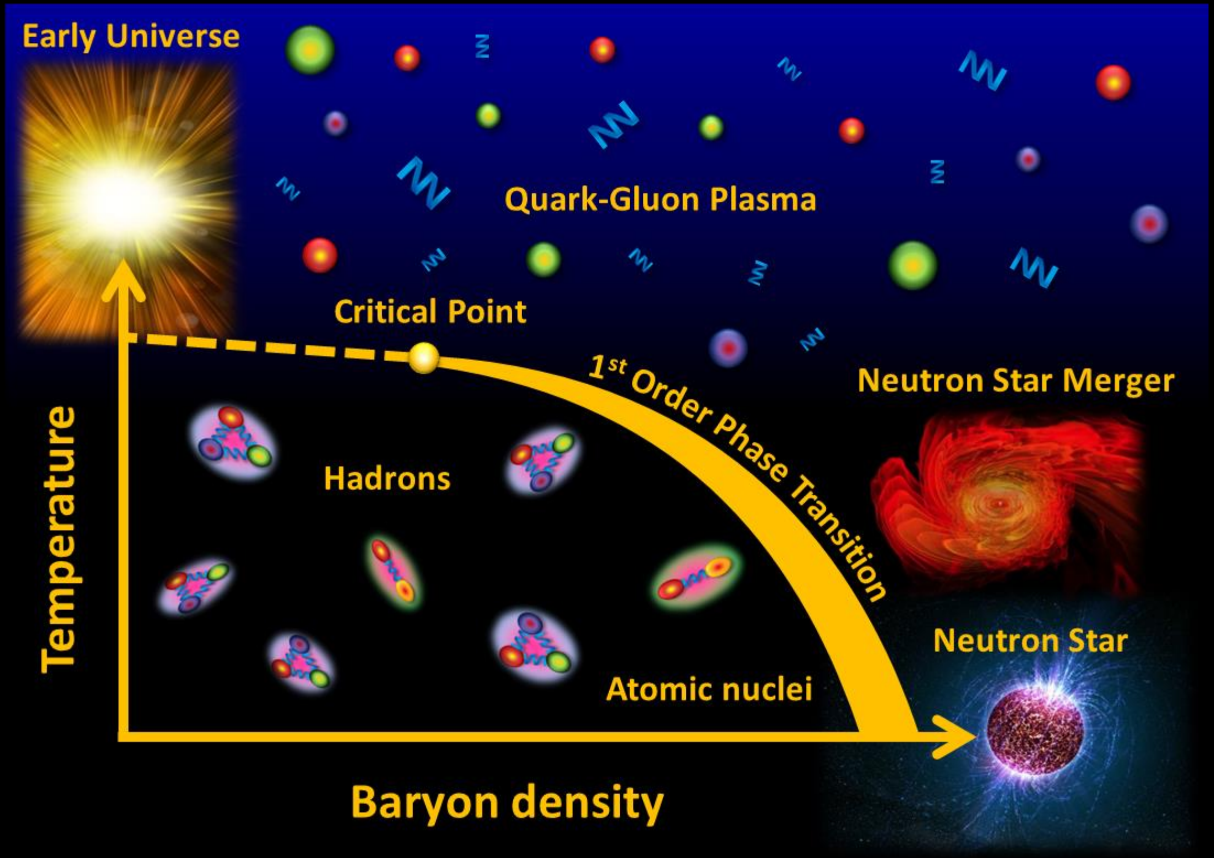
Cosmic Matter in the Laboratory – The Compressed Baryonic Matter experiment at FAIR

Peter Senger GSI and Univ. Frankfurt

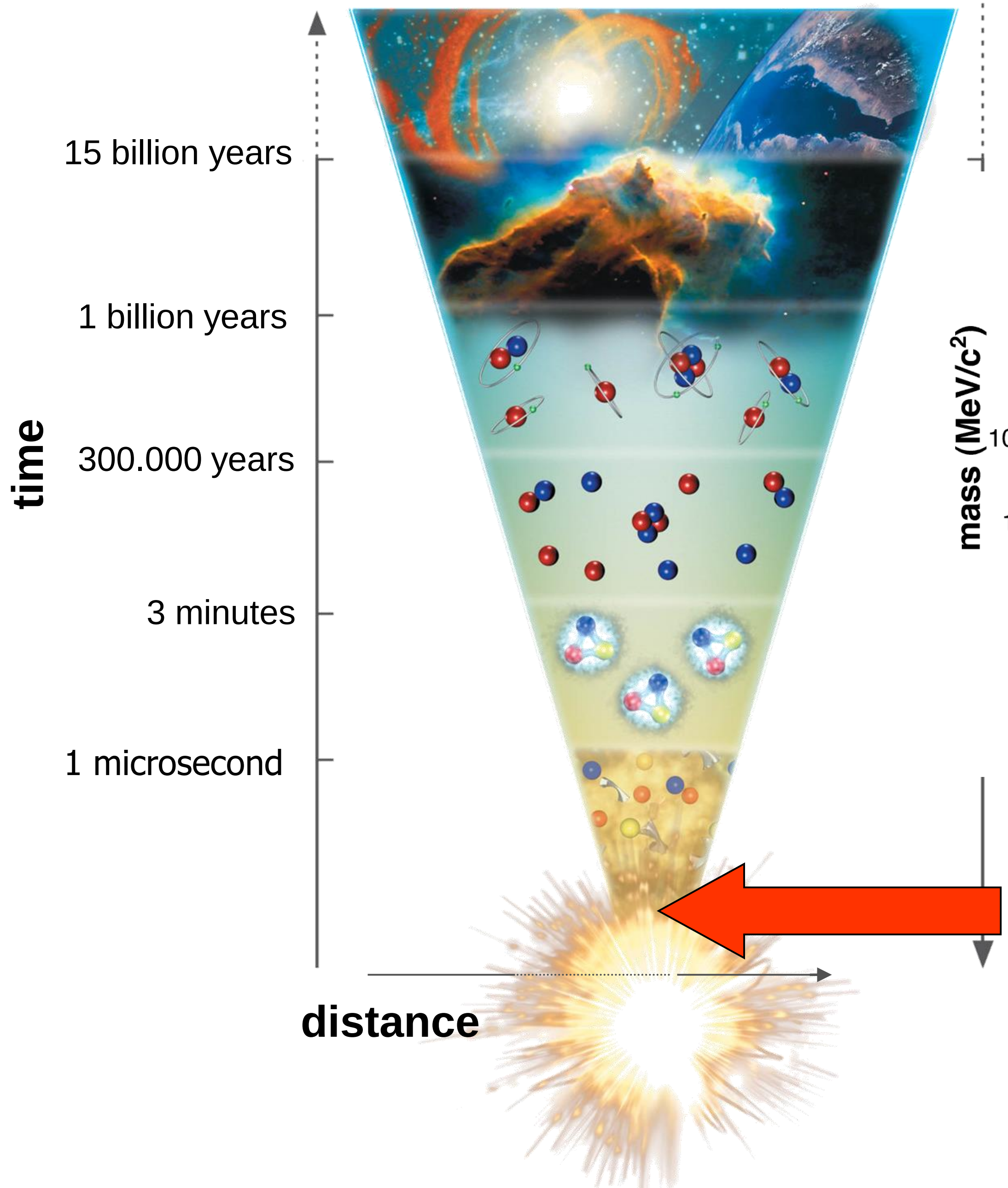


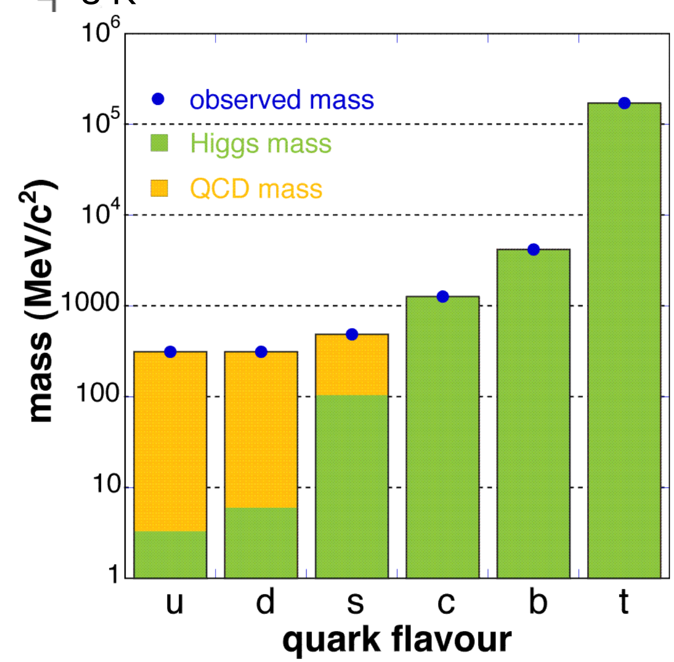
Outline:

- Cosmic matter
- The Facility of Antiproton and Ion Research
- The Compressed Baryonic Matter experiment

XXXVII Physics In Collision (PIC 2017), September 4- 8, 2017, Prague, Czech Republic

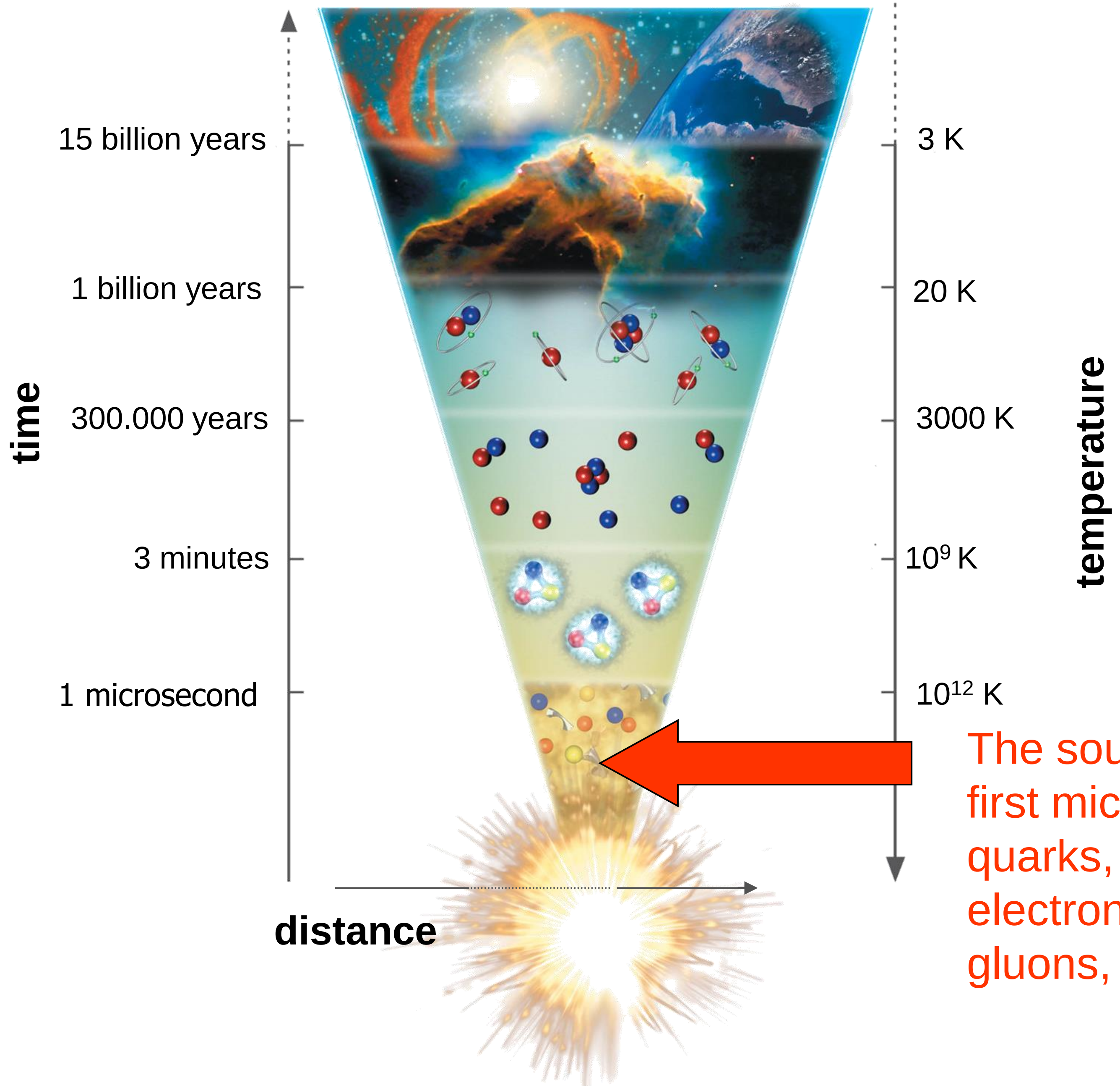
The evolution of matter in the universe





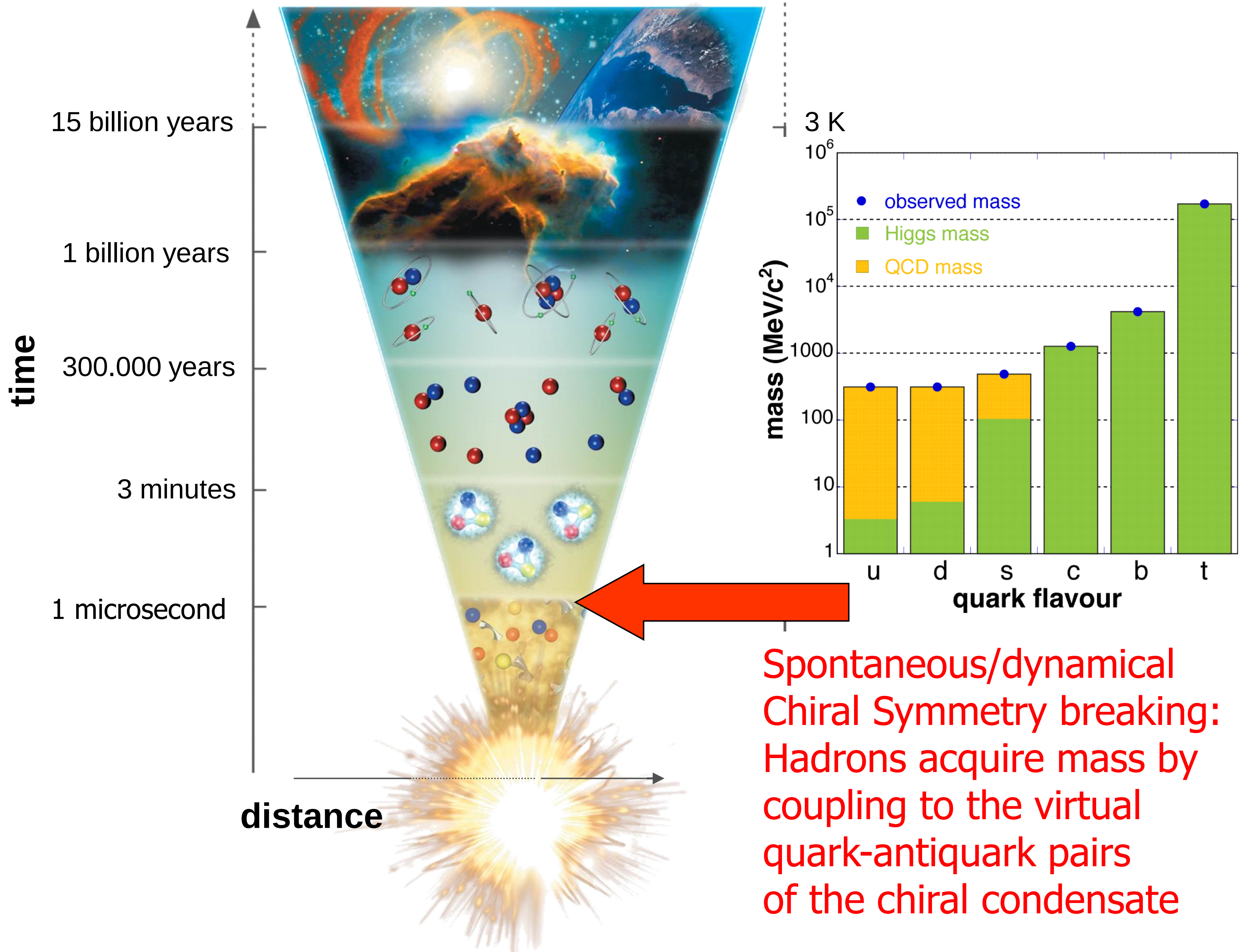
Explicit breaking
of Chiral Symmetry
(Higgs mechanism)
$m_u \approx 5$ MeV,
$m_d \approx 10$ MeV,
$m_s \approx 150$ MeV

The evolution of matter in the universe



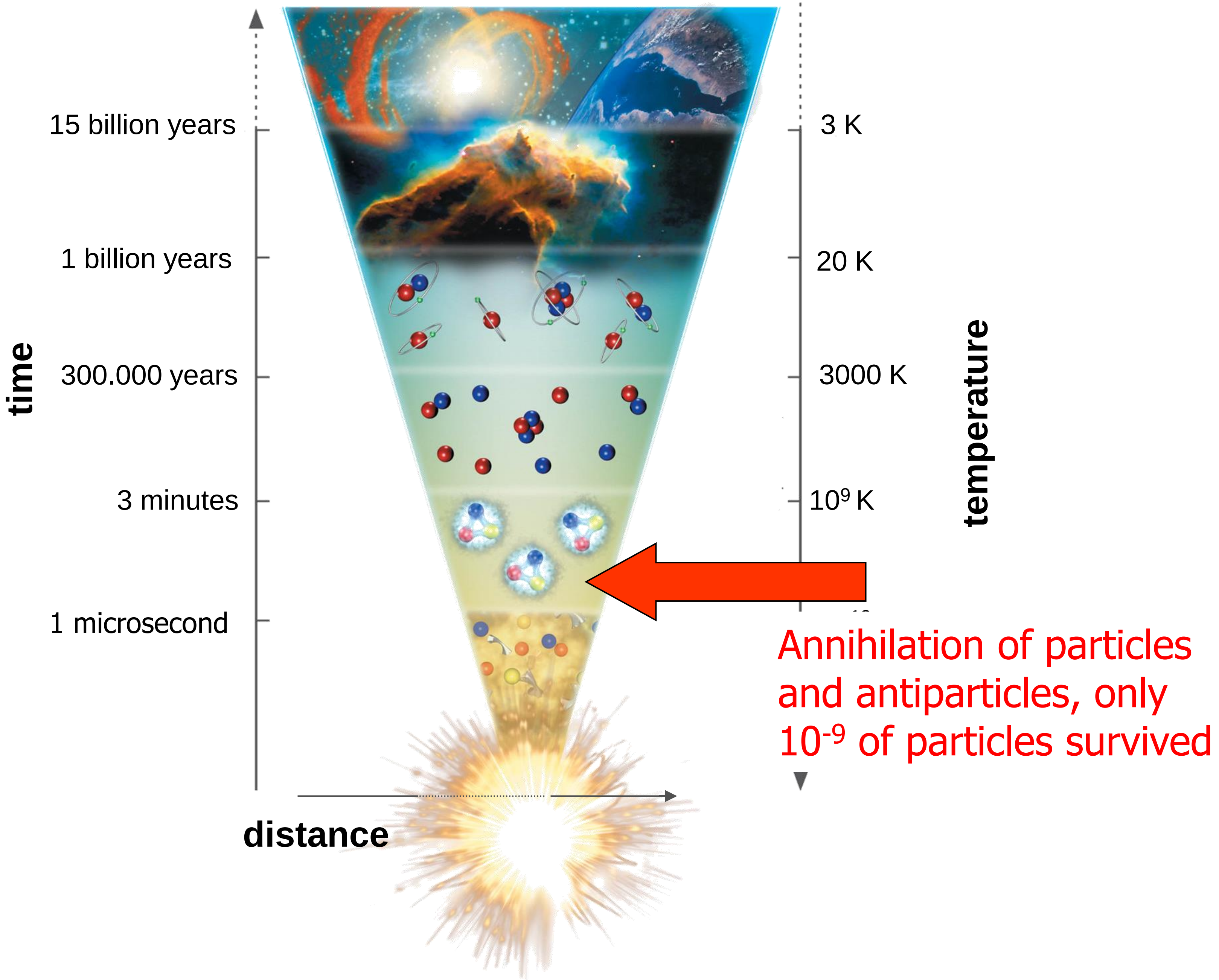
The soup of the first microsecond: quarks, antiquarks, electrons, positrons, gluons, photons

The evolution of matter in the universe

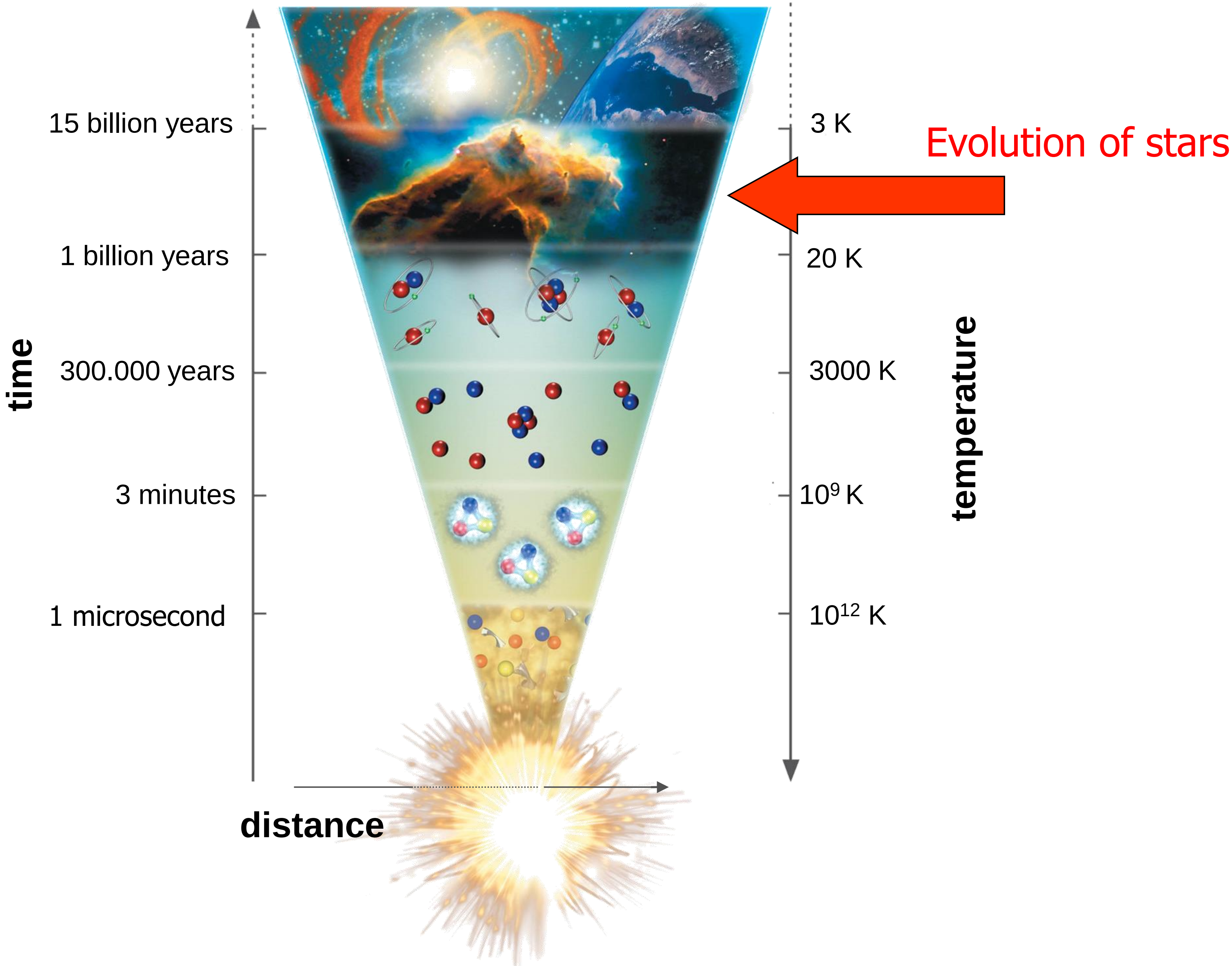


Spontaneous/dynamical
Chiral Symmetry breaking:
Hadrons acquire mass by
coupling to the virtual
quark-antiquark pairs
of the chiral condensate

The evolution of matter in the universe



The evolution of matter in the universe

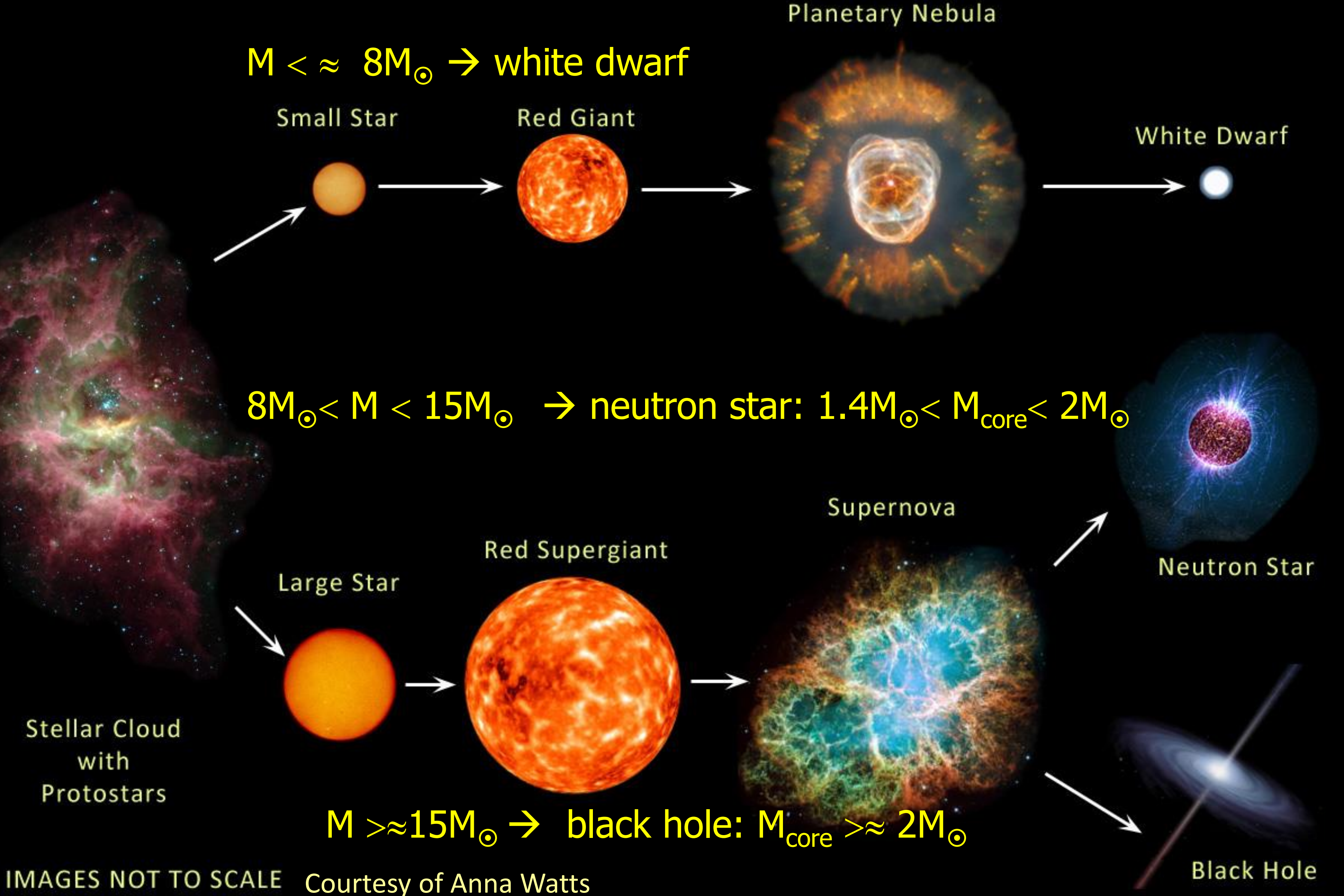


The evolution of stars

$M <\approx 8M_\odot \rightarrow$ white dwarf

$8M_\odot < M < 15M_\odot \rightarrow$ neutron star: $1.4M_\odot < M_{core} < 2M_\odot$

$M >\approx 15M_\odot \rightarrow$ black hole: $M_{core} >\approx 2M_\odot$



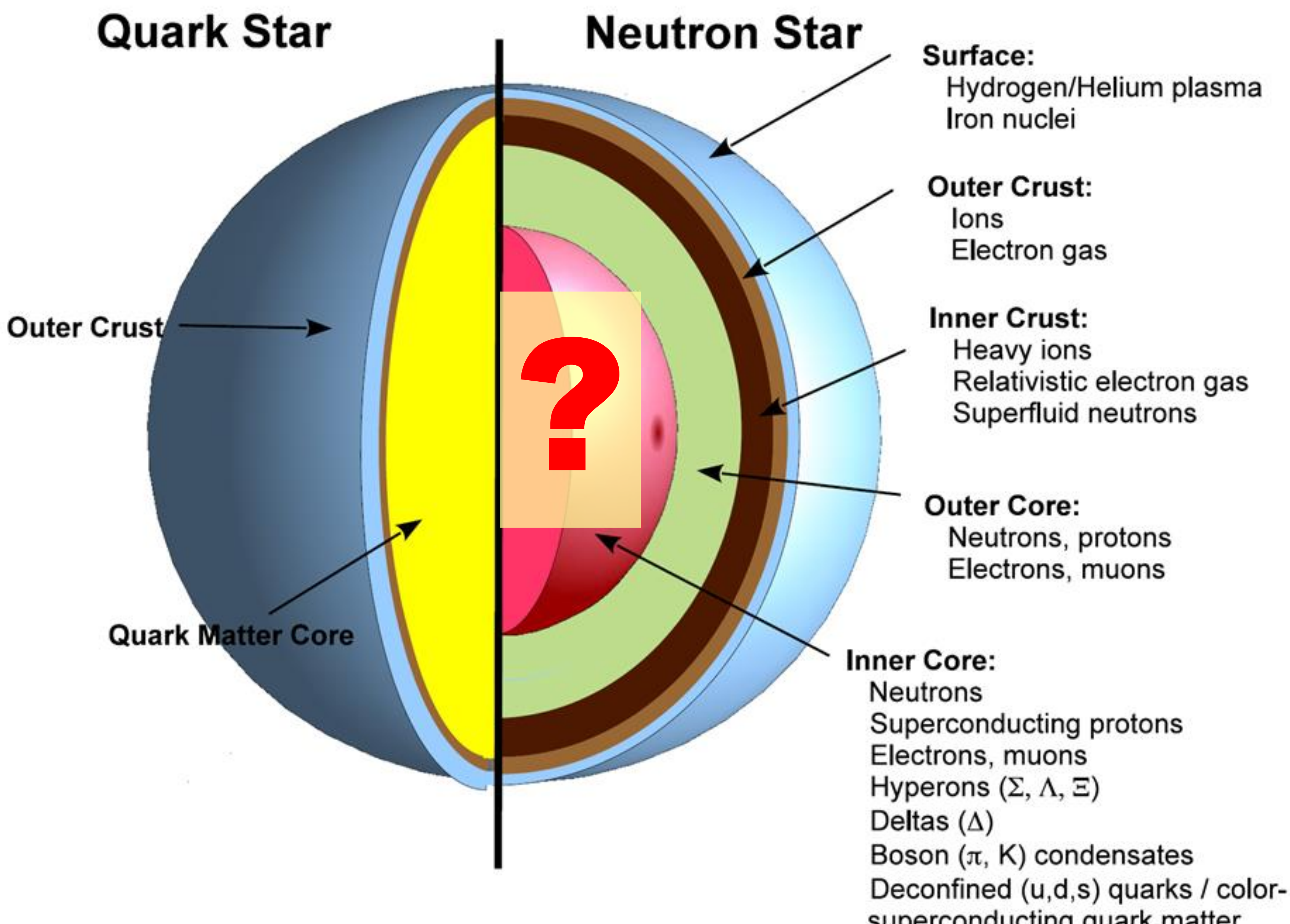
Courtesy of Anna Watts

Discovery of the first pulsar in 1968

Crab nebula:

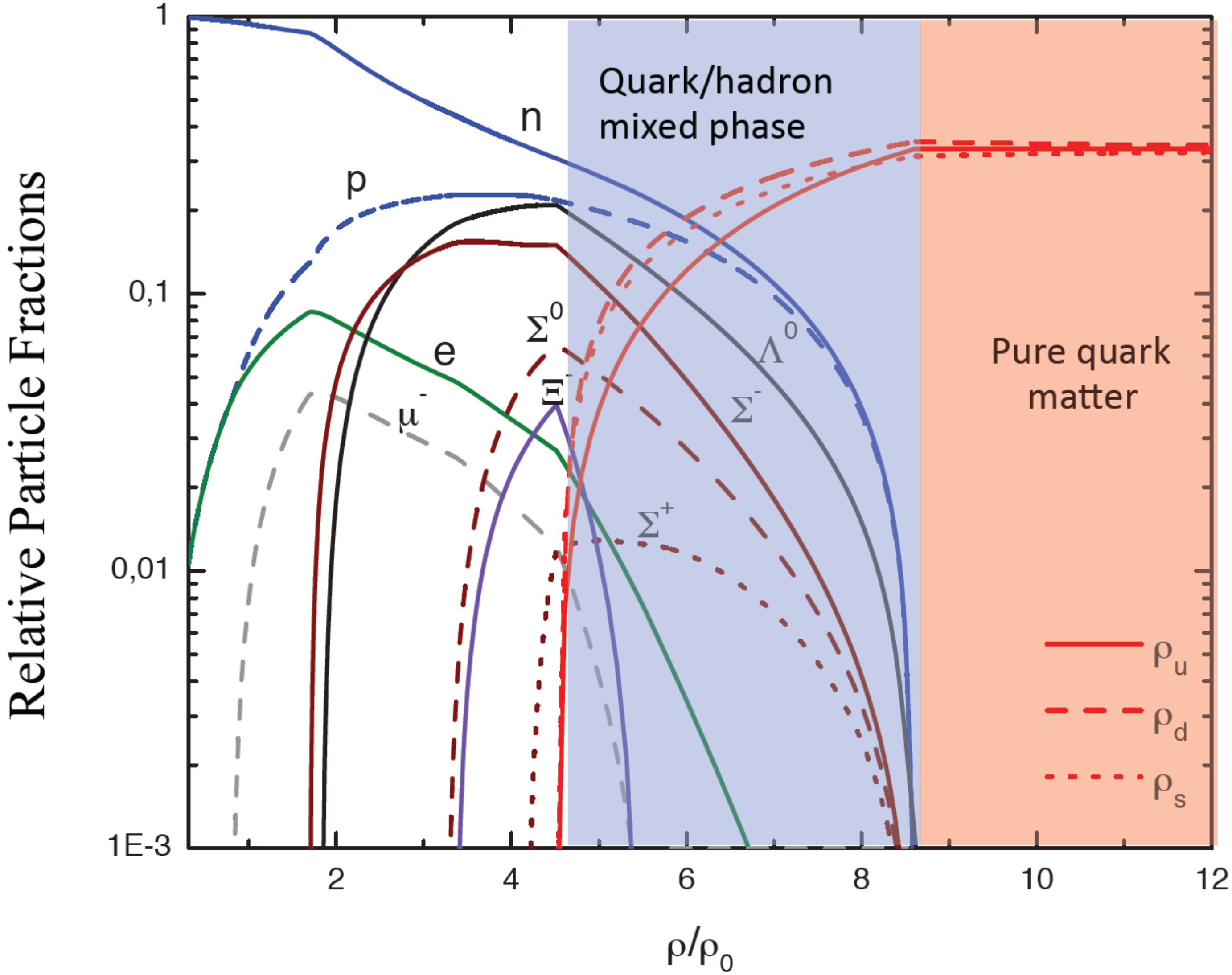
ashes of a core collapse supernova observed in 1054 by Chinese astronomers.

The “visiting star” was as bright as the Venus for more than 20 days.


Quark Star
Neutron Star
Surface:
Hydrogen/Helium plasma
Iron nuclei
Outer Crust:
Ions
Electron gas
Inner Crust:
Heavy ions
Relativistic electron gas
Superfluid neutrons
Outer Core:
Neutrons, protons
Electrons, muons
Inner Core:
Neutrons
Superconducting protons
Electrons, muons
Hyperons (Σ, Λ, Ξ)
Deltas (Δ)
Boson (π, K) condensates
Deconfined (u,d,s) quarks / color-superconducting quark matter
Outer Crust
Quark Matter Core
?

Quark matter in massive neutron stars?

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



Fundamental questions

What is the origin of the mass of the universe?

What is the origin of the elements ?

What is the structure of neutron stars?

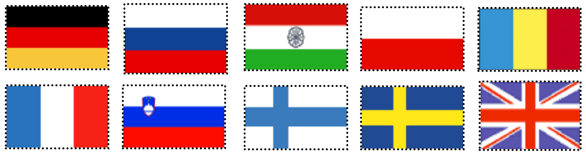
Can we ignite the solar fire on earth ?

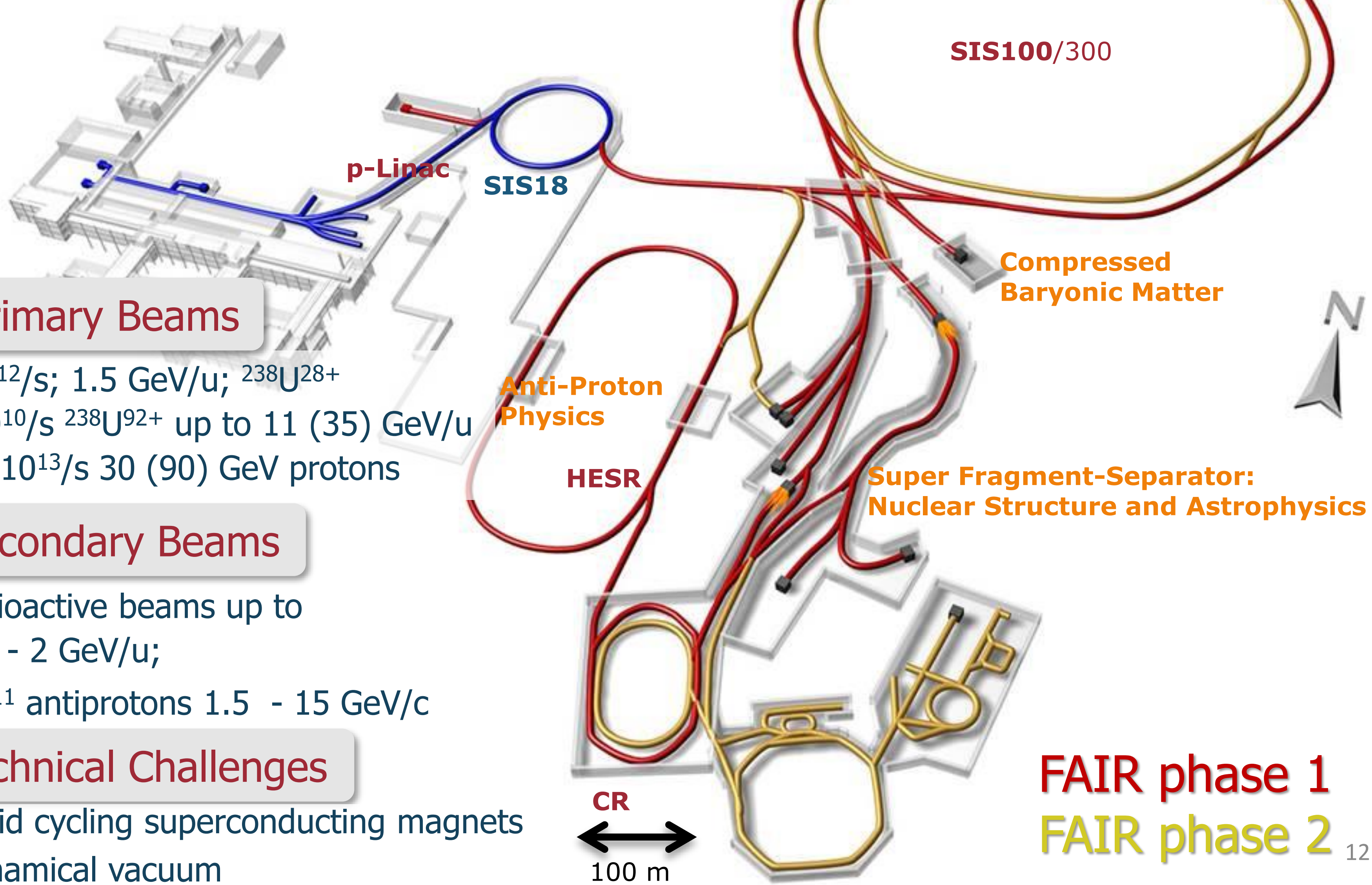
Does matter differ from antimatter ?

Why do we not observe individual quarks ?

→ to be explored at the future international Facility for Antiproton and Ion Research (FAIR)

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

Secondary Beams

- radioactive beams up to 1.5 - 2 GeV/u;
- 10^{11} antiprotons 1.5 - 15 GeV/c

Technical Challenges

- rapid cycling superconducting magnets
- dynamical vacuum

Facility for Antiproton & Ion Research

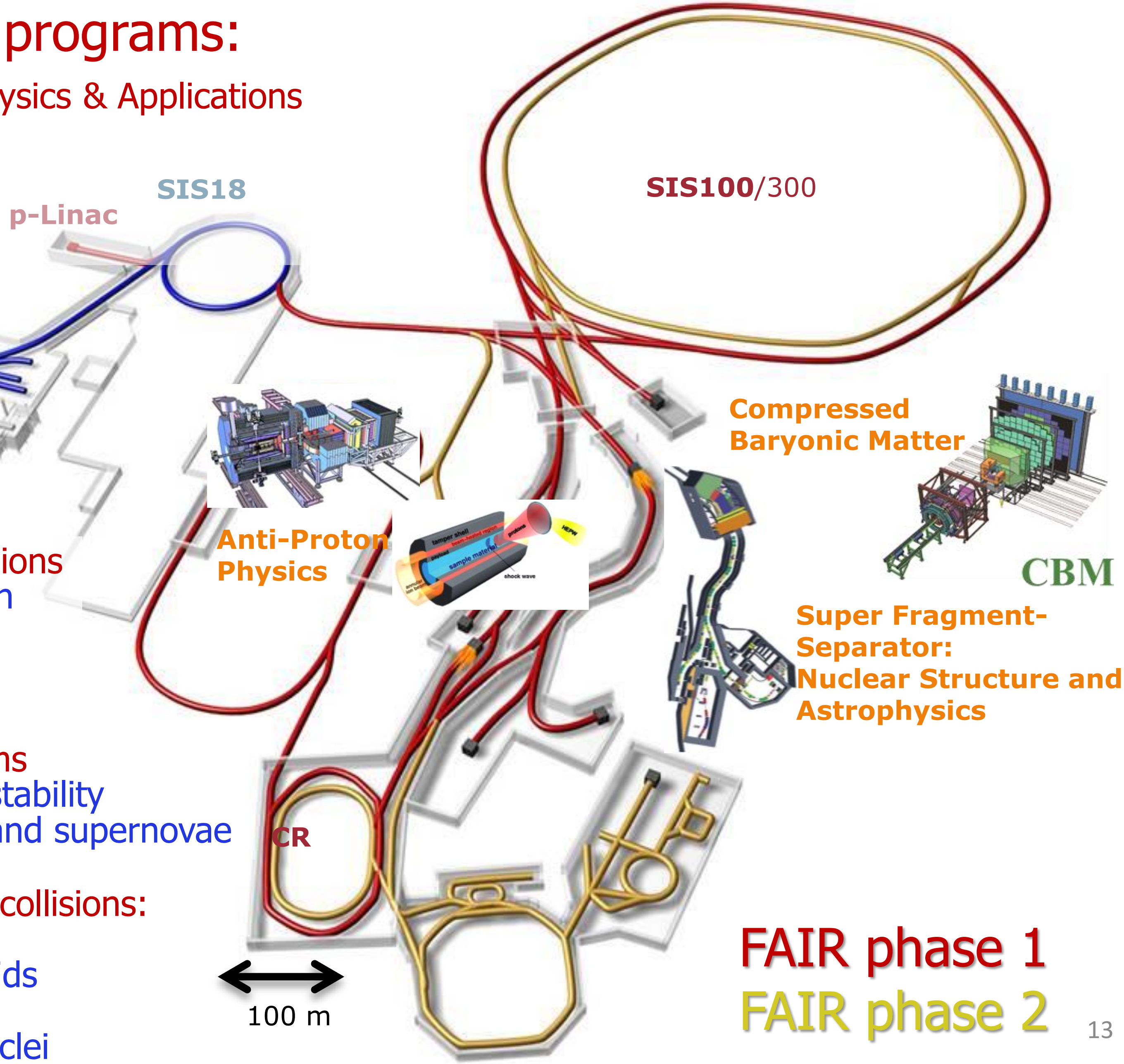
Experimental programs:

APPA: Atomic & Plasma Physics & Applications
- Highly charged atoms
- Plasma physics
- Radiobiology
- Material science

CBM: Nucleus-nucleus collisions
- Nuclear matter at neutron star core densities
- Phase transitions from hadrons to quarks

NUSTAR: Rare Isotope beams
- Nuclear structure far off stability
- Nucleosynthesis in stars and supernovae

PANDA: Antiproton-proton collisions:
- Charmed hadrons (XYZ)
- Gluonic matter and hybrids
- Hadron structure
- Double Lambda hypernuclei



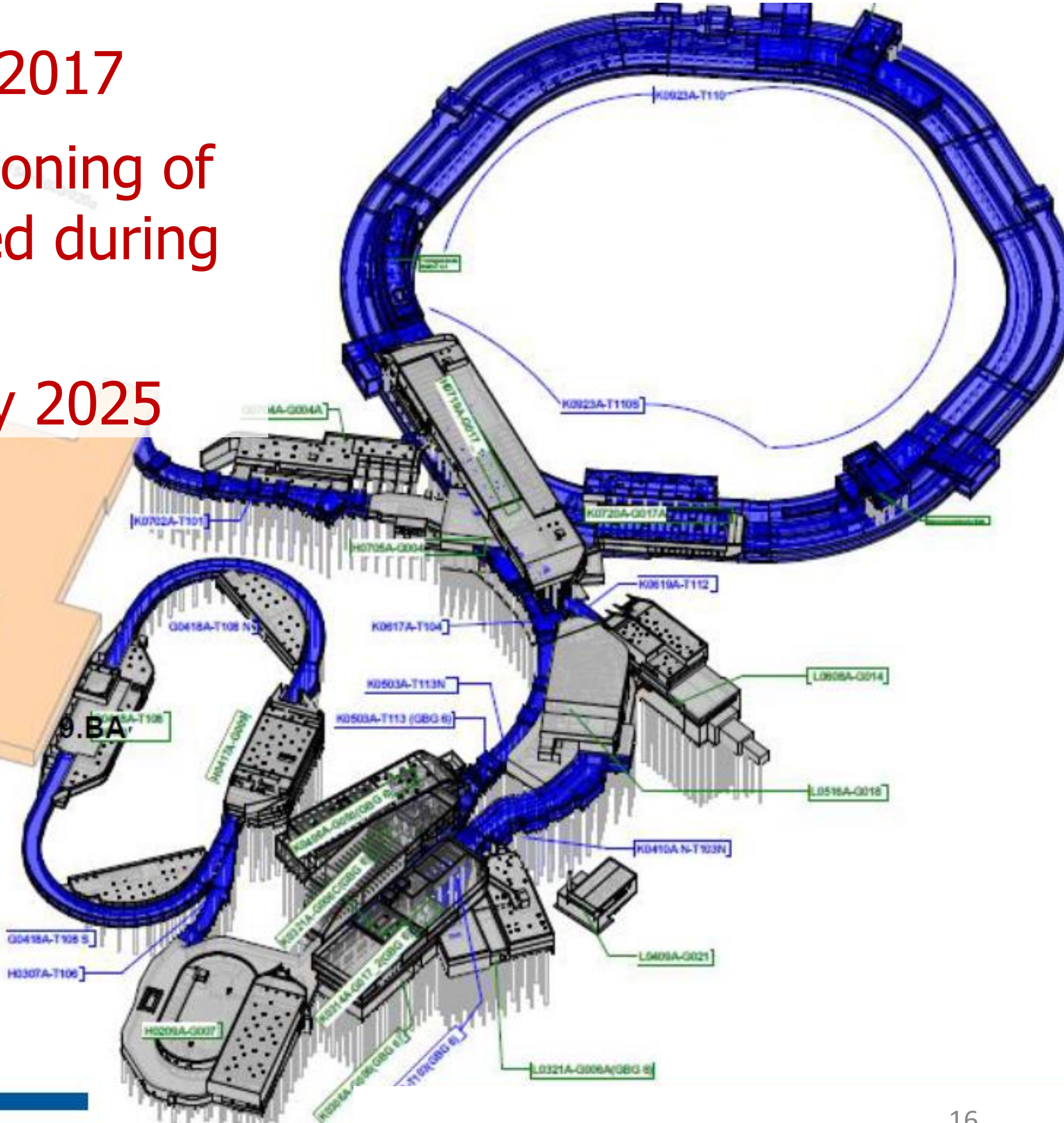
In 2014: Four worldwide largest drilling machines put down 1350 reinforced concrete pillars of 60 m depth and 1.2 m diameter.

Status of FAIR

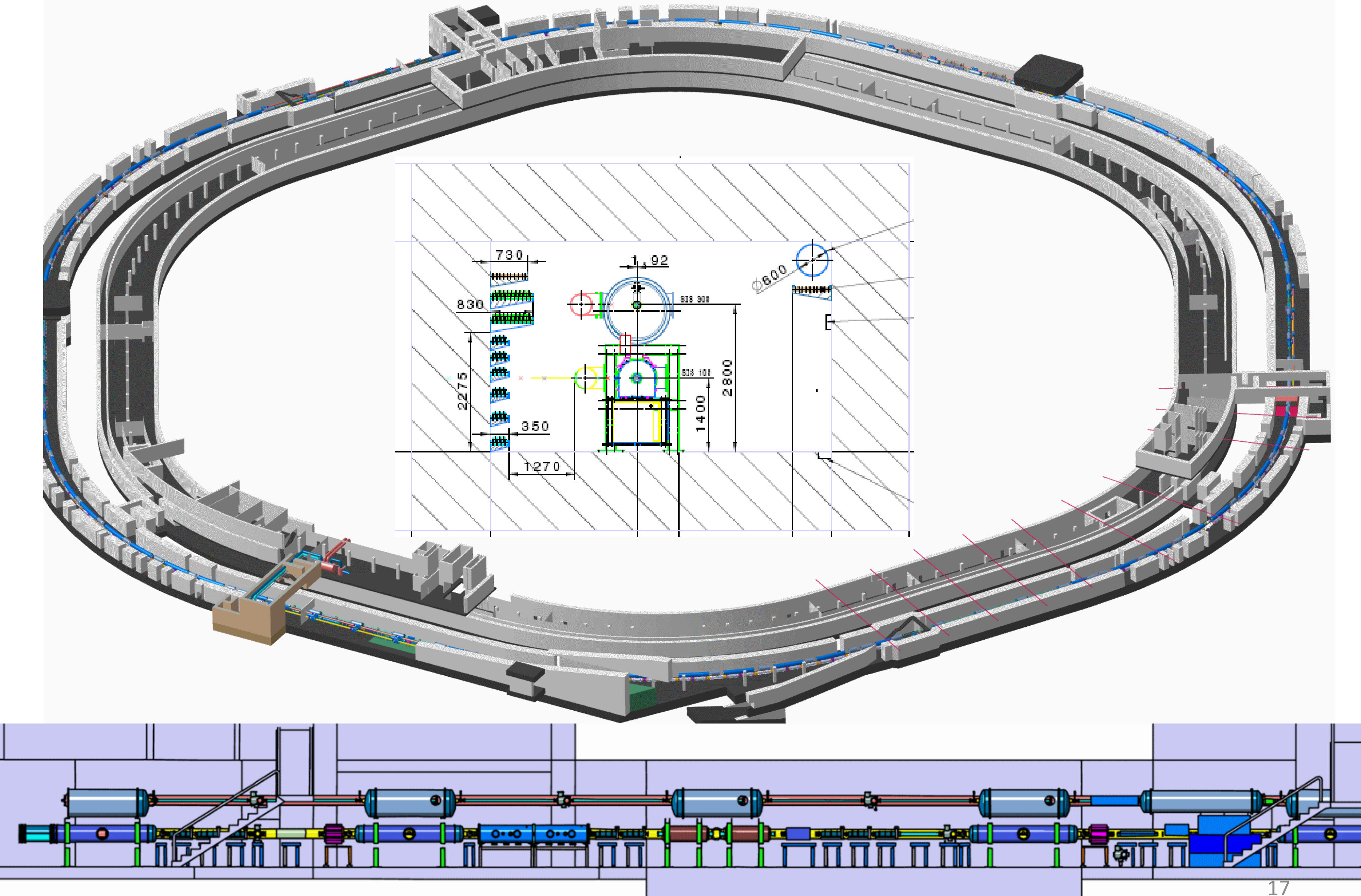
Construction started July 2017

Installation incl. commissioning of the experiments is planned during 2021-2024

Full completion of FAIR by 2025



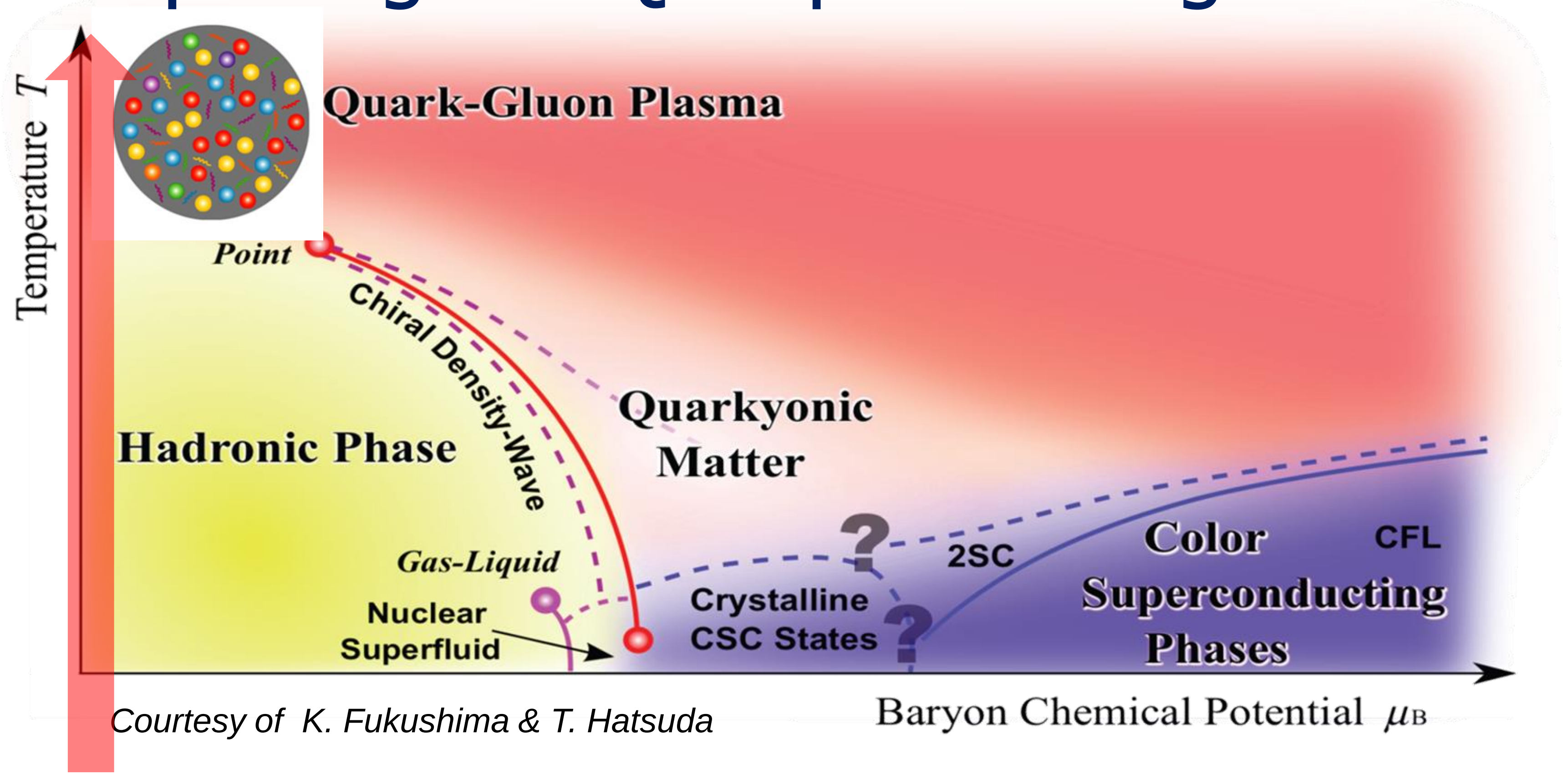
Tunnel for SIS100/300



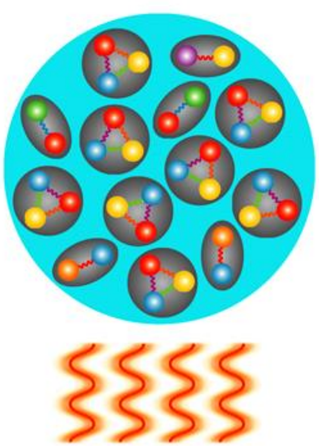

FAIR
Groundbreaking
4 July 2017 | Darmstadt
CAT

The Compressed Baryonic Matter (CBM) experiment

Exploring the QCD phase diagram



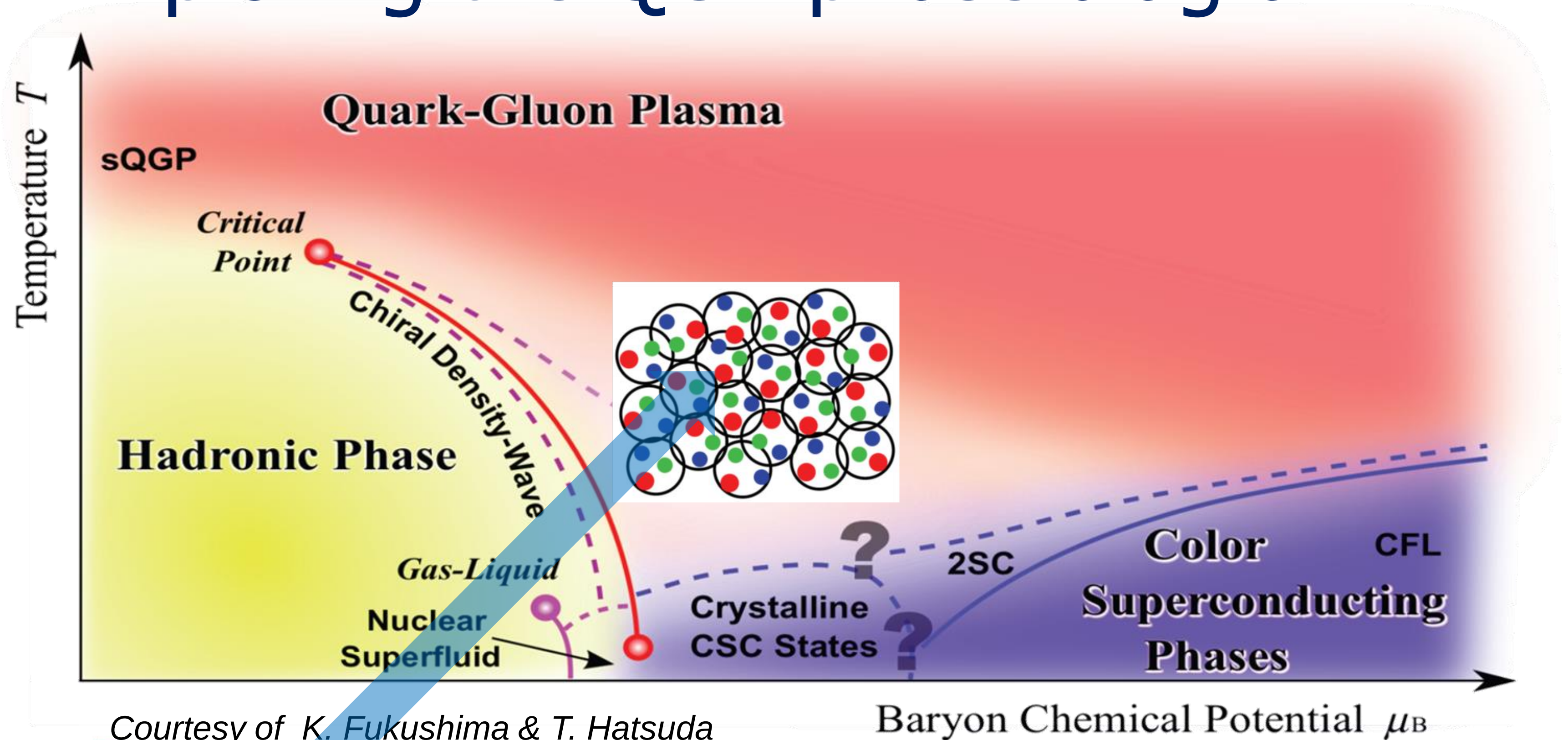
Courtesy of K. Fukushima & T. Hatsuda



<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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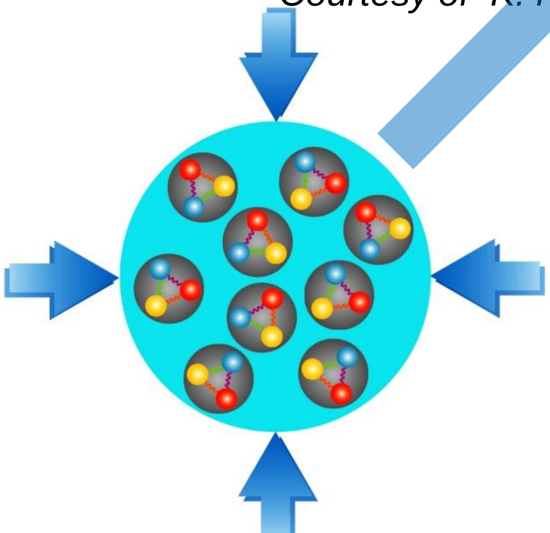


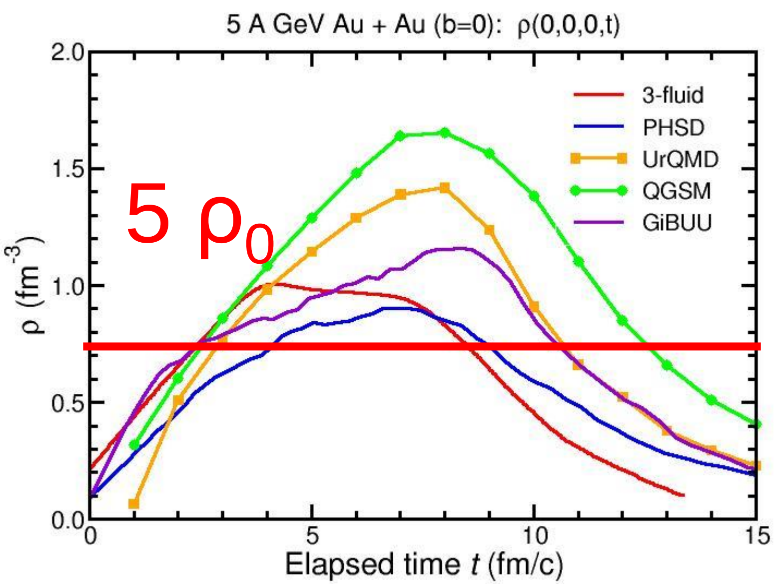
At high baryon density:

- 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

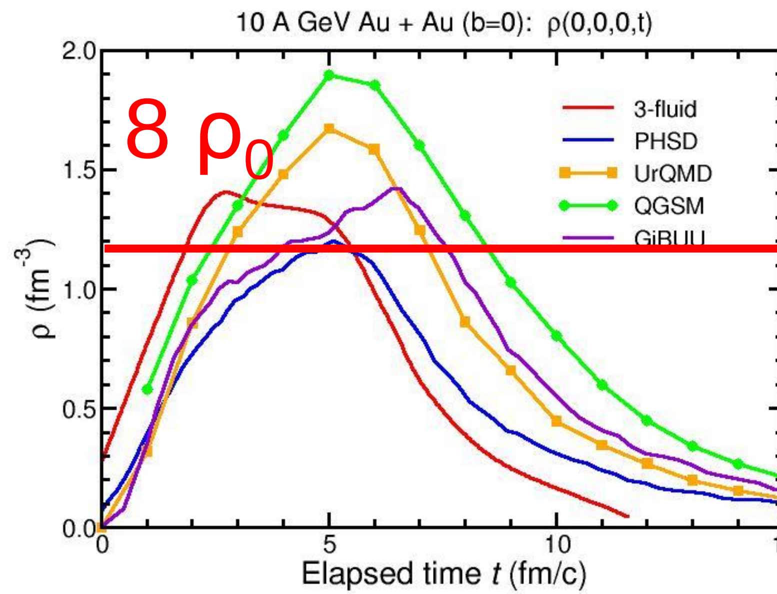
Baryon densities in central Au+Au collisions

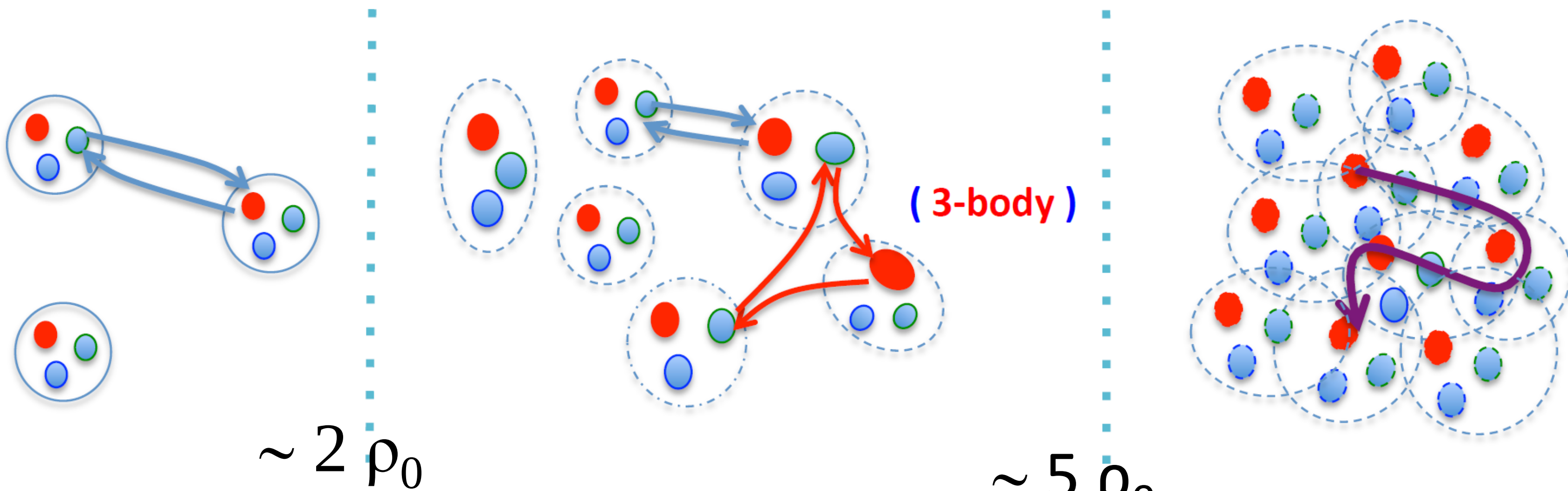
I.C. Arsene et al., Phys. Rev. C 75, 24902 (2007)

5 A GeV



10 A GeV





courtesy Toru Kojo (CCNU)

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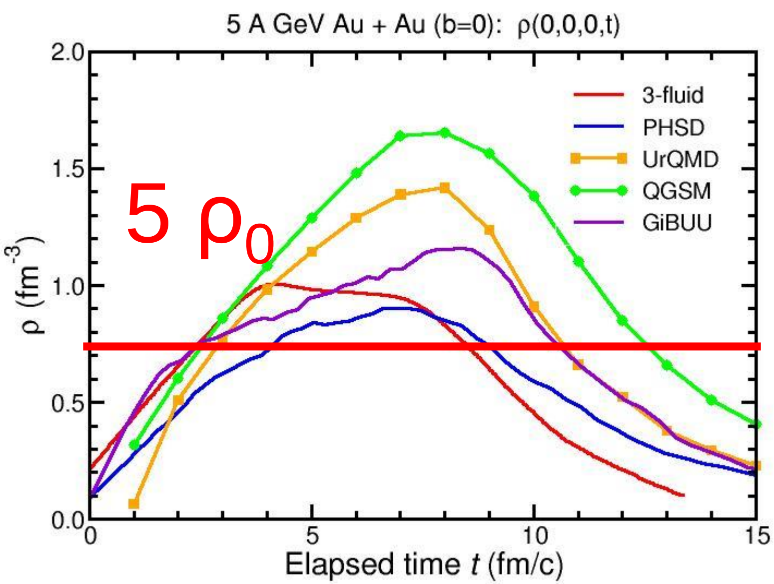

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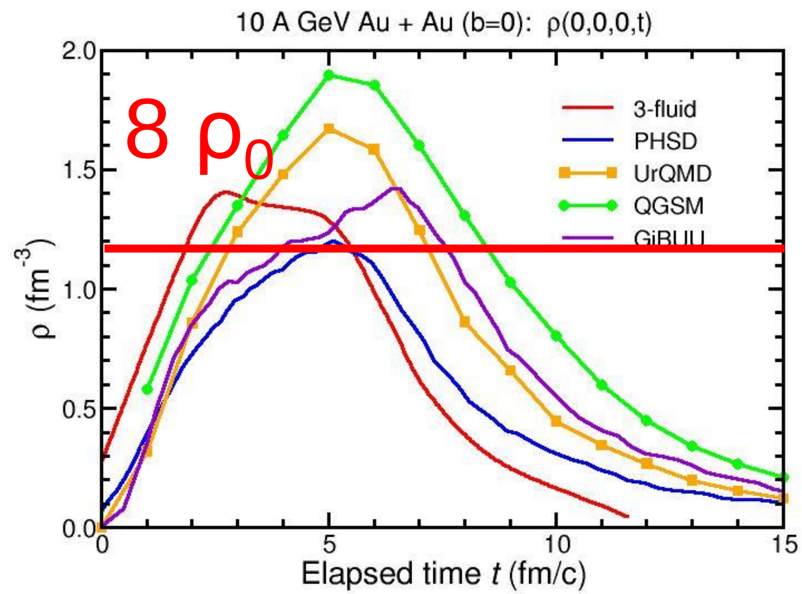
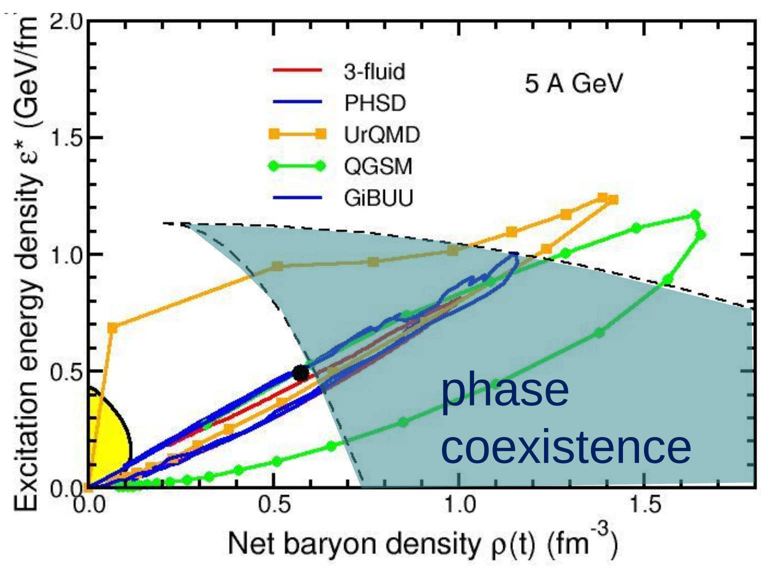
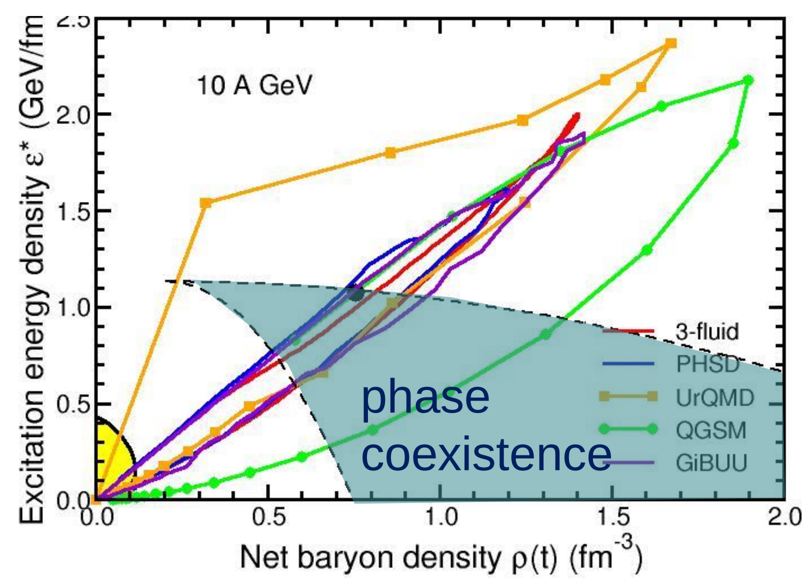
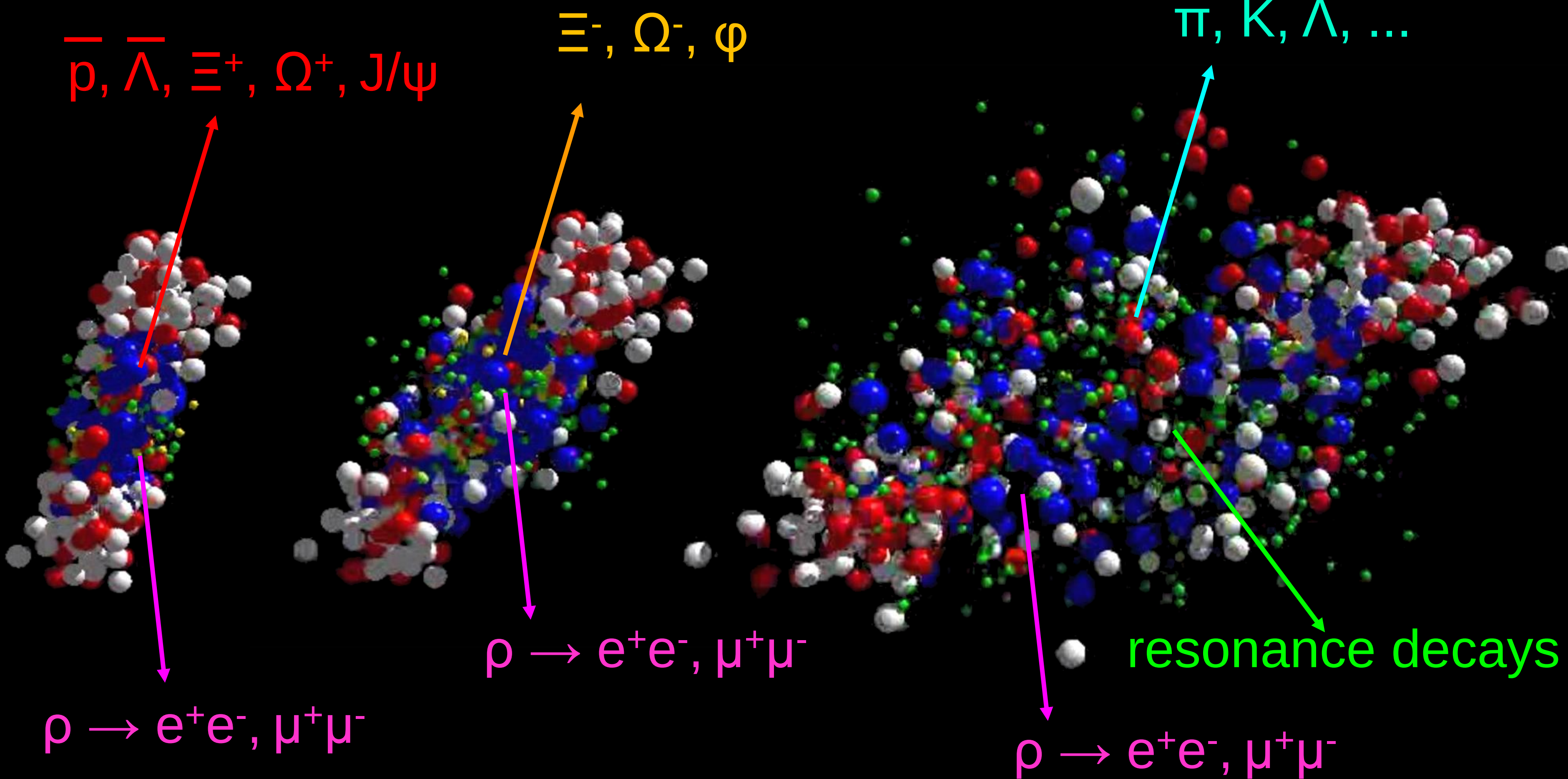






Messengers from the dense fireball: CBM at FAIR

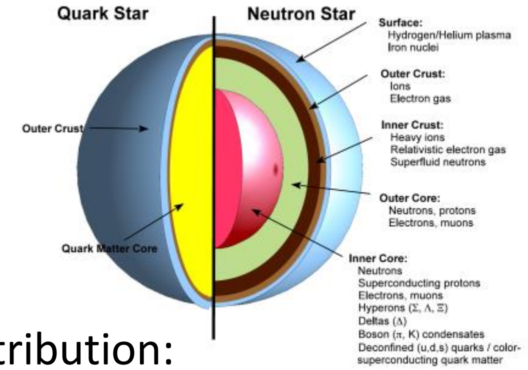
UrQMD transport calculation Au+Au 10.7 A GeV



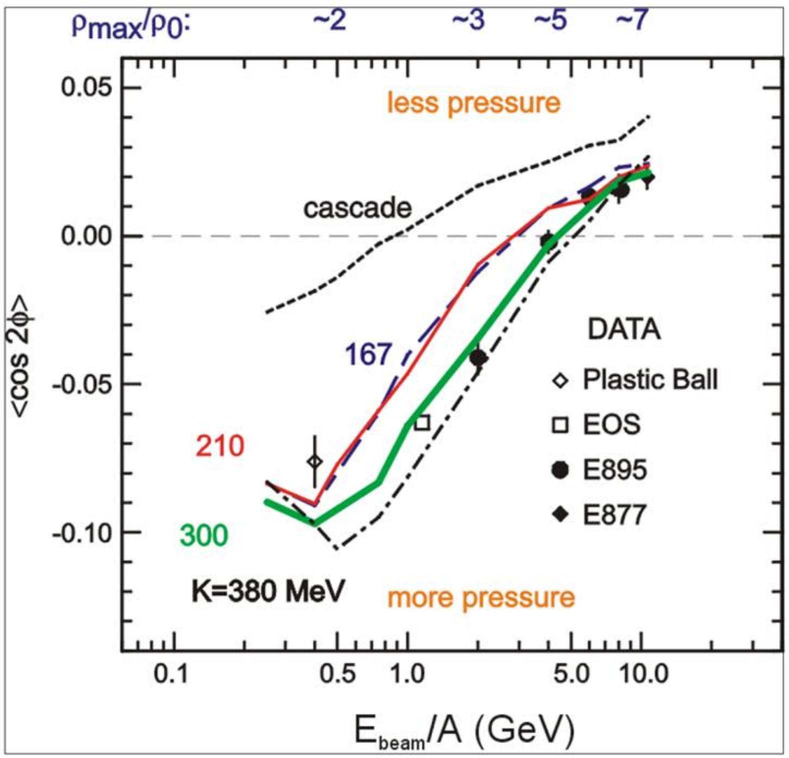
CBM physics case and observables

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



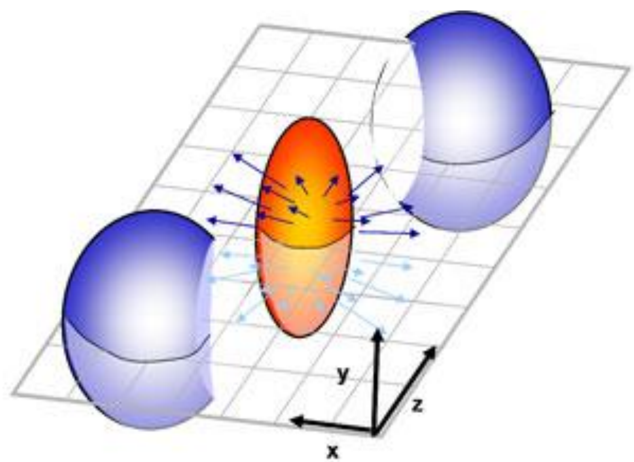
AGS: proton flow in Au+Au collisions



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

Azimuthal angle distribution:

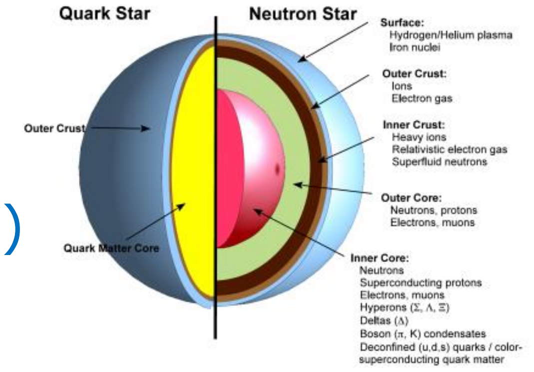
$dN/d\phi = C\,(1 + v_1 \cos(\phi) + v_2 \cos(2\phi) + ...)$



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)



Direct multi-strange hyperon production:

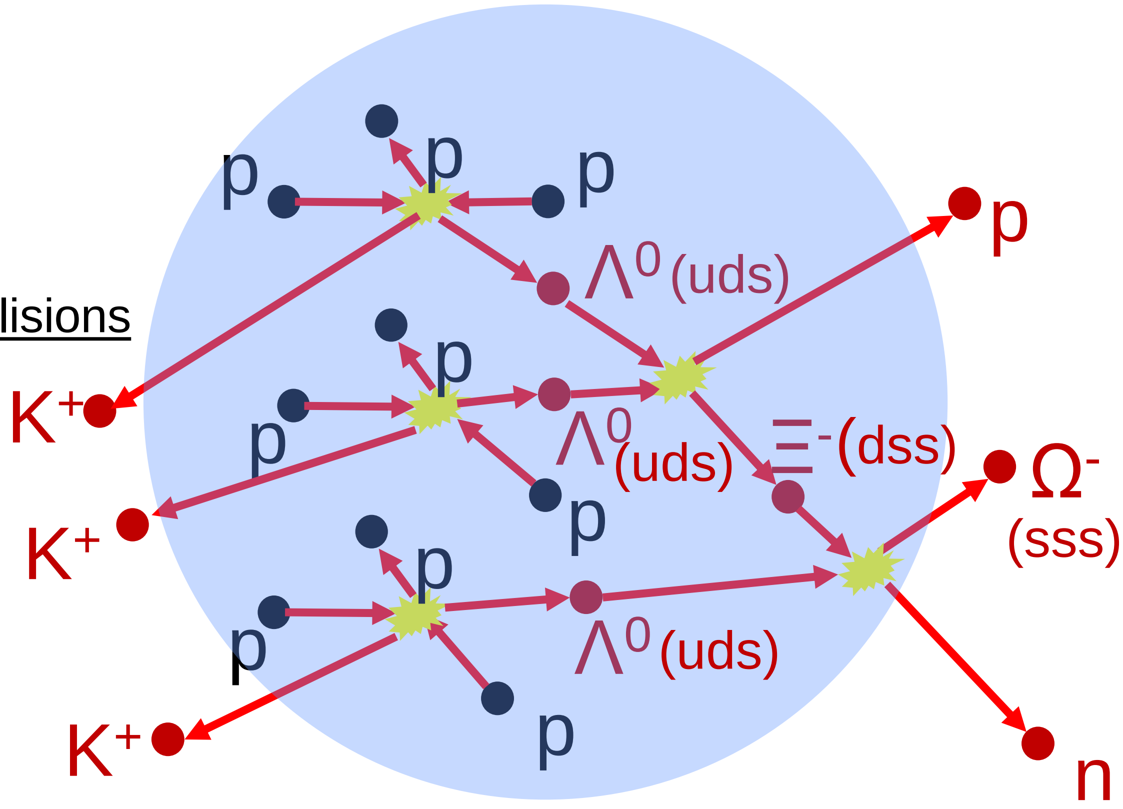
pp → Ξ^- K^+K^+p (E_{thr} = 3.7 GeV)
pp → Ω^- $K^+K^+K^0p$ (E_{thr} = 7.0 GeV)
pp → $\Lambda^0\bar{\Lambda}^0$ pp (E_{thr} = 7.1 GeV)
pp → Ξ^+ Ξ^- pp (E_{thr} = 9.0 GeV)
pp → Ω^+ Ω^- pp (E_{thr} = 12.7 GeV

Hyperon production via multiple collisions

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

Antihyperons

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



CBM physics case and observables

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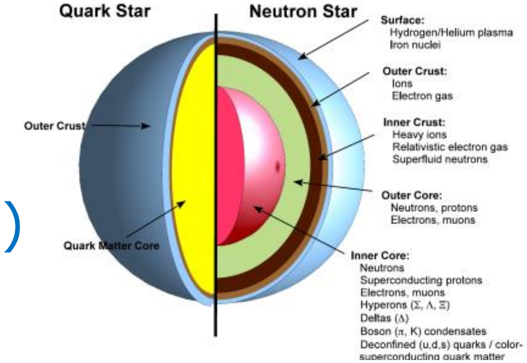

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$pp \rightarrow \Omega^- K^+K^+K^0p$ (E_{thr} = 7.0 GeV)
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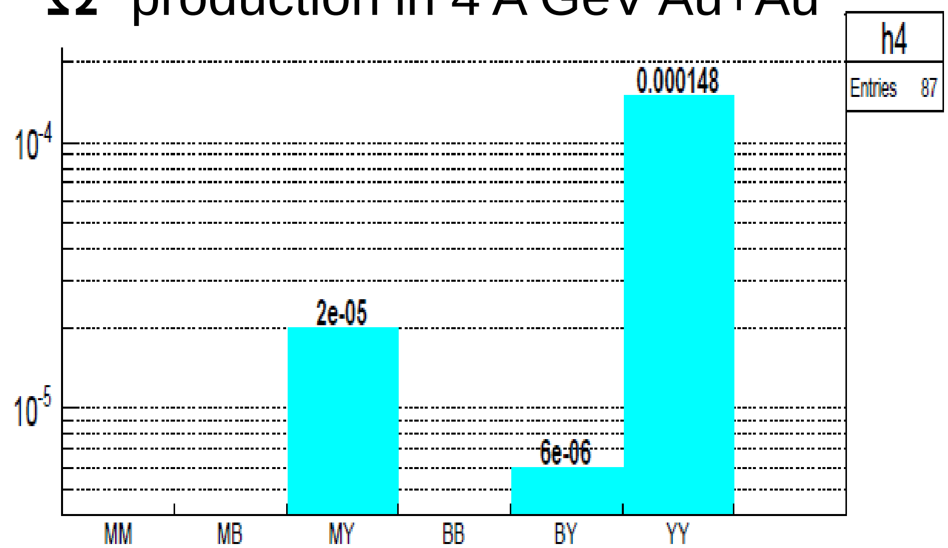
Ω^- production in 4 A GeV Au+Au



HYPQGSM calculations , K. Gudima et al.

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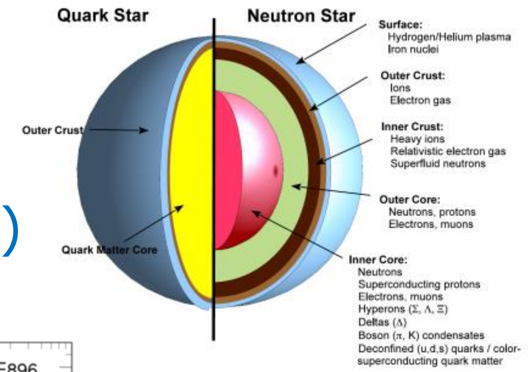

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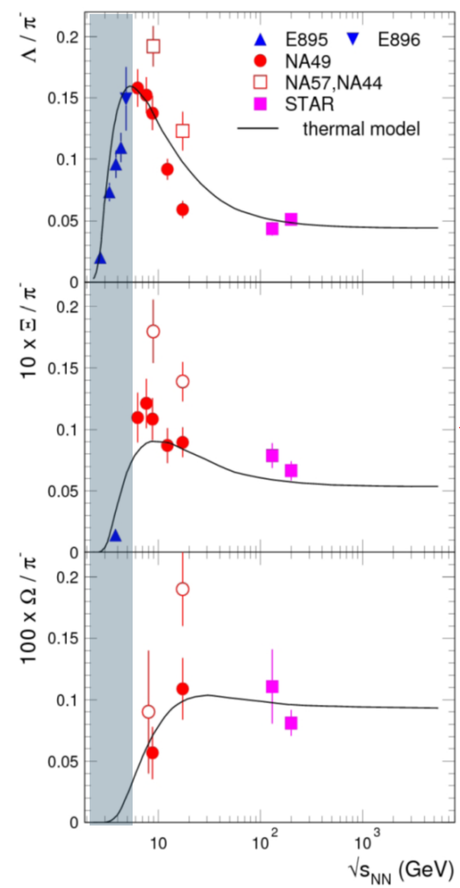


Very few data at FAIR energies

CBM physics case and observables

Phase transitions from partonic to hadronic matter

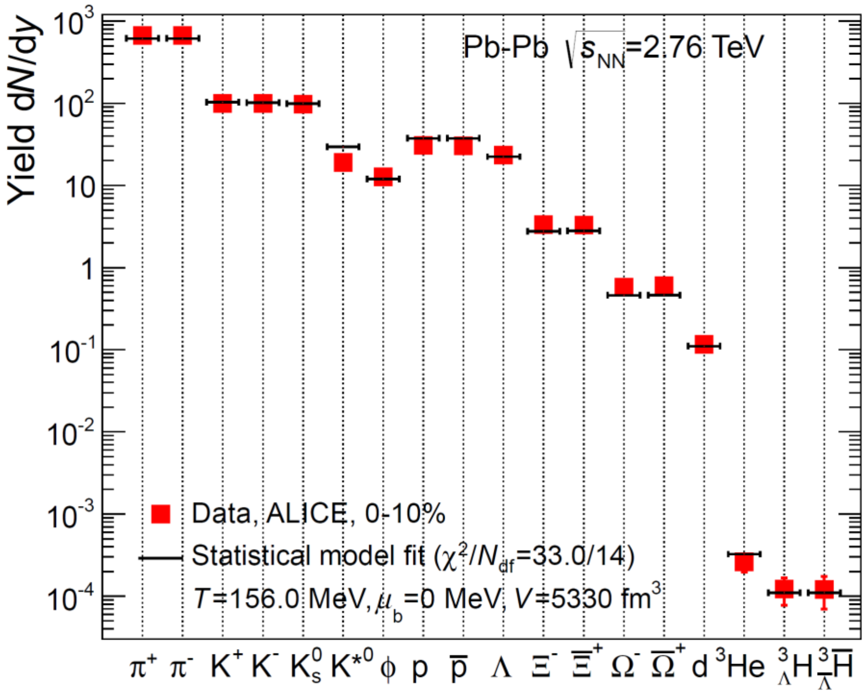
- excitation function of strangeness: Ξ^-(dss), Ξ^+($\overline{\text{dss}}$), Ω^-(sss), Ω^+($\overline{\text{sss}}$)
  → chemical equilibration at the phase boundary

Particle yields and thermal model fits

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

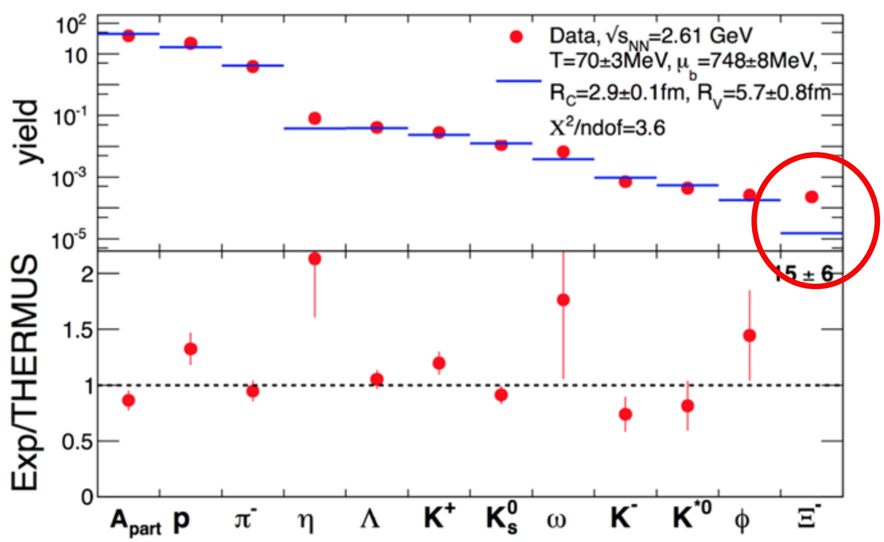
Very few data at FAIR energies

A. Andronic et al., Jour. Phys. G38 (2011)



HADES: Ar + KCl 1.76 A GeV

G. Agakishiev et al., arXiv:1512.07070



CBM physics case and observables

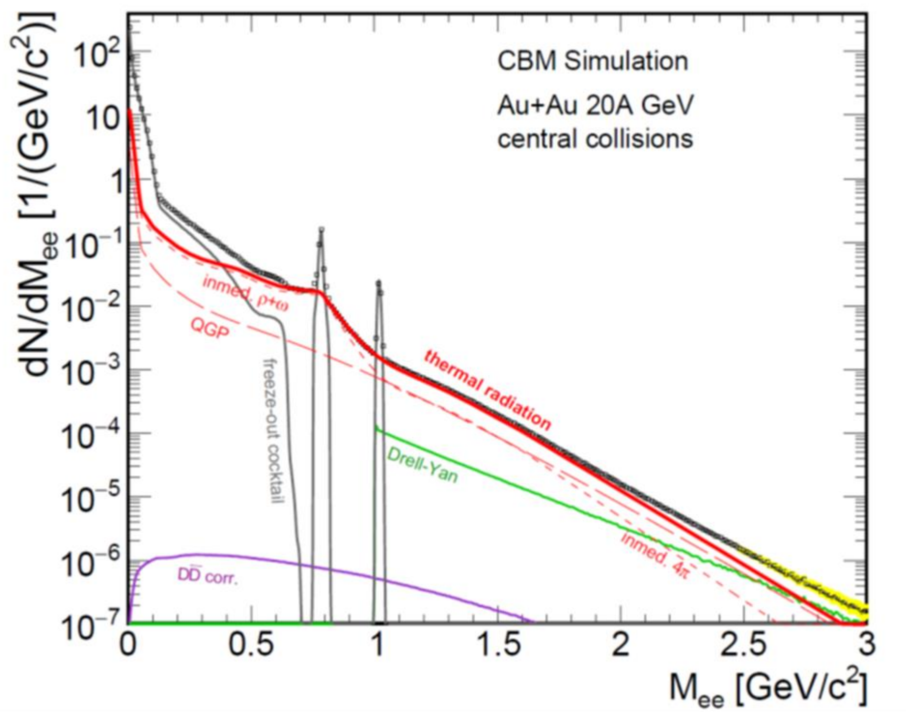
Phase transitions from partonic to hadronic matter

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

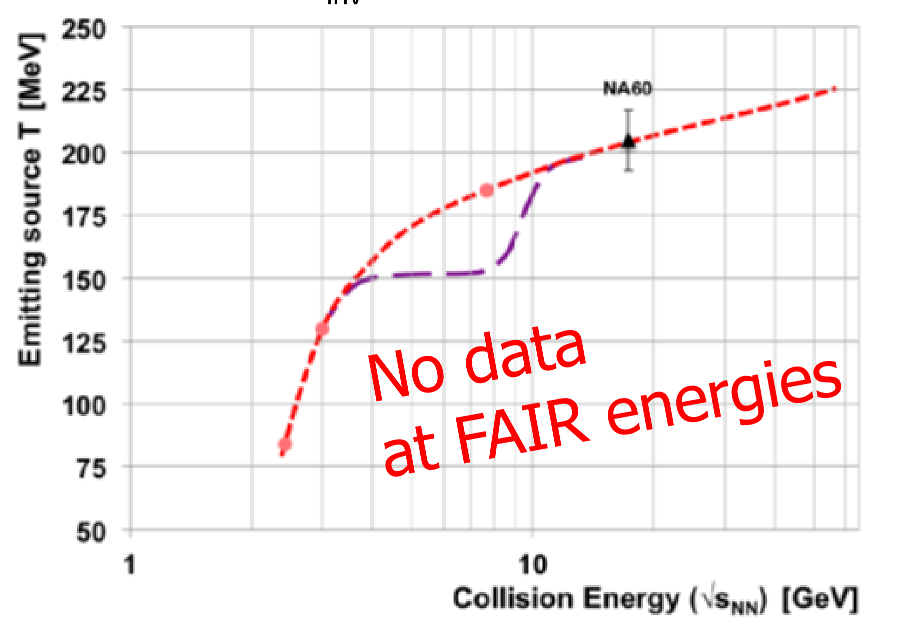
Phase coexistence

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

Invariant mass distribution of lepton pairs



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



The CBM Collaboration, arXiv:1607.01487

CBM physics case and observables

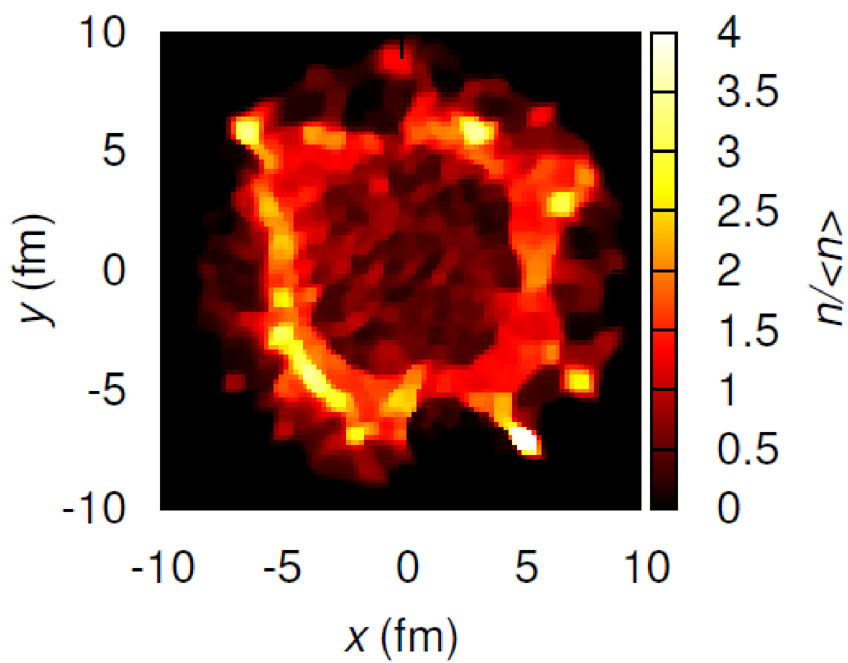
Phase transitions from partonic to hadronic matter

- 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: net baryon number density fluctuations



C. Herold, M. Nahrgang, I. Mishustin, M.Bleicher
Nuclear Physics A 925 (2014) 14

Jan Steinheimer, Jorgen Randrup
Phys. Rev. C 87, 054903 (2013)
Eur. Phys. J. A (2016) 52: 239

CBM physics case and observables

Phase transitions from partonic to hadronic matter

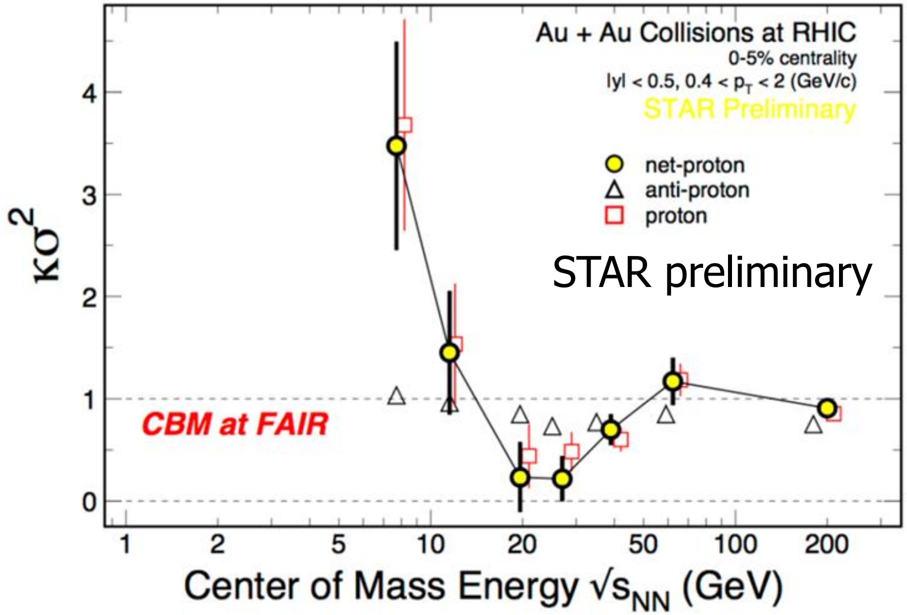
- excitation function of strangeness: Ξ^-(dss),Ξ^+(dss),Ω^-(sss),Ω^+(sss)
  $\rightarrow$ chemical equilibration at the phase boundary

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"



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

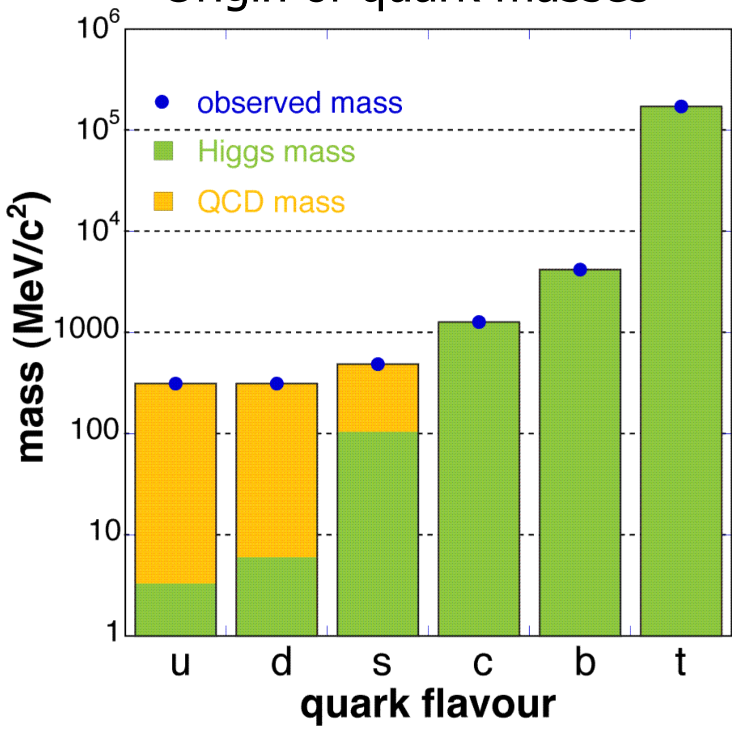
No data at FAIR energies

CBM physics case and observables

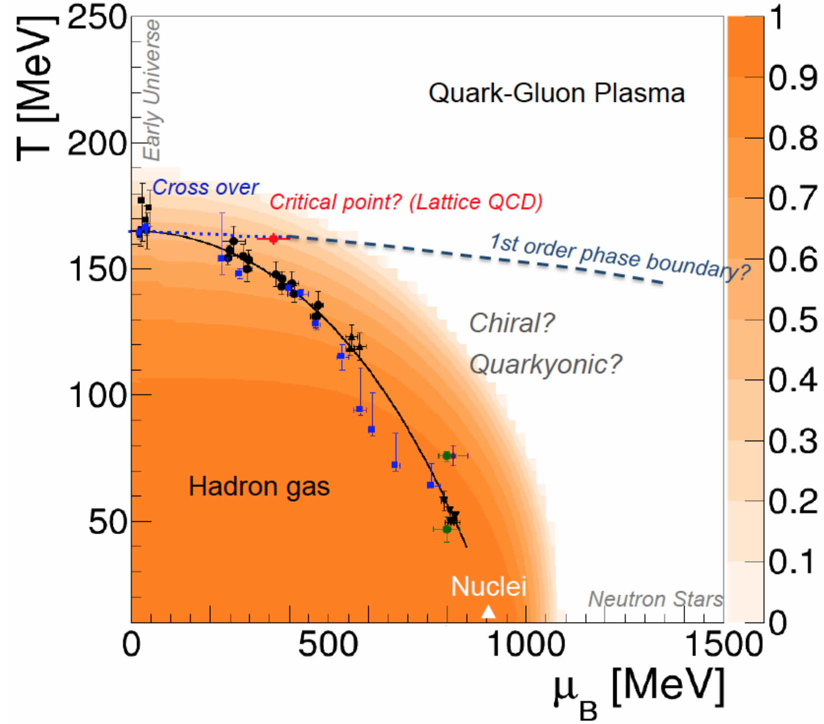
Onset of chiral symmetry restoration at high ρ_B

- 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

Origin of quark masses



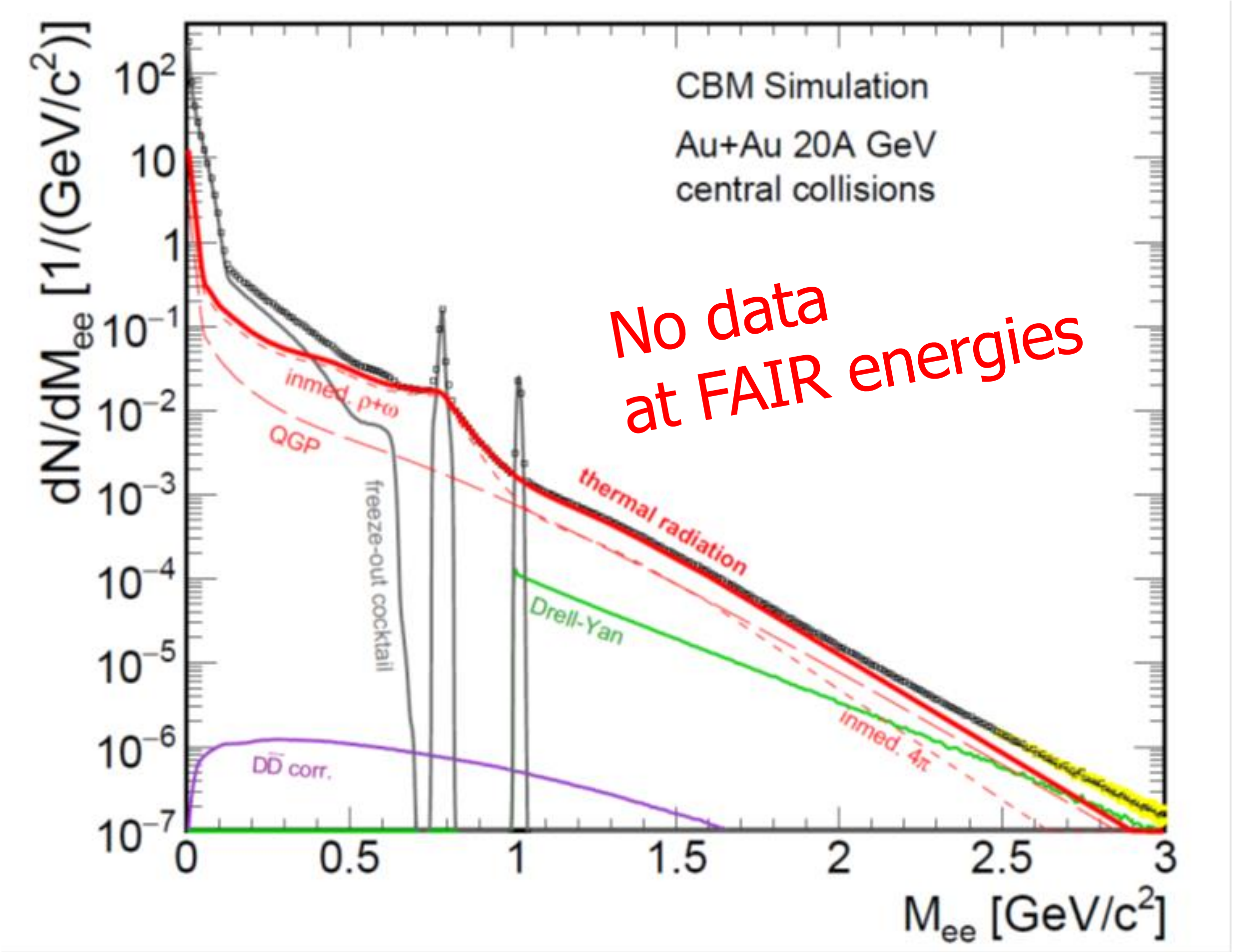
Orange region: Chiral condensate



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

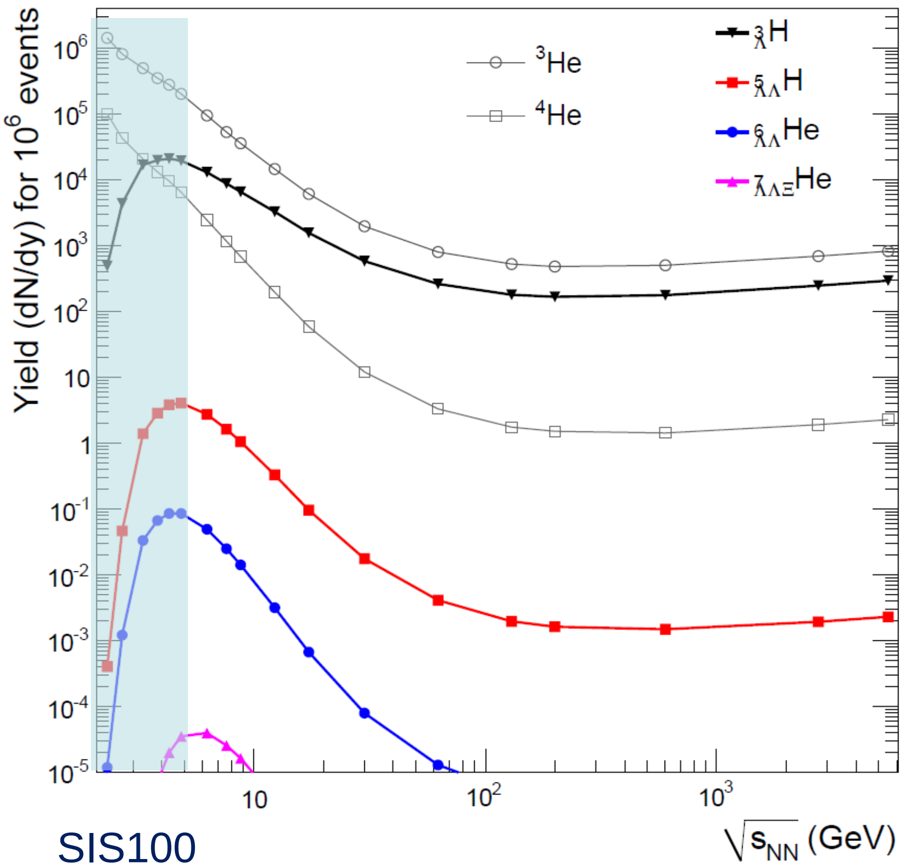


CBM physics case and observables

N-Λ, Λ-Λ interaction, strange matter?

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

No data at FAIR energies



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

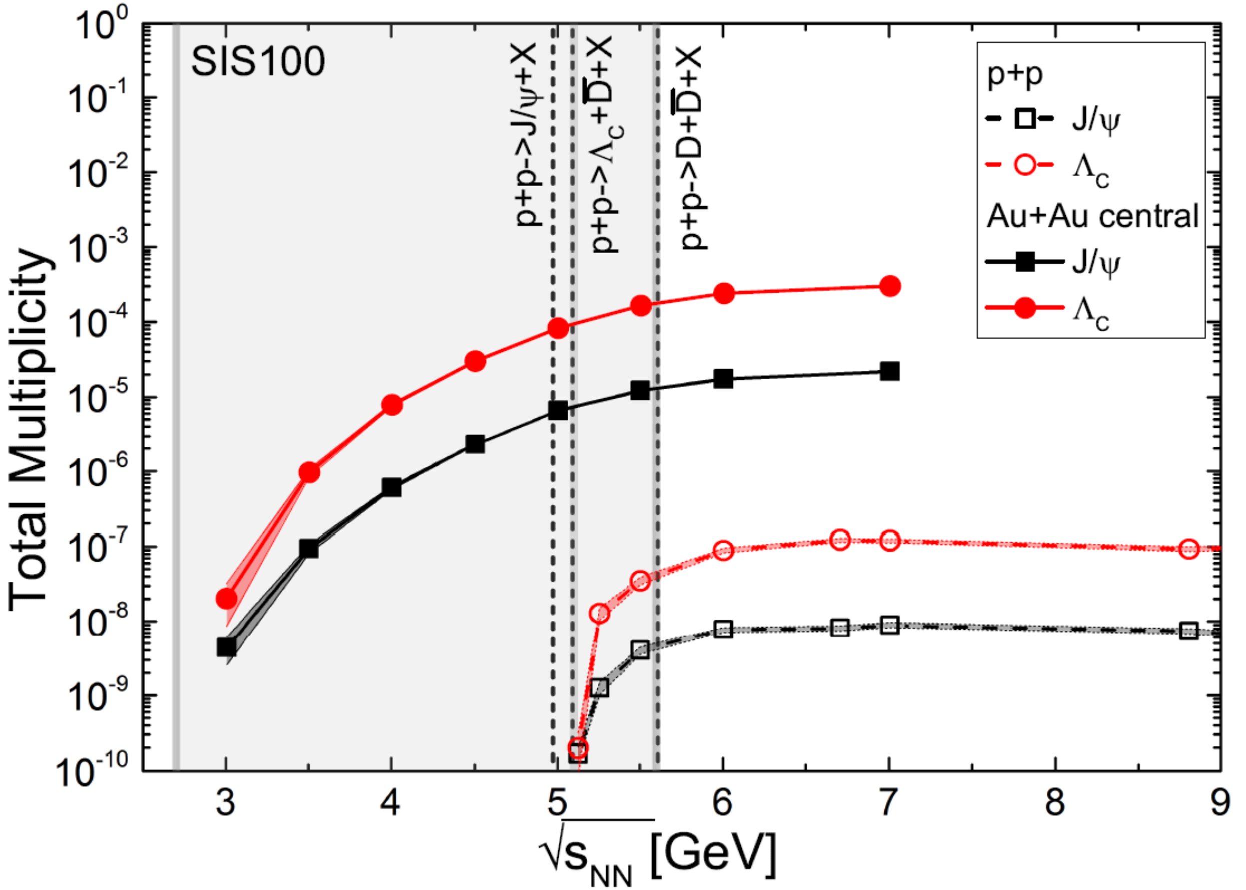
Assumption for yield calculation:
Reaction Rate 1 MHz
BR 10% (2 sequential weak decays)
Efficiency 1%

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, $D^{\pm}$)

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



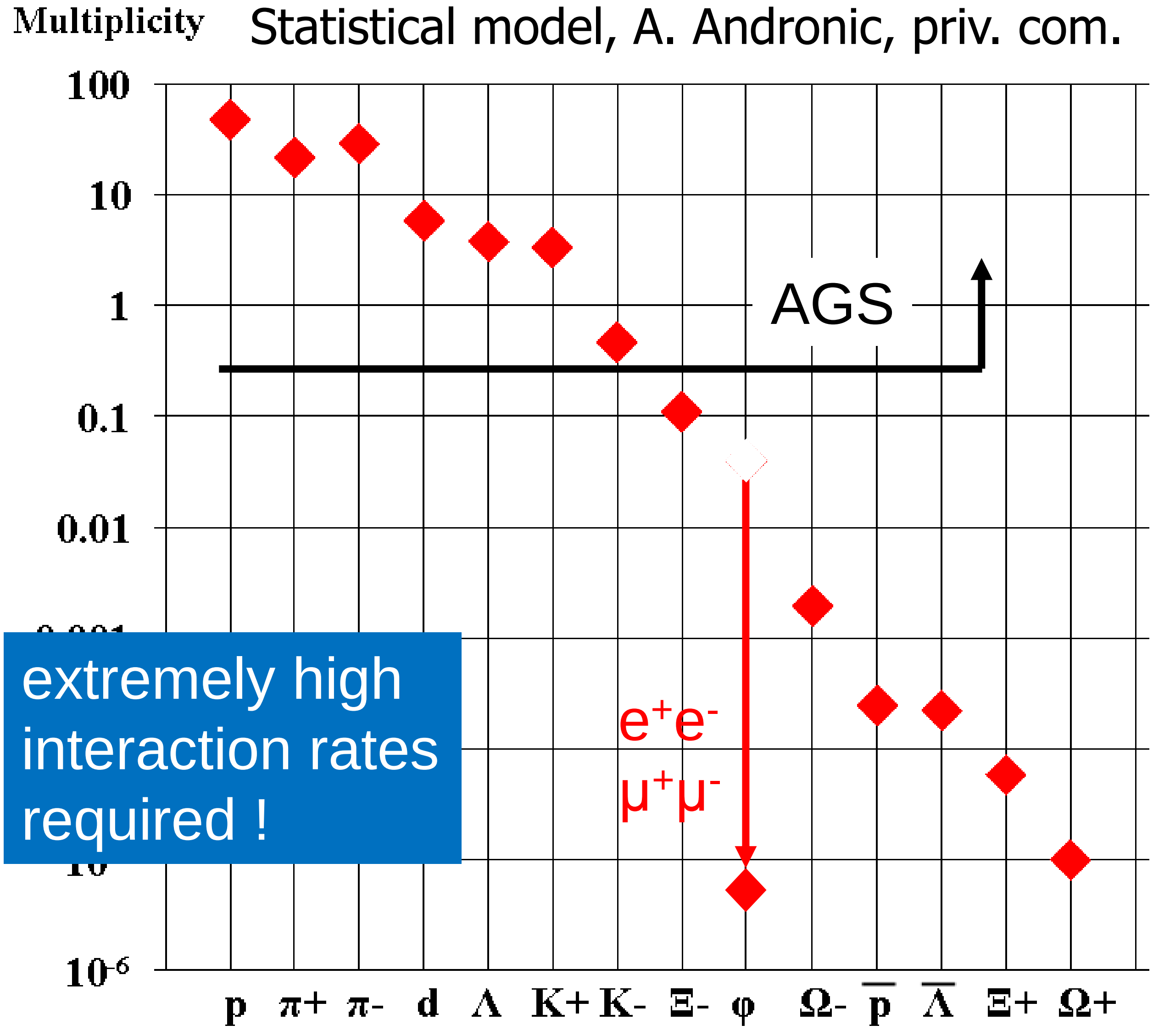
No data at FAIR energies

J. Steinheimer, A. Botvina, M. Bleicher, Phys. Rev. C 95, 014911 (2017), arXiv:1605.03439v1

Experimental challenges

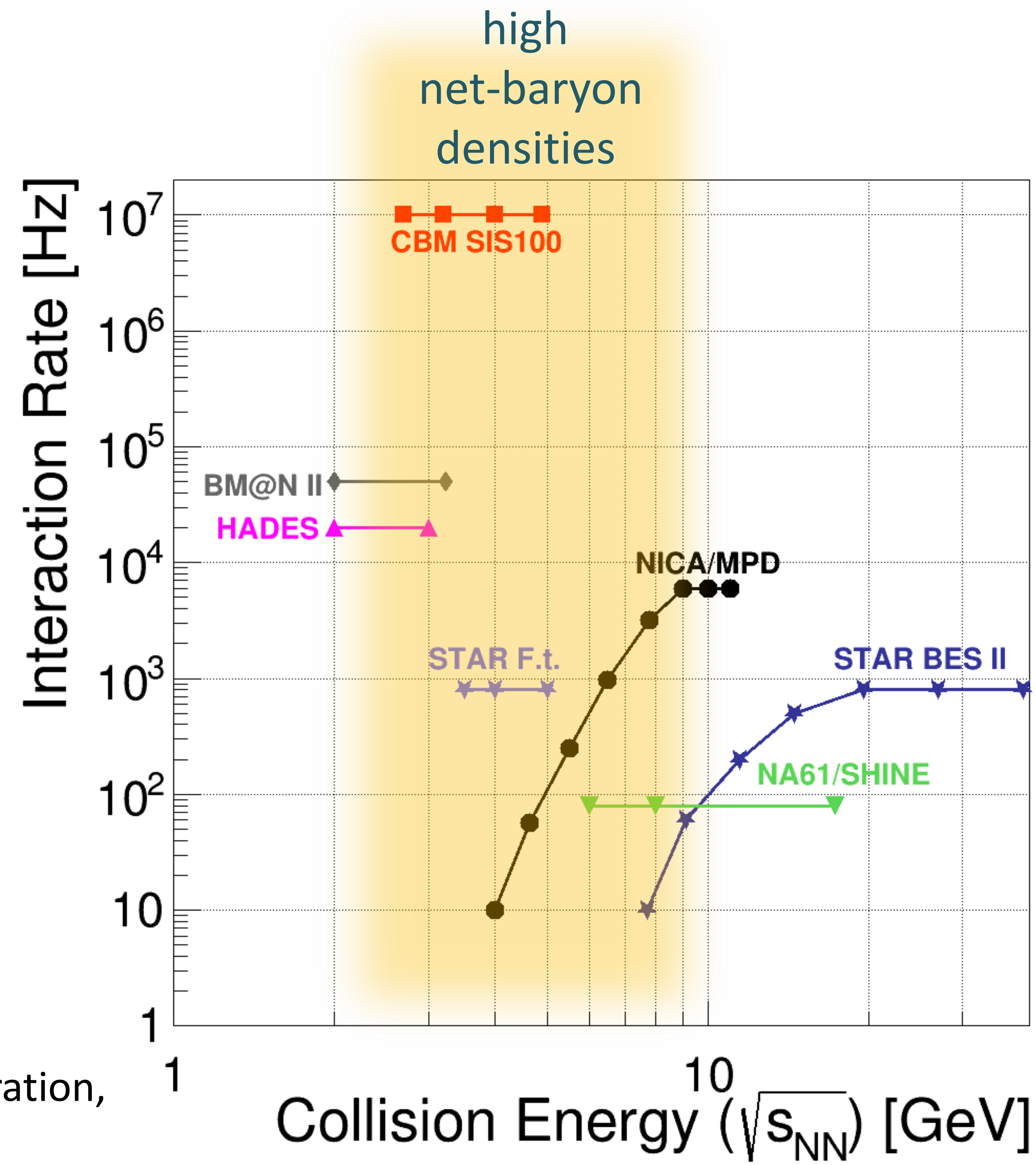
Particle yields in central Au+Au 4 A GeV

Statistical model, A. Andronic, priv. com.



extremely high interaction rates required !

Experiments exploring dense QCD matter



The CBM Collaboration, arXiv:1607.01487

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

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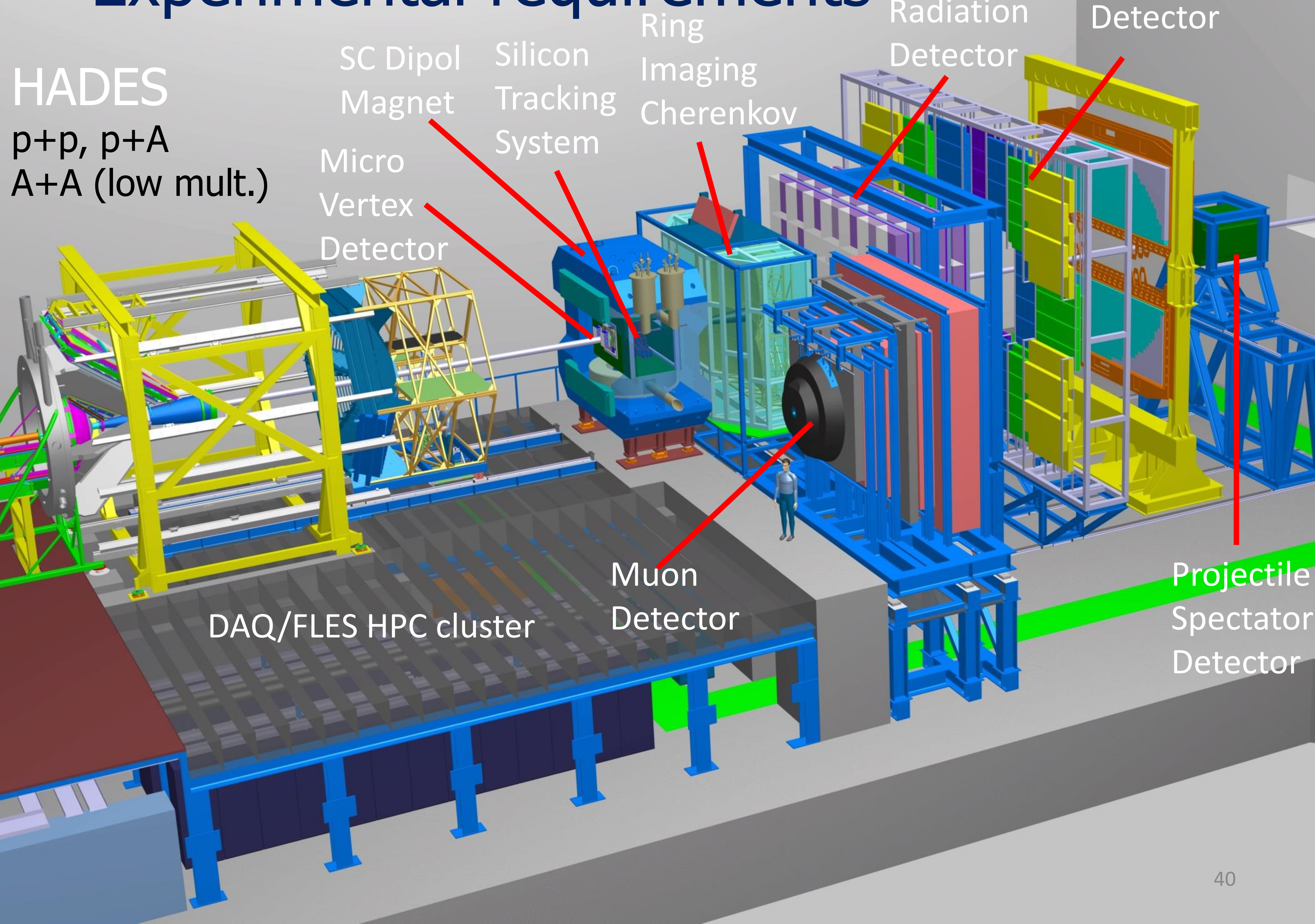
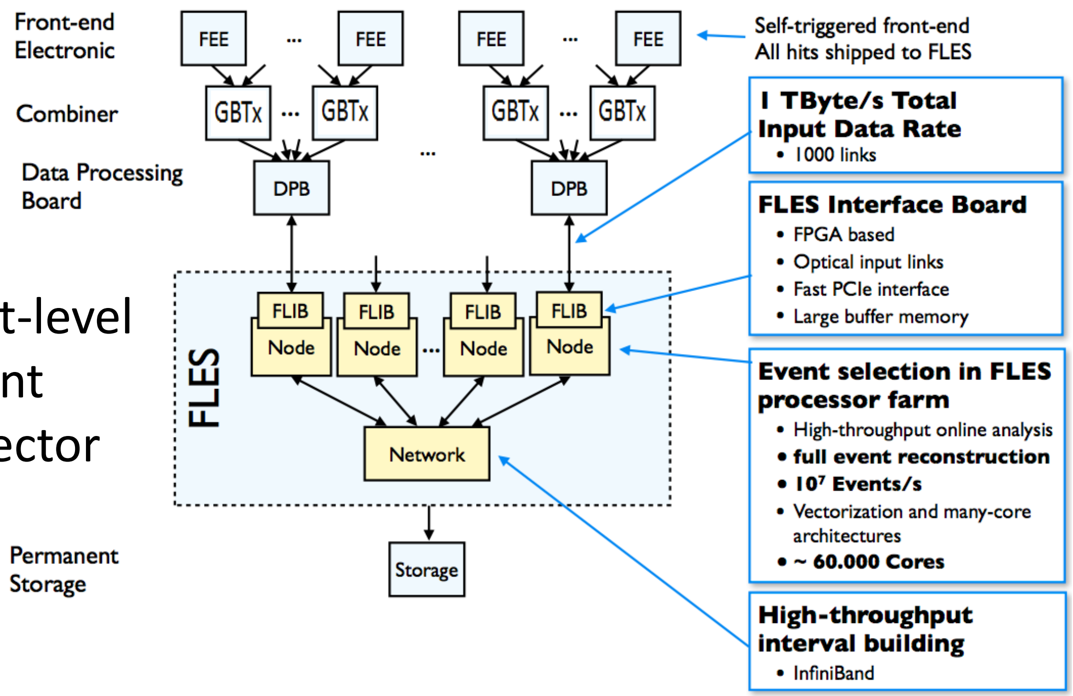
Experimental requirements



CBM DAQ and online event selection

First-level Event Selector



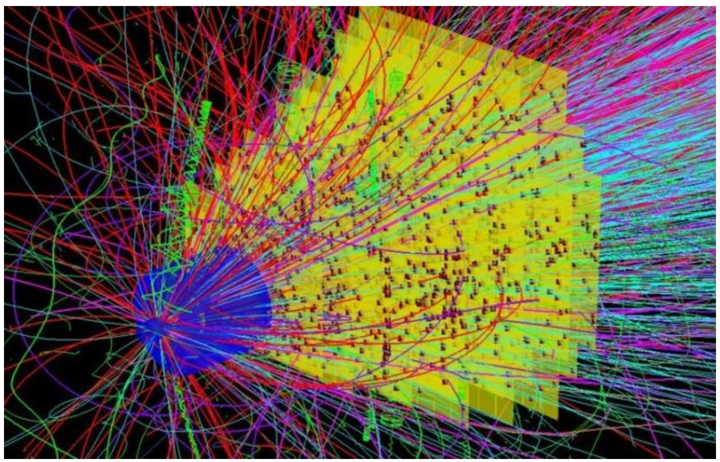
Novel readout system: no hardware trigger on events, detector hits with time stamps, full online 4-D track and event reconstruction.

Test beams at CERN

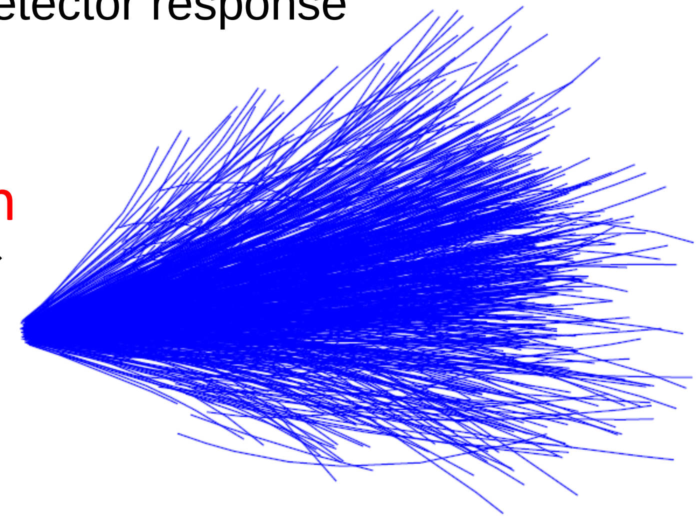
- Prototype TOF, GEM, TRD and diamond detectors with common free-streaming readout system and DAQ successfully tested.
- Pb+Pb collisions with energies of 13, 30 and 160 A GeV.
- Teams from China, Germany, India, Romania

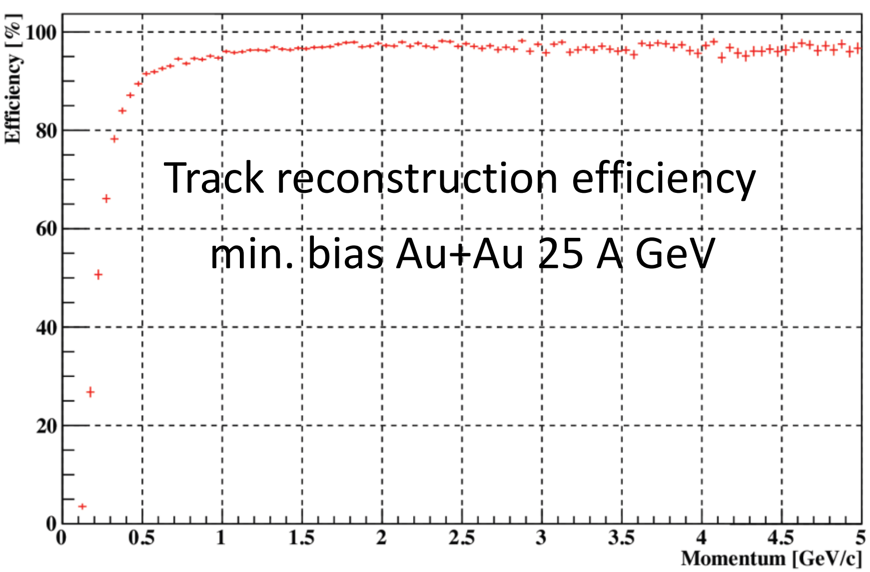
Simulation and reconstruction

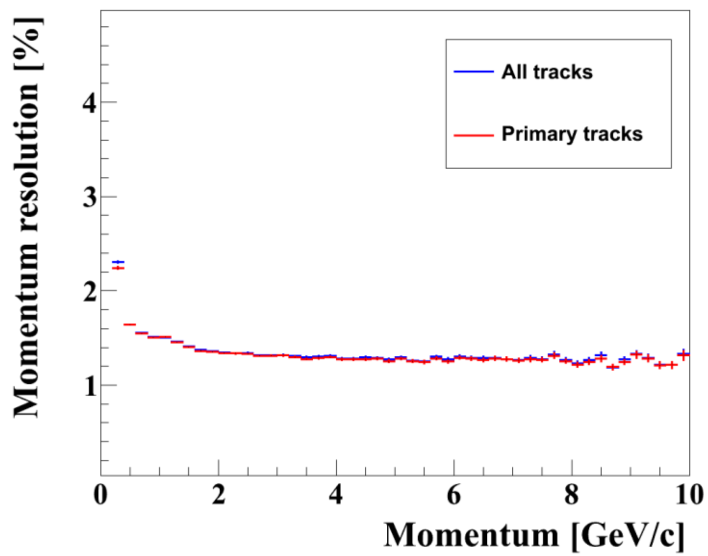
Event generators UrQMD 3.3
Transport code GEANT3, FLUKA
Realistic detector geometries, material budget and detector response



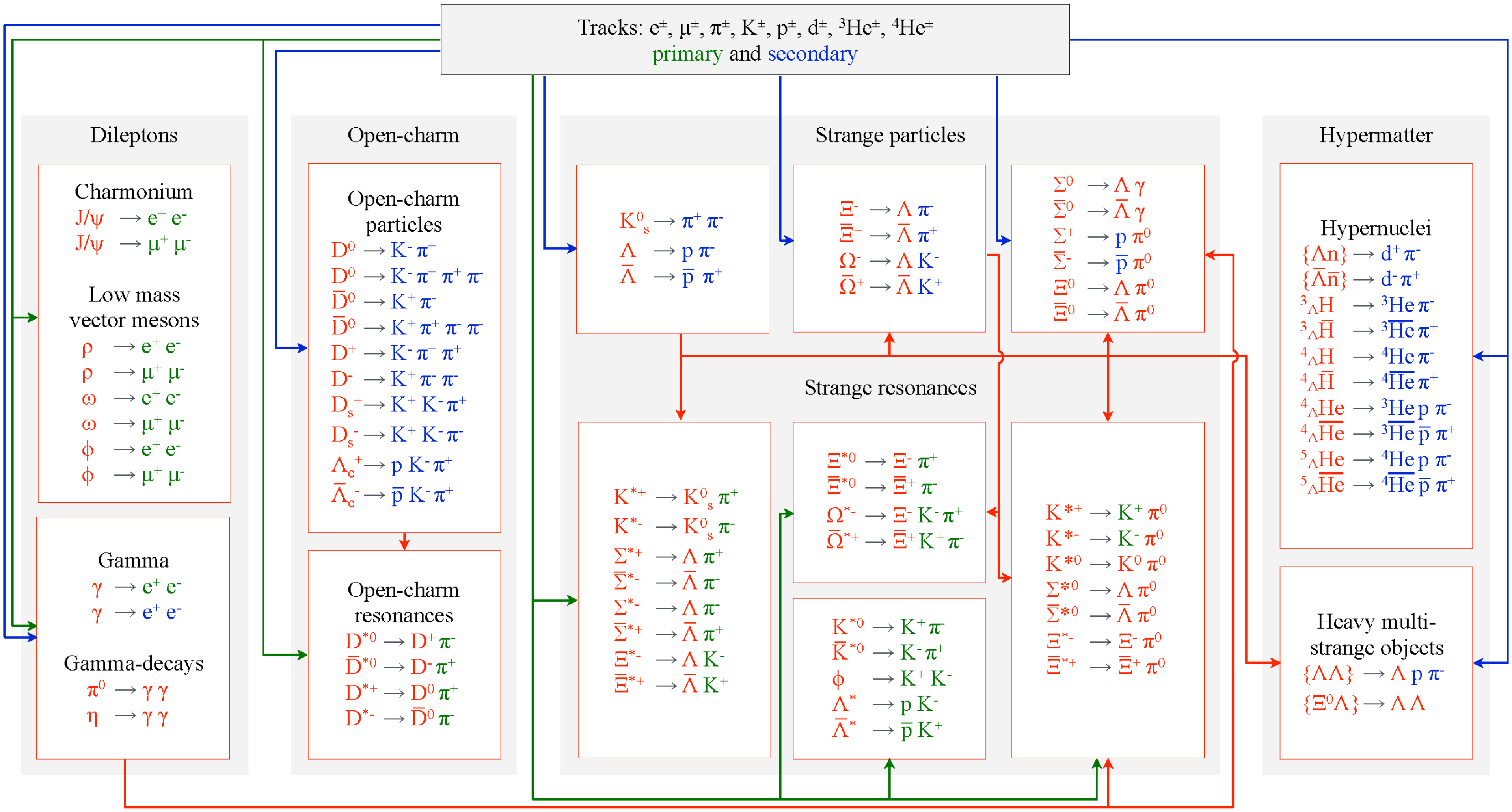
reconstruction







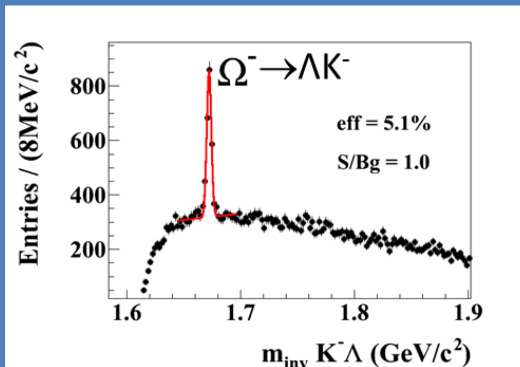
Online particle identification in CBM: The KF Particle Finder

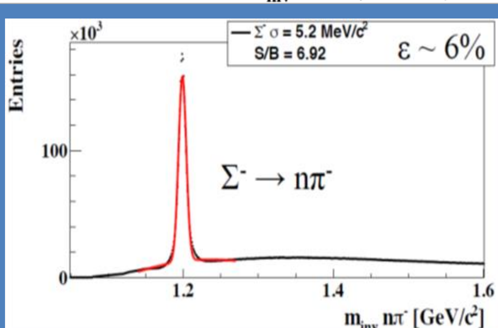


successfully used online in the STAR experiment

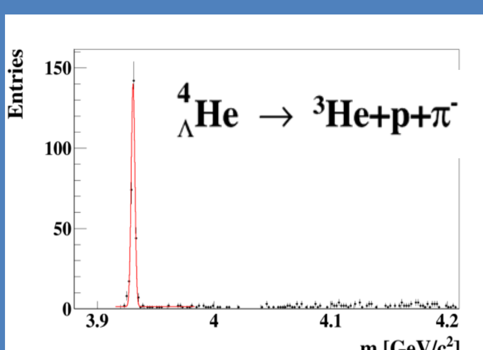
Simulations: central Au+Au collisions at 8A GeV and 10A GeV

Hyperons at 10 A GeV

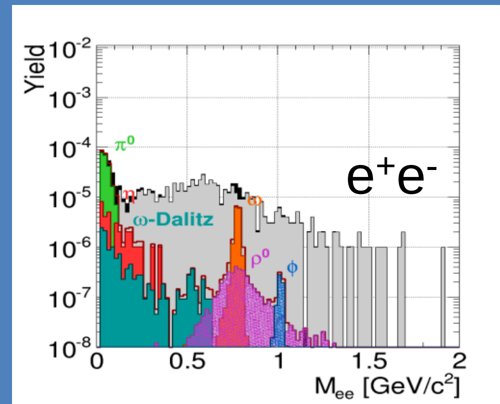


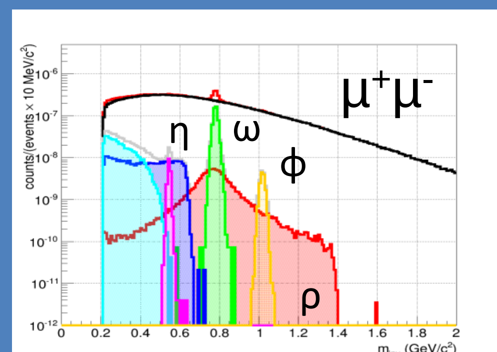


Hypernuclei at 10 A GeV

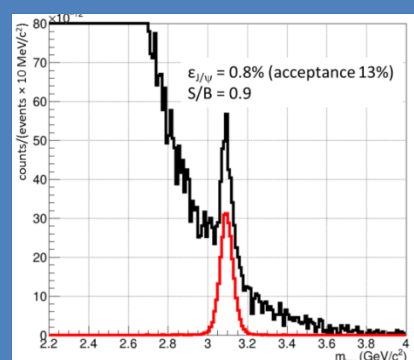


Dileptons 8A GeV

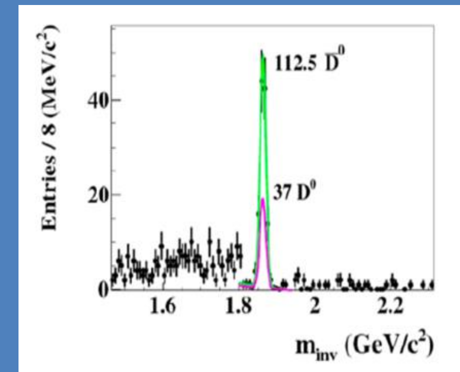


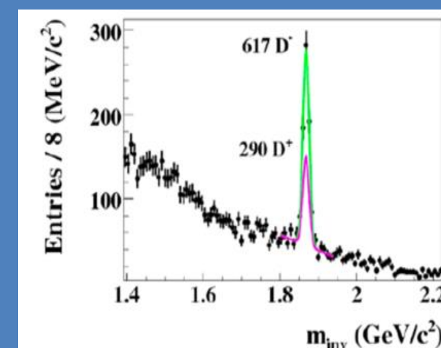


Charmonium at 10 A GeV

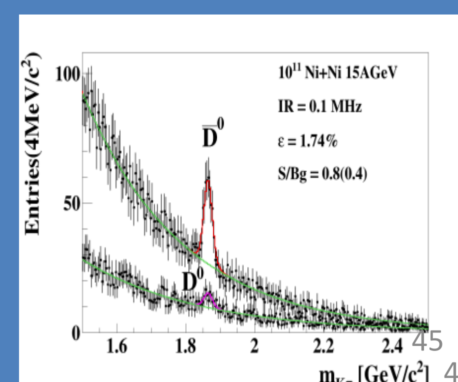


D mesons 30 GeV p+Au





D mesons Ni+Ni 15A GeV



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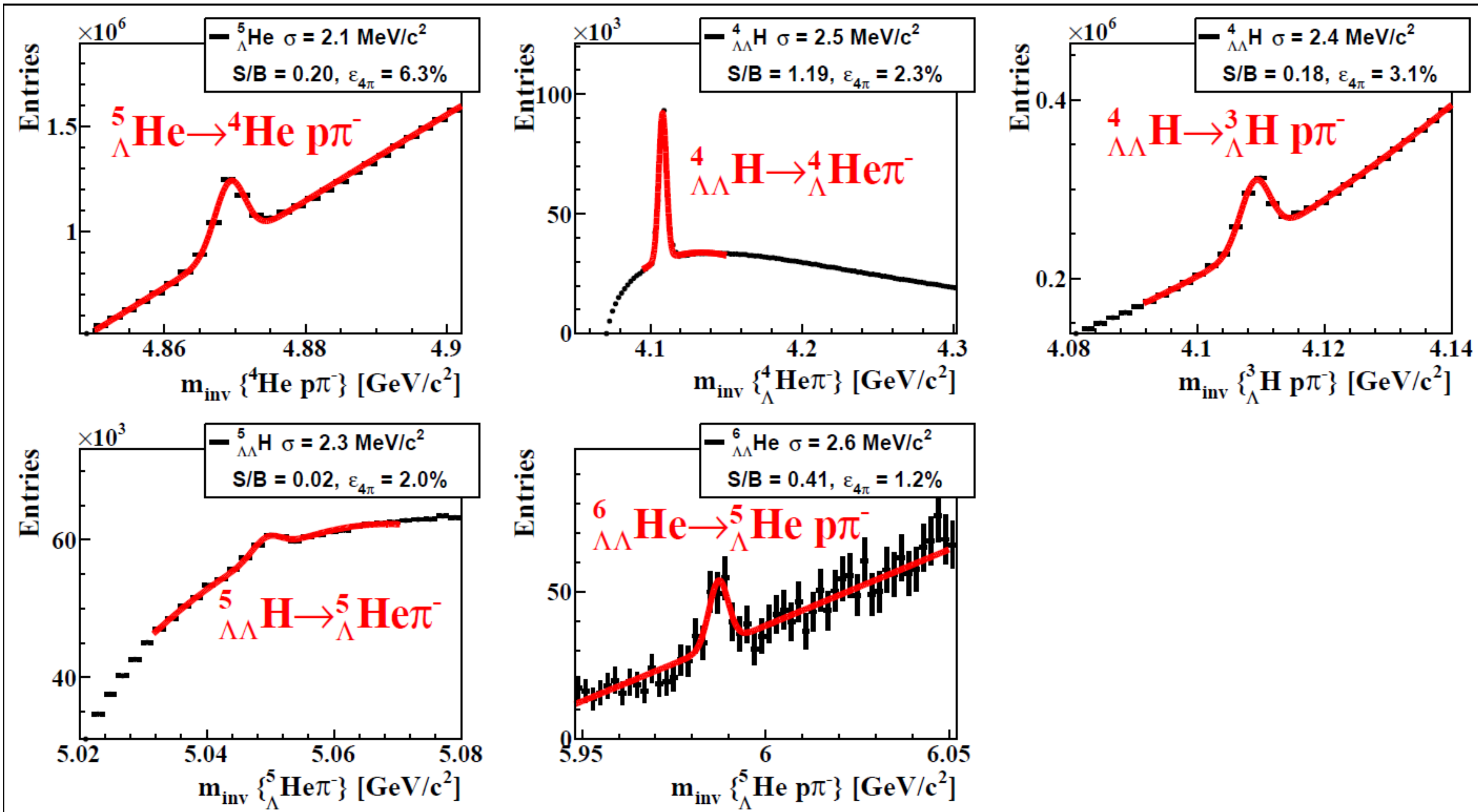
Simulation and reconstruction

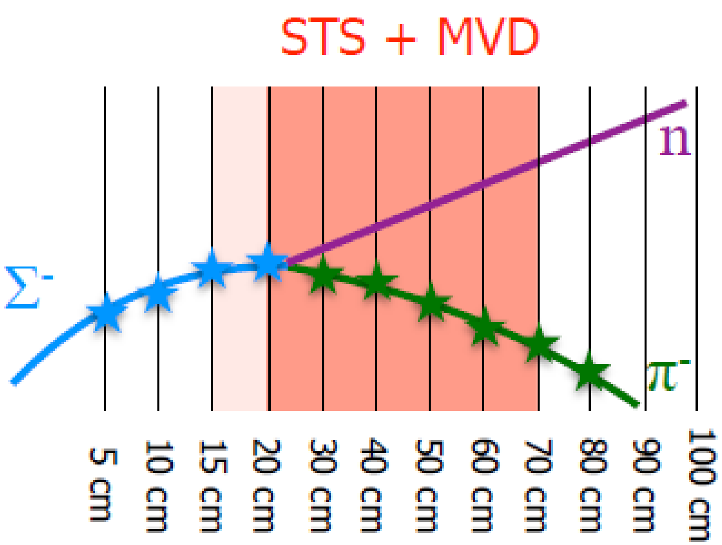
Hypernuclei in central Au+Au 10 AGeV

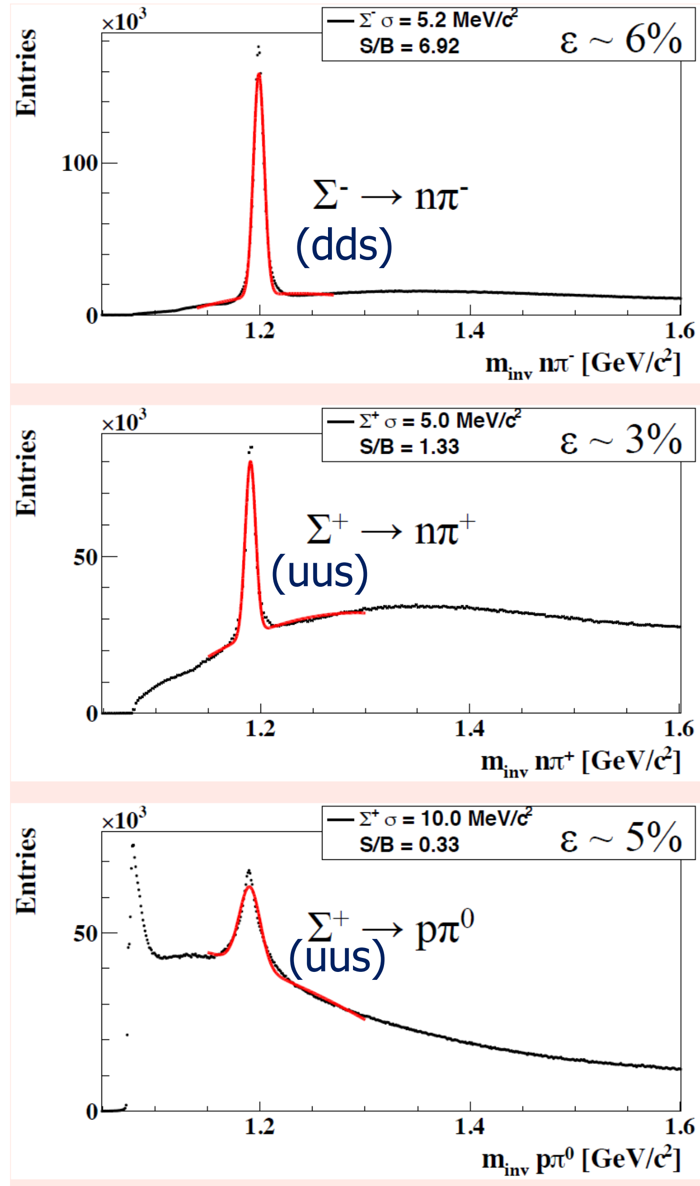


Simulation and reconstruction

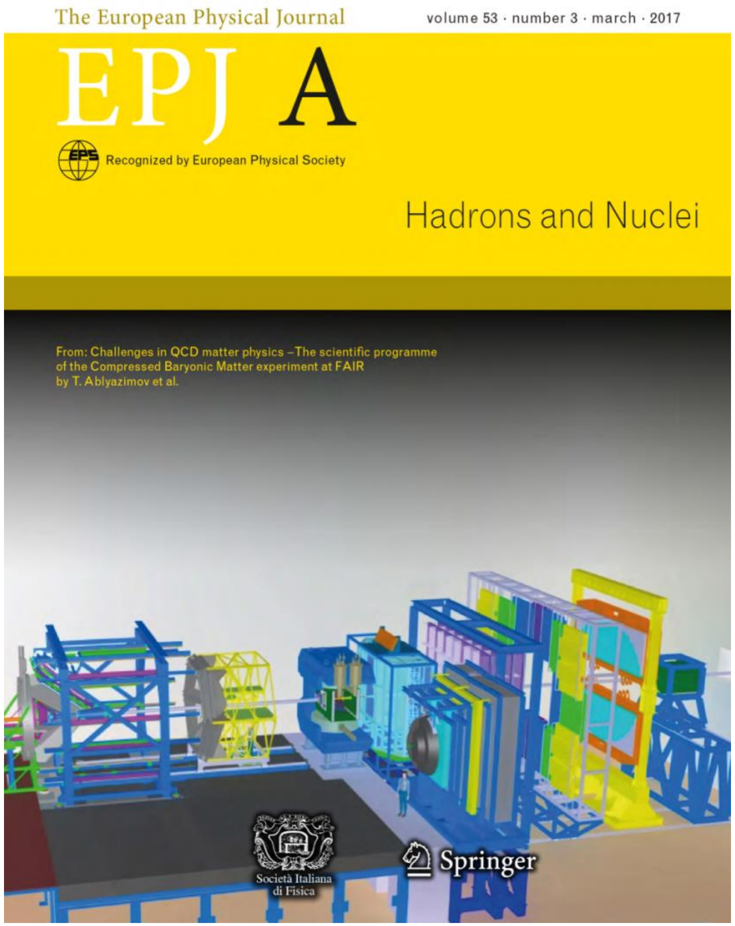
Hyperons in Au+Au 10 AGeV

missing mass analysis





For further reading ...



"Challenges in QCD Matter Physics – the scientific programme of the Compressed Baryonic Matter Experiment at FAIR"

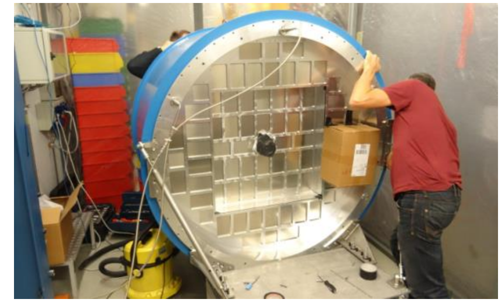
Ablyazimov, T. et al. Eur. Phys. J. A (2017) 53: 60. doi:10.1140/epja/i2017-12248-y

135 contributions, 220 pages

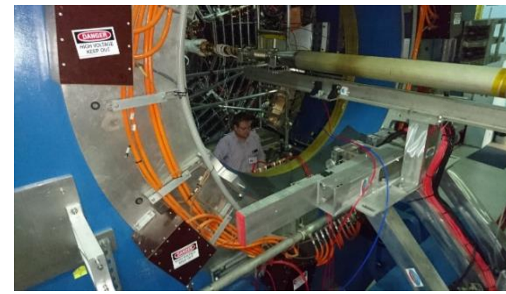
ISBN 978-3-9815227-4-7.

[https://repository.gsi.de/record/186952/files/CBM-PR-2015%20[pdf].pdf](https://repository.gsi.de/record/186952/files/CBM-PR-2015%20[pdf].pdf)

FAIR phase 0 experiments on dense QCD matter

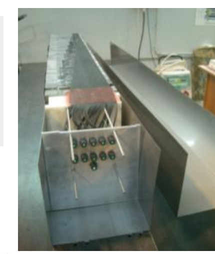


1. Install, commission and use 430 out of 1100 CBM RICH multi-anode photo-multipliers (MAPMT) in HADES RICH photon detector

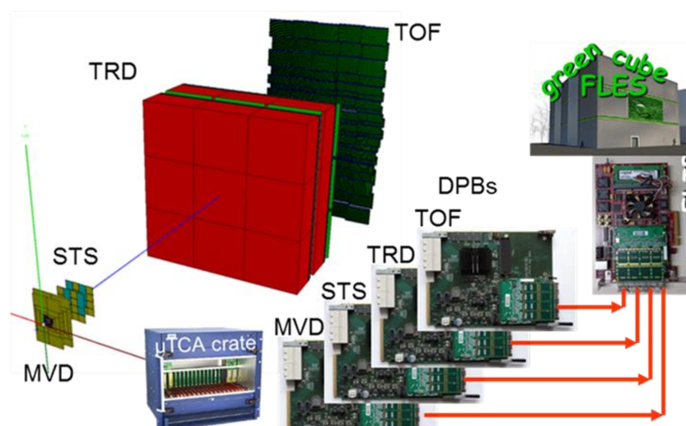


2. Install, commission and use 10% of the CBM TOF modules including read-out chain at STAR/RHIC (BES II 2019/2020)

3. Install, commission and use 4 Silicon Tracking Stations and the Project Spectator Detector in the BM@N experiment at the Nuclotron in JINR/Dubna (start 2019 with Au-beams up to 4.5 A GeV)



4. Build miniCBM at GSI/SIS18 for a full system test with high-rate nucleus-nucleus collisions from 2018 - 2021



The CBM Collaboration: 55 institutions, 460 members

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei
CTGU Yichang

Czech Republic:
CAS, Rez
Techn. Univ. Prague

France:
IPHC Strasbourg

Hungary:
KFKI Budapest
Eötvös 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.

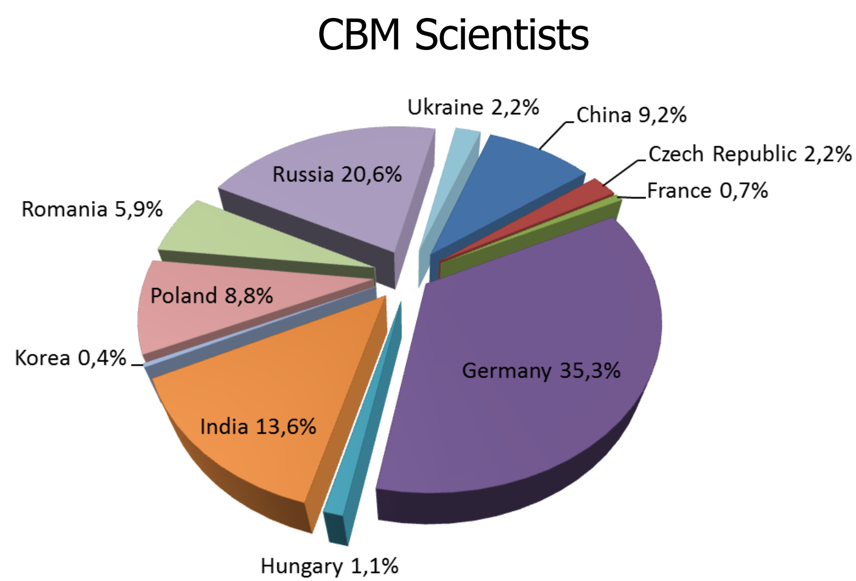
Korea:
Pusan Nat. Univ.

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

Romania:
NIPNE Bucharest
Univ. Bucharest

Russia:
IHEP Protvino
INR Troitzk
ITEP Moscow
Kurchatov Inst., Moscow
VBLHEP, JINR Dubna
LIT, JINR Dubna
MEPHI Moscow
PNPI Gatchina
SINP MSU, Moscow

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



Summary

- FAIR: Forefront research in nuclear, hadron, atomic, plasma and applied physics. Construction started, full operational in 2025. Installation/commissioning of experiments planned 2021-2024.
- CBM scientific program at SIS100: Exploration of the QCD phase diagram in the region of neutron star core densities $\rightarrow$ large discovery potential.
- CBM concept: High-rate detectors combined with free streaming data readout and online event selection enable 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 detectors fulfill CBM requirements. Mass production starts in 2018
- FAIR Phase 0: HADES experiments with CBM RICH photon detector, use CBM detectors at STAR/BNL and BM@N/JINR,
- and miniCBM at GSI