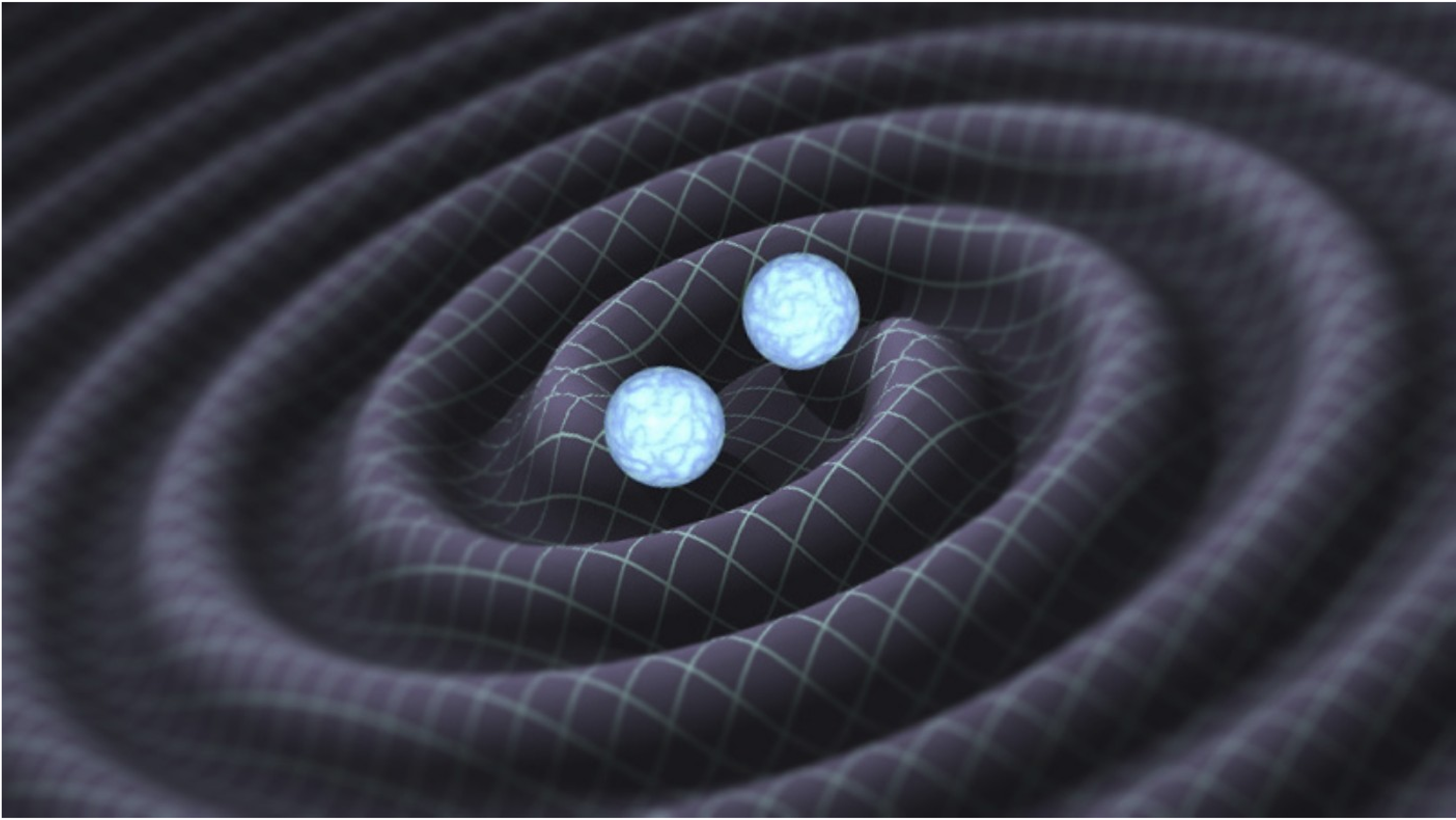
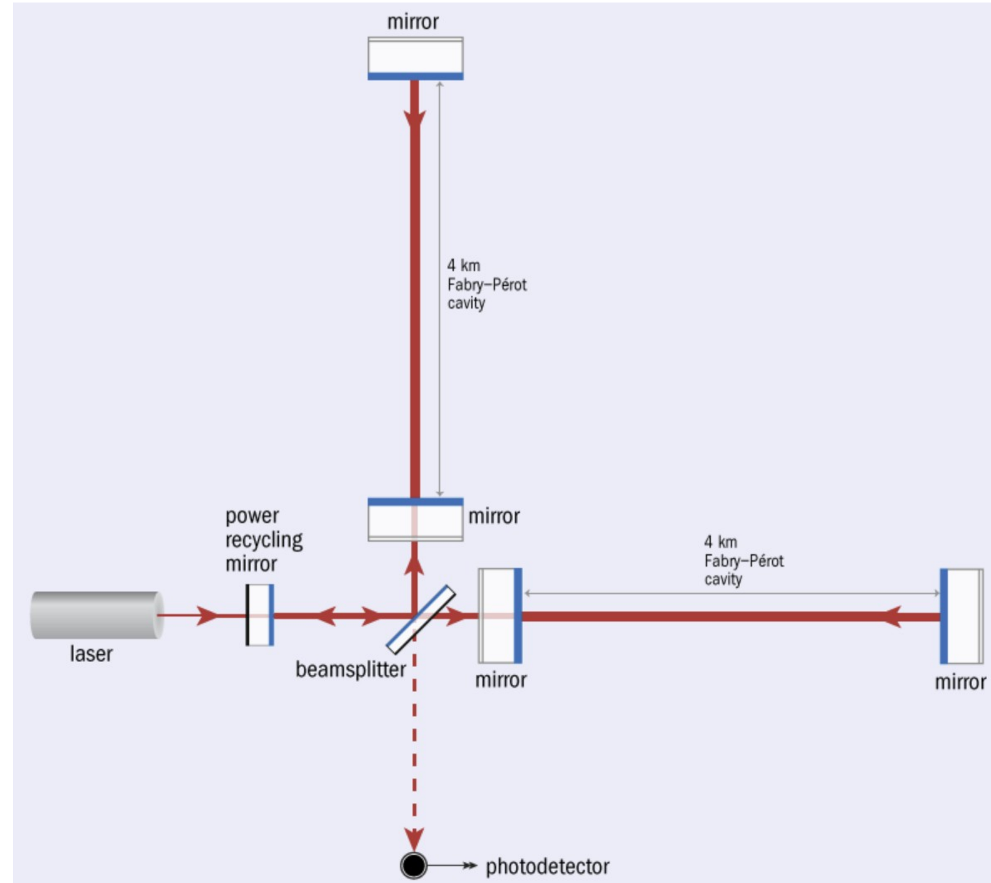
In all fields, there are Golden Ages

Colliding black holes => ripples in space-time = gravity waves

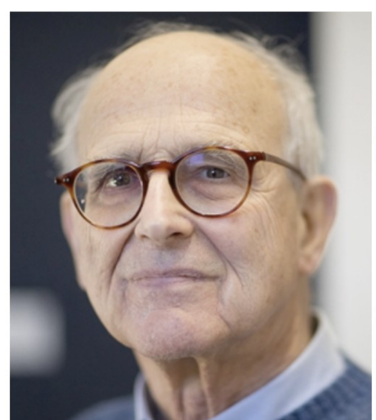


Astronomy: not with light, but with gravity waves

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

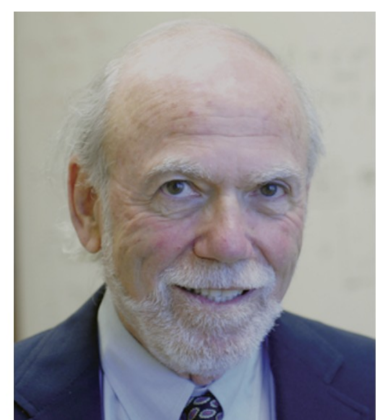


First event: 2015, (39 + 29) M_{sun} BH's
$2M_{sun}$ in *gravity waves*.
$2x10^6$ light years away
~ 10^3 physicists,
~ $\$10^9$ to build, run...
Nobel, 2017:



Bryce Vickmark

Rainer Weiss

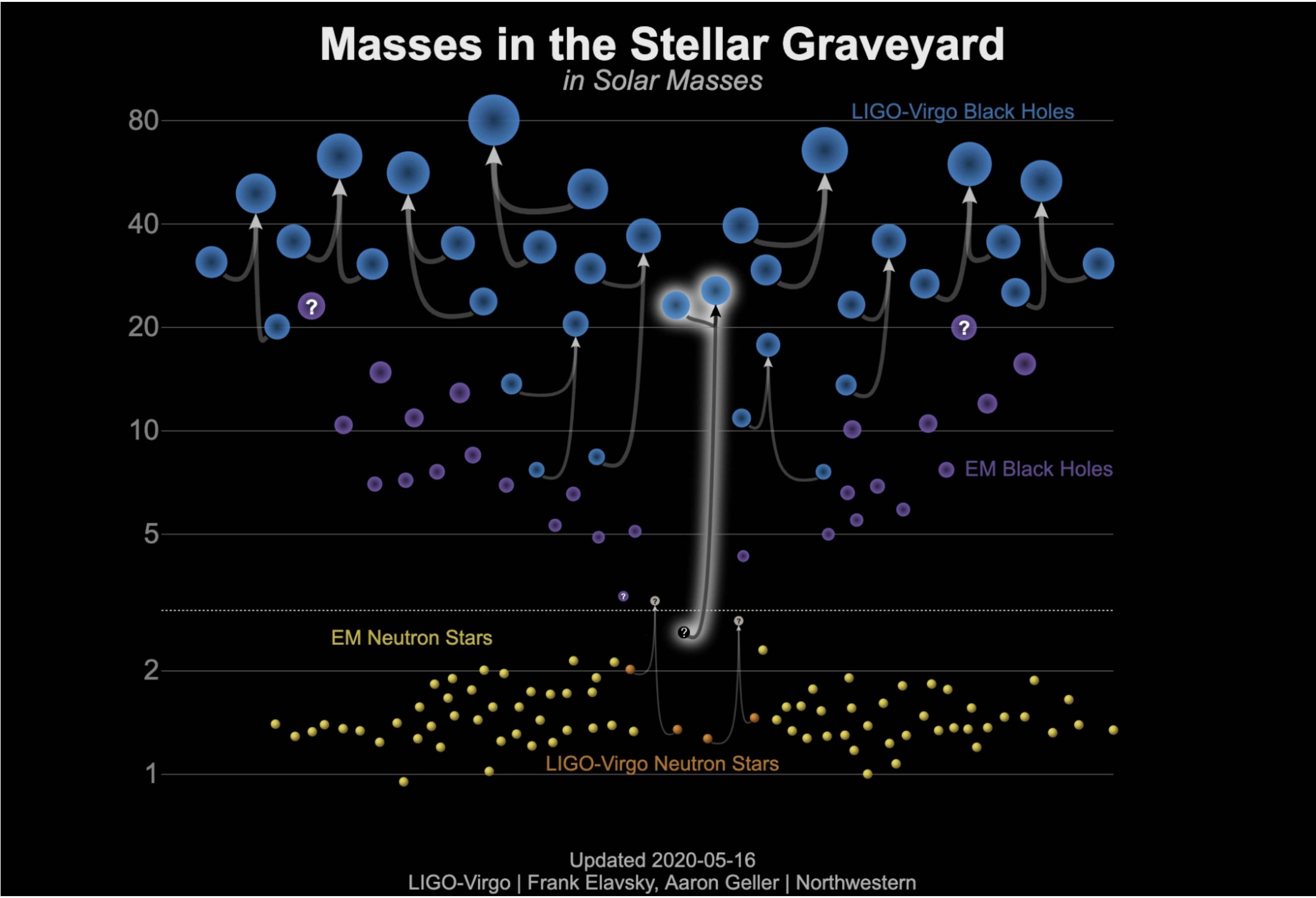


Caltech

Barry Barish

Jon Rou

Kip S. Thorne

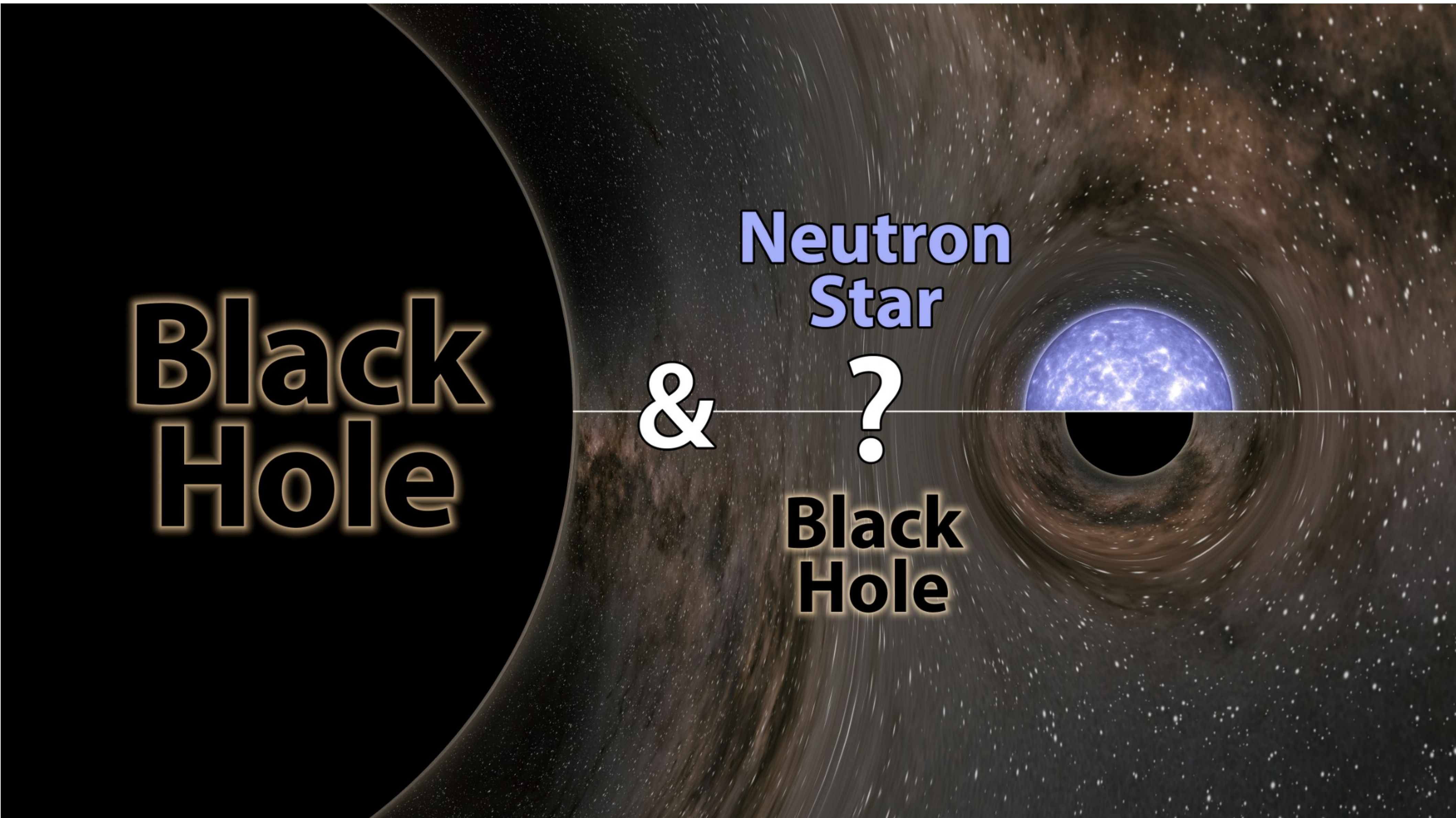

Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
80
40
20
10
5
2
1
Updated 2020-05-16
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

August, 2019: GW190814: merger of black hole, 23 M_{sun} & object 2.6 M_{sun}

2.6 M_{sun}! Lightest known black hole is ~ 5 M_{sun}; heaviest neutron star 2.0 M_{sun}.

We don’t understand either black holes or neutron stars

Gravitational observatories will yield much info about neutron/quark stars



Finding the "Higgs" boson

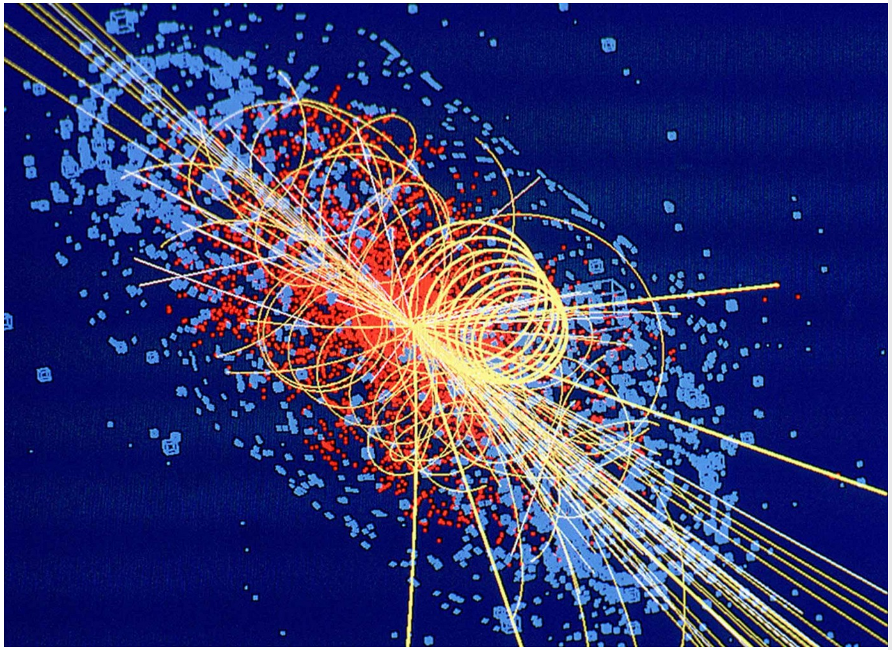
"Higgs" boson: particle that gives most particles ~ 95% of their mass

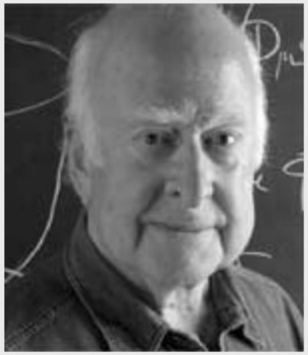
proton-proton collisions at the Large Hadron Collider (LHC), CERN (Geneva):

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

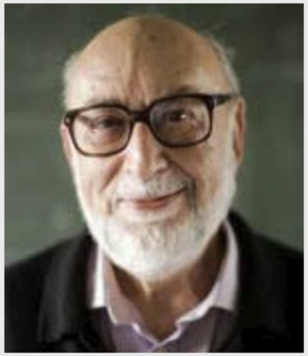
Physics from '10, discovered Higgs in '12, Nobel, 2013:

But *no* signs of supersymmetry!





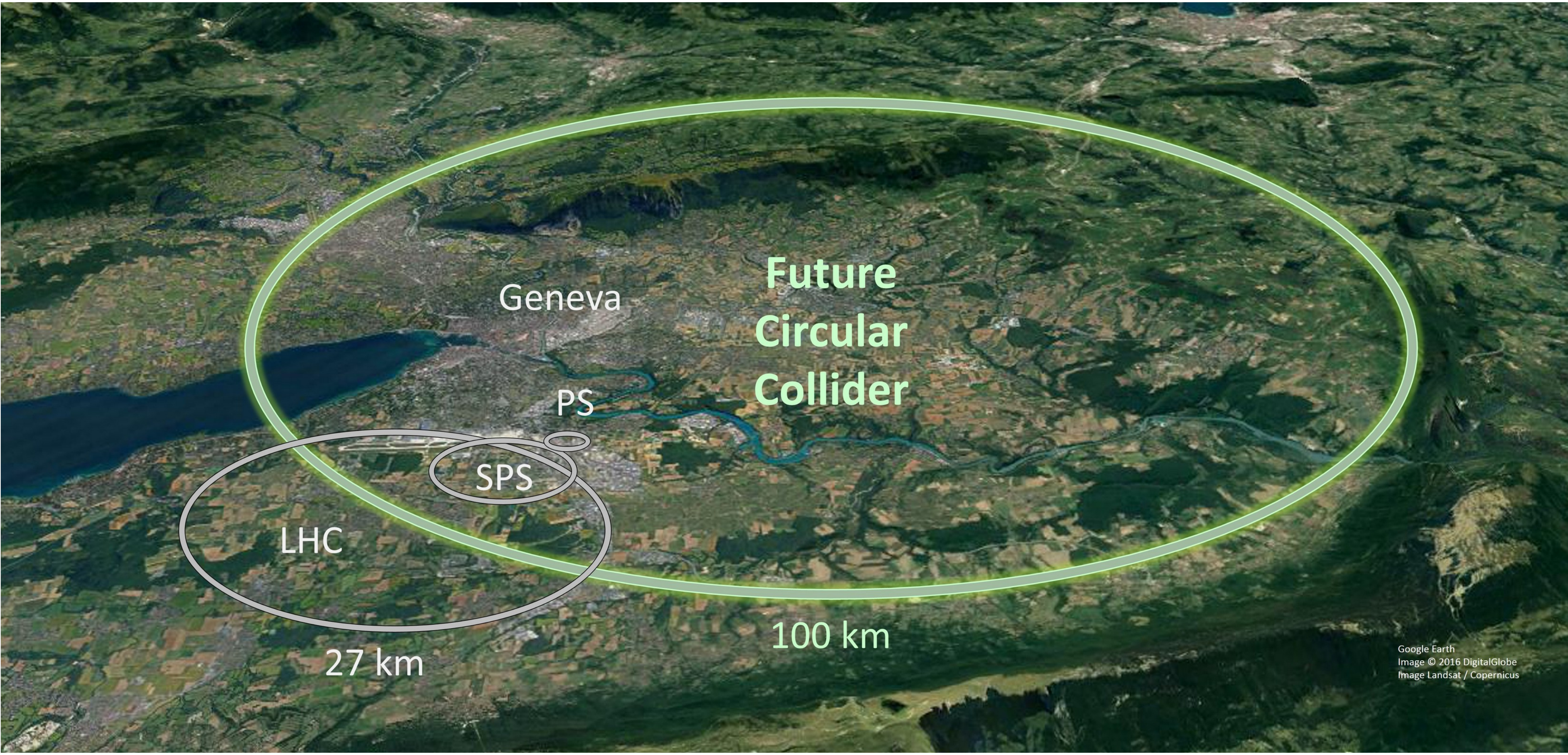
Peter Higgs



Francois Englert

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.

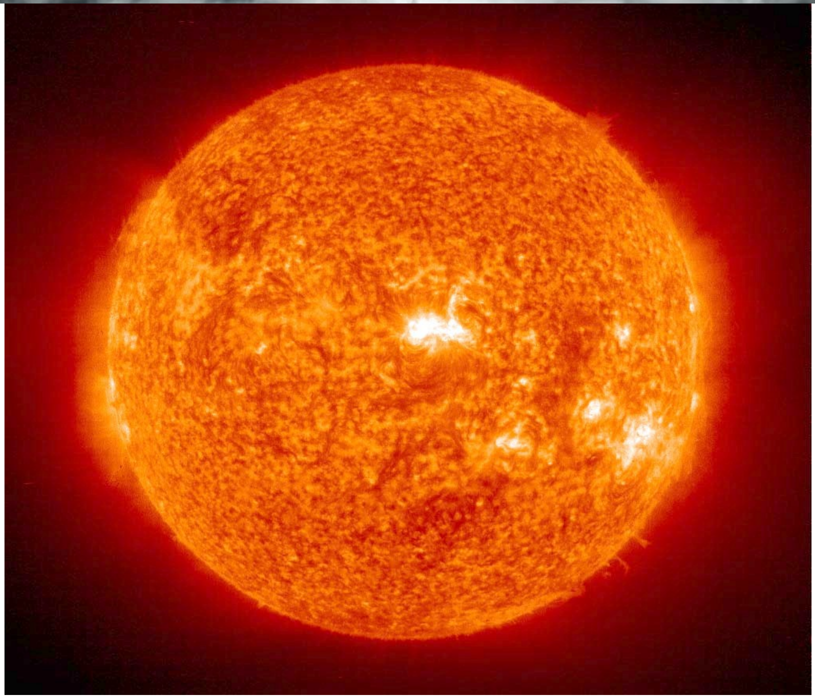
Fourth state: plasma

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

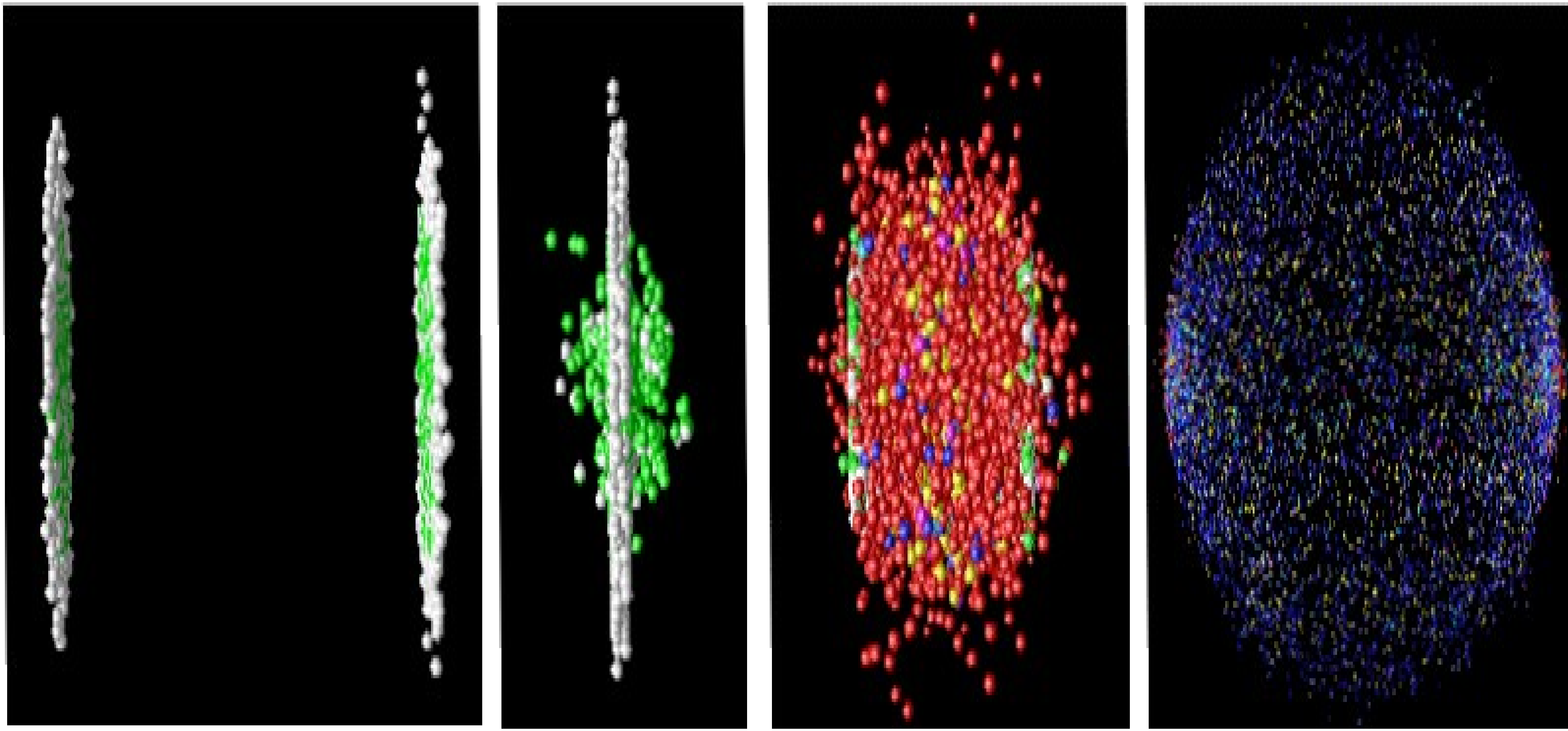
Plasma: charges move freely, independently
Need heat +… to shake atoms apart

Flourescent bulb: electric field E
Flame, 10^3 ^oK
Sun: exterior 10^4 ^oK, interior 10^7 ^oK

Quark-Gluon Plasma: trillion^{o}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.

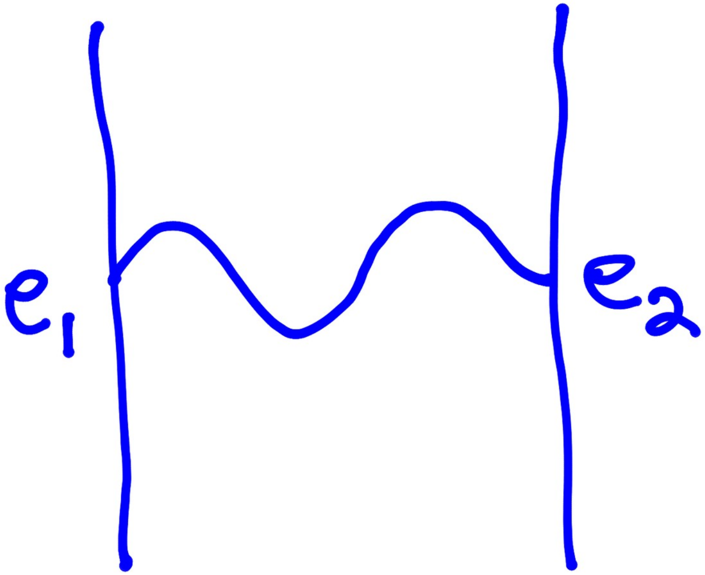
E.g.: electrons, e-, and protons, p+.

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...

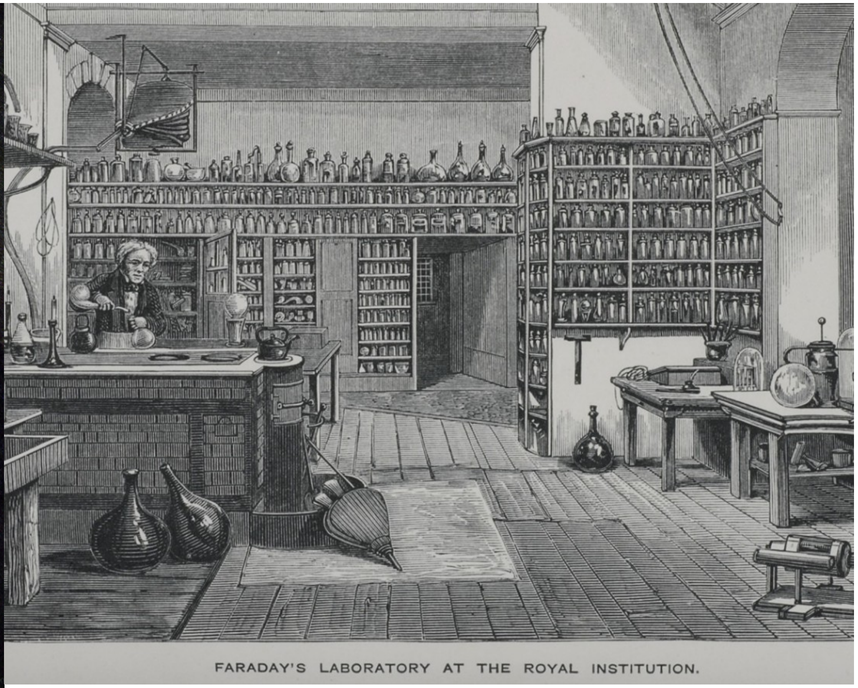
Potential due to exchange of photons (light)



ElectroMagnetism

Michael Faraday, 1791-1865

Discovered EM induction
Saw lines of EM force
Faraday cage...



Faraday & his lab

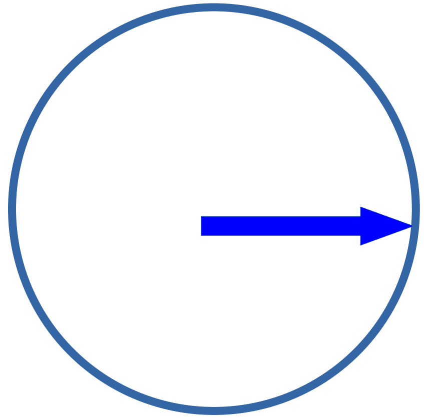
James Clerk Maxwell, 1831-1878
Unified EM equations into 4:

$$\nabla \cdot E = \rho \;\; ; \;\; \nabla \cdot B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \;\; ; \;\; \nabla \times B = J + \frac{\partial E}{\partial t}$$

Maxwell

What is light?



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

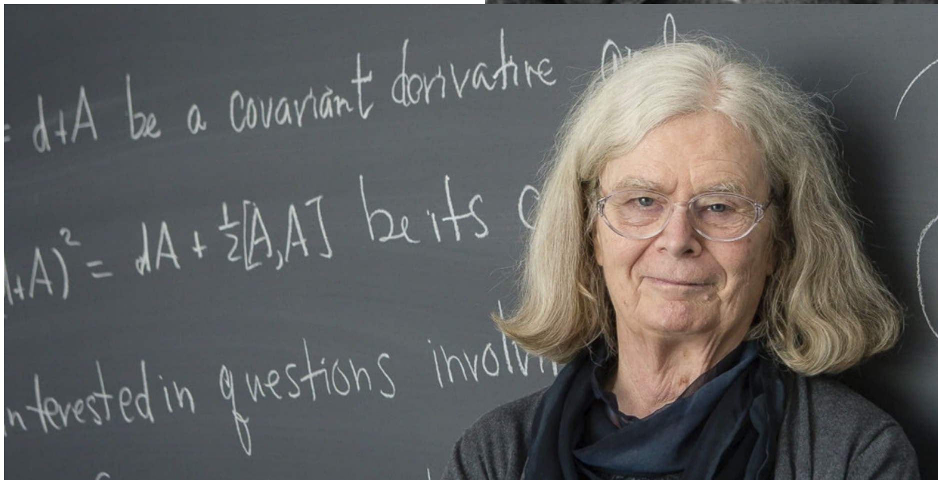
Order of rotations doesn't matter: $\theta_1 + \theta_2 = \theta_2 + \theta_1$.
This is an "*Abelian*" group (Niels Abel, 1802-1829)

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

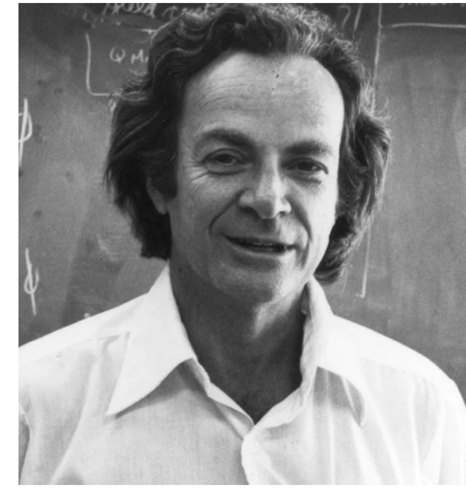
Abel

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

Uhlenbeck



Modern view of light



Feynman

Photons A_μ & charged particles ψ. In one line:

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

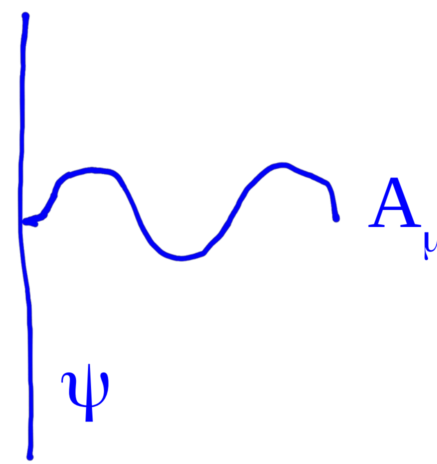
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \; , \; D_\mu = \partial_\mu - ieA_\mu$$

Tomanaga

Quantum ElectroDynamics (QED)

Nobel, 1965: Feynman, Schwinger, Tomonaga

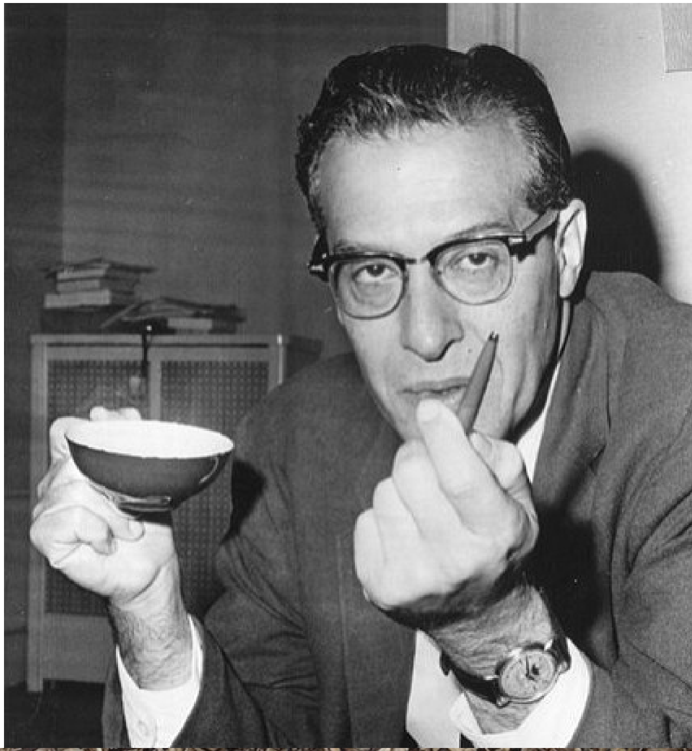
Charged particles interact with photons as:



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",

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

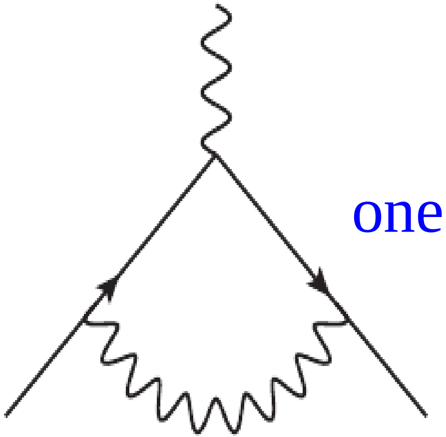
Small α means pencil and paper ok

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, $= \alpha/2\pi$



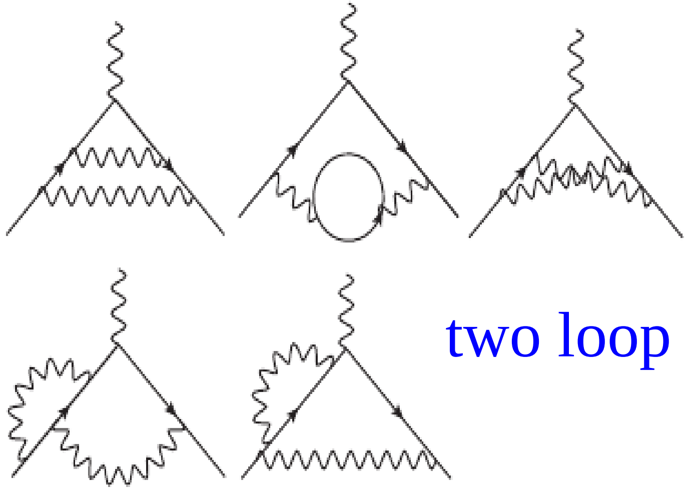
Today: corrections to *five* loop order, $\sim (\alpha/2\pi)$^5

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

For muon (~ heavy electron) difference between EXPeriment and the Standard Model is 10^(-9)

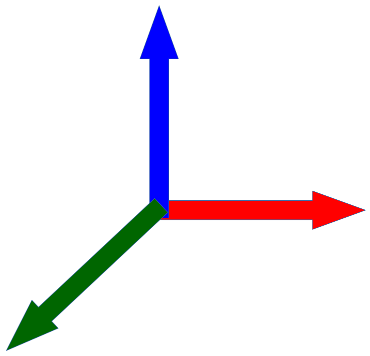
$$a_{muon}^{EXP} - a_{muon}^{SM} = (27.6 \pm 8.0) \times 10\text{^}(-10)$$

This difference is now a big deal:
hints of new physics (supersymmetry)?



Modern theory of nuclei

Nuclei = neutrons & protons = “baryons”: *strong* interactions



Each baryon = *three* quarks + gluons.

Quarks & gluons carry “color”

Color charges are complex 3x3 matrices

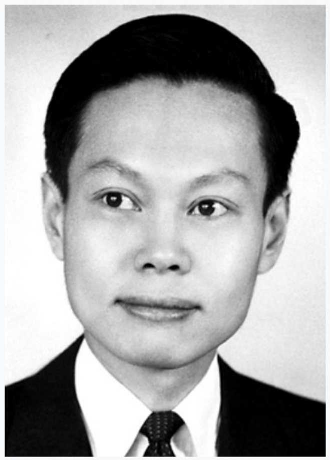
Can rotate by complex 3x3 matrix phases: *non*-Abelian ($U_1 \, U_2 \neq U_2 \, U_1$)

= 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

Yang Chen-Ning
楊振寧



Yang in 1957

←Robert Mills

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

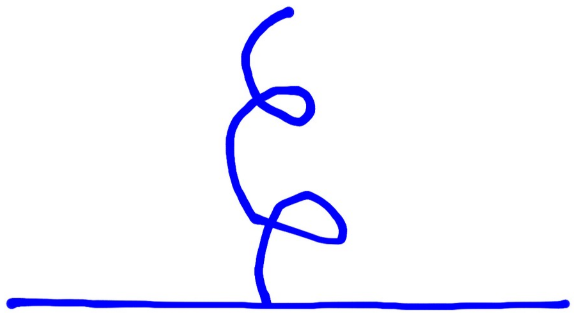
Like QED, for QCD we can write the theory down in two lines:

q = quark, A_μ = gluon, coupling $\alpha_s = g^2/4\pi$

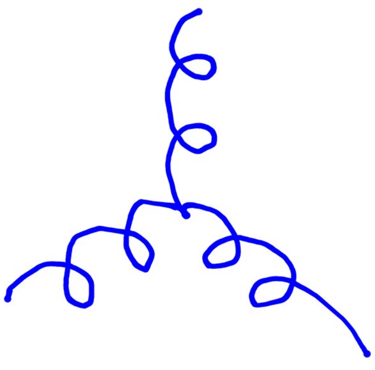
$$\mathcal{L} = \frac{1}{4}\text{tr}\; G_{\mu\nu}^2 + \overline{q}\gamma^\mu D_\mu^f q$$

$$G_{\mu\nu} = -1/(ig)[D_\mu, D_\nu]\;,\; D_\mu = \partial_\mu - ig[A_\mu,]\;,\; D_\mu^f = \partial_\mu - igA_\mu$$

Interactions:
qqg ~ same,



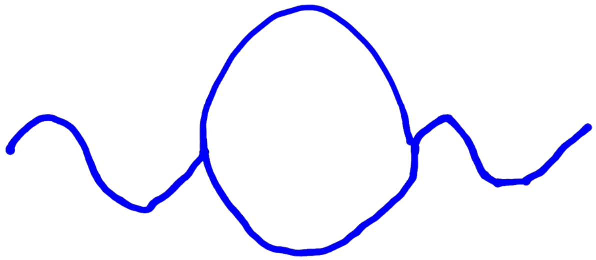
Plus interactions for
3 & 4 gluons:



How couplings run, QED & QCD

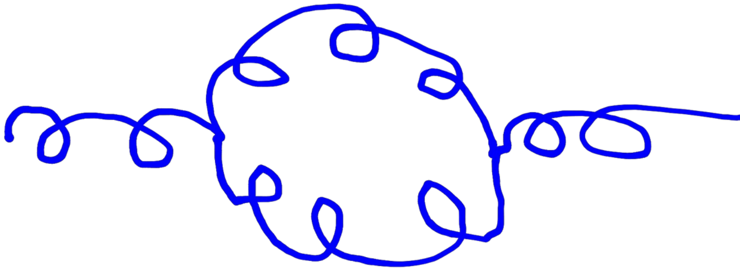
Couplings "run": change with distance:

In QED, coupling α 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

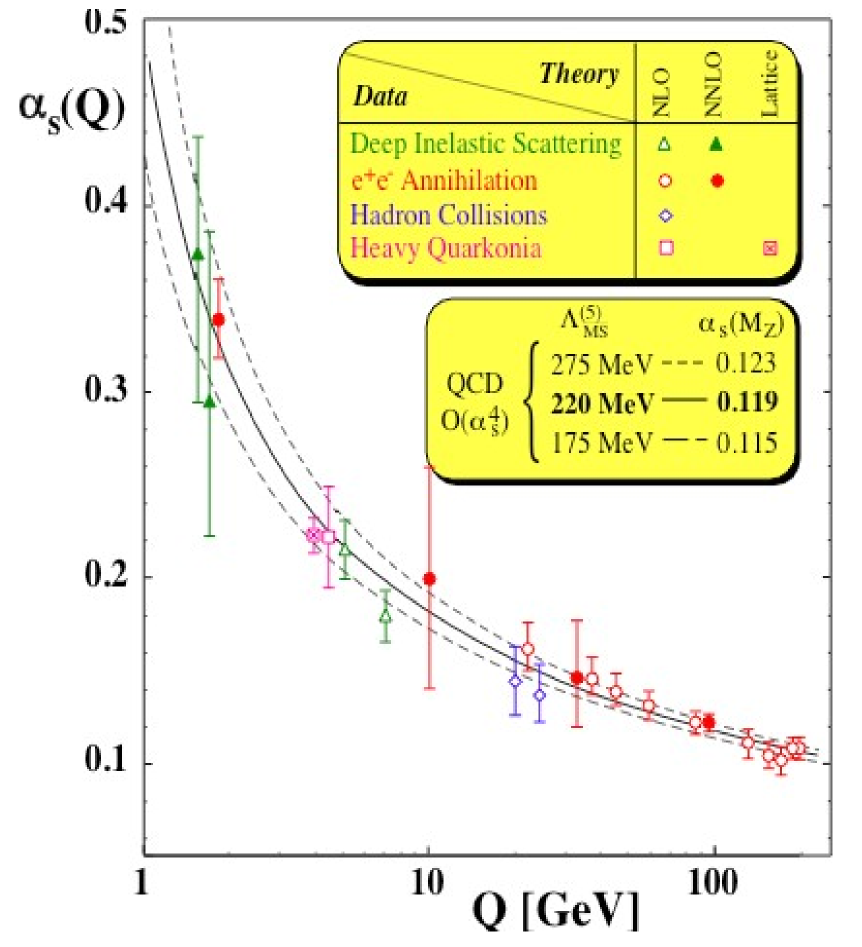
QCD coupling decreases logarithmically at short distances:

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

N_f = # quark “flavors” (~ 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:

David J. Gross

H. David Politzer

Frank Wilczek

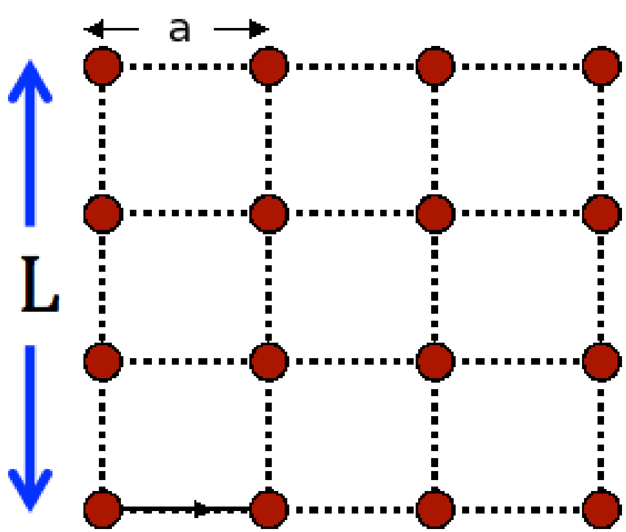
How to compute in QCD?

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 => correct as lattice spacing a -> 0

So put QCD on a lattice and use a computer!

Gordian Knot

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

LLSC, MIT

“Ο, τι δεν λυνεται, υπολογιζεται”

Cut what you cannot untie

Simulate what you cannot solve

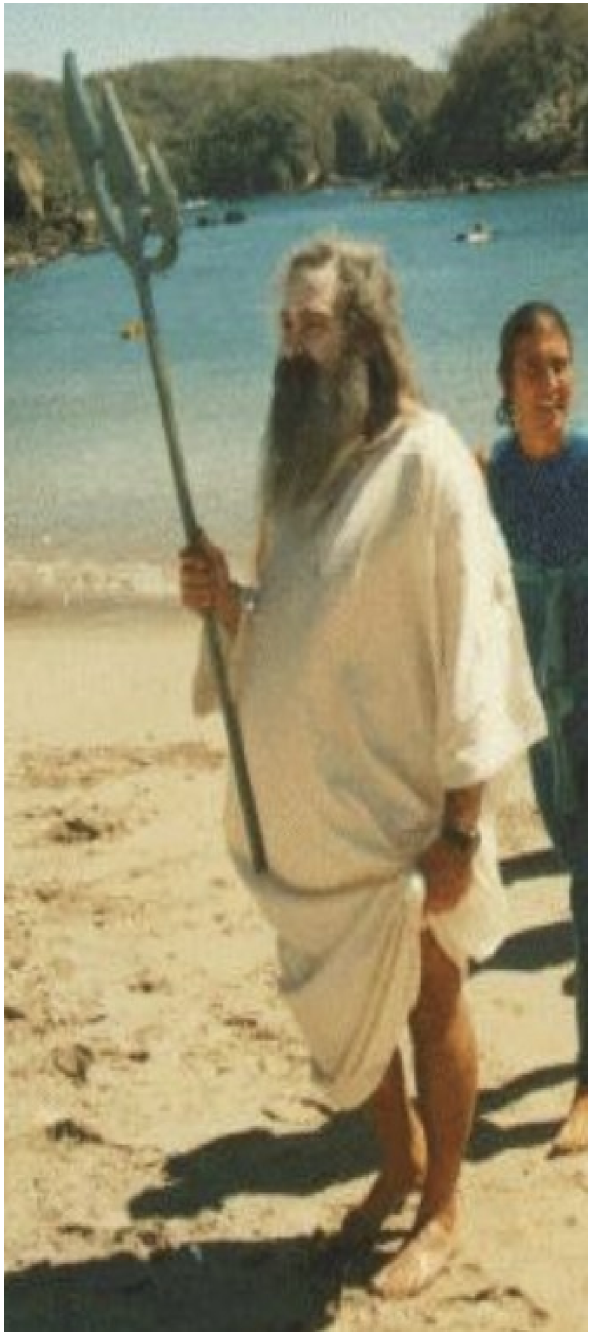
Confinement in QCD

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

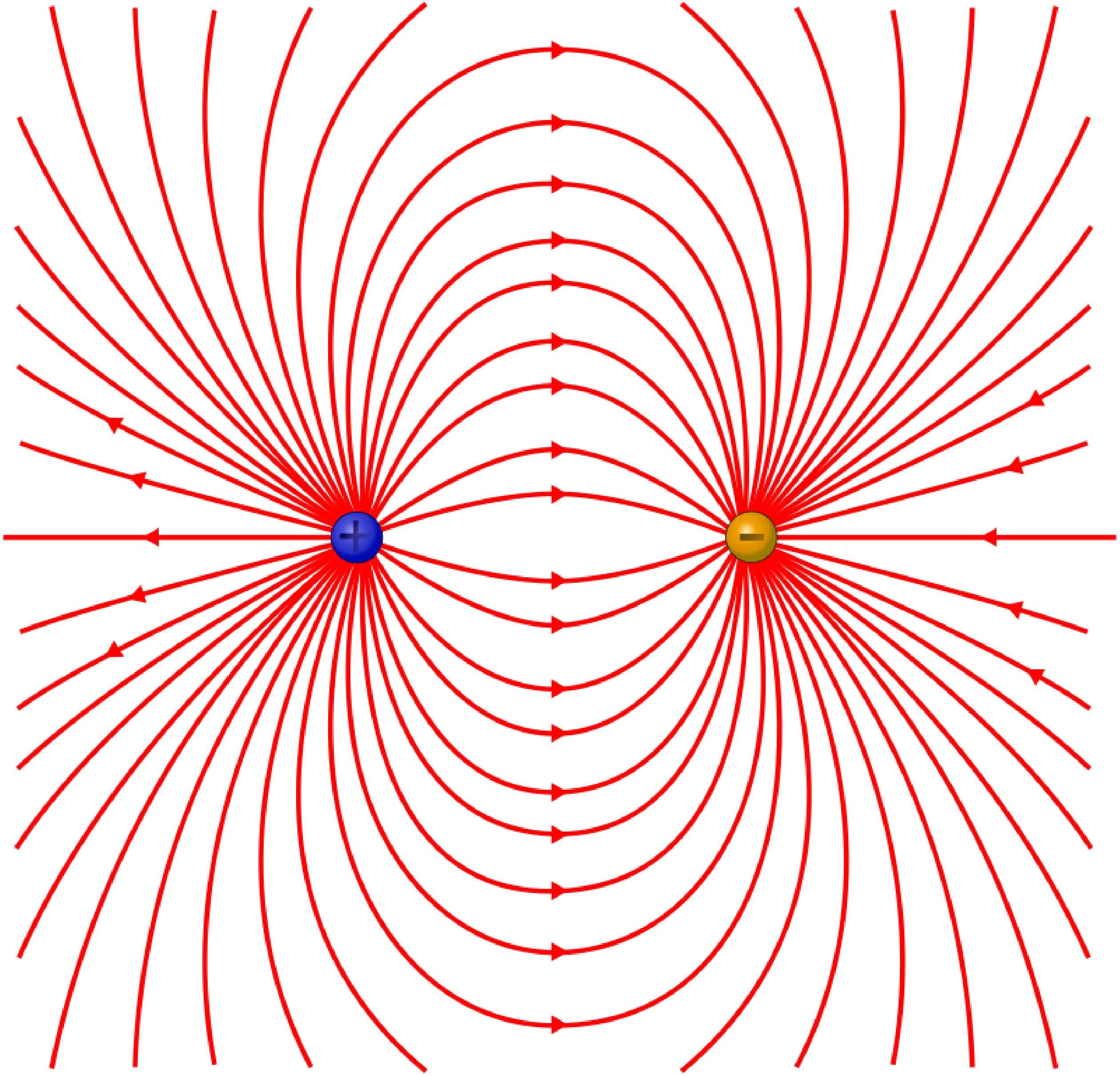


Creutz

Flux lines in QED

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

$$V_{QED}(r) = -\frac{\alpha_{em}}{r}$$

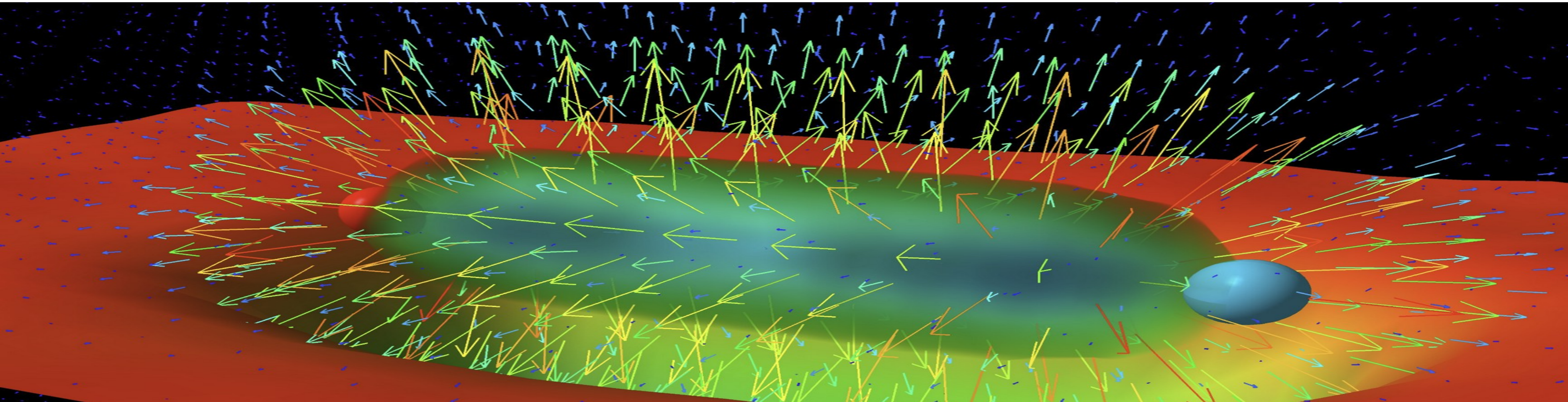


Confinement in QCD

At short distances, quark potential like QED, ~ 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 -> ∞, infinitely strong potential: "infrared slavery". σ = string tension.
Can*not* produce a single quark, only states with *zero* net color: *confinement*.
Picture of flux tube from quark + anti-quark ↓ (Leinweber)



Need *big* computers

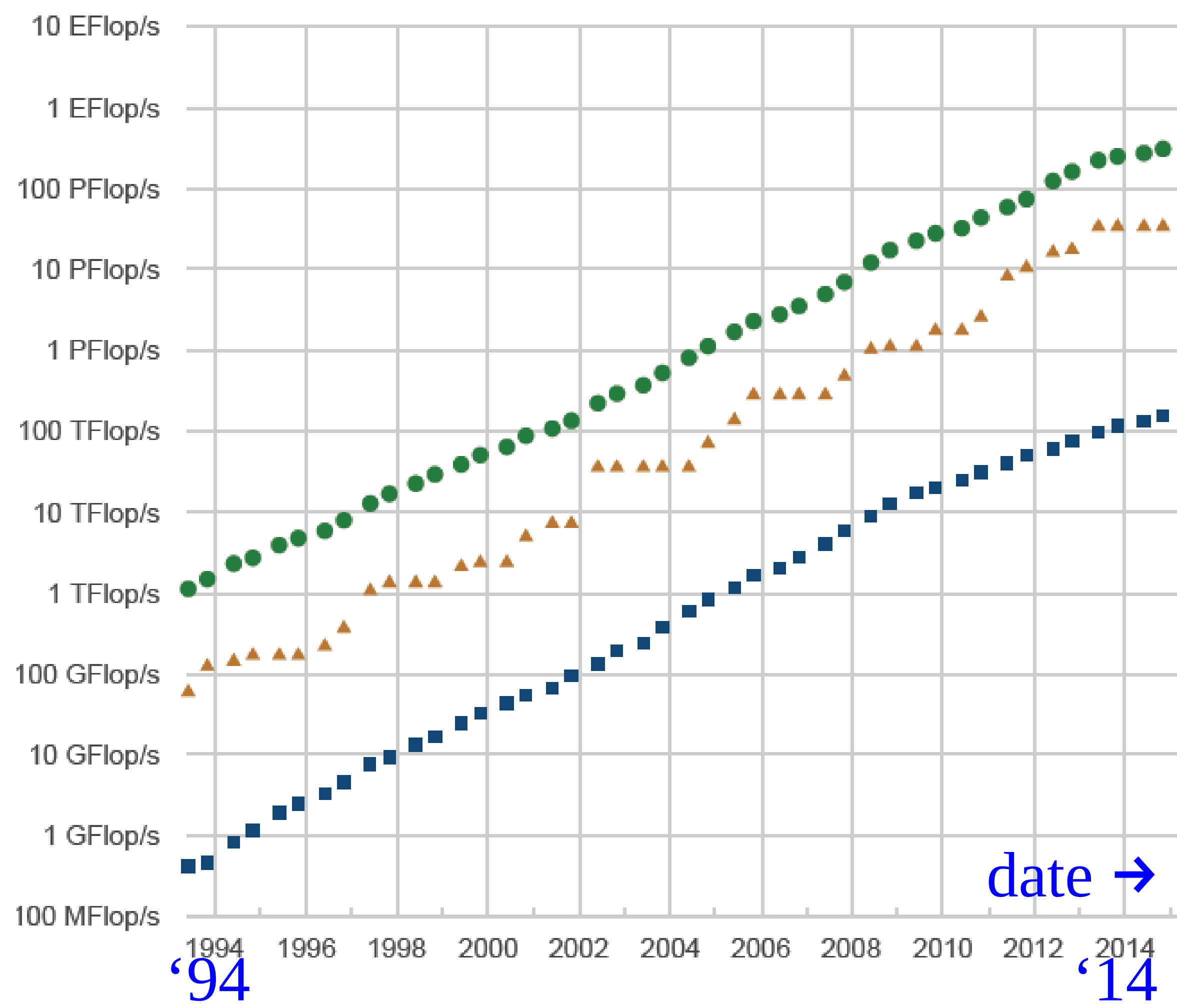
Miracle: from the 90's, possible to compute, *near* a = 0, with*out* quarks

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

2018: near a = 0 for simplest quantities.

log(computing power) ↑

COURTESY: PROF. JACK DONGARRA



Digression: Fermi & nuclear fission

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

Enrico Fermi: m*any*, *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

Fermi

Noddack

Nuclear Fission

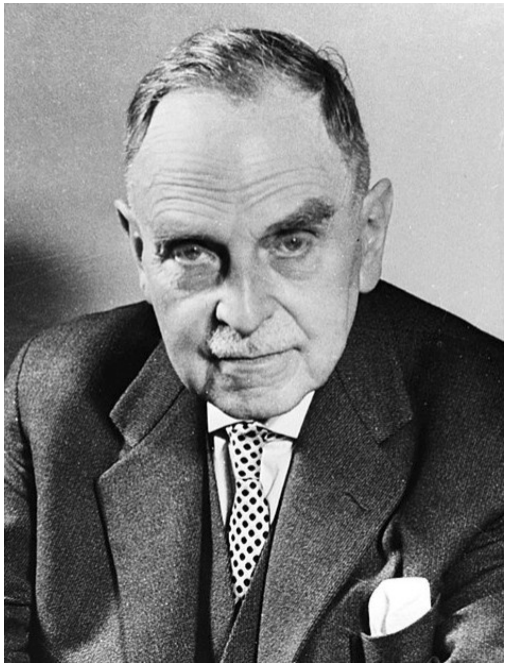
Fission: Otto Hahn, F. Strassmann: Jan. 6 & Feb. 10, 1939
Decay products lighter than lead

$$^{235}\mathrm{U} + \mathrm{n} \rightarrow {}^{92}\mathrm{Kr} + {}^{141}\mathrm{Ba}$$

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.



Hahn

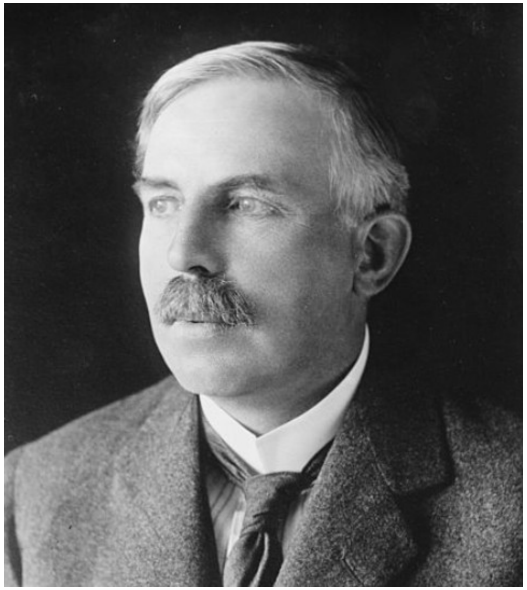
Meitner

Perils of Assumptions

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

Because p + Li → 2 α ,

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



Rutherford

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…

Szilard

Common assumptions are often wrong!

Units in QCD: *small, quick, hot*

Proton is *small:* 10^(-15) meter = fermi (fm)

Time scales are *quick:* 1fm/c ~ 10^(-24) sec (c = speed of light)

Proton is *light*: 10^(-27) kg Masses equivalent to temperature:

And *hot*: mass of proton ~ 5 x10^(12) ^{o}K = *5 trillion degrees*

Typically use mass of proton ~ 940 MeV.

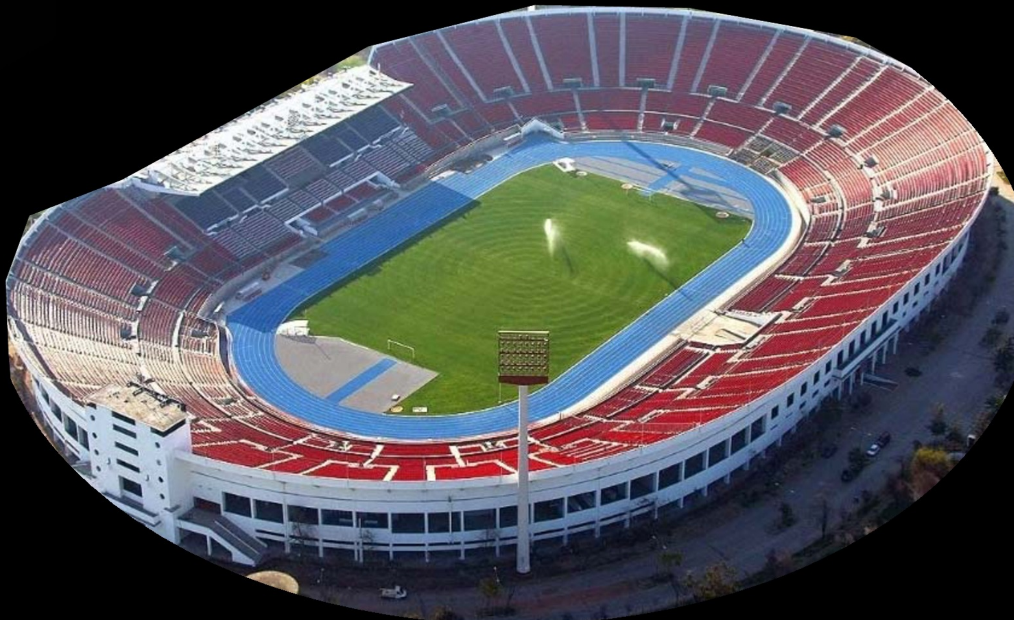
Six quark "flavors": up (u), down (d), strange (s), charm (c), bottom (b), top (t)

1st three flavors, u, d, & s, are *very* light: "chiral" symmetry

Lightest particles pions (π), kaons (K), etc. mass pion ~ 140 MeV; kaon ~ 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.

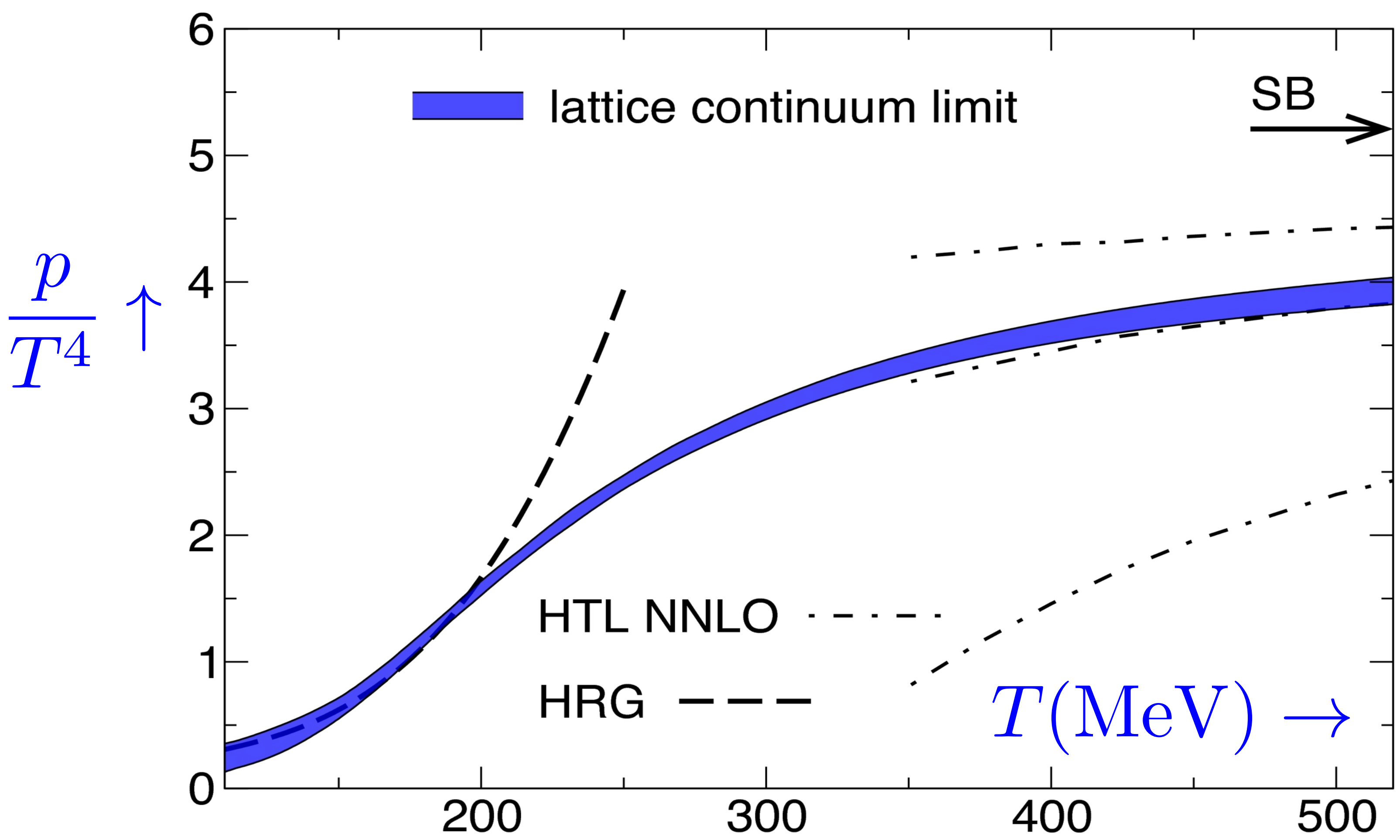
Expect *large* increase in pressure in going from confined phase to QGP

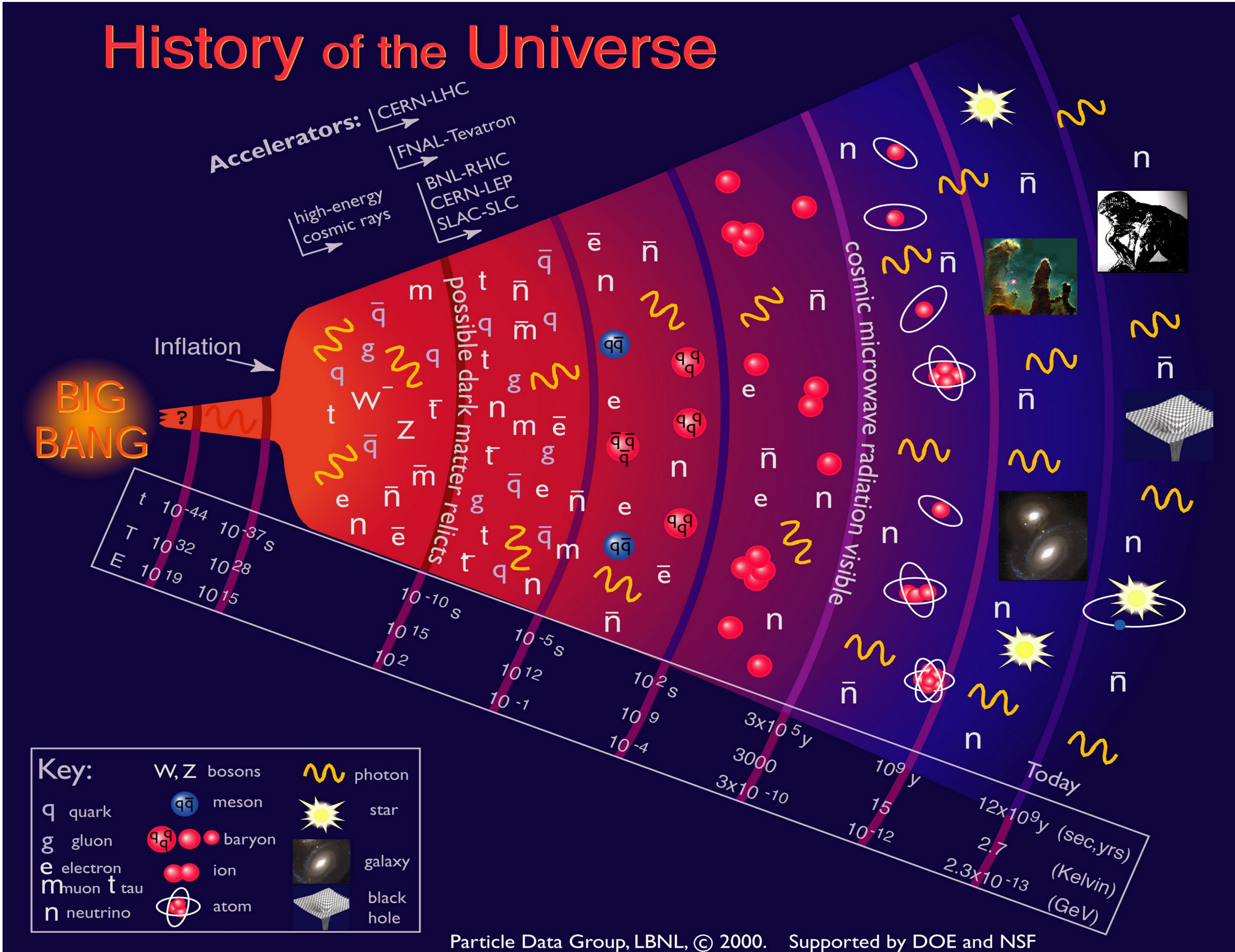
Lattice: thermodynamics of QGP

~ 2014: Lattice can measure pressure at temperature T ≠ 0 (μ = 0).

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

From chiral order parameters, T_χ = 154 ± 9 MeV Errors from a -> 0





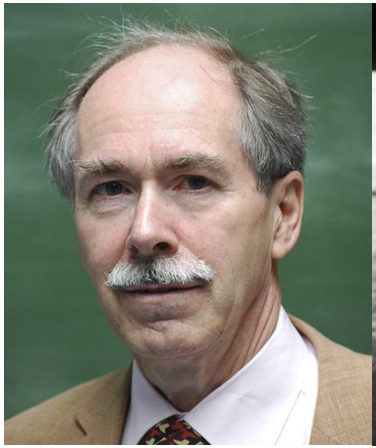
History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
?
possible dark matter relicts
cosmic microwave radiation visible
t 10^{-44} 10^{-37} s
T 10^{32} 10^{28}
E 10^{19} 10^{15}
10^{-10} s
10^{15}
10^{2}
10^{-5} s
10^{12}
10^{-1}
10^{2} s
10^{9}
10^{-4}
$3x10^{5}$ y
3000
$3x10^{-10}$
10^{9} y
15
10^{-12}
Today
$12x10^{9}$ y (sec,yrs)
2.7 (Kelvin)
$2.3x10^{-13}$ (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

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 ~ 200 (Au, Pb)

Radius ~ A^(1/3): ~ 1 fm for proton, ~ 7 fm for Au, Pb

Two thermodynamic parameters: T = temperature and μ = chemical potential

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

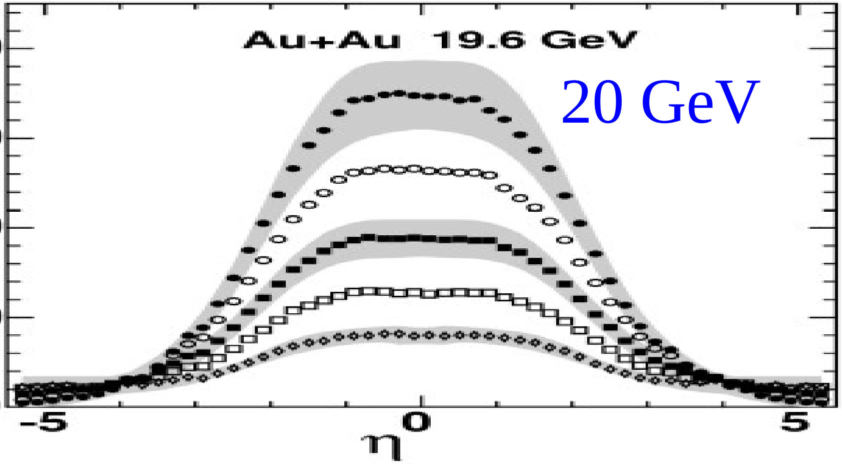
Because of “sign problem”, lattice (today) can *only* do $\mu_{qk} = 0$.

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

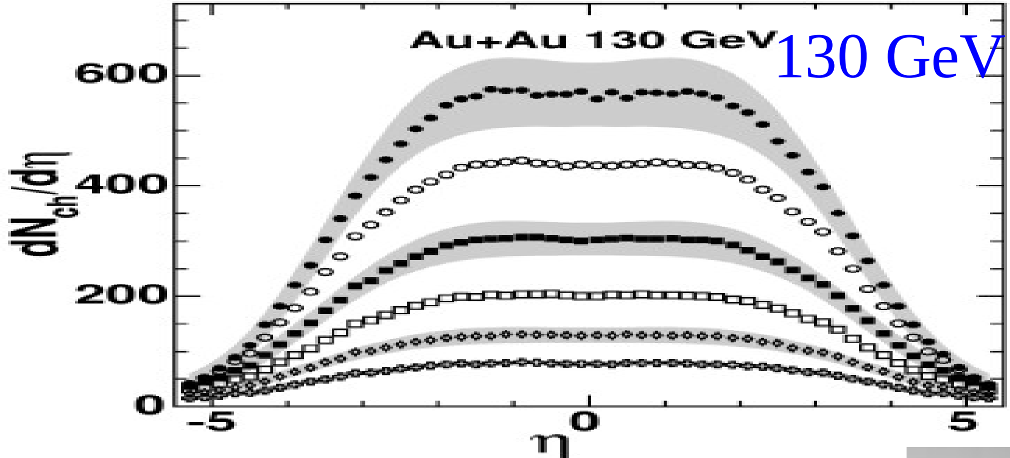
To probe baryon free region, need *high* energy. How high?

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



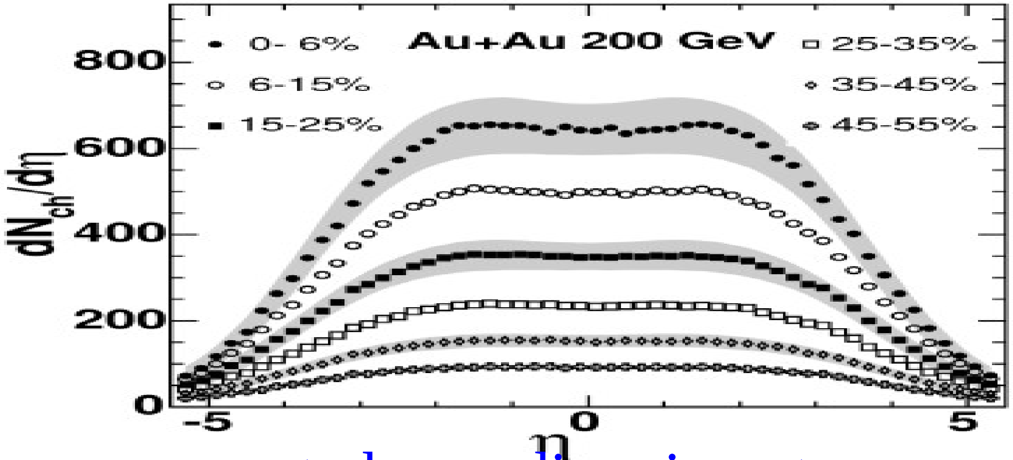
20 GeV



130 GeV

200 GeV

particles ↑
/unit rapidity

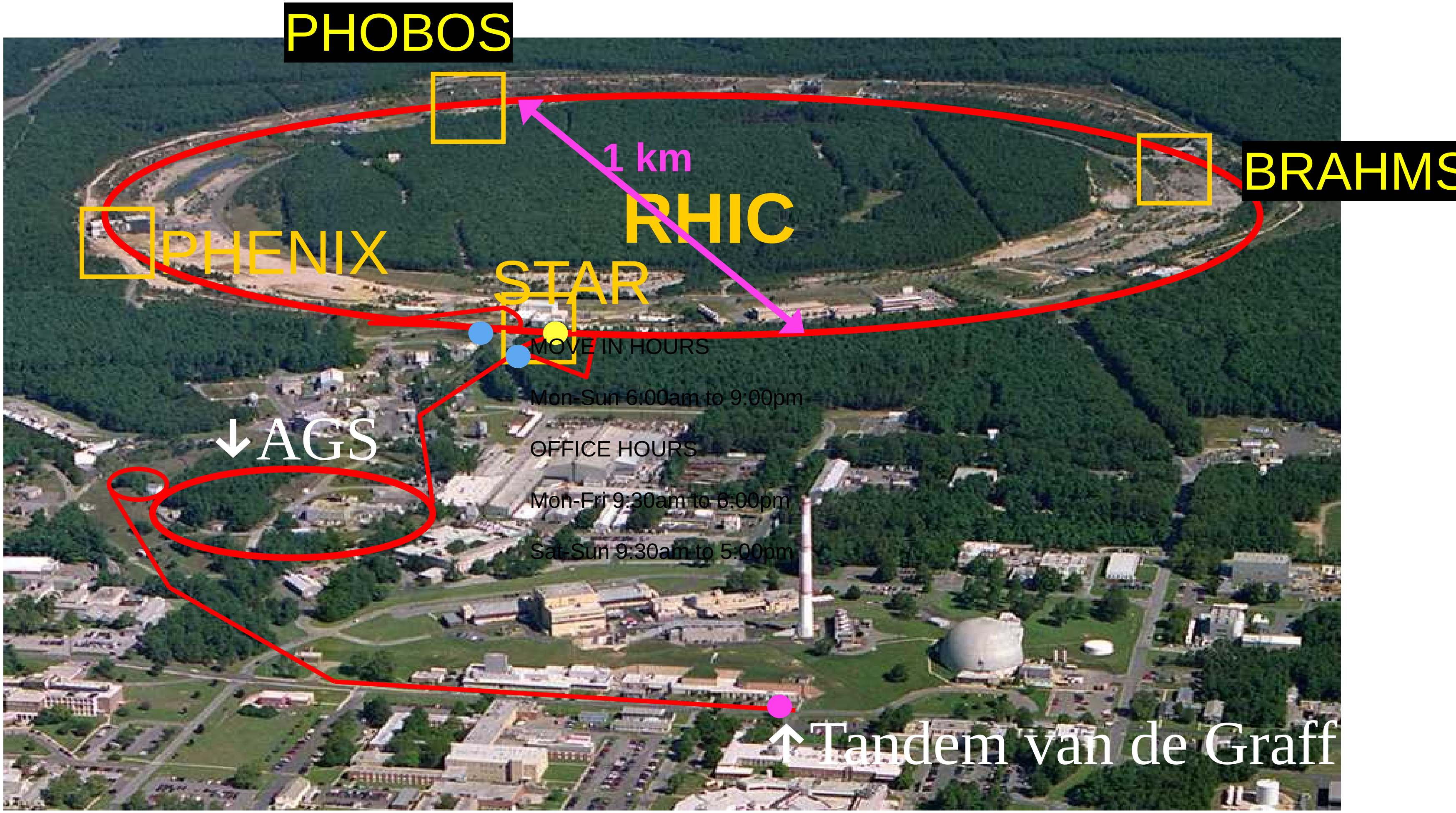


<= beam direction =>

J. Bjorken, '83

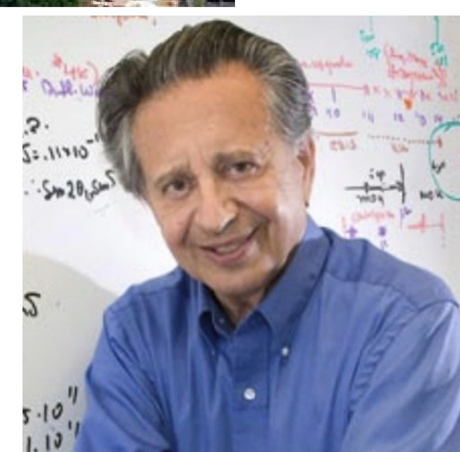
Relativistic Heavy Ion Collider @ BNL

animation by
Mike Lisa

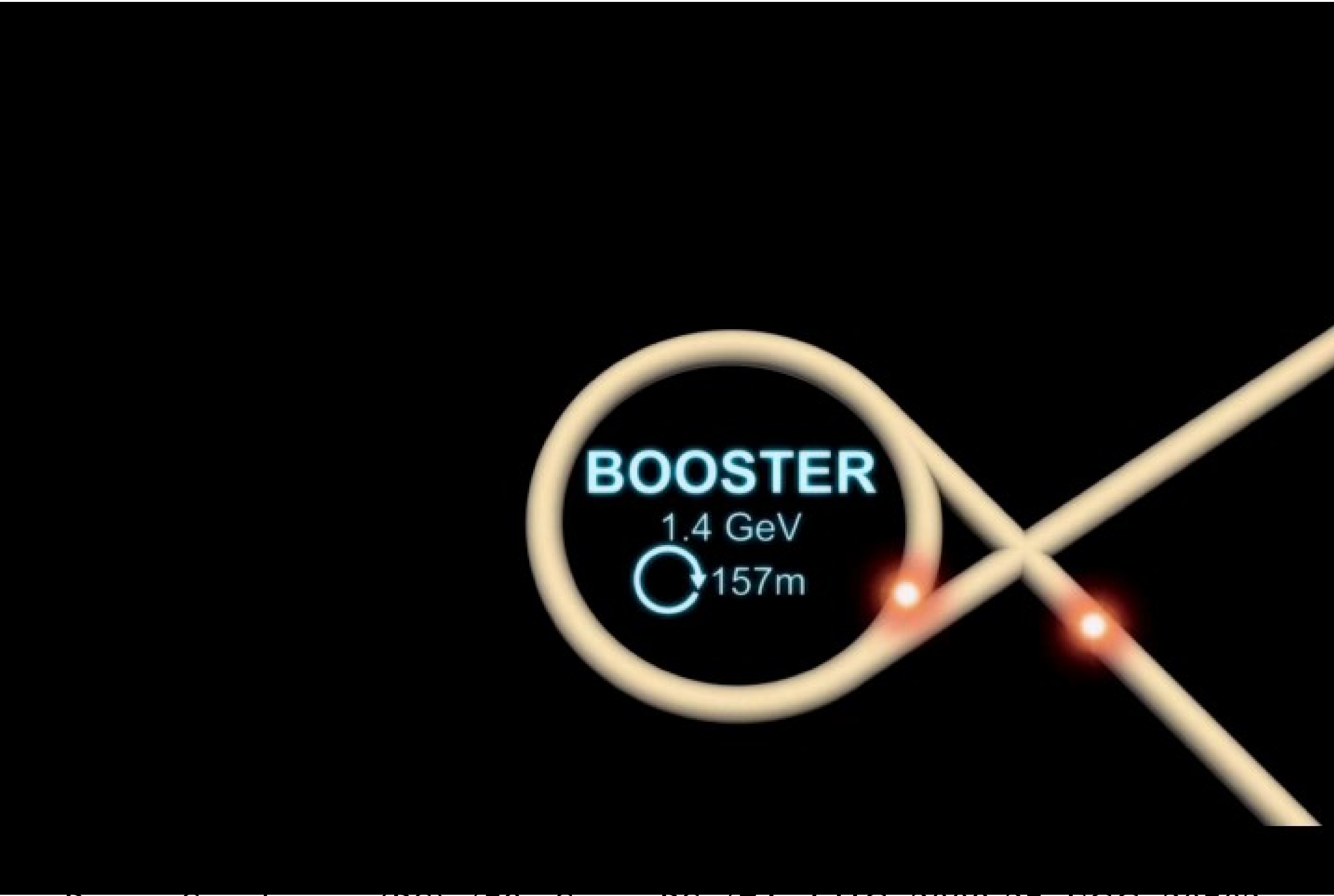


AGS: ‘60. Tandem: ‘70.
Isabelle: pp @ 200 GeV, cancelled in ‘83
(Because of SSC, cancelled in ‘93)
RHIC: 1991 → 2000. E/A: 7 to 200 GeV

Samios ‘83

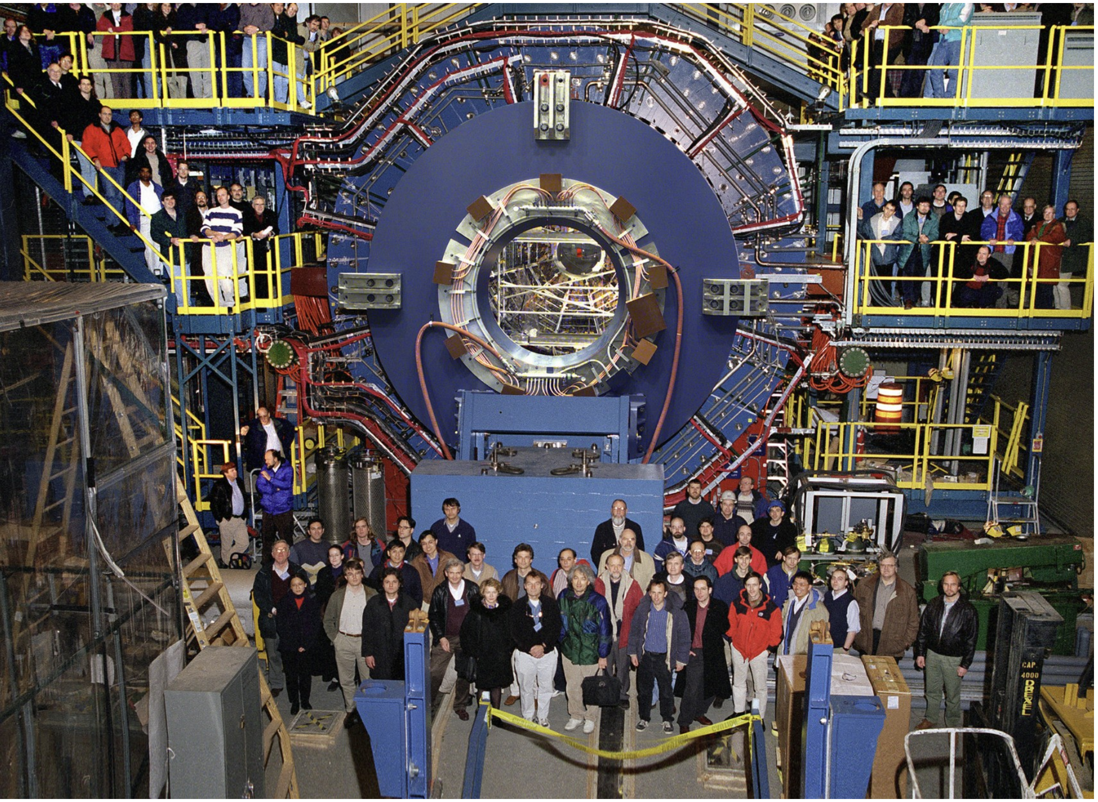


Large Hadron Collider @ CERN, Geneva: E/A ~ 3000 GeV



Proton Synchotron (PS): '59. Super PS: '74. LHC: 2008-35 FCC: 2050?

RHIC experiments: PHENIX, STAR (BRAHMS, PHOBOS)



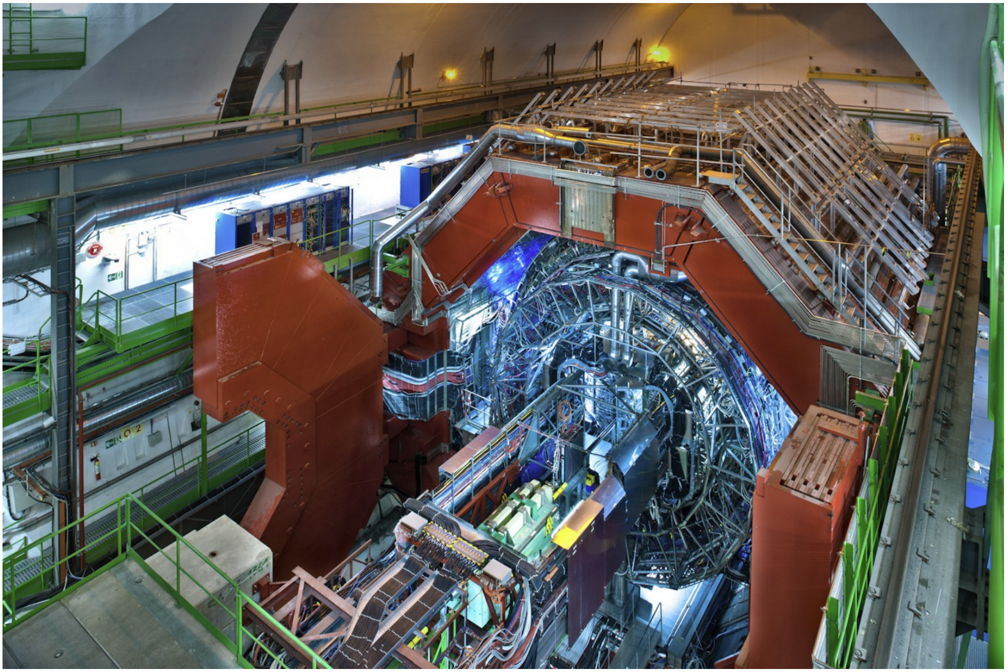
STAR↑

PHOBOS

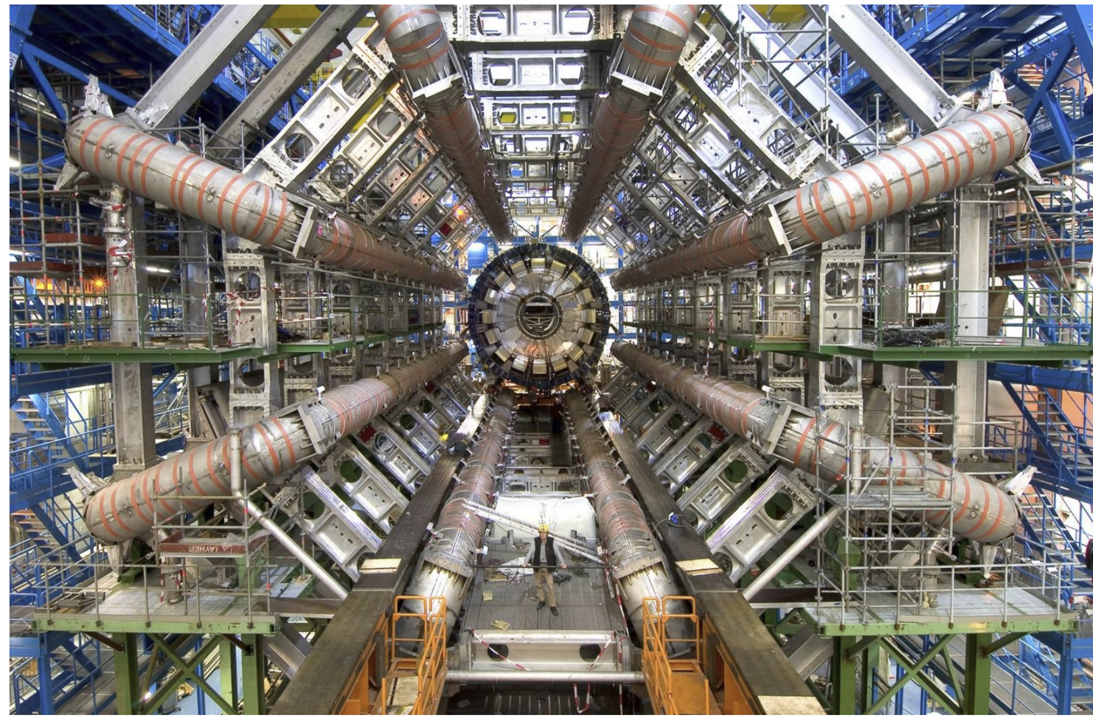
BRAHMS

PHENIX↓

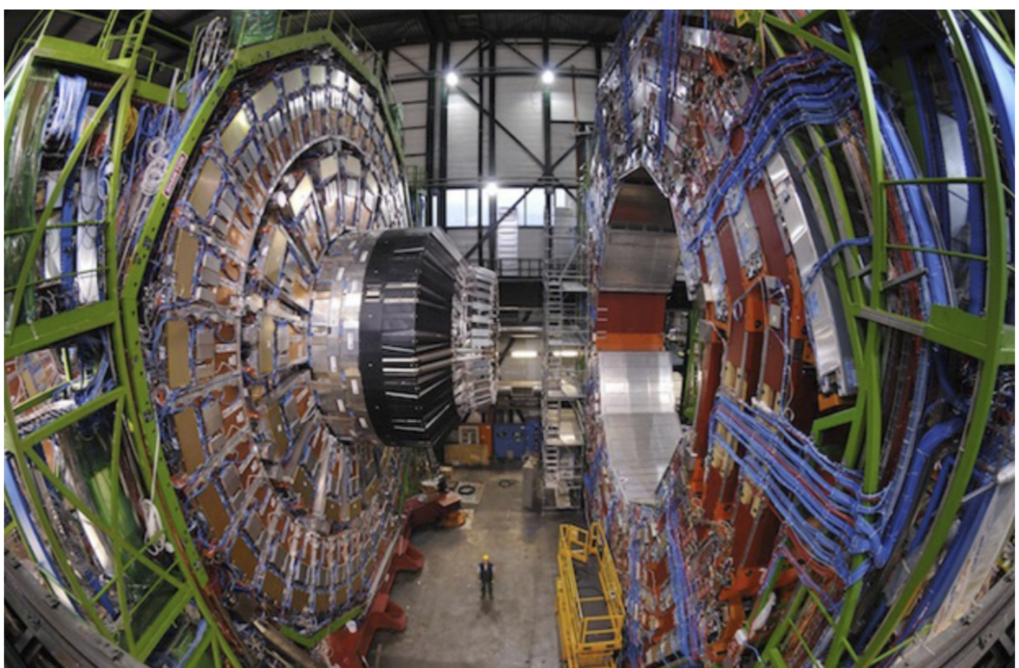
LHC experiments: ALICE, CMS, ATLAS



ALICE



ATLAS



CMS

Why skepticism about AA?

“Everyone knows”: in high energy physics, understanding (& simplicity)

from studying collisions of *few* particles

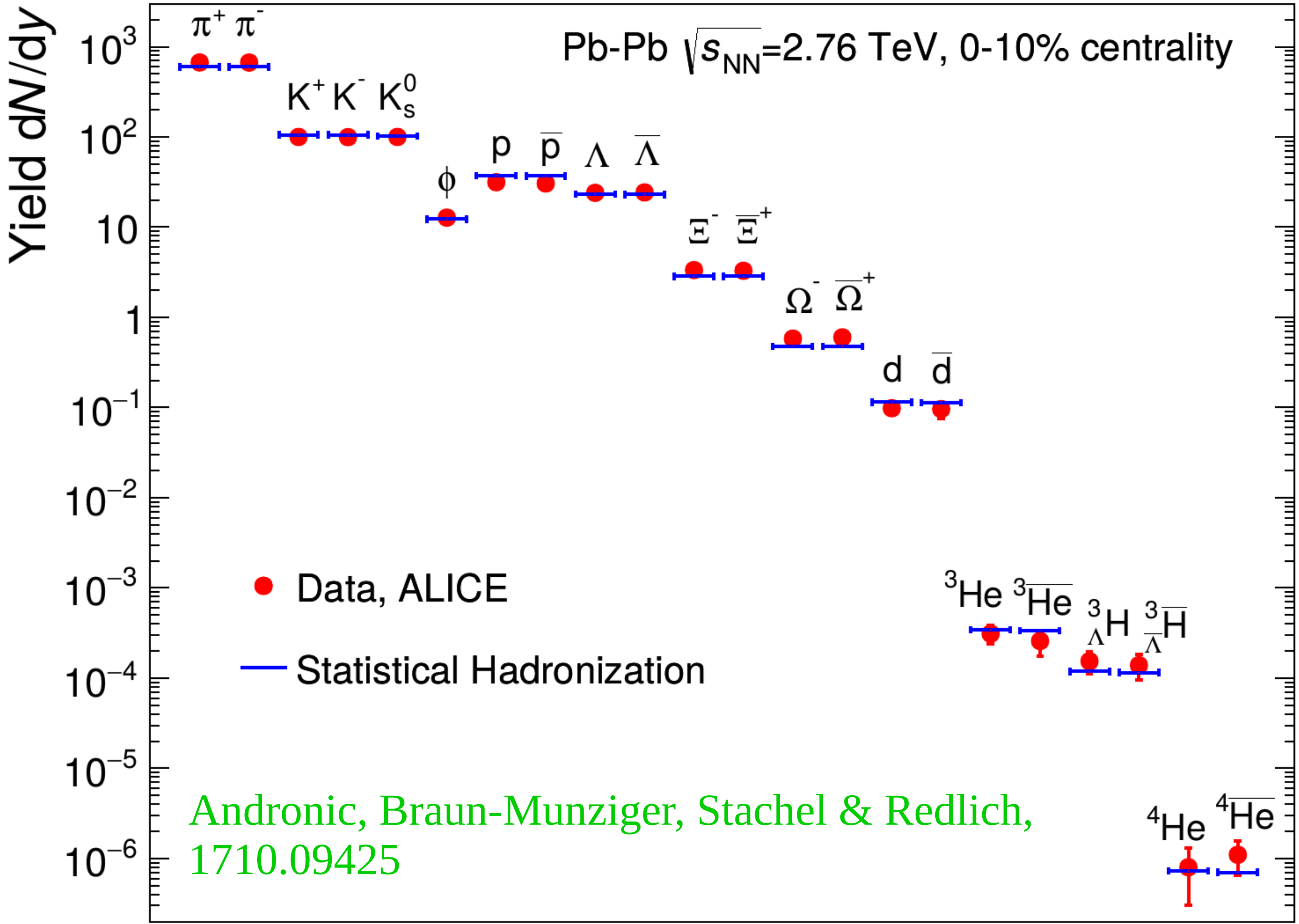
But: in statistical mechanics, simplicity from complexity,

from the production of *many* particles

Is it thermal?

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

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



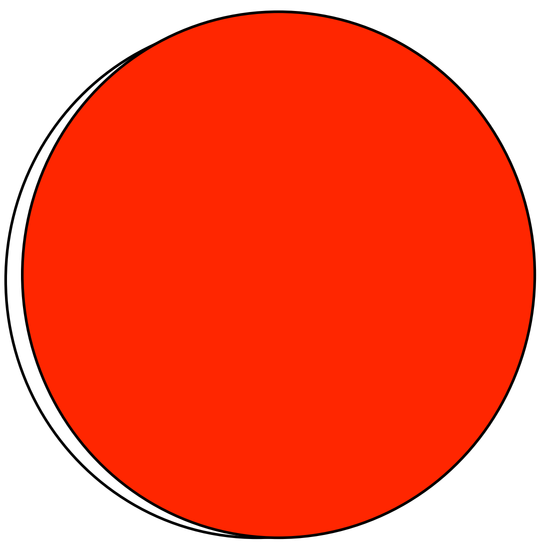
Andronic, Braun-Munziger, Stachel & Redlich, 1710.09425

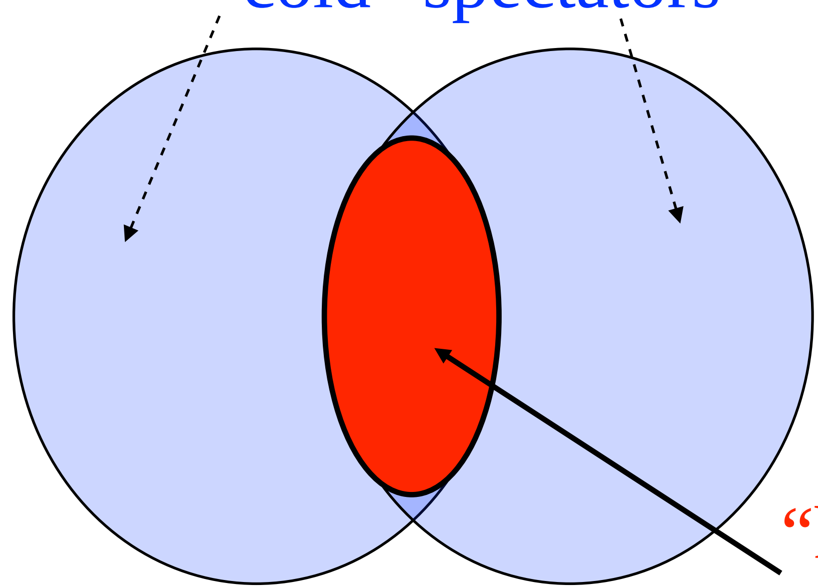
Elliptic flow
“the more perfect liquid on earth”

With many particles: fixing geometry

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

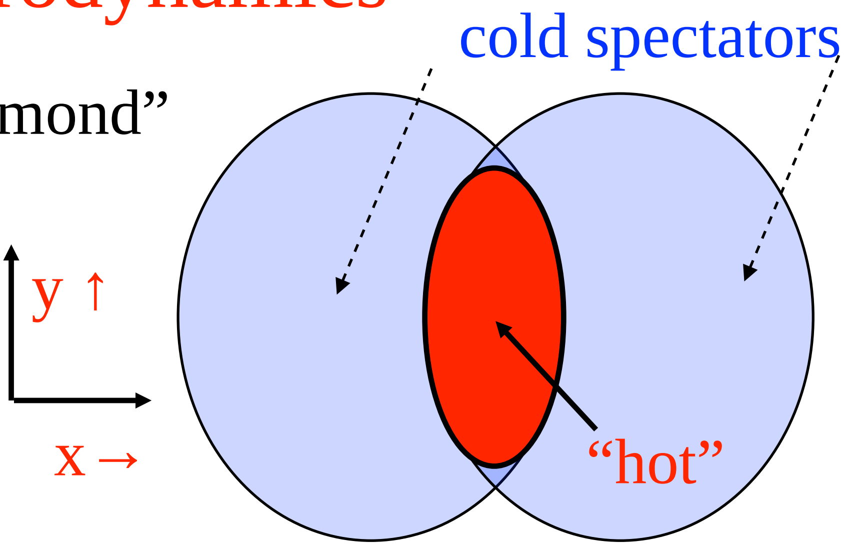
Exp.'y, can determine *# participants* when > 100; maximum 400 for A ~ 200





Elliptic flow & hydrodynamics

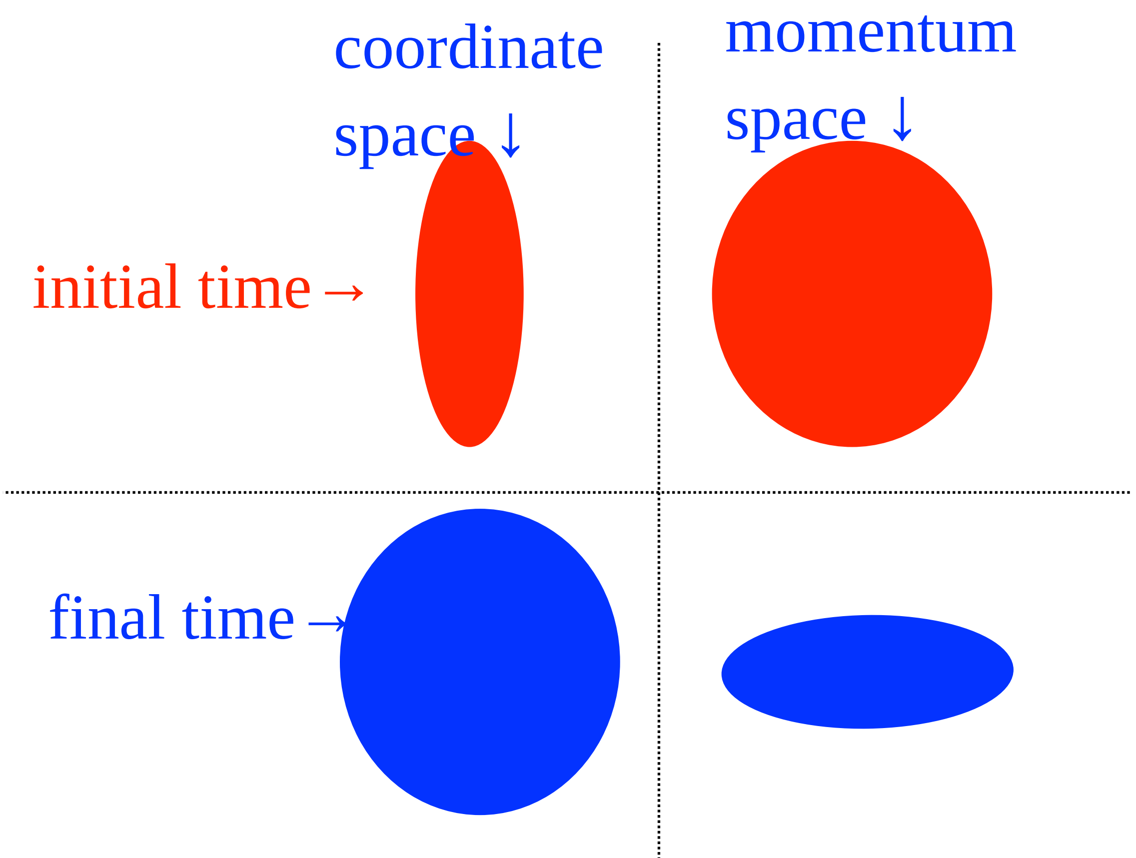
For peripheral collisions, overlap region is “almond”
Start with spatial anistropy,



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

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

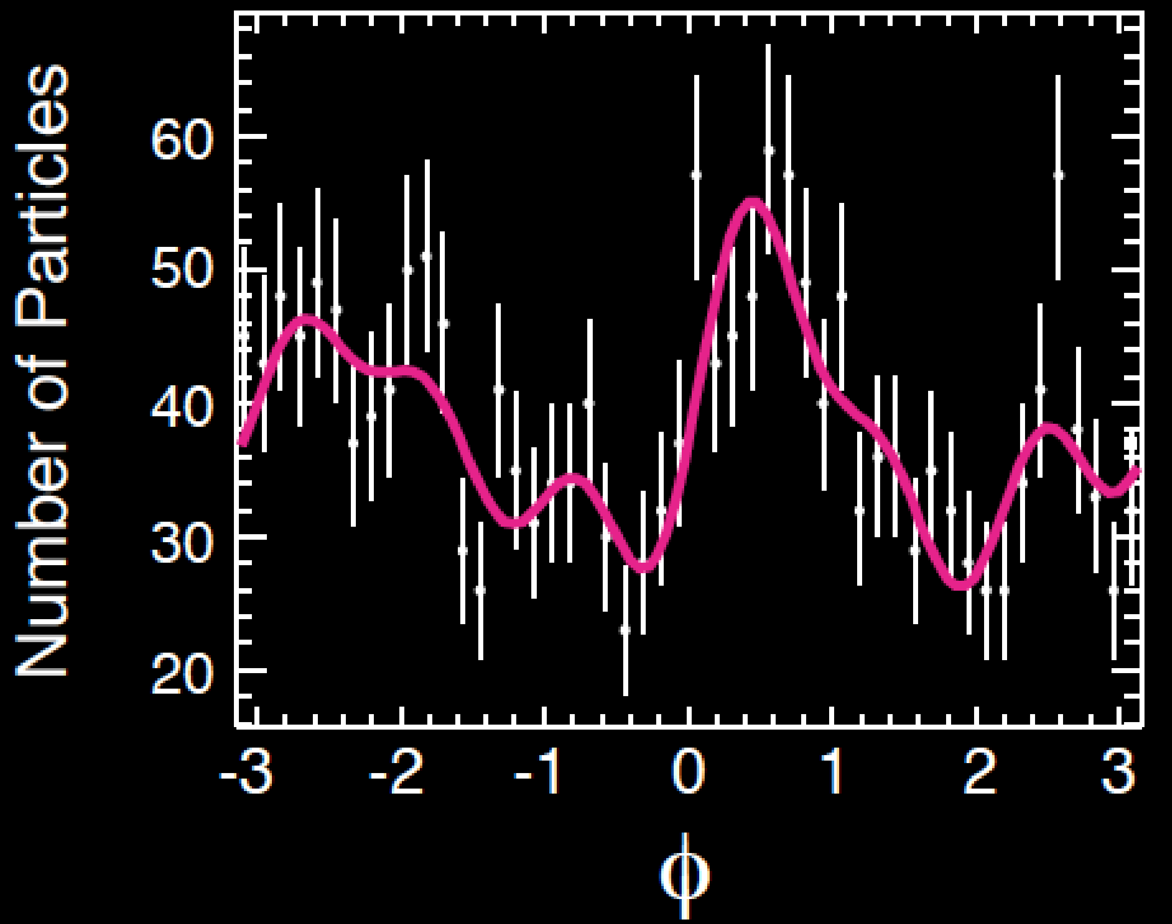
$$v_2 = \frac{\langle p_y^2 - p_x^2 \rangle}{\langle p_y^2 + p_x^2 \rangle}$$



Use ~ ideal hydrodynamics
Basic parameter η/s:
η = shear viscosity
s = entropy

ANGULAR PARTICLE DISTRIBUTION

EXPERIMENTAL DATA: ATLAS COLLABORATION



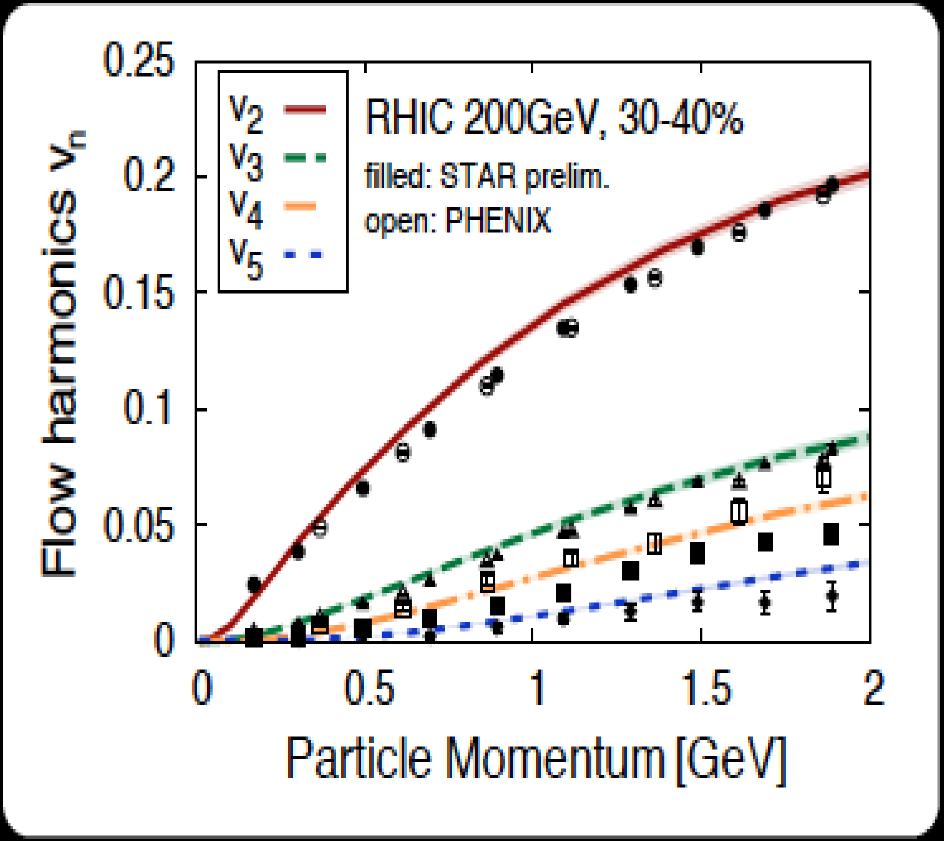
$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2(v_1 \cos(\phi) + v_2 \cos(2\phi) + v_3 \cos(3\phi) + v_4 \cos(4\phi) + \ldots)\right)$$

slide from Bjorn Schenke

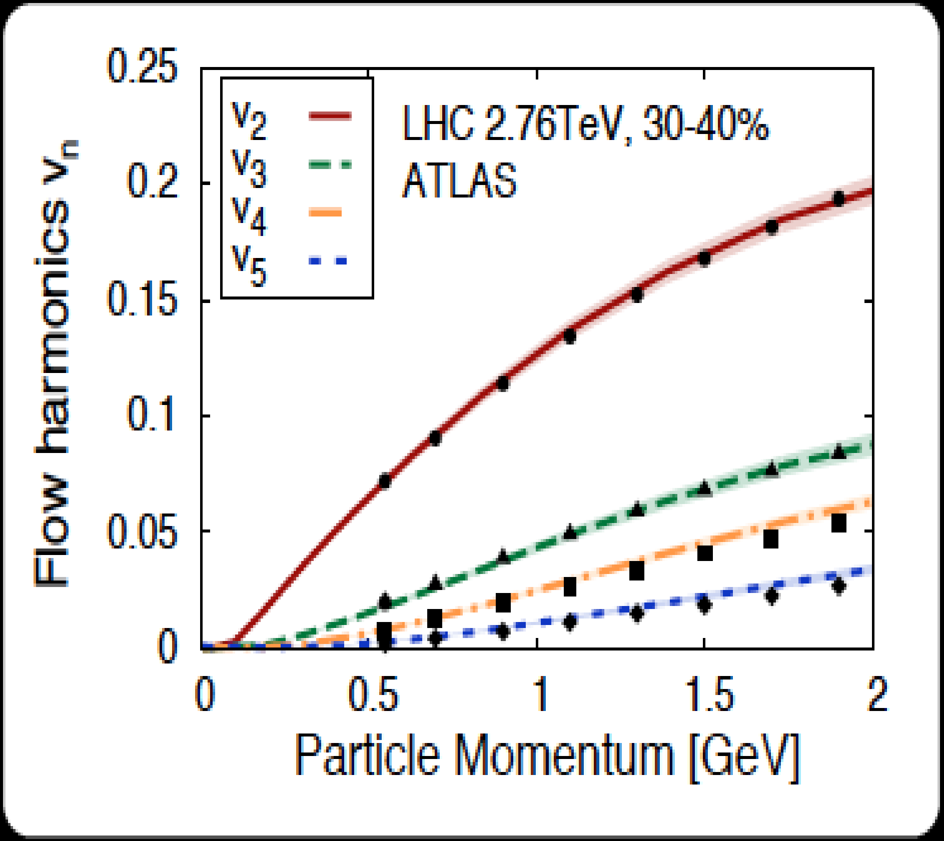
slide from Bjorn Schenke

VISCOSITY AT RHIC AND LHC

RHIC



LHC ~14 x higher energy



RHIC viscosity $\eta/s = 0.12$

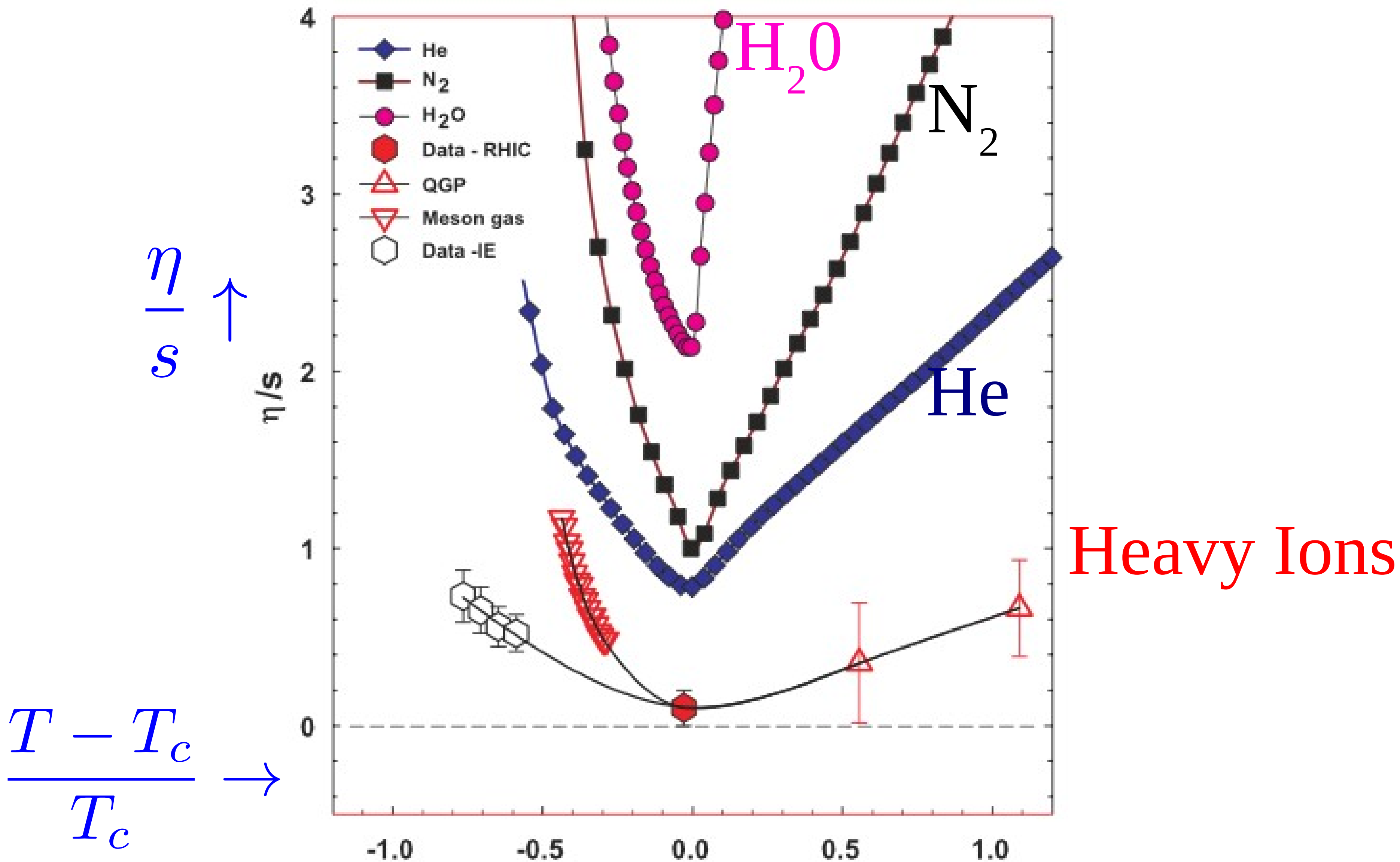
LHC viscosity $\eta/s = 0.2$

Hints at increasing viscosity η/s with increasing temperature

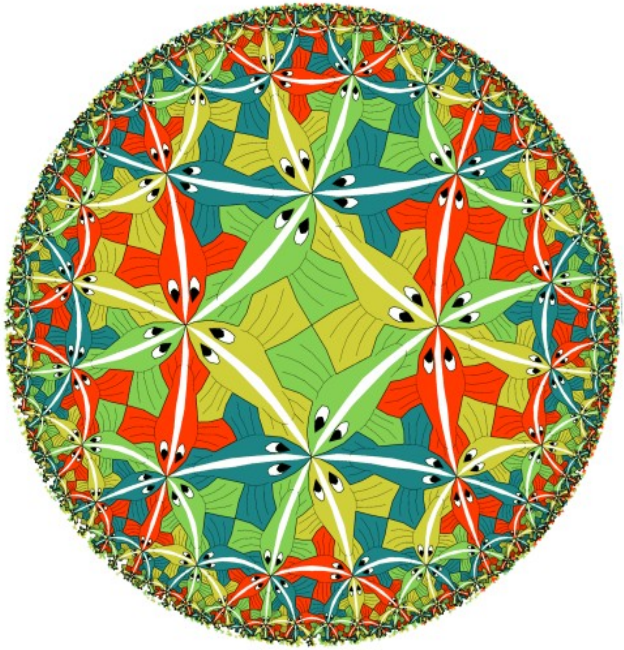
η/s in heavy ions & molecules

While η is big (~ 10^4 pitch tar), so is the entropy!

But η/s is *really* small, ~ 1/10 anything else “The most perfect liquid on earth”



Lower bound on η/s ?



η ~ 1/g^4: *small* in *strong* coupling.

Maldacena '99: *duality*, gauge theory with ∞ # colors, most "supersymmetry" (between quarks & gluons) *and* "string theory", on Anti-diSitter$_5$ x S^5

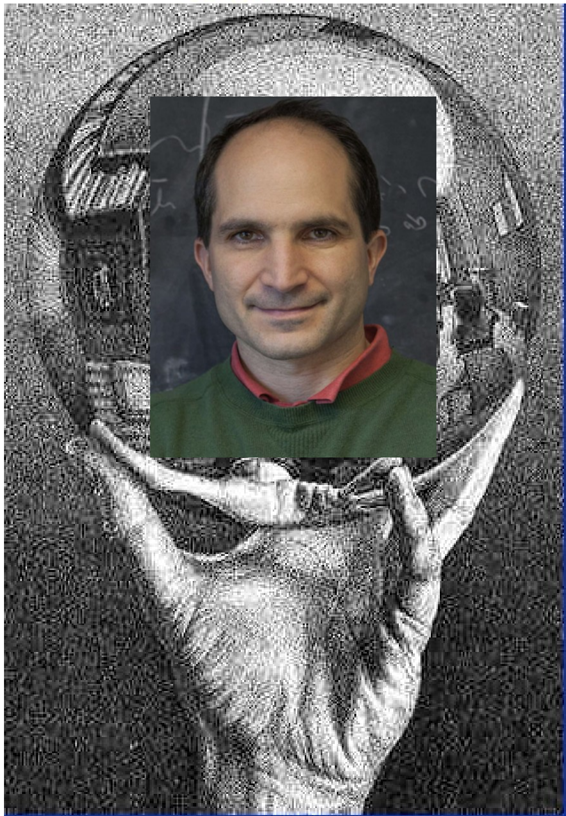
Both conformal field theories: same at all distances

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

Bound: Son, Starinets, Kovtun '05

Results for η/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 ~ 2 GeV, ~ 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 ¼ fm/c.

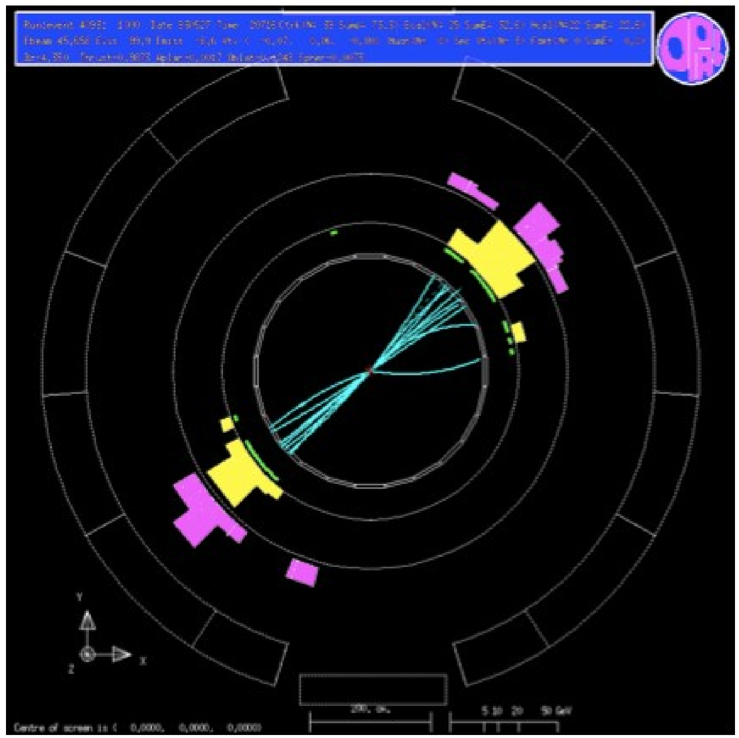
Jet quenching:
the QGP “eats” jets

Jets in QCD

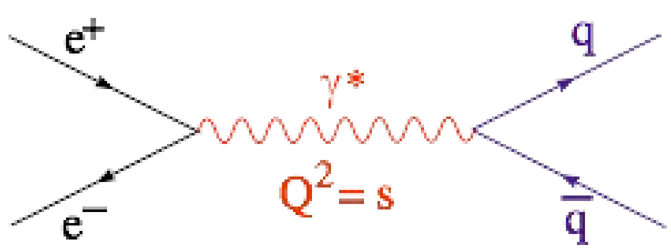
Hydro deals with most particles, concentrated at “soft” momenta, < 1 GeV
But in QCD, by asymptotic freedom *hard* particles are distinctive,
form “jets”: leading hard particle + soft spray

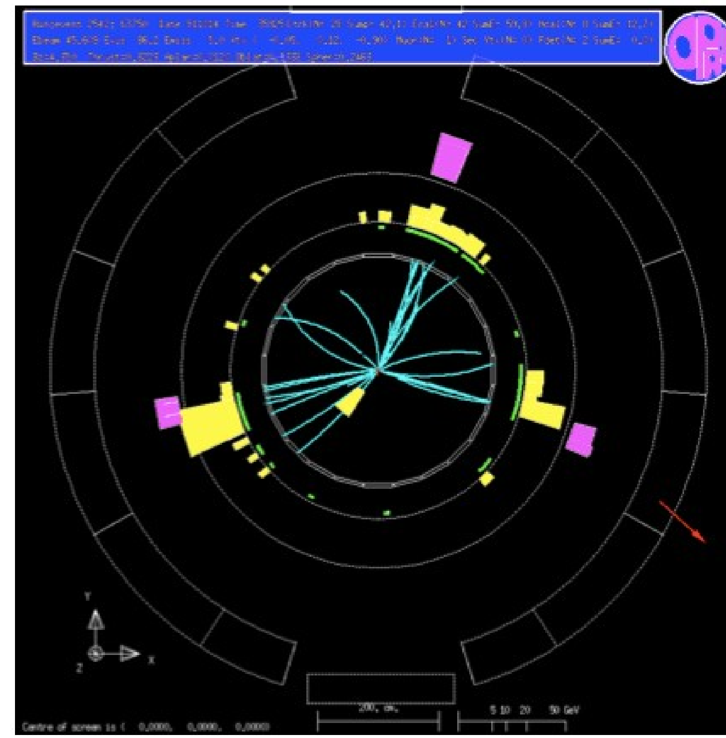
Jets at LEP,
Large Electron-Positron Collider
@ CERN

‘89 → 2000,
LEP tunnel used for LHC

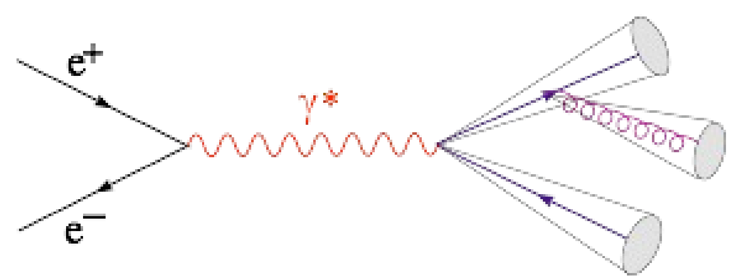


2 jets



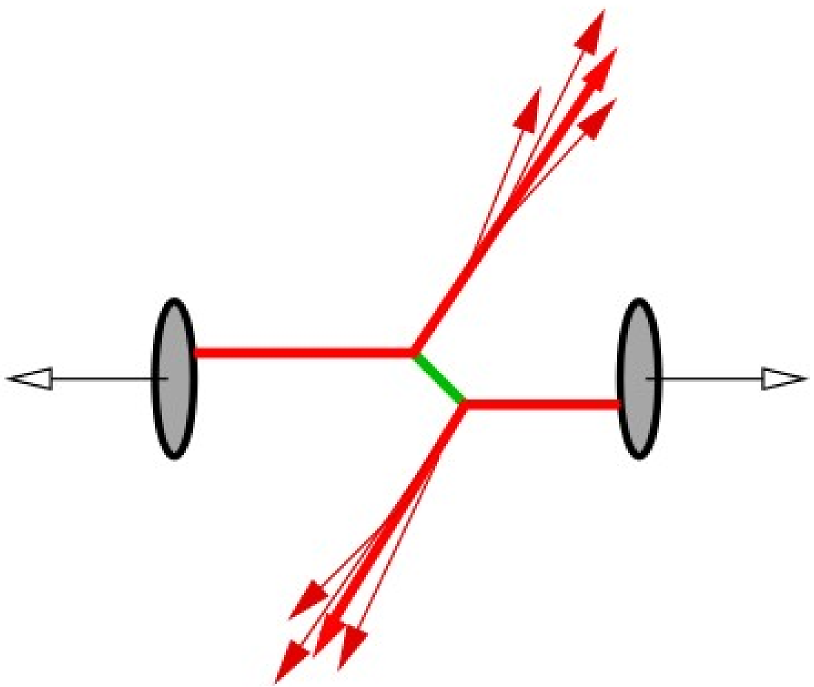


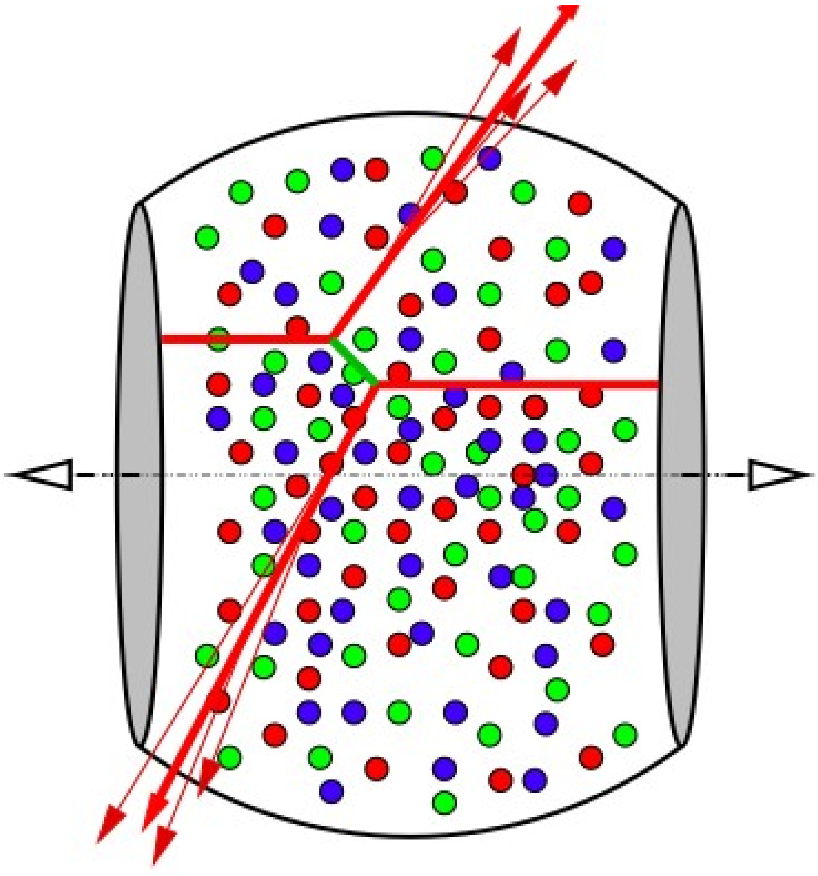
3 jets



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"

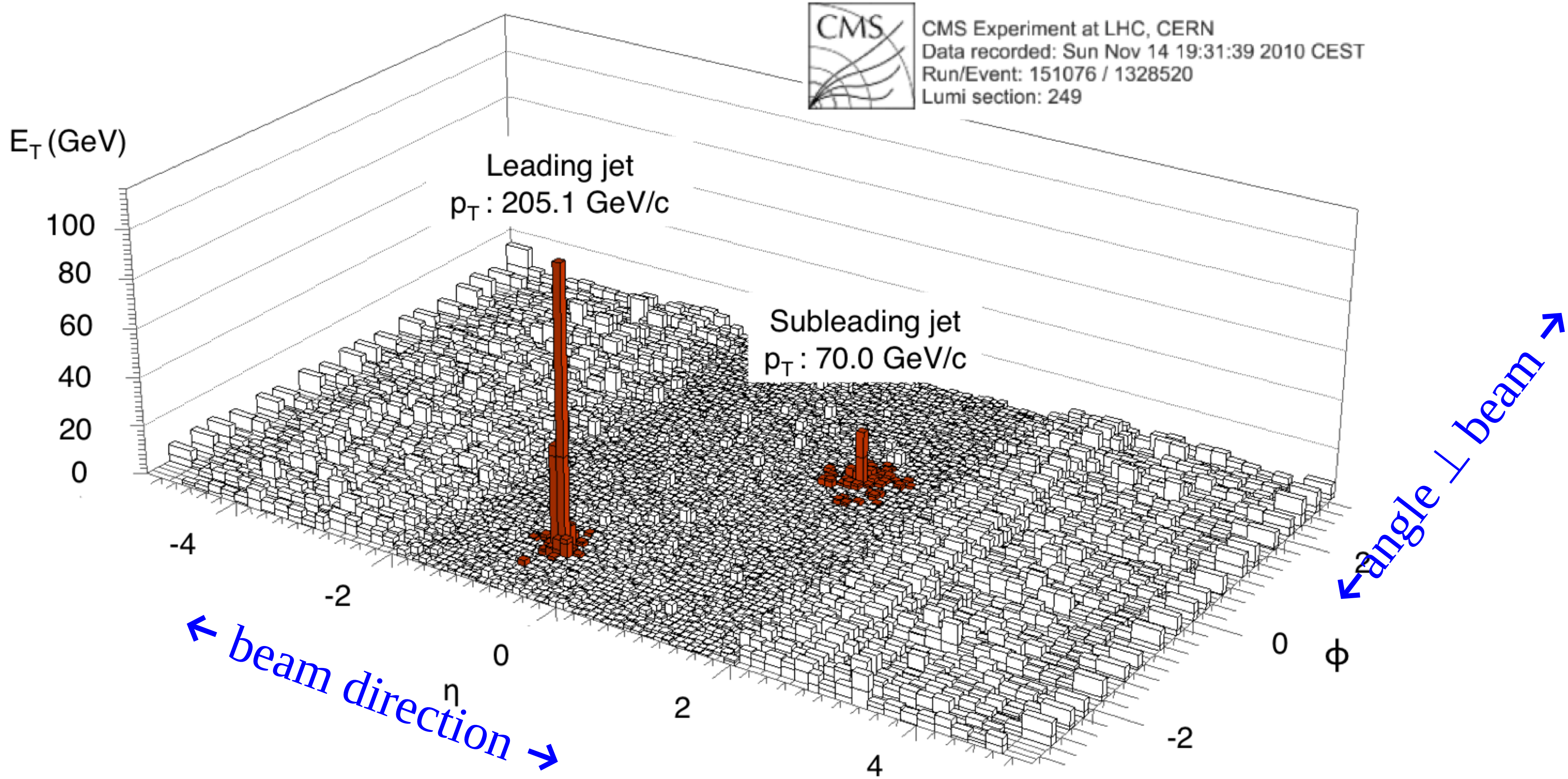




QGP "eats" jets @ LHC

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.



QGP “eats” jets @ RHIC

Hydro deals with most particles, concentrated at “soft” momenta, < 1 GeV

But in QCD, by asymptotic freedom *hard* particles are distinctive,

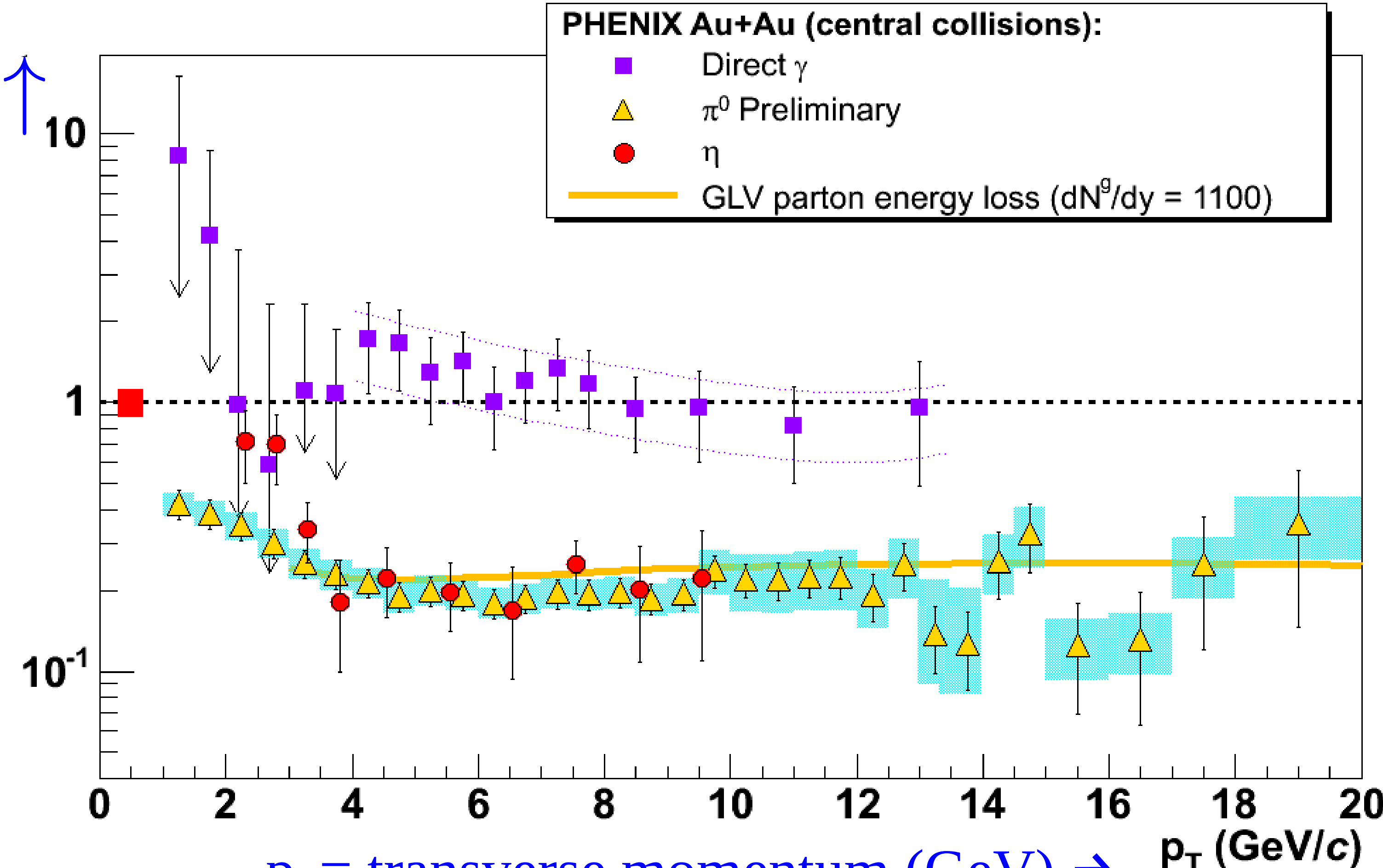
form “jets”: leading hard particle + soft spray

RHIC: only can measure particles up to ~ 20 GeV

R_{AA} ↑

R_{AA} =
particles in AA/
particles in pp

R_{AA} < 1 shows
“jet” quenching



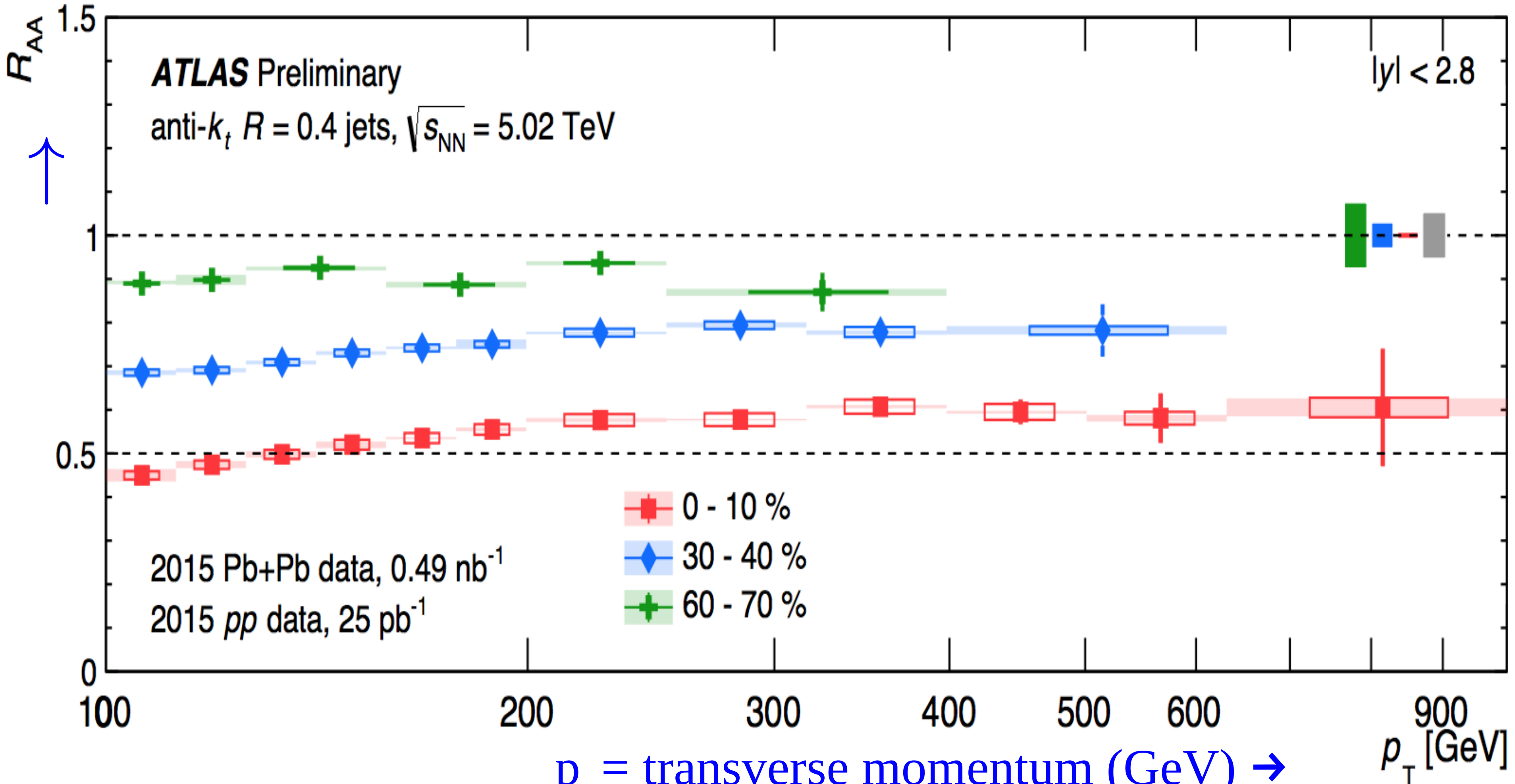
p_t = transverse momentum (GeV) →

(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!

$R_{AA} \uparrow$



p_t = transverse momentum (GeV) →
(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 pt ~ 40 GeV.

From '22 - '24

+ data from LHC @ CERN

Phase diagram of QCD: moving back *down* in energy

QCD at *non*zero 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 *not* use standard Monte Carlo.

Can use Hamiltonian:

$$e^{pV} = \Sigma_i \; e^{-E_i/T+\mu N_i}$$

Above calculable, *in principle*, using quantum computers

Deriving the properties of nuclear matter, *from first principles*,

is one of the great problems of physics in the 21st century

QCD at *non*zero quark density

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

$$e^{pV} = \Sigma_i \, e^{-E_i/T + \mu N_i}$$

Turn into “path integral” (∞-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 $\mu = 0$

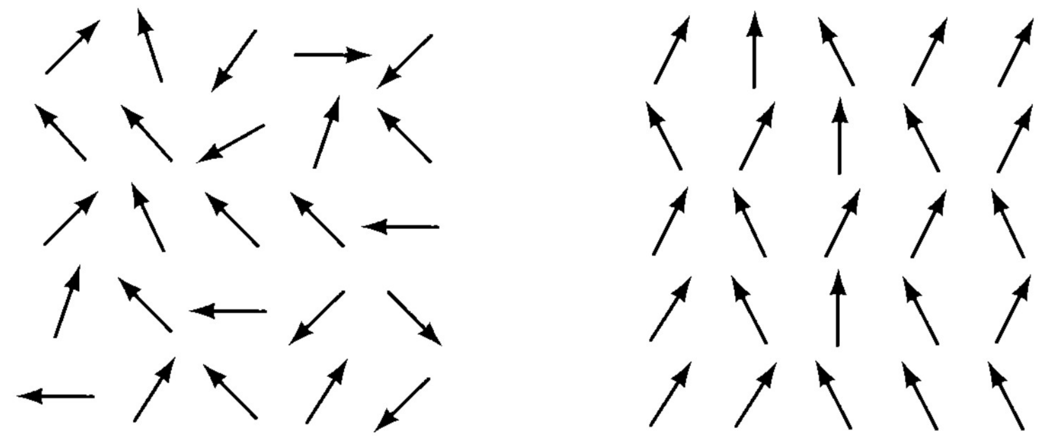
$\mu \neq 0$ is measurable in heavy ion experiments at *low* energy

Above calculable, *in principle*, using quantum computers

Nuclear matter is one of the great problems of physics in the 21st century

Spins & phase transitions

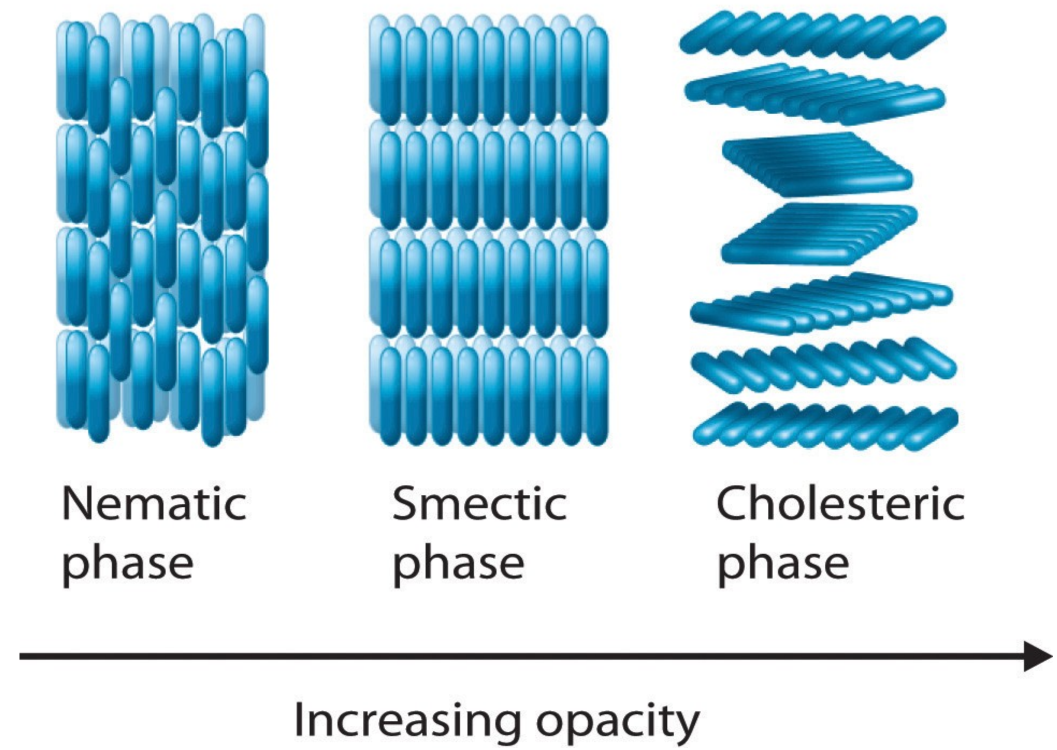
Symmetry of light quarks ~ spins:
spin line up, “order” at low T,
spins random, disordered, at high T



disordered ordered

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

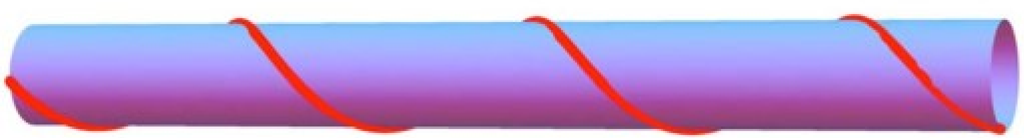
Chiral symmetry kind of spin, $SU(3)_L$ x $SU(3)_R$ x $U(1)_A$.

Low temperature: ordered = confined

High temperature: disordered = Quark-Gluon Plasma

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

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



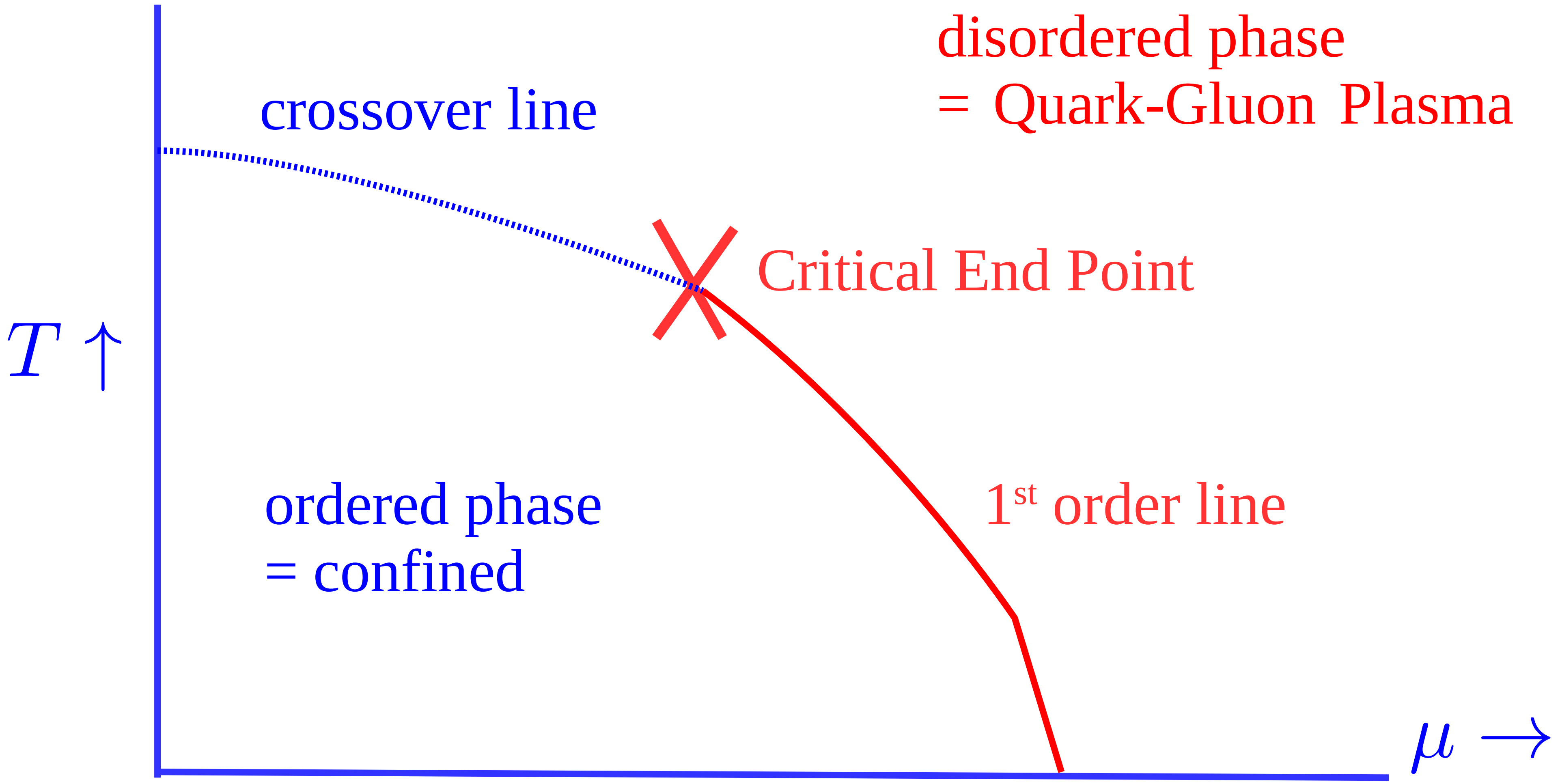
Can find exact solutions in 1+1 dimensions:

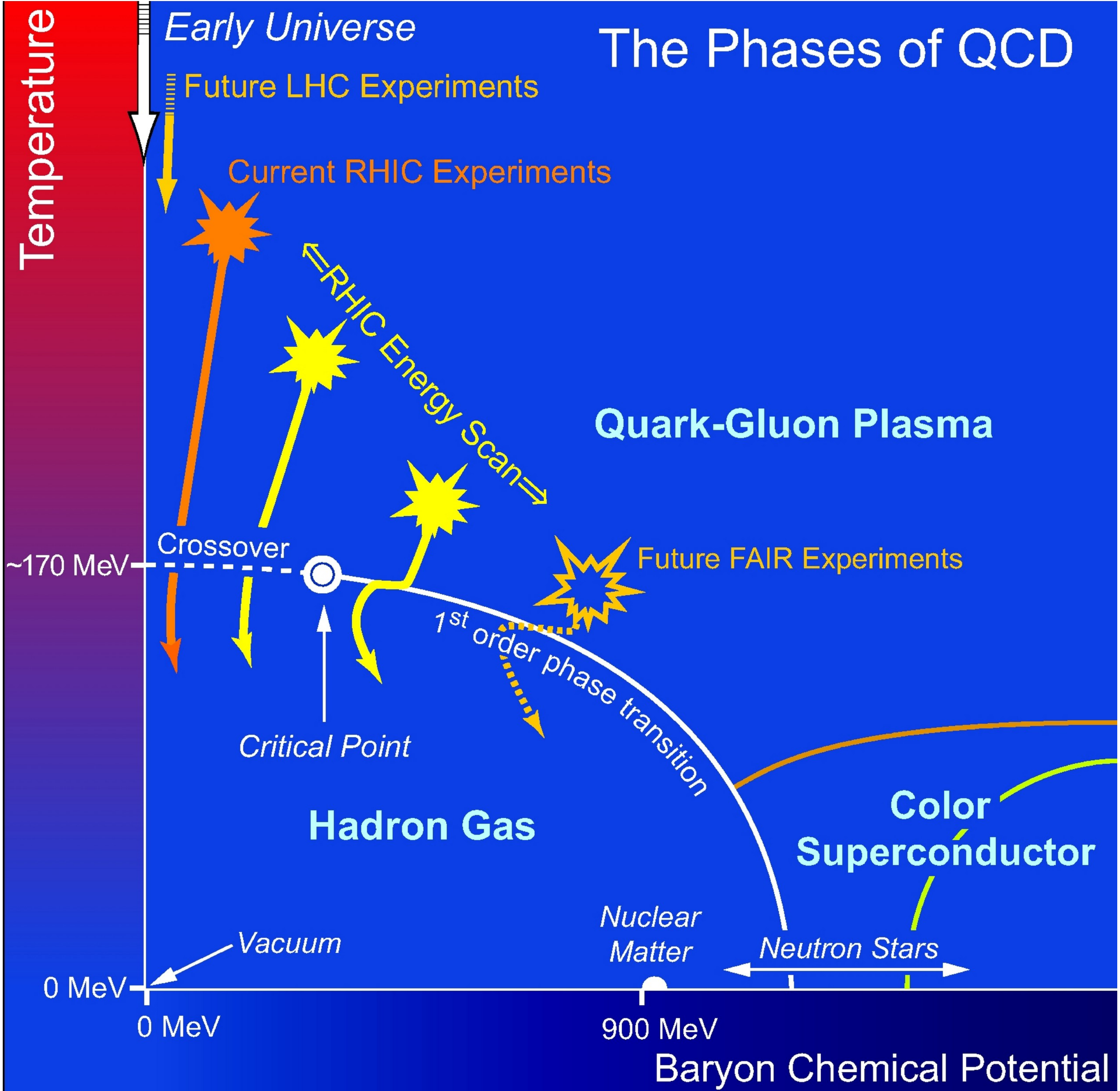
Phase diagram for QCD in T & μ: usual picture

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

Lattice: find crossover at $\mu = 0$. Perhaps: turns into 1st order at some μ ?

If so, *must* be Critical End Point: massless mode at CEP.

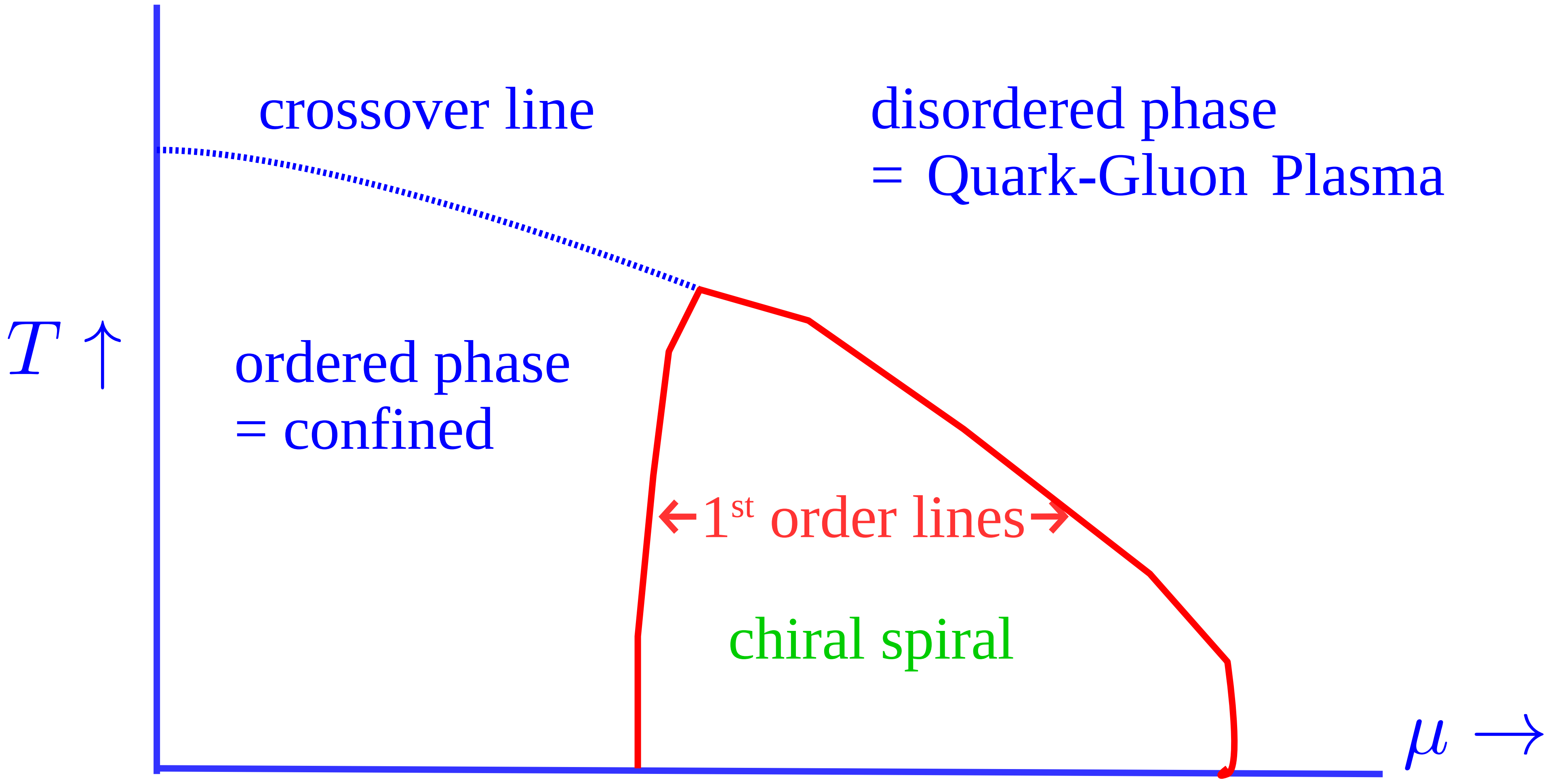



The Phases of QCD
Temperature
Early Universe
Future LHC Experiments
Current RHIC Experiments
⇐RHIC Energy Scan⇒
Quark-Gluon Plasma
Crossover
~170 MeV
Future FAIR Experiments
1st order phase transition
Critical Point
Hadron Gas
Color Superconductor
Nuclear Matter
Vacuum
Neutron Stars
0 MeV
0 MeV
900 MeV
Baryon Chemical Potential

Phase diagram with chiral spirals

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

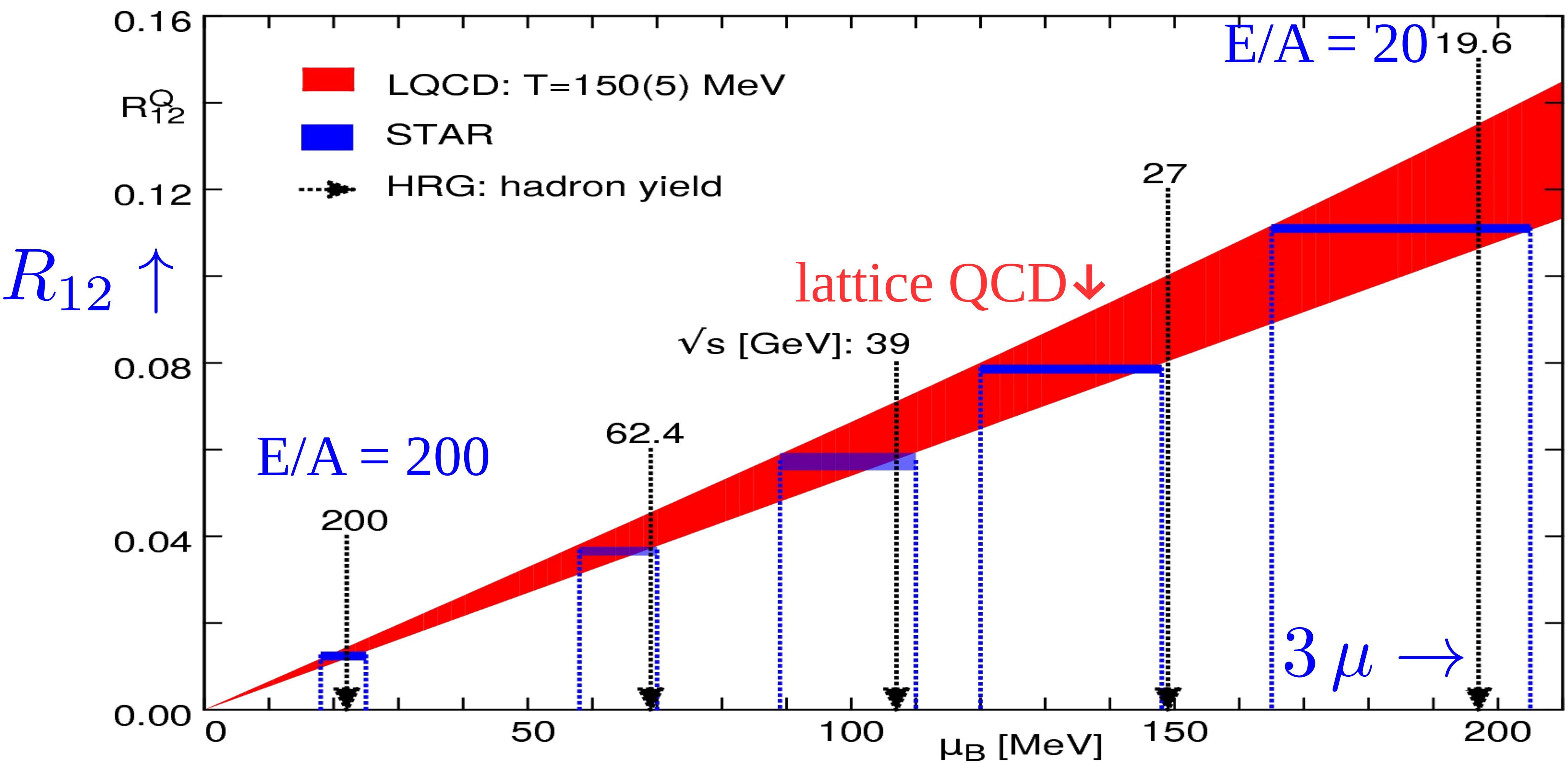
Instead, intermediate phase with chiral spirals, separated by 1st order lines



Using the lattice to *calculate* μ

Compute moments with respect to a conserved charge, fix μ *directly* from STAR experiment @ RHIC

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



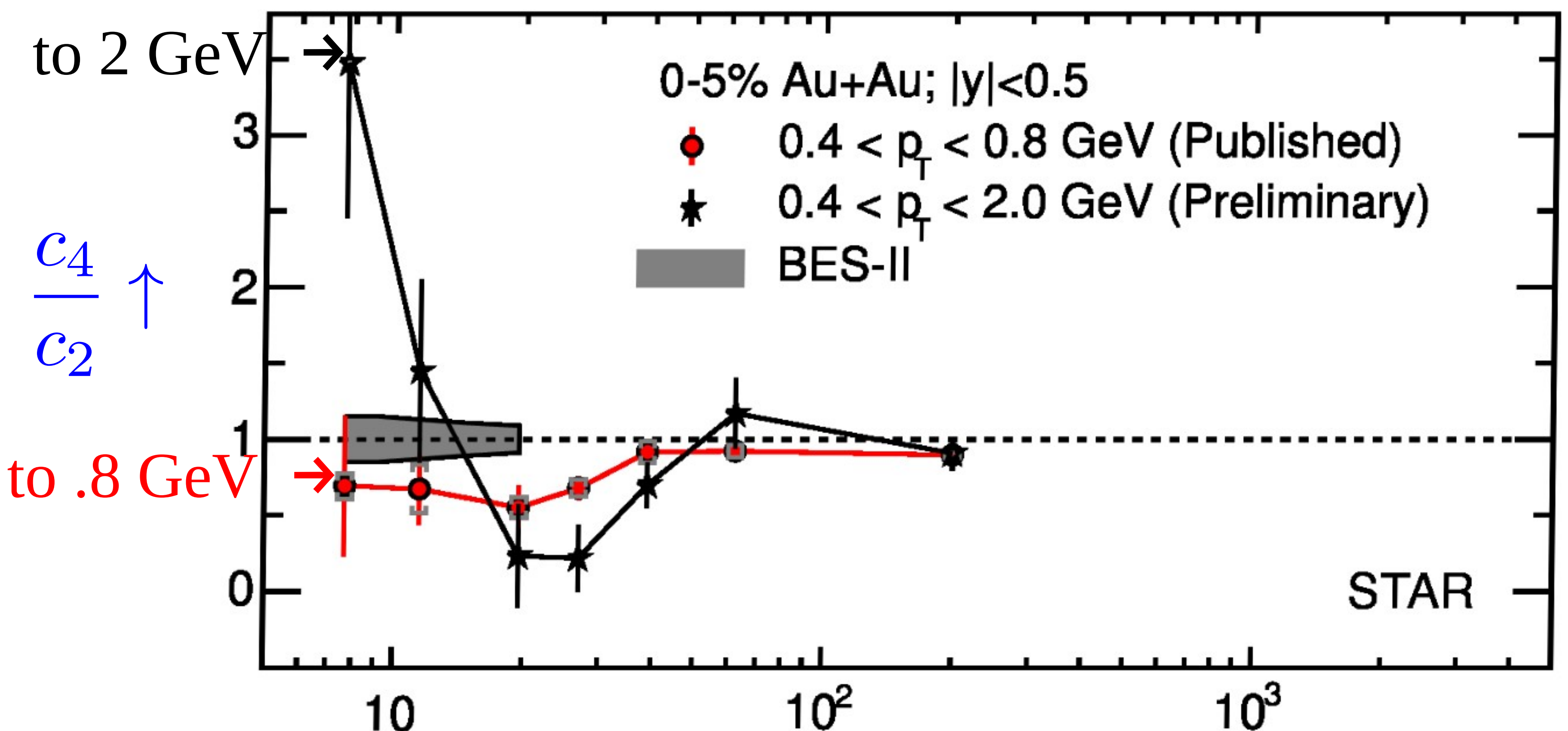
Large fluctuations @ low energy?

Can measure derivatives of pressure with respect to μ:

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

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 satelites

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 → affects the propagation of quarks, pions:

$$\vec{j}_{\rm em} = \sigma_5 \, \vec{B}$$

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, ${}_{44}^{96}$Zr vs ${}_{40}^{96}$Ru: same A, different Z.

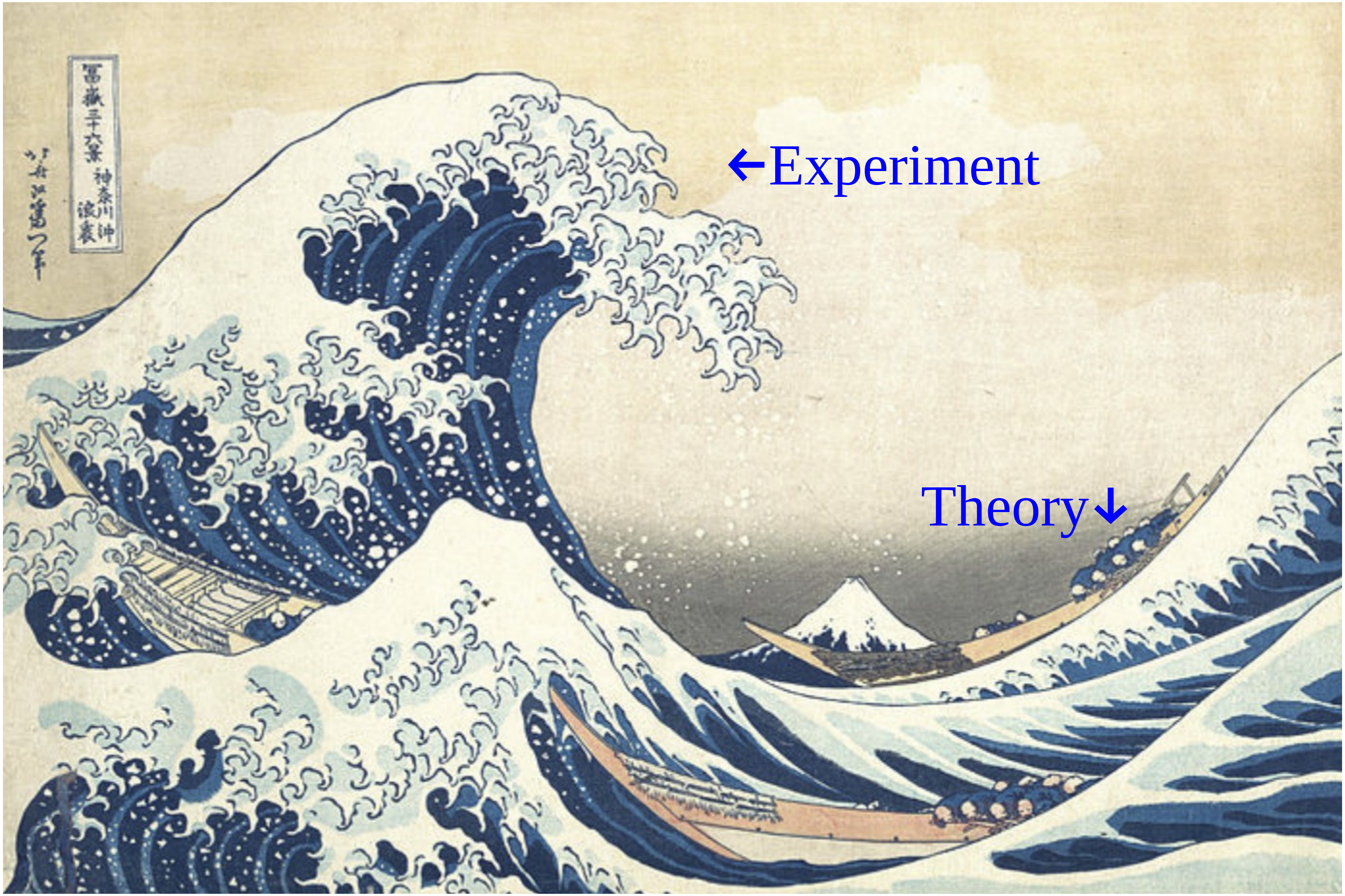
pA, pp at *very* high multiplicity, LHC:

Usually, ~ 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