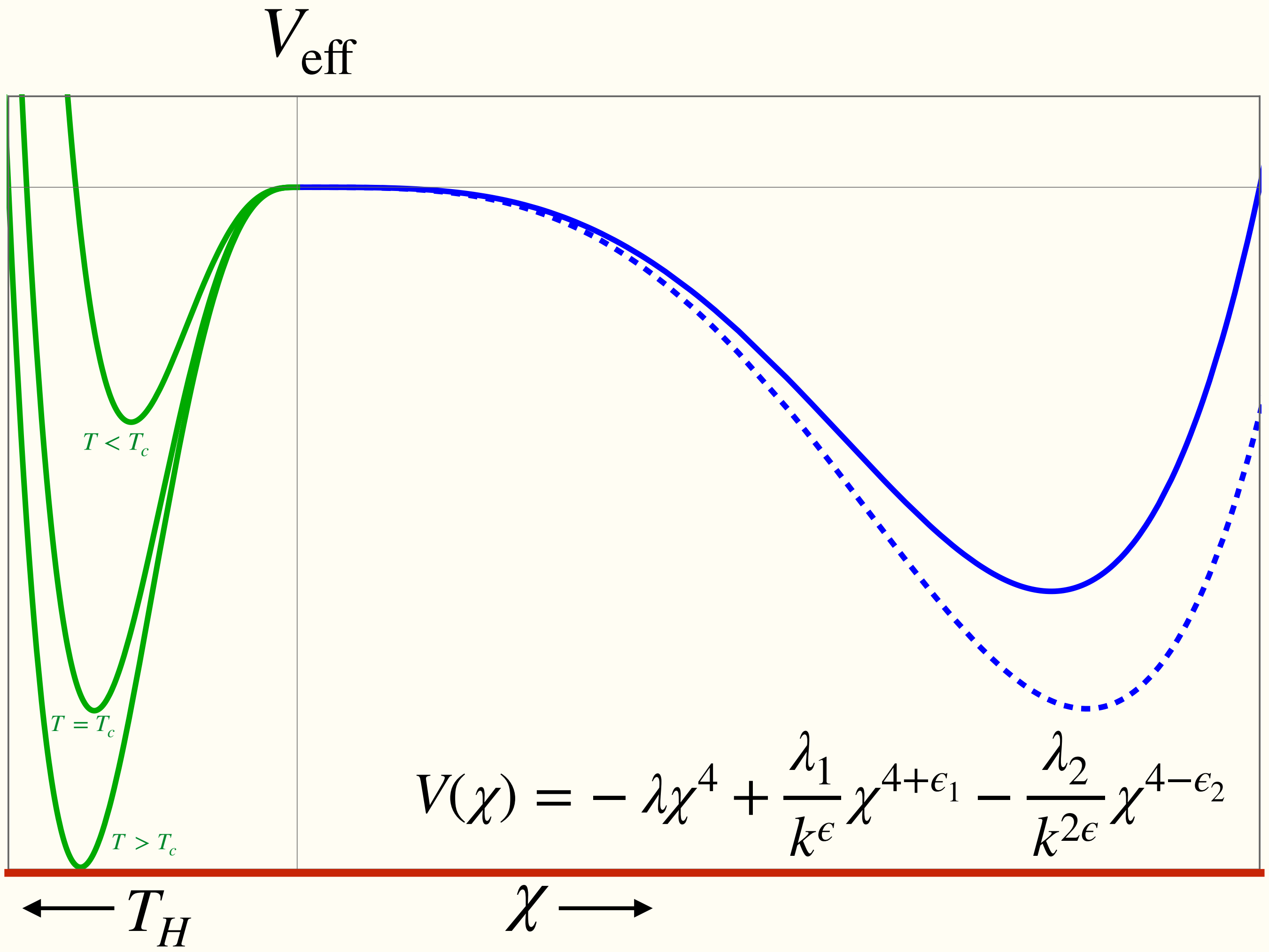
$$\chi_* \sim \lambda_2^{1/\epsilon_2} k$$

Two Phases



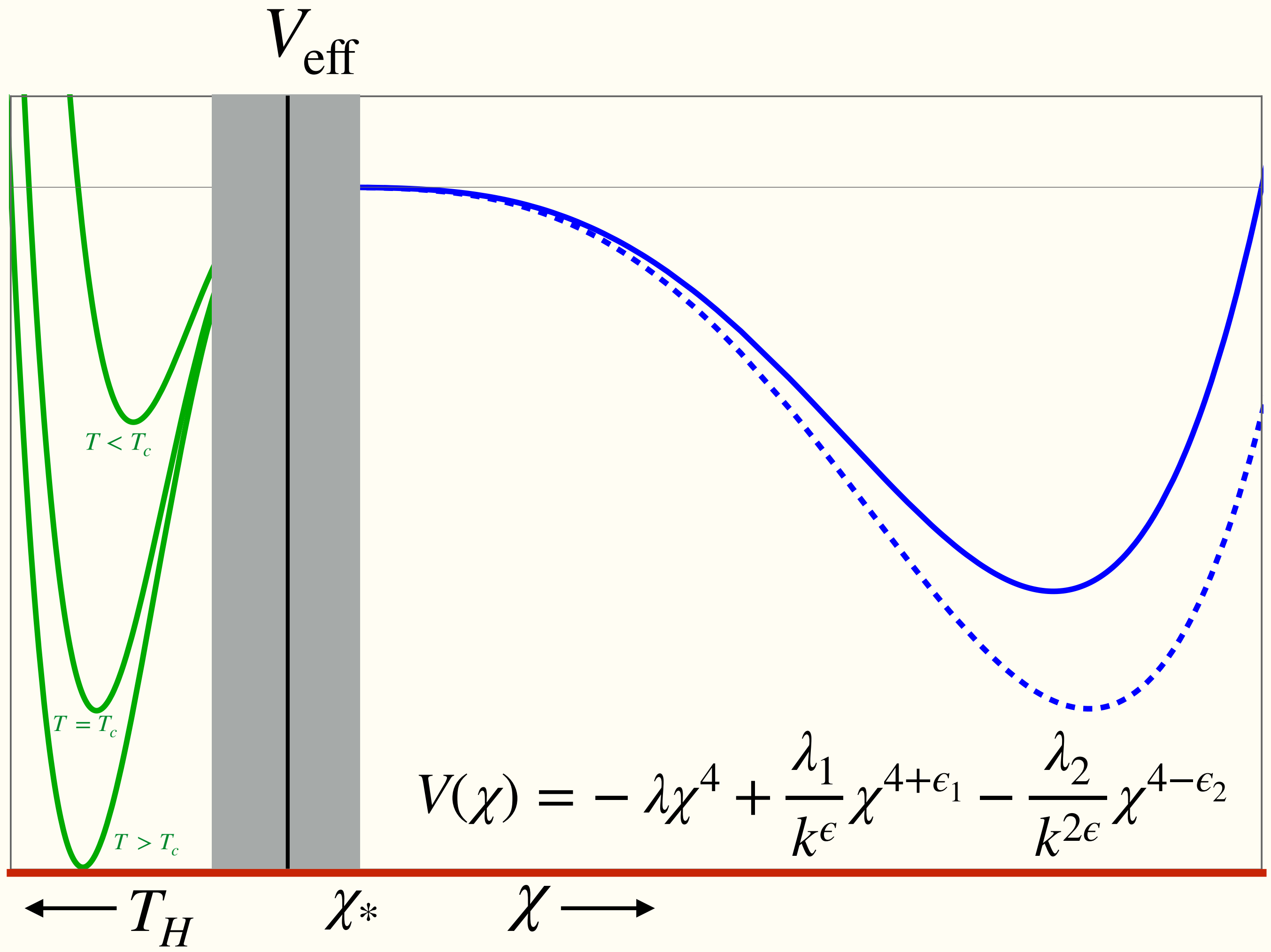
$V_{\rm eff}$
$T < T_c$
$T = T_c$
$T > T_c$
$V(\chi) = -\lambda\chi^4 + \frac{\lambda_1}{k^\epsilon}\chi^{4+\epsilon} + \frac{\lambda_2}{k^{2\epsilon}}\chi^{4+2\epsilon}$
$\longleftarrow T_H$
$\chi \longrightarrow$

Two Phases



V_{eff}
$T < T_c$
$T = T_c$
$T > T_c$
$V(\chi) = -\lambda\chi^4 + \frac{\lambda_1}{k^{\epsilon}}\chi^{4+\epsilon_1} - \frac{\lambda_2}{k^{2\epsilon}}\chi^{4-\epsilon_2}$
$\leftarrow T_H$
$\chi \longrightarrow$

Two Phases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$\leftarrow T_H$
χ_*
$\chi \rightarrow$

The Phase Transition

The Bounce Action

- 2 Contributions:

    1. $O(4)$-symmetric @ $T = 0$

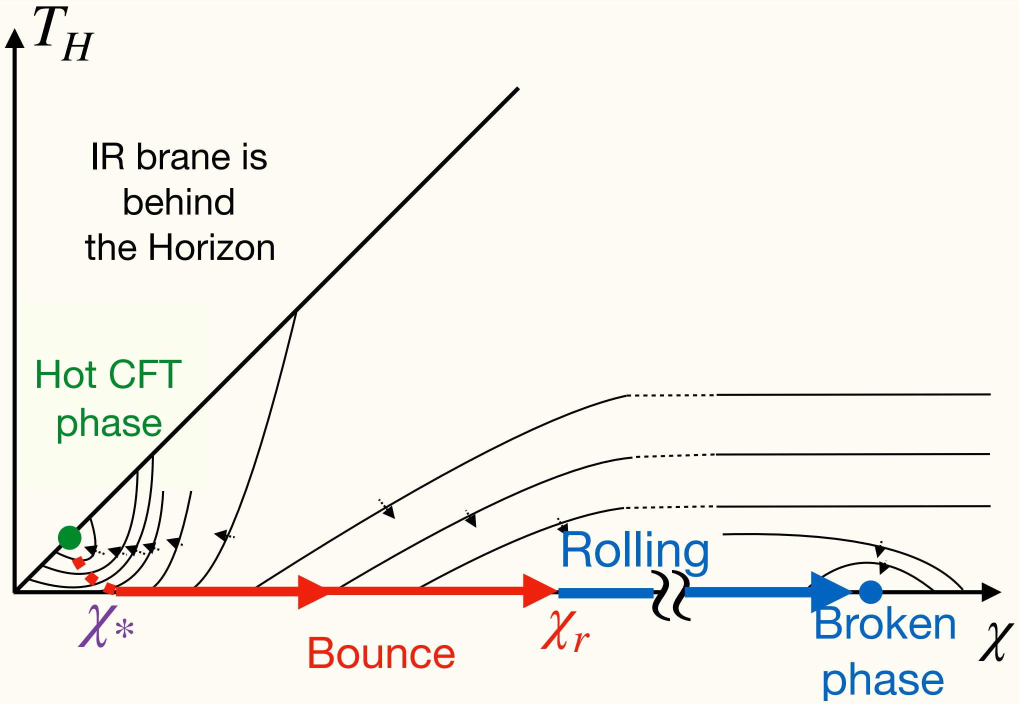
    2. $O(3)$-symmetric @ $T \neq 0$

- Transition between two contributions occurs when $R_{\rm bubble} \sim 1/T$.

O(3)-Symmetric Bounce

$$\phi'' + \frac{2}{r}\phi' - V'(\phi, T) = 0$$

$$\phi(r = 0) = \phi_r(T)$$
$$\phi(r \to \infty) = \phi_{\text{false}}(T)$$



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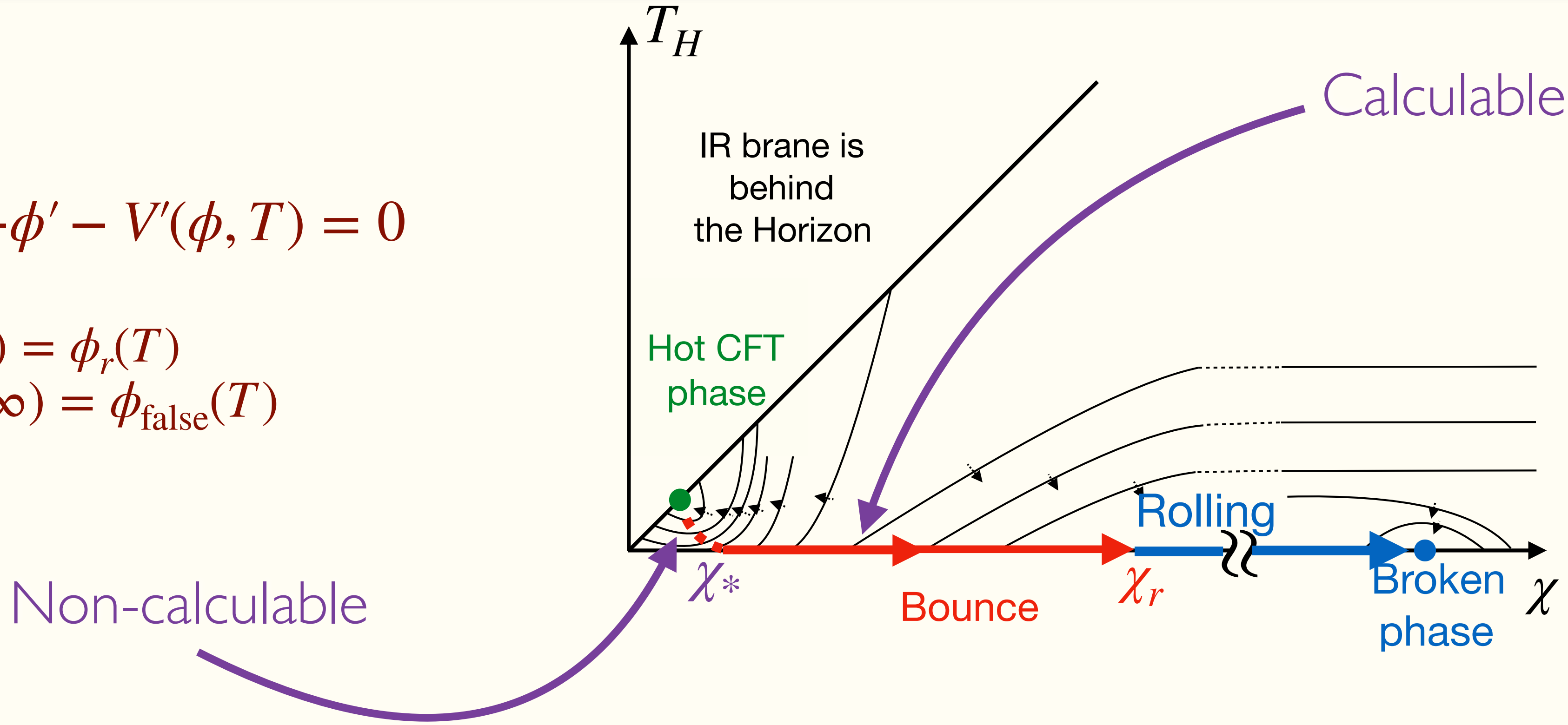

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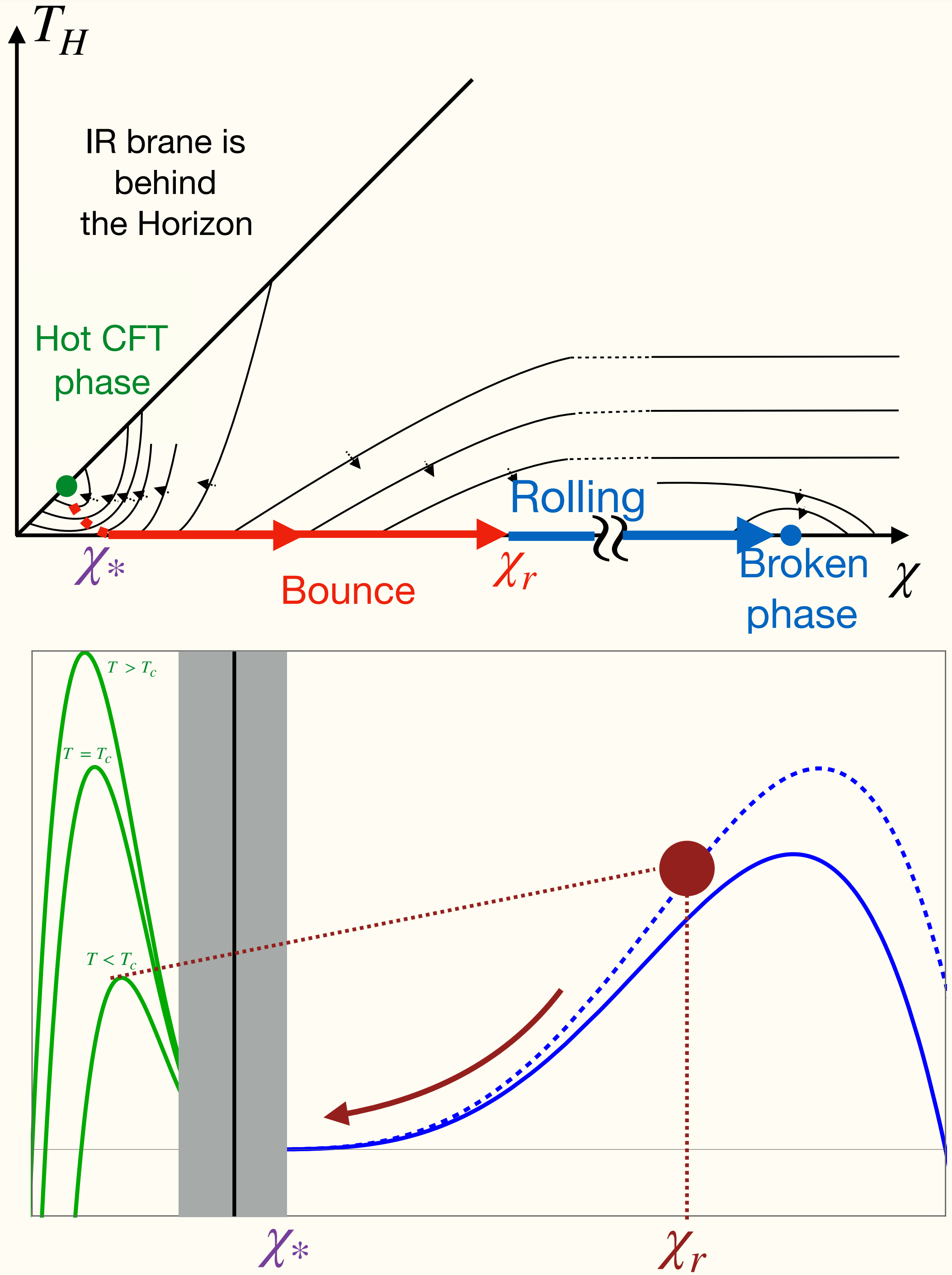

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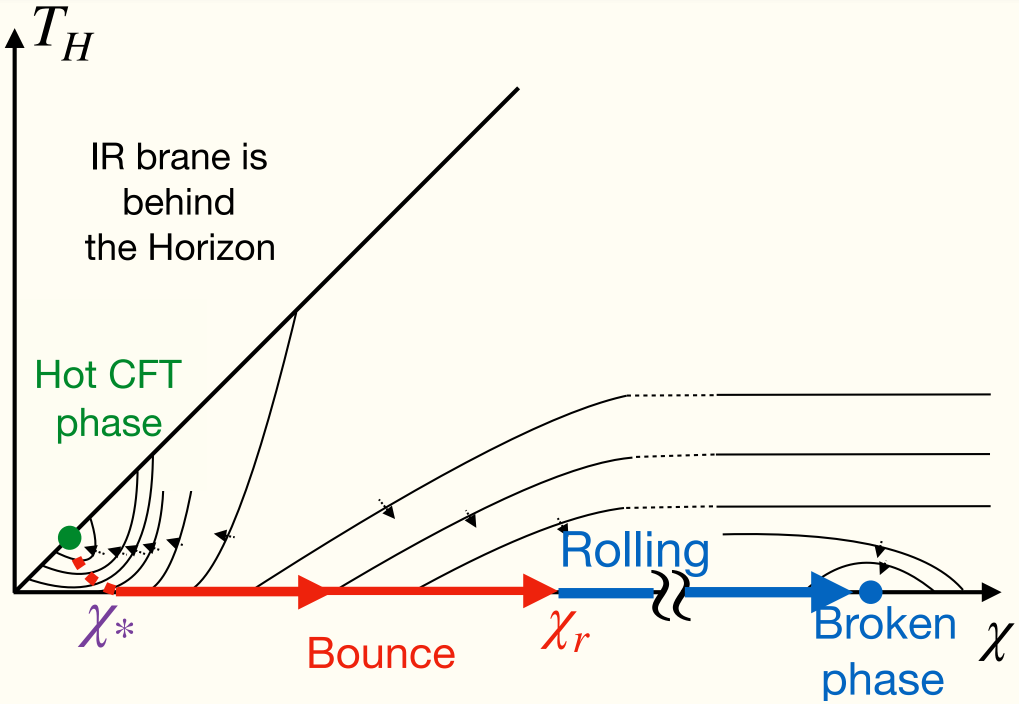
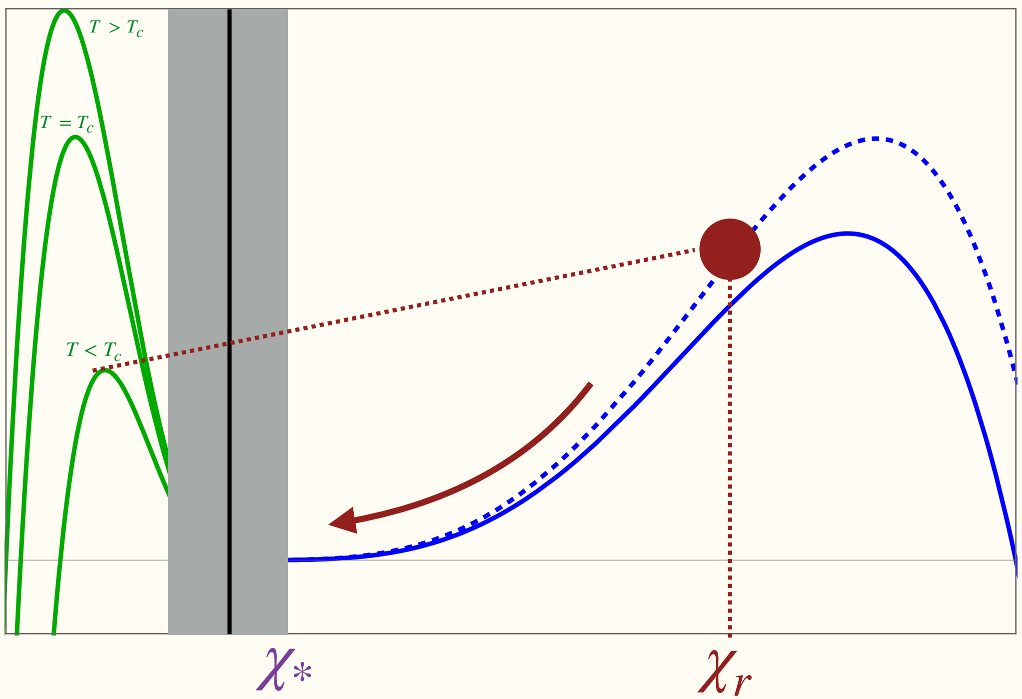


- As $T \to 0 \Rightarrow \chi_r \to 0$

- Define T_*:

$$\chi_r(T = T_*) = \chi_*$$



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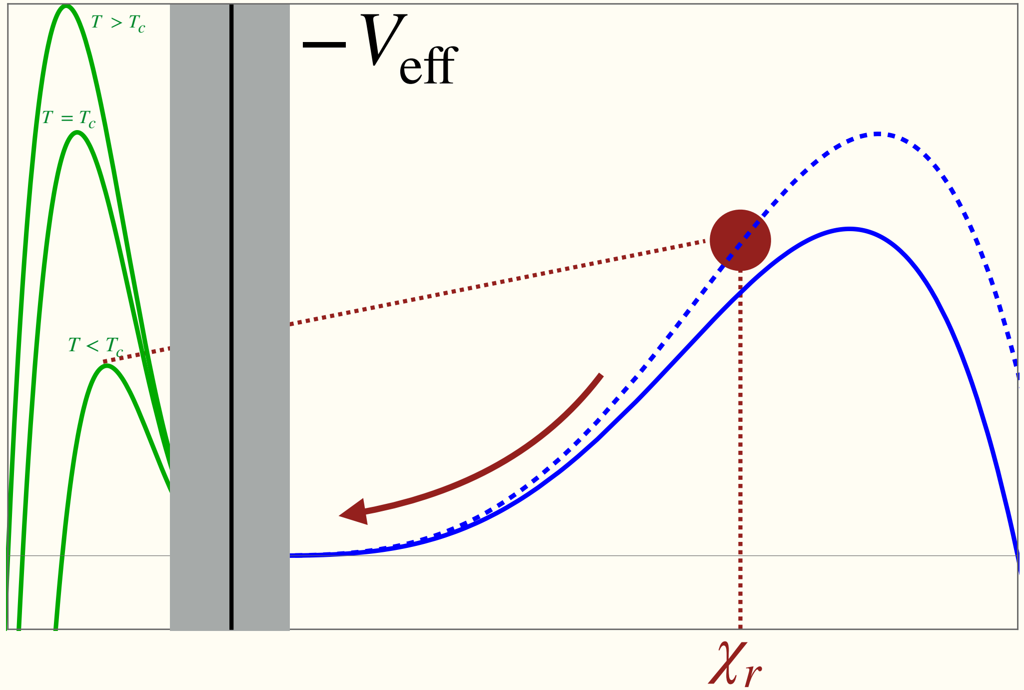

- Estimate:

  Neglect friction.

  χ_r is taken from energy conservation:

$$N^2T^4 \sim V_{\rm CFT}(T) = V_{\rm eff}(\chi) \sim \lambda\chi^4 + \lambda_2\chi^{4-\epsilon_2}$$

$$\Longrightarrow \qquad \chi_r \sim \chi_* \min\left[\left(\frac{T}{T_*}\right)^{\frac{1}{1-\epsilon_2/4}}, \left(\frac{3N^2}{2\pi^2(4-\epsilon_2)(3-\epsilon_2)\lambda}\right)^{1/4}\frac{T}{T_*}\right]$$

O(3)-Symmetric Bounce

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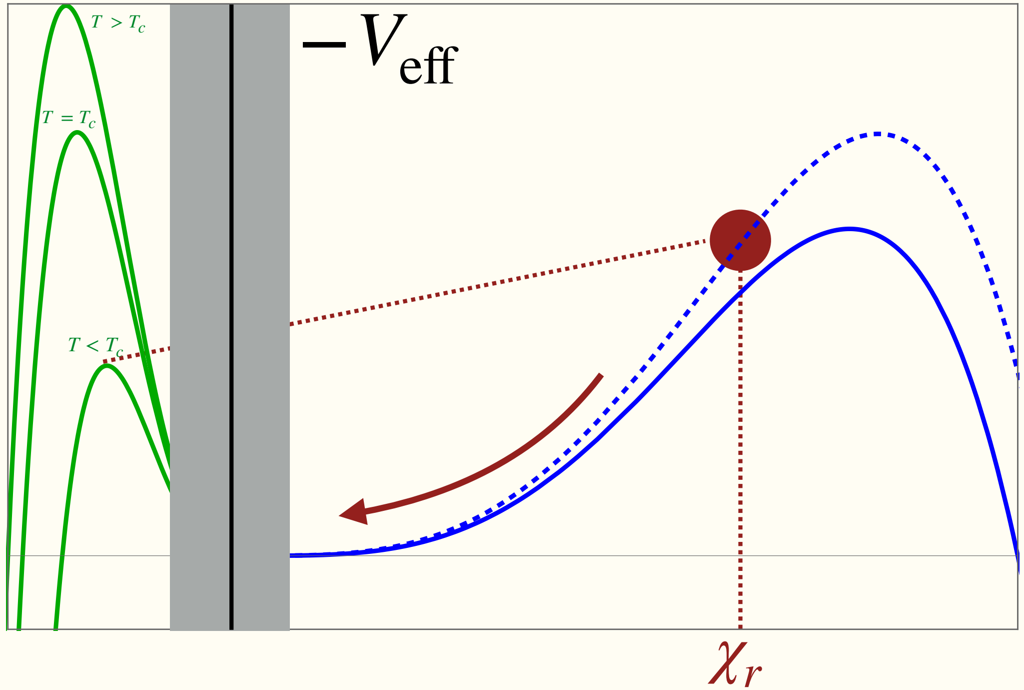

- Size of bubble can also be estimated:

$$R_{\text{bubble}} \sim N[V''_{\text{eff}}(\chi_r)]^{-1/2} = \frac{1}{\sqrt{2}} N\chi_r^{-1}\left[N^2\left(\frac{\chi_*}{\chi_r}\right)^{\epsilon_2} + 8\pi^2\lambda\right]^{-1/2}$$

- Note: $R_{\text{bubble}}(T = T_*) \sim \chi_*^{-1} \sim T_*^{-1}$

O(3)-Symmetric Bounce

$$S_3(T) = 4\pi \int_0^\infty dr \cdot r^2 \left[\frac{\bar{\chi}'^2}{2} + \overline{V}(\bar{\chi}, T) \right] \sim N^2 \chi_r^2 R_{\rm bubble}$$

$$\frac{S_3(T)}{T} \sim \ \text{min}\left[N^2 \left(\frac{T}{T_*} \right)^{\frac{3\epsilon_2/4}{1-\epsilon_2/4}}, \quad N^{7/2} \left(\frac{1}{2\pi^2 \lambda} \right)^{3/4} \right]$$

Explicit
conformal breaking

T-independent
Conformal limit

O(3)-Symmetric Bounce

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Weak T-dependence

Unless $\epsilon_2 = \mathcal{O}(1)$

$$\frac{S_3(T)}{T} \sim \min \left[N^2 \left(\frac{T}{T_*} \right)^{\frac{3\epsilon_2/4}{1-\epsilon_2/4}}, \quad N^{7/2} \left(\frac{1}{2\pi^2 \lambda} \right)^{3/4} \right]$$

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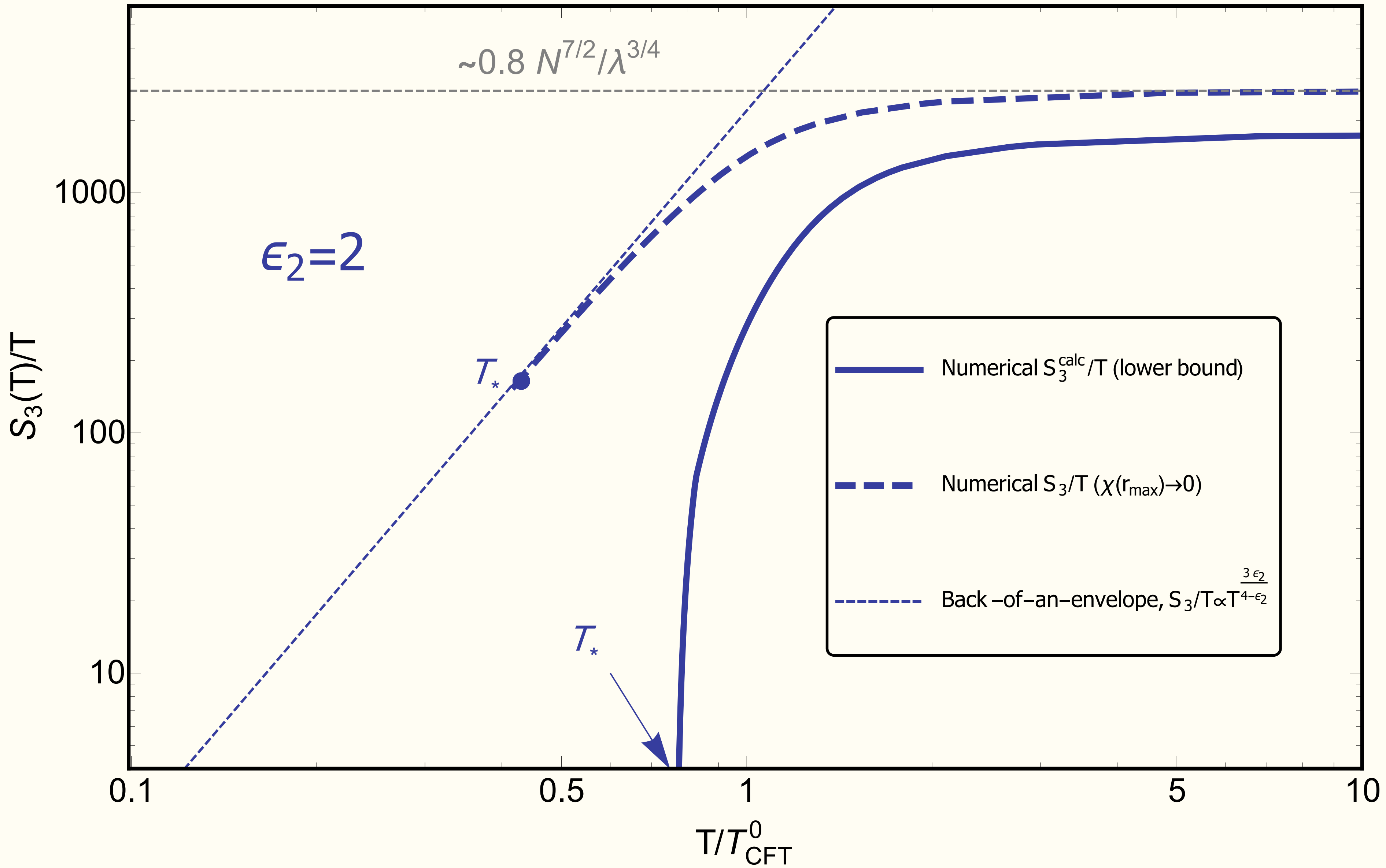

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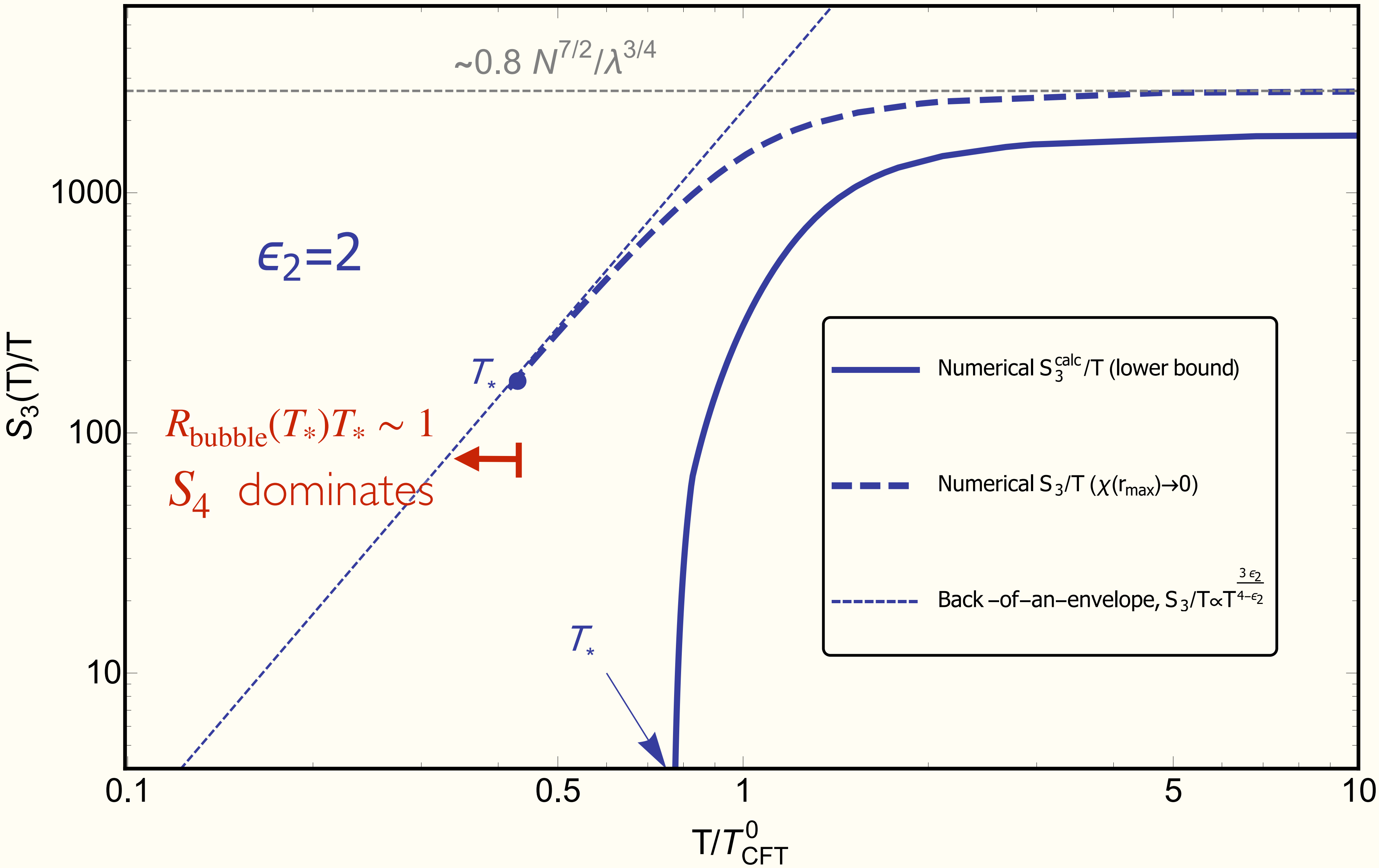
O(3)-Symmetric Bounce



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O(4)-Symmetric Bounce

- Relevant at $T \to 0$, so $\chi_r \ll \chi_*$.
- Depends on non-calculable part of the potential.
- On dimensional grounds:

$$S_4 = 2\pi^2 \int_0^\infty dr \cdot r^3 \left[\frac{\bar{\chi}'^2}{2} + \overline{V}(\bar{\chi}) \right] \sim N^2 \chi_r^2 R_{\text{bubble}}^2 \sim N^2 \left(\frac{\chi_r}{\chi_*} \right)^{\epsilon_2} \lesssim N^2$$

Tunneling Rates

$$\frac{S_3(T)}{T} \sim \min\left[N^2 \left(\frac{T}{T_*}\right)^{\frac{3\epsilon_2/4}{1-\epsilon_2/4}}, \quad N^{7/2}\left(\frac{1}{2\pi^2\lambda}\right)^{3/4} \right]$$

$$\frac{\Gamma}{V} \sim \begin{cases} T^4\, e^{-S_3(T)/T} & T \gtrsim T_* \\ T_*^4\, e^{-N^2} & T < T_* \end{cases}$$

Phase transition occurs when: $\dfrac{\Gamma}{V} \simeq H_\Lambda^4$

Crunching occurs at T_*

Choose $T_* \sim T_{0,\mathrm{CFT}}$

Results

The Maximal CC

- Three constraints:

  1. Our patch should survive until today.

$$\left.\frac{\Gamma}{V}\right|_{T_{\rm CFT}\geq T^0_{\rm CFT}} < H_0^4 \qquad \Longrightarrow \qquad \left.\frac{S_3(T)}{T}\right|_{T_{\rm CFT}=T^0_{\rm CFT}} \gtrsim 280$$

$$T_* \lesssim T_{0,\rm CFT}$$

The Maximal CC

- Three constraints:

    1. Our patch should survive until today.

    2. $N_{\rm eff} < N_{\rm eff}^{\rm obs}$.

$$T^0_{\rm CFT} \leq 0.034 \text{ meV} \left(\frac{N}{4.5}\right)^{-1/2}$$

$$T_* \lesssim T_{0,\rm CFT} \lesssim T_0$$

The Maximal CC

- Three constraints:

  1. Our patch should survive until today.

  2. $N_{\rm eff} < N_{\rm eff}^{\rm obs}$.

  3. No eternal inflation.

$$\left.\frac{\Gamma}{V}\right|_{T_{\rm CFT}=H_\Lambda} > H_\Lambda^4$$

$$T_* \lesssim T_{0,\rm CFT} \lesssim T_0 \qquad \Lambda \lesssim \Lambda_{\rm max} \equiv \sqrt{T_* \bar{M}_{\rm Pl}}\; e^{-3N^2/128}$$

The Maximal CC

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$$\Downarrow$$

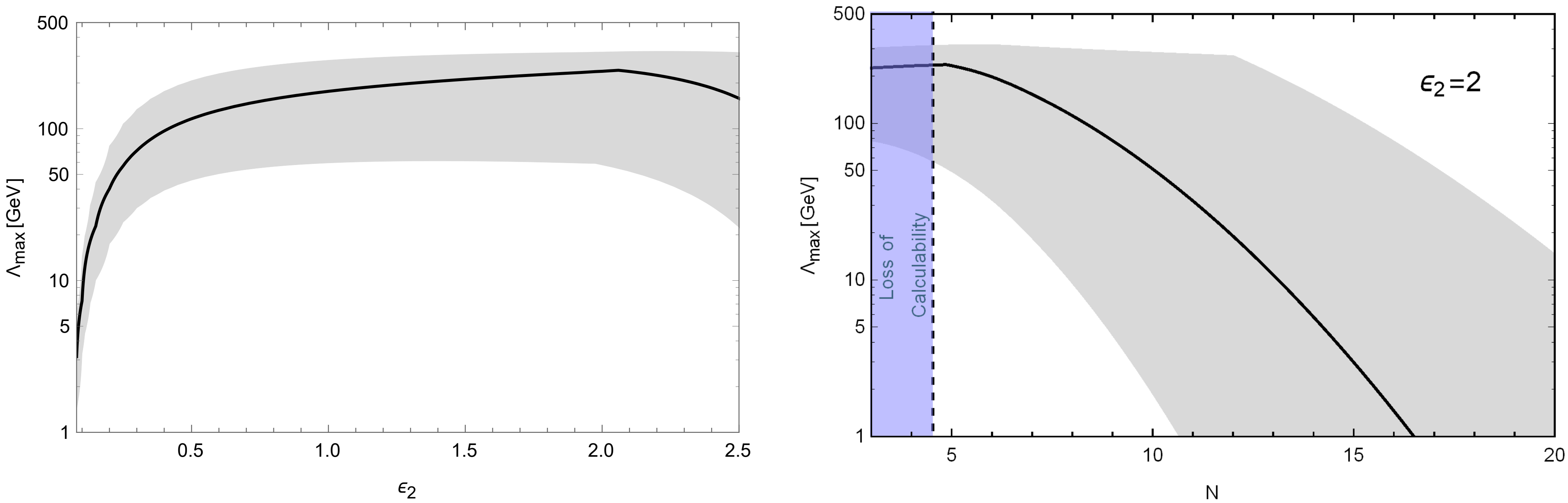
$$\Lambda_{\mathrm{max}} \lesssim \sqrt{T_0 \bar{M}_{\mathrm{Pl}}}\; e^{-3N^2/128} \lesssim 1.2\ \mathrm{TeV}$$

Contributions above this scale require cancellation

New physics at the weak scale!

The CC Miracle

The Maximal CC



Need $\epsilon_2 \sim \mathcal{O}(1)$

How can we get ϵ_2 $\mathcal{O}(1)$?

$z = 1/k$ $\quad\quad\quad$ $z = z_{\mathrm{IR}}$

$$ds^2 = \frac{1}{k^2 z^2}\left(dx_\mu dx^\mu - dz^2\right)$$

ϕ_{GW} + **QCD'**

UV $\quad\quad\quad$ IR

- Adding a confining gauge group in the bulk gives a new source of explicit CFT breaking.

[von Harling, Servant, 2017; Baratella, Pomarol, Rompineve, 2018]

- Equivalent to weakly gauging a global symmetry of the CFT, with RGE:

$$\frac{1}{g^2(Q,\chi)} = -\frac{b_{\mathrm{CFT}}}{8\pi^2}\log\frac{k}{\chi} - \frac{b_{\mathrm{UV}}}{8\pi^2}\log\frac{k}{Q} - \frac{b_{\mathrm{IR}}}{8\pi^2}\log\frac{\chi}{Q} + \tau_{\mathrm{UV}} + \tau_{\mathrm{IR}}$$

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CFT DOFs.

$b_{\rm CFT} = -\dfrac{8\pi^2}{k g_5^2}$

UV and IR DOFs

UV and IR threshold

How can we get ϵ_2 $\mathcal{O}(1)$?

$z = 1/k$ $\qquad\qquad$ $z = z_{\rm IR}$

$$ds^2 = \frac{1}{k^2 z^2}\left(dx_\mu dx^\mu - dz^2\right)$$

$\phi_{\rm GW}$ + **QCD'**

UV $\qquad\qquad$ IR

- The QCD' confining scale is then:

$$\Lambda(\chi) = \Lambda_0 \left(\frac{\chi}{\chi_{\rm min}}\right)^n \qquad\qquad n = \frac{b_{\rm IR} - b_{\rm CFT}}{b_{\rm UV} + b_{\rm IR}}$$

- Effective potential (due to e.g. gluon condensation) is then:

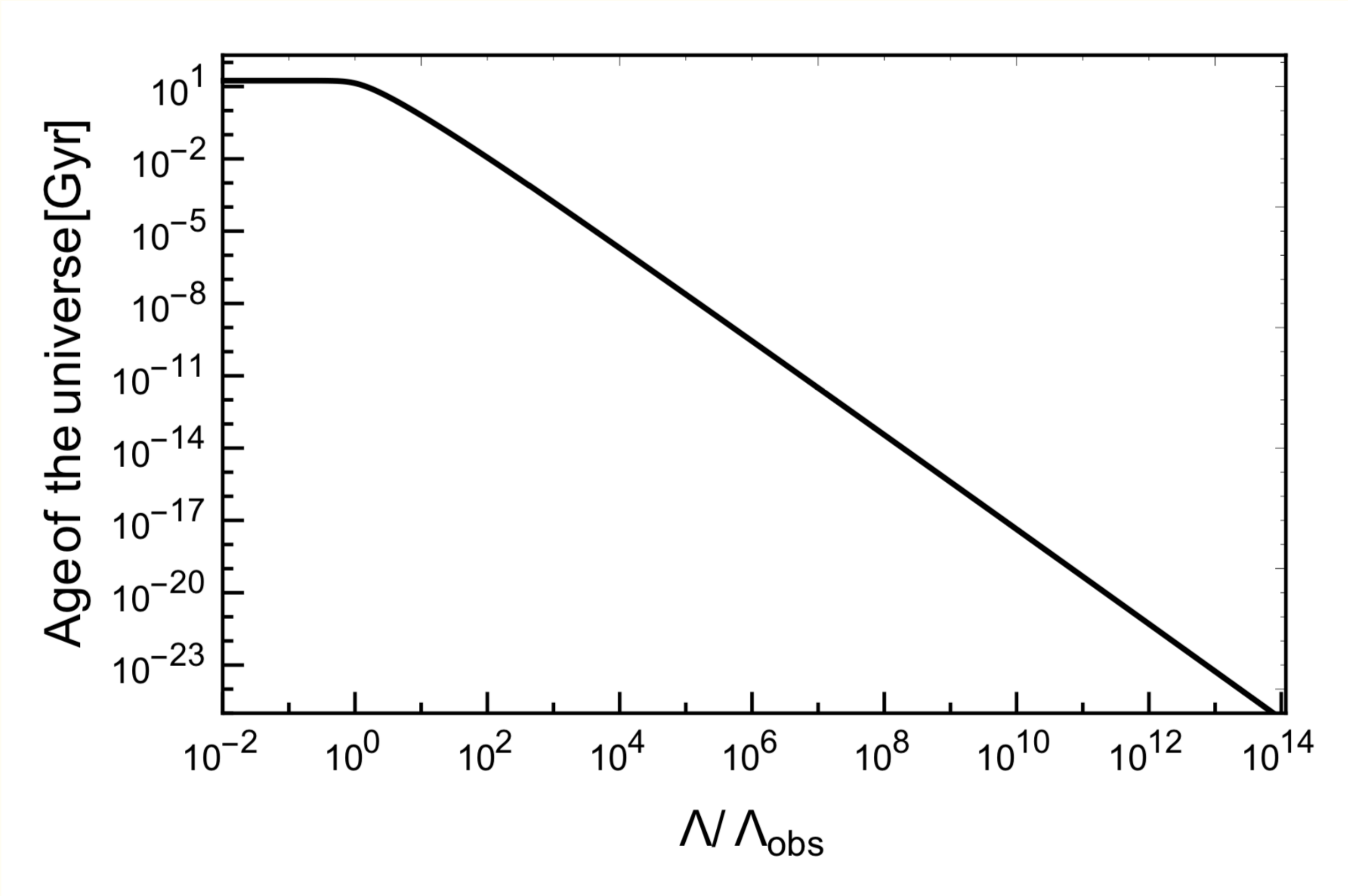
$$V_G = -\alpha \Lambda_0^4 \left(\frac{\chi}{\chi_{\rm min}}\right)^{4n}$$

$$\Longrightarrow \qquad \epsilon_2 = 4(1-n)$$

Phenomenological Implications

The Coincidence Problem

Mechanism implies relation between age of patch and CC value



If CC would have taken over earlier, our universe would have decayed

Predictions

- Measureable N_{eff}:

$$\Delta N_{\mathrm{eff}} \simeq 0.23 \left(\frac{\Lambda_{\mathrm{max}}}{260\,\mathrm{GeV}} \right)^8$$

Predictions

- Measureable $N_{\rm eff}$:

$$\Delta N_{\rm eff} \simeq 0.23 \left(\frac{\Lambda_{\rm max}}{260\,{\rm GeV}} \right)^8$$

- New physics at the weak scale, e.g. supersymmetry.

The CC Little Hierarchy Problem

Hierarchy Problem

EWPT + Direct searches

$$\frac{1}{\Delta_H} \sim \left(\frac{m_H}{M_{\rm NP}}\right)^2 \sim 0.004\,\%$$

CC Problem

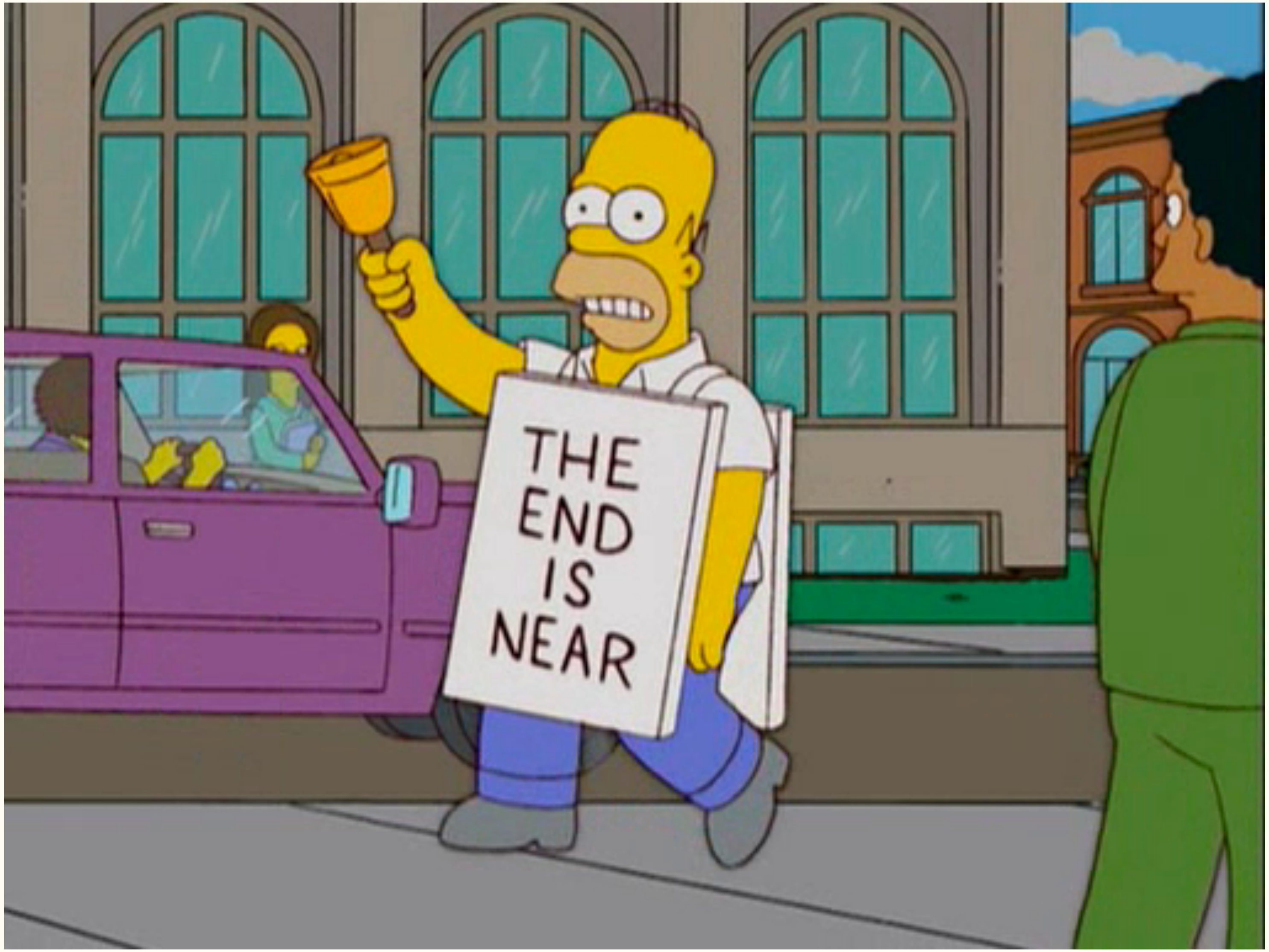
CMB + Direct searches

$$\frac{1}{\Delta} \sim \left(\frac{\Lambda_{\rm max}}{M_{NP}}\right)^4 \sim 0.03\,\% \sqrt{\frac{0.23}{\Delta N_{\rm eff}}}$$

SUSY around the corner?

Wait for CMB-S4

One more prediction..



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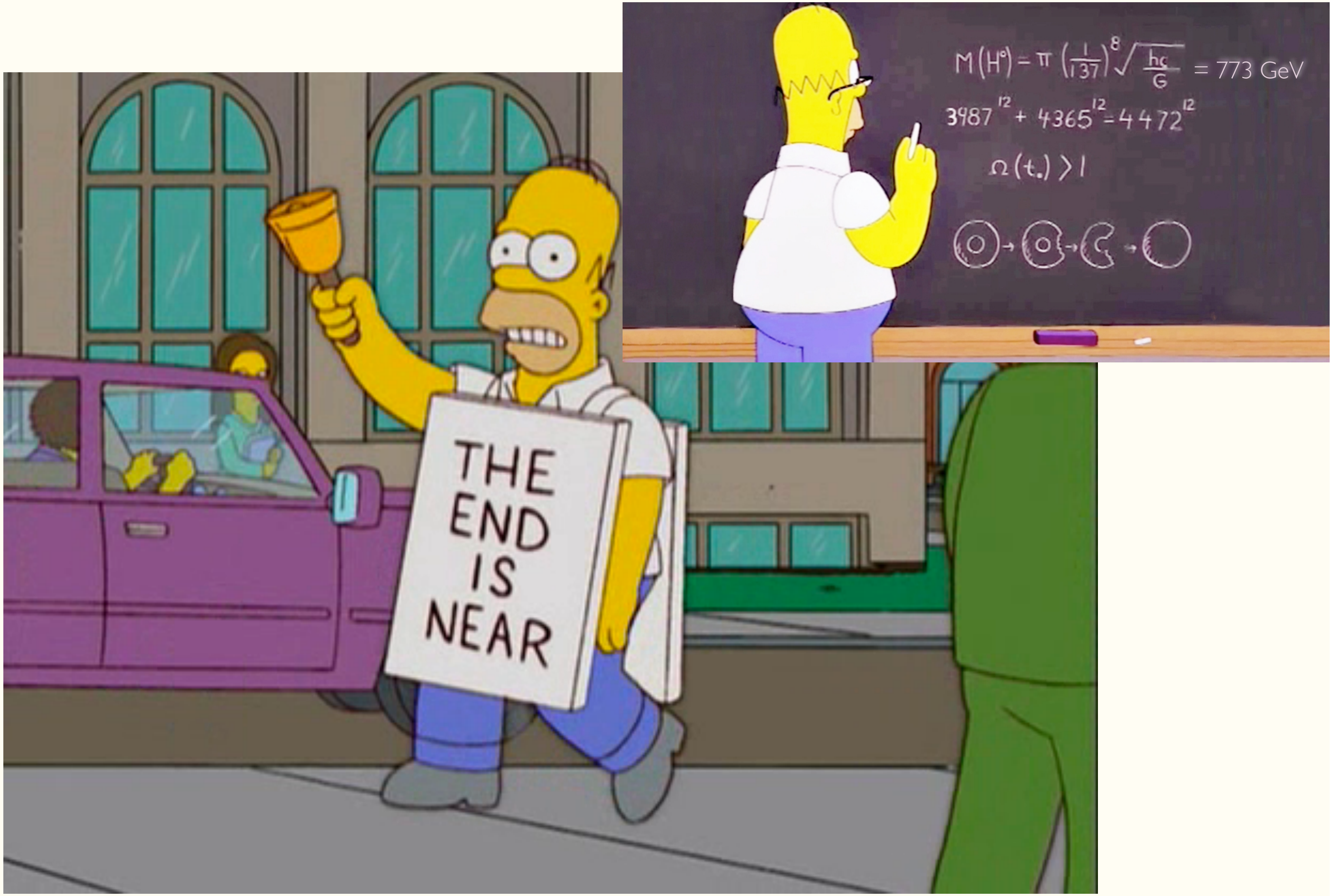


One more prediction..

Discussion

Anthropics?

- So far we did not mention observers. From the bird's eye view the universe just wants to have a small CC..
- However, one may still wonder why we live in such an old universe?
- We provide no answer to that. Requires (weak) anthropics?

Anthropics?

- So far we did not mention observers. From the bird's eye view the universe just wants to have a small CC..
- However, one may still wonder why we live in such an old universe?
- We provide no answer to that. Requires (weak) anthropics?

More provocative thoughts:

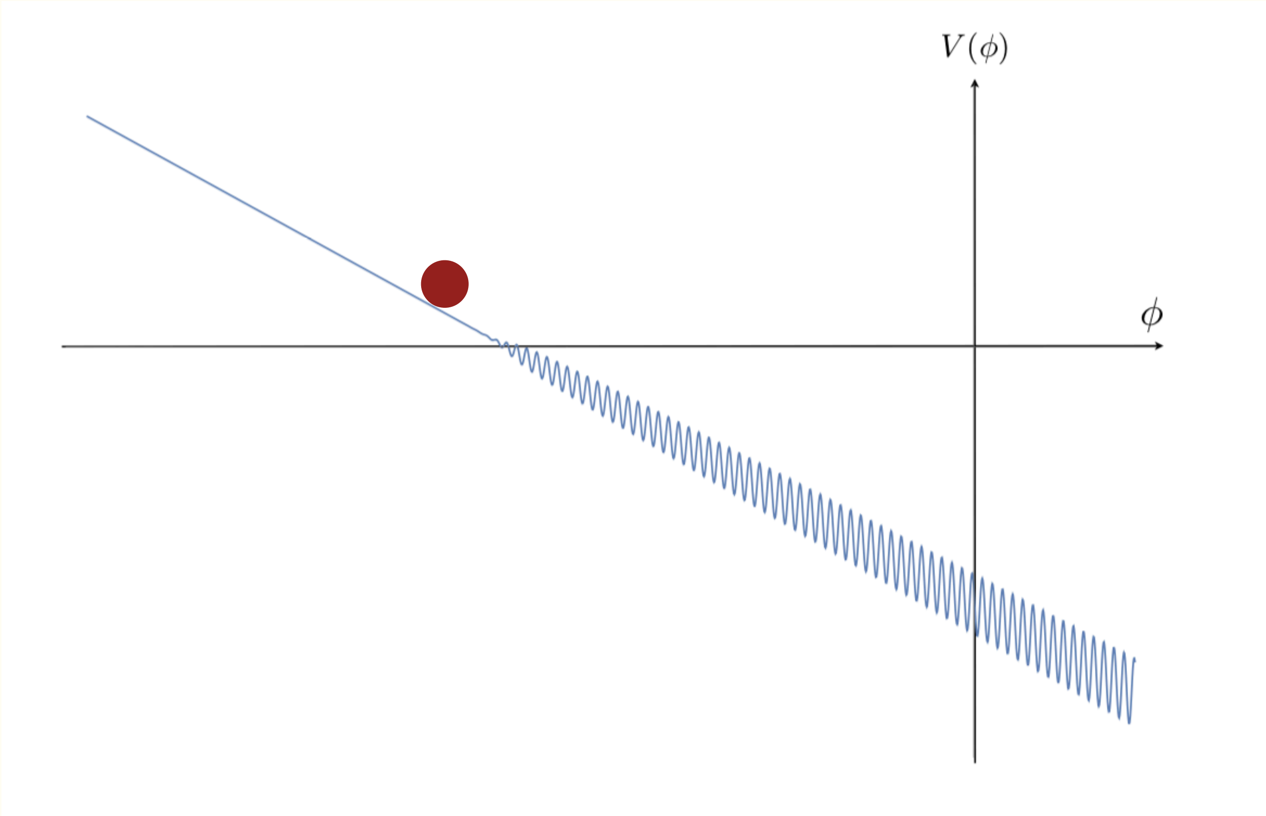
- Copernican Principle implies we should be living in the most likely place: oldest universe with most observers.
- Just like the Doomsday argument: if most likely is today, then demolition may be around the corner.

Just as our model predicts!

What's Next?

- Relaxing the weak scale.

Idea requires solution to the CC beyond (standard) anthropics.



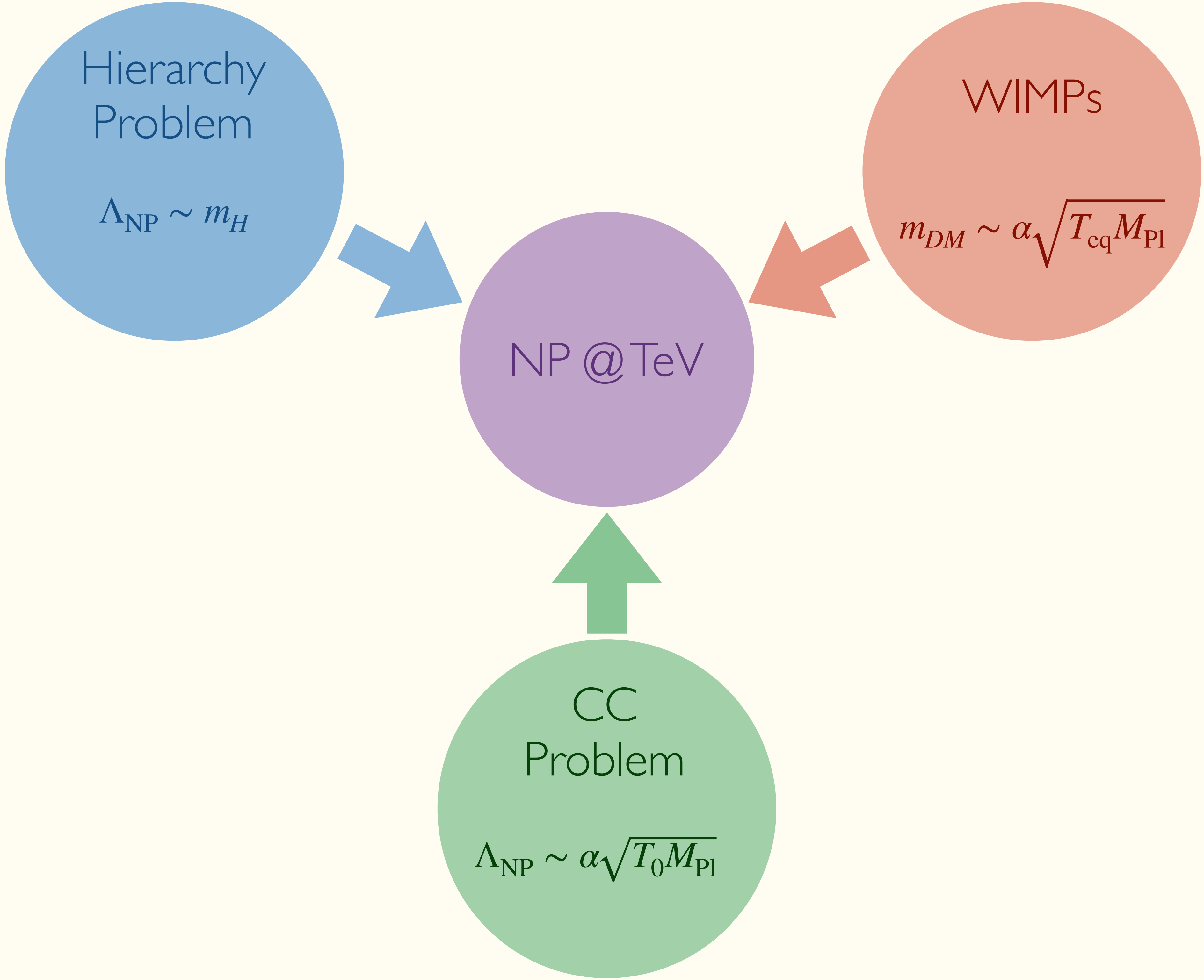
Crunching solution works!   Can we build attractive unified models?

[see e.g. Giudice, Kehagias, Riotto, 2019]

What's Next?

- Relaxing the weak scale.
- Different models? Direct reaction to the CC. Do all predict the NP@TeV?
- UV completions. (Supersymmetric?).
- More experimental implications?
- DM from the CFT?
- …

Lots more to do!


Hierarchy Problem
$\Lambda_{\mathrm{NP}} \sim m_H$
WIMPs
$m_{DM} \sim \alpha\sqrt{T_{\mathrm{eq}} M_{\mathrm{Pl}}}$
NP @ TeV
CC Problem
$\Lambda_{\mathrm{NP}} \sim \alpha\sqrt{T_0 M_{\mathrm{Pl}}}$

Hierarchy Problem

$\Lambda_{\rm NP} \sim m_H$

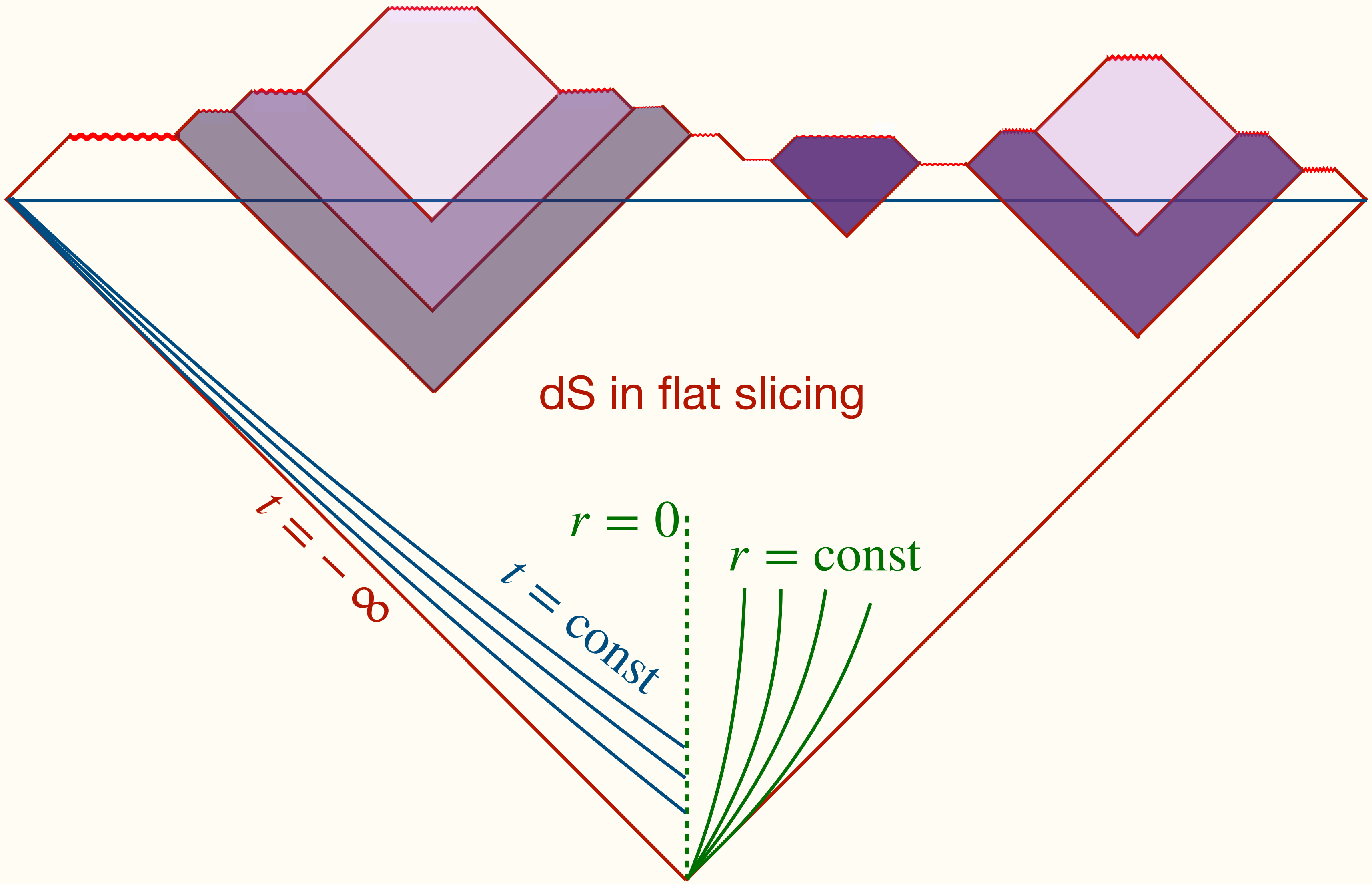
WIMPs

$m_{DM} \sim \alpha\sqrt{T_{\rm eq} M_{\rm Pl}}$

Maybe the (near) future is not so depressing after all..
(if we survive the coronavirus…)

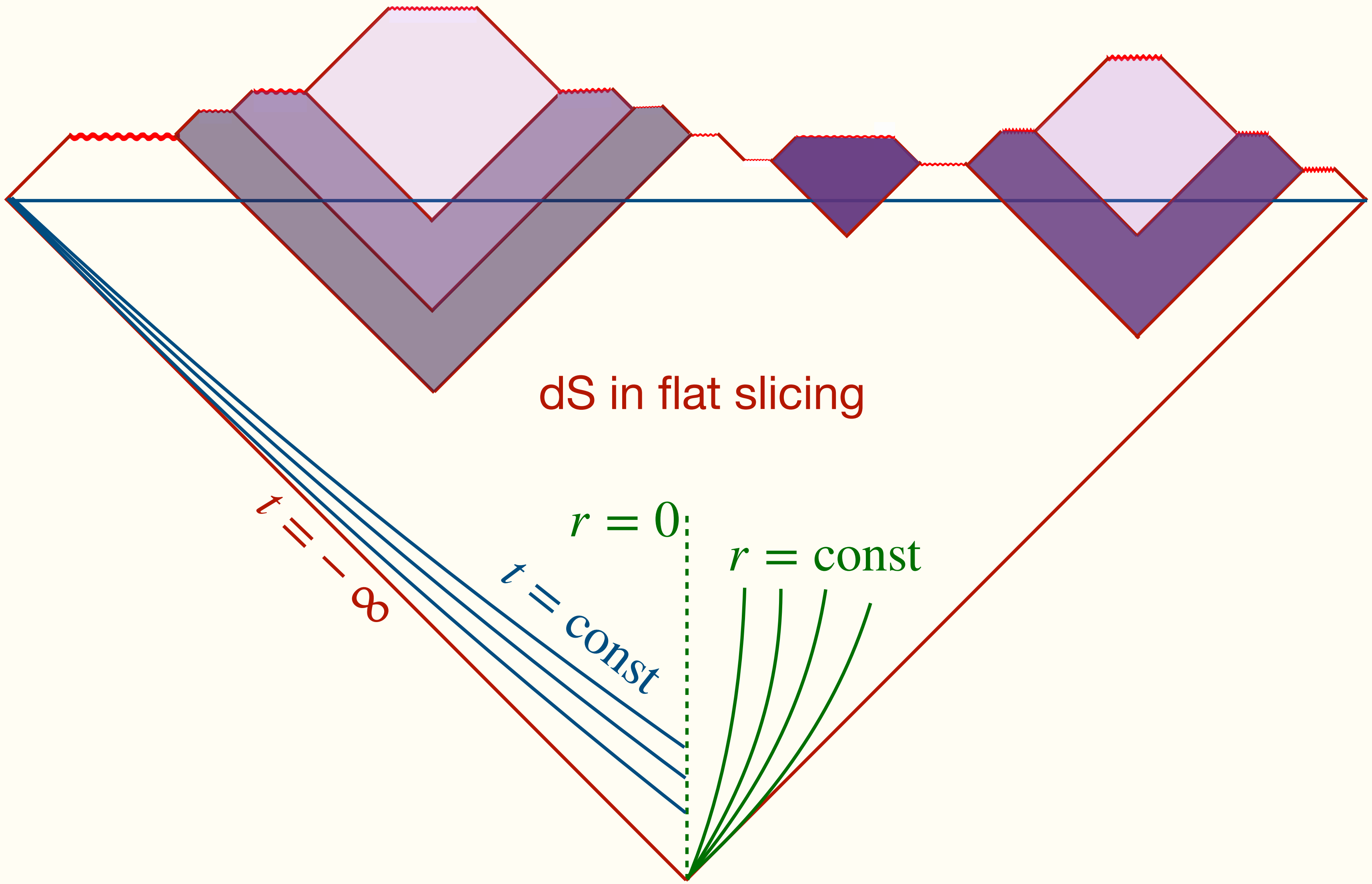
$\Lambda_{\rm NP} \sim \alpha\sqrt{T_0 M_{\rm Pl}}$

Cosmic History



Extras

Cosmic History



Randall-Sundrum: $T \neq 0$

- At finite T, we expect the CFT to be restored into a thermal conformal state.

- The effective finite-T contribution:

[Creminelli, Nicolis, Rattazzi, 2001]

$$\Delta V_{\text{eff}}(\chi; T) \sim \begin{cases} -\dfrac{T^8}{\chi^4} & T \ll \chi \\ -\dfrac{T^5}{\chi} & \chi < T < \dfrac{\chi}{k} M_* \end{cases}$$

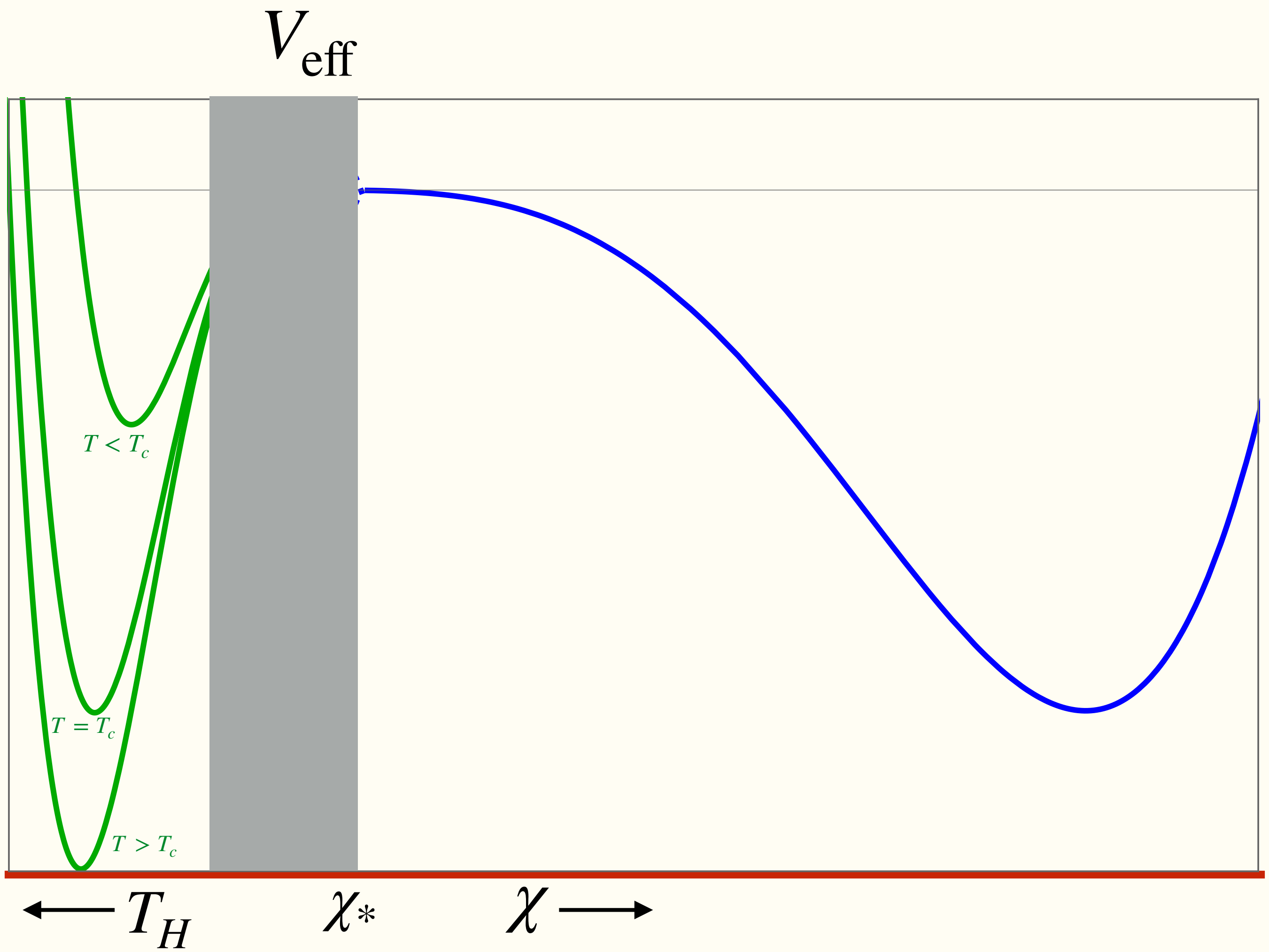
- Effective potential pushes $\chi \to 0$ (IR brane $\to \infty$).

- Effective theory breaks down earlier. When $\chi < (k/M)T$, thermal energy is larger than local Planck scale $\Longrightarrow$ Black brane forms.

At finite T, theory is driven to a different phase. What is it?

O(4)-Symmetric Bounce

- Relevant at $T \to 0$, so $\chi_r \ll \chi_*$.
- Depends on non-calculable part of the potential.



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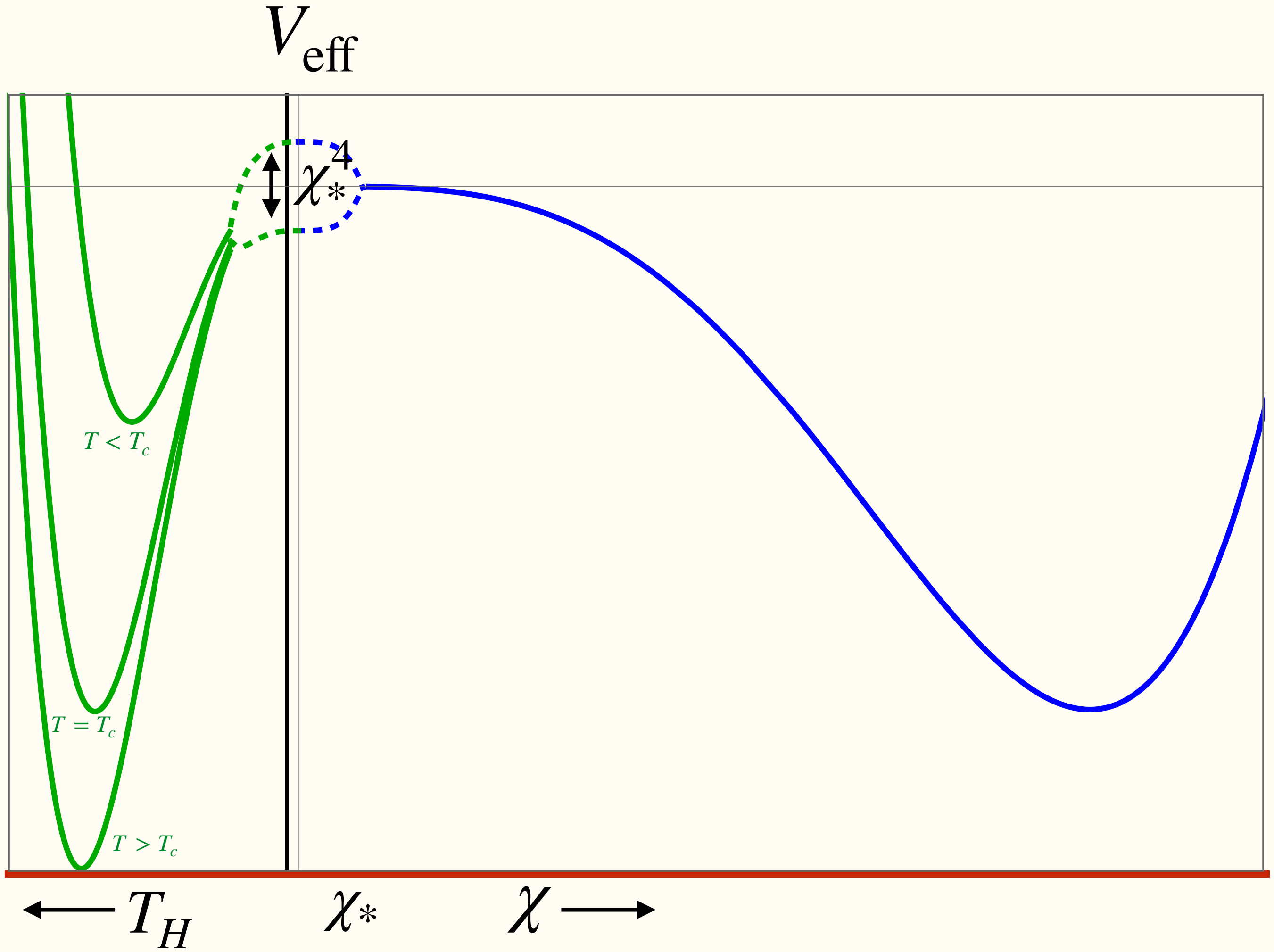

Inflationary and Scanning Sectors

Skip

$\mathcal{N}_e$

- Minimal number of e-folds required to populate the patches.
- For simplicity assume landscape is a large number of vacua separated by barriers.
- Decay rate: $$\frac{\Gamma_{\rm land}}{V} < H_0^4$$
- Inflation lasts: $\dfrac{\mathcal{N}_e}{H_{\rm inf}}$ with number of patches: $e^{\mathcal{N}_e}$
- Average number of decays:

$$\langle N_{\rm dec}\rangle = N_{\rm patch}P_{\rm dec} \simeq e^{3\mathcal{N}}\frac{\Gamma_{\rm land}}{V}\frac{\mathcal{N}}{H_{\rm inf}^4} < e^{3\mathcal{N}}\mathcal{N}\frac{H_0^4}{H_{\rm inf}^4}$$

$\mathcal{N}_e$

- By requiring a minimal number of decays to produce enough patches with different CC values:

$$N_{\rm dec} > \frac{\Lambda_{\rm max}^4}{\Lambda_{\rm obs}^4} \simeq 4 \times 10^{58} \left(\frac{\Lambda_{\rm max}}{\rm TeV}\right)^4$$

- We find,

$$\mathcal{N} \gtrsim 133 + 1.3 \log\left(\frac{\Lambda_{\rm max}\Lambda_{\rm inf}^2}{\rm TeV^3}\right)$$

Need only small number of e-folds!