Meeting inaugurale del Centro di Studi Avanzati GGI

15 febbraio 2018

Il futuro della fisica teorica delle particelle

G.F. Giudice

CERN

Congratulations!

A moment of satisfaction for the Italian theory community

Galileo Galilei was born in Pisa on 15 February 1564

From 1592 to 1610 he was a professor at the University of Padua

"Consumai li diciotto anni migliori di tutta la mia età" (lettera a Fortunio Liceti in Padova, Arcetri 23 giugno 1640)

He lived in Villa il Gioiello, Arcetri, from 1631 to his death, in 1642

Galileo is considered the founder of the scientific method

"Measure what is measurable, and make measurable what is not"

But his scientific method is based on logical deduction from observation and the use of mathematics

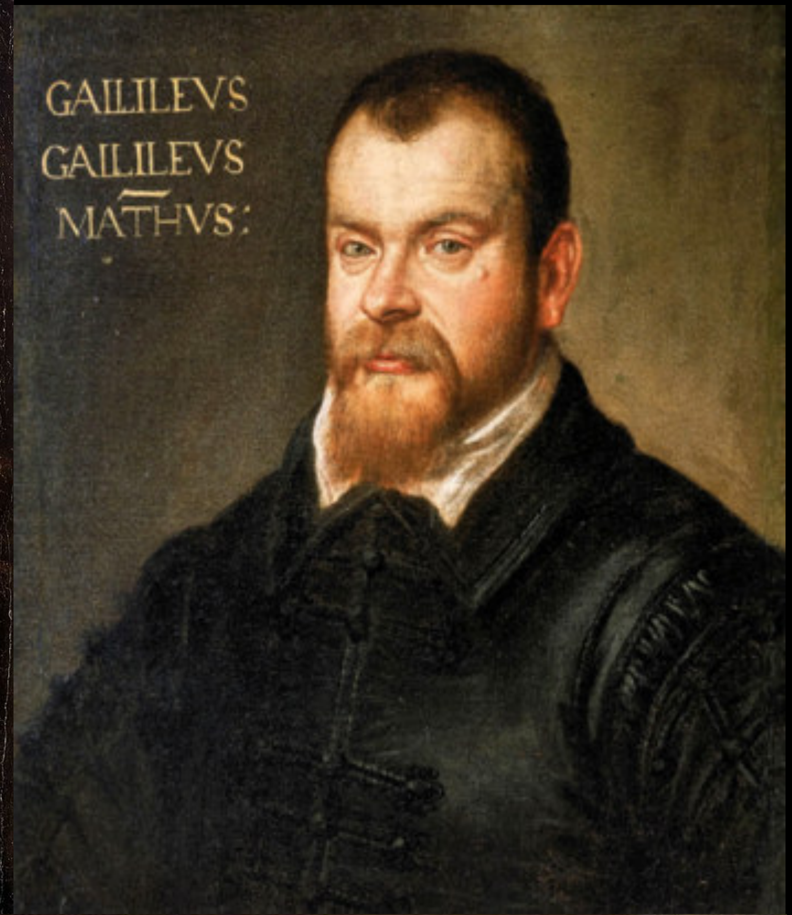
"È forza confessare che il voler trattare le quistioni naturali senza geometria è un tentar di fare quello che è impossibile ad esser fatto." Dialogo sopra i due massimi sistemi

"Questo grandissimo libro […] non si può intendere se prima non s'impara a intender la lingua, e conoscer i caratteri, ne' quali è scritto. Egli è scritto in lingua matematica; […] senza questi è un aggirarsi vanamente per un oscuro laberinto." Il Saggiatore

Galileo is the first theoretician ... in all respects

"Contro il portar la toga"

Volgo poi l'argomento, e ti conchiudo,
E ti fo confessare a tuo dispetto,
Che 'l sommo ben sarebbe andare ignudo.
[…]
Dicon ch'è grave errore, e troppo importa,
Ch'un dottor vadia a casa le puttane:
La togal gravità non lo comporta.
[…]
Ma ch'io sia per voler portar la toga,
Come s'io fussi qualche Fariseo,
O qualche scriba o archisinagoga,
Non lo pensar; ch'io non son mica Ebreo,
[…]
Se tu gli tasti, o son pieni di vento,
O di belletti o d'acque profumate,
O son fiascacci da pisciarvi drento.


GALILEVS
GALILEVS
MATHVS:

… and the future?

The Higgs (2012)

- LEP: how EW symmetry is broken
- LHC: how it is UV completed

Now, no more `how' questions,
but ambitious `why' questions

14 new fundamental non-gauge forces???

Going deeper into the nature of the Higgs:

LHC, LHC-HL, LHC-HE, ILC, CLIC, CEPC, FCC, μ-Coll

Where are we in Higgs precision?

Observable	Experiment
$\mu_{\gamma\gamma}$	1.14 ± 0.14
μ_{ZZ^*}	1.17 ± 0.23
μ_{WW^*}	0.99 ± 0.15
$\mu_{b\bar{b}}$	0.98 ± 0.20
$\mu_{\tau\tau}$	1.09 ± 0.23
μ_{tth}	1.56 ± 0.42
$\mu_{\mu\mu}$	< 2.8
μ_{ee}	$< 4 \times 10^5$

Observable	Experiment
$\mathrm{BR}(t \to ch)$	$\leq 2.2 \times 10^{-3}$
$\mathrm{BR}(t \to uh)$	$\leq 2.4 \times 10^{-3}$
$\mathrm{BR}(h \to \tau\mu)$	$\leq 2.5 \times 10^{-3}$
$\mathrm{BR}(h \to \tau e)$	$\leq 6.1 \times 10^{-3}$
$\mathrm{BR}(h \to \mu e)$	$\leq 3.4 \times 10^{-4}$

Observable	Experiment
$\mathrm{BR}(h \to \mathrm{inv})$	≤ 0.28
$\mathrm{BR}(h \to \mathrm{untagged})$	≤ 0.34

What can we reach in Higgs precision?

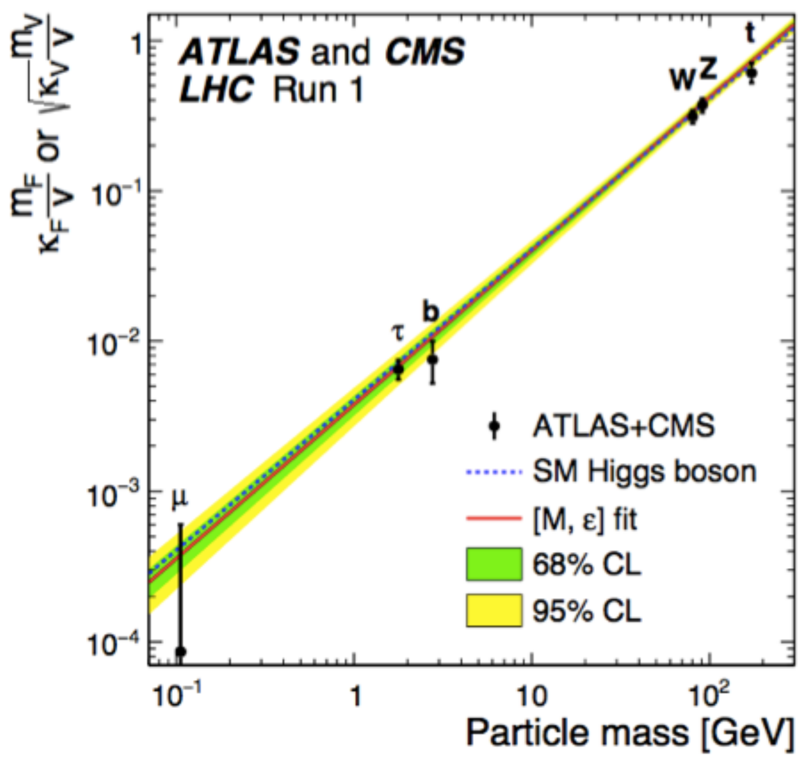
Parameter	HL-LHC	FCC-ee	FCC-ee	ILC	CLIC	CEPC	μ-Coll
$\sqrt{s}$[TeV]	14	350	240	250	1400	240	125
Lum/IP[E34]	5	1.9	8.5	1.35	1.5	2	0.01?
total[ab^{-1}]	3+(3)	1.3+1.3	5+5	2	1.5	2+2	0.002?
years[Sn'm'ss]	6	6.8	5.9	15	10	10	2?
Δm_h[MeV]	$\sim$ 100			14	47	5.9	0.06
Γ_h[%]	-	1.2	2.4	3.9	3.7	2.7	3.6
Δg_{hZZ}[%]	4	0.15	0.16	0.38	0.8	0.26	
Δg_{hWW}[%]	4.5	0.19	0.85	1.8	0.9	1.2	2.2
Δg_{hbb}[%]	11	0.42	0.88	1.8	1.0	1.3	2.3
$\Delta g_{h\tau\tau}$[%]	9	0.54	0.94	1.9	1.7	1.4	2.3
$\Delta g_{h\gamma\gamma}$[%]	4.1	1.5	1.7	1.1	5.7	4.7	5
Δg_{hcc}[%]	-	0.71	0.71	2.4	2.3	1.7	10
Δg_{hgg}[%]	6.5	0.8	0.80	2.2	1.8	1.5	-
Δg_{htt}[%]	8.5	-	-	-	4.2	-	-
$\Delta g_{h\mu\mu}$[%]	7.2	6.2	6.4	5.6	14.1	8.6	2.1
Δg_{hhh}[%]	-400,1200	-	-	-	40	-	
References	ATL-PHYS-PUB -2014-016	1308.6176	1308.6176	1710.07621 1711.00568	1608.07538	IHEP-CEPC-DR -2015-01	1304.5270 1308.2143

What do we learn from Higgs precision?

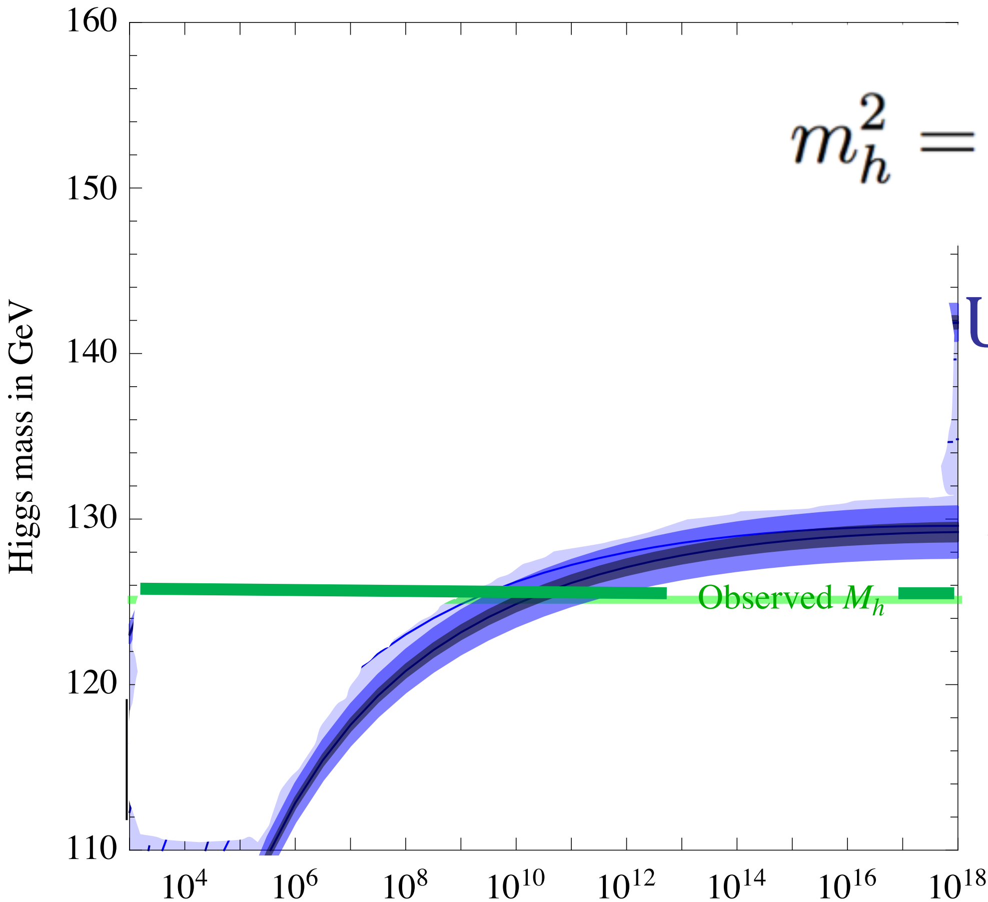
- Higgs substructure and extended Higgs sectors

$$\Delta = \frac{v^2}{f^2} \quad \Rightarrow \quad \text{compositeness scale } \; 4\pi f > \sqrt{\frac{0.1\%}{\Delta}} \; 100 \text{ TeV}$$

- Higgs/DM coupling and Higgs portals
  (invisible width)
- EW phase transition
  (triple Higgs coupling)
  3-5% precision at FCC-hh
- Flavour structure
  (2nd generation couplings
  and flavor-violating decays)



What have we learned from the Higgs mass?



$$m_h^2 = c\Lambda^2 + \frac{3\sqrt{2}G_F m_t^4}{\pi^2} \log \frac{\Lambda}{m_h}$$

UV part   IR part

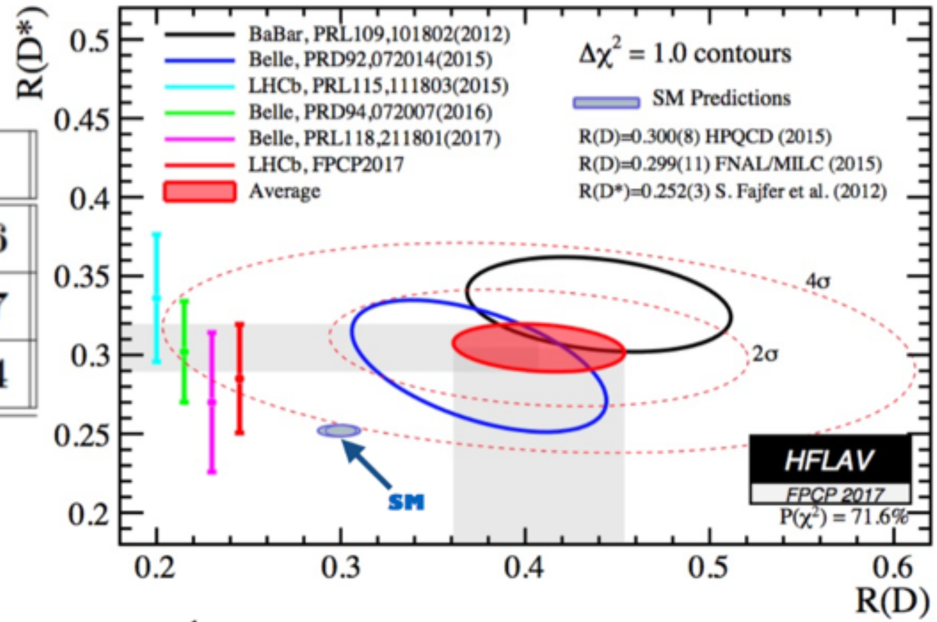
The IR contribution saturates the exptl value of m_h !!!

Exptl fact: the SM matches at large Λ a theory with $V(H) \approx 0$!!!

Flavour:
the big question in the SM and the big theoretical embarrassment

Experiments come to rescue?

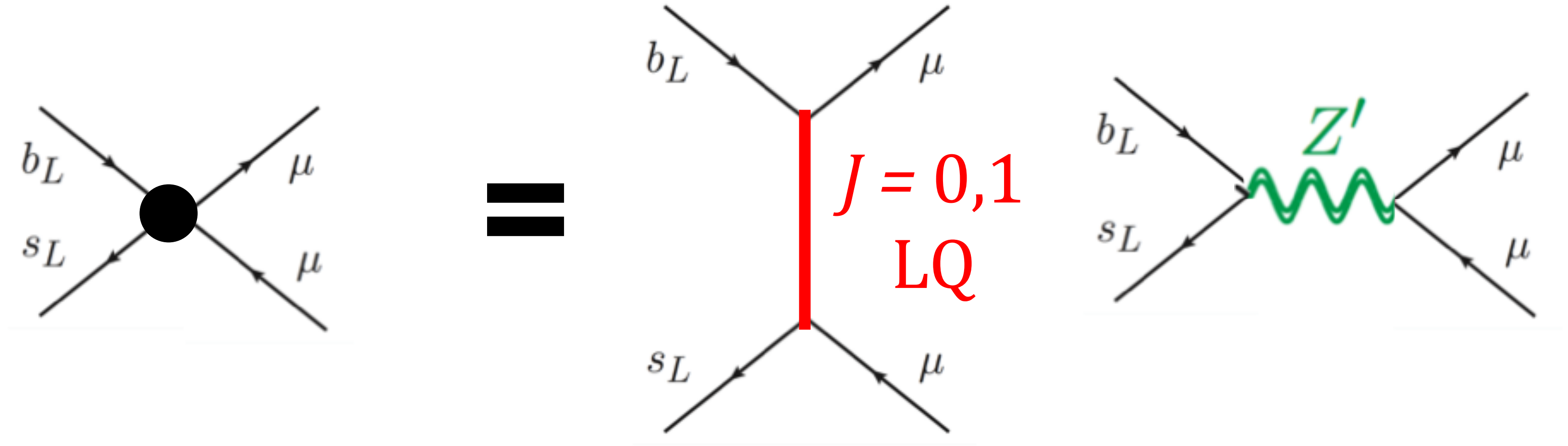
m_{ll} [mass range]	SM	Exp.
$R_K^{[1-6]}$	1.00 ± 0.01	$0.745^{+0.090}_{-0.074} \pm 0.036$
$R_{K^*}^{[1.1-6]}$	1.00 ± 0.01	$0.685^{+0.113}_{-0.069} \pm 0.047$
$R_{K^*}^{[0.045,1.1]}$	0.91 ± 0.03	$0.660^{+0.110}_{-0.070} \pm 0.024$



$$\mathcal{L} = \frac{1}{\Lambda_K^2}\,\bar{s}_L\gamma^\mu b_L\,\bar{\mu}_L\gamma_\mu\mu_L - \frac{1}{\Lambda_D^2}\,\bar{c}_L\gamma^\mu b_L\,\bar{\tau}_L\gamma_\mu\nu_L$$

$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)} \quad \Longrightarrow \quad \Lambda_K \sim 30\ \mathrm{TeV}$$

$$R_{D^{(*)}} = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\mu\nu)} \quad \Longrightarrow \quad \Lambda_D \sim 3\ \mathrm{TeV}$$

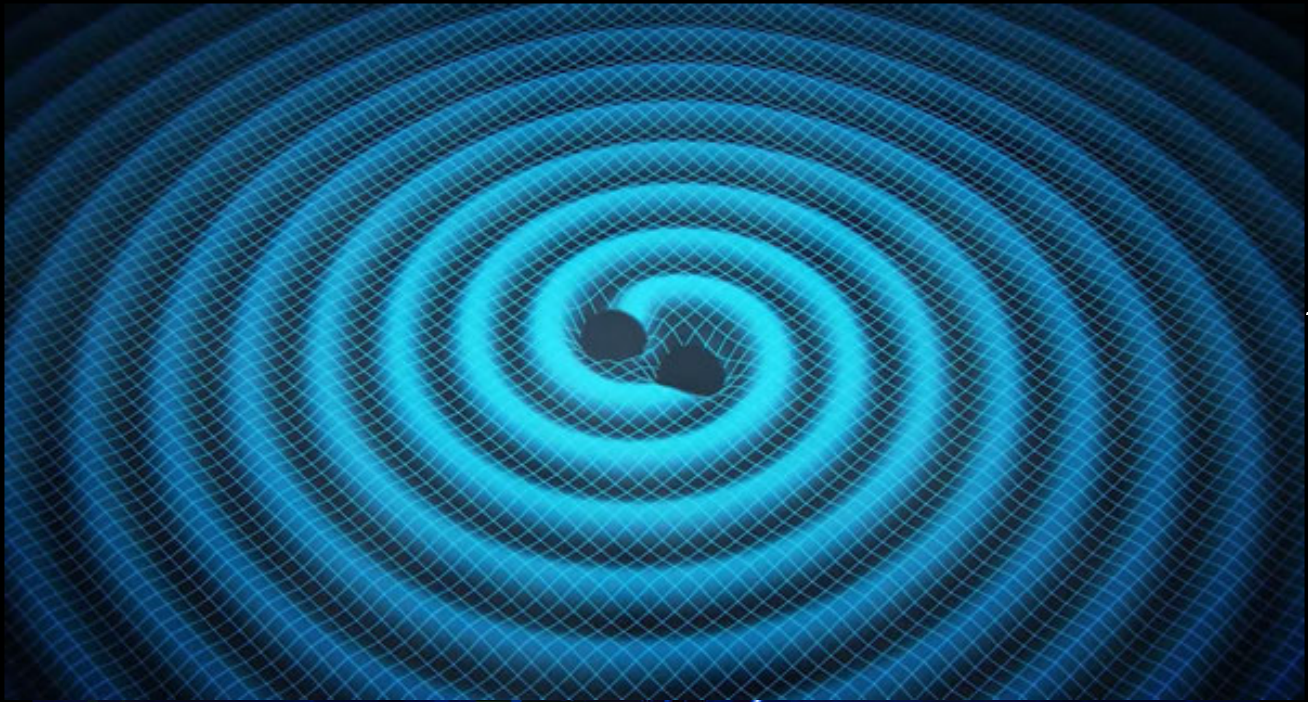


For CC: either exchange $SU(2)_W$ non-singlet or mixing with sterile neutrino

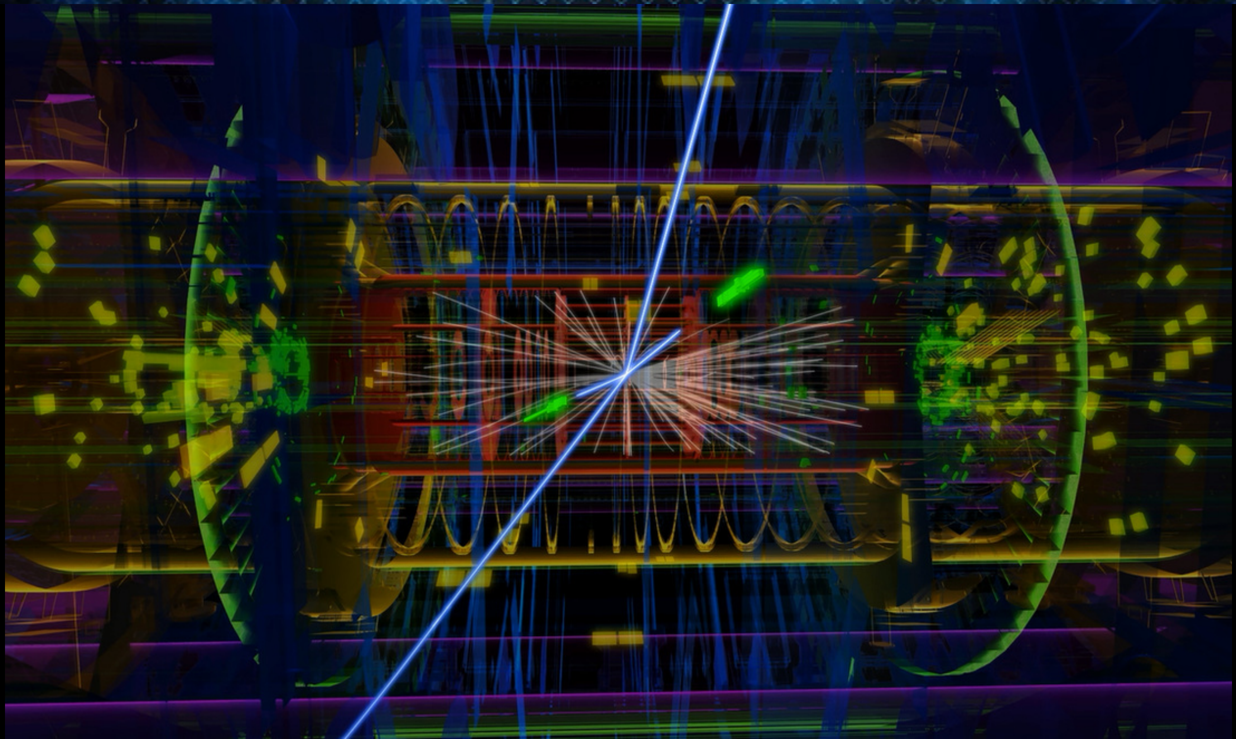
Many model-building attempts

Weird? Only weird flavour theories have chances to be true!

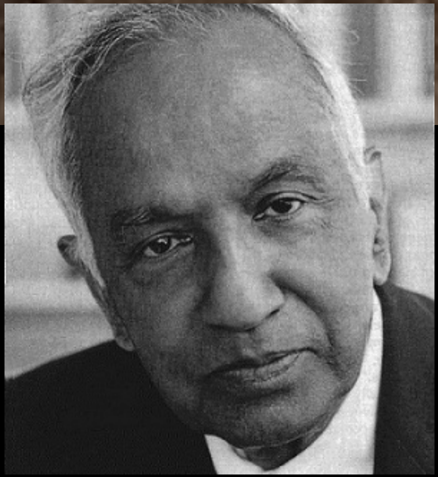
Learning about fundamental physics with another kind of collisions



$M \approx 10^{55}$ TeV
($=10\ M_\odot$)
$d \approx 10^{25}$ m



$M = 6.5$ TeV
($=6 \times 10^{-54}$
$M_\odot$)
$d \approx 10^{-19}$ m



“Black holes are, almost by definition, the most perfect objects there are in the universe” S. Chandrasekhar

No hair theorem $\Rightarrow$

M, L, Q

Classical electron radius

Electric Coulomb potential ≈ rest mass $\Rightarrow$

$$r_{em} = \frac{\alpha\hbar}{mc} = 3\times10^{-15}\ \text{m}$$

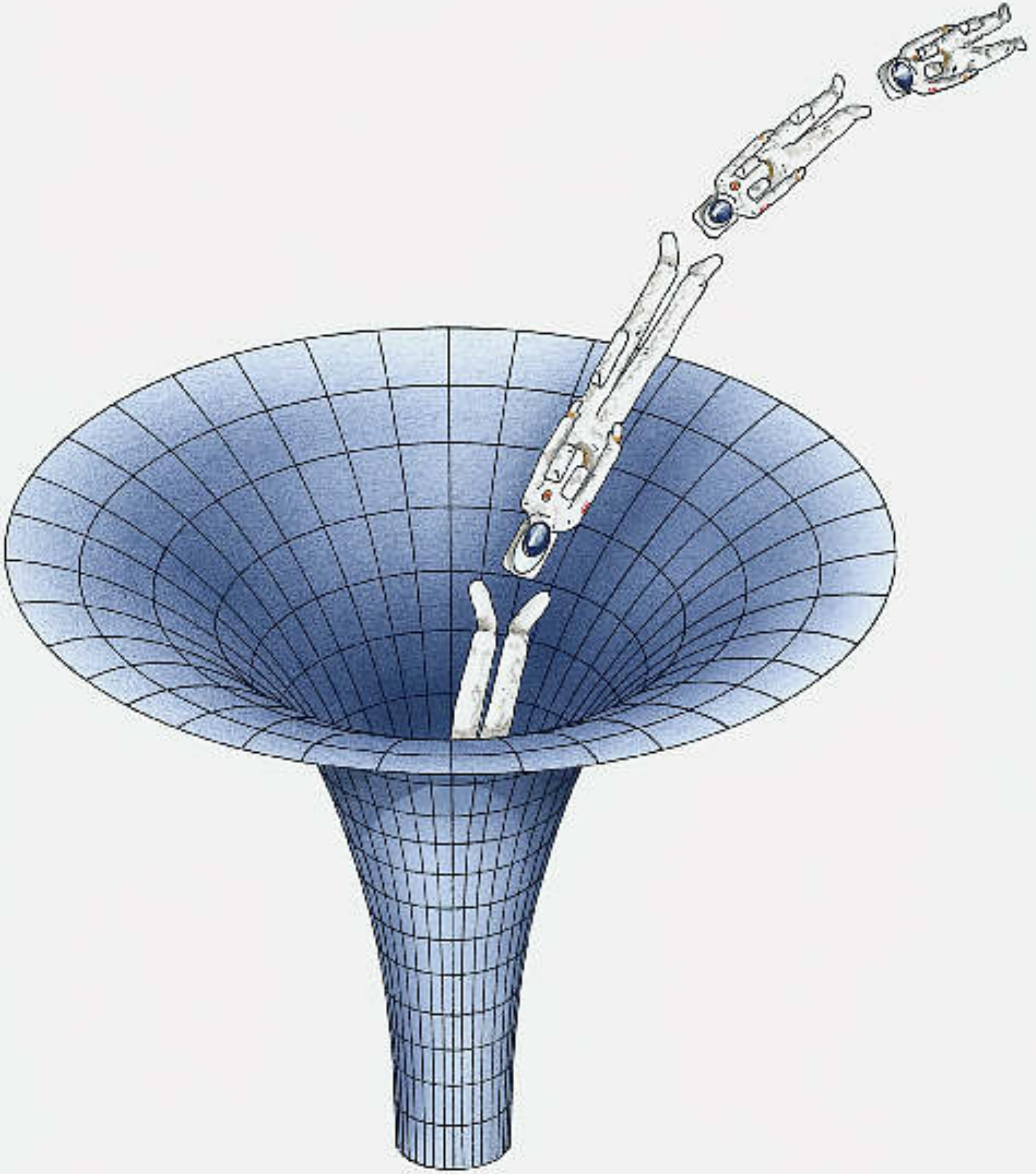
Gravitational potential ≈ rest mass $\Rightarrow$

$$r_s = \frac{2G_N m}{c^2} = 10^{-57}\ \text{m}$$

Different mass dependence $\Rightarrow$

$$r_s \gtrsim r_{em} \Rightarrow m \gtrsim M_P$$

These radii do not correspond to a physical size or solid crust, but only a dynamical size in terms of interactions



Quantum effects

Compton wavelength: $r_c = \frac{\hbar}{mc} = 4\times10^{-13}$ m

Coulomb radius: $r_{em} = \frac{\alpha\hbar}{mc} = 3\times10^{-15}$ m

$r_c \gtrsim r_{em} \Rightarrow$ for any m

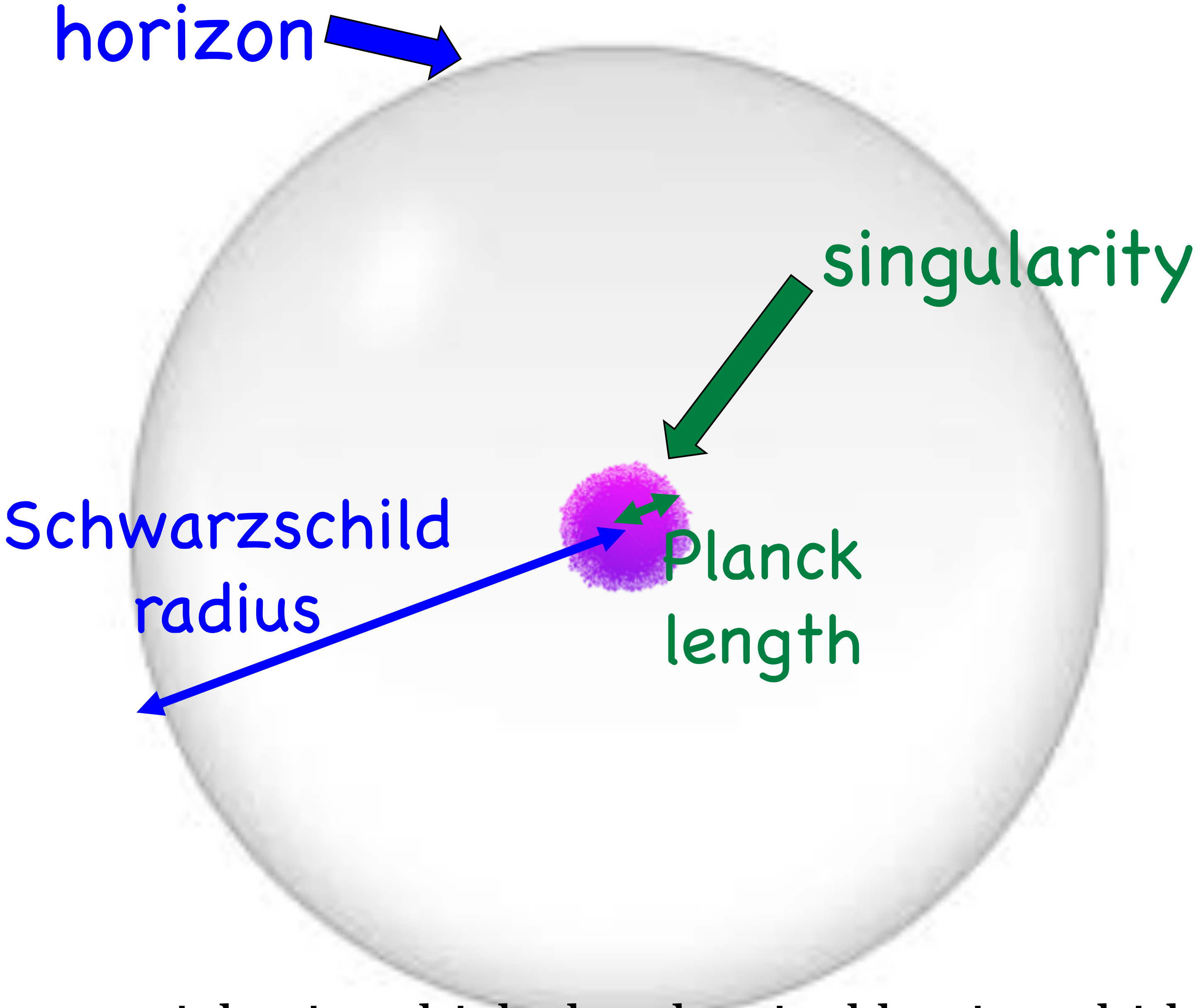
Particle physics is always quantum!

Gravity

Schwarzschild radius: $r_s = \frac{2G_N m}{c^2}$

$r_s \gtrsim r_c \Rightarrow$ for $m \gtrsim M_P$

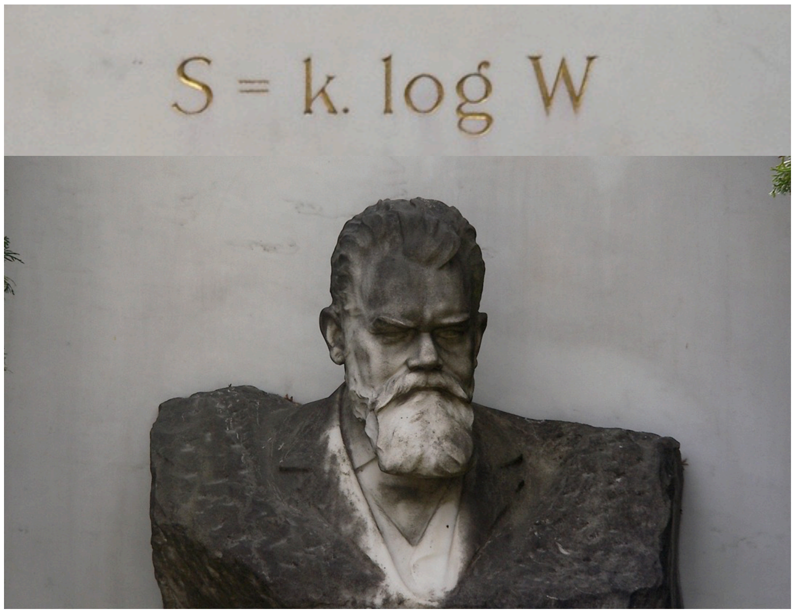
Super-Planckian BH are classical particles!



BH are particles in which the classical horizon hides to an external observer the quantum behavior of the singularity

BH entropy ∝ area ⇒ $S_{BH} = \frac{k_B c^3 \pi R^2}{G_N \hbar}$

Bekenstein bound ⇒ $S_{BH} \geq S(R)$



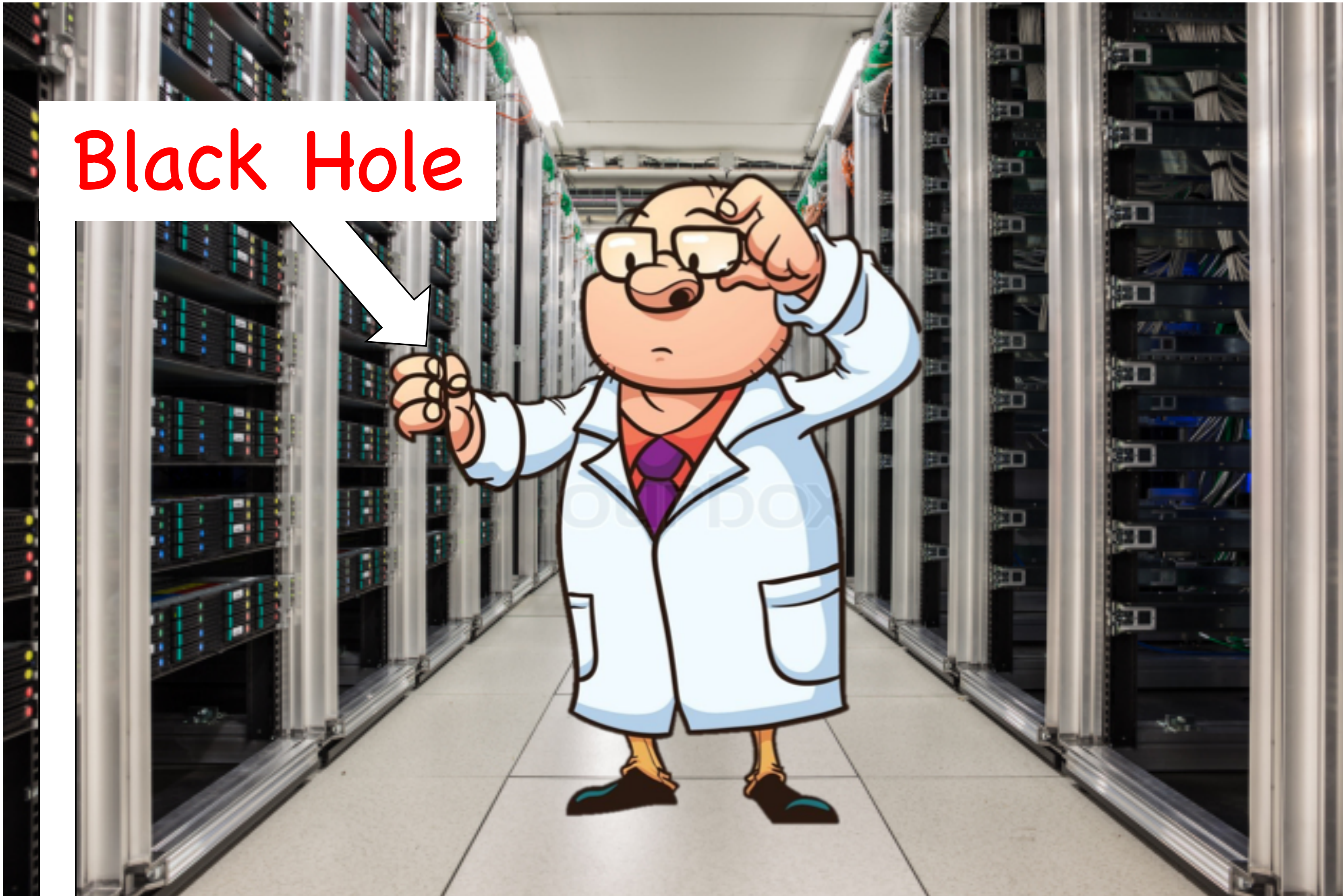
⇒

Number of microstates for a 10 $M_\odot$ BH:

$$W = 10^{5\times10^{63}}$$

Information stored in a BH of mass M (or radius R):

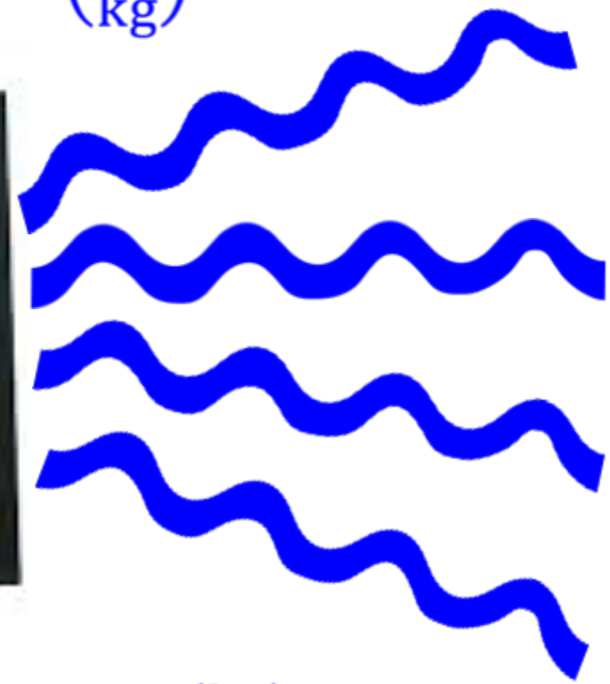
$$\frac{\pi\, G_N M^2}{\hbar c \ln 4} = 5\left(\frac{M}{\text{kg}}\right)^2 \text{petabytes} = 2\left(\frac{R}{10^{-27}\ \text{m}}\right)^2 \text{petabytes}$$



$$=5\left(\frac{M}{\text{kg}}\right)^2 \text{ petabytes} = 2\left(\frac{R}{10^{-27}\text{ m}}\right)^2 \text{ petabytes}$$

The black-hole quantum computer

$$\tau \approx \left(\frac{M}{\text{kg}}\right)^3 10^{-21}\ \text{s}$$



$$E \approx \left(\frac{\text{kg}}{M}\right) 10^{11}\ \text{GeV}$$

Hawking radiation!

Symmetry: the triumph of fundamental physics

Symmetry principles determine dynamics

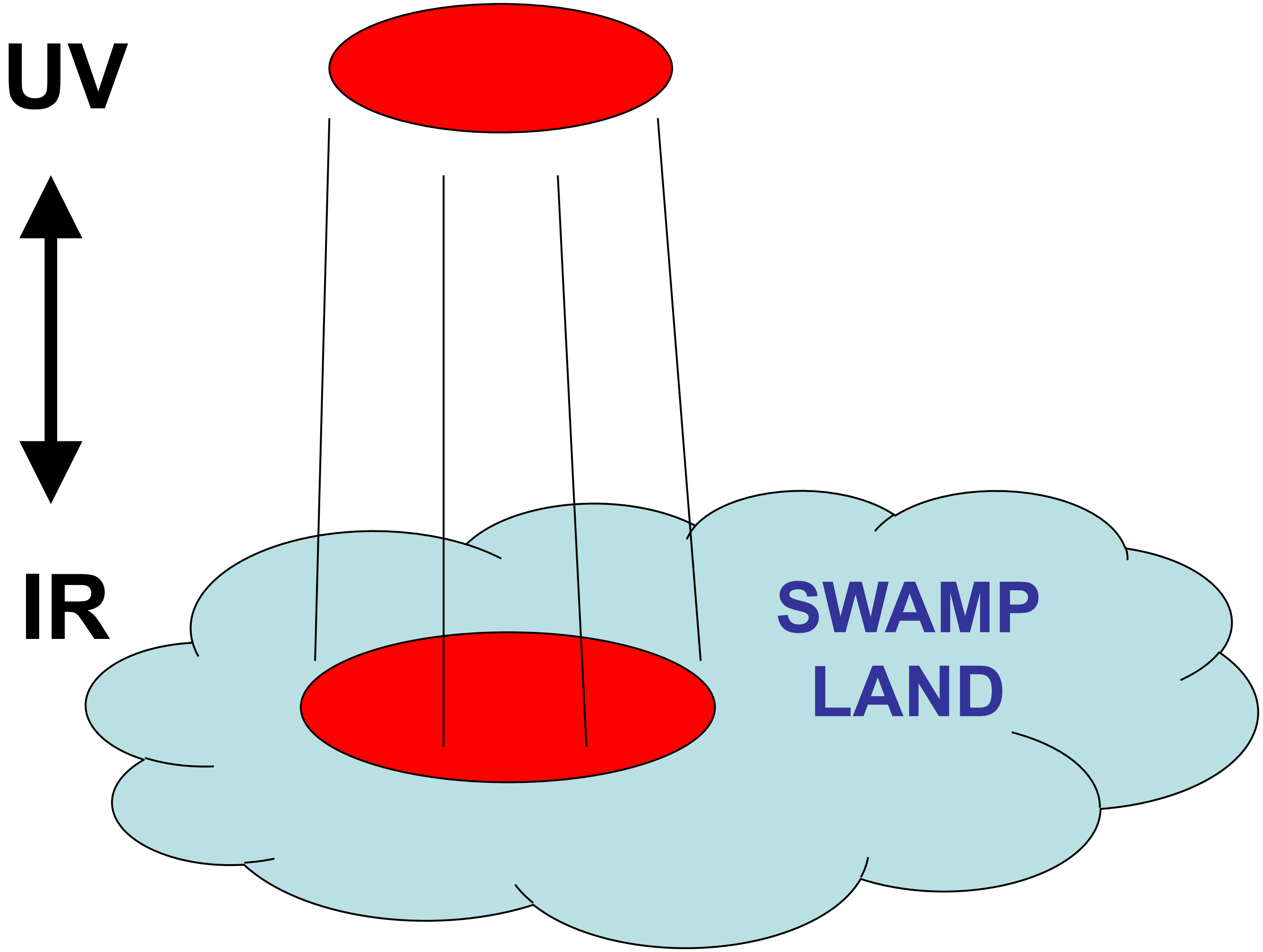
Gauge symmetry ⇒ SM
Space-time symmetry ⇒ GR
Global symmetry ⇒ selection rules (ν mass)
GUT symmetry? ⇒ unification of forces
Supersymmetry? ⇒ scale hierarchies

The decline of symmetry?

- Global symmetries are violated in Quantum Gravity
- Local symmetries are not symmetries
  (act trivially on Hilbert space)
- Gauge symmetries can be emergent
- Symmetries may not be sufficient to determine the low-energy theory

(Examples: anomaly matching condition; WGC; constraints from analyticity, unitarity, crossing, and Lorentz give non-trivial limitations on UV completions.)

Some theories allowed by symmetry live in the swampland



It challenges the EFT intuition

Hierarchy and CC problems are based on EFT intuition

New emerging concepts?
Duality: new faces of reality

(neither language of dual theory captures reality)

- Beyond a Lagrangian description?
- AdS/CFT: gravity/gauge duality
- Tensor networks (description of complex many-body systems based on their entanglement structure) reproduce properties of AdS/CFT
- Quantum gravity as a quantum information theory?
- Many new exciting ideas, but many crackpots too (and physics blogs are infested by insane non-science)

Back to GGI

- GGI must seize the opportunity for a quantum leap
- Focal point for graduate education and hub for theoretical physics
- The GGI must be for Italy what CERN-TH is for Europe or what Perimeter is for Canada
- Now it is time for an aggressive program of ambitious objectives
- Anything less than that would be a failure

Long live the GGI !