Femtoscopy in heavy-ion collision experiments at various μ_B

Hanna Zbroszczyk

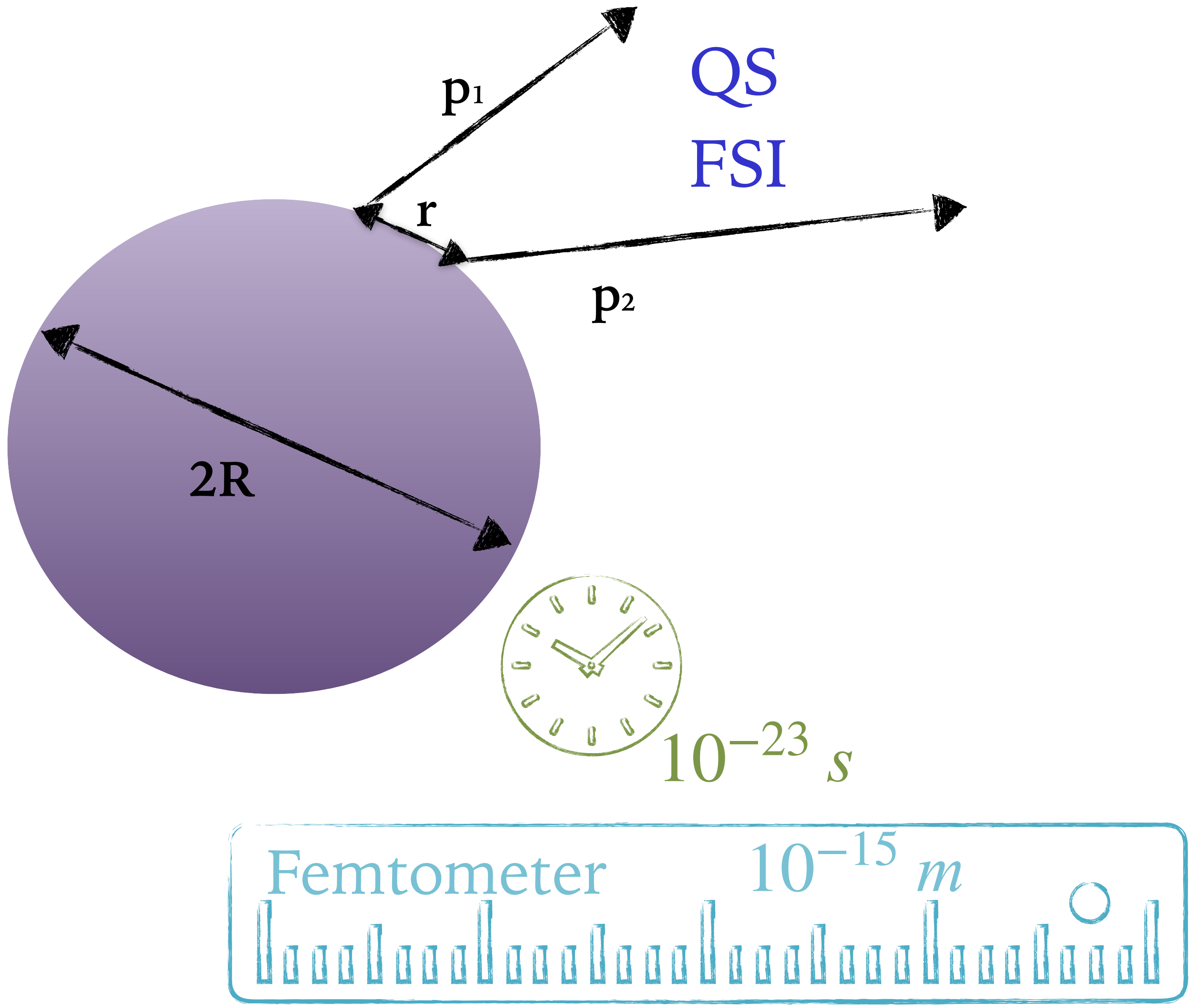
Introduction

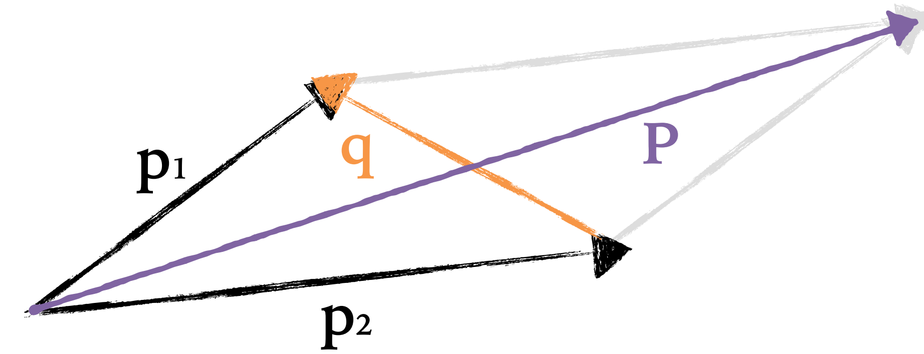
Scanning QCD phase diagram:

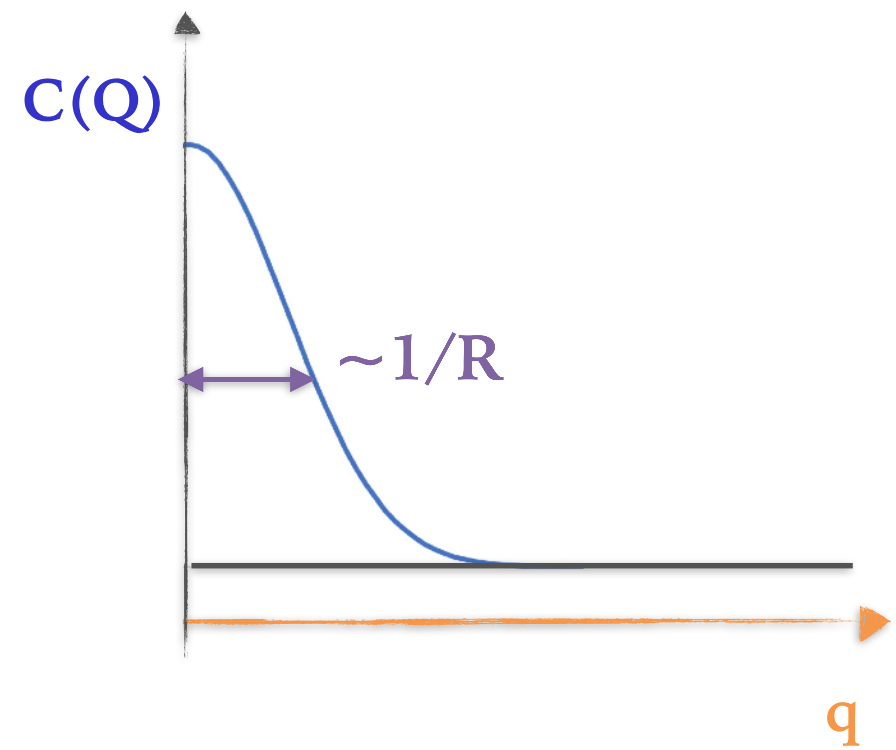
- neutron stars
- neutron star mergers
- phase transitions

Summary

WPCF 2023, November 6-10, 2023, Catania, Italy





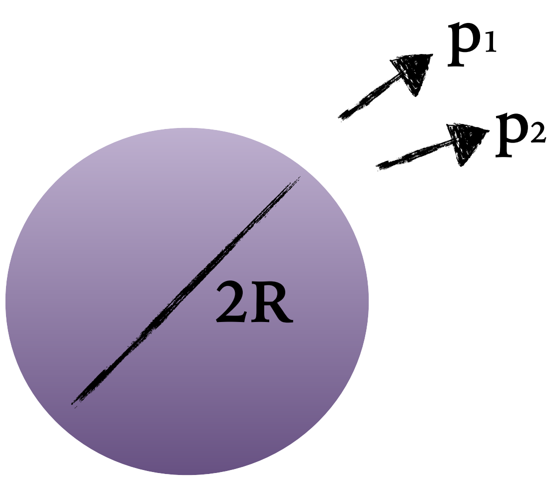


Femtoscopy

… the method to probe **geometric** and **dynamic** properties of the source

Classic femtoscopy

Femtoscopy (originating from HBT):
the method to probe **geometric** and **dynamic** properties of the source



Space-time properties $(10^{-15}m,\ 10^{-23}s)$ determined thanks to two-particle correlations:

Quantum Statistics (Fermi-Dirac, Bose-Einstein);

Final State Interactions (Coulomb, strong)

determined assumed measured

$$C(k^*, r^*) = \int S(r^*)\,|\Psi(k^*, r^*)|^2\, d^3r^* = \frac{Sgnl(k^*)}{Bckg(k^*)}$$

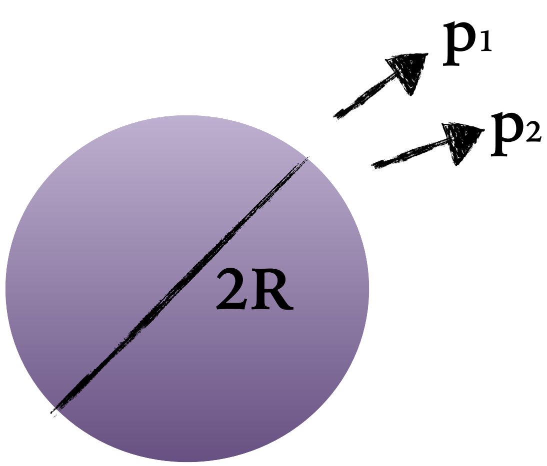
$S(r^*)$ - source function

$\Psi(k^*, r^*)$ - two-particle wave function (includes e.g. FSI interactions)

$\frac{Sgnl(k^*)}{Bckg(k^*)}$ - correlation function

Gateway to study interactions

If we assume we know the **source function**, measured **correlations** are used to determine **interactions in the final state.**



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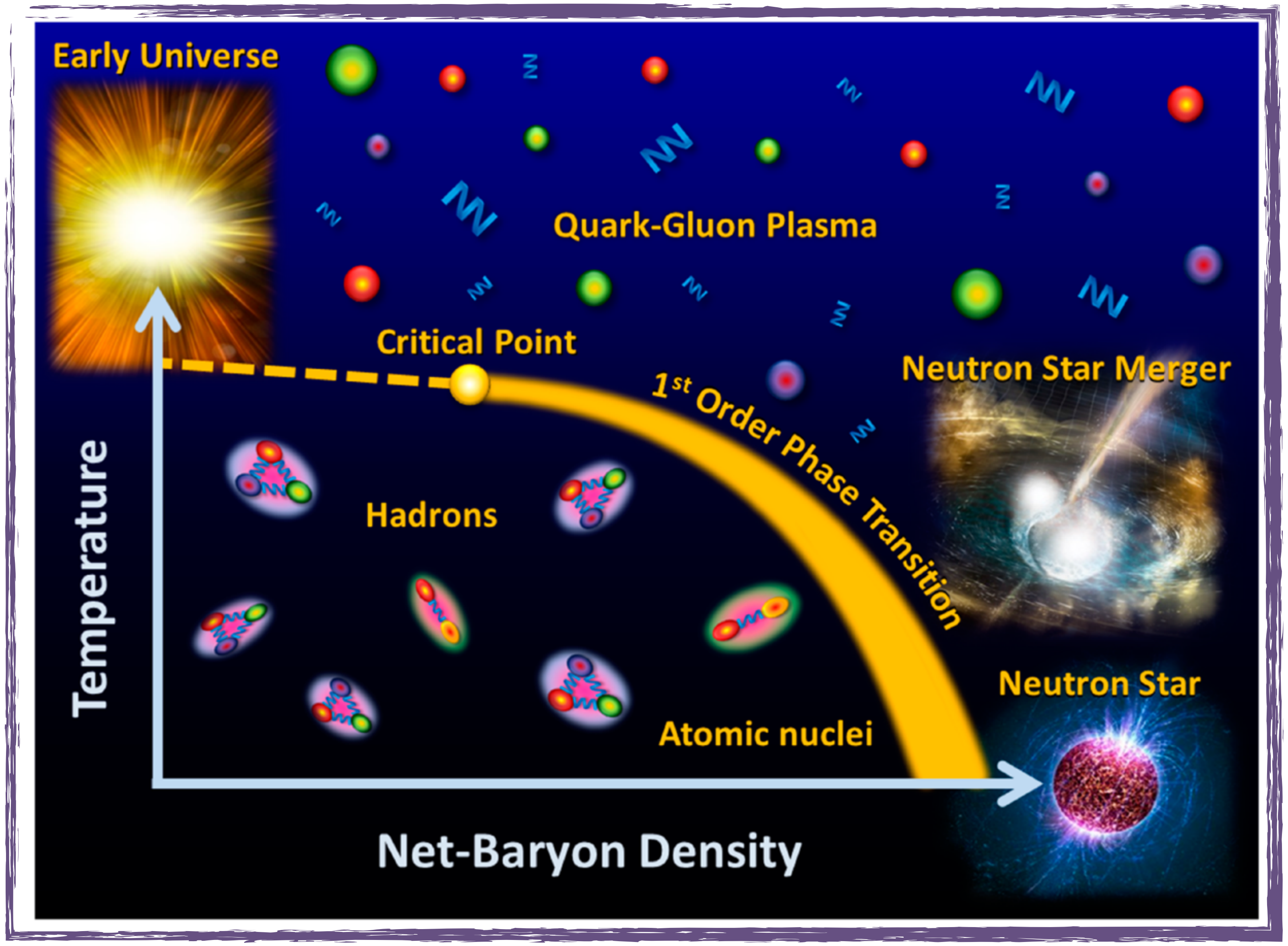


https://www.researchgate.net

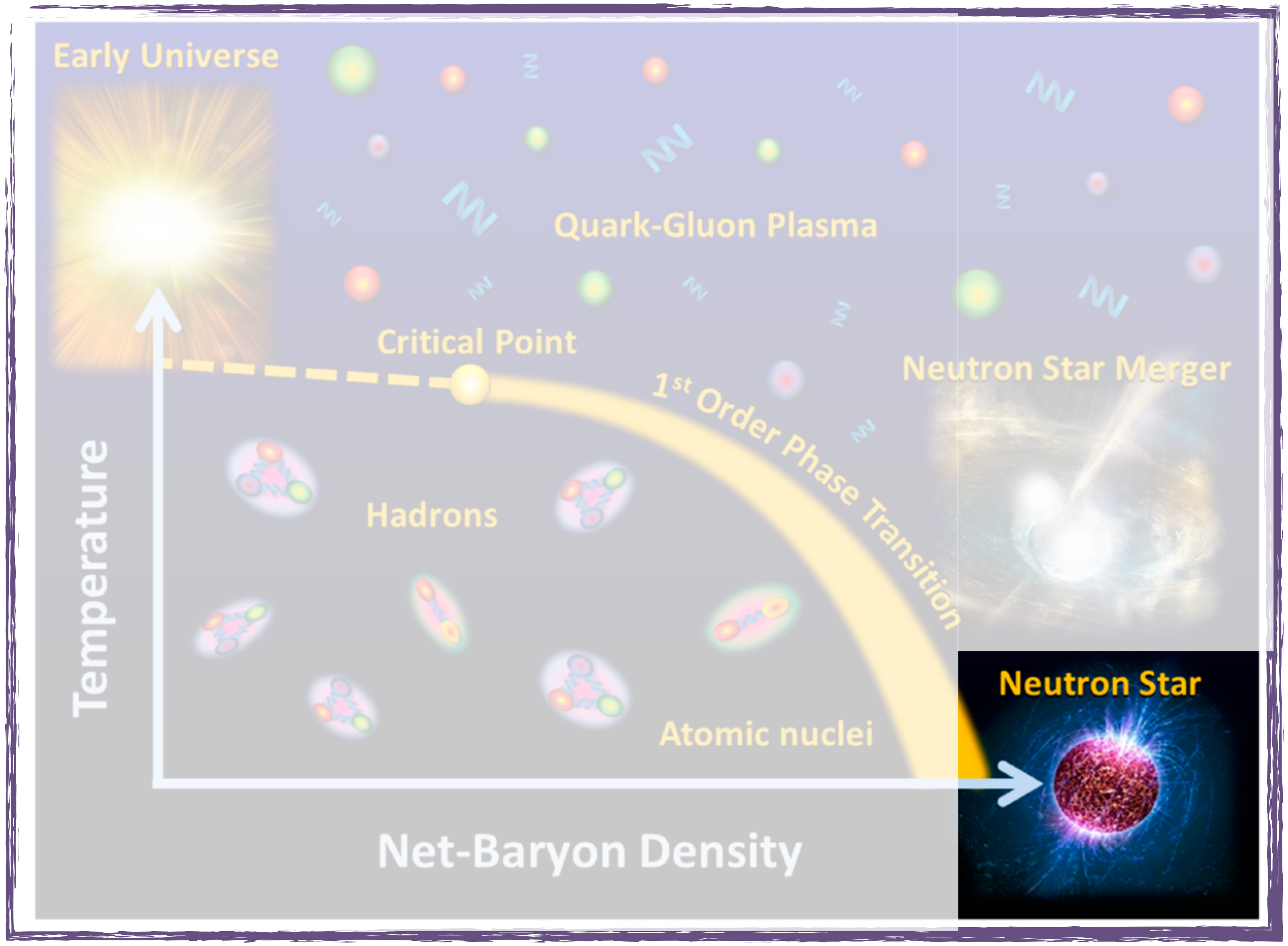
Scanning various μ_B

.. to study strongly interacting matter

.. to explore unknown QCD territory

Neutron stars

Exploration of unknown QCD territory: high μ_B



https://www.researchgate.net

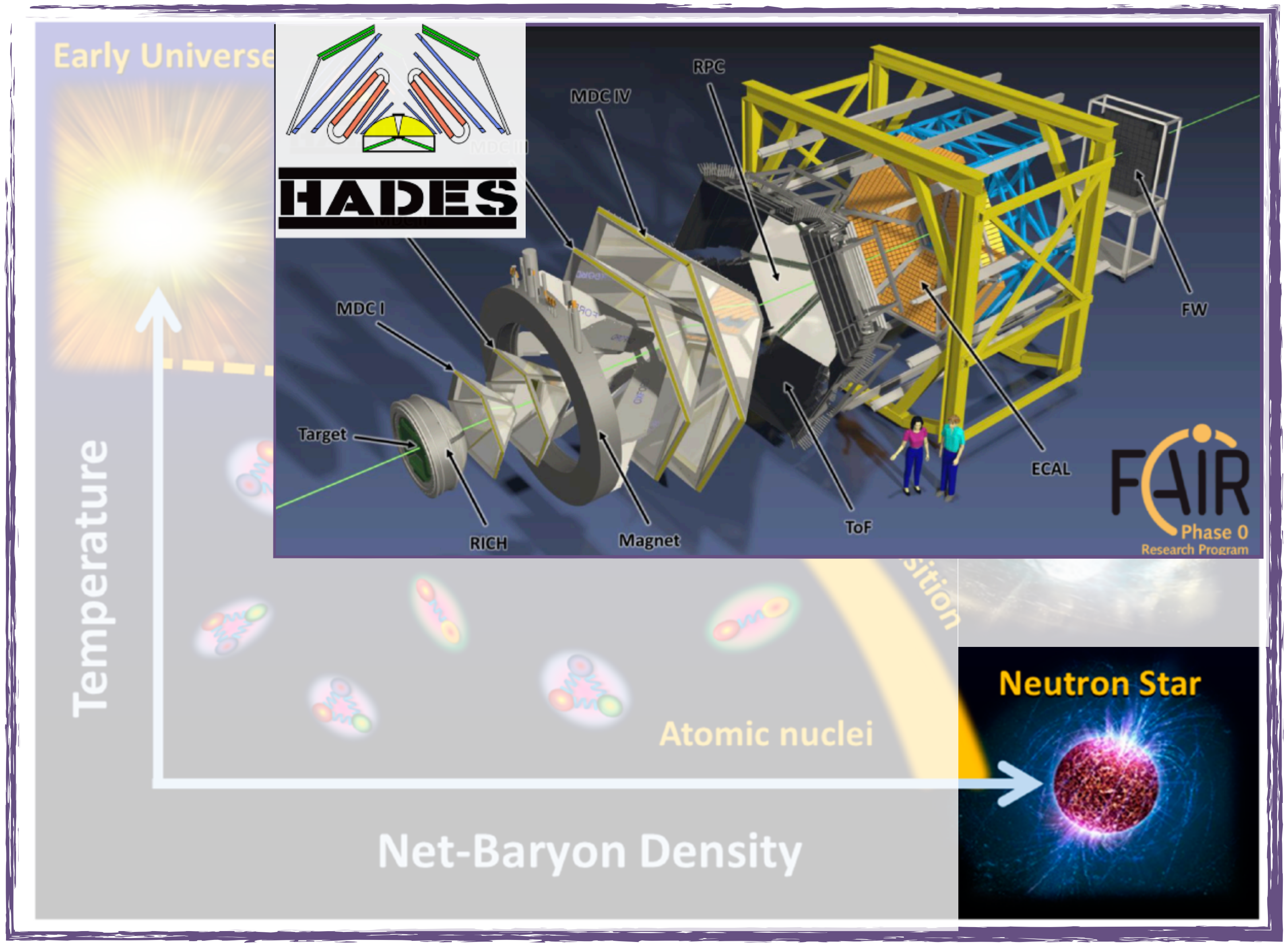
Temperature
T<10 MeV

Density
$n < 10n_0$

Lifetime
t ~ long

Neutron stars

Exploration of unknown QCD territory: high μ_B



https://www.researchgate.net

Temperature
T<10 MeV

Density
$n < 3n_0$

Lifetime
t ~ long

Neutron star puzzle

- **Hyperons**: expected in the core of neutron stars; **conversion of N into Y energetically favorable.**

- Appearance of Y: The relieve of Fermi pressure → **softer EoS → mass reduction (incompatible with observation).**

$M_{NS} \approx 1 \div 2\ M_\odot$

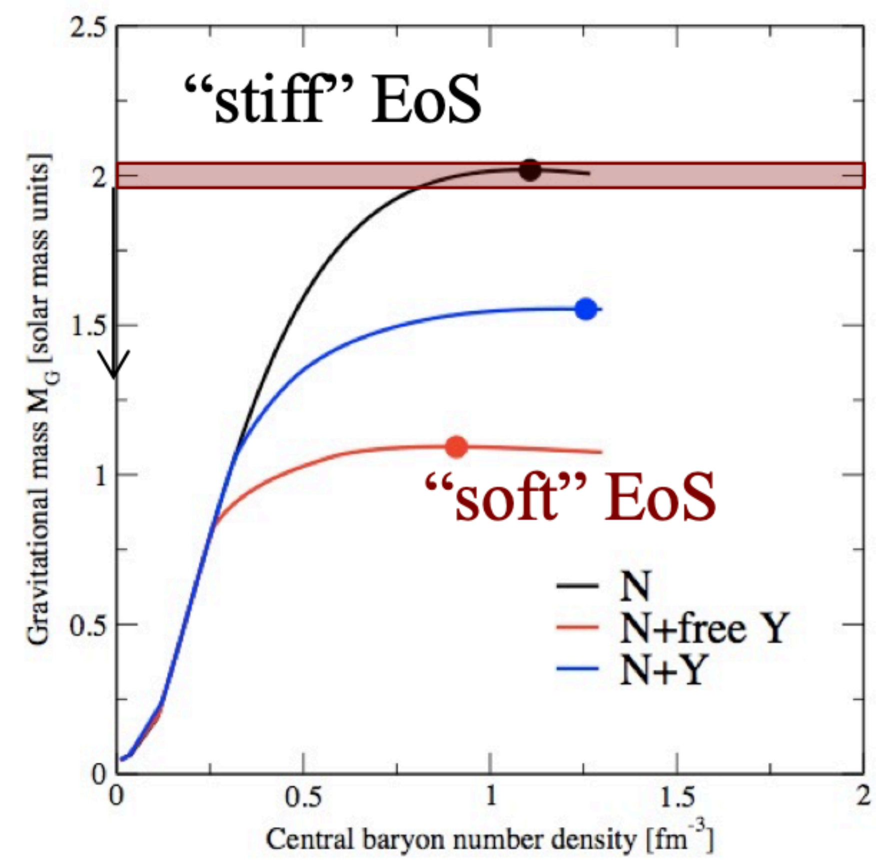
$R \approx 10\text{-}12$ km

$\rho \approx 3 \div 5\ \rho_0$

The solution requires a mechanism that could provide the **additional pressure** at high densities needed to make the EoS stiffer.

A few possible mechanisms, one of them:

- **Two-body YN & YY interactions**

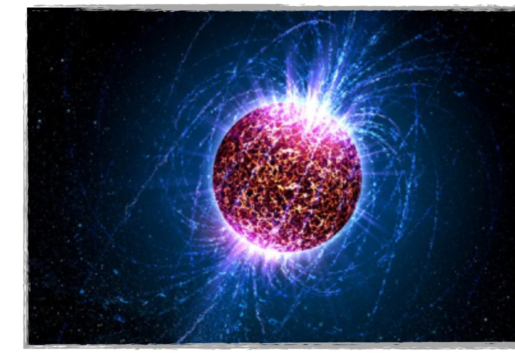


A lot of experimental and theoretical effort to understand:

- The **KN** interaction, governed by the presence of **Λ(1405)**
- The nature of **Λ(1405)**, the consequences of **KNN** formation
- **K** and $\bar{K}$ investigated to understand kaon condensation

$\rho_0 \approx 2.8 \times 10^{14}$ g/cm^3

YN and YY interactions



- **Experiment**: More … and more!
  interest about YN and YY interactions!

- **Theory**: Major steps forward have been taken (Lattice QCD).

- **Numerous theoretical predictions** exist, **many experimental searches look for** evidence for **bound states**.

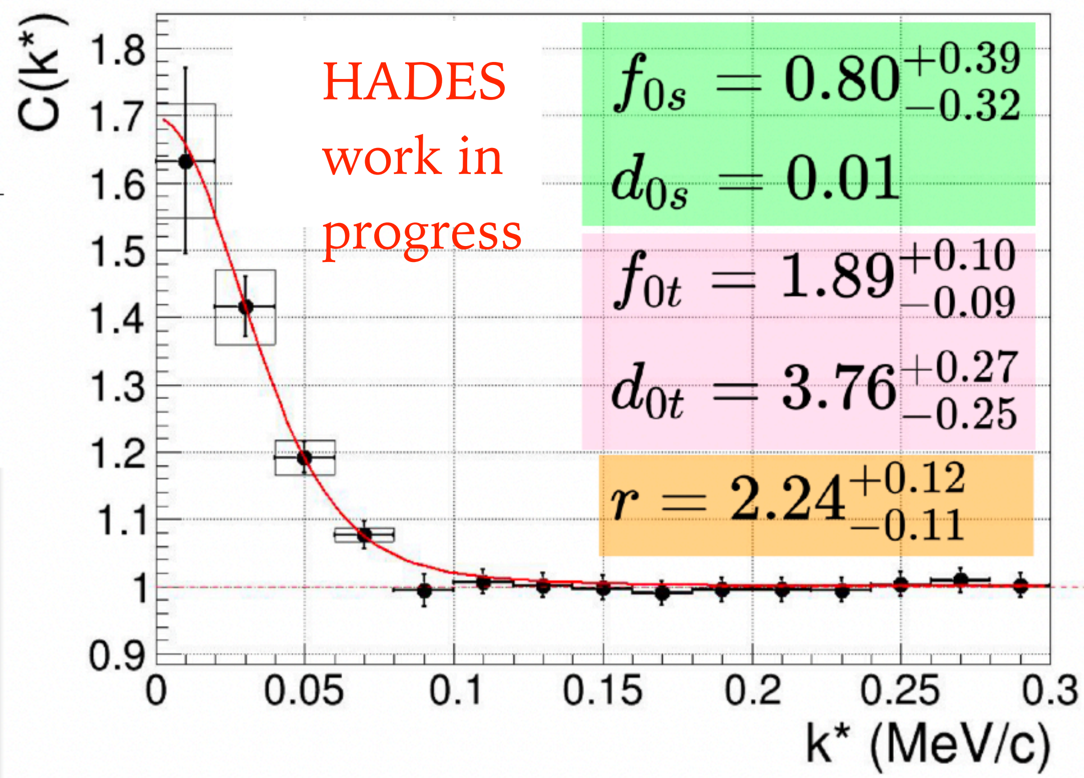
- The existence of **hypernuclei** (confirmed by attractive YN interaction) → indicates the possibility to bind Y to N.

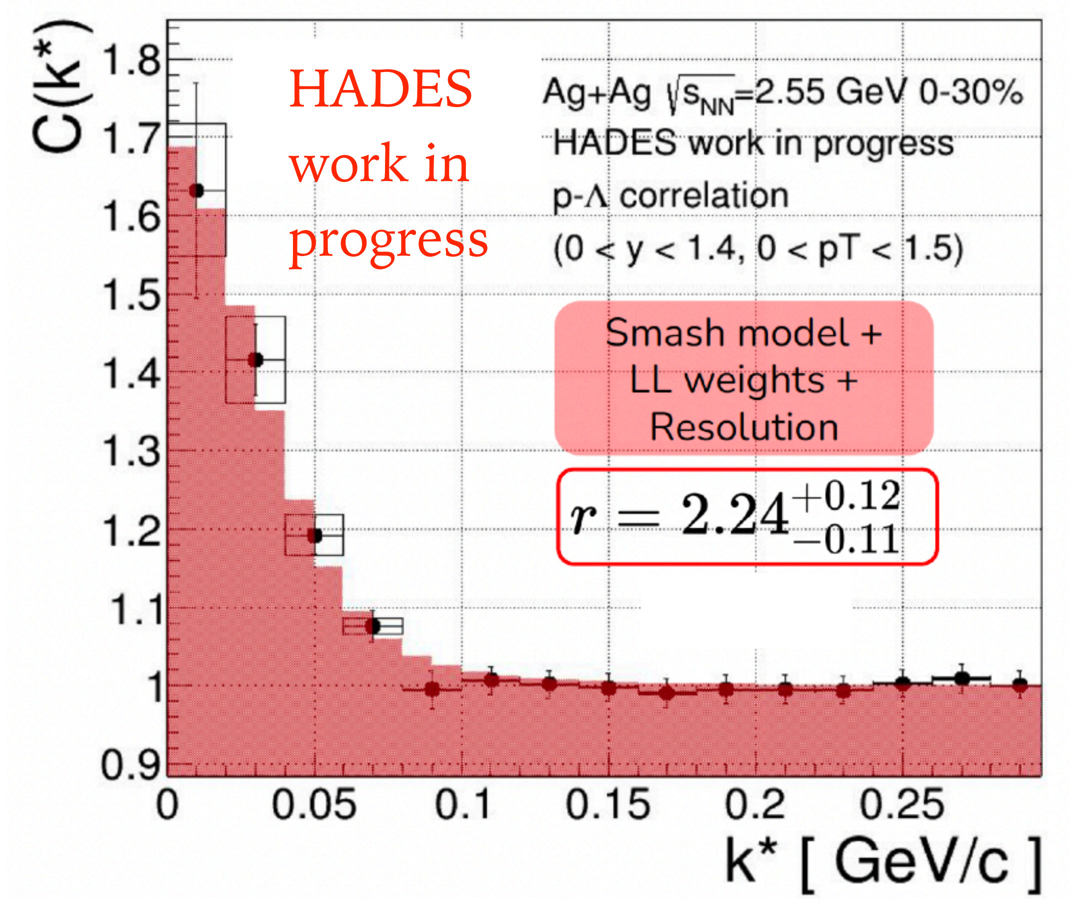
- The measurement of the YN and YY interactions leads to important implications for the possible formation of **YN** or **YY bound states**.

- A precise knowledge of these interactions help to explore unknown structure of neutron stars.

YN interactions at HADES

Narendra Rathod





Physics Image Extraction

Formalism with Lednicky-Lyuboshitz (L-L) approach

- R_G : spherical Gaussian source of pairs
- f_0 : scattering length
- d_0 : effective range

Major assumptions:

- Smoothness approximation for source function
- Effective range expansion for $\Psi(\boldsymbol{r}^*, \boldsymbol{k}^*)$
- Static and spherical Gaussian source
  - Single particle source: $S_i(x_i, p_i^*)$
  - Pair source (radius R_G): $S(x, p^*) \propto e^{-x^2/2R_G{}^2}\delta(t - t_0)$
- Approximate the wave function by its asymptotic form

$$C(\boldsymbol{k}^*) \approx 1 + \frac{|f(k)|^2}{2R_G{}^2}F(d_0) + \frac{2\mathrm{Re}f(k)}{\sqrt{\pi}R_G}F_1(2kR) - \frac{\mathrm{Im}f(k)}{R_G}F_2(2kR_G)$$

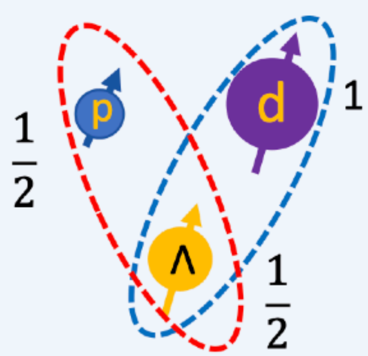
$$\frac{1}{f(k)} \approx \frac{1}{f_0} + \frac{d_0 k^2}{2} - ik$$

Different f_0 and d_0 for different spin states

Separate spin-states

YN interactions at STAR

Zhi Qin

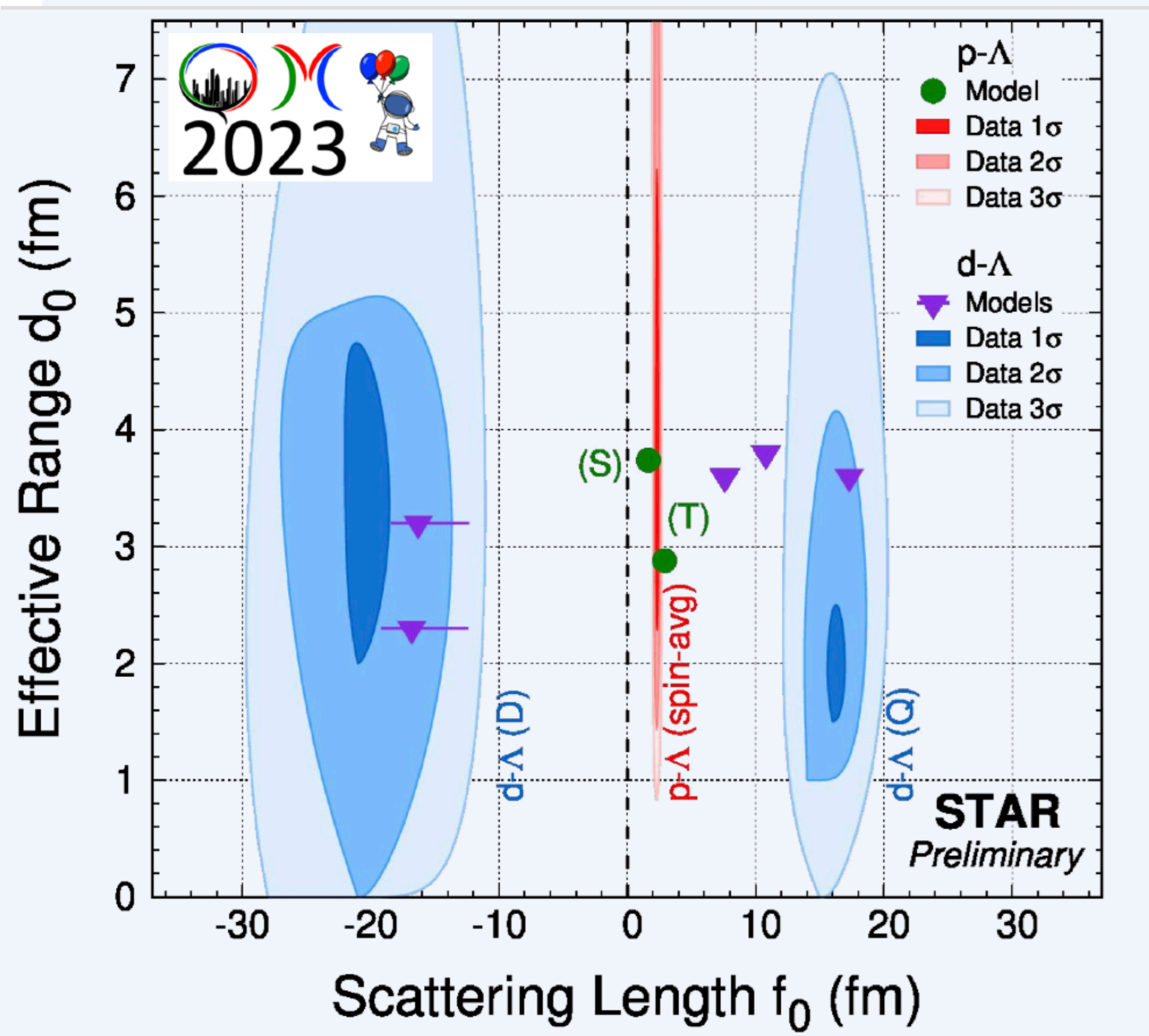


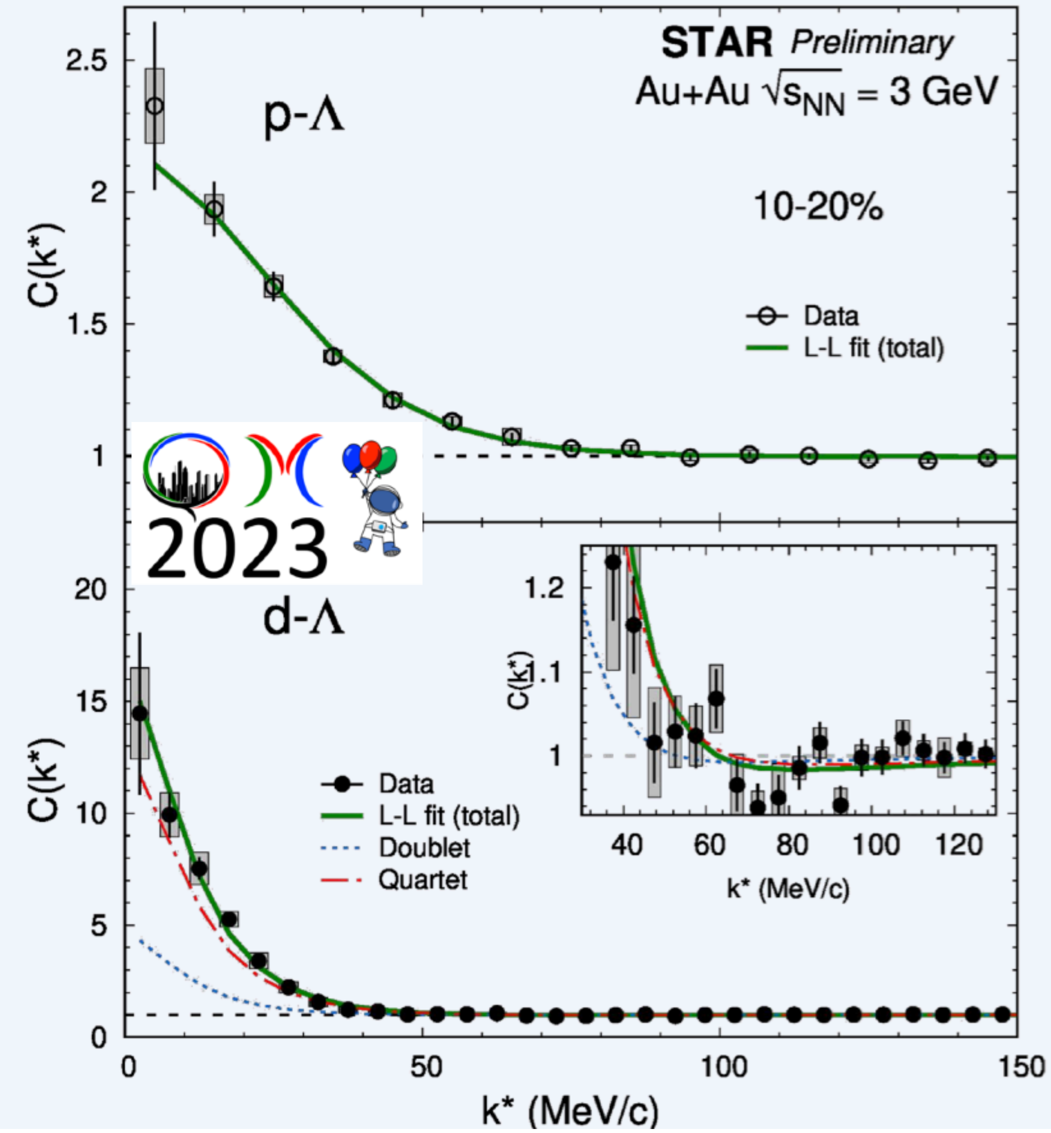
Singlet State $^1S_0$ (S)
Triplet State $^3S_1$ (T)

Doublet State $^2S_{1/2}$ (D)
Quartet State $^4S_{3/2}$ (Q)

p-Λ: $|\psi(r,k)|^2 \rightarrow \frac{1}{4}|\psi_0(r,k)|^2 + \frac{3}{4}|\psi_1(r,k)|^2$

d-Λ: $|\psi(r,k)|^2 \rightarrow \frac{1}{3}|\psi_{1/2}(r,k)|^2 + \frac{2}{3}|\psi_{3/2}(r,k)|^2$





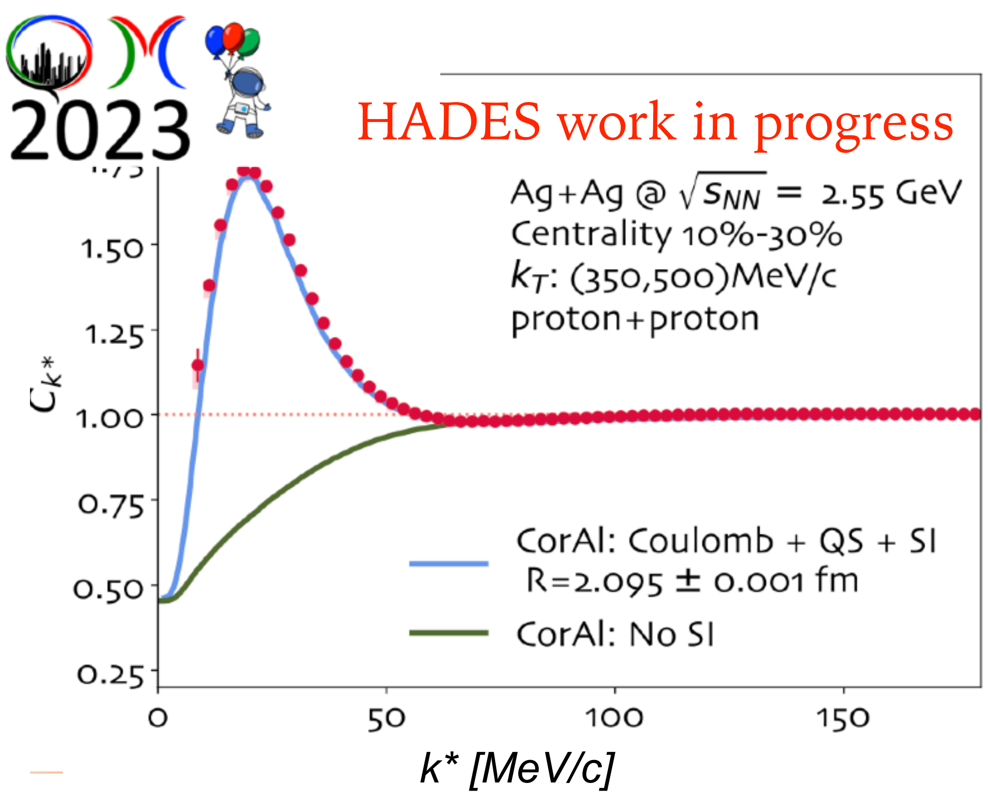
Different spin states with different FSI parameters

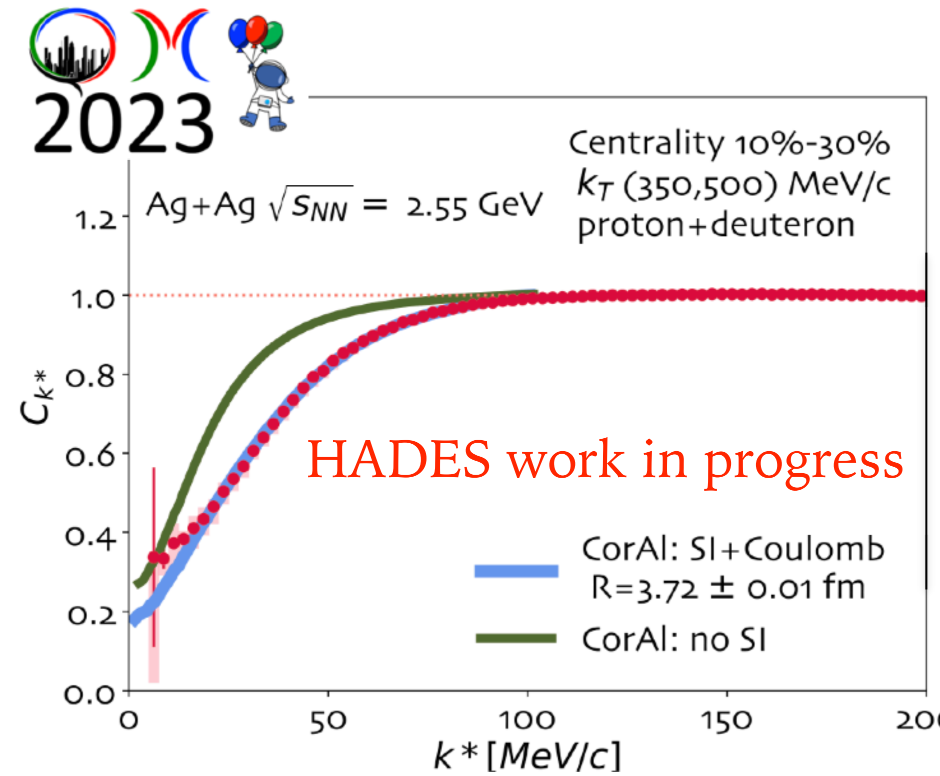
p-Λ correlation: currently spin-averaged fit

d-Λ correlation: spin-separated fit

Light nuclei production at HADES

Maria Stefaniak





Door to study fundamental interactions, additional nucleons: $p \to d \to t$ and ${}^3_2He$
What is the production mechanisms of nuclear fragments / clusters?
- thermal production?
- coalescence?

Proton-proton and proton-deuteron FSI described by potentials:
p-p: V.G.J.Stoks et al., Phys.Rev.C 49,2950 (1994)
p-d: T.C. Black et al., Phys.Lett.B 471, 103 (1999)

THERMINATOR 2

Sz. Harabasz, J. Kołaś, HZ, et. al
Phys. Rev. C 107, 034917

Jędrzej Kołaś

Thermal models of hadron production have been successful in **describing hadron** yields in various collision processes.

Matter is treated as **non-interacting hadron resonance gas.**

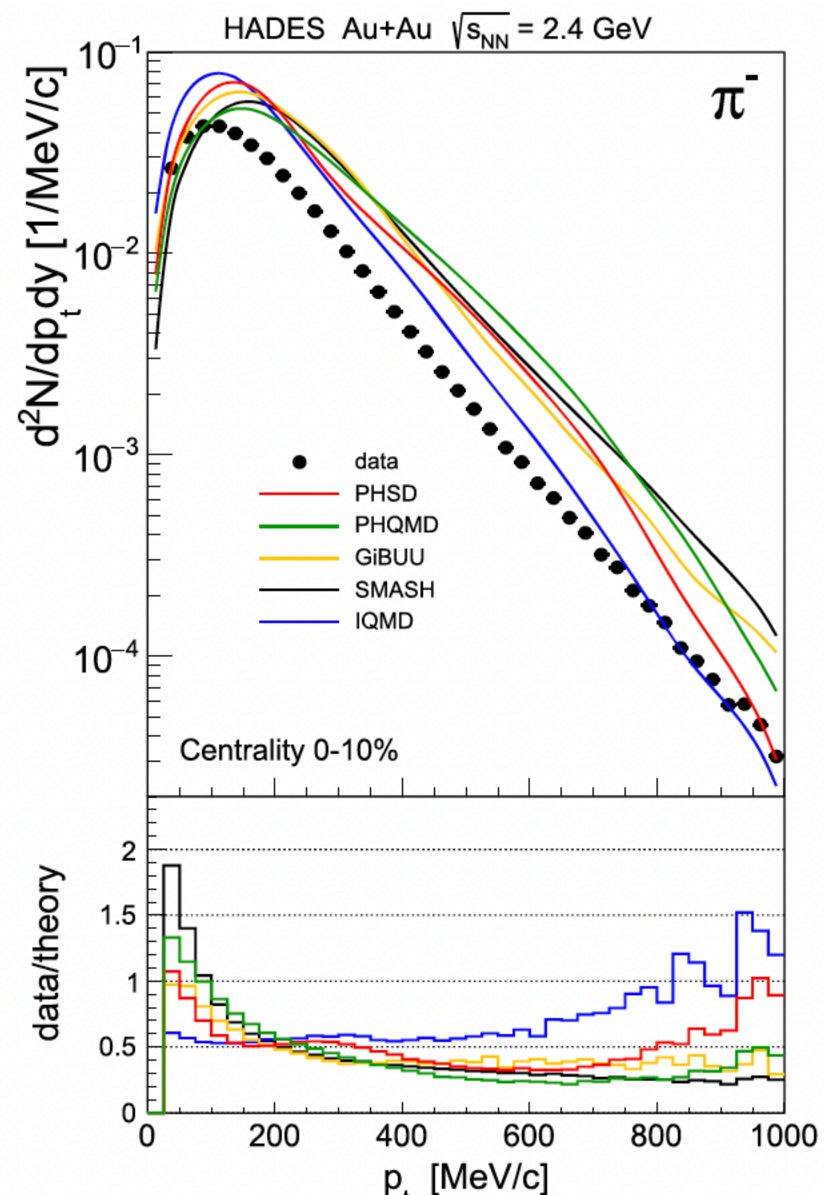
Ratios of measured particle yields → location on the phase diagram.

A few thermodynamic parameters fixed→ **hadron yields.**

The role of hadronic resonances crucial **at high energies** (~400 states). At **lower energies** their role is **diminished**.

Is the fireball in few-GeV energy regime thermalized? Debate..
The study of hadron yields and spectra is crucial here.

A few-GeV regime still puzzling for the transport models.
Instead of determining freeze-out conditions from hydrodynamic / transport one can **model the freeze-out conditions (hypersurface and flow).**



HADES, Eur.Phys.J.A 56 (2020) 259

Light nuclei production at HADES with THERMINATOR 2 model

Jędrzej Kołaś

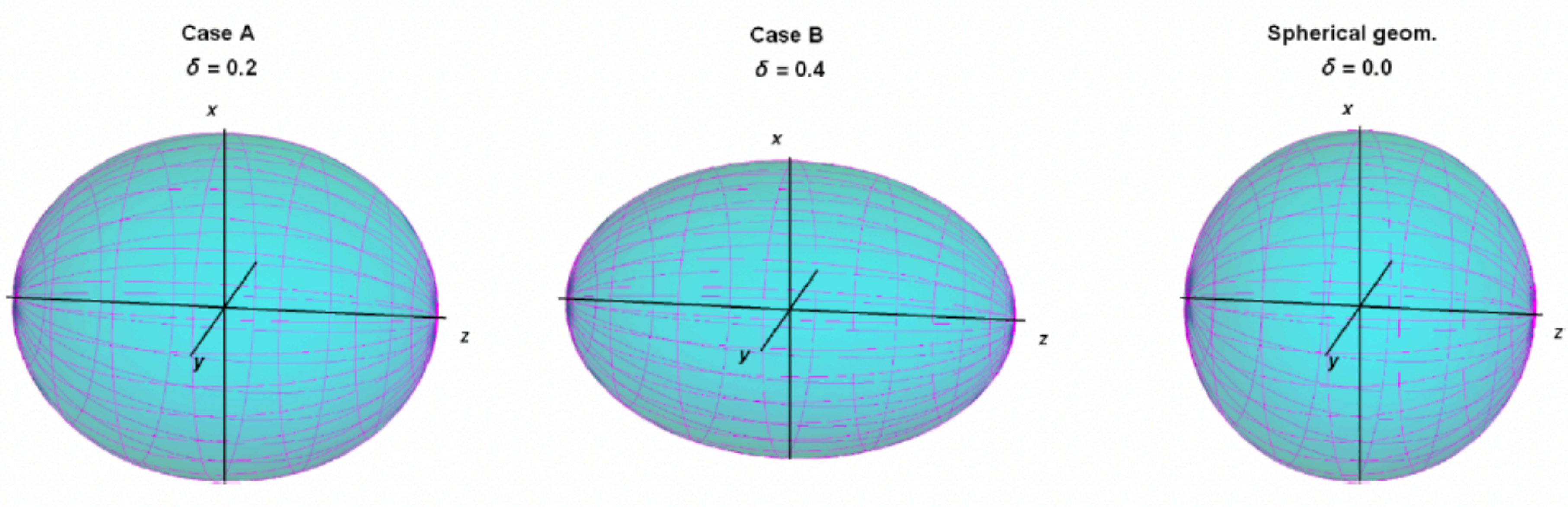
In the original formulation of the blast-wave model by **Siemens and Rasmussen** (SR) the freeze-out was spherical and the flow was radial.

→ Modified for RHIC and LHC (boost-invariance and cylindrical symmetry).

SR model is re-examined in low-energy collision measurements by HADES (boost-invariance is not observed).

Parameter	Case A	Case B	Case C
T (MeV)	49.6	70.3	63.1
R (fm)	15.7	6.06	9.29
μ_B (Mev)	776	876	782
μ_S (MeV)	123.4	198.3	145.7
μ_{I_3} (MeV)	−14.1	−21.5	−24.5
γ_S	0.16	0.05	0.04
χ^2/N_{df}	$N_{df} = 0$	1.13/2	62.30/5
H (GeV)	0.01	0.0225	0.016
δ	0.2	0.4	0.4
$\sqrt{Q^2}$	0.238	0.256	0.323

Coalescence Thermal



Sz. Harabasz, J. Kołaś, HZ, et. al Phys. Rev. C 107, 034917

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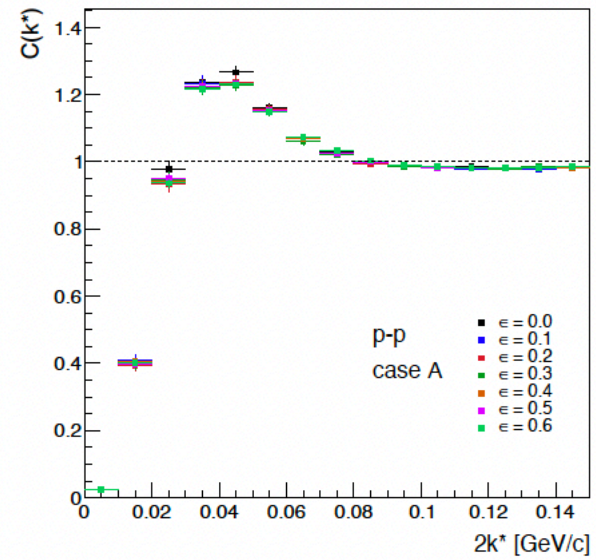
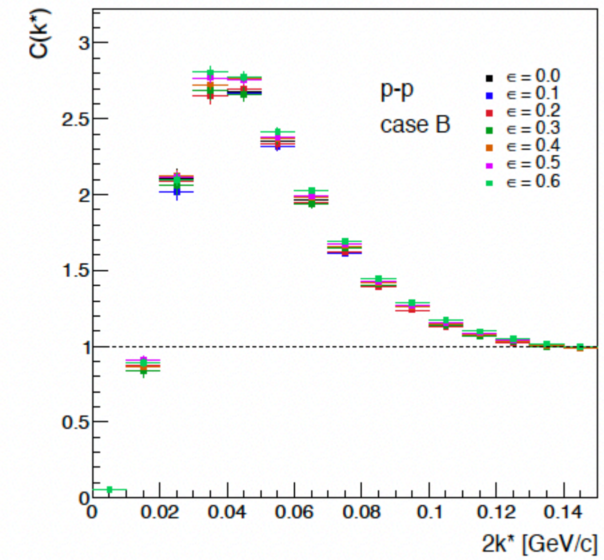
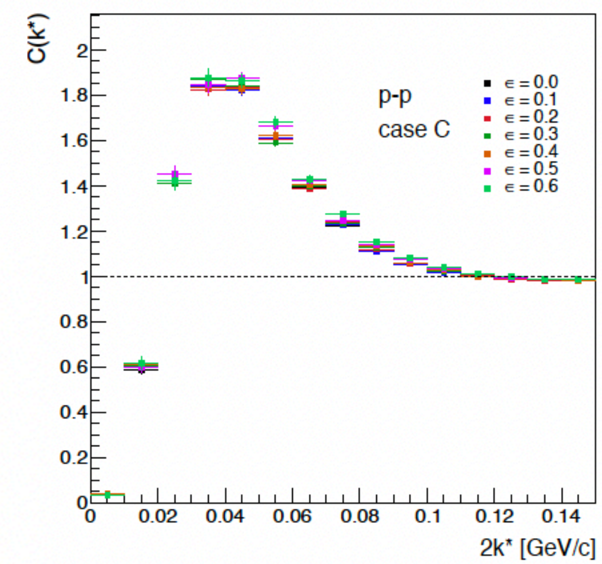


(a) Case A.

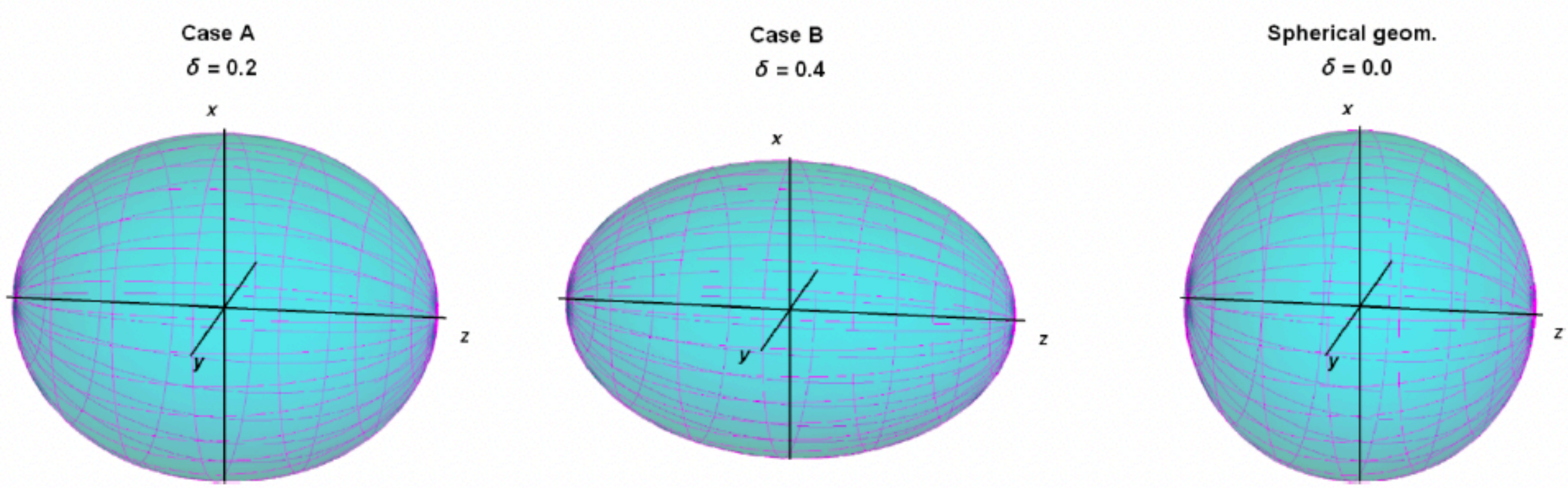


(b) Case B.



(c) Case C.

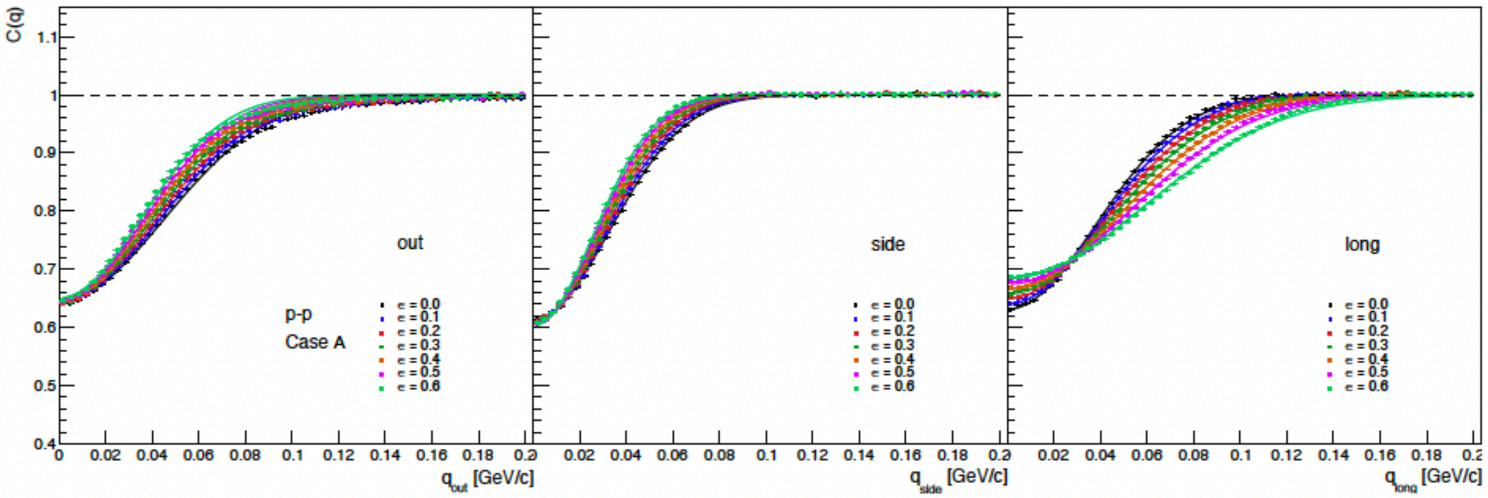
M. Kurach, B.Sc. thesis, WUT'23



Phys. Rev. C **107**, 034917

Light nuclei production at HADES

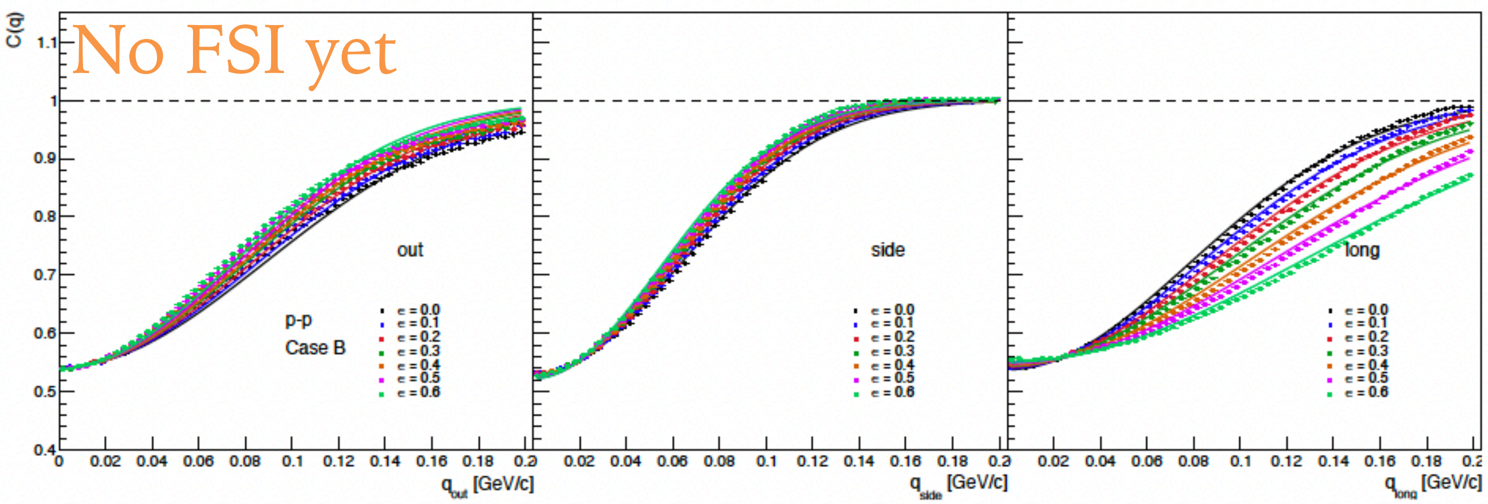
Jędrzej Kołaś



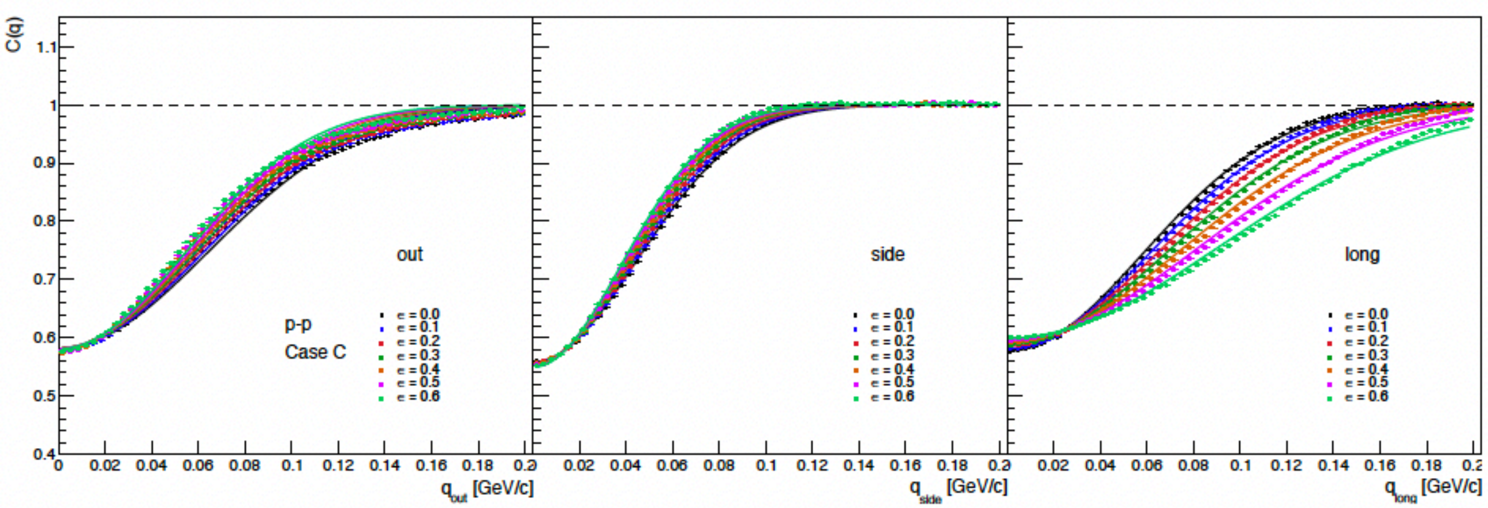
(a) Case A.

Only FD correlations

No FSI yet



(b) Case B.



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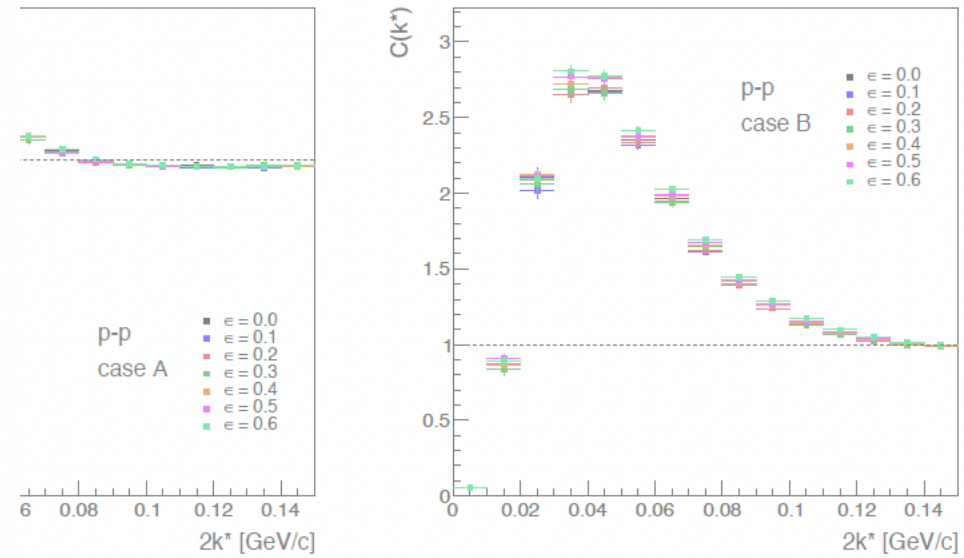
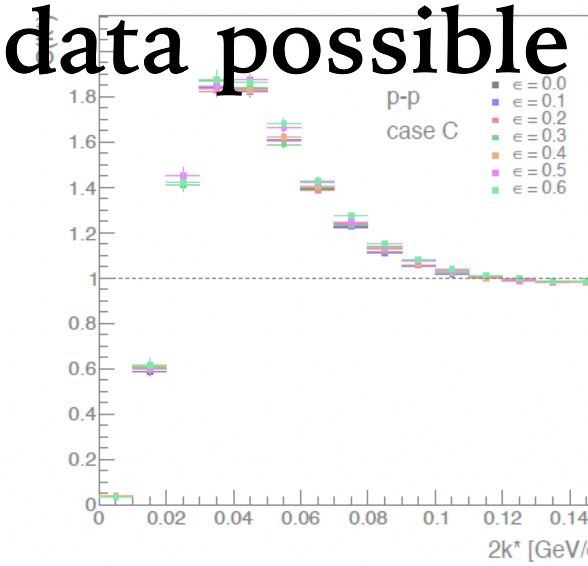


) Case A. (b) Case B.

Comparison to HADES data possible in future



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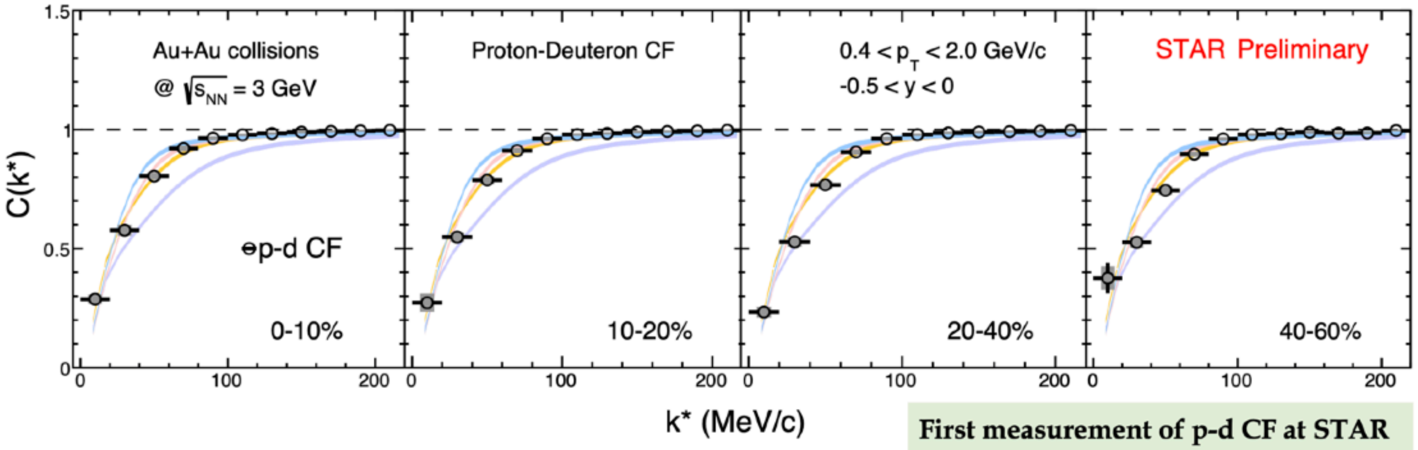
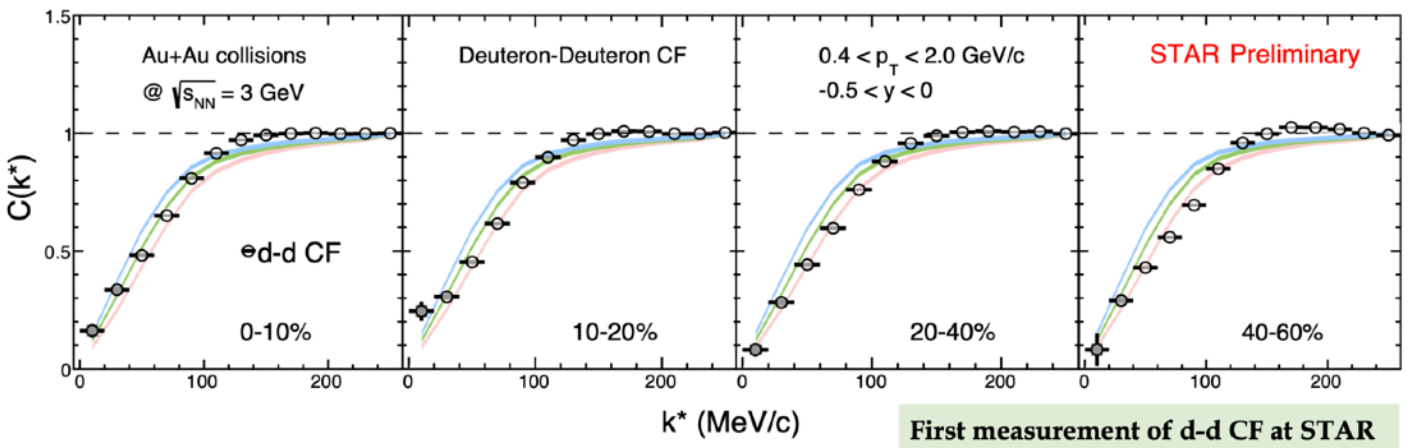
M. Kurach, B.Sc. thesis, WUT'23

Light nuclei production at STAR

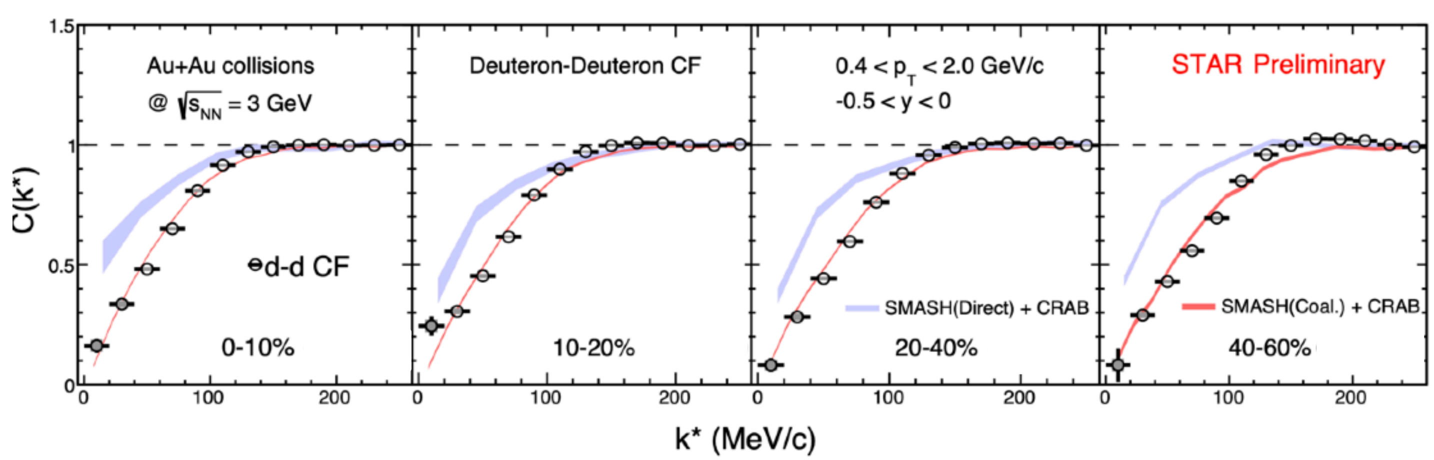


- First measurement of **proton-deuteron** and **deuteron-deuteron** correlation functions from STAR



- **Proton-deuteron** and **deuteron-deuteron** correlations qualitatively described by theory;

QUARK MATTER KRAKÓW 2022



- Deuteron-deuteron correlations described better by the model including **coalescence**. Light nuclei are likely to be formed via coalescence.

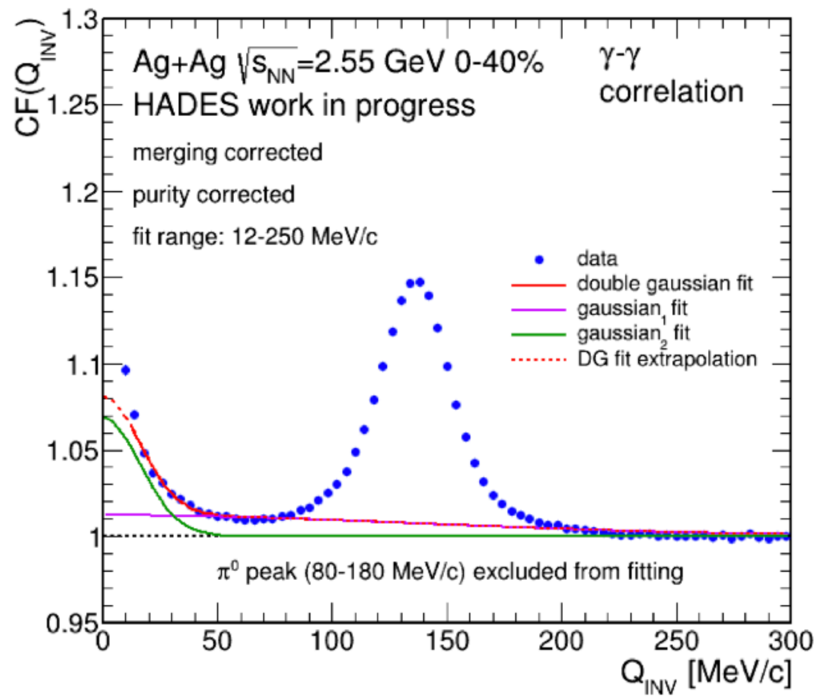
E-M probes at HADES

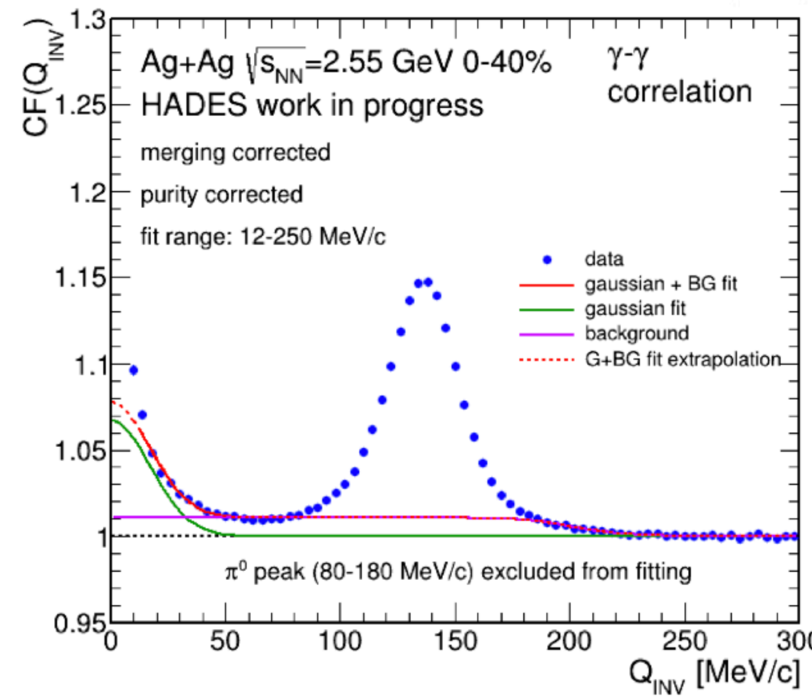
Mateusz Grunwald

What if:
Non-interacting bosons → assuming 2 sources
(double gaussian or gaussian + some background)

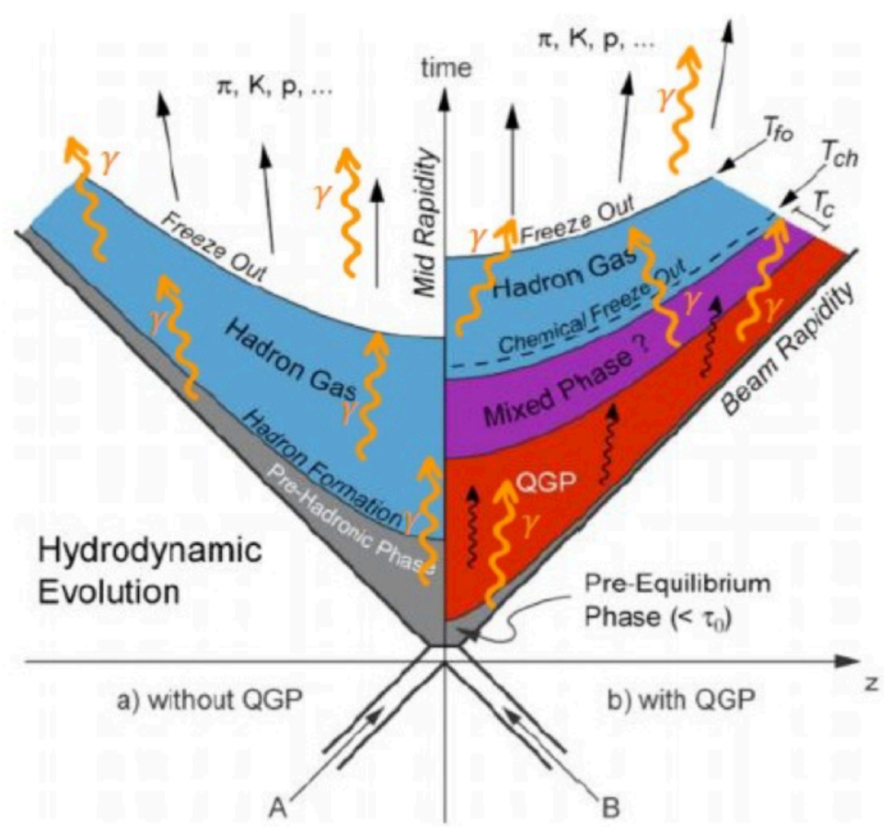
$$CF(Q_{inv}) = 1 + \lambda_1 e^{(-Q_{inv}^2 \cdot R_1^2)} + \lambda_2 e^{(-Q_{inv}^2 \cdot R_2^2)}$$

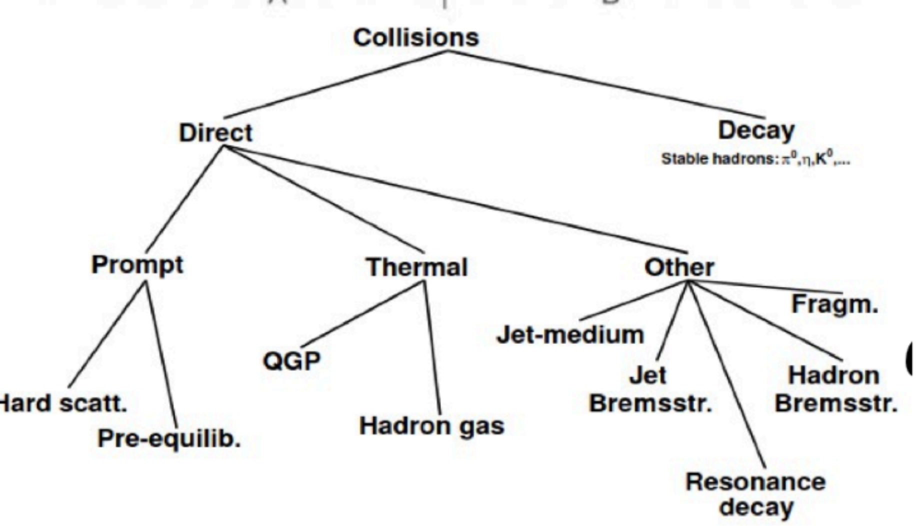
$$CF(Q_{inv}) = 1 + \lambda e^{(-Q_{inv}^2 \cdot R^2)} + \frac{a_0}{(1+(a_1 \cdot Q_{inv})^{a_2})}$$





HADES work in progress

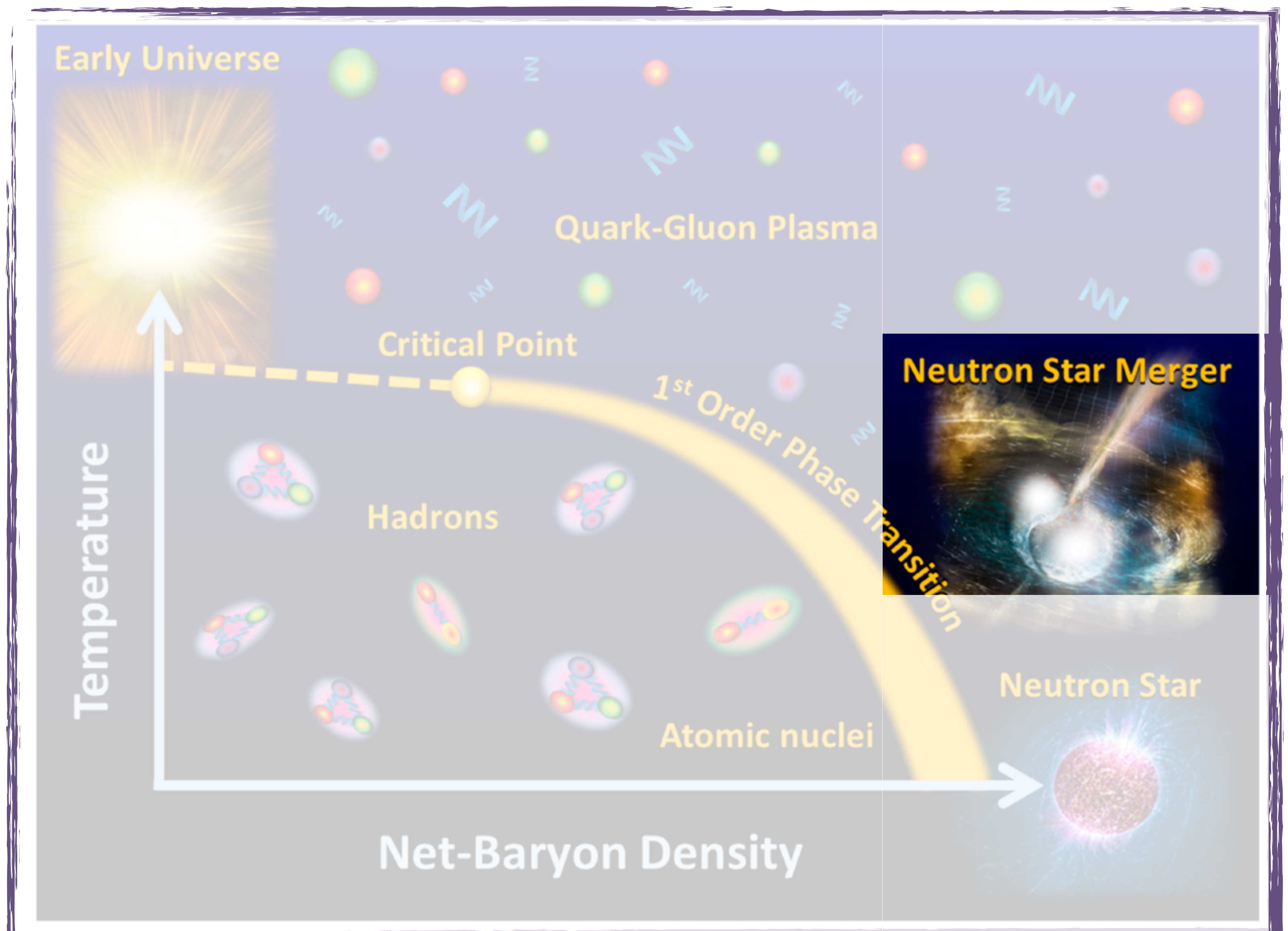




E-M probes signal various stages of the system's evolution;
Information about early stages
(inaccessible for hadrons);
Access before freeze-out era;
A way to hunt for direct photons.

Neutron star mergers

Exploration of unknown QCD territory: still high μ_B



https://www.researchgate.net

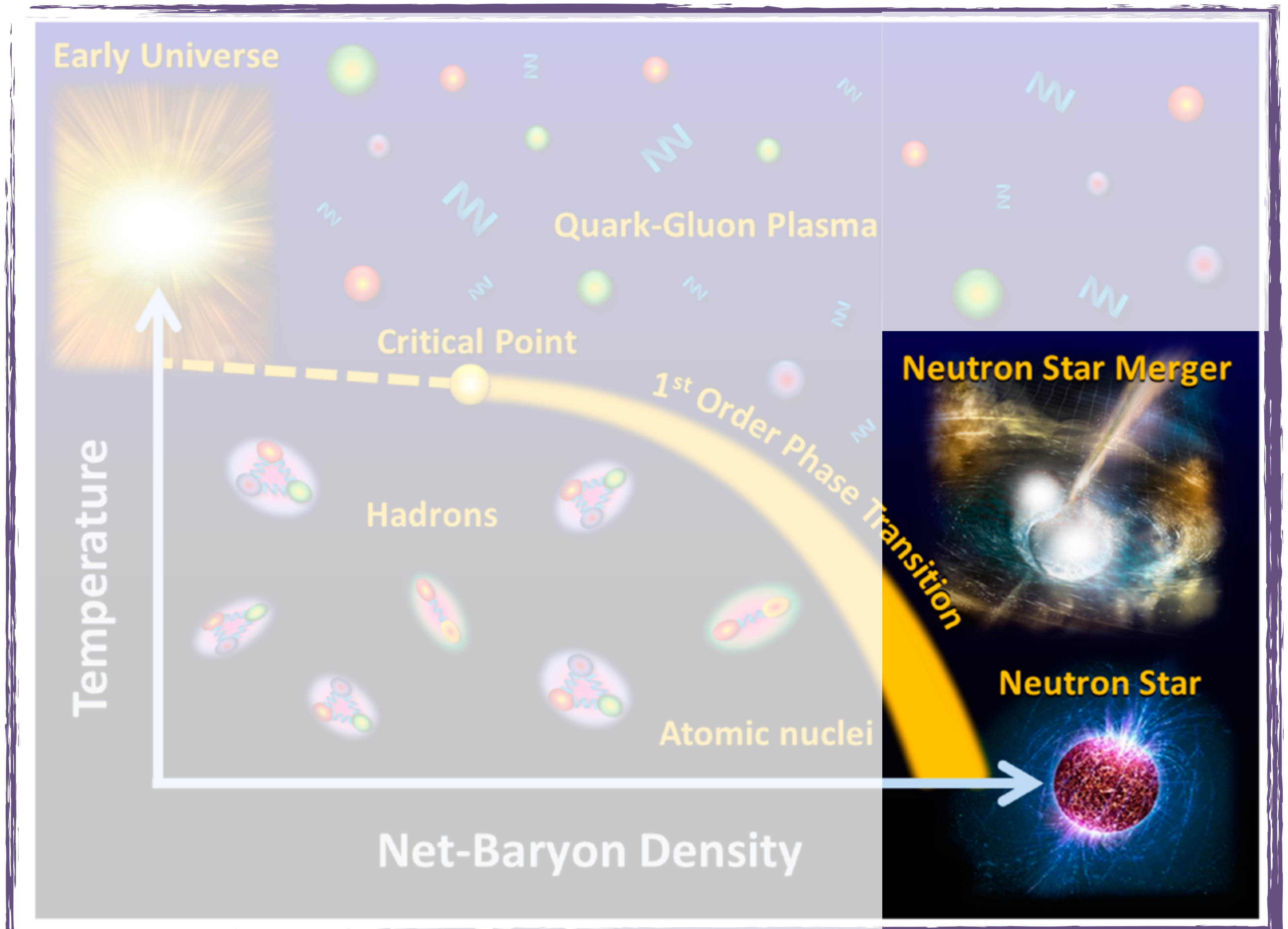
Temperature
T<50 MeV

Density
$n < 2 - 6n_0$

Reaction time
t ~ 10 ms
(GW170817)

Neutron star mergers

CBM and HADES future



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Temperature
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Density
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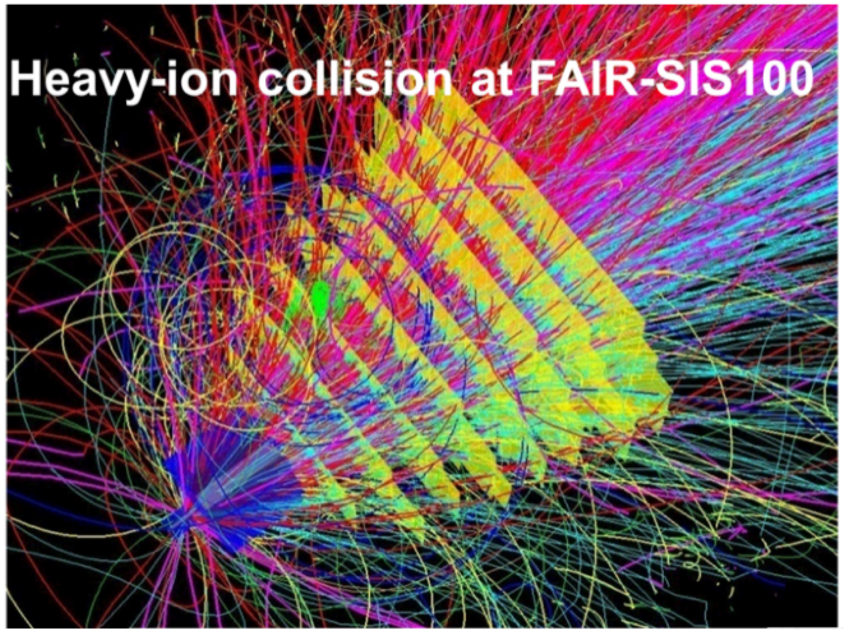
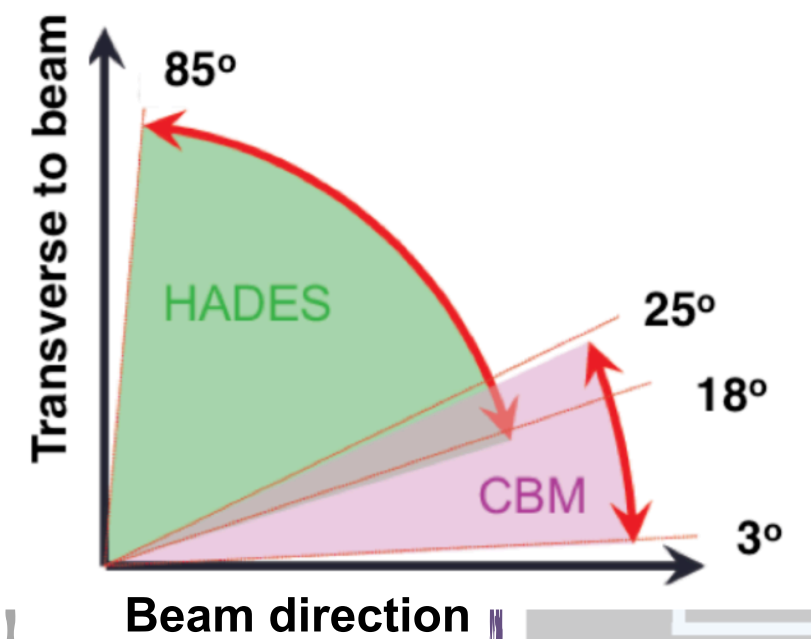
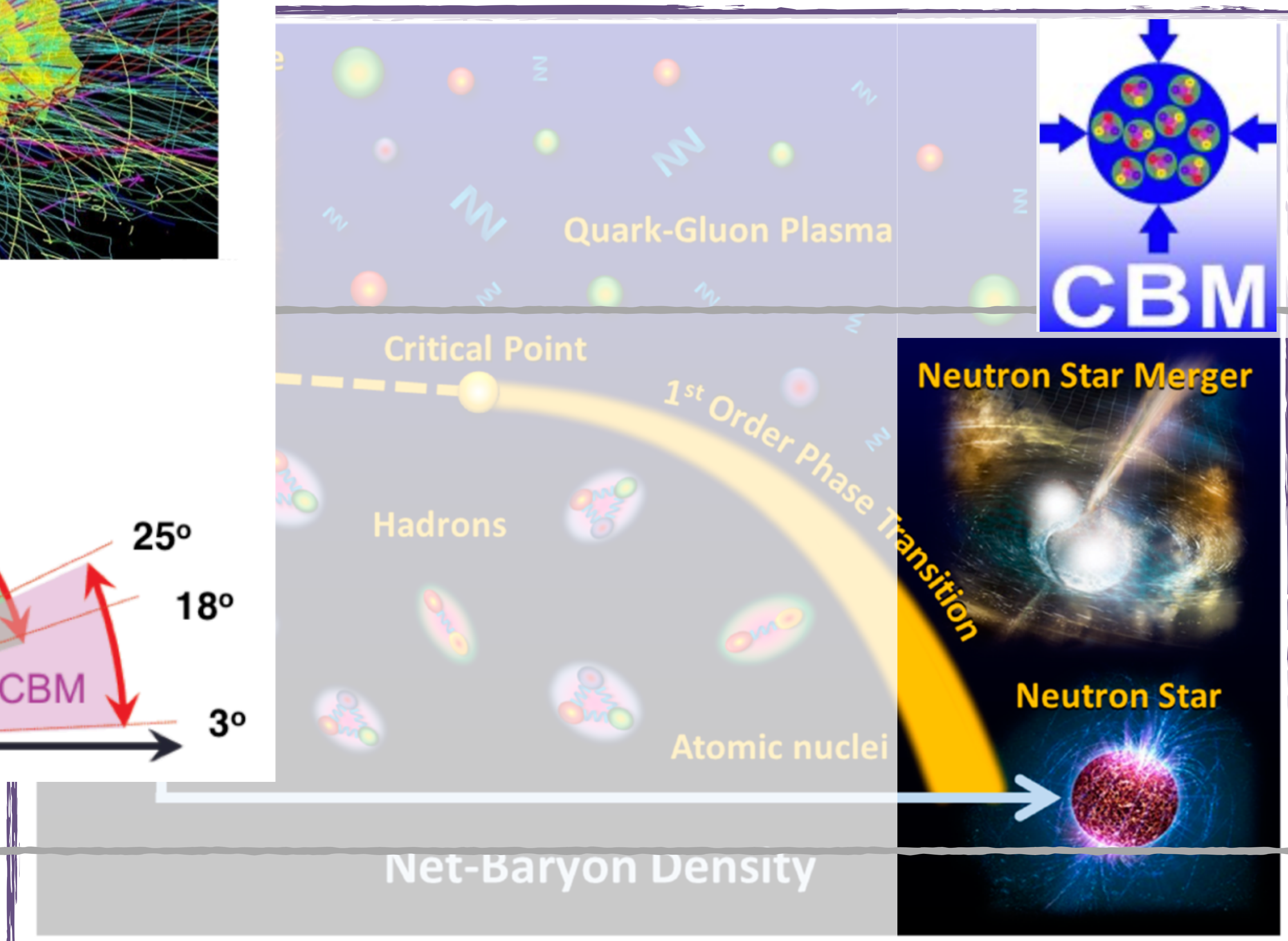
Lifetime
t ~ infinity

CBM and HADES future

Daniel Wielanek







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Temperature
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Reaction time
t ~ 10 ms
(GW170817)

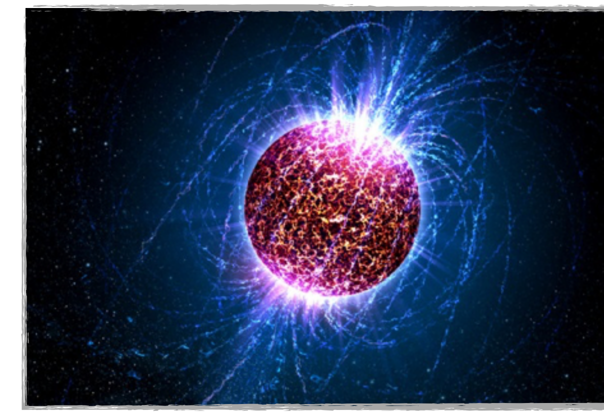
Temperature
T<10 MeV

Density
$n < 10n_0$

Lifetime
t ~ infinity

SIS-100: Temperature T<120 MeV | Density $n < 8n_0$ | Reaction time t $\sim 10^{-23}$ s

NSM and HIC

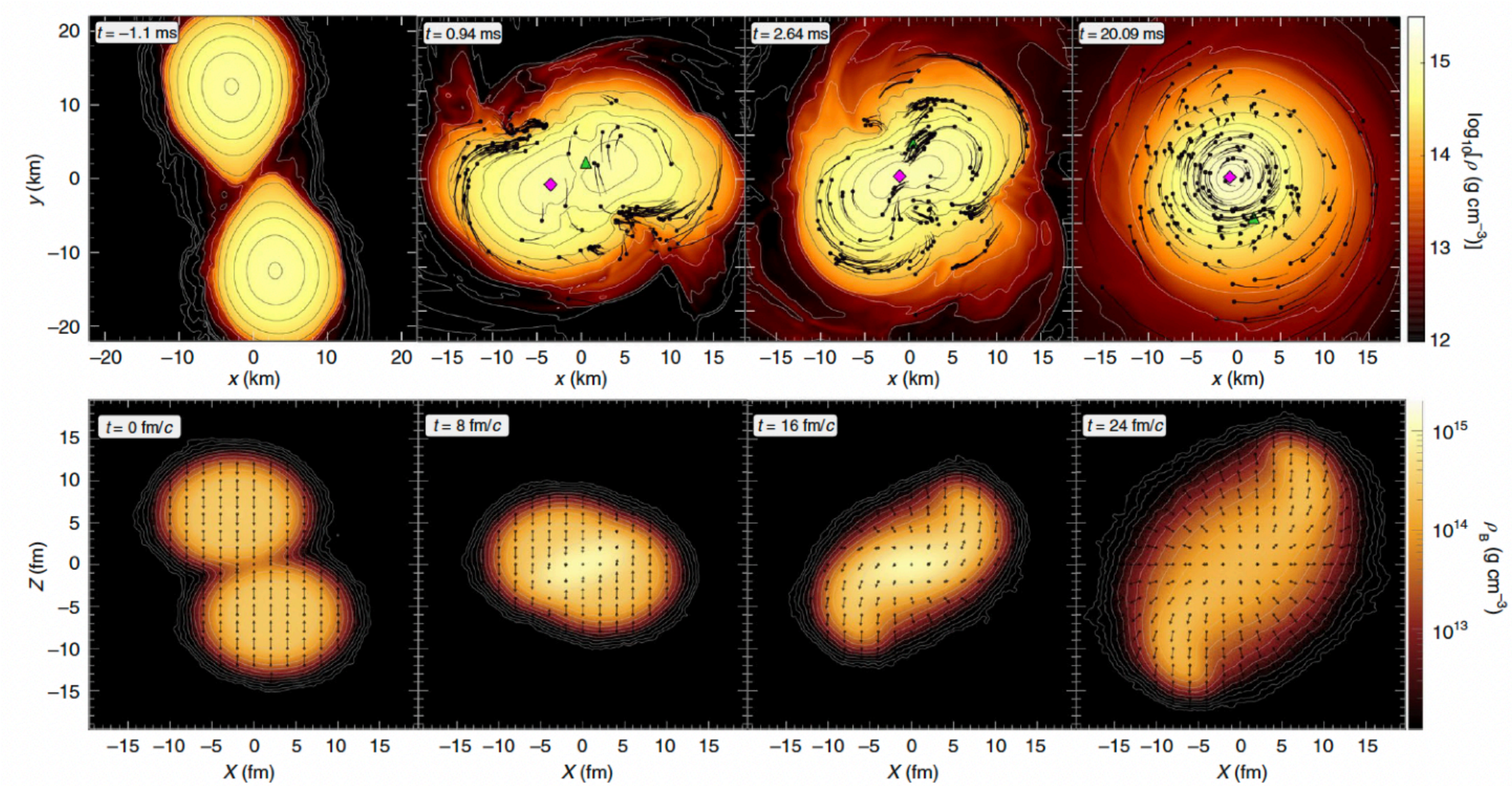


Top row: simulation of **neutron stars mergers**
2 neutron stars of 1.35 M⊙ each,
merging into a single object (2R ∼ 10 km, $n \simeq 5n_0$, $T \leq 20$ MeV).
Overlap region: $t \simeq 20$ms, $n \simeq 2n_0$, $T \simeq 75$ MeV

▲ - max. temperature
◆ - max. density

Bottom row: non-central-**collision Au+Au** at $\sqrt{s_{NN}} = 2.42$ GeV
$n \simeq 3n_0$, $T \simeq 80$ MeV

HADES, Nature Phys. 15, 1040–1045 (2019)

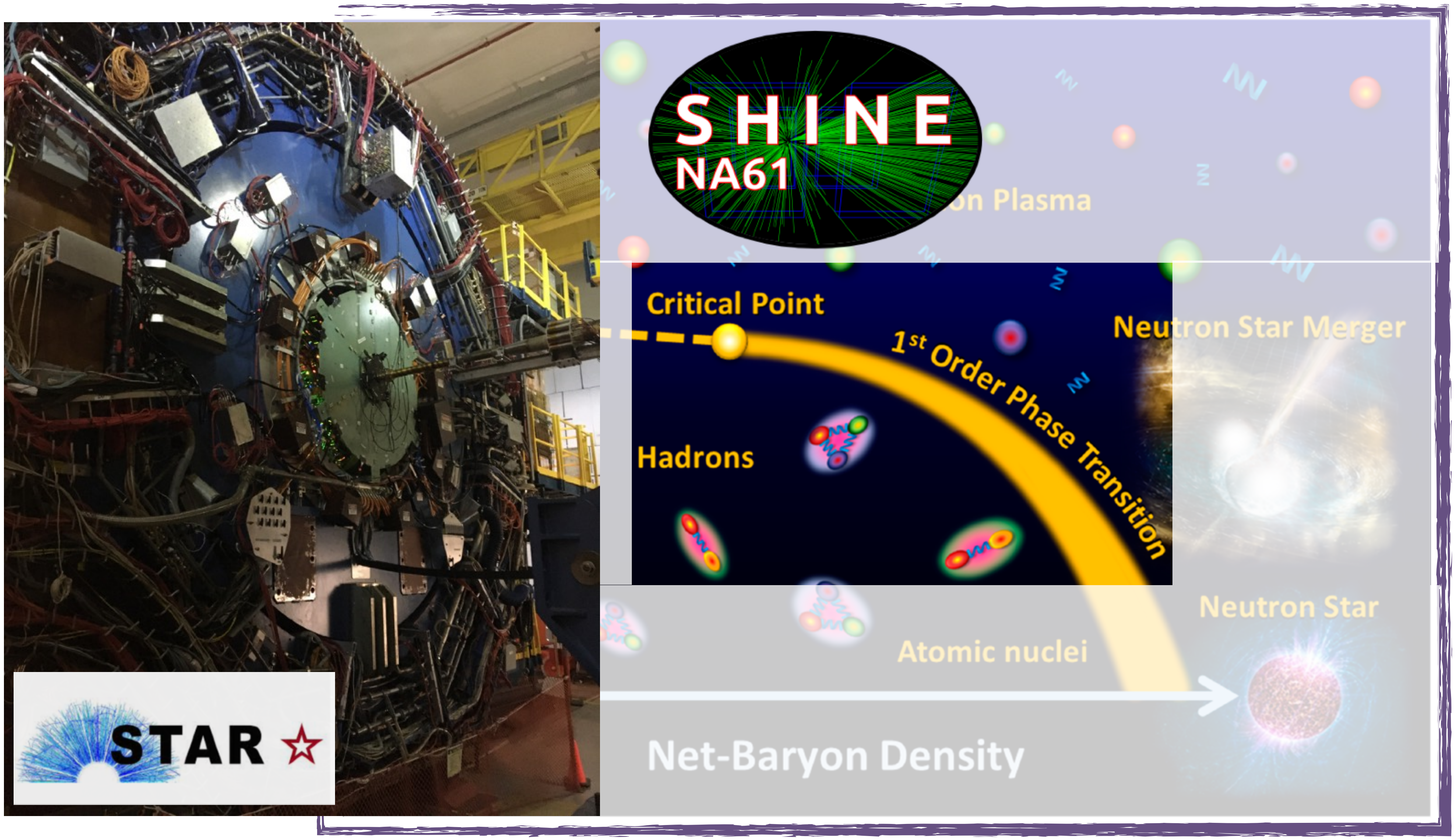


Similar **densities** and **temperatures** are achieved.

Space and **time** scales are vastly different (km - NS, fm - HIC). The collision events differ in duration by 20 orders of magnitude.

Phase transitions

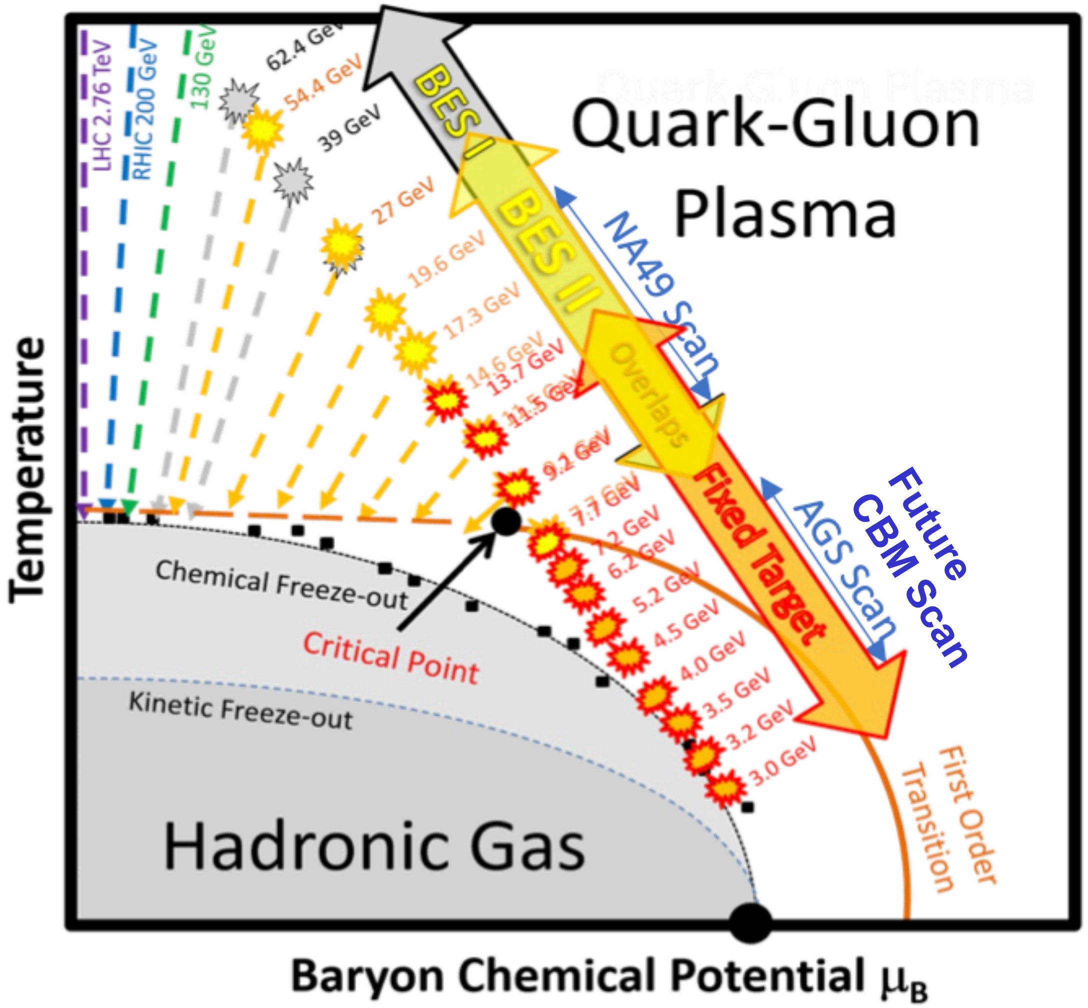
Exploration of unknown QCD territory: moderate μ_B

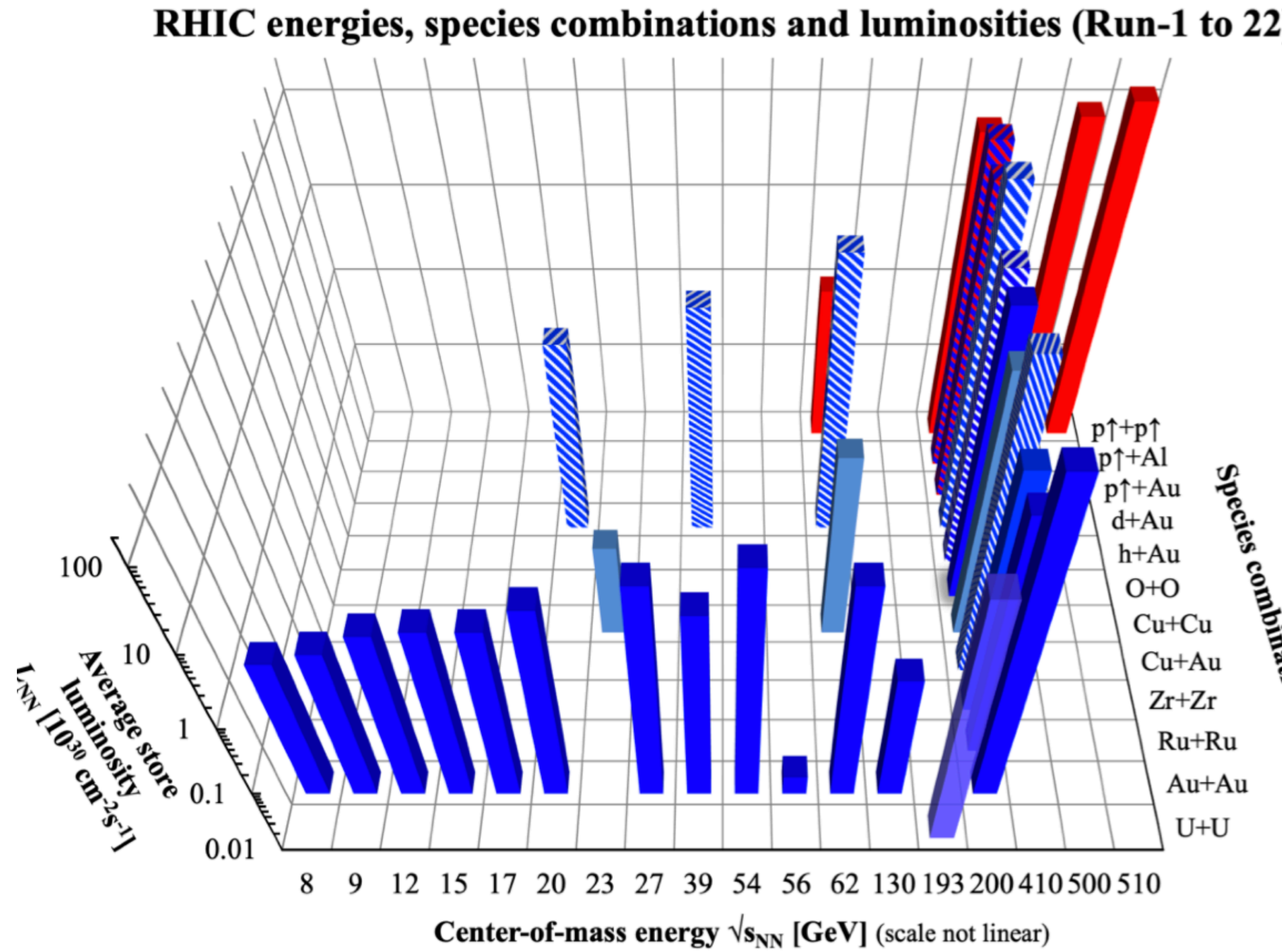


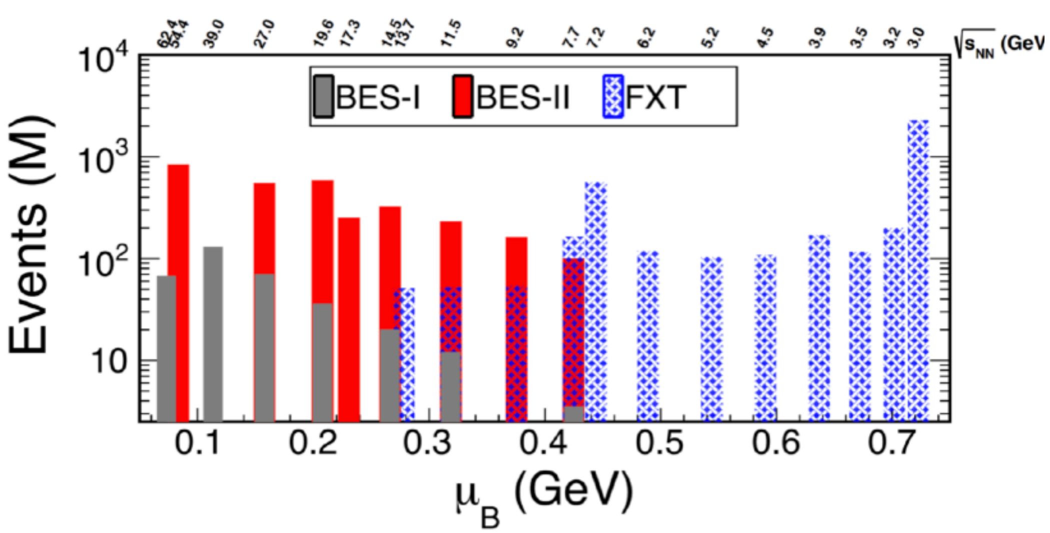
https://www.researchgate.net

Searching for phase transitions signatures

Beam Energy Scan at STAR





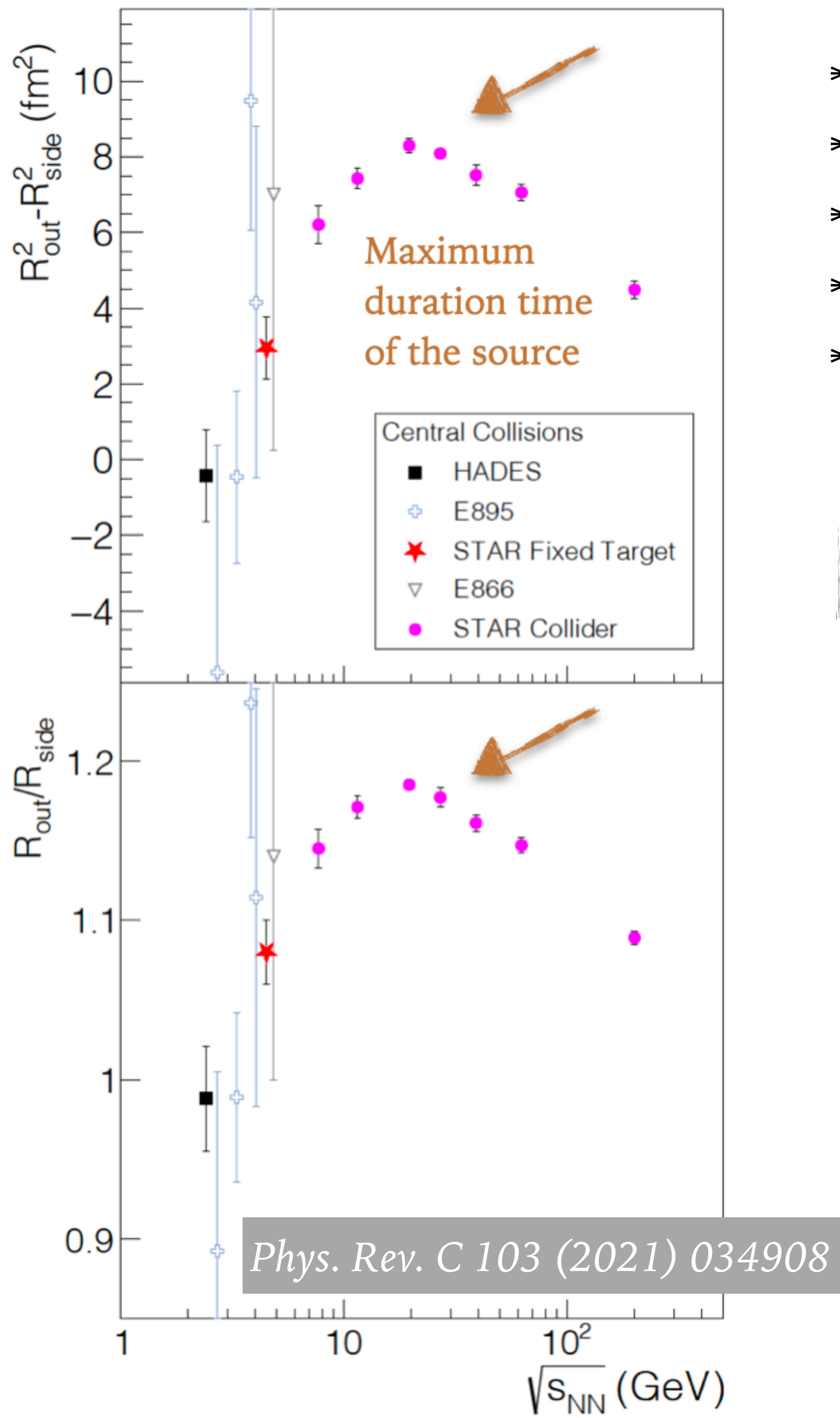


Beam Energy Scan: Au+Au 3-62.4 GeV

1. Search for **turn-off** of **QGP** signatures
2. Search for signals of the **first-order phase transition**
3. Search for QCD **critical point**

Fixed-Target Program: Au+Au: 3.0-13.7 GeV

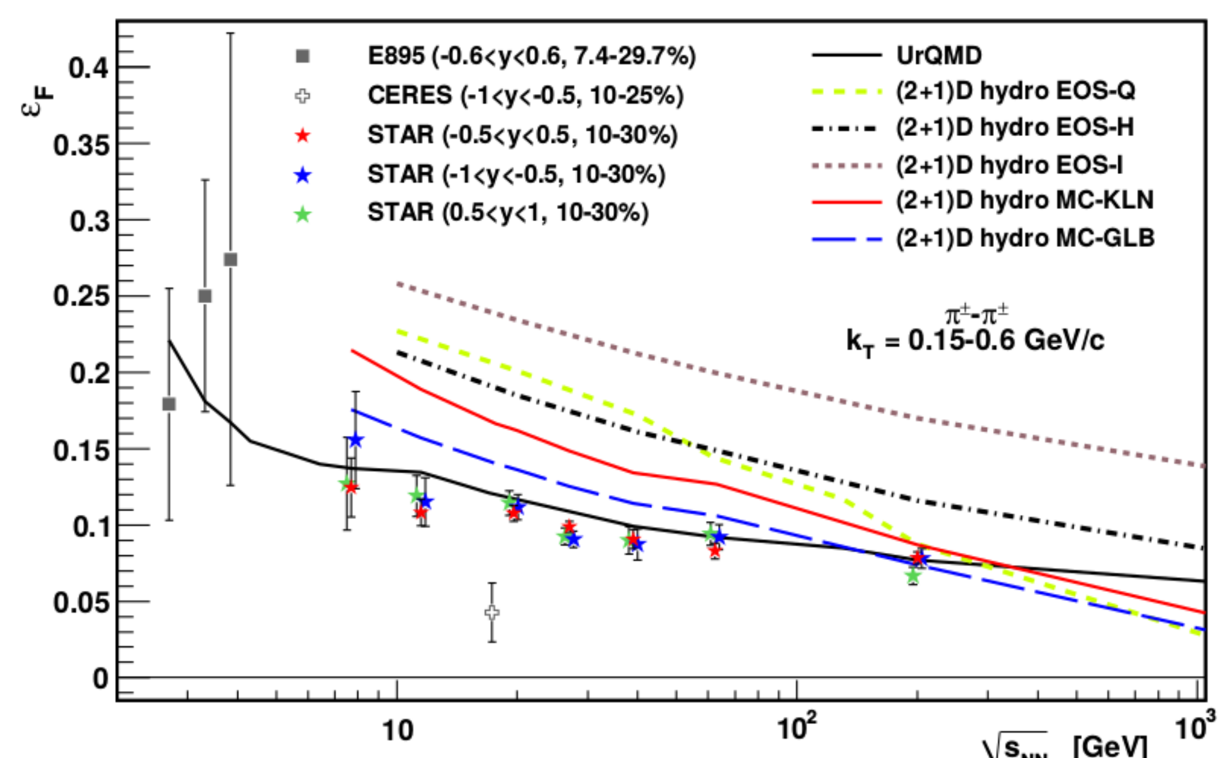
Looking for phase transition



Phys. Rev. C 103 (2021) 034908

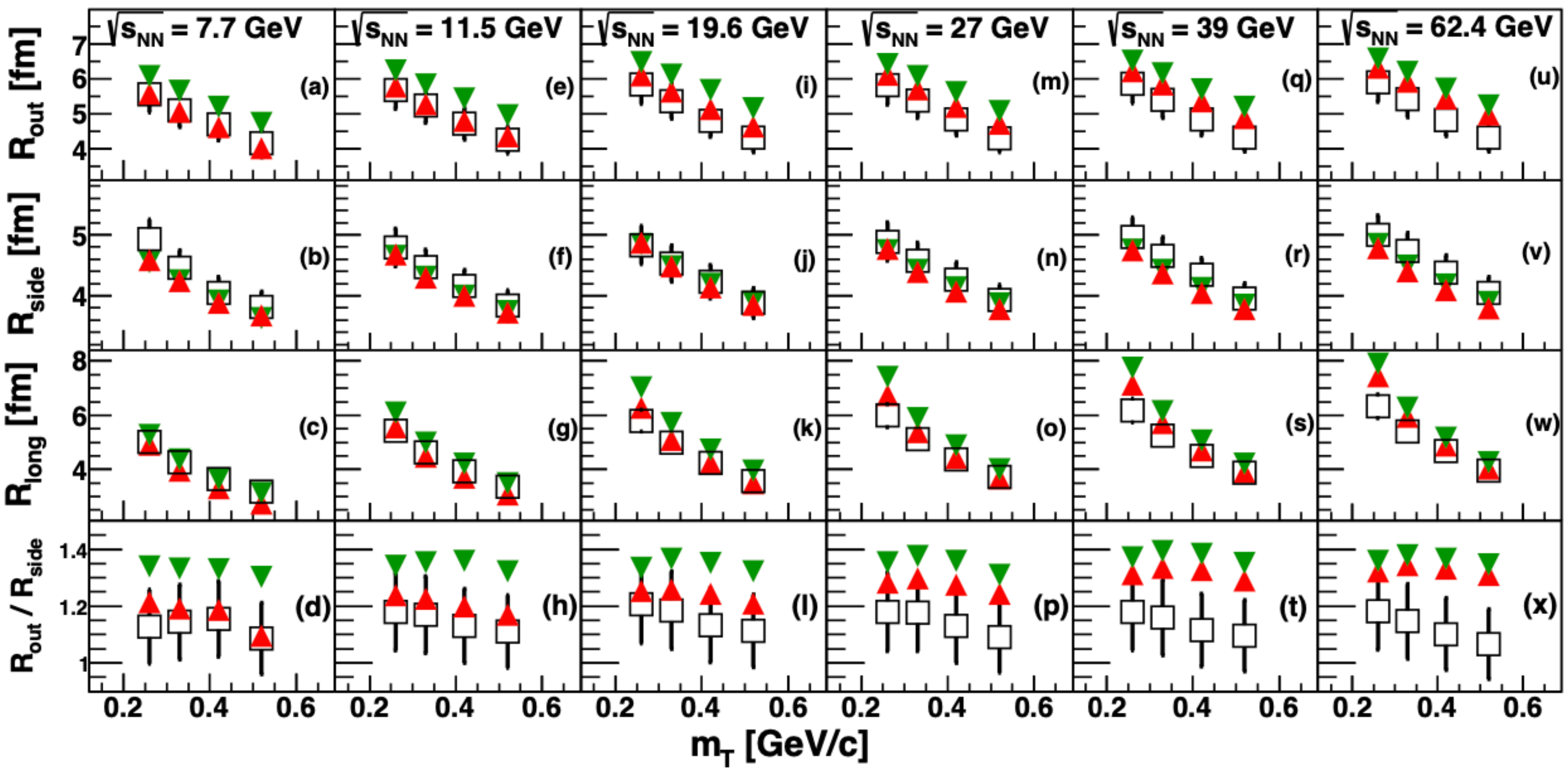
- R_{side} spatial source evolution in the transverse direction
- R_{out} related to spatial and time components
- R_{out}/R_{side} signature of phase transition
- $R_{out}{}^2 - R_{side}{}^2 = \Delta\tau^2 \beta_t{}^2$; $\Delta\tau$ – emission time
- R_{long} temperature of kinetic freeze-out and source lifetime

System evolves faster in the reaction plane



Phys. Rev. C 92 (2015) 14904

How to measure phase transition?



STAR Data
1st order Phase Tr.
Cross-over Tr.

vHLLE (3+1)-D viscous hydrodynamics: Iu. Karpenko, P. Huovinen, H. Petersen, M. Bleicher; Phys.Rev. C 91, 064901 (2015), arXiv:1502.01978, 1509.3751

Pre-thermal → Hydrodynamical phase → Hydronic cascades

UrQMD — vHLEE — UrQMD

HadronGas + Bag Model → 1st order PT ; P.F. Kolb, et al, PR C 62, 054909 (2000)

Chiral EoS → crossover PT (XPT); J. Steinheimer, et al, J. Phys. G 38, 035001 (2011)

vHLEE+UrQMD model verify **sensitivity of HBT measurements to the first-order phase tran**sition

Phys. Rev. C 96 (2017) no.2, 024911

How to measure a phase transition? CP?

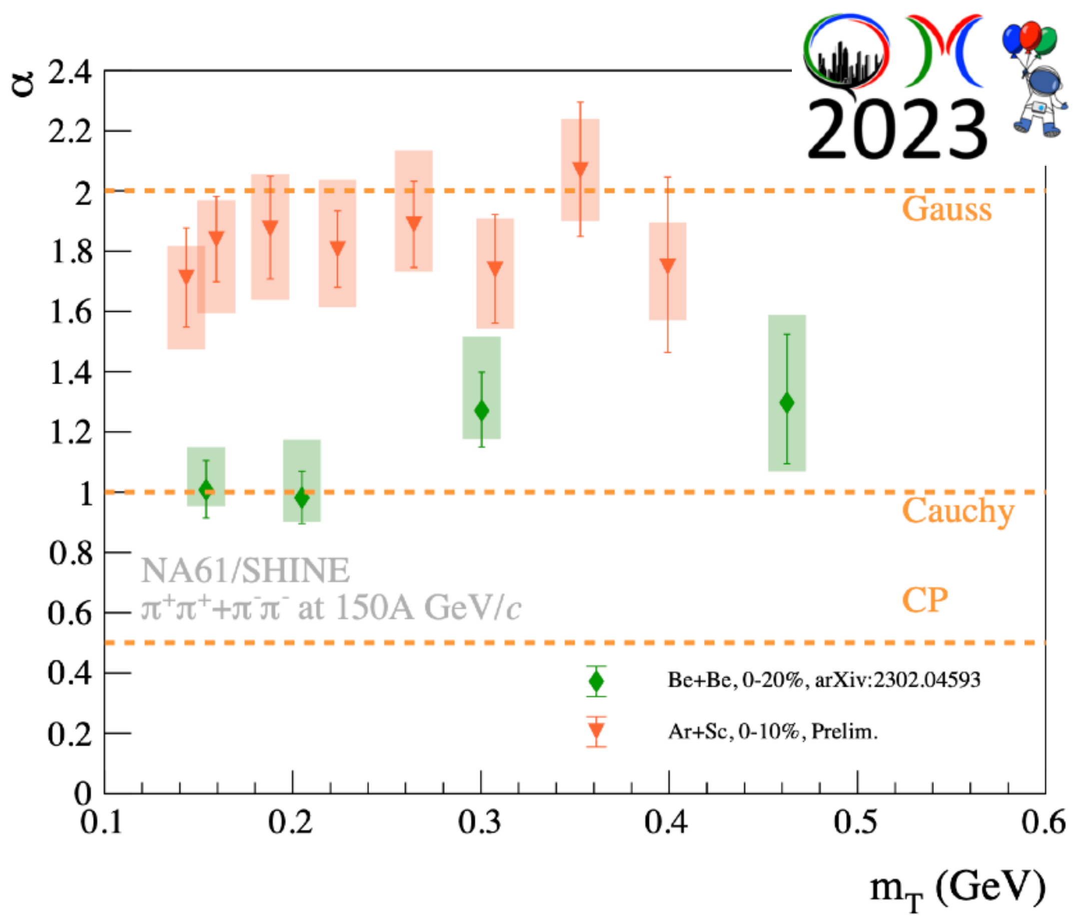
Barnabas Porty

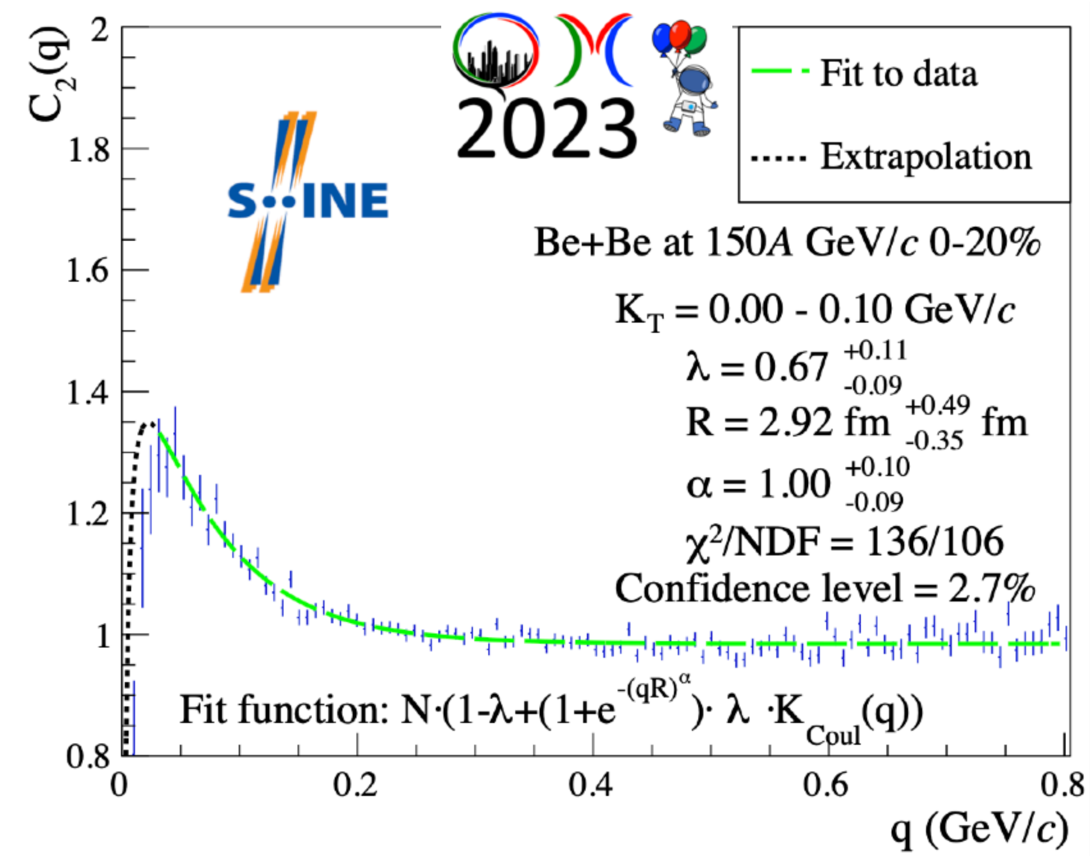
Levy-stability index

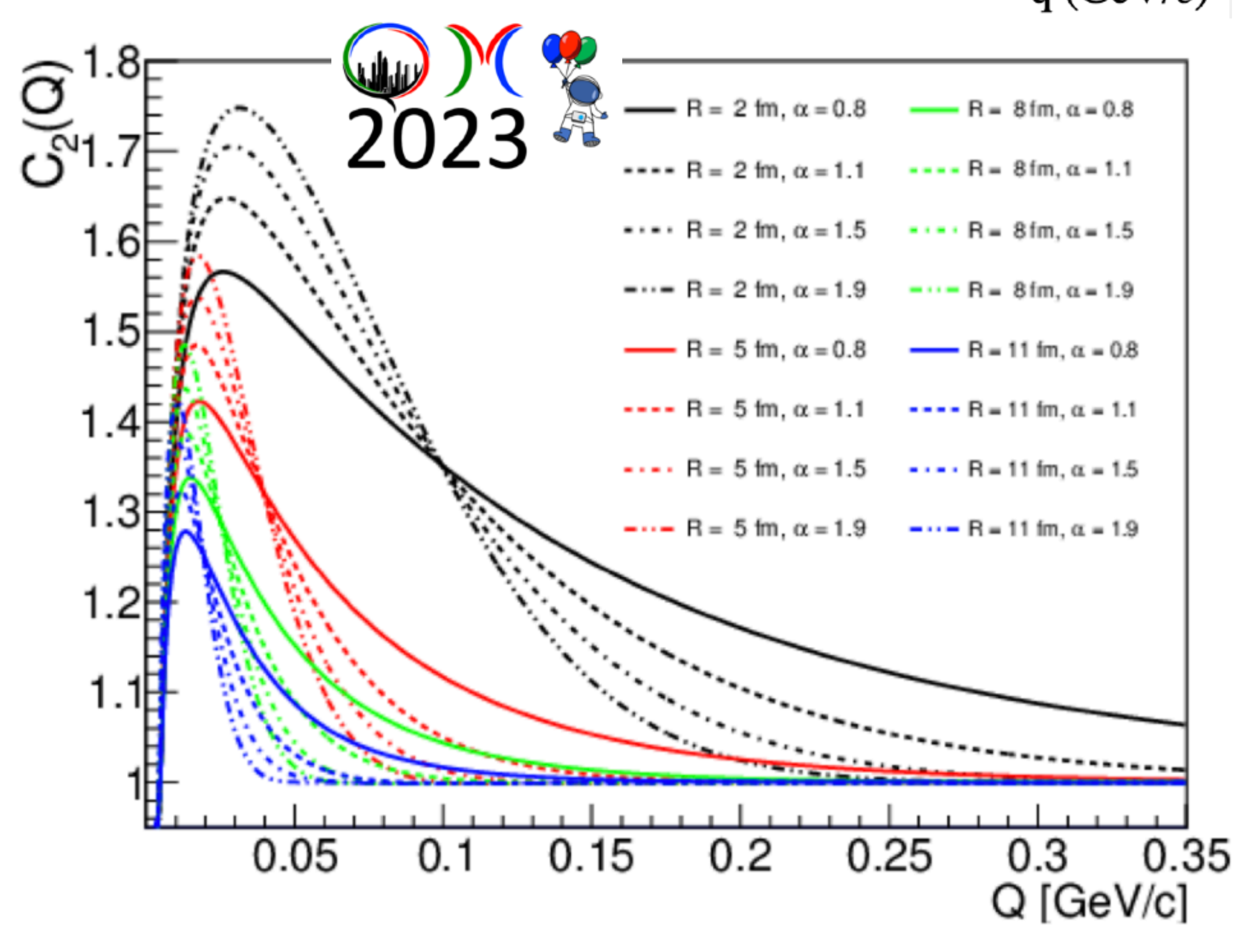
$\alpha = 2$ - Gauss

$\alpha = 1$ - Cauchy

$\alpha = 0.5$ - expected near the CP





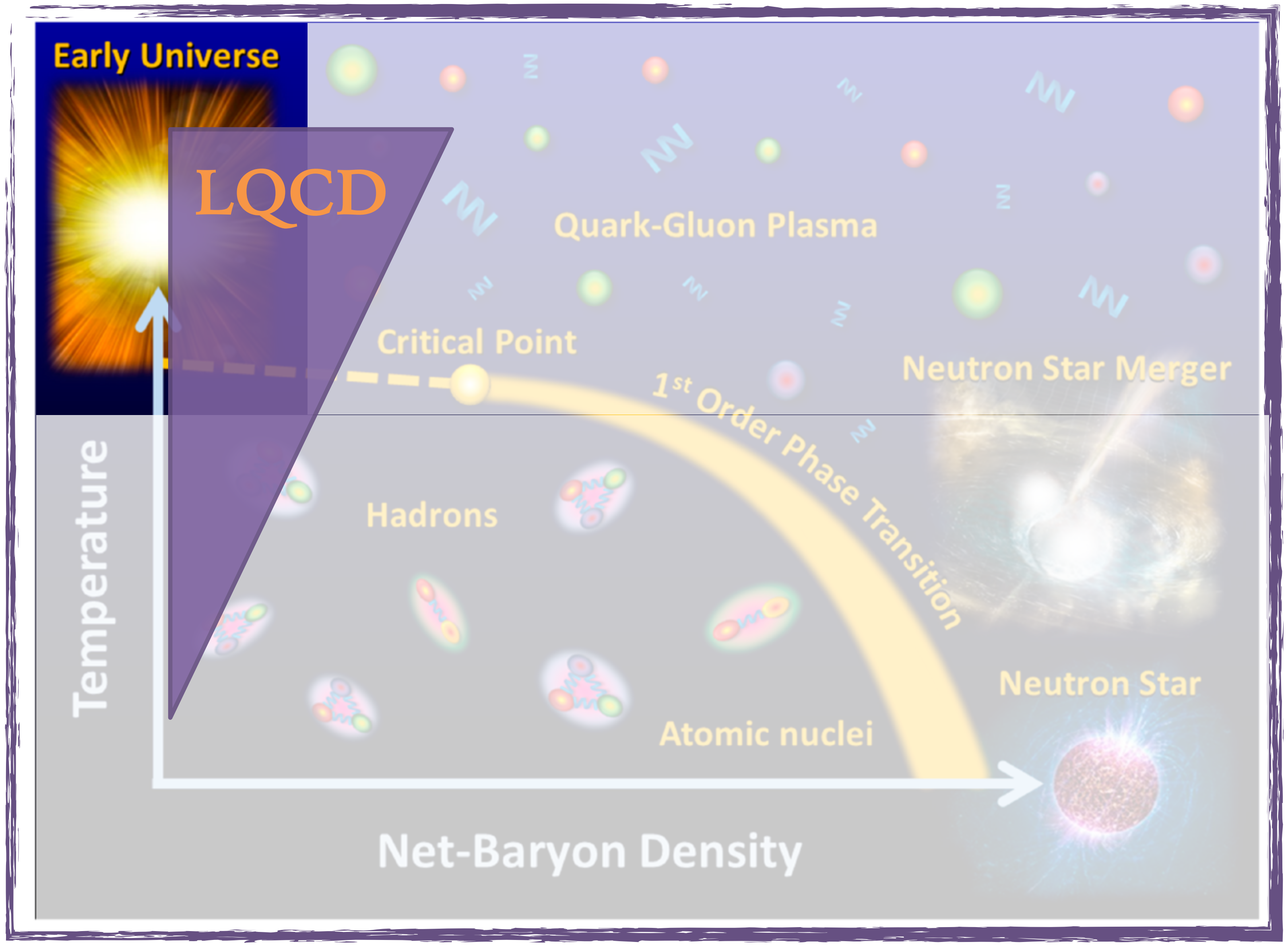


Levy-stability index

Far away from the CP

Early Universe

Exploration of ~~un~~**known** from lattice QCD: vanishing μ_B

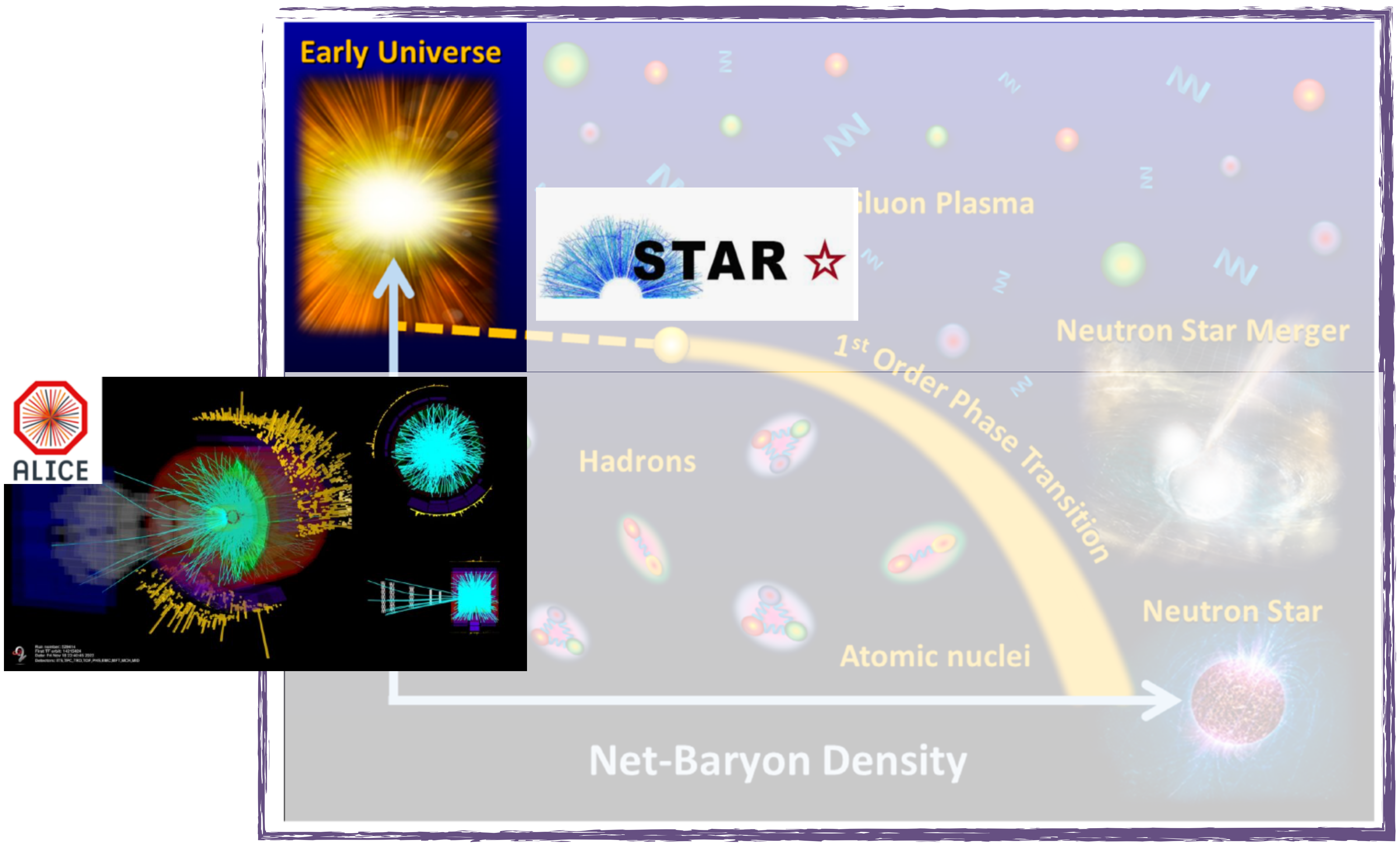


https://www.researchgate.net

Studies of Early Universe

Early Universe

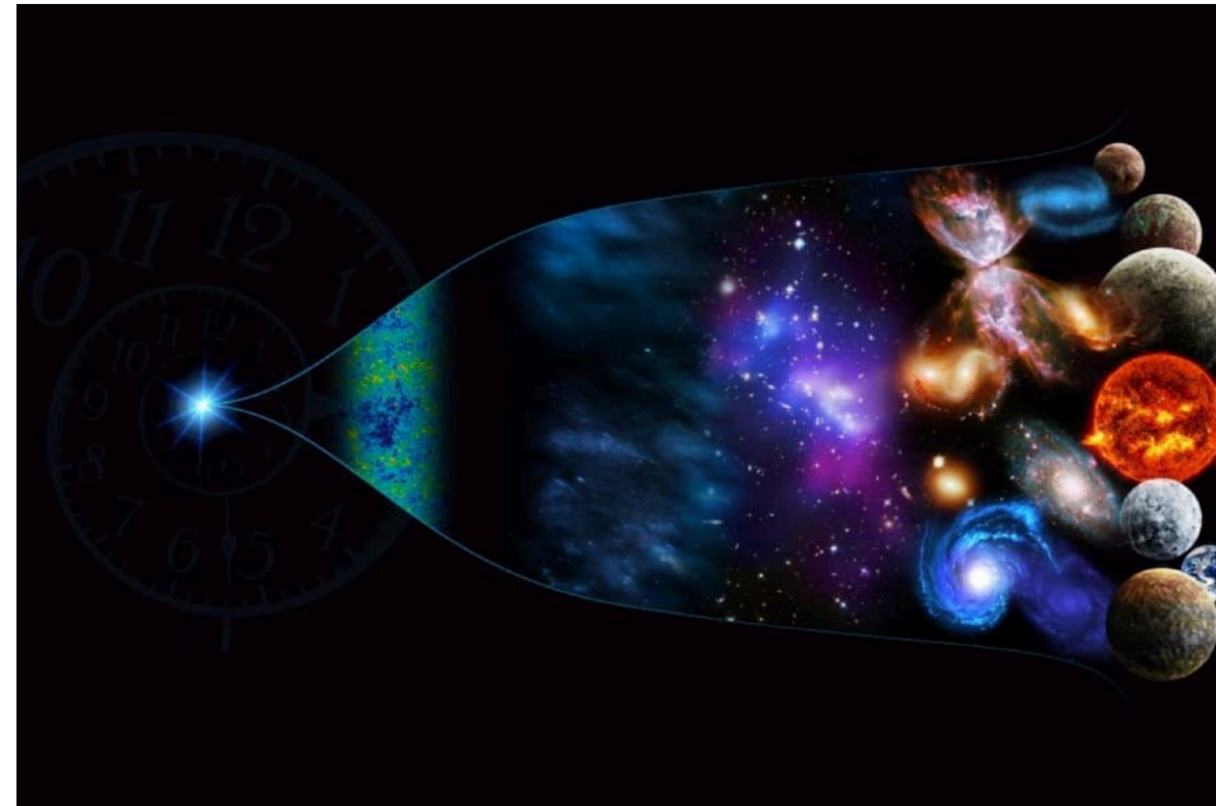
Exploration of ~~un~~**known** from lattice QCD: vanishing μ_B



https://www.researchgate.net

Studies of Early Universe

Early Universe, vanishing μ_B



https://insidetheperimeter.ca/the-universe-before-atoms/

- Probe the condition ~Early Universe,
- Very high abundances of particles produced,
- Statistical heaven to study exotic particles,
- Studies of heavy-flavor,
- Incredible laboratory of anti-matter.

A few speakers:

Marcin Kucharczyk - Bose-Einstein correlations at LHCb

Dimitar Mikhaylov - Studying the low-energy scattering among hadrons using correlation techniques at the LHC

Małgorzata Janik - Matter -antimatter interactions

Wioleta Rzęsa - First measurement of properties of strong interaction between (anti-)deuterons and charged kaons in Pb–Pb collisions with ALICE

… and more!

Summary

Collisions of (heavy) ions give us access to:

High T, low μB

- Cross-over to QGP → Investigations of properties of QGP
- LQCD: no CP indication for $\mu_B/T < 3$

Lower T, high μB

- Phase structure?
  - first-order phase transition?
  - CP?
  - New phases of QCD?
- Characterization of dense matter,
- EOS?
- Properties of hadrons?

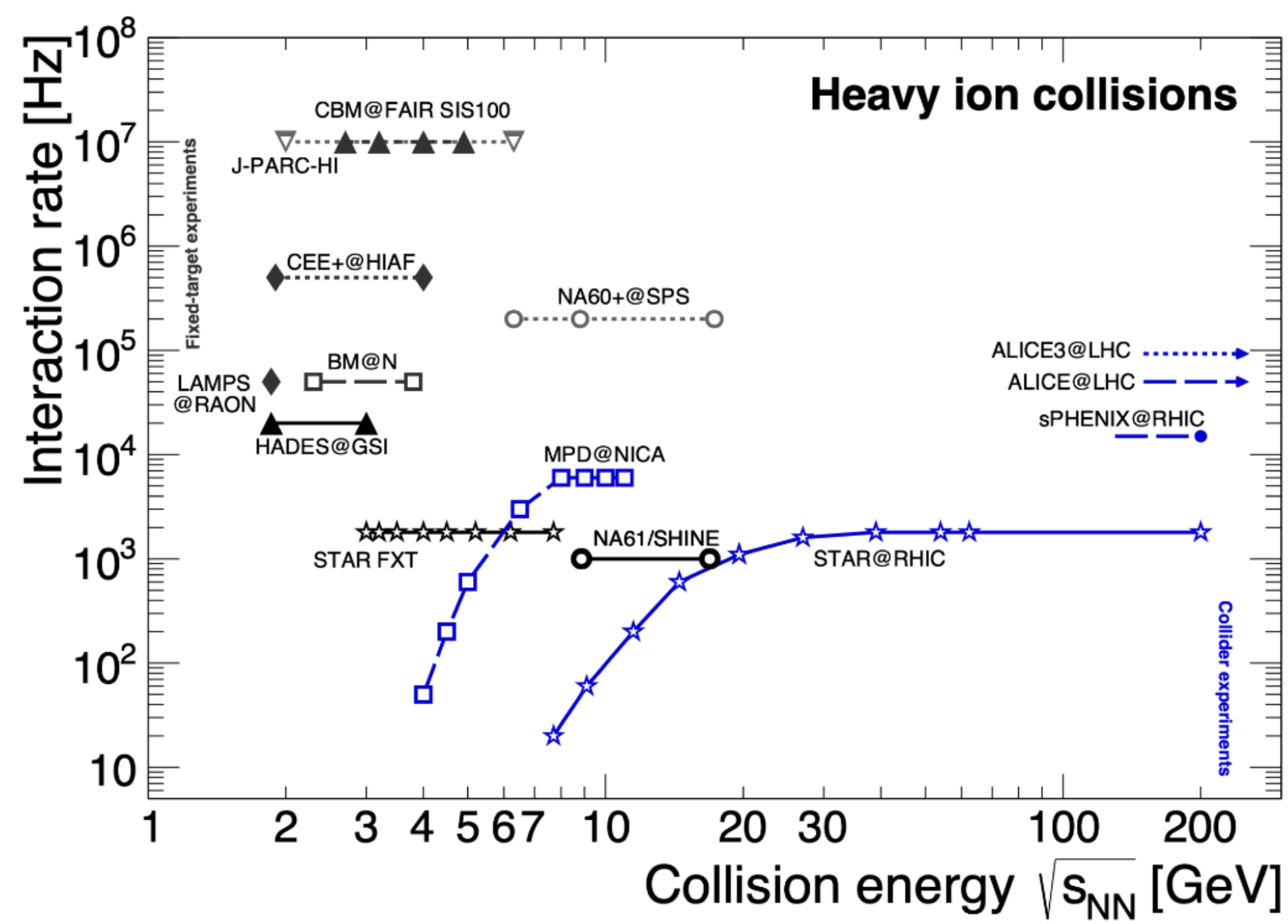
Collisions of (heavy) ions give us access to:

High T, low μ_B

- Cross-over to QGP → Investigations of properties of QGP
- LQCD: no CP indication for $\mu_B/T < 3$

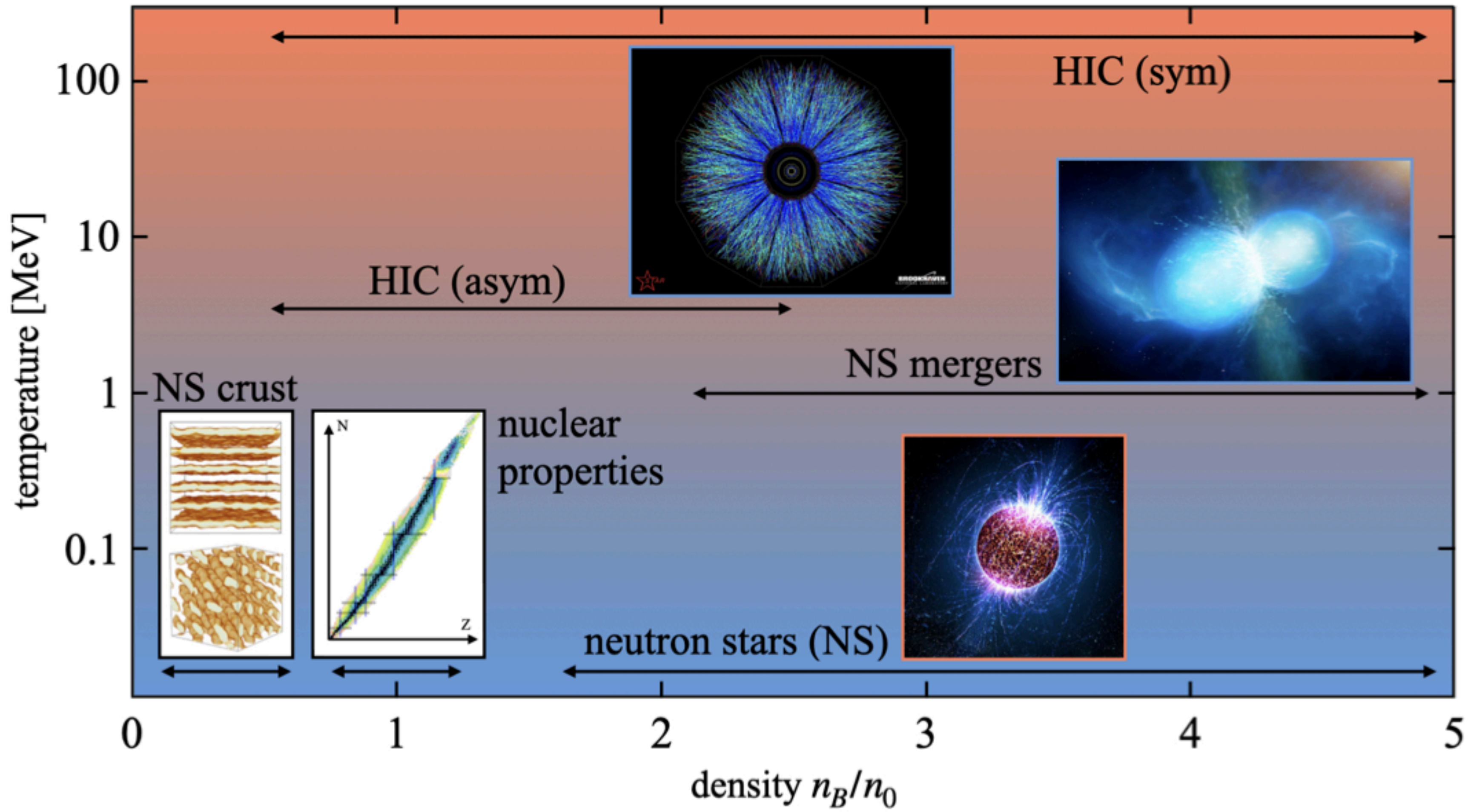
Lower T, h

- Phase str
  - first-c
  - CP?



Various nuclear densities

A. Sorensen, HZ et al.
arXiv:2301.13253 [nucl-th]



$\epsilon(n_n, n_p) = \epsilon_{SNM}(n) + S(n)\delta^2$

$\epsilon_{SNM}(n)$ - energy per nucleon of symmetric nuclear matter

$\delta > 0.8$ - neutron stars

HIC (asym): < 600 AMeV

HIC (sym): broad range of energy, including high-energies