Ultrarelativistic heavy ion collisions: the first billion seconds

Gordon Baym
University of Illinois

QM 2015, Kobe

28 September 2015

2015 KOBE JAPAN

Why ultrarelativistic heavy ion collisions?

The first serious planning for an ultrarelativistic heavy ion collider, RHIC, began in the summer of 1983, a mere 1.0163 X 10^{9} sec ago

*What did we have in mind when we planned and built RHIC and incorporated heavy ion collisions at LHC?

*The scientific motivations?

*Connections envisioned with the rest of physics:
Astrophysics, cosmology, condensed matter, ...?

*How have we shed light on the scientific issues?

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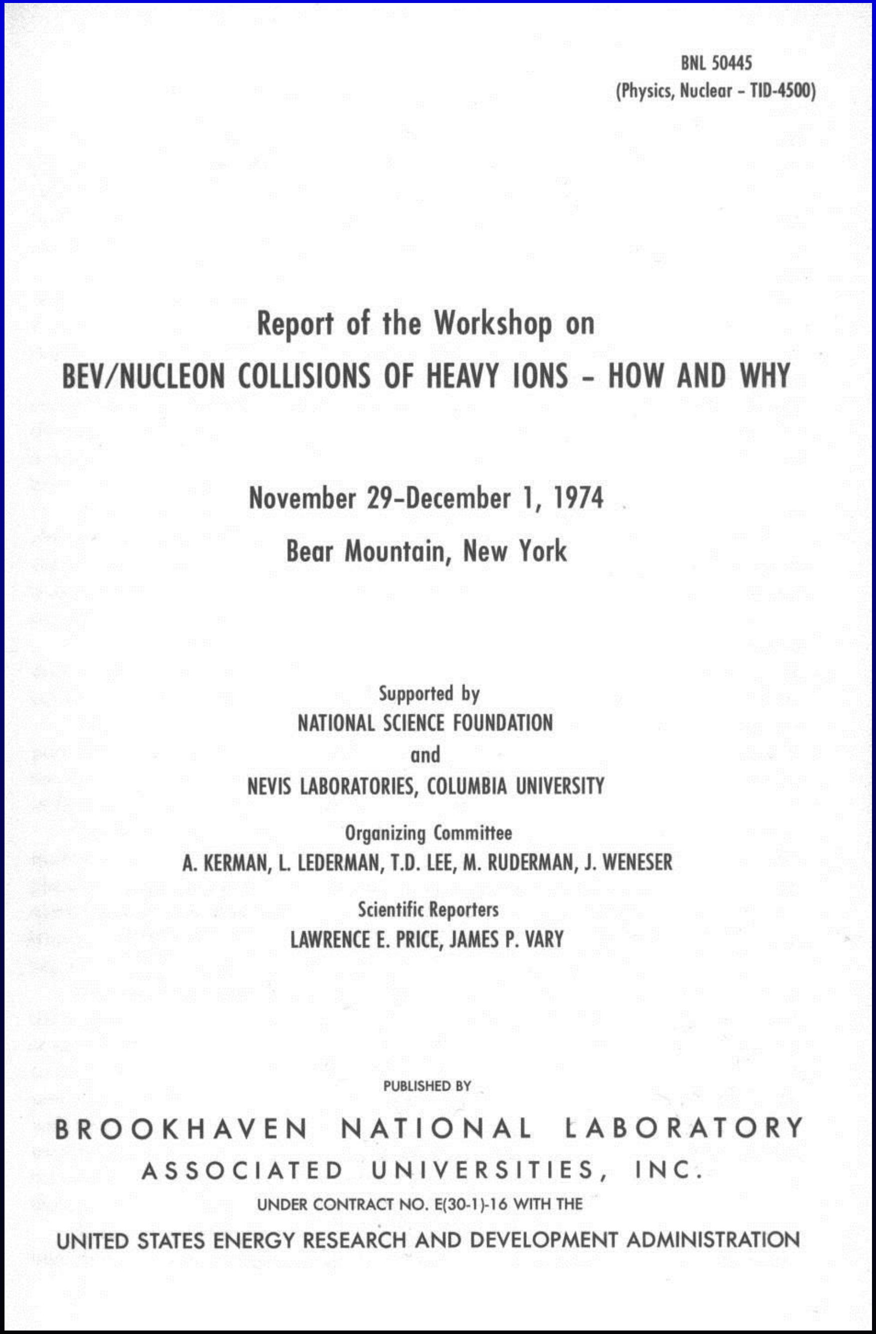
Astrophysics, cosmology, condensed matter, ...?
*How have we shed light on the scientific issues?

Pre-history of ultrarelativistic heavy ion collisions

Workshop at Bear Mountain, NY, Fall 1974 (t = - 0.25 X 10^9 sec.)

"The workshop addressed itself to the intriguing question of the possible existence of a nuclear world quite different from the one we have learned to accept as familiar and stable."

Bear Mountain was the turning point: workshop brought heavy ion physics to forefront as research tool!



BNL 50445
(Physics, Nuclear - TID-4500)

Report of the Workshop on
BEV/NUCLEON COLLISIONS OF HEAVY IONS - HOW AND WHY

November 29-December 1, 1974
Bear Mountain, New York

Supported by
NATIONAL SCIENCE FOUNDATION
and
NEVIS LABORATORIES, COLUMBIA UNIVERSITY

Organizing Committee
A. KERMAN, L. LEDERMAN, T.D. LEE, M. RUDERMAN, J. WENESER

Scientific Reporters
LAWRENCE E. PRICE, JAMES P. VARY

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"I name this place Terra Incognita."

Stability and variability of the vacuum

Is the vacuum a medium whose properties we can change?

``We should investigate … phenomena by distributing high energy or high nucleon density over a relatively large volume.”
T.D. Lee

Possibly restore broken (chiral) symmetries, create dense abnormal states of nuclear matter at high ρ by heavy ion collisions:

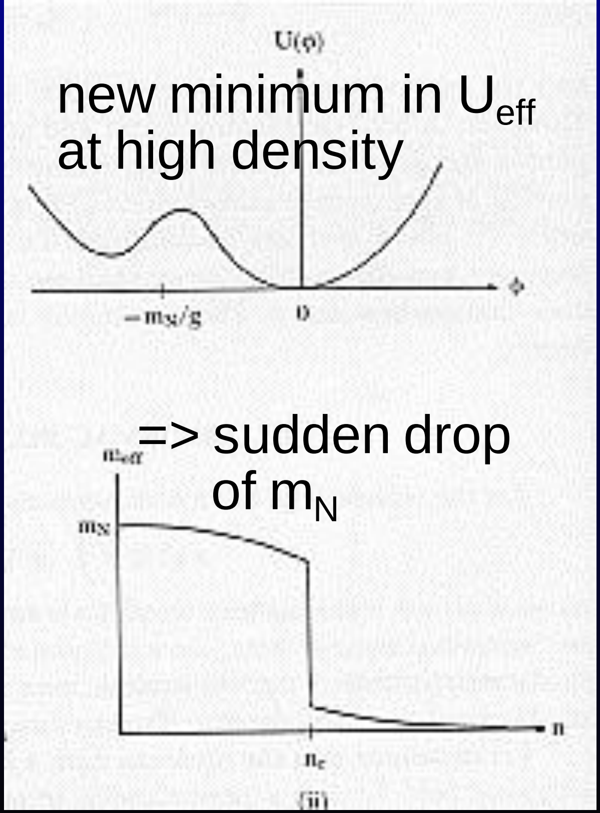
Lee-Wick low mass nucleon matter?

$m_N = g\, U_{eff}$

stable abnormal nuclei?

detectable in high energy cosmic rays?

(foreshadowing chiral symmetry restoration but with nucleonic degrees of freedom)



new minimum in U_{eff} at high density

=> sudden drop of m_N

Li Keran 1989 (T.D. Lee)

What are the properties of matter under extreme conditions? High temperature, high densities!

Bear Mountain 1974:

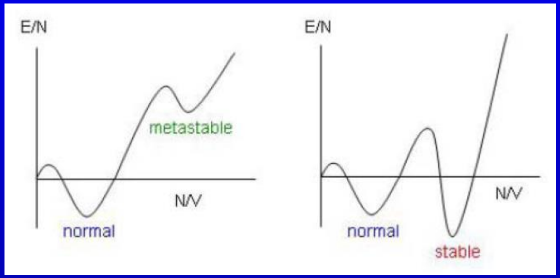
Lee-Wick abnormal nucleon matter
Hagedorn hadronic resonance gas
Walecka mean field model

Quark matter as the ultimate state:

- Itoh 1970: in neutron stars
- Carruthers 1973: "quarkium, a bizarre Fermi liquid"
- Gross, Wilczek & Politzer: Asymptotic freedom of QCD, 1973
- Cabbibo & Parisi, 1975: Deconfinement transition
- Collins & Perry, 1975: Ultrahigh density and temperature ⇔ asymptotic freedom. Weakly interacting "quark soup"
- Quark matter in neutron stars: "Can a neutron star be a giant MIT bag?" -- GB and Chin, 1976

Were we playing with fire?

Could seeds of unusual states set off a global catastrophe?



New ground state, stable or metastable?

"Lee-Wick theory indicates that 10^8 or 10^9 [abnormal superdense nuclei] have already been produced on the moon, and that the moon is still there, albeit with large holes." Leon Lederman

The New York Times
nytimes.com

March 29, 2008

Asking a Judge to Save the World, and Maybe a Whole Lot More

By DENNIS OVERBYE

The New York Times

April 15, 2008
Essay

Gauging a Collider's Odds of Creating a Black Hole

By DENNIS OVERBYE

The New York Times
nytimes.com

September 11, 2001

Physicists Strive to Build A Black Hole

By GEORGE JOHNSON

At RHIC startup

... and even now!

9/14/2015 Are we all going to die next Wednesday? | Daily Mail Online

Are we all going to die next Wednesday?

Two nightmare scenarios, two ends of the world. In the first, there is little warning. For maybe a month there would be no sign that life was about to come to an abrupt and nasty end for all living things on Earth.

Then, earthquakes would start unexpectedly, alerting geologists that something terrible, unimaginable, was amiss.

After a few days, these seismic disturbances would reach catastrophic proportions.

Cities would be levelled, the oceans would rise and wash in a series of mega-tsunamis that would attack the world's coasts, killing millions.

Is the end of the world nigh? Doom-mongers fear the consequences of scientists replicating the Big Bang

Medieval sk
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The world's
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create £20m

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The crime-fig
style plastic
is latest wea

The superc
you'll DIE: E
supercomp

Apple reveal
iPhone 6s ar
than 10 MILL

Some folk h
are genetica

Sept. 7, 2015

THE DAILY REPORTER

NEWS NOW Coldwater downs Marshall 9-7 to improve to 2-0 ... Wolverines fall in Harbaugh's op

We should be very scared about CERN

Page 2 of 3 - Within CERN, large bunches of molecular particles are accelerated to 99.9 percent of the speed of light, eventually colliding head on, which releases unbelievable energy, heat and many dangerous things such as worm holes, dark (anti) matter and black holes. In particular, it is the creation of the dark (anti) matter and the black holes by CERN that could destroy our universe in less time than it takes to blink an eye.

Sept. 14, 2015

Significant early meetings

First workshop on ultra-relativistic nuclear collisions, Berkeley, May 1979 (w. GSI) (*L. Schroeder*) = QM 0

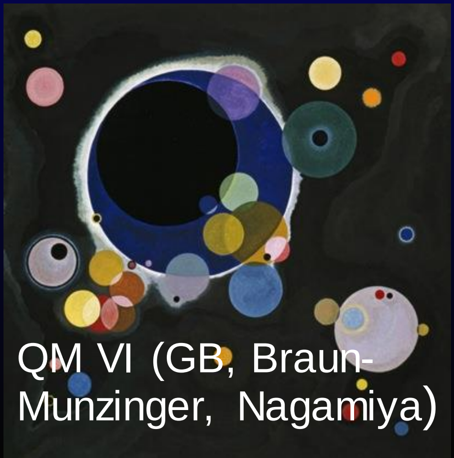
High-energy nuclear interactions and the properties of dense nuclear matter, Hakone (*K. Nakai & A. Goldhaber*), July 1980.

Statistical mechanics of quarks and hadrons, Bielefeld (*H. Satz*), Aug. 1980 = QM IA (theory)

Workshop on future relativistic heavy ion experiments, GSI, Oct. 1980 (*R. Bock & R. Stock*) = QM IB (expt.)

Quark matter formation and heavy ion collisions, Bielefeld, May 1982 (*M. Jacob & H.Satz*) = QM II *[= (n+1)A.B.]*

Quark Matter '83, Brookhaven, Sept. 1983 (*T. Ludlam and H. Wegner*) = QM 3



QM VI (GB, Braun-Munzinger, Nagamiya)

A. B. Migdal G. Baym T. D. Lee Mayor of Bielefeld H. Satz

International Symposium

Statistical Mechanics of Quarks and Hadrons

Bielefeld, August 24-31, 1980

Getting going

Fixed target heavy ion machines
  Bevalac at Berkeley -- 1974
  Numatron (INS Tokyo) ~1979-82, up to U ≤ 1.3 GeV/A– not built

Interest in U.S., Europe, and Japan in colliding heavy ions – 1983.
  VENUS at LBL

Open meeting of U.S. Nuclear Science Advisory Committee (NSAC) Aurora, N.Y., July 1983:

During the meeting Isabelle (or Colliding Beam Accelerator) 200 X 200 GeV protons at Brookhaven was cancelled, in favor of building the Superconducting Super Collider (SSC, or Desertron) 20 X 20 TeV -- itself cancelled in 1993

Forlorn beam tunnel of
the CBA (Isabelle), 1983

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Decision in 1983 to build the "tunnel stuffer," the Relativistic Heavy Ion Collider (RHIC) at BNL. First suggestion by J. Bjorken (March 1983 – 50 GeV/A). Proposal (1984) with first beams in 1990. Actual first beams in 2000.

AGS fixed target heavy ion program proposed 1983.
Ran 1986 - ~2002, Au from 1992 at $\sqrt{s_{NN}} \leq 4.3$ GeV

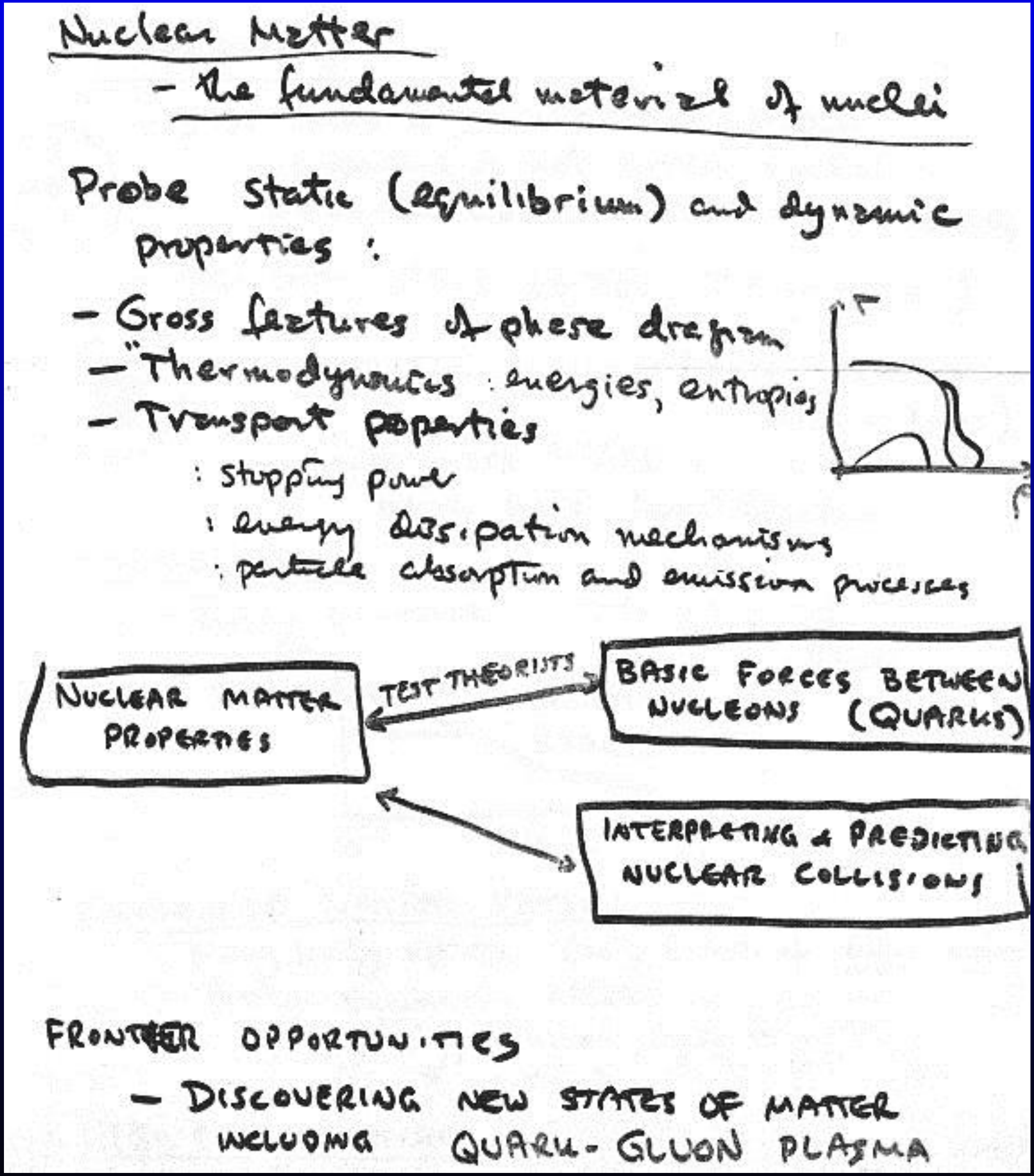
First glimmer of RHIC

NSAC Meeting at Wells College, Aurora, N.Y. July 11-15, 1983

Aurora, N.Y., July 1983

Subgroup on nuclear matter under extreme conditions*:*

Arthur Kerman, Arthur Schwarzschild, GB, Miklos Gyulassy, Tom Ludlam, Larry McLerran, Lee Schroeder, Steve Vigdor, & Steve Koonin



Nuclear Matter

– the fundamental material of nuclei

Probe static (equilibrium) and dynamic properties :

– Gross features of phase diagram
– "Thermodynamics : energies, entropies
– Transport properties
  : stopping power
  : energy dissipation mechanisms
  : particle absorption and emission processes

NUCLEAR MATTER PROPERTIES

TEST THEORISTS

BASIC FORCES BETWEEN NUCLEONS (QUARKS)

INTERPRETING & PREDICTING NUCLEAR COLLISIONS

FRONTIER OPPORTUNITIES

– DISCOVERING NEW STATES OF MATTER INCLUDING QUARK-GLUON PLASMA

Promised connections of heavy ions to outside

Neutron stars

$\rho > \rho_{nm}$, T < 1-10 MeV, R ~ 10-12 km, M ~ 1.2-2 M_{sun}

--birth, evolution and cooling (x-ray satellite observations)

--upper mass limits, black hole identification

Supernova and gravitational collapse

-- bounce above ρ_{nm}, energy release

-- hot n-rich nuclei

Cosmology

-- confinement phase transition?

-- mini- black holes M~ $M_{jupiter}$ ~ 10^{-2} M_{sun}

Cosmic rays

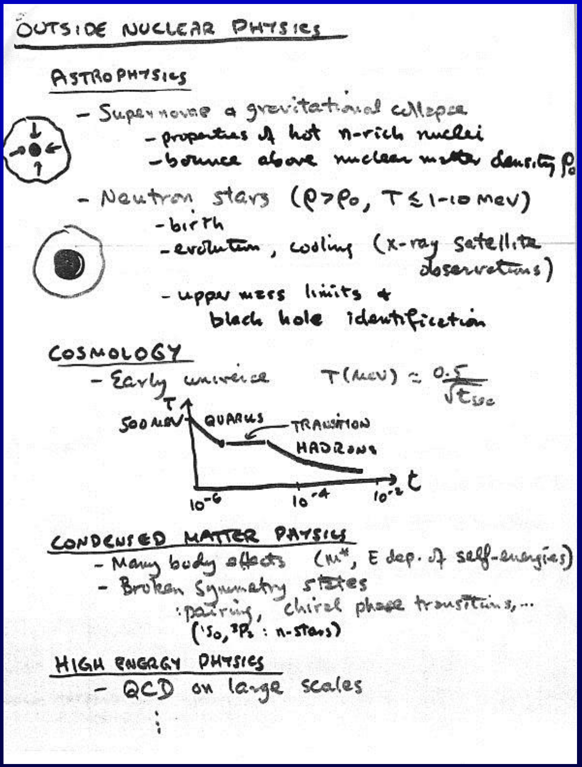
Condensed Matter Physics

-- many body effects (quasiparticles, ...)

-- broken symmetry states (pairing, chiral phase transitions)

High energy physics

-- QCD on large distance scales



OUTSIDE NUCLEAR PHYSICS

ASTROPHYSICS

- Supernovae & gravitational collapse
  - properties of hot n-rich nuclei
  - bounce above nuclear matter density ρ_0
- Neutron stars ($\rho > \rho_0$, $T \lesssim 1-10$ MeV)
  - birth
  - evolution, cooling (x-ray satellite observations)
  - upper mass limits & black hole identification

COSMOLOGY

- Early universe $T(\text{MeV}) \simeq \frac{0.5}{\sqrt{t_{sec}}}$

CONDENSED MATTER PHYSICS

- Many body effects (m^*, E dep. of self-energies)
- Broken Symmetry states
  : pairing, chiral phase transitions, ...
  ($^1S_0$, $^3P_2$: n-stars)

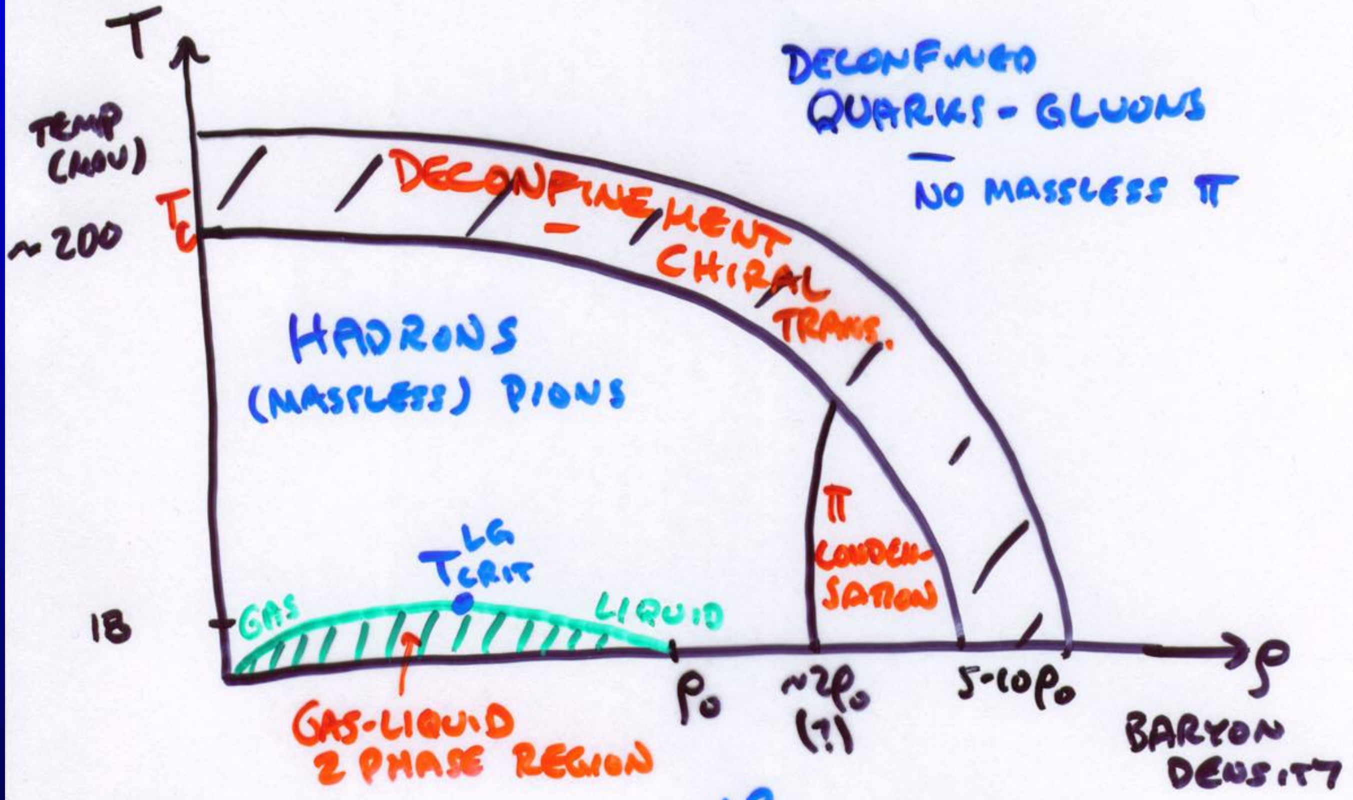
HIGH ENERGY PHYSICS

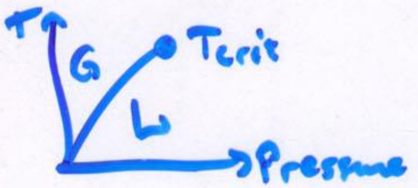
- QCD on large scales

⋮

EXPECTED PHASE DIAGRAM

⇒ MANY OPPORTUNITIES

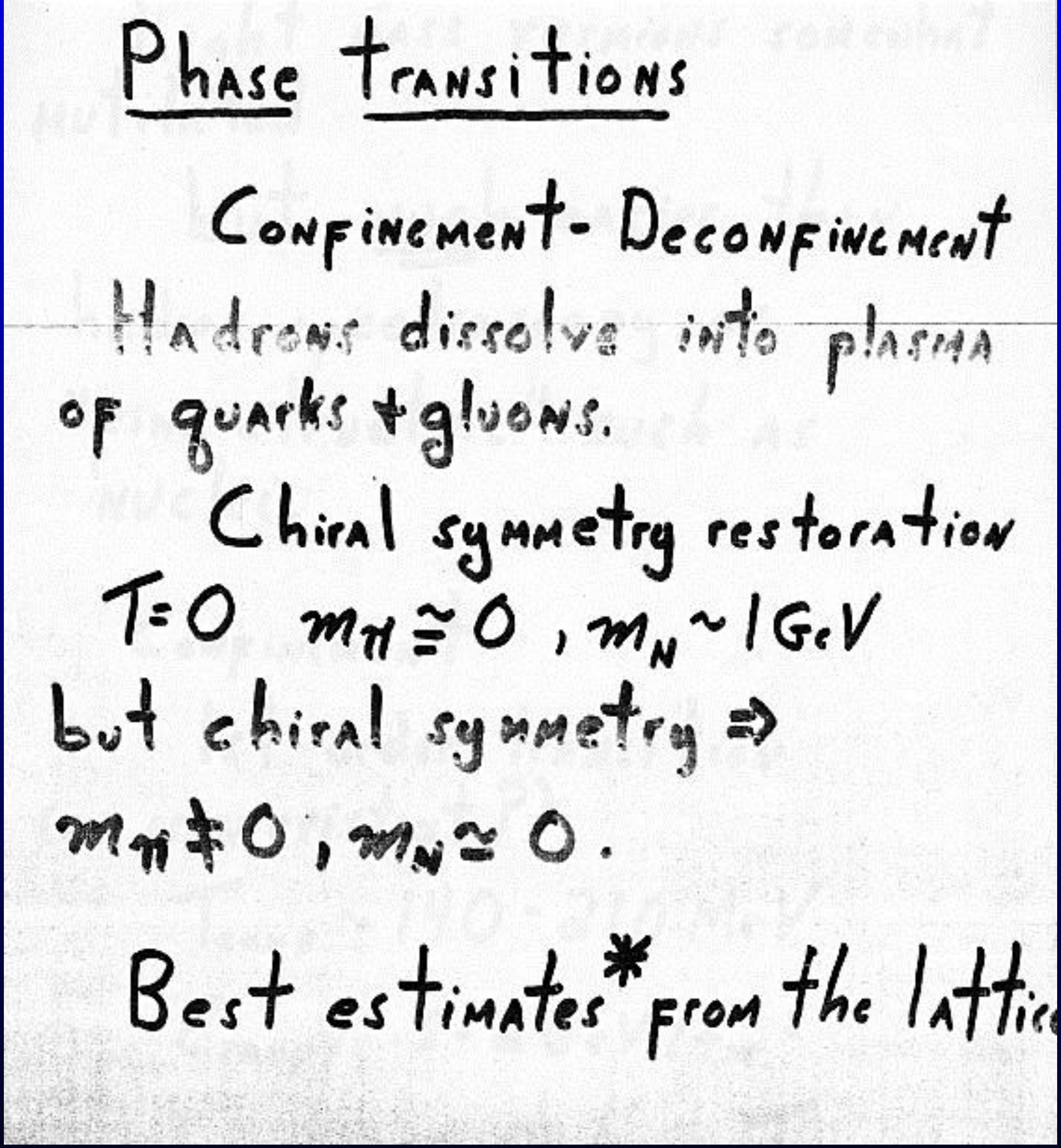




PLUS

- Z/A DEPENDENCE
- HIGH ANGULAR MOMENTUM DEPENDENCE
- PAIRING ($^1S_0$, $^3P_2$) TRANSITIONS (T$_c$ ~ 5 MeV)

Possibility of deconfinement phase transition



Phase transitions

Confinement-Deconfinement

Hadrons dissolve into plasma of quarks + gluons.

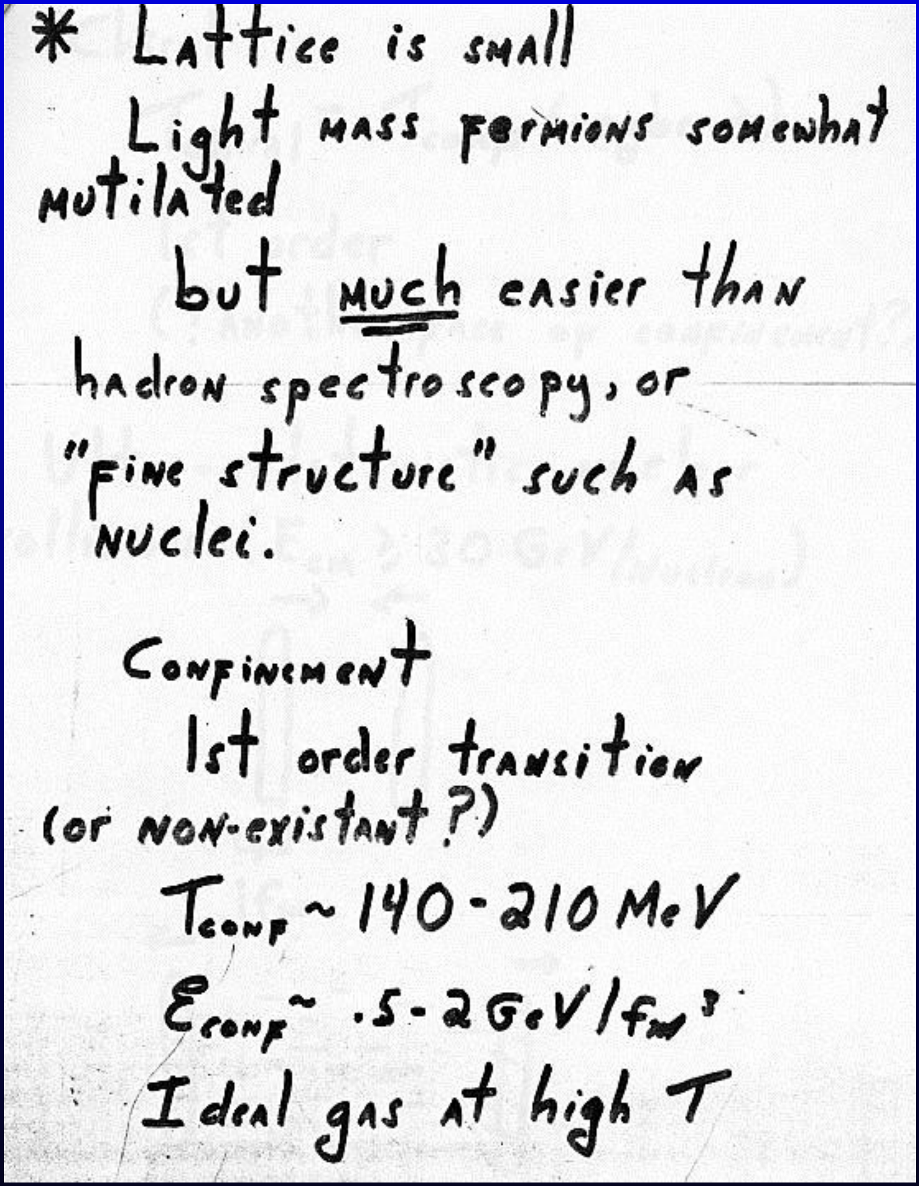
Chiral symmetry restoration

T=0 $m_\pi \cong 0$, $m_N \sim 1$ GeV

but chiral symmetry ⇒

$m_\pi \neq 0$, $m_N \cong 0$.

Best estimates* from the lattic



* Lattice is small

Light mass fermions somewhat mutilated

but much easier than hadron spectroscopy, or "fine structure" such as nuclei.

Confinement

1st order transition (or non-existant?)

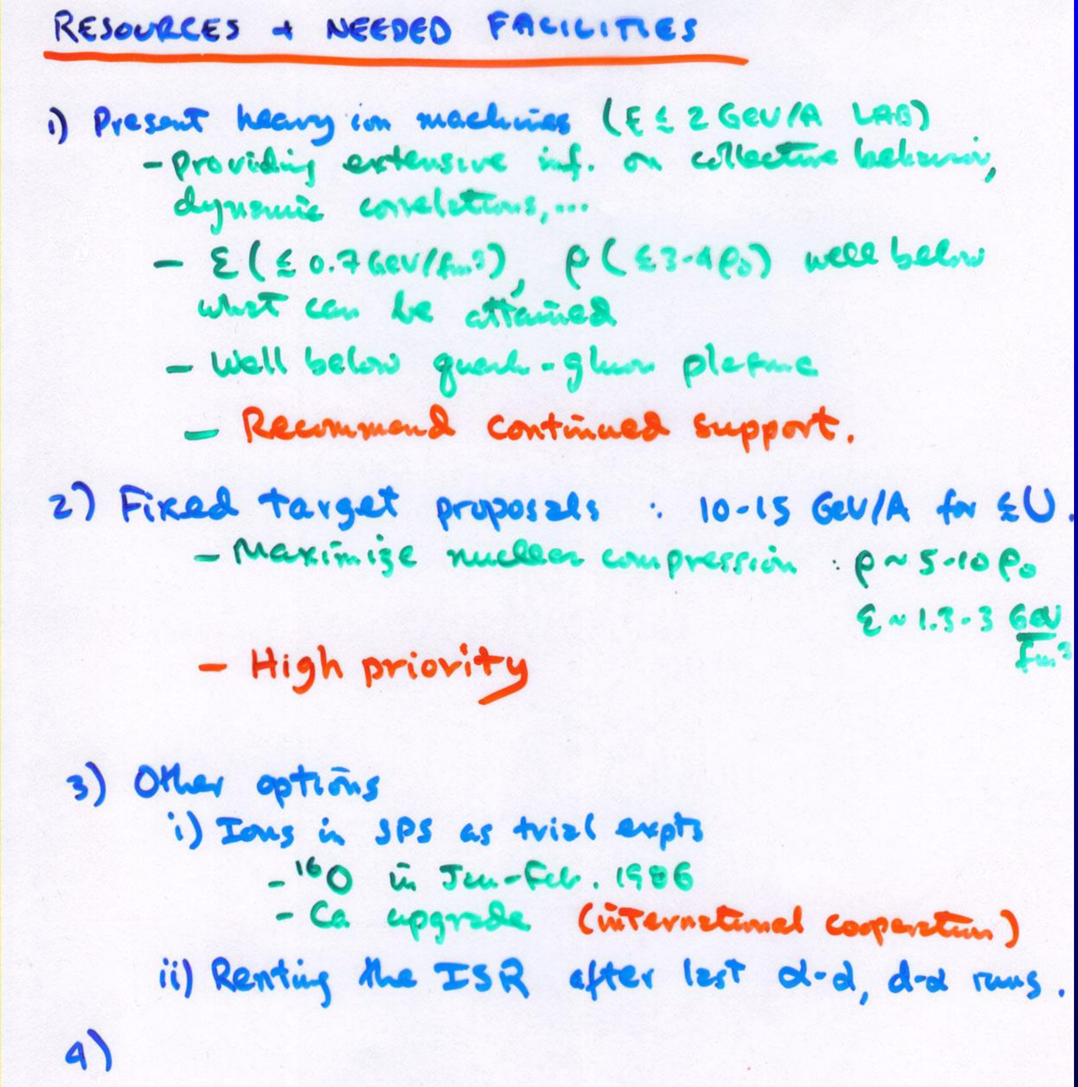
$T_{conf} \sim 140-210$ MeV

$\varepsilon_{conf} \sim .5-2$ GeV/fm^3

Ideal gas at high T

L. McLerran

Heavy ion resources and needed facilities



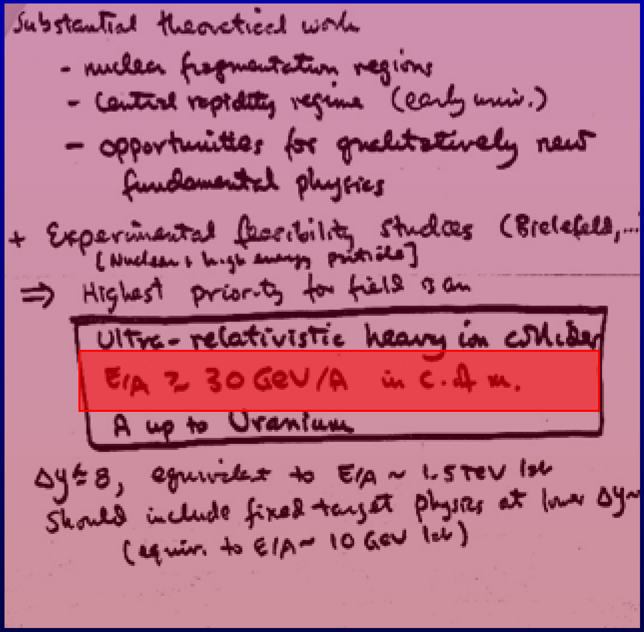
RESOURCES + NEEDED FACILITIES

1) Present heavy ion machines ($E \lesssim 2$ GeV/A LAB)
  - Providing extensive inf. on collective behavior, dynamic correlations, ...
  - ε ($\lesssim 0.7$ GeV/fm^3), ρ ($\lesssim 3$-$4\rho_0$) well below what can be attained
  - Well below quark-gluon plasma
  - Recommend continued support.

2) Fixed target proposals : 10-15 GeV/A for ≤U.
  - Maximize nuclear compression : $\rho \sim 5$-$10\rho_0$
    $\varepsilon \sim 1.3$-3 $\frac{\text{GeV}}{\text{fm}^3}$
  - High priority

3) Other options
  - i) Ions in SPS as trial expts
    - ^{16}O in Jan-Feb. 1986
    - Ca upgrade (international cooperation)
  - ii) Renting the ISR after last α-α, d-d runs.

4)



Substantial theoretical work
- nuclear fragmentation regions
- central rapidity regime (early univ.)
- opportunities for qualitatively new fundamental physics

+ Experimental feasibility studies (Bielefeld, ...
[Nuclear + high energy particle]

⇒ Highest priority for field is an

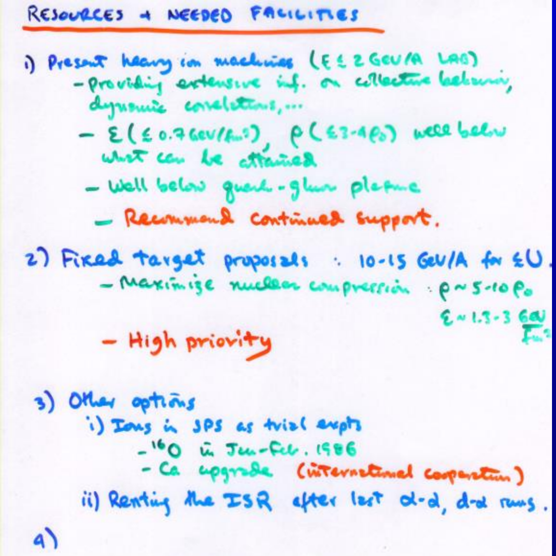
Ultra-relativistic heavy ion collider
$E/A \gtrsim 30$ GeV/A in c. of m.
A up to Uranium

$\Delta y \simeq 8$, equivalent to $E/A \sim 1.5$ TeV lab
Should include fixed-target physics at lower Δy~
(equiv. to $E/A \sim 10$ GeV lab)

Shutting down of CBA in favor of the SSC set the stage for building colliding beam heavy ion accelerator in the CBA tunnel!

Construction at 100 GeV/A driven by possibiity of producing jets that propagate through collision volume -- a wise decision.

Heavy ion resources and needed facilities



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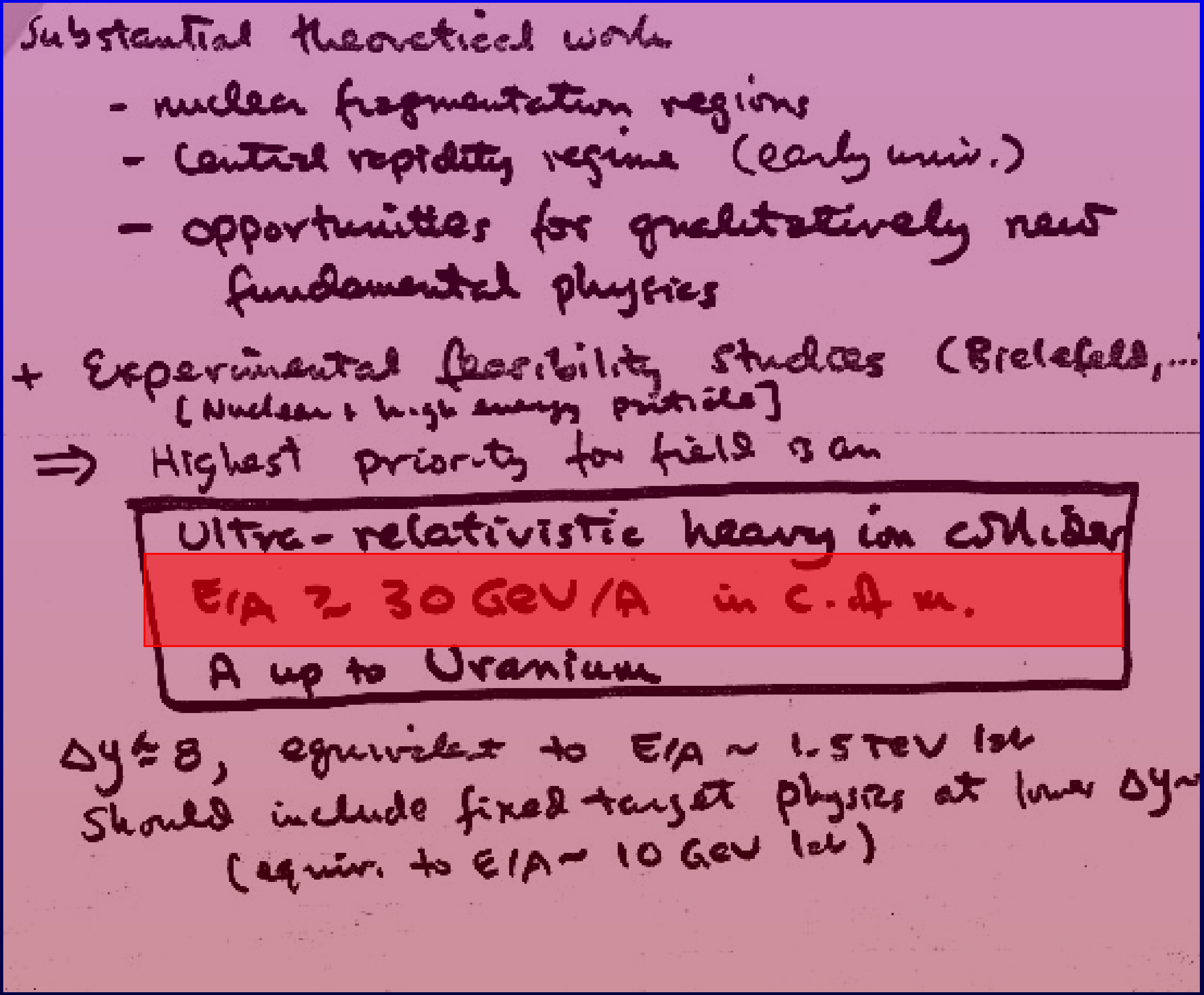

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Scientific questions in the 1983 NSAC Long Range Plan:

"What is the nature of nuclear matter at energy densities comparable to those of the early universe?"

"What are the new phenomena and physics associated with the simultaneous collision of hundreds of nucleons at relativistic energies?"

The most outstanding opportunity opened by an ultrarelativistic heavy ion collider is "the creation of extended regions of nuclear matter at energy densities beyond those ever created in the laboratory over volumes far exceeding those excited in elementary particle experiments and surpassed only in the early universe."

Physics goals of RHIC

Main issue for RHIC was to discover the properties of nuclear matter under extreme conditions -- high temperatures, high densities:

-- entropy and equation of state
-- the nature of its excitations: quasiparticles, collective modes
-- transport of conserved quantities: energy-momentum, baryons, etc.
-- dynamics
-- stopping of hadronic and quark projectiles; energy dissipation
-- particle emission

Possible discovery of new states of matter

-- quark-gluon plasma: A GOAL, NOT *THE* GOAL!
-- insights into π condensation, liquid-gas phase transition at low density and temperature.

Physics goals of RHIC, II

Study behavior of QCD at large distance scales:

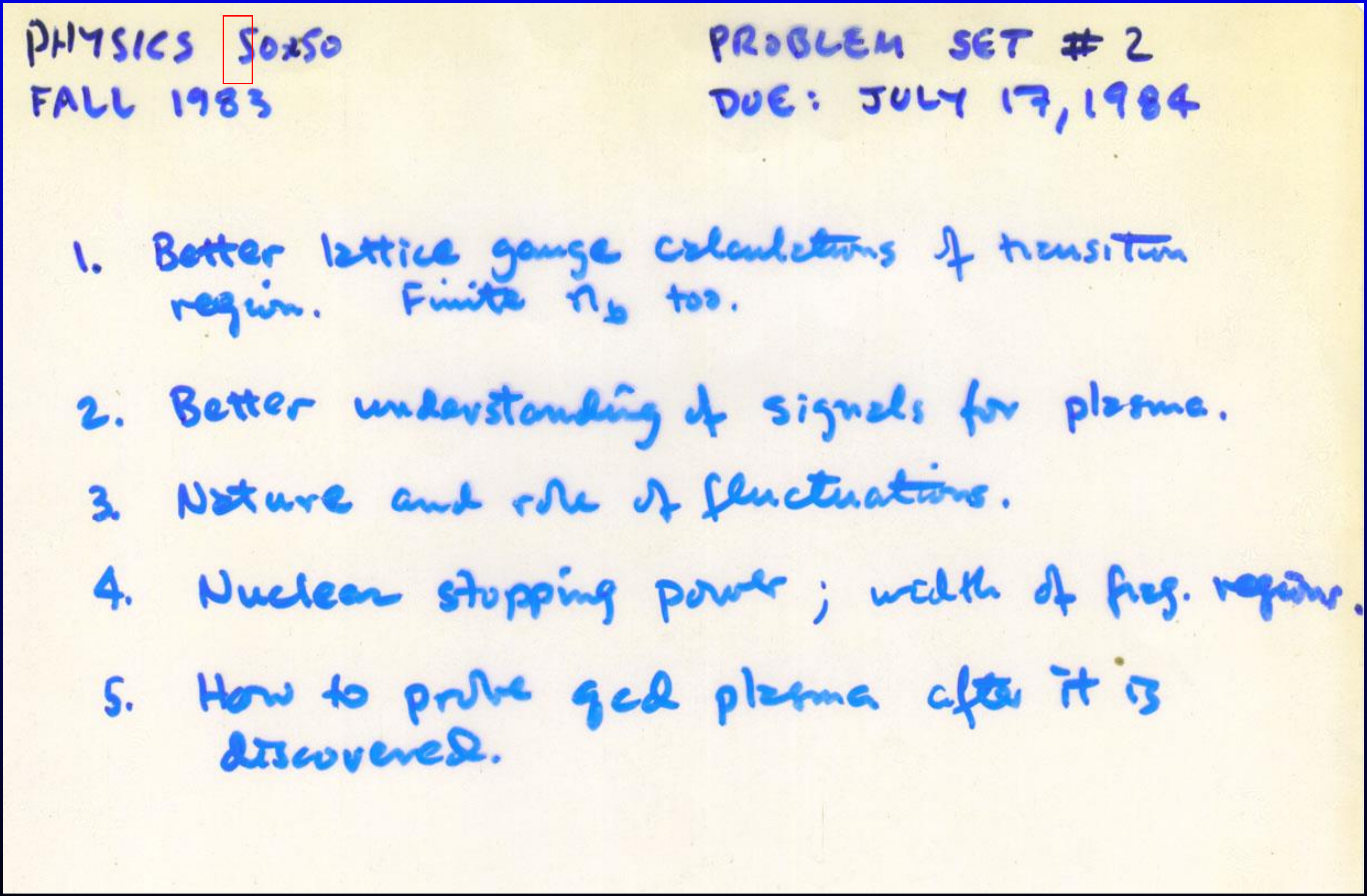
- -- long range forces between q, gluons at 5-10 fm?
- -- deconfinement transition, order? sharp? Measure Λ_{QCD}
- -- chiral symmetry restoration
- -- plasma modes

System would be strongly interacting!

Unusual objects:

- -- multiquark states
- --hadrons with heavy quarks
- --extended droplets of large strangeness
- --multi-baryon states of unusual chiral topology
- --π-μ and other exotic atoms
- --production of free quarks

Homework assignment at Quark Matter ‘83 at BNL



PHYSICS 50x50
FALL 1983

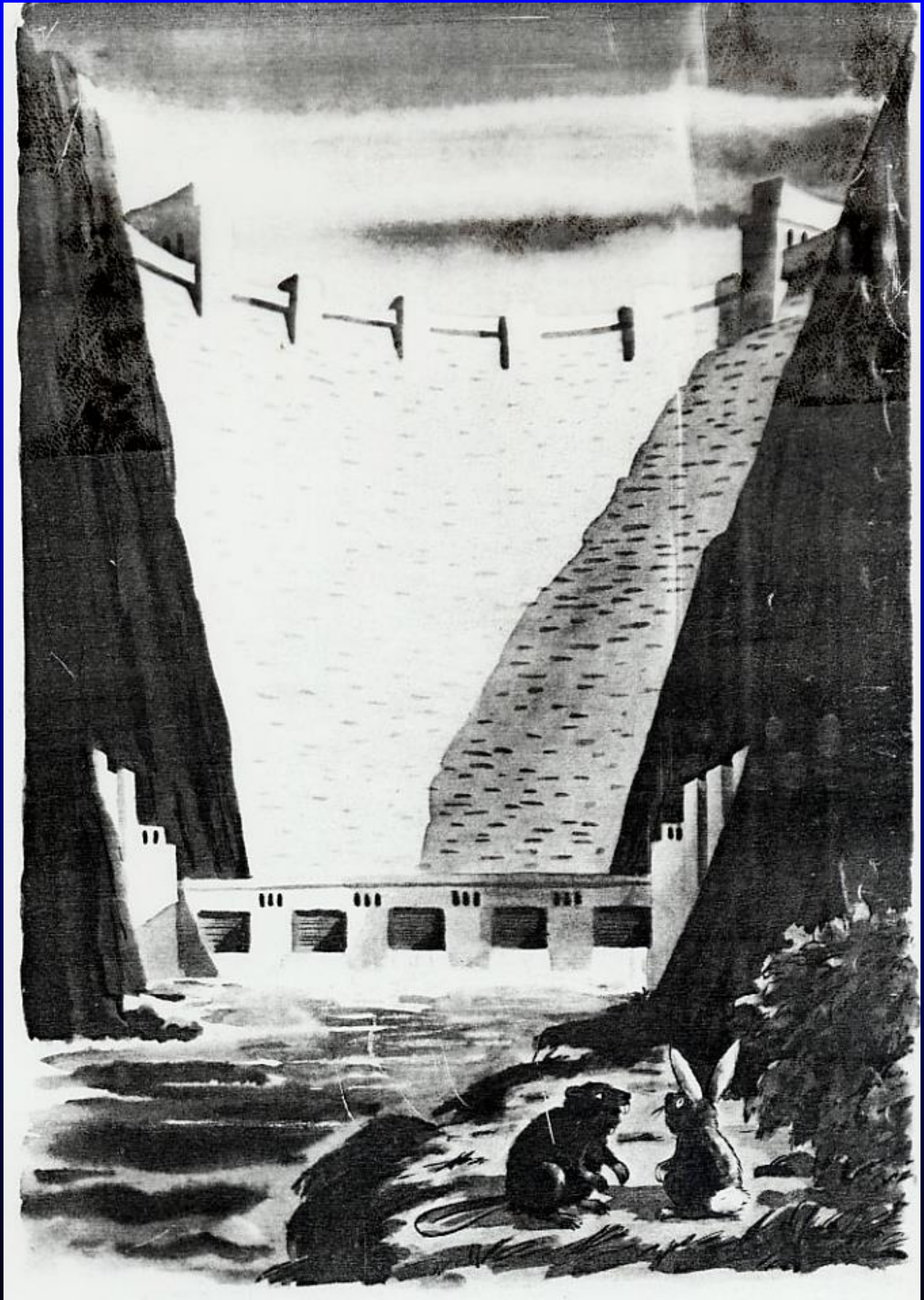
PROBLEM SET # 2
DUE: JULY 17, 1984

1. Better lattice gauge calculations of transition region. Finite n_b too.
2. Better understanding of signals for plasma.
3. Nature and role of fluctuations.
4. Nucleon stopping power; width of frag. regions.
5. How to probe qcd plasma after it is discovered.

RHIC Policy Committee 1985-95

Figure 3. 1991 RHIC Policy Committee. Front row: J Ball, J Sandweiss, T D Lee, J Symons, E Henley, S Hayakawa, W Willis, H Feshbach; back row: S Ozaki, R Bock, N P Samios, J Schiffer, G Baym, P Darriulat, M Schwartz, A Kerman.

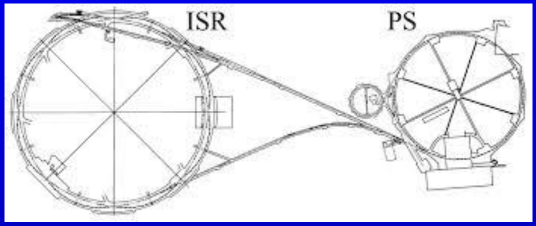
1995-97 Creation of RIKEN BNL Research Center
T.D. Lee, first director



"I didn't actually build it, but it was based on my idea."

In 2000, a mere 17 years later, the first beams at RHIC.

Heavy Ions at CERN

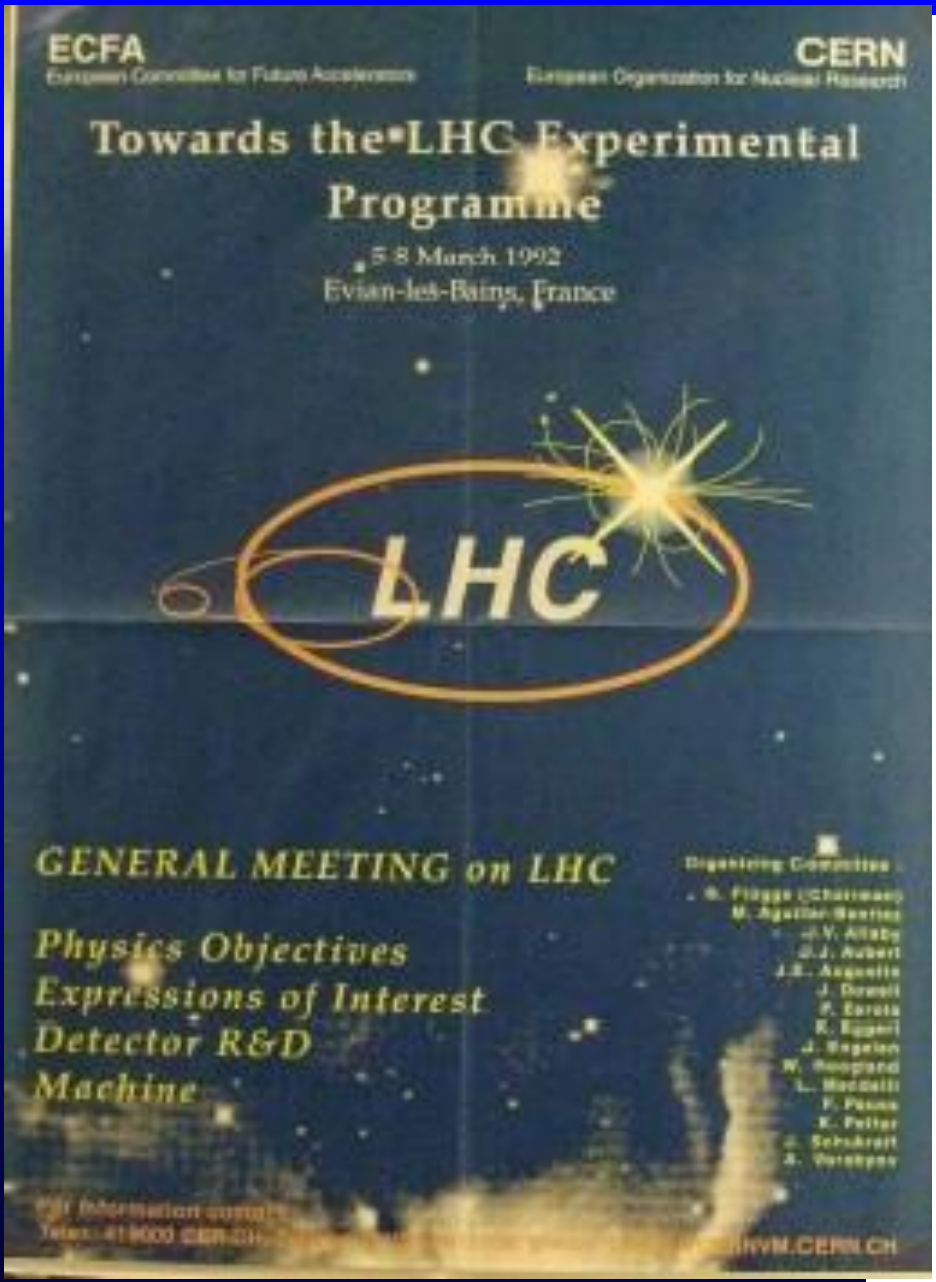


Intersecting Storage Rings (ISR), 1971–1984:
- discussions about injecting heavy ions.

G. Cocconi at Bear Mountain: transfer ions up to $^{16}0$ (and even U) from PS to ISR and eventually to SPS.

Super Proton Synchrotron (SPS), 1986-
- heavy ion experiments: NA34 (Helios), NA44, NA49, ...
- first results (^{16}O at SPS & AGS) reported at QM VI – Nordkirchen 1987

1984 ECFA-CERN workshop laid down foundations of LHC



ECFA
European Committee for Future Accelerators

CERN
European Organization for Nuclear Research

Towards the LHC Experimental Programme

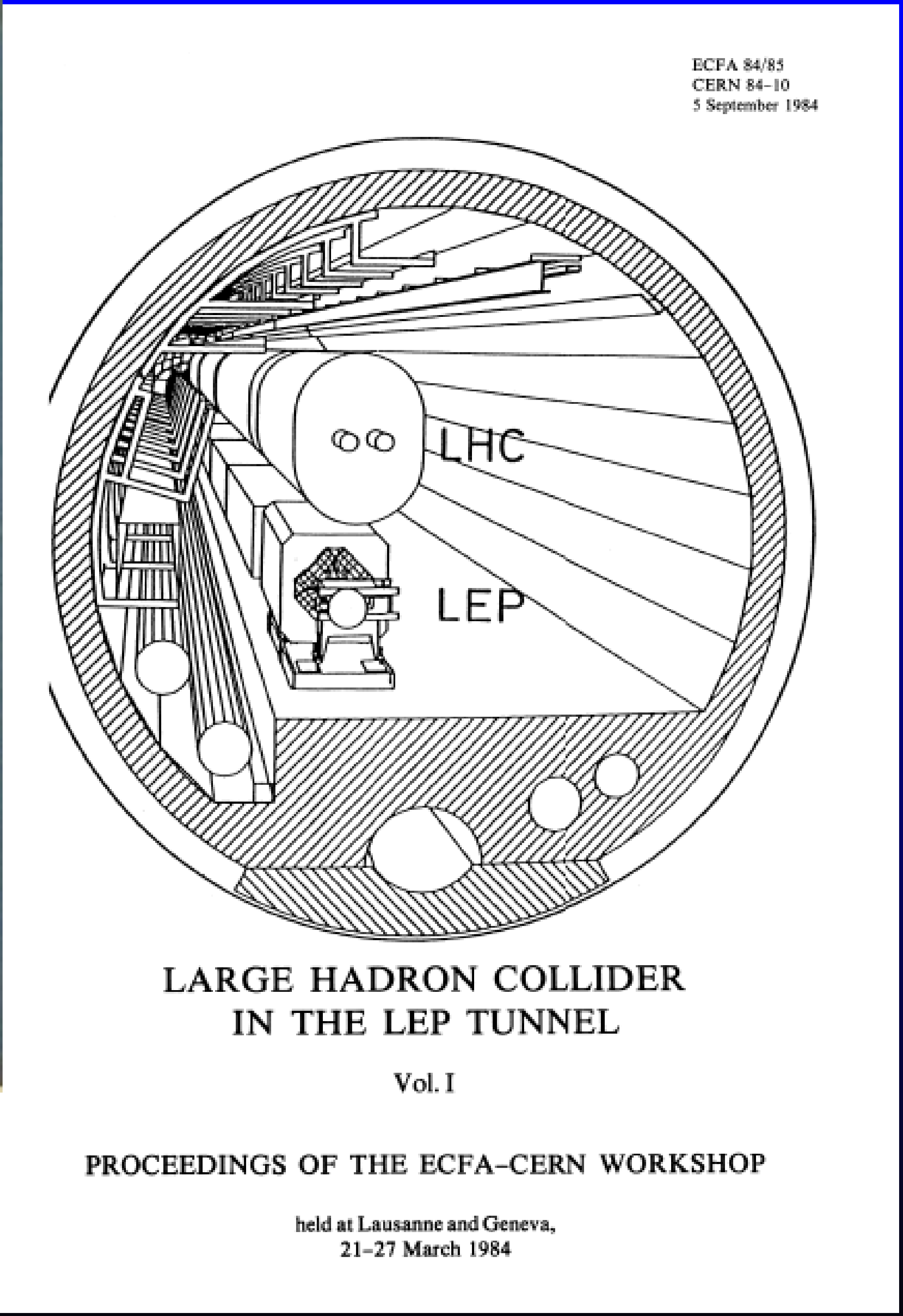
5-8 March 1992
Evian-les-Bains, France

GENERAL MEETING on LHC

Physics Objectives
Expressions of Interest
Detector R&D
Machine

Organizing Committee :
G. Flügge (Chairman)
M. Aguilar-Benitez
J.V. Allaby
J.J. Aubert
J.E. Augustin
J. Dowell
P. Eerola
K. Eggert
J. Engelen
W. Hoogland
L. Mandelli
F. Pauss
K. Potter
J. Schukraft
A. Vorobyov

For information contact:
Telex: 419000 CERN CH [illegible] HVM.CERN.CH



ECFA 84/85
CERN 84-10
5 September 1984

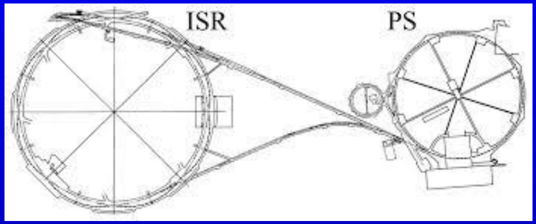
LARGE HADRON COLLIDER IN THE LEP TUNNEL

Vol. I

PROCEEDINGS OF THE ECFA-CERN WORKSHOP

held at Lausanne and Geneva,
21-27 March 1984

Heavy Ions at CERN



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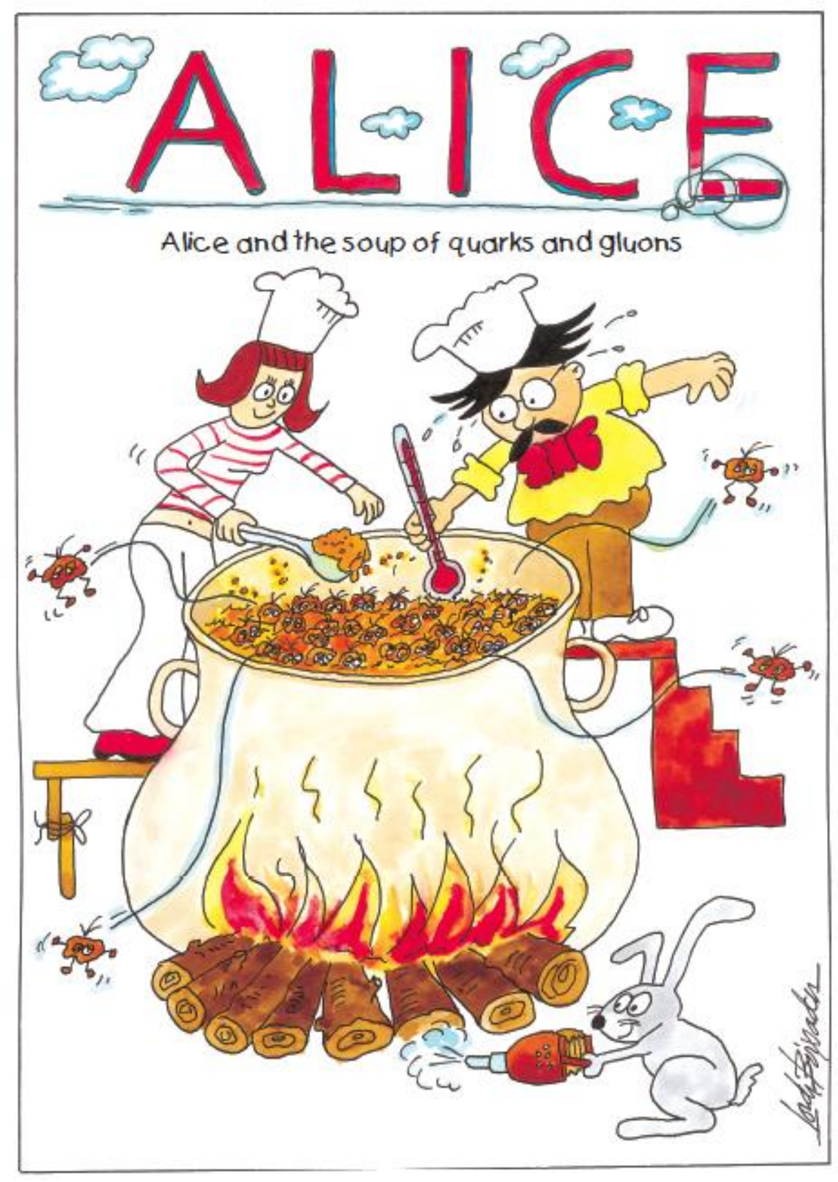
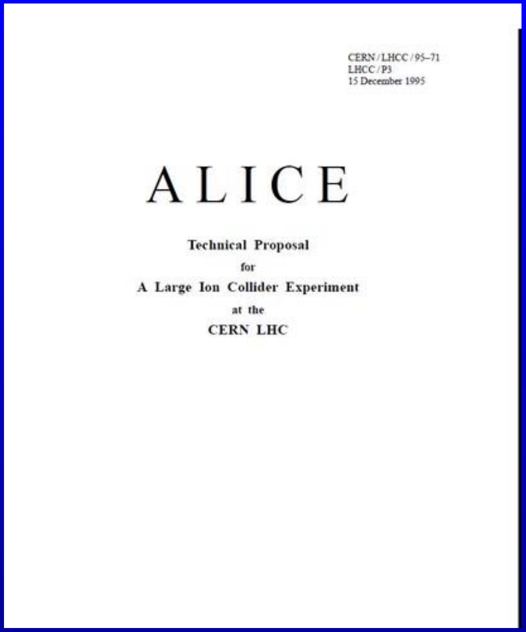
1992 Evian-les-Bains meeting on LHC experimental program. Call for proposals. Suggestion of heavy ion collisions.

1993-5 ALICE Letter of Intent, and Proposal

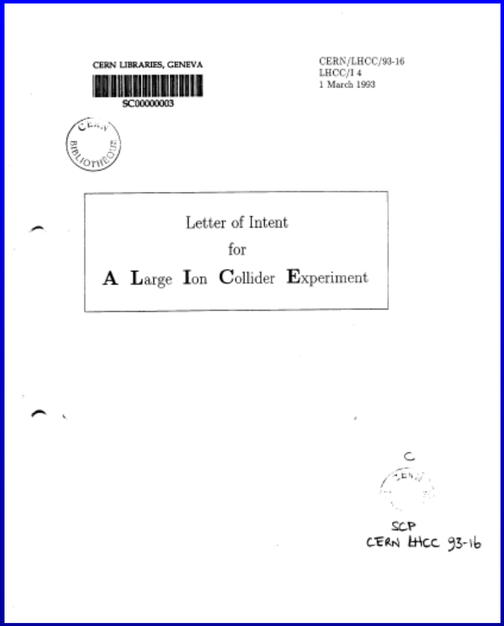
2010 (26 years later) first exptl. runs at LHC: Pb-Pb at 2.76 TeV/A




CERN / LHCC / 95–71
LHCC / P3
15 December 1995

ALICE

Technical Proposal
for
A Large Ion Collider Experiment
at the
CERN LHC

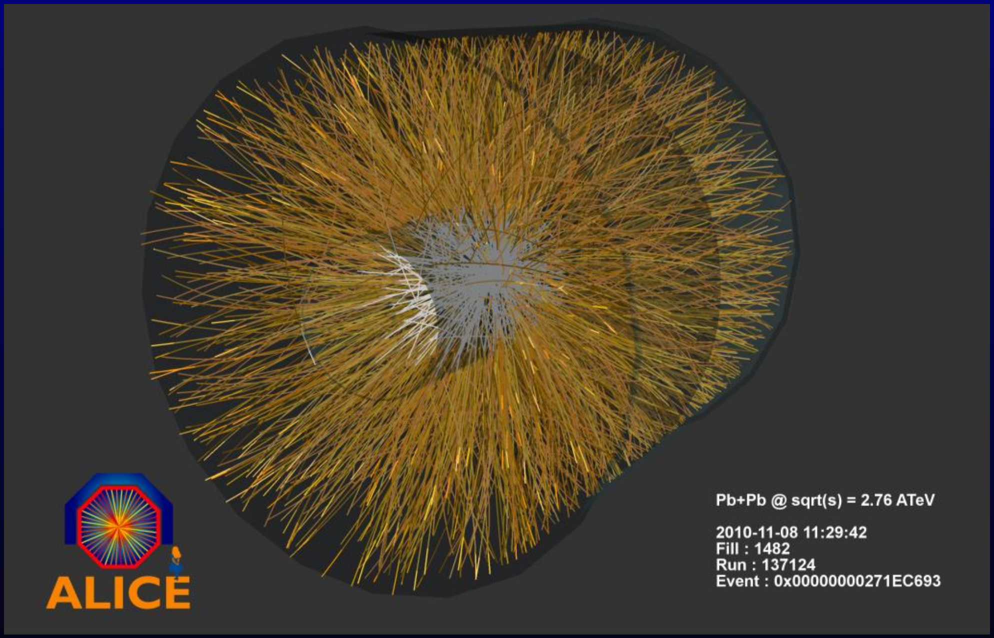


CERN/LHCC/93-16
LHCC/I 4
1 March 1993

Letter of Intent
for
A Large Ion Collider Experiment

From Letter of Intent
(1993)

to Proposal
(1995)


Pb+Pb @ sqrt(s) = 2.76 ATeV

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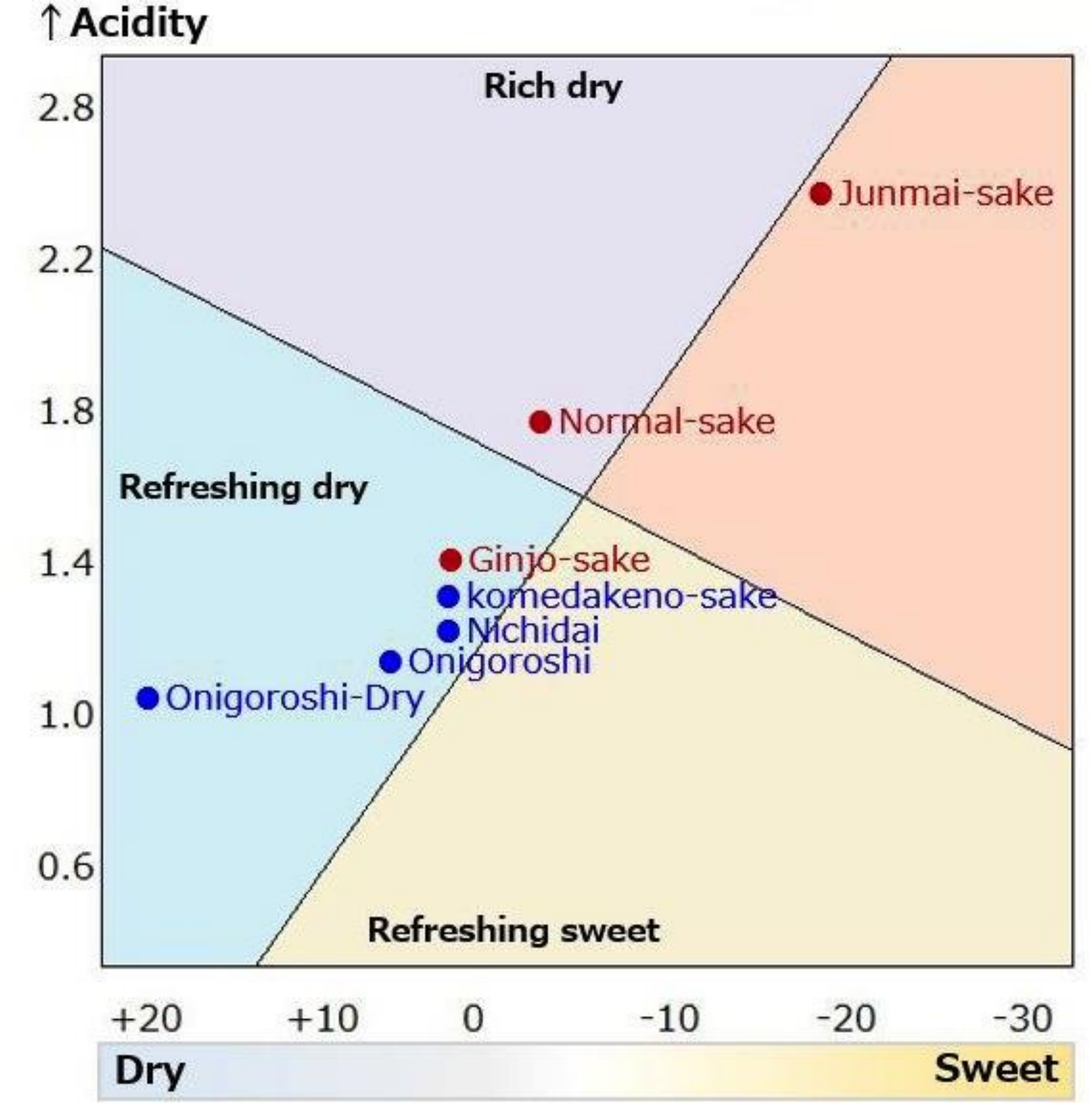
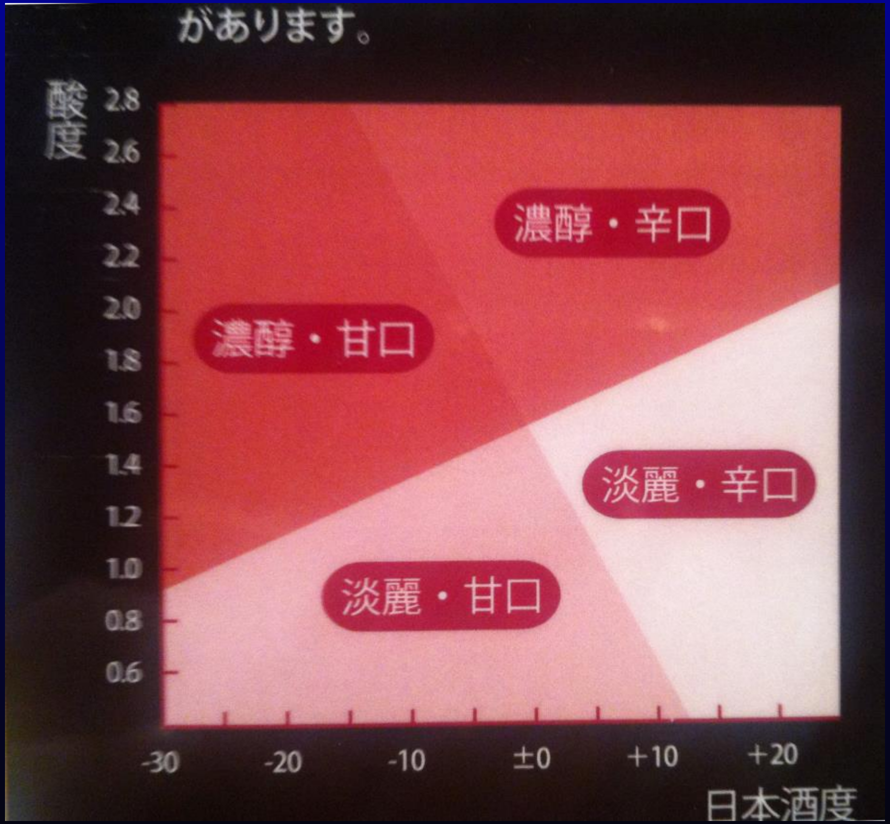
to first results (2010)

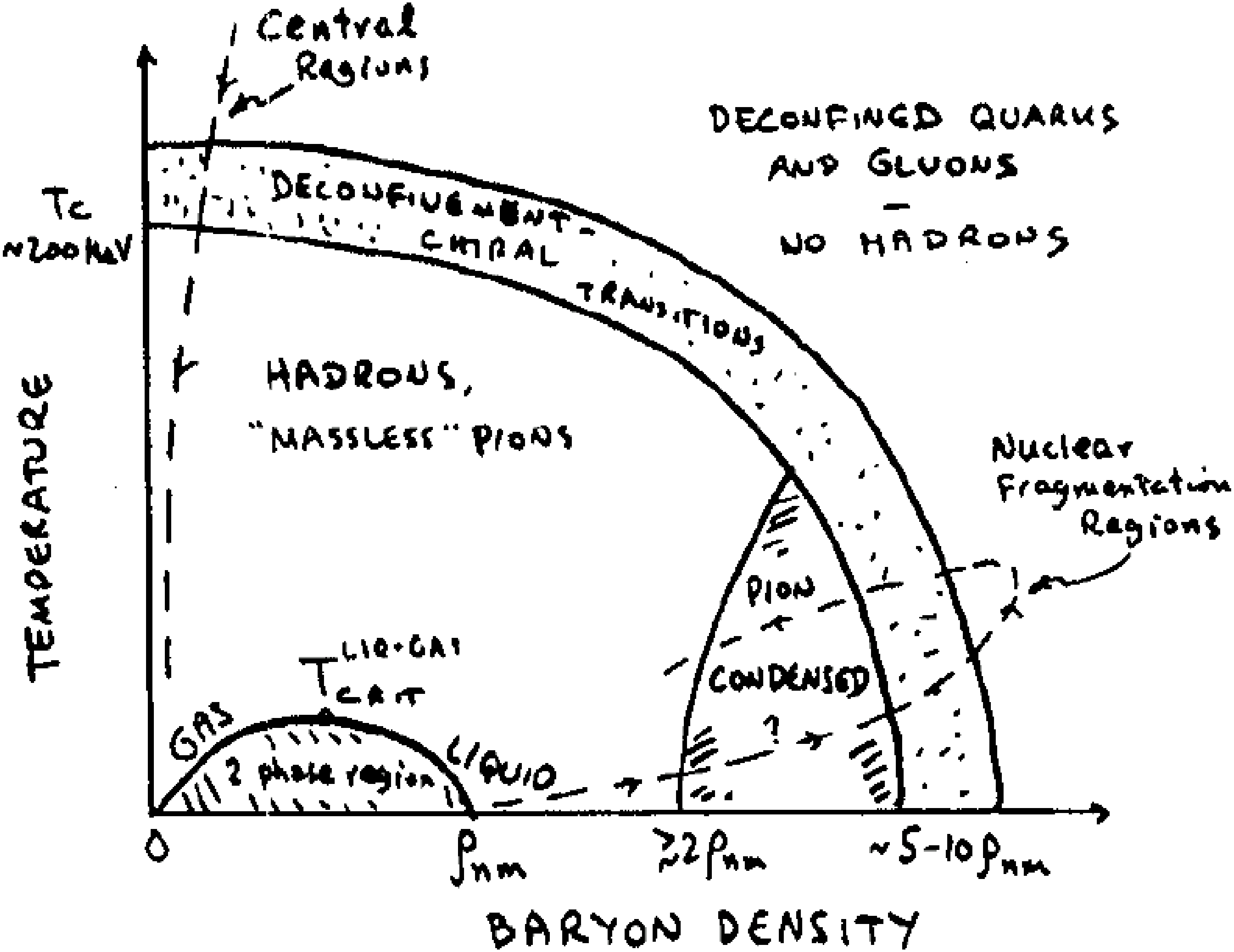
The QCD phase diagram



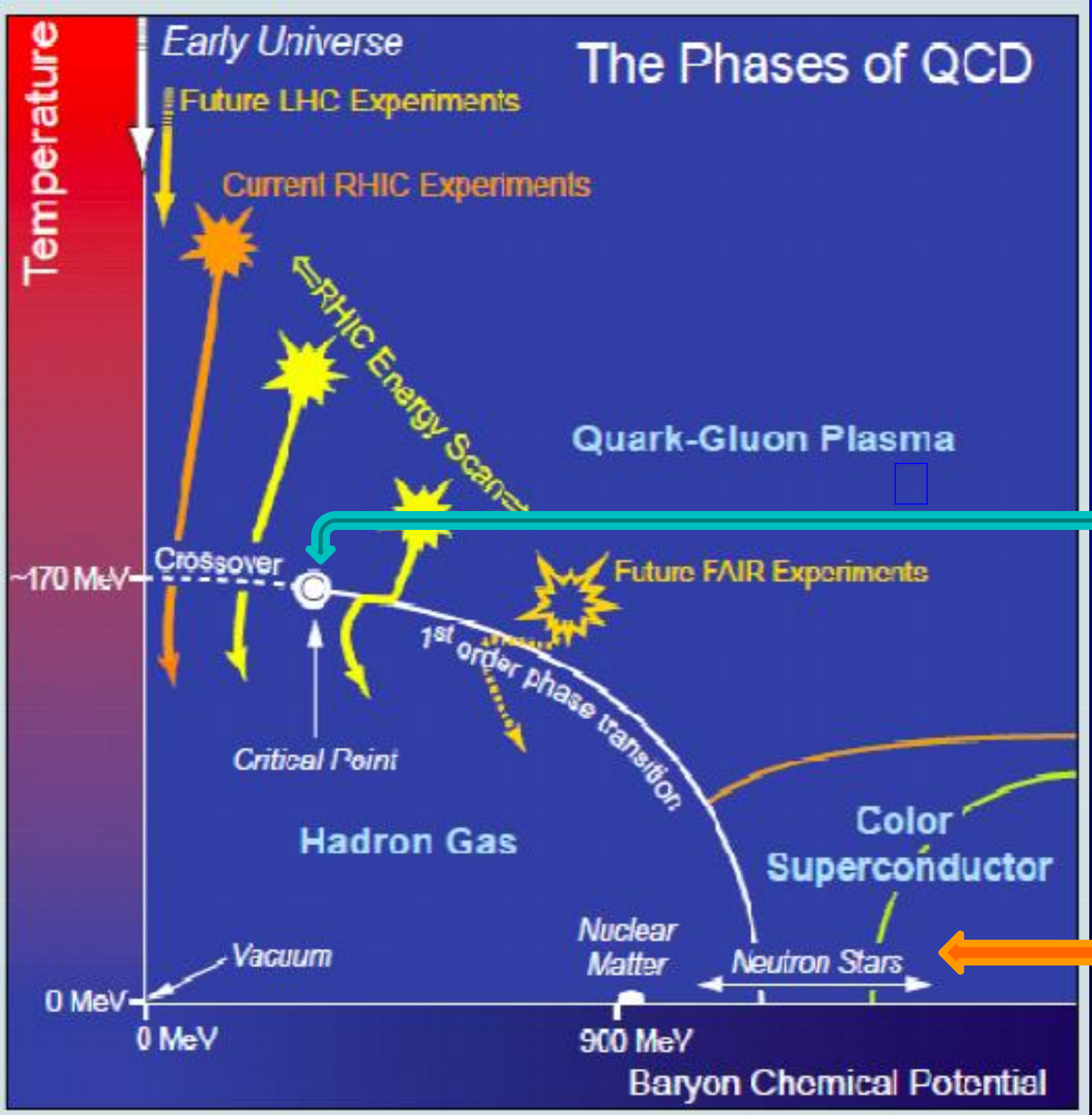


Phase diagram of sake

PHASE DIAGRAM OF NUCLEAR MATTER



Further features in phase diagram



Asakawa-Yazaki critical point (1989)

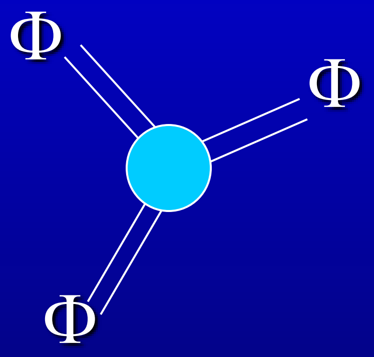
Search in RHIC & SPS energy scans.

States of color superconductivity – diquark BCS pairing

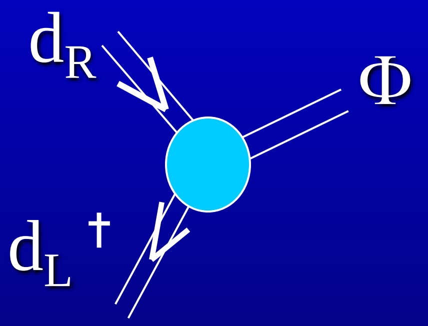
2SC / Color flavor locked
(Alford, Rajagopal, Wilczek, ...)

Possible new low temperature critical point

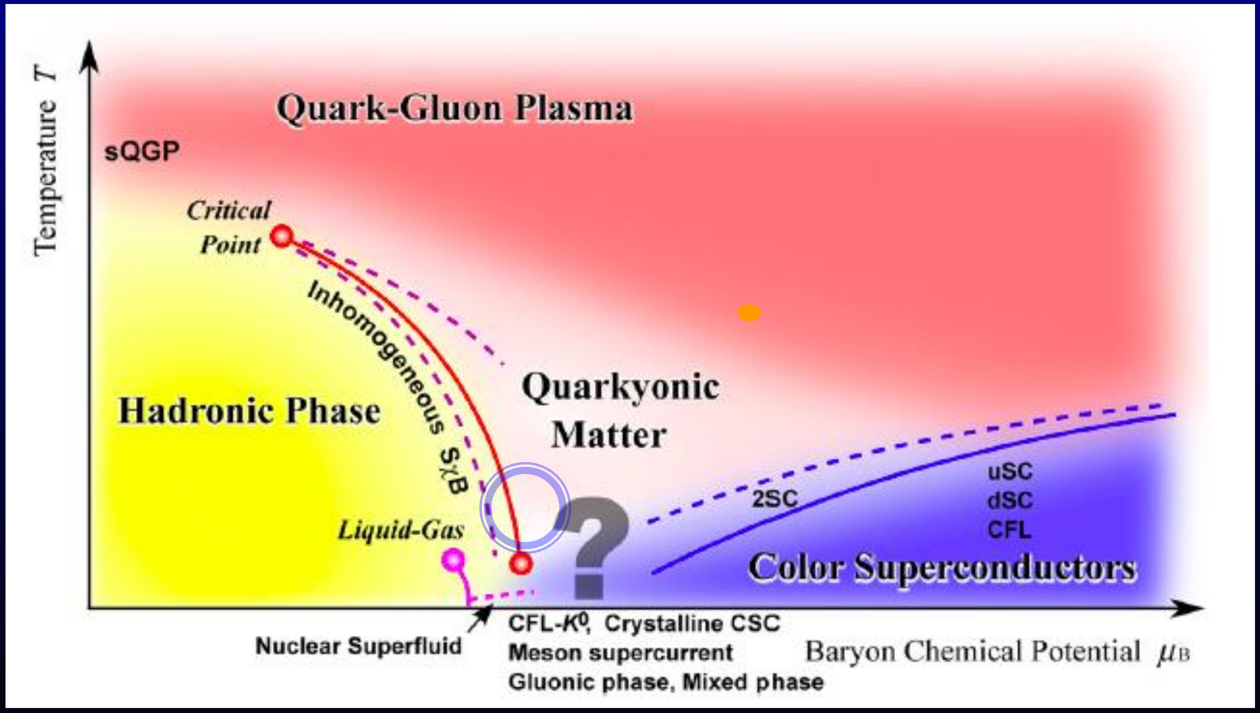
Chiral condensate **(Φ)** – diquark (d) coupling, induced by 6 quark Kobayashi-Miskawa- ‘t Hooft interaction via $U(1)_A$ axial anomaly (T. Hatsuda et al. 2007)



$\sim \Phi^3$



$\sim d_L{}^\dagger d_R \Phi$



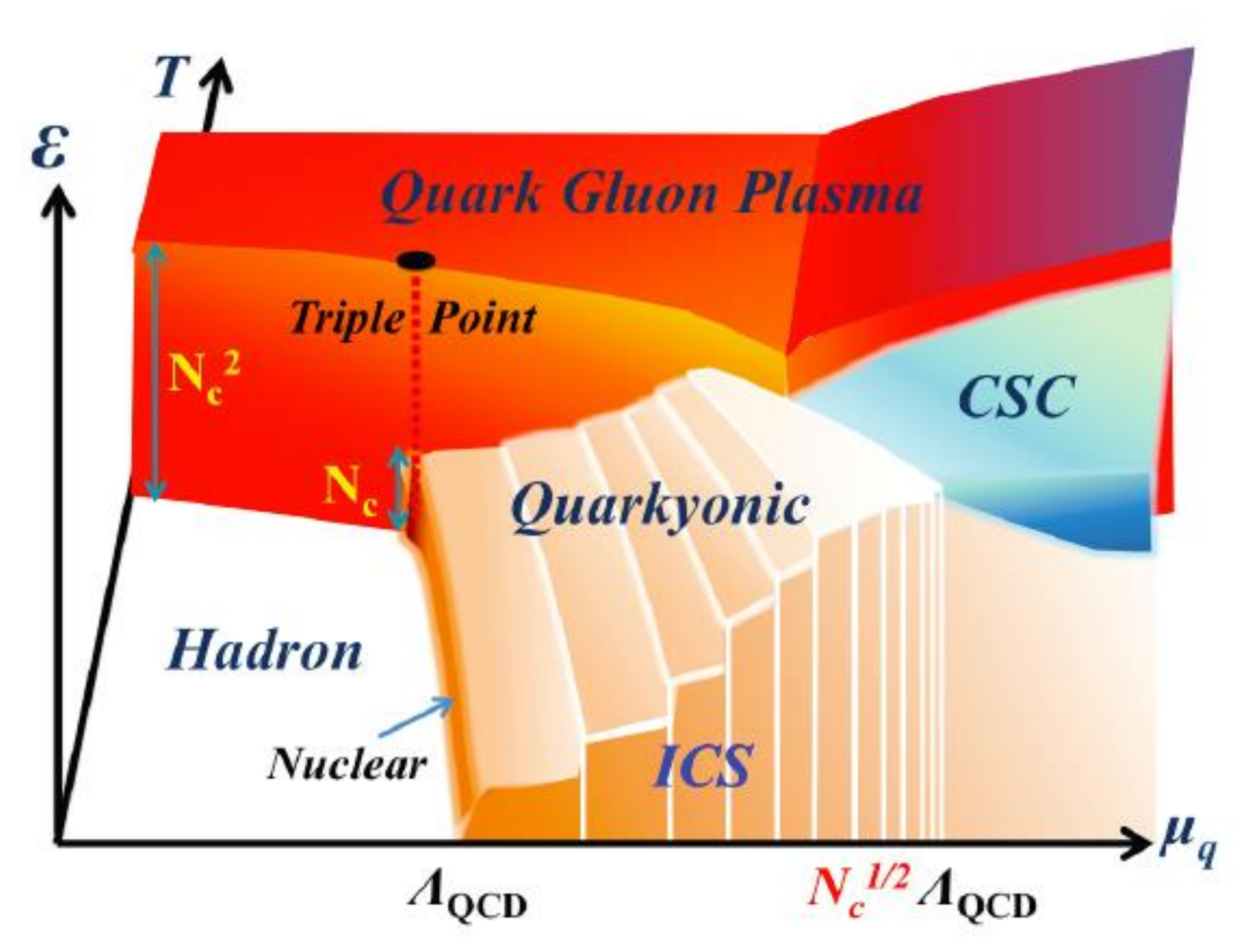
Too cold to be accessible experimentally at RHIC. Possibly at FAIR.

Consistent with quark-hadron continuity (*Schäfer-Wilczek 1999*) – cf. quarks in neutron stars

Fukushima & Hatsuda, Rep. Prog. Phys. **74** (2011) 014001

Spatially ordered chiral transition = quarkyonic phases

(Kojo, Hidaka, Fukushima, McLerran, & Pisarski 2012)

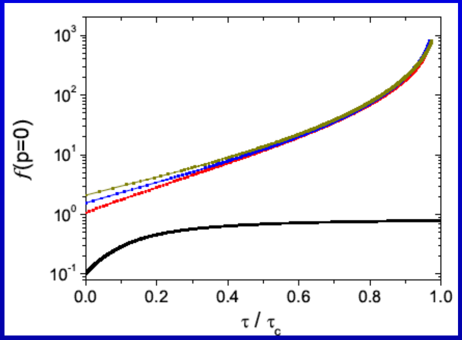


Structure deduced in limit of large number of colors, N_c

K. Fukushima (I-Pad)

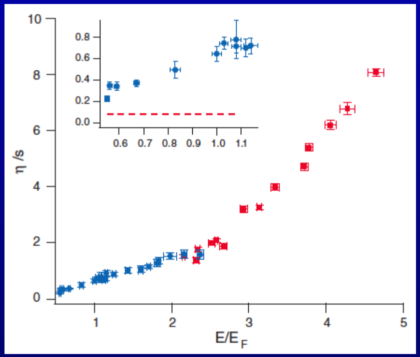
Connections with ultracold atomic physics: a 2-way street

* Bose-Einstein condensation of overpopulated gluons in collisions at early times: (*Blaizot, McLerran, …*)



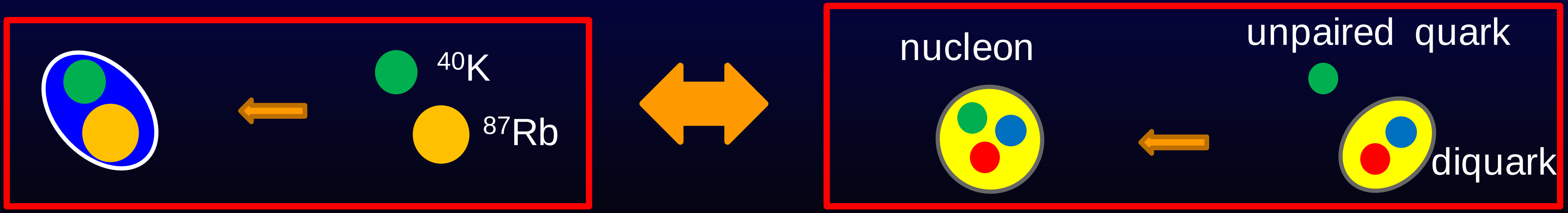
growth of condensate arXiv: 1503.07260

* Viscosity/entropy in ultracold ^{6}Li gas at unitarity $\gtrsim 0.2\ \hbar$ (*Schãfer, Thomas, …*)



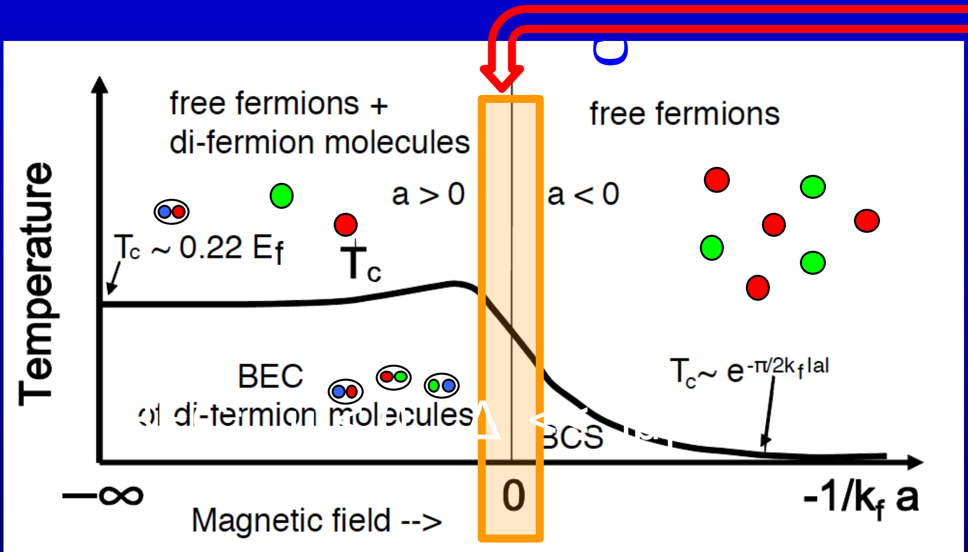
Science 58, 311 (2011)

* Analog systems: boson-fermion mixtures of ultracold atoms. *K. Maeda, ..*
Bosons (^{87}Rb) ⇔ diquarks, Fermions (^{40}K) ⇔ unpaired quarks
Formation of b-f molecules ⇔ transition to nucleons



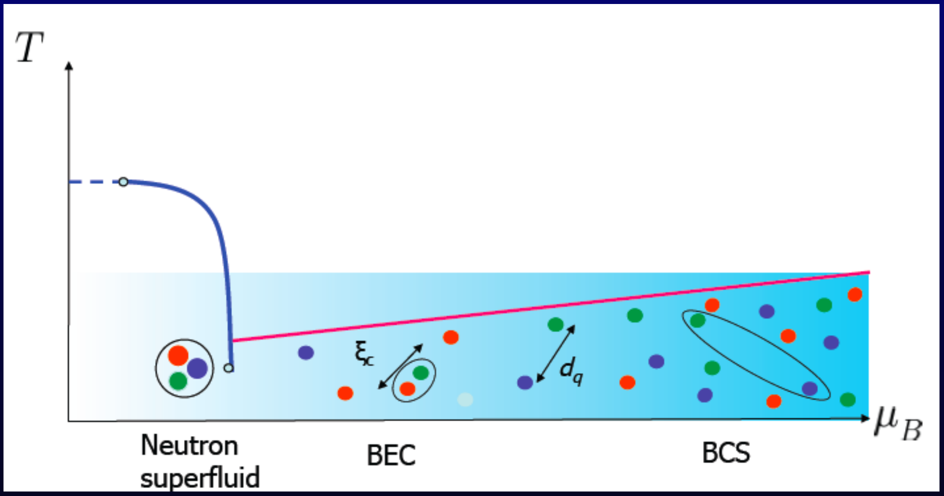
Connections with ultracold atomic physics:

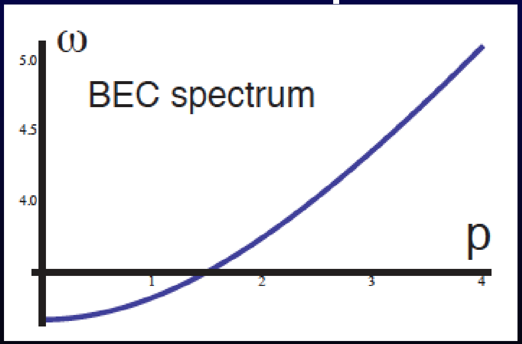
*BEC-BCS crossover in fermions ⇔ quark hadron continuity
Continuously transform from molecules to Cooper pairs:

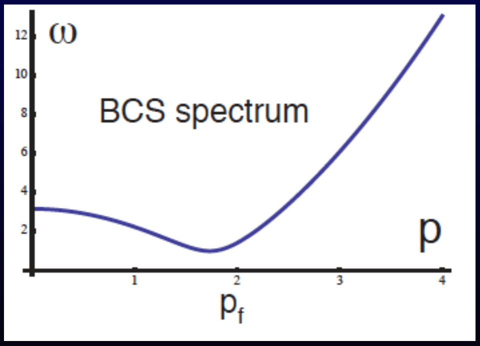


Unitary regime (Feshbach resonance) in gas of ultracold fermions.
No phase transition through crossover

In cold dense matter gradual transition from quark pairs (diquarks) to BCS paired quark matter.



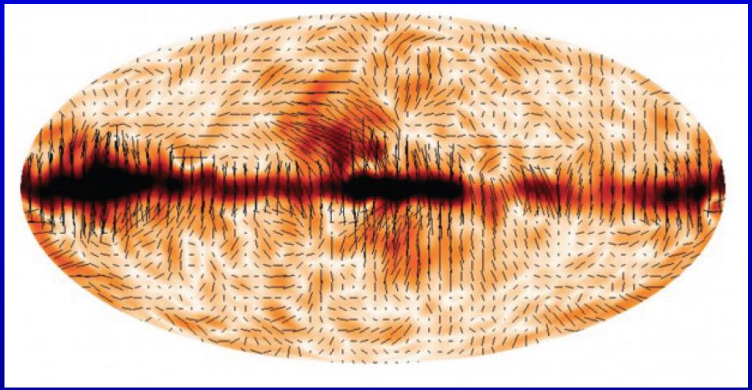




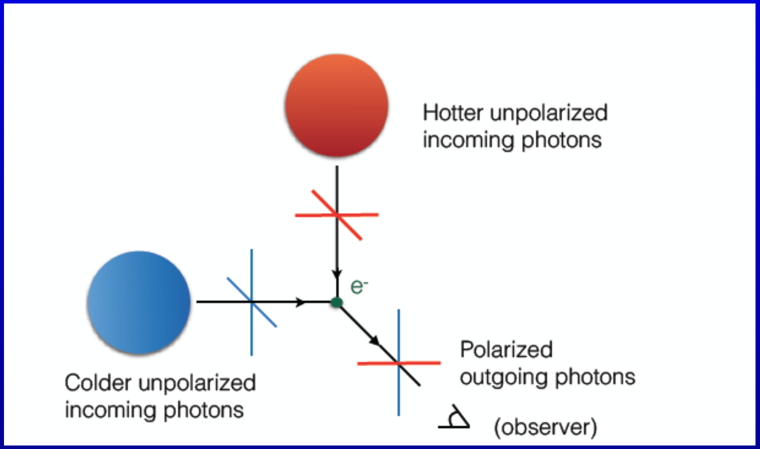
BEC: $\mu < 0$, $\Delta << |\mu|$

BCS: $\mu > 0$, $\Delta < \mu$

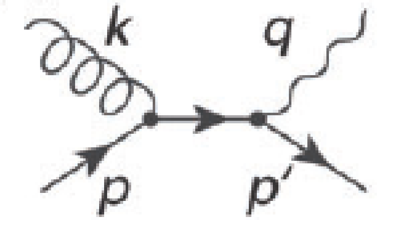
From polarization of the cosmic microwave background to photon polarization in ultrarelativistic collisions

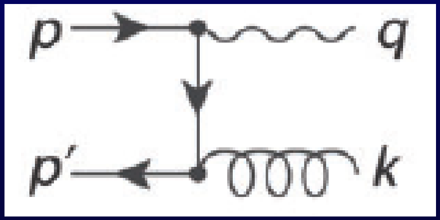


Planck polarization map of entire sky



Thomson scattering at last scattering preserves polarization (⊥ to momentum); polarization reflects momentum anisotropy of photons

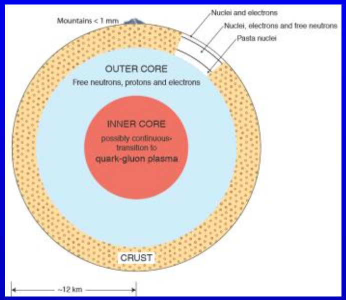




Similar effects in gluon to photon Compton scattering and quark-anti quark annihilation into gluon and photon Direct photon (and dilepton) polarization measures initial gluon anisotropy. *Hatsuda, GB, Strickland, Ipp*

Neutron stars: cold quark matter

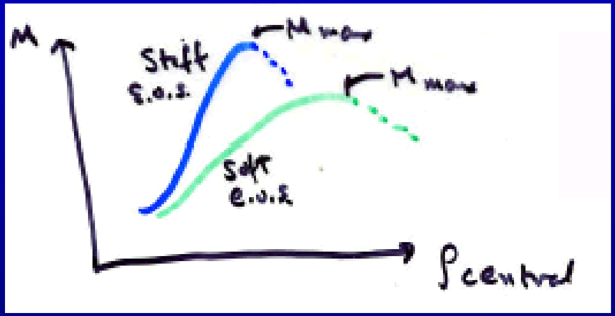
Masses ~ 1.3-2 $M_\odot$
Baryon no. ~ 10^{57} ~$(Gm_p^2/\hbar c)^{-3/2}$
Radii ~ 10-12 km
Temperatures ~ 10^6-10^9 K



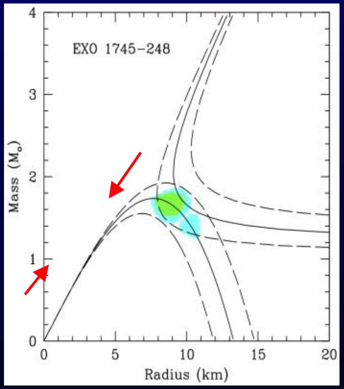
*Recent observations of 2 massive neutron stars requires very stiff equation of state:

PSR J1614-2230 : $M_{\text{neutron star}} = 1.97 \pm 0.04 M_\odot$

PSR J0348+0432: $M_{\text{neutron star}} = 2.01 \pm 0.04 M_\odot$

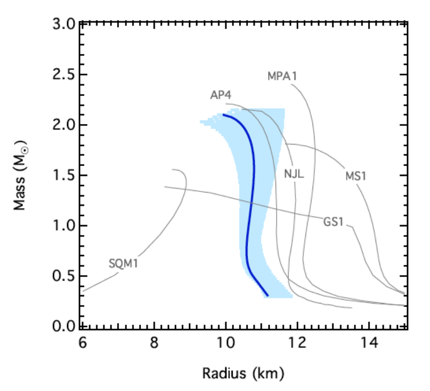


*Recent inferences of mass & radius for ~12 neutron stars



R ~ 10 -11 km

Özel et al.



What can we learn about cold QCD matter from these observations?

Neutron stars: cold quark matter

Fundamental limitations of equation of state based on nucleon-nucleon interactions alone

Accurate for n~ n_0.   But for n >> n_0:

-can forces be described with static few-body potentials?

-Force range ~ $1/2m_\pi$ => relative importance of 3 (and higher) body forces ~ $n/(2m_\pi)^3 \sim 0.4n_{\mathrm{fm}^{-3}}$.

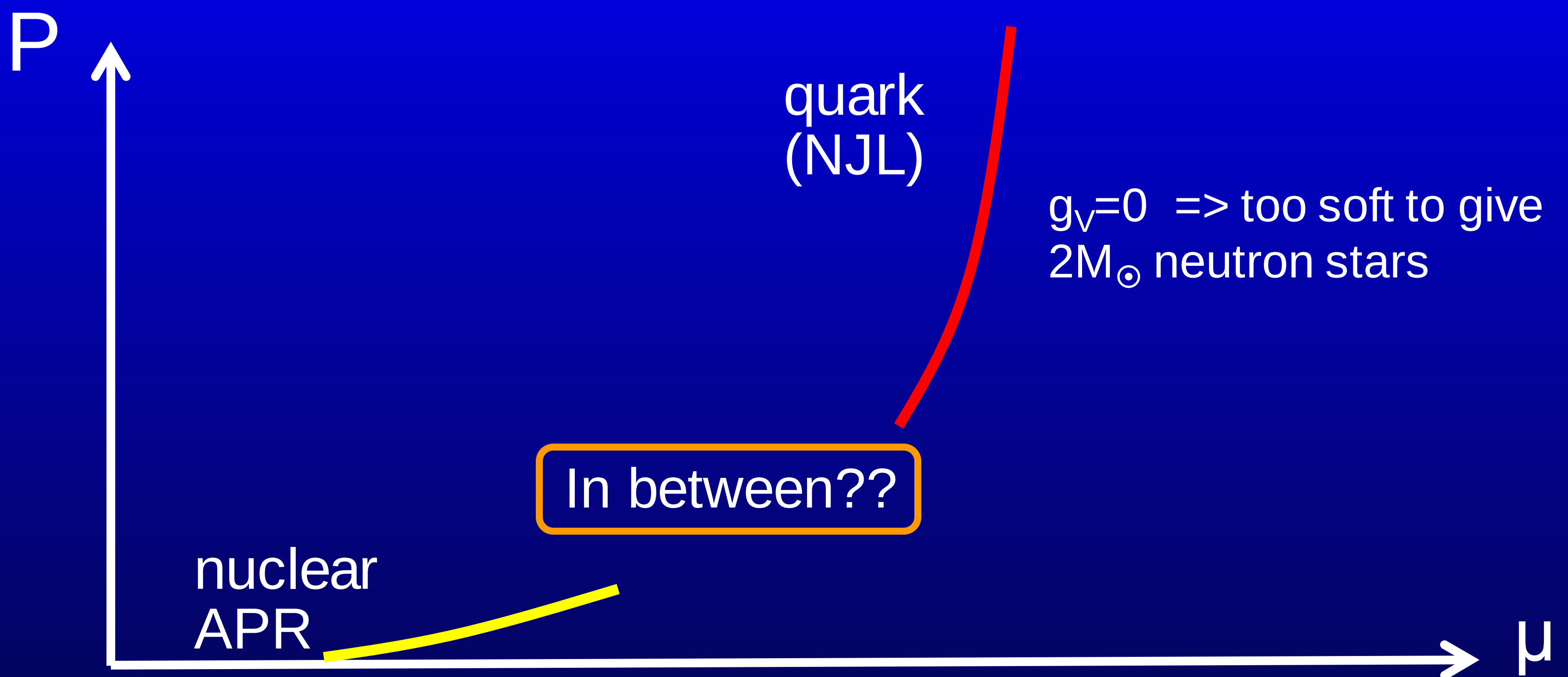
-No well defined expansion in terms of 2,3,4,...body forces.

-Can one even describe system in terms of well-defined ``asymptotic'' laboratory particles? Early percolation of nucleonic volumes!

How can quark matter give stiff eq. of state, to explain large mass?

Construct neutron star from equation of state (pressure vs. baryon chemical potential. We do not know much about the transition region from hadronic to quark degrees of freedom – between about 2 to 8 times nuclear matter saturation density n_0.

Have good idea of equation of state at nuclear densities and at high densities.   Look at pressure vs. baryon chemical potential

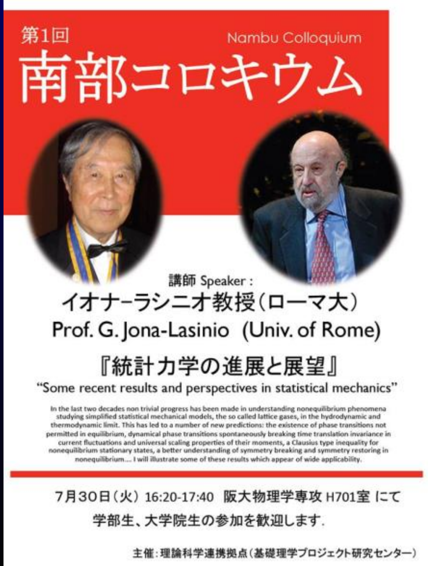


$g_V=0$ => too soft to give $2M_\odot$ neutron stars

Quarks in Nambu-Jona-Lasinio (NJL) model with universal repulsive short-range qq coupling (*Kunihiro*)

$$\mathcal{L}_V^{(4)} = -g_V\left(\overline{q}\gamma^\mu q\right)^2$$

APR = Akmal, Pandharipande, Ravenhall nucleonic equation of state with nucleonic potentials (2 and 3 body) fit to NN scattering and light nuclei



第1回 Nambu Colloquium

南部コロキウム

講師 Speaker :

イオナ-ラシニオ教授（ローマ大）

Prof. G. Jona-Lasinio (Univ. of Rome)

『統計力学の進展と展望』

“Some recent results and perspectives in statistical mechanics”

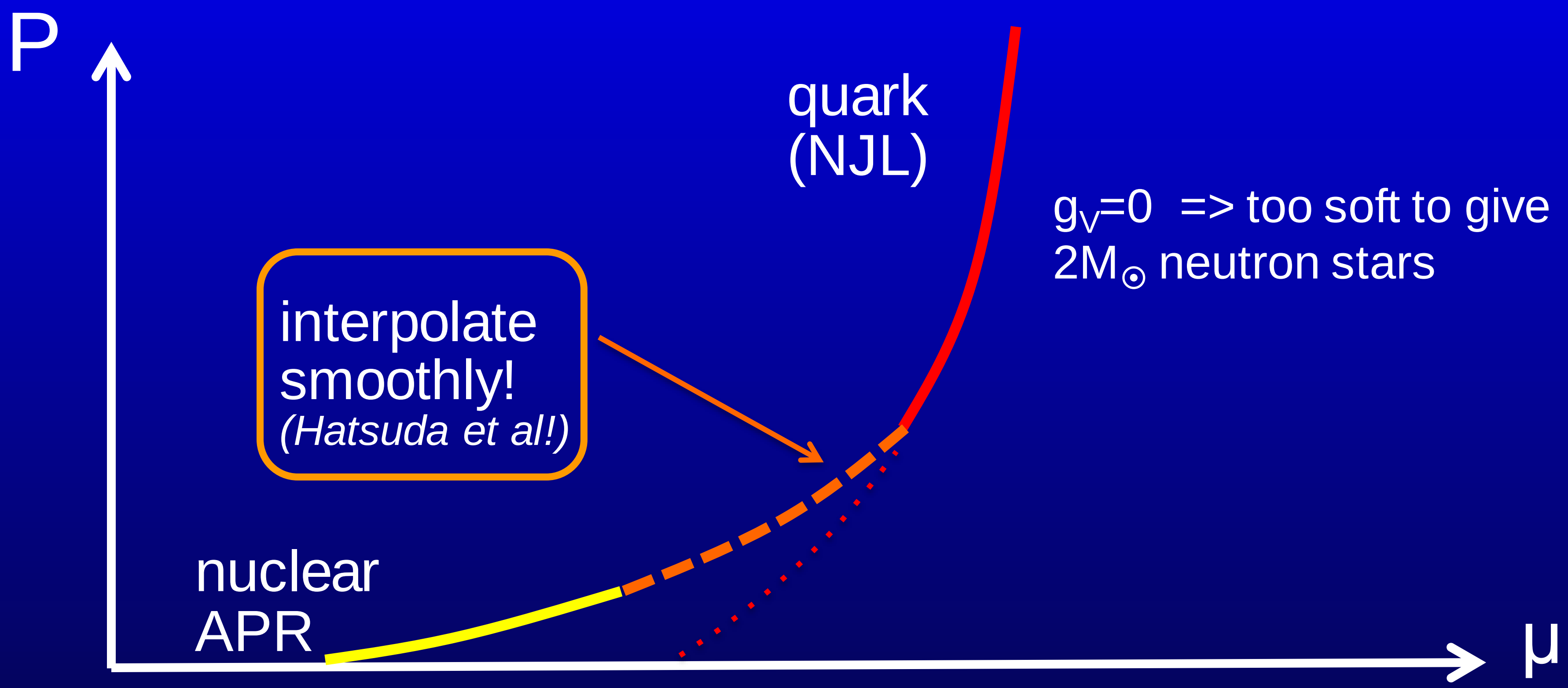
In the last two decades non trivial progress has been made in understanding nonequilibrium phenomena studying simplified statistical mechanical models, the so called lattice gases, in the hydrodynamic and thermodynamic limit. This has led to a number of new predictions: the existence of phase transitions not permitted in equilibrium, dynamical phase transitions spontaneously breaking time translation invariance in current fluctuations and universal scaling properties of their moments, a Clausius type inequality for nonequilibrium stationary states, a better understanding of symmetry breaking and symmetry restoring in nonequilibrium.... I will illustrate some of these results which appear of wide applicability.

7月30日（火） 16:20-17:40 阪大物理学専攻 H701室 にて

学部生、大学院生の参加を歓迎します.

主催：理論科学連携拠点（基礎理学プロジェクト研究センター）

Have good idea of equation of state at nuclear densities and at high densities. Look at pressure vs. baryon chemical potential



$g_V=0$ => too soft to give $2M_\odot$ neutron stars

interpolate smoothly!
(Hatsuda et al!)

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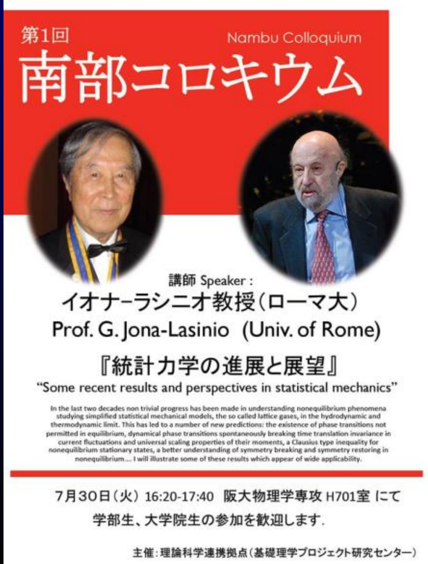
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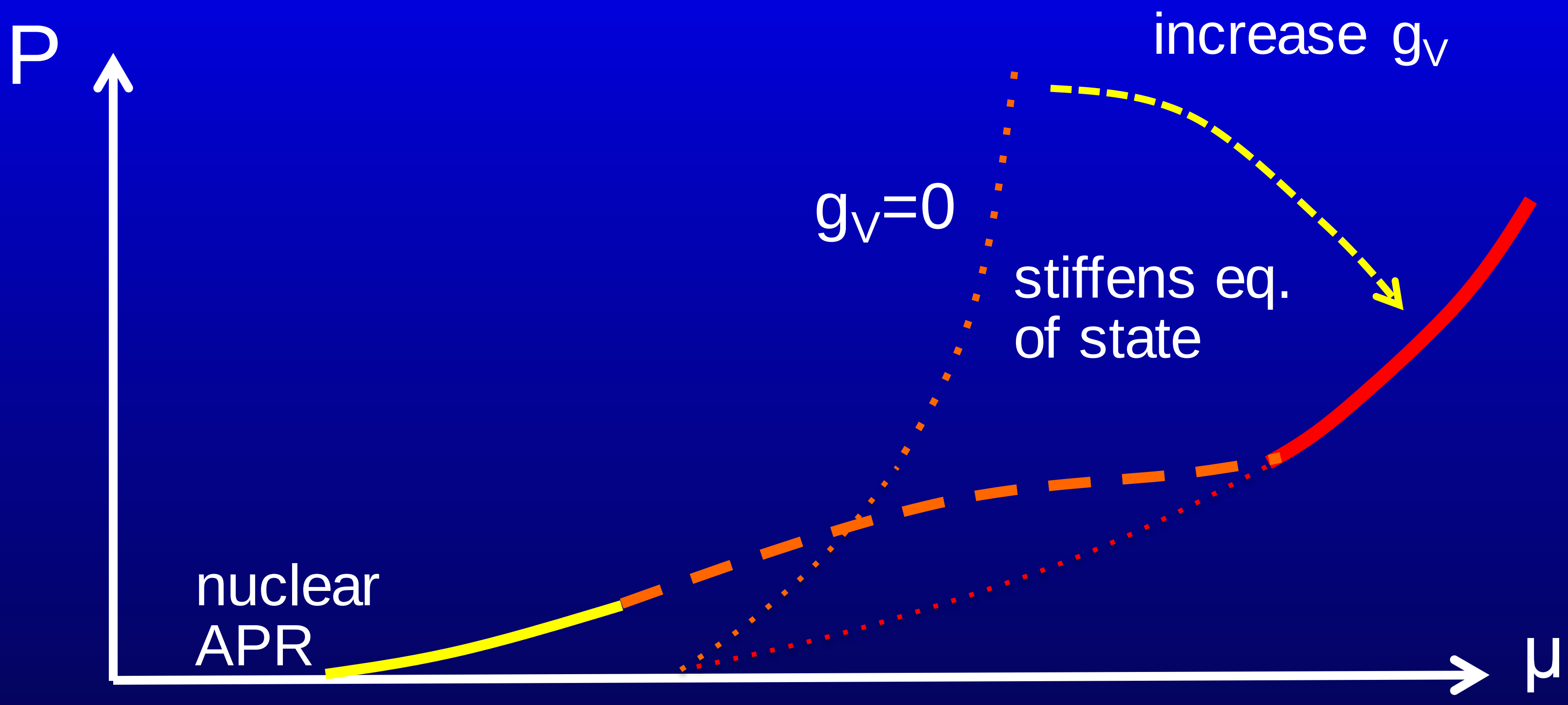
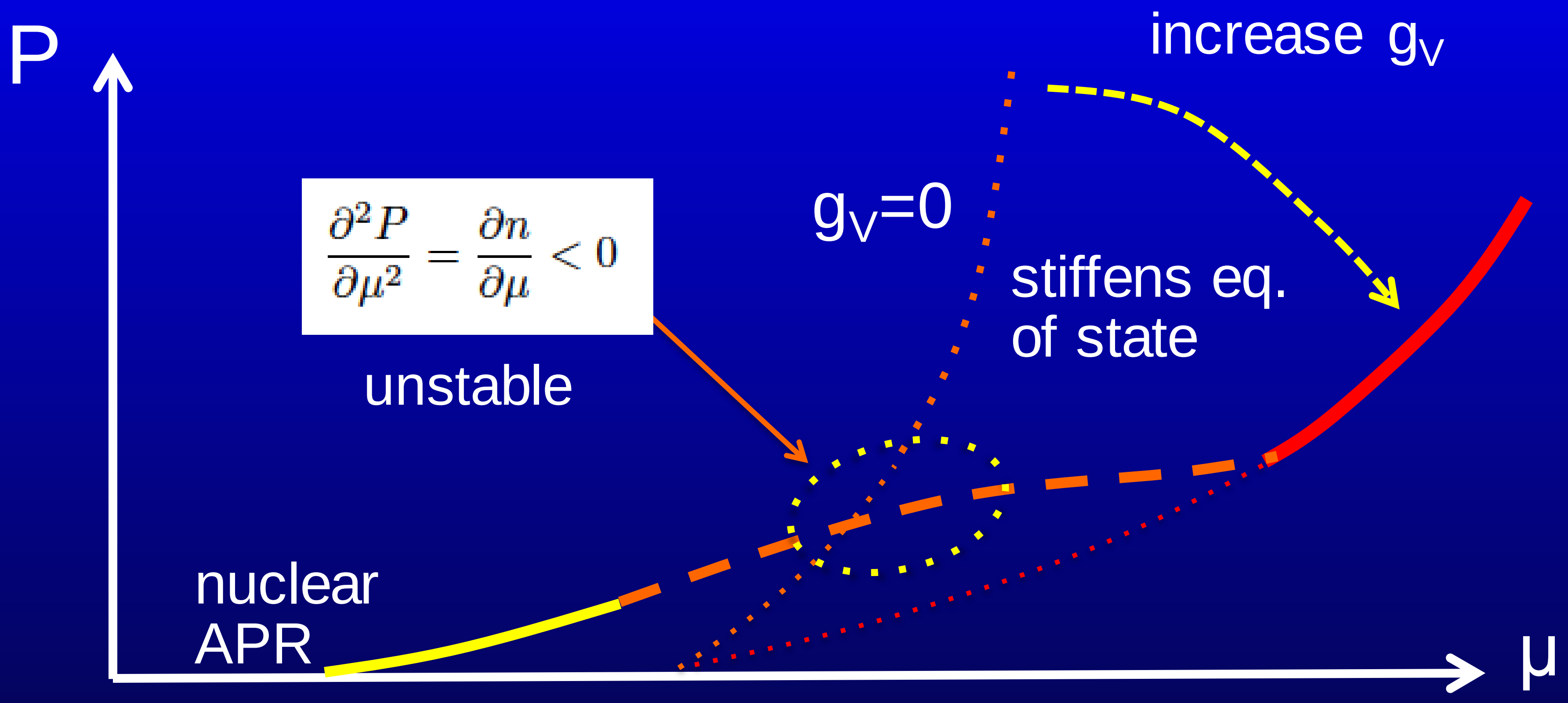
Increasing g_V stiffens equation of state



Shift of pressure in quark phase towards higher μ introduces unphysical thermodynamic instability

Increasing g_V stiffens equation of state

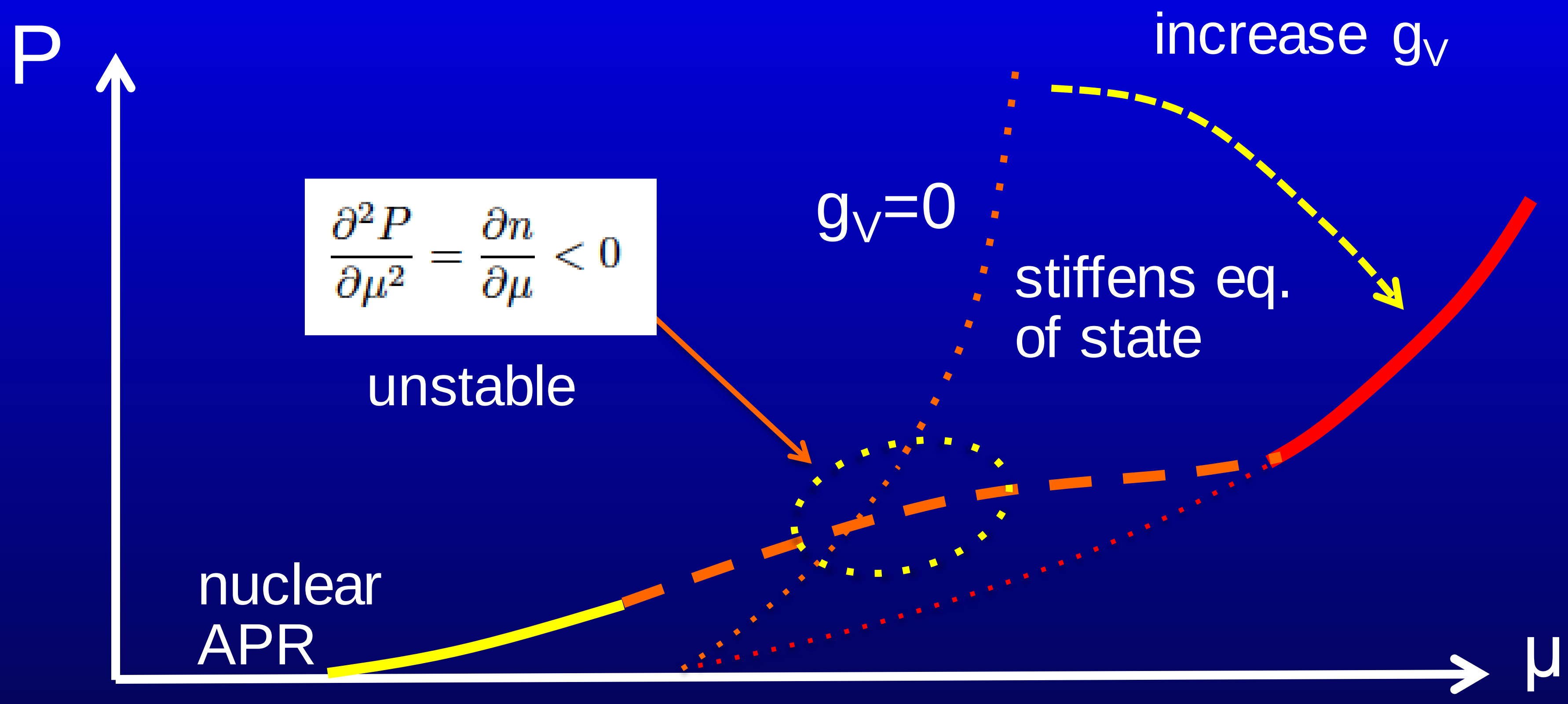


$$\frac{\partial^2 P}{\partial \mu^2} = \frac{\partial n}{\partial \mu} < 0$$

Shift of pressure in quark phase towards higher μ introduces unphysical thermodynamic instability


In this house, we obey
the laws of thermodynamics!

Increasing g_V stiffens equation of state



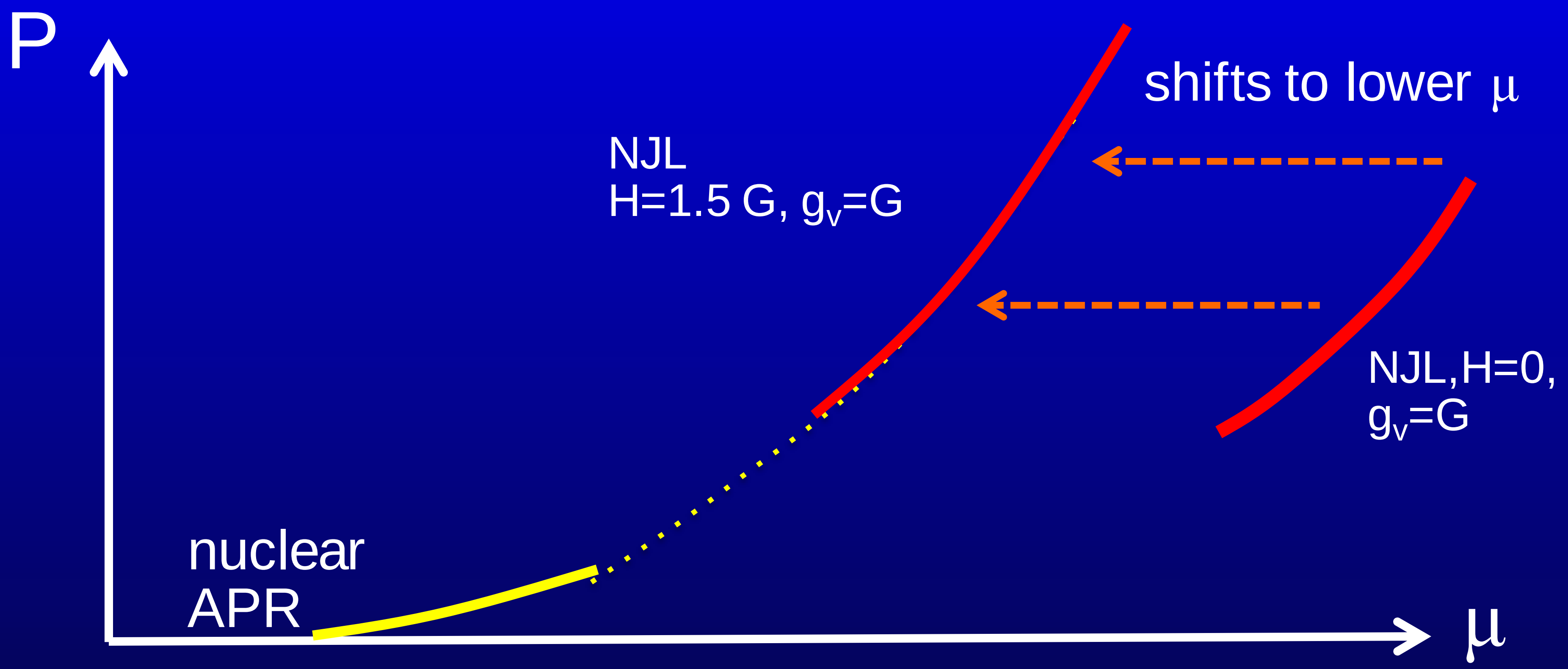
$$\frac{\partial^2 P}{\partial \mu^2} = \frac{\partial n}{\partial \mu} < 0$$

unstable

Shift of pressure in quark phase towards higher μ introduces unphysical thermodynamic instability

Stability restored with increased BCS (diquark) pairing strength, H

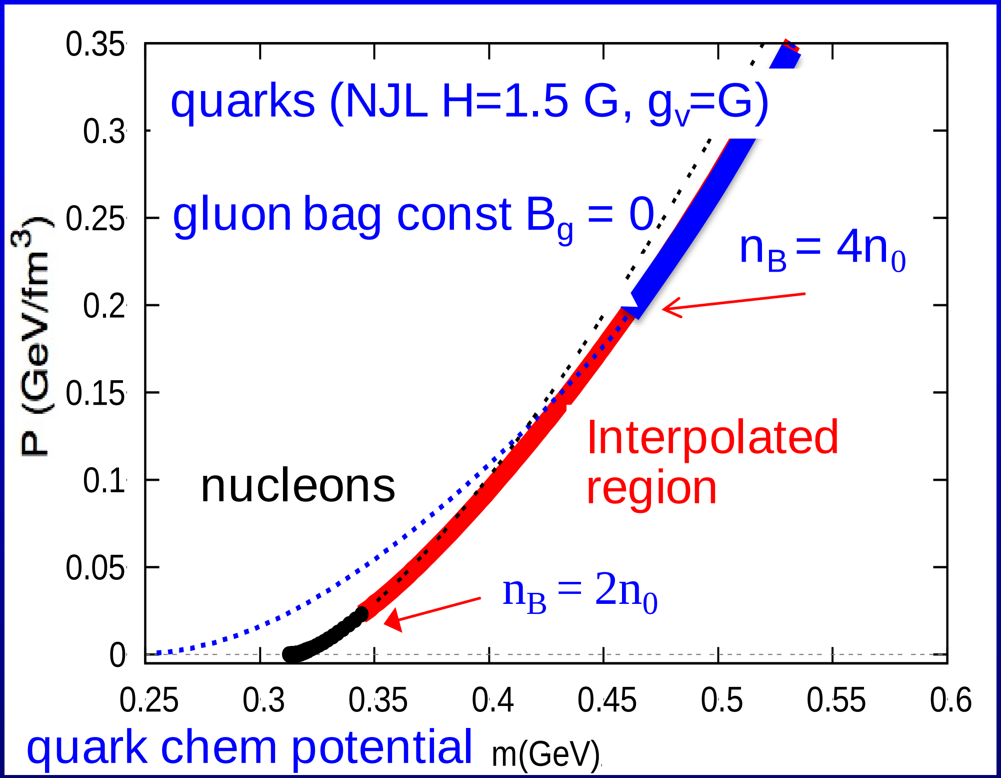
$$\mathcal{L}_d^{(4)} = H \sum_{A,A'=2,5,7} [(\bar{q} i\gamma_5 \tau_A \lambda_{A'} C \bar{q}^T)(q^T C i\gamma_5 \tau_A \lambda_{A'} q)$$

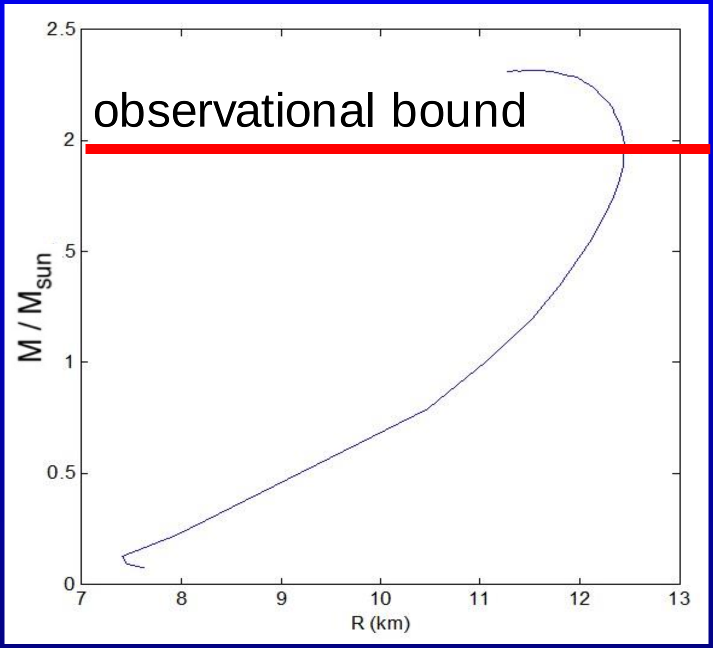


Increased diquark pairing (onset of stronger 2-body correlations) as quark matter approaches confinement

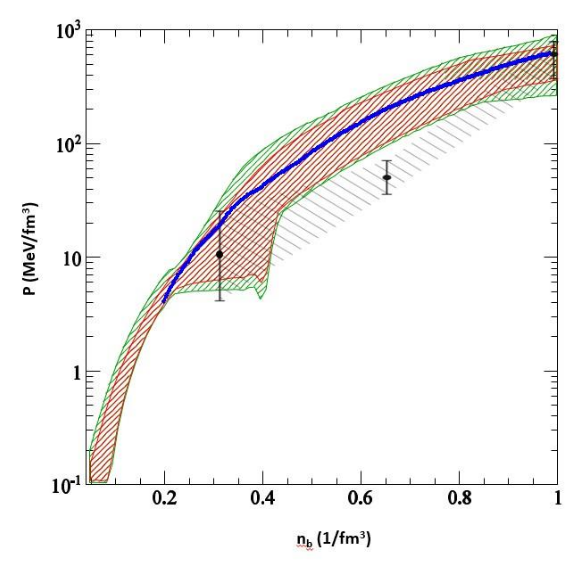
Sample "unified" equation of state

T. Kojo et al.





M-R relation similar to results of nucleonic (APR) equation of state but with correct high density degrees of freedom



<= Reasonable agreement with eq. of state inferred from M vs. R measurements.

Quark eqs. of state can be stiffer than previously thought: allow for n.s. masses > 2 $M_{\odot}$, and with substantial quark cores in neutron stars!!!

Reaching original goals and beyond

Discovery of new state of matter, the quark gluon plasma:
High energy densities achieved.
Plasma very strongly interacting; behaves collectively.

Dynamical evolution: From initial (weakly interacting?) system to hydrodynamics?
Quasiparticle structure *(Blaizot-Iancu)*
Corrections to relativistic hydro. Triangle anomalies *(Dam Son)*
Freezeout? Final state interactions?
Dynamics of heavy quarks – diffusion over large distances;
screening of J/Ψ, B's to probe deconfinement?
Effects of system size? Prepackaged statistics mimicking collectivity?
Correlations and event-by-event fluctuations to set systematics.

Transport properties: Very small viscosity; consistent with AdS/CFT bound on η/s.
Jets, shocks, and stopping power.

Phase diagram: Undergoing continuous refinement.
Search for critical point(s).

Reaching original goals and beyond

Impact on cosmology: QGP in early universe highly correlated system. Transition to hadrons expected to be 2nd order.

Cold dense matter (neutron stars) - to extract equation of state from experiment need to extrapolate from high T to sub-MeV degenerate regime. Theoretical framework?? Onset of quark degrees of freedom with increasing ρ? Informed by parallel studies of neutron stars.

A few evolving connections to further areas of physics:

Experimental realization of non-Abelian artificial gauge fields in cold atomic systems. Future atomic simulations of lattice gauge theory!

Cold atomic plasmas (*Rolston, Killian, …*) Study strongly coupled plasmas on tabletop: dynamical evolution, instabilities, ...

Role of topology in heavy-ions (e.g., chiral magnetic effect – *Kharzeev*) closely related to topologically interesting condensed matter systems. Transitions in energy scans? Cold atom analogs!

Be on the lookout for Nature to surprise us!!!

どうもありがとう

THANK YOU