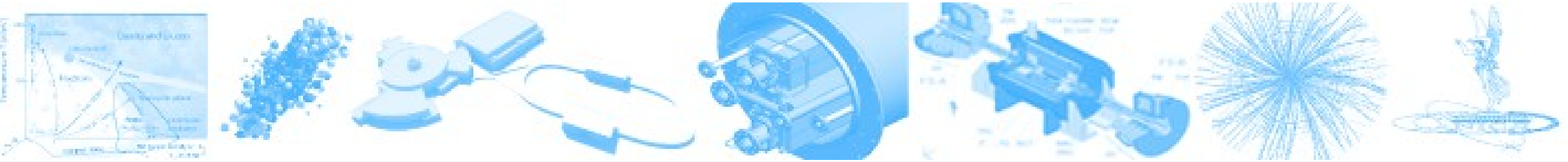
Joint Institute for Nuclear Research
International Intergovernmental Organization

Towards a Scientific Program for NICA at JINR

D. Blaschke and A. Sorin
(for the NICA/MPD collaboration)



EMMI Seminar
Darmstadt, November 5, 2014

Joint Institute for Nuclear Research
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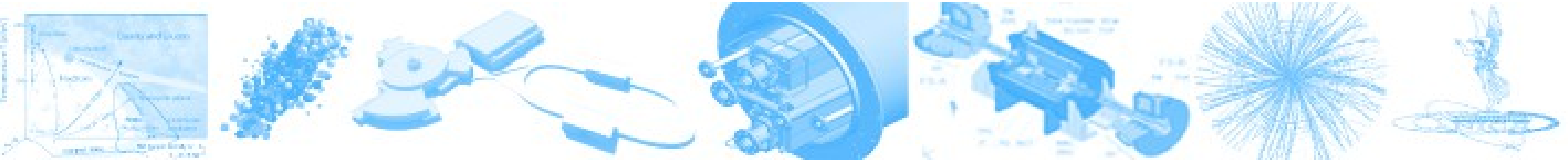
Towards a Scientific Program for NICA at JINR

D. Blaschke and A. Sorin
(for the NICA/MPD collaboration)

1. The Facility and Experiments
2. The NICA White Paper
3. Possible Highlights



EMMI Seminar
Darmstadt, November 5, 2014


NICA
Volga
river

NICA (Nuclotron based Ion Colider fAcility)
– the flagship project in HEP of Joint Institute for Nuclear Research (JINR)

Main targets of "NICA Complex":

- ***study of hot and dense baryonic matter***
- *investigation of nucleon spin structure, polarization phenomena*

- *development of accelerator facility for HEP @ JINR providing intensive beams of relativistic ions from p to Au polarized protons and deuterons with max energy up to √SNN= 11 GeV (Au79+) and =27 GeV (p)*

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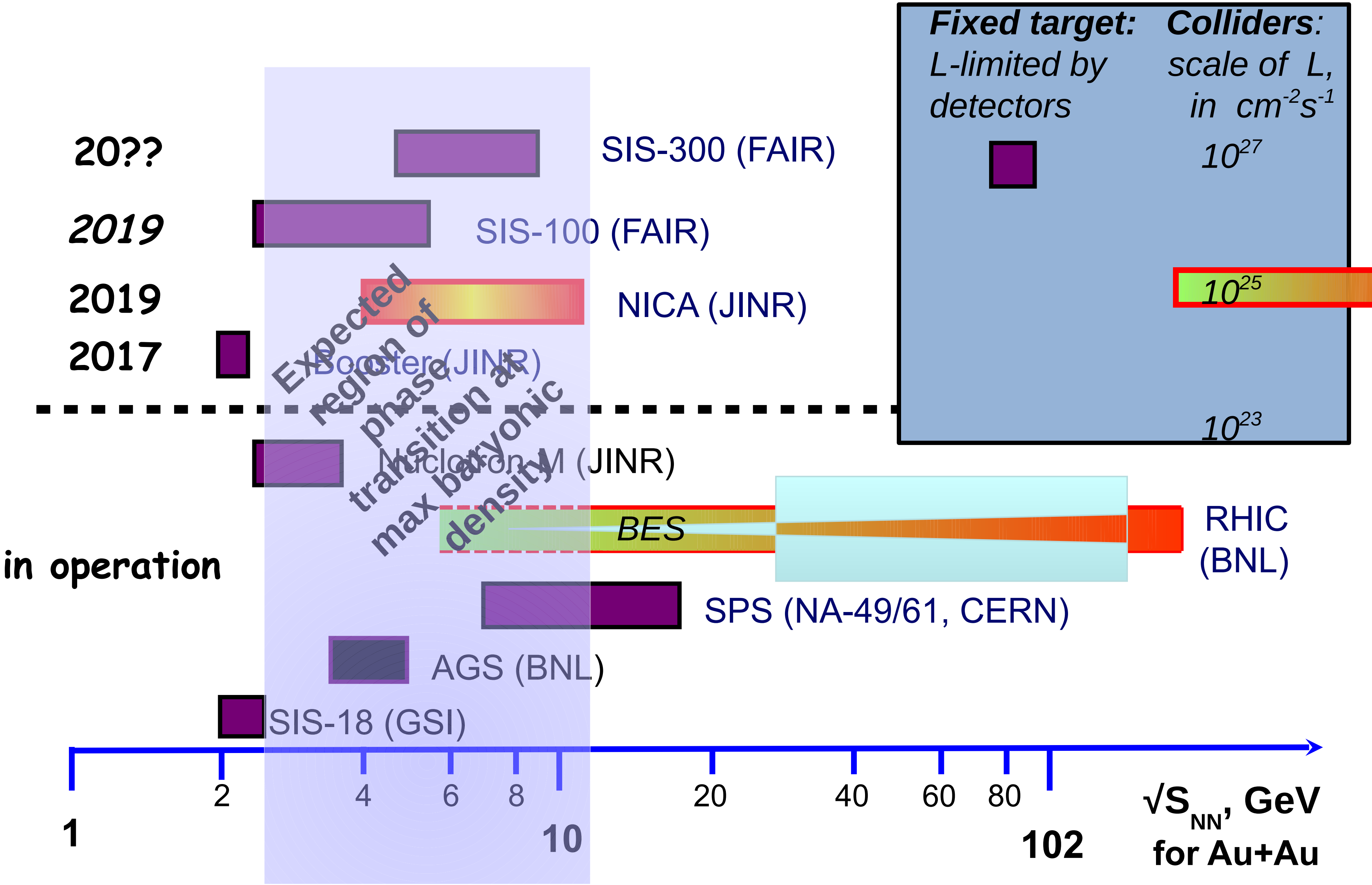
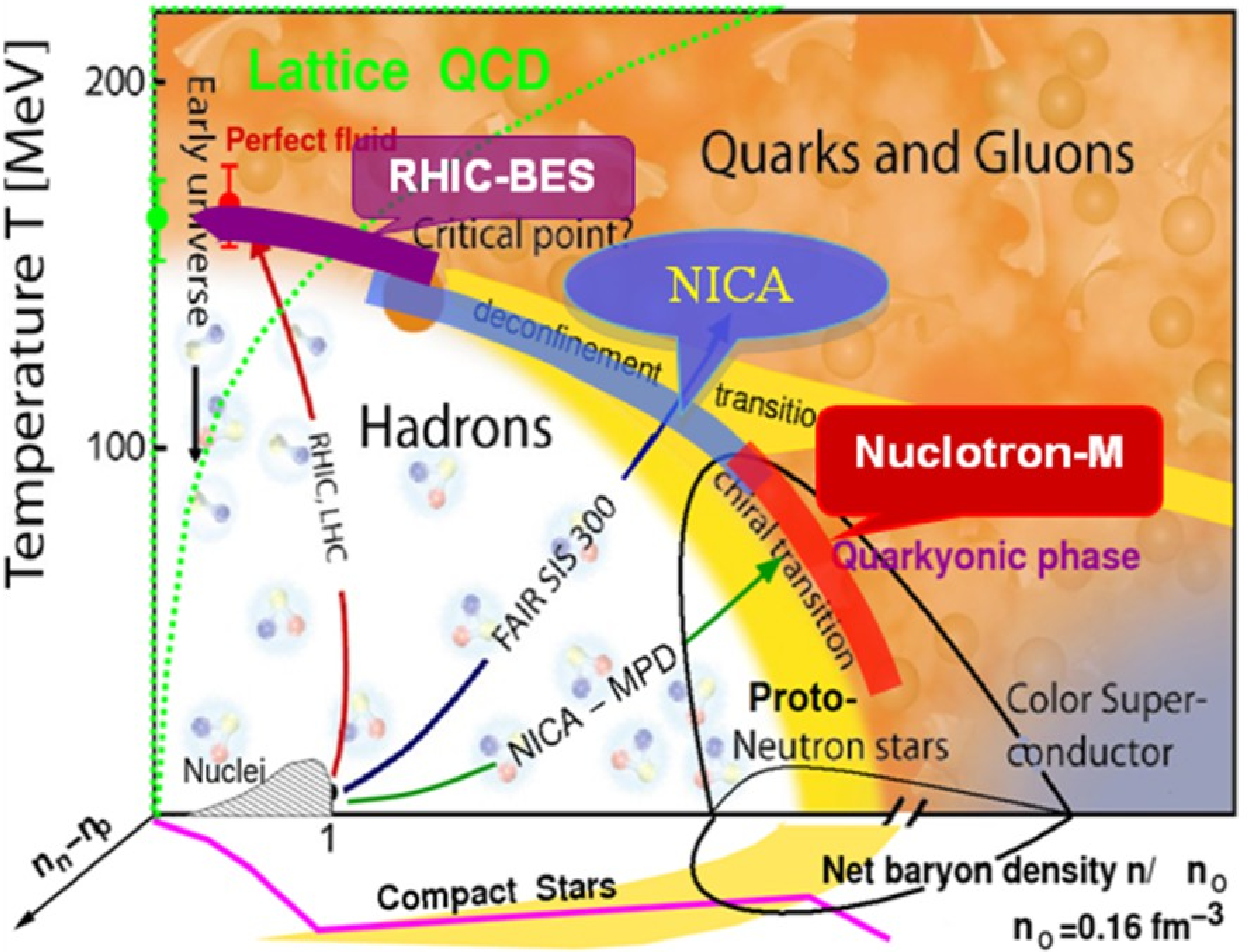
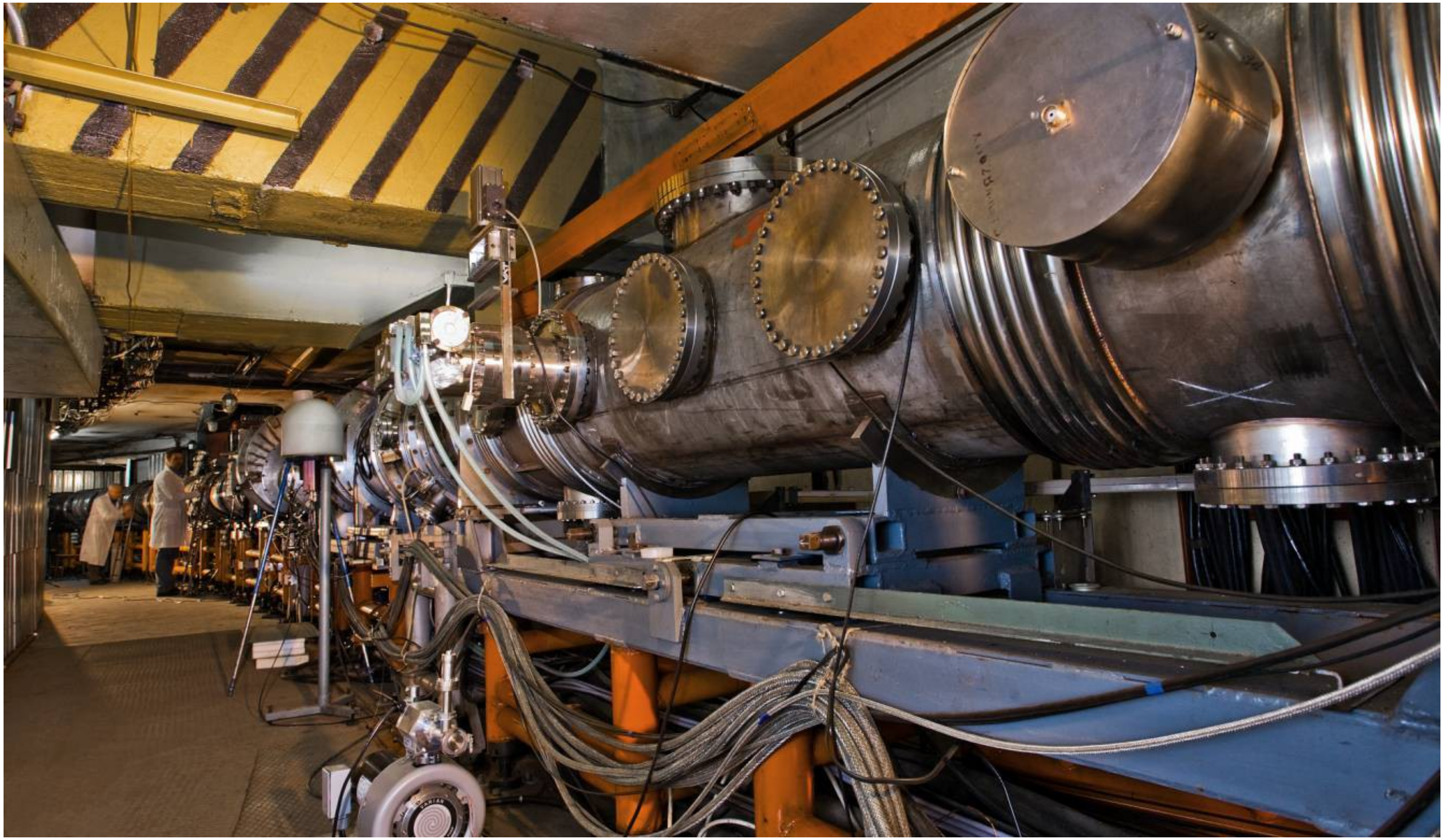
Present and future HI machines




Temperature T [MeV]
200
100
Lattice QCD
Early universe
Perfect fluid
RHIC-BES
Critical point?
Quarks and Gluons
NICA
deconfinement
transition
Hadrons
RHIC, LHC
Nuclotron-M
chiral transition
Quarkyonic phase
FAIR SIS 300
NICA – MPD
Proto-
Neutron stars
Color Super-
conductor
Nuclei
1
$n_n - n_p$
Compact Stars
Net baryon density n/ n_0
$n_0 = 0.16\ \mathrm{fm}^{-3}$

Synchrotron **Nuclotron,** in operation since 1993 – *based on superconducting magnets developed in Dubna*

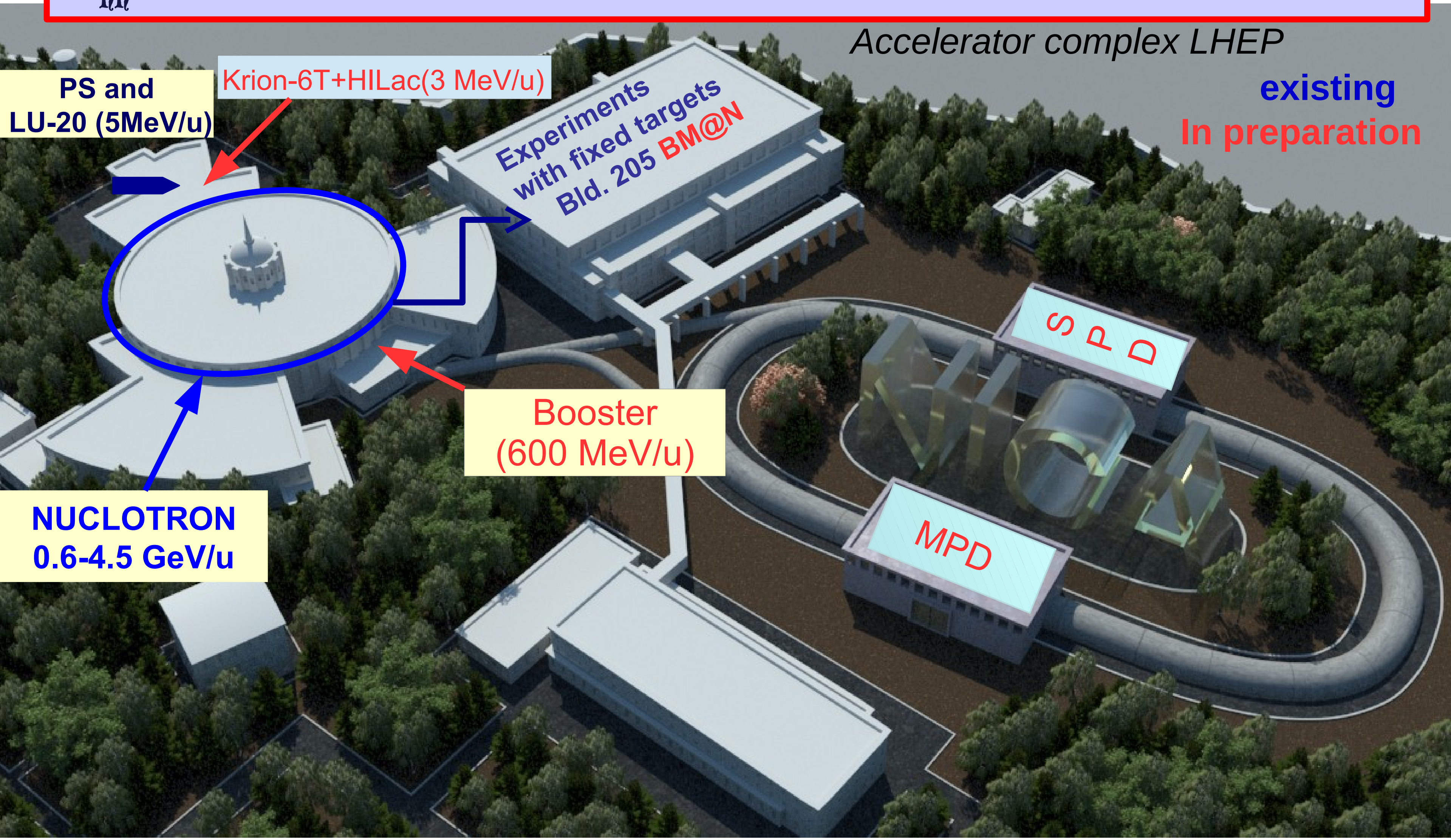


Nuclotron provides accelerated proton and ion beams (up to *Xe^{42+}, A=124*) with energies up to 6 AGeV (Z/A = 1/2)

Complex NICA

Collider basic parameters:

$\sqrt{s_{nn}}$ = 4 - 11 GeV; ***beams**: from* p to Au; $L \sim 10^{27}$ cm^{-2} s^{-1} (Au), $\sim 10^{32}$ cm^{-2} s^{-1} (p)



Accelerator complex LHEP

existing

In preparation

PS and LU-20 (5MeV/u)

Krion-6T+HILac(3 MeV/u)

Experiments with fixed targets Bld. 205 BM@N

Booster (600 MeV/u)

NUCLOTRON 0.6-4.5 GeV/u

NICA – basic milestones

- The project of **NICA complex** is approved **2010**
- The 1-st stage of **Nuclotron** modernization is completed **2010**

  10 runs have been carried out in **2010 – 2014**

- The projects: approval – completion
  - ✓ **accelerator complex 2010 – 2019**
  - ✓ **MPD (MultiPurpose Detector) 2010 – 2019**
  - ✓ **experiment with fixed target BM@N (I stage) 2012 - 2017**

- The project preparation for **Spin Physics Detector (SPD)**

  is in progress

Status of the accelerator complex

Nuclotron Beams

Parameter	*Project (2017)*		*Achieved*	
Magnetic field, T	2.0 (B≅ = 42.8 T≅ m)		2.0	
Field ramp, T/s	1.0		0.8	
Repetition period, s	5.0		8.0	
	Energy, GeV/u	Ions/ cycle	Energy, GeV/u	Ions/ cycle
Light ions ≅ d	6.0	5≅ 1010	5.6	1≅ 1010
Heavy ions	*With KRION-6T & Booster*		*Without KRION-2*	
40Ar18+	4.9	2≅ 1010	3.5	5≅ 106
56Fe26+	5.4	1≅ 1010	2.5	2≅ 106
124Xe48/42+	4.0	2≅ 109	1.5	1≅ 103
197Au79+	4.5	2≅ 109	---	---
Polarized beams	*With SPI & Siberian snake*		*With POLARIS*	
p≅	11.9	1≅ 1010	---	---
d≅	5.6	1≅ 1010	2.0	5≅ 108

NICA – Stage II
(Heavy Ion Mode)

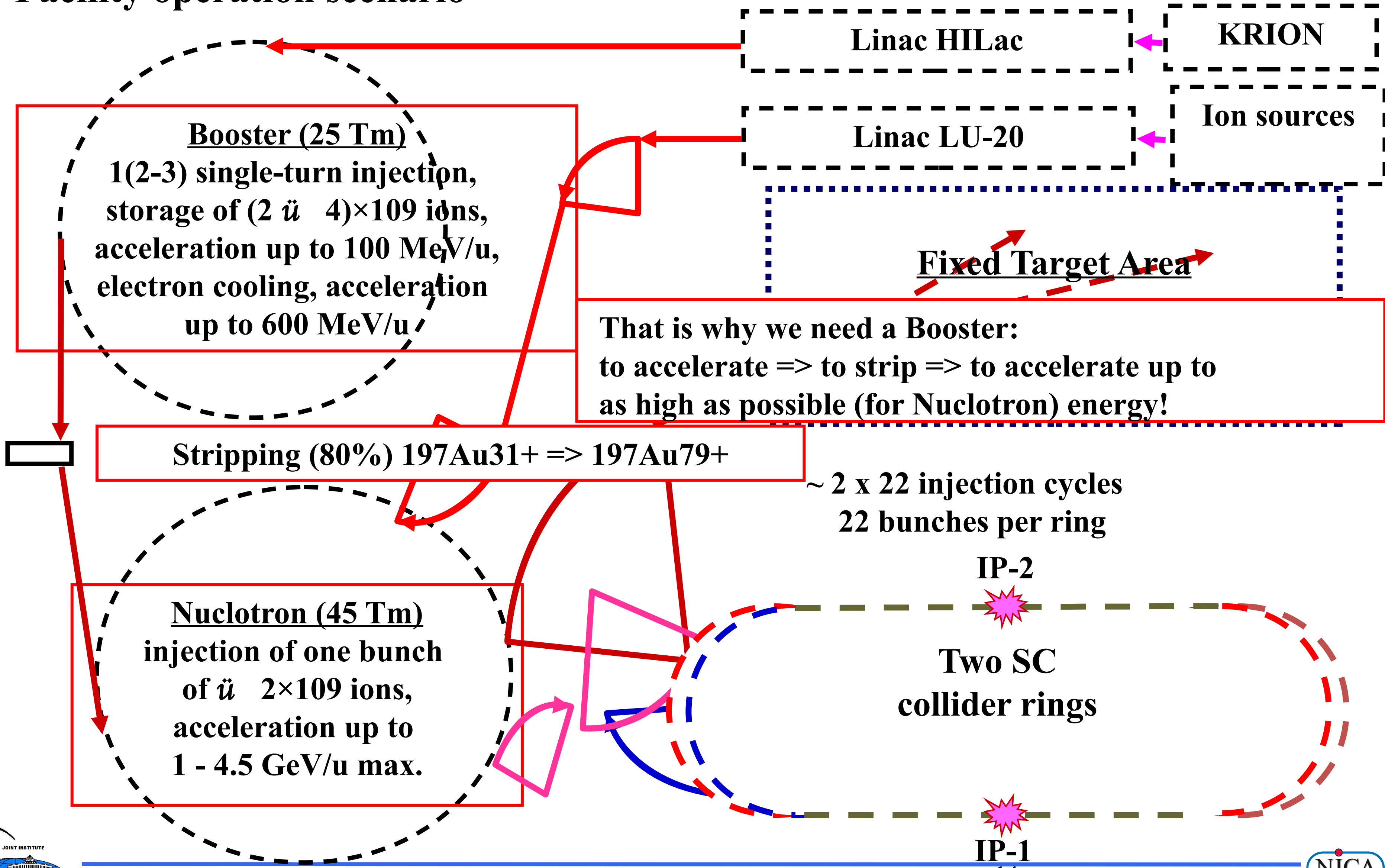
Key Parameters of The NICA Collider

Collider lattice:
FODO,
12 cells x 900
each arc,

Ring circumference, m	503,04		
Number of bunches	22		
R.m.s. bunch length, m	0.6		
Ring acceptance, π x mm x mrad	40.0		
Long. Acceptance, Δp/p	≅ 0.01		
$\gamma_{transition}$ ($E_{transition}$, GeV/u)	7.091 (5.72)		
β*, m	0.35		
Ion Energy, GeV/u	1.0	3.0	4.5
Ion number/bunch, 1e9	0.275	2.4	2.2
R.m.s. emittance, h/v π x mm x mrad	1.1/1.0	1.1/0.9	1.1/0.76
R.m.s. Δp/p, 1e-3	0.62	1.25	1.65
IBS growth time, s	190	700	2500
Peak luminosity, $cm^{-2}\,s^{-1}$	1.1e25	1e27	1e27

NICA – Stage II: Structure and Operation Regimes (Heavy Ion Mode)

Facility operation scenario



Linac HILac

KRION

Linac LU-20

Ion sources

Fixed Target Area

Booster (25 Tm)
1(2-3) single-turn injection,
storage of (2 ü 4)×109 ions,
acceleration up to 100 MeV/u,
electron cooling, acceleration
up to 600 MeV/u

That is why we need a Booster:
to accelerate => to strip => to accelerate up to
as high as possible (for Nuclotron) energy!

Stripping (80%) 197Au31+ => 197Au79+

~ 2 x 22 injection cycles
22 bunches per ring

Nuclotron (45 Tm)
injection of one bunch
of ü 2×109 ions,
acceleration up to
1 - 4.5 GeV/u max.

IP-2

Two SC
collider rings

IP-1

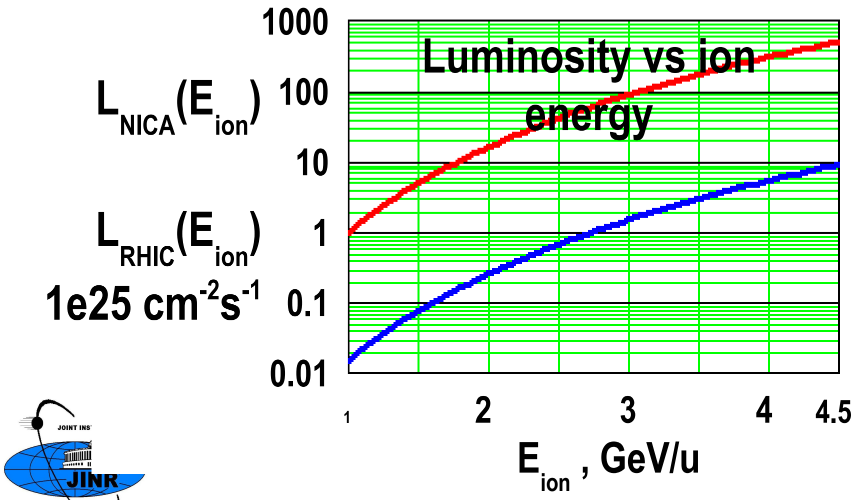
NICA – Stage II: Structure and Operation Regimes (Heavy Ion Mode)

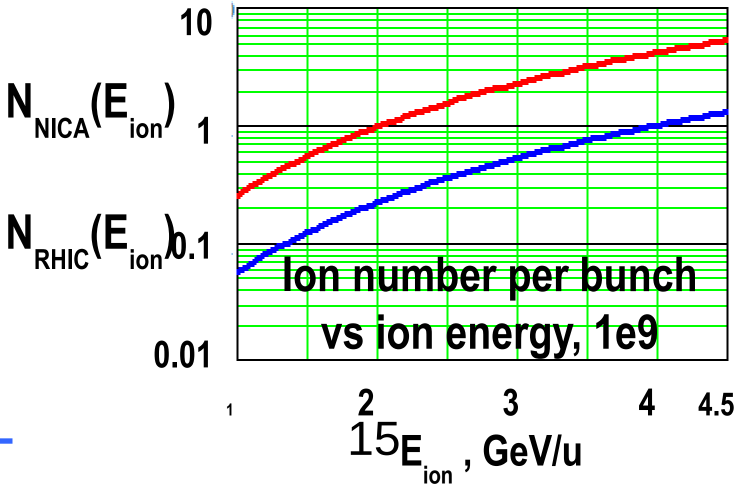
Why RHIC has low luminosity at the energy where luminosity of NICA is relatively high? The reason is the beam space charge:

$$N_{bunch} \text{ x } 1/C_{ring} \text{ ,} \qquad L \text{ x } (N_{bunch})^2 \text{ x } 1/(C_{ring})^2 \text{ !}$$

$$C_{RHIC}/C_{NICA} = 7.62 \text{ ,} \quad L_{NICA} / L_{RHIC} = (C_{RHIC}/C_{NICA})^2 \text{ x } 58.1$$

Parameter	RHIC	NICA
CRing, m	**3834**	**503**
Bunch length, m	1.0	0.6
Beam emittance, ≅ ≅ mm≅ mrad	1.0	1.0
Number of intersections	6	2
*, m	1.0	0.35
Hour-glass factor	0.8	0.6





NICA – Stage III : Collider of polarized beams

1st concept of the collider beams has been developed

It assumes acceleration of polarized protons and deuterons in Nuclotron avoiding the Booster.

Concept of polarized protons in Nuclotron has been developed, but its realization requires significant upgrade of Nuclotron.

New concept with polarized particles acceleration in the Booster and storage in the Collider rings is under preliminary consideration.

Analysis of depolarization effects in the Collider is in progress.

NICA – Stage III : Collider of polarized beams

Source of Polarized p↑ & d ↑ Ions (SPI)

Collaboration of INR (Troitsk) & JINR

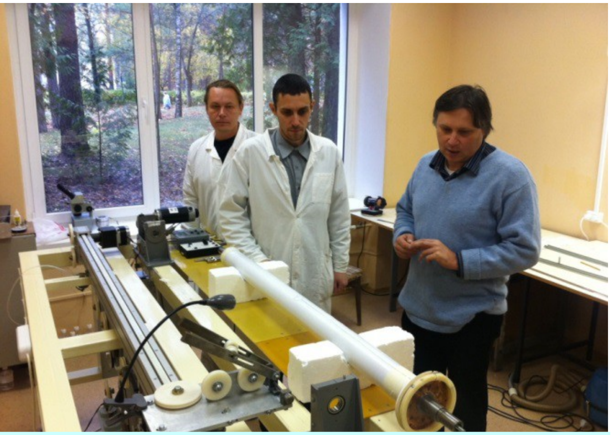
SPI at JINR, May 2013

SPI test at Nuclotron with d↑ is planned for winter 2015.

It will be beginning of new stage of experiments with polarized beams at Nuclotron.

NICA Elements Fabrication

Heavy Ion Source KRION-6T/ESIS (Electron String Ion Source modification)



6T solenoid fabrication (2012)

KRION-6T/ESIS has been assembled and being tested (March 2014)

Test results (April 2014) : B= 5.4T magnetic field reached in a working regime.

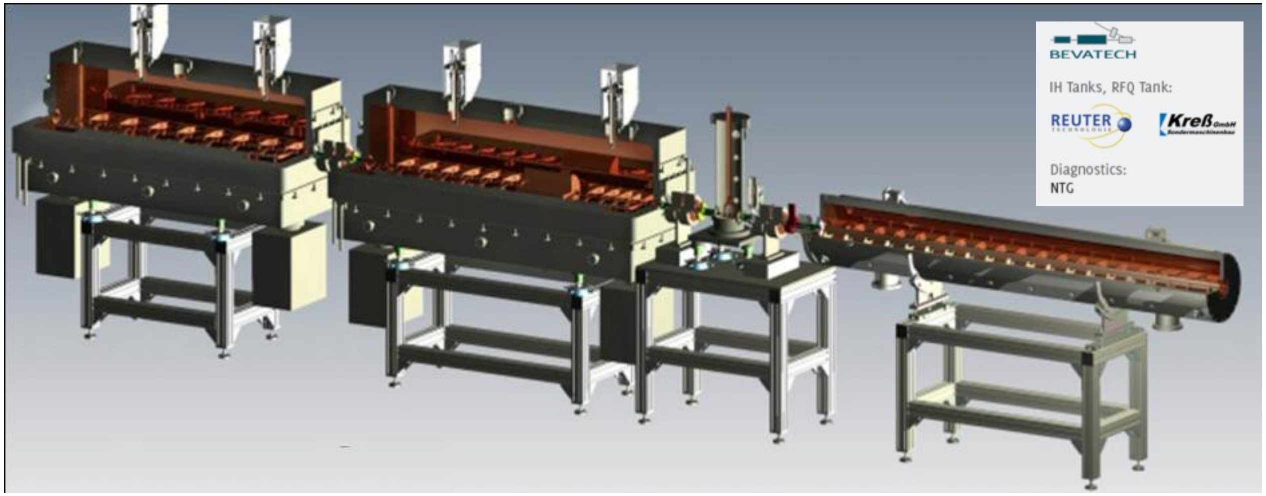
Test of gold ion beams has been produced:

- ≅ $Au^{30+} \div Au^{32+}$, 6×10^8, $T_{ioniz} = 20$ ms for
- ≅ Au^{32+} -> repetition rate 50 Hz.
- ≅ ion beams $Au^{51+} \div Au^{54+}$ are produced.

NICA Elements Fabrication

Heavy Ion Linear Accelerator (HILAC, 3 MeV/u)

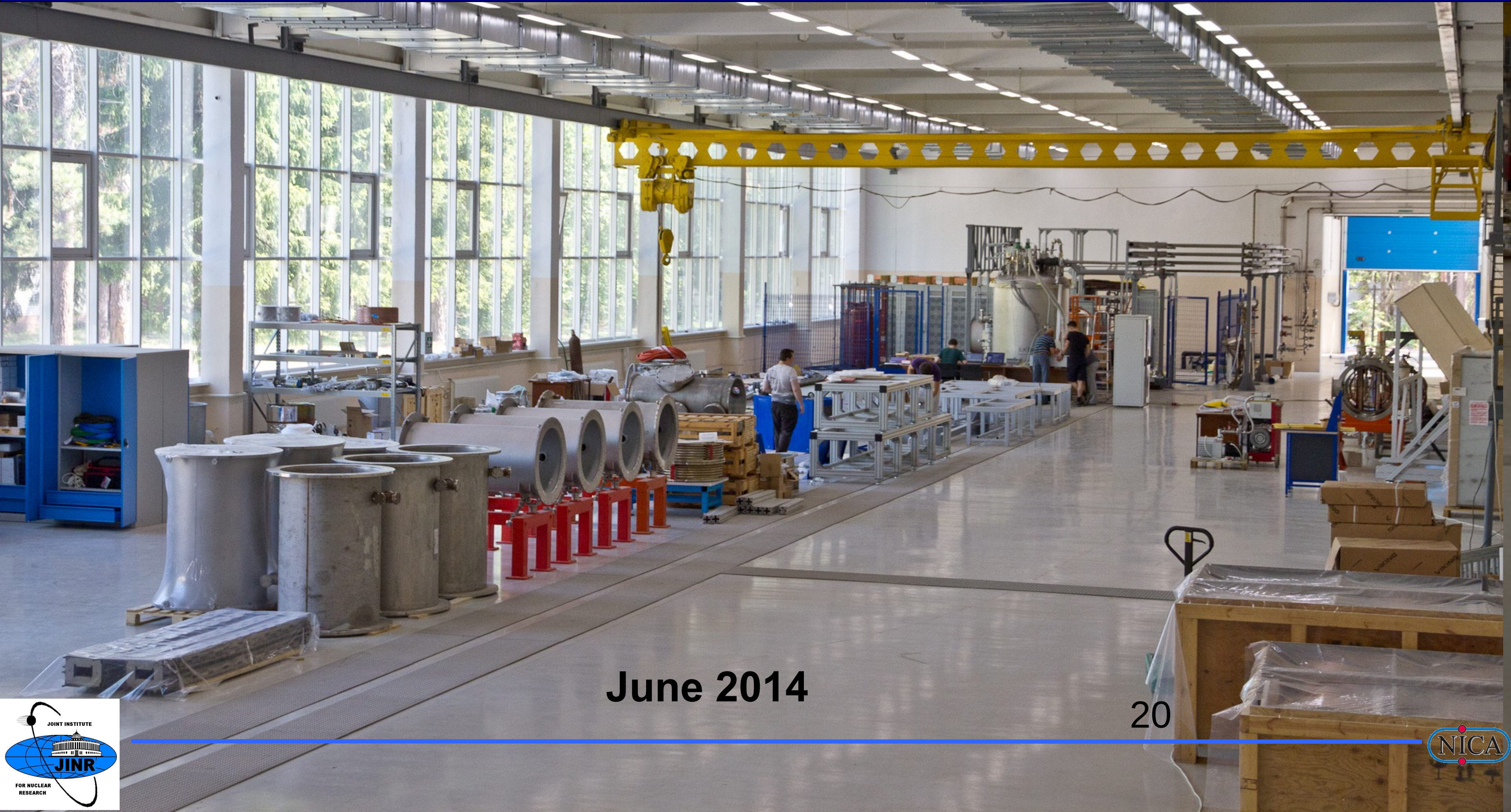
- **under construction at BEVATECH (Frankfurt)**
- **first section delivery - October 2014**
- **final delivery - June 2015**



SC Magnets for Booster, Collider & SIS-100 (FAIR)

1st pre-production magnet prototype (Booster dipole) – September 2014

1st production magnet sample ("serial" Booster dipole) –
– December 2014

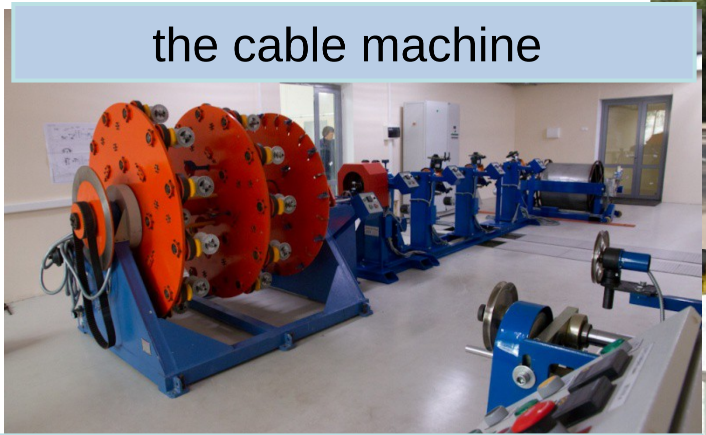


June 2014

Magnet assembly workshop at LHEP JINR

~ 450 SC magnets will be assembled & tested in the workshop for ***NICA*** *& SIS-100* ***FAIR***

Starts production in 2014



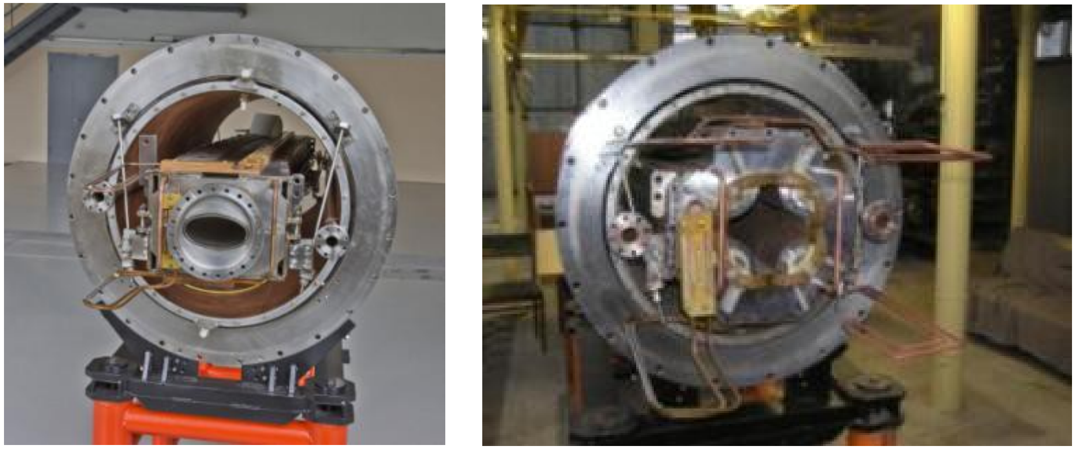
the cable machine

area for SC coil fabrication

NICA Elements Fabrication

SC Magnets for Booster, Collider & SIS-100 (FAIR)

The Booster Magnets



Booster dipole and quadrupole lens

UH vacuum beam chamber (curved)

HTSC current leads 17 kA

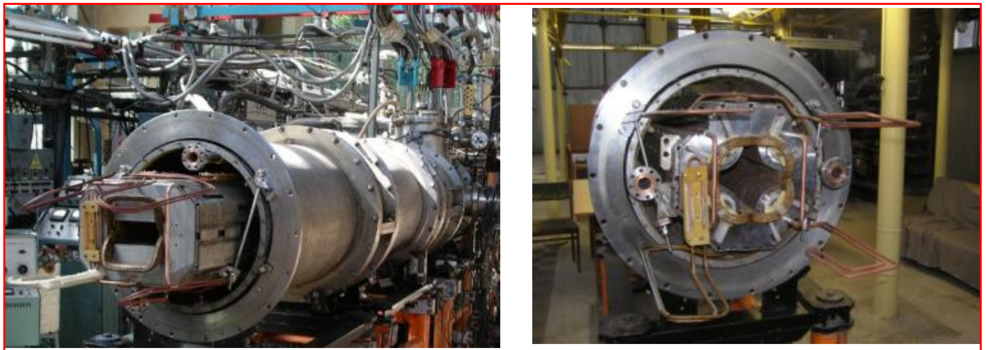
The Collider “twin” dipole

Full-scale Nuclotron–type superconducting prototypes of dipole and quadrupole magnets for the NICA Booster and Collider were manufactured at LHEP JINR, have successfully passed the cryogenic test on the bench. Serial production of the magnets for the Booster will be started in December 2014.

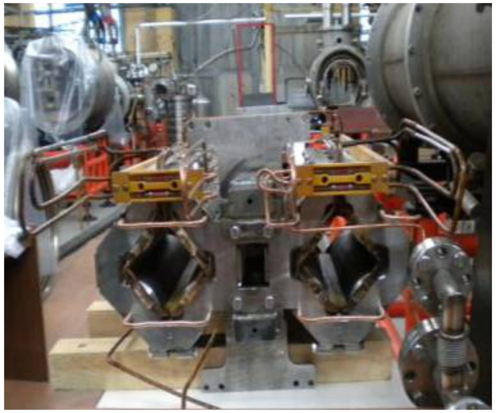
NICA Elements Fabrication

SC Magnets for Booster, Collider & SIS-100 (FAIR)

The SIS 100 & NICA Magnets



Dipole & quadrupole prototypes for SIS100 (FAIR)



The Collider quadrupole lens

Sextupole corrector prototype for SIS100 and NICA Booster and its assembly

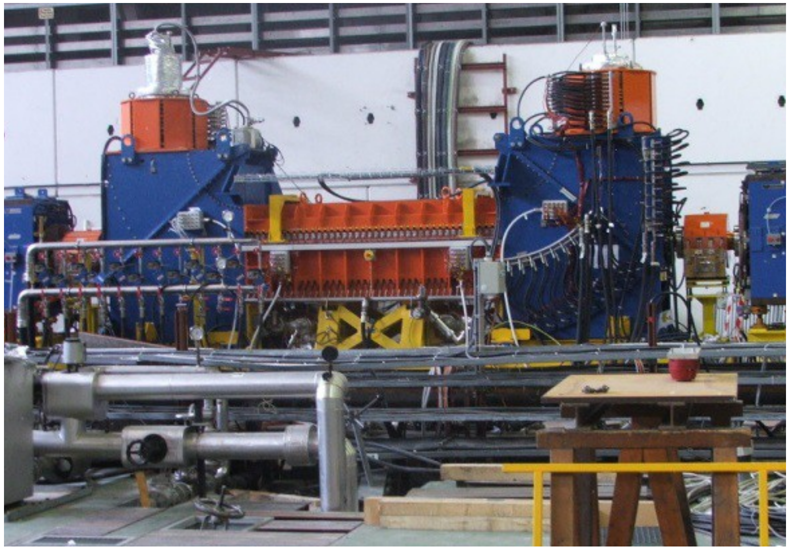
Budker INP (Novosibirsk) - design and fabrication

RF acceleration systems for Booster

BINP, RF for Booster (June 2013)
Will be delivered to JINR in 2014

Electron cooler for Booster

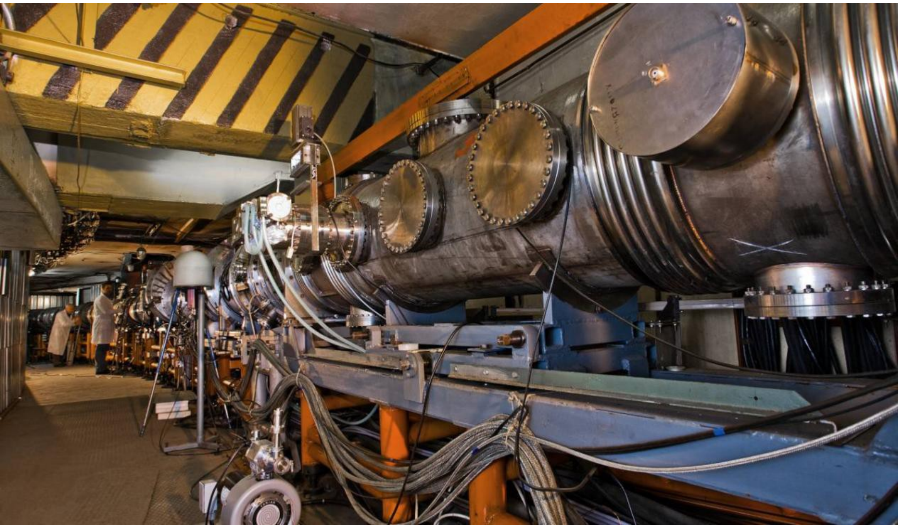
(stage of working design)



Electron cooler for Booster (prototype)

Booster Synchrotron Construction

Nuclotron Upgrade



Nuclotron is SC synchrotron accelerating ions and delivering presently ion beams:

deuterons Emax = 4.8 GeV/u (B = 1.7 T)

124Xe42+ Emax = 3.0 GeV/u (B = 1.7 T).

The Nuclotron upgrade tasks for collider mode:

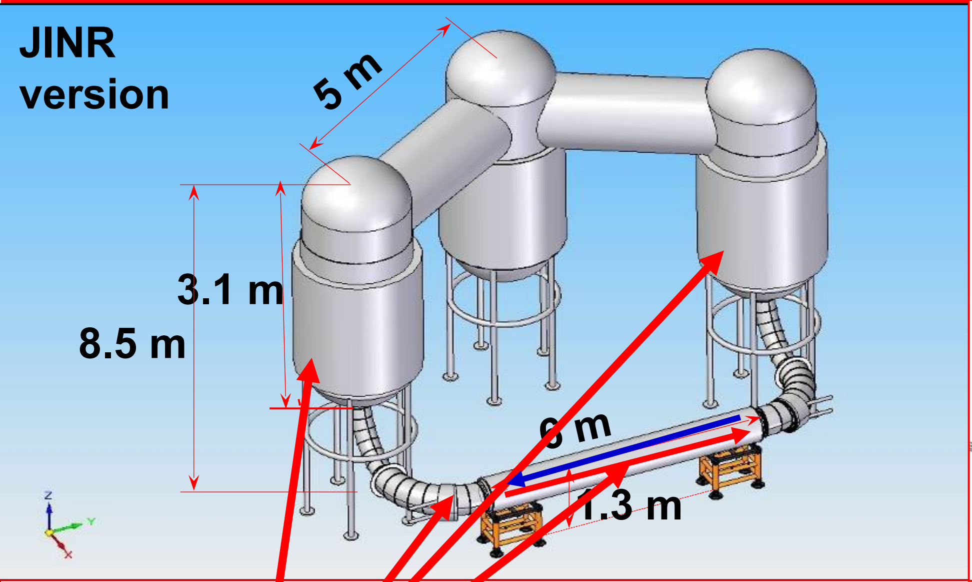
- Acceleration of ^{197}Au^{79+} up to 4.5 GeV/u
- Injection system for ^{197}Au^{79+} at 600 MeV/u
- Upgrade of RF system
- Extraction system for ^{197}Au^{79+} at 1 - 4.5 GeV/u
- Upgrade of control system (synchronization)

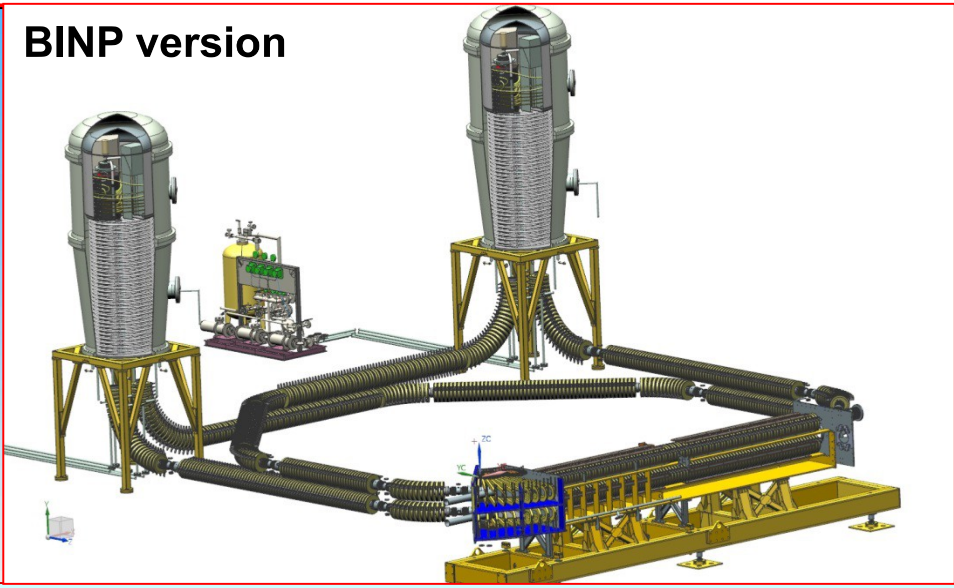
The work is in steady progress

NICA Elements Fabrication

JINR + BINP + AREI + Fermilab + NEC + Geliymash (Moscow)

Electron Cooler for NICA Collider – Two Versions





Electron energy 0.5 ≅ 2.5 MeV, electron beam current 0.1 ≅ 1 A

SC solenoids

(JINR version)

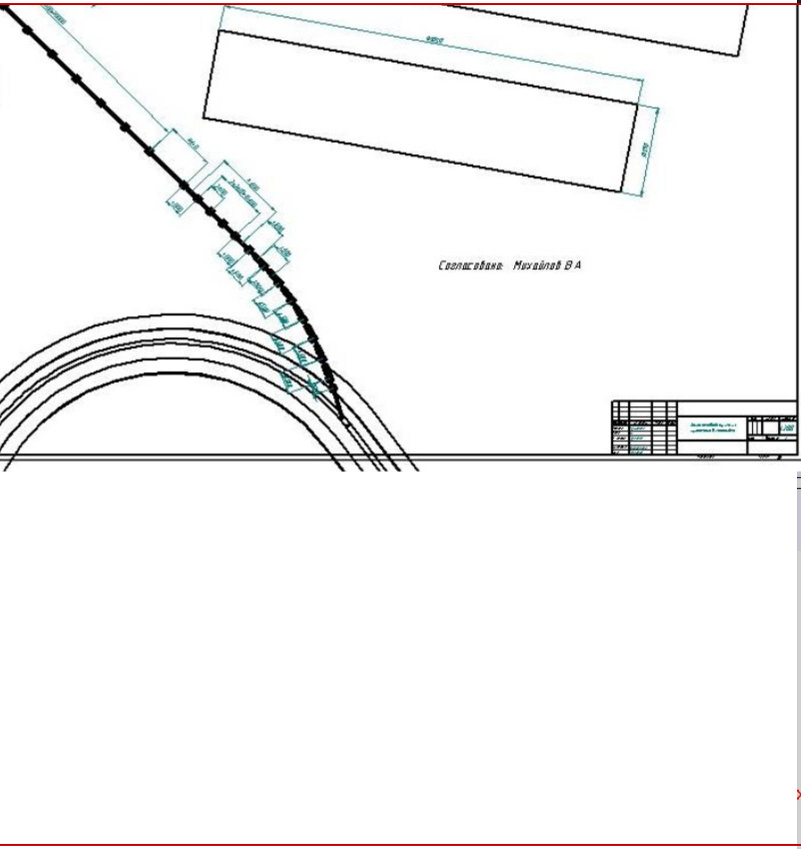
NbTi cable ⌀ *0.5* мм L = 275 km $ 250,000

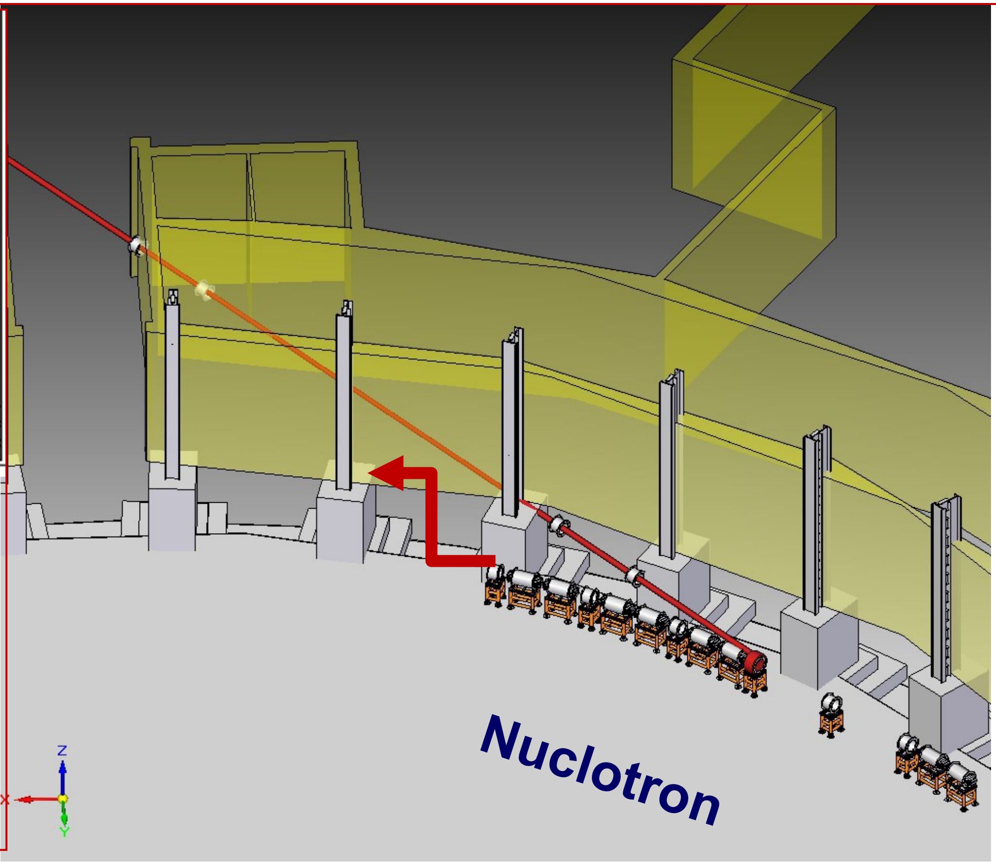
HTSC band 12 x 0.5 мм2 L = 11.5 km $ 350,000

Maximum electron energy, MeV	2.5
Electron beam current, A	0.1 – 1.0
Solenoids’ magnetic field, T	0.2

NICA Elements Fabrication

JINR + BINP Beam transfer channel Nuclotron - Collider
(stage of working design)



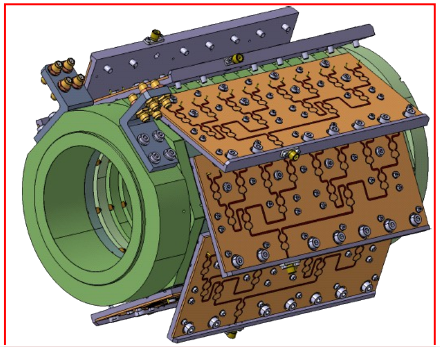


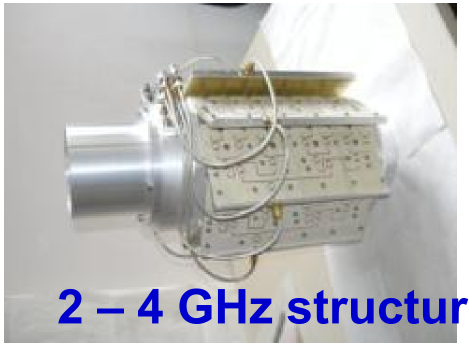
Channel lattice:
pulsed magnets, 35 dipoles, 56 quadrupoles, $P_{average}$ ~ 200 kW

NICA Elements Fabrication

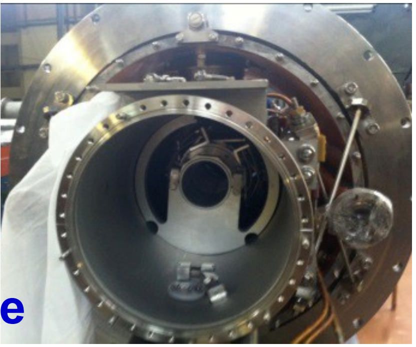
JINR + FZ Jülich Stochastic Cooling for NICA Collider

Pick-Up/Kicker Station (FZJ)





2 – 4 GHz structure



Stochastic Cooling

Test experiment at Nuclotron

March 2013 Schottky-signal spectrum

Before (blue) and after (yellow) cooling

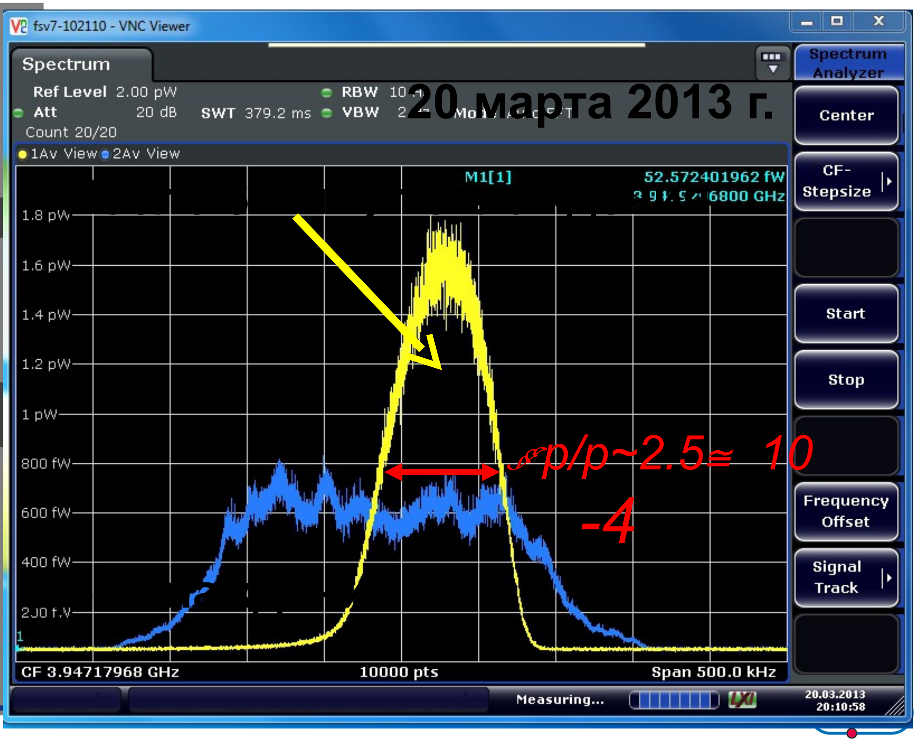
Deuterons, 3 GeV/u, h = 3500, Nion = 2e9

December 2013 Carbon ions 12C6+

3 GeV/u, Nion = 5e8

Coasting beam ≅ cool = 27 sec (h = 2500)

Bunched beam ≅ cool = 50 sec (h =2000)



20 марта 2013 г.

fsv7-102110 - VNC Viewer

Ref Level 2.00 pW
Att 20 dB
SWT 379.2 ms
RBW 10
VBW 2
Count 20/20
1Av View 2Av View
M1[1] 52.572401962 fW
CF 3.94717968 GHz
10000 pts
Span 500.0 kHz
Measuring...
20.03.2013 20:10:58

$\wp p/p \sim 2.5 \cong 10^{-4}$

Summary: The NICA Beams

Heavy ion colliding beams up to 197Au79+ + 197Au79+

at ≅ sNN = 4 ÷ 11 GeV , Laverage= 1x1027 cm-2≅ s-1

Light-Heavy ion colliding beams of the same ≅ sNN and the same or higher Laverage

Polarized beams of protons and deuterons in collider mode:

p≅ p≅ ≅ spp = 12 ÷ 26 GeV Lmax ≈ 1x1032 cm-2≅ s-1

d≅ d≅ ≅ sNN = 4 ÷ 13.8 GeV

Extracted beams of light ions and polarized protons and deuterons for fixed target experiments:

The set of NICA beams provides unique possibility both for basic and applied researches in the forthcoming decades

Applied research on ion beams at kinetic energy above 3 MeV/u

Experiments at NICA:

MultiPurpose Detector (MPD)

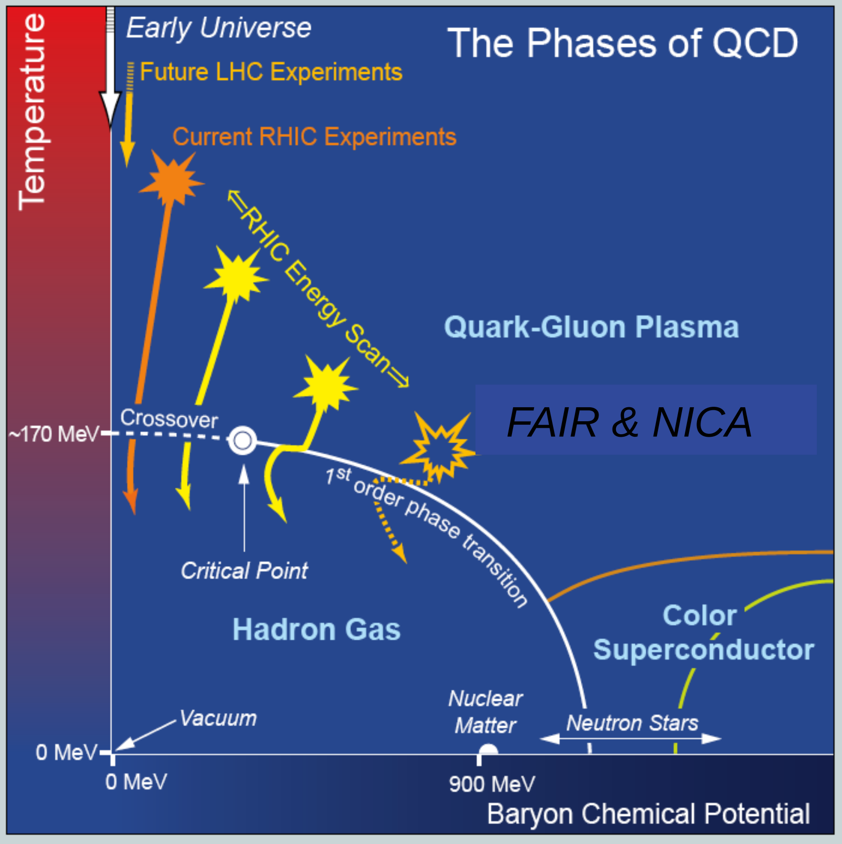
at the Collider

and

Baryonic Matter at Nuclotron (BM@N)

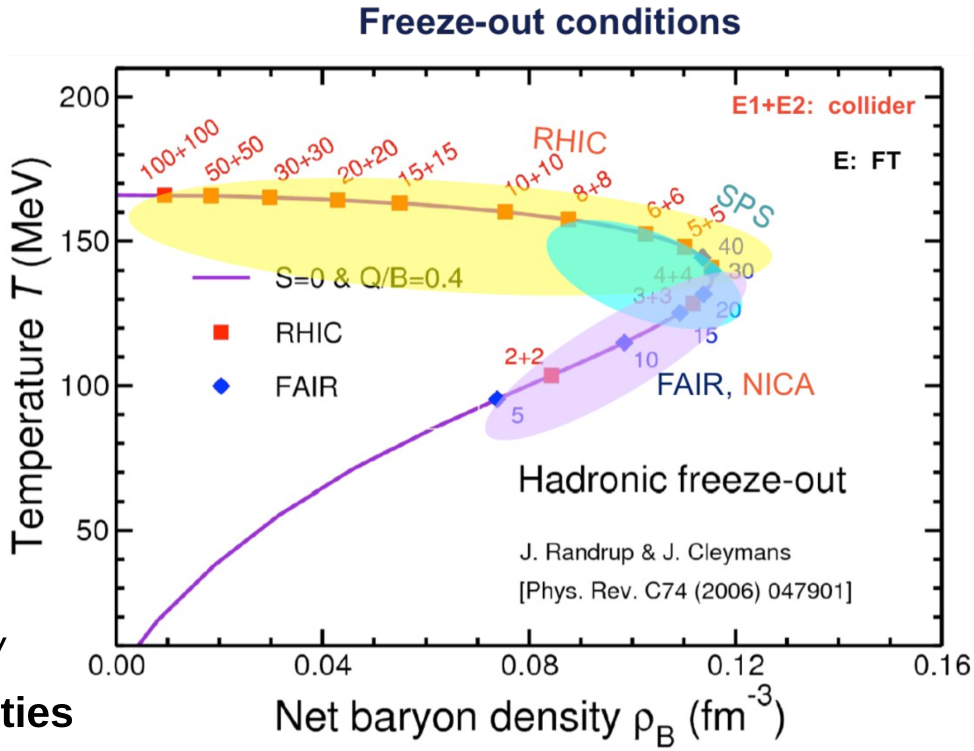
at extracted Nuclotron beam

Physics


The Phases of QCD

QCD matter at NICA :

- *Highest net baryon density*
- *Energy range covers onset of deconfinement*
- *Complementary to the RHIC/BES, FAIR and CERN experimental programs*


Freeze-out conditions

- **Bulk properties, EOS** - *particle yields & spectra, ratios, femtoscopy, flow*
- **In-Medium modification of hadron properties**
- **Deconfinement (chiral), phase transition at high rB** *- enhanced strangeness production*
- **QCD Critical Point -** *event-by-event fluctuations & correlations*
- **Strangeness in nuclear matter -** *hypernuclei*

MPD detector for Heavy-Ion Collisions @ NICA

Tracking: up to |h|<2 (TPC)
PID: hadrons, e, g (TOF, TPC, ECAL)
Event characterization:
centrality & event plane (ZDC)

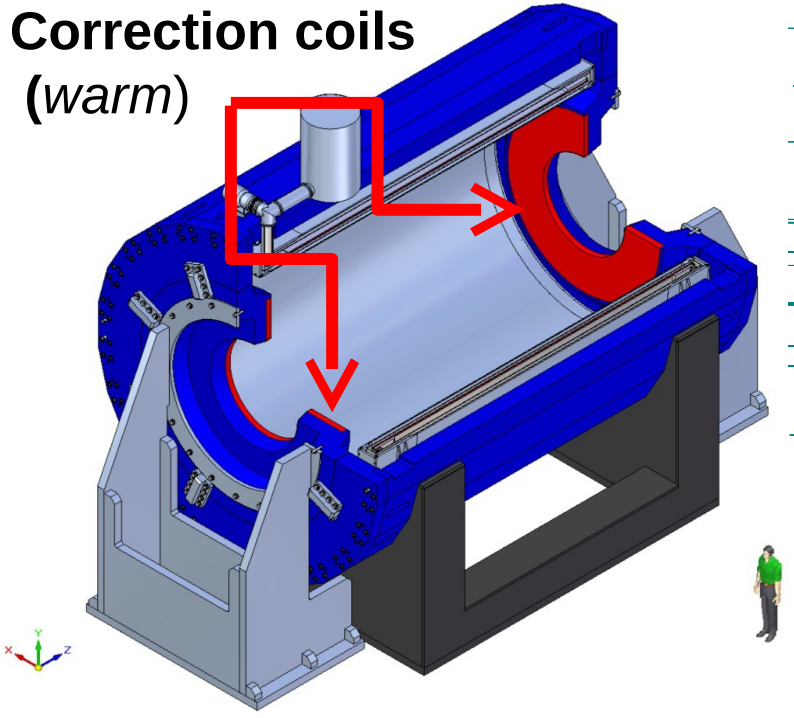
Stage 1: TPC, TOF, ECAL, ZDC, FD FFD

Stage 2: IT + Endcaps (tracker, TOF, ECAL)

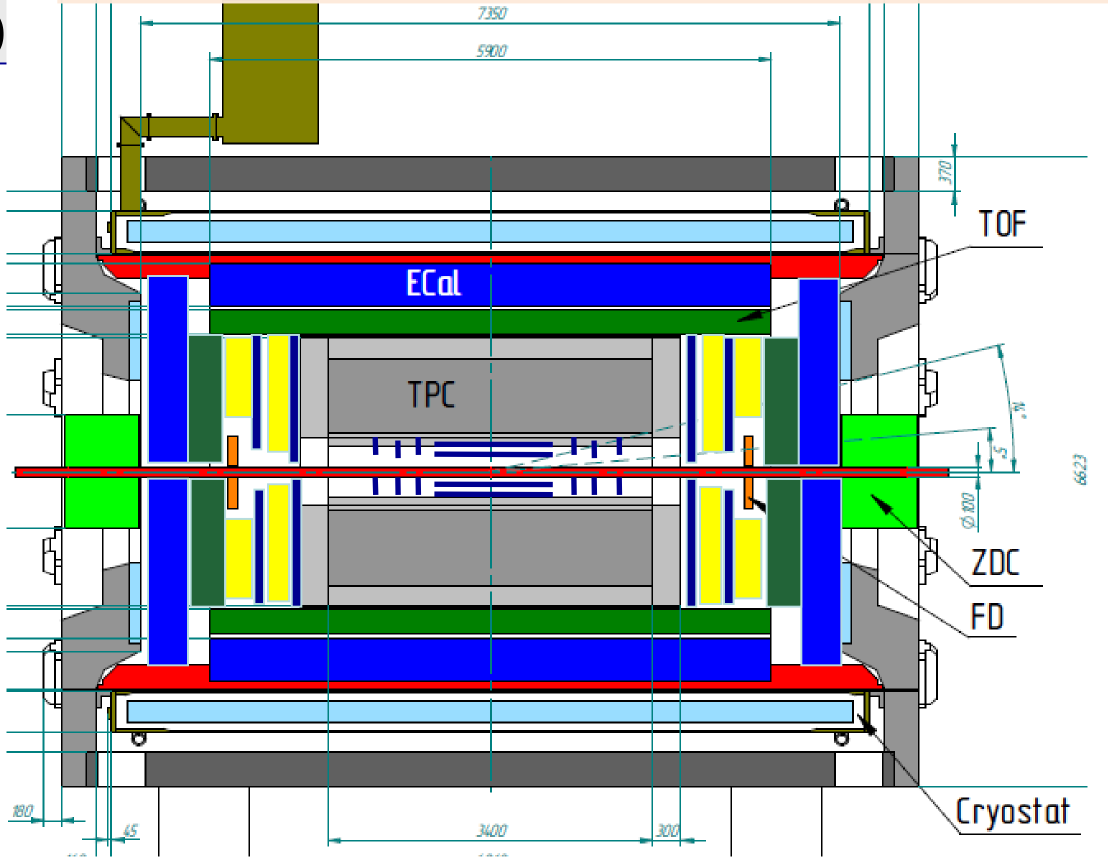
Superconducting solenoid:

high level (~ 10-4) of magnetic field homogeneity

B0=0.66 T

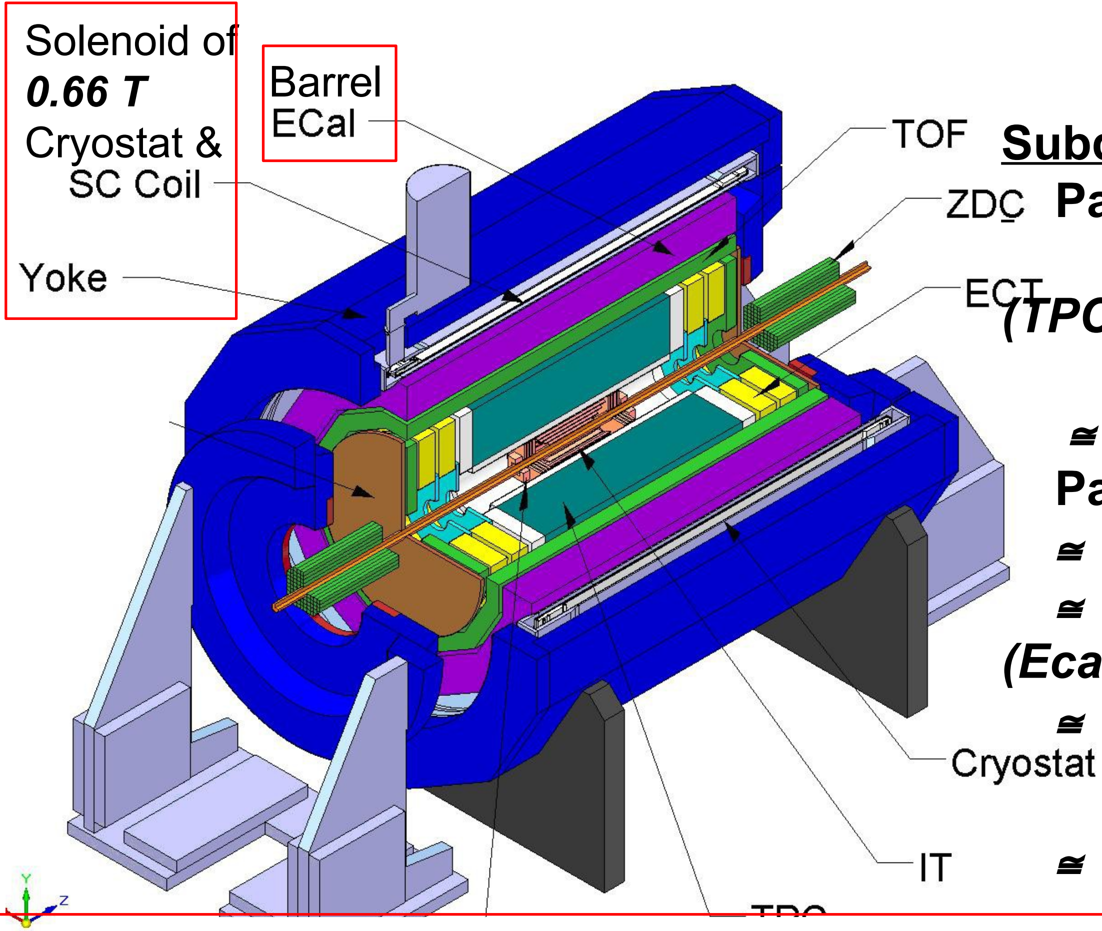


Correction coils (*warm*)



Status:
technical design – completed;
survey for producers

MultiPurpose Detector (MPD)



<u>Subdetectors & probes' identification:</u>

Particle Tracking:

- ≅ ***Time projection chamber (TPC)***
- ≅ ***Inner tracker (IT)***
- ≅ ***End Cap Tracker (ECT)***

Particle identification:

- ≅ ***Time-of-flight detector (TOF)***
- ≅ ***Electromagnetic calorimeter (Ecal)***
- ≅ ***Time projection chamber (TPC)***

Triggering (T0)

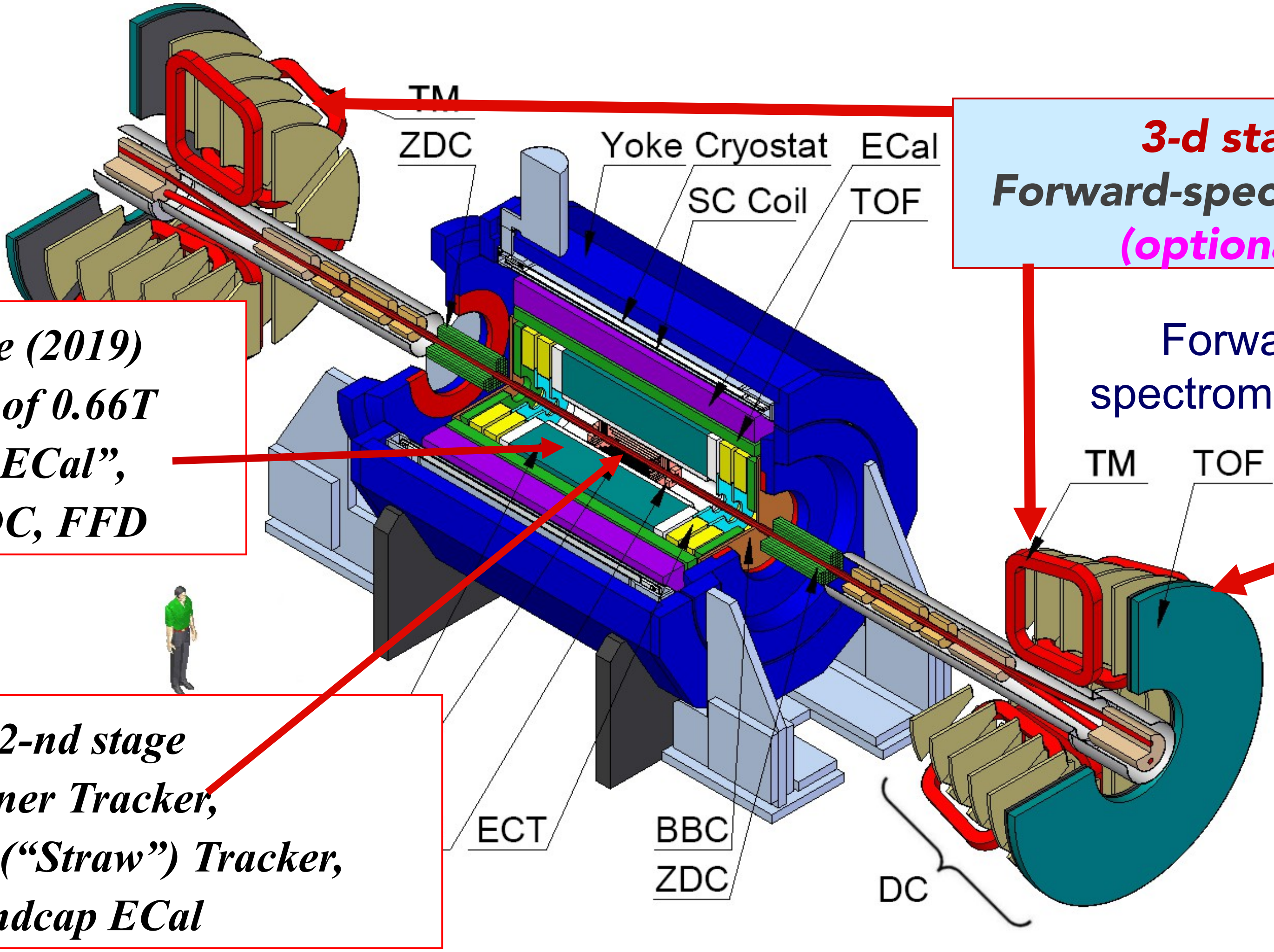
- ≅ ***Fast Forward Detector (FFD)***

<u>MPD advantages:</u> **<u>Disadvantage</u>: weight ≅ 1200 tons**

- ✓ ***maximum and homogeneous detection efficiency (2≅ ≅ symmetry),***
- ✓ ***high "transparency" for particles (small amount of matter;***
- ✓ ***high quality of trajectories' reconstruction and particle identification***
- ✓ ***high detection rate (~ 7 kHz)***

MultiPurpose Detector (MPD)

3 stages of MPD commissioning



3-d stage
Forward-spectrometers
(optional ?)

1-st stage (2019)
Solenoid of 0.66T
"Barrel ECal",
TPC, ZDC, FFD

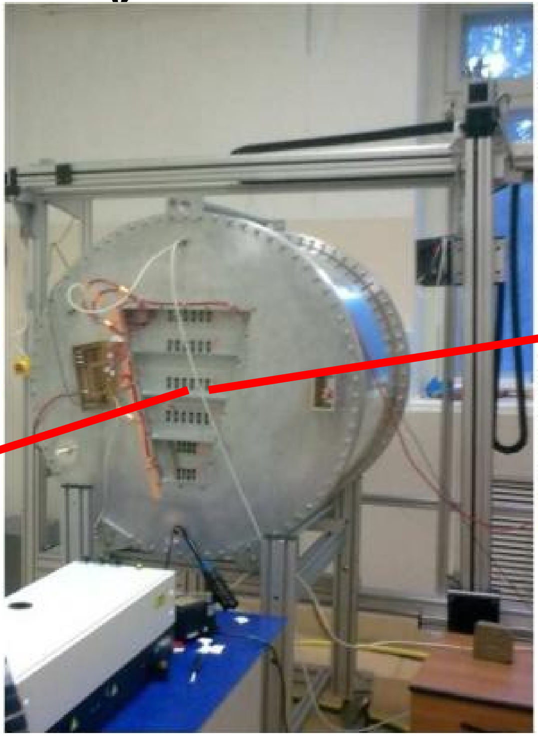
2-nd stage
Inner Tracker,
EndCap ("Straw") Tracker,
Endcap ECal

MultiPurpose Detector (MPD)

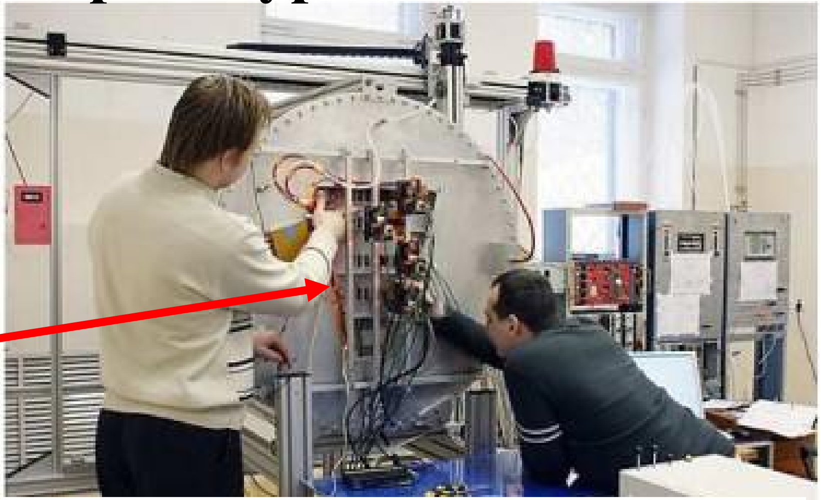
MPD Subdetectors' Development

Time Projection Chamber - prototype 1

Field Cage prototype



The general view of the TPC Prototype-1

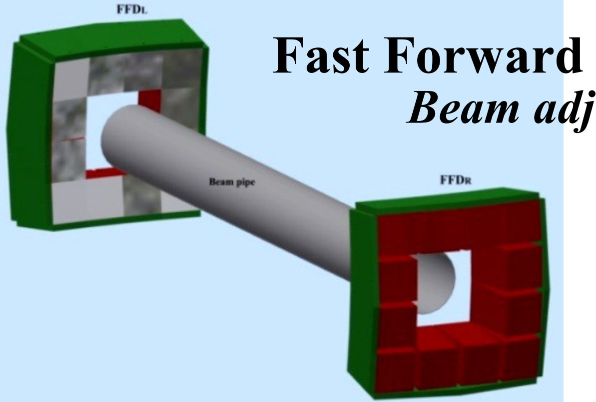


Preparation for test with UV laser.

Cylinder C3 (Dec. 2013)
(carbon-filled plastic)

MultiPurpose Detector (MPD)

MPD Subdetectors' Development

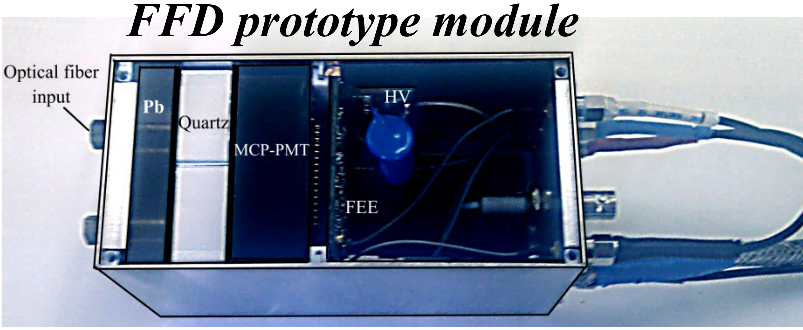


Fast Forward Detector (FFD)

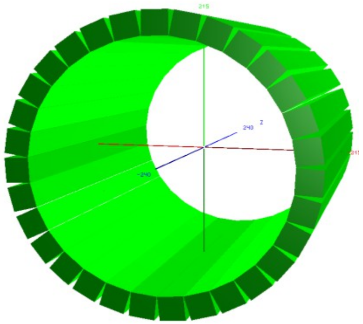
Beam adjustment and collision trig

(30 ps)

FFD prototype module



JINR (VBLHEP) + Radium Institute (St.Petersburg).)



Electromagnetic Calorimeter (ECAL "Shashlyk")

JINR (VBLHEP & DLNP) + ISM (Kharkov)

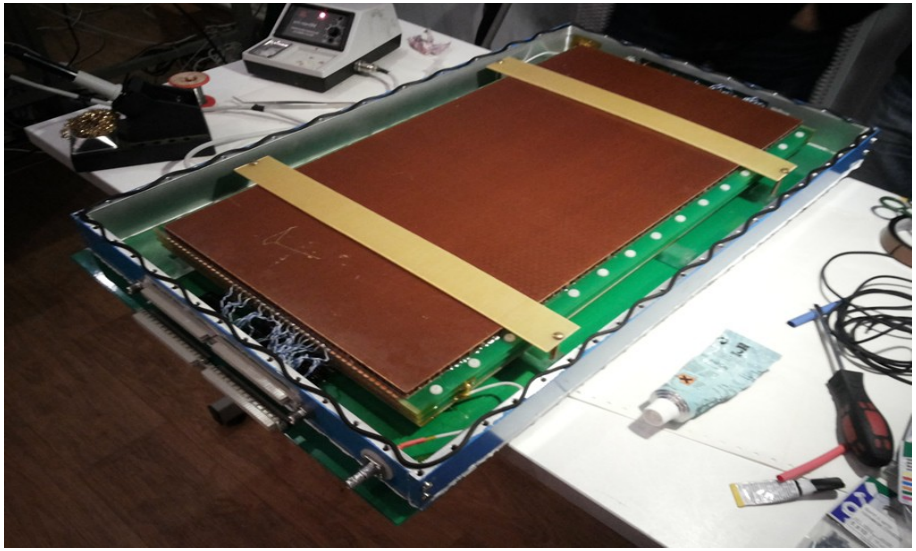
Zero Degree Calorimeter (ZDC)

INR (Troisk) + JINR (VBLHEP)

Pb + scintillator sampling (51)
Read-out: fibers+ Avalanche PDs
ZDC coverage: $2.2<|h|<4.8$

MultiPurpose Detector (MPD)

MPD Subdetectors’ Development

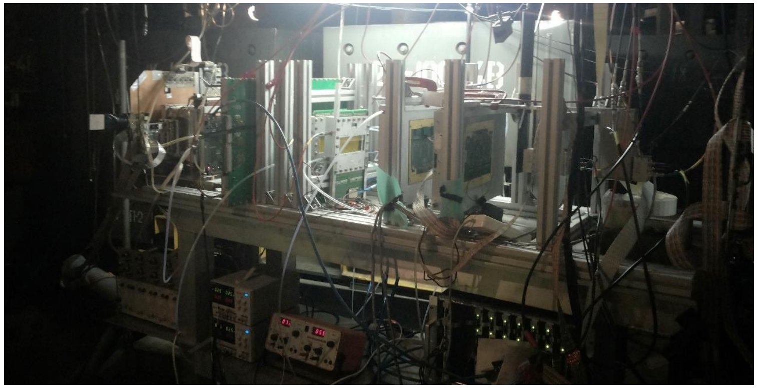


A full-scale double-stack mRPC prototype

MultiResistive Plate Counter (mRPC)

JINR (VBLHEP) + Hefei, Beijing (China))

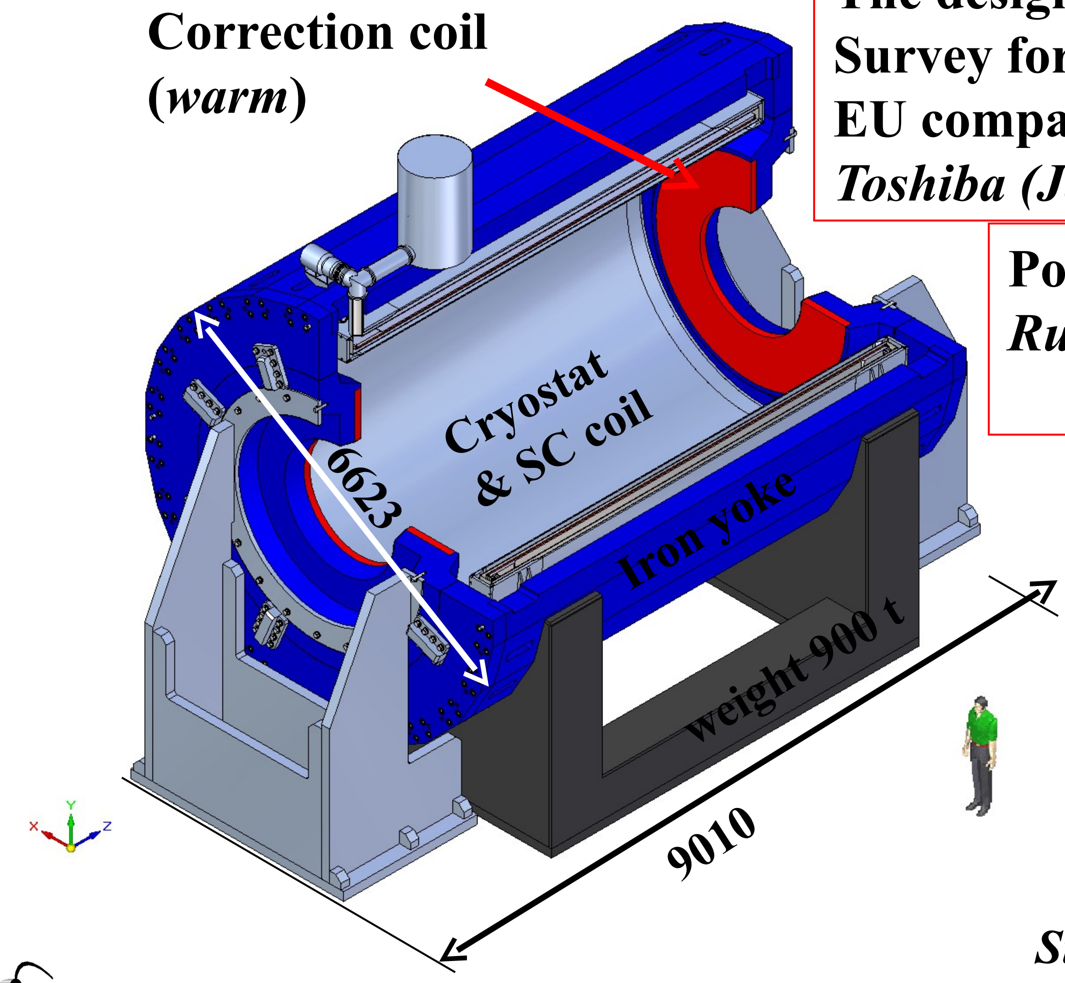
Experimental setup for mRPC tests at Nuclotron (March 2013))



MultiPurpose Detector (MPD)

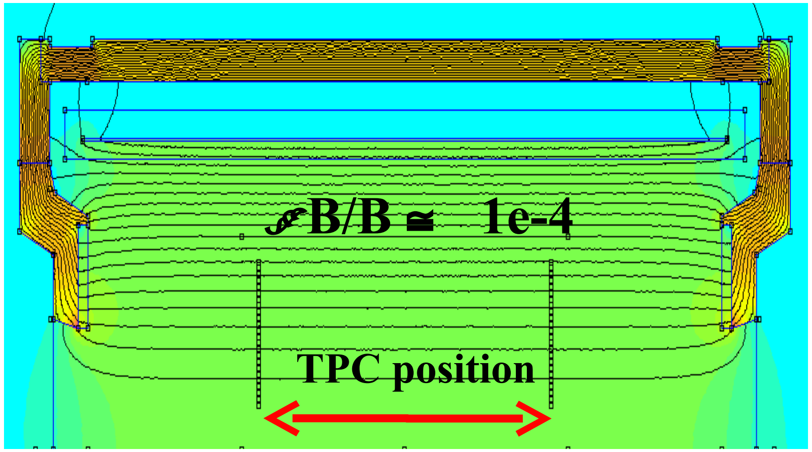
MPD SC solenoid, B0=0.66 T

Design: Scientific Prodctn Association "Neva - Magnet" (St.Petersburg)



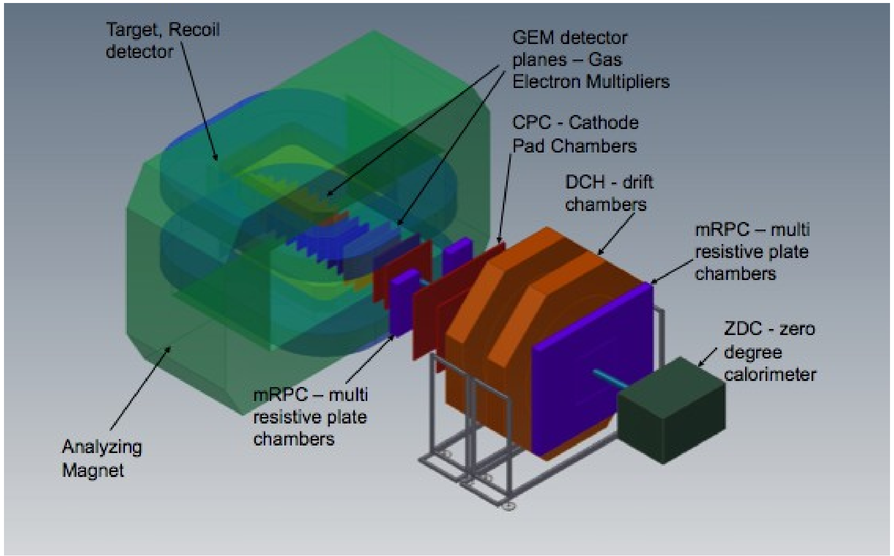
The design – close to completion;
Survey for contractors – negotiations with EU companies *(ASG, Genova, Germany)* & *Toshiba (Japan)*

Possible subcontractors:
Russian & Ukrainian companies



Simulated map of magnetic field

BM@N (**B**aryonic **M**atter at **N**uclotron)**:** *the 1st stage*

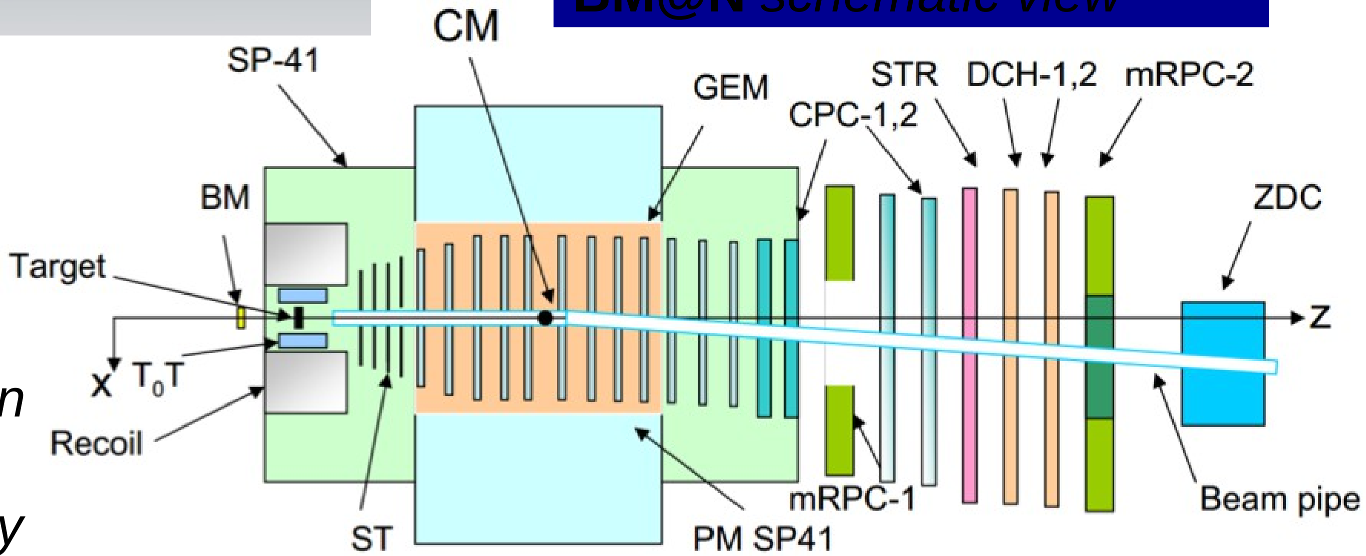


Collaboration of scientific centers:
INR, SINP MSU, IHEP + S-PSUniversity (Russia);
GSI, Frankfurt U., Gissen U. (Germany): + CBM-MPD IT-Consortium,

Physics:

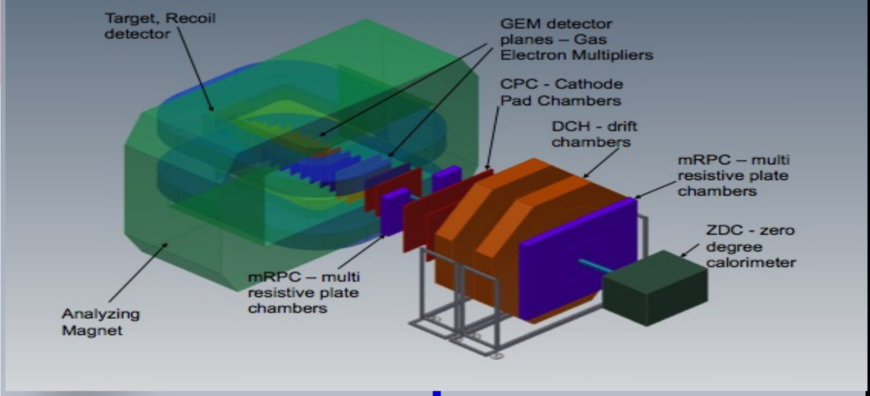
- *in-medium effects for strangeness & vector mesons*
- *hyperon production*
- *hadron femtoscopy*
- *electromagnetic probes (optional)*

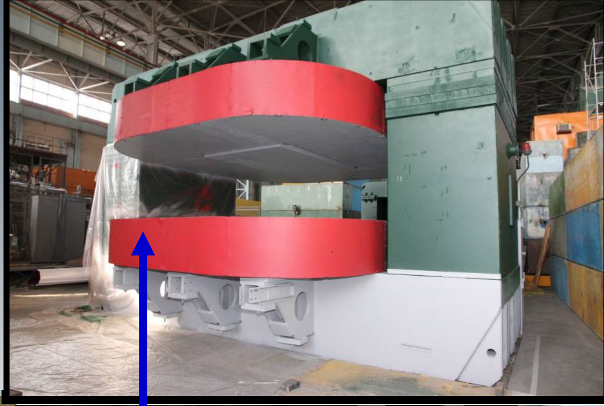
BM@N *schematic view*

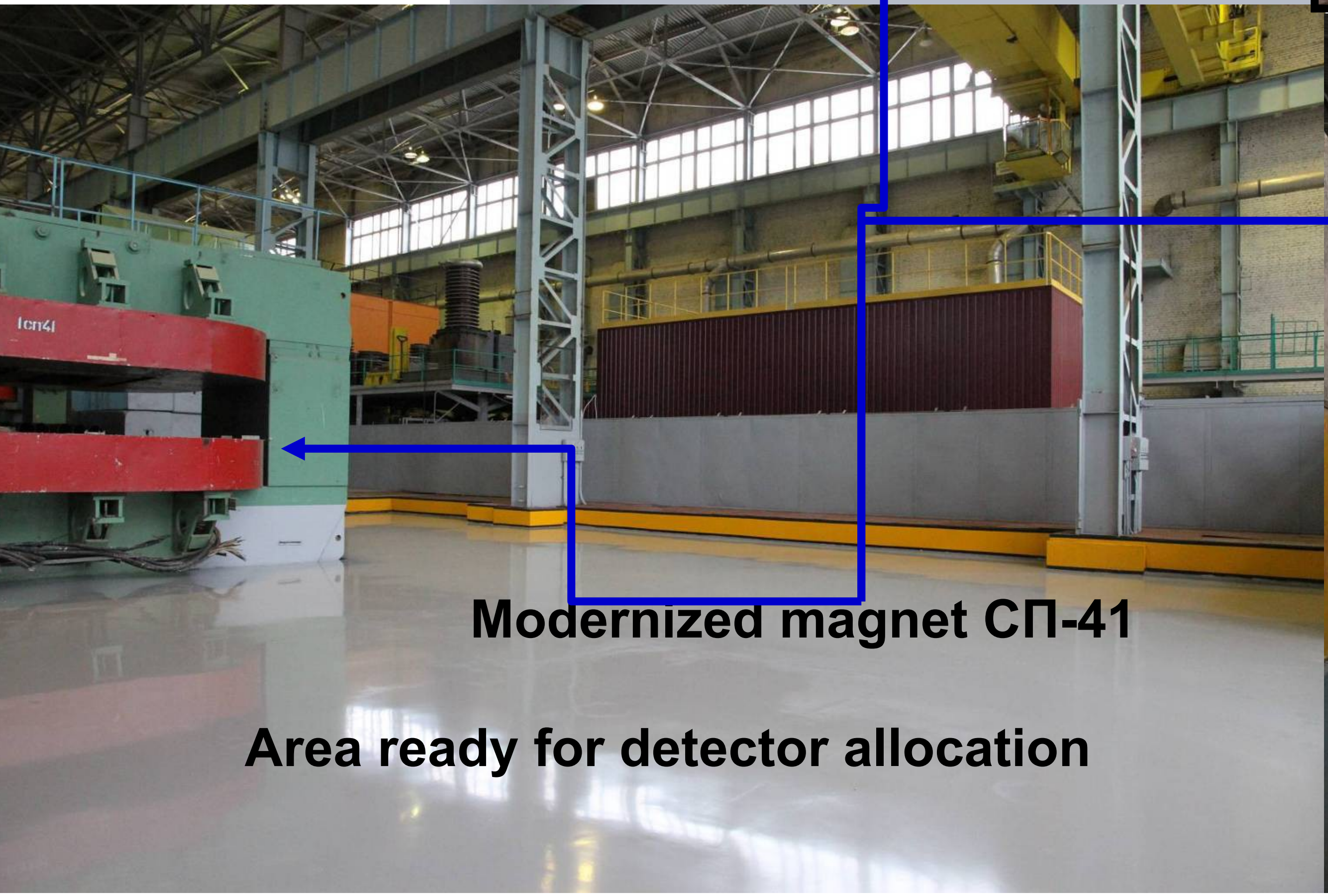


NICA – Stage I

Project BM@N, Preparation in Bld. 205







Modernized magnet СП-41

Area ready for detector allocation

counting rooms

SPD (Spin Physics Detector) at NICA

Collider provides both:
transversally & longitudinally
polarized ***p*** & ***d***
*with energy up to √S = **27 GeV***

The issues to be studied:

- ► *MMT-DY processes*
- ► *J/Υ production processes*
- ► *Spin effects in inclusive high-pT reactions*
- ► *Spin effects in one and two hadron production processes*
- ► *Polarization effects in heavy ion collisions*

WELCOME

The Veksler and Baldin Laboratory of High Energy Physics of the Joint Institute for Nuclear Research is organizing the International Workshops,

"NICA-SPIN 2013",

which will take place in Dubna, Russia.

The Workshops are open to all scientists, regardless of their citizenship and nationality. The Workshop are hosted by the Joint Institute for Nuclear Research.

We invite you and your colleagues to participate in these Workshops at Dubna in 2013.

The first meeting is temporary scheduled for March 17-19, the next one - for June-July (to be specified), and the last one - during the DSPIN-2013 (Dubna, September 17-22) as a separate session:" Proposals for spin physics experiments at NICA".

The Collaboration is forming

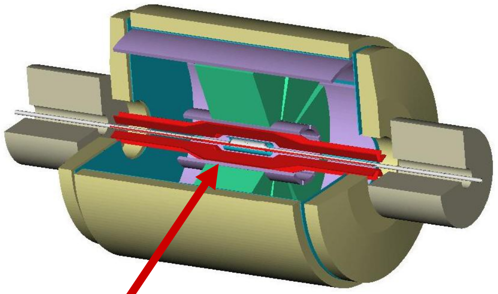
Project is under preparation

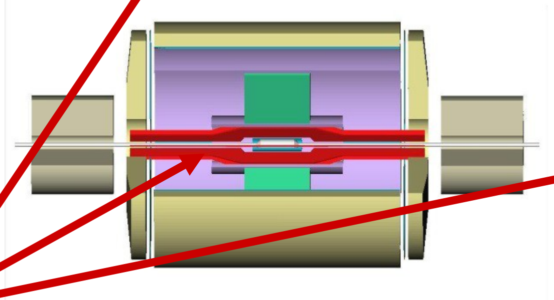
NICA – Stage III : Collider of polarized beams

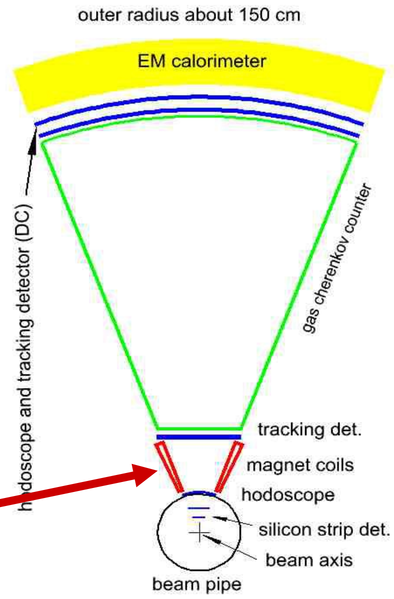
Spin Physics Detector (SPD) – Very First Concept

Main elements of the detector:

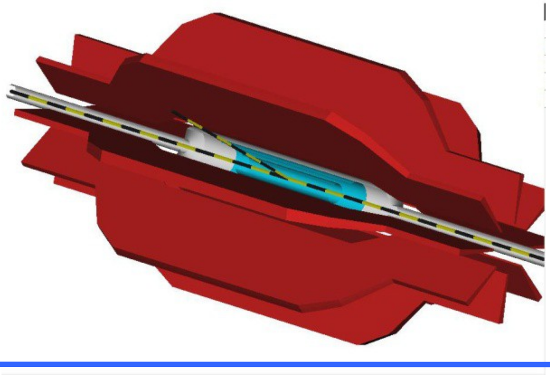
- Silicon or MicroMega (inner tracking)
- Drift chambers or straw (for tracking)
- Cherenkov counter (for PID and trigger)
- EM calorimeter
- Trigger counters
- EndCap detectors

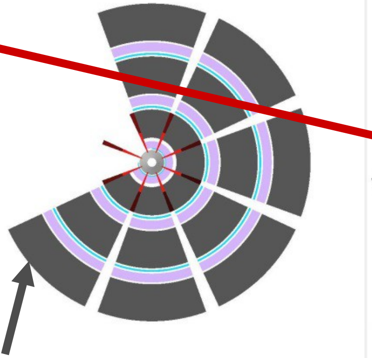


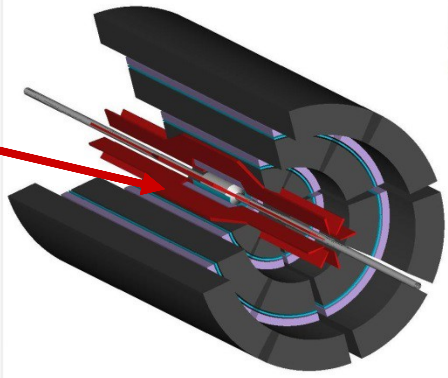




Toroidal magnet



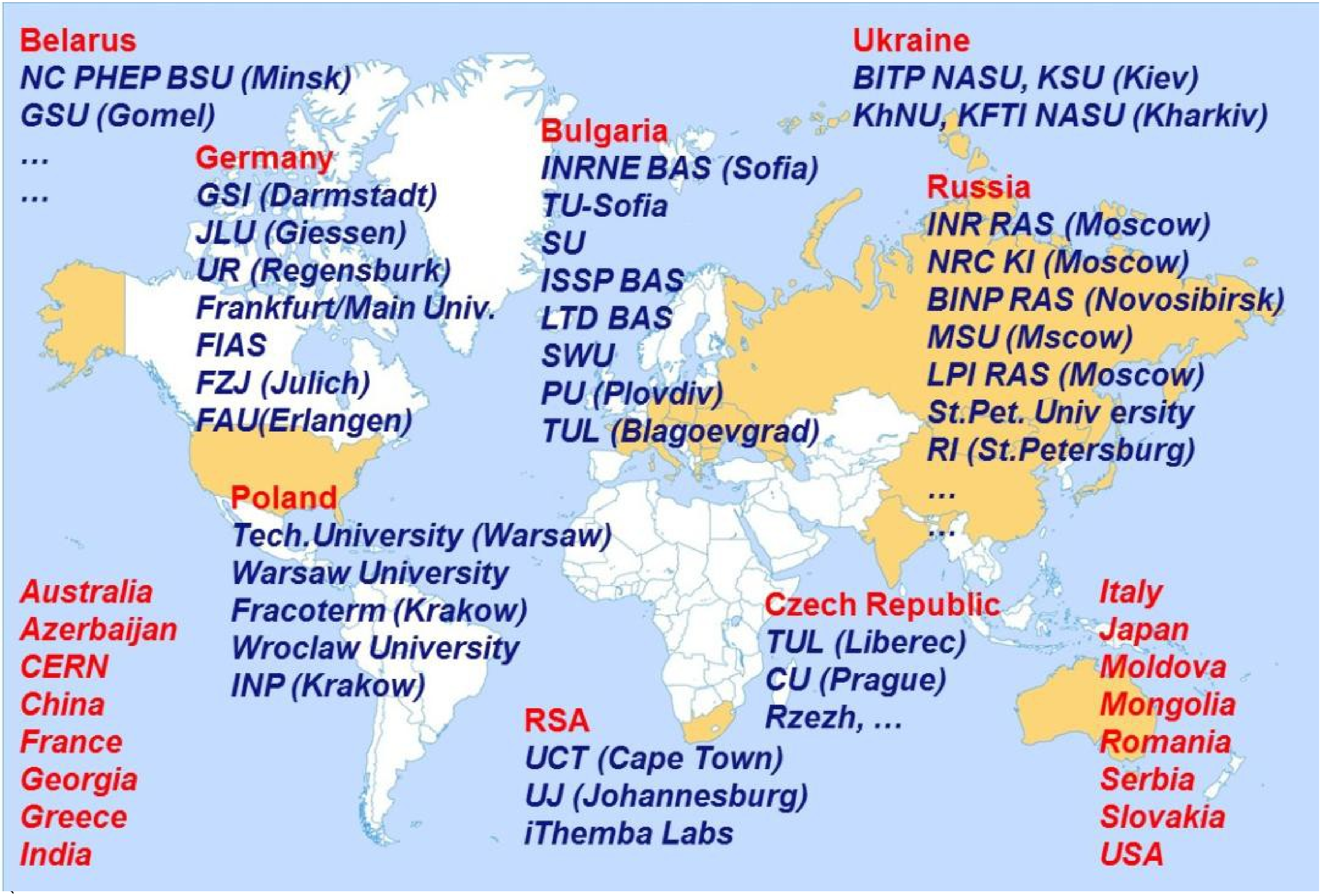




Subdetector for muon pairs

First proposal of SPD concept is expected at the end of 2015

NICA Collaboration



Belarus
NC PHEP BSU (Minsk)
GSU (Gomel)
…
…

Germany
GSI (Darmstadt)
JLU (Giessen)
UR (Regensburk)
Frankfurt/Main Univ.
FIAS
FZJ (Julich)
FAU(Erlangen)

Poland
Tech.University (Warsaw)
Warsaw University
Fracoterm (Krakow)
Wroclaw University
INP (Krakow)

Australia
Azerbaijan
CERN
China
France
Georgia
Greece
India

Bulgaria
INRNE BAS (Sofia)
TU-Sofia
SU
ISSP BAS
LTD BAS
SWU
PU (Plovdiv)
TUL (Blagoevgrad)

RSA
UCT (Cape Town)
UJ (Johannesburg)
iThemba Labs

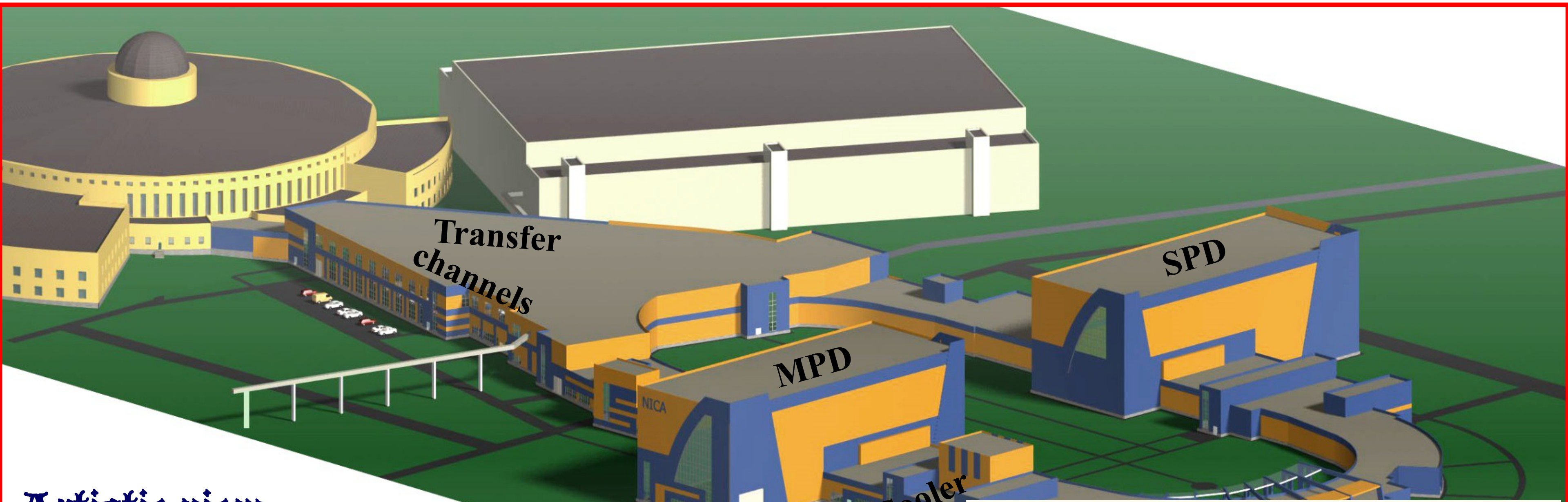
Ukraine
BITP NASU, KSU (Kiev)
KhNU, KFTI NASU (Kharkiv)

Russia
INR RAS (Moscow)
NRC KI (Moscow)
BINP RAS (Novosibirsk)
MSU (Mscow)
LPI RAS (Moscow)
St.Pet. Univ ersity
RI (St.Petersburg)
…
…

Czech Republic
TUL (Liberec)
CU (Prague)
Rzezh, …

Italy
Japan
Moldova
Mongolia
Romania
Serbia
Slovakia
USA

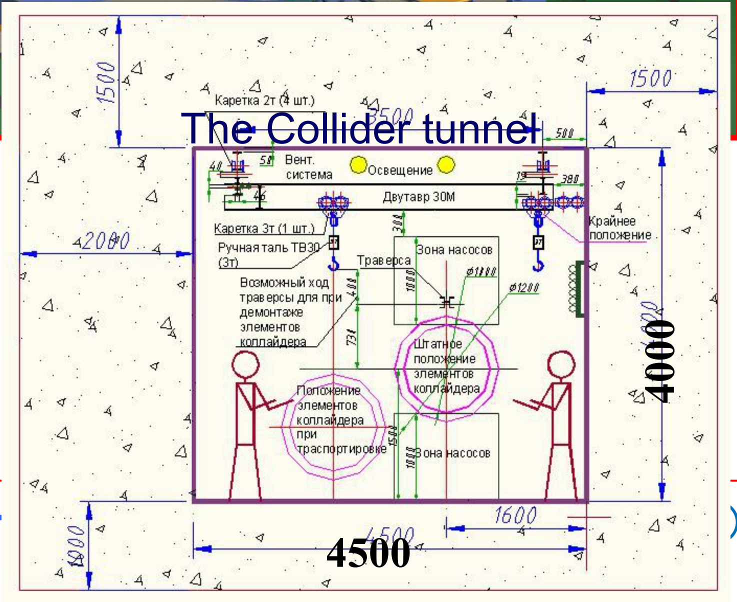
Civil engineering – Status and Plans



Artistic view of the NICA facility

The technical project of NICA

(civil engineering, equipment description and disposition) has been completed in 2013 and has passed State Expertise (Sept. 2013)



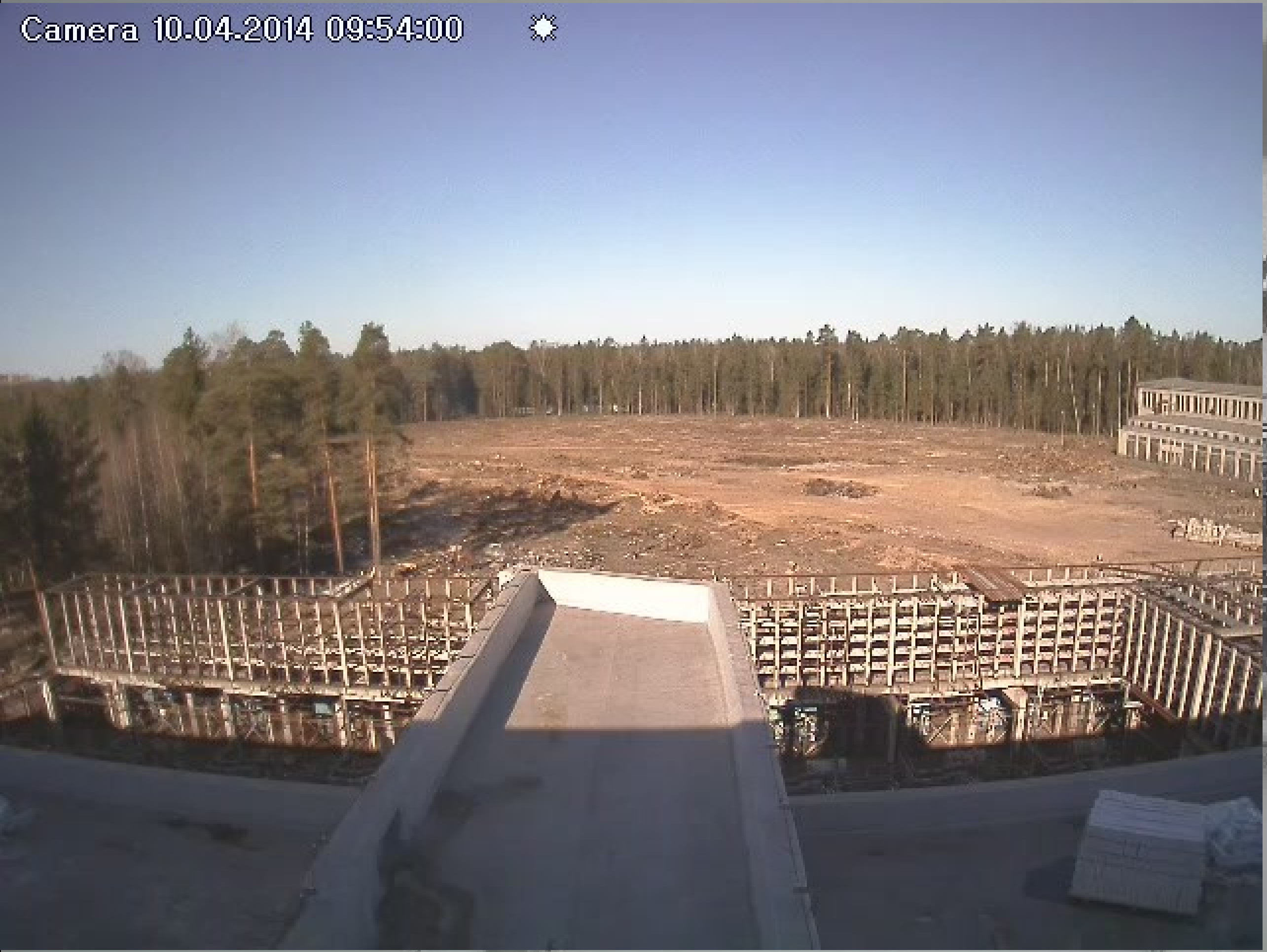
The Collider tunnel

Civil engineering – Status and Plans

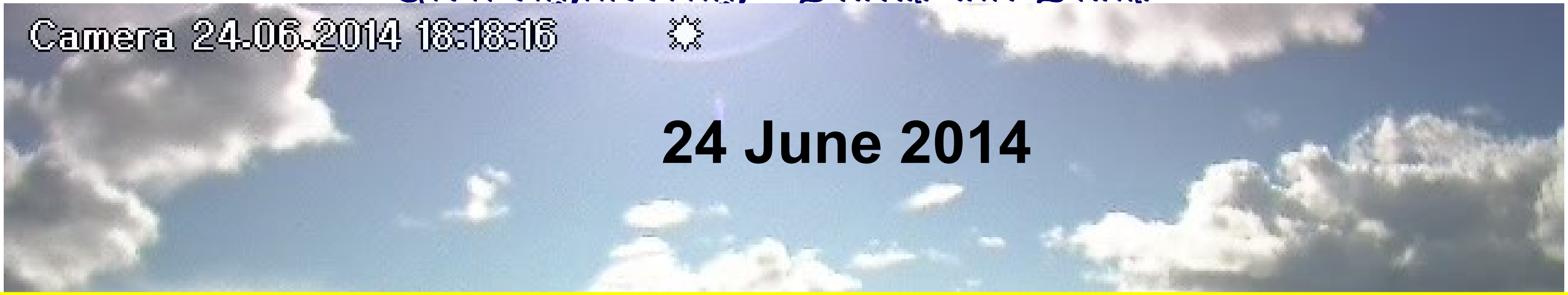
Civil construction is started

On-line web-camera (Feb.2014)

http://nucloweb.jinr.ru/nucloserv/205corp.htm



Civil engineering – Status and Plans



24 June 2014

Signing of the contract with the building company “Strabag”, Austria (the winner of the tender) is close to completion.

Presently => stage of requirement specification based on NICA Technical Project

Civil construction duration is estimated as 36 months!

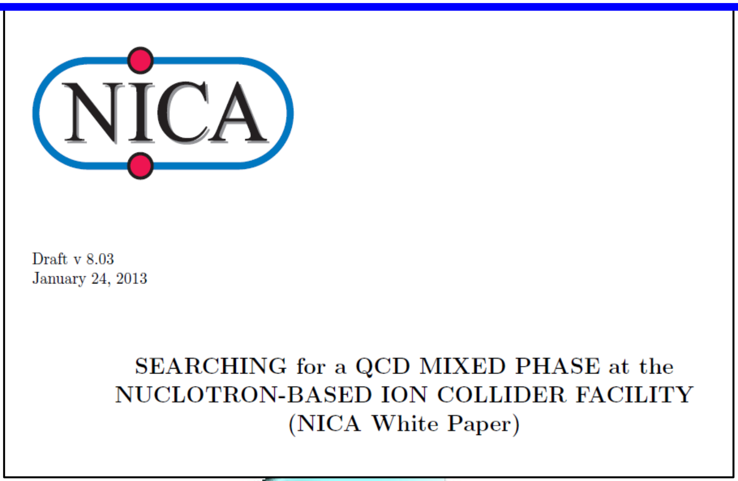
Beginning of Collider mounting – September 2017

Start up version of NICA commissioning is planned for 2019

Conclusion Part I

- **NICA complex has a potential for competitive research** ***in the fields of dense baryonic matter and spin physics***
- **Construction of the** ***accelerator complex and its elements are in progress***
- **Constructions of both detectors BM@N & MPD** ***are progressing as well***
- **The SPD project is in preparation**
- **The international collaboration around the NICA is growing**
- **New partners are invited to join NICA**

NICA White Paper



NICA

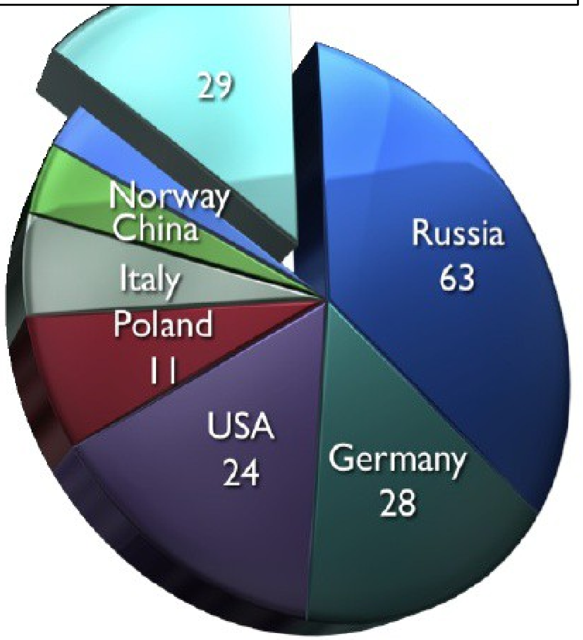
Draft v 8.03
January 24, 2013

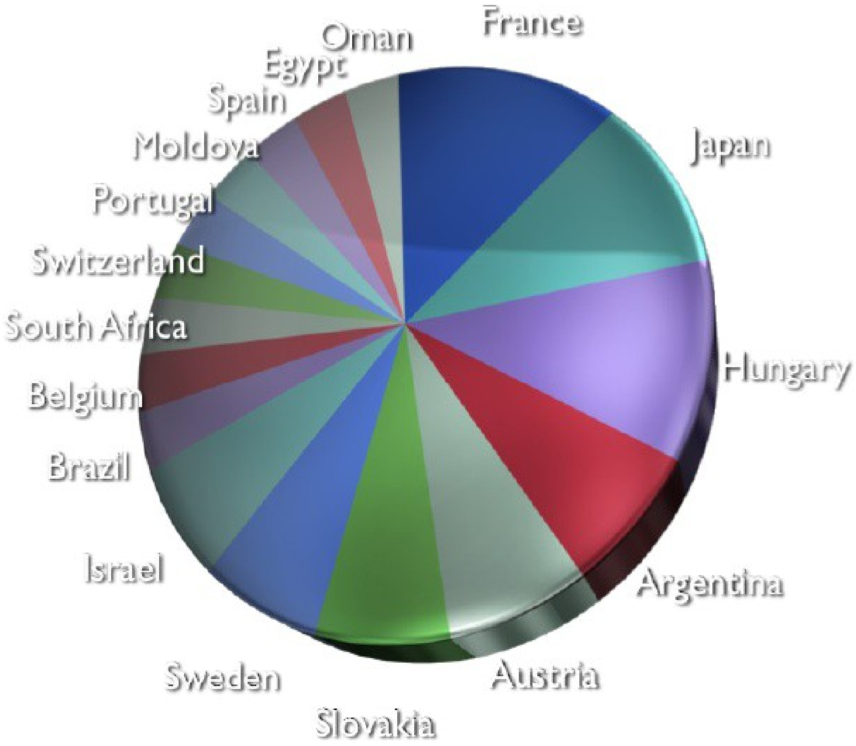
SEARCHING for a QCD MIXED PHASE at the
NUCLOTRON-BASED ION COLLIDER FACILITY
(NICA White Paper)

Statistics of White Paper Contributions

111 *contributions:*
188 *authors from* **70** *centers in* **24** *countries*

Indicates wide international interest
to the physics at MPD & BM@N





White Paper prioritization stage plan

- Stage 1: Selection of relevant contributions

  - preparatory meeting, team nomination (06.08.2013)

  - online questionaire (07.09.2013 → 20.10.2013)

  - meeting in Dubna (28.10.-01.11.2013)

  - summary report “NICA priorities” → White Paper
- Stage 2: Preparation of programs for simulation of physical effects selected in Stage 1
- Stage 3: Event simulation including detector characteristics – physics performance of

  BM @ N and MPD / SPD

Stage 1.1: Nomination of the Team

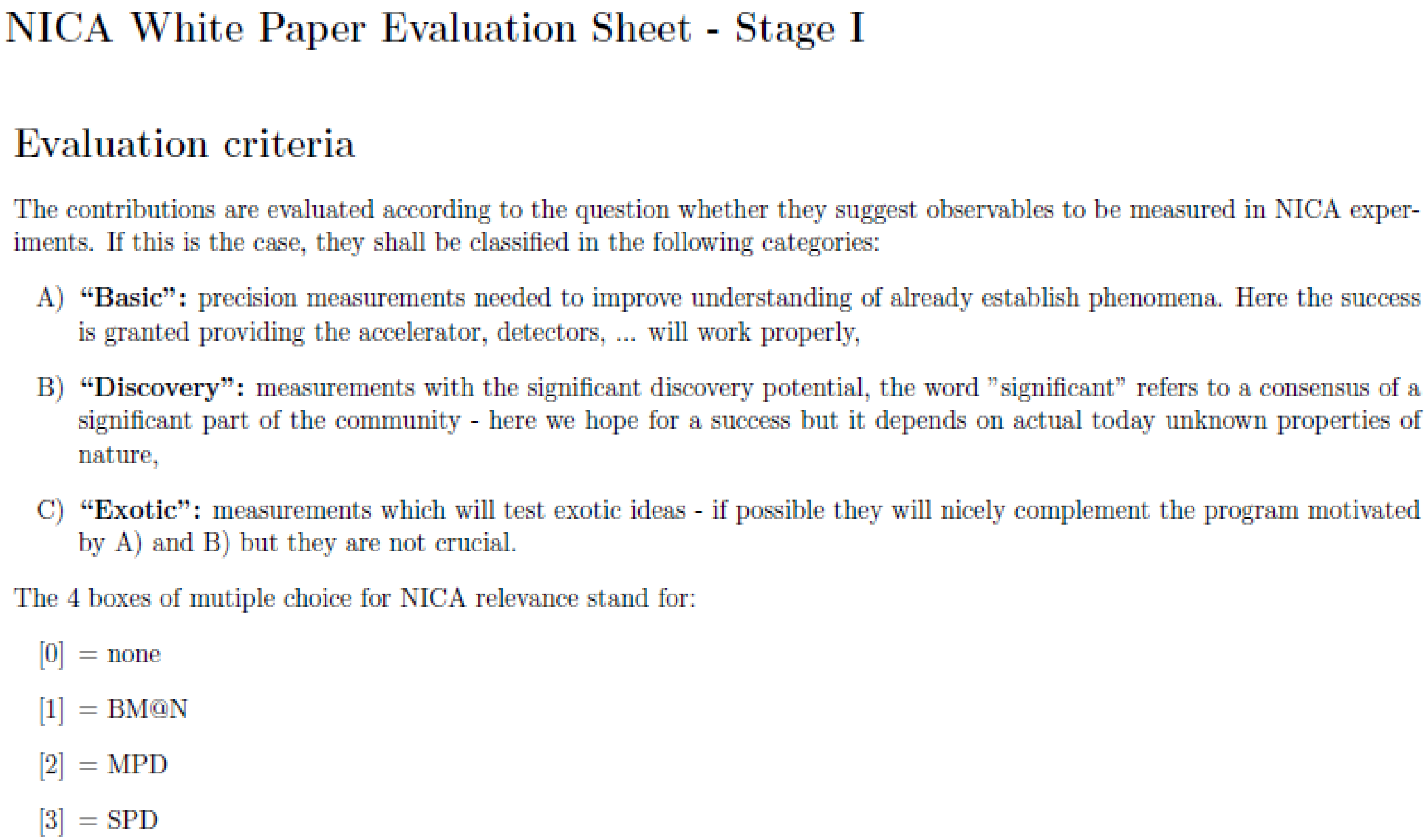
THEORY

J. Aichelin (SUBATECH Nantes, France)
D. Blaschke (JINR & Univ. Wroclaw, Poland)
E. Bratkovskaya (Univ. Frankfurt, Germany)
J. Randrup (LBNL Berkeley, USA)
V. Toneev (JINR)
O. Teryaev (JINR)

EXPER.

V. Friese (GSI Darmstadt, Germany)
M. Gazdzicki (Univ. Frankfurt, Germany & Univ. Kielce, Poland)
O. Rogachevsky (JINR)

Stage 1.2: The Questionaire



NICA White Paper Evaluation Sheet - Stage I

Evaluation criteria

The contributions are evaluated according to the question whether they suggest observables to be measured in NICA experiments. If this is the case, they shall be classified in the following categories:

A) **“Basic”:** precision measurements needed to improve understanding of already establish phenomena. Here the success is granted providing the accelerator, detectors, ... will work properly,

B) **“Discovery”:** measurements with the significant discovery potential, the word "significant” refers to a consensus of a significant part of the community - here we hope for a success but it depends on actual today unknown properties of nature,

C) **“Exotic”:** measurements which will test exotic ideas - if possible they will nicely complement the program motivated by A) and B) but they are not crucial.

The 4 boxes of mutiple choice for NICA relevance stand for:

[0] = none

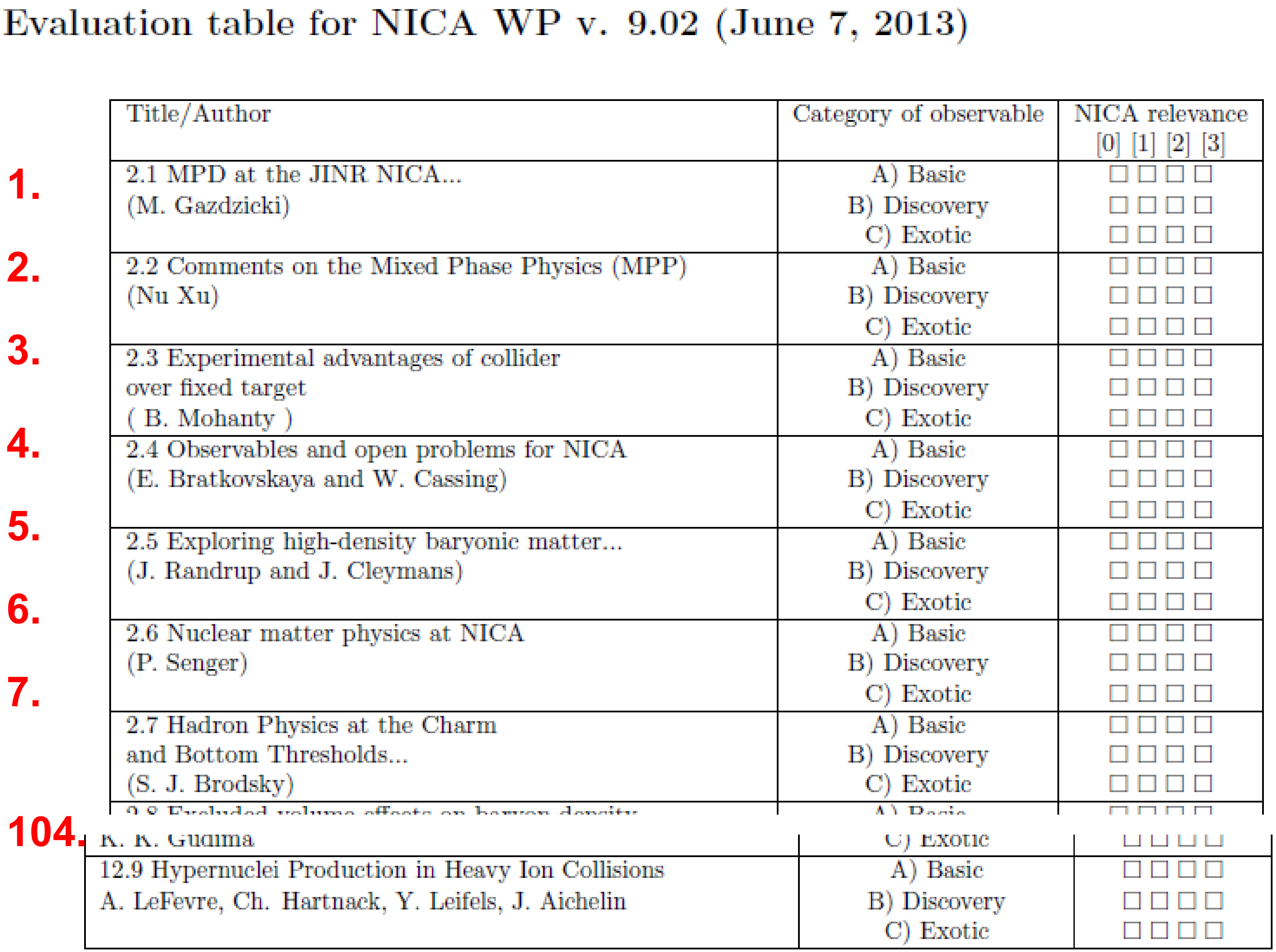
[1] = BM@N

[2] = MPD

[3] = SPD

Stage 1.2: The Questionaire

NICA White Paper Evaluation Sheet - Stage I



Evaluation table for NICA WP v. 9.02 (June 7, 2013)

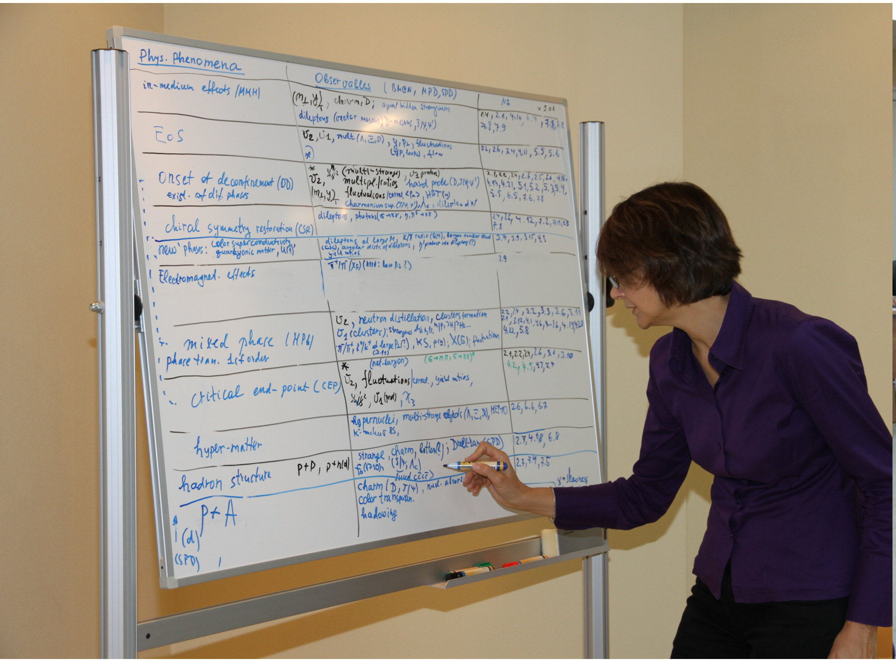
	Title/Author	Category of observable	NICA relevance [0] [1] [2] [3]
1.	2.1 MPD at the JINR NICA... (M. Gazdzicki)	A) Basic B) Discovery C) Exotic	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
2.	2.2 Comments on the Mixed Phase Physics (MPP) (Nu Xu)	A) Basic B) Discovery C) Exotic	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
3.	2.3 Experimental advantages of collider over fixed target (B. Mohanty)	A) Basic B) Discovery C) Exotic	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
4.	2.4 Observables and open problems for NICA (E. Bratkovskaya and W. Cassing)	A) Basic B) Discovery C) Exotic	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
5.	2.5 Exploring high-density baryonic matter... (J. Randrup and J. Cleymans)	A) Basic B) Discovery C) Exotic	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
6.	2.6 Nuclear matter physics at NICA (P. Senger)	A) Basic B) Discovery C) Exotic	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
7.	2.7 Hadron Physics at the Charm and Bottom Thresholds... (S. J. Brodsky)	A) Basic B) Discovery C) Exotic	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
	2.8 Excluded volume effects on baryon density	A) Basic	☐ ☐ ☐ ☐
	K. K. Gudima	C) Exotic	☐ ☐ ☐ ☐
104.	12.9 Hypernuclei Production in Heavy Ion Collisions A. LeFevre, Ch. Hartnack, Y. Leifels, J. Aichelin	A) Basic B) Discovery C) Exotic	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐

Stage 1.3: Meeting in Dubna

28.10.-01.11.2014

The task: Select White Paper contributions which address experimental observables relevant for characterizing QCD phases

Stage 1.3: Meeting in Dubna



Step 1: Discussion of the results of the questionaire

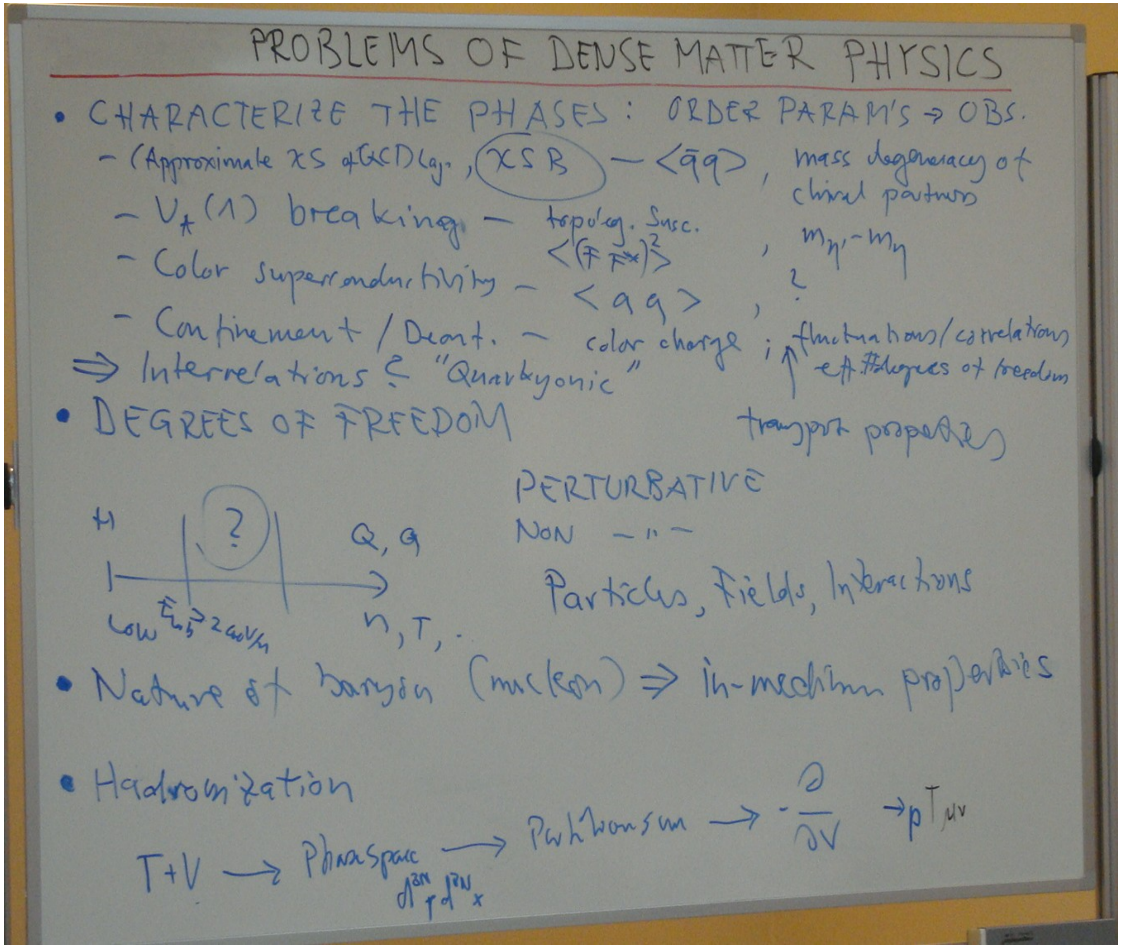
Stage 1.3: Meeting in Dubna

Step 2: Creation of “The Table”: Phenomena - Observables - WP contrib.

Stage 1.3: Results at the Meeting

“Hilbert Problems” of Dense Matter Physics:

- which phases?
- which degrees of freedom?
- nature of the nucleon?
- how proceeds hadronization?
- ...



PROBLEMS OF DENSE MATTER PHYSICS

• CHARACTERIZE THE PHASES: ORDER PARAM'S → OBS.

- (Approximate χS of QCD Lagr., χSB — $\langle \bar{q}q \rangle$, mass degeneracy of chiral partners
- $U_A(1)$ breaking — topolog. susc. $\langle (F\tilde{F}^*)^2 \rangle$, $m_{\eta'} - m_\eta$
- Color superconductivity — $\langle qq \rangle$, ?
- Confinement / Deconf. — color charge ; fluctuations/correlations ↑ eff. degrees of freedom

⇒ Interrelations? "Quarkyonic"

• DEGREES OF FREEDOM

transport properties

PERTURBATIVE

NON —"—

Particles, Fields, Interactions

H

?

Q, G

Low $\varepsilon_c > 2$ GeV/fm

n, T, ..

• Nature of baryon (nucleon) ⇒ in-medium properties

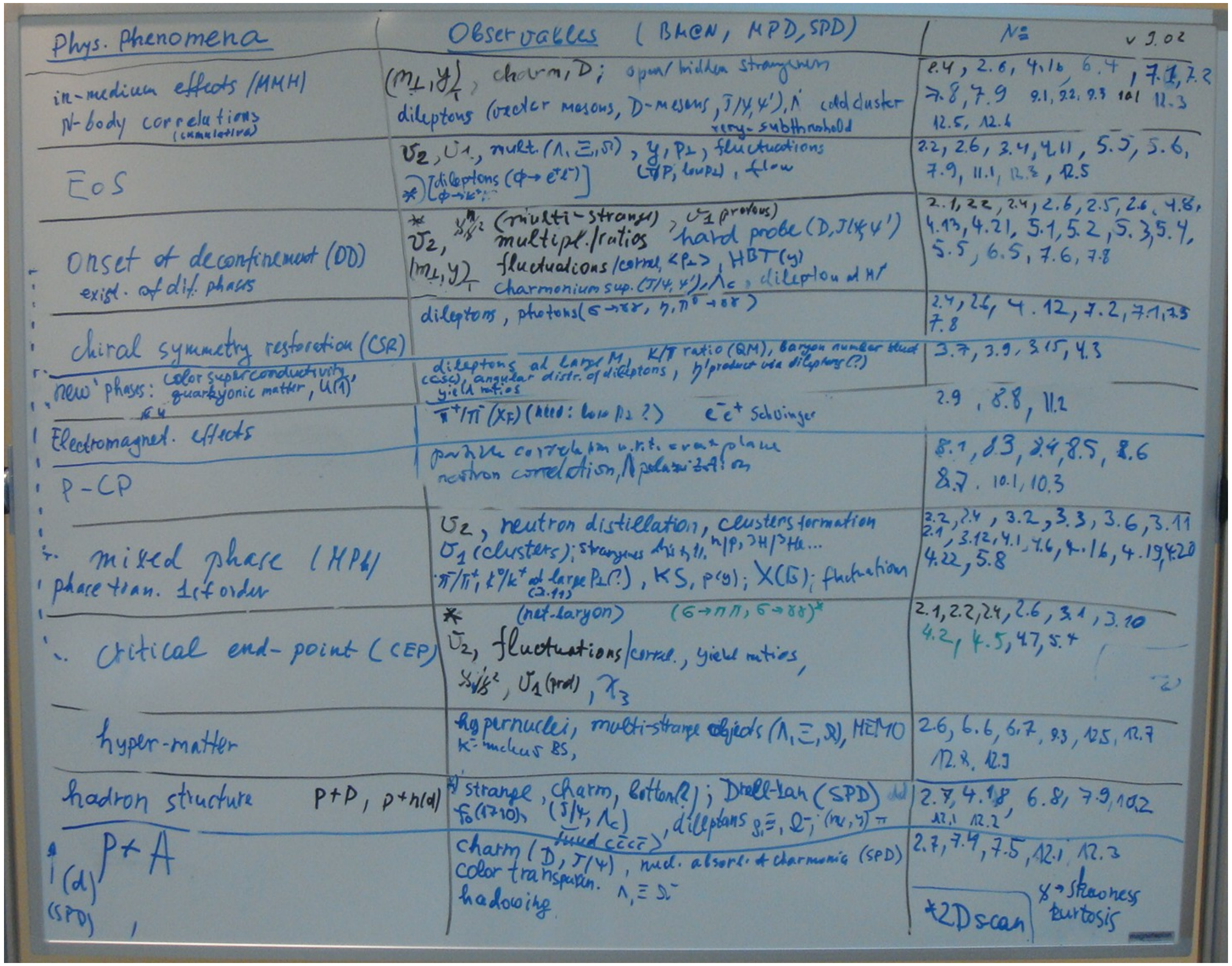
• Hadronization

T+V → Phasespace $d^{3N}p\, d^{3N}x$ → Partitionsum → $-\frac{\partial}{\partial V}$ → $p\, T_{\mu\nu}$

Stage 1.3: Results at the Meeting:

"The Table", relating:

- physical phenomena (phases of QCD)
- observables at BM @ N, MPD and SPD
- contribution in NICA WP

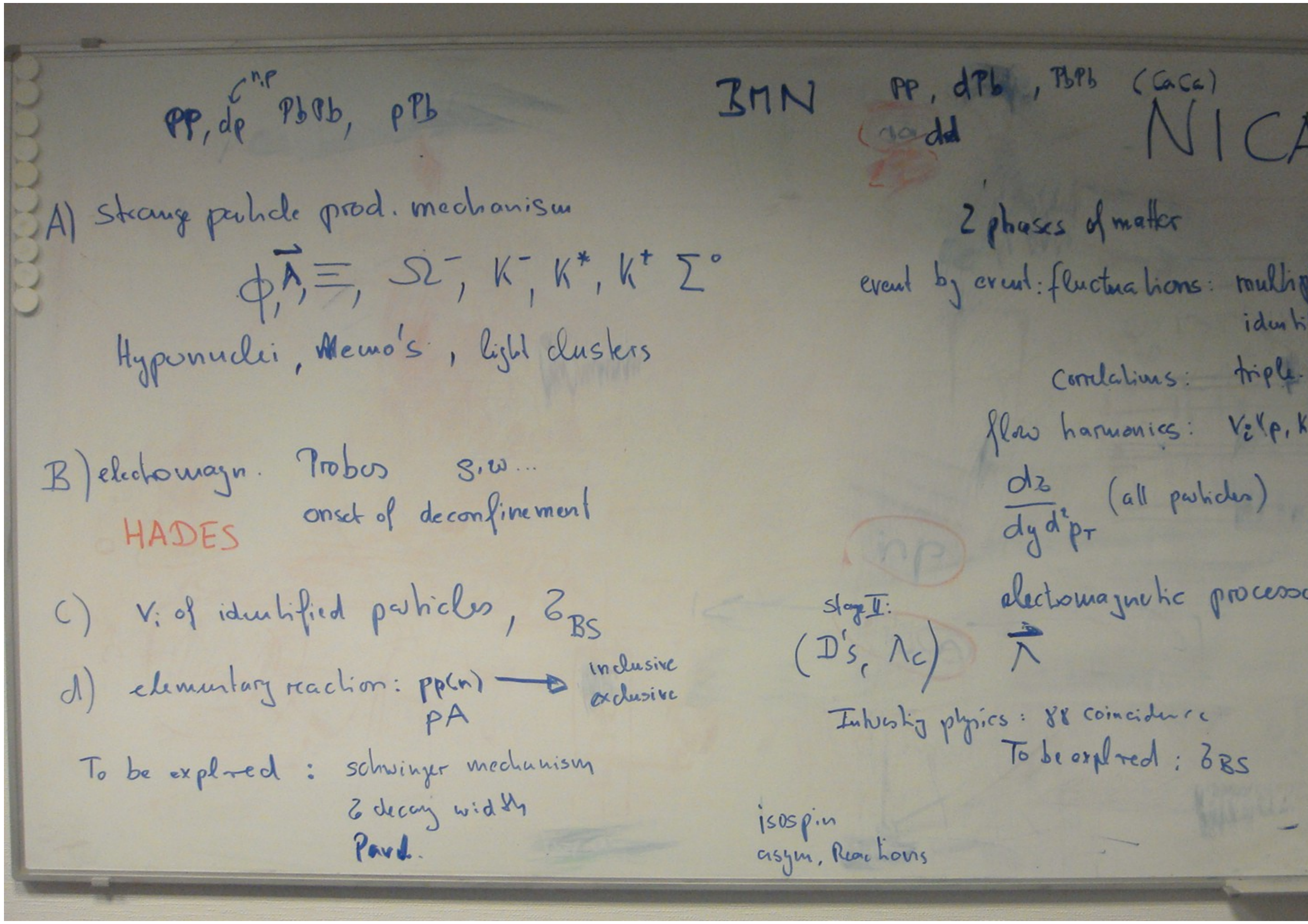


Phys. Phenomena	Observables (BM@N, MPD, SPD)	№ v 1.02
in-medium effects /(MMH) N-body correlations (cumulative)	$(m_\perp, y)_1$, charm, D; open/hidden strangeness dileptons (vector mesons, D-mesons, J/ψ, ψ'), Λ cold cluster very-subthreshold	2.4, 2.6, 4.16, 6.4, 7.1, 7.2 7.8, 7.9 9.1, 9.2, 9.3 10.1 11.3 12.5, 12.6
EoS	v_2, v_1, mult. (Λ, Ξ, Ω), y, $p_\perp$, fluctuations (TOF, low $p_\perp$), flow *) [dileptons ($\phi \to e^+e^-$) $\phi \to K^+K^-$]	2.2, 2.6, 3.4, 4.11, 5.5, 5.6, 7.9, 11.1, 12.3, 12.5
Onset of deconfinement (OD) exist. of dif. phases	* v_2, [illegible] (multi-strange), v_1 (protons) multipl./ratios, hard probe (D, J/ψ, ψ') $(m_\perp, y)_1$ fluctuations/correl, $\langle p_\perp \rangle$, HBT(y) charmonium sup. (J/ψ, ψ'), Λ_c, dilepton at M/	2.1, 2.2, 2.4, 2.6, 2.5, 2.6, 4.8, 4.13, 4.21, 5.1, 5.2, 5.3, 5.4, 5.5, 6.5, 7.6, 7.8
chiral symmetry restoration (CSR)	dileptons, photons ($\sigma \to \gamma\gamma$, $\eta, \pi^0 \to 0\gamma$)	2.4, 2.6, 4.12, 7.2, 7.1, 7.5 7.8
'new' phases: color superconductivity, quarkyonic matter, U(1)'	dileptons at large M, K/π ratio (QM), baryon number fluct. (CSC), angular distr. of dileptons, η' product via dileptons (?) yield ratios	3.7, 3.9, 3.15, 4.3
Electromagnet. effects	π^+/π^- (x_F) (need: low $p_\perp$?) e^-e^+ Schwinger	2.9, 8.8, 11.2
P-CP	particle correlation w.r.t. event plane neutron correlation, Λ polarization	8.1, 8.3, 8.4, 8.5, 8.6 8.7, 10.1, 10.3
mixed phase (MPh) phase tran. 1st order	v_2, neutron distillation, clusters formation v_1 (clusters); strangeness [illegible], n/p, ³H/³He... π^-/π^+, K^0/K^+ at large $p_\perp$(?) (2.11), KS, p(y); X([illegible]); fluctuation	2.2, 2.4, 3.2, 3.3, 3.6, 3.11 2.1, 3.12, 4.1, 4.6, 4.16, 4.19, 4.20 4.22, 5.8
critical end-point (CEP)	* (net-baryon) ($\sigma \to \pi\pi$, $\sigma \to \gamma\gamma$)* v_2, fluctuations/correl., yield ratios, [illegible], v_1 (prod), χ_3	2.1, 2.2, 2.4, 2.6, 3.1, 3.10 4.2, 4.5, 4.7, 5.4
hyper-matter	hypernuclei, multi-strange objects (Λ, Ξ, Ω), MEMO K^--nucleus BS,	2.6, 6.6, 6.7, 9.3, 12.5, 12.7 12.8, 12.9
hadron structure p+p, p+n(d)	strange, charm, bottom(?); Drell-Yan (SPD) $f_0(1710)$, (J/ψ, Λ_c) fixed $c\bar{c}c\bar{c}$, dileptons [illegible]	2.7, 4.18, 6.8, 7.9, 10.2 12.1, 12.2
p+A (d) (SPD)	charm (D, J/ψ), nucl. absorpt. of charmonia (SPD) color transparen. Λ, Ξ, Ω⁻ shadowing	2.7, 7.4, 7.5, 12.1, 12.3 *2D scan γ → skewness kurtosis

Stage 1.3: Results @ Meeting:

Recommendations for the experiments:

BM @ N, MPD, SPD



$\overset{n,p}{\swarrow}$
pp, dp PbPb, pPb

A) strange particle prod. mechanism

$\phi, \vec{\Lambda}, \Xi, \Omega^-, K^-, K^*, K^+ \Sigma^0$

Hypernuclei, Memo's, light clusters

B) electromagn. Probes ρ, ω...

HADES onset of deconfinement

C) v_i of identified particles, σ_{BS}

d) elementary reaction: pp(n) → inclusive
pA exclusive

To be explored: schwinger mechanism
σ decay width
Pard.

BMN pp, dPb, PbPb (CaCa)
dd

NICA

2 phases of matter

event by event: fluctuations: multip
identi

Correlations: triple

flow harmonics: v_i γ p, K

$\frac{d\sigma}{dy\, d^2p_T}$ (all particles)

np

Stage II:
(D's, Λ_c)

electromagnetic processe

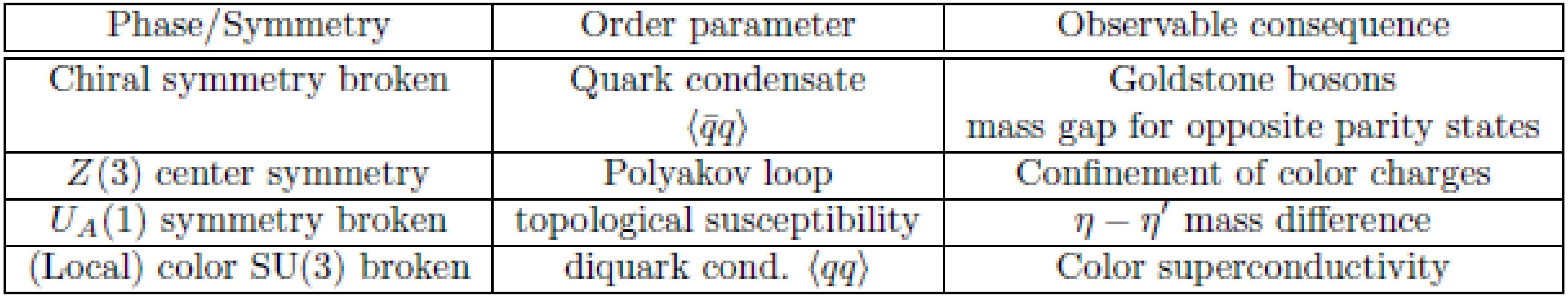
$\vec{\Lambda}$

Interesting physics: $\gamma\gamma$ coincidence
To be explored: σ_{BS}

isospin
asym. Reactions

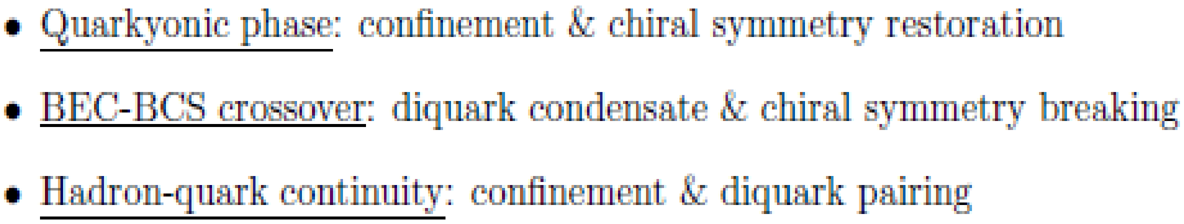
Stage 1.4: The Summary Report

Characterization of phases and observable consequences:



Phase/Symmetry	Order parameter	Observable consequence
Chiral symmetry broken	Quark condensate $\langle \bar{q} q \rangle$	Goldstone bosons mass gap for opposite parity states
$Z(3)$ center symmetry	Polyakov loop	Confinement of color charges
$U_A(1)$ symmetry broken	topological susceptibility	$\eta - \eta'$ mass difference
(Local) color SU(3) broken	diquark cond. $\langle qq \rangle$	Color superconductivity

Interesting:
Possible Coexistence,
In particular in dense matter!

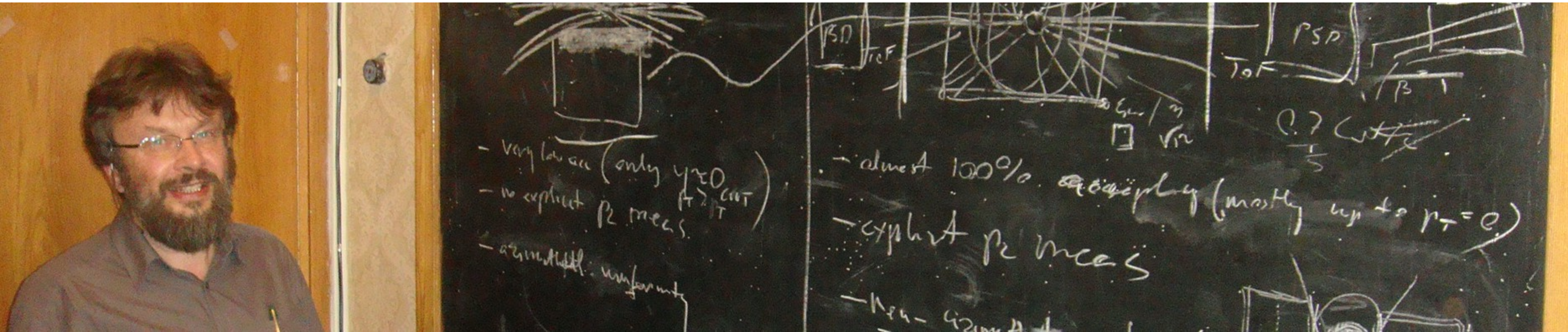


- Quarkyonic phase: confinement & chiral symmetry restoration
- BEC-BCS crossover: diquark condensate & chiral symmetry breaking
- Hadron-quark continuity: confinement & diquark pairing

Stage 1.4: The Summary Report

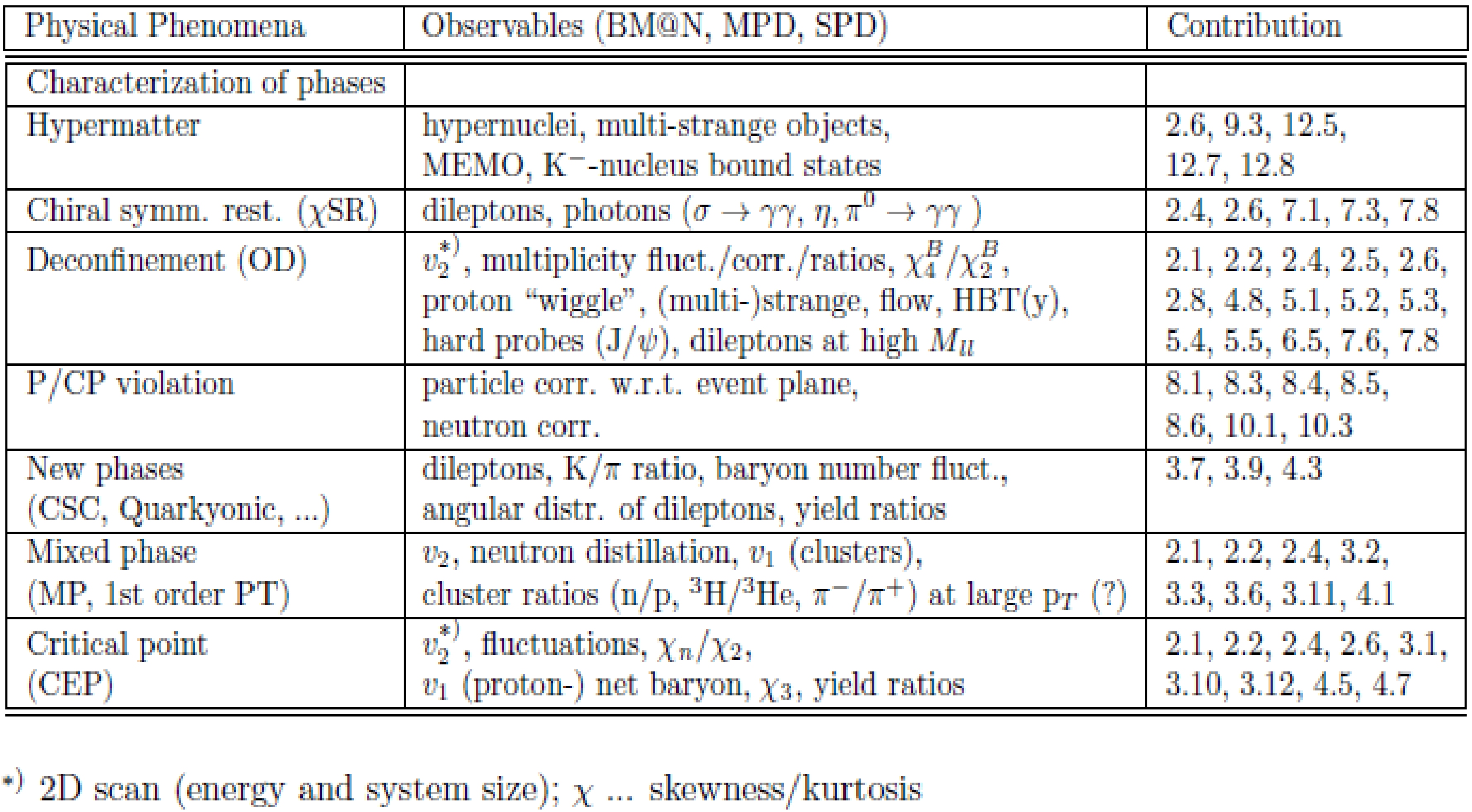
The Table (part I): Baseline measurements

Physical Phenomena	Observables (BM@N, MPD, SPD)	Contribution
Hadron structure (p+p, p+n(d))	strange, charm, bottom (intrinsic ...), DY (SPD), f(1710), dileptons, dd	2.7, 4.18, 6.8, 7.9, 10.2, 12.1, 12.2
Nuclear structure (p+A, $d\uparrow$+A)	charm (D, J/ψ), nucl. abs. + charmonia (SPD), color transparency, shadowing	2.7, 7.4, 7.5
Medium-modified hadrons (N-body effects)	$(m_\perp, y)$, open/hidden strangeness, charm, D, dileptons (vector mesons, D-mesons, J/ψ, ψ'), scaling of spectra, Λ (angular), cold cluster, very subthreshold	2.4, 2.6, 4.16, 6.4, 7.1, 7.2, 7.8, 7.9, 9.1, 9.2, 9.3, 10.1, 12.3, 12.4, 12.5, 12.6
Electromagnetic effects	π^+/π^- (low-p_T ?), e^+e^- Schwinger mechanism	2.9, 8.8, 11.2
Equation of state (EoS)	v_1, v_2, mult (Λ, Ξ, Ω), fluctuations, low-p_T, dileptons ($\phi \to e^+e^-$, $\phi \to K^+K^-$)	2.2, 2.4, 2.6, 3.4, 7.9, 11.1, 12.5



Stage 1.4: The Summary Report

The Table (part II): QCD phases characterization measurements



Physical Phenomena	Observables (BM@N, MPD, SPD)	Contribution
Characterization of phases		
Hypermatter	hypernuclei, multi-strange objects, MEMO, K^--nucleus bound states	2.6, 9.3, 12.5, 12.7, 12.8
Chiral symm. rest. (χSR)	dileptons, photons ($\sigma \to \gamma\gamma, \eta, \pi^0 \to \gamma\gamma$)	2.4, 2.6, 7.1, 7.3, 7.8
Deconfinement (OD)	$v_2^{*)}$, multiplicity fluct./corr./ratios, χ_4^B/χ_2^B, proton "wiggle", (multi-)strange, flow, HBT(y), hard probes (J/ψ), dileptons at high M_{ll}	2.1, 2.2, 2.4, 2.5, 2.6, 2.8, 4.8, 5.1, 5.2, 5.3, 5.4, 5.5, 6.5, 7.6, 7.8
P/CP violation	particle corr. w.r.t. event plane, neutron corr.	8.1, 8.3, 8.4, 8.5, 8.6, 10.1, 10.3
New phases (CSC, Quarkyonic, ...)	dileptons, K/π ratio, baryon number fluct., angular distr. of dileptons, yield ratios	3.7, 3.9, 4.3
Mixed phase (MP, 1st order PT)	v_2, neutron distillation, v_1 (clusters), cluster ratios (n/p, ^{3}H/^{3}He, π^-/π^+) at large p_T (?)	2.1, 2.2, 2.4, 3.2, 3.3, 3.6, 3.11, 4.1
Critical point (CEP)	$v_2^{*)}$, fluctuations, χ_n/χ_2, v_1 (proton-) net baryon, χ_3, yield ratios	2.1, 2.2, 2.4, 2.6, 3.1, 3.10, 3.12, 4.5, 4.7

*) 2D scan (energy and system size); χ ... skewness/kurtosis

Editorial board:
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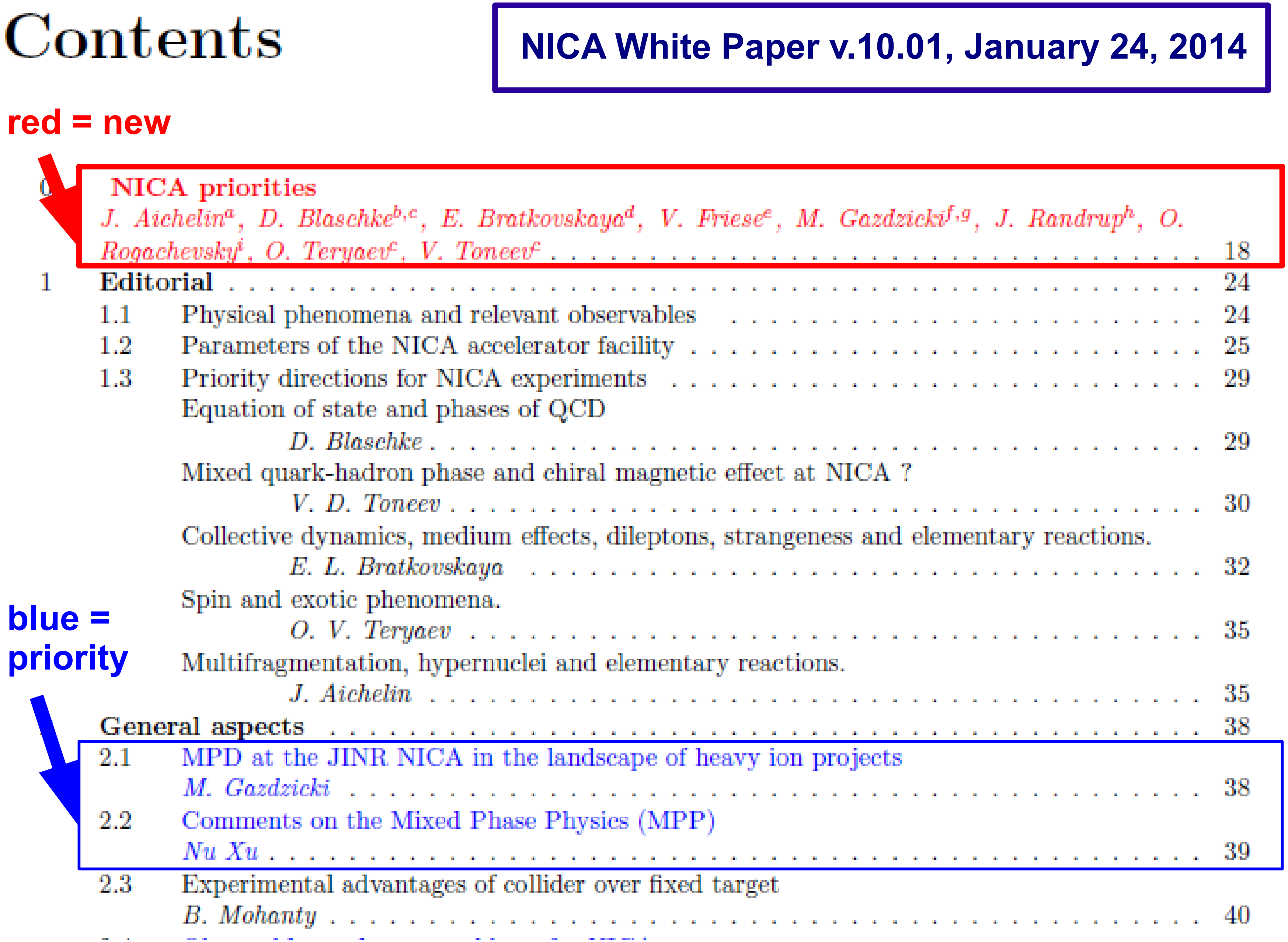
I. Tserruya
N. Xu

Draft v 10.01
January 24, 2014

SEARCHING for a QCD MIXED PHASE at the NUCLOTRON-BASED ION COLLIDER FACILITY
(NICA White Paper)

http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome

NICA White Paper v.10.01, January 24, 2014



Contents

red = new

blue = priority

NICA White Paper - Contents

60 prioritized

Forewords to the ten Editions, Table of contents

1 Editorial (7)

8

10

Hydrodynamics and hadronic observables (22; 7)

4

3

8

5

3

3

1

- 12 Fixed Target Experiments (9; 8)

NICA White Paper - Contents

60 prioritized

Forewords to the ten Editions, Table of contents

1 Editorial (7)

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Hydrodynamics and hadronic observables (22; 7)

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3

8

5

3

3

1

- 12 Fixed Target Experiments (9; 8)

NICA Priorities

1 Introduction
2 Priorities for experiments at NICA
2.1 Fixed target experiments at the Nuclotron
2.2 Collider experiments at MPD
2.3 Collider experiments at SPD
3. Possibility of event-by-event simulations

Fixed Target Experiments at the Nuclotron

→ Ideally suited for exploration of reaction mechanisms & in-medium properties
→ Energy range formerly not accessible or of limited experimental information
→ Expectation of a rich structure of the QCD phase diagram @ high densities

TOOL:

→ Subthreshold production of (multi-)strange hadrons: Φ, K^*, $\overline{K}^*$, Λ, Σ, Ξ, Ω^-

→ Extend studies at SIS18, observe Ω^- as result of multi-step production here
→ Extract information about densities reached in the collision → EoS

Important:
→ Systematic study of production mechanisms by measurement of excitation functions for hadron production in p+p, d+p
→ High enough statistics for multi-dimensional analysis (centrality, y, p_T)

Production of hypernuclei: → study recommended!

→ Two mechanisms: (1) Absorption of produce Λ by spectator nuclei
(2) Coalescence of Λ nucleons at midrapidity
→ Important for hypernuclei spectroscopy: extract Y-N, Y-Y interactions

Fixed Target Experiments at the Nuclotron (II)

Electromagnetic probes: @ Nuclotron

→ medium modification of vector mesons at high ρ_B
→ eventually important for onset of deconfinement

Elementary reactions: p+p, n+p (d+p) above COSY energy range

→ multi-pion production, resonant intermediate state contributions
→ transition from 3D (hadronic) to 1D (partonic) phase space

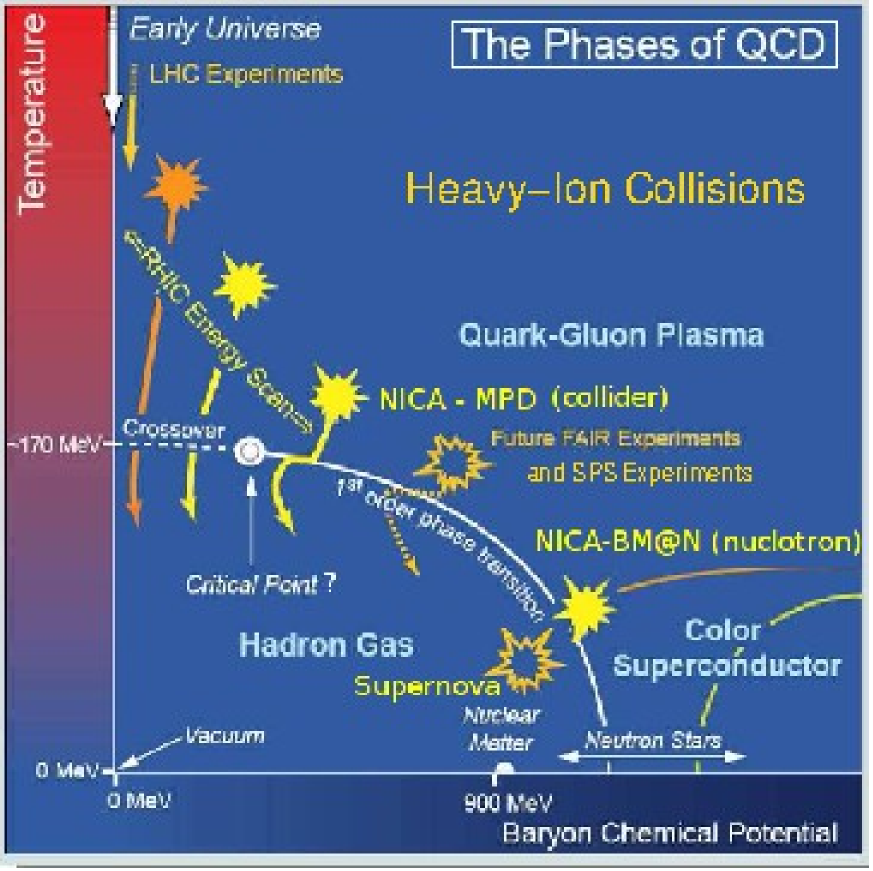
Simulations: → PHSD, UrQMD and other event generators shall be used
→ Computer replicas of the detector acceptance to bedeveloped
→ Predict the expected results on the basis of known physics

White Paper proposals to be studied further: width of $\sigma \rightarrow \gamma\gamma$ (χSR)

Advantages of Nuclotron over SIS100 and CBM:
→ experiments can be optimized to low energy range (lower half of SIS-100)
→ could start already in 2015, after completion of Nuclotron upgrade

Recommendation: investigate to use existing equipment (HADES, TAPS)

Collider Experiments at MPD



Theory predicts at least 2 QCD phases:
QGP = deconf. & χSR at high density
HRG = conf. & χSB at lower density

From SPS, RHIC, LHC at ultra-high energy nuclear collisions circumstantial evidence for existence of QGP phase.

Transition to HRG phase in NICA range.

NICA energy range large enough to encompass both phases, QGP and HRG

Exploration of QGP → HRG transition is top priority for NICA programme!

However:
- **theoretical understanding of transition yet rather poor (→ “Hilbert problems”)**
- **quantitative predictions cannot be made with confidence (no lattice QCD here)**
- **phenomenological models as key tools, but different predictions! Calibration?**

Challenging question: Character of the transition? Signals for 1st order? CP?

Collider Experiments at MPD (II)

Recommendation for first round of NICA experiments:

- → diagnostic observables of beam energy scan programs at SPS, RHIC
- → MPD detector to be optimized to study fluctuations an correlations
- → excitation functions of fluct./corr., dependence on centrality & system size

Observables:

- → EBE fluctuations of multiplicty and p_T of charged and identified part. (p,K,π)
- → long-range angular correlations like v_1, v_2 of (p,K,π,Λ) and light clusters
- → three-body correlations (for CME) and short-range two-particle corr. (size)
- → coverage in rapidity and p_T shall be large, low p_T extremely important!
- → measurements as function of collison energy for following systems:
  - – p+p collisions
  - – d+d collisions with possibility of off-line event selection of reactions with (p,p), (p,n), (n,n) spectators
  - – d+Pb collisions
  - – collisions of identical heavy nuclei, such as Pb+Pb (later also smaller A)
- → second stage: open-charm hadrons, di-leptons, di-photons at NICA

Collider Experiments at MPD (III)

Simulations:

→ Existing PHSD and UrQMD have no phase transition included but reproduce basic features and can be used to provide a reference against which the measured data can be compared.
→ It is essential to perform such simulations before detector operation starts
→ A software replica of the detector must be developed so that the simulation can be corrected for the detector acceptance

White Paper propositions that shall be pursued further:

1) to measure the width of the σ with help of γγ coincidences
2) to explore further baryon-strangeness correlations
3) to explore the valence strangeness and charm contributions
4) the experimental confirmation of the Schwinger mechanism by measuring the creation of electron-positron pairs in the ultracritical field of adjacent fully stripped ions
5) the different propositions by Stan Brodsky [cf. Contribution 2.7]

White Paper prioritization stage plan

- ✓ Stage 1: Selection of relevant contributions

  - preparatory meeting, team nomination (06.08.2013)

  - online questionaire (07.09.2013 → 20.10.2013)

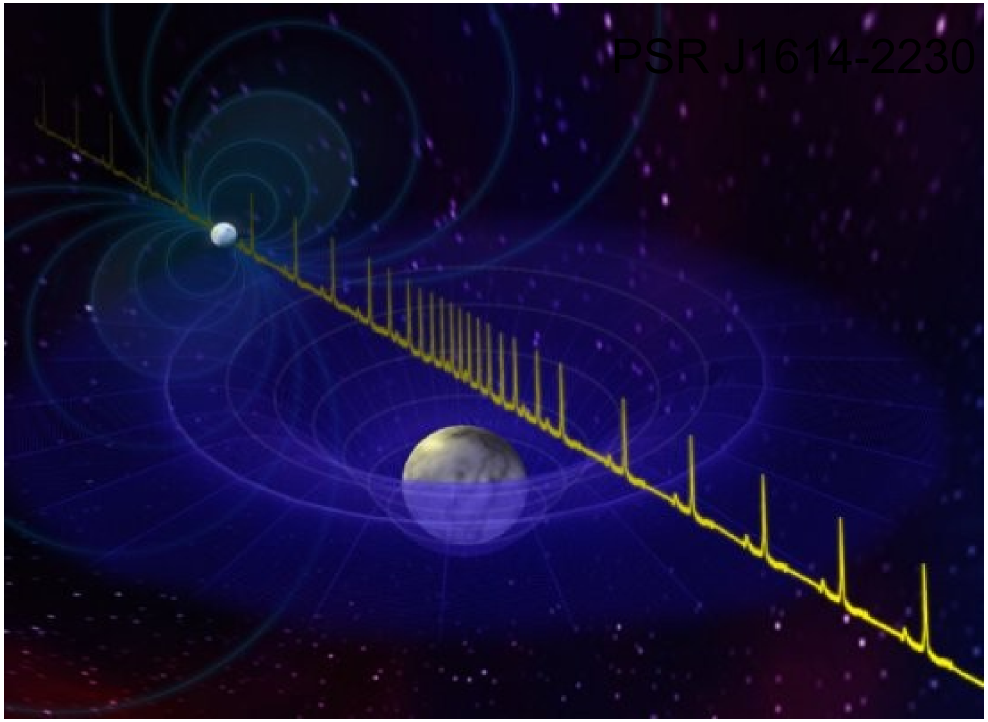
  - meeting in Dubna (28.10.-01.11.2013)

  - summary report “NICA priorities” → White Paper

- Stage 2: Preparation of programs for simulation of physical effects selected in Stage 1

Quark Matter in Compact Stars?

1. Goal: Find 1st order PT
2. Observation: M & R
3. Theory: QCD based EoS
4. Holy Grail: Twins !
5. Hot: BH formation
6. Future: SKA, NICER, …



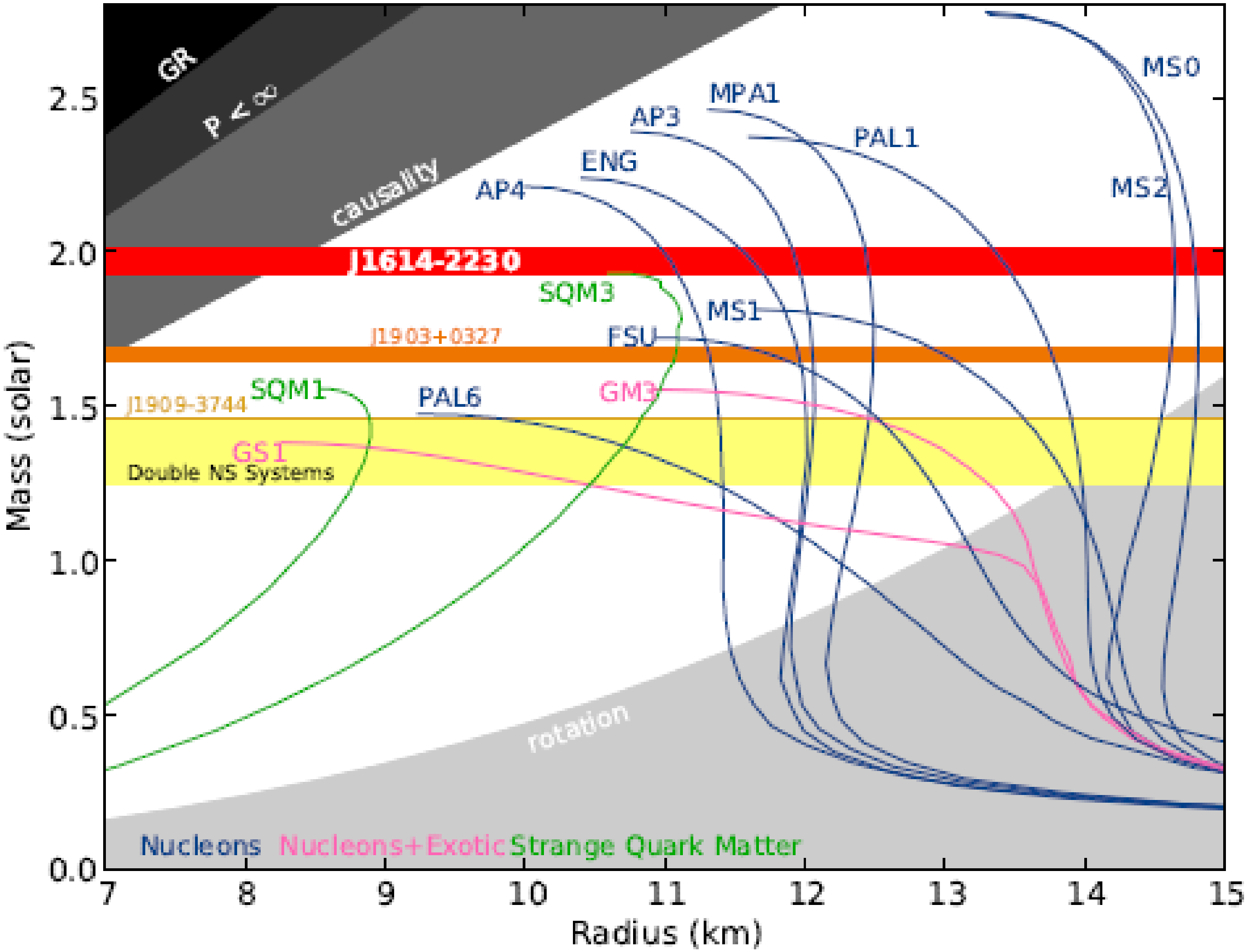
JINR DUBNA

RFBR

NARODOWE CENTRUM NAUKI

Uniwersytet Wrocławski

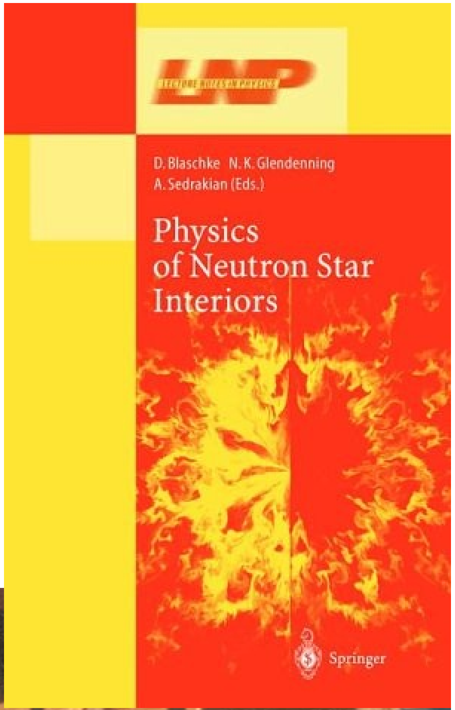
Mass-Radius relations and EoS for neutron stars



Tolman-Oppenheimer-Volkoff (TOV) equations (1939) provide a unique relationship P(ε) ←→ M(R)

Quark matter in compact stars?
– A fundamental question!

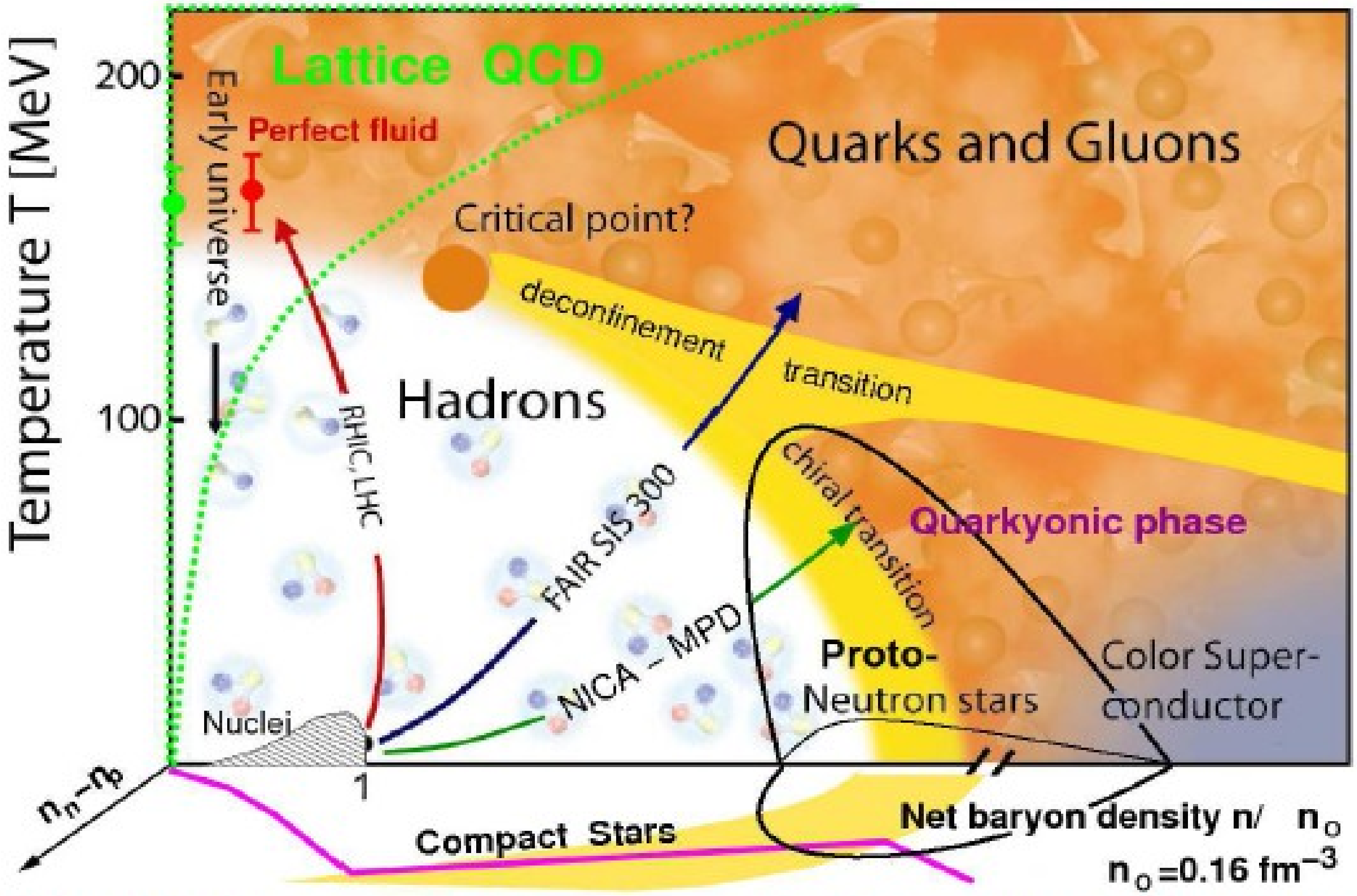
Proof that deconfinement at high densities is possible!
Observation?
First idea after proof of asymptotic freedom in QCD
(Gross, Politzer, Wilczek 1974 – Nobel prize 2004)
Collins & Perry (1975), PRL 34, 1353:
"Superdense matter – neutrons or asymptotically free quarks?"



Field is driven by observations:

- Submillisecond pulsars (1988)
  → Glendenning: strange stars !
- Spectrum and parallaxe of RXJ 1856
  → NASA: strange stars (2004) !
- Redshift z=0.35 for EXO 0748-676
  → high mass, no quark matter !
  [Oezel (2006), Nature 441, 1115]
  → contra: Alford et al. (2007) 445, E7
- Pulsars with 2 Mo: Demorest et al. (2010)
  Antoniadis et al. (2013)
  → high mass twin (HMT) conjecture,
  proof of QM in compact stars?

Support a CEP in QCD phase diagram with Astrophysics?



NICA White Paper, http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome

Crossover at finite T (Lattice QCD) + First order at zero T (Astrophysics) = Critical endpoint exists!

Quark matter in compact stars

Modern topics (selected):

- QCD phase diagram → critical point (D. Alvarez, DB, S. Benic et al.)
- Hyperon puzzle (M. Baldo et al.; P. Haensel at al..; ...)
- Direct Urca problem (T. Klaehn et al.)
- Supernova explosion mechanism (T. Fischer et al.)

Solutions can be provided by

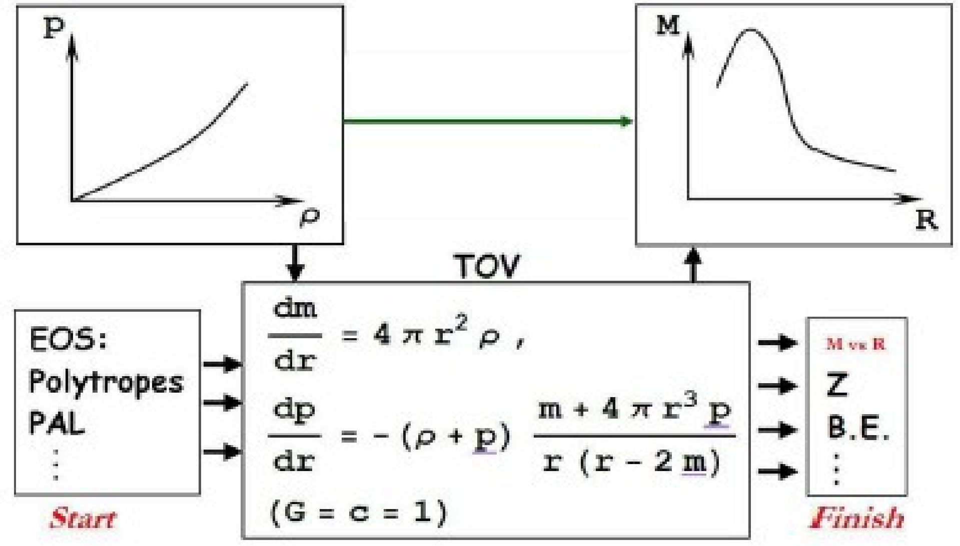
- Stiffening of hadronic matter by quark substructure effects
  (Pauli blocking → excluded volume: DB, H. Grigorian, G. Roepke)
- Stiffening of quark matter at high densities
  (e.g., by multiquark interactions: S. Benic et al.)
- Resulting early onset of quark matter and large latent heat

Cross-talk with Heavy-Ion Collision Experiments

Goal 1: Measure the cold EoS !

Direct approach:

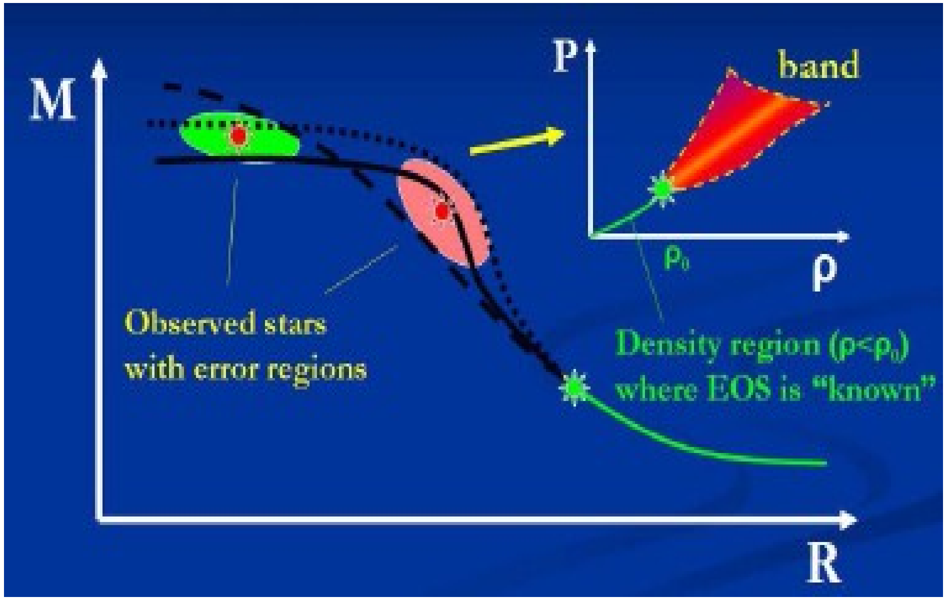
EoS is given as P(ρ)
→ solve the TOV Equation
to find M(R)



Idea: Invert the approach

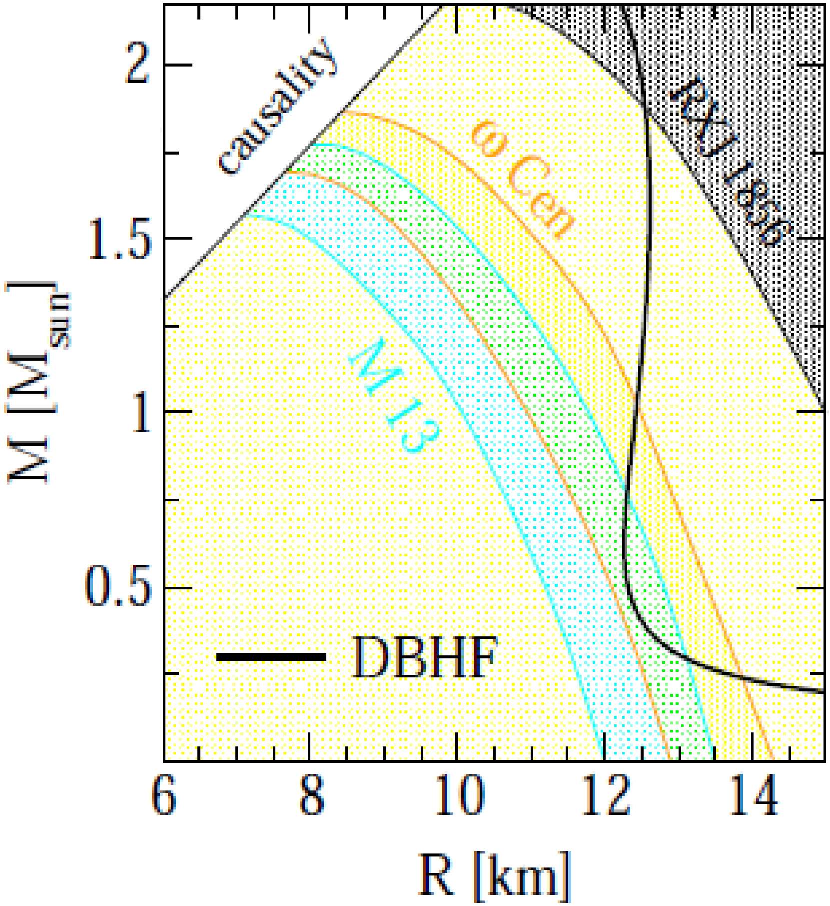
Given M(R) → find the EoS

Bayesian analysis



Plots: M. Prakash, Talk Hirschegg 2009

Measure masses and radii of CS!



- Distance measured
- Spectrum measured (ROSAT, XMM, Chandra)
- Luminosity measured

→ effective temperature T_∞

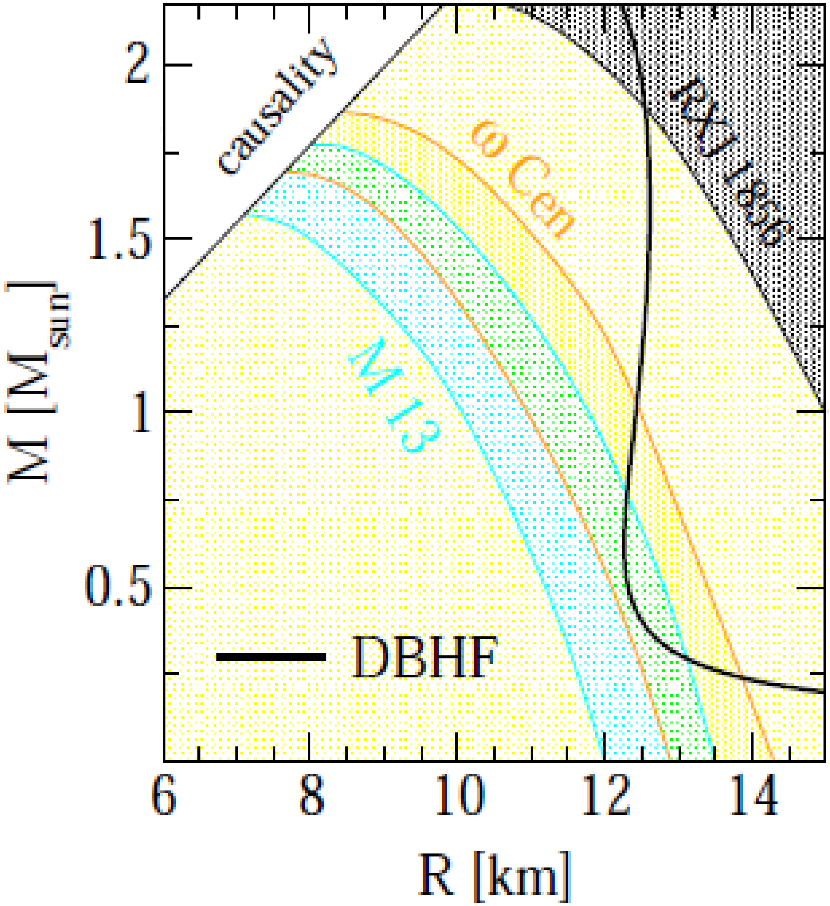
→ photospheric radius

$$R_\infty = R/\sqrt{1 - R/R_S}\,, \quad R_S = 2GM/R$$

Object	R_∞ [km]	Reference
RXJ 1856	16.8	Trümper et al. (2004)
ωCen	13.6 ±0.3	Gendre et al. (2003)
M13	12.8 ±0.4	Gendre et al. (2004)

Lower limit from RXJ 1856 incompatible with ω Cen and M13 ?

Measure masses and radii of CS!



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Lower limit from RXJ 1856 incompatible with ω Cen and M13 ?

... unless the latter sources emit X-rays from “hot spots” → lower limit on R

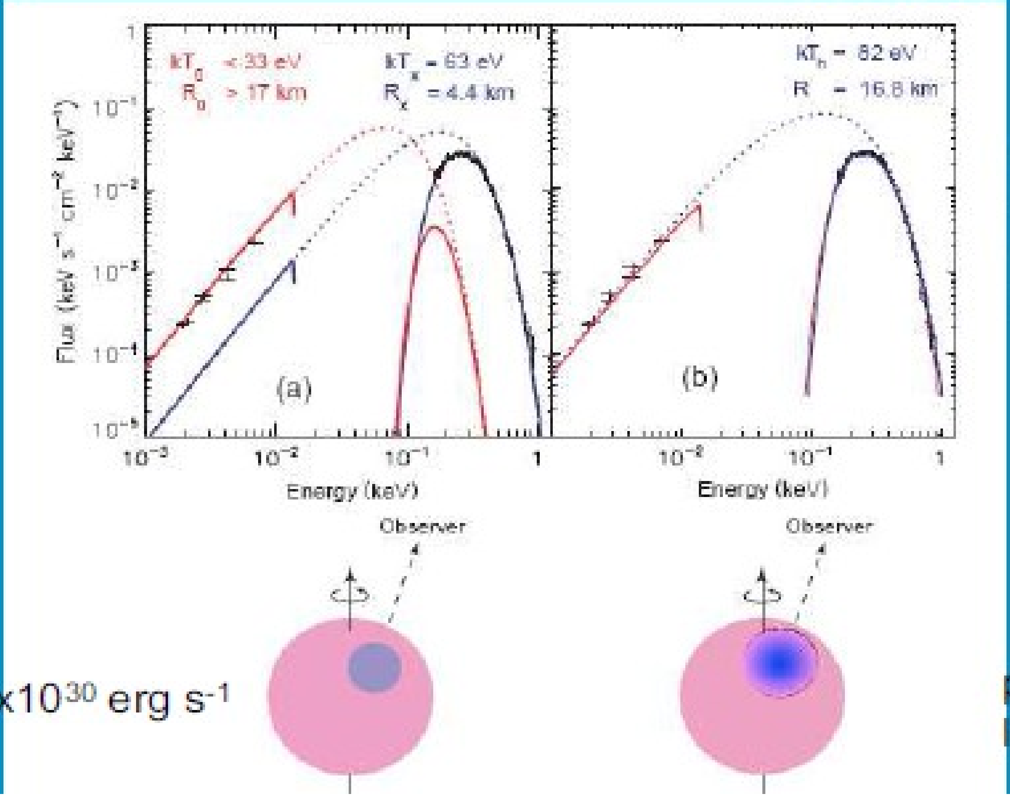
The lesson learned from RX J1856

blackbody fits to the optical and X-ray spectra of RX J1856.5-3754 (Trümper,2004)

radius determination ⇒ EoS ⇒ state of matter at high densities

two-component model

model with continuous T-distribution



completely featureless X-ray spectrum: condensed surface? ⇒ strong B?

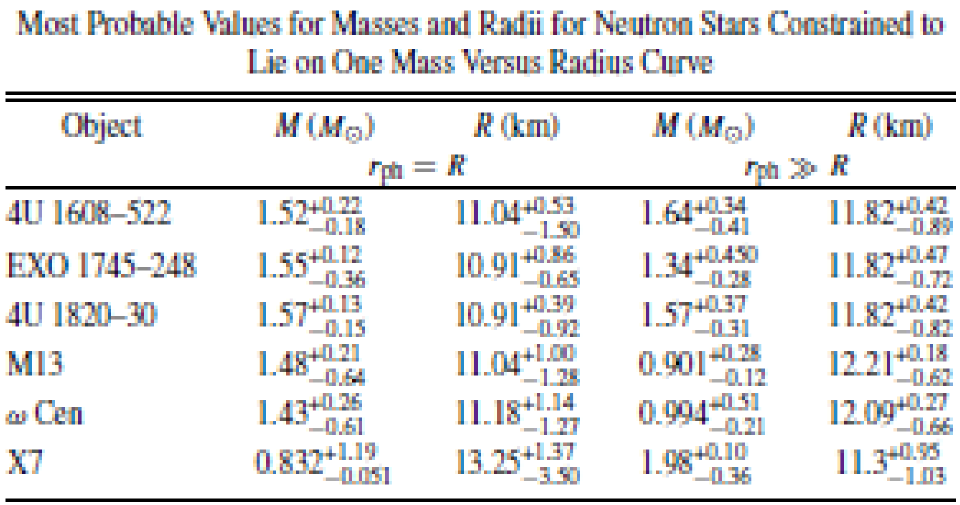
L_x =5.4x10^{30} erg s^{-1}

pulsed fraction < 1% ⇒ line of sight || rotation axis?

-ray emitting region is a “hot spot”, J. Trumper et al., Nucl. Phys. Proc. Suppl. 132 (2004) 5

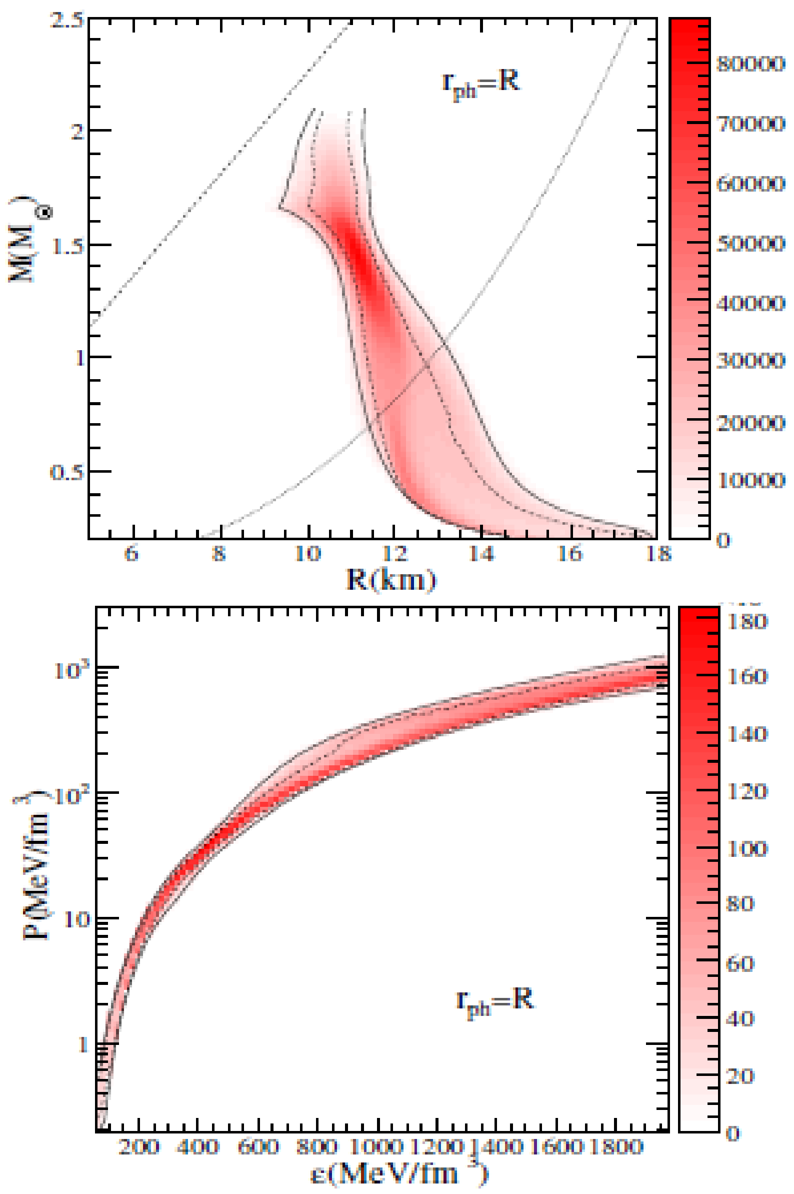
Goal 1: Measure the cold EoS !

Bayesian TOV analysis:
Steiner, Lattimer, Brown, ApJ 722 (2010) 33



Most Probable Values for Masses and Radii for Neutron Stars Constrained to Lie on One Mass Versus Radius Curve

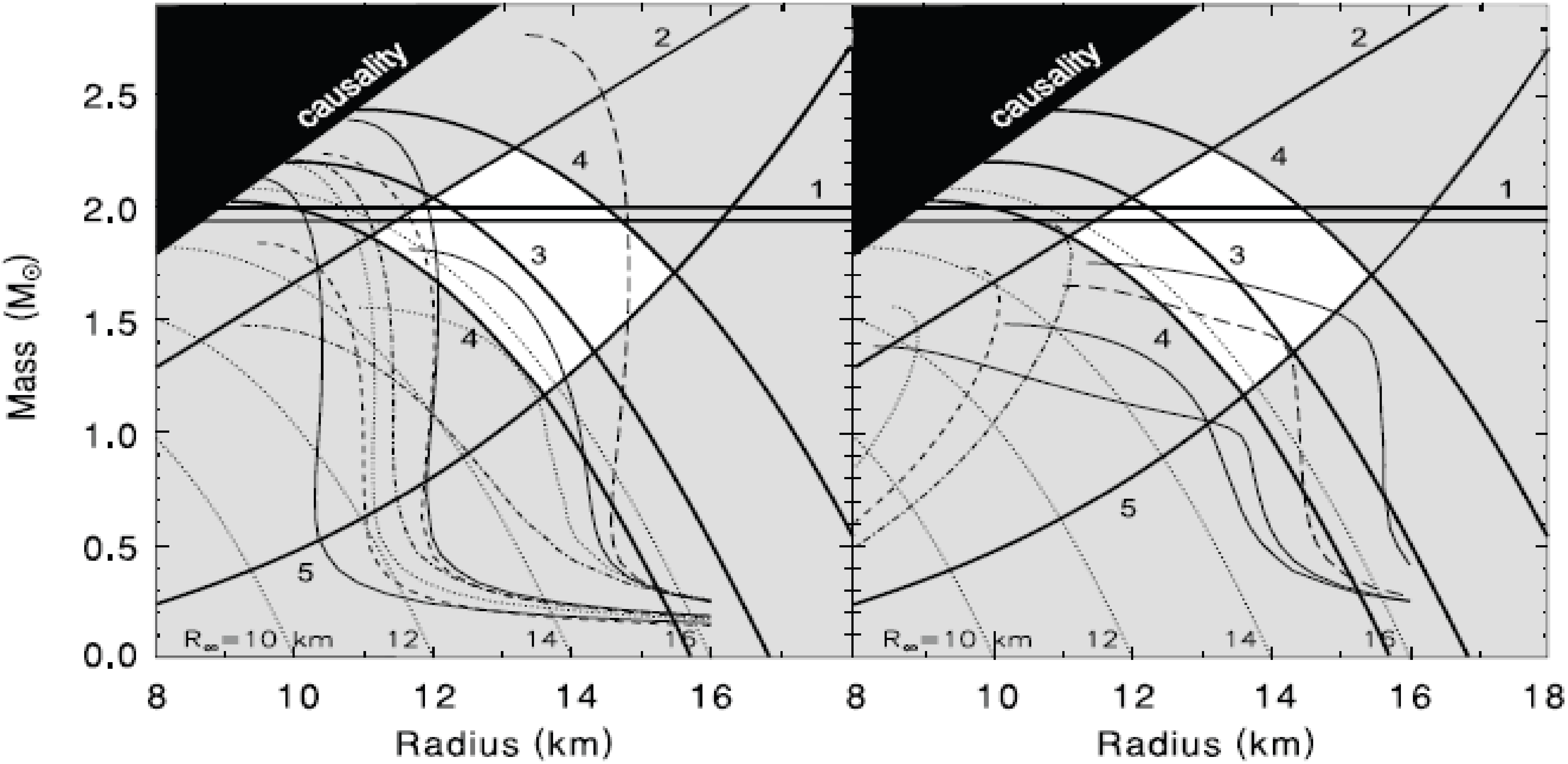
Object	$M\ (M_\odot)$	R (km)	$M\ (M_\odot)$	R (km)
	$r_{\rm ph} = R$		$r_{\rm ph} \gg R$	
4U 1608–522	$1.52^{+0.22}_{-0.18}$	$11.04^{+0.53}_{-1.50}$	$1.64^{+0.34}_{-0.41}$	$11.82^{+0.42}_{-0.89}$
EXO 1745–248	$1.55^{+0.12}_{-0.36}$	$10.91^{+0.86}_{-0.65}$	$1.34^{+0.450}_{-0.28}$	$11.82^{+0.47}_{-0.72}$
4U 1820–30	$1.57^{+0.13}_{-0.15}$	$10.91^{+0.39}_{-0.92}$	$1.57^{+0.37}_{-0.31}$	$11.82^{+0.42}_{-0.82}$
M13	$1.48^{+0.21}_{-0.64}$	$11.04^{+1.00}_{-1.28}$	$0.901^{+0.28}_{-0.12}$	$12.21^{+0.18}_{-0.62}$
ω Cen	$1.43^{+0.26}_{-0.61}$	$11.18^{+1.14}_{-1.27}$	$0.994^{+0.51}_{-0.21}$	$12.09^{+0.27}_{-0.66}$
X7	$0.832^{+1.19}_{-0.051}$	$13.25^{+1.37}_{-3.50}$	$1.98^{+0.10}_{-0.36}$	$11.3^{+0.95}_{-1.03}$



Caution:
If optical spectra are not measured, the observed
X-ray spectrum may not come from the entire surface
But from a hot spot at the magnetic pole!
J. Trumper, Prog. Part. Nucl. Phys. 66 (2011) 674

Such systematic errors are not accounted for in
Steiner et al. → M(R) is a lower limit → softer EoS

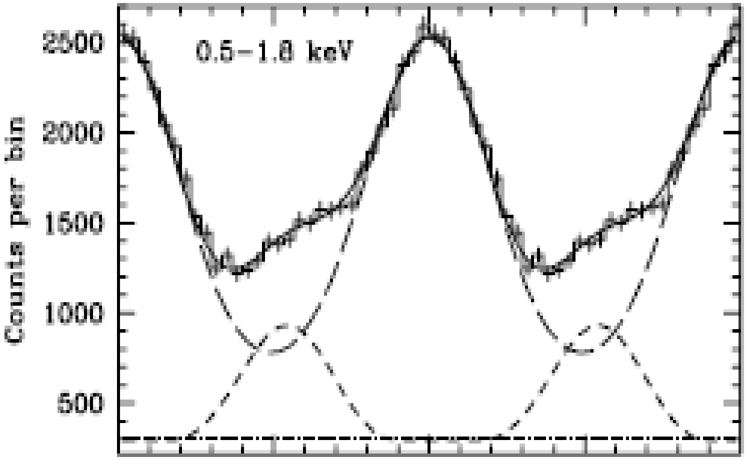
Which constraints can be trusted ?

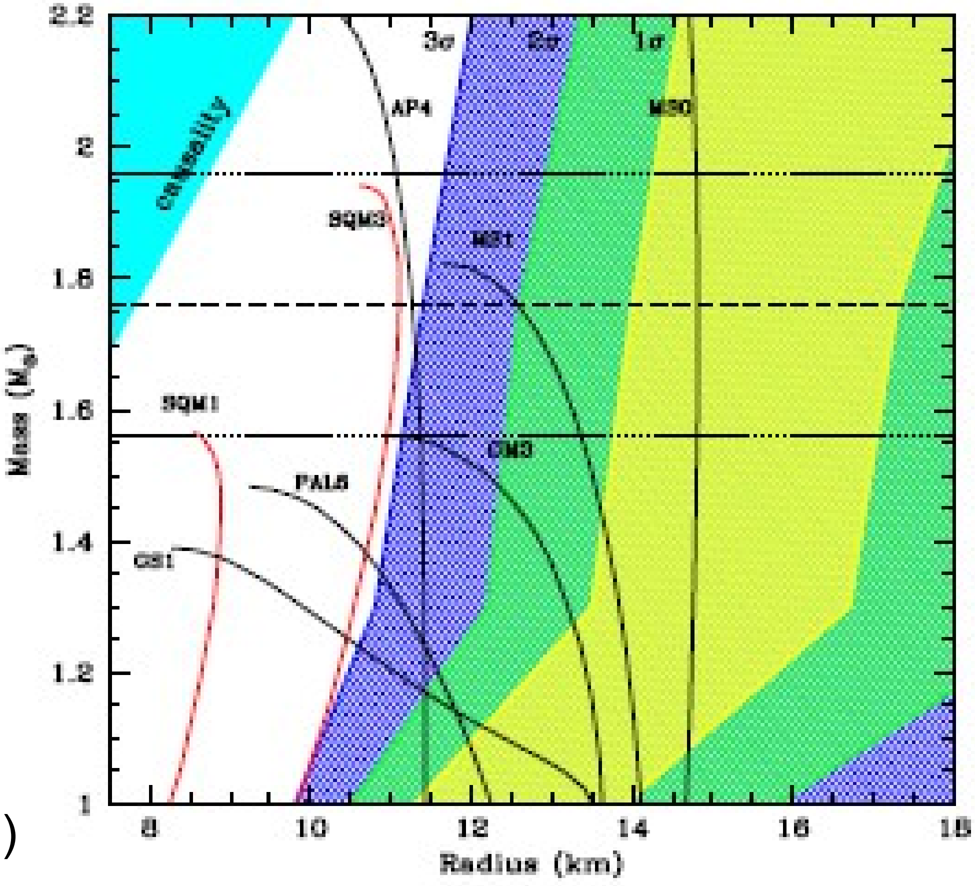


1 – Largest mass J1614 – 2230 (Demorest et al. 2010)
2 – Maximum gravity XTE 1814 – 338 (Bhattacharyya et al. (2005)
3 – Minimum radius RXJ 1856 – 3754 (Trumper et al. 2004)
4 – Radius, 90% confidence limits LMXB X7 in 47 Tuc (Heinke et al. 2006)
5 – Largest spin frequency J1748 – 2446 (Hessels et al. 2006)

Which constraints can be trusted ?

Nearest millisecond pulsar PSR J0437 – 4715 revisited by XMM Newton
Distance: d = 156.3 +/- 1.3 pc
Period: P= 5.76 ms, dot P = 10^-20 s/s, field strength B = 3x10^8 G





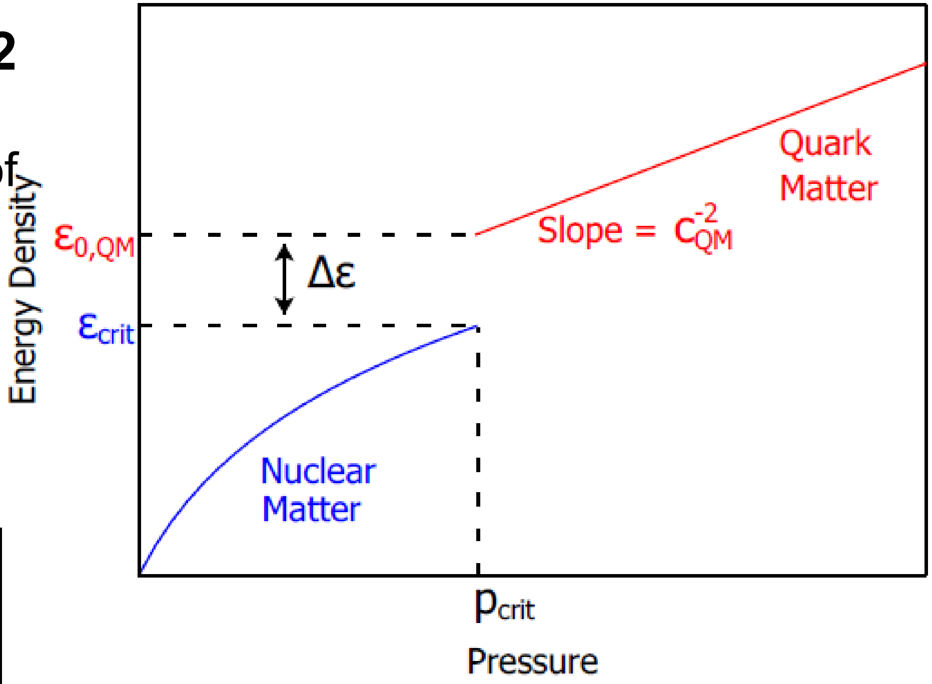
Three thermal component fit
R > 11.1 km (at 3 sigma level)
M = 1.76 M_sun

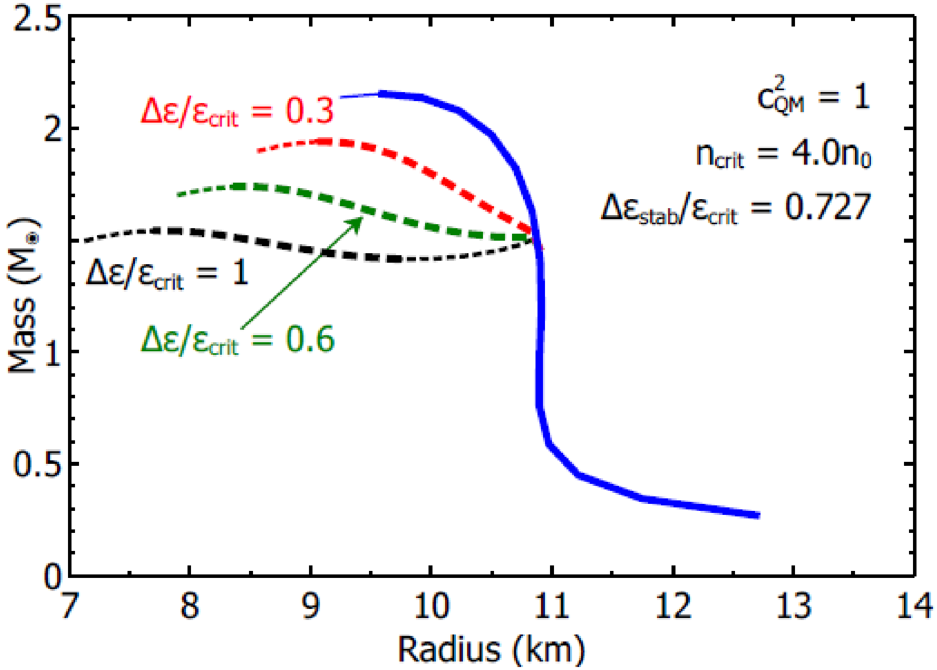
S. Bogdanov, arxiv:1211.6113 (2012)

Goal 2: Be lucky – detect a 1st order PT

Alford, Han, Prakash, arxiv:1302.4732

First order PT can lead to a stable branch of hybrid stars with quark matter cores which, depending on the size of the “latent heat” (jump in energy density), can even be disconnected from the hadronic one by an unstable branch → **“third family of CS”**.





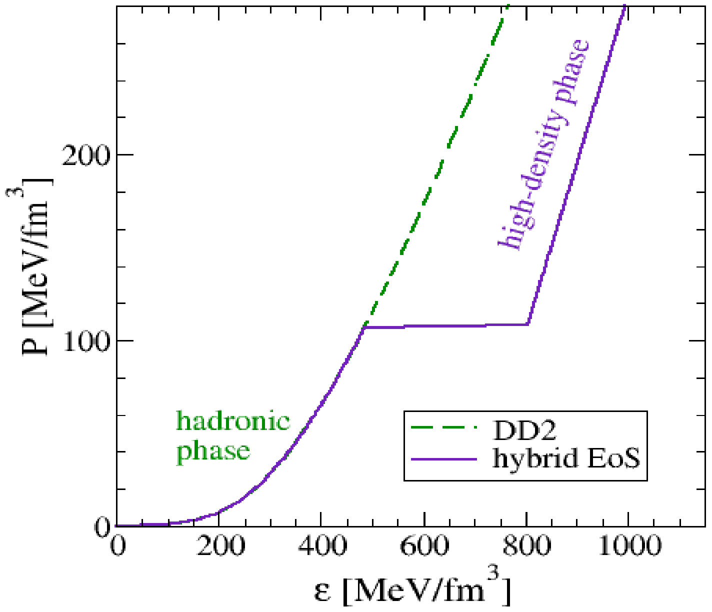
Measuring two **disconnected populations** of compact stars in the M-R diagram would be the **detection of a first order phase transition** in compact star matter and thus the indirect proof for the existence of a **critical endpoint (CEP) in the QCD phase diagram**!

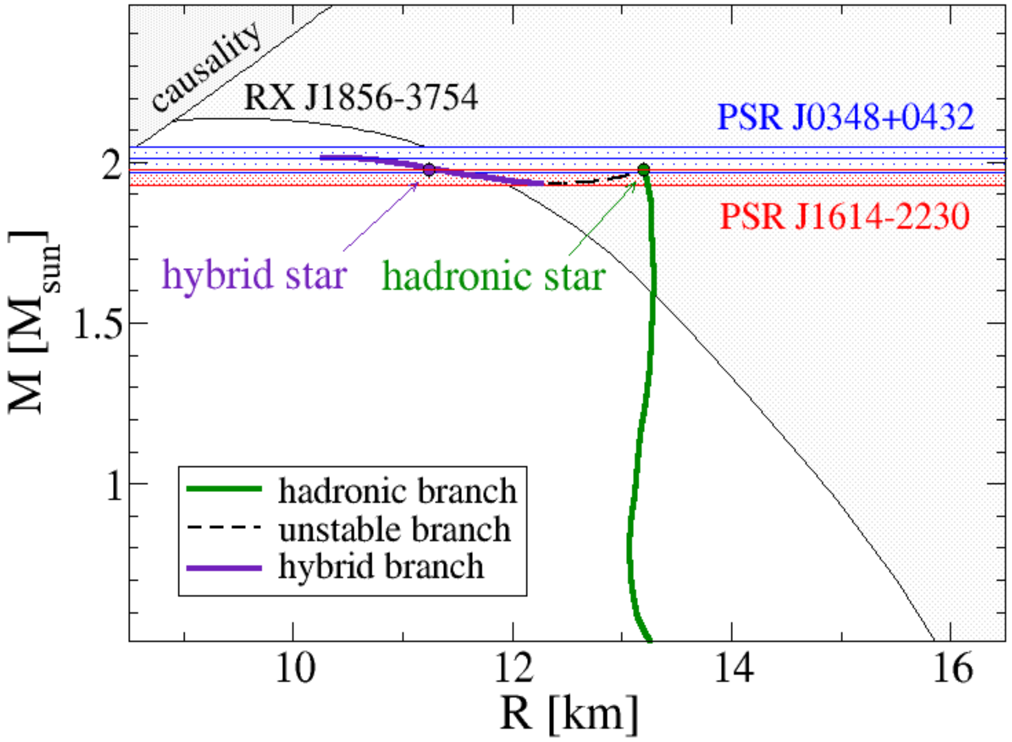
Goal 2: Observe High-Mass Twin Stars

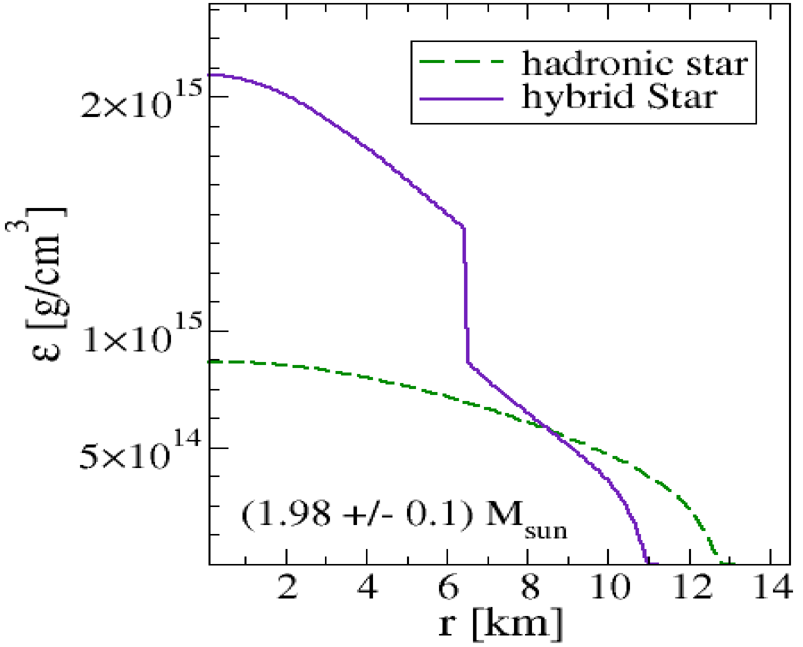
Twins prove exitence of **disconnected populations** (third family) in the M-R diagram

Consequence of a **first order phase transition**

Question: Do twins prove the 1st order phase trans.







Alvarez & Blaschke, arxiv:1304.7758

Quark matter in compact stars

Modern topics (selected):

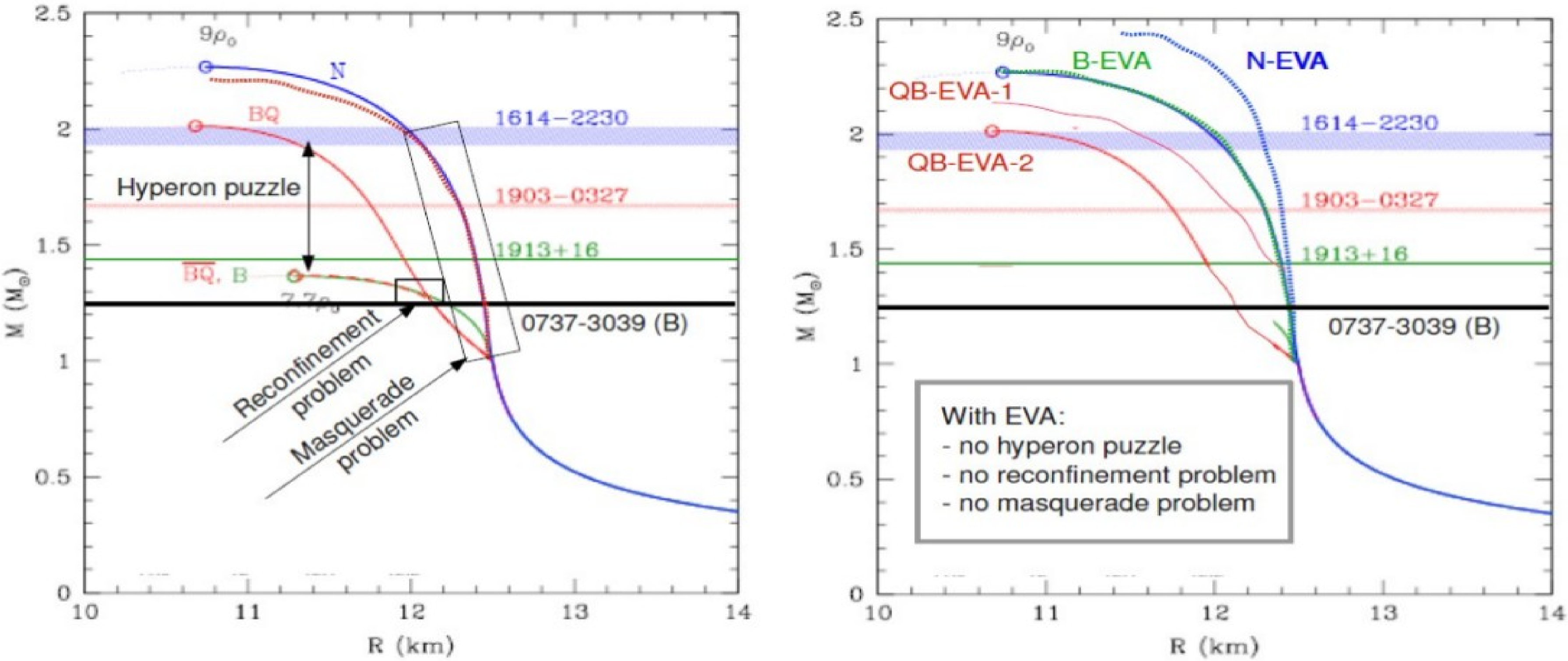
- QCD phase diagram → critical point (D. Alvarez, DB, S. Benic et al.)
- Hyperon puzzle (M. Baldo et al.; P. Haensel at al..; ...)
- Direct Urca problem (T. Klaehn et al.)
- Supernova explosion mechanism (T. Fischer et al.)

Solutions can be provided by

- Stiffening of hadronic matter by quark substructure effects
  (Pauli blocking → excluded volume: DB, H. Grigorian, G. Roepke)
- Stiffening of quark matter at high densities
  (e.g., by multiquark interactions: S. Benic et al.)
- Resulting early onset of quark matter and large latent heat

Cross-talk with Heavy-Ion Collision Experiments

Hyperon puzzle & quark matter

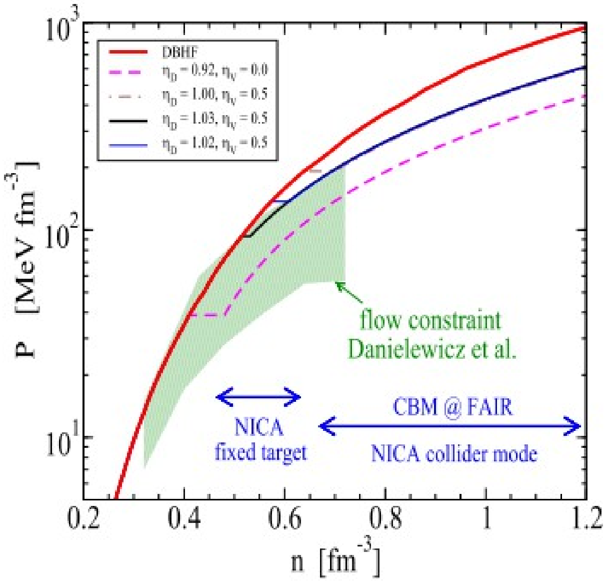


Mass-radius sequences for different model equations of state (EoS) illustrate how the **three major problems** in the theory of exotic matter in compact stars (left panel) can be solved (right panel) by taking into account the baryon size effect within a excluded volume approximation (EVA). Due to the EVA both, the nucleonic (N-EVA) and hyperonic (B-EVA) EoS get sufficiently stiffened to describe high-mass pulsars so that the hyperon puzzle gets solved which implies a removal of the reconfinement problem. Since the EVA does not apply to the quark matter EoS it shall be always sufficiently different from the hadronic one so that the masquerade problem is solved.

Exploring hybrid star matter at NICA

T.Klähn (1), D.Blaschke (1,2), F.Weber (3)
(1) Institute for Theoretical Physics, University of Wroclaw, Poland
(2) Joint Institute for Nuclear Research, Dubna
(3) Department of Physics, San Diego State University, USA

Heavy-Ion Collisions



- stiff EoS
(at flow limit)

- low ncrit
(at NICA fixT)

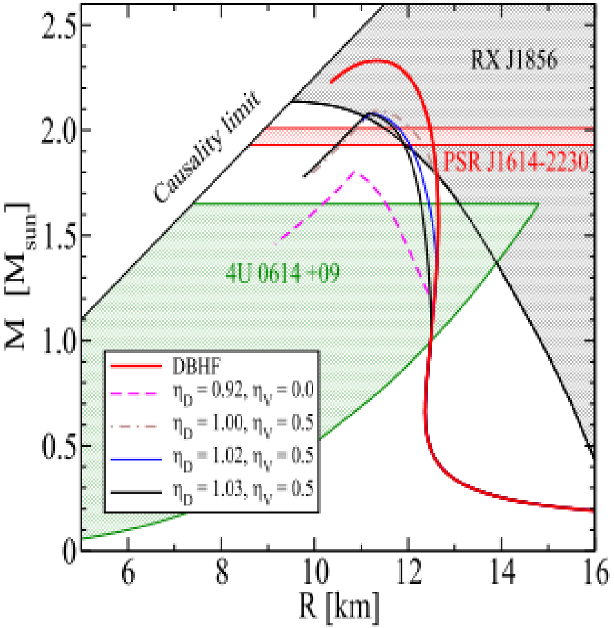
- soft EoS
(dashed line)

Compact Stars

- high Mmax
(J1614-2230)

- low Monset
(all NS hybrid)

- excluded
(J1614-2230)

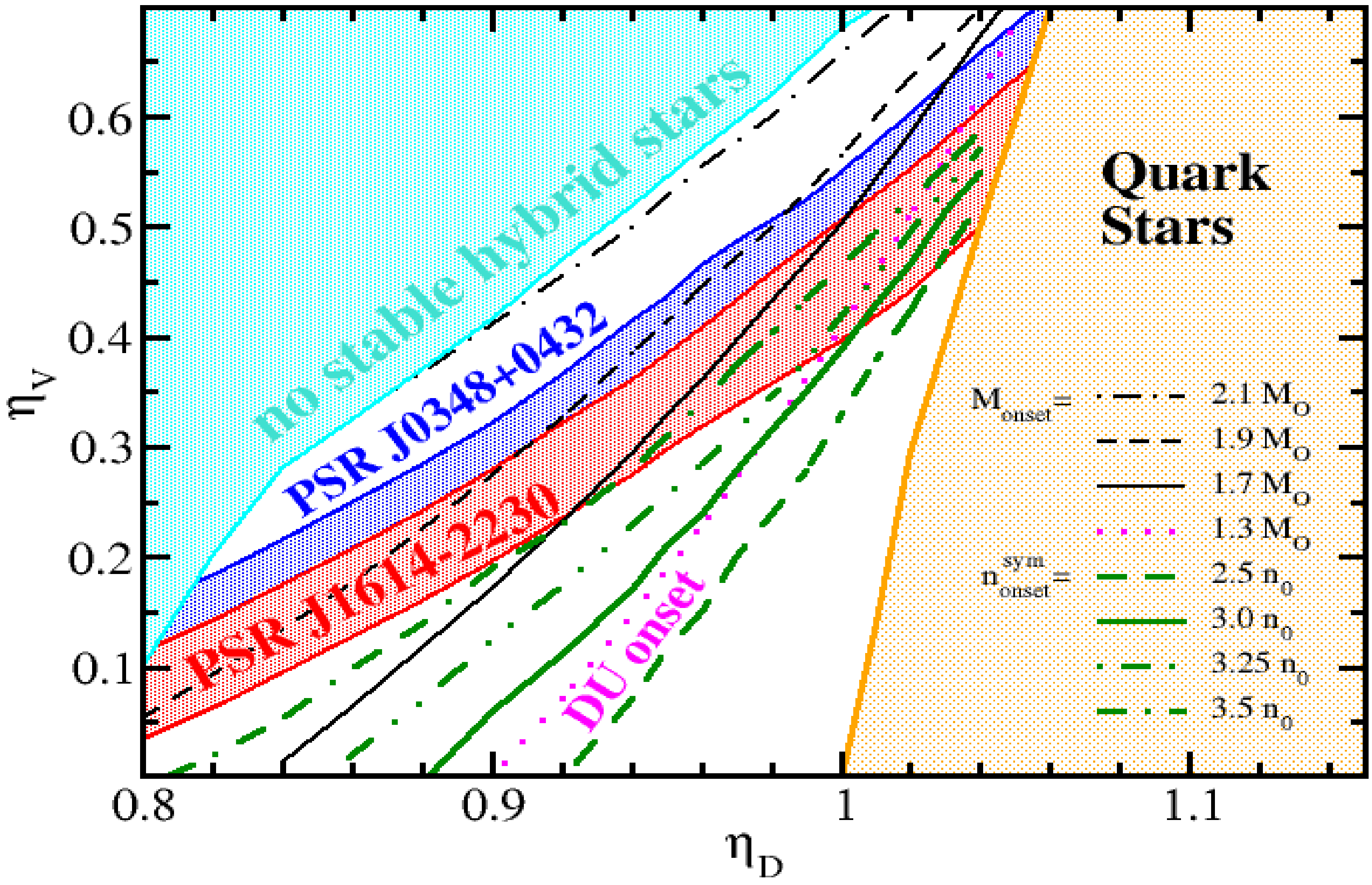


Proposal:

1. Measure transverse and elliptic flow for a wide range of energies (densities) at NICA and perform Danielewicz's flow data analysis ---> constrain stiffness of high density EoS
2. Provide lower bound for onset of mixed phase ---> constrain QM onset in hybrid stars

„The CBM Physics Book“, Springer LNP 841 (2011), pp.158-181
NICA White Paper, http://theor.jinr.ru → BLTP TWikipages

Quark matter in 2Msun neutron stars?
→ only color superconducting + vector int.



T. Klahn et al., PRD 88 (2013) 085001; arxiv:1307.696

Baryon substructure effect (EVA)

Excluded volume approximation (EVA)):

$$p_{\rm ex}(\mu, T) \;=\; p(\tilde{\mu}, T)\,, \quad \tilde{\mu} = \mu - v_0(\mu, T)\,p_{\rm ex}(\mu, T)$$

$$n_{\rm ex}(\mu, T) \;=\; \frac{\partial p_{\rm ex}}{\partial \mu} = \frac{\partial \tilde{\mu}}{\partial \mu}\,\frac{\partial p(\tilde{\mu}, T)}{\partial \tilde{\mu}} \;=\; \left[1 - v_0 n_{\rm ex}(\mu, T) - \frac{\partial v_0}{\partial \mu} p_{\rm ex}(\mu, T)\right] n(\tilde{\mu}, T)$$

Thermodynamic consistency:

$$\epsilon_{\rm ex}(\mu, T) = -p_{\rm ex}(\mu, T) + \mu n_{\rm ex}(\mu, T) + T s_{\rm ex}(\mu, T)$$

Parametrization of excluded volume with nonlinear dependence on the chemical potential:

$$v_0(\mu, T) = (4\pi/3) r^3(\mu) \;\;,\;\; r^3(\mu) = r_0 + r_1(\mu/\mu_c)^2 + r_2(\mu/\mu_c)^4$$

NJL model with multiquark interactions

$$\mathcal{L} = \bar{q}(i\partial\!\!\!/ - m)q + \mu_q \bar{q}\gamma^0 q + \mathcal{L}_4 + \mathcal{L}_8 \ , \ \mathcal{L}_4 = \frac{g_{20}}{\Lambda^2}[(\bar{q}q)^2 + (\bar{q}i\gamma_5\tau q)^2] - \frac{g_{02}}{\Lambda^2}(\bar{q}\gamma_\mu q)^2 \ ,$$

$$\mathcal{L}_8 \ = \ \frac{g_{40}}{\Lambda^8}[(\bar{q}q)^2 + (\bar{q}i\gamma_5\tau q)^2]^2 - \frac{g_{04}}{\Lambda^8}(\bar{q}\gamma_\mu q)^4 - \frac{g_{22}}{\Lambda^8}(\bar{q}\gamma_\mu q)^2[(\bar{q}q)^2 + (\bar{q}i\gamma_5\tau q)^2]$$

Meanfield approximation: $\mathcal{L}_{\mathrm{MF}} = \bar{q}(i\partial\!\!\!/ - M)q + \tilde{\mu}_q \bar{q}\gamma^0 q - U \ ,$

$$M = m + 2\frac{g_{20}}{\Lambda^2}\langle\bar{q}q\rangle + 4\frac{g_{40}}{\Lambda^8}\langle\bar{q}q\rangle^3 - 2\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle\langle q^\dagger q\rangle^2 \ ,$$

$$\tilde{\mu}_q = \mu_q - 2\frac{g_{02}}{\Lambda^2}\langle q^\dagger q\rangle - 4\frac{g_{04}}{\Lambda^8}\langle q^\dagger q\rangle^3 - 2\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle^2\langle q^\dagger q\rangle \ ,$$

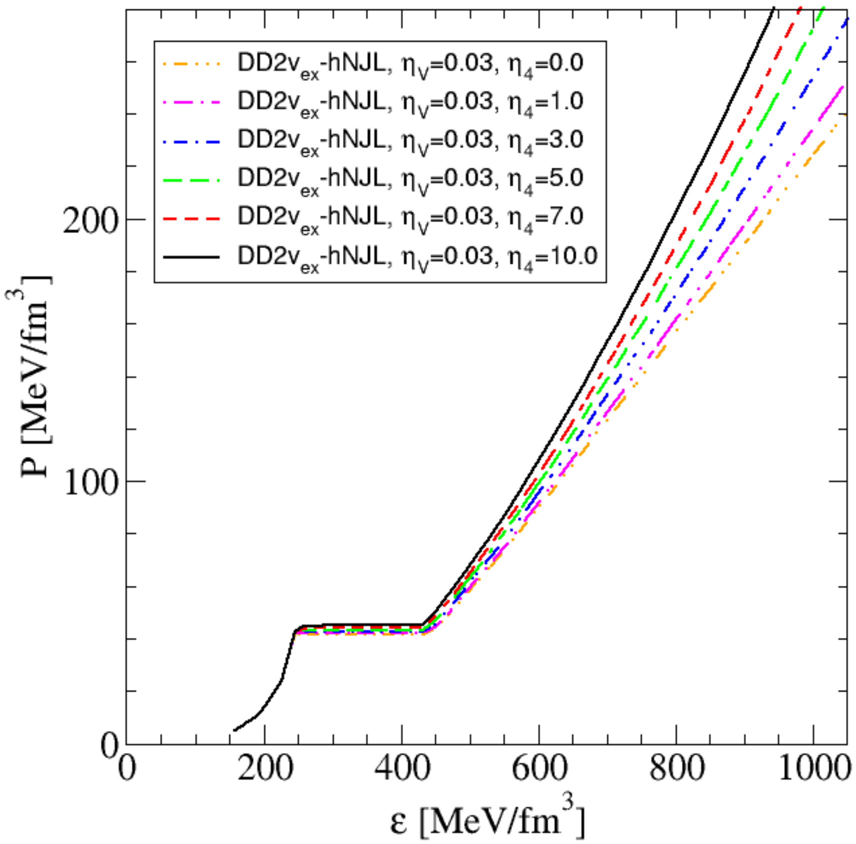
$$U \ = \ \frac{g_{20}}{\Lambda^2}\langle\bar{q}q\rangle^2 + 3\frac{g_{40}}{\Lambda^8}\langle\bar{q}q\rangle^4 - 3\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle^2\langle q^\dagger q\rangle^2 - \frac{g_{02}}{\Lambda^2}\langle q^\dagger q\rangle^2 - 3\frac{g_{04}}{\Lambda^8}\langle q^\dagger q\rangle^4 \ .$$

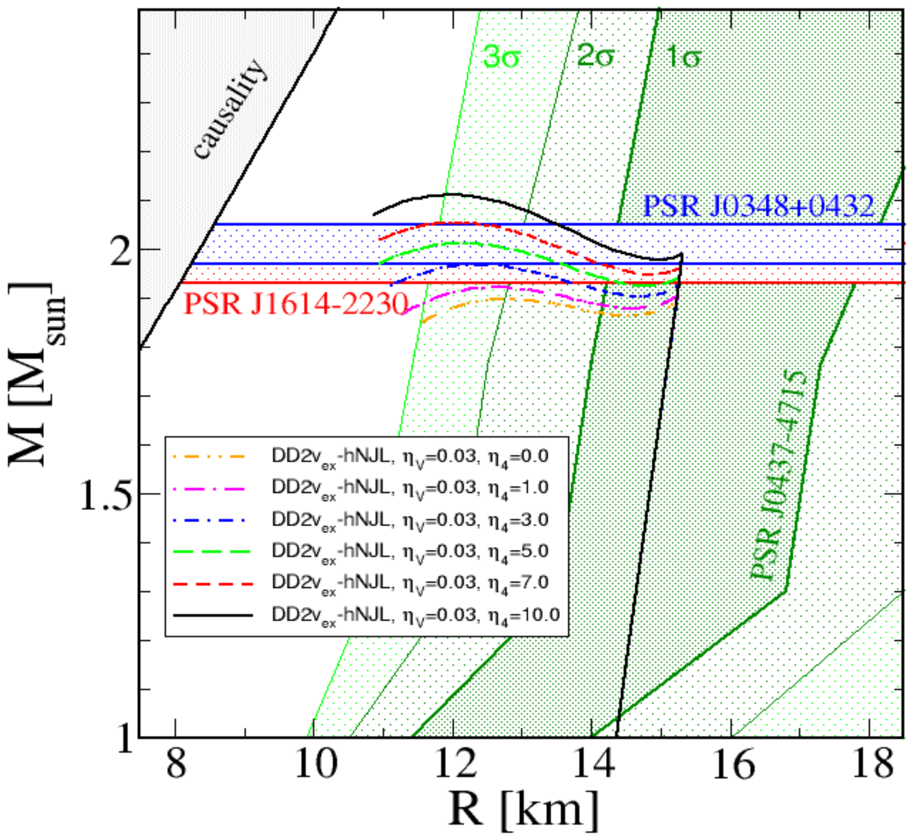
Thermodynamic Potential:

$$\Omega \ = \ U - 2N_f N_c \int \frac{d^3p}{(2\pi)^3}\left\{E + T\log[1 + e^{-\beta(E-\tilde{\mu}_q)}] + T\log[1 + e^{-\beta(E+\tilde{\mu}_q)}]\right\} + \Omega_0$$

Result: high-mass twins ↔ 1st order PT

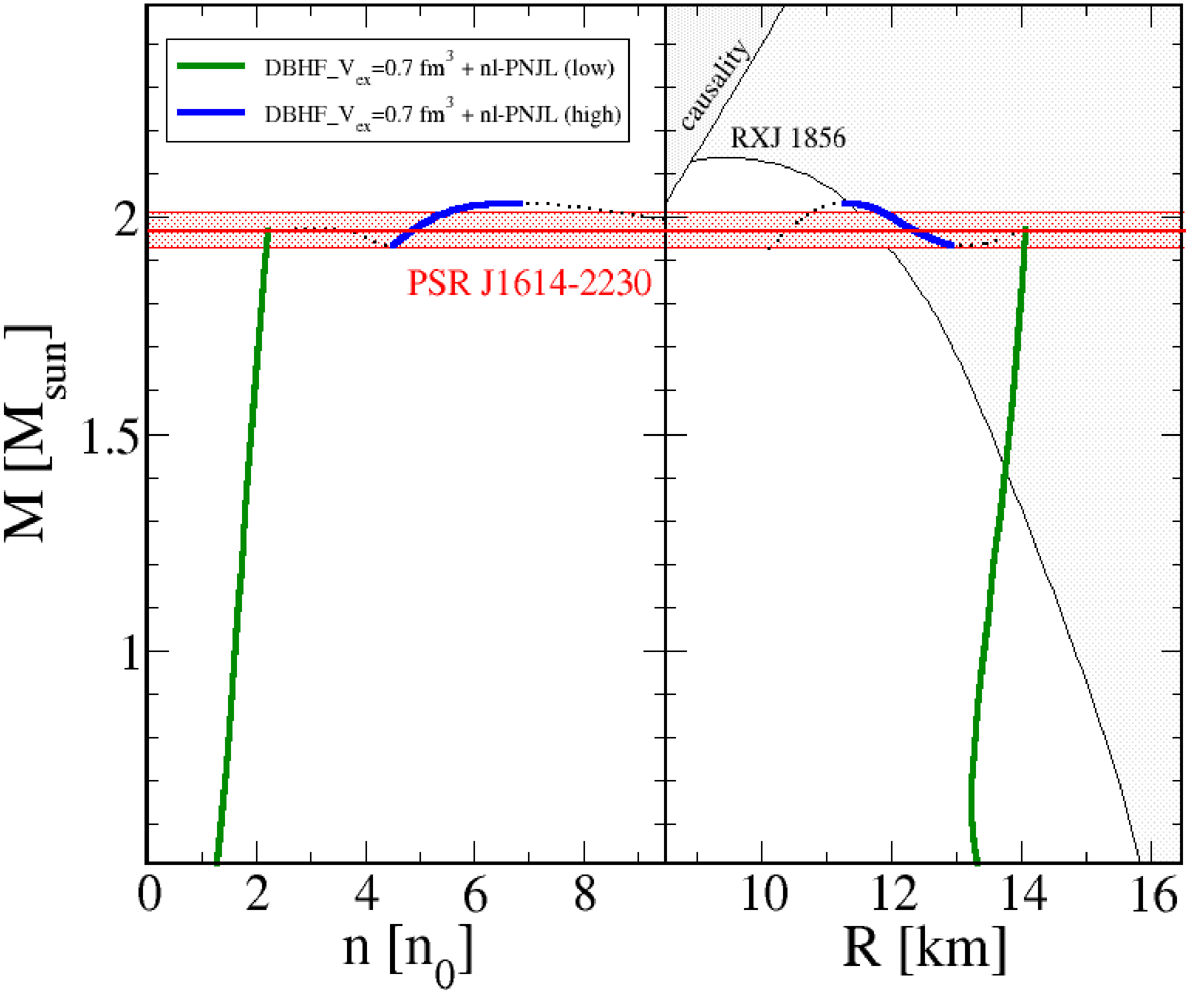
S. Benic, D. Blaschke, D. Alvarez-Castillo, T. Fischer, in progress (2014)

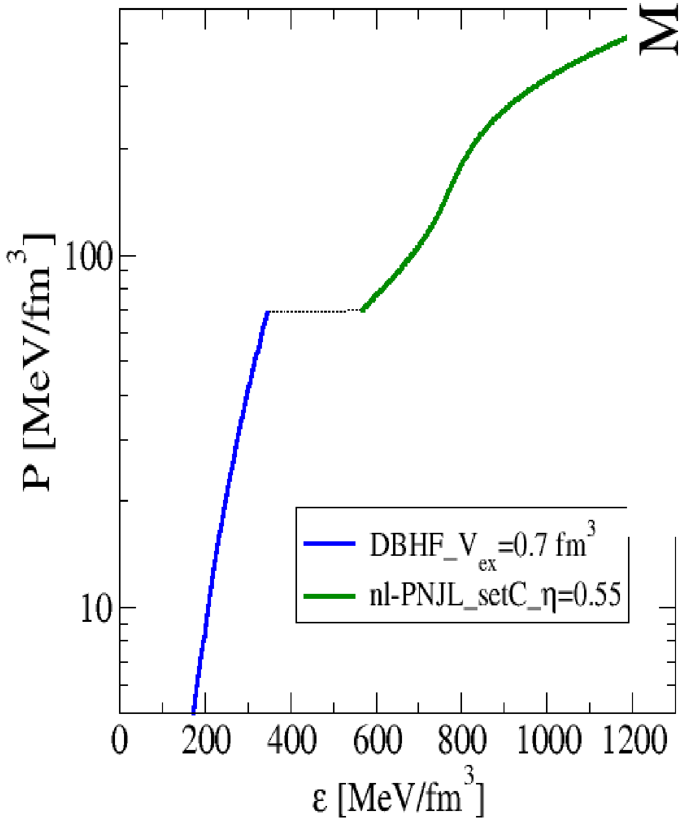




Hybrid EoS supports M-R sequences with high-mass twin compact stars

Result 2:
High mass twins are possible !



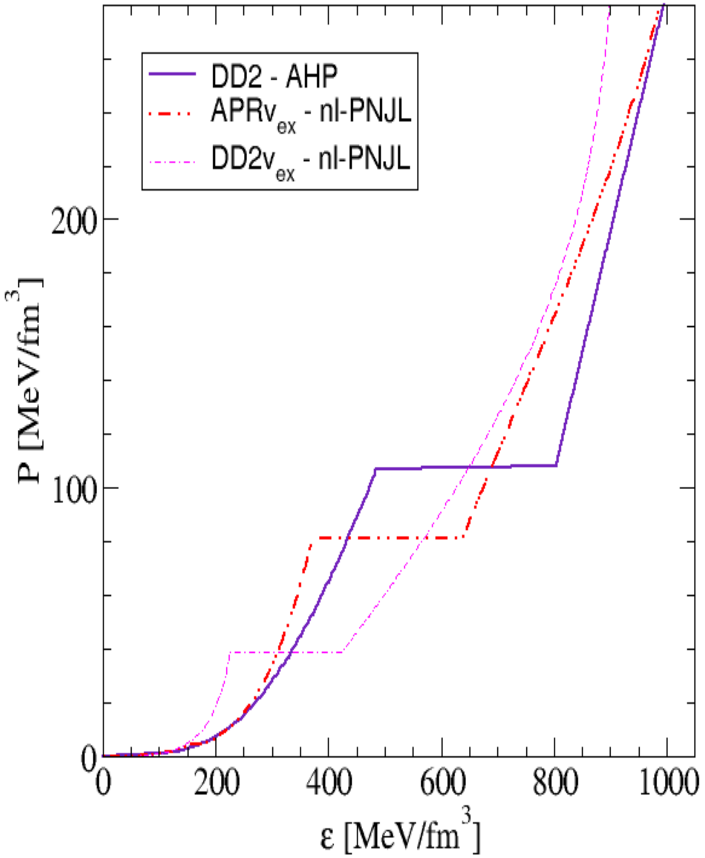


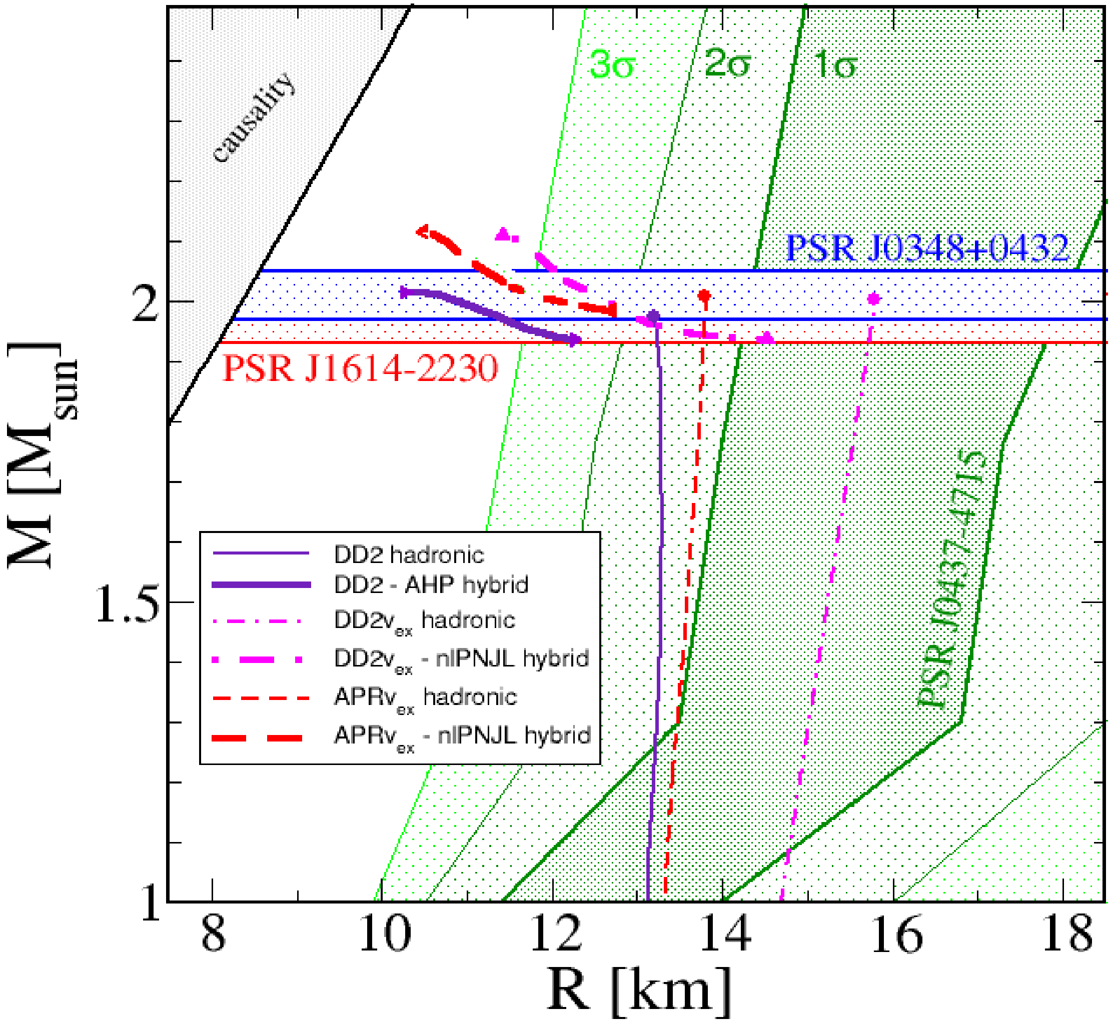
SUMMARY:

- excluded volume (quark Pauli blocking) in DBHF
- high-density quark matter slightly stiffer eta_v=0.25
- the scaled energy density jump (0.65) fulfills the twin condition of the schematic model by Alford et al. (2013

→ **Find the disconnected star branches !!**

Result 3:
High mass twins:
more examples !





DB, Alvarez, Benic, arxiv

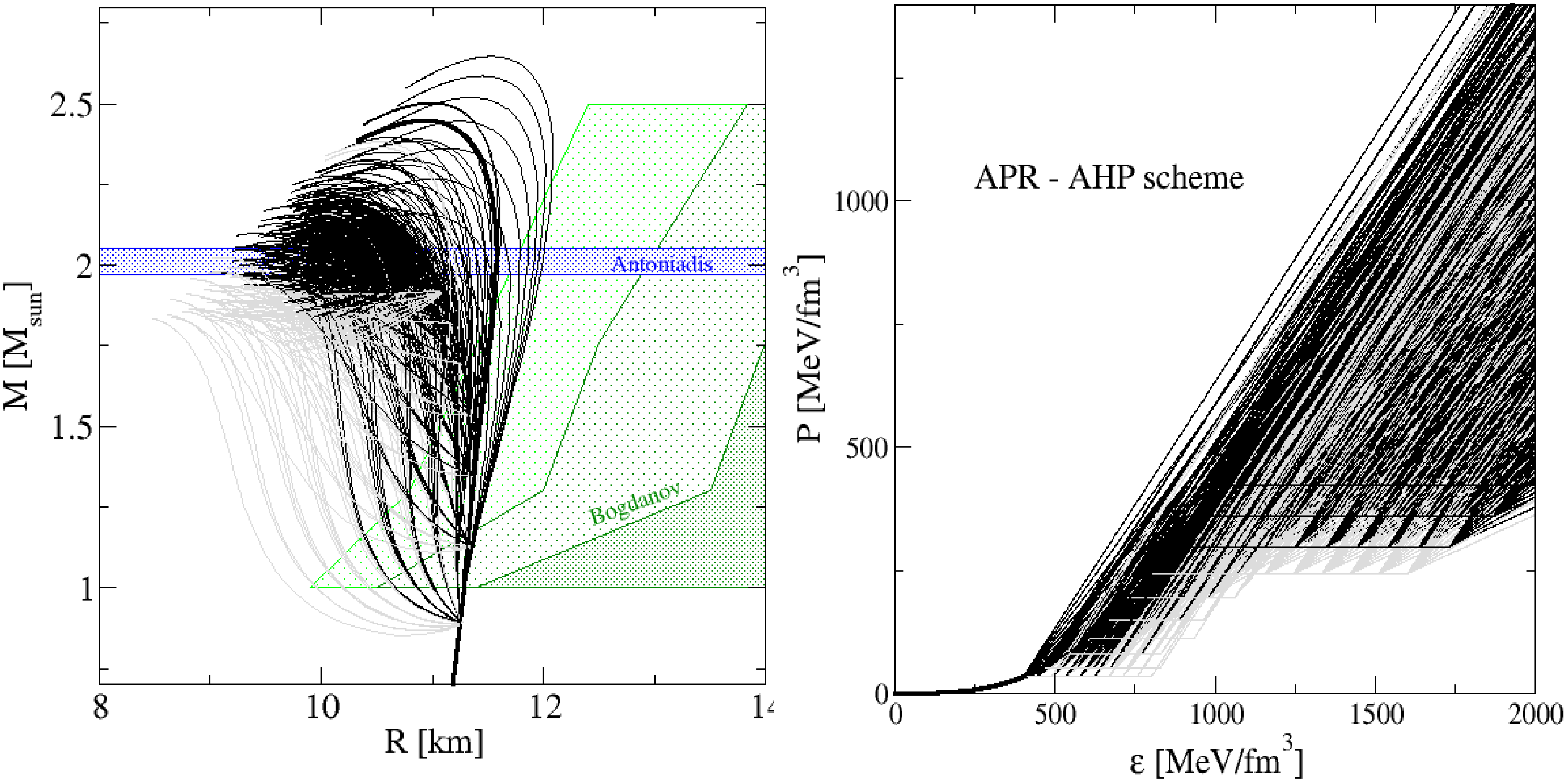
SUMMARY:

- excluded volume (quark Pauli blocking) important
- high-density quark matter slightly stiffer eta_v=0.25
- the scaled energy density jump (0.65) fulfills the twin condition of the schematic model by Alford et al. (2013

→ **Astronomers: Find disconnected star branches !!**

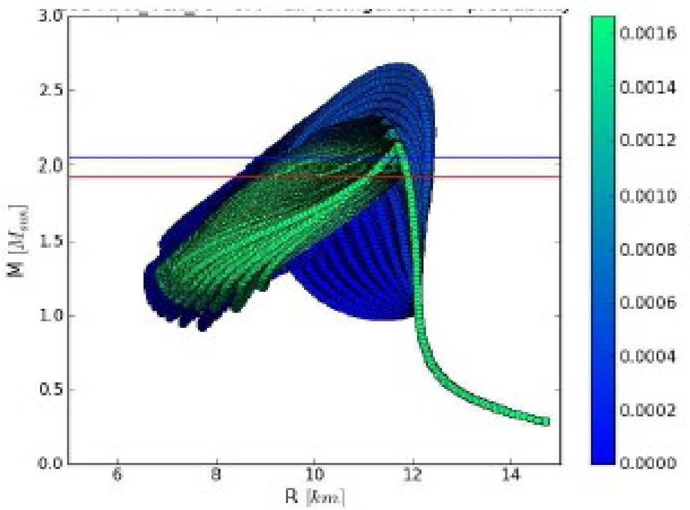
Main Problem:
Measure Compact Star Radii!

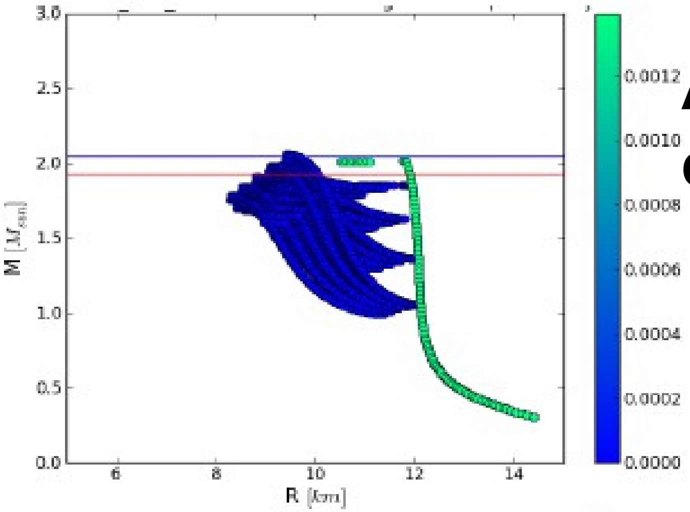
Disjunct M-R constraints for Bayesian analysis !



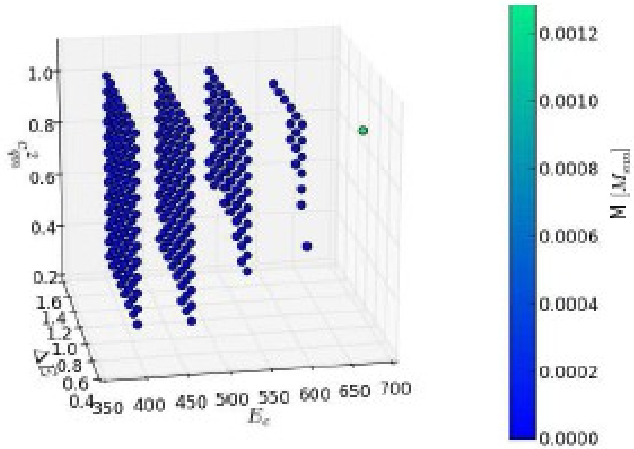
Blaschke, Grigorian, Alvarez, Ayriyan, J. Phys. Conf. Ser. 496 (2014) 012002

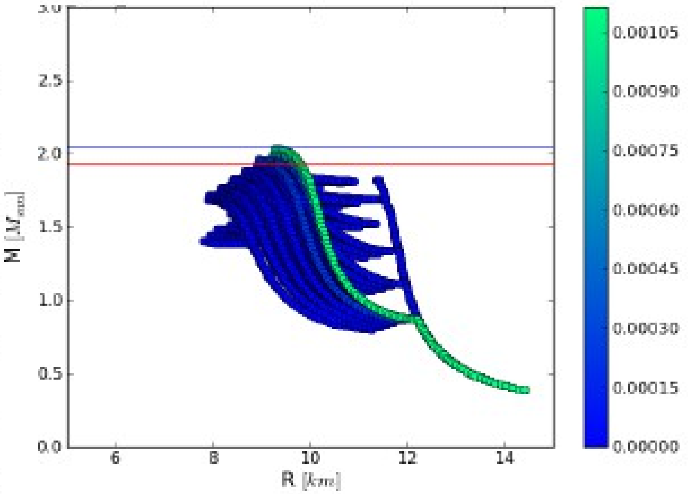
Phase transition? Measure different radii at 2Mo !





APR EoS with excluded volume

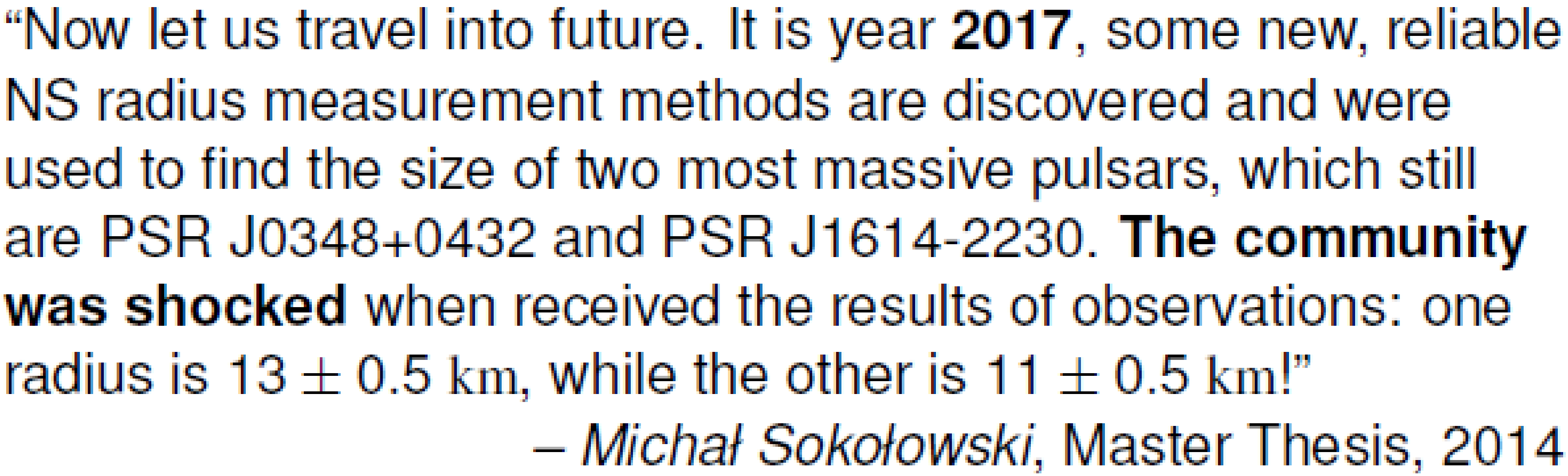




APR EoS without excluded volume

arez, Ayriyan, Blaschke, Grigorian, Sokolowski (in progress, 2014)

Phase transition? Measure different radii at 2Mo !

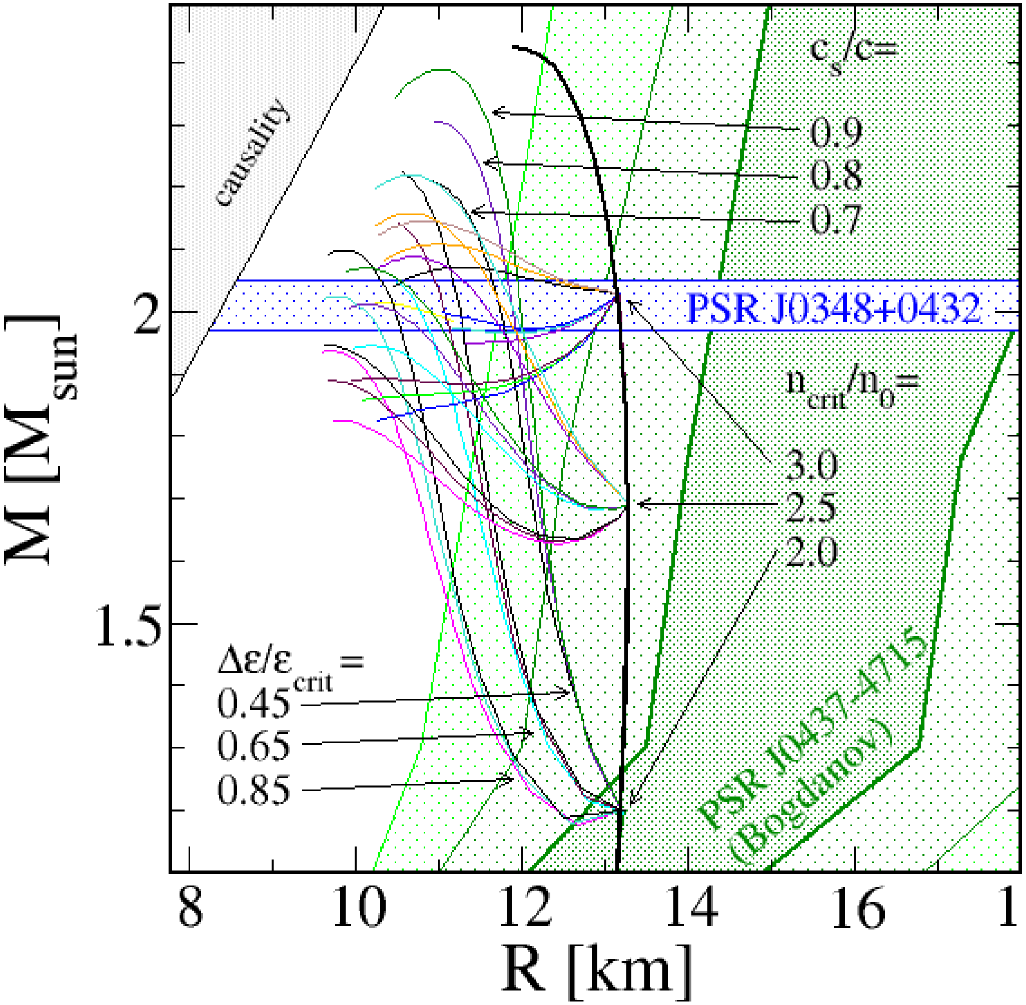


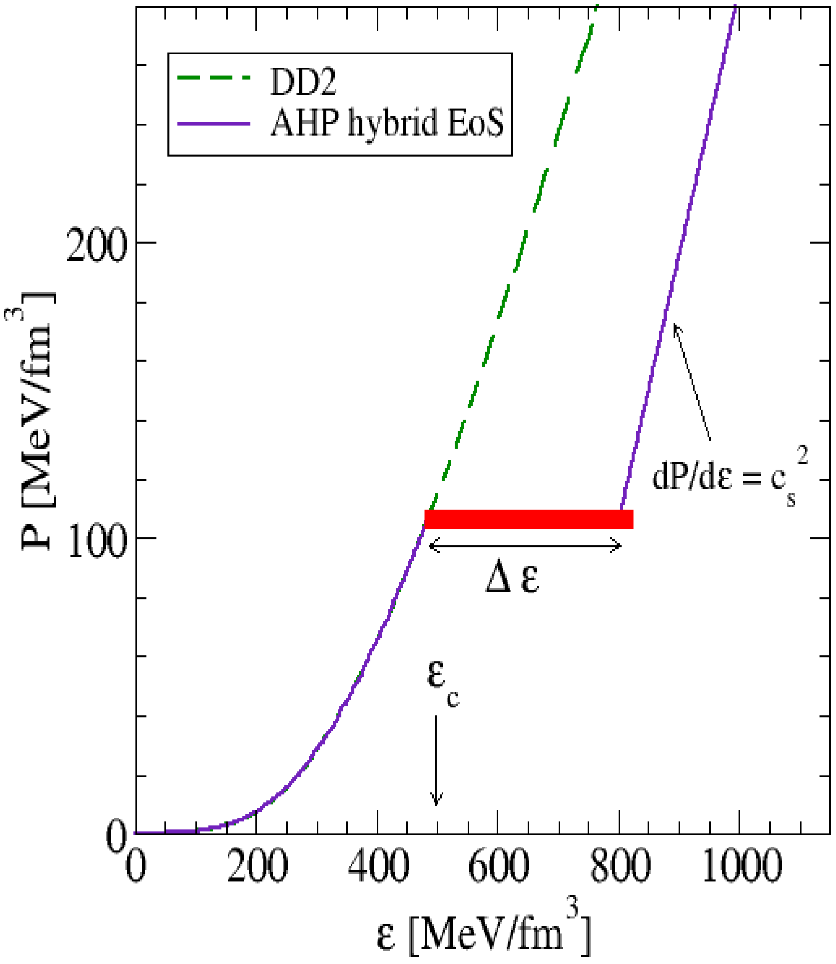
"Now let us travel into future. It is year **2017**, some new, reliable NS radius measurement methods are discovered and were used to find the size of two most massive pulsars, which still are PSR J0348+0432 and PSR J1614-2230. **The community was shocked** when received the results of observations: one radius is 13 ± 0.5 km, while the other is 11 ± 0.5 km!"

– *Michał Sokołowski*, Master Thesis, 2014

Alvarez, Ayriyan, Blaschke, Grigorian, Sokolowski (in progress, 2014)

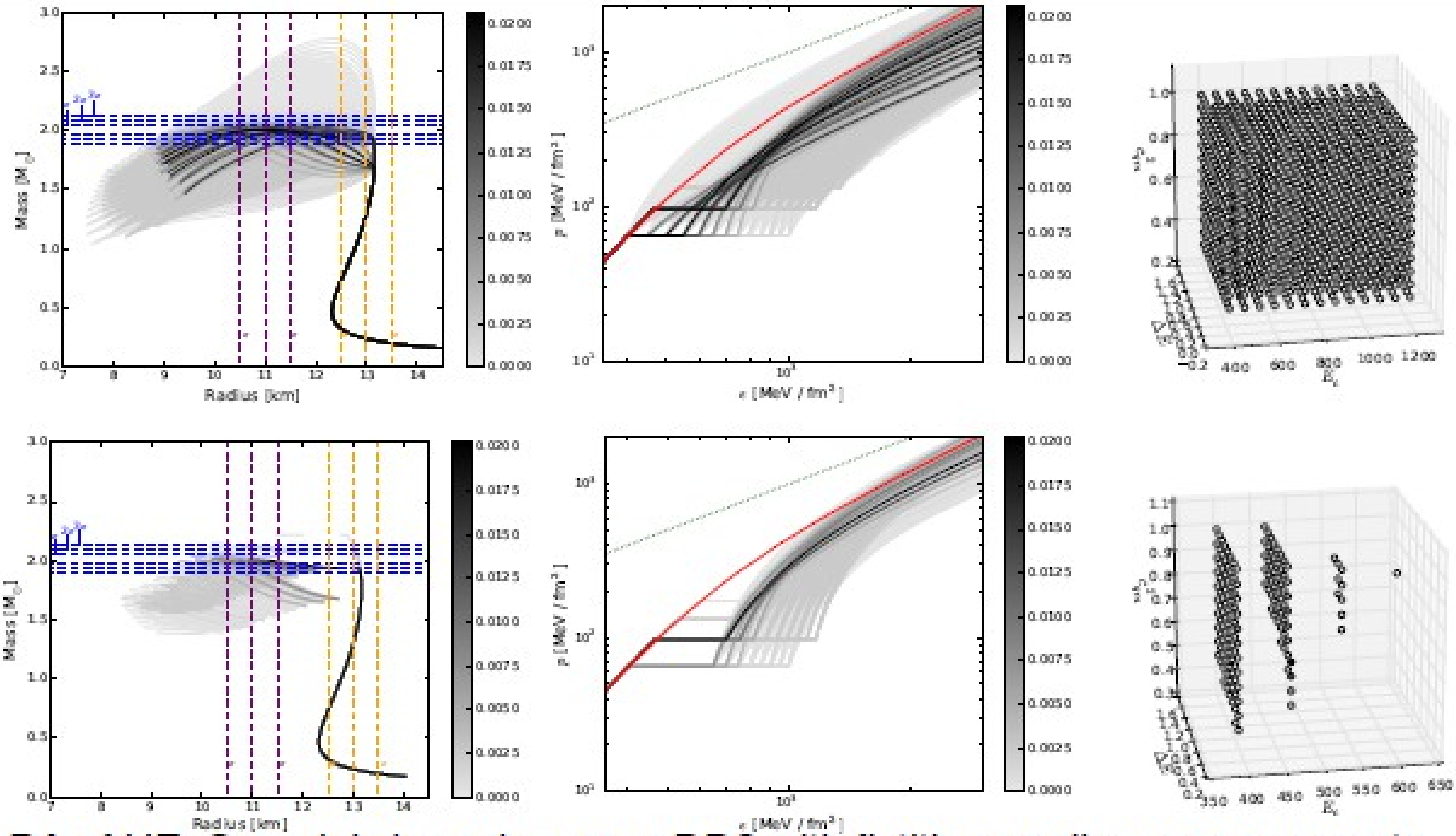
Phase transition? Measure different radii at 2Mo !





Alvarez, Ayriyan, Blaschke, Grigorian, Sokolowski (work in progress, 2014)

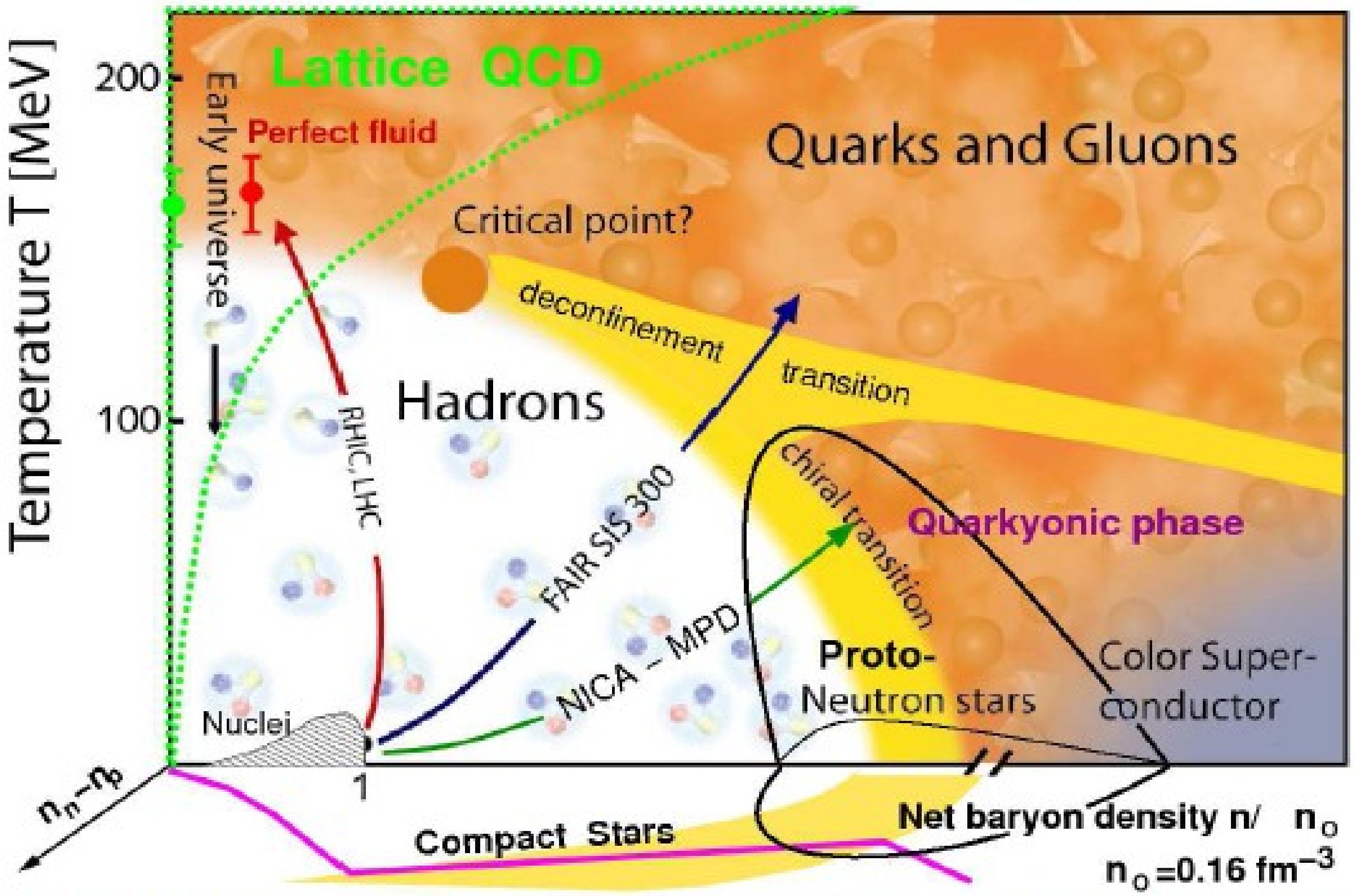
Phase transition? Measure different radii at 2Mo !



BA of HEoS models based on pure DD2 with fictitious radius measurements.

Alvarez, Ayriyan, Blaschke, Grigorian, Sokolowski (work in progress, 2014)

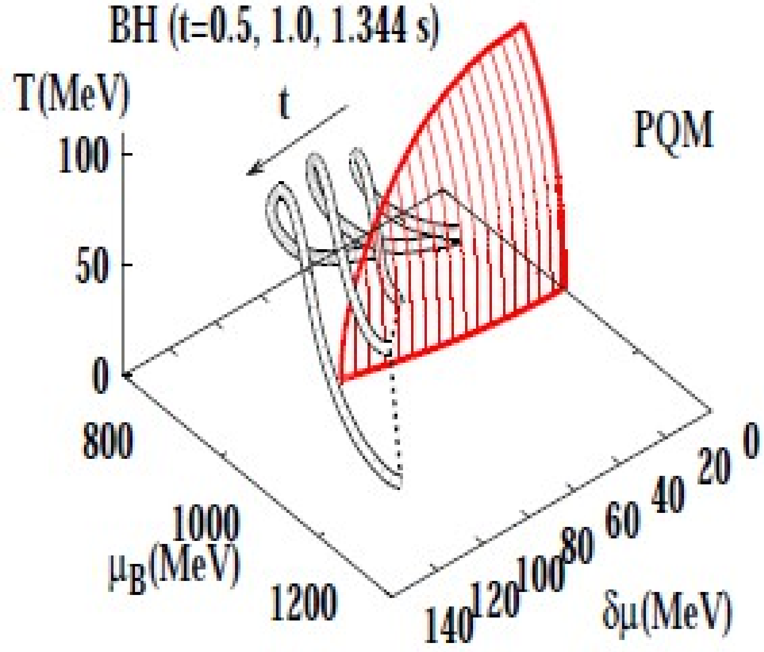
How to probe the line of CEP's in Astrophysics?

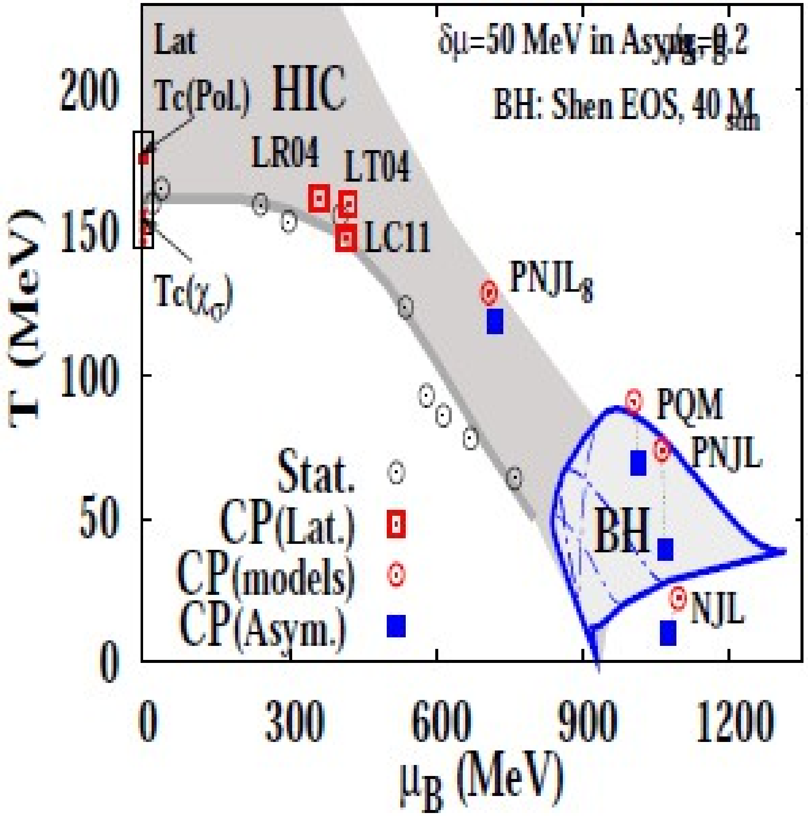


NICA White Paper, `http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome`

How to probe the line of CEP's in Astrophysics?

by sweeping (“flyby”) the critical line in SN collapse and BH formatio



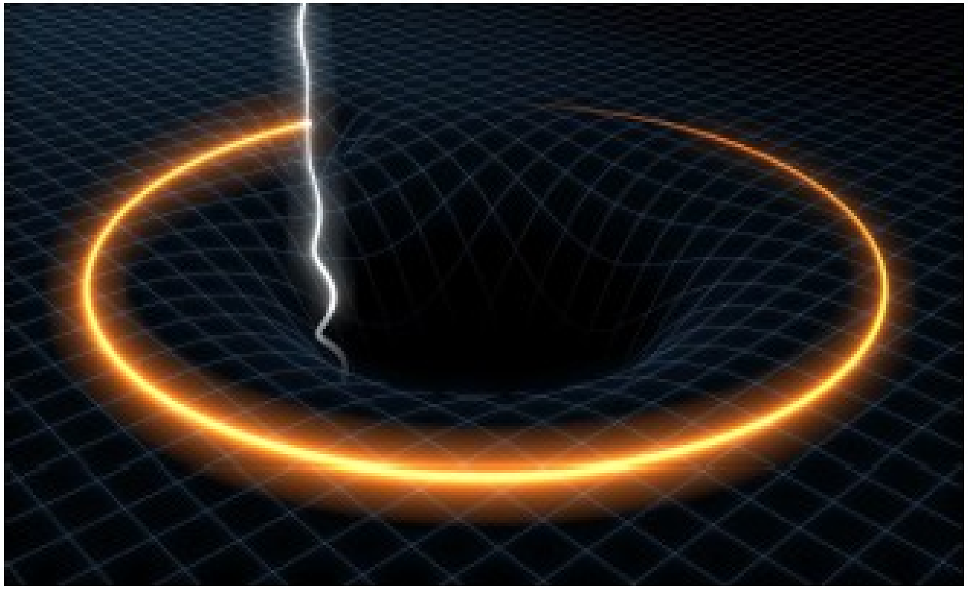


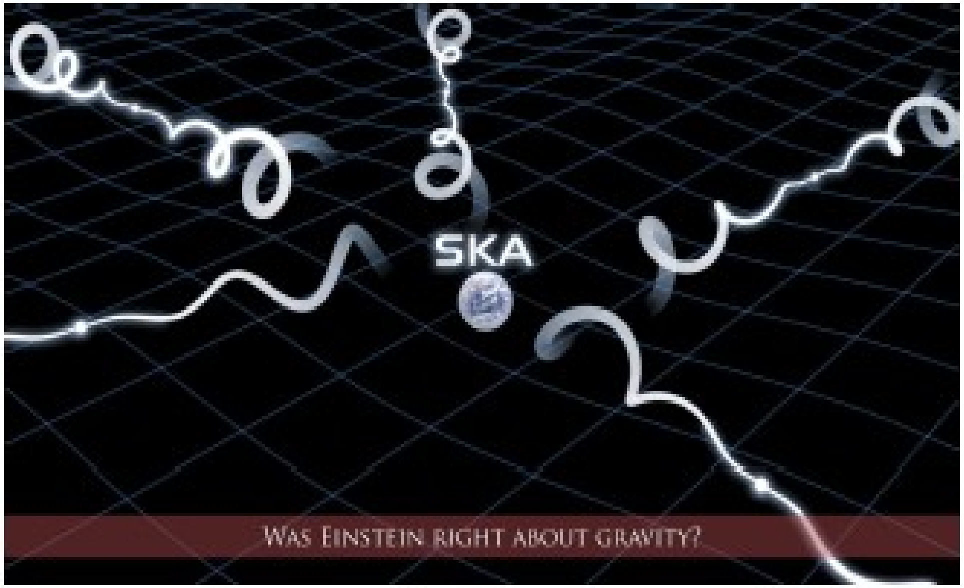
A. Ohnishi, H. Ueda, T. Nakano, M. Ruggieri, K. Sumiyoshi, Phys. Lett. B **704**, (2011) 284.

Perspectives for new Instruments?

THE FUTURE: SKA - SQUARE KILOMETER ARRAY

THE FUTURE: SKA - SQUARE KILOMETER ARRAY



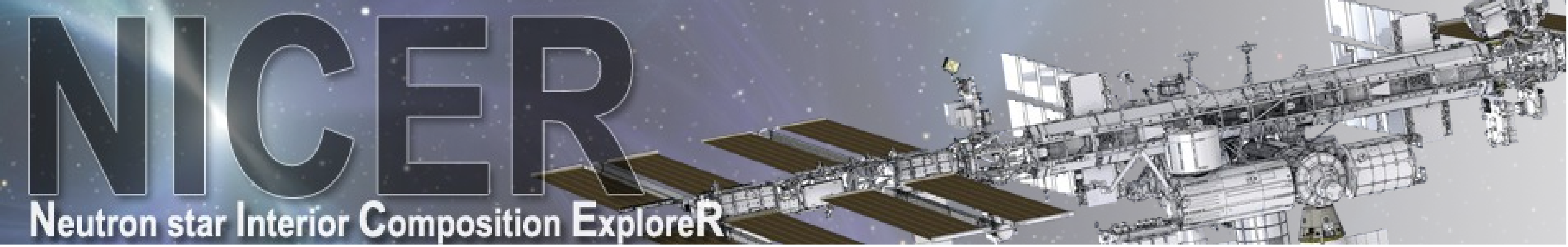


SKA Facts:

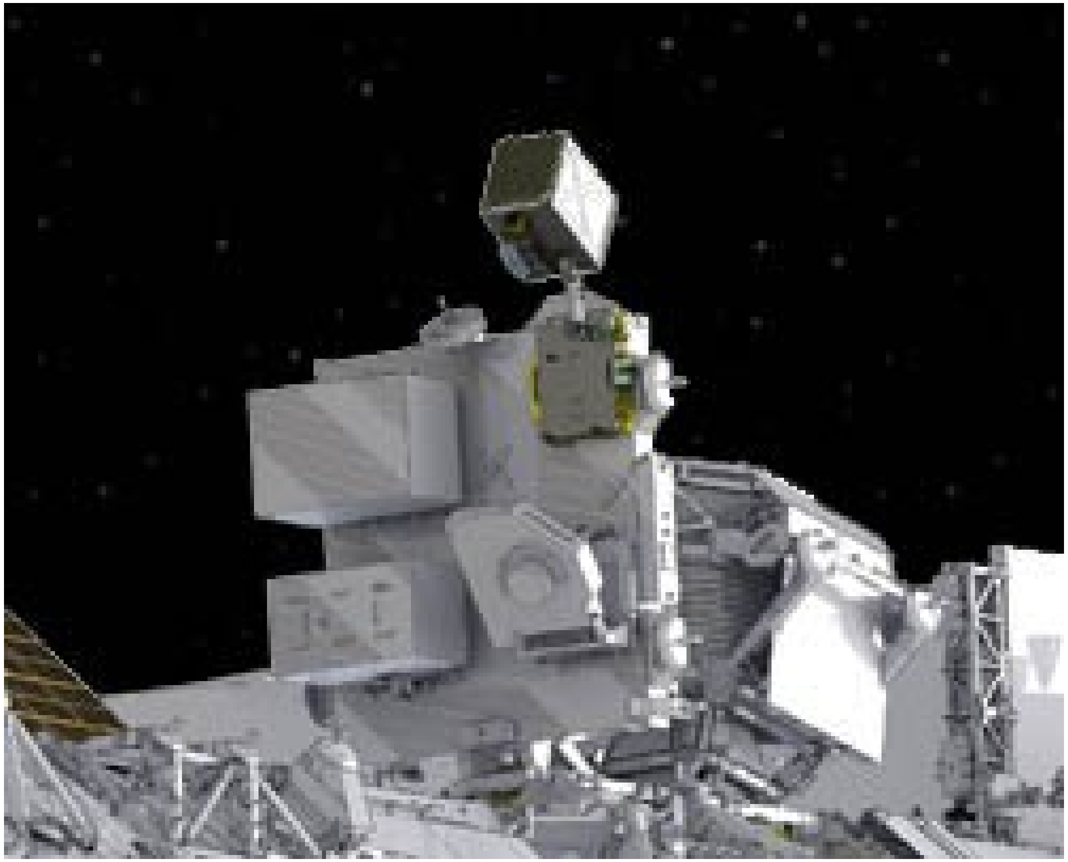
- The dishes of the SKA will produce 10 times the global internet traffic
- The data collected by the SKA in a single day would take nearly two million years to playback on an ipod
- The SKA will be so sensitive that it will be able to detect an airport radar on a planet 50 light years away

Discovery Potential:

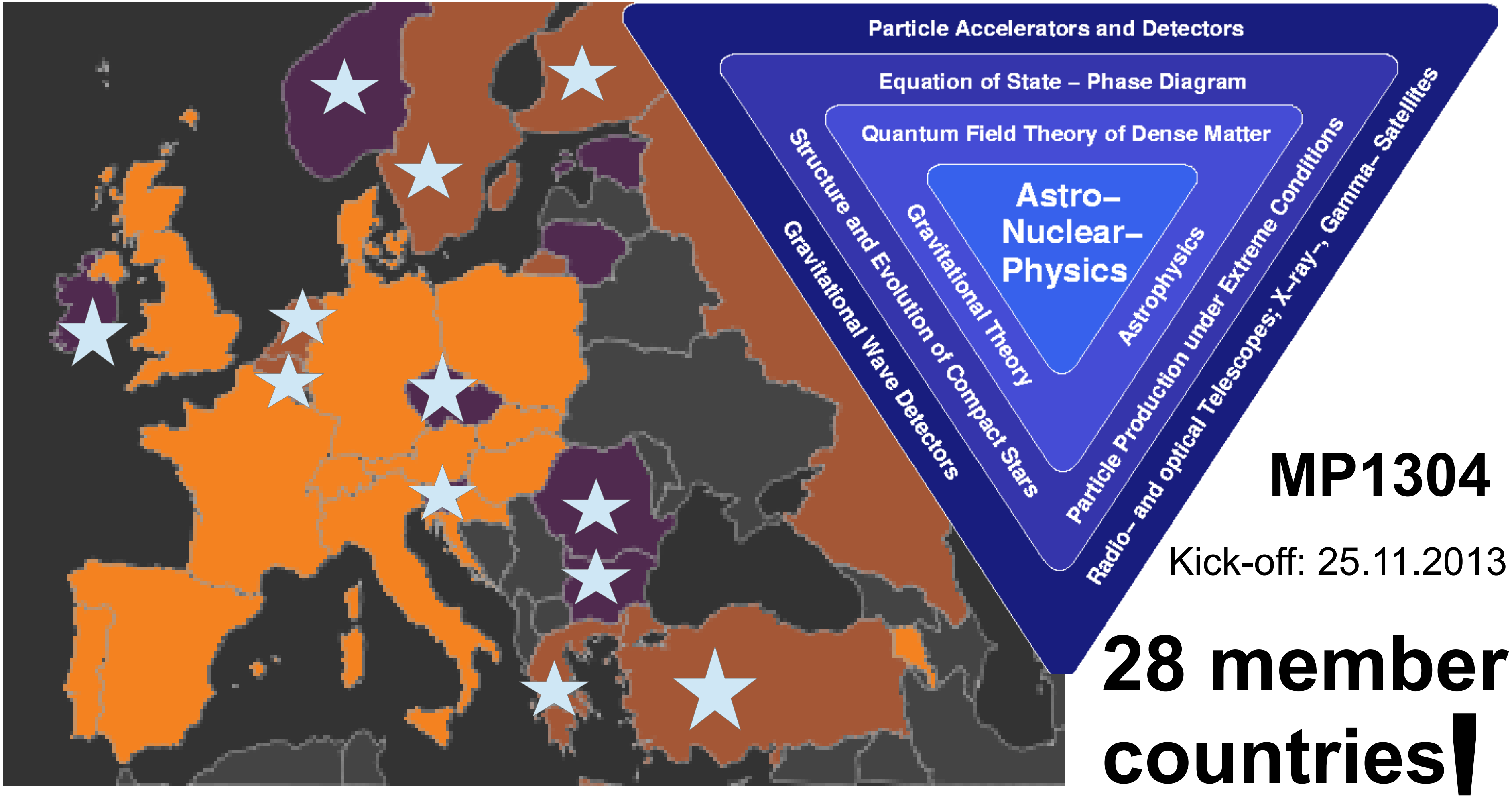
- Find a Pulsar - Black Hole Binary
- Constrain Einstein Gravity
- Gravitational waves



- approved NASA Explorer Mission of Opportunity dedicated to the study of the extraordinary gravitational, electromagnetic, and nuclear-physics environments embodied by neutron stars.
- NICER will explore the exotic states of matter inside these stars, where density and pressure are higher than in atomic nuclei, confronting theory with unique observational constraints.
- rotation-resolved spectroscopy of the thermal and non-thermal emissions of neutron stars in the soft (0.2-12 keV) X-ray band with unprecedented precision.
- lowing launch in late 2016, an X-ray timing and spectroscopy instrument aboard the International Space Station (ISS).



NICER Mission:
Study exotic states of matter in neutron stars!
Launch: late 2016



MP1304

Kick-off: 25.11.2013

28 member countries!

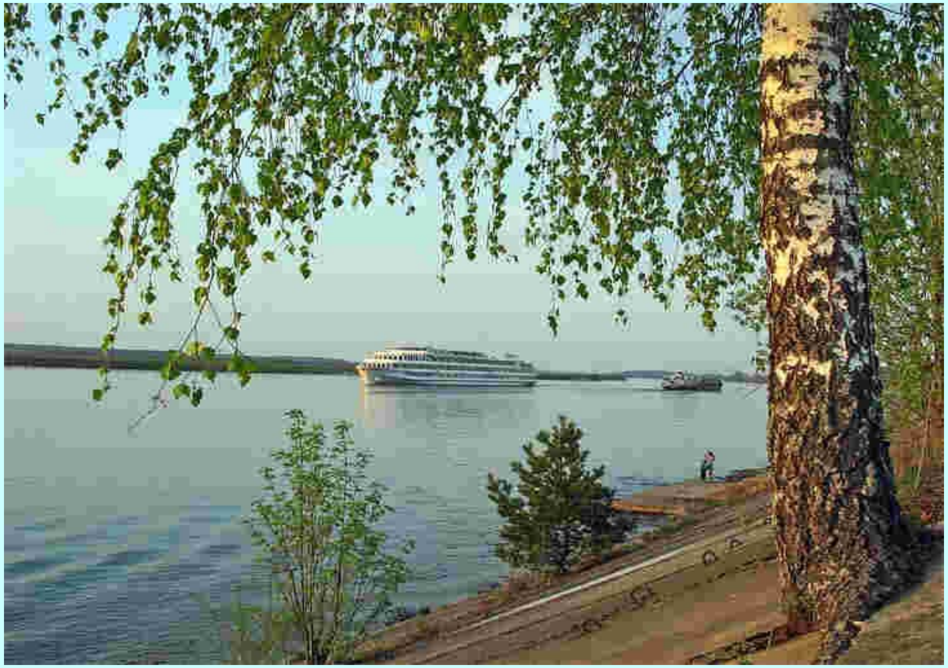
New compstar !

cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

http://compstar.uni-frankfurt.de

Strangeness in Quark Matter 2015

Dubna, 6.-11. July 2015



Official Logo:

SQM

DUBNA 2015

Email: sqm@jinr.ru

Website: http://sqm.jinr.ru

Satellite Meetings:

Summer School “Dense Matter”, Dubna, June 29 – July 4, 2015

Roundtable “Physics at NICA”, Dubna, 5. July 2015

Welcome to the collaboration!

JOINT INSTITUTE
JINR
FOR NUCLEAR
RESEARCH

NICA

Thank you for attention!