Unearthing the intersections:

positivity bounds, weak gravity conjecture, and asymptotic safety landscapes from photon-graviton flows

Alessia Platania

Based on:

Basile, Platania - arXiv:2107.06897

Knorr, Platania - arXiv:2405.08860

Quantum Gravity and Cosmology

Shanghai, 04.07.2024

The Niels Bohr International Academy

VILLUM FONDEN

UNIVERSITY OF COPENHAGEN

Some reflections on the status of the field

- ***QG is a multi-scale problem***

    - Different theories / UV completions ⇒ different fundamental properties (and different conceptual and technical problems). Details relevant at trans-Planckian scales.
    - Observations spanning intermediate to large distances (cosmology, dark energy, gravitational waves)
    - EFT: consistency constraints in the IR

- ***Technical and conceptual interrelated difficulties in connecting UV and IR, and different UVs***

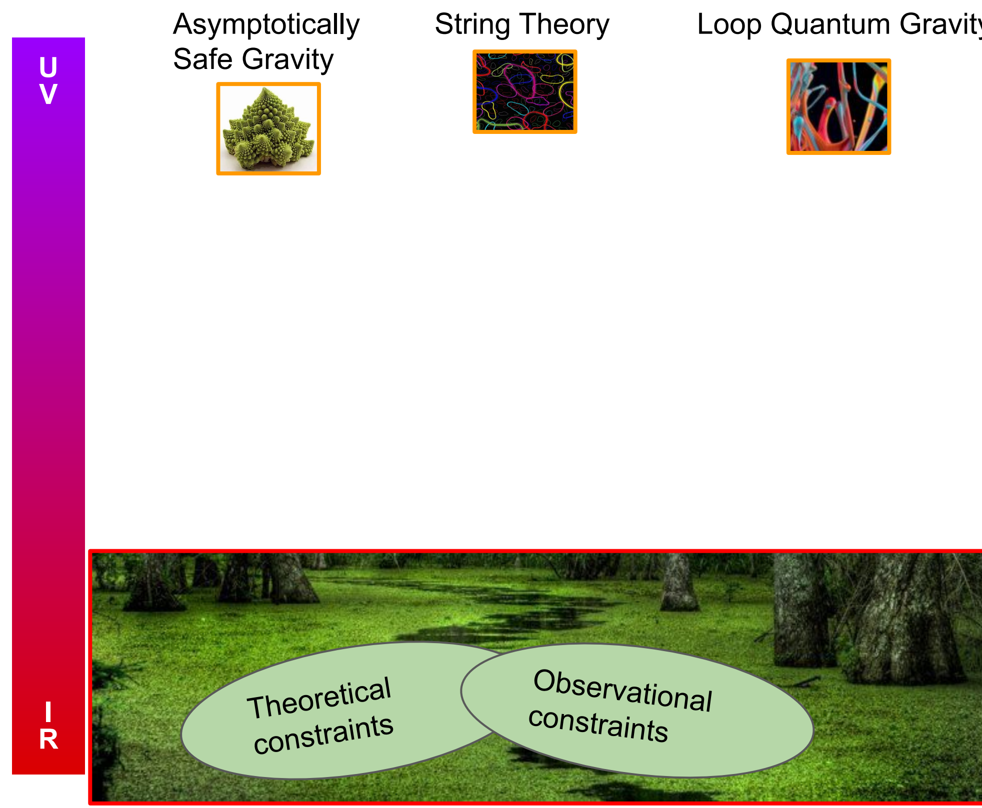
    - Theory is not driven by experiment (scale separation)
    - Difficult to make predictions from scratch
    - Equivalent theories?

      Comparing approaches in the UV is like comparing apples with bananas!

- ***A "decoupling phenomenon" in gravity***

    - "Formal" QG communities: much focus on the UV
    - Pheno & EFT communities: much focus on the IR

- **Task**: define map/recipe to connect UV and IR
- **Expectation/hope**: not everything goes, QG is predictive



Quantum gravity through the lens of effective field theory

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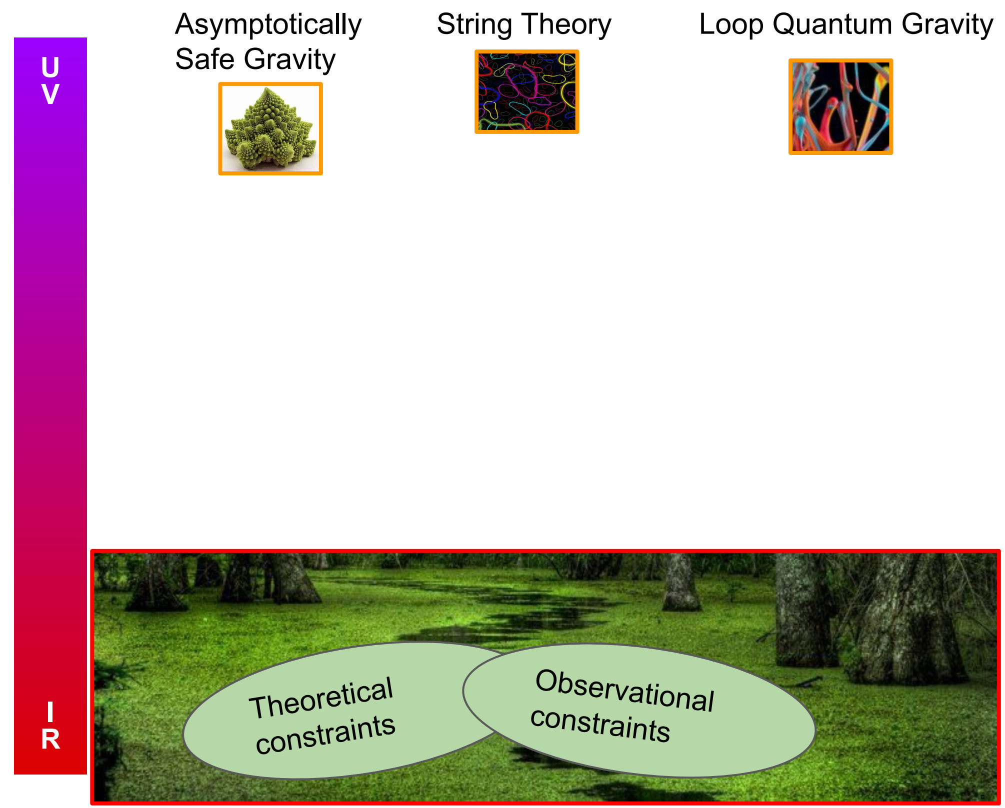

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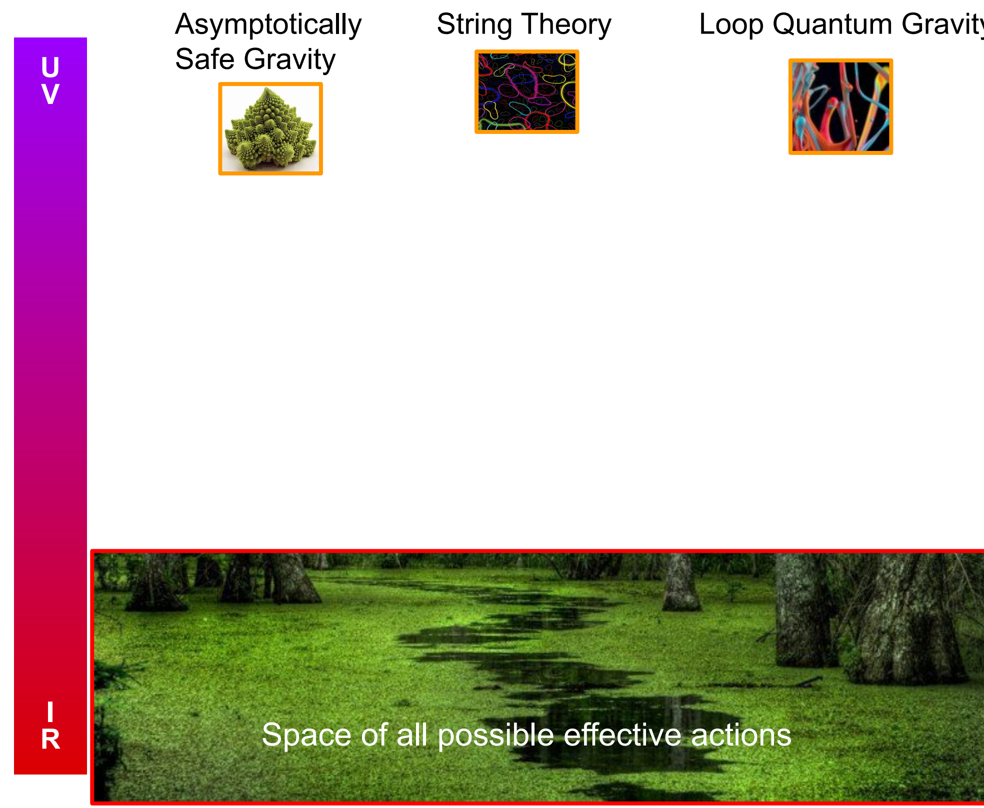

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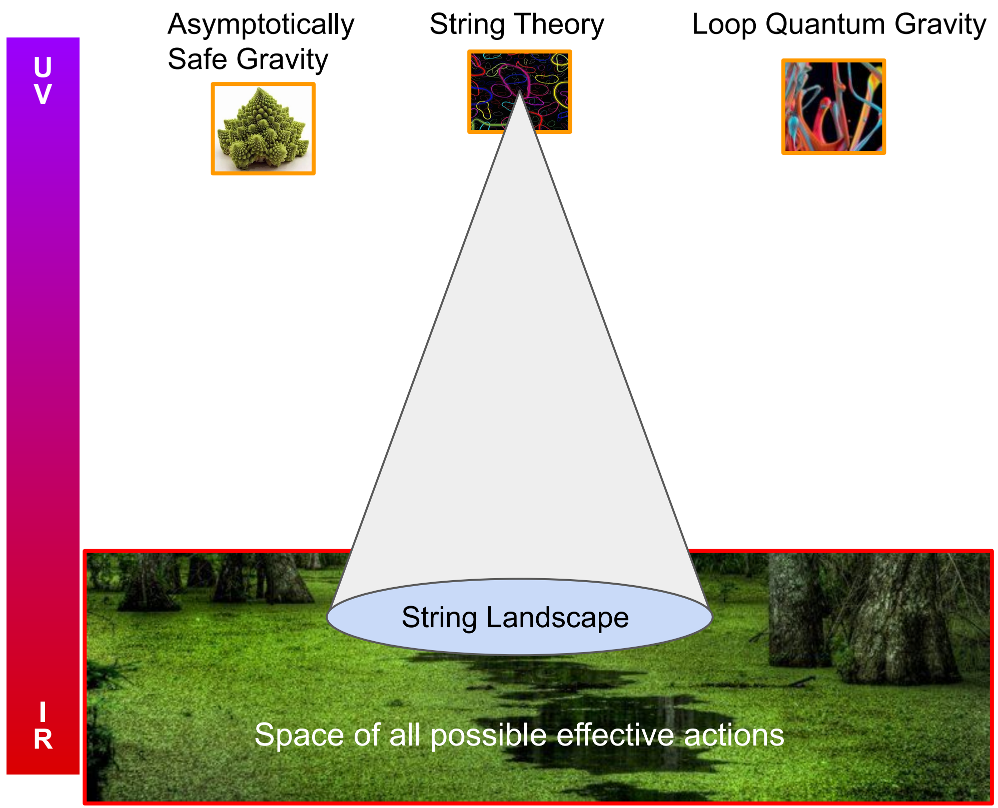
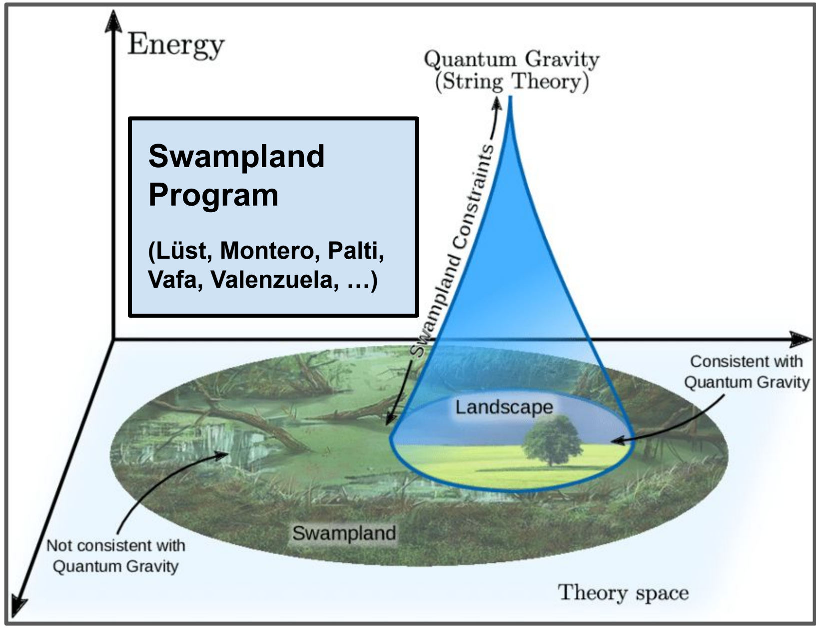
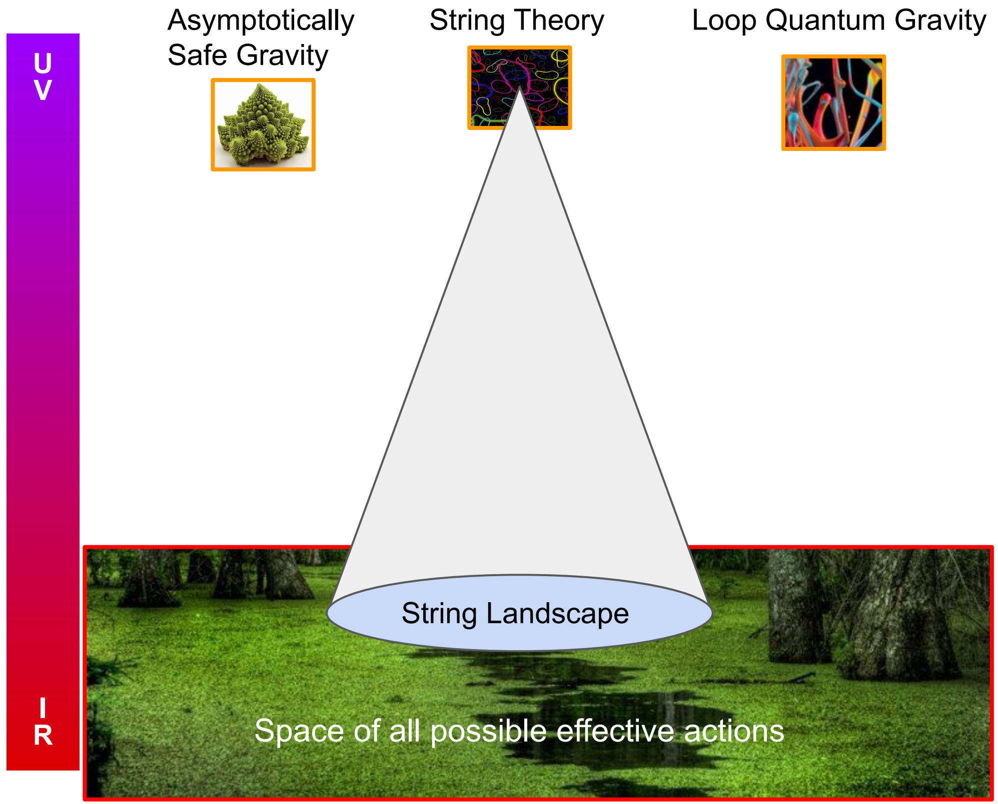


Quantum gravity through the lens of effective field theory

One attempt within String Theory: the "swampland program"

- **Find criteria that select consistent EFTs (that come from UV-complete QG+matter)**
- **Criteria inspired by universal patterns in string constructions or derived by EFT/BH arguments (a few based on solid grounds or even proofs)**

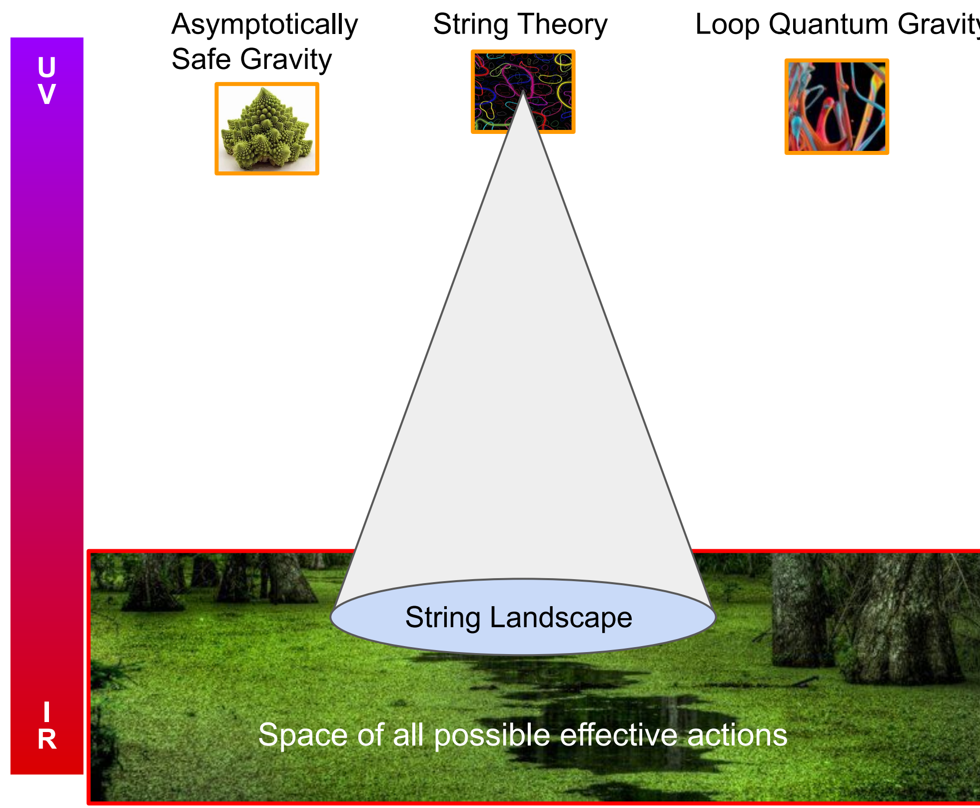




Quantum gravity through the lens of effective field theory

Can the "big picture" of the swampland program be generalized?

[Basile, AP, '21]



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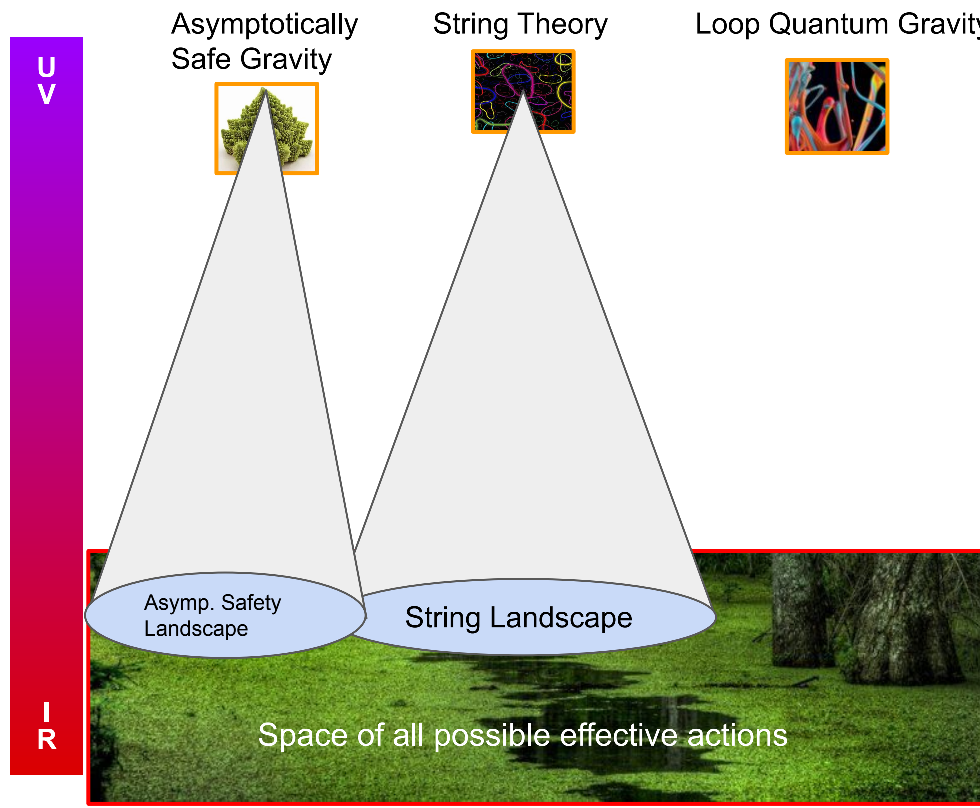

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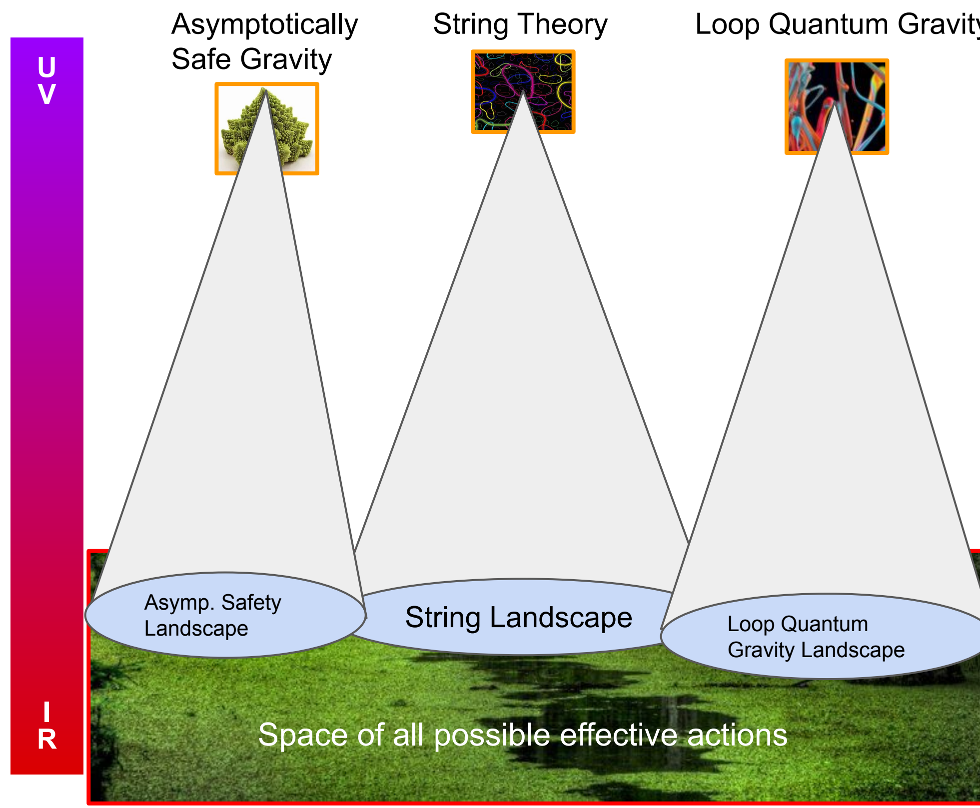

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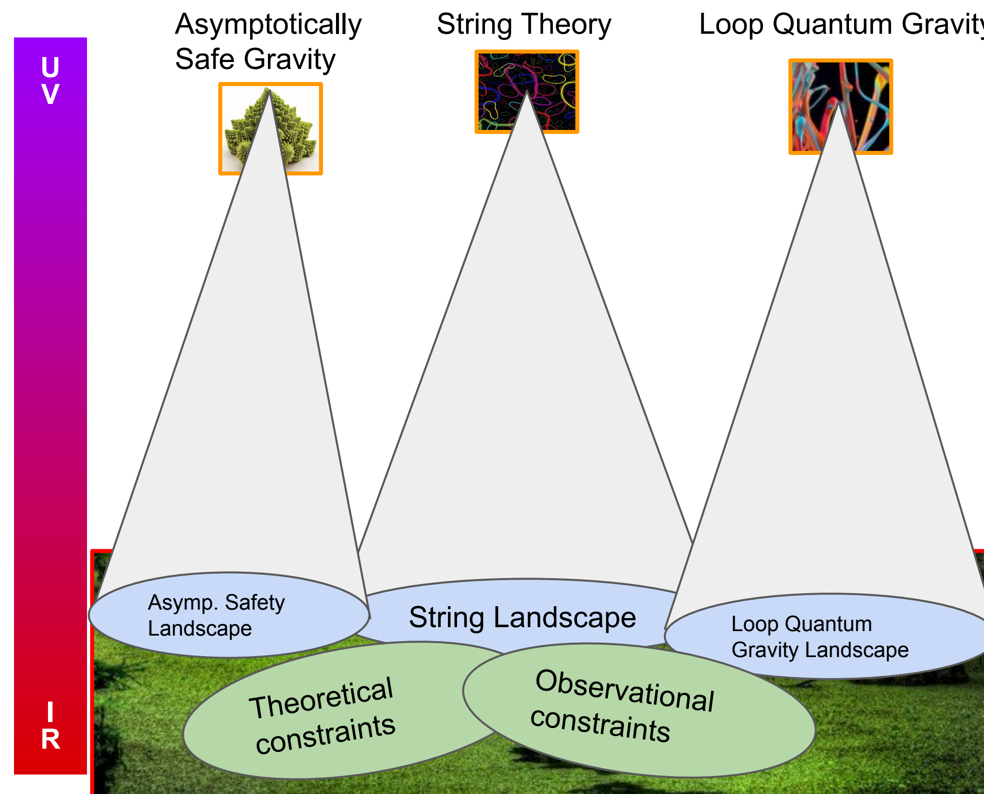


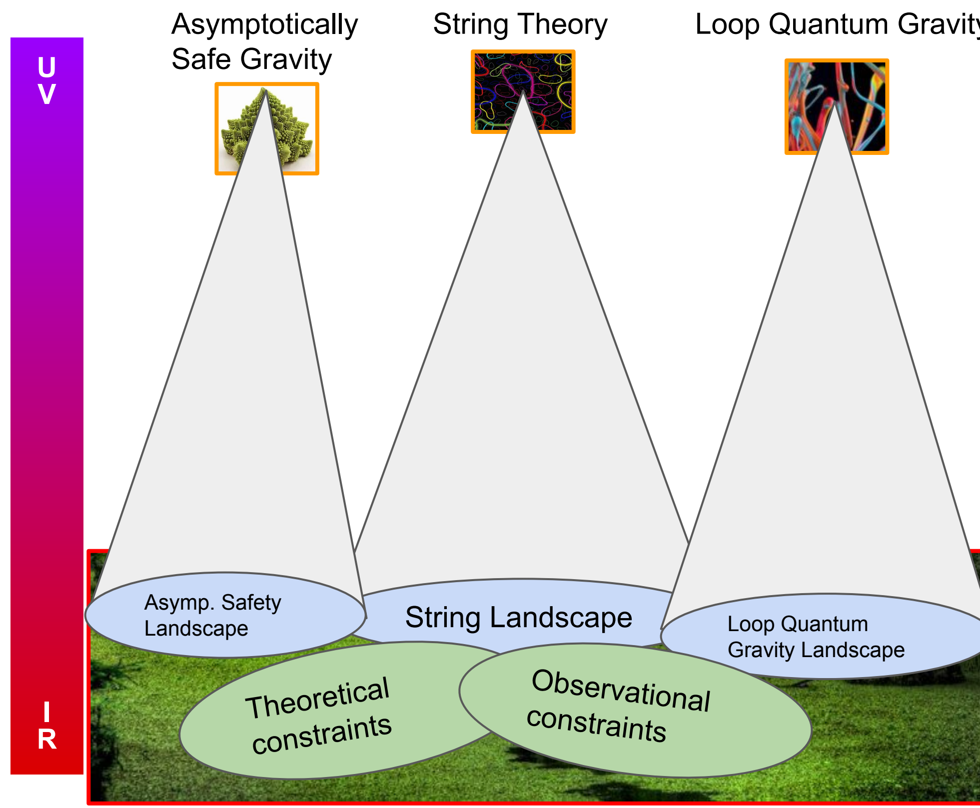
Quantum gravity through the lens of effective field theory

Several interesting questions at the intersections:

- **Consistency**, e.g., compatibility of QG predictions with positivity bounds (unitarity, causality, stability)
- **Tests of Swampland Constraints & string "universality"**: are they all general? Do they apply to all (consistent) QG or they only identify EFTs stemming from ST?

  c.f. String Lamppost Principle [Montero, Vafa, '21]: *"All consistent quantum gravity theories are part of the string landscape"*

- Comparison between **predictions of different QG approaches**? Connections between approaches?
- Comparison with bounds from **observations**?



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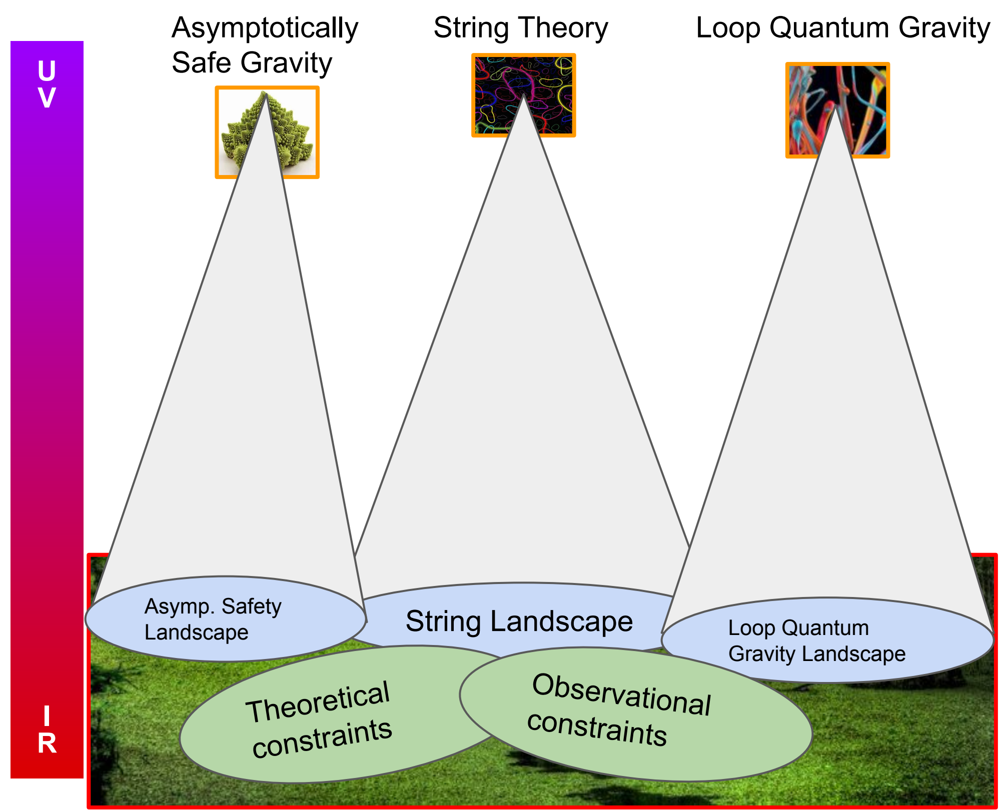
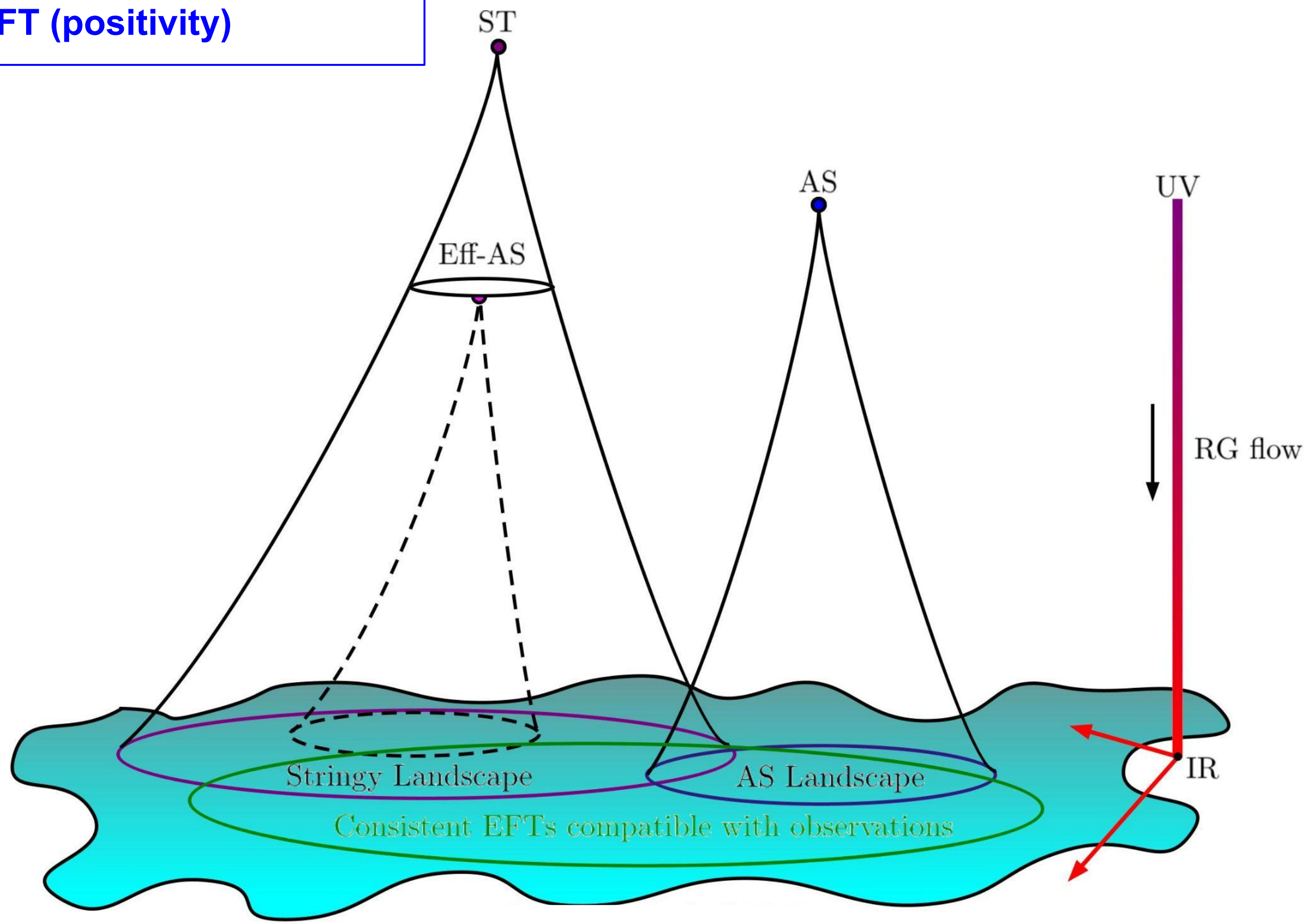
Focus of this talk: AS



This talk:

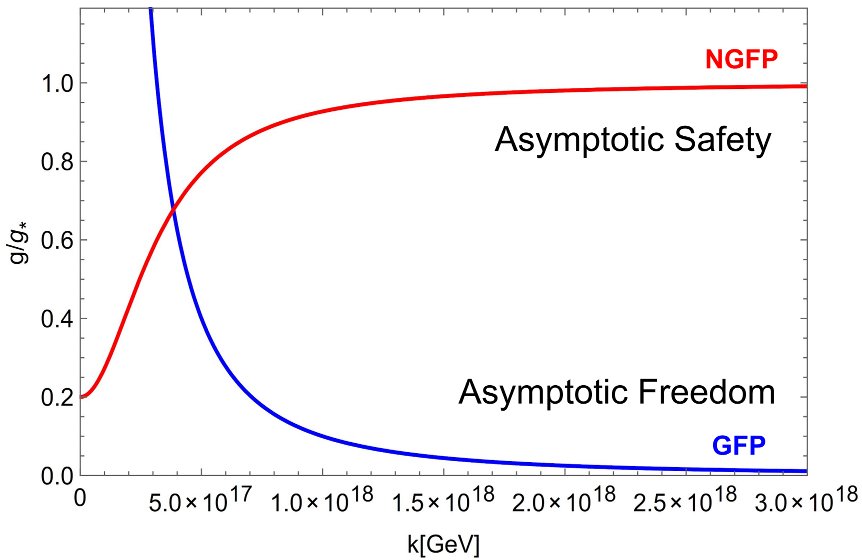
- **AS vs ST (some swamp conjs)**
- **AS vs EFT (positivity)**

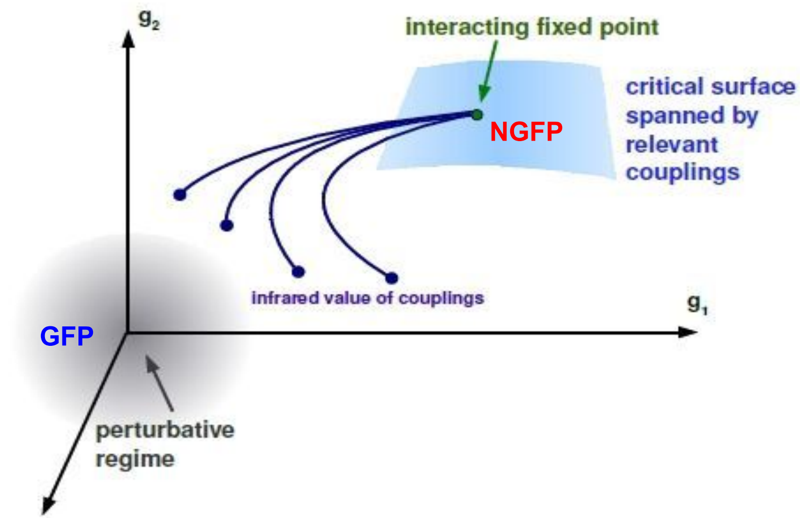


Landscapes

in Asymptotically Safe Gravity

Asymptotic Safety in a Nutshell





Idea: *gravity non-perturbatively renormalizable, interacting UV-completion* (Weinberg, '76)

Testing asymptotic safety:

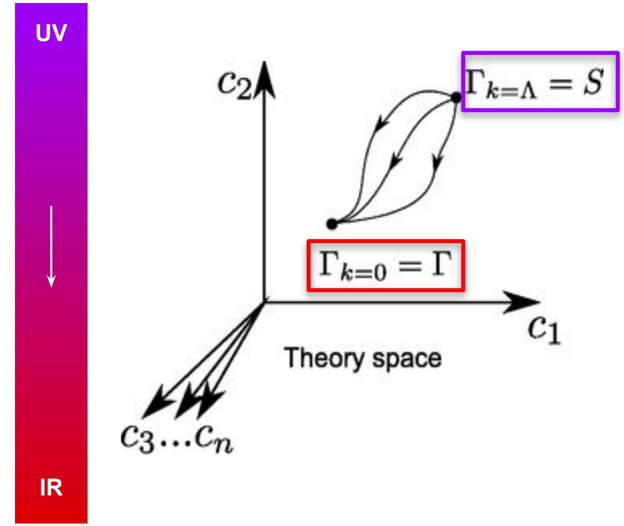
- **Lattice-like computations**: causal/euclidean dynamical triangulations
- **Semi-analytical computations**: exact renormalization group ("AS community")

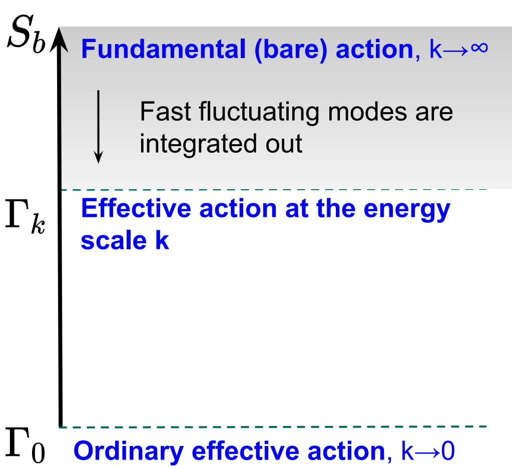
Functional Renormalization Group

Solving the **quantum theory** is equivalent to solve the functional **renormalization group equation**

$$k\partial_k \Gamma_k = \frac{1}{2}\mathrm{STr}\left\{\left(\Gamma_k^{(2)} + \mathcal{R}_k\right)^{-1} k\partial_k \mathcal{R}_k\right\}$$

C. Wetterich. *Phys. Lett. B* 301:90 (1993)
M. Reuter. *Phys. Rev*. D. **57** (2): 971 (1998)





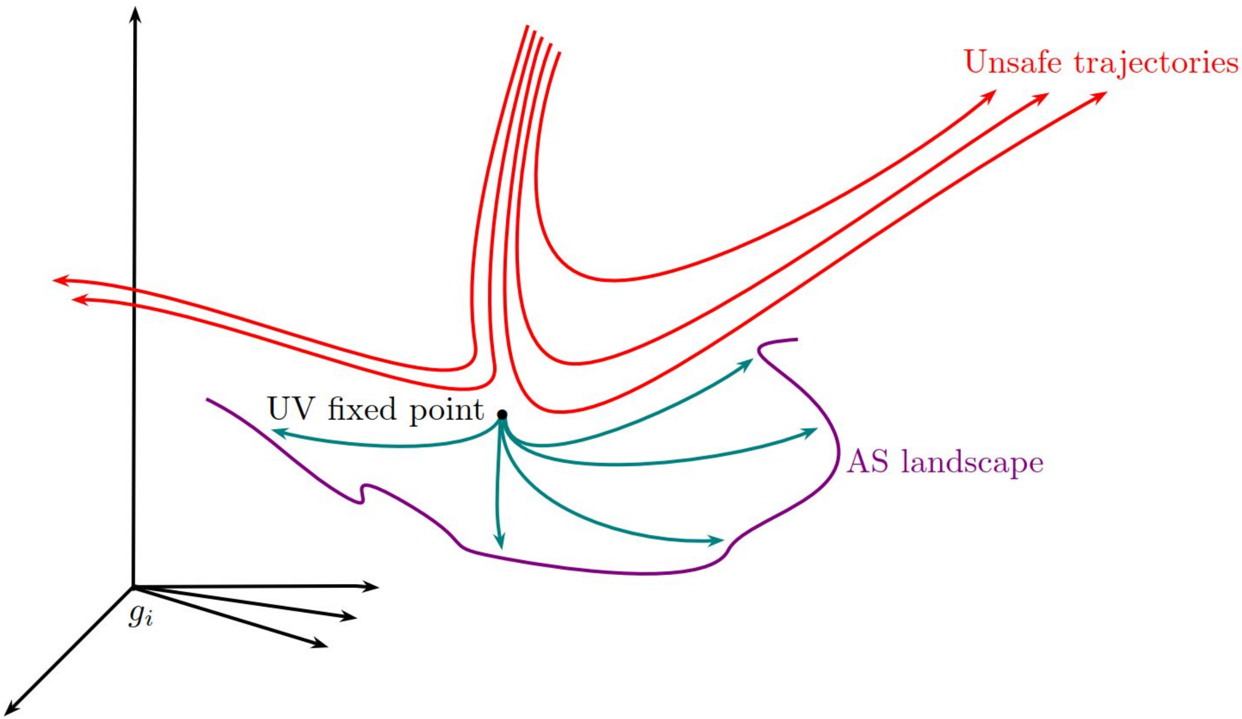
<u>UV fixed points</u> = bare actions, <u>N relevant directions</u>

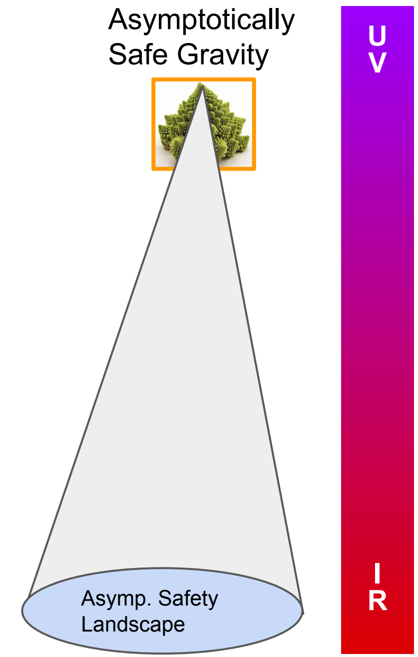
<u>Effective action</u> (limit k→0), infinitely many terms parametrized by <u>N free parameters</u>

⇒ **S-matrix**, **Wilson coefficients**, **observables**

Implementation in AS: defining the asymptotic safety landscape

Theory space of dimensionless running couplings

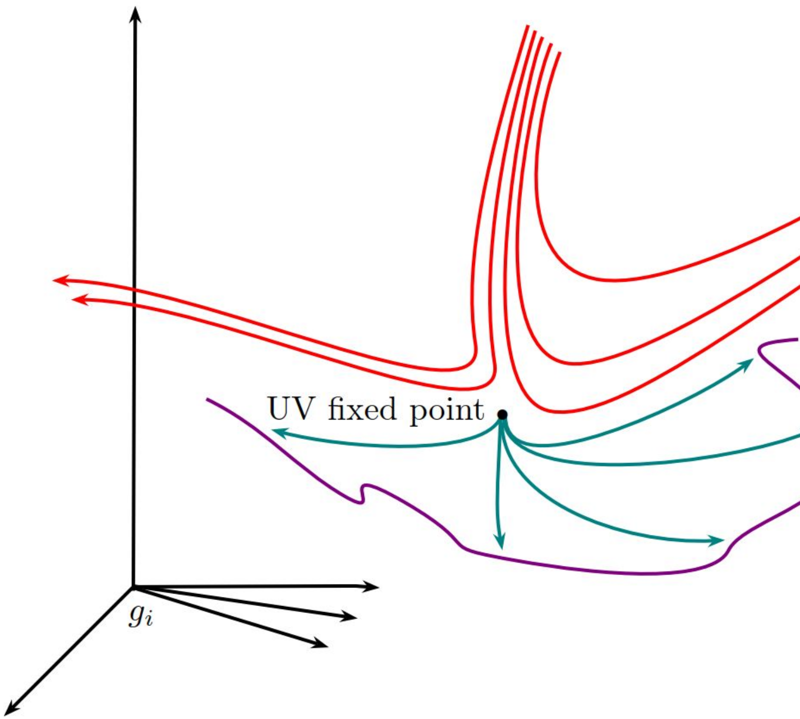




So far:

- Much focus of the AS community on UV fixed points and a few RG trajectories
- Less about constraining the Wilson coefficients and their intersections with bounds

Implementation in AS: defining the asymptotic safety landscape



Recipe (*generalizable to other approaches?*)

- **Cosider a model of AS** (truncation of the action)
- **Run FRG machinery**: compute beta functions, solve beta functions for a sample of UV-complete trajectories, identify the "**AS landscape**" in terms of Wilson coefficients in the effective action + its **geometry**
- Use the same Wilson coefficients to identify the **region allowed by positivity bounds / swampland conjectures (string landscape) / other QG landscapes / observational bounds…**
- **Find the intersections** between AS landscape and other sets

Implementation in AS: defining the asymptotic safety landscape

Defining the Wilson Coefficients (+ caveats)

- **Defining the Wilson coefficients with the FRG:**

$$W_{G_i} \equiv \lim_{k\to 0} G_i(k)$$

- **Or, actually: we only measure dimensionless quantities, thus we need one unit mass scale (e.g., Newton coupling) and N-1 dimensionless Wilson coefficients to parametrize the landscape of EFTs (N=number of relevant directions)**

$$w_{G_i} \equiv \lim_{k\to 0} G_i(k) M_{Pl}^p$$

- **CAVEAT 1: Wick rotation needed! FRG is typically based on Euclidean computations. But the results may be the same as in Lorentzian settings**

[Fehre, Litim, Pawlowski, Reichert '21]

- **CAVEAT 2: Defining Wilson coefficients in the presence of Log running in the IR is ambiguous, and one needs a prescription. Our prescription: use the transition scale to QG.**

$$w = a + b\,\log(k^2/M_{Pl}^2) + b(\log(k_0^2) - \log(k_0^2))$$
$$= \tilde{a} + \tilde{b}\,\log(k/k_0^2)$$

[Basile, AP '21]
[Knorr, AP '24]

Case Study 1

AS landscapes in one-loop quadratic gravity
vs
Swampland Constraints

- **AS toy model**: one-loop quadratic gravity

$$\mathcal{L} = \frac{2\Lambda - R}{16\pi G} + \frac{1}{2\lambda} C^2 - \frac{\omega}{3\lambda} R^2 + \frac{\theta}{\lambda} E$$

- **Three dimensionless Wilson coefficients** (+ gauss-bonnet, but decoupled)
  One dimensionful coupling sets the mass unit scale!

$$G\Lambda, \qquad g_R = -\frac{\omega}{3\lambda}, \qquad g_C = \frac{1}{2\lambda}$$

- Beta function and fixed points [(Codello, Percacci, 2006)]

$$\lambda_* = 0\,, \qquad \omega_* = \omega_\pm \equiv \frac{-549 \pm 7\sqrt{6049}}{200}\,, \qquad \theta_* = \frac{56}{171}$$

$$\tilde{\Lambda}_* \approx 0.221\,, \qquad \tilde{G}_* \approx 1.389$$

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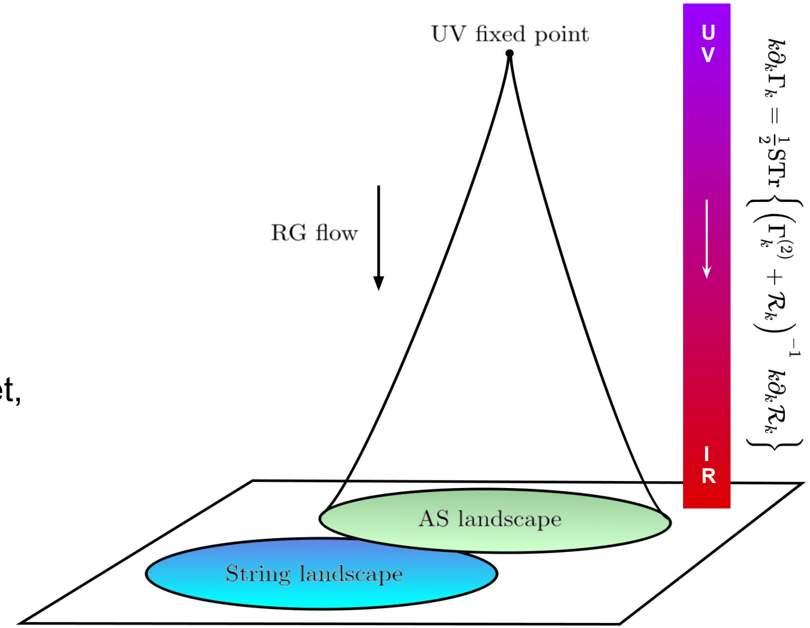

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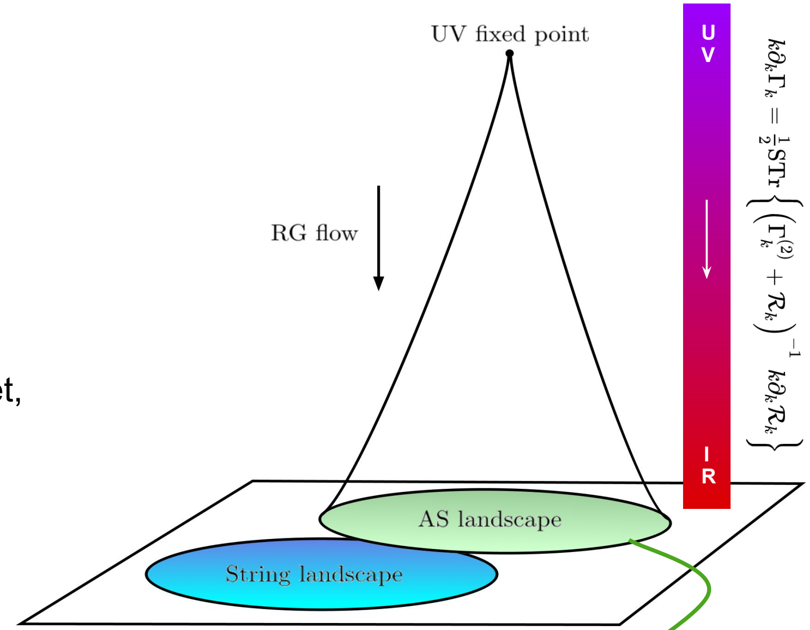

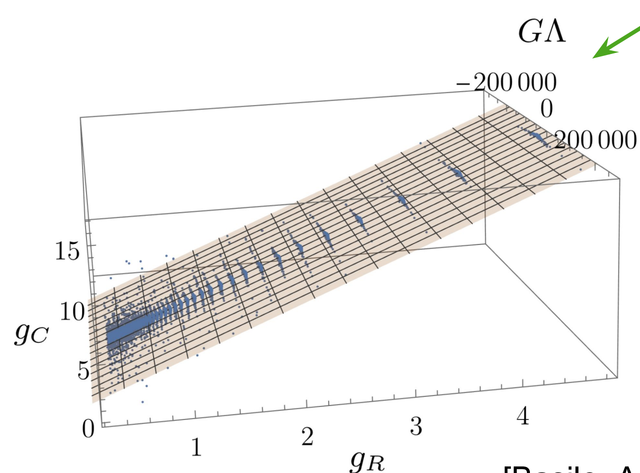

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[Basile, AP. 2107.06897]

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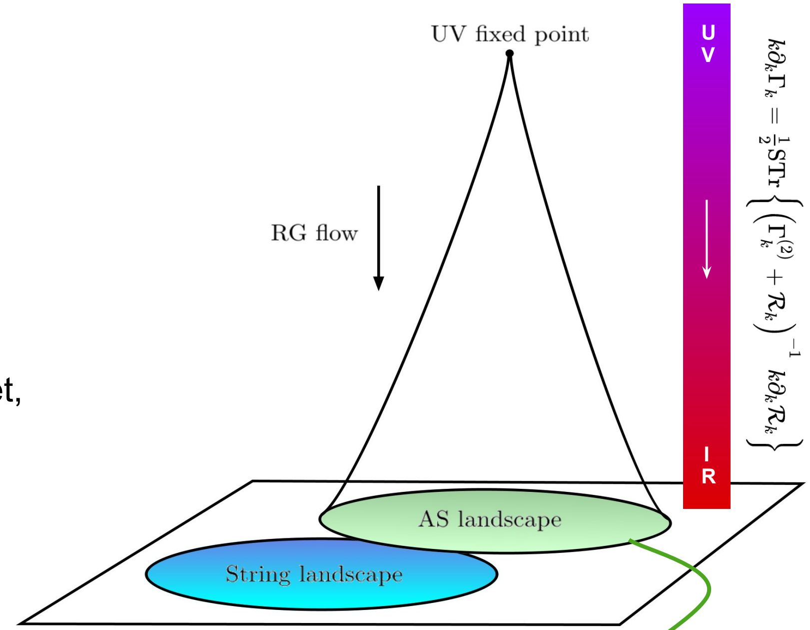
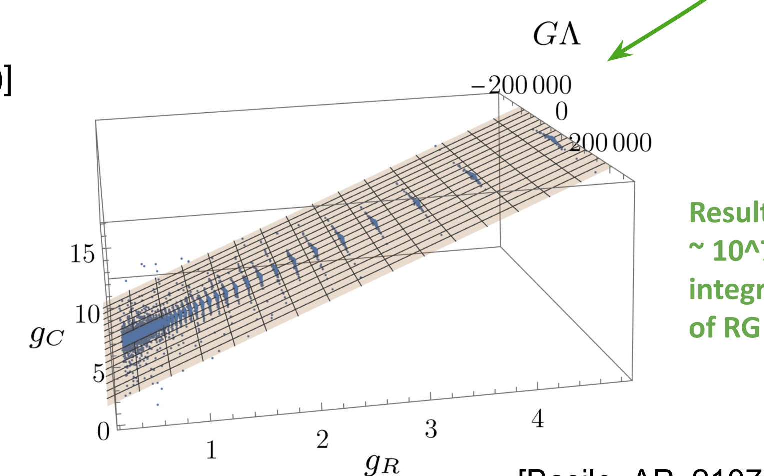
The Wilson coefficients stemming from an AS fixed point lie on a plane

$$\mathrm{EFT}_{\mathrm{AS}} \approx \{g_R = -0.74655 - \frac{2}{3}\,\omega_-\, g_C\}$$

$$g_C > 0$$





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- **Swampland conjectures**:

  - **Weak gravity conjecture** (Arkani-Hamed, Motl, Nicolis, Vafa, 2006)

    $$m/M_{Pl} \leq q\,\mathcal{O}(1)$$

    Black holes remain sub-extremal:

    $$Q/M \leq (Q/M)_{extr}$$

    Higher derivative corrections [(Kats, Motl, Padi, 2007), (Charles, Larsen, Mayerson, 2017), (Cheung, Liu, Remmen, 2018), (Hamada, Noumi, Shiu, 2019), (Charles, 2019)]:

    $$Q/M \leq (Q/M)_{extr}\left(1 - \frac{\Delta}{M^2}\right) \qquad \mathcal{L}_{HD} = c_1\,R^2 + c_2\,R_{\mu\nu}R^{\mu\nu} + c_3\,R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}$$

    $$\Delta \propto (1-\xi)^2\,(c_2 + 4\,c_3) + 10\,\xi\,(1+\xi)\,c_3 \overset{\text{WGC}}{>} 0\,, \qquad \xi \equiv \sqrt{1 - \frac{Q^2}{M^2}}$$

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  In terms of dimensionless couplings, this condition yields

  $$\boxed{g_C > 0}$$ **(satisfied by AS-EFT)**

- **Swampland conjectures**:

  - **De Sitter conjecture** [(Obied, Ooguri, Spoyneiko, Vafa, 2018), (Ooguri, Palti, Shiu, Vafa, 2019)]

$$M_{Pl}||\nabla V|| \geq cV \quad \text{for } \Delta\phi \leq f M_{Pl} \qquad f, c \sim \mathcal{O}(1)$$

  - **Trans-Planckian conjecture** [(Bedroya, Vafa, 2020)]

    Relevant for early-universe cosmology. Special value of c:

$$c = \frac{2}{\sqrt{(d-1)(d-2)}}$$

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$$V(\phi) = \frac{M_{\rm Pl}^2}{8\pi} e^{-2\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm Pl}}} \left(\frac{3m^2}{4} \left(e^{\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm Pl}}} - 1 \right)^2 + \Lambda \right) \qquad g_R = -\frac{M_{\rm Pl}^2}{(8\pi)\cdot 12m^2}$$

$\Rightarrow$ **Non-trivial bounds for different f and c**

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Can be violated in AS:
deSitter solutions can be found in AS

[Basile, AP. 2107.06897]

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$\Rightarrow$ Non-trivial bounds for different f and c.

Case Study 2

Non-perturbative AS landscapes
of quadratic photon-graviton systems
vs
Positivity Bounds
& the Weak Gravity Conjecture

[Knorr, AP, 2405.08860]

- **AS model**: **photon-graviton** systems at quadratic order, only **essential couplings** included

[see Knorr's talk!]

$$\mathcal{L} = -\frac{R}{16\pi G_N} + \Theta_E\, E + \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + G_2\,(F^{\mu\nu} F_{\mu\nu})^2 + G_4\, F^{\mu}{}_{\nu} F^{\nu}{}_{\rho} F^{\rho}{}_{\sigma} F^{\sigma}{}_{\mu} + G_{CFF}\, C^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

- **Three dimensionless Wilson coefficients (redefined for convenience; only one log-presc. ambiguity)**

$$w_+ = \frac{1}{2}\frac{G_2 + G_4}{(16\pi G_N)^2}\,, \quad w_- = \frac{1}{2}\frac{G_2 - G_4}{(16\pi G_N)^2} + b\,\ln\left[16\pi G_N k^2\right]\,, \quad w_C = \frac{G_{CFF}}{16\pi G_N}$$

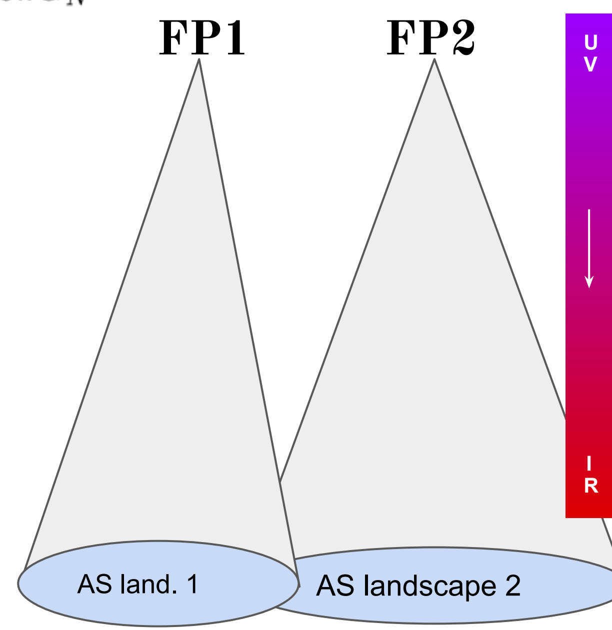
- **Two UV fixed points:**

FP1: **one relevant direction (most predictive!)**

⇒ once the QG scale is fixed, this is a zero-parameter theory =
1 point in the space of dimensionless Wilson coefficients

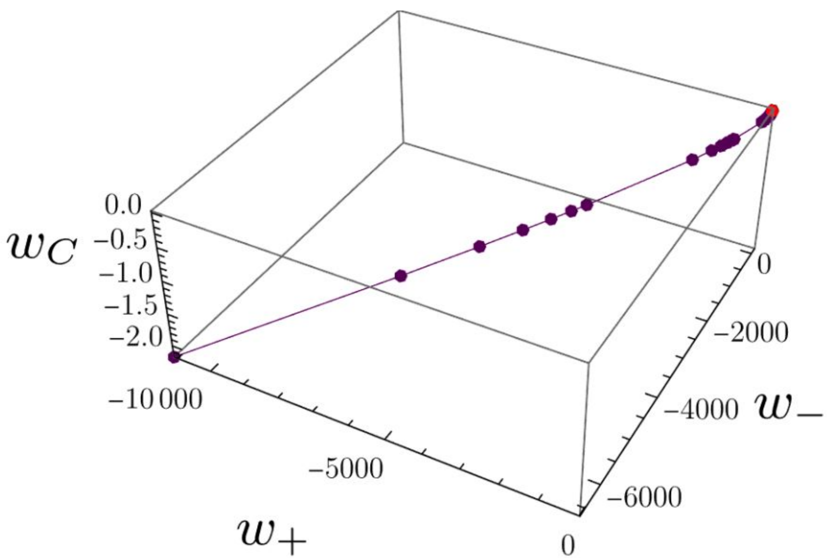
FP2: **two relevant directions**

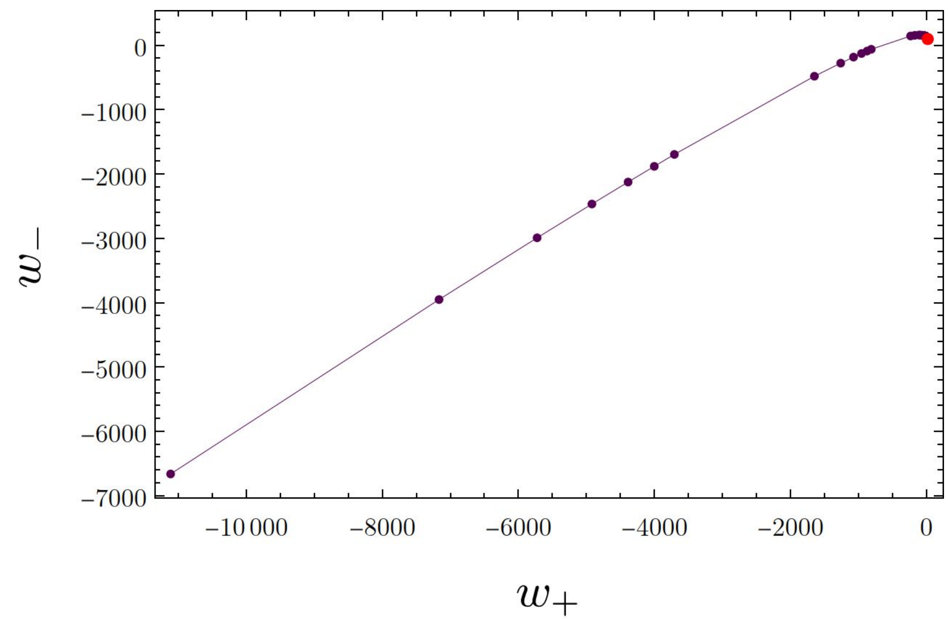
⇒ effective action parametrized by 1 dimensionless parameter
(line of EFTs)



Asymptotic Safety Landscapes

[Knorr, AP, 2405.08860]





AS landscape from FP1: 1 single point

AS landscape from FP2: almost straight line

Asymptotic Safety Landscapes

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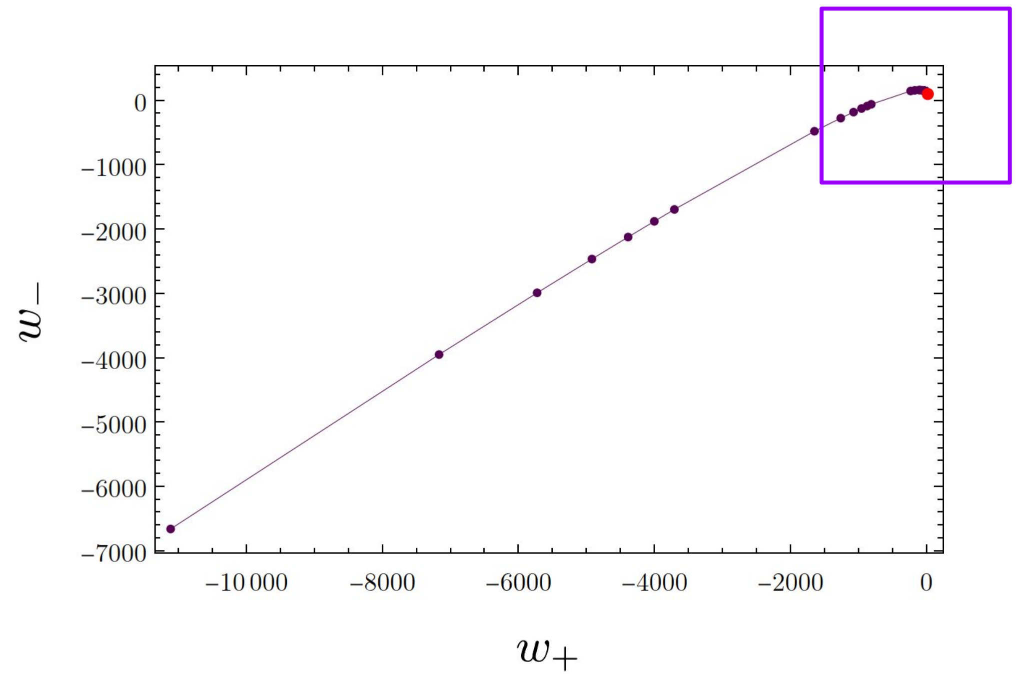

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+ small "candy cane" regime which connects the two

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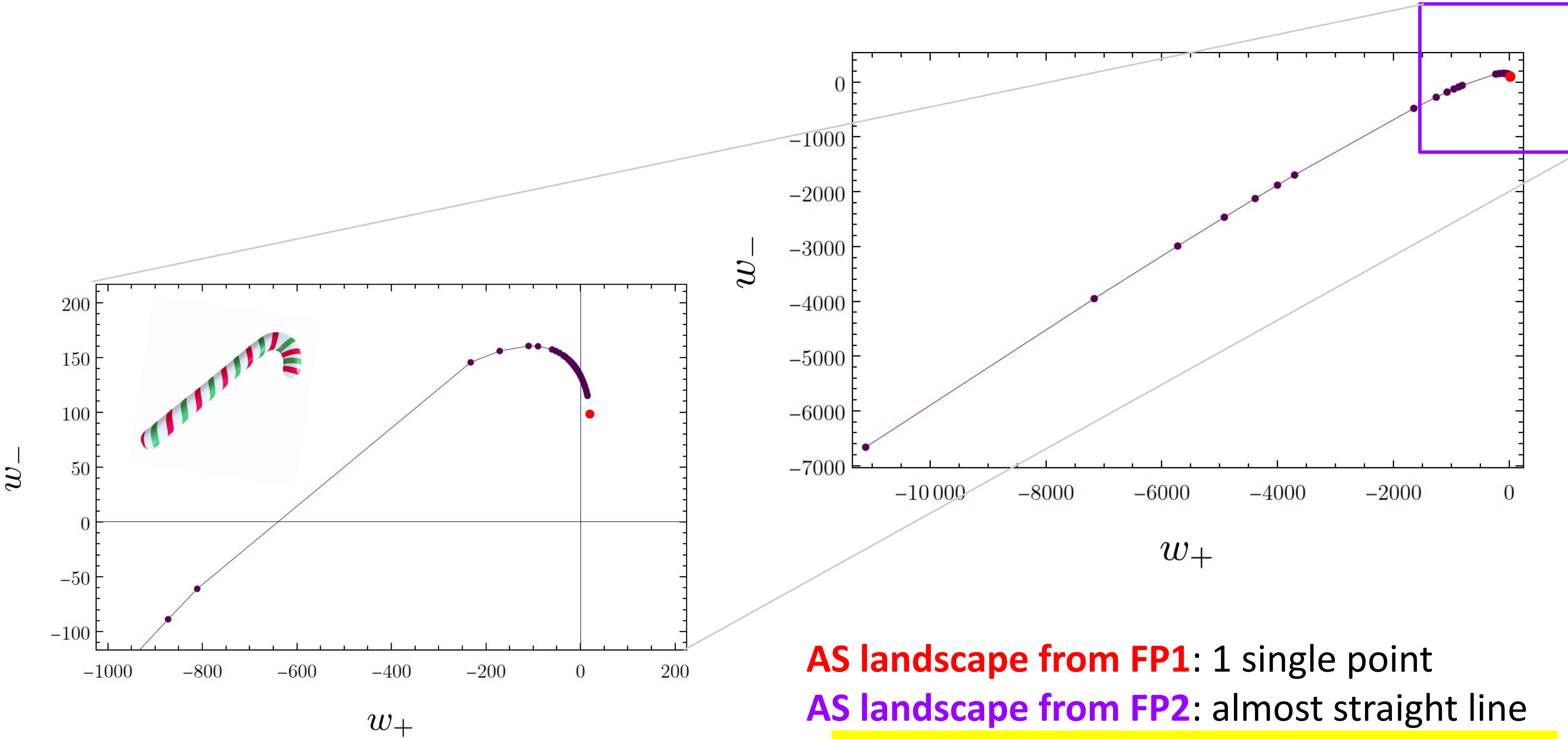

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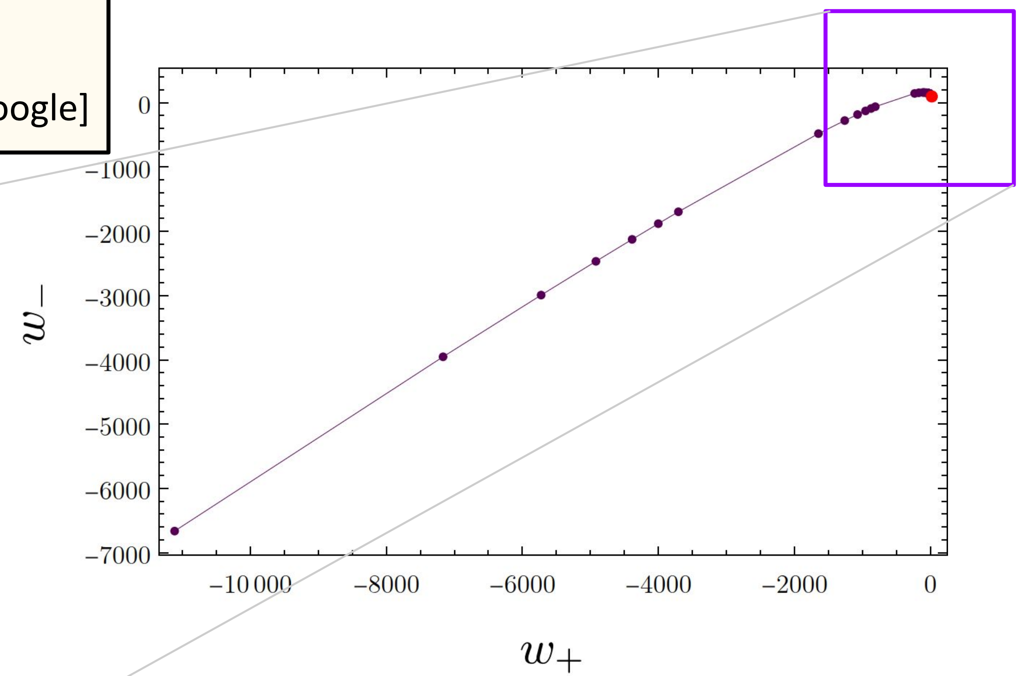
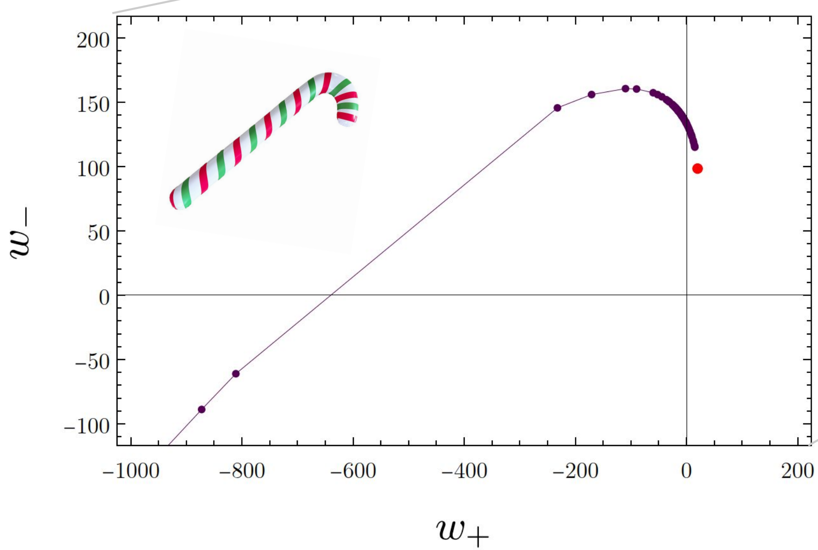
Some important nomenclature…
"*The curved part of the candy cane is called the* ***warble****, and the straight part is called the* ***strabe****.*"
[Google]





AS landscape from FP1: 1 single point

AS landscape from FP2: almost straight line

+ small "candy cane" regime which connects the two

(Some) positivity bounds and the Weak Gravity Conjecture

- **Positivity bounds:**

$$w_+ > w_- \,, \quad 3w_+ - w_- - 2|w_C| > 0$$

[Carrillo González, de Rham, Jaitly, Pozsgay, Tokareva, '23]

- **Electric WGC in the presence of higher derivatives**

$$3w_+ - w_- + 2w_C > 0$$

[Cheung, Liu, Remmen, '18]

Caveats

- **CAVEAT: ambiguity in defining the logs in the presence of massless poles, positivity bounds are typically identified in theories with massive DOF that are integrated out**

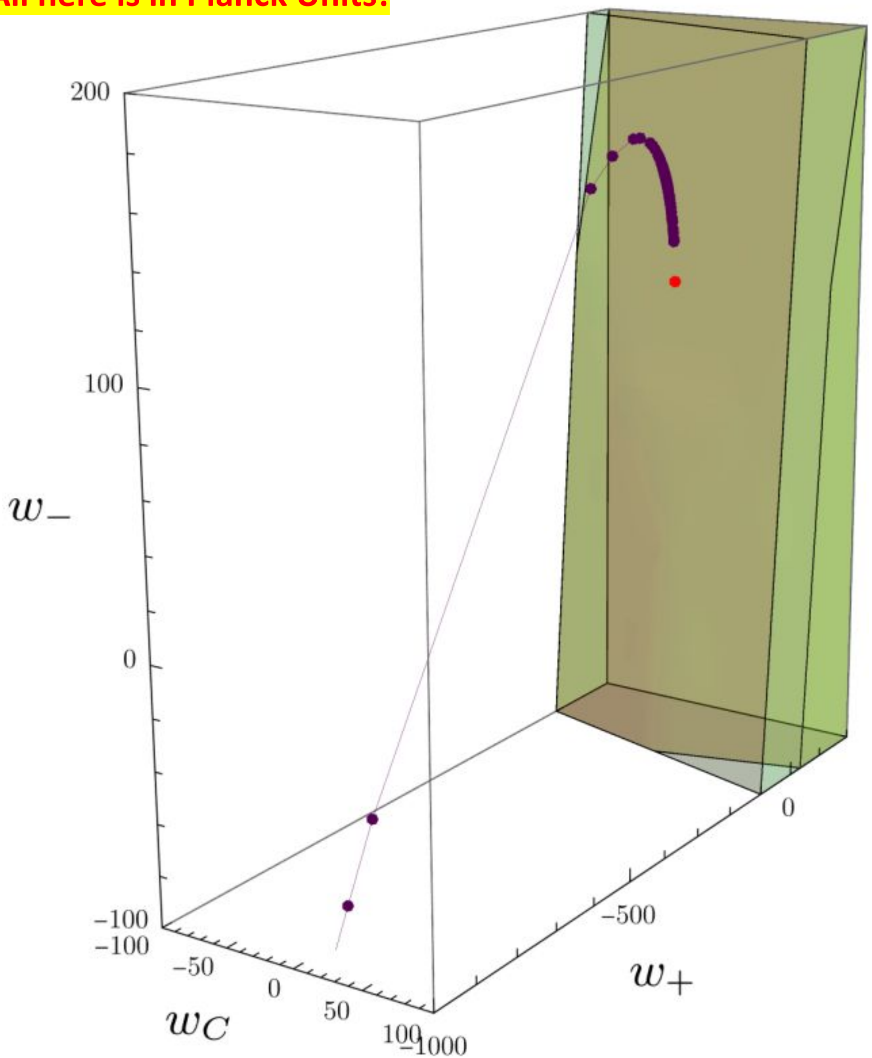
- **EXPECTATION: Standard positivity bounds may be violated in the presence of gravity**

$$c > 0 \quad \rightarrow \quad c > -\mathcal{O}(1)\, M^{-2} M_{Pl}^{-2}$$

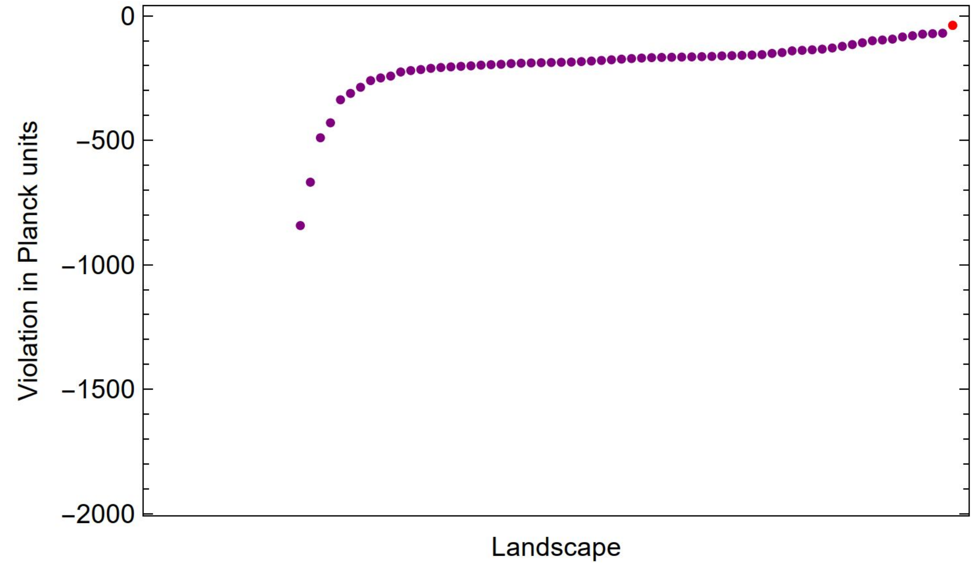
[See talk by Shuang-Yong Zhou]

[Alberte, de Rham, Jaitly, Tolley, '20+'21)]

All here is in Planck Units!



[Knorr, AP, 2405.08860]



Planck-scale suppressed violations of WGC and positivity bounds:

- In the "*strabe*" part of the landscape the violation gets larger, in the "*warble*" it is minimized.
- The landscape from the most predictive FP minimizes the violation.

Compatible with expectations/conjectures from EFT in the presence of massless poles:
Alberte, de Rham, Jaitly, Tolley, PRD 102, 125023 (2020)

Summary

- *Computing QG landscapes: "killing N birds with one stone"*
  Testing swampland conjectures in other approaches to quantum gravity, e.g., asymptotic safety
  Testing consistency of QG predictions (from different approaches): positivity positivity bounds
  ST vs AS landscape (vs others?): comparing predictions
  String Lamppost Principle: do swampland conjectures identify the string landscape or are more general?

- **Very clear recipe in asymptotic safety**:
  - Start from UV fixed point, integrate the FRG flow down to the IR, identify AS landscape
  - Find intersections: swampland constraints, positivity bounds, observations, other QG landscapes

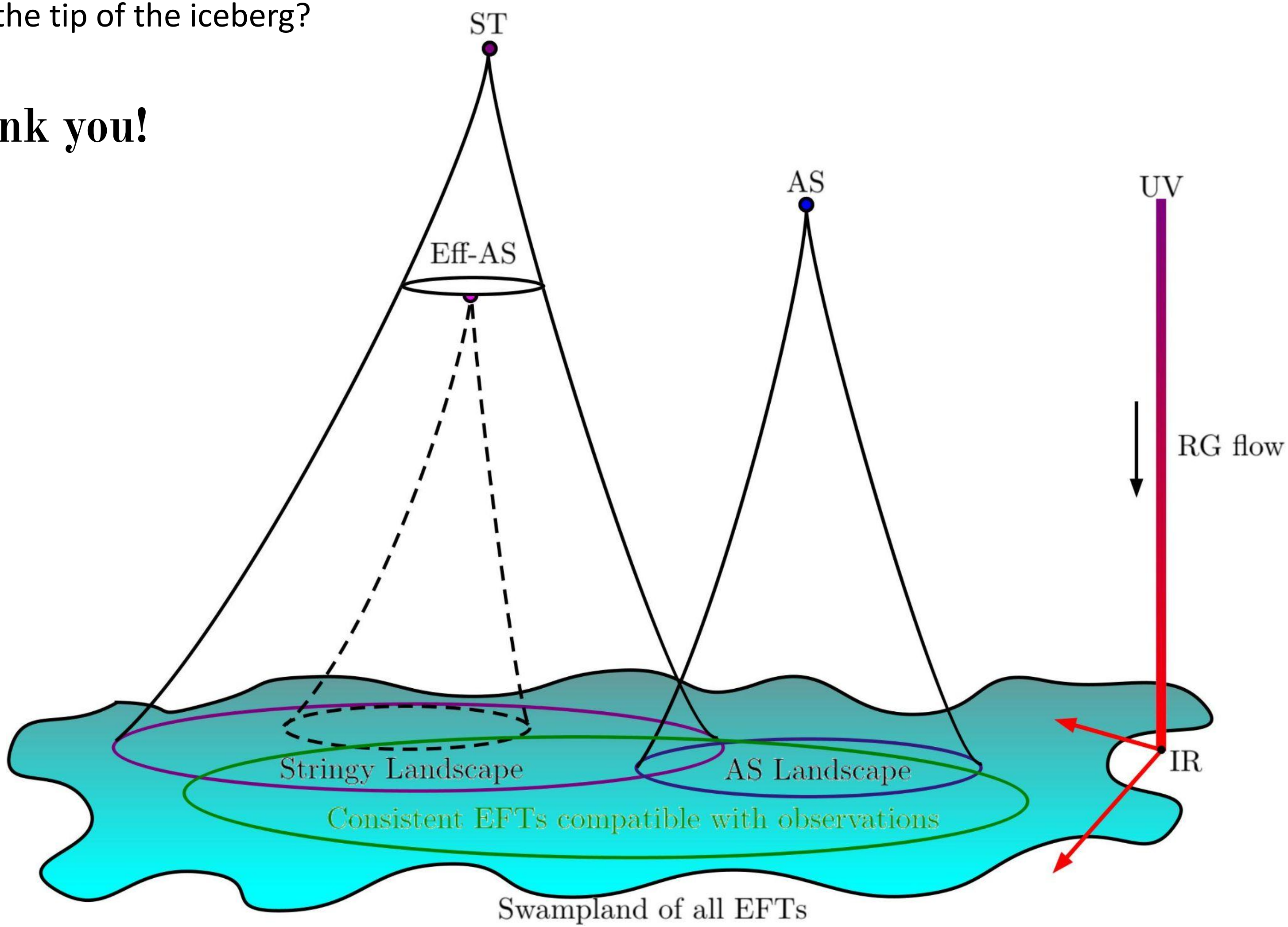
- **<u>Case study 1</u>: AS landscapes in one-loop quadratic gravity**
  Caveats: toy model, not full FRG computation, not all swampland criteria, electromagnetic duality assumed
  - Non-trivial intersection
  - WGC is satisfied, de Sitter and trans-Planckian can be violated

- **<u>Case study 2</u>: AS landscapes in non-perturbative photon-graviton systems**
  Caveats: toy model, definitions of Wilson coefficients with logs is ambiguous
  - Planck-scale-suppressed violations of positivity bounds
  - Violation is minimized by the most predictive fixed point / the smaller sub-landscape (one point)

- **Common feature of models 1 and 2: *<u>Near-flatness of the AS landscape?</u>***
  Coincidence or universal pattern? Implications? Fundamental explanation?

…merely the tip of the iceberg?

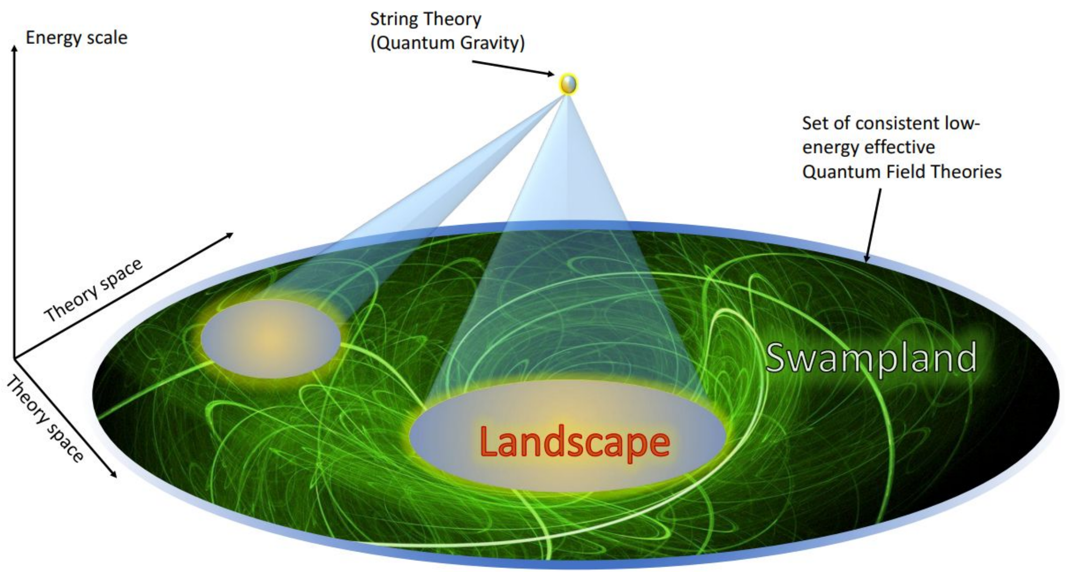
Thank you!



One Attempt within String Theory: The Swampland Program

- **What: Swampland Program**: aims at identifying the "string landscape" of EFTs coming from its UV completion

- **How: via Swampland "Criteria"**, tied to string (mostly susy) constructions:
    - Partially inspired by ST (but also from general considerations, e.g., BH physics and cosmology);
    - Tested within string models, no counterexamples

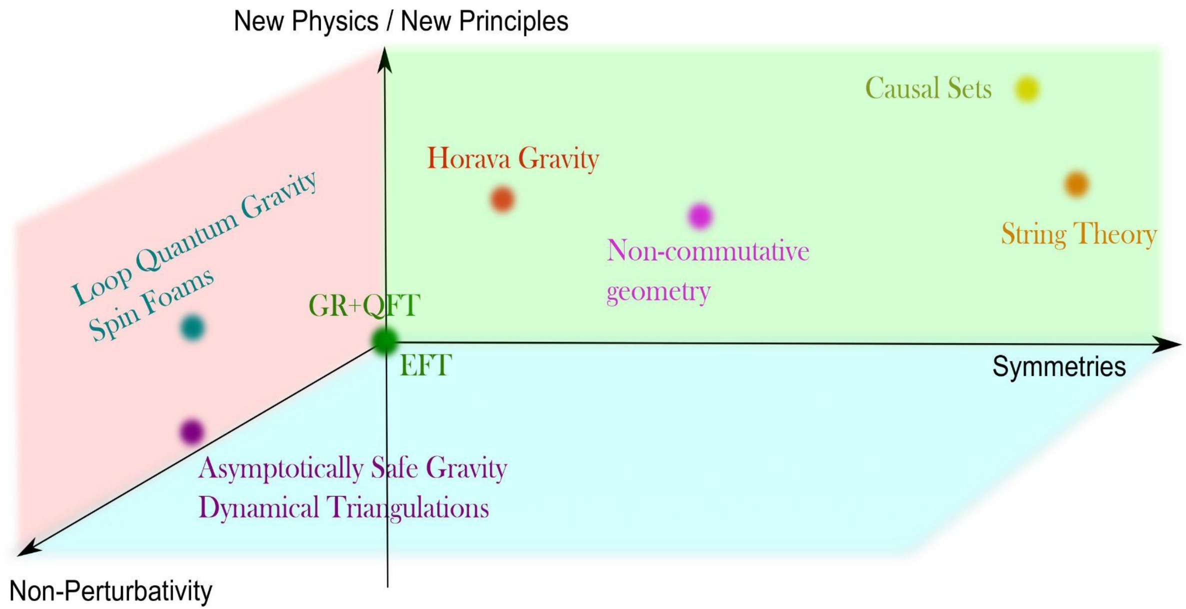


E. Palti (2019)

The realm of Quantum Gravity

Several theories:

- String Theory
- Asymptotically Safe Gravity
- Dynamical Triangulation
- Non-local gravity
- Loop quantum gravity
- Group field theory
- Causal sets
- Horava gravity
- ...

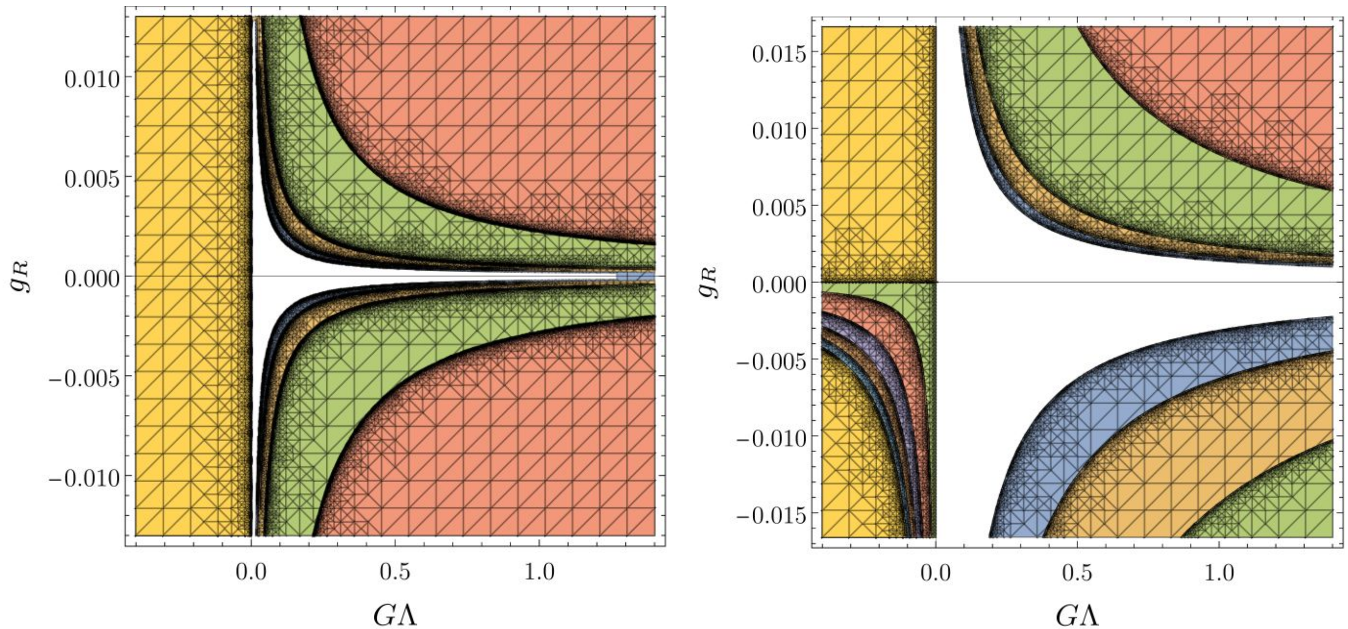


Goals:

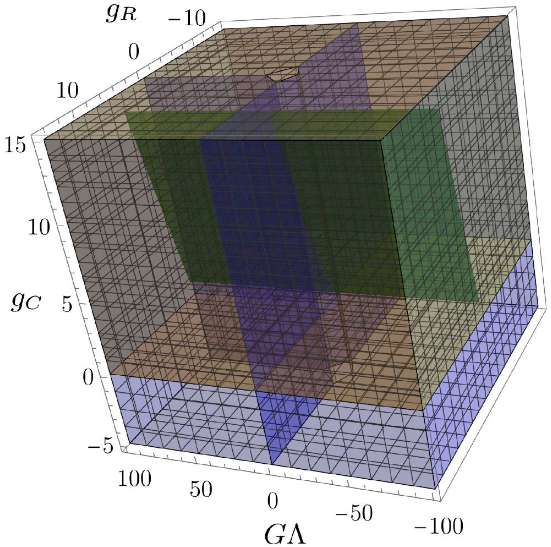
- Consistency: Renormalizability, unitarity, compatibility with large scale physics & observations
- Predictions: quantum cosmology, quantum black holes, scattering amplitudes, grav. Waves
- Comparison between approaches?

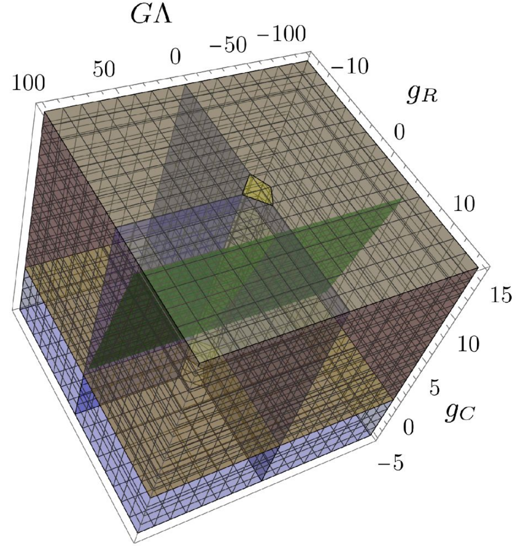
- **<u>Swampland conjectures</u>**:

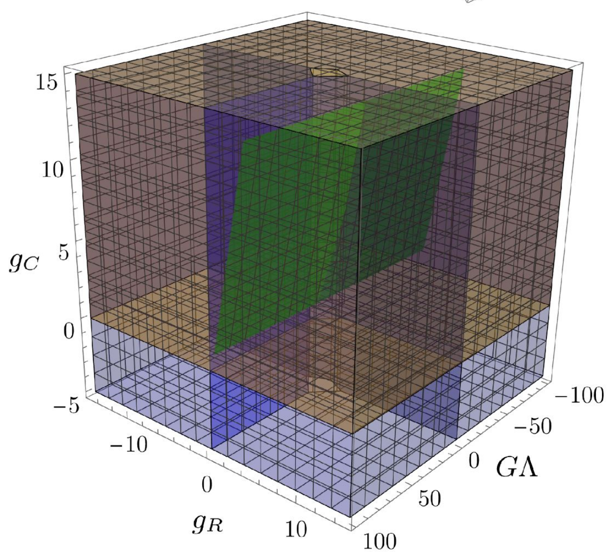
  ➔ **De Sitter and trans-Planckian conjectures**

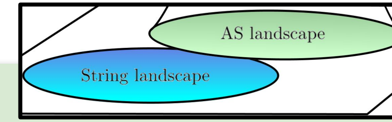


$$0 \leq c \leq 3.5, \quad f = 0.1 \text{ (left)}, \quad f = 1 \text{ (right)}$$







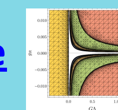


Green plane:

AS landscape [one-loop quadratic approx]

$$\mathrm{EFT}_{\mathrm{AS}} \approx \{g_R = -0.74655 - \frac{2}{3}\,\omega_-\, g_C\} \qquad g_C > 0$$

$\forall g_C$



Blue hyperplane:

Stringy “no de Sitter” conjecture

[~ no positive cosmological constant]

Yellow hyperplane:

Weak gravity conjecture

[~ gravity is the weakest force] $g_C > 0$

Within this simple model of AS, and only some swampland conjectures

⇒ **non-trivial intersection (partial compatibility?)**

[Basile, AP. 2107.06897]

- **Swampland conjectures**:

  - **De Sitter conjecture** [(Obied, Ooguri, Spoyneiko, Vafa, 2018), (Ooguri, Palti, Shiu, Vafa, 2019)]

$$M_{Pl}||\nabla V|| \geq cV \quad \text{for } \Delta\phi \leq f M_{Pl} \qquad f, c \sim \mathcal{O}(1)$$

  - **Trans-Planckian conjecture** [(Bedroya, Vafa, 2020)]

    Relevant for early-universe cosmology. Special value of c:

$$c = \frac{2}{\sqrt{(d-1)(d-2)}}$$

In the case of higher-derivative gravity V is the potential of the additional scalar mode in the F(R) part of the action. In our case this is a **Starobinsky-like potential:**

$$V(\phi) = \frac{M_{\text{Pl}}^2}{8\pi} e^{-2\sqrt{\frac{2}{3}}\frac{\phi}{M_{\text{Pl}}}} \left(\frac{3m^2}{4} \left(e^{\sqrt{\frac{2}{3}}\frac{\phi}{M_{\text{Pl}}}} - 1 \right)^2 + \Lambda \right) \qquad g_R = -\frac{M_{\text{Pl}}^2}{(8\pi)\cdot 12m^2}$$

$\Rightarrow$ Non-trivial bounds for different f and c.

[Knorr, AP, 2405.08860]

- **AS model**: photon-graviton systems at quadratic order, only **essential couplings** included

[see Knorr's talk!]

$$\mathcal{L} = -\frac{R}{16\pi G_N} + \Theta_E\, E + \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + G_2\,(F^{\mu\nu}F_{\mu\nu})^2 + G_4\, F^{\mu}{}_{\nu} F^{\nu}{}_{\rho} F^{\rho}{}_{\sigma} F^{\sigma}{}_{\mu} + G_{CFF}\, C^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

- **Three dimensionless Wilson coefficients (redefined for convenience; only one log-presc. ambiguity)**

$$w_+ = \frac{1}{2}\frac{G_2 + G_4}{(16\pi G_N)^2}\,, \quad w_- = \frac{1}{2}\frac{G_2 - G_4}{(16\pi G_N)^2} + b\,\ln\left[16\pi G_N k^2\right]\,, \quad w_C = \frac{G_{CFF}}{16\pi G_N}$$

- **Two UV fixed points:**

FP1: one relevant direction (most predictive!)

$$g^* = 0.131\,, \quad g_+^* = 0.351\,, \quad g_-^* = 3.327\,, \quad g_{CFF}^* = 0.00375$$
$$\theta_1 = 1.845\,, \quad \theta_{2,3} = -0.239 \pm 0.0155\mathbf{i}\,, \quad \theta_2 = -0.291$$

FP2: two relevant directions

$$g^* = 0.126\,, \quad g_+^* = -0.308\,, \quad g_-^* = 4.001\,, \quad g_{CFF}^* = -0.00410$$
$$\theta_1 = 1.936\,, \quad \theta_2 = 0.184\,, \quad \theta_3 = -0.141\,, \quad \theta_4 = -0.236$$