Crunching Naturalness

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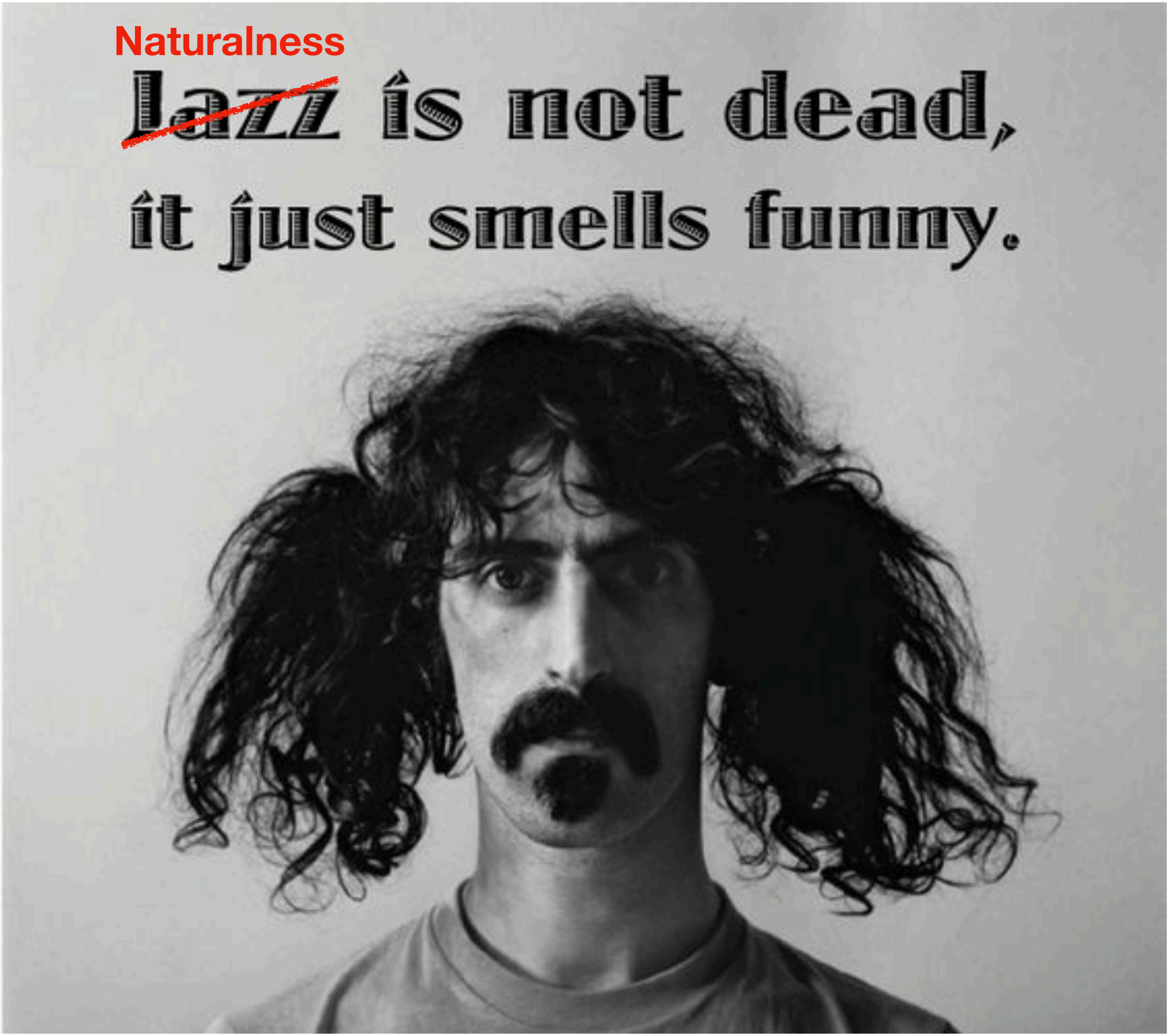

Naturalness
~~Jazz~~ is not dead,
it just smells funny.

Naturalness Problem

- Naturalness - potential problem in the UV completions of the SM.
- Direct UV completions of the SM will only be compatible with observations if unnatural connections between different parameters exist.
- The UV completions are necessary - GUT, Planck.
- This property gets worse as the departure from SM occurs at higher energy scales.

Motivation

- What dynamics or mechanisms can depend on the Higgs mass (or VEV)?
- Can we think of consistent and simple EFTs where an “unnatural” Higgs mass is selected via such a dependence?
- Can we hope to experimentally observe a dependence like that?

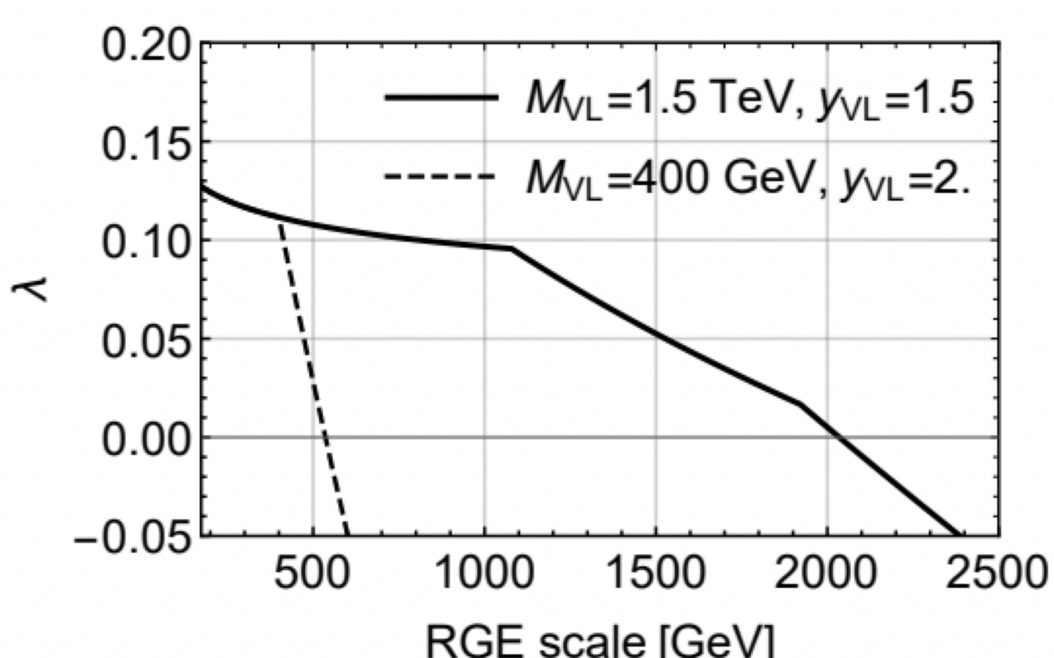
Example

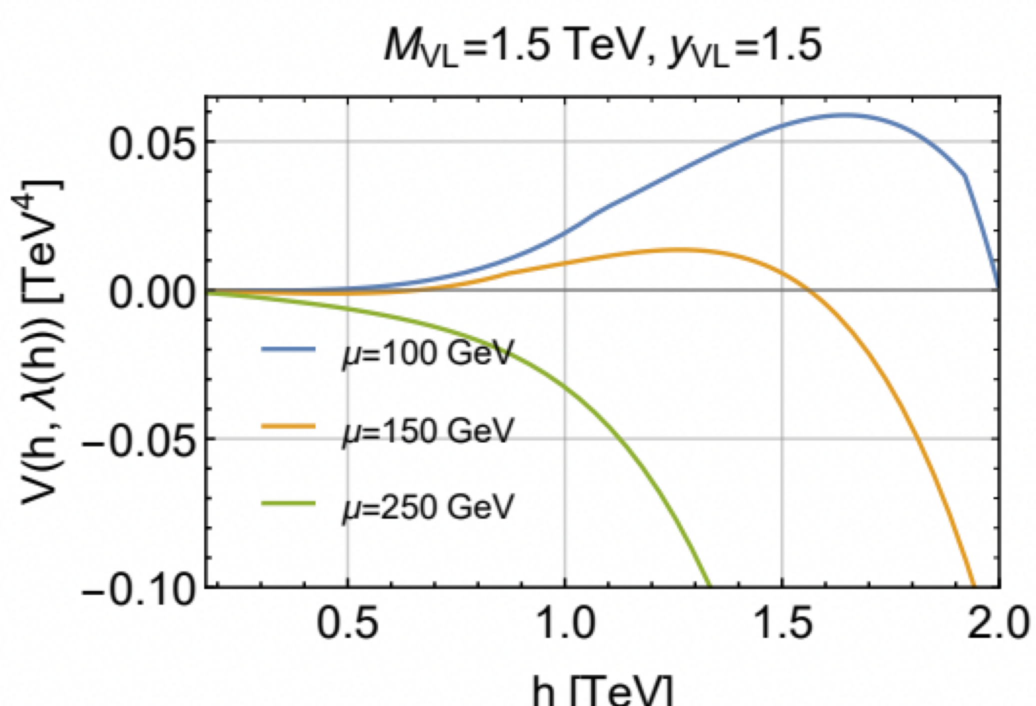
Giudice, McCullough, You , 21’

- Consider a new SU(2) doublet fermion ψ and a singlet fermion χ, with couplings to the Higgs:

$$(a)\ \ \mathcal{L} = -y_{VL}\bar{\psi}\chi H_h + \text{h.c.}\ , \qquad (b)\ \ \mathcal{L} = -y_{VL}\bar{\psi}L H_h + \text{h.c.}\ ,$$

- This affects the running of the Higgs quartic, and as a result - the Higgs mass has a drastic effect!



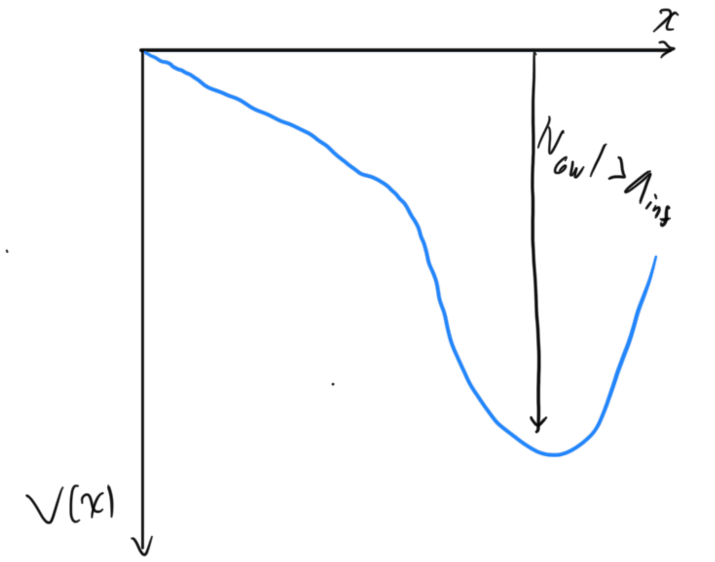


Our Idea

- The Higgs mass is multivalued in the landscape
- Higgs mass above EW destabilizes a dark sector (dark sector close to criticality)
- The universe is expanding (and not crunching) only when the Higgs mass is EW or less

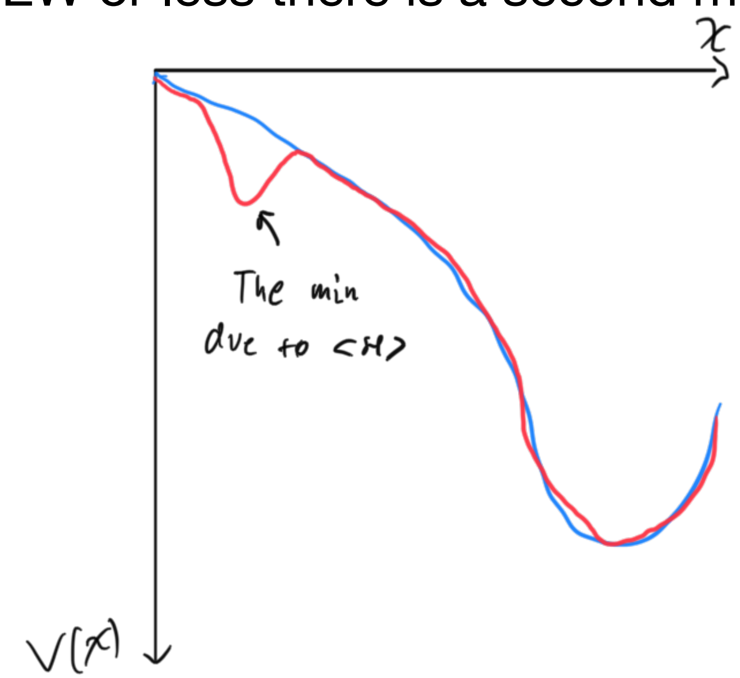
The Mechanism

- The Higgs is coupled to a CFT whose "techni-quarks" carry SU(2) charges. The dilaton has a deep and negative minimum.



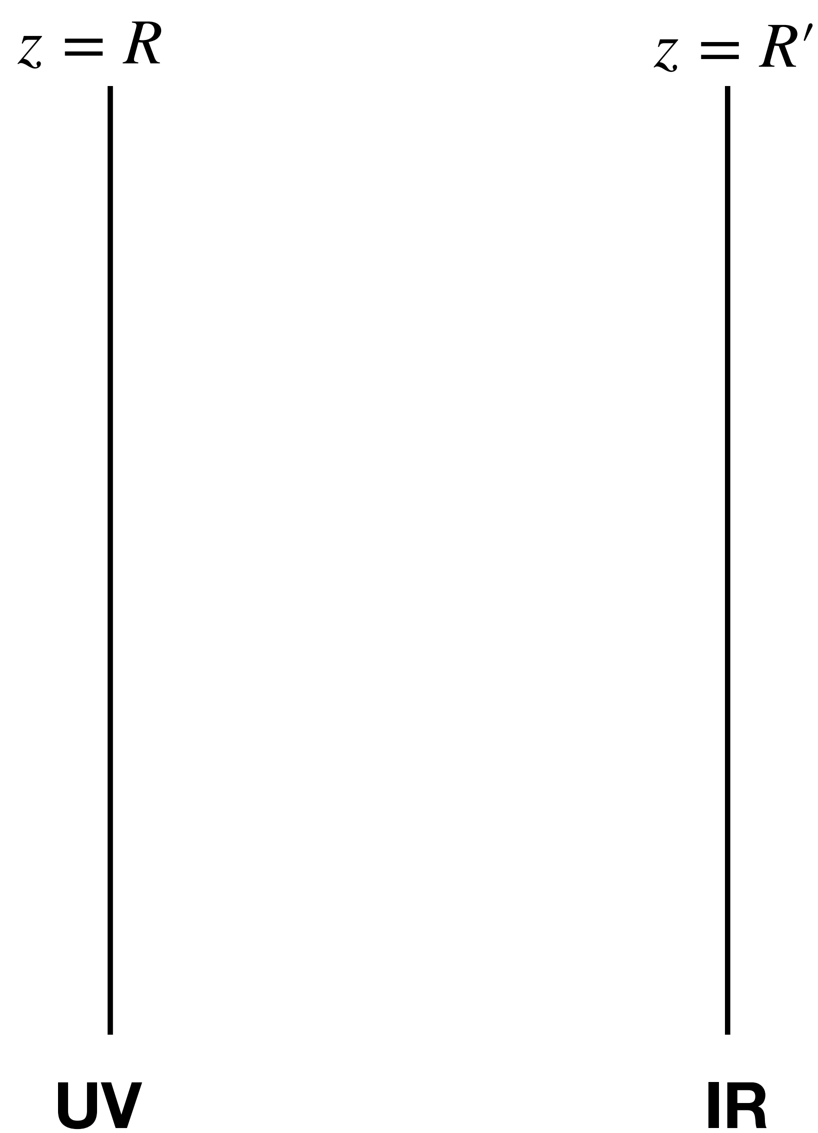
- If the Higgs VEV is zero or too large, this is the only minimum.

- If the Higgs VEV is EW or less there is a second minimum very close to the origin



Reminder: RS with GW stabilization

- GW scalar in the bulk



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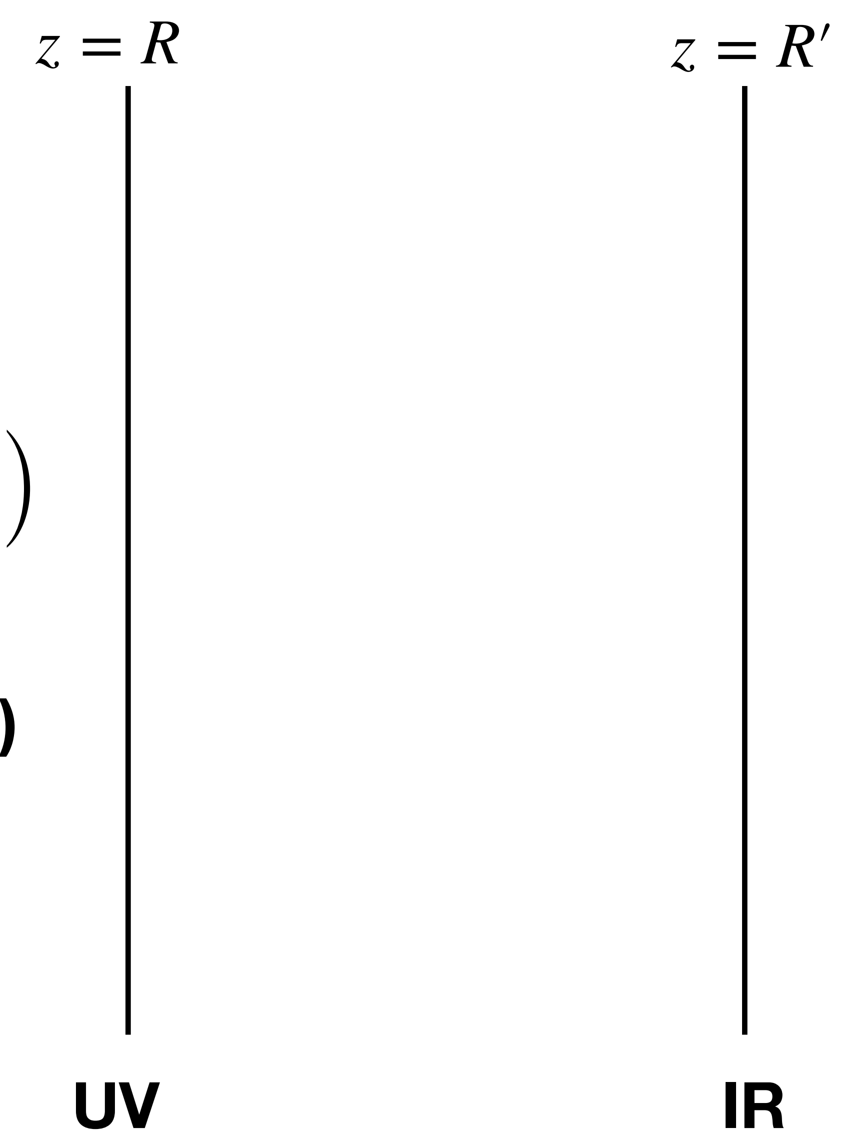

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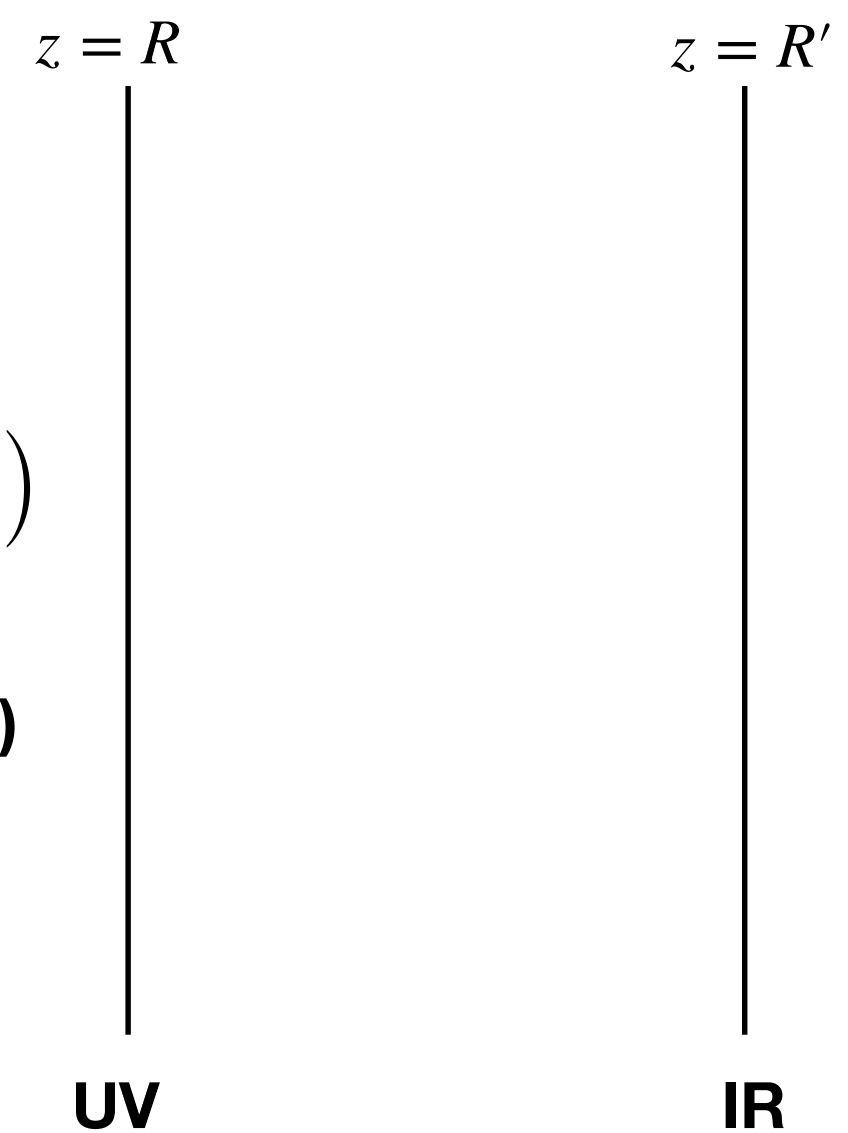

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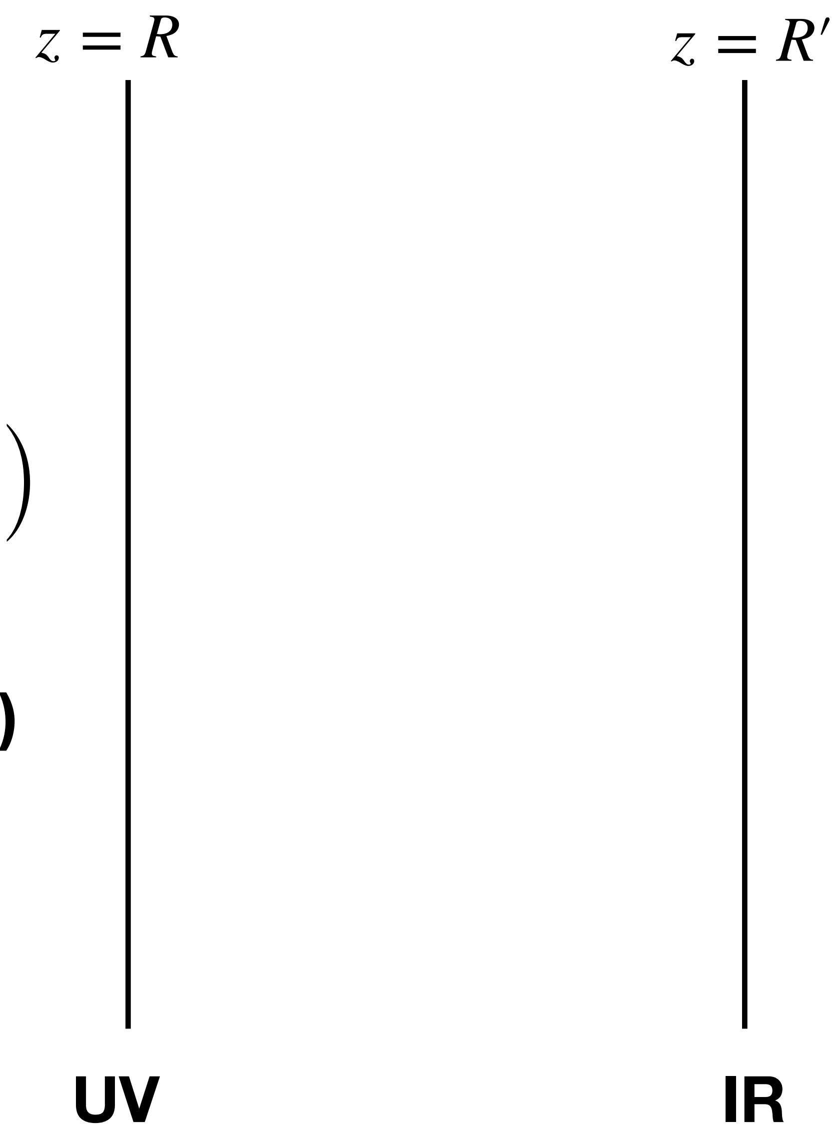

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The CFT/RS model

- In our RS model the Higgs and the EW gauge bosons are also in the bulk.

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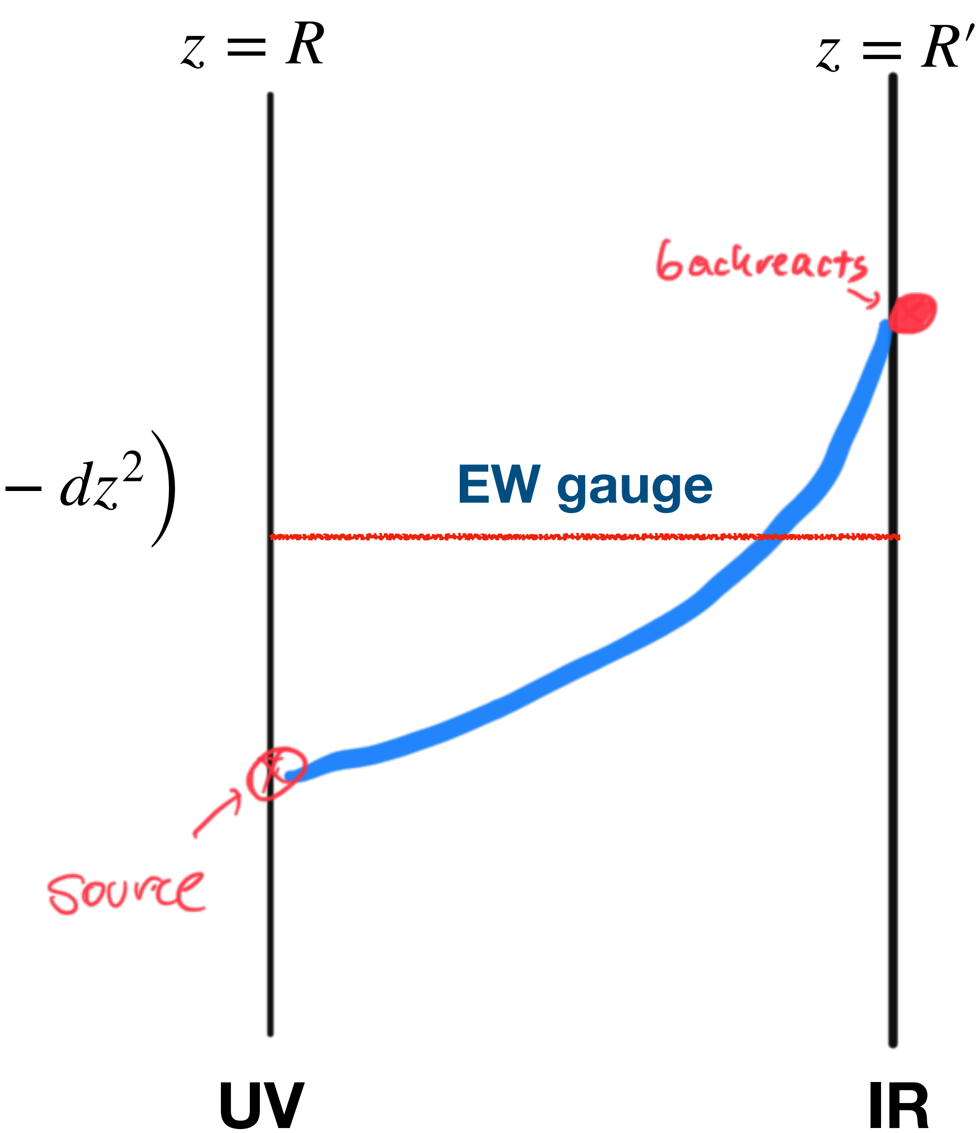

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The CFT/RS model

- The bulk mass of the Higgs is:

$$\frac{m_b^2}{k^2} \approx -3 + \alpha$$

- On the UV brane the Higgs gets a VEV. (which is scanned)

- On the IR brane: $H_{\rm UV}\chi^{\sqrt{4+m_b^2}-2} = H_{\rm UV}\chi^{\frac{\alpha}{2}-1}$

- We get terms:

$$|H|^2\chi^{2+\alpha} \qquad |H|^4\chi^{2\alpha} \qquad |H|^2\chi^{2+\alpha+\epsilon}$$

From coupling to the GW or another marginal scalar with dim 4-ϵ

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$$\begin{aligned} V_{eff} = a_0 \chi^4 + a_1 \tilde{\lambda}_H^2 H^2 \chi^{2+\alpha} + a_2 \tilde{\lambda}_H^4 H^4 \chi^{2\alpha} \\ + a_3 \tilde{\lambda}_\epsilon \chi^{4+\epsilon} + a_4 \tilde{\lambda}_\epsilon \tilde{\lambda}_H^2 H^2 \chi^{2+\alpha+\epsilon} + \ldots \end{aligned}$$

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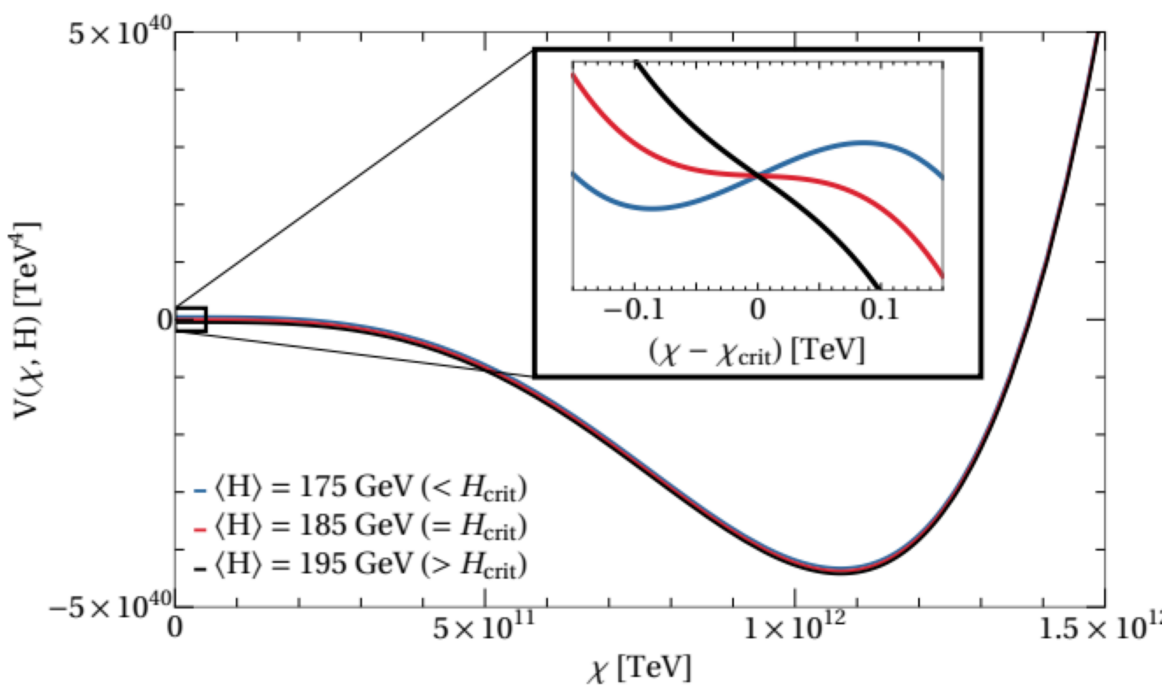

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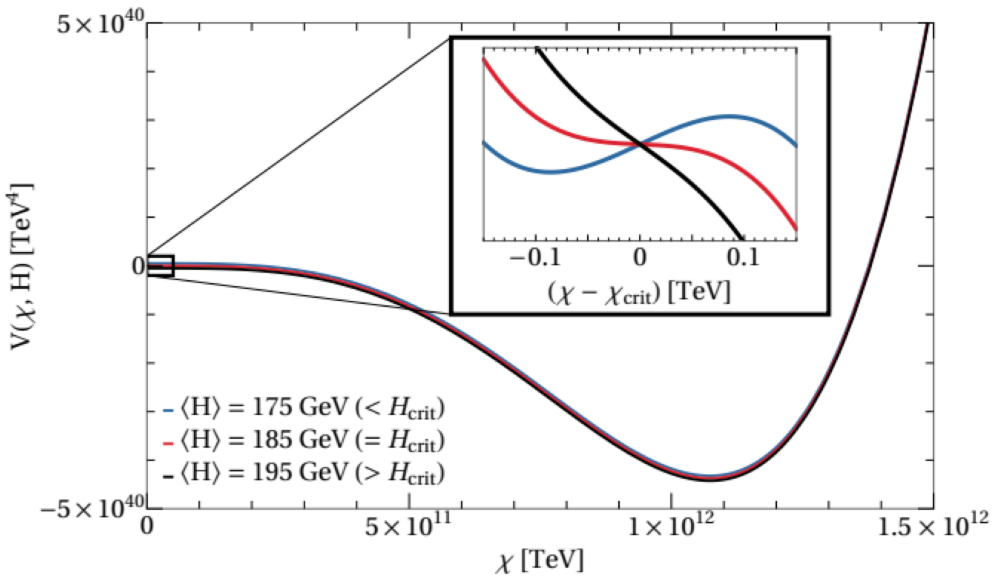

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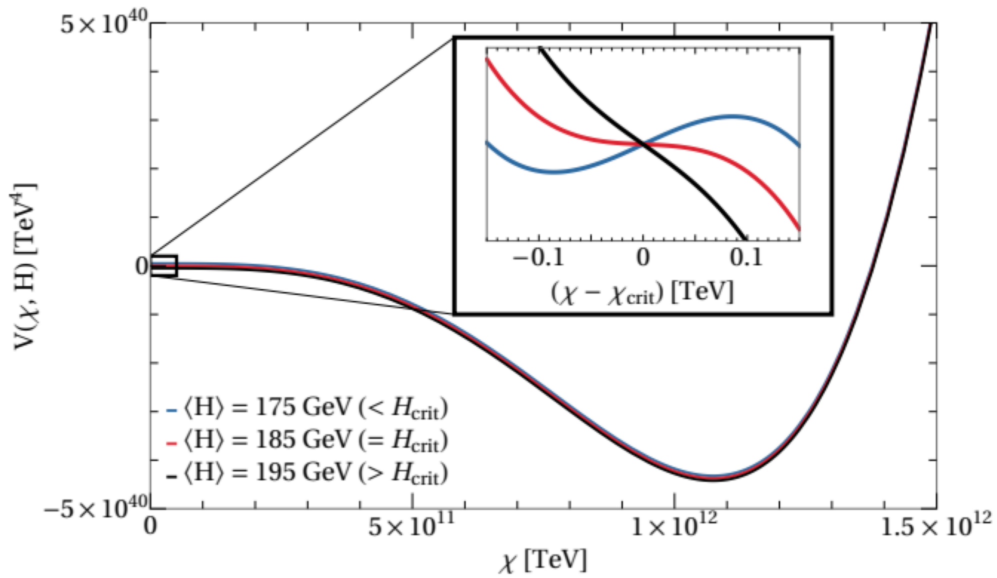

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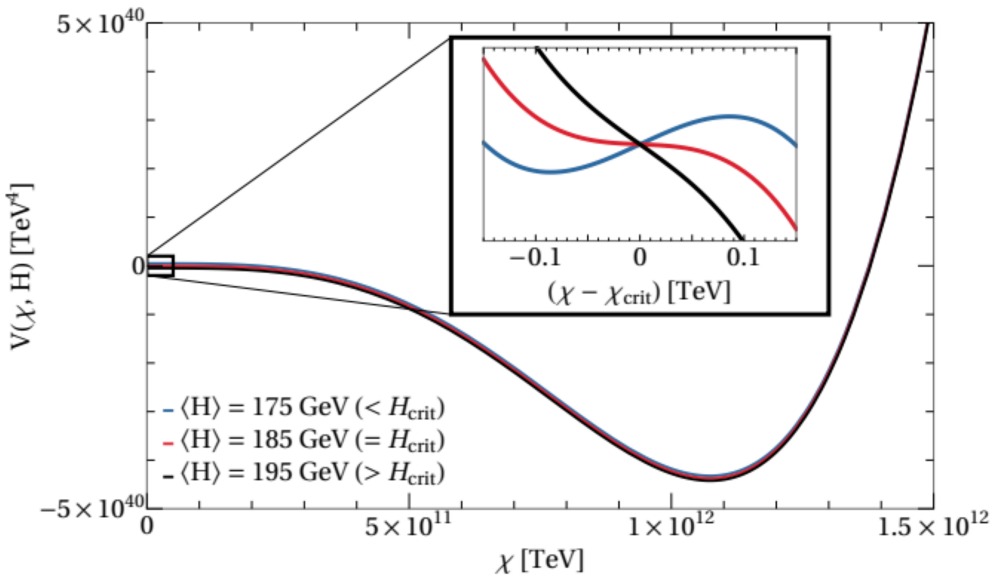

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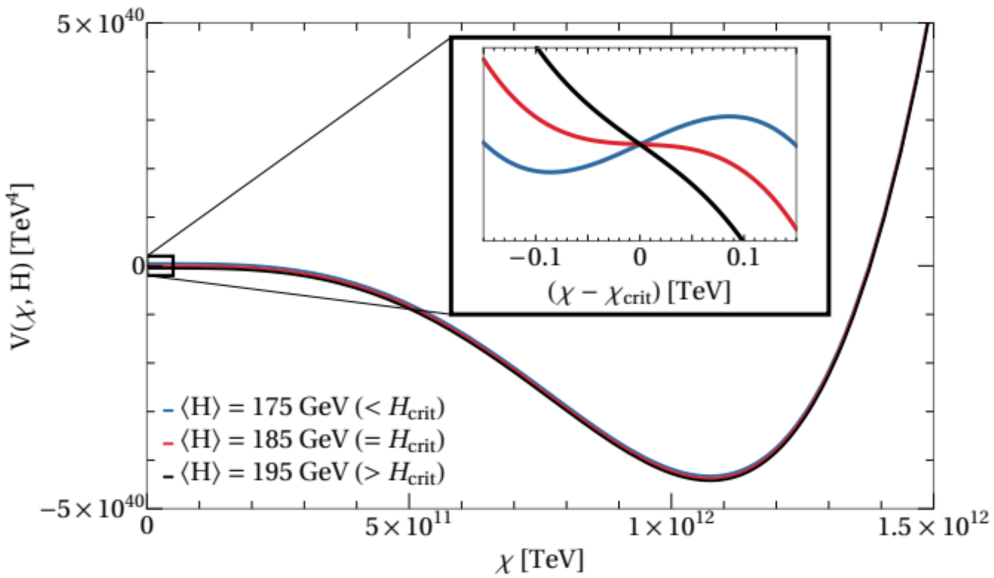

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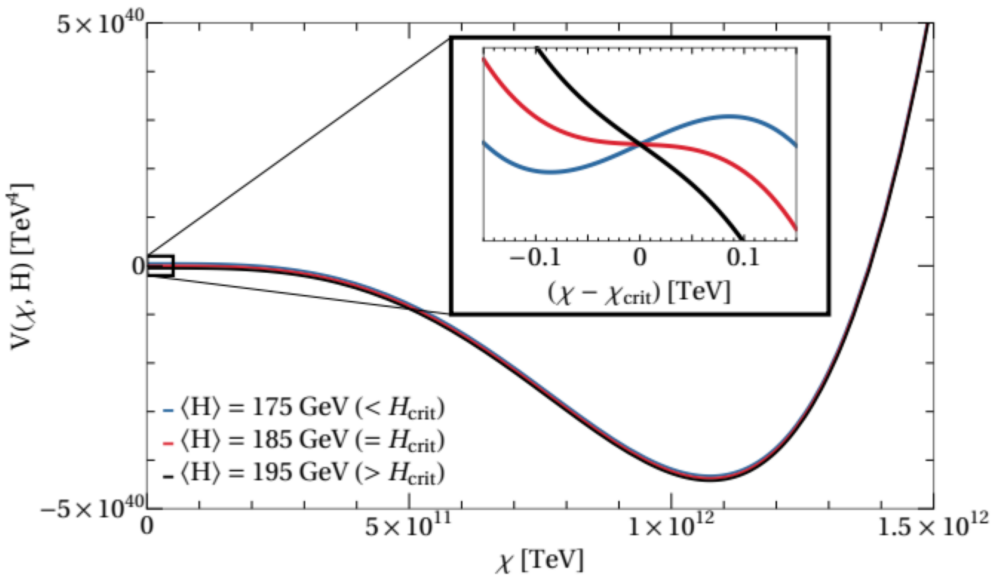

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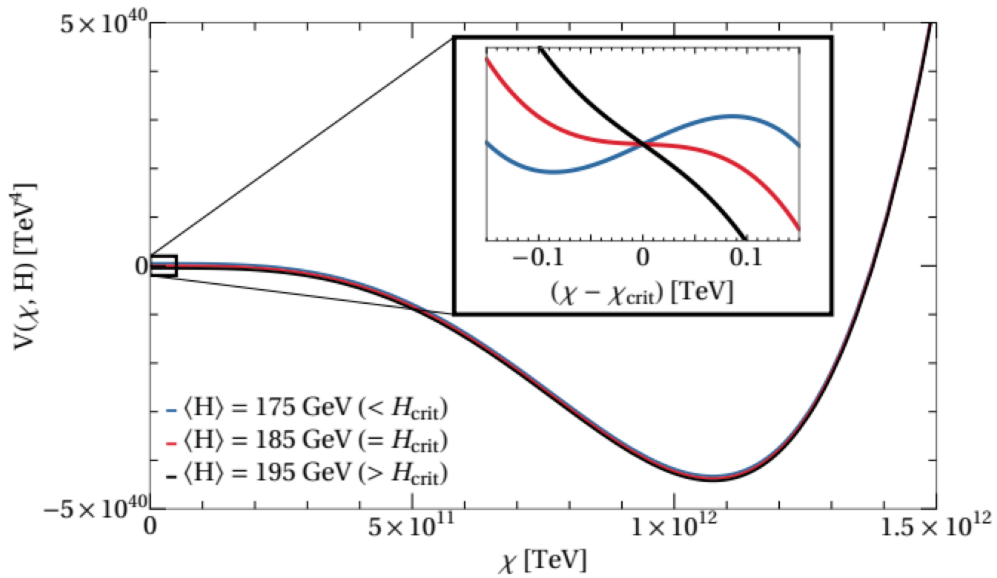

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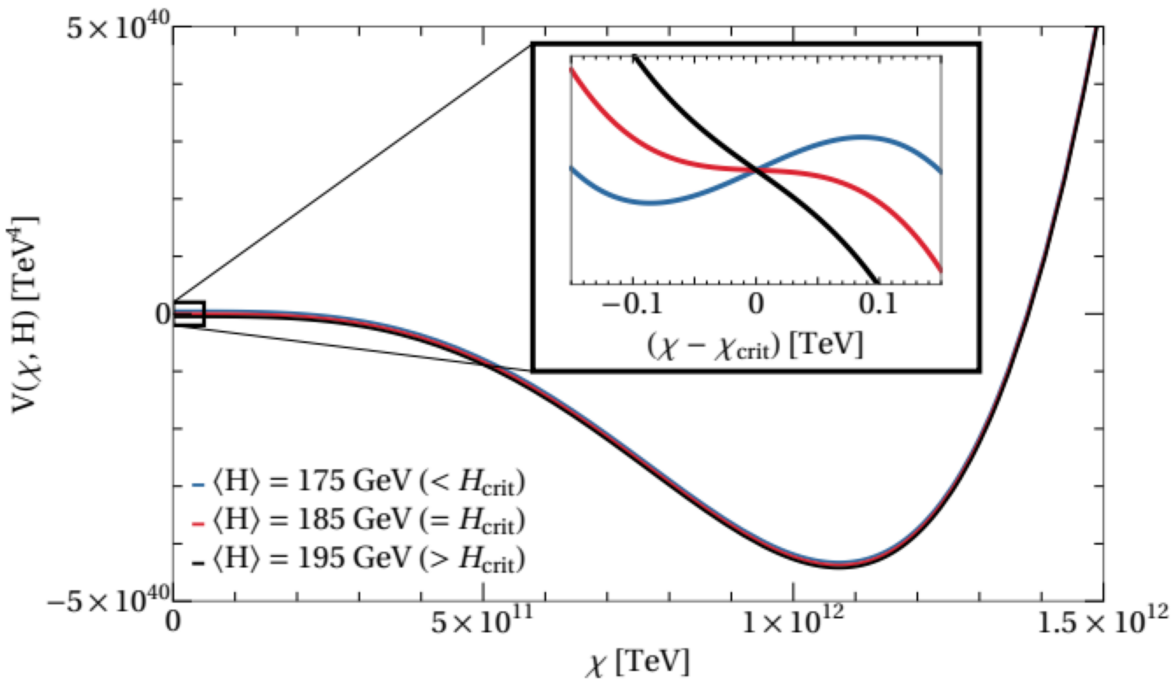
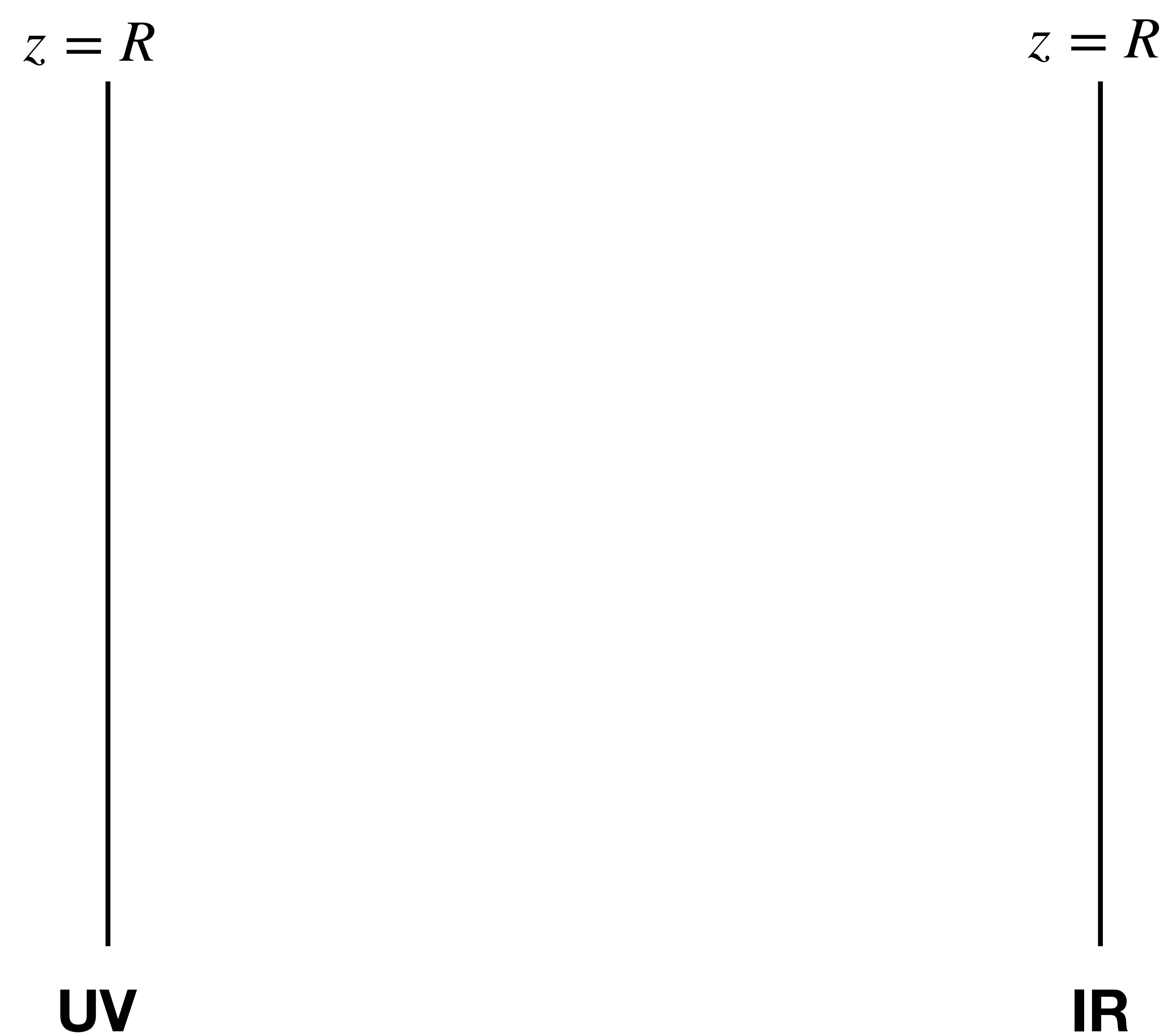
- The minimum $\chi_{\rm min} \simeq \left(\frac{h^2}{k^\alpha} \frac{2\alpha\lambda_4}{(2+\alpha)\lambda_2}\right)^{\frac{1}{2-\alpha}}$

Higgs Dependent RS dynamics

What happens when we increase the Higgs VEV?





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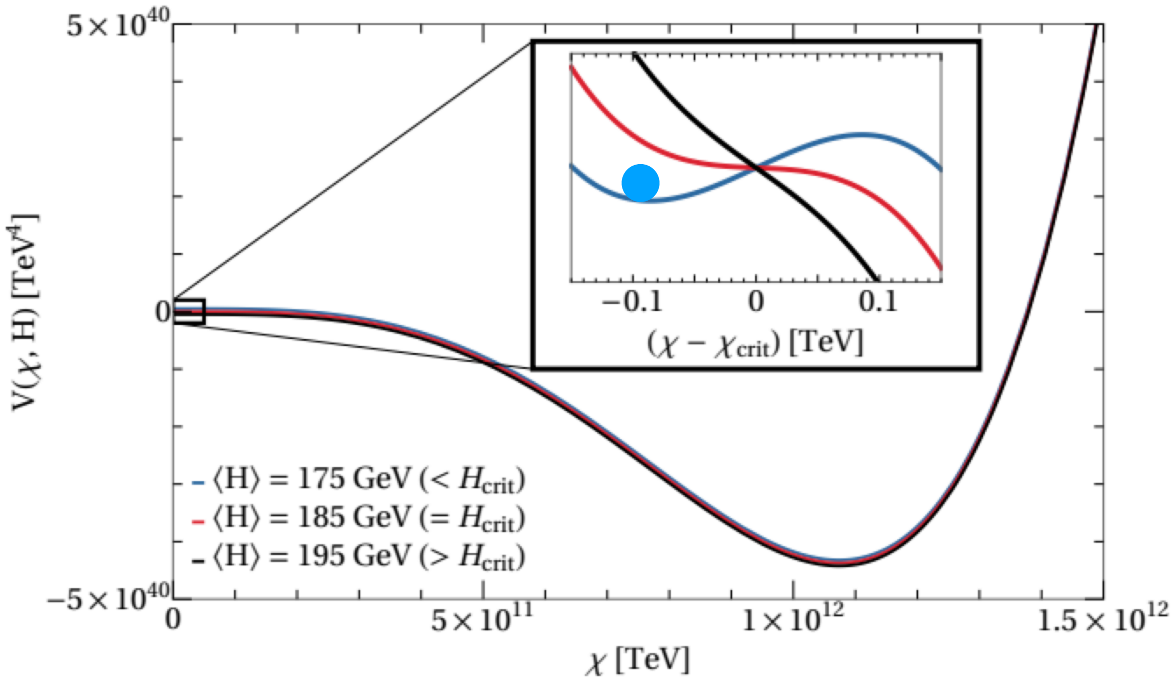

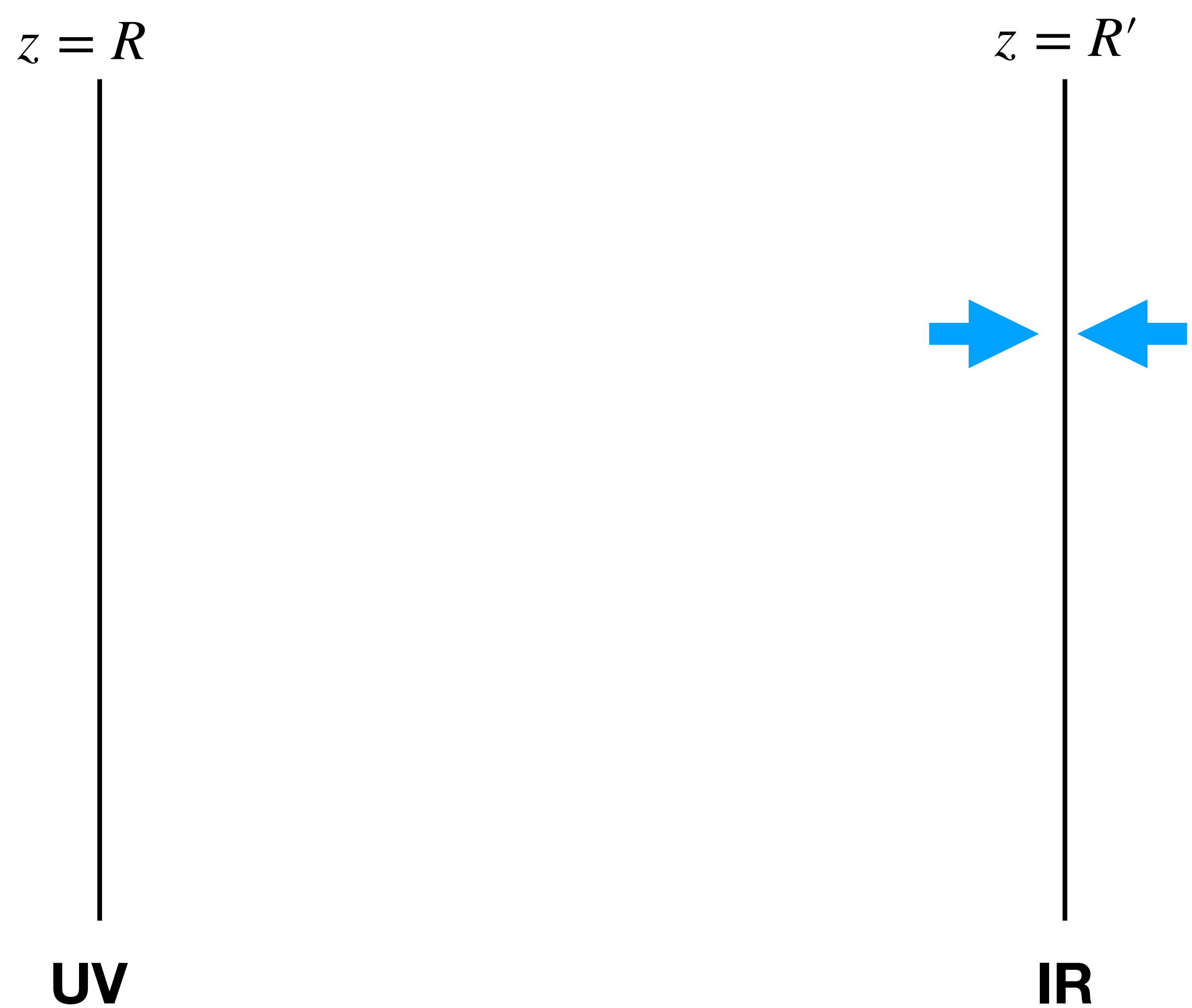

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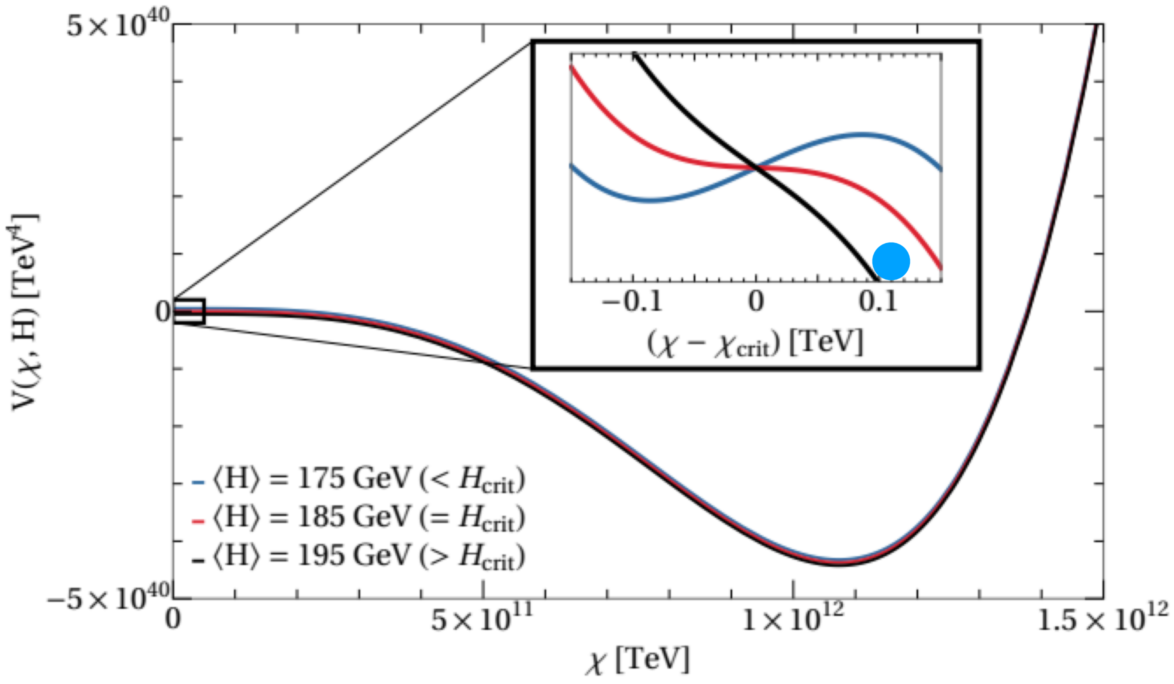

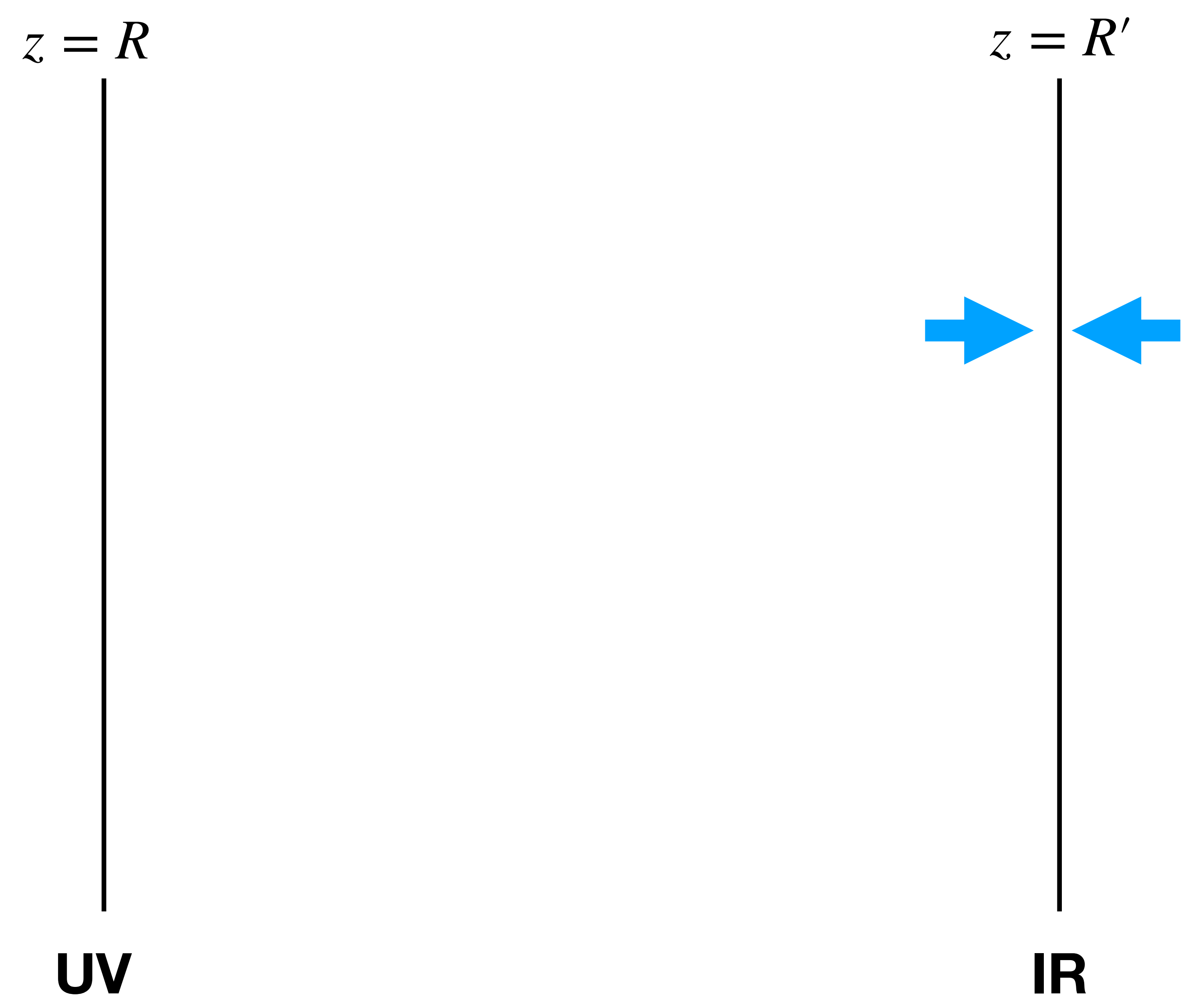

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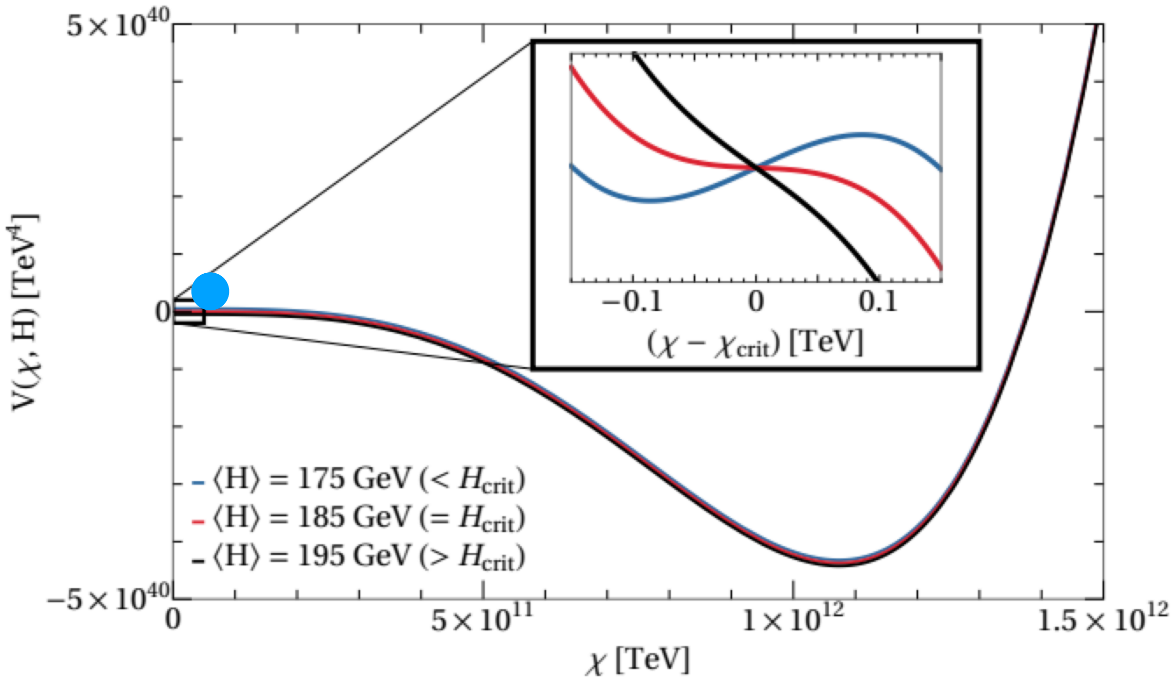

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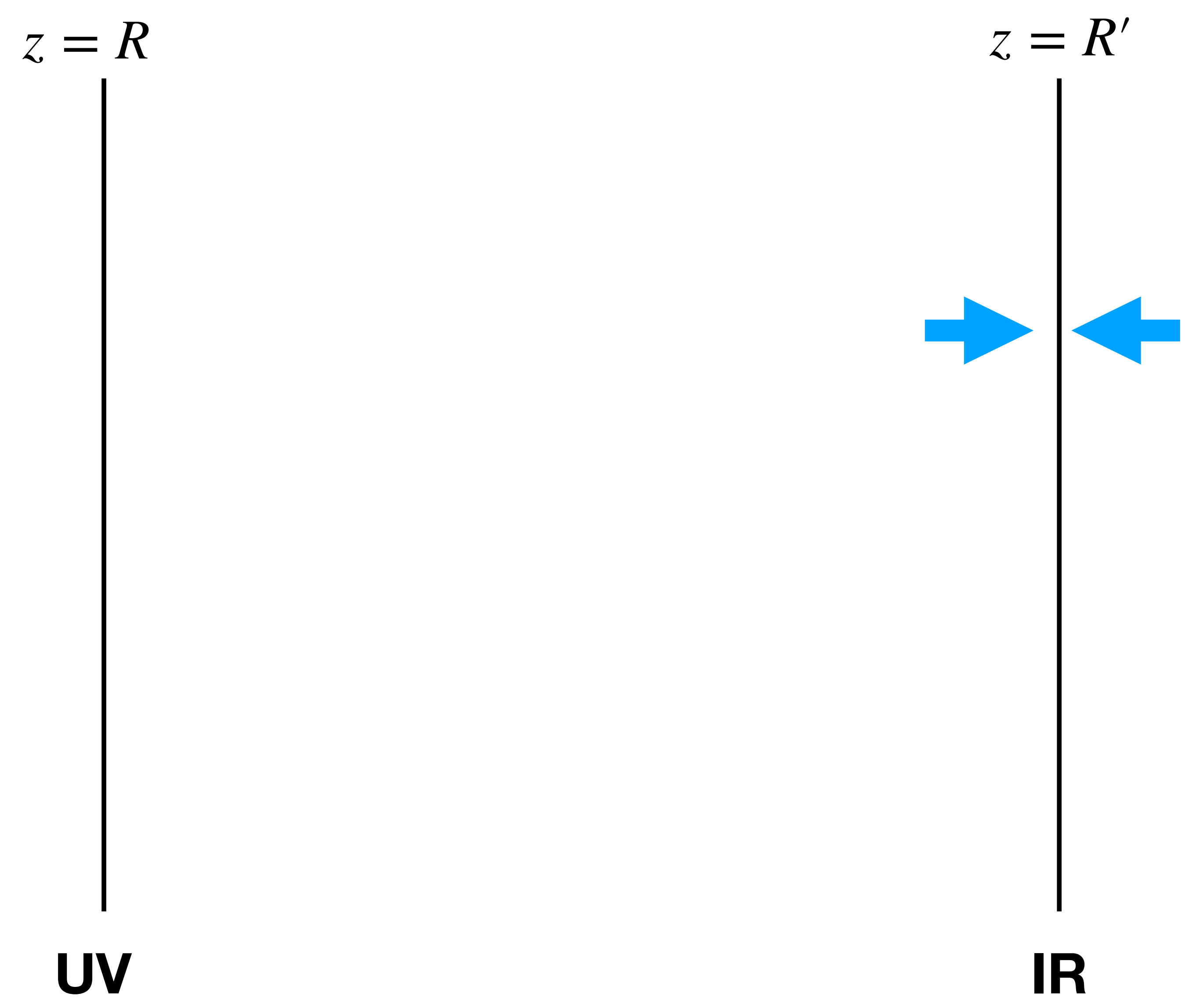

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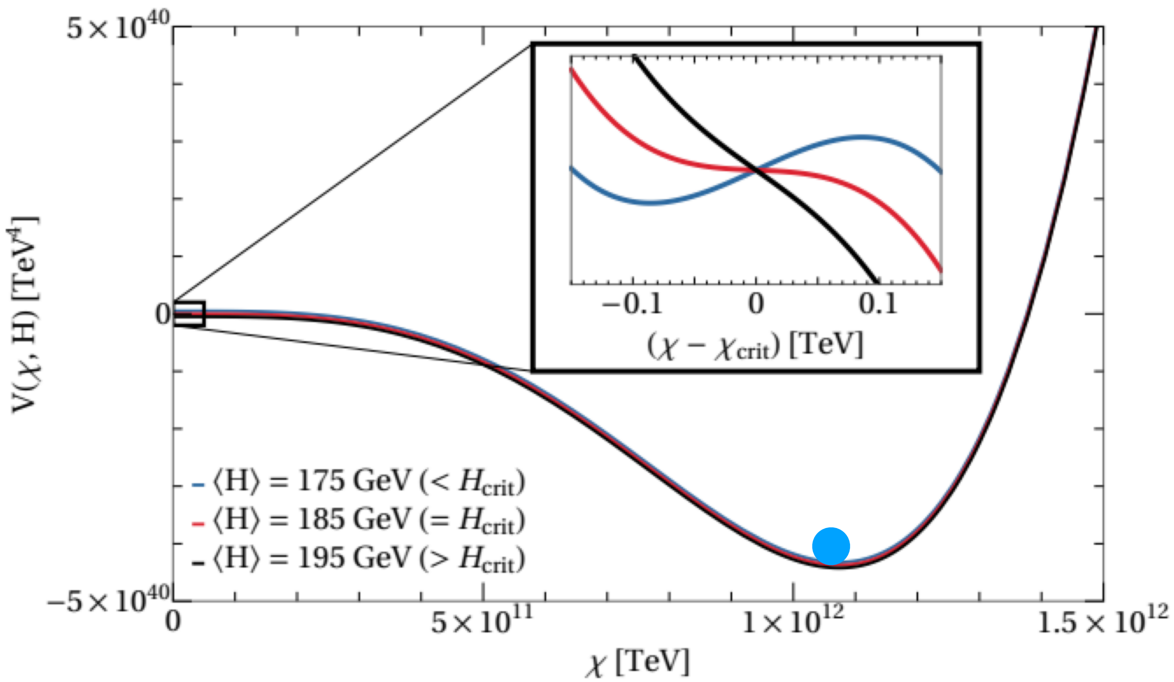

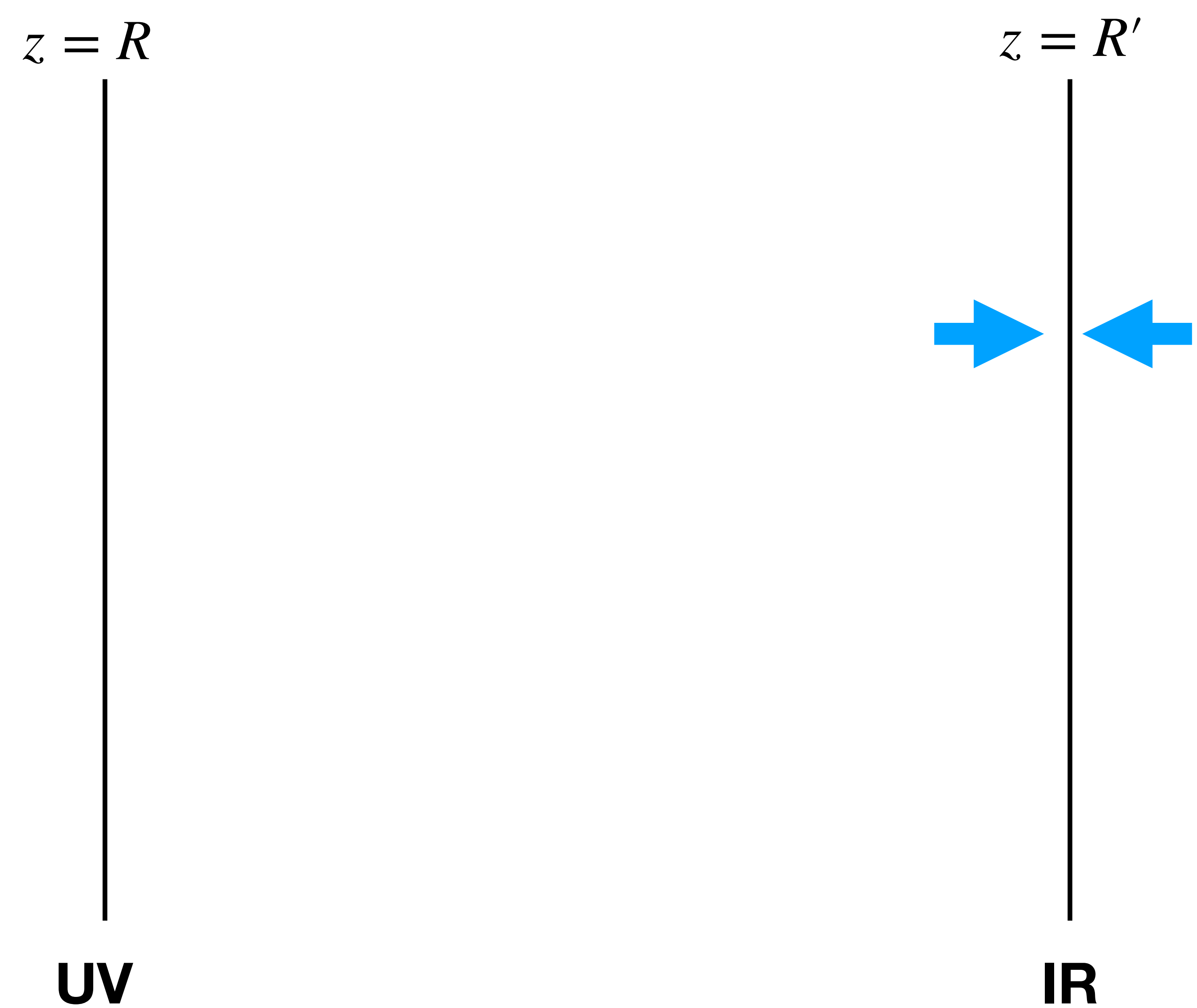

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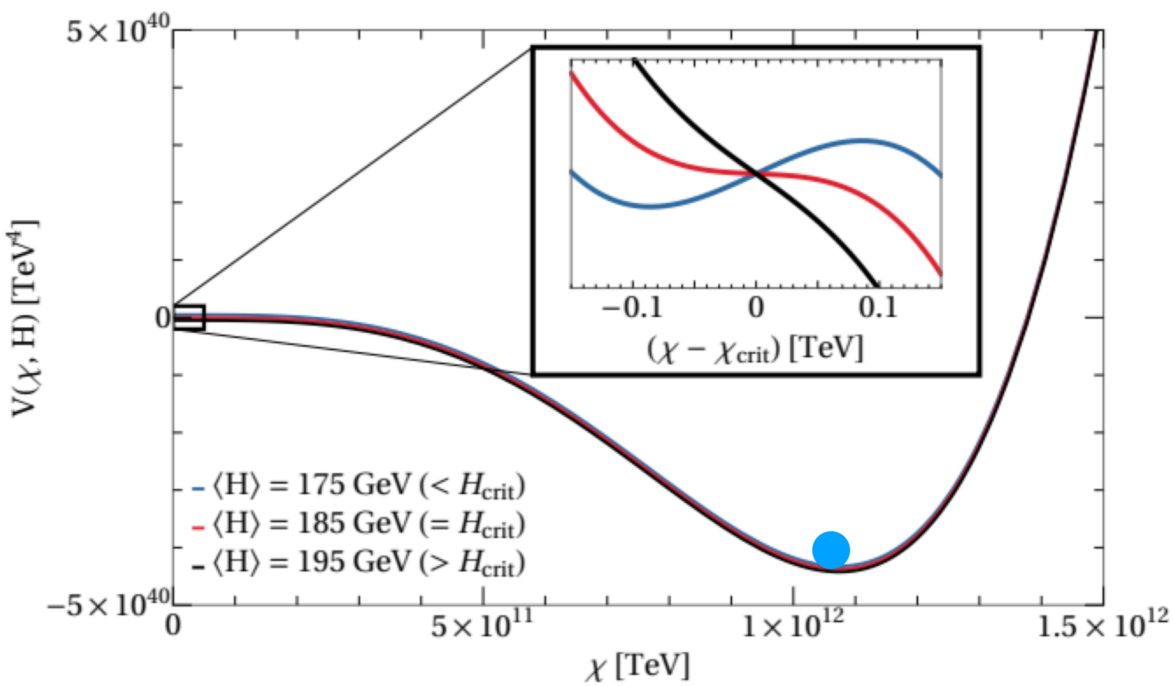

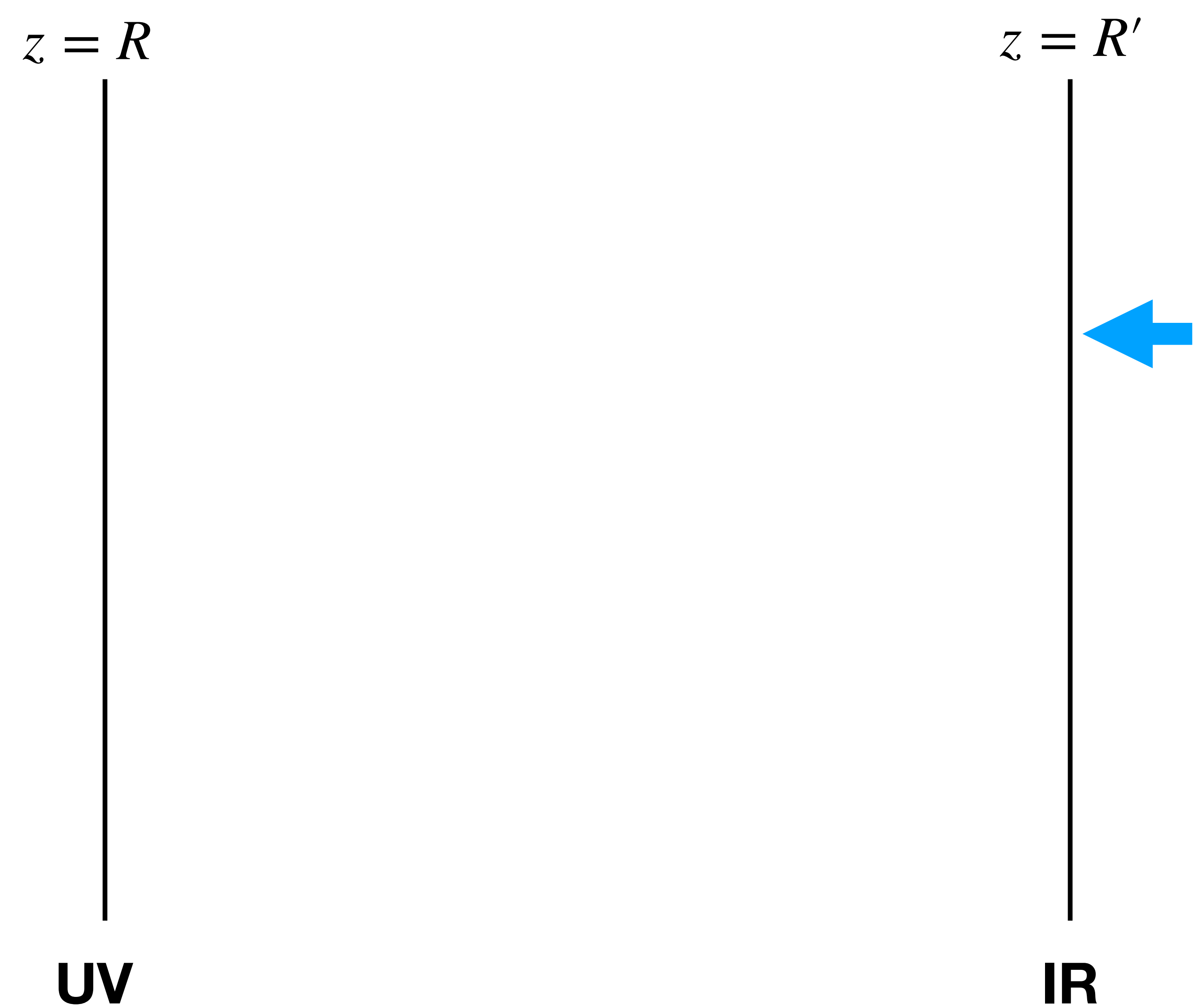

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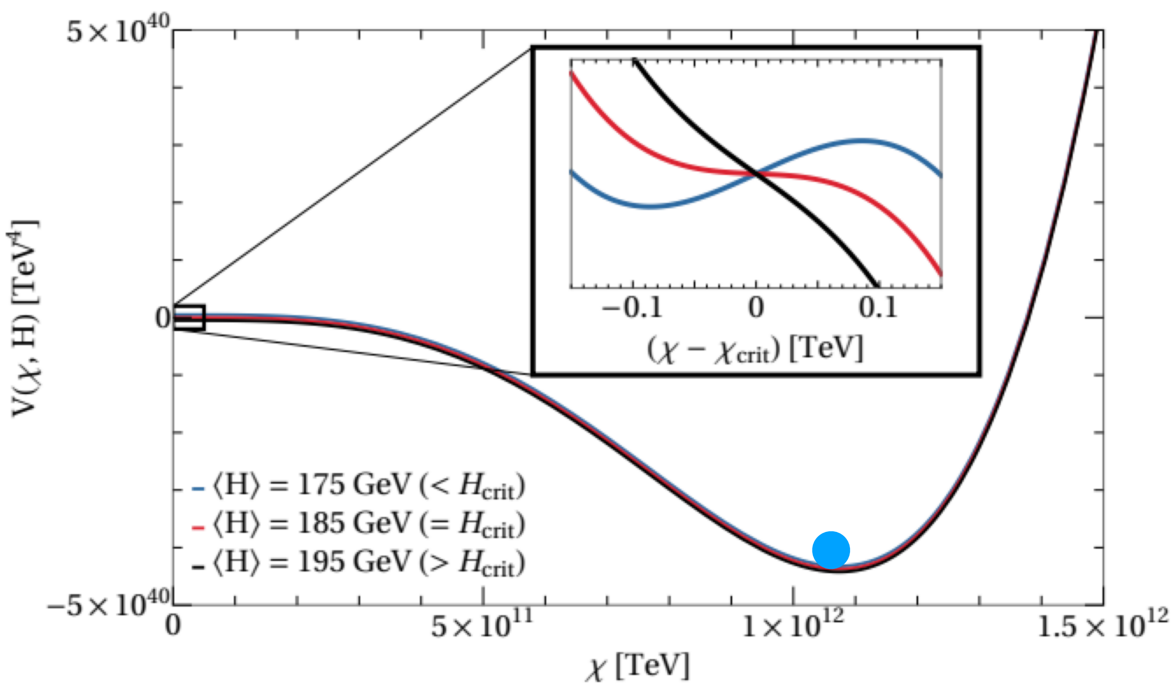

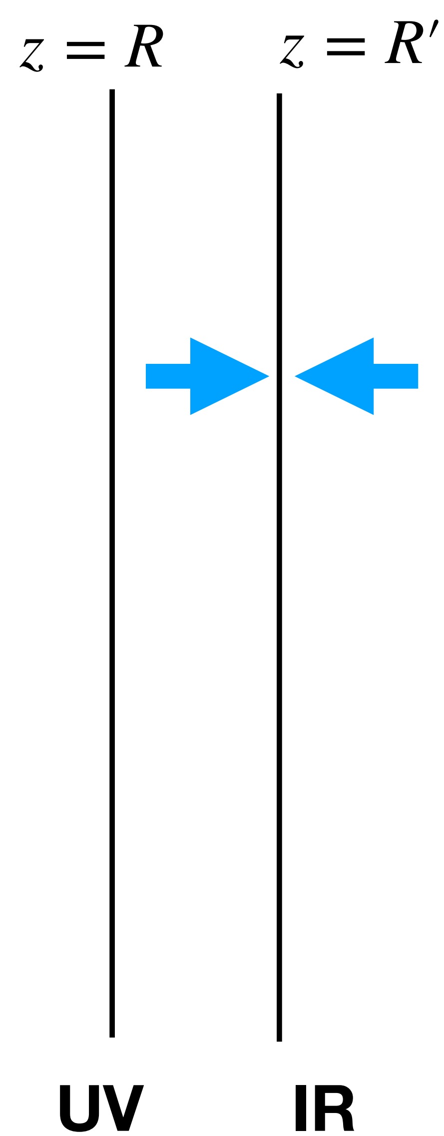

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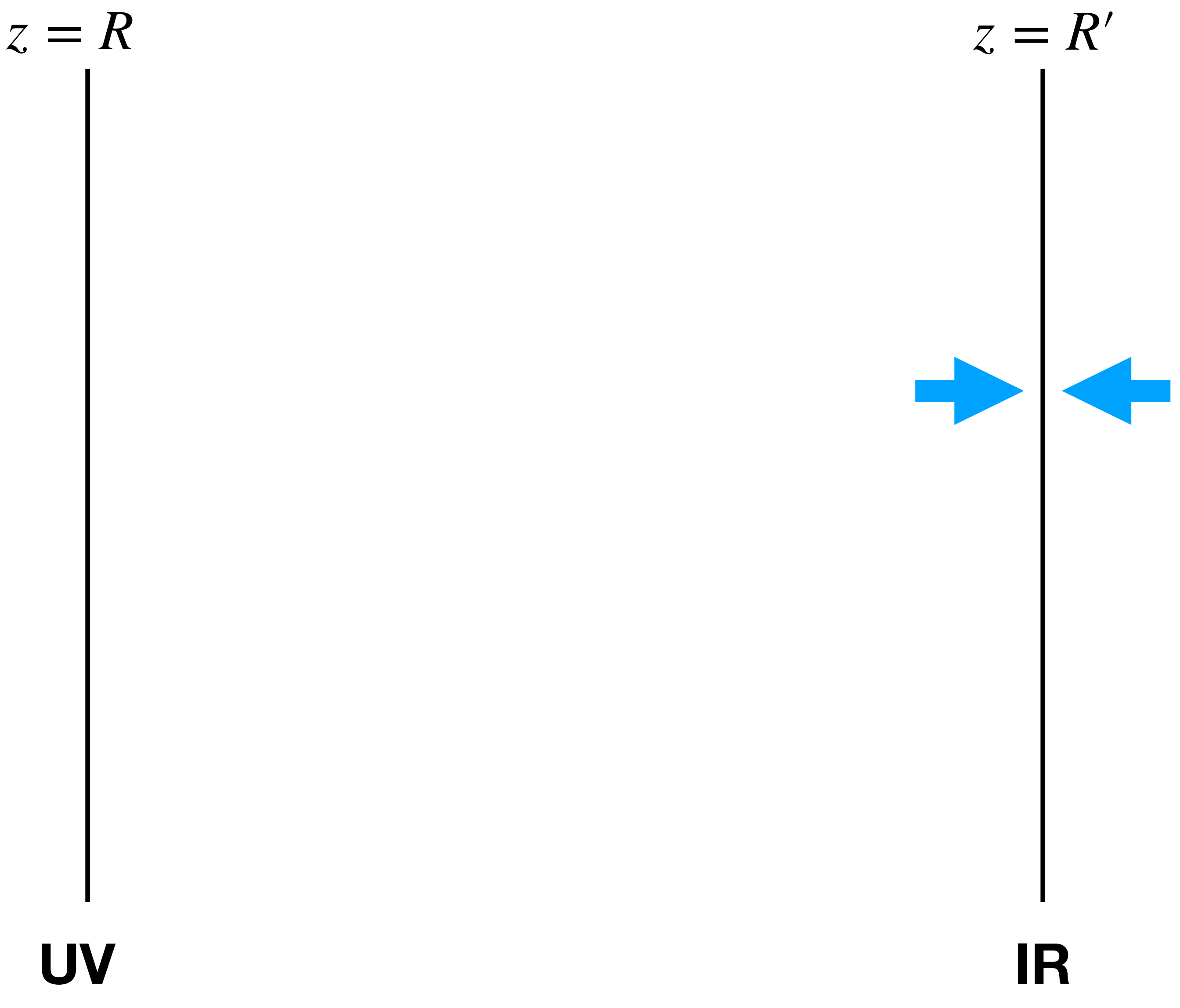

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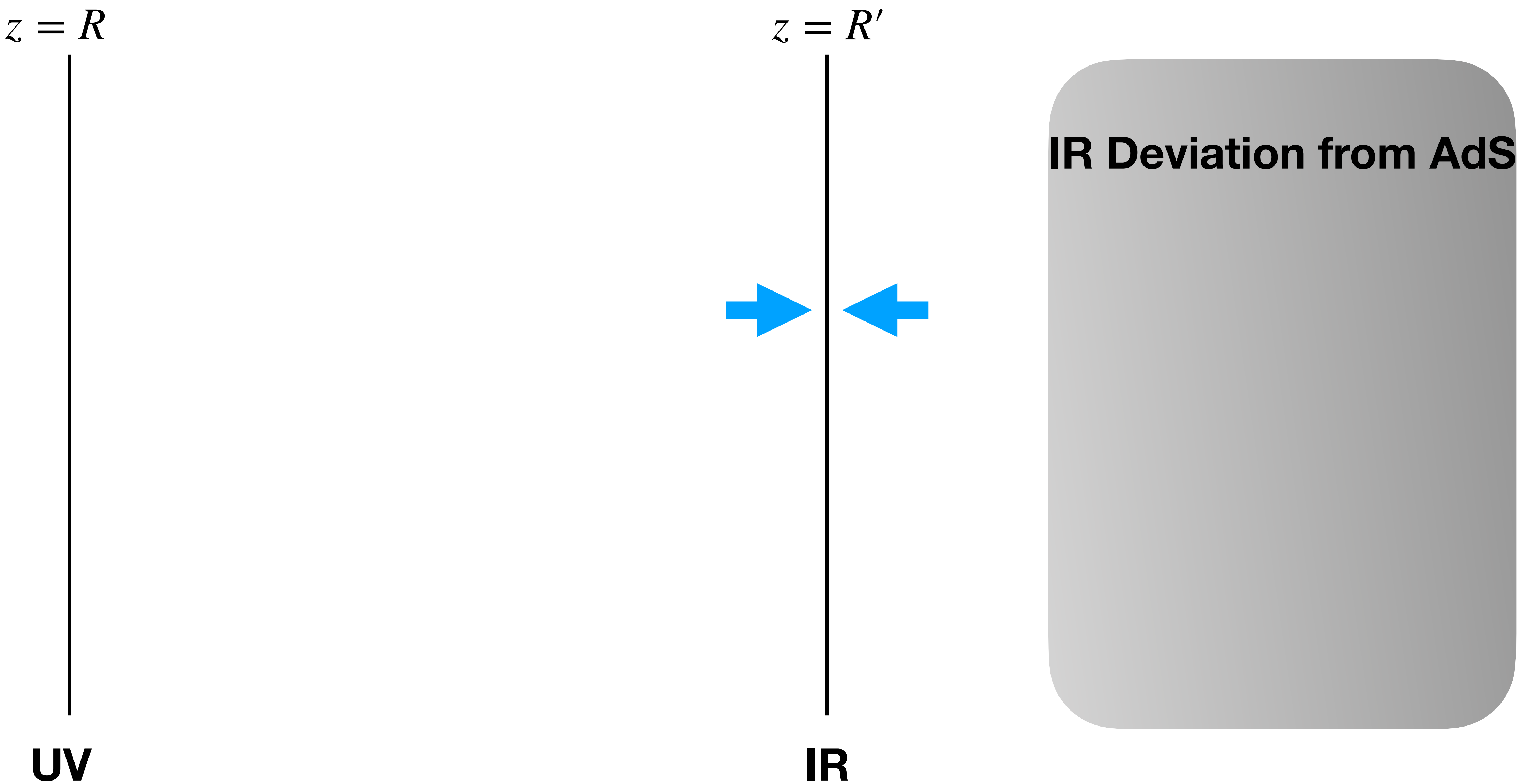
$$V_{H\chi}(\chi, H) = \lambda_2 |H|^2 \frac{\chi^{2+\alpha}}{k^{\alpha}} - \lambda_{H\epsilon} |H|^2 \frac{\chi^{2+\alpha+\epsilon}}{k^{\alpha+\epsilon}} - \lambda_4 |H|^4 \frac{\chi^{2\alpha}}{k^{2\alpha}}$$



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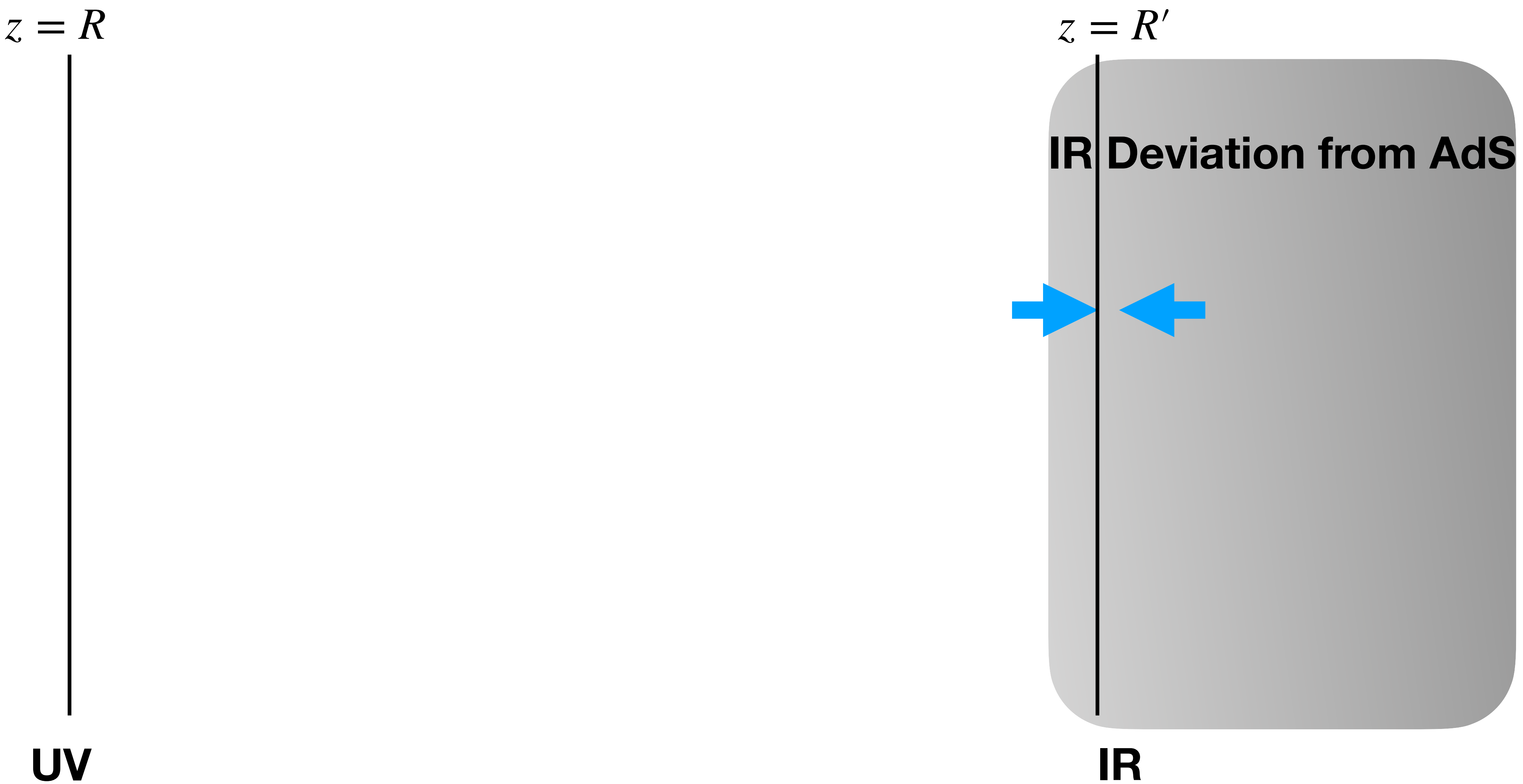

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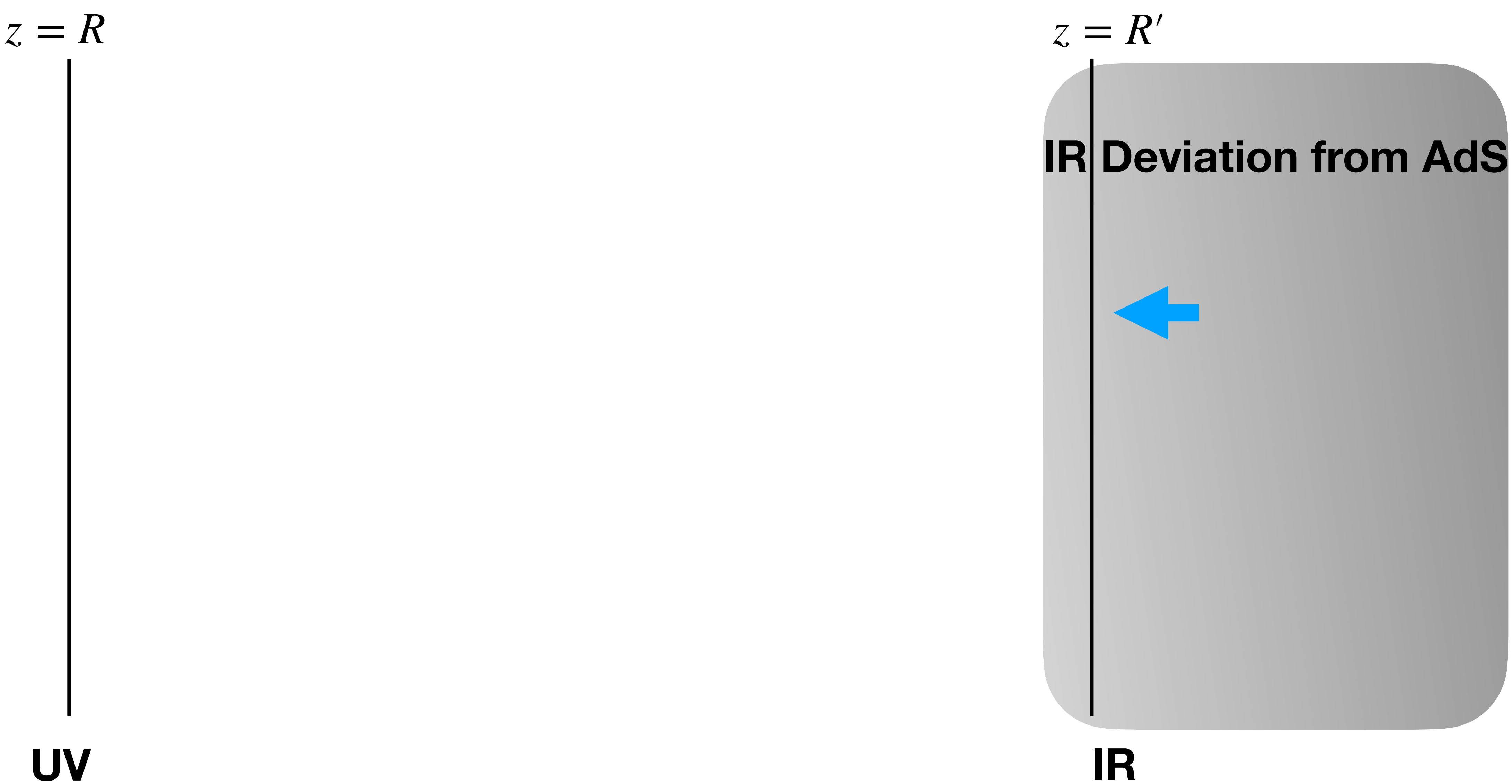

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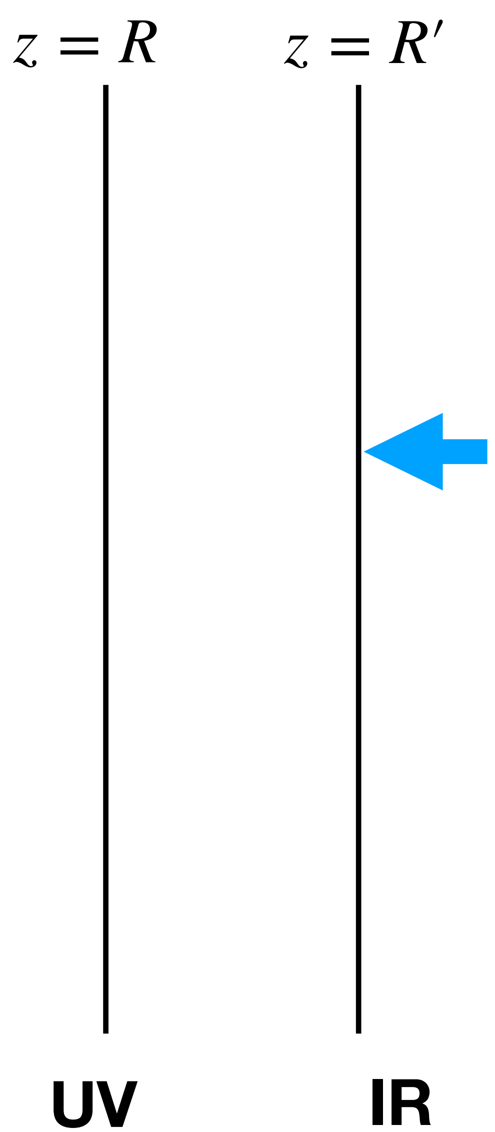


IR Deviation from AdS

IR Deviation from AdS

- Requires a relevant operator that is negligible in the UV.
- Simple Example - confining SU(N) in the bulk, could be QCD

Von Harling, Servant 18'
Baratella, Pomarol, Rompineve 19'

- The Confinement scale has a non-trivial dependence on the IR scale.

$$\frac{1}{g^2(Q,\chi)} = \frac{\log\frac{k}{\chi}}{kg_5^2} - \frac{b_{\mathrm{UV}}}{8\pi^2}\log\frac{k}{Q} - \frac{b_{\mathrm{IR}}}{8\pi^2}\log\frac{\chi}{Q} + \tau$$

$$\tilde{\Lambda}(\chi) = \left(k^{b_{\mathrm{UV}}}\chi^{b_{\mathrm{IR}}}e^{-8\pi^2\tau}\left(\frac{\chi}{k}\right)^{-b_{\mathrm{CFT}}}\right)^{\frac{1}{b_{\mathrm{UV}}+b_{\mathrm{IR}}}} = \Lambda_0\left(\frac{\chi}{\chi_{\mathrm{min}}}\right)^n$$

- Effectively $\lambda(\chi)\chi^4$ where $\lambda(\chi)$ blows up when $\chi \to \chi_*$
- Require $\chi_* \ll \chi_{crit}$

Generating the hierarchy

- The critical Higgs value:

$$h_{crit} = \sim k \left(\frac{\lambda_2}{\lambda_{H\epsilon}} \right)^{1/\epsilon}$$

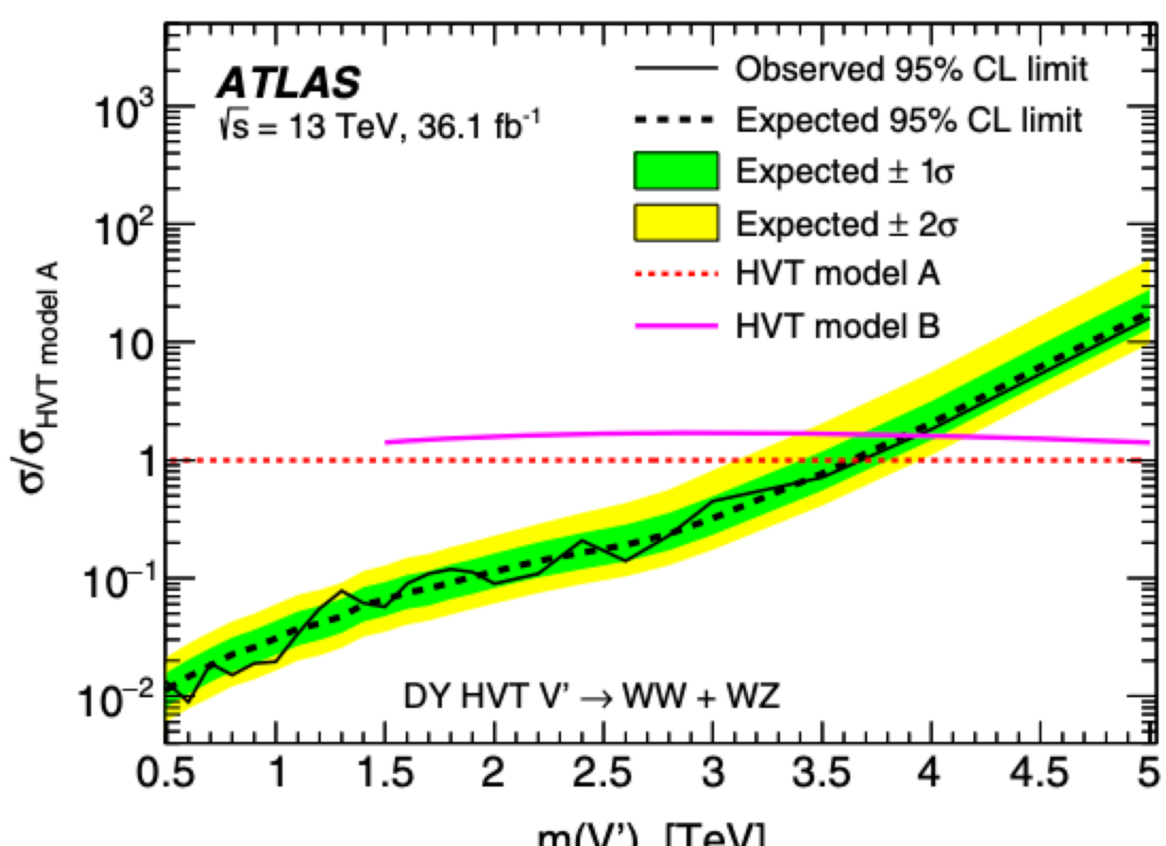
- We want to generate a large hierarchy. We can take small ϵ and $\lambda_2 \lesssim \lambda_{H\epsilon}$.

- Generating the hierarchy with a marginal dimension - reminiscent of Goldberger-Wise.

The Little Hierarchy

- Since SU(2) is in the bulk we have bounds from ATLAS and CMS at the 3-4 TeV range.

- Their production is due to the mixing of composite-elementary, and so is similar in our case to standard bulk-RS.



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$$\lambda_2, \lambda_{H\epsilon} < 10^{-2}\alpha\lambda_4$$

and also

$$\lambda, \lambda_{\rm GW} \lesssim 10^{-5}$$

The Little Hierarchy

- Contrary to other landscape ideas, the model is too predictive!
- The status is similar to other solutions to the hierarchy problems.
- This is just the first idea:
  - Currently working on variations that are safe
  - For now - accept the tuning and move on.

The light dilaton

- The little hierarchy results in a light dilaton (stabilized by the smaller Higgs VEV)

$$m_\chi \simeq m_h \sqrt{\frac{h}{\chi_{\rm min}} \frac{\pi \sin\theta}{\sqrt{6} N} - \frac{8\pi^2(\lambda - \lambda_{\rm GW})}{N^2} \frac{\chi^2_{\rm min}}{m_h^2}}$$

$$\sin\theta \sim \frac{(\lambda_2 - \lambda_{H\epsilon})}{N} \frac{h \chi_{\rm min}}{m_h^2}$$

$$\lambda_2, \lambda_{H\epsilon} < 10^{-2} \alpha \lambda_4$$

$$\lambda, \lambda_{\rm GW} \lesssim 10^{-5}$$

- Smoking gun prediction - light dilaton mixing with the Higgs.

The couplings of the dilaton

- The coupling to the Higgs is through the mixing.

- Doesn't couple directly to fermions which live on the UV.

- Coupling to gauge bosons in the bulk

$$\frac{\chi}{2\chi_{\min}\log\frac{R'}{R}}\left(F_{\mu\nu}^2+Z_{\mu\nu}^2+2W_{\mu\nu}^2\right) \xrightarrow[\text{for Z,W - subdominant}]{} \frac{1}{4\Lambda_{\gamma\gamma}}\tilde{\chi}F_{\mu\nu}^2$$

Parameter Scan

- Run a scan with the requirements:

1. The metastable minimum must exist and be located at $\chi_{min} > 1$ TeV.

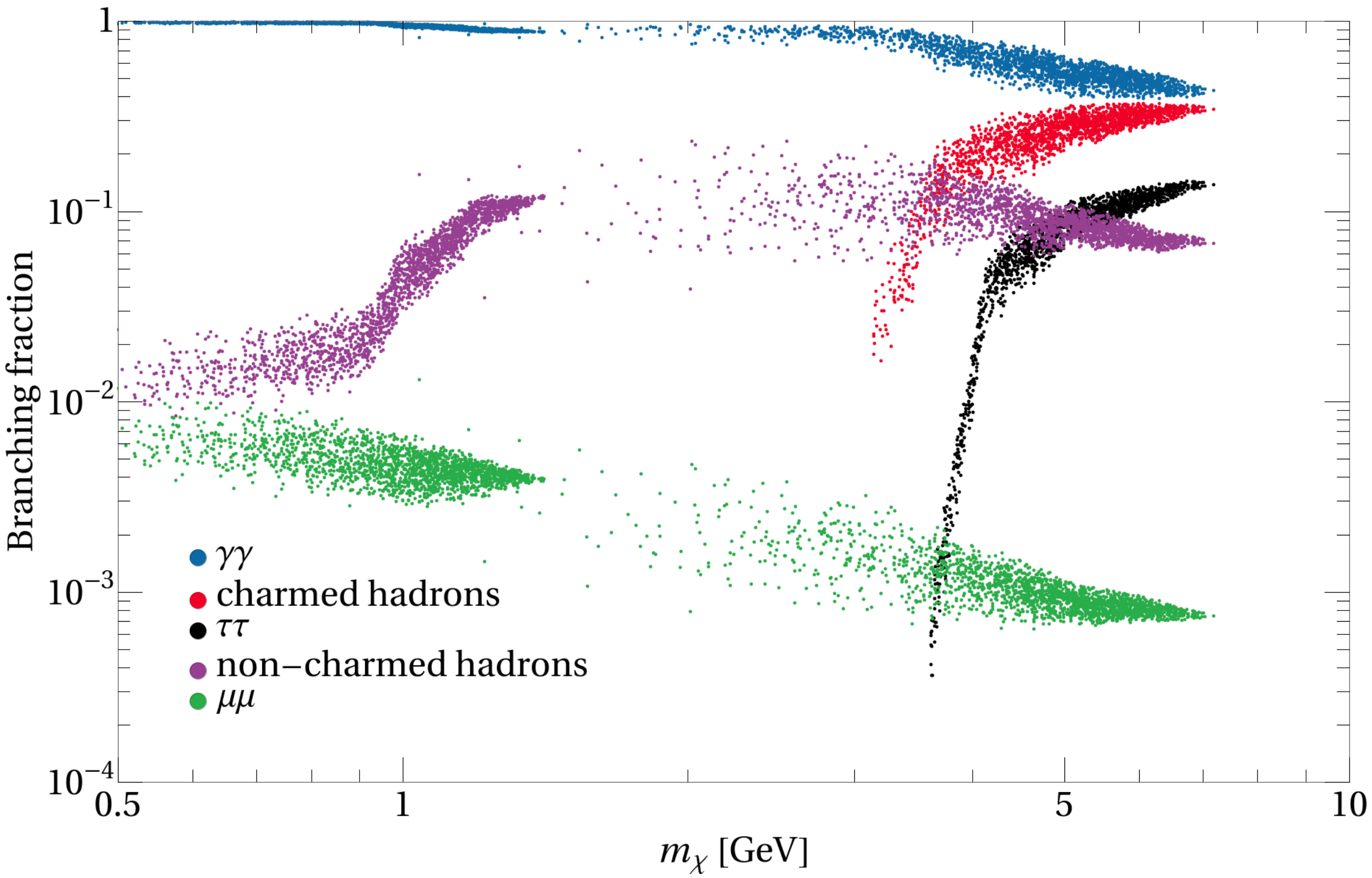
2. $h_{crit} \leq 2$ TeV so that the Higgs VEV is not tuned

3. The metastable vacuum reproduces the SM values of the Higgs mass and VEV and corresponds to a stable local minimum of the 2-dim potential

4. The tunnelling between the vacua is suppressed on cosmo-scales.

Dilaton properties

- Light Dilaton - less that 10 GeV
- Couplings - Higgs mixing, direct photon coupling
- Branching fraction



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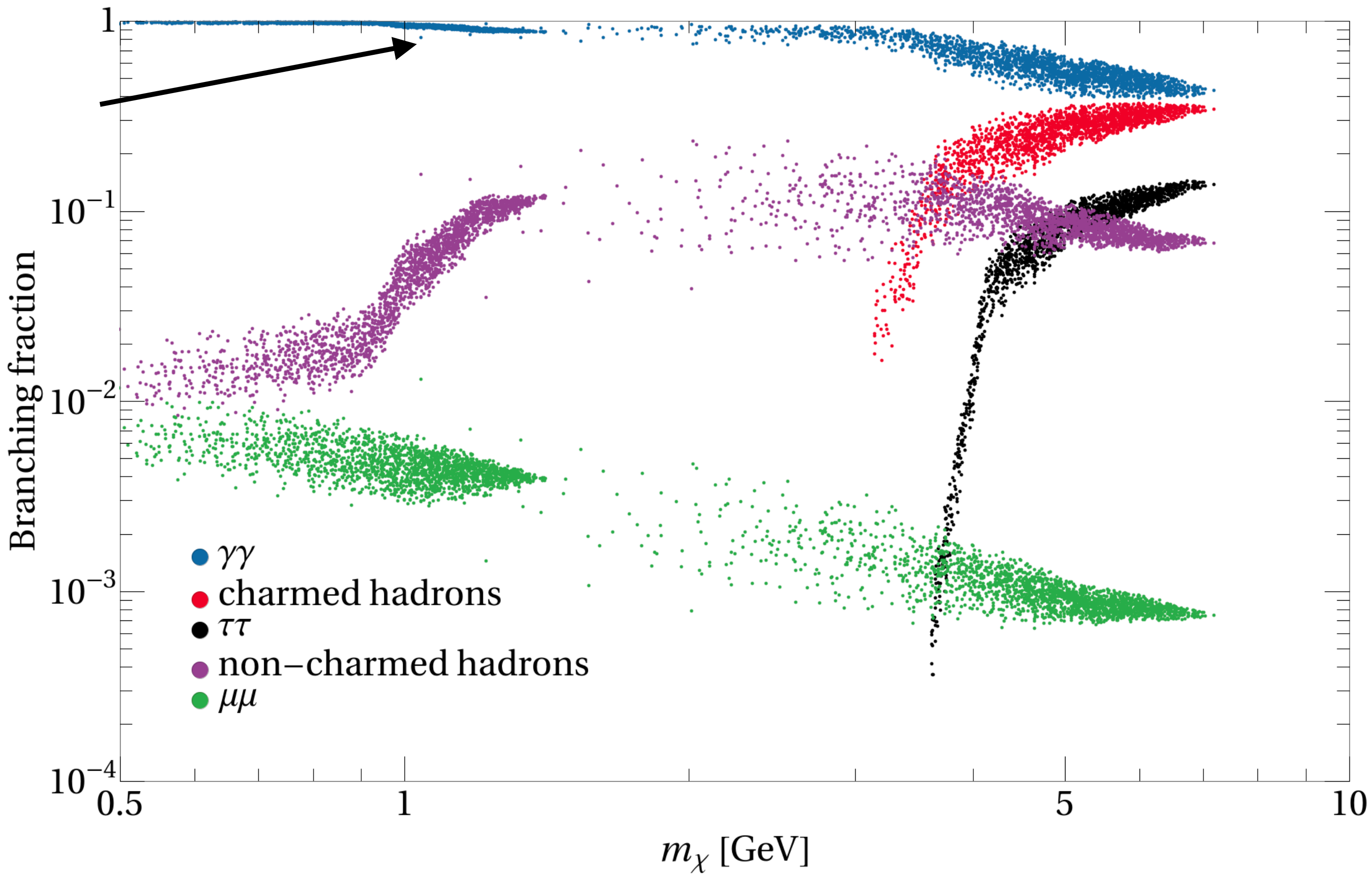

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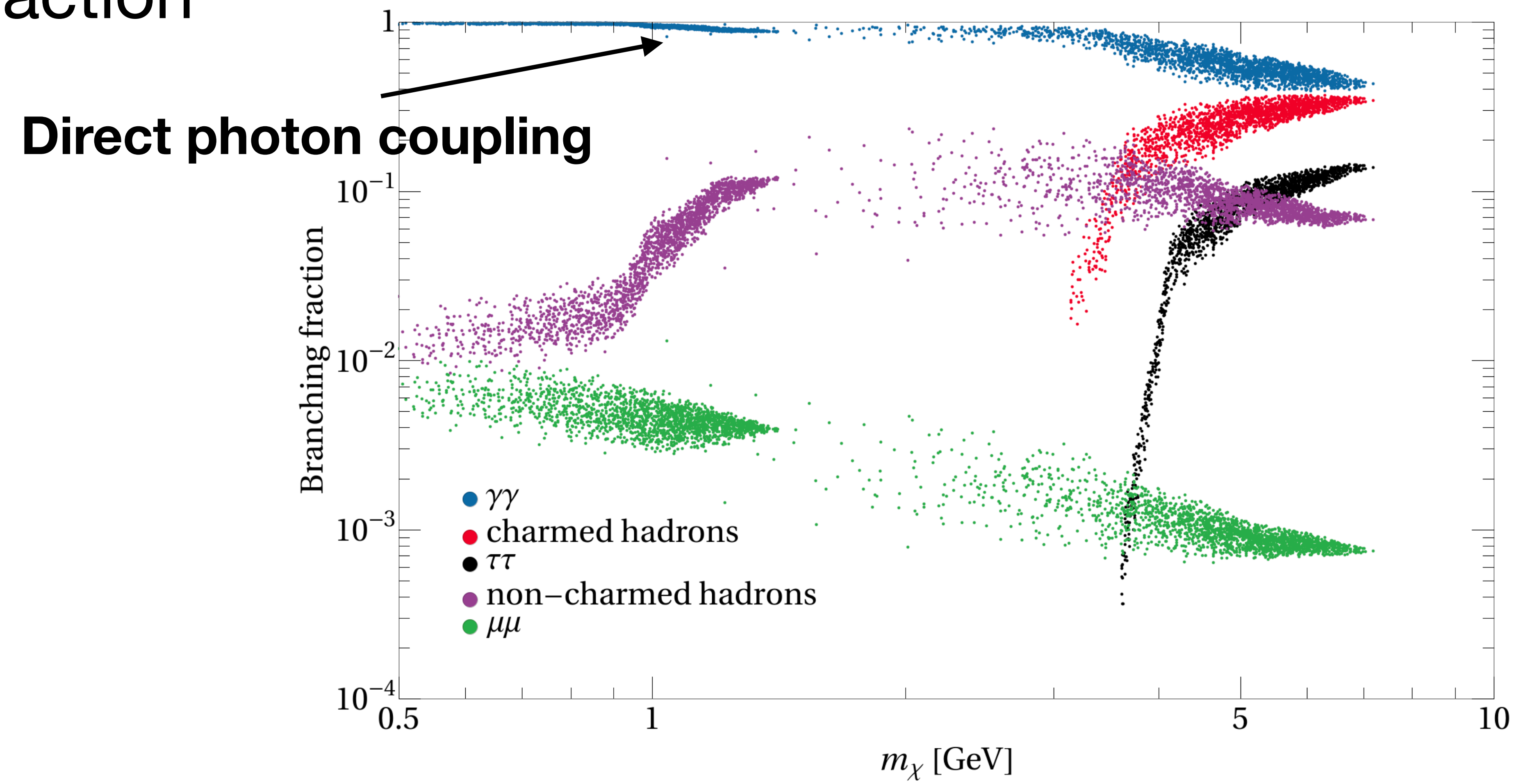

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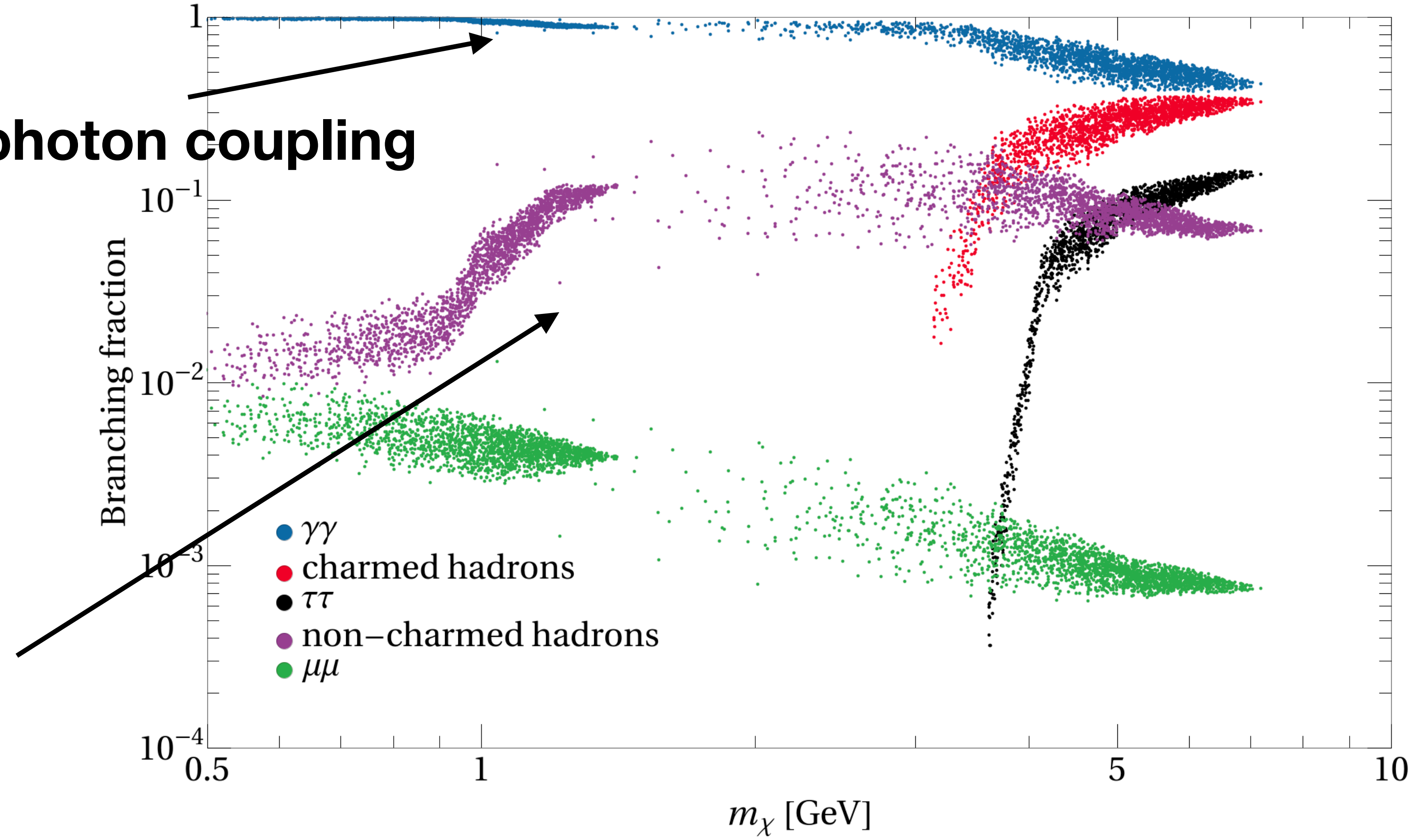

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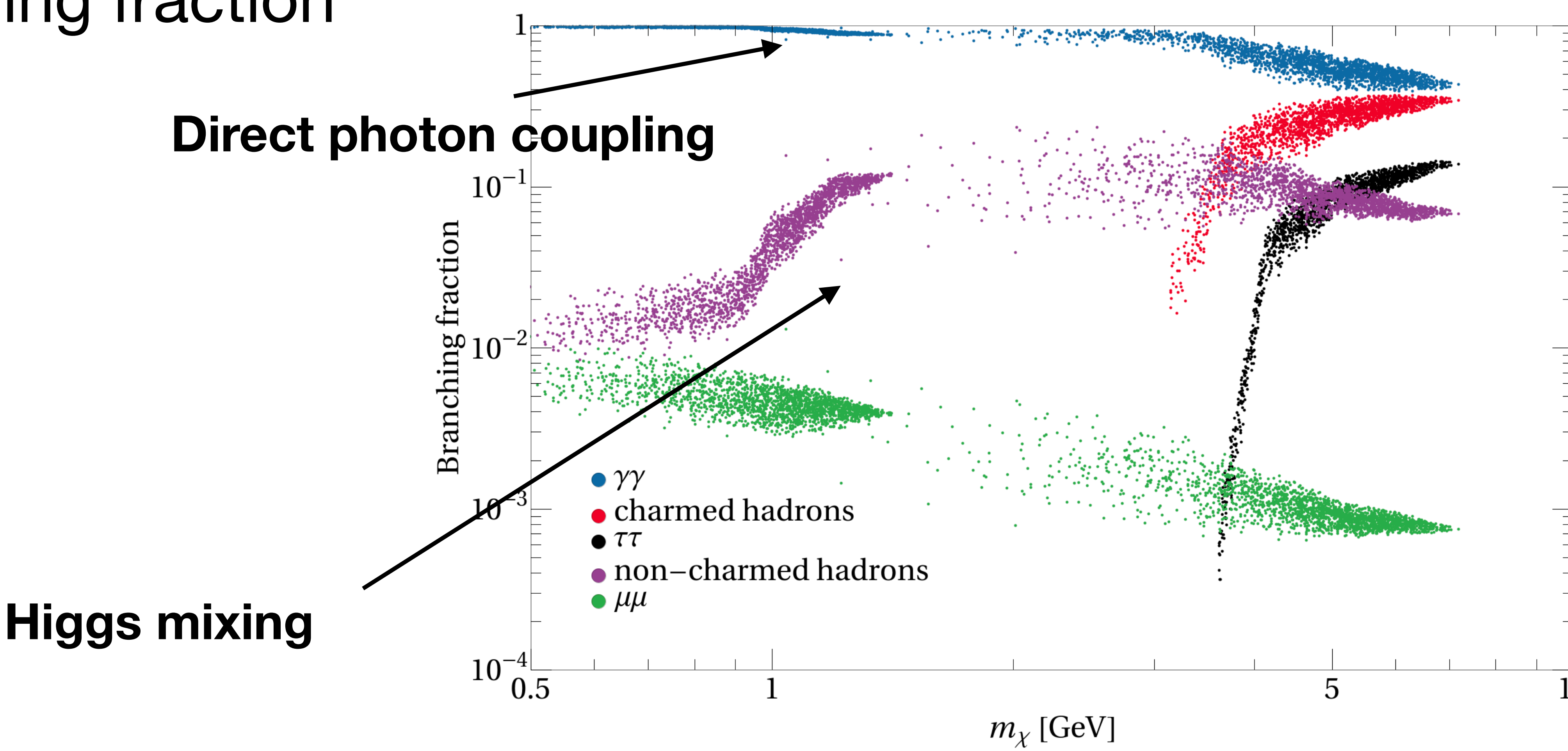
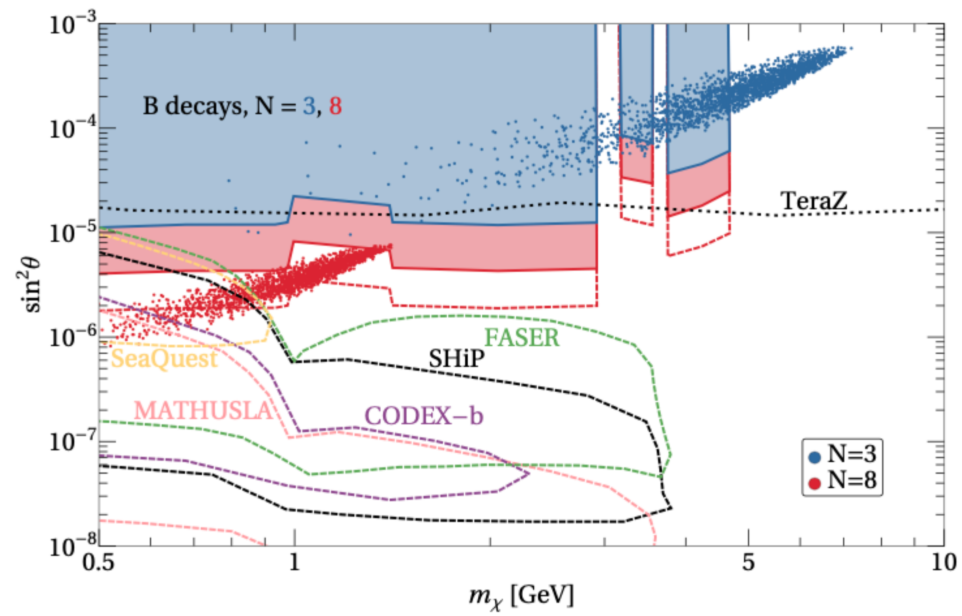
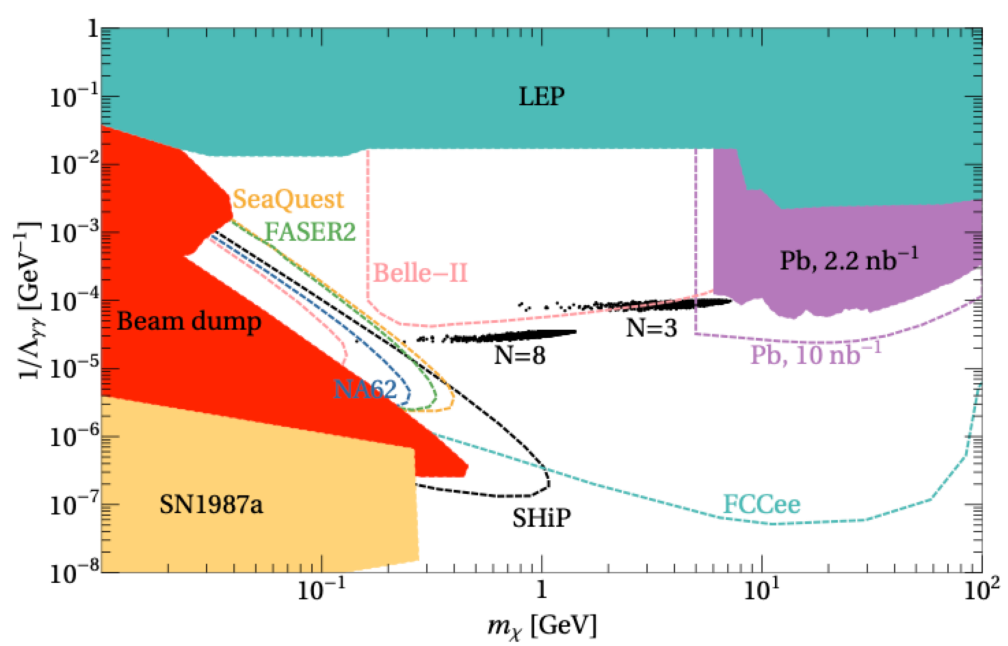


Pheno

- Constraints and projections due to Higgs mixing:



- Photon decay



Future Directions

- Casimir force:
  - When the Higgs mass is tuned there is a “zero mode” that contributes to the dilaton effective action.
  - When the mass is not tuned the state is gone.
  - Large effect when the Higgs is tuned for $\chi \sim m_H$
  - Alternatively: The Higgs is not in the bulk (no KK gauge constraint) and use the UV coupling to a bulk singlet fermion.

Future Directions

- Assume a SUSY bulk.
  - Can allow small couplings.
  - Squarks are on the UV brane where SUSY is broken at a high scale.
  - Supersymmetric dilaton and KK spectra+ electroweakinos.

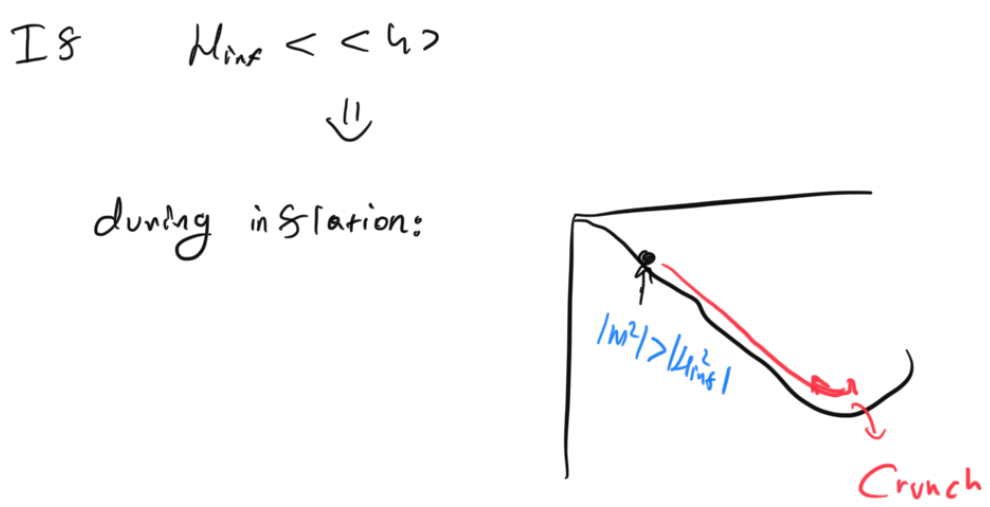
Conclusions

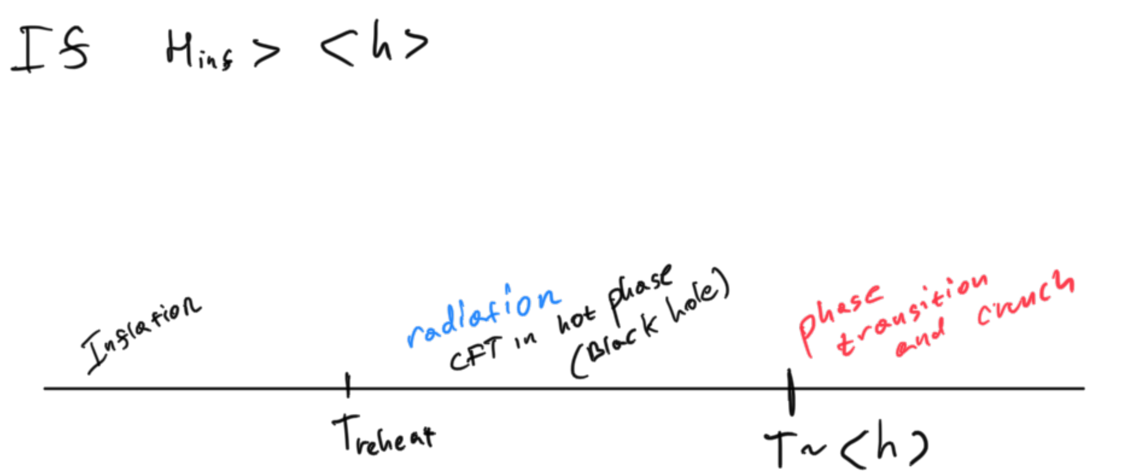
- Engineered a Higgs dependent catastrophic phase transition.
- Predictive (too much so) framework
- Light dilaton and heavy KK mode pheno.
- New ideas to solve the little hierarchy problem/simplify the setting.
- The cosmological history is non-trivial.

Backup

Cosmological Dynamics

- For large Higgs VEV -





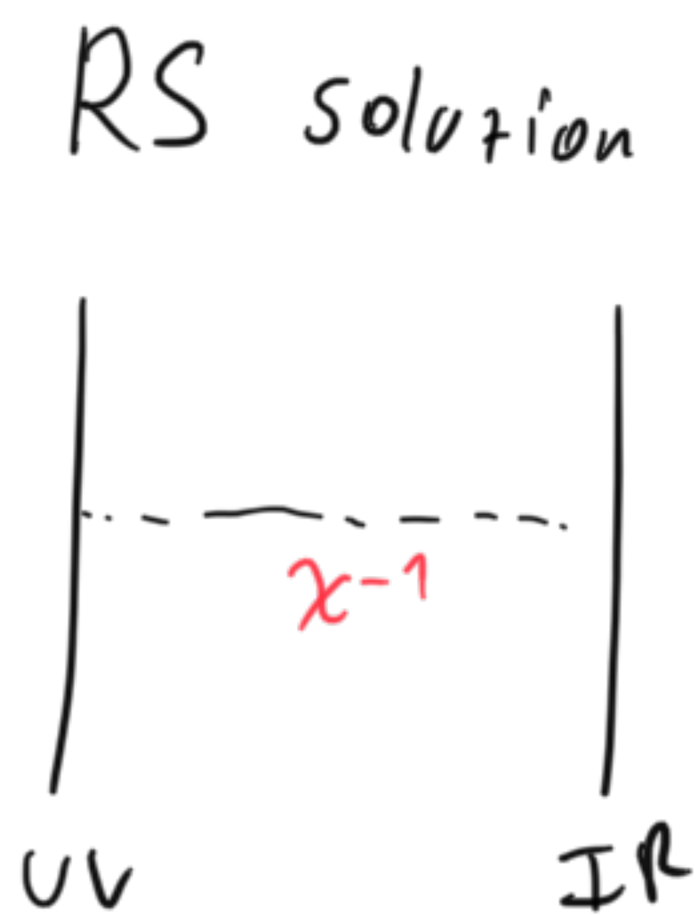
- For zero Higgs VEV - can get stuck in the hot phase and never transition.

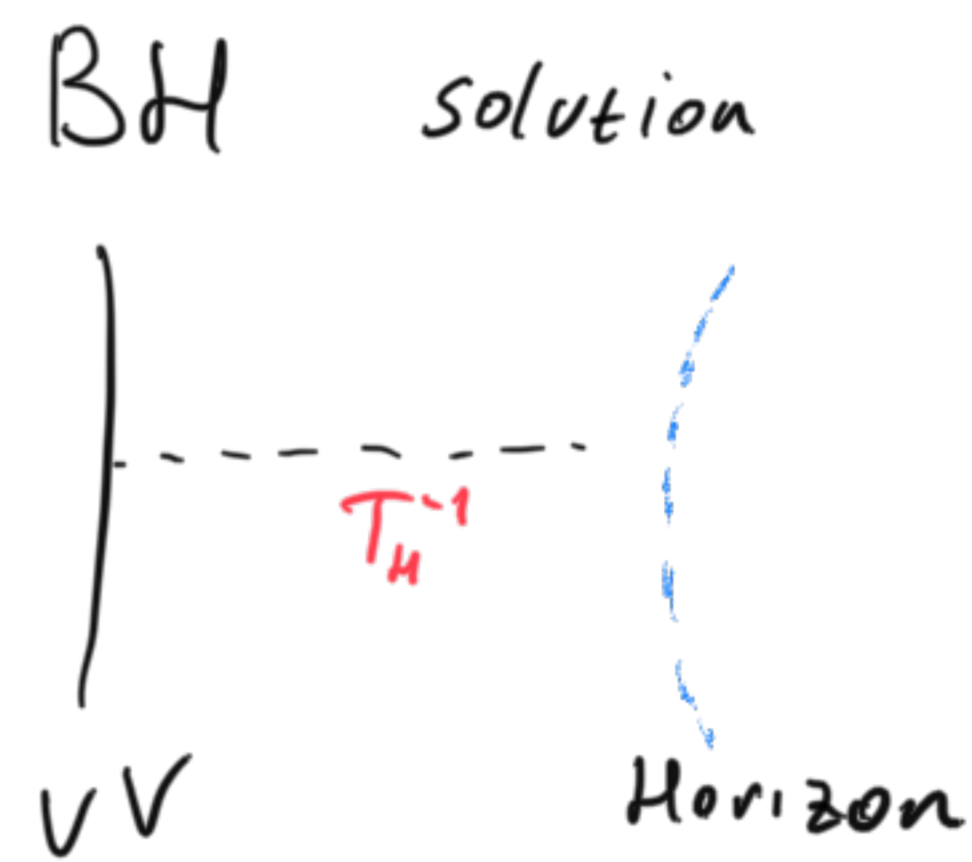
- Need to have a limit on the supercooling of the CFT.

Conformal Phase Transition

Creminelli, Nicolis, Rattazzi, 02'

At finite temperature:





Breaking the supercooling

- Big departure from AdS in the IR - the BH phase disappears.

- CFT is explicitly broken - the unbroken phase is no longer a solution.

- Nucleation temperature - same order as the scale of CFT breaking.

Breaking the supercooling

- Possible solution: have QCD in the bulk. Use the contribution of QCD confinement to the potential to break CFT.

- Running coupling: $$\frac{1}{g^2(Q,\chi)} = \frac{\log\frac{k}{\chi}}{kg_5^2} - \frac{b_{\rm UV}}{8\pi^2}\log\frac{k}{Q} - \frac{b_{\rm IR}}{8\pi^2}\log\frac{\chi}{Q} + \tau$$

$$\begin{aligned}\tilde{\Lambda}(\chi) &= \left(k^{b_{\rm UV}}\chi^{b_{\rm IR}}e^{-8\pi^2\tau}\left(\frac{\chi}{k}\right)^{-b_{\rm CFT}}\right)^{\frac{1}{b_{\rm UV}+b_{\rm IR}}} \\ &= \Lambda_0\left(\frac{\chi}{\chi_{\rm min}}\right)^n\end{aligned}$$

CFT breaking scale

$$\chi_* \sim 10 - 100 \text{ MeV}$$