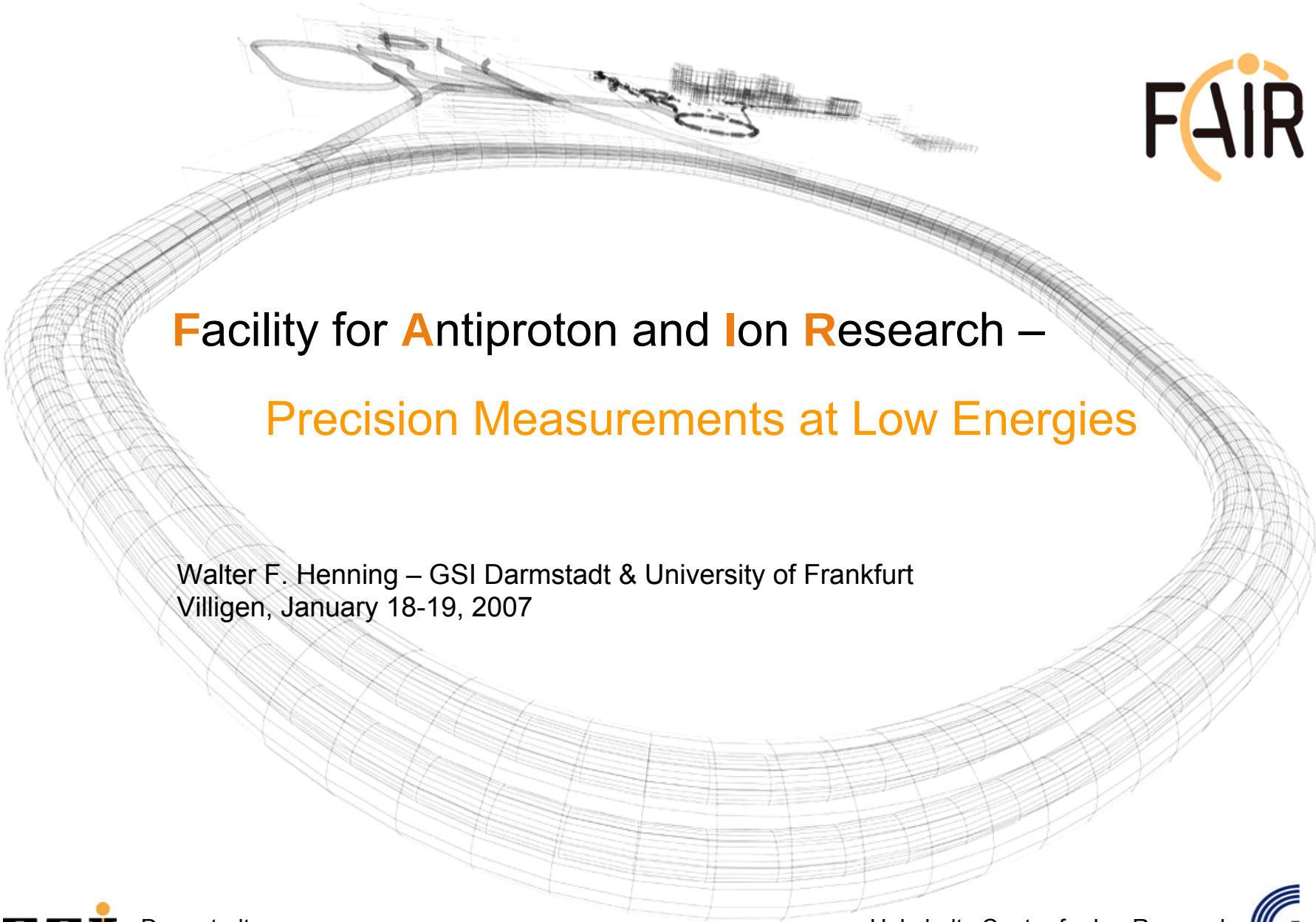


Facility for Antiproton and Ion Research –

Precision Measurements at Low Energies

Walter F. Henning – GSI Darmstadt & University of Frankfurt
Villigen, January 18-19, 2007

Precision Measurements at Low Energies

- Atomic Physics: Low energy QED and tests of the SM (cooled U^{91+})
  Low energy CPT tests (antiproton/hydrogen-atom/molecule)
  Parity violation
  Fermion condensates
- Nuclear Physics: Masses (SBD & CKM matrix; I & CE effects; dripline nuclei)
  Weak decays (ß-v correlations & SM)
  Baryonic molecules (shape isomers; nucleon driplines)
  Cold Coulomb barrier reactions (SHE)
- Hadron Physics: Low momentum, non-perturbative QCD
  Low energy meson spectrum and QCD exotics
  Infra-red divergence of gluon fields ($x<<1$)
- Nuclear (QCD) Matter Physics:
  Low temperature QCD phase diagram
  Phase boundary and QCD Critical point

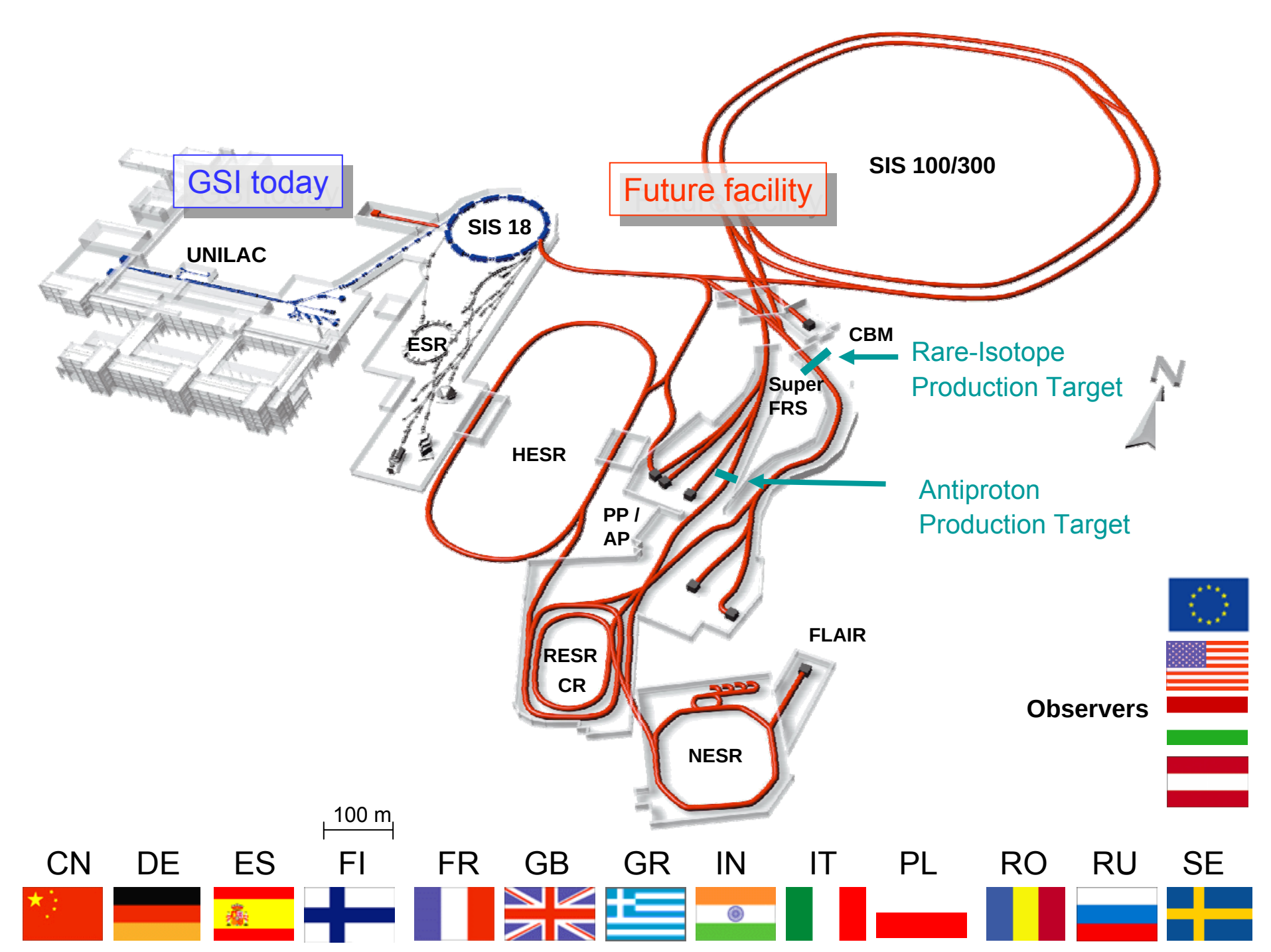
Facility for Antiproton and Ion Research –

Precision Measurements at Low Energies

Walter F. Henning – GSI
Villigen, January 18-19, 2007

- Introduction - a (very) brief description of the Facility
- Science Motivation and Goals
- Outlook

Brief Description of the Facility


GSI today
Future facility
SIS 100/300
SIS 18
UNILAC
ESR
CBM
Rare-Isotope
Production Target
Super
FRS
HESR
Antiproton
Production Target
PP /
AP
FLAIR
RESR
CR
NESR
Observers
100 m
CN
DE
ES
FI
FR
GB
GR
IN
IT
PL
RO
RU
SE

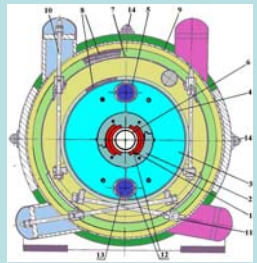
Two Stage Synchrotron SIS100/300

- **SIS100: High Intensity Booster and Compressor**

  rapidly-cycling s.c. magnets (B_{max} = 2 T; dB/dt = 4 T/s)
  U^{28+} up to 2.7 GeV/u Protons up to 30 GeV

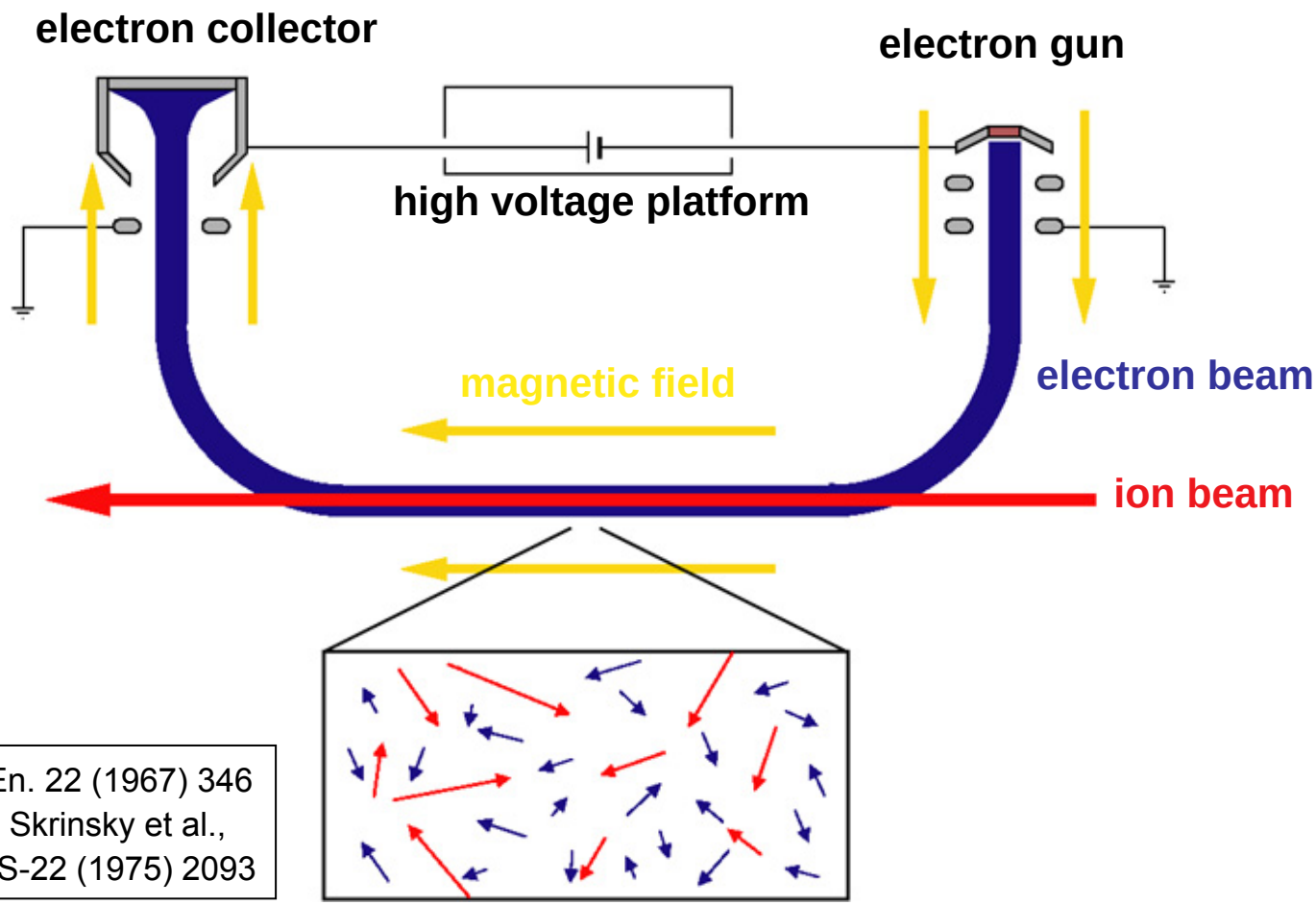
- **SIS300 High Energy Ring and Stretcher**

  fast s.c. high-field magnets (B_{max} = 4.5 T - dB/dt = 1 T/s)
  U^{92+} up to 34 GeV/u (q/A=0.5 45 GeV/u)
  U^{28+}at 1.5 to 2.7 GeV/u with 100% duty cycle



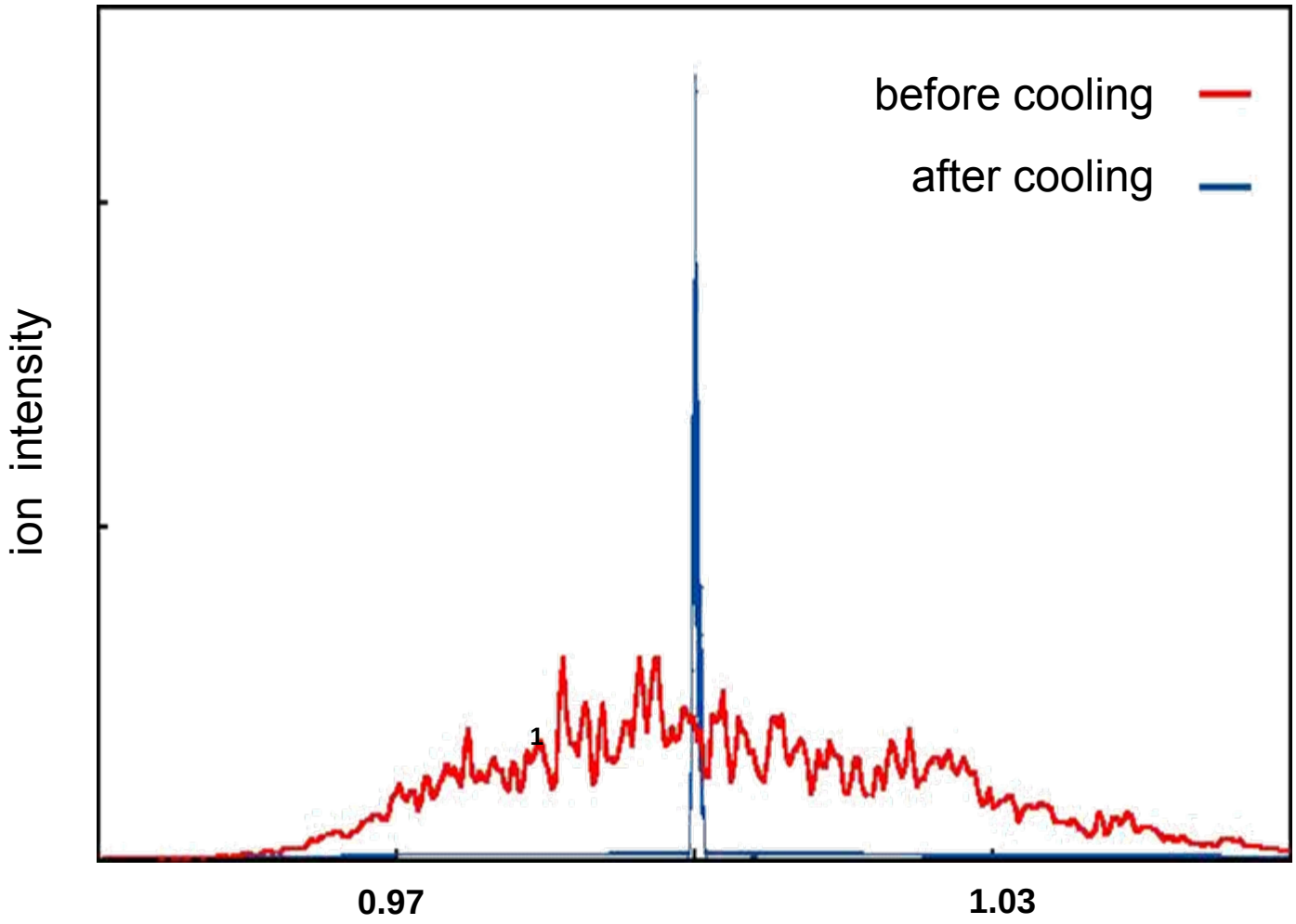
SIS100	
Heavy Ion Operation	U^{28+} : Fast Extract.: $6x10^{11}$ ppp Slow Extract. Possible
Proton Operation	p: Fast Extract.: 2.5 – $5x10^{13}$ ppp
SIS300	
Heavy Ion Stretcher Mode	U^{28+} : Slow Extract.: $3x10^{11}$ pps (d.c.)
Heavy Ion High Energy Mode	U^{92+} : Slow Extract.: $1x10^{10}$ pps

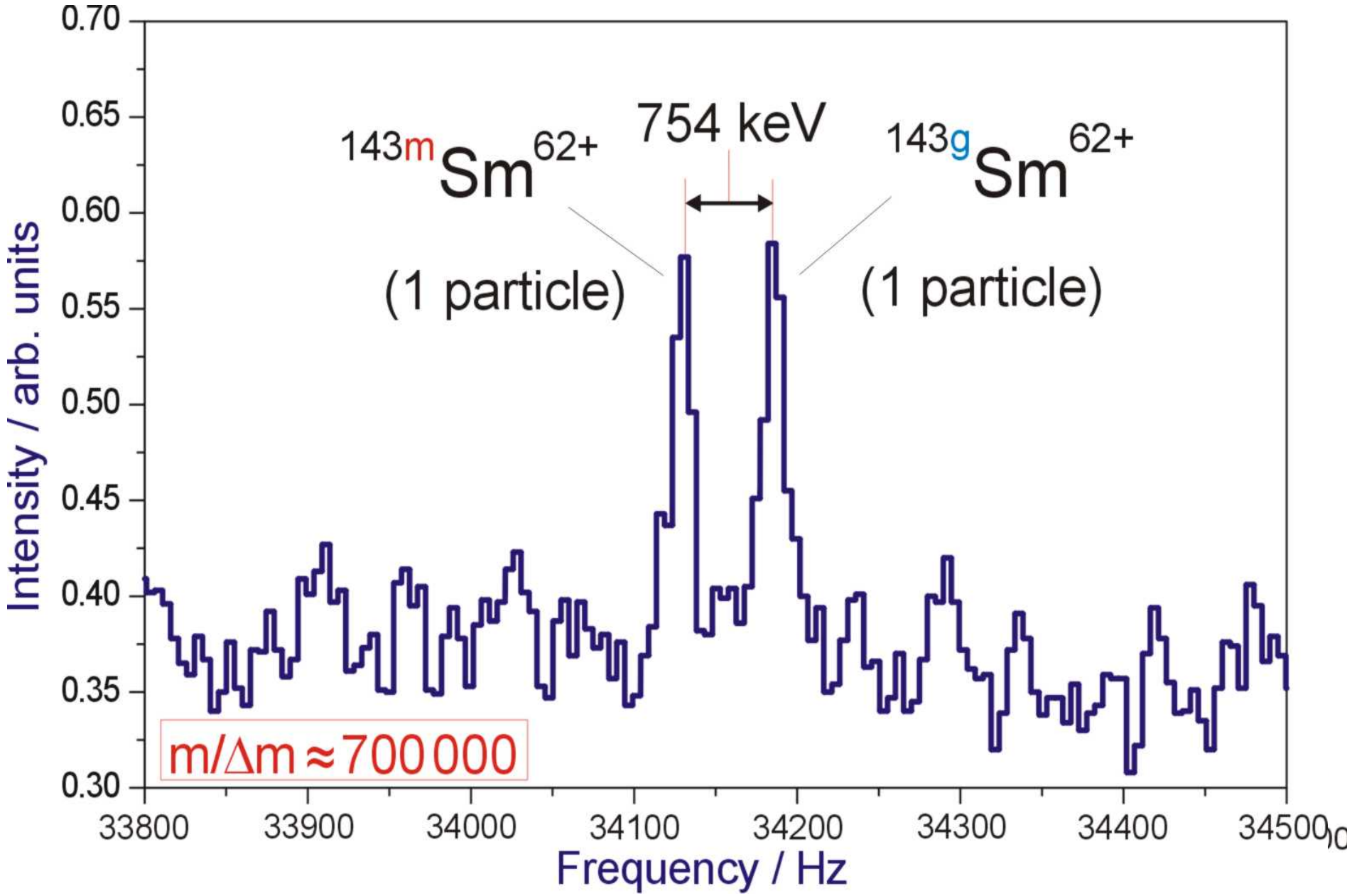
Electron-Beam Cooled Ion & Antiproton Beams



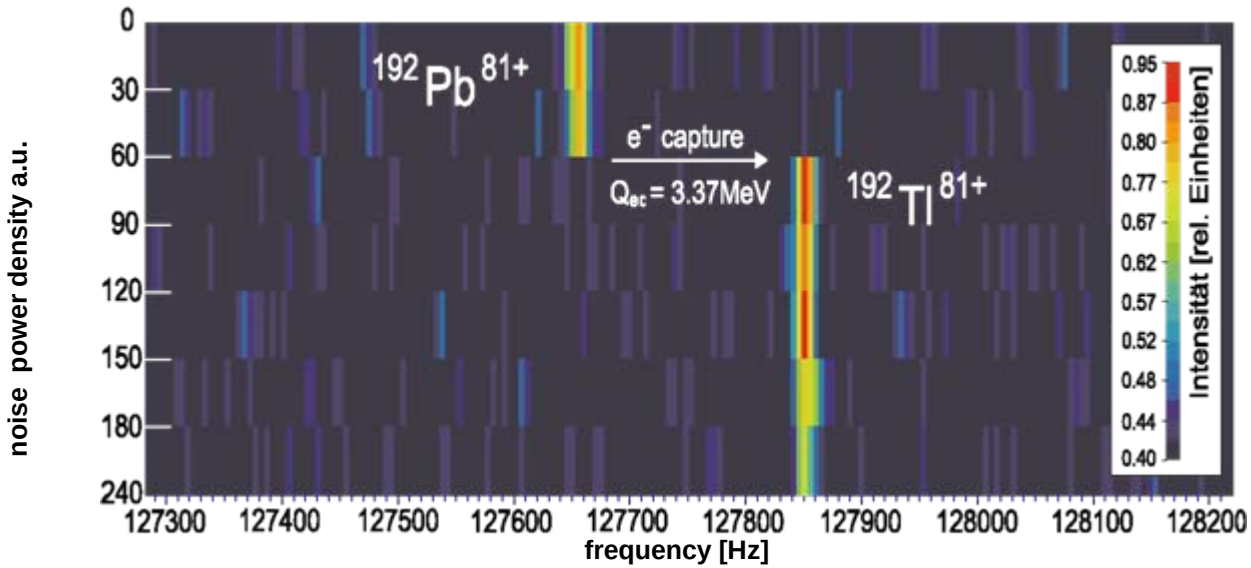
G.I. Budker, At. En. 22 (1967) 346
G.I. Budker, A.N. Skrinsky et al.,
IEEE NS-22 (1975) 2093

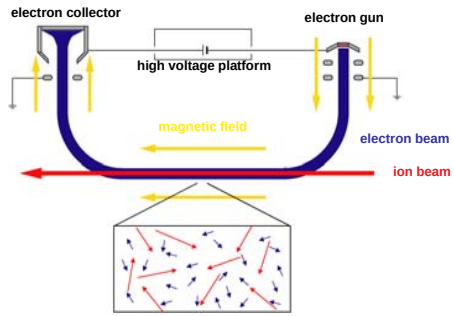
Ion Beam Cooling ...

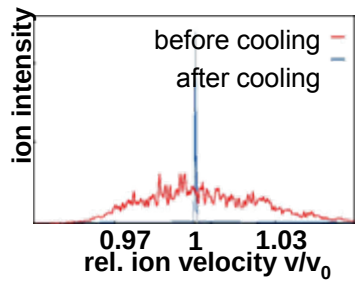


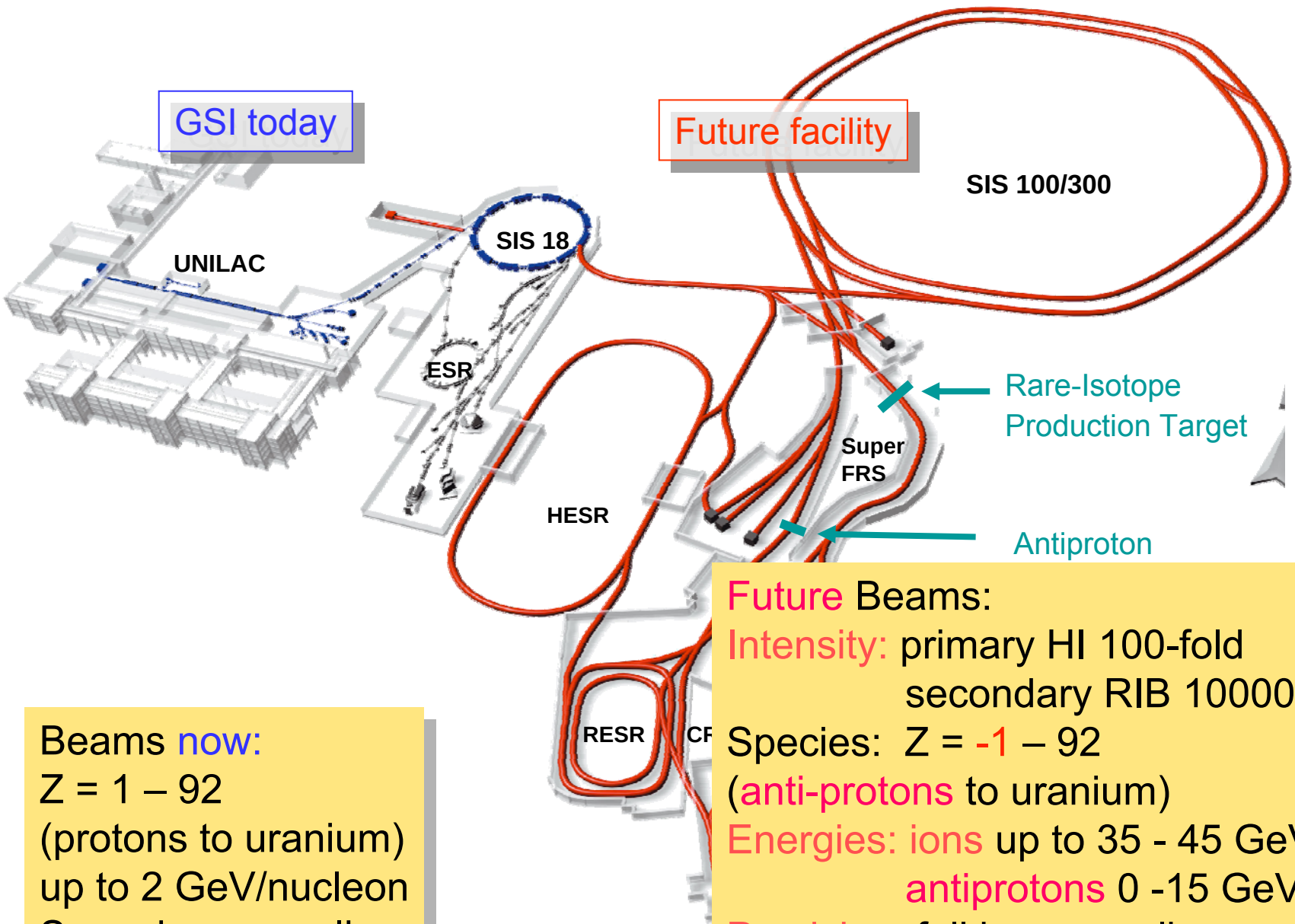

0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
Intensity / arb. units
143m Sm 62+
754 keV
143g Sm 62+
(1 particle)
(1 particle)
m/Δm ≈ 700 000
33800
33900
34000
34100
34200
34300
34400
34500
Frequency / Hz

Storage Rings: Cooled Ion Beams









Beams now:
Z = 1 – 92
(protons to uranium)
up to 2 GeV/nucleon
Some beam cooling

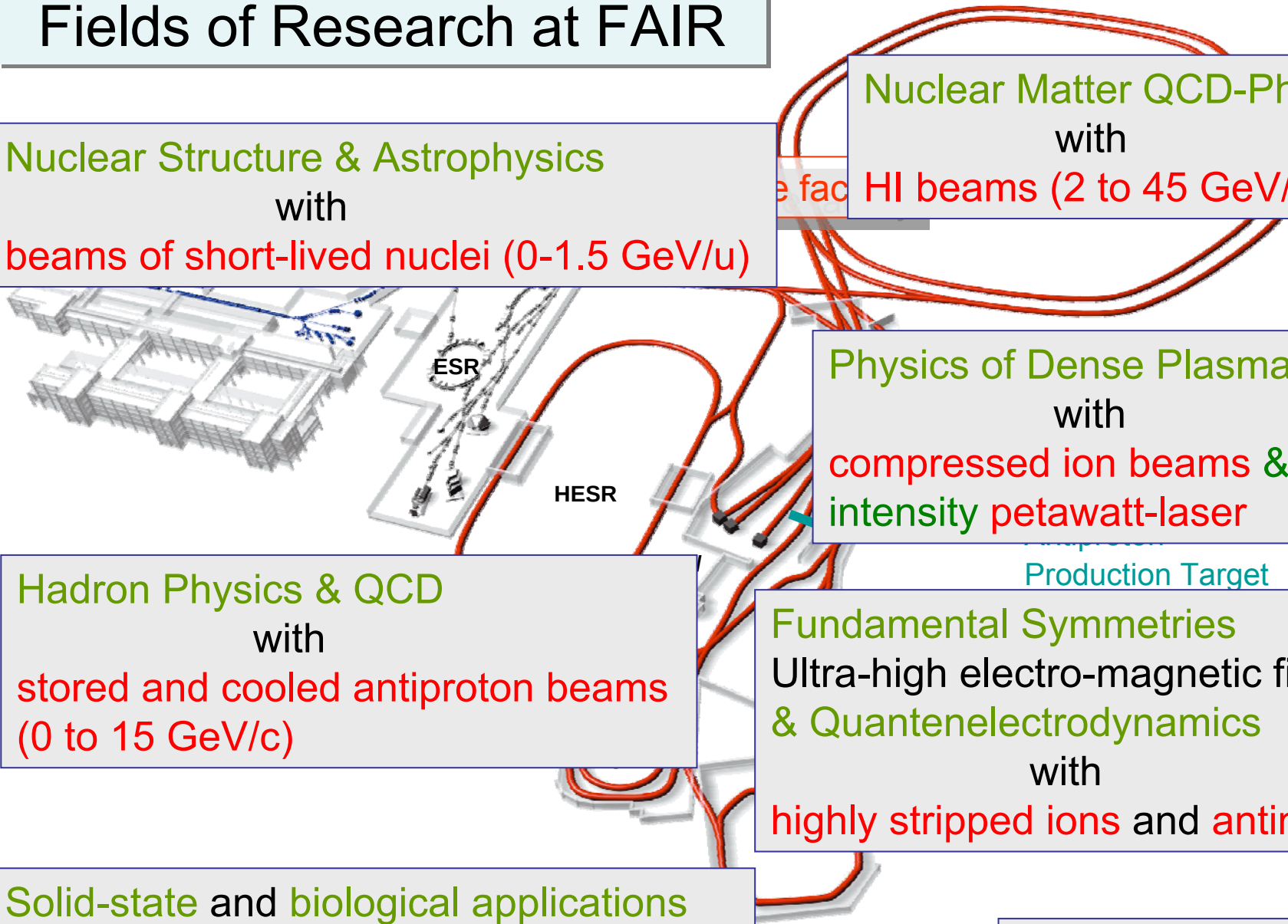
Future Beams:
Intensity: primary HI 100-fold
secondary RIB 10000-fold
Species: Z = -1 – 92
(anti-protons to uranium)
Energies: ions up to 35 - 45 GeV/u
antiprotons 0 -15 GeV/c
Precision: full beam cooling

Science Motivation & Research Programs

Fields of Research at FAIR

Nuclear Structure & Astrophysics
with
beams of short-lived nuclei (0-1.5 GeV/u)

Nuclear Matter QCD-Physics
with
HI beams (2 to 45 GeV/u)



Physics of Dense Plasmas
with
compressed ion beams & high-intensity petawatt-laser

Hadron Physics & QCD
with
stored and cooled antiproton beams
(0 to 15 GeV/c)

Fundamental Symmetries
Ultra-high electro-magnetic fields
& Quantenelectrodynamics
with
highly stripped ions and antimatter

Solid-state and biological applications
with
ion (& antiproton?) beams

Accelerator Physics

FAIR Baseline Technical Report 2006

Volume 1: Executive Summary

Volume 2: Technical Report A
ca. 700 pages

Volume 3: Techn. Experimen
ca. 450 pages

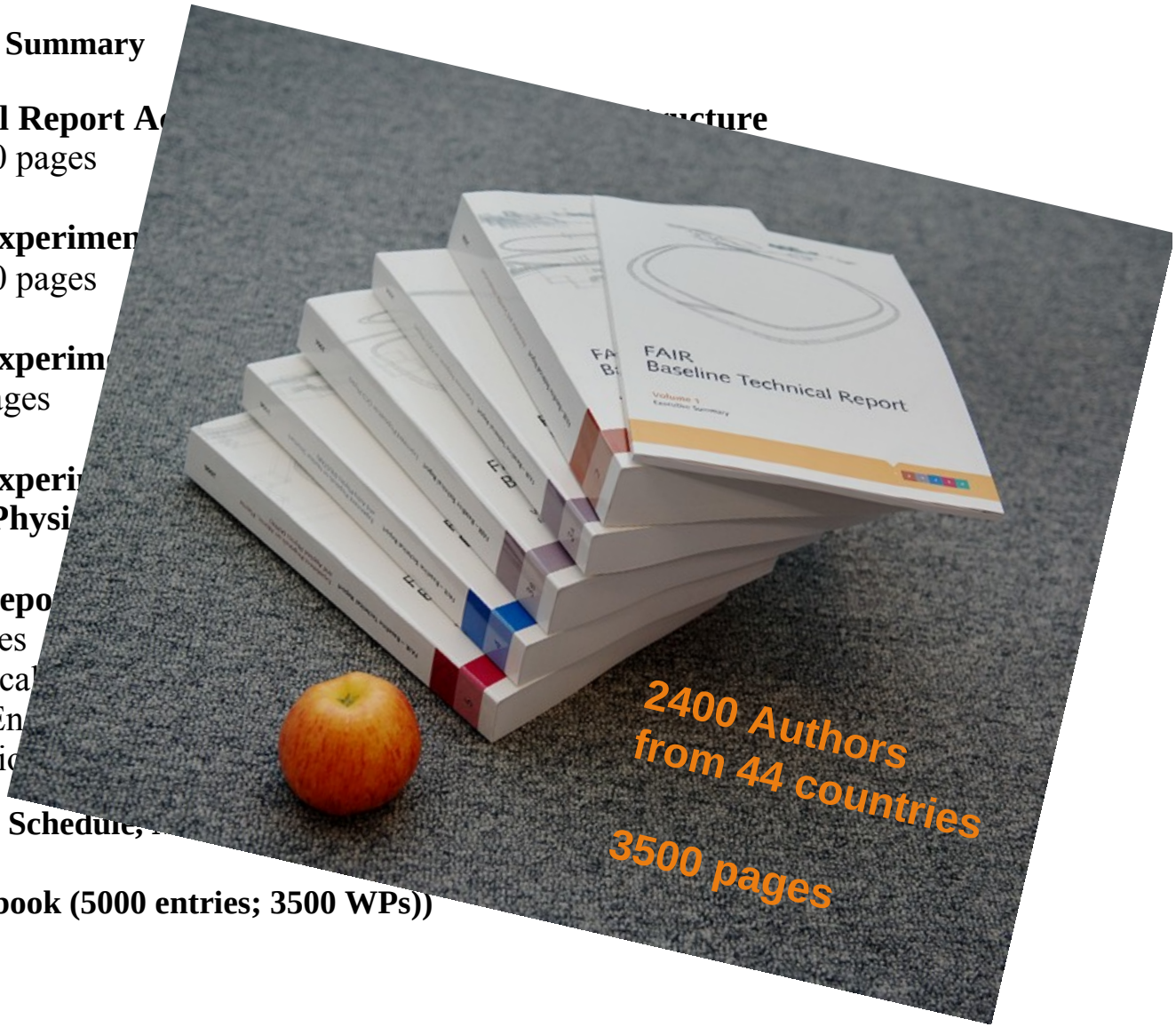
Volume 4: Techn. Experim
ca. 700 pages

Volume 5: Techn. Experi
Applied Physi

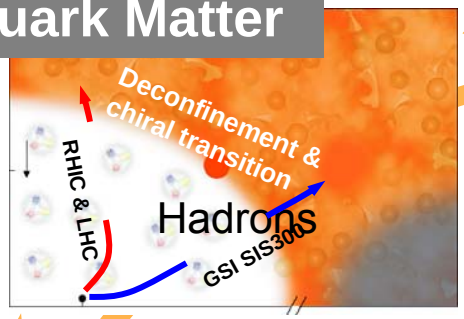
Volume 6: Techn. Repo
a. Supplies
b. Electrical
c. Civil En
d. Radiatio

Supplement 1: Cost, Schedule,

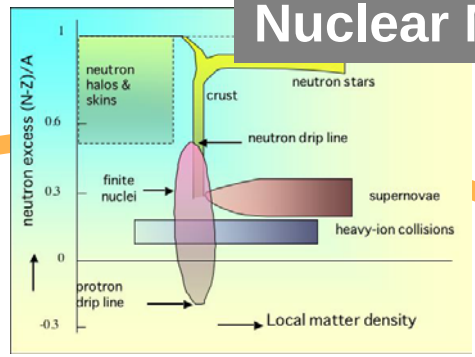
Supplement 2: Costbook (5000 entries; 3500 WPs))

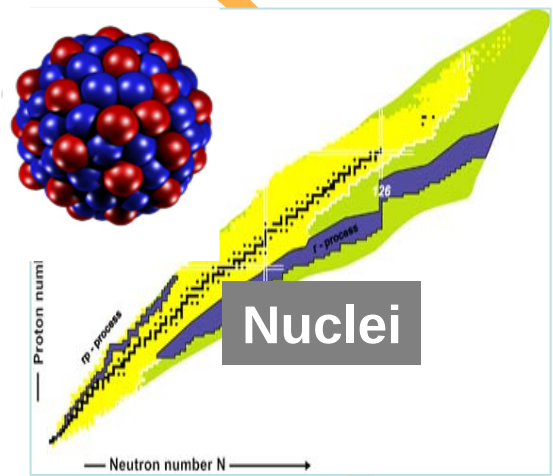


Quark Matter



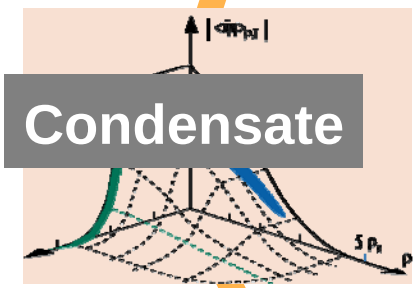
Nuclear Matter



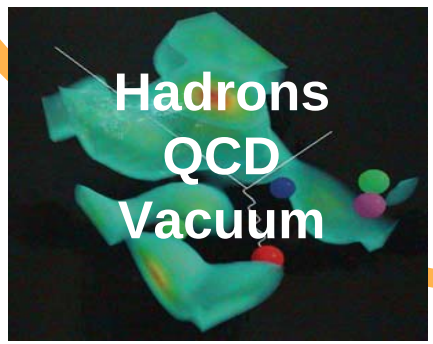


Nuclei

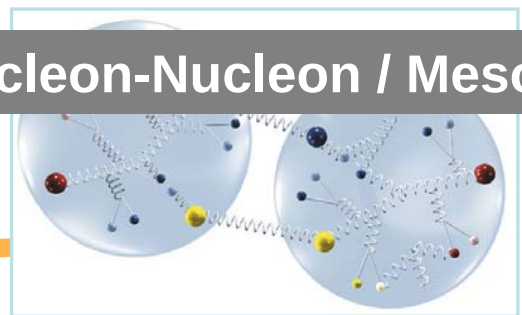
Condensate

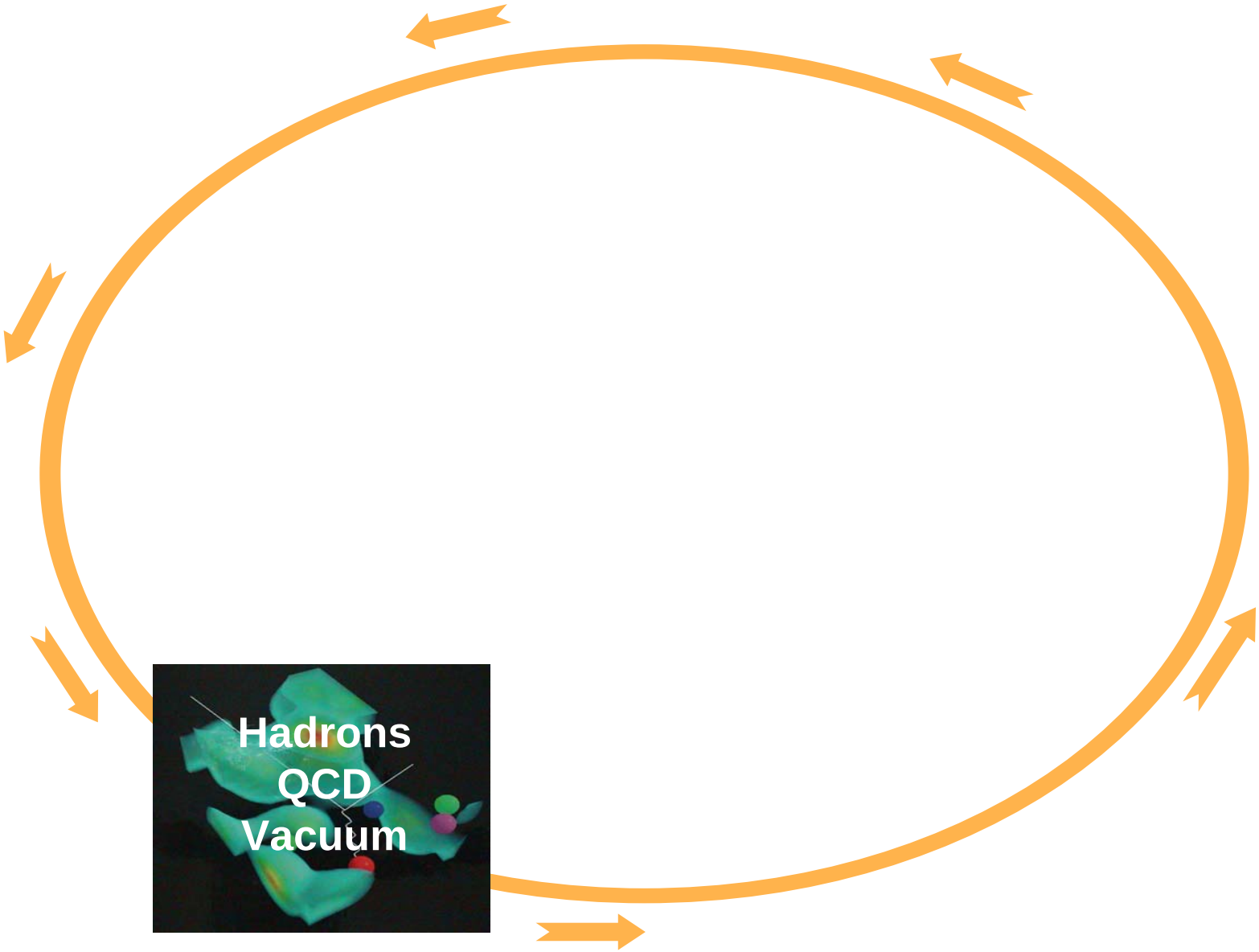


Hadrons
QCD
Vacuum



Nucleon-Nucleon / Meson

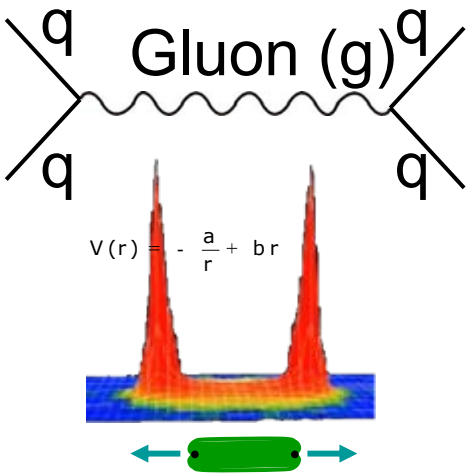



Hadrons
QCD
Vacuum

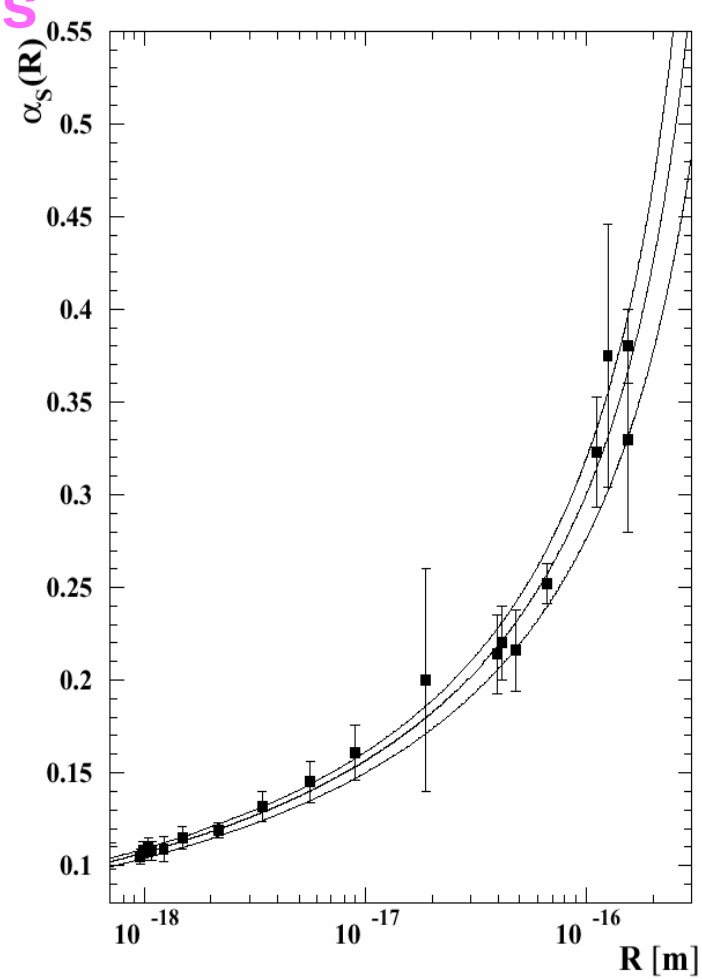
Transition from the perturbative to the non-perturbative regime of Quantum-Chromodynamics (QCD)

Particle physics

perturbative:
QCD: $a_S << 1$

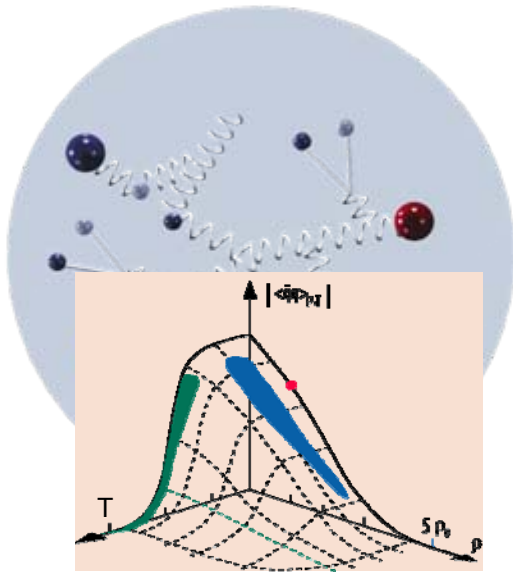


Quarks, Gluons
One-Gluon Exchange



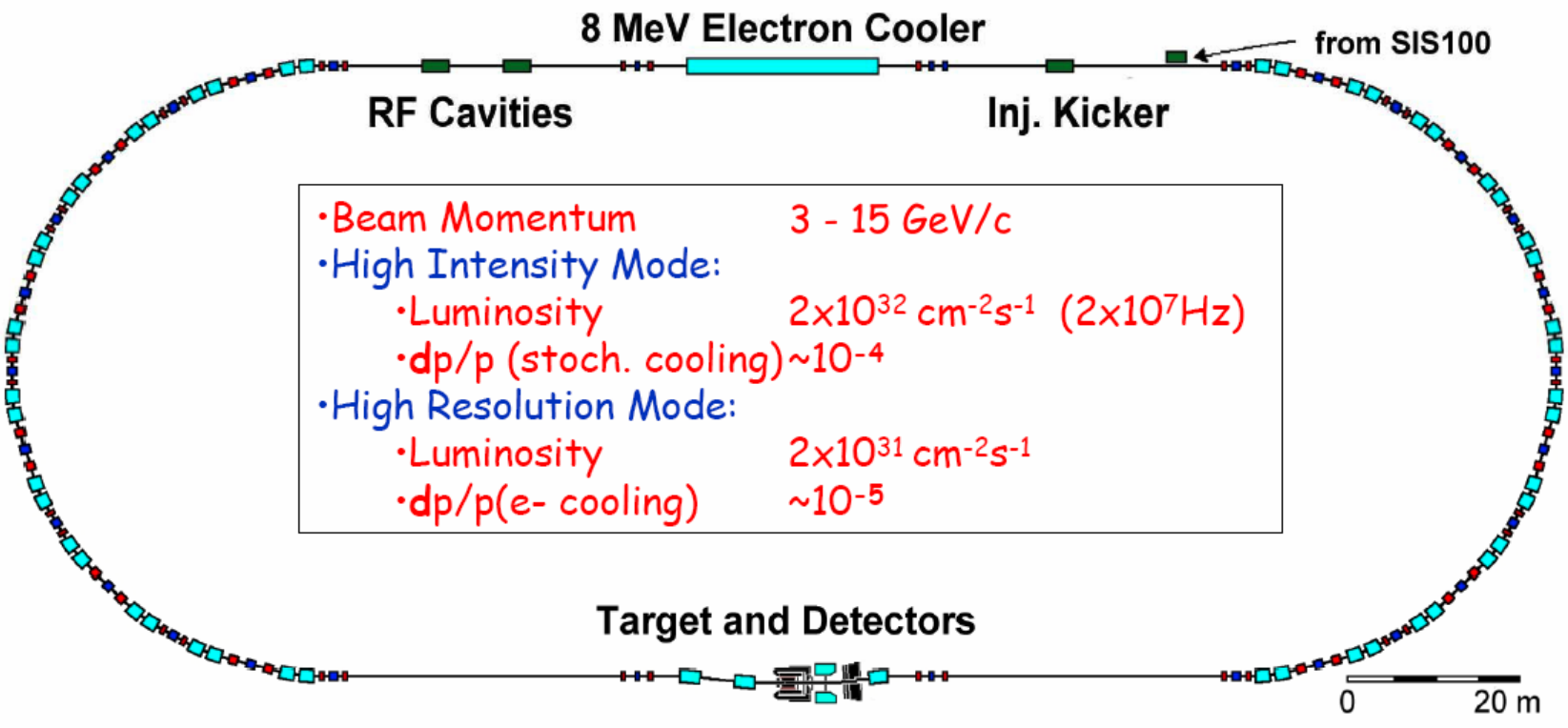
Nuclear physics

non-perturbative:
QCD: $a_S \leq 1$



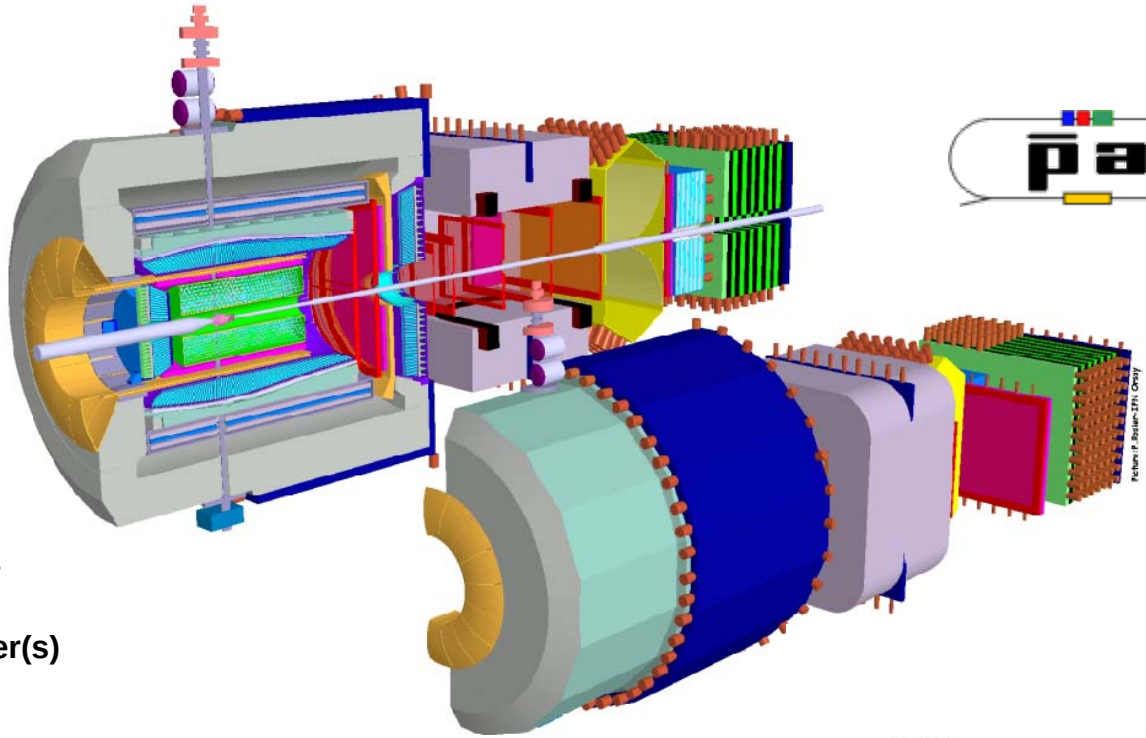
Hadrons:
Baryons, Mesons
Models, Lattice QCD

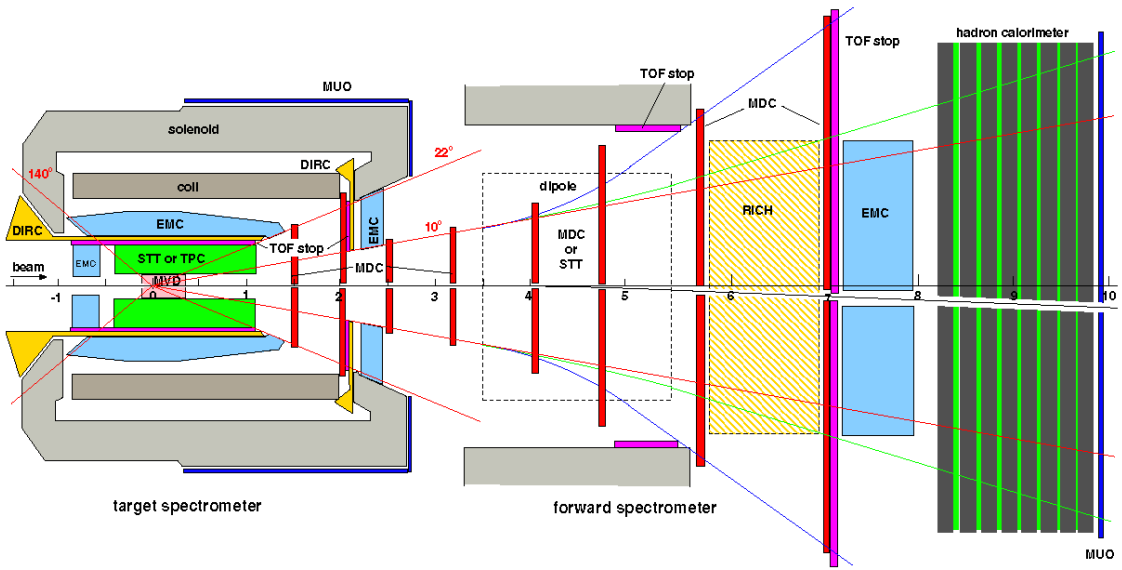
High **E**nergy **S**torage **R**ing, HESR

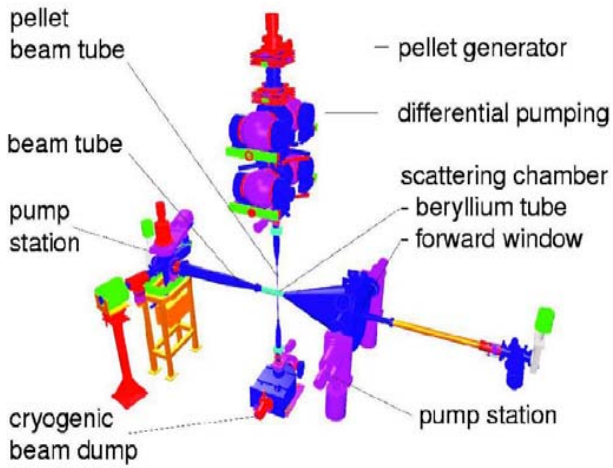


p̄anda

- **High Rates**
  - Total σ ~ 55 mb
  - peak > 10^7 int/s
- **Vertexing**
  - (σ_p,K_S,Λ,…)
- **Charged particle ID**
  - ($e^{\pm}$,$\mu^{\pm}$,$\pi^{\pm}$,p,…)
- **Magnetic tracking**
- **El-mag. Calorimetry**
  - (γ,π^0,η)
- **Forward capabilities**
  - (leading particles)
- **Sophisticated Trigger(s)**





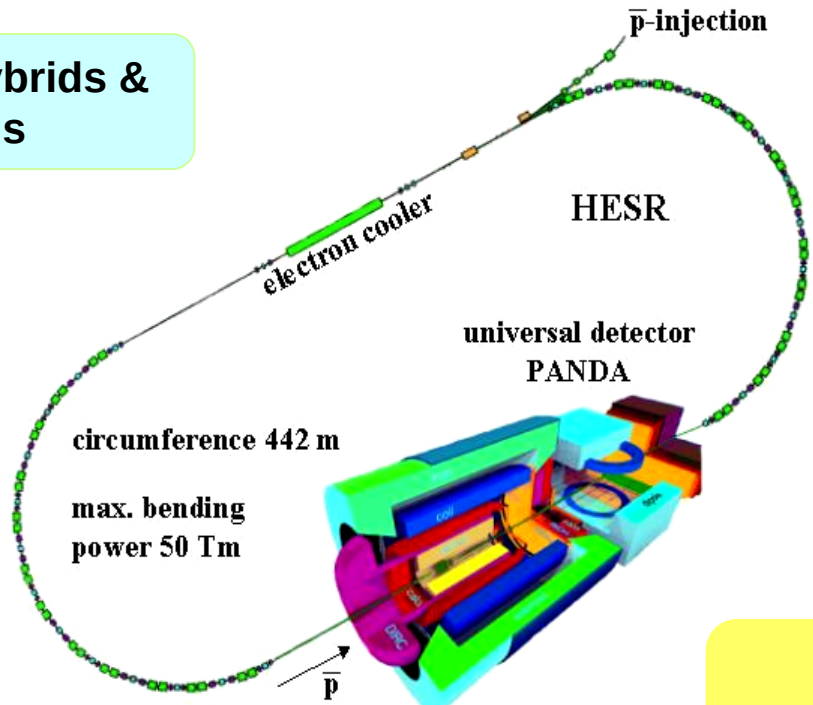


PANDA Physics Program

Charmonium spectroscopy

Exotics: charmed hybrids & heavy glueballs

Time-like form factors



Medium modifications of charmed mesons

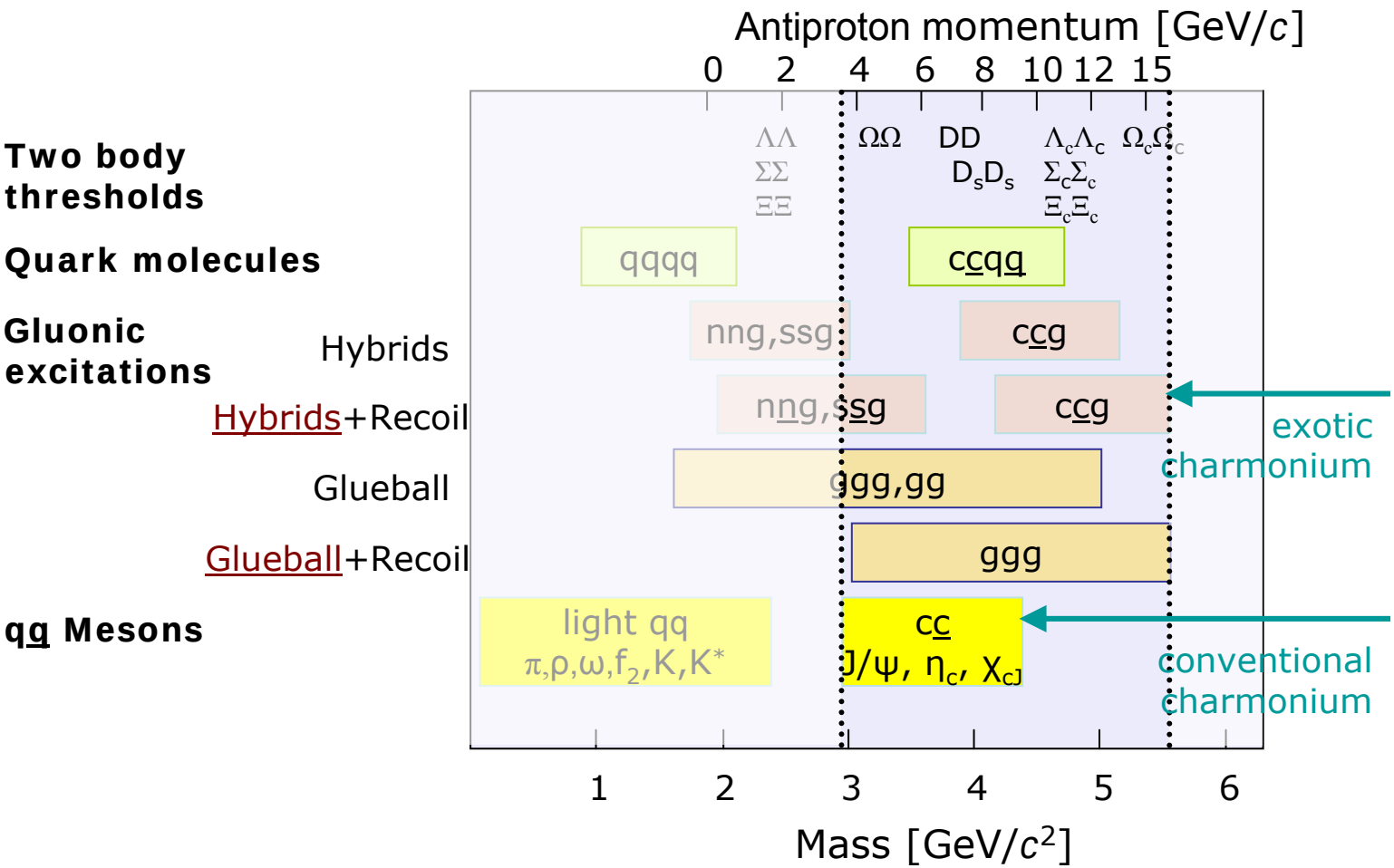
Drell-Yan processes

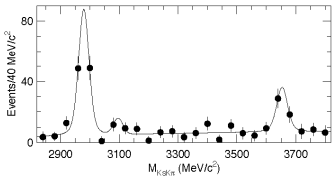
CP-violation (D & Λ - sector)

Hard exclusive processes

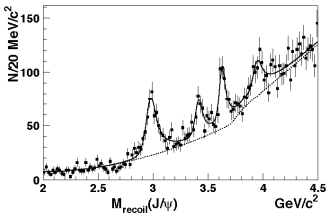
Hypernuclei

Charmed Hadrons @ PANDA

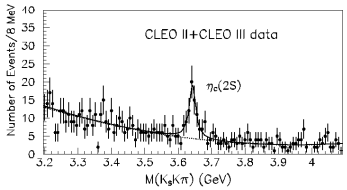




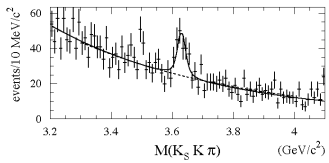
Belle: 42 fb^{-1} ($B \to K(K_S K\pi)$)



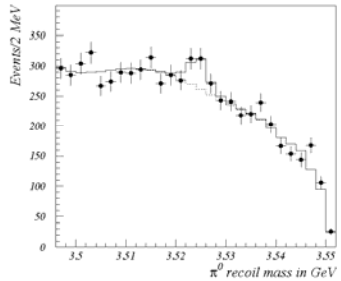
Belle: 350 fb^{-1} ($e^+e^- \to J/\psi + c\bar{c}$)



CLEO II+III: 27 fb^{-1} ($\gamma\gamma \to K_S K\pi$)

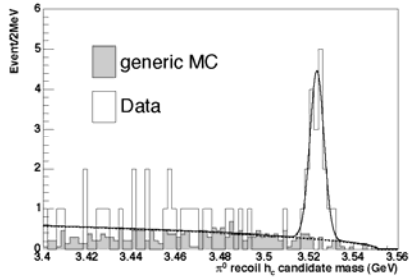


BaBar: 86 fb^{-1} ($\gamma\gamma \to K_S K\pi$)



INCLUSIVE

significance $= 3.8\sigma$



EXCLUSIVE

significance $= 6.1\sigma$

The overall result is

$$M(h_c) = 3524.4 \pm 0.6 \pm 0.4 \text{ MeV, or}$$

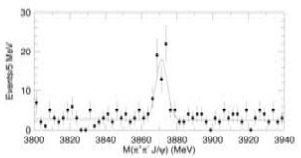
$$\Delta M_{hf}(1P) = \langle M(\chi_{cJ}) \rangle - M(h_c) = +1.0 \pm 0.6 \pm 0.4 \text{ MeV}$$

Two conclusions follow:

- Simple pQCD expectation is not strongly violated.
- The magnitude and sign of ΔM_{hf} is not well determined.
- CLEO plans for factor 10 improvement in statistics with the new sample of 25 million ψ'

The Veteran of Surprises—X(3872)

The experimental observations (2003–4)

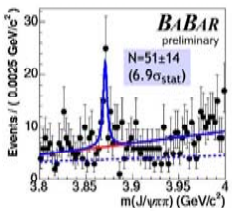


275M $B\bar{B}$ decays

$M = 3872.0 \pm 0.8$ MeV

(Belle, left)

$N = 49.1 \pm 8.4$ events

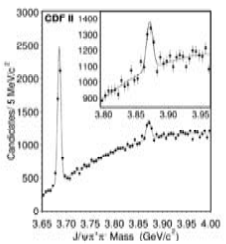


226M $B\bar{B}$ decays (BaBar)

$M = 3871.3 \pm 0.6$ MeV

(BaBar [13], right)

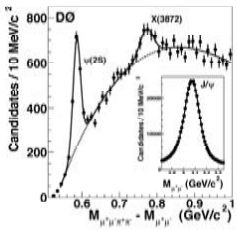
$N = 51 \pm 14$ events



$M = 3871.3 \pm 0.8$ MeV

(CDF, left)

$N = 730 \pm 30$ events



$M = 3873.4 \pm 1.4$ MeV

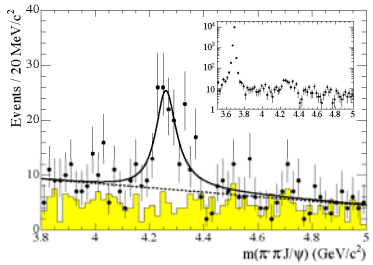
(DØ, right)

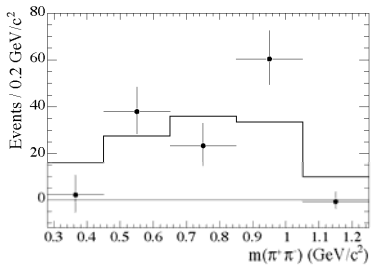
$N = 522 \pm 100$ events

$$\langle M \rangle = 3871.5 \pm 0.4 \text{ MeV}, \quad \langle \Gamma \rangle \leq 2.3 \text{ MeV}$$

The V(4260) by BaBar

BaBar: 233 fb^{-1} at $\sqrt{s} = 10.58$ GeV, $e^+e^- \to \gamma_{ISR}(e^+e^-) \to \gamma(\pi^+\pi^- J/\psi)$.





$N(\mathrm{V}) = 125 \pm 23$ events, sig.$> 8\sigma$

$M(V) = 4259 \pm 8(\text{stat})^{+2}_{-6}(\text{syst})$ MeV, $\Gamma(\mathrm{V}) = 89 \pm 24$ MeV

$\Gamma(\mathrm{V} \to e^+e^-) \times \mathcal{B}(\mathrm{V} \to \pi^+\pi^- J/\psi) = 5.5 \pm 1.3$ eV

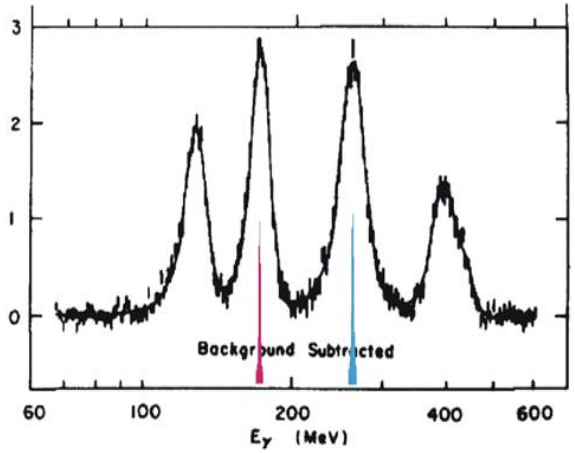
Comparison e^+e^- versus $p\bar{p}$

e^+e^- interactions:
only 1^{--} states formed
other states populated in secondary decays
(moderate mass resolution)

production of $\chi_{1,2}$

$$e^+e^- \rightarrow \psi'$$
$$\hookrightarrow \gamma\chi_{1,2}$$
$$\hookrightarrow \gamma\gamma\ J/\psi$$
$$\hookrightarrow \gamma\gamma e^+e^-$$

Crystal Ball

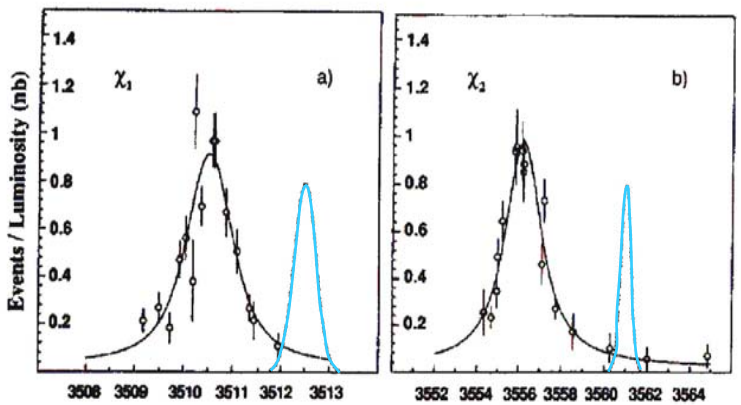


$p\bar{p}$ reactions:
all states directly formed
(very good mass resolution)

formation of $\chi_{1,2}$

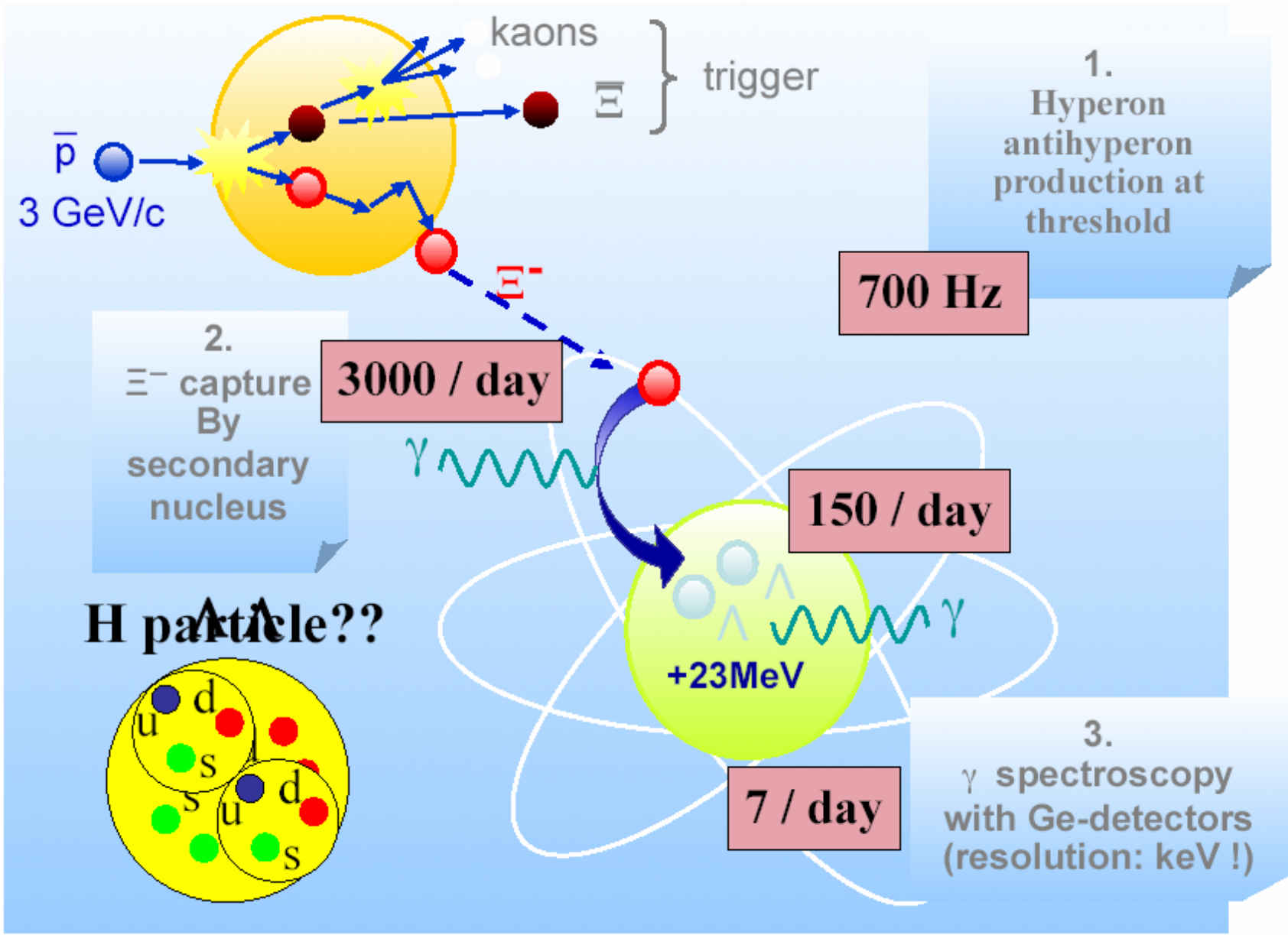
$$\bar{p}p \rightarrow \chi_{1,2}$$
$$\hookrightarrow \gamma\ J/\psi$$
$$\hookrightarrow \gamma e^+e^-$$

E 760 (Fermilab)

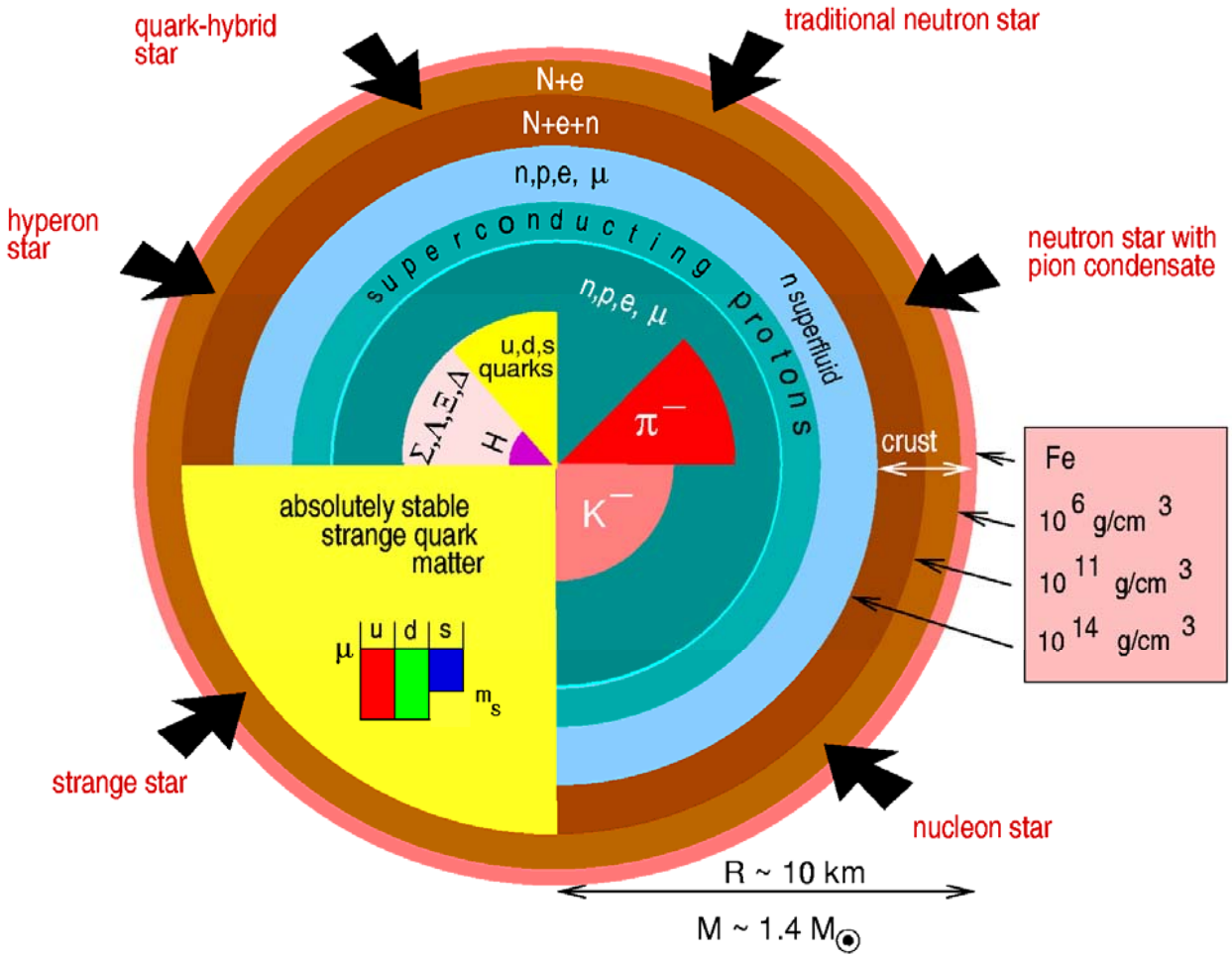


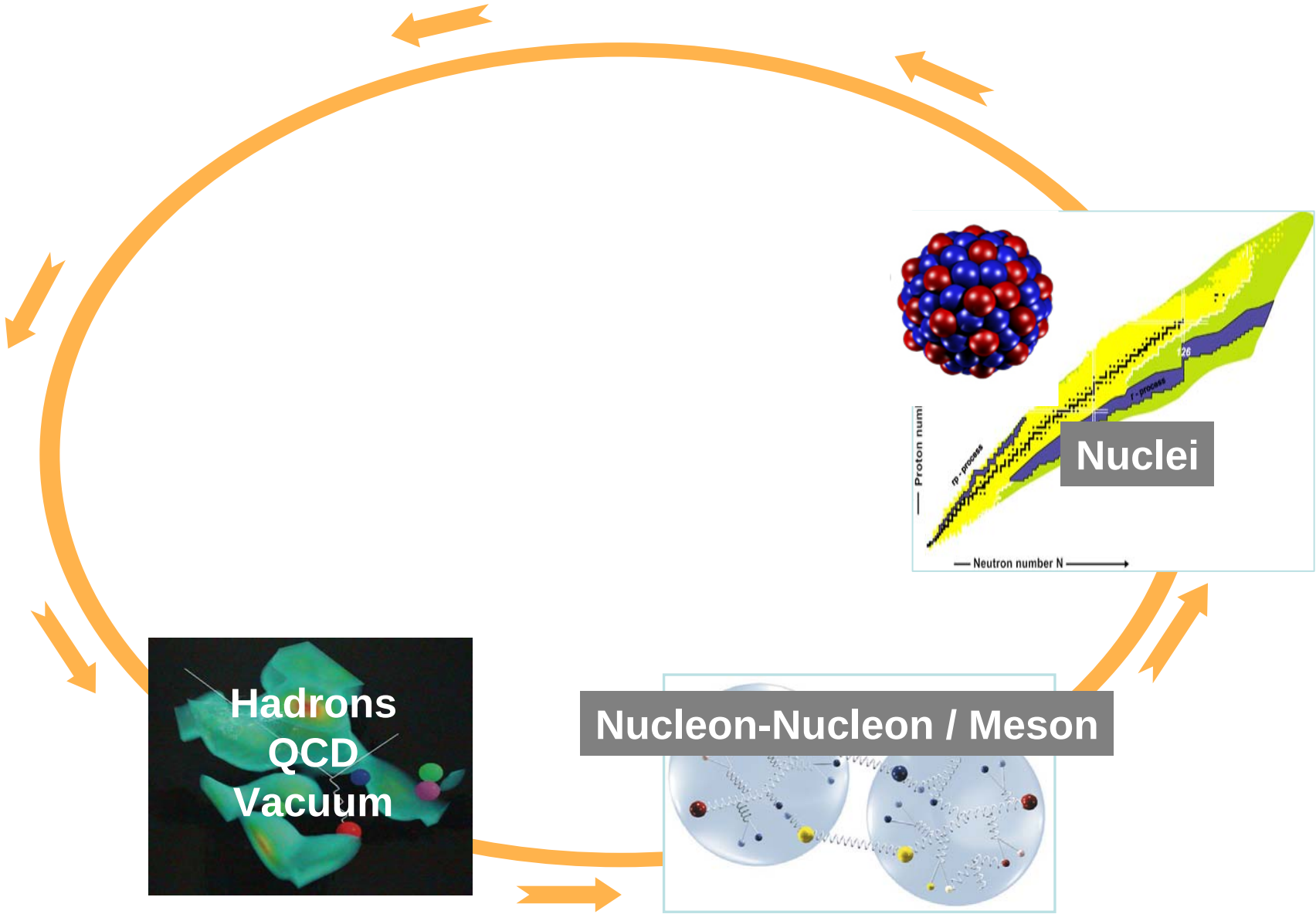
σ_m (beam) = 0.5 MeV

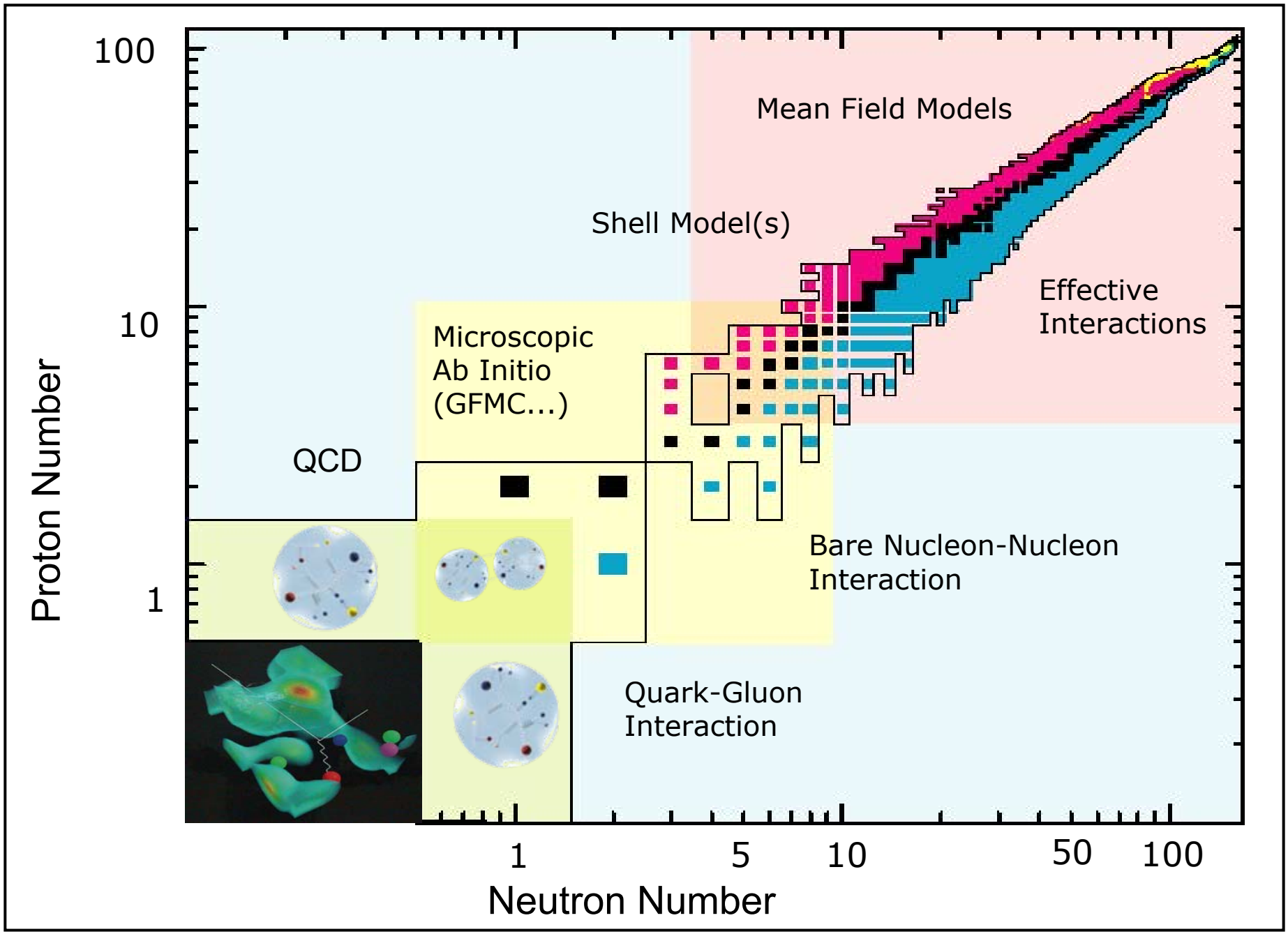
Production of double hypernuclei



Properties of neutron stars

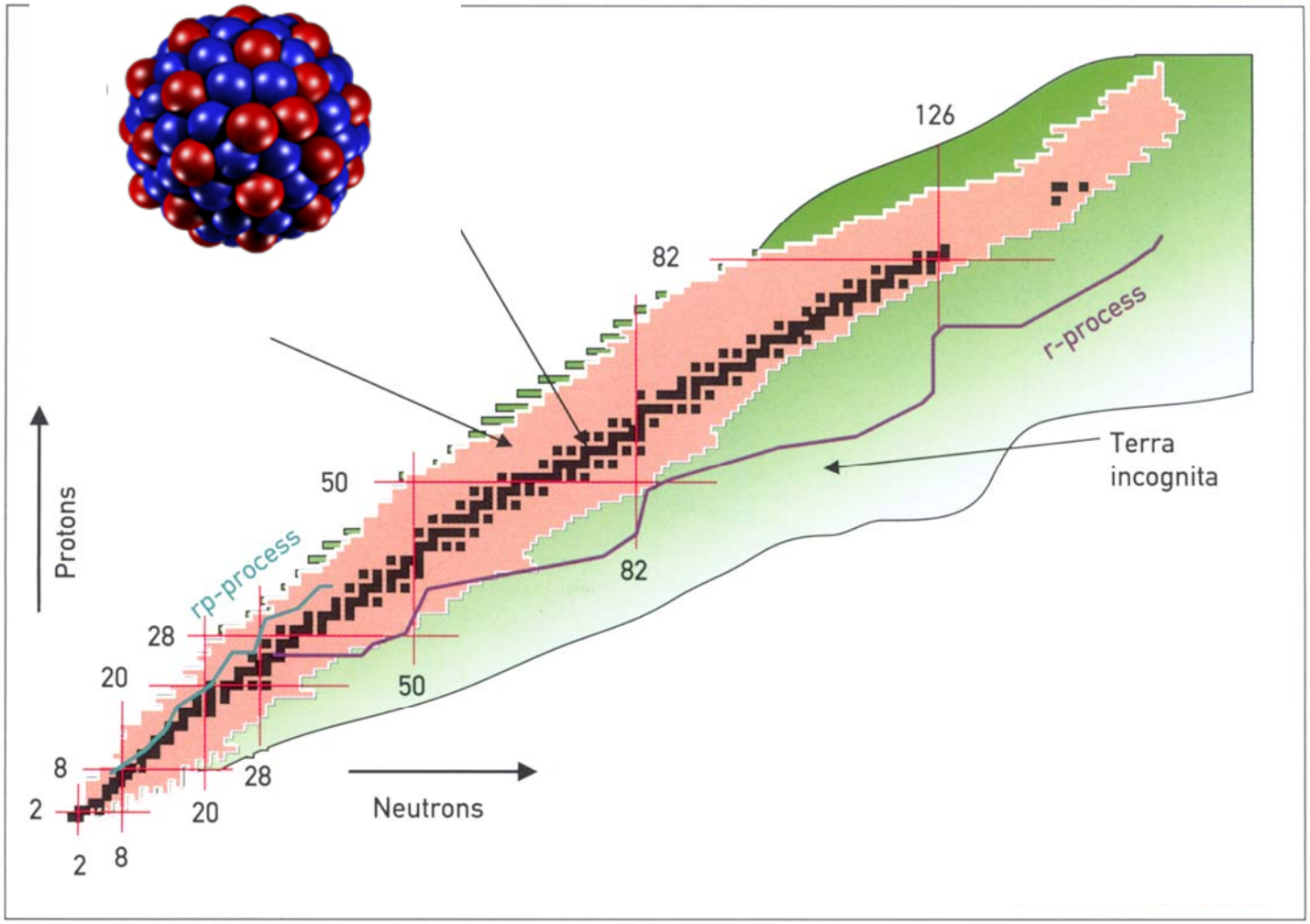



Nuclei
Proton numb
Neutron number N
rp - process
r - process
126
Hadrons
QCD
Vacuum
Nucleon-Nucleon / Meson

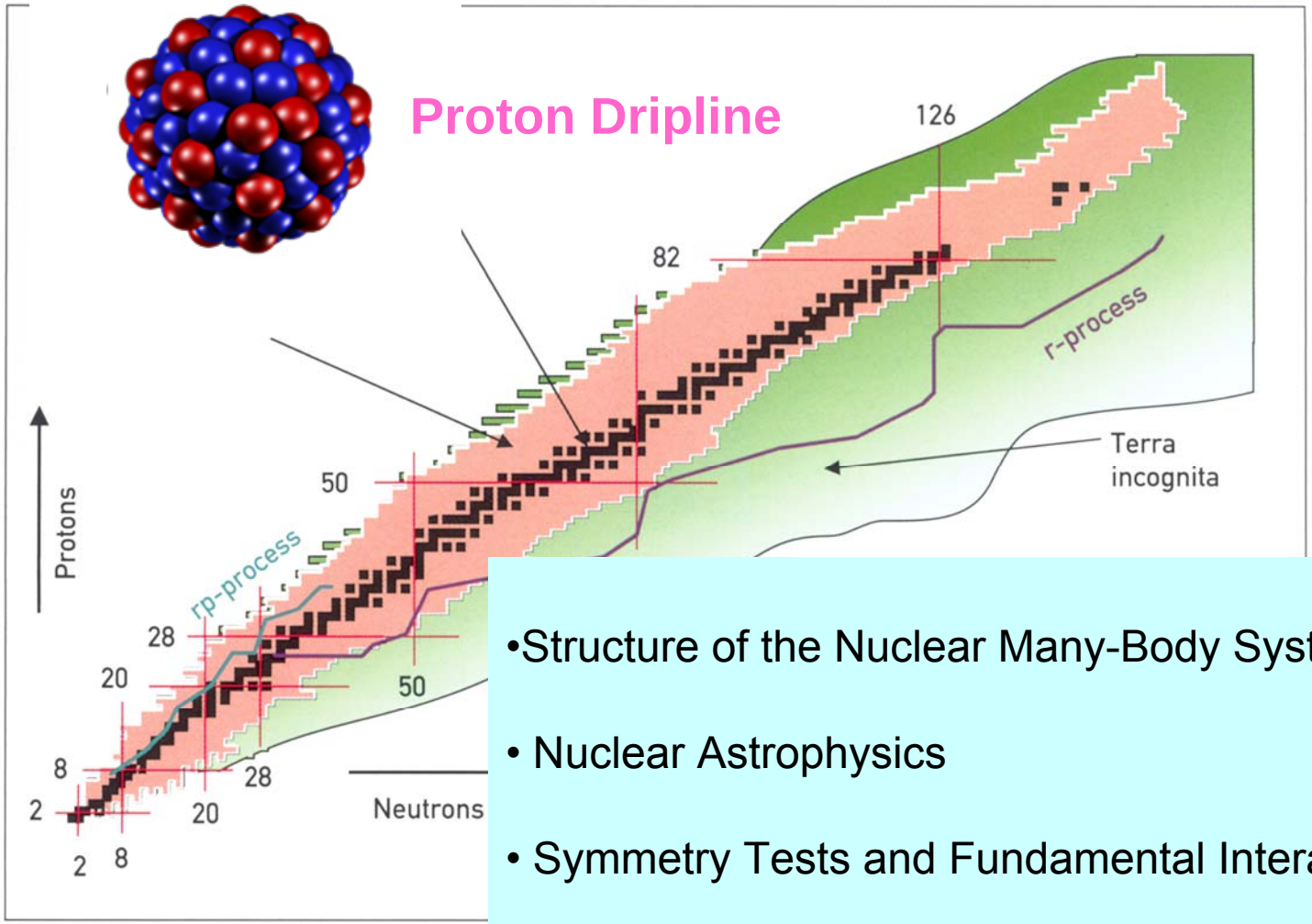

100
10
1
Proton Number
Mean Field Models
Shell Model(s)
Effective
Interactions
Microscopic
Ab Initio
(GFMC...)
QCD
Bare Nucleon-Nucleon
Interaction
Quark-Gluon
Interaction
1
5
10
50
100
Neutron Number

The Nuclear Landscape

Superheavy Elements



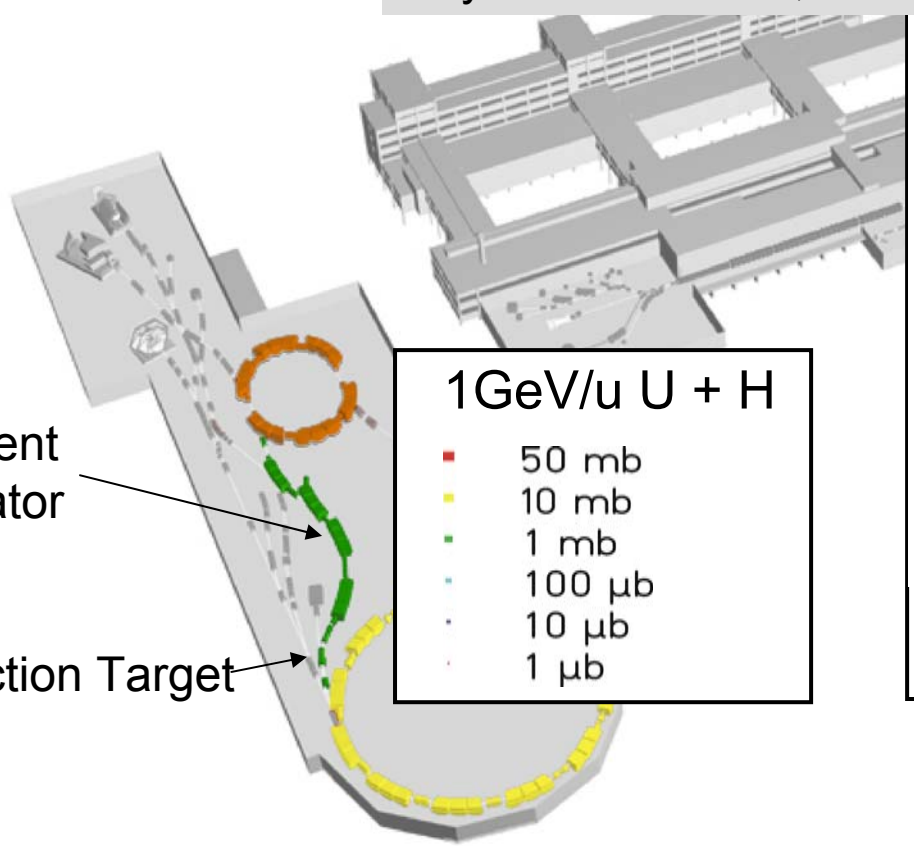
The Nuclear Landscape



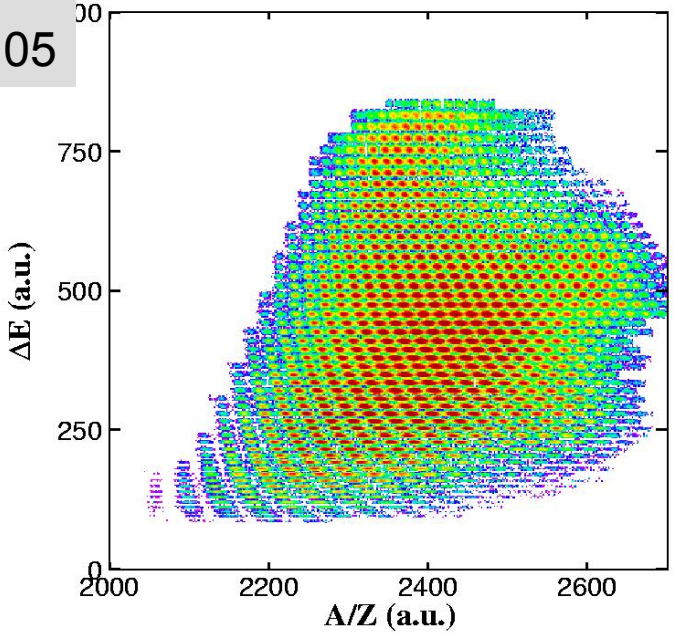
- Structure of the Nuclear Many-Body System
- Nuclear Astrophysics
- Symmetry Tests and Fundamental Interactions

Secondary Beams of Short-Lived Nuclei

P. Armbruster et al.;
Phys. Rev. Letters, Jan. 05



About 1000 nuclear residues identified

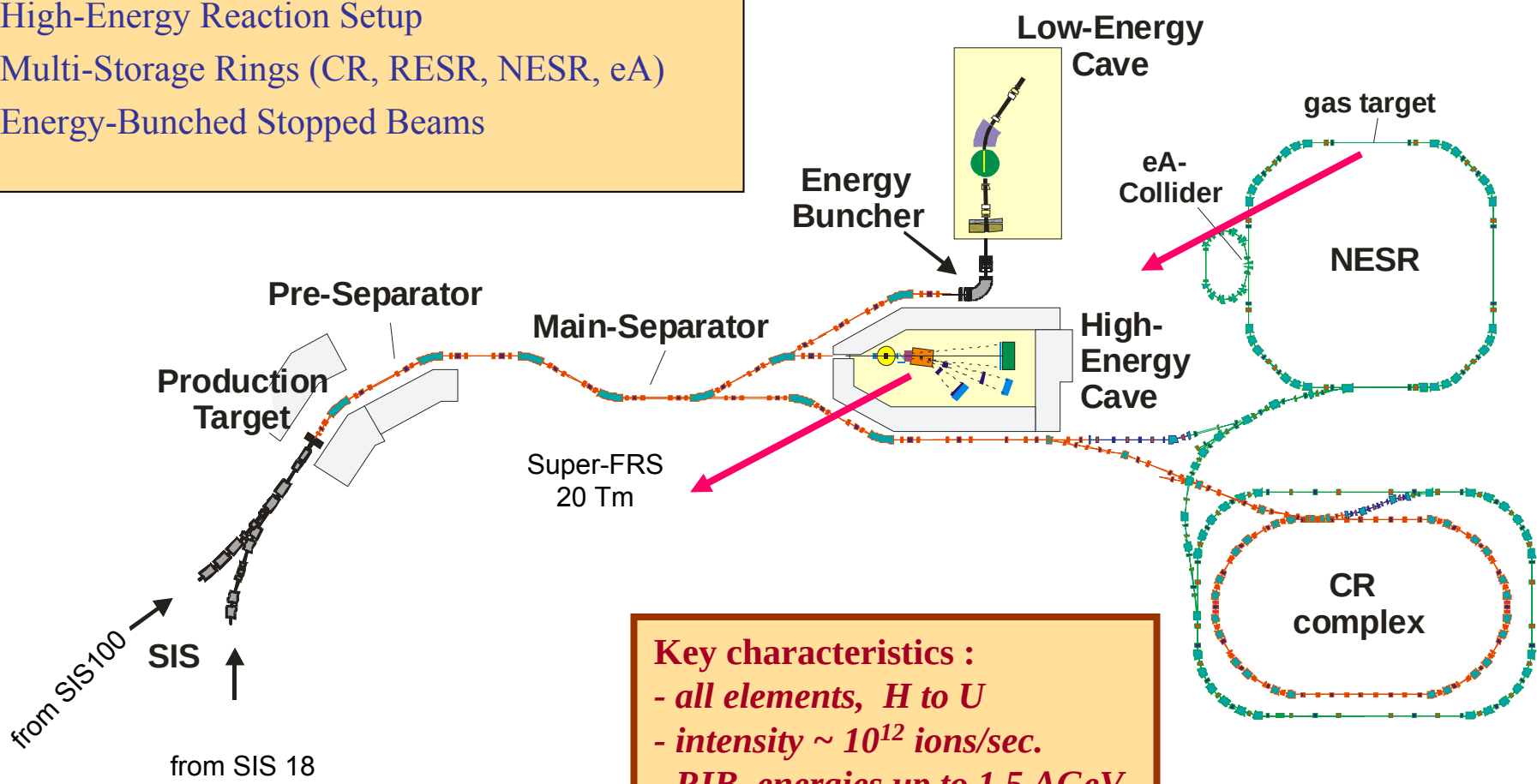


A/Z-resolution ~10^{-3}

The NUSTAR-Project at FAIR (NUclear STructure, Astrophysics and Reactions)

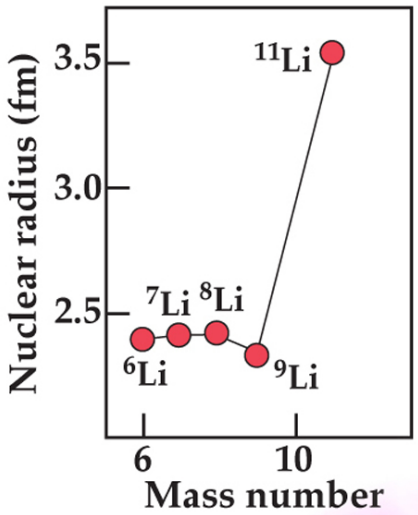
- Superconducting FRagment Separator
- High-Energy Reaction Setup
- Multi-Storage Rings (CR, RESR, NESR, eA)
- Energy-Bunched Stopped Beams

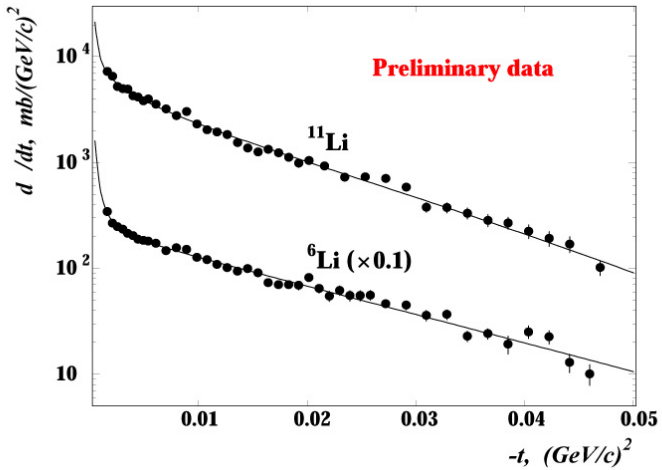
Three experimental areas

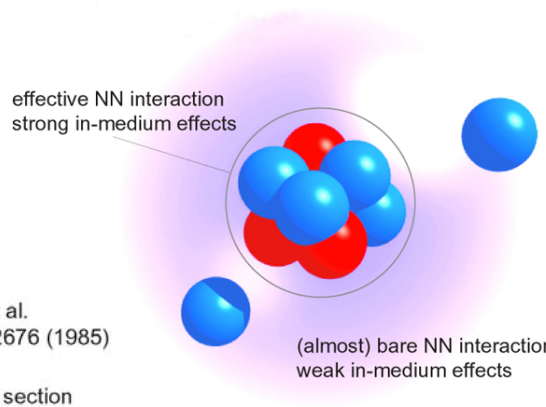


Key characteristics :

- *all elements, H to U*
- *intensity ~ 10^{12} ions/sec.*
- *RIB energies up to 1.5 AGeV*
- *pulsed and CW beams*

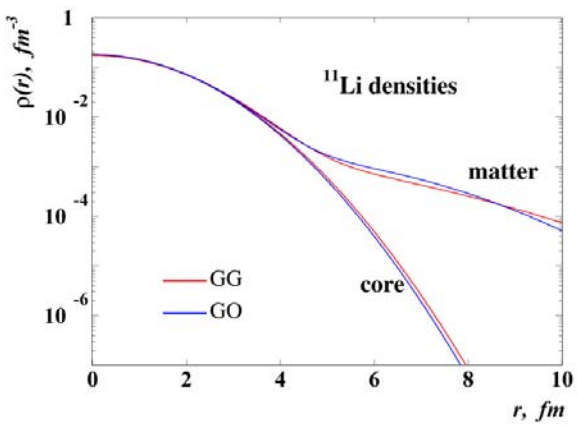




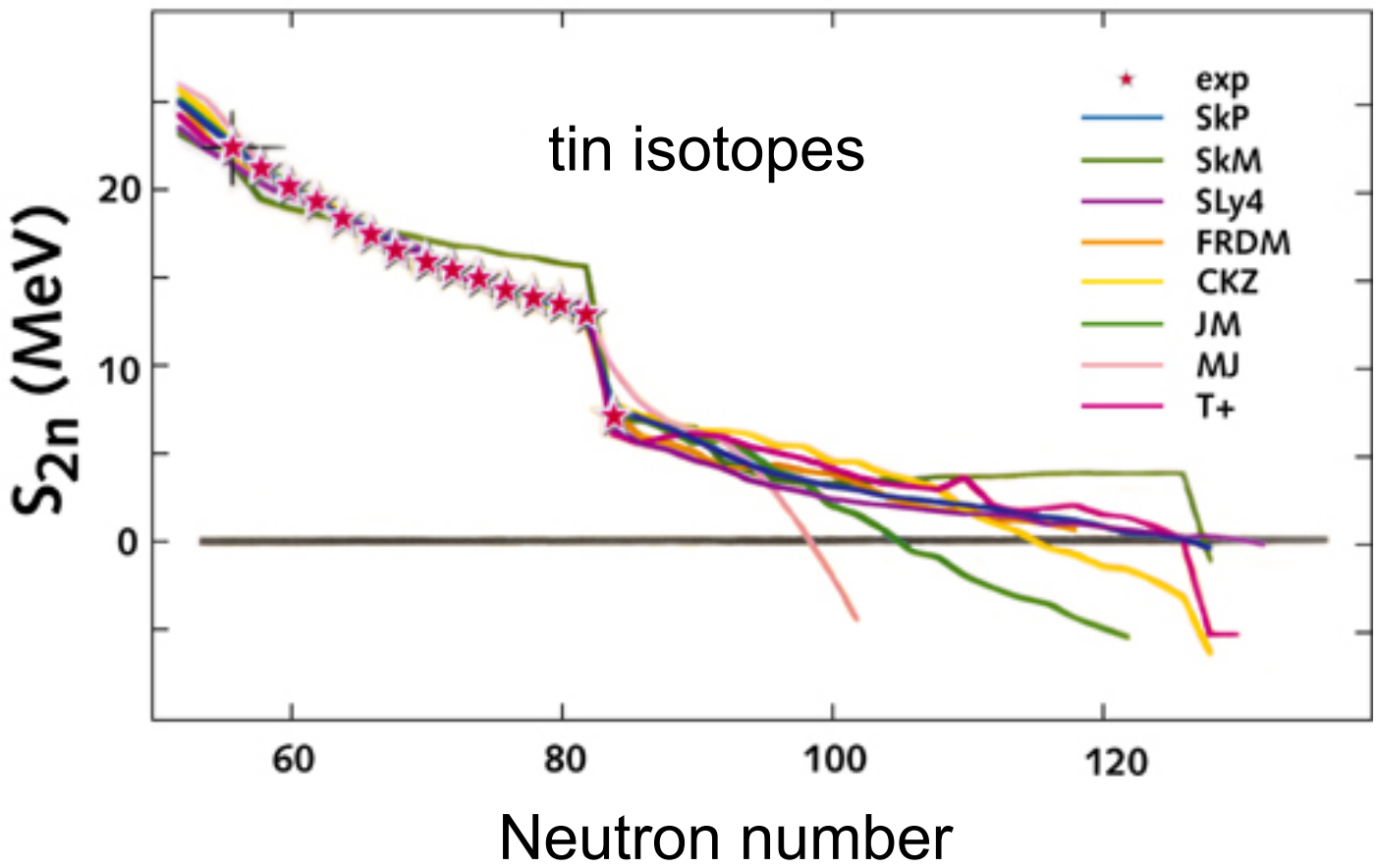


I. Tanihata et al.
Phys. Rev. Lett. 55, 2676 (1985)

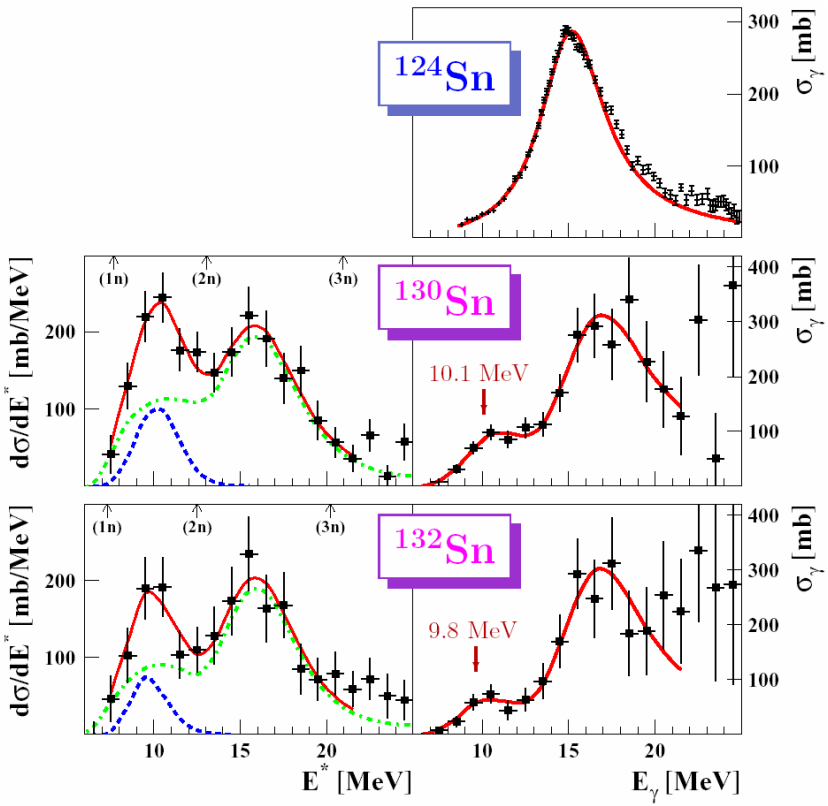
Interaction cross section
measurements at Bevalac
(790 MeV/u)



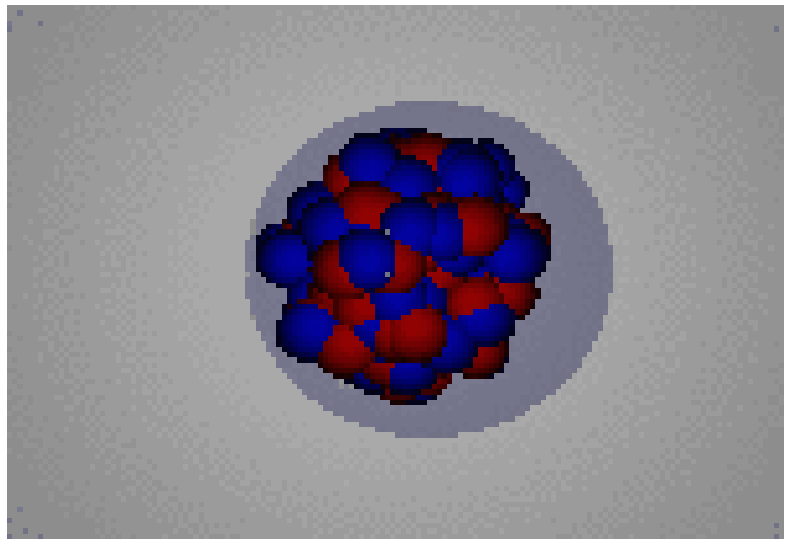
- A.V. Dobrovolsky et al., unpublished
- P.Egelhof, private communication


tin isotopes
exp
SkP
SkM
SLy4
FRDM
CKZ
JM
MJ
T+
S_{2n} (MeV)
20
10
0
60
80
100
120
Neutron number

Evidence for pygmy dipole in unstable neutron-rich Sn isotopes



P. Adrich et al., PRL 95 (2005) 132501
LAND Collaboration



at LAND - GSI:

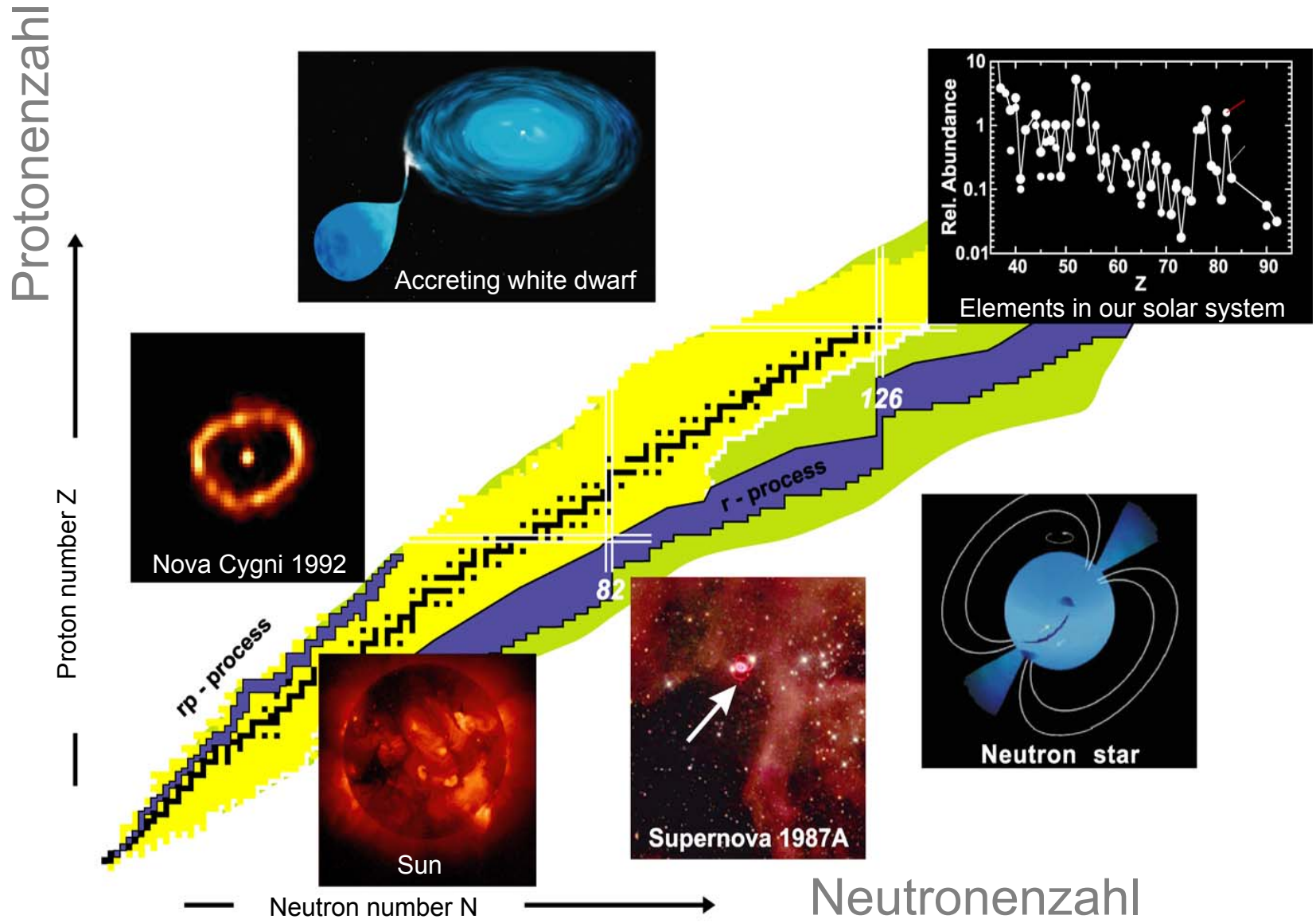
Measurement ~ **10 days**

Resolution ~ 1 - 2 MeV

at R^3B - FAIR:

Measurement ~ **100 seconds**

Resolution ~ order of 100 keV


Protonenzahl
Proton number Z
Accreting white dwarf
Rel. Abundance
10
1
0.1
0.01
40
50
60
70
80
90
Z
Elements in our solar system
Nova Cygni 1992
126
r - process
82
rp - process
Sun
Supernova 1987A
Neutron star
Neutron number N
Neutronenzahl

Masses of more than 1100 Nuclides were measured

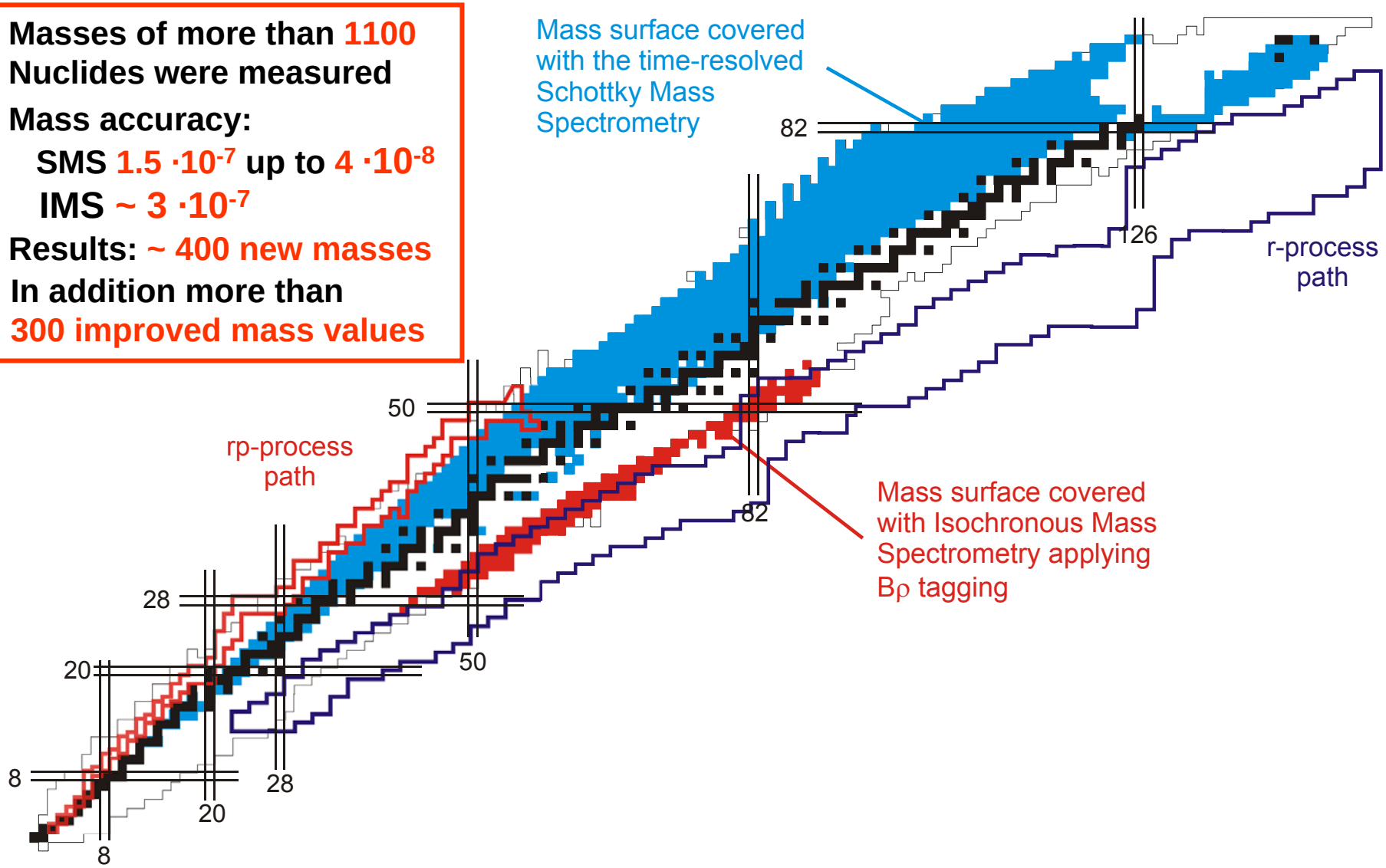
Mass accuracy:

SMS 1.5 ·10^{-7} up to 4 ·10^{-8}

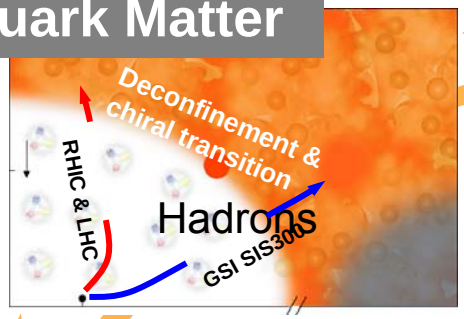
IMS ~ 3 ·10^{-7}

Results: ~ 400 new masses

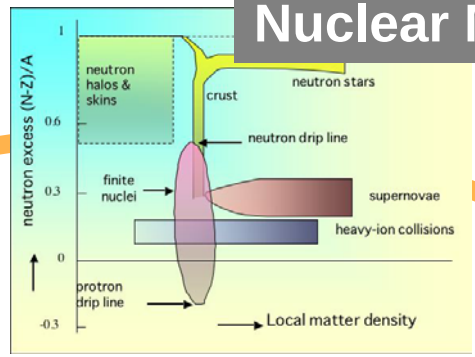
In addition more than 300 improved mass values

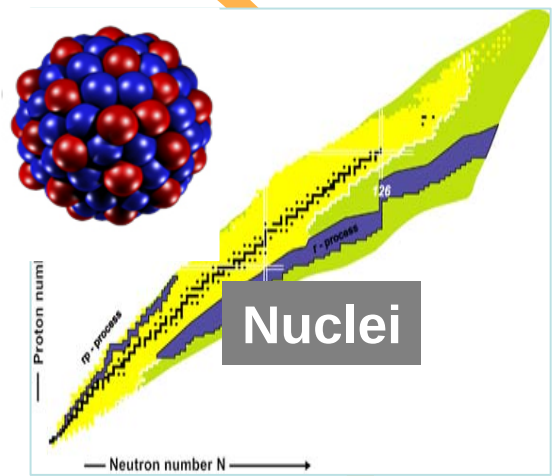


Quark Matter



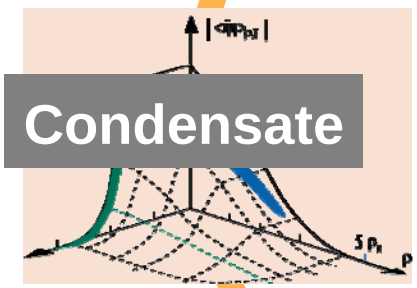
Nuclear Matter



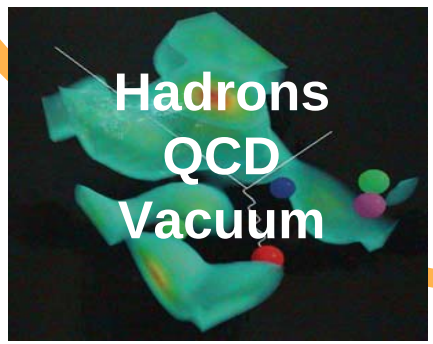


Nuclei

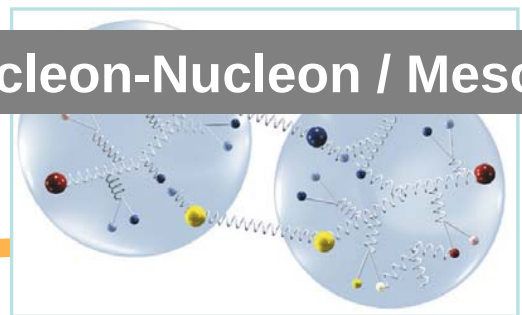
Condensate



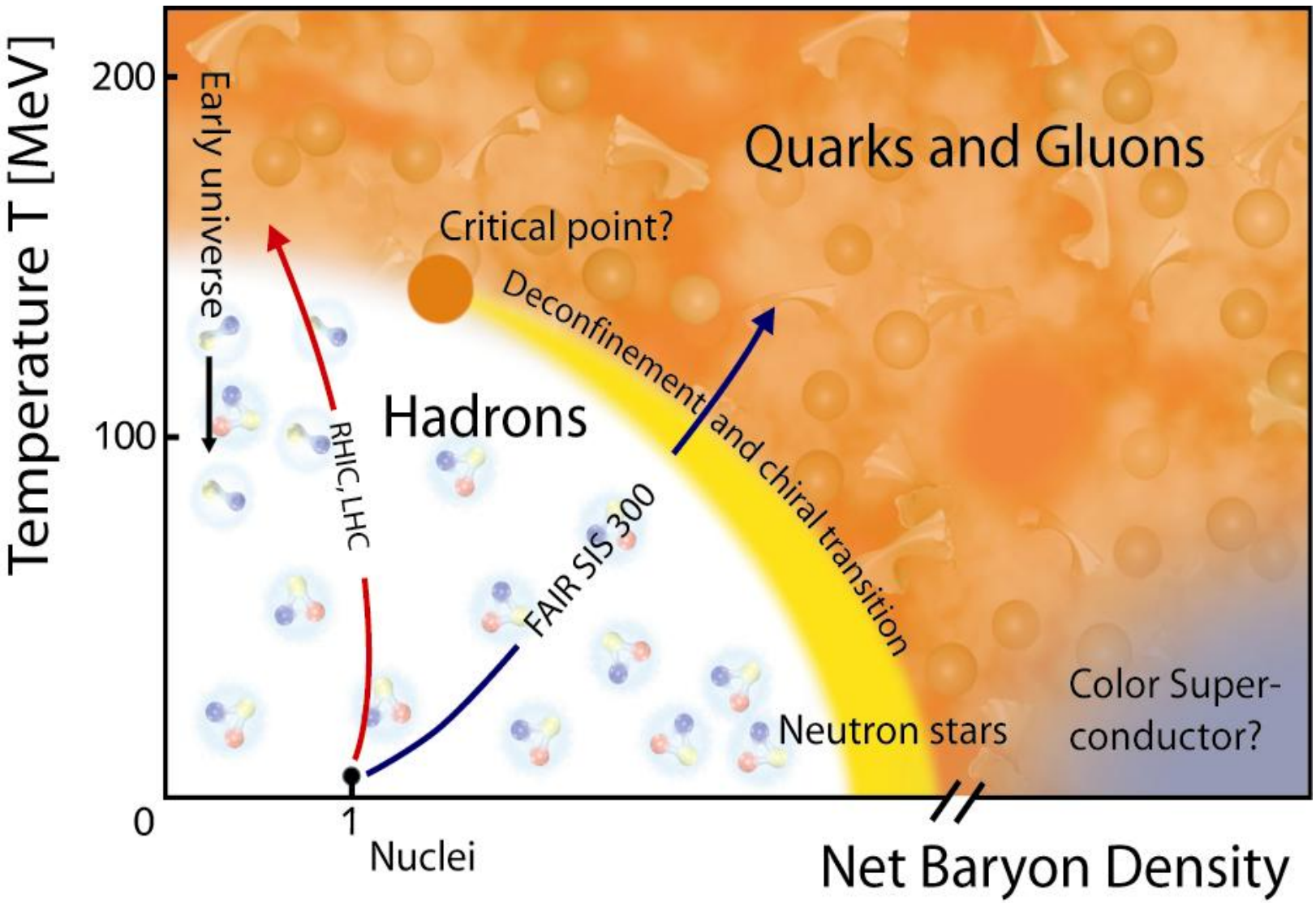
Hadrons
QCD
Vacuum



Nucleon-Nucleon / Meson

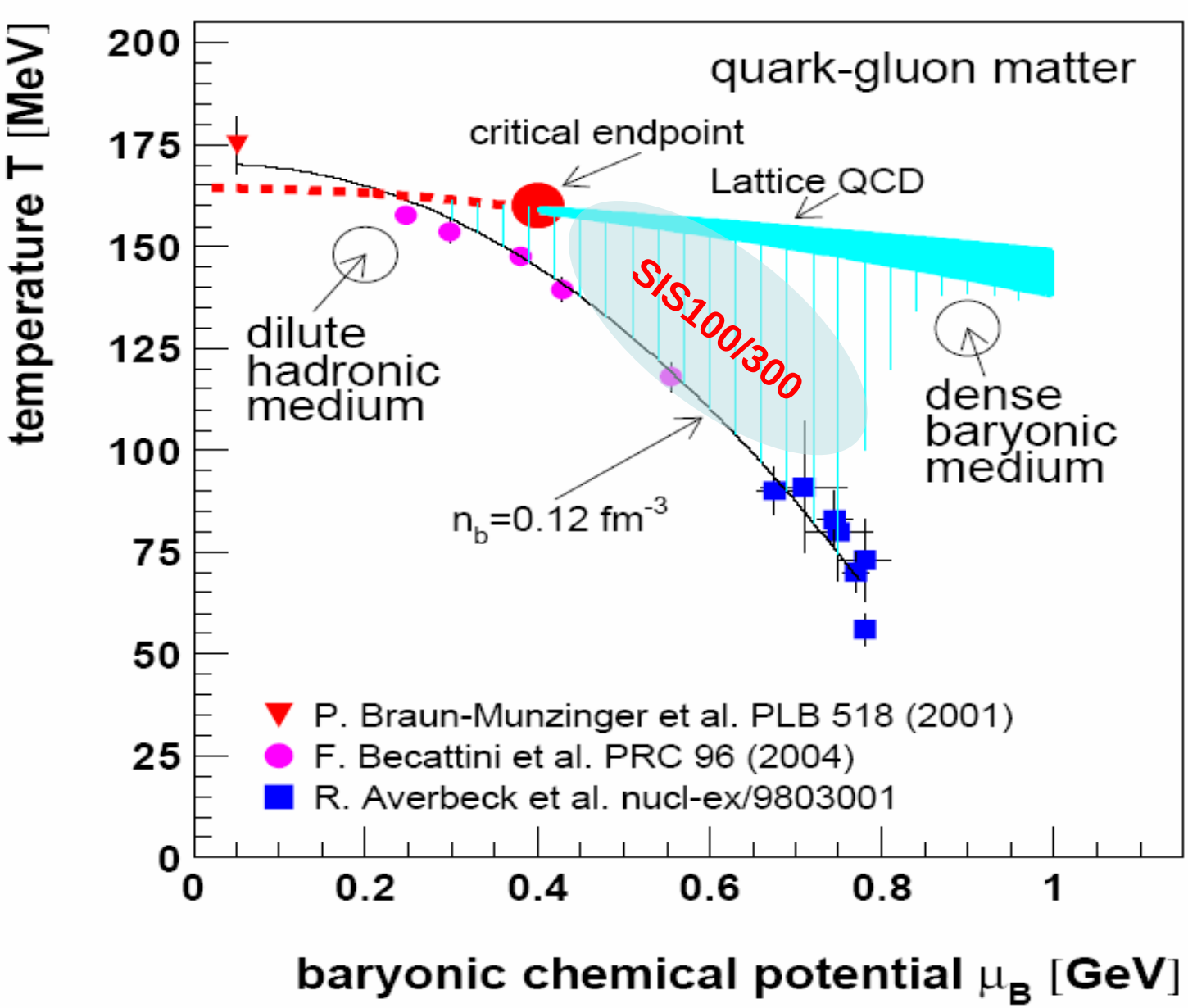


The phase diagram of strongly interacting matter

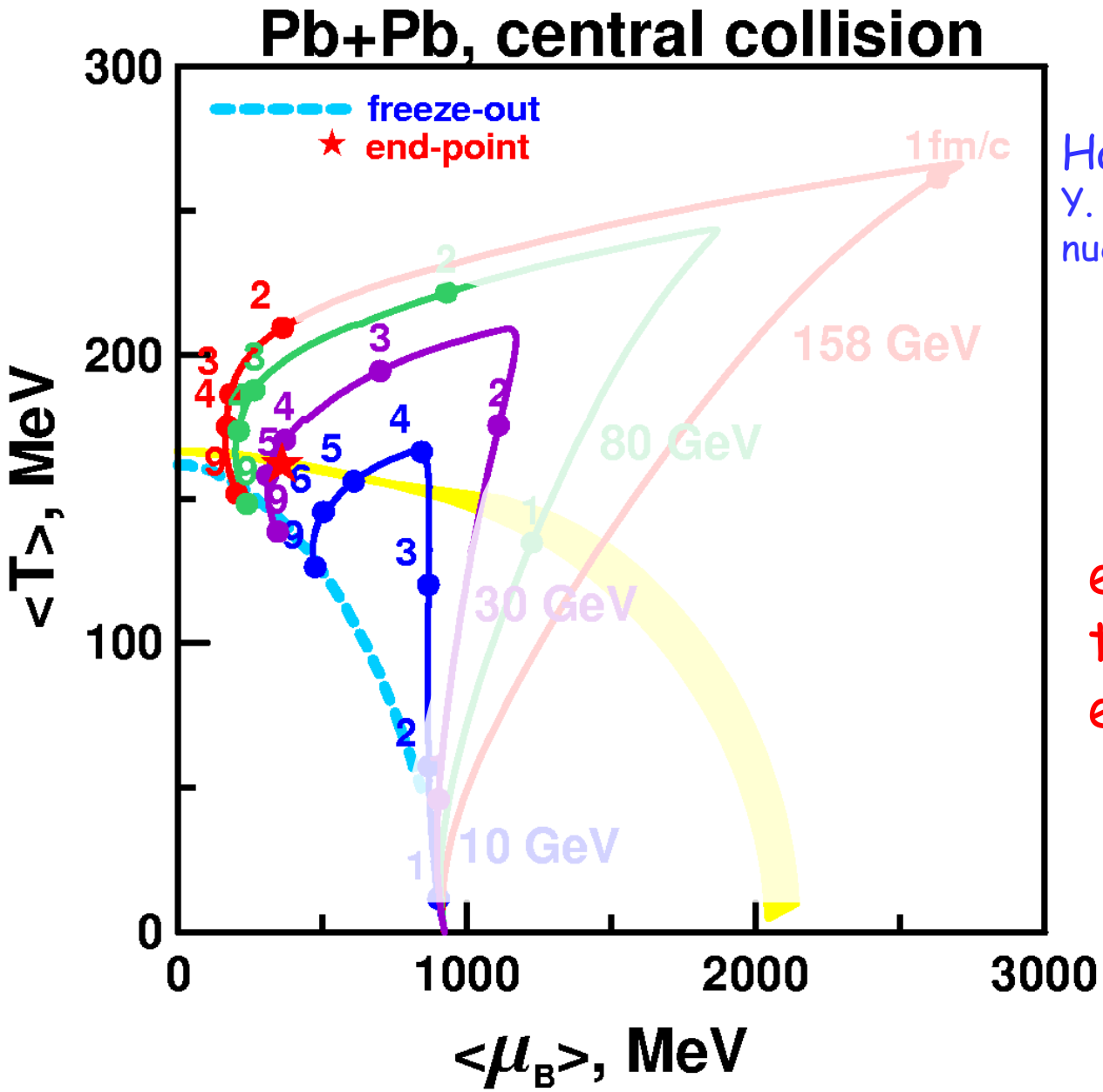


RHIC, LHC: high temperature, low baryon density
FAIR: moderate temperature, high baryon density

Mapping the QCD phase diagram



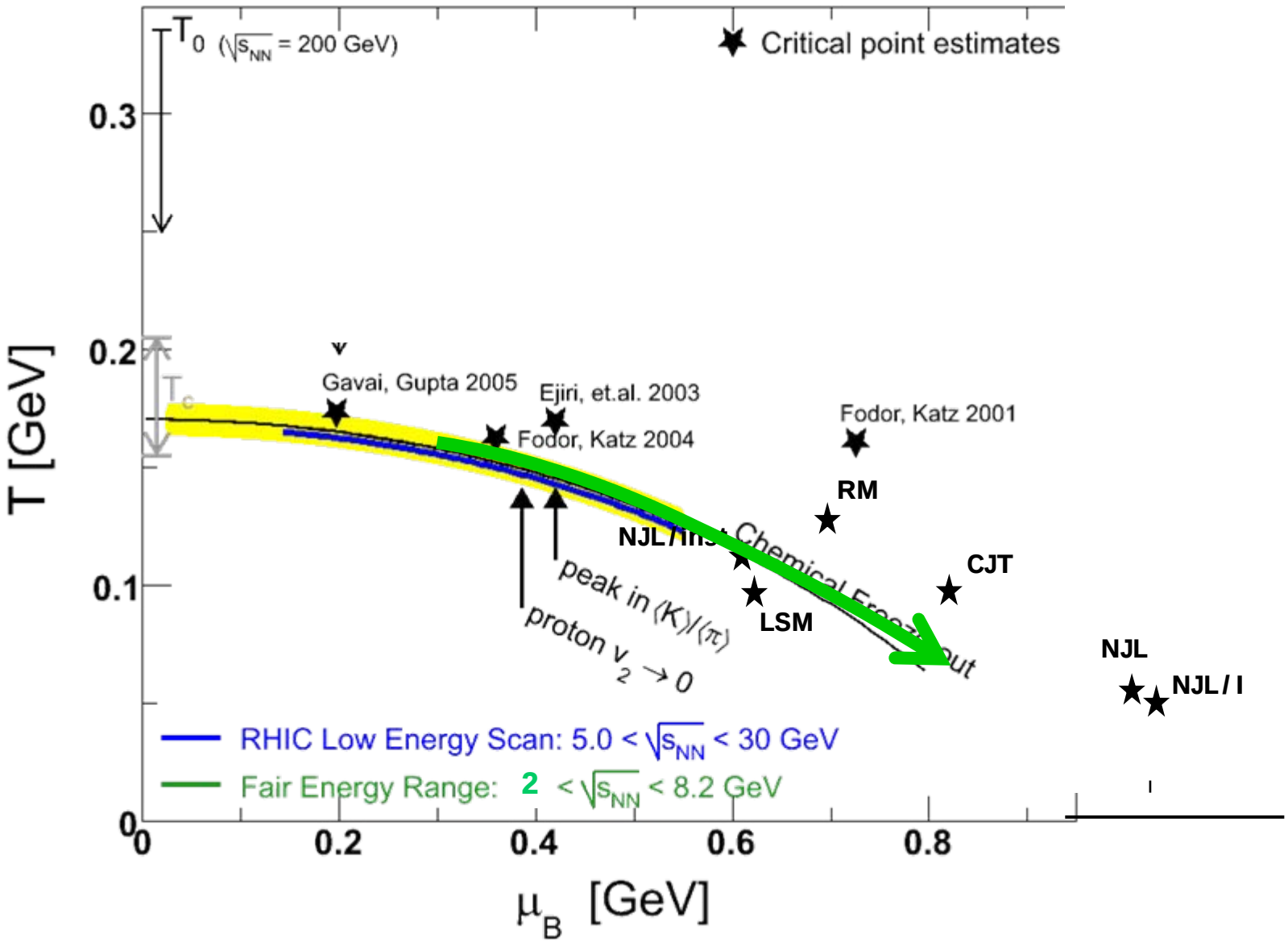
"Trajectories" from 3 fluid hydrodynamics



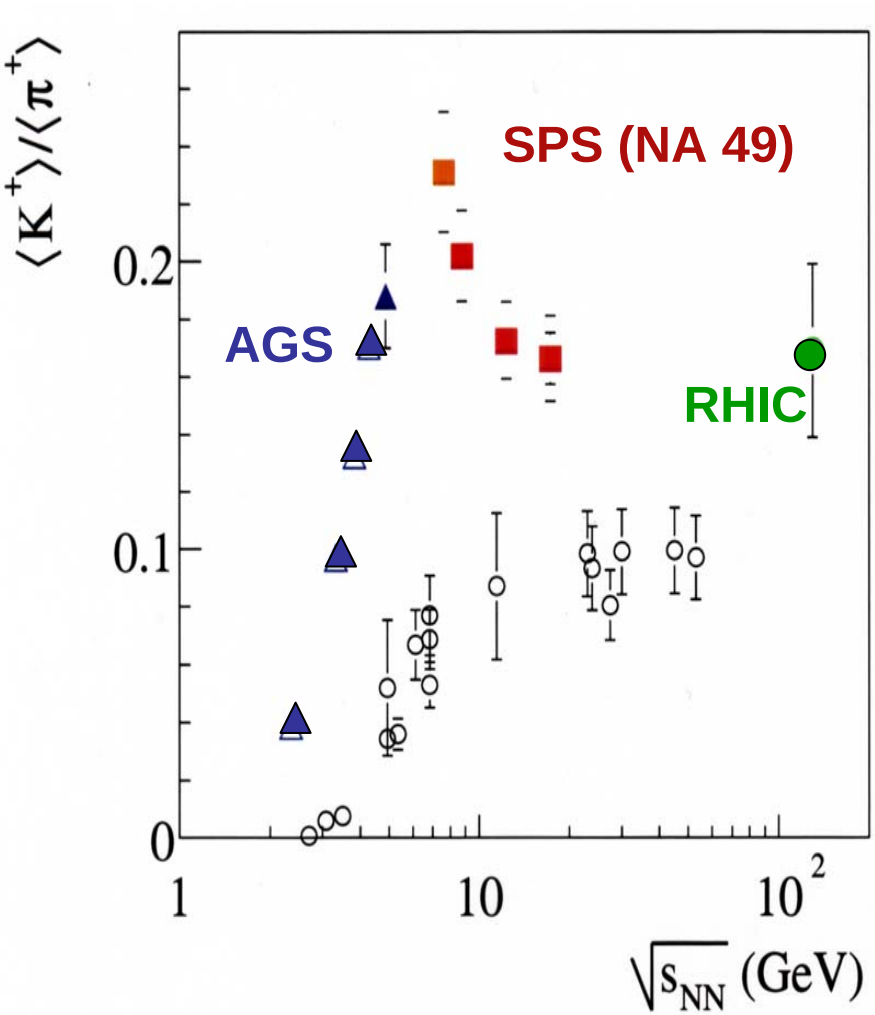
Hadron gas EOS:
Y. Ivanov, V. Russkikh, V.Toneev
nucl-th/0503088

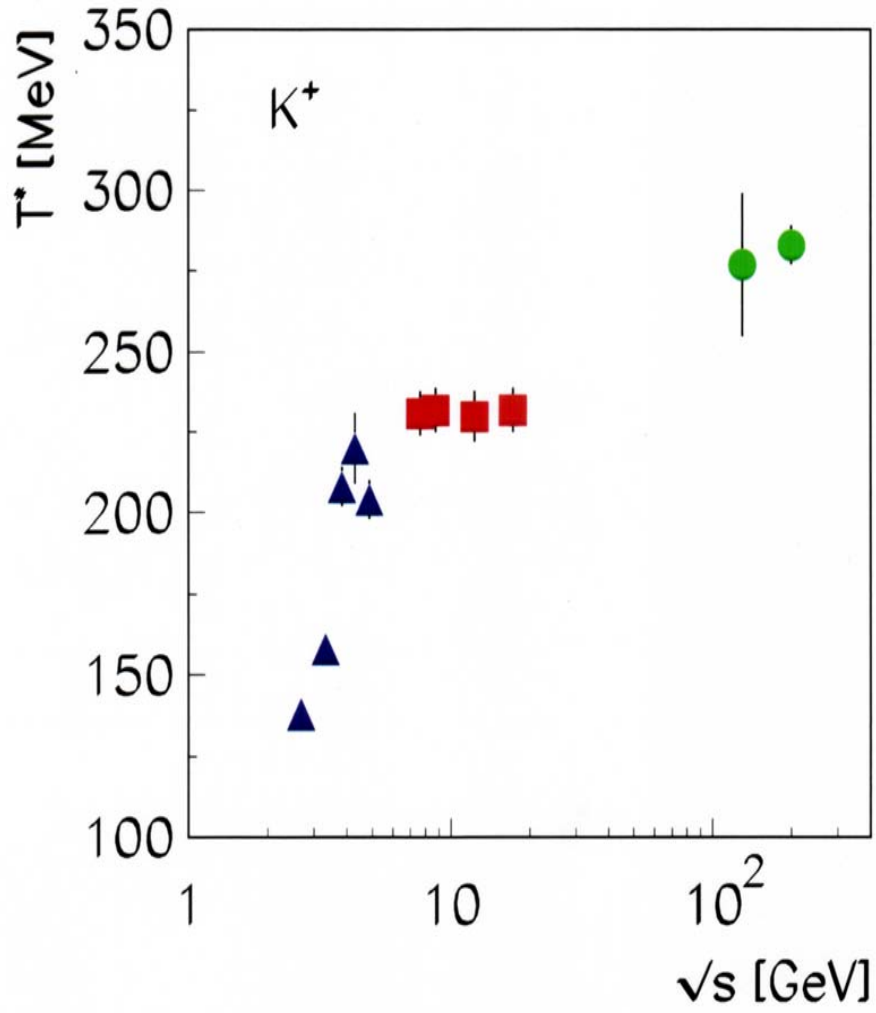
early phase not in thermodynamic equilibrium !

The critical point: can we locate it?



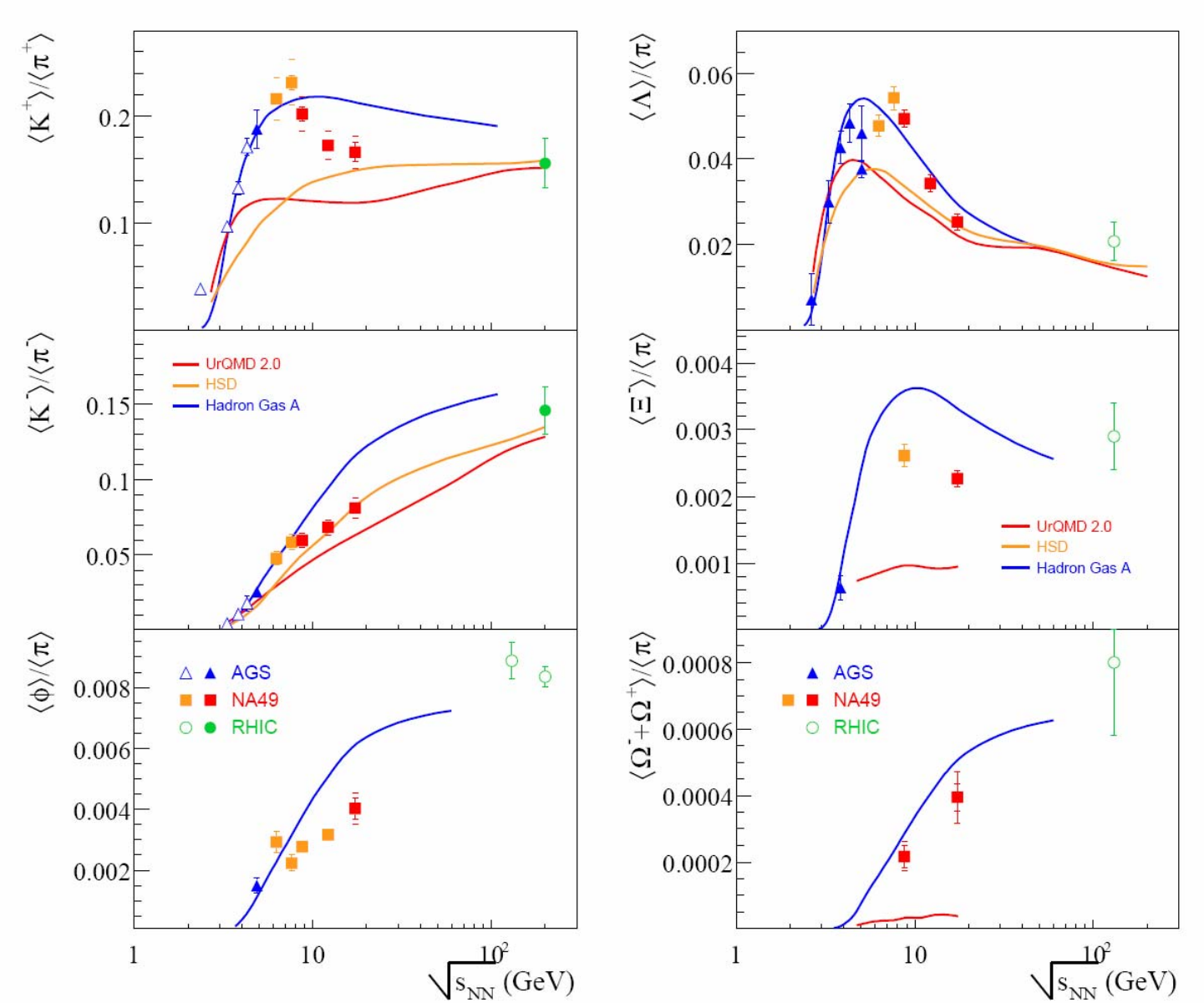
Strangeness Production in Au+Au / Pb+Pb





Strangeness/pion ratios from central Au+Au (Pb+Pb) collisions

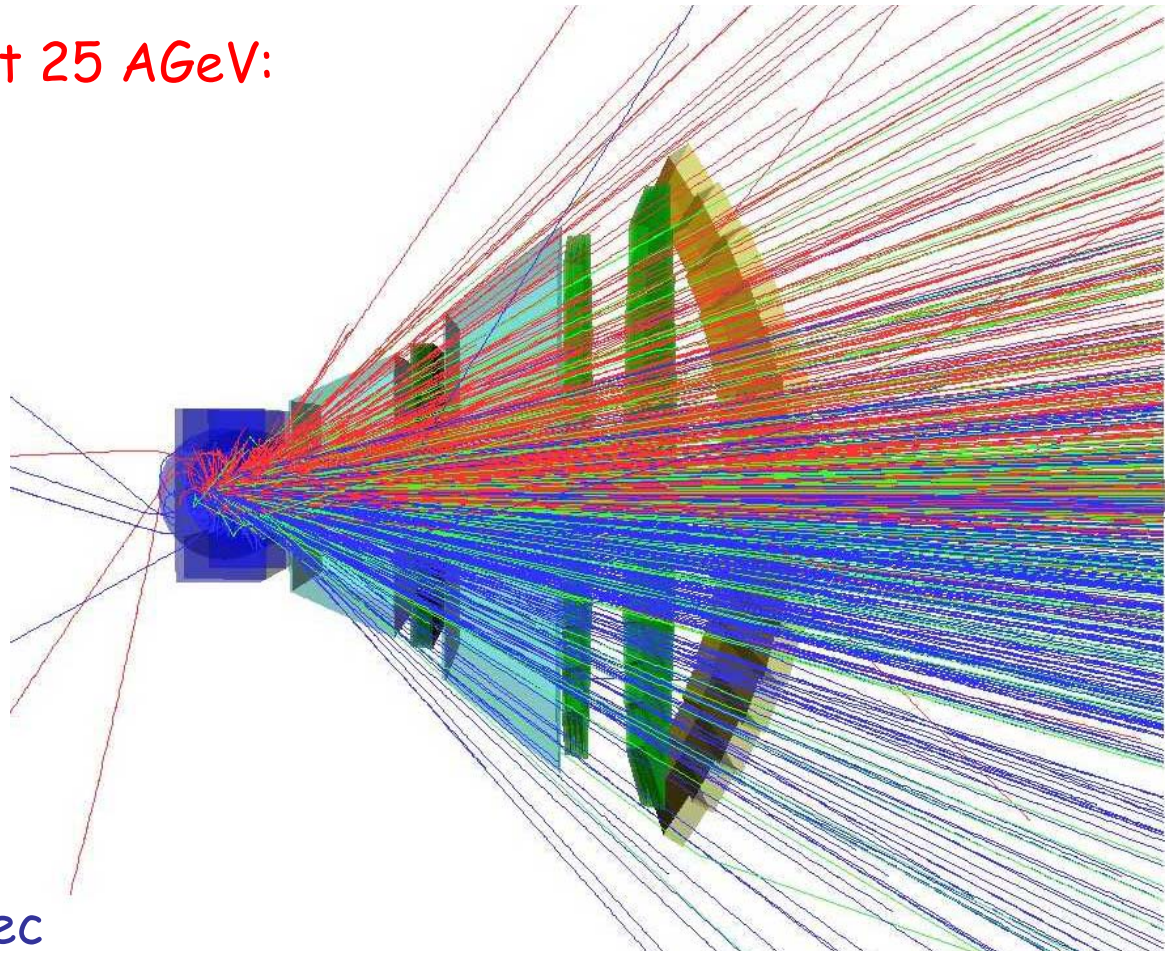
C. Blume for the NA49 collaboration, nucl-ex/0409008



Experimental challenges

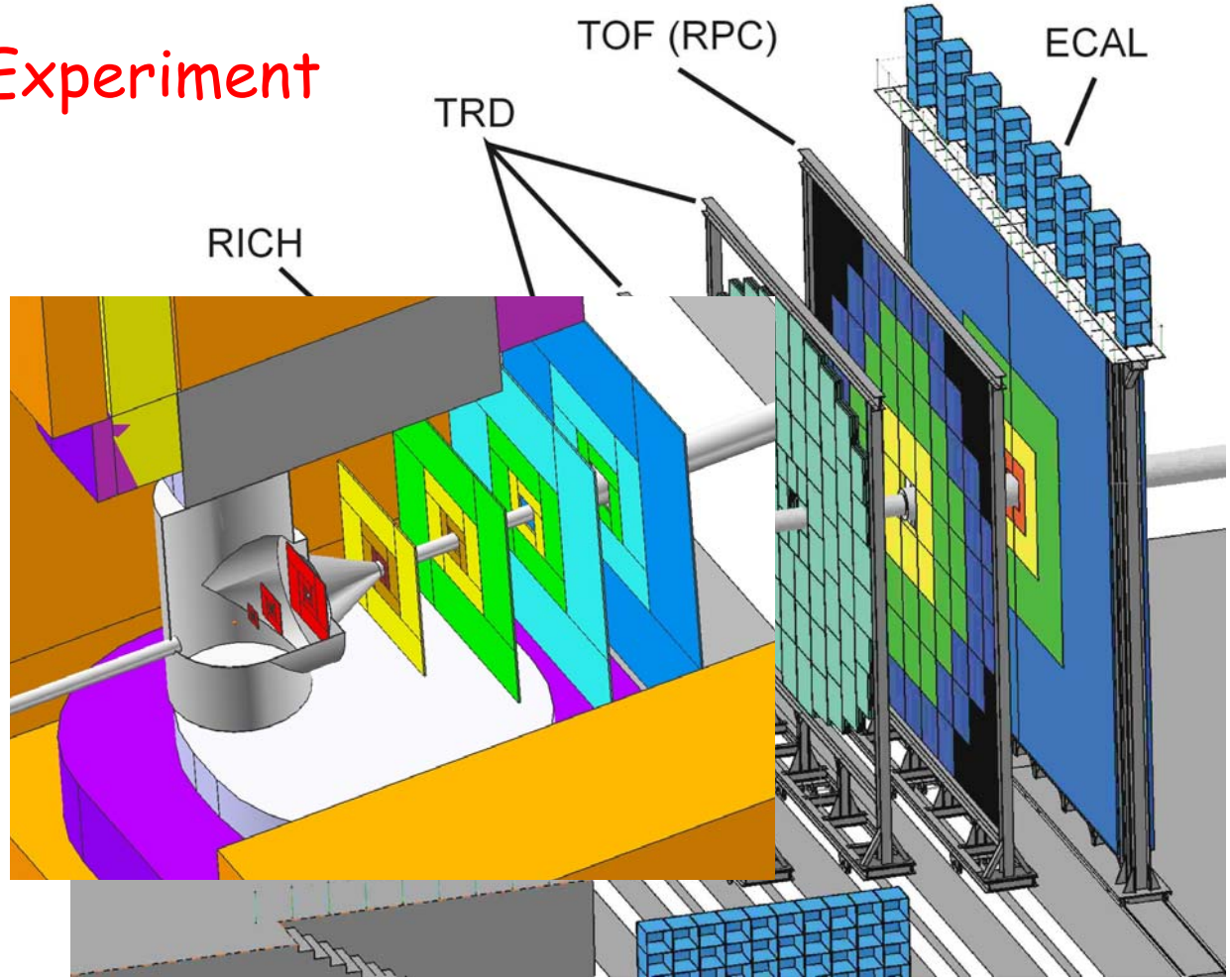
Central Au+Au collision at 25 AGeV:
URQMD + GEANT4

160 p
400 π^-
400 π^+
44 K^+
13 K^-



- 10^7 Au+Au reactions/sec
  (beam intensities up to 10^9 ions/sec, 1 % interaction target)
- determination of (displaced) vertices with high resolution ($\approx$ 50 μm)
- identification of electrons and hadrons

The CBM Experiment

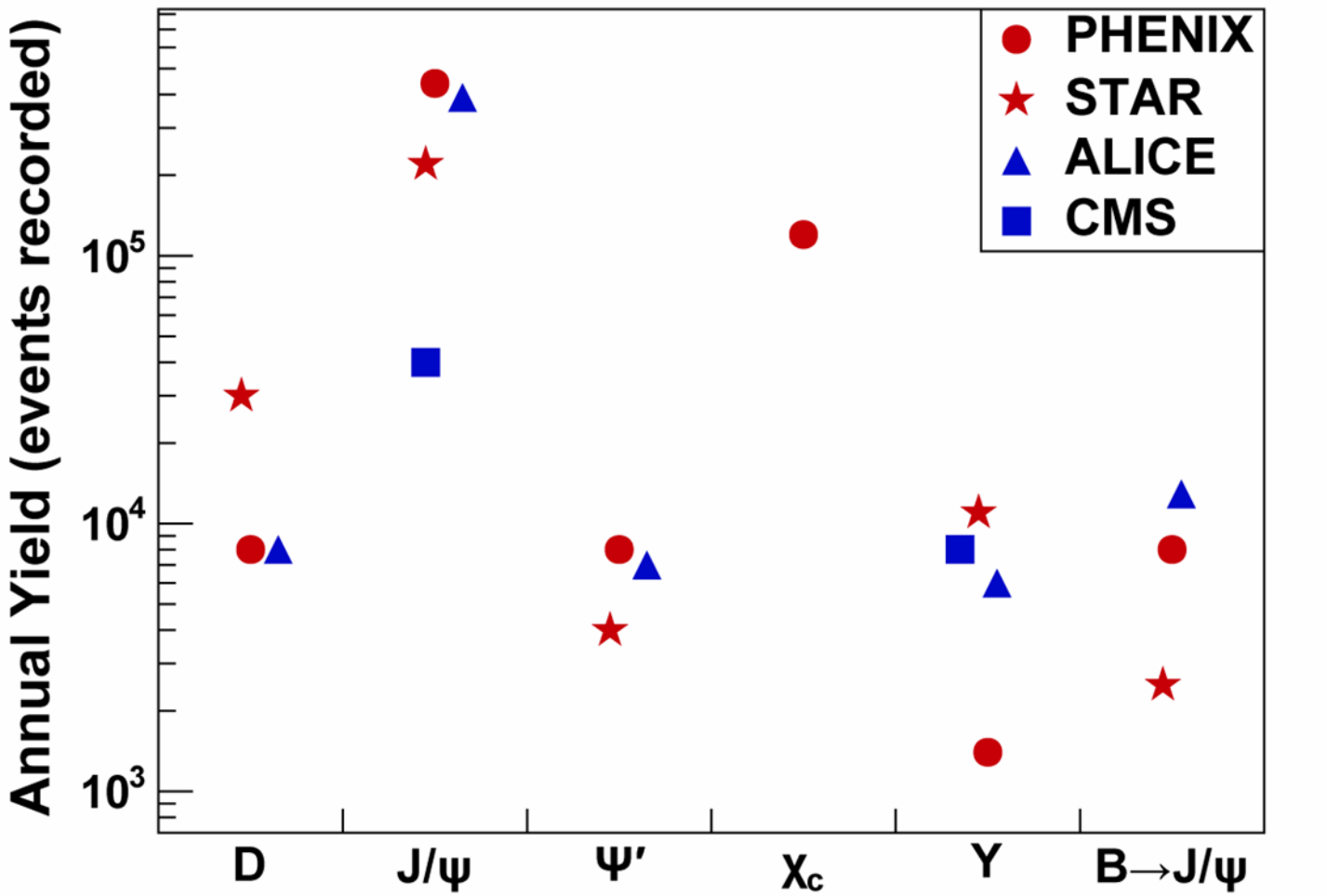


- Radiation hard Silicon (pixel/strip) Tracking System in a magnetic dipole field
- Electron detectors: RICH & TRD & ECAL: pion suppression better 10^4
- Hadron identification: TOF-RPC
- Measurement of photons, π, η, and muons: electromagn. calorimeter (ECAL)
- High speed data acquisition and trigger system

Annual yields at RHIC II & LHC

(from Tony Frawley RHIC Users mtg.)

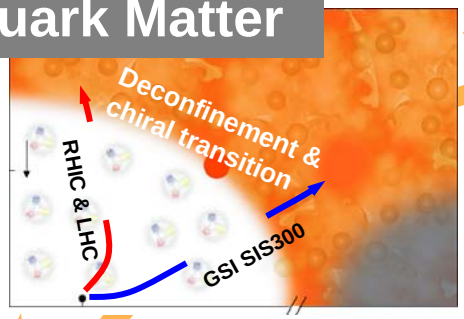
FAIR



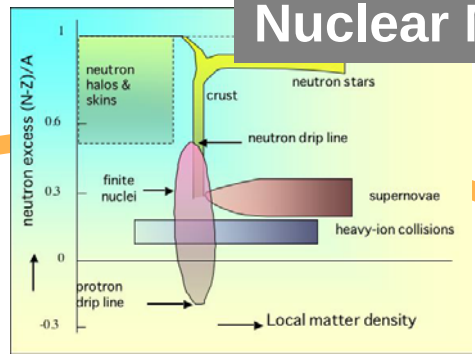
at LHC: (10-50) x σ ~10% of ℒ 25% running time

- Phase Diagram
- EOS
- matter & constit. prop.

Quark Matter



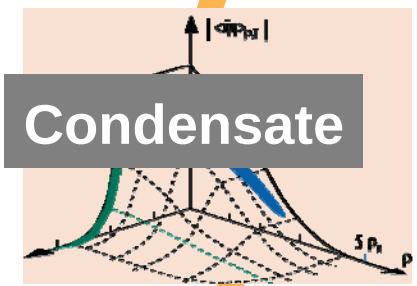
Nuclear Matter



- N-Hyperon Int.
- n-skin & beta matter
- n-star & Q-matter

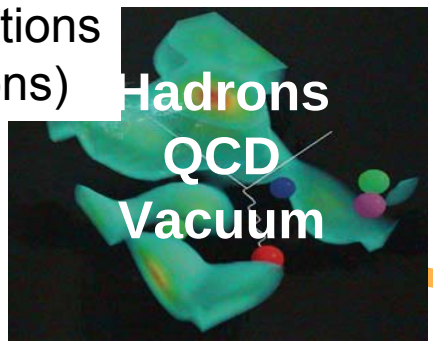
- thermal prop. of charmonium states...

Condensate

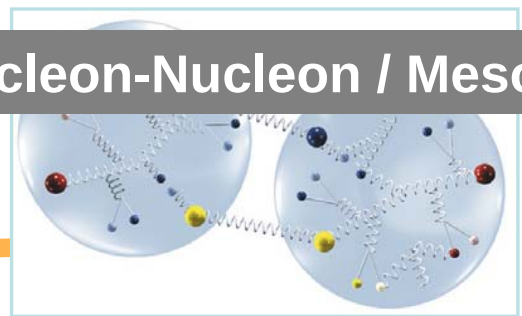


- spectral functions (vector mesons)

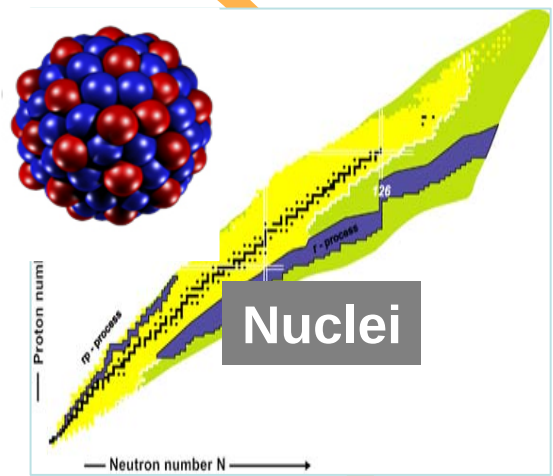
Hadrons
QCD
Vacuum



Nucleon-Nucleon / Meson



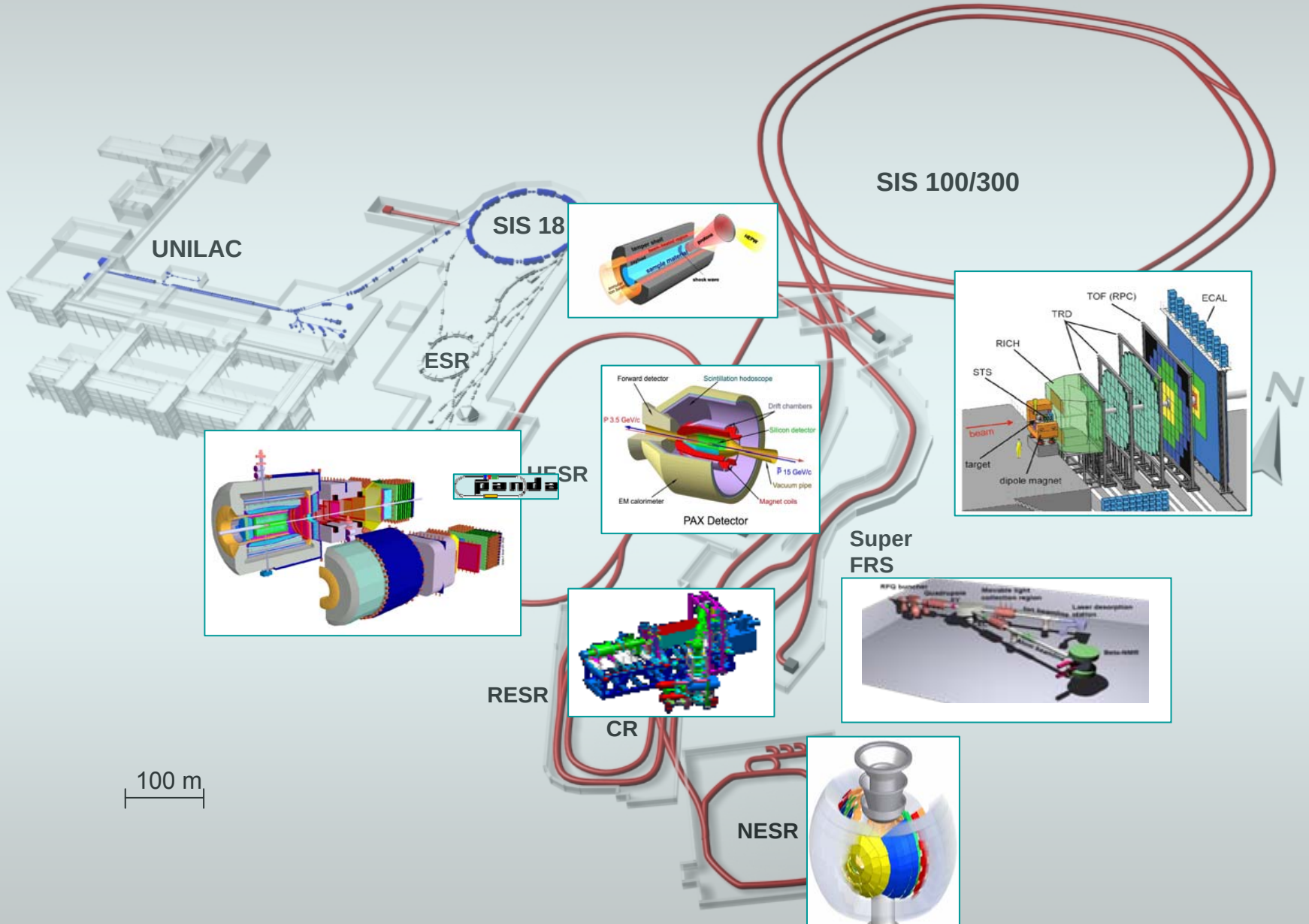
Nuclei



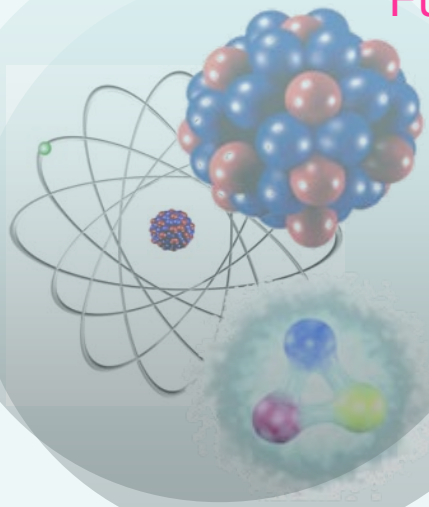
- SRC & PD
- 3NF
- p (N) structure in-medium

Outlook

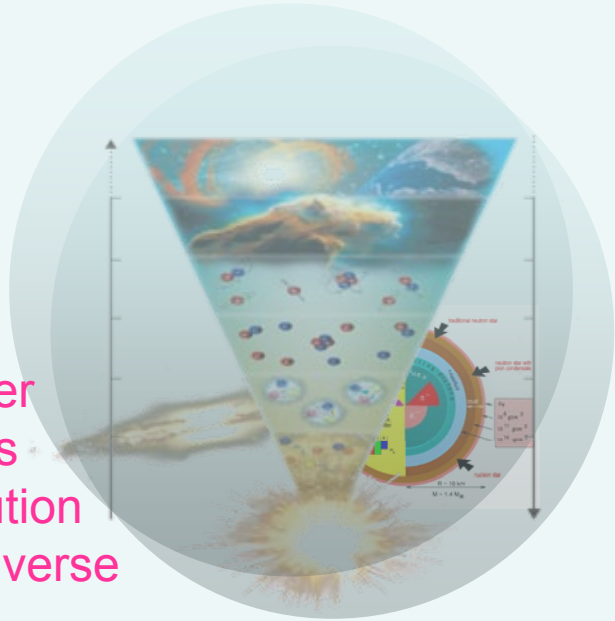
FAIR – Planned Experimental Facilities



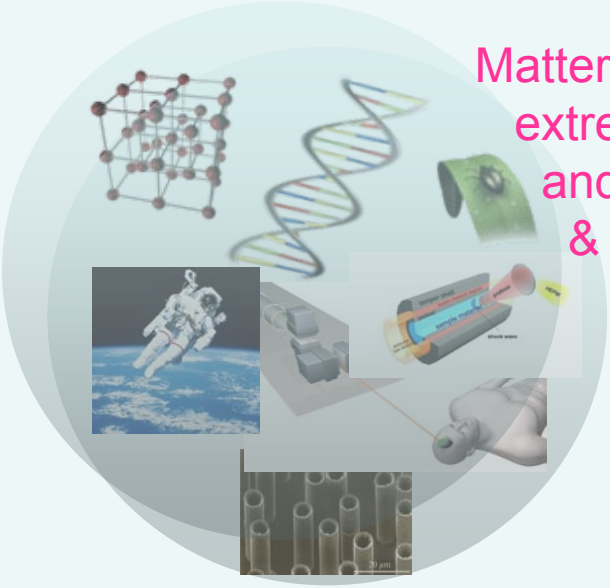
Highest Intensity Precision Beams of Energetic Ions



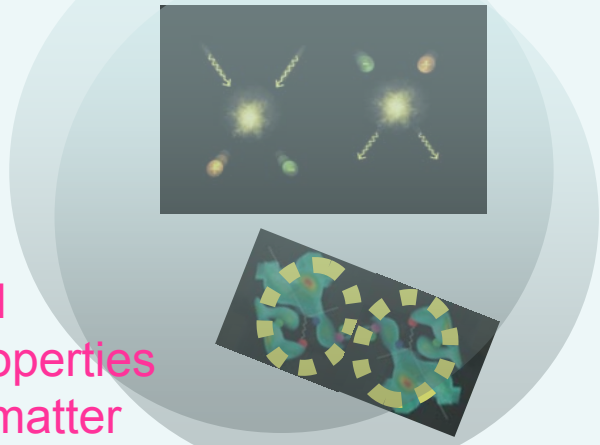
Fundamental Research
into the microscopic
structure of matter



Creation of matter
nucleosynthesis
and the evolution
of the Universe

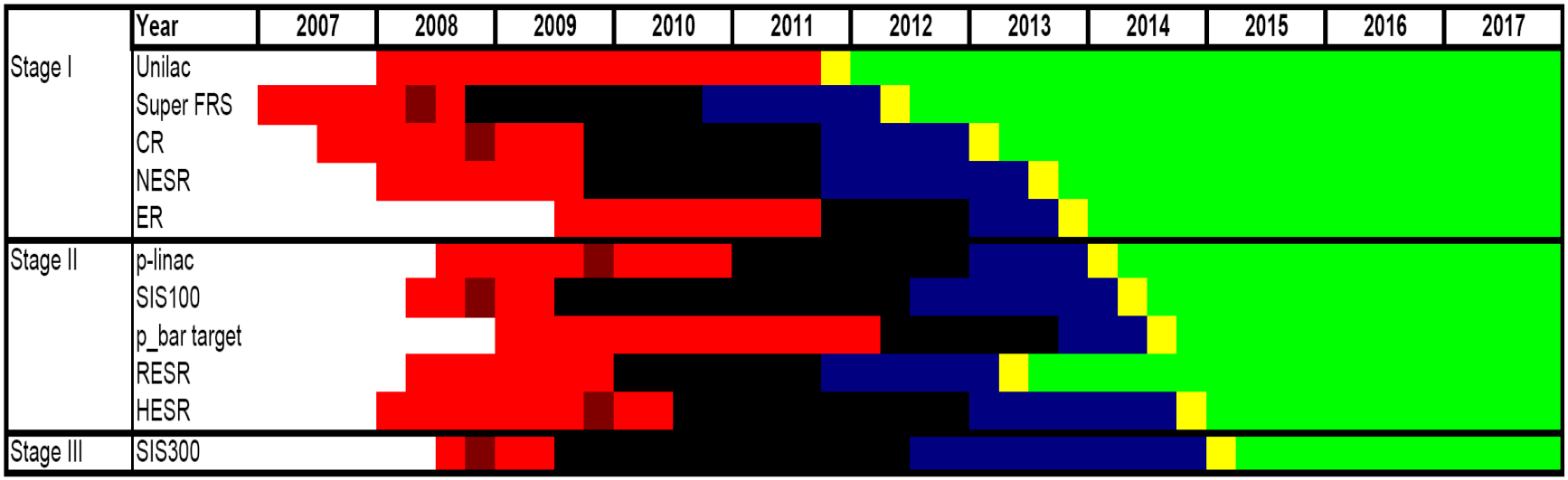


Matter in
extreme states
and material studies
& applications



Structure and
fundamental properties
of anti-matter

Master Schedule

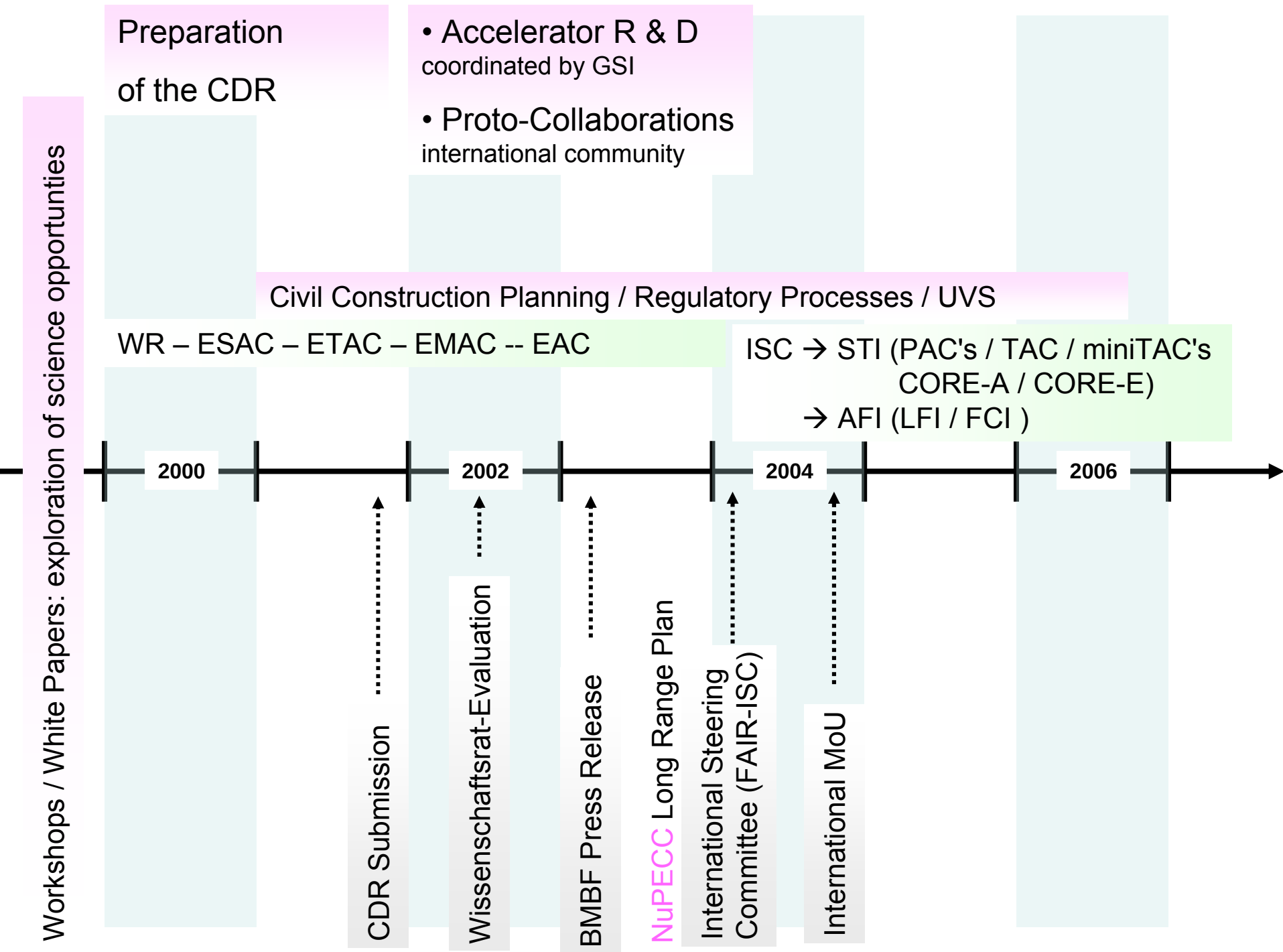


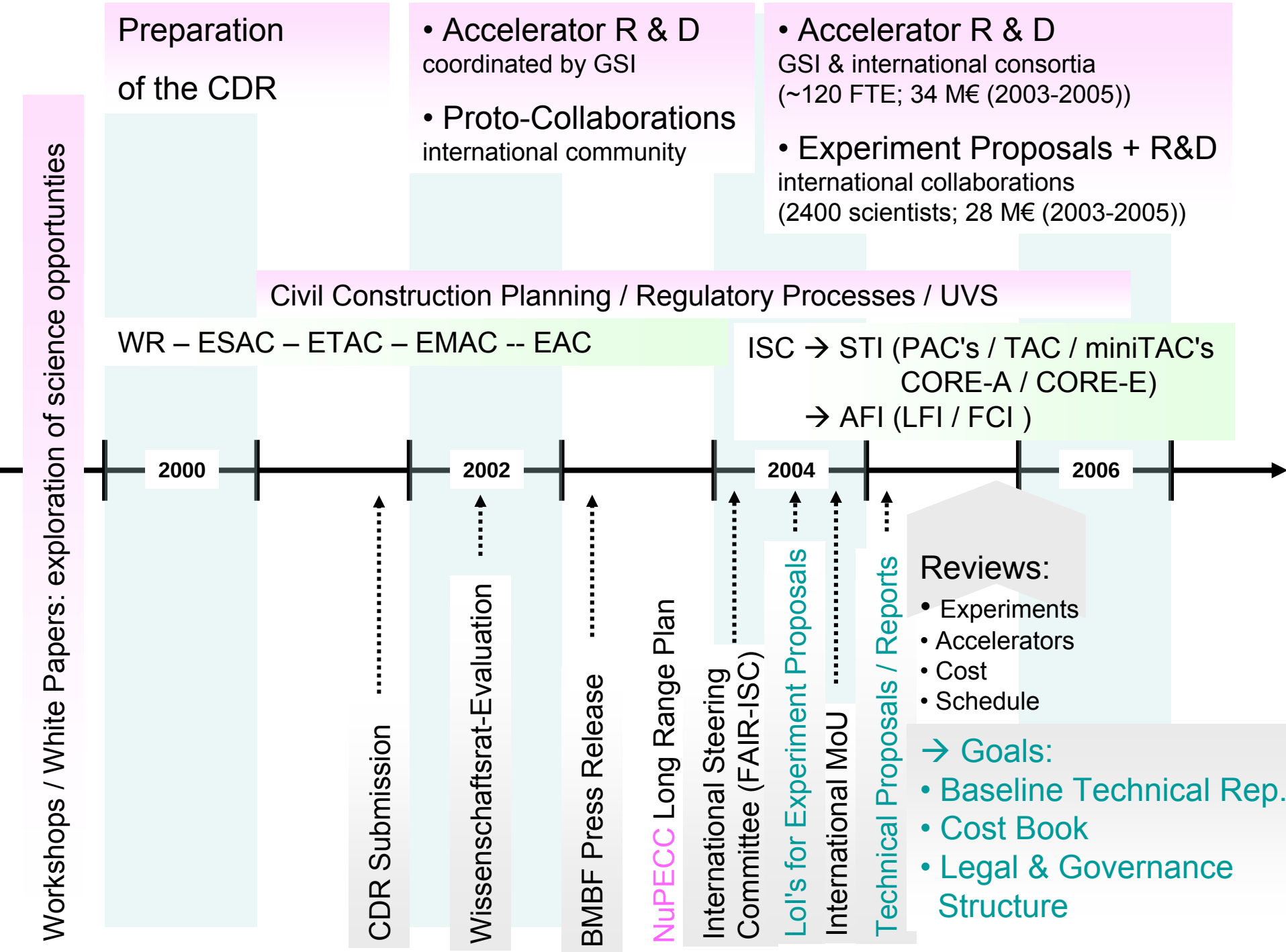
Based on Civil Construction Schedule

Construction
Commissioning
Operation
Prototype test
Series Production
Installation&test

Thank You !

CN DE ES FI FR GB GR IN IT PL RO RU SE


Preparation
of the CDR
• Accelerator R & D
coordinated by GSI
• Proto-Collaborations
international community
Civil Construction Planning / Regulatory Processes / UVS
WR – ESAC – ETAC – EMAC -- EAC
ISC → STI (PAC's / TAC / miniTAC's
CORE-A / CORE-E)
→ AFI (LFI / FCI)
Workshops / White Papers: exploration of science opportunties
2000
2002
2004
2006
CDR Submission
Wissenschaftsrat-Evaluation
BMBF Press Release
NuPECC Long Range Plan
International Steering
Committee (FAIR-ISC)
International MoU


Preparation
of the CDR
• Accelerator R & D
coordinated by GSI
• Proto-Collaborations
international community
• Accelerator R & D
GSI & international consortia
(~120 FTE; 34 M€ (2003-2005))
• Experiment Proposals + R&D
international collaborations
(2400 scientists; 28 M€ (2003-2005))
Civil Construction Planning / Regulatory Processes / UVS
WR – ESAC – ETAC – EMAC -- EAC
ISC → STI (PAC's / TAC / miniTAC's
CORE-A / CORE-E)
→ AFI (LFI / FCI)
Workshops / White Papers: exploration of science opportunities
2000
2002
2004
2006
CDR Submission
Wissenschaftsrat-Evaluation
BMBF Press Release
NuPECC Long Range Plan
International Steering
Committee (FAIR-ISC)
LoI's for Experiment Proposals
International MoU
Technical Proposals / Reports
Reviews:
• Experiments
• Accelerators
• Cost
• Schedule
→ Goals:
• Baseline Technical Rep.
• Cost Book
• Legal & Governance
Structure

Structure of FAIR for Preparatory Phase (MoU)

CN DE ES FI FR GB GR IN IT PL RO RU SE

ISC
International Steering Committee
H. Schunck

STI Working Group
Scientific + Technical Issues
H. Wenninger

AFI Working Group
Administrative + Funding Issues
Ö. Skeppstedt

FAIR Project

- Baseline Technical Report
  - accelerator TR's
  - experiment proposals
  - civil construction plans

  (~ 3500 pages)
- PAC & TAC Review Reports
- Cost Book
- Cost Review Reports
  - accelerator & civil construction (CORE-A)
  - experiments (CORE-E)

Mini-TACs
- Cryogenics
- Warm magnets
- Cold magnets
- Power Supplies
- Beam Instrumentation
- p-Linac

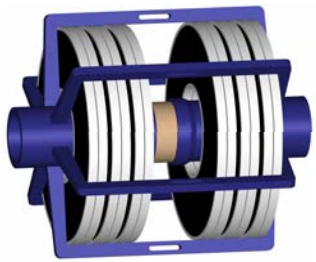
- Convention
- Articles of Association
- By-Laws
- Final Act Document
- Legal Framework Report (LFI)
- Full Cost Structure Report (FCI)

Observers:

Accelerator Physics and Key Technology / R&D for FAIR

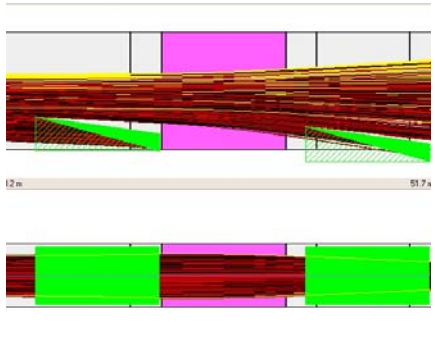
High gradient, low frequency RF cavities

CR compressor cavity



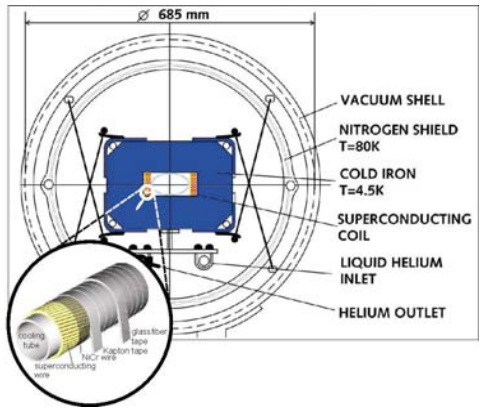
Novel lattice/collimation design: Beam optics studies

control of stripping losses

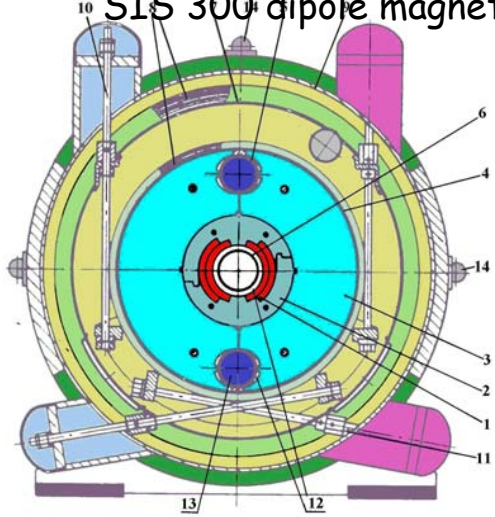


Superconducting, fast ramping synchrotron magnets

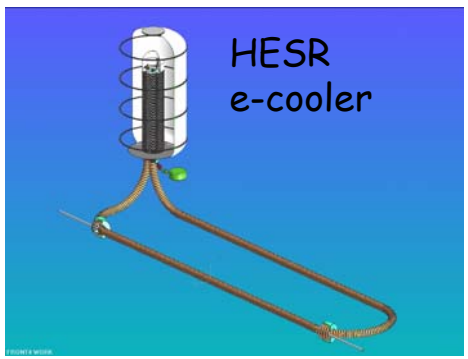
SIS 100 dipole magnet



SIS 300 dipole magnet

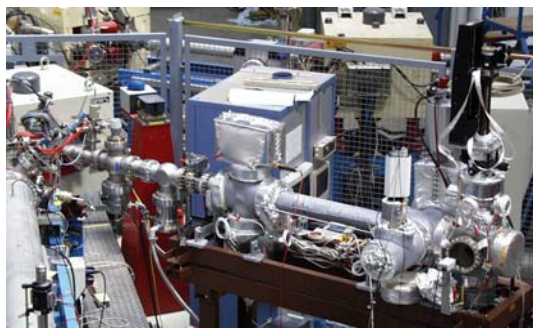


Fast stochastic and electron cooling

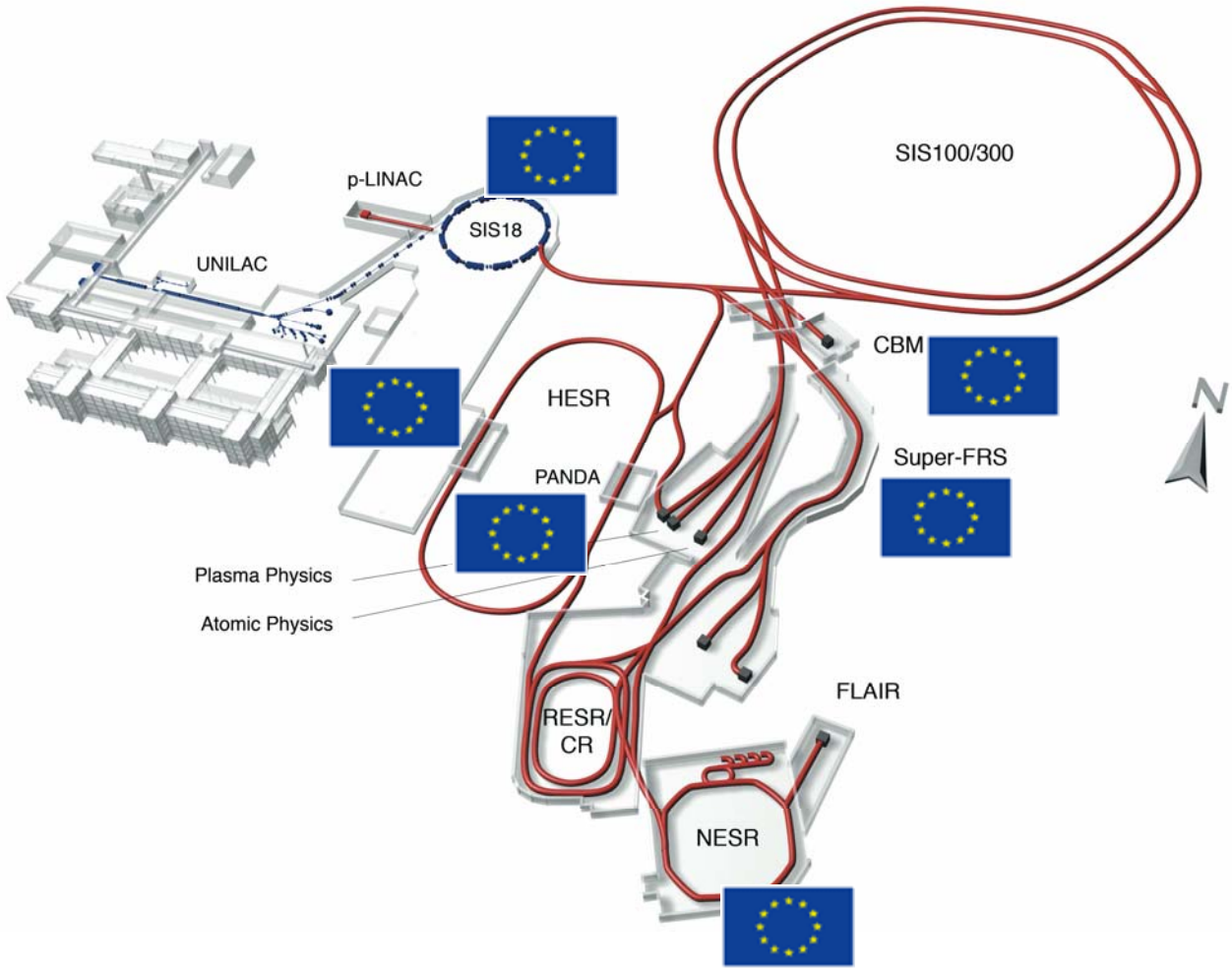


Ultra high vacuum for intense beams

Desorption test-stand



Strong EU support for FAIR related activities in FP6



EU-FP6-CNI:
⇒ FAIR injector SIS18 intensity upgrade, HADES upgrade + R3Bmagnet
EU-Support: 10,4 M€

EU-FP6-Design Study:
⇒ Secondary Beams (RIB and Antiprotons)
EU-Support: 9 M€

EU-FP6-I3 programs
⇒ **I3HadronPhysics:** FAIR related EU-Support: 10,8 M€
⇒ **EURONS:** FAIR related EU-Support: 2 M€