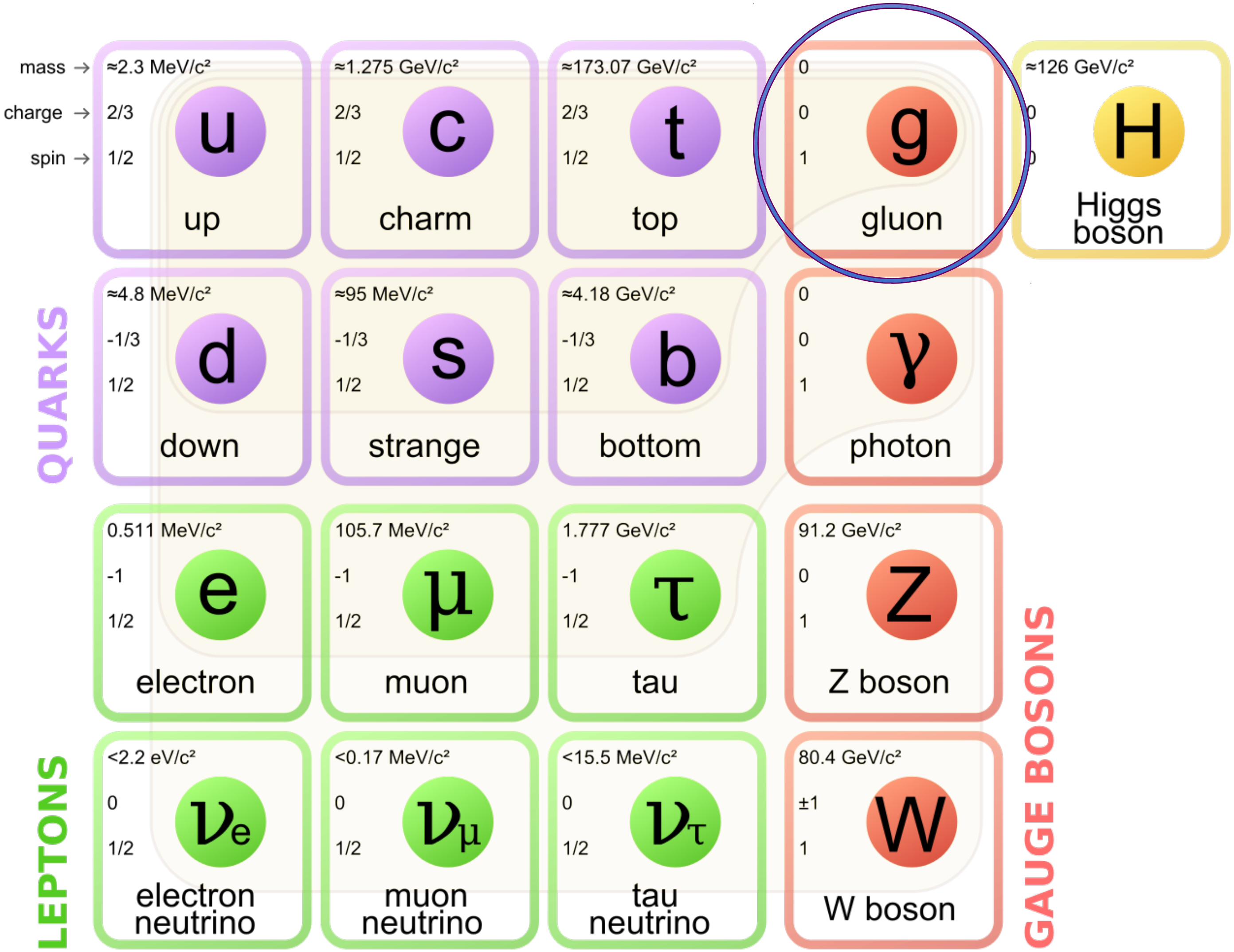
QCD as a many-body theory: an existential tale in four acts

Raju Venugopalan

Brookhaven National Laboratory

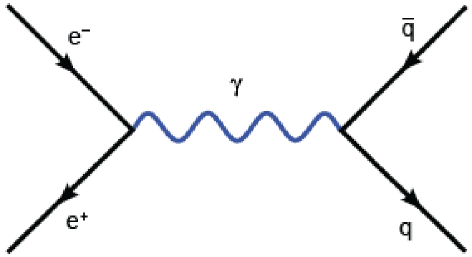
Student lecture, July 16, 2019

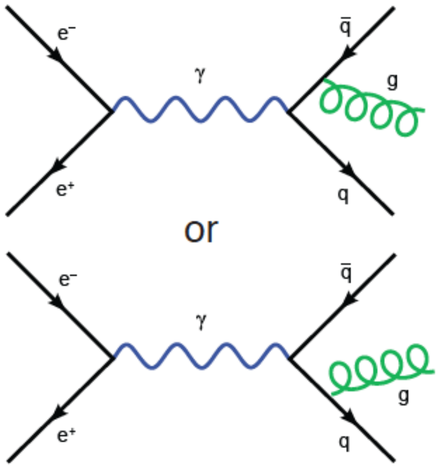
Act 1: The mysterious gluon

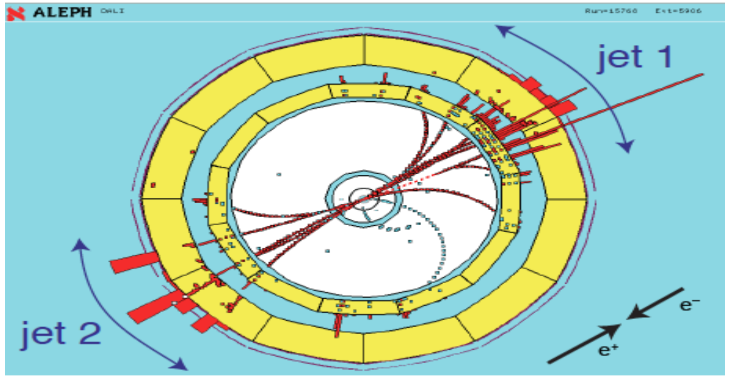


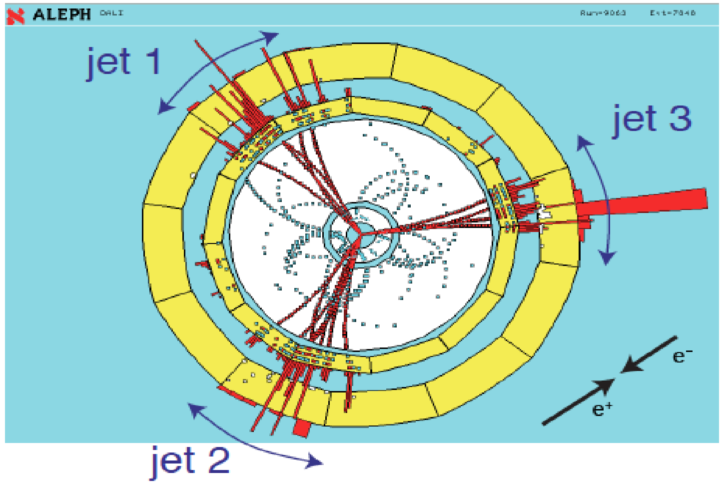
Gluons, the force carriers of the strong force,
are a fundamental building block of the standard model

Discovery of the gluon





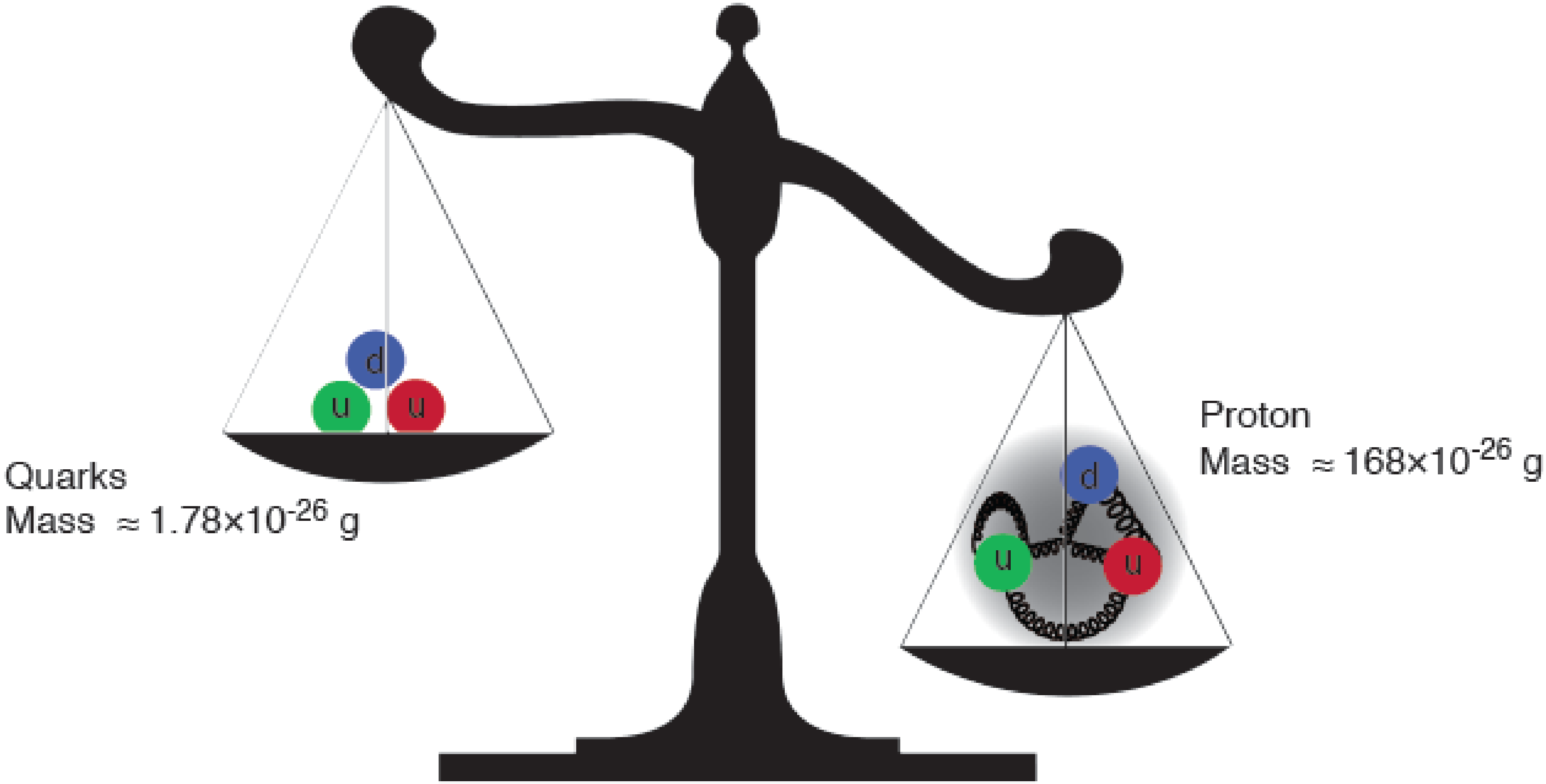




EVIDENCE FOR A SPIN-1 GLUON IN THREE-JET EVENTS

High-energy e^+e^--annihilation events obtained in the TASSO detector at PETRA have been used to determine the spin of the gluon in the reaction $e^+e^- \to q\bar{q}g$. We analysed angular correlations between the three jet axes. While vector gluons are consistent with the data (55% confidence limit), scalar gluons are disfavoured by 3.8 standard deviations, corresponding to a confidence level of about 10^{-4}. Our conclusion is free of possible biases due to uncertainties in the fragmentation process or in determining the $q\bar{q}g$ kinematics from the observed hadrons.

Physics Letters B, 15 December 1980

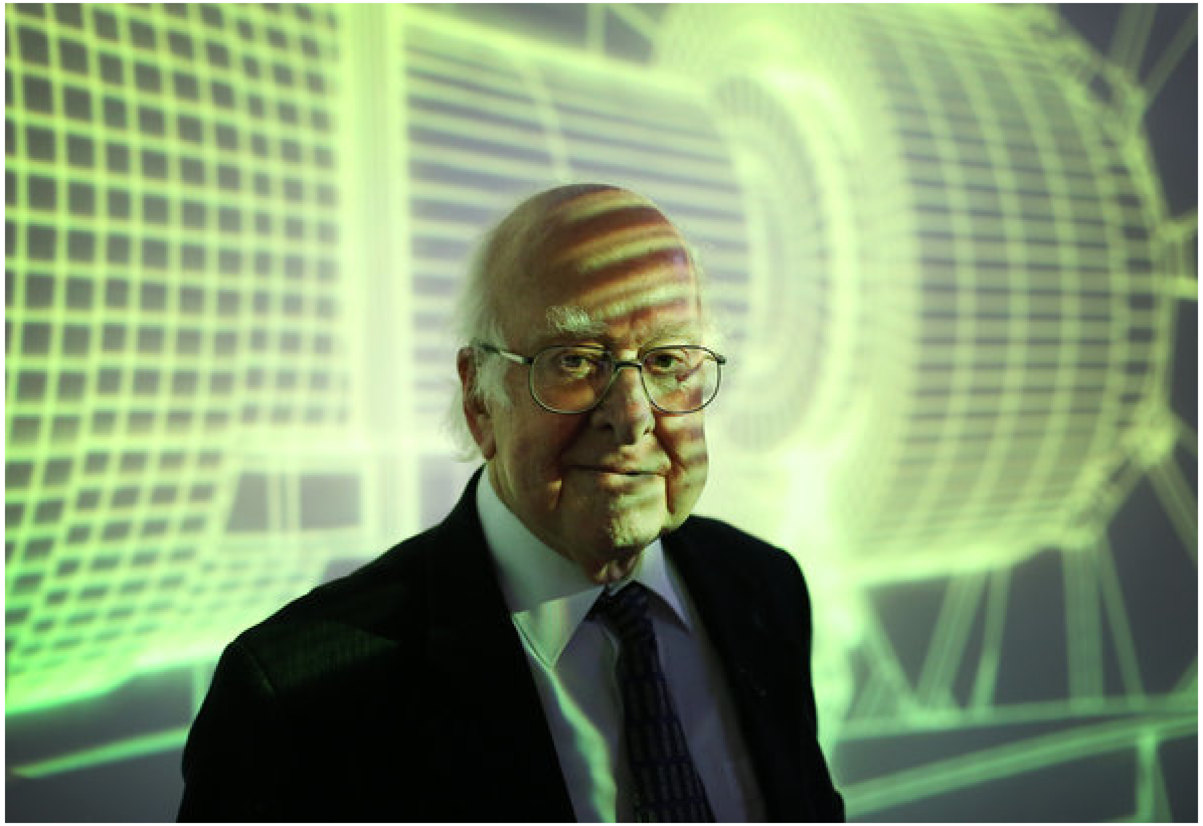


Gluons are massless…yet their dynamics is responsible for (nearly all) the mass of visible matter

The Higgs "God particle" is responsible for quark masses ~ 1-2% of the proton mass.


SAY "GOD PARTICLE"
AGAIN!!!
memegenerator.net

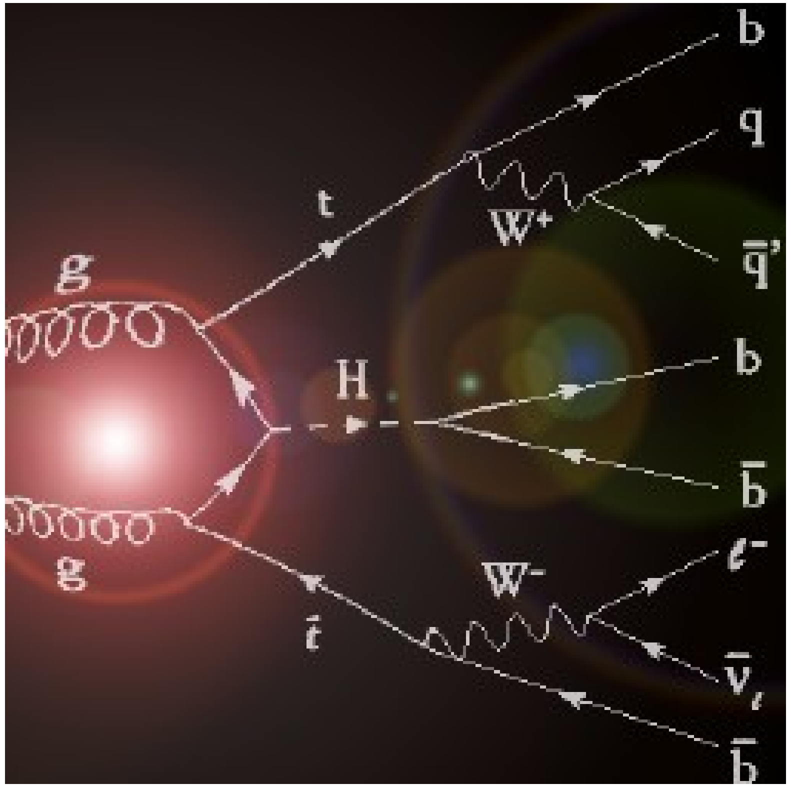
Higgs and the strong force



When he invented his boson in 1964, he said, "I wasn't sure it would be important."
He explained, "At the time the thought was to solve the strong force."

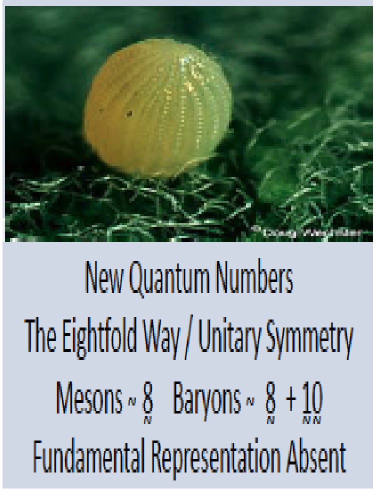
NY Times, Sept. 15, 2014

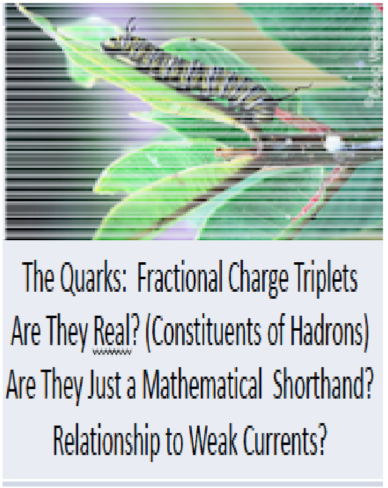
Higgs from Gluon fusion

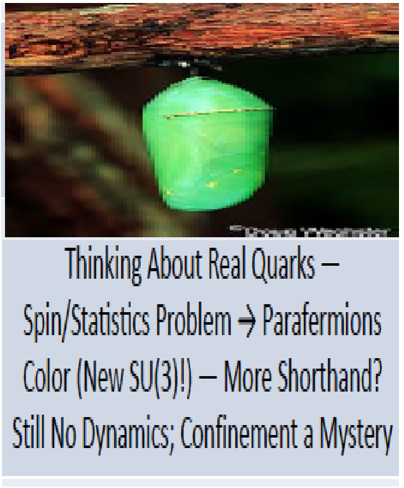


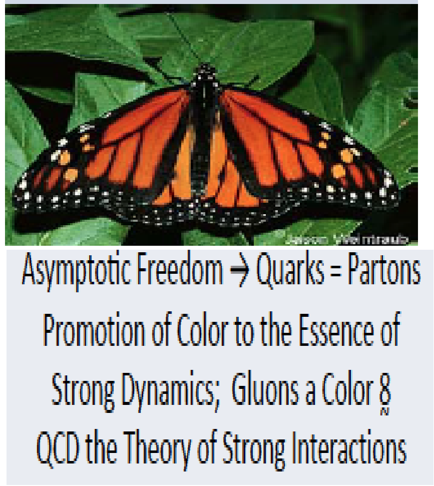
Quantum Chromodynamics

First QCD paper: Gell-Mann, Fritzsch, Leutwyler (1973)





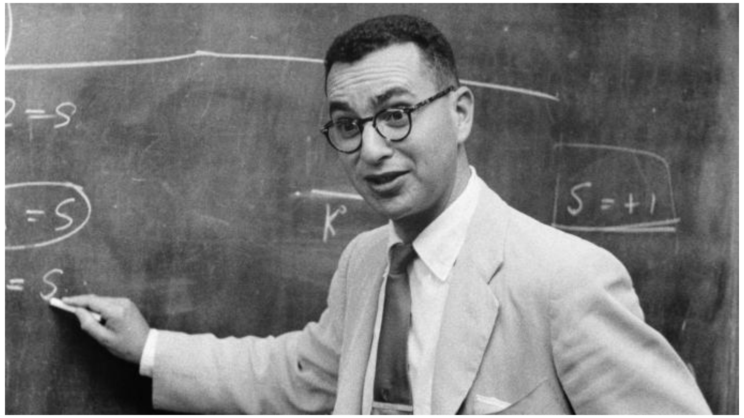




From Gell-Mann's 8-fold way to QCD: A lepidopteral metaphor

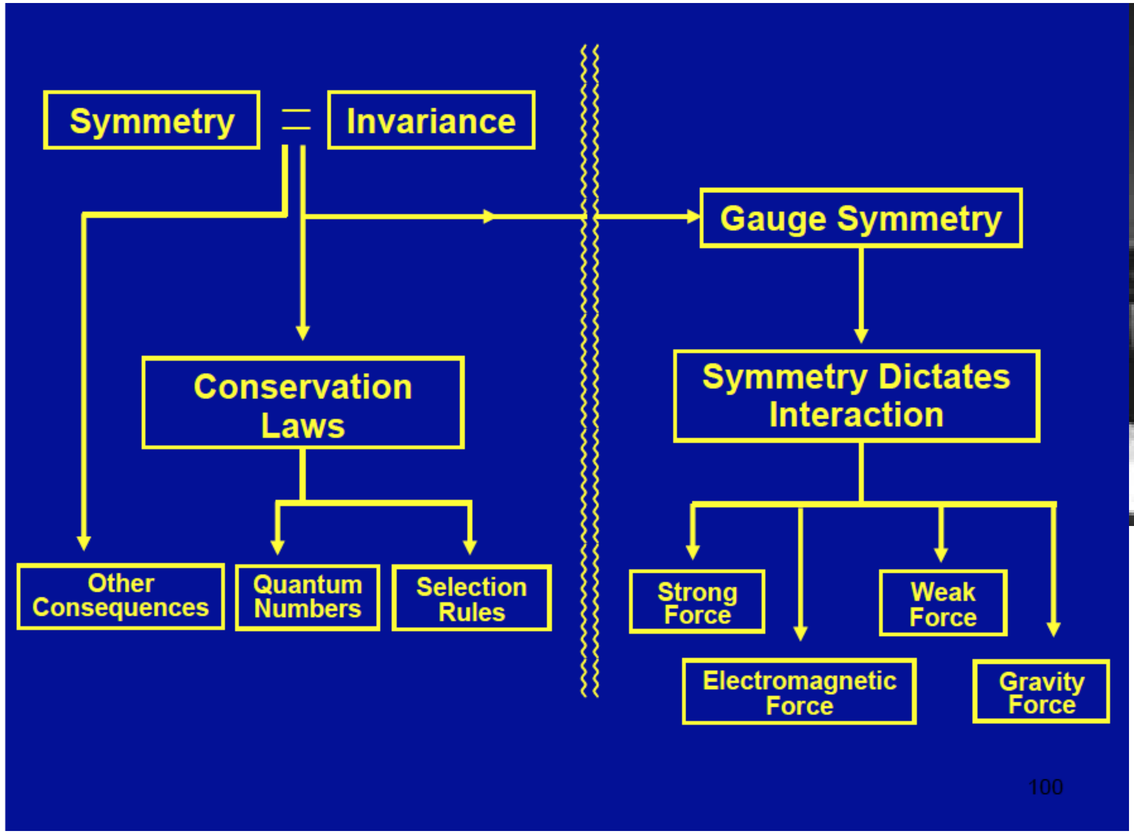
Jeffrey Mandula, Creutz-Fest 2014, BNL

N. P. Samios



M. Gell-Mann

Symmetries dictate interactions



C. N. Yang

Fundamental feature of QCD:
Yang-Mills Theory

PHYSICAL REVIEW VOLUME 96, NUMBER 1 OCTOBER 1, 1954

Conservation of Isotopic Spin and Isotopic Gauge Invariance*

C. N. YANG † AND R. L. MILLS
Brookhaven National Laboratory, Upton, New York

(Received June 28, 1954)

It is pointed out that the usual principle of invariance under isotopic spin rotation is not consistant with the concept of localized fields. The possibility is explored of having invariance under local isotopic spin rotations. This leads to formulating a principle of isotopic gauge invariance and the existence of a **b** field which has the same relation to the isotopic spin that the electromagnetic field has to the electric charge. The **b** field satisfies nonlinear differential equations. The quanta of the **b** field are particles with spin unity, isotopic spin unity, and electric charge $\pm e$ or zero.

Possibly the most important paper from BNL

From the Yang-Mills paper,

ISOTOPIC GAUGE TRANSFORMATION

Let ψ be a two-component wave function describing a field with isotopic spin $\frac{1}{2}$. Under an isotopic gauge transformation it transforms by

$$\psi = S\psi', \tag{1}$$

where S is a 2×2 unitary matrix with determinant unity. In accordance with the discussion in the previous section, we require, in analogy with the electromagnetic case, that all derivatives of ψ appear in the following combination:

$$(\partial_\mu - i\epsilon B_\mu)\psi.$$

B_μ are 2×2 matrices such that[7] for $\mu = 1, 2$, and 3, B_μ is Hermitian and B_4 is anti-Hermitian. Invariance requires that

$$S(\partial_\mu - i\epsilon B_\mu')\psi' = (\partial_\mu - i\epsilon B_\mu)\psi. \tag{2}$$

Combining (1) and (2), we obtain the isotopic gauge transformation on B_μ:

$$B_\mu' = S^{-1}B_\mu S + \frac{i}{\epsilon} S^{-1}\frac{\partial S}{\partial x_\mu}. \tag{3}$$

The last term is similar to the gradiant term in the gauge transformation of electromagnetic potentials. In analogy to the procedure of obtaining gauge invariant field strengths in the electromagnetic case, we

define now

$$\boxed{F_{\mu\nu} = \frac{\partial B_\mu}{\partial x_\nu} - \frac{\partial B_\nu}{\partial x_\mu} + i\epsilon(B_\mu B_\nu - B_\nu B_\mu).} \tag{4}$$

One easily shows from (3) that

$$F_{\mu\nu}' = S^{-1}F_{\mu\nu}S \tag{5}$$

we shall use the following total Lagrangian density:

$$\mathfrak{L} = -\tfrac{1}{4}\mathbf{f}_{\mu\nu}\cdot\mathbf{f}_{\mu\nu} - \bar{\psi}\gamma_\mu(\partial_\mu - i\epsilon\boldsymbol{\tau}\cdot\mathbf{b}_\mu)\psi - m\bar{\psi}\psi. \tag{11}$$

All the elements, except…color

SU(3) gauge symmetry

Y. Nambu

M.-Y. Han

PHYSICAL REVIEW VOLUME 139, NUMBER 4B 23 AUGUST 1965

Three-Triplet Model with Double $SU(3)$ Symmetry*

M. Y. HAN
Department of Physics, Syracuse University, Syracuse, New York

AND

Y. NAMBU
The Enrico Fermi Institute for Nuclear Studies, and the Department of Physics, The University of Chicago, Chicago, Illinois

(Received 12 April 1965)

With a view to avoiding some of the kinematical and dynamical difficulties involved in the single-triplet quark model, a model for the low-lying baryons and mesons based on three triplets with integral charges is proposed, somewhat similar to the two-triplet model introduced earlier by one of us (Y. N.). It is shown that in a $U(3)$ scheme of triplets with integral charges, one is naturally led to three triplets located symmetrically about the origin of I_3-Y diagram under the constraint that the Nishijima–Gell-Mann relation remains intact. A double $SU(3)$ symmetry scheme is proposed in which the large mass splittings between different representations are ascribed to one of the $SU(3)$, while the other $SU(3)$ is the usual one for the mass splittings within a representation of the first $SU(3)$.

Also, earlier work by O. Greenberg on the quark model

Quantum Chromodynamics (QCD)

- QCD - “nearly perfect” fundamental quantum theory of quark and gluon fields F.Wilczek, hep-ph/9907340

- Theory is rich in symmetries: “Symmetries dictate interactions” – C.N Yang

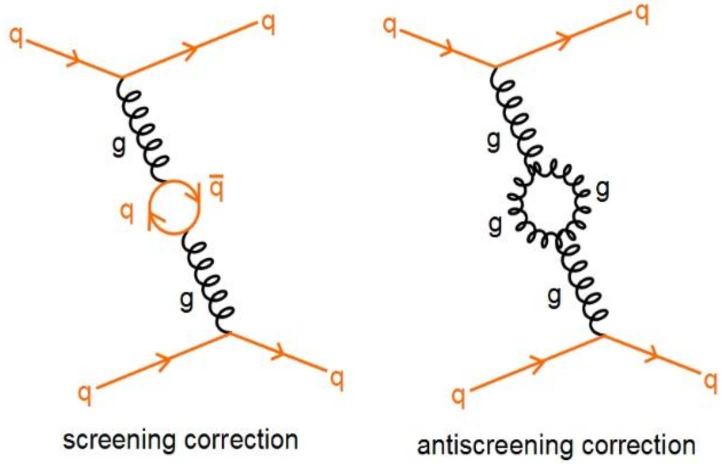
$$\underbrace{SU(3)_c}_{\text{i}} \times \underbrace{SU(3)_L \times SU(3)_R}_{\text{ii}} \times \underbrace{U(1)_A \times U(1)_B}_{\text{iii}}$$

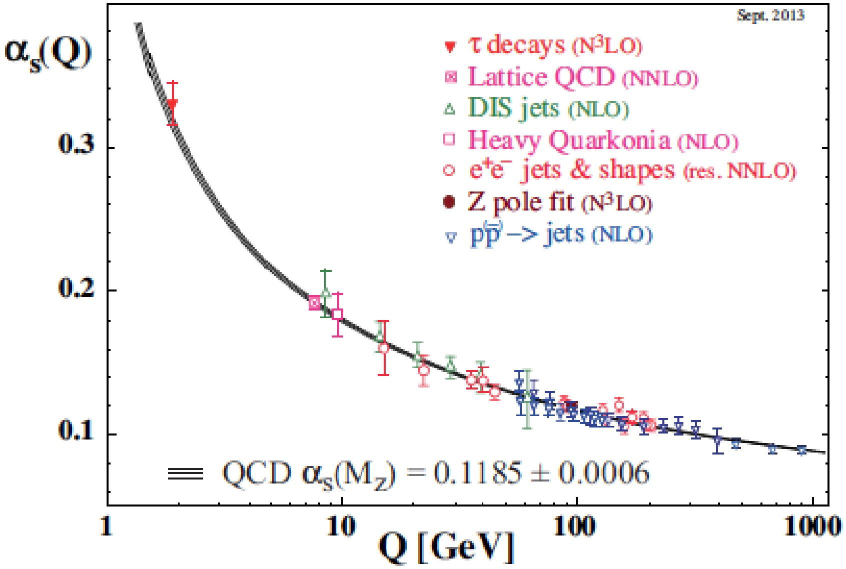
i) Gauge “color” symmetry: unbroken but confined
ii) Global “chiral” symmetry: exact for massless quarks
iii) Baryon number and axial charge (m=0) are conserved
iv) Scale invariance of quark (m=0) and gluon fields
v) Discrete C,P & T symmetries

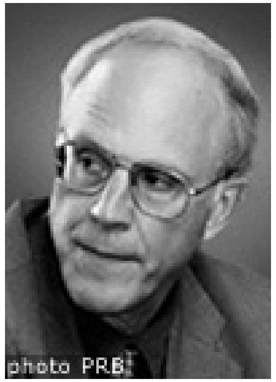
- Chiral, Axial, Scale and (in principle) P &T broken by vacuum/quantum effects - ”emergent” phenomena

- Inherent in QCD are the deepest aspects of relativistic Quantum Field Theories (confinement, asymptotic freedom, anomalies, spontaneous breaking of chiral symmetry)

Asymptotic freedom: the role of glue

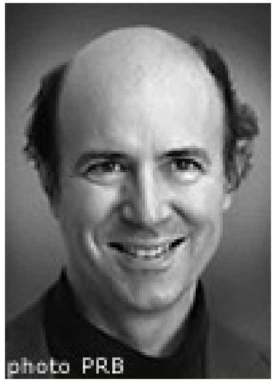






David Gross

David Politzer

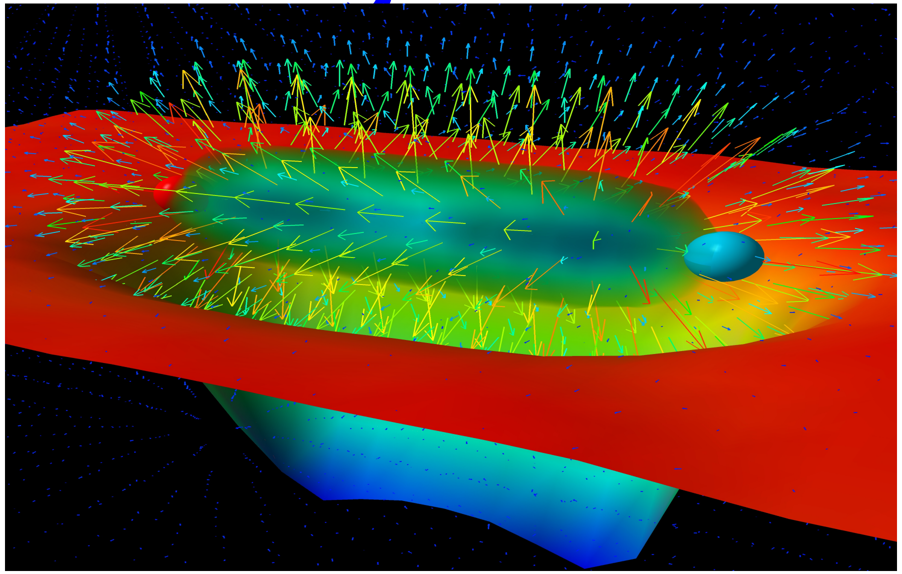


Frank Wilczek

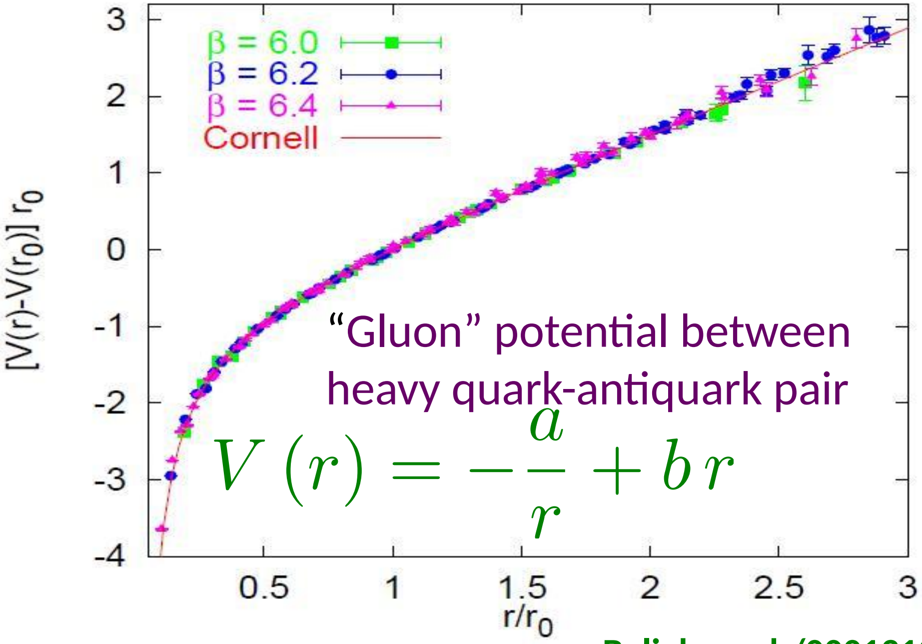
2004

The self-interaction (of color charged) gluons is fundamentally responsible for the asymptotic freedom of quarks and gluons in Quantum Chromodynamics (QCD)

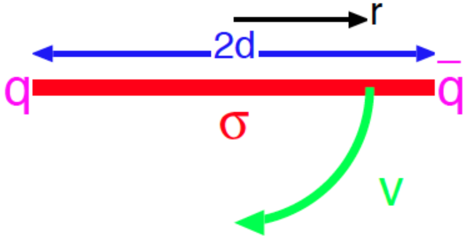
Quark (and Gluon) confinement: the role of glue ?



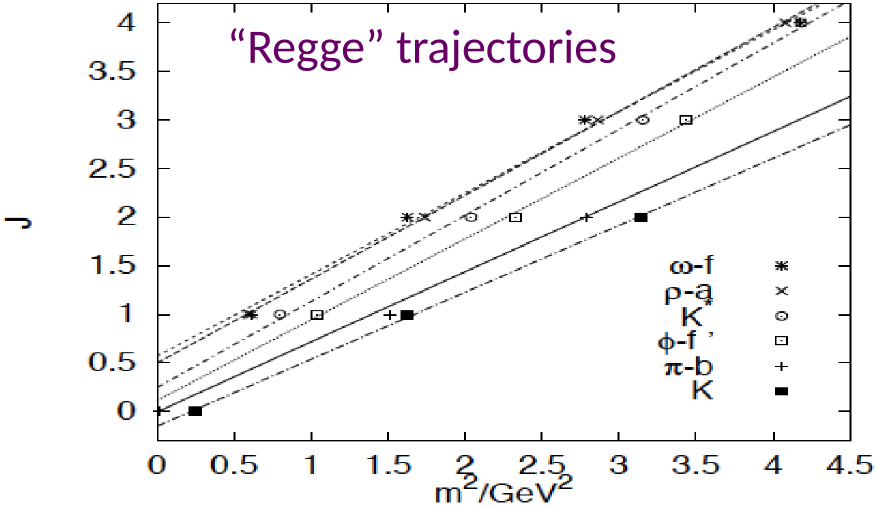
Quarks experience force of 16 tons at distances of ~ 1 Fermi (10^{-15} m)



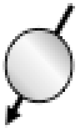
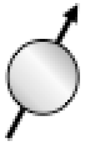
Bali, hep-ph/0001312



Intuitive picture of quark confinement and stringy pictures of mesons



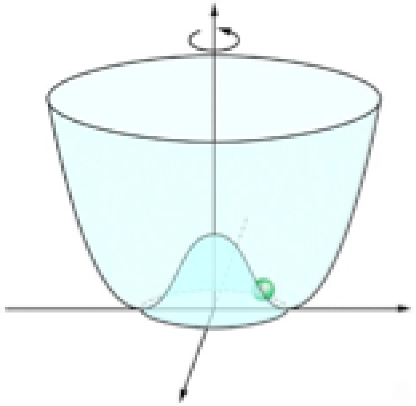
QCD: Chiral symmetry breaking

Chiral basis :  $q_L = \frac{1}{2}(1-\gamma_5)q, \quad q_R = \frac{1}{2}(1+\gamma_5)q$ 

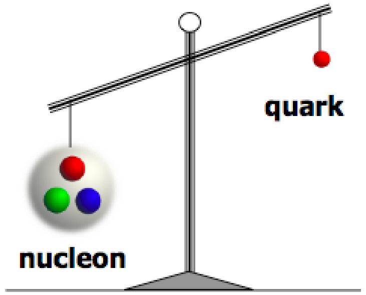
QCD Lagrangian : $\mathcal{L}_{cl} = \mathcal{L}_{cl}(q_L, A) + \mathcal{L}_{cl}(q_R, A)$

Quantum QCD vacuum:

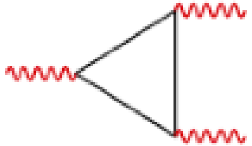
Chiral condensate: spontaneously generate mass via the Nambu-Goldstone mechanism



$$\langle \bar{q}_R q_L \rangle \neq 0$$



m_q ~ 10 MeV ; m_N ~ 1 GeV

Axial anomaly:  Quantum violation of $U(1)_A$ $\partial_\mu J^\mu_A = -2n_f \frac{\alpha_S}{8\pi} F^{\mu\nu,a} \tilde{F}^a_{\mu\nu}$

The essential mystery

- (Nearly) all visible matter is made up of quarks and gluons

- But quarks and gluons are not visible

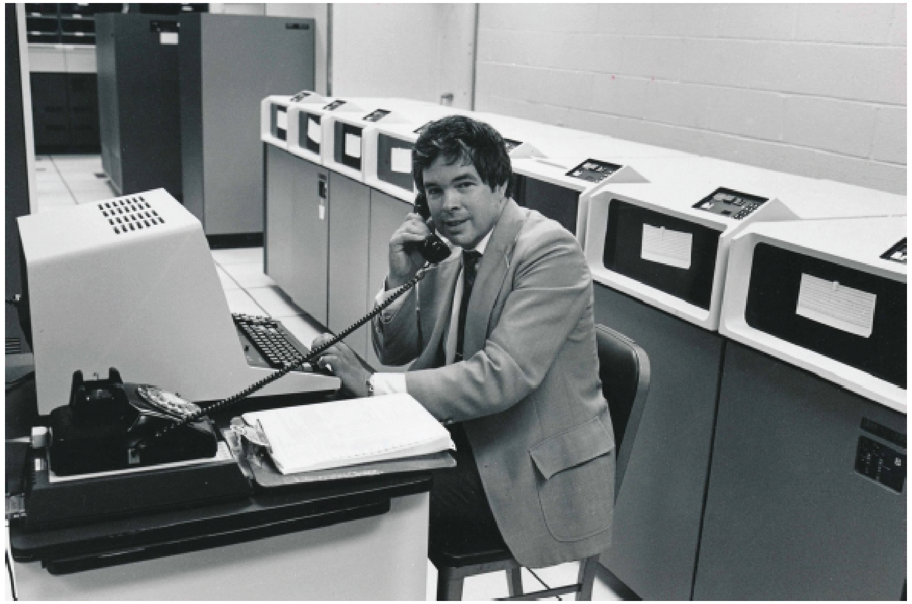
- All strongly interacting matter is an emergent consequence of
  many-body quark-gluon dynamics.
  Example: Mass from massless gluons and (nearly) massless quarks

- There is an elegance and simplicity to nature’s strongest force we do not understand

- Understanding the origins of matter demands we
  develop a *deep and varied knowledge* of this emergent dynamics

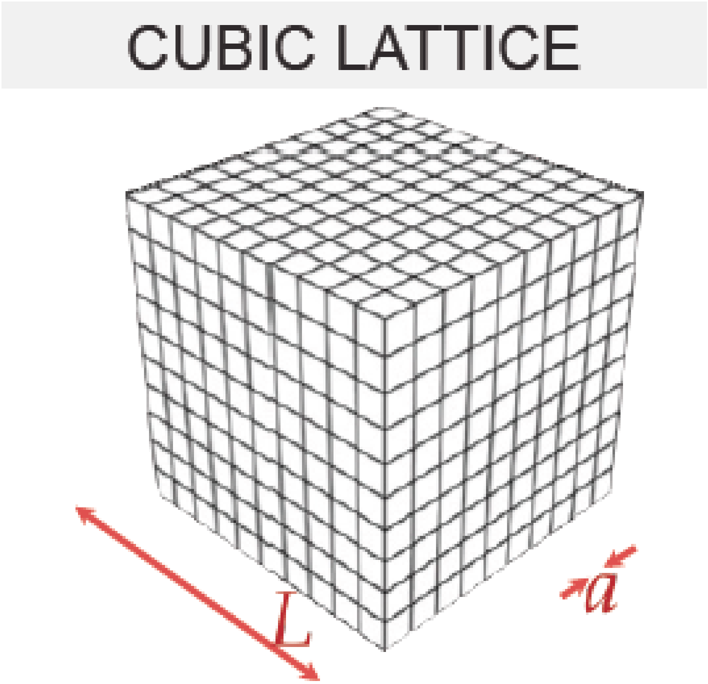
Act 2. QCD: The Power and the Glory

Numerical realization: Lattice QCD



Kenneth G. Wilson

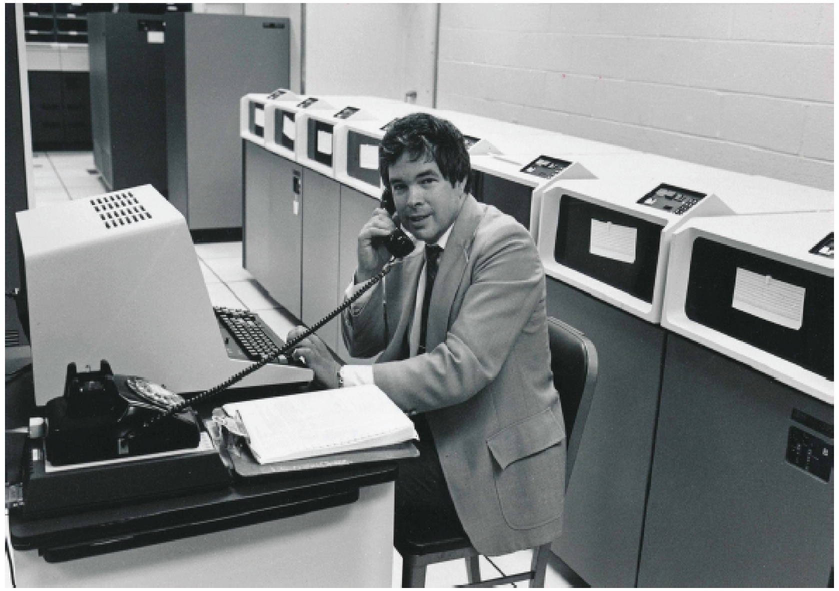
(1982)



Lattice regularization (UV&IR) of QCD

First principles treatment of static properties of QCD: masses, moments, thermodynamics at finite T (& μ_B ?)

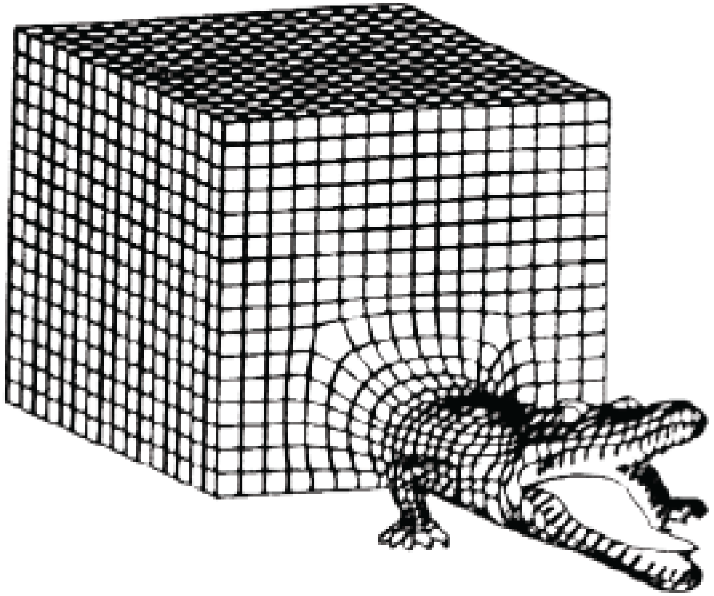
Numerical realization: Lattice QCD



Kenneth G. Wilson

(1982)

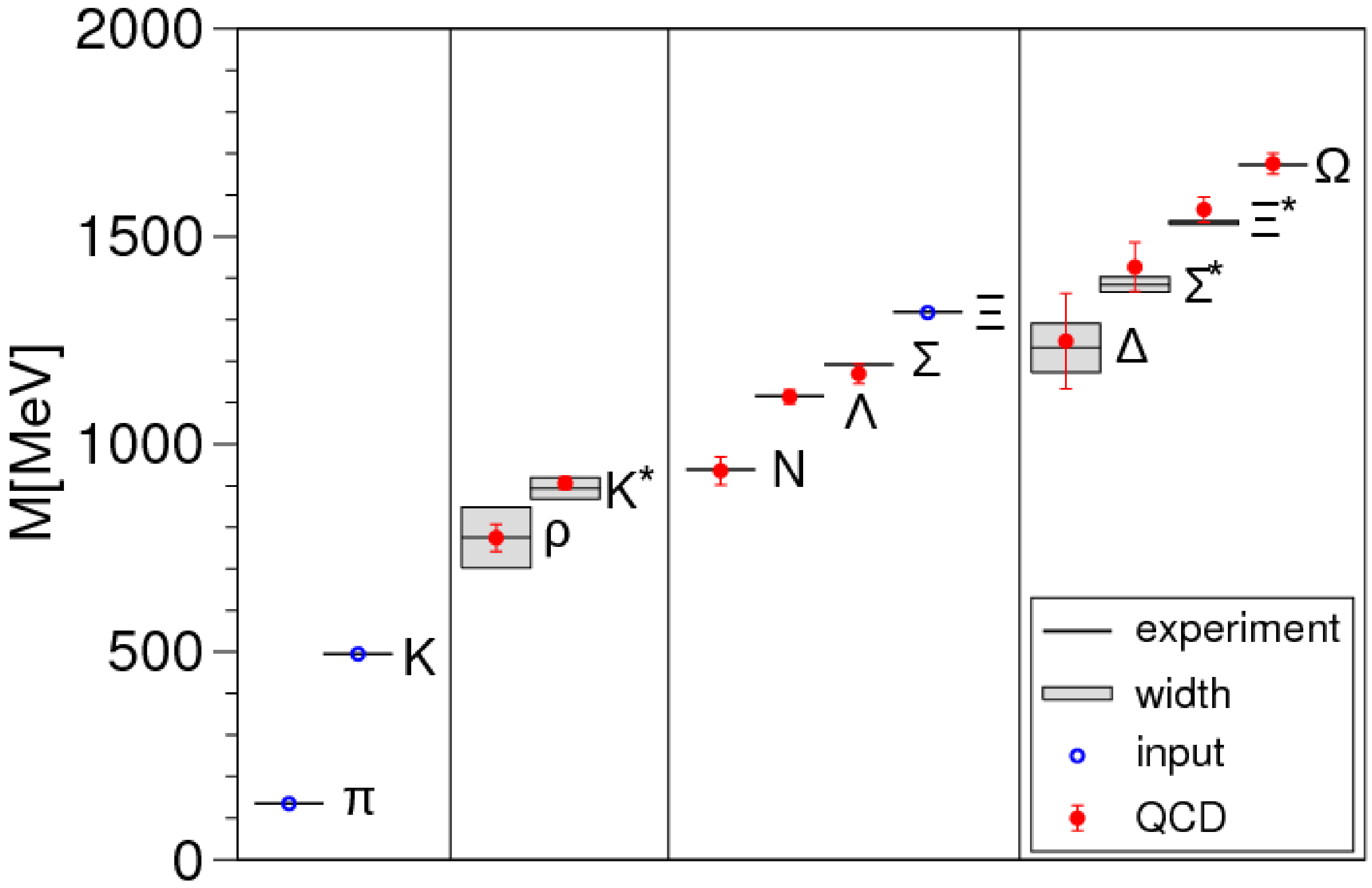
CUBIC LATTICE



Formidable computational problem

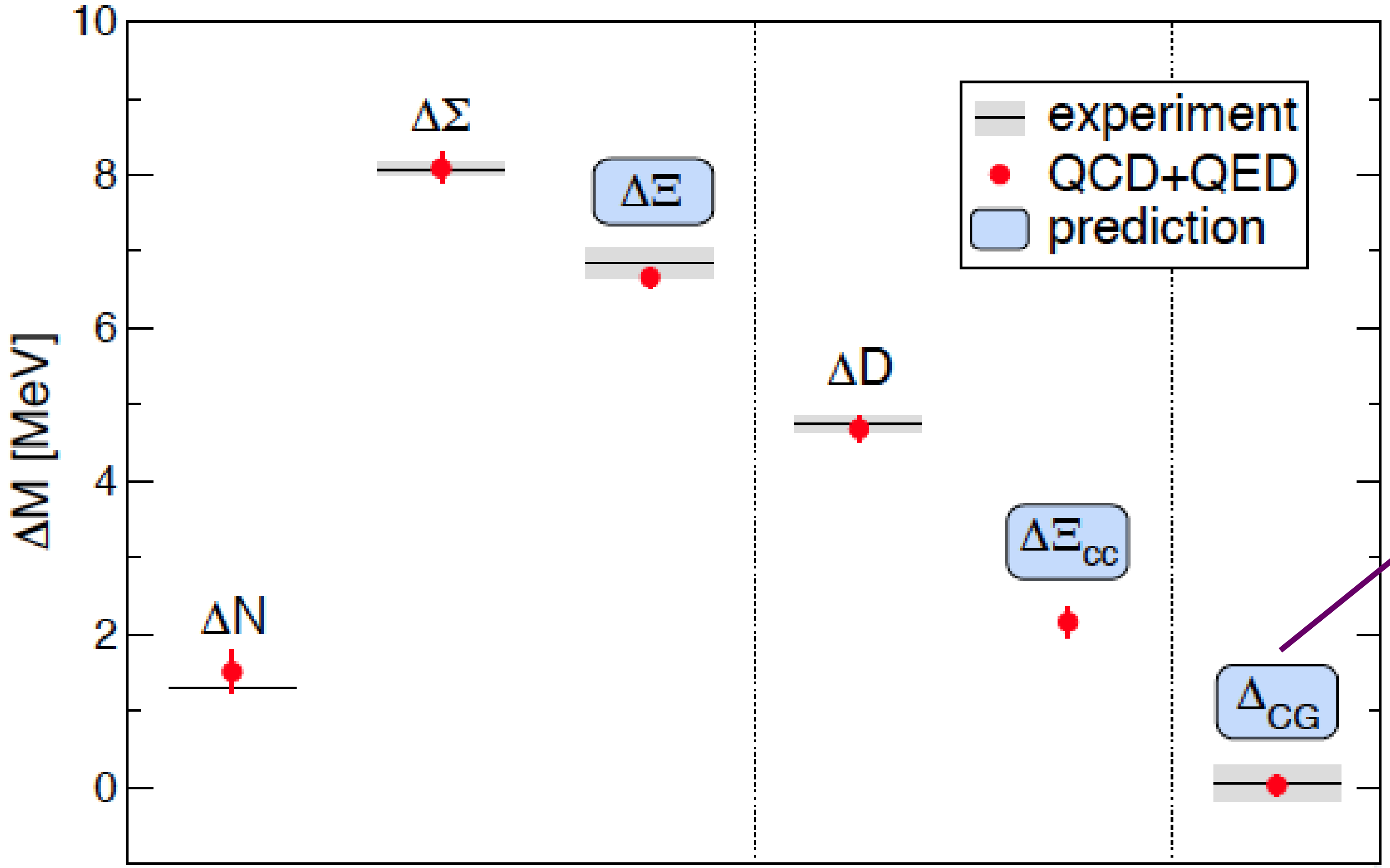
Very challenging for *dynamical processes*...

Precision QCD on the lattice



Durr et al., Science, 322 (2008)

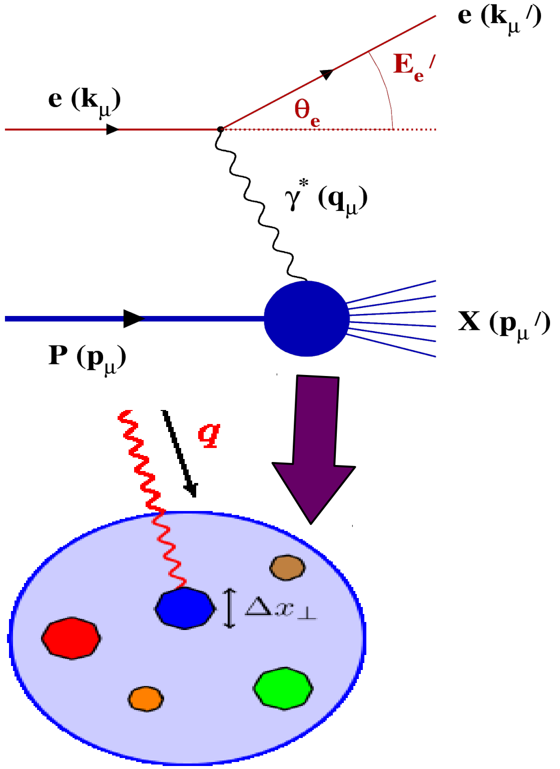
Precision QCD+QED on the lattice



Coleman-Glashow relation among mass splittings

Budapest-Marseille-Wuppertal (BMW) Coll., arXiv:1406.4088

The deeply inelastic scattering (DIS) femtoscope



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 4E_e E'_e \sin^2\left(\frac{\theta'_e}{2}\right)$$

Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Bjorken variable: Measure of momentum fraction of struck quark

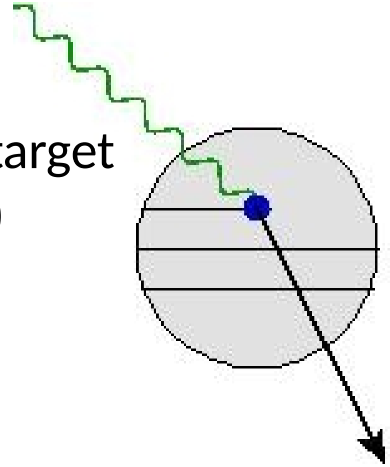
$$\frac{d^2\sigma^{eh\to eX}}{dx dQ^2} = \frac{4\pi\alpha_{em}^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

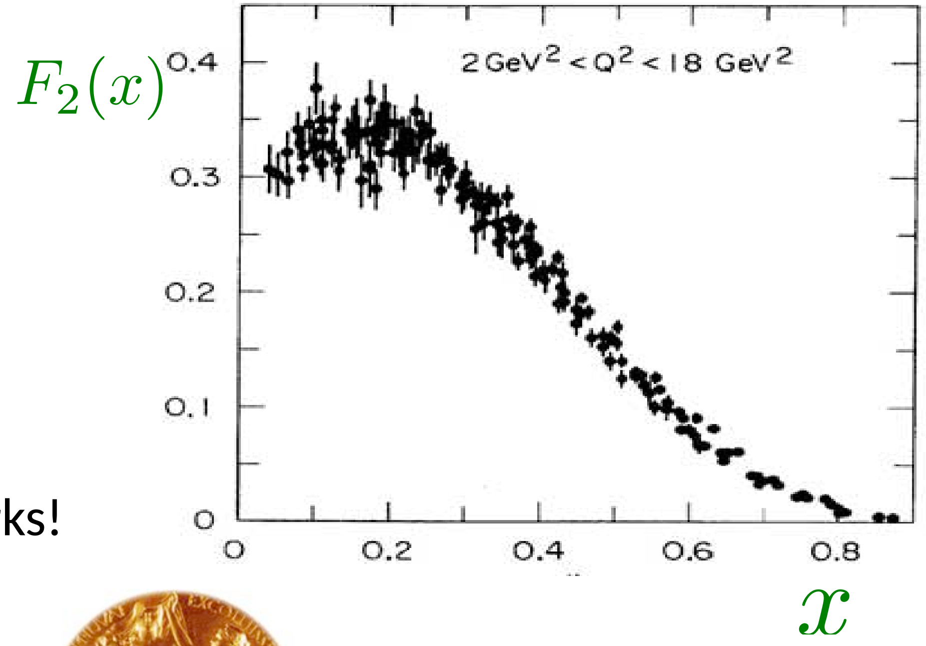
quark+anti-quark momentum distributions

gluon momentum distribution

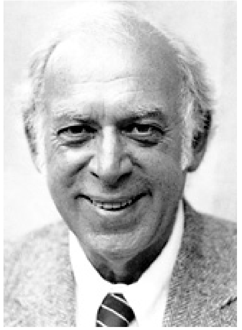
The deeply inelastic scattering (DIS) femtoscope

From SLAC fixed target DIS… (**late 1960s**)

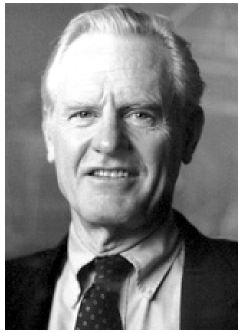




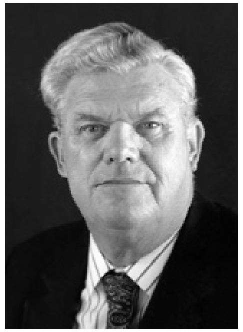
Discovery of quasi-free point-like quarks!



Friedman



Kendall

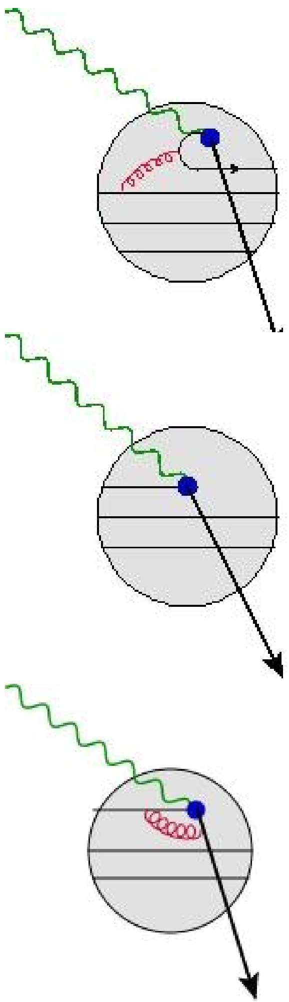


Taylor

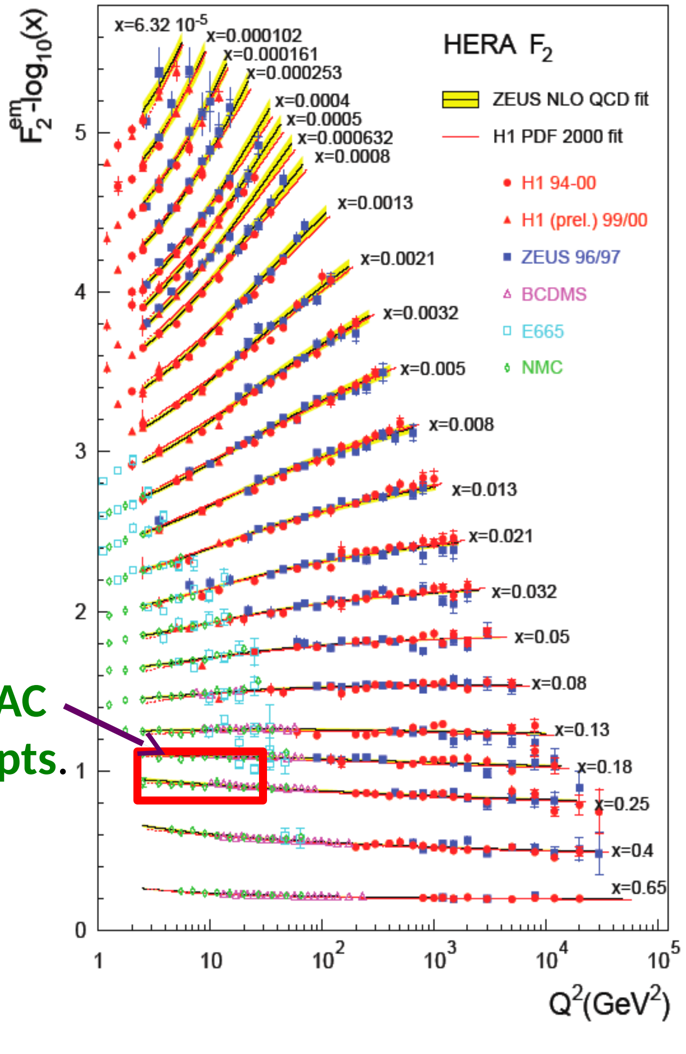
(**1990**)

The deeply inelastic scattering (DIS) femtoscope

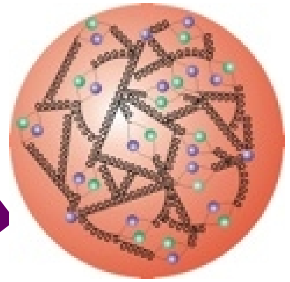
…to the HERA DIS collider (1990s)

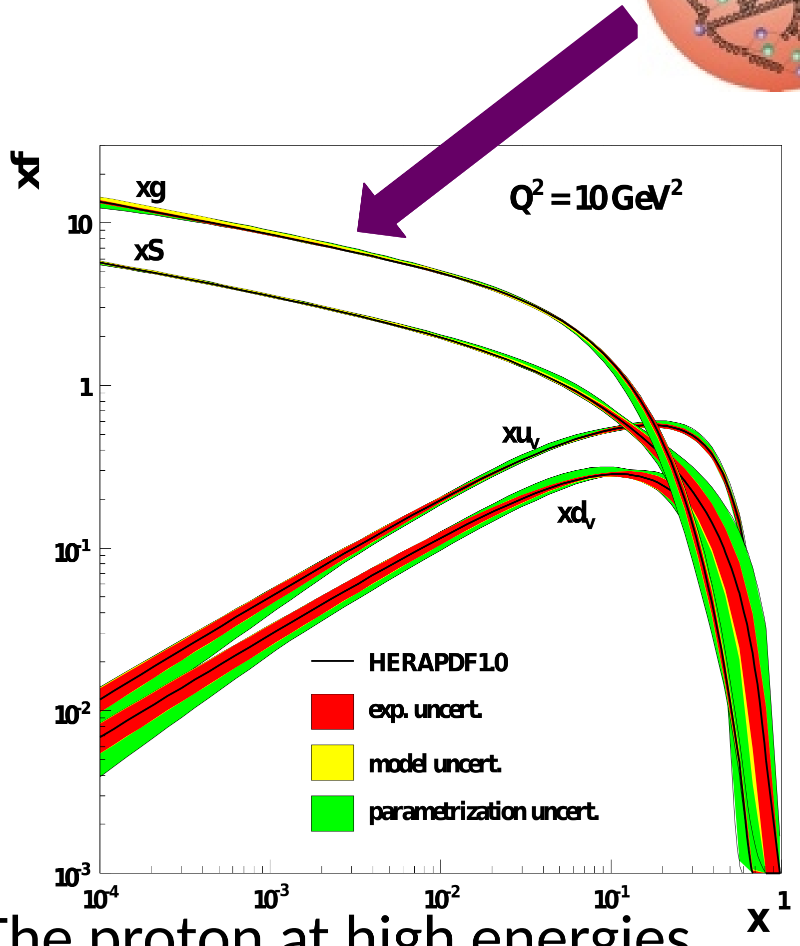


SLAC
expts.



Gluons and "sea" quarks

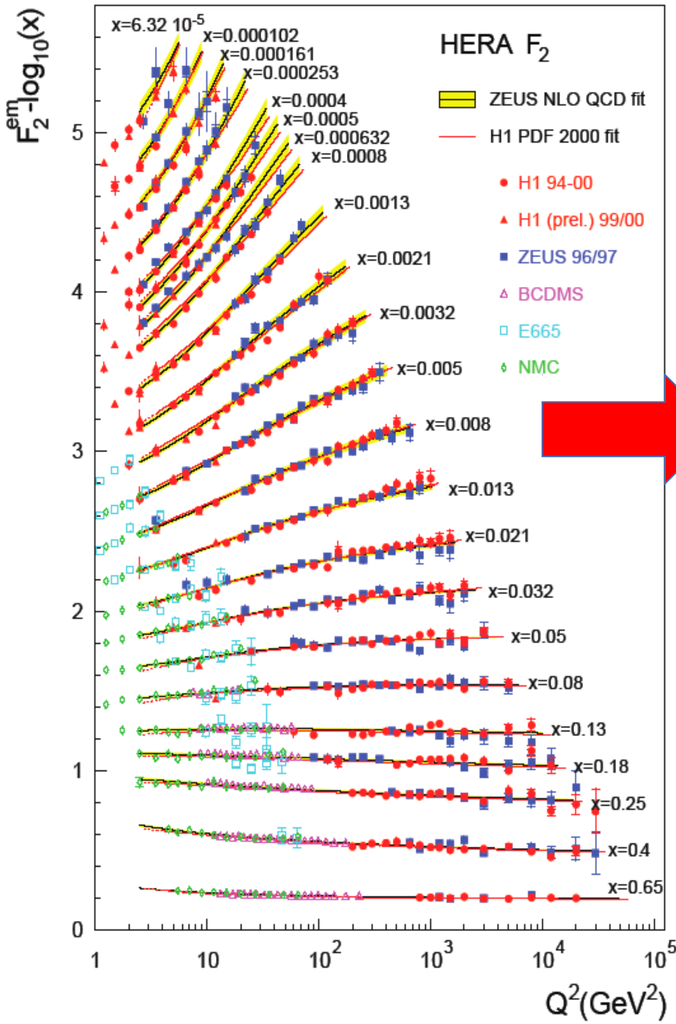




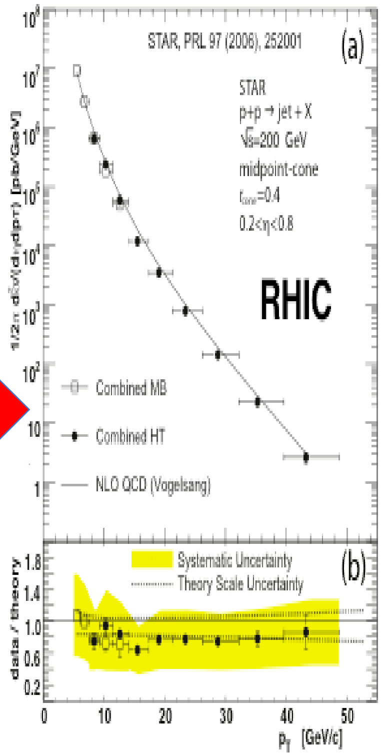
The proton at high energies
(small x) is dominated by glue!

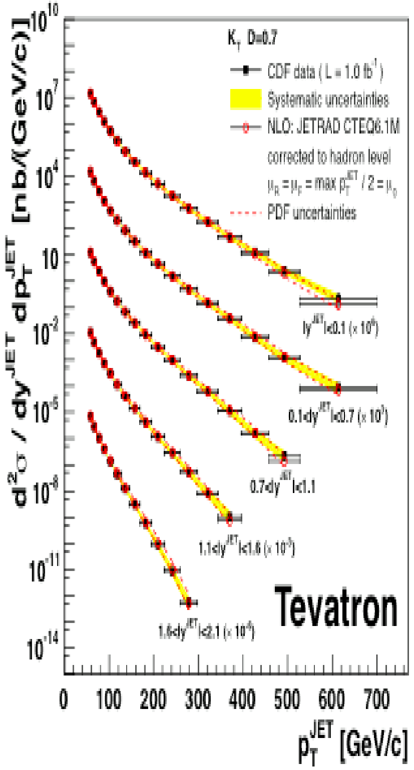
Perturbative QCD: now benchmark for new physics

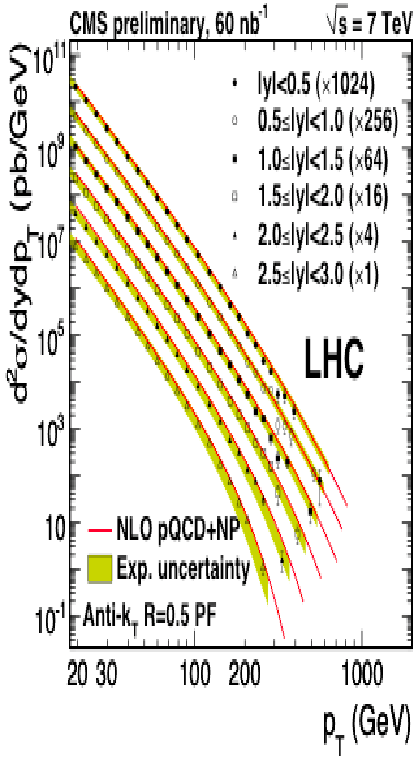
Structure functions measured at HERA electron-proton collider



Jet cross-sections: proton-proton collisions (RHIC &LHC) and proton-antiproton collisions at Fermilab

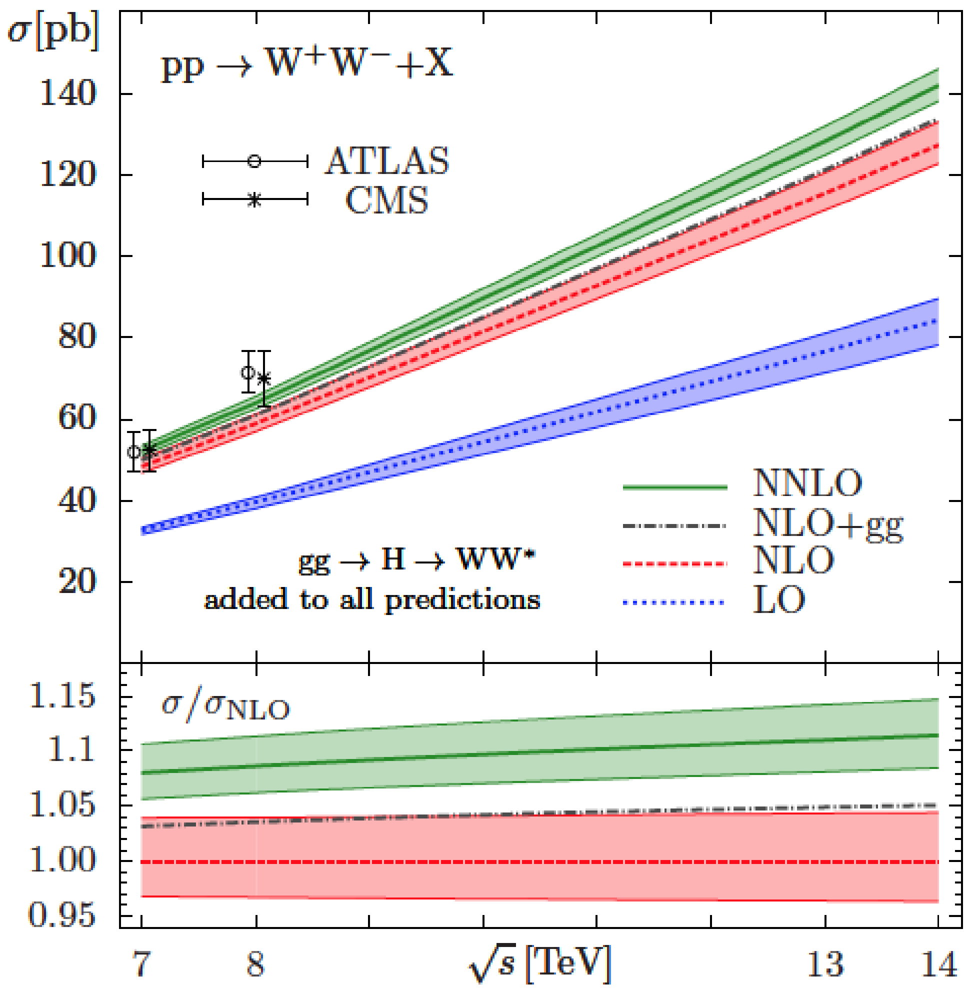






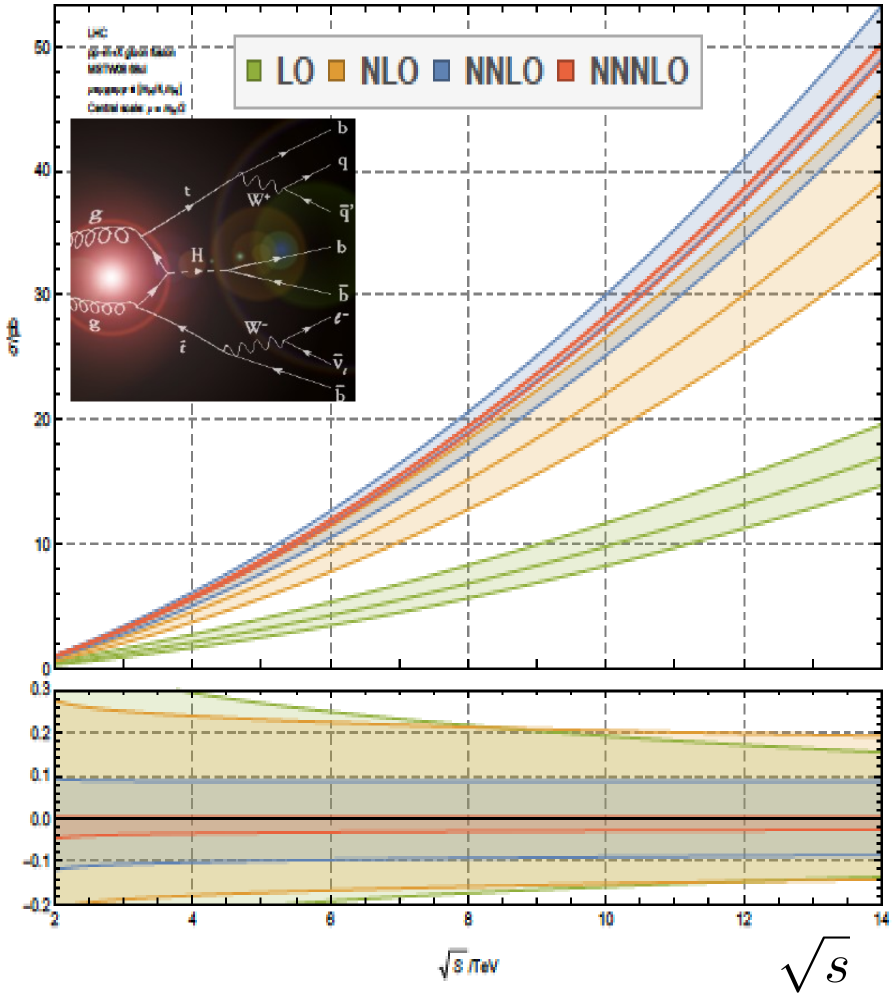
At large momenta, the weak QCD coupling (asymptotic freedom!) enables systematic computations

Perturbative QCD: benchmark for new physics



Gehrmann et al., arXiv:1408.5243

Gluon fusion to Higgs cross-section



Anastasiou et al., arXiv:1503.06056

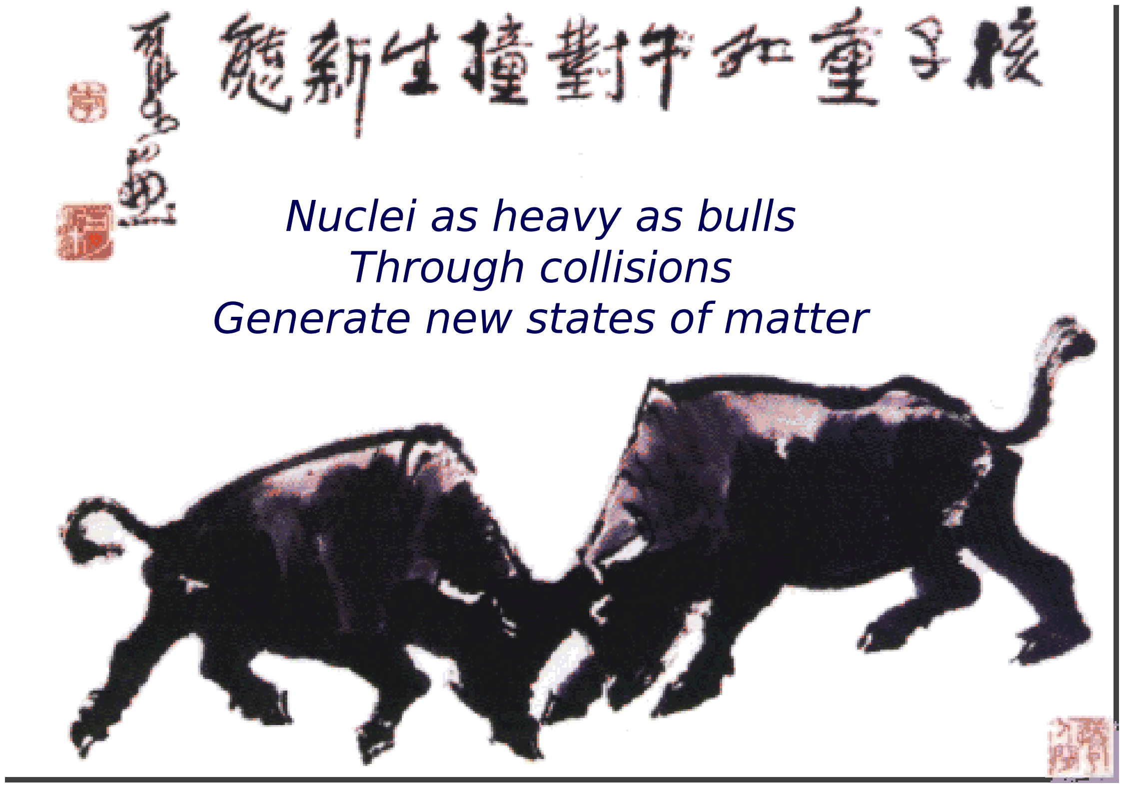
The study of the strong interactions is now a mature subject - we have a theory of the fundamentals* (QCD) that is correct* and complete*.

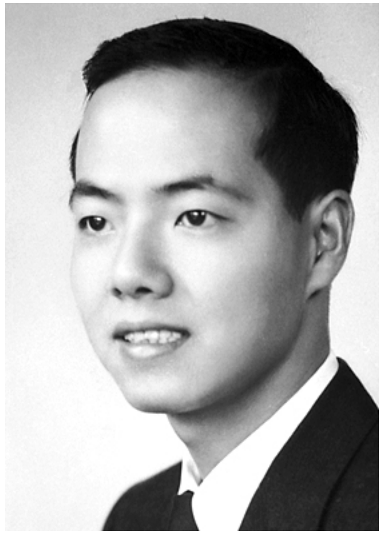
In that sense, it is akin to atomic physics, condensed matter physics, or chemistry. The important questions involve emergent phenomena and "applications".

F. Wilczek , "Quarks (and Glue) at the Frontiers of Knowledge"
Talk at Quark Matter 2014

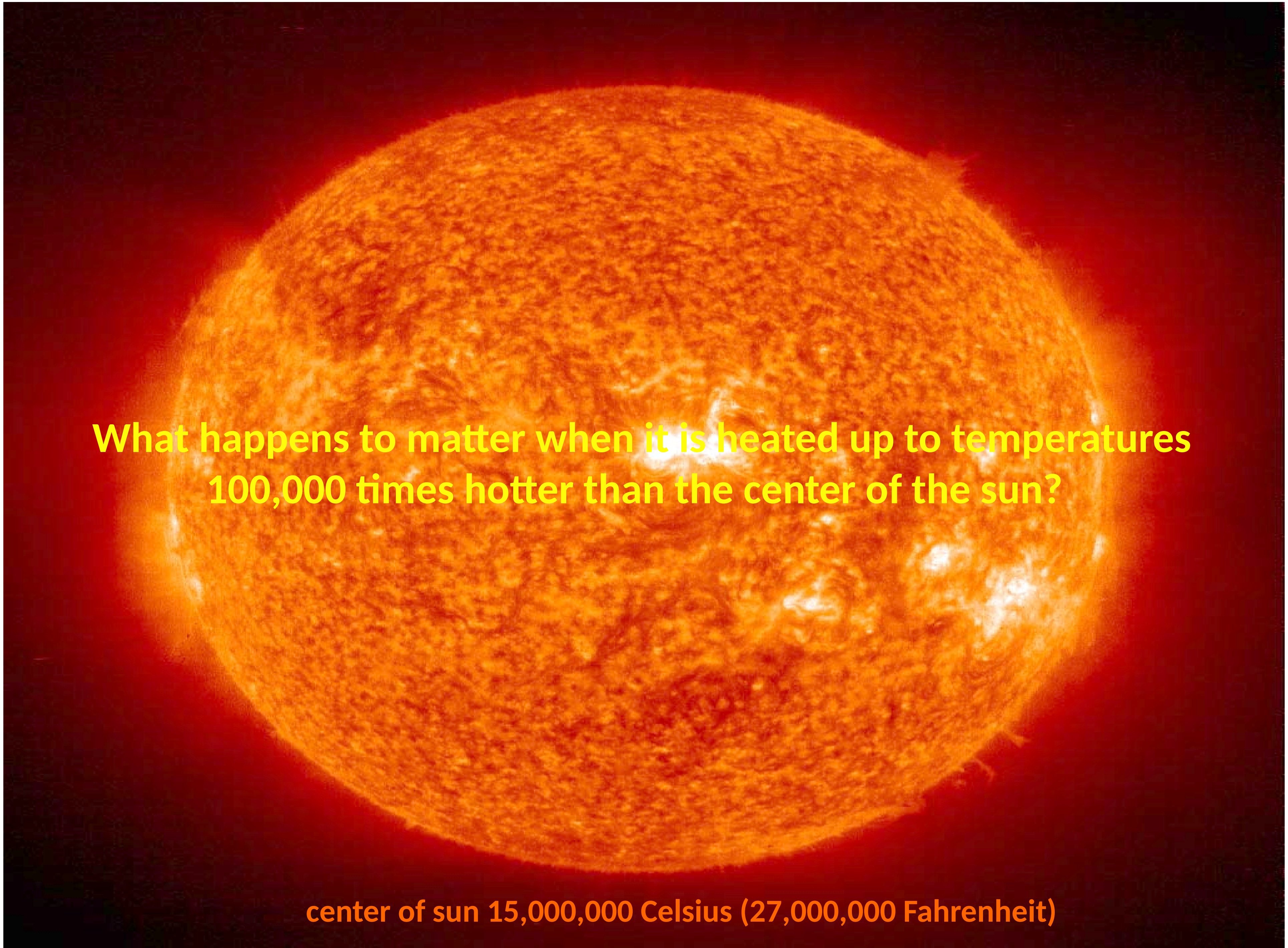
Are we done ?

Act 3: Surprises from boiling the QCD vacuum



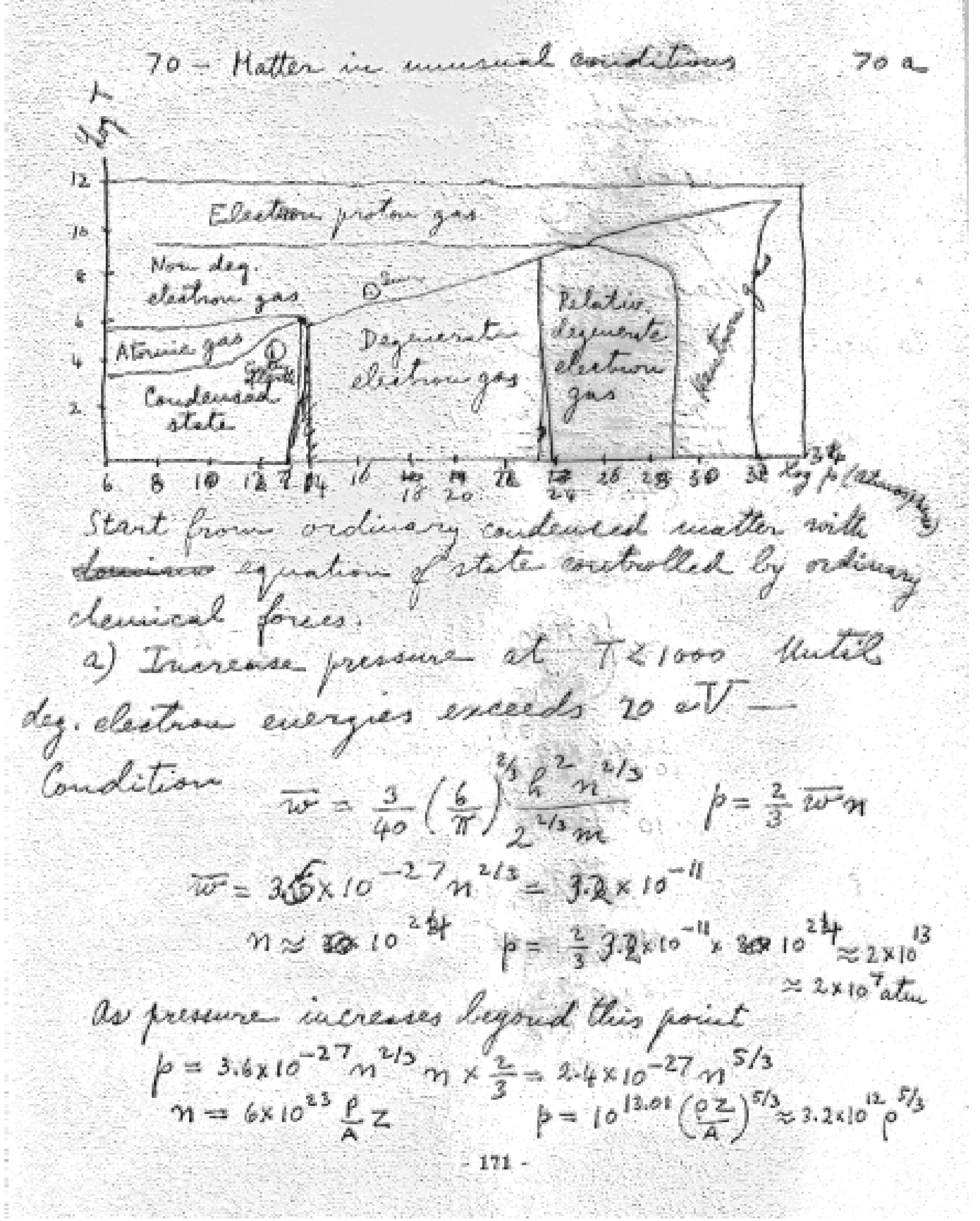


TD Lee, Nobel Laureate (1957)


What happens to matter when it is heated up to temperatures 100,000 times hotter than the center of the sun?
center of sun 15,000,000 Celsius (27,000,000 Fahrenheit)

Matter in unusual conditions

E. Fermi: " Notes on Thermodynamics and Statistics " (1953)



Start from ordinary condensed matter with ~~dominion~~ equation of state controlled by ordinary chemical forces.

a) Increase pressure at $T < 1000$ until deg. electron energies exceeds 20 eV —

Condition $\overline{w} = \frac{3}{40}\left(\frac{6}{\pi}\right)^{2/3}\frac{h^2 n^{2/3}}{2^{2/3} m}$ $\quad p = \frac{2}{3}\overline{w} n$

$\overline{w} = 3.5\times10^{-27} n^{2/3} = 3.2\times10^{-11}$

$n \approx 30\ 10^{24}$ $\quad p = \frac{2}{3}\, 3.2\times10^{-11}\times 30\times10^{24} \approx 2\times10^{13}$

$\approx 2\times10^{7}$ atm

As pressure increases beyond this point

$p = 3.6\times10^{-27} n^{2/3}\, n \times \frac{2}{3} = 2.4\times10^{-27} n^{5/3}$

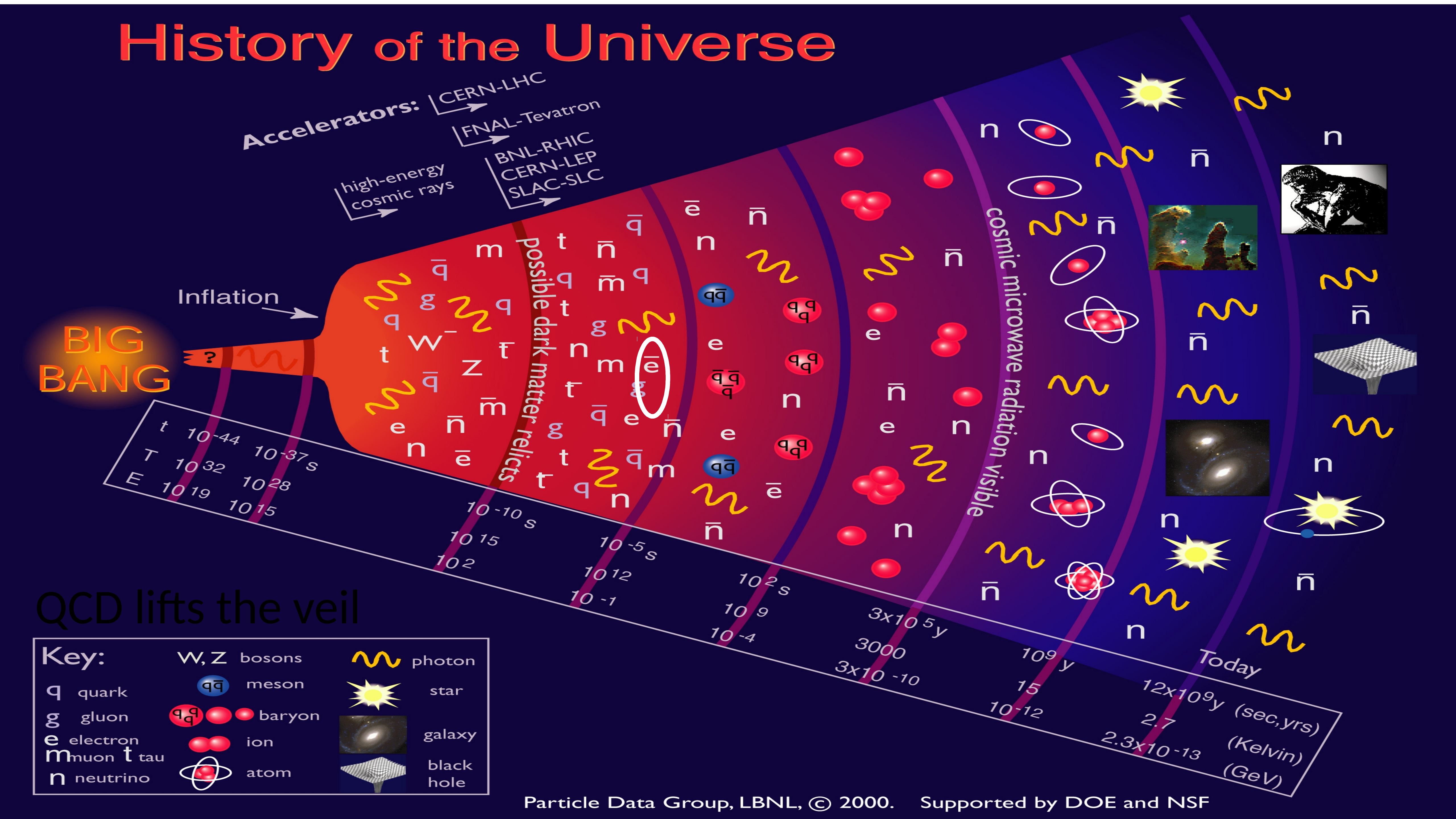
$n = 6\times10^{23}\frac{\rho}{A}Z$ $\quad p = 10^{13.01}\left(\frac{\rho Z}{A}\right)^{5/3} \approx 3.2\times10^{12}\rho^{5/3}$

- 171 -

Pre-QCD: *Thus, our ignorance of the microscopic physics stands as a veil, obscuring our view of the very beginning*

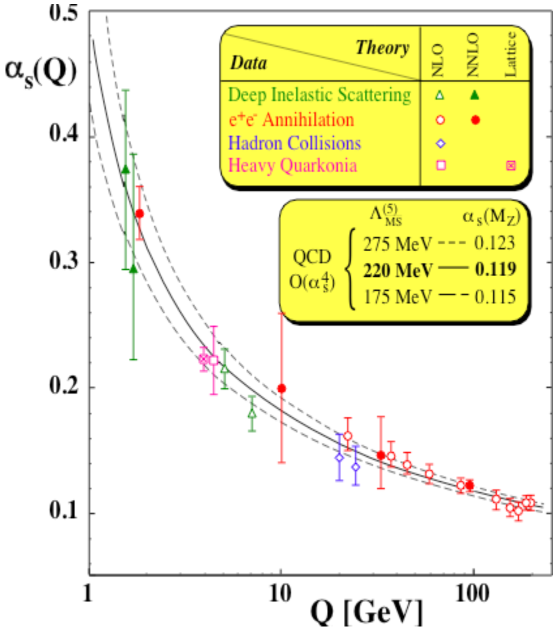
Steven Weinberg, The First Three Minutes (1973)

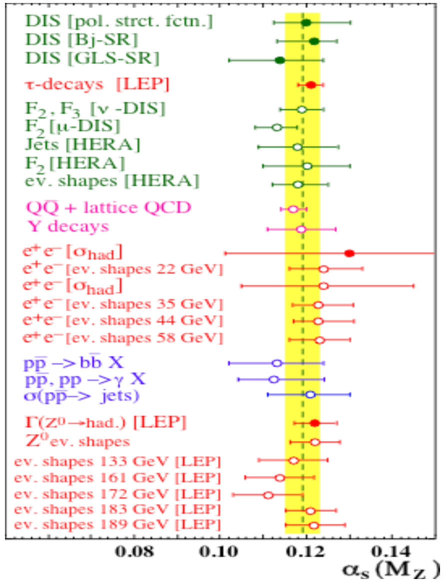
QCD lifts the veil



QCD: asymptotic freedom

Gross,Wilczek, Politzer





Coupling grows weaker
with increasing momentum
transfer (shorter distances)

$$\alpha_S(Q^2) = \frac{12\pi}{(11\,N_c - 2\,n_f)\ln\left(\frac{Q^2}{\Lambda^2_{\rm QCD}}\right)}\left[1 - \frac{6(153-19n_f)}{(11N_c-2n_f)^2}\frac{\ln(\ln(Q^2/\Lambda^2_{\rm QCD}))}{\ln(Q^2/\Lambda^2_{\rm QCD})}\right] + \cdots$$

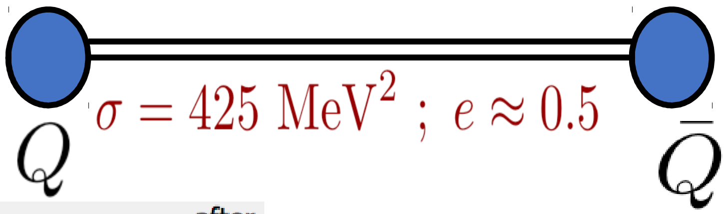
Super-dense and Super-hot QCD matter is a weakly coupled gas of quarks and gluons – “lifting the veil” to the early universe
-- analytical computations feasible

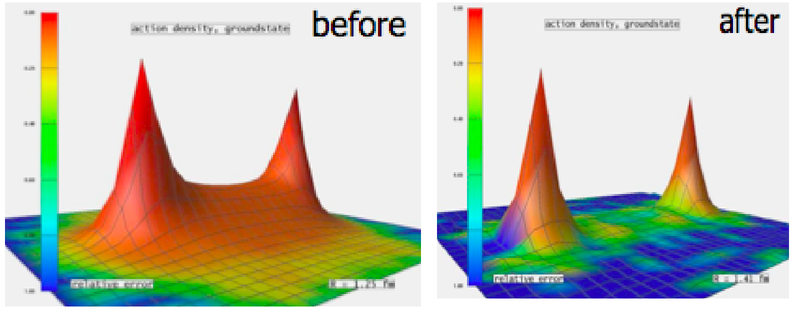
Collins-Perry (1974)
Cabibo-Parisi (1975)

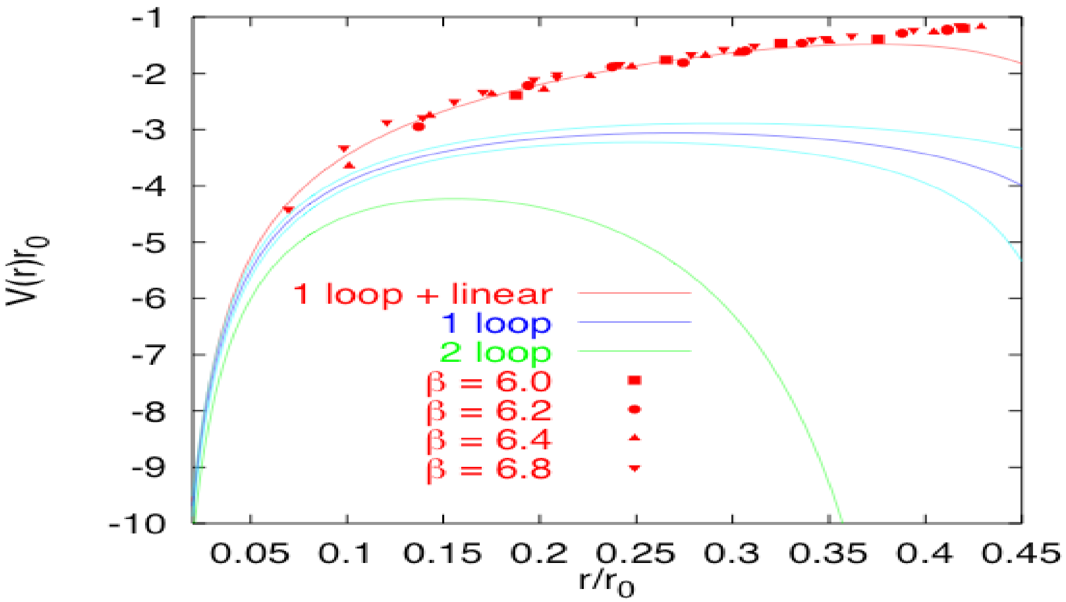
QCD: Infrared Slavery


Wilson

$$V(r) = \sigma r - \frac{e}{r}$$





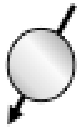
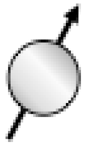


Potential between static
quark-anti-quark pair
grows linearly at large distances -
intuitive picture of confinement

QCD matter is strongly interacting at low Temperature and Density
- static properties computed using numerical lattice methods

QCD: Chiral symmetry breaking

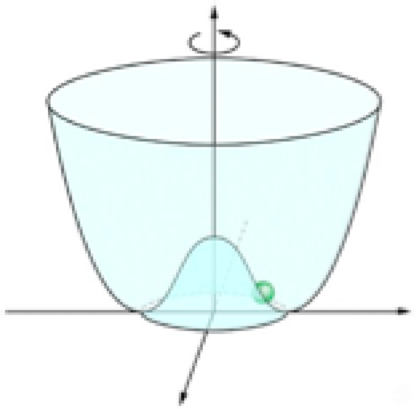

Nambu

Chiral basis :  $q_L = \frac{1}{2}(1-\gamma_5)q, \quad q_R = \frac{1}{2}(1+\gamma_5)q$ 

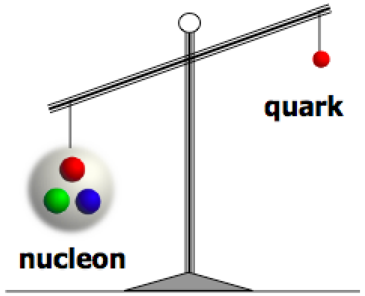
QCD Lagrangian : $\mathcal{L}_{cl} = \mathcal{L}_{cl}(q_L, A) + \mathcal{L}_{cl}(q_R, A)$

Quantum QCD vacuum:

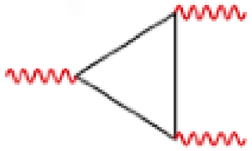
Chiral condensate: spontaneously generate mass via Nambu-Goldstone mechanism



$\longrightarrow \langle \bar{q}_R q_L \rangle \neq 0$



m_q ~ 10 MeV ; m_N ~ 1 GeV

Axial anomaly: 

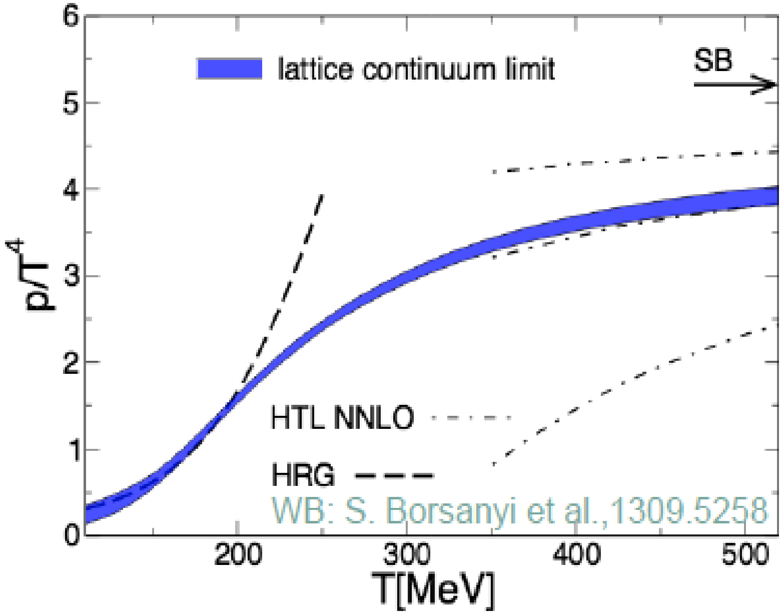
Quantum violation of $U(1)_A$ $\partial_\mu J^\mu_A = -2n_f \frac{\alpha_S}{8\pi} F^{\mu\nu,a} \tilde{F}^a_{\mu\nu}$

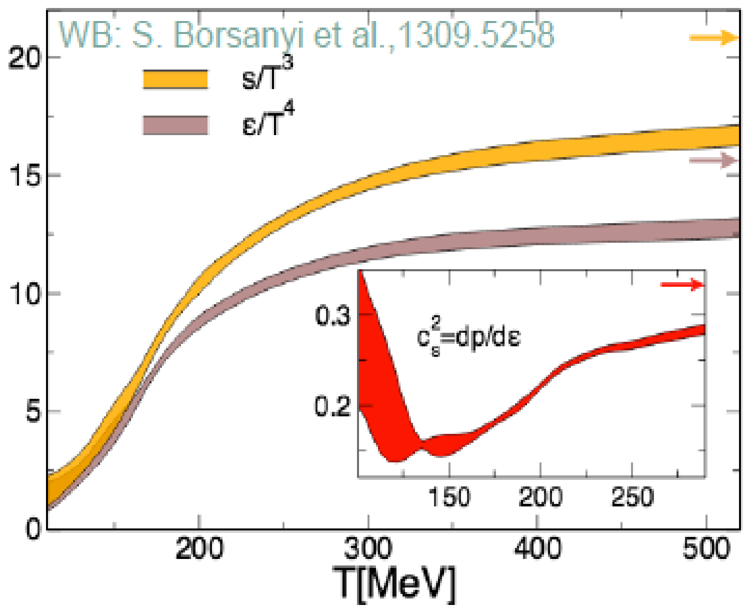
Chiral symmetry restoration at large T: $\langle \bar{q} q \rangle \longrightarrow 0$

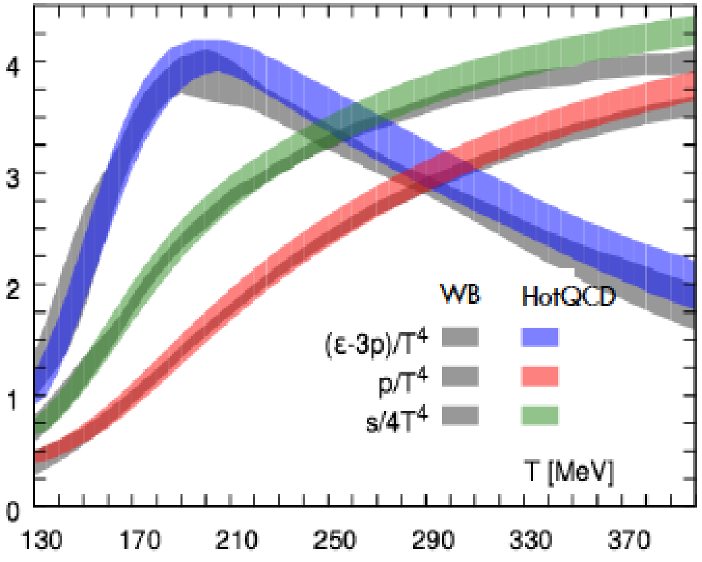
Summit, built by IBM, occupies floor space equivalent to two tennis courts, slurps 4,000 gallons of water a minute around a circulatory system to cool its 37,000 processors. Oak Ridge says its new baby can deliver a peak performance of 200 quadrillion calculations per second (that's 200 followed by 15 zeros) using a standard measure used to rate supercomputers, or 200 petaflops. *That's about a million times faster than a typical laptop*

From Wired magazine

Finite temp. lattice results: hadron gas to QGP





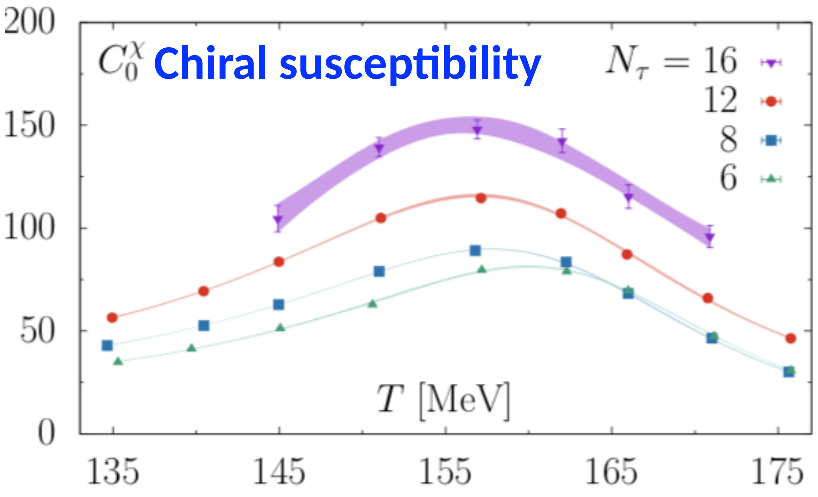


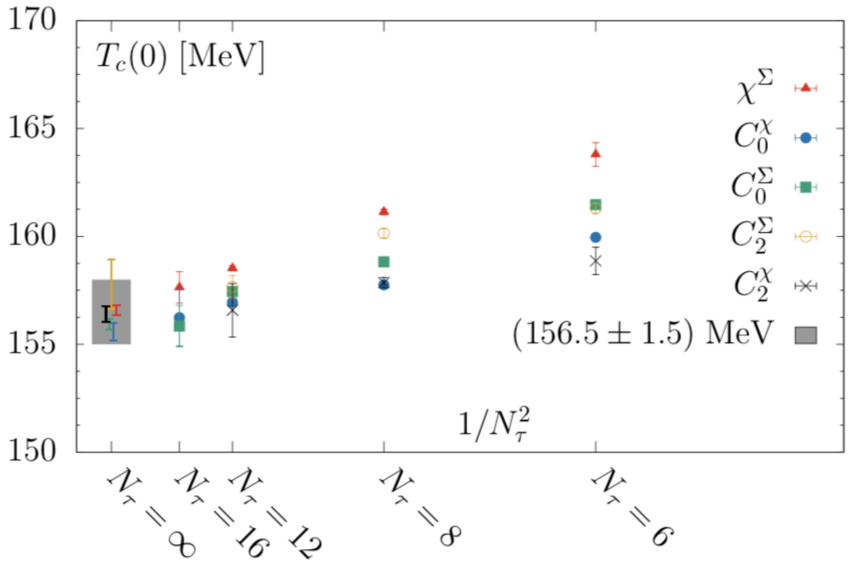
- EoS available in the continuum limit, with realistic quark masses
- Agreement between stout and HISQ action for all quantities

WB: S. Borsanyi et al., 1309.5258, PLB (2014)
HotQCD: A. Bazavov et al., 1407.6387, PRD (2014)

QCD at finite T: Chiral Symmetry Restoration

O(4) scaling of chiral susceptibility $\chi_{m,l} = 2\,\dfrac{\partial\langle\bar{\Psi}\Psi\rangle_l}{\partial m_l}$





Crossover temperature from Hadron Gas to Quark-Gluon Plasma

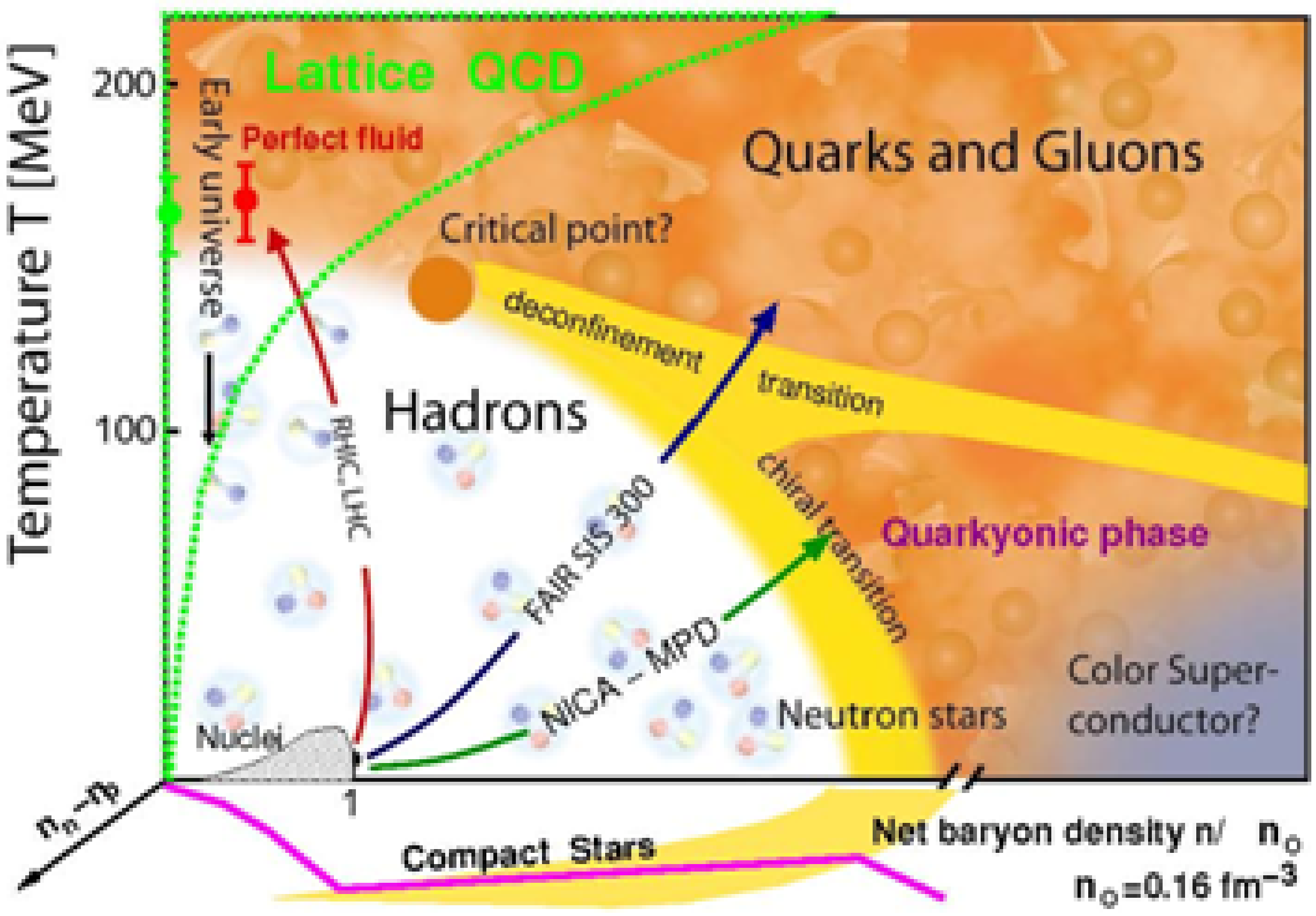
$T_c = 156 \pm 1.5\ MeV$ ≈ 156

≈ 1.8 Trillion Kelvin!

1 eV = 11,600 Kelvin

Hot QCD collaboration, Bazavov et al., arXiv:1812.08325

QCD phase diagram



Much more on the phase diagram in the lectures by Pisarski the universe a micro-second after the Big Bang was similar stuff and had the same temperature

"The early universe was "liquid-like"

BBC NEWS | Science/Nature | Early Universe was 'liquid-like'

http://news.bbc.co.uk/2/hi/science/nature/4462209.stm

rhic bbc

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ON THIS DAY
EDITORS' BLOG

Last Updated: Tuesday, 19 April, 2005, 16:26 GMT 17:26 UK

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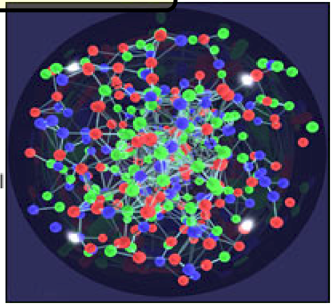
Early Universe was 'liquid-like'

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms.



The impression is of matter that is more strongly interacting than predicted

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

The details, presented to the American Physical Society in Florida, will be published across a number of papers in the journal Nuclear Physics A.

"People like me, who use model calculations, are already so excited about the data because we believe they have actually found the elusive state known as the quark-gluon plasma"

Asst Prof Steffen Bass, Duke University

They summarise the work of four collaborative experiments - dubbed Brahms, Phenix, Phobos and Star - which have been running on Brookhaven's

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News feeds

Perfect fluidity across energy scales

"Bjorken Hydrodynamics"

$$\frac{d\varepsilon}{d\tau} = -\frac{\left(\varepsilon + P - \frac{4}{3}\frac{\eta}{\tau}\right)}{\tau}$$

Viscous term smaller than ideal term for

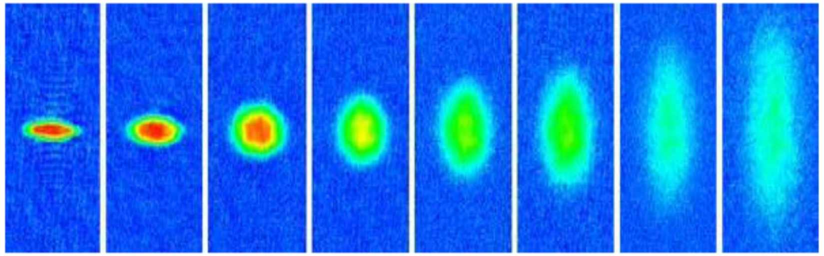
$$\frac{\eta}{\varepsilon + P}\frac{1}{\tau} = \frac{\eta}{s}\frac{1}{\tau T} << 1$$

From kinetic theory

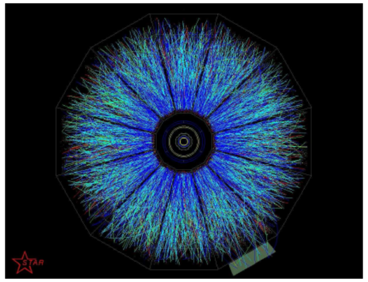
$$\boxed{\frac{\eta}{s} \sim \frac{\hbar}{k_B}\frac{\tau_{\text{relax.}}}{\tau_{\text{quant.}}}}$$

H_2O

^{4}He



^{6}Li



sQGP

Schafer,Teaney, Rep.Prog.Phys.72 (2009) 126001

Perfect fluidity across energy scales

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From kinetic theory

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Fluid	T [K]	η [$Pa \cdot s$]	η/n [$\hbar$]	η/s [$\hbar/k_B$]
H_20	370	2.9×10^{-4}	85	8.2
^4He	2	1.2×10^{-6}	0.5	1.9
^6Li ($\lvert a_s \rvert \simeq \infty$)	23×10^{-6}	$\leq 1.7 \times 10^{-15}$	≤ 1	≤ 0.5
QGP	2×10^{12}	$\leq 5 \times 10^{11}$	-	≤ 0.4

Perfect fluidity across energy scales

"Bjorken Hydrodynamics"

$$\frac{d\varepsilon}{d\tau} = -\frac{\left(\varepsilon + P - \frac{4}{3}\frac{\eta}{\tau}\right)}{\tau}$$

Viscous term smaller than ideal term for

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From kinetic theory

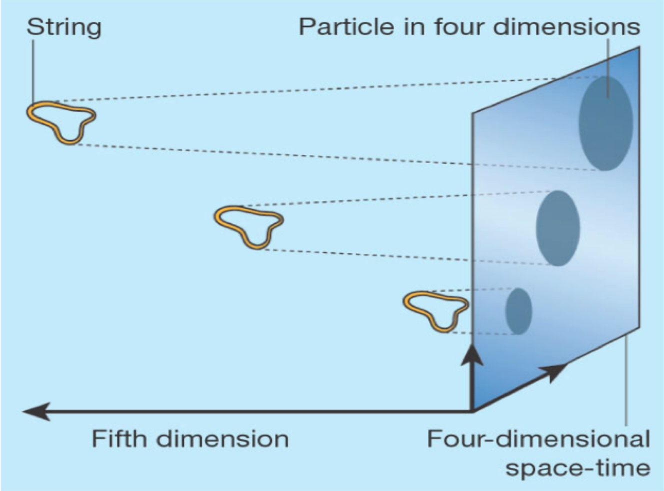
$$\boxed{\frac{\eta}{s} \sim \frac{\hbar}{k_B}\frac{\tau_{\text{relax.}}}{\tau_{\text{quant.}}}}$$

QGP is ~ 10^4 times more viscous than pitch tar...

Viscosity of strongly coupled relativistic fluids

AdS/CFT conjecture:

Duality between strongly coupled
N=4 supersymmetric Yang-Mills theory
at large coupling and Nc
& classical 10 dimensional gravity in the
background of D3 branes



J.Maldacena, Nature 2003

KSS bound:

Conjectured lower bound for
a ``perfect fluid”

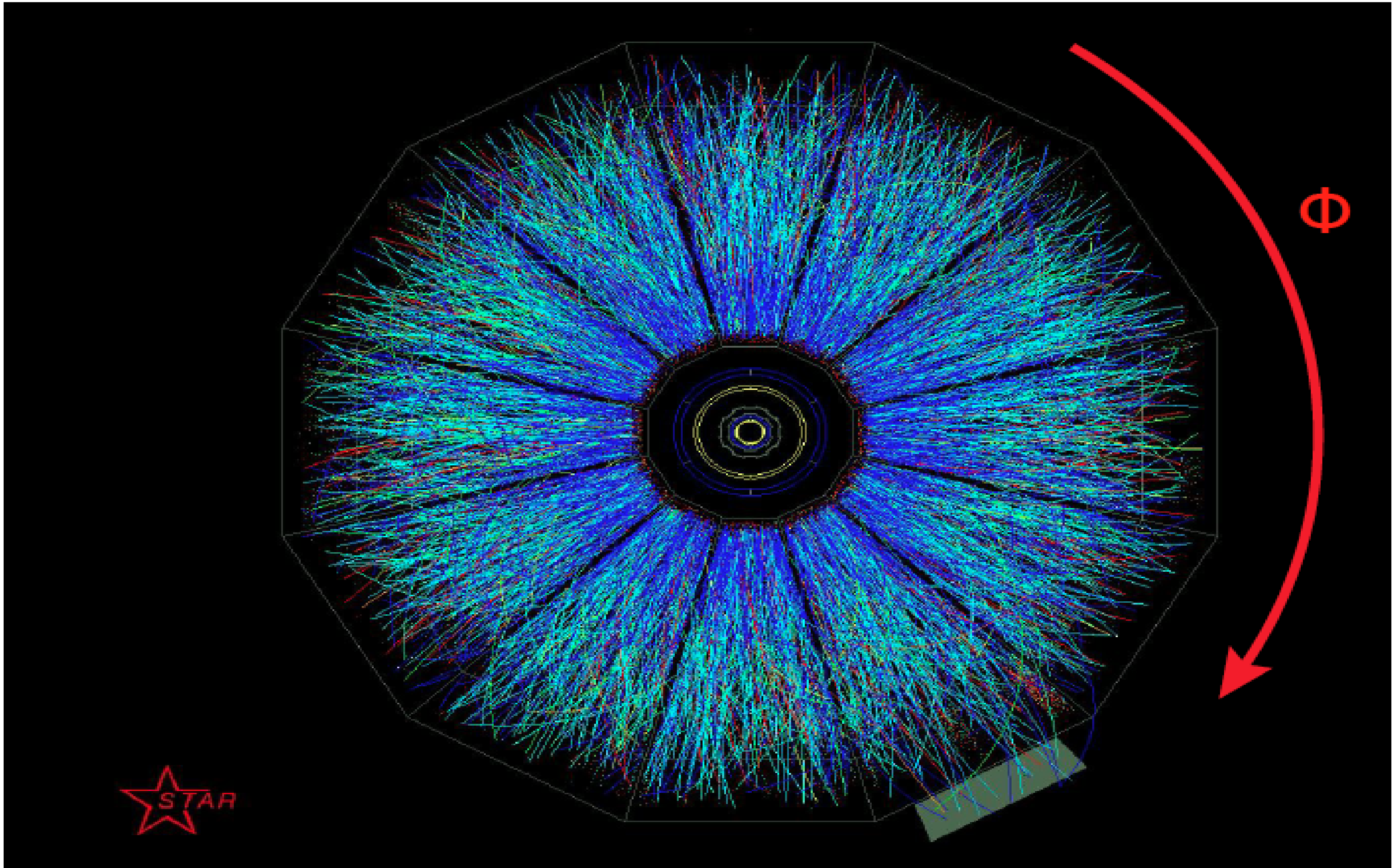
Kovtun,Son,Starinets (2006)

$$\frac{\eta}{s} = \frac{\hbar}{k_B}\frac{1}{4\pi}$$

Derived using classical absorption cross-section of a graviton
with energy ω on a black brane and Bekenstein’s formula relating its
Entropy to its area

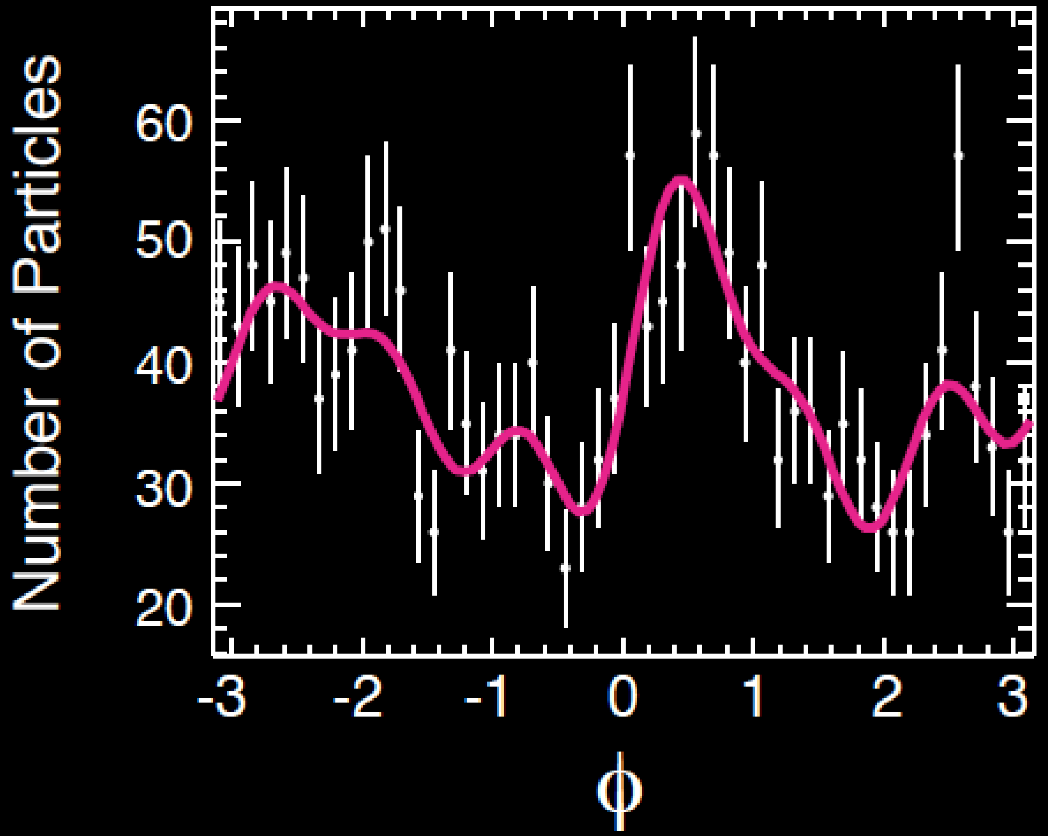
$$\sigma(\omega) = \frac{8\pi G}{\omega}\int dt d\mathbf{x}\, e^{i\omega t}\langle[T_{xy}(t,\mathbf{x}), T_{xy}(0,0)]\rangle$$

Deconstructing lumpiness to find a perfect fluid



ANGULAR PARTICLE DISTRIBUTION

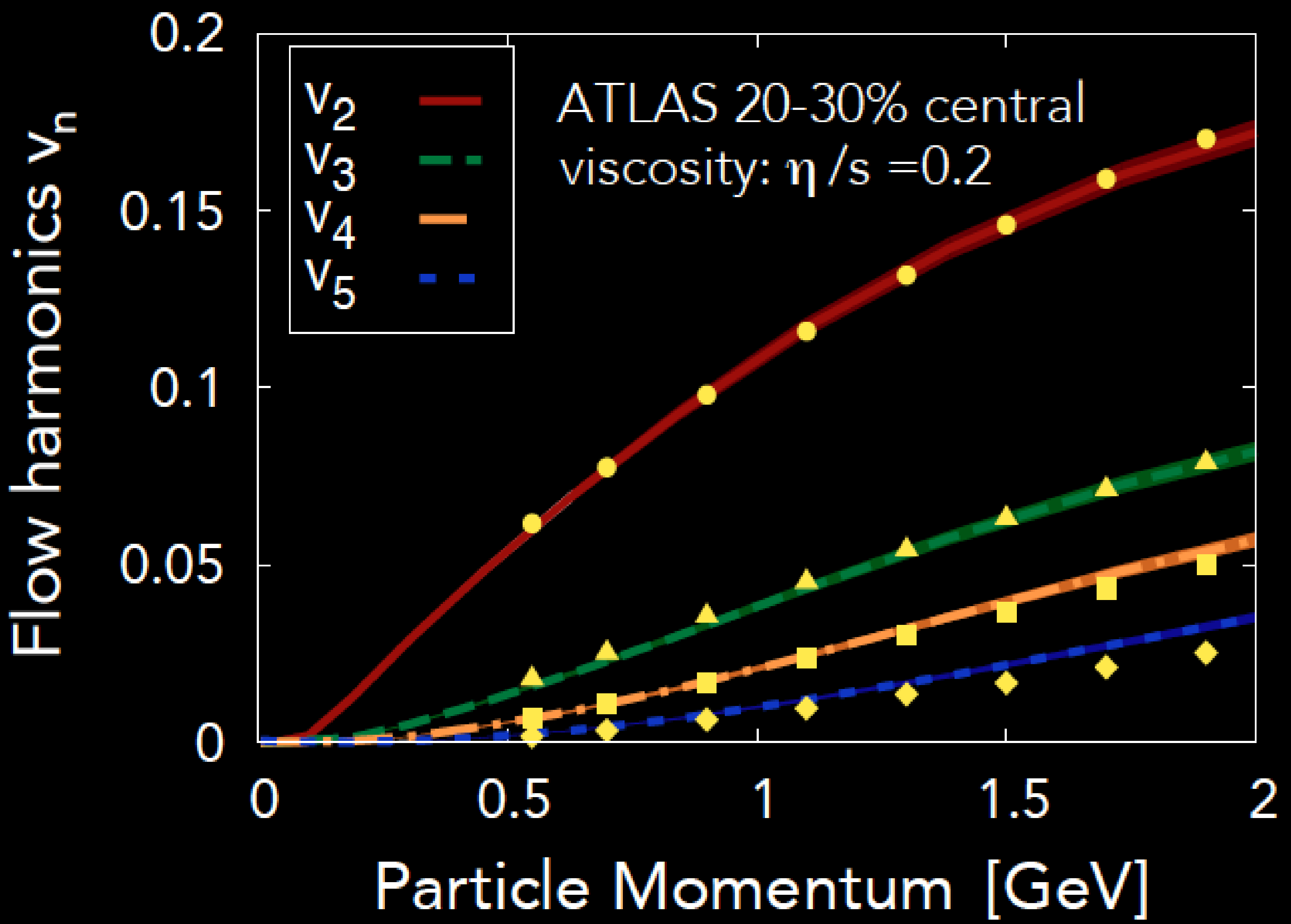
EXPERIMENTAL DATA: ATLAS COLLABORATION



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

VISCOUS FLOW AT LHC

C.GALE, S.JEON, B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PHYS.REV.LETT.110, 012302 (2013)

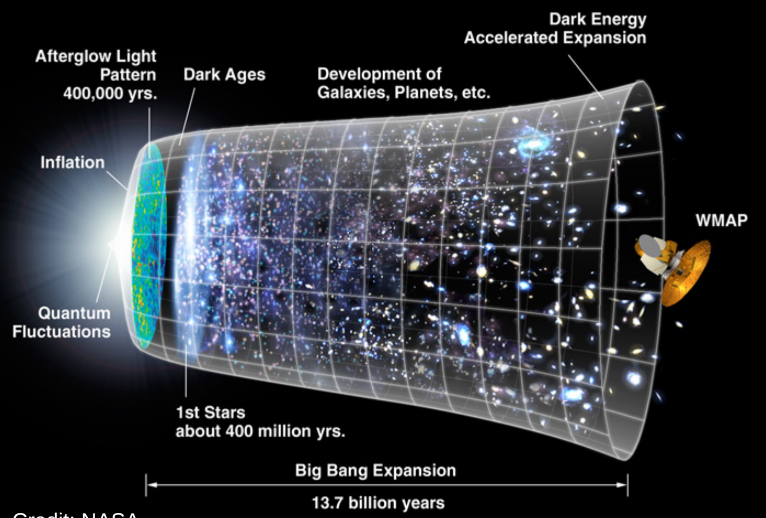


EXPERIMENTAL DATA: ATLAS COLLABORATION, PHYS. REV. C86, 014907 (2012)

Flow moments: analogy with the Early Universe

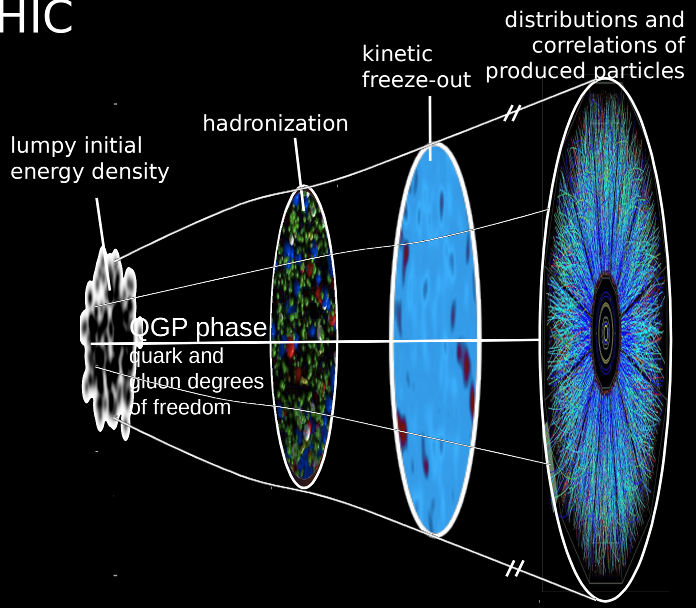
Mishra et al; Mocsy- Sorensen;
Floerchinger, Wiedemann

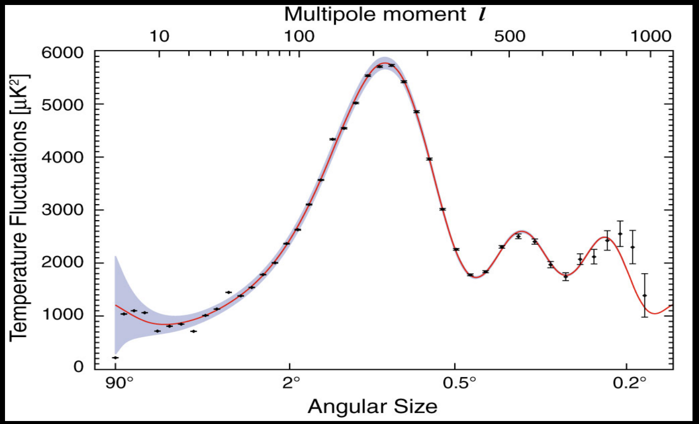
The Universe



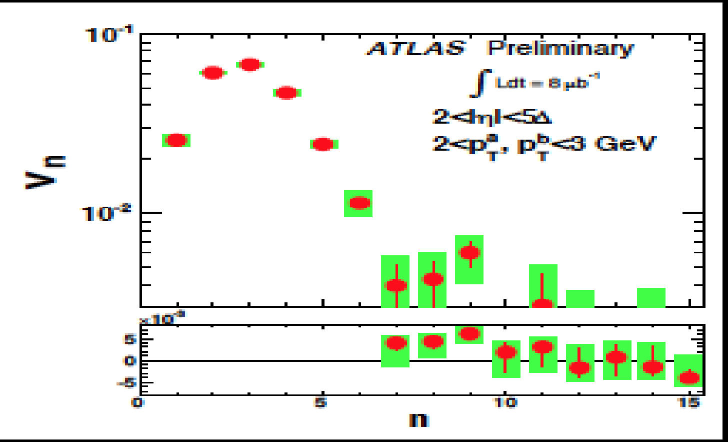
Credit: NASA

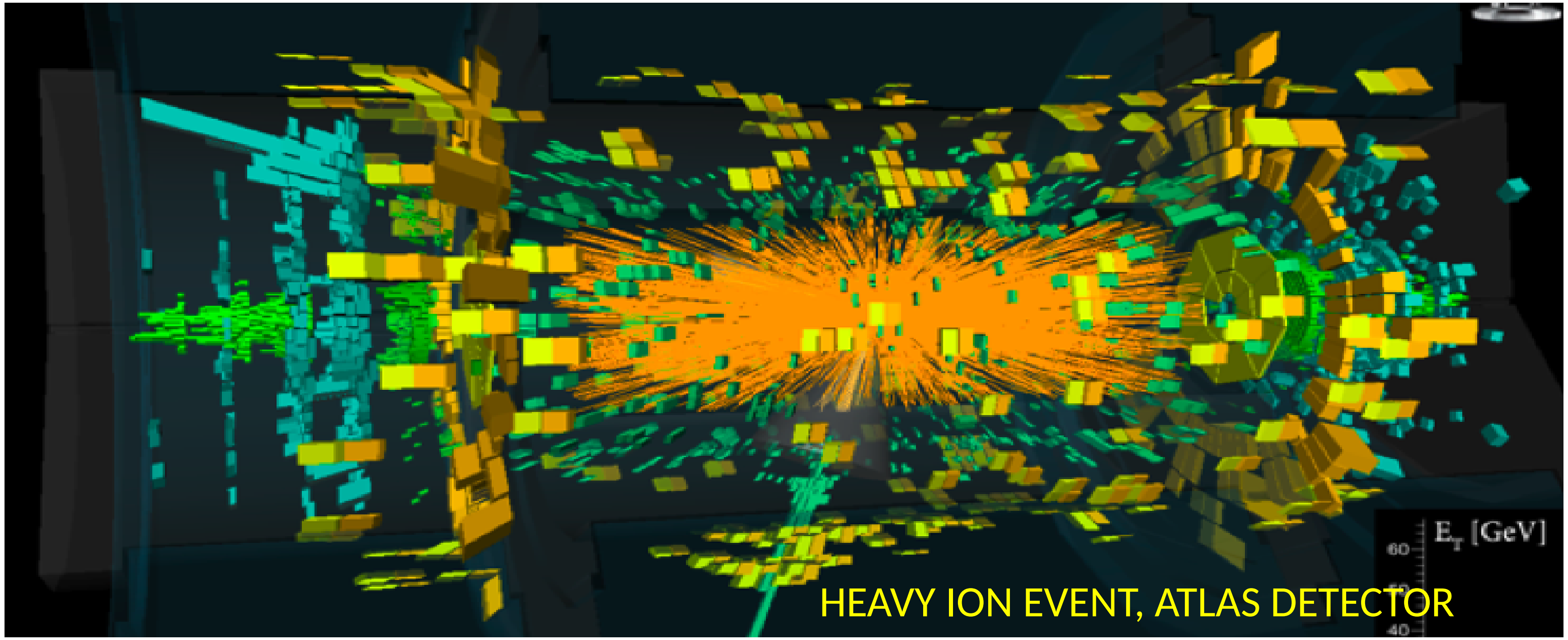
HIC

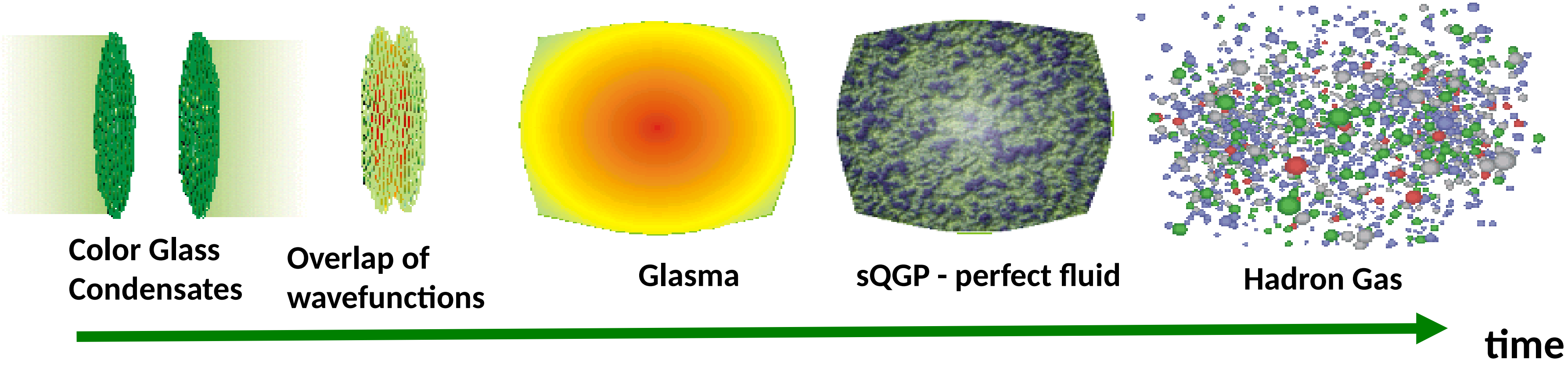




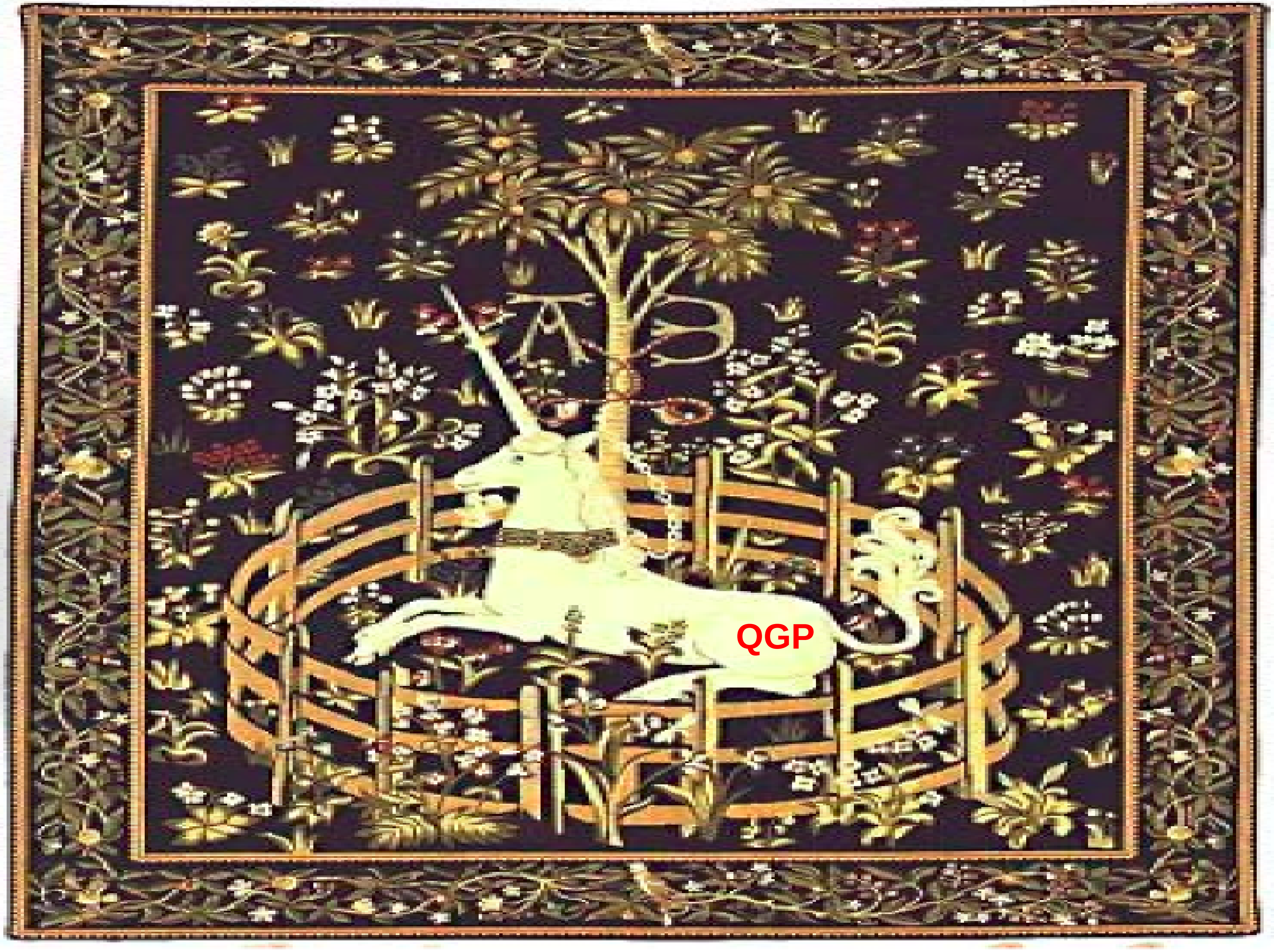
WMAP



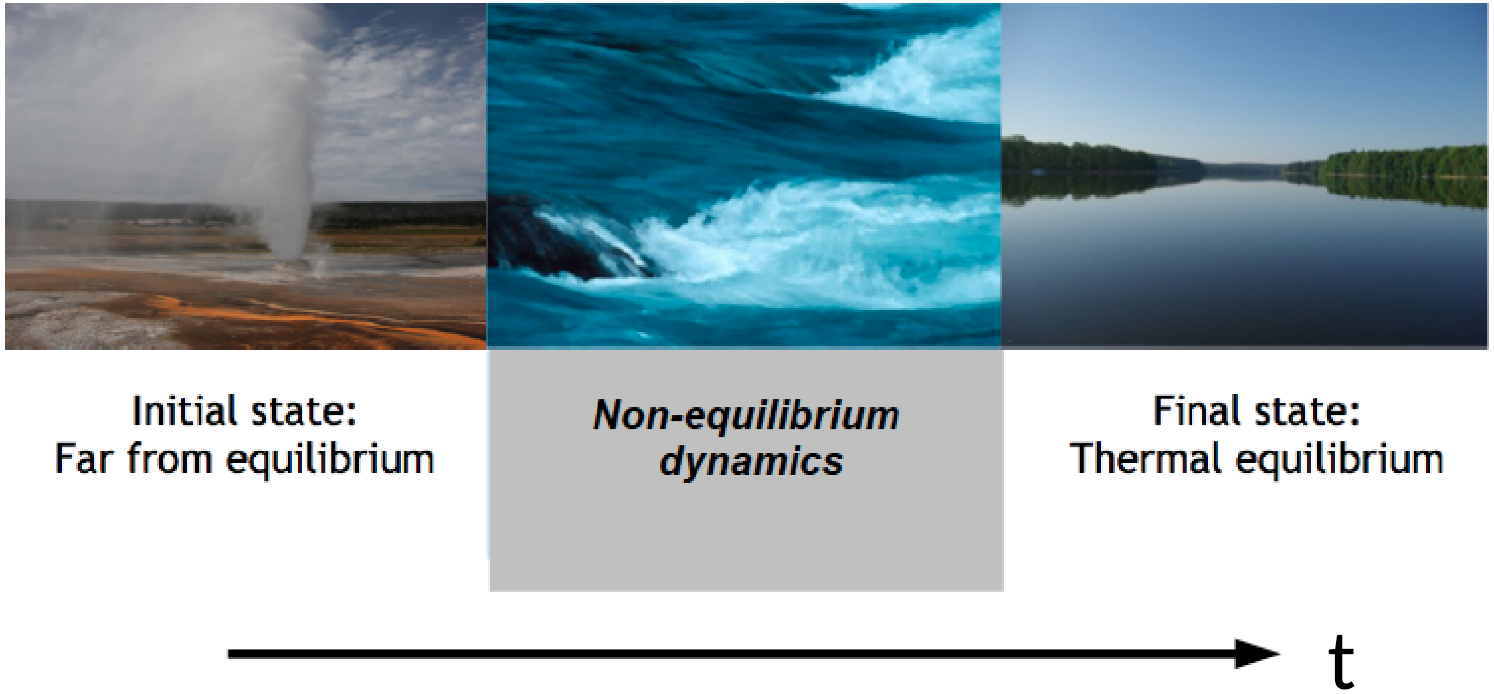


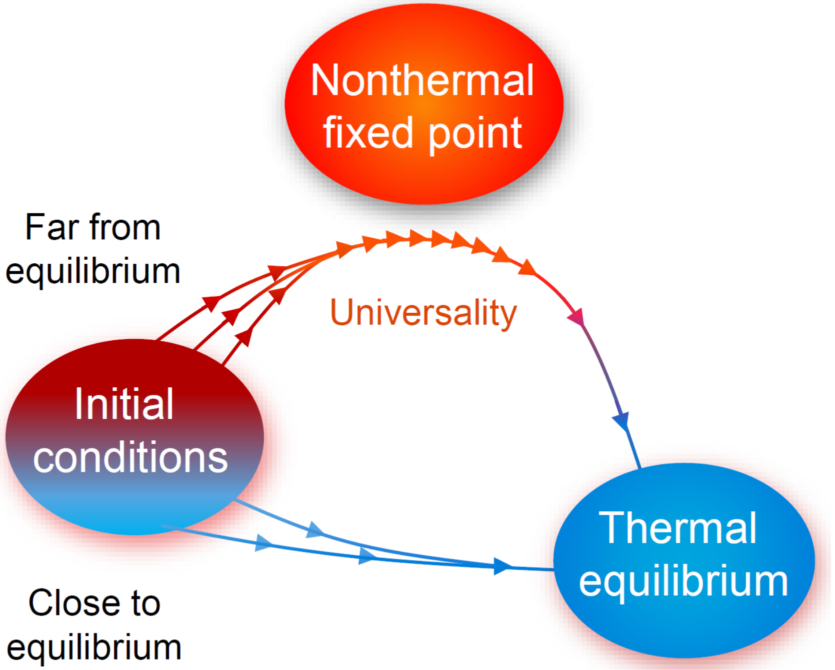


Color Glass Condensate: Highly dense gluon matter in nuclear wavefunction
Glasma: Out of equilibrium QGP formed from decay of CGCs


QGP

How does quark-gluon plasma thermalize in a HI-collision ?





Properties independent of initial conditions

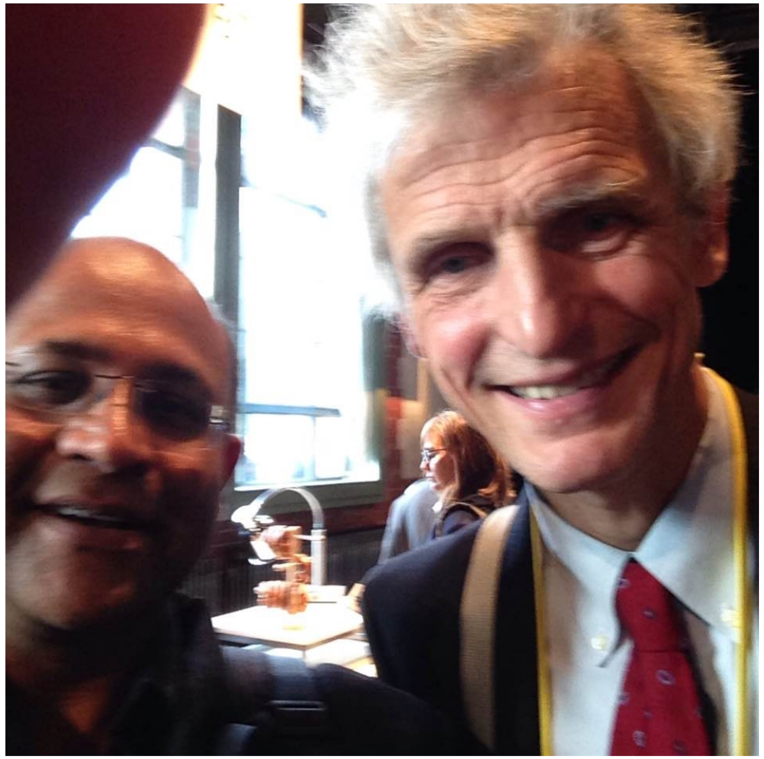
Self-similar evolution characterized by universal scaling exponents

Turbulence is everywhere yet baffles deep thinkers

I am an old man now, and when I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am rather optimistic.

Horace Lamb

Universality: hotness is also cool

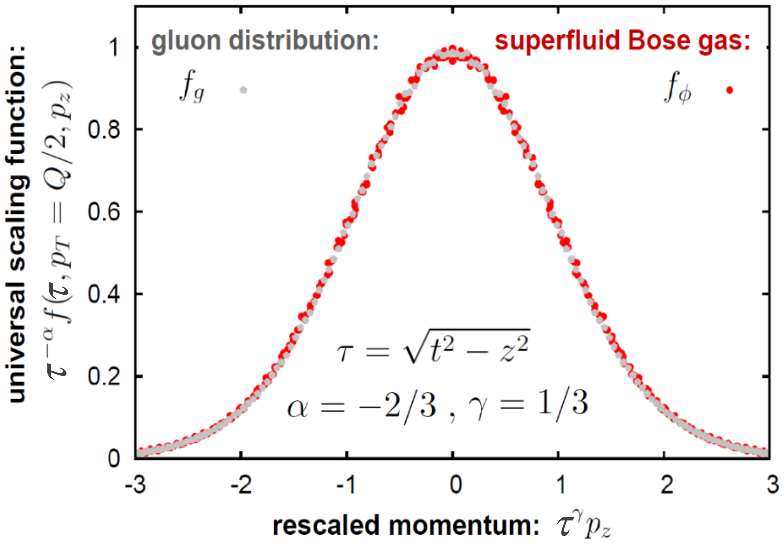


Wolfgang Ketterle, Nobel Prize (2001)

For the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates

The Glasma and overoccupied quantum gases

Remarkable universality of longitudinally expanding world's hottest and coolest fluids

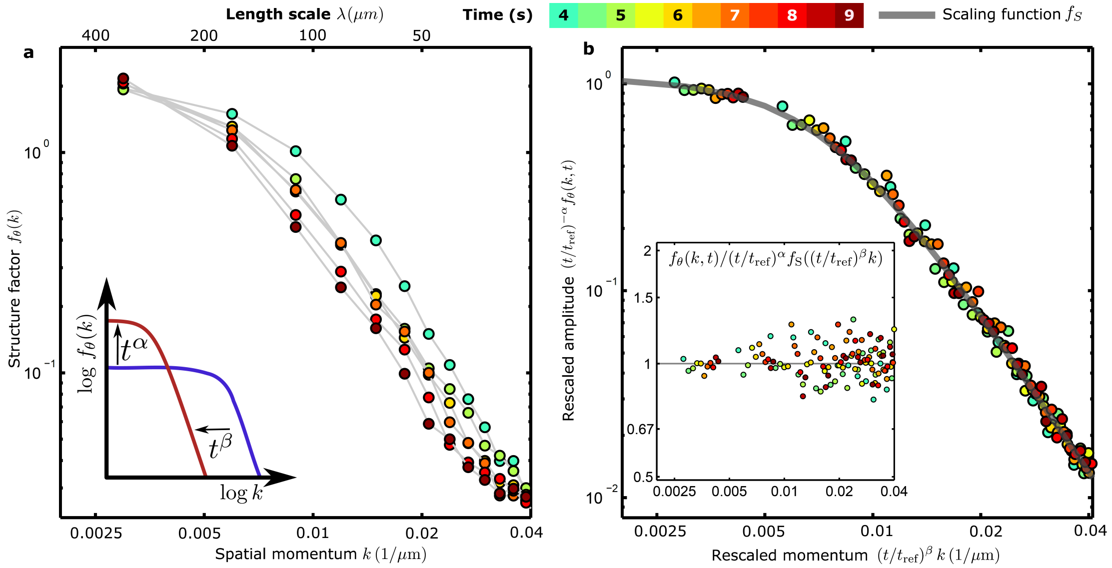


Berges,Boguslavski,Schlichting,RV, PRL (2015)

Editor's suggestion

$$f(p_T, p_z, \tau) = \tau^\alpha f_S(\tau^\beta p_T, \tau^\gamma p_z)$$

In a wide inertial range, scalar & gauge fields have identical scaling exponents & functions



[87]Rb BEC in a quasi 1D optical trap
Only isotropic geometry thus far

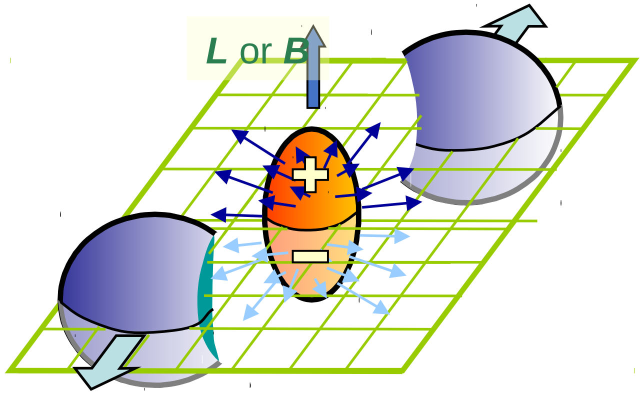
$$f_\theta(k,t) = t^\alpha f_S(t^\beta k)$$

$\alpha = 0.33\pm0.08 \quad \beta = 0.54\pm0.06$

Oberthaler BEC Labs
Prüfer et al, arXiv:1805.11881, *Nature* (2018)

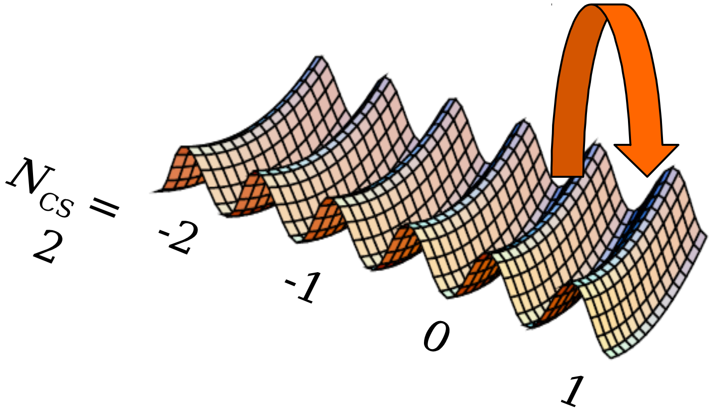
Topology in heavy-ion collisions: The Chiral Magnetic Effect

Kharzeev,McLerran,Warringa (2007)



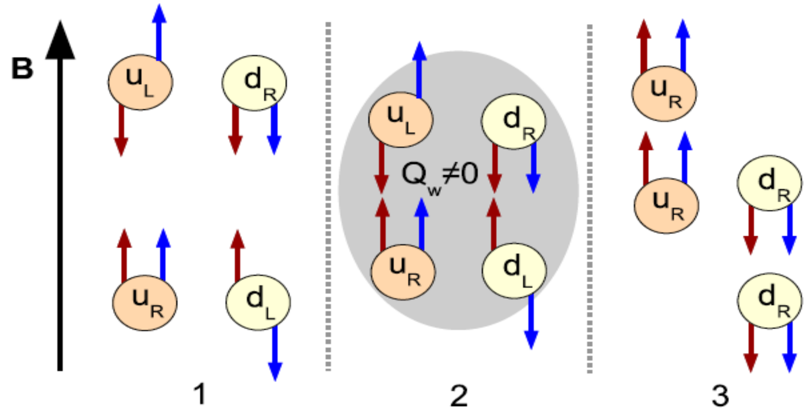
External (QED) magnetic field
- As strong as 10^{18} Gauss !

+



Over the barrier (sphaleron) transitions between different topological sectors of QCD vacuum...analogous to proposed mechanism for Electroweak Baryogenesis

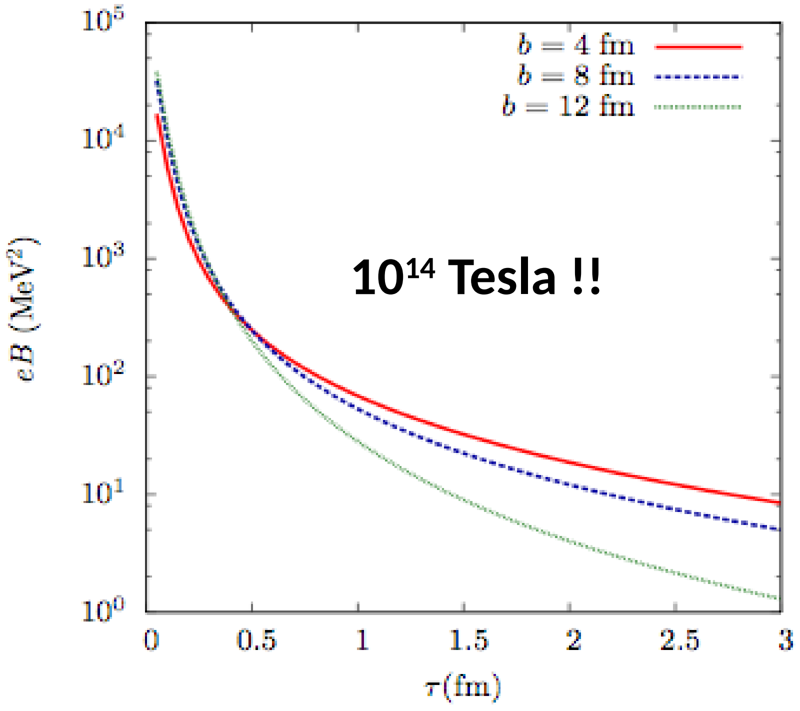
=



$$\vec{J}_{\mathrm{CME}} = \frac{e^2}{2\pi^2}\,\mu_5\,\vec{B}$$

Chiral magnetic effect

Topology in heavy-ion collisions: The Chiral Magnetic Effect

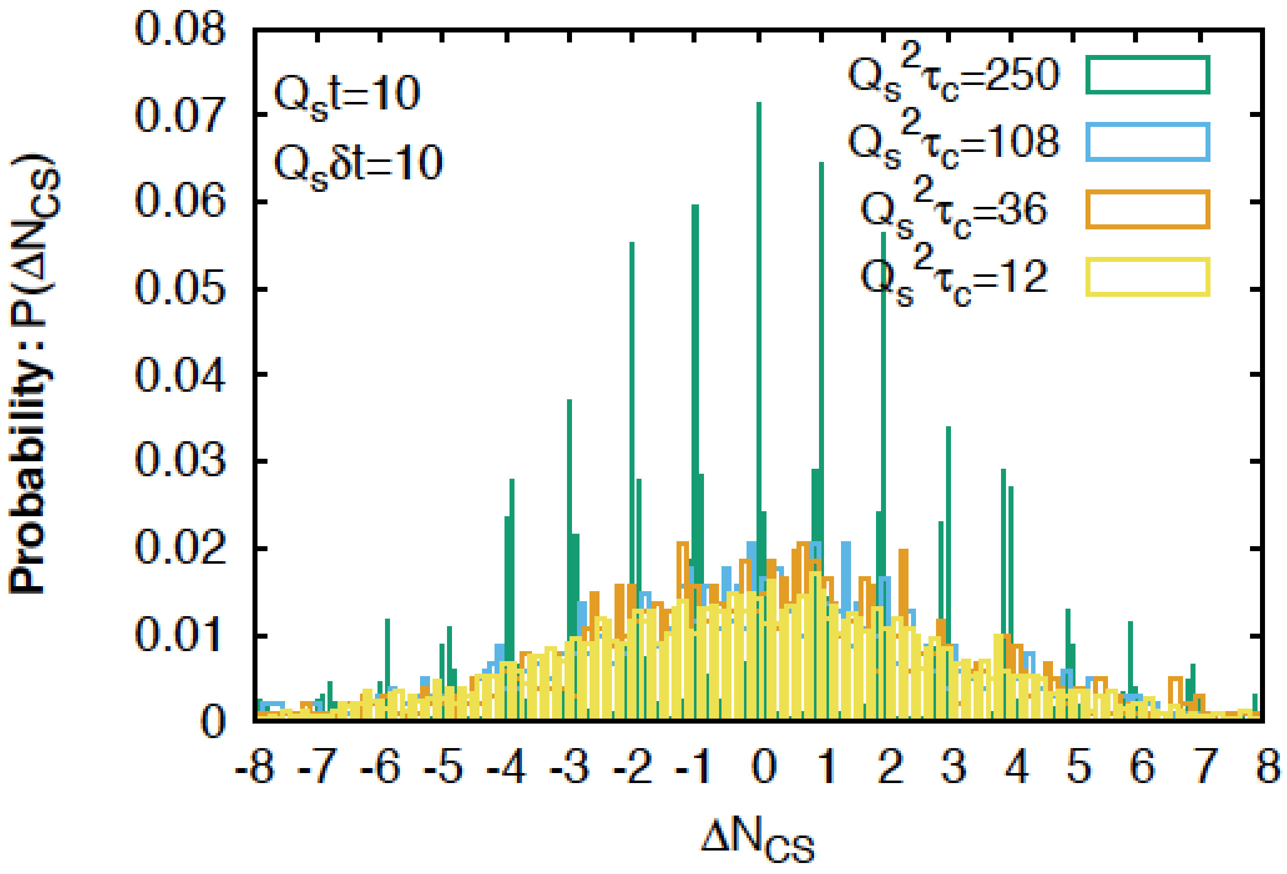


External B field dies rapidly…effect most significant, for transitions at early times

Consistent (caveat emptor!) with results from STAR and ALICE…active searches underway

Chiral Magnetic Effect seen in condensed matter systems **Q. Li et al., Nature Physics (2015)**

Topological transitions in the Glasma

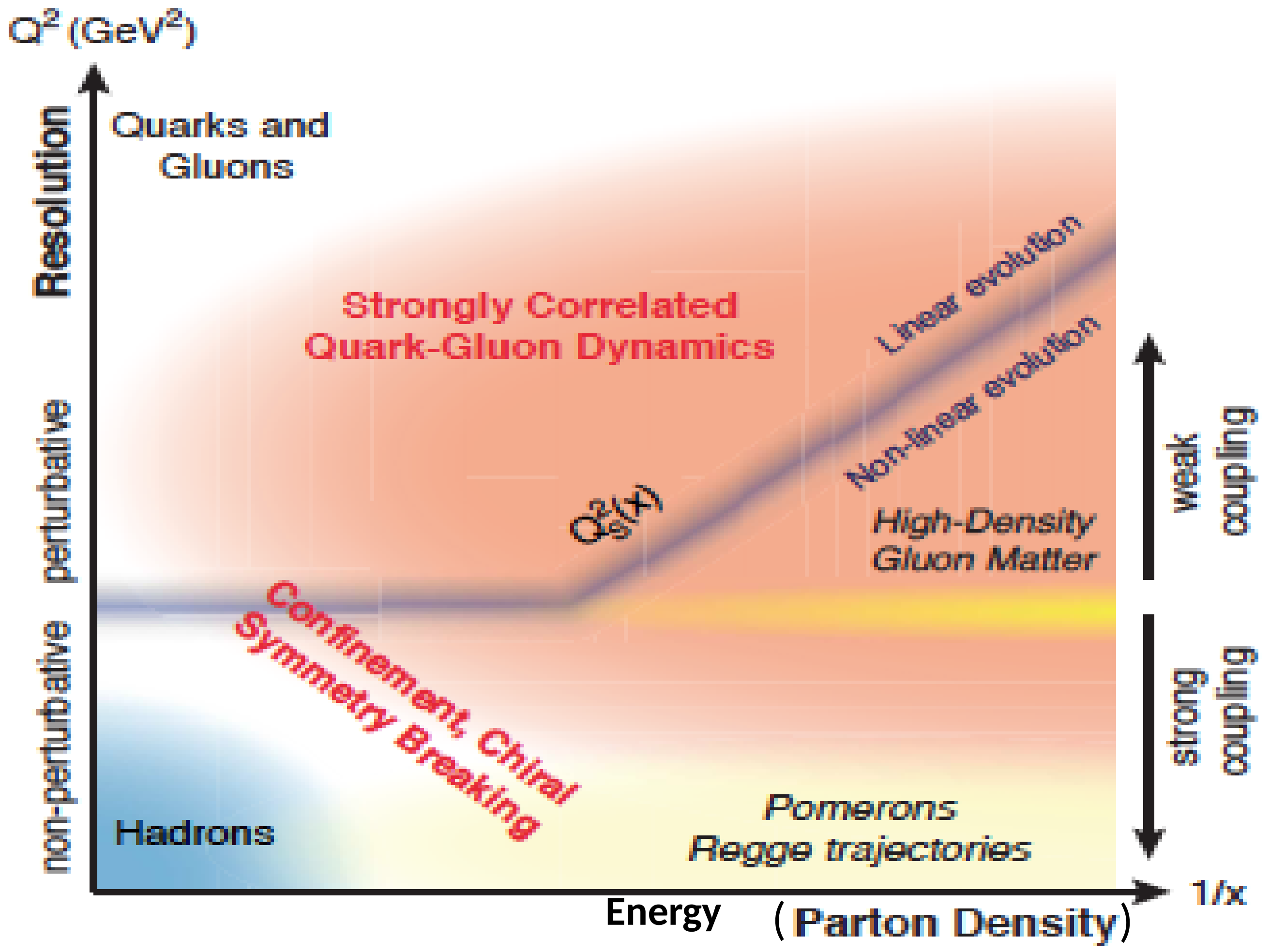


"Cooled" soft Glue configurations in the Glasma are topological !

Mace,Schlichting,Venugopalan, PRD (2016)

Act 4. Towards EIC: The ultimate IMAX experience

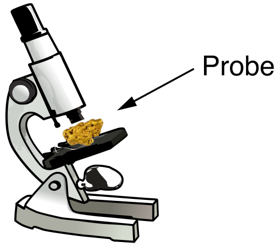
Terra-incognita (mostly) of scattering in the strong interactions



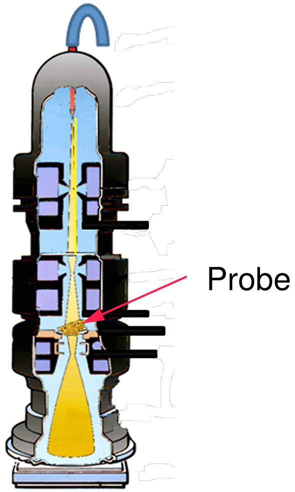
Aschenauer et al., arXiv:1708.01527
Rep.Prog. Phys. 82, 024301 (2019)

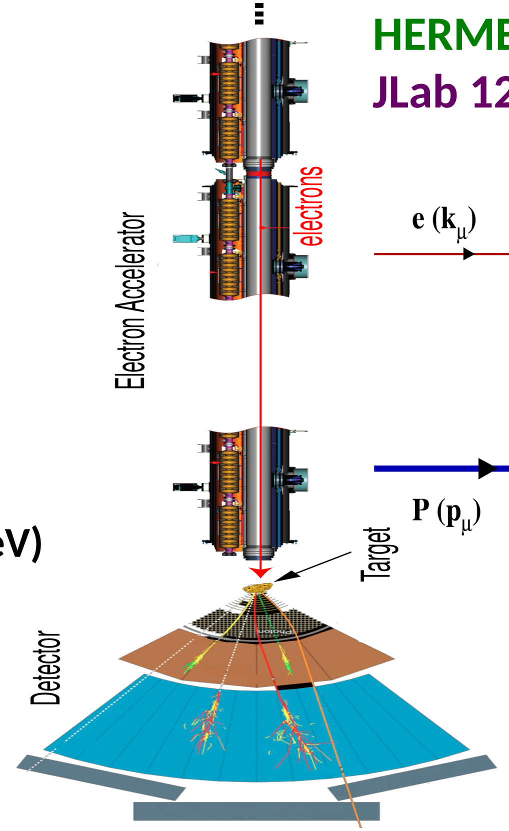
Structure of matter: Microscopes to Femtoscopes

Light Microscope
Wave length: 380-740 nm
Resolution: > 200 nm



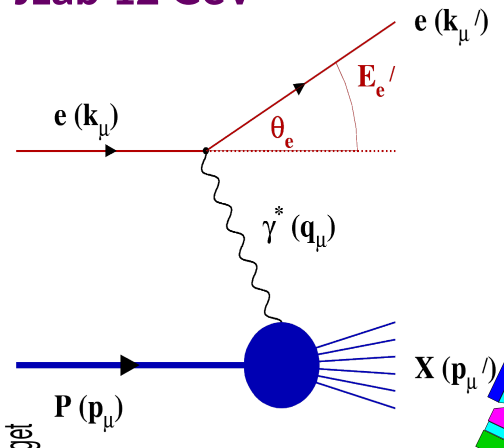
Electron Microscope
Wave length: 0.002 nm (100 keV)
Resolution: > 0.2 nm

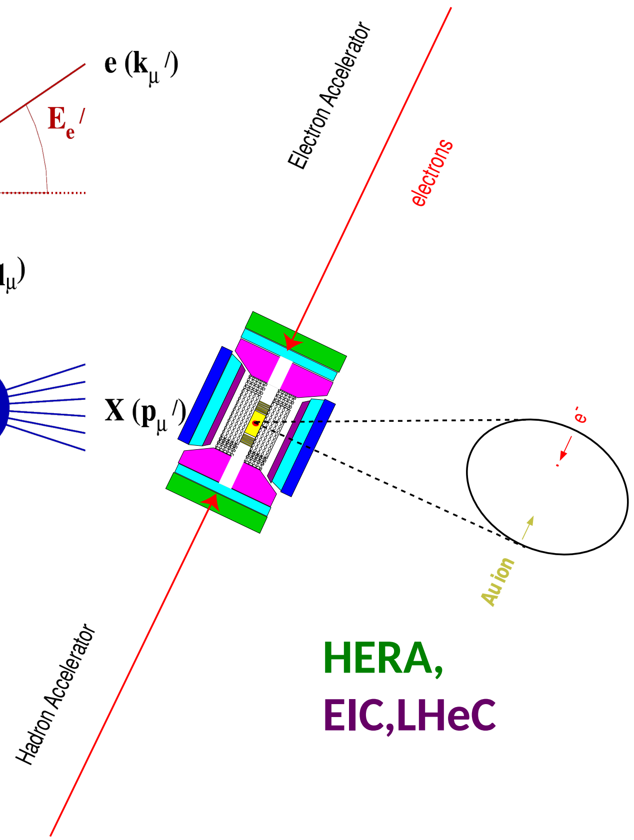




Fixed Target Particle Accelerator Experiments
Wave length: 0.01 fm (20 GeV)
Resolution: ~ 0.1 fm

SLAC,EMC,NMC,E665,BCDMS, HERMES,JLab,COMPASS…
JLab 12 GeV





HERA,
EIC,LHeC

Collider Experiments
Wave Length: 0.0001 fm
(EIC: 20 GeV + 100 GeV)
Resolution: 0.01-0.001 fm

The glue that binds us all:

Imaging matter below 10^{-15} m with an Electron-Ion Collider

What does the proton look like ?

Static pictures | **Glue dominated boosted proton**

Bag model:

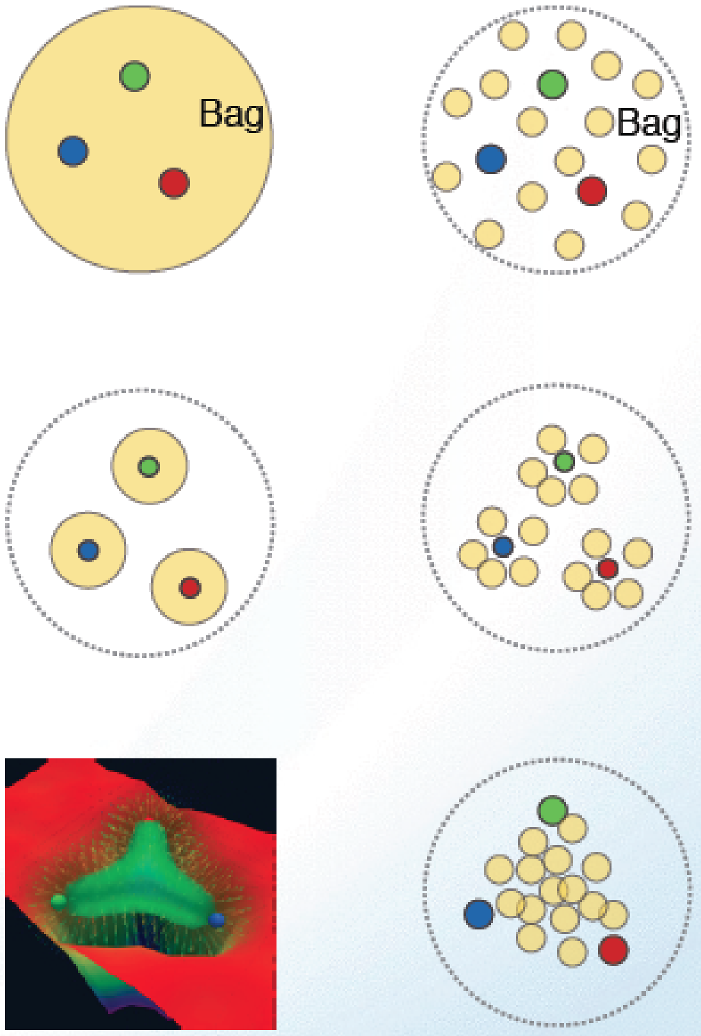
- Field energy distribution is wider than the distribution of fast moving light quarks

Constituent quark model:

- Gluons and sea quarks “hide” inside massive quarks
- Sea parton distribution similar to valence quark distribution

Lattice gauge theory:

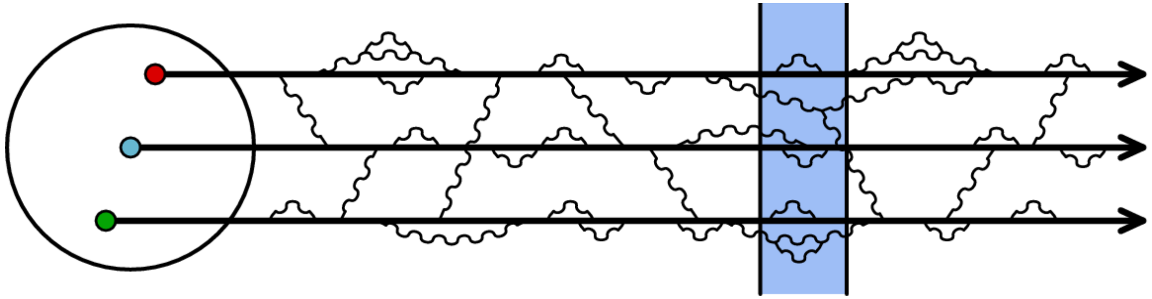
- (with slow moving quarks)
- gluons are more concentrated than quarks



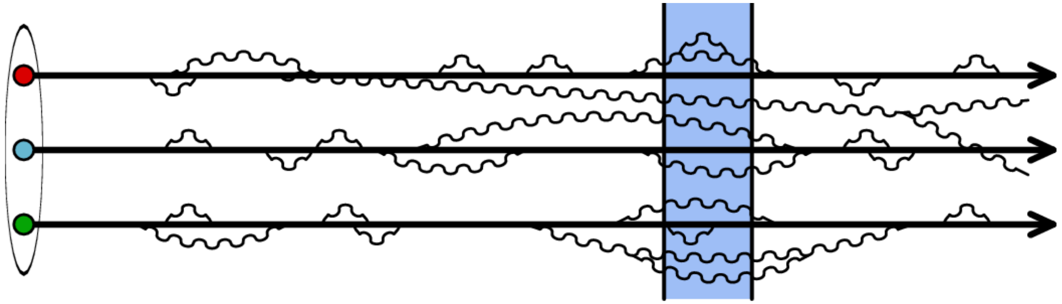
The boosted proton

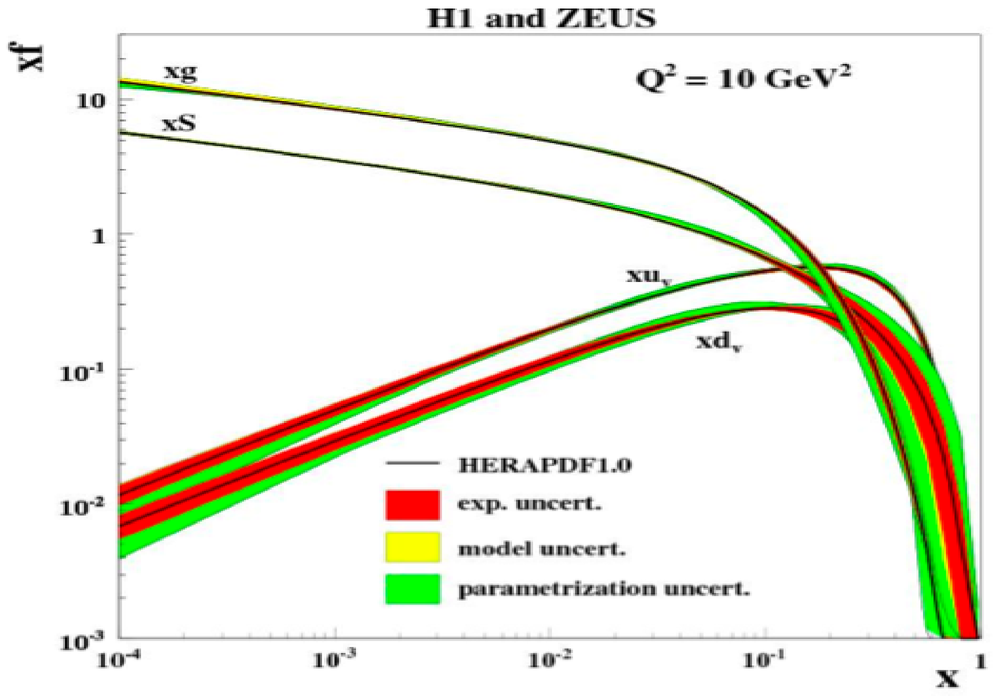
In QCD, the proton is made up of quanta that fluctuate in and out of existence

Low Energy
or large x



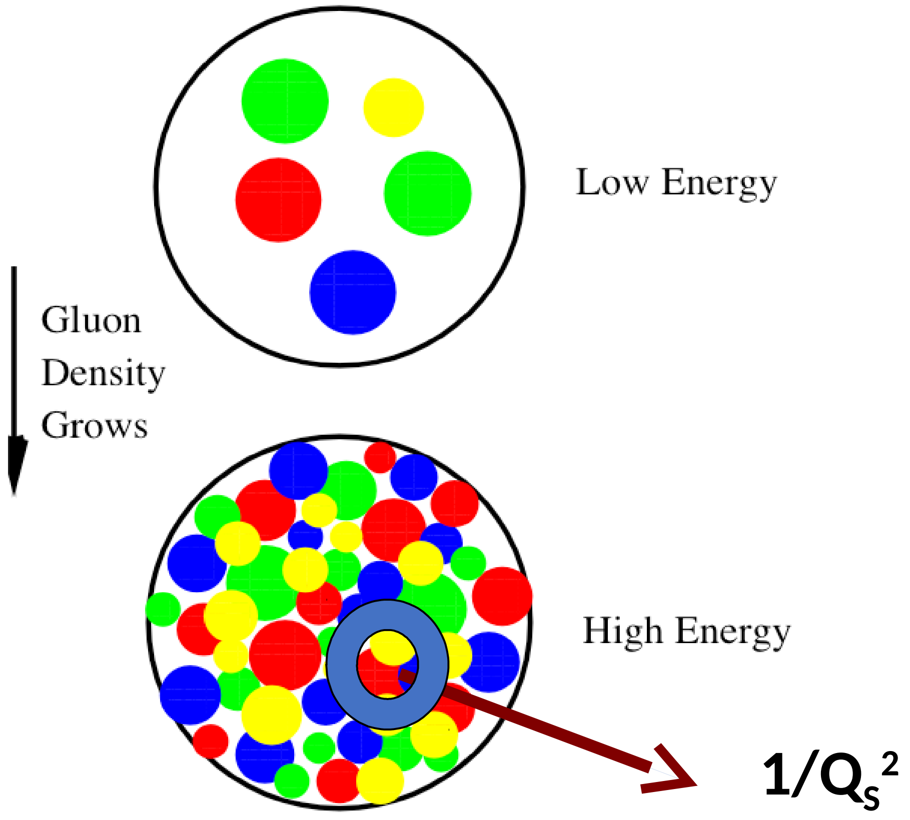
High Energy
or small x

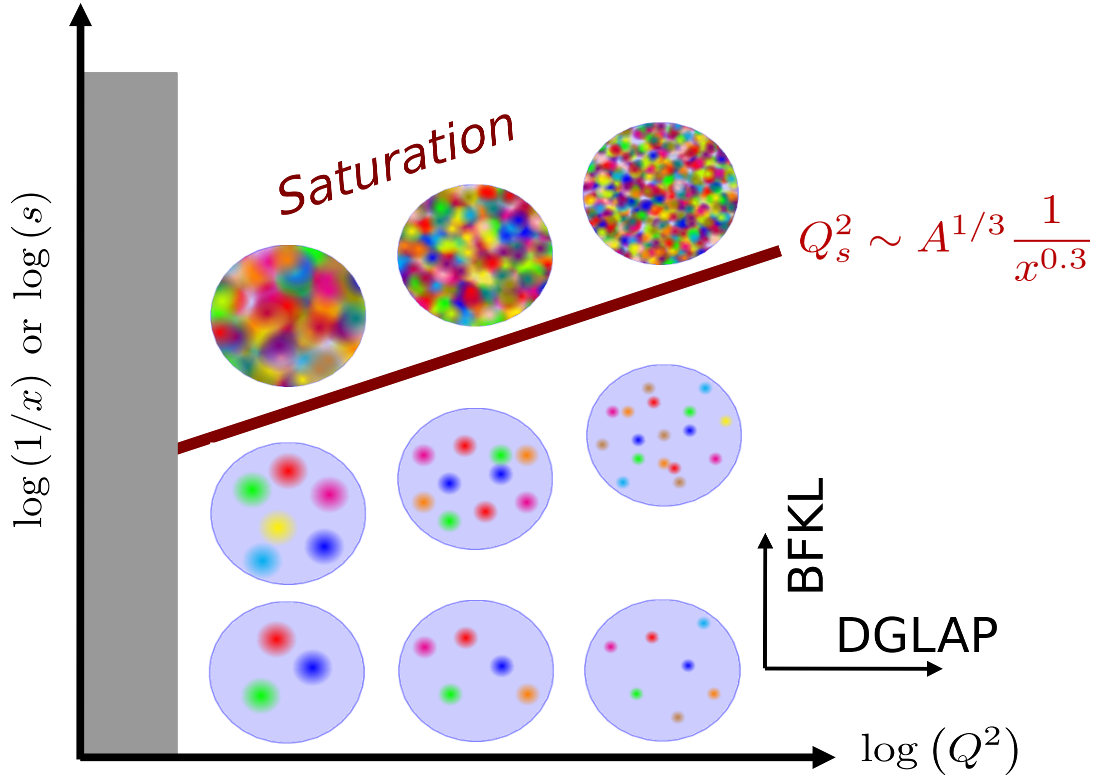




The boosted proton

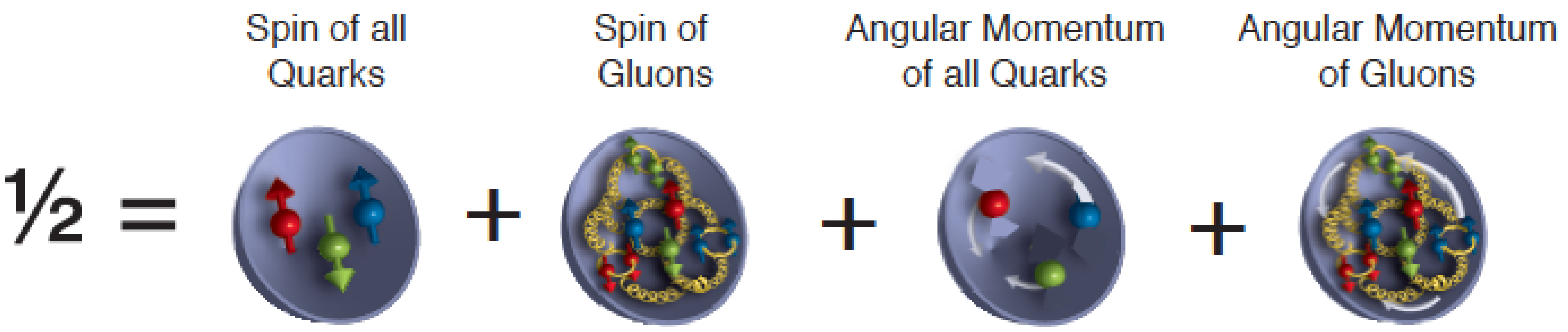
Boosted protons: classical coherence from quantum fluctuations

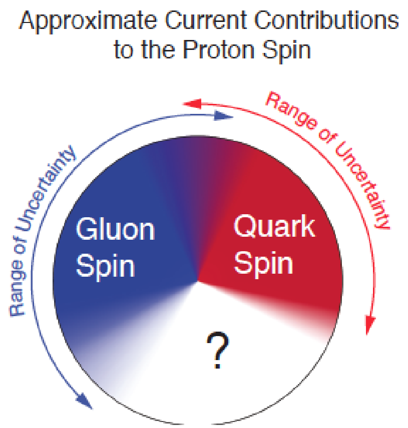




Stability of QCD matter requires saturation of over-occupied gluons:
Emergent dynamical saturation scale grows with energy

The proton's spin puzzle

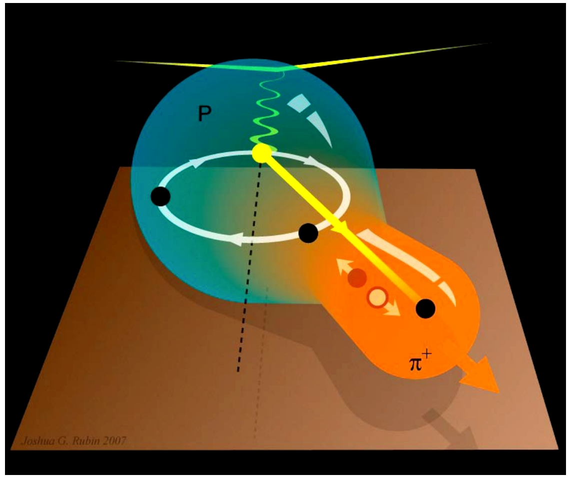


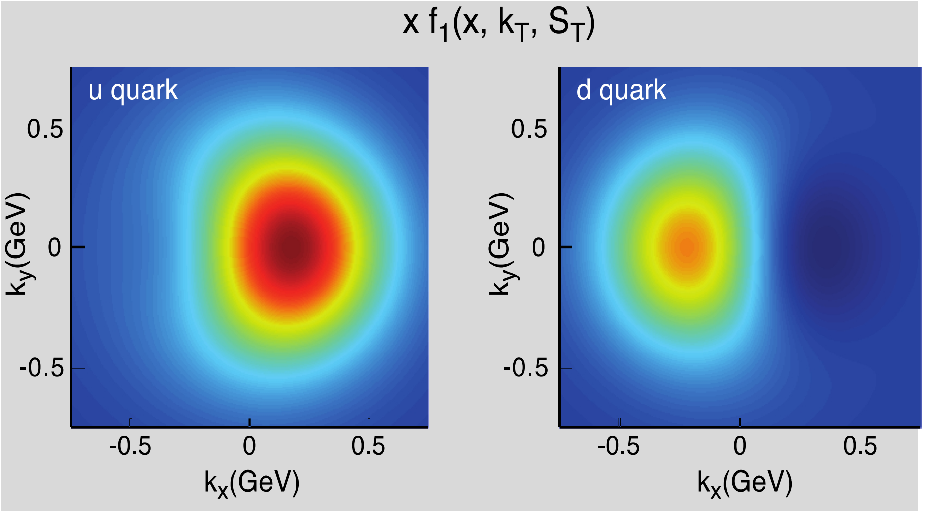


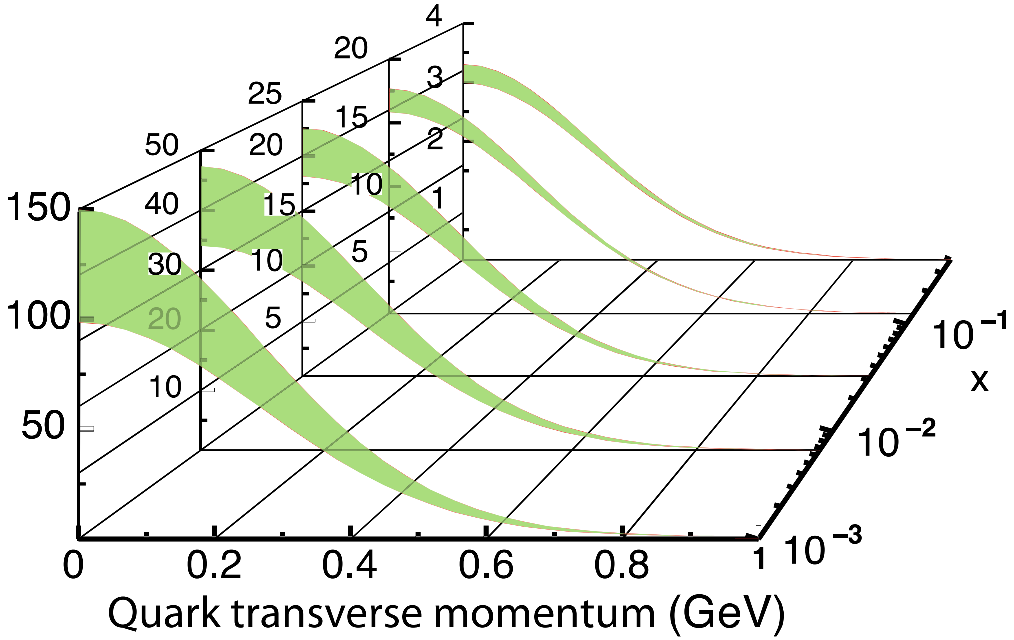
Fixed target deep inelastic scattering experiments showed that quarks carry only about 30% of the proton's spin

"Spin crisis" – a failure of the quark model picture of three relativistic "constituent" quarks

3-D imaging in semi-inclusive reactions

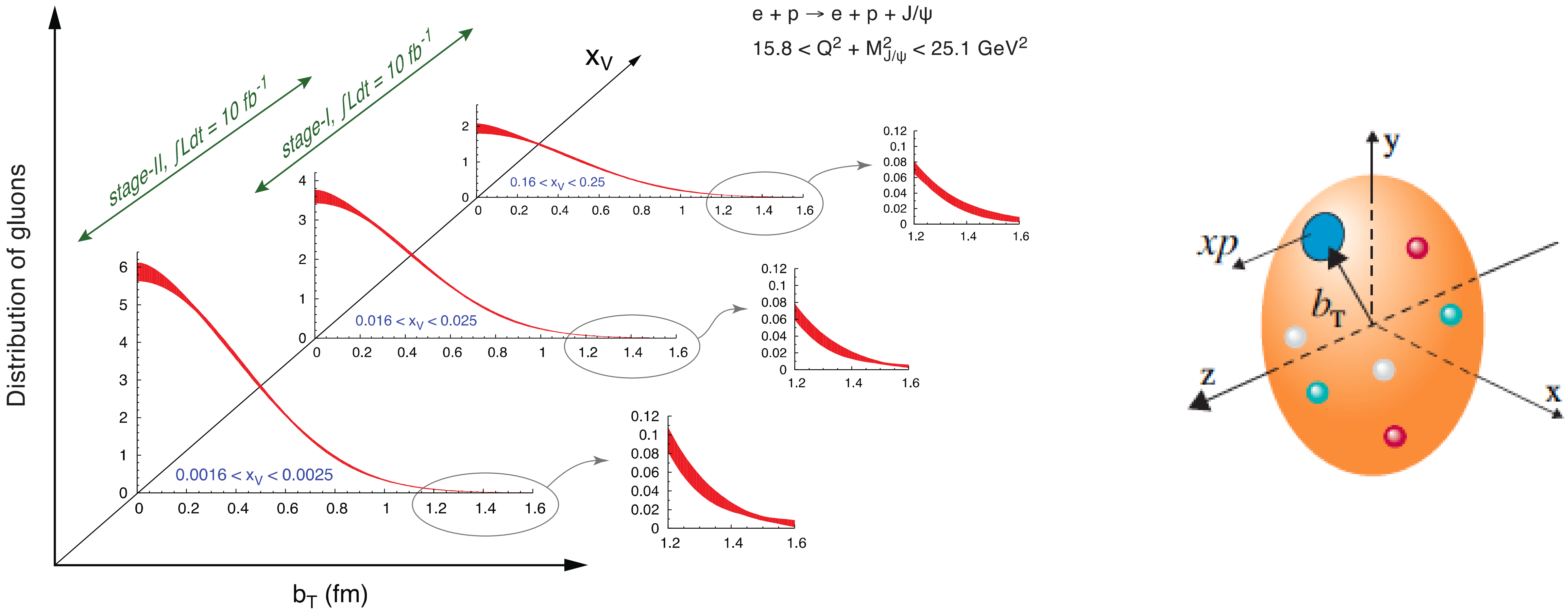






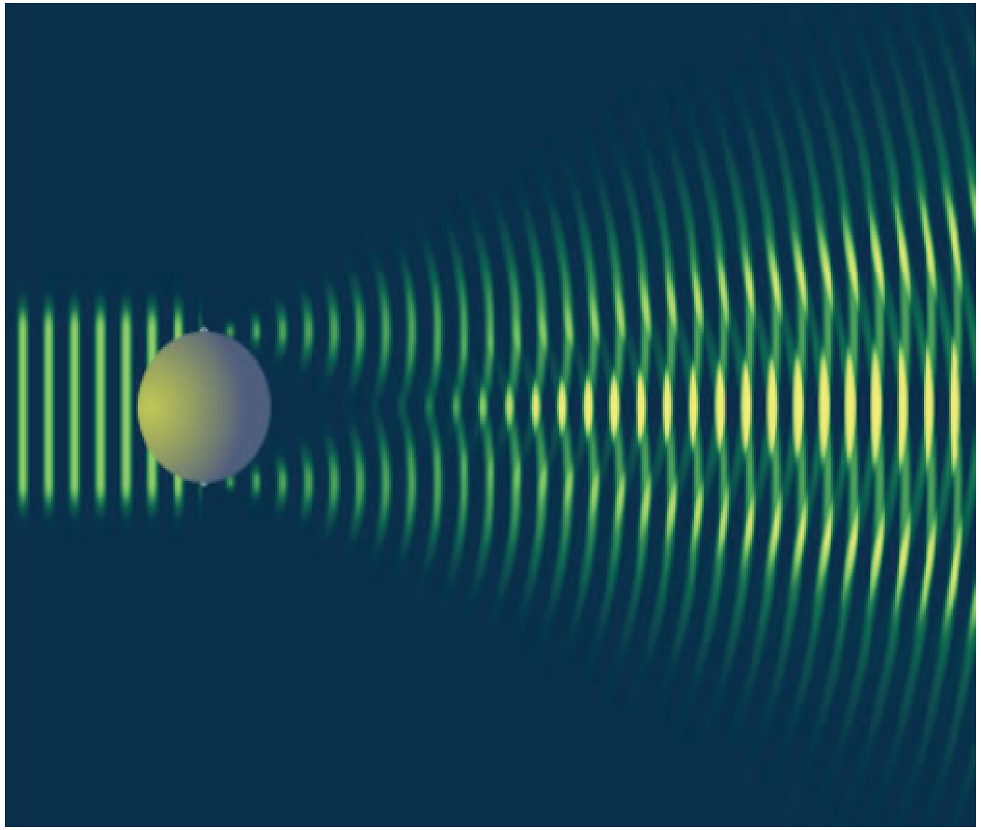
x

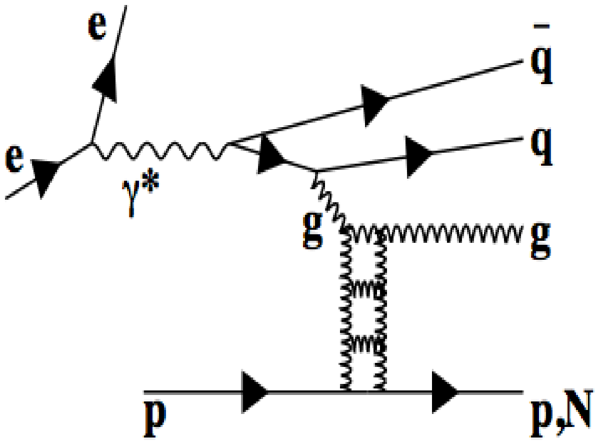
Projected images of spatial gluon distributions



High precision spatial tomography of gluon and sea quark distributions !

Quark-gluon wave patterns: Diffraction for the 21st Century





M_X

Colorless exchange

$$|e^-\rangle = |e_B\rangle + |e_B\,\gamma^*\rangle + |e_B\,\gamma^*\,q\bar{q}\rangle + |e_B\,\gamma^*\,q\bar{q}\,g\rangle + \cdots$$

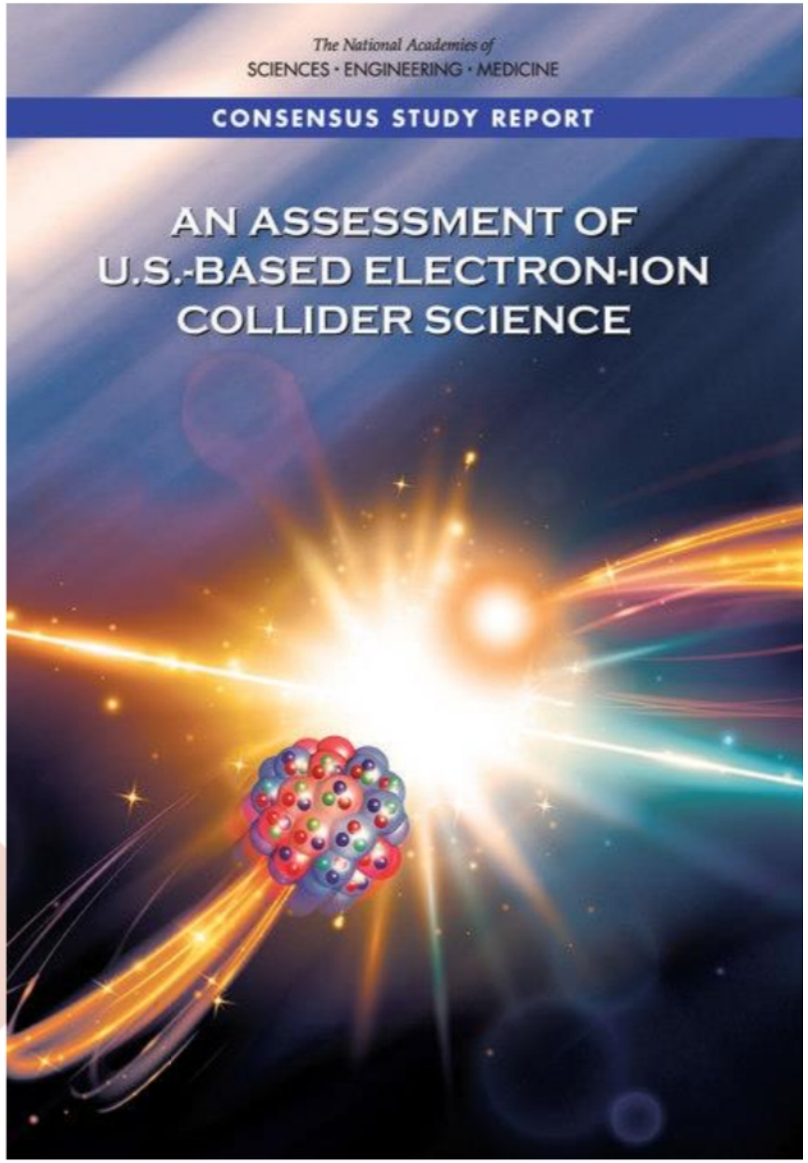
A TeV electron hits a nucleus (binding energy of 8 MeV/nucleon)

Day 1 prediction: nucleus remains intact in at least 1 in 5 events

Recent endorsement of EIC by an NAS panel

- How does the mass of the proton arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons

Awaiting Critical Decision zero – this year



PARTICLE PHYSICS

the glue that binds us

Physicists have known for decades that particles called gluons keep protons and neutrons intact—and thereby hold the universe together. Yet the details of how gluons function remain surprisingly mysterious

By Rolf Ent, Thomas Ullrich and Raju Venugopalan

Illustration by Maria Corte