Swampland Constraints on Neutrino Masses and BSM Physics

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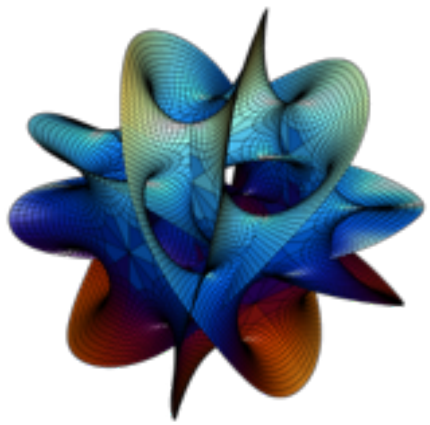
In collaboration with Luis Ibanez and Victor Martin-Lozano

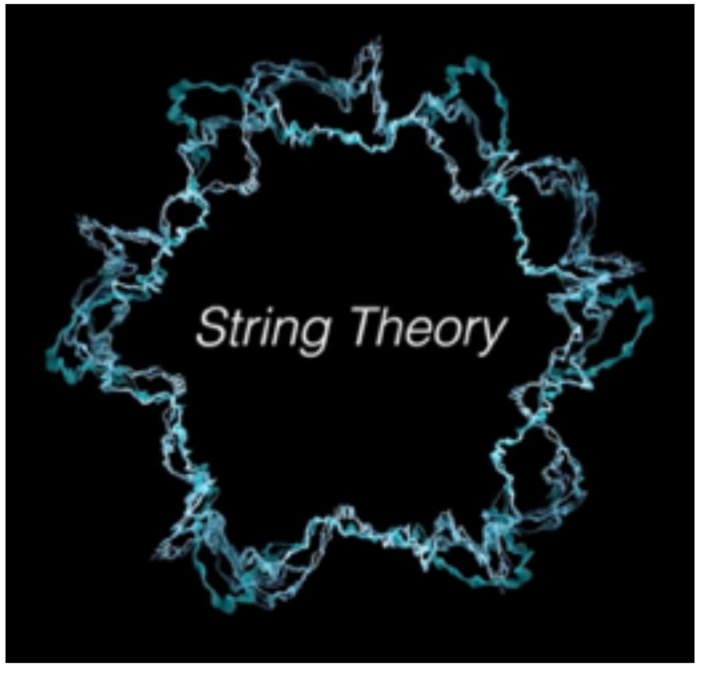
Invisibles 19, Valencia, Spain 2019

String Theory



Our universe

How to test it or get predictions for our universe?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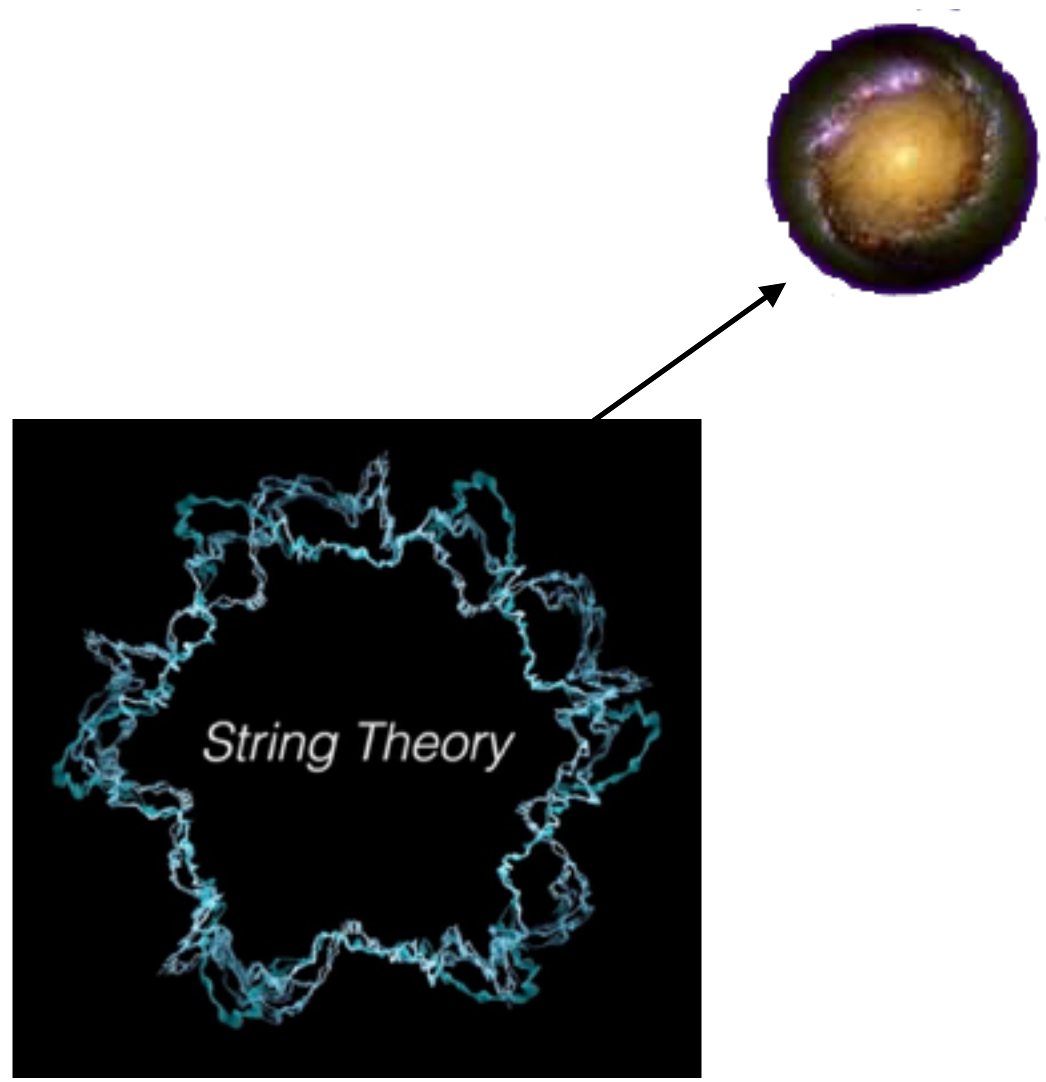
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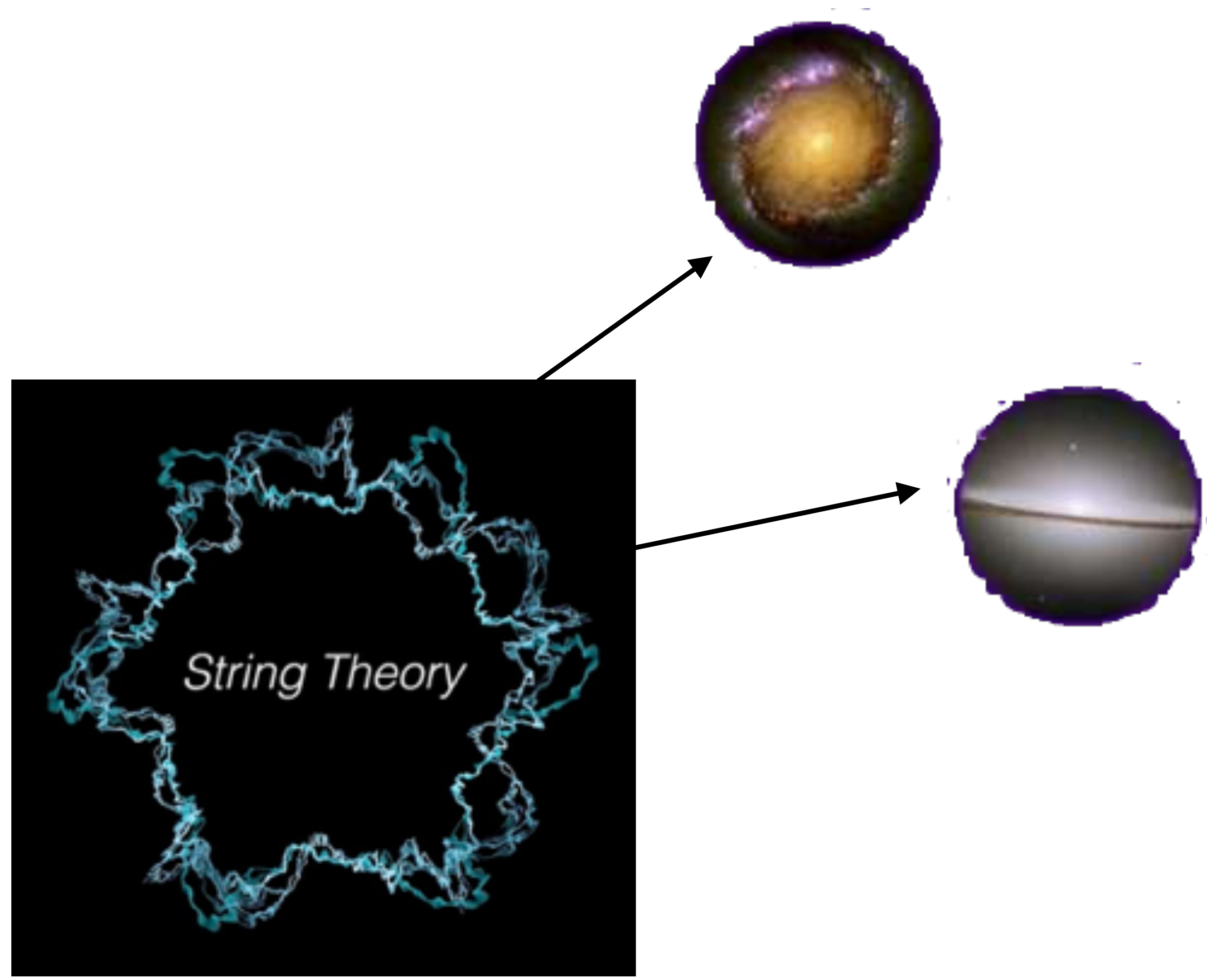
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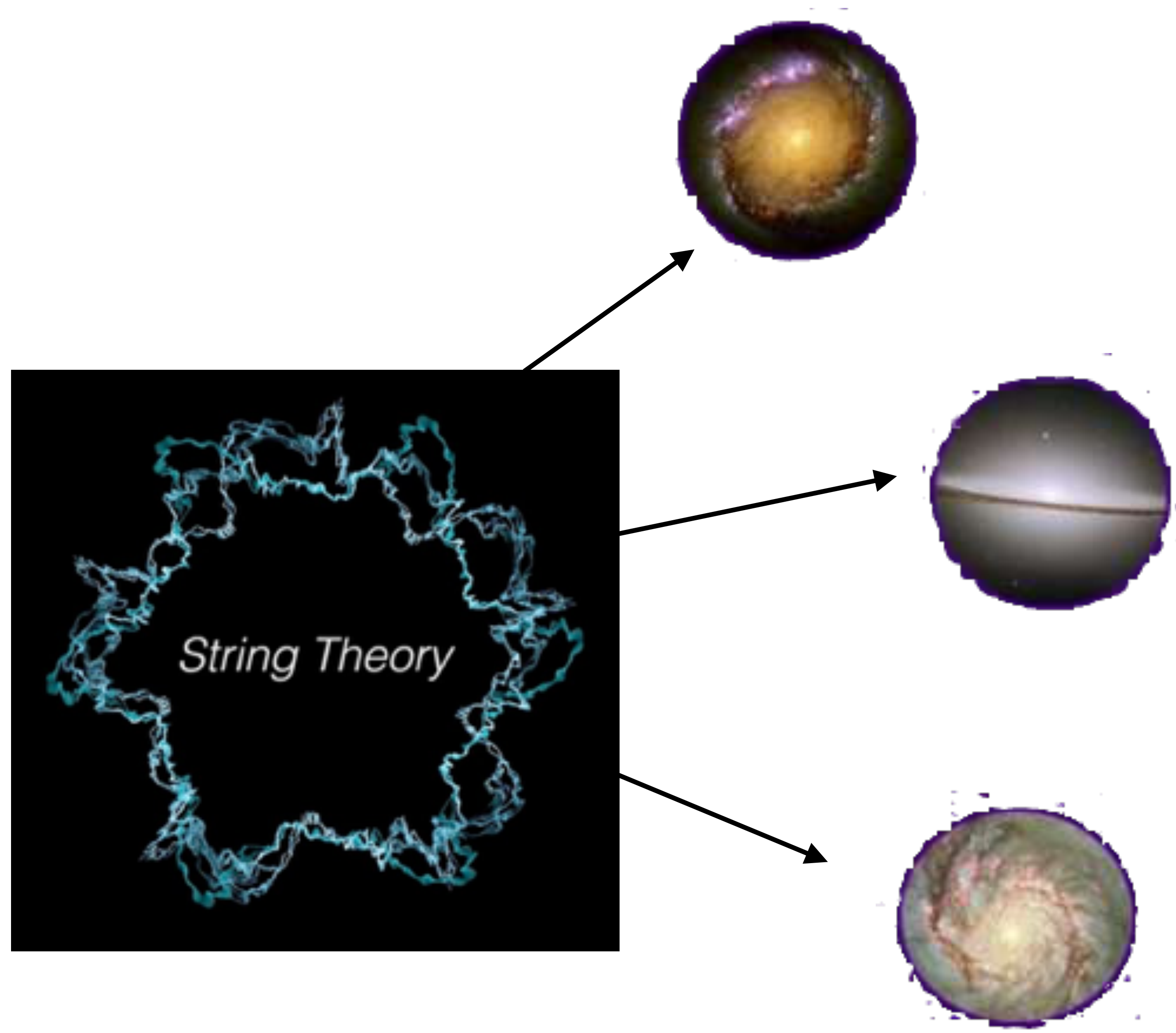
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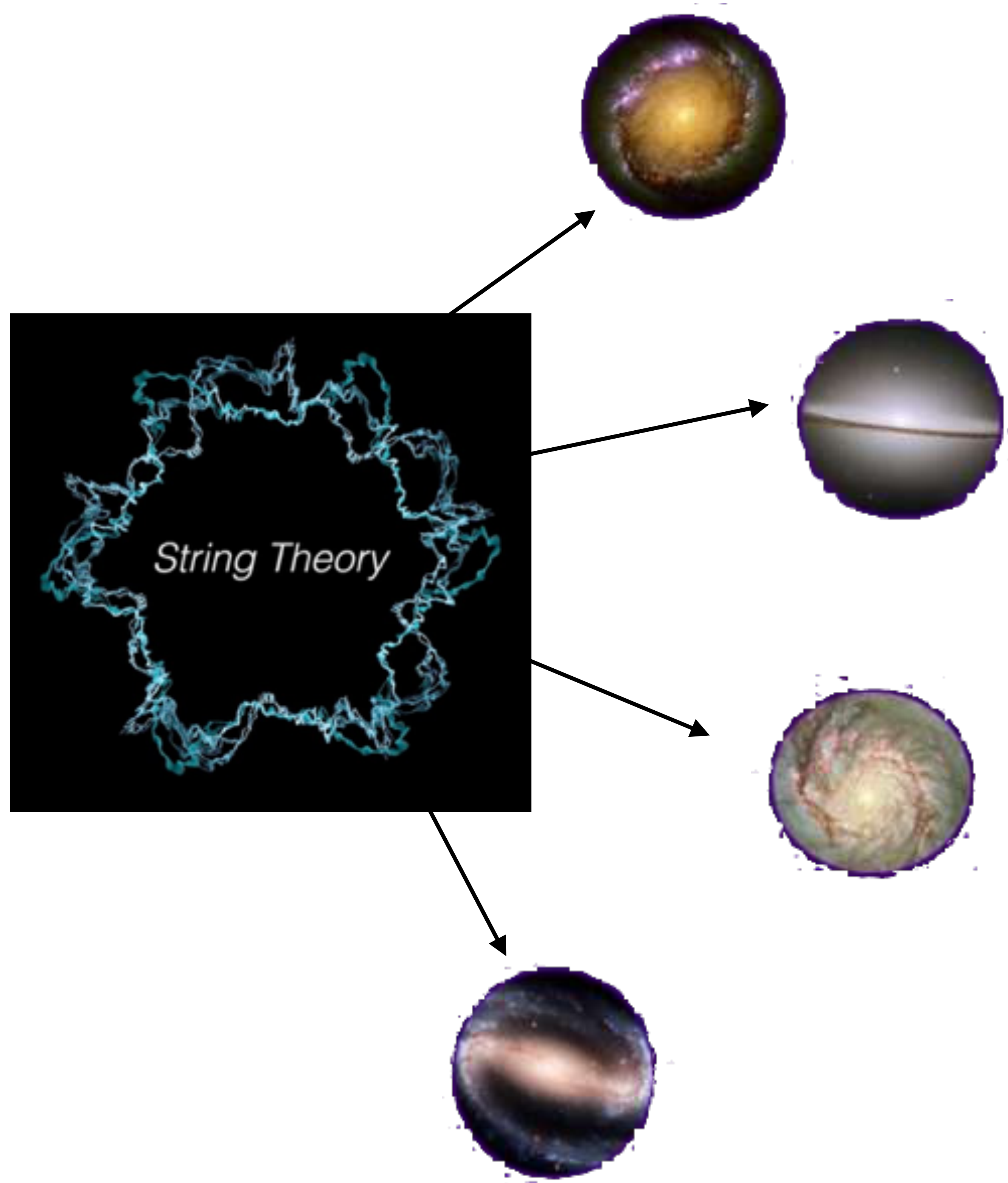
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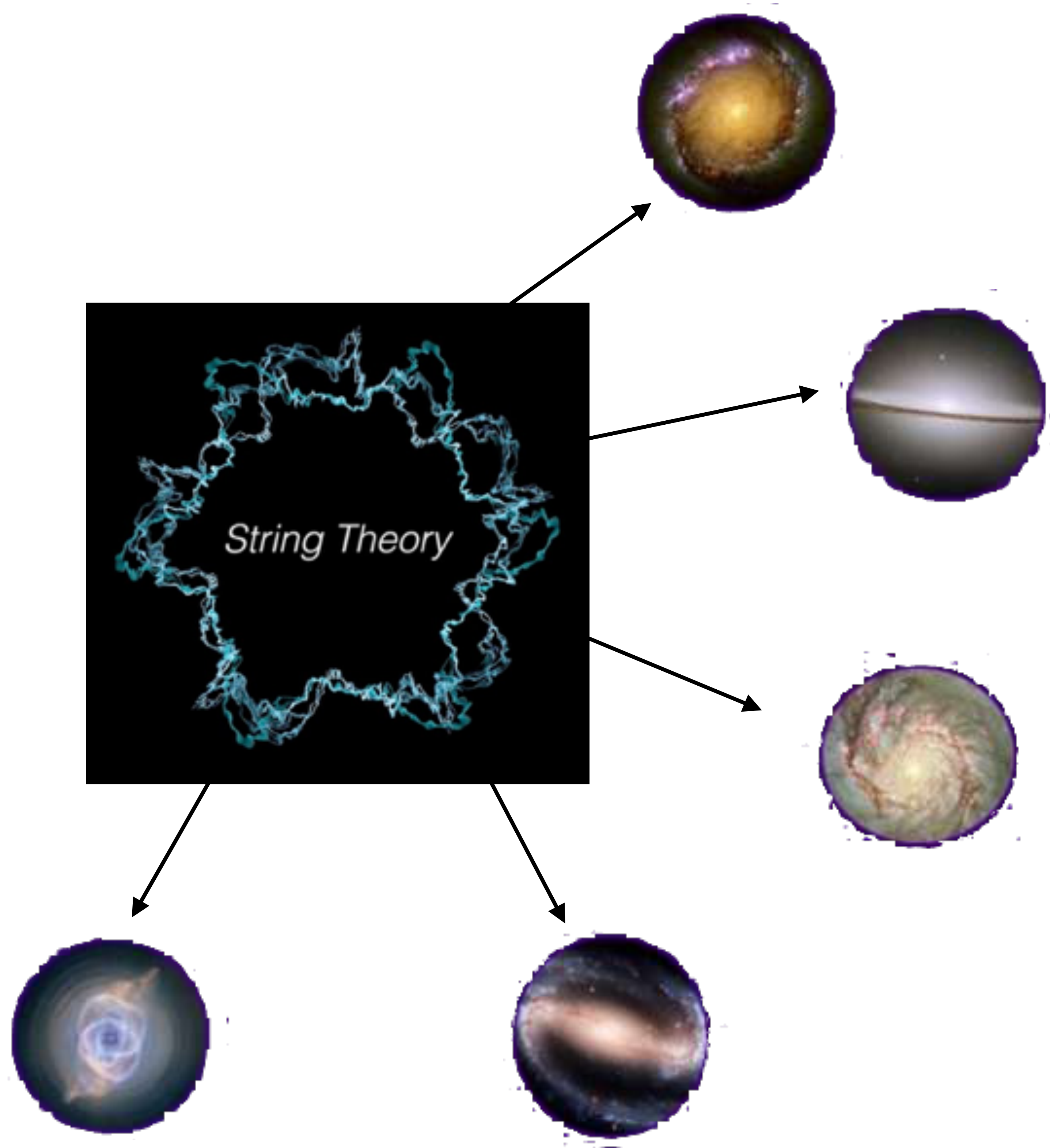
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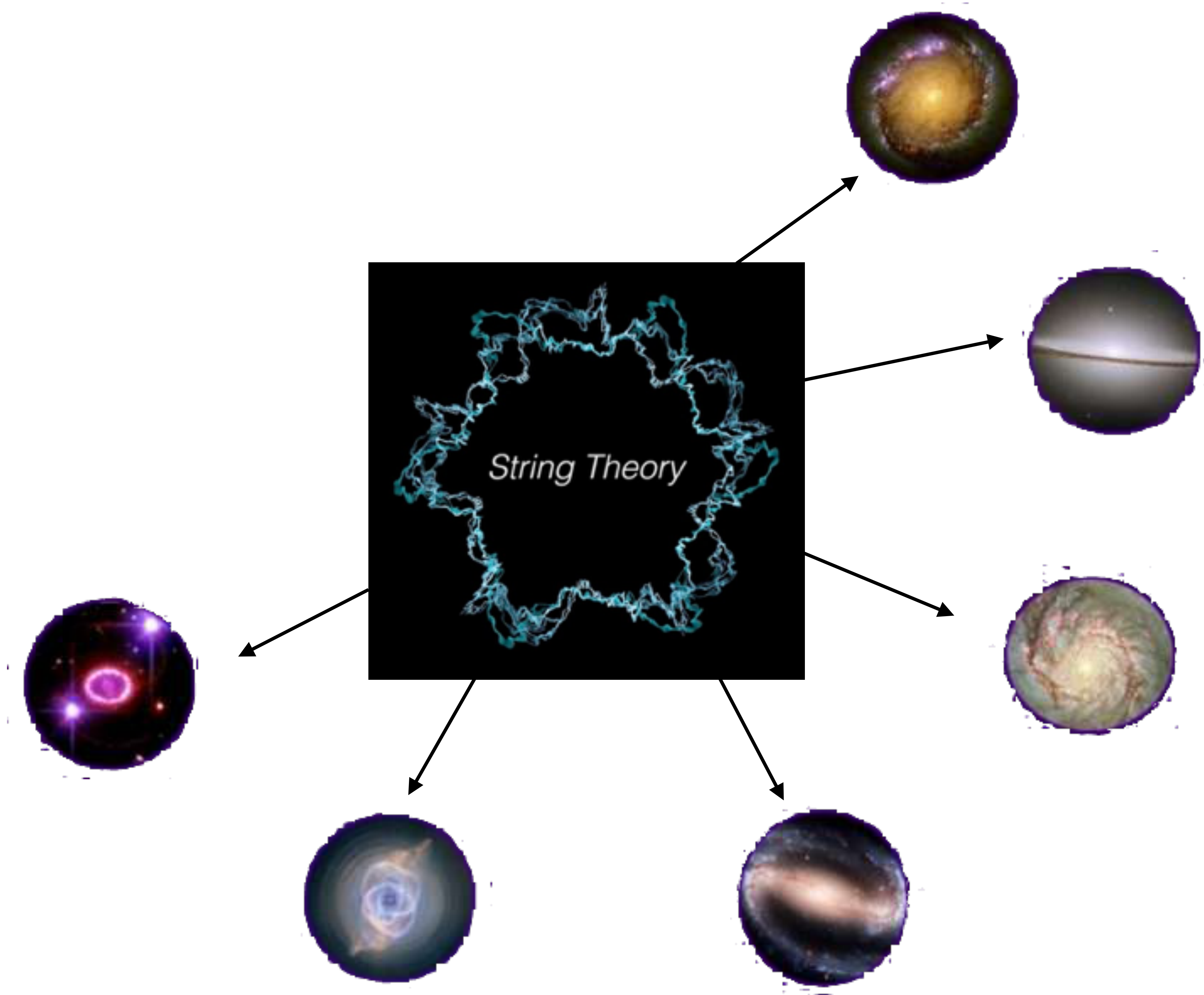
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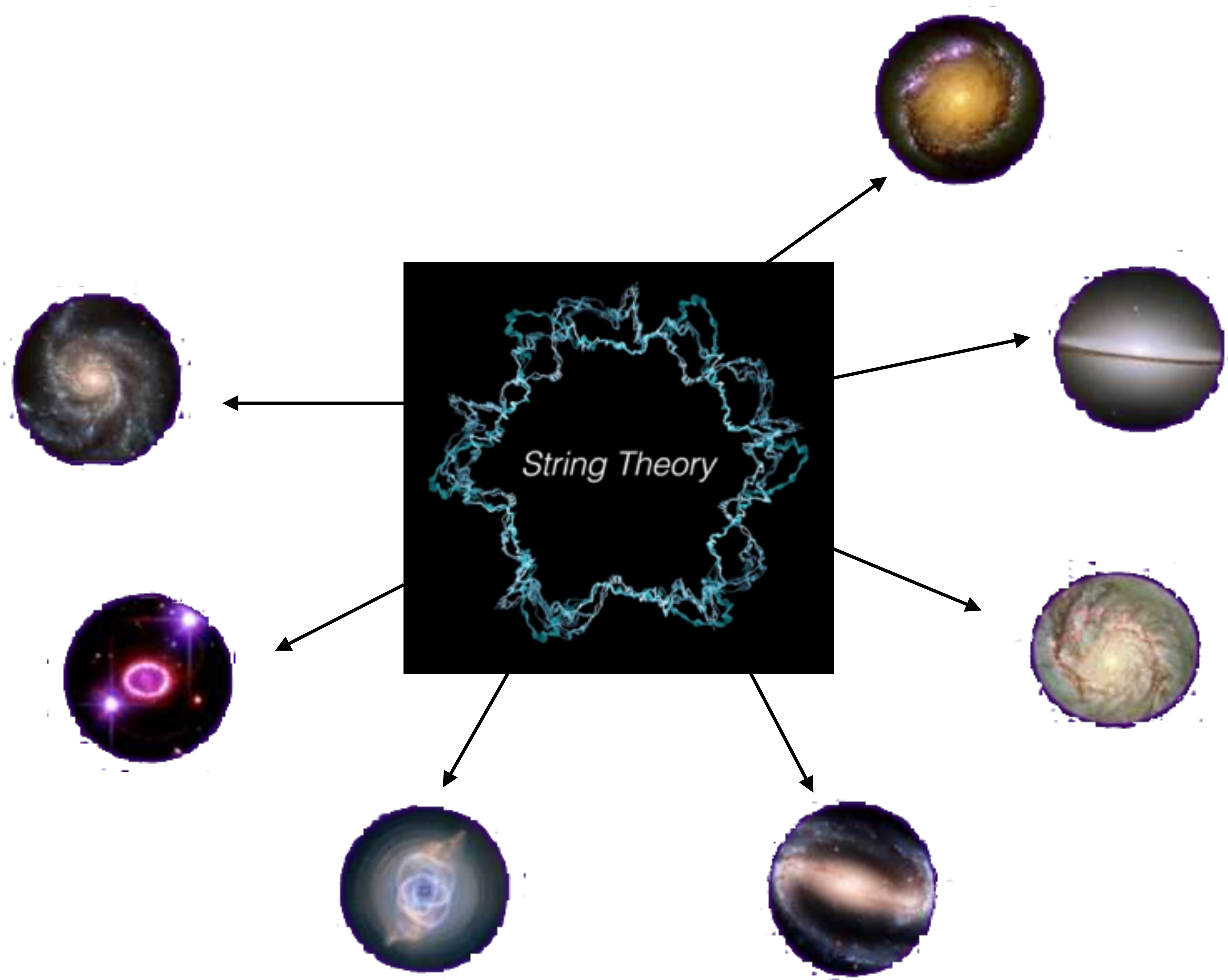
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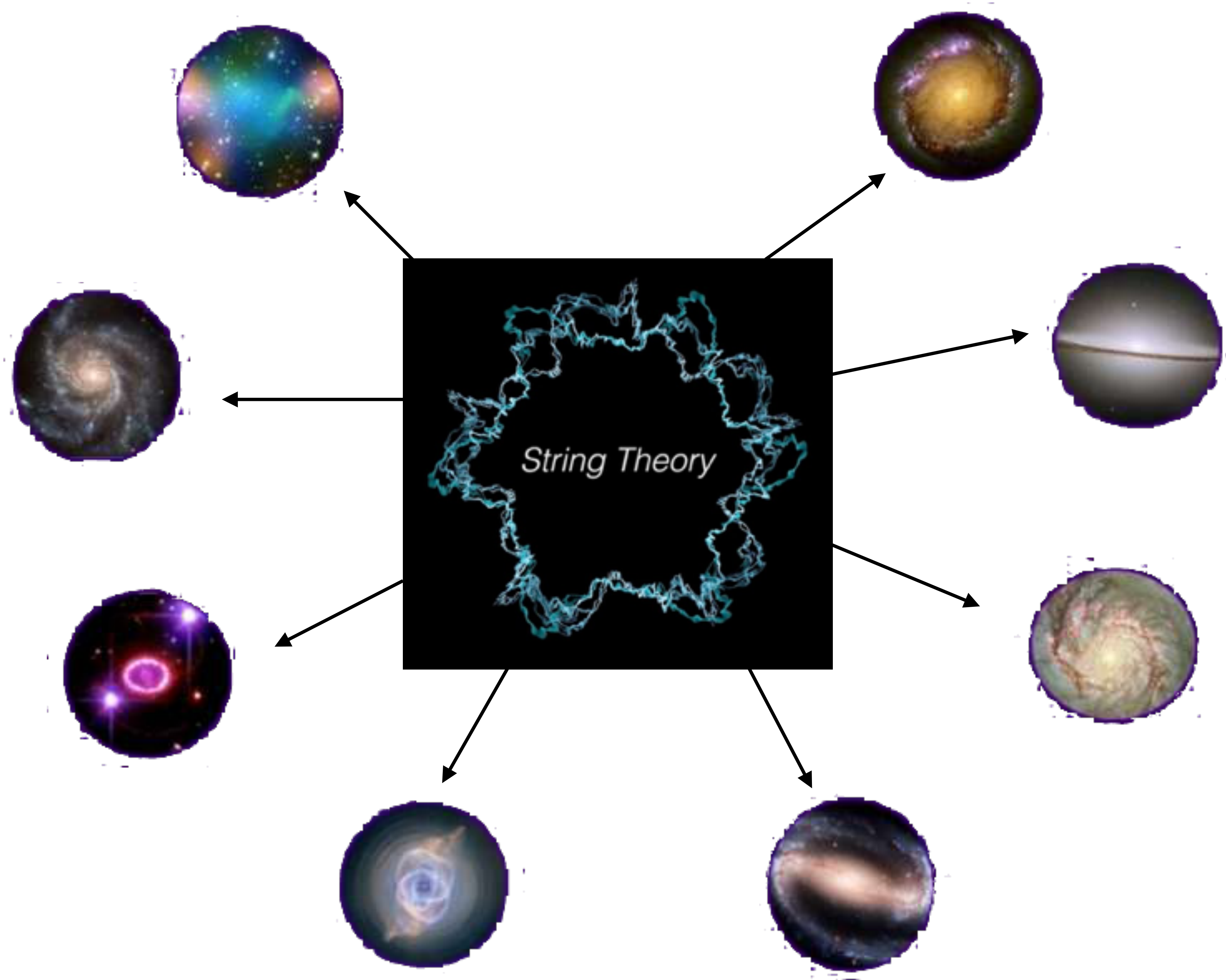
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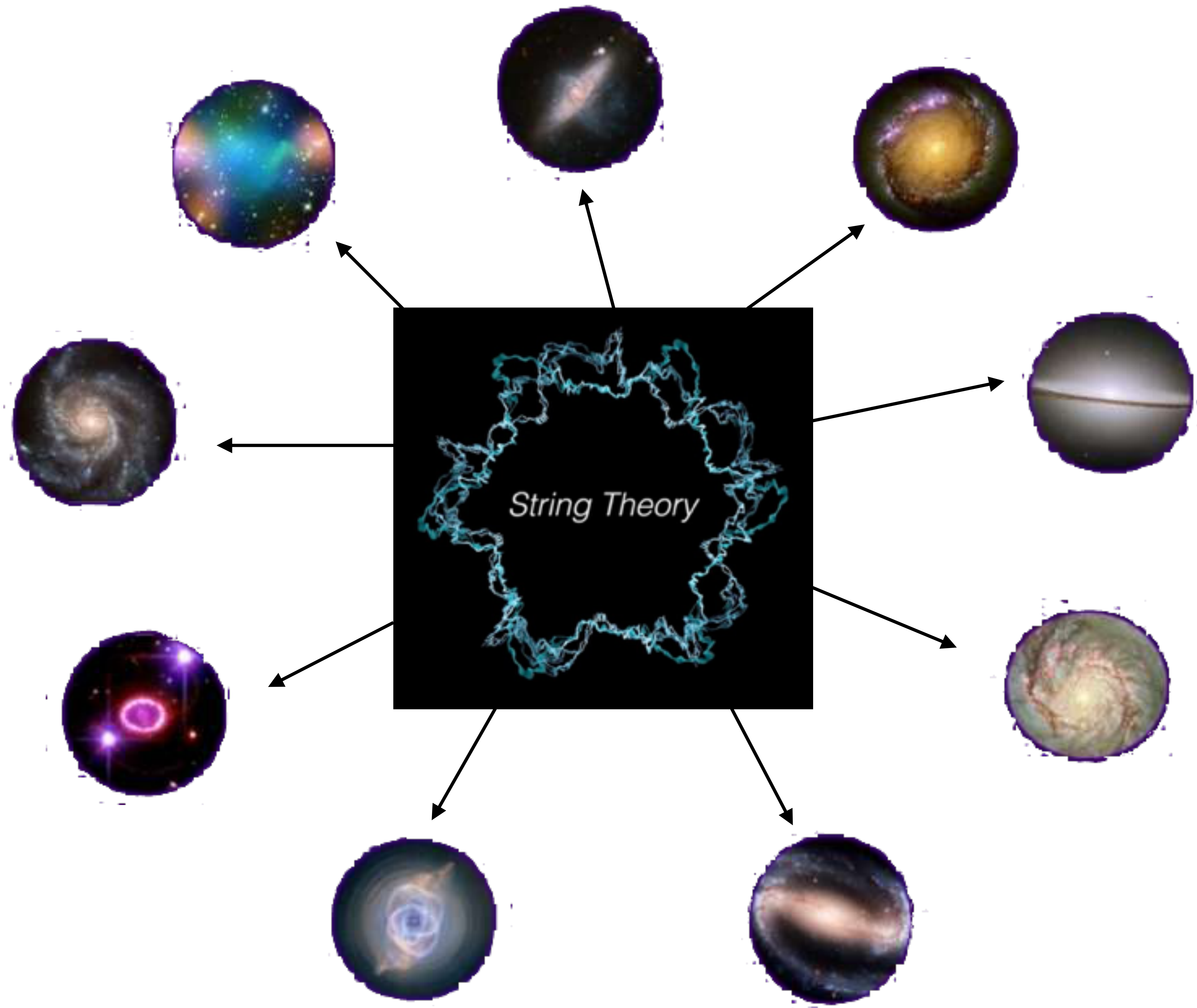
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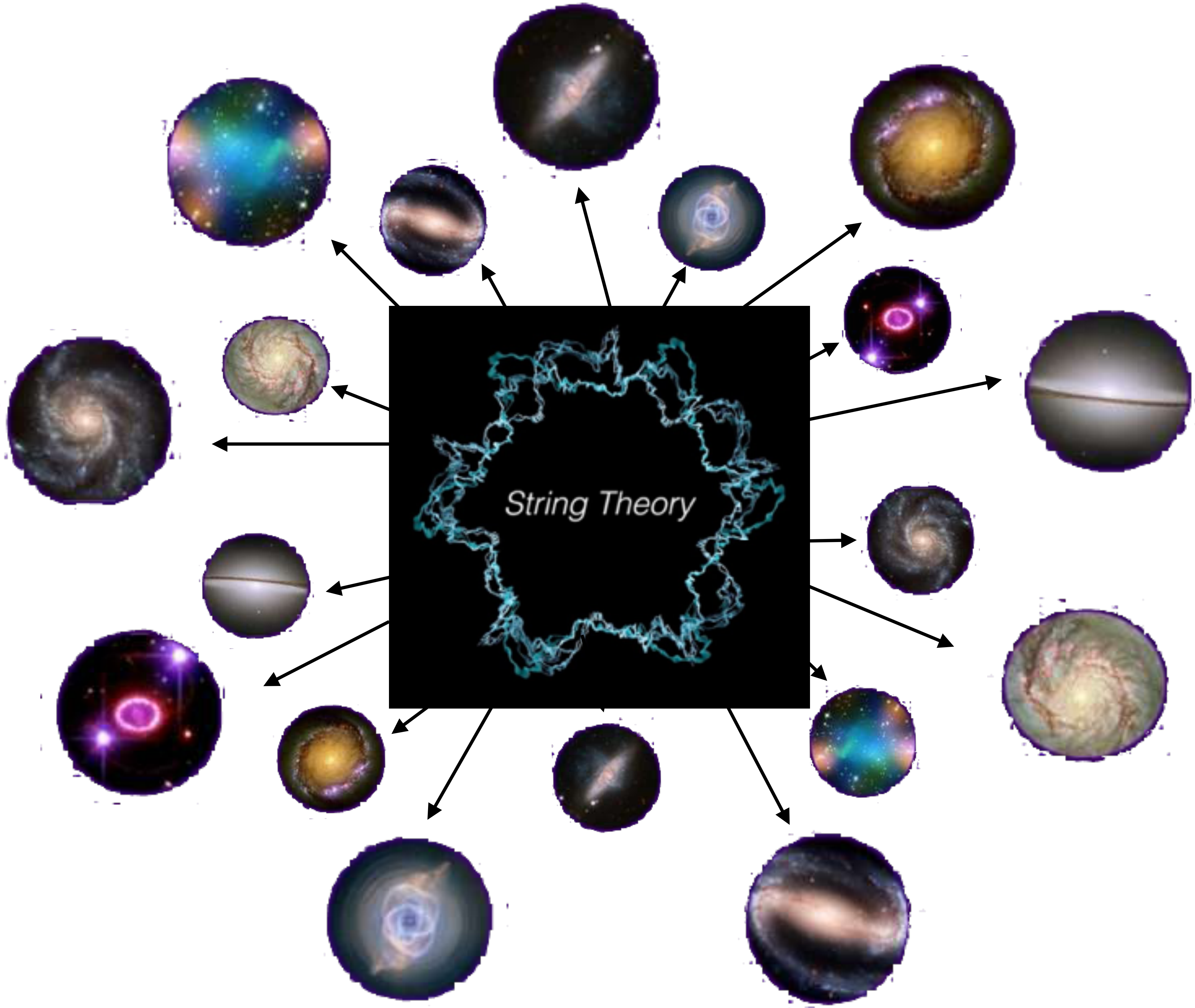
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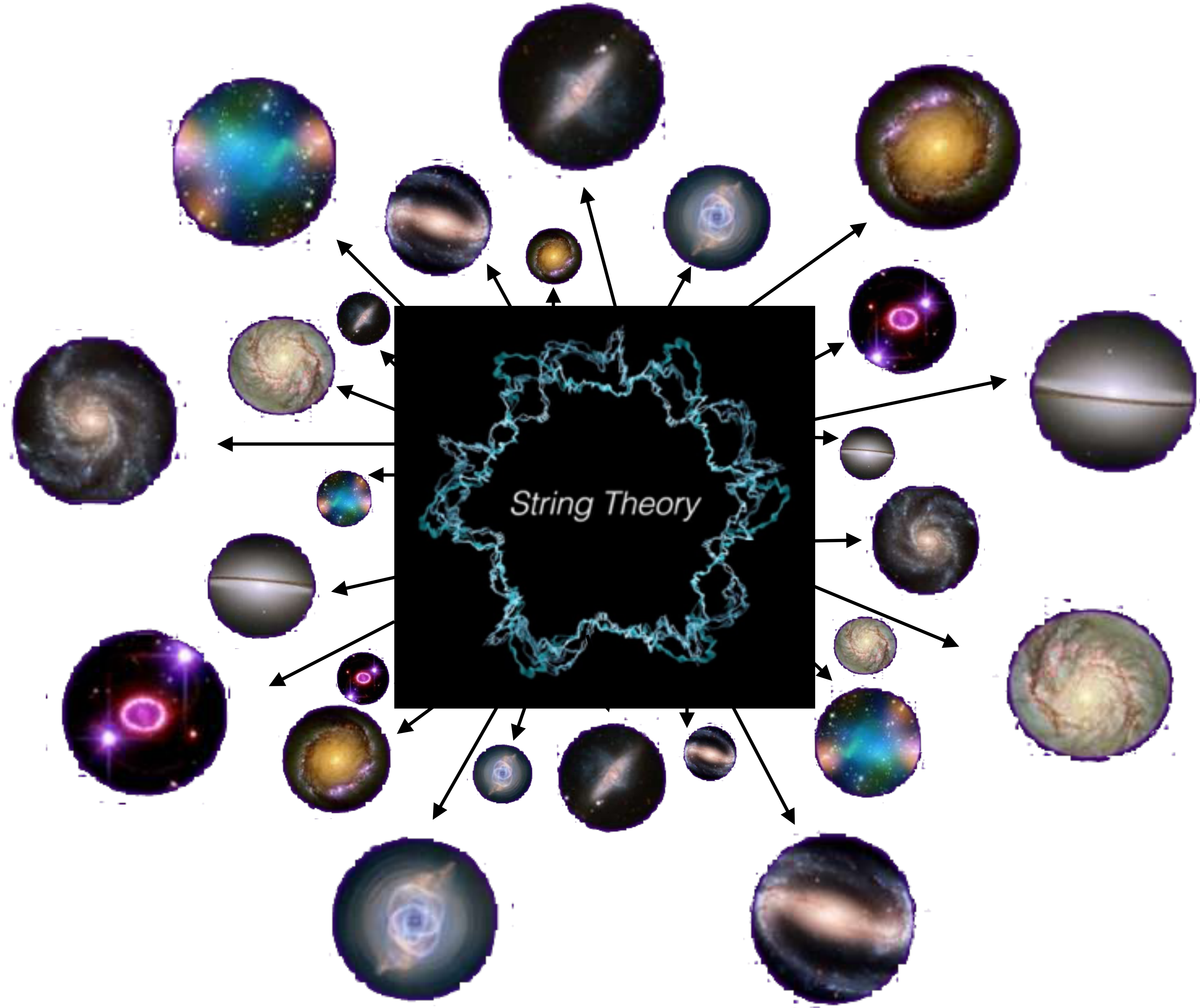
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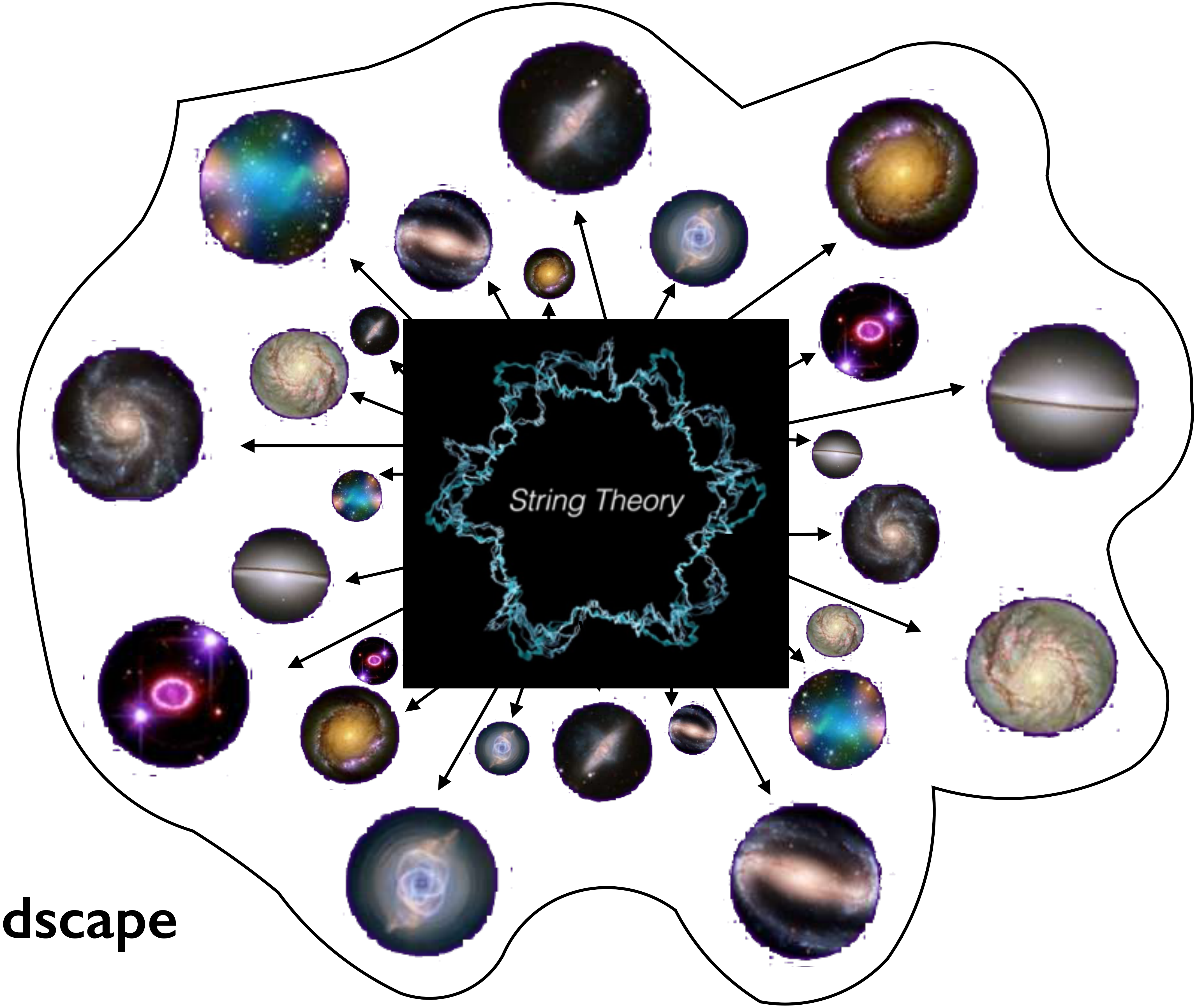
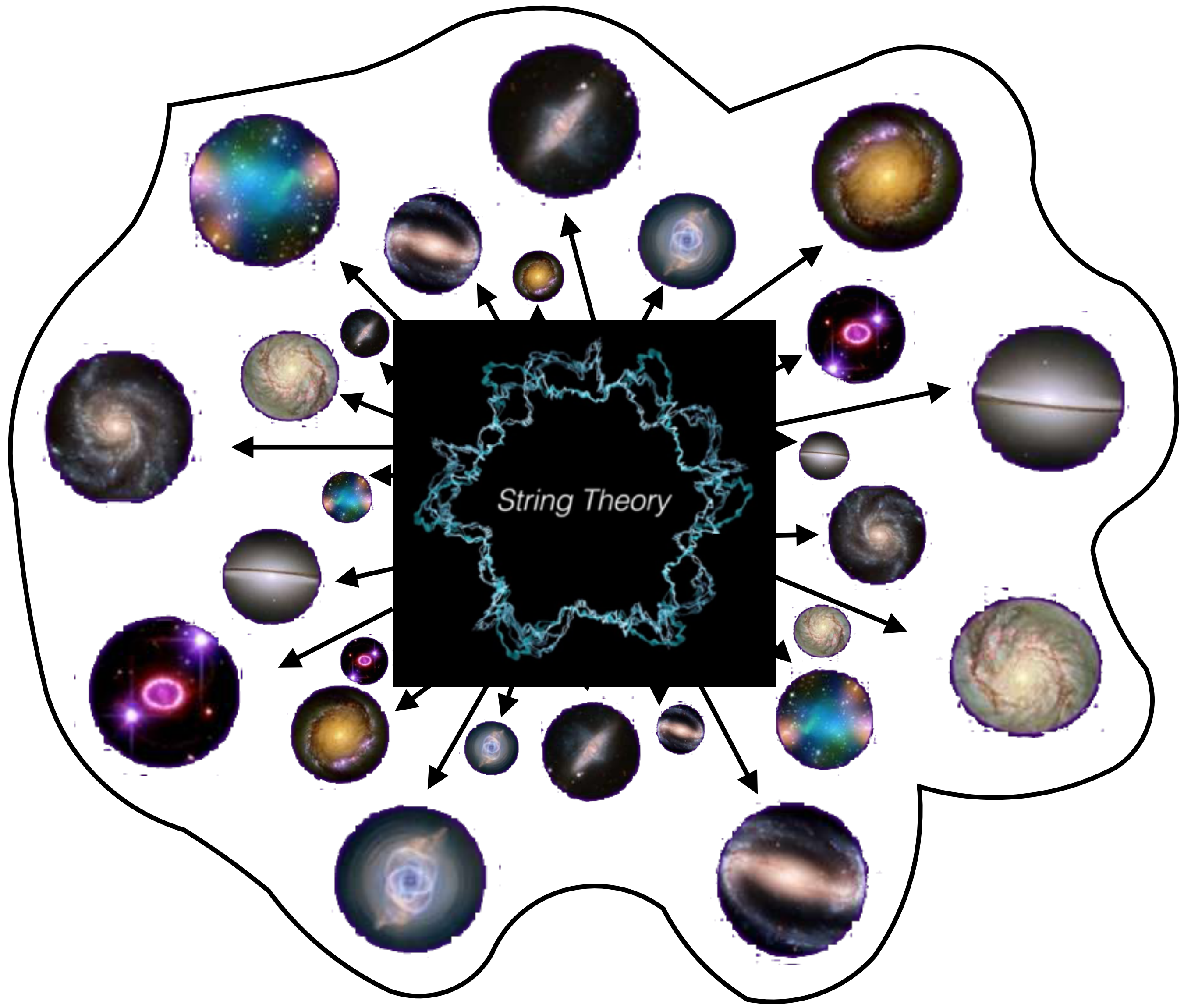


Landscape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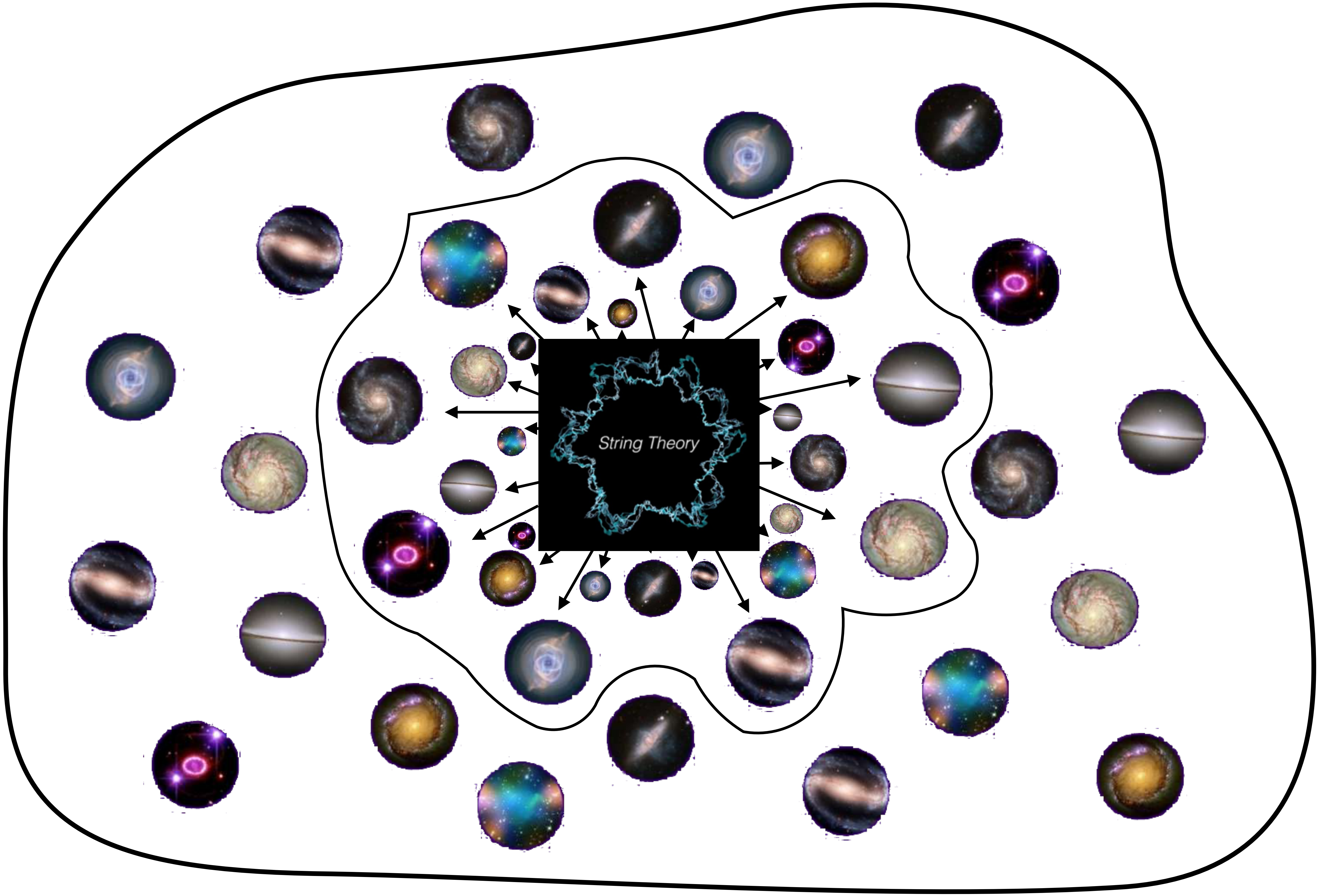
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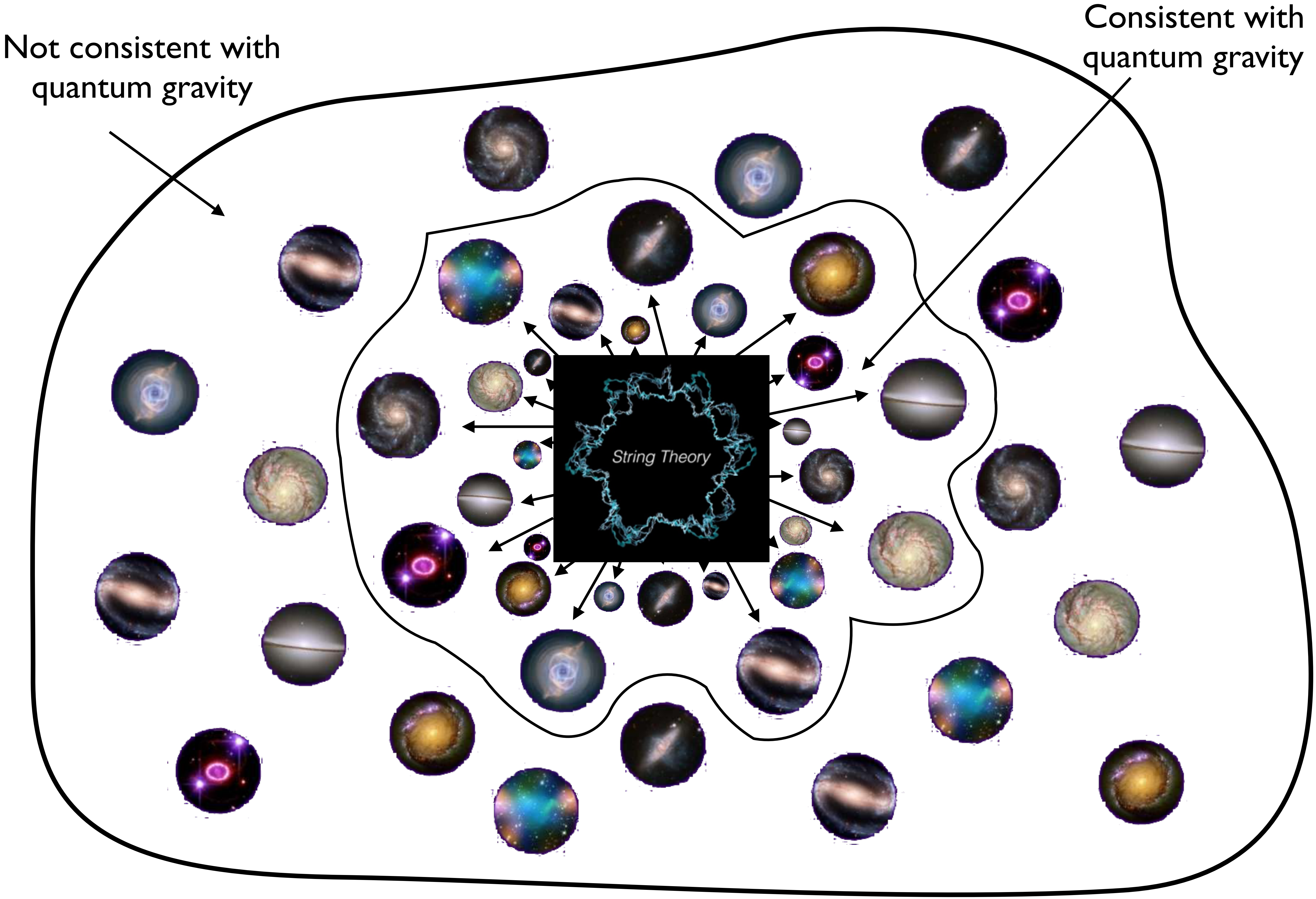
Not consistent with
quantum gravity
Consistent with
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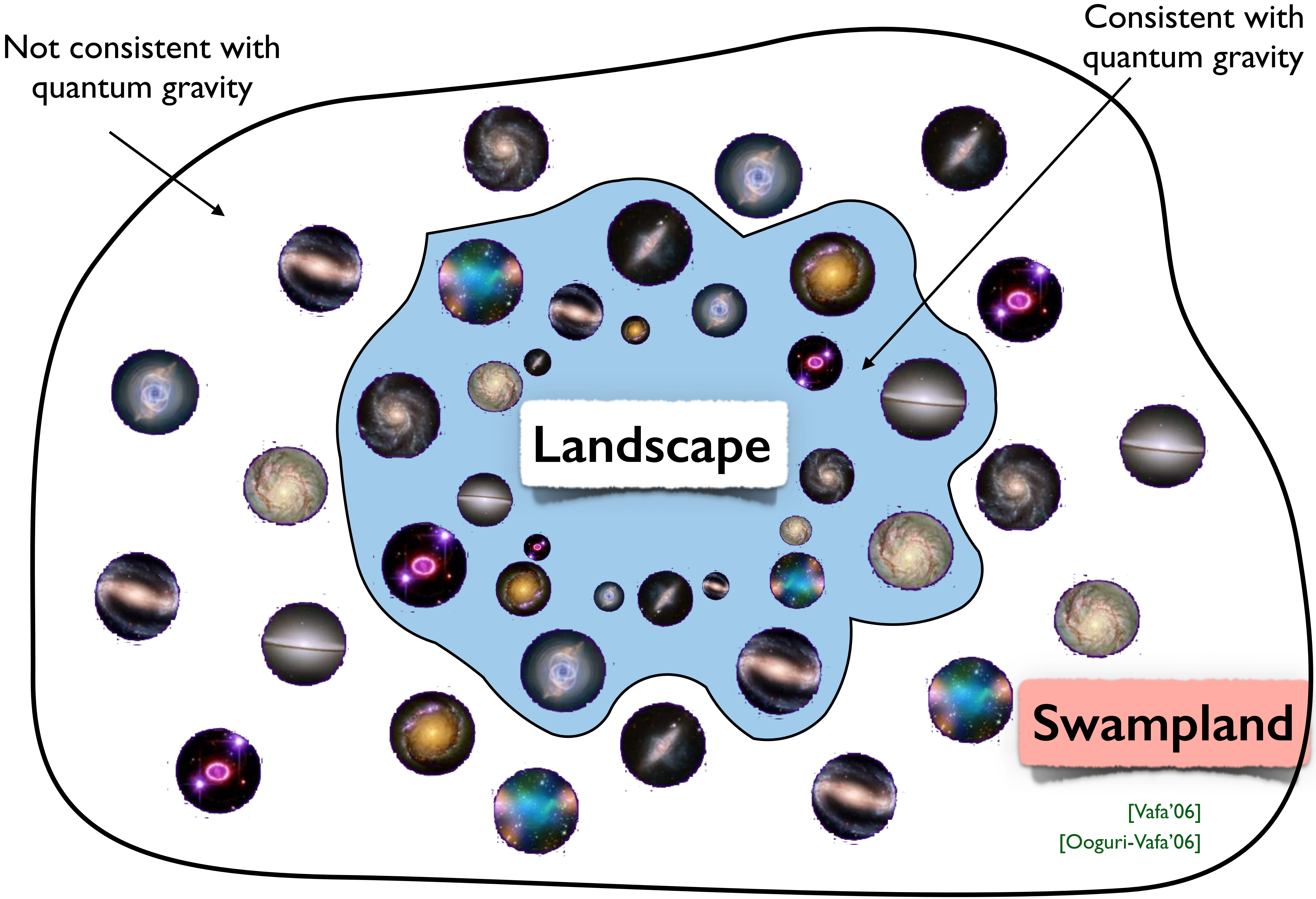
String Theory


Not consistent with quantum gravity
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Landscape
Swampland
[Vafa'06]
[Ooguri-Vafa'06]

Not everything is possible in string theory/quantum gravity!!!

Swampland:

Apparently consistent (anomaly-free) quantum effective field theories that cannot be UV embedded in quantum gravity

(they cannot arise from string theory)

Not everything is possible in string theory/quantum gravity!!!

There are additional constraints that any effective QFT must satisfy to be consistent with quantum gravity

➡ UV imprint of quantum gravity at low energies

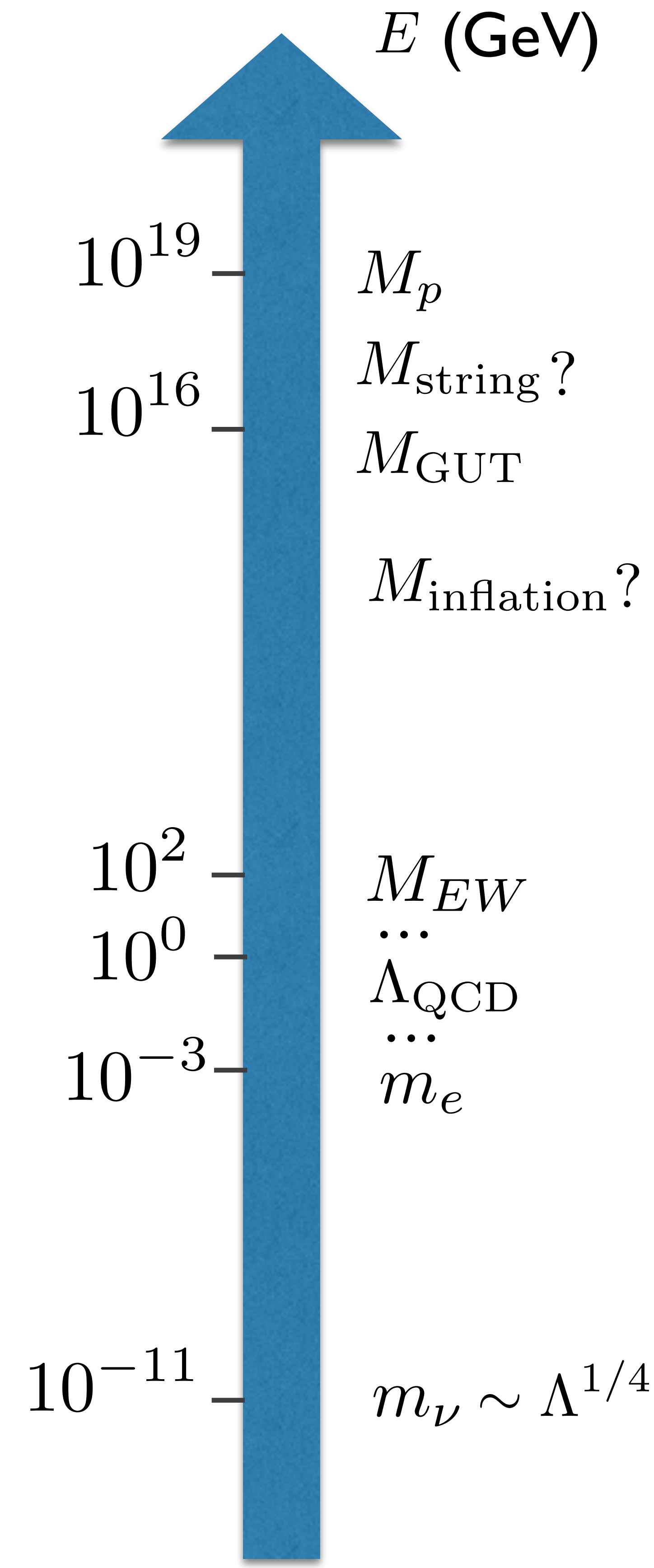
Outstanding phenomenological implications!

Effective field theories

Modern physics based on a Wilsonian effective field theory approach

Expectation of 'separation of scales':

IR effective theory not very sensitive to UV physics



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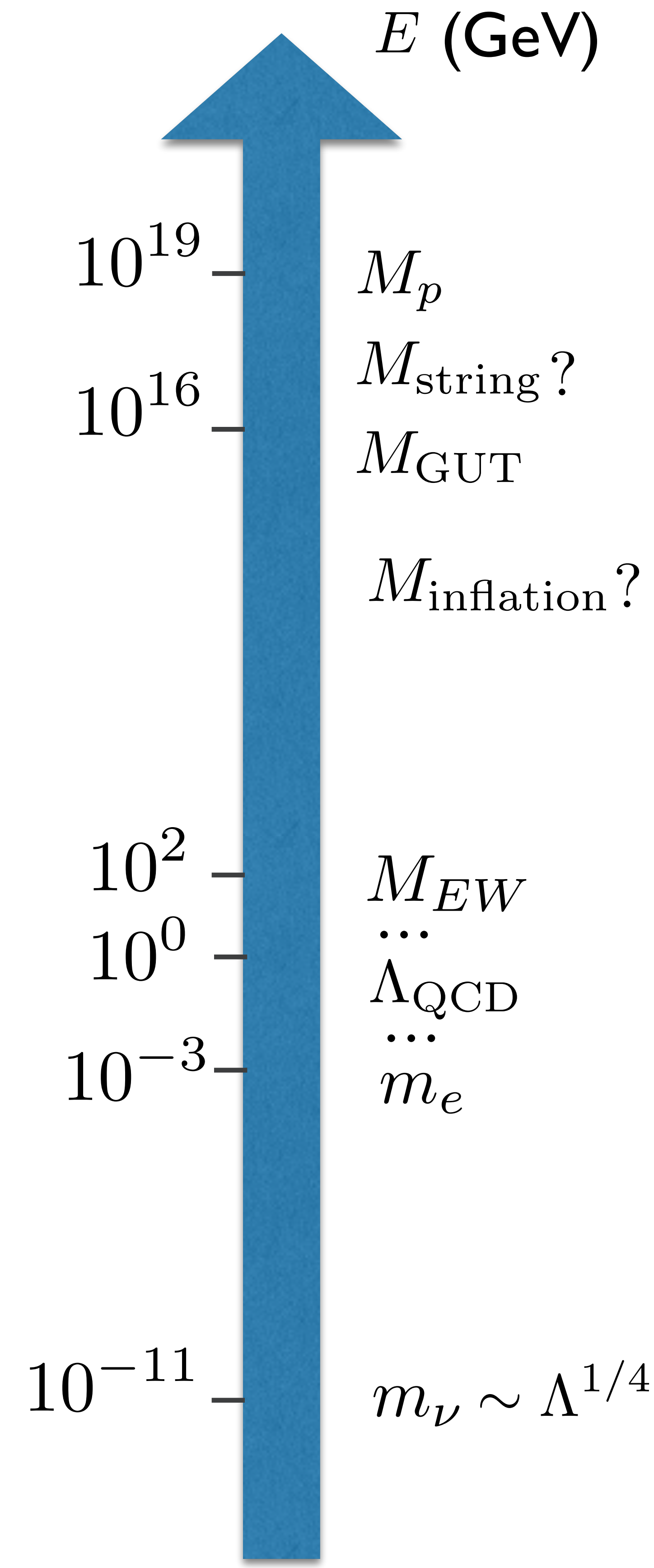
This picture can fail!



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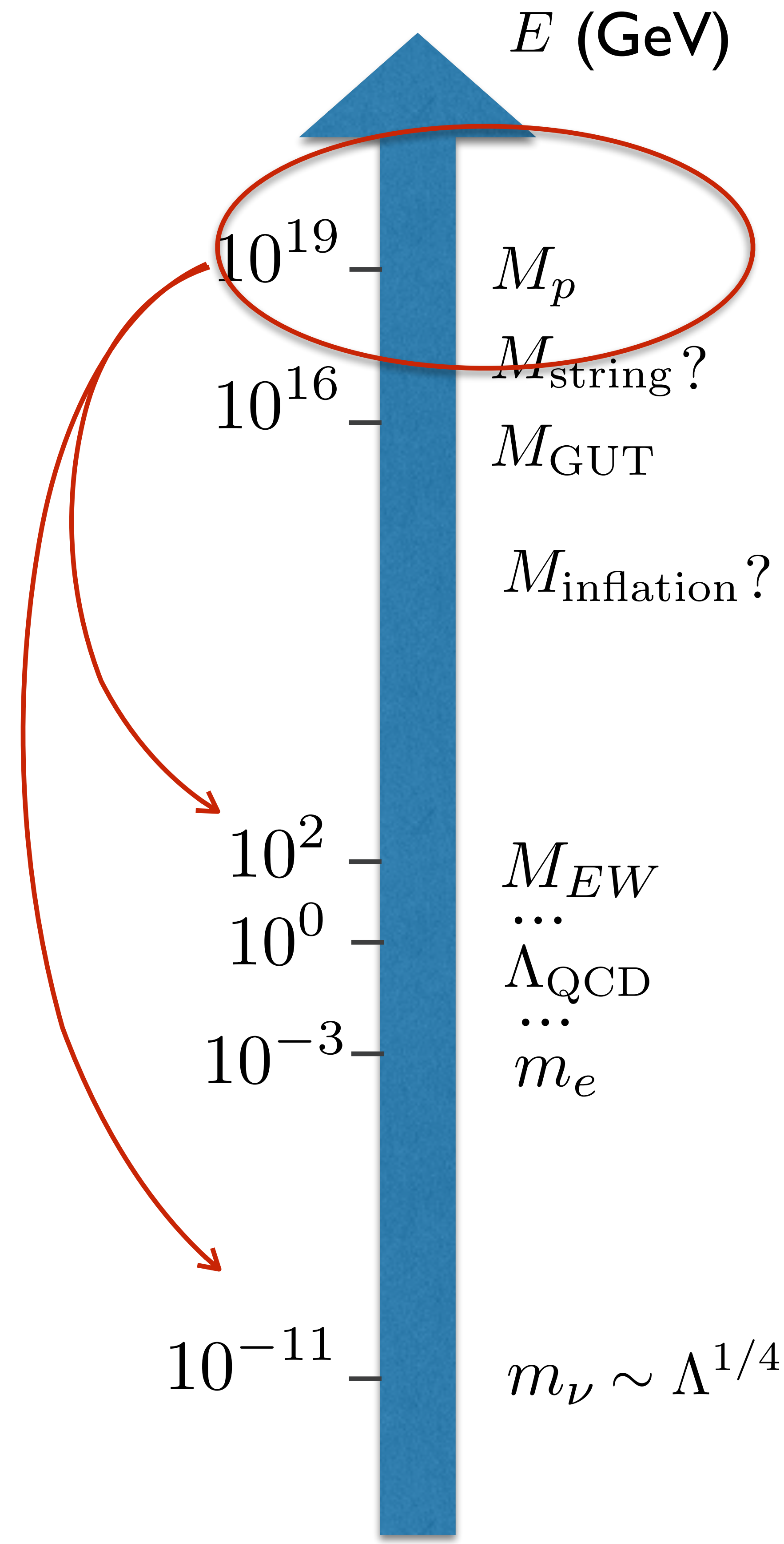

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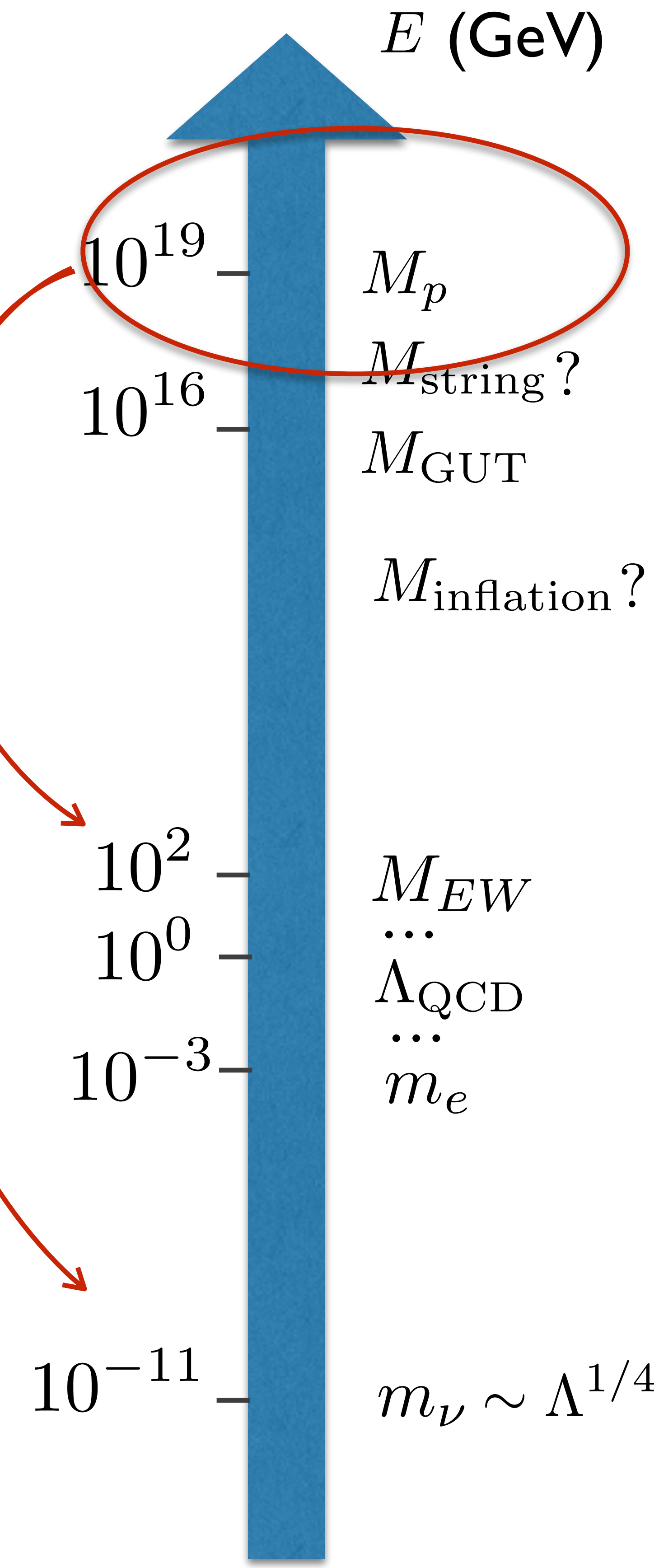
Quantum gravity constraints → **induce UV/IR mixing**

non-trivial implications at low energies!



Effective field theories

Modern physics based on a Wilsonian effective field theory approach

Expectation of 'separation of scales':

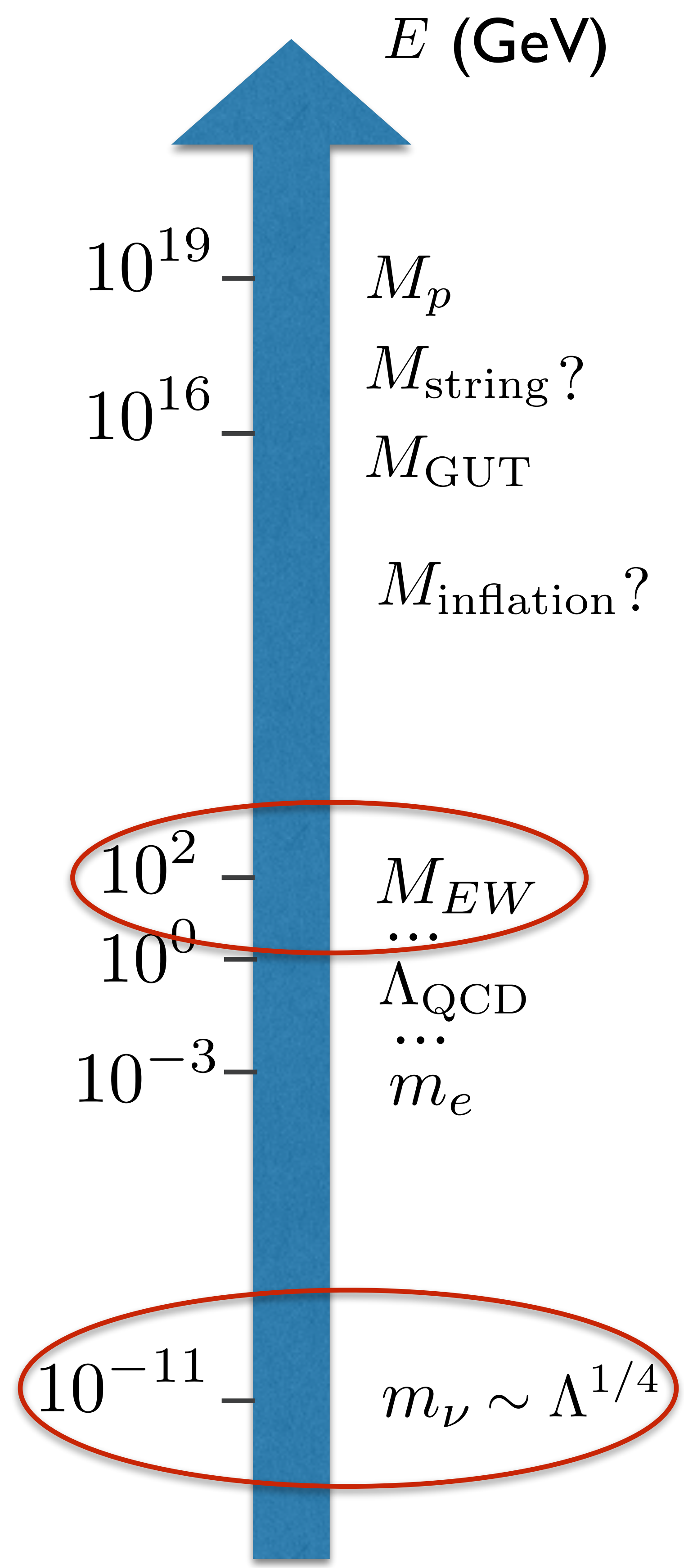
It is already failing…

Naturalness problems:

- Cosmological constant
- EW hierarchy problem

New approach?

Quantum gravity constraints = Missing piece for hierarchy problems?



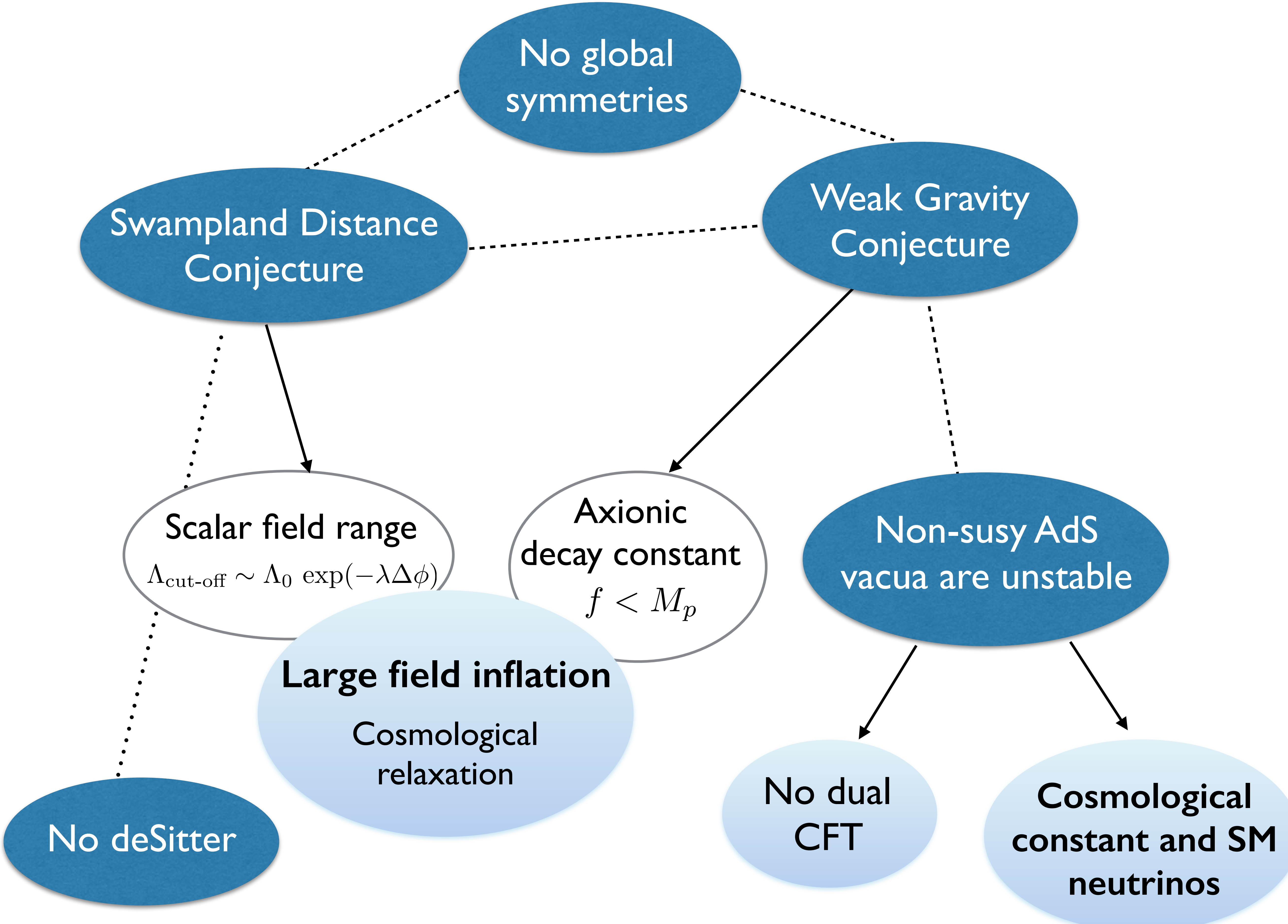
What are the constraints that an effective theory must satisfy to be consistent with quantum gravity?

What distinguishes the landscape from the swampland?

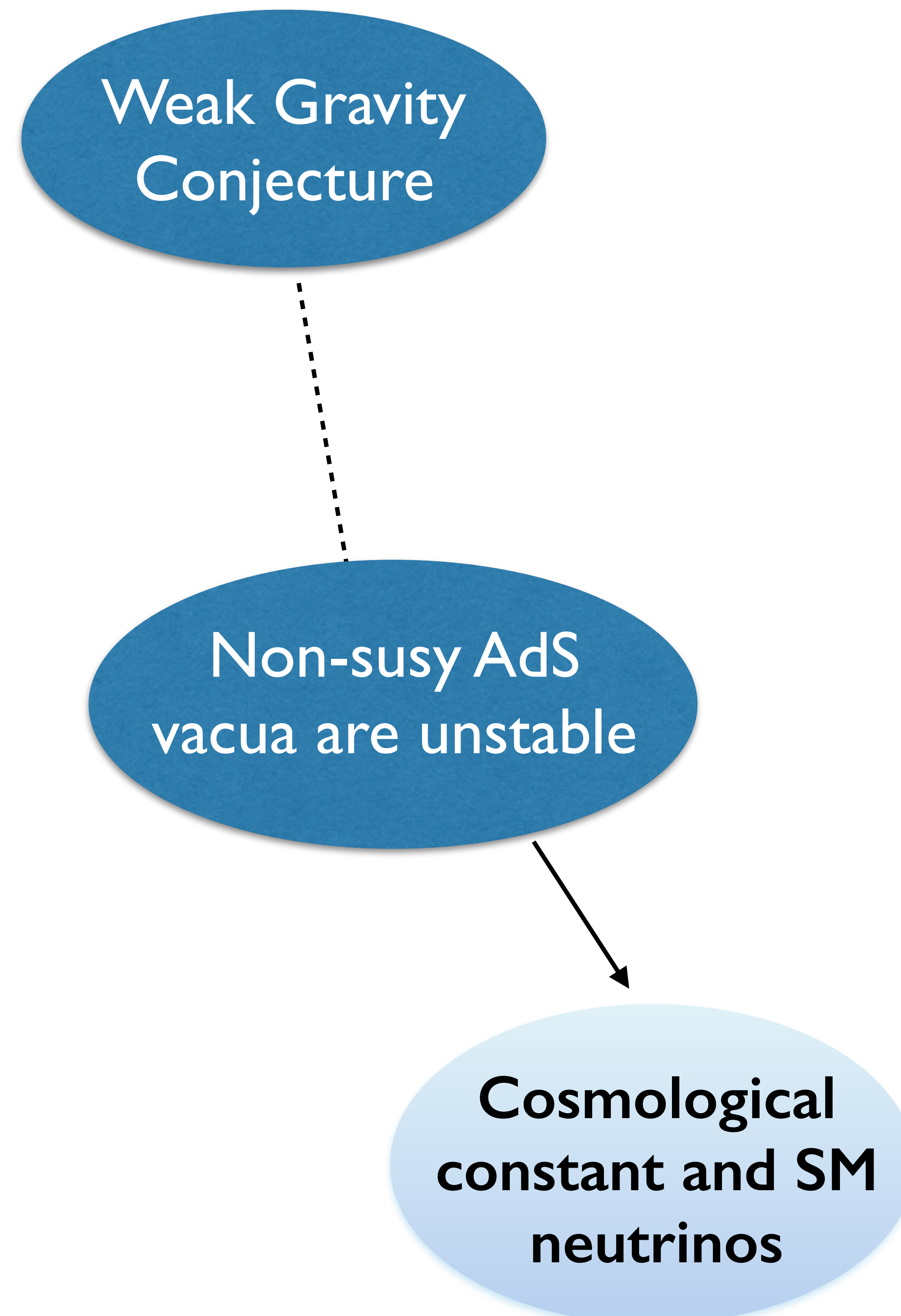
Proposals: **Quantum Gravity Conjectures**

(or Swampland Conjectures)

Motivated by String Theory as well as Black Hole physics



No global symmetries
Swampland Distance Conjecture
Weak Gravity Conjecture
Scalar field range
$\Lambda_{\text{cut-off}} \sim \Lambda_0 \exp(-\lambda \Delta\phi)$
Axionic decay constant
$f < M_p$
Non-susy AdS vacua are unstable
Large field inflation
Cosmological relaxation
No deSitter
No dual CFT
Cosmological constant and SM neutrinos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Weak Gravity Conjecture

Instability of non-susy vacua

Phenomenological implications for Particle Physics

Weak Gravity Conjecture

There exist at least a particle in which gravity acts weaker than the gauge force

$$\boxed{\frac{q}{m} \geq 1}$$

[Arkani-Hamed,Motl,Nicolis,Vafa'06]

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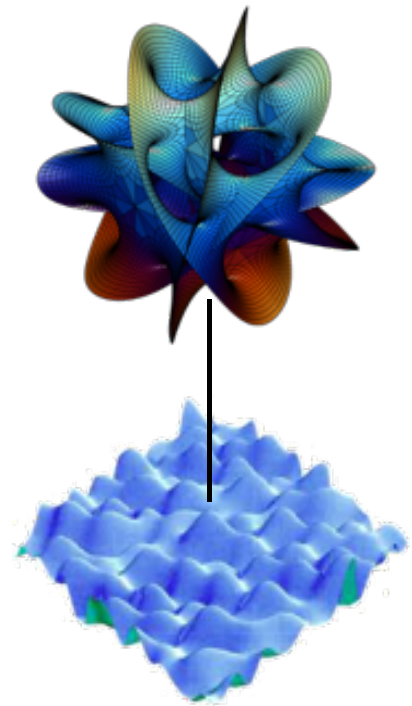
$q = m$ only allowed if supersymmetric

[Ooguri-Vafa'17]

Weak Gravity Conjecture for fluxes

Extra dimensions



4d space-time

There can be gauge fields propagating in the extra dimensions

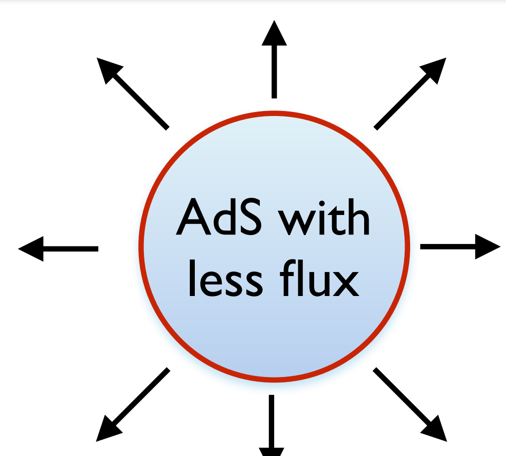
$$\downarrow$$

$$f_0 \sim \int_{\Sigma_p} F_p \quad \text{(fluxes in 4d)}$$

WGC applied to the fluxes (in a non-susy vacuum) implies: [Ooguri-Vafa'17]

$\exists$ Brane (domain wall) with $T < Q$ Bubble instability of the vacuum!

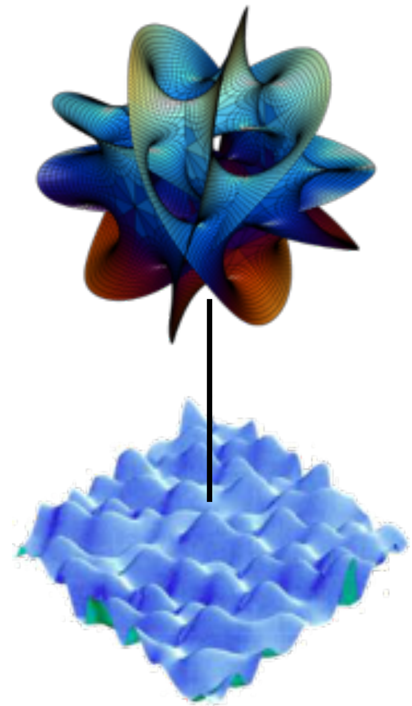
[Maldacena et al.'99]



AdS vacuum

Weak Gravity Conjecture for fluxes

Extra dimensions



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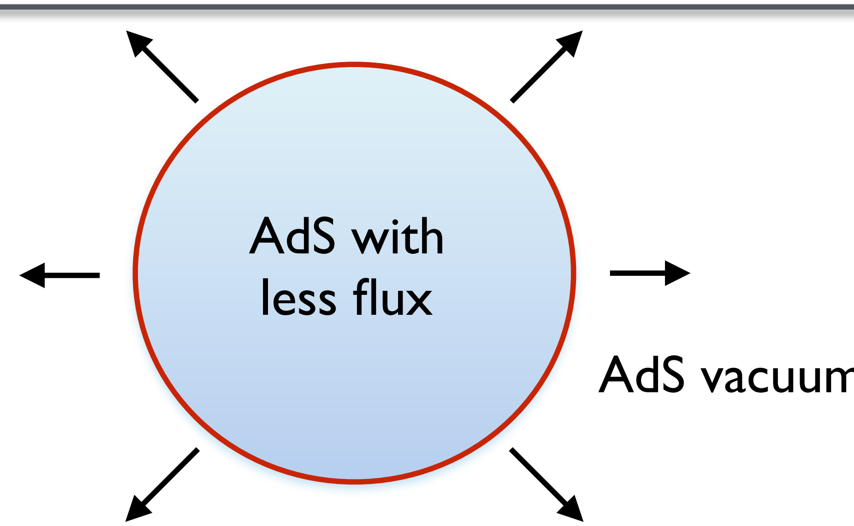

AdS-Phobia Conjecture

Non-susy vacua are at best metastable

[Ooguri-Vafa'16]
[Freivogel-Kleban'16]

Non-susy stable AdS vacua are in the Swampland
(inconsistent with Quantum Gravity)!

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- Our universe must be metastable ✓

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Background independence of QG:

If our 4d SM is consistent with QG → Compactifications of SM should also be consistent

We should not get stable non-susy AdS vacua from compactifying the SM!

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Solution: [Ibanez,Martin-Lozano,IV'17]

We impose the absence of non-susy stable 3d AdS vacua → Constraints on light spectra of SM

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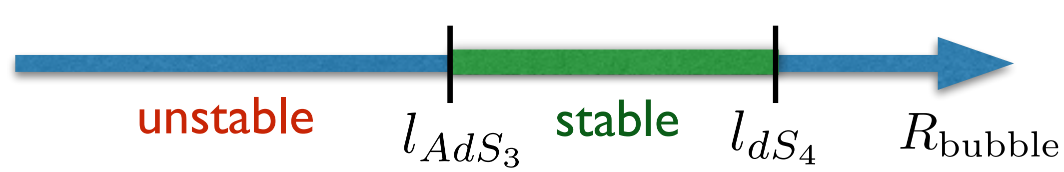
We impose the absence of non-susy stable 3d AdS vacua → Constraints on light spectra of SM

Assumption: 4d instabilities are not transferred to 3d

$$R_{\text{buble}} > l_{AdS_3} \quad \text{(large bubbles)}$$



Compactification of the SM to 3d

Standard Model + Gravity on S^1: [Arkani-Hamed et al.'07] (also [Arnold-Fornal-Wise'10])

$$V(R) = \frac{2\pi\Lambda_4}{R^2} \quad + \text{Casimir energy}$$

$R \equiv$ scalar parametrising the radius of the circle S^1

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tree-level

one-loop corrections → exponentially suppressed for $m \gg 1/R$

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tree-level (for $\frac{2\pi\Lambda_4}{R^2}$)

one-loop corrections (for Casimir energy) → exponentially suppressed for $m \gg 1/R$

Depending on the light mass spectra and the cosmological constant, we can get AdS, Minkowski or dS vacua in 3d

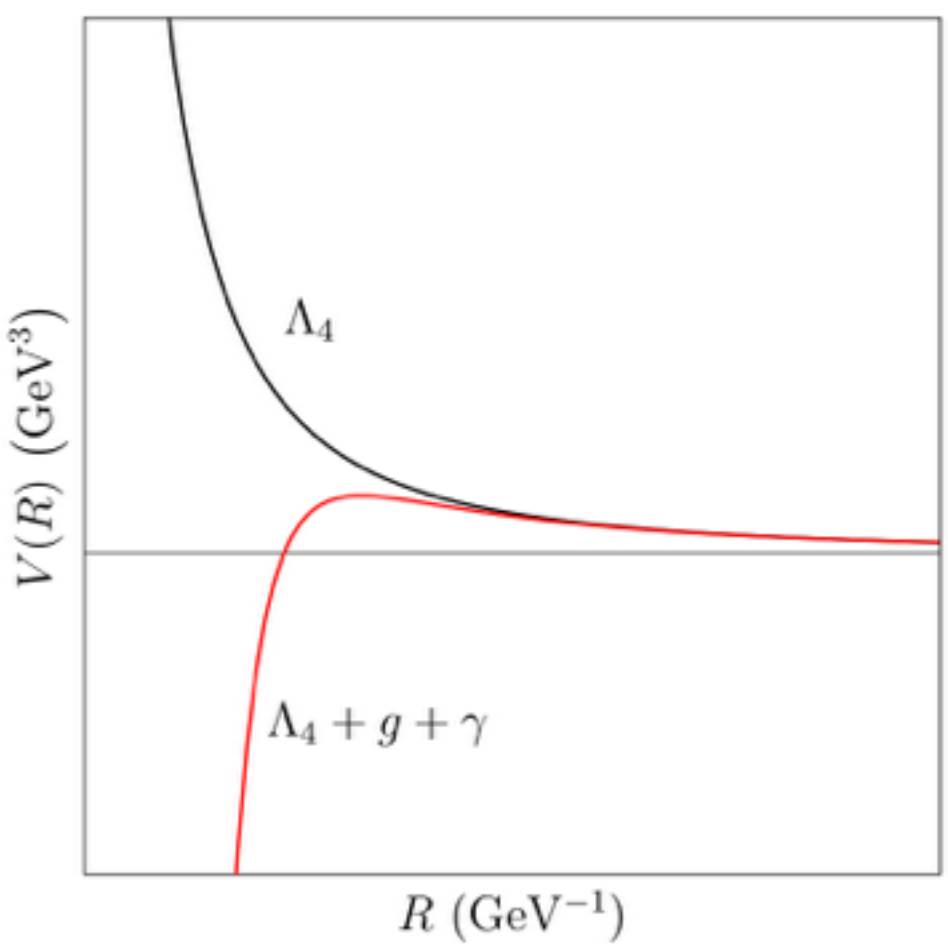
$R \equiv$ scalar parametrising the radius of the circle S^1

Compactification of the SM to 3d

Standard Model + Gravity on S^1:

massless particles:
graviton, photon

$$V(R) = \frac{2\pi\Lambda_4}{R^2} - \frac{4}{720\pi R^6}$$



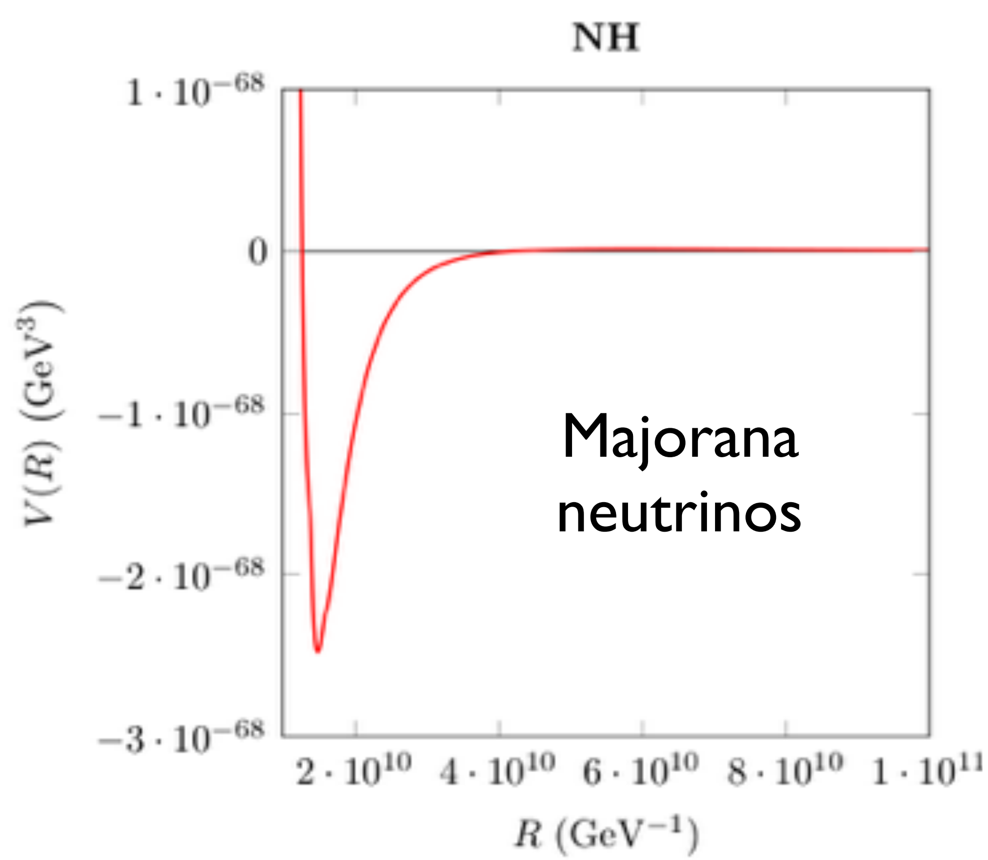
Compactification of the SM to 3d

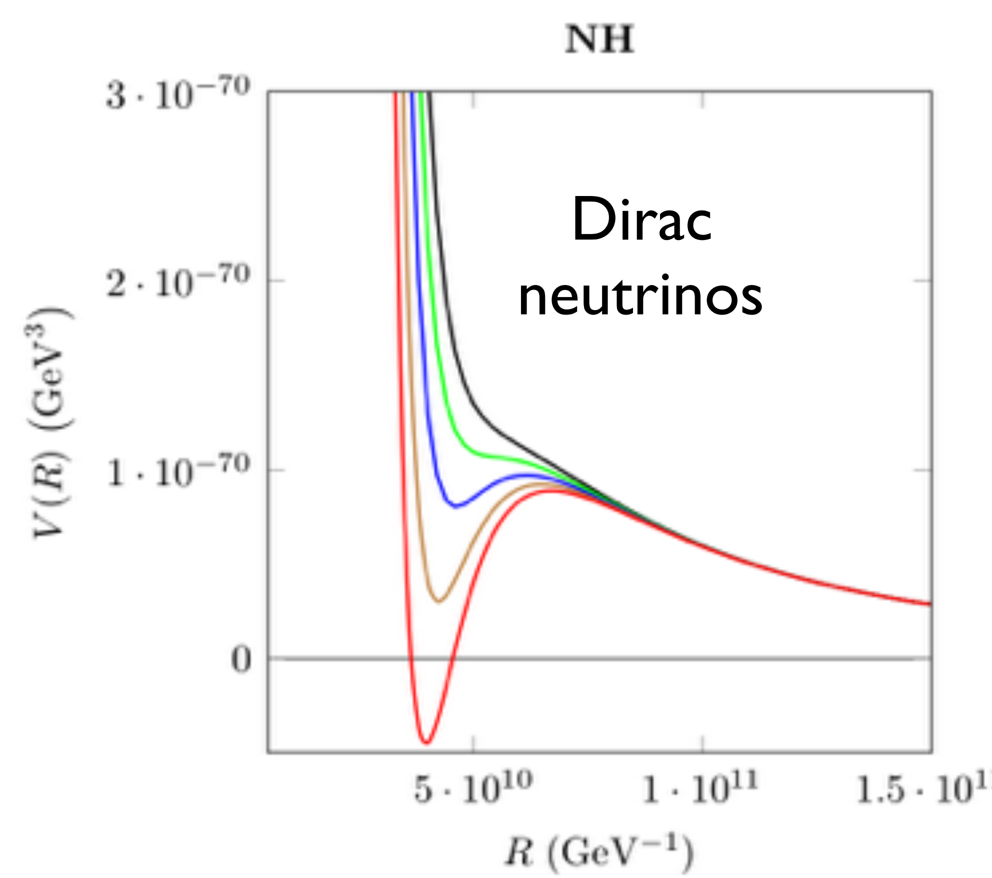
Standard Model + Gravity on S^1:

massless particles: graviton, photon

massive particles: neutrinos,…

$$V(R) = \frac{2\pi\Lambda_4}{R^2} - \frac{4}{720\pi R^6} + \sum_i \frac{(2\pi R)}{R^3}(-1)^{s_i} n_i \rho_i(R)$$





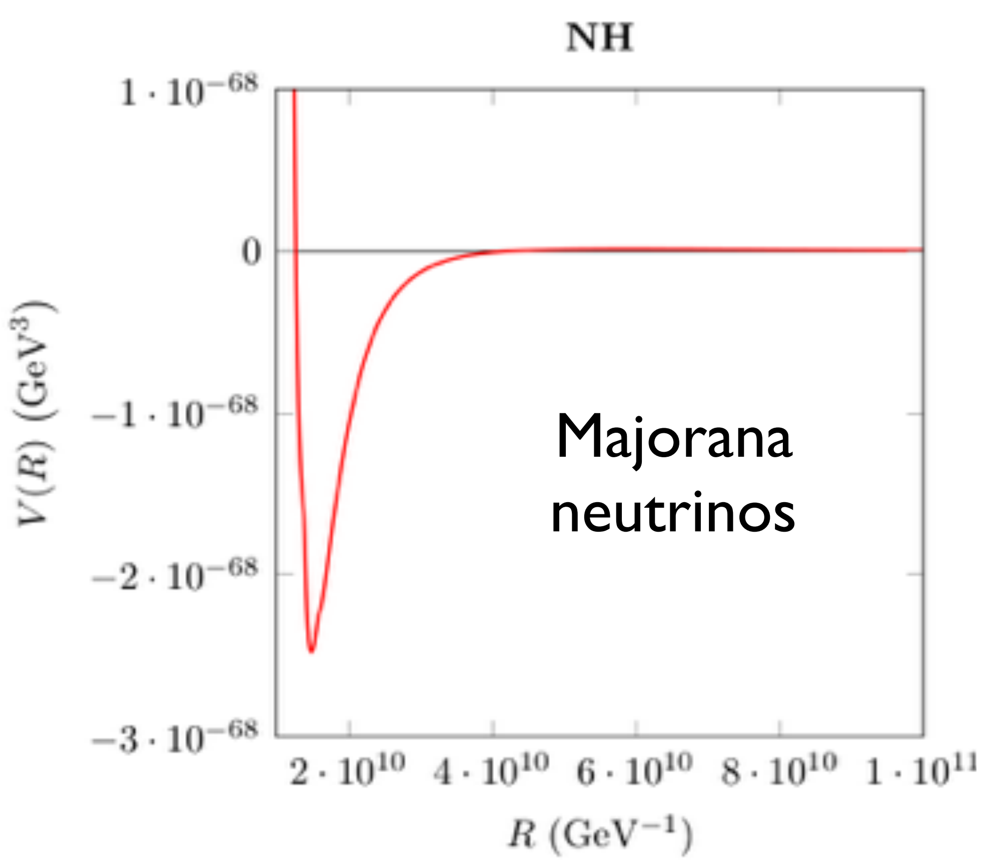
The more massive the neutrinos, the deeper the AdS vacuum

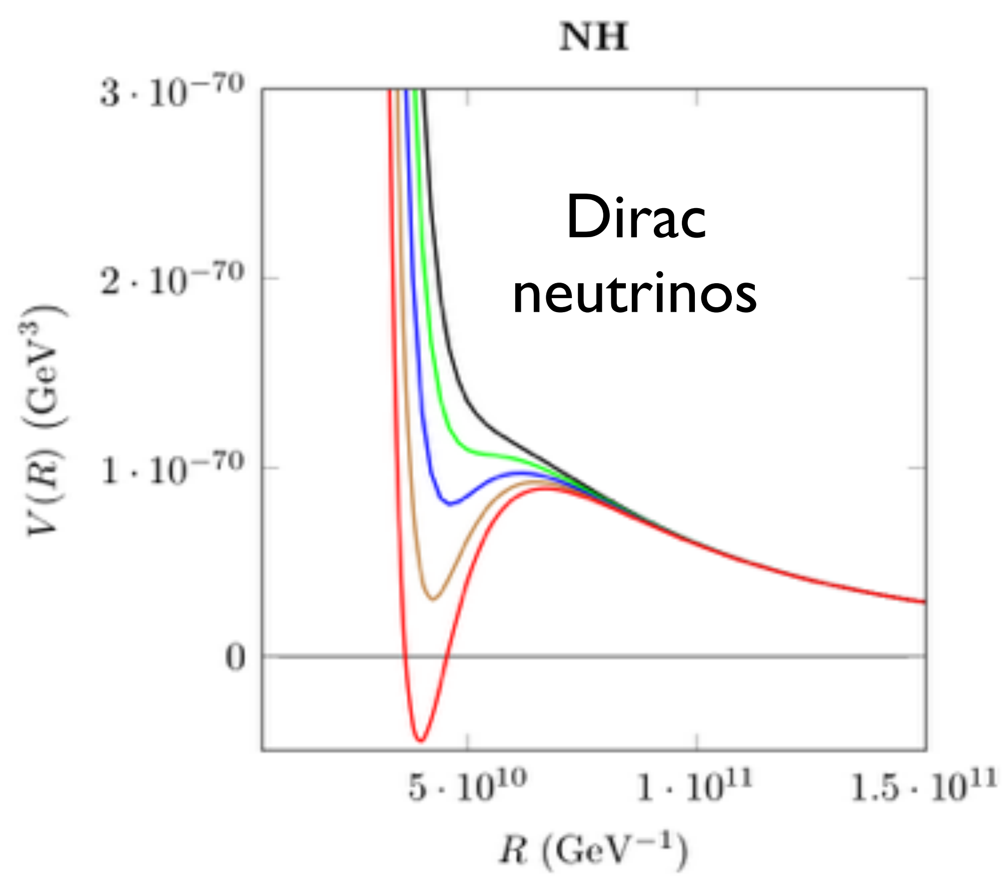
[Ibanez,Martin-Lozano,IV'17] (see also [Hamada-Shiu'17])

Compactification of the SM to 3d

Standard Model + Gravity on S^1:

Absence of AdS vacua implies:





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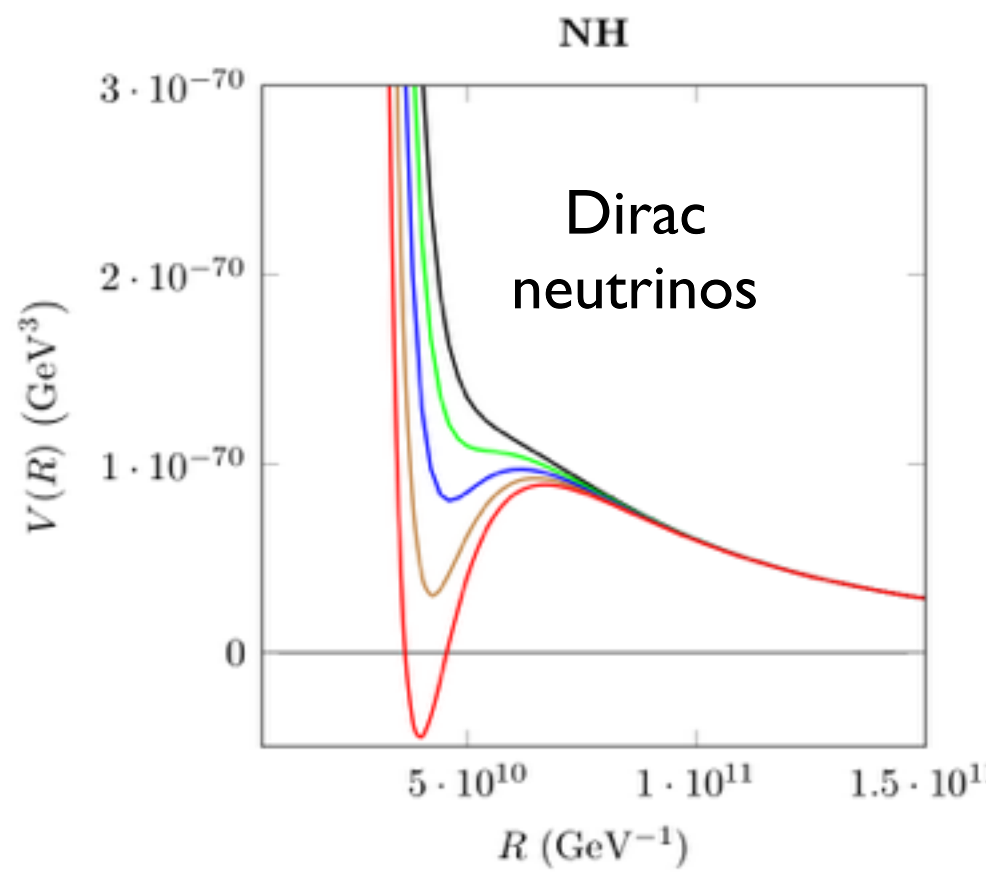
Majorana neutrinos ruled out!



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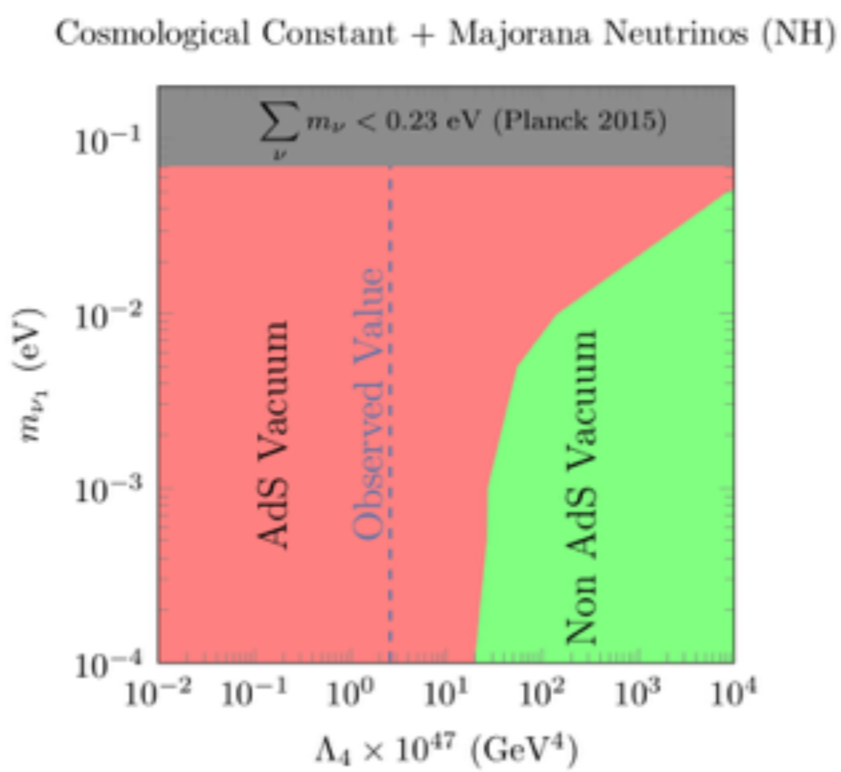
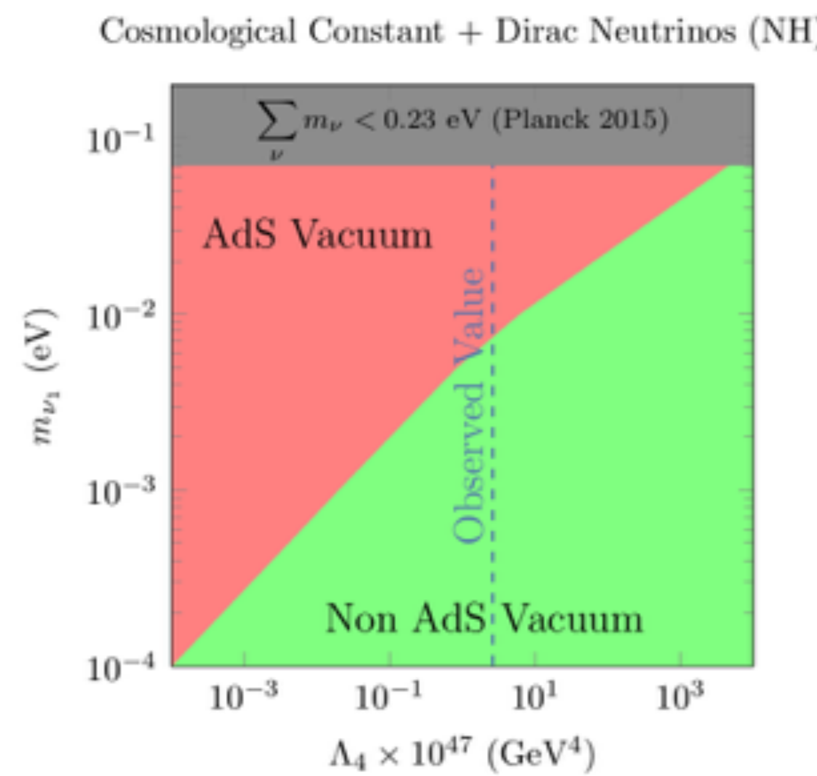
Upper bound for Dirac mass!

$$m_{\nu_1} < 7.7 \text{ meV (NH)}$$
$$m_{\nu_1} < 2.1 \text{ meV (IH)}$$

Lower bound on the cosmological constant





The bound for Λ_4 scales as m_ν^4 (as observed experimentally)

$$\Lambda_4 \geq \frac{a(n_f)30(\Sigma m_i^2)^2 - b(n_f,m_i)\Sigma m_i^4}{384\pi^2}$$

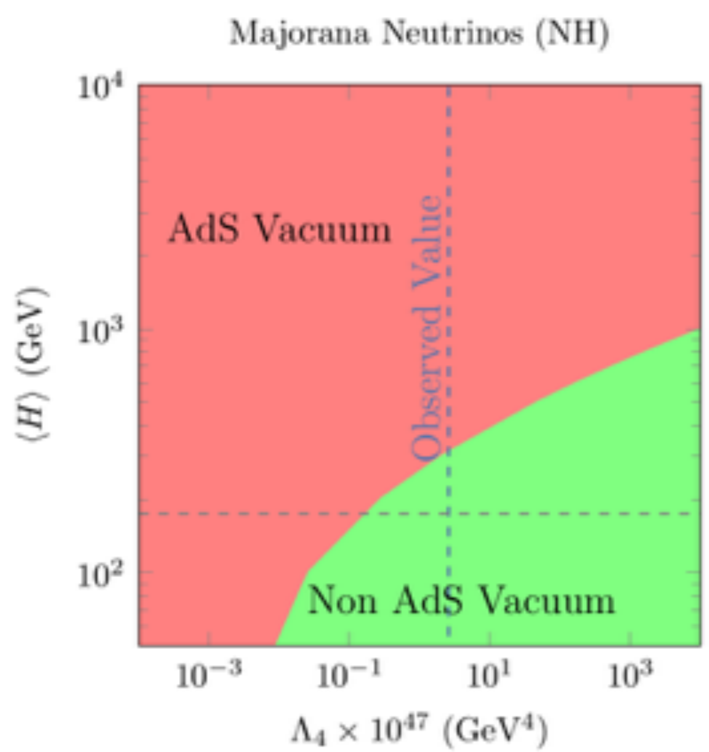
with $a(n_f) = 0.184(0.009)$, $b(n_f,m_i) = 5.72(0.29)$ for Majorana (Dirac)

First argument (not based on cosmology) to have $\Lambda_4 \neq 0$

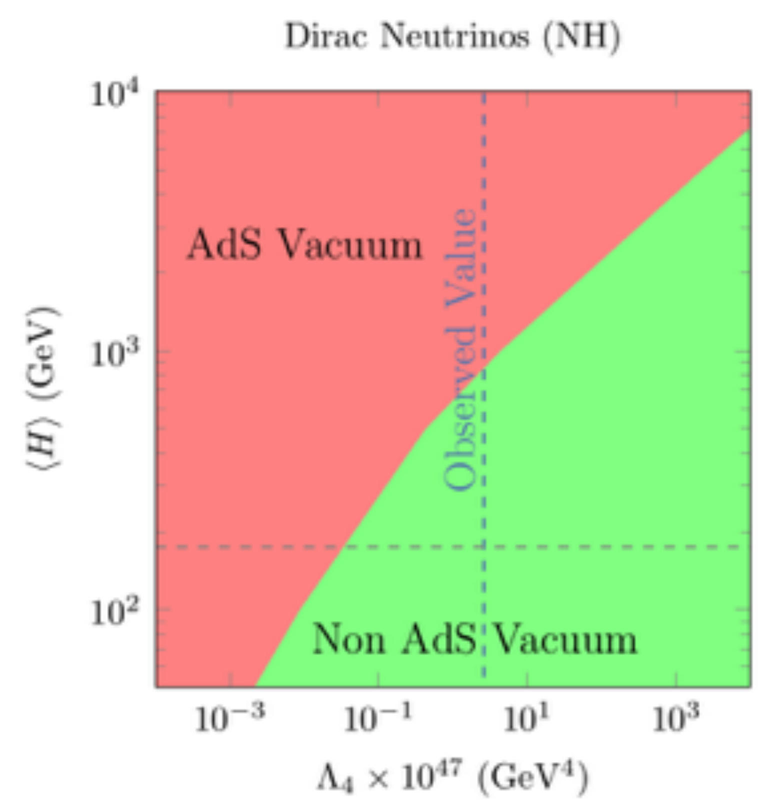
Upper bound on the EW scale

<u>Majorana case:</u> $\langle H \rangle \lesssim \frac{\sqrt{2}}{Y_{\nu_1}} \sqrt{M \Lambda^{1/4}}$

<u>Dirac case:</u> $\langle H \rangle \lesssim 1.6 \frac{\Lambda^{1/4}}{Y_{\nu_1}}$



$M = 10^{10}$ GeV, $Y = 10^{-3}$



$Y = 10^{-14}$

Parameters leading to a higher EW scale do not yield theories consistent with quantum gravity

→ No EW hierarchy problem

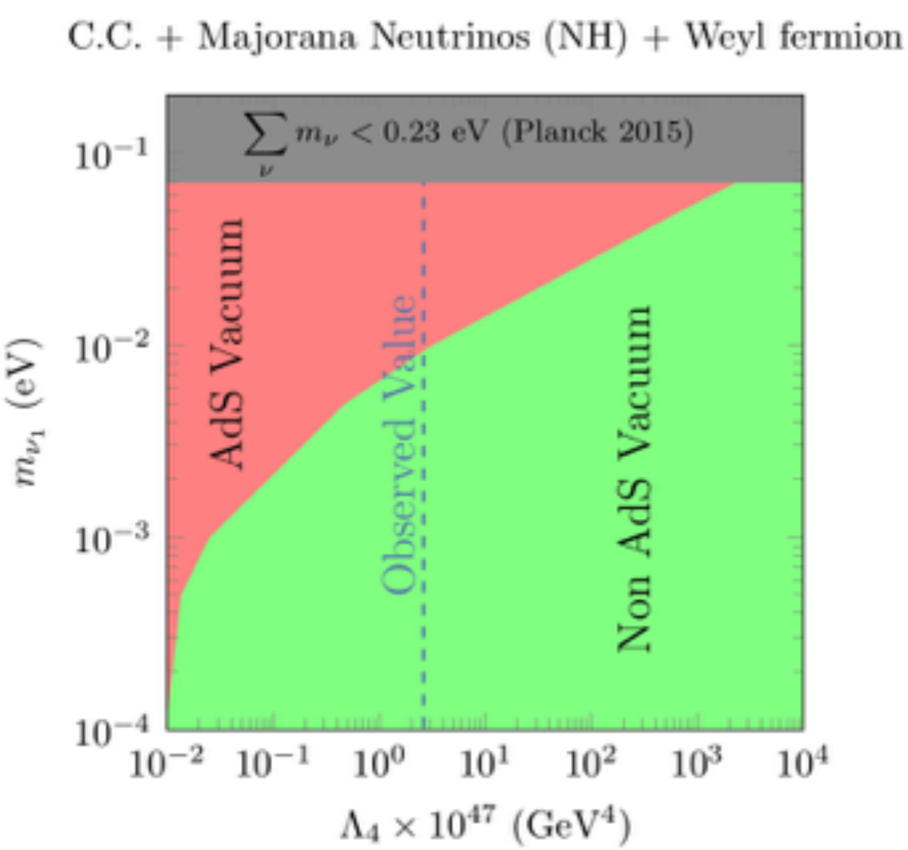
Adding BSM physics

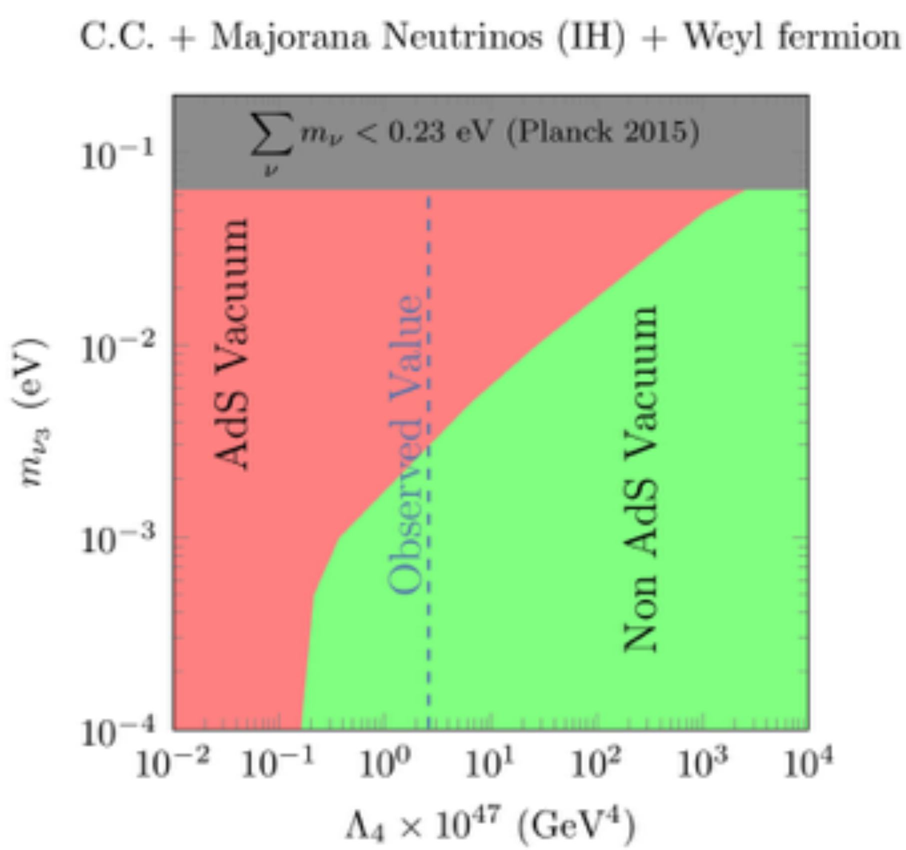
- **Light fermions**

Positive Casimir contribution $\longrightarrow$ helps to avoid AdS vacuum

Majorana neutrinos are consistent if adding $m_\chi \lesssim 2\ \mathrm{meV}$

example. For $m_\chi = 0.1\ \mathrm{meV}$:



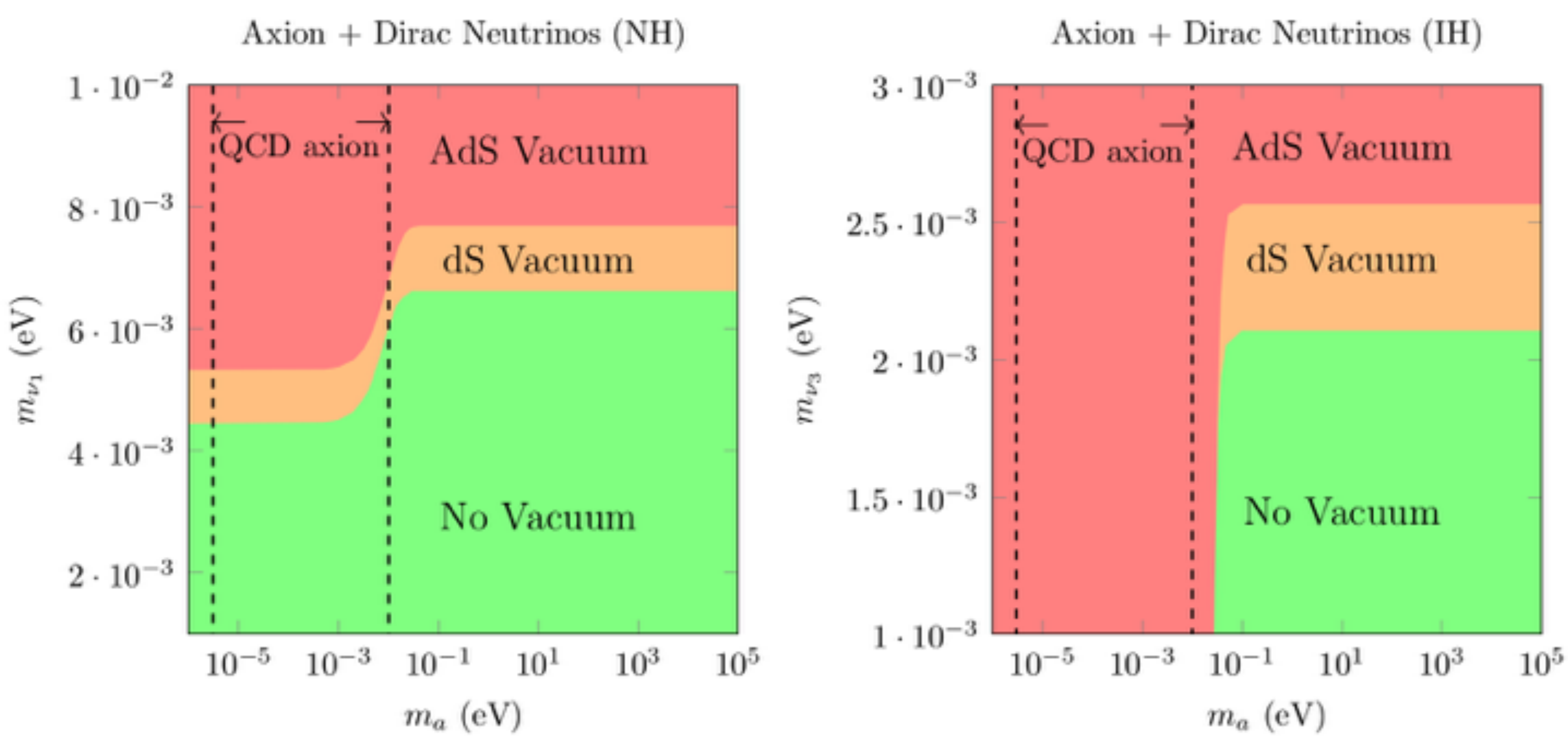


Adding BSM physics

- **Axions**

  1 axion: negative contribution ⟶ bounds get stronger

  - IH Dirac neutrinos are ruled out in the presence of QCD axion



Multiple axions: can destabilise AdS vacuum ⟶ bounds disappear

Other SM compactifications

- Circle compactification on S^1 ✓ [Ibanez,Martin-Lozano,IV'17]

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There are not new minima (no new bounds) arising at smaller radius when adding the rest of SM particles

… but there can be runaways due to Wilson lines
[Hamada-Shiu'17]

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- Orbifold compactifications on S^1/Z_2 and T^2/Z_4 (no Wilson lines)
  [Gonzalo,Herraez,Ibanez'18]

→ Same bounds on neutrino masses

→ New minima that cannot be avoided unless SM is completed with more bosons, like MSSM

(but MSSM at a multi-TeV region at least)

Naturalness and Swampland

- Space of parameters is smaller than expected, not everything goes!

  → Provide IR rules to identify non-trivial correlations among parameters of the EFT

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- Emergence from integrating out large number of states [Grimm, Palti, IV'18] [Heidenreich,Reece,Rudelius'18]

Quantum corrections to gauge coupling from integrating out N massive particles:

$$\frac{1}{g_{IR}^2} = \frac{1}{g_{UV}^2} - \sum_k^N \left(\frac{8q_k^2}{3\pi^2} \log \frac{\Lambda_{UV}}{m_k} \right) \left\{ \begin{array}{l} \dfrac{1}{g_{IR}^2} \propto \log m_0 \to \infty \quad \text{for single field} \\ \text{(logarithmic running)} \\ \dfrac{1}{g_{IR}^2} \propto \dfrac{1}{\Delta m^2} \to \infty \quad \text{for infinite tower} \\ \text{(power law!)} \end{array} \right.$$

Qualitatively different results!

Naturalness and Swampland

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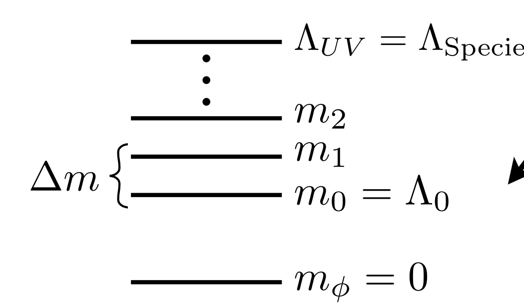
Qualitatively different results!

We integrate up to the species bound: $\Lambda_{UV} = \dfrac{M_p}{\sqrt{N}}$



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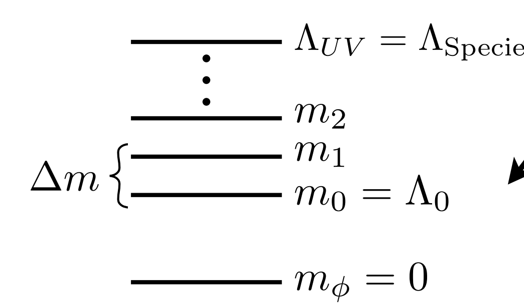
Emergence



We recover the WGC! $q^2 g_{IR}^2 = m^2$

(no miraculous correlation, natural from point of view of RGE)

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Swampland conjectures emerge from integrating out large number of states

↓

These towers of states arise at the limits of recovering approximate global symmetries and weakly coupled Einstein gravity

ongoing work

Summary

- String Landscape vs Swampland

  Not every EFT can be UV embedded in String Theory

  ↳ Quantum Gravity Constraints

- Consistency with quantum gravity implies constraints on low energy physics:

  Conjecture: Non-susy stable AdS vacua are inconsistent with QG

  ↳ Low energy constraints on SM and BSM light spectra

  ↓

  Upper bound on the EW scale in terms of the cosmological const.

  New approach to hierarchy problems? UV/IR mixing?

  Assumptions:

  - Conjecture holds (motivated from WGC if there are fluxes in extra dimensions)
  - No additional 3d non-perturbative instabilities transferred from higher dimensions

Summary

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  Upper bound on the EW scale in terms of the cosmological const.

  New approach to hierarchy problems? UV/IR mixing?

- We need more evidence for these conjectures! ongoing work

Thank you!

back-up slides

Bounds on the SM + light BSM physics

Model	Majorana (NI)	Majorana (IH)	Dirac (NH)	Dirac (IH)
SM (3D)	no	no	$m_{\nu_1} \leq 7.7 \times 10^{-3}$	$m_{\nu_3} \leq 2.56 \times 10^{-3}$
SM(2D)	no	no	$m_{\nu_1} \leq 4.12 \times 10^{-3}$	$m_{\nu_3} \leq 1.0 \times 10^{-3}$
SM+Weyl(3D)	$m_{\nu_1} \leq 0.9 \times 10^{-2}$ $m_f \leq 1.2 \times 10^{-2}$	$m_{\nu_3} \leq 3 \times 10^{-3}$ $m_f \leq 4 \times 10^{-3}$	$m_{\nu_1} \leq 1.5 \times 10^{-2}$	$m_{\nu_3} \leq 1.2 \times 10^{-2}$
SM+Weyl(2D)	$m_{\nu_1} \leq 0.5 \times 10^{-2}$ $m_f \leq 0.4 \times 10^{-2}$	$m_{\nu_3} \leq 1 \times 10^{-3}$ $m_f \leq 2 \times 10^{-3}$	$m_{\nu_1} \leq 0.9 \times 10^{-2}$	$m_{\nu_3} \leq 0.7 \times 10^{-2}$
SM+Dirac(3D)	$m_f \leq 2 \times 10^{-2}$	$m_f \leq 1 \times 10^{-2}$	yes	yes
SM+Dirac(2D)	$m_f \leq 0.9 \times 10^{-2}$	$m_f \leq 0.9 \times 10^{-2}$	yes	yes
SM+1 axion(3D)	no	no	$m_{\nu_1} \leq 7.7 \times 10^{-3}$	$m_{\nu_3} \leq 2.5 \times 10^{-3}$ $m_a \geq 5 \times 10^{-2}$
SM+1 axion(2D)	no	no	$m_{\nu_1} \leq 4.0 \times 10^{-3}$	$m_{\nu_3} \leq 1 \times 10^{-3}$ $m_a \geq 2 \times 10^{-2}$
$\geq 2(10)$ axions	yes	yes	yes	yes

Compactifications of SM on T_2 $\longrightarrow$ qualitatively similar, but a bit stronger

(see also [Hamada-Shiu'17])

Casimir energy

Potential energy in 3d:

$$V(R) = \frac{2\pi r^3 \Lambda_4}{R^2} + \sum_i (2\pi R) \frac{r^3}{R^3} (-1)^{s_i} n_i \rho_i(R)$$

Casimir energy density:

$$\rho(R) = \mp \sum_{n=1}^{\infty} \frac{2m^4}{(2\pi)^2} \frac{K_2(2\pi R m n)}{(2\pi R m n)^2}$$

For small mR:

$$\rho(R) = \mp \left[\frac{\pi^2}{90(2\pi R)^4} - \frac{\pi^2}{6(2\pi R)^4}(mR)^2 + \frac{\pi^2}{48(2\pi R)^4}(mR)^4 + \mathcal{O}(mR)^6 \right]$$


Swampland