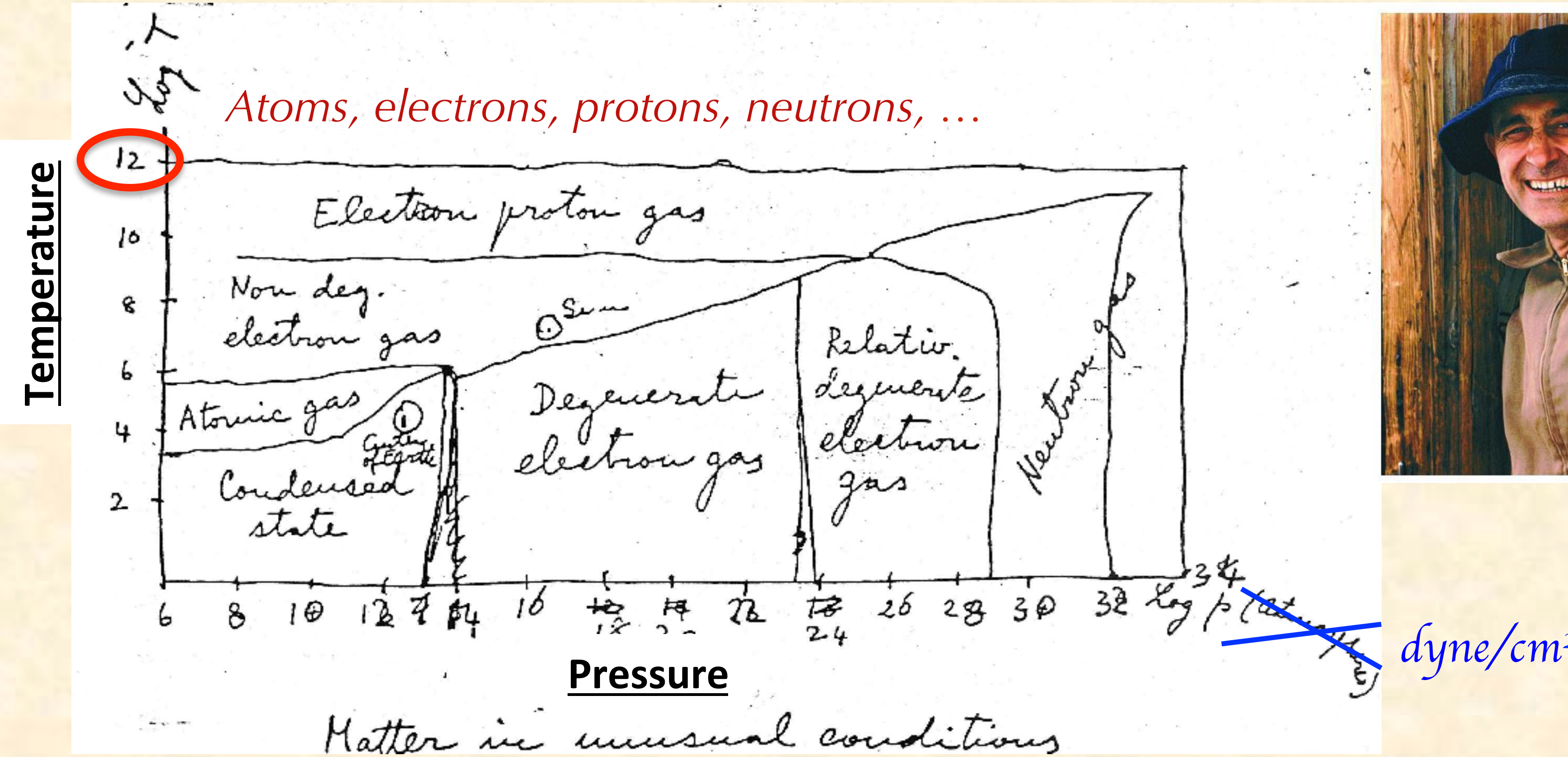
Gazing at Matter above a Trillion of degrees

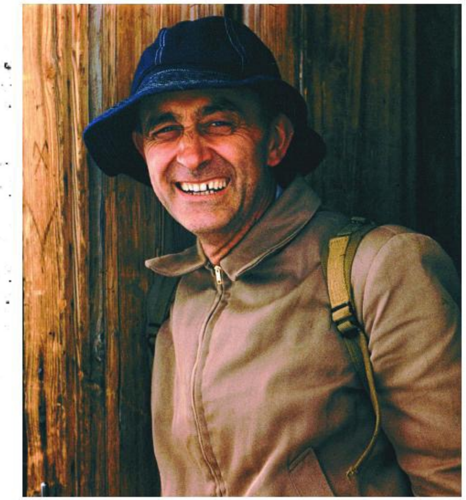
Vincenzo Greco - University of Catania

Inaugural Lecture AE P&E sciences, 3rd September 2017, Budapest, Hungary

Matter in unusual conditions…

Fermi's Notes on Thermodynamics and Statistics (1953)





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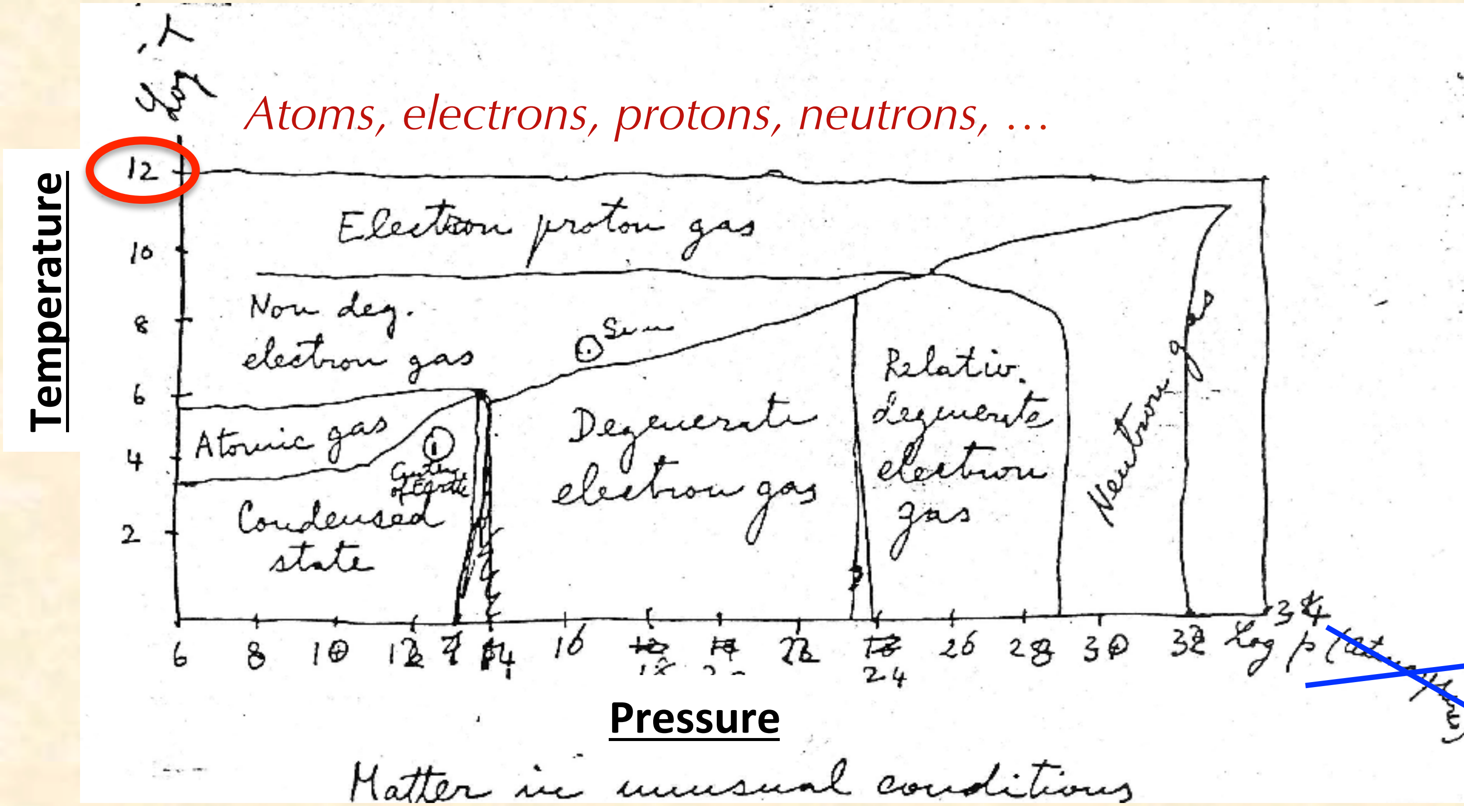
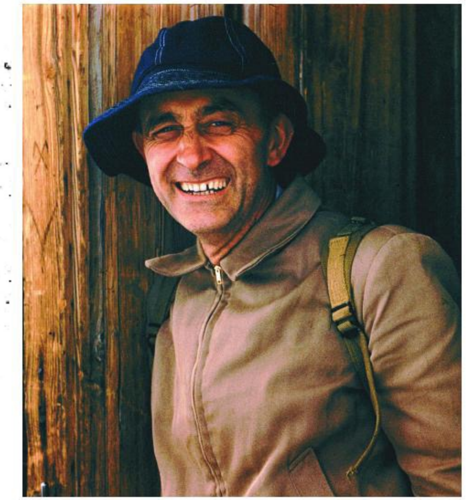




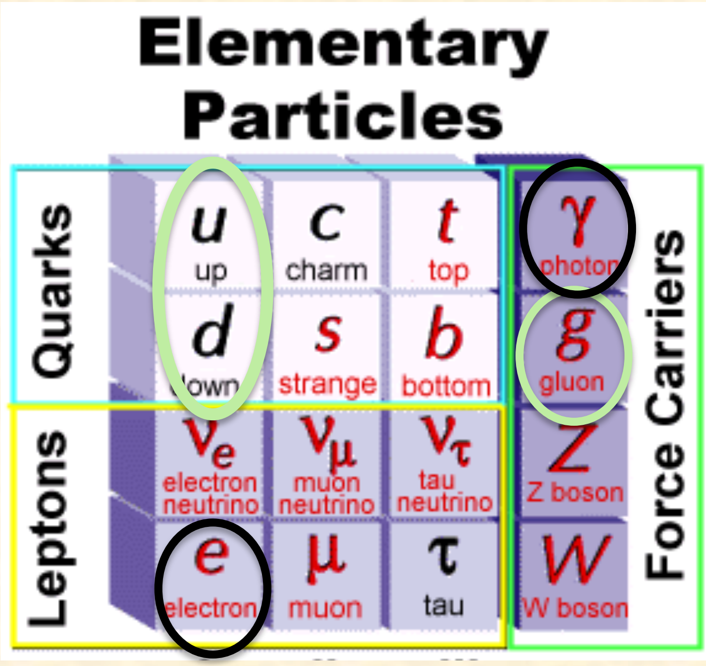
Fermi put Nothing above 10^{12}K!

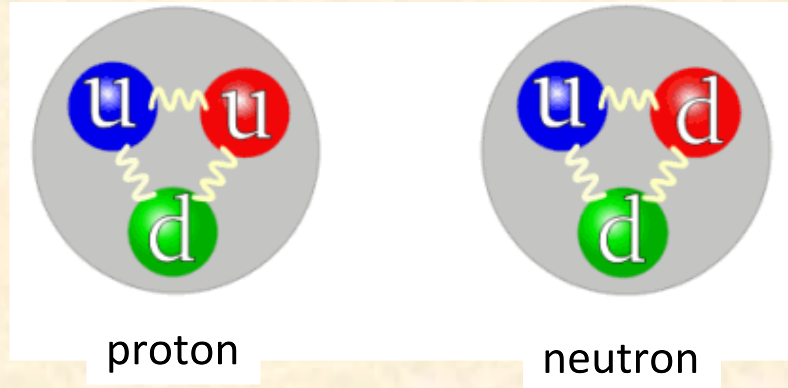
if T $>10^{12}$K ≈ 200 MeV → KT= E ≈ 1/L

→ L < 1 fm go inside a proton

In the '50 and '60 there was nothing inside a proton

Now we know that…

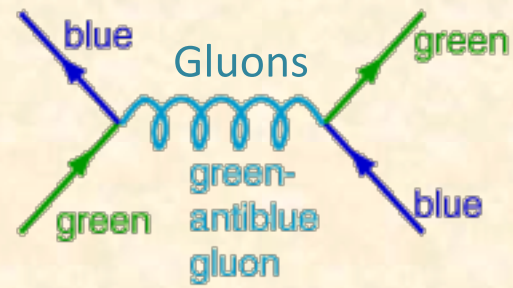




Quarks and Gluons dynamics is driven by The Strong Interaction

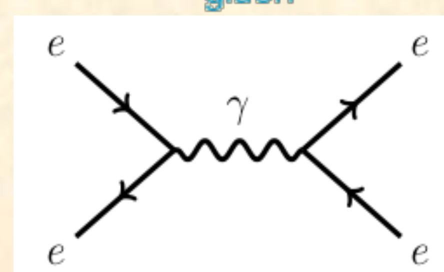
QuantumChromoDynamics (QCD) - 1973

$$L_{QCD} = \bar{\Psi}\left(i\gamma_\mu \partial_\mu - m_i\right)\Psi - gA_a^\mu \bar{\Psi}\gamma_\mu t_a \Psi - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}$$



Quantum Electrodynamics (QED)

$$L_{QED} = \bar{\Psi}\left(i\gamma_\mu \partial_\mu - m_i\right)\Psi - gA^\mu \bar{\Psi}\gamma_\mu \Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$



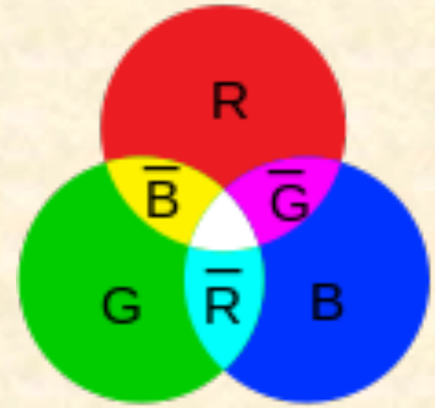
Quantum Chromodynamics

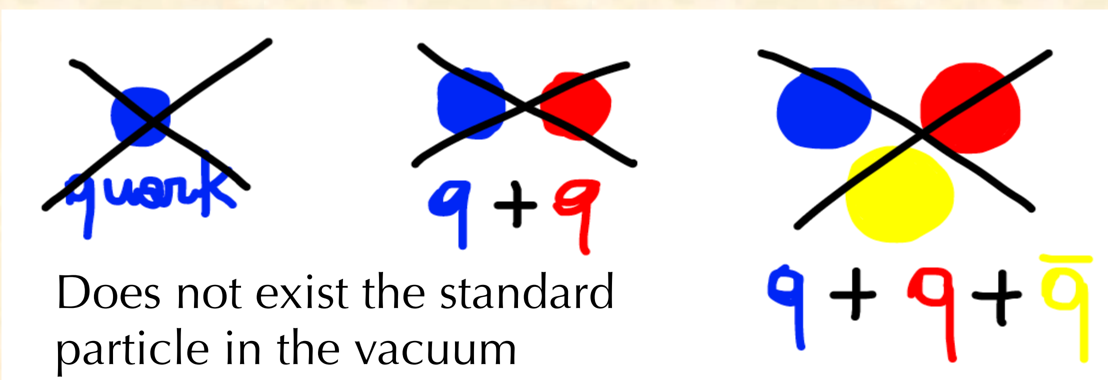
✧ There are no free quark! → **Confinement**

✧ There are *only* ***white (neutral)*** *objects*

Baryons: qqq   Mesons : qq

with 2 colors "protons" would have been bosons!

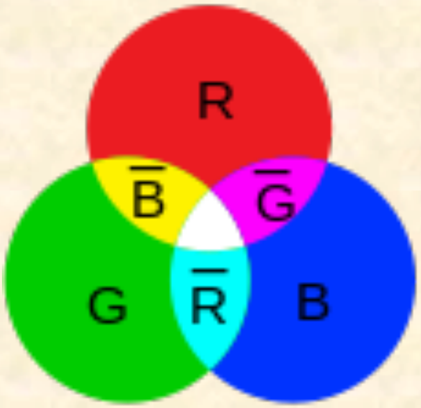




All non-white combination do not exist!

❖ QCD is very strange and unique: **built on particles that cannot be detected experimentally**. *Before QCD this would have been seen as anti(pre)-scientific!*

Quantum Chromodynamics ≠ QED



- ✧ There are no free quark! → **Confinement**
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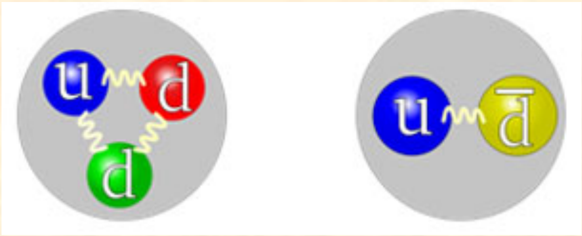
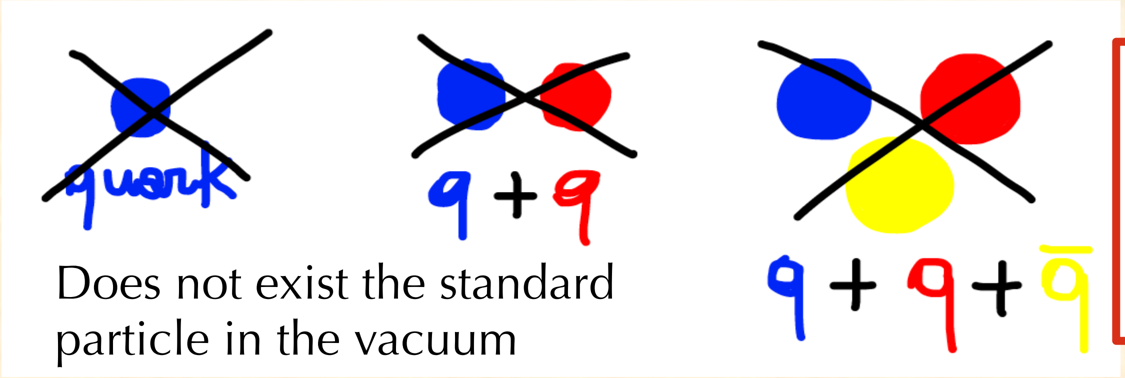
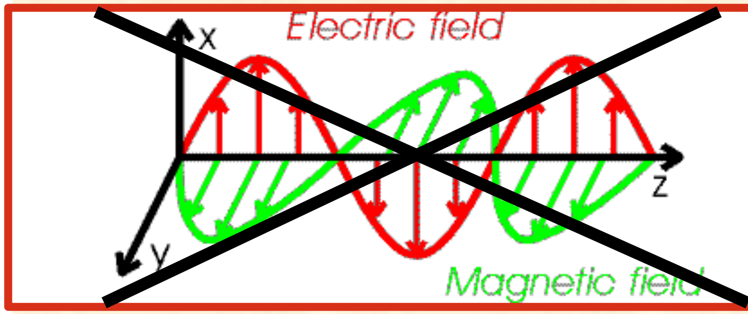


Baryons: qqq Mesons : qq





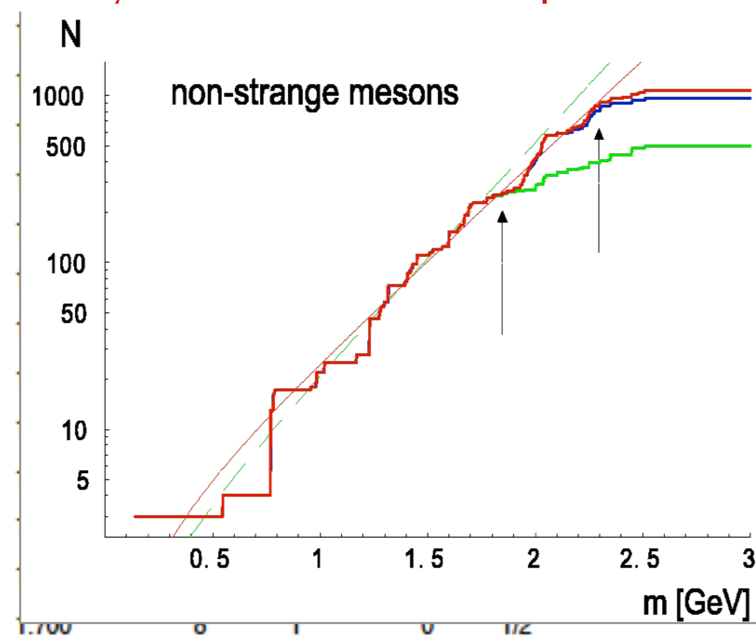
- ❖ QCD is very strange and unique: **built on particles that cannot be detected experimentally**. *Before QCD this would have been seen as anti(pre)-scientific!*

- ❖ **No Chromomagnetic waves propagating in the vacuum!**

There are still a lot of hadrons …

hadron	m_i (GeV)	d_i	B_i	S_i	I_i	hadron	m_i (GeV)	d_i	B_i	S_i	I_i
π	0.140	3	0	0	1	N (1535)	1.530	4	1	0	1/2
K	0.496	2	0	1	1/2	π_1 (1600)	1.596	9	0	0	1
$\overline{K}$	0.496	2	0	-1	1/2	Δ (1600)	1.600	16	1	0	3/2
η	0.543	1	0	0	0	Λ (1600)	1.600	2	1	-1	0
ρ	0.776	9	0	0	1	Δ (1620)	1.630	8	1	0	3/2
ω	0.782	3	0	0	0	η_2 (1645)	1.617	5	0	0	0
K^*	0.892	6	0	1	1/2	N (1650)	1.655	4	1	0	1/2
$\overline{K}^*$	0.892	6	0	-1	1/2	ω (1650)	1.670	3	0	0	0
N	0.939	4	1	0	1/2	Σ (1660)	1.660	6	1	-1	1
η'	0.958	1	0	0	0	Λ (1670)	1.670	2	1	-1	0
f_0	0.980	1	0	0	0	Σ (1670)					
a_0	0.980	3	0	0	1	ω_3 (1670)					
ϕ	1.020	3	0	0	0	π_2 (1670)					
Λ	1.116	2	1	-1	0	Ω^-					
h_1	1.170	3	0	0	1	N (1675)					
Σ	1.189	6	1	-1	1	ϕ (1680)					
a_1	1.230	9	0	0	1	K^* (1680)					
b_1	1.230	9	0	0	1	$\overline{K}^*$ (1680)					
Δ	1.232	16	1	0	3/2	N (1680)					
f_2	1.270	5	0	0	0	ρ_3 (1690)					
K_1	1.273	6	0	1	1/2	Λ (1690)					
$\overline{K}_1$	1.273	6	0	-1	1/2	Ξ (1690)					
f_1	1.285	3	0	0	1	ρ (1700)					
η (1295)	1.295	1	0	0	0	N (1700)	1.700	[illegible]	1	0	1/2
π (1300)	1.300	3	0	0	1	$\Delta(1700)$	1.700	16	1	0	3/2

Density of state increase exp. with m



Quantum Chromodynamics

Strong coupling constant

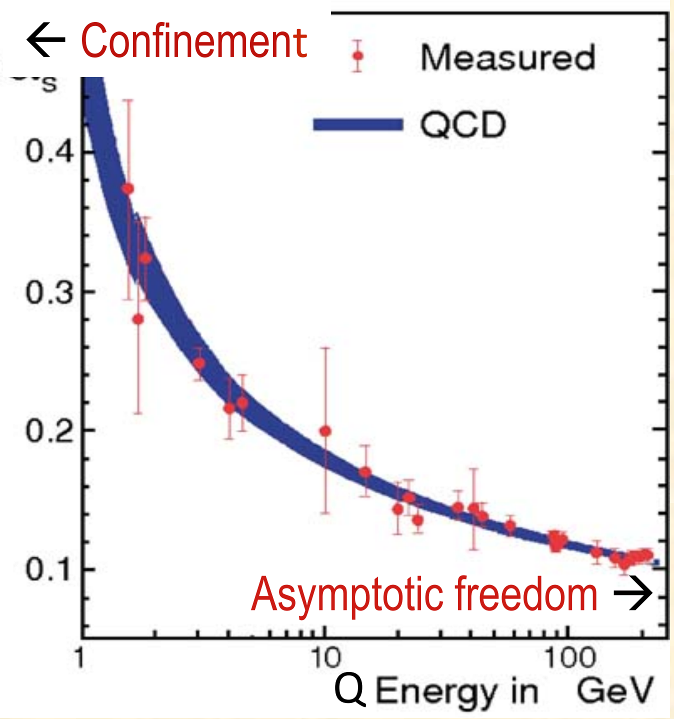
$$\alpha_s(Q^2) = \frac{g^2}{4\pi} \approx \log^{-1}\left(\frac{Q^2}{\Lambda^2_{QCD}}\right)$$

$$\Lambda_{QCD} \approx 200\, MeV \approx 1\, fm^{-1}$$

e.m. coupling

$$\alpha_{e.m.}(Q^2) = \frac{e^2}{4\pi} = \frac{1}{137}$$

$$V(Q) \approx \frac{\alpha(Q^2)}{r}$$



Two regimes:

➢ **Perturbative: Asymptotic freedom** ($Q \geq 20\ \Lambda_{QCD}$)

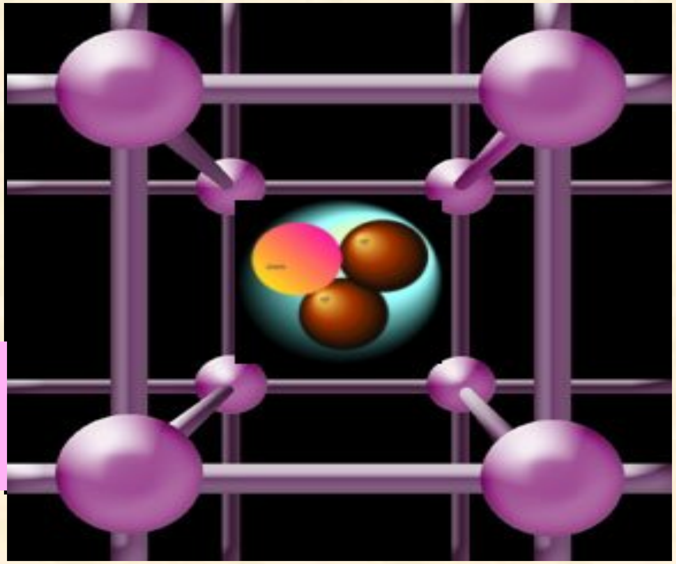
→ Interaction Increase with distance ≠ other interaction

→ precise results for Early Universe at energies we can reach on Earth!!!

➢ **Non-Perturbative : Confinement**

→ solvable only on Lattice QCD

(i.e. integrating over about 10^7 variables…)



❖ Confinement **means "No Ionization" → No colored plasma** ("charged" gas) like for atoms!?

If you have to stay confined to white spots how can you move freely?

A skier (quark) is Confined inside snow patches (hadrons)

If you have to stay confined to white spots how can you move freely?

A skier (quark) is Confined inside snow patches (hadrons)

Temperature

The skier can move further … a new phase develops

.. goes up

A skier (quark) can move freely … over long distances

.. this way

Quark-Gluon Plasma (5th state of matter)

1975: **J.C. Collins M.J. Perry**, "Superdense Matter or **Asymptotically Free** Quarks?", Phys. Rev. Lett. 34, 1353: *"…matter at densities higher than nuclear consists of a quark soup. The **quarks become free** at sufficiently high density or temperature."*

2000 – CERN Statement, Nature 403 : "evidence for the existence of a new state of quark-gluon matter in which quarks … are liberated **to roam freely**… in which quarks and gluons are no longer confined but **free to move** around over a volume… quarks would then **freely roam**."

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1975: **Cabibbo & Parisi**, Phys.Lett.B 59, 67, "**Exponential hadronic spectrum** and quark liberation". An hadronic resonance gas has a **divergency in the partition function** at $T=T_0 \approx 160$ MeV → phase transitions.

Note: *Before "73 there was nothing to transit to. T_0 was limiting Temperature (Hagedorn)*

Density of states ρ(m) of hadronic matter wins over Boltmann suppression factor

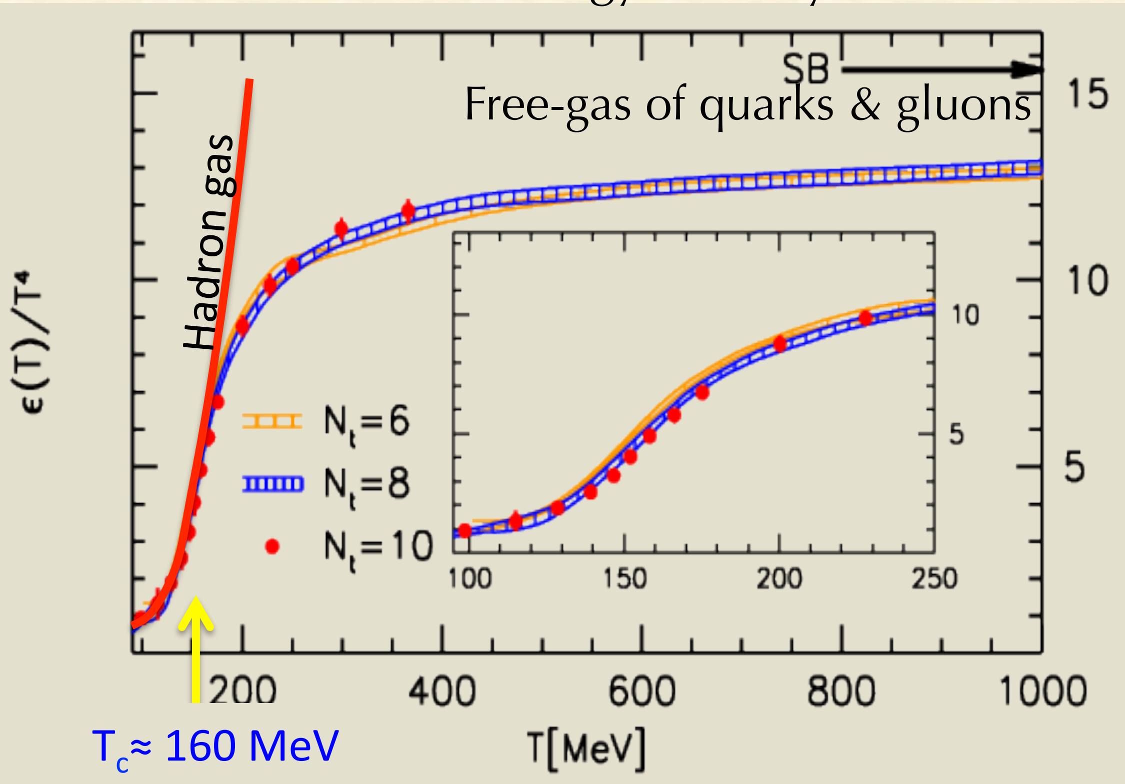
$$\log Z(T,V) \propto \int_{m_0}^{\infty} dm\, m^{3/2}\, \rho(m) e^{-\frac{m}{T}} \propto \int_{m_0}^{\infty} dm\, m^{\alpha+3/2}\, e^{-m\left(\frac{1}{T}-\frac{1}{T_0}\right)}$$

Integral diverges for $T \to T_0$:

Not related to Asymptotic Freedom!

Beyond naive argument: lattice QCD

Rescaled Energy Density



$$\frac{\varepsilon_{SB}}{T^4} = \frac{\pi^2}{30}\left[\frac{7}{8}d_{q+\bar{q}} + d_g\right] \approx \frac{1}{3}\# d.o.f$$

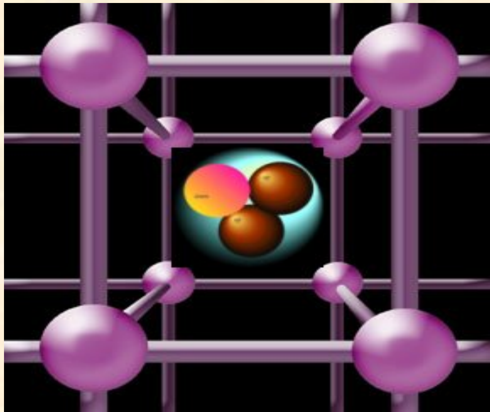
Colored Matter
about 45 d.o.f.

$d = 3_{fl} * 3_{col} * 2_s * 2_{anti} + 16_{gluon}$

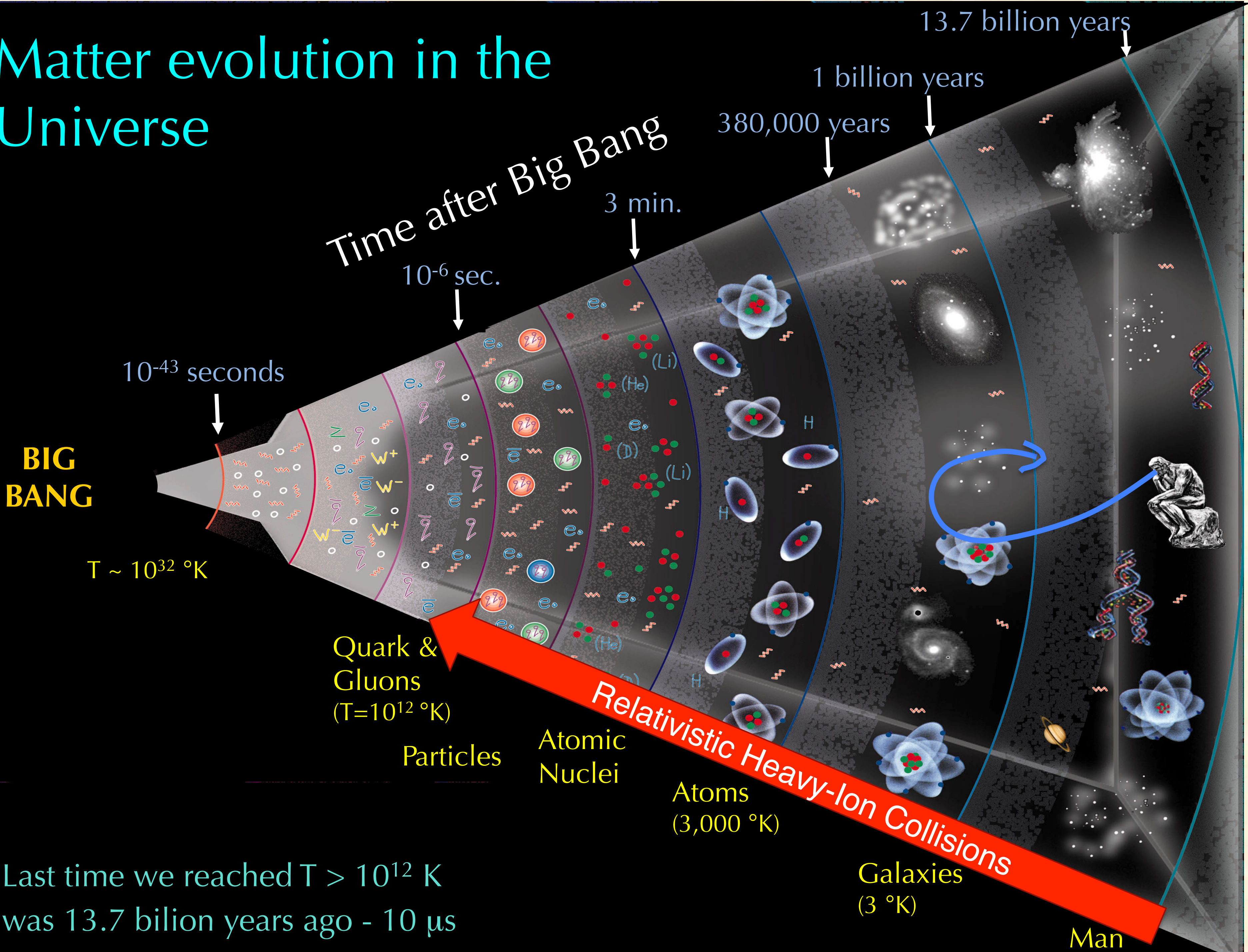
Wuppertal-Budapest Collab. (2010)

Stefan-Boltzmann limit not reached
by 15-20 % : QGP as a weak interacting gas?

But ε-3p>>0 strong interaction …



Matter evolution in the Universe

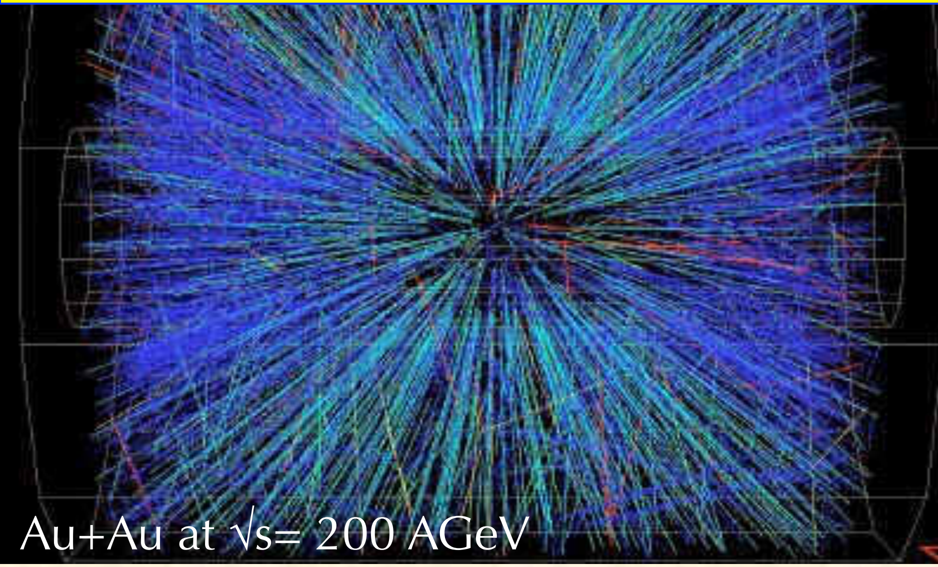


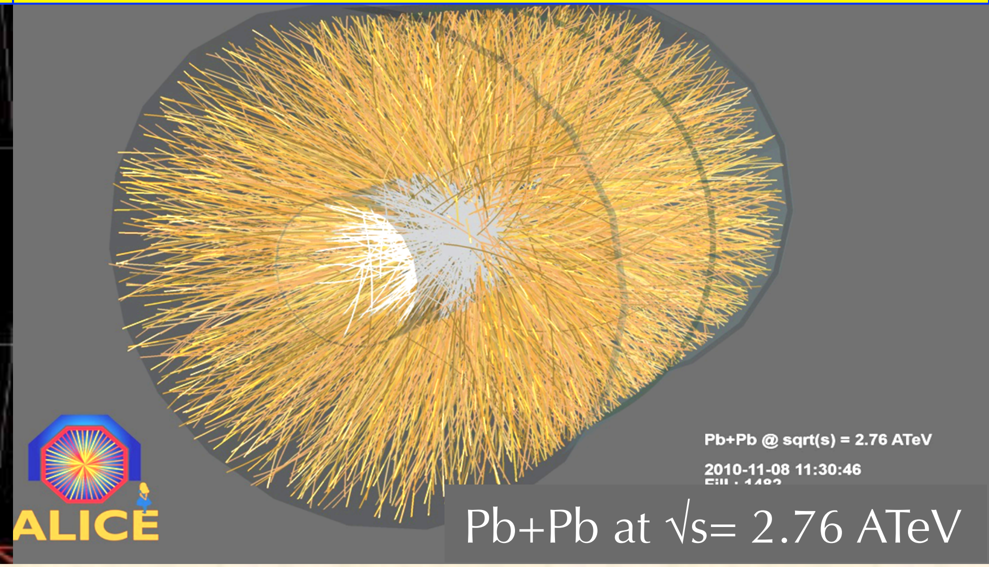
Last time we reached T > 10^{12} K was 13.7 bilion years ago - 10 μs

- Uninteresting question:

  What happens when I crash two gold nuclei together?

RHIC-BNL	LHC-CERN

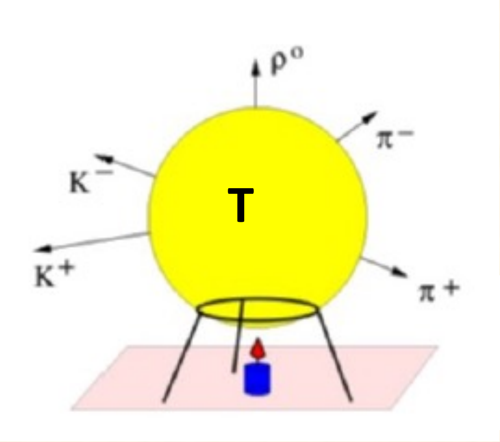




Do we create fireworks?

Or a plasma at some finite temperature?

Hadrons produced at $T<T_0$

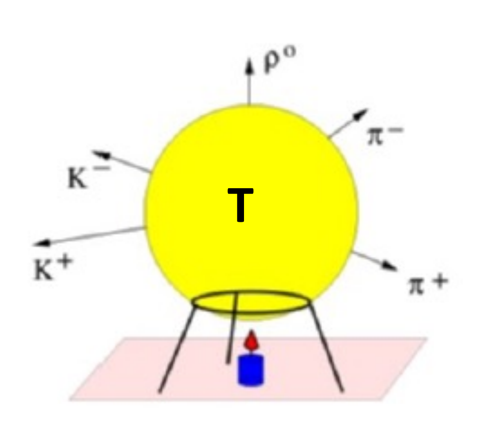


$E=mc^2$ (+) $E=KT$ energy used to produced new particles of mass m_j ($j= \pi, K, p, \Lambda, \Omega, \ldots$)

<u>Particle Abundancy</u>

$$n_j \approx e^{-\frac{m_j}{T}}$$

Hadrons produced at $T<T_0$

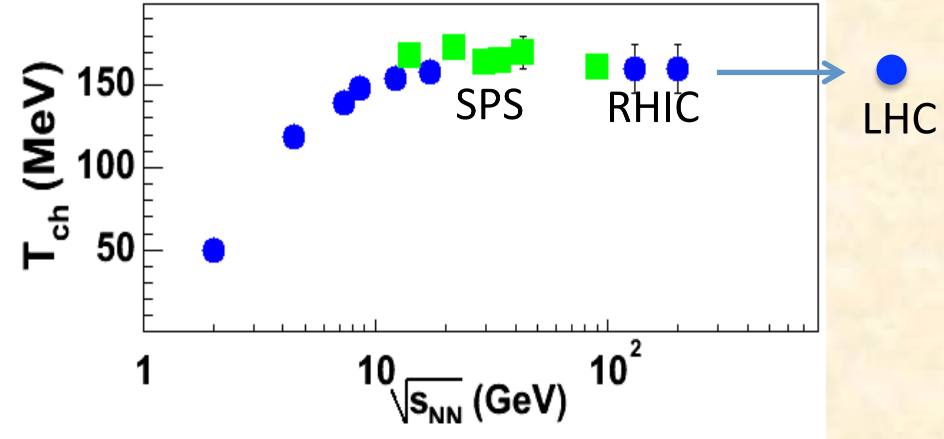


$E=mc^2$ (+) $E=KT$ energy used to produced new particles of mass m_j ($j=\pi, K, p, \Lambda, \Omega, \ldots$)

Particle Abundancy – Statistical Hadronization

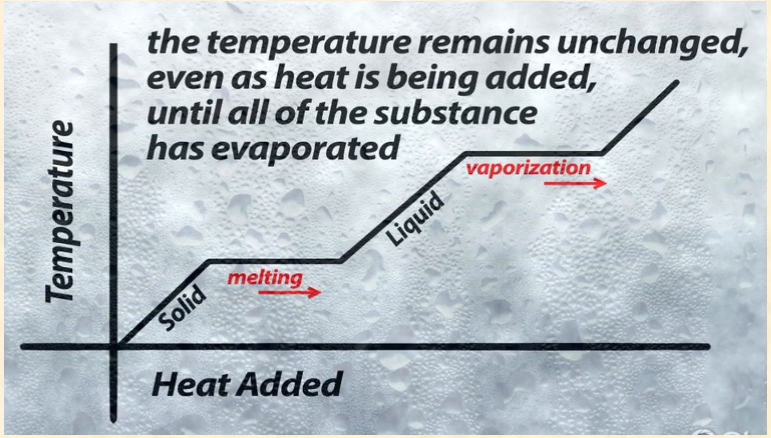
$$\langle n_j \rangle = \frac{(2J_j+1)V}{(2\pi)^3} \int d^3p \left[e^{\sqrt{p^2+m_j^2}/T + \mu\cdot q_j/T} \pm 1 \right]^{-1}$$

Hot QCD matter from HIC



Energy – Heat →

Water Phase transition



Does this mean it is a first order phase transition?

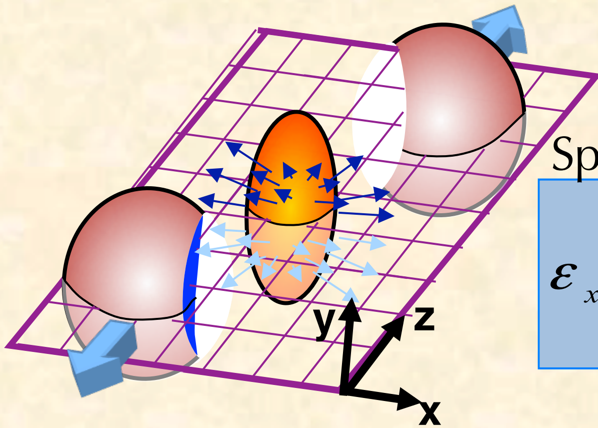
- No, lattice QCD says it is a cross-over.
- No, this behavior is due to confinement. This is a special matter!

How to study the properties of this strange QGP matter!

Having a sample of 10^{-14} m that last for 10^{-23} sec?

I will pick-up one example …

Anisotropic Expansion in the tranverse plane



Space Eccentricity

$$\varepsilon_x = \left\langle \frac{y^2 - x^2}{y^2 + x^2} \right\rangle$$

η/s viscosity

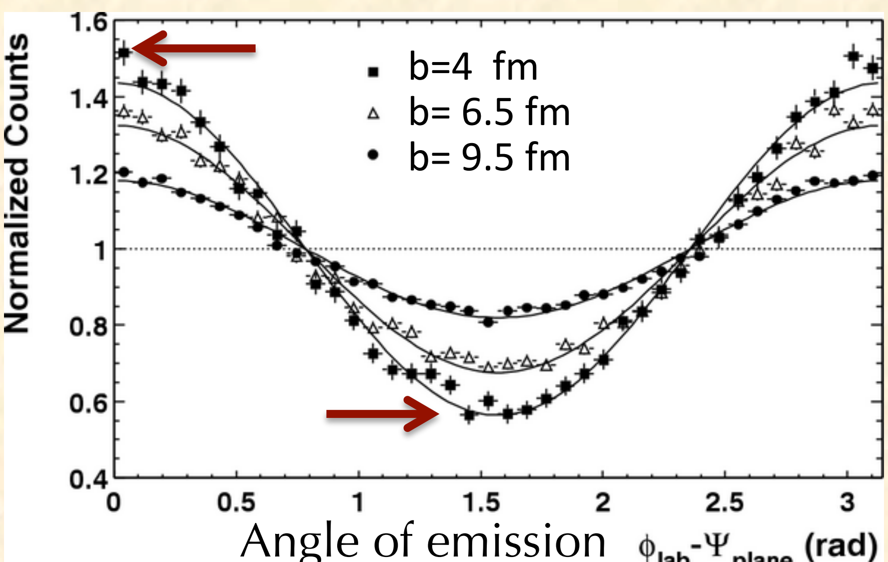
$c^2_s = dP/d\varepsilon$ - EoS

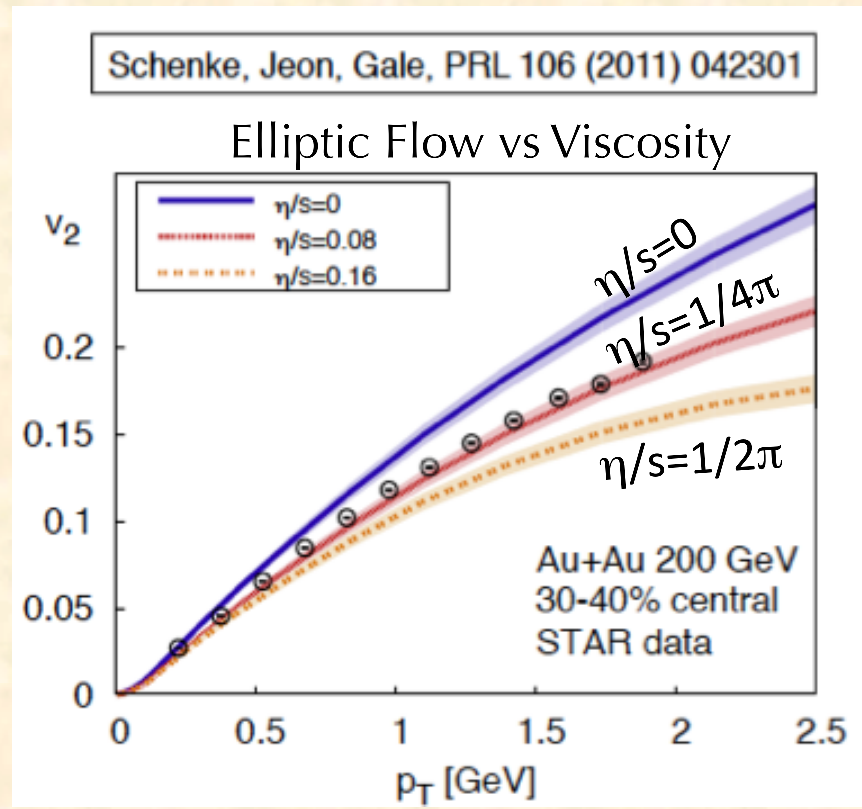
Elliptic Flow

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \left\langle \cos(2\phi_p) \right\rangle$$

Coefficient Fourier expansion

$$\frac{dN}{dp_T d\phi} = \frac{dN}{dp_T}\left[1 + 2\,v_2 \cos(2\phi) + \ldots\right]$$





Just one Note ...

1) Trivial after solving .... Relativistic Viscous Hydrodynamics at II° order

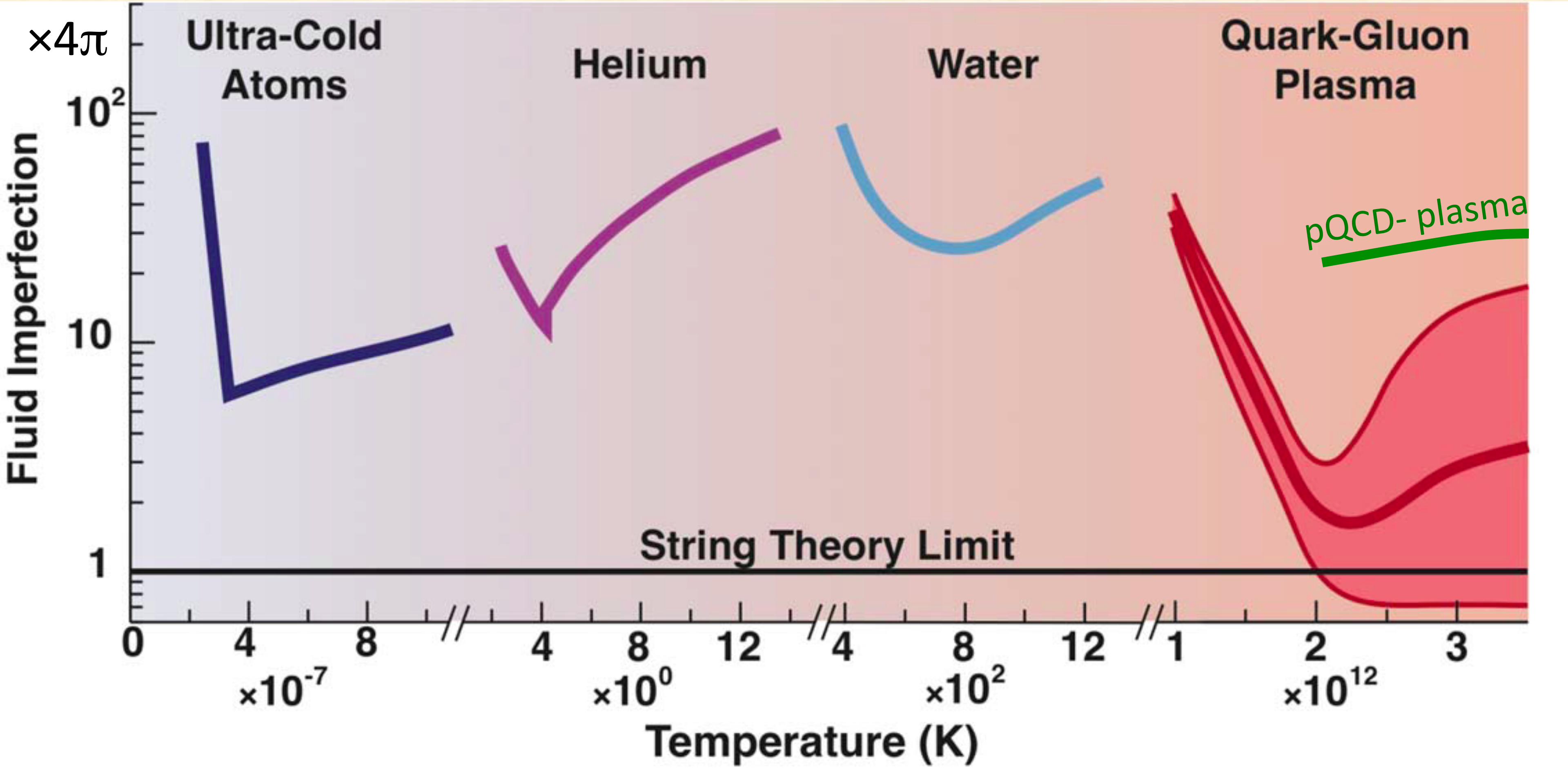
$$\tau_\Pi \dot{\Pi} + \Pi = \Pi_{NS} + \tau_{\Pi q}\, q\cdot\dot{u} - \ell_{\Pi q}\,\partial\cdot q - \zeta\,\hat{\delta}_0\,\Pi\,\theta$$
$$+ \lambda_{\Pi q}\, q\cdot\nabla\alpha + \lambda_{\Pi\pi}\,\pi^{\mu\nu}\sigma_{\mu\nu}$$

$$\tau_q\,\Delta^{\mu\nu}\dot{q}_\nu + q^\mu = q^\mu_{NS} - \tau_{q\Pi}\,\Pi\,\dot{u}^\mu - \tau_{q\pi}\,\pi^{\mu\nu}\,\dot{u}_\nu$$
$$+ \ell_{q\Pi}\,\nabla^\mu\Pi - \ell_{q\pi}\,\Delta^{\mu\nu}\,\partial^\lambda\pi_{\nu\lambda} + \tau_q\,\omega^{\mu\nu}\,q_\nu - \frac{\kappa}{\beta}\hat{\delta}_1\,q^\mu\,\theta$$
$$- \lambda_{qq}\,\sigma^{\mu\nu}\,q_\nu + \lambda_{q\Pi}\,\Pi\,\nabla^\mu\alpha + \lambda_{q\pi}\,\pi^{\mu\nu}\,\nabla_\nu\alpha$$

$$\tau_\pi\,\dot{\pi}^{<\mu\nu>} + \pi^{\mu\nu} = \pi^{\mu\nu}_{NS} + 2\,\tau_{\pi q}\,q^{<\mu}\dot{u}^{\nu>}$$
$$+ 2\,\ell_{\pi q}\,\nabla^{<\mu}q^{\nu>} + 2\,\tau_\pi\,\pi_\lambda{}^{<\mu}\omega^{\nu>\lambda} - 2\,\eta\,\hat{\delta}_2\,\pi^{\mu\nu}\,\theta$$
$$- 2\,\tau_\pi\,\pi_\lambda{}^{<\mu}\sigma^{\nu>\lambda} - 2\,\lambda_{\pi q}\,q^{<\mu}\nabla^{\nu>}\alpha + 2\,\lambda_{\pi\Pi}\,\Pi\,\sigma^{\mu\nu}$$

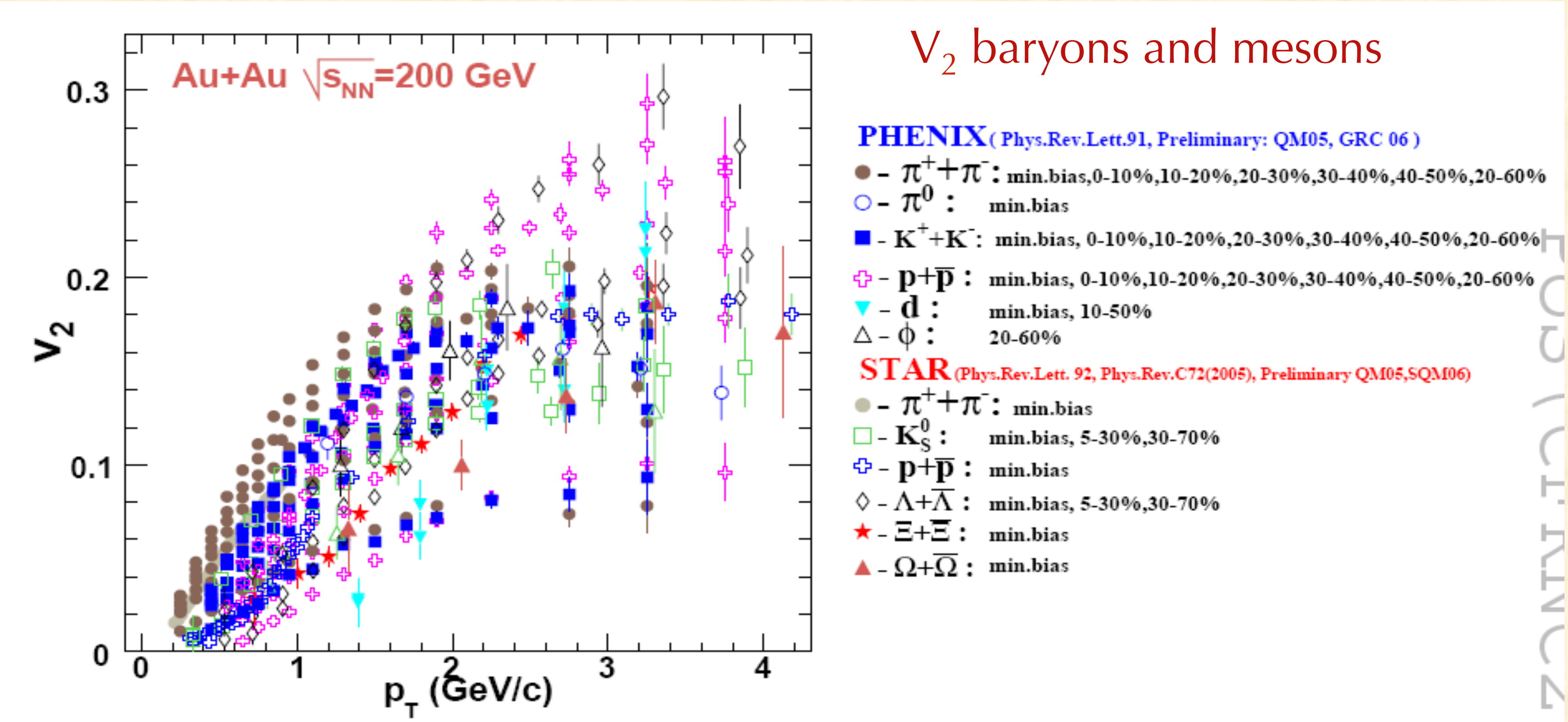
All is done assuming that matter created is thermal at $\tau \approx O(1fm/c)$

Shear Viscosity for systems in 20 order of T magnitudes!



Report to the Nuclear Science Advisory Committee in 2013

One more thing about elliptic flow

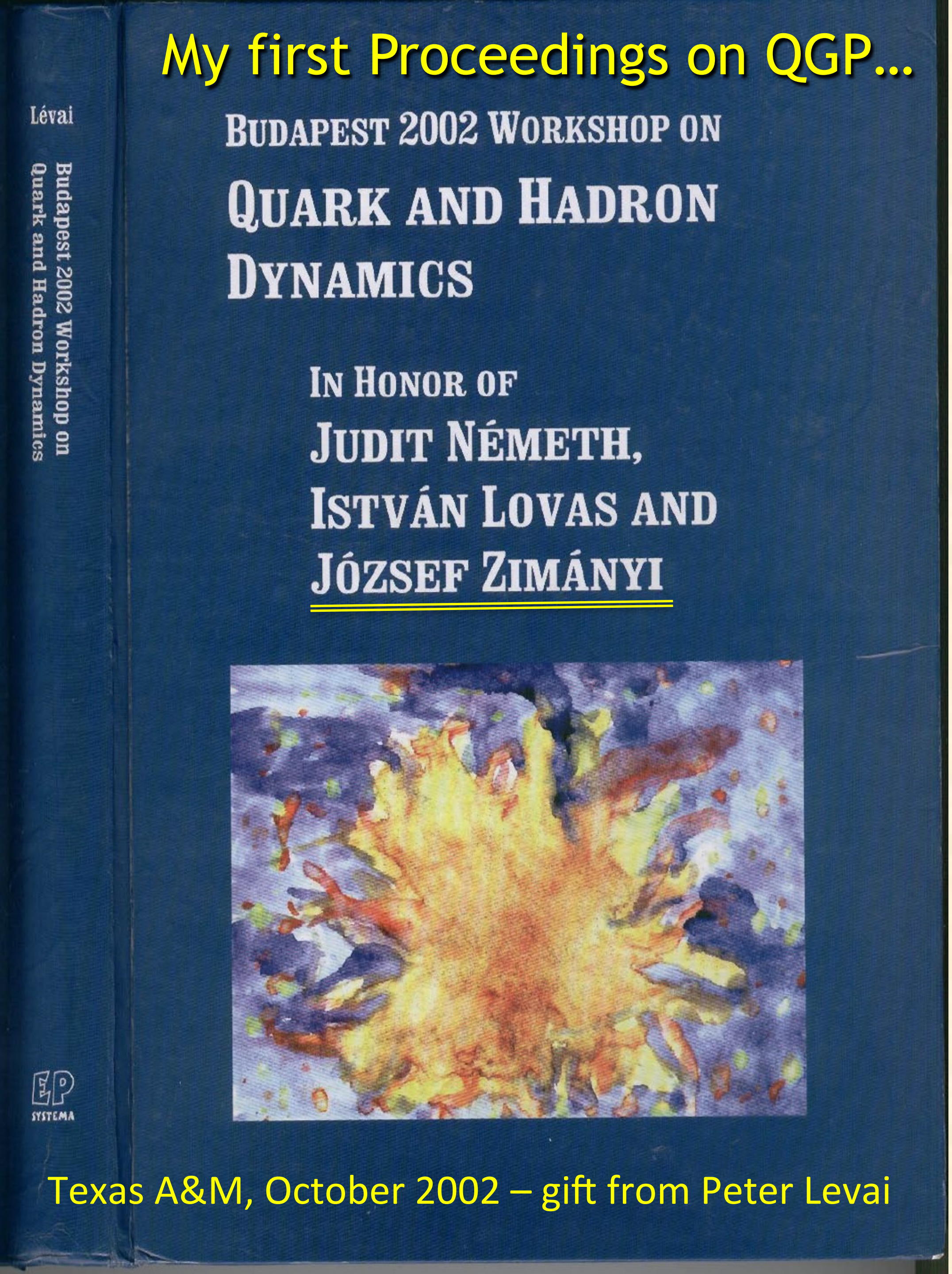


Always **one question bounces back**!

Can we see how and if quarks are flowing?

Confinement: we can see only hadrons flowing

My first Proceedings on QGP…



Texas A&M, October 2002 – gift from Peter Levai

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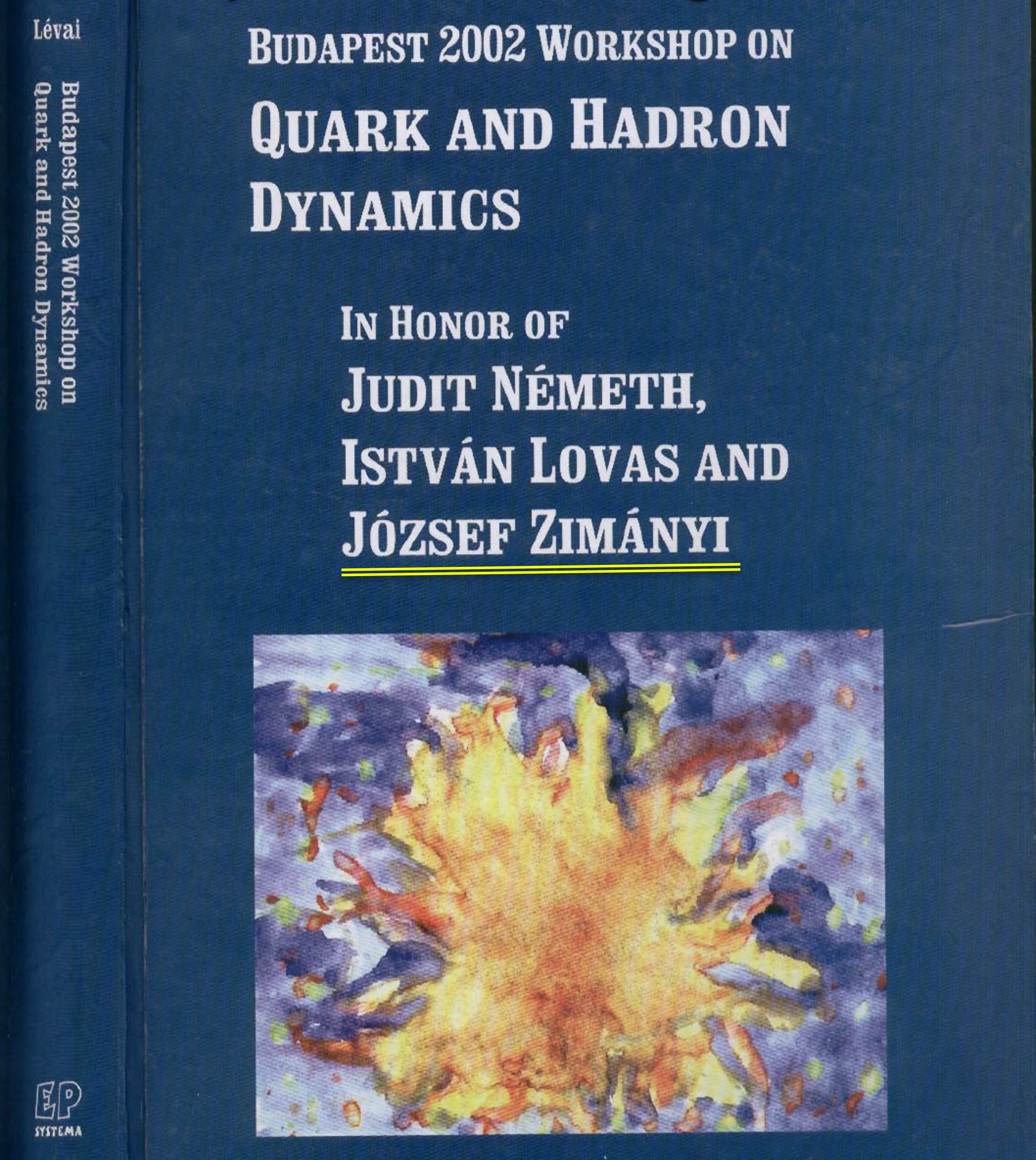

Texas A&M, October 2012 – gift from Peter Levai

Disccusing at lunch with **Peter Levai**
(Director of MTA Wigner-Budapest…)

P. Levai

V. Greco

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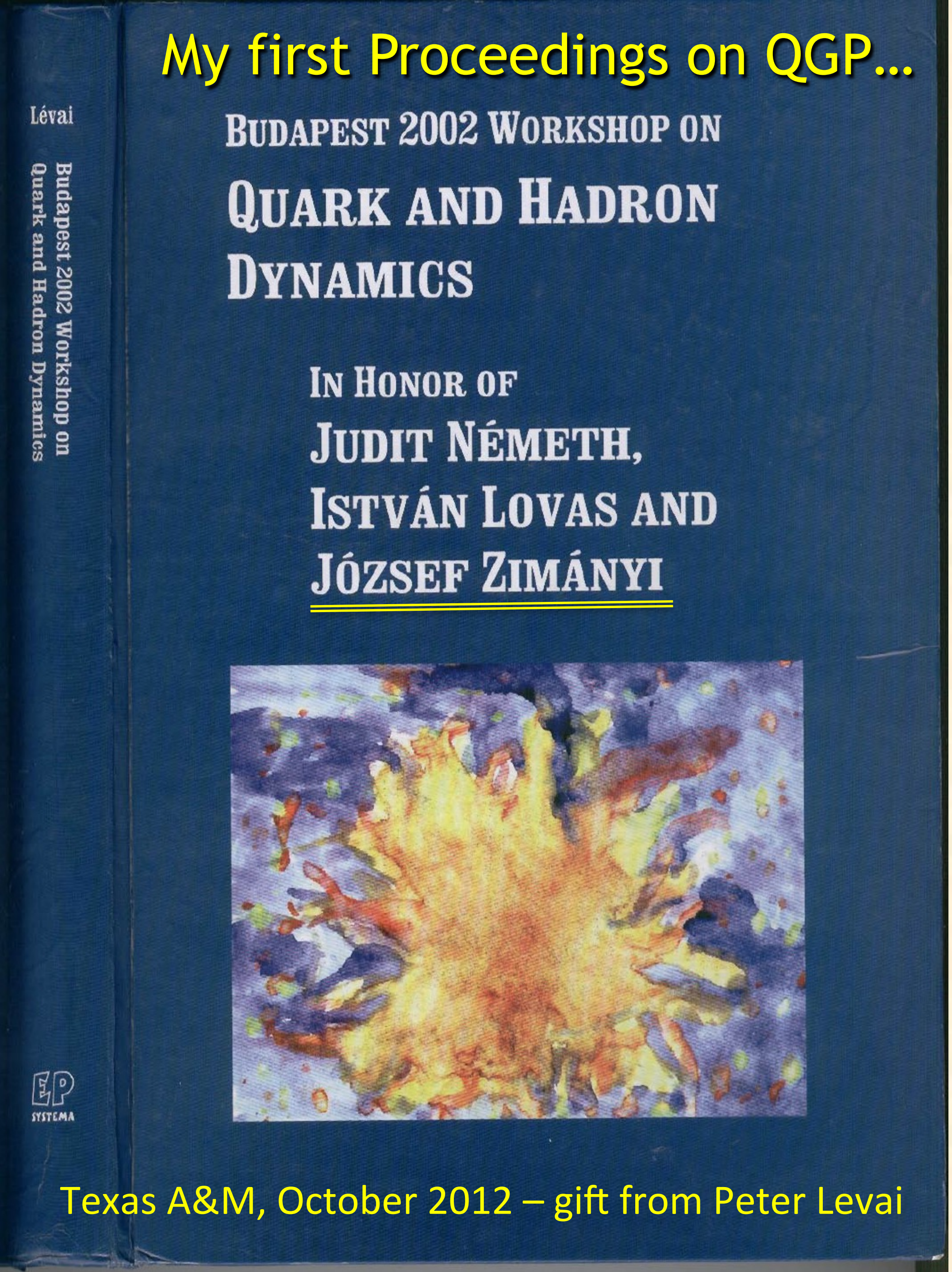
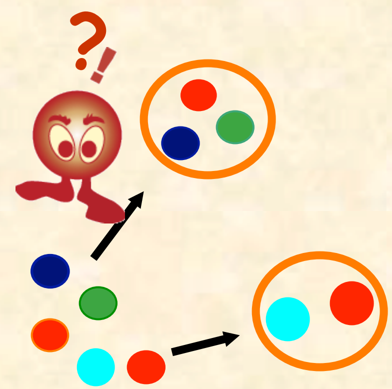


Texas A&M, October 2012 – gift from Peter Levai

"In **AL**gebraic **CO**alescence**R**ecombination model we assume that just before the hadronization the dense matter can be described as a mixture of dressed up, **massive quarks and antiquarks** … "

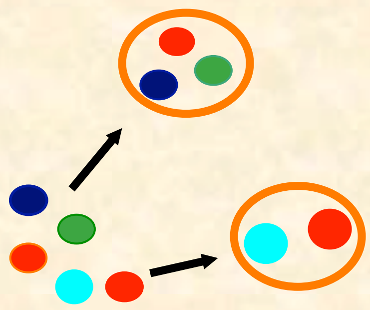
By J. Zimanyi and the Budapest group

If you have a medium of quarks
Why you need the vacuum to
hadronize?



In Texas we moved to
observables in momentum space

Recombination enhances Anisotropies



Meson recombination(qq)

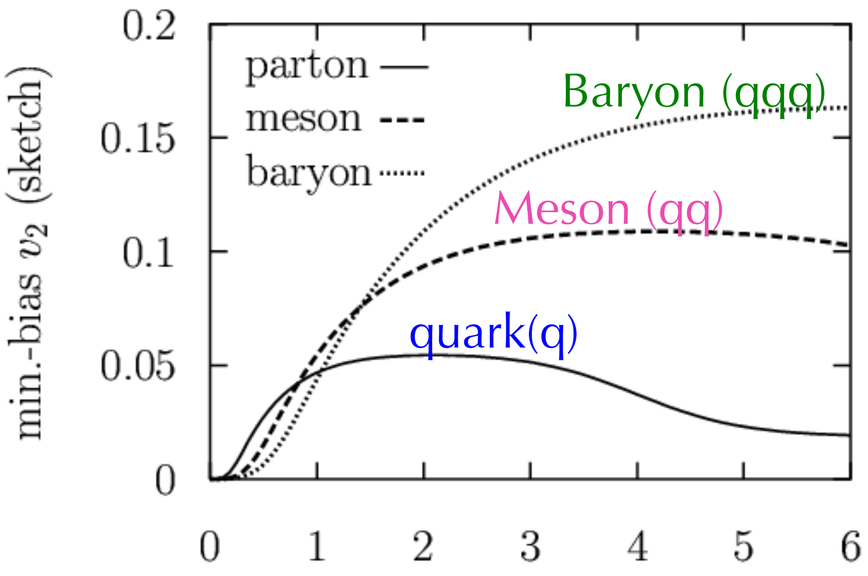
$$f_H(\mathbf{P}_H = 2\mathbf{p}_T) \approx f_q(\mathbf{p}_T) \otimes f_{\bar{q}}(\mathbf{p}_T)$$

$$\approx \left[1 + v_{2q}(p_T)\cos(2\varphi_p) + ..\right]^2 \approx 1 + 2v_{2q}(2p_T)\cos(2\varphi_p) + ..$$

Baryon recombination(qqq)

$$f_H(\mathbf{P}_H = 3\mathbf{p}_T) \approx f_q(\mathbf{p}_T) \otimes f_q(\mathbf{p}_T) \otimes f_q(\mathbf{p}_T)$$

$$\approx \left[1 + v_{2q}(p_T)\cos(2\varphi_p) + ..\right]^3 \approx 1 + 3v_{2q}(3p_T)\cos(2\varphi_p) + ..$$



VG, Ko, Levai, PRL 90(2003)

Two branches

$$v_{2,M}(p_T) \approx 2v_{2,q}(p_T/2)$$

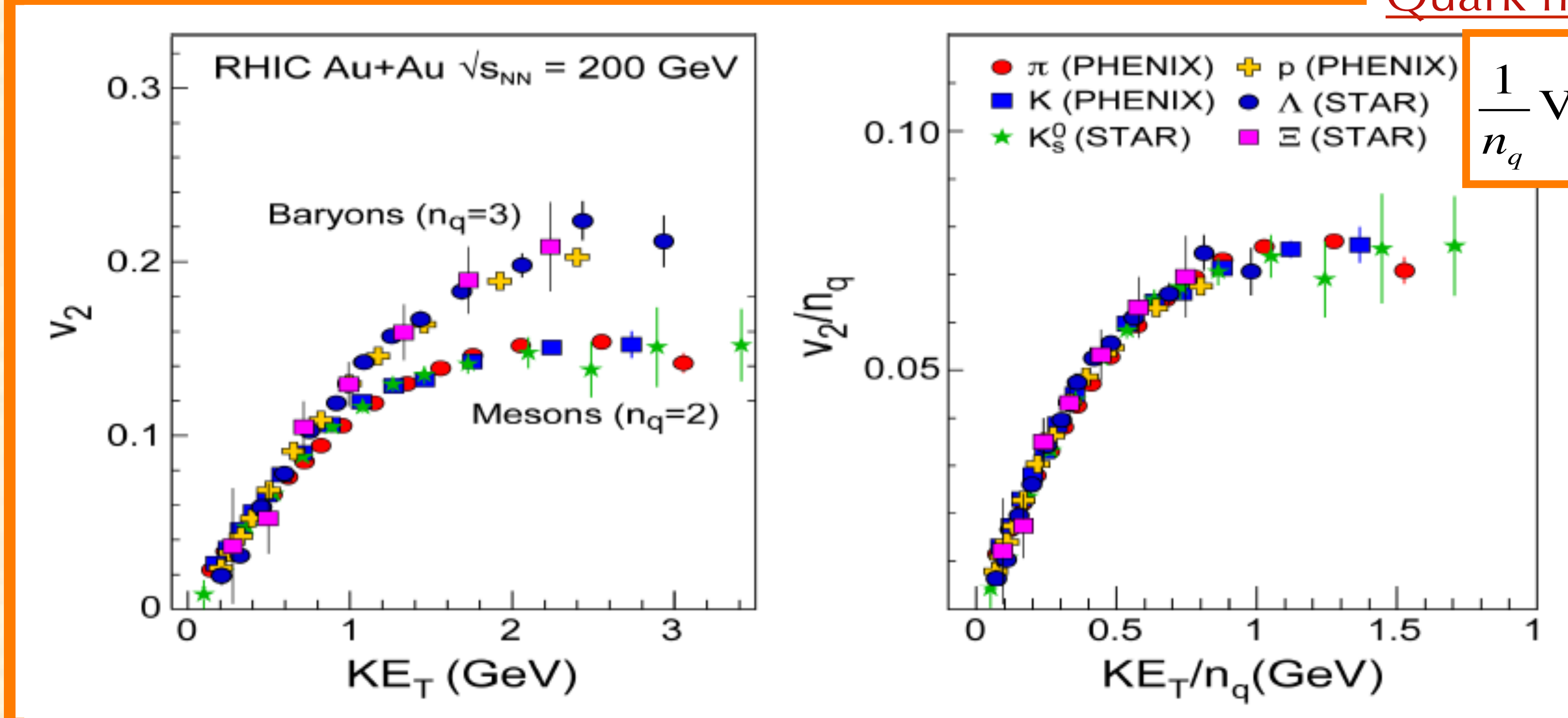
$$v_{2,B}(p_T) \approx 3v_{2,q}(p_T/3)$$

Discarding space-momentum correlation,
hadron wave function width,
event-by-even fluctuations, Resonance decays, ...

Too beautiful to be true? …

Quark n_q scaling

$$\frac{1}{n_q} V_2\left(\frac{p_T}{n_q}\right)$$

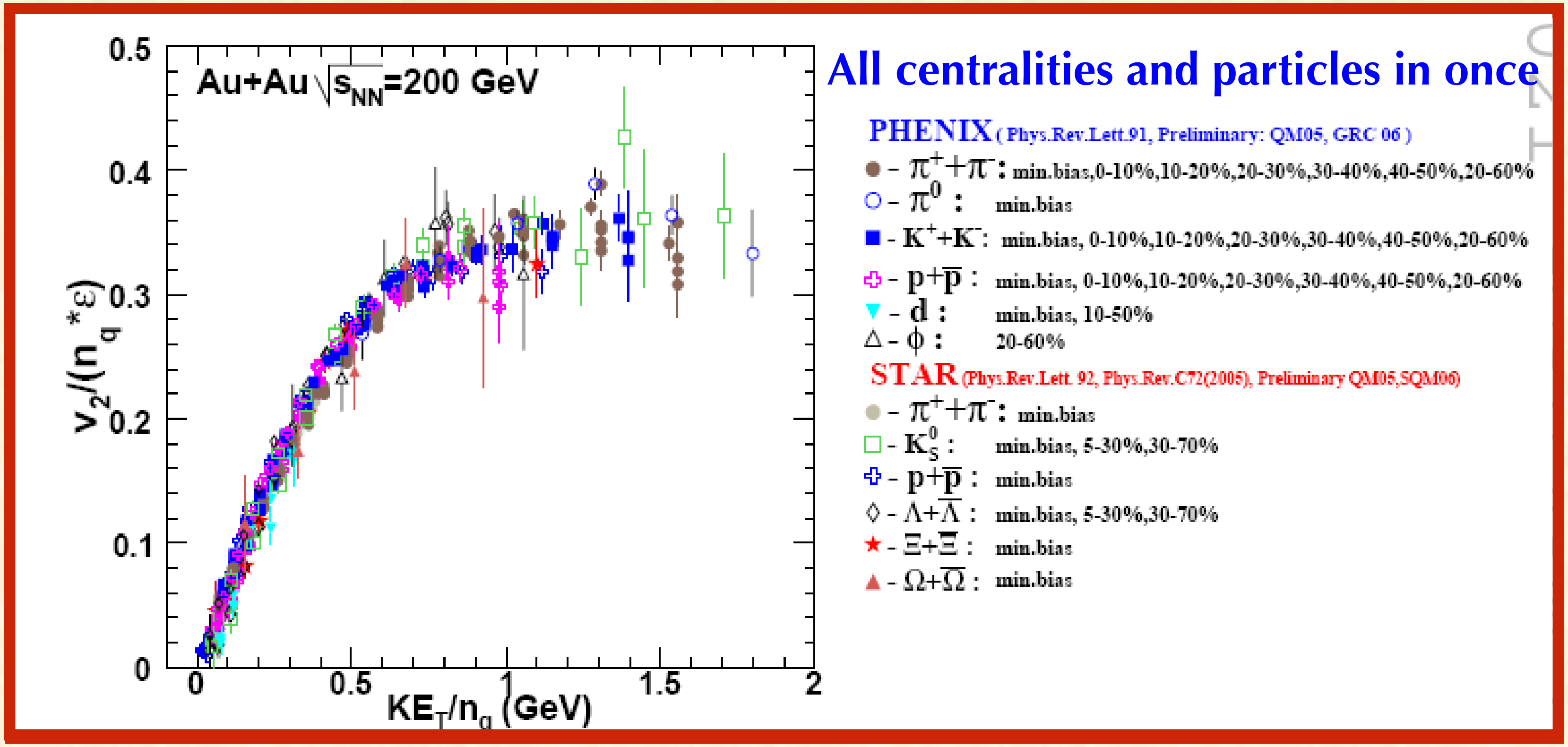


PHENIX, PRL 98(2007)

Anisotropic Flow formed at partonic level, one common QGP flow

Flow depends on quark content → two branches; Meson and Baryon

Too beautiful to be true …

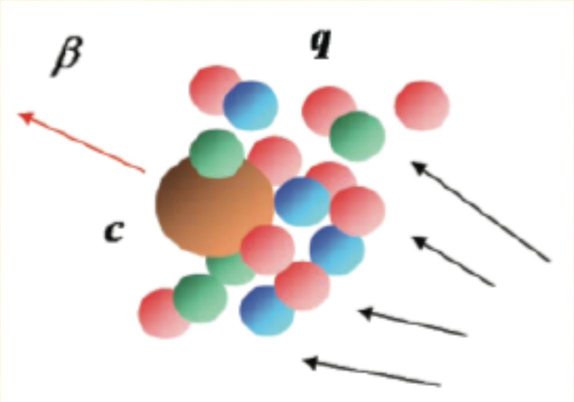


Everything rescales in one common flow!

We “see” the underlying quark flow.. with some distorsion

an elephant in the liquid

An elephant in the liquid: Heavy Charm Quark



Brownian motion

$$\frac{\partial f_{c,b}}{\partial t} = \gamma \frac{\partial (p f_{c,b})}{\partial p} + D \frac{\partial^2 f_{c,b}}{\partial p^2}$$

Drag　　Diffusion

QGP created is made by 99% of q=u,d,s, $\mathbf{m_q \approx 10}$ **MeV**

+ few Heavy Charm Quarks: $\mathbf{M_c \approx 1500}$ **MeV**

Standard Kinetic theory:

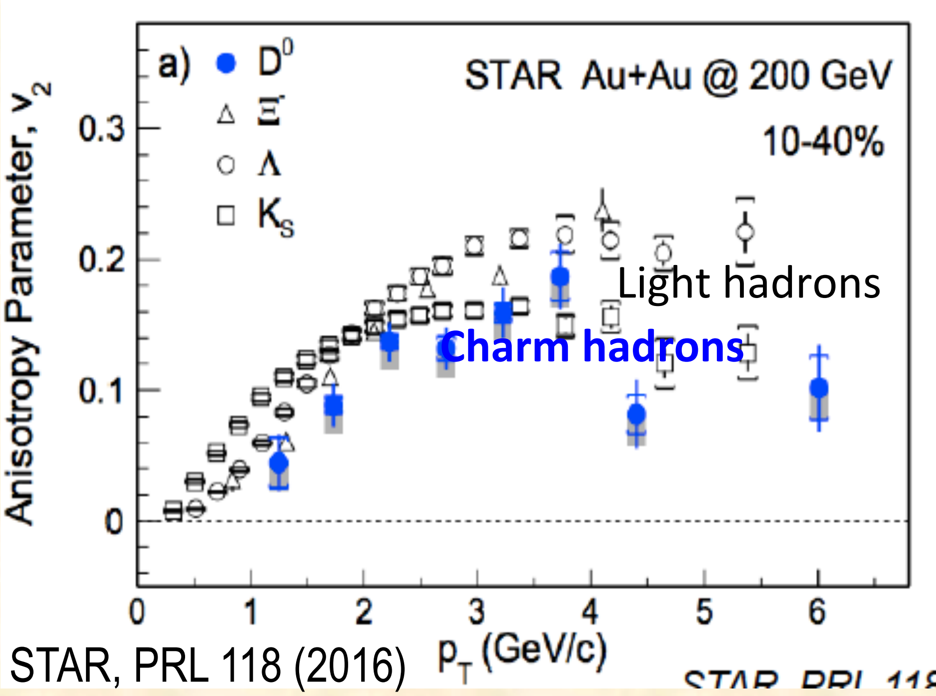
Poorly dragged & long thermalization time

$$\tau_{c,therm} \approx O(10^2) >> \tau_{QGP} >> \tau_{q,therm} \approx O(1)\ \mathrm{fm/c}$$

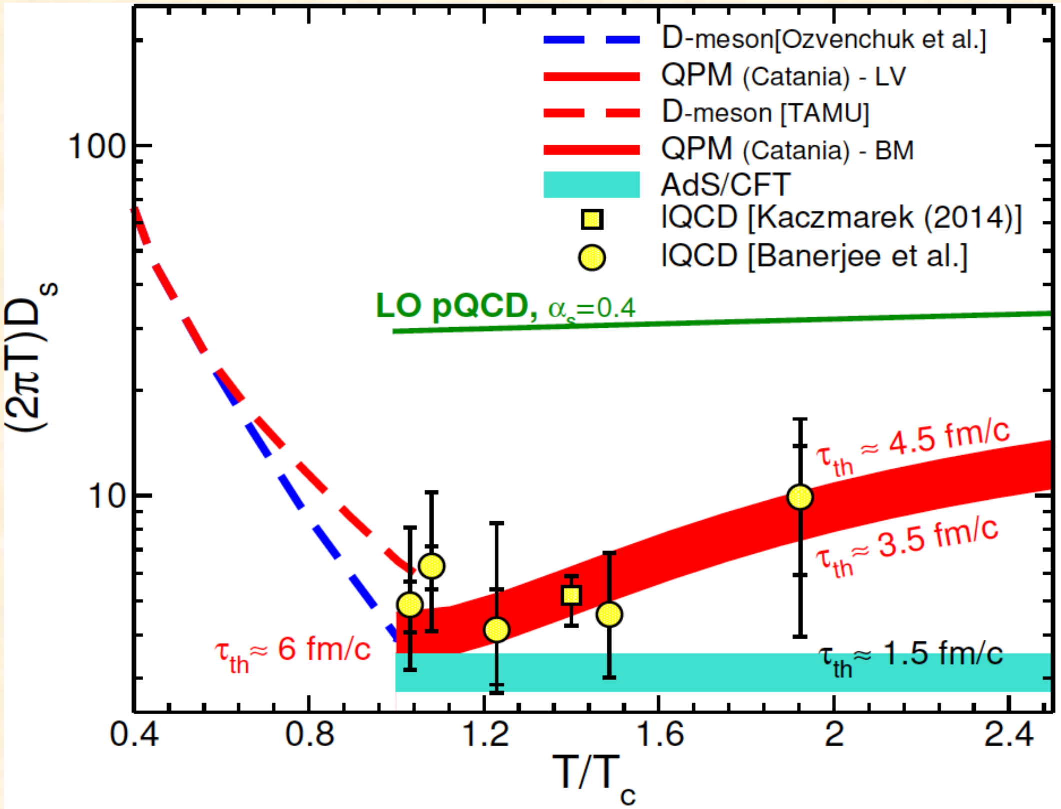
1992: B. Muller, NATO Advanced Study Institute

"For plasma conditions realistically obtainable in the nuclear collisions (T ~250 MeV, g = 2) the ***effective quark & gluon mass m*~400 MeV***. We must conclude, therefore, that the notion of almost ***free gluons and quarks in the high T phase of QCD is quite far from the truth.***"

How they flow



Diffusion Coefficient of Charm Quark



$$\tau_{th} = \frac{M}{2\pi T^2}(2\pi T D_s) \cong 1.8 \frac{2\pi T D_s}{(T/T_c)^2} \text{ fm/c}$$

Asymptotic free regime

Not a model fit to lQCD data!

Phenomenology ≈ lattice QCD

Infinite Strong Coupling (AdS/CFT)

- Created matter is the **Hot QCD matter in non perturbative regime!**
- Likely a U shape typical of matter undergoing a phase transition
- T→ Tc gets close to the AdS/CFT limit

Perspectives…

- **Characterizing viscosity η/s, bulk ζ/σ, conductivity σ_{el}, diffusion D_s :**
  - Important to understand QCD at high T up to pert. QCD regime
  - Provide a precise background for cosmology
    (Ex. WIMP relic density…)

- **Study Matter behavior under Huge Magnetic fields (10^{18} Gauss)**
  - Charge-Parity violation in Strong Interaction?

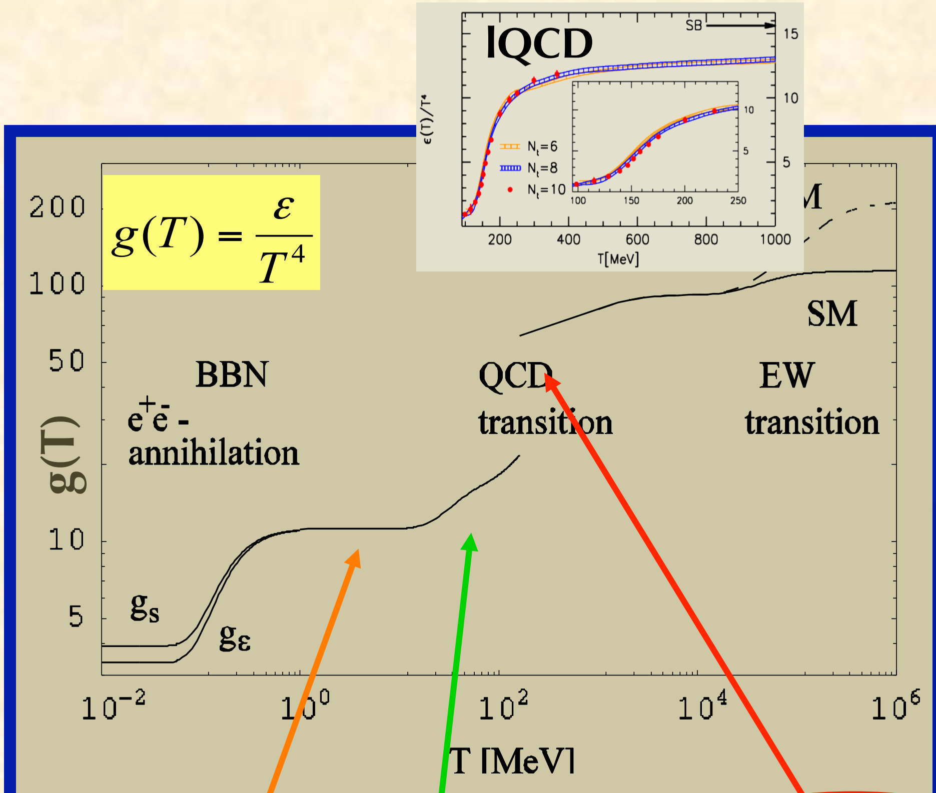
- **At TeV scale new view on pp collisions is emerging**
  → relevance for High-Energy Astrophysics at PeV scale and above

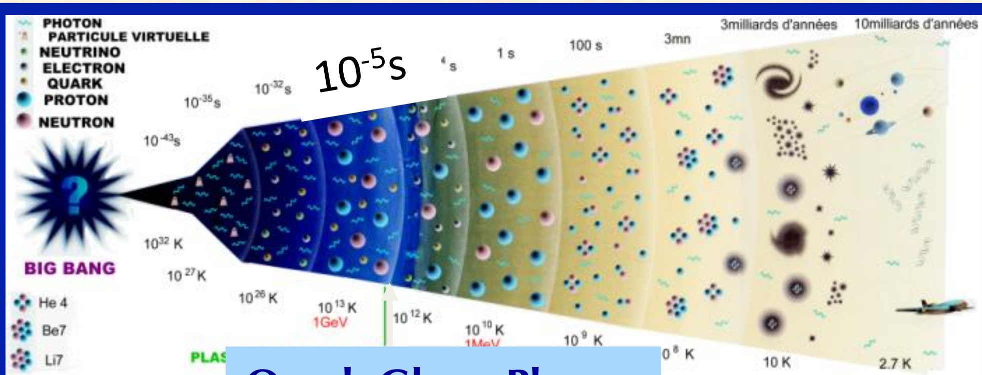
A Great Honor to be a member of this Academia!

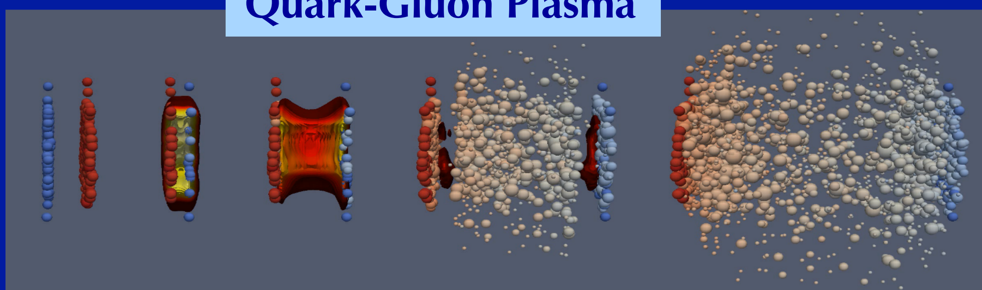
A very pleasant feeling to see the benevolent view of elder Collegueas!

An emotional coincidence to enter AE in Budapest!

Degrees of freedom in the Universe





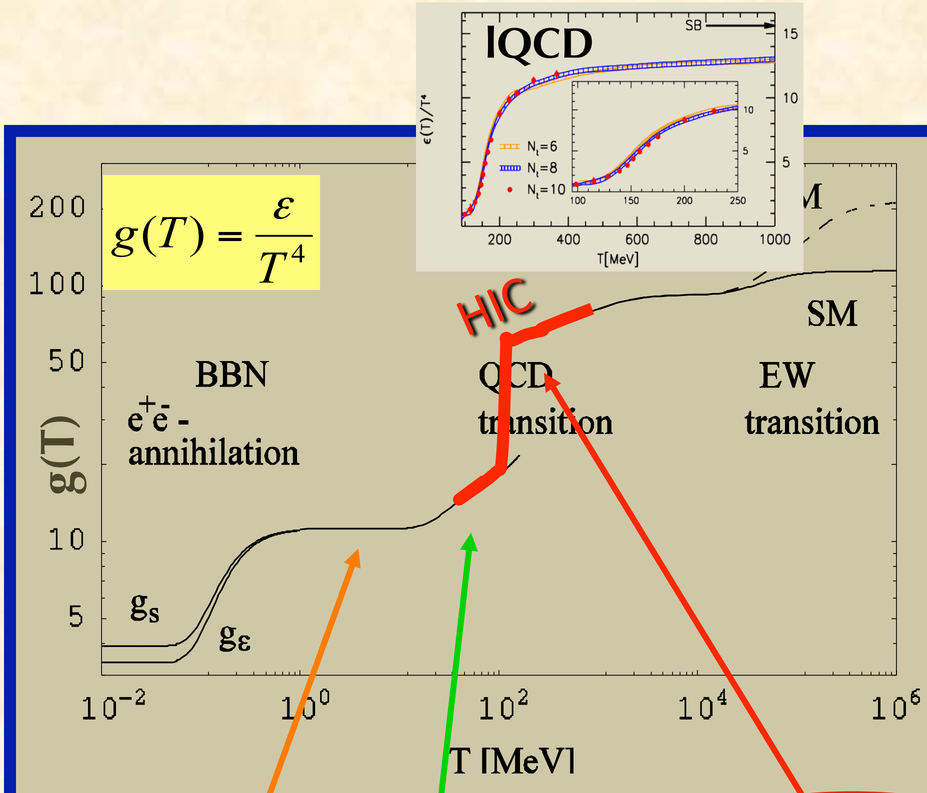


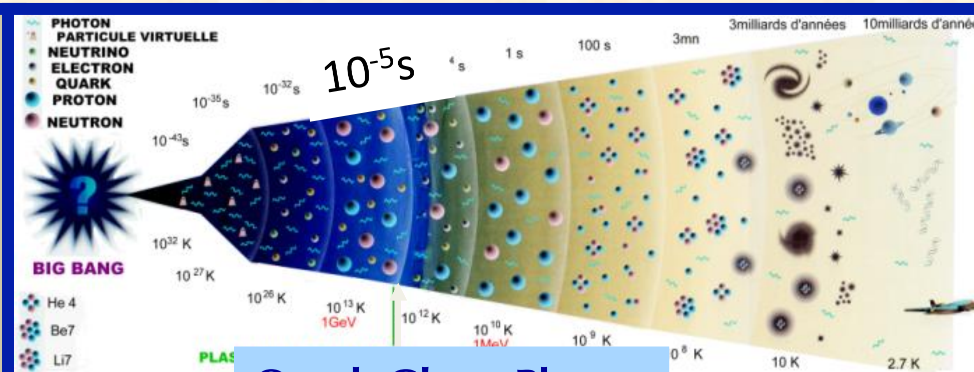
$$g(T) = 2_\gamma + 4_e + 4_\nu + 3_\mu + 3_\pi + \ldots + 16_g + 31.5_{uds} + 21_{cb} + \ldots$$

Disappeareance of colored matter the most drastic event

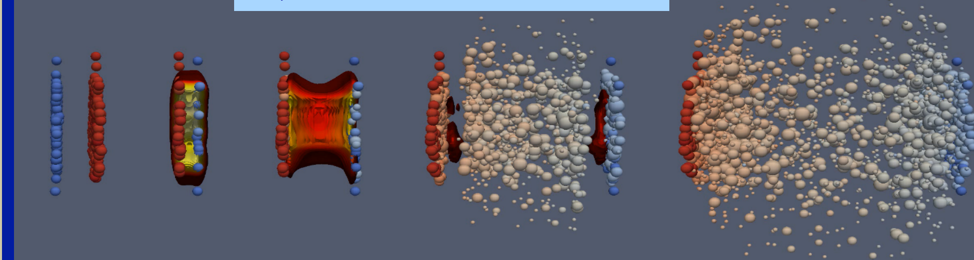
D.J.Schwartz, Ann. Phys. 2004

Degrees of freedom in the Universe





Quark-Gluon Plasma

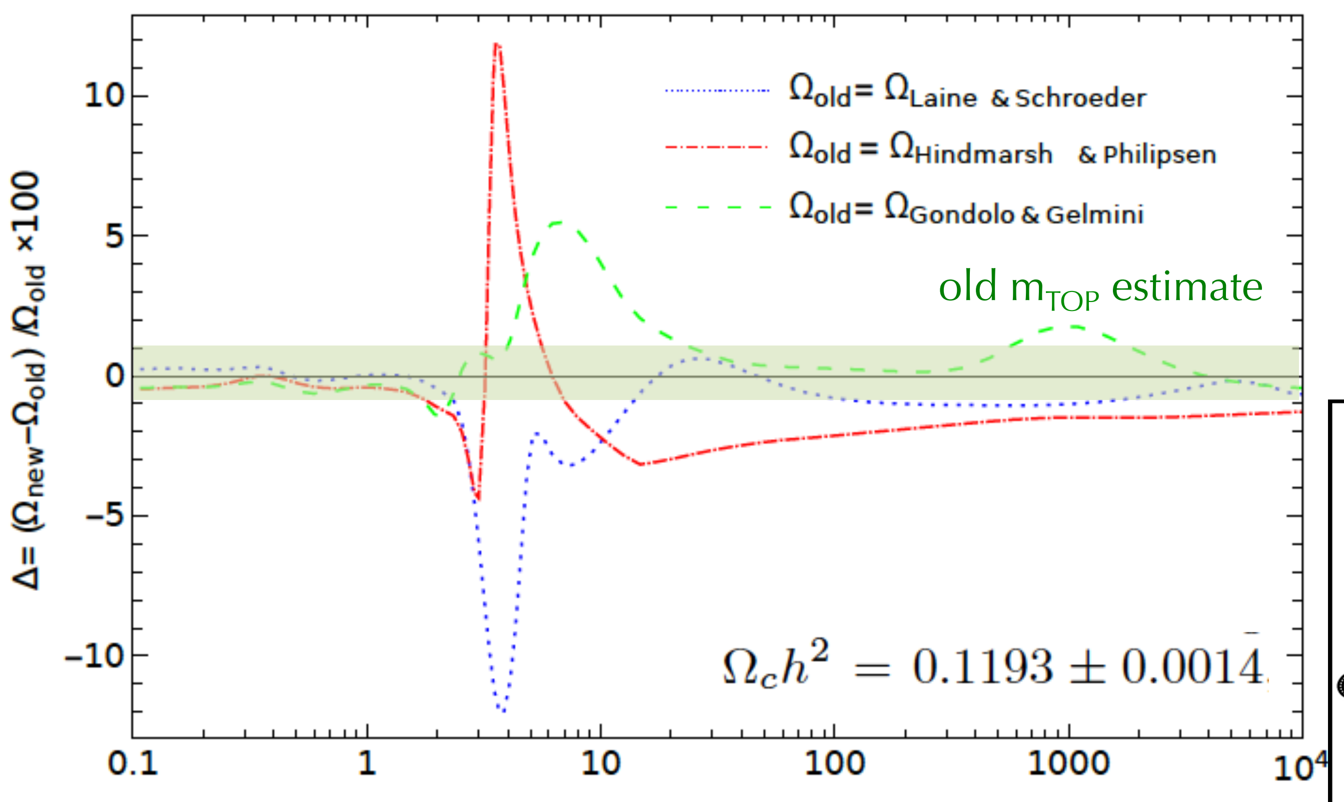


$$g(T) = 2_{\gamma} + 4_{e} + 4_{\nu} + 3_{\mu} + 3_{\pi} + \ldots + 16_{g} + 31.5_{uds} + 21_{cb} + \ldots$$

Disappeareance of colored matter the most drastic event

QCD EoS and the Relic WIMP Dark Matter

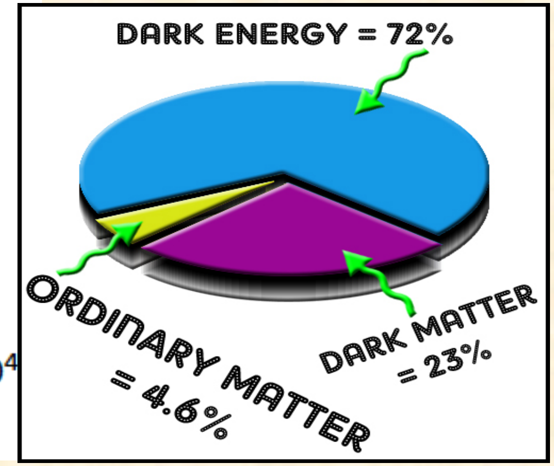
% variation of Ω due to different QCD EoS



M. Drees et al., JCAP 1506 (2015)

PLANCK estimate to determine Ω with 1% precisions

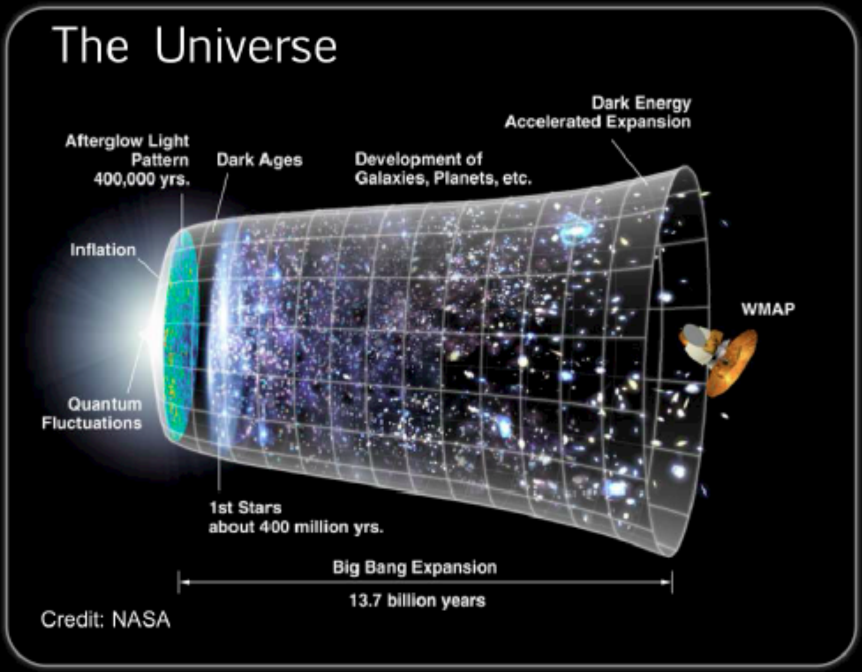
$$\Omega_c = \frac{\rho_{DM}}{\rho_c}$$

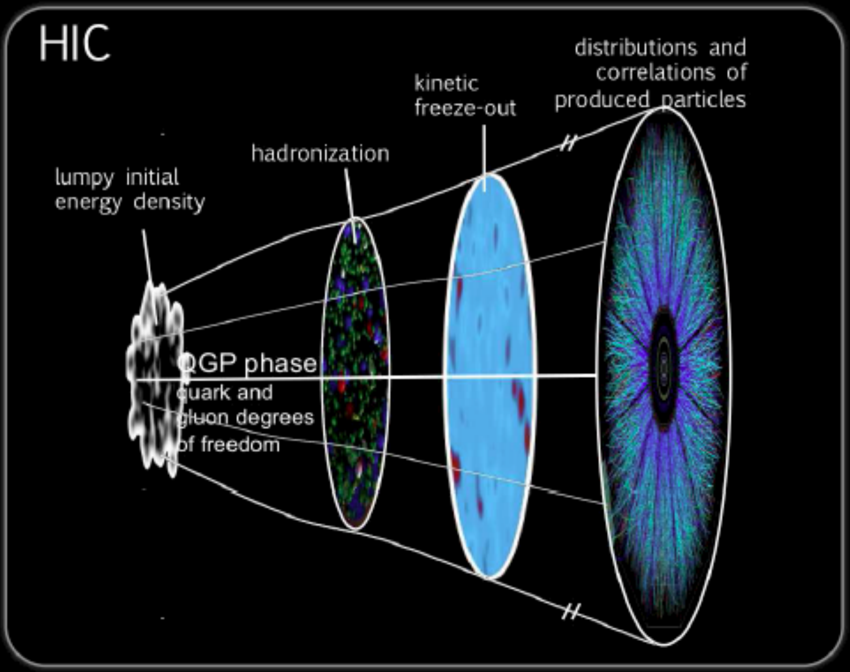


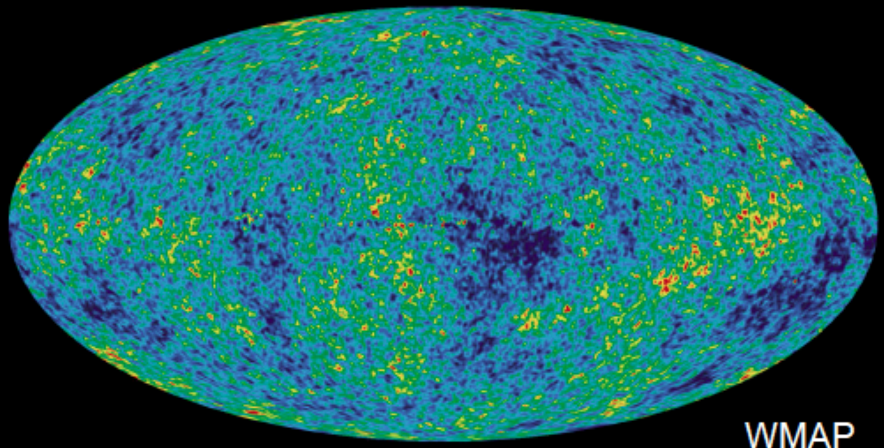
Under the assumption of isoentropic Early Universe expansion

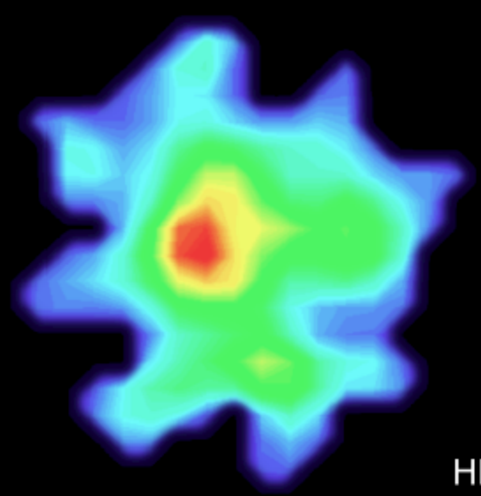
- We are now determining visccosities η/s(T), ζ/s(T) → entropy production
- We will see in the future the impact of the knowledge of Hot QCD

Another analogy with Early Universe expansion

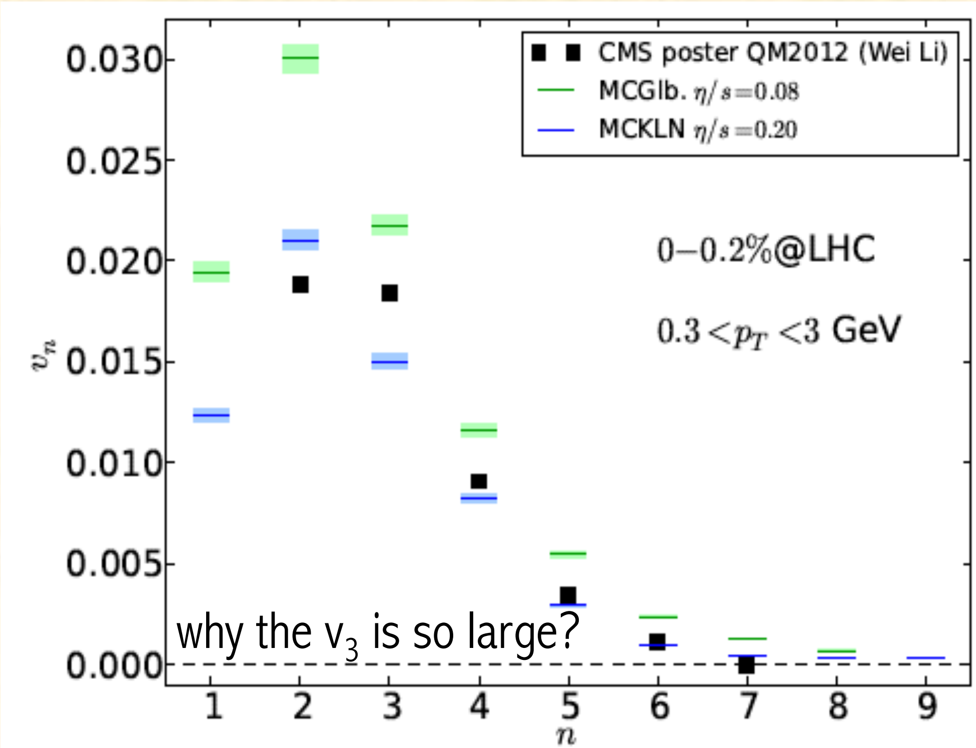


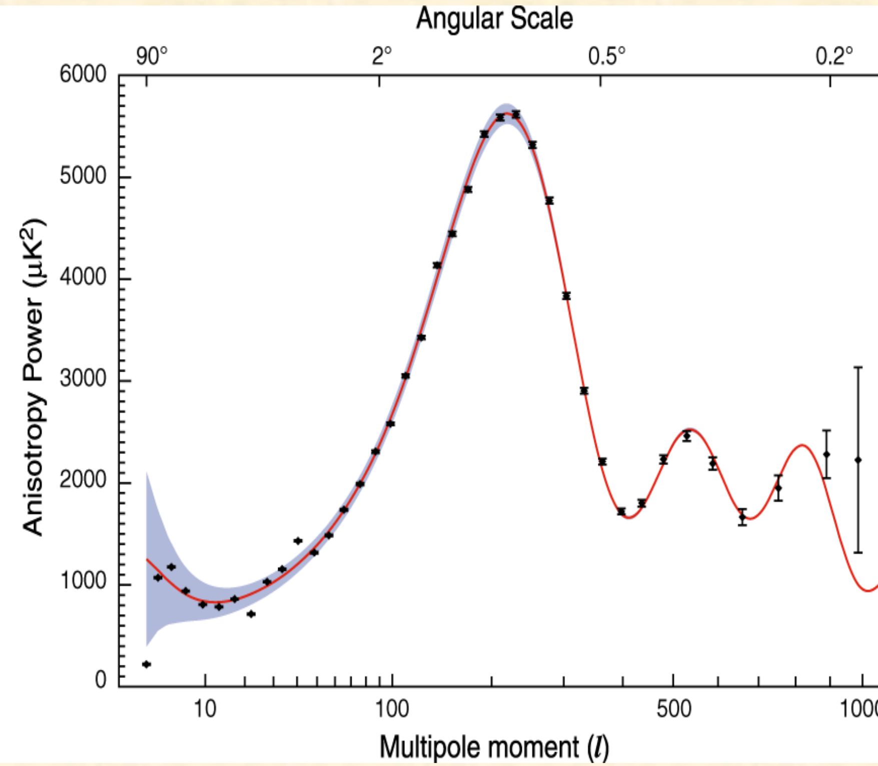






Going deeply into Hot QCD matter





- Initial QCD quantum fluctuations
- T dependence of η/s
- Equation of State
- Freeze-out dynamics

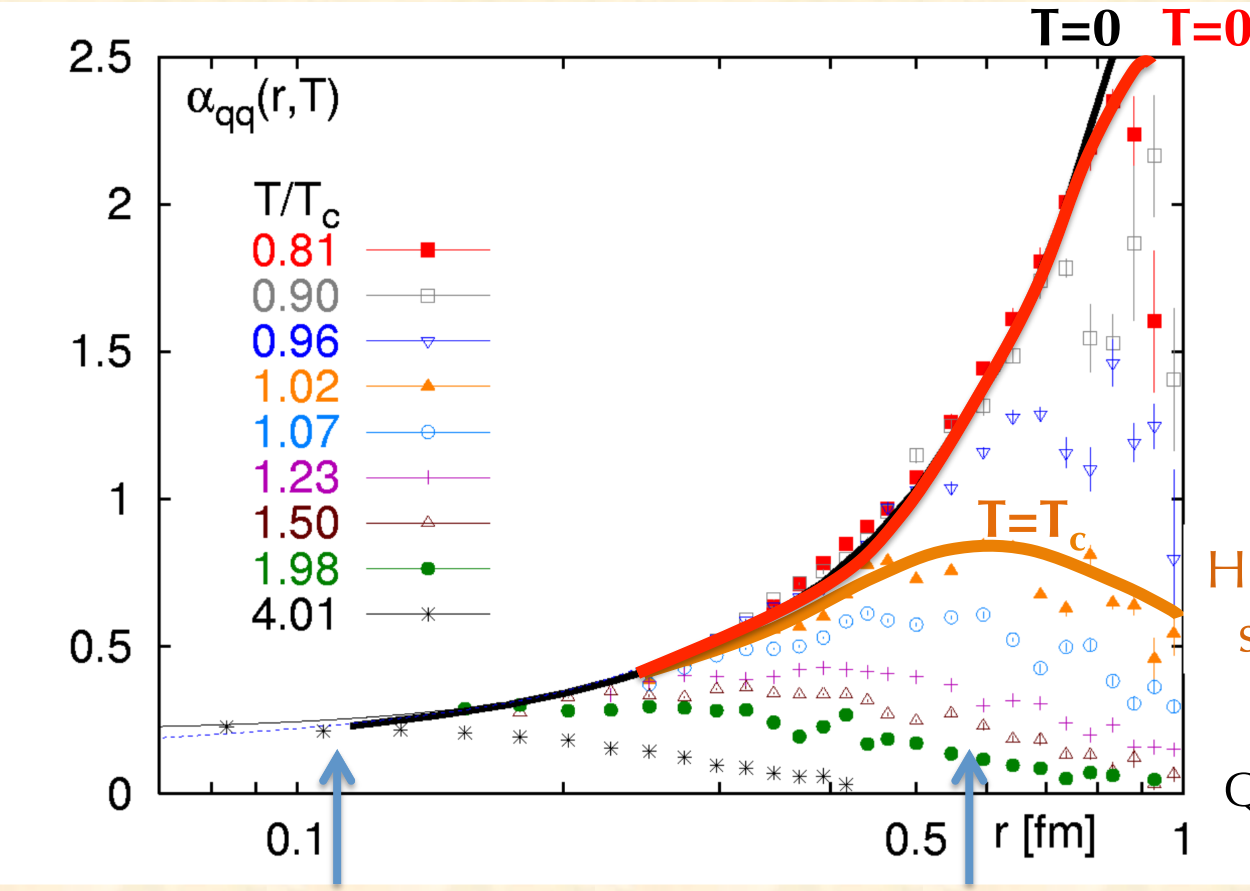
Keeping size and life-time of QGP

- Standard Model Matter
- Cold Dark Matter
- Dark Energy
- Hubble Constant

Keeping Age and Flatness of the Universe

Possible because at LHC one starts to create about than 10,000 particle per event

Beyond naive argument: lattice QCD



$$V(r,T) = \frac{4}{3}\frac{\alpha(r,T)}{r}$$

$\alpha \approx r^2 \rightarrow V \approx Kr$

$$\alpha(r, T > T_c) = \alpha_{eff}(T)\, e^{-m_D(T)\, r}$$

High- Temperature medium screens the Confinement

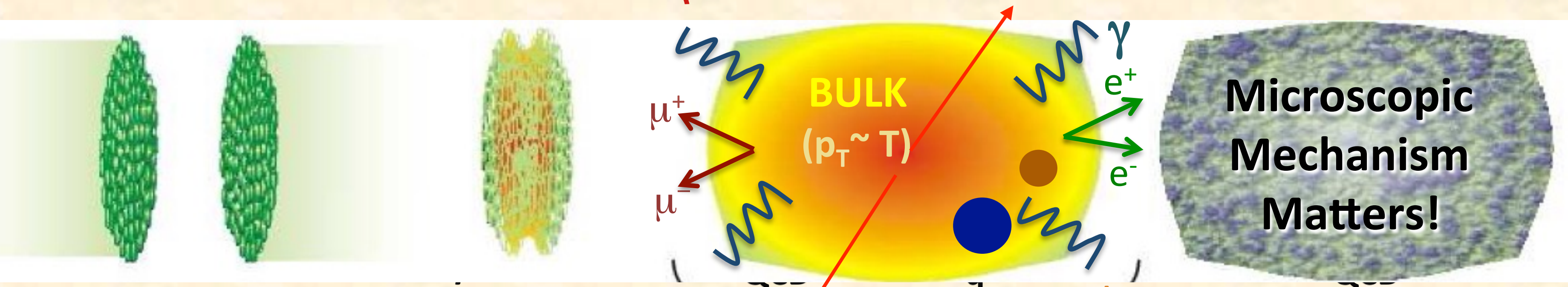
QCD vacuum is diamagnetic: repels fields lines

Perturbative regime
$\alpha \approx \log(r/r_0) \leq 0.25$

Average distance at ρ_c

Multifacets Physics

Initial Conditions | Quark-Gluon Plasma | Hadronization

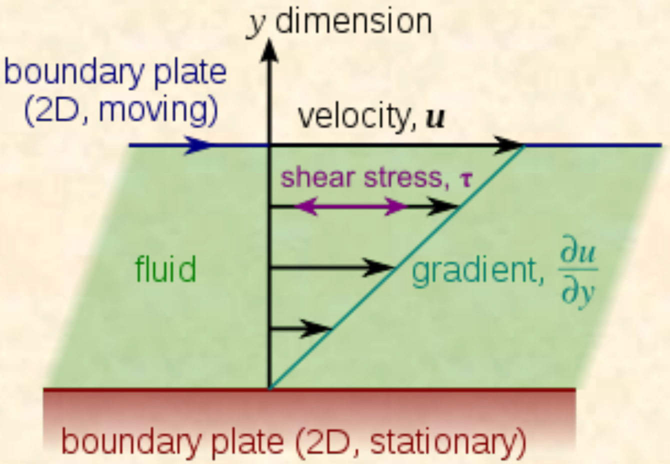


ColorGlassCond.
Gluon saturation

JETS
(p_T>>>T,Λ_{QCD})

Heavy Quarks
(m_q>>T,Λ_{QCD})

Why is Shear Viscosity is relevant



$$\frac{F_x}{A_{yz}} = -\eta \frac{\partial v_x}{\partial y}$$

pitch

$\eta = (2.3 \pm 0.5) \cdot 10^8 Pa \cdot s$

8 drops 1932-2013

Text book kinetic theory

$$\frac{\eta}{s} \approx \frac{1}{15} < p > \cdot \lambda$$

Small η/s → small mean free path λ
→ strongly coupled system

At limits of Quantum mechanism (<p>≈ ΔE, λ≈ cΔt)

$$\Delta E \cdot \Delta t \geq 1 \quad \rightarrow \eta / s > 1/15$$

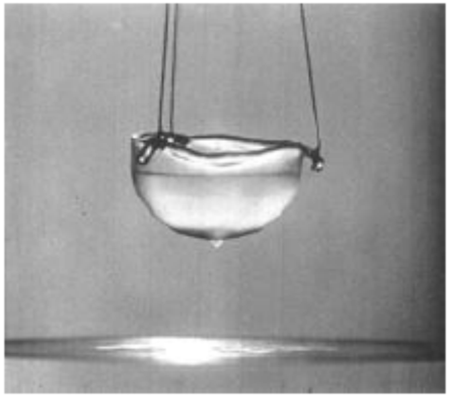
which for QGP mean η> 10^{11} Pa•s

AdS/CFT, based on the conjecture that a Gauge theory in 4D (in the infinite coupling limit) is dual to a gravitational calculation in 5D gives η/s> 1/4π

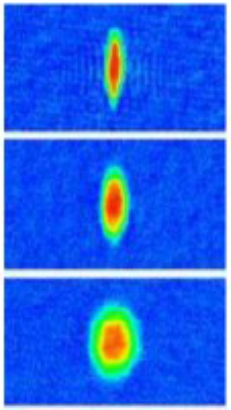
Shear viscosity of some substances

honey:
$\eta \sim (2 - 10) Pa \cdot s$

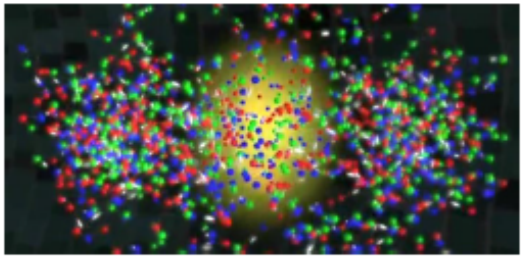
water:
$\eta \sim (10^{-3} - 10^{-4}) Pa \cdot s$



liquid ^{4}He:
$T = 5.1$ K
$\eta = 1.7 \cdot 10^{-6} Pa \cdot s$



trapped ^{6}Li:
$T = 23 \cdot 10^{-6}$ K
$\eta \leq 1.7 \cdot 10^{-15} Pa \cdot s$



QGP:
$T = 2 \cdot 10^{12}$ K
$\eta \leq 5 \cdot 10^{11} Pa \cdot s$

Two Notes …

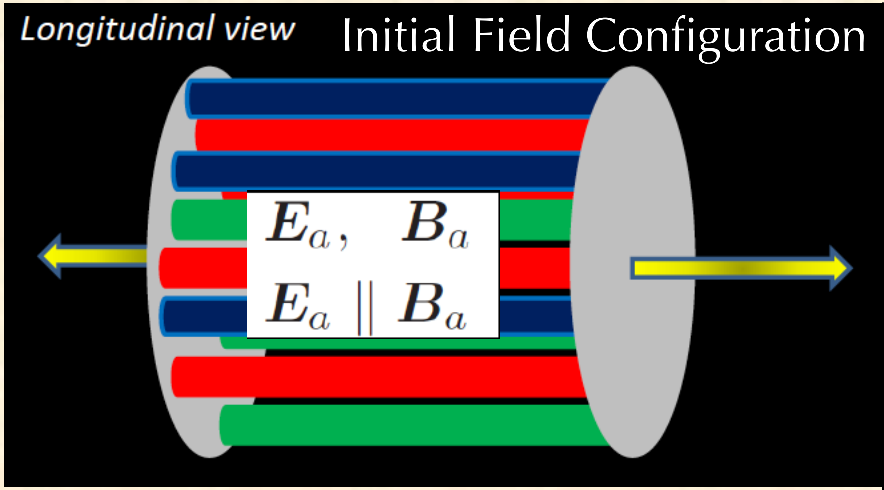
1) Trivial after solving …. Relativistic Viscous Hydrodynamics at II° order

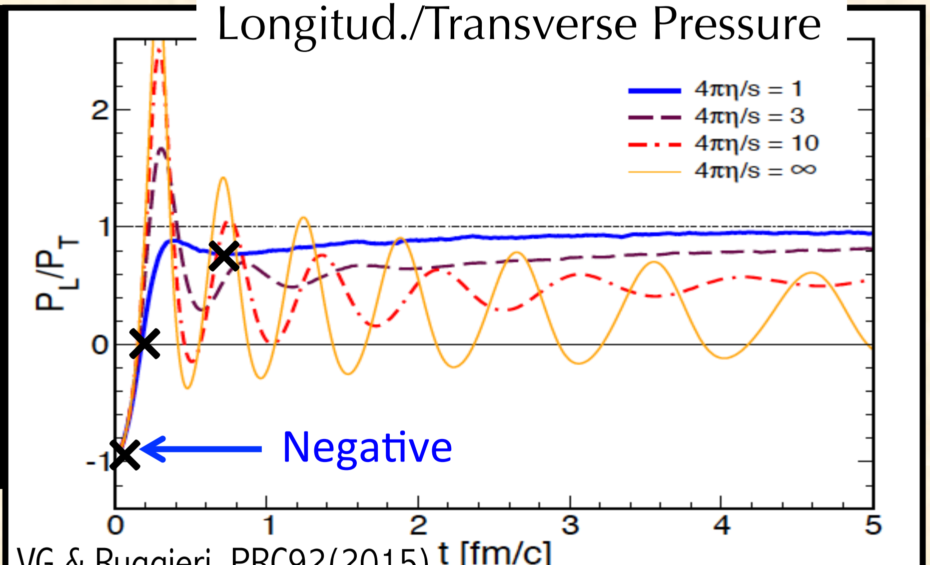
$$\tau_\Pi \dot{\Pi} + \Pi = \Pi_{NS} + \tau_{\Pi q}\, q\cdot\dot{u} - \ell_{\Pi q}\,\partial\cdot q - \zeta\,\hat{\delta}_0 \Pi\,\theta + \lambda_{\Pi q}\, q\cdot\nabla\alpha + \lambda_{\Pi\pi}\,\pi^{\mu\nu}\sigma_{\mu\nu}$$

$$\tau_q\,\Delta^{\mu\nu}\dot{q}_\nu + q^\mu = q^\mu_{NS} - \tau_{q\Pi}\,\Pi\,\dot{u}^\mu - \tau_{q\pi}\,\pi^{\mu\nu}\,\dot{u}_\nu + \ell_{q\Pi}\,\nabla^\mu\Pi - \ell_{q\pi}\,\Delta^{\mu\nu}\,\partial^\lambda\pi_{\nu\lambda} + \tau_q\,\omega^{\mu\nu}\,q_\nu - \frac{\kappa}{\beta}\,\hat{\delta}_1\,q^\mu\,\theta - \lambda_{qq}\,\sigma^{\mu\nu}\,q_\nu + \lambda_{q\Pi}\,\Pi\,\nabla^\mu\alpha + \lambda_{q\pi}\,\pi^{\mu\nu}\,\nabla_\nu\alpha$$

$$\tau_\pi\,\dot{\pi}^{<\mu\nu>} + \pi^{\mu\nu} = \pi^{\mu\nu}_{NS} + 2\,\tau_{\pi q}\,q^{<\mu}\dot{u}^{\nu>} + 2\,\ell_{\pi q}\,\nabla^{<\mu}q^{\nu>} + 2\,\tau_\pi\,\pi_\lambda{}^{<\mu}\omega^{\nu>\lambda} - 2\,\eta\,\hat{\delta}_2\,\pi^{\mu\nu}\,\theta - 2\,\tau_\pi\,\pi_\lambda{}^{<\mu}\sigma^{\nu>\lambda} - 2\,\lambda_{\pi q}\,q^{<\mu}\nabla^{\nu>}\alpha + 2\,\lambda_{\pi\Pi}\,\Pi\,\sigma^{\mu\nu}$$

2) All is done assuming that matter created is thermal at τ ≈ O(1fm/c)



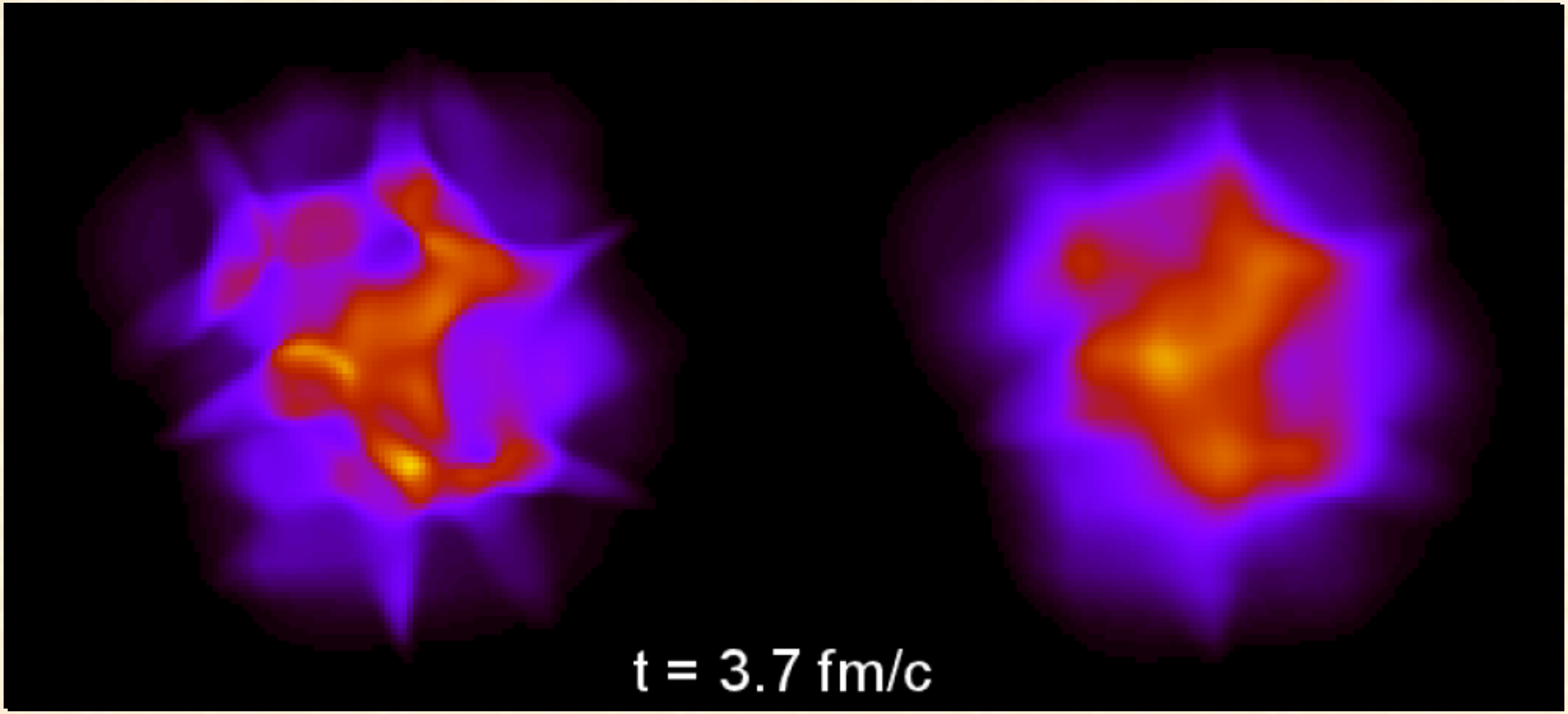


VG & Ruggieri, PRC92(2015)

η/s smoothen fluctuations and affect more higher harmonics

Ideal

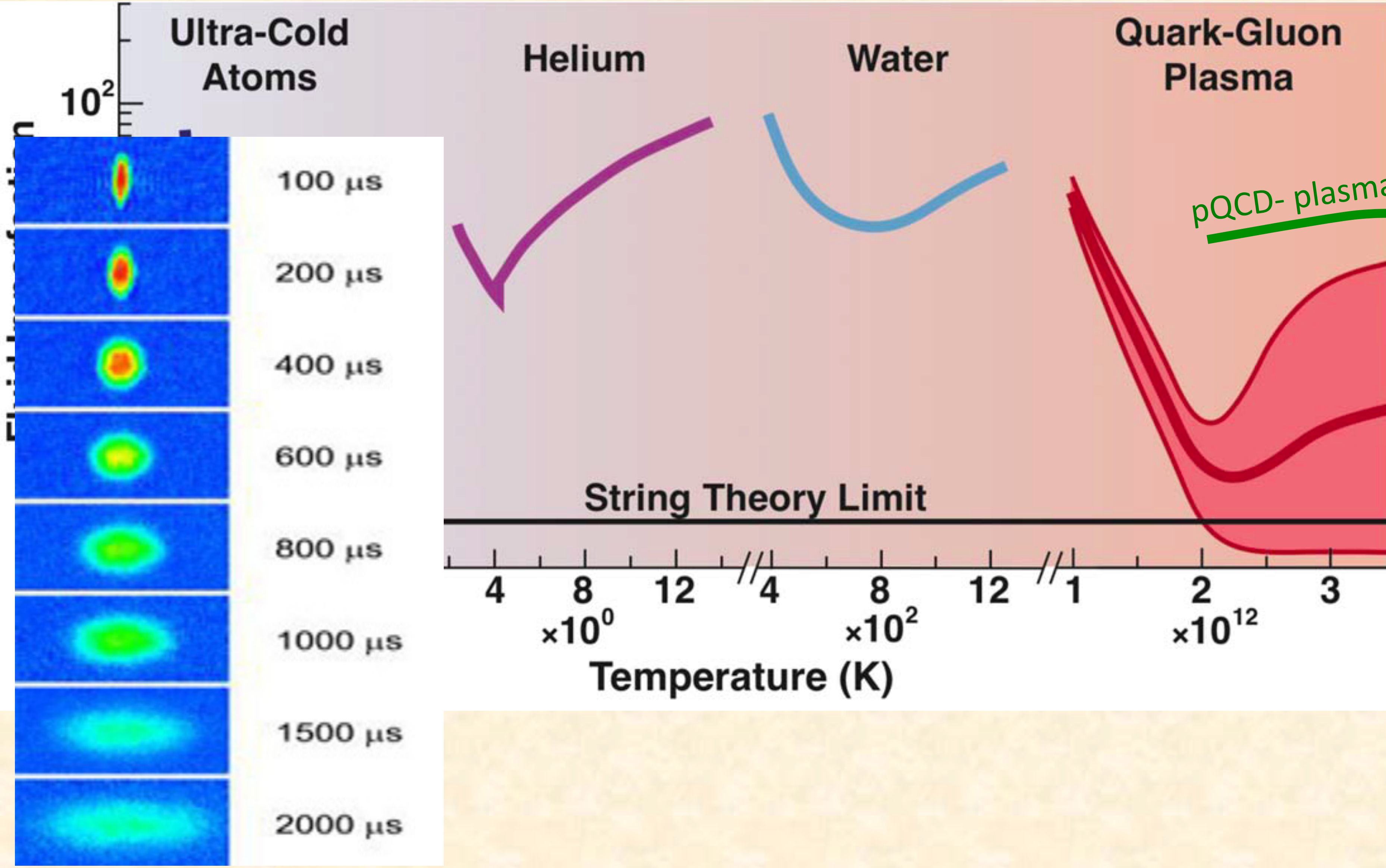
Viscous



$\eta/s=0$

$\eta/s=0.16$

Shear Viscosity for systems in 20 order of T magnitudes!

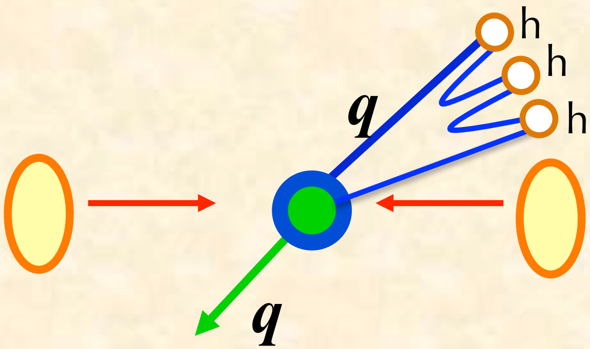


O'Hara et al., Science 298(2002)

Modified Hadronization in AA w.r.t. to ee, ep, pp

Fragmentation: e^+e^-,ep,pp

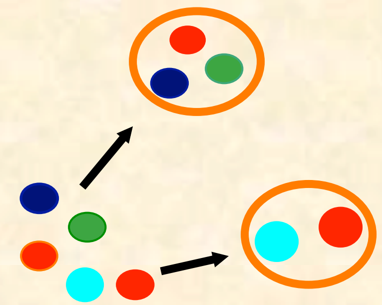
$$f_H(P_H = zp_T) = f_{q,g}(p_T) \otimes D_{q,g\to H}(z) \quad , z<1$$



Forced by Confinement

Quark recombination

$$f_H(P_H = 2p_T) \approx f_q(p_T) \otimes f_{\bar{q}}(p_T)$$



Favored by DeConfinement

Meson recombination(qq)

$$f_H(P_H = 2\mathbf{p}_T) \approx f_q(\mathbf{p}_T) \otimes f_{\bar{q}}(\mathbf{p}_T)$$

$$\approx \left[1 + v_{2q}(p_T)\cos(2\varphi_p) + ..\right]^2 \approx 1 + 2v_{2q}(2p_T)\cos(2\varphi_p) + ..$$

Ideal Hydrodynamics: a perfect fluid?

$$\begin{cases} \partial_\mu T^{\mu\nu}(x) = 0 \\ \partial_\mu j_B^\mu(x) = 0 \end{cases}$$

$$T^{\mu\nu}(x) = [\varepsilon + p]u^\mu u^\nu - p g^{\mu\nu}$$

$$T^* \approx T_f + \frac{1}{2} m \langle \beta_T^2 \rangle$$

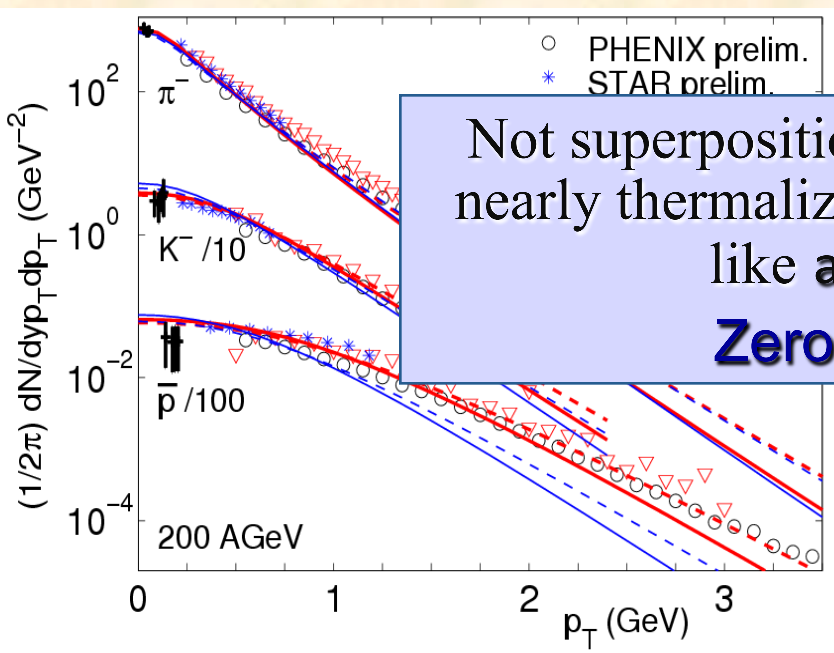
$T_f \sim 120$ MeV

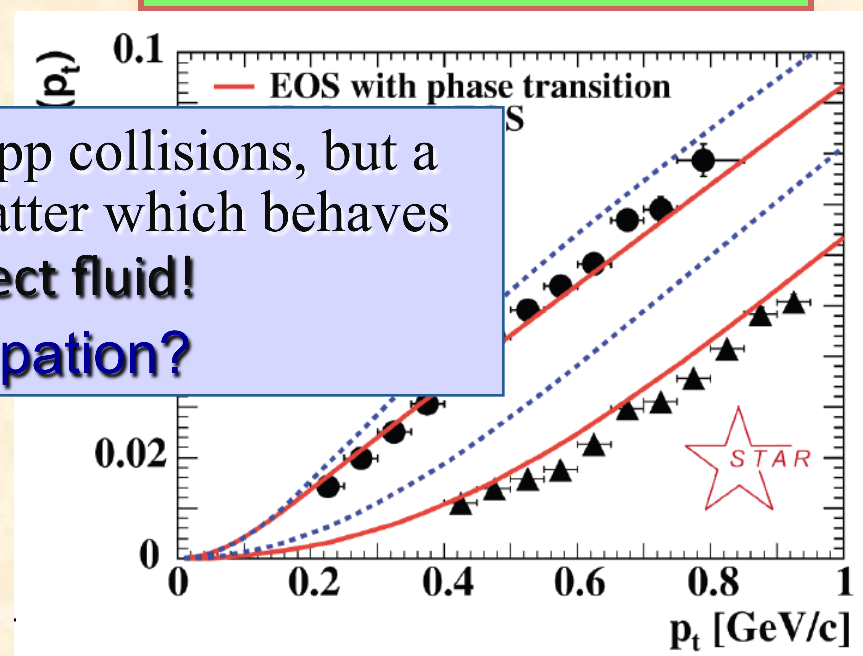
$\langle \beta_T \rangle \sim 0.5$

No microscopic description ($\lambda \to 0$), no dissipation,...only conservation laws!

- Blue shift of dN/dp_T hadron spectra
- Large v_2/ε
- Mass ordering of $v_2(p_T)$

For the first time very close to ideal Hydrodynamics



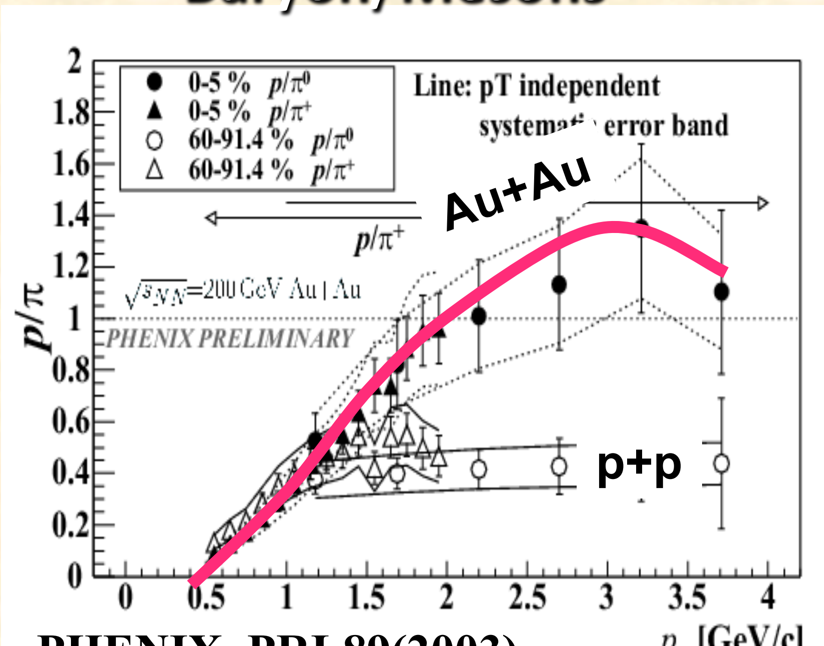


Not superposition of pp collisions, but a nearly thermalized matter which behaves like **a perfect fluid!**

Zero dissipation?

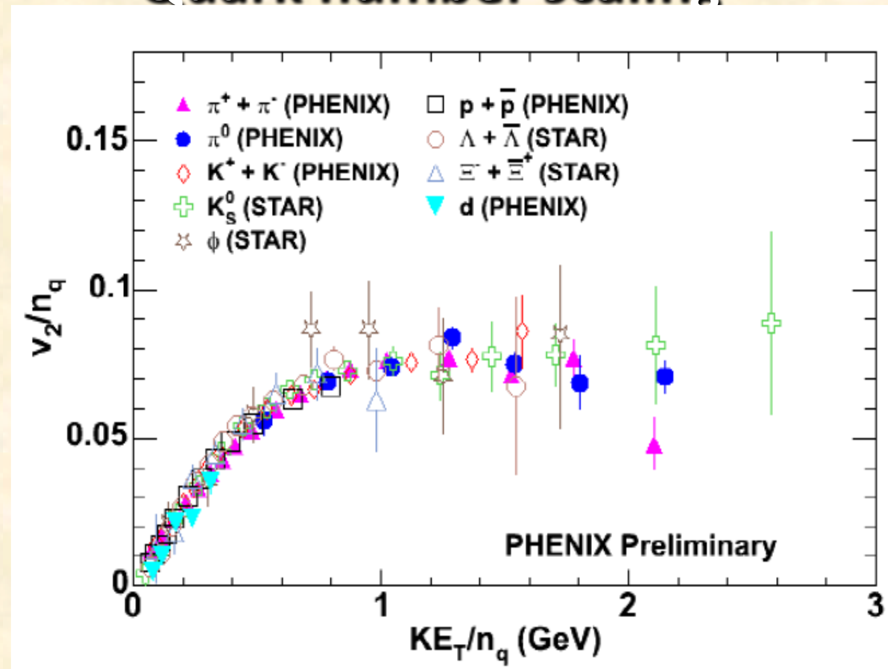
Hadronization Modified

Baryon/Mesons



PHENIX, PRL89(2003)

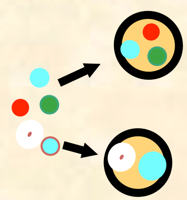
Quark number scaling



Use medium and not vacuum

-> Quark coalescence

More easy to produce baryons!



$$v_{2,M} \quad (p_T/2)$$
$$v_{2,B} \quad (p_T/3)$$
$$\frac{1}{n} V_2\left(\frac{p_T}{n}\right)$$

$$\frac{dN_M}{d^3P} = \sum_{a,b} f_a(r_a, p_a) \otimes f_b(r_b, p_b) \otimes \Phi_M(r_{ab}, q_{ab})$$

Hadronization is modified

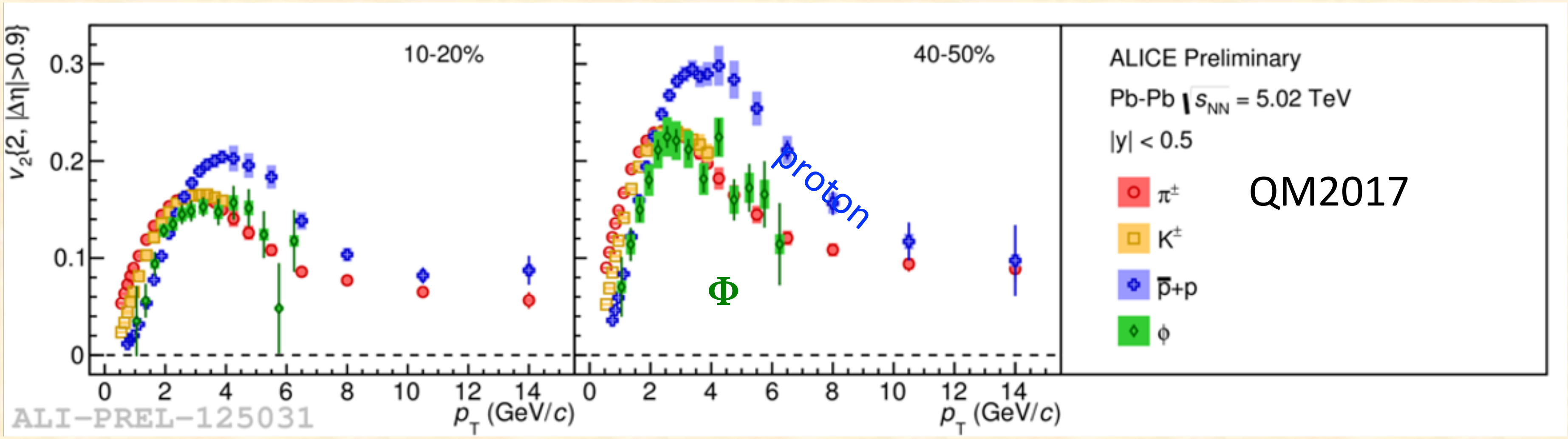
Dynamical quarks are visible

Fries-Greco-Sorensen - Ann. Rev. Part. Sci. 58, 177 (2008)

Last Result from LHC: ϕ flows also with n_q

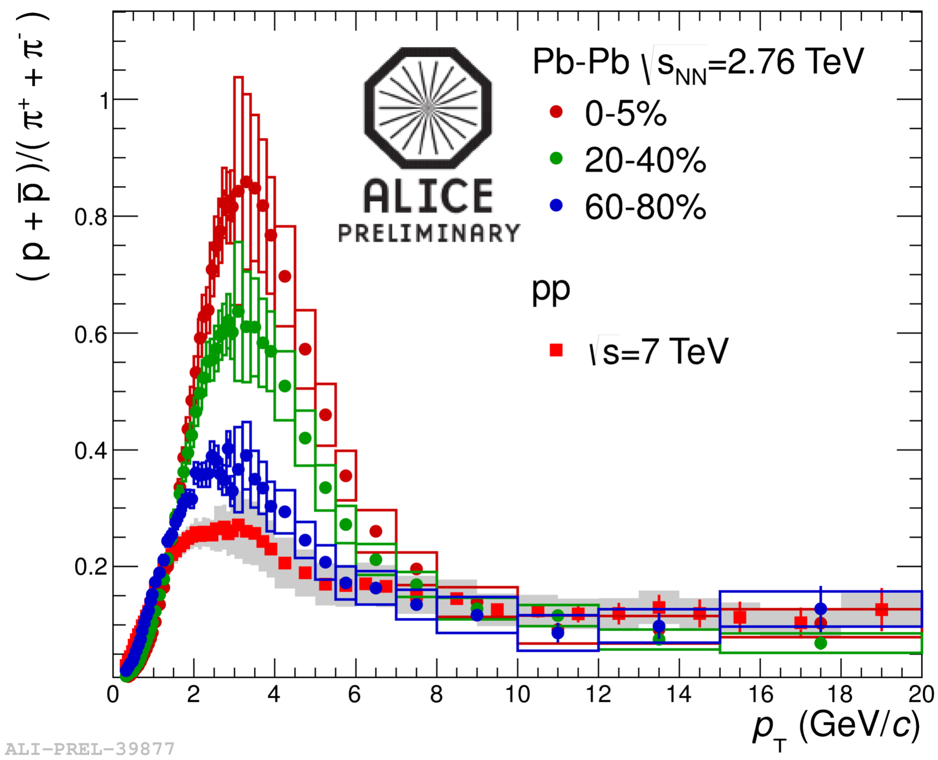
P (qqq), ϕ(qq) with $\mathbf{M_p \approx M_\phi}$

So do they flow at the same way: hydrodynamic flow?

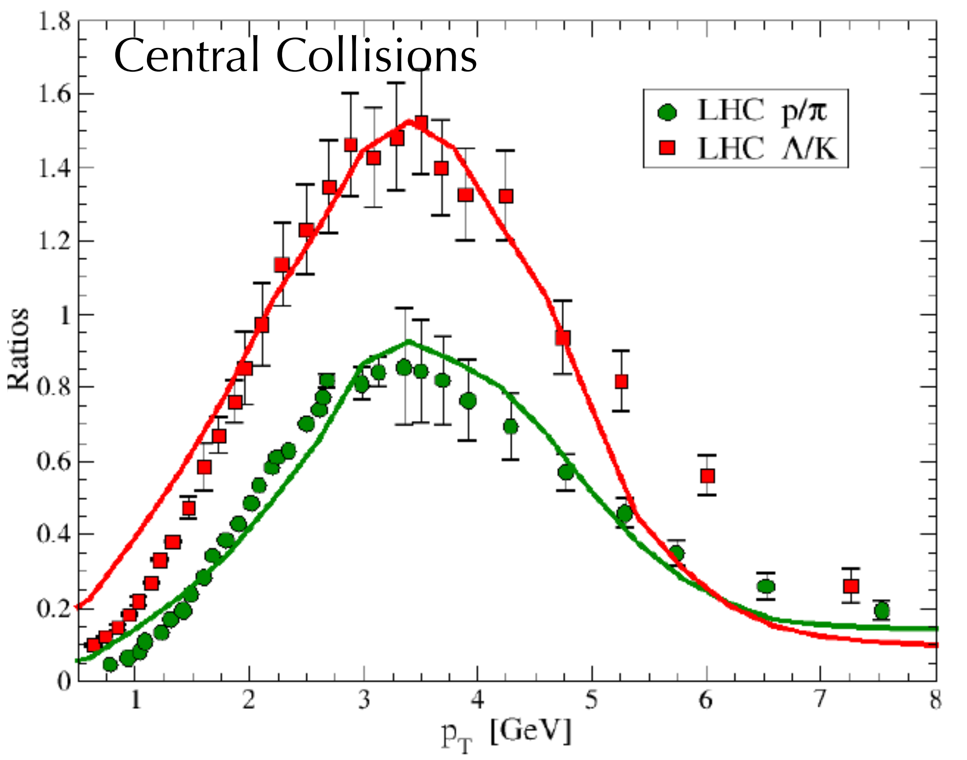


Φ flow with its constituent quark number!!!

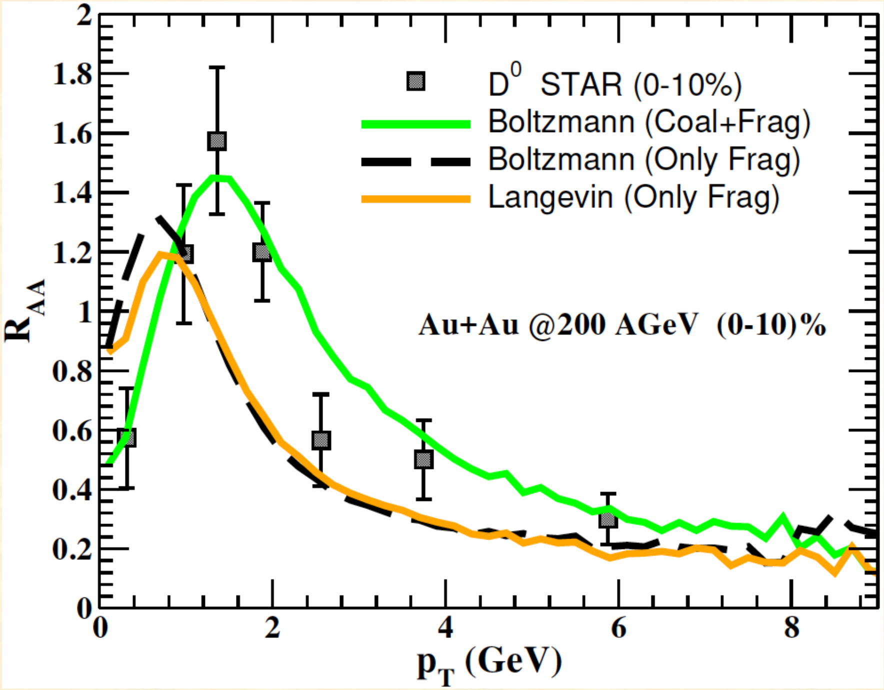
Hadronization Modified: B/M Ratios

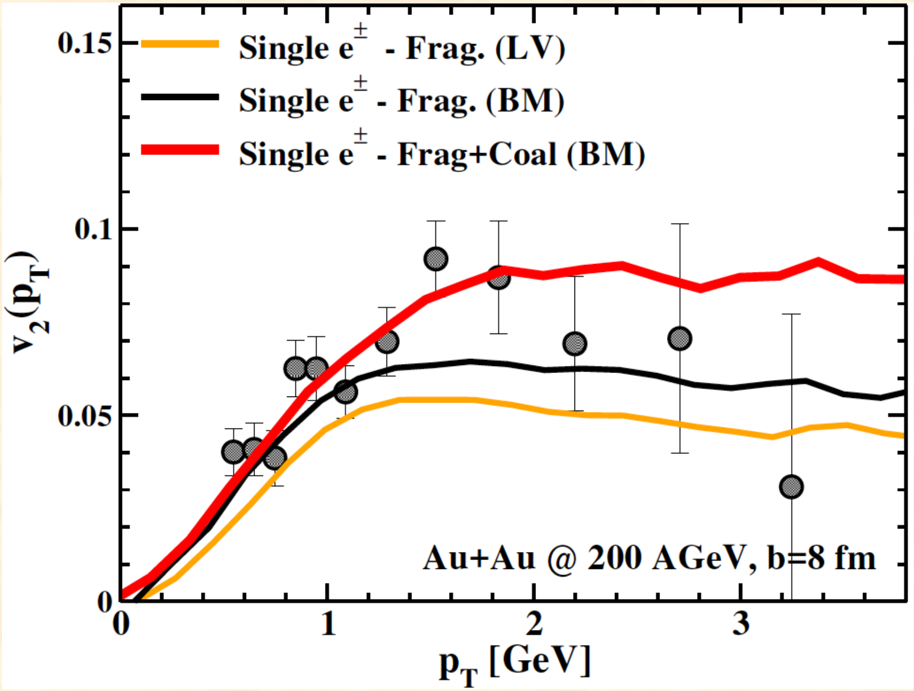


Ratio in Hadronization by Coalecence

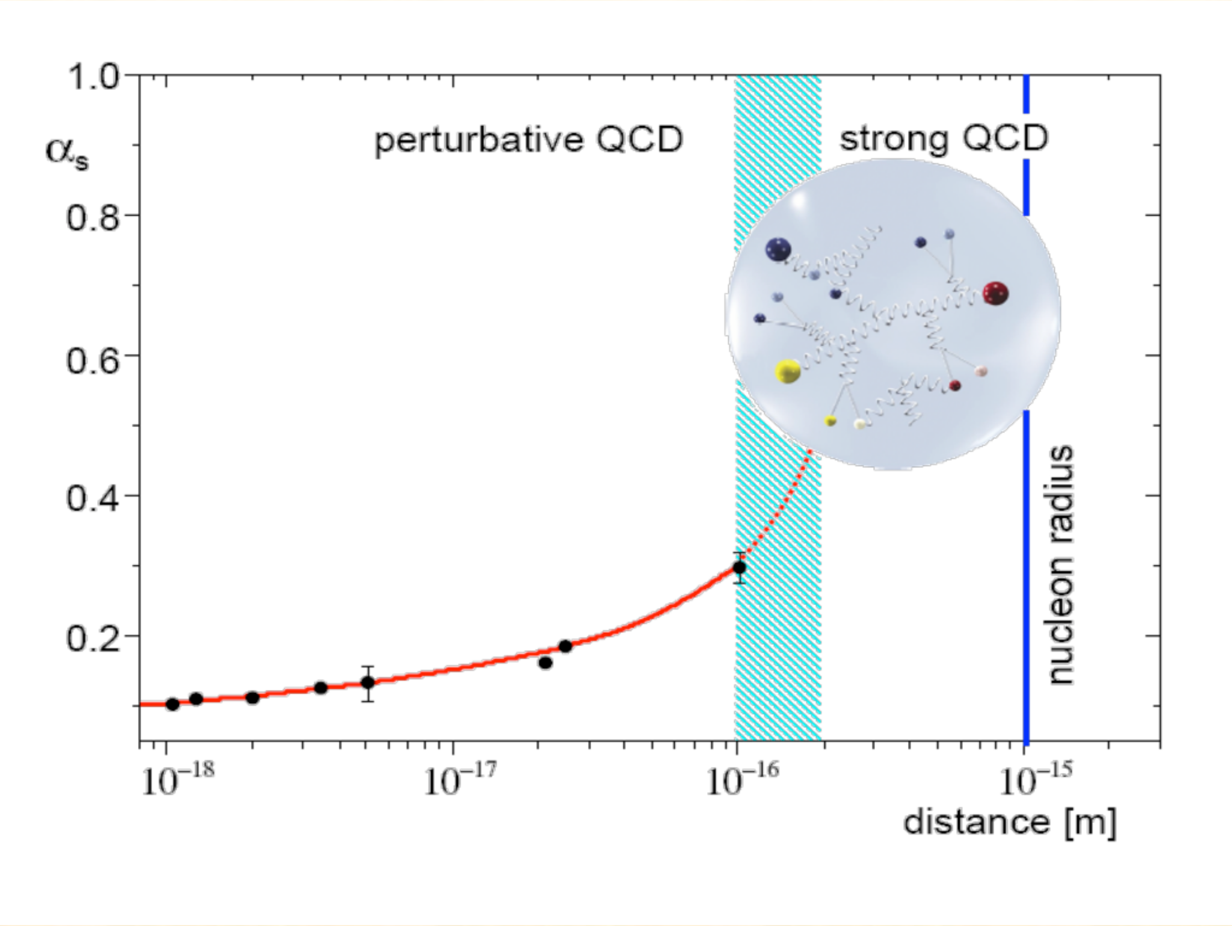


What is the impact of coalescence?





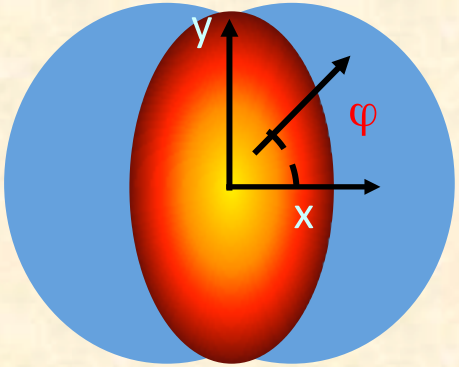
- $R_{AA}(p_T)$ signficant reshaped → exp. data
- *Opposite to energy loss Coalescence brings up both R_{AA} and v_2*



1.0
α_s
0.8
0.6
0.4
0.2
perturbative QCD
strong QCD
nucleon radius
10^{-18}
10^{-17}
10^{-16}
10^{-15}
distance [m]

Relativistic Heavy-Ion Collision when I was Young

<u>Transverse view of HIC</u>

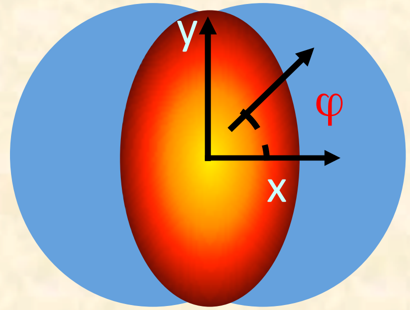


<u>Longitudinal View</u>

With years we have been able to look inside the created matter deeper than expected …

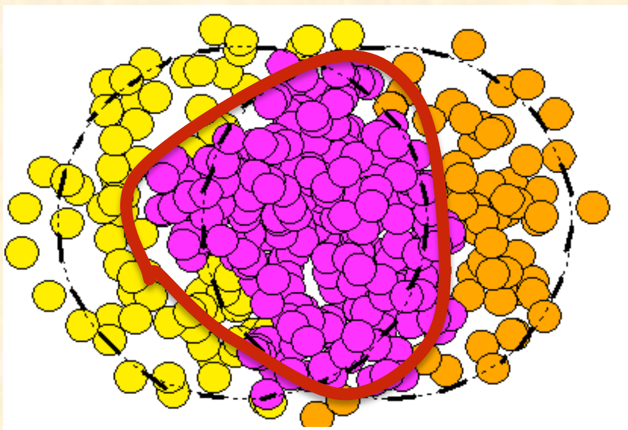
Upgrading the view on the matter created in HIC

Transverse view of HIC



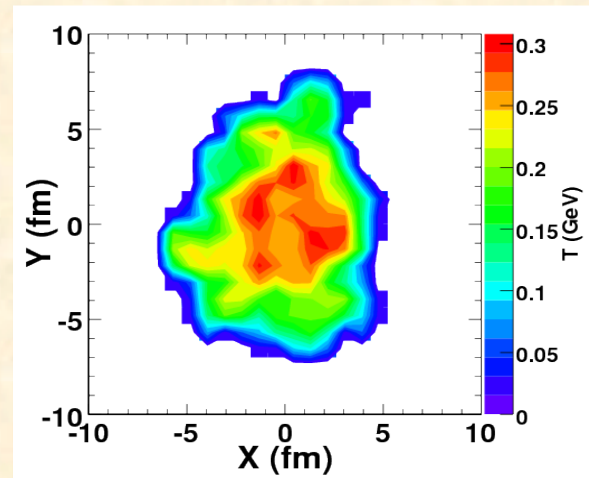
Relativistic HIC
in '90s, '00 till about 2005

Anisotropies v_n=<cos($n\phi_p$)> only with **even** parity due to symmetry



Jacak & Muller, Science 337 (2012)

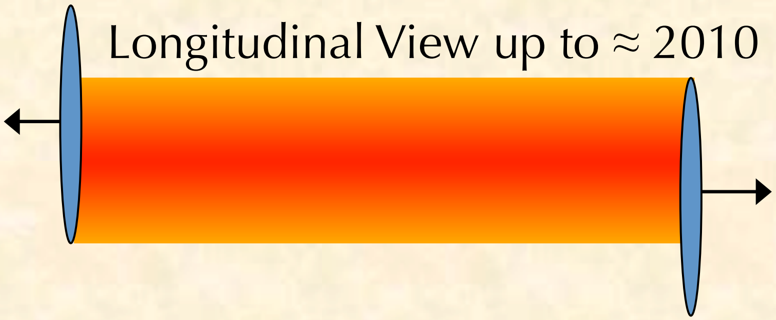
Due to fluctuations
we can have odd v_3 harmonic!

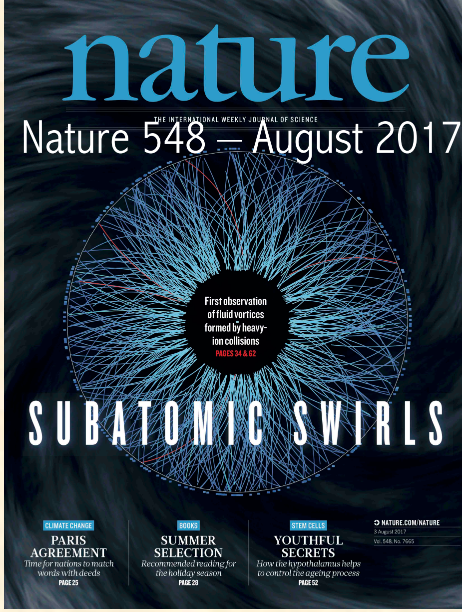


All harmonics appearing
with different weights.

Thanks to the great endeavor of experimentalist to measure even-by-event
[Prof. R. Snelling at 17.50]

Upgrading Longitudinal View





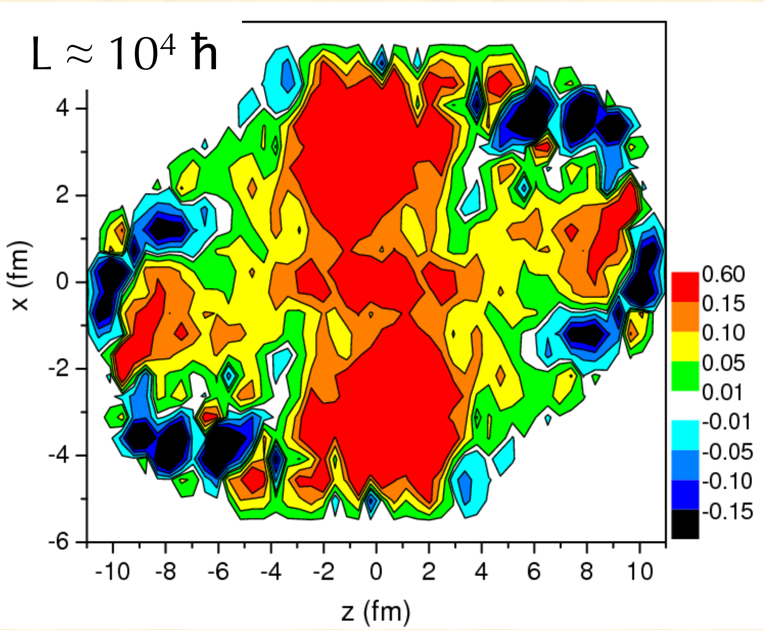
Vorticity → Polarization

$$S^\mu(p) \approx \frac{1}{m}\epsilon^{\mu\nu\rho\sigma} p_\sigma \frac{\int_\Sigma d\Sigma_\tau p^\tau n_F (1-n_F)\partial_\nu (u^\mu/T)}{\int_\Sigma d\Sigma_\tau p^\tau n_F}$$

F. Becattini et al.,Ann. Phys. 338 (2013)32

Quantum-Relativistic effect

Theory from Becattini & Csernai (MAE)



In Hydrodynamics

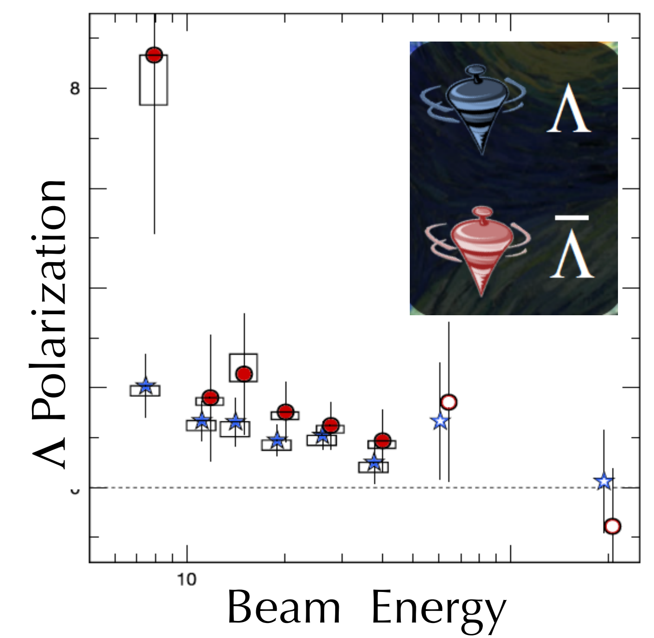
$\hbar\omega \approx K_B T \mathcal{P}_\Lambda$

↓

$\omega \approx 10^{22}\ s^{-1}$

Superfluid nanodroplets

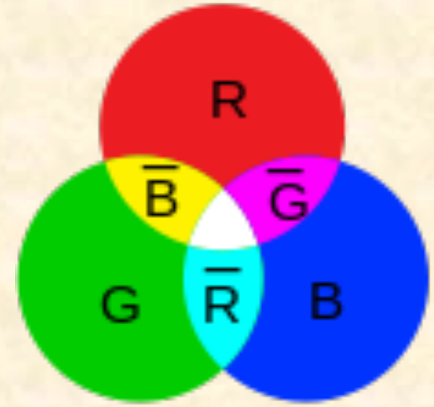
$\omega \approx 10^{7}\ s^{-1}$



Quantum Chromodynamics

$$L_{QCD} = \bar{\Psi}\left(i\gamma_\mu\partial_\mu - m_i\right)\Psi - gA_a^\mu\bar{\Psi}\gamma_\mu t_a\Psi - \frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu}$$

$$F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu + i f_{abc} A_b^\mu A_c^\mu$$

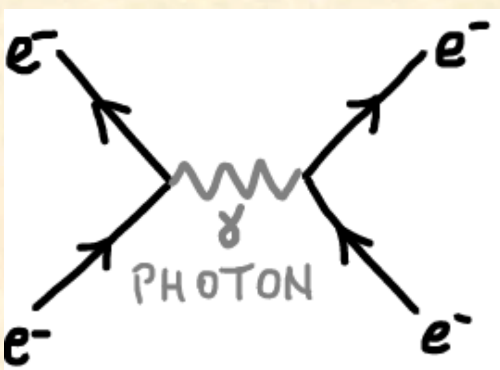


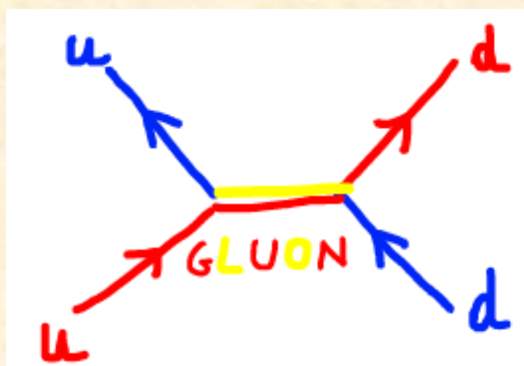
Similar to QED but 3 charges!!!

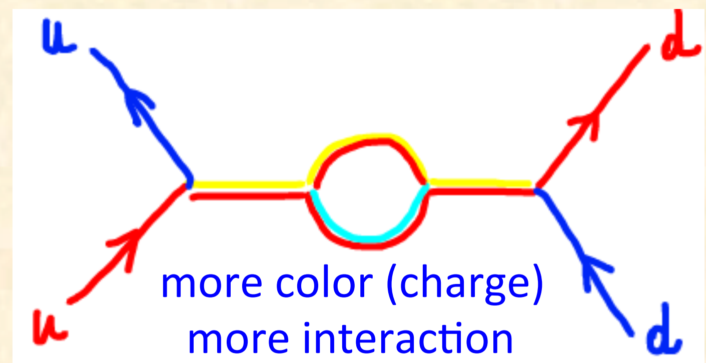
Because they are "3" they are named "color charges":

With more than 1 charge → carrier of the interaction

→ must also be colored "charged"





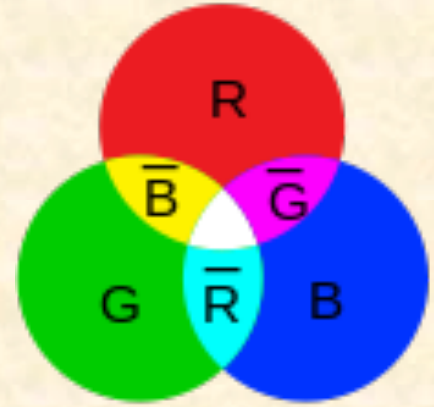


Quantum Flutuations

Quantum Chromodynamics

$$L_{QCD} = \bar{\Psi}\left(i\gamma_{\mu}\partial_{\mu} - m_i\right)\Psi - gA_a^{\mu}\bar{\Psi}\gamma_{\mu}t_a\Psi - \frac{1}{4}G_{\mu\nu}^{a}G_a^{\mu\nu}$$

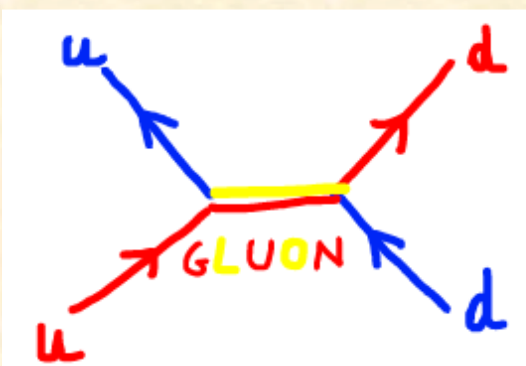
$$F_a^{\mu\nu} = \partial^{\mu}A_a^{\nu} - \partial^{\nu}A_a^{\mu} + i f_{abc}A_b^{\mu}A_c^{\mu}$$

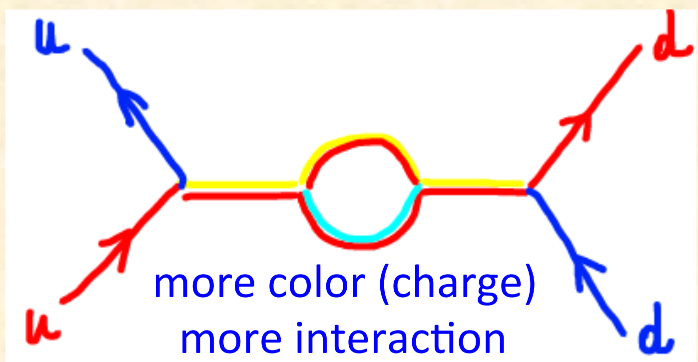


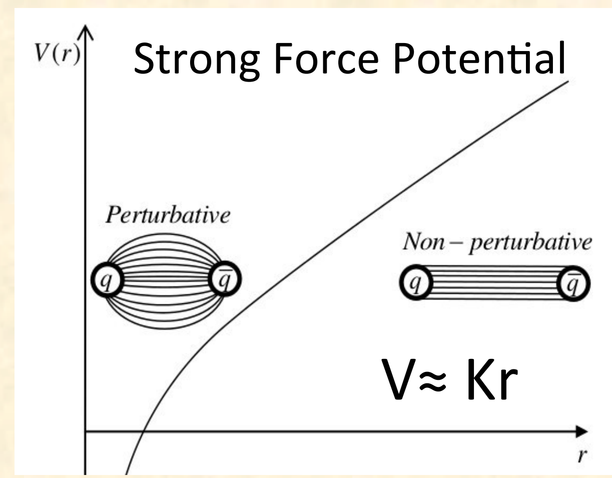
Similar to QED but 3 charges!!!

Because they are "3" they are named "color charges"

→ With more than 1 charge → carrier of the interaction has to be colored → ***completely different from QED!***







Difference #1: At small distance quarks interacts less, this is a different World!

Asymptotic freedom (Nobel 2004)