Strangeness in Nuclear Matter

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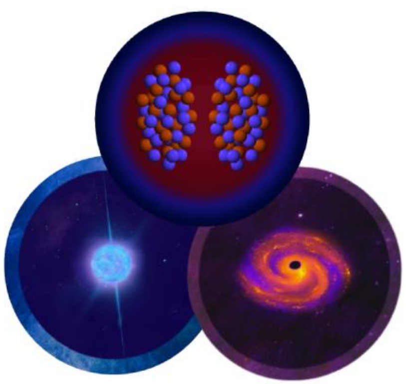
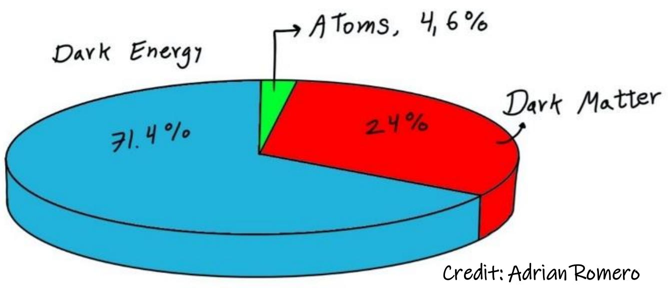


Second DMLab Meeting

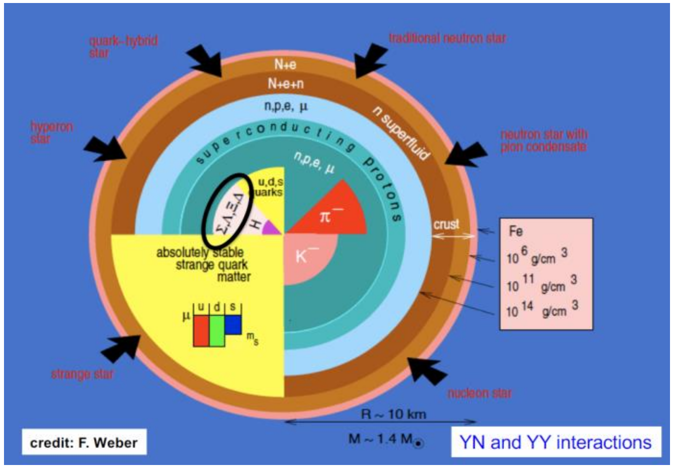
12-13 December 2022 (DESY)

Strangeness in Universe



Nuclear matter is strangeness neutral
→ built of u,d quarks
Strangeness conservation: s-sbar quarks are produced in pairs only

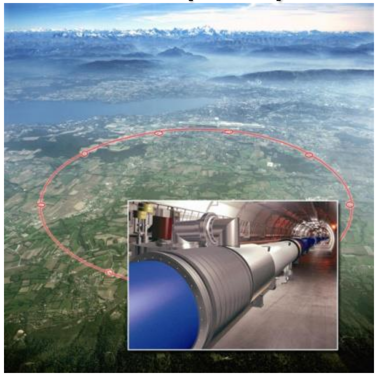
Strangeness in Universe:
in the core of neutron stars

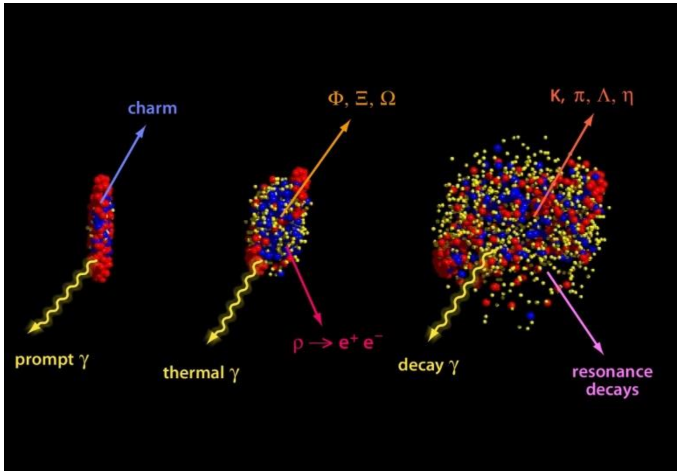


Strangeness in Laboratory:
produced in heavy-ion experiments

SIS & FAIR (GSI)

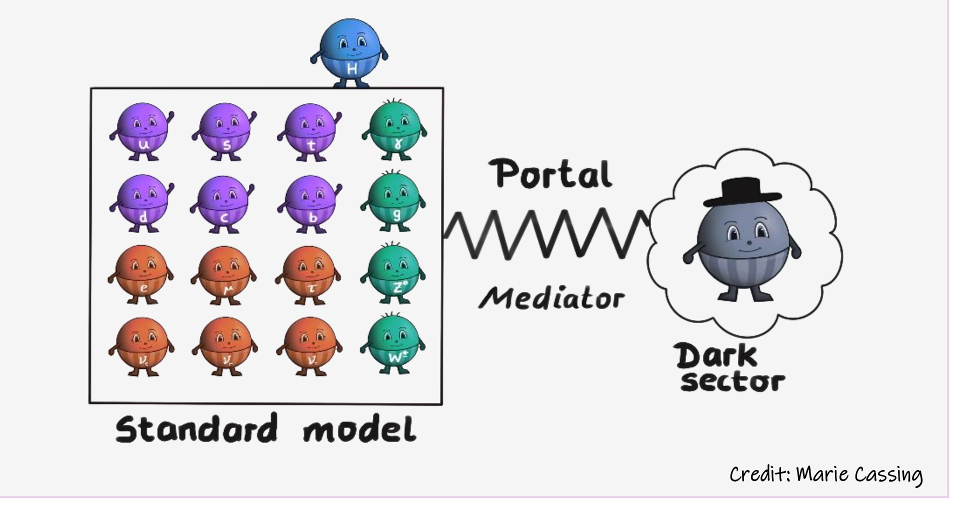
LHC (CERN)





‚Strangeness' in DMLab

DMLab: search for **non-gravitational dark matter (DM) interactions with normal matter,** i.e. with standard model (SM) particles



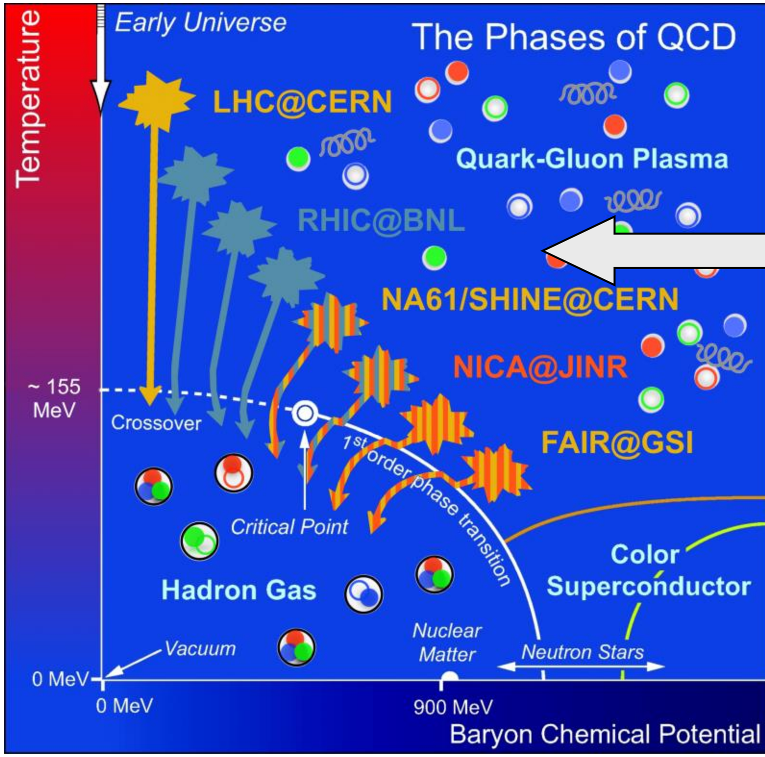
Strange particles are important probes of the **properties of ‚standard' matter:**

- Equation-of-State (EoS)
- medium modification of hadron properties in dense and hot matter and chiral symmetry restoration
- formation of the quark-gluon plasma (QGP) at high T and μ_B
- formation of hypernuclei
- strangeness in neutron stars

Strange particles can couple to **DM particles**

➔ search for DM candidates in heavy-ion experiments

Heavy-ion physics:



The phase diagram of QCD:

- Equation-of-State of hot and dense matter?
- Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma
- Search for possible critical point
- Search for signatures of chiral symmetry restoration
- Study of the in-medium properties of hadrons (including strange mesons and baryons) at high baryon density and temperature

Our goal: to study the properties and dynamics of strongly interacting matter created in heavy-ion collisions on a microscopic basis

Theory: QCD + many body theory + microscopic transport theory

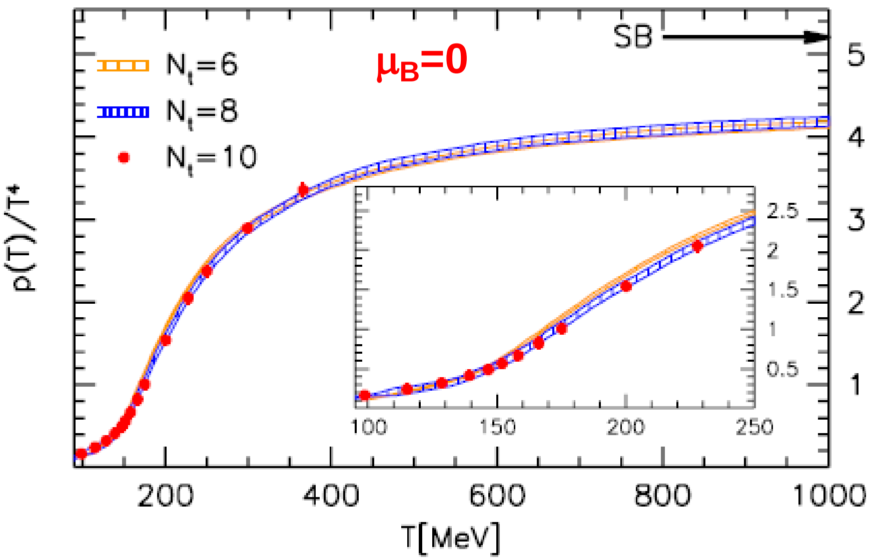
Realization: dynamical transport approaches → PHSD & PHQMD

PHSD PHQMD

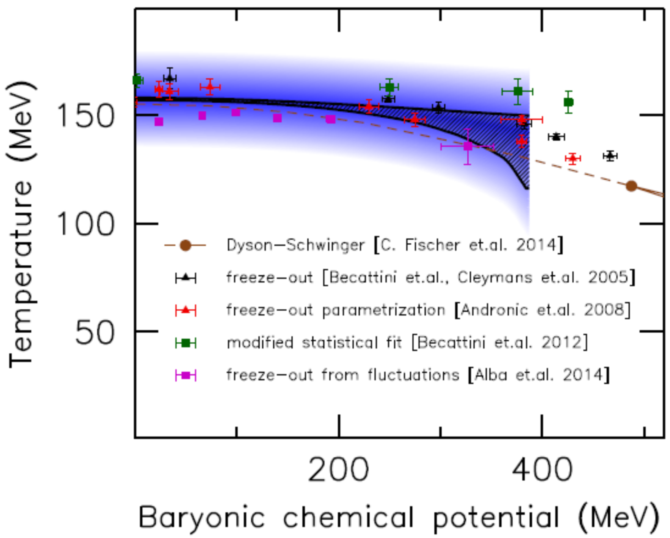
Thermodynamics of QCD at finite T and μ_B

- **For the microscopic transport description of the system one needs to know all degrees of freedom (hadronic and partonic) as well as their properties and interactions!**

Thermal properties of QCD in (T, μ_B) plane
→ lattice QCD – limited to the low μ_B < 400 MeV



lQCD: J. Guenther et al., Nucl. Phys. A 967 (2017) 720



Lattice QCD results up to $\mu_B < 400\ MeV$:

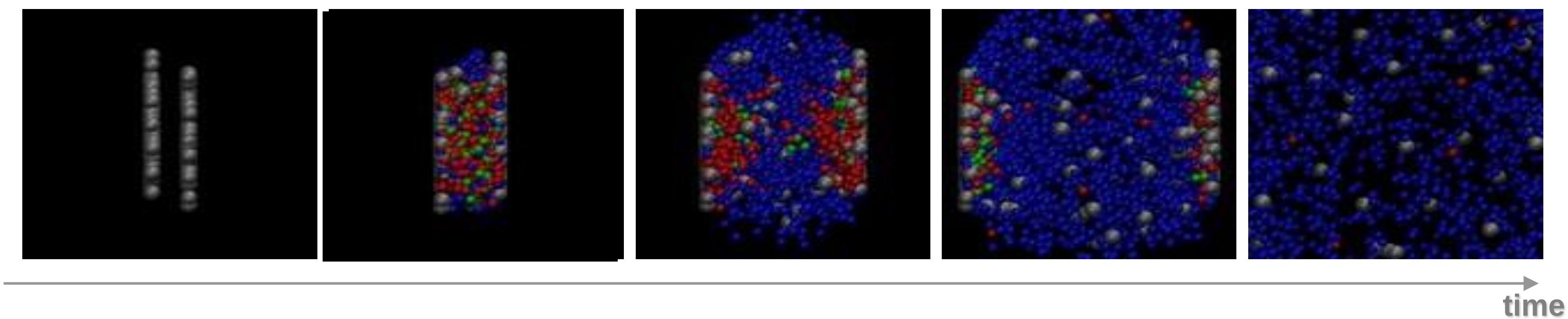
Crossover: hadron gas → QGP

How to learn about the EoS and degrees-of-freedom of the matter from HICs?
➔ microscopic transport approaches ➔ comparison to HIC experiments

Dynamical modeling of heavy-ion collisions - PHSD

Parton-Hadron-String Dynamics (PHSD) is a non-equilibrium microscopic transport approach for the description of dynamics of strongly-interacting hadronic and partonic matter created in heavy-ion collisions

Dynamics: based on the solution of generalized off-shell transport equations derived from Kadanoff-Baym many-body theory (beyond semi-classical BUU)

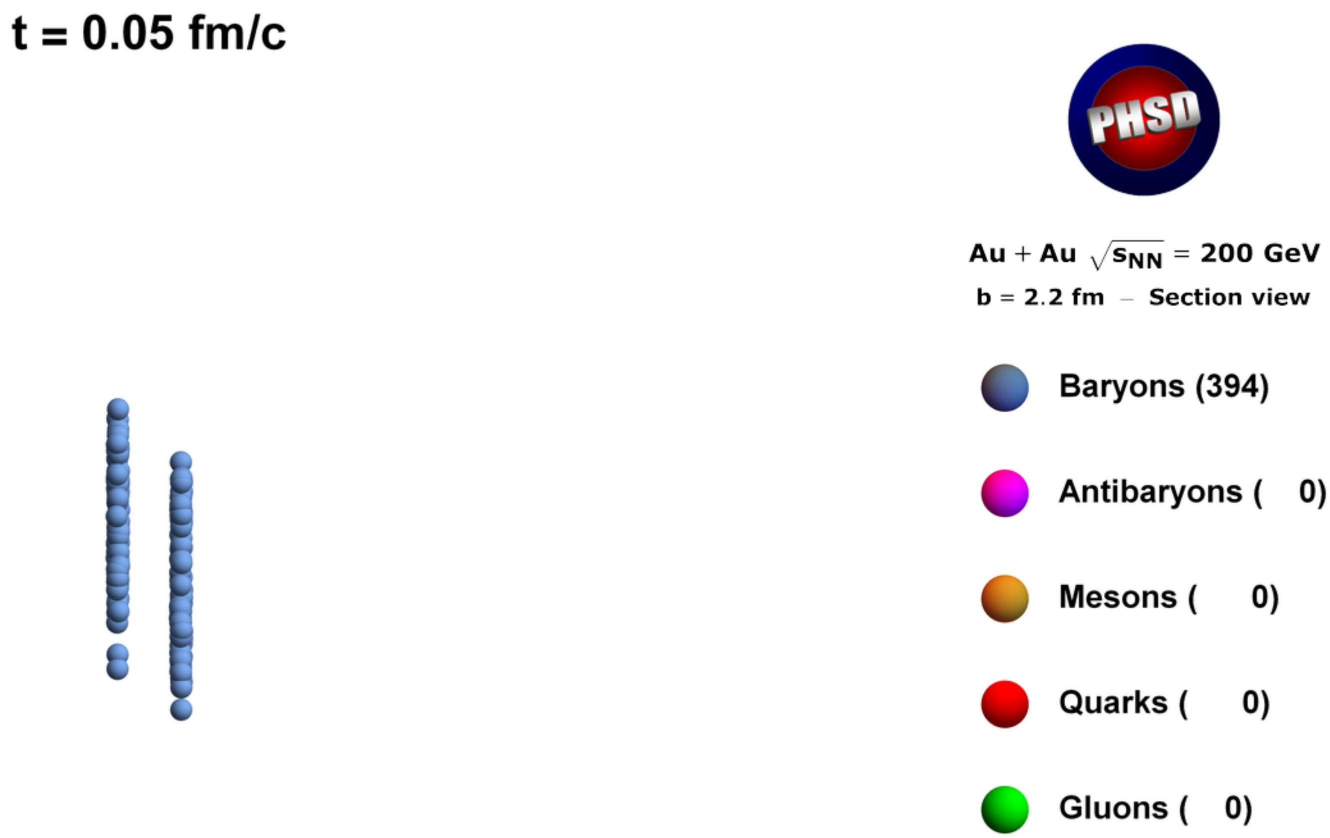


→ **PHSD provides a good description of 'bulk' hadronic and electromagnetic observables from SIS to LHC energies**

→ **PHSD can be used for the theoretical study of the DM production in HICs: cf. recent extension beyond SM sector: dark photon production in HICs**

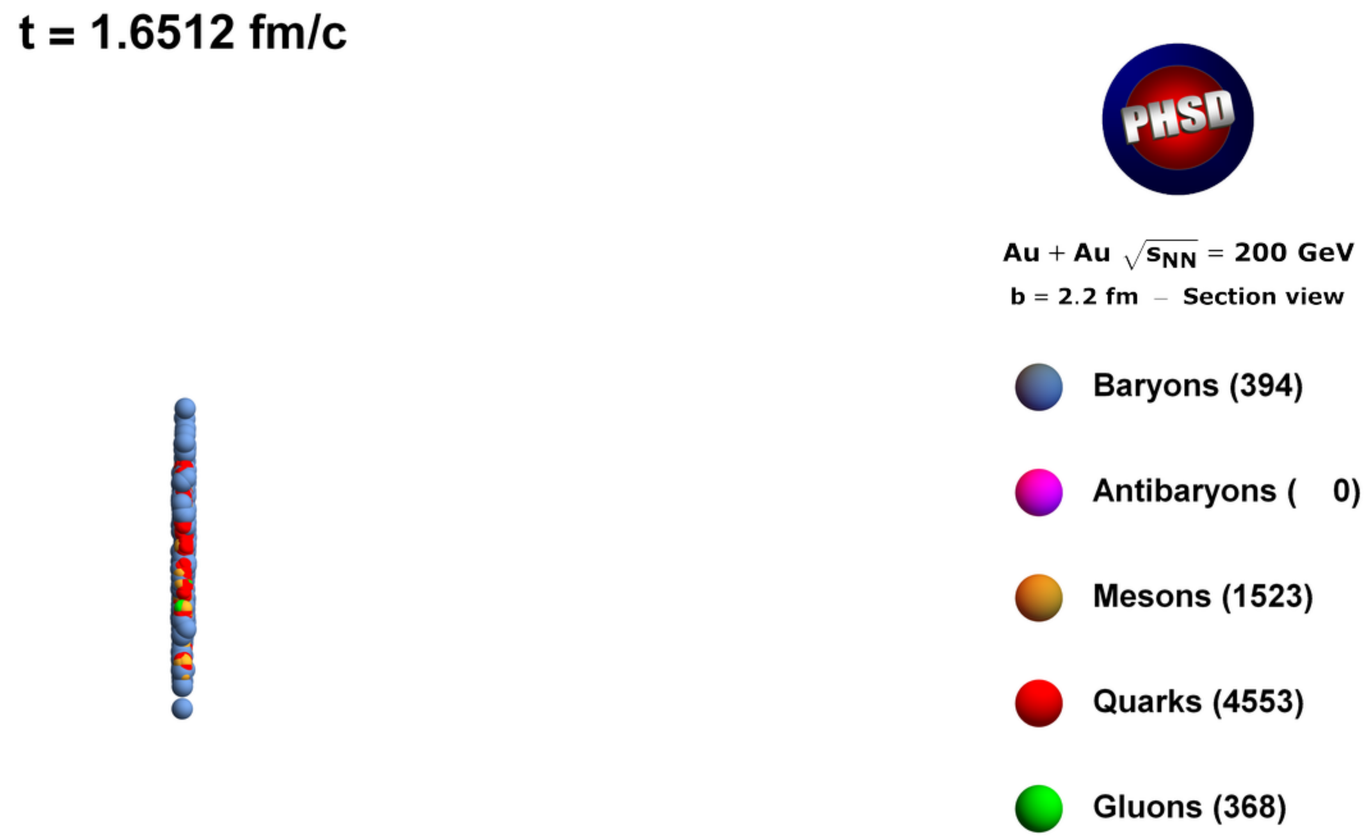
PHSD: W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; P. Moreau et al., PRC100 (2019) 014911

Stages of a collision in PHSD



P.Moreau

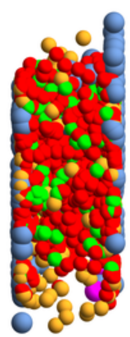
Stages of a collision in PHSD



P.Moreau

Stages of a collision in PHSD

t = 3.91921 fm/c



Au + Au $\sqrt{s_{NN}}$ = 200 GeV

b = 2.2 fm – Section view

Baryons (426)

Antibaryons (29)

Mesons (1189)

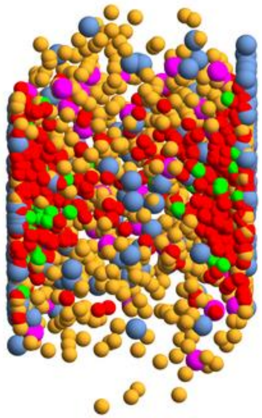
Quarks (4459)

Gluons (783)

P.Moreau

Stages of a collision in PHSD

t = 7.31921 fm/c



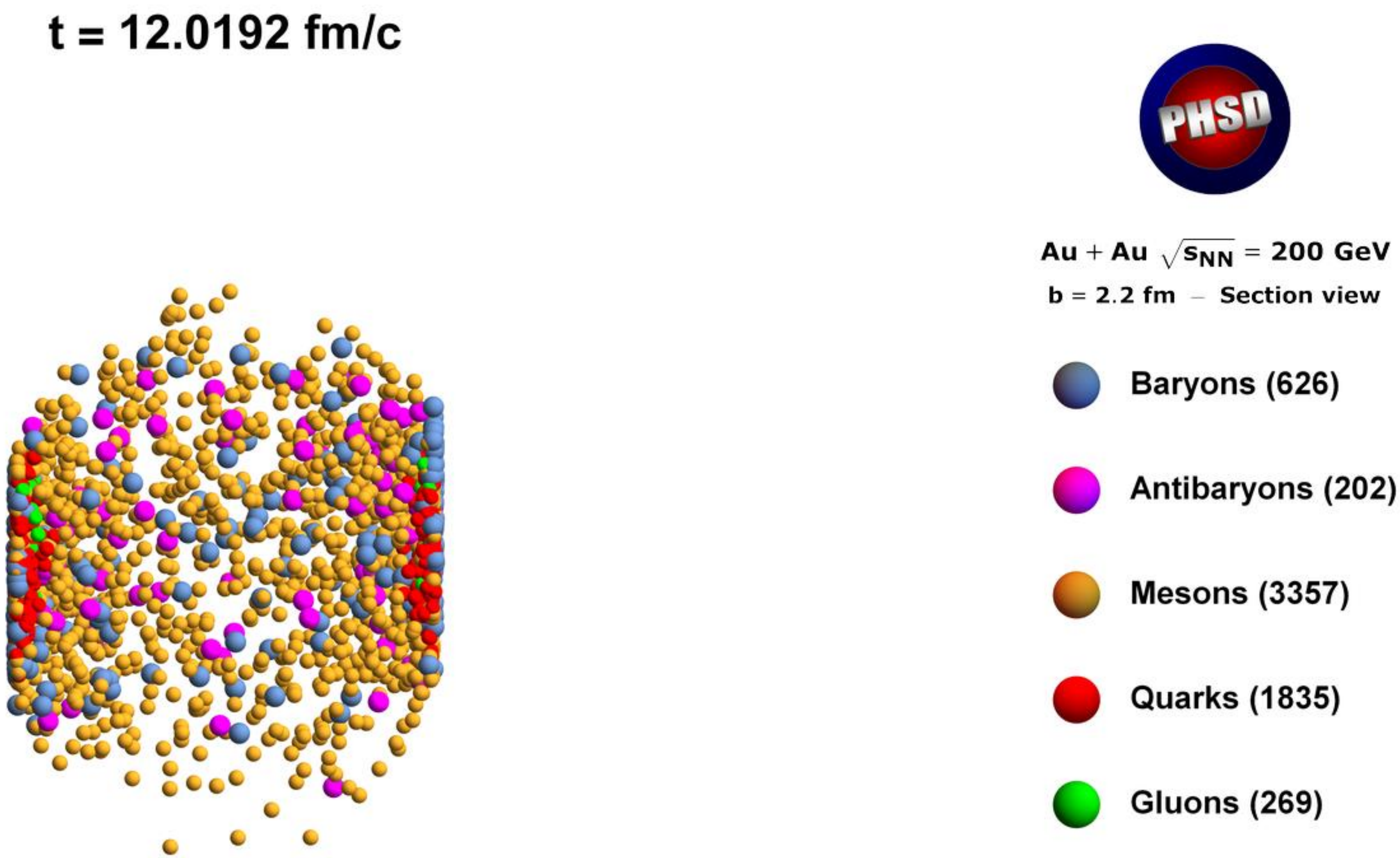
Au + Au $\sqrt{s_{NN}}$ = 200 GeV

b = 2.2 fm – Section view

- Baryons (540)
- Antibaryons (120)
- Mesons (2481)
- Quarks (2901)
- Gluons (492)

P.Moreau

Stages of a collision in PHSD



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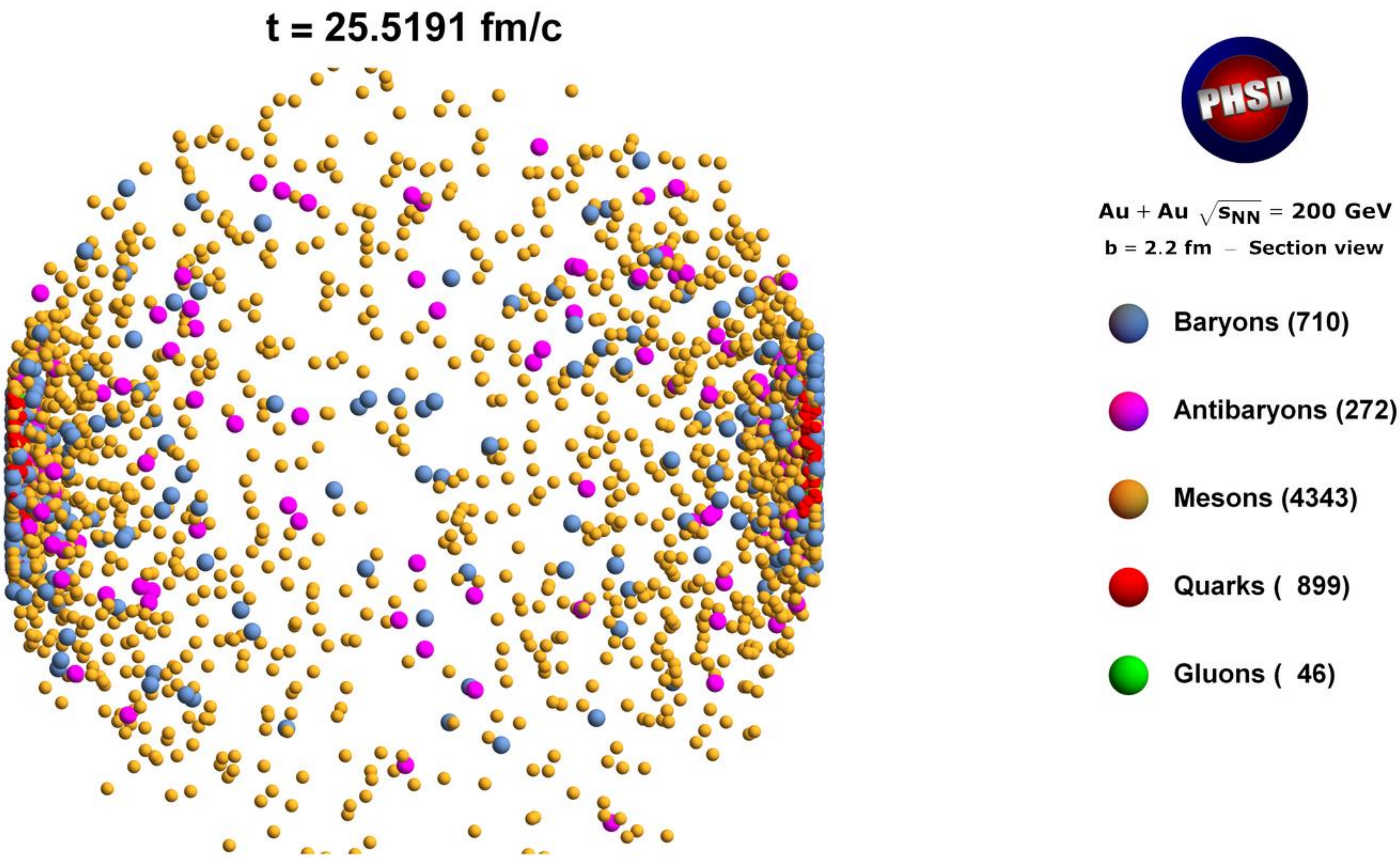
Stages of a collision in PHSD



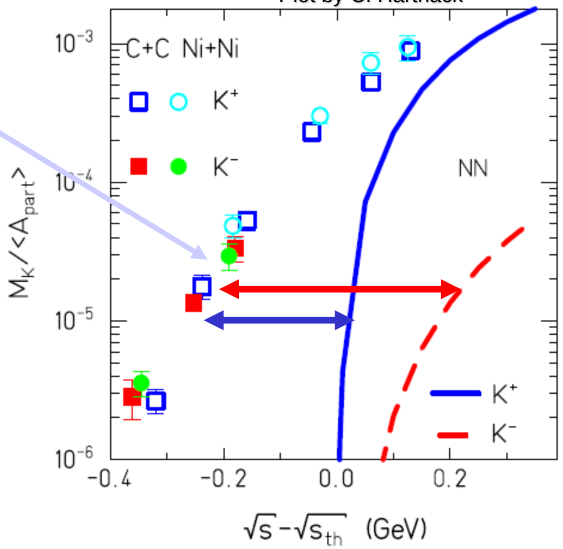
P.Moreau

Strangeness production in HICs

GSI: study strange meson (K, Kbar) production **in A+A at (sub-)threshold energies**

- experimental observation of K^+, K^- production below the NN-threshold

Plot by C. Hartnack



I. Strangeness production channels at low energies

- baryon-baryon collisions:

$$B+B \rightarrow B+Y+K$$

$$B+B \rightarrow B+B+K+\overline{K}$$

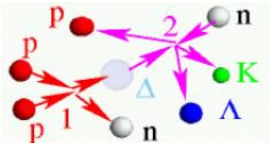
$$B+Y \rightarrow B+B+\overline{K}$$

$$K=(K,K^0)$$

$$\overline{K}=(K^-,\overline{K}^0)$$

$$B=(N,\Delta,...)$$

$$Y=(\Lambda,\Sigma)$$



- meson-baryon collisions:

$$\pi+B \rightarrow Y+K$$

$$\pi+B \rightarrow B+K+\overline{K}$$

$$\pi+Y \rightarrow B+\overline{K}$$

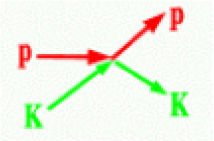
dominant channel for low energy K^- production → $\pi+Y \rightarrow B+\overline{K}$

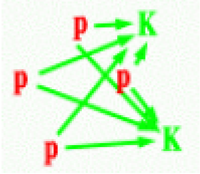
Strange quark exchange between K^- and hyperons $Y=(\Lambda, \Sigma)$

- meson-meson collisions: $\pi+\pi \rightarrow K+\overline{K}$
- resonance decays: $\phi \rightarrow K+\overline{K}$

II. Strangeness rescattering

= (quasi-)elastic scattering with baryons and mesons





The **production cross sections** and **self-energies** of K, Kbar are **modified in the nuclear medium** !

In-medium effects for strange mesons

The hadrons - in particular strange mesons (K, Kbar and K*) - modify their properties in the dense and hot nuclear medium due to the strong interaction with the environment

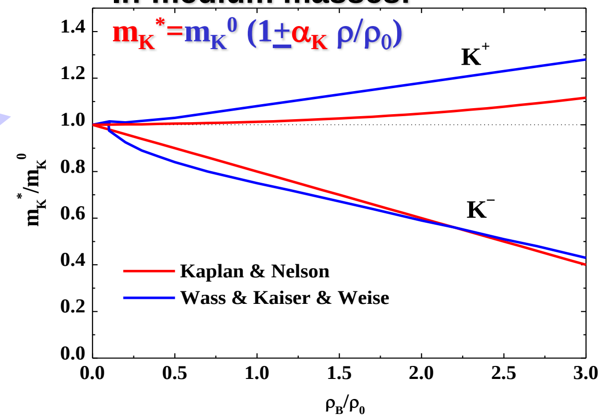
… long history …

Models:

- **chiral SU(3) model, chiral perturbation theory, relativistic mean-field models: KN-potential ➔ dropping' of K^- mass and enhancement' of K^+ mass**

Kaplan and Nelson, PLB 175 (1986) 57;
Weise, Brown, Schaffner, Krippa, Oset, Lutz, Mishra, ... et al.

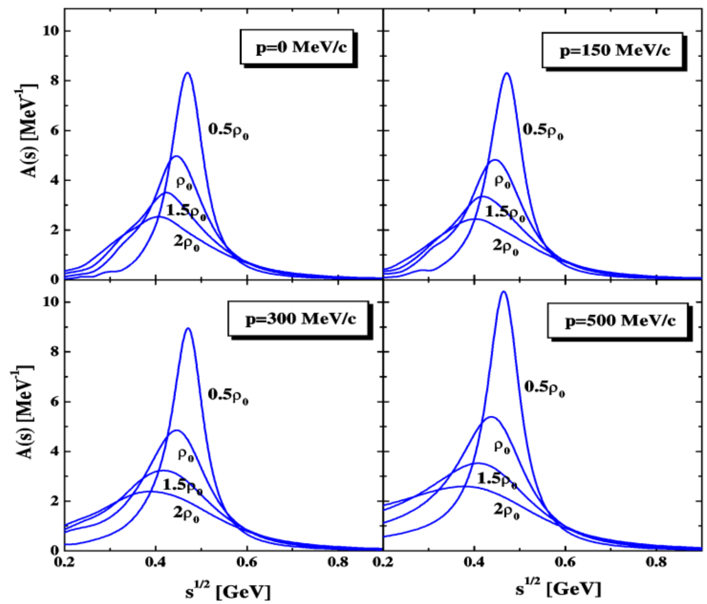
In-medium masses:



- **self-consistent coupled-channel approach - G-matrix:**

➔ momentum, density and temperature dependent spectral function of antikaons $A(p_K,\rho,T)$: in-medium modification of the real and imaginary part of the self-energy Σ (mass and width)

L. Tolos et al., NPA 690 (2001) 547



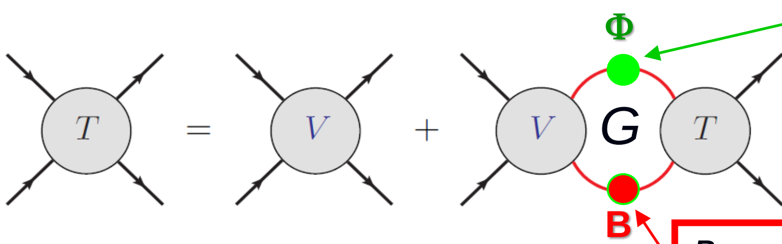
➔ off-shell HSD: W. Cassing et al., Nucl.Phys.A 727 (2003) 59

Cf. review: C. Hartnack et al., Phys.Rept. 510 (2012) 119

The coupled-channel G-matrix approach

Solution of the Bethe-Salpeter equation in coupled channels:

Medium:



Meson selfenergy and spectral function

Baryons: Pauli blocking and potential dressing

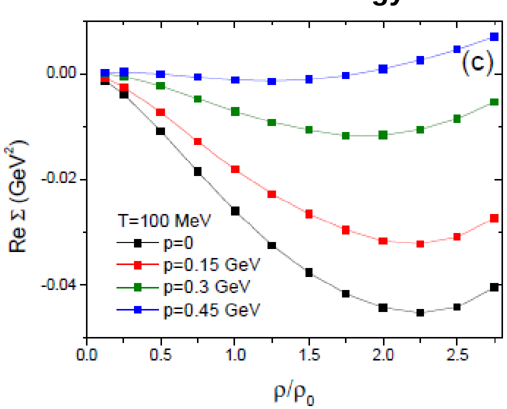
$$\mathcal{T}_{ij}(\rho,T) = V_{ij} + V_{il}\, G_l(\rho,T)\, \mathcal{T}_{lj}(\rho,T)$$

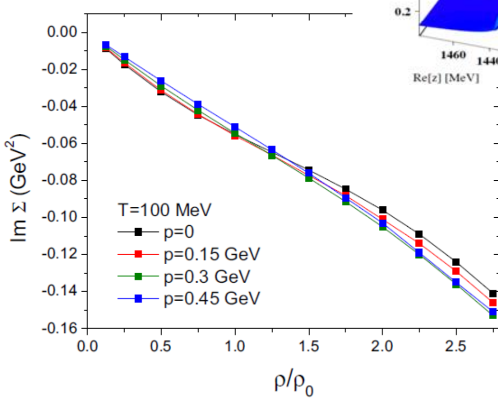
$$P \propto |T|^2$$

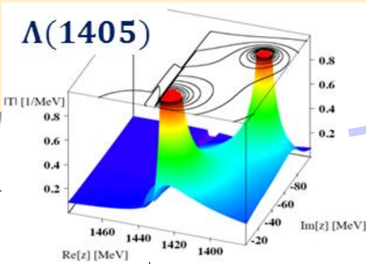
Coupled-channels [full $SU(3)$ basis, isospin $I = 0,1$]

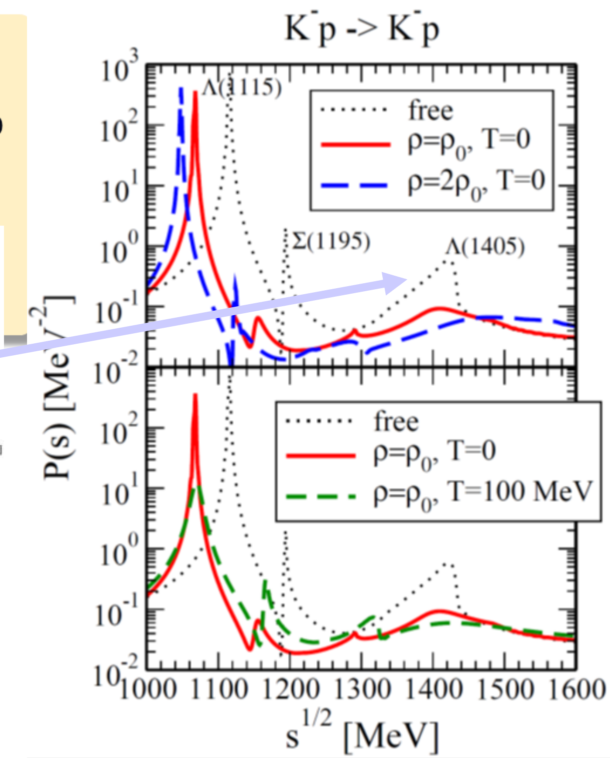
- $S = -1$: $K^-p,\ \bar{K}^0n,\ \pi^0\Lambda,\ \pi^0\Sigma^0,\ \eta\Lambda,\ \eta\Sigma^0,\ \pi^+\Sigma^-,\ \pi^-\Sigma^+,\ K^+\Xi^-,\ K^0\Xi^0$
  $K^-n,\ \pi^0\Sigma^-,\ \pi^-\Sigma^0,\ \pi^-\Lambda,\ \eta\Sigma^-,\ K^0\Xi^-$
- $S = +1$: $K^+p;\ K^+n,\ K^0p$

In-medium K$^-$ self-energy: $\Sigma = \mathrm{Re}\Sigma + i\,\mathrm{Im}\Sigma$





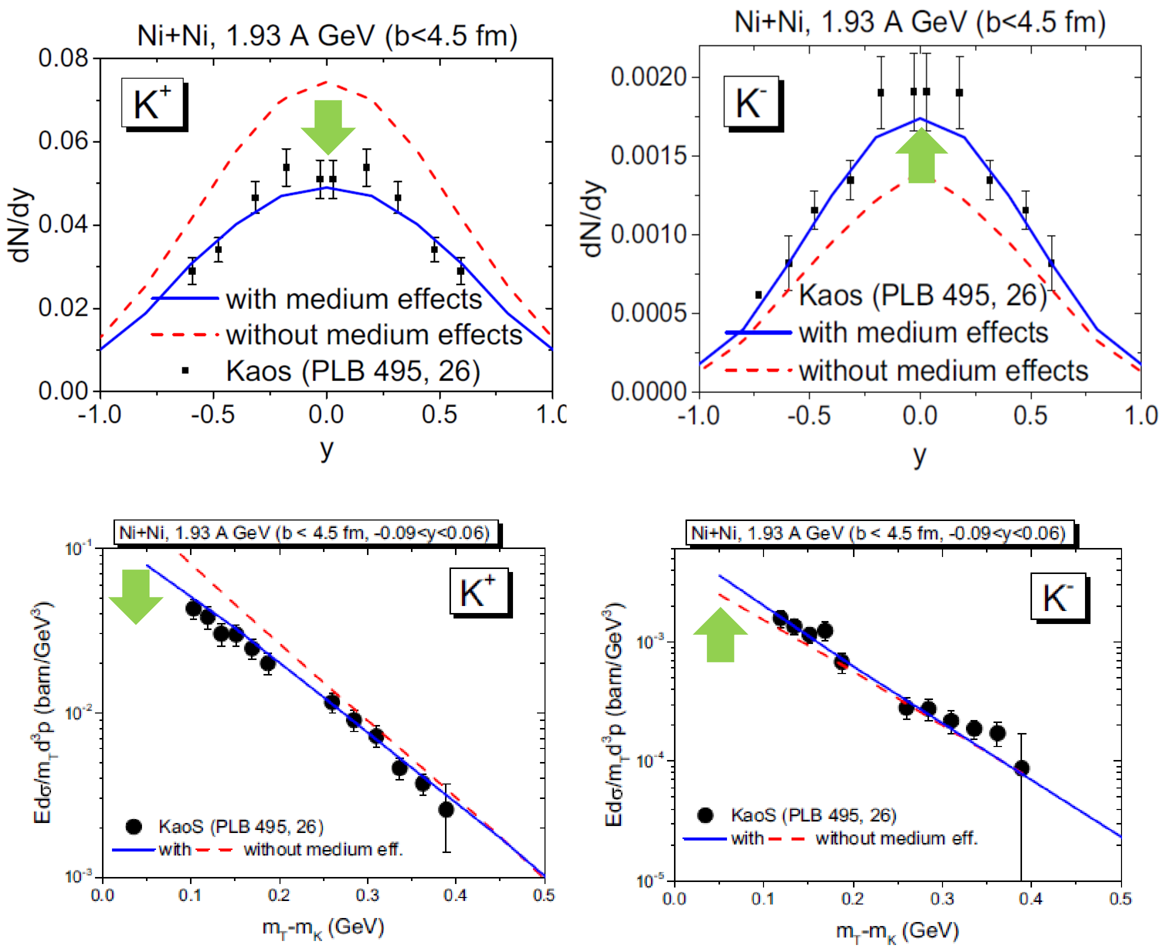




G-matrix (based on the Jülich meson-exchange model): L. Tolos et al., NPA 690 (2001) 547

Improved (based on SU(3) mB chiral Lagrangian): D. Cabrera, L. Tolos, J. Aichelin, E.B., PRC90 (2014) 055207

y- and m_T spectra of (anti)kaons in central Ni+Ni collisions at 1.93 A GeV



In-medium effects :

- **suppresses kaon production**
- **hardens kaon spectrum**
- **enhances antikaon production**
- **softens antikaon spectrum**

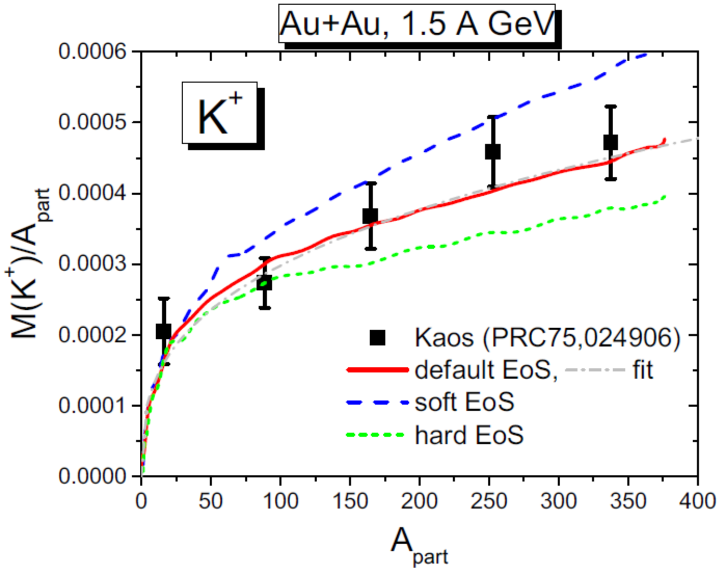
Heavy-ion experiments at SIS energies (FOPI, KaoS, HADES):

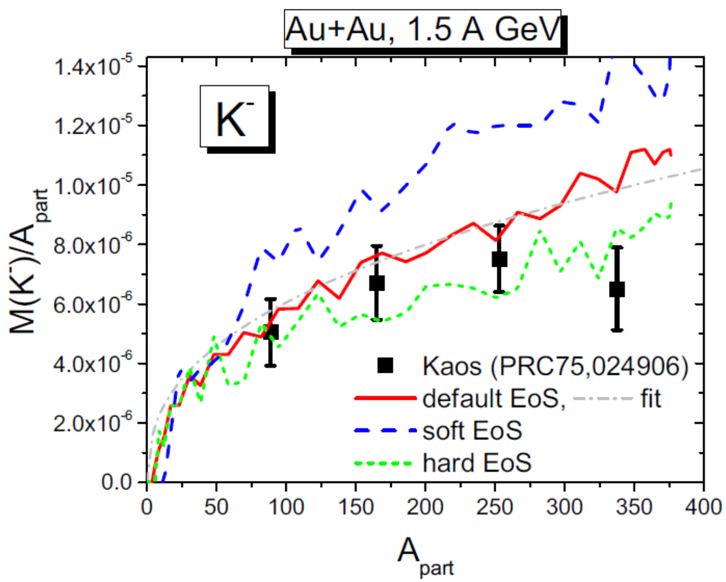
Observables: invariant yield, rapidity spectra, ratios, flow, angular distributions ➔

- **Moderate repulsive potential for K^+**
- **Stronger attractive potential for K^-**
- **K+ and K- exhibit different freeze-out conditions**

T. Song et al., PRC 103, 044901 (2021)

Probing of EoS with strangeness

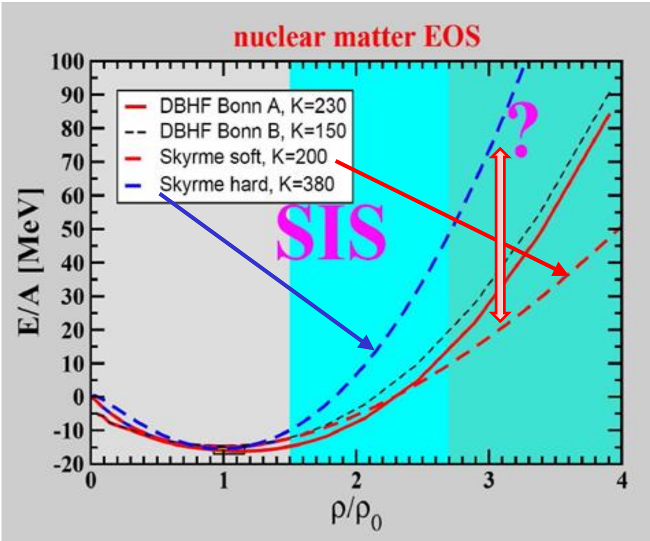




Skyrme potential: $U(\rho) = a\left(\frac{\rho}{\rho_0}\right) + b\left(\frac{\rho}{\rho_0}\right)^{\gamma}$

where $a = -153$ MeV, $b = 98.8$ MeV, $\gamma = 1.63$.

Compression modulus K : $K = -V\frac{dP}{dV} = 9\rho^2 \frac{\partial^2(E/A)}{\partial \rho^2}\Big|_{\rho_0}$



DBHF model: Dirac-Brückner-Hartree-Fock G-matrix – density and momentum dependent potential

Sensitivity to EoS:

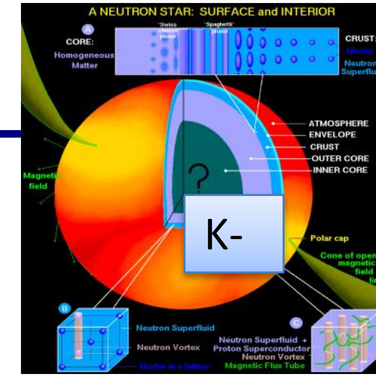
Hard EoS: K=380 MeV → hard to be compressed, less NN collisions to produce (anti)kaons

Default EoS: K=300 MeV

Soft EoS: K= 210 MeV→ easy to be compressed, more NN collisions to produce (anti)kaons

T. Song et al., PRC 103, 044901 (2021)

From kaons in HICs …. to stars



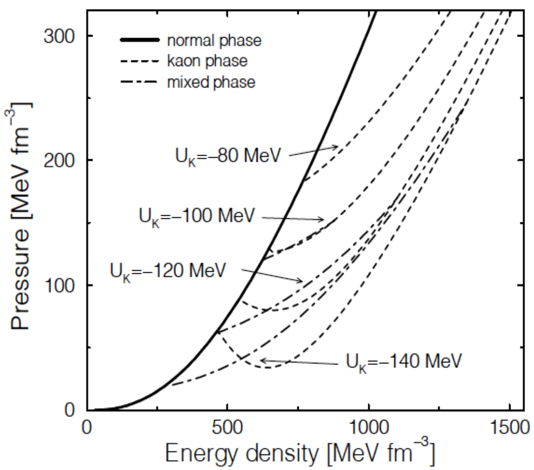
Kaon condensation in neutron stars ?

* Kaplan and Nelson '86 :

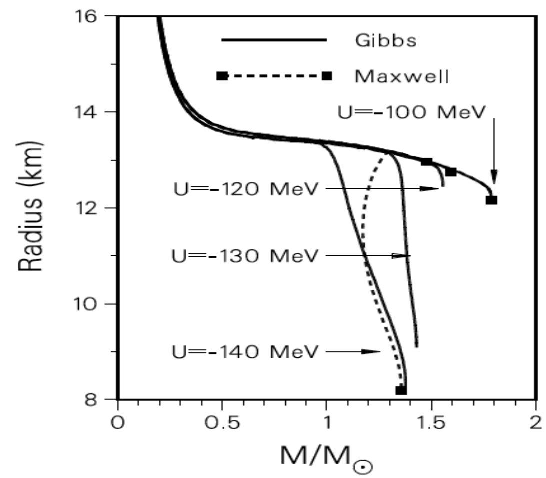
In-medium effects on (anti)kaons can be pronounced so as to have kaon condensation

* Glendenning and Schaffner-Bielich '99 :

Antikaon potential at saturation density is deeper than -120 MeV



EoS is softened due to kaon condensation



The maximum star mass is lowered with increasing attractive K^-N potential

Constraints from theory and HICs:

* Tolos, Polls, Ramos '01; Cabrera, Tolos, Aichelin and E.B.'14; Song et al.,'21

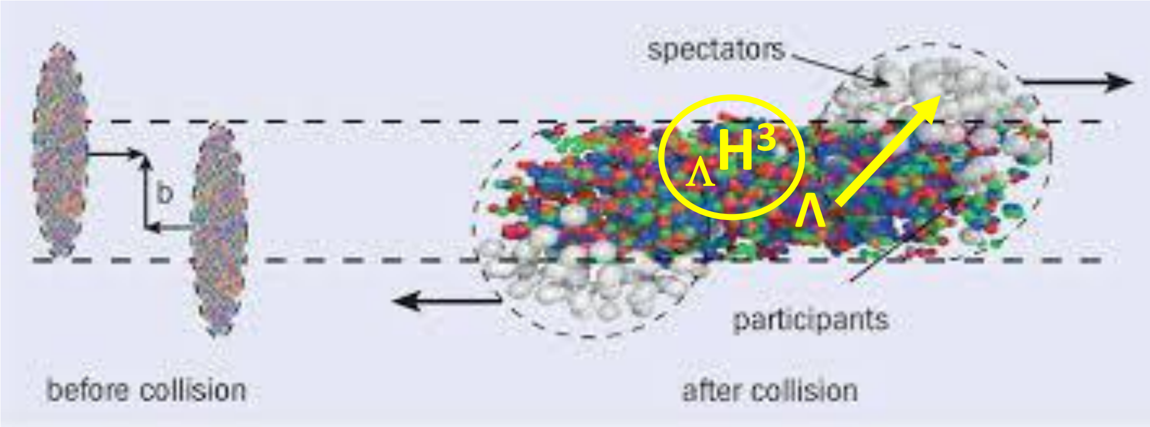
G-matrix unitarized scheme based on meson-exchange models or chiral Lagrangians predicts a moderate attraction in nuclear matter ← consistent with heavy-ion results!

➔ kaon condensation in neutron stars seems very unlikely according to G-matrix model

Credit: Laura Tolos

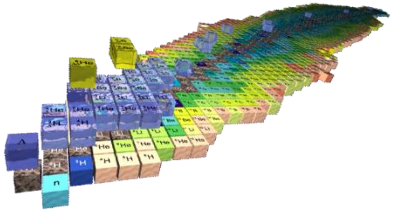
Why do we study hypermatter production?

Hyperons Y=(Λ, Σ) are produced by elementary reactions during the heavy-ion collisions in the middle of the fireball and traverse to the target/projectile region by interactions with nuclear matter. They can form hypernuclei.



Hypernuclei as bound objects:

- **give information on hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions**
- **EoS including strangeness**
- **give access to the third dimension of the nuclear chart (strangeness)**
- **important for neutron stars (production of hypermatter at high density and low temperature)**
- **new field of hyperon spectroscopy**



PHQMD

PHQMD: a **unified n-body microscopic transport approach for the description of heavy-ion collisions and dynamical cluster formation from low to ultra-relativistic energies**

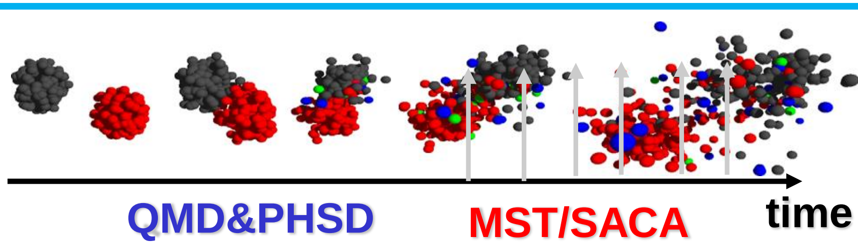
Realization: **combined model PHQMD = (PHSD & QMD) & (MST/SACA)**

Parton-Hadron-Quantum-Molecular Dynamics

Initialization → propagation of baryons:
QMD (Quantum-Molecular Dynamics)

Propagation of partons (quarks, gluons) and mesons
+ collision integral = interactions of hadrons and partons (QGP)
from PHSD (Parton-Hadron-String Dynamics)

Cluster recognition:
SACA (Simulated Annealing Clusterization Algorithm)
or MST (Minimum Spanning Tree)

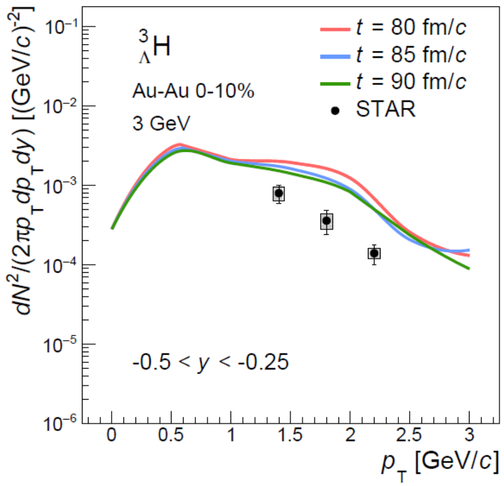


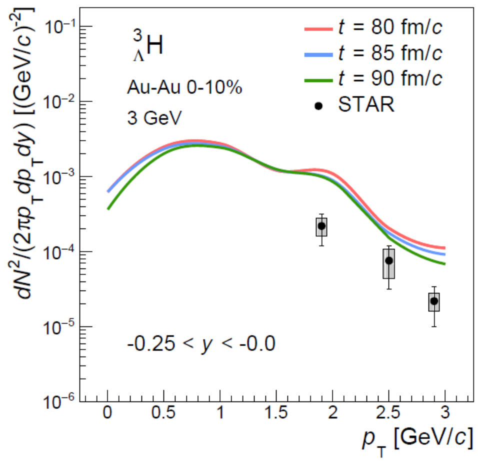
J. Aichelin et al., PRC 101 (2020) 044905;
S. Gläßel et al., PRC 105 (2022) 014908

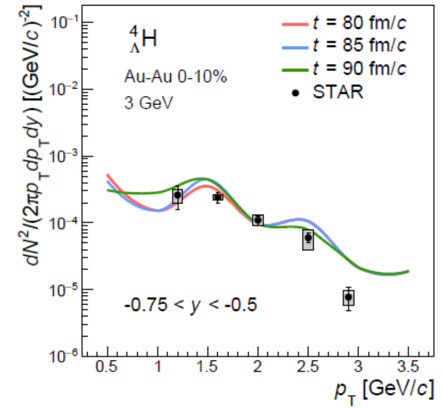
Hypernuclei production at $s^{1/2}$ = 3 GeV

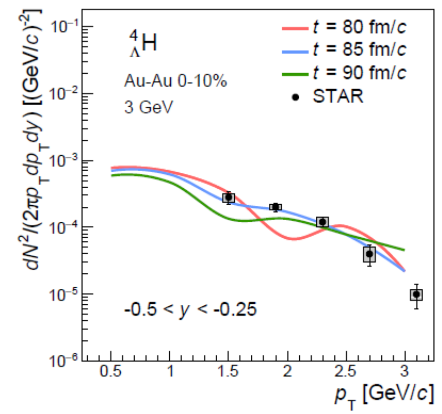
The PHQMD comparison with most recent STAR fixed target distribution of $^3H_\Lambda$, $^4H_\Lambda$ from Au+Au central collisions at $\sqrt{s}$ =3 GeV

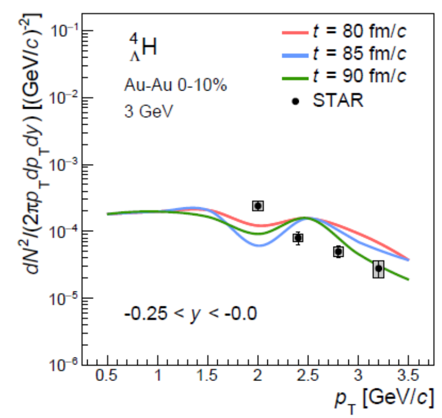
- **Assumption for nucleon-hyperon potential: $V_{N\Lambda}$ = 2/3 V_{NN}**











➔ **Reasonable description of hypernuclei production**

- ❑ **PHQMD predicts the dynamical formation of clusters from low to ultra-relativistic energies due to the interactions**
- ❑ **Cluster formation is sensitive to the YN and NN potential ➔ sensitivity to EoS**

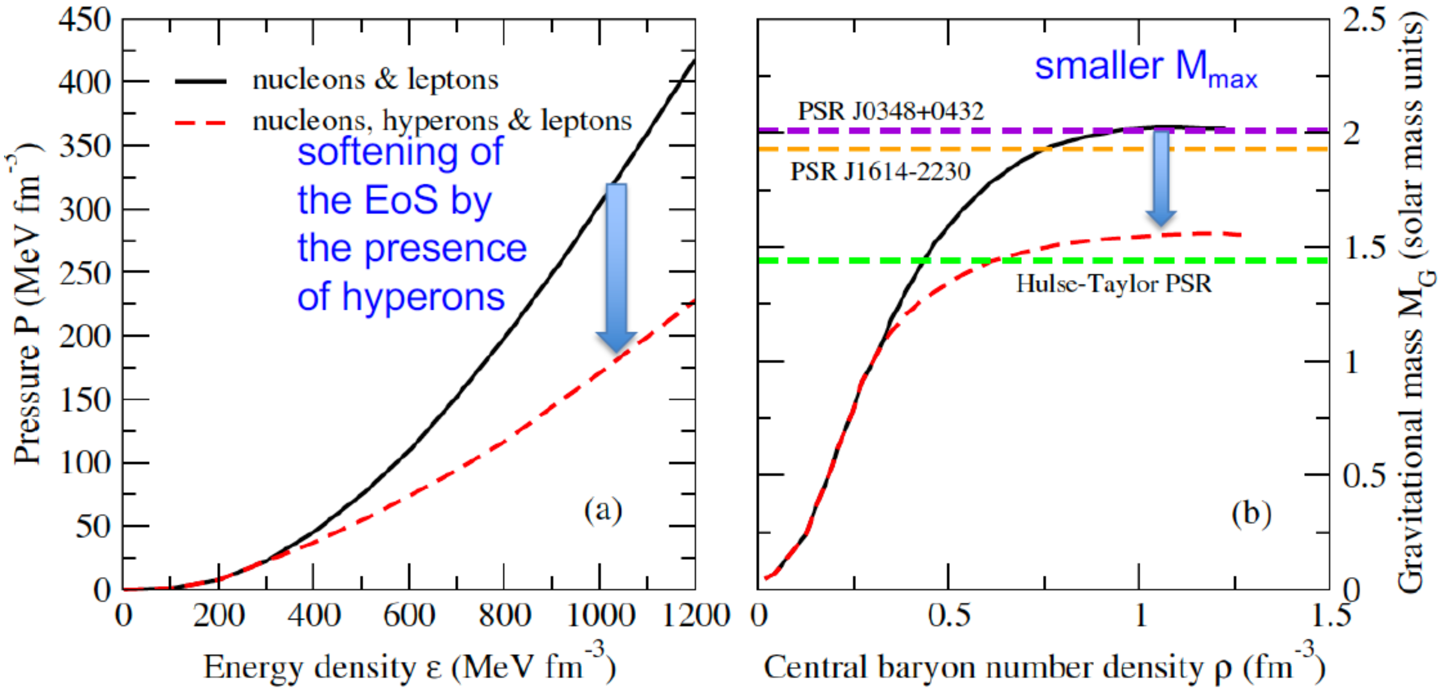
S. Gläßel et al., PRC 105 (2022) 014908

Neutron stars with hyperons

The presence of hyperons in neutron stars
➔ softening of EoS:

β–stable hyperonic matter:

$$n + n \rightarrow n + \Lambda$$
$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$
$$n + n \rightarrow p + \Sigma^-$$
$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$



Chatterjee and Vidana '16; Vidana '18

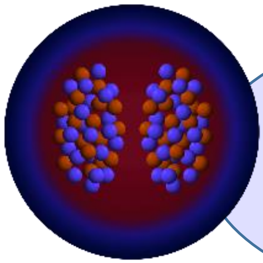
Credit: Laura Tolos

'Hyperon puzzle': induces a strong softening of the EoS that leads to $M_{max} < 2M_\odot$

– possible solution of 'hyperon puzzle': dark matter inside stars ➔

Search for DM particles: DMLab theory

DM ‚candidate‘ 



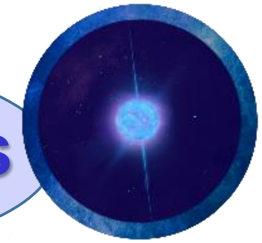
Heavy-ion physics

- Search for DM particles in HIC based on SM-DM interactions via possible portals:

$$\mathcal{L} \supset \begin{cases} -\dfrac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}\,, & \text{vector portal} \\ (\mu\phi + \lambda\phi^2) H^\dagger H\,, & \text{Higgs portal} \\ y_n L H N\,, & \text{neutrino portal} \\ \frac{a}{f_a} F_{\mu\nu} \widetilde{F}^{\mu\nu}\,, & \text{axion portal.} \end{cases}$$

➔ Constraints on masses and coupling constants of DM candidates by comparison of theory results with experimental data

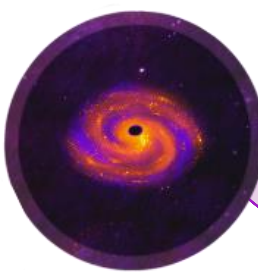
Astrophysics



➔ Constraints from astrophysical observations: masses, radii of stars, star cooling (e.g. $\Lambda \rightarrow \pi^0 + X^0$), gravitational waves

Camalich et al., PRD 103 (2021) L12301

Cosmology

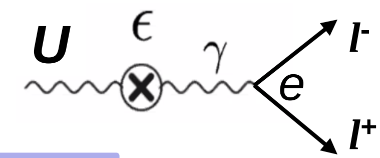


➔ Constraints from cosmological observations: evolution of Universe, matter density, cosmic microwave background, rotation of galaxis

Light dark photons searches with heavy-ions

The **'vector' portal :** existence of a **U(1)-U(1)′** gauge symmetry group mixing

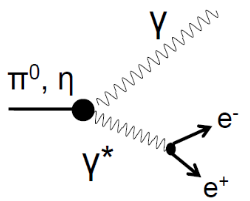
$$\mathcal{L}_{A'} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}B^{\mu\nu}F'_{\mu\nu} - \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu}$$



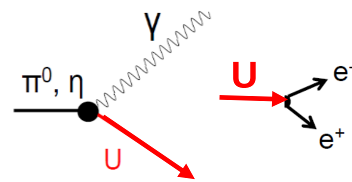
Notation for 'dark photon': A' or U- boson

Unknown: kinetic mixing parameter ϵ and mass M_U

B. Holdom, PL B 166, 196 (1986)
B. Batell et al., PRD 80, 095024 (2009)

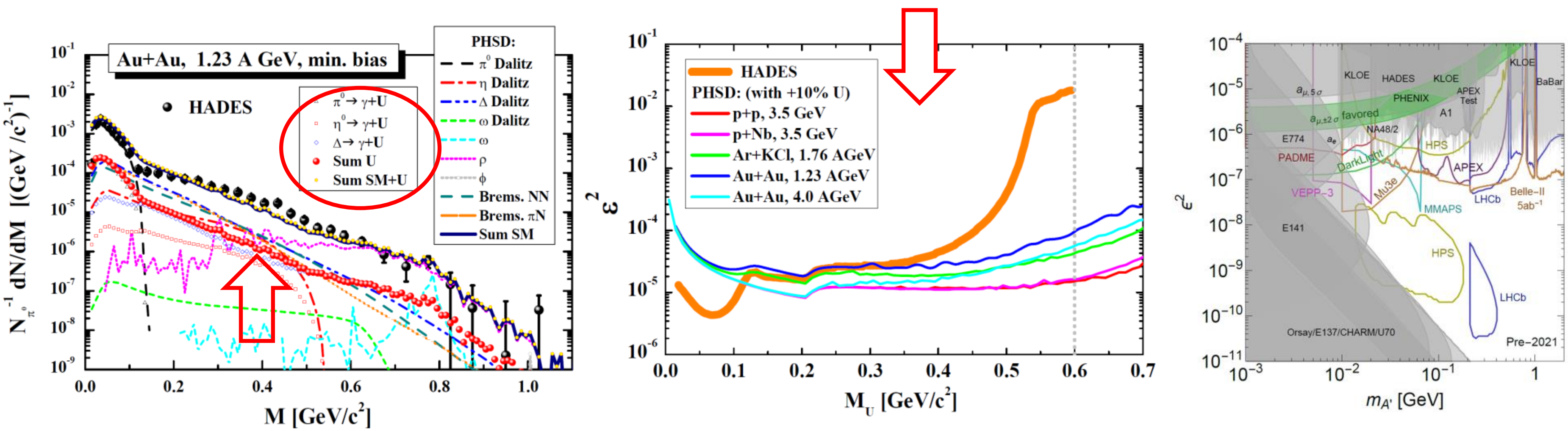


U(1)-U(1)′ kinetic mixing

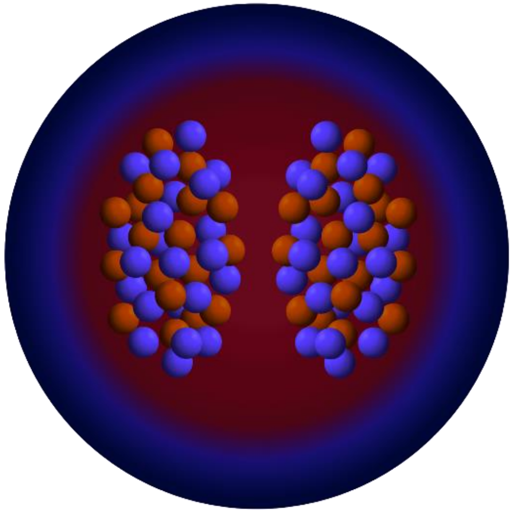


$\pi^0 \rightarrow \gamma+U$,
$\eta \rightarrow \gamma+U$, $U \rightarrow e^+e^-$
$\Delta \rightarrow N+U$

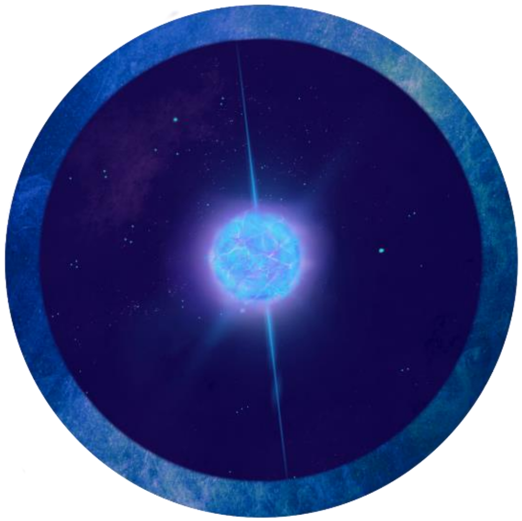
The **upper limit for the kinetic mixing parameter $\varepsilon^2(M_U)$** of light dark photons extracted from the **PHSD** dilepton spectra - with 10% allowed surplus of the total SM yield by an additional **DM yield** at given M:



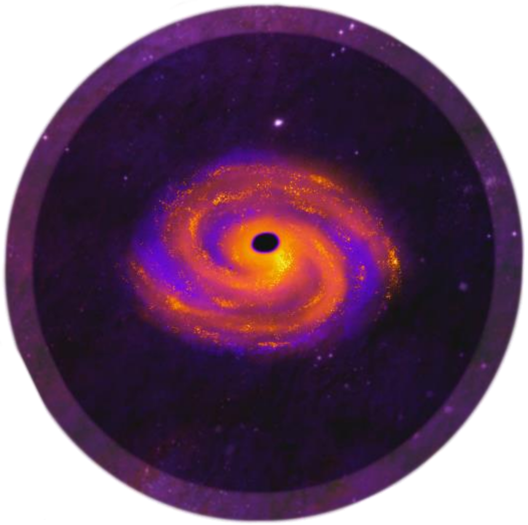
Ida Schmidt, E.B., Malgorzata Gumberidze, Romain Holzmann, Phys.Rev.D 104 (2021) 015008



Thank you for your attention !



DARK MATTER LAB



Credit: Marie Cassing