The Swampland and Neutrino Physics

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Swampland Program

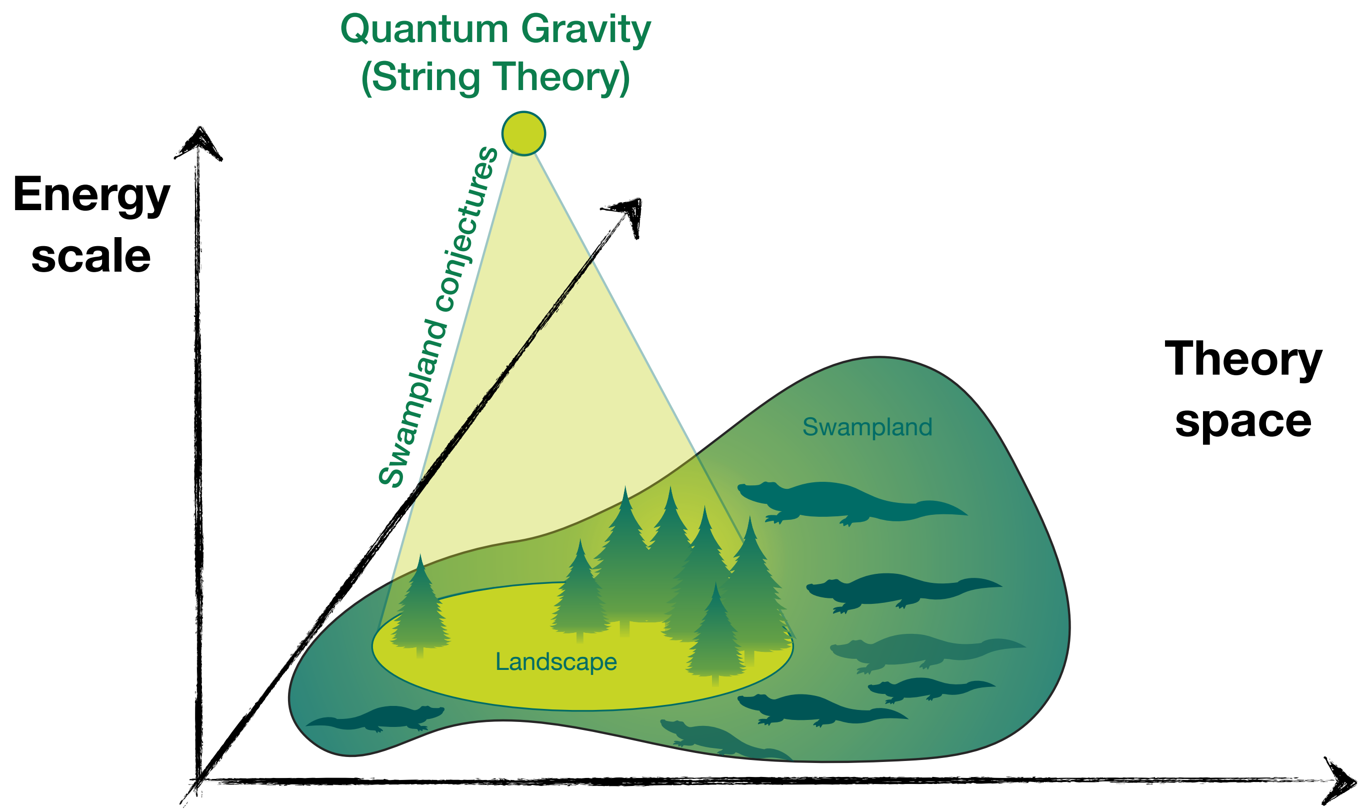
➢ Not all effective field theories can consistently coupled to gravity

- anomaly cancellation is not sufficient

- consistent ultraviolet completion can bring non-trivial constraints

"good" theories live in landscape and "bad" ones live in swampland

Vafa '05



➢ In theory space ☛ frontier discerning good theories from those downgraded to swampland is drawn by family of conjectures classifying properties that theory must call for/avoid to enable consistent completion into QG

- criteria => conjectures

supported by arguments based on string theory and black-hole physics

➢ Swampland conjectures provide bridge from quantum gravity to astrophysics, cosmology, and particle physics

Where Do We Live in String Landscape?

Distance Conjeture

➢ At large distance in field space $\phi \Rightarrow$ tower of exponentially light states

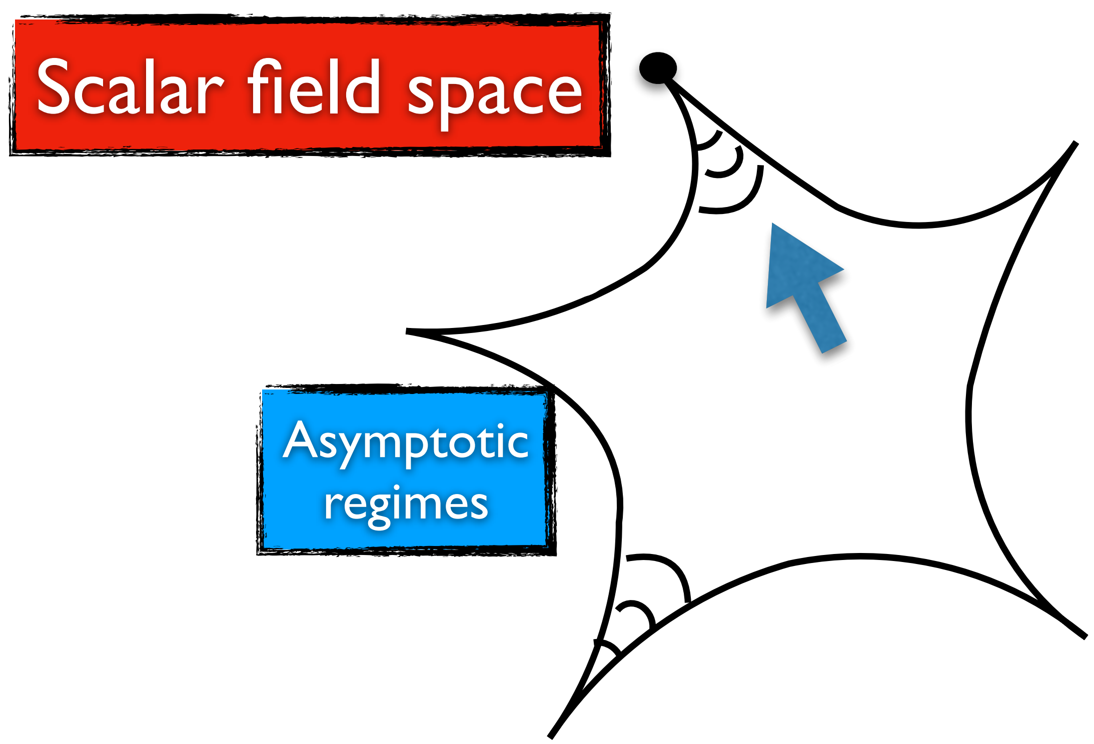
$m \sim e^{-\alpha\phi}$ with $\alpha \sim \mathcal{O}(1)$ parameter in Planck units Ooguri-Vafa '06

➢ Kaluza-Klein tower ☛ decompactification of *d* extra dimensions

$\phi = \ln R$ ☛ $m \sim 1/R$

➢Species scale where gravity becomes strong ☛ $\Lambda_{\rm QG} = (m^d M_p^2)^{1/(d+2)}$

Dvali '07



➢ Smallness of some physical parameters might signal a large distance corner in the string landscape of vacua

➢ Such parameters can be ☛ scales of dark energy and neutrino masses

Dark Dimension Proposal for Dark Energy

- AdS distance conjecture $\phi = -\ln|\Lambda|$ Lüst-Palti-Vafa '19
- Extension to dS ☛ $m \sim \frac{1}{\lambda}\left(\frac{\Lambda}{M_p^4}\right)^a M_p \Rightarrow 1/4 \leq a \leq 1/2$ Montero-Vafa-Valenzuela '22
- $a \leq 1/2$ unitarity bound $m^2_{\text{spin}-2} \geq 2H^2 \sim \Lambda$ Higuchi '87
- $a \geq 1/4$ estimate of 1-loop contribution $\Lambda \gtrsim m^4$

Observations ☛

$\Lambda \sim 10^{-120} M_p^4$ (No deviations from Newton's law $R < 30\ \mu\text{m}$) $\Rightarrow a = 1/4$

Consistent with string computations LAA-Antoniadis-Lüst-Lüst '23

astrophysical constraints $\Rightarrow d = 1$ extra dimension

$\Rightarrow$ species scale (5d Planck mass) ☛ $\Lambda_{\text{QG}} \sim m^{1/3} M_p^{2/3} \sim 10^9\ \text{GeV}$

$$10^{-4} \lesssim \lambda \lesssim 10^{-2}$$

More Physics Implications of Dark Dimension

- Neutrino masses originate in 5D bulk brane interactions of the form

lepton doublets (localized on SM brane)

$\tilde{H} = -i\sigma_2 H^*$

$$\mathcal{L} \supset h_{ij} \; \bar{L}_i \; \tilde{H} \; \Psi_j(y=0)$$

coupling constants

3 bulk R-neutrinos

(evaluated at position of SM brane $y=0$ in 5th-dimension coordinate y)

- Expanding Ψ_j into modes canonically normalized leads to Yukawa 3x3 matrix suppressed by square root of bulk volume

$$Y_{ij} = \frac{h_{ij}}{\sqrt{\pi R M_s}} \sim h_{ij} \frac{M_s}{M_p} \qquad M_s \lesssim \Lambda_{\rm QG}$$

- Mesoscopic extra dimension produces suppression of 4-dimensional Yukawa couplings ☛ yielding naturally light Dirac neutrinos
- Recent analysis of ν-oscillation data with 3 bulk neutrinos $\Longrightarrow$

$$m \gtrsim 2.5\,\text{eV} \;\vee\; R \lesssim 0.4\,\mu\text{m} \Rightarrow \lambda \lesssim 10^{-3} \;\wedge\; \Lambda_{\rm QG} \sim 10^9 \text{ GeV}$$

Forero-Giunti-Ternes-Tyagi '22

- Bound can be relaxed in presence of bulk $\nu_{\rm R}$-neutrino masses

LAA-Antoniadis-Cunat '23

Dark Energy, Gravitino, and KK Towers

- ➢ Gravitino conjecture

Cribiori-Lüst-Scalisi ’21
Castellano-Font-Herraez-Ibanez ’21

$$\tilde{m} = \frac{1}{\lambda_{3/2}} \left(\frac{m_{3/2}}{M_p} \right)^n M_p \qquad n > 0$$

- ➢ Combine gravitino conjecture with dark dimension proposal ☛ two possibilities

- ➢ One KK Tower

$$\tilde{m} = m \Rightarrow m_{3/2} \sim 1 \text{ eV}$$

- ➢ Two KK towers ☛ one for dark energy and one for SUSY breaking

$$\tilde{m} \neq m \Rightarrow m_{3/2} \sim 250 \text{ TeV}$$

LAA-Antoniadis-Cribiori-Lust-Scalisi ’23

Dark Dimension Hierarchy from Inflation

➢ Interesting possibility ☛ extra dimension expands with time

$R_0 \sim 1/M_s$ to $R \sim \mu$m requires ~ 42 e-folds! LAA-Antoniadis-Lüst '22

$$ds_5^2 = a_5^2(-d\tau^2 + d\vec{x}^2 + R_0^2\ dy^2)$$ R_0 ☛ initial size prior to inflation

$$= \frac{ds_4^2}{R} + R^2 dy^2 \quad ; \quad ds_4^2 = a^2(-d\tau^2 + d\vec{x}^2) \quad \Rightarrow \ a^2 = R^3$$

After 5d inflation of $N = 42$ e-folds $\Rightarrow$ 63 e-folds in 4d with $a = e^{3N/2}$

➢ Dark Dimension from 5D inflation

- **connect weakness of gravity to size of observable universe**
- **scale invariant density fluctuations from 5D inflation**
- **radion stabilization**

LAA-Antoniadis-Arkani-Hamed to appear.

Neutrino-Modulino Mixing

- ➢ Modulino s ☛ fermionic partner of radion

- ➢ Simple construct ☛ relevant light scale for SM singlets is $m_{3/2}$

  and dimensionless coupling constant with visible matter is $\lambda_i = \alpha_i \frac{m_{3/2}}{M_p}$

- ➢ Modulino mass is generated by SUSY breaking as the coupling λ_i

  but @ 2nd order in $m_{3/2}$ ☛ $m_4 \sim \beta \frac{m_{3/2}^2}{M_p}$

$$m_{3/2} \sim 250 \text{ TeV} \;\wedge\; \beta \sim 2 \Rightarrow m_4 \sim 50 \text{ eV}$$

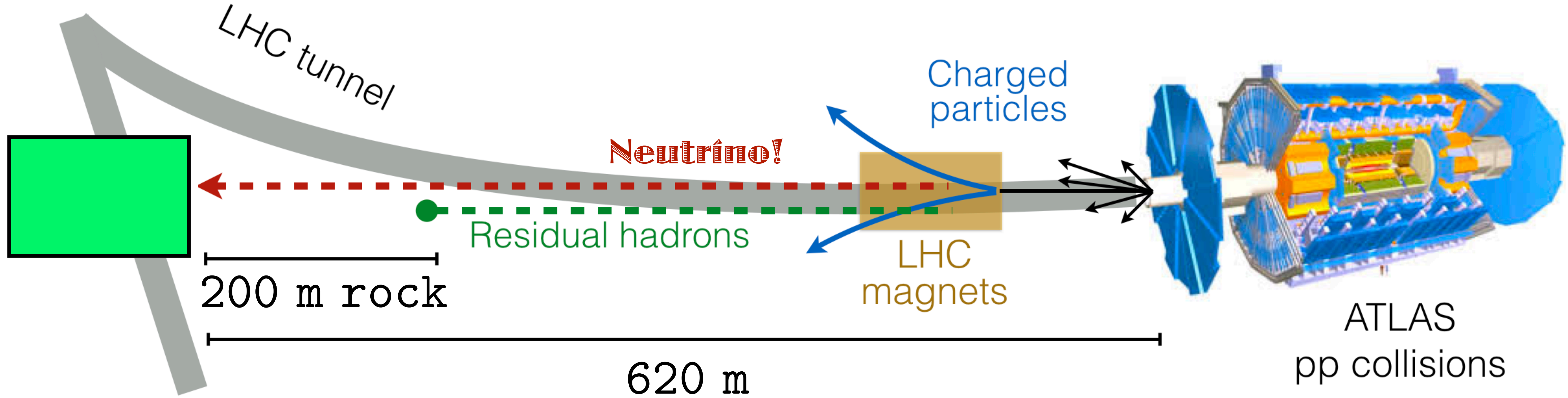
- ➢ s mixing with active SM neutrinos involves the electroweak symmetry breaking

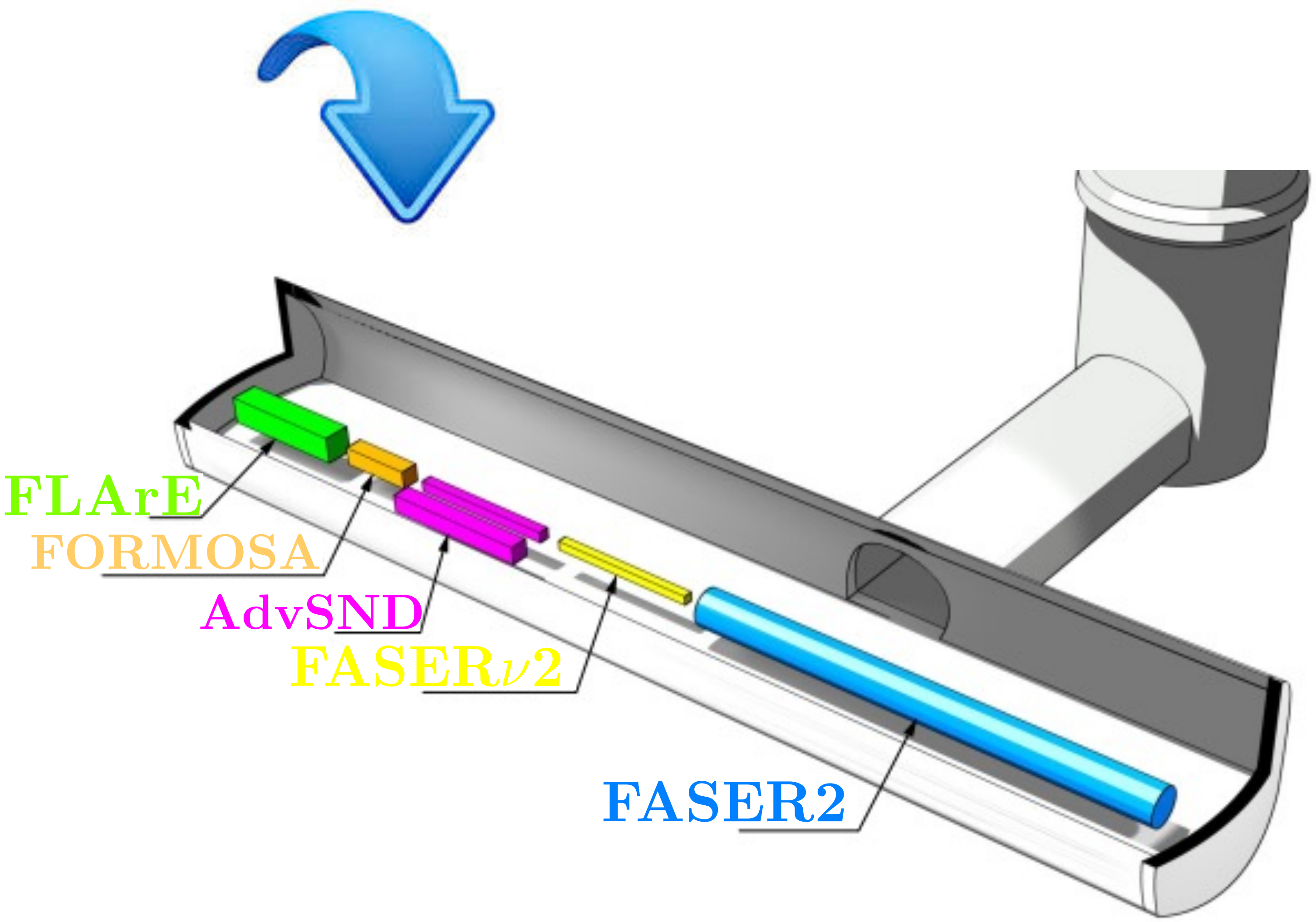
- ➢ Simplest effective operator $\lambda_i \; \bar{L}_i s H$ ☛ $m_{\nu s} \sim m_{3/2} \langle H \rangle / M_p \ll m_4$

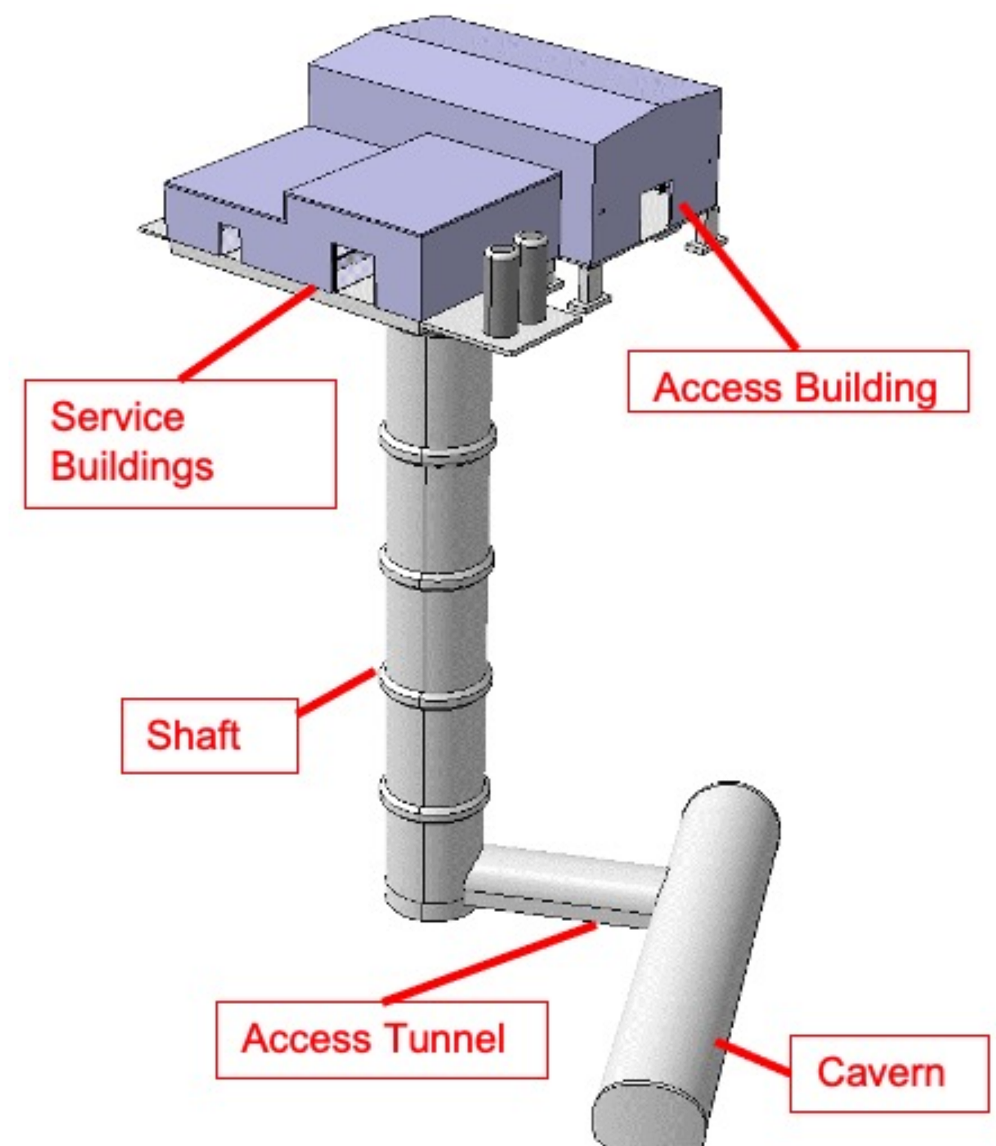
  analog to 3 + 1 scheme

LAA-Antoniadis-Benakli-Cunat- Lüst '23

Forward Physics Facility







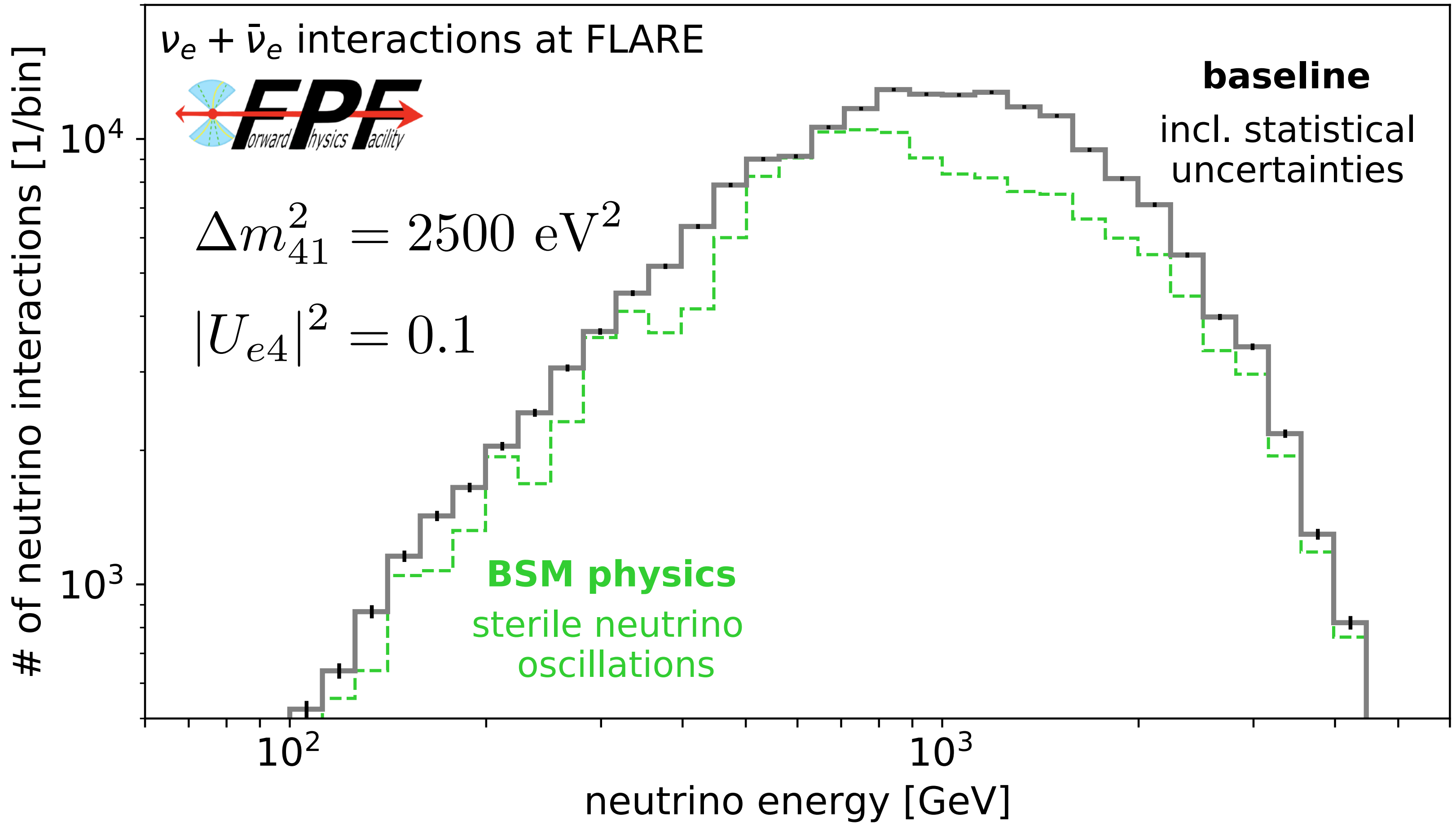
Neutrino-Modulino Oscillations

➢ Survival probability ☛ 3 + 1 scheme

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)\sin^2\frac{\Delta m_{41}^2 L}{4E}$$

➢ FLArE sensitive to neutrino square mass difference satisfying $\frac{\Delta m_{41}^2 L}{4E} = \frac{\pi}{2}$

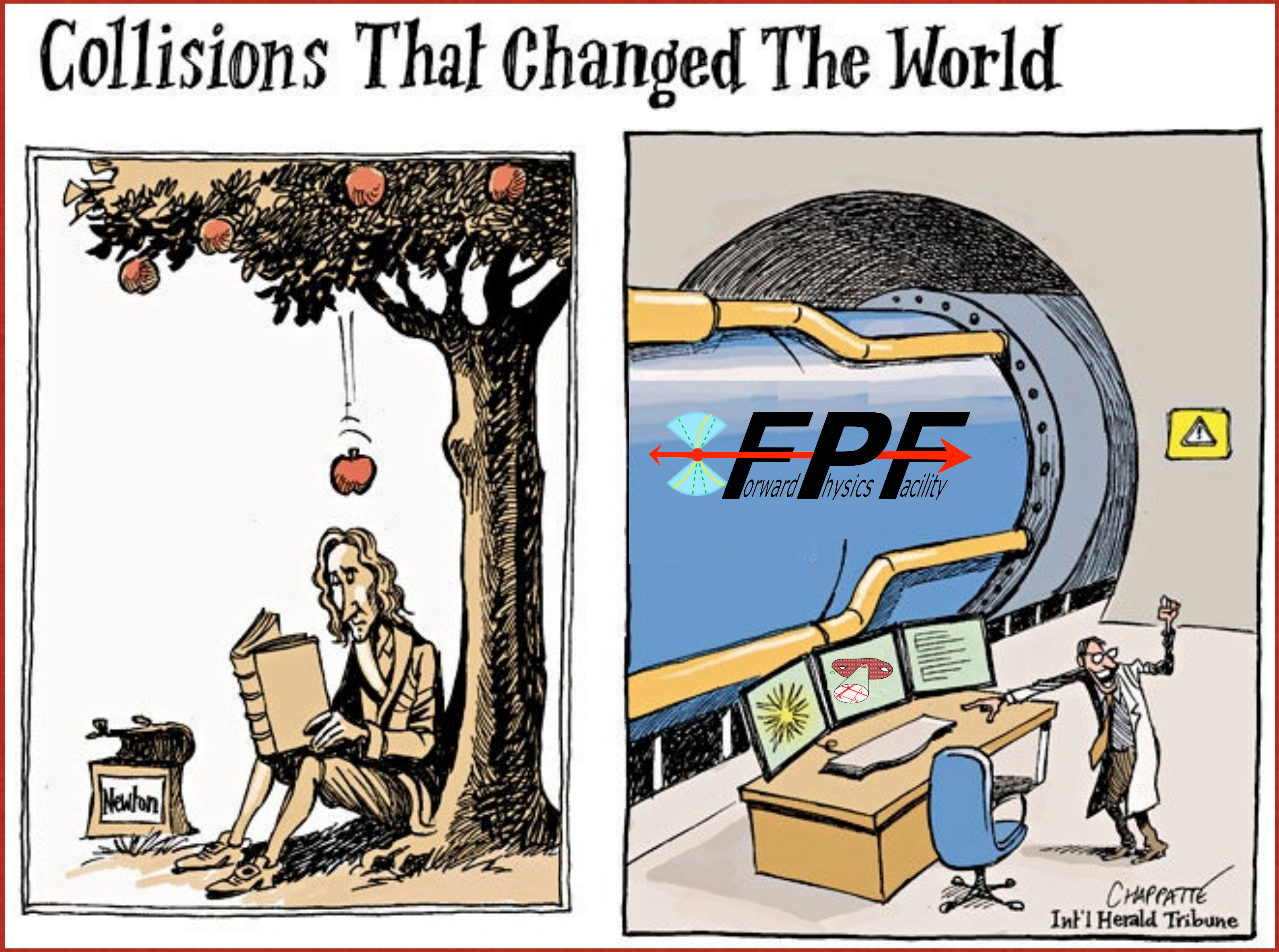
for $L \sim 620\ \mathrm{m}\ \wedge\ E \sim \mathrm{TeV} \Rightarrow \Delta m_{41}^2 \sim 2500\ \mathrm{eV}^2$



Study of FPF sensitivity to $U_{\alpha 4}$ is underway ☛ Kling-Trojanowski-Makela to appear

Take Home Message

- FPF experiments will be able to probe models with high scale SUSY breaking by searching for neutrino-modulino oscillations
- This highlights complementarity between ATLAS/CMS and FPF experiments in exploring the SUSY parameter space




That's all Folks!