In all fields, there are Golden Ages
Colliding black holes => ripples in space-time = gravity waves
Astronomy: not with light, but with gravity waves

Laser Interferometer Gravitational-Wave Observatory, LIGO.
Two detectors (WA & LA), each with 2 arms, 4 km long.

First event: 2015, \((39 + 29) \, M_{\text{sun}}\) BH’s \(2M_{\text{sun}}\) in gravity waves.
\(2 \times 10^6\) light years away
\(~ 10^3\) physicists,
\(~ 10^9\) to build, run...
Nobel, 2017:
Masses in the Stellar Graveyard

in Solar Masses

LIGO-Virgo Black Holes

EM Black Holes

EM Neutron Stars

LIGO-Virgo Neutron Stars

Updated 2020-05-16

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern
August, 2019: GW190814: merger of black hole, $23 \, M_{\odot}$ & object $2.6 \, M_{\odot}$

2.6 $M_{\odot}$! Lightest known black hole is $\sim 5 \, M_{\odot}$; heaviest neutron star $2.0 \, M_{\odot}$.

We don’t understand either black holes or neutron stars

Gravitational observatories will yield much info about neutron/quark stars
Finding the “Higgs” boson

“Higgs” boson: particle that gives most particles ~ 95% of their mass

proton-proton collisions at the Large Hadron Collider (LHC), CERN (Geneva):

~ 10^4 physicists, ~ $10^{10}$ to build, run...

Physics from ‘10, discovered Higgs in ‘12, Nobel, 2013:

But no signs of supersymmetry!
Future Circular Collider: ~ 2049

LHC: 7+7 = 14 TeV. protons travel at 0.999999990 x speed of light
FCC: 50+50 = 100 TeV, to find physics Beyond the Standard Model (BSM)
Four states of matter

Usual states of matter: gas, liquid, solid.

Fourth state: plasma

Atoms: negative e- & positive nuclei (p+, n)

Plasma: charges move freely, independently
Need heat +… to shake atoms apart

Flourescent bulb: electric field E
Flame, $10^3 \, ^\circ K$
Sun: exterior $10^4 \, ^\circ K$, interior $10^7 \, ^\circ K$

Quark-Gluon Plasma: trillion$^\circ K$
Made in nuclear collisions @ high energy
Cartoon of heavy ion collision at high energy, creating a Quark-Gluon Plasma

Relativistic Heavy Ion Collider, RHIC, @ Brookhaven; and LHC: *Discovery of the Quark-Gluon Plasma*

~ $10^3$ physicists, ~ $10^9$ to build, run = $10^6$/experimentalist
Brief intro to “gauge” theories
Electric charge

Usual electric charge: just a number. What matters is the sign, plus and minus.

E.g.: electrons, e-, and protons, p+.

Two charges at a distance “r” interact according to the potential,

\[ V(r) = + \frac{e_1 e_2}{r} \]

Overall sign: charges of opposite sign attract, like sign, repel. Like...

Potential due to exchange of photons (light)
ElectroMagnetism

Michael Faraday, 1791-1865
Discovered EM induction
Saw lines of EM force
Faraday cage...

James Clerk Maxwell, 1831-1878
Unified EM equations into 4:

\[ \nabla \cdot E = \rho ; \quad \nabla \cdot B = 0 \]

\[ \nabla \times E = -\frac{\partial B}{\partial t} ; \quad \nabla \times B = J + \frac{\partial E}{\partial t} \]
What is light?

Light = photons. Couple only to a number, the electric charge.
There is a “hidden” phase, θ: 0 -> 2π.
Like the rotations of a circle =>

Order of rotations doesn’t matter: \( \theta_1 + \theta_2 = \theta_2 + \theta_1 \).
This is an “Abelian” group (Niels Abel, 1802-1829)

Phase can be rotated independently at each point in space(-time): Abelian gauge theory
Abel Prize, 2019: Karen Uhlenbeck =>
https://www.abelprize.no/nyheter/vis.html?tid=74161

Inspired by Sir Michael Atiyah:
See talk by Nigel Hitchin,
https://cmsa.fas.harvard.edu/literature-lecture-series/

Uhlenbeck
Modern view of light

Photons $A_\mu$ & charged particles $\psi$. In one line:

$$\mathcal{L} = \frac{1}{4} F_{\mu\nu}^2 + \bar{\psi} D_\mu \gamma^\mu \psi$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad D_\mu = \partial_\mu - ieA_\mu$$

Quantum ElectroDynamics (QED)

Nobel, 1965: Feynman, Schwinger, Tomonaga

Charged particles interact with photons as:

But photons don’t interact with themselves
Computing in QED

Julian Schwinger: “physicist who only needs pencil and paper to do physics” (and coffee)

With pencil and paper:
compute in power series of the “coupling constant”,

$$\alpha = \frac{e^2}{4\pi} = 1/137.035999157(33)$$

Small $\alpha$ means pencil and paper ok

One thing he was particulary proud of:
QED: magnetic moment

Example: “anomalous magnetic moment” (coupling to magnetic field)

First correction at one loop: Schwinger, 1948, $= \frac{\alpha}{2\pi}$

Today: corrections to five loop order, $\sim (\frac{\alpha}{2\pi})^5$

$$a_{\text{electron}} = 0.00115965218073(28)$$

For muon ($\sim$ heavy electron) difference between EXPeriment and the Standard Model is $10^{-9}$

$$a_{\text{muon}}^{\text{EXP}} - a_{\text{muon}}^{\text{SM}} = (27.6 \pm 8.0) \times 10^{-10}$$

This difference is now a big deal: hints of new physics (supersymmetry)?
Nuclei = neutrons & protons = “baryons”: *strong interactions*

Each *baryon* = *three* quarks + gluons.

Quarks & gluons carry “color”

Color charges are complex 3x3 matrices

Can rotate by complex 3x3 matrix phases: *non*-Abelian ($U_1 U_2 \neq U_2 U_1$)

= SU(3) gauge symmetry. *Quantum ChromoDynamics, QCD*
History of Non-Abelian Gauge Theories

QCD = non-Abelian gauge theory. First devised by Chen-Ning Yang (1922-) and Robert Mills (1927-1999) at Brookhaven, 1954

Recollection of Chen-Ning Yang:

In 1953–1954, I was visiting Brookhaven and Bob was my office mate. We discussed many things in physics, from the experimental results pouring out of the new Cosmotron, to theoretical topics like renormalization and the Ward identity. It was in that year that we found the very elegant and unique generalization of Maxwell’s equation. We were pleased by the beauty of the generalization, but neither of us had anticipated its great impact on physics 20 years later.
Quantum ChromoDynamics

Like QED, for QCD we can write the theory down in two lines:

\[ q = \text{quark}, \quad A_\mu = \text{gluon}, \quad \text{coupling } \alpha_s = \frac{g^2}{4\pi} \]

\[ \mathcal{L} = \frac{1}{4} \text{tr} \; G_{\mu\nu}^2 + \bar{q} \gamma^\mu D^f_\mu q \]

\[ G_{\mu\nu} = -1/(ig)[D_\mu, D_\nu], \quad D_\mu = \partial_\mu - ig[A_\mu,], \quad D^f_\mu = \partial_\mu - igA_\mu \]

Interactions:

qqg ~ same,  

Plus interactions for 3 & 4 gluons:
How couplings run, QED & QCD

Couplings “run”: change with distance:

In QED, coupling $\alpha$ gets smaller at large distances.

In QCD, gluons interact with quarks and one another

In QCD, coupling smaller at short distances.

“Asymptotic freedom”

Only true for non-Abelian gauge theories
Asymptotic freedom in QCD

QCD coupling decreases logarithmically at short distances:

$$\alpha_s(r) \approx (-) \frac{\#}{(33 - 6N_f) \log(r \Lambda) + \ldots}$$

$$N_f = \# \text{ quark “flavors”} (\sim 3)$$

Well measured experimentally by working from short to long distances:
Asymptotic freedom in QCD

Unlike *any* other theory: for most theories, *simple* at *short* distances.

Conversely: at *large* distances, coupling is *large*, theory is complicated!

Nobel, 2004:
How to compute in QCD?

How to compute at large distances in QCD, where the coupling is large?

*Not* with pencil and paper!

Put QCD on a lattice: gluons on links, quarks on sites

Nobel, 1982: K. Wilson
Lattice QCD?

Asymptotic freedom $\Rightarrow$ correct as lattice spacing $a \to 0$

So put QCD on a lattice and use a computer!

Gordian Knot

“Ο, τι δεν λυνεται, κοβεται”
(Alexander the Great)

Cut what you cannot untie

Simulate what you cannot solve

M. Constantinou, Temple Univ.
Confinement in QCD

Wilson: in ‘70’s, no point in even trying to use the lattice, need much bigger computers

Mike Creutz, BNL, ‘79: whatever, lemme try...

Spawned golden age in lattice QCD
Flux lines in QED

Ordinary electric charges interact weakly, as the flux lines spread out over large distances

\[ V_{QED}(r) = -\frac{\alpha_{em}}{r} \]
Confinement in QCD

At short distances, quark potential like QED, $\sim 1/r$. But at large distances, color flux lines don’t spread out, but form flux tube. Creutz ‘80: from lattice, quark potential linear at large $r$:

$$V_{\text{quark}}(r) \approx \sigma r - \frac{\alpha_s}{r}$$

As $r \to \infty$, infinitely strong potential: “infrared slavery”. $\sigma = \text{string tension}$. **Cannot produce a single quark, only states with zero net color: confinement.** Picture of flux tube from quark + anti-quark ↓ (Leinweber)
**Need big computers**

*Miracle:* from the 90’s, possible to compute, *near* $a = 0$, *without* quarks

With *light* quarks, *much* harder. (With quarks, K. Wilson was right.)

2018: near $a = 0$ for simplest quantities.
**Digression: Fermi & nuclear fission**

*Size* of the proton: $10^{-15}$ meter = fermi (fm).

Enrico Fermi: *many, many* fundamental contributions:
Fermi exclusion, Fermi statistics, neutrinos...

Nobel (1938):
- artificial radioactivity, 1934: slow neutrons + $^{235}$U ->
- Only looked for decay products down to $^{207}$Pb
- Claim: 2 new elements, hesperium & ausonium

Ida Noddack: following Fermi, said look for decays $<^{207}$Pb.
First proposed possibility of nuclear fission
Ida & Walter Noddack nominated for Nobel thrice,
- discovery of $^{186}$Re & $^{98}$Tc

“Everyone knows:” Fermi is brilliant, fission impossible
Nuclear Fission

Decay products lighter than lead

\[ ^{235}\text{U} + n \rightarrow ^{92}\text{Kr} + ^{141}\text{Ba} \]

Otto Frisch & Lise Meitner, Feb. 11, 1939:
Predicted *enormous* release of energy in fission.

Meitner: 1st woman, Prof. of physics in Germany, 1926
Jewish, left Germany for Sweden in 1938

Hahn: Nobel Prize, 1943.
Perils of Assumptions

E. Rutherford, “father of nuclear physics”, 1932:

Because \( p + Li \rightarrow 2 \alpha \),

“...anyone who looked for a source of power in the transformation of atoms is talking moonshine.”

L. Szilard: very annoyed with Rutherford.

Patented neutron-induced nuclear chain reaction in 1933, Granted in 1936, military secret until 1949.

Did not know about nuclear fission! Szilard later wrote to FDR with Einstein to initiate the Manhattan project; worked with Fermi on the first nuclear Reactor…

Common assumptions are often wrong!
Units in QCD: small, quick, hot

Proton is \textit{small}: $10^{(-15)}$ meter = fermi (fm)

Time scales are \textit{quick}: $1\text{fm/c} \sim 10^{(-24)}$ sec ($c =$ speed of light)

Proton is \textit{light}: $10^{(-27)}$ kg  Masses equivalent to temperature:

And \textit{hot}: mass of proton $\sim 5 \times 10^{(12)}$ $^\circ\text{K} = \text{5 trillion degrees}$

Typically use mass of proton $\sim 940$ MeV.

Six quark “flavors”: up (u), down (d), strange (s), charm (c), bottom (b), top (t)

1st three flavors, u, d, & s, are \textit{very} light: “chiral” symmetry

Lightest particles pions ($\pi$), kaons (K), etc. mass pion $\sim 140$ MeV; kaon $\sim 540$
Pack the entire Earth inside a stadium

These densities can be achieved in particle colliders
Phase transition to a QGP

Low temperature: *confined* phase

Infrared slavery: *no* free quarks or gluons, mainly pions, kaons + ....

Pressure *small*, from a few degrees of freedom

High temperature:

*Lose confinement at a temperature $T_c$, transition to Quark-Gluon Plasma*

Asymptotic freedom: coupling $g^2(T) \sim 1/\log(T)$, so *ideal* QGP at $T = \infty$

Pressure *large*, from many quarks & gluons.

Expect *large* increase in pressure in going from confined phase to QGP
Lattice: thermodynamics of QGP

~ 2014: Lattice can measure pressure at temperature $T \neq 0 (\mu = 0)$.

Large increase in pressure, but no true phase transition: crossover.

From chiral order parameters, $T_\chi = 154 \pm 9 \text{ MeV}$  Errors from $a \rightarrow 0$
Finding the Quark-Gluon Plasma in heavy ion collisions
Hunting for the “Unicorn” in Heavy Ion Collisions

Unicorn = QGP. Hunters = experimentalists. So: all theorists are...dogs?

Proved non-Abelian gauge theories make sense: Nobel 1999: G. ‘t Hooft & M. Veltman
Why heavy ions?

Details of nuclear physics don’t really matter. Bigger is better.

Sociologically, the field was treated with some skepticism....

“Everyone knows” heavy ion collisions will be complicated

But in systems with many particles, average properties can be simple

*Especially* if they thermalize
Why heavy ions @ *high* energy?

Expect thermal behavior only for BIG systems. The bigger the nuclei, the better

Atomic number $A = 1$ for protons, up to $A \sim 200$ (Au, Pb)

Radius $\sim A^{(1/3)}$: $\sim 1$ fm for proton, $\sim 7$ fm for Au, Pb

*Two* thermodynamic parameters: $T = \text{temperature}$ and $\mu = \text{chemical potential}$

Equal # of baryons & anti-baryons: $\mu_{qk} = 0$.

Because of “sign problem”, lattice (today) can only do $\mu_{qk} = 0$.

Low energy: 2 nuclei from 1 big blob. Net baryons, so $\mu_{qk} \neq 0$

To probe baryon free region, need *high* energy. How high?
Plateau in particle production, with many particles

Highest energies @ collider: two beams in opposite direction.
Relativistic: E/A >> 1 GeV. Below: # particles produced along the beam, AuAu

In QCD, “plateau” @ high energy, just like flux tube for quark potential
Plateau is ~ baryon free, mainly pions, kaons +.... Many particles, ~ $10^3$

J. Bjorken, ‘83
AGS: ‘60. Tandem: ‘70.
Isabelle: pp @ 200 GeV, cancelled in ‘83
(Because of SSC, cancelled in ‘93)

Samios ‘83
Large Hadron Collider @ CERN, Geneva: E/A ~ 3000 GeV

RHIC experiments: PHENIX, STAR (BRAHMS, PHOBOS)
LHC experiments: ALICE, CMS, ATLAS
Why skepticism about AA?

“Everyone knows”: in high energy physics, understanding (& simplicity) from studying collisions of *few* particles

But: in statistical mechanics, simplicity from complexity, from the production of *many* particles
Is it thermal?

“Statistical hadronization”: excellent fit to all chemical abundances, using $T_{\text{freezeout}} = 156$ MeV. *Down to anti-$^4$He!* Exceptions: $J/\psi + (c\&b)$

Why only a *single* $T_{\text{freezeout}}$?

Andronic, Braun-Munziger, Stachel & Redlich, 1710.09425

![Graph showing yield $dN/dy$ for various particles in Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV, 0-10% centrality. The graph compares data from ALICE with statistical hadronization models.]
Elliptic flow
“the more perfect liquid on earth”
With many particles: fixing geometry

Nuclei overlap completely: central collision (Beam into the plane)
Nuclei overlap partially ("almond"): peripheral collision

Exp.’y, can determine # participants when > 100; maximum 400 for A ~ 200

central collision

peripheral collision:
# participants in “hot” almond

“cold” spectators

“hot” almond
Elliptic flow & hydrodynamics

For peripheral collisions, overlap region is “almond”

Start with spatial anistropy,

$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

*If* collective effects present, end up with almond in momentum space: “elliptic flow”

$$v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_y^2 + p_x^2 \rangle}$$

Use ~ ideal hydrodynamics

Basic parameter $\eta/s$:

$\eta = \text{shear viscosity}$

$s = \text{entropy}$
\[
\frac{dN}{d\phi} = \frac{N}{2\pi} \left( 1 + 2(v_1 \cos(\phi) + v_2 \cos(2\phi) + v_3 \cos(3\phi) + v_4 \cos(4\phi) + \ldots) \right)
\]
VISCOSITY AT RHIC AND LHC

RHIC

LHC \sim 14 \times \text{higher energy}

RHIC viscosity $\eta/s = 0.12$

LHC viscosity $\eta/s = 0.2$

Hints at increasing viscosity $\eta/s$ with increasing temperature
While $\eta$ is big (~ $10^4$ pitch tar), so is the entropy!
But $\eta/s$ is really small, ~ 1/10 anything else “The most perfect liquid on earth”
Lower bound on $\eta/s$?

$\eta \sim 1/g^4$: small in strong coupling.

Maldacena ‘99: duality, gauge theory with $\infty$ # colors, most “supersymmetry” (between quarks & gluons) and “string theory”, on Anti-diSitter $5 \times S^5$

Both conformal field theories: same at all distances

**AdS/CFT correspondence.** By duality compute for infinite coupling from classical (super)-gravity

**Bound:** Son, Starinets, Kovtun ‘05

Results for $\eta/s$ very close to bound from AdS

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

Coupling weak at high T, so strong at low T.
Open questions about using hydro

Hydro depends upon Equation of State (EoS), get that from lattice

Details sensitive to initial conditions (~ “Color Glass Condensate”), especially odd $v_n$.

Works too well: up to momenta $\sim 2$ GeV, $\sim 1/10$ fm

for both light (u, d, s) and heavy (c, b) quarks

Need to start at very short time: not 1 fm/c, but $\frac{1}{4}$ fm/c.
Jet quenching:
the QGP “eats” jets
Jets in QCD

Hydro deals with most particles, concentrated at “soft” momenta, < 1 GeV
But in QCD, by asymptotic freedom *hard* particles are distinctive,
form “jets”: leading hard particle + soft spray

Jets at LEP,
Large Electron-Positron Collider @ CERN

‘89 → 2000,
LEP tunnel used for LHC

2 jets

3 jets
QGP “eats” jets

In proton-proton (pp) collisions, jets travel without further interaction. In nucleus-nucleus (AA), if there is a medium (QGP?), then it should strongly affect jets: the hard particle goes into a soft spray much easier. “Jet quenching”
QGP “eats” jets @ LHC

At LHC, energy ~ 10 x RHIC, but temperature is not: pressure ~ $T^4$.
So not a large difference for soft particles: hydro works, etc.

But: more hard particles: jet quenching very dramatic, can measure @ high $p_t$. 
Hydro deals with most particles, concentrated at “soft” momenta, < 1 GeV
But in QCD, by asymptotic freedom hard particles are distinctive, form “jets”: leading hard particle + soft spray
RHIC: only can measure particles up to ~ 20 GeV

\[ R_{AA} \uparrow \]
\[ R_{AA} = \] 
\# particles in AA/ 
\# particles in pp

\[ R_{AA} < 1 \] shows “jet” quenching

\[ p_t = \text{transverse momentum (GeV)} \rightarrow \]
(perpendicular to beam direction)
QGP “eats” jets @ LHC

Expect jet quenching more dramatic for central than peripheral collisions: more “stuff” to scatter off of.
Jet quenching valid up to *hundreds* of GeV!

\[ p_t = \text{transverse momentum (GeV)} \rightarrow (\text{perpendicular to beam direction}) \]
Open questions about jet quenching

QCD theory: jet quenching *different* for:

- quarks vs gluons: color charge gluons > quarks, so gluon jets should quench *more*.
- light quarks (u, d, s) vs heavy quarks (c, b): color charge same, but scattering off of massless gluons much *less* for heavy quarks than light.

Experimentally: *all* particles quench ~ the same. Difference in charge, mass?

sPHENIX detector: upgrade to PHENIX detector @ RHIC
  Specialized to measure high $p_t$ particles & $R_{AA}$ up to $p_t \sim 40$ GeV.
  From ‘22 - ‘24

+ data from LHC @ CERN
Phase diagram of QCD: moving back down in energy
QCD at \textit{nonzero} quark density

Usual path integral: Lagrangian, simulate with standard Monte Carlo.

For three or more colors, at nonzero chemical potential $\mu \neq 0$, quark determinant is complex. Can \textit{not} use standard Monte Carlo.

Can use Hamiltonian:

\[ e^{pV} = \sum_i e^{-E_i/T + \mu N_i} \]

Above calculable, \textit{in principle}, using quantum computers

Deriving the properties of nuclear matter, \textit{from first principles}, is one of the great problems of physics in the 21\textsuperscript{st} century.
QCD at nonzero quark density

Pressure determined from sum over states, “i”:
partition (characteristic) function

\[ e^{pV} = \sum_i e^{-E_i/T + \mu N_i} \]

Turn into “path integral” ($\infty$-dimension integral):
weights are complex when $\mu \neq 0$ for three (or more) colors (pressure real)

Sign problem for $\mu \neq 0$: lattice can only compute moments about $\mu = 0$

$\mu \neq 0$ is measurable in heavy ion experiments at low energy

Above calculable, in principle, using quantum computers

Nuclear matter is one of the great problems of physics in the 21st century
Spins & phase transitions

Symmetry of light quarks ~ spins: spin line up, “order” at low T, spins random, disordered, at high T

Another possibility: “lamellar” phase. Ordered in one direction, but liquid in transverse directions.

Occurs in liquid crystals: nematic like ordinary spins smectic ordered in one direction, liquid in transverse
Chiral symmetry in QCD

Chiral symmetry kind of spin, $SU(3)_L \times SU(3)_R \times U(1)_A$.

Low temperature: ordered = confined

High temperature: disordered = Quark-Gluon Plasma

Also: possible to have lamellar phase = chiral spiral. Only at low $T$, $\mu \neq 0$

$$(\sigma, \pi^0) = f_\pi(\cos(k_0 z), \sin(k_0 z))$$

Can find exact solutions in 1+1 dimensions:
Phase diagram for QCD in T & μ: usual picture

Chiral symmetry $SU(3)_L \times SU(3)_R \times U(1)_A$, spin.

Lattice: find crossover at $\mu = 0$. Perhaps: turns into 1st order at some $\mu$? If so, must be Critical End Point: massless mode at CEP.

ordered phase
= confined

crossover line

ordered phase
= confined
disordered phase
= Quark-Gluon Plasma

Critical End Point

1st order line
Phase diagram with chiral spirals

Also possible that because of strong fluctuations, no Critical End Point

Instead, intermediate phase with chiral spirals, separated by 1st order lines.
Using the lattice to calculate $\mu$

Compute moments with respect to a conserved charge, fix $\mu$ directly from STAR experiment @ RHIC

$$R_{12} = \frac{\bar{N}}{(\delta N)^2}, \quad \bar{N} = \langle N \rangle, \quad (\delta N)^2 = \langle (N - \bar{N})^2 \rangle$$

![Graph showing $R_{12}$ vs $\mu_B$ for different energies (E/A) and temperatures (T).]
Large fluctuations @ low energy?

Can measure derivatives of pressure with respect to $\mu$:

$$c_n = \frac{\partial^n}{\partial \mu^n} p(T, \mu)$$

STAR @ RHIC: $c_4 / c_2$ for pions with $p_t$ up to 0.8 GeV, and to 2.0 GeV

Large increase at lowest E/A at high $p_t$: evidence for chiral spiral?
The next Golden Age: low energy

Lattice = bedrock. Need to solve the sign problem

Quantum computers + Lefshetz thimbles?

Data from Beam Energy Scan @ RHIC: Critical End Point? Chiral Spirals?

Beam Energy Scan II, STAR @ RHIC, 2020 → 2022

New AA accelerators @ low energy:
   NICA, Russia. E/A: 1 → 4 GeV, > 2020
   FAIR, Germany. E/A: 1 → 10 GeV, > 2025
   J-PARC Heavy Ions, Japan. E/A: 2 → 6 GeV > ?

Many implications for neutron (quark/quarkyonic) stars: LIGO, X-ray satellites
Gertrude Stein about Oakland, California, ~ 1890:

“There’s no there, there.”
Heavy ion collisions at low energy:

There is a there, there

But what is it?
What I didn’t have time to cover

Chiral Magnetic Effect:
In heavy ion collisions, generate a strong electromag. B field at early times
STAR: prove early B from dielectrons at soft momenta, 1806.02295

Chiral anomaly $\rightarrow$ affects the propagation of quarks, pions:

$$\vec{j}_{\text{em}} = \sigma_5 \vec{B}$$

Kharzeev, McLerran, Warringa, 0711.0850; Fukushima, Kharzeev, Warringa, 0808.3382
Burnier, Kharzeev, Liao, Yee, 1103.1307; Kharzeev, Liao, Voloshin, Wang, 1511.04050

Test: isobar run 2018, $^{44}$Zr vs $^{40}$Ru: same A, different Z.

pA, pp at very high multiplicity, LHC:
Usually, $\sim$ 5 particles/unit rapidity
So many events, trigger on 1 in $10^6$ events with 50-100 particles/unit rapidity

Really looks like “little bit” of QGP: hydrodynamics vs Color Glass.
“The Great Wave” of High Energy Heavy Ion Physics

“The Great Wave off Kanagawa”, by Hokusai
“Everyone knows”: We understand everything about AA collisions at high energy