Weak gravity conjecture, Multiple point principle and SM landscape

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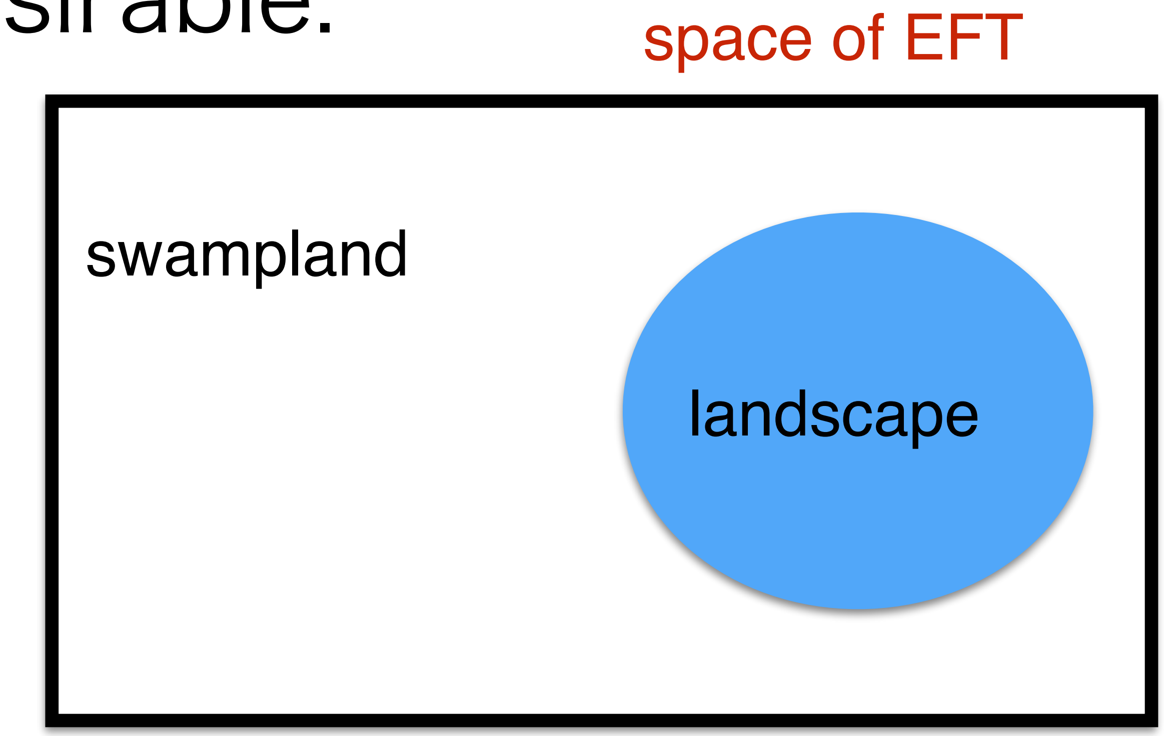
w/ Gary Shiu

arXiv:1707.06326, and in progress

String & low energy EFT

- Due to sting landscape,
  String theory seems to predict anything.
- Universal Prediction of string theory
  (or quantum gravity) is desirable.
- Swampland vs. landscape



[Vafa ‘06]

Purpose of talk

- Utilizing the conjectures which are considered as universal, implication on SM and beyond is investigated.

- Messages

  - Neutrino is Dirac, $m_{\nu,\text{lightest}}$ = O(1-10)meV

  - If Higgs potential is bounded from below, SM with M_t=173GeV, M_H=125GeV may not be consistent with QG.

Talk Plan

1. Conjectures
2. Standard Model in 4 dimension [YH, Shiu in progress]
3. Standard Model in 2 and 3 dimensions

[YH, Shiu 1707.06326]

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[YH, Shiu 1707.06326]

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

Weak gravity conjecture(WGC)

- Conjecture:

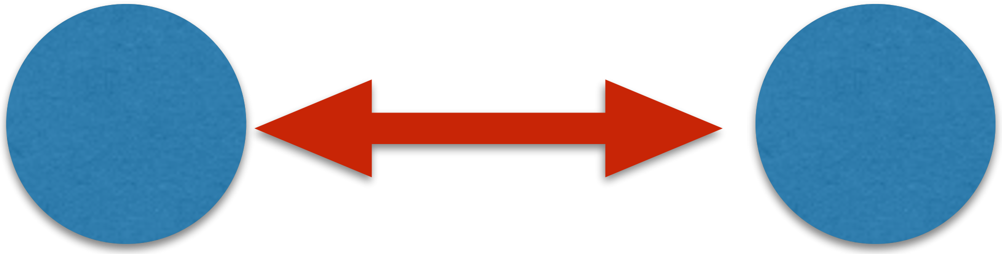
  Gravity is weakest force.

- q: gauge charge.

  WGC requires

  (gauge force) ≧ (gravity force)

$q \geqq m/M_P$



q, m

Why WGC?

- Original argument comes from requirement that extremal BH can decay.

- More convincing arguments might be

  [Cheung, Remman ‘14]

  - From analyticity, unitarity and causality in IR QFT

$$
\begin{aligned}
\mathcal{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}R \\
&+ a_1(F_{\mu\nu}F^{\mu\nu})^2 + a_2(F_{\mu\nu}\tilde{F}^{\mu\nu})^2 \\
&+ b_1 F_{\mu\nu}F^{\mu\nu}R + b_2 F_{\mu\rho}F_{\nu}{}^{\rho}R^{\mu\nu} + b_3 F_{\mu\nu}F_{\rho\sigma}R^{\mu\nu\rho\sigma} \\
&+ c_1 R^2 + c_2 R_{\mu\nu}R^{\mu\nu} + c_3 R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma},
\end{aligned}
$$

  - From perturbative heterotic string w/ modular inv. [Montero, Shiu, Soler ’16, Heidenreich, Reece, Rudelius ‘16]

magnetic WGC

- If we apply the WGC to magnetic dual, the cutoff scale is

$$m_{\rm mag} \lesssim g_{\rm mag} M_P \simeq \frac{1}{g} M_P \qquad m_{\rm mag} \simeq \frac{1}{g^2}\Lambda$$

$$\Lambda \lesssim g M_P$$

- In the SM, $\Lambda_{SM} \lesssim 10^{17}{\rm GeV}$

[Ooguri, Vafa ‘16]

Ooguri-Vafa conjectures

- Conjecture1:

Motivation: It is unnatural that non-BPS state saturates WGC under quantum correction.

Except for BPS state, gravity is strictly weakest force.

⇓ Implication of conjecture1.

All non-SUSY AdS vacua supported by flux are unstable.

- Conjecture2: All non-SUSY AdS vacua are unstable.

Motivation: (All known construction from M/string theory, AdS is supported by some flux.) + (Conjecture1)

[Froggatt, Nielsen ’95][Bennett ‘96]

Multiple point principle(MPP)

- Conjecture:
  The parameters of the theory are tuned so that many vacua are degenerate in energy.

- Possible principle to extract predictions from vast landscape.

Motivation of MPP

	Statical mechanics	QFT
micro-canonical	$\Omega(E) = \sum_n \delta(H_n - E)$	?
Equivalent in thermodynamic limit	↕	
canonical	$Z(\beta) = \sum_n e^{-\beta H_n}$	$Z(\{\lambda\}) = \int [d\varphi]\, e^{-S(\{\lambda\})[\varphi]}$

In statical mechanics, micro-canonical ensemble is fundamental.
First, E(extensive variable) is given, and T(intensive variable) appears as a result.

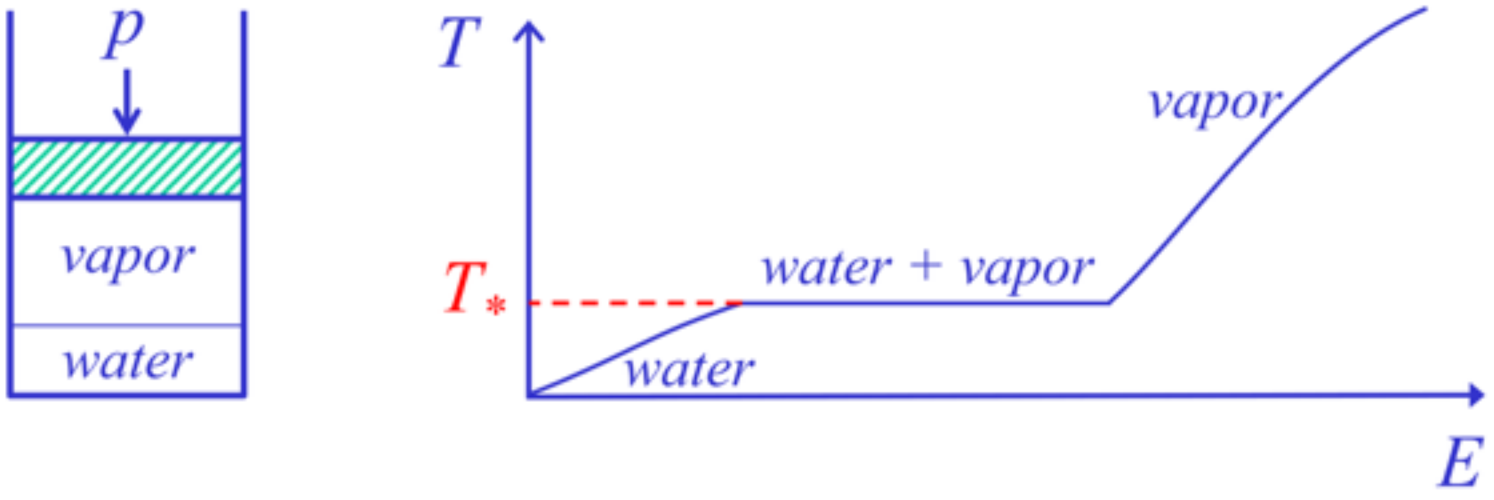
Motivation of MPP

	Statical mechanics	QFT
micro-canonical	$\Omega(E) = \sum_n \delta(H_n - E)$	$\int [d\varphi]\, e^{-S_{\rm extra}}\, \delta\Big(\int d^4x\, \varphi^2 - I_2\Big)$ Proposal in [Froggatt, Nielsen '95]
	⇕ Equivalent in thermodynamic limit	
canonical	$Z(\beta) = \sum_n e^{-\beta H_n}$	$Z(\{\lambda\}) = \int [d\varphi]\, e^{-S(\{\lambda\})[\varphi]}$

Correspondence:
T↔coupling(intensive variable),
E ↔∫ φ² (extensive variable).

Coexisting phase

- Add heat to water under constant pressure.
- Point: For wide range of E, the temperature T is tuned to be boiling point T_*.



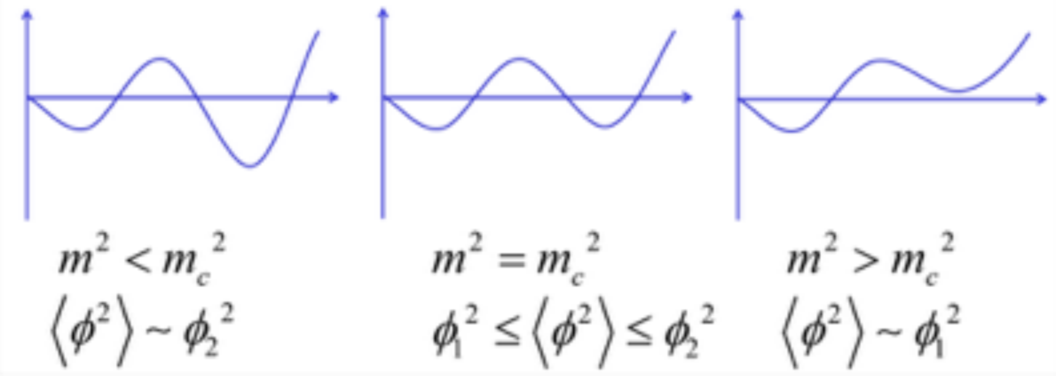
QFT version

- Inspired by micro-canonical ensemble, we fix I_2.

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

- Taking natural value $I_2 = O(V_4 M_P^2)$, the constraint is realized as an average between two vacuum.

- To maintain coexisting phase, vacua should be degenerate.



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2. Standard Model in 4 dimension [YH, Shiu in progress]
3. Standard Model in 2 and 3 dimensions [YH, Shiu 1707.06326]

Conjectures

- In the following, we consider application of two conjectures to SM.
  - Conjecture: All non-SUSY AdS vacua are unstable. (We refer this as WGC)
  - Conjecture: Parameters of the theory are tuned so that many vacua are degenerate in energy. (We refer this as MPP)

Higgs potential

- Higgs potential for $h \gg E_{EW}$

$$V_H = \lambda_{\rm eff}(h)\frac{h^4}{4} + c_6\frac{h^6}{8M_P^2} + c_8\frac{h^8}{16M_P^2} + \dots$$

- The running of self coupling λ

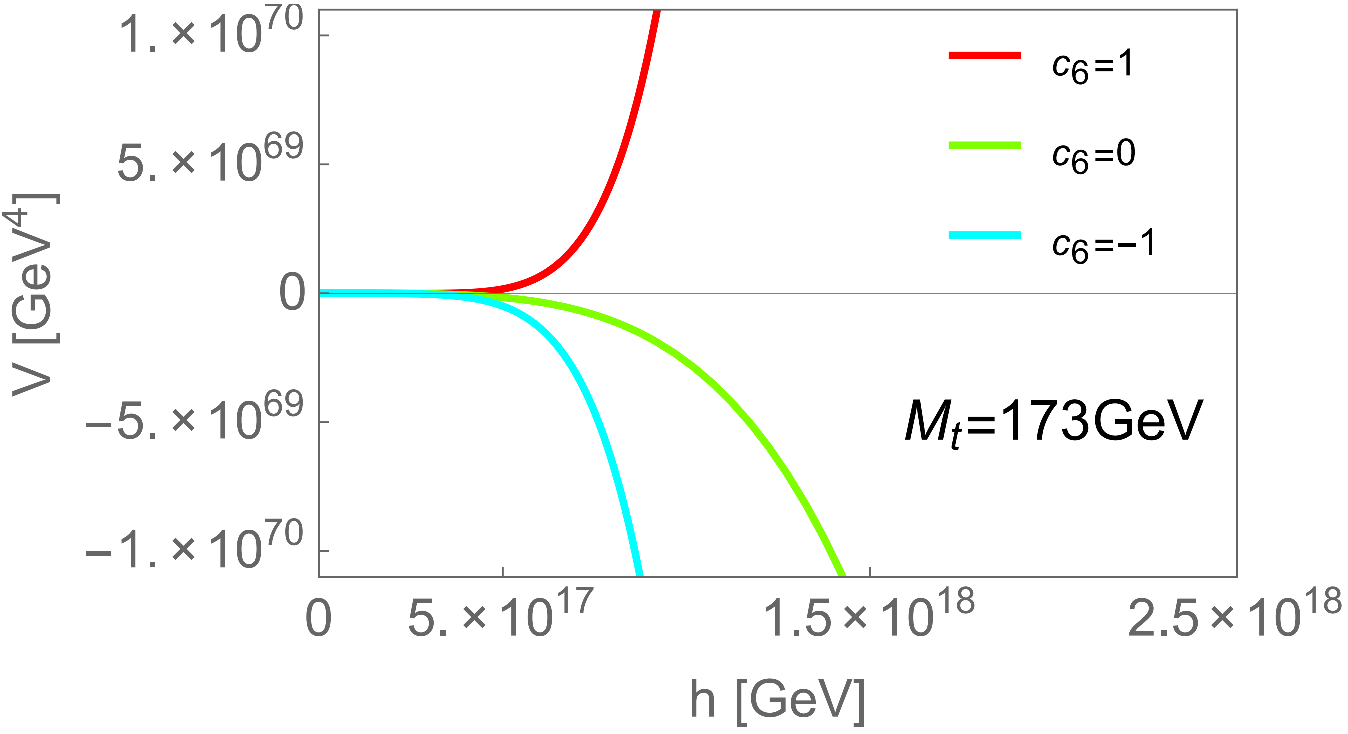
$$\frac{d\lambda}{dt} = \frac{1}{16\pi^2}\left(\underbrace{24\lambda^2 + \frac{3}{8}g_Y^4 + \frac{3}{4}g_Y^2 g_2^2 + \frac{9}{8}g_2^4}_{\text{boson: positive contribution}} \underbrace{- 6y_t^4}_{\text{top: negative contribution}} + \dots\right)$$

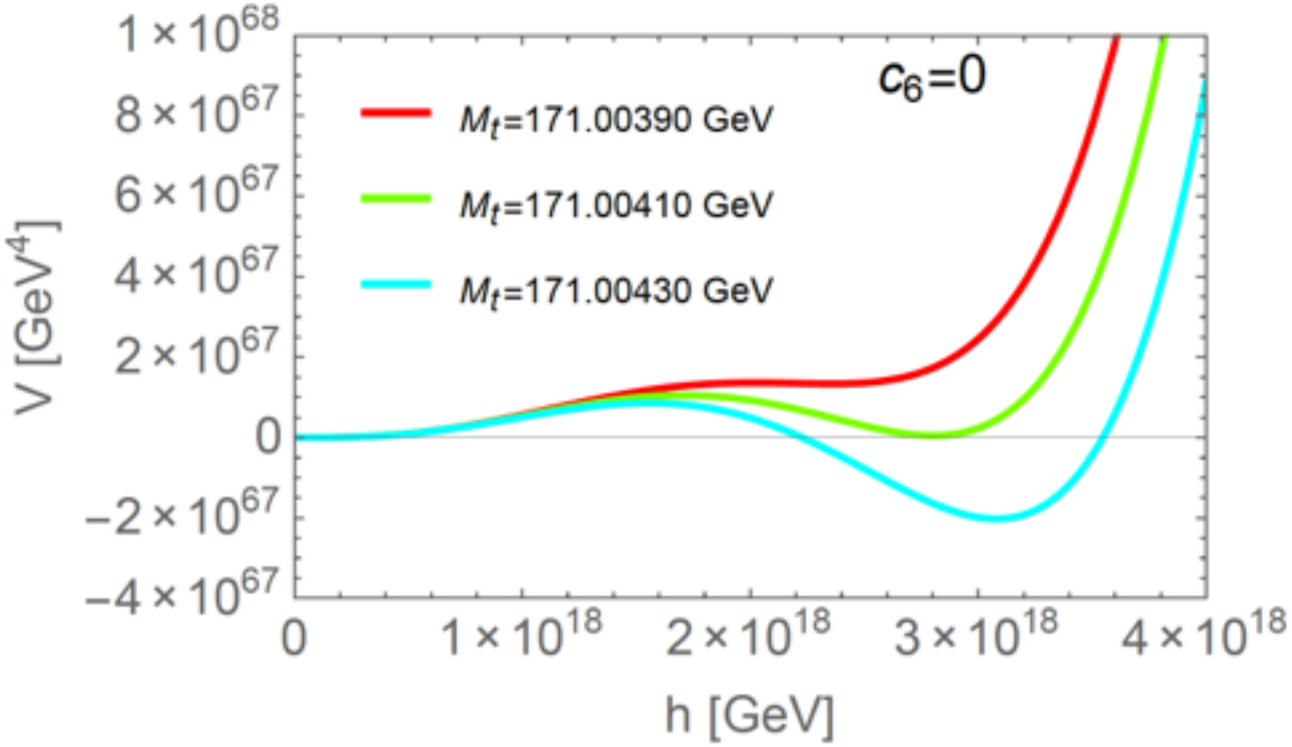
Higgs potentials

[Degrassi et. al. ’12, and many references]

central value M_t=173GeV & c_6=0,
EW vacuum is metastable.

smaller $M_t \lessapprox$ 171GeV,
EW vacuum is absolutely stable.



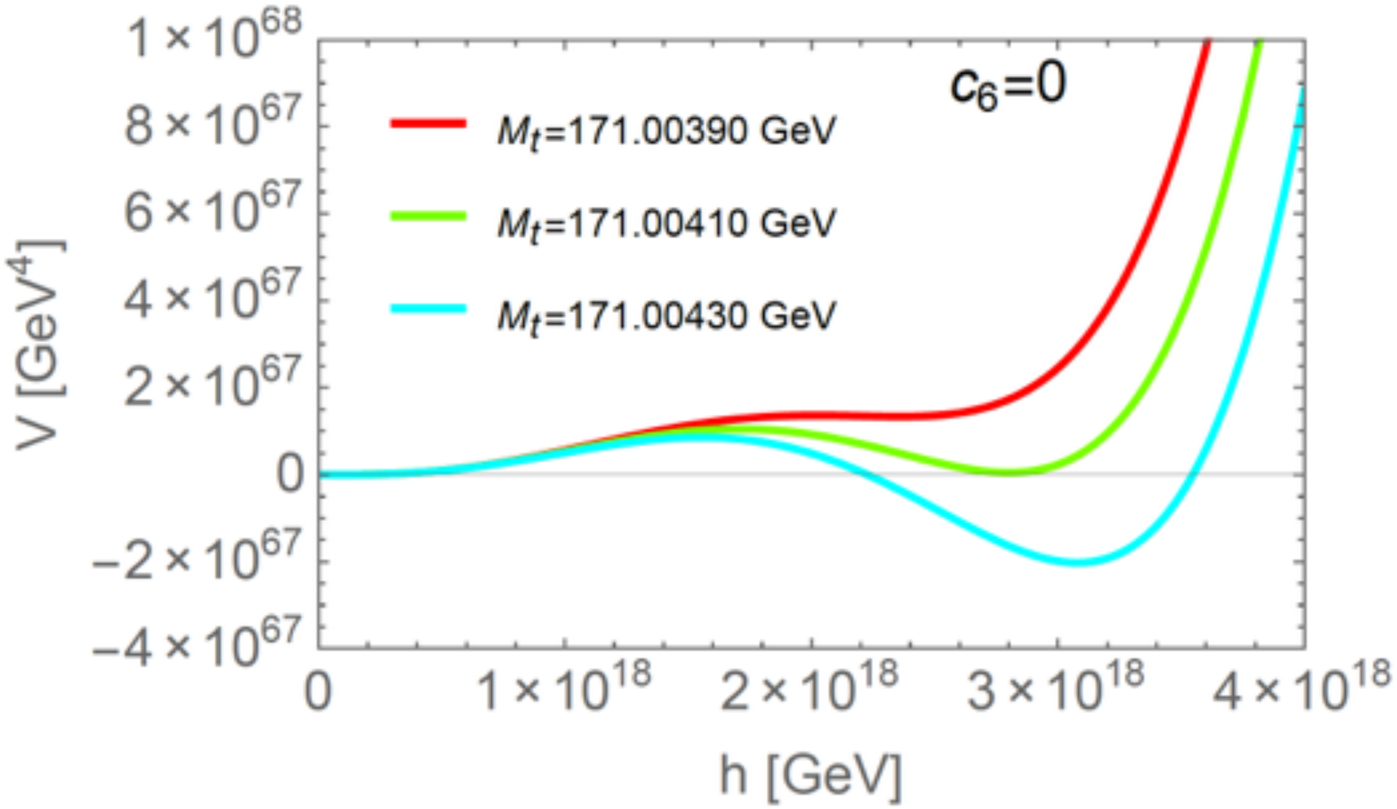


$\lambda<0$ for h > 10^{10}GeV .

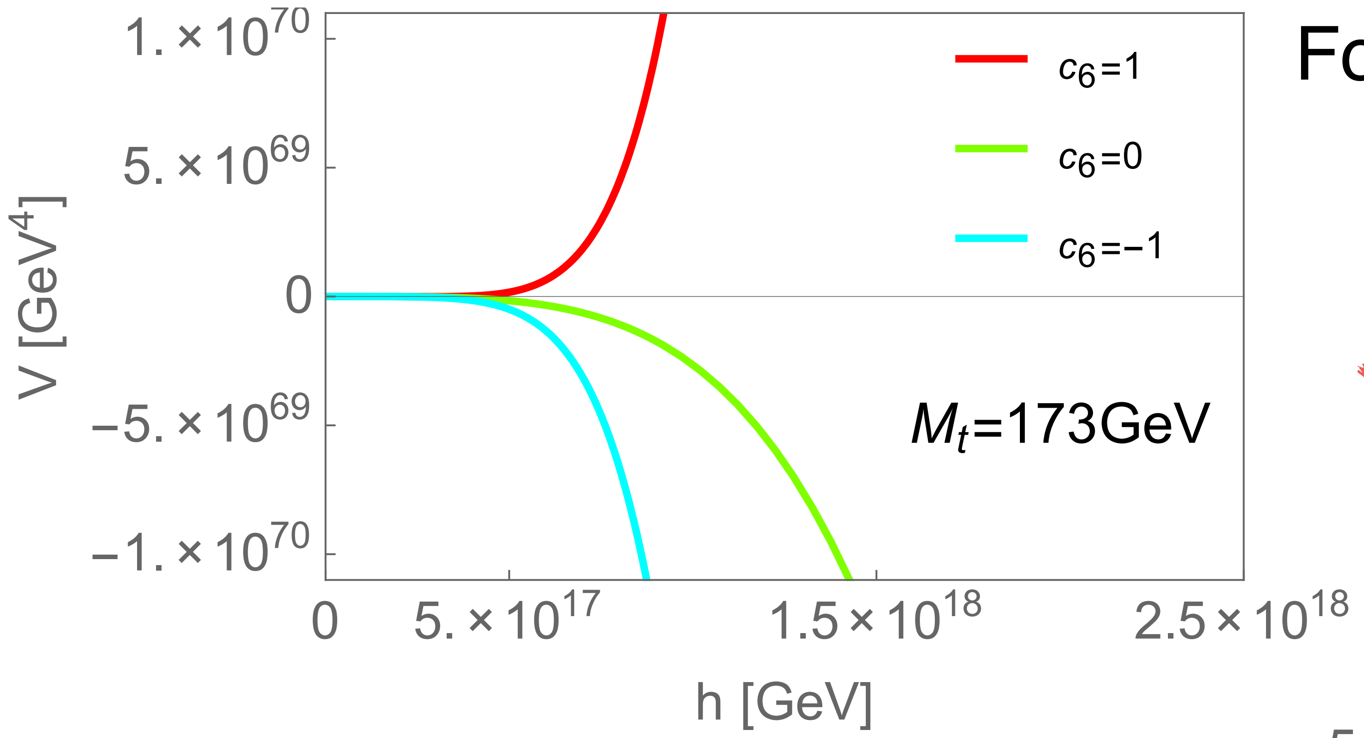
[Froggatt, Nielsen '95]

Applying conjectures

- MPP
  - The two vacua at $h=E_{EW}$ and $h=M_P$ should be degenerate in energy. → M_t=171GeV, M_H=125GeV.

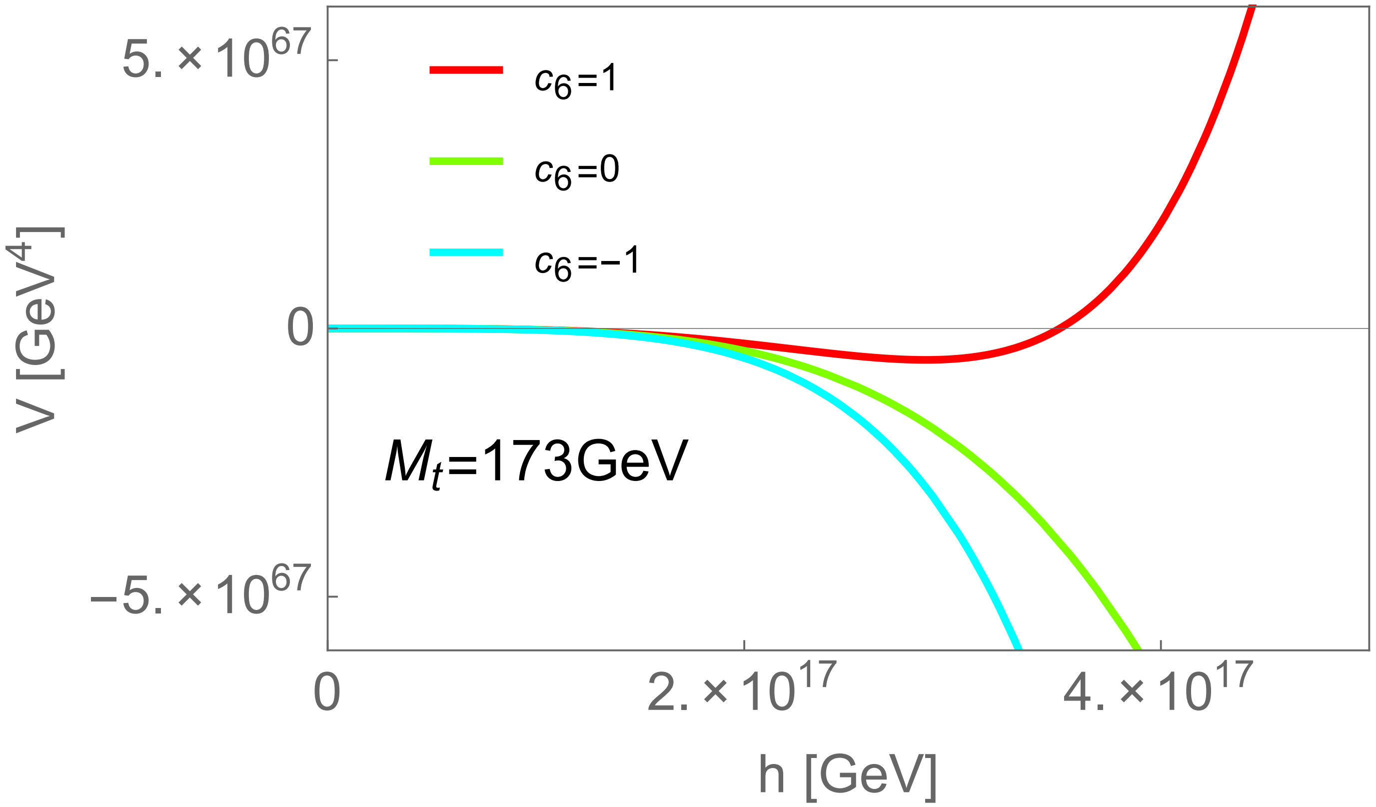


Applying WGC



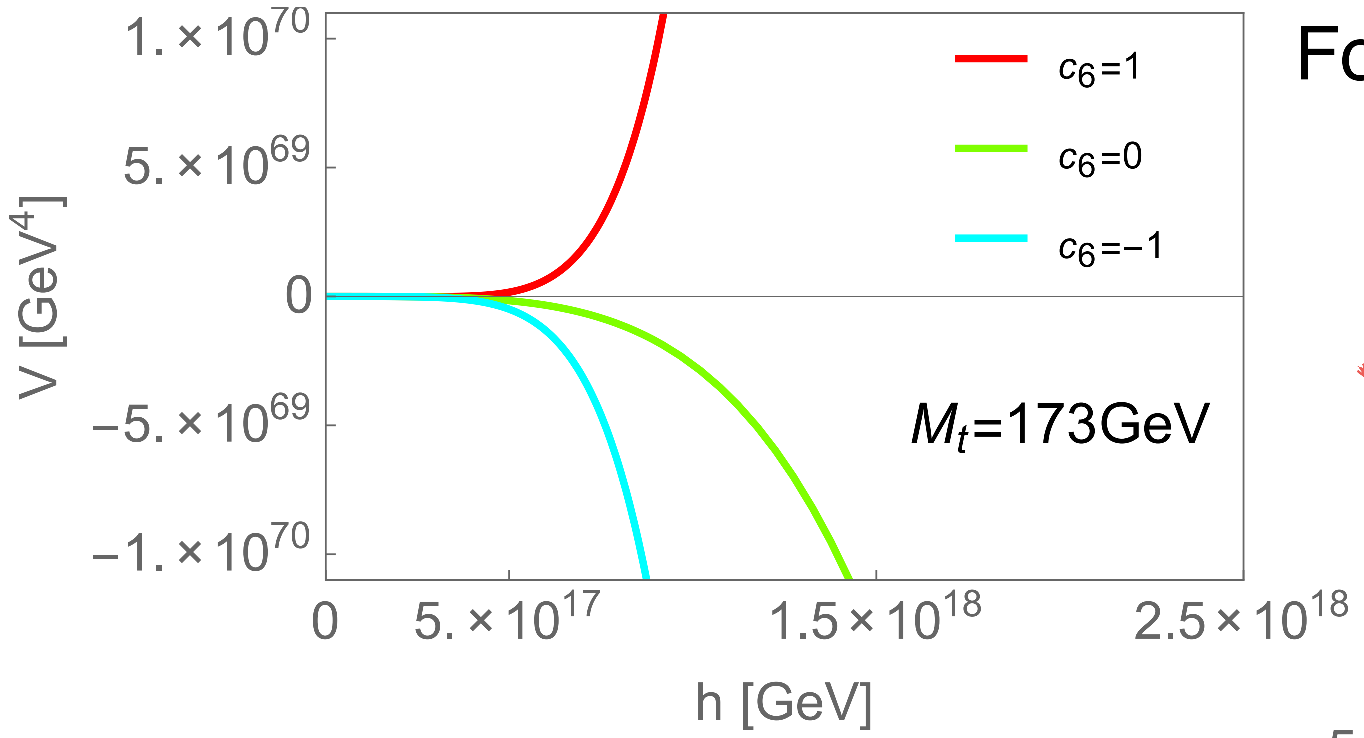
Focus on central value case M_t=173GeV

Magnification around 3×10^{17}GeV



c_6=1 leads to stable AdS,
(within SM up to M_P)
which is not consistent with WGC.

Applying WGC



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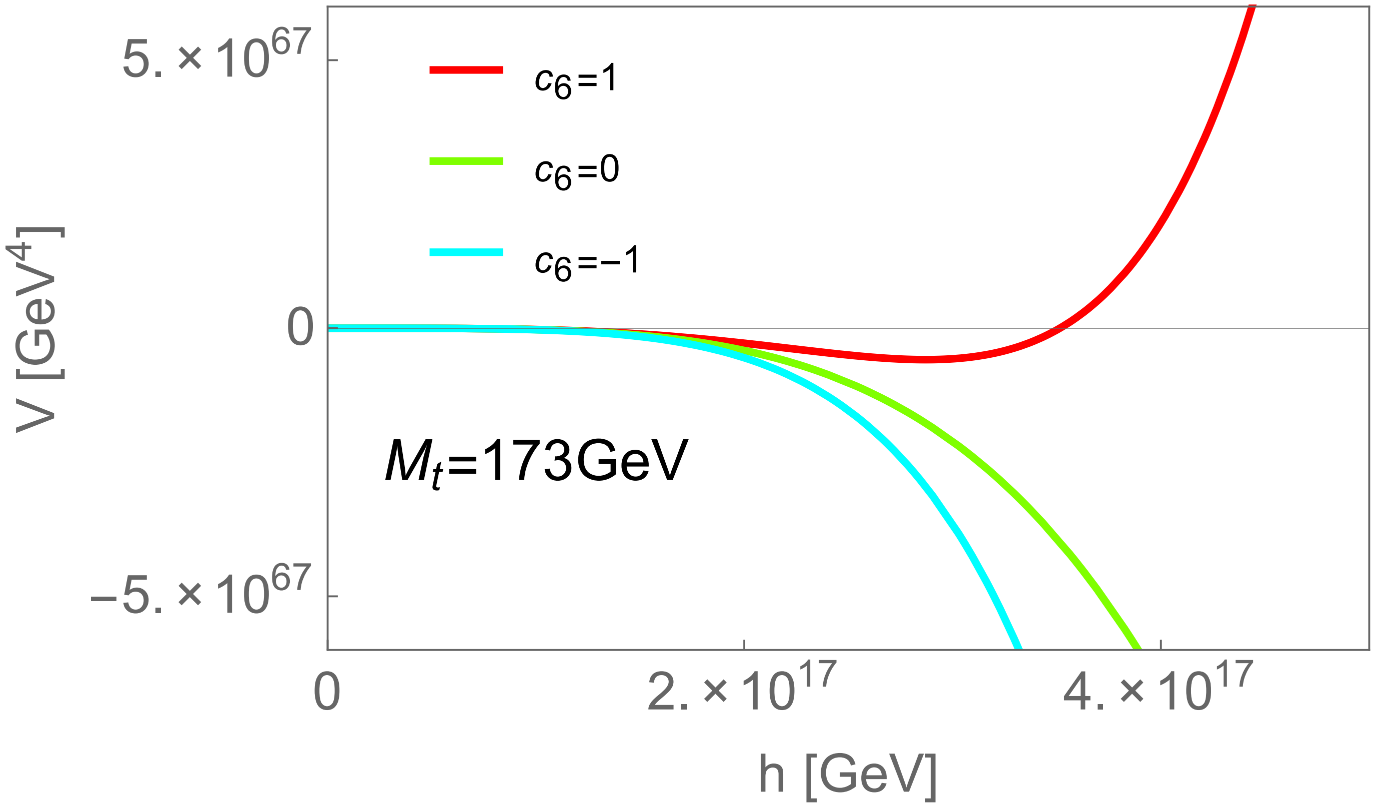


c_6=1 leads to stable AdS,
(within SM up to M_P)
which is not consistent with WGC.

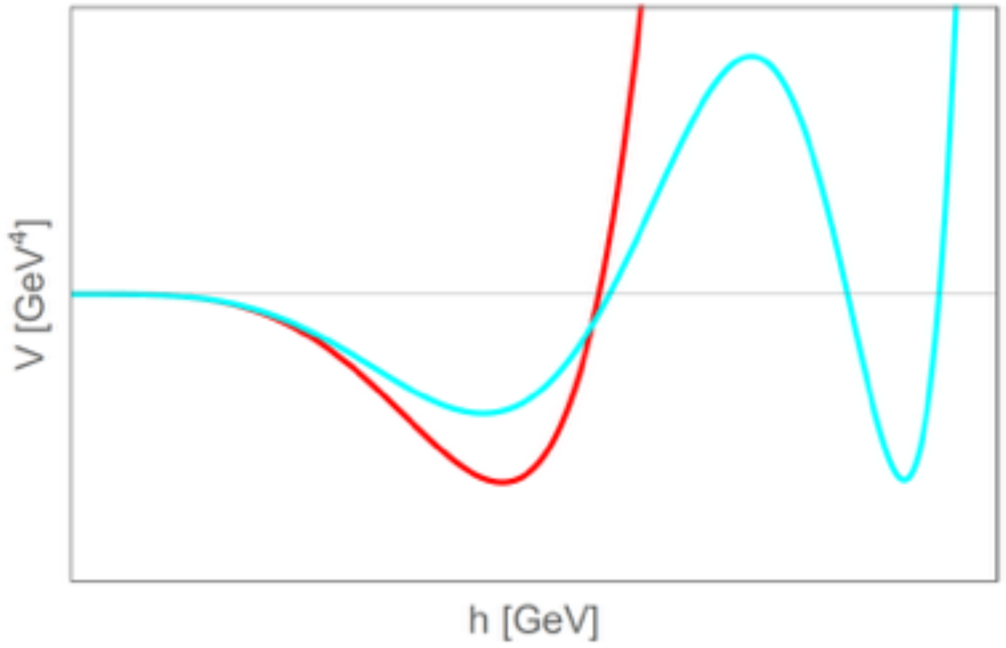
How about other value of c_6(&c_8)?

Possibilities above M_P

- possibility1:

  Higgs potential is bounded from below.

stable AdS→inconsistency with WGC

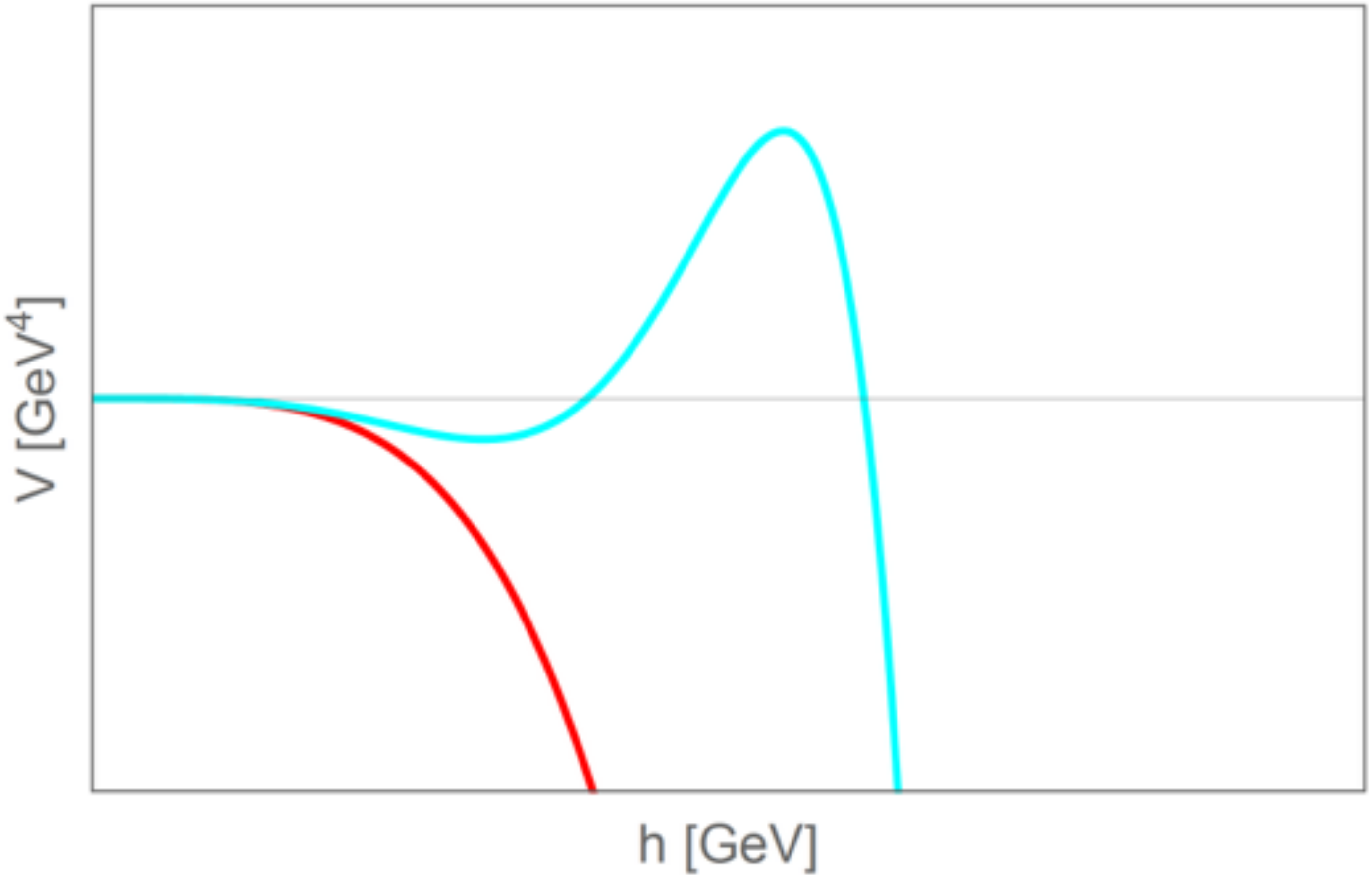


Possibilities above M_P

- possibility2:

  Higgs potential is not bounded from below.

consistency with WGC,
but seems to be pathological?



If Higgs potential is bounded from below, SM with M_t=173GeV, M_H=125GeV may not be consistent with quantum gravity.

Precision of M_t

- Precise measurement of M_t is important.

2017 Review of Particle Physics.
C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update.

QUARKS

t $I(J^P) = 0(1/2^+)$

Charge = $\frac{2}{3}$ e Top = +1

Review: The Top Quark (rev.)

t-QUARK MASS

t-Quark Mass (Direct Measurements)	173.1 ± 0.6 GeV (S = 1.6)
t-Quark Mass from Cross-Section Measurements	160^{+5}_{-4} GeV
t-Quark Pole Mass from Cross-Section Measurements	173.5 ± 1.1 GeV

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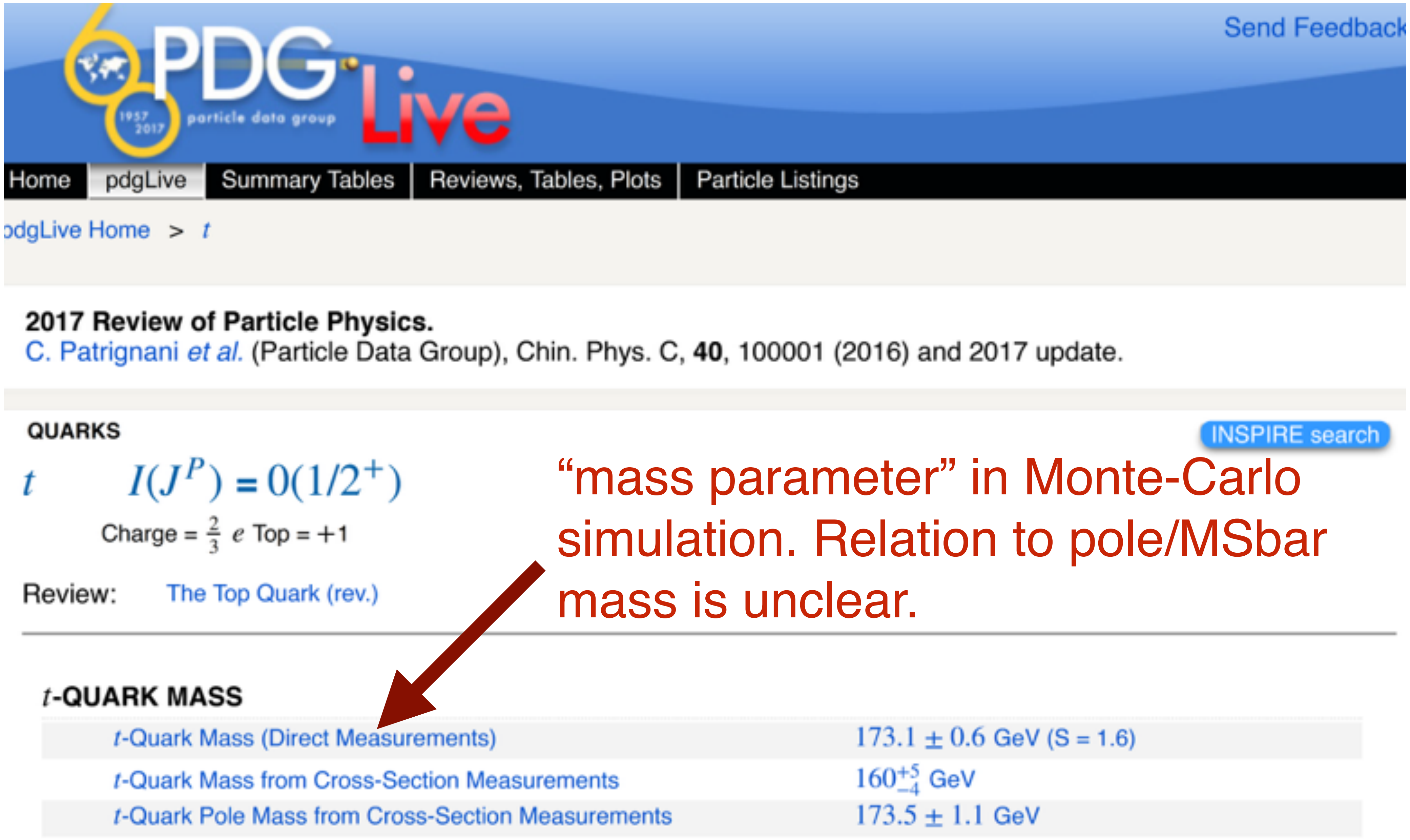

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"mass parameter" in Monte-Carlo simulation. Relation to pole/MSbar mass is unclear.

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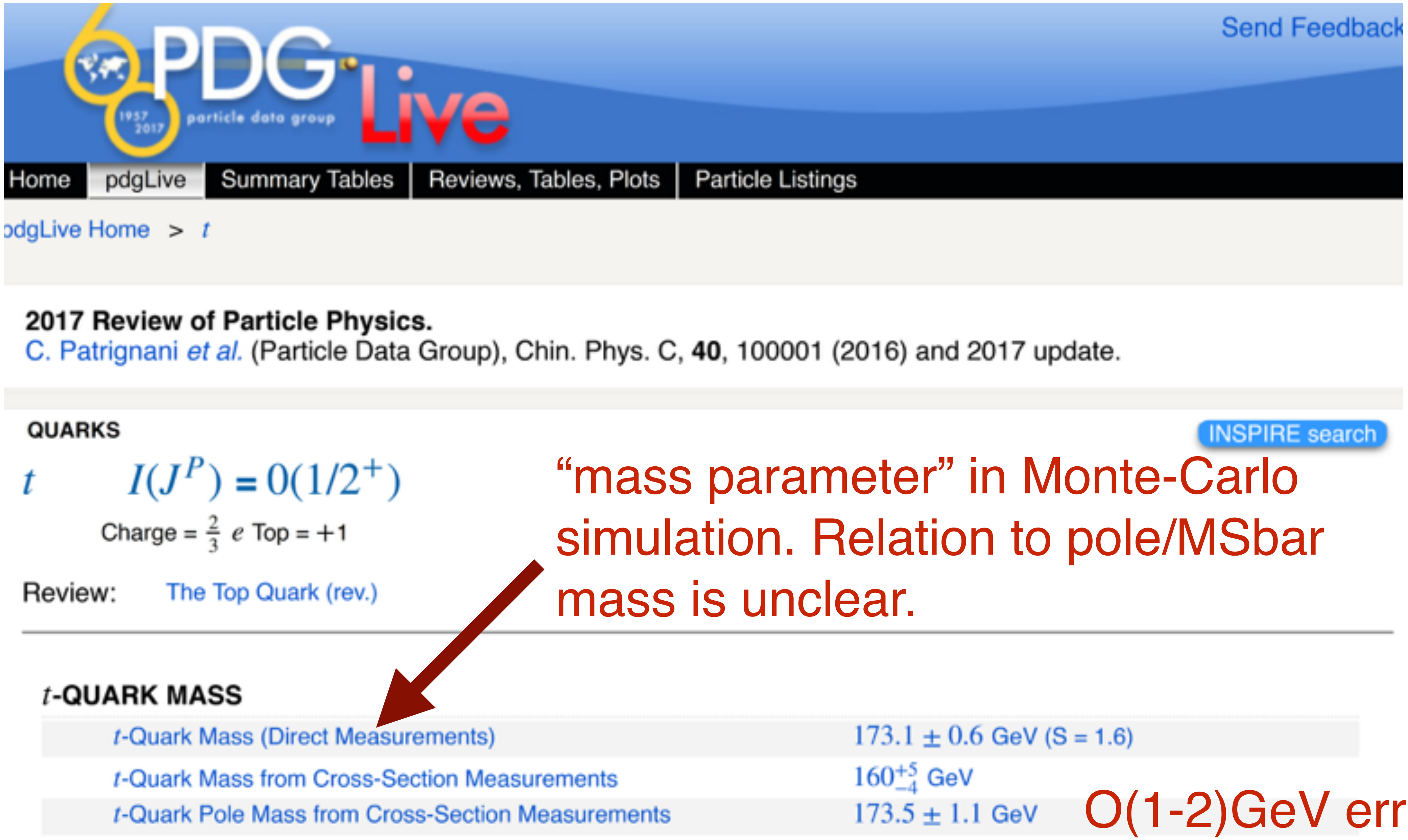

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“mass parameter” in Monte-Carlo simulation. Relation to pole/MSbar mass is unclear.

O(1-2)GeV error

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[YH, Shiu 1707.06326]

SM landscape

- The conjectures are applicable to vacua in string landscape.

- SM itself has rich structure of landscape.

  [Arkani-Hamed et. al. ‘07]

  - S^1 and T^2 compactifications.

  - Originally investigated in the context of AdS/CFT, we revisit in different context.

S^1 compactification

4D action

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

Casimir energy

Dimensional reduction

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

potential for radius L.

Boundary condition

- The single valuedness of action(or path integral?) is required.

$$\psi_{\text{lepton}}(x_3+2\pi L)=\begin{cases}\pm\psi_{\text{lepton}}(x_3) & \text{for Majorana neutrino,}\\ \\ e^{iQ_L}\psi_{\text{lepton}}(x_3) & \text{for Dirac neutrino.}\end{cases}$$

U(1)$_L$

$$\psi_{\text{baryon}}(x_3+2\pi L)=e^{iQ_B}\psi_{\text{baryon}}(x_3).$$

U(1)$_B$

- $(z+1)\pi := Q_L = Q_B$ is taken in the following.

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

Casimir energy

- Casimir energy is calculated from 1-loop Det w/ ζ functional regularization.

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

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

$$V_{S^1}^{(1)}(L, 0, 0) = -\frac{1}{360 L^4} \frac{1}{(2\pi)^2}, \quad V_{S^1}^{(1)}(L, 0, 1/2) = \frac{7}{2880 L^4} \frac{1}{(2\pi)^2},$$

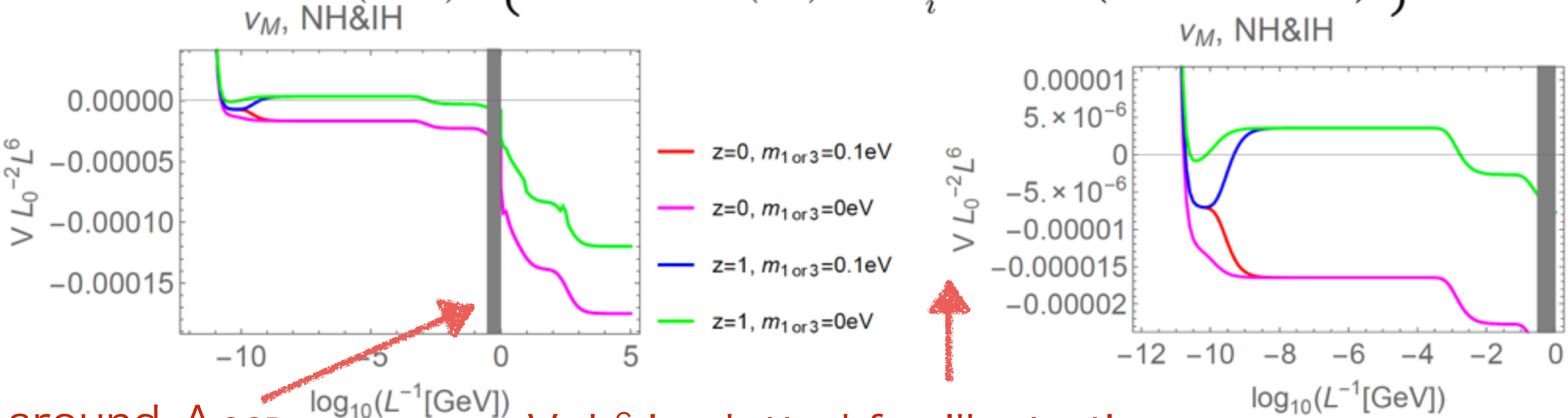
n_p: degrees of freedom, s_p: spin, M_p: mass, q_p: charge

Majorana neutrino

- AdS vacuum around neutrino mass scale ~ meV.
- The balance among 3 contributions:

cc γ ,graviton neutrino

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



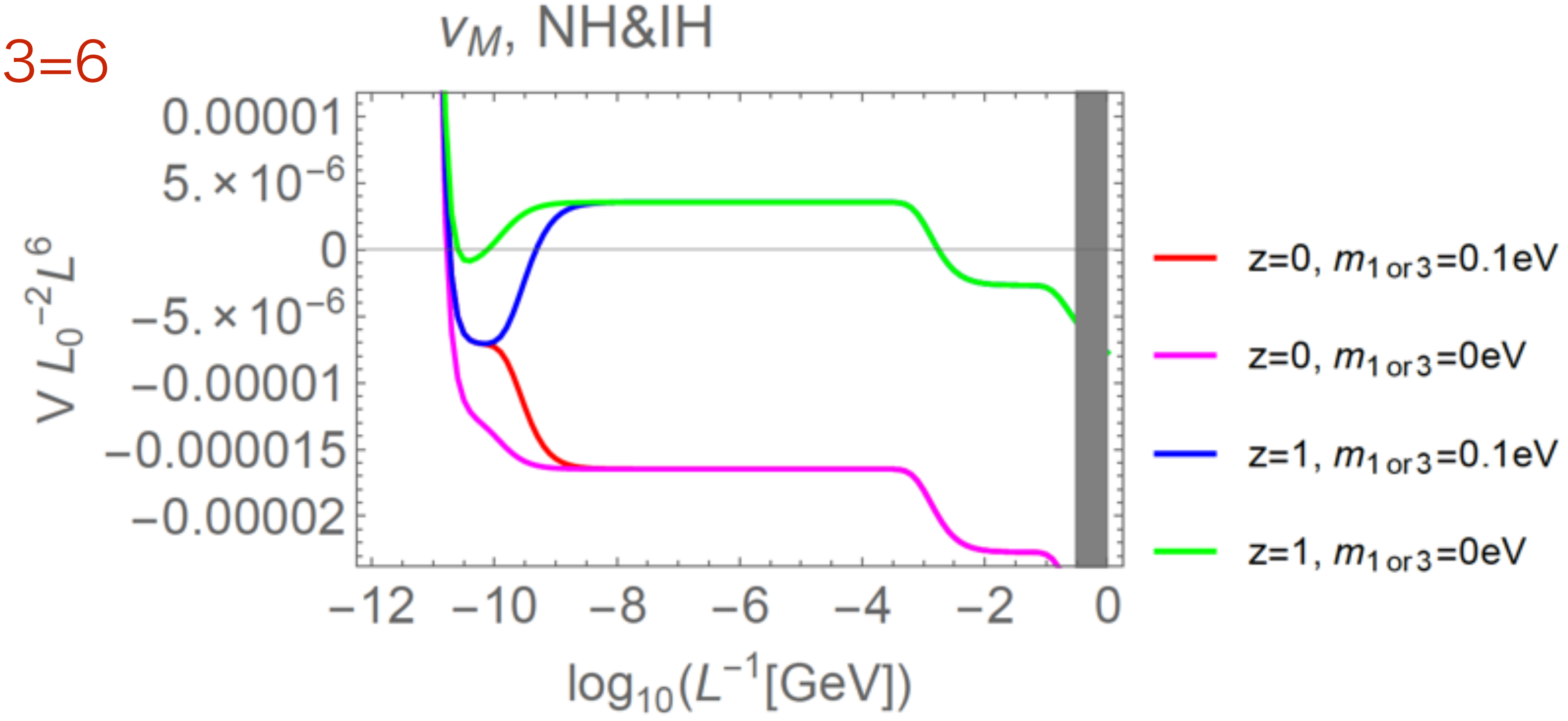
around Λ_{QCD}

V×L^6 is plotted for illustration.

neutrino vacuum

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

d.o.f.
γ+graviton: 4
ν: 2×3=6



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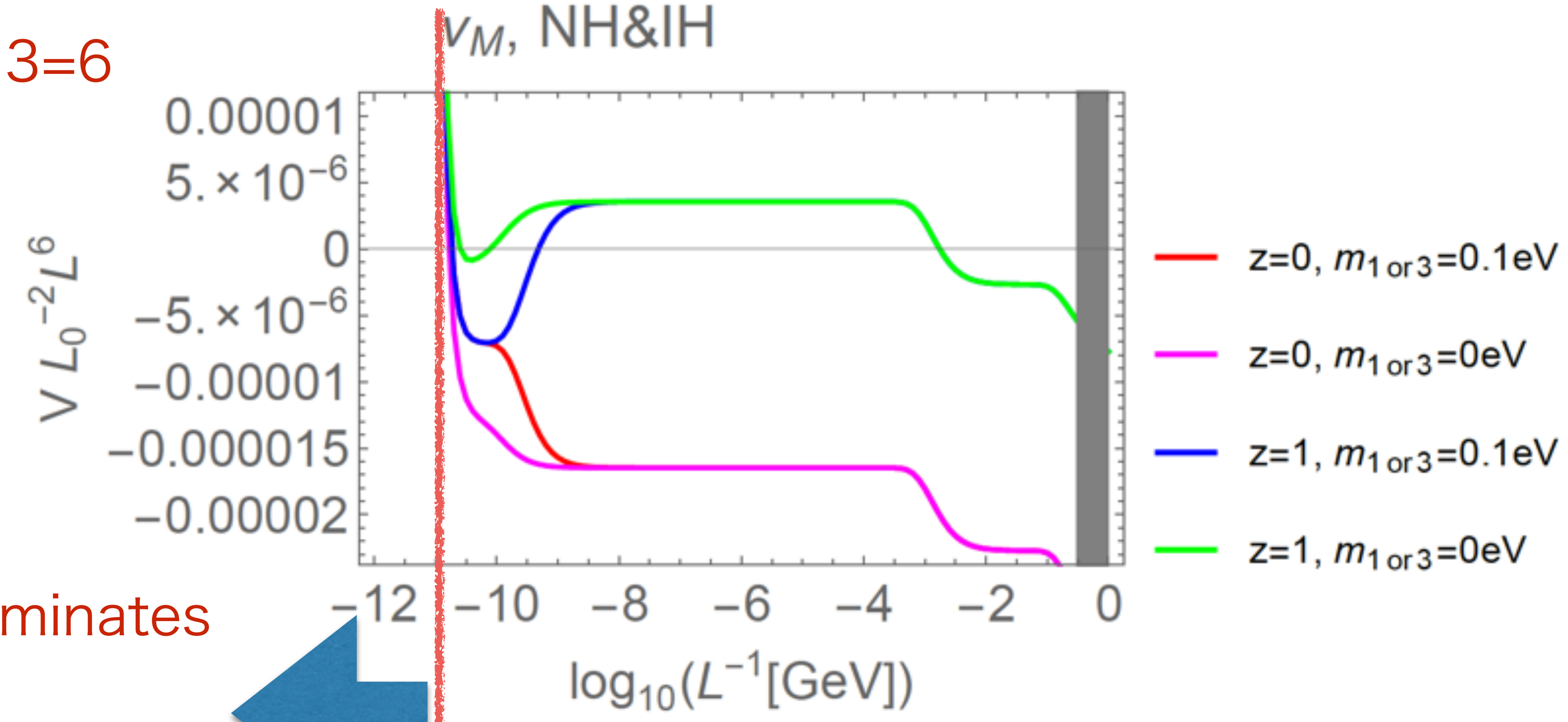

cc dominates

neutrino vacuum

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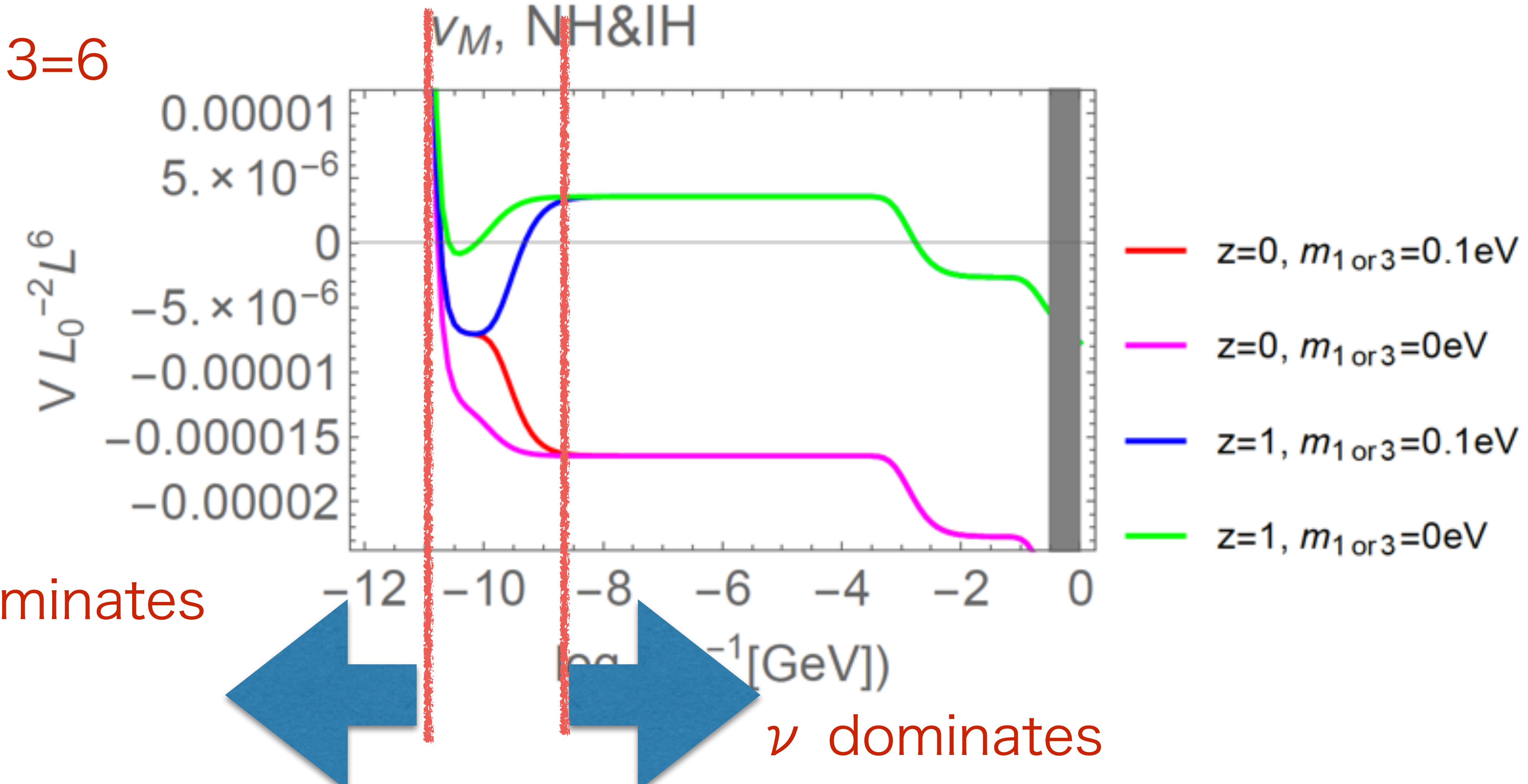


cc dominates

ν dominates

neutrino vacuum

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

d.o.f.

γ+graviton: 4

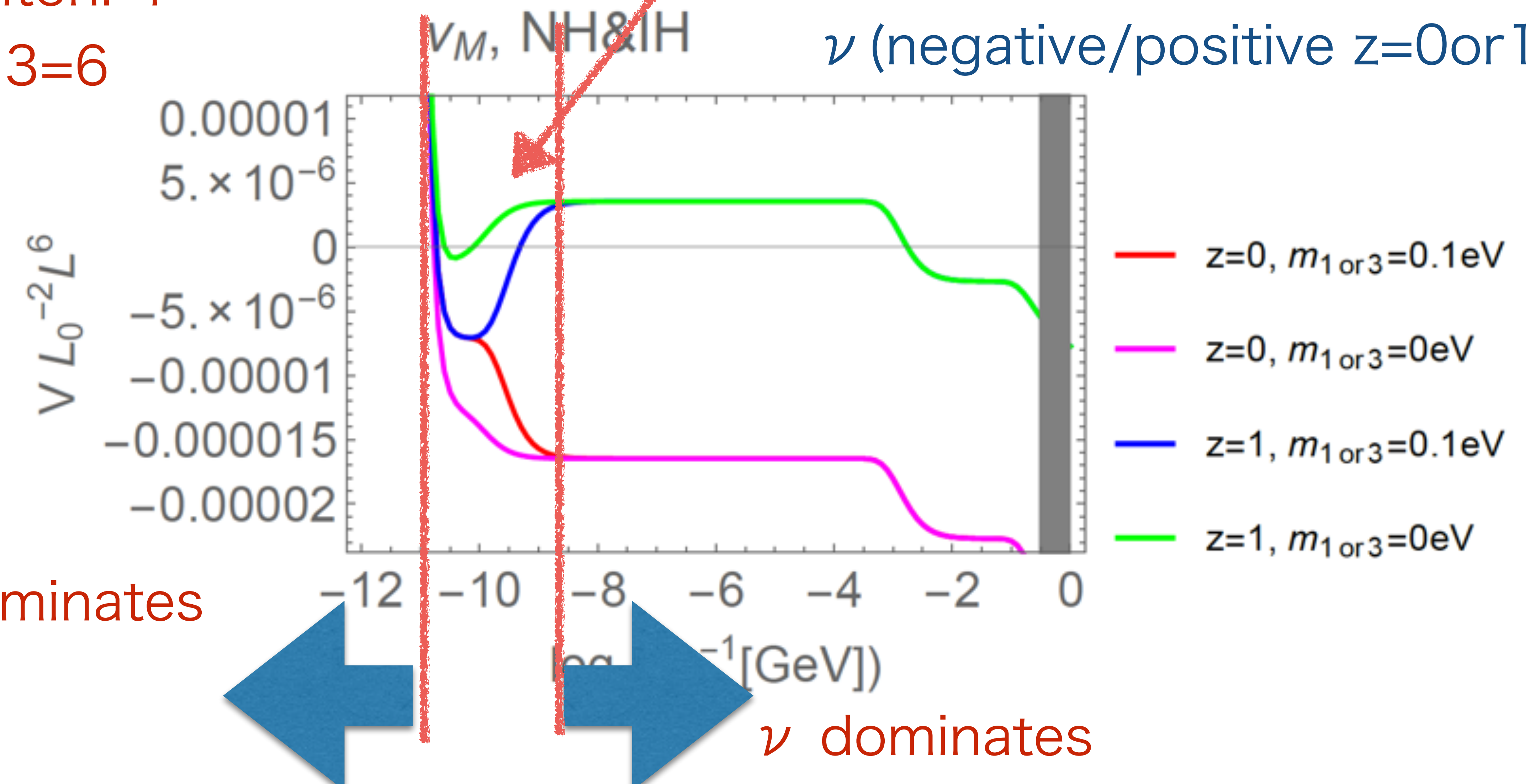
ν: 2×3=6

balance among

Λ4(positive)

γ+graviton(negative)

ν(negative/positive z=0or1)



cc dominates

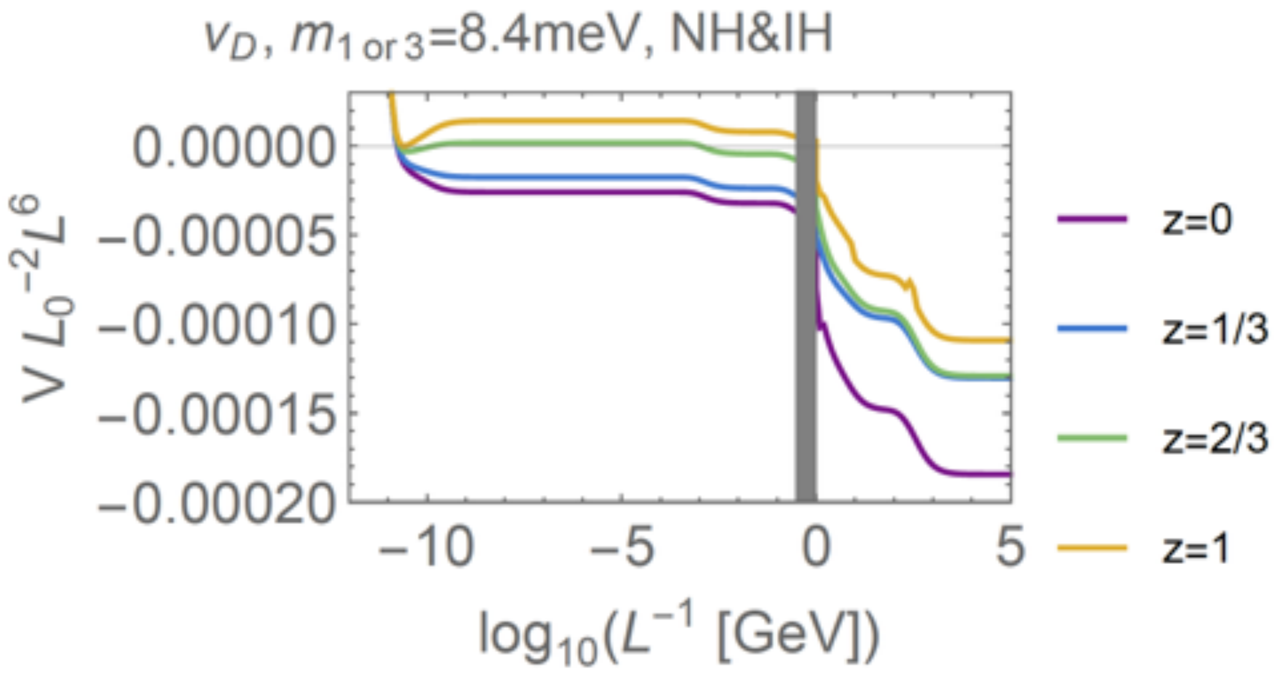
ν dominates

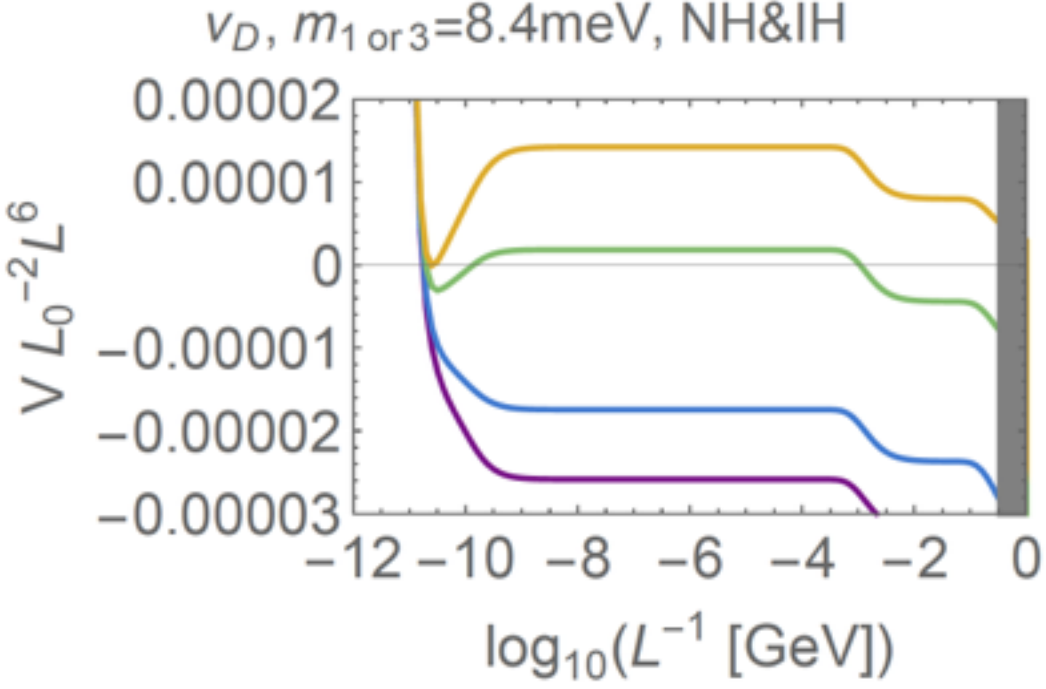
Dirac neutrino

- Neutrino vacuum with dS, flat or AdS, depending on lightest neutrino mass.

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

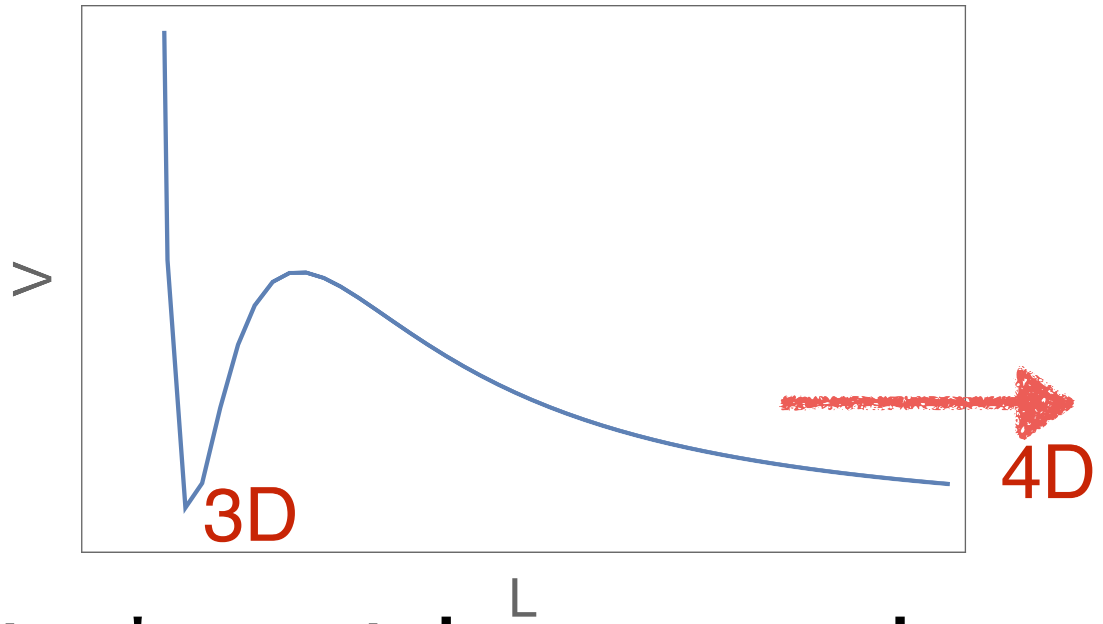
Difference! 2(Majorana)→4(Dirac)





Application of MPP

- We may consider the degeneracy between 3D and 4D vacua.

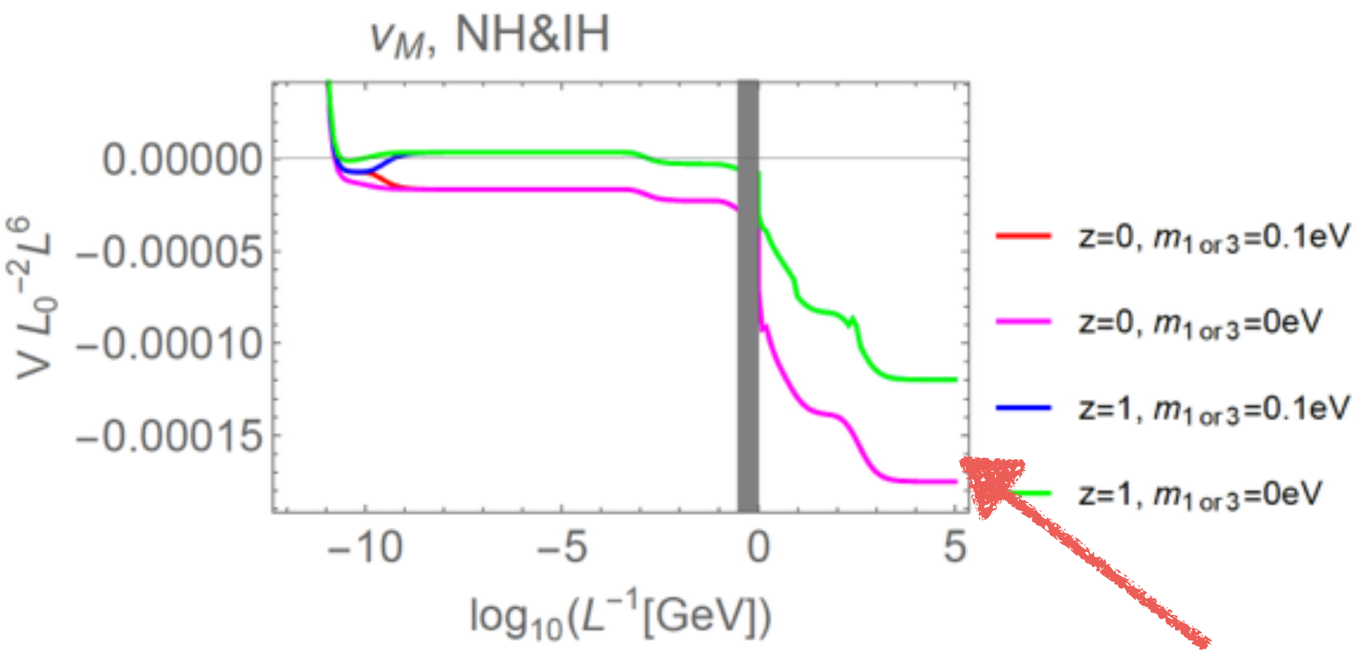


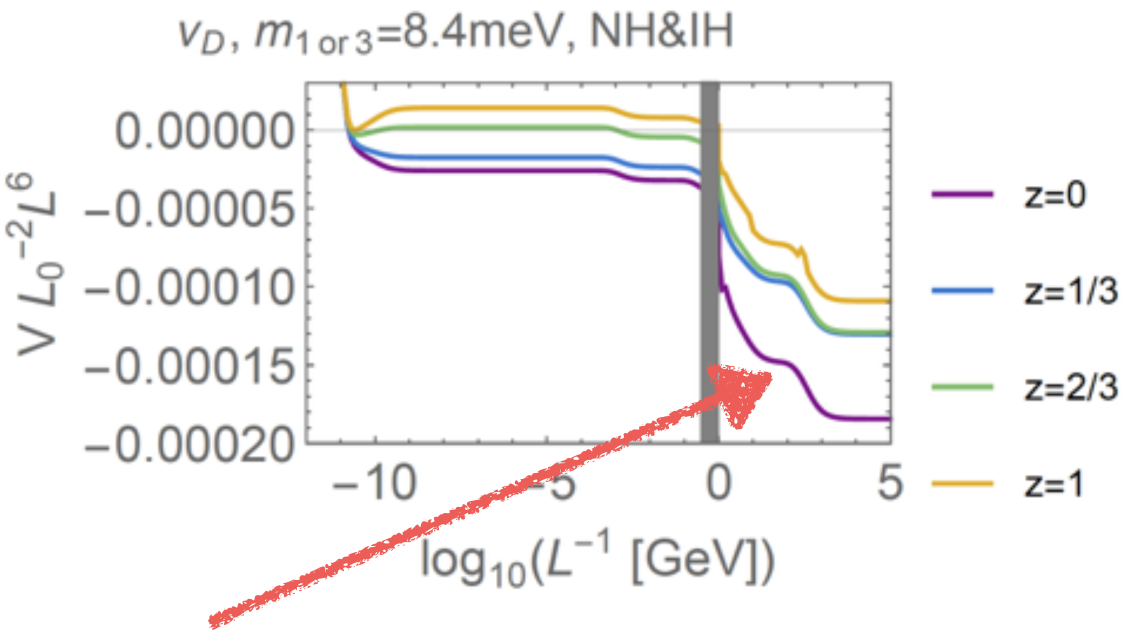
- Predicted neutrino mass is $m_{\nu,\mathrm{lightest}}=O(1\text{-}10)\,\mathrm{meV}$, and neutrino is Dirac.

Application of WGC

- Neutrino vacuum can be AdS, but it is likely to decay non-perturbatively.

- No prediction from WGC.





Runaway behavior for small radius

T^2 compactification

- The calculation is similar to S^1,

  but technically complicated due to many moduli.

$$ds^2 = g_{\alpha\beta} dx^\alpha dx^\beta + \rho \gamma_{ij} dy^i dy^j + B^i_\alpha dx^\alpha dy^i$$

shape of T^2

ρ: area of T^2

$$\gamma_{ij} = \frac{1}{\tau_2} \begin{pmatrix} 1 & \tau_1 \\ \tau_1 & |\tau|^2 \end{pmatrix}$$

- Qualitatively same conclusion is obtained.

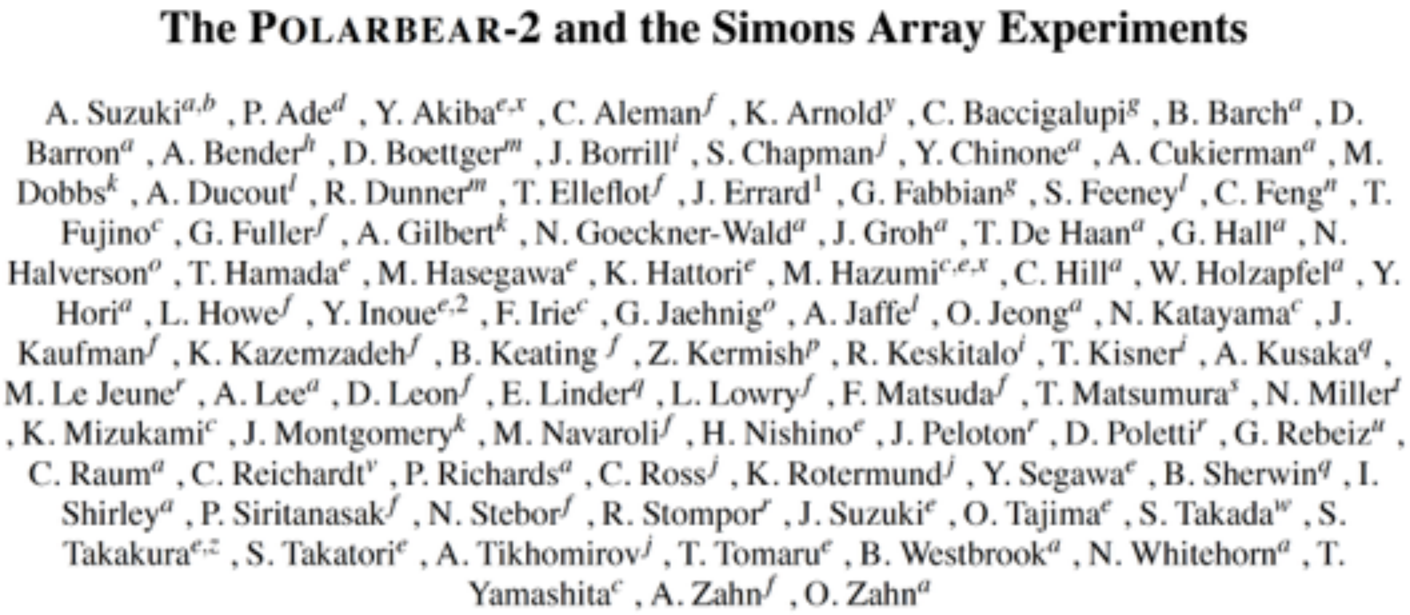
  - existence of ν vacuum, runaway direction.

Detectability of m_ν

- future CMB observation

[1512.07299]

- e.g.



The POLARBEAR-2 and the Simons Array Experiments

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, 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.
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Yamashita[c] , A. Zahn[f] , O. Zahn[a]

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

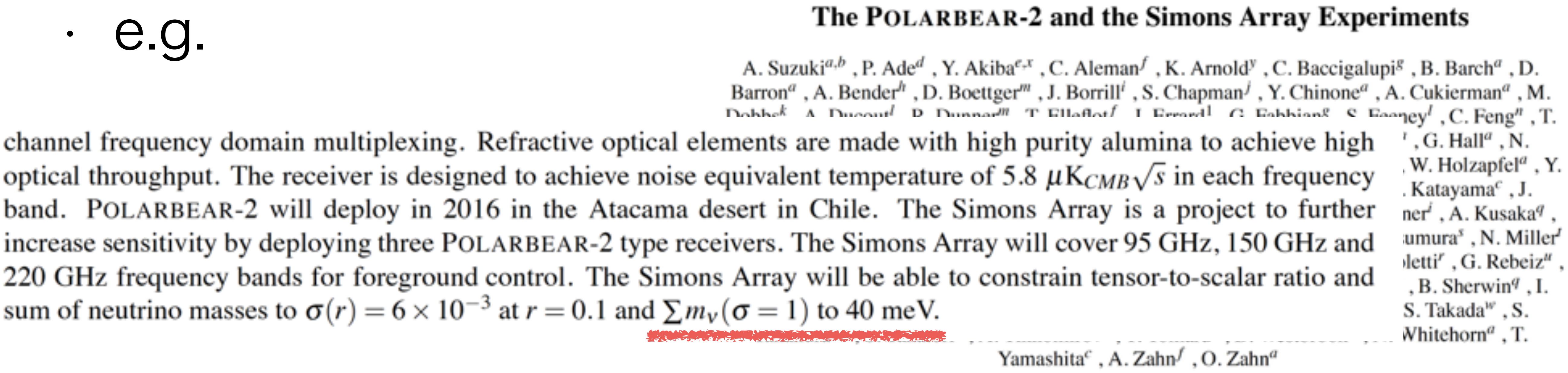
- Please let me know if you know good experiment.

Detectability of m ν

- future CMB observation

[1512.07299]

- e.g.



The POLARBEAR-2 and the Simons Array Experiments

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W. Holzapfel[a], Y.
Katayama[c], J.
ner[j], A. Kusaka[q],
umura[s], N. Miller[f]
letti[r], G. Rebeiz[u],
, B. Sherwin[q], I.
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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 $\sigma(r) = 6 \times 10^{-3}$ at $r = 0.1$ and $\sum m_\nu(\sigma = 1)$ to 40 meV.

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

- Please let me know if you know good experiment.

Summary

- Message of talk
  - Neutrino is Dirac,

    $m_{\nu,\mathrm{lightest}}$ = O(1-10)meV (from MPP).
  - If Higgs potential is bounded from below,

    SM with M_t=173GeV, M_H=125GeV may not

    be consistent with QG (from WGC).