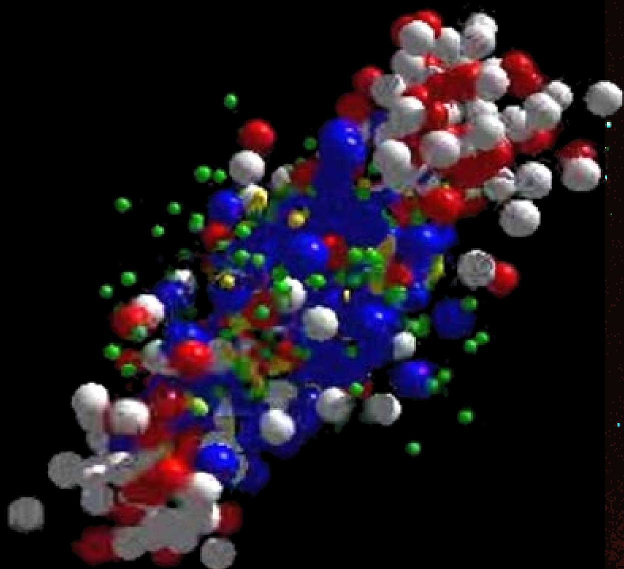
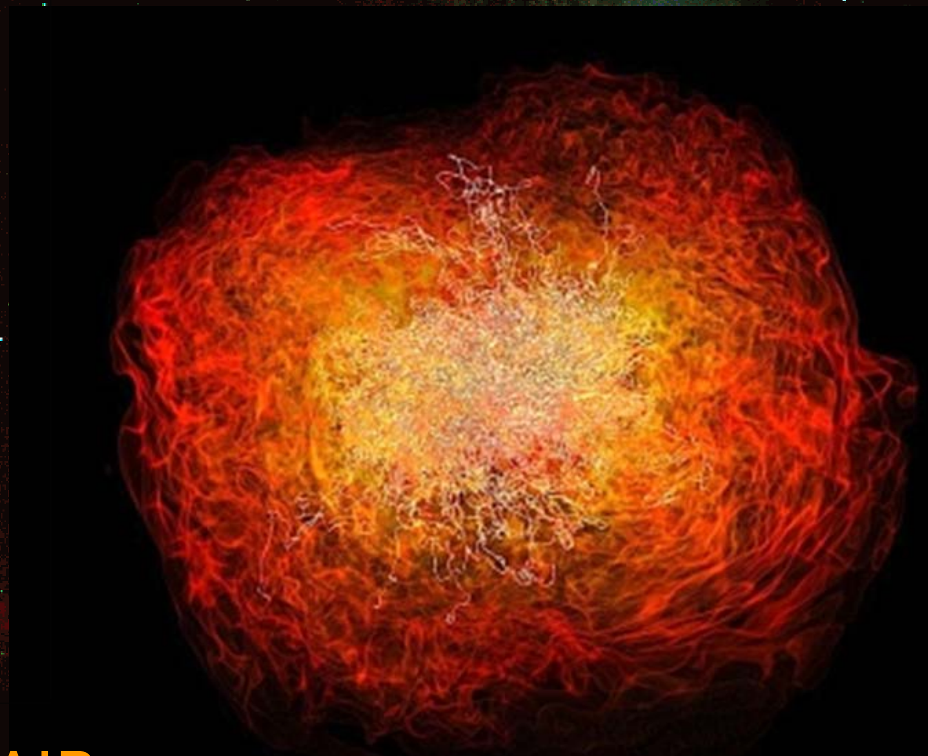
The heavy-ion program at FAIR

Peter Senger · GSI and Univ. Frankfurt





Outline:

- The status of FAIR
- The CBM physics case
- The CBM experiment

ICPPA 2016, Moscow, October 10 – 14, 2016

Facility for Antiproton & Ion Research

FAIR is the largest upcoming fundamental science project worldwide this decade.

Forefront research in nuclear, hadron, atomic, plasma and applied physics.

- Construction until 2022
- 10 member states up to date
- 2500 - 3000 users
- Total cost ~1.6 Billion € (German funds 70%, rest from International partners)

Germany	
Russia	
Finland	
France	
India	
Poland	
Romania	
Slovenia	
Sweden	
UK (associated)	

FAIR Signatory Countries

Facility for Antiproton & Ion Research

Primary Beams

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- 10^{10}/s $^{238}U^{92+}$ up to 11 (35) GeV/u
- 3x10^{13}/s 30 (90) GeV protons

Technical Challenges

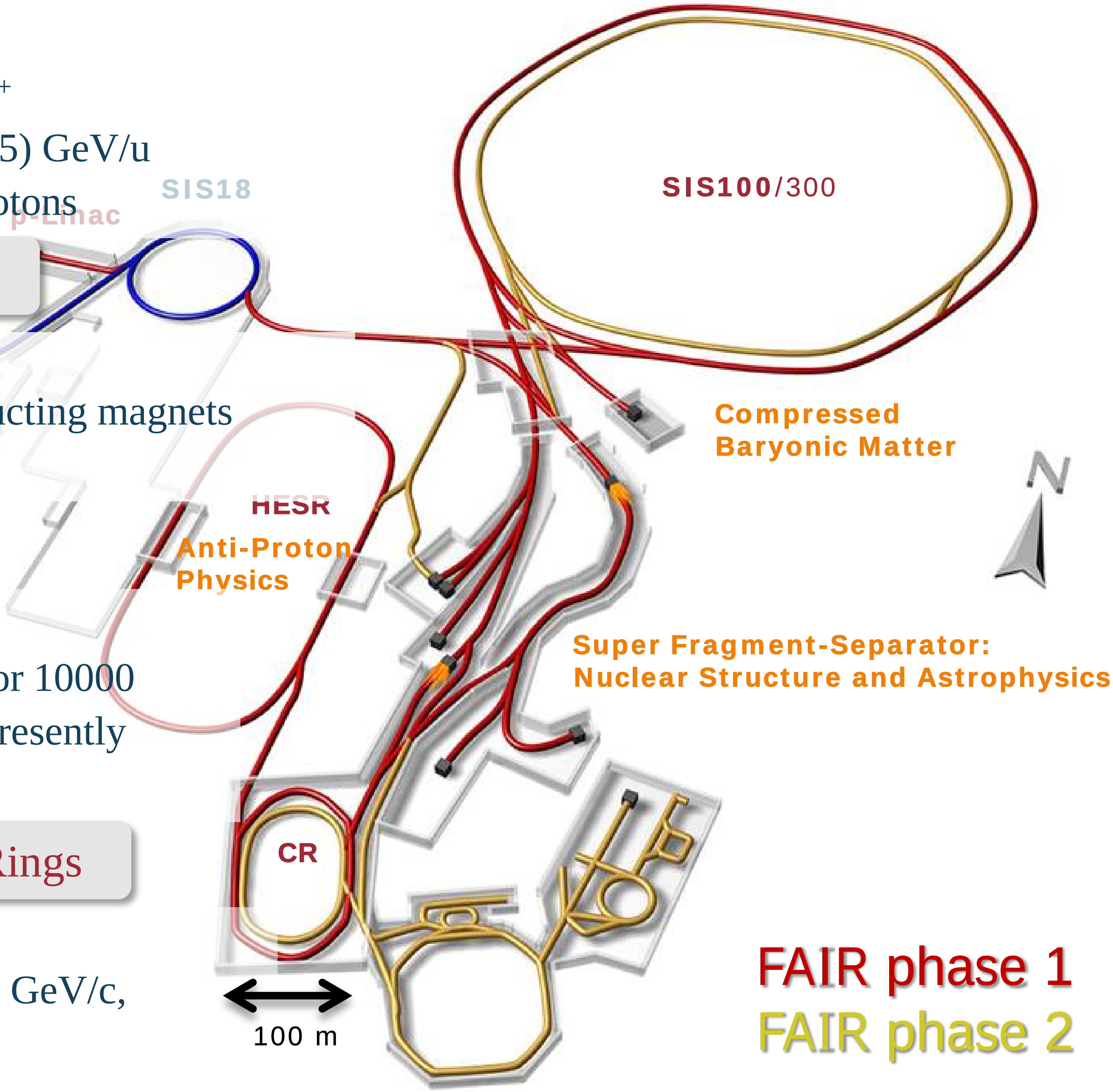
- cooled beams
- rapid cycling superconducting magnets
- dynamical vacuum

Secondary Beams

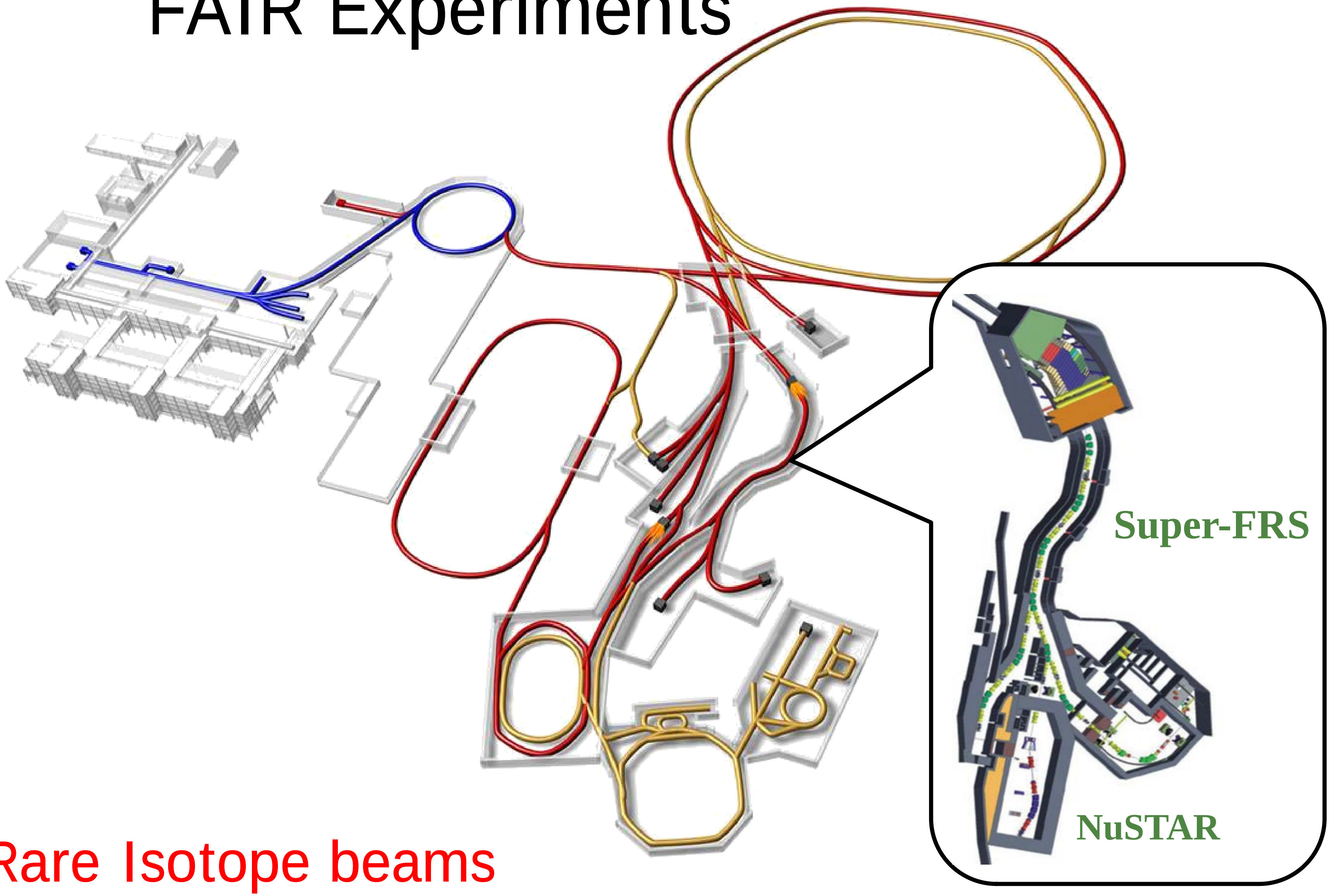
- radioactive beams up to 1.5 - 2 GeV/u; up to factor 10000 higher in intensity than presently
- antiprotons 3 - 30 GeV

Storage and Cooler Rings

- radioactive beams
- 10^{11} antiprotons 1.5 - 15 GeV/c, stored and cooled



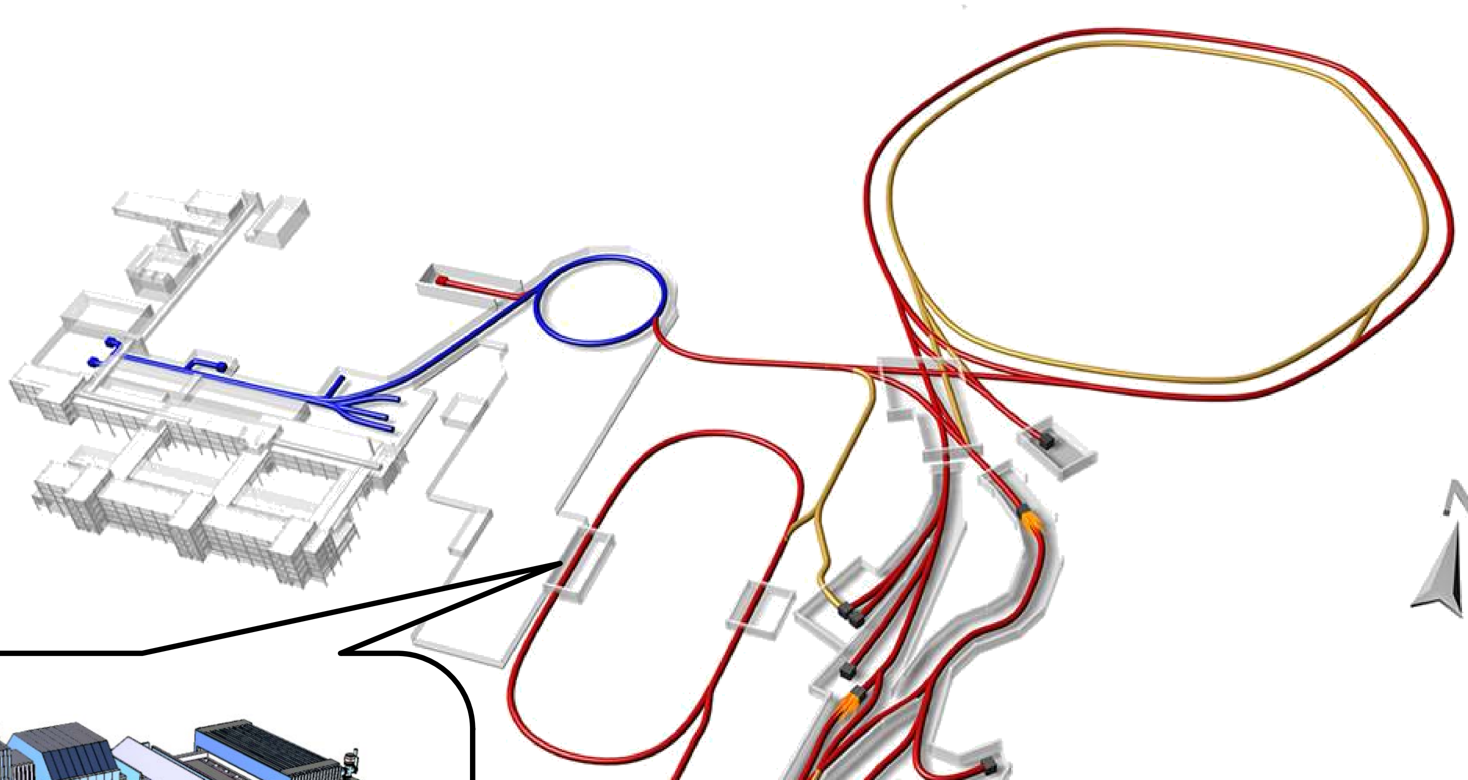
FAIR Experiments

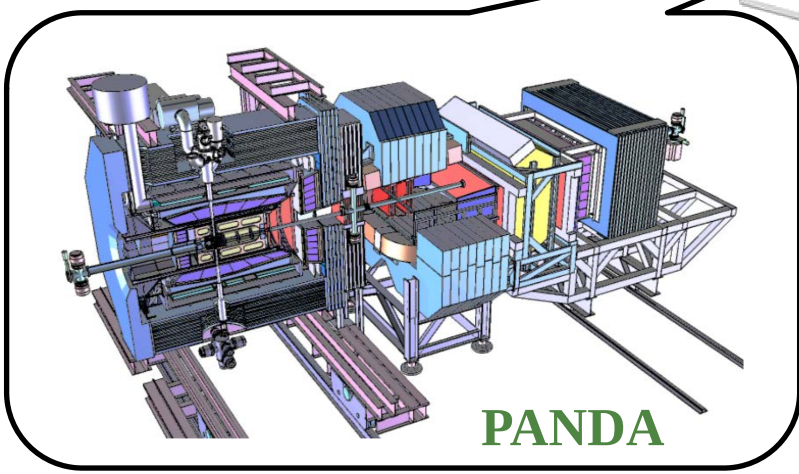


Rare Isotope beams

- Nuclear structure far off stability
- Nucleosynthesis in stars and supernovae

FAIR Experiments

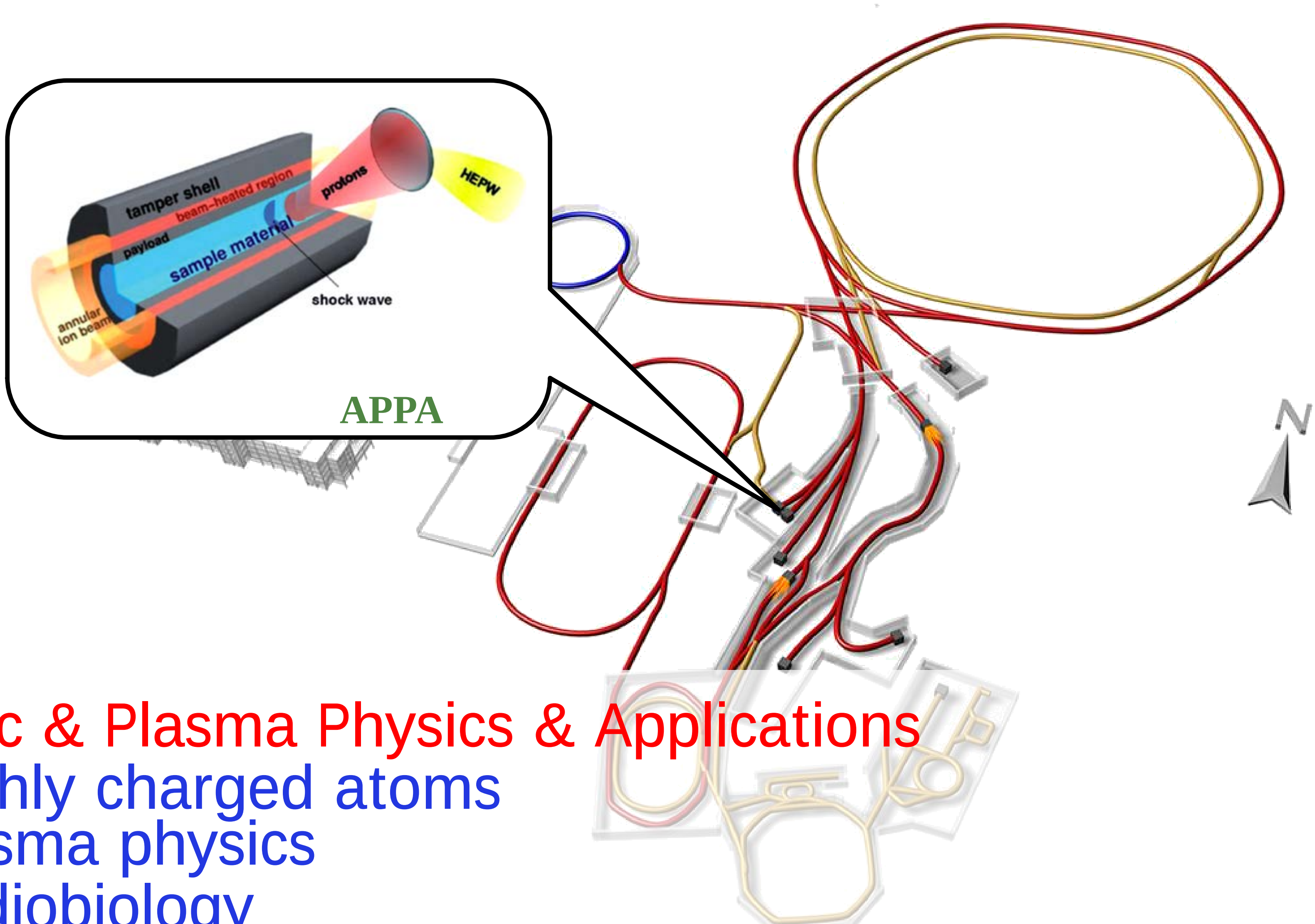




Antiproton-proton collisions:

- Charmed hadrons (XYZ)
- Gluonic matter and hybrids
- Hadron structure
- Double Lambda hypernuclei

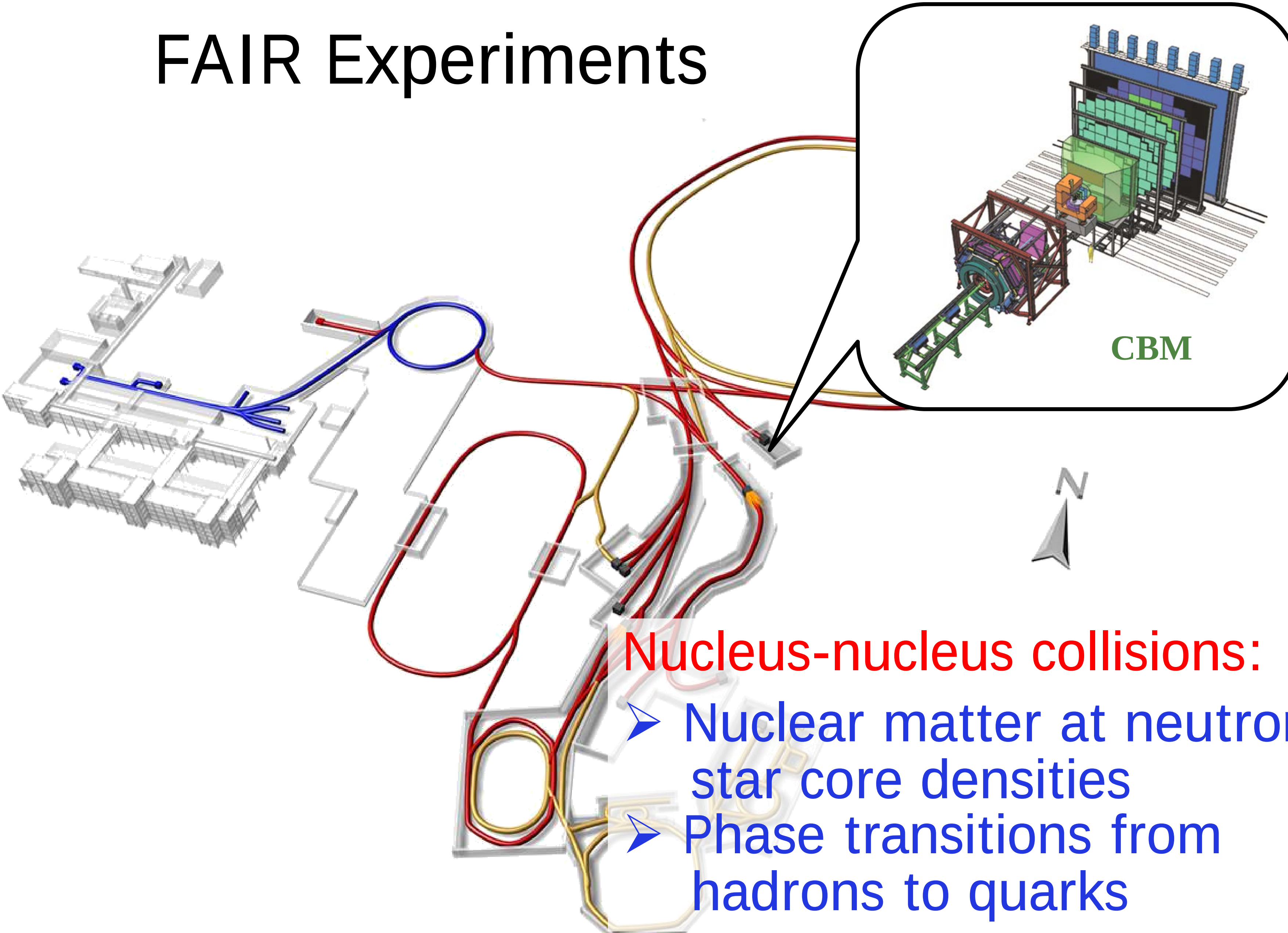
FAIR Experiments



Atomic & Plasma Physics & Applications

- Highly charged atoms
- Plasma physics
- Radiobiology
- Material science

FAIR Experiments



Nucleus-nucleus collisions:

- Nuclear matter at neutron star core densities
- Phase transitions from hadrons to quarks

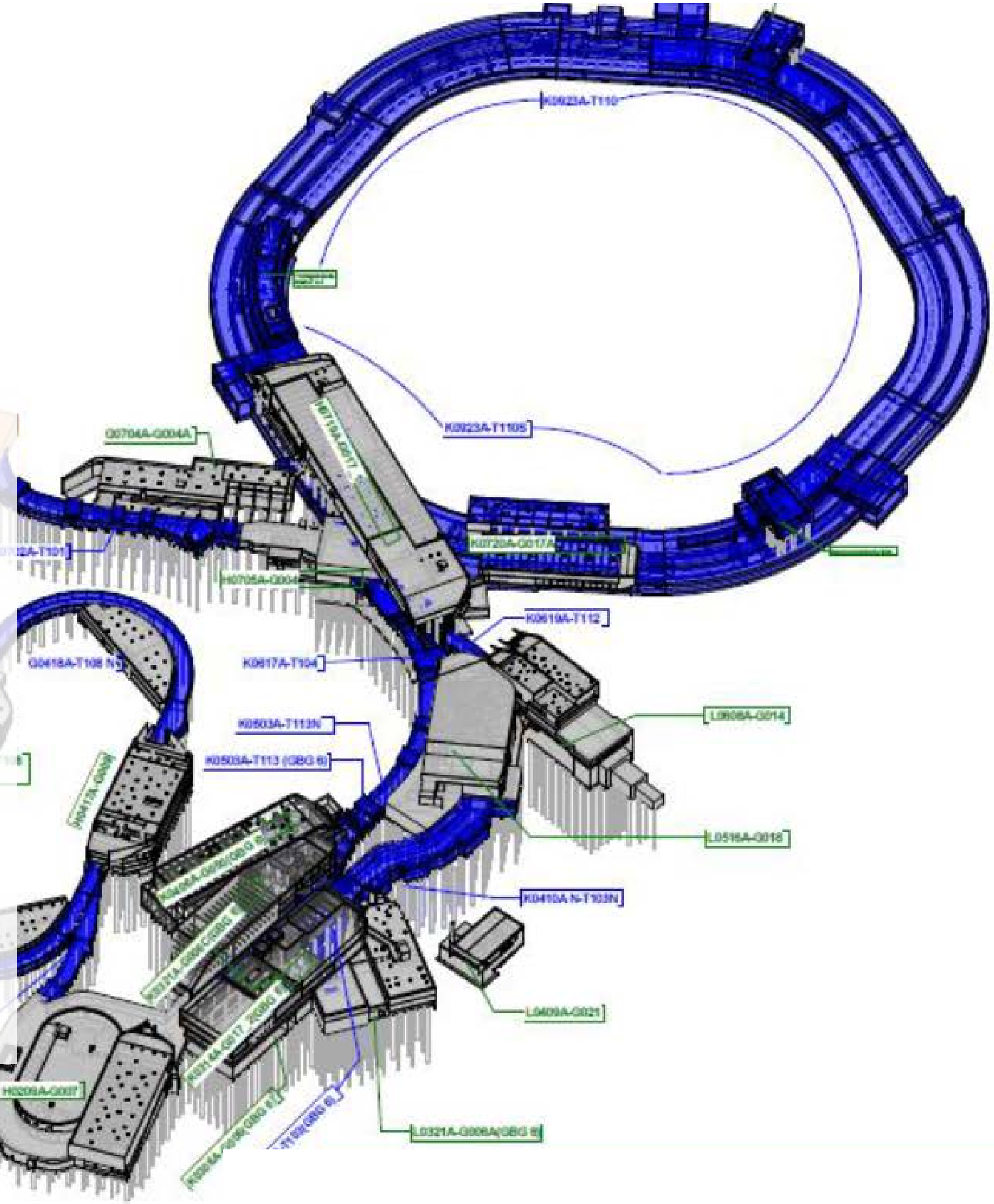
Status of FAIR

On Sept. 13, 2016 BMBF gave green light and 203 M€ to start civil construction.

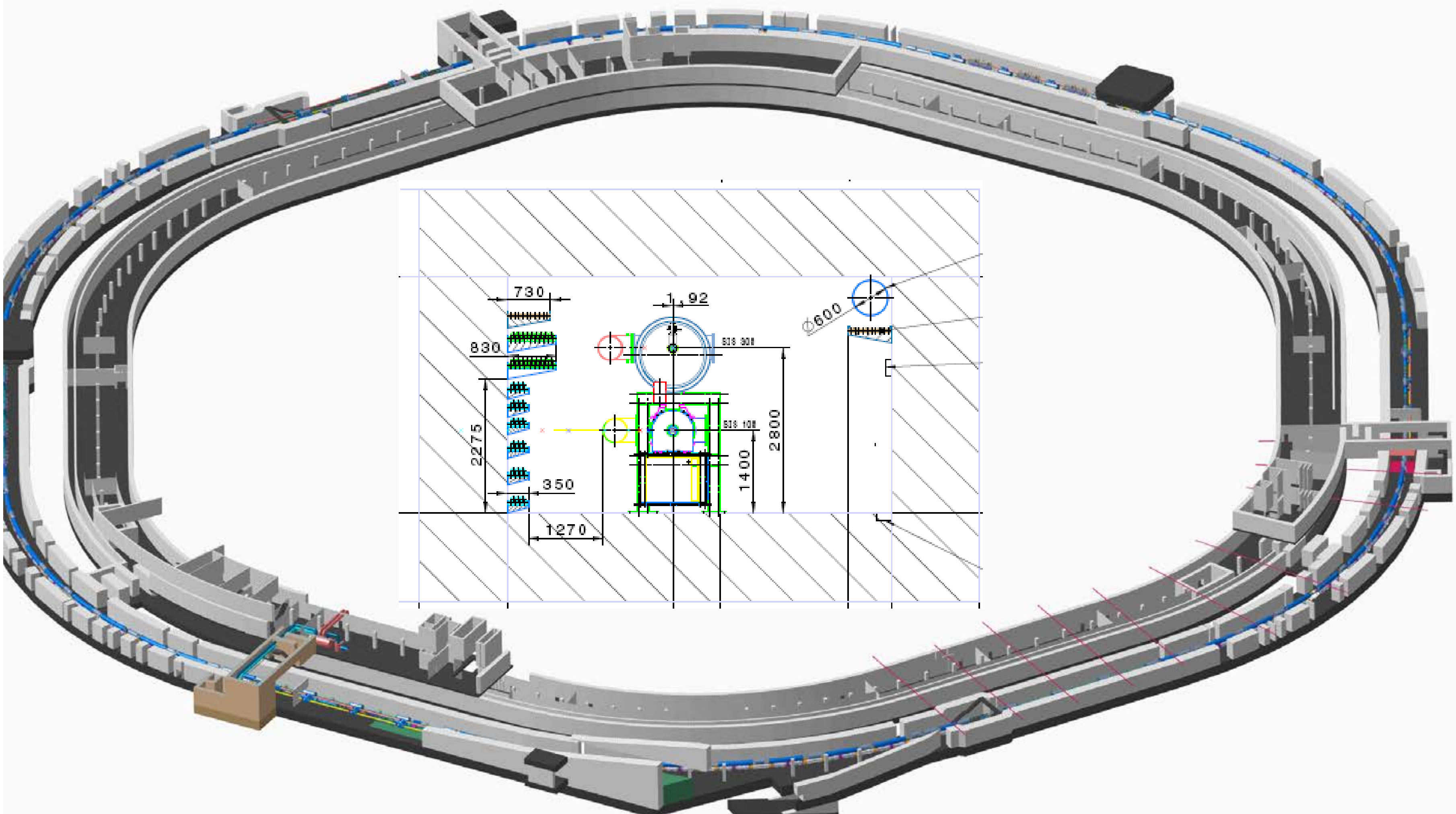
1st call for tender on Sept. 22: water management and excavation

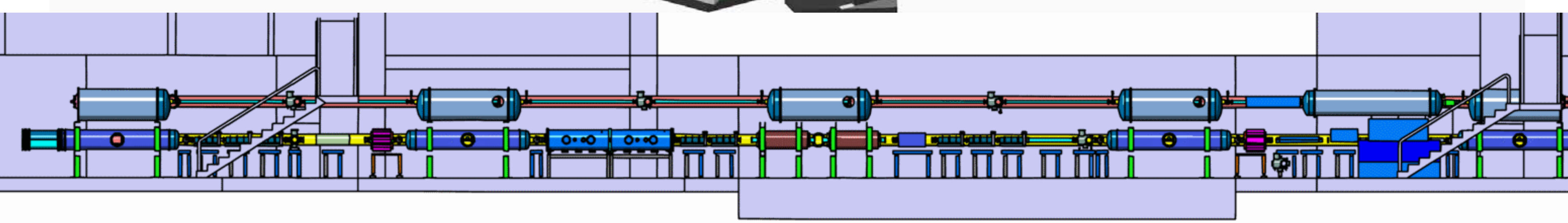
2nd call for tender in Nov.: shell construction 'north area', includes SIS100 and CBM cave

Start of construction mid of 2017



Tunnel for SIS100/300

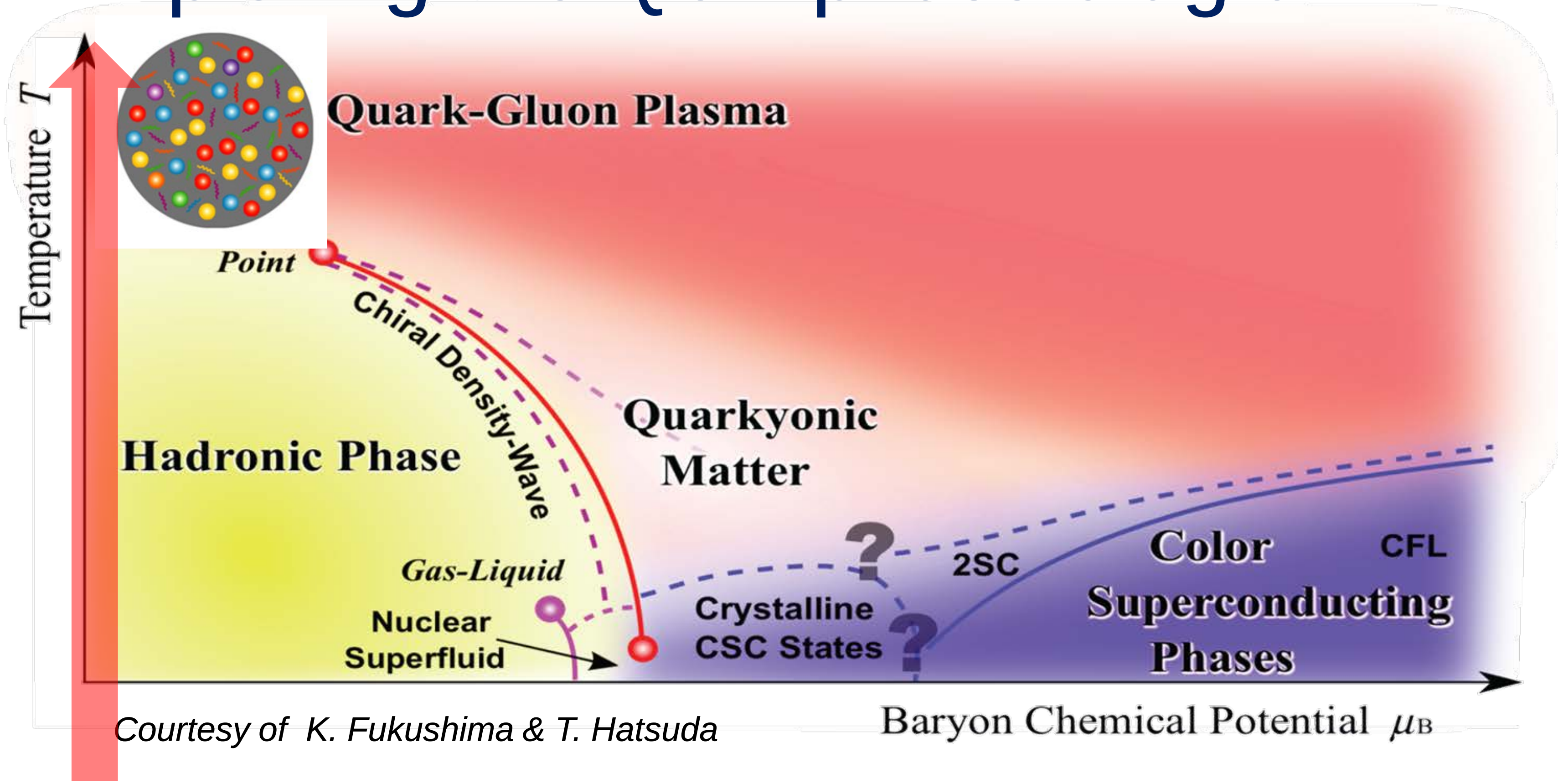




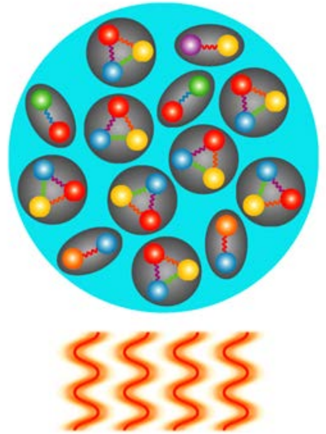
The Compressed Baryonic Matter (CBM) experiment

4000 tons of steel plates transported from KIT to FAIR for the CBM beam dump

Exploring the QCD phase diagram



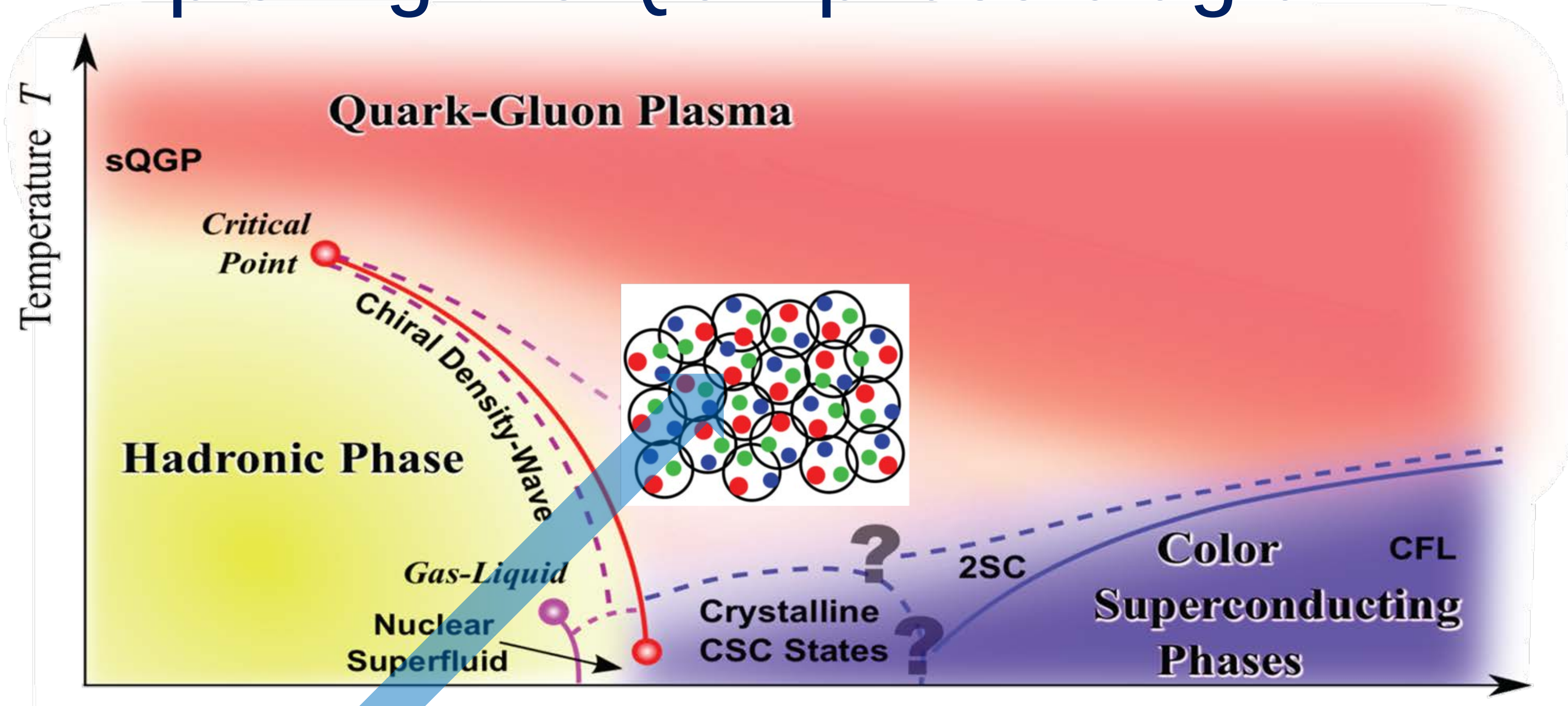
Courtesy of K. Fukushima & T. Hatsuda



<u>At very high temperature:</u>

- N of baryons ≈ N of antibaryons
  Situation similar to early universe
- L-QCD finds crossover transition between hadronic matter and Quark-Gluon Plasma
- Experiments: ALICE, ATLAS, CMS at LHC
  STAR, PHENIX at RHIC

Exploring the QCD phase diagram



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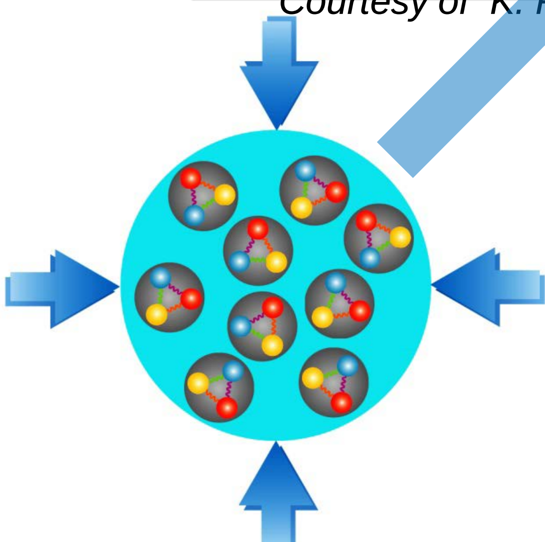
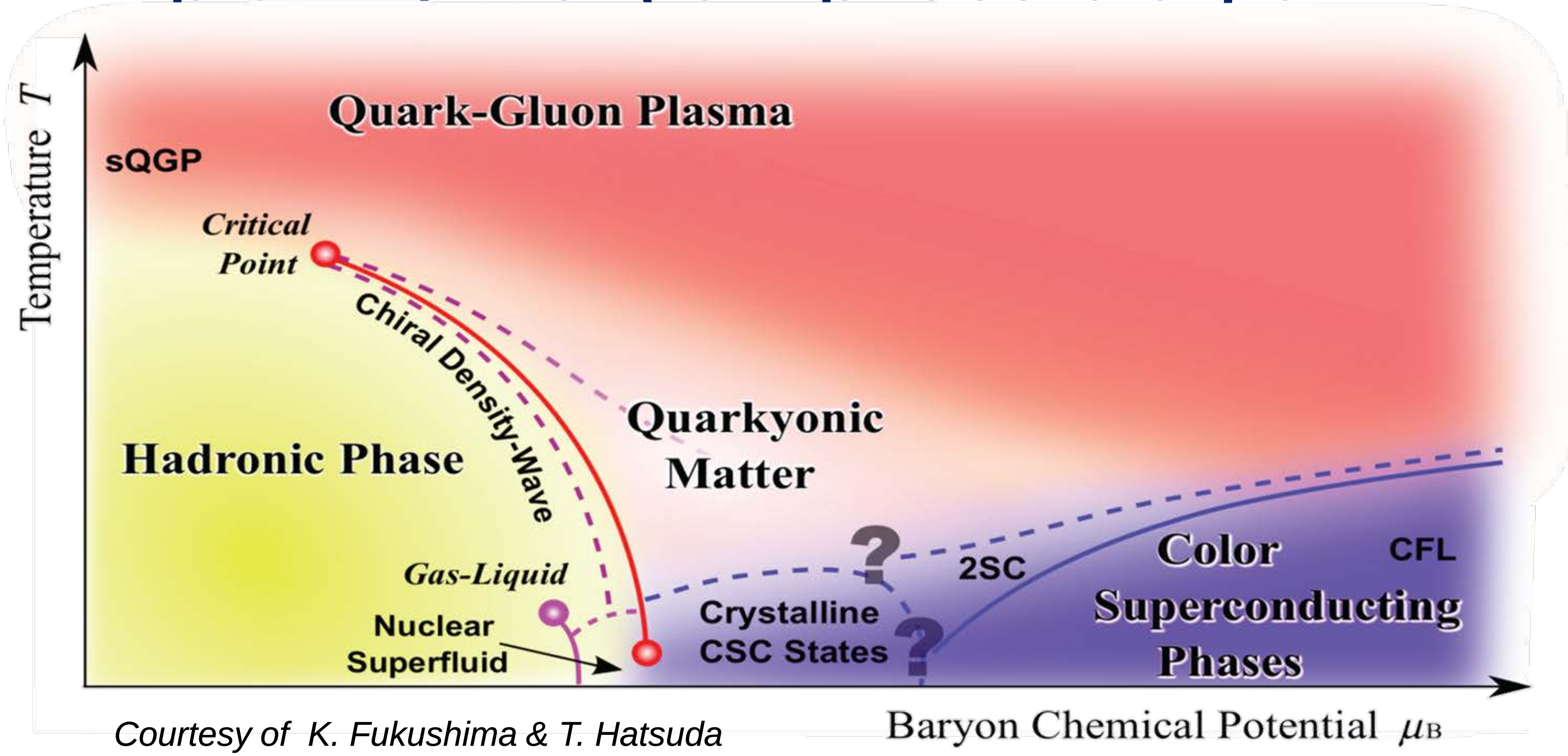


At high baryon density:

- N of baryons >> N of antibaryons
  Densities like in neutron star cores
- L-QCD not (yet) applicable
- Models predict first order phase transition with mixed or exotic phases
- Experiments: BES at RHIC, NA61 at CERN SPS, CBM at FAIR, NICA at JINR, J-PARC

Exploring the QCD phase diagram



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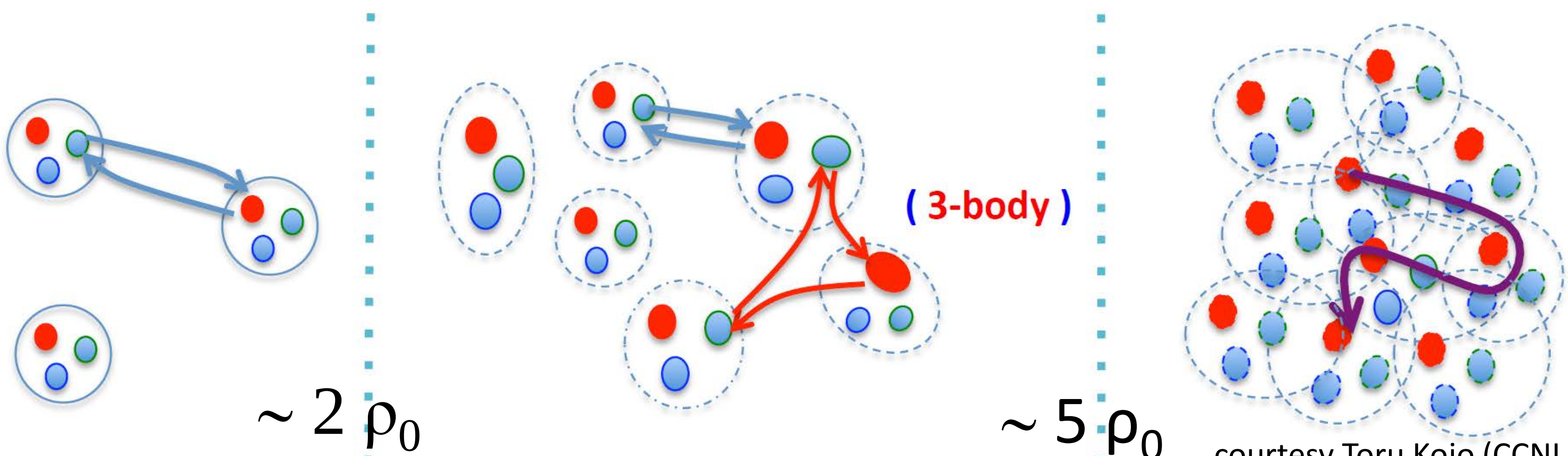
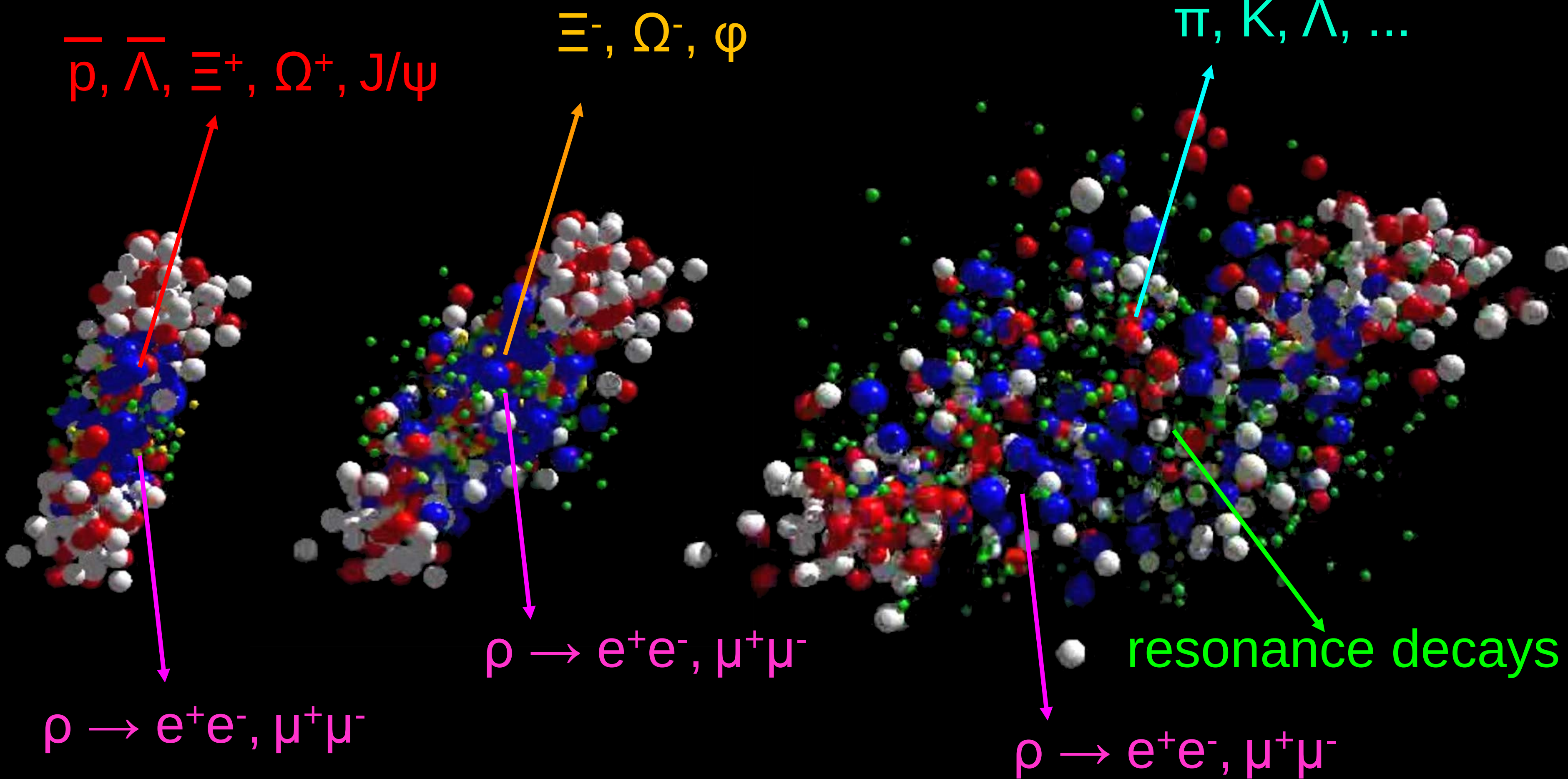


courtesy Toru Kojo (CCNU)

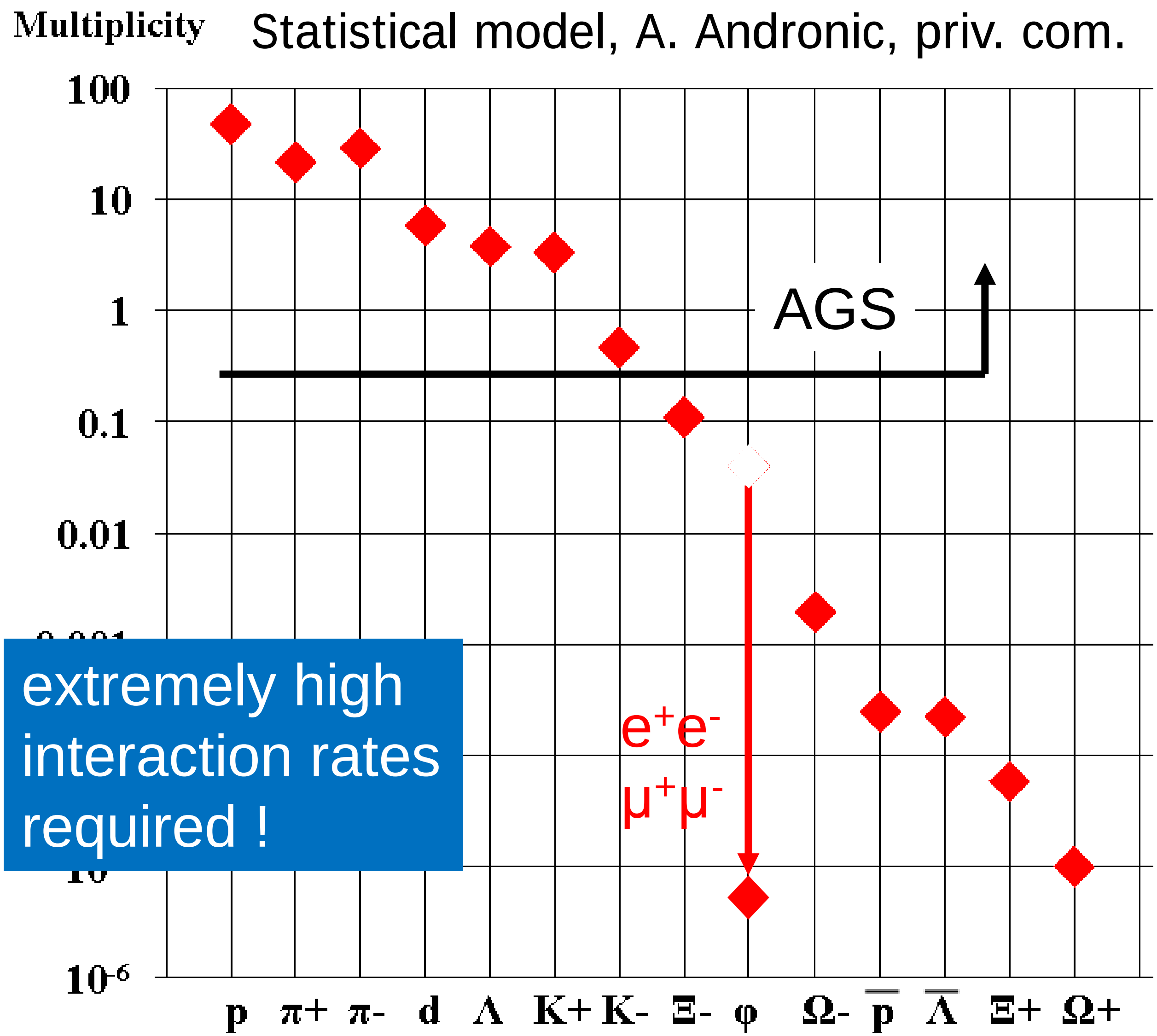
Messengers from the dense fireball: CBM at FAIR

UrQMD transport calculation Au+Au 10.7 A GeV

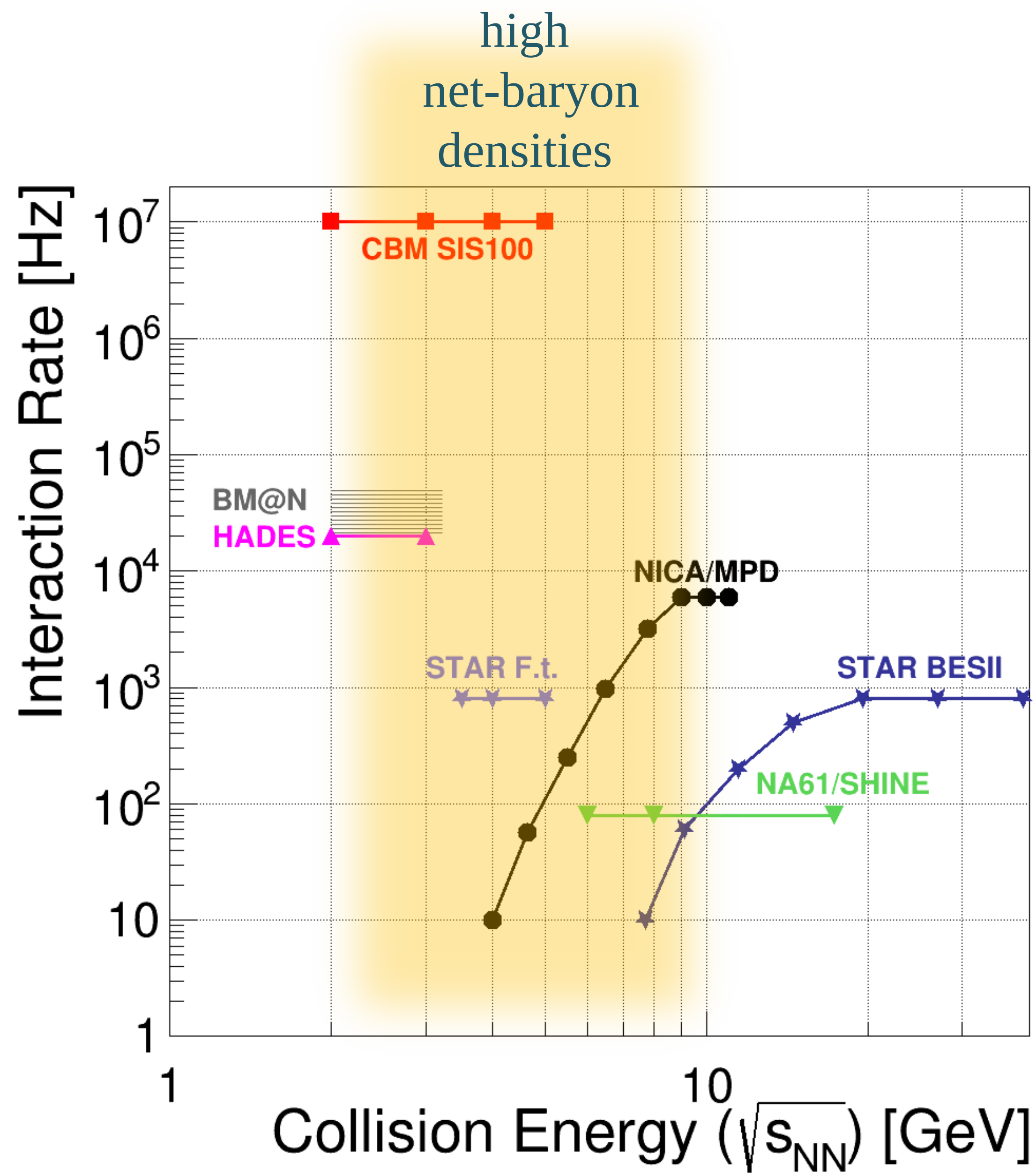


Experimental challenges

Particle yields in central Au+Au 4 A GeV



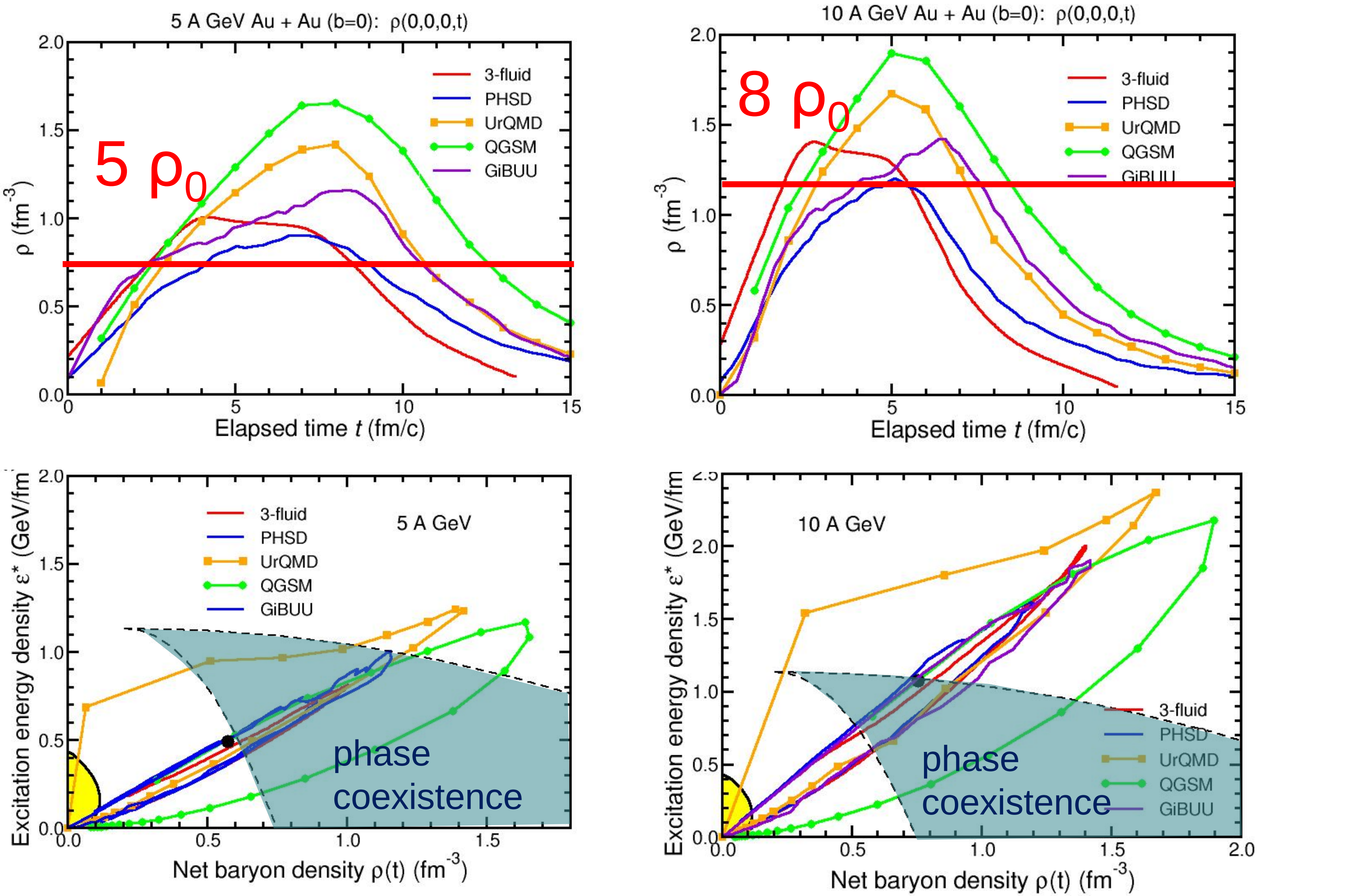
Experiments exploring dense QCD matter



Baryon densities in central Au+Au collisions

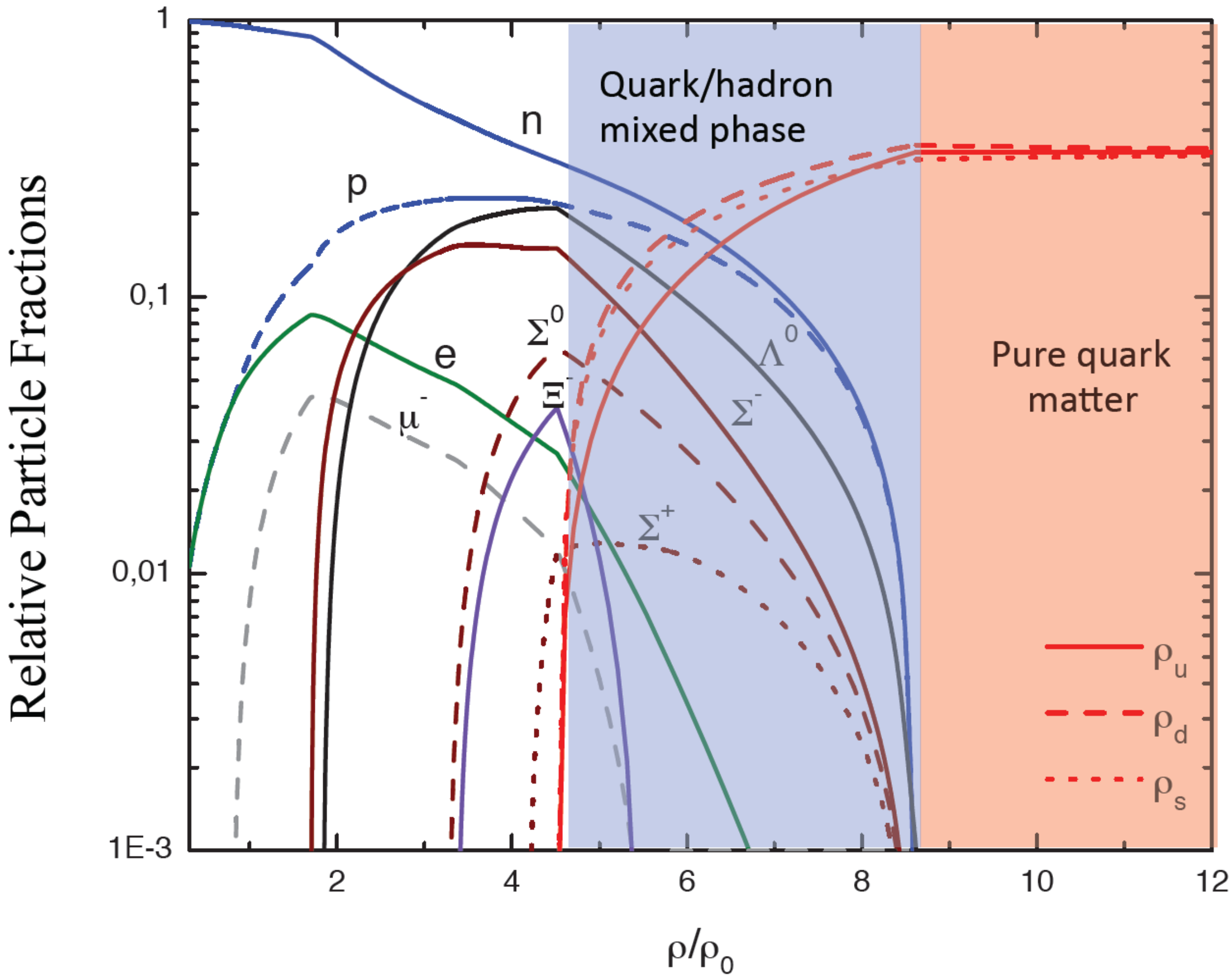
I.C. Arsene et al., Phys. Rev. C 75, 24902 (2007)

5 A GeV **10 A GeV**



Quark matter in massive neutron stars?

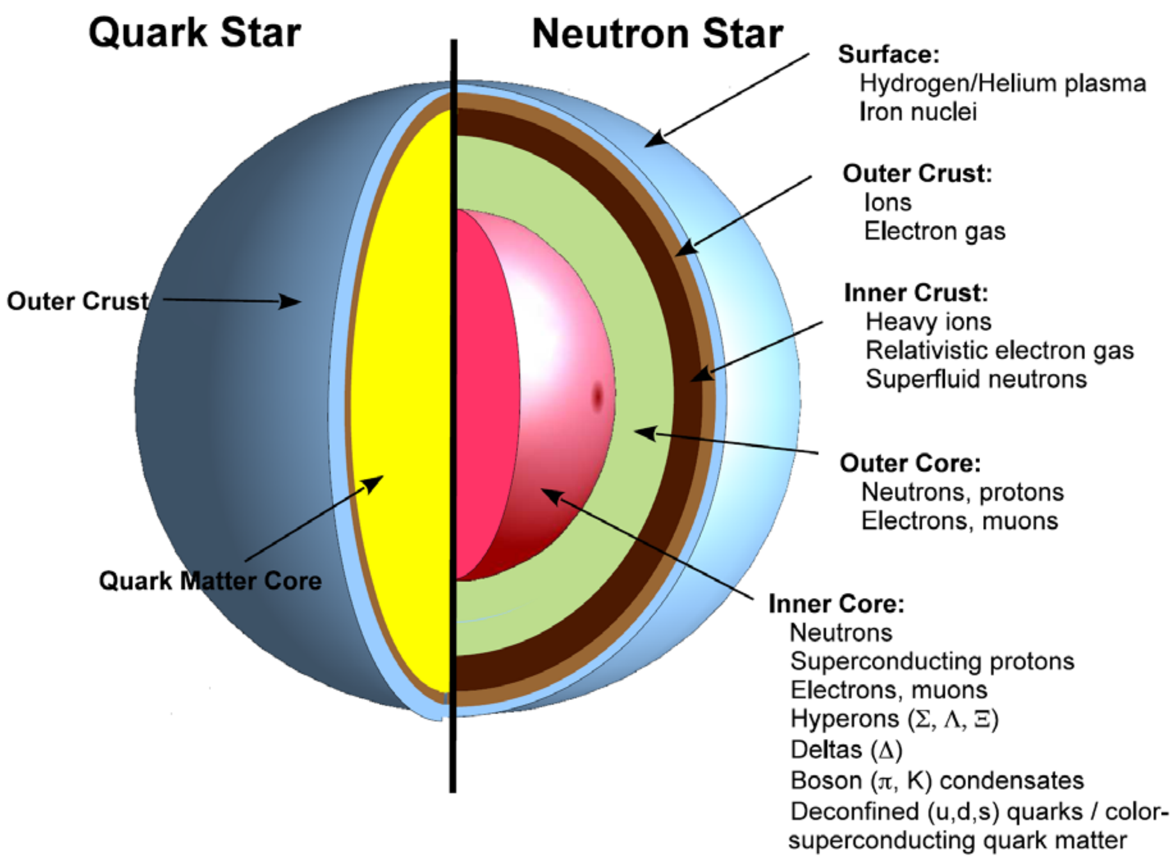
M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, arXiv:1308.1657
Phys. Rev. C 89, 015806, 2014



CBM physics case and observables

The equation-of-state at neutron star core densities

- collective flow of hadrons (driven by pressure)
- particle production at threshold energies (multi-strange hyperons)



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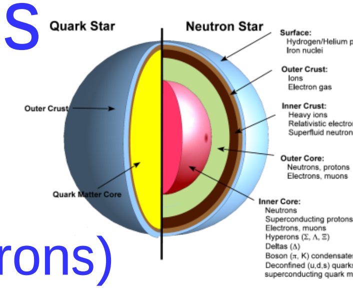


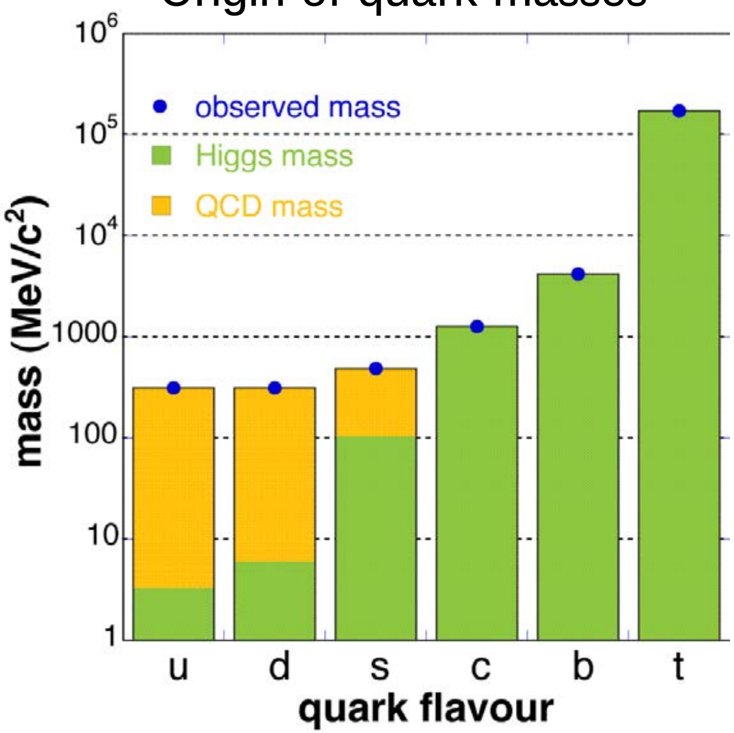
The equation-of-state at neutron star core densities

- collective flow of hadrons
- particle production at threshold energies (multi-strange hyperons)

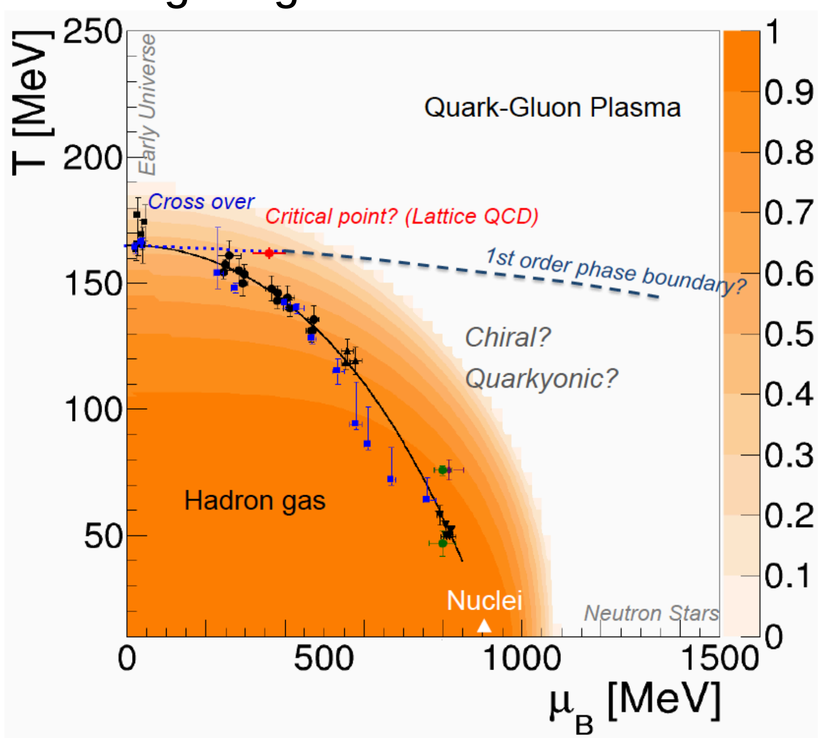
Onset of chiral symmetry restoration at high ρ_B

- in-medium modifications of hadrons ($\rho,\omega,\phi \rightarrow e^+e^-(\mu^+\mu^-)$)
- dileptons at intermediate invariant masses: ρ-a_1 chiral mixing

Origin of quark masses



Orange region: Chiral condensate



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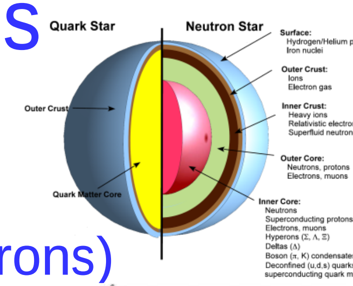

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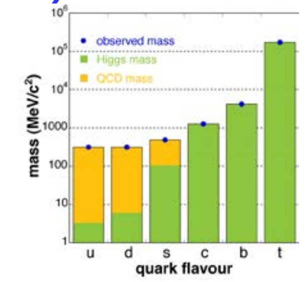

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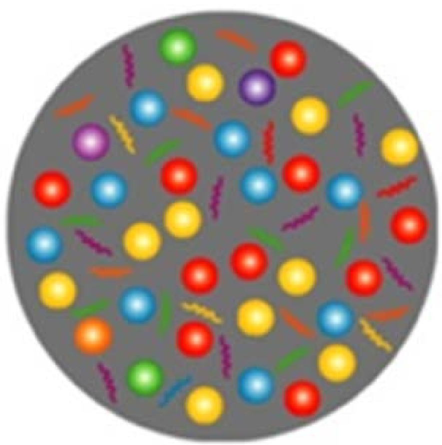
Phase transitions from partonic to hadronic matter

- excitation function of strangeness: Ξ^-(dss), Ξ^+(dss), Ω^-(sss), Ω^+(sss)
  $\rightarrow$ chemical equilibration at the phase boundary
- excitation function and flow of charm (J/ψ, ψ', D^0, $D^\pm$, Λ_c)



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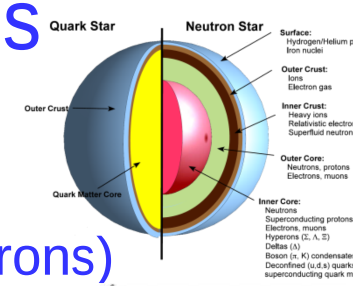

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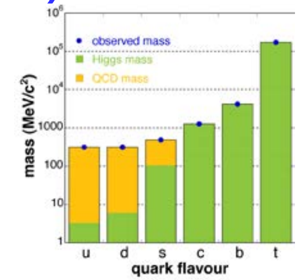

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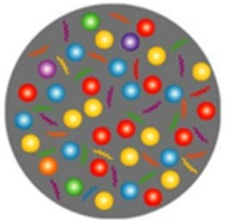

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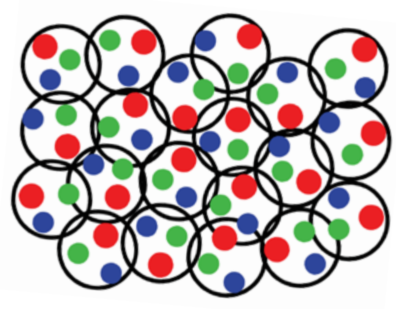
Phase coexistence, critical point, new states of matter

- excitation function (invariant mass) of lepton pairs:
  thermal radiation from fireball: “caloric curve”
- anisotropic azimuthal angle distributions: “spinodal decomposition”
- event-by-event fluctuations of B, C, S: “critical opalescence”



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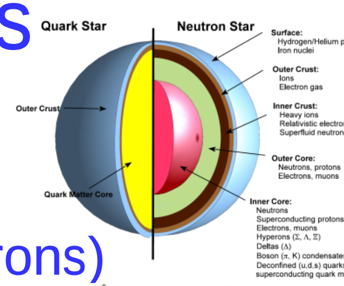

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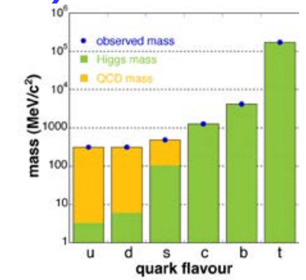

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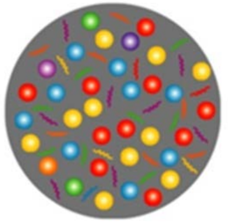

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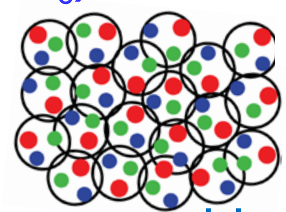
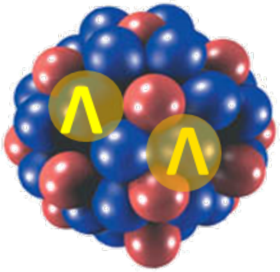
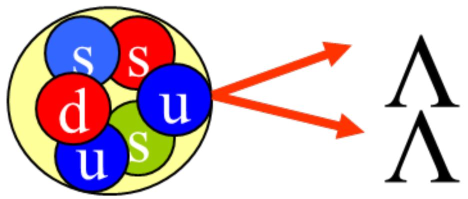


Strange matter
- (double-) lambda hypernuclei
- strange meta-stable objects (e.g. strange dibaryons)

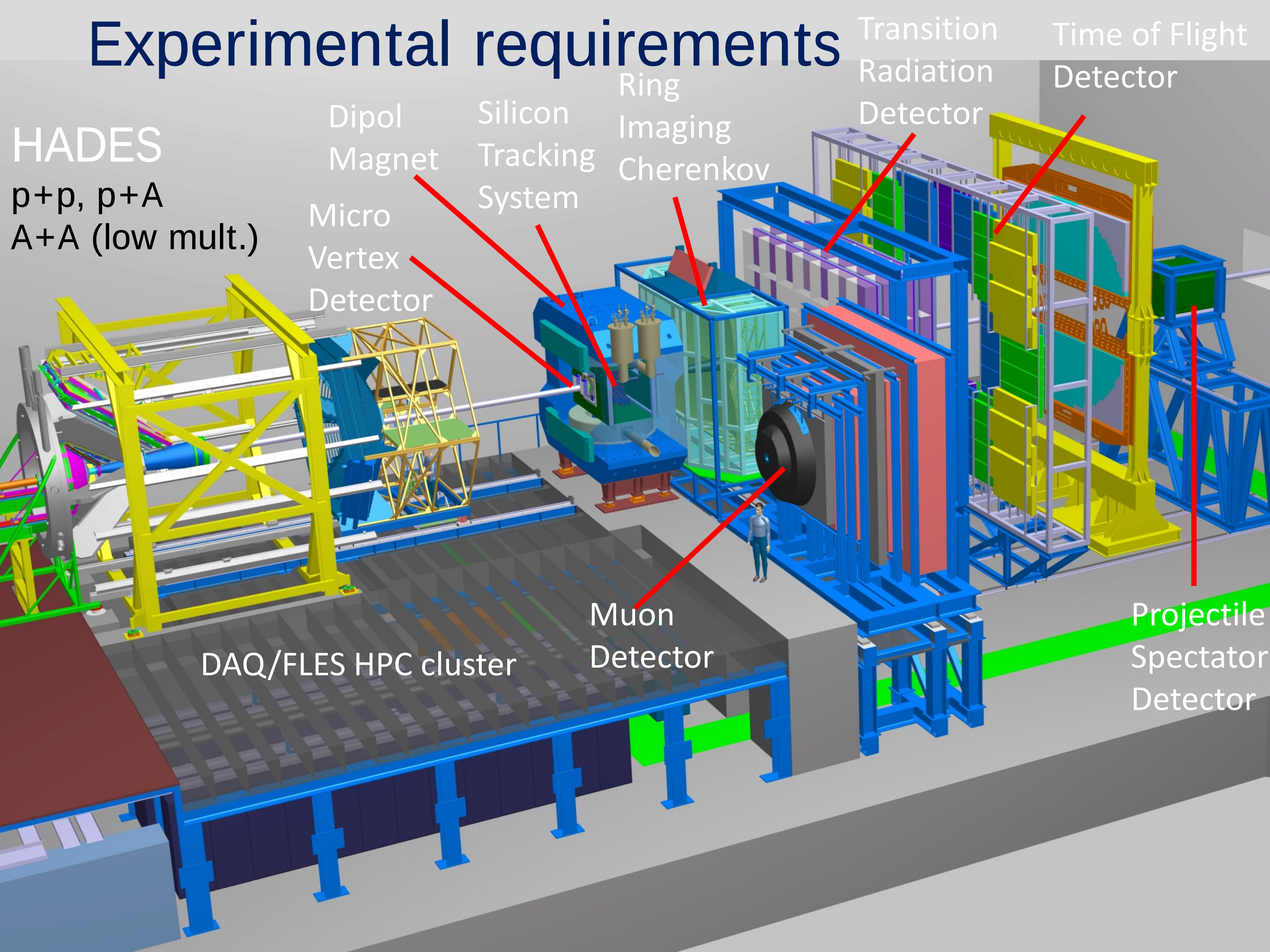




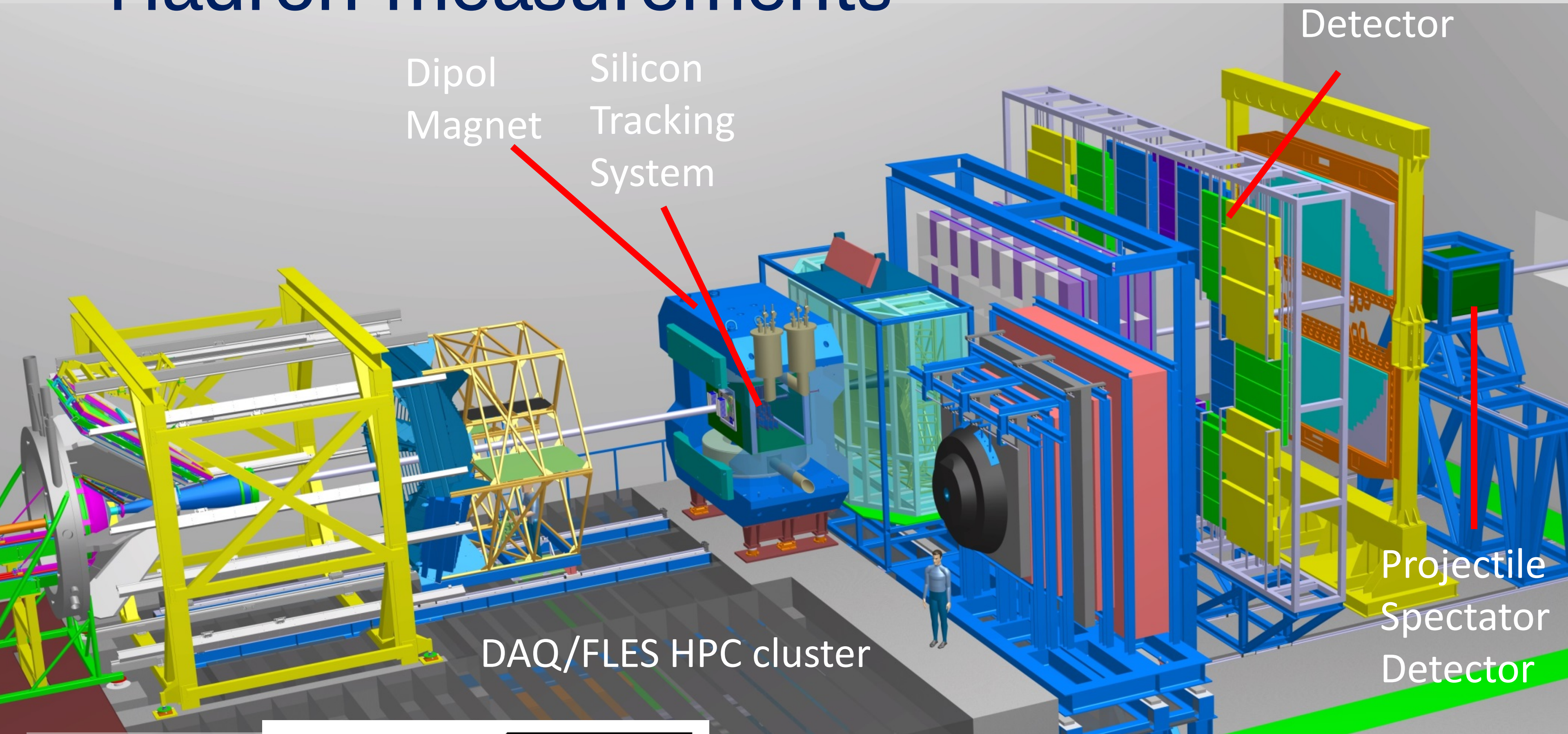
Experimental requirements

- 10^5 - 10^7 Au+Au reactions/sec
- determination of displaced vertices ($\sigma \approx 50\ \mu$m)
- identification of leptons and hadrons
- fast and radiation hard detectors and FEE
- free-streaming readout electronics
- high speed data acquisition and high performance computer farm for online event selection
- 4-D event reconstruction

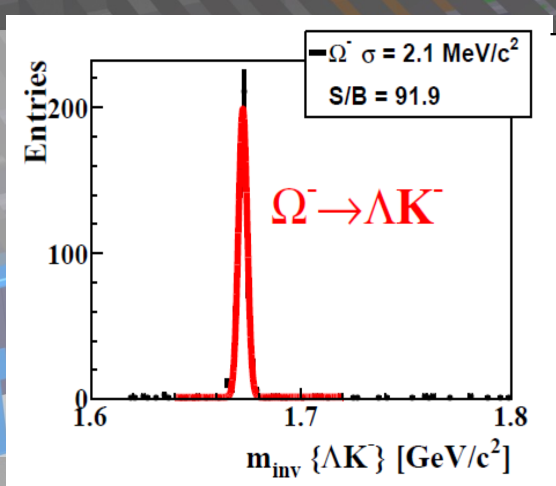
Experimental requirements

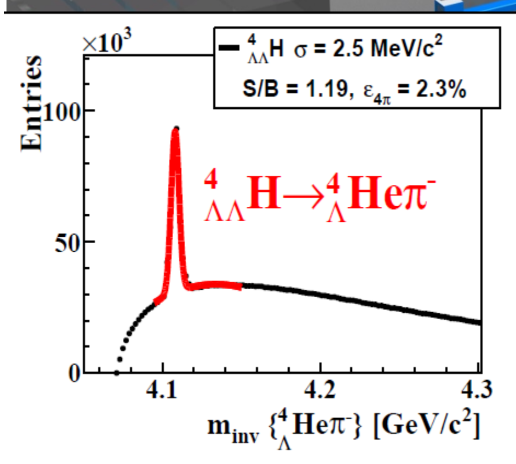


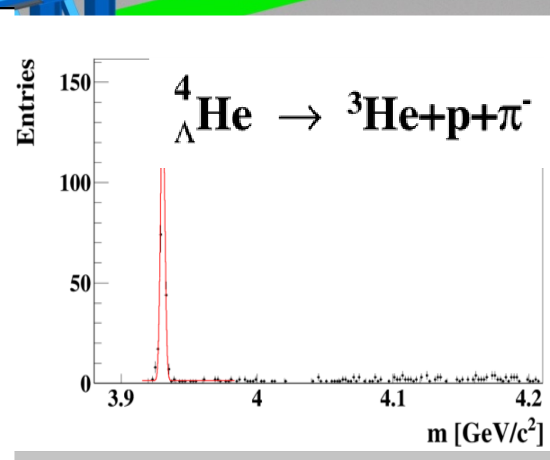
Hadron measurements



Hyperons and hypernuclei in central Au+Au collisions at 10A GeV







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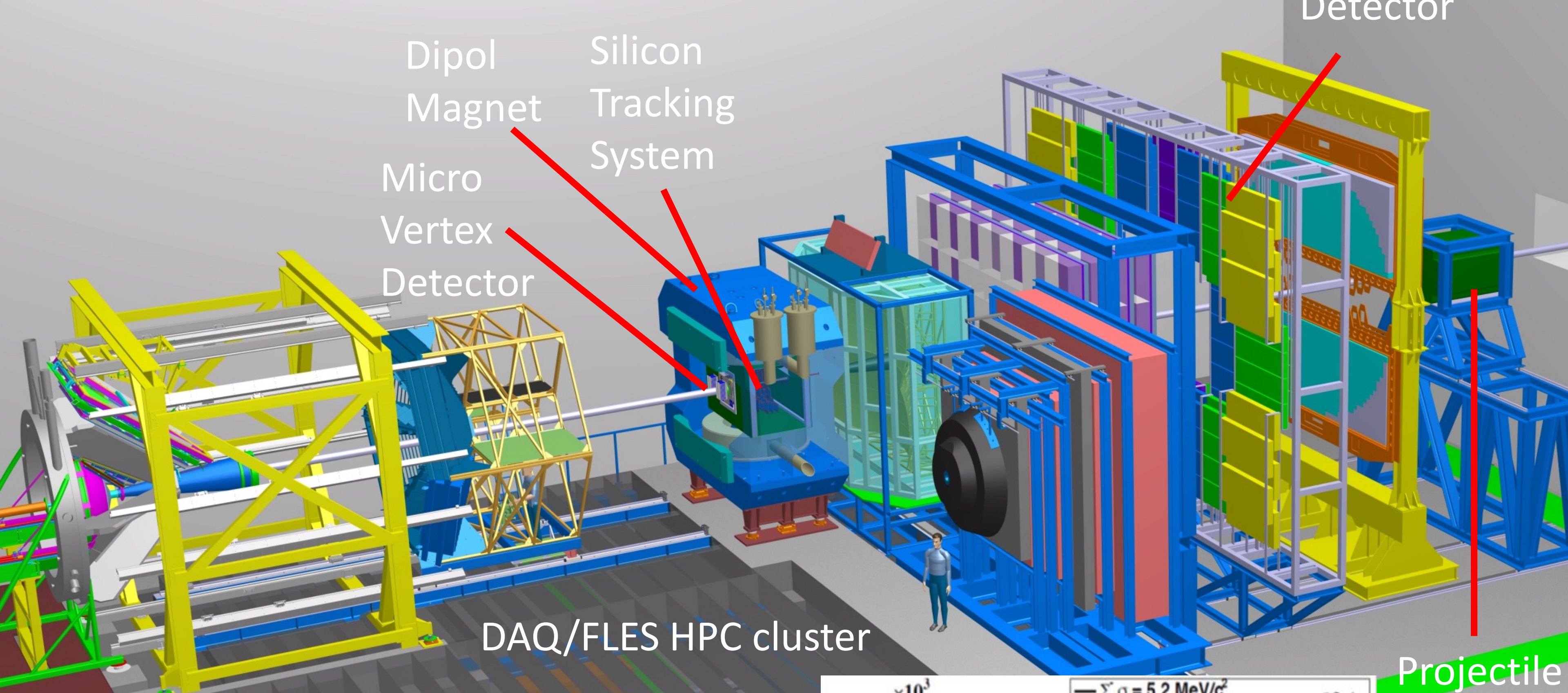
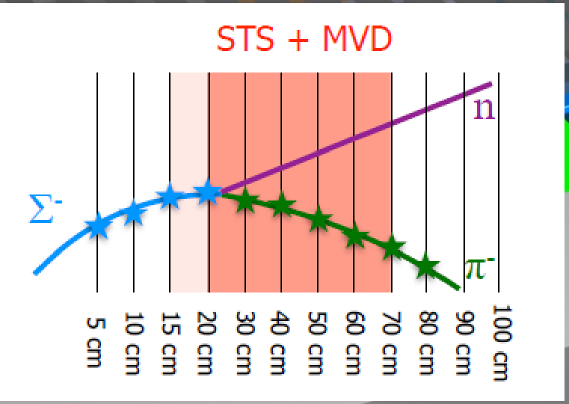
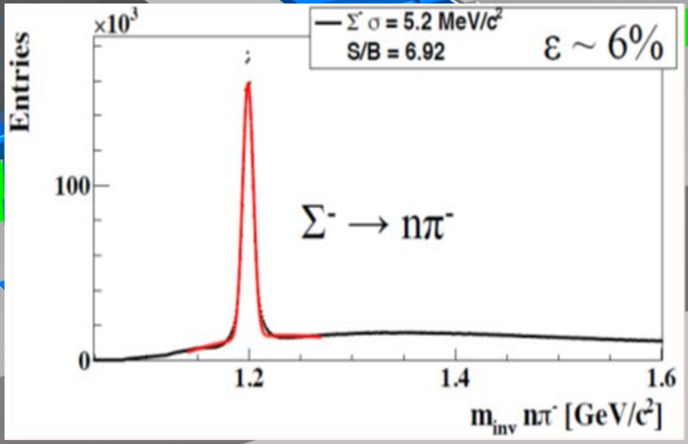
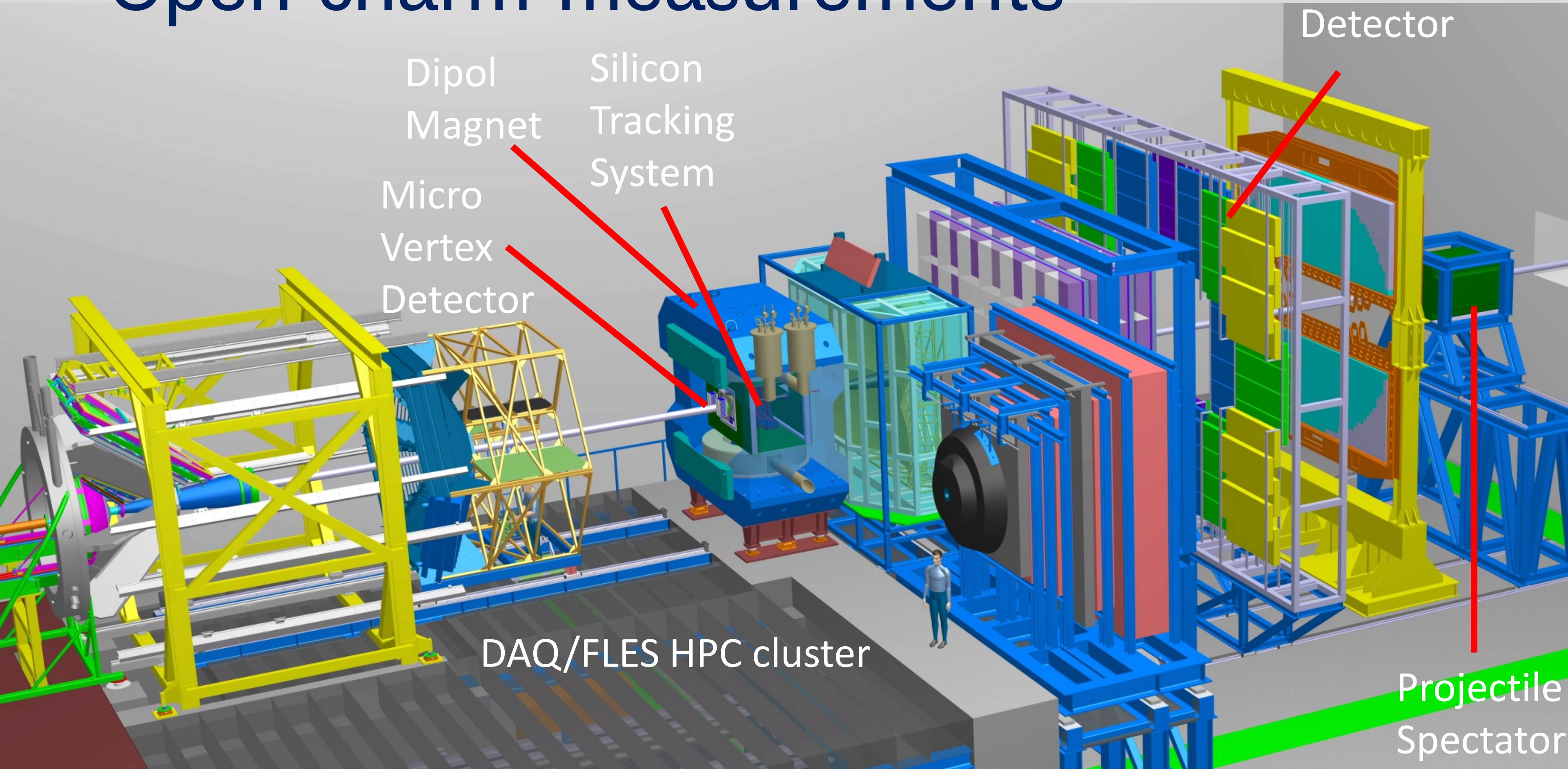


Hyperons with neutral daughter in central Au+Au collisions at 10A GeV

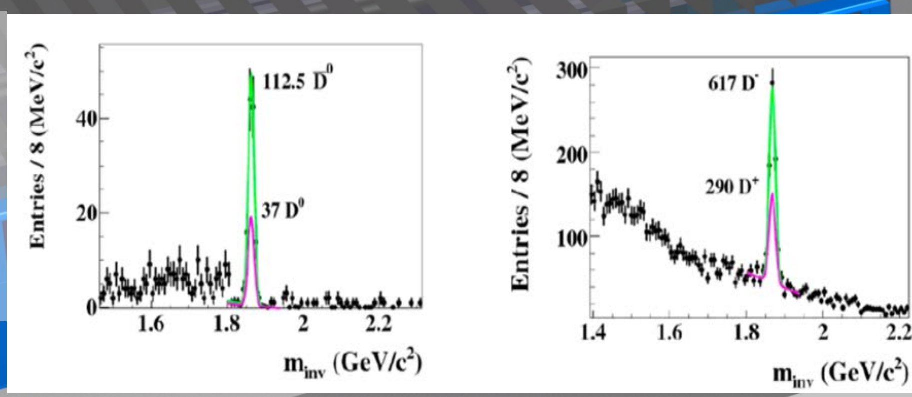


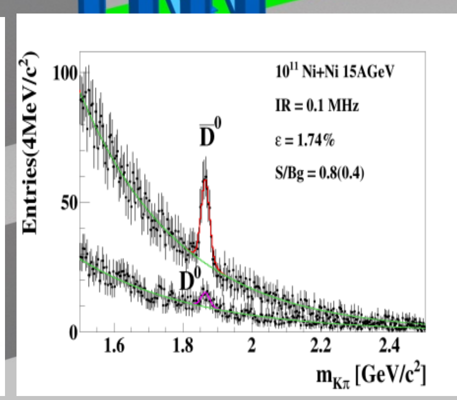


Open charm measurements

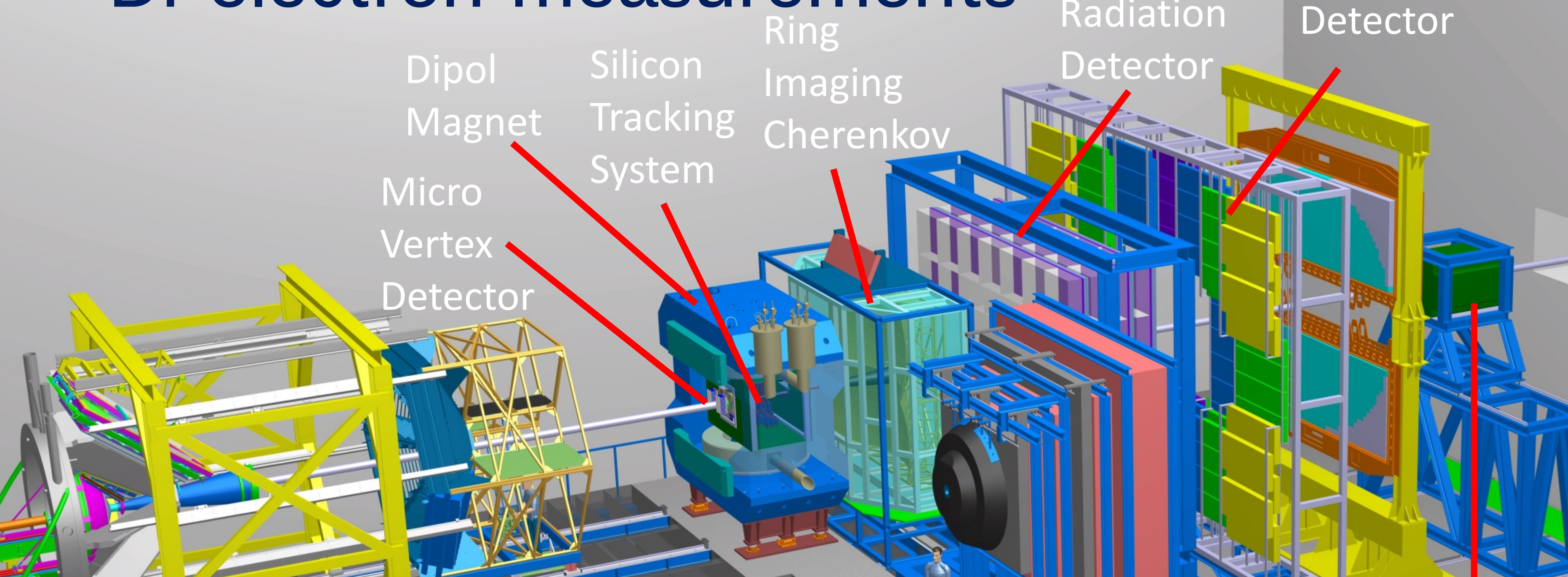


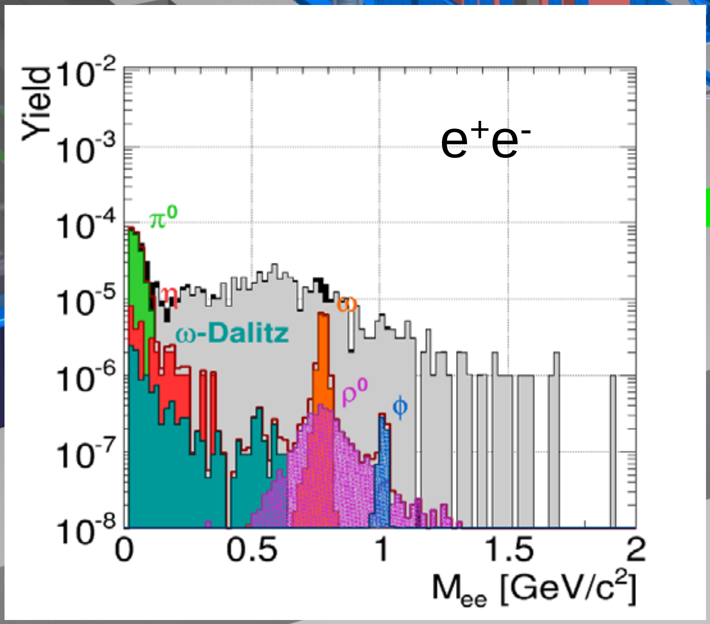
Open Charm in p+A 30 GeV and Ni+Ni 15A GeV





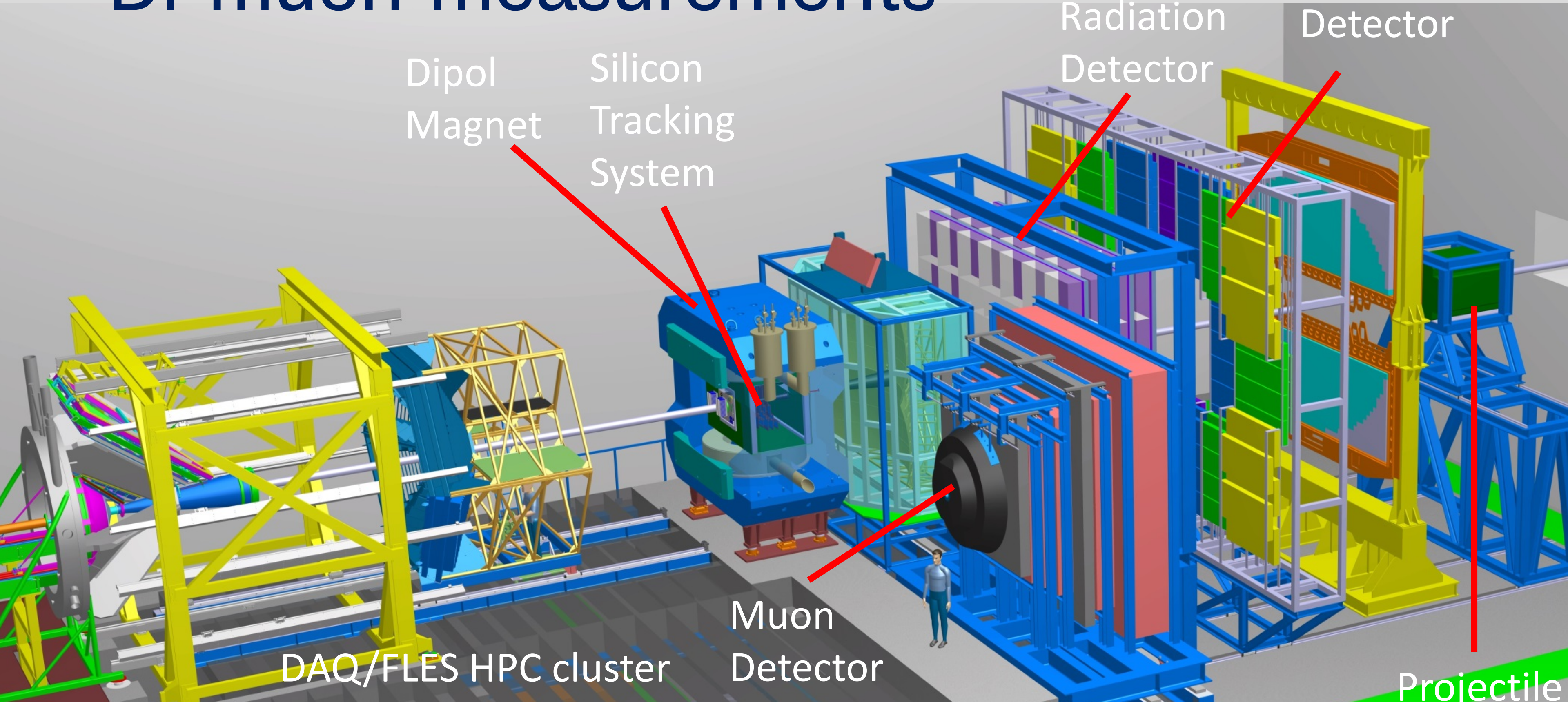
Di-electron measurements



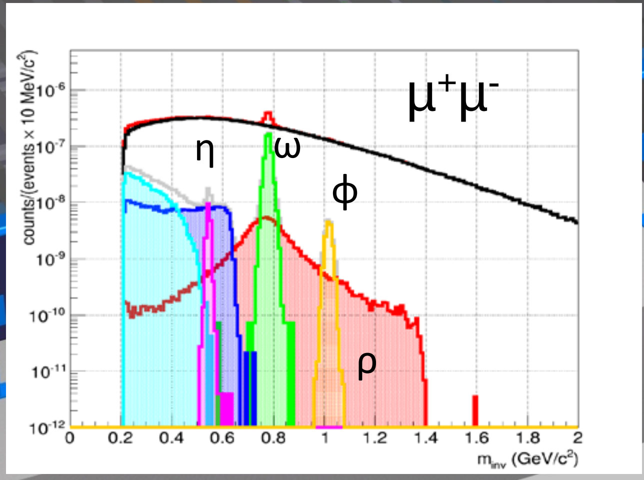


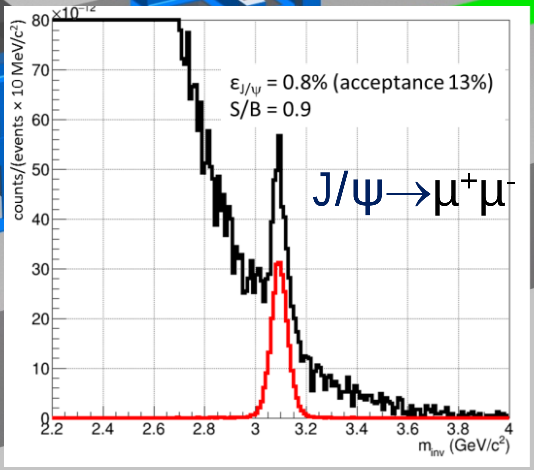
Dileptons in central
Au+Au collisions at 8A GeV

Di-muon measurements

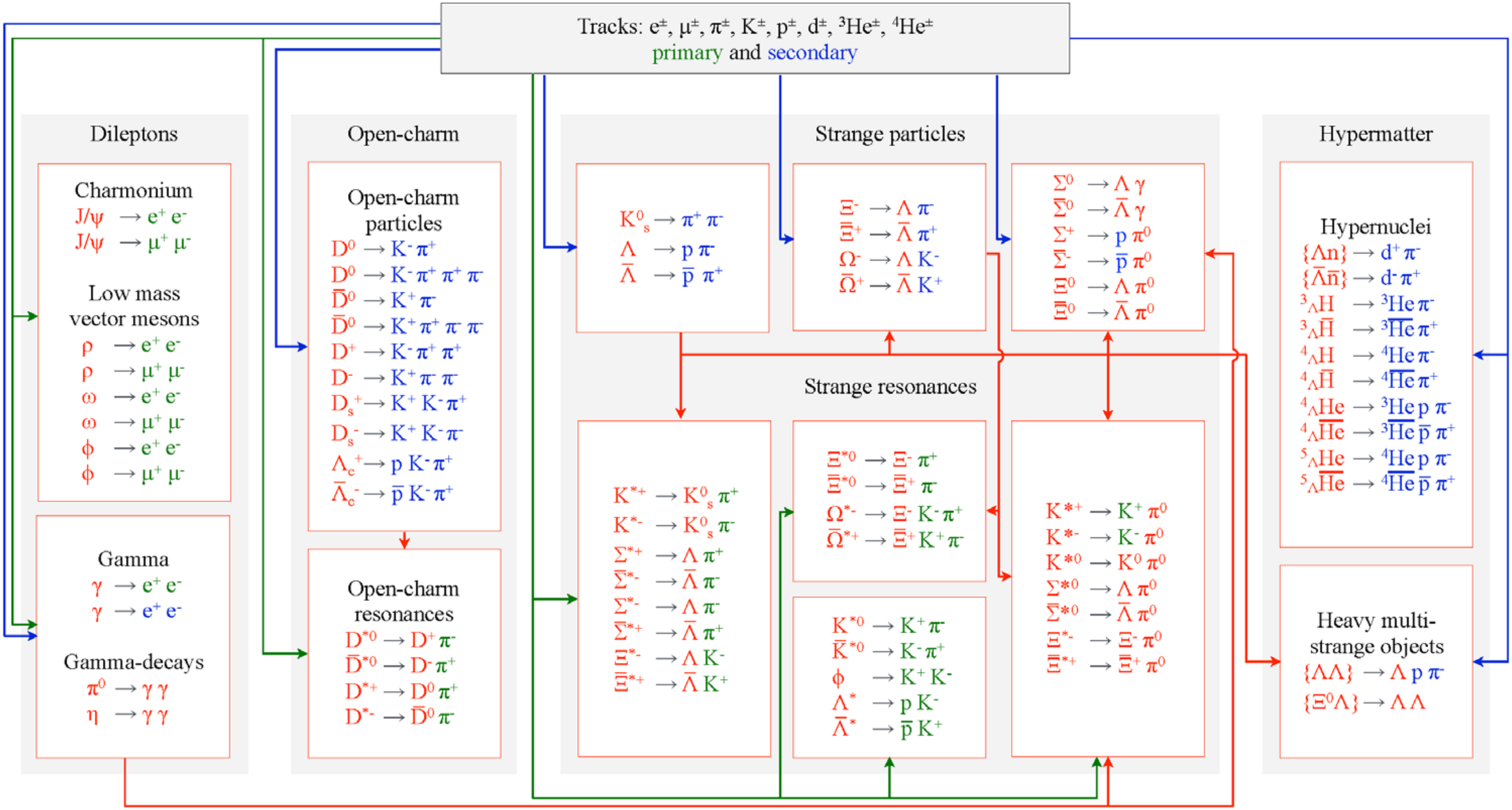


Di-muons in central Au+Au collisions at 8A GeV and 10A GeV (J/ψ)





Online particle identification in CBM: The KF Particle Finder



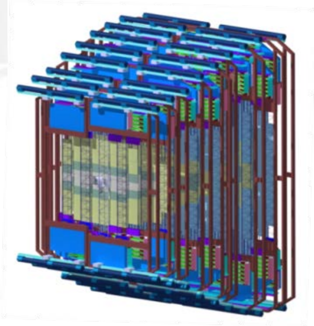
successfully used online in the STAR experiment

Status experiment preparation

Superconducting Dipole Magnet

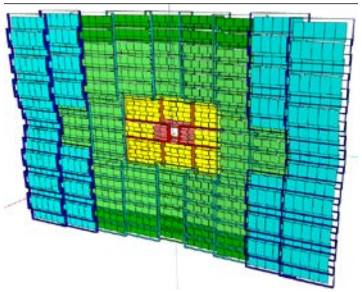
- TDR approved
- Funding: Russia
- JINR Dubna, BINP Novosibirsk, GSI

Silicon Tracking System



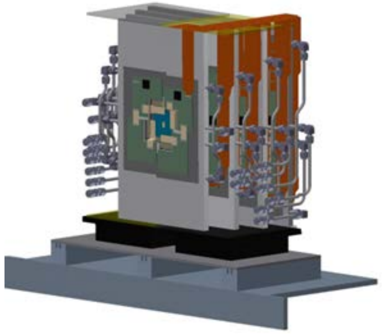
- TDR approved
- Funding: Germany, Russia, Poland
- GSI, JINR Dubna, KIT, INR Kiev, AGH and UJ Krakow, Univ. Tübingen, Warsaw UT

High-rate MRPC TOF wall



- TDR approved
- Funding: Germany, Romania, China, Russia
- THU Beijing, NIPNE Bucharest, GSI Darmstadt, TU Darmstadt, IfI Frankfurt, USTC Hefei, Univ. Heidelberg, ITEP Moscow, HZDR Rossendorf, CCNU Wuhan

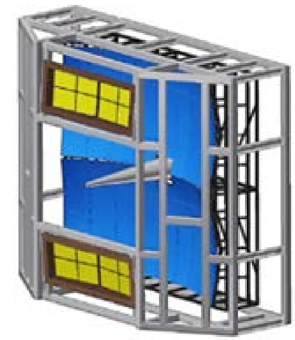
Micro-Vertex Detector



- Funding: Germany, France
- Univ. Frankfurt, IPHC Strasbourg

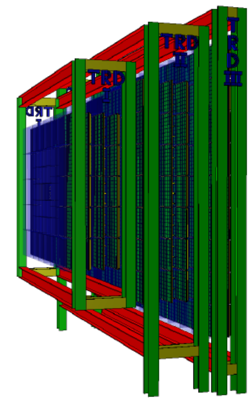
Status experiment preparation

Ring Imaging Cherenkov Detector



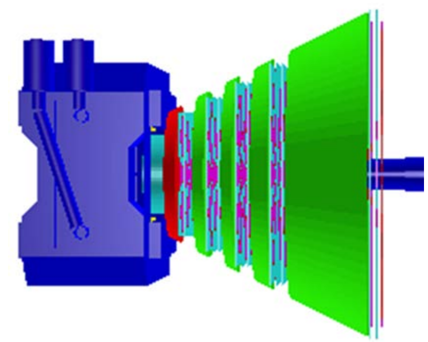
- TDR approved
- Funding: Germany, Russia
- Univ. Gießen, Univ. Wuppertal, PNPI Gatchina

Transition Radiation Detector



- Funding: Germany, Romania
- NIPNE Bucharest, JINR Dubna, Univ. Frankfurt, Univ. Heidelberg, Univ. Münster, WI Budapest

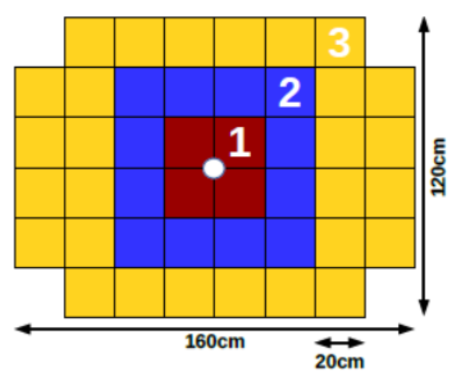
Muon Chambers



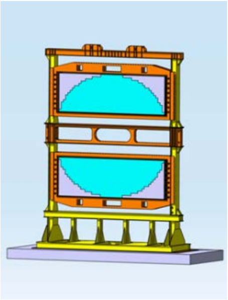
- TDR approved
- Funding: India, Russia
- VECC Kolkata + 12 Indian Inst., PNPI Gatchina, JINR Dubna

Projectile-Spectator Detector

- TDR approved
- Funding: Russia, Czechia, Germany
- INR Moscow, Prague, Rez, TU Darmstadt



Status experiment preparation

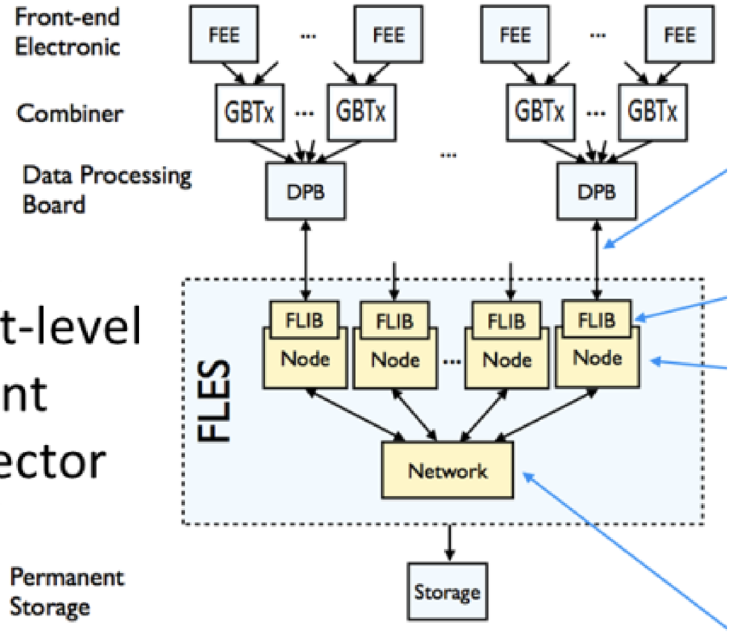


Electromagnetic Calorimeter

- Funding: Russia (EOI)
- ITEP Moscow

DAQ, First Level Event Selection

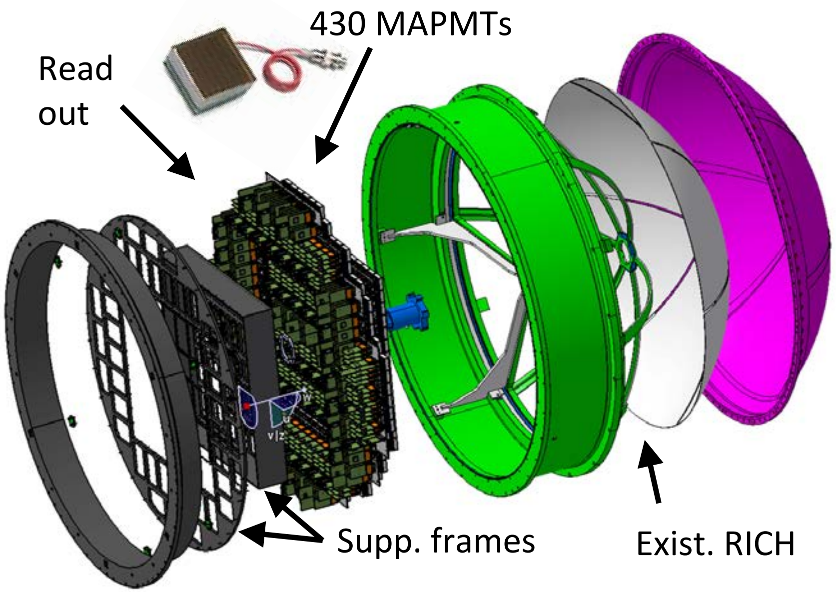
- Funding: Germany, Poland
- Univ. Frankfurt, FIAS, GSI, KIT Karlsruhe, IIT Kharagpur, Warsaw UT, ZIB Berlin



GSI GreenIT Cube

FAIR Phase 0 experiments

1. Install, commission and use 430 out of 1100 CBM RICH multi-anode photo-multipliers (MAPMT) in HADES RICH photon detector



FAIR Phase 0 experiments

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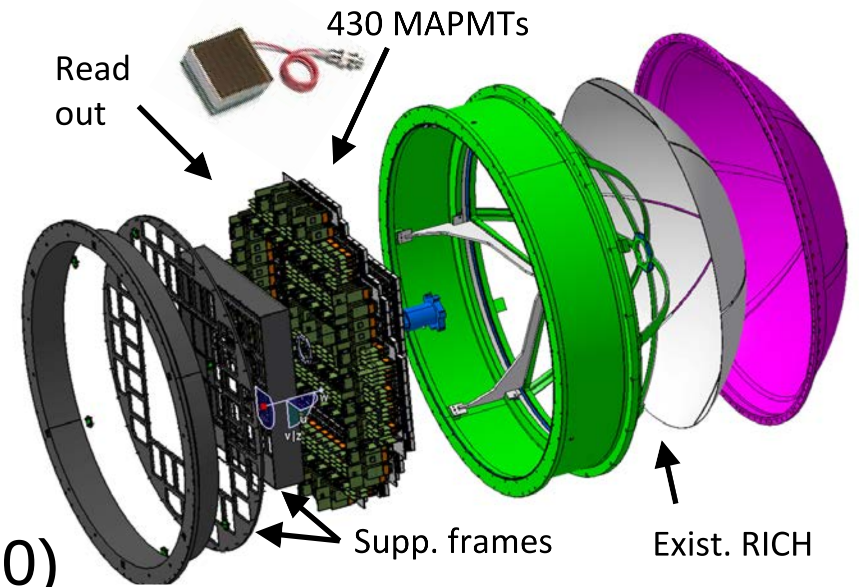
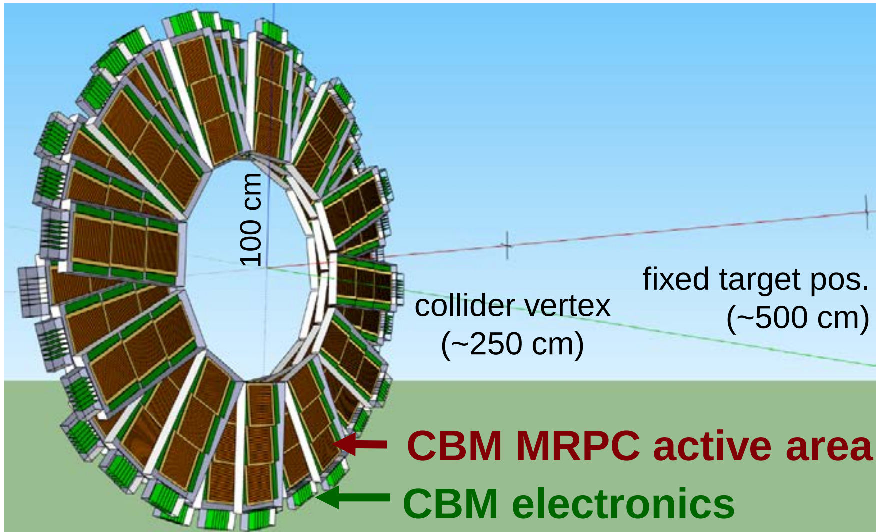
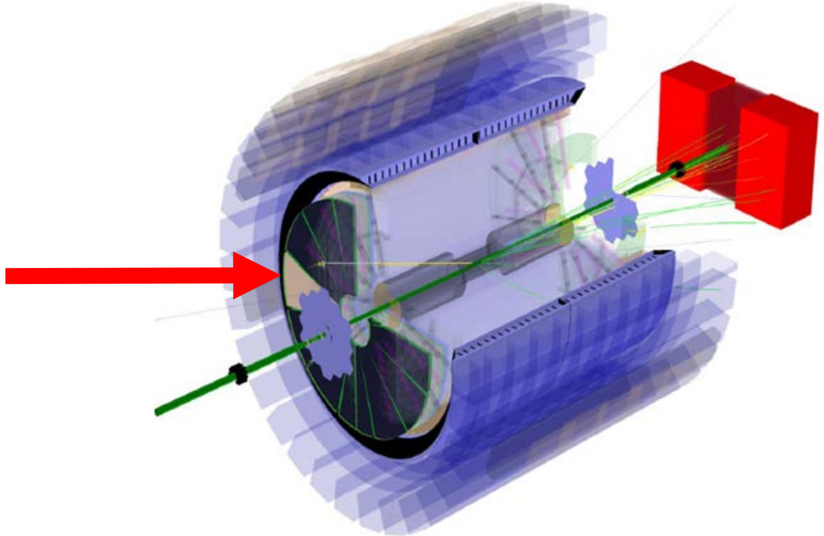


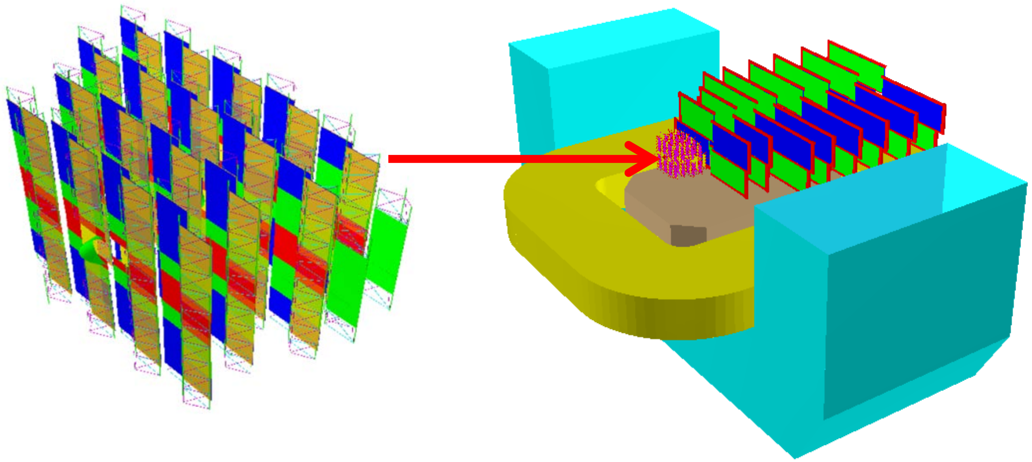
2. Install, commission and use 10% of the CBM TOF modules including read-out chain at STAR/RHIC (BES II 2019/2020)

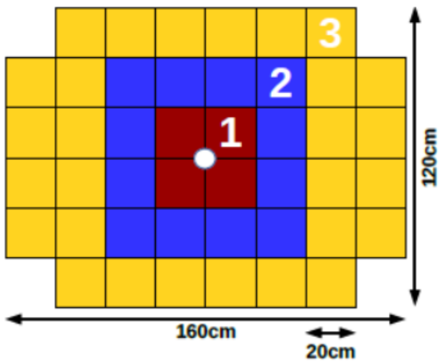




FAIR Phase 0 experiments

3. Install, commission and use 4 Silicon tracking layers and the Project Spectator Detector at the BM@N experiment at the Nuclotron in JINR/Dubna (Au-beams up to 4.5 A GeV in 2018/19)





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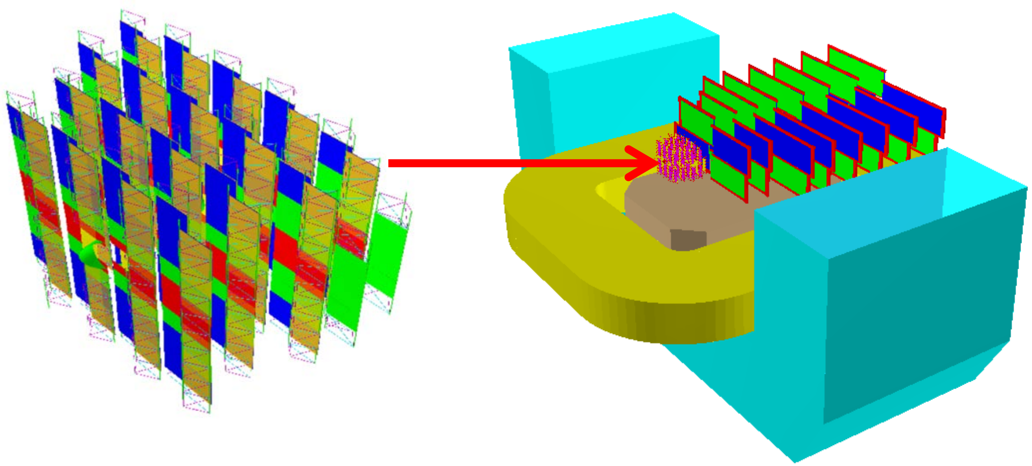
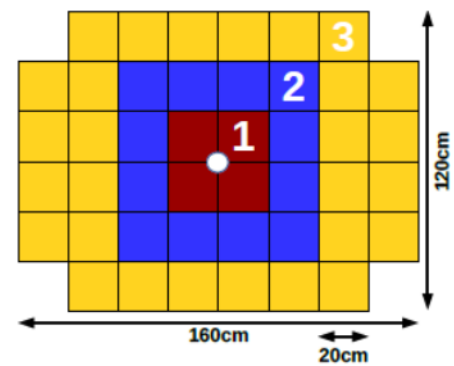
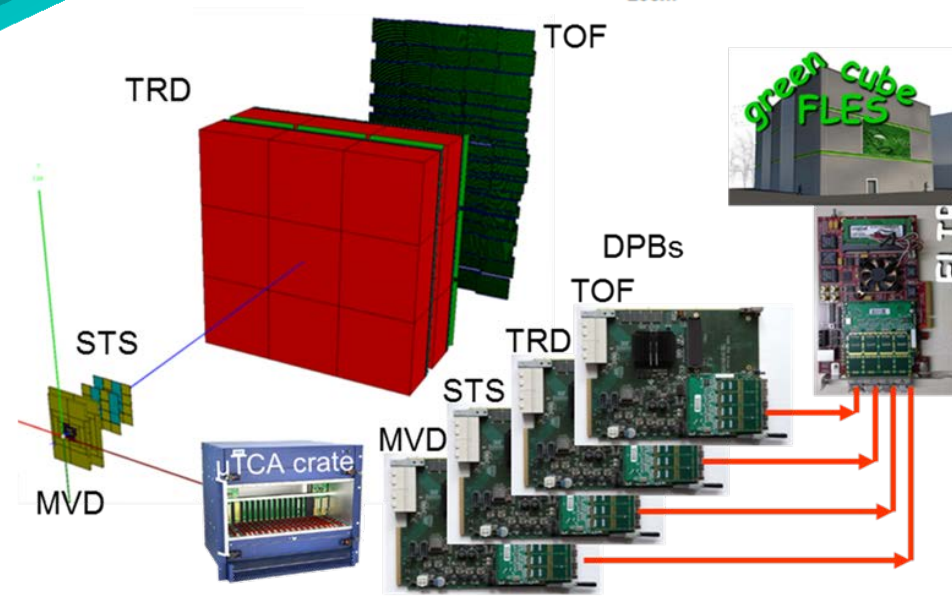




4. Build mCBM at GSI/SIS18 for a full system test with high-rate nucleus-nucleus collisions from 2018 - 2020



The CBM Collaboration: 59 institutions, 530 members

Croatia:
Split Univ.

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei
CTGU Yichang

Czech Republic:
CAS, Rez
Techn. Univ.Prague

France:
IPHC Strasbourg

Hungary:
KFKI Budapest
Budapest Univ.

Germany:
Darmstadt TU
FAIR
Frankfurt Univ. IKF
Frankfurt Univ. FIAS
Frankfurt Univ. ICS
GSI Darmstadt
Giessen Univ.
Heidelberg Univ. P.I.
Heidelberg Univ. ZITI
HZ Dresden-Rossendorf
KIT Karlsruhe
Münster Univ.
Tübingen Univ.
Wuppertal Univ.
ZIB Berlin

India:
Aligarh Muslim Univ.
Bose Inst. Kolkata
Panjab Univ.
Rajasthan Univ.
Univ. of Jammu
Univ. of Kashmir
Univ. of Calcutta
B.H. Univ. Varanasi
VECC Kolkata
IOP Bhubaneswar
IIT Kharagpur
IIT Indore
Gauhati Univ.

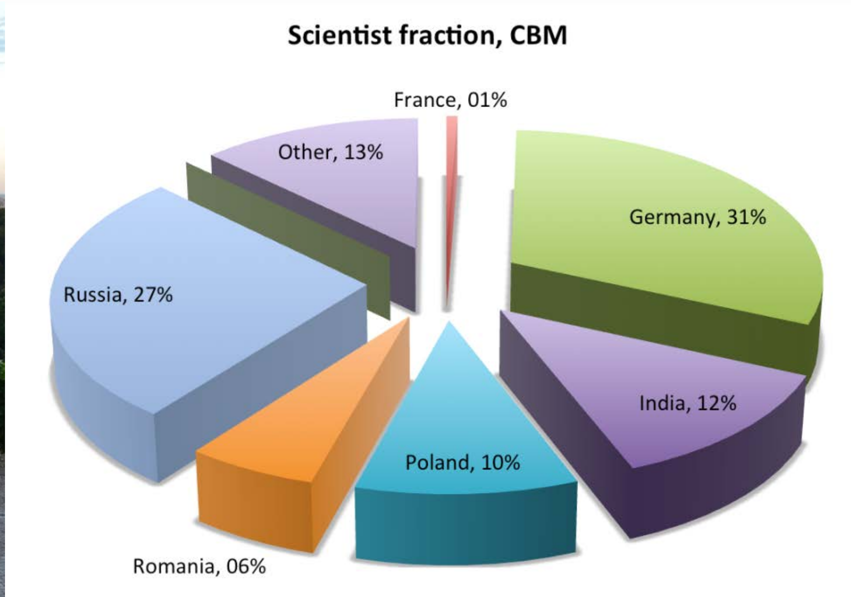
Korea:
Pusan Nat. Univ.

Poland:
AGH Krakow
Jag. Univ. Krakow
Silesia Univ. Katowice
Warsaw Univ.
Warsaw TU

Romania:
NIPNE Bucharest
Univ. Bucharest

Russia:
IHEP Protvino
INR Troitzk
ITEP Moscow
Kurchatov Inst., Moscow
LHEP, JINR Dubna
LIT, JINR Dubna
MEPHI Moscow
PNPI Gatchina
SINP MSU, Moscow
St. Petersburg P. Univ.
Ioffe Phys.-Tech. Inst. St. Pb.

Ukraine:
T. Shevchenko Univ. Kiev
Kiev Inst. Nucl. Research



Summary

- CBM scientific program at SIS100:
  Exploration of the QCD phase diagram in the region of neutron star core densities $\rightarrow$ large discovery potential.
- First measurements with CBM:
  High-precision multi-differential measurements of hadrons incl. multistrange hyperons, hypernuclei and dileptons for different beam energies and collision systems $\rightarrow$ terra incognita.
- Status of experiment preparation:
  Prototype detector performances fulfill CBM requirements.
  7 TDRs approved, 4 TDRs in preparation.
- Funding:
  CBM start version is financed by about 2/3 (+ EoI).
- FAIR Phase 0:
  HADES with CBM RICH photon detector,
  use CBM detectors at STAR/BNL and BM@N/JINR

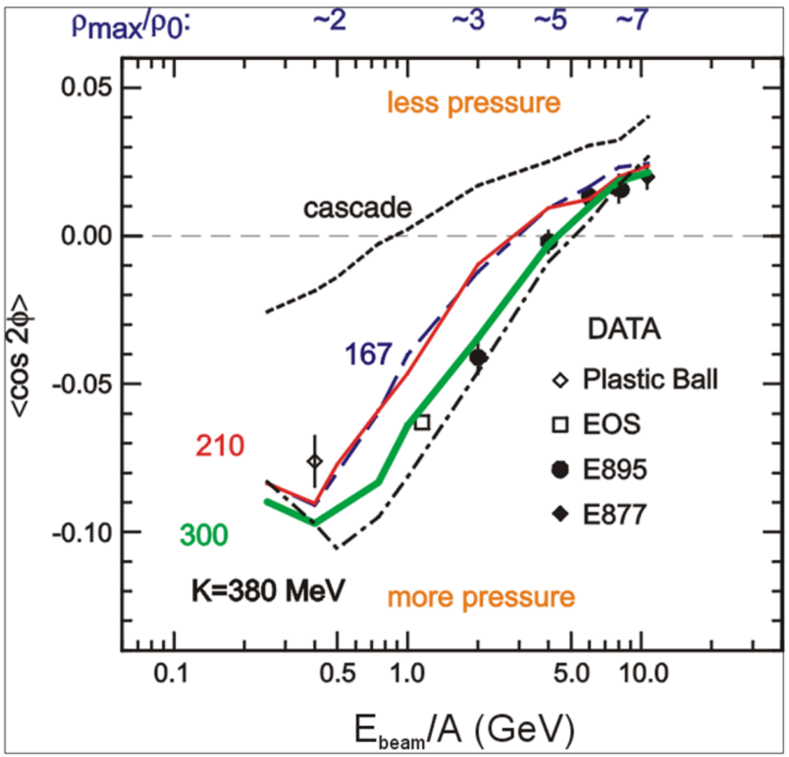
Backup

CBM physics case and observables

The QCD matter equation-of-state at neutron star core densities

- collective flow of identified particles (π,K,p,Λ,Ξ,Ω,...)
  driven by the pressure gradient in the early fireball

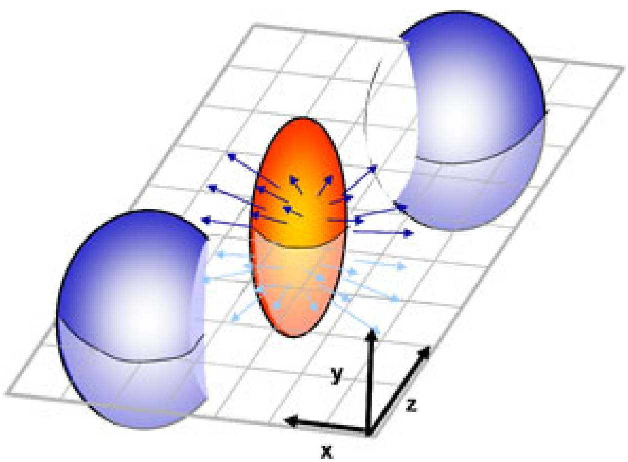
AGS: proton flow in Au+Au collisions



P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

Azimuthal angle distribution:

$dN/d\phi = C\,(1 + v_1 \cos(\phi) + v_2 \cos(2\phi) + \ldots)$



CBM physics case and observables

The QCD matter equation-of-state at neutron star core densities

- collective flow of identified particles (π,K,p,Λ,Ξ,Ω,...) driven by the pressure gradient in the early fireball
- particle production at (sub)threshold energies via multi-step processes (multi-strange hyperons, charm)

<u>Direct multi-strange hyperon production:</u>

$pp \rightarrow \Xi^- K^+K^+p$ (E_{thr} = 3.7 GeV)
$pp \rightarrow \Omega^- K^+K^+K^0p$ (E_{thr} = 7.0 GeV)
$pp \rightarrow \Lambda^0\bar{\Lambda}^0 pp$ (E_{thr} = 7.1 GeV)
$pp \rightarrow \Xi^+ \Xi^- pp$ (E_{thr} = 9.0 GeV)
$pp \rightarrow \Omega^+ \Omega^- pp$ (E_{thr} = 12.7 GeV

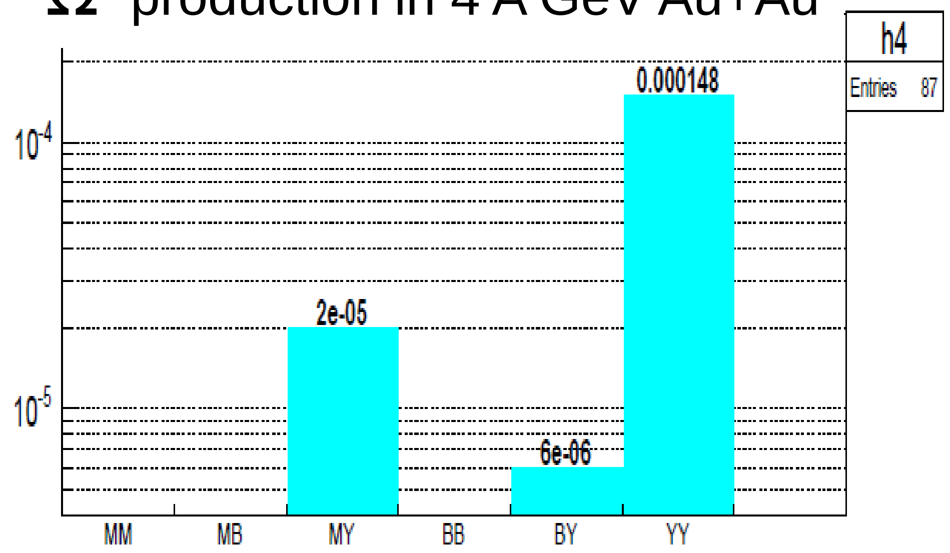
<u>Hyperon production via multiple collisions</u>

1. $pp \rightarrow K^+\Lambda^0 p$, $pp \rightarrow K^+K^-pp$,
2. $p\Lambda^0 \rightarrow K^+ \Xi^- p$, $\pi\Lambda^0 \rightarrow K^+ \Xi^- \pi$,
   $\Lambda^0\Lambda^0 \rightarrow \Xi^- p$, $\Lambda^0 K^- \rightarrow \Xi^- \pi^0$
3. $\Lambda^0 \Xi^- \rightarrow \Omega^- n$, $\Xi^- K^- \rightarrow \Omega^- \pi^-$

Antihyperons

1. $\bar{\Lambda}^0 K^+ \rightarrow \Xi^+ \pi^0$,
2. $\Xi^+ K^+ \rightarrow \Omega^+ \pi^+$.

Ω^- production in 4 A GeV Au+Au



HYPQGSM calculations , K. Gudima et al.

CBM physics case and observables

The QCD matter equation-of-state at neutron star core densities

- ➢ collective flow of identified particles ($\pi, K, p, \Lambda, \Xi, \Omega, \ldots$) driven by the pressure gradient in the early fireball
- ➢ particle production at (sub)threshold energies via multi-step processes (multi-strange hyperons, charm)

<u>Direct multi-strange hyperon production:</u>

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Antihyperons

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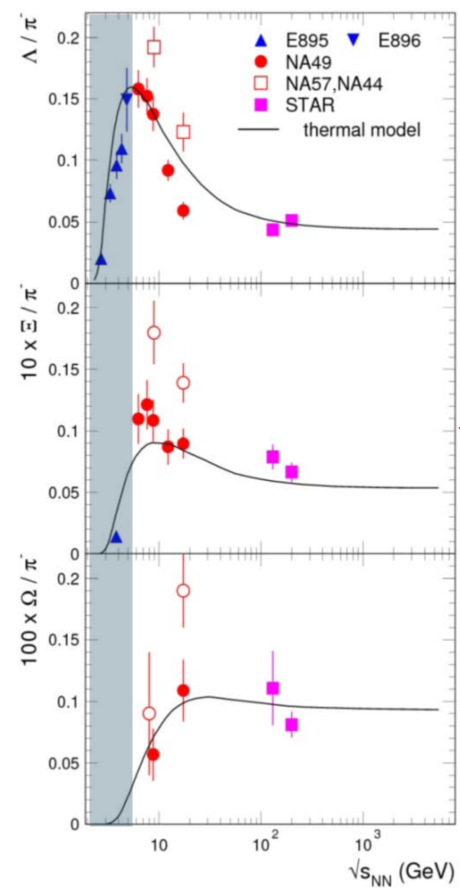


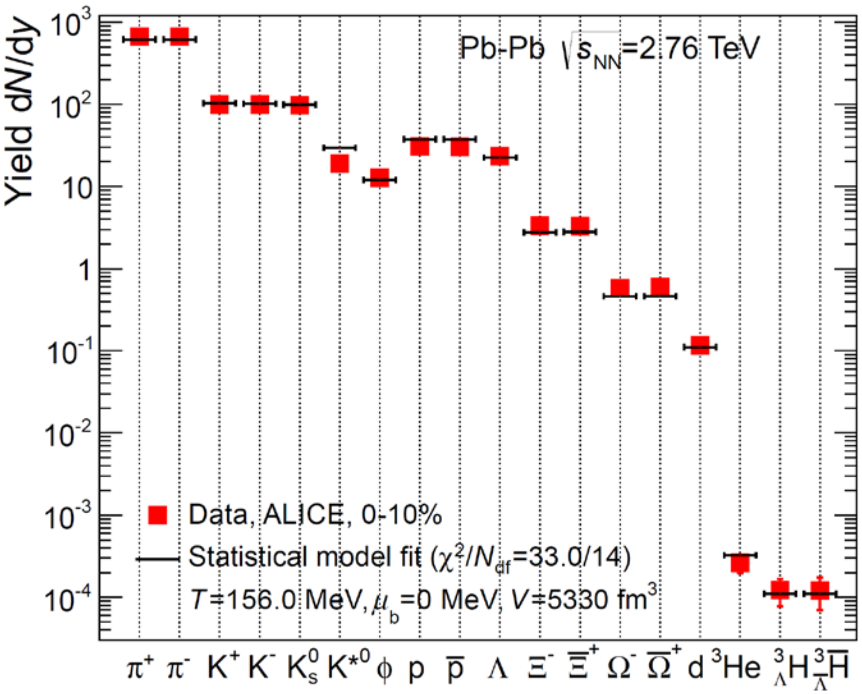
Very few data at FAIR energies

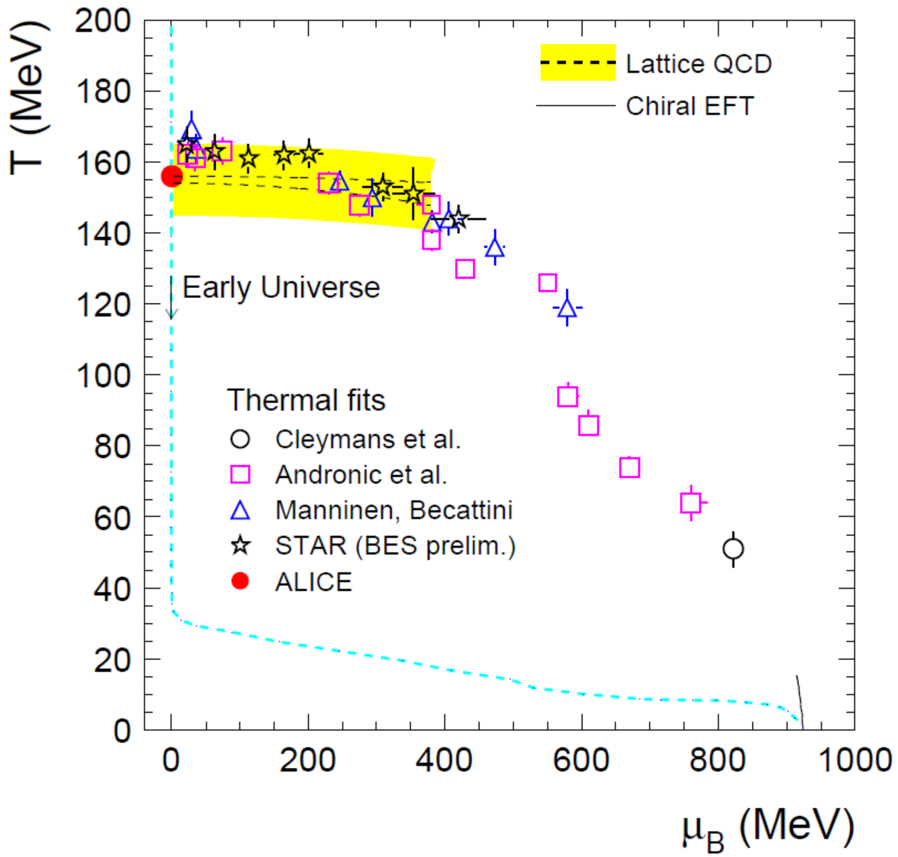
CBM physics case and observables

Phase transitions from partonic to hadronic matter

- ➢ excitation function of strangeness: $\Xi^-(dss)$, $\Xi^+(\overline{dss})$, $\Omega^-(sss)$, $\Omega^+(\overline{sss})$
  $\rightarrow$ chemical equilibration at the phase boundary

$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i-\mu_i)/T] \pm 1}$$





A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Jour. Phys. G38 (2011)

CBM physics case and observables

Phase transitions from partonic to hadronic matter

- excitation function of strangeness: $\Xi^-(dss)$, $\Xi^+(\overline{dss})$, $\Omega^-(sss)$, $\Omega^+(\overline{sss})$
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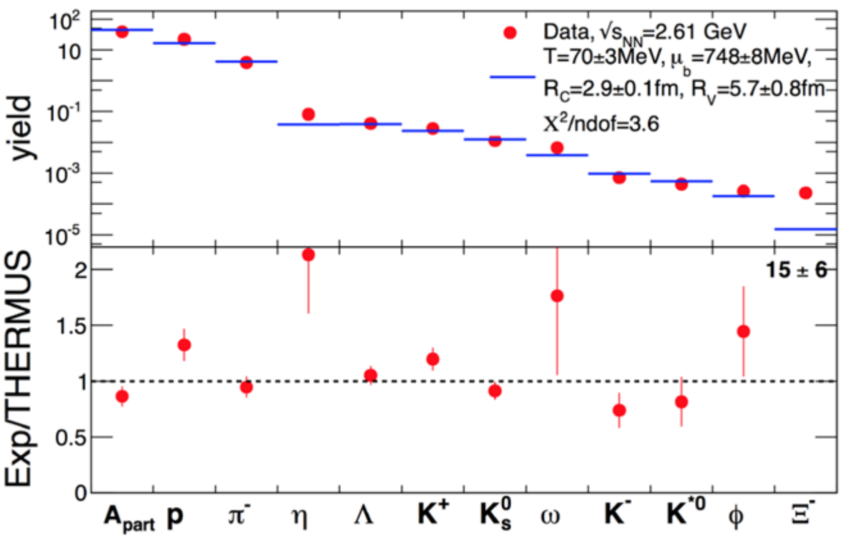
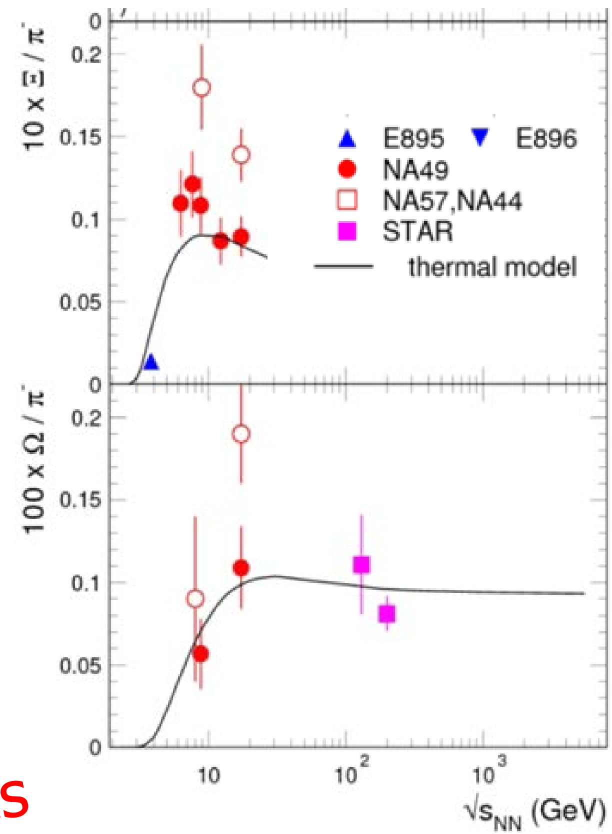
Particle yields and thermal model fits

HADES: Ar + KCl 1.76 A GeV
G. Agakishiev et al., arXiv:1512.07070





Very few data
at FAIR energies

CBM physics case and observables

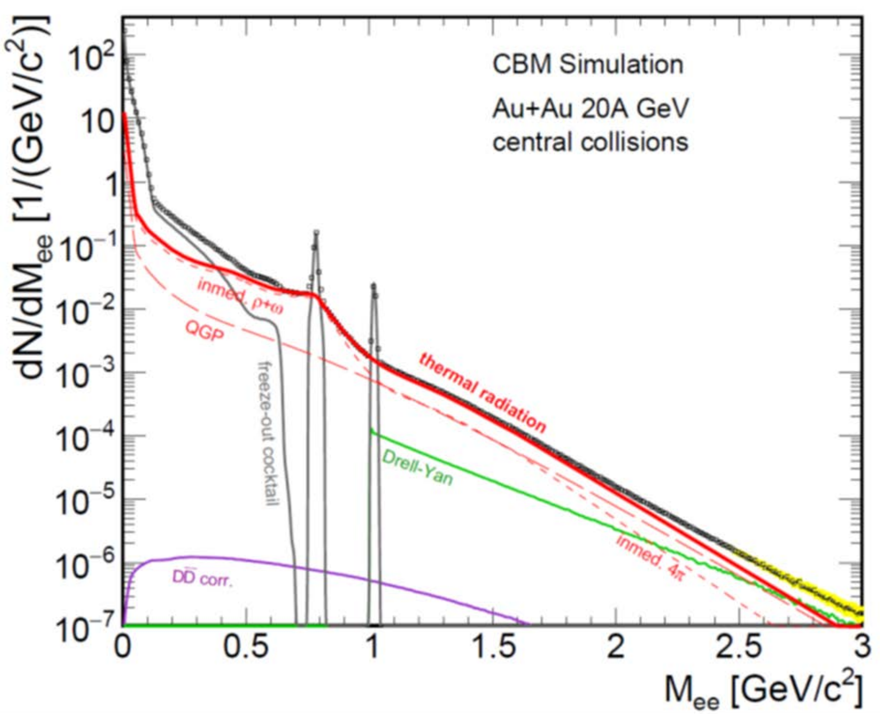
Phase transitions from partonic to hadronic matter

- excitation function of strangeness: Ξ^-(dss),Ξ^+($\overline{\text{dss}}$),Ω^-(sss),Ω^+($\overline{\text{sss}}$)
  $\rightarrow$ chemical equilibration at the phase boundary

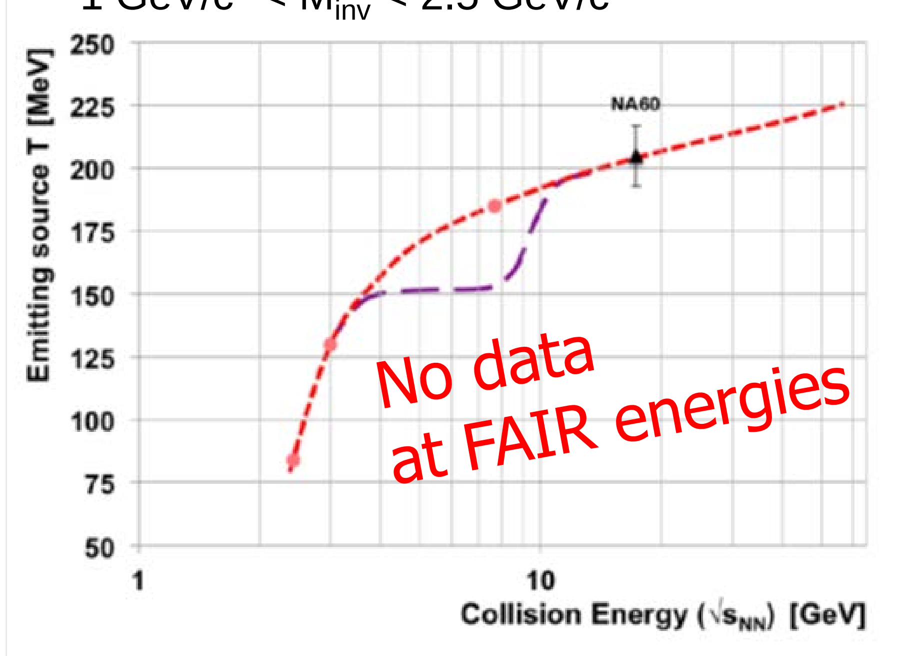
Phase coexistence

- excitation function (invariant mass) of lepton pairs:
  thermal radiation from QGP, caloric curve

Invariant mass distribution of lepton pairs



Slope of dilepton invariant mass spectrum
1 GeV/c^2 < M_{inv} < 2.5 GeV/c^2



CBM physics case and observables

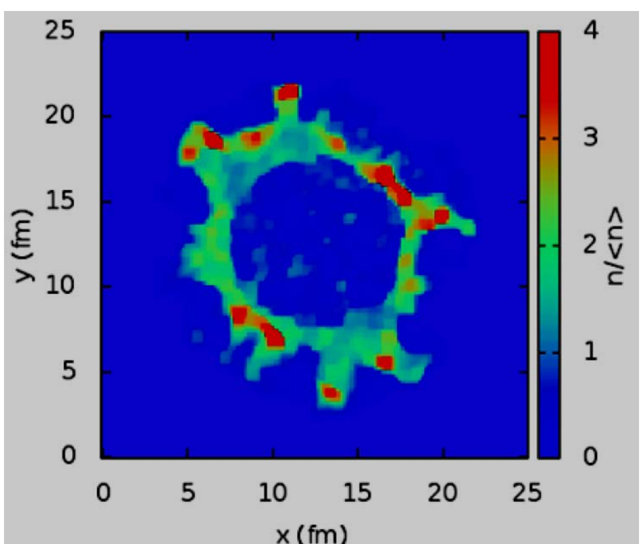
Phase transitions from partonic to hadronic matter

- excitation function of strangeness: $\Xi^-(dss)$,$\Xi^+(\bar{d}\bar{s}\bar{s})$,$\Omega^-(sss)$,$\Omega^+(\bar{s}\bar{s}\bar{s})$
  $\rightarrow$ chemical equilibration at the phase boundary

Phase coexistence

- excitation function (invariant mass) of lepton pairs:
  thermal radiation from QGP, caloric curve
- anisotropic azimuthal angle distributions: "spinodal decomposition"

Spinodal decomposition of the mixed phase



Slope of dilepton invariant mass spectrum
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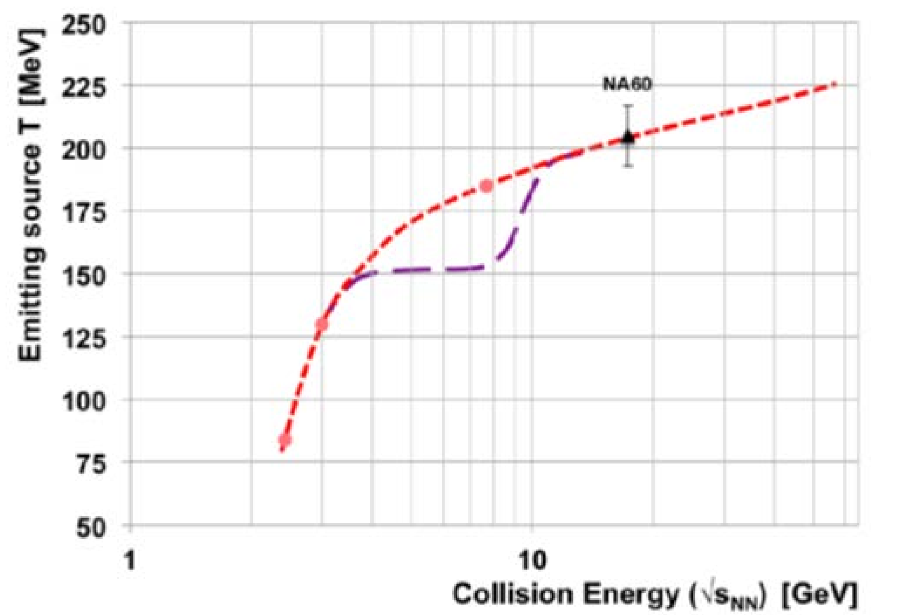


CBM physics case and observables

Phase transitions from partonic to hadronic matter

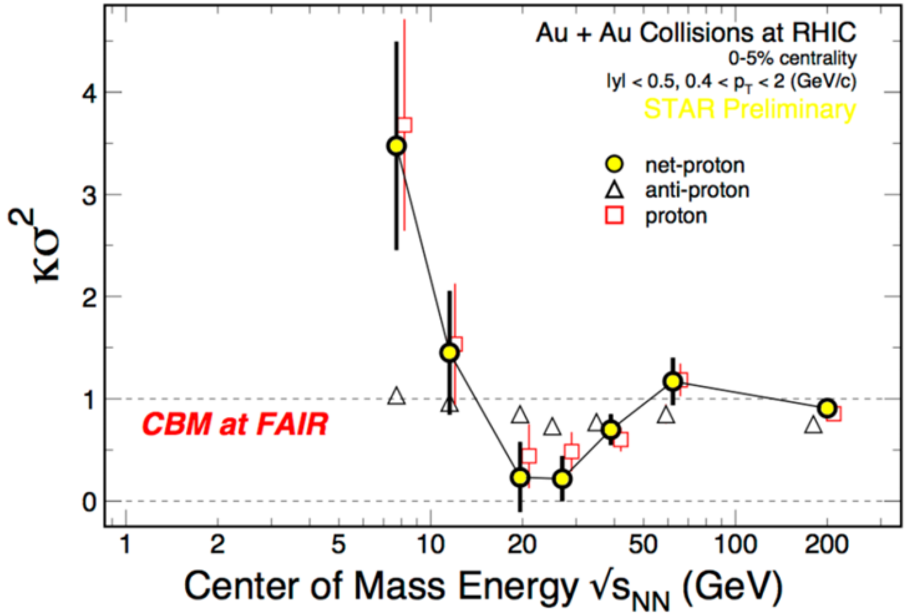
- excitation function of strangeness: Ξ^-(dss),Ξ^+(dss),Ω^-(sss),Ω^+(sss)
  $\rightarrow$ chemical equilibration at the phase boundary

Phase coexistence

- excitation function (invariant mass) of lepton pairs:
  thermal radiation from QGP, caloric curve
- anisotropic azimuthal angle distributions: "spinodal decomposition"

Critical point

- event-by-event fluctuations of conserved quantities (B,S,Q)
  "critical opalescence"



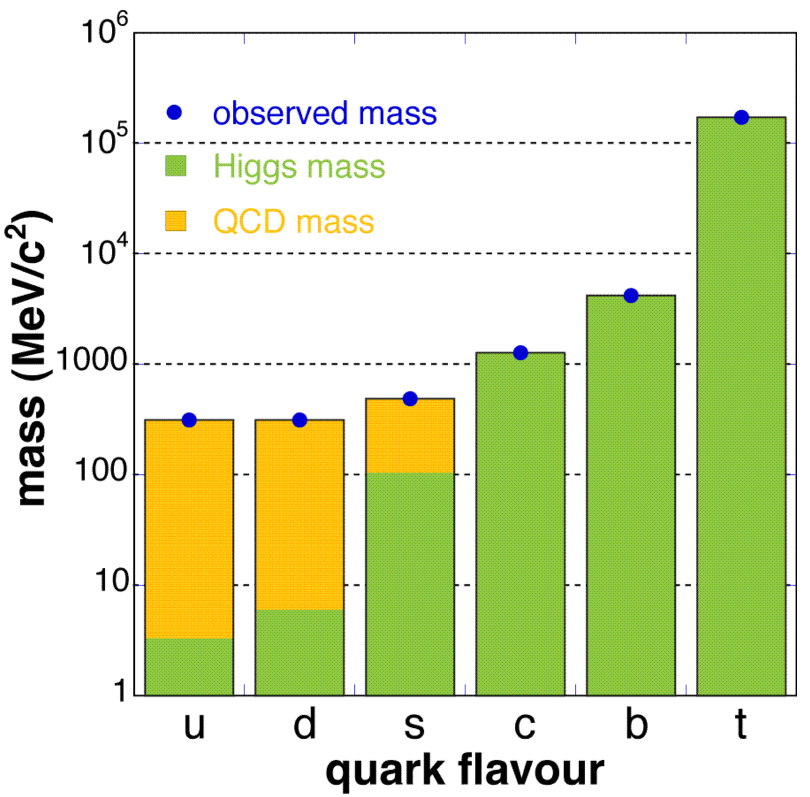
4th moment of net-proton multiplicity distribution: critical fluctuations

No data at FAIR energies

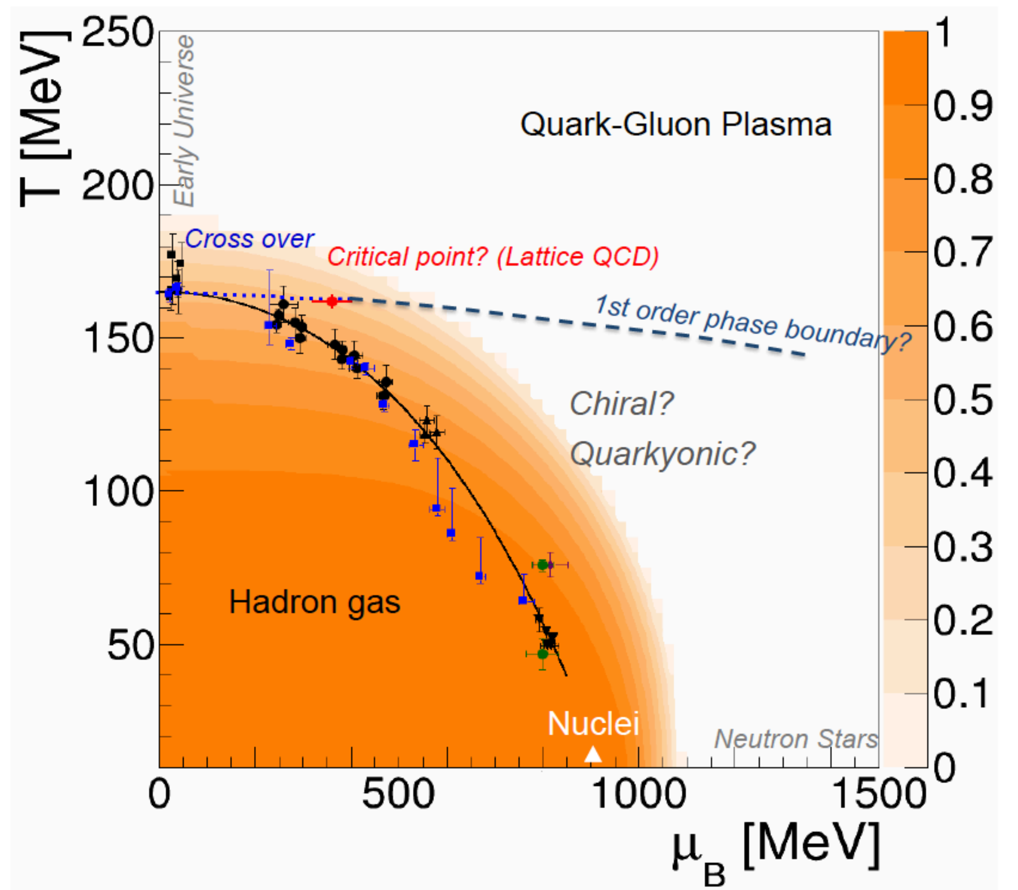
CBM physics case and observables

Onset of chiral symmetry restoration at high ρ_B

Origin of quark masses



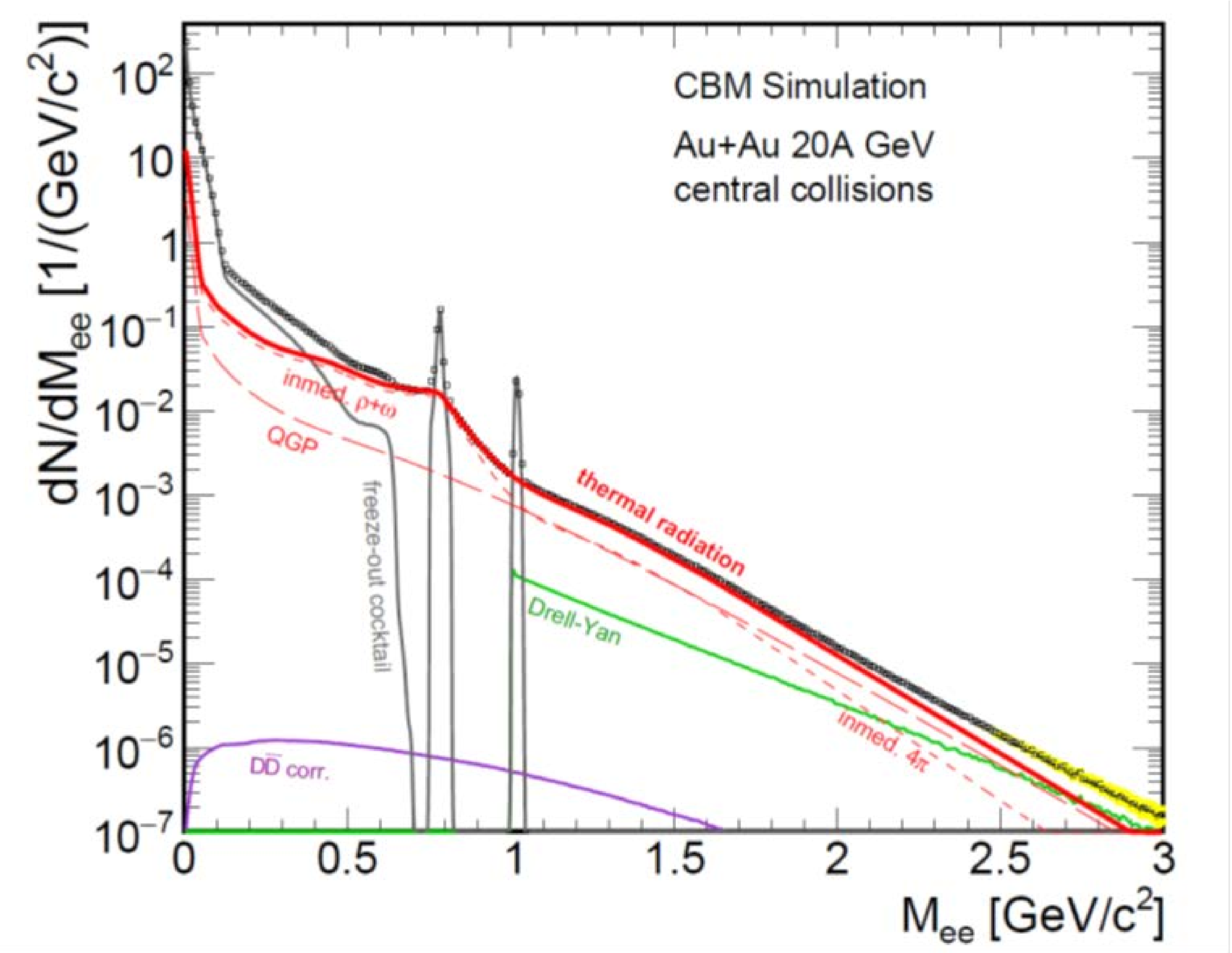
Chiral condensate: orange region



CBM physics case and observables

Onset of chiral symmetry restoration at high ρ_B

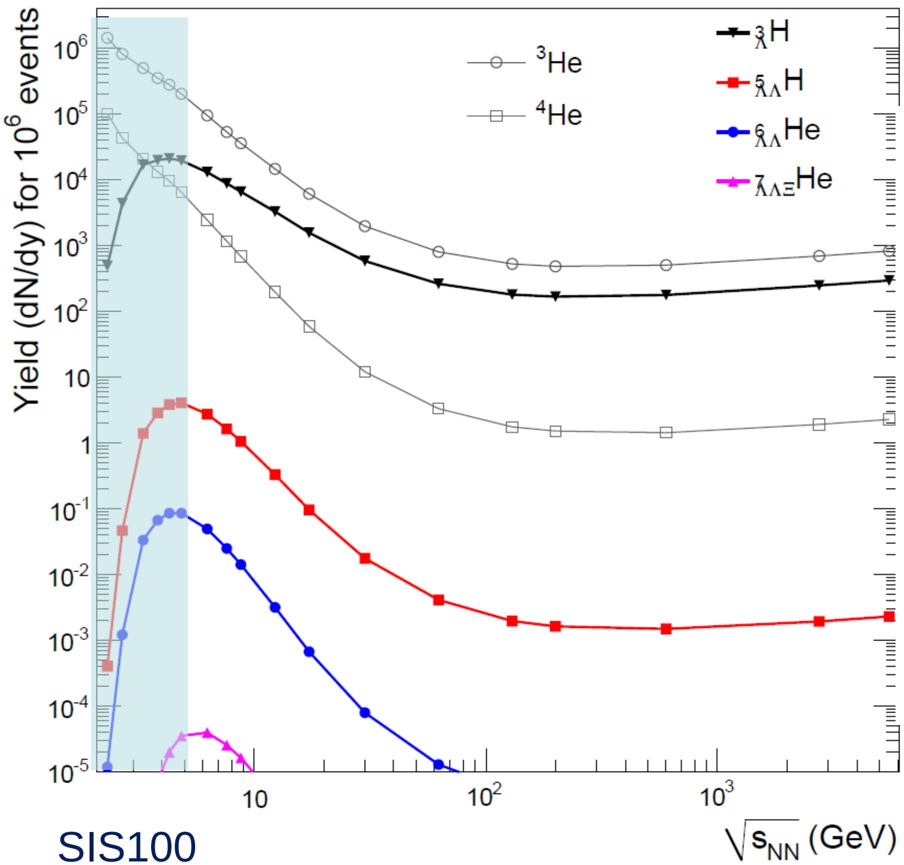
- in-medium modifications of hadrons: $\rho,\omega,\phi \rightarrow e^+e^-(\mu^+\mu^-)$
- dileptons at intermediate invariant masses: $4\,\pi \rightarrow \rho\text{-}a_1$ chiral mixing

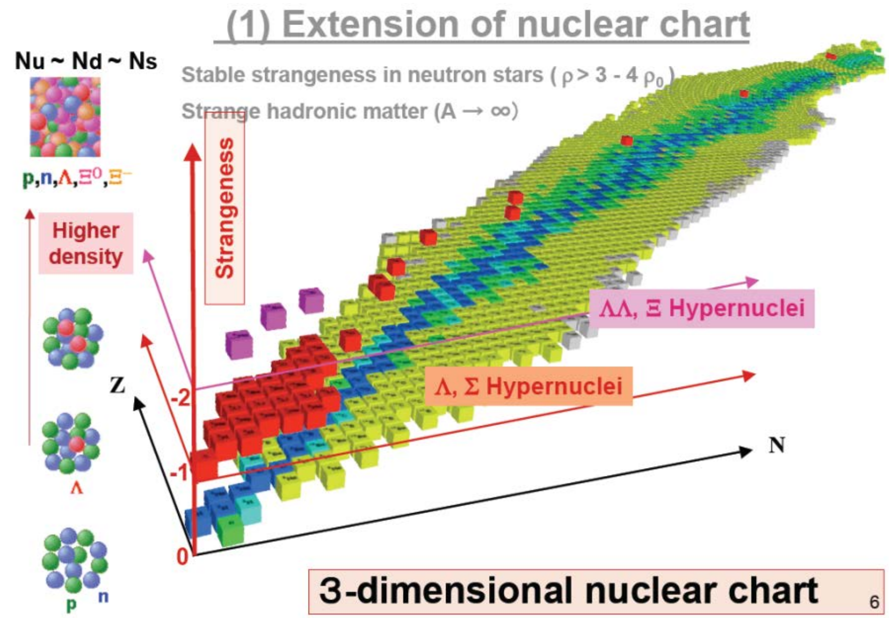


CBM physics case and observables

N-Λ, Λ-Λ interaction, strange matter?

- (double-) lambda hypernuclei
- meta-stable objects (e.g. strange dibaryons)



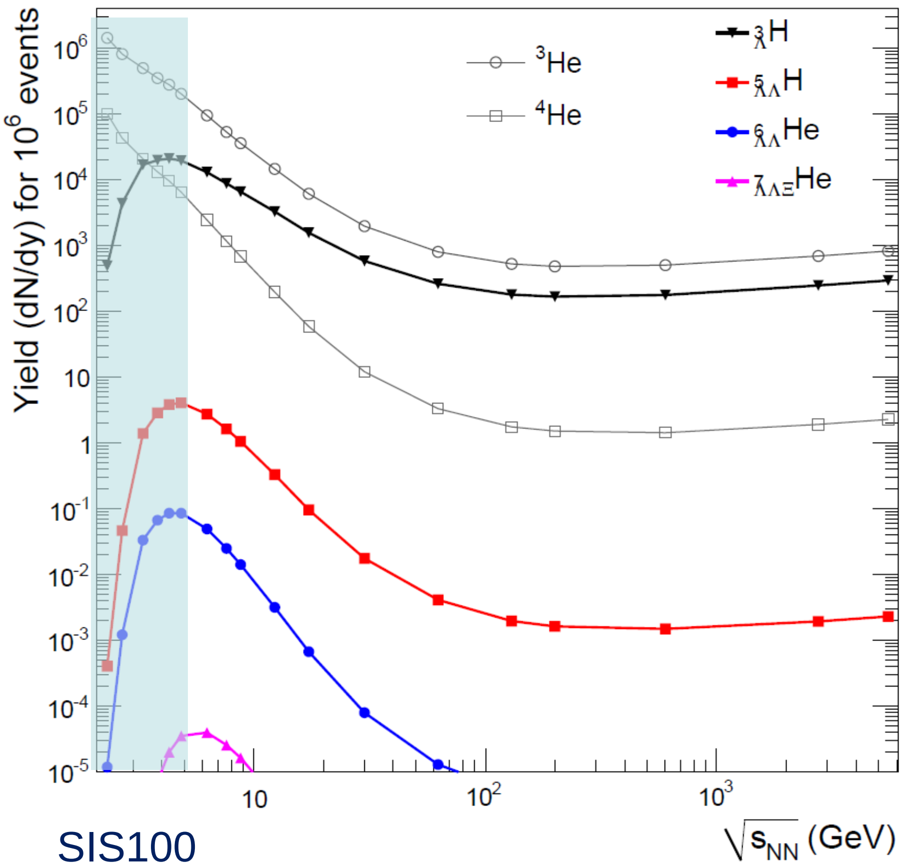


A. Andronic et al., Phys. Lett. B697 (2011) 203

CBM physics case and observables

N-Λ, Λ-Λ interaction, strange matter?

- (double-) lambda hypernuclei
- meta-stable objects (e.g. strange dibaryons)



A. Andronic et al., Phys. Lett. B697 (2011) 203

Double lambda hypernuclei production in central Au+Au collisions at 10 A GeV:

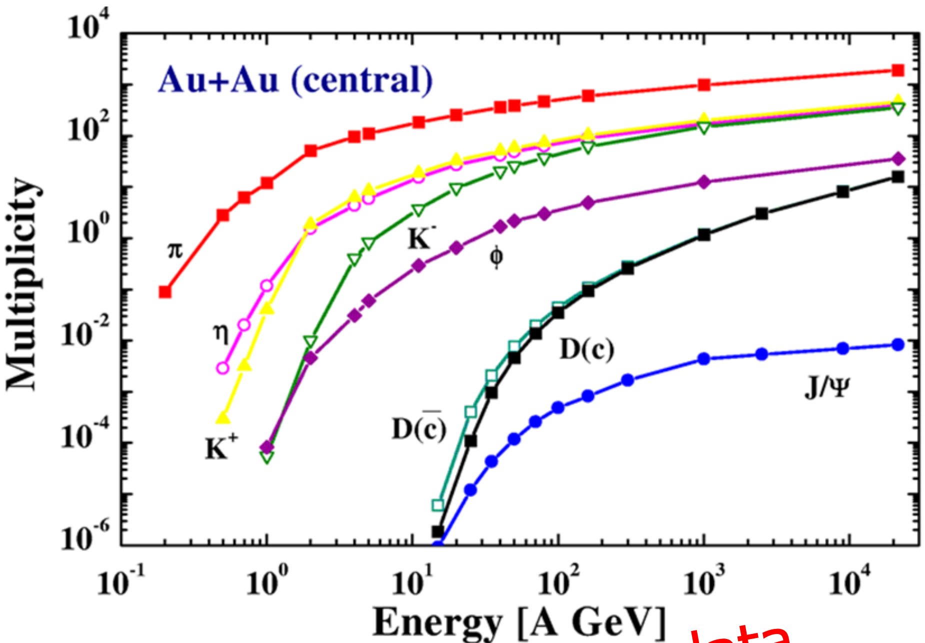
	Multiplicity	Yield in 1 week
${}^5_{\Lambda\Lambda}H$	$5 \cdot 10^{-6}$	3000
${}^6_{\Lambda\Lambda}He$	$1 \cdot 10^{-7}$	60

Assumption for yield calculation:
Reaction Rate 1 MHz
BR 10% (2 sequential weak decays)
Efficiency 1%

CBM physics case and observables

Charm production at threshold energies in cold and dense matter

- excitation function of charm production in p+A and A+A   (J/ψ, D^0, $D^{\pm}$)

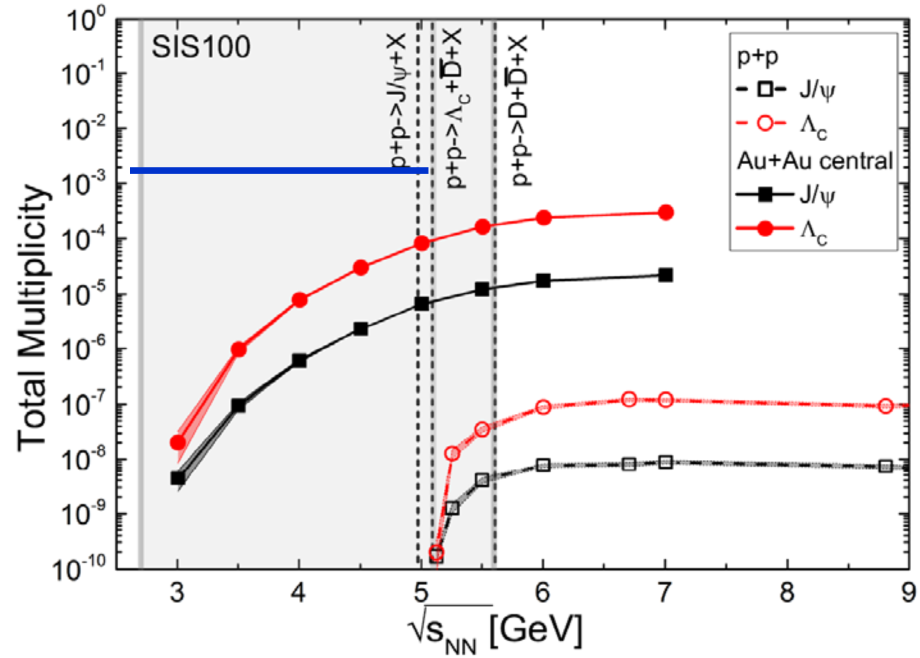


HSD calculation

No data at FAIR energies

Central coll. Au+Au 10 A GeV :
$M_{J/\psi} = 1.7 \cdot 10^{-7}$

W. Cassing, E. Bratkovskaya, A. Sibirtsev, Nucl. Phys. A 691 (2001) 753



UrQMD calculation including subthreshold charm production via
$N^* \rightarrow \Lambda_c + D$ and $N^* \rightarrow N + J/\psi$

Central Au+Au collisions 10 A GeV:
$M_{J/\psi} = 5 \cdot 10^{-6}$

J. Steinheimer, A. Botvina, M. Bleicher, arXiv:1605.03439v1