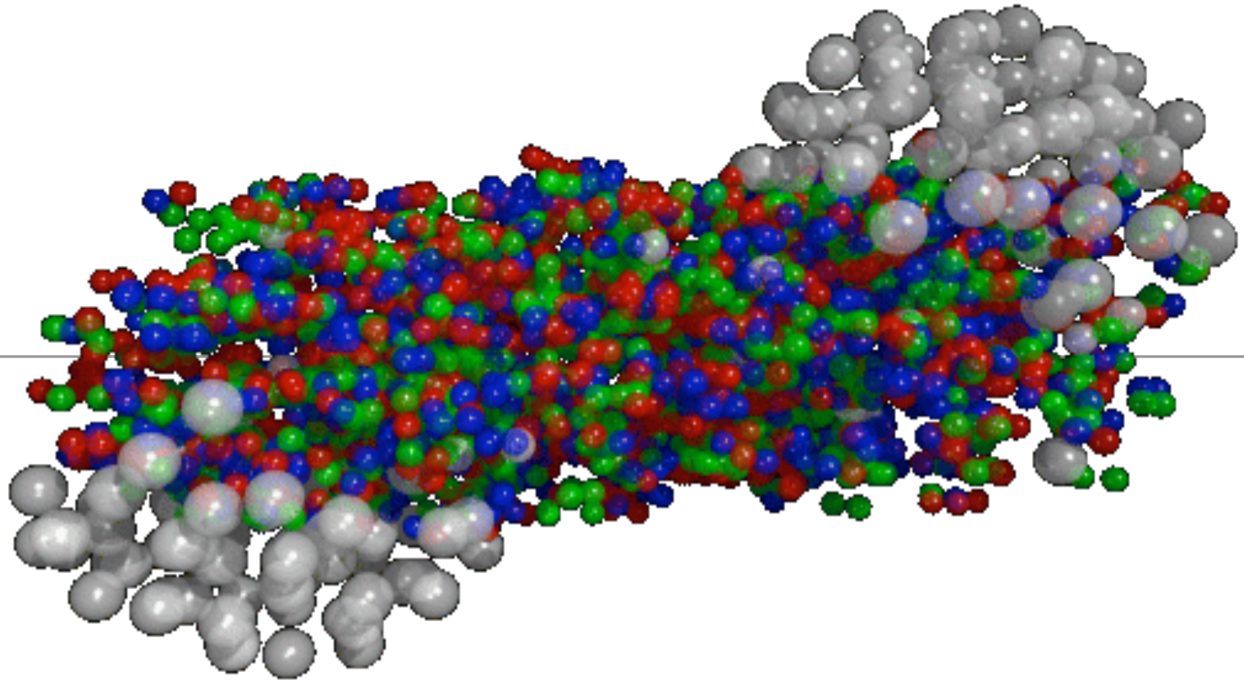
Photon Signals from Quarkyonic Matter



Sascha Vogel, Giorgio Torrieri

Hard Probes 2013

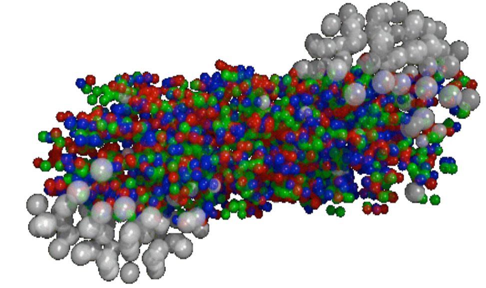
based on arXiv:1302.1119, PRL 111 (2013) 012301

FIAS Frankfurt Institute for Advanced Studies

HIC for FAIR Helmholtz International Center

HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

The next 20
(highly speculative) minutes...

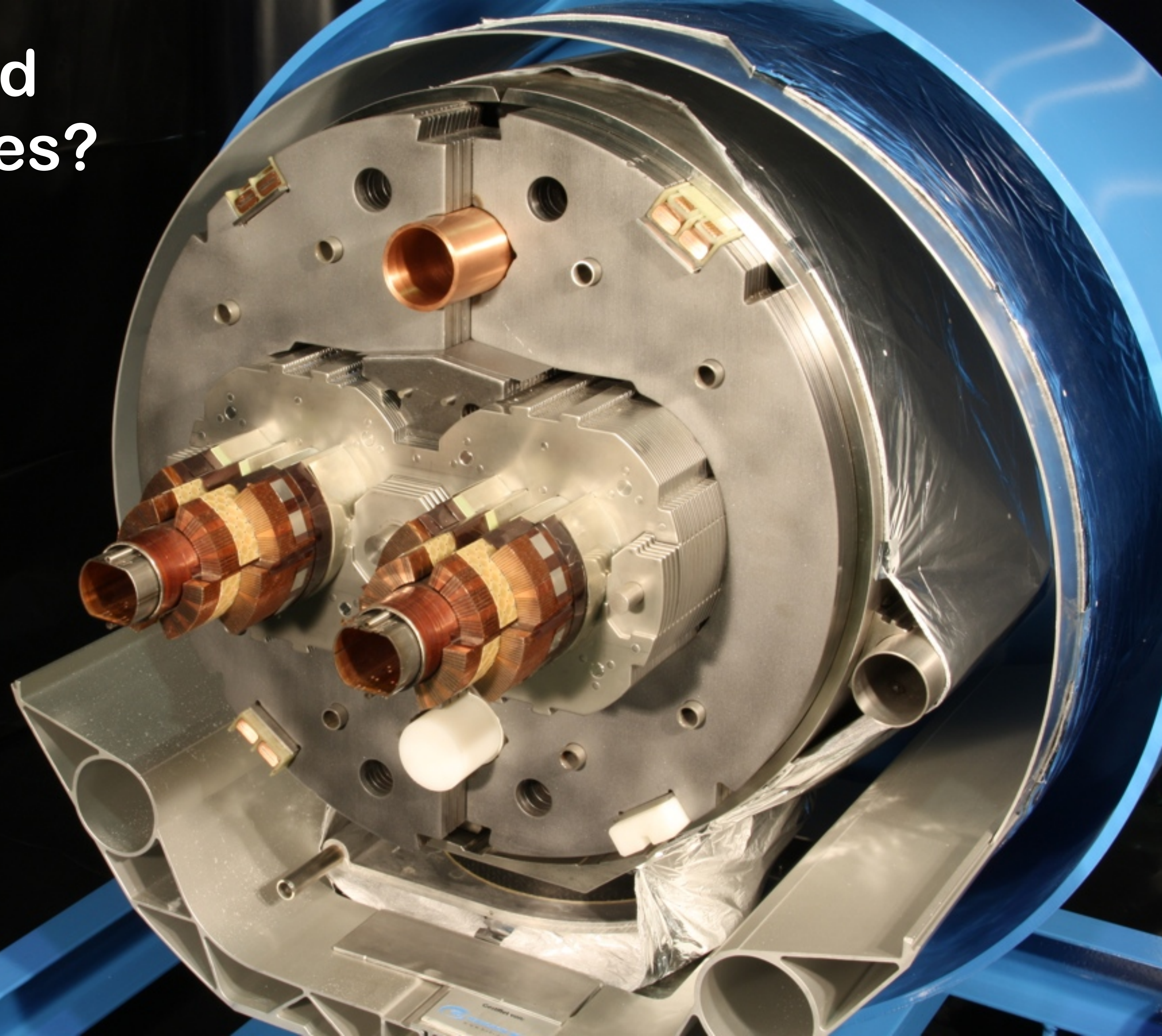


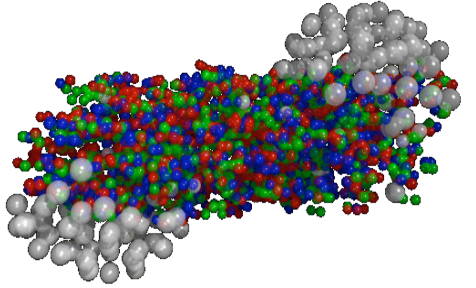
Quarkyonic Matter - why care and how deal with it?

Photons from Quarkyonic Matter - a signal at FAIR?

Next steps ...

Hard Probes?





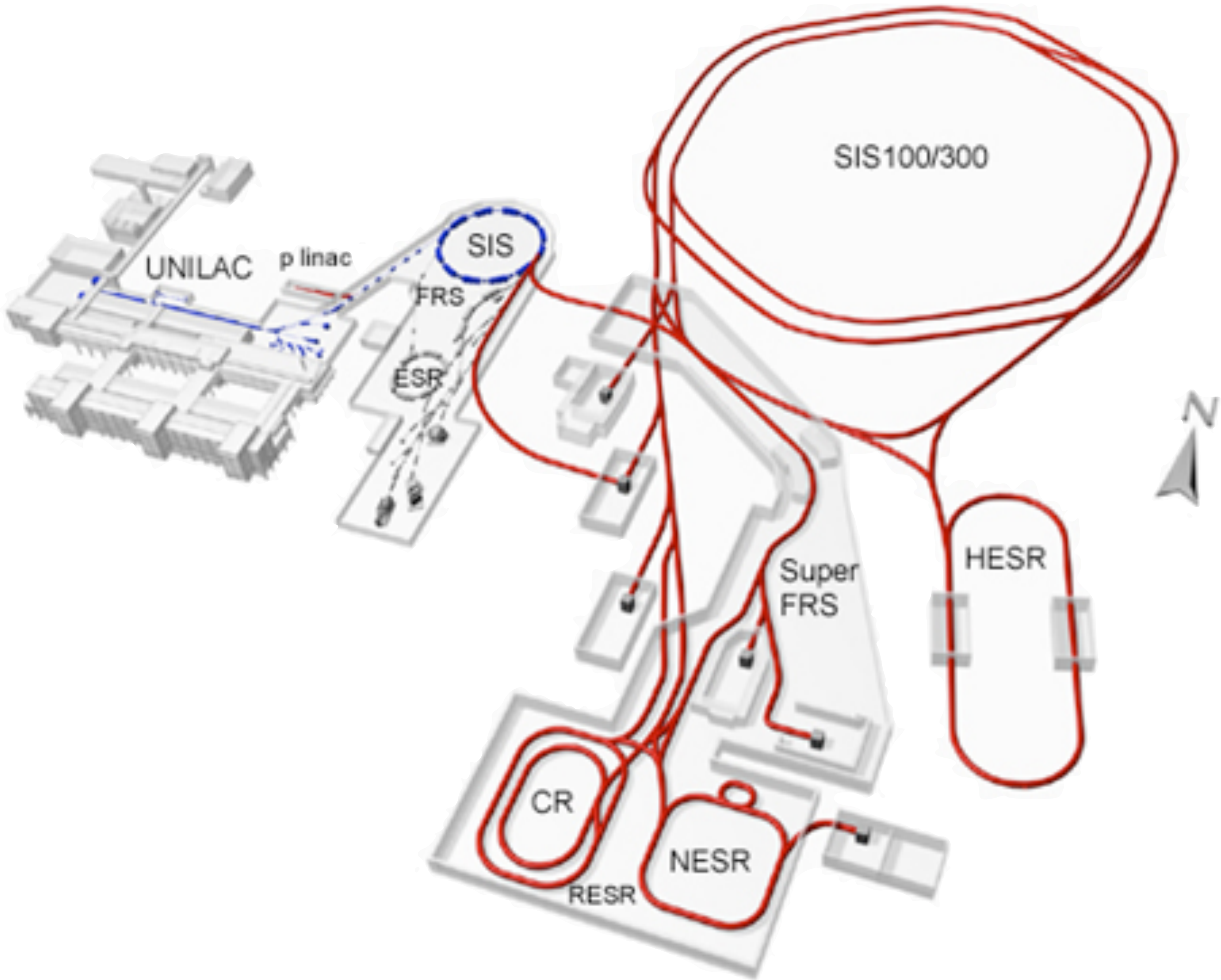
Why lower energies?

Plenty of exciting physics still not understood at lower energies!

Revisiting experiments at $\mu_B > \Lambda_{QCD}$ and $T < T_c$ with up to date detectors, luminosity and analysis techniques!

Additionally, more theoretical understanding...

FAIR



SIS100/300
UNILAC
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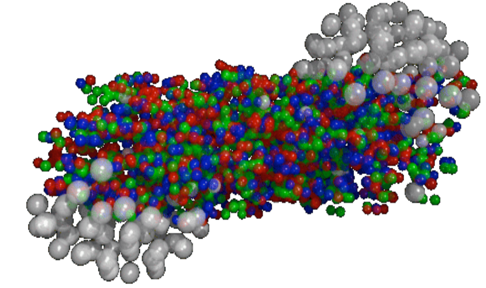
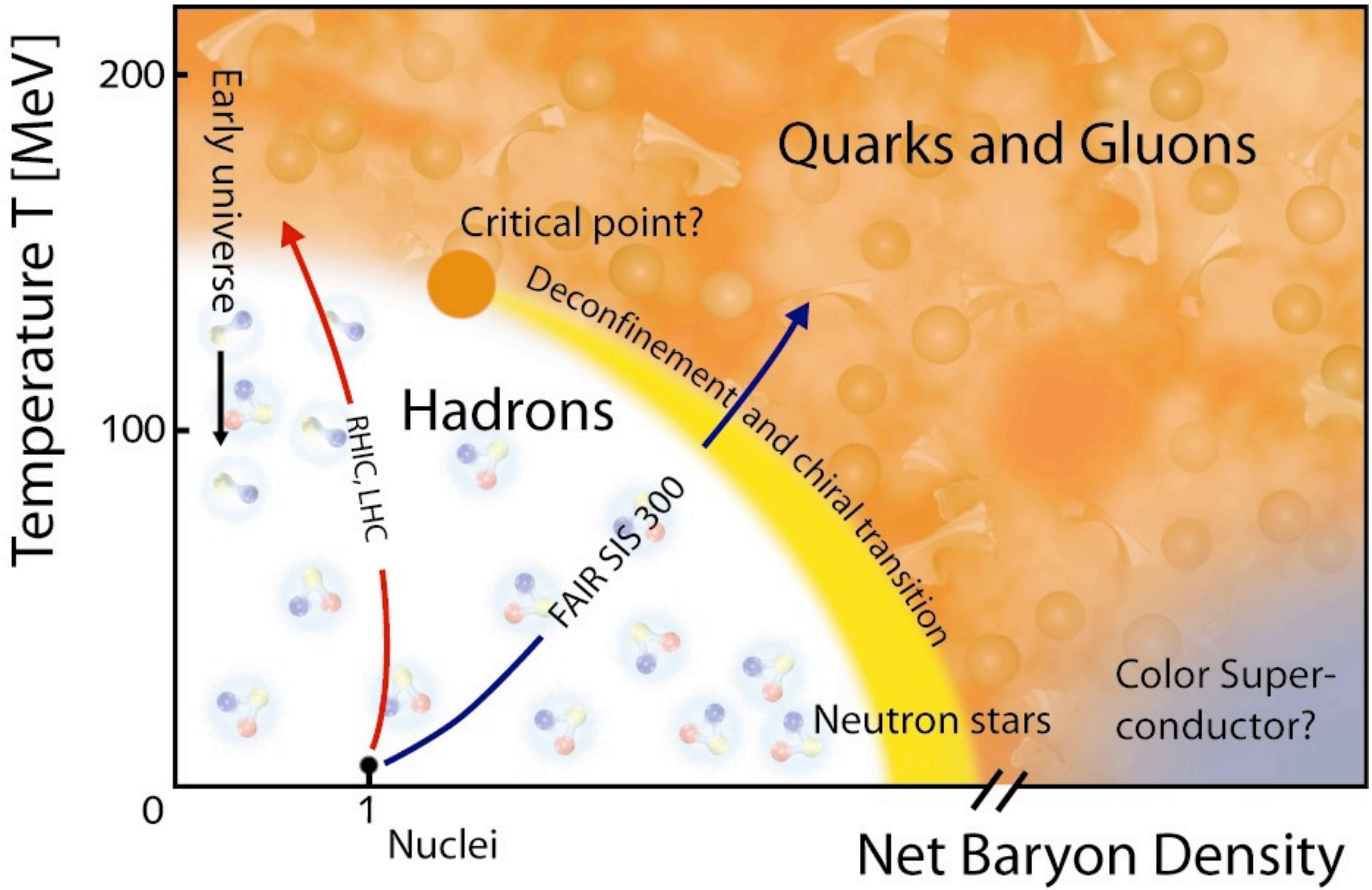
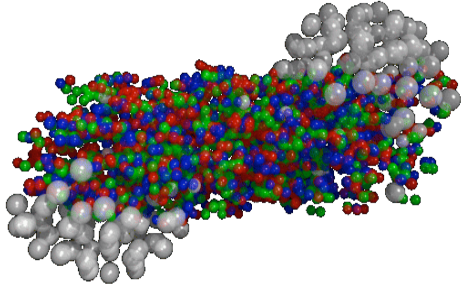
SIS
FRS
ESR
Super
FRS
HESR
CR
RESR
NESR
N

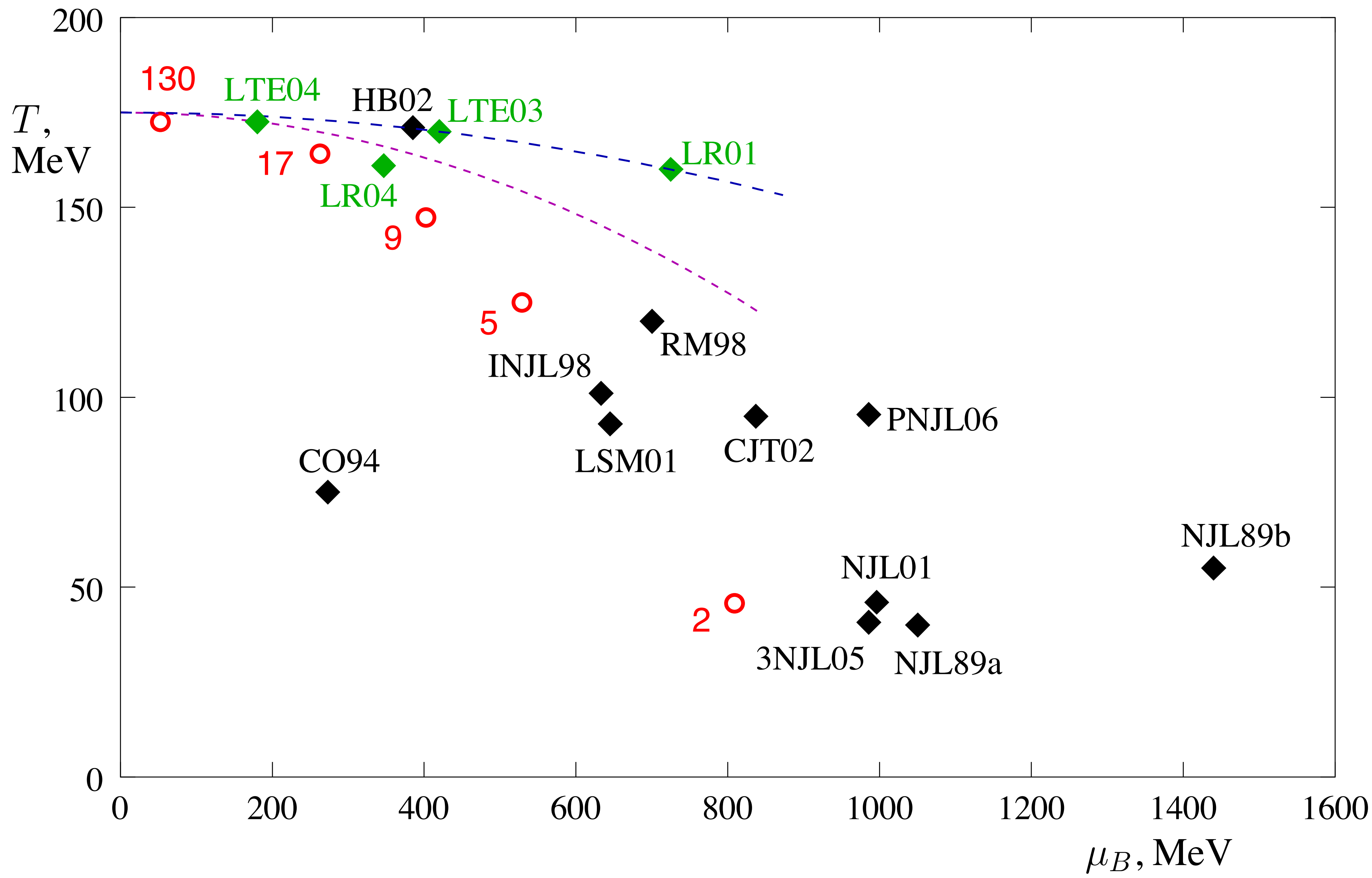
Phases of nuclear matter





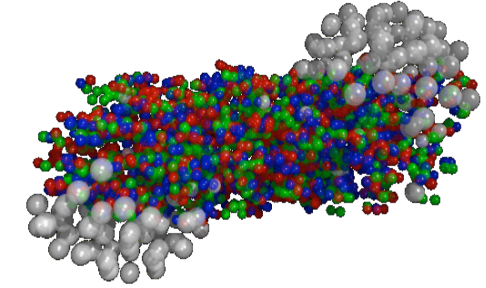
Critical Point(s)





Various critical point predictions around!

Is there one at all (de Forcrand, Philipsen)?



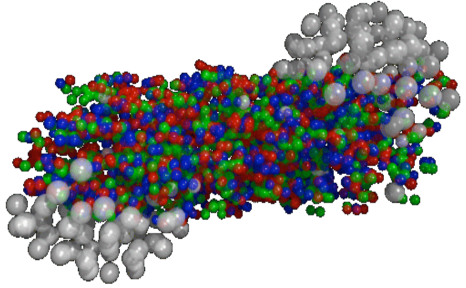
Problems at high μ_B

QCD at $\mu_B > \Lambda_{QCD}$ and $T < T_c$ is very poorly understood.

EFT: not fully working/understood

Lattice: sign problem (works for $\mu_B \ll T$ though)

AdS/CFT: needs $N_c \rightarrow \infty$, apart from many other unrealistic assumptions

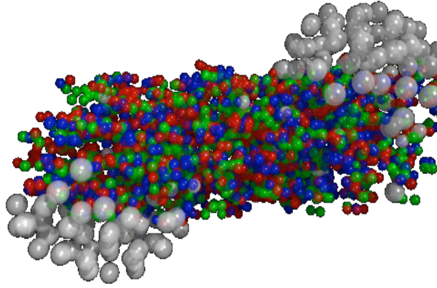


Problems at high μ_B

Put provocatively:

Any high density calculation of QCD is an educated guess!
Surprises possible!

The FAIR program requires a what if phenomenology.
"If we expect effect X, we should see observable Y."



Quarkyonic Matter

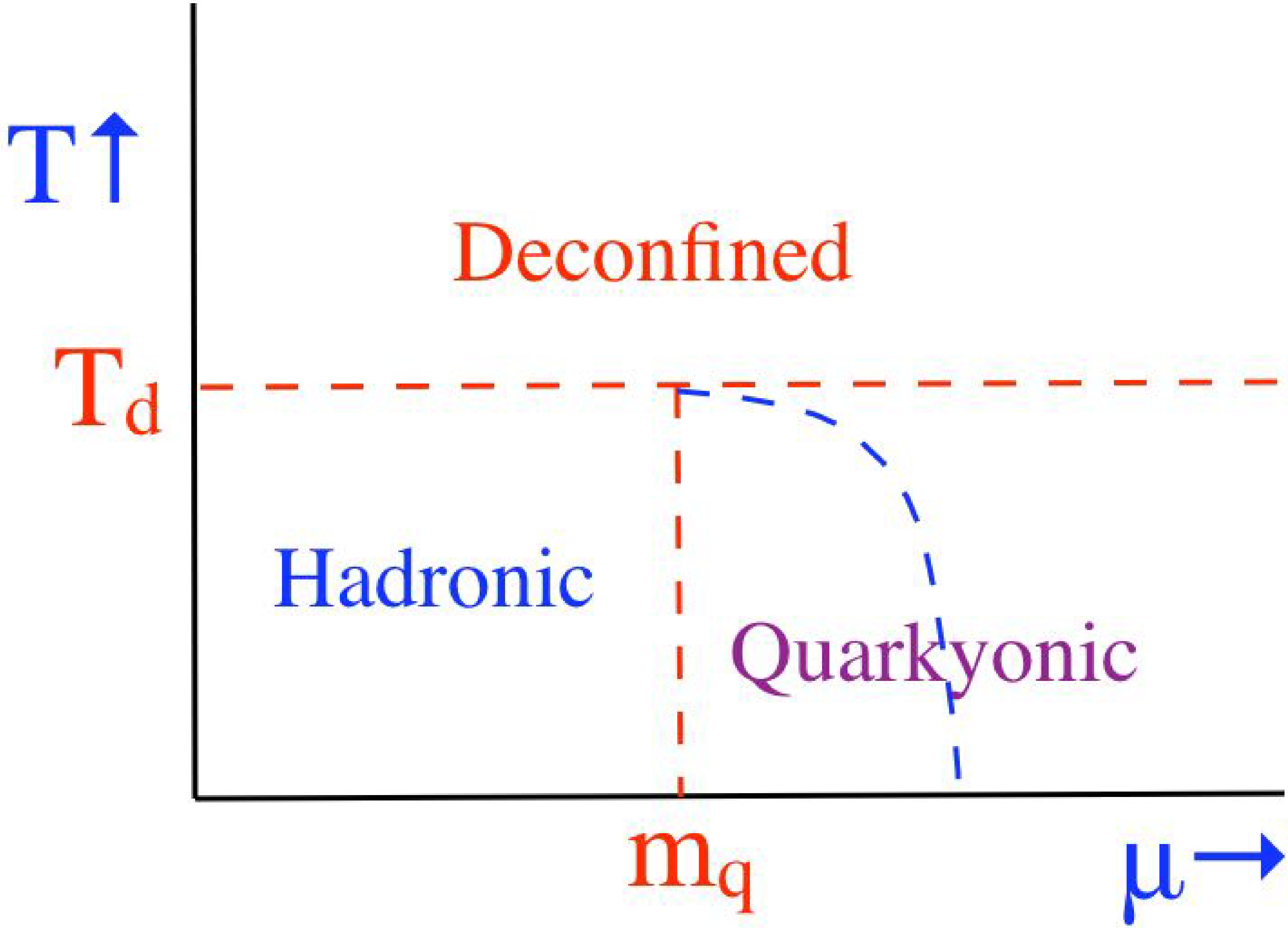
Name first introduced by

McLerran and Pisarki, NPA796 (2007) 83-100

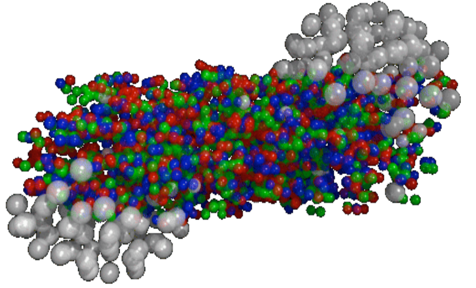
definitions in the literature include (among others...)

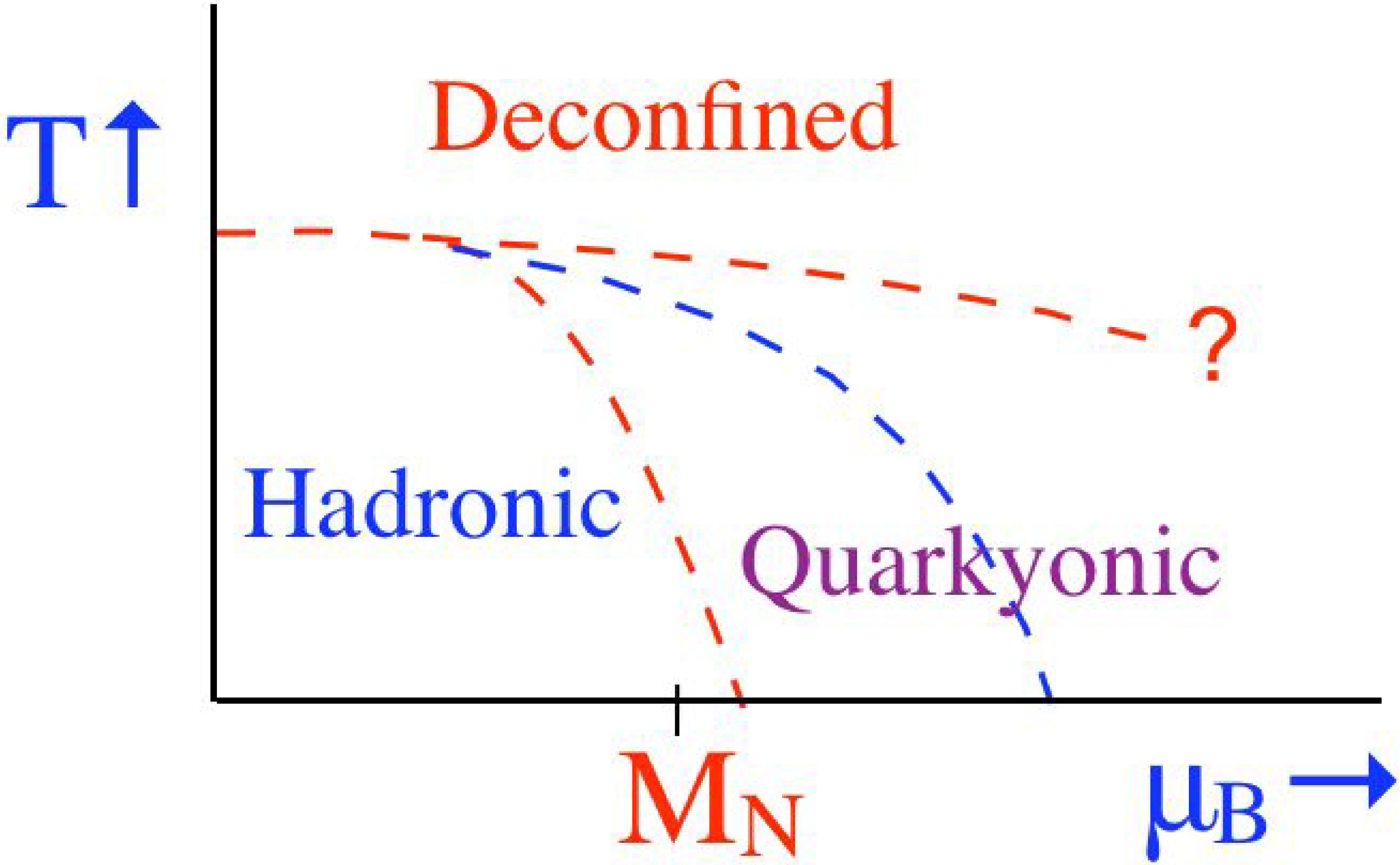
- Coexistence between confinement and pQCD
  - McLerran, Pisarski (2007)
- Confinement + chiral symmetry restoration
  - Fukushima, McLerran (2008)
- Deconfinement + chirally broken
  - Satz, Csernai...
- Chiral spiral inhomogeneities
  - Kojo, Pisarski, Tsvelik (2009)
- Generic chirally inhomogeneous regions
  - Buballa et al. (2007)
- Condensation of “baryons” in 2 color QCD
  - Hands, Skullerud, Giudice

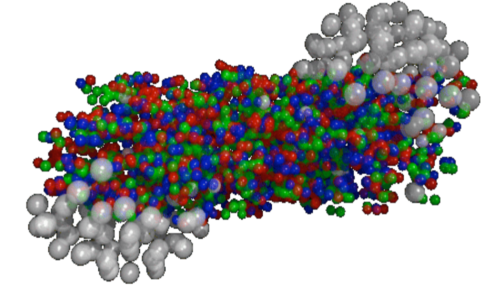
Quarkyonic phase diagram



Quarkyonic phase diagram







Dynamical vs. background

The only hierarchy that seems to be roughly correct is the large N_c limit

$$N_c \gg 1$$

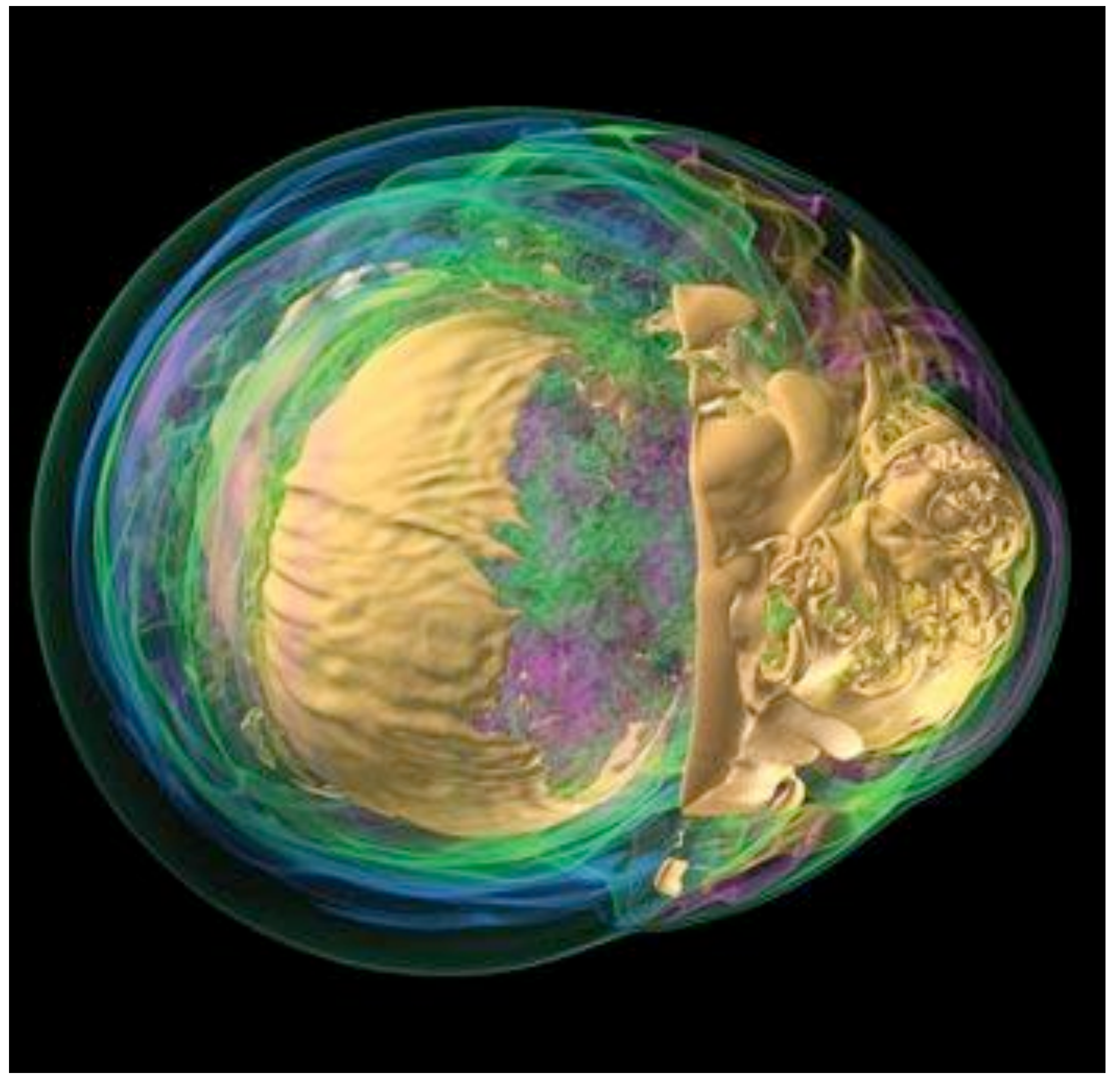
$$N_c^{-1} \ll 1$$

Looks strange, but gives a strict hierarchy in terms of

"fast" quarks (quantum d.o.f.)

"slow" baryons (immobile heavy classical background)

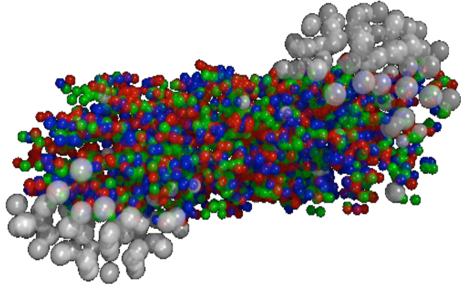
Astrophysical implications

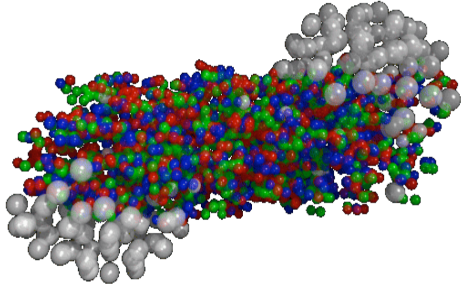


Quarkyonic phase changes the EoS

➜ impact on supernova explosions?

The big elephant in the room...



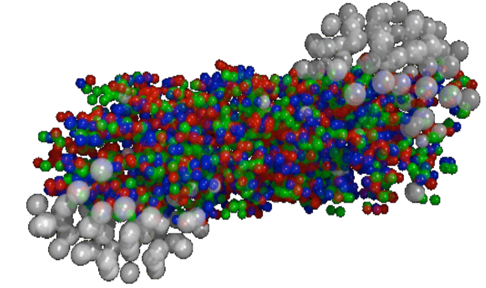


How to...

1) baryon distribution from microscopic calculation

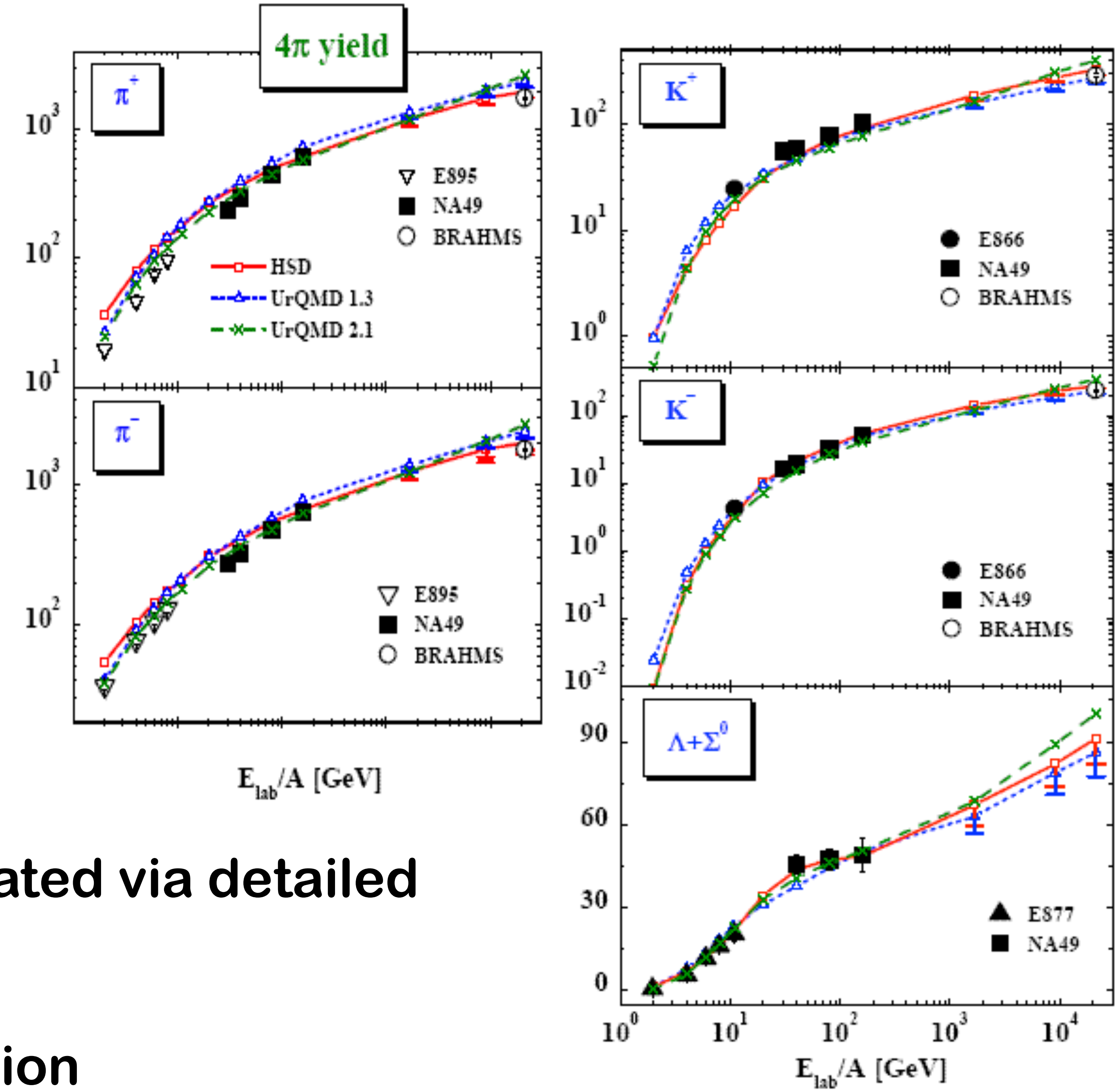
2) use it as input to calculate quark wave function

3) calculate γ Bremsstrahlung spectrum
for qq ➜ qqγ



The tool - UrQMD

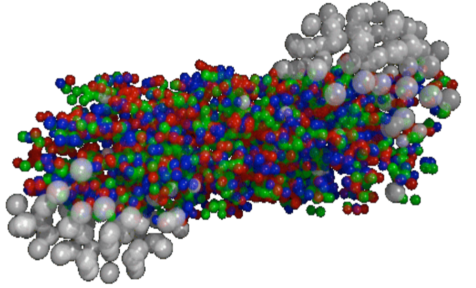
- Ultra Relativistic Quantum Molecular Dynamics
- Non equilibrium transport model
- All hadrons and resonances up to 2.2 GeV included
- Particle production via string excitation and -fragmentation
- Cross sections are fitted to available experimental data or calculated via detailed balance or the additive quark model
- Does account for canonical suppression



No explicit implementation of in-medium modifications!

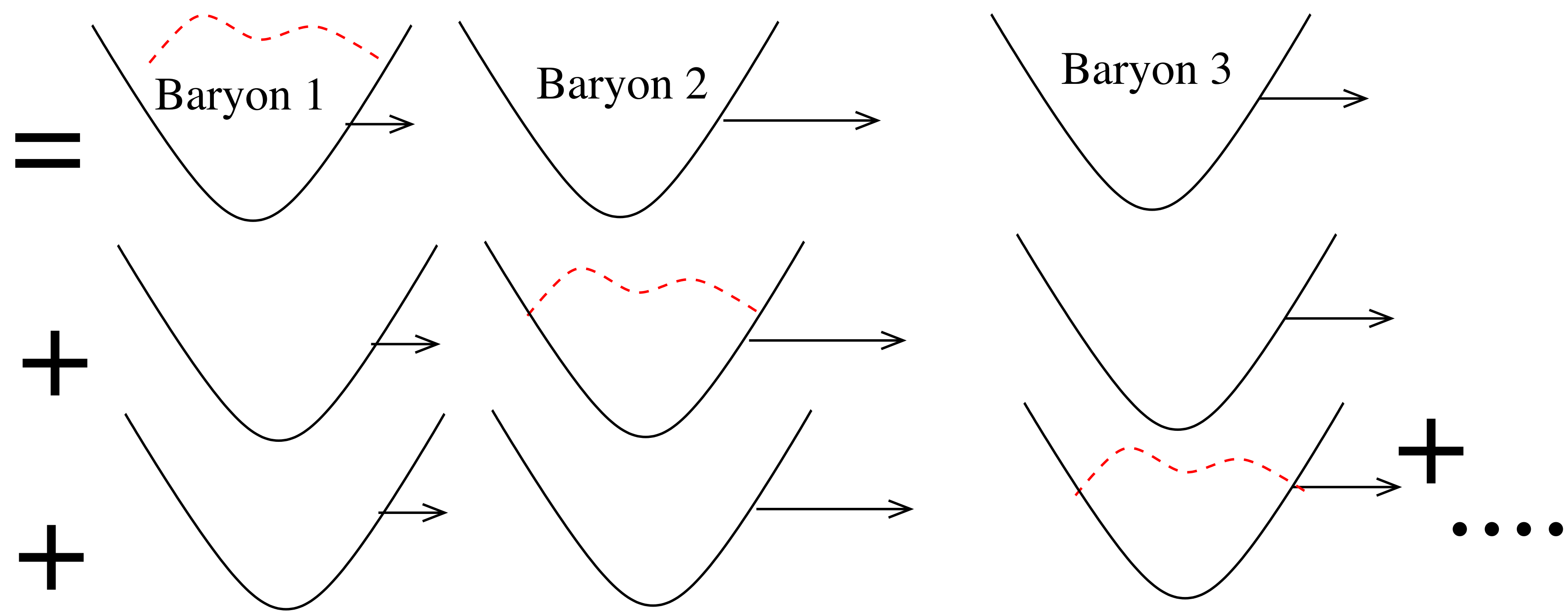
Phys.Rev.C69:054907,2004

Phys.Rev.C74:034902,2006



Quarkyonic Matter

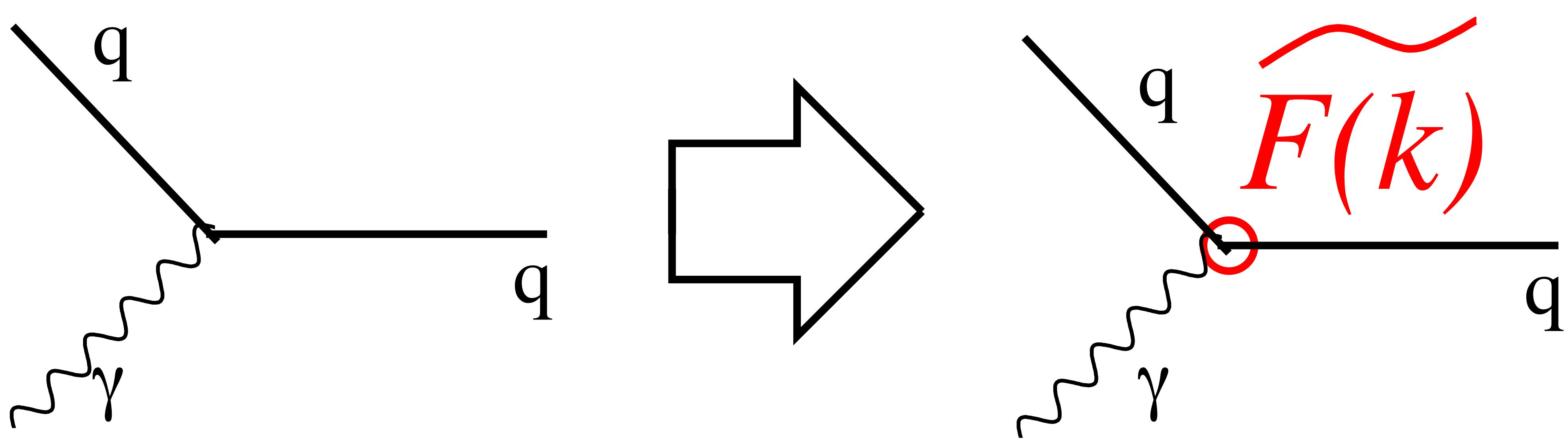
$$\tilde{\Psi}(K_i) =$$



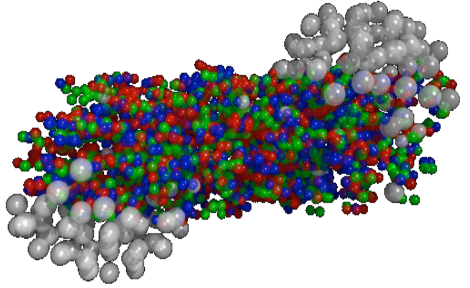
Use the baryon positions as gaussian sources
➜ calculate the wave-function from that

Description by form factor

“Quarkyonic vacuum” is a classical dense baryon state
➜ description as a mean field will give a k-dependent form factor!

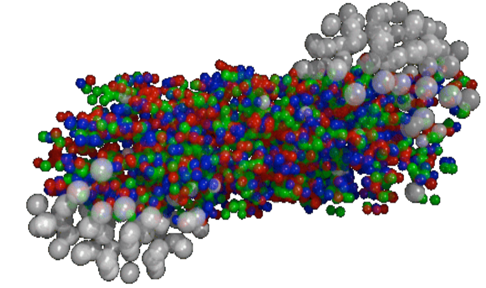


NB: Baryon movement is a N_c^{-1} correction to quarks
(see later - boosted quarkyonic)



Wave function

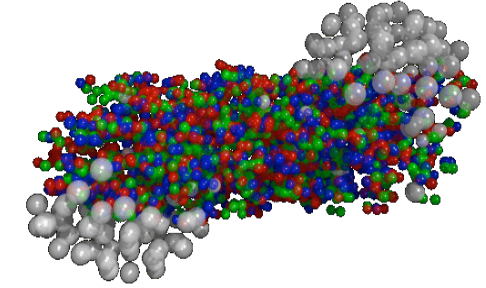
$$\Psi(k) \sim \exp \sum_i \left[ikx_{0i}\right] F(k) \sim \exp\left[ikx_{0i} - \frac{k^2}{\Lambda_{QCD}}\right]$$



Wave function

$$\Psi(k) \sim \exp \sum_i [ikx_{0i}] F(k) \sim \exp\left[ikx_{0i} - \frac{k^2}{\Lambda_{QCD}}\right]$$

quark function inside the “classical” proton potential well (Gaussian)



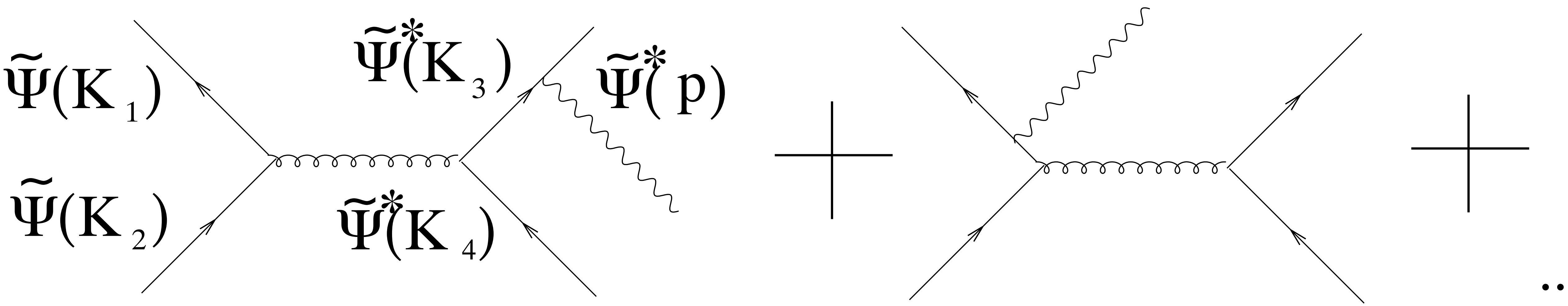
Wave function

$$\Psi(k) \sim \exp \sum_i [ikx_{0i}] F(k) \sim \exp \left[ikx_{0i} - \frac{k^2}{\Lambda_{QCD}} \right]$$

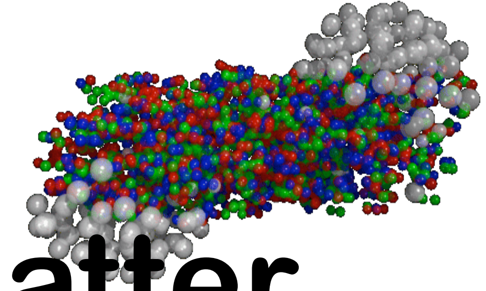
quark locations (from UrQMD)

quark function inside the “classical” proton potential well (Gaussian)

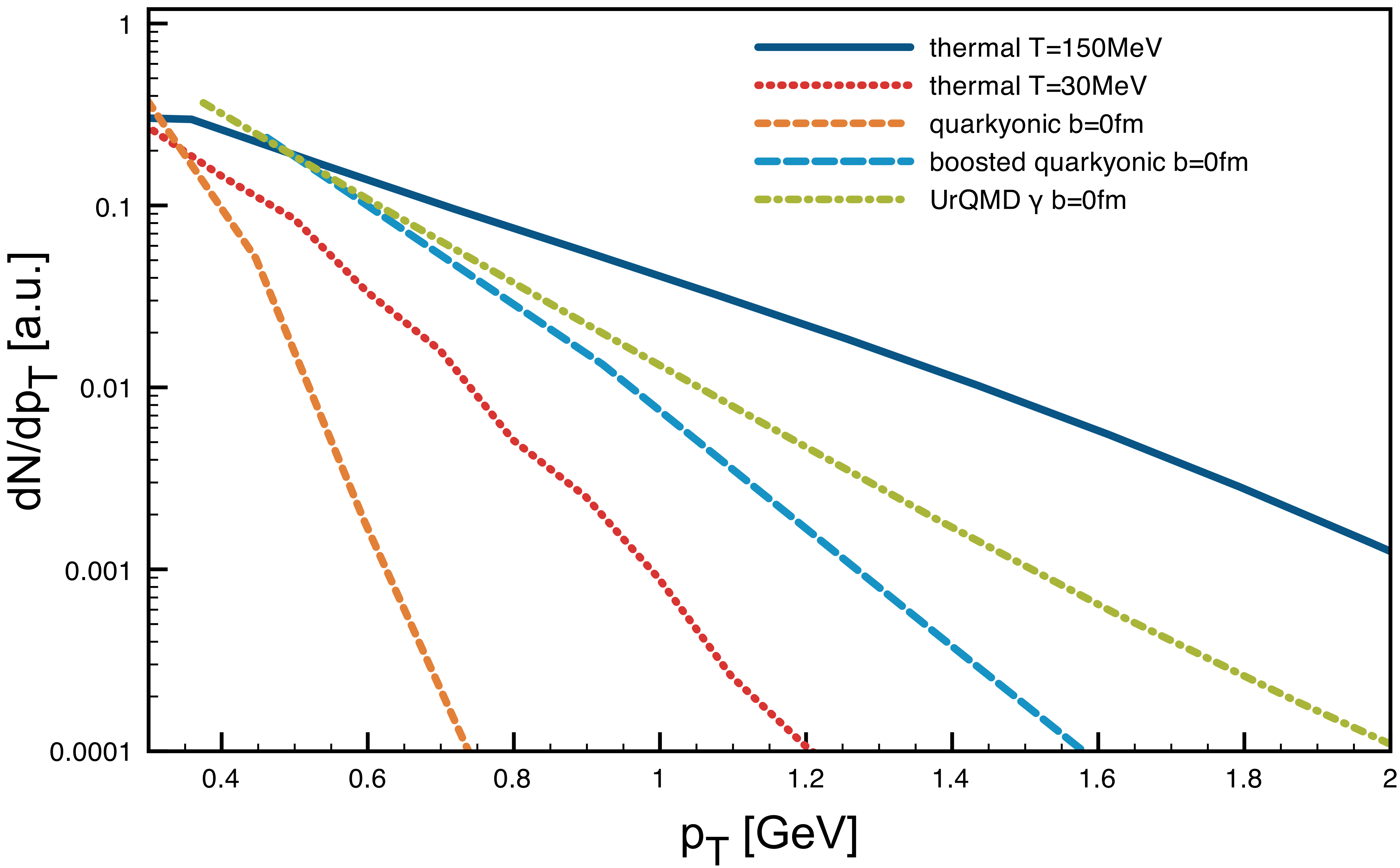
Quarkyonic Matter



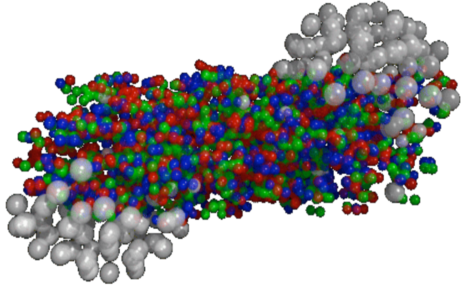
$$\frac{dN_\gamma}{d^3p} = \int \frac{d^4k_1}{k_1^0}\frac{d^4k_2}{k_2^0}\frac{d^4k_3}{k_3^0}\frac{d^4k_4}{k_4^0}\left(\mathcal{M}\left(k_1, k_2 \to k_3, k_4, p\right)\Psi(k_1)\Psi(k_2)\right)^2$$



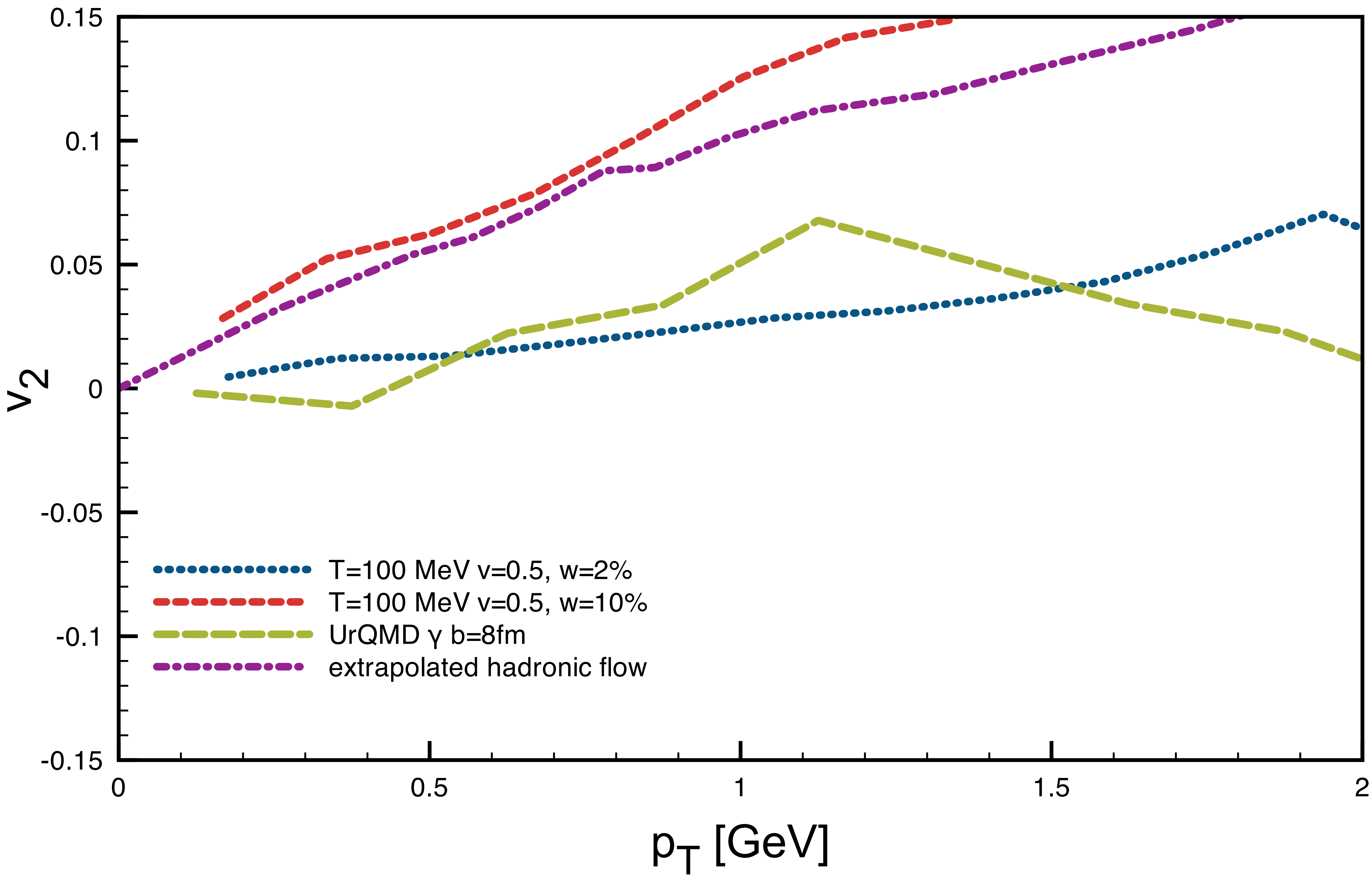
γ p_T spectrum from quarkyonic matter



(Torrieri, Vogel, arXiv:1302.1119, PRL 111 (2013) 012301)



γ v_2 from quarkyonic matter



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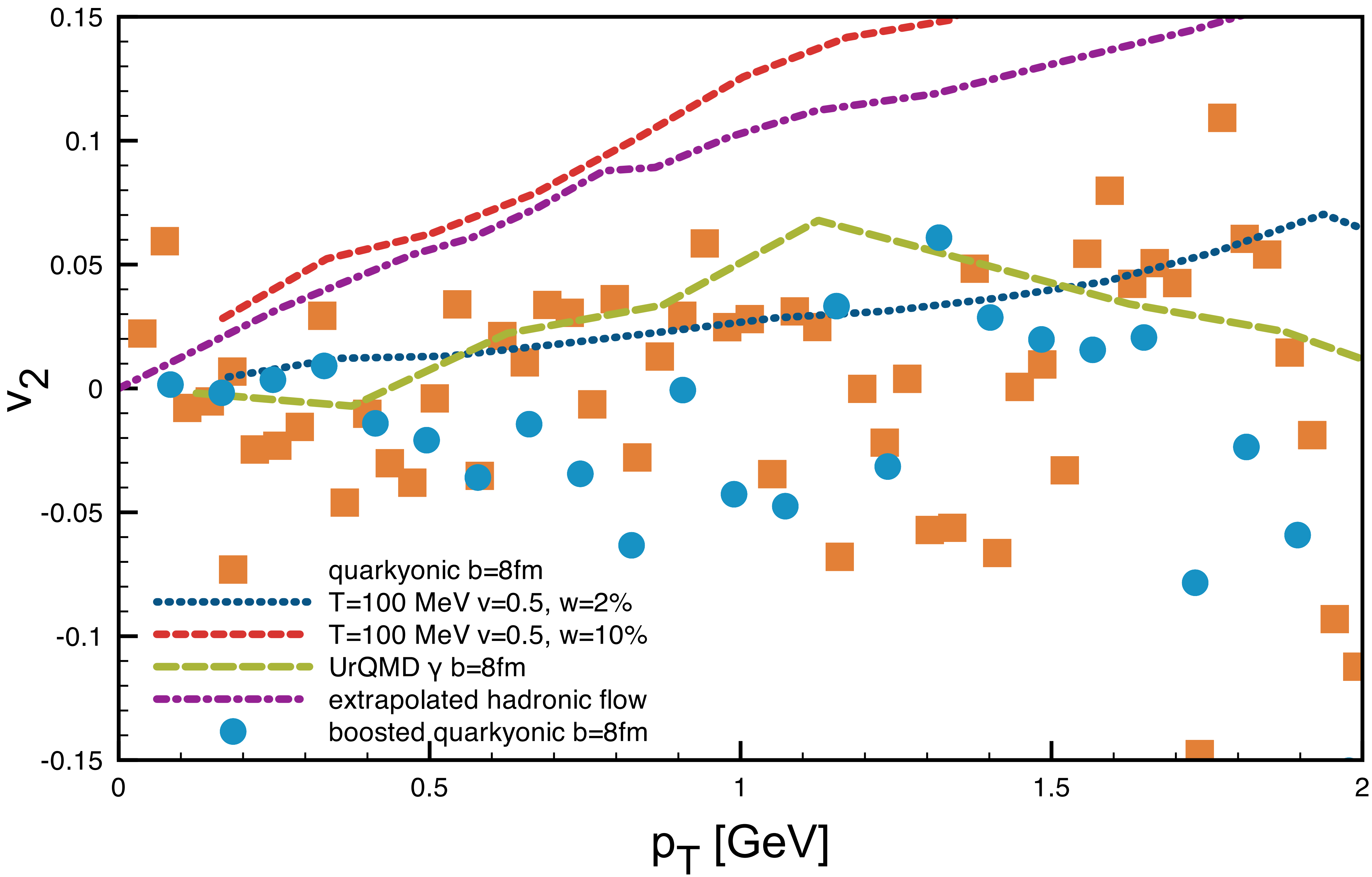

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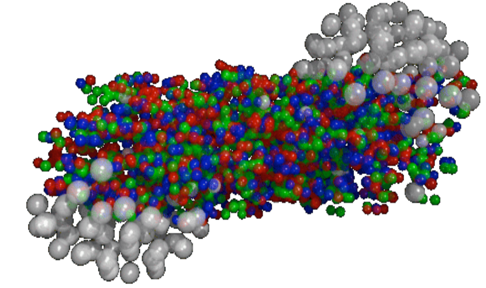
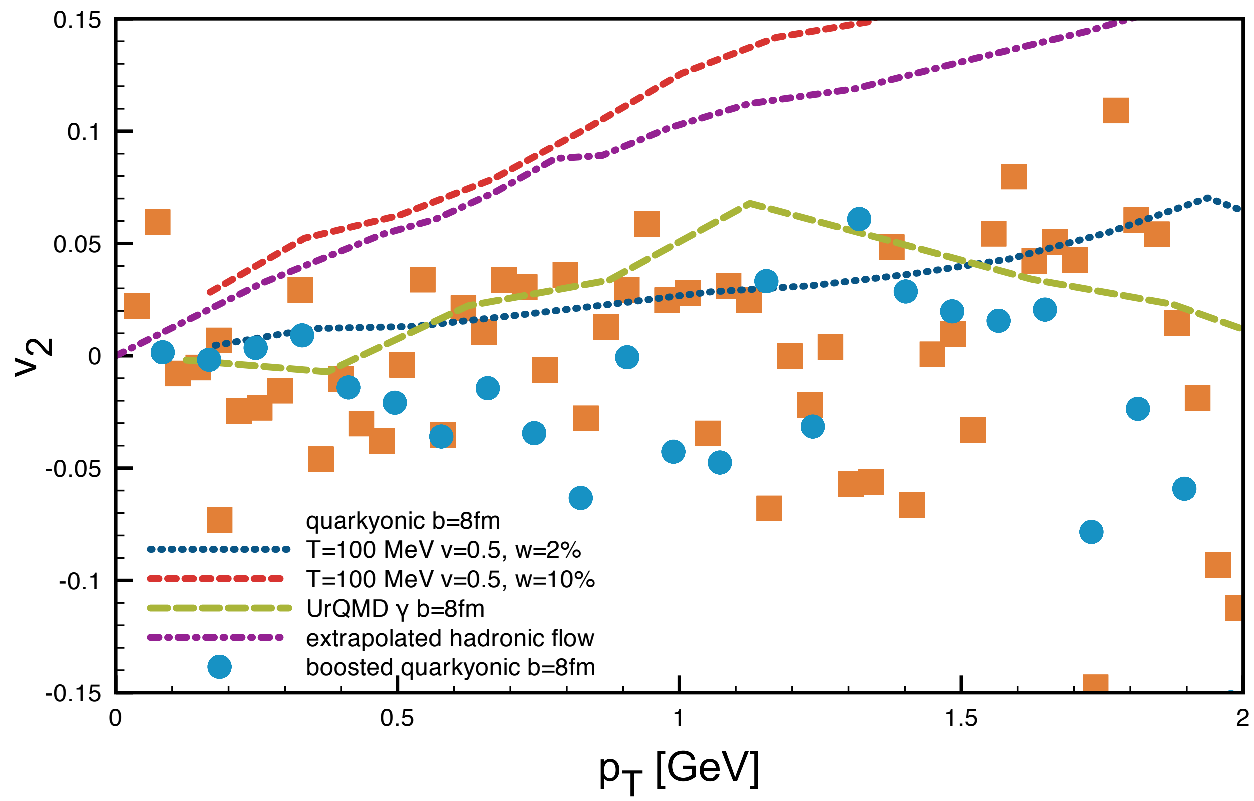
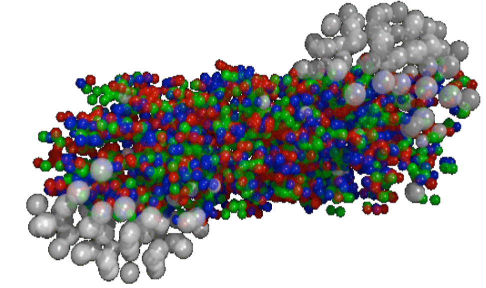


Strong fluctuations



Strong v_2 fluctuations, both event by event and within the same event in p_T

collapse of v_2 might be a signal we can look for!



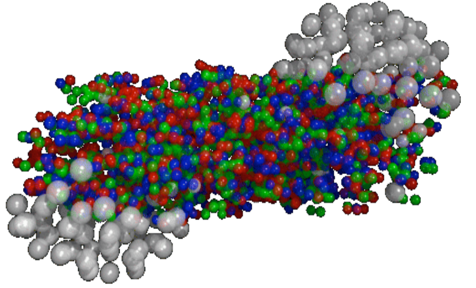
Take home messages

First steps towards a phenomenology of quarkyonic matter done

Photons seem interesting, what about dileptons?
➜ currently under investigation

“background” crucial - experimental sensitivity?
what about model sensitivity?

Take home messages



First steps towards a phenomenology of quarkyonic matter done

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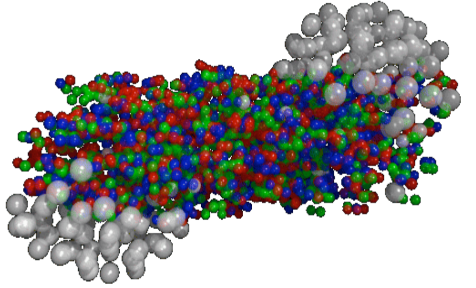
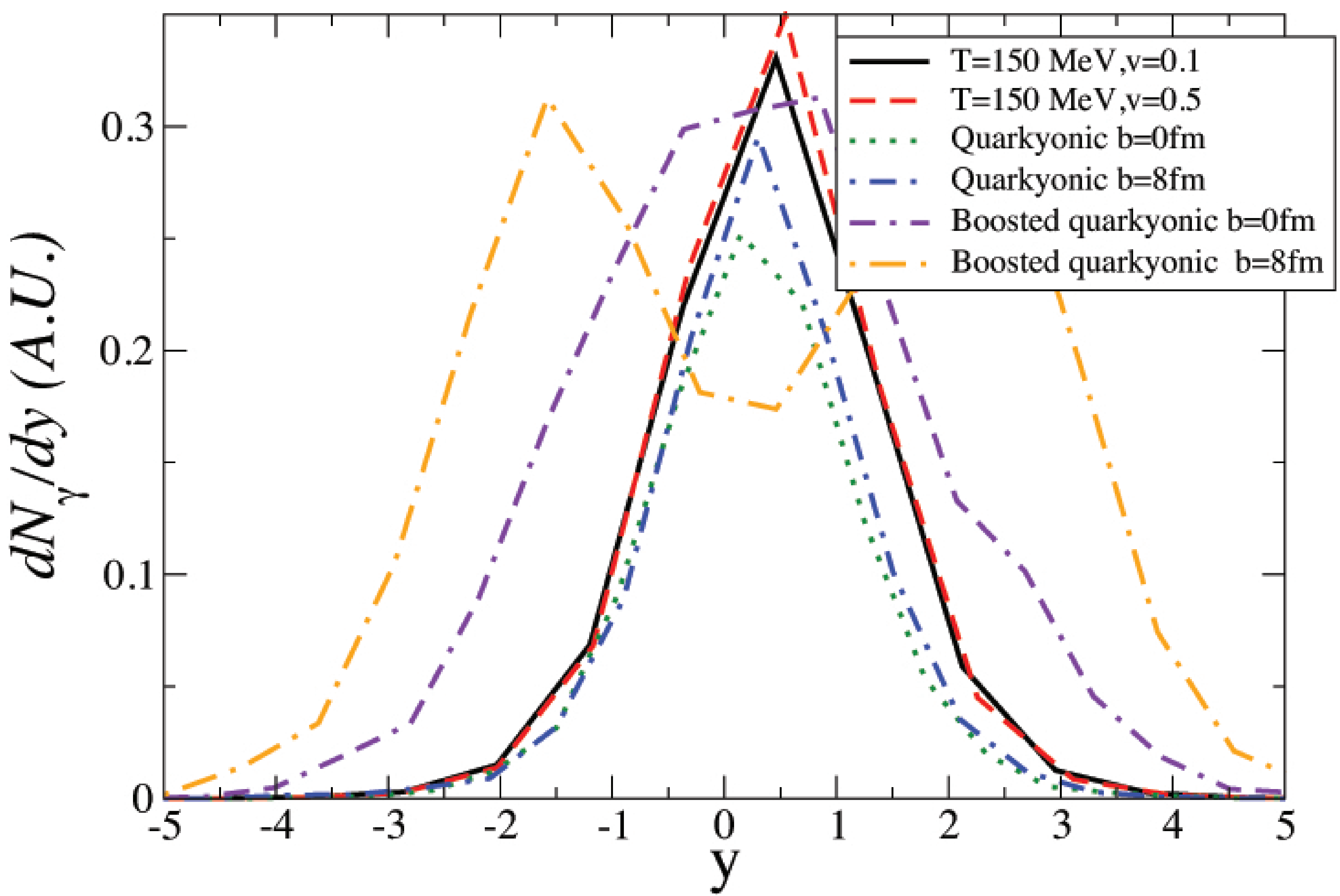
what about model sensitivity?

Thanks!

Backup

Rapidity distribution





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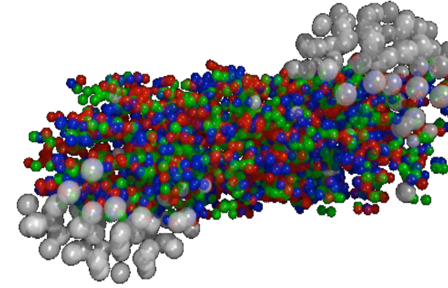


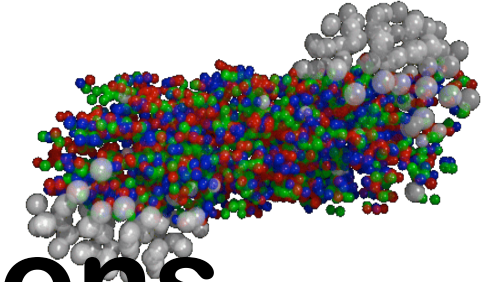
Photon production

$$\frac{dN_\gamma}{d^3p} = \int \frac{d^4k_1}{k_1^0}\frac{d^4k_2}{k_2^0}\frac{d^4k_3}{k_3^0}\frac{d^4k_4}{k_4^0}\left(\mathcal{M}\left(k_1,k_2 \to k_3,k_4,p\right)\Psi(k_1)\Psi(k_2)\right)^2$$

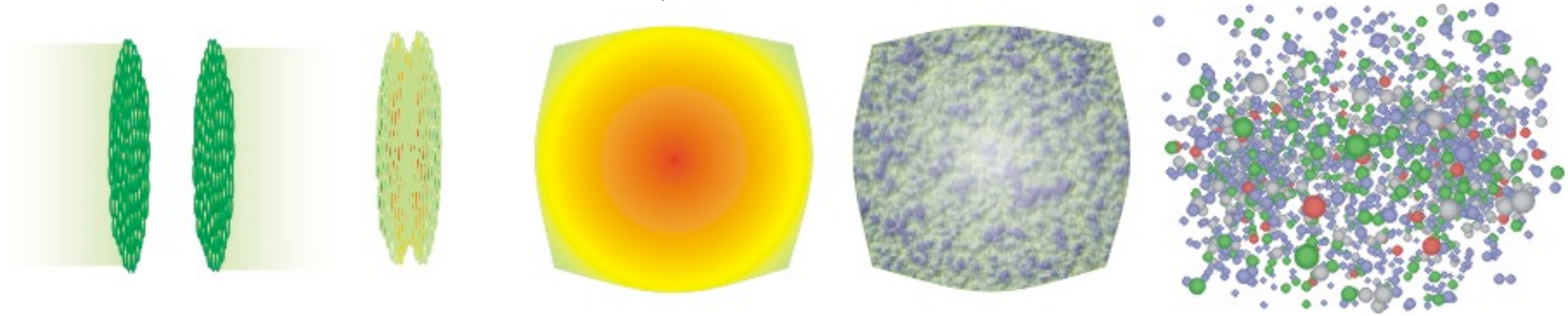
$$\mathcal{M}^2 = L^2(k_1,k_2 \to k_3,k_4,p) + L^2(k_1 \leftrightarrow k_2, k_3 \leftrightarrow k_4)$$

$$L^2 = -\frac{1}{4}e^2\lambda^2 N_c^{-2}(k_2-k_4)^{-4} Tr\left[\not{k}_4\gamma^\sigma\not{k}_2\gamma_\rho\right] Tr\left[\not{k}_3 Z^\mu_\sigma \not{k}_1 Z^\rho_\mu\right]$$

$$Z^\beta_\alpha = \gamma_\alpha(k_1-p)^{-1}\gamma^\beta + \gamma^\beta(k_3+p)^{-1}\gamma_\alpha$$



The need for dynamical simulations



Lattice gauge-theory (lQCD):

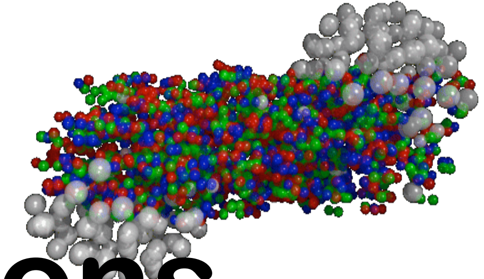
- ab initio calculation of QCD quantities
- usually in thermodynamic limit

Experiments:

- Observes the final state and penetrating probes
- Relies on theoretical predictions for the interpretation of the data

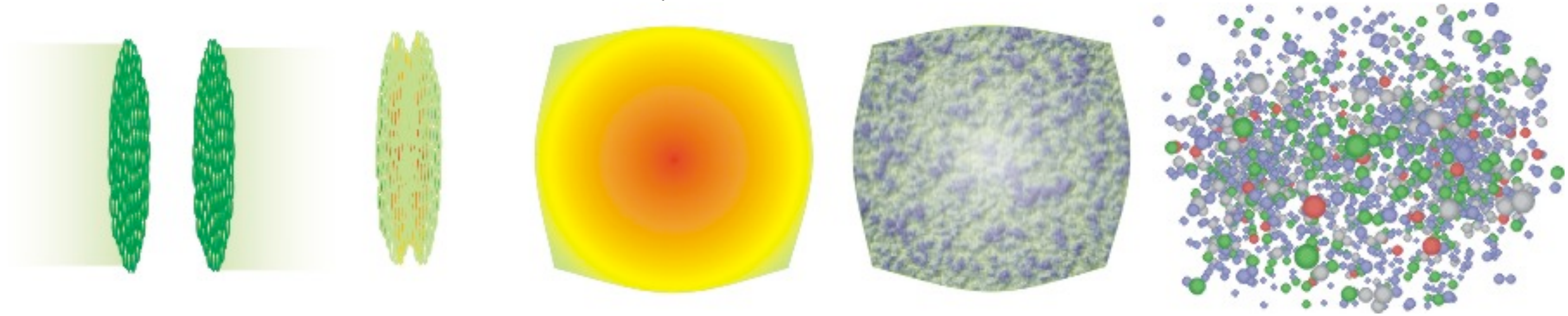
Transport models & phenomenology:

- Provides explicit time and space dependence
- Direct view into the hot and dense matter
- Connects between fundamental calculations and observation



The need for dynamical simulations

Initial state QGP Hadronic interactions



Pre-equilibrium Hadronisation

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