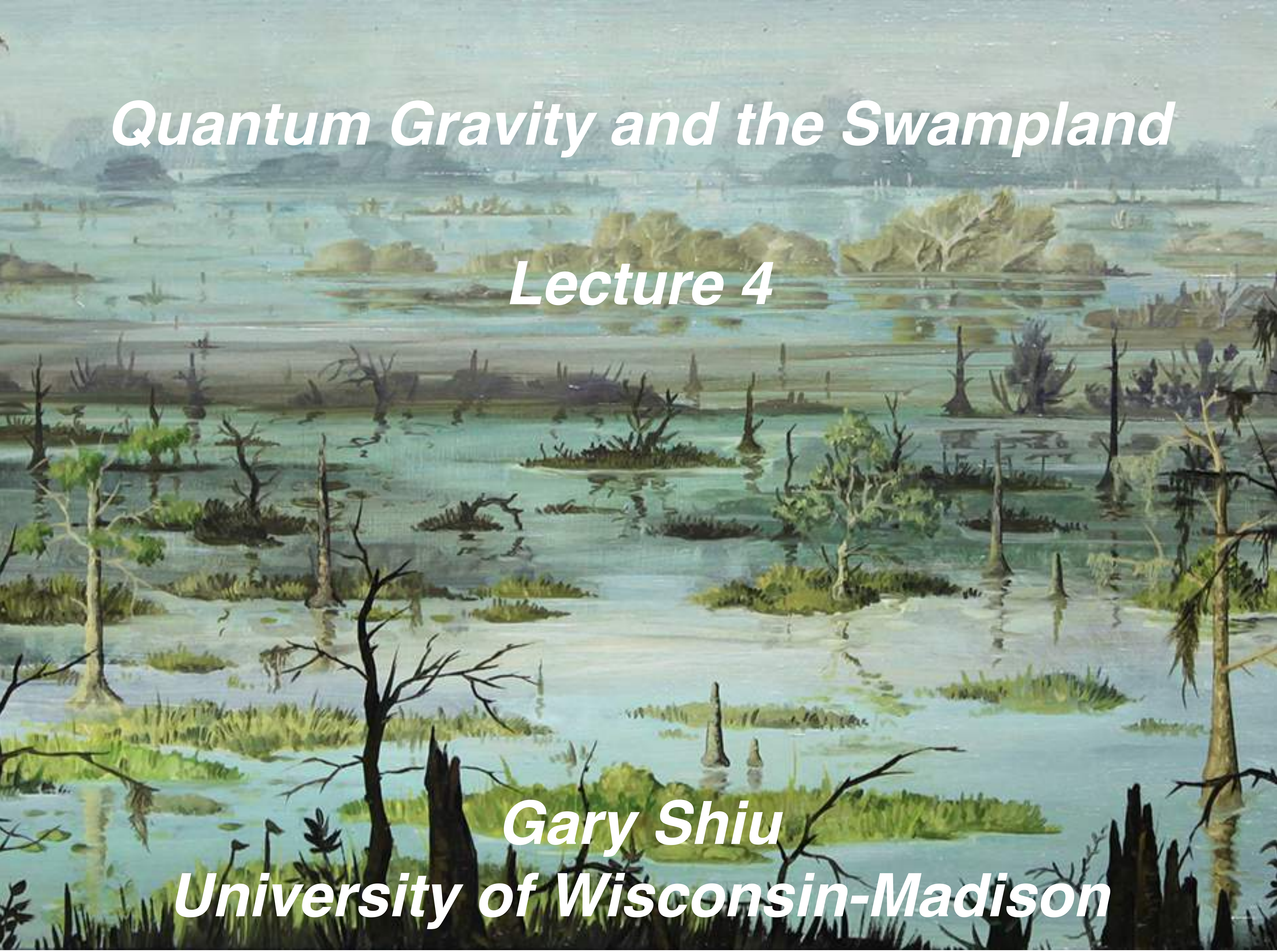

Quantum Gravity and the Swampland

Lecture 4

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Web of Conjectures

No global symmetry
[Banks, Dixon,'88];[Harlow, Ooguri,'18]
Lecture 1

$g \neq 0$

Weak Gravity Conjecture (WGC)
[Arkani-Hamed, Motl, Nicolis, Vafa. '06]
Lectures 1 and 2

$\geqq \to >$

Non-SUSY AdS
[Ooguri, Vafa,'16]
Lecture 4

non-SUSY

Distance Conjecture
[Ooguri, Vafa,'06]

Lecture 4

$g \to 0$

Tower WGC
[Andriolo, Junghans, Noumi, GS, '18]
sLWGC
[Montero, GS, Soler '16];[Heidenreich et al, '16]

[Ooguri, Palti, GS, Vafa,'18]
Lecture 4

dS Conjecture
[Obied, Ooguri, Spodyneiko, Vafa,'18]

Swampland, Duality, & de Sitter Entropy

de Sitter vacua in String Theory

- Observation of accelerating universe poses the dark energy puzzle. Simplest explanation is that we are living in a metastable dS vacuum.

- Despite heroic efforts (e.g., **[Silverstein]; [KKLT]; [LVS]**), ***explicit, controlled*** de Sitter vacua seem difficult to construct.

- Attempts to find simpler de Sitter vacua run into potentials with too steep a gradient or tachyonic directions

  [Hertzberg, Kachru, Taylor, Tegmark];[Silverstein];[Haque, GS, Underwood, Van Riet];[Flauger, Paban, Robbins, Wrase];[Caviezel, Koerber, Kors, Lust, Wrase, Zagermann];[Danielsson, Haque, GS, Van Riet];[Danielsson, Haque, Koerber, GS, Van Riet, Wrase]; [GS, Sumitomo];[Danielsson, Haque, Van Riet, Wrase]; …

- This state of affairs motivated **[Obied, Ooguri, Spodyneiko, Vafa]** to conjecture:

$$|\nabla V| \geq \frac{c}{M_p} \cdot V \qquad c \sim \mathcal{O}(1) > 0$$

- Could there be some general physics underlying this behavior?

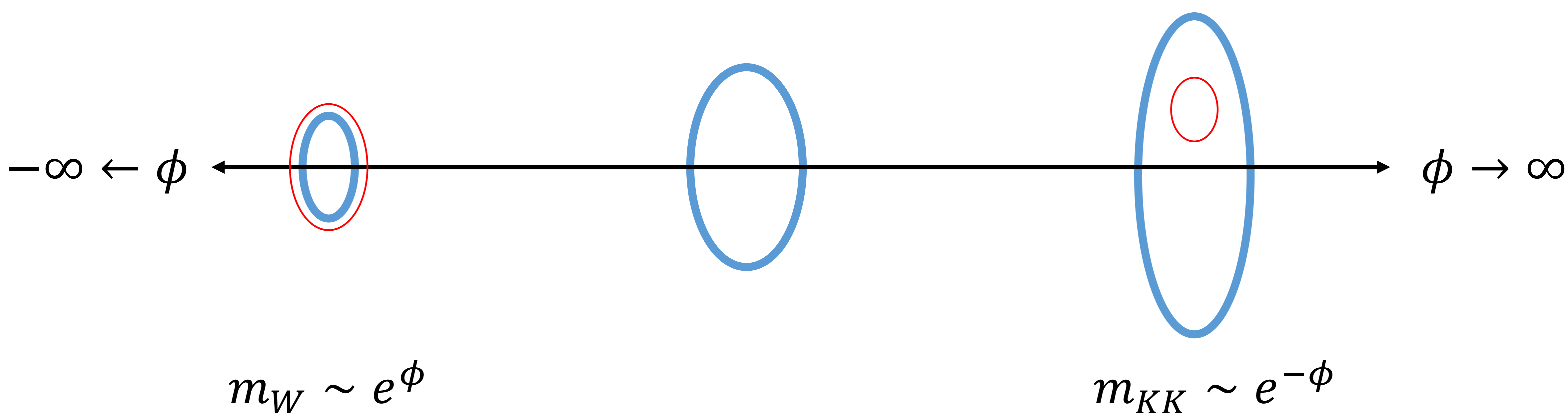
Swampland Distance Conjecture

- Approaching any infinite distance locus in moduli space, there is an infinite tower of states which becomes exponentially light:

$$m_{\text{tower}} \sim e^{-a\phi} \quad \text{for} \quad \phi \to \infty$$

[Ooguri, Vafa, '06]

- Simple example: compactification on a circle



- This conjecture has passed some non-trivial tests (at least for theories with 8 supercharges) **[Cecotti,'15];[Grimm,Palti, Valenzuela,'18]; [Lee, Lerche, Weigand,'18]**

Swampland Distance Conjecture

- While there are open questions **[Landete, GS];[Hebecker, Henkenjohann, Witkowski]** regarding what is $\Delta\phi$ at the onset of this exponential behavior:

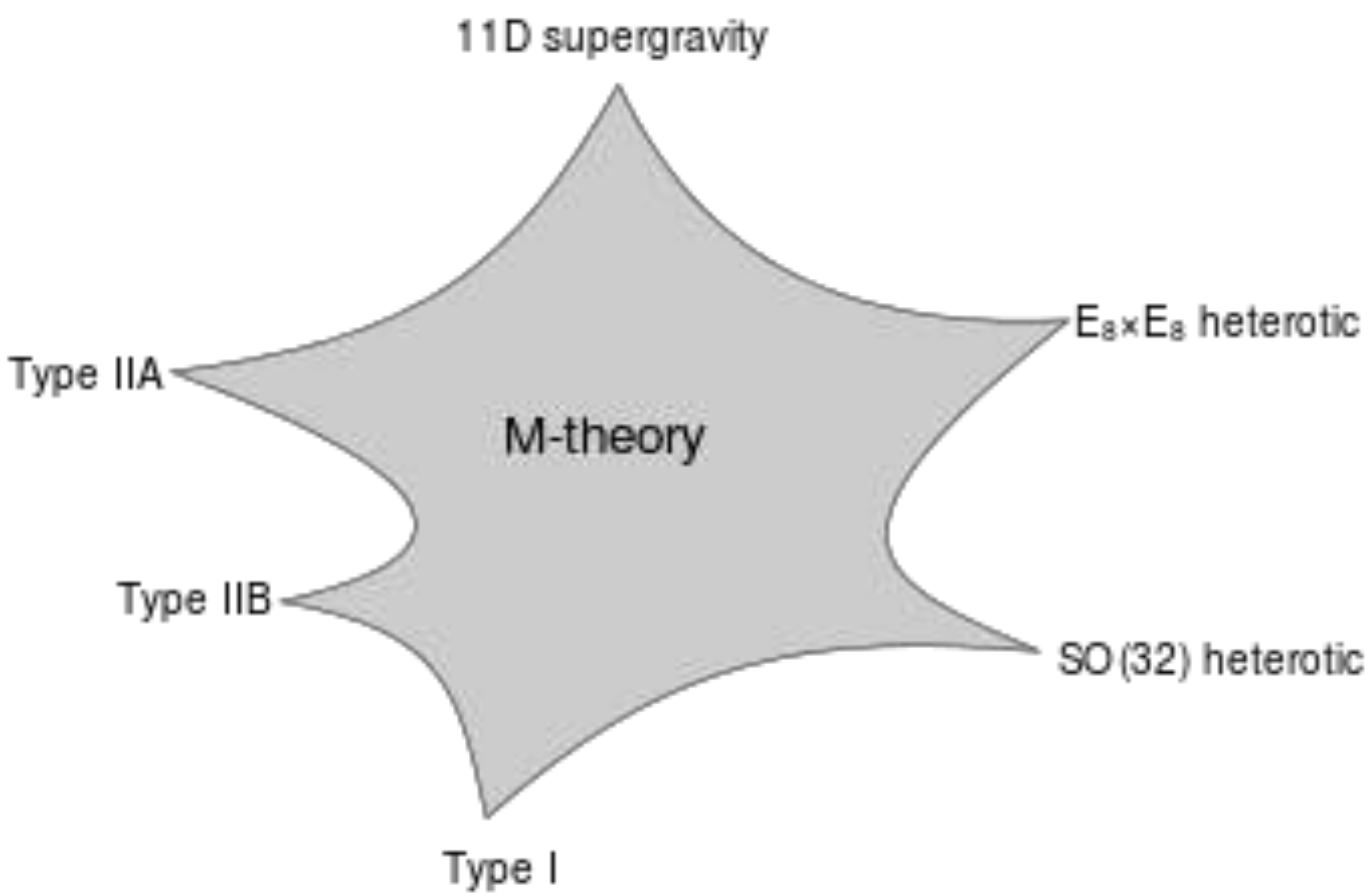
$$m_{\text{tower}} \sim e^{-a\phi} \quad \text{for} \quad \phi \to \infty$$

  and the notion of distance in the presence of a potential V(ϕ), such subtleties do not affect the proposed universal behavior at $\phi\to\infty$.

- The infinite distance regime is where we will use this conjecture for our entropy argument.

Swampland Distance Conjecture & Duality

- The underlying motivation for this conjecture is **duality**: at large distance, there is a dual description in terms of the light states.



Couplings in string theory are scalar fields

$$\text{Weak Coupling } g \to 0 \quad \Leftrightarrow \quad \text{Large distance } \phi \to \infty$$

Swampland Distance Conjecture & Duality

- We interpret the Swampland Distance Conjecture as:

Any weakly coupled region in string theory should have a dual description in terms of the tower of light states.

- We argued how this tower of states may provide a dual description of the potential $V(\phi)>0$ and the associated entropy.

de Sitter Entropy

- The Gibbons-Hawking entropy of de Sitter space:

$$S_{\rm GH} = R^2 = 1/\Lambda$$

- This entropy has been interpreted in terms of:

$$\dim \mathcal{H} = e^{1/\Lambda}$$

in an observer's causal domain **[Banks];[Witten].**

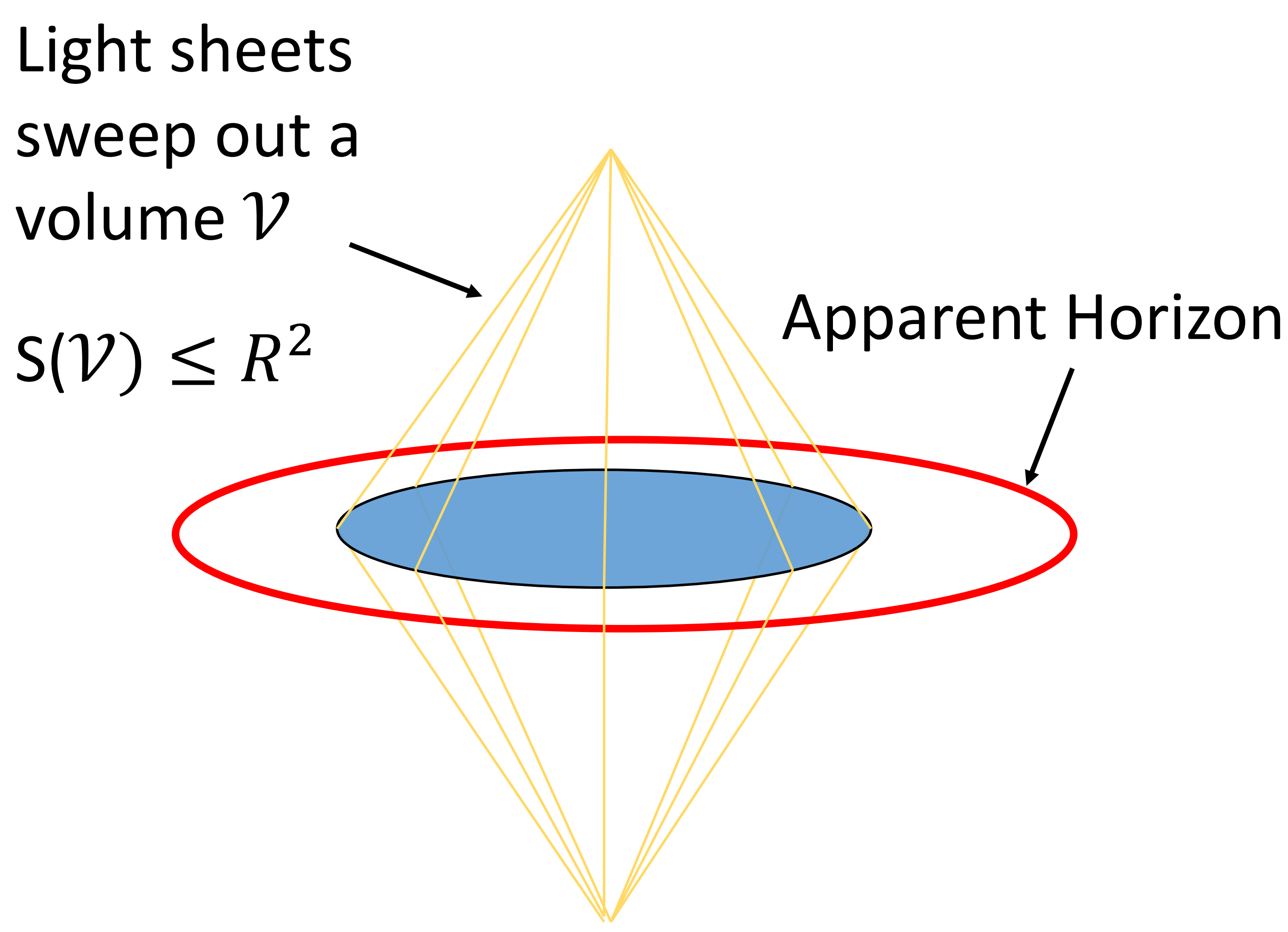
- Instead of Λ, we have $V(\phi)>0$. If $V(\phi)$ has a local minimum, we have a long-lived metastable de Sitter vacuum, and S_{GH} is meaningful.

- Even if V has a non-zero gradient, as long as $|\nabla V|/V < \sqrt{2}$, there is an **apparent horizon** with

$$R = \frac{1}{\sqrt{V}}$$

Bousso Bound

- Since the apparent horizon is always inside of a cosmic event horizon (if the latter exists), lightsheets emanating from it will close at caustics:



[Fischler, Susskind, '98];[Bousso, '99]

de Sitter Entropy

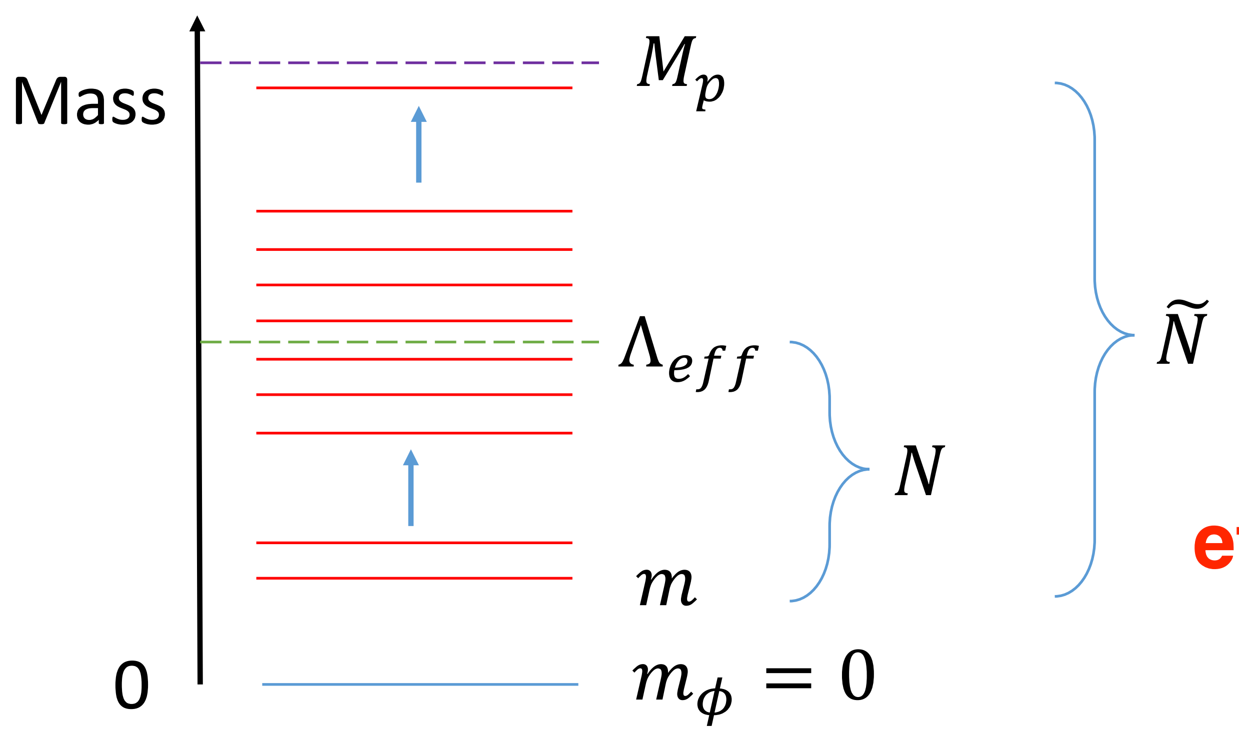
- This semi-classical picture is valid provided quantum fluctuations of ϕ are negligible.
- If the Hessian $\nabla_i \nabla_j V$ has a negative eigenvalue below $-c'/R^2$, with $c' \sim \mathcal{O}(1)$, the zero point fluctuations at horizon crossing becomes **tachyonic** $\Rightarrow$ semi-classical picture breaks down.
- If V is positive and satisfies:

$$|\nabla V| \leq \sqrt{2} \cdot V \quad \text{and} \quad \min(\nabla_i \nabla_j V) \geq -c' V$$

  there is an accelerating universe, and the entropy inside of its apparent horizon is bounded by R^2.
- The second inequality also ensures that the first inequality holds for at least one Hubble time.

Tower of States

- In the weak coupling regime, we have towers of light states with exponentially small masses.
- This should increase the entropy and influence how $V(\phi)$ behaves.



$$N(\phi) \sim n(\phi)e^{b\phi}$$

effective # of towers

b ≠ a in general

- We expect $n(\phi)$ to increase toward the weak coupling limit.

Entropy and Tower of States

- The entropy associated with the light states is a function of N and R:

$$S_{\text{tower}}(N, R)$$

- Since N, R ≫ 1, S_{tower} (N,R) should be dominated by a single term:

$$S_{\text{tower}}(N, R) \sim N^{\gamma} R^{\delta}$$

- The Bousso bound applied to the tower:

$$N^{\gamma} R^{\delta} \leq R^2$$

- Since the tower of states dominate the Hilbert space in the weak coupling regime, we expect them to saturate the Bousso bound:

$$V(\phi) \sim R^{-2} \sim N^{-\frac{2\gamma}{2-\delta}}$$

The Refined de Sitter Conjecture

- The gradient condition follows from the exponential behavior of N(ϕ)

$$|\nabla V| \geq \frac{c}{M_p} \cdot V \qquad \text{with} \qquad c = \frac{2b\gamma}{2-\delta}$$

- A prerequisite for the notion of entropy is:

$$\min(\nabla_i \nabla_j V) \geq -c' V$$

- Our analysis naturally led to the **Refined de Sitter Conjecture:**

$$|\nabla V| \geq \frac{c}{M_p} \cdot V \ , \quad \textbf{or} \quad \min\left(\nabla_i \nabla_j V\right) \leq -\frac{c'}{M_p^2} \cdot V$$

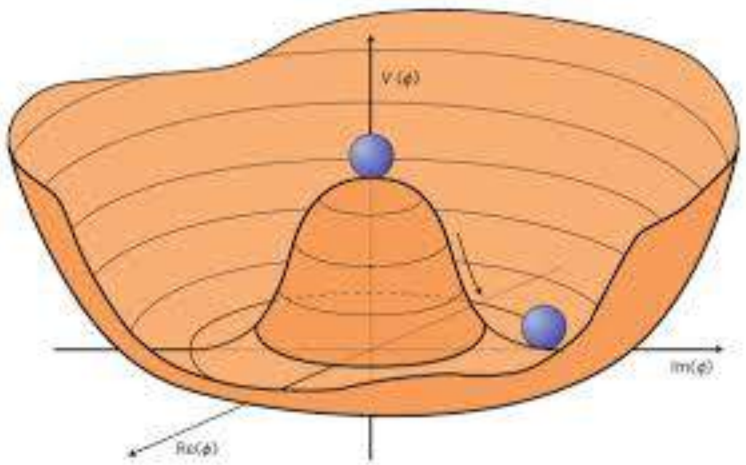
[Ooguri, Palti, GS, Vafa]

The Refined de Sitter Conjecture

- While not our motivation, our refined de Sitter conjecture can evade some counterexamples **[Denef, Hebecker, Wrase];[Conlon];[Murayama, Yamazaki, Yanagida]; [Choi, Chway,Shin];[Hamaguchi, Ibe, Moroi]** to the original de Sitter conjecture.

- The top of the Higgs potential:

$$|\nabla V| \sim \frac{10^{-55}}{M_{Pl}} V \qquad \min(\nabla_i \nabla_j V) \sim -\frac{10^{35}}{M_{Pl}^2} V$$



- The top of the potential for the pion or QCD axion

$$\min(\nabla_i \nabla_j V) \sim -\frac{1}{f^2} V$$

The WGC for axions gives $f \leq M_{Pl}$

The Refined de Sitter Conjecture

[Ooguri, Palti, GS, Vafa]

Recall our assumptions:

- The Swampland Distance Conjecture holds for potentials
- In a weakly coupled regime where the tower is a dual description.
- In a quasi de Sitter setting (accelerating expansion with horizon)

$$\Rightarrow \quad \boxed{|\nabla V| \geq \frac{c}{M_p} \cdot V \,, \quad \text{or} \quad \min\left(\nabla_i \nabla_j V\right) \leq -\frac{c'}{M_p^2} \cdot V}$$

Entropy Counting

- While the de Sitter conjecture is insensitive to the microstate counting, the cosmology depends on γ and δ.

- There is no known method to compute $S_{tower}(N,R)$ by enumerating all states in the Hilbert space of quantum gravity in a quasi-dS space.

- There are (at least) three types of states:

    - QFT states localized within the bulk of de Sitter
    - Black holes
    - States localized on the horizon

- We can count their subset when the low energy theory consists of N free particles, this can be regarded as a **lower bound** on $S_{tower}(N,R)$.

Entropy of Free Particles

- Consider a single free field with mass m in a box of size R, up to a maximum momentum k_{max}, the associated entropy and energy are:

$$S_{N=1} \sim (k_{\max} R)^3 \ , \quad E_{N=1} \sim \omega \, (k_{\max} R)^3$$

- The maximum energy associated to these modes is:

$$E_{N=1} \sim k_{max} \left(k_{max} R \right)^3$$

- For such configuration to not collapse into a blackhole: $E_{N=1} < R$

$$k_{max} < R^{-\frac{1}{2}} \ , \quad S_{\text{tower}} < R^{\frac{3}{2}}$$ **[Page'81];[Banks, '05]**

- Though this cannot saturate the Bousso bound, it may be possible with large N species of particles.

Entropy of a Tower of Free Particles

- Consider N species of such particles. To maximize the entropy, we can regard them to be in a thermal bath of a common temperature T.

$$S_N \sim N T^3 R^3 \ , \quad E_N \sim N T^4 R^3 \ .$$

- Not forming black holes implies:

$$T \leq N^{-\frac{1}{4}} R^{-\frac{1}{2}} \ , \quad S_N \sim N^{\frac{1}{4}} R^{\frac{3}{2}}$$

- S_N can saturate the Bousso bound for an extremely large number of species, with the minimum entropy assigned to each:

$$N \sim R^2 \quad T \sim \frac{1}{R} \quad S_1 \sim 1$$

- The low temperature and entropy per species means at borderline of thermodynamics, but can explicitly check by counting microstates.

Cosmological Implications

- While the de Sitter conjecture is insensitive to the O(1) values of γ and δ, the phenomenology is.
- How would these bounds apply to our universe, with $R \sim 10^{60}$?
- Consider an evenly spaced tower: $m_n \sim nm$ and a cutoff scale Λ_N below which there are N states contributing to the entropy:

$$N^{-\frac{1}{2}} < \Lambda_N < 1$$

- The tower of states have masses in the range: $R^{\frac{3(\delta-2)}{2\gamma}} < m < R^{\frac{\delta-2}{\gamma}}$
- For free particles, $\gamma = 1/4$, $\delta = 3/2$ give an unrealistic spectrum. If the entropy bound is saturated, our universe is not at parametrically weak coupling.
- Taking different values, $\gamma = 1$, $\delta = 7/4$ gives $N \sim 10^{15}$ and MeV<m<TeV.
- The mass of the tower is time-dependent as the quintessence field evolves and could lead to interesting pheno **[See e.g., Matsui, Takahashi, Yamada]**

AdS Instability Conjecture

WGC for Branes

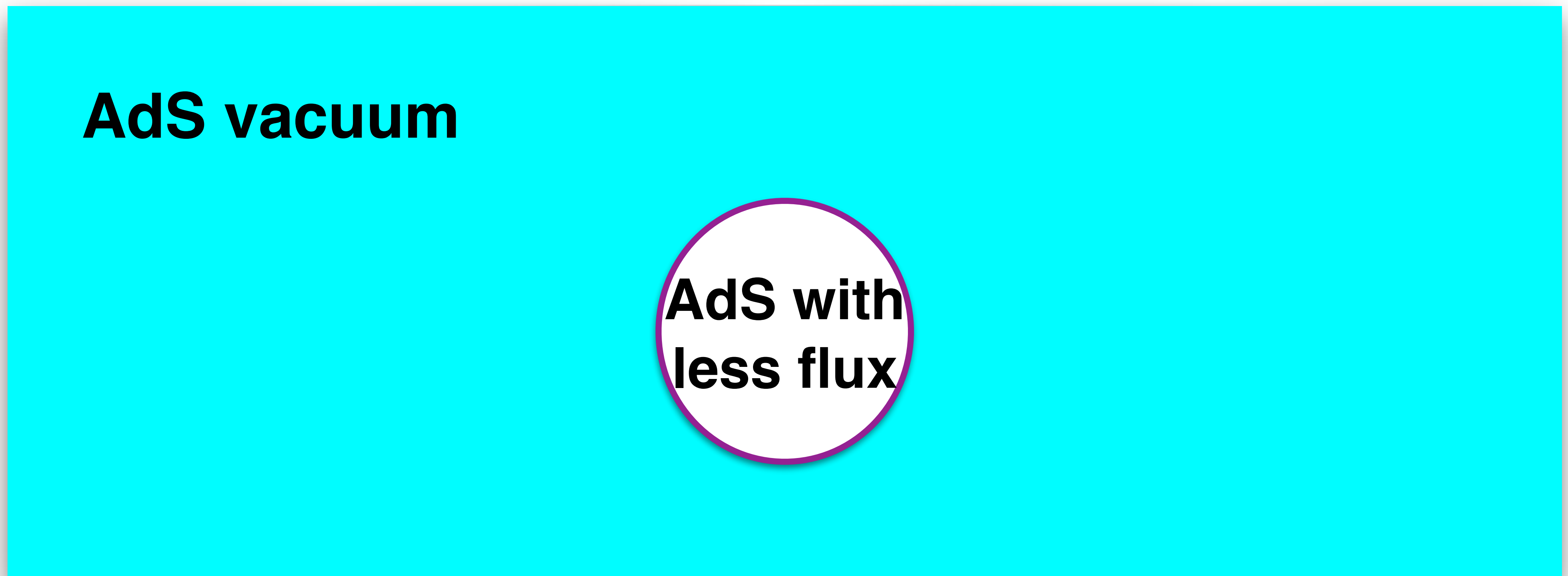
- We have seen the applications of the WGC to particles (and instantons). Analogously, the WGC for branes is:

$$``T_p \leq Q_p"$$

- A stronger form [Ooguri,Vafa, '16]: **this bound is saturated only for a BPS state in a SUSY theory.**
- A ***corollary*** of this strong form: **non-SUSY AdS vacua supported by fluxes are unstable.**
- In AdS space, a brane with T < Q leads to an instability (AdS fragmentation) [Maldacena, Michelson, Strominger, '99].
- This brane gets nucleated and expands. It reaches the boundary of AdS within a finite time and dilute the flux.

AdS Instability

- Instability if there exists a T<Q brane (bubble wall) in AdS:



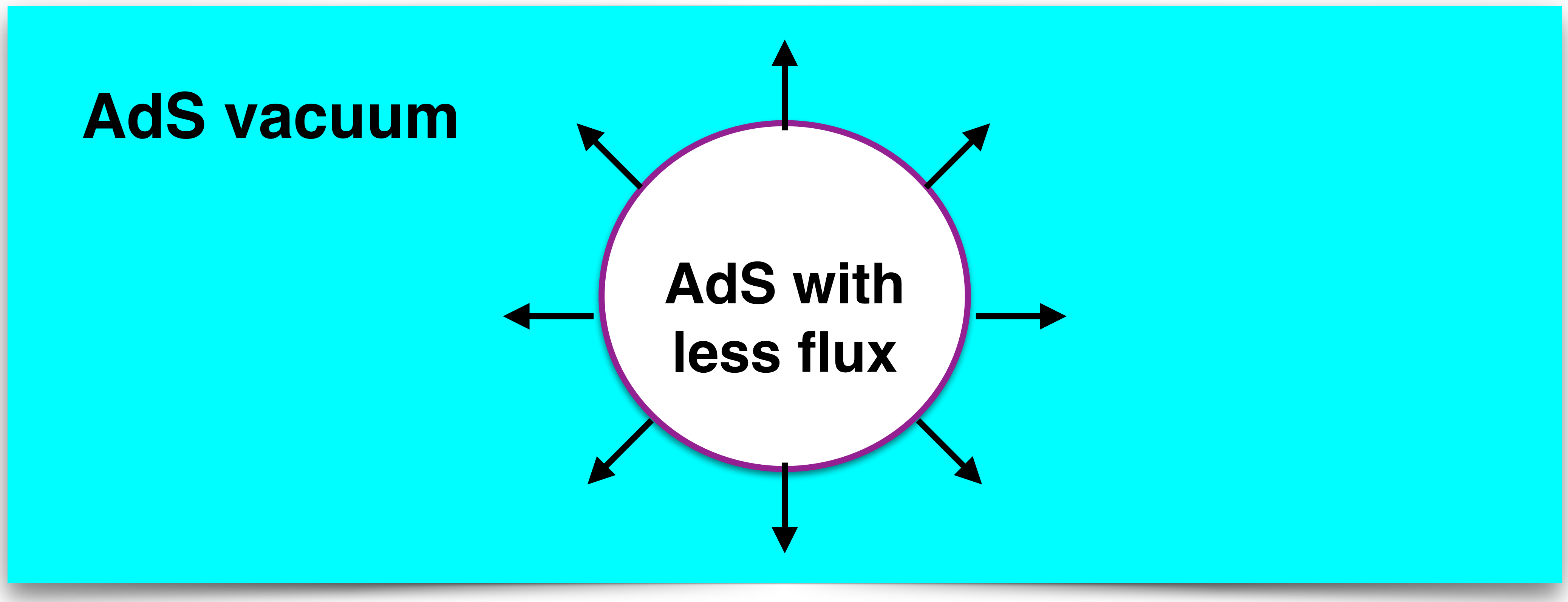
- A stronger form of the Ooguri-Vafa conjecture:

  "all non-SUSY AdS (in theories whose low energy description is Einstein gravity coupled to a finite # of fields) **are unstable"**

- **How do we test this conjecture?**

AdS Instability

- Instability if there exists a T<Q brane (bubble wall) in AdS:



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- **How do we test this conjecture?**

The Standard Model Landscape

The Standard Model in the Deep IR

- The deep IR of the SM, below the electron mass scale, is simple:
    - **Bosonic dof:** photon (2) and graviton (2)
    - **Fermionic dof:** ν's (6 or 12 for **Majorana/Dirac** ν's)
- The **mass scale of neutrinos**:

$$m_\nu \simeq 10^{-1} - 10^{-2} eV$$

- The only other known IR scale is the **cosmological constant**:

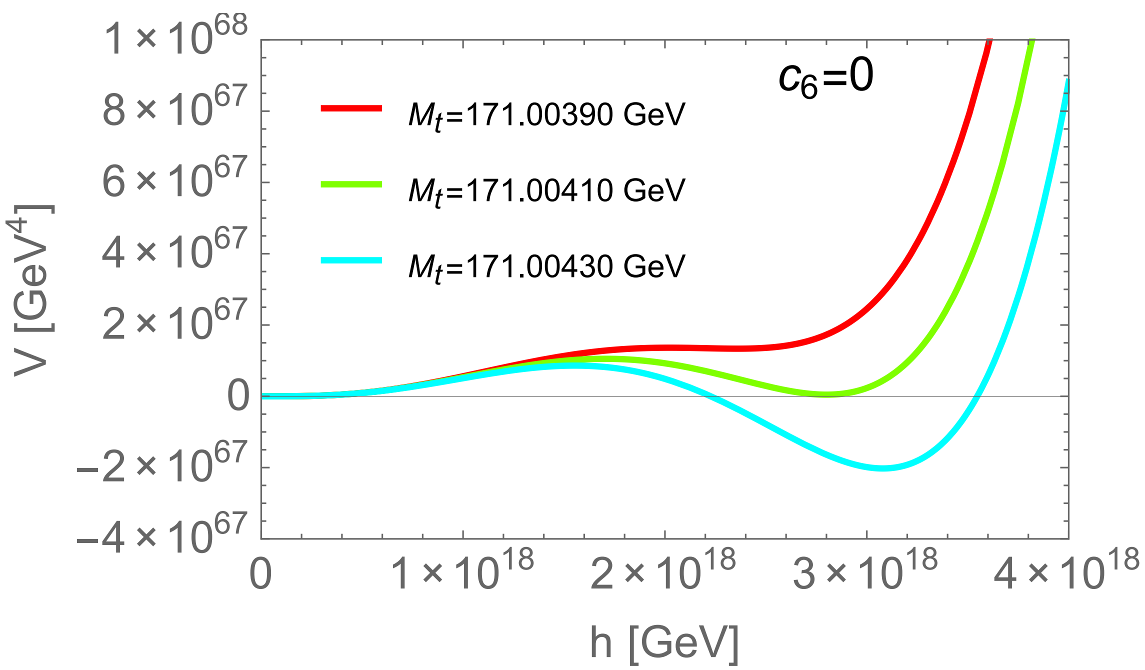
$$\Lambda \simeq 3.25 \times 10^{-11} eV^4 = (0.24 \times 10^{-2} eV)^4$$

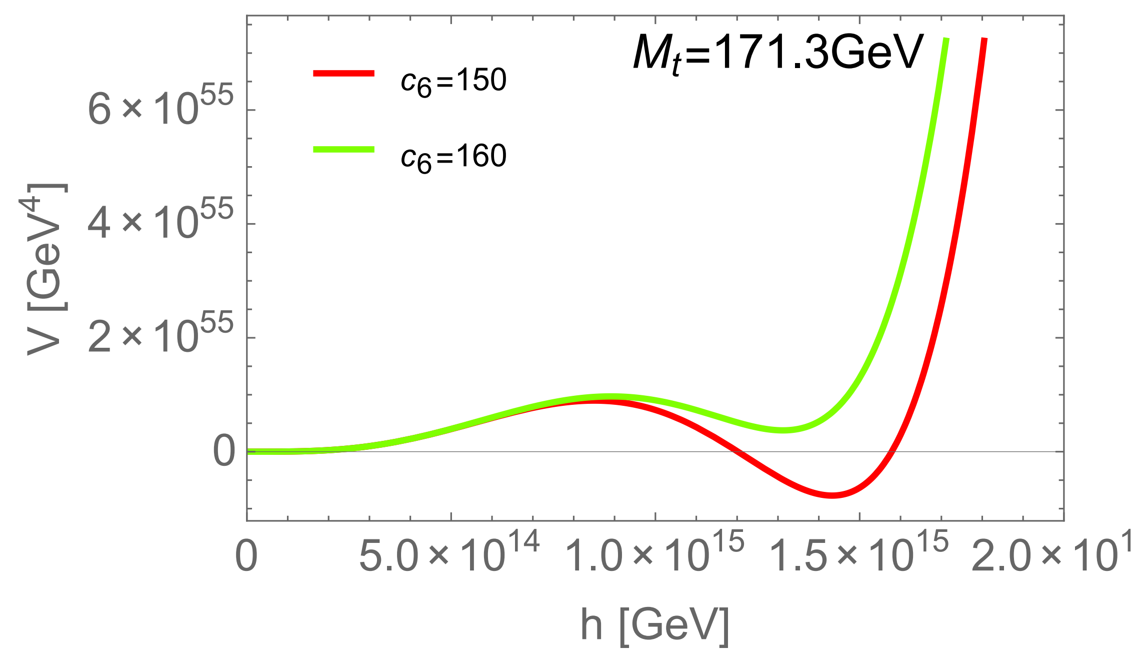
- This coincidence (?) has been a source of inspiration/speculations:

$$\Lambda \simeq m_\nu^4$$

The Higgs Potential

- After the Higgs discovery, we know that there is an additional Higgs vacuum at high scale, other than the EW vacuum:





- This high scale vacuum can be AdS_4, M_4, or dS_4 depending on the **top quark mass** and the **higher-dimensional operators**.
- Applying this conjecture to the SM landscape, we can constrain the **top mass, Higgs potential,** and **BSM physics**. **[Hamada, GS].**

Standard Model Landscape

- Upon compactification, the SM gives rise to a rich landscape of 3d vacua **[Arkani-Hamed, Dubovsky, Nicolis, Villadoro].**

4D action

$$S=\int d^4x\sqrt{-g}\left(\frac{1}{2}M_P^2R-\Lambda_4-V_{S^1}^{\rm all}-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}+\dots\right)$$

Dimensional reduction

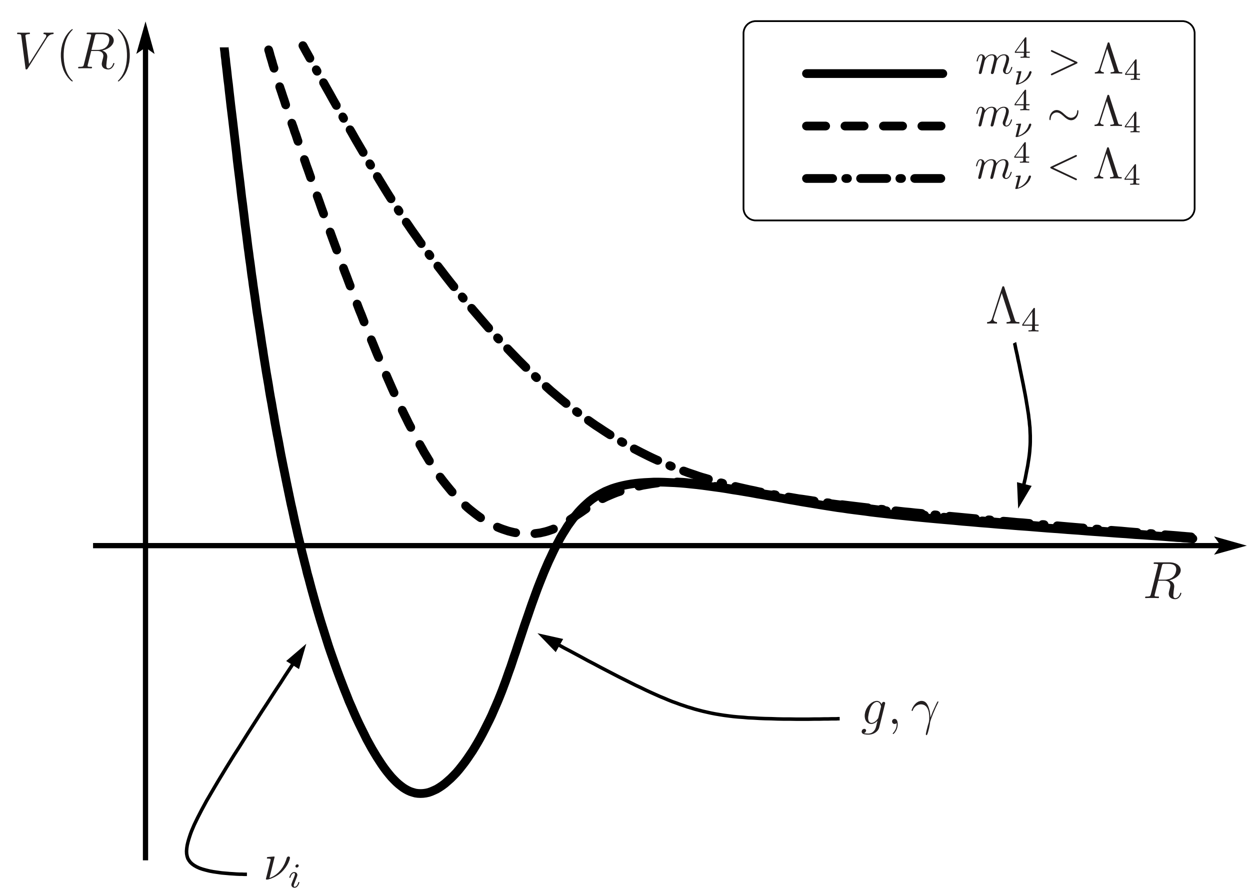
Casimir energy

$$S=\int_{x_{3d},E}(L_0)\left[\frac{1}{2}M_P^2R^{E(3)}-M_P^2\frac{g^{Eij}\partial_iL\partial_jL}{L^2}-\frac{1}{4}\left(\frac{L}{L_0}\right)^4B_{ij}B^{ij}-\frac{\Lambda_4L_0^2}{(2\pi L)^2}-\frac{V_{S^1}^{\rm all}L_0^2}{(2\pi L)^2}\right]$$

Potential for L

Standard Model Landscape

- The Casimir energy depends on the mass, spin, # dof, boundary conditions of the particles; negligible unless mL << 1.
- Photon + graviton (4 dofs) contribute negatively to the potential while Λ_4 contributes positively; the crossover L ~ 14 microns.
- Below $L_{crossover}$, L wants to shrink until L reaches the mass scale of neutrinos (or other light BSM particles) whose contribution can be positive.



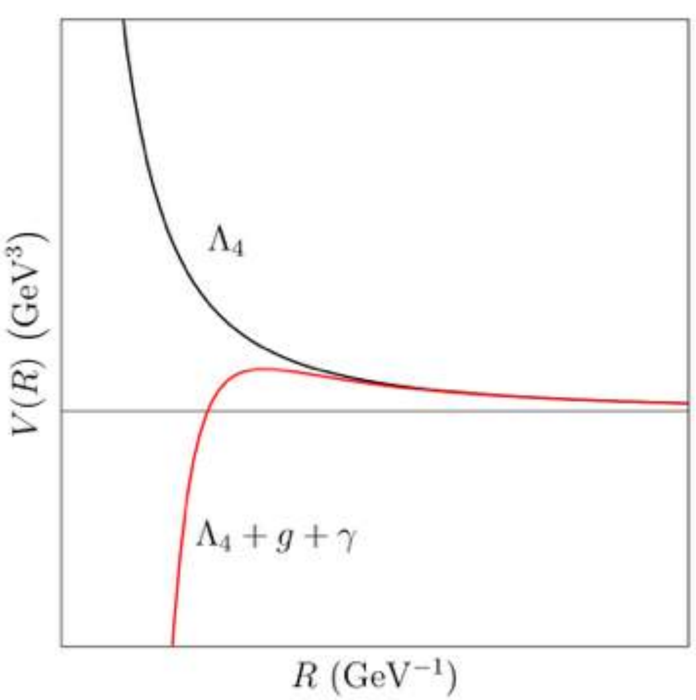
Casimir Energy

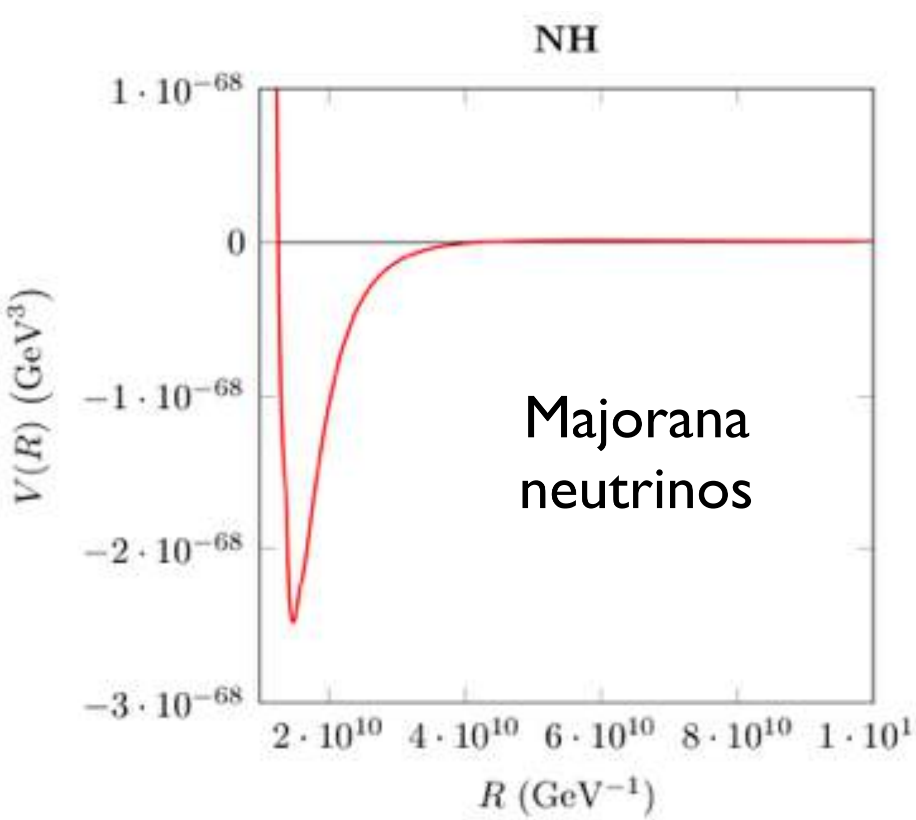
- The Casimir energy on S^1 : $$\frac{V_{S^1}^{\rm all}}{(2\pi L)^2} = \sum_{\rm particle} (-1)^{2s_p} n_p \frac{V_{S^1}^{(1)}\left(L, M_p, q_p A_\phi + \frac{1-z_p}{2}\right)}{(2\pi L)^2},$$

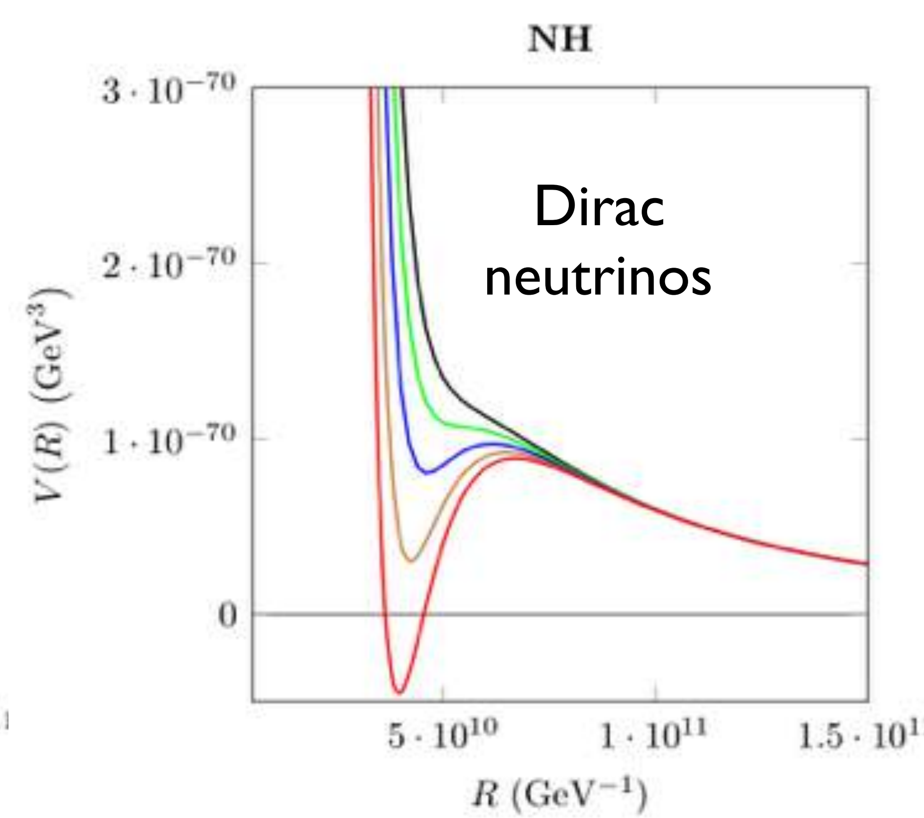
  where $$V_{S^1}^{(1)}(L, M, \theta) = -\frac{M^4}{2\pi^2}\sum_{n=1}^{\infty}\frac{\cos(2\pi n\theta)}{(2\pi LMn)^2}K_2(2\pi LMn),$$

  z=0: anti-periodic,
  z=1: periodic

- **For mL >> 1,** $V_{S^1} \sim e^{-2\pi mL}$
- **For mL << 1,** $V_{S^1} \sim \mp L^{-4}$ **(sign depends on spin & charge)**







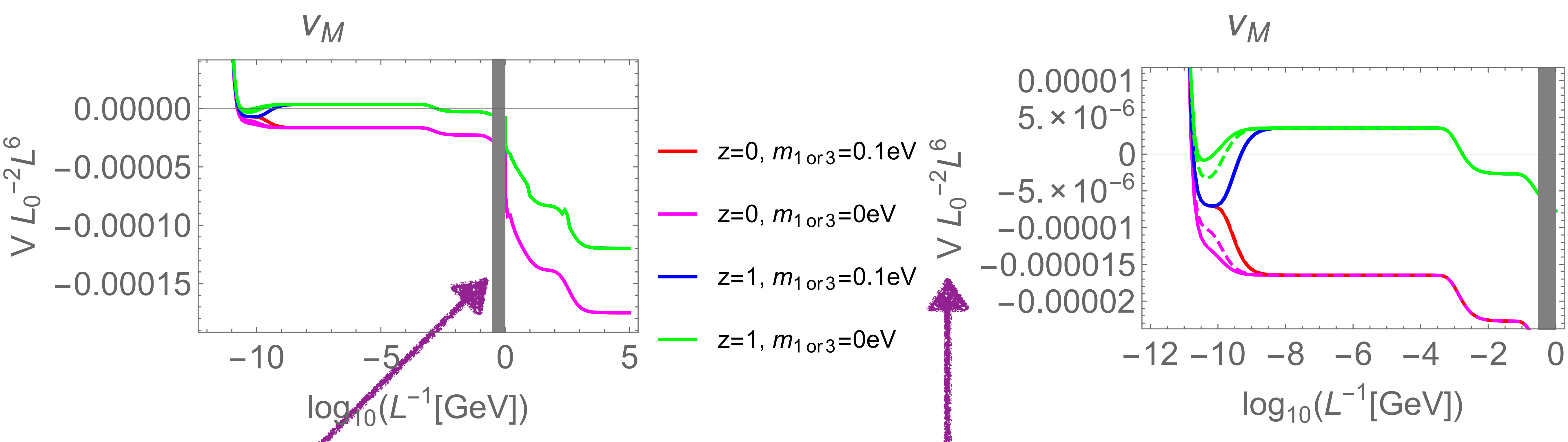
- **The more massive the neutrinos, the deeper the AdS vacuum.**

Majorana Neutrinos

- AdS3 vacuum around the neutrino mass scale ~ meV
- Balancing three contributions (z=0: anti-periodic, z=1: periodic):

cc **γ,graviton** **neutrino**

$$\frac{L_0^2}{(2\pi L)^2}\left\{\Lambda_4 - \frac{1}{180L^4(2\pi)^4} - \sum_i 2V_{S^1}^{(1)}\left(L, M_{\nu_i}, \frac{1-z}{2}\right)\right\}$$



around Λ_{QCD}

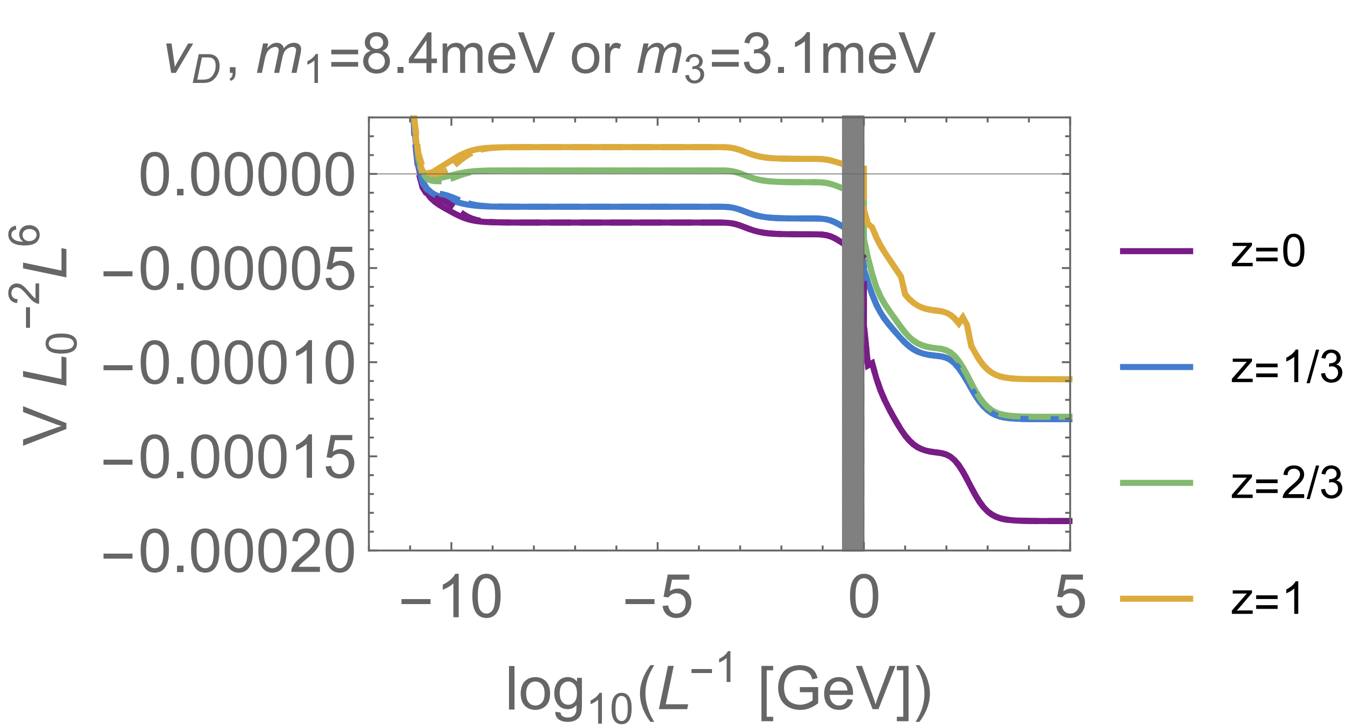
V×L⁶ is plotted for illustration.

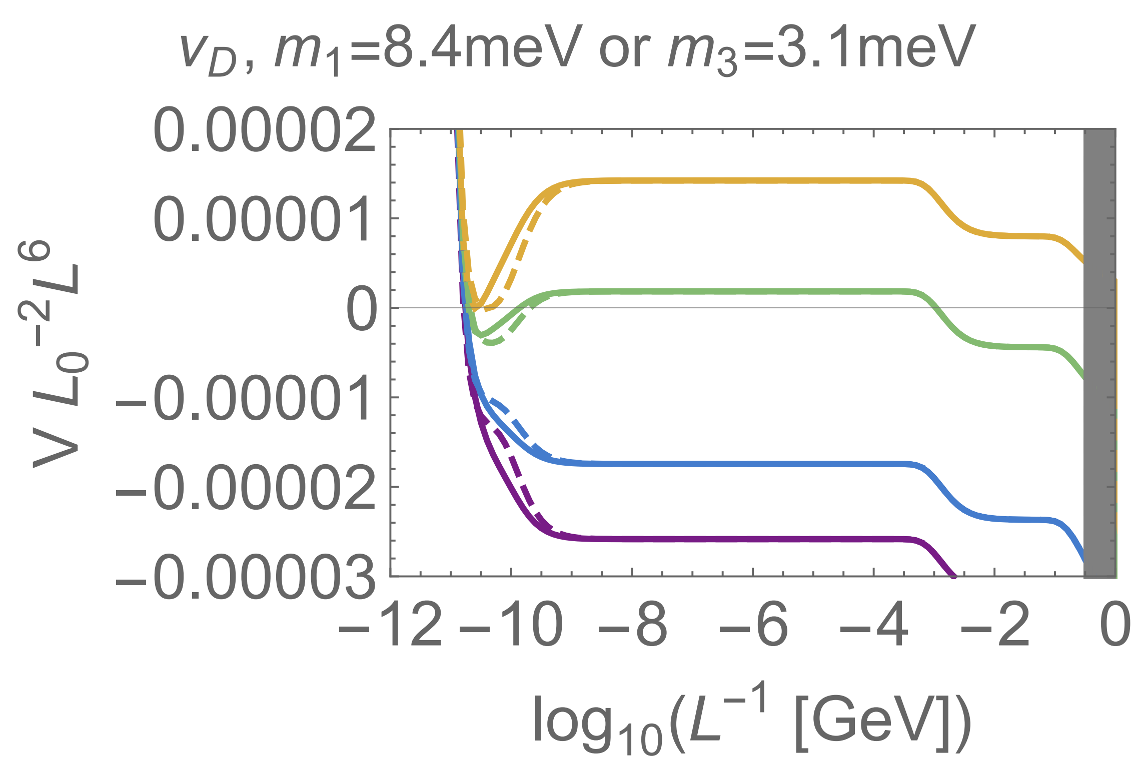
Dirac Neutrinos

- The neutrino vacuum can be AdS, Minkowski, or dS depending on the lightest neutrino mass

$$\frac{L_0^2}{(2\pi L)^2}\left\{\Lambda_4 - \frac{1}{180L^4(2\pi)^4} - \sum_i 4V_{S^1}^{(1)}\left(L, M_{\nu_i}, \frac{1-z}{2}\right)\right\}$$

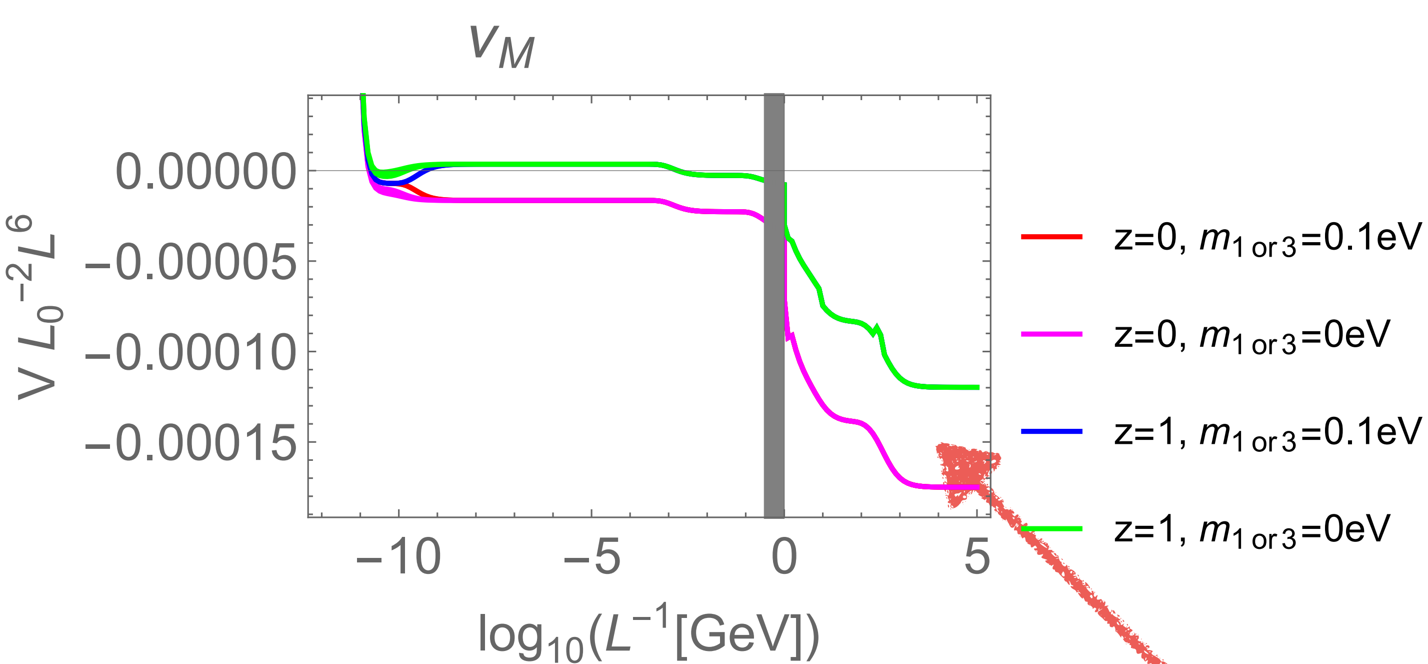
Difference! 2 (Majorana)→ 4 (Dirac)

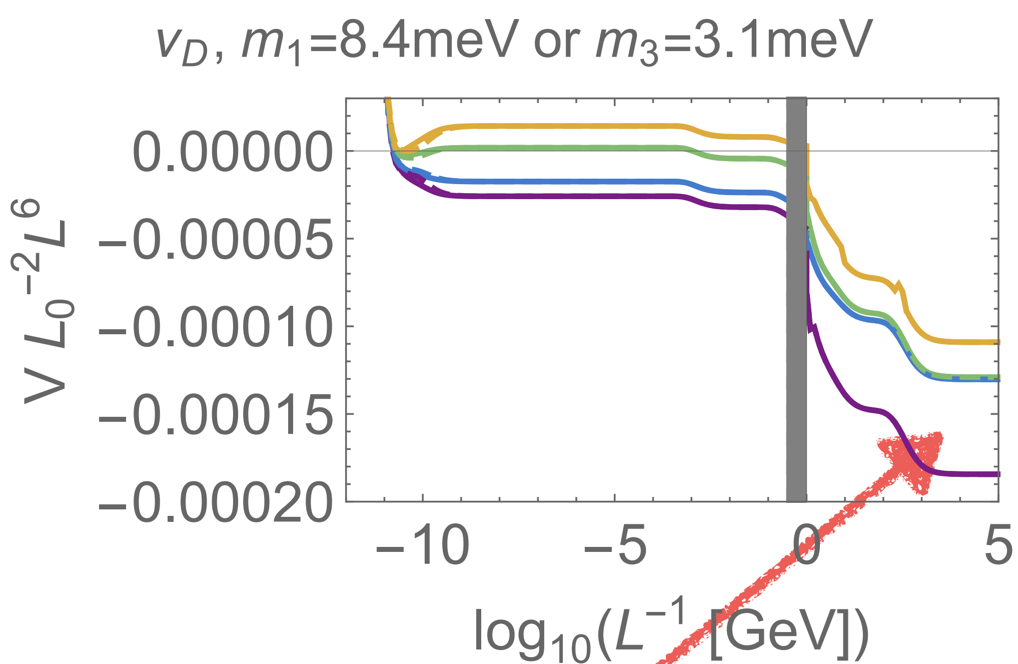




Runaway Behavior

- The SM with minimal Majorana neutrino masses seems to give rise to a non-SUSY AdS vacuum. Is it in the swampland?





Runaway behavior for small radius

- The AdS vacuum can decay non-perturbatively, a possibility overlooked in **[Arkani-Hamed, Dubovsky, Nicolis, Villadoro]; [Ibanez, Martin-Lozano, Valenzuela].**
- The Wilson line is stabilized by the heavier charged particles of the SM, making the charged fermion contributions negative at small L.
- We carried out a systematic study of the SM landscape in 2d and 3d, including Wilson line and more general BCs and fluxes **[Hamada, GS]**.

Multiple Point Criticality Principle

- Are there other principles to correlate neutrino mass scale with Λ?
- The **Multiple Point Criticality principle (MPP)** **[Froggatt, Nielsen, '96];[Bennett, '96]** which demands the coexistence of degenerate phases had some successes in predicting the Higgs mass.

Physics Letters B

Volume 368, Issues 1–2, 25 January 1996, Pages 96-102

ELSEVIER

Standard model criticality prediction top mass 173 ± 5 GeV and Higgs mass 135 ± 9 GeV

C.D. Froggatt [a], H.B. Nielsen [b]

- The MPP applied to 2/3d and 4d vacua of the SM suggests that the **νs are Dirac w/ the mass of lightest $\nu \simeq \mathcal{O}$ (1-10) meV** **[Hamada, GS, '17].**
- Our predictions can be tested by correlating $0\nu\beta\beta$ decay experiments with future CMB, large-scale structure, and 21cm line observations.
- Addition of light BSM particles (sterile neutrino, gravitino, …) can allow for Majorana neutrinos; correlated signatures in $0\nu\beta\beta$ decay and searches for these light particles.

Coexisting Phases

- In statistical mechanics, the micro-canonical ensemble is fundamental. Given E (extensive variable)→ T (intensive variable)

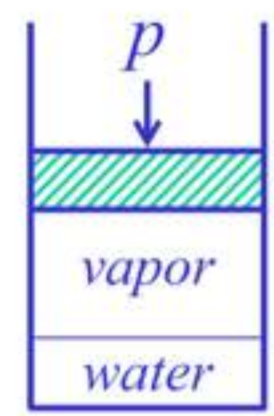
Micro-canonical

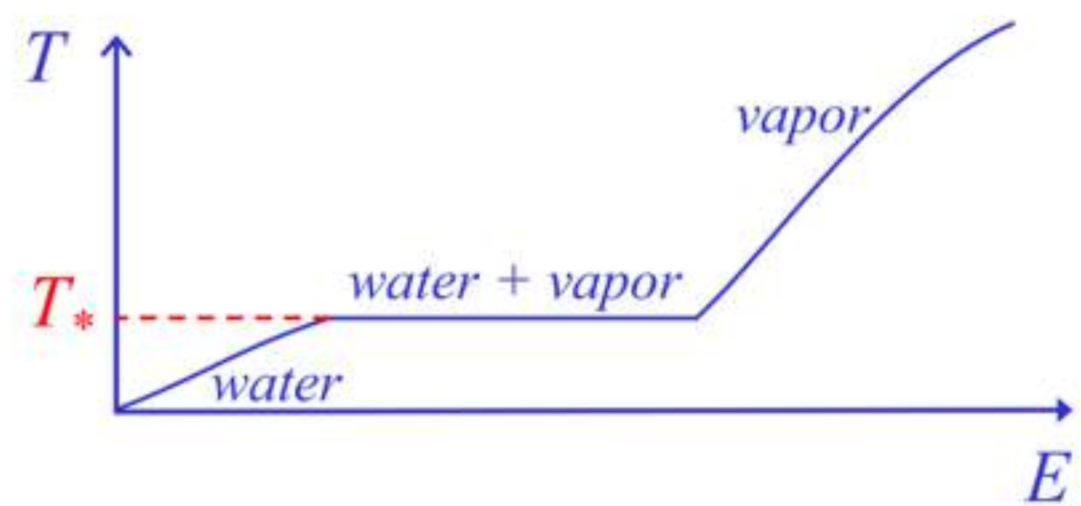
$$\Omega(E) = \sum_n \delta(H_n - E)$$

Equivalent in the thermodynamic limit

Canonical

$$Z(\beta) = \sum_n e^{-\beta H_n}$$





Multiple Point Criticality Principle

	Statistical mechanics	**QFT**
Micro-canonical	$\Omega(E) = \sum_n \delta(H_n - E)$	$\int [d\varphi]\, e^{-S_{\text{extra}}} \delta\left(\int d^4x\, \varphi^2 - I_2\right)$
	Equivalent in the thermodynamic limit ⇕	[Froggatt, Nielsen '95]
Canonical	$Z(\beta) = \sum_n e^{-\beta H_n}$	$Z(\{\lambda\}) = \int [d\varphi]\, e^{-S(\{\lambda\})[\varphi]}$

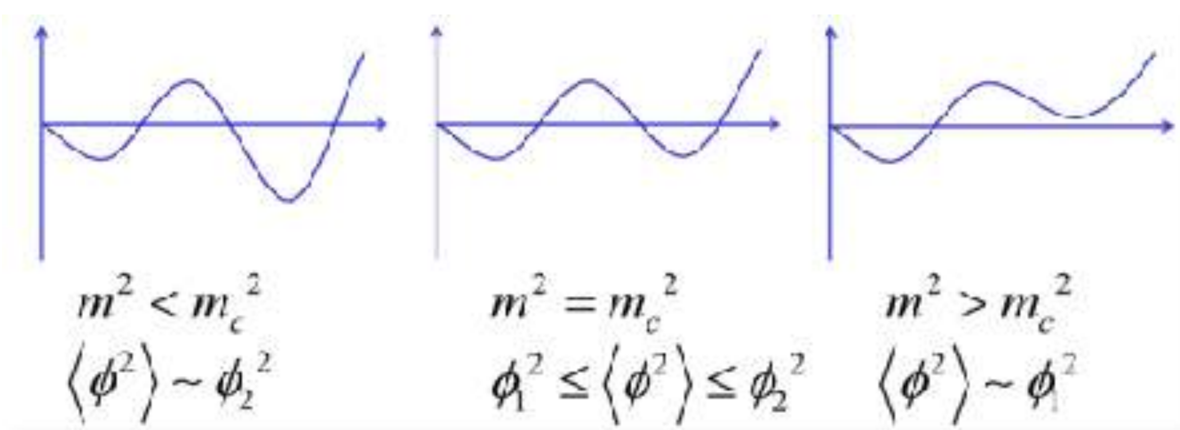
Correspondence:
T ↔ coupling (intensive variable),
E ↔ $\int \phi^2$ (extensive variable).

Degenerate Vacua

- Inspired by the micro-canonical ensemble for statistical systems:

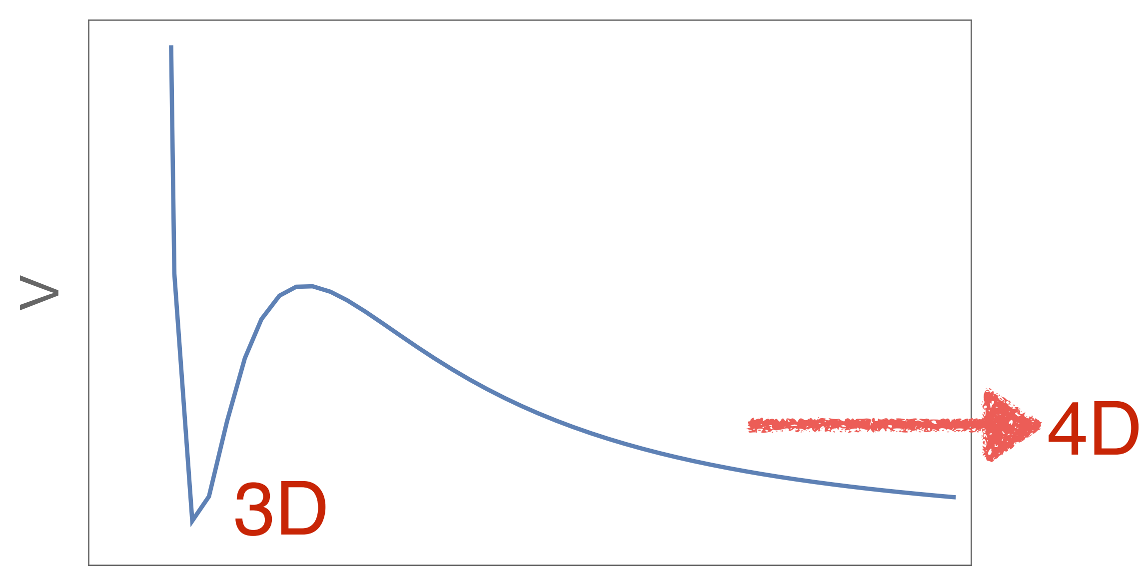
$$\int [d\varphi]\, e^{-S_{\rm extra}}\, \delta\left(\int d^4x\, \varphi^2 - I_2 \right)$$

- Taking natural values of $I_2 = O(V_4 M_P^2)$, the constraint is realized as an average of two vacua.



To maintain coexisting phases, vacua should be degenerate.

- We apply this argument to vacua in different dimensions:



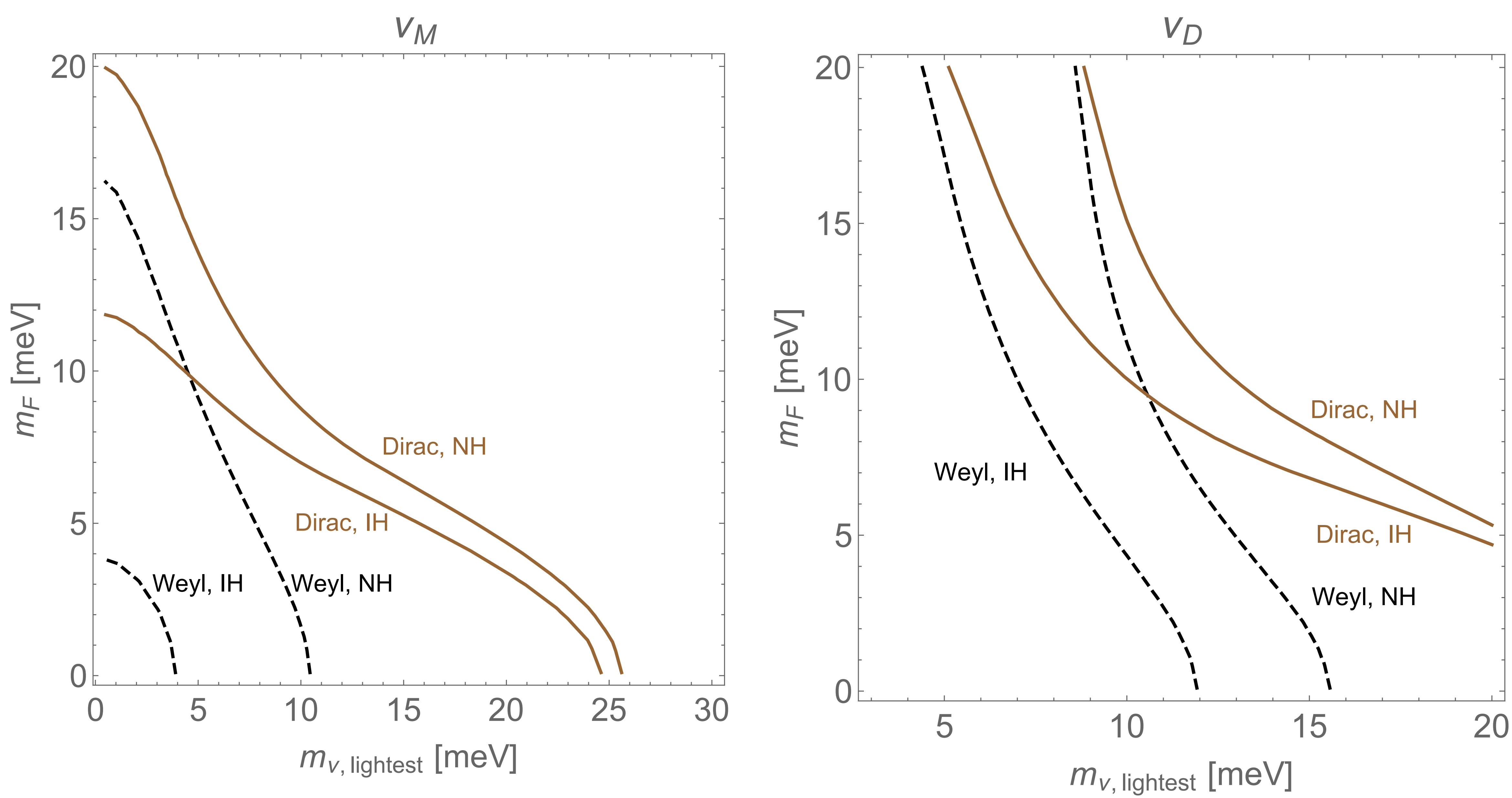
Summary of Results

	model	AdS	flat	dS
S^1	$U(1)$, neutral	$\Lambda_4 \lesssim 10^{-2.8} M_e^4$	$\Lambda_4 \simeq 10^{-2.8} M_e^4$	$10^{-2.8} M_e^4 \lesssim \Lambda_4 \lesssim 10^{-2.6} M_e^4$
	$U(1)$, charged	–	–	–
	SM, ν_M	always	–	–
	SM, ν_D, NH	$8.4\,\text{meV} \lesssim m_{\nu,\text{lightest}}$	$m_{\nu,\text{lightest}} \simeq 8.4\,\text{meV}$	$7.3\,\text{meV} \lesssim m_{\nu,\text{lightest}} \lesssim 8.4\,\text{meV}$
	SM, ν_D, IH	$3.1\,\text{meV} \lesssim m_{\nu,\text{lightest}}$	$m_{\nu,\text{lightest}} \simeq 3.1\,\text{meV}$	$2.5\,\text{meV} \lesssim m_{\nu,\text{lightest}} \lesssim 3.1\,\text{meV}$
	SM, ν_M, high scale	–	–	–
	SM, ν_D, high scale	$\Lambda_4 \ll (\text{neutrino mass})^4$	–	–
	axion	$\Lambda_4 < 0$	–	–
T^2	$U(1)$, neutral	$\Lambda_4 \lesssim 10^{-2.1} M_e^4$	$\Lambda_4 \simeq 10^{-2.1} M_e^4$	$10^{-2.5} M_e^4 \lesssim \Lambda_4 \lesssim 10^{-2.1} M_e^4$
	$U(1)$, charged	–	–	–
	SM, ν_M	always	–	–
	SM, ν_D, NH	$4.5\,\text{meV} \lesssim m_{\nu,\text{lightest}}$	$m_{\nu,\text{lightest}} \simeq 4.5\,\text{meV}$	$4.5\,\text{meV} \lesssim m_{\nu,\text{lightest}} \lesssim 6.5\,\text{meV}$
	SM, ν_D, IH	$1.1\,\text{meV} \lesssim m_{\nu,\text{lightest}}$	$m_{\nu,\text{lightest}} \simeq 1.1\,\text{meV}$	$1.1\,\text{meV} \lesssim m_{\nu,\text{lightest}} \lesssim 1.55\,\text{meV}$
	axion	$\Lambda_4 < 0$	–	–

- We have compactified the SM on S^1 and T^2, starting from both the electroweak vacuum and the high scale vacuum.
- The MPP can be satisfied by Dirac neutrinos with the mass of the lightest neutrino ~ $\mathcal{O}$(1-10) meV.

Adding BSM Physics

- Additional light fields can change the vacuum structure:

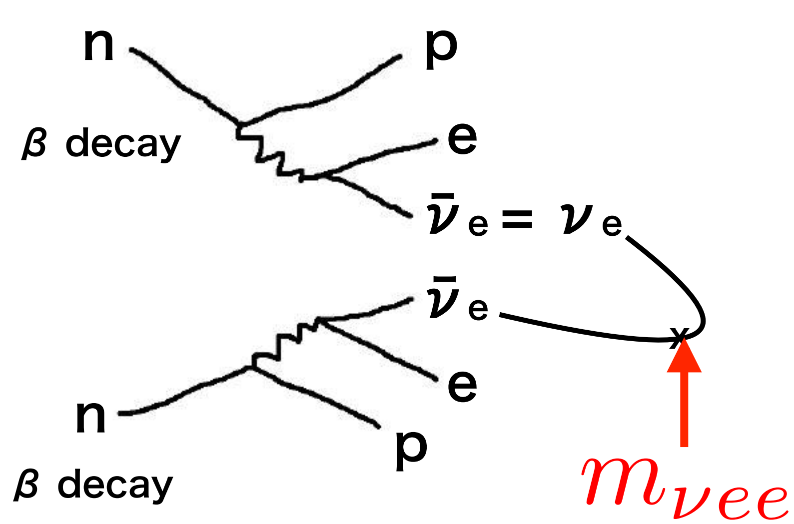


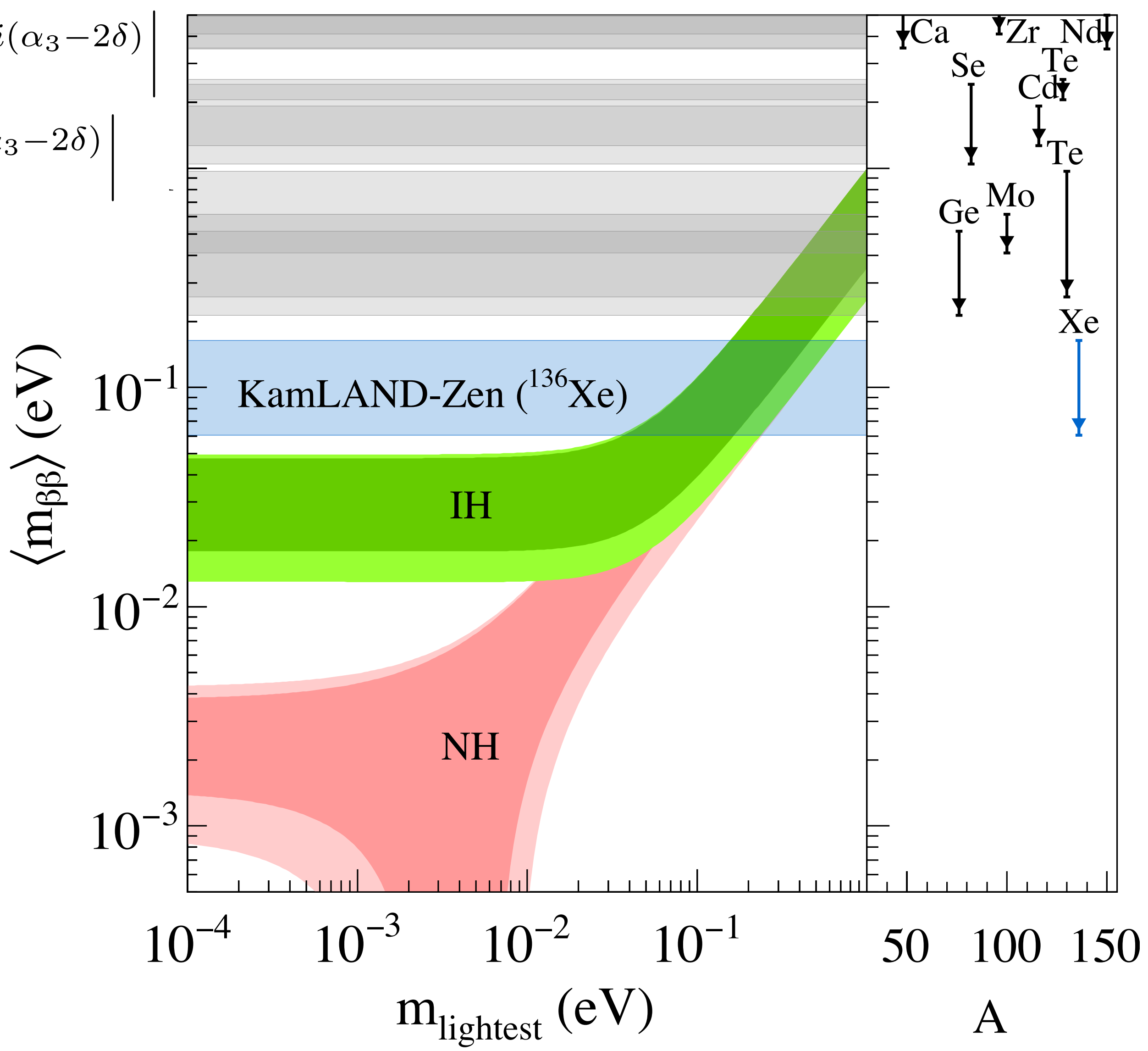
[Hamada, GS]

0$\nu\beta\beta$ Decay & light BSM Particles

- Adding more light fermions can increase the ν masses that satisfy the MPP, making them more detectable via 0$\nu\beta\beta$ decay.

$$m_{\nu ee} = \left| m_{\nu 1}|U_{e1}|^2 + m_{\nu 2}|U_{e2}|^2 e^{i\alpha_2} + m_{\nu 3}|U_{e3}|^2 e^{i(\alpha_3 - 2\delta)} \right|$$
$$\simeq \left| 0.68\, m_{\nu 1} + 0.30\, m_{\nu 2} e^{i\alpha_2} + 0.023\, m_{\nu 3} e^{i(\alpha_3 - 2\delta)} \right|$$





Target of experiments such as
CUORE, CUPID@MIT, KamLAND-Zen, NuDot

KamLAND-ZEN Collaboration, Phys. Rev. Lett. 117, 082503 (2016)

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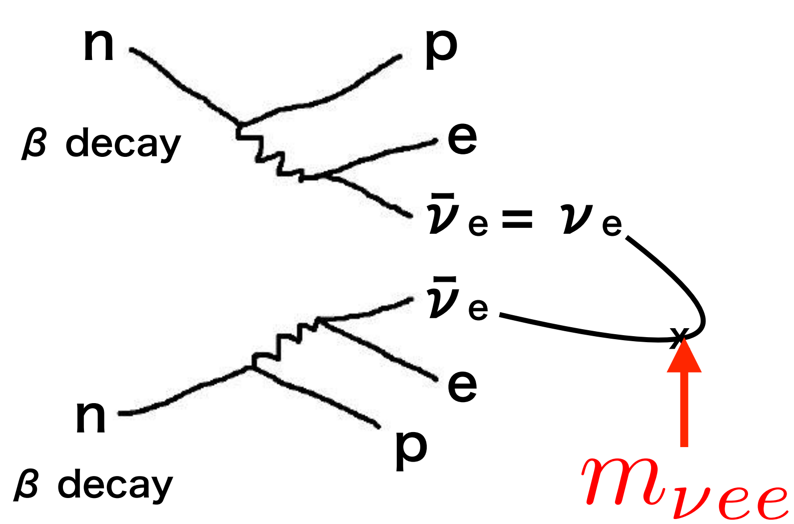

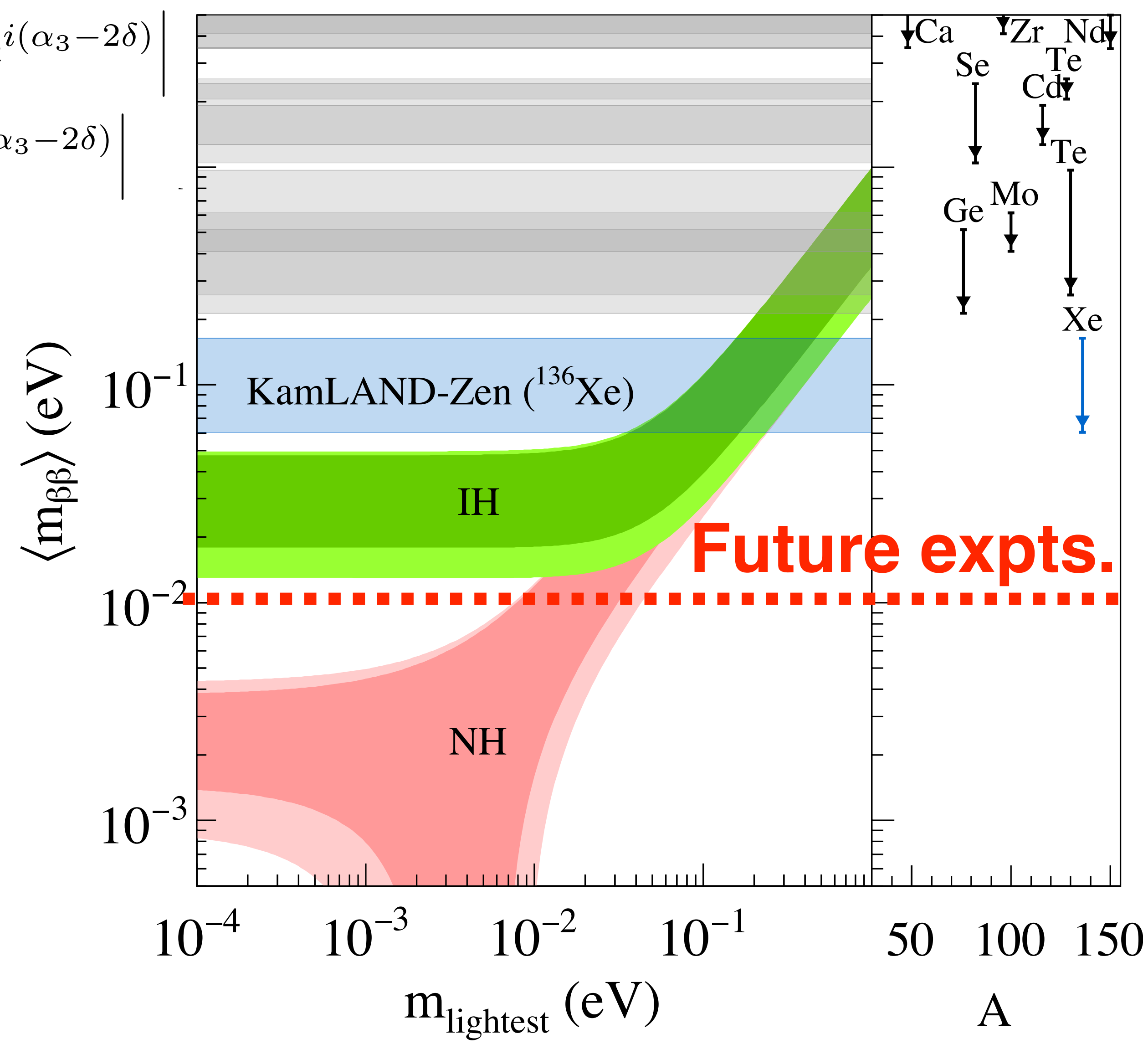

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Detectability of m_ν

- future CMB observation

[1512.07299]

- e.g.

The POLARBEAR-2 and the Simons Array Experiments

A. Suzuki[a,b], P. Ade[d], Y. Akiba[e,z], C. Aleman[f], K. Arnold[y], C. Baccigalupi[g], B. Barch[a], D. Barron[a], A. Bender[h], D. Boettger[m], J. Borrill[i], S. Chapman[j], Y. Chinone[a], A. Cukierman[a], M. Dobbs[k], A. Ducout[l], R. Dunner[m], T. Elleflot[f], J. Errard[1], G. Fabbian[g], S. Feeney[l], C. Feng[n], T. Fujino[c], G. Fuller[f], A. Gilbert[k], N. Goeckner-Wald[a], J. Groh[a], T. De Haan[a], G. Hall[a], N. Halverson[o], T. Hamada[e], M. Hasegawa[e], K. Hattori[e], M. Hazumi[c,e,z], C. Hill[a], W. Holzapfel[a], Y. Hori[a], L. Howe[f], Y. Inoue[c,2], F. Irie[c], G. Jaehnig[o], A. Jaffe[l], O. Jeong[a], N. Katayama[c], J. Kaufman[f], K. Kazemzadeh[f], B. Keating[f], Z. Kermish[p], R. Keskitalo[i], T. Kisner[i], A. Kusaka[q], M. Le Jeune[r], A. Lee[a], D. Leon[f], E. Linder[q], L. Lowry[f], F. Matsuda[f], T. Matsumura[s], N. Miller[t], K. Mizukami[c], J. Montgomery[k], M. Navaroli[f], H. Nishino[e], J. Peloton[r], D. Poletti[r], G. Rebeiz[u], C. Raum[a], C. Reichardt[v], P. Richards[a], C. Ross[j], K. Rotermund[j], Y. Segawa[e], B. Sherwin[q], I. Shirley[a], P. Siritanasak[f], N. Stebor[f], R. Stompor[r], J. Suzuki[e], O. Tajima[e], S. Takada[w], S. Takakura[e,z], S. Takatori[e], A. Tikhomirov[j], T. Tomaru[e], B. Westbrook[a], N. Whitehorn[a], T. Yamashita[c], A. Zahn[f], O. Zahn[a]

- Our value: $\Sigma m_\nu \sim 60$meV for NH, 100meV for IH.

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channel frequency domain multiplexing. Refractive optical elements are made with high purity alumina to achieve high optical throughput. The receiver is designed to achieve noise equivalent temperature of 5.8 $\mu K_{CMB}\sqrt{s}$ in each frequency band. POLARBEAR-2 will deploy in 2016 in the Atacama desert in Chile. The Simons Array is a project to further increase sensitivity by deploying three POLARBEAR-2 type receivers. The Simons Array will cover 95 GHz, 150 GHz and 220 GHz frequency bands for foreground control. The Simons Array will be able to constrain tensor-to-scalar ratio and sum of neutrino masses to $\sigma(r) = 6\times10^{-3}$ at $r = 0.1$ and $\sum m_\nu(\sigma = 1)$ to 40 meV.

- Our value: Σm_ν~60meV for NH, 100meV for IH.

Summary

Web of Conjectures

No global symmetry
[Banks, Dixon,'88];[Harlow, Ooguri,'18]
Lecture 1

$\downarrow$ $g \neq 0$

Weak Gravity Conjecture (WGC)
[Arkani-Hamed, Motl, Nicolis, Vafa. '06]
Lectures 1 and 2

$\longrightarrow$

Tower WGC
[Andriolo, Junghans, Noumi, GS, '18]
sLWGC
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$\downarrow$ $\geqq \to >$

Non-SUSY AdS
[Ooguri, Vafa,'16]
Lecture 4

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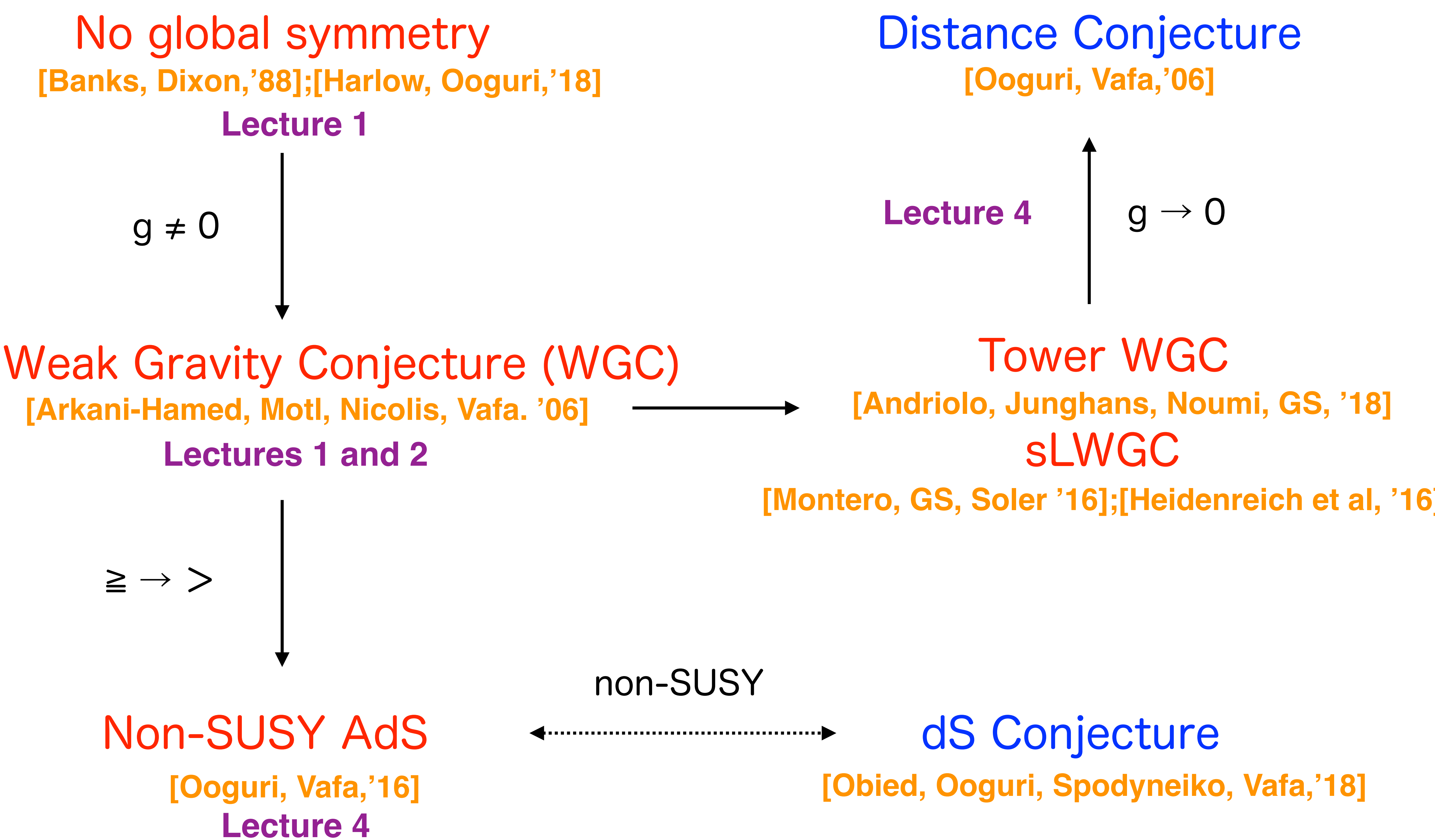

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dS Conjecture

[Obied, Ooguri, Spodyneiko, Vafa,'18]

Summary

- A web of inter-related swampland conjectures with a variety of interesting applications in **cosmology** & **particle physics**.
- Ongoing global experimental effort in detecting inflationary gravity wave imprinted on CMB B-mode, targeting $r \sim 10^{-2}$ (or even 10^{-3})
- A detection at the targeted level would strongly suggest that the inflaton potential is nearly flat over a super-Planckian field range:

$$\Delta\phi \gtrsim \left(\frac{r}{0.01}\right)^{1/2} M_{\rm Pl}$$ **[Lyth, '96]**

- The WGC has been used to argue that some large-field inflation models are in the swampland **[Brown, Cottrell, GS, Soler].** Models that evade this bound include:
    - Axion monodromy **[Silverstein, Westphal];[McAllister, Silverstein, Westphal]; [Marchesano, GS, Uranga];[Blumenhagen, Plauschinn];[Hebecker, Kraus, Witkowski].**
    - Multi-axion models using alignment **[Kim, Nilles, Peloso]** or clockwork **[Choi, Im]; [Kaplan, Rattazzi]**, ***but only w/ "spectator instantons"*** **[Brown,Cottrell,GS,Soler]**

Summary

- The dS conjecture naturally suggests the possibility that dark energy can be realized as a quintessence field, and can be tested experimentally by Euclid, DES, DESI, …
- The WGC for branes suggest that non-SUSY AdS vacua are unstable **[Ooguri, Vafa, '16]**. This AdS-instability conjecture has interesting consequences in particle physics **[Ibanez, Martin-Lozano, Valenzuela];[Hamada, GS].**
- We showed the WGC (mild form) for a wide class of theories, including generic string setups with dilation or moduli stabilized below M_s.
- We pointed out a connection between the distance conjecture and a refined version of the dS conjecture in any parametrically controlled regime of string theory.
- The refined de Sitter conjecture **[Ooguri, Palti, GS, Vafa]**:

$$|\nabla V| \geq \frac{c}{M_p} \cdot V \,, \quad \text{or} \quad \min\left(\nabla_i \nabla_j V\right) \leq -\frac{c'}{M_p^2} \cdot V$$

turns out evade all counterexamples raised about scalar potential maxima.

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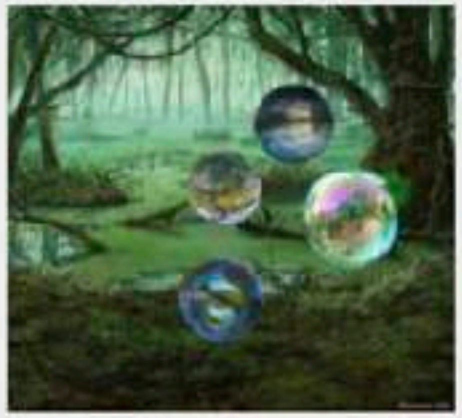
The String Swampland and Quantum Gravity Constraints on Effective Theories

Coordinators: Hiroshi Ooguri, Gary Shiu, Cumrun Vafa, and Irene Valenzuela

The idea that the string landscape is too large to lead to concrete predictions has been countered by the idea that most of the naively consistent effective theories of gravity coupled to matter are actually inconsistent and belong to the swampland. The identification of criteria distinguishing the true string landscape from the swampland, which has been studied for more than a decade now, is beginning to reach a more mature stage with the developments of the last few years. In particular a conjectured consistency condition for quantum gravity known as the Weak Gravity Conjecture (WGC), which postulates that gravity is always the weakest force among all the forces, has found an unexpectedly broad range of applications.

The WGC on the one hand has been used to constrain cosmological models of inflation including scenarios being tested by the present generation of CMB experiments and on the other hand has been connected to the cosmic censorship conjecture of general relativity. Furthermore, ideas from holography have been found to be nicely consistent with the WGC. Moreover a sharpened version of the WGC has been used to put constraints on particle phenomenology and in particular has been used to place bounds on the neutrino masses. This program will bring together the diverse communities of string theorists, cosmologists, general relativists, particle phenomenologists and researchers working on holography and the conformal bootstrap to further develop consistency criteria for quantum theories of gravity and possibly extract concrete predictions from these ideas for the observable universe as well as deepen our understanding of the structure of string vacua.



DATES

Feb 18, 2020 - Mar 13, 2020

INFORMATION

Apply

Application deadline is:
Nov 18, 2018.
Applications will be considered and invitations will be issued after the above deadline.

QUICK LINKS