QCD medium in relativistic heavy-ion collisions

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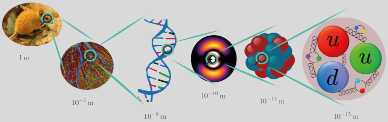
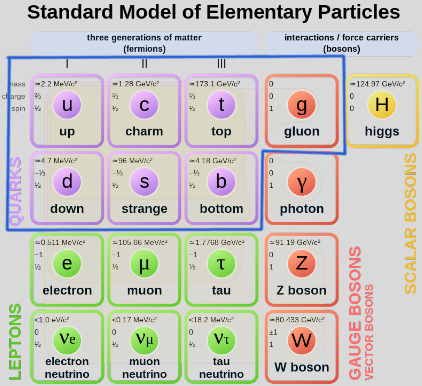
QCD degrees of freedom





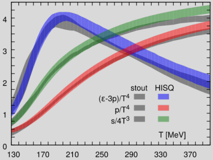
Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass charge spin	≈2.2 MeV/c² ⅔ ½ u up	≈1.28 GeV/c² ⅔ ½ c charm	≈173.1 GeV/c² ⅔ ½ t top	0 0 1 g gluon	≈124.97 GeV/c² 0 0 H higgs
QUARKS	≈4.7 MeV/c² −⅓ ½ d down	≈96 MeV/c² −⅓ ½ s strange	≈4.18 GeV/c² −⅓ ½ b bottom	0 0 1 γ photon	SCALAR BOSONS
	≈0.511 MeV/c² −1 ½ e electron	≈105.66 MeV/c² −1 ½ μ muon	≈1.7768 GeV/c² −1 ½ τ tau	≈91.19 GeV/c² 0 1 Z Z boson	
LEPTONS	<1.0 eV/c² 0 ½ νe electron neutrino	<0.17 MeV/c² 0 ½ νμ muon neutrino	<18.2 MeV/c² 0 ½ ντ tau neutrino	≈80.433 GeV/c² ±1 1 W W boson	GAUGE BOSONS VECTOR BOSONS

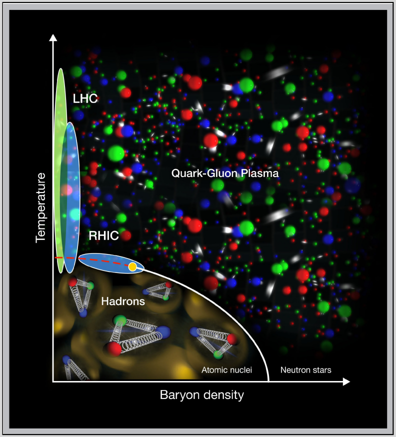
$$\mathcal{L} = -\frac{1}{4} F^{a}_{\mu\nu} F^{a,\mu\nu} + \bar{\psi}(i\not{D} - M)\psi$$

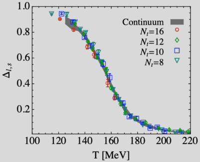
QCD Phase Diagram

R.A.Soltz *et al.*, Ann. Rev.Nucl.Part.Sci. 65 (2015) 379



bnl.gov

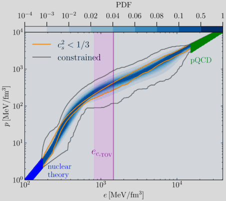




Wuppertal-Budapest,

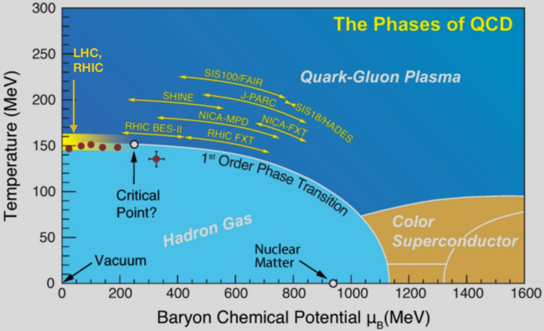
JHEP 09, 073 (2010)

S. Altiparmak *et al.*, Astrophys. J. Lett.939 (2022)2,L34



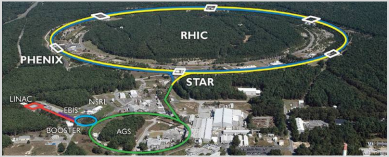
QCD Phase Diagram and HICs

A. Bazavov *et al.*, 1904.09951



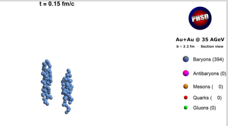
GSI/FAIR

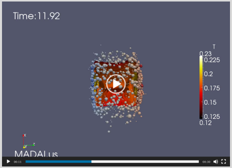
SPS/LHC

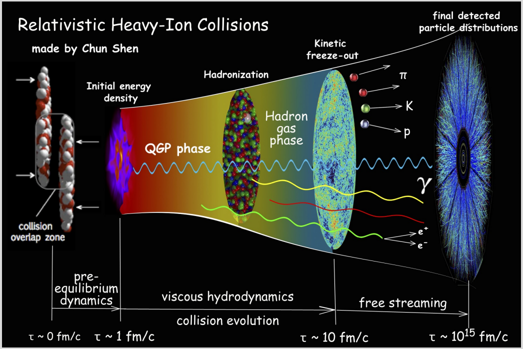


RHIC

Simulating RHICs





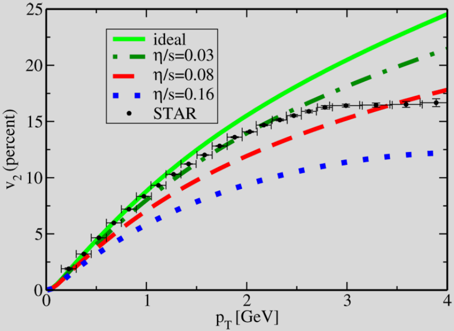


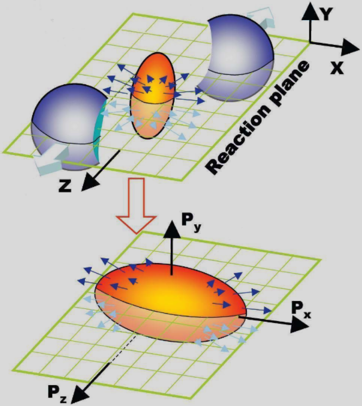
- Kinetic description (Wigner / BUU eqs.)
- Relativistic hydrodynamic evolution
- Hybrid approach

Viscous Hydrodynamics

Dissipation: $\frac{\eta}{s} = \frac{\text{shear viscosity}}{\text{entropy density}}$

P. Romatschke, U. Romatschke,
Phys. Rev. Lett. 99 (2007) 172301



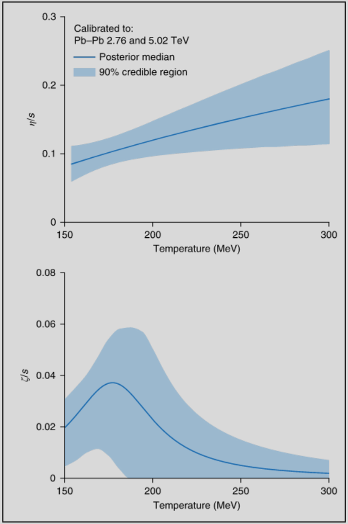


Hiroshi Masui (2008)

$$\boxed{E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + 2v_2\cos[2(\phi - \Psi_2)] + \ldots\right]}$$

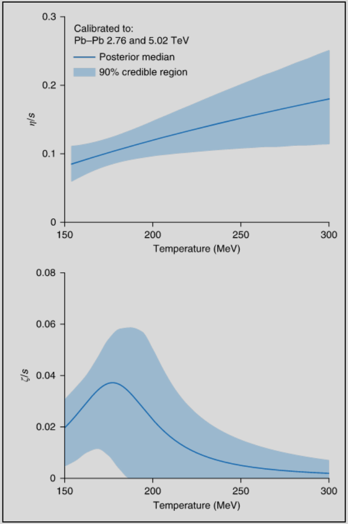
v_2: Elliptic Flow

QGP — Most perfect fluid?

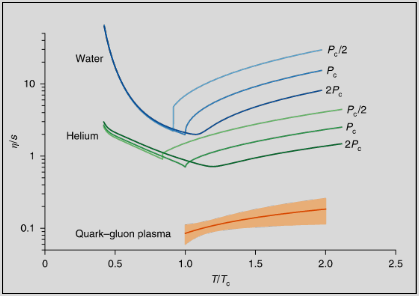


J. Bernhard *et al.*
Nature Phys. 15 (2019) 11, 1113-1117

QGP — Most perfect fluid?



J. Bernhard *et al.*
Nature Phys. 15 (2019) 11, 1113-1117



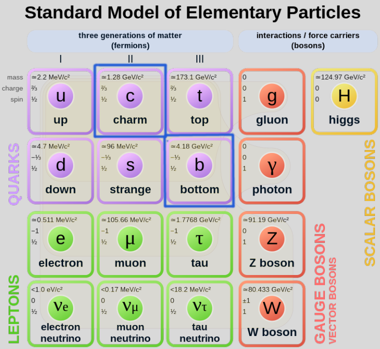
The Quark-Gluon Plasma, a nearly perfect fluid

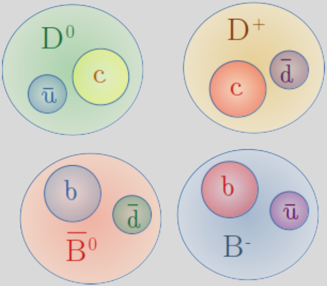
L. Cifarelli[1], L.P. Csernai[2] and H. Stöcker[3] - DOI: 10.1051/epn/2012206
[1] Dipartimento di Fisica, Universita di Bologna, 40126 Bologna, Italy;
[2] Department of Physics and Technology, University of Bergen, 5007 Bergen, Norway;
[3] GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany

We are living in interesting times, where the World's largest accelerator, the Large Hadron Collider, has its most dominant successes in Nuclear Physics: collective matter properties of the Quark-Gluon Plasma (QGP) are studied at a detail which is not even possible for conventional, macro scale materials.

L. Cifarelli *et al.*, Eur. News Vol. 43, 2012, 29

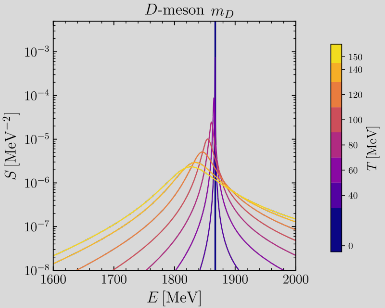
Heavy flavor: c/b quarks and $D, \bar{B}$ mesons





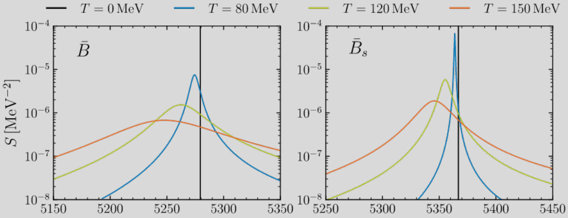
QCD → **Thermal effective field theory for heavy mesons**

Heavy-meson spectral functions



$$S(E,\boldsymbol{q}) = -\frac{1}{\pi}\,\mathrm{Im}\left(\frac{1}{E^2-\boldsymbol{q}^2-m^2-\Pi(E,\boldsymbol{q})}\right)$$

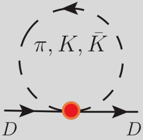
G. Montaña *et al.* (JMT-R),
Phys.Lett.B 806 (2020) 135464,
Phys.Rev.D 102 (2020) 9, 096020

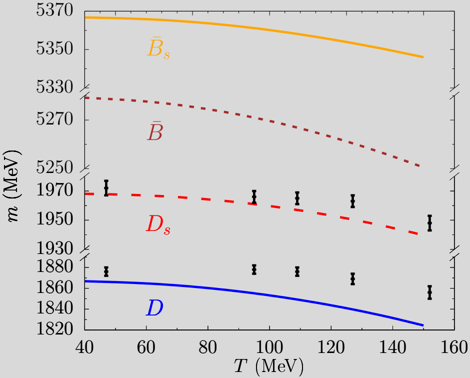


G. Montaña, PhD Thesis,
U. Barcelona, 2022.
APS Dissertation
Award 2023!

Heavy-meson thermal masses

G. Montaña *et al.* (JMT-R),
Phys.Lett.B 806 (2020) 135464,
Phys.Rev.D 102 (2020) 9, 096020

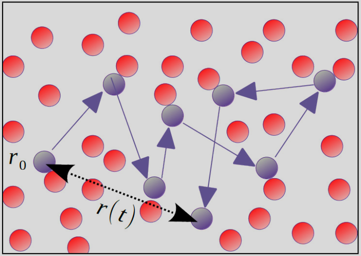




Chiral symmetry restoration:
JMT-R, Symmetry 13 (2021) 1400

Lattice-QCD data:
G. Aarts *et al.*, 2209.14681

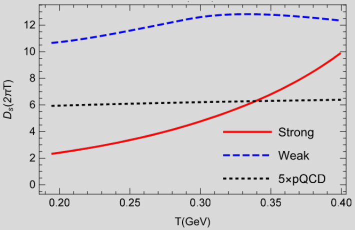
Brownian motion and diffusion coefficient

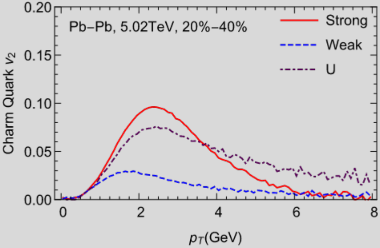


Brownian motion
Mean squared displacement

$$\langle [r(t) - r_0]^2 \rangle = 6\boldsymbol{D_s}t$$

S.Y.F. Liu *et al.*,
Phys.Rev.C 99, 055201 (2019)





Fokker-Planck equation

Many-body EFT with real time: Kadanoff-Baym approach

Off-shell Fokker-Planck equation

$$\frac{\partial}{\partial t} G_D^<(t,k) = \frac{\partial}{\partial k^i}\left\{ \hat{A}(k;T) k^i G_D^<(t,k) + \frac{\partial}{\partial k^j}\left[\hat{B}_0(k;T)\Delta^{ij} + \hat{B}_1(k;T)\frac{k^i k^j}{\boldsymbol{k}^2}\right] G_D^<(t,k)\right\}$$

where $\Delta^{ij} = \delta^{ij} - k^i k^j/\boldsymbol{k}^2$

JMT-R, G. Montaña, À. Ramos, L. Tolos, Phys.Rev.C 105, 025203 (2022)

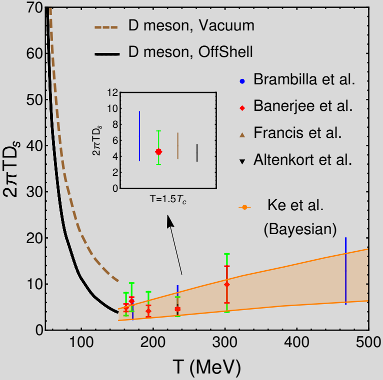
$$\boxed{\text{Wigner function: } iG_D^<(t,k) = 2\pi S_D(t,k^0,\boldsymbol{k}) f_D(t,k^0)}$$

Off-shell Transport Coefficients

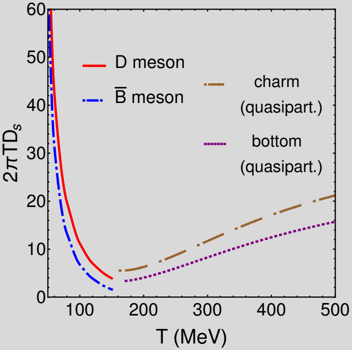
$$\begin{cases} \hat{A}(k^0,\mathbf{k};T) \equiv \left\langle 1 - \frac{\boldsymbol{k}\cdot\boldsymbol{k}_1}{\boldsymbol{k}^2}\right\rangle \\ \hat{B}_0(k^0,\mathbf{k};T) \equiv \frac{1}{4}\left\langle \boldsymbol{k}_1^2 - \frac{(\boldsymbol{k}\cdot\boldsymbol{k}_1)^2}{\boldsymbol{k}^2}\right\rangle \\ \hat{B}_1(k^0,\mathbf{k};T) \equiv \frac{1}{2}\left\langle \frac{[\boldsymbol{k}\cdot(\boldsymbol{k}-\boldsymbol{k}_1)]^2}{\boldsymbol{k}^2}\right\rangle \end{cases}$$

Diffusion coefficient

JMT-R, G. Montaña,
À. Ramos, L. Tolos,
Phys.Rev.C 105, 025203 (2022)

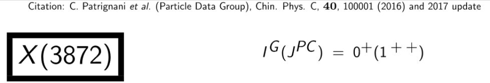


G. Montaña, PhD Thesis,
U. Barcelona, 2022.
APS Dissertation Award 2023!



Quasiparticle model for QGP:
S.K. Das *et al.* (JMT-R)
Phys.Rev.D 94, 114039 (2016)

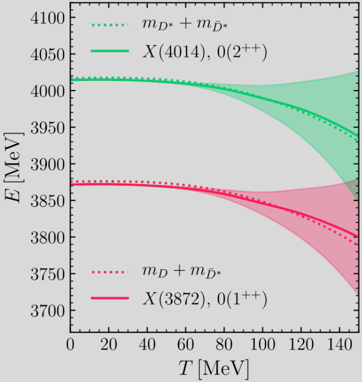
Exotic hadrons as molecular states

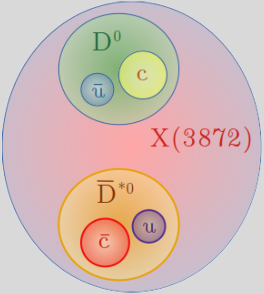


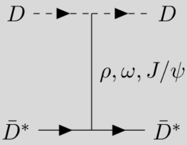
Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

$X(3872)$

$I^G(J^{PC}) = 0^+(1^{++})$





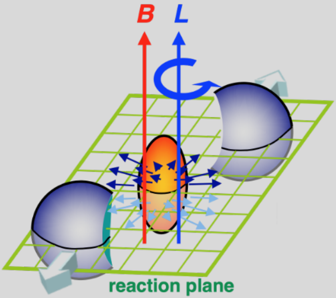


G. Montaña, À. Ramos, L. Tolos and JMT-R, arXiv: 2211.01896

Vorticity and EM fields

Large magnetic fields

$$B \sim m_\pi^2 \sim 10^{13}\ \mathrm{T}$$

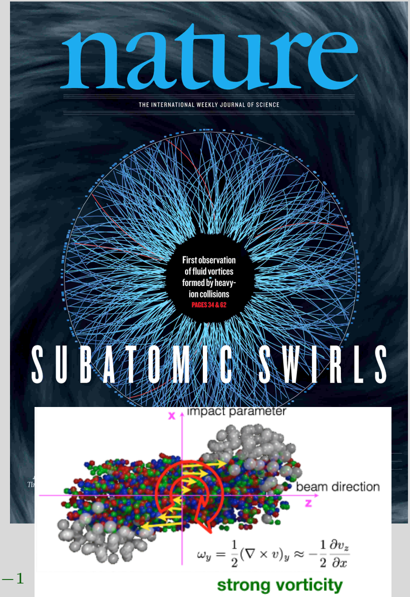


M. Chernodub, 2021

Large angular momentum

$$L \sim bA\sqrt{s_{NN}} \sim 10^5\hbar$$

$$\omega \sim (9 \pm 1)10^{21}\mathrm{s}^{-1}$$


nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

First observation of fluid vortices formed by heavy-ion collisions

PAGES 34 & 62

SUBATOMIC SWIRLS

$$\omega_y = \frac{1}{2}(\nabla \times v)_y \approx -\frac{1}{2}\frac{\partial v_z}{\partial x}$$

strong vorticity

STAR coll. Nature 548, 62 (2017)

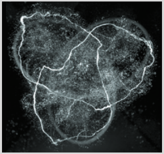
Total helicity (non)conservation

Perfect relativistic magnetohydrodynamics

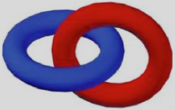
C. Manuel and JMT-R, 2211.13697

$$\overbrace{\partial_\mu(h^2\omega^\mu + hB^\mu) + E\cdot B}^{\text{Fluid + Mixed + EM helicities}} = (2h\omega^\mu + B^\mu)(T\partial_\mu\bar{s} + \overbrace{\mu_5\partial_\mu x_5}^{\text{chiral imbalance}})$$

$$\underbrace{h}_{\text{enthalpy density}} = \mu + T\underbrace{\bar{s}}_{=s/n} + \mu_5\underbrace{x_5}_{=n_5/n}$$



D. Kleckner, W.T. Irvine,
Nature Physics, 9, 253 (2013)



$$H_M = \int \mathbf{A}\cdot\mathbf{B}dV = 2\phi\cdot\phi$$

E.G. Blackman,
Space Sci. Rev. (2015) 188:59–91

Extension of works by H.K.Moffatt (1969), J.D.Bekenstein (1987), and A.G. Abanov and P.B. Weigmann (2022)

Summary

Summary

1. RHICs phenomenology from the microscopic, fundamental side
2. Heavy-meson ($D/\bar{B}$) masses as functions of temperature.
   Predictions checked against lattice-QCD calculations
3. Control over low-energy hadron interactions. Transport coefficients.
   Not just theoretical, but useful for prior knowledge for HICs
4. Description of exotics as molecular states.
   Outlook: simulations and connection to RHICs
5. (Non)conservation laws in relativistic magnetohydrodynamics

QCD medium in relativistic heavy-ion collisions

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06/02/2022

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