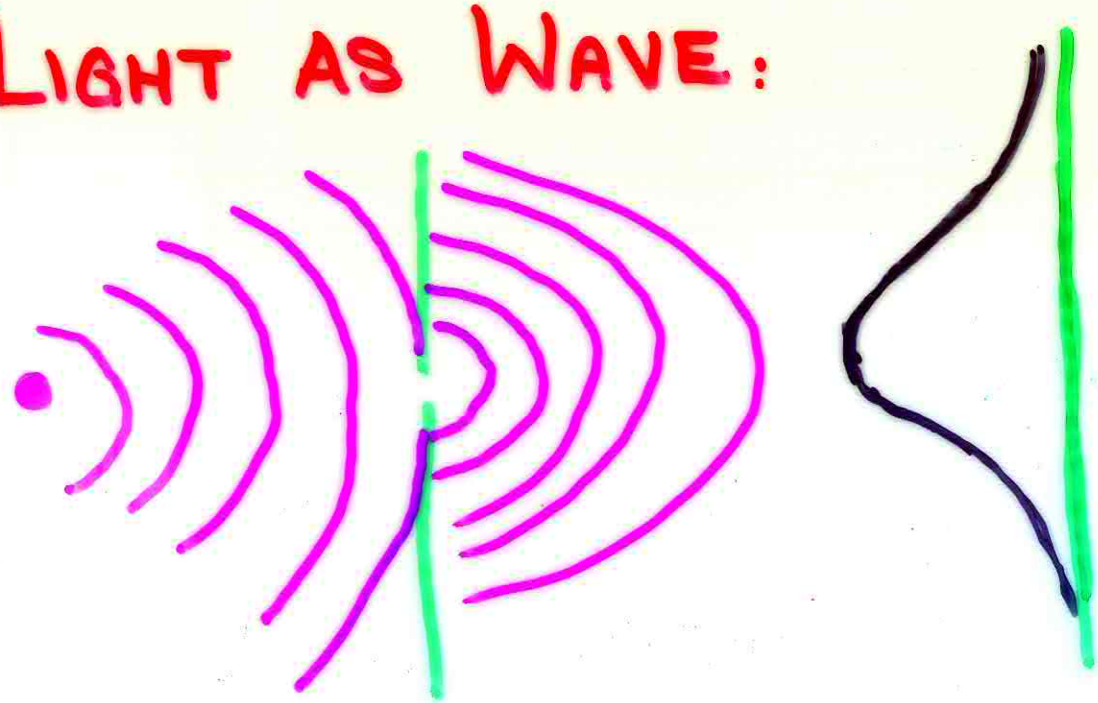
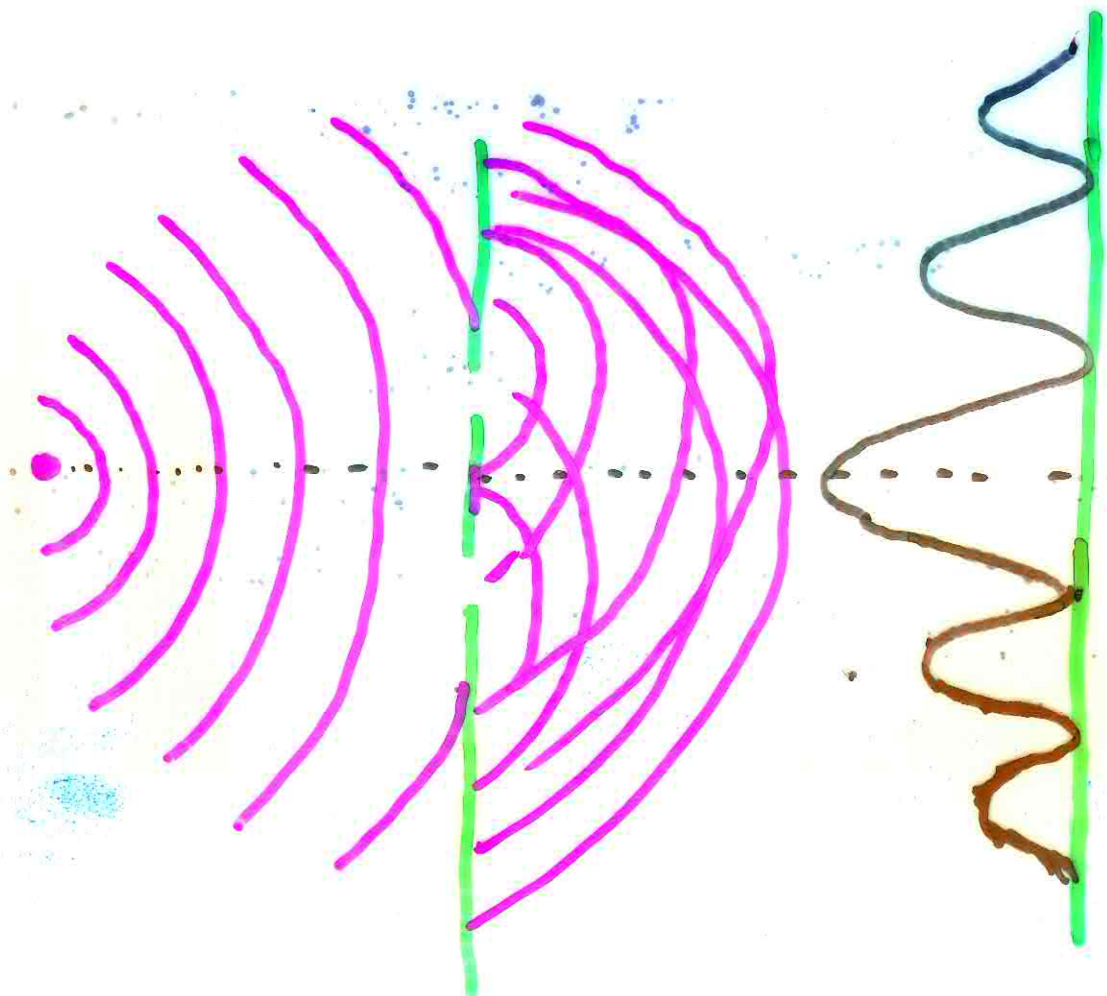
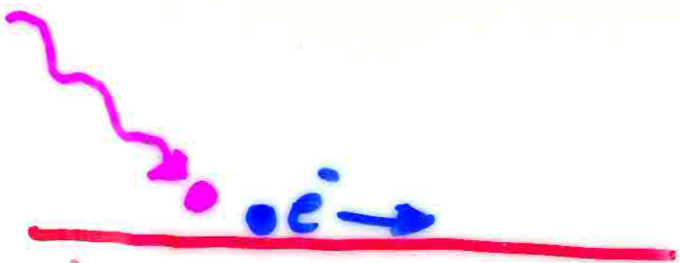
Microscopic Weirdness

Light as Wave:





BUT LIGHT ALSO ACTS LIKE PARTICLES – PHOTOELECTRIC EFFECT



METAL
(LIGHT-SENSITIVE)

LIGHT EJECTS ELECTRONS
⇒ ELECTRICITY

IF LIGHT = WAVES
INCREASING BRIGHTNESS
⇒ MORE ENERGY
⇒ ELECTRON MOVING FASTER

INSTEAD: SPEED NOT CHANGE

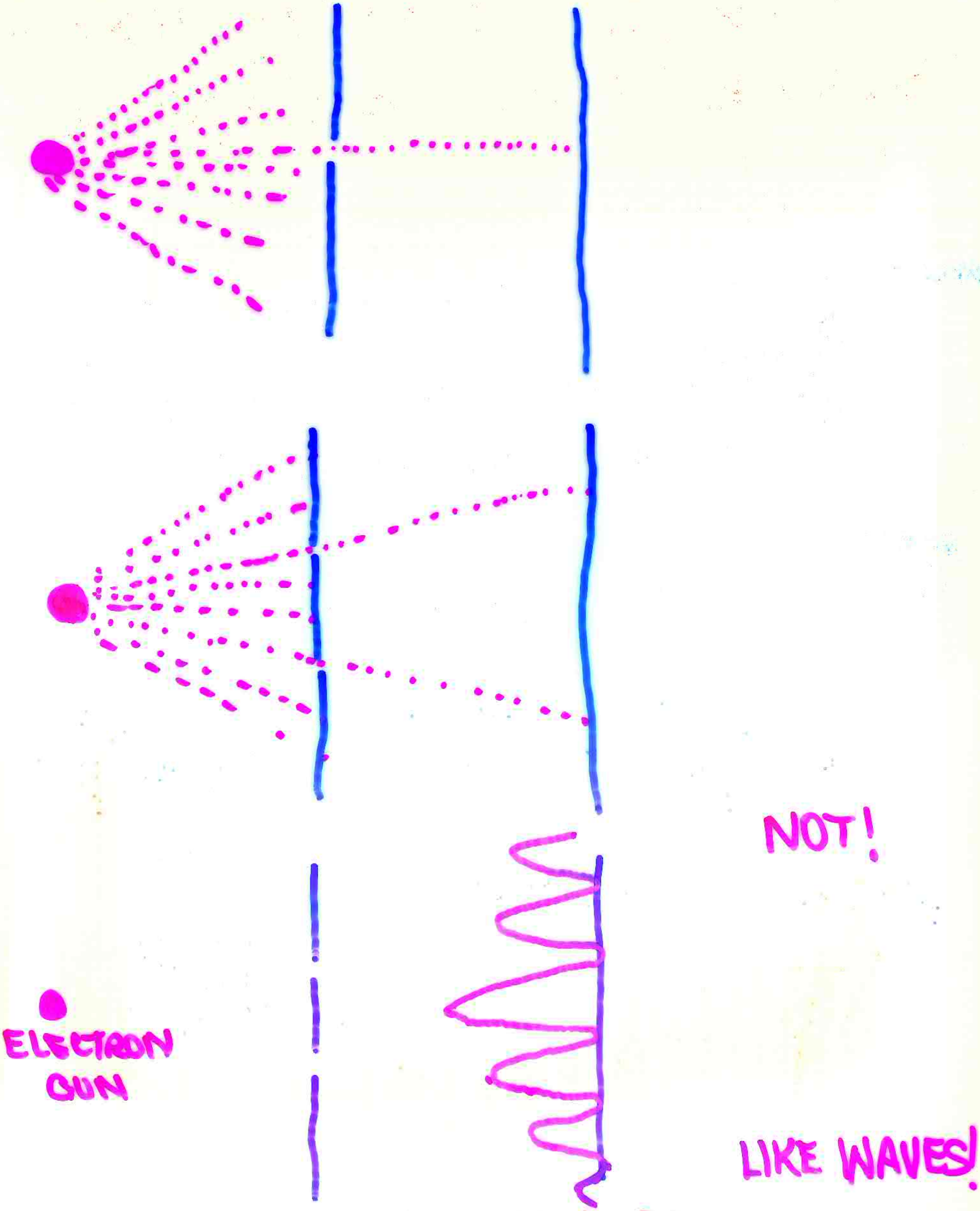
BUT MORE ELECTRONS EJECTED.

SPEED CHANGES IF FREQUENCY / WAVELENGTH CHANGED:

$$E_\gamma = h\nu = \frac{hc}{\lambda}$$

LIGHT ACTS LIKE STREAM OF PARTICLES WITH ENERGY E_γ. IF $E_\gamma >$ THRESHOLD, ELECTRON IS EJECTED. 1 PHOTON → 1 ELECTRON

WHAT ABOUT MATTER?



* TRUE EVEN IF ONE ELECTRON

WHAT IS WAVELENGTH OF MATTER?

$$E = m_e c^2 \qquad m_e = \frac{m_{eo}}{\sqrt{1 - \frac{v^2}{c^2}}}$$

RECALL: $E = \frac{hc}{\lambda}$

$$\lambda = \frac{hc}{(m_e c^2)} = \frac{h}{m_e c} \qquad \lambda_c \equiv \frac{h}{m_{eo} c}$$

<u>WAVE</u>-PARTICLE DUALITY [COMPLEMENTARITY]

IF SCALE OF MEASUREMENT $> \lambda$

$\Rightarrow$ RESULTS EQUIV TO PARTICLE

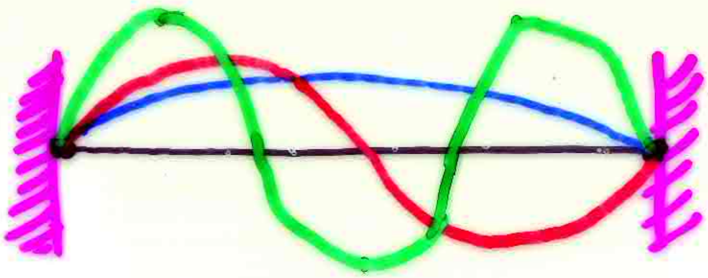
WHEN SCALE IS COMPARABLE OR LESS,

$\Rightarrow$ WAVE

UNCERTAINTY: <u>OBS</u> DISTORTS/CHANGES

$$\left.\begin{array}{l}\Delta X \text{ OR } \Delta V \\ \Delta E \text{ OR } \Delta t\end{array}\right\} \text{QUANTUM TUNNELING.}$$

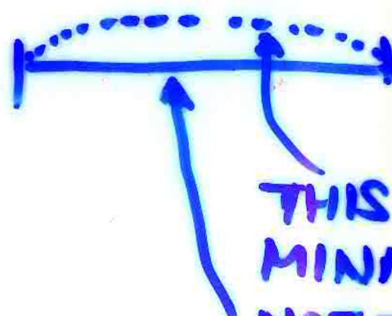
BOX OF VACUUM WITH WAVES:



SKIPPING ROPE
WITH FIXED ENDS

ONLY CERTAIN
KINDS OF WAVES
$\Rightarrow$ DISCREET!

QUANTUM MECHANICS $\Rightarrow$



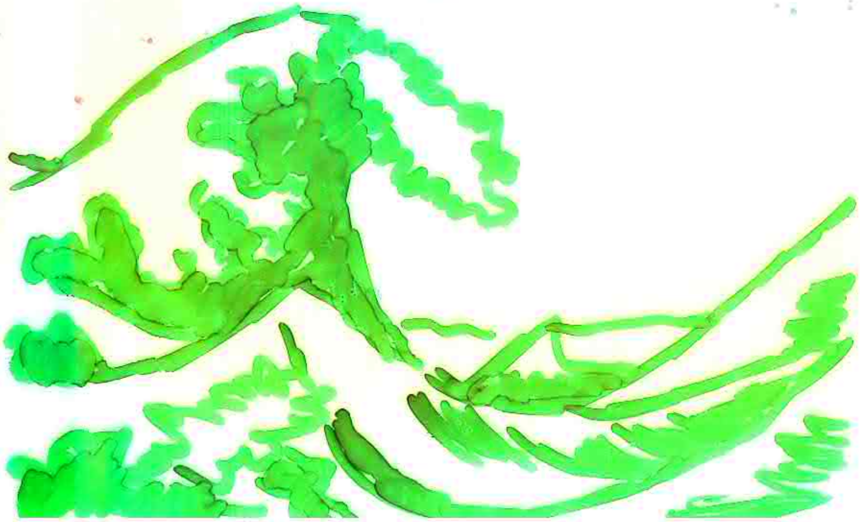
THIS IS
MINIMUM
NOT THIS

ZERO-PT ENERGY $\neq 0$

$$E = \frac{hc}{\lambda_0 +}$$

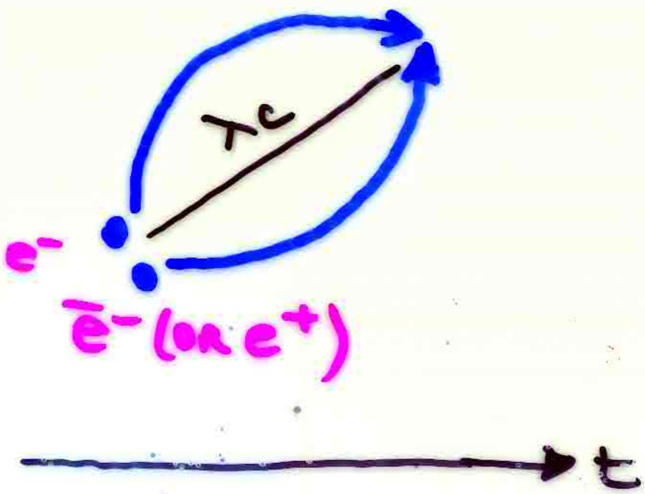
CONSEQUENCE OF UNCERTAINTY PRINCIPLE

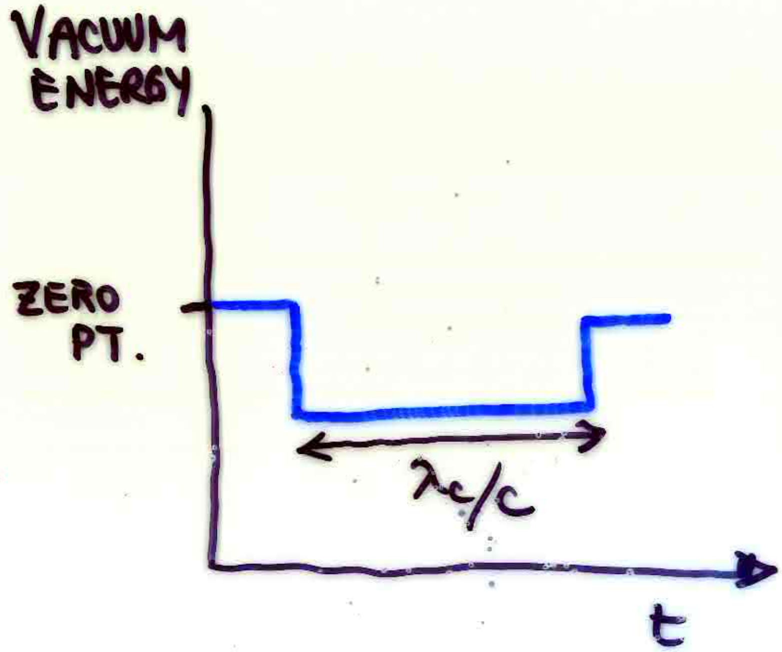
- AT ANY GIVE TIME, MINIMUM ENERGY IS NOT ZERO BUT FLUCTUATING.



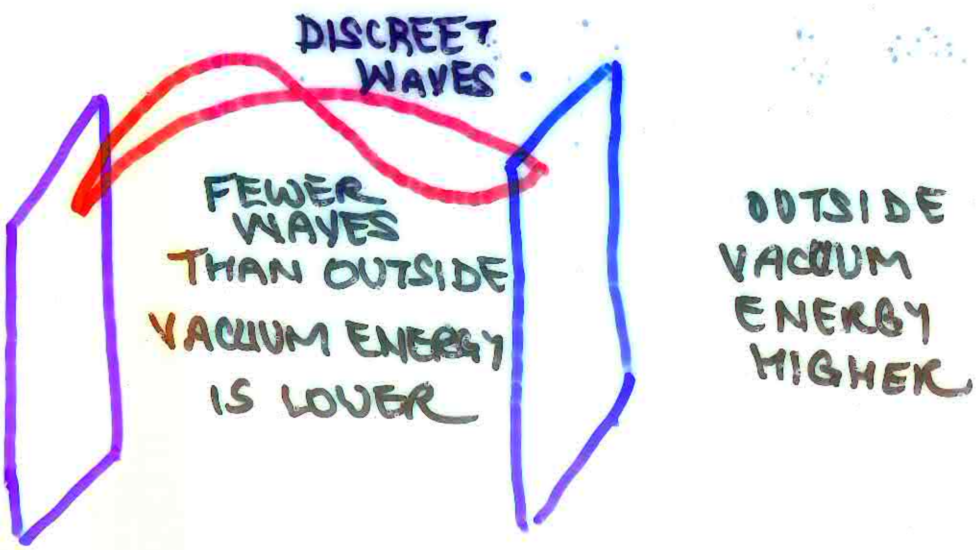
- THINK OF AN OCEAN SURFACE IN TURMOIL

WAVE CAPS FROTH
$\rightarrow$ DROPS SEPARATE
FALL BACK





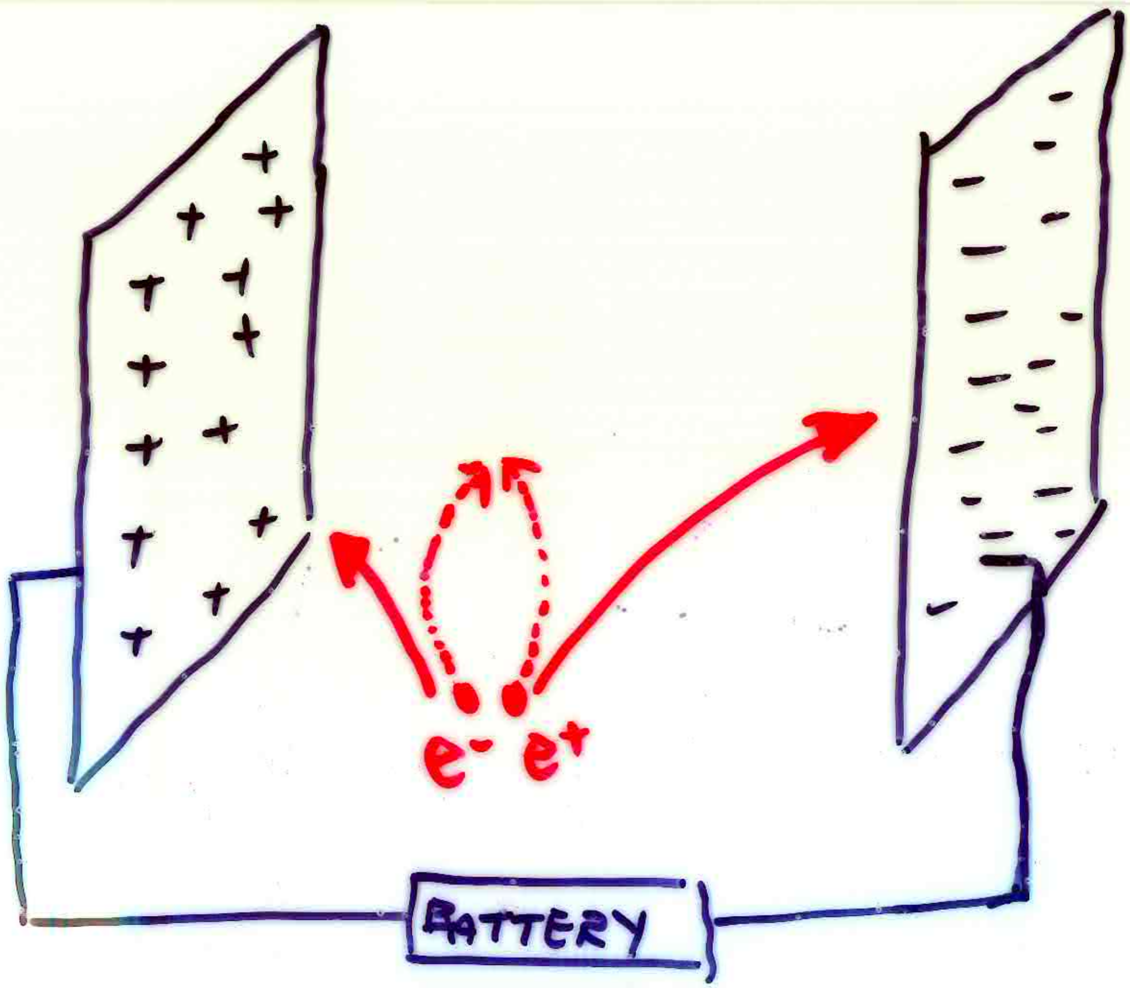
- VIRTUAL PARTICLES OF ALL TYPE FORMING (IN PAIRS) & ANNIHILATE
- ZERO PT. ENERGY FLUCTUATING.



PRESSURE PUSHES PLATES TOGETHER
↓
CASIMIR EFFECT.

METAL PLATES

CASIMIR EFFECT



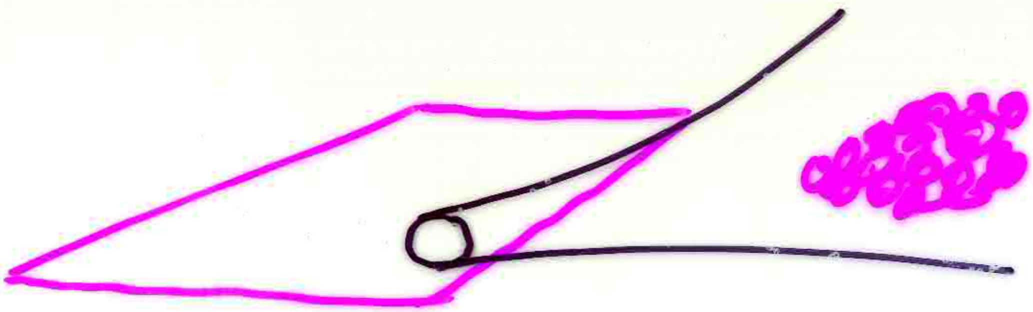
- IF PARTICLES LIVE LONGER THAN

$$\Delta t_c = \frac{\lambda_c}{c} \Rightarrow \text{MEASUREABLE!}$$

- PARTICLES & ANTI-PARTICLES SUDDENLY (SPONTANEOUS) APPEAR OUT OF NOWHERE

MASS → WORK → BATTERY

SPACETIME ITSELF, ON SMALLEST SCALES
IS DISCREET & FUZZY & FLUCTUATING



EINSTEIN'S THEORY CAN'T HANDLE THIS!

ORIGINAL QM WAS GALILEAN.
IF WE MAKE IT LORENTZ (SPECIAL RELATIVITY)

EQUATION DON'T JUST GIVE ONE
ANSWER BUT TWO, EACH SAME
YET DIFFERENT

→ ANTIMATTER!

SPECIAL RELATIVITY + QM :

⇒ PHOTON IS SMALLEST BUNDLE OF EM ENERGY !

⇒ ELECTROMAGNETIC INTERACTIONS IS EXCHANGE OF REAL/VIRTUAL PHOTONS.

EXPANDING ON WORK RELATED TO EM

- DISCOVERED THAT WEAK FORCE IS SIMILAR TO EM YET DIFFERENT

- BUT AT HIGH ENERGY, WEAK & EM ARE INDISTINGUISHABLE.
    - WATER CRYSTALIZE WHEN TEMP ↓

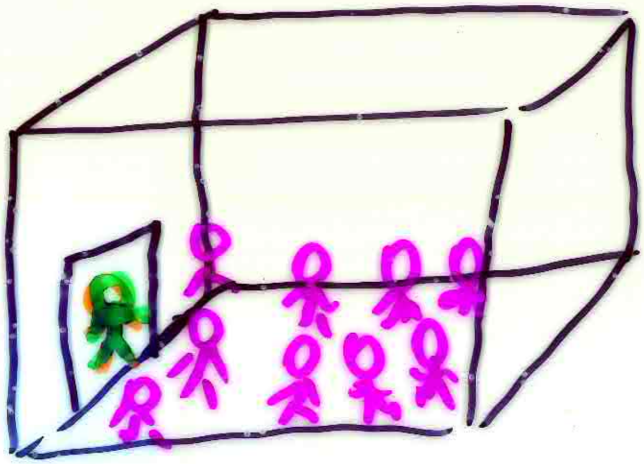
- MESSENGERS OF EM : PHOTONS
- MESSENGERS OF WEAK : W, Z BOSONS
  [3 W^+, W^-, Z^0]

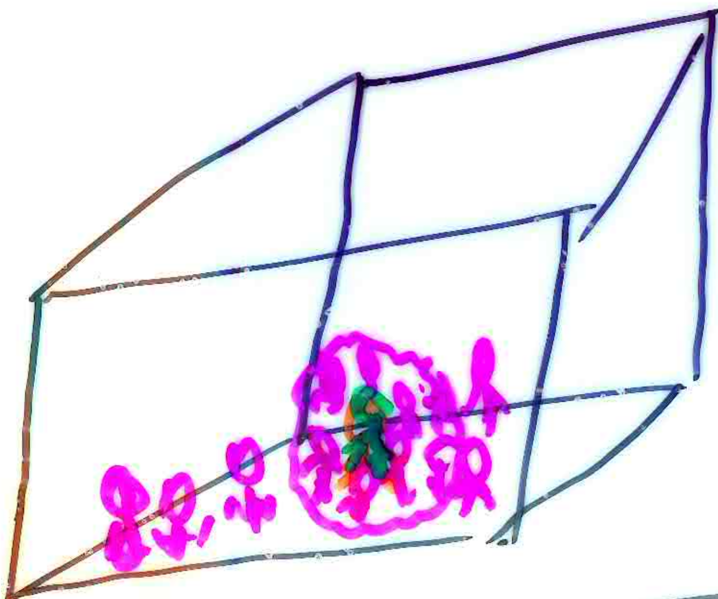
- AT HIGH T, ALL MASSLESS, NEUTRAL
  IE ONLY ONE CARRIER

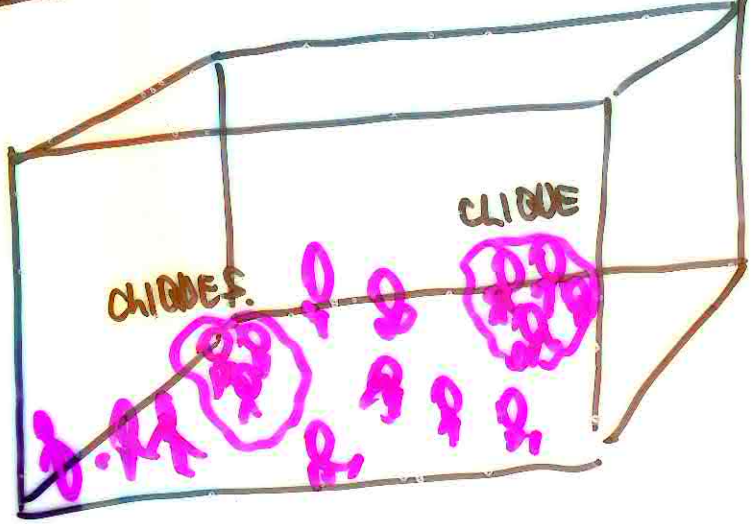
- AT LOW T : 1 MASSLESS NEUTRAL → PHOTON
  3 MASSIVE [CHARGED] → W, Z

HOW DID MASS COME ABOUT?

HIGGS FIELD

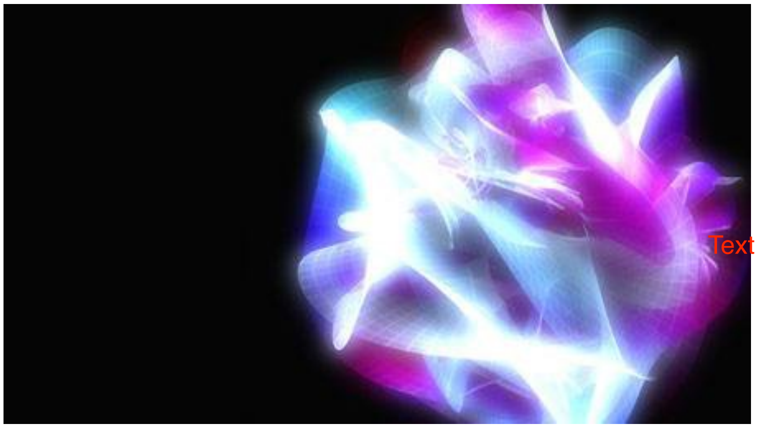






https://www.pbs.org/wgbh/nova/series/the-elegant-universe/

WATCH THE THREE EPISODES AT THIS WEBSITE OVER READING BREAK



Text

SHARE TOPIC: PHYSICS + MATH

The Elegant Universe

THE ELEGANT UNIVERSE

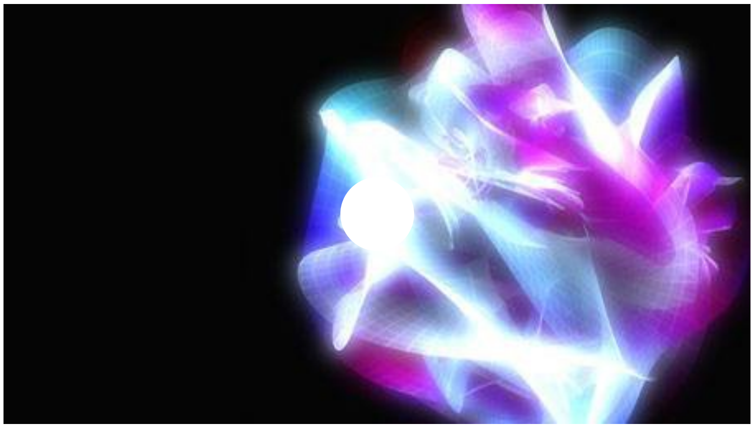
Eleven dimensions, parallel universes, and a world made out of strings. It's not science fiction, it's string theory.

One of the most ambitious and exciting theories ever proposed—one that may be the long-sought "theory of everything," which eluded even Einstein—gets a masterful, lavishly computer-animated explanation from bestselling author-physicist Brian Greene, when NOVA presents the nuts, bolts, and sometimes outright nuttiness of string theory.

Also known as superstring theory, the startling idea proposes that the fundamental ingredients of nature are inconceivably tiny strings of energy, whose different modes of vibration underlie everything that happens in the universe. The theory successfully unites the laws of the large—general relativity—and the laws of the small—quantum mechanics—breaking a conceptual logjam that has frustrated the world's smartest scientists for nearly a century.

EPISODES

ALL EPISODES >



PREMIERED OCTOBER 28, 2003 AT 6PM ON PBS

The Elegant Universe: Pt 1

Einstein's Dream: Combining the laws of the universe in one theory that explains it all is the Holy Grail of physics.

PREMIERED OCTOBER 28, 2003 AT 7PM ON PBS

The Elegant Universe: Pt 2

String's the Thing: Do miniscule vibrating strands of energy hold the key to a unified theory of physics?

Explore More

ALL EXTRAS >

SKIP THE COMPLICATED SLIDES

What Is String Theory?

An Introduction for Data Scientists

Tom Rudelius
IAS

String Data 2017

Financial Support: Carl Feinberg

Illustration Credit: Aliisa Lee Bocarsly

Outline

I. Illustrated Introduction to String Theory

II. The String Landscape and the Swampland

III. String Theory and Big Data

Illustrated Introduction to String Theory

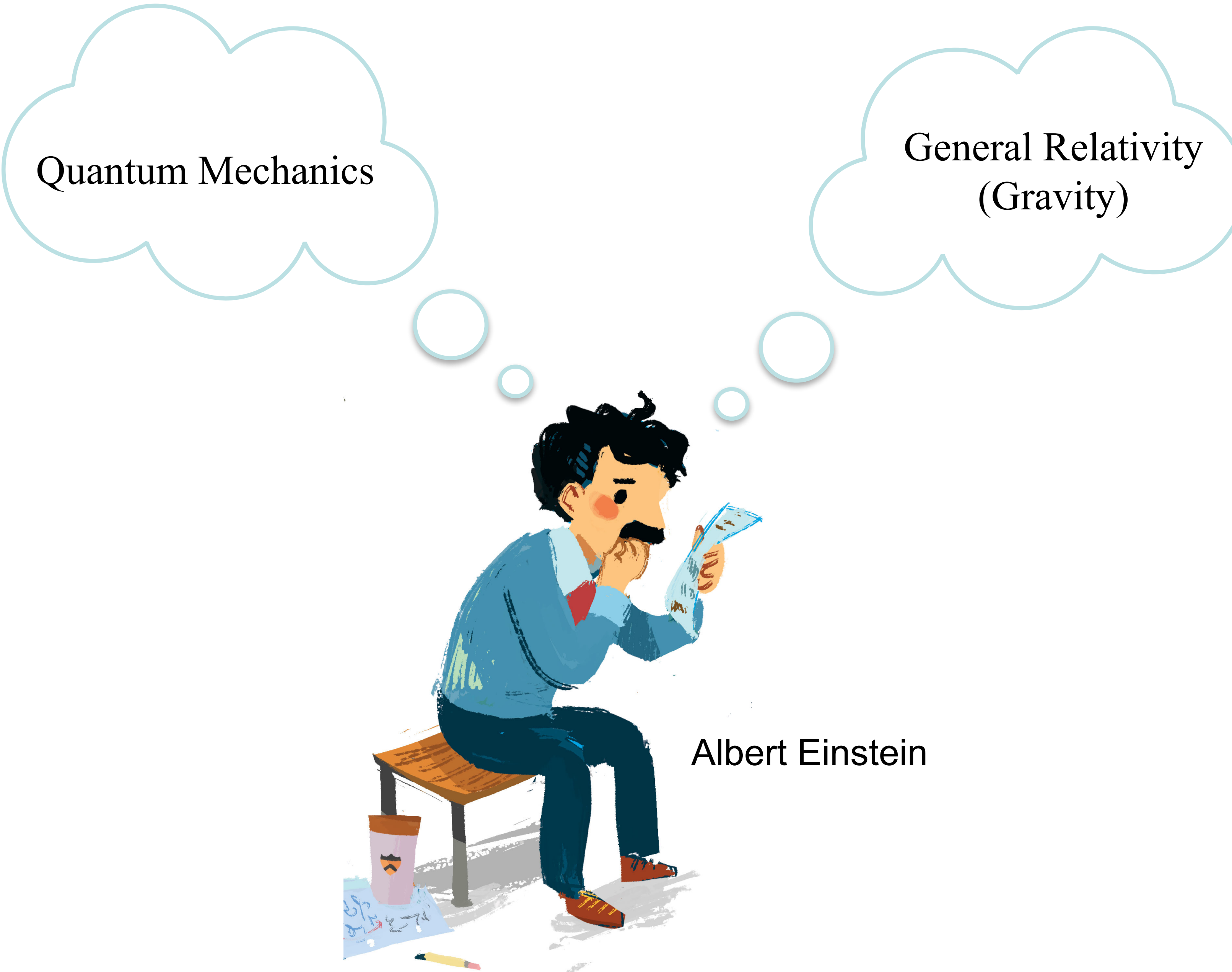
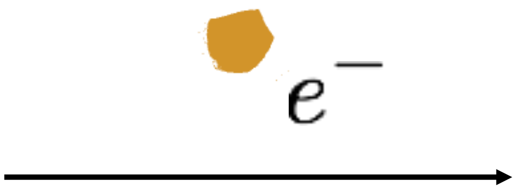


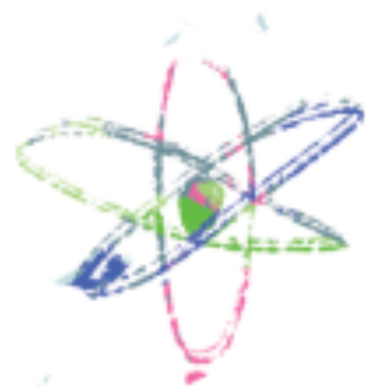
Illustration Credit: Aliisa Lee Bocarsly

Quantum Mechanics: Theory of "Small Things"



Electrons

Positrons

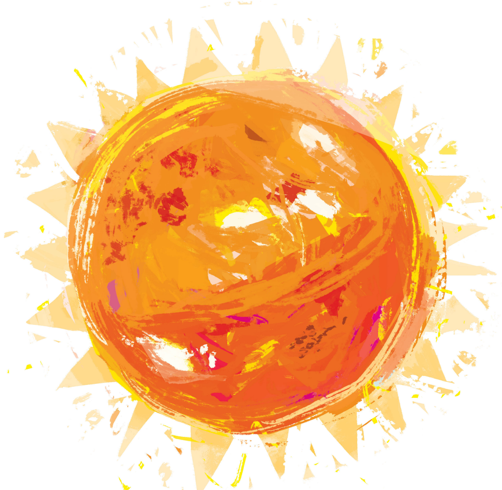


Atoms

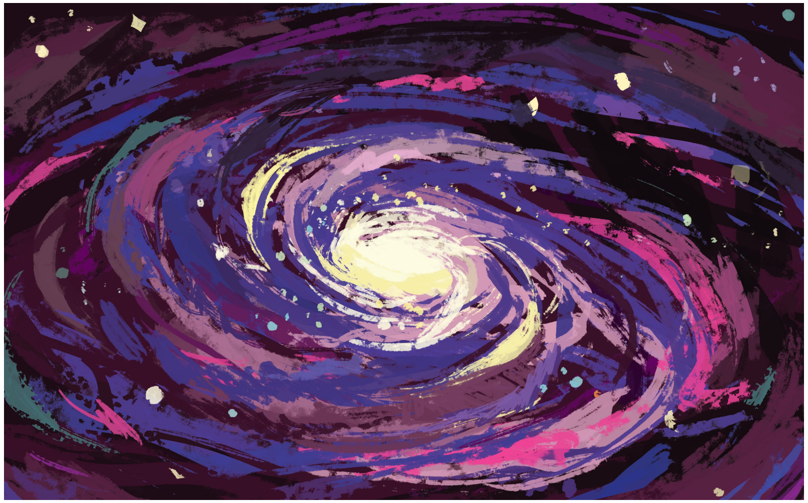
Illustration Credit: Aliisa Lee Bocarsly

General Relativity: Theory of "Heavy Things"

Planets



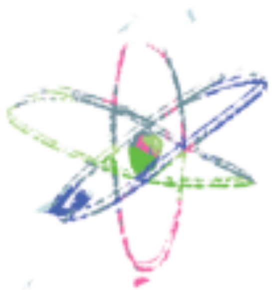
Stars



Galaxies

Illustration Credit: Aliisa Lee Bocarsly

What About “Small” *and* “Heavy” Things?



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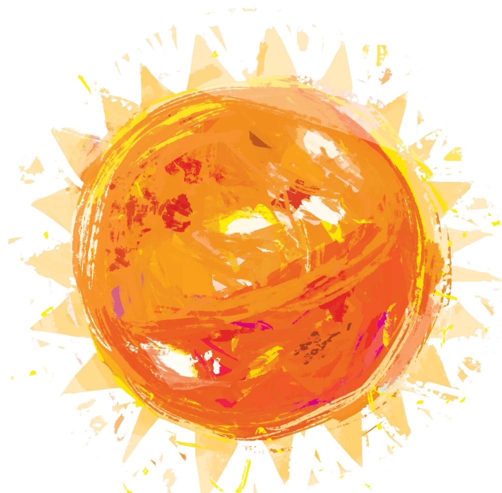


=

?

Quantum Mechanics

General Relativity
(Gravity)

Illustration Credit: Aliisa Lee Bocarsly

What About “Small” *and* “Energetic” Things?

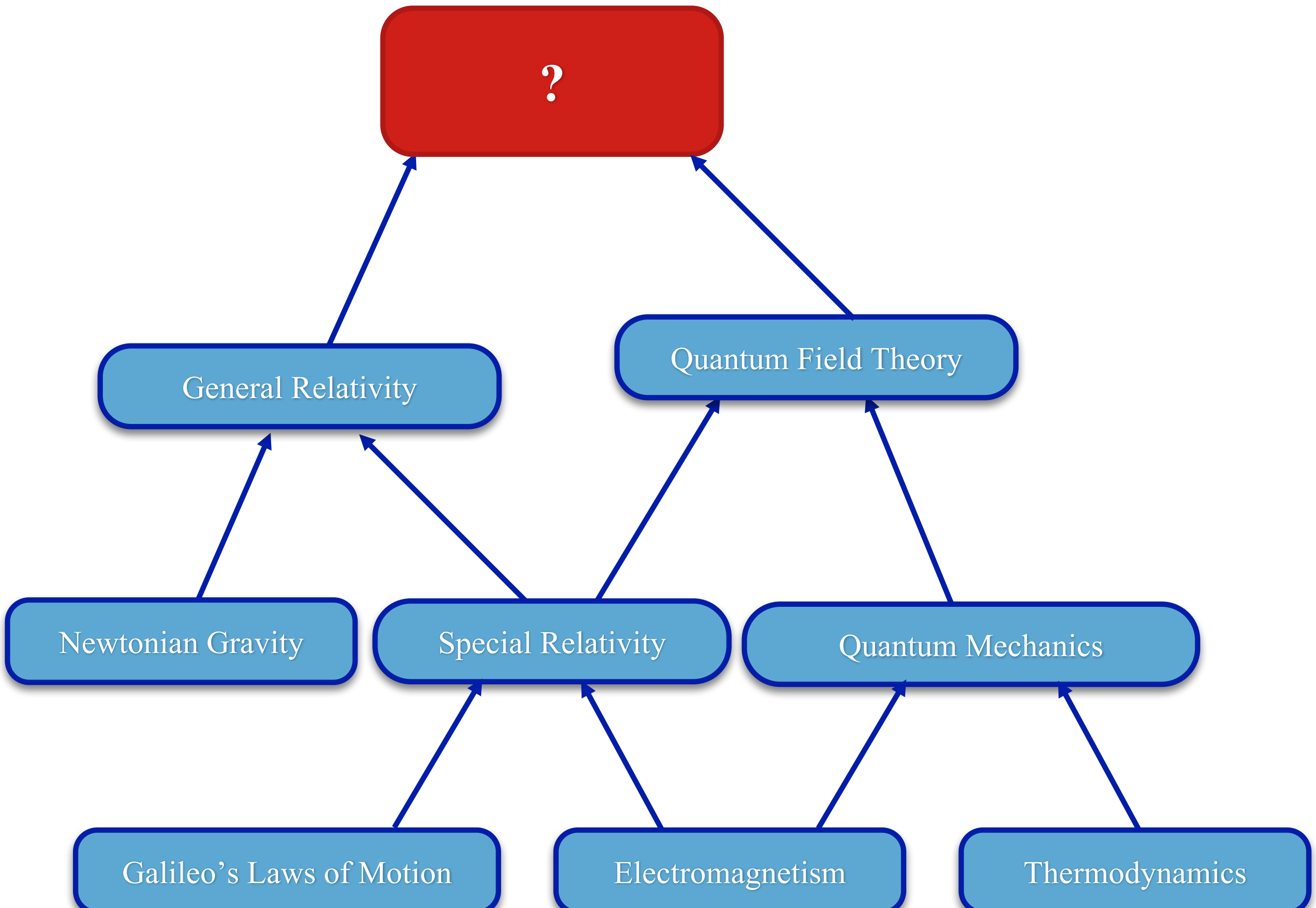
$$E = mc^2 \quad \Longrightarrow$$ “Heavy” = “Energetic”

Illustration Credit: Aliisa Lee Bocarsly

Answer: We Don’t Know!

Illustration Credit: Aliisa Lee Bocarsly

Incompatibility of QM and GR

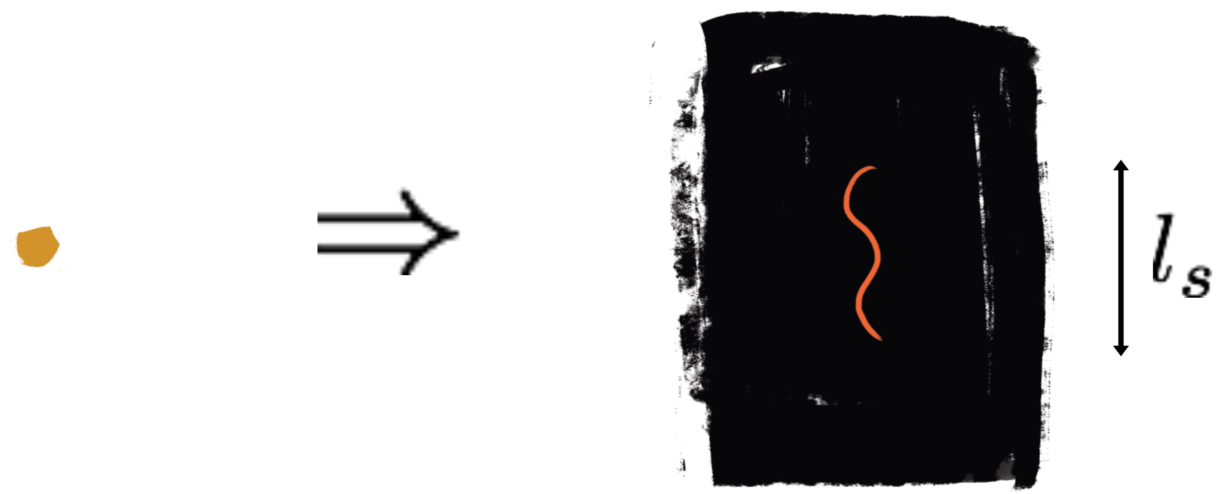


Slide Credit: Andy Strominger Strings 2015

Illustration Credit: Aliisa Lee Bocarsly

Illustration Credit: Aliisa Lee Bocarsly

Solution: String Theory



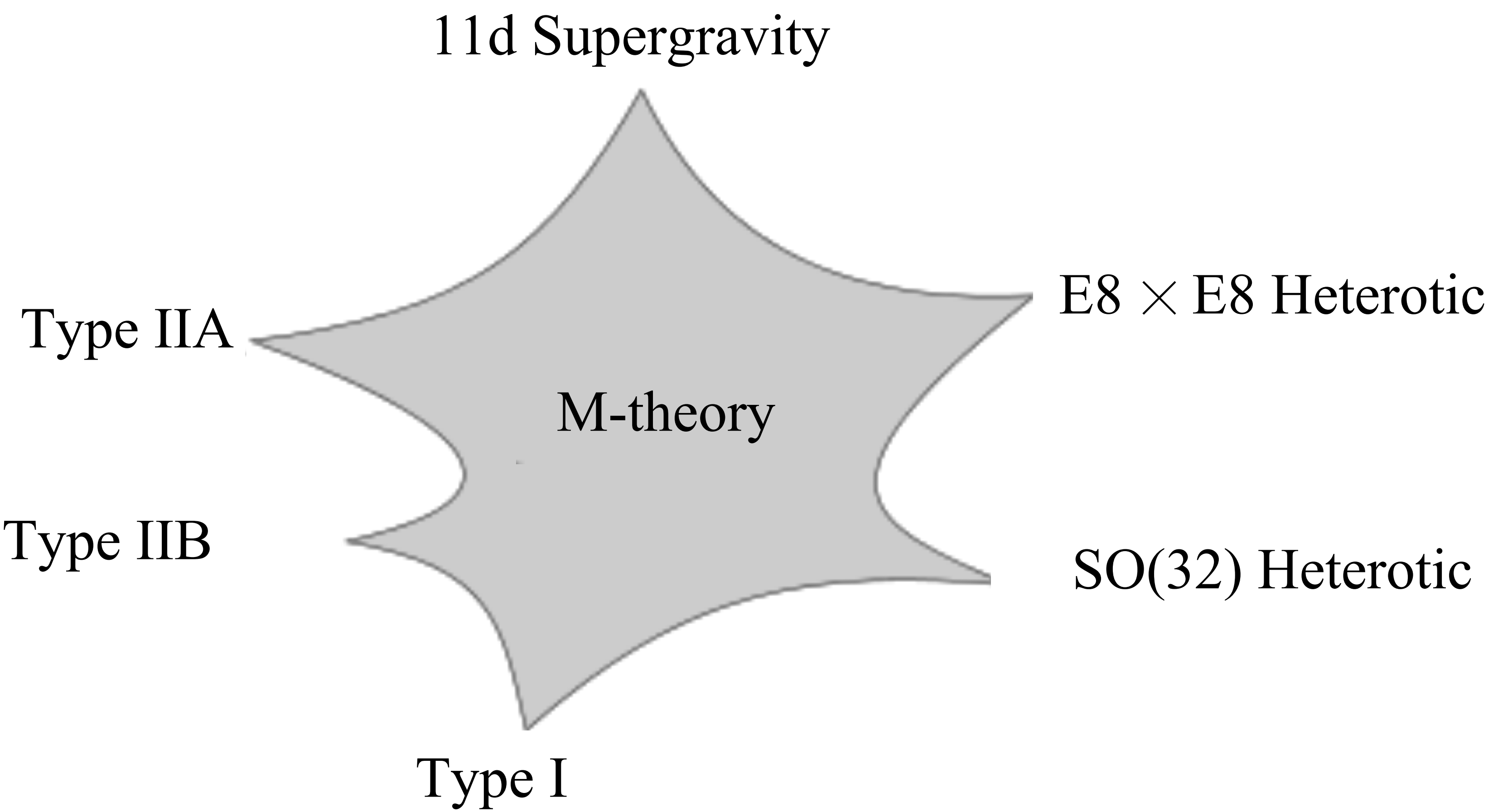
Particle

String

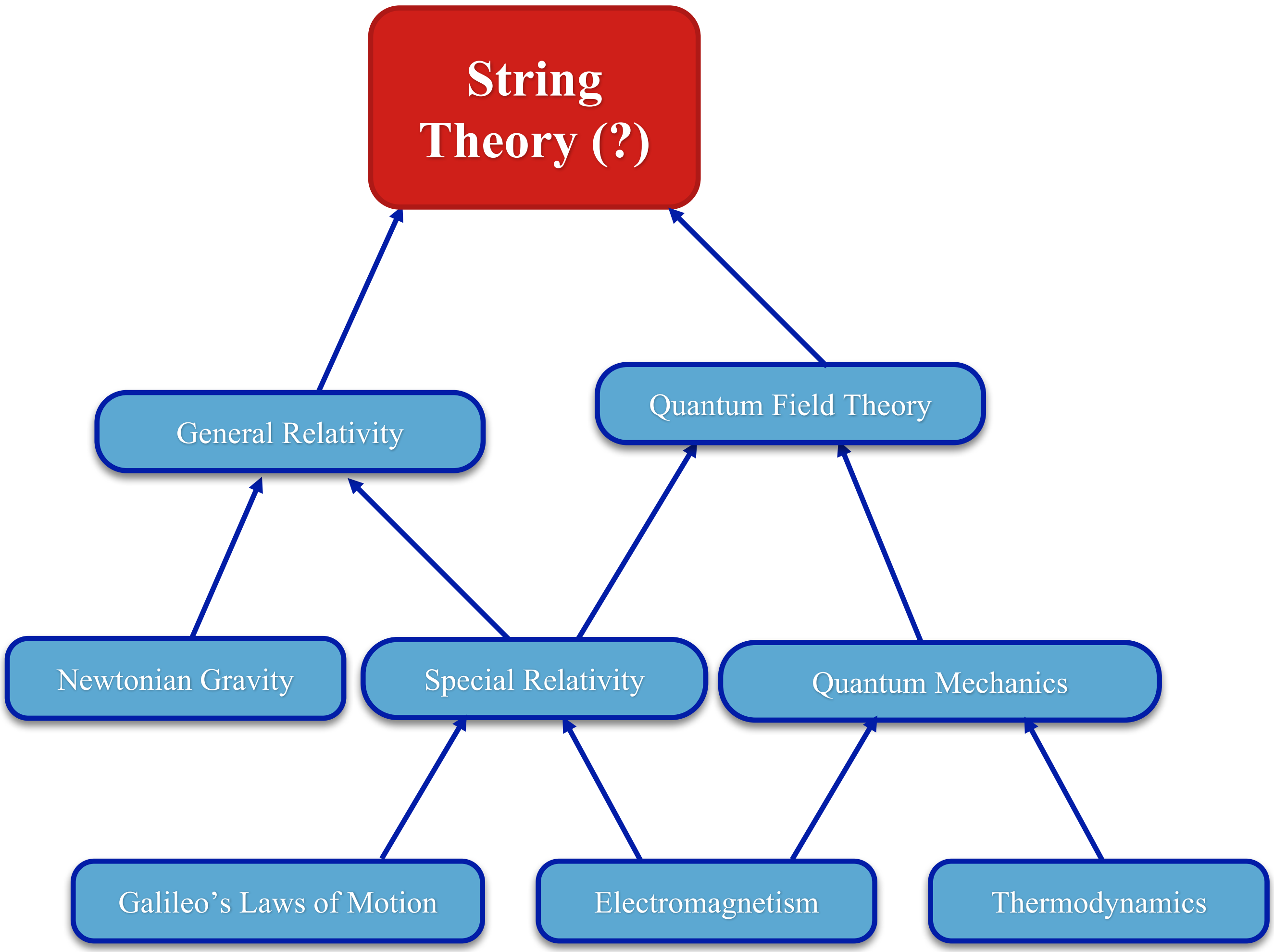
Illustration Credit: Aliisa Lee Bocarsly

The String Duality Web

Witten '95



Incompatibility of QM and GR



Slide Credit: Andy Strominger Strings 2015

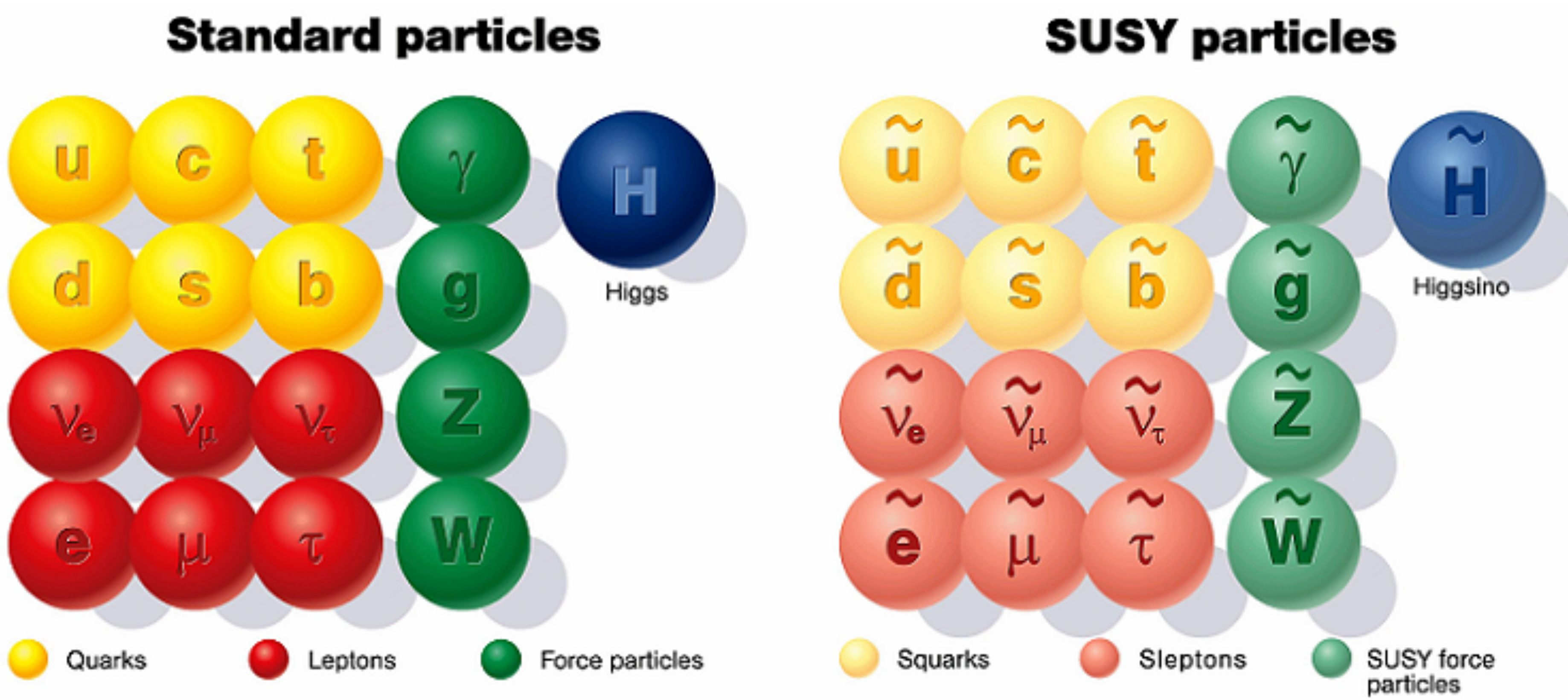
String Theory is the only known mathematically-consistent quantum theory of gravity

(a.k.a. theory of “quantum gravity”)

Bizarre Postulates of String Theory

- Nature is supersymmetric
- The world has nine (or ten or eleven) dimensions of space, not three, plus one dimension of time
- The fundamental degrees of freedom are "extended objects" like strings, not just particles

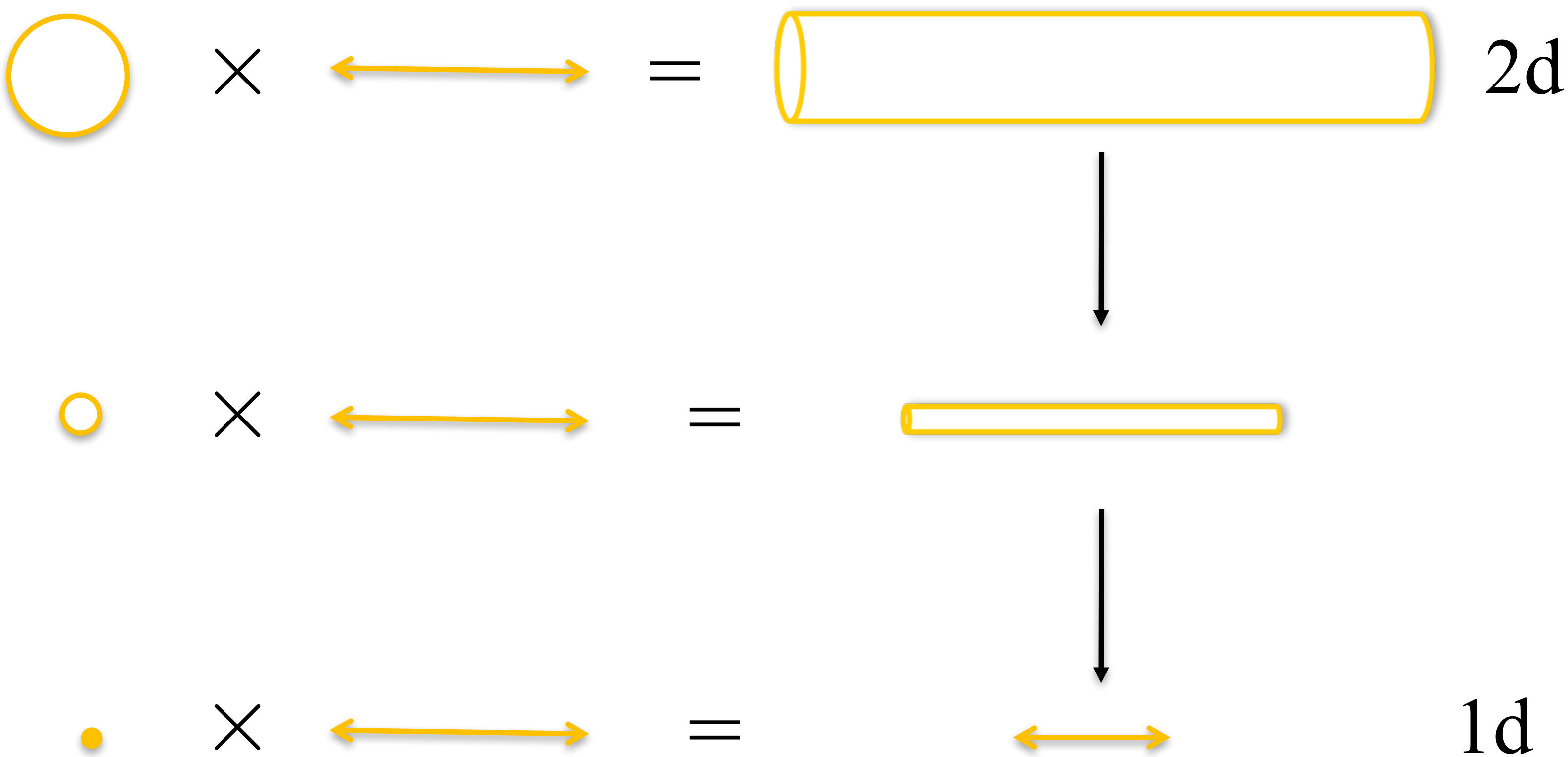
Supersymmetry (SUSY)



$\cancel{\text{SUSY}}$

Slide Credit: University of Glasgow Physics

Extra Dimensions



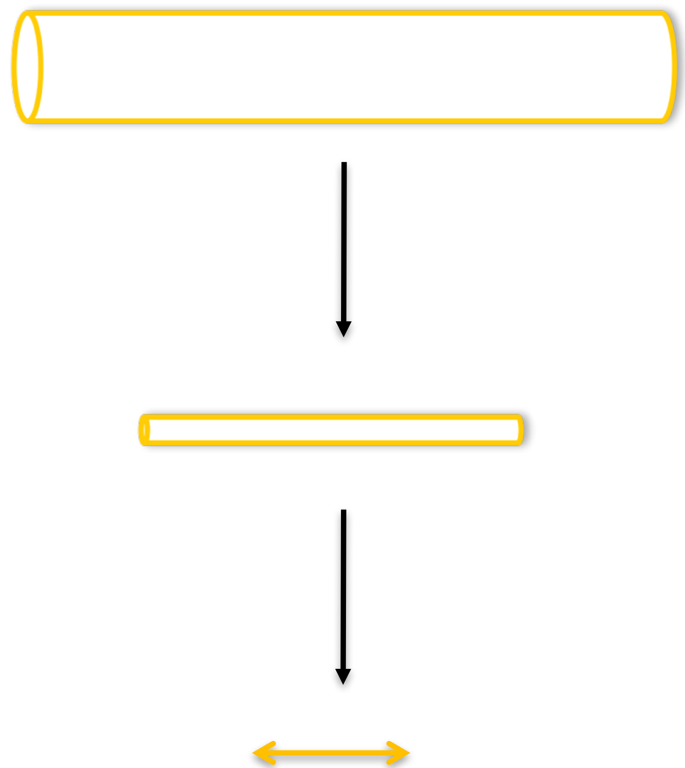
At long distances (low energies), the circular dimension of a cylinder disappears

Extra Dimensions

In 10d type I/type II/heterotic string theory, 6 dimensions are “compactified”

In 11d M-theory, 7 dimensions are compactified

In 12d F-theory, 8 dimensions are compactified

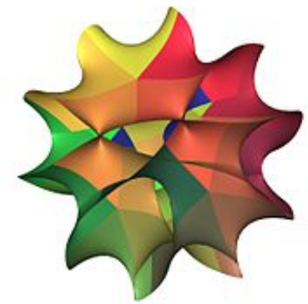


10d/11d/12d

4d

Compactification Constraints*

Compactification manifold $\mathcal{M}$:

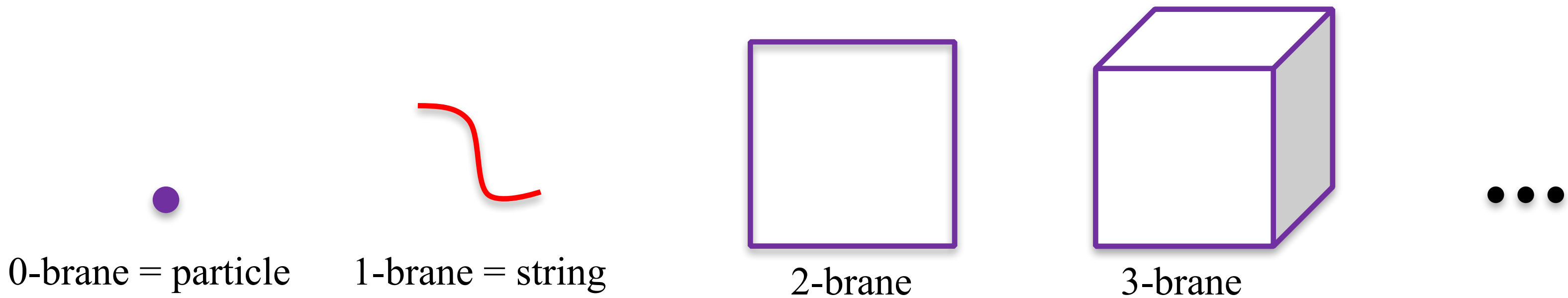


4d supersymmetry $\Longrightarrow$ $\mathcal{M}$ must be complex, "Kahler" and "Ricci-flat"

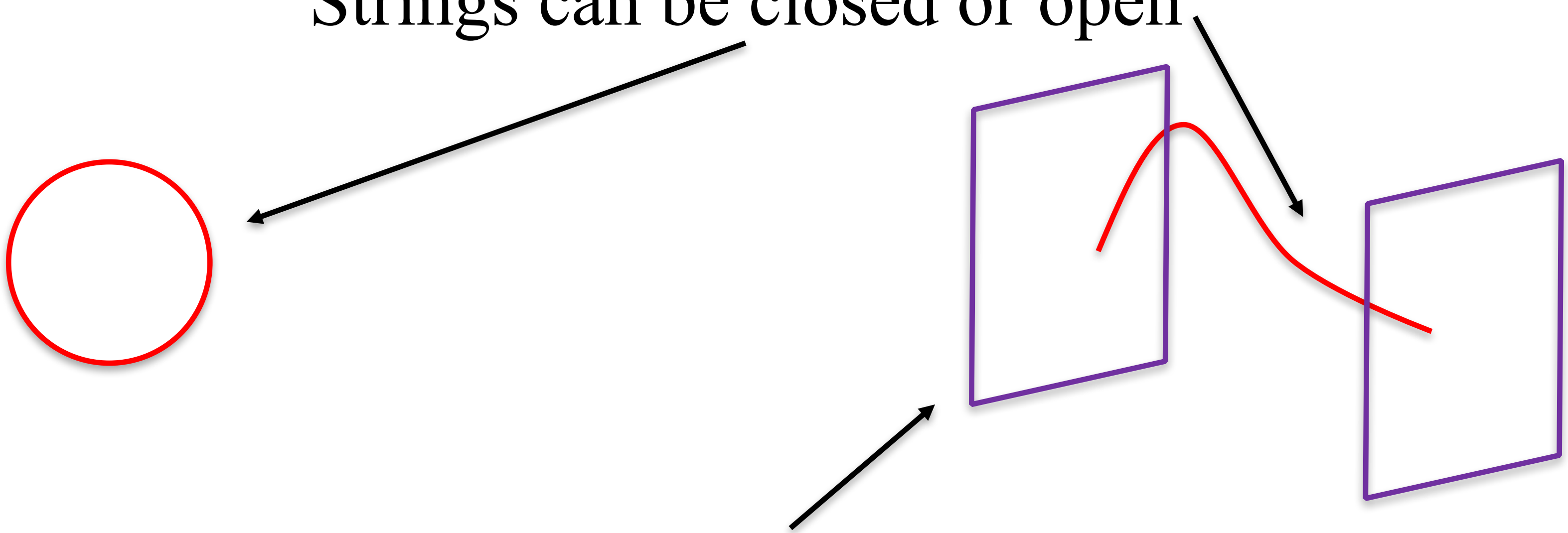
$\Longleftrightarrow$ $\mathcal{M}$ must be a "Calabi-Yau manifold"

*Here and henceforth, we are ignoring the case of 11d M-theory

Branes



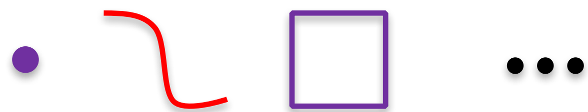
Strings can be closed or open



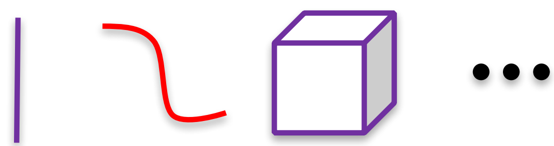
Open strings end on “D-branes”

Branes in IIA/IIB

IIA Branes: D0 F1 D2 D4 NS5 D6 D8



IIB Branes: D(-1) D1 F1 D3 D5 NS5 D7 D9



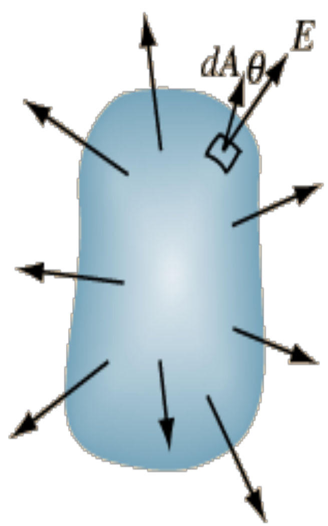
Fluxes

Gauss's Law:

$$\oint_S *F_2 = \oint_S \vec{E} \cdot d\vec{A} = \frac{Q}{\varepsilon_0}$$

Electric Flux through surface

Charge enclosed by surface



Fluxes in IIA/IIB

$$\text{IIA Fluxes: } F_0, F_2, H_3, F_4, F_6$$

$$\text{IIB Fluxes: } F_1, H_3, F_3, F_5$$

Fluxes thread "cycles" C_i of appropriate dimensionality i:

$$\oint_{C_i} F_i \,, \quad \oint_{C_{10-i}} *F_i$$

The Scientific Method

- Find some gap in present knowledge
- Develop a hypothesis that explains that gap
- Test this hypothesis with experiment and observation

Physics Across Distance/Energy

Illustration Credit: Aliisa Lee Bocarsly

Effective Field Theories

- Consider a theory with "Lagrangian":

$$\mathcal{L} = -(\partial\phi)^2 - \underbrace{m^2\phi^2 - \lambda_3\Lambda\phi^3}_{\text{Relevant}} - \underbrace{\lambda_4\phi^4}_{\text{Marginal}} - \underbrace{\sum_{i=5}^{\infty} \lambda_i \frac{\phi^i}{\Lambda^{i-4}}}_{\text{Irrelevant}}$$

- At low energies ($\phi \ll \Lambda$), can neglect "irrelevant" terms in sum
- The result is an "effective theory" with Lagrangian:

$$\mathcal{L} = -(\partial\phi)^2 - m^2\phi^2 - \lambda_3\Lambda\phi^3 - \lambda_4\phi^4$$

The Standard Model

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) \\
& +(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.}) \\
& -\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right] \\
& +(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.}) \\
& -\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix}\right] \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right] \\
& +\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.
\end{aligned}
$$

The standard model is an "effective theory" that arises at low energies/long distances from an underlying quantum theory of gravity (e.g. string theory)

Does String Theory imply the standard model of particle physics?

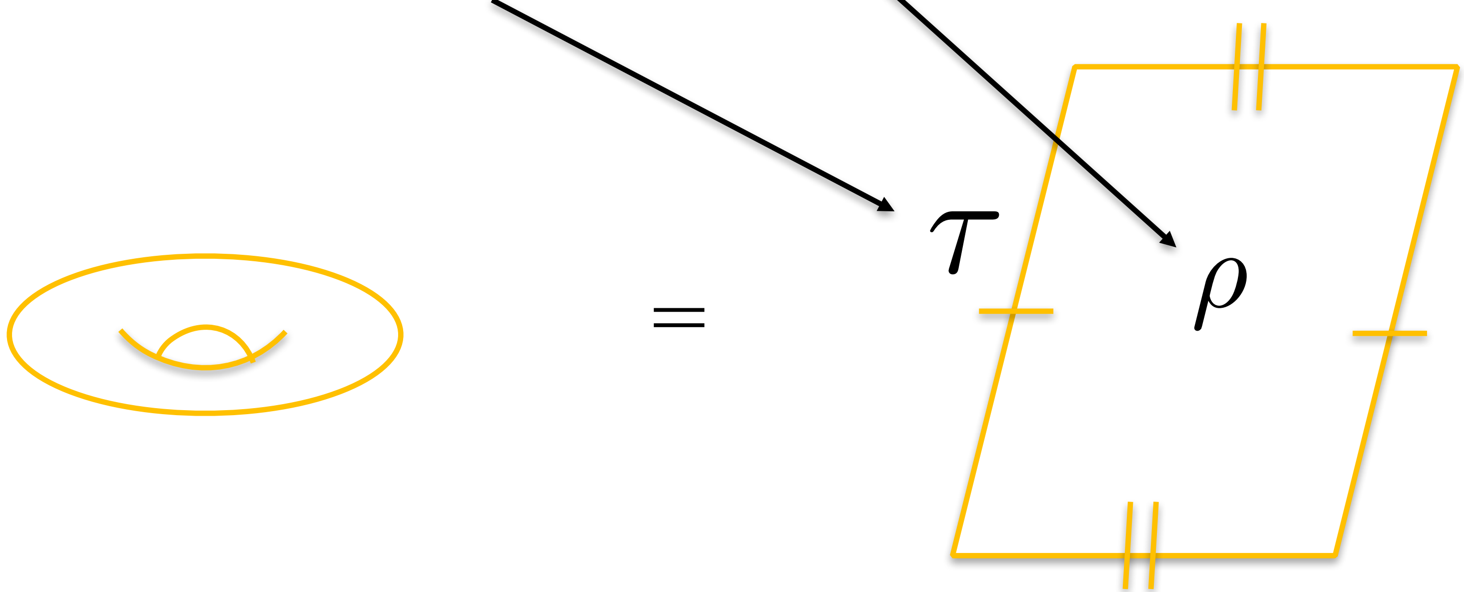
No!

String Theory supports a vast “landscape” of possible effective theories
(standard model is just one of many)

The String Landscape and the Swampland

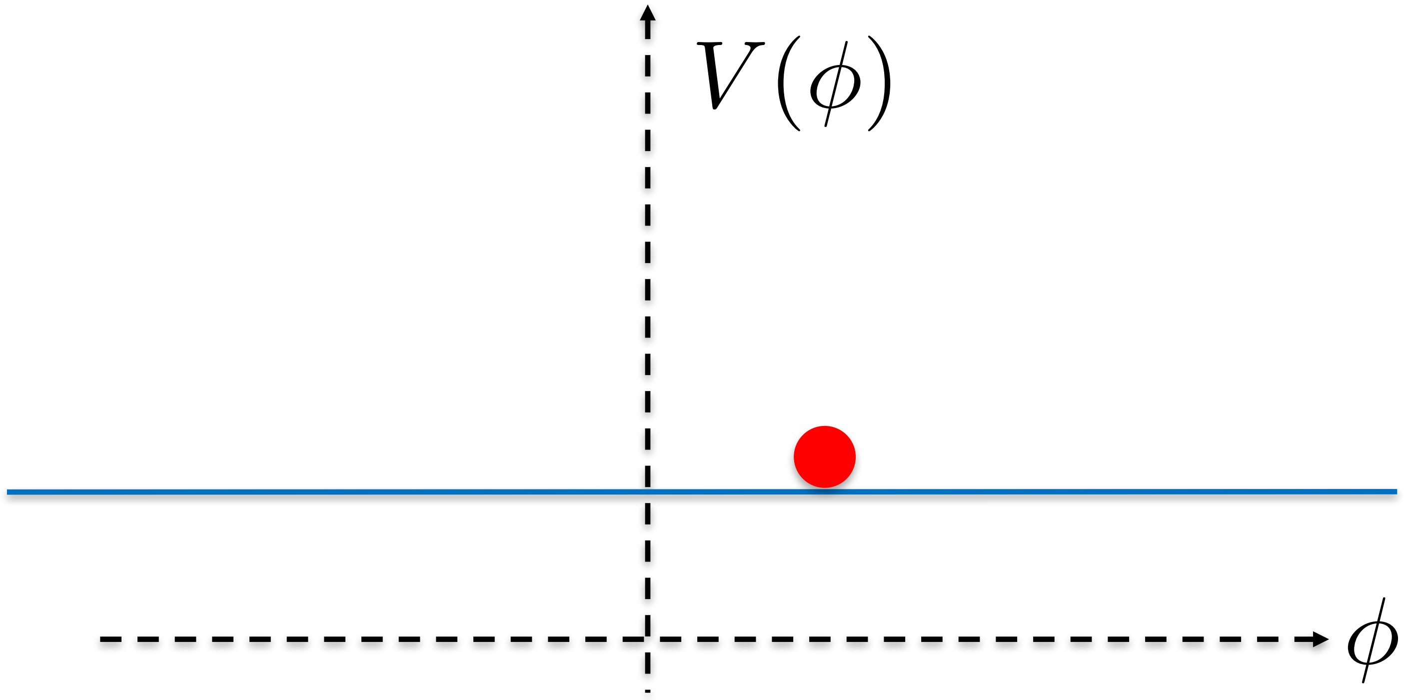
String Compactification

- Given Calabi-Yau compactification manifold $\mathcal{M}$, can deform $\mathcal{M}$ in two ways to get Calabi-Yau $\mathcal{M}'$:
  - "Kahler" deformations
  - "Complex structure" deformations



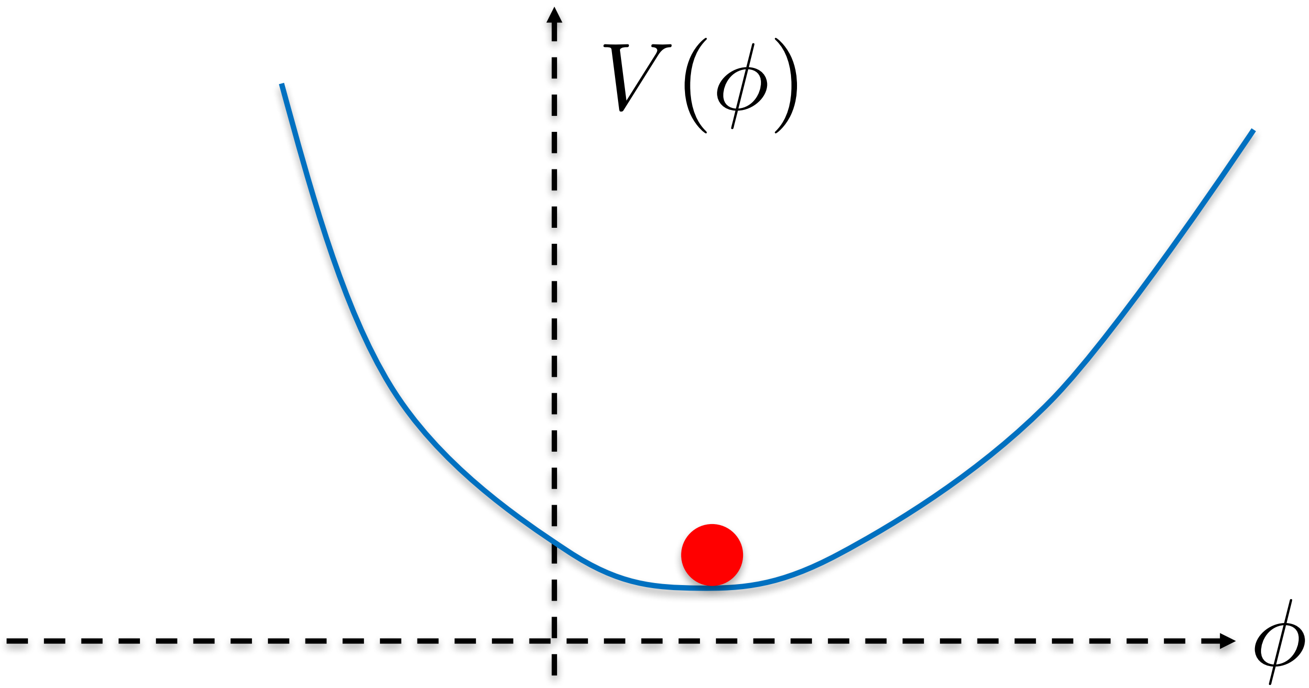
Moduli

- These deformations lead to massless fields called "moduli" in 4d



Moduli

- In practice, these moduli must be “stabilized” by fluxes and branes, making them massive

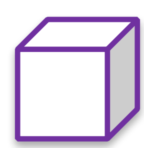


Building an "Effective Theory"

- Choose a string "duality frame" (e.g. IIB, heterotic, etc.)

- Choose a compactification geometry

- Choose an "ensemble of fluxes" threading cycles of this geometry, and a collection of branes to wrap these cycles



$$\oint_{C_i} F_i$$

The String Landscape

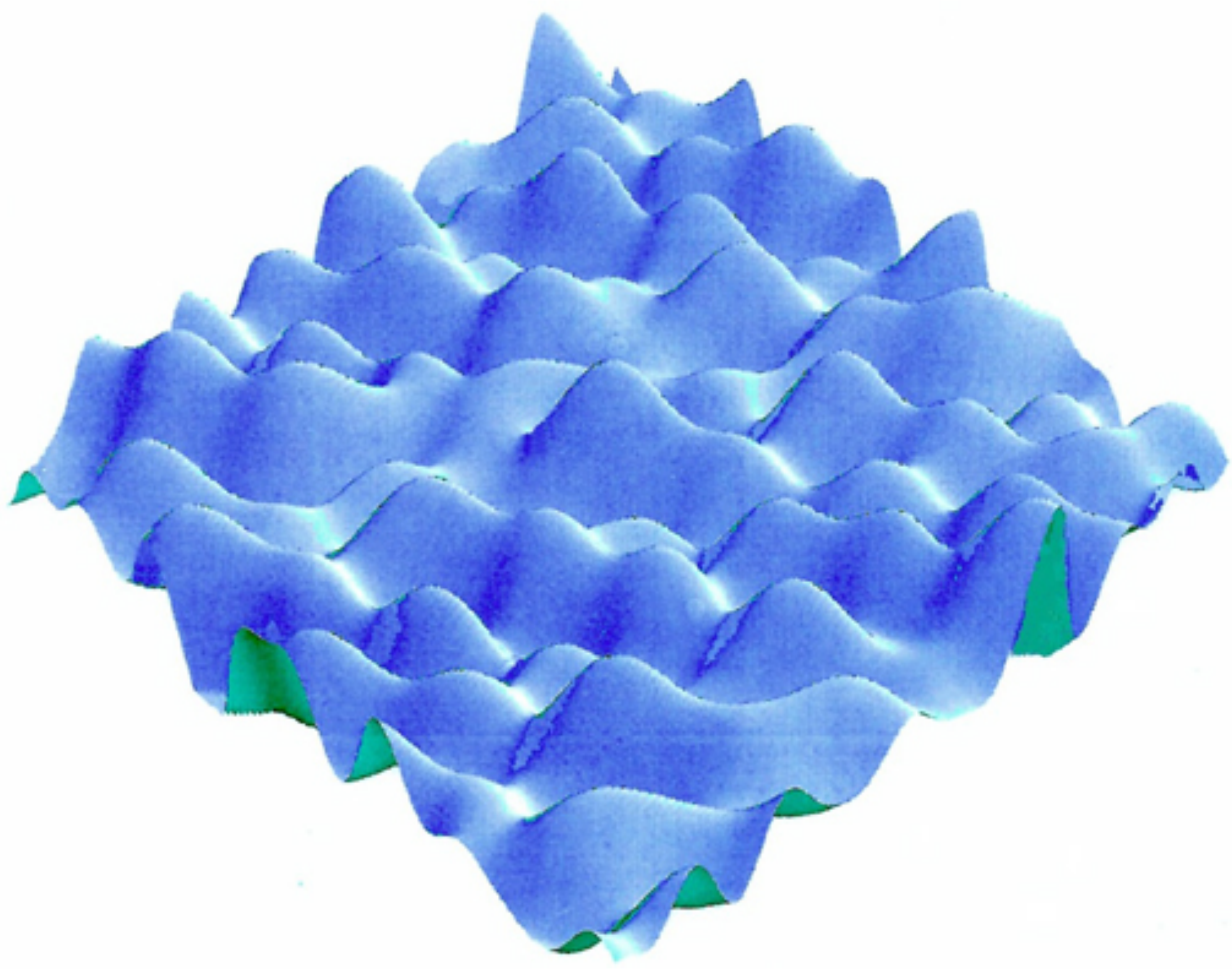


Image Credit: cosmology.com

How Many Effective Theories?

- Ashok, Douglas, Denef, ’04: 10^{500} estimated per geometry
- Taylor, Wang, ’15: $\leq 10^{272,000}$ estimated per geometry
- Halverson, Long, Sung, ‘17: $>10^{755}$ geometries estimated
- Taylor, Wang, ‘17: 10^{3000} geometries estimated
- HUGE NUMBER!!!

The Swampland

Vafa ’06, Ooguri, Vafa ‘06

- However, the string landscape is likely only a small part of an even larger “swampland” of effective theories that are not compatible with string theory

- For instance, effective theories with an infinite number of massless particles, particles with forces weaker than gravity are likely on the “swampland”


Swampland
Landscape

Goal of the Landscape/Swampland Program

- Determine universal features of effective theories on the landscape
- Determine universal features of effective theories on the swampland
- Devise an experiment that will distinguish between the two

String Theory and Big Data

String theory and Big Data

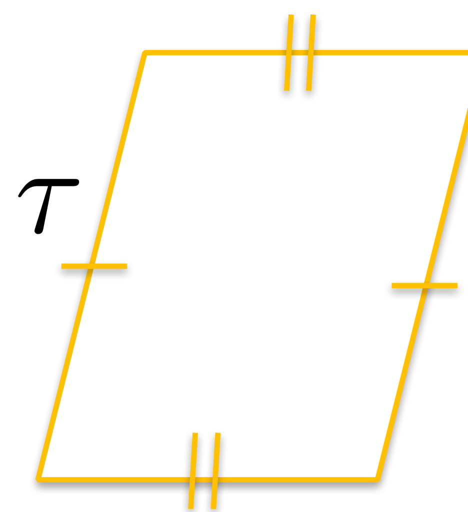
- Machine learning may help identify universal features of the string landscape
- This requires string theorists to express compactification data in terms of numerical data for mining
- F-theory is especially conducive to this task

What is F-theory?

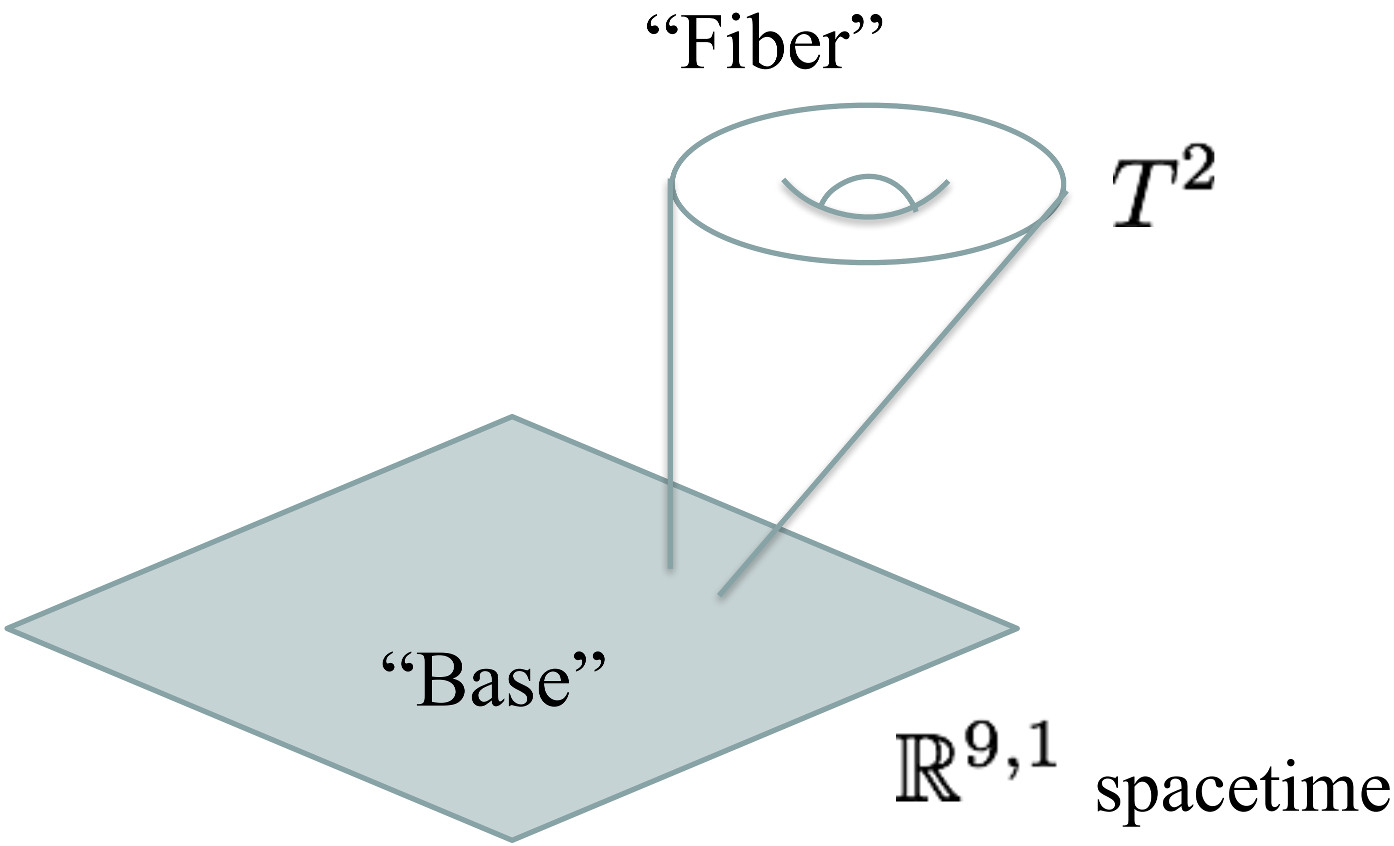
Vafa '96

- Type IIB string theory has 10 dimensions, and a "axiodilaton" τ , a complex scalar field

- In F-theory, this axiodilaton is viewed as the complex structure of a torus fibered over spacetime

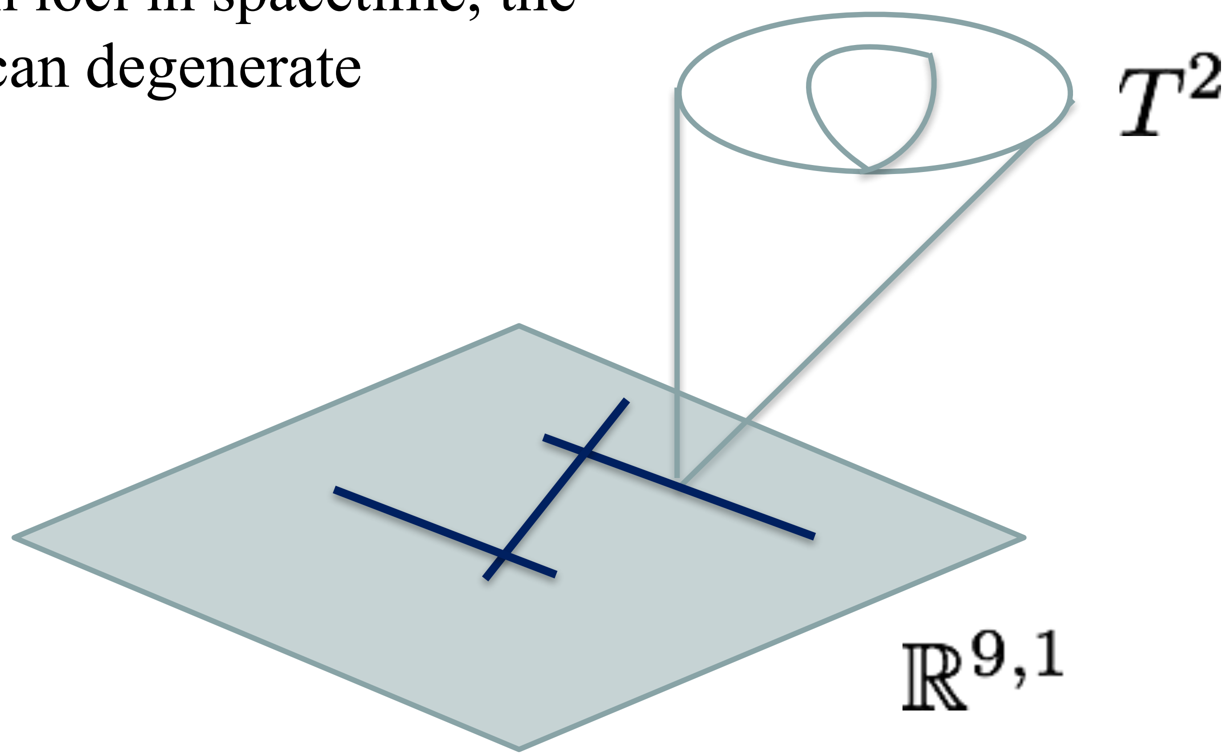


What is F-theory?



What is F-theory?

Over certain loci in spacetime, the torus fiber can degenerate



These loci correspond to the positions of 7-branes in IIB language, and produce forces in the 4d effective theory

Fiber Degenerations

"Weierstrass Model" for Elliptic Fiber:

$$y^2 = x^3 + f(z)x + g(z) \qquad \Delta := 4f^3 + 27g^2$$

$$f(z) = \# z^{\mathrm{ord}(f)} + \# z^{\mathrm{ord}(f)+1} + \ldots$$

$$g(z) = \# z^{\mathrm{ord}(g)} + \# z^{\mathrm{ord}(g)+1} + \ldots$$

$$\Delta(z) = \# z^{\mathrm{ord}(\Delta)} + \# z^{\mathrm{ord}(\Delta)+1} + \ldots$$

Fiber Degenerations

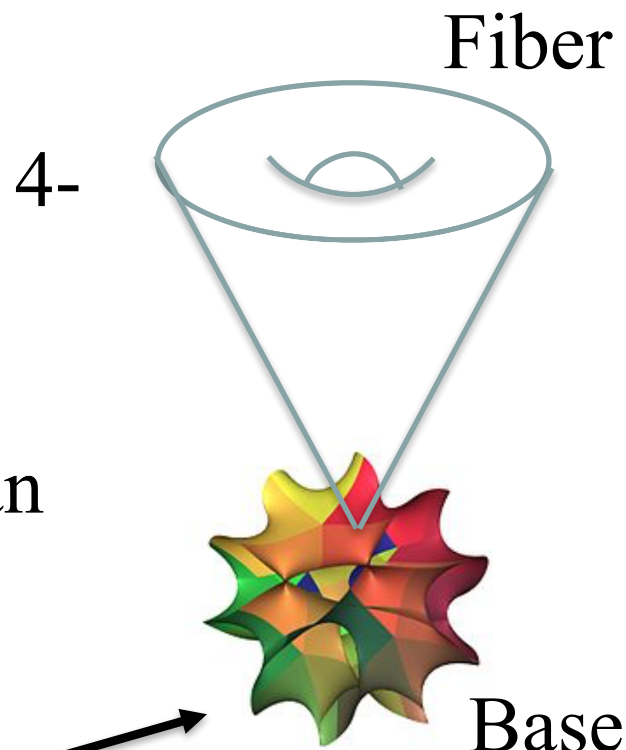
Fiber degenerations classified by ord(f), ord(g), ord($\triangle$):

Kodaira '63

ord(f)	ord(g)	ord(Δ)	type	singularity
≥ 0	≥ 0	0	I_0	none
0	0	1	I_1	none
0	0	$n \geq 2$	I_n	A_{n-1}
≥ 1	1	2	II	none
1	≥ 2	3	III	A_1
≥ 2	2	4	IV	A_2
≥ 2	≥ 3	6	I_0^*	D_4
2	3	$n \geq 7$	I_{n-6}^*	D_{n-2}
≥ 3	4	8	IV*	E_6
3	≥ 5	9	III*	E_7
≥ 4	5	10	II*	E_8
≥ 4	≥ 6	≥ 12	non-minimal	-

F-theory compactifications

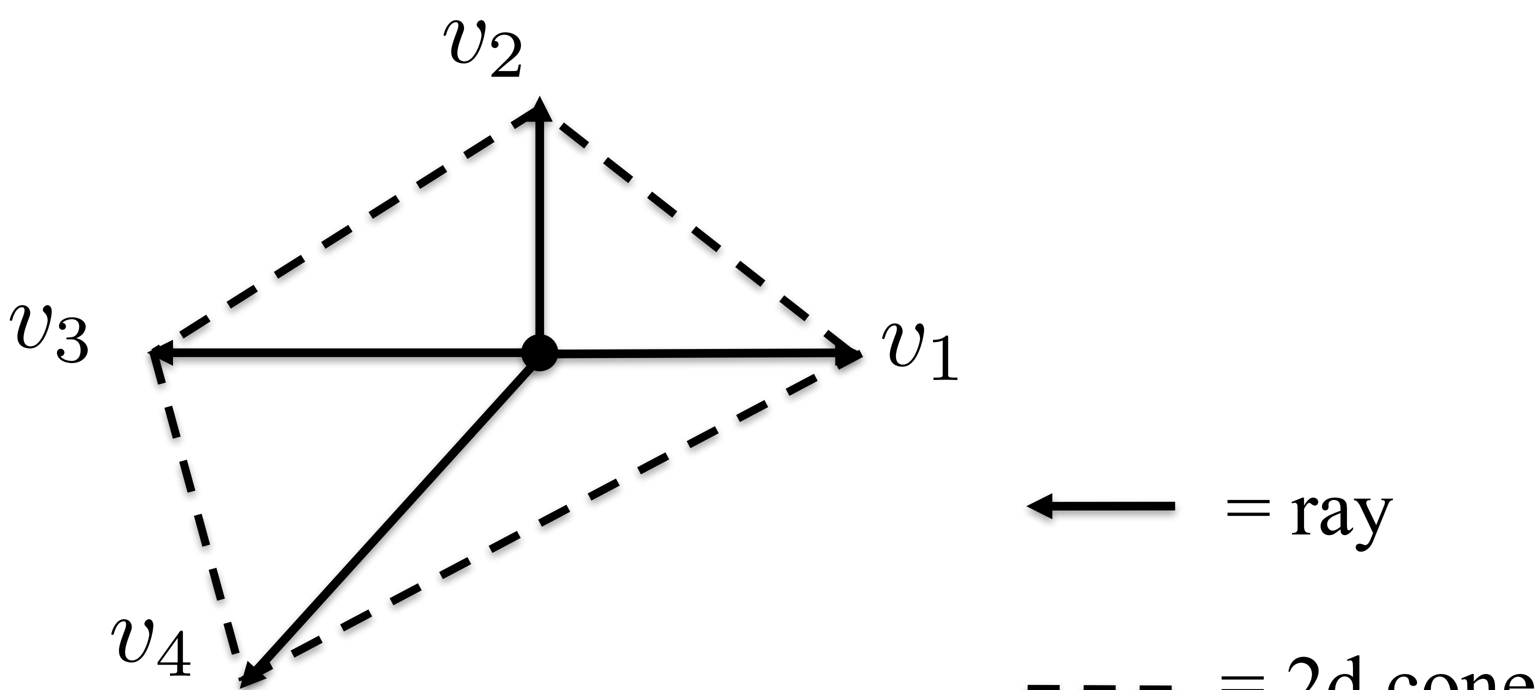
- To get a 4d effective theory, we need an 8-dimensional (complex 4-dimensional) compactification manifold
- This manifold must have admit an elliptic (i.e. torus) fibration
- Thus, we are led to considering *elliptically-fibered Calabi-Yau 4-folds*



Toric Geometry

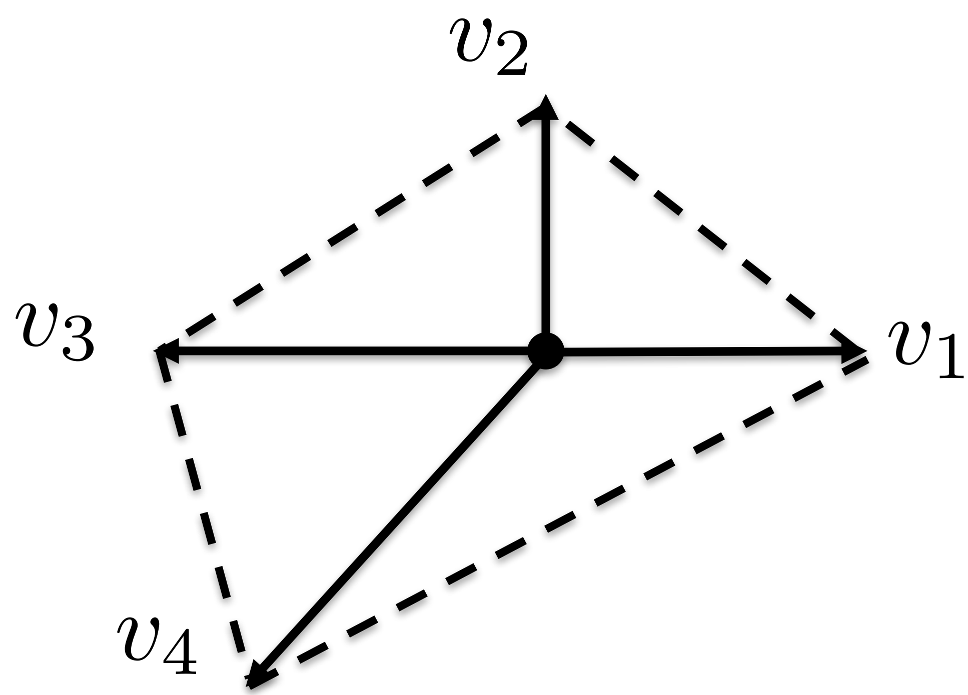
Toric geometry offers a useful playground for constructing such compactification manifolds, represented by numerical data:

Fan Σ



Toric Geometry

Fan Σ

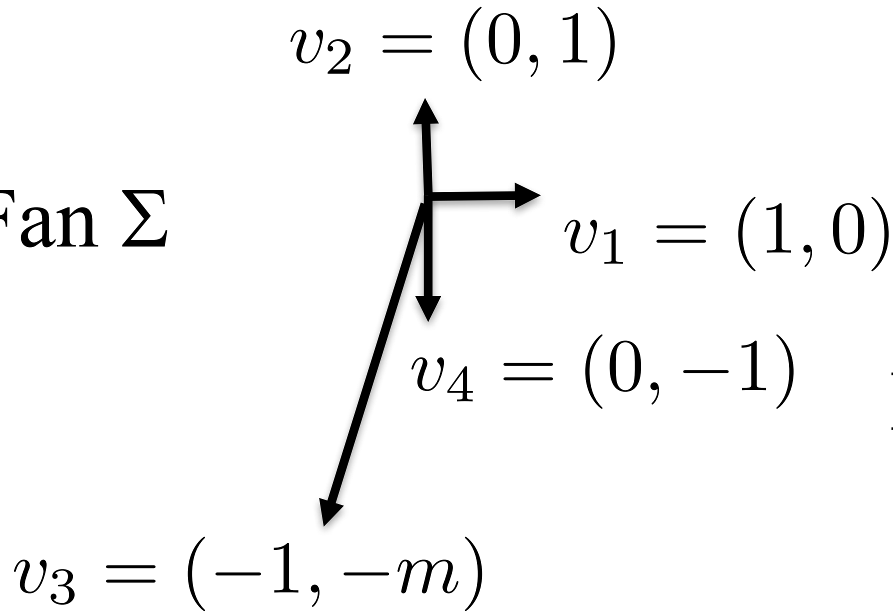


Rays label "divisors" (codim-1 hypersurfaces) of manifold

*n*d cones label codimension-*n* hypersurfaces of manifold

Example: Hirzebruch Surface $\mathbb{F}_m$

Fan Σ



Ray $v_i \to$ divisor D_i

$$D_i \cap D_j = \begin{pmatrix} 0 & 1 & 0 & 1 \\ 1 & m & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & -m \end{pmatrix}$$

Canonical Class $K = -\sum_i D_i \neq 0 \Rightarrow$ Not CY

Towards F-theory Compactifications

- Given a toric 3-fold, can produce Calabi-Yau 4-fold by adding an elliptic fibration

- Given a toric $(n+1)$-fold X, can produce Calabi-Yau n-fold by considering hypersurface inside X

- More on each of these in days ahead…

Summary

- String theory is the only known mathematically-consistent quantum theory of gravity
- String theory is hard to test experimentally because it supports a vast landscape of effective theories at low energies
- Machine learning could give us new insight into the string landscape