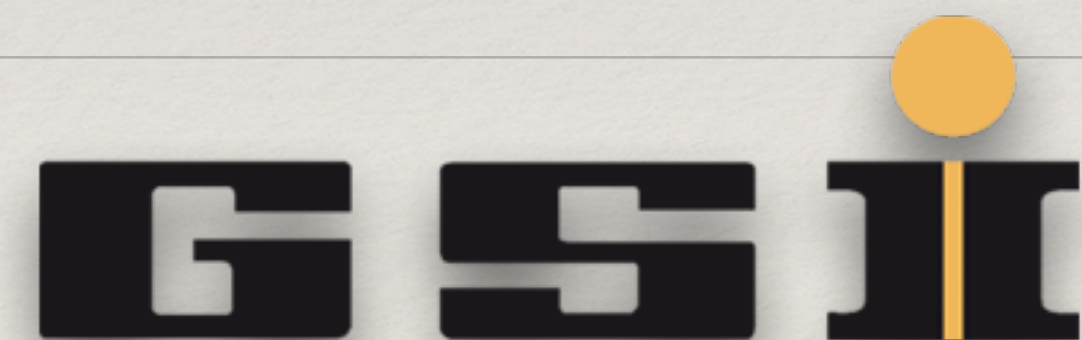
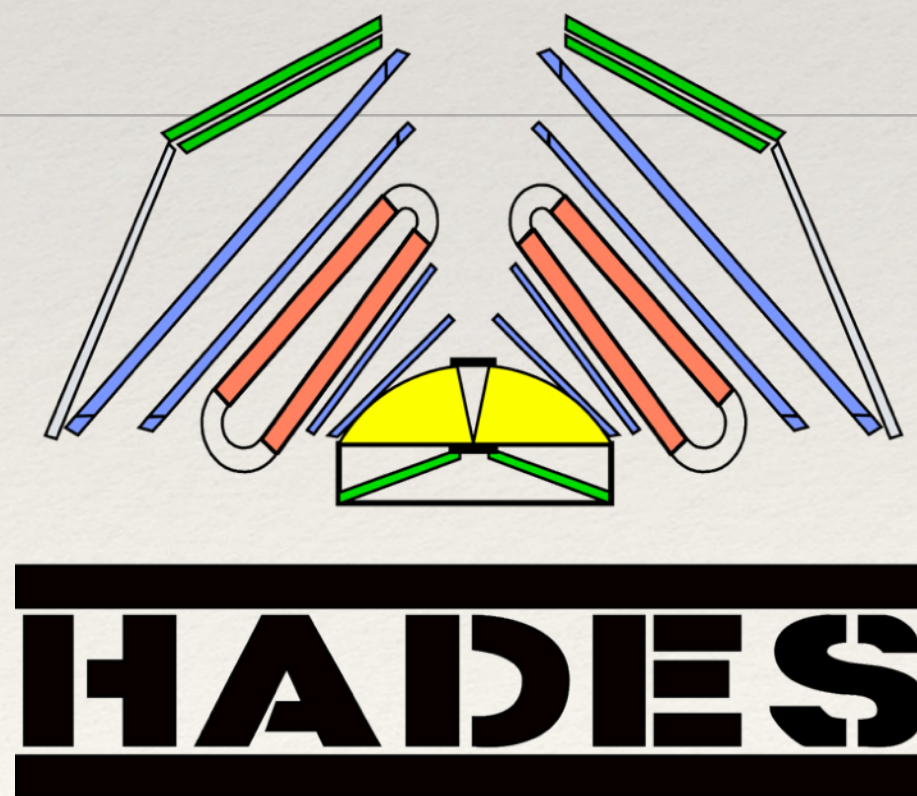


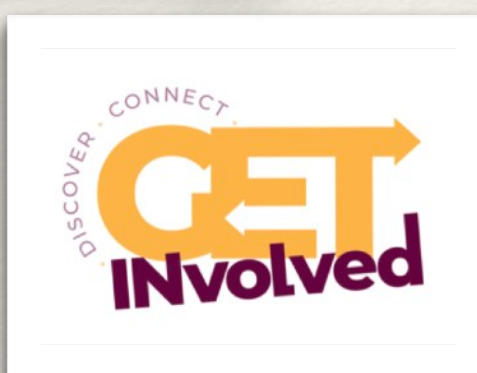
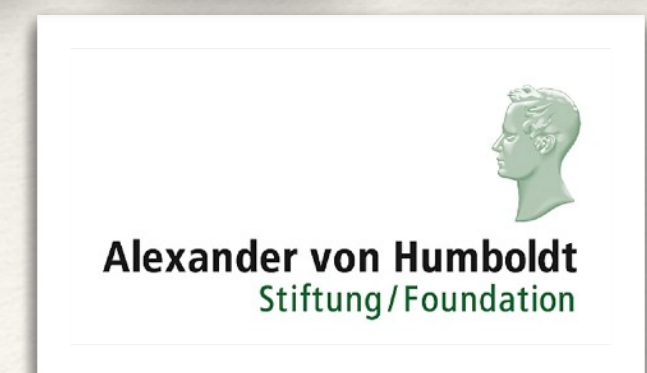


*Maria Stefaniak*

# Studies of EoS with experiment



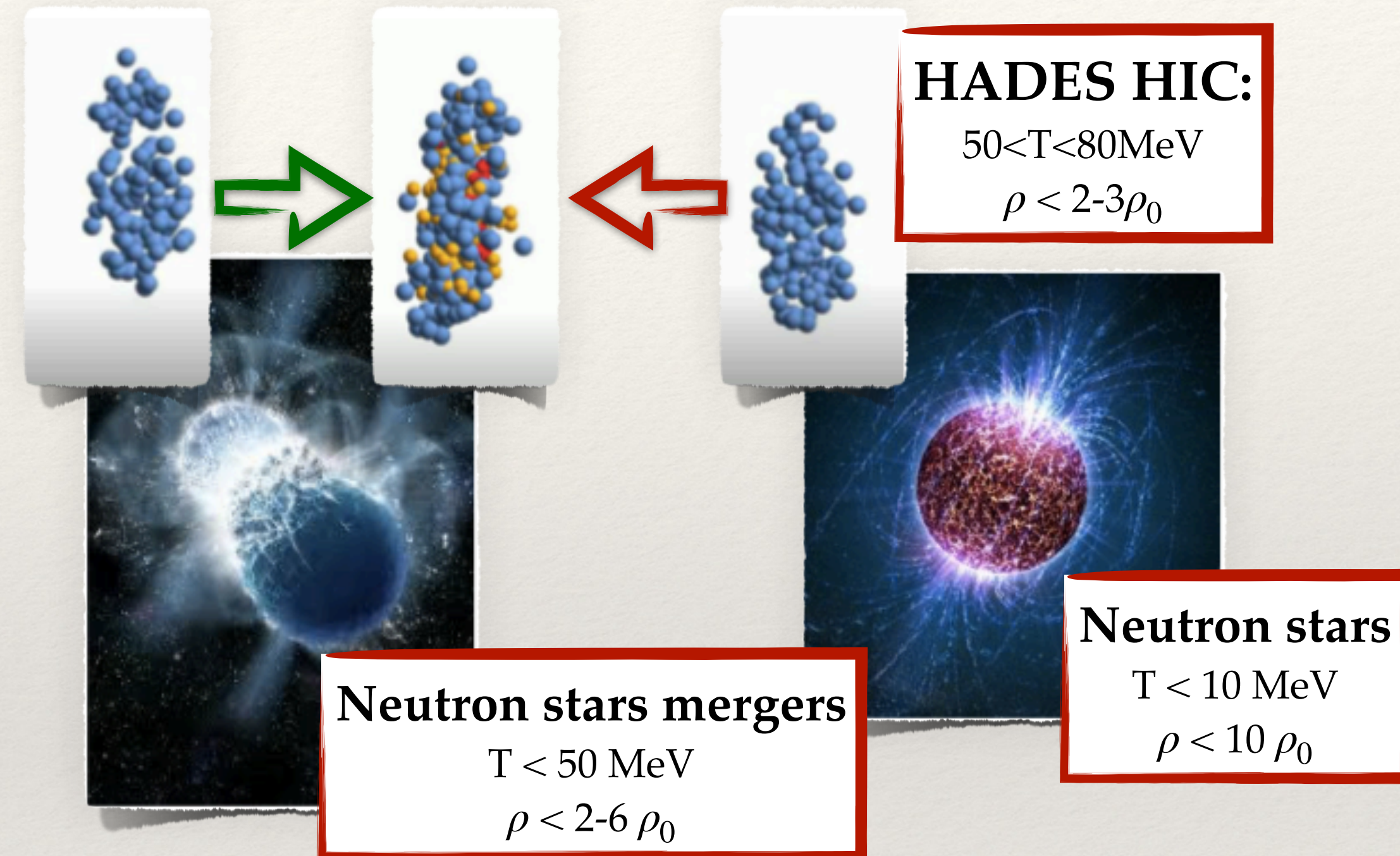
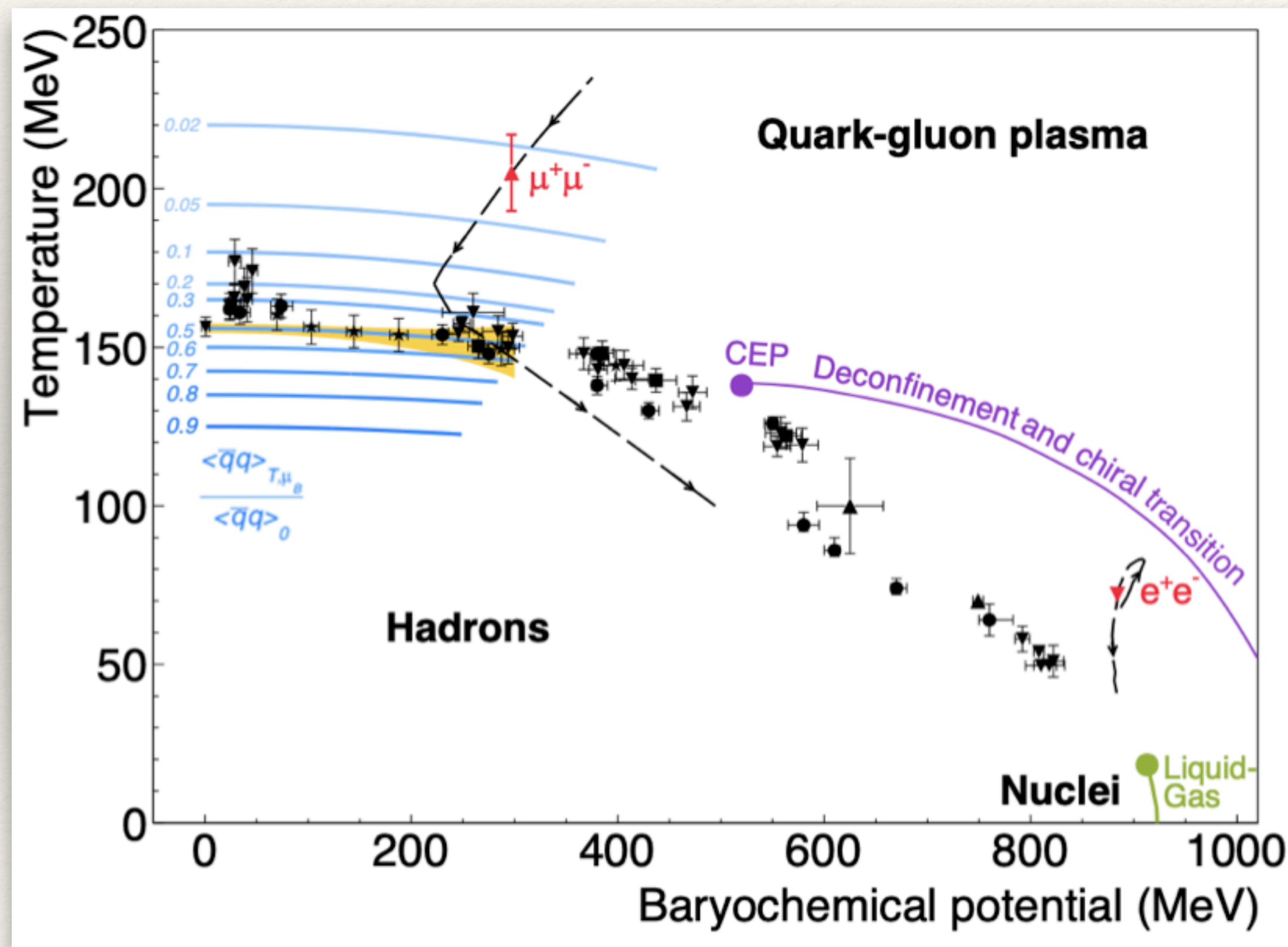
**Warsaw University  
of Technology**





# Equation of state of nuclear matter

Description of the equilibrium properties of QCD matter.



HADES provides access to the high  $\mu_B$  region of the phase diagram!



# HADES Experiment

## High Acceptance Di-Electron Spectrometer

**Fixed target** setup provides high interaction probability

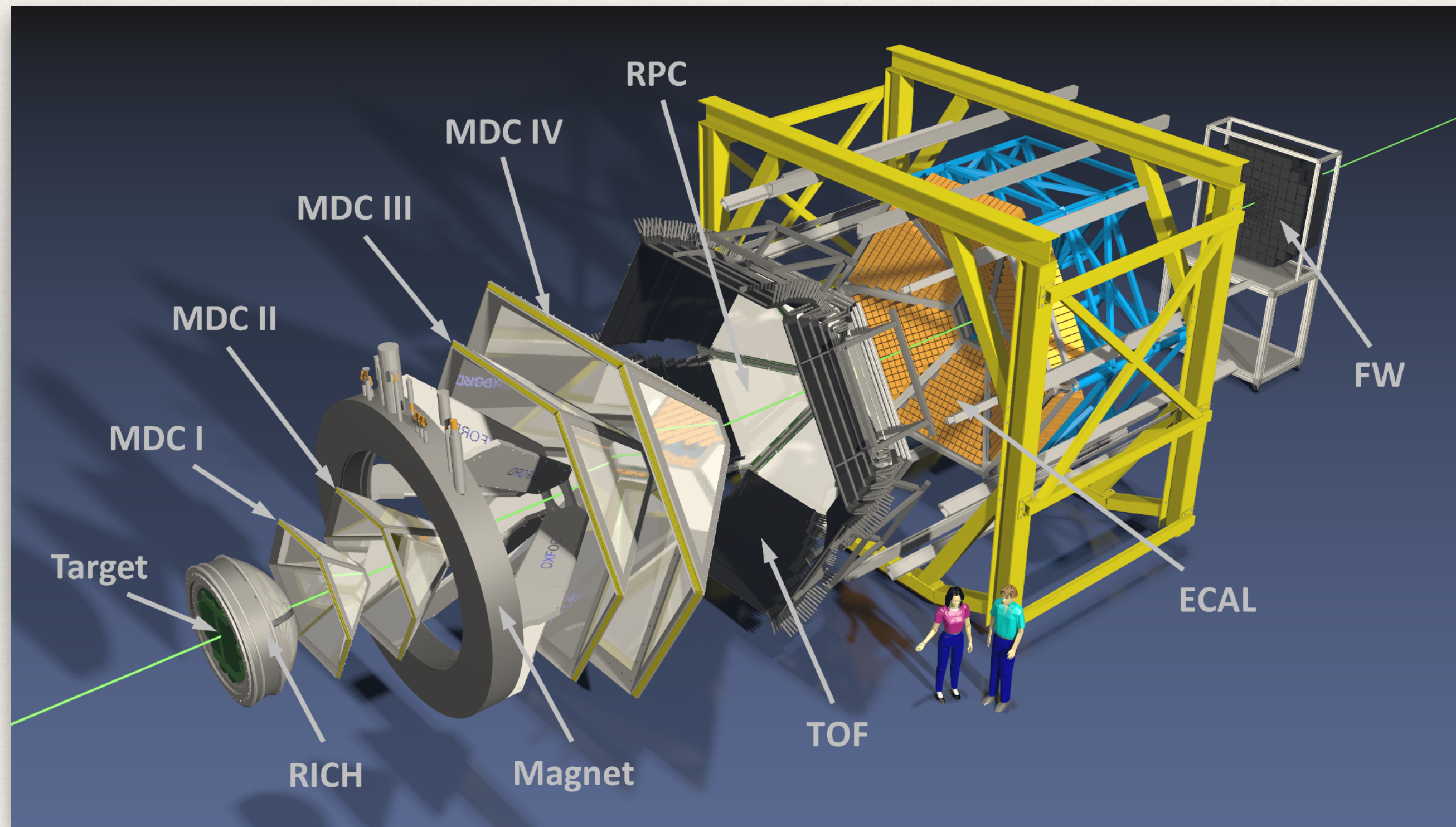
### Two main scientific goals:

#### 1) Heavy-ion collisions at $\sqrt{s_{NN}} = 2\text{-}2.4\text{ GeV}$ :

- ★ Microscopic properties of baryon dominated matter
- ★ Equation-of-State

#### 2) Pion and nucleon beams:

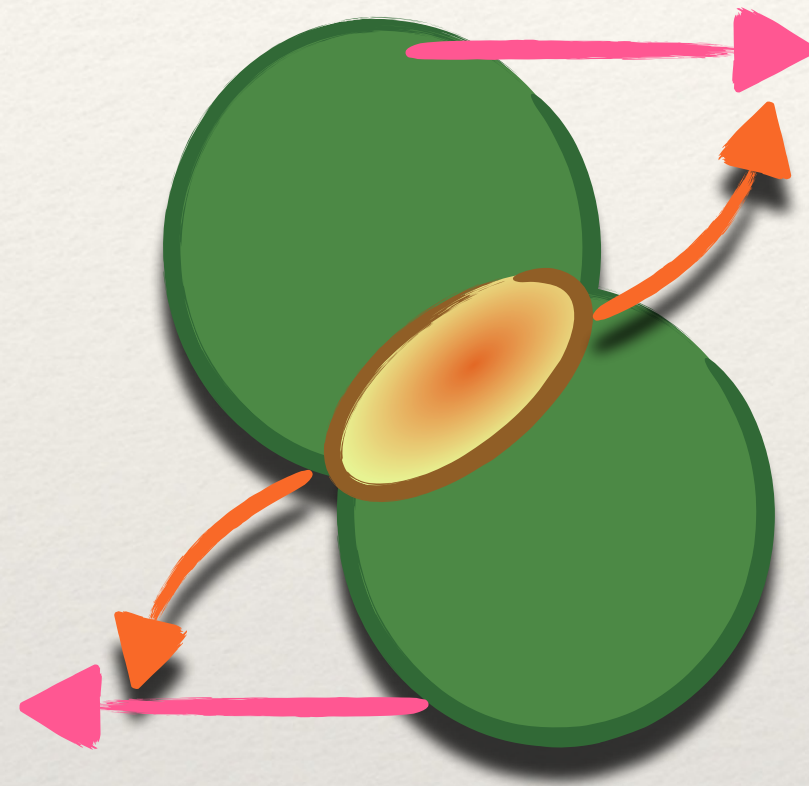
- ★ Reference measurements (vacuum, cold QCD matter)
- ★ Electromagnetic structure of baryons and hyperons



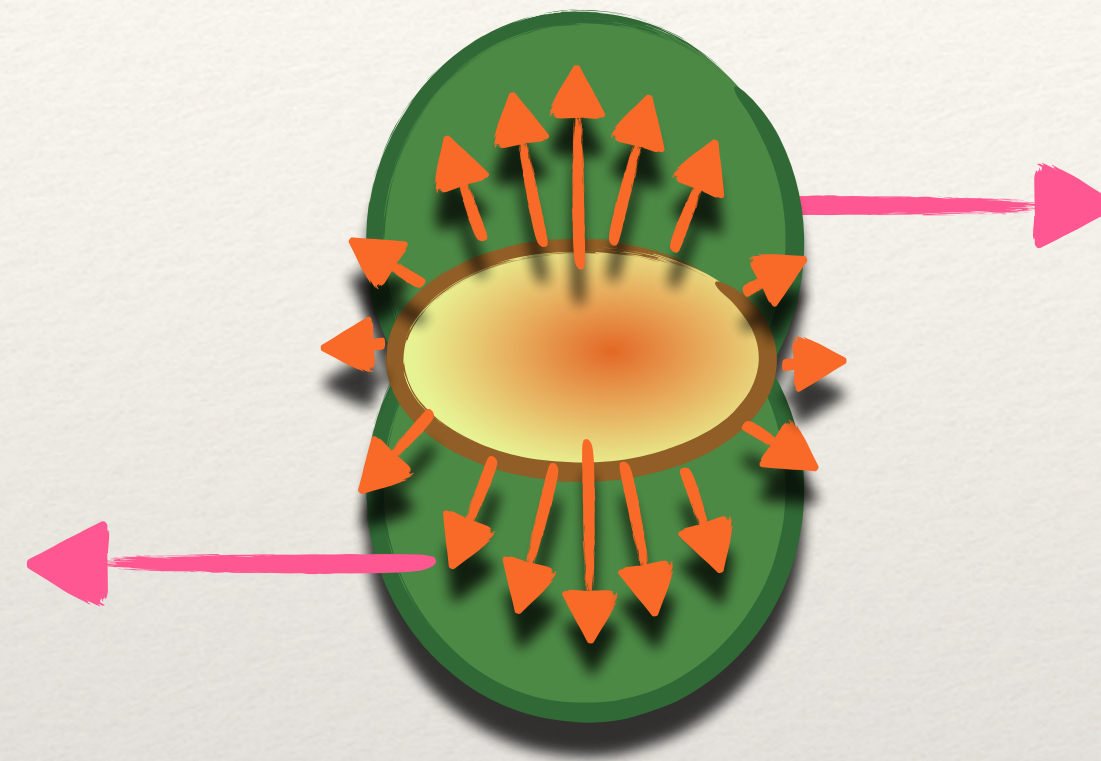


# EoS with HADES

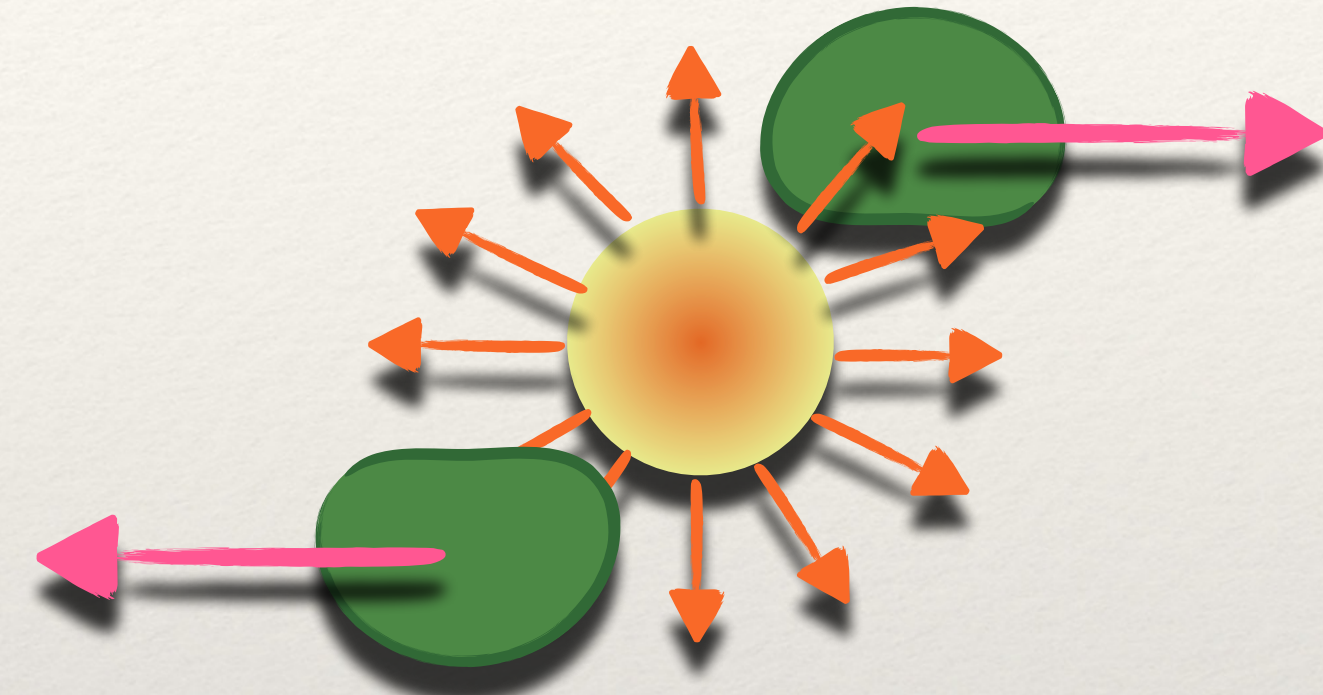
## 1. Flow measurements



directed flow  
 $v_1 = \langle \cos(\phi) \rangle$



elliptic flow  
 $v_2 = \langle \cos(2\phi) \rangle$



radial flow

$$E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_{RP})] \right)$$

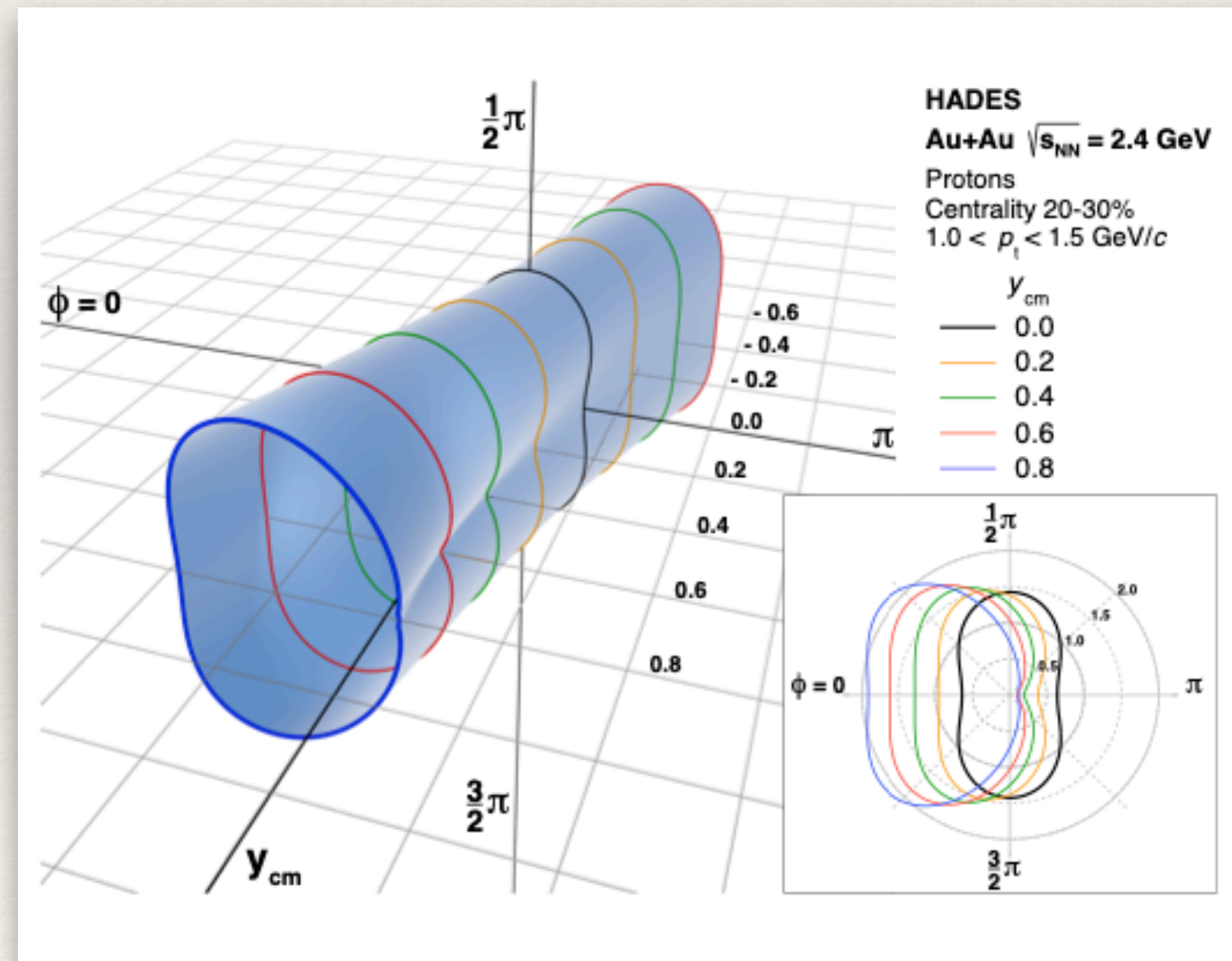
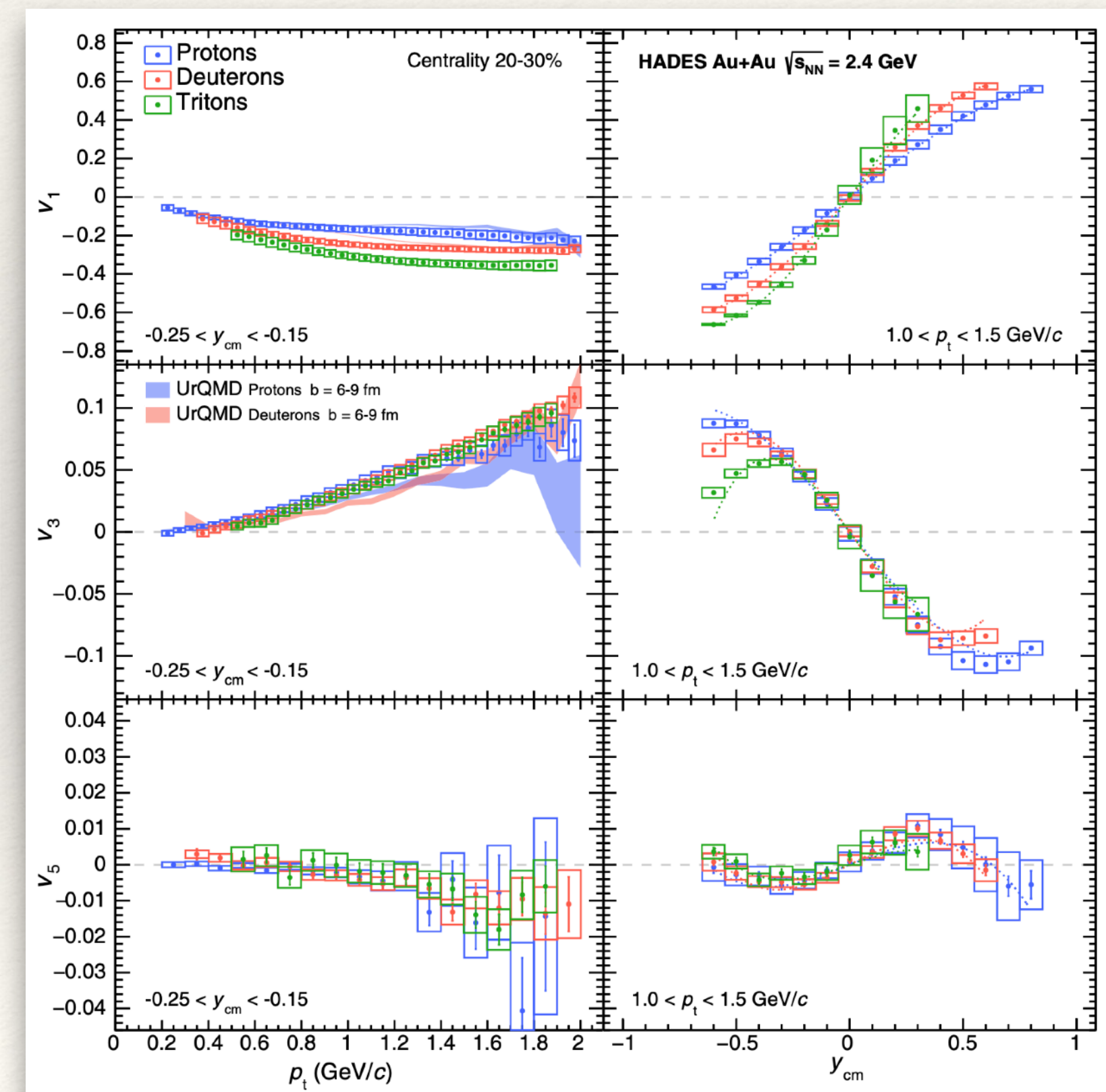


# EoS with HADES

## 1. Flow measurements

HADES Collaboration: *Phys.Rev.Lett.* 125 (2021) 26, 262301  
arXiv:2208.02740

Combining the flow coefficients  $v_1 - v_6$  allows to construct a complete, multi-differential picture of the emission pattern of light nuclei as a function of rapidity and transverse momentum.



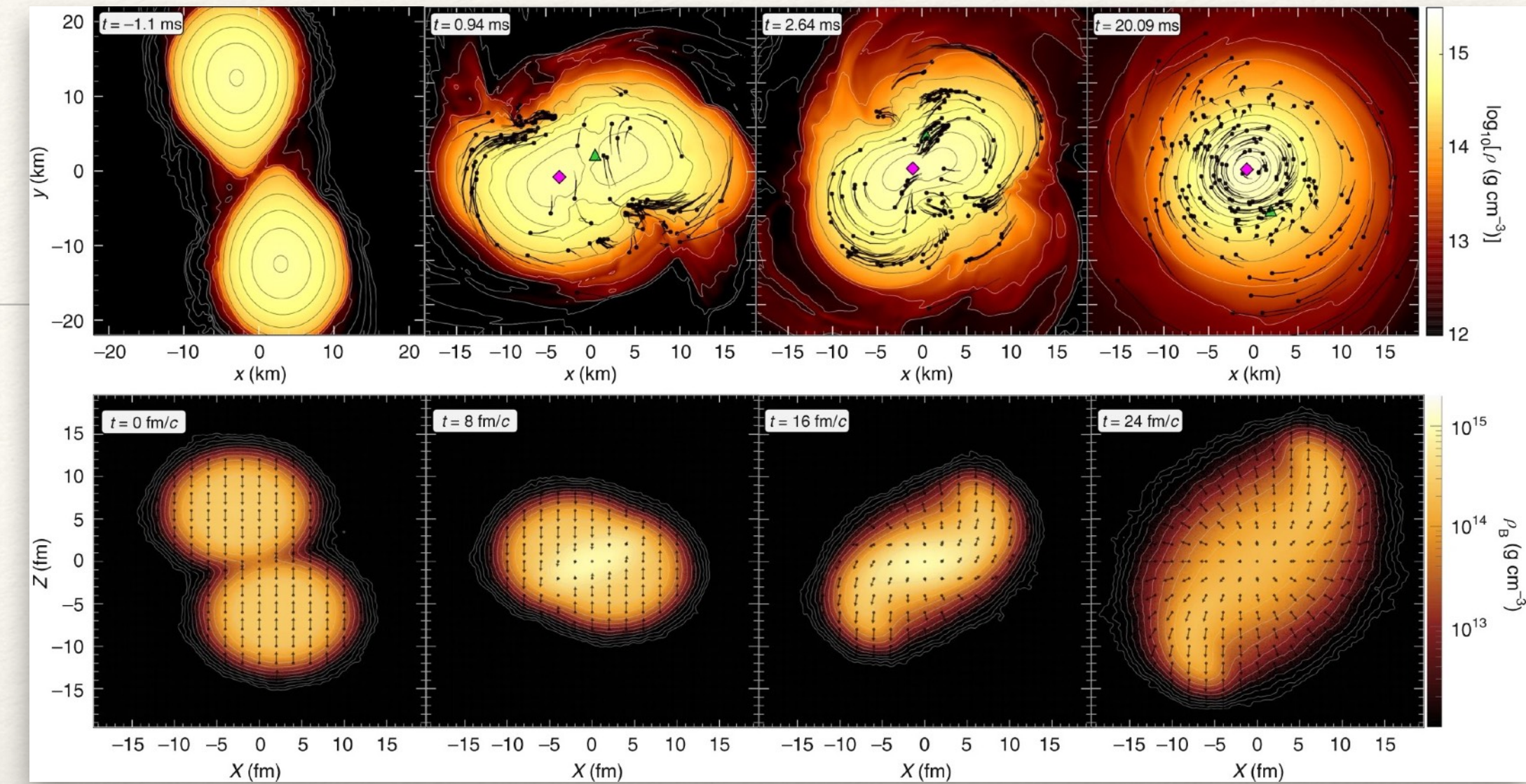
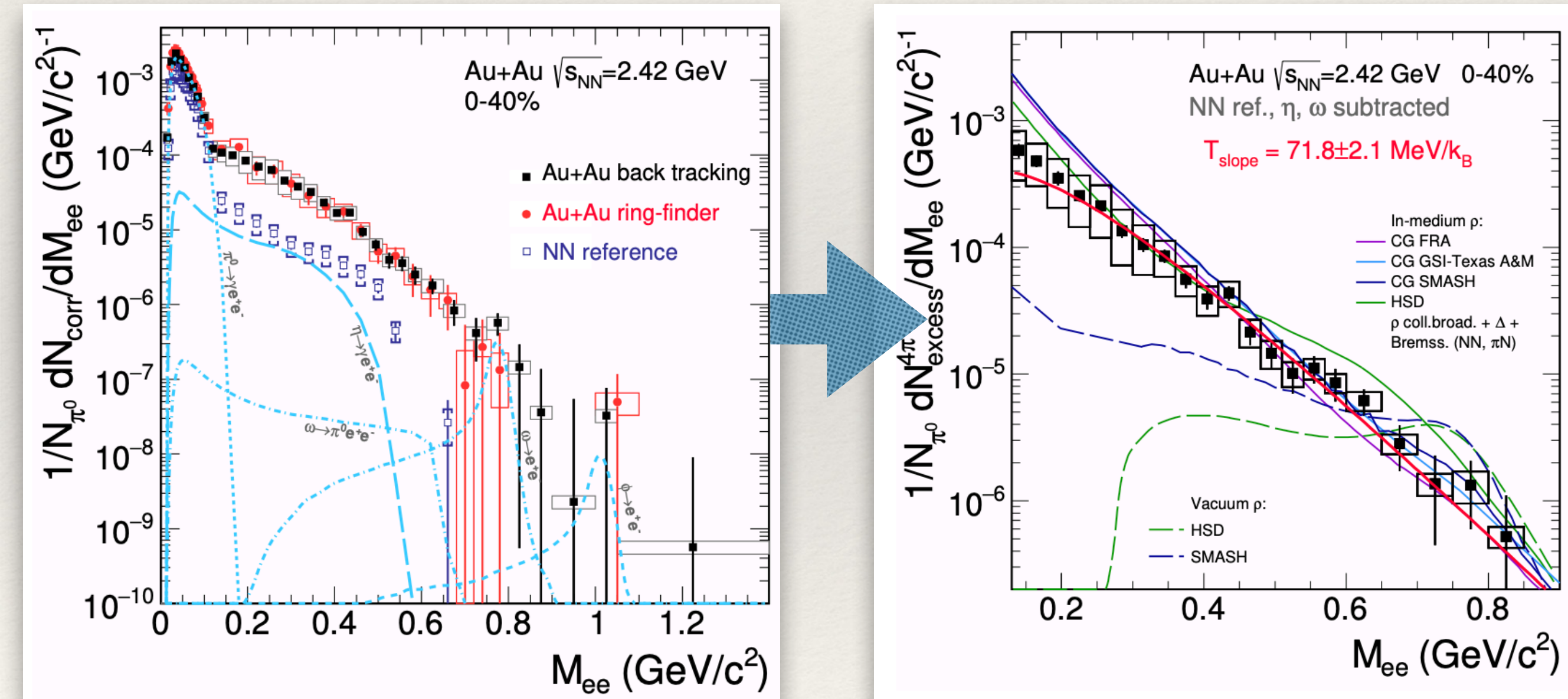
The angular emission pattern of protons showing the interplay between the pressure in central fireball and interactions with spectator matter.



# EoS with HADES

## 2. Fireball temperature with dilepton measurements

Reconstructed  $e^+e^-$  mass distribution - manifestation of virtual photons



Different scales, but **similar matter properties:**  
Relation pressure - energy density - temperature - density

**The excess radiation:**

- Nearly-exponential fall-off
- Extraction of temperature:  $T = 71.8 \pm 2.1 \text{ MeV}/k_B$

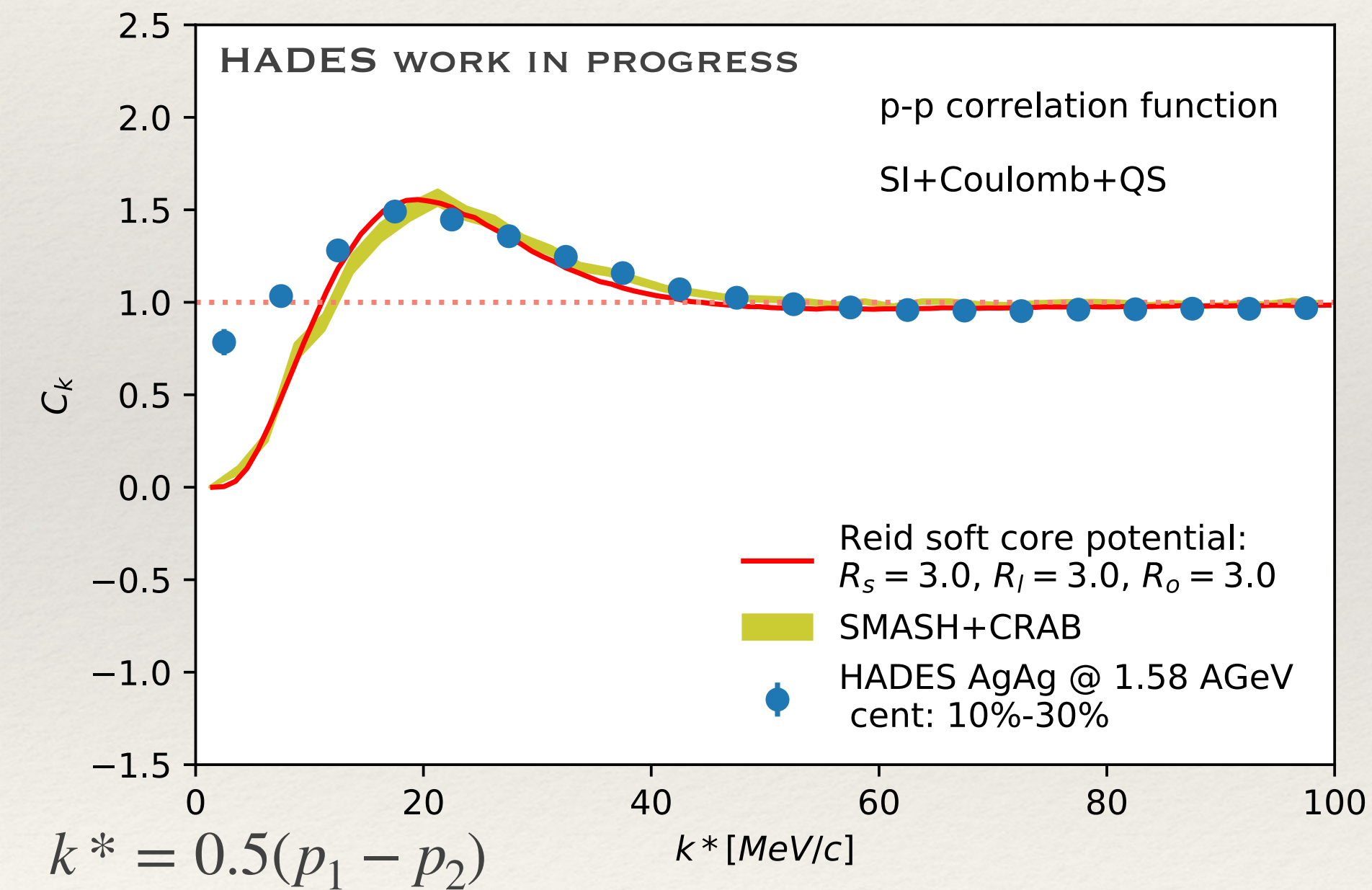
Models predict the  $T = 50 - 80 \text{ MeV}$  of the post-merger neutron star around the dense remnant core



# EoS with HADES

## 3. Femtoscopic correlation measurements

### Proton-proton: Ag+Ag @ 1.58 A GeV

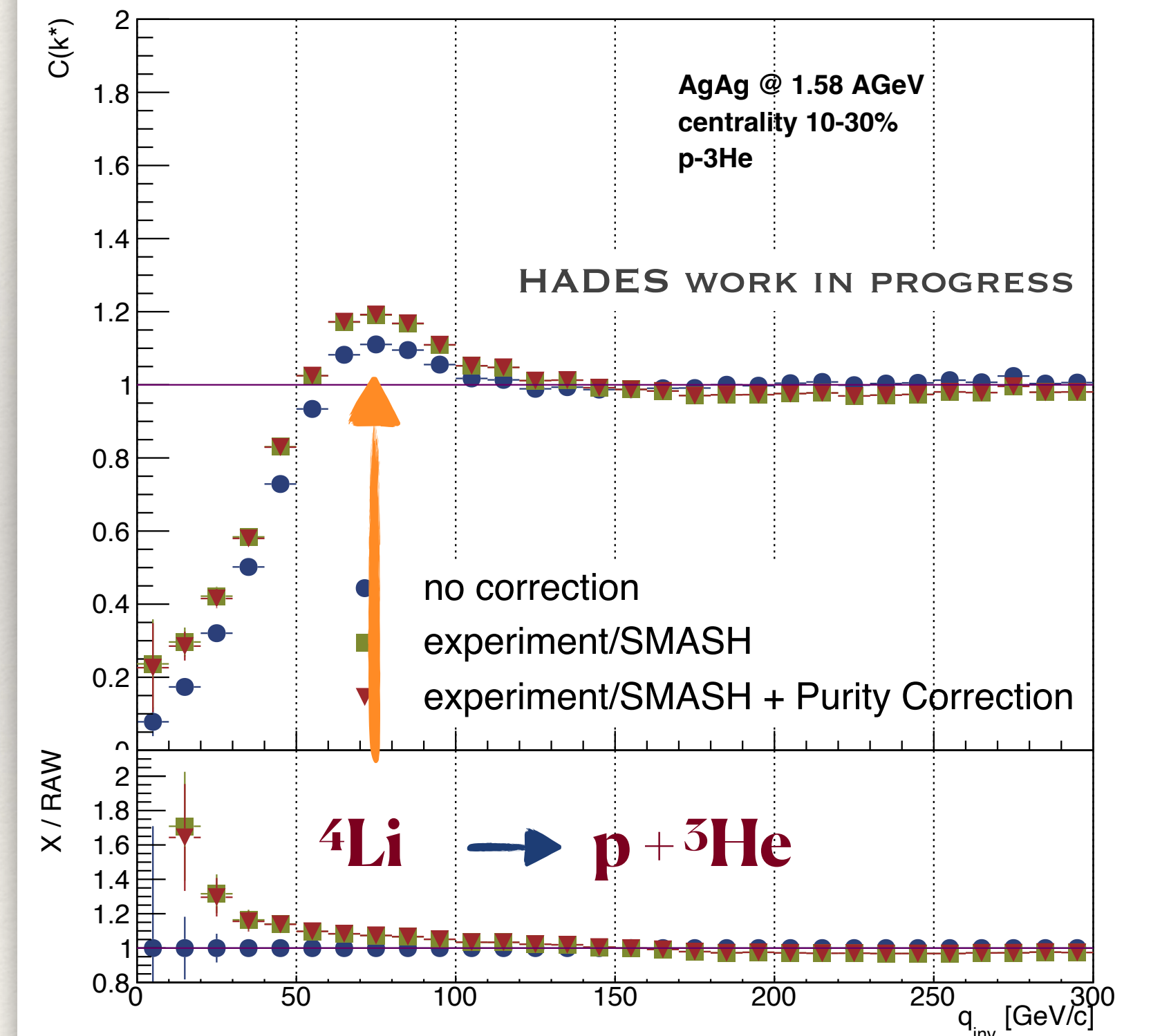


Proton-proton HBT -  
sensitive to EoS

Searches for the  
bound states

Work in progress...

### Proton - $^3\text{He}$ : Ag+Ag @ 1.58 A GeV





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# HADES Collaboration

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Many fascinating results serving as reference for the studies of EoS and nuclear QCD matter properties!



THANK YOU