

Terascale Gravity: Braneworld at the Center of a Star Shape Bulk

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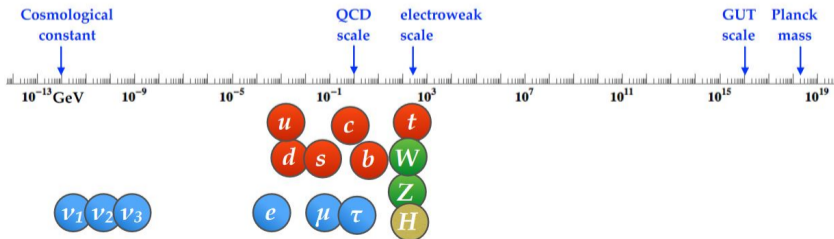
Introduction – Naturalness vs Flavor & Electroweak Hierarchies

Flavor Hierarchy vs Naturalness

- **Mass Hierarchy:** $M_\nu \ll M_e \ll M_t \Rightarrow$ Dynamical Mechanism?
- **Technically Natural:** Custodial Chiral Symmetry BUT \perp Dirac Naturalness (Aestheticism).

Electroweak Hierarchy vs Naturalness

- **Gauge Hierarchy:** $\Lambda_{EW} \ll \Lambda_P \perp$ Dirac Naturalness \Rightarrow Dynamical Mechanism?
- **Technically Unnatural:** Higgs Boson Mass $\delta M_H^2 \propto \Lambda_{UV}^2 \Rightarrow$ New Custodial Symmetry?
- **Naturalness Under Stress:** No Evidence for TeV Scale Mechanism \Rightarrow Beyond Simplest Scenarios?



Talk: [Electroweak](#) & [Neutrino Hierarchies](#) via [Braneworld Models](#).

1 Introduction – Naturalness vs Flavor & Electroweak Hierarchies

2 Braneworlds with Large Extra Dimensions (LED's)

- Effective Field Theory
- Terascale Gravity
- Geometrical Hierarchy Problem
- Collider Phenomenology

3 Star Shape Bulk

- Stringy Inspiration
- Dandelion Universe Model
- 1st Glance at Phenomenology
- Tiny Neutrino Masses
- Landscape or Swampland?

4 Summary & Outlook

Braneworlds with LED's – Effective Field Theory

[Sundrum, Phys. Rev. D 59 (1999) 085009], [Nortier, arXiv:2007.04266]

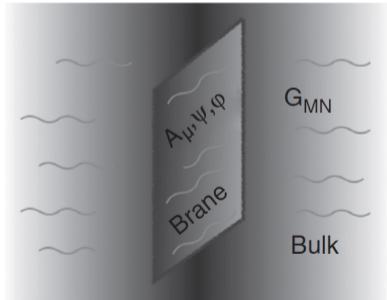
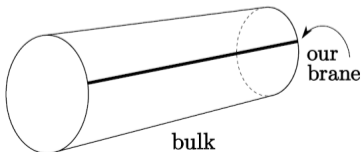
- **Bottom-Up Models:** Compactified Extra Dimensions of Space + δ -like Branes + UV Cutoff Λ_{UV} .
- 5D e.g. 1 Flat Extra Dimension + 1 Brane Embedded in Bulk at $y = 0$:

$$S_{5D} = \int d^4x dy [\mathcal{L}_{bulk} + \Delta(y) \mathcal{L}_{brane}], \quad \Delta(y) = \delta(y) + \sum_{k=1}^{\infty} \frac{\delta^{(k)}(y)}{\Lambda_{UV}^k}.$$

- **Kaluza-Klein (KK) Dimensional Reduction** (5D \rightarrow 4D):
 - 4D KK modes $\phi_n(x)$ + Bulk Wave Functions $f_n(y)$:

$$\Phi(x, y) = \sum_n^{\infty} f_n(y) \phi_n(x).$$

- **KK Mass Spectrum** (\sim QM: Particle in Box).

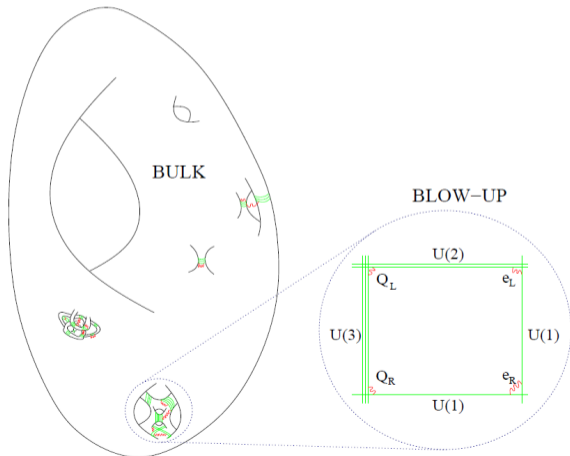


Braneworlds with LED's – Terascale Gravity

[Arkani-Hamed, Dimopoulos, Dvali, Phys. Lett. B 429 (1998) 263-272],

[Antoniadis, Arkani-Hamed, Dimopoulos, March-Russell, Phys. Lett. B 436 (1998) 257-263]

- **EFT**: $q \in \mathbb{N}^*$ Compactified Extra Dimensions of Space + (4D) SM Fields "Stuck" on 3-Brane.
- **Interest**: (4D) Planck Scale Λ_P vs Fundamental Gravity Scale Λ_G
 $\Rightarrow \Lambda_P^2 = \Lambda_G^{q+2} \mathcal{V}_q$
 - Λ_P just an Effective Scale.
 \Rightarrow Gravity Strongly Coupled at Λ_G .
 - Large Compactification Volume \mathcal{V}_q
 $\Rightarrow \Lambda_G \ll \Lambda_P!$
- **Terascale Gravity**: $\Lambda_G \sim 1 \text{ TeV}$
 $\Rightarrow \Lambda_{EW} \lesssim$ Fundamental Scale!
- **UV Completion**: String Theory?
 \Rightarrow D-brane Stacks.



Braneworlds with LED's – Geometrical Hierarchy Problem

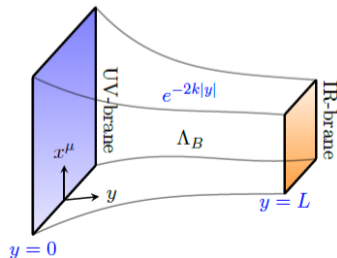
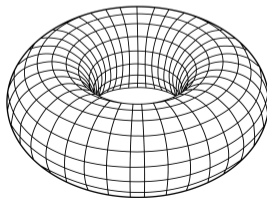
[Arkani-Hamed, Dimopoulos, Dvali, Phys. Rev. D 59 (1999) 086004], [Randall, Sundrum, Phys. Rev. Lett. 83 (1999) 3370-3373],

[Arkani-Hamed, Dimopoulos, March-Russell, Phys. Rev. D 63 (2001) 064020]

- **Geometry:** Compactification on a q -Dimensional **Square Torus** \mathbb{T}^q of Volume $\mathcal{V}_q = (2\pi R)^q$.
- **Spectrum of Gravitons:** $M_n = n/R$, $n \in \mathbb{N} \Rightarrow$ 1 zero mode \equiv **Massless Graviton!**
- **Geometrical Hierarchy Problem:** For $q \leq 6$ (Superstring Theories) $\Rightarrow R \gg \ell_G$.
 - \Rightarrow **Difficult to Stabilize** (Crystal of $N \gg 1$ Branes).
 - \Rightarrow Motivation for **Warped Extra Dimensions**.

q	R (m)	R/ℓ_G	M_{KK} (eV)
2	8×10^{-5}	4×10^{14}	3×10^{-3}
4	2×10^{-12}	8×10^6	1×10^5
6	4×10^{-15}	2×10^4	5×10^7

Table for $\Lambda_G = 1/\ell_G = 1$ TeV.

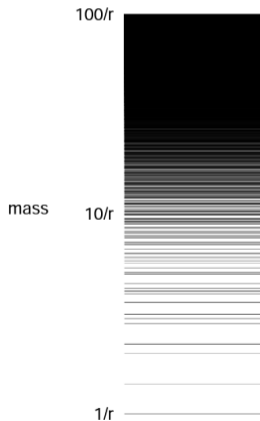
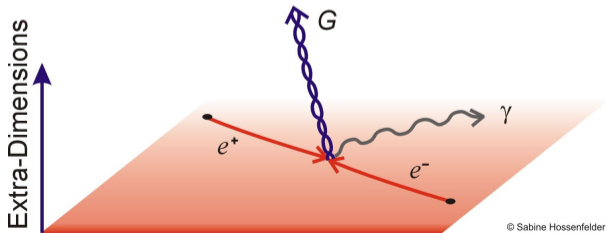


Braneworlds with LED's – Collider Phenomenology (1/2)

[Particle Data Group, PTEP 2022 (2022) 083C01]

Sub-Planckian Regime ($\sqrt{s} \ll \Lambda_G$):

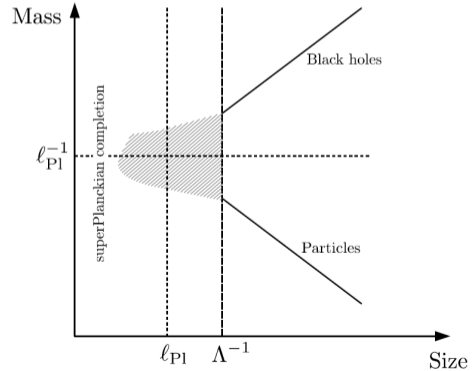
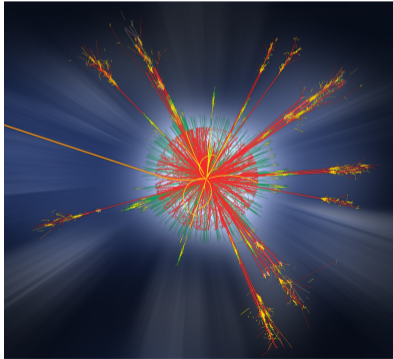
- Quasi-Continuum of KK-Gravitons at LHC $\sqrt{s} = 13$ TeV ($M_n = n/R$ with $R \ll \Lambda_G \sim 1$ TeV).
- $N_G \sim 10^{30} \gg 1$ KK-Gravitons Coupled to SM Fields.
- Effective Suppression $\sim 1/\Lambda_G^{q+2}$, not $1/\Lambda_P^{q+2} \Rightarrow$ Can Be Probed at LHC!
- LHC Bounds: $\Lambda_G \gtrsim 5 - 10$ TeV \Rightarrow Little Hierarchy Problem!



Braneworlds with LED's – Collider Phenomenology (2/2)

[Park, Prog. Part. Nucl. Phys. 67 (2012) 617-650]

- **Trans-Planckian Regime** ($\sqrt{s} \gg \Lambda_G$): Semi-Classical \rightarrow **Mini Black Hole Production!**
 \Rightarrow Not Possible at LHC but at FCC pp ($\sqrt{s} = 100$ TeV)!
- **Planckian Regime** ($\sqrt{s} \sim \Lambda_G$): **Quantum Gravity!** \Rightarrow Can Be Probed at LHC!
BUT: Can Only Be Described in (Unknown) **UV Completion!**



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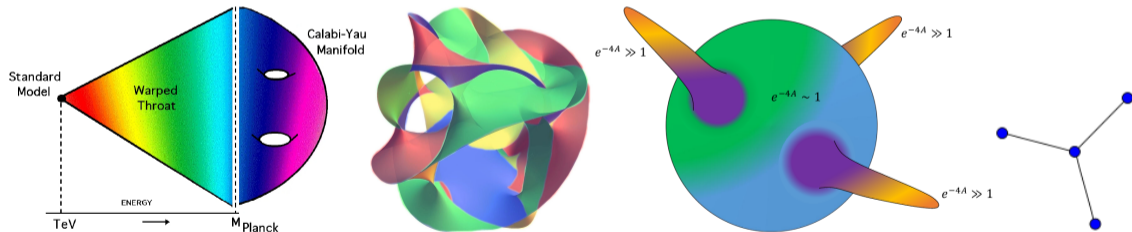
Star Shape Bulk – Stringy Inspiration

[Kim, JHEP 01 (2006) 090], [Cacciapaglia, Csaki, Grojean, Terning, Phys. Rev. D 74 (2006) 045019]

- **Braneworld Literature:** Compactification on Simple Geometries (Torus and its Orbifolds).

- **Type IIB Superstring Theory:**

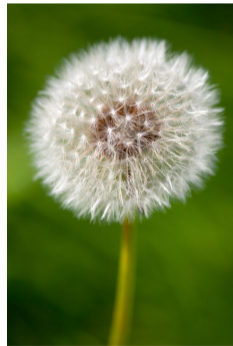
Warped Conifolds Glued on Calabi-Yau Manifold $\xrightarrow{\text{IR Limit}}$ Star Graph with Warped Leaves.



\Rightarrow New Compactifications on **Quantum Graphs** to Investigate in **Bottom-Up Approaches!**

Star Shape Bulk – Dandelion Universe Model

- **Publication:** Nortier, *Int. J. Mod. Phys. A* 35 (2020) 30, 2050182.
- **Geometry:** Compactification on **Star Graph** with $N \gg 1$ **Leaves** \Rightarrow **Dandelion Universe Model**.
+ **Permutation Symmetry** Σ_N btw **Leaves** of Length ℓ + **Flatness** Limit.
 \Rightarrow Volume $L = N\ell \gg \ell$.
- **Benchmark Point:** $\Lambda_G \sim 1 \text{ TeV} + \ell \sim 1/\Lambda_{EW} \Rightarrow N \sim 10^{30} \gg \gg 1! \Rightarrow$ Technical Naturalness Only!
- **Braneworld:** (4D) **SM Fields** "Stuck" on the **Central Vertex** \equiv **SM-Brane**.



Star Shape Bulk – 1st Glance at Phenomenology (1/2)

[Nortier, Int. J. Mod. Phys. A 35 (2020) 30, 2050182]

KK Dimensional Reduction of Bosonic Fields (5D \rightarrow 4D) \Rightarrow KK Scale $M_{KK} = 1/\ell$:

- 2 Kinds of KK-Modes: Wave Functions = 0 or $\neq 0$ on SM-Brane (Because of Σ_N Symmetry).
- KK Spectrum – Tower 1 (Coupled to SM-Brane):

$$M_n^{(1)} = n_1 \left(\frac{\pi}{\ell} \right), \quad n_1 \in \mathbb{N}.$$

Zero Mode + Each Level $n_1 \rightarrow$ Not Degenerate.

- KK Spectrum – Tower 2 (Not Coupled to SM-brane):

$$M_n^{(2)} = \left(n_2 + \frac{1}{2} \right) \frac{\pi}{\ell}, \quad n_2 \in \mathbb{N}^*.$$

No Zero Mode + Each Level $n_2 \rightarrow N - 1$ Degenerate.
 \Rightarrow Large Hidden Sector!



Star Shape Bulk – 1st Glance at Phenomenology (2/2)

[Nortier, Int. J. Mod. Phys. A 35 (2020) 30, 2050182]

- **Benchmark Point:** $N_G \sim 1$ KK-Gravitons Coupled to SM-Brane with **Suppression** $1/\Lambda_P^{3/2}$.
⇒ **Invisible at LHC!** \neq Toroidal Compactification!
- Including **Brane Width:**

$$\Delta(y) = \delta(y) + \sum_{k=1}^{k_*} \frac{\delta^{(k)}(y)}{\Lambda_G^k}.$$

- $k_* \in \mathbb{N}^*$ ⇒ Only Tower 1 Coupled to SM Still True **Perturbatively**.
- $k_* = \infty$ ⇒ **Nonperturbative** Regime + **UV Completion** ($\sqrt{s} \sim \Lambda_G$).
- **Nonperturbative Gravity Effects** for $\sqrt{s} \gtrsim \Lambda_G$
~ Toroidal Compactification (To Be Studied).
- Extra **Global Flavor Symmetries** (No Proton Decay, ...)
⇒ Forbid Dangerous SMEFT Operators on SM-Brane.



Star Shape Bulk – Tiny Neutrino Masses

[Arkani-Hamed, Dimopoulos, Dvali, March-Russell, Phys. Rev. D 65 (2001) 024032], [Nortier, Int. J. Mod. Phys. A 35 (2020) 30, 2050182]

- Toy Model:

- Global Flavor Symmetries $\supset U(1)_{B-L}$.

- Left-Handed Neutrino $\nu_L \equiv$ 4D Field "Stuck" on SM-Brane.

- Right-Handed Neutrino $\nu_R \equiv$ Chiral Zero Mode of 5D Gauge Singlet Fermion $N = \begin{pmatrix} N_L \\ N_R \end{pmatrix}$.

- 5D Yukawa Coupling $Y_5 \nu_L^\dagger H N_R \delta(y) \Rightarrow$ Dirac Mass (Higgs VEV v).

- Natural Tiny Neutrino Mass (Benchmark Point & $Y_5 \sim \sqrt{\ell_G}$):

$$M_\nu = \frac{Y_5 v}{\sqrt{2L}} \sim v \left(\frac{\Lambda_G}{\Lambda_P} \right) \sim 10^{-4} \text{ eV}.$$

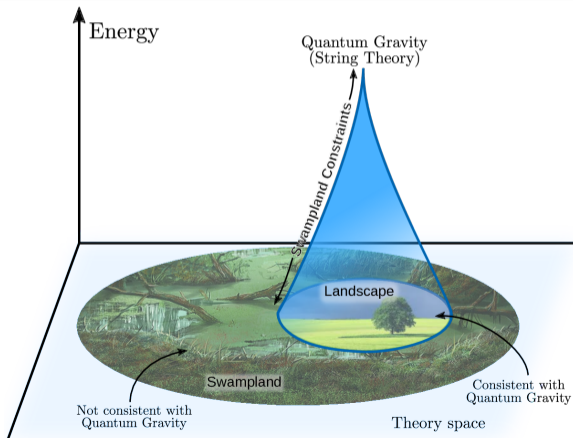
Approximation: $M_\nu \ll M_{KK} \Rightarrow$ KK Mixing Neglected.



Star Shape Bulk – Landscape or Swampland? (1/5)

Landscape vs Swampland [van Beest, Calderon-Infante, Mirfendereski, Valenzuela, Phys. Rept. 989 (2022) 1-50]

Swampland \equiv Set of apparently consistent (anomaly free) quantum EFTs that **cannot be embedded** in a UV consistent theory of quantum gravity \perp **Landscape**.

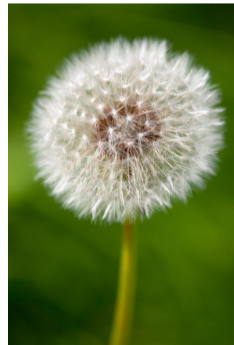
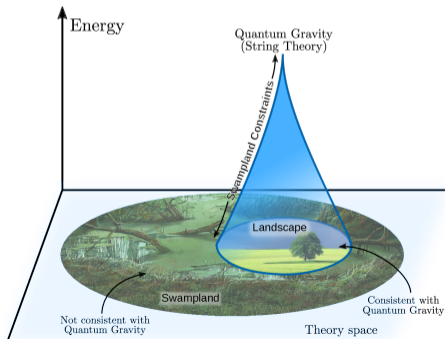


Star Shape Bulk – Landscape or Swampland? (2/5)

No Global Symmetries Conjecture [Banks, Seiberg, Phys. Rev. D 83 (2011) 084019]

Theory with Finite Number of States + Gravity \Rightarrow No Exact Global Symmetries.

- **Global Symmetries of the Dandelion Universe Model:**
Discrete Permutation Symmetry Σ_N + Continuous Flavor Symmetries.
- **Question:** Is the Dandelion in the Landscape or the Swampland?



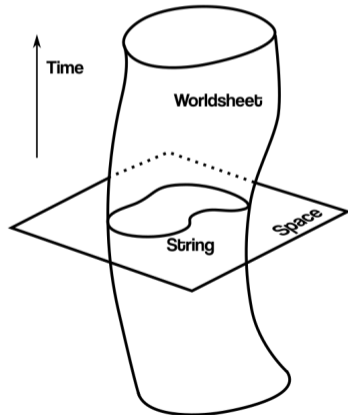
Star Shape Bulk – Landscape or Swampland? (3/5)

Arguments [van Beest, Calderon-Infante, Mirfendereski, Valenzuela, Phys. Rept. 989 (2022) 1-50]

- **String Theory:** Global Symmetry on **Worldsheet** \Rightarrow Gauge Symmetry in **Target Space**.
- **Semi-Classical Gravity:** No Hair Theorem for **Black Holes** (BH's) & Gravitational **Instantons**.

Keeping the Dandelion in the Landscape:

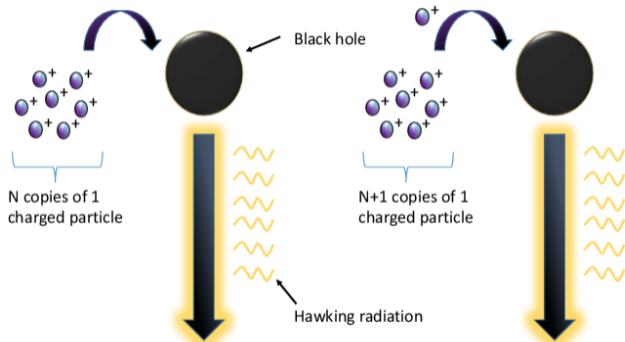
- Continuous & Discrete Symmetries
 \equiv Remnants of Gauge Symmetries (UV Completion?).
- Only Approximate Symmetries (Tiny Breaking)
 \Rightarrow All KK Modes Couple to SM-Brane (No Hidden Sector).
 \Rightarrow Chaotic KK Spectrum + More Constraints!
- Non-Stringy UV Completion:
Robustness of Semi-Classical Arguments?



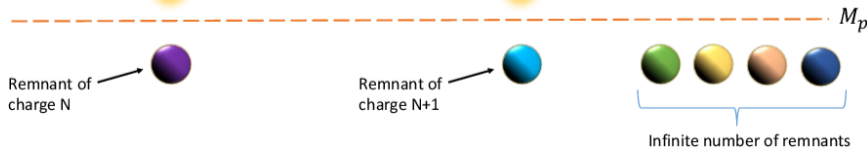
Star Shape Bulk – Landscape or Swampland? (4/5)

[Palti, Fortsch. Phys. 67 (2019) 6, 1900037], [Dvali, Gomez, Phys. Lett. B 719 (2013) 419-423]

Continuous Global Symmetries: BH Evaporation + Global Charge $\Rightarrow \infty$ Number of Remnants!



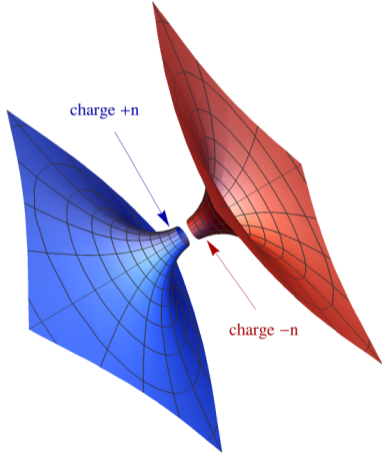
BUT: Quantum Hair?
e.g. Corpuscular Gravity.



Star Shape Bulk – Landscape or Swampland? (5/5)

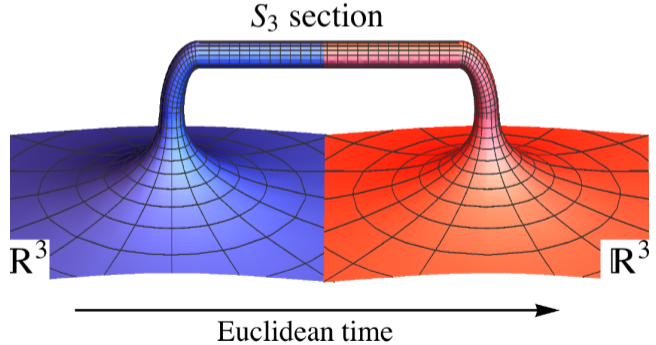
[Hebecker, Mikhail, Soler, Front. Astron. Space Sci. 5 (2018) 35], [Alonso, Urbano JHEP 02 (2019) 136]

Global Symmetry Breaking by Gravitational Instantons: Euclidean Baby Universes / Wormholes.



Instanton

Anti-instanton



BUT: Topology Changes in Euclidean Gravity: **Highly Controversial!** (Wick Rotation, Stability, ...)

Summary & Outlook

Naturalness vs Flavor & Electroweak Hierarchies:

- **Flavor Hierarchy:**
 - \perp Dirac Naturalness.
 - Part of SM Flavor Puzzle + Origin of Neutrino Masses.
- **Electroweak Hierarchy:**
 - \perp Dirac + Technical Naturalness.
 - Many BSM Ideas BUT No Experimental Evidences (Yet) \Rightarrow New Ideas!

II. Braneworlds with LED's:

- **Reformulation:** Electroweak + Neutrino Hierarchies \mapsto Geometrical Hierarchy.
- **Collider Phenomenology:** Quasi-Continuum of KK-Gravitons + TeV Scale Planckian Gravity + Trans-Planckian Mini BH's.

III. Star Shape Bulk:

- **Dandelion Universe Model:** No Geometrical Hierarchy + Invisible KK-Gravitons.
- **Swampland Conjectures:** Global Symmetries BUT Possible Solutions.

Outlook: Neutrino Phenomenology? Nonperturbative Phenomena? Cosmology? UV Completion?