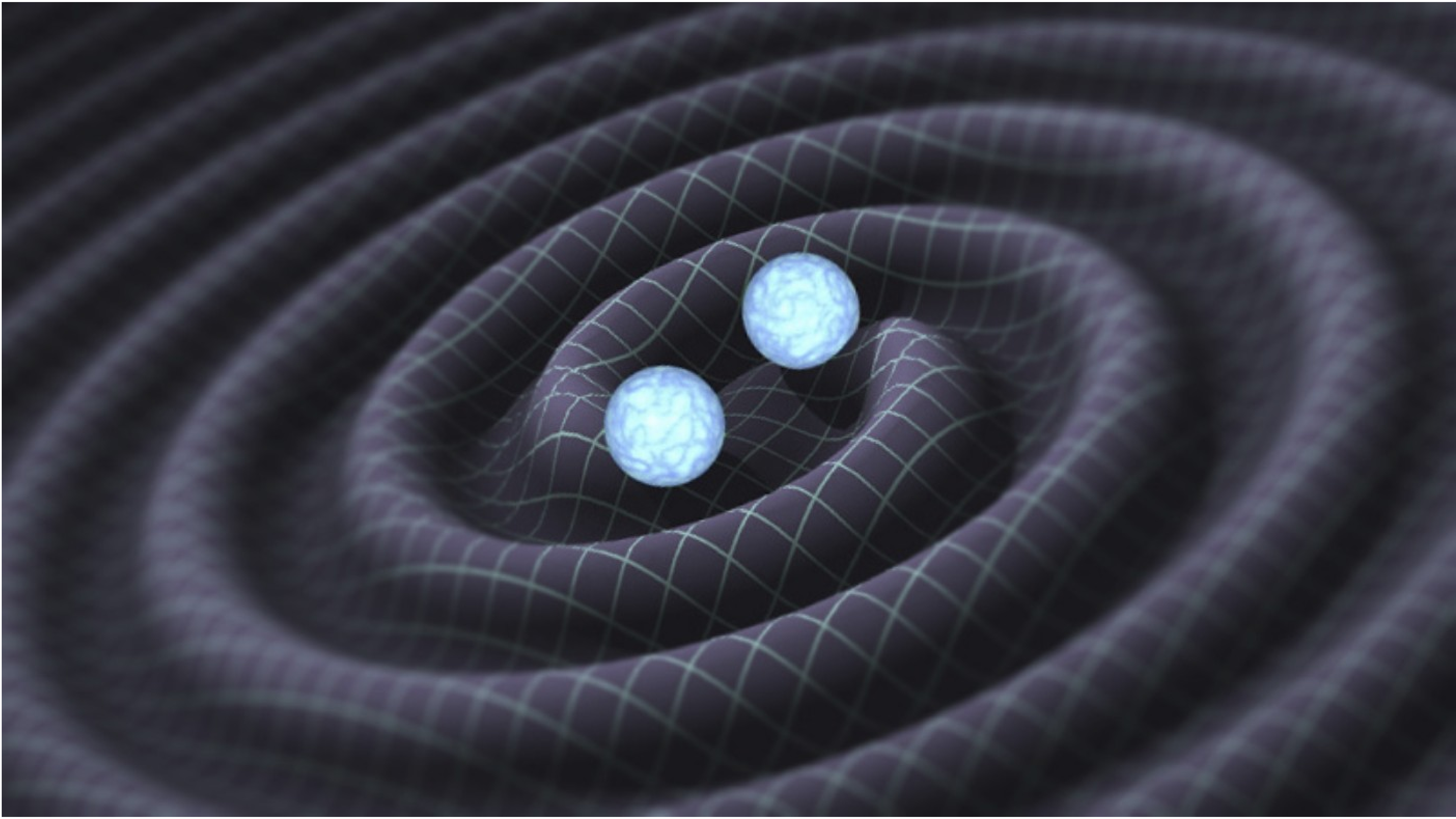
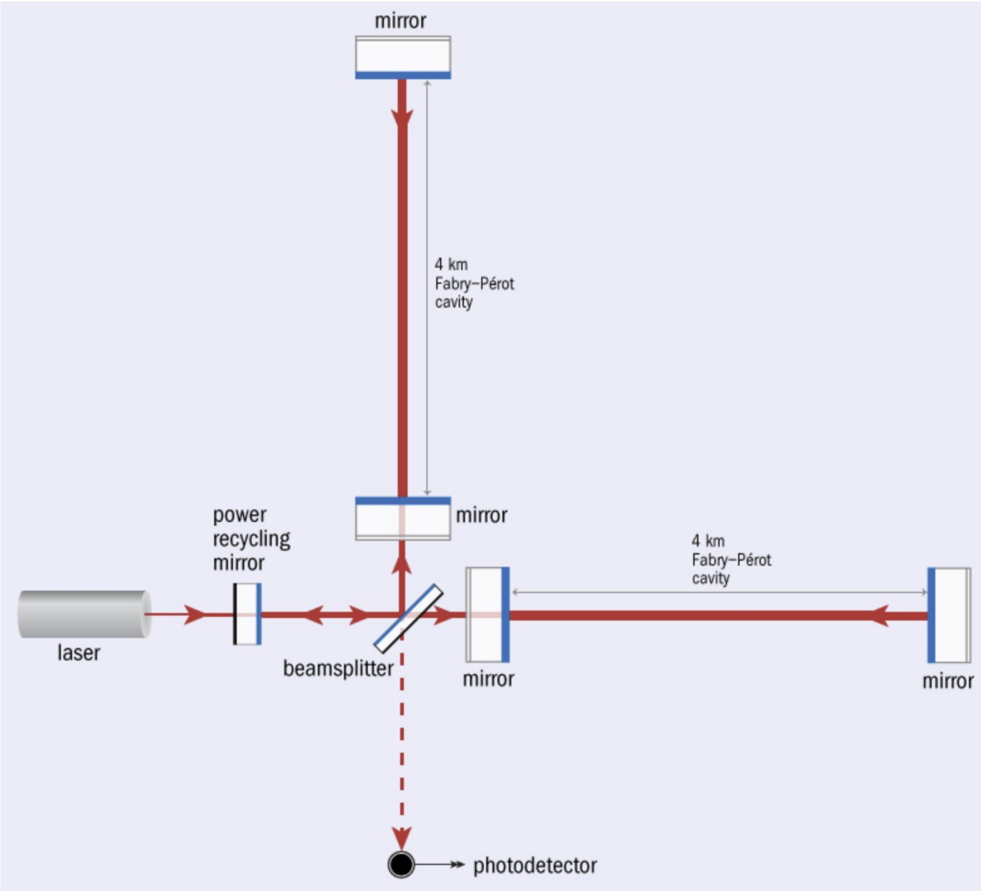
In all fields, there are Golden Ages

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



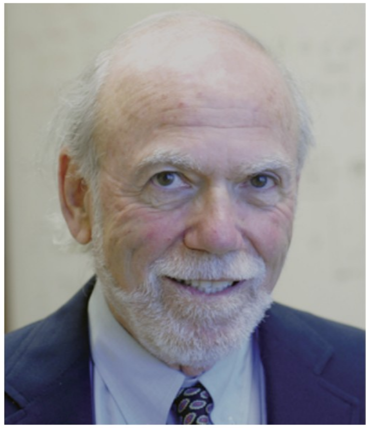
Astronomy: not with light, but with gravity waves

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*.
2×10^6 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

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):

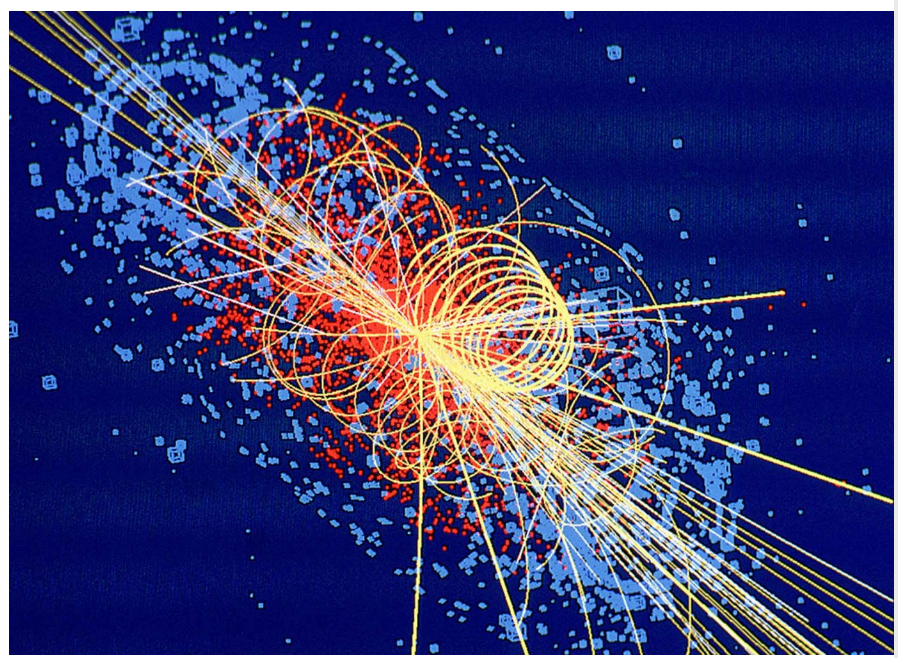
~ 10^4 physicists, ~ \$$10^{10}$ to build, run...

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

Peter Higgs

Francois Englert

But *no* signs of supersymmetry!



Four states of matter

Usual states of matter: gas, liquid, solid.

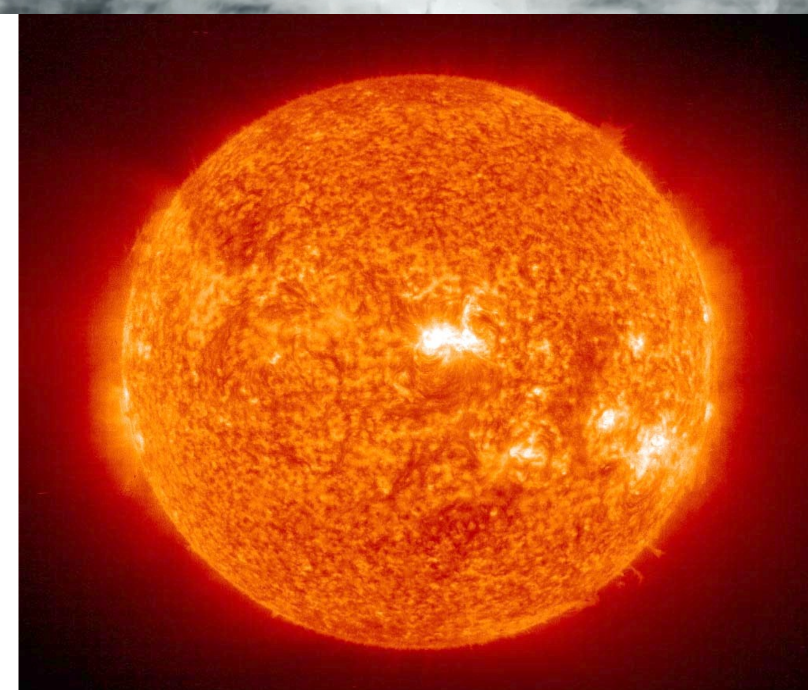
Fourth state: plasma

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

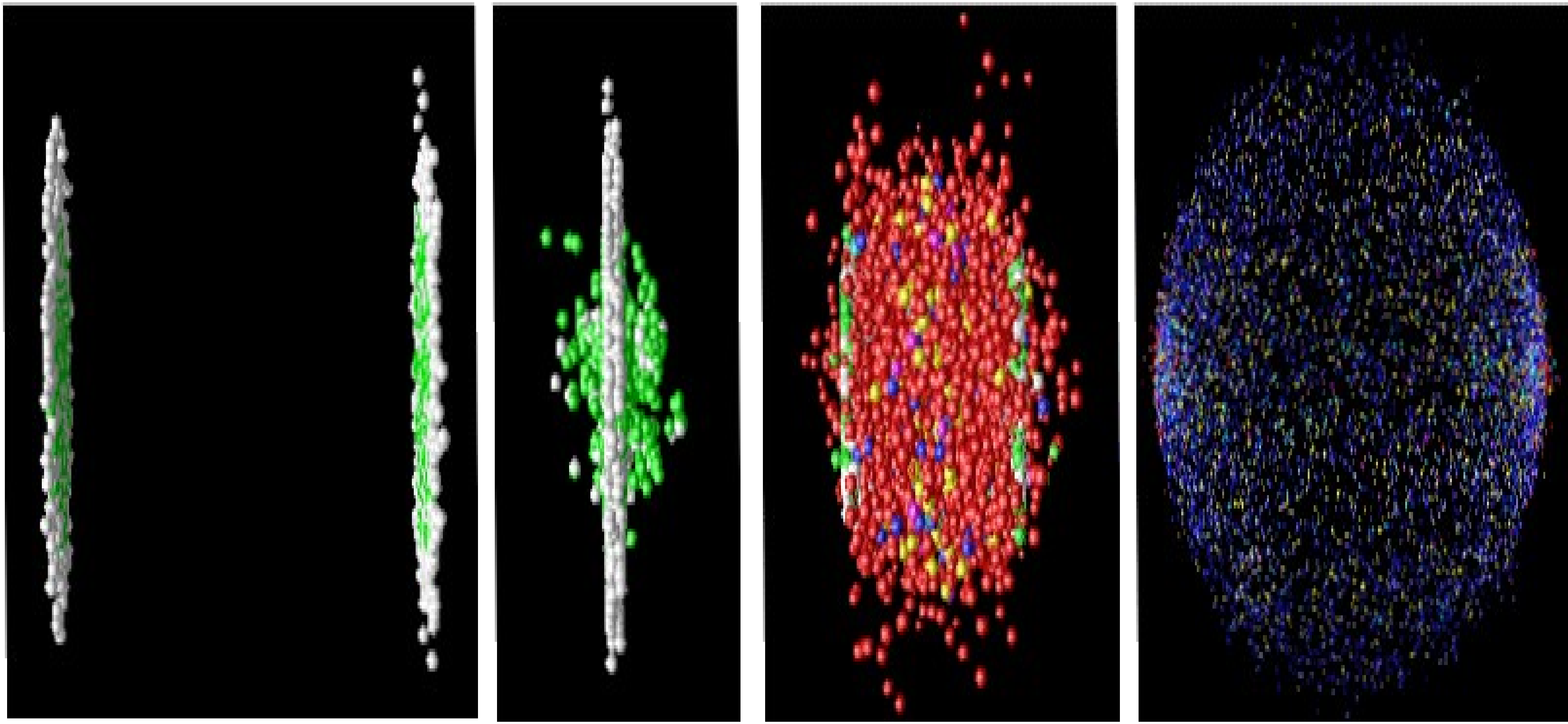
Plasma: charges move freely, independently
Need heat +… to shake atoms apart

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

Gauge theories

Electric charge

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

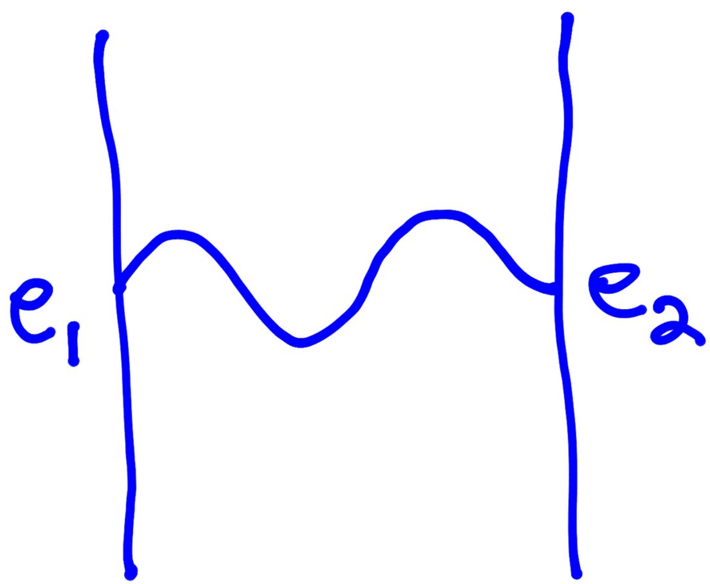
E.g.: electrons, e-, and protons, p+.

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...

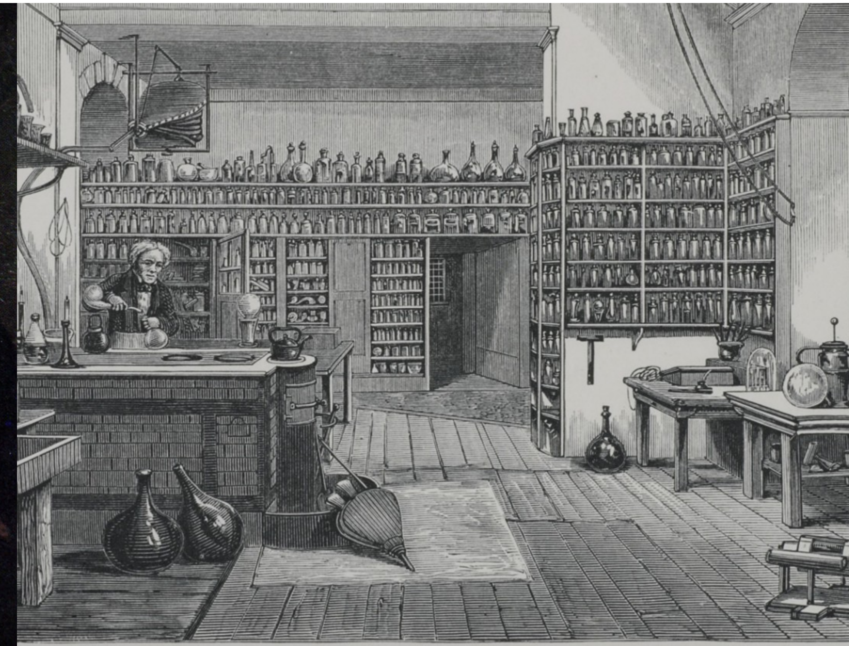
Potential due to exchange of photons (light)



ElectroMagnetism

Michael Faraday, 1791-1865

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



FARADAY'S LABORATORY AT THE ROYAL INSTITUTION.

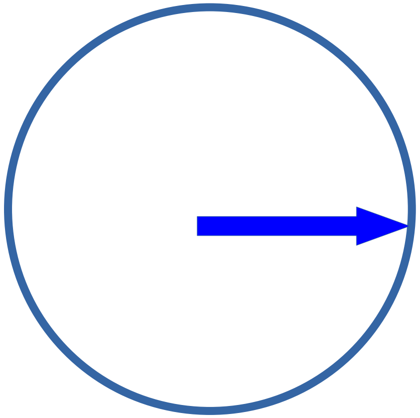
James Clerk Maxwell, 1831-1878
Unified EM equations into 4:

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

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

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 =>



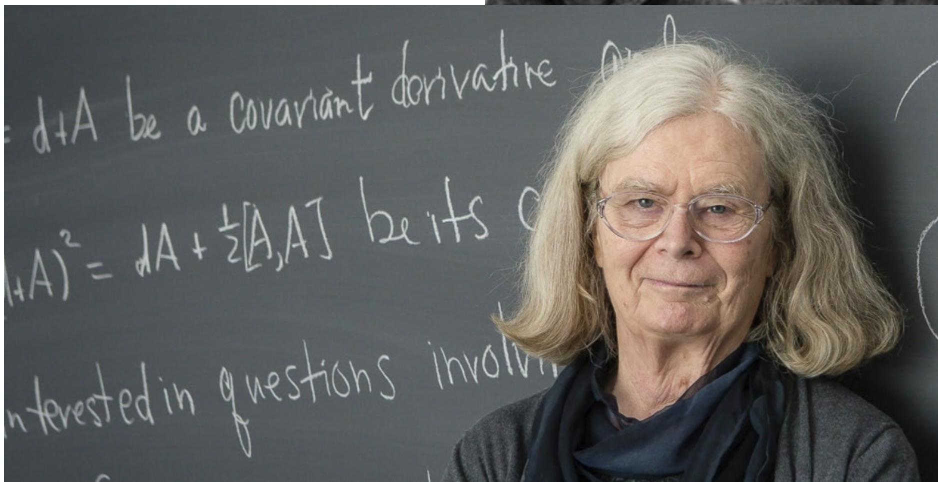
Order of rotations doesn't matter: $\theta_1 + \theta_2 = \theta_2 + \theta_1$.
This is an "*Abelian*" group (Niels Abel, 1802-1829)

Phase can be rotated *in*dependently
at *each* point in space(-time) :

Abel

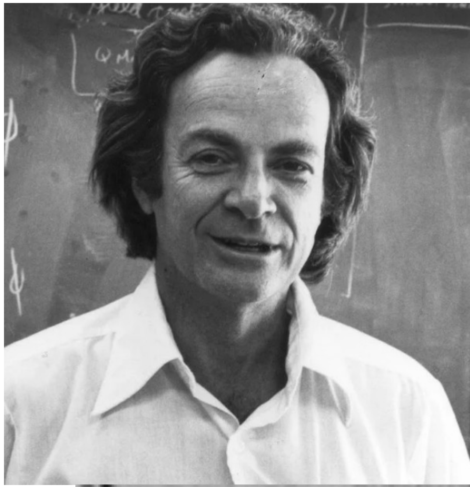
Abelian gauge theory

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/

Modern view of light



Photons A_μ & charged particles ψ. In one line:

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

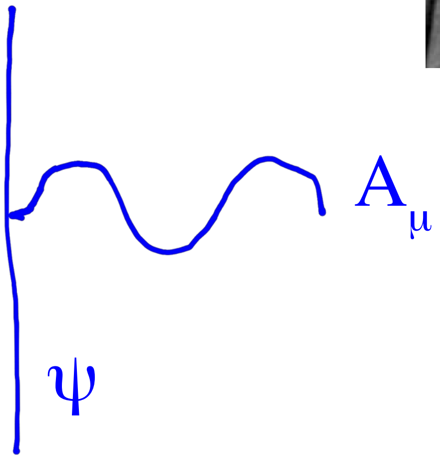
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \ , \ D_\mu = \partial_\mu - ieA_\mu$$

Quantum ElectroDynamics (QED)

Nobel, 1965: Feynman (top), Schwinger, Tomonaga (bottom)

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)

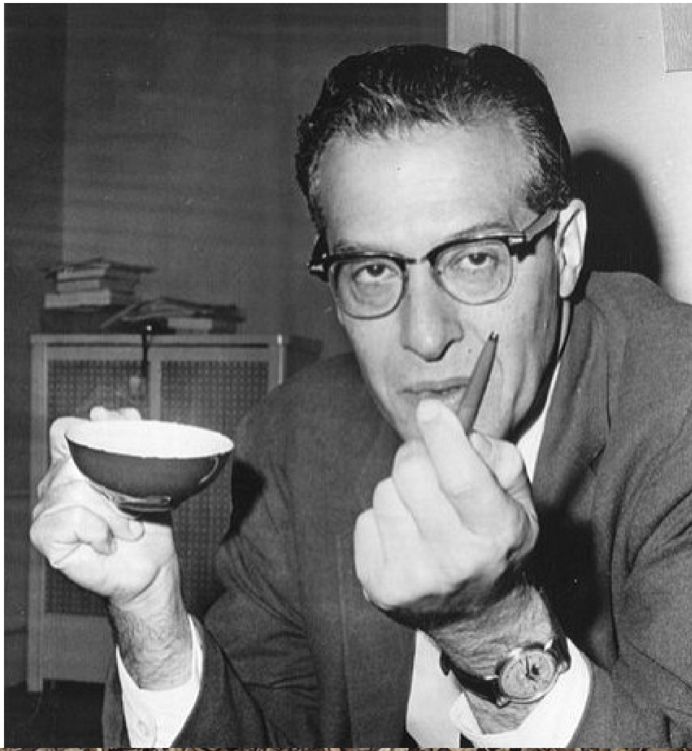
With pencil and paper:

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:



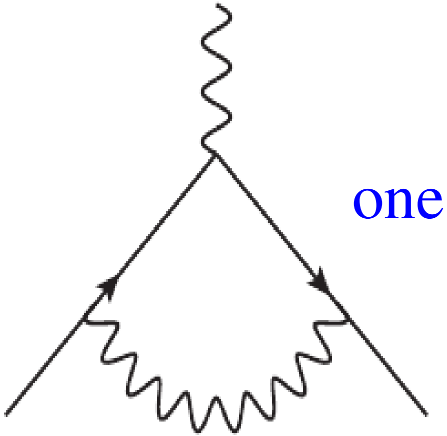
QED: magnetic moment

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

First correction at one loop: Schwinger, 1948, $= \alpha/2\pi$

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

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



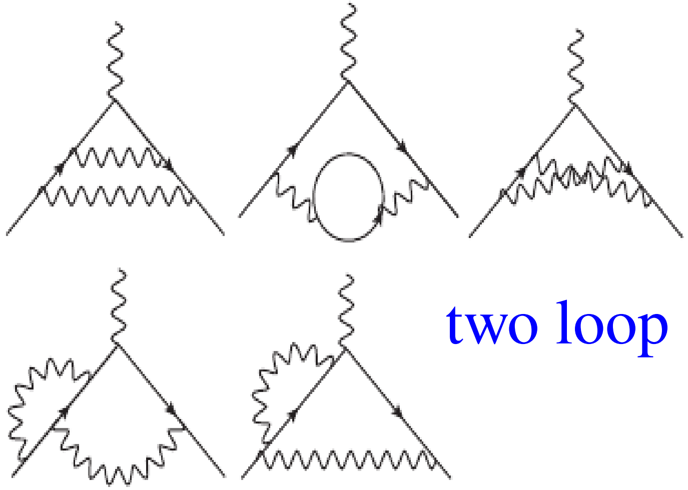
one loop

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

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

This difference is now a big deal:

hints of new physics (supersymmetry)?

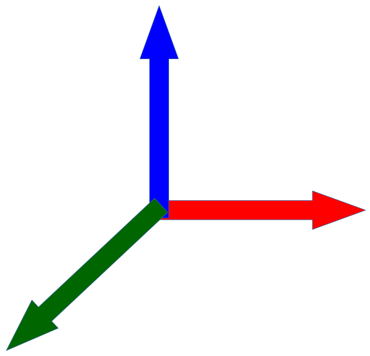


two loop

Modern theory of nuclei

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

Each baryon = *three* quarks + gluons.



Quarks & gluons carry “color” (just a name)

Color charges are complex 3x3 *matrices, U.*

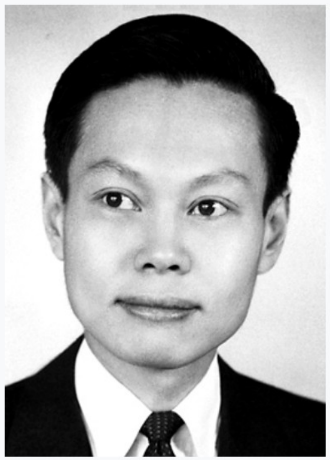
As matrices, do not commute, $U_1 U_2 \neq U_2 U_1$. *Non*-Abelian symmetry.

= SU(3) gauge symmetry. Quantum ChromoDynamics, QCD

Birth 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:

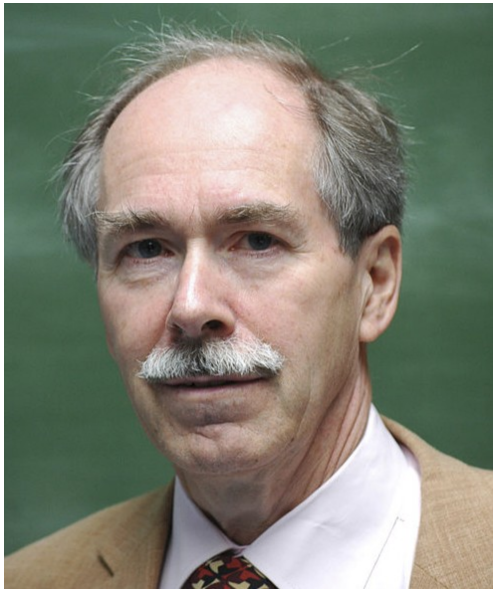
In 1953–1954, I was visiting Brookhaven and Bob was my office mate. We discussed many things in physics, from the experimental results pouring out of the new Cosmotron, to theoretical topics like renormalization and the Ward identity. It was in that year that we found the very elegant and unique generalization 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.

Non-Abelian gauge theories make sense

In non-Abelian gauge theories, it is essential that one can compute order by order in "loops" (the coupling constant) to ensure they make sense.

Because of infinities at short distances, this is known as "renormalizability". During the 50's and 60's, non-Abelian gauge theories were *scorned* because, it was thought, they were *not* renormalizable.

'71, '72: G. 't Hooft & M. Veltman showed that they *are* renormalizable, and so sensible theories.



G. 't Hooft

M. Veltman

Quantum ChromoDynamics

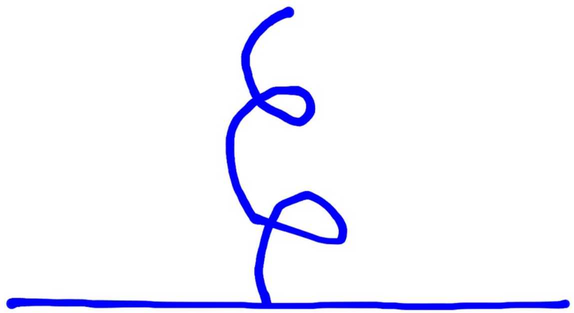
Like QED, for QCD we can write the theory down in two lines:

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

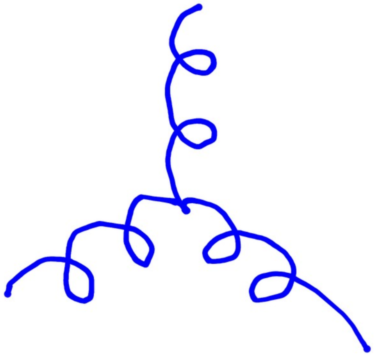
$$\mathcal{L} = \frac{1}{4}\mathrm{tr}\; G^2_{\mu\nu} + \overline{q}\gamma^\mu D^f_\mu q$$

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

Interactions:
qqg ~ same,



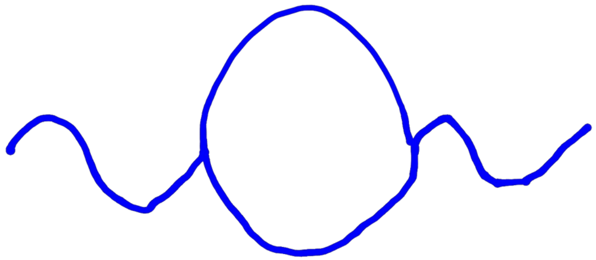
Plus interactions for
3 & 4 gluons:



How couplings run, QED & QCD

Couplings "run": change with distance:

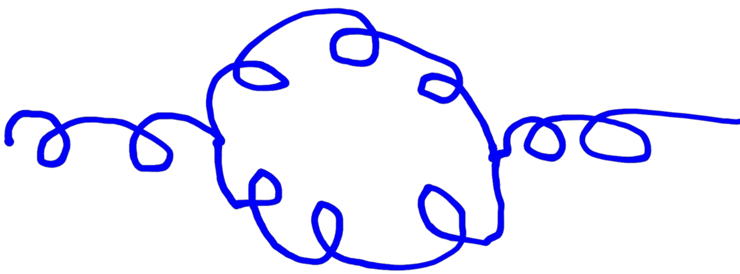
In QED, coupling α gets *smaller* at *large* distances.



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

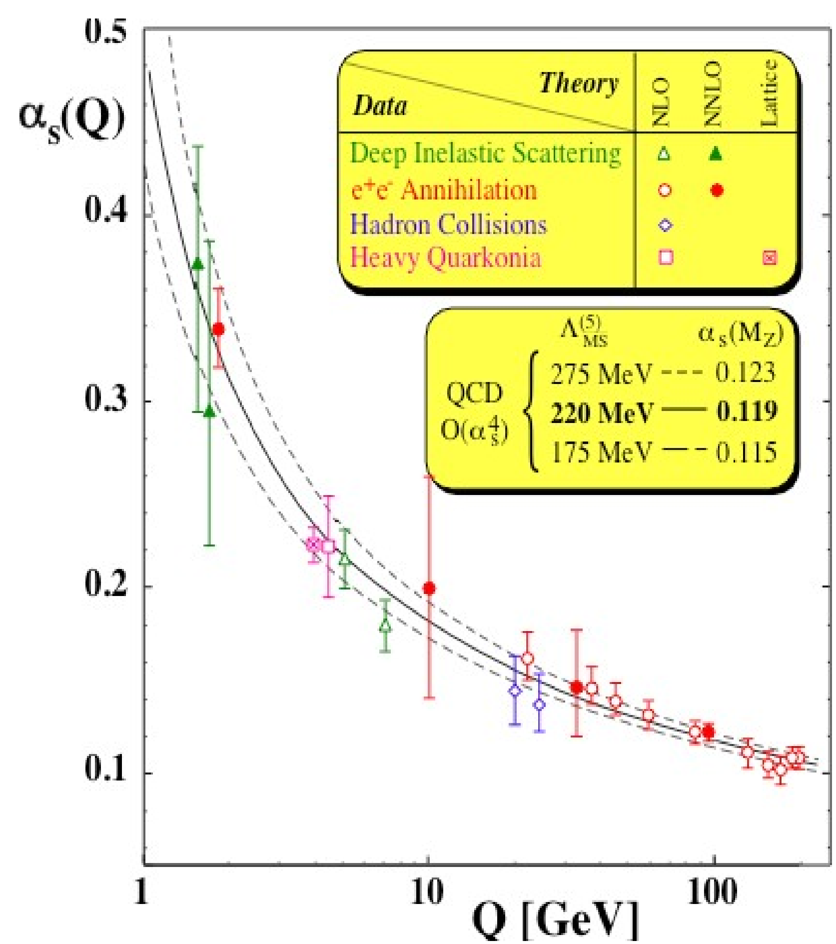
QCD coupling decreases logarithmically at short distances:

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

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!

First computed in 1973, Nobel, 2004:

David I. Gross

H. David Politzer

Frank Wilczek

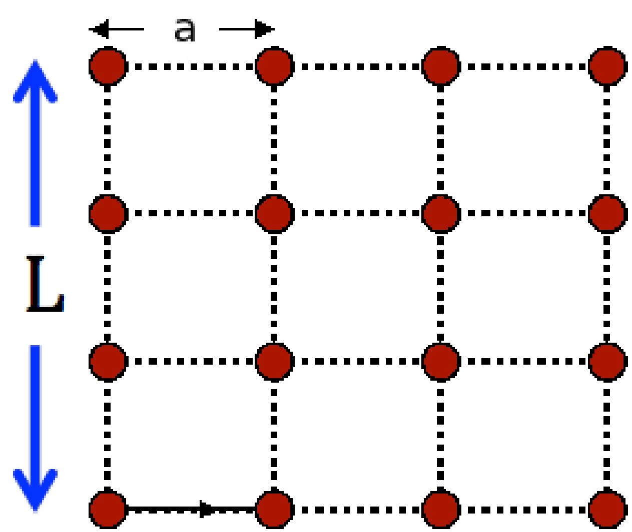
How to compute in QCD?

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

K. Wilson, '74, Nobel in '82 (for something else, "renormalization group")



K. Wilson

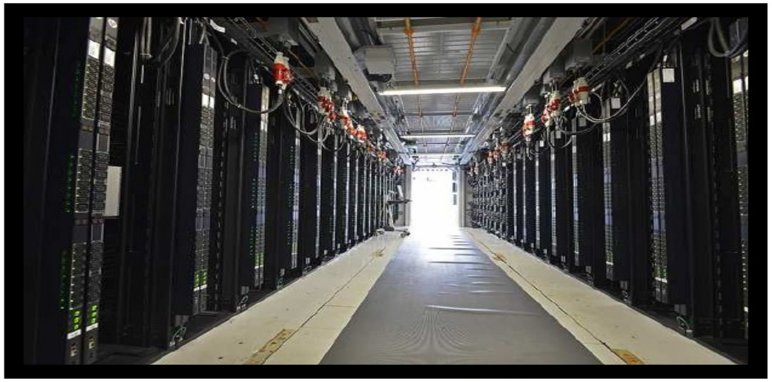
Lattice QCD?

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

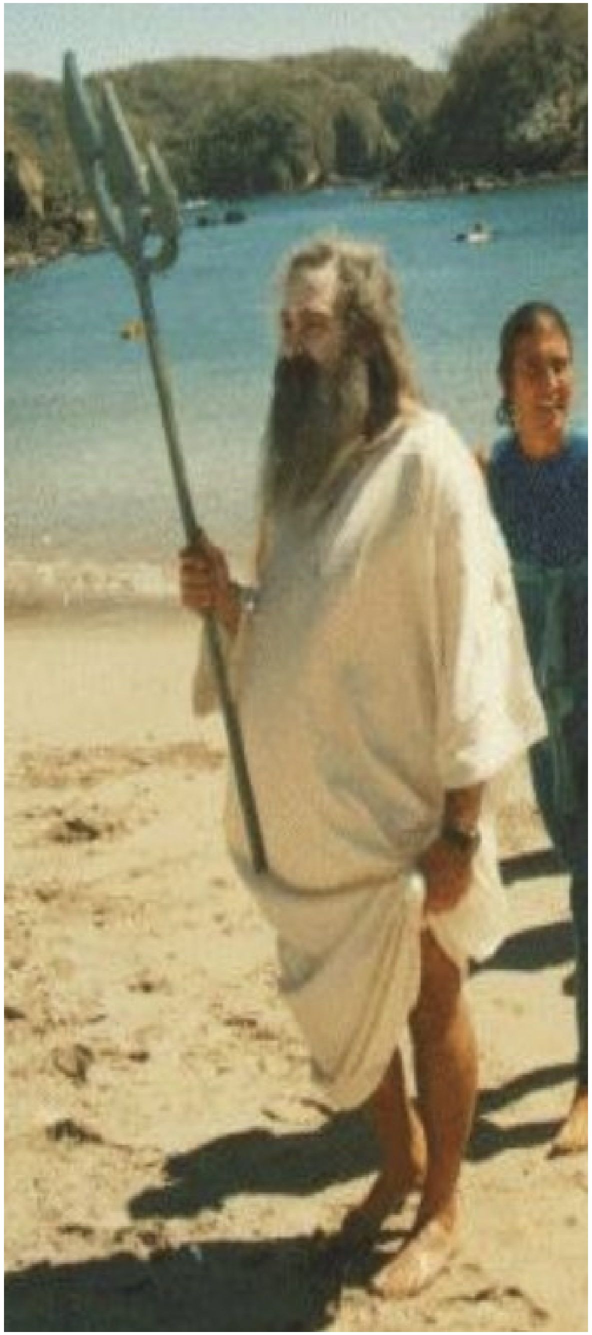
Confinement in QCD

Wilson: in ‘70’s, *no* point in even trying to

use the lattice, need *much* bigger computers

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

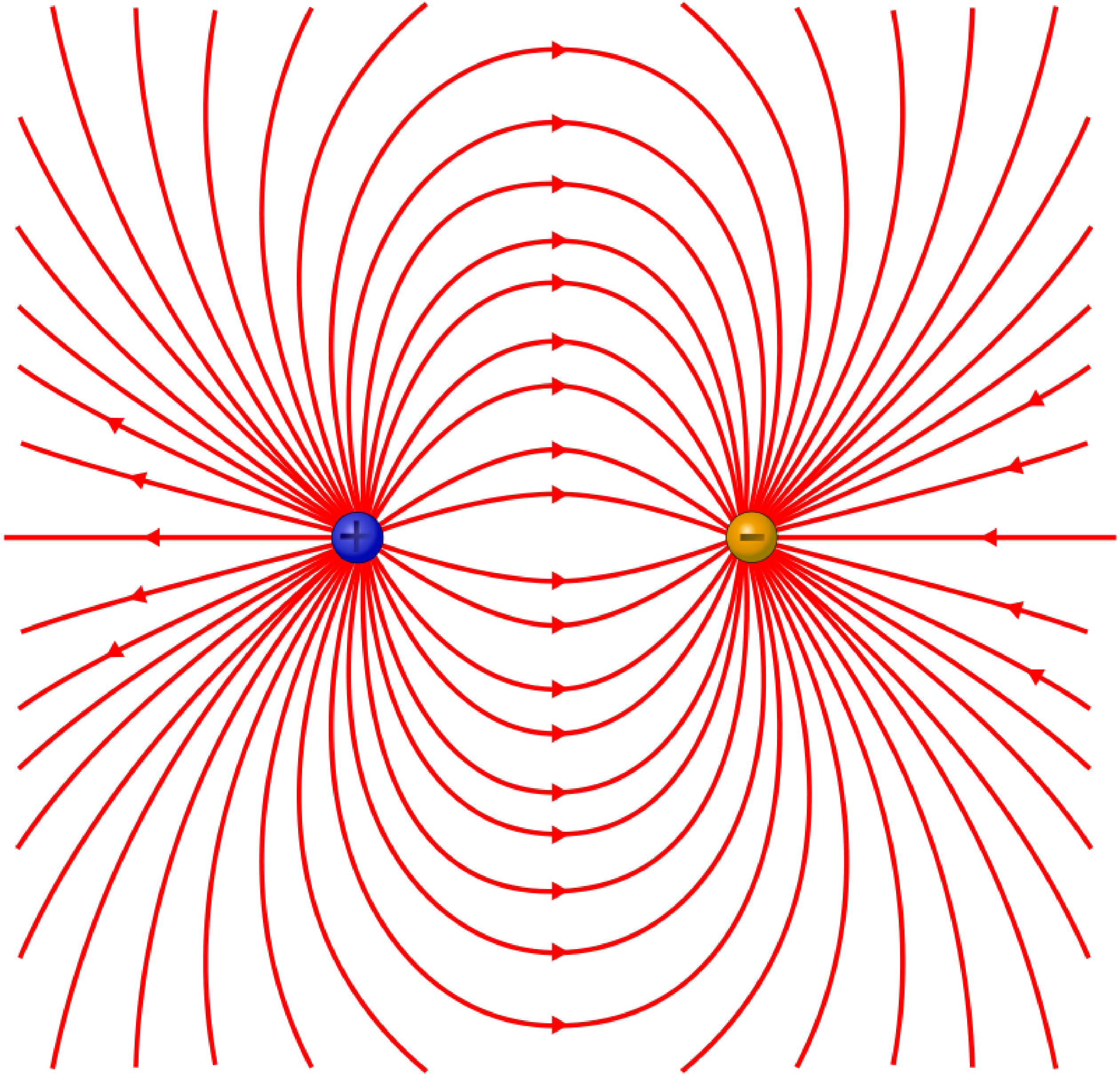
Spawned golden age in lattice QCD



Flux lines in QED

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

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

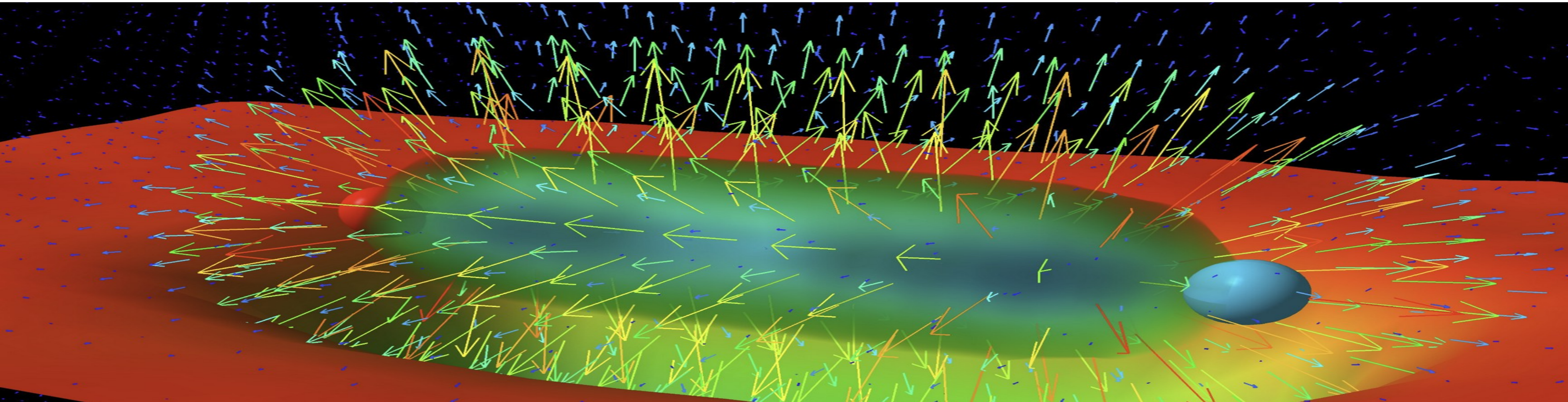


Confinement in QCD

At *short* distances, quark potential like QED, ~ 1/r.
But at large distances, color flux lines *don't* spread out, but form a flux tube.
Creutz '80: from lattice, quark potential *linear* at large r:

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

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

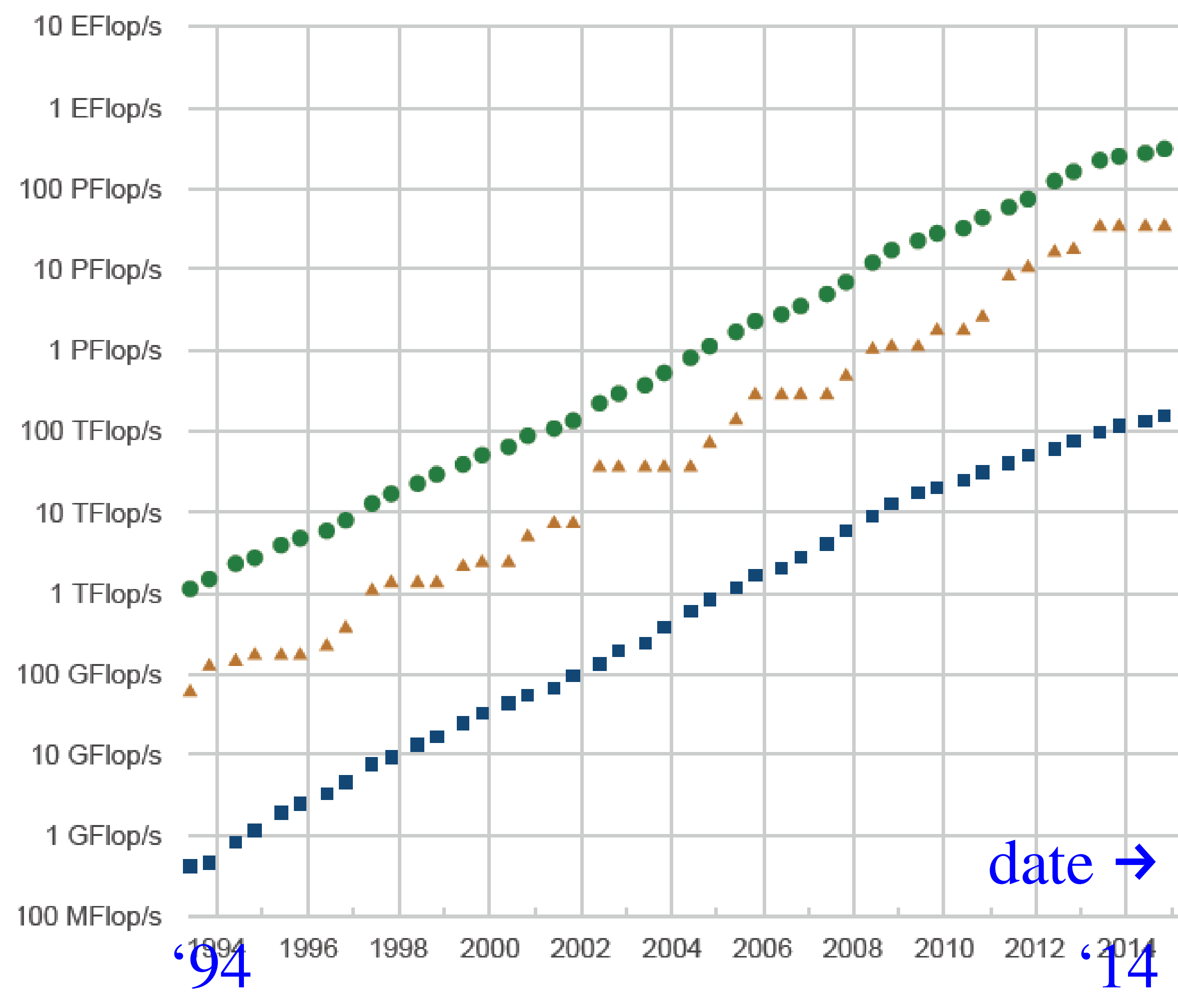
Miracle: from the 90's, possible to compute, *near* a = 0, with*out* quarks

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

2022: near a = 0 for simplest quantities. (Masses, couplings...)

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

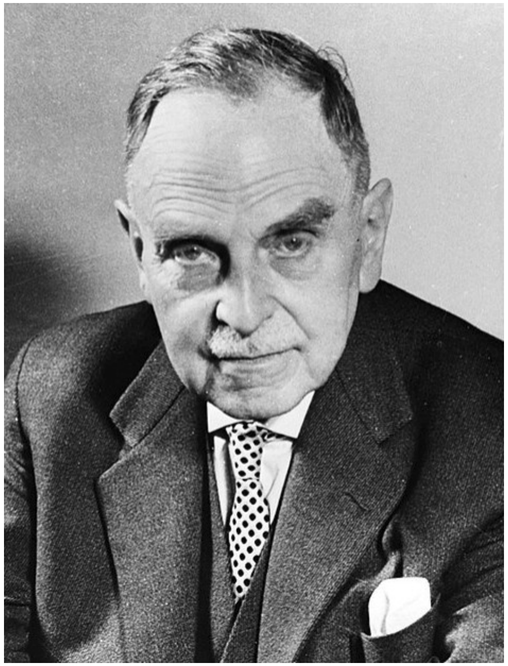
Fission: Otto Hahn, F. Strassmann: Jan. 6 & Feb. 10, 1939
Decay products lighter than lead

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

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

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) °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

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

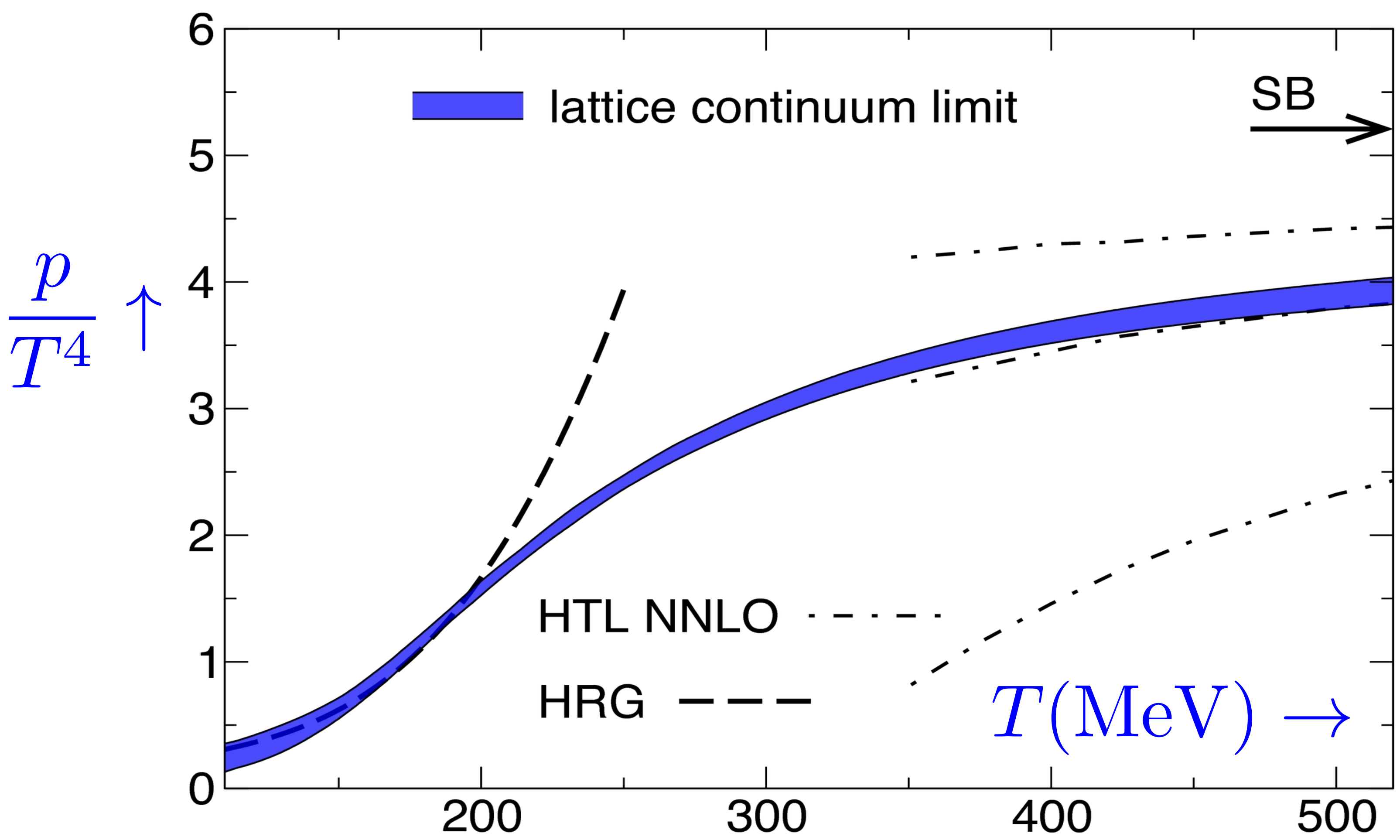
Lattice: thermodynamics of QGP

~ 2022: 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 = 156 ± 2 MeV Errors from a -> 0

But *broad* crossover. SB = Stefan-Boltzmann = free quarks & gluons



Hunting for the "Unicorn" = Quark-Gluon Plasma in Heavy Ion Collisions

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 $\mu_{qk} \neq 0$

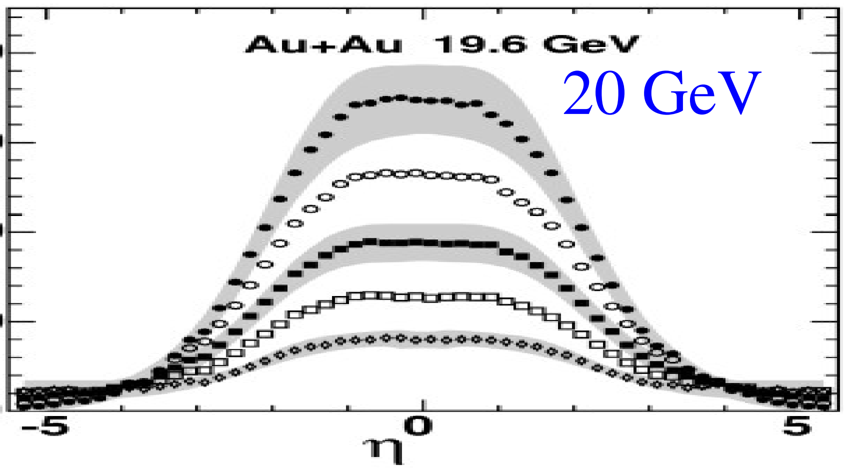
To probe baryon free region, need *high* energy. How high?

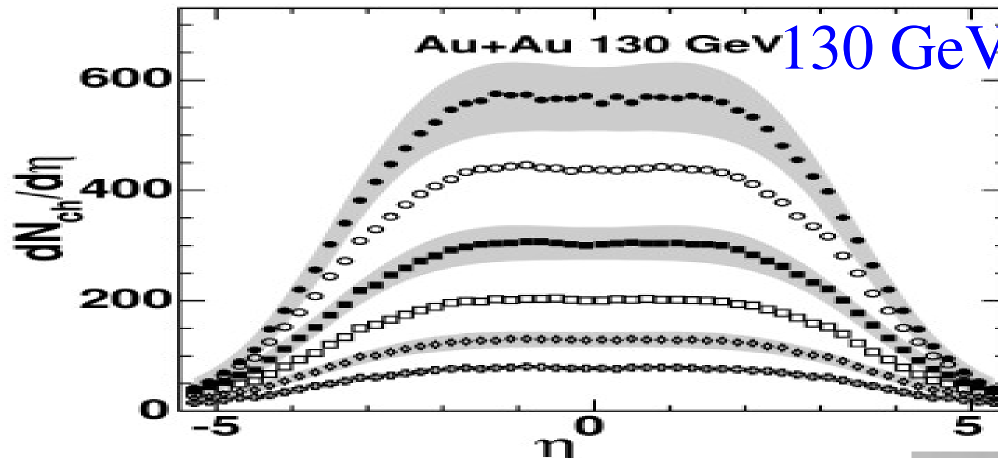
Plateau in particle production, with *many* particles

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

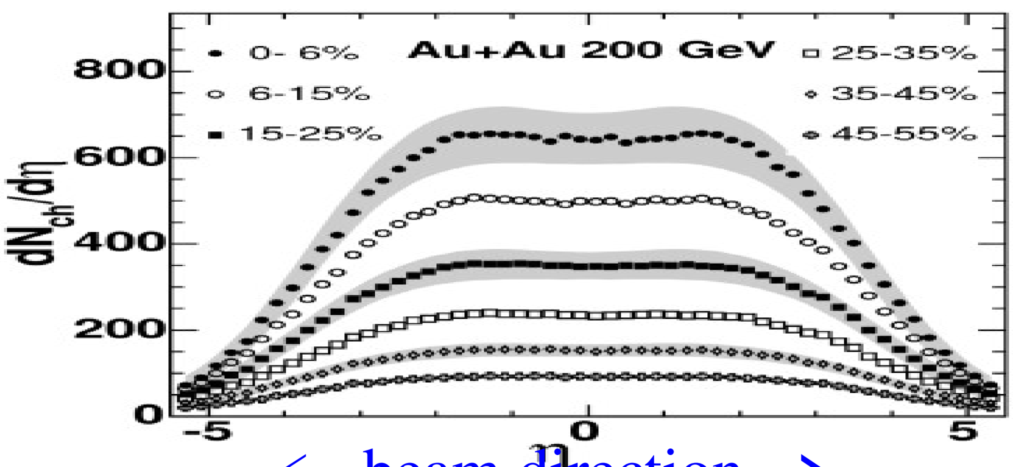
Plateau is ~ baryon free, mainly pions, kaons +.... *Many* particles, ~ 10^3





200 GeV

particles ↑
/unit rapidity

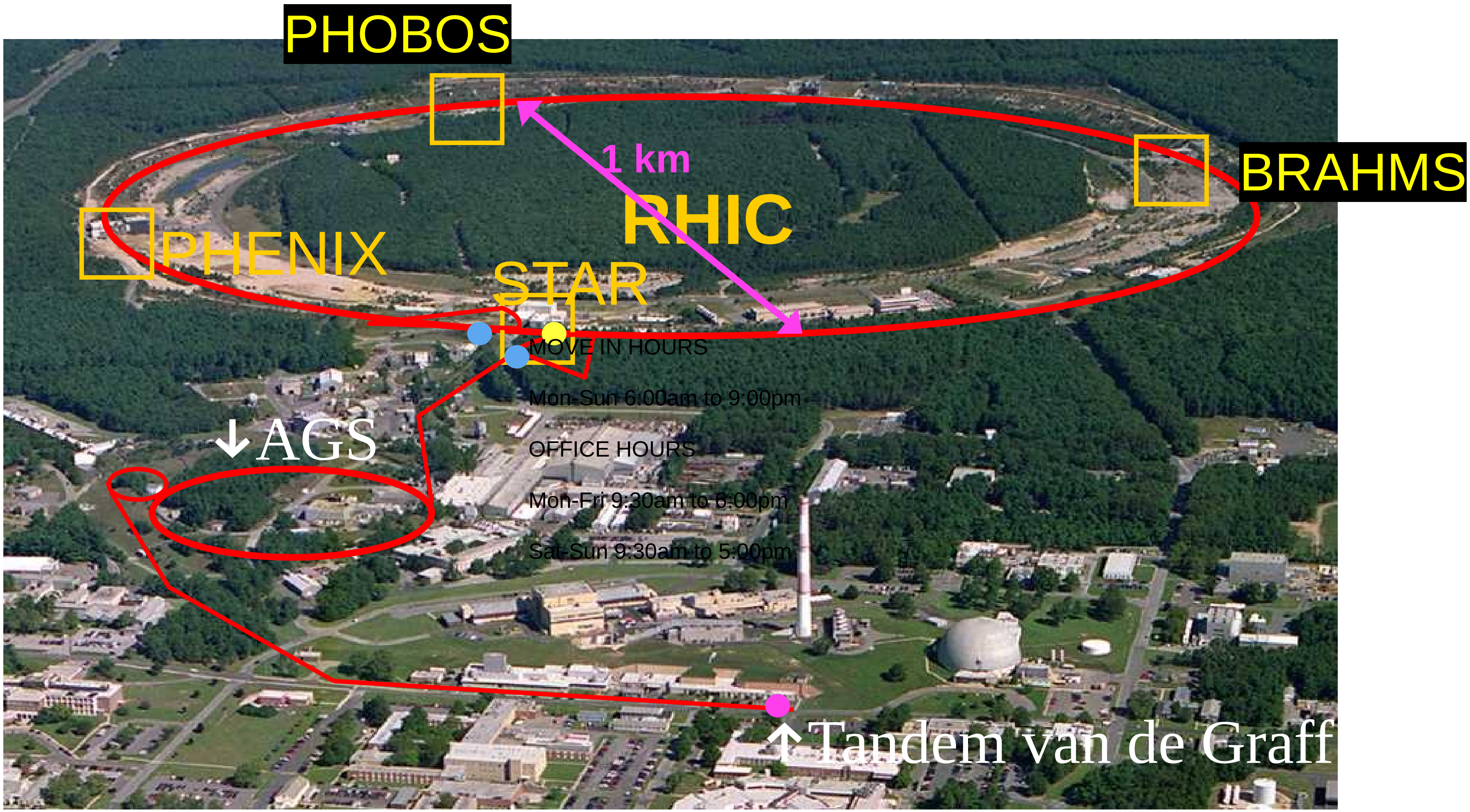


<= beam direction =>

J. Bjorken, '83

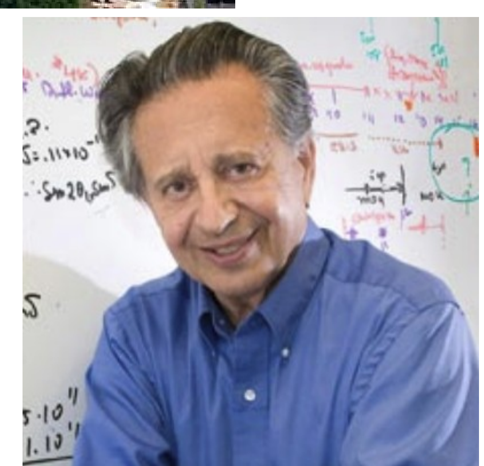
Relativistic Heavy Ion Collider @ BNL

animation by
Mike Lisa

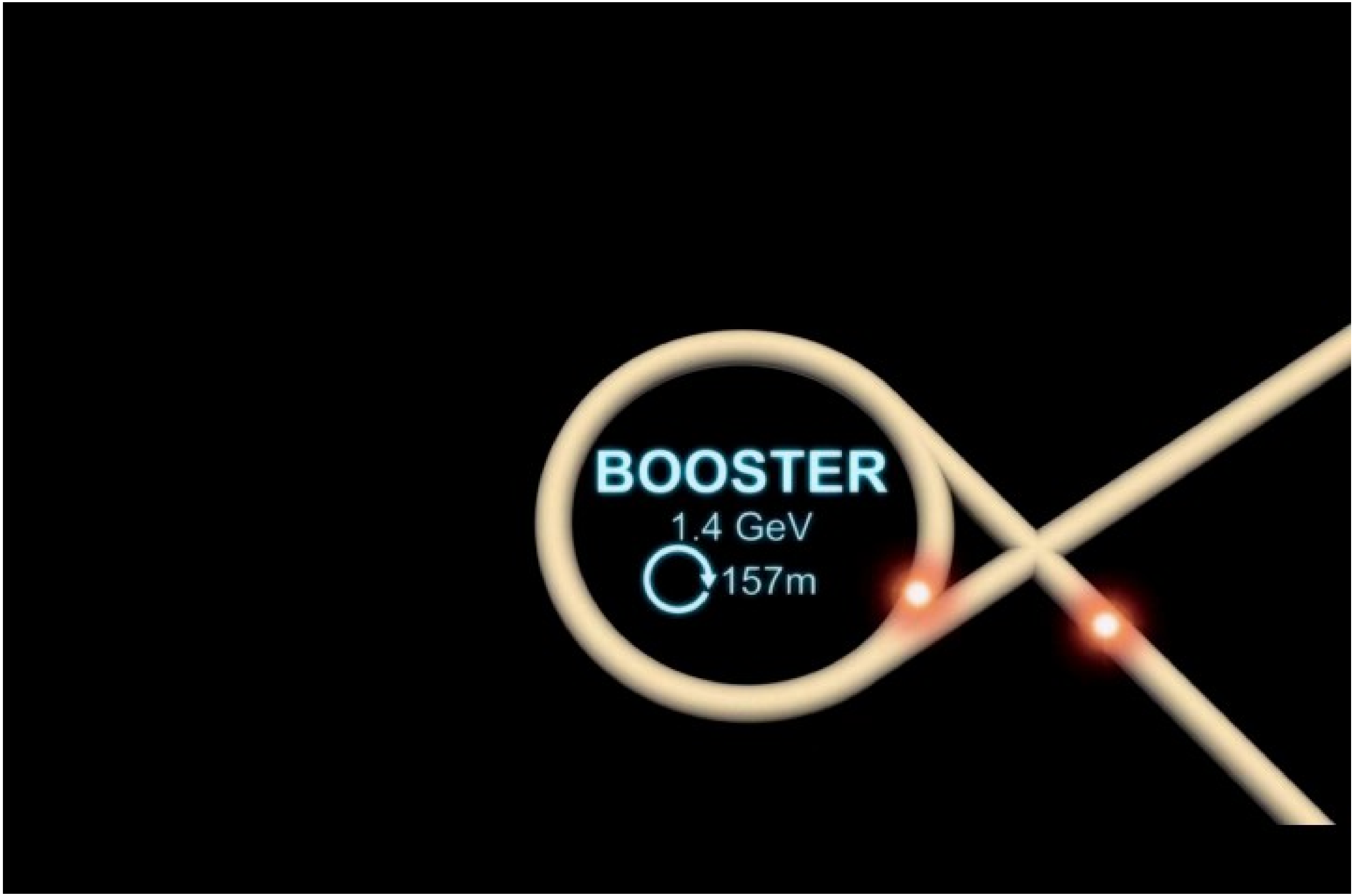


AGS: ‘60. Tandem: ‘70.
Isabelle: pp @ 200 GeV, cancelled in ‘83
(Because of SSC, cancelled in ‘93)
RHIC: 1991 → 2000. E/A: 7 to 200 GeV

Nick Samios ‘83

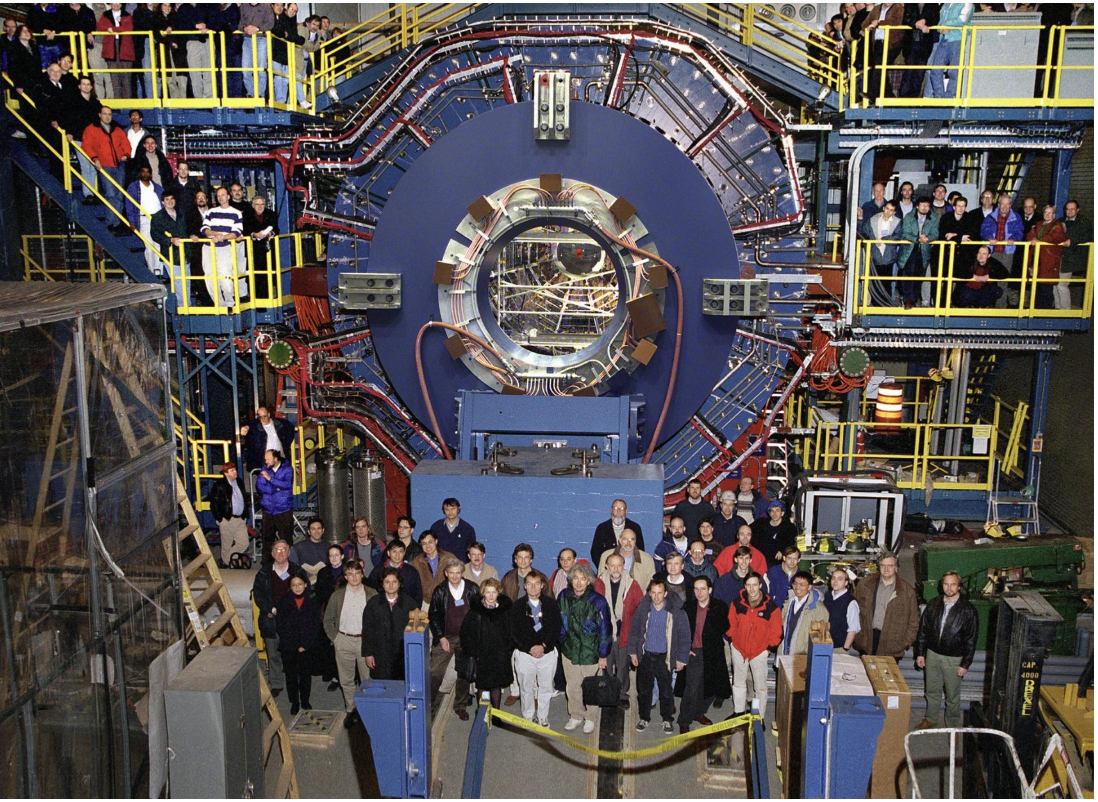


Large Hadron Collider @ CERN, Geneva: E/A ~ 3000 GeV



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

RHIC experiments: PHENIX, STAR (BRAHMS, PHOBOS)



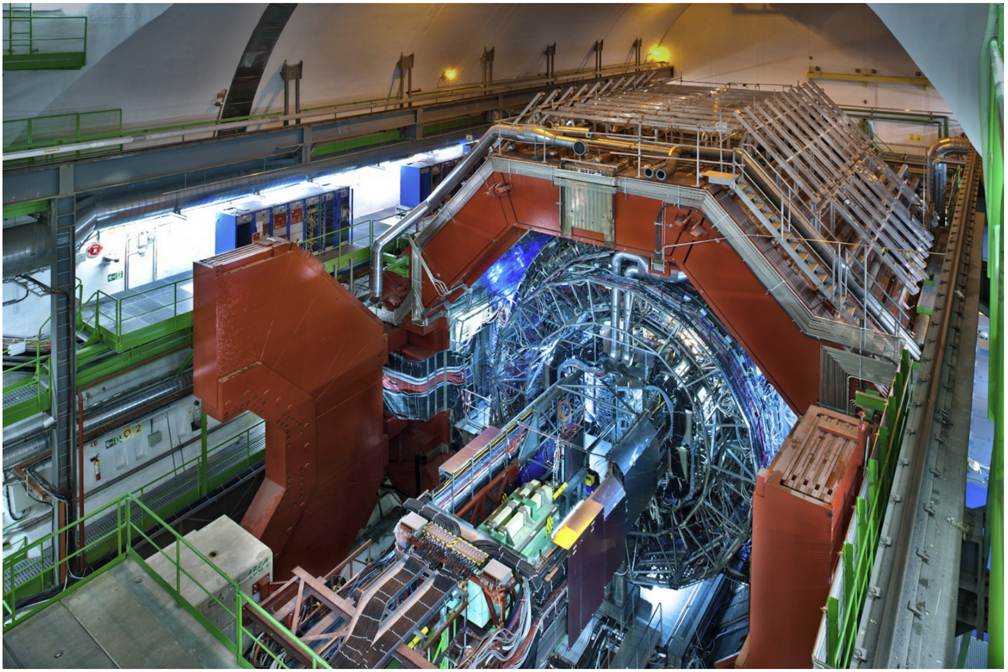
STAR↑

BRAHMS

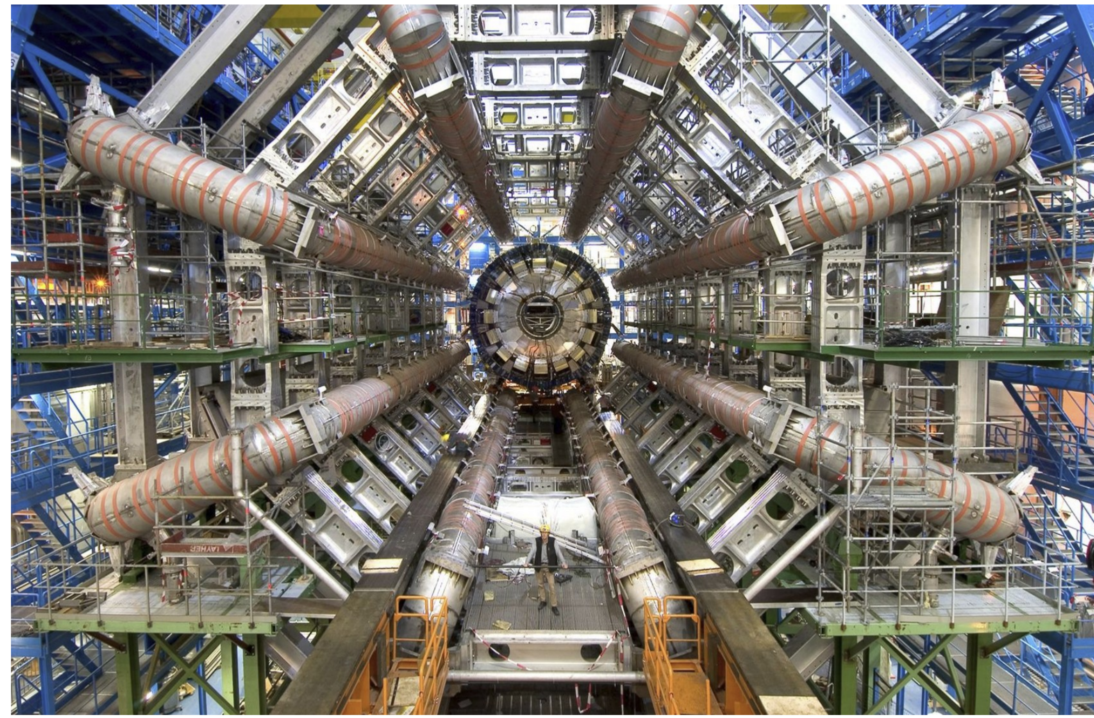
PHENIX↓

PHOBOS

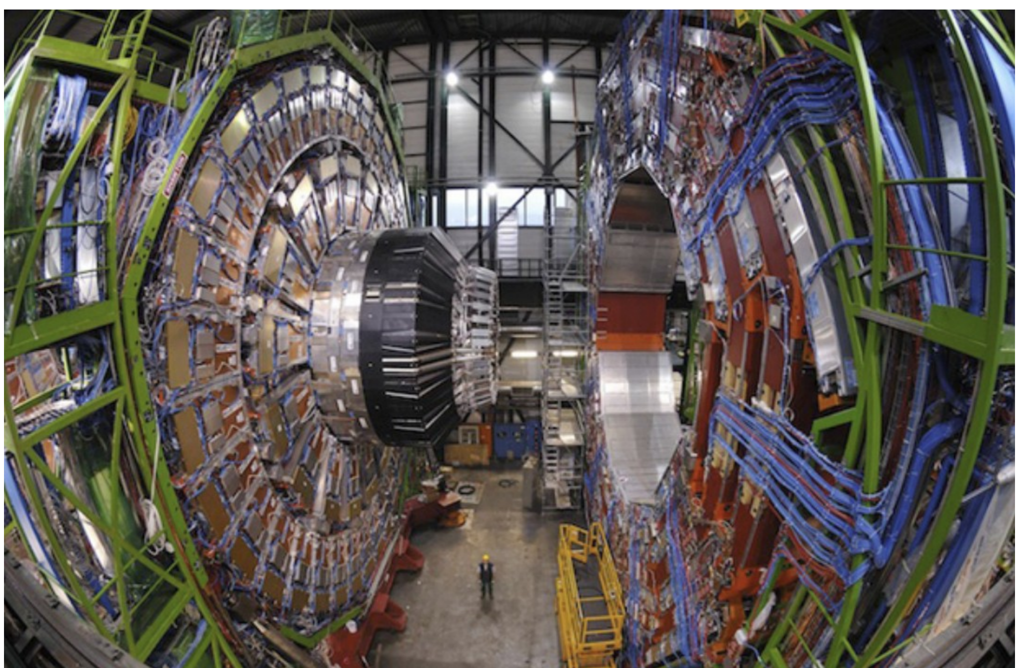
LHC experiments: ALICE, CMS, ATLAS



ALICE



ATLAS



CMS

Why skepticism about AA?

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

from studying collisions of *few* particles

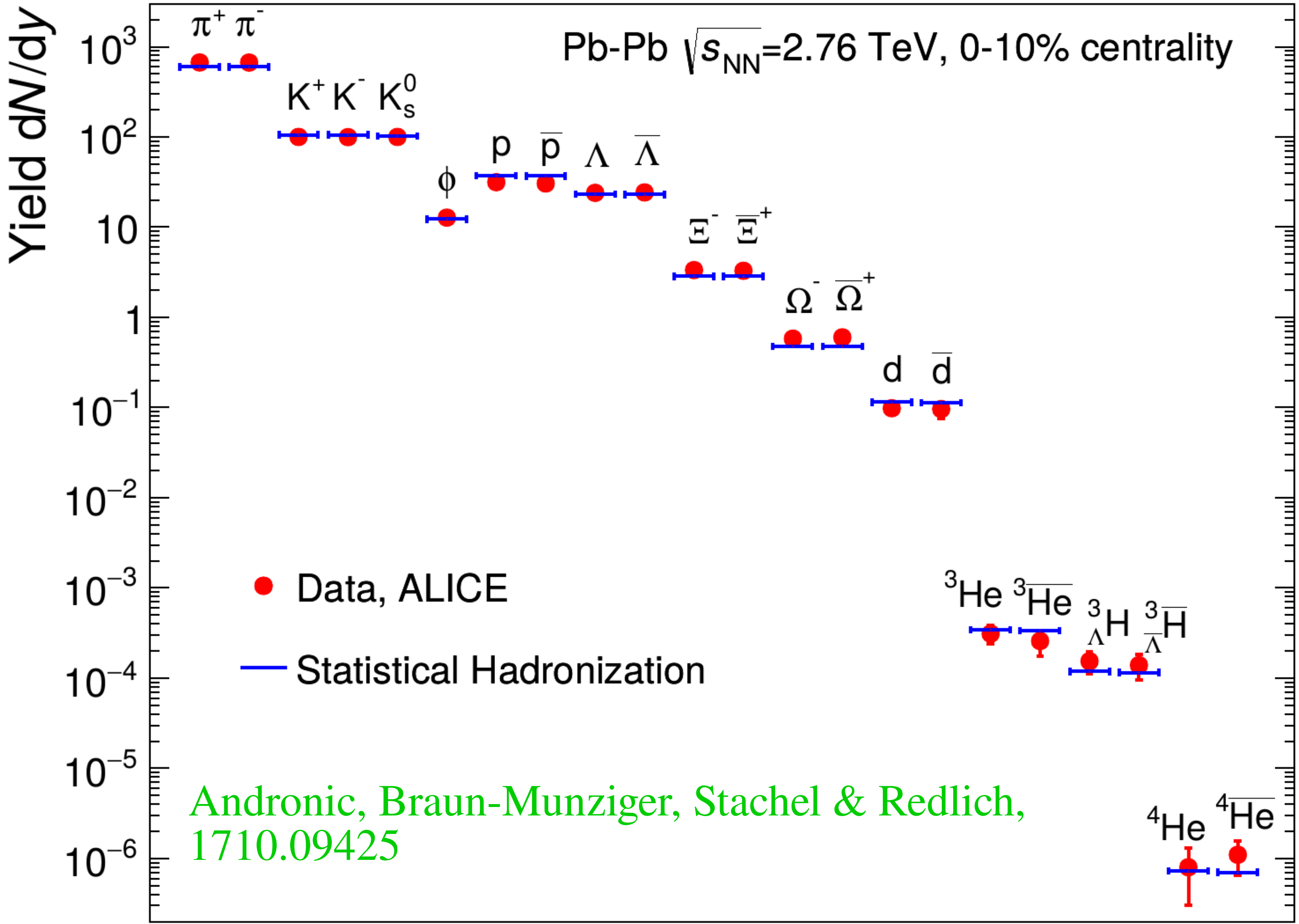
But: in statistical mechanics, simplicity from complexity,

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* $T_{freezeout}$?

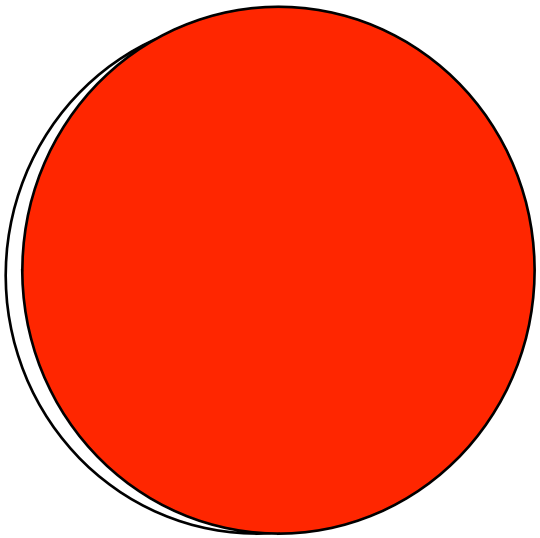


Elliptic flow
“the more perfect liquid on earth”

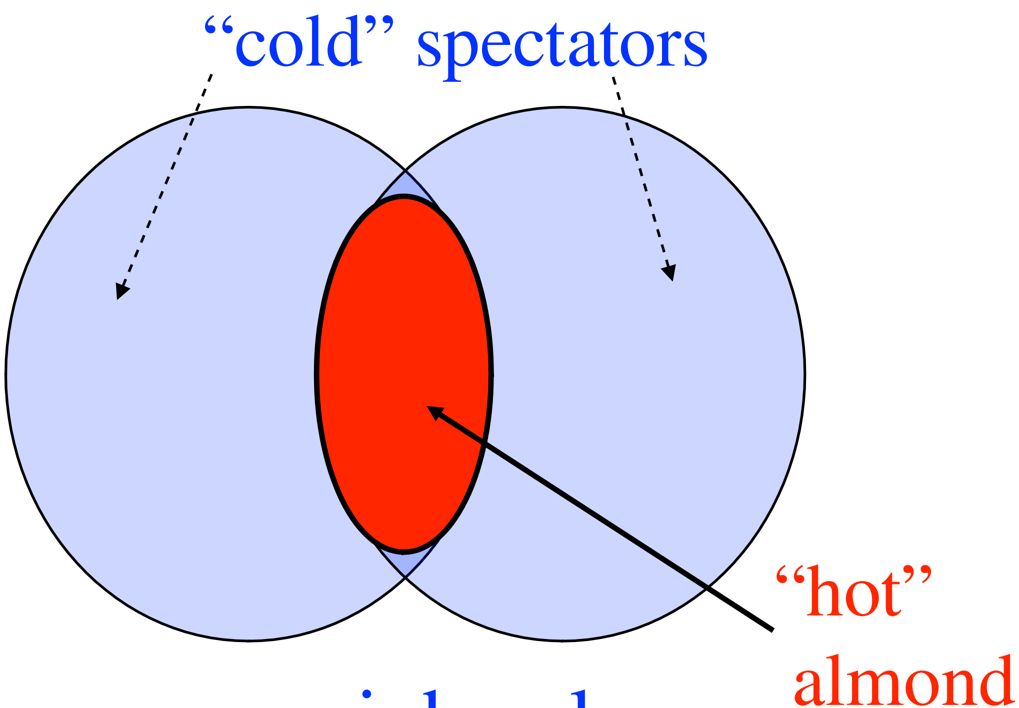
With many particles: fixing geometry

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

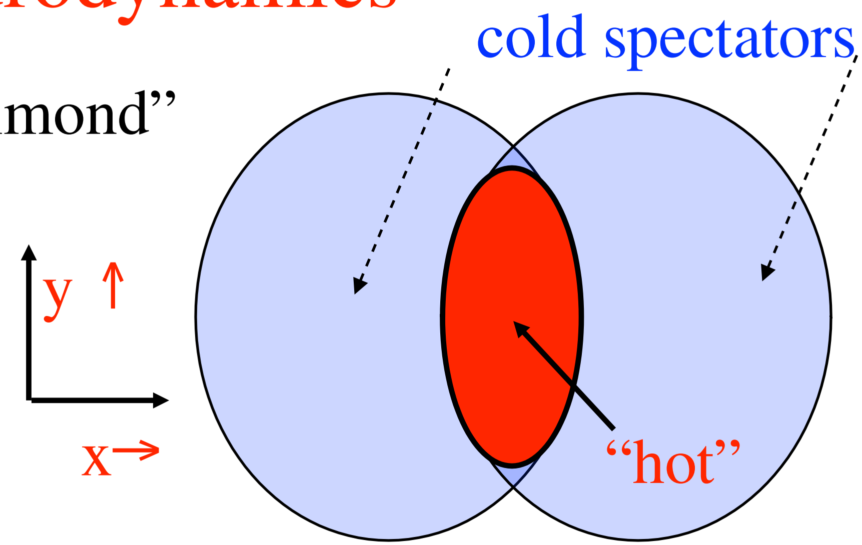


peripheral
collision:
participants in "hot" almond

Elliptic flow & hydrodynamics

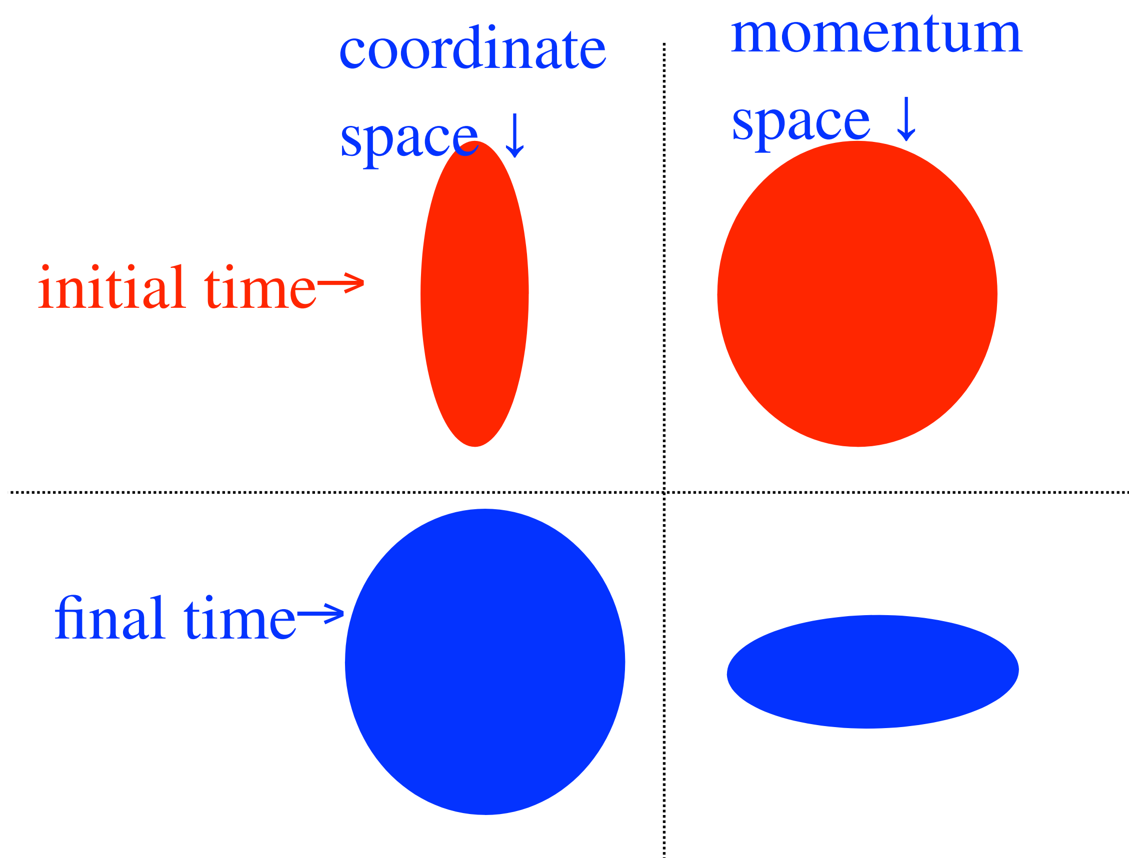
For peripheral collisions, overlap region is "almond"
Start with spatial anistropy,

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



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

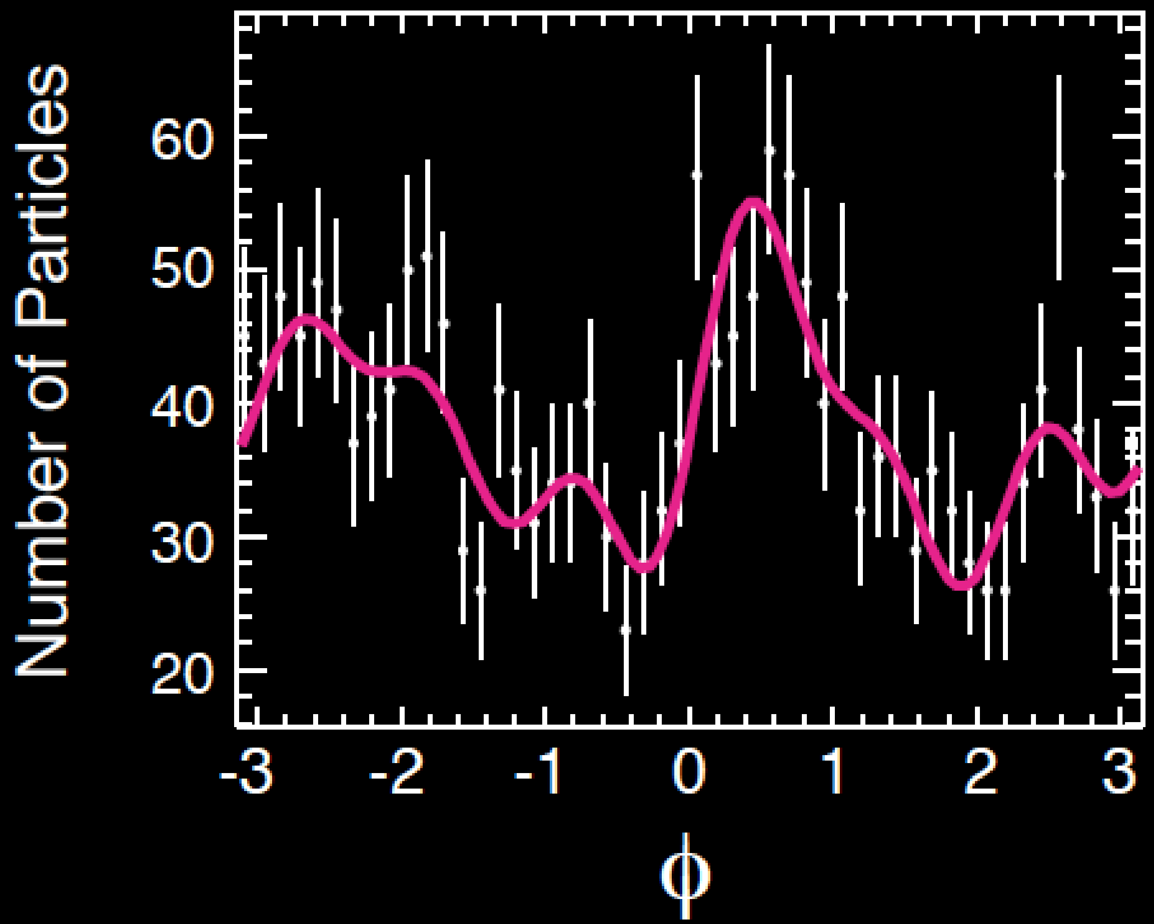
$$v_2 = \frac{\langle p_y^2 - p_x^2 \rangle}{\langle p_y^2 + p_x^2 \rangle}$$



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

ANGULAR PARTICLE DISTRIBUTION

EXPERIMENTAL DATA: ATLAS COLLABORATION



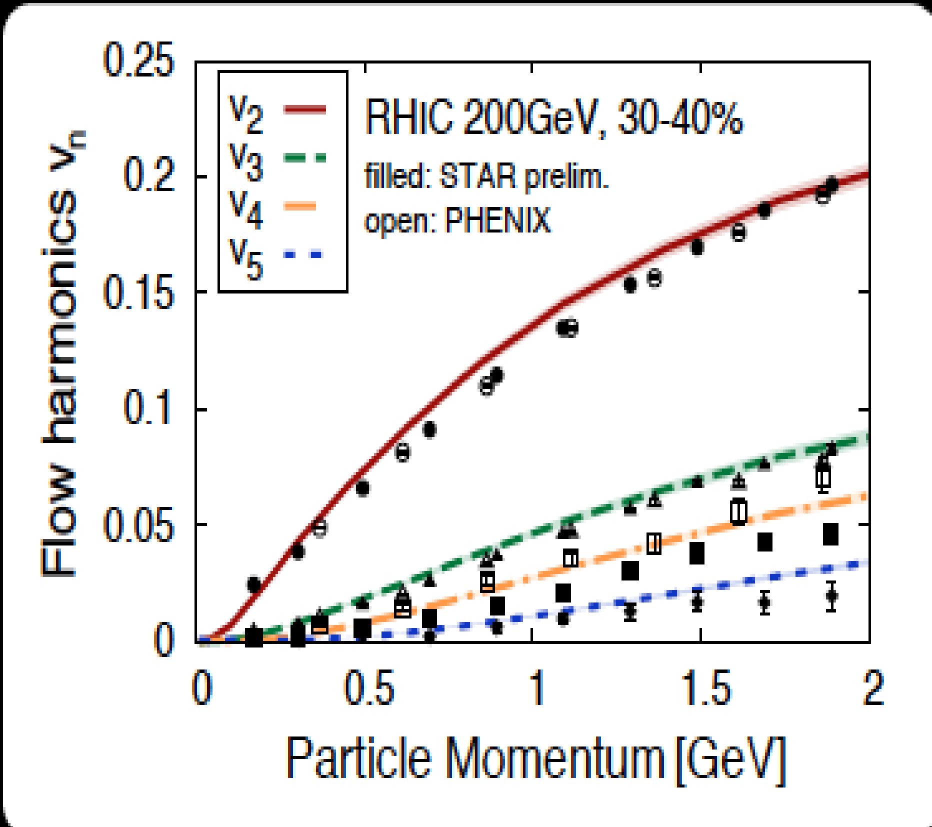
$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2\left(v_1 \cos(\phi) + v_2 \cos(2\phi) + v_3 \cos(3\phi) + v_4 \cos(4\phi) + \ldots\right)\right)$$

slide from Bjorn Schenke

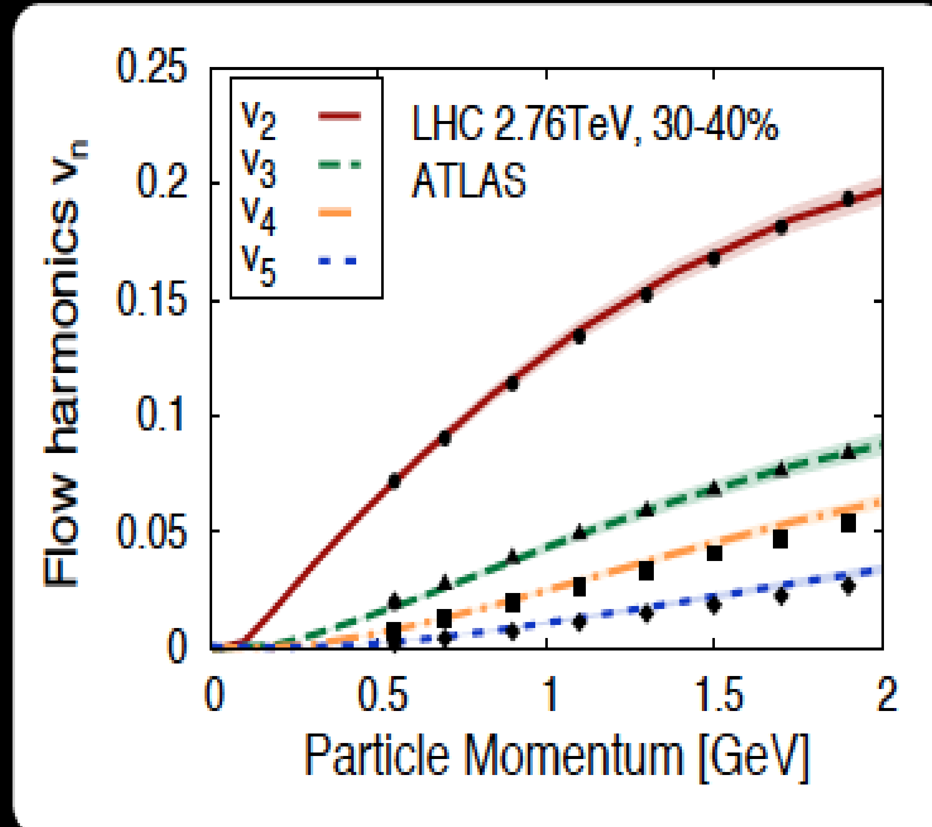
slide from Bjorn Schenke

VISCOSITY AT RHIC AND LHC

RHIC



LHC ~14 x higher energy



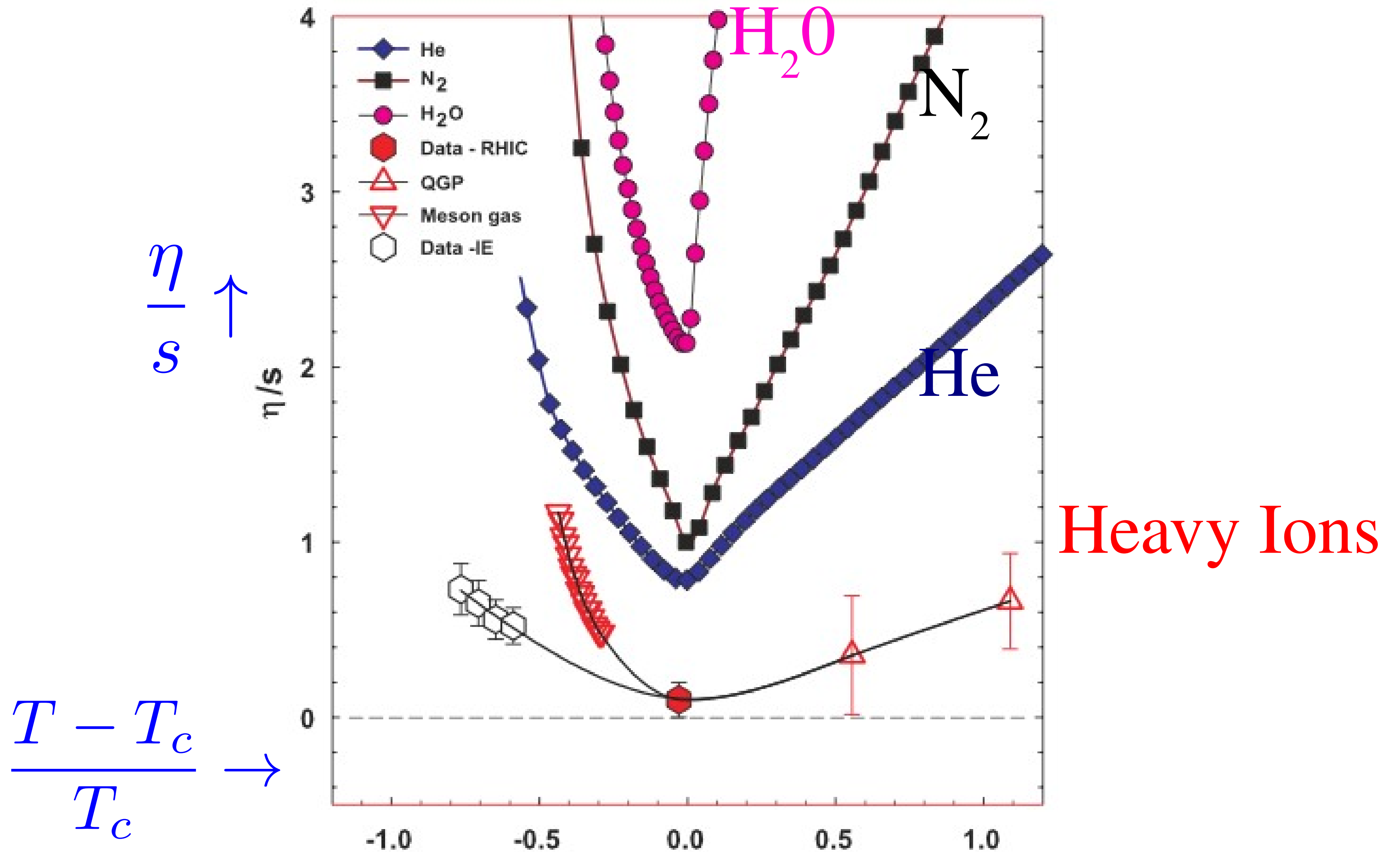
RHIC viscosity $\eta/s = 0.12$ LHC viscosity $\eta/s = 0.2$

Hints at increasing viscosity η/s with increasing temperature

η/s in heavy ions & molecules

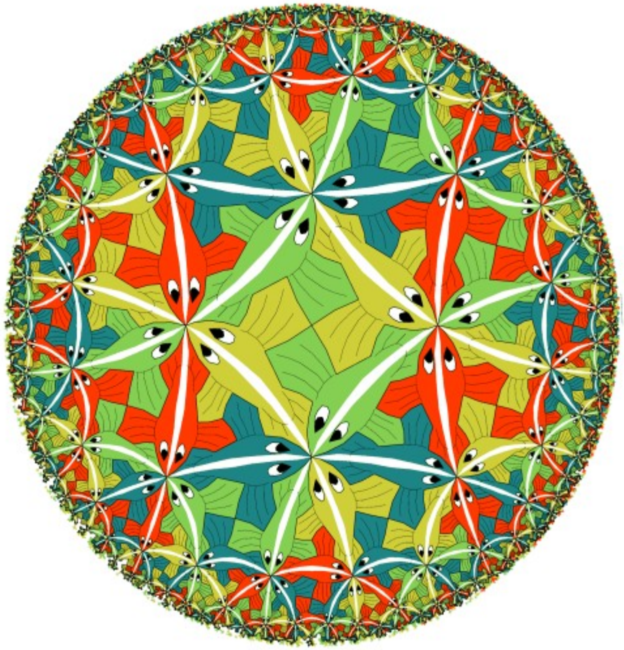
While η is big (~ 10^4 pitch tar), so is the entropy!

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



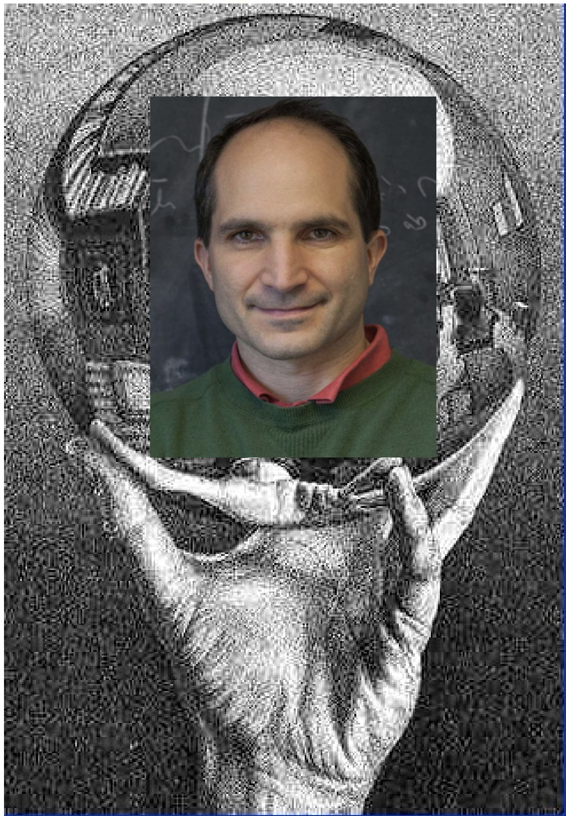
Lower bound on η/s ?

$\eta \sim 1/g^4$: *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/CFT.

Coupling weak at high T, so strong at low T.

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

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.

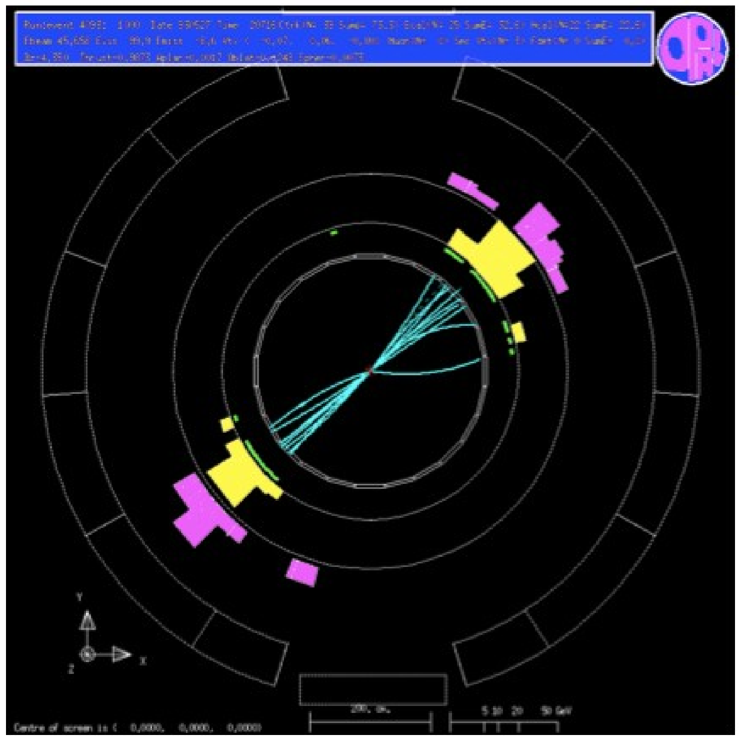
Jet quenching:
the QGP “eats” jets

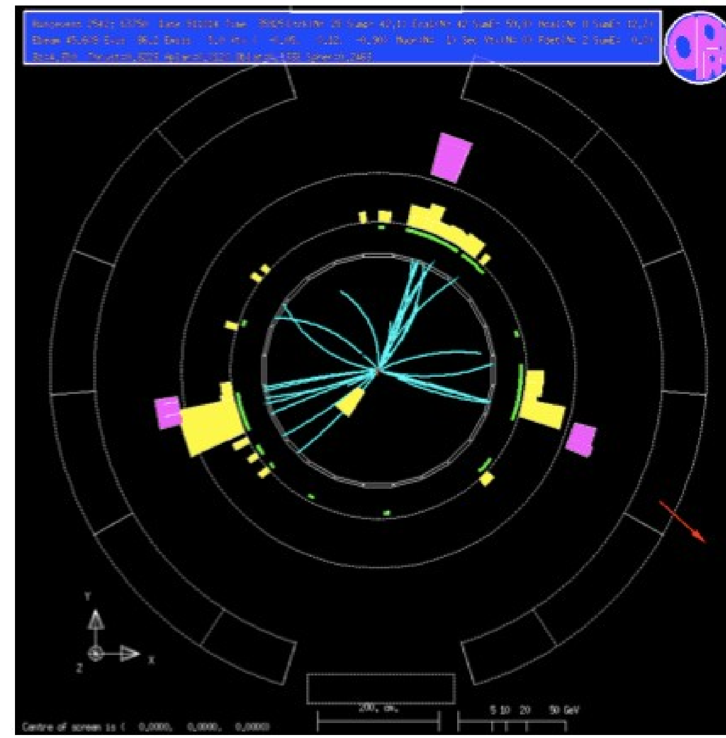
Jets in QCD

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

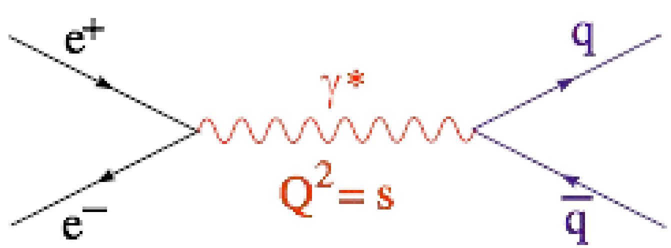
'89→2000,
LEP tunnel used for LHC

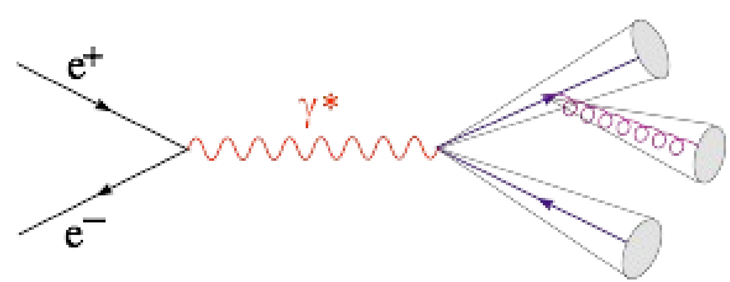




2 jets

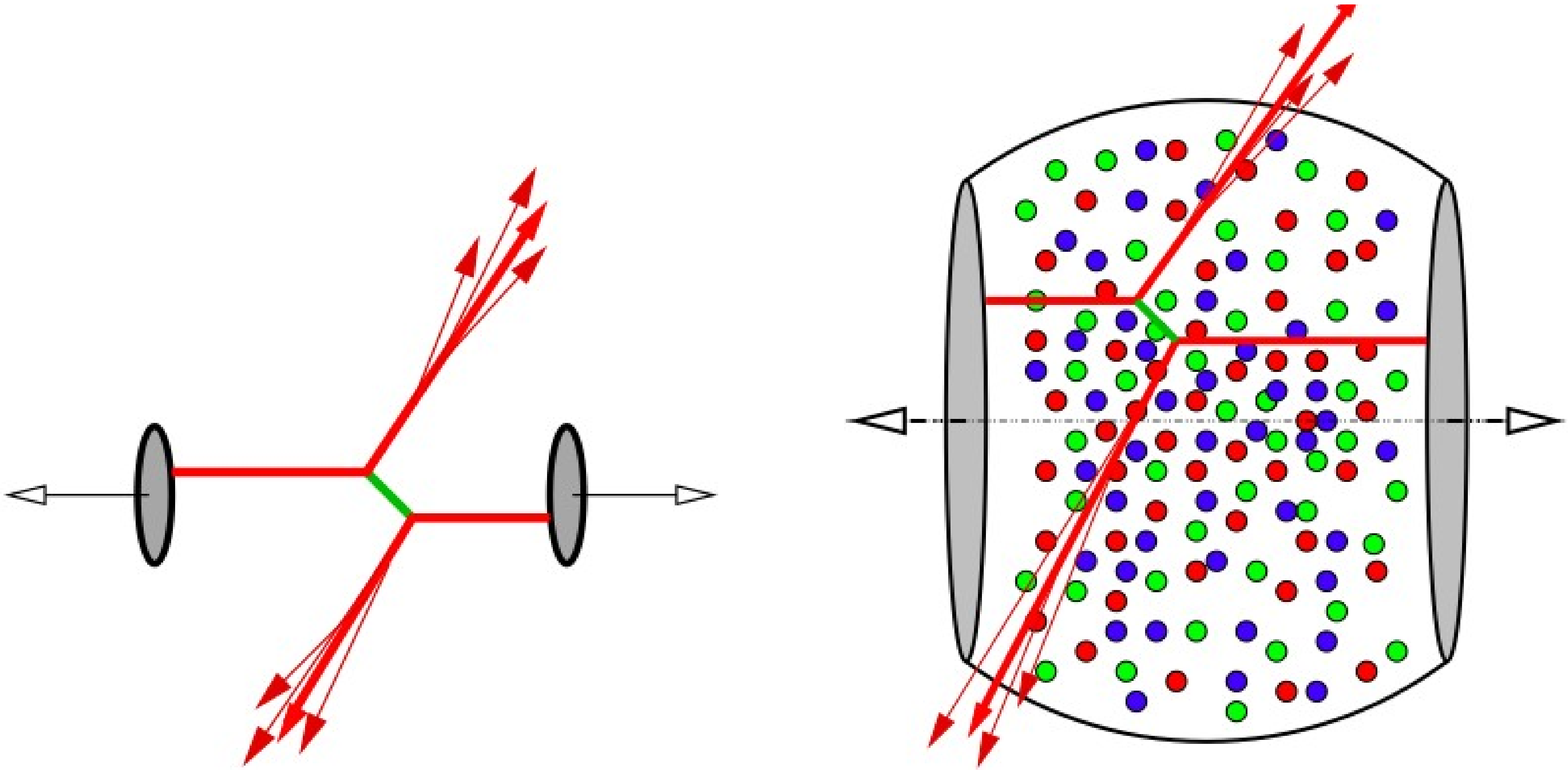
3 jets





QGP "eats" jets

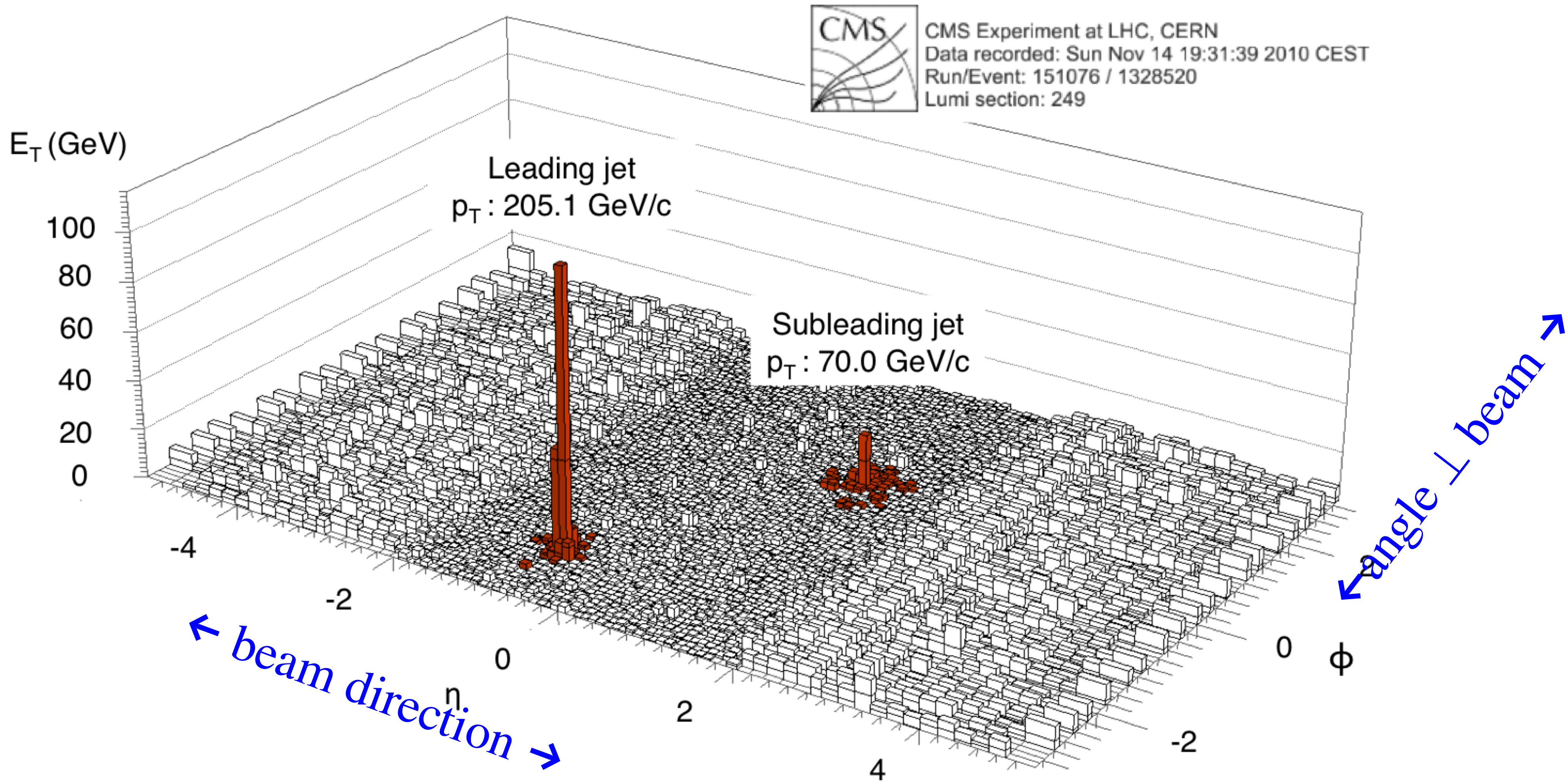
In proton-proton (pp) collisions, jets travel without further interaction.
In nucleus-nucleus (AA), if there is a medium (QGP?), then it should *strongly* affect jets: the hard particle goes into a soft spray *much* easier.
"Jet quenching". J. Bjorken, 1983



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.



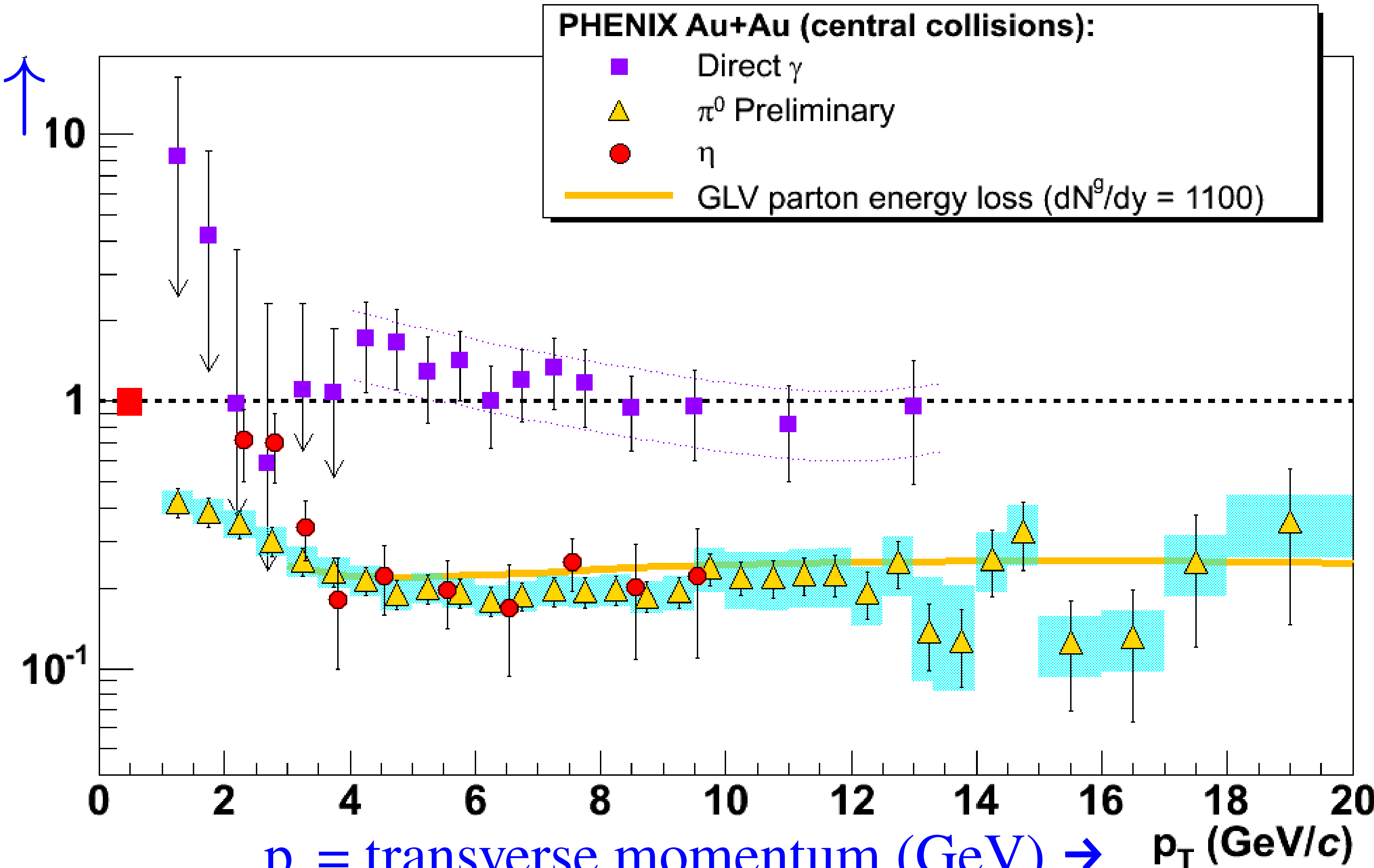
QGP "eats" jets @ RHIC

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

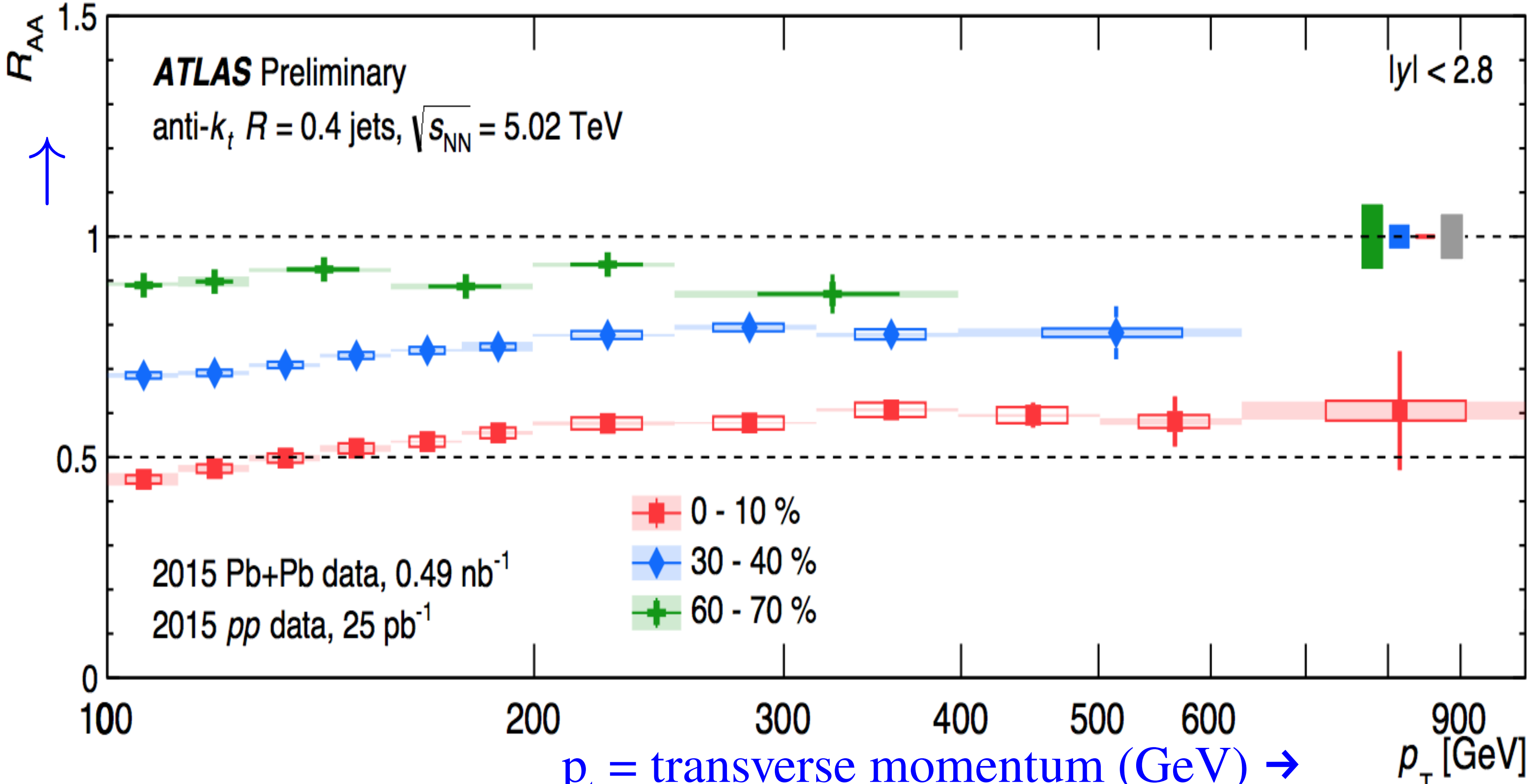


p_t = transverse momentum (GeV) →
(perpendicular to beam direction)

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

The next frontier:
moving back *down* in energy

QCD at *non*zero quark density

For AA collisions, went *up* in (collision) energy to get a baryon free regime.

Thus go down in energy to get baryons, (hopefully)
at temperature $T \neq 0$ and quark chemical potential $\mu \neq 0$

Lattice: turn Lagrangian 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 $\mu = 0$

Can compute in Hamiltonian form:

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

Above calculable, *in principle*, using quantum computers

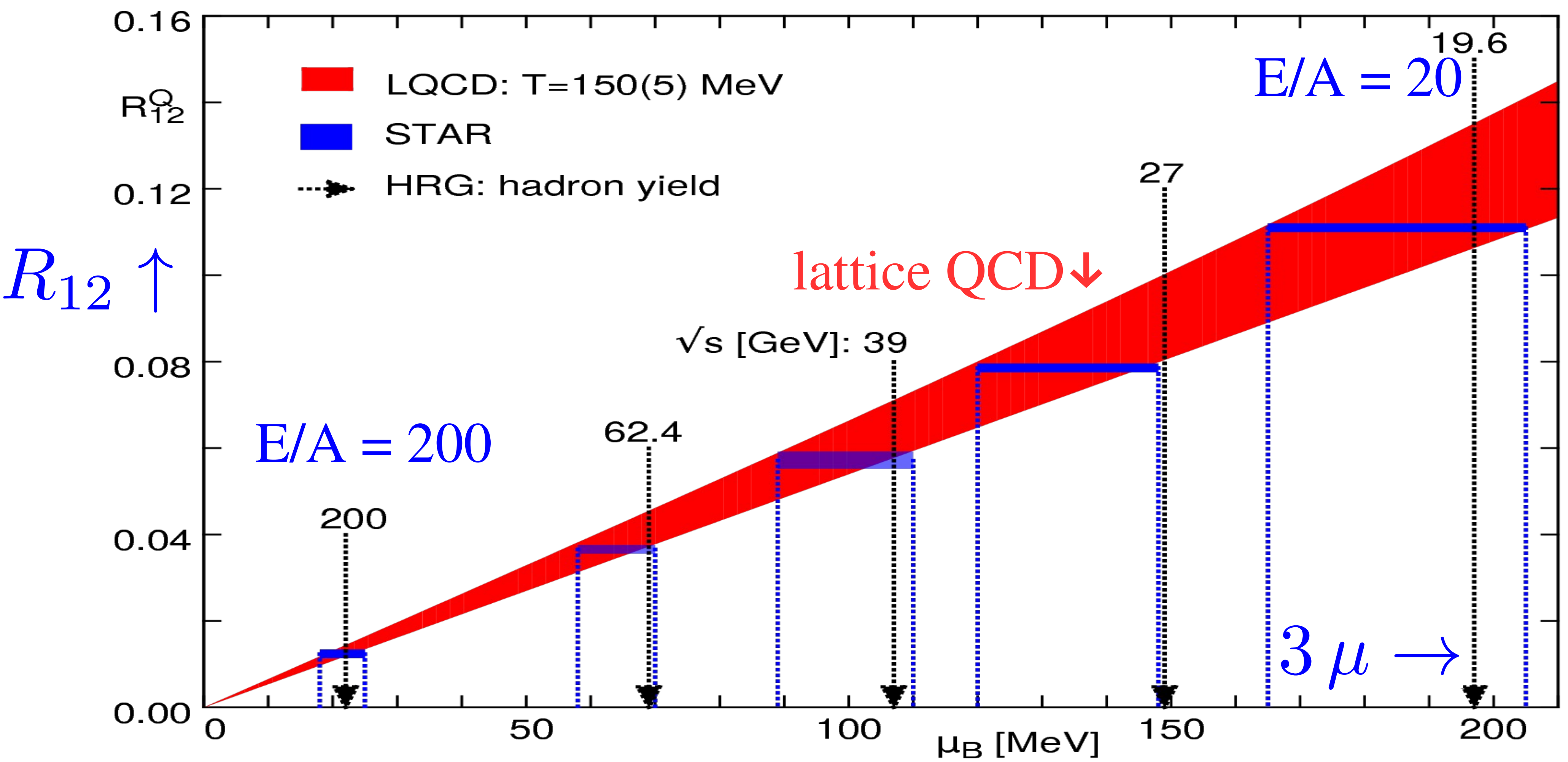
Nuclear matter is one of the great problems of physics in the 21st century

But: the sum over states is exponentially large. Need to restrict somehow.

Using the lattice to *calculate* μ

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

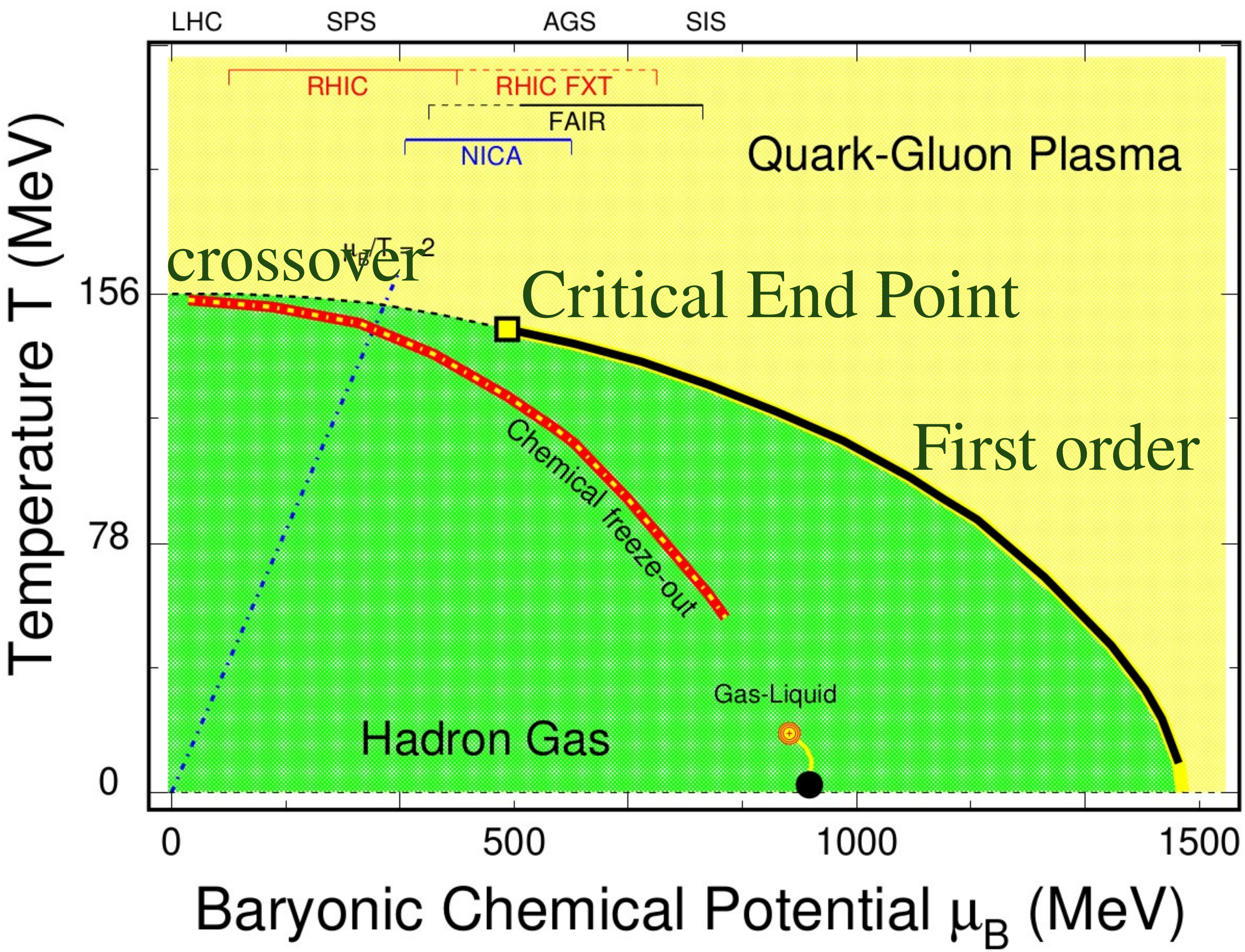
$$R_{12} = \frac{\overline{N}}{(\delta N)^2}\ ,\ \overline{N} = \langle N \rangle\ ,\ (\delta N)^2 = \langle (N - \overline{N})^2 \rangle$$



Phase diagram in T and μ

Remember: At $T \neq 0$, $\mu = 0$, chiral transition is crossover.

Need not be true at $\mu \neq 0$: at low μ, may be first order.



Accelerators:

RHIC fixed target

FAIR: GSI, Germany

NICA: Russia

Very low T:
Relevant to neutron
Stars, LIGO...

How to get a Critical End Point?

Consider usual effective Lagrangian for an O(4) vector:

$$\mathcal{L} = (\partial_\mu \phi)^2 + m^2\phi^2 + \lambda\phi^4 + \kappa\phi^6 + h\phi \qquad \phi = (\sigma, \vec{\pi})$$

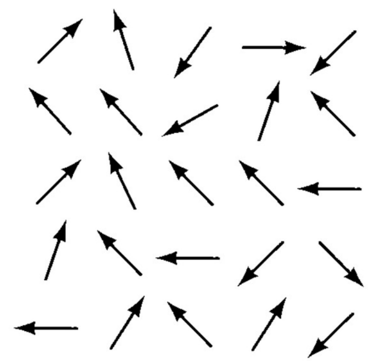
h=0: Usually, take $\lambda > 0$.

For $m^2 > 0$, symmetric state, $\langle\varphi\rangle = 0$.
(high temperature in QCD)

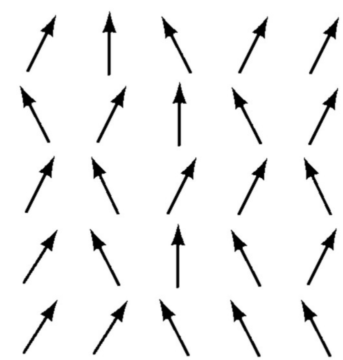
For $m^2 < 0$, broken state, $\langle\varphi\rangle \neq 0$.

(low temperature in QCD)
As $m^2 \rightarrow 0$, 2nd order phase transition.

symmetric



broken



But can also take $\lambda \rightarrow 0$. Then one has a tri-critical point, going from
2nd order 1st order transition.

$h \neq 0$: gives pions a mass at low T. Then 2nd order $\rightarrow$ crossover.

Tri-critical point $\rightarrow$ critical end point! *True* 2nd order phase transition.

Asakawa & Yazaki '89; Rajagopal, Stephanov & Shuryak '99 +….

CEP: large fluctuations @ low energy?

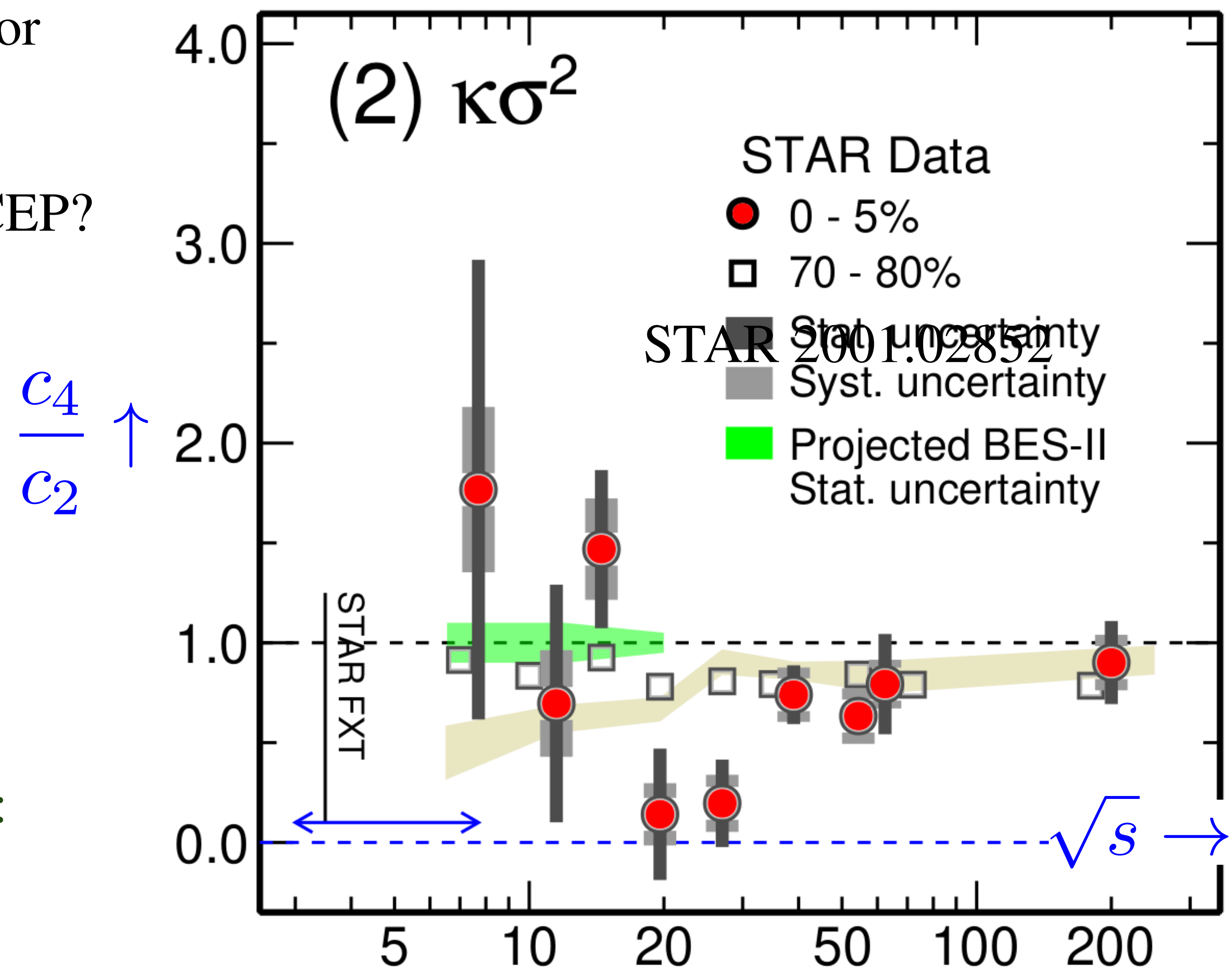
Can measure derivatives of pressure with respect to μ:

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

STAR @ RHIC: *Large* increase at lowest E/A

Non-monotonic behavior in c_4/c_2:

Possible evidence for CEP?



Bzdak, Esumi, Koch, Liao, Stephanov, & Xu: 1906.00936

Also possible: chiral spirals

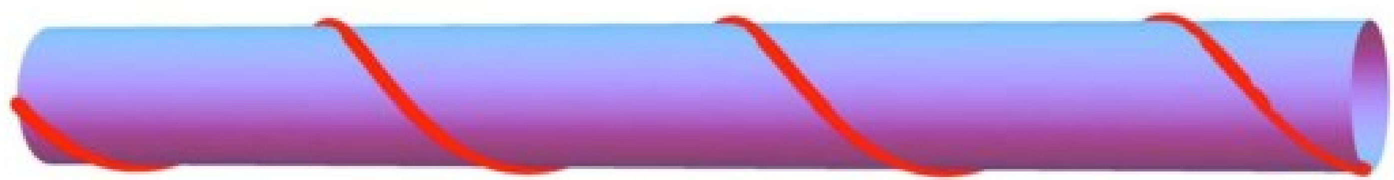
Other phenomena are possible

$$\mathcal{L} = (\partial_0 \phi)^2 + Z(\partial_i \phi)^2 + (\partial^2 \phi)^2/M^2 + V(\phi)$$

Have Causality → only 2 time derivatives. But one can have $Z < 0$!

Very common in condensed matter. In nuclear matter, pion/kaon condensates:

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



Can find exact solutions in 1+1 dimensions:

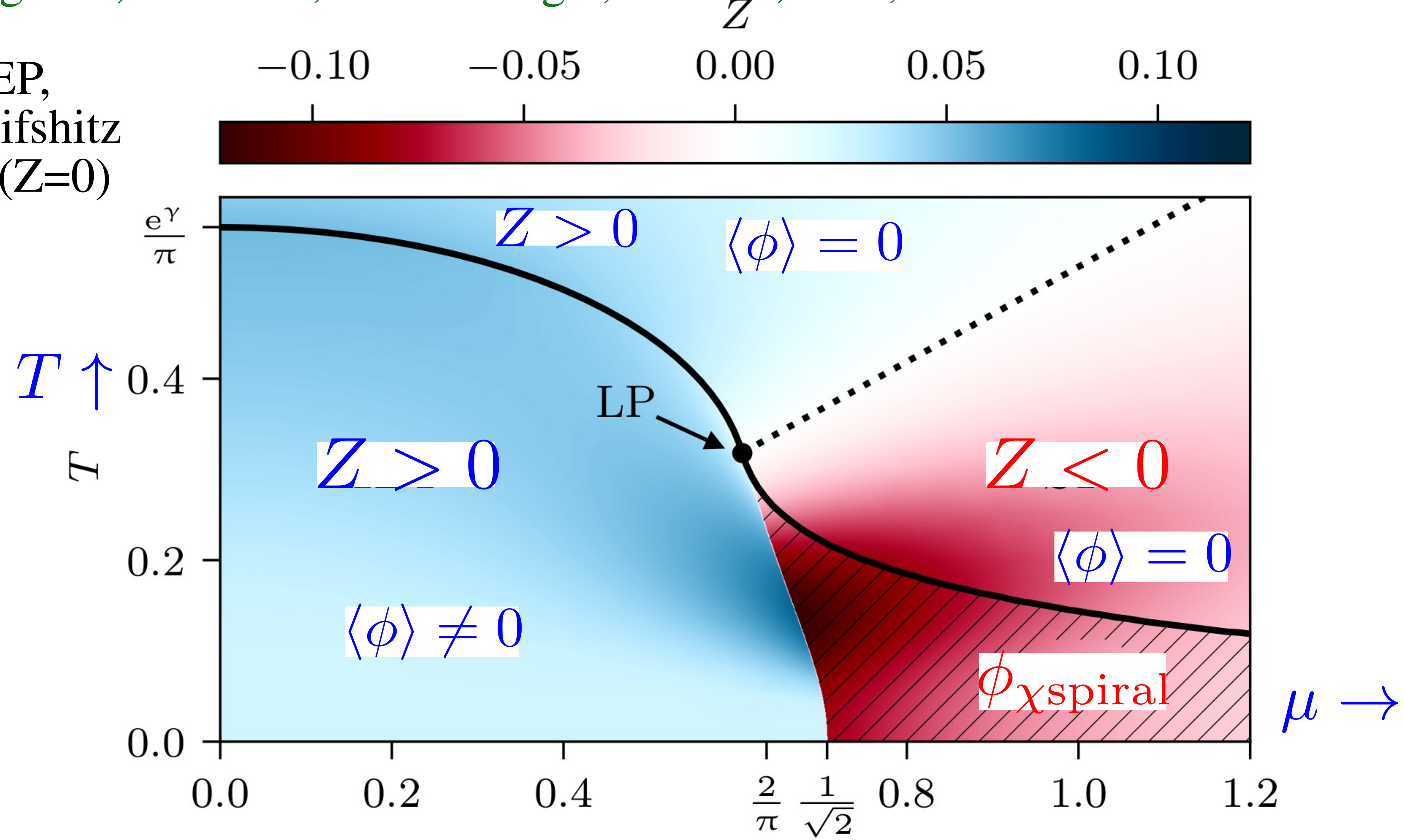
Model phase diagram

Gross-Neveu model in 1+1 dimensions: $\mathcal{L} = \overline{\psi} i \partial\!\!\!/ \psi + g^2 (\overline{\psi}\psi)^2$

Chiral spirals appear at low T, high mu: Basar, Dunne, Thies, 0903.1868

Koenigstein, Pannullo, Rechenberger, Winstel, Steil, 2112.07024: Z < 0!

No CEP,
Just Lifshitz
Point (Z=0)

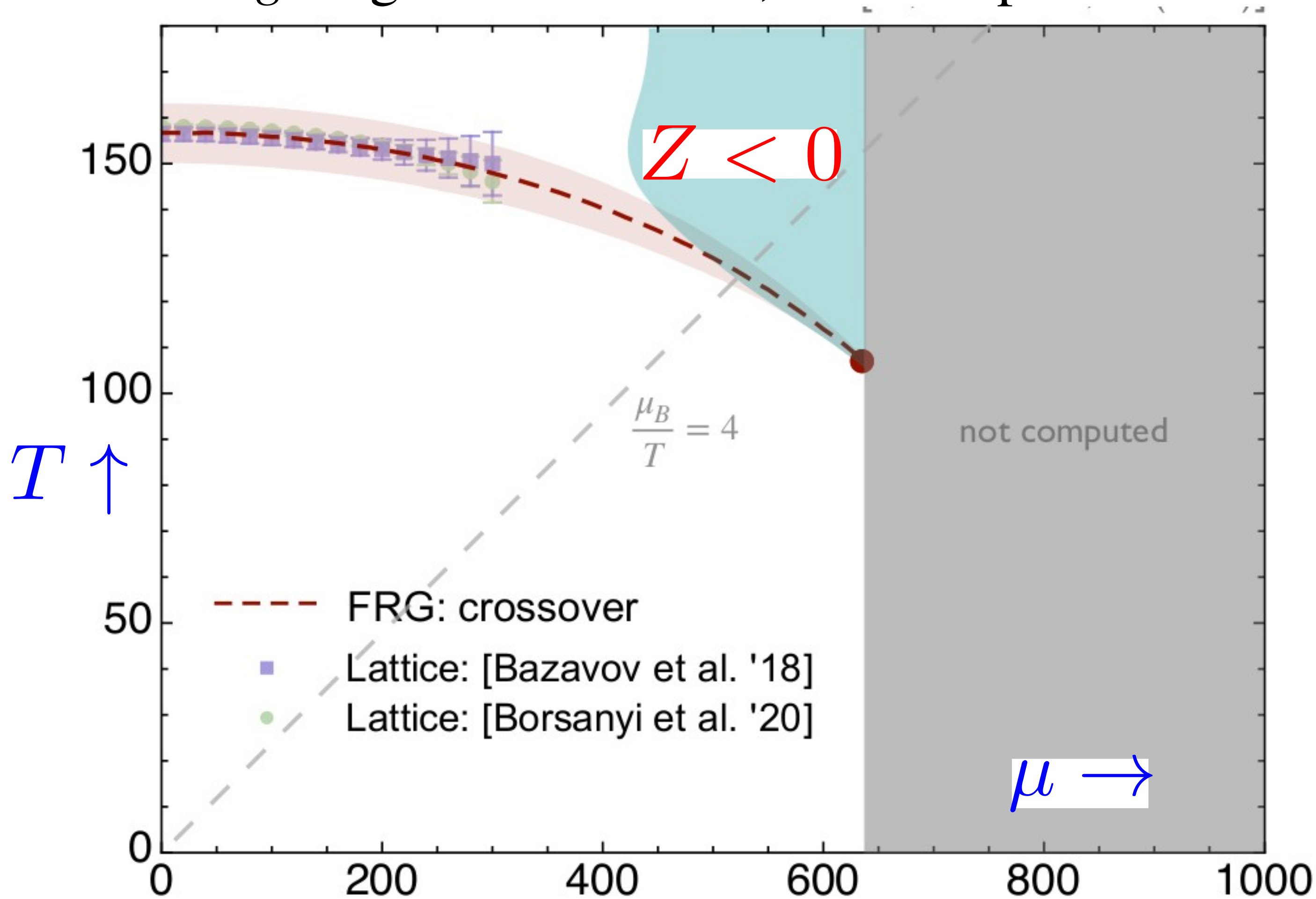


FRG phase diagram

Functional Renormalization Group phase diagram:
Fu, Pawlowski, Rennecke, 1909.02991

Basin of attraction to CEP is very small (sigma heavy at T = 0, massles @ CEP)

But appears to be *large* regime with Z < 0, “moat” spectrum

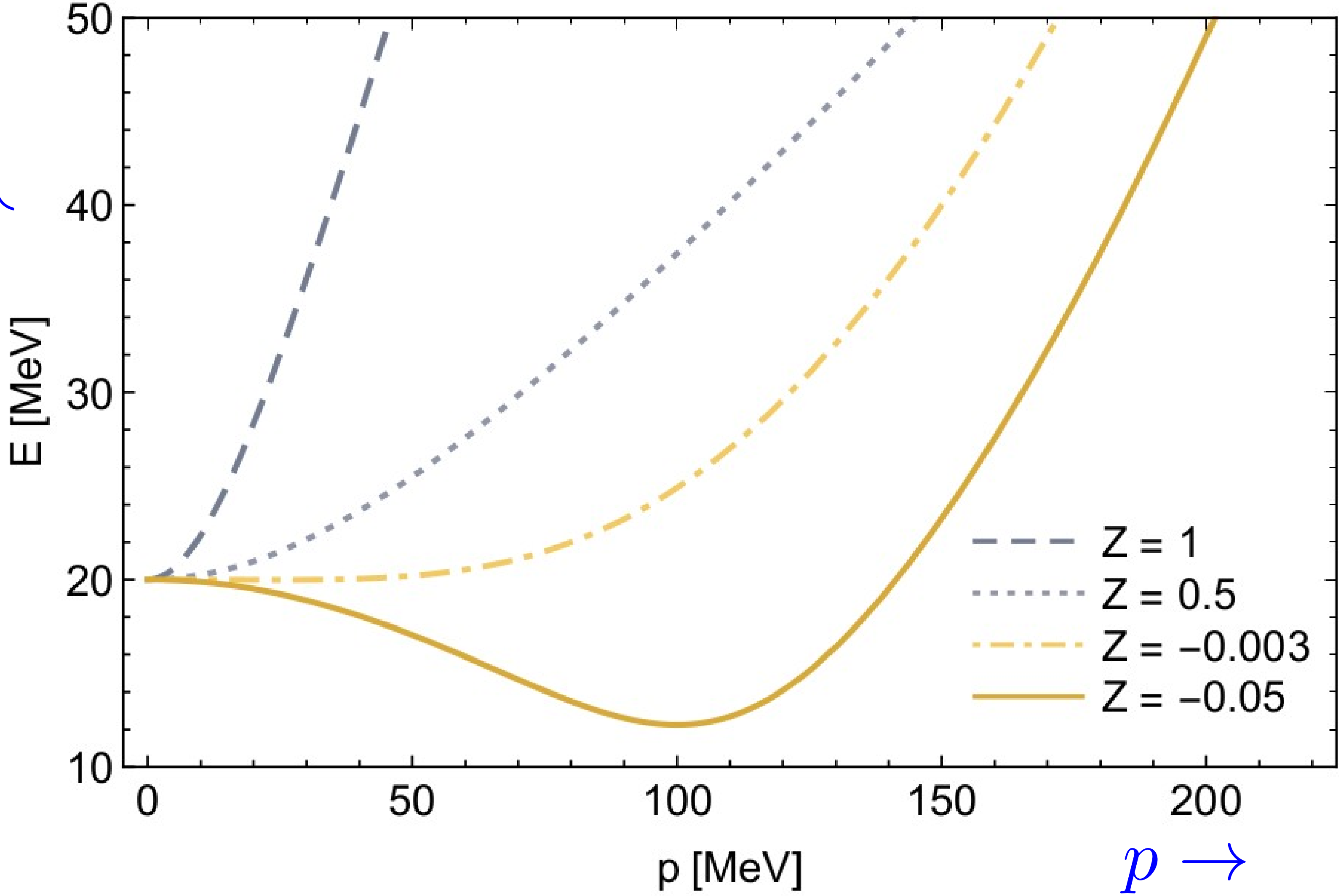


Moat spectra

With a moat spectrum, minimum of energy is at *non*zero momentum:

$$E_{\text{moat}}(p) = \sqrt{p^4/M^2 - Zp^2 + m_{\text{eff}}^2}$$

$E(p) \uparrow$

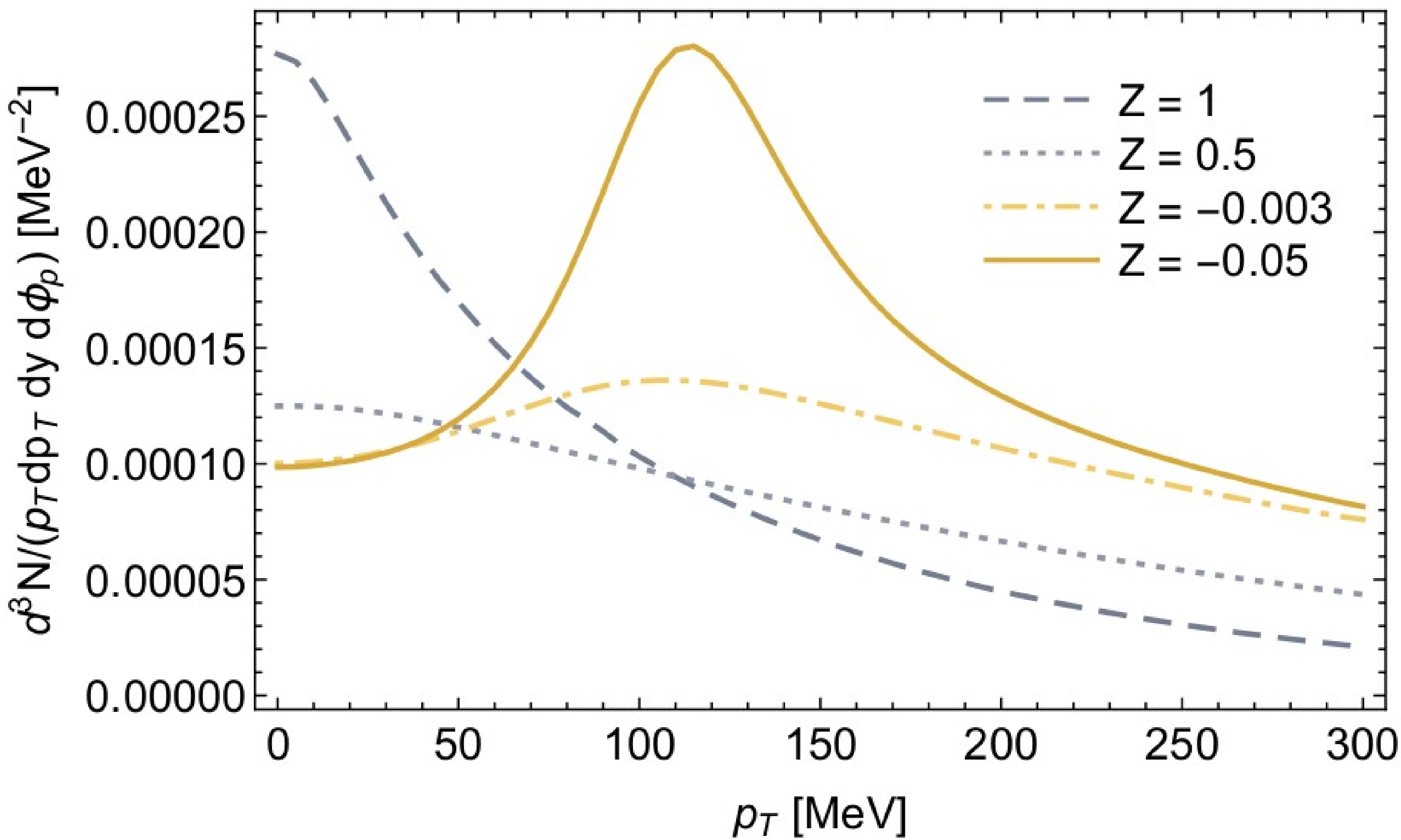


$p \rightarrow$

Moat spectra: non-thermal behavior

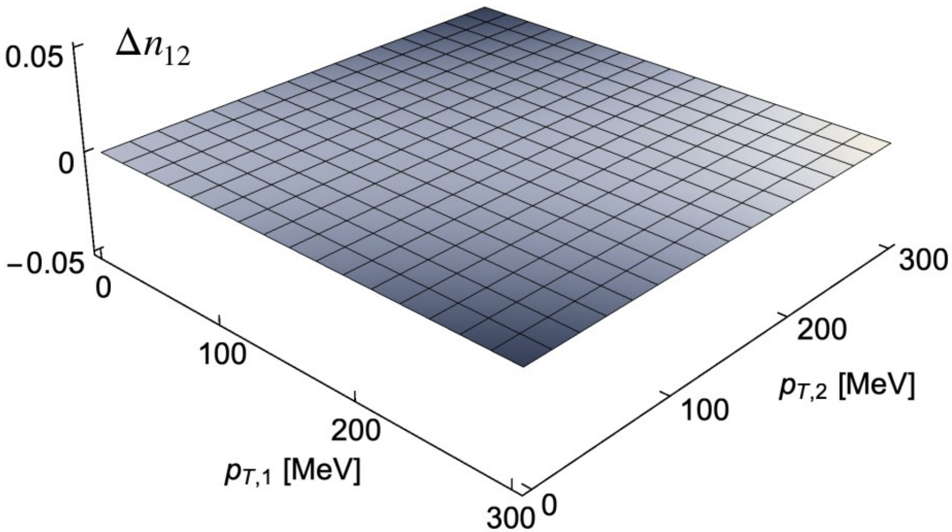
Because dispersion relation changed, even with Bose-Einstein statistics,
Single particle function will peak at *non*zero momentum:

$$n(E_{\mathrm{moat}}) = 1/(\exp(E_{\mathrm{moat}}(p)) - 1)$$



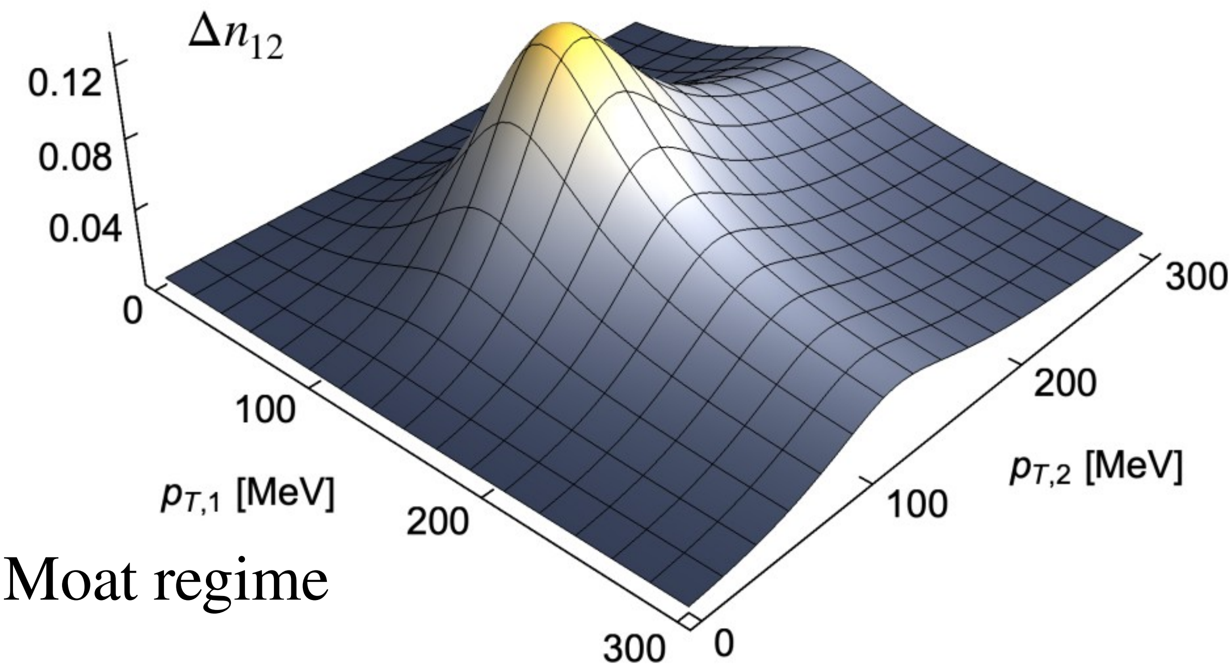
Moat spectra: two particle correlations

Besides single particle correlations, can also look at two particle correlations:
RDP & Rennecke, 2103.06890: enhancement by 10^2.



Normal regime

$$\left\langle \left(\frac{d^3N}{dp^3} \right)^2 \right\rangle \Big/ \left\langle \left(\frac{d^3N}{dp^3} \right) \right\rangle^2$$

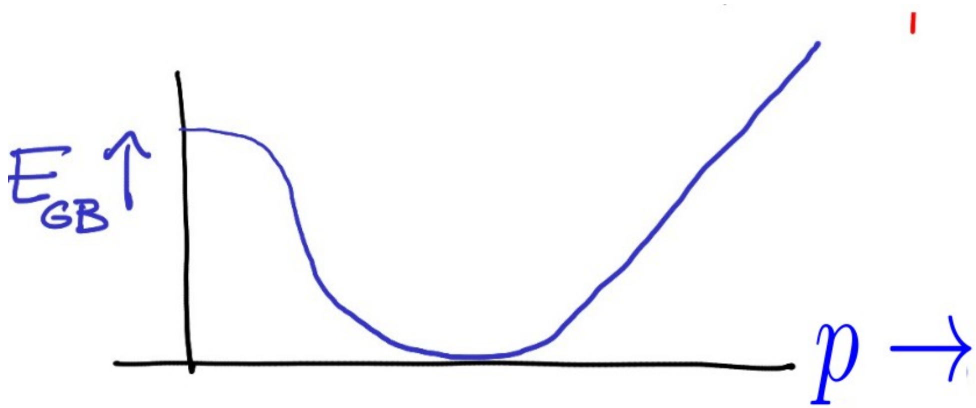


Moat regime

Chiral spirals and Quantum Pion Liquids

In condensed matter, usually Z < 0 for O(1), O(2).
Consider O(N), N > 2. RDP, Valgushev, Tsvelik, 2005.10259

Expect Goldstone bosons. Find that $E_{GB}=0$ at *non*zero momentum, not zero!



$$E_{GB} \sim (\vec{p}^2 - p_0^2)^2 \sim (p - p_0)^2$$

But then there are severe infrared divergences:

$$\delta m^2 \sim \int \frac{d^3p}{(p^2 - p_0^2)} \sim \int \frac{d\delta p}{(\delta p)^2}$$

Instead of a chiral spiral, the GB's disorder
The system. Can compute at large N, a mass gap for the GB's is generated *dynamically*. Type of "Quantum Pion Liquid"

Example in condensed matter?

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: $J_5^\mu = \mu_5 \vec{B}$

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

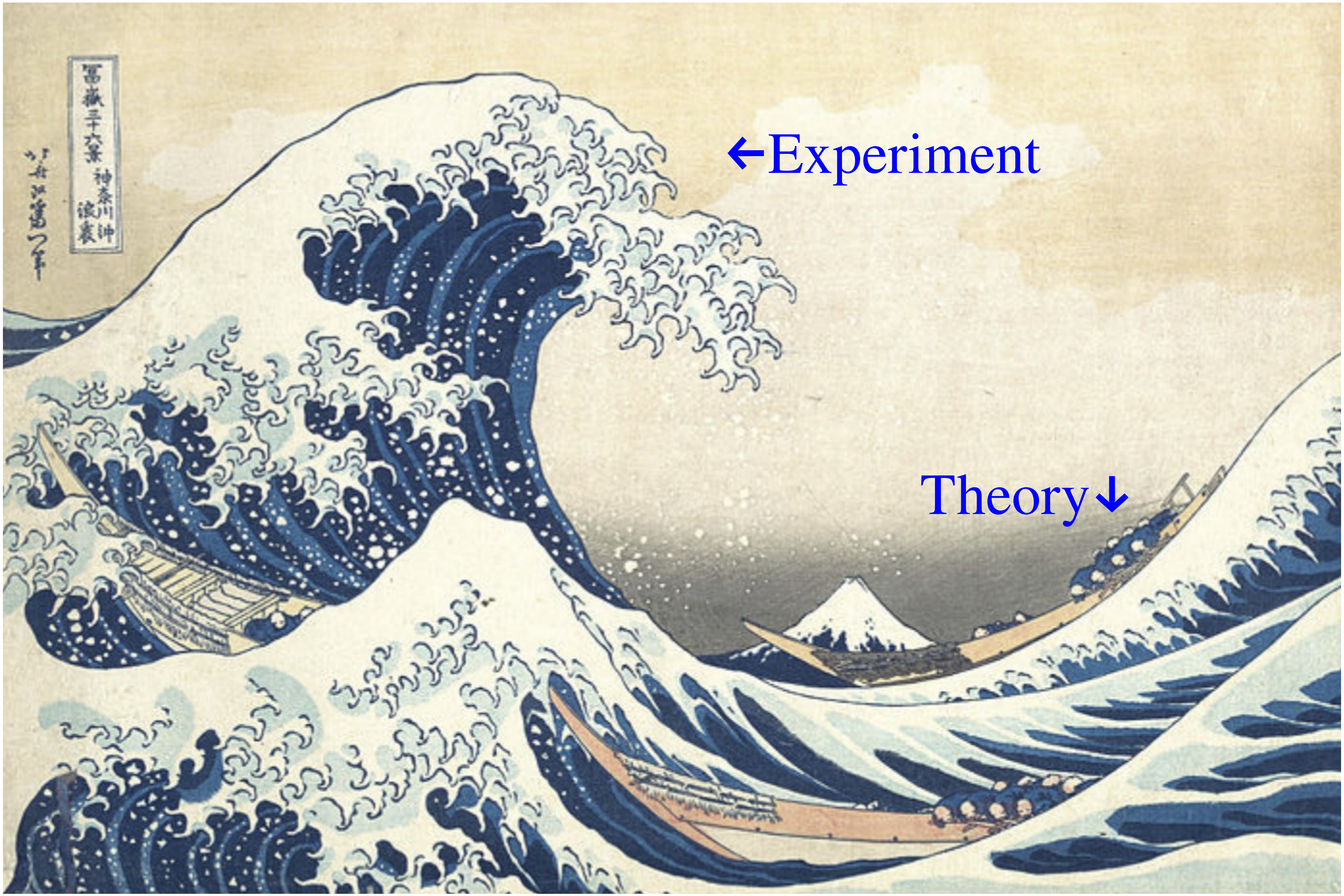
STAR: *no* CME, 2109.00131
Theory: *perhaps:* Kharzeev, Liao, Shi, 2205.00120

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