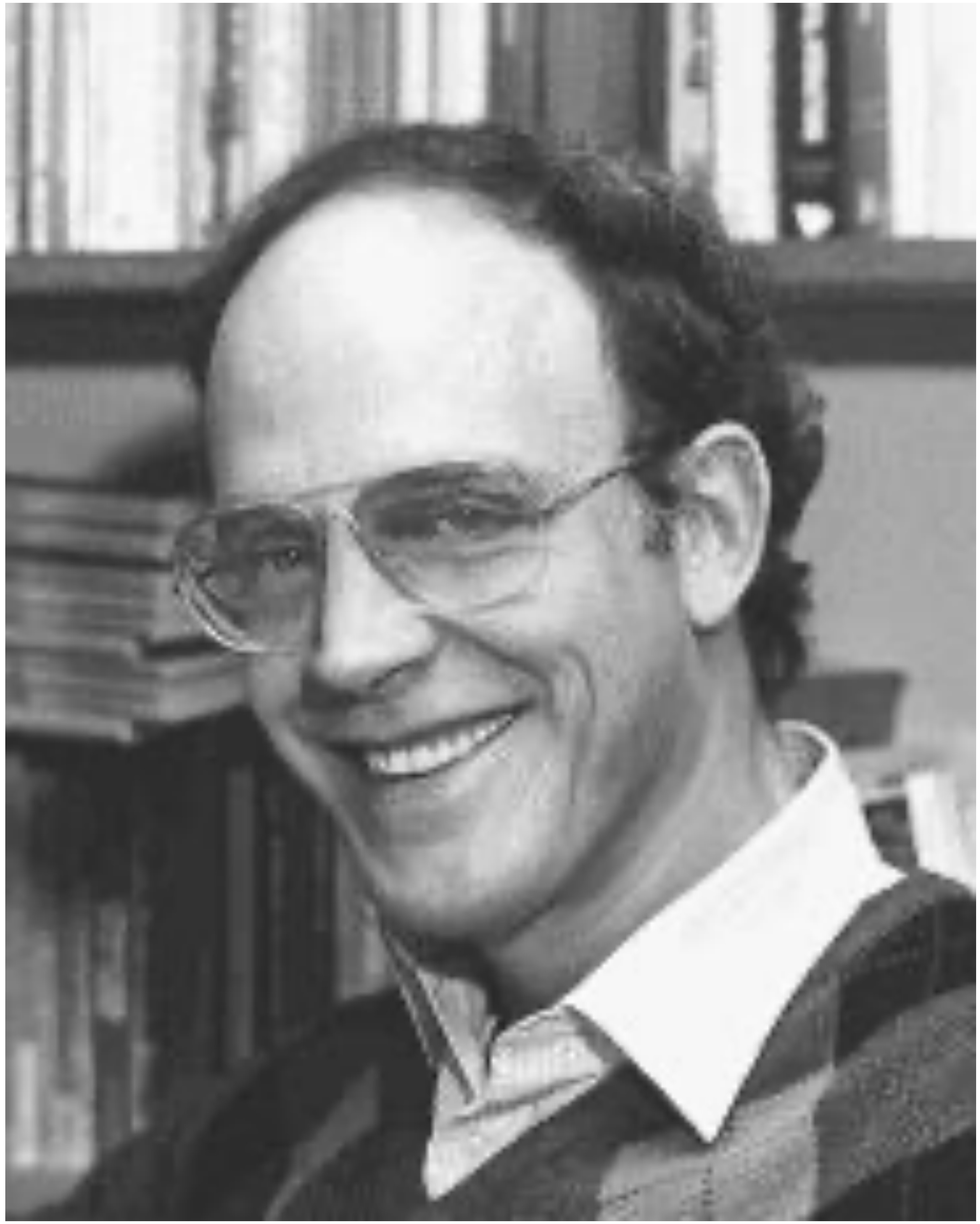
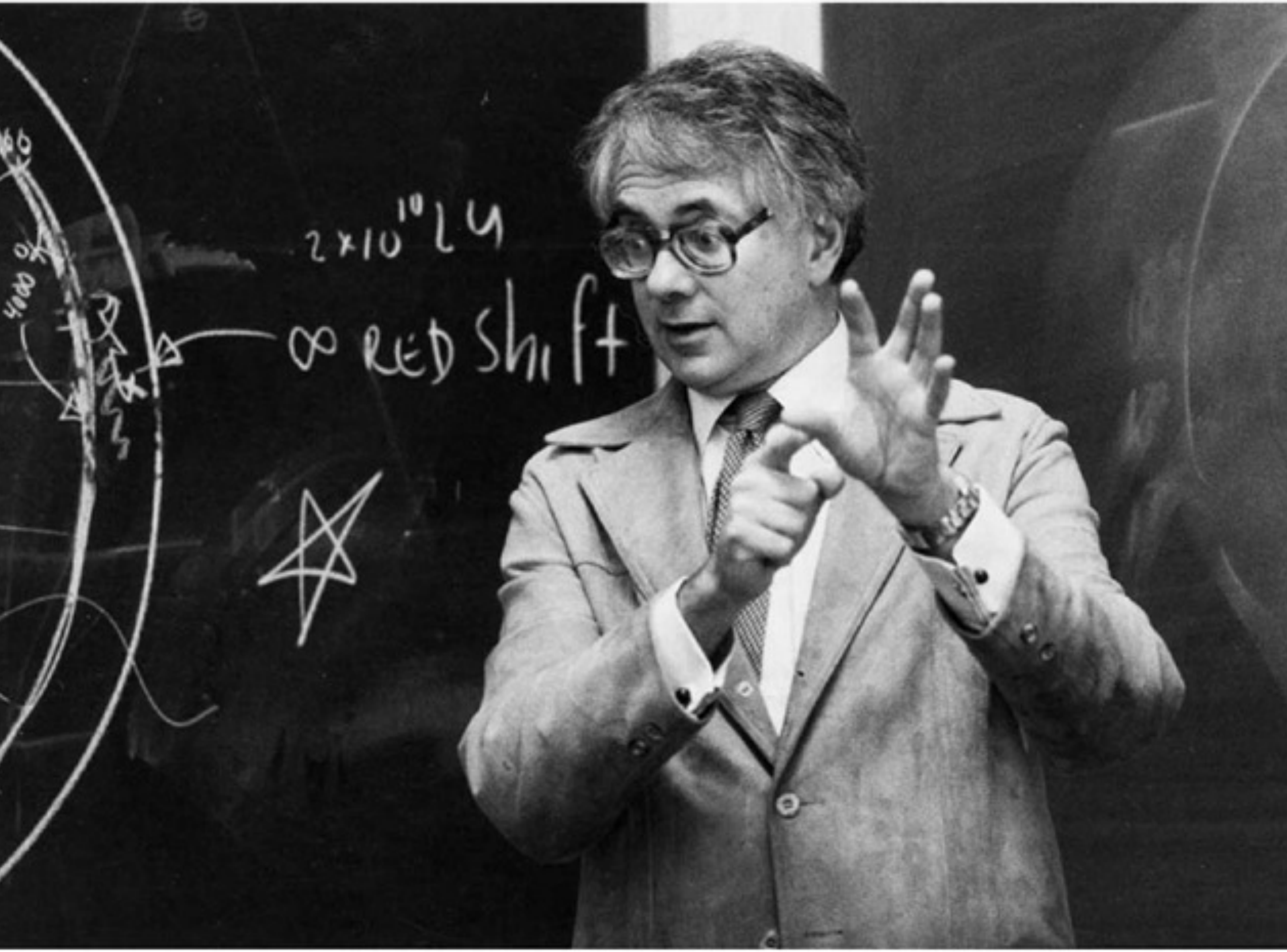
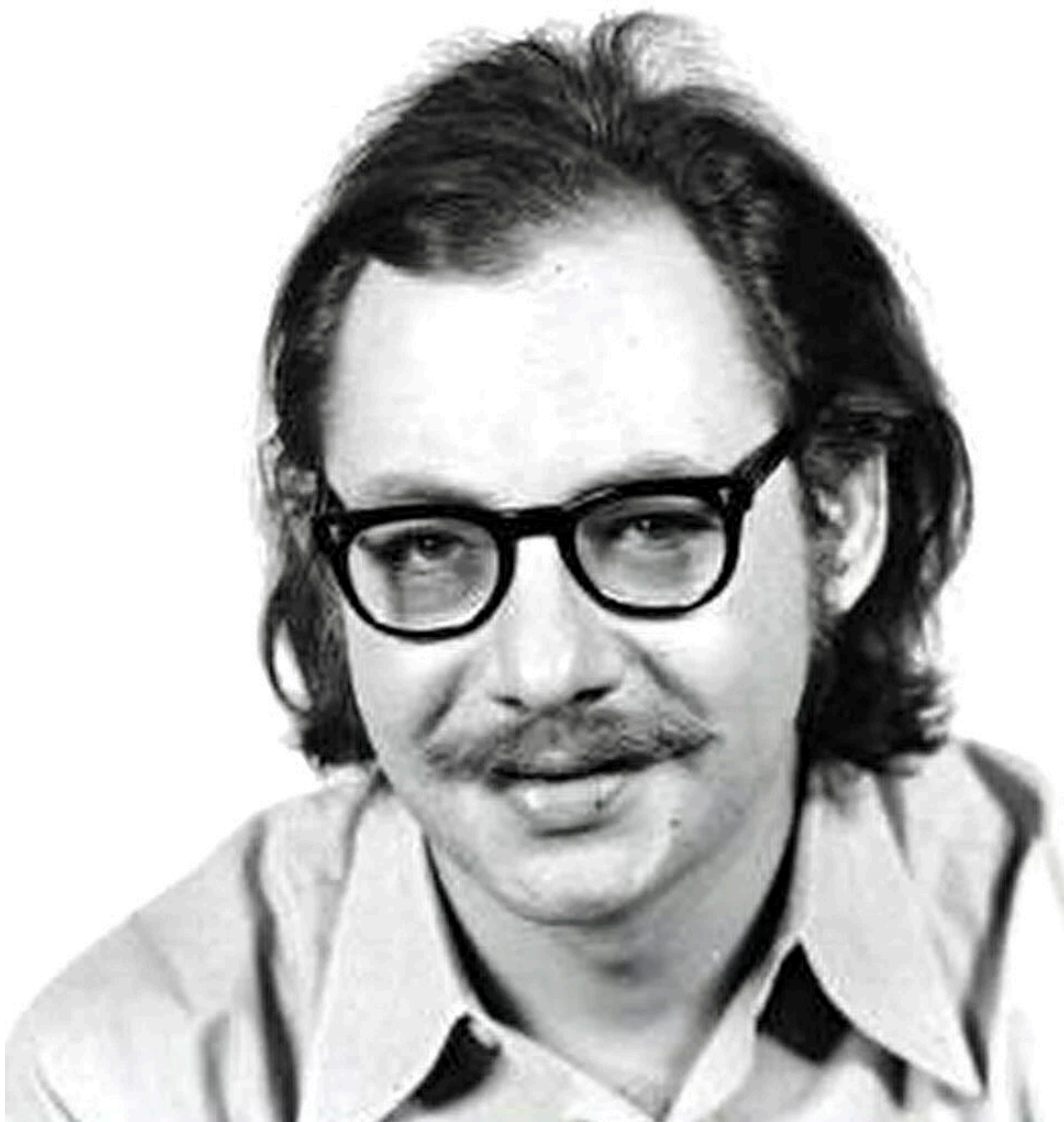
Golden Memories

I’ve Had a Few …

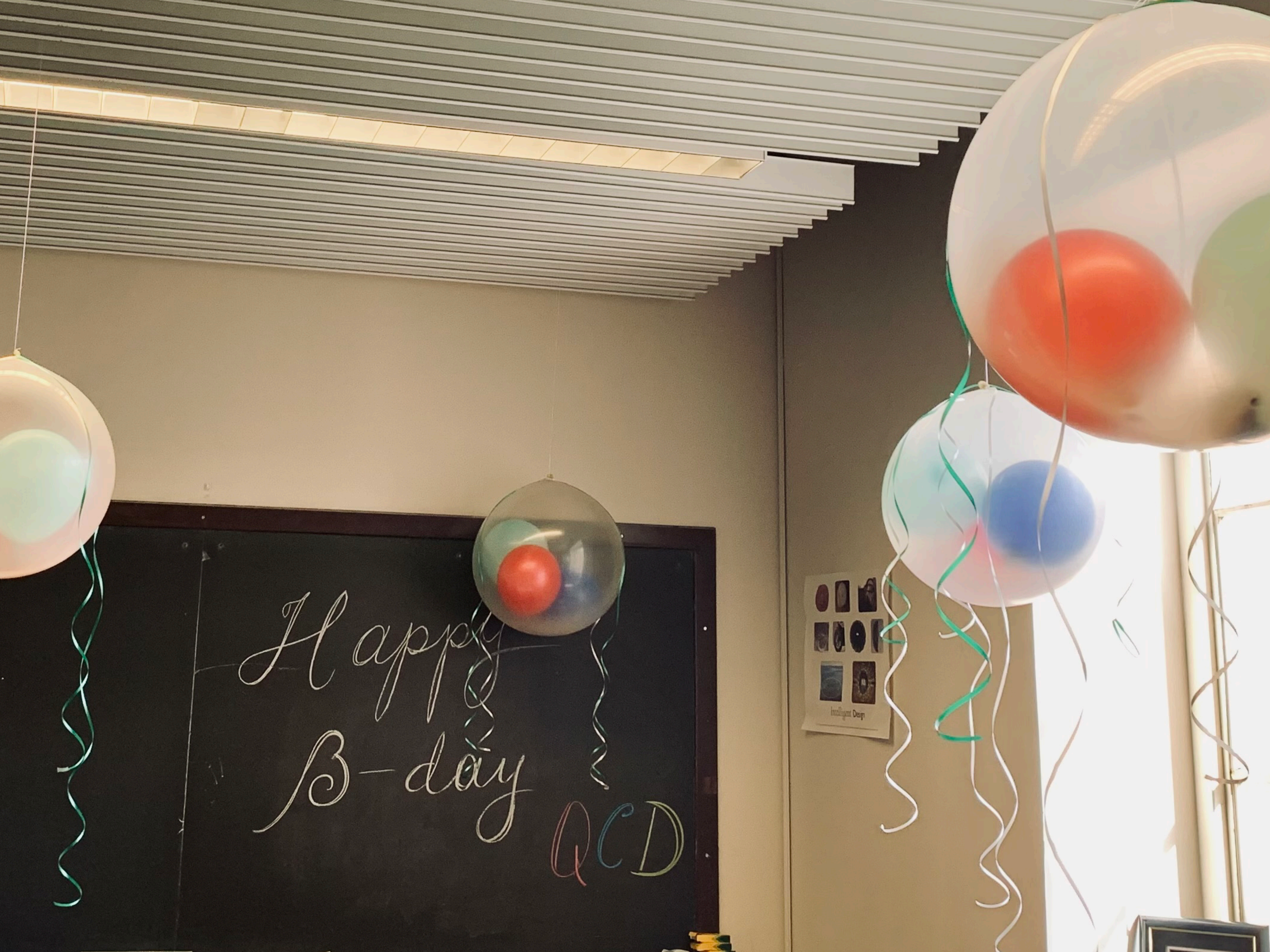



2×10^{10} LY
∞ RED Shift



Real Virtuality

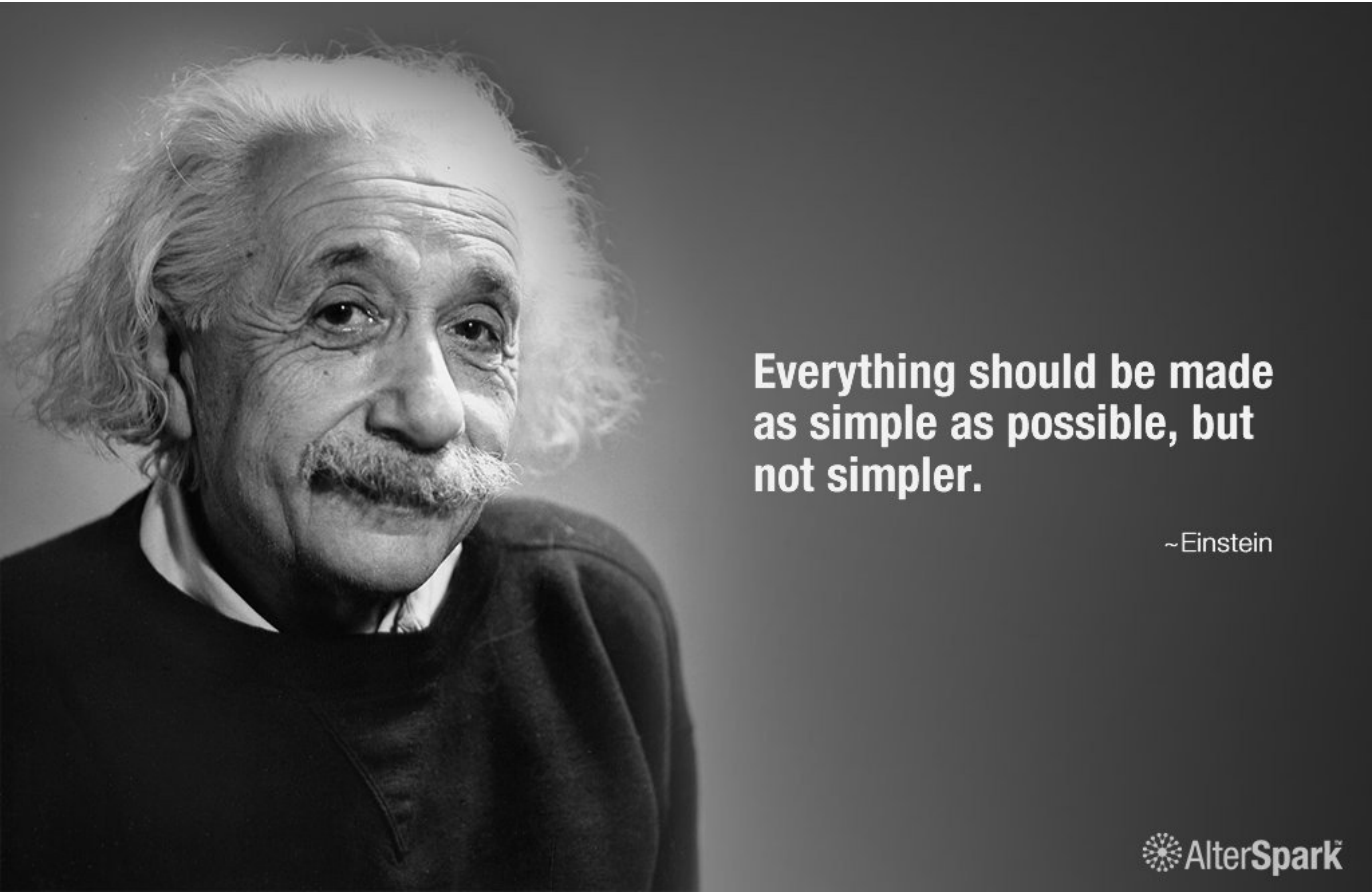
Confinement and Freedom


Happy
β-day
QCD

The tension between confinement and freedom is a basic feature of the strong interaction and QCD.

Some people still find it disturbing.

To ease our minds, and to clarify our ideas, it is useful to consider simpler systems that have the same kind of tension.


Everything should be made as simple as possible, but not simpler.
~Einstein
AlterSpark

(1) QED in 1+1 Dimensions

"As simple as possible, but no simpler"

3+1 dimensional non-abelian gauge theories are gloriously difficult.

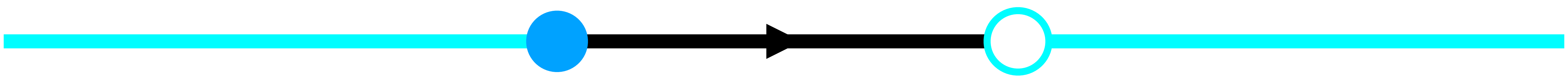
1+1 dimensional gauge abelian gauge theories are much easier to deal with. Fortunately, they still shine a brilliant light on the issues around freedom versus confinement and *real virtuality*.

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{Q}\Big(\gamma^\mu(i\partial_\mu - qA_\mu) + m\Big)\,Q$$

We can choose $A_1 = 0$ gauge. Then the gauge field part contains no time derivatives, and we can use the equation of motion to eliminate it.

The resulting theory is easy to visualize:

Electric flux “tubes” run from particles to antiparticles.



There is a constant force, reflecting the energy cost of extending the flux tube.

“I try to avoid hard work. When things look complicated, that is often a sign that there is a better way to do it.”

FRANK WILCZEK
Nobel Prize in Physics 2004

(2) Real Virtuality

Sharpening the Paradox

The force is inexorable, so charge is confined.

But the force is weak, so the quarks move almost freely.

(Note that $[q] = [m] = 1$, so it makes sense to say that $m > > q$ defines weak coupling.)

We can calculate the spectrum and the wave-functions of the bound states ("mesons").

There is a discrete spectrum of stable mesons starting at approximately $2m$ and extending to the threshold, at approximately $4m$, for producing two mesons.

The highly excited mesons above threshold slowly decay through a non-perturbative "string breaking" process.

Now, as a thought experiment, let us consider a process analogous to e^+e^- in this world.

To do that, we introduce a second even more weakly coupled gauge field that couples both to relatively light “electrons” and to our “quarks”.

On the one hand, it is obvious that for $E_\gamma > 2m$ quark-antiquark pairs produced with a decent amount of energy will be happy to pop into existence and move around. In particular, something observable happens!

On the other hand, remember that the spectrum is discrete, and where there are no states the S-matrix is basically trivial.

(The photon coupling will allow - very slow - decays into electrons, and thus broaden our mesons a bit, but that does not solve the paradox.)

(3) Time-Energy Uncertainty

Reconciling Eternal and Transient

The resolution:

The spectrum and the S-matrix reflect behavior over infinitely long times …

… but life is finite.

$$[X, Y] = iZ$$

$$X - \langle X \rangle \leftarrow X \qquad Y - \langle Y \rangle \leftarrow Y$$

$$0 \leq \langle (X - i\lambda Y)(X + i\lambda Y) \rangle$$

$$= \langle X^2 \rangle + \lambda^2 \langle Y^2 \rangle + \lambda \langle Z \rangle$$

No real roots ⇒ $\langle Z \rangle^2 \leq 4 \langle X^2 \rangle \langle Y^2 \rangle$

$$[X, Y] = iZ$$

$$\langle Z \rangle^2 \leq 4 \langle X^2 \rangle \langle Y^2 \rangle$$

Applied to

$$[H, A] = i \frac{dA}{dt}$$

$$\Rightarrow \boxed{\frac{1}{2} \leq \frac{\langle (\Delta E)^2 \rangle^{1/2} \; \langle (\Delta A^2) \rangle^{1/2}}{|\langle \frac{dA}{dt} \rangle|}}$$

One can solve for the bound states using the Schrödinger equation.

For large quantum numbers - many nodes - one can get the spacing by WKB methods (next slide).

One finds energies $E(n) \propto n^{\frac{2}{3}} \frac{Q^{\frac{4}{3}}}{m^{\frac{1}{3}}}$

and

splittings $\Delta E(n) \propto n^{-\frac{1}{3}} \frac{Q^{\frac{4}{3}}}{m^{\frac{1}{3}}}$

$$2\pi n = \int dx\, p = 4\sqrt{2m} \int_0^{\frac{2E_n}{Q^2}} dx \sqrt{E_n - \frac{Q^2}{2}x}$$

$$E(n) \propto n^{\frac{2}{3}} \frac{Q^{\frac{4}{3}}}{m^{\frac{1}{3}}}$$

These energy splittings are small in absolute terms (i.e., in units of m), and shrink as n grows.

Thus, to resolve the spectral structure you must take a long time.

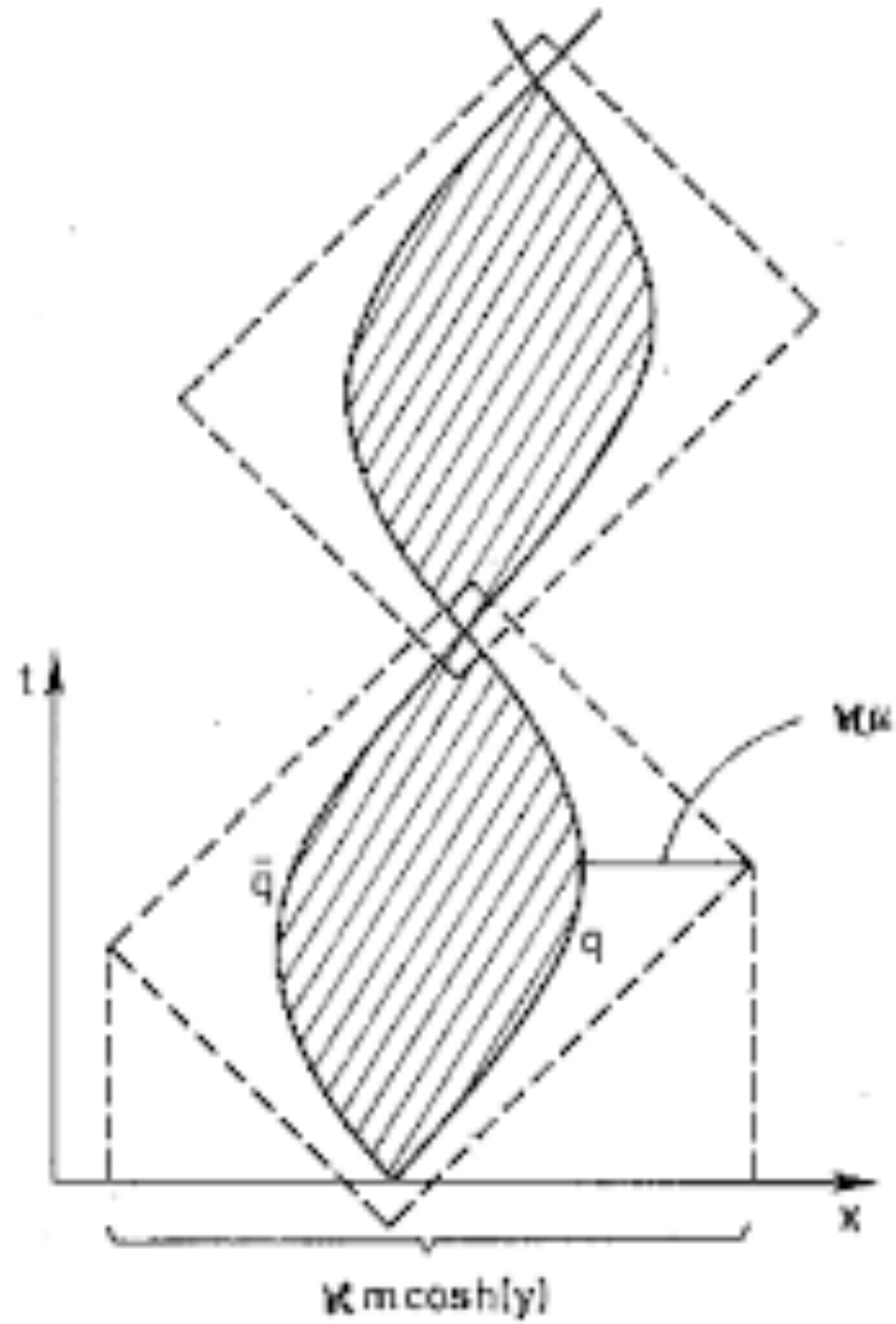
The weird picture of dynamics that is (superficially) suggested by the spectrum and S-matrix need not apply to less leisurely observations -

- and it doesn't!

It is entertaining to visualize how the long-time description builds up.

Our quark-antiquark pairs start moving apart, eventually run out of energy, and then return, … and do it over and over again.

If our measurements sample these events for a long time, there can be destructive interference!


t
x
q̄
q
γ(κ
γκ m cosh(y)

Similar to how a pattern of sharp lines emerges from a many-slit diffraction grating, here after many transits we build up a sharp spectrum of mesons over time.

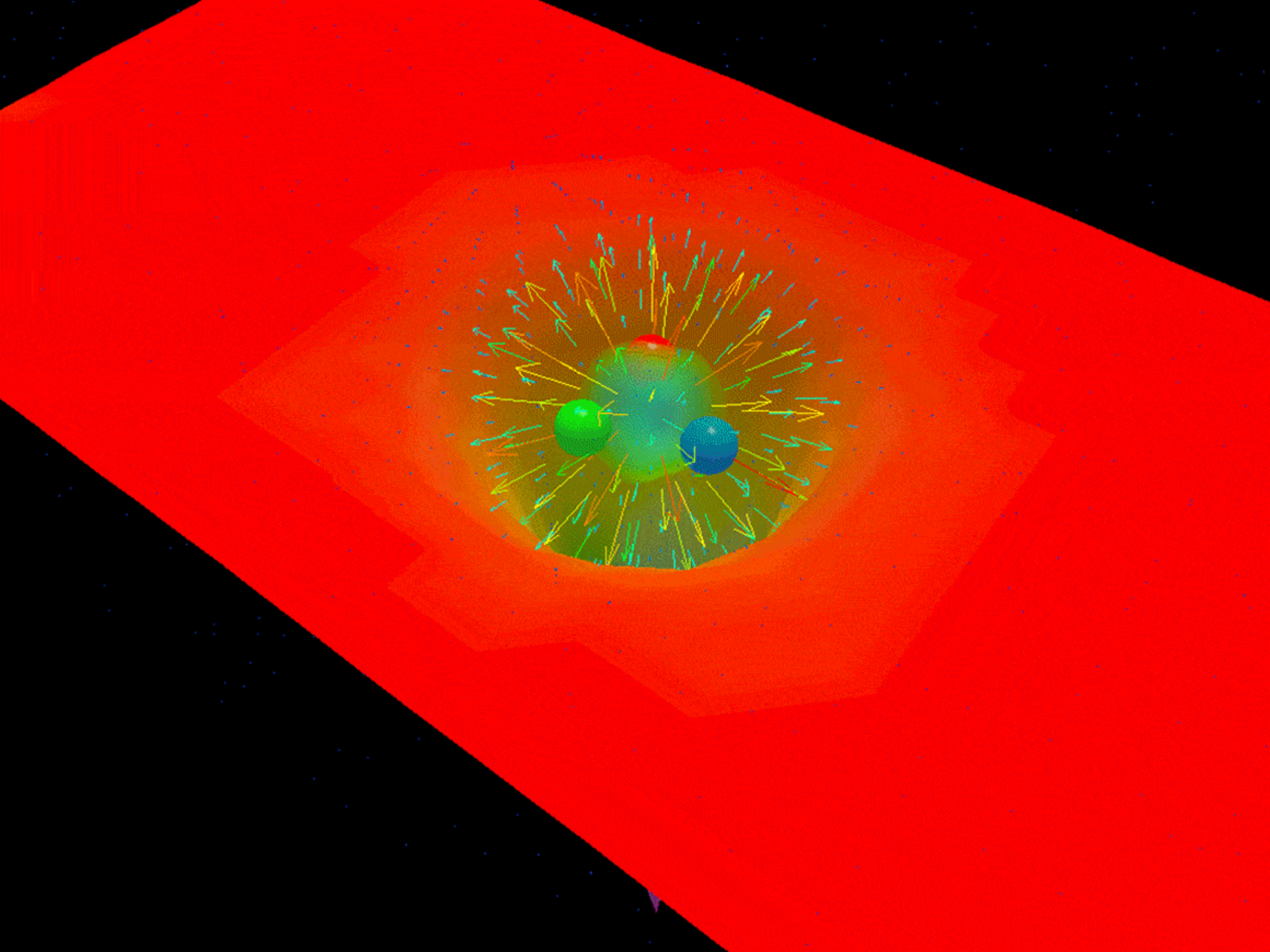
Taking spatial structure of the interference into account, we also get associated wave-functions.

Freedom and confinement are a splendid example of complementary, closely related to the complementarity of time and energy.

Freedom, using perturbative QFT, is the appropriate description if want good time resolution. Confinement, using the spectrum and S-matrix, is the appropriate description if you want good energy resolution.

(4) Back to QCD

Sticky Gluons - and Vertons



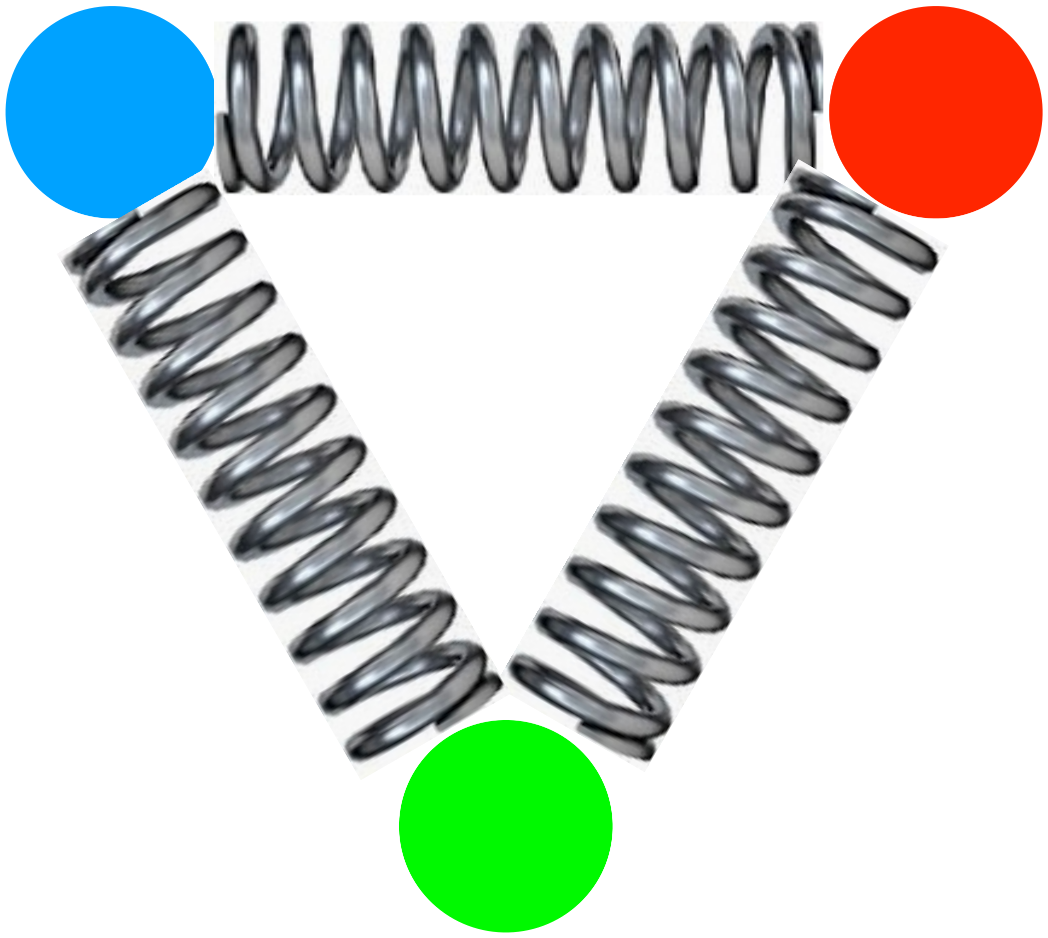
The essential dynamics that makes 3+1 QCD resemble 1+1 QED is that electric flux does not spread out, but rather forms tubes.

There is an attraction among gluons, that makes them want to stick together.

Asymptotic freedom ($\beta < 0$) shows the onset of that behavior.

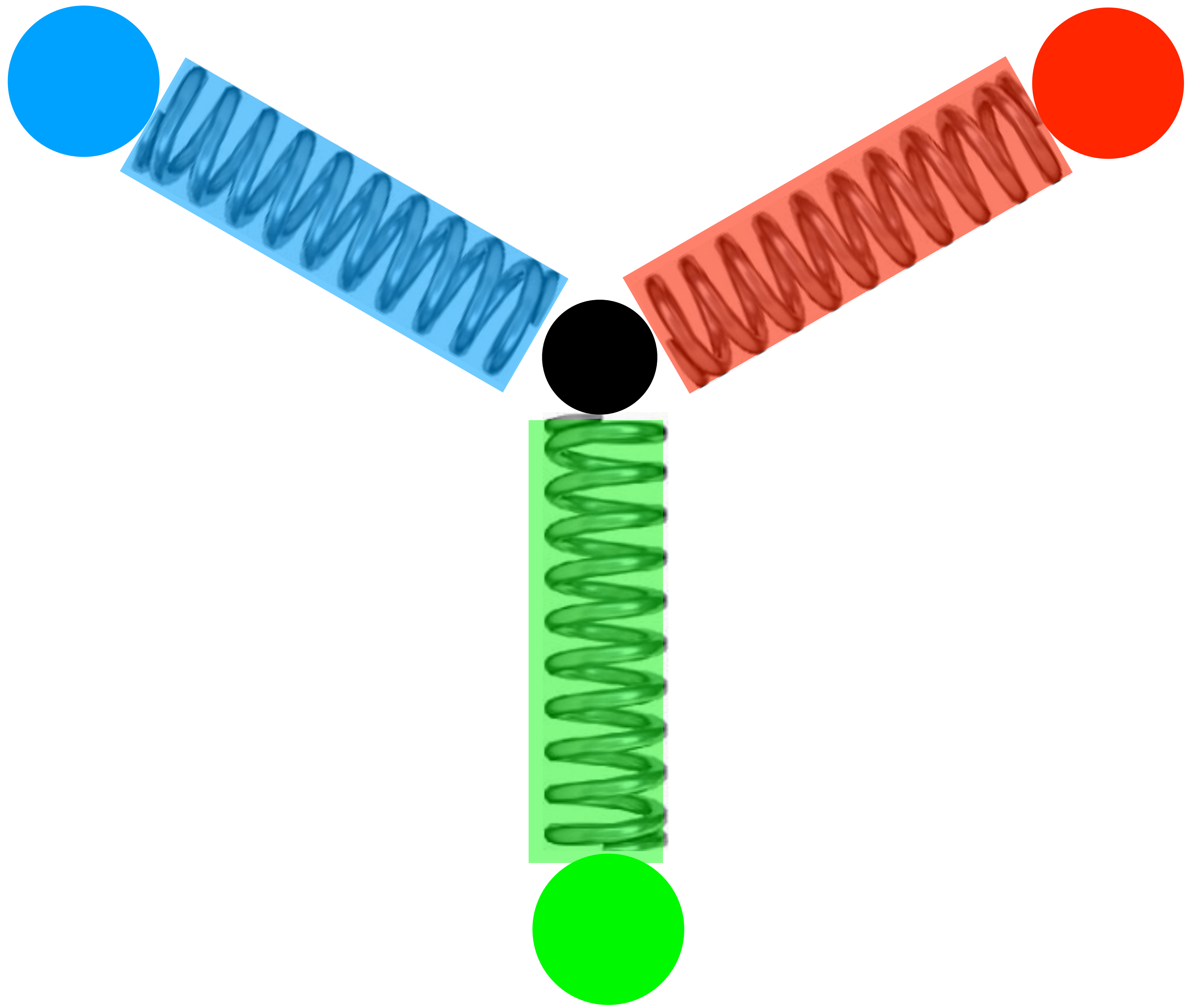
A widely used and amazingly successful model of hadronization - the Lund model - takes off from the idea of flux tubes connecting quarks.

To mimic the “3” in color $SU(3)$, we can use $U(1) \times U(1) \times U(1)$ with an appropriate charge spectrum:



$$(1, -1, 0) \ \& \ (-1, 0, 1) \ \& \ (0, 1, -1)$$

Or, better:



(1,0,0) & (0,1,0) & (0,0,1) + verton (−1, −1, −1)

We can implement the verton concept mathematically by introducing the interaction: $\Delta\mathscr{L} = \kappa F^1 F^2 F^3$, where $F^1 \equiv \epsilon^{\mu\nu} F^1_{\mu\nu}$ etc.

In real world QCD we have some very light quarks (and hadrons). Stretched flux tubes can fragment easily - “string breaking” - and so the virtual particles are difficult to discern directly.

On the other hand, because string breaking is easy it is a soft process. So at high energies we get jets that follow the energy-momentum flow of the underlying hard quarks and gluons.

(5) Real Virtuality Elsewhere

A Conceptual Tool

Much of the preceding discussion applies, with appropriate modifications, to the dynamics of domain walls separating discretely different “ground states” in 1+1 dimensional systems.

The (real) virtual fluctuations appear in several contexts, notably as avatars of false vacuum decay when there is metastability (or stability).

One also has weak confinement of quarks in 2+1 dimensions, by a similar mechanism, since $V(r) \sim Q^2 \ln r$.

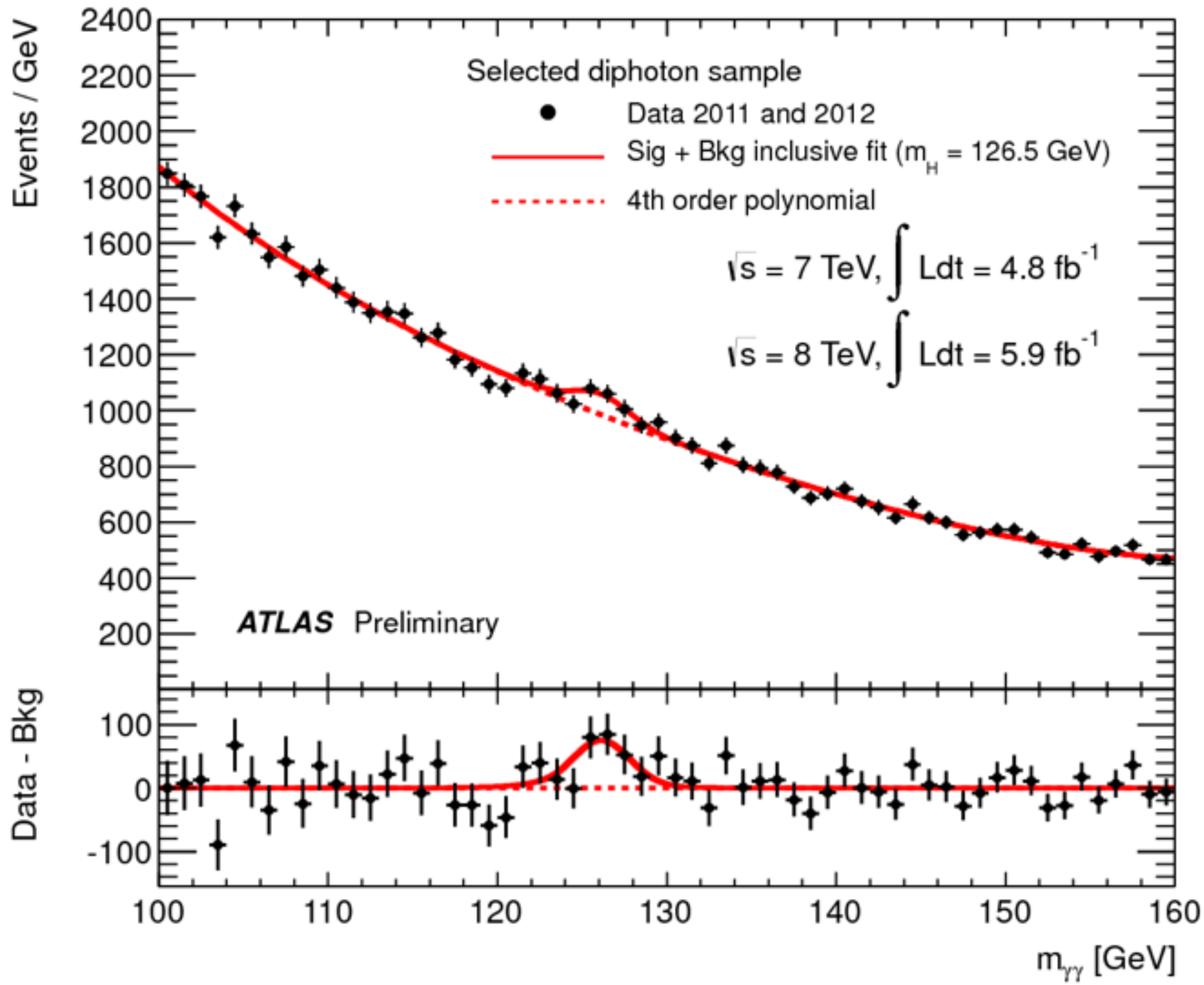
(As shown by Polyakov, here a non-perturbative mechanism “confines” the photon too, albeit with an exponentially small gap at weak coupling.)

In the real world we can have modified QED force laws inside cavities …

… and no doubt other embodiments.

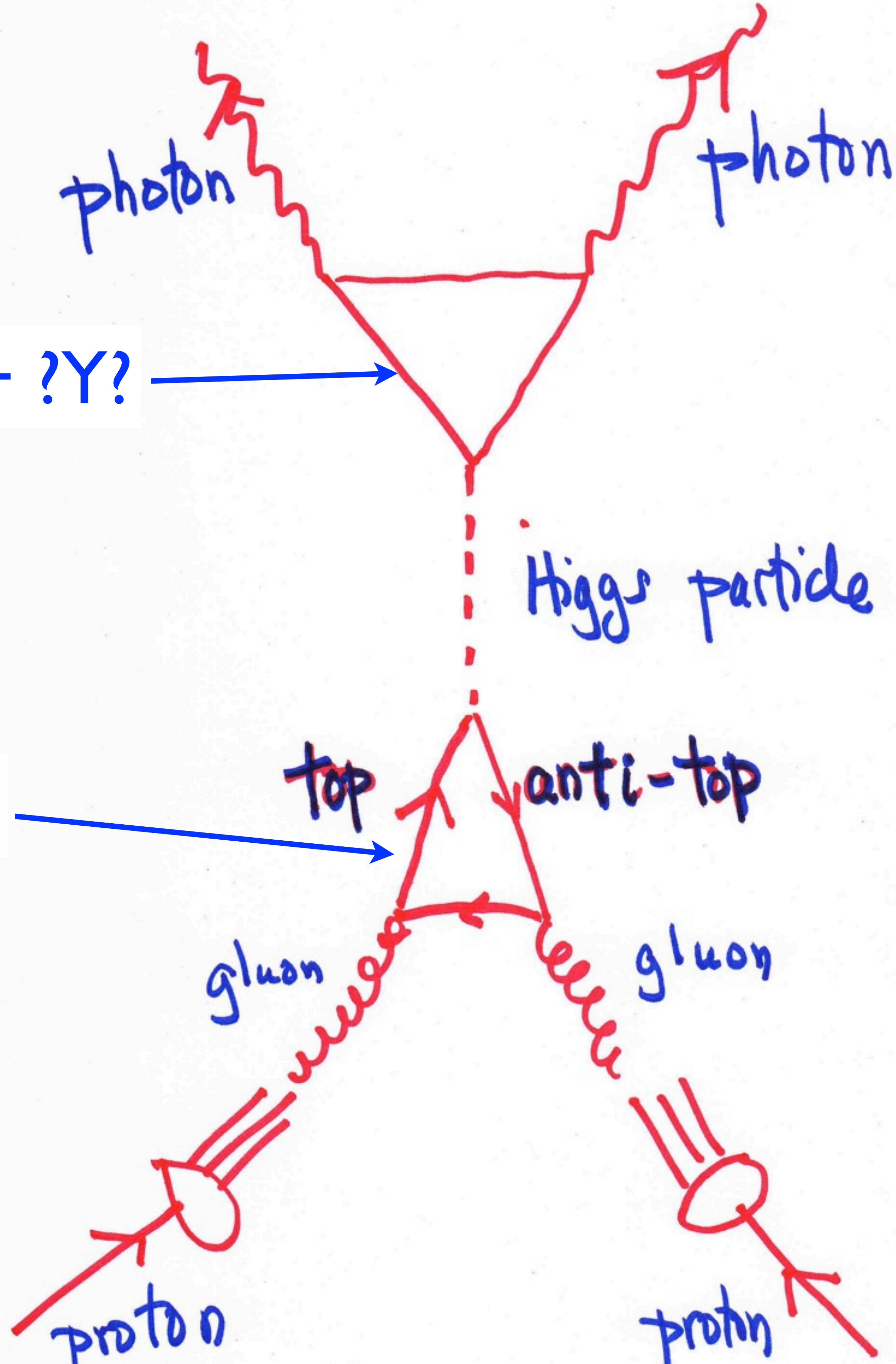
Quo Vadis, QCD?

Foundation and Platform


Events / GeV
Selected diphoton sample
Data 2011 and 2012
Sig + Bkg inclusive fit (m_H = 126.5 GeV)
4th order polynomial
√s = 7 TeV, ∫ Ldt = 4.8 fb^-1
√s = 8 TeV, ∫ Ldt = 5.9 fb^-1
ATLAS Preliminary
Data - Bkg
m_γγ [GeV]
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
100
0
-100
100
110
120
130
140
150
160

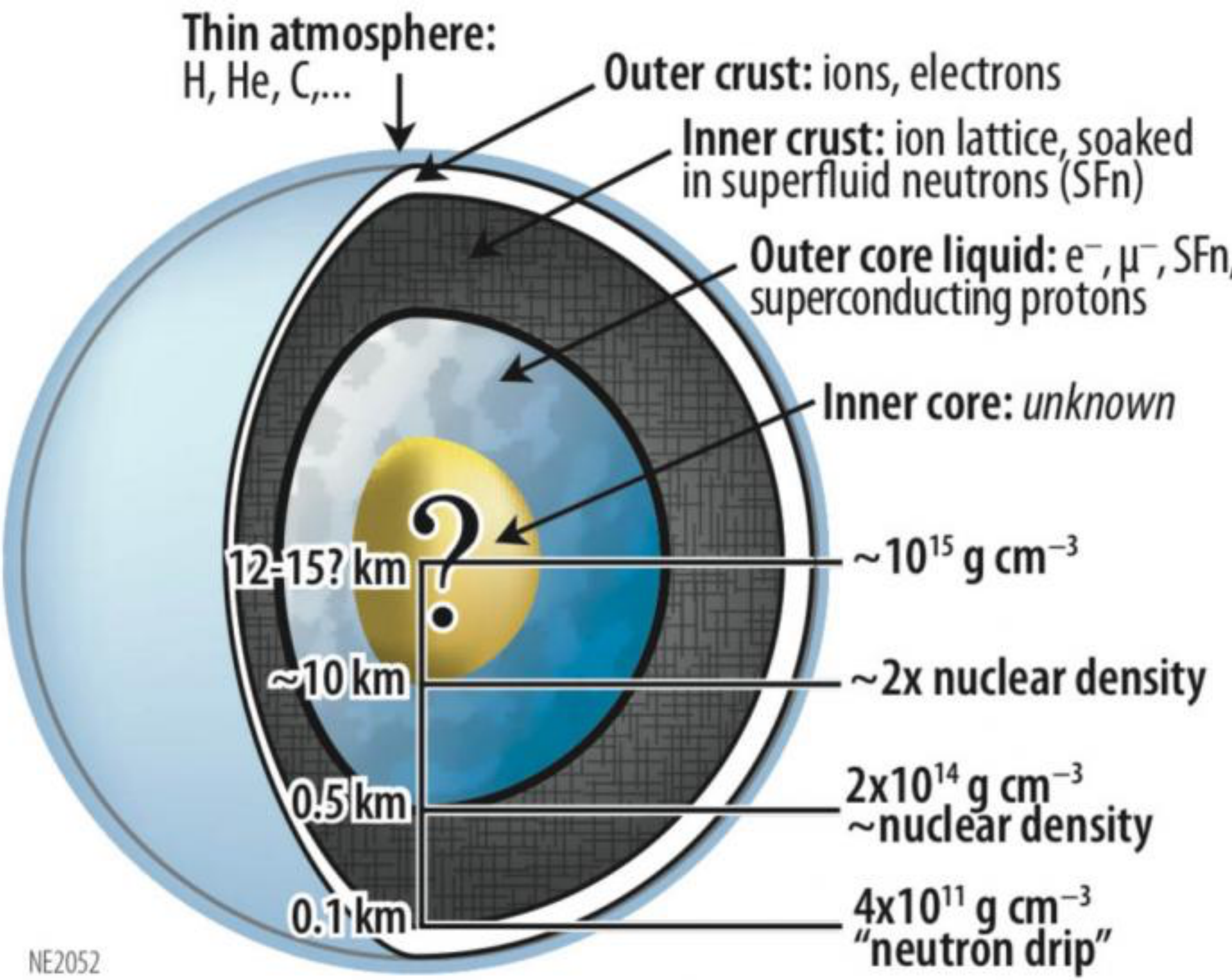
$t\bar{t}$ + W^+W^- + ?Y?

$t\bar{t}$ + ?X?



decay

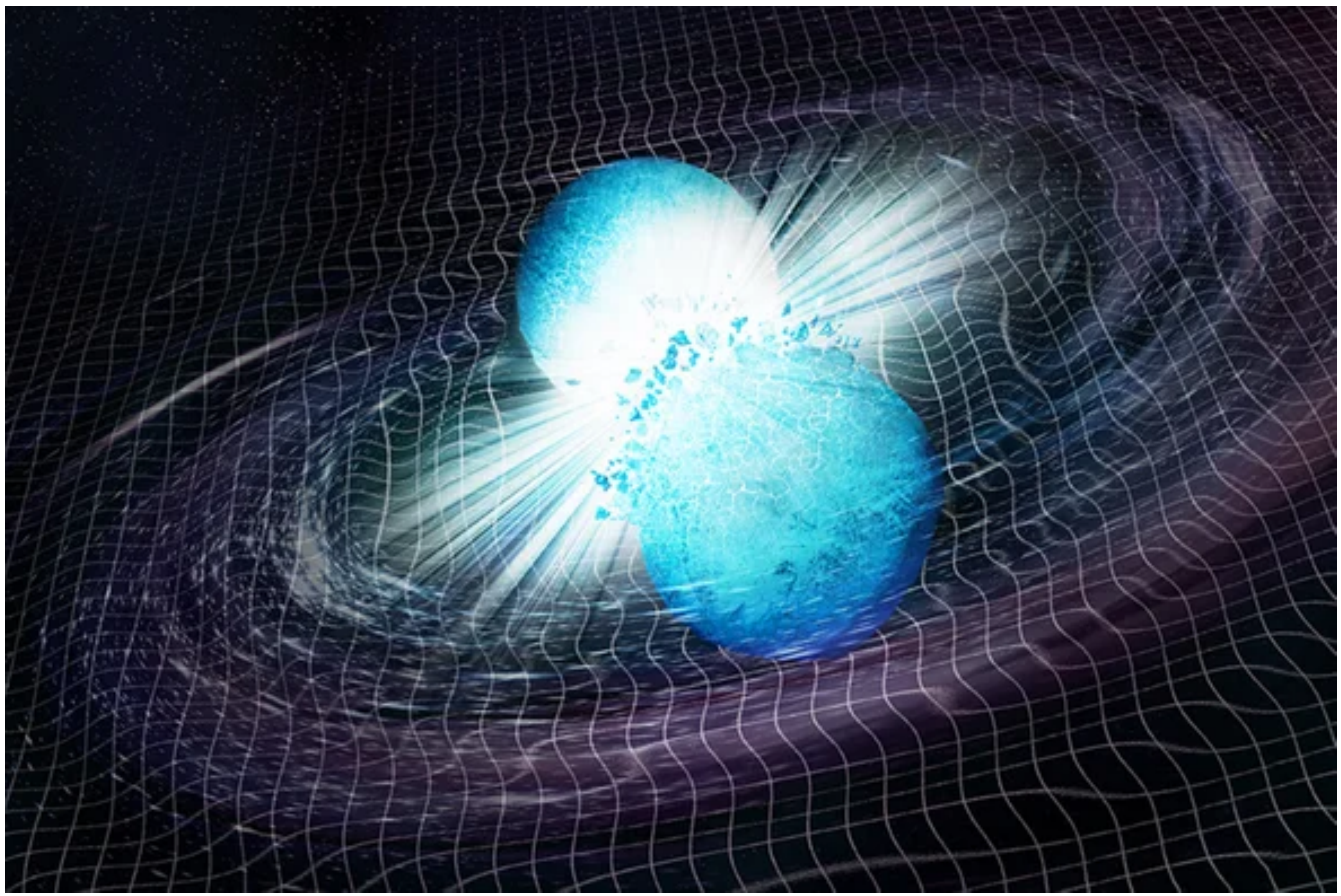
production


Thin atmosphere:
H, He, C,...
Outer crust: ions, electrons
Inner crust: ion lattice, soaked in superfluid neutrons (SFn)
Outer core liquid: e⁻, μ⁻, SFn, superconducting protons
Inner core: unknown
12-15? km
~10 km
0.5 km
0.1 km
~10^15 g cm^-3
~2x nuclear density
2x10^14 g cm^-3
~nuclear density
4x10^11 g cm^-3
"neutron drip"
NE2052

SPACE

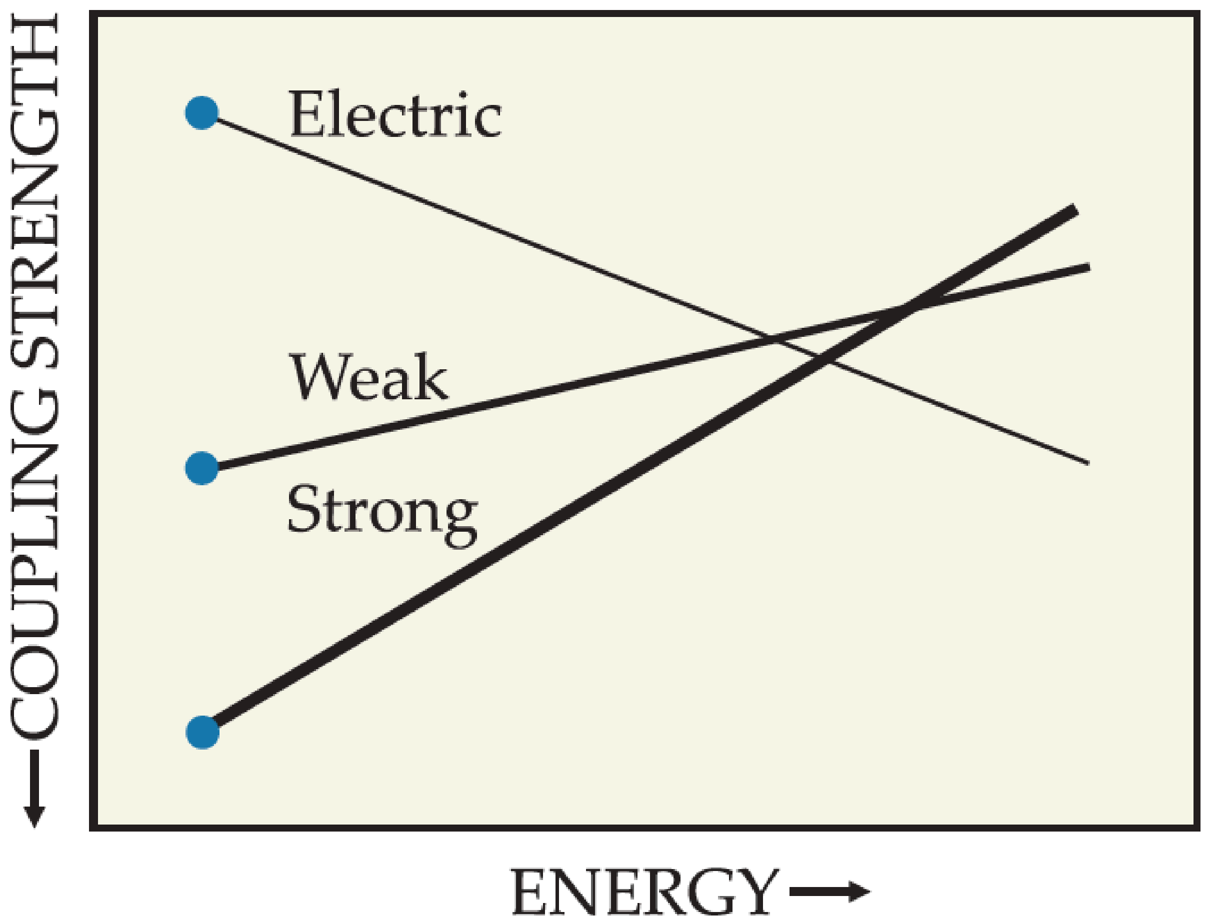
Gravitational Waves Reveal the Hearts of Neutron Stars

Scientists are mapping the extreme interiors of exotic stars with unprecedented clarity, and setting new boundaries on the births of black holes



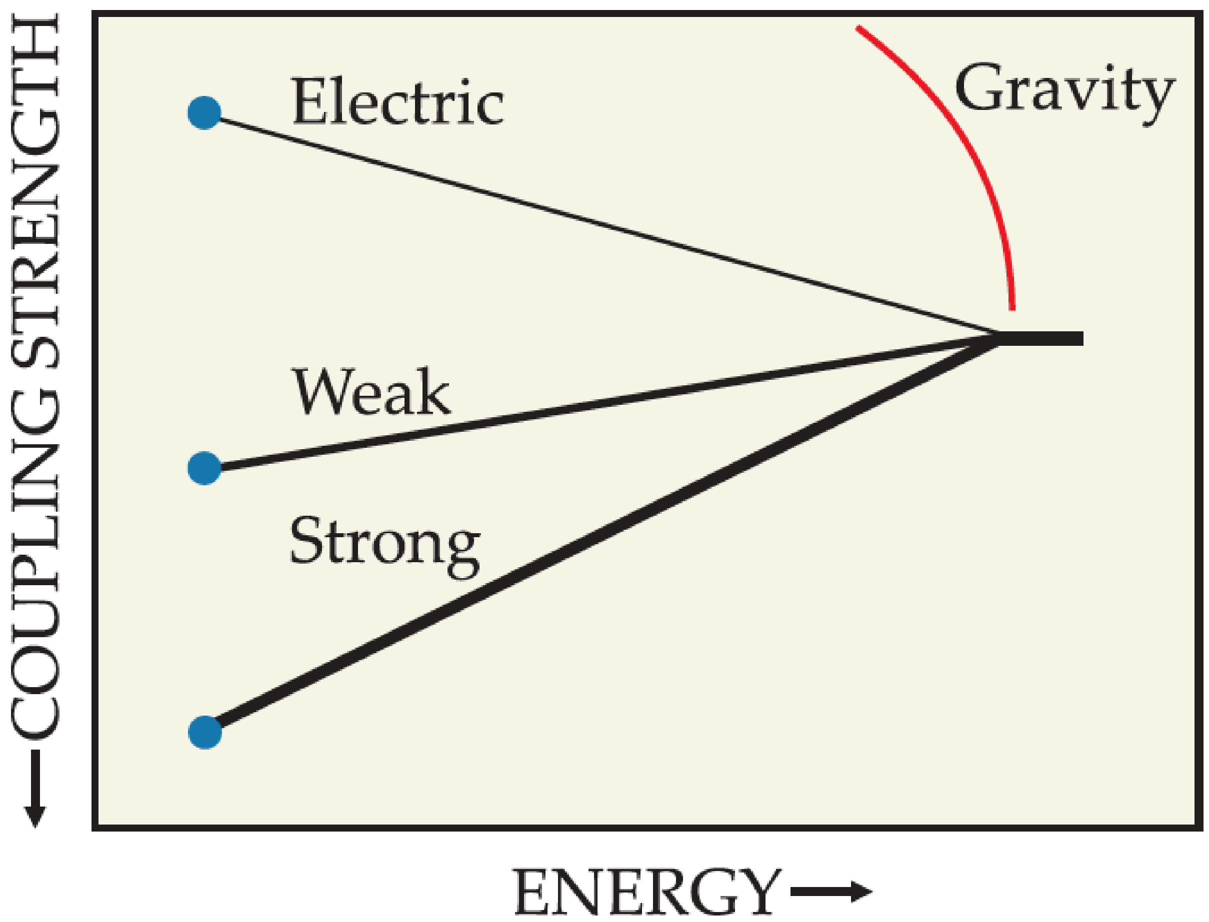
J. Sokol, Scientific American June 2018

Robert Forward, "Dragon's Egg": Life on a Neutron Star known particles



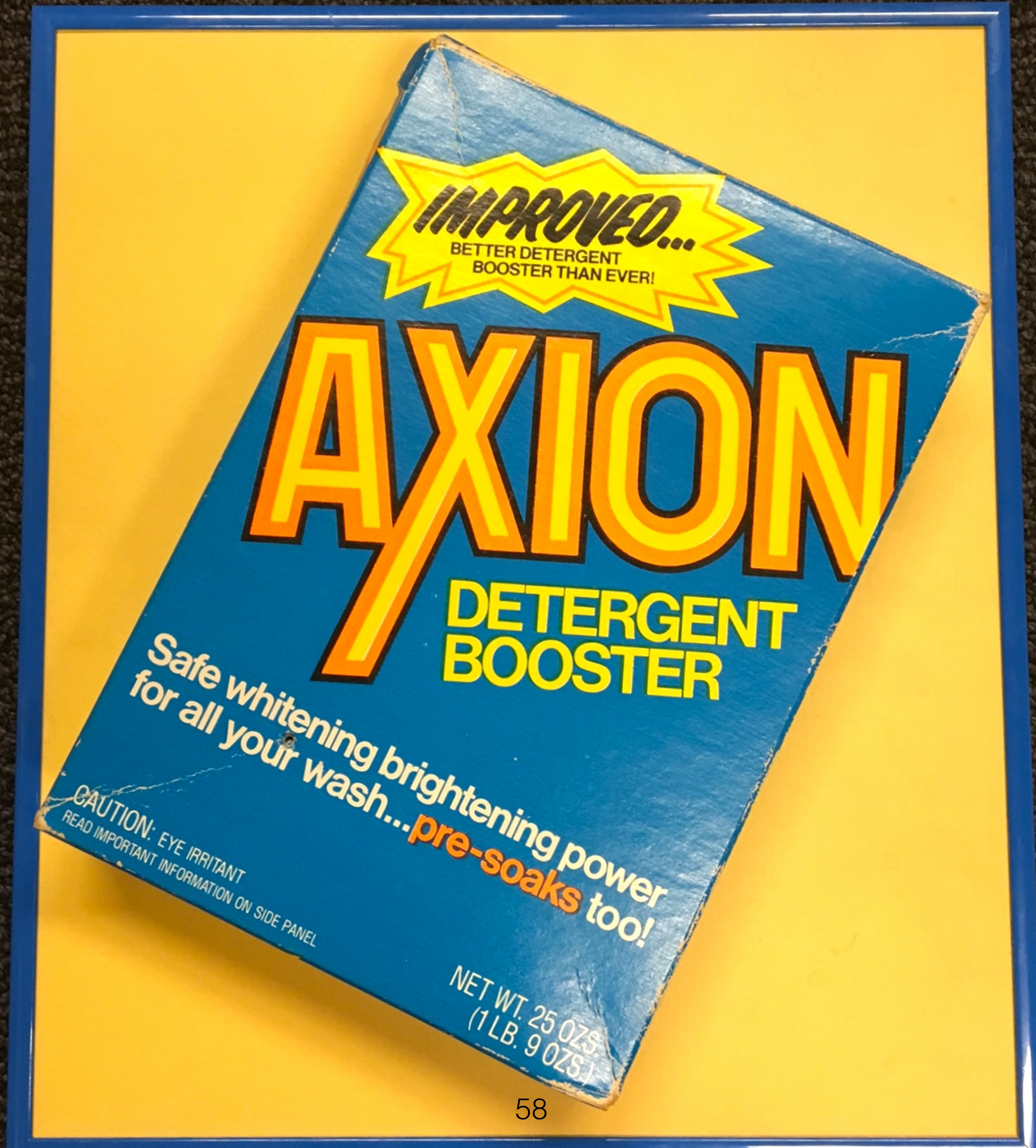
(Logarithmic scale)

adding SUSY



(Logarithmic scale)

unification of forces


IMPROVED...
BETTER DETERGENT
BOOSTER THAN EVER!
AXION
DETERGENT
BOOSTER
Safe whitening brightening power
for all your wash...pre-soaks too!
CAUTION: EYE IRRITANT
READ IMPORTANT INFORMATION ON SIDE PANEL
NET WT. 25 OZS.
(1 LB. 9 OZS.)