ANTHROPIC (or environmental) SELECTION

Dark Energy and the Electroweak Scale

" Innumerable suns exist
Innumerable earths revolve around these suns
in a manner similar to the way the
planets revolve around sun.
Living beings inhabit these worlds "

Giordano Bruno, 1584

Barrow - Tipler   British School
Carter, Hawking, Carr, Rees
Banks, Linde, Weinberg, Vilenkin

Rees, Tegmark

Barr, Donoghue, Seckel

Bousso, Polchiski

Kachru, Kallosh, Linde, Trivedi ; Douglas

S. Thomas etc ; L.Susskind ; Banks-Dine-Gorbatov

Kallosh, Kratoshuil, Linde, Lindner, Shmakova ;

Garriga, Linde, ·Vilenkin
          with

N. Arkani-Hamed,   S. Thomas ,

M. Zaldariaga

Why Anthropic ?

· Successful approach to <u>both</u> CCPs .
  "predicted" ρ_{vac} to within ~100 .

· If a good approach, it should predict more.

· What is its domain of applicability ?

· Can it be applied to problems which have
  standard explanations e.g., symmetries ?

· To the hierarchy problem? instead of SUSY ?

· Fermion Masses?

L. J. Henderson

The fitness of the environment:

An inquiry into the Biological significance of the properties of Matter

date ?.

fear of

Premature Application

apply it to the Fundamentel Theory

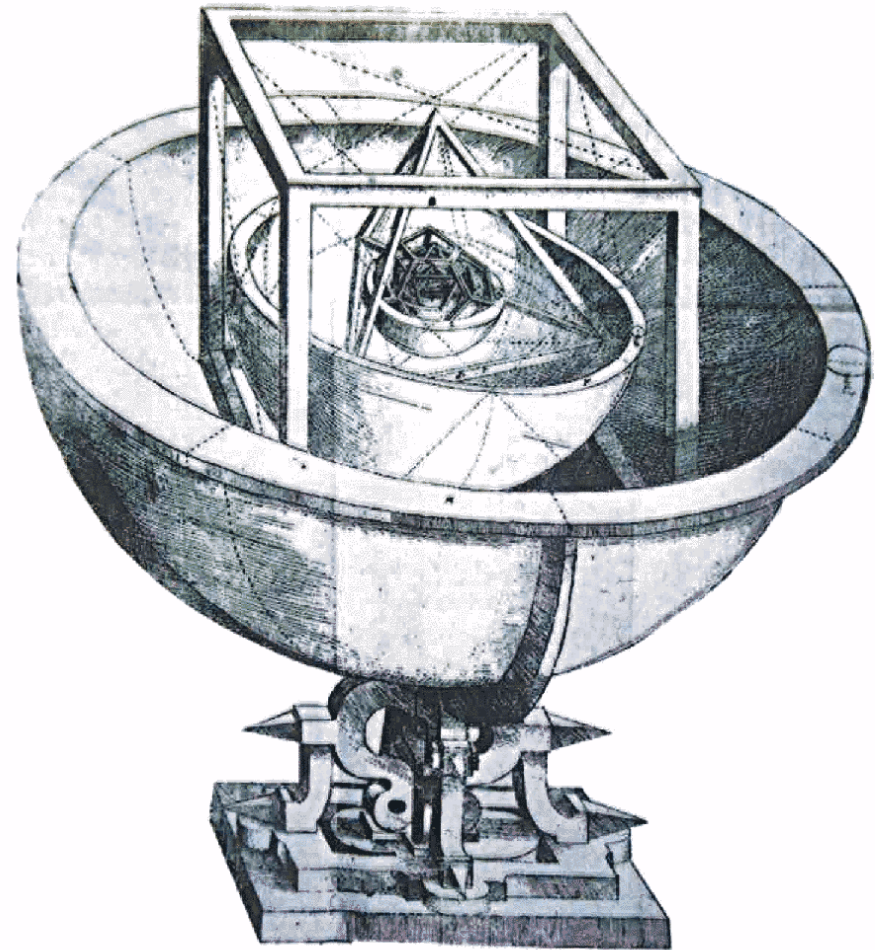<u>not</u>   an   Effective Theory

do   not   know   beforehand

favor theories which produce a multiverse

OUTLINE

1) Multiverse ~~Hypothesis~~ Reasoning

2) Applications to Dark Energy, Electroweak Scale and beyond.

3) Multiverse Relation between the cosmological constant and gauge hierarchy problems.

N. Arkani-Hamed
M. Zaldariaga
S. D.

Kepler's model

To Kepler, the six planets (Copernican paradigm) orbited crystalline spheres. The thickness of a sphere was the minimum to contain the elliptical orbit of its planet. The five gaps between these six concentric spheres were spaced by the Platonic solids.

Gap #1: Saturn/Jupiter, the cube
harmonic ratio = sqrt(3) ~= 1.732
Gap #2: Jupiter/Mars, the tetrahedron
harmonic ratio = 3
Gap #3: Mars/Earth, the dodecahedron
harmonic ratio ~= 1.258
Gap #4: Earth/Venus, the icosahedron
harmonic ratio ~= 1.258
Gap #5: Venus/Mercury, the octahedron
harmonic ratio = sqrt(3) ~= 1.732

in Kepler's : distances are predicted

Newton's theory disappointing.

is "giving up"

distances are historical accidents.

Liquid H_2O a miracle ?

Some predictivity maintained if:

(1) There are many planets

(2) Habitable planets must contain H_2O liquid

(3) We live in a "typical" habitable planet

$\Rightarrow$ Earth-Sun distance can be computed !

(3) is crucial for anthropic predictivity

If Earth is "atypical" habitable planet, anthropic predictivity is lost.

• Earth

Sun

parabolic mirror
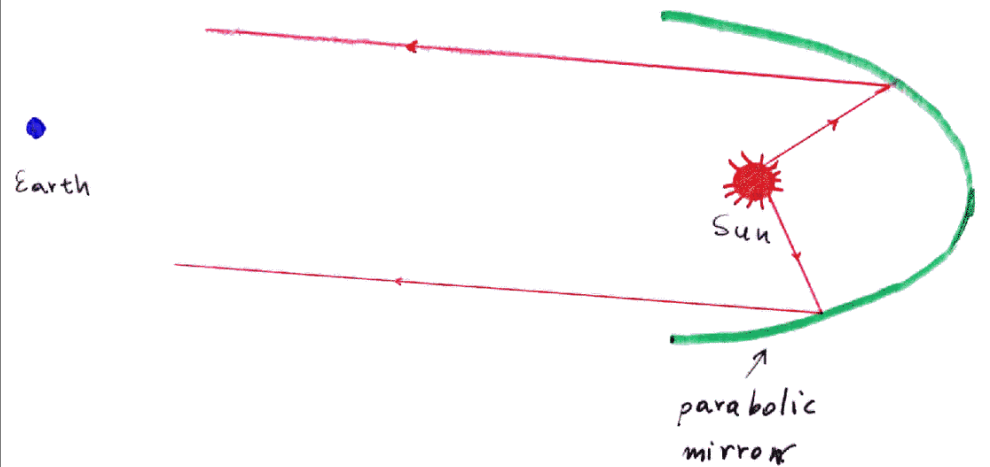
average properties irrelevant for us ; auroras

need ⟨ providence or dynamics

Generalization:

   Planet $\longrightarrow$ Universe

(1) There are many Universes

   "Multiverse"   (e.g. big bangs, vacua)

(2) Habitable Universes require X

(3) Ours is a typical   habitable

                      Universe

$\Longrightarrow$ predict Y in our universe

.. Y fails, look for symmetries, dynamics

Examples:

(1) X = galaxies

     $Y = \rho_{vacuum} < \sim 10^2 \rho_{observed}$

                                  w
                                    $\downarrow$

(2) X = H and heavy atoms

     $Y = \sim m_u, m_d, \Lambda_{QCD}$

(3) $X = {}^{12}C$

                                       s

     $Y = \alpha, m_u, m_d, \dots \pm$ few %

(4) $X = \sim p$ stability vs
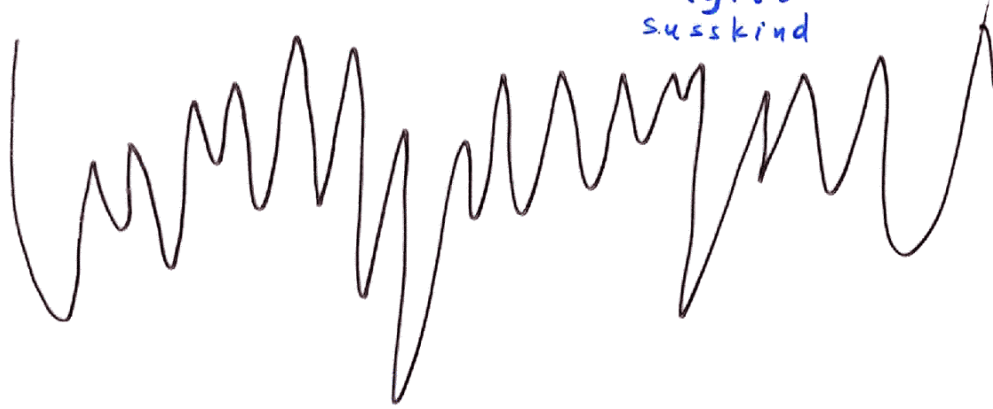
     $Y = \tau_{proton} \gtrsim 10^{16}$ years

it fails! $\Rightarrow$ need $\begin{cases} \text{symmetry} \\ \text{or} \\ \text{dynamics} \end{cases}$
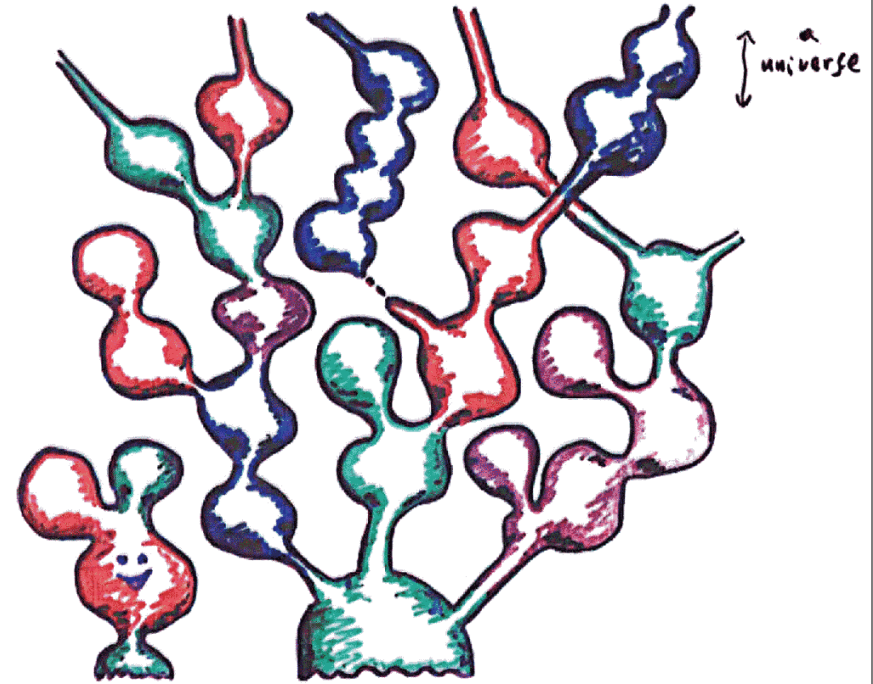
we do not "live dangerously"

Discretuum

L. Abbott
Banks, Dine, Seiberg

Bousso - Polchinski

Kachru et. al.

Douglas
Susskind

"dense"

metastable

"Prediction": $w = -1$

Chaotic Multiverse

$\updownarrow$ a universe

THE UNIVERSE
as it is

thanks to A. Linde

Anthropic Reasoning

1) Is it predictive ?   YES

(α) ρ_{vacuum}

  "Principle of living dangerously"

(β) W(z)   to be tested at SNAP

(γ) if applied to the GHP ⟹

  LHC will see just the Higgs

  υ determined by ∃ atoms ; ^{12}C ; pp ...

(Also, predictivity overrated, e.g. Darwin's
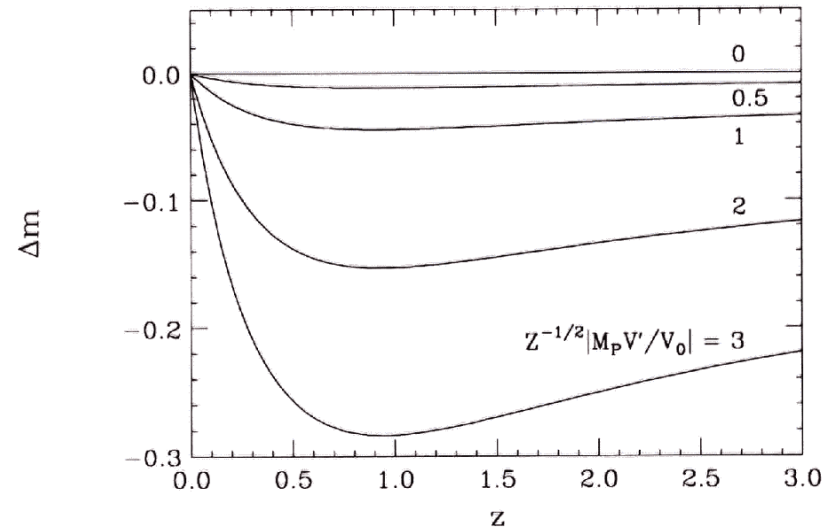
theory has explanatory power ...   )

2) Do we have to give up the

  successes of   SGUTs ?

SNAP

S. Thomas et.al.   R. Kallosh et.al.
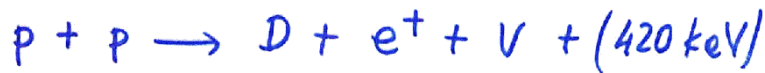
                       Garriga et.al.

Plot: Δm versus z. Curves labeled 0, 0.5, 1, 2, with annotation $Z^{-1/2}|M_P V'/V_0| = 3$.

Existence of Atoms

$$0 < m_n - m_p - m_e < E_{binding} \simeq 8 MeV$$

$\underbrace{}$ 1.5 MeV

.5 MeV

H-stable

$v\downarrow$

others stable

$v\uparrow$

Deuturon bottleneck:

$E_{binding} \sim 2.2 MeV$

$$p + p \longrightarrow D + e^+ + v + (420 keV)$$

$$m_\pi^2 \propto \underset{=}{v} \frac{\langle q\bar{q} \rangle}{f_\pi^2}$$

Existence of the Sun

EXISTENCE OF CARBON

Hoyle
Salpeter

$C^{12}{}^*$

$\overset{}{\underline{}}$ 300 keV

$T = 30$

$Be^8 + He^4$

$\downarrow$
unstable

$C^{12} + He^4$

43 keV

O^{16}

oberhumer
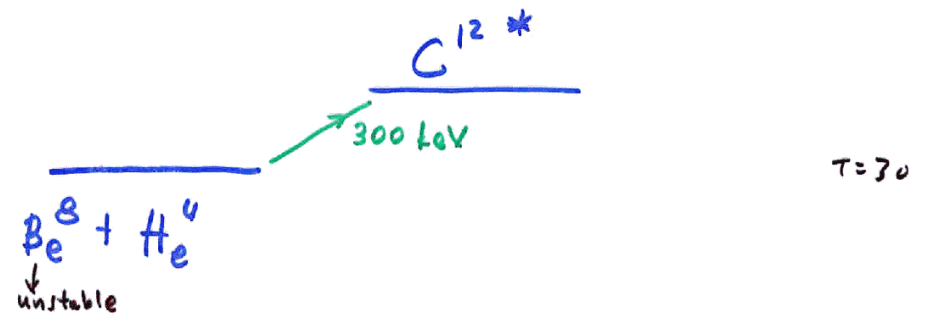
v tightly determined by anthropics

What quantities are Antropic?

Possibility

?

——————— M_{PL}

——————— M_{GUT} $g_1, g_2, g_3, \lambda_t, \lambda_b, \lambda_\tau$

"Large parameters": Successful^{Symmetries}

Rest Messy Numbers experimentally.

$$\frac{\lambda <\Phi>}{M_{PL}} \quad \bar{e} e H$$

$\longmapsto$ discreetuum dependent ?

<u>AND</u> Theoretically very sensitive to Plankean Physics!^{R} ●

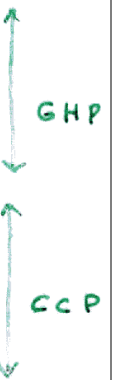SYMMETRIES   +   ANTHROPIC !
heavy   light

Mystery of the Equidistant Scales

——————— M_{PL}

——————— $M_W = M_{DM}$

——————— $\rho_{vac}^{1/4}$

$\uparrow$ GHP $\downarrow$

$\uparrow$ CCP $\downarrow$

$$\rho_{vac}^{1/4} \simeq \frac{M_W^2}{M_{PL}}$$

Deep ?

Anthropic relation of cosmological constant and gauge hierarchy problems.

if both $\rho_{vac}^{1/4}$ and M_w are variable,

$\Rightarrow$

Structure formation (galaxies) requires:

$$\rho_{vac}^{1/4} \lesssim \frac{M_w^2}{M_{PL}} \left(\frac{\delta\rho}{\rho}\right)^{3/4} \frac{1}{\pi\alpha^2}$$

- Relation may <u>not</u> be deep, but antropic.

- One problem instead of two $\Big\langle$ one dynamical
  one anthropic

typical $\sim$ "living dangerously"

$\frac{\delta\rho}{\rho} \sim 10^{-5\pm1}$ (Rees, Tegmark)

           Cooling ; BHs ... ; planetary orbits

Derivation

decoupling $n_\gamma\sigma \sim \frac{T_d^2}{M_{PL}}$

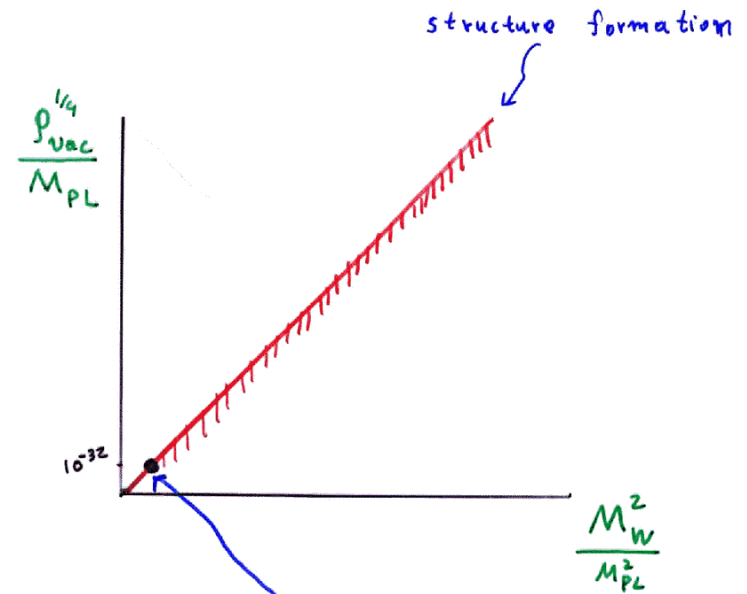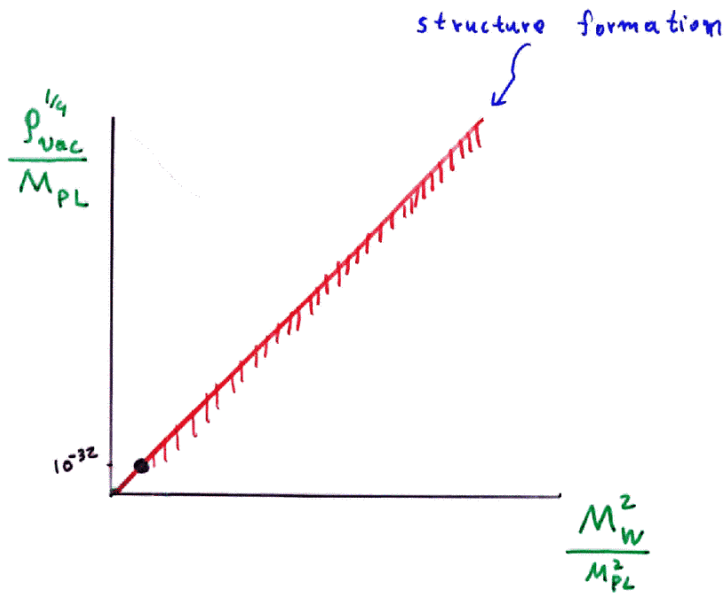$\frac{n_d}{n_\gamma} \sim \frac{1}{\pi\alpha^2} \frac{m}{M_{PL}}$

matter = radiation $T_{m=r} \sim \frac{1}{\pi\alpha^2} \frac{m^2}{M_{PL}}$

$$\frac{\delta\rho}{\rho} \sim t^{2/3}$$

galaxy formation

$$\rho_{non-linear} \sim \rho_{m=r} \left(\frac{\delta\rho}{\rho}\right)^3$$

$\rightarrow$ $\rho_{non-linear}^{1/4} \sim \frac{m^2}{M_{PL}} \frac{\left(\frac{\delta\rho}{\rho}\right)^{3/4}}{(\pi\alpha)^3}$

structure formation

$\dfrac{\rho_{vac}^{1/4}}{M_{PL}}$

10^{-32}

$\dfrac{M_W^2}{M_{PL}^2}$

structure formation

$\dfrac{\rho_{vac}^{1/4}}{M_{PL}}$

10^{-32}

$\dfrac{M_W^2}{M_{PL}^2}$

Why do we live here?

Moving up $(M_{PL}$ down$)$ is vastly favored by the

CCP

Tighten habitability criteria ...

$$H = stars$$

but stars still form if

$$t_{cool} \sim \frac{1}{\rho} \sim M_{PL}^4 < t_{grav.} \sim \frac{1}{\sqrt{G\rho}} \sim M_{PL}^3$$

star lifetime shorter $t_{\star} \sim M_{PL}^2$

still, can live near a low mass red star

Normally $t_{\star} \sim 10^{14} years$, so

M_{Pl} can drop by 100, and still have $t_{\star} \sim 10^{10} years$

Preferred by $\sim (100)^4 \sim 10^8$

Furthermore, living near a star is unnecessary:

Can live on a "lonely planet" powered by:

1) Internal radiactive heating. (Earth)

e.g. thermofiles at deep-sea vents, ancestors to all life?

2) Tidal deformations   (Europa)

$0.08 M_{\odot}$ Lonely Planets give ample opportunity for complex structures to form.

allow M_{PL} to drop by $\sim 10^4$

favored by 10^{16}

a   challenge for anthropics

Why are we so atypical ?

Why is gravity so much weaker than it

needs to be ?

Atypical ⟶ missing crucial dynamics

antropic predictivity lost

(e.g. τ_{proton})

Possibilities:

Let $\rho(\rho_{vac}^{1/4}, m_w)$ = density of states

(1) $\rho \sim \delta(\rho_{vac}^{1/4} - meV)\, \delta(m_w - TeV)$,

no need for antropics

(2) $\rho \sim \delta(m_w - TeV)$; can use antropics to

set ρ_{vac}.

(3) $\rho \sim \dfrac{1}{m^2}$

$\longrightarrow \; N(m_w) = \displaystyle\int_0^{m^2/M_{PL}} d\Lambda \; \rho(\Lambda, m_w) = $ constant $\longrightarrow \cdots$

$m_w \sim e^{-\frac{1}{\alpha}}$

(4) $\cdots$

• They demand a huge amount of dynamics

• & recasts the CCP problem in a new form

p-stability

$$\rho(\Lambda, m_w) = \frac{d}{d\Lambda} \log F + \frac{d}{d\Lambda}\left(\Lambda \log G\right) \frac{1}{m^2}$$

$$F = F(\Lambda, m_w) \quad ; \quad G = G(\Lambda, m_w) \quad \text{polynomial}$$
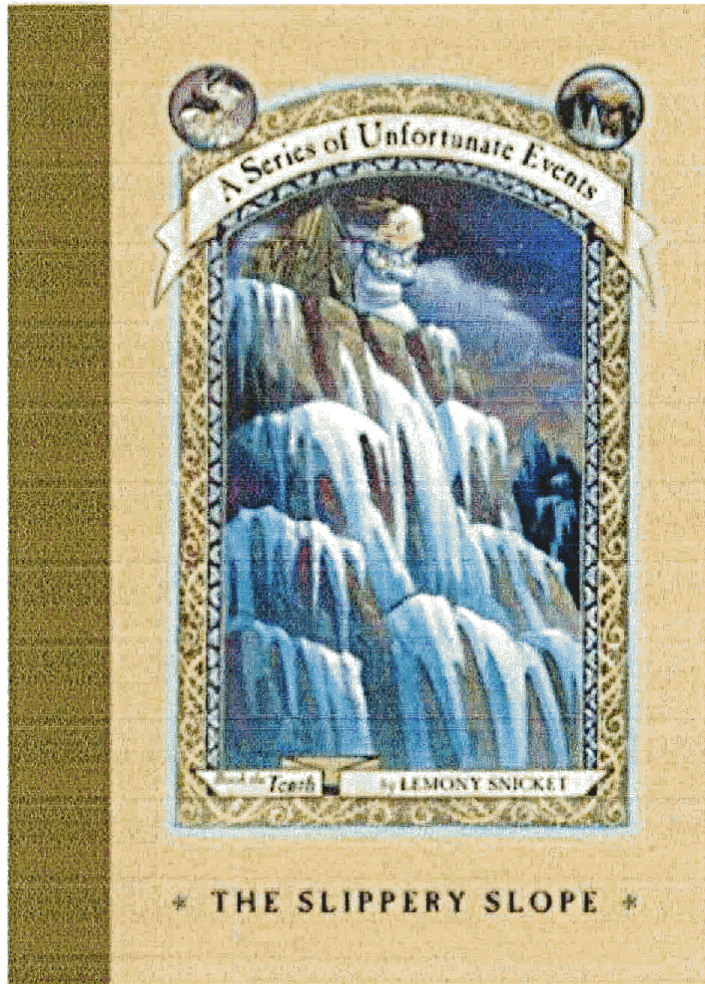$$\text{(non-exponential)}$$

Conclusions

The Multiverse

(1) May relate parameters,

  reducing the number of independent problems!

(2) Recasts old problems, broadens possible appraches.

e.g., new forms of $\rho(x, y...)$

BUT

(3) The challenges for ~~these~~ novel approaches

  remain enormous

Back to Work !