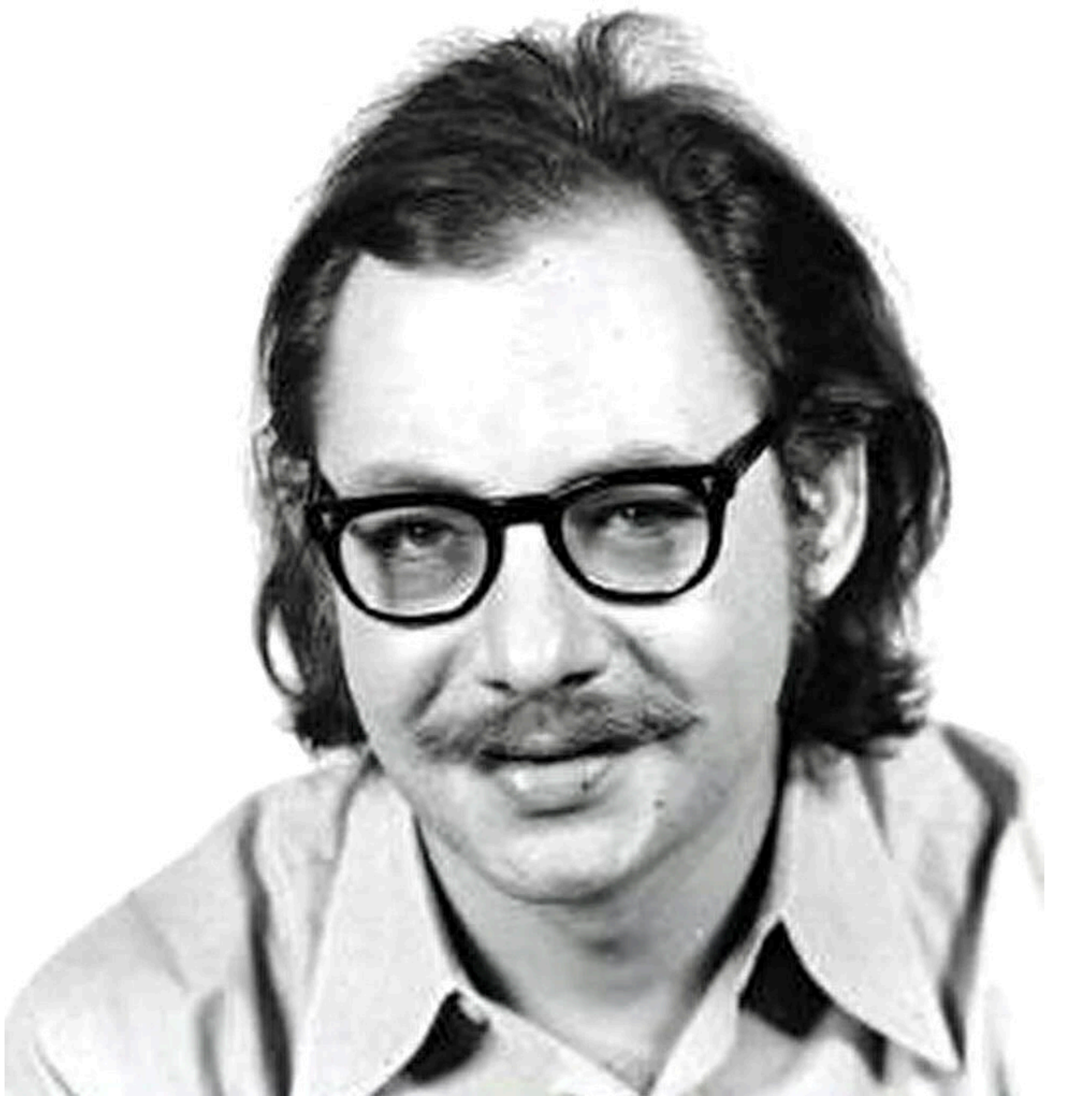
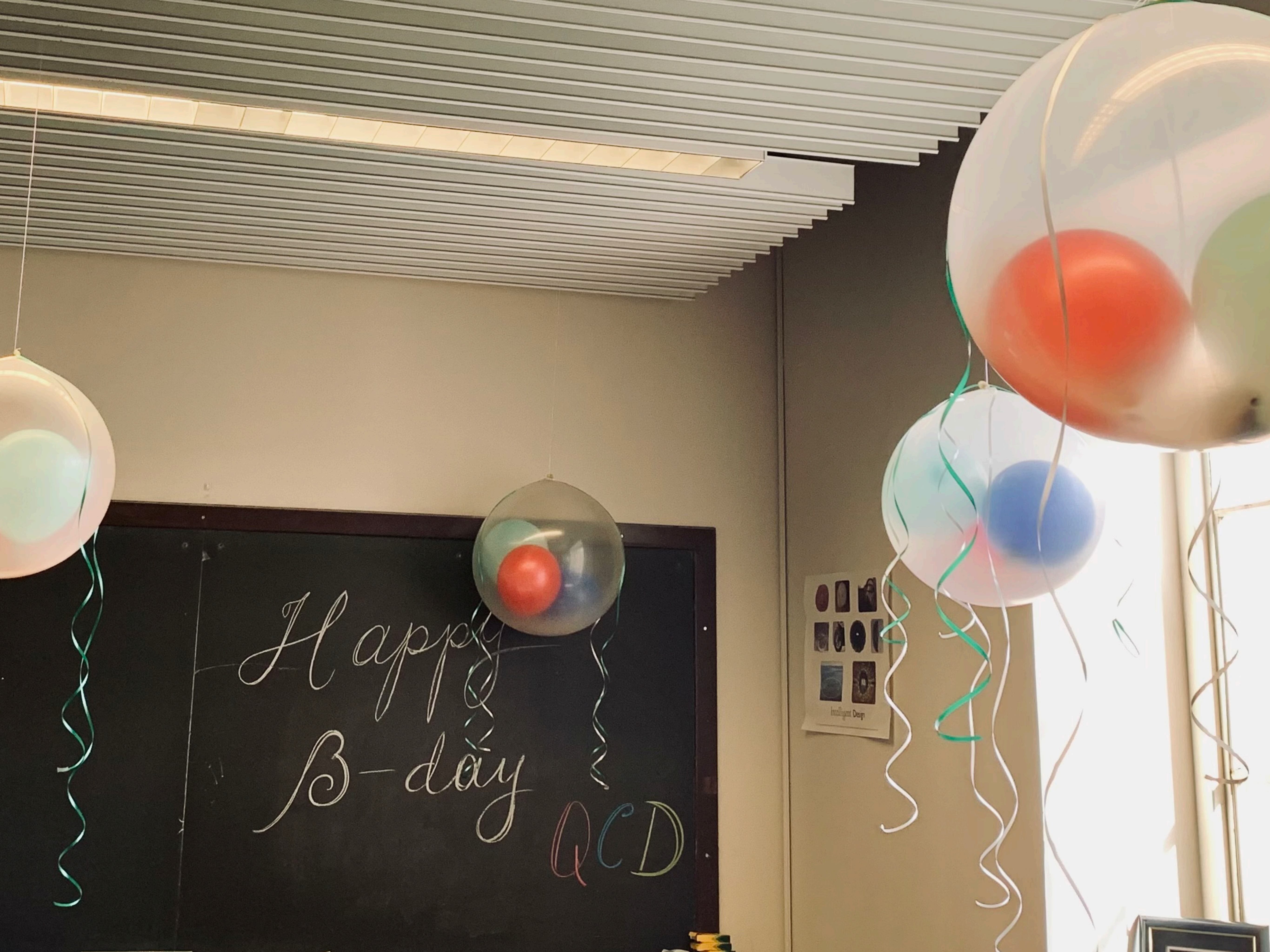
Golden Memories

I've Had a Few …



Real Virtuality

Confinement and Freedom


Happy
β-day
QCD

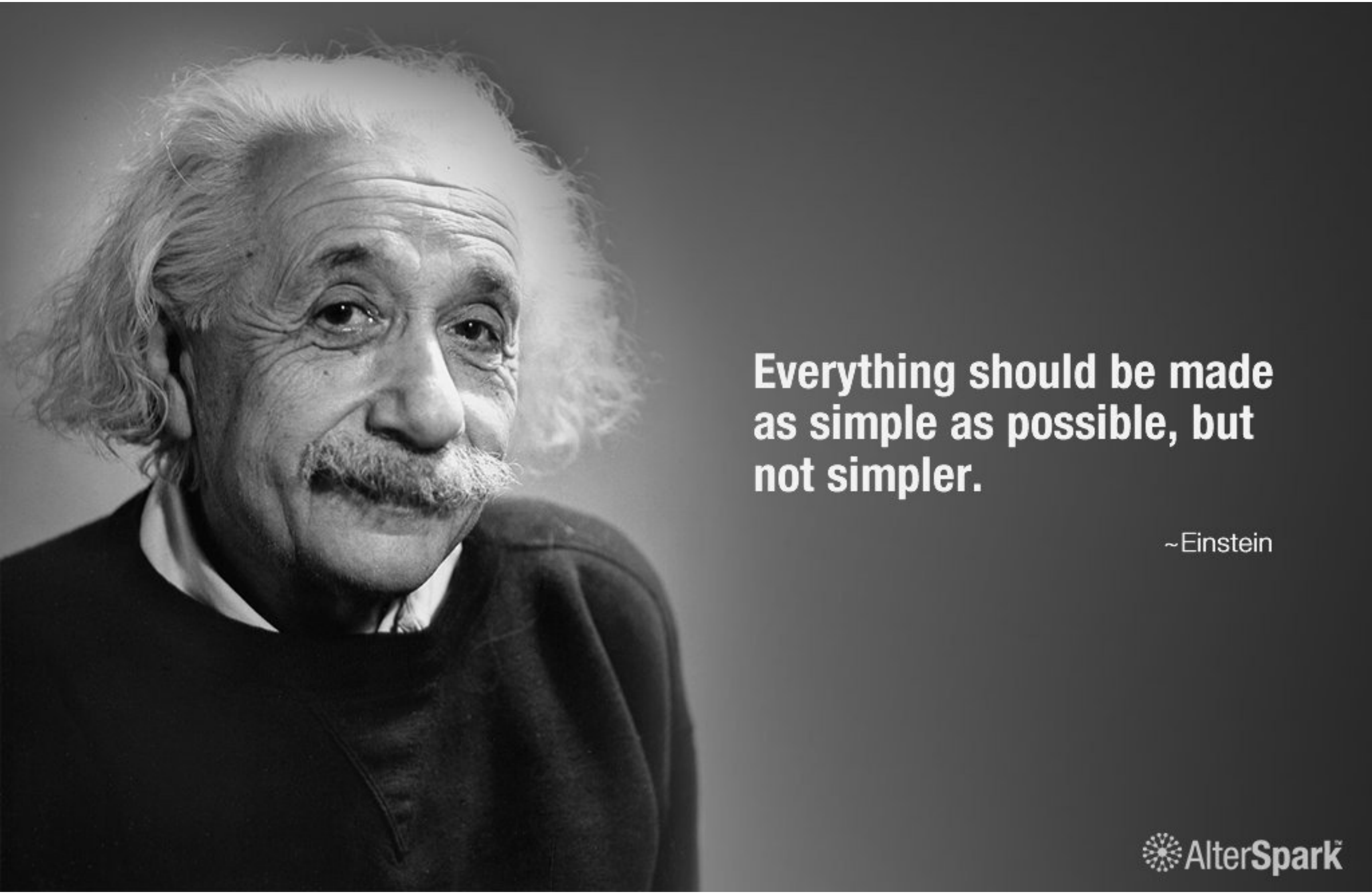
The tension between confinement and freedom is a basic feature of the strong interaction and of QCD.

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.

(1) "As simple as possible, but no simpler"

QED in 1+1 Dimensions


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

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

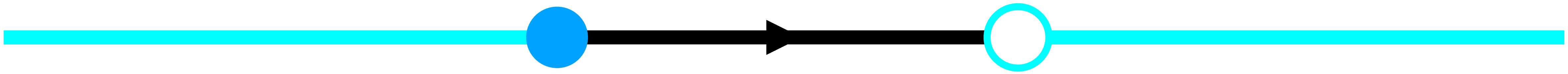
1+1 dimensional gauge abelian gauge theories are much easier to deal with. Fortunately, they still shine a brilliant light on the issues around freedom versus confinement and *real virtuality*.

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

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 runs from particles to antiparticles.



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

(2) Real Virtuality

Crafting a 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.

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, the spectrum starts 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 tiny bit.)

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

(3) Reconciling Eternal and Transient

Energy-Time Uncertainty

The resolution:

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

… but life is finite.

Energy-Time Uncertainty, 1

$$[X, Y] = iZ$$

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

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

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

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

Energy-Time Uncertainty, 2

$$[X, Y] = iZ$$

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

Applied to $[H, A] = i\frac{dA}{dt} \quad \Rightarrow$

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

The meson 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 -

- which comes as a relief, because it doesn't!

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

and

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

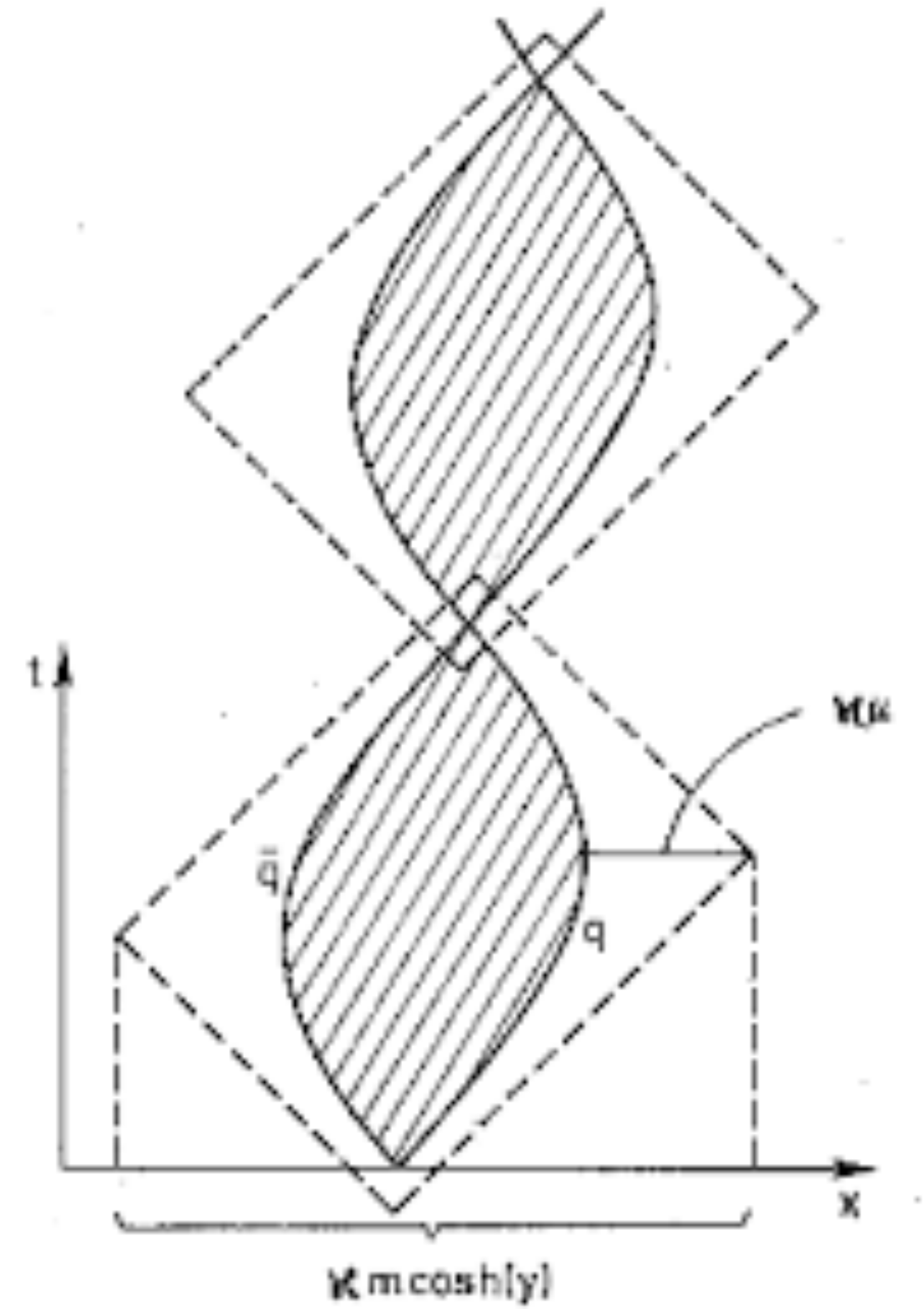
$$2\pi n = \int dx\, p = 4\sqrt{2m} \int_0^{\frac{2E_n}{Q^2}} dx \sqrt{E_n - \frac{Q^2}{2}x}$$

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

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
γκ
γκ m cosh(y)

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

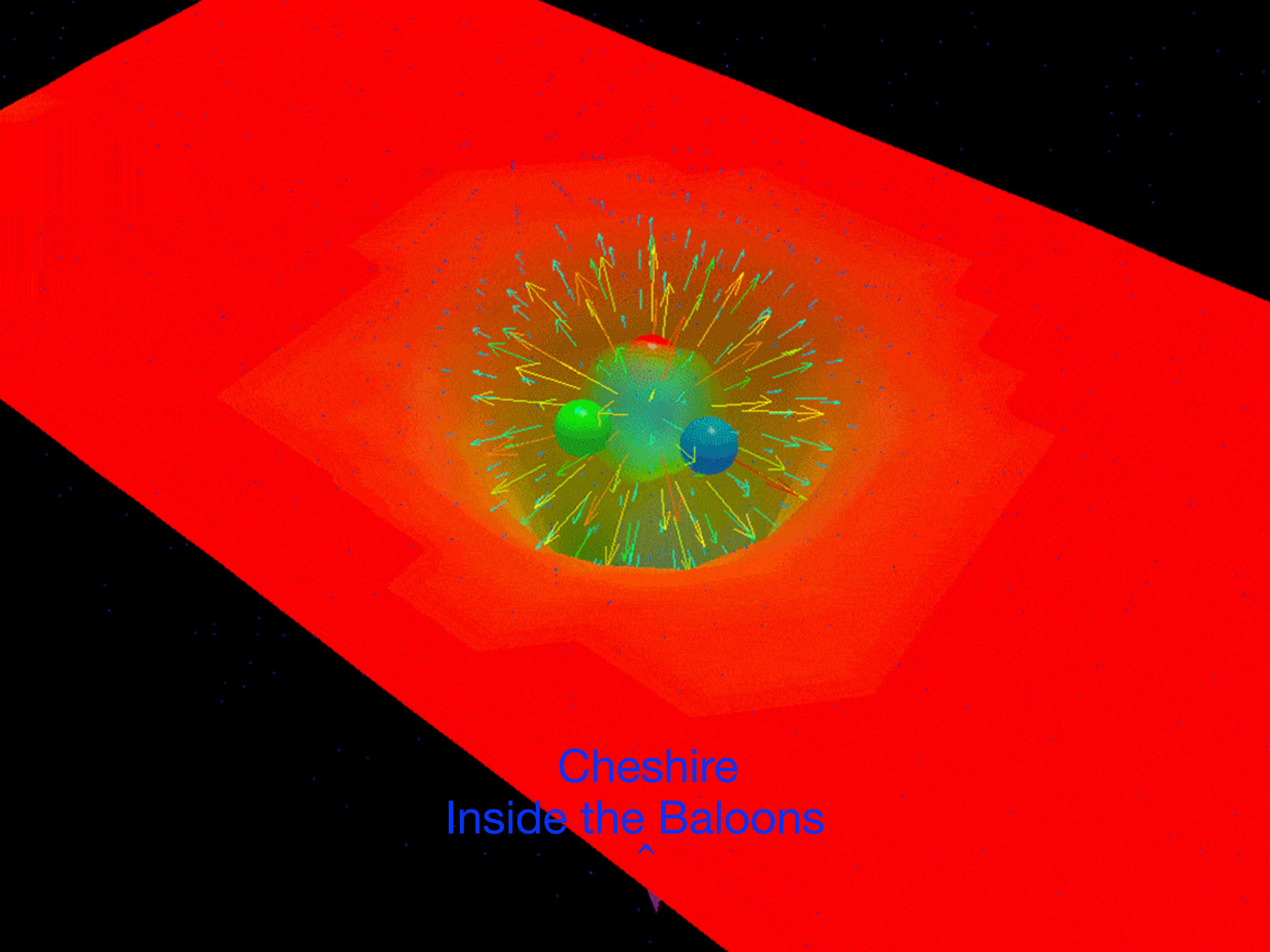
Taking spatial structure of the interference into account, we also get associated wave-functions.

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 you 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?


Cheshire
Inside the Baloons
^

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.

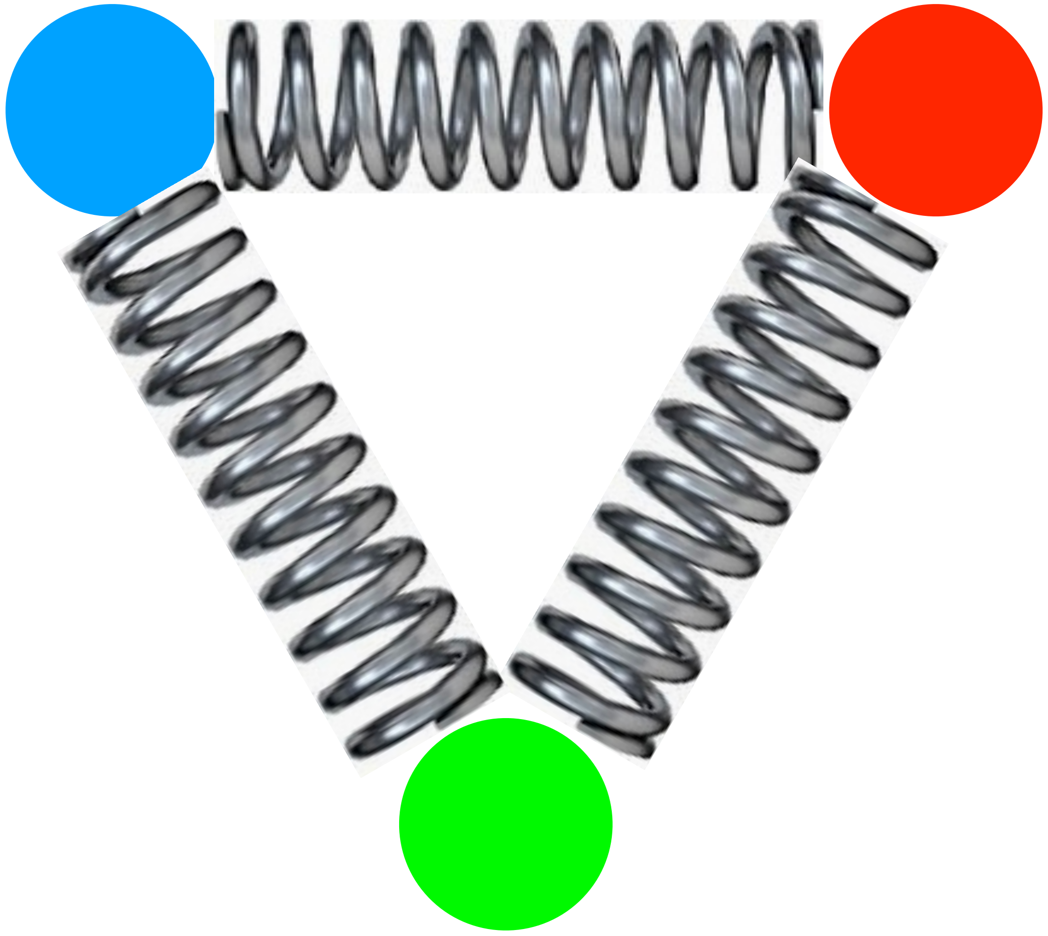
Asymptotic freedom ($\beta < 0$) shows the onset of that behavior; the strong coupling expansion pushes it to the extreme.

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.

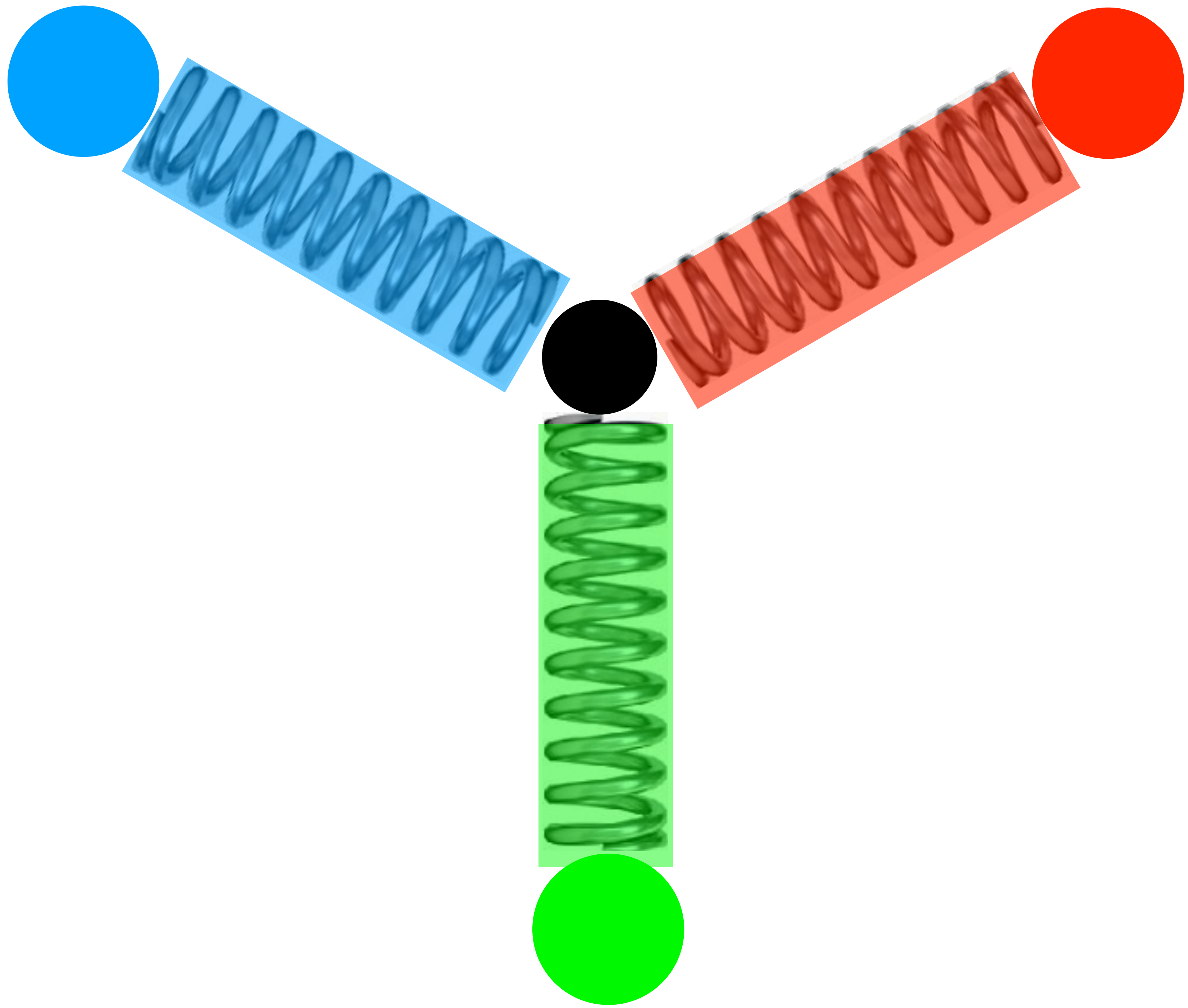
A widely used and amazingly successful model of hadronization - the Lund model - takes off from the idea of flux tubes connecting quarks.

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



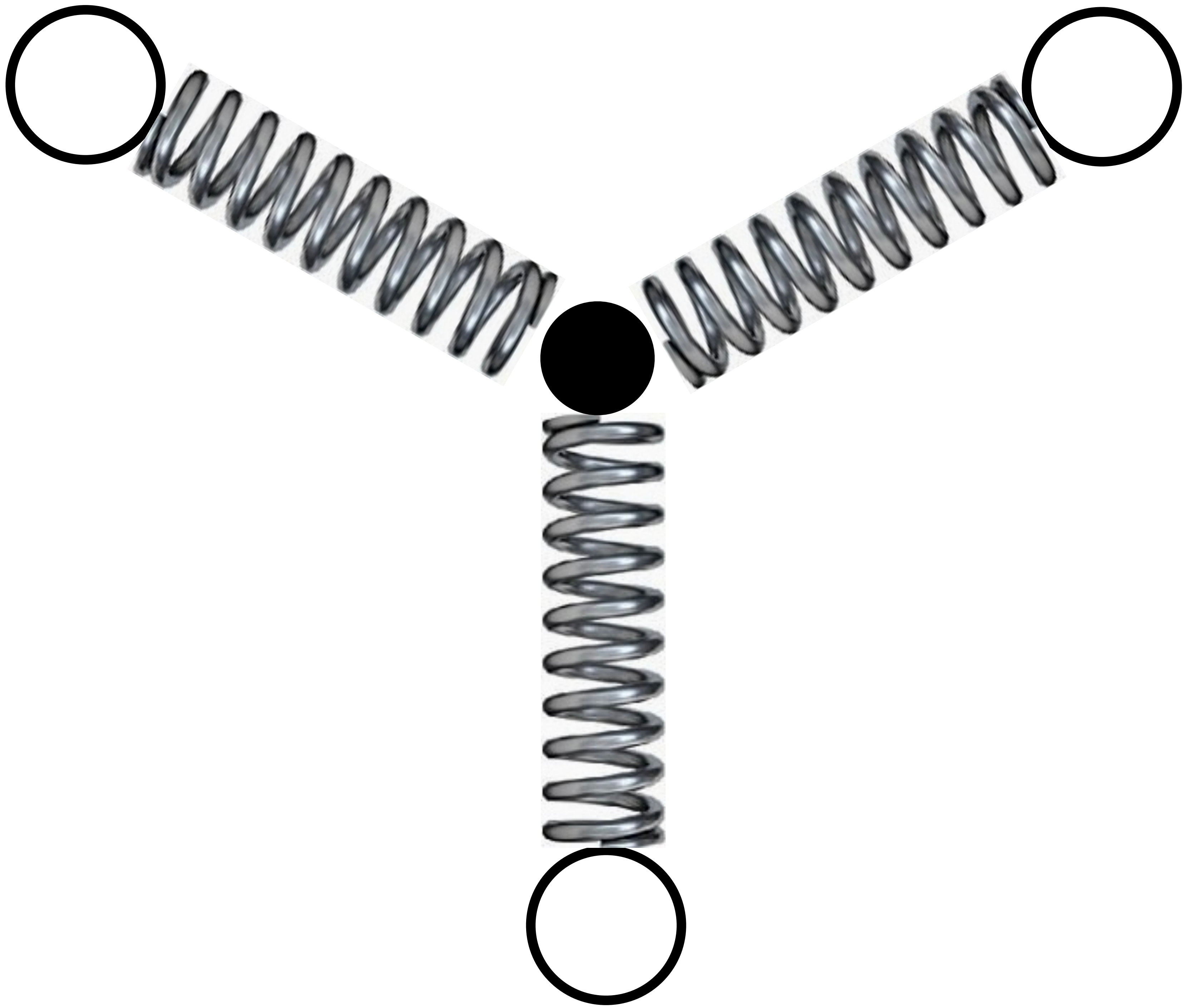
$$(1, -1, 0) \ \& \ (-1, 0, 1) \ \& \ (0, 1, -1)$$

Or, better:



$(1,0,0)$ & $(0,1,0)$ & $(0,0,1)$ + verton $(-1,-1,-1)$

Or, likely best of all in this vein: just U(1), unit charged quarks and a charge -3 verton.



1 & 1 & 1 + verton − 3

We can implement the verton concept mathematically by introducing a scalar field that carries the appropriate charges.

This adds a parameter or two (i.e., the verton mass and self-interaction) while it raises many interesting possibilities like “nuclei”, “glueballs”, “exotics”, condensation …

(5) Real Virtuality Elsewhere

Models of physics beyond the standard model - and maybe the standard model itself - can support metastable “false vacua” with extremely long lifetimes, because their instability involves quantum tunneling over large barriers.   It is interesting to inquire whether we might inhabit one.


DOOM

Are there avatars of doom? - or of safety?

Indeed there are. There are “tribulations” that occur on much shorter time-scales than the potential transition.

The world-lines (or sheets, or membranes) of domain walls associated with the transition are close relatives of our “really virtual” quarks.

Here the “virtually real” objects are produced out of quantum fluctuations, rather than e^+e^- collisions.

.

Ising Tribulations

Quench Simulations and Analytics

G. Langnese, F. Surace, S. Morampudi, F.W. arXiv:2308.08340

$$H = -\sum_i \left[\sigma_i^z \sigma_{i+1}^z - h_z \sigma_i^z - h_x \sigma_i^x\right]$$

1. With $h_z = 0$, prepare ground state by relaxing "all down" state.
2. Apply small h_z to destabilize (or not) this state.
3. Evolve and compare.

$$S_z(\omega) = \frac{1}{T}\int_0^T \mathrm{d}t \langle S_z(t)\rangle e^{i\omega t} = \frac{1}{2NT}\sum_i \int_0^T \mathrm{d}t \langle \sigma_i^z(t)\rangle e^{i\omega t}$$

Phew! **Yikes!**

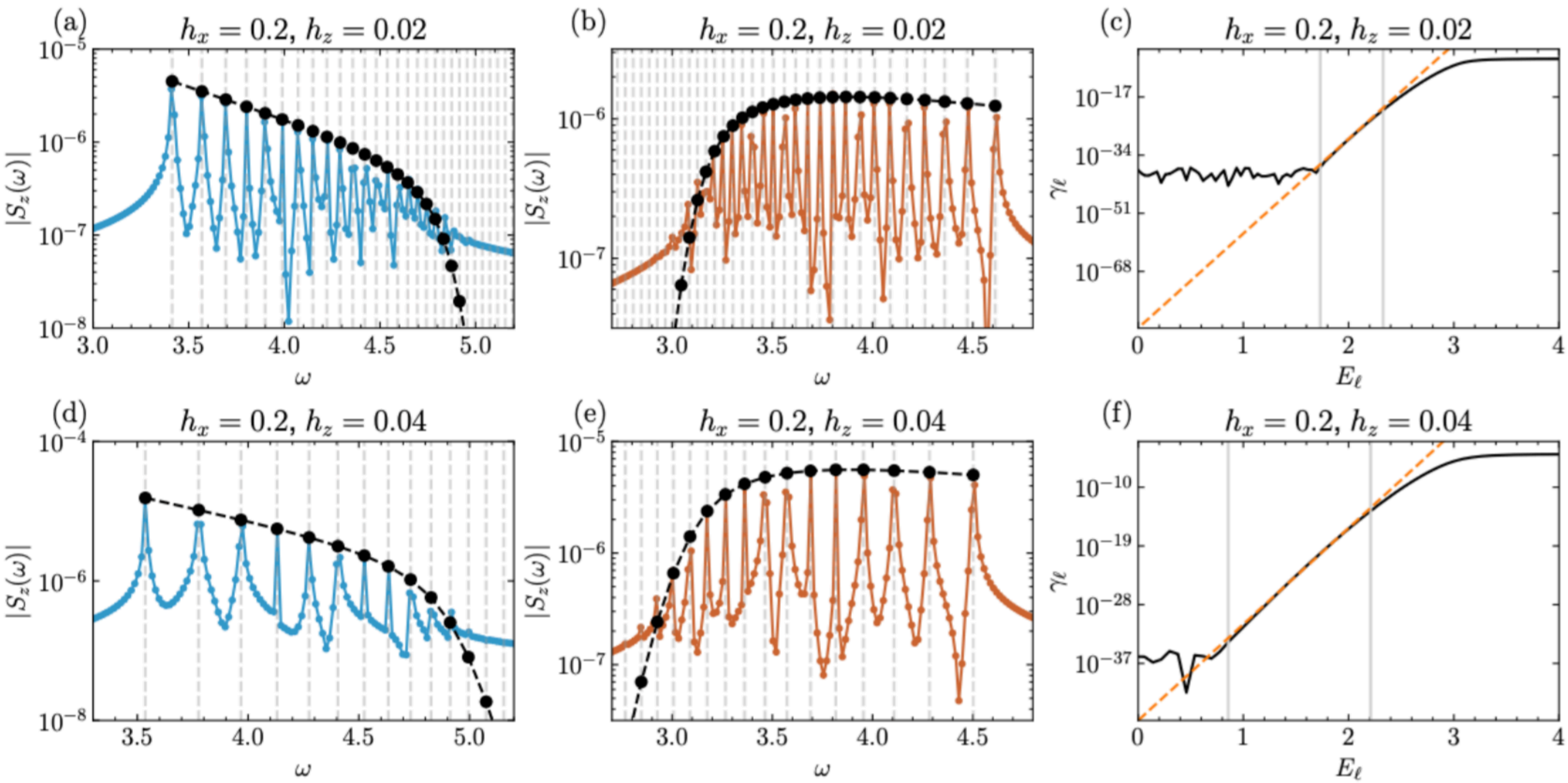


FIG. 2. Fourier transform of the real-time evolved magnetization after a quench from the true vacuum [(a) and (d)] and false vacuum [(b) and (e)]. Parameters are $h_x = 0.2$ and different h_z: in (a) and (b) $h_z = 0.02$, in (d) and (e) $h_z = 0.04$. The Fourier spectrum is compared with the predicted peaks positions E_ℓ and amplitudes $|S^z(\omega = \pm E_\ell)|$ extracted from Eq. (4) and (7). Panels (c) and (f): exponential fitting of the amplitudes of the off-resonant bubbles and $E_\ell \to 0$ extrapolation of the decay rate γ according to Eq. (8).

There are excellent prospects for accessing models like this in quantum simulators.

Prospects in Real Virtuality

More Realizations, Engineering Bubbles, Hawking/Unruh Radiation, Cosmology

More Realizations

Any first-order transition is a candidate for this style of analysis.

Hysteresis loops can be tedious to sort out near their corners. Cleverness can substitute for patience.

Engineering Bubbles

Near-critical bubbles give long-lived particles, strings, or membranes in dimensions 1, 2, 3.

To create them efficiently we can do clever quenches, flipping some spins (or whatever) at the same time as we turns on the dis-orienting field.

Flipping in structured ways can probe the bubble wave-functions, too.

Hawking/Unruh Radiation

Expanding bubbles give a physical implementation of “moving mirror” models, and should be associated with non-trivial Unruh-Hawking radiation.

Cosmology

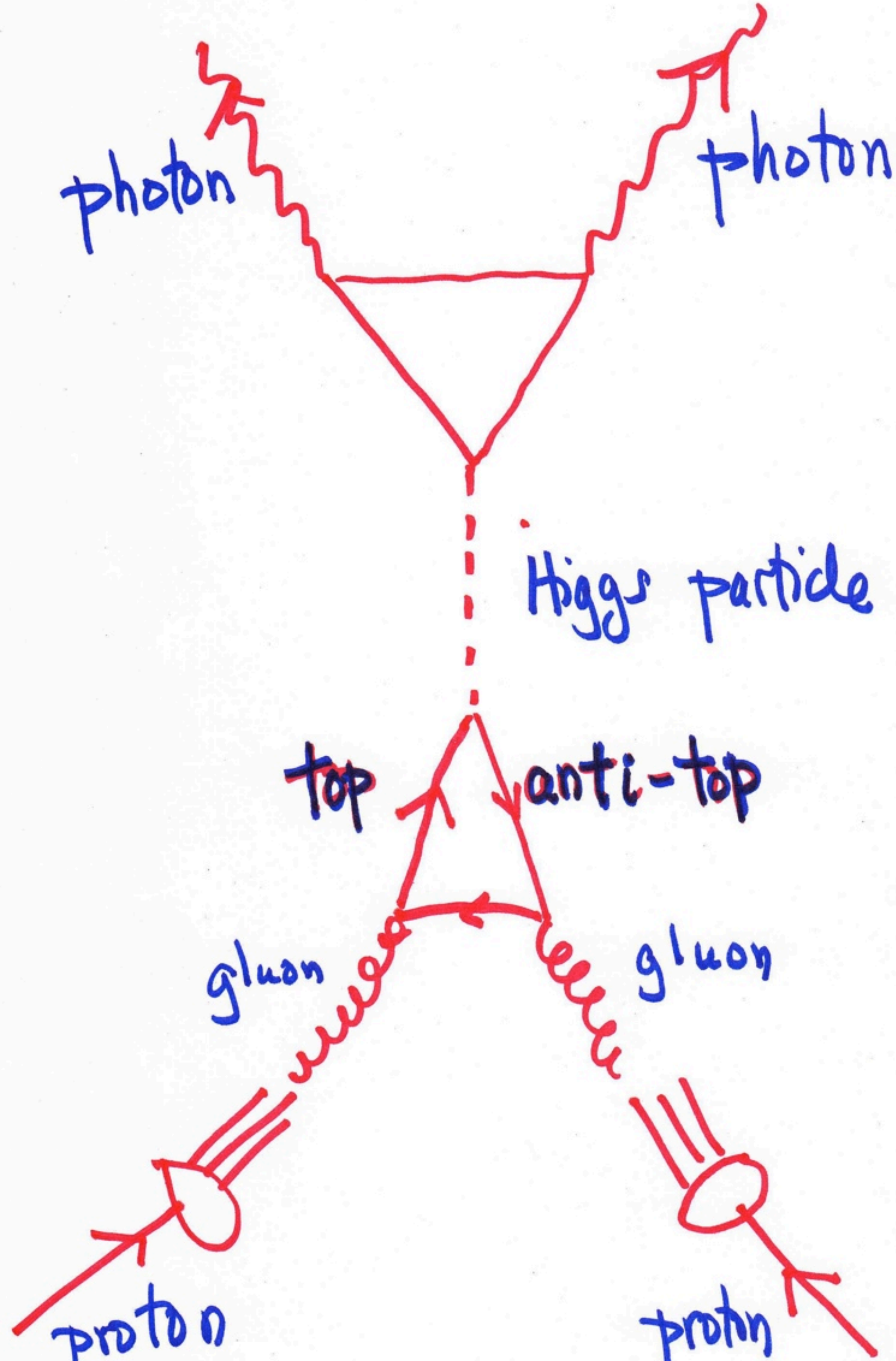
In the context of cosmological phase transitions, one must bring in the effect that higher vacuum energy density also expand faster!

A hole-y universe? !!

Quo Vadis, QCD?

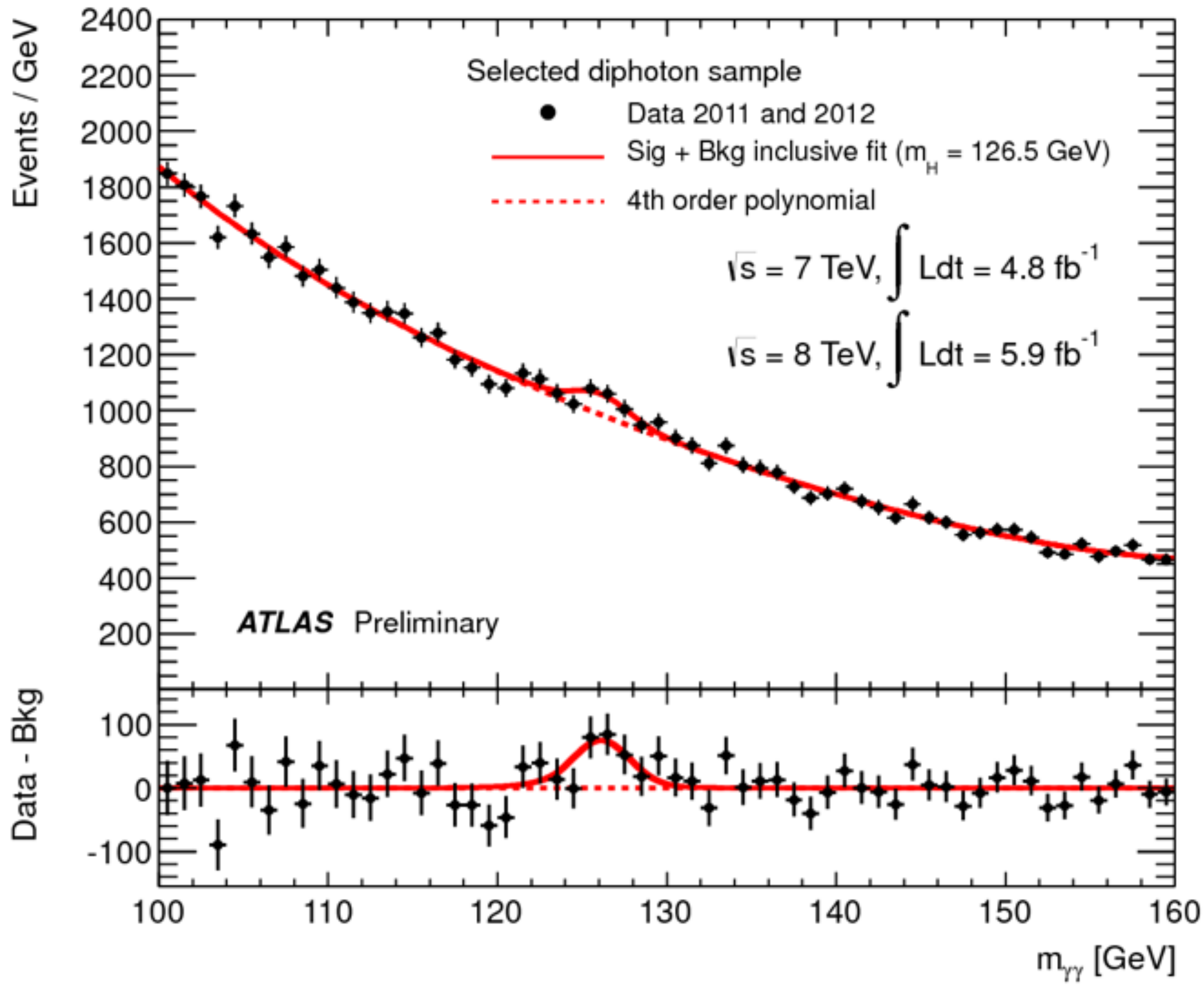
Foundation and Platform

A tool for high energy physics



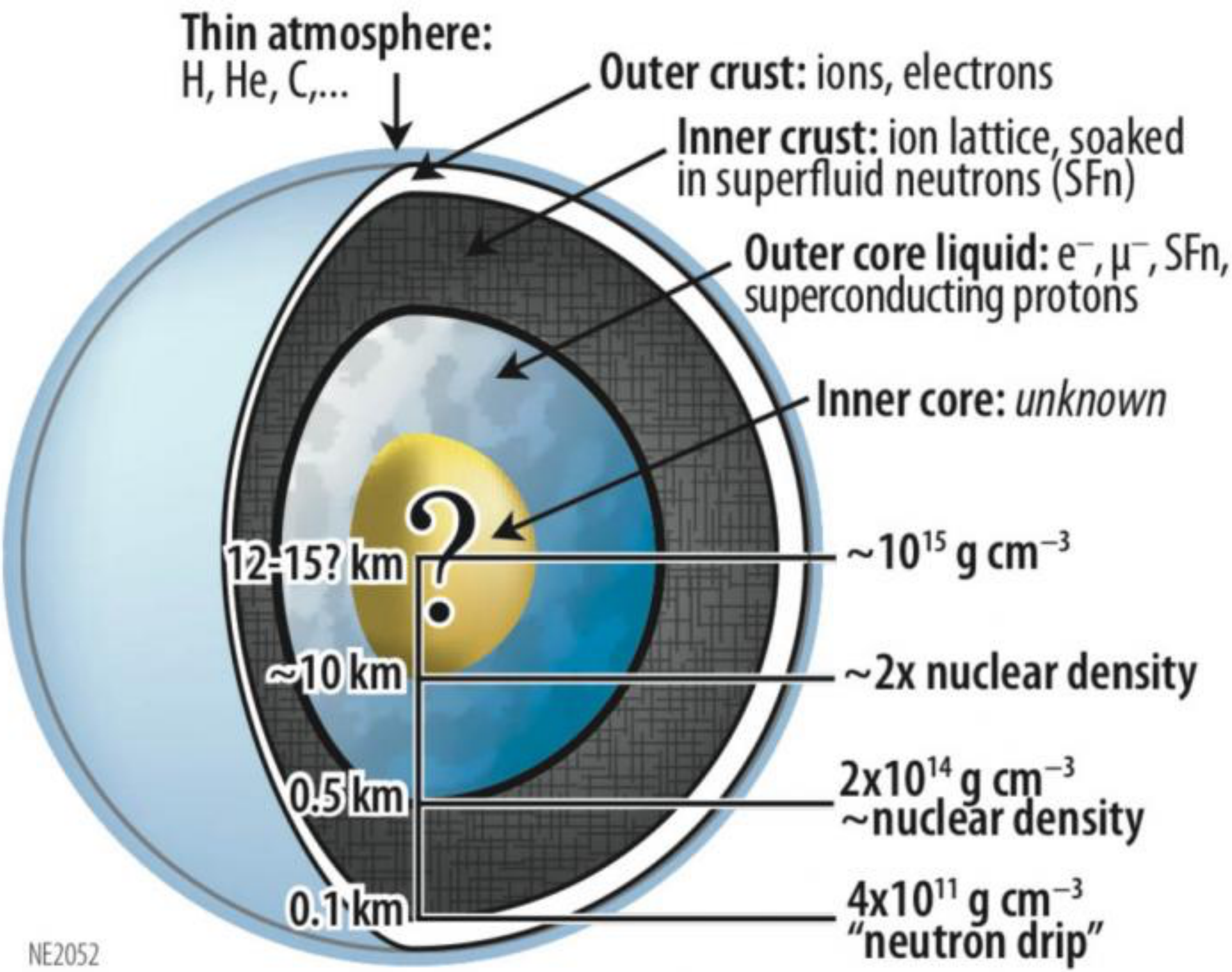
decay

production



Events / GeV
Selected diphoton sample
Data 2011 and 2012
Sig + Bkg inclusive fit (m_H = 126.5 GeV)
4th order polynomial
$\sqrt{s}$ = 7 TeV, $\int Ldt$ = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV, $\int Ldt$ = 5.9 fb^{-1}
ATLAS Preliminary
Data - Bkg
$m_{\gamma\gamma}$ [GeV]

A tool for astrophysics and nuclear technology

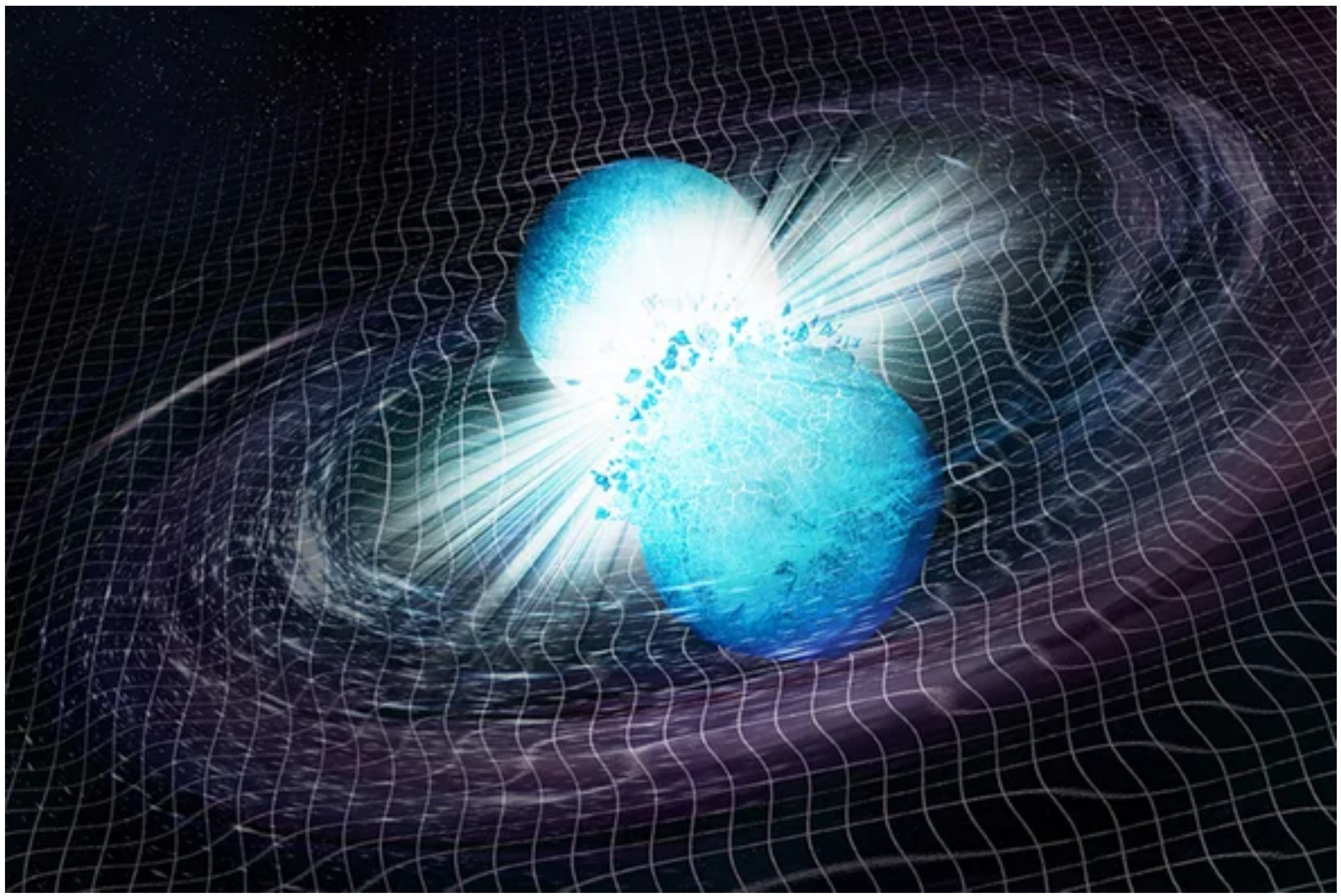


Thin atmosphere:
H, He, C,...
Outer crust: ions, electrons
Inner crust: ion lattice, soaked in superfluid neutrons (SFn)
Outer core liquid: e⁻, μ⁻, SFn, superconducting protons
Inner core: unknown
?
12-15? km
~10 km
0.5 km
0.1 km
~10^15 g cm^-3
~2x nuclear density
2x10^14 g cm^-3
~nuclear density
4x10^11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



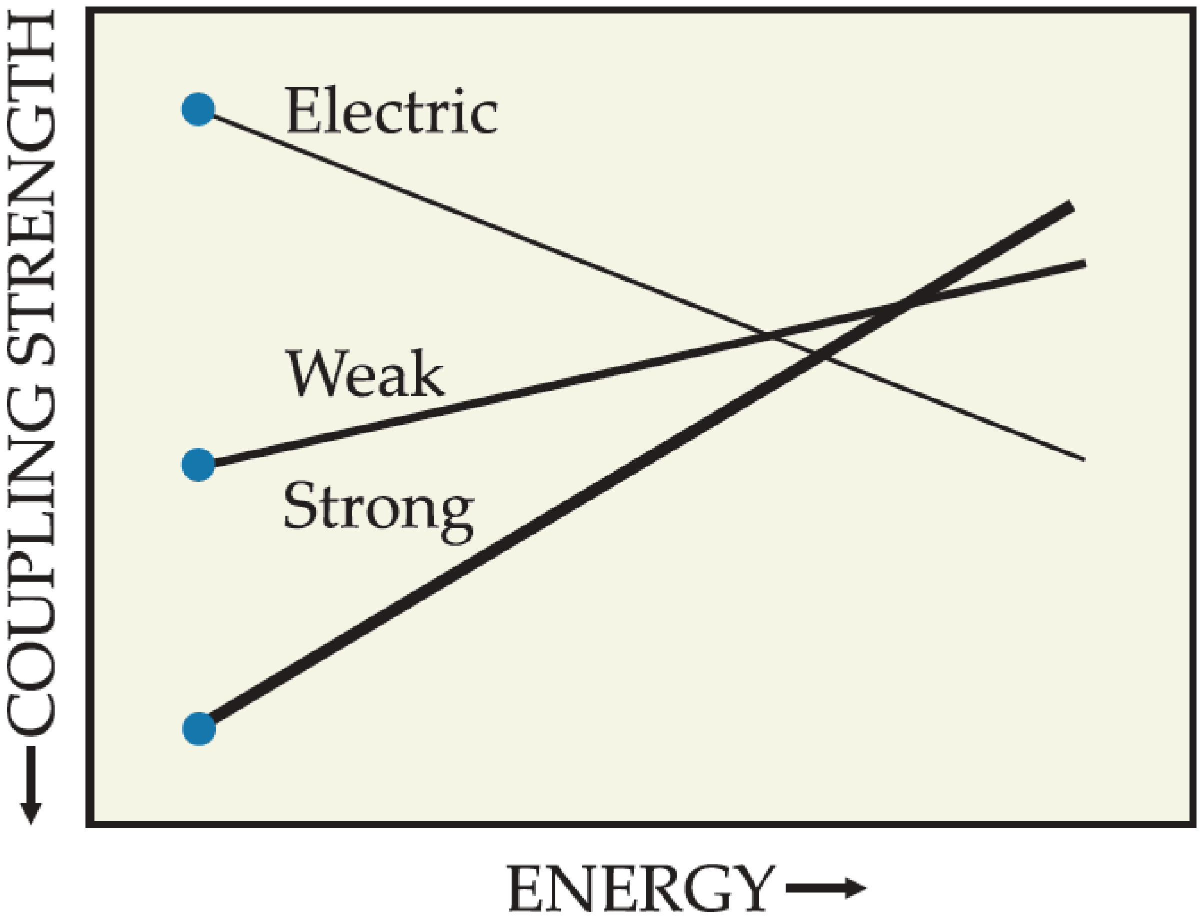
J. Sokol, Scientific American June 2018

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

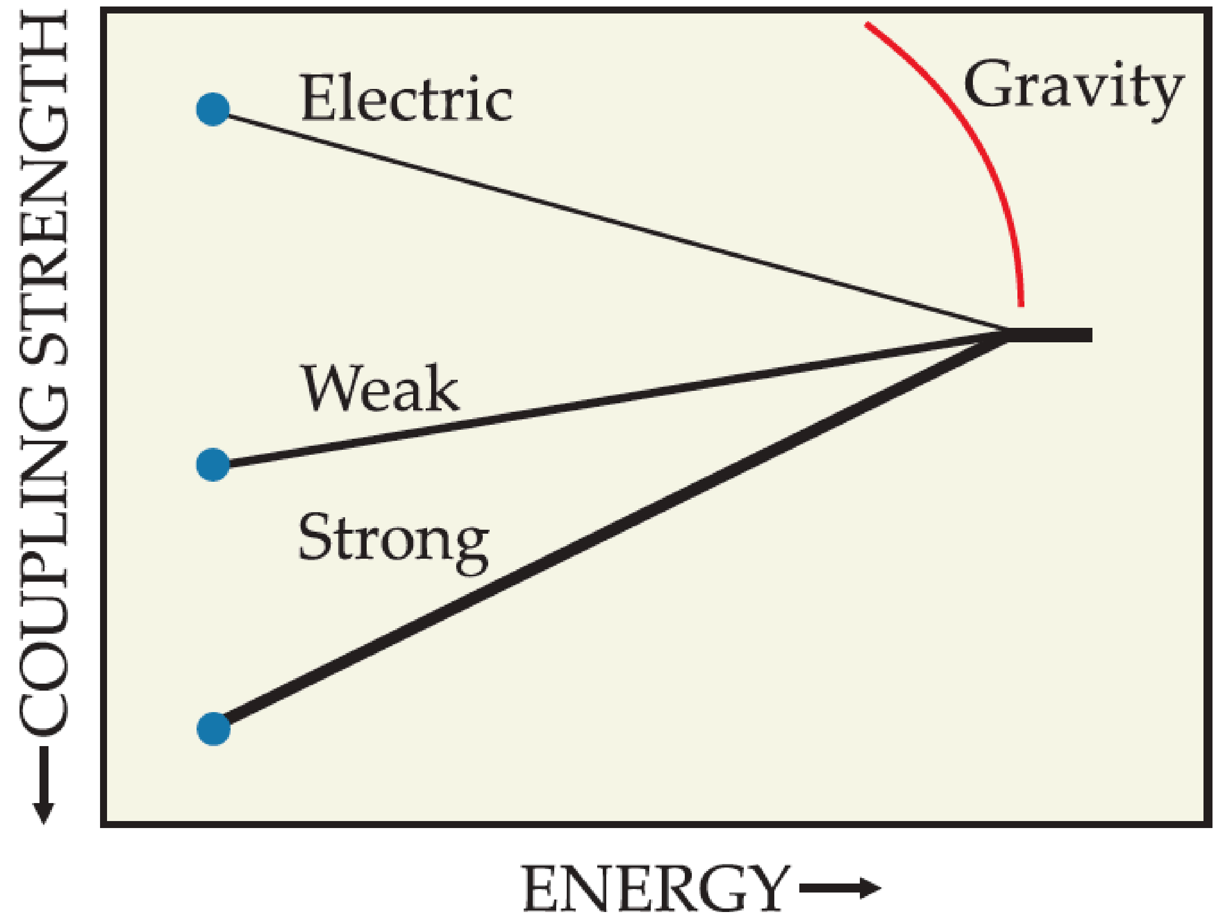
A pointer to new realities

known particles

adding SUSY



(Logarithmic scale)



(Logarithmic scale)

unification of forces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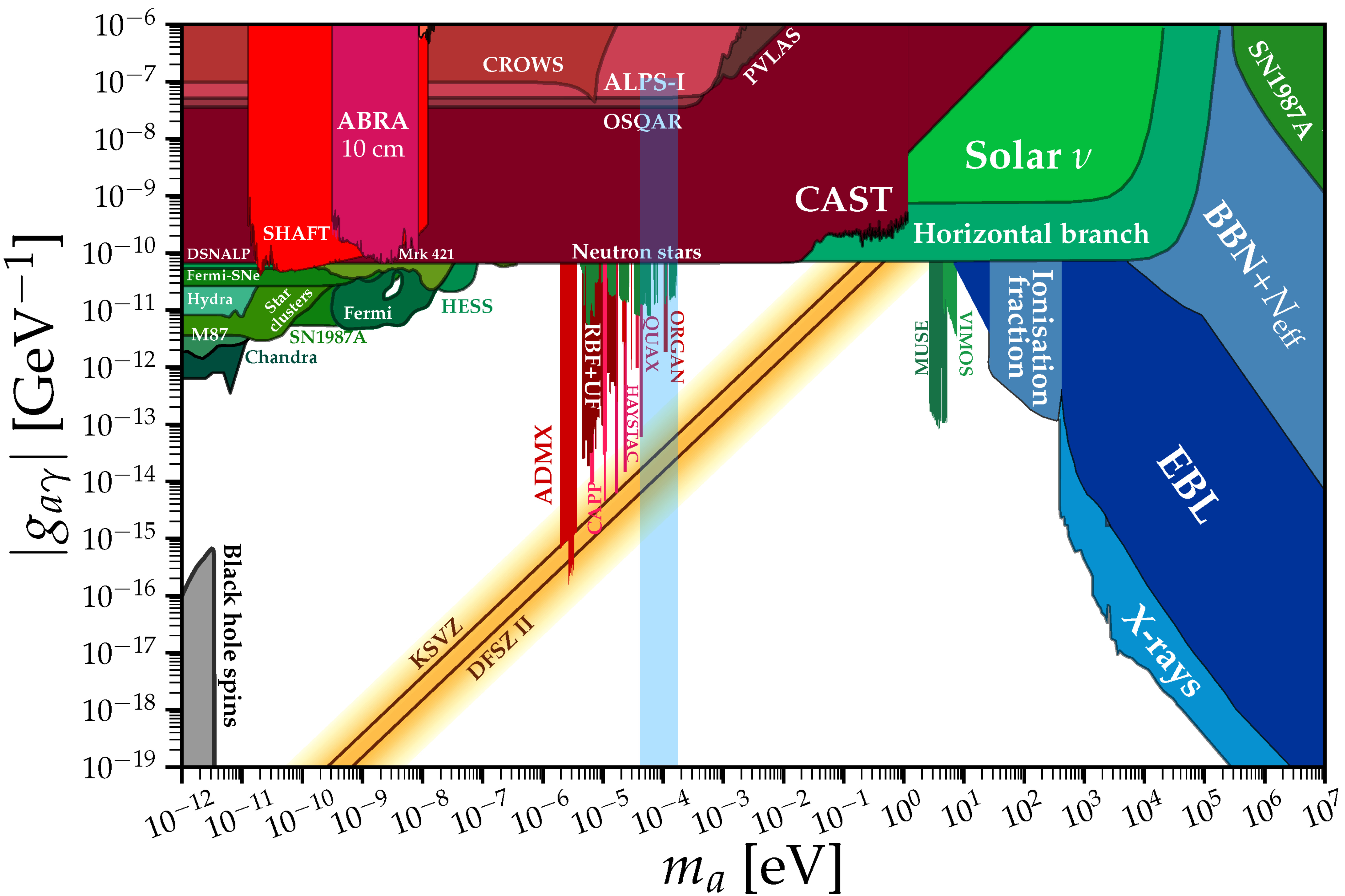
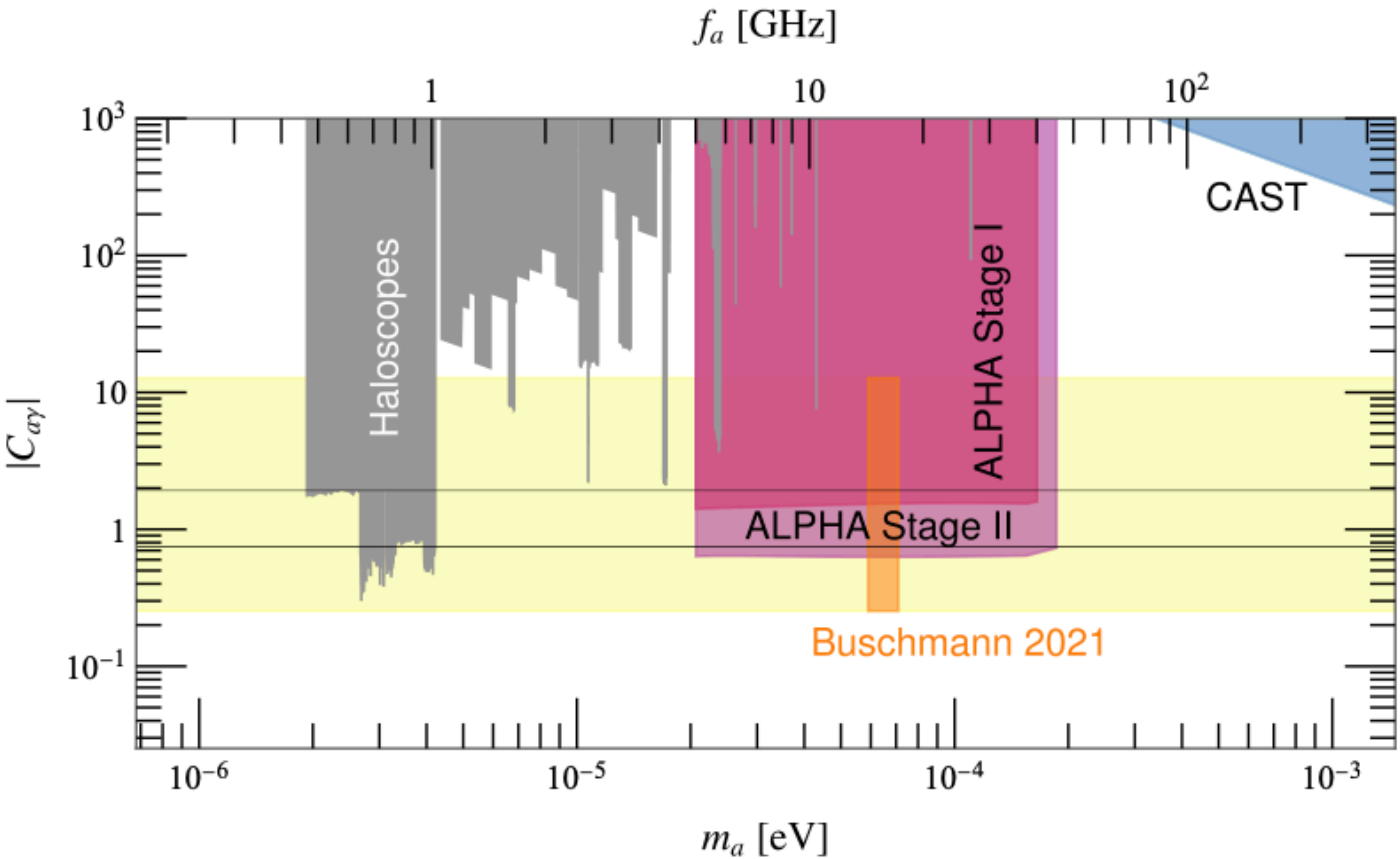
CAUTION: EYE IRRITANT
READ IMPORTANT INFORMATION ON SIDE PANEL
NET WT. 25 OZS. (1 LB. 9 OZS.)



$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
CROWS
ALPS-I
PVLAS
OSQAR
ABRA
10 cm
SHAFT
CAST
Solar ν
Horizontal branch
SN1987A
BBN+N_{eff}
DSNALP
Mrk 421
Neutron stars
Fermi-SNe
Hydra
Star clusters
Fermi
HESS
M87
SN1987A
Chandra
ADMX
RBF+UF
CAPP
HAYSTAC
QUAX
ORGAN
MUSE
VIMOS
Ionisation fraction
EBL
X-rays
KSVZ
DFSZ II
Black hole spins


f_a [GHz]
1
10
10^2
10^3
10^2
10
1
10^{-1}
$|C_{a\gamma}|$
Haloscopes
ALPHA Stage I
ALPHA Stage II
CAST
Buschmann 2021
10^{-6}
10^{-5}
10^{-4}
10^{-3}
m_a [eV]

Grattis på födelsedagen Kvantkromodynamik!

"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