THE EDGES OF THE UNIVERSE: BLACK HOLES, HORIZONS & STRINGS

International Centre for Theoretical Sciences

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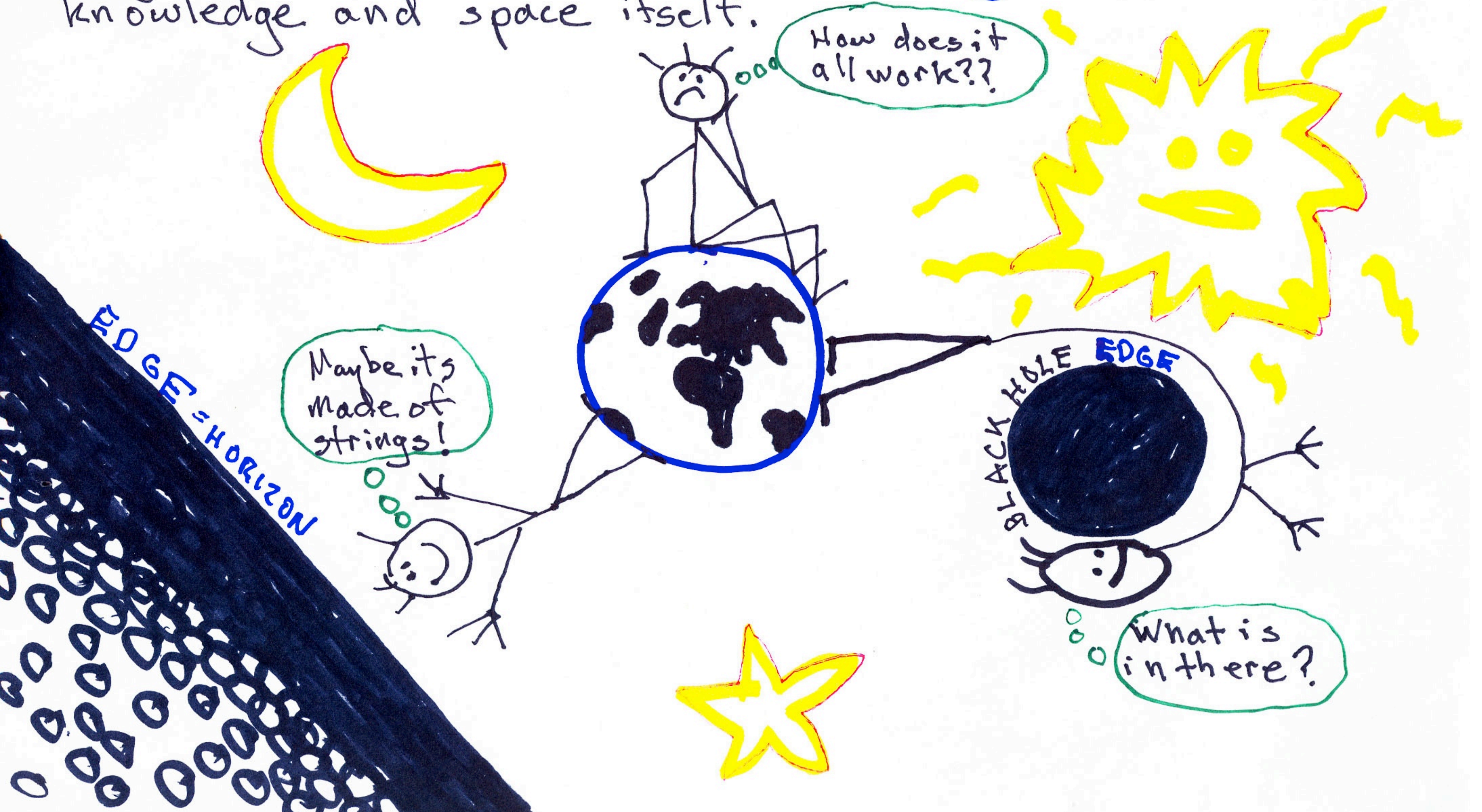
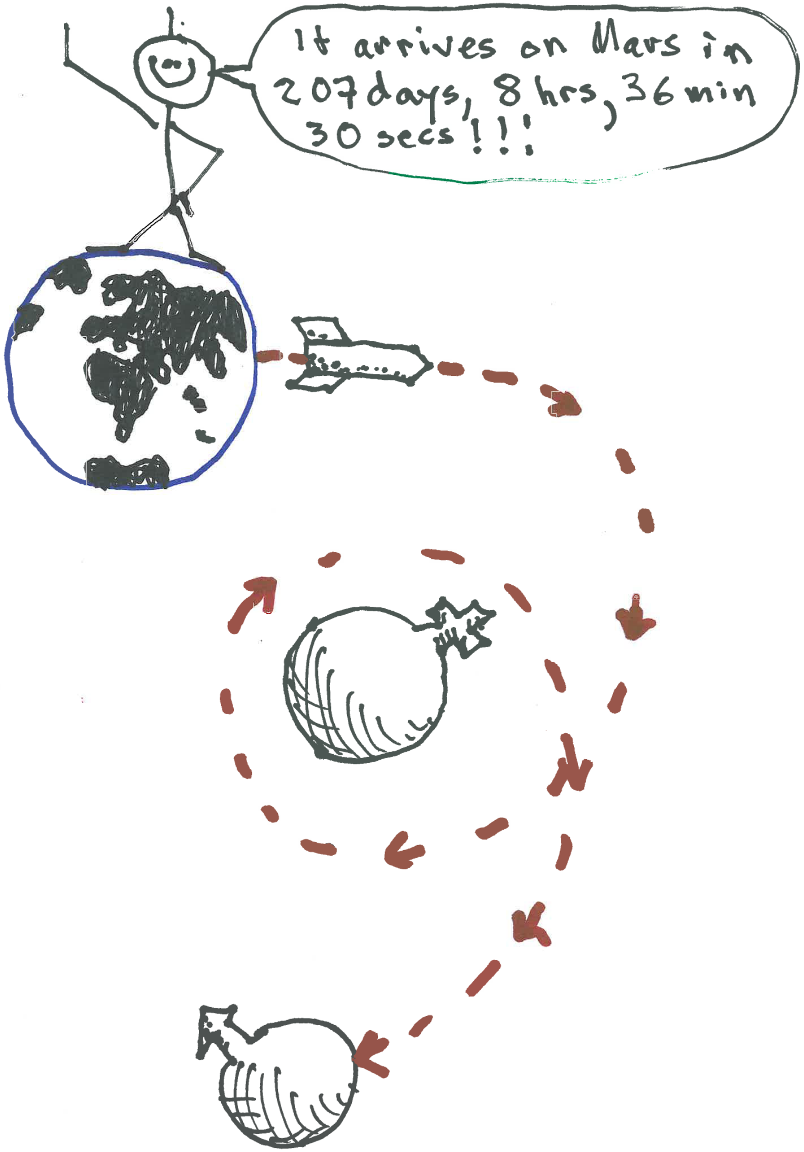
The scientific quest to understand the fundamental laws of nature has been ongoing for centuries. This lecture will describe some of our ongoing confusion, progress & excitement about the edges of both our knowledge and space itself.



We understand an amazing amount about the universe:



but there is an even more amazing amount we don't understand!

In the pursuit of knowledge, a contradiction or puzzle is our best friend

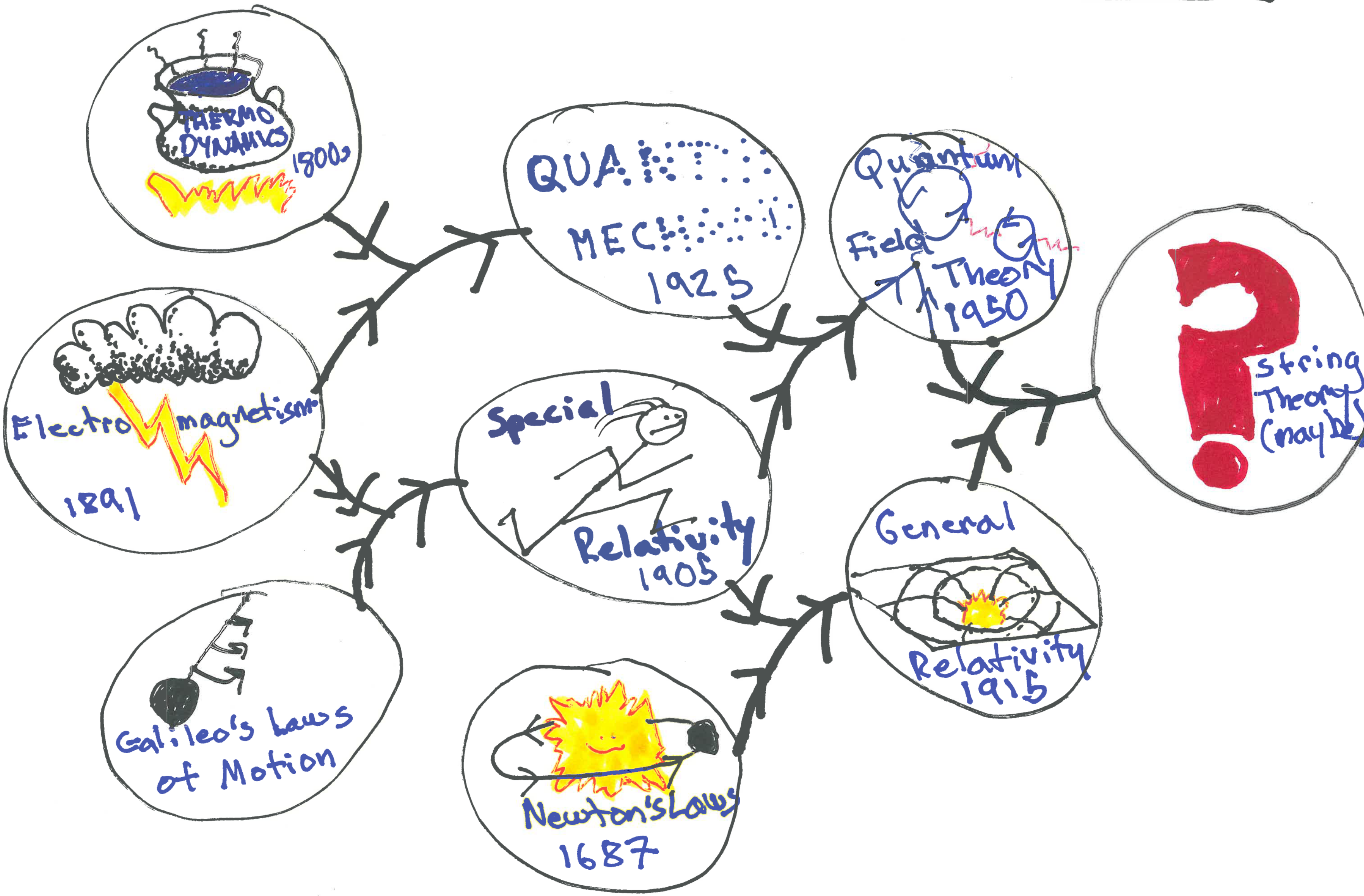
In 1905 Einstein wondered what he would see in the mirror if he ran faster than lightspeed.

Resolving this **contradiction** led to a shocking conclusion

NOTHING CAN TRAVEL FASTER THAN LIGHT

and transformed our view of space, time & the universe around us. All such revolutions in physics have been seeded by **contradictions.**

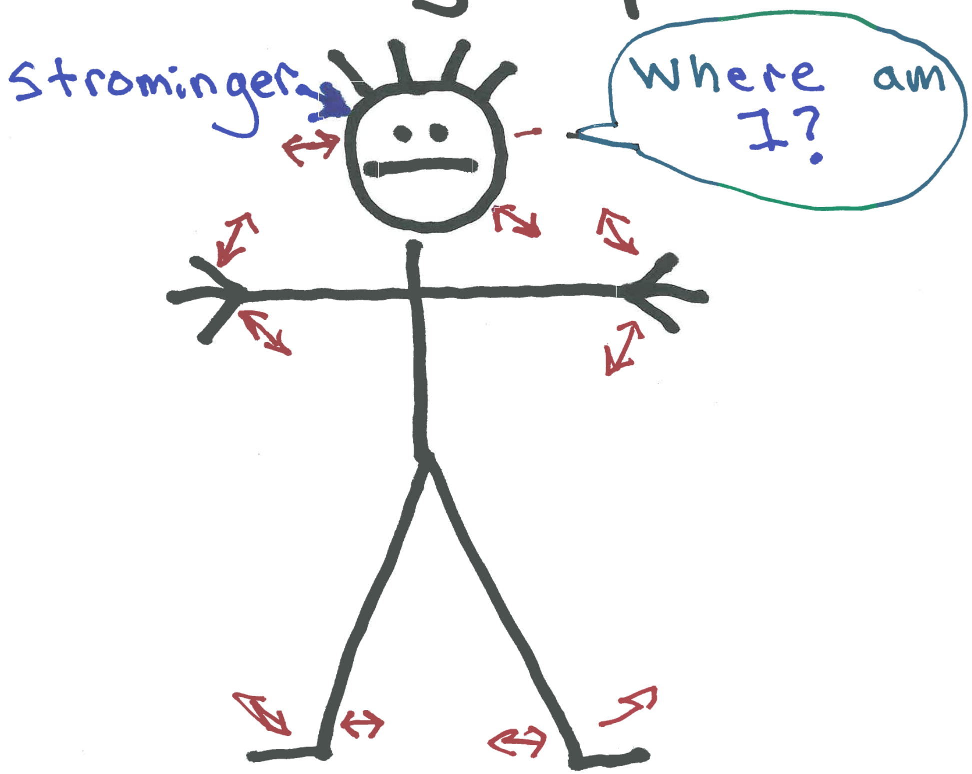
CONTRADICTON LEADS TO PROGRESS



Einstein's 1915 general theory of relativity says that the force of gravity is an illusion

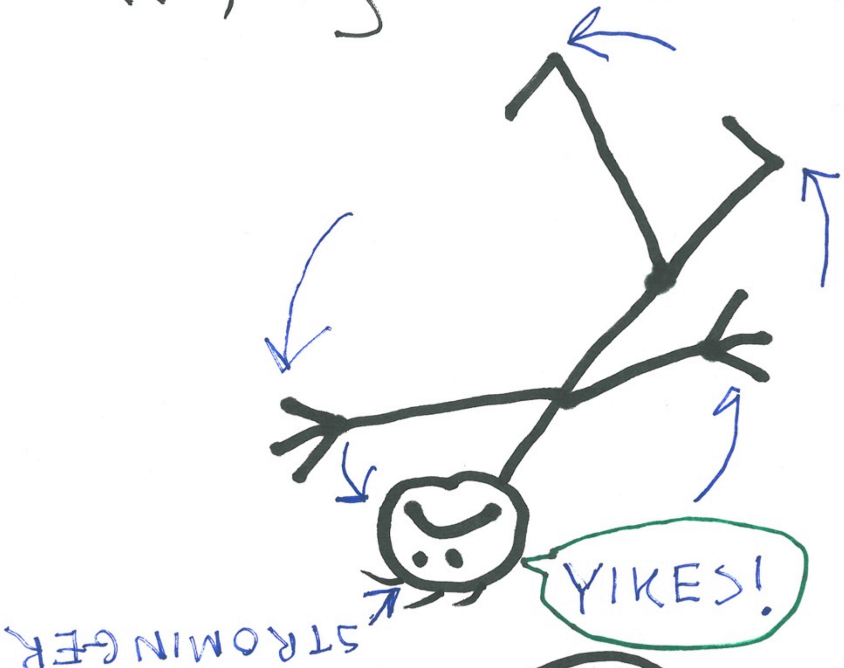
the earth moves in a straight line in a spacetime curved by the sun!

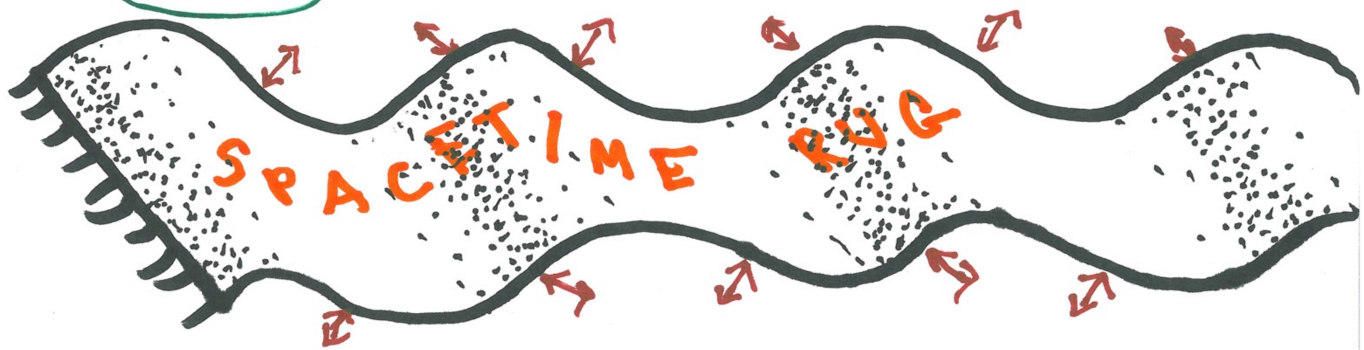
The uncertainty principle of quantum mechanics says that all spacetime positions are slightly uncertain



THE PROBLEM OF QUANTUM GRAVITY

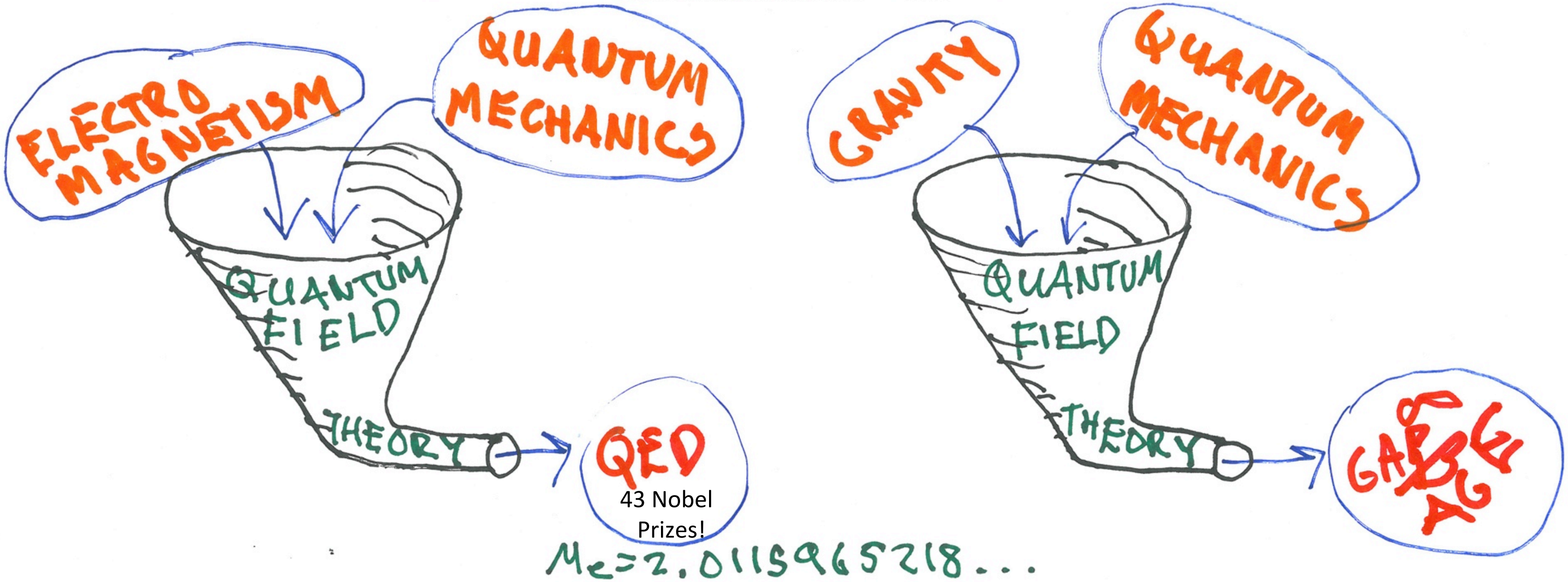
Applying the uncertainty principle to Einstein's curved spacetime, we find the rug of physics pulled from under our feet.





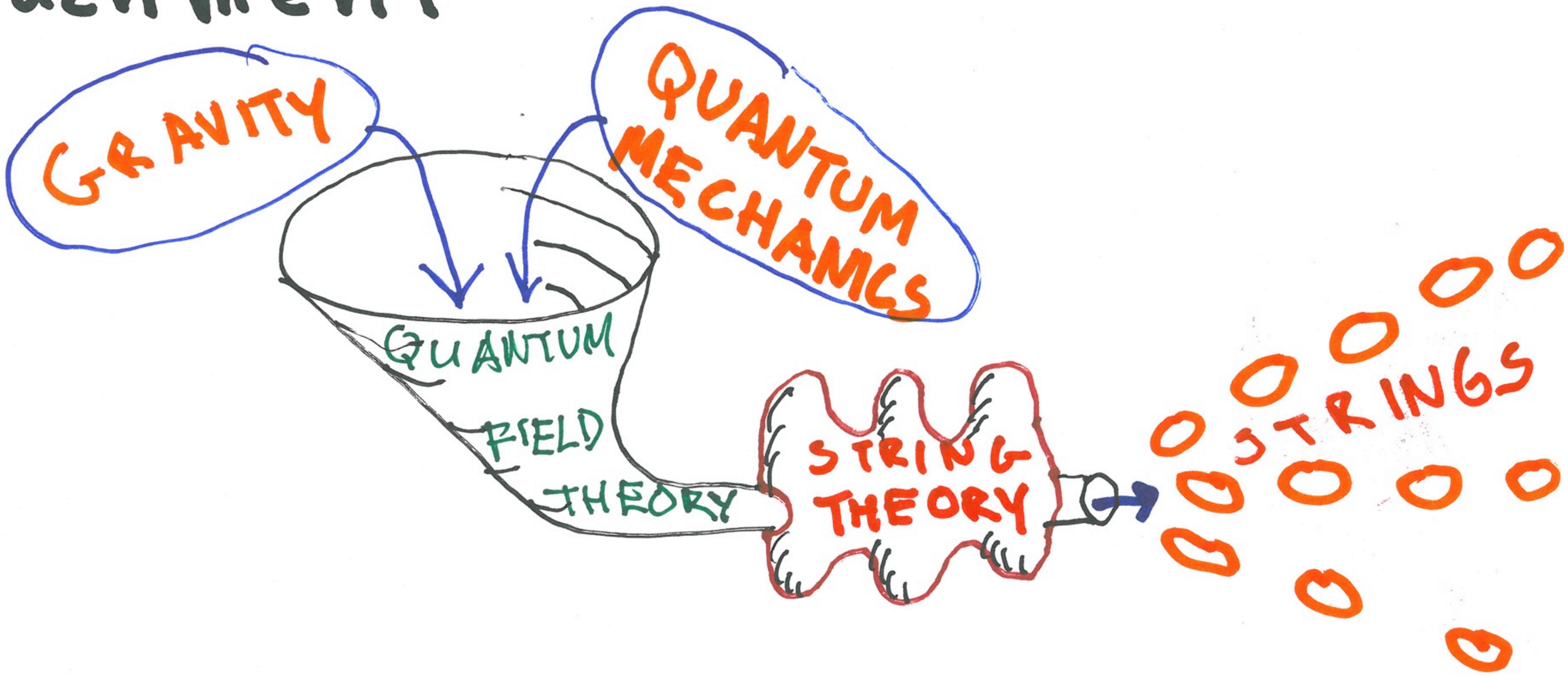
This conceptual problem translates into mathematical inconsistencies and physical paradoxes. New rug needed!

MATHEMATICAL INCONSISTENCY PAULI 1990s



QFT is the most accurately tested theory in the history of human thought. Works spectacularly for weak, strong and electromagnetic forces. Many many Nobel prizes. Gives garbage for gravity....

This mathematical inconsistency can be fixed with a string attachment



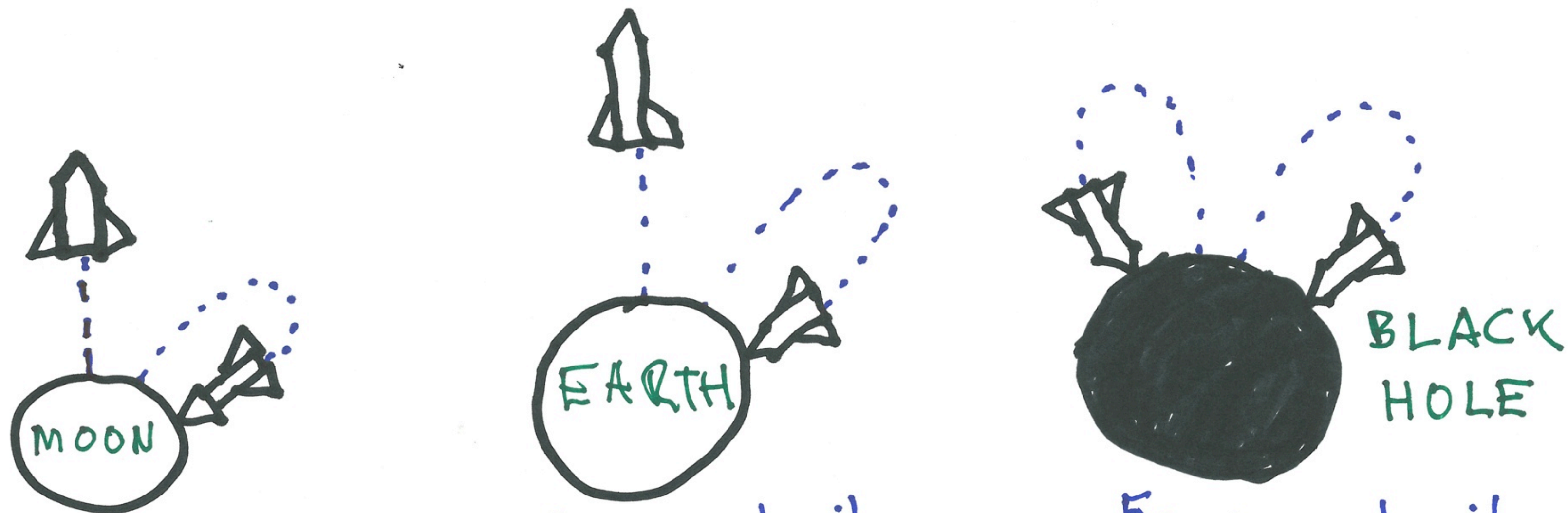
but we don't know if this attachment was ordered by nature. (more later)

For this reason, the laws of physics as taught in Harvard Physics 15-253* are inconsistent!

Bekenstein & Hawking (1974) showed there are further deep physical paradoxes for QM + gravity in the presence of **BLACK HOLES** to which we now turn....

* String Theory is Harvard Physics 287

WHAT IS A BLACK HOLE?



Escape velocity
= 2 km/sec

Escape velocity
= 11 km/sec

Escape velocity
= speed of light

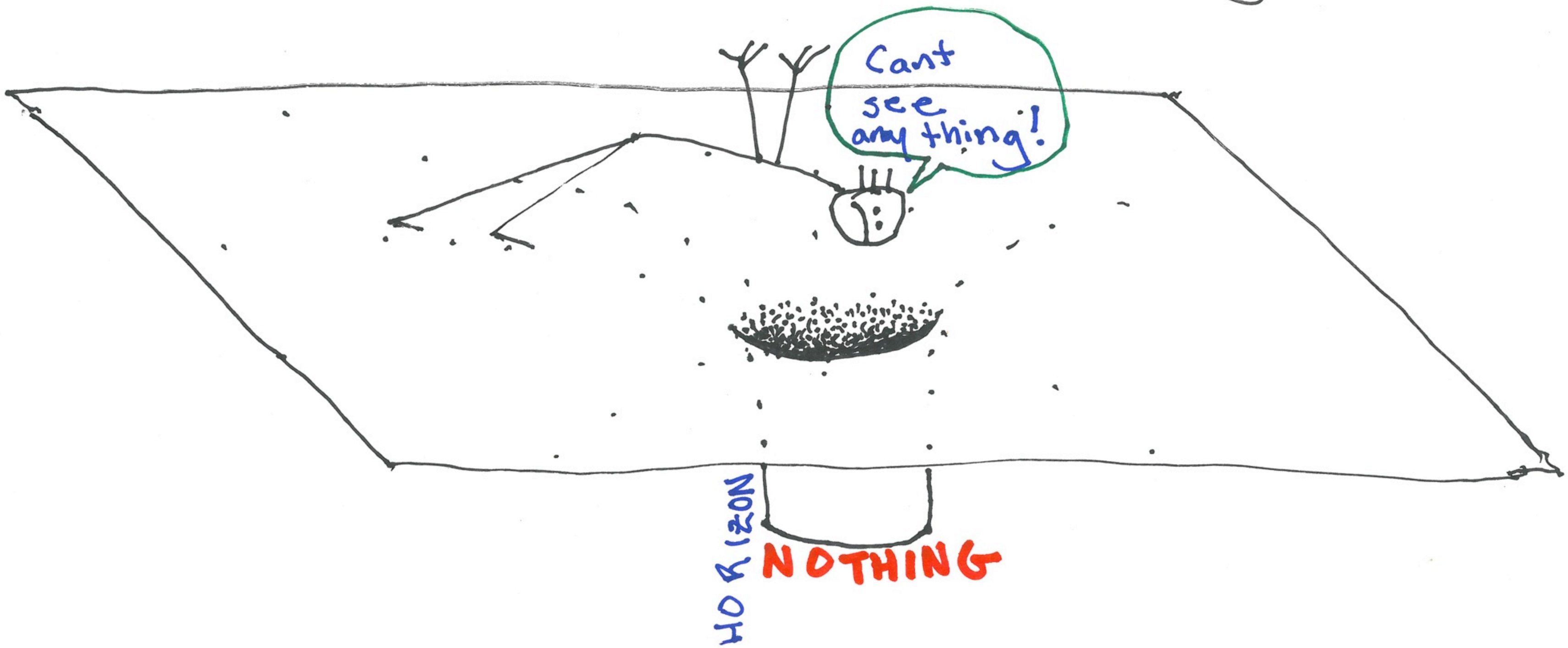
NOTHING CAN GET OUT!

Schwarzschild (1916) showed that Einstein's general relativity (1915) ⇒ BLACK HOLES. But they are so strange & confusing that Einstein himself concluded they do not exist!:

"the Schwarzschild singularity does F not appear [in nature] for the reason that matter cannot be concentrated arbitrarily ... otherwise the constituting particles would approach the speed of light"
AE 1939

It took **60 years** to understand their classical properties!!! Now we believe we orbit around a million km diameter BH in center of galaxy. They are plentiful in the sky.

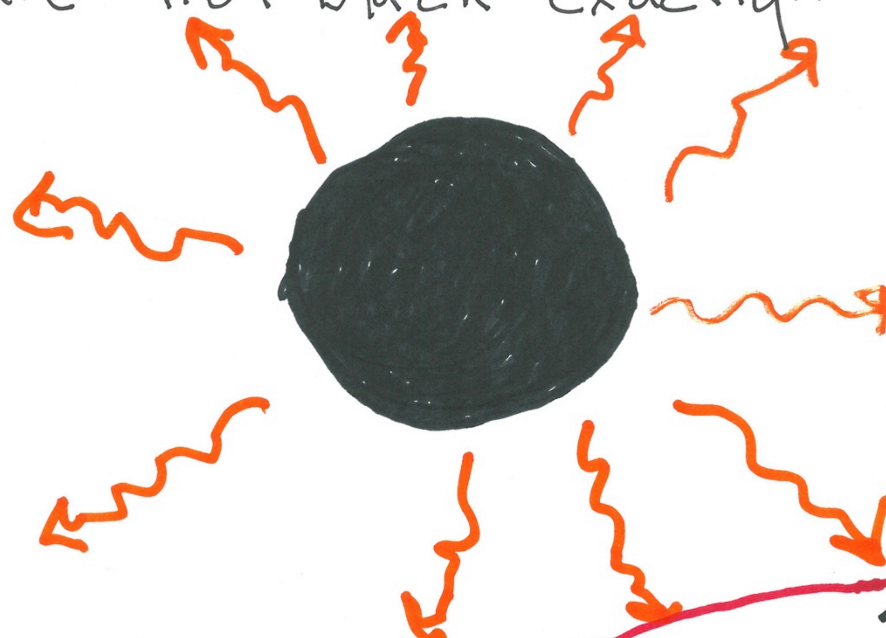
Classically, a black hole is a hole in empty space with NOTHING inside the EDGE = HORIZON. Anything crossing the



horizon dissolves into nothingness. BLACK HOLES = SIMPLEST objects in the universe

QUANTUM TROUBLE!

Hawking (1974) applied the uncertainty principle to black holes and showed they are not black exactly – they radiate



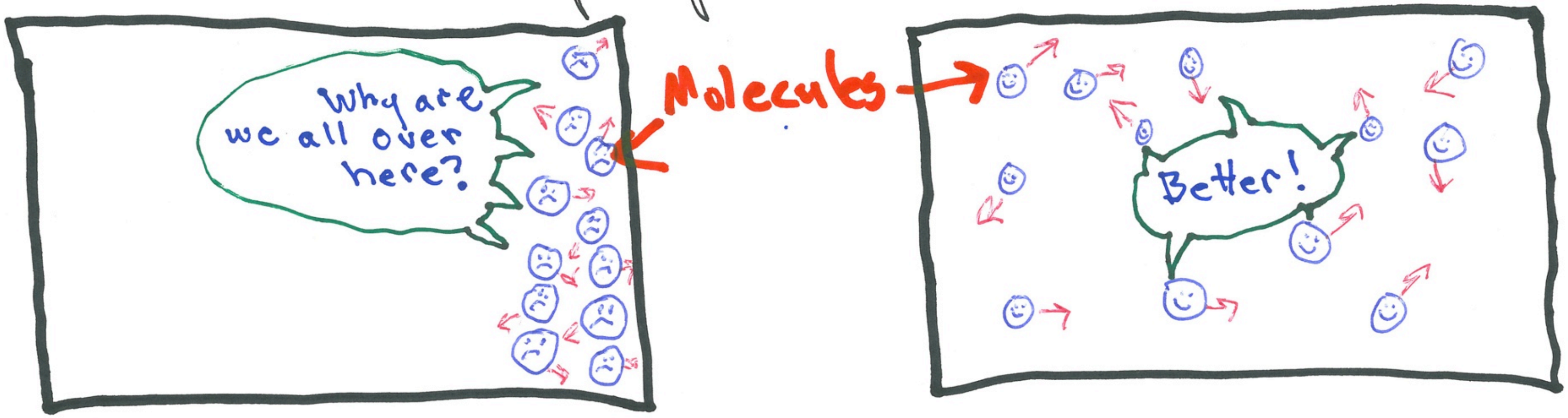
Thermodynamic law

a temperature

$$\boxed{T_H = \frac{\hbar}{8\pi\, GM}}$$

mass

In one of the most beautiful developments in the history of scientific thought, Boltzmann (1872) and others showed **thermodynamic laws** follow from statistical properties of molecules



A key ingredient is the notion of

entropy $\leftrightsquigarrow$ information

$$S \sim \log[\#\text{ of microstates}]$$

at fixed energy

= measure of **complexity** of the system.

Applying Boltzmann's reasoning to the thermodynamic law of black holes gives the famous **Bekenstein-Hawking** area entropy law

Entropy

Horizon area

$$S_{BH} = \frac{\text{Area}}{4\, G\, \hbar}$$

Newtons constant

Plancks constant

a very fundamental & very mysterious formula

THIS IS VERY BIG!

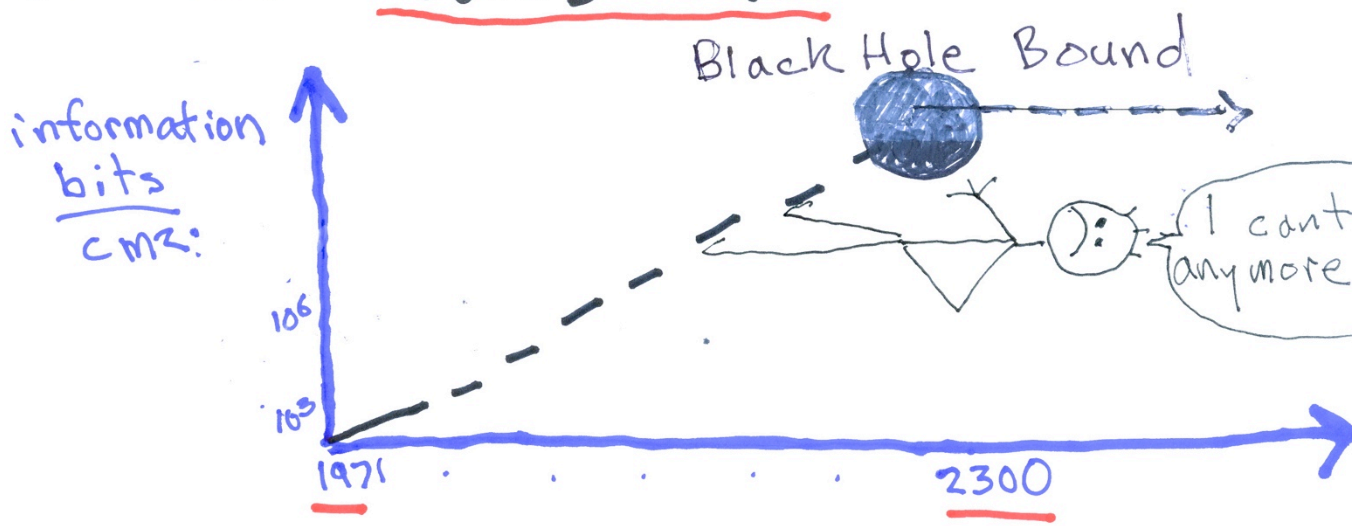
tiny black hole

10^{-24} mm

$\approx \frac{1}{\text{trillion} \times \text{trillion}}$ mm

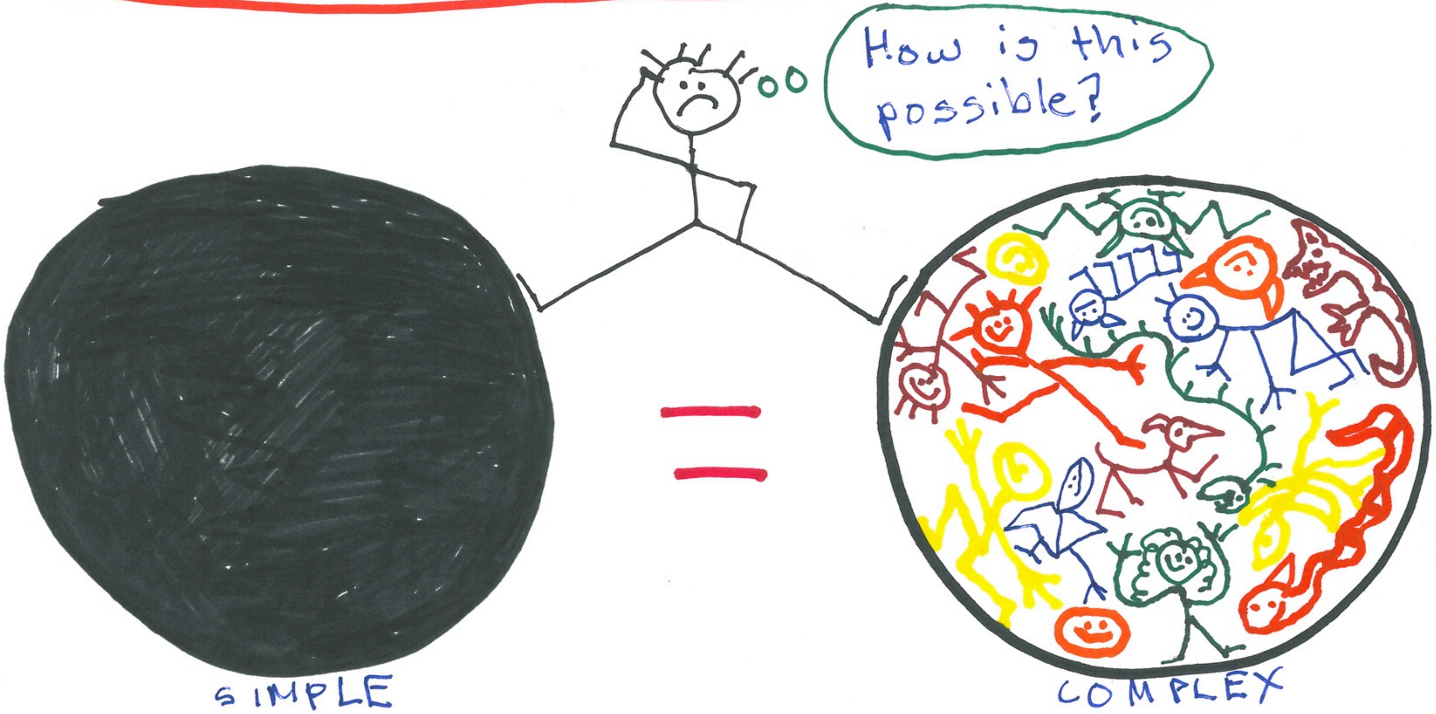
All the information in Google data banks fits in a 10^{-24} mm black hole!

We expect **BLACK HOLES** are the **MOST COMPLEX** possible objects in the physical universe. This is trouble for Moore's law



in 300 years!

THE BLACK HOLE INFORMATION PUZZLE

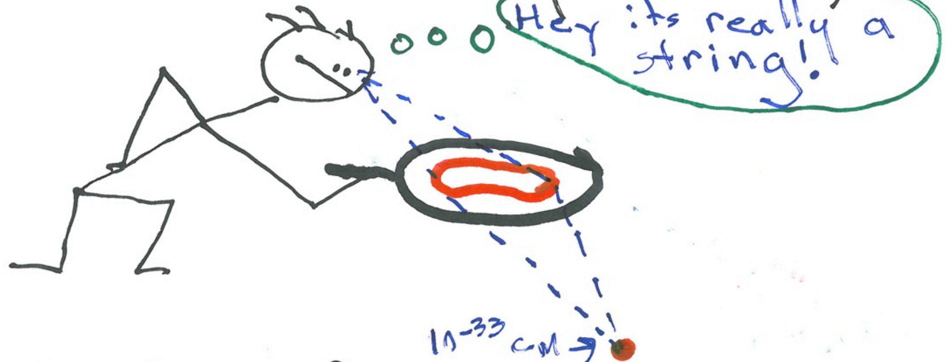


How do black holes store so much information in a hole of nothingness?

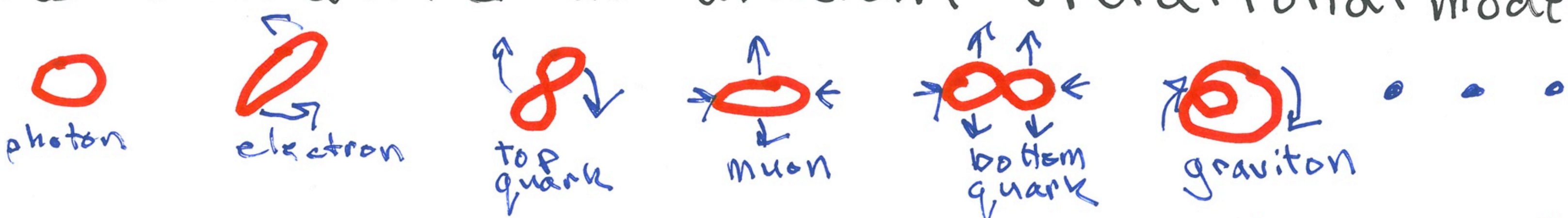
Enter string theory....

STRING THEORY

began life in the 70's with the idea that all particles, on closer inspection, are strings:

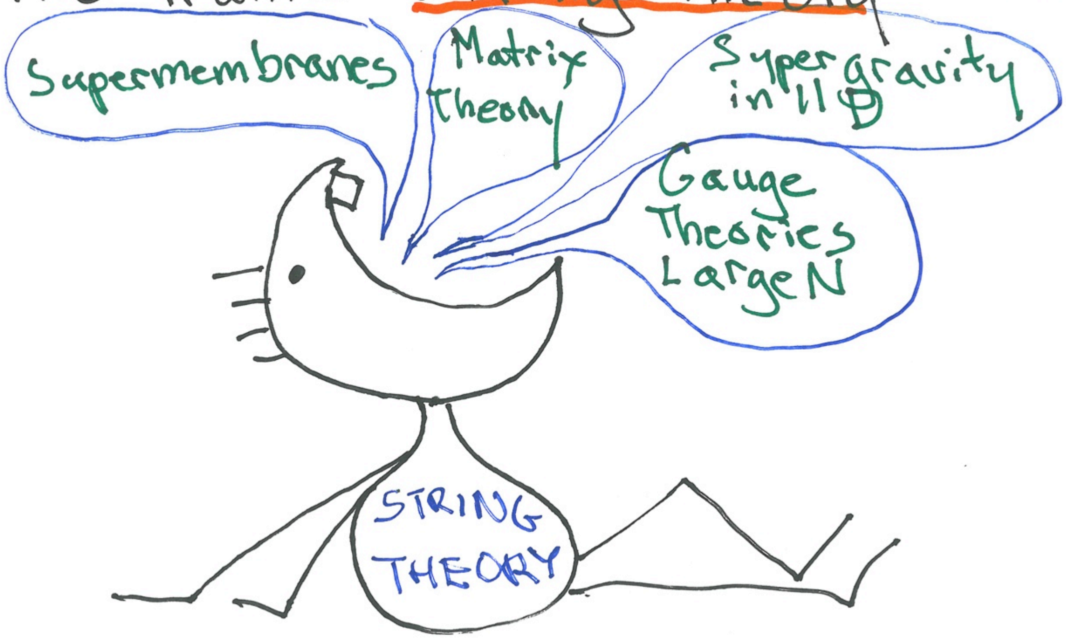


Amazingly this gives the so-far unique solution of **Pauli's ∞ problem.** It also realizes Einstein's dream of **unification** of all the particles and forces of nature as different vibrational modes.



We shall see it may also solve the **black hole puzzle.**

The theory has progressed over the decades into a large and highly cohesive framework incorporating nearly all approaches to beyond-the-standard model physics. We have learned that strings are just one of many equivalent descriptions but the name "String Theory" has stuck.

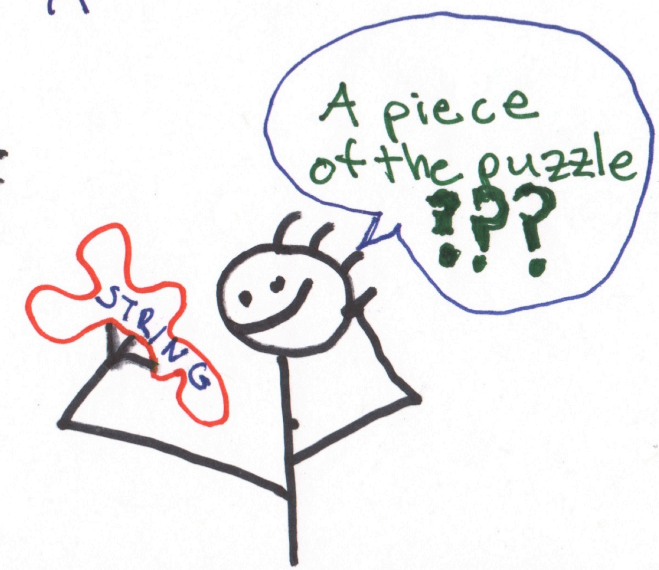


String theory has no competitors because it eats them all up. The flavors harmonize perfectly!

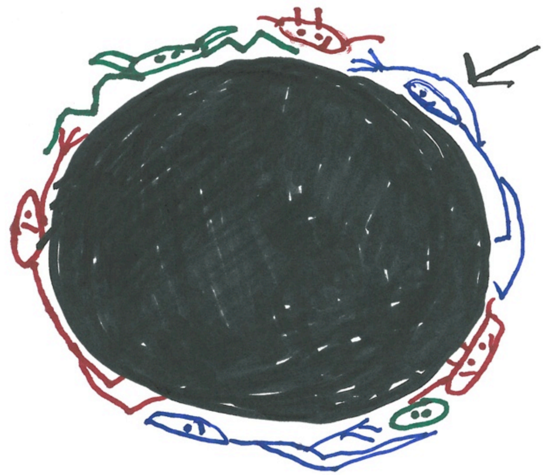
No matter how beautiful, no one will be confident that string theory is THE theory of nature until there is direct experimental confirmation. As strings are so tiny, this is unlikely in the coming decades. Wonderfully, research on string theory has led to progress on a number of important problems that does not depend on the assumption that string theory is THE theory of nature, simply by illustrating how seemingly irreconciliable phenomena are compatible. A beautiful example is the

BLACK HOLE PUZZLE

to which we now return.



In 1996 string theory was used to give a a complete microscopic quantum description of a class of especially simple "supersymmetric" black holes. (AS & Vafa) The vast information content was found to be stored in a hologram on the horizon



Black hole has fully equivalent "dual" two dimensional description!

and the Bekenstein-Hawking area-entropy law $S_{BH} = \frac{\text{Area}}{4G\hbar}$ exactly reproduced. The **maximally simple** and **maximally complex** descriptions of black holes were found to be complimentary but perfectly compatible.

to put it more precisely...

left-moving oscillator degeneracy for unitary conformal theories at level $L_0 = n$ goes for $n >> 1$ as [39][8]

$$d(n,c) \sim \exp(2\pi\sqrt{\frac{nc}{6}}) \tag{3.2}$$

In our case

$$\begin{aligned} c &= 6(\frac{1}{2}Q_F^2 + 1), \\ n &= Q_H, \end{aligned} \tag{3.3}$$

so we get for the growth of the elliptic genus, or equivalently the degeneracy of BPS solitons for $Q_H >> 1$

$$S_{stat} = \ln d(Q_F, Q_H) \sim 2\pi\sqrt{Q_H(\frac{1}{2}Q_F^2 + 1)}. \tag{3.4}$$

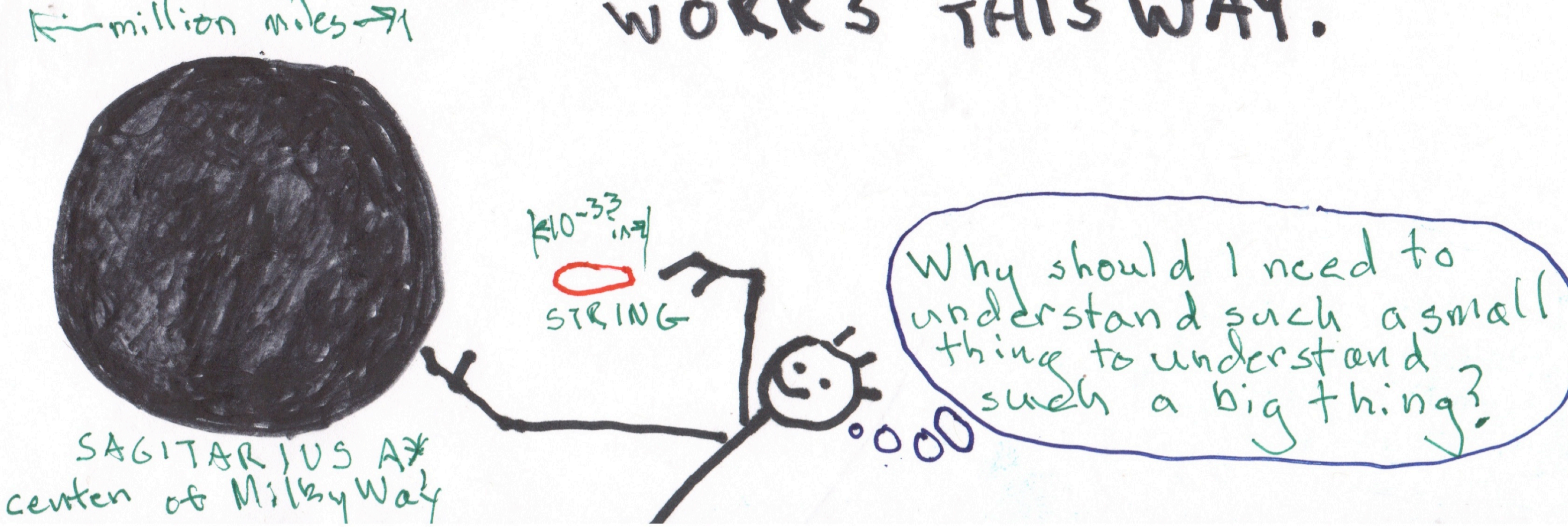
This agrees to leading order with the expected Bekenstein-Hawking entropy (2.11) for large Q_F^2, in which case (2.11) is reliable[9]

or, more simply put...

What is the turnout for the lecture on black holes & strings?

The theater holds 66 = 65 + 1, EUREKA THEY AGREE!!

This is progress, but we seek to understand black holes in the sky w/o presuming string theory. In fact, the trick used by string theory (a hologram) for storing lots of info in a hole of nothing does not require string theory! Recent simplified derivations rely largely on the symmetries of the Einstein equation - especially for the case of the extreme Kerr black hole to which we now turn. **SCIENCE OFTEN WORKS THIS WAY.**



EXTREME KERR

Black holes have a maximal spin $J = GM^2$, as the horizon can't exceed light speed.

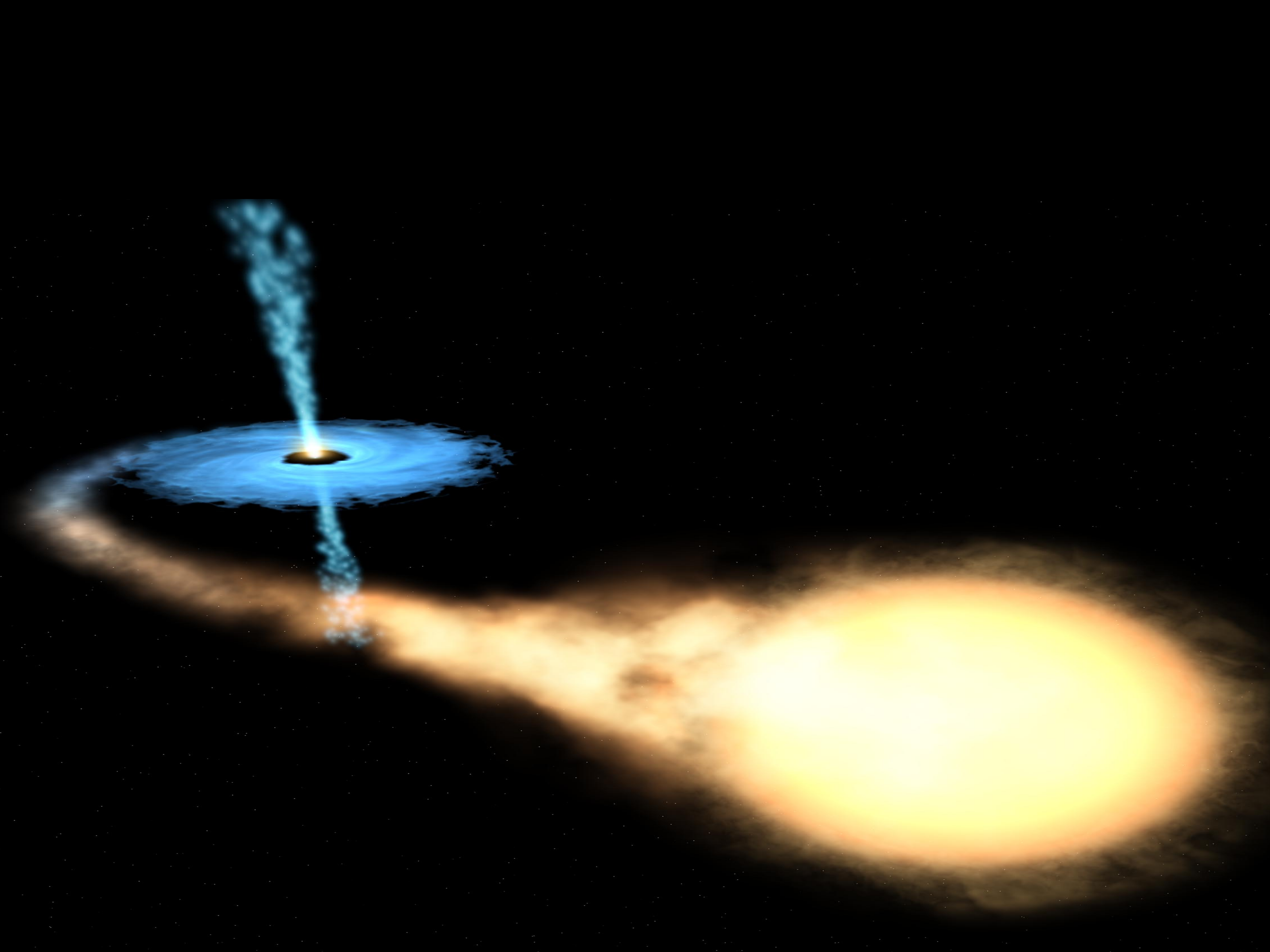
reminiscent of 1+1 dimensional CFT

The extreme ones are simple because everything is constrained to move at the speed of light when near the horizon.

GRS 1915+105 $\lesssim$ 2% below lightspeed McClintock Shafee Narayan Remillard Davis

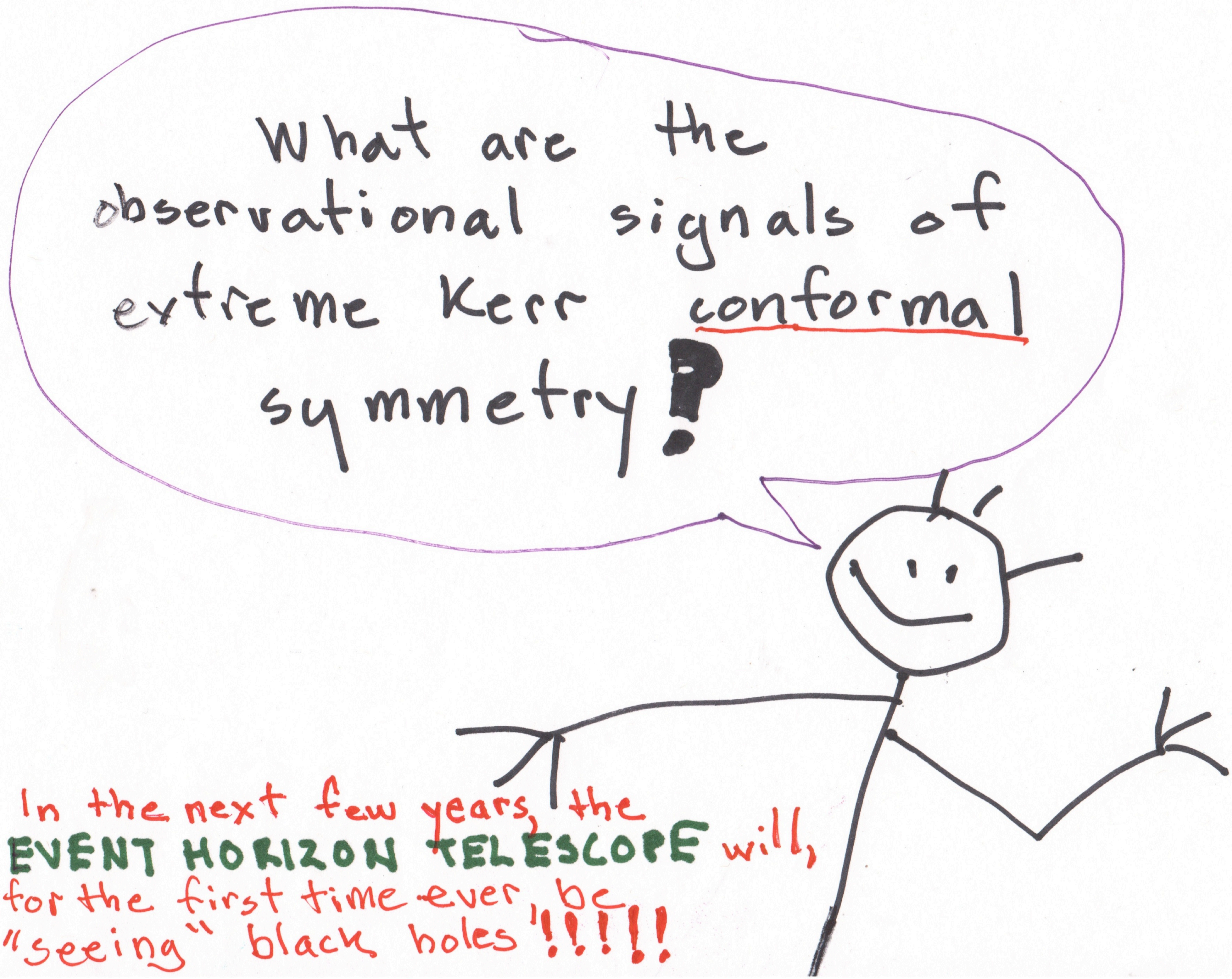
MC-6-30-15 $\lesssim$ 1% below lightspeed Brenneman & Reynolds

Cygnus X1 $\lesssim$ 2% below lightspeed Gou McClintock Remillard Steiner Reid Orosz Narayan Hanke García

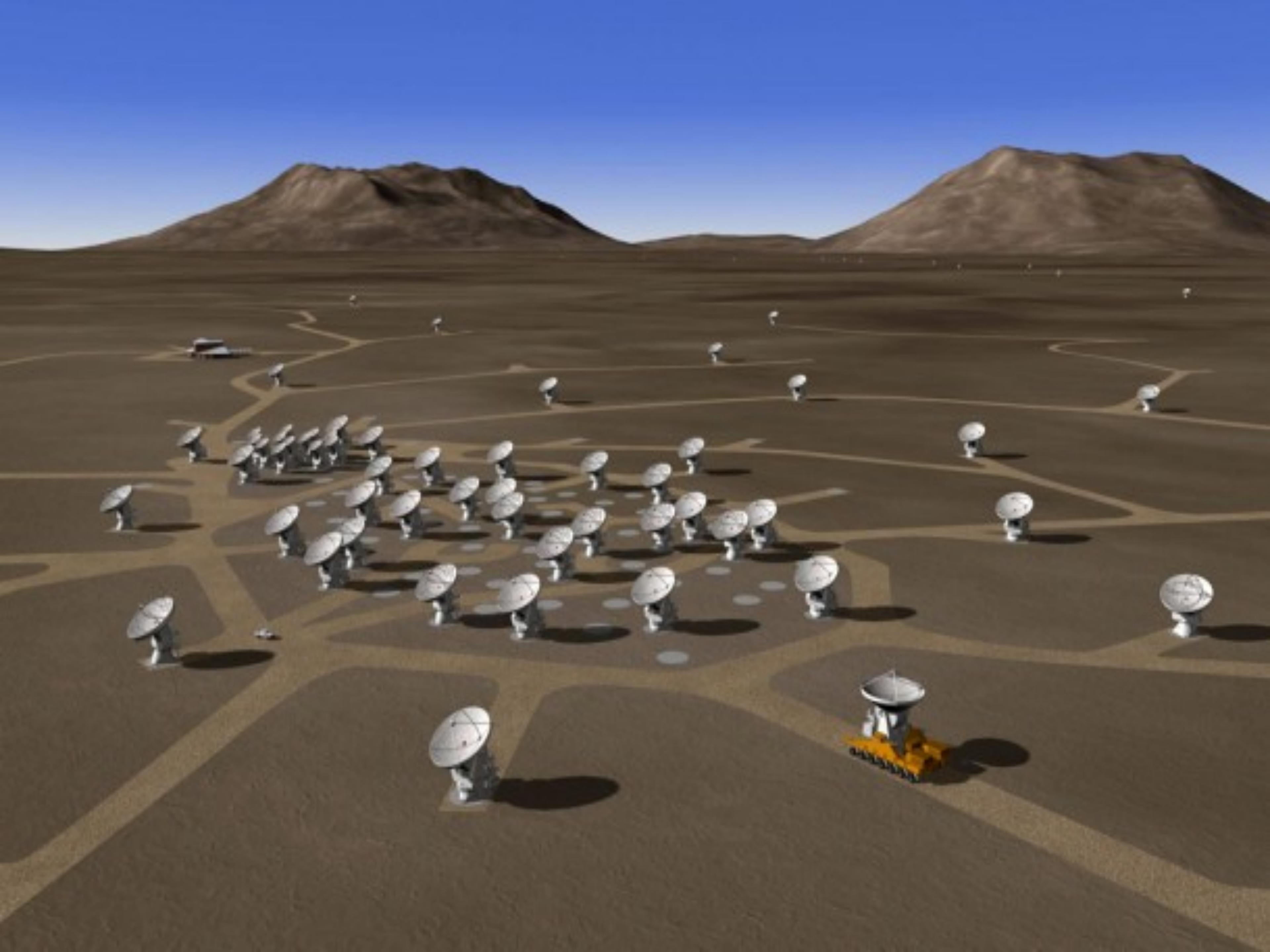


The Einstein equation has been shown to imply an ∞ of emergent "conformal" symmetries very near the horizon. Guica, Hartman, Song & AS 2008

Such ∞ of conformal symmetries have been observed in condensed matter experiments, and also were the central feature of the stringy BH analysis. They suggest the information inside GRS1915+105 is stored in a hologram on it's horizon!

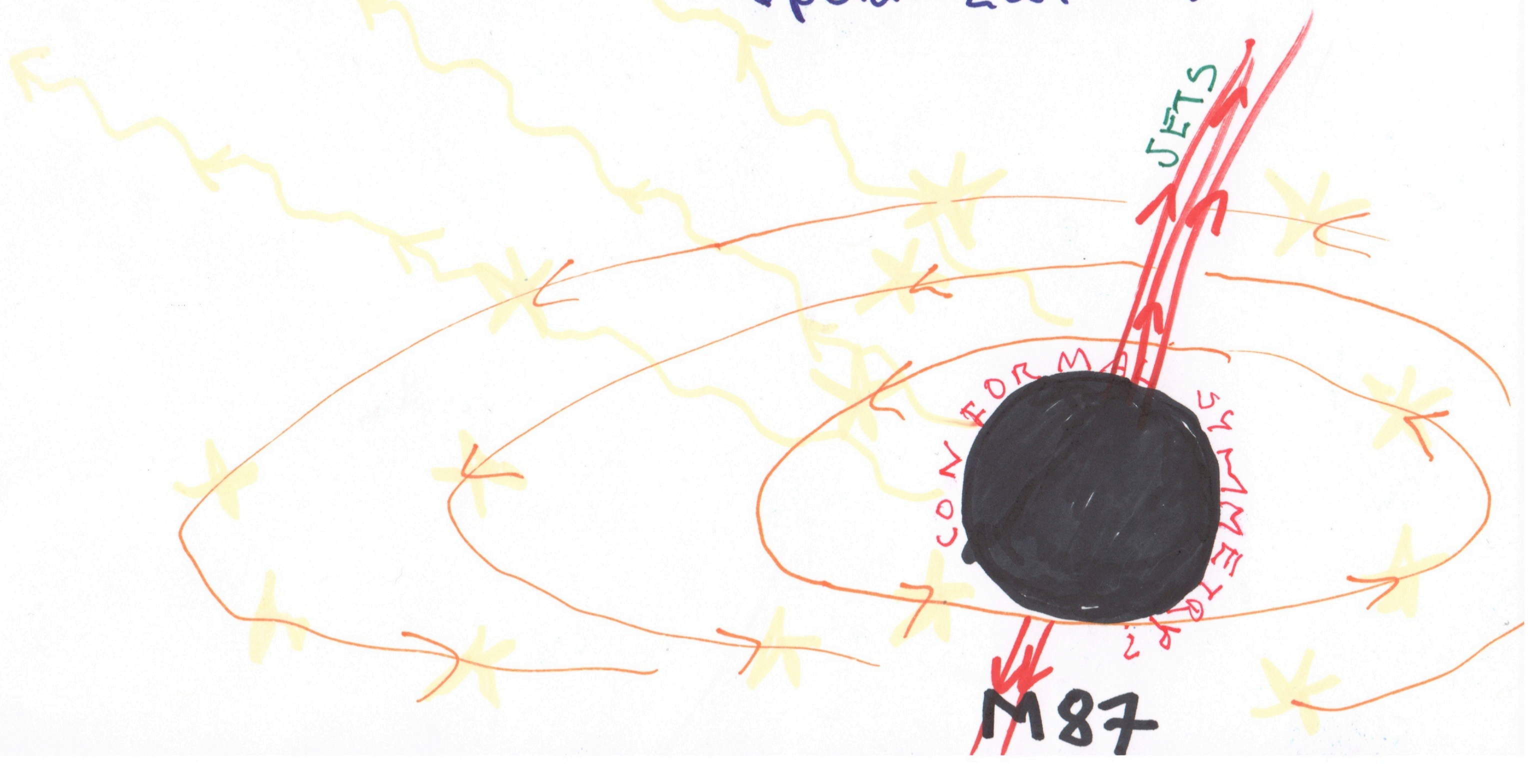


In the next few years, the **EVENT HORIZON TELESCOPE** will, for the first time ever, be "seeing" black holes!!!!!



IN PROGRESS

The Event Horizon Telescope proposes to resolve the BH at the center of M87 galaxy, observing submillimeter radiation. Highly collimated jets suggest a large spin. What are the predictions of conformal symmetry for the profile & polarization?



Behind all these words are precise, beautiful & mathematically powerful equations. Describing w/o equations is like trying to convey the beauty of the Grand Canyon with words but no photos. But its the best I can do in an hour!

6.3.2 CFT greybody factors

Now we compute the scattering microscopically, using the finite-temperature CFT Green function (5.10). Instead of the identification (5.13) we take

$$h_L = h_R = \frac{1}{2} + \beta, \quad T_{L,R} = T_{L,R}, \quad \omega_L = 2\pi T_L \tilde{n}_L, \quad \omega_R = 2\pi T_R \tilde{n}_R. \tag{6.60}$$

In order to ~~shorten the formulae we have here absorbed~~ the chemical potential terms appearing in (5.9) by shifts in the definitions of $\omega_{L,R}$. Substituting into (5.10) and using (5.9), we get

SO BEAUTIFUL!

$$\Gamma \sim \frac{(T_L T_R)^{2\beta}}{\Gamma(1+2\beta)^2} e^{-\pi\tilde{n}_R - \pi\tilde{n}_L} |\Gamma(\frac{1}{2}+\beta+i\tilde{n}_R)|^2 |\Gamma(\frac{1}{2}+\beta+i\tilde{n}_L)|^2 \tag{6.61}$$

$$\sigma_{abs} \sim \frac{(T_L T_R)^{2\beta}}{\Gamma(1+2\beta)^2} \sinh(\pi\tilde{n}_R + \pi\tilde{n}_L) |\Gamma(\frac{1}{2}+\beta+i\tilde{n}_R)|^2 |\Gamma(\frac{1}{2}+\beta+i\tilde{n}_L)|^2. \tag{6.62}$$

Noting that $T_R \propto \sigma$, we precisely reproduce the macroscopic result (6.51), up to some factors containing β.

6.4 5D extreme Kerr

In this subsection we specialize the results of the preceding subsections to the case when all the 5D black hole charges vanish, but the angular momentum J remains nonzero. This corresponds to $\delta_1 = \delta_5 = \delta_p = 0$. We then have $M = \frac{3M_0}{2} = 6a^2$. The 6D metric collapses to

IT'S GLORIOUS!

$$\begin{aligned} ds^2 &= -\left(1 - \frac{4a^2}{f}\right) d\hat{t}^2 + d\hat{y}^2 + f\left(\frac{\hat{r}^2 d\hat{r}^2}{f - 4a^2\hat{r}^2} + d\hat{\theta}^2\right) \\ &\quad + f(\cos^2\hat{\theta} d\hat{\psi}^2 + \sin^2\hat{\theta} d\hat{\phi}^2) + \frac{4a^4}{f}(\cos^2\hat{\theta} d\hat{\psi} + \sin^2\hat{\theta} d\hat{\phi})^2 \\ &\quad - \frac{8a^3}{f} d\hat{t}(\cos^2\hat{\theta} d\hat{\psi} + \sin^2\hat{\theta} d\hat{\phi}), \end{aligned}$$

where $f = \hat{r}^2 + a^2$. This is the 5d Kerr solution [44] (times a trivial $\hat{y}$ circle). The coordinate transformation (6.11) degenerates, so we work in the unshifted coordinates (6.11). One finds that

$$V_H = 0, \quad \Omega_R = \frac{1}{a}, \quad K_0 = 2a^2. \tag{6.63}$$

The near-horizon geometry is

$$\frac{2}{a^2} ds^2 = -w_+ w_- + \sigma_1^2 + \sigma_2^2 + 2(d\psi + \cos\theta d\phi + r dt)^2 + \frac{2}{a^2} dy^2, \tag{6.64}$$

CONCLUSIONS

The road to understand the fundamental laws of nature has been full of unexpected twist, turns & colorful characters like black holes, horizons and strings. We can see only a few bends ahead, but its enough to know we are moving forward.