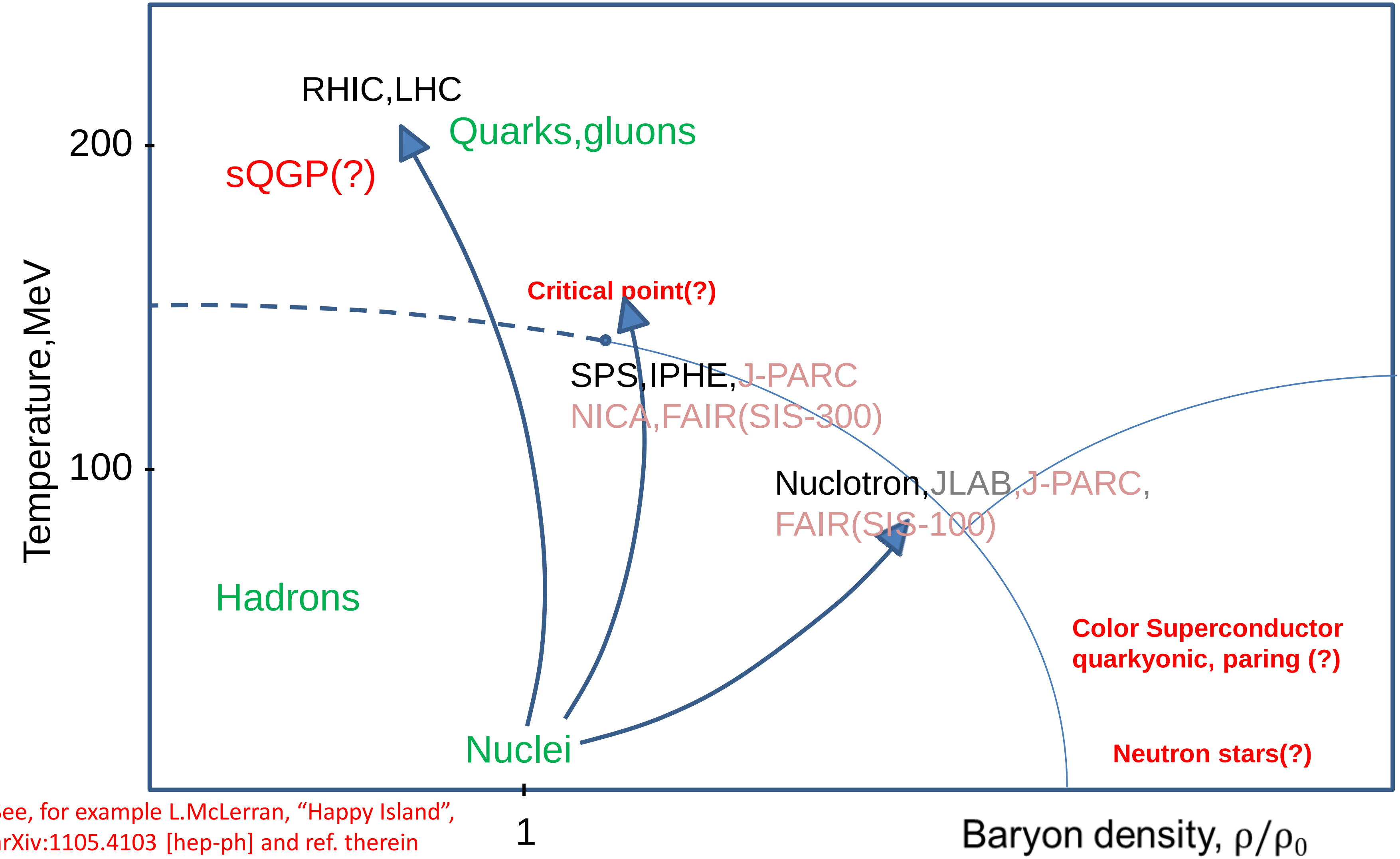
Cold dense baryonic matter

A.V.Stavinskiy (ITEP, Moscow)

Motivation

Perturbative aspects of QCD have been tested to a few percent. In contrast,
non-perturbative aspects of QCD
(hadronization, confinement, etc)
have barely been tested. The study of the quark matter at different temperature and baryon density is part of effort to consolidate the grand theory of particle physics.



See, for example L.McLerran, "Happy Island",
arXiv:1105.4103 [hep-ph] and ref. therein

Tools:1).Special final state selection (flucton-flucton interaction with quasi-two-body final state)
+ Correlation measurements including femtoscopy

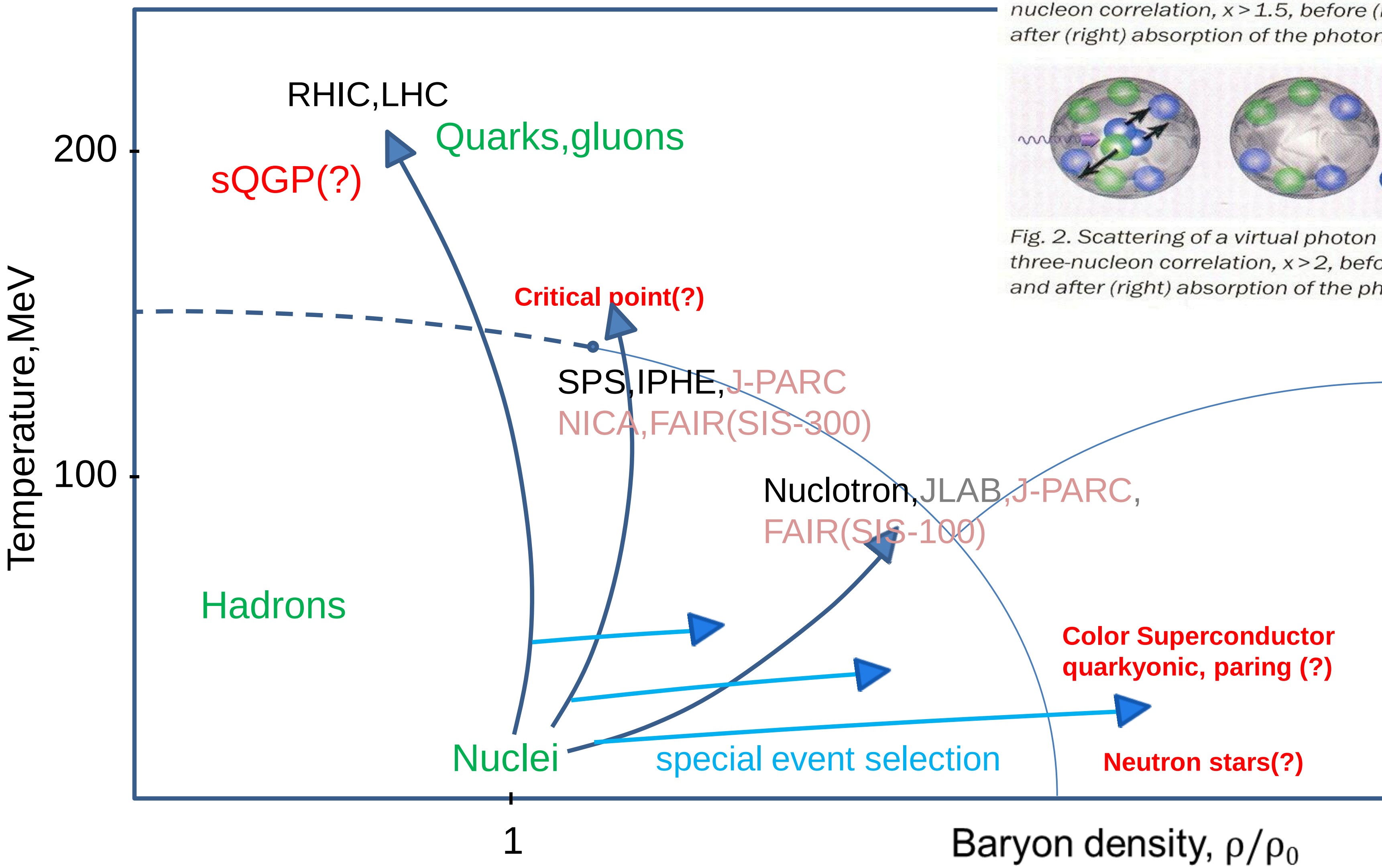


Figure from: M.Strikman, CERN Courier Nov.2,2005

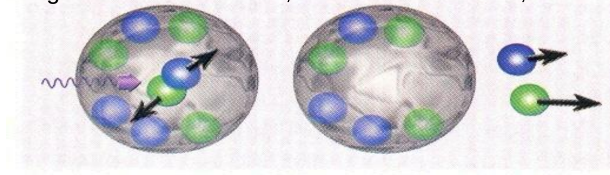


Fig. 1. Scattering of a virtual photon off a two-nucleon correlation, x > 1.5, before (left) and after (right) absorption of the photon.

Fig. 2. Scattering of a virtual photon off a three-nucleon correlation, x > 2, before (left) and after (right) absorption of the photon.

JLAB

Phys.Rev.Lett. 96 (2006) 082501

Measurement of 2- and 3-Nucleon Short Range Correlation Probabilities in Nuclei

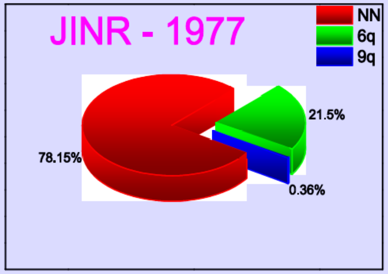
K.S. Egiyan,[1] N.B. Dashyan,[1] M.M. Sargsian,[10] M.I. Strikman,[28] L.B. Weinstein,[27] G. Adams,[30] P. Ambrozewicz,[10] M. Anghinolfi,[16] B. Asavapibhop,[22] G. Asryan,[1] H. Avakian,[34] H. Baghdasaryan,[27] N. Baillie,[38] J.P. Ball,[2]

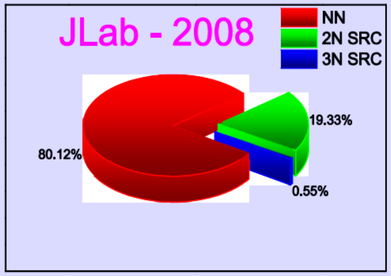
RNP – program at JINR

V.V.B., V.K.Lukyanov, A.I.Titov, PLB, 67, 46(1977)

***eA* – program at JLab**

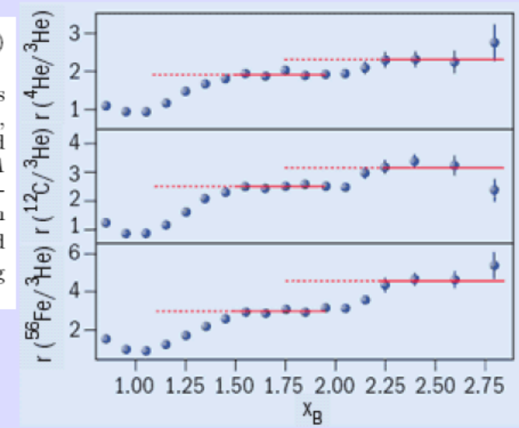
R.Subedi et al., Science 320 (2008) 1476-1478
e-Print: arXiv:0908.1514 [nucl-ex]





$$r(A,{}^3\mathrm{He}) = \frac{A(2\sigma_{ep}+\sigma_{en})}{3(Z\sigma_{ep}+N\sigma_{en})}\frac{3\mathcal{Y}(A)}{A\mathcal{Y}({}^3\mathrm{He})}C^A_{\mathrm{rad}}, \qquad (2)$$

where Z and N are the number of protons and neutrons in nucleus A, σ_{eN} is the electron-nucleon cross section, $\mathcal{Y}$ is the normalized yield in a given (Q^2, x_B) bin [30] and C^A_{rad} is the ratio of the radiative correction factors for A and ^{3}He ($C^A_{\mathrm{rad}} = 0.95$ and 0.92 for ^{12}C and ^{56}Fe respectively). In our Q^2 range, the elementary cross section correction factor $\frac{A(2\sigma_{ep}+\sigma_{en})}{3(Z\sigma_{ep}+N\sigma_{en})}$ is 1.14 ± 0.02 for C and ^{4}He and 1.18 ± 0.02 for ^{56}Fe. Fig. 1 shows the resulting ratios integrated over $1.4 < Q^2 < 2.6$ GeV^2.



- No rescattering

$x_B = Q^2/2m_N U$

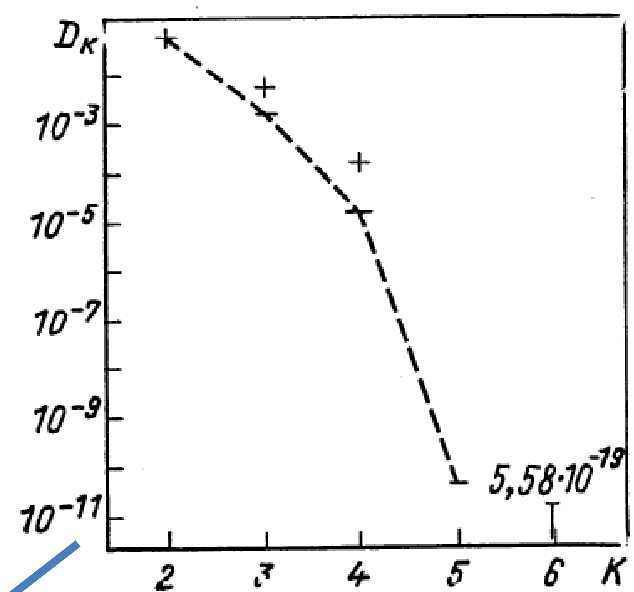
Probing Cold Dense Nuclear Matter,

R.Subedi et al.,arXiv:0908.1514v1[nucl-ex]

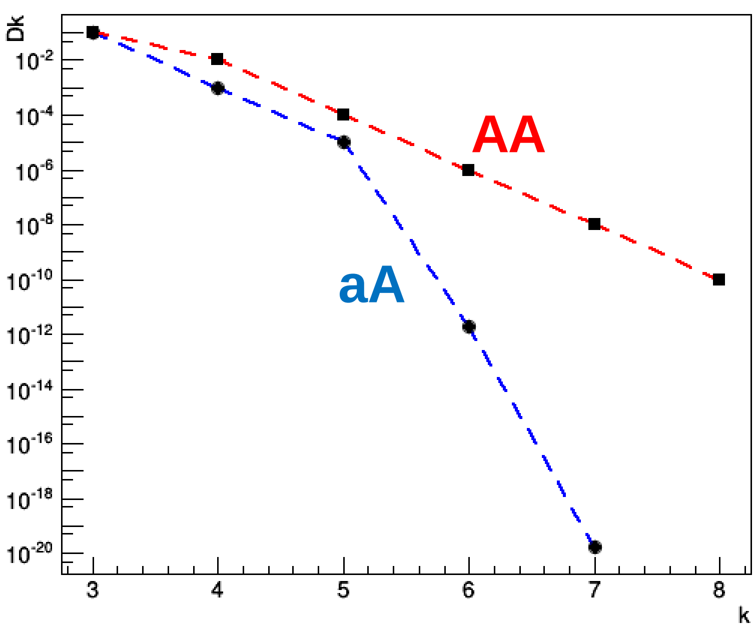
The protons and neutrons in a nucleus can form strongly correlated nucleon pairs. Scattering experiments, where a proton is knocked-out of the nucleus with high momentum transfer and high missing momentum, show that in ^{12}C the neutron-proton pairs are nearly twenty times as prevalent as proton-proton pairs and, by inference, neutron-neutron pairs. This difference between the types of pairs is due to the nature of the strong force and has implications for understanding cold dense nuclear systems such as neutron stars.

Why AA ?

	a_{2N}, %	a_{3N}, %	$(a_{2N})^2$, %
^{3}He	8.0±1.6	0.18±0.06	0.64
^{4}He	15.4±3.3	0.42±0.14	2.4
^{12}C	19.3±4.1	0.55±0.17	3.7



Flucton probability as a function of number of nucleons. V.K.Luk'yanov,A.I.Titov, PEPAN,1979,vol.10(4),p.815

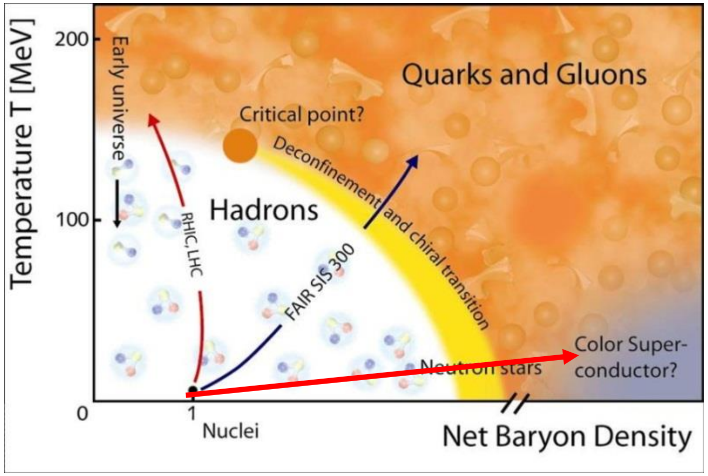


dramatic decreasing of the cross sections with N:
----> max N~4

Flucton+flucton probability as a function of total number of nucleons.

FLINT experiment @ ITEP

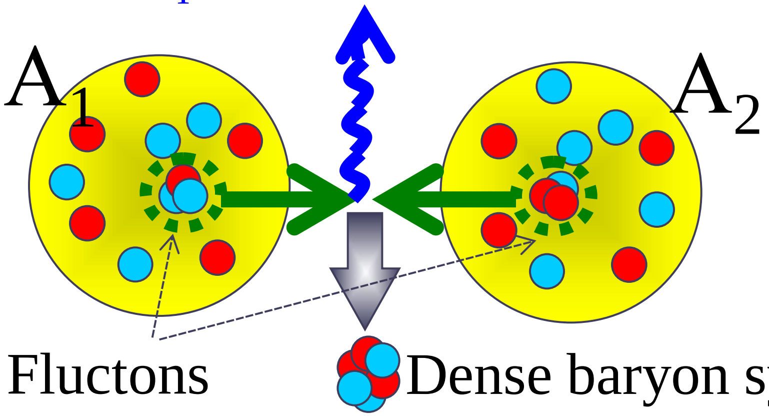
Phase diagram*



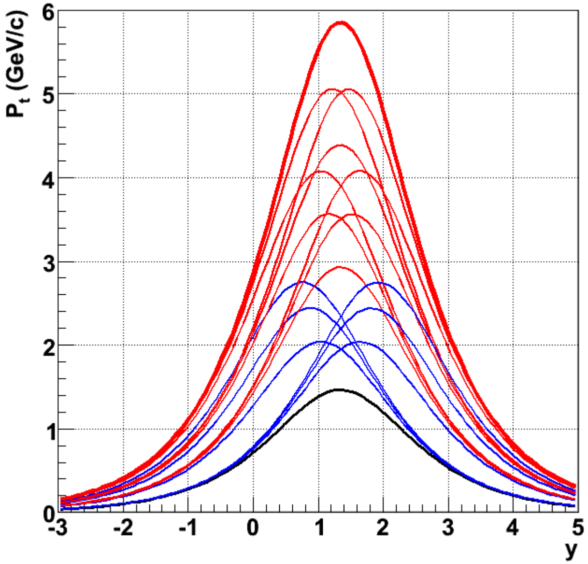
*http://www.gsi.de/forschung/fair_experiments/CBM/

Scheme of process

High p_T trigger $\gamma,\gamma(\pi^o)$,…

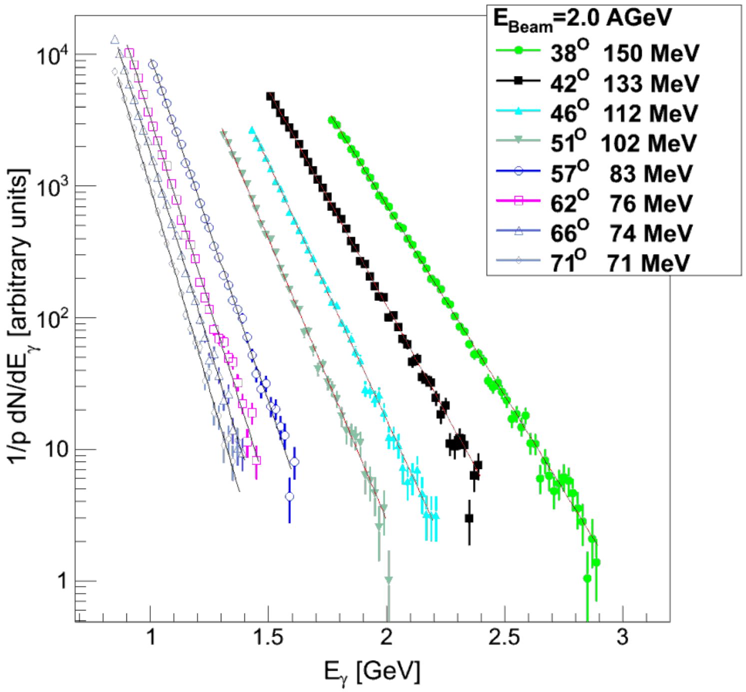


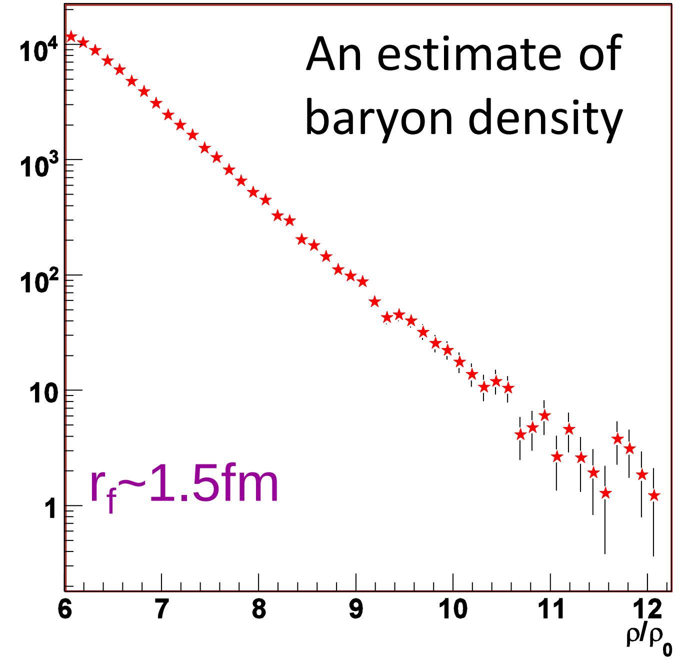
He+He @ 6 AGeV



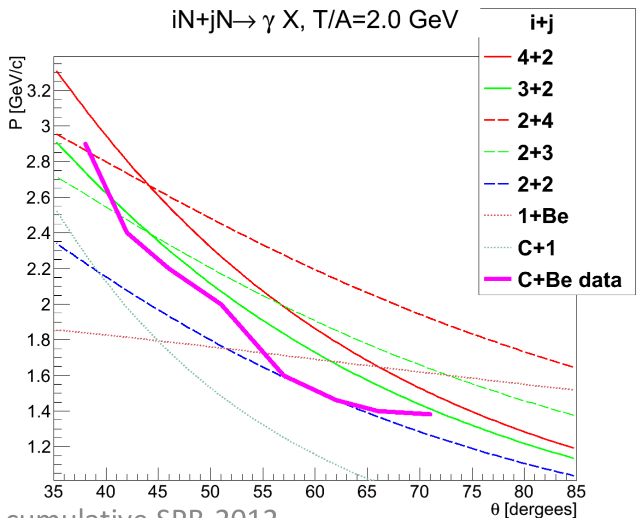
Kinematical limits for different subprocesses:
1N+1N(black line)
1N+Flucton(2N,3N,4N)&Flucton+1N(blue lines)
Flucton+Flucton(red lines)

FLINT DATA: Photon spectra
CBe→γX





FLINT have got data for fluctonflucton
interaction up to 6 nucleons
kinematical
region, which cannot be explained
neither p+Be nor C+p interactions
Six nucleons system: n!n¡p!p¡+??
Does we already see phase transition?



Experimental program:

1). Search for and the study of new state of matter at high density and low temperature corner of phase diagram

- search for the dense baryonic droplet in correlation measurements with high p_t cumulative trigger
- femtoscopy measurements for the dense baryonic droplet
- izotopic properties of the droplet
- strangeness production in the droplet
- fluctuations
- search for an exotic in the droplet

2) Dense cold matter contribution in ordinary nuclear matter and its nature SRC,flucton,…

- nuclear fragmentation
- hard scattering

Proposed measurements:

1. Beams and targets: A_1(p(anti p),d,^{3}He,^{4}He,C; A_2(^{3}He,^{4}He,C,Pb);
2. Beam energy(for fix target): ~1-10 GeV/nucleon

3.Trigger's particles: γ, π, K^-,K^+,p, d, …(p_t /E_0~1)

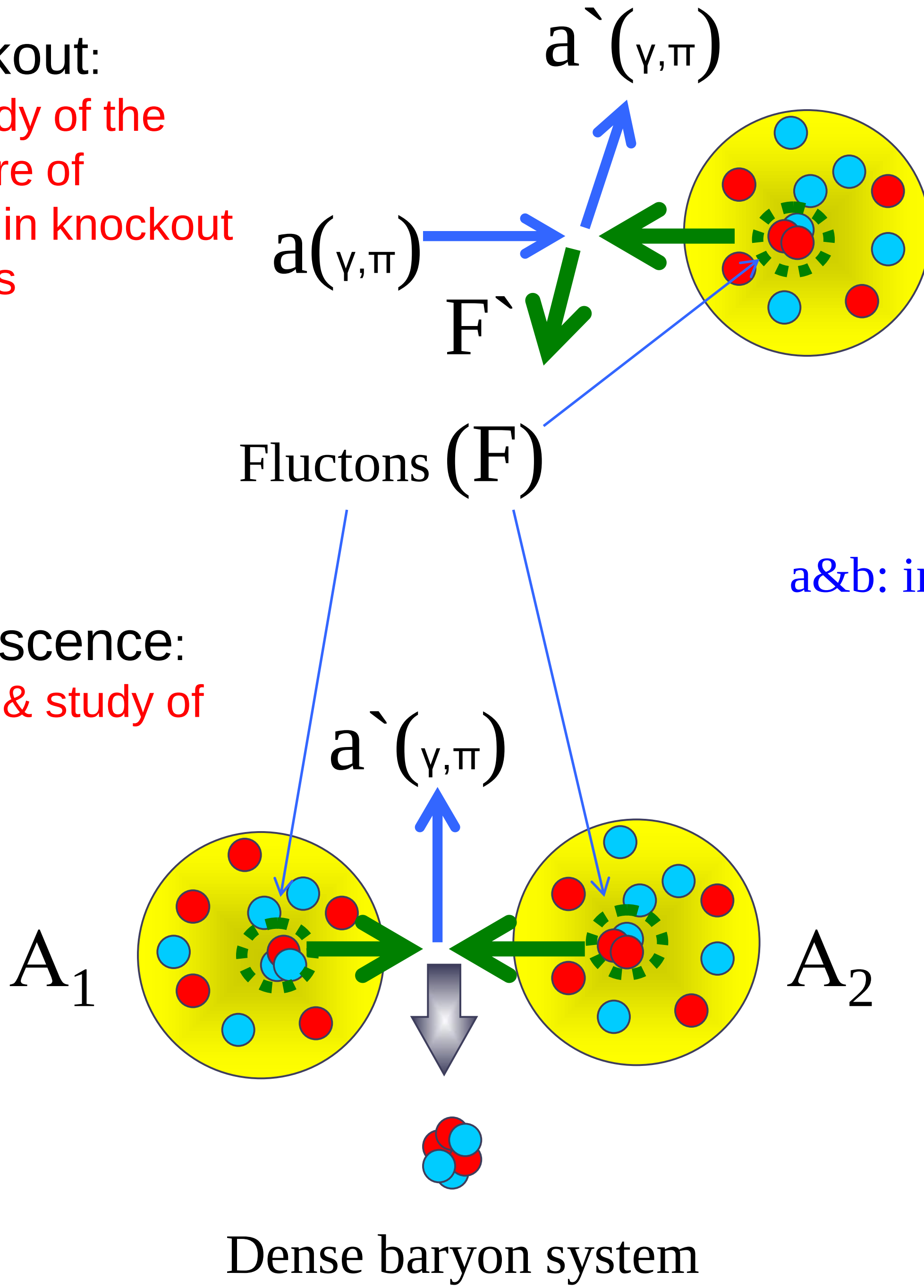
4. Recoil particles: nucleon, multinucleon systems, nuclear fragments, exotic states
5. Measurement values: <N(p_t ,y)> vs X_{trig} and E_0(2-6GeV/nucleon);

-ratios(p/n, ^{3}He/t,…);correlations between recoil particles

S.S. Shimansky, in Proc. of the VIII Intern. Workshop on Relativistic Nuclear Physics: from Hundreds of MeV to TeV, May 23-28, 2005, 297 (Dubna, 2006); nucl-ex/0604014.

a) Knockout:

the study of the structure of flucton in knockout process



b) Coalescence:

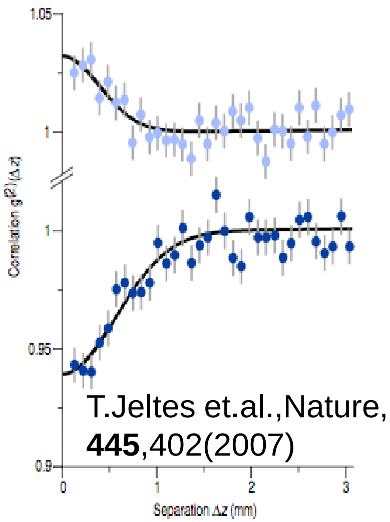
search for & study of DCM

a&b: in both cases high p_T trigger
$(\pi, \gamma, \gamma(\pi^o), \ldots)$

A_1, A_2: He, Be, C, …

– femtoscopy measurements for the dense baryonic droplet

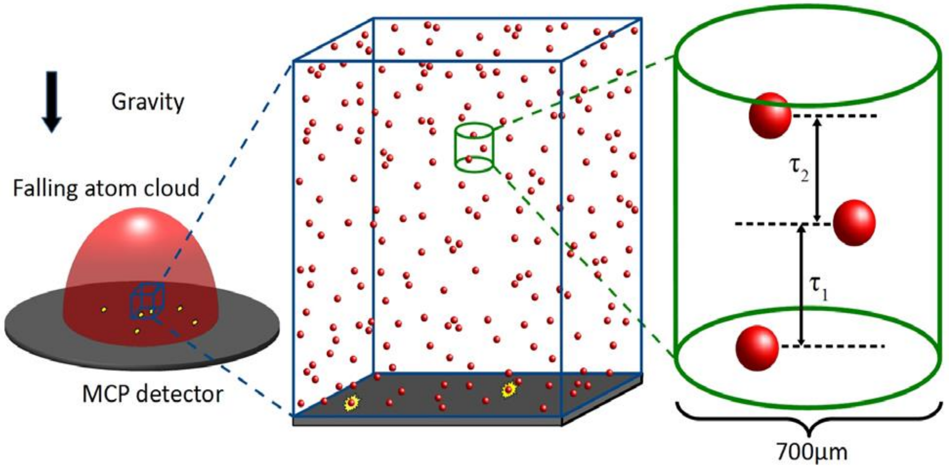
Condensed matter(not an analog in the state of matter but for the statistical properties of the system):Advances in atom cooling and detection have led to the observation and full characterisation of the atomic analogue of the HBT effect



T.Jeltes et.al.,Nature, **445**,402(2007)

Caption for figure 1: Normalised correlation functior for 4He* (bosons) in the upper graph, and 3He* (fermions) in the lower graph. Both functions are measured at the same cloud temperature (0.5 μK), and with identical trap parameters.The correlation length for 3He* is expected to be 33% larger than that for 4He* due tc the smaller mass. We find 1/e values for the correlation lengths of 0.75±0.07 mm and 0.56±0.08 mm for fermions and bosons respectivel

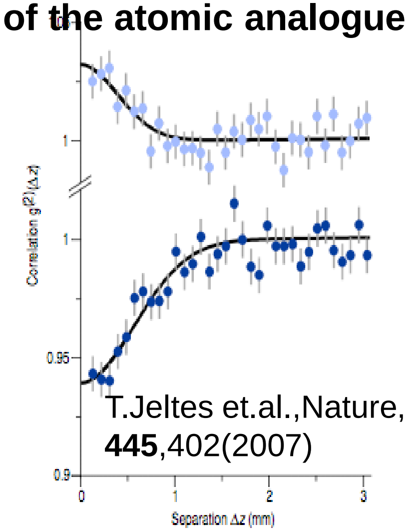
Caption for figure 1: The experimental setup. A cold cloud of metastable helium atoms is released at the switch-off of a magnetic trap. The cloud expands and falls under the effect of gravity onto a time resolved and position sensitive detector (micro-channel plate and delay-line anode), that detects single atoms. The inset shows conceptually the two 2-particle amplitudes (in black or grey) that interfere to give bunching or antibunching: S1 and S2 refer to the initial positions of two identical atoms jointly detected at D1 and D2.



– **femtoscopy measurements for the dense baryonic droplet**

Bose-Einstein Condensation(BEC)

Condensed matter(not an analog in the state of matter but for the statistical properties of the system):Advances in atom cooling and detection have led to the observation and full characterisation of the atomic analogue of the HBT effect



T.Jeltes et.al.,Nature, **445**,402(2007)

Caption for figure 1: Normalised correlation functions for 4He* (bosons) in the upper graph, and 3He* (fermions) in the lower graph. Both functions are measured at the same cloud temperature (0.5 μK), and with identical trap parameters.The correlation length for 3He* is expected to be 33% larger than that for 4He* due to the smaller mass. We find 1/e values for the correlation lengths of 0.75±0.07 mm and 0.56±0.08 mm for fermions and bosons respectively.

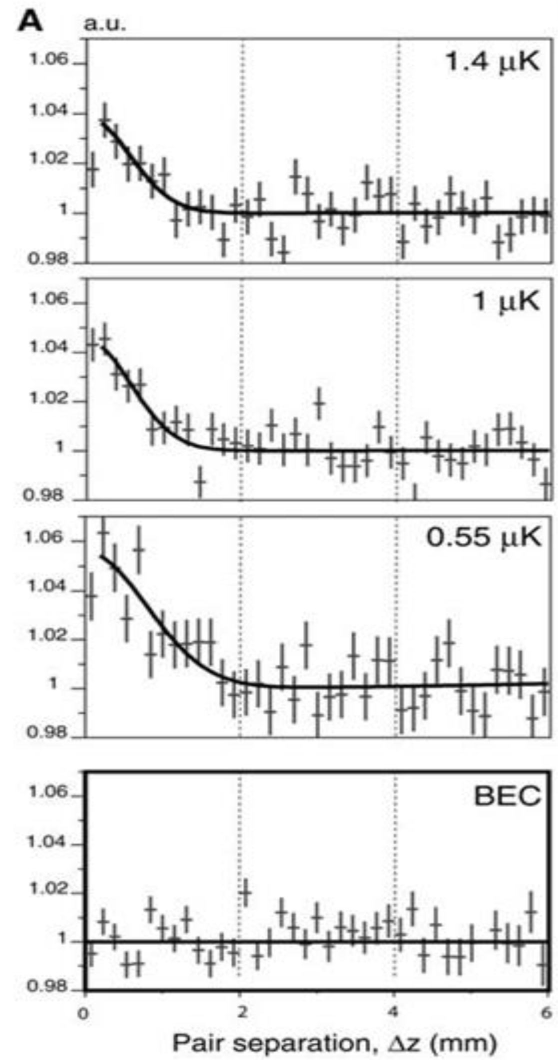


Fig. 2. (A) Normalized correlation functions along the vertical (z) axis for thermal gases at three different temperatures and for a BEC.

Science,v.310,p.648(2005)

Opposite sign correlations

Our purpose here is to point out that if a manyboson or many-fermion system exhibits opposite sign correlations, then the state in question necessarily has a certain complexity. For example,
consider a fermion gas. If the gas exhibits any positive pair correlations when it has been prepared in a certain state, then that state cannot be represented by a simple Slater determinant wavefunction. In general, if one probes a many-boson or many-fermion state and finds that it exhibits opposite sign correlations, then, even without any model for the unknown state, one may infer that it is not a “free” state, i.e., it does not have the form of a grand canonical ensemble for noninteracting indistinguishable particles. We believe that opposite sign correlations can be observed in current experimental setups and may even have already been observed and passed unnoticed.

Ref.:Alex D. Gottlieb and Thorsten Schumm, arXiv:0705.3491 [quant-ph]

Experimental program:

1). Search for and the study of new state of matter at high density and low temperature corner of phase diagram

– **fluctuations**

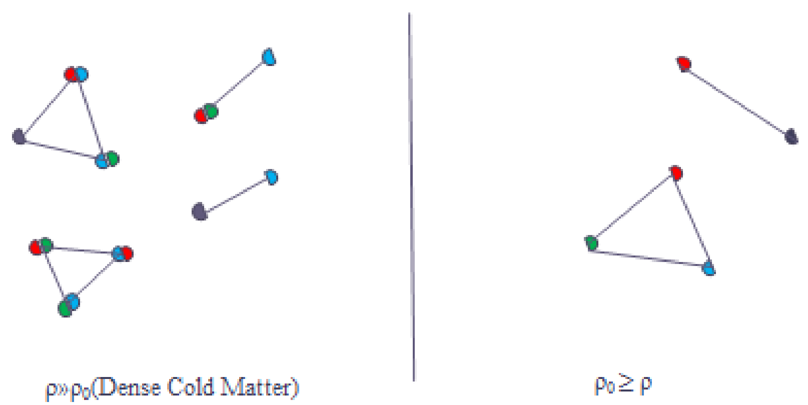
Phase space volume vs flucton probability ->

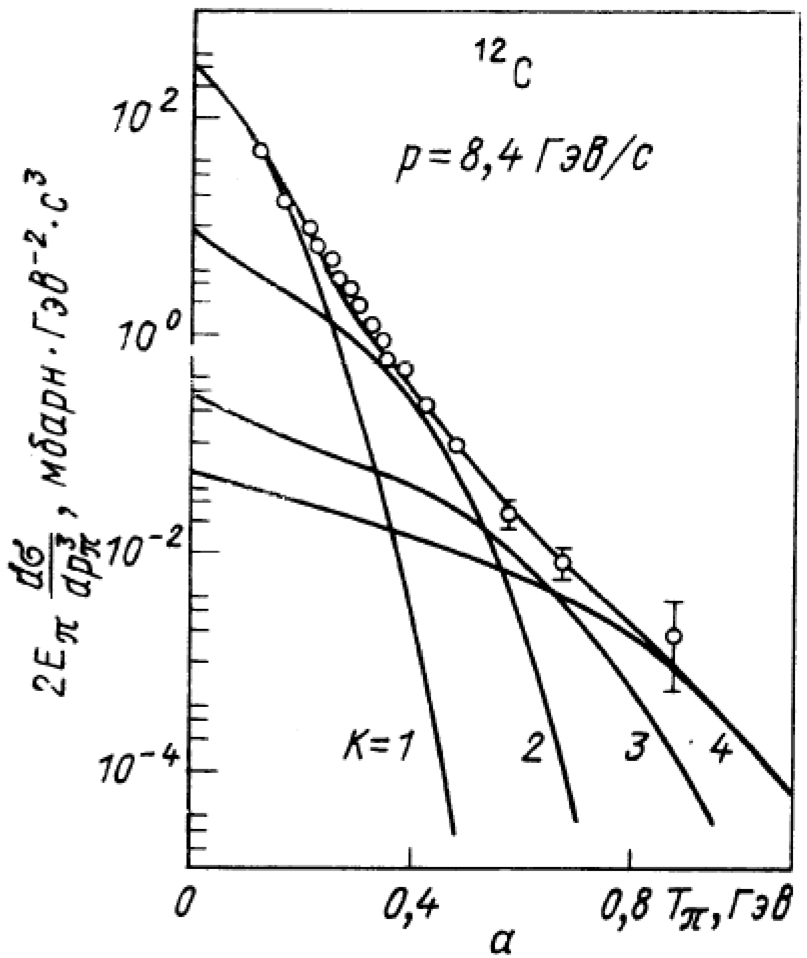
Baryon system temperature fluctuations

from event to event

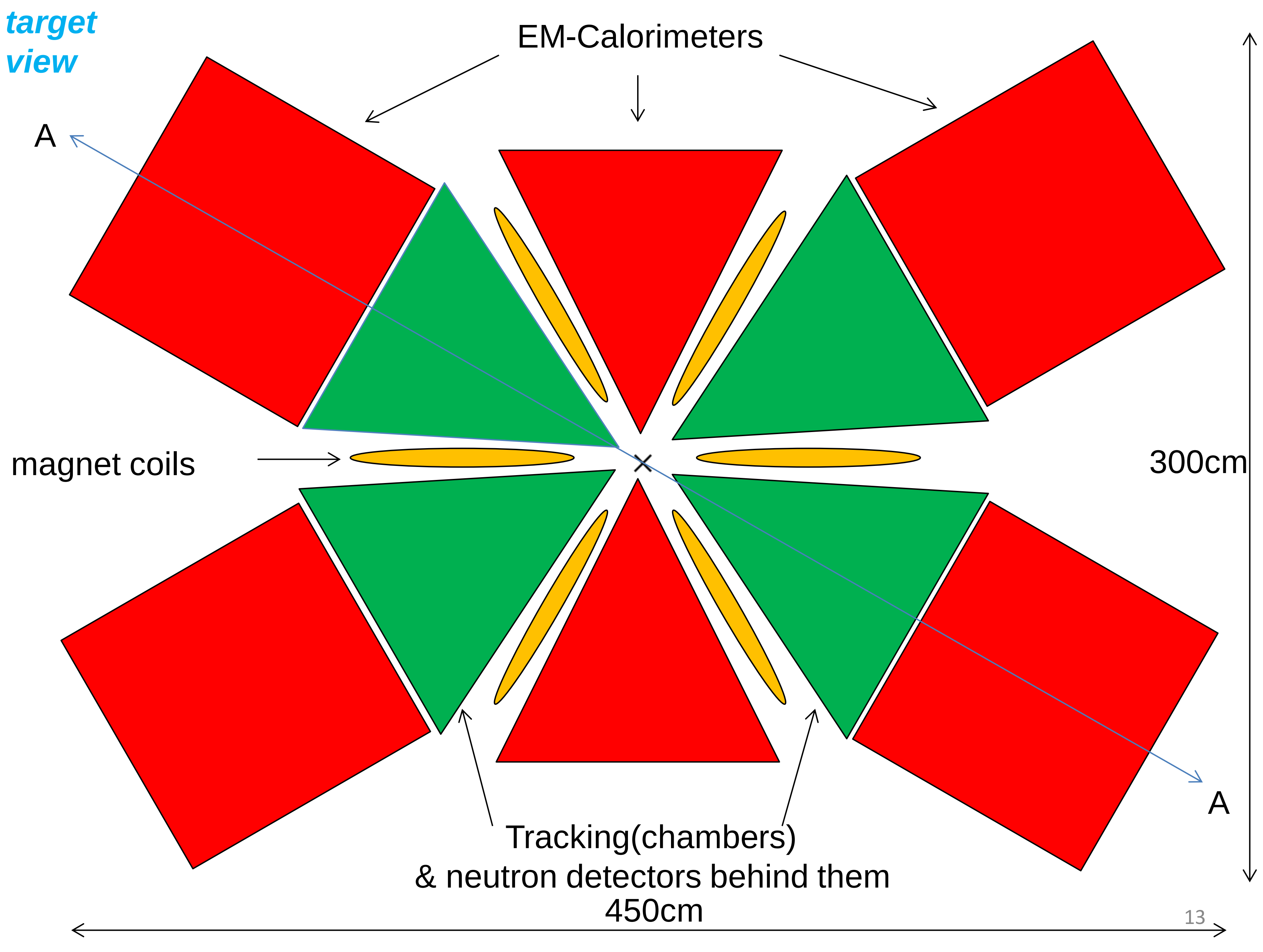
– **search for an exotic in the droplet**

Exotica in dense and cold nuclear matter
K.R. Mikhailov, A.V. Stavinskiy, V.L. Stolin, G.B. Sharkov Phys.Atom.Nucl. 77 (2014) p.576

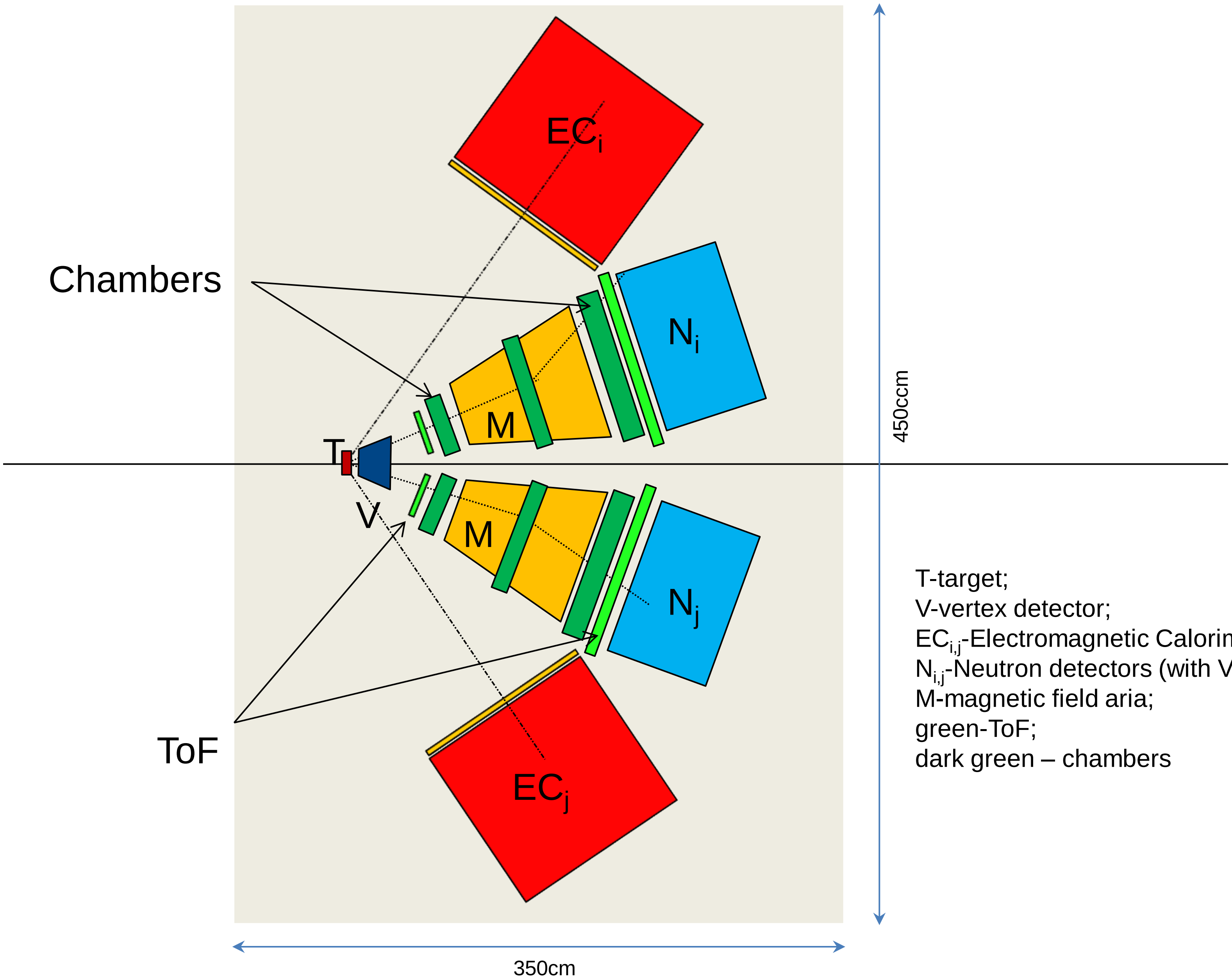




V.K.Luk'yanov,A.I.Titov, PEPAN,1979,vol.10(4),p.815

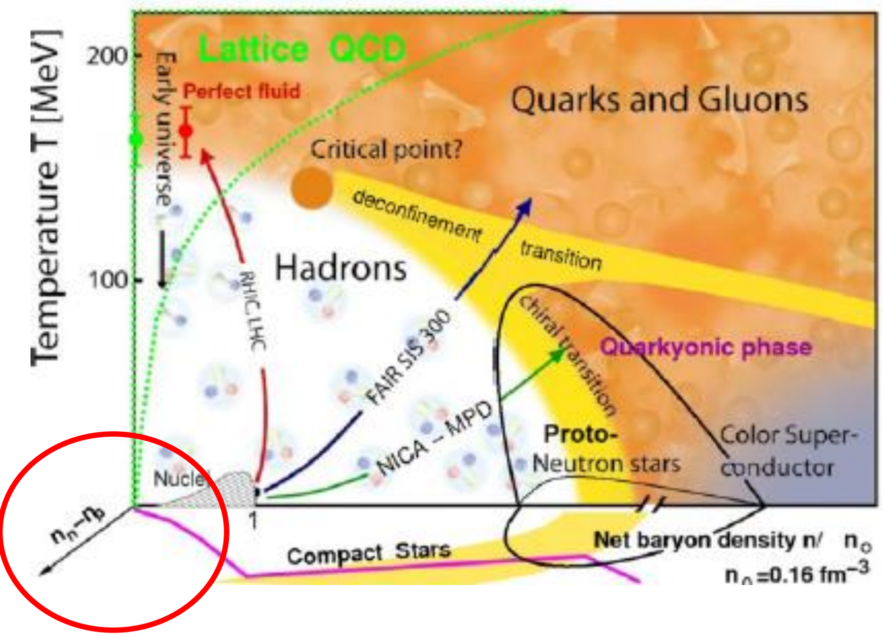

target
view
EM-Calorimeters
A
magnet coils
300cm
A
Tracking(chambers)
& neutron detectors behind them
450cm

DCM detector(project version), AA plane



T-target;
V-vertex detector;
$EC_{i,j}$-Electromagnetic Calorimeters;
$N_{i,j}$-Neutron detectors (with VETO);
M-magnetic field aria;
green-ToF;
dark green – chambers

Neutron detector. Motivation



1. Neutron is one of the main particle specie for AA collision at Nuclotron-NICA energy range;
2. State of nuclear matter depends on n/p ratio;
3. To identify some strange particles one need identify neutrons (for example $\Sigma^+ \rightarrow n\pi^+$);
4. Femtoscopy measurements: space time parameters for np and pp, nn are different.

⇒ **Need to measure neutrons**

Accuracy and kinetic energy range?

Temperature of the order of **100 MeV**

=>**Energy range** for neutron

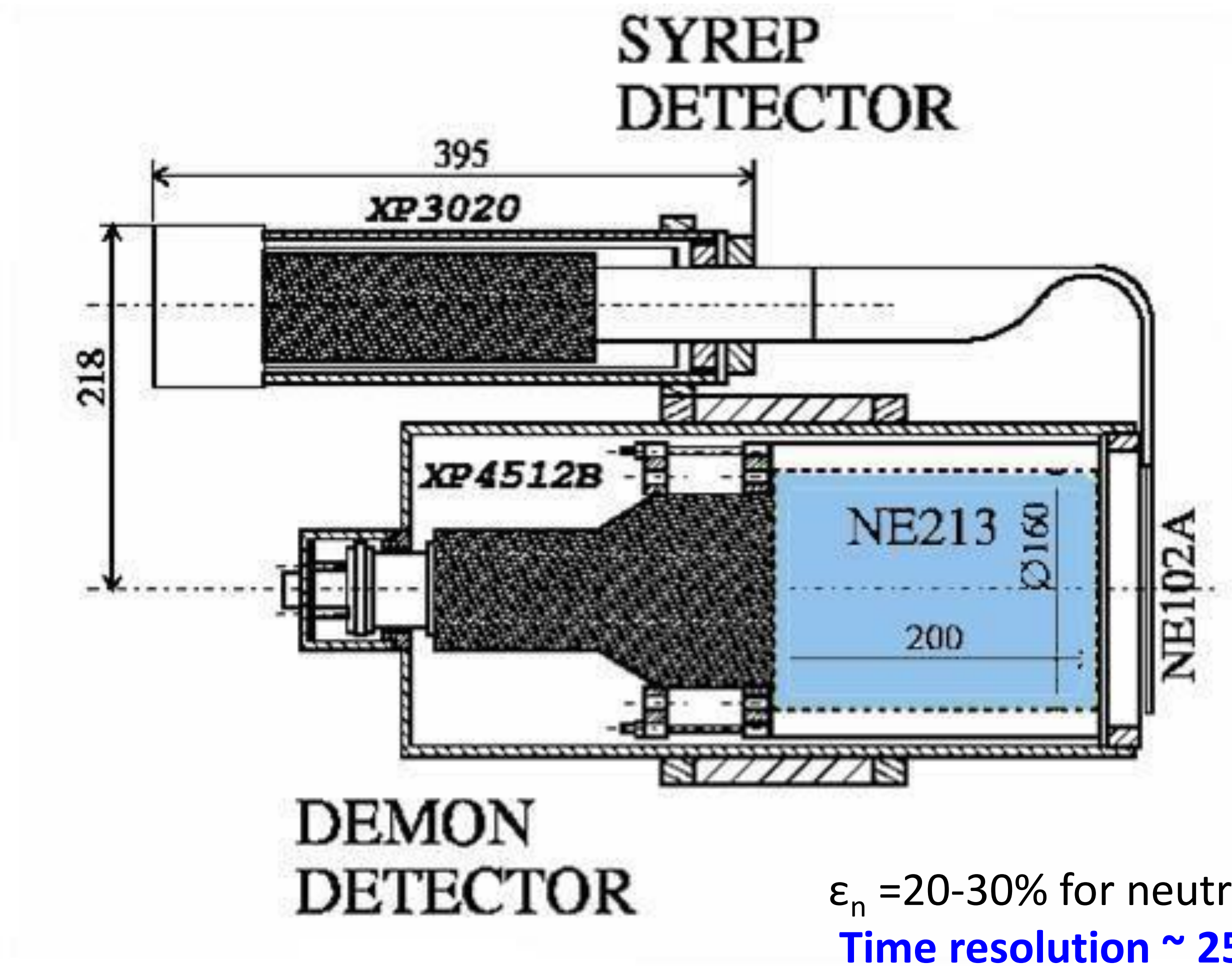
Ekin~ 10(1?) – 200MeV

Femtoscopy : the **width** of the effect

~**30MeV/c** => **Δp~10 MeV/c,**

cross-talk problem

Neutron detectors



ε_n =20-30% for neutrons of Tn=60-250MeV

Time resolution ~ 250psec

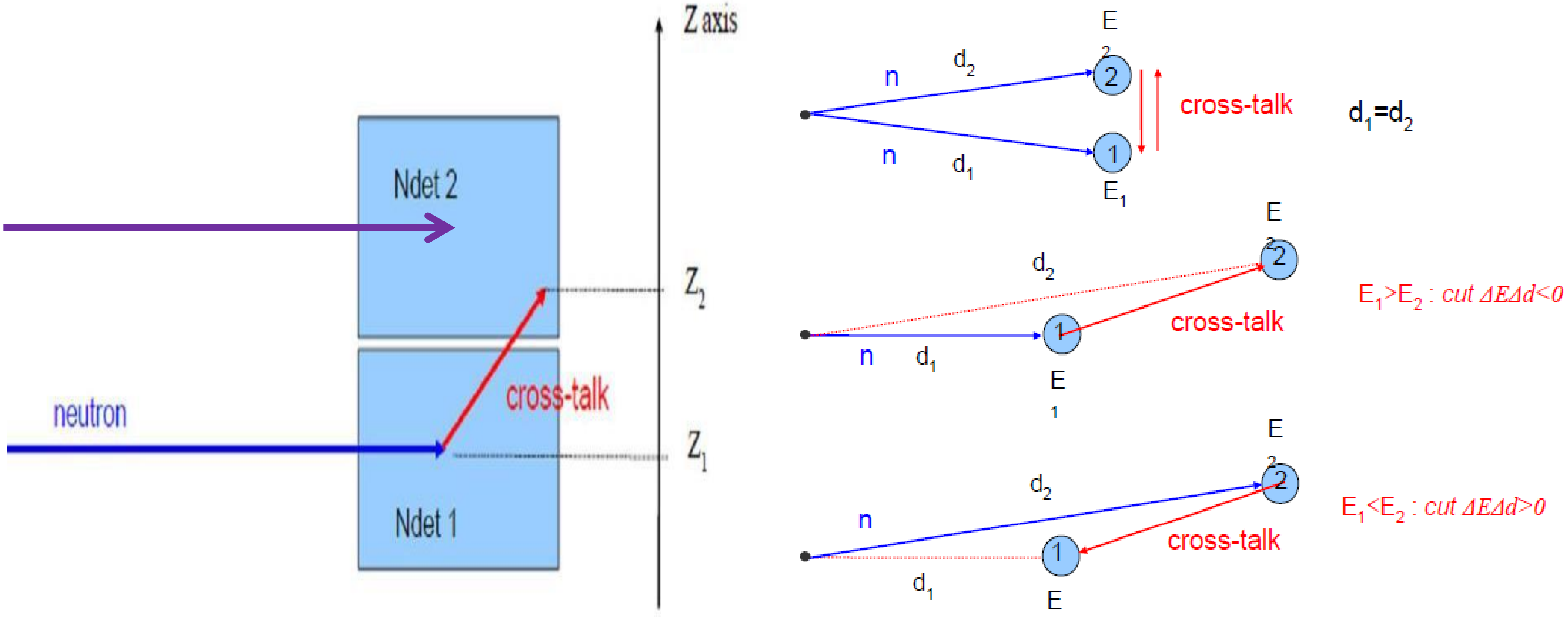
Liquid scintillator-> different signal shape for n/γ

Large total volume V ~ 50 dm^3 and small sensitive volume V ~ 4 dm^3

[Tilquin I. et al., Nucl. Instrum. Methods A365, 1995,p.446]

Cross-Talks problem

If the same neutron is registered in two or more detectors – the cross-talk effect occurs.
It simulates registration of two or more neutrons in neighbor modules → to a strong false correlation. In case of single particle measurements the cross-talk effects are usually small, but in femtoscopy measurements this effect is quite important and dangerous.

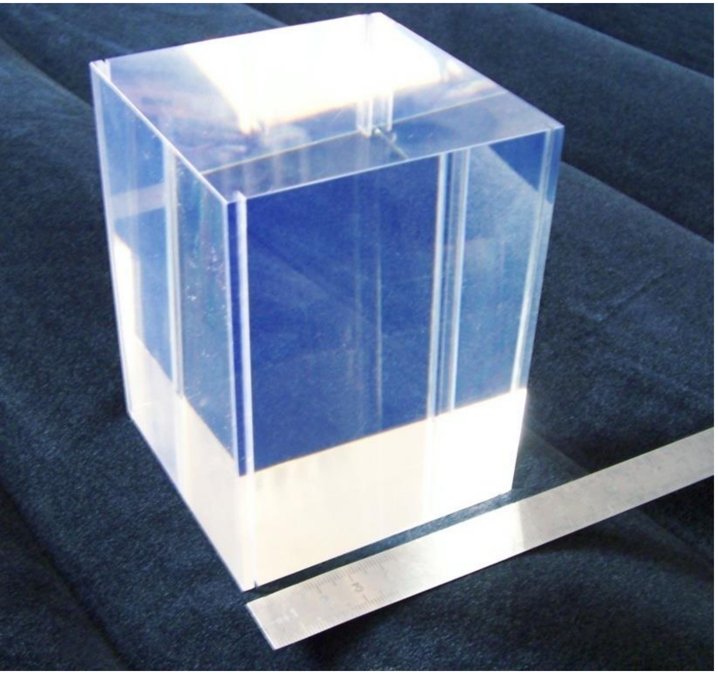


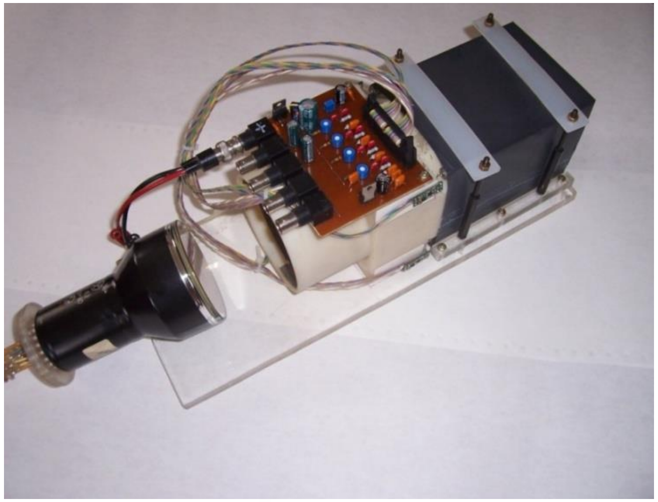
Solution: position sensitive detector

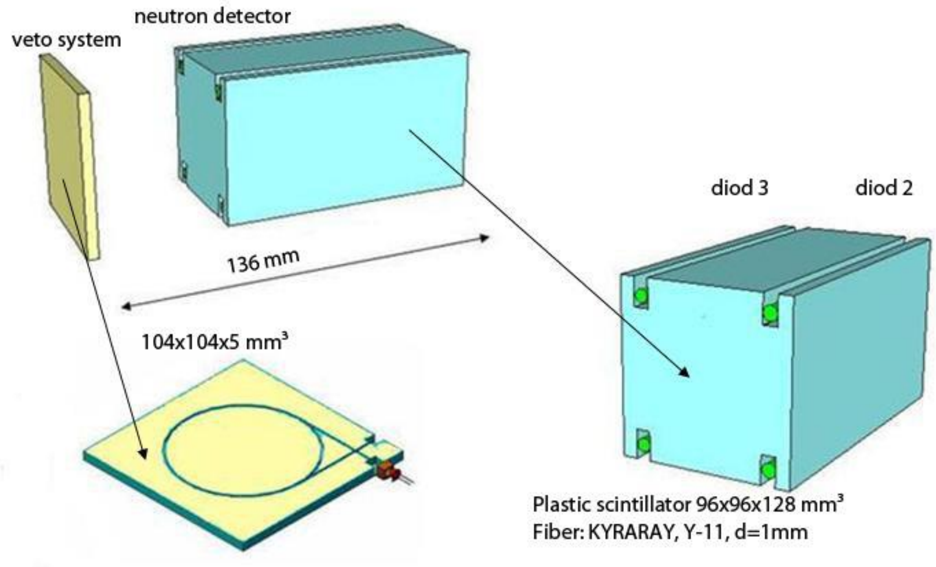
Required features for neutron detector

- **Neutron energy range of 2 MeV to 200 MeV**
- **Accuracy for neutron momentum 10-20 MeV/c**
- **Modular structure of detector for corelation measurements**
- **Compact installation modules to create large acceptance detector**
- **Position resolution one order better than module size (about 1 cm)**
- **Time resolution 150-200 psec**
- **Gamma-neutron separation**
- **Compact module**

Neutron detector (prototype 1)-ITEP







Plastic Scintillator 96 * 96 * 128 mm^3

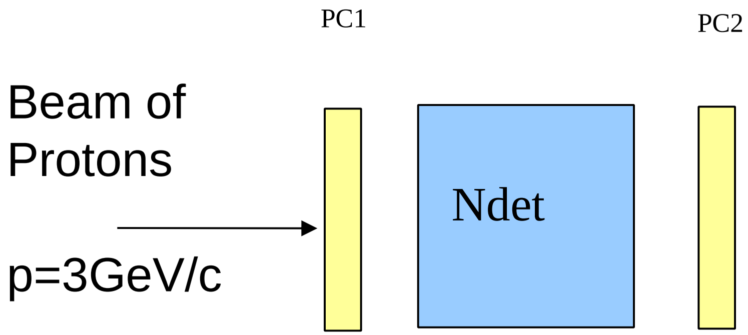
Fiber: KYRARAY,Y-11,d =1mm,

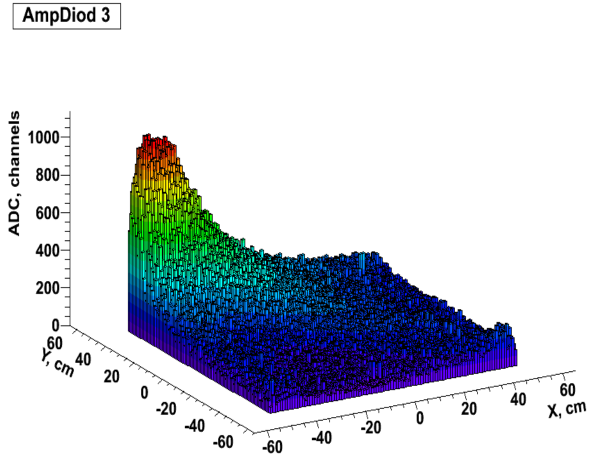
wavelength shift

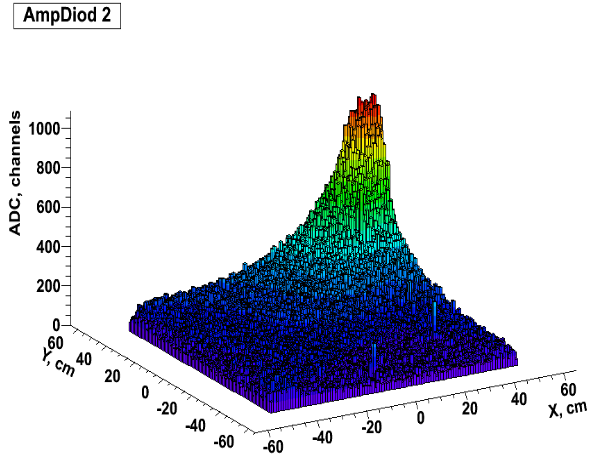
4 SiPM & Amplifier - CPTA(Golovin)

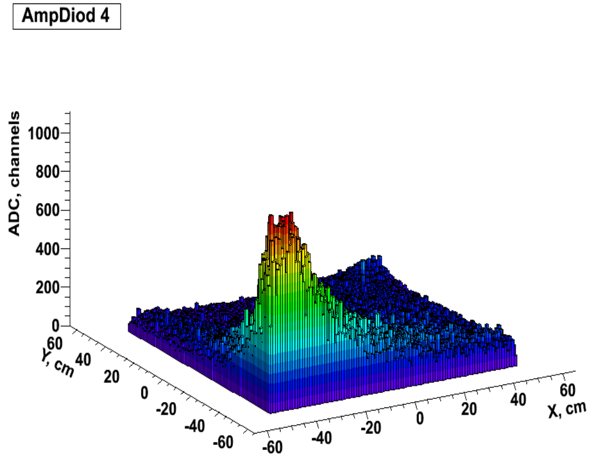
Efficiency (estimate) 15%

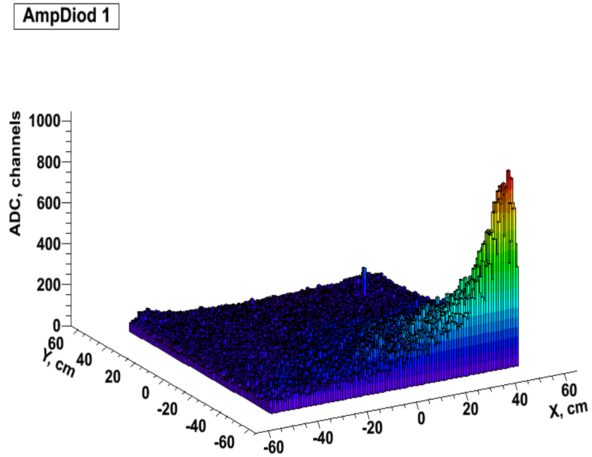
Tests of prototype 1 with proton beam(ITEP)



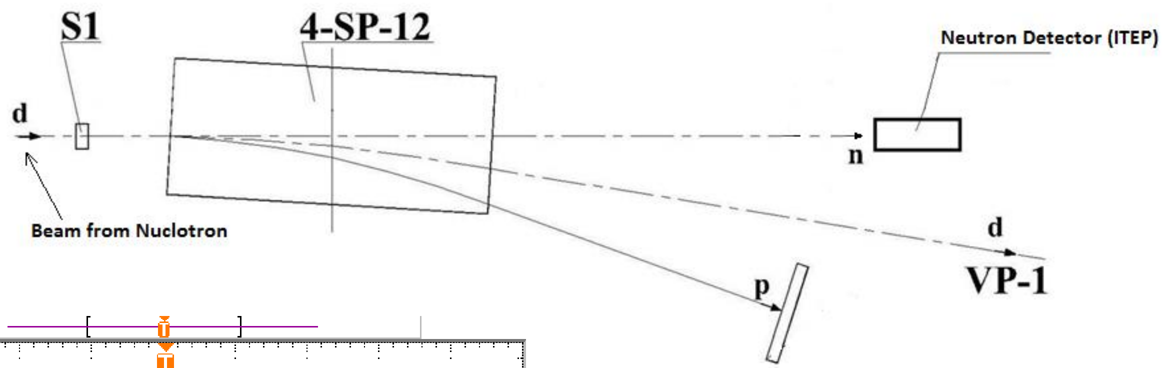


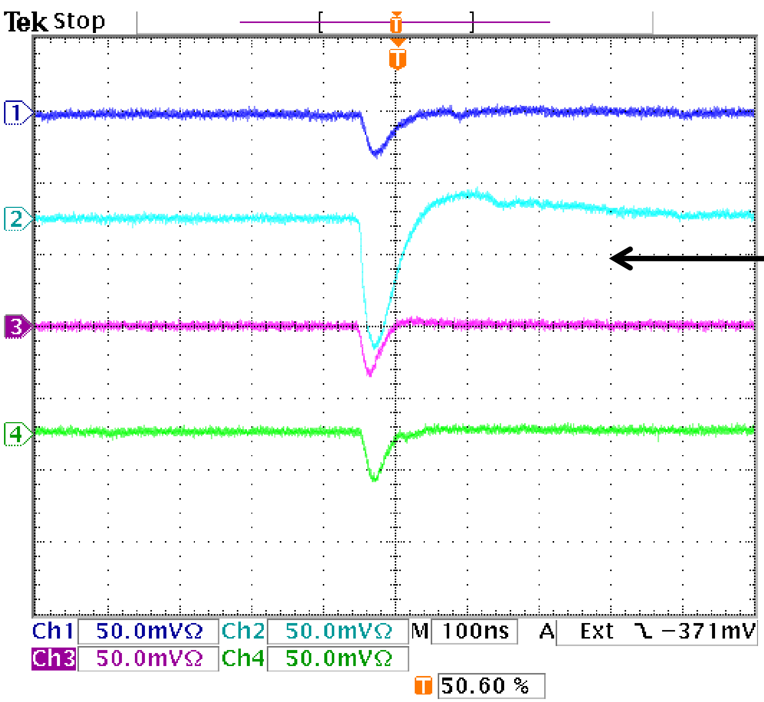




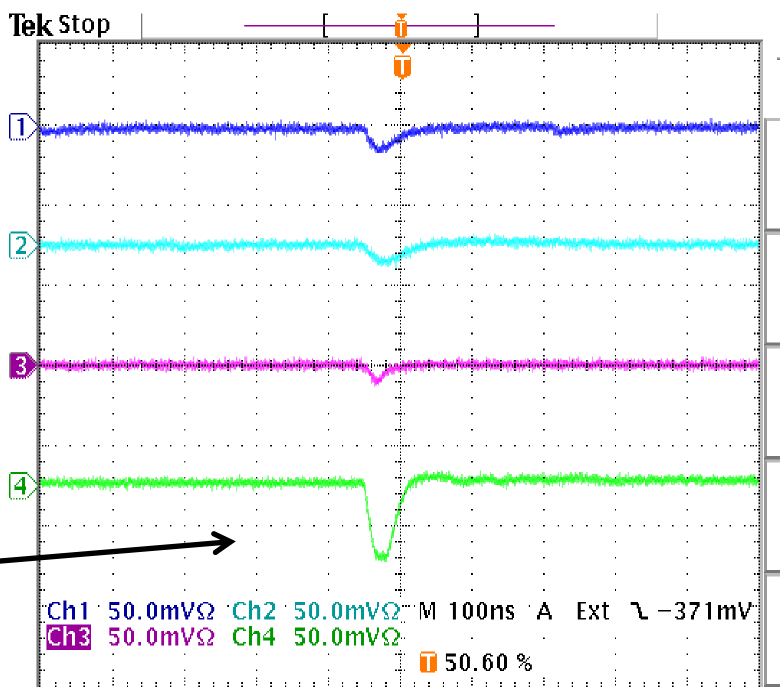


Tests of prototype 1 with neutron beam (MARUSYA)



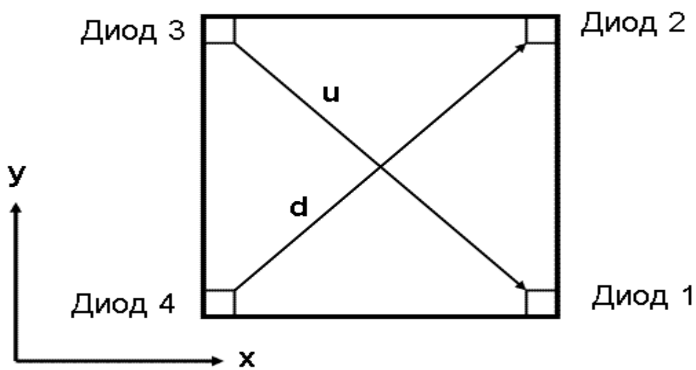


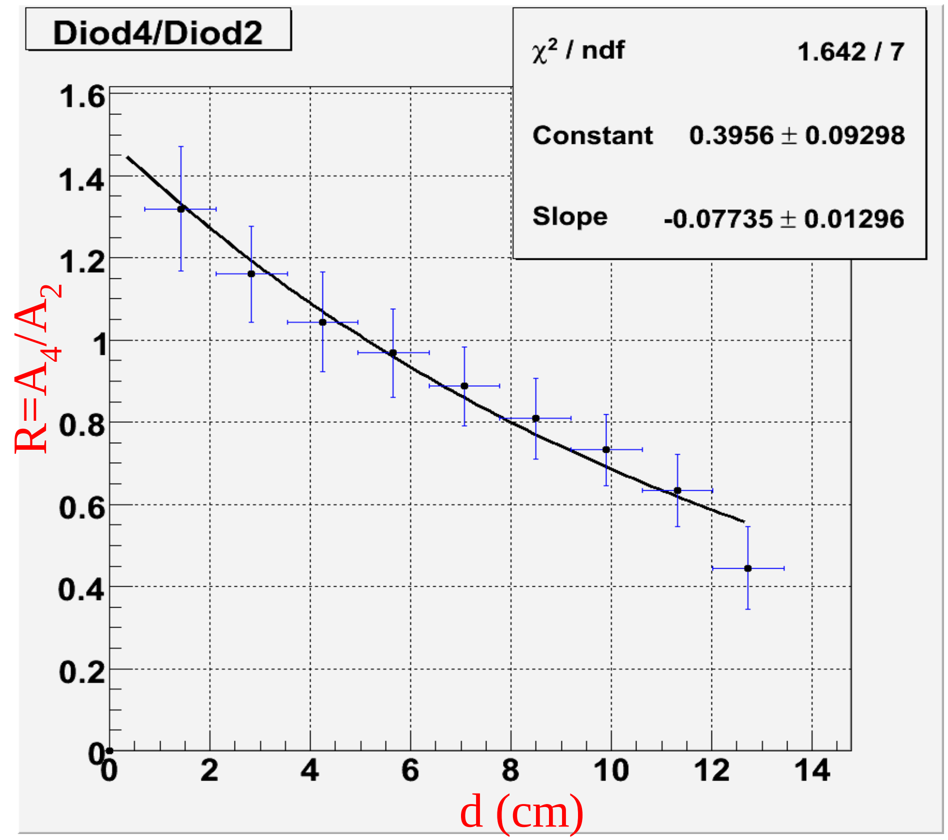
Neutron near 2 diode



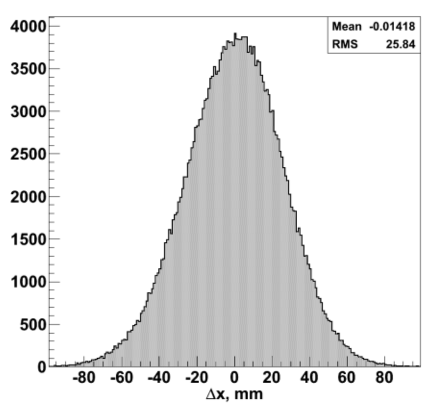
Neutron near 4 diode

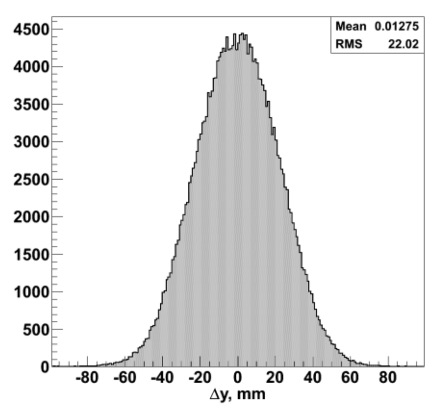
Neutron detector (prototype 1)





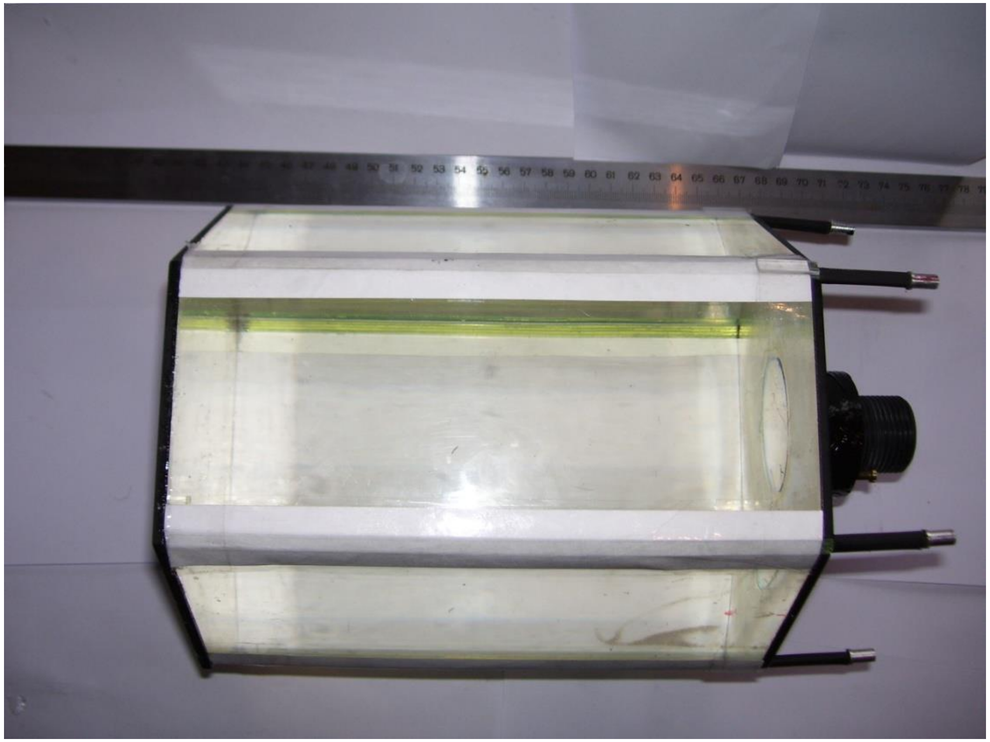
spatial resolution for the first prototype ~ 2.5 cm





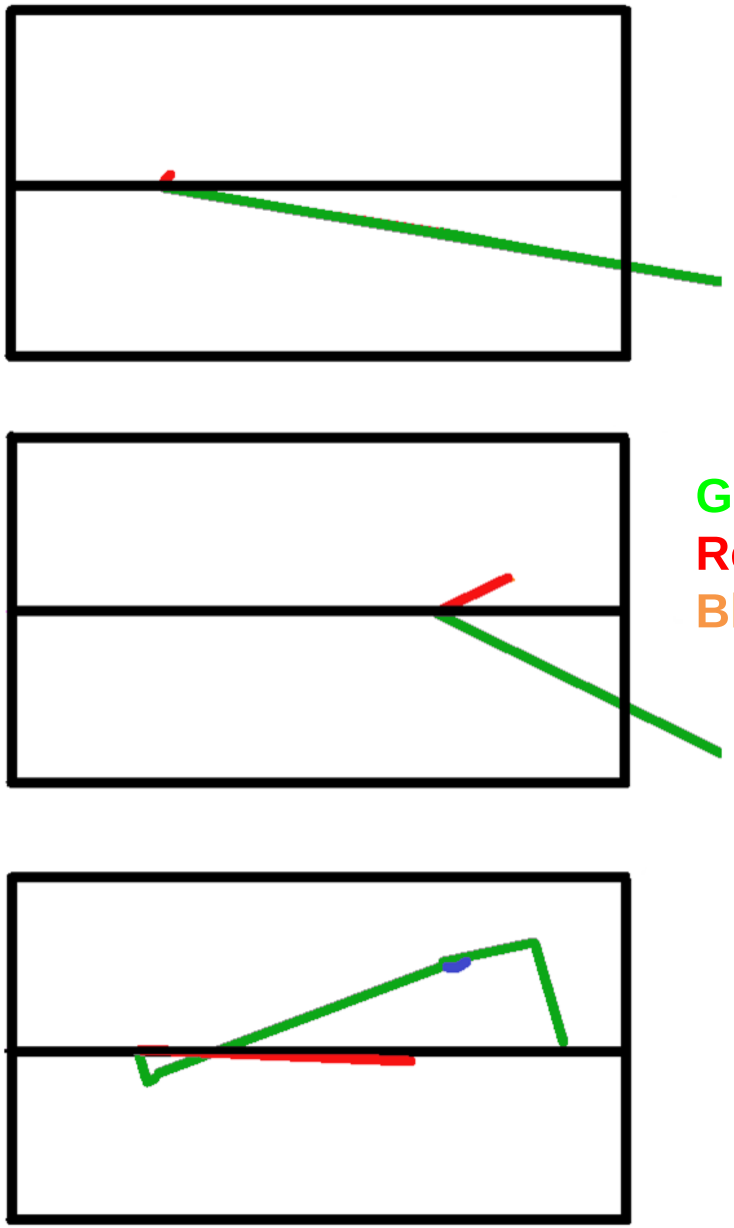
Next step to improve spatial resolution from 2,5 to ~1 cm.
Prototype1 4 diodes * 1 mm^2 → Prototype2 6 diodes * 4 mm^2

- -registration of neutrons with energies in the range 10-200 MeV
- -expected dimensional resolution ~ 1 sm
- -used avalanche photodiodes
- -possibility to work in magnetic field
- -small space for the module and compact packing



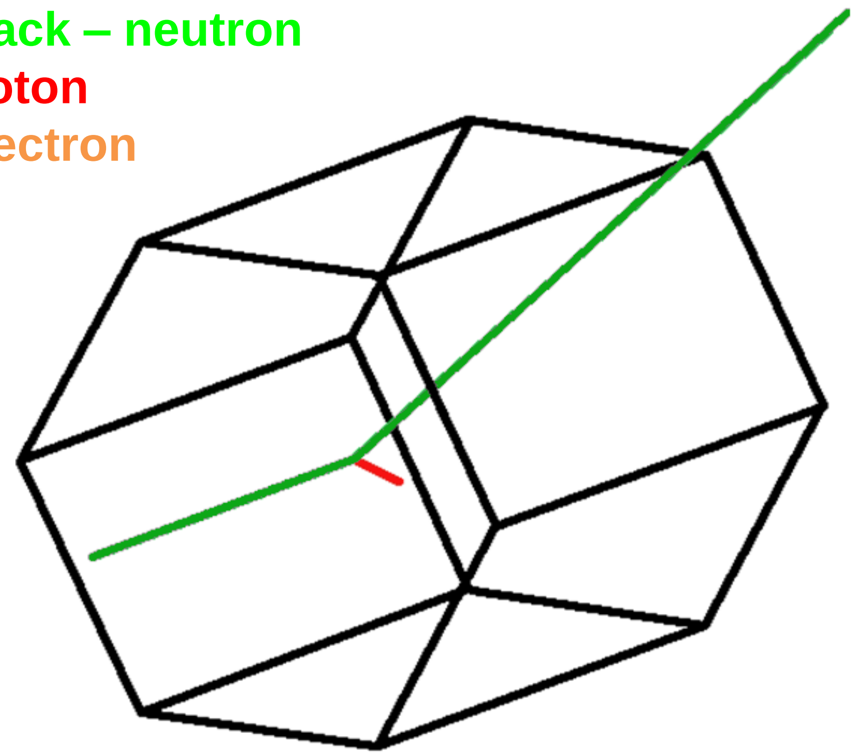
version without PMT

Principal restriction for neutron coordinate resolution



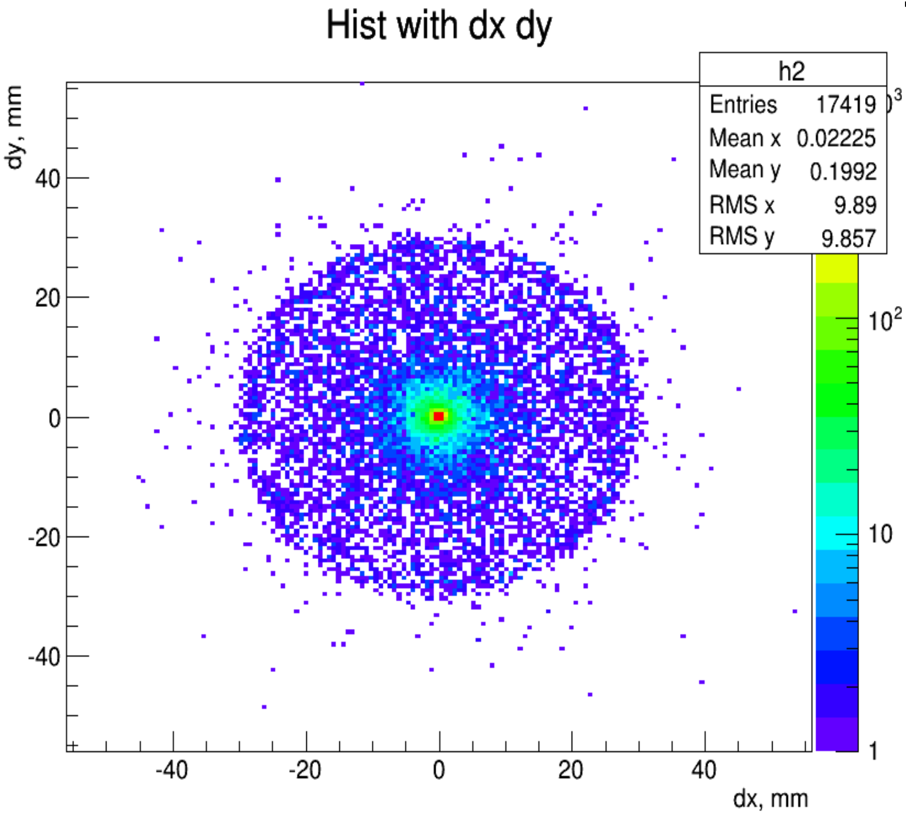
Purpose of simulation – estimation difference between neutron coordinate and recoil proton coordinate.
In framework Geant4 n+detector interaction for different neutron energy was simulated. H/C ~ BC400 (1.103). 10^5 neutrons for each energy. Neutrons shoot to detector centre. Event selection criteria: one proton realize after first interaction.

Green track – neutron
Red - proton
Blue - electron

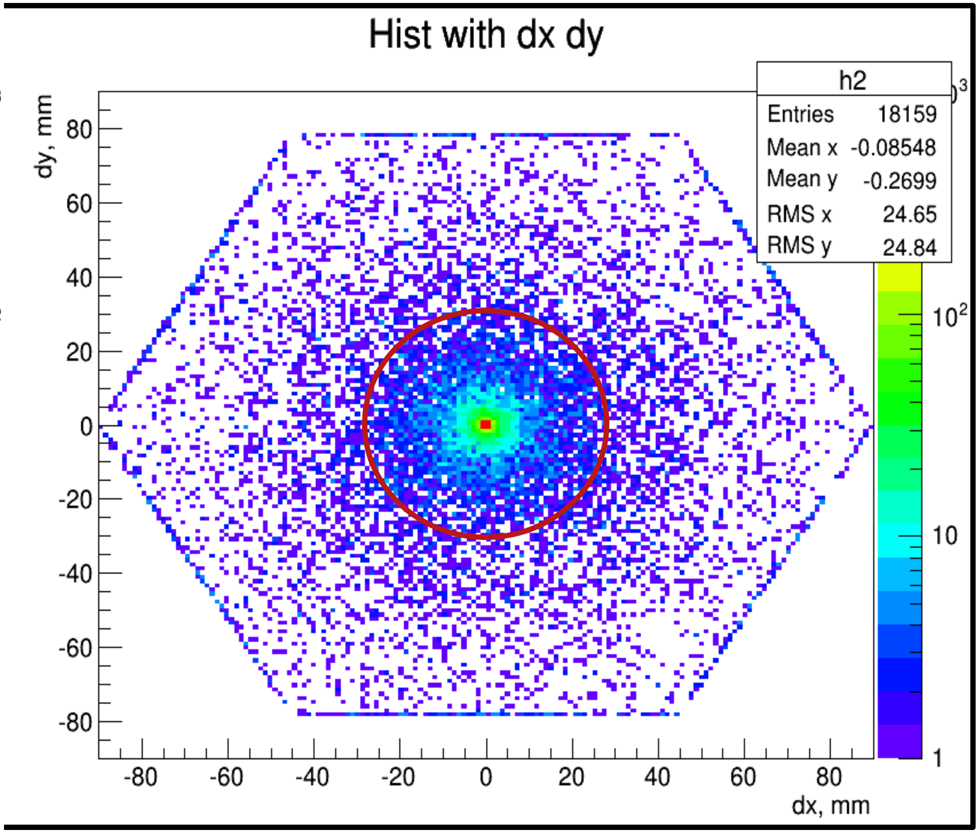


Simulation neutron detector (prototype 2)-ITEP

150MeV

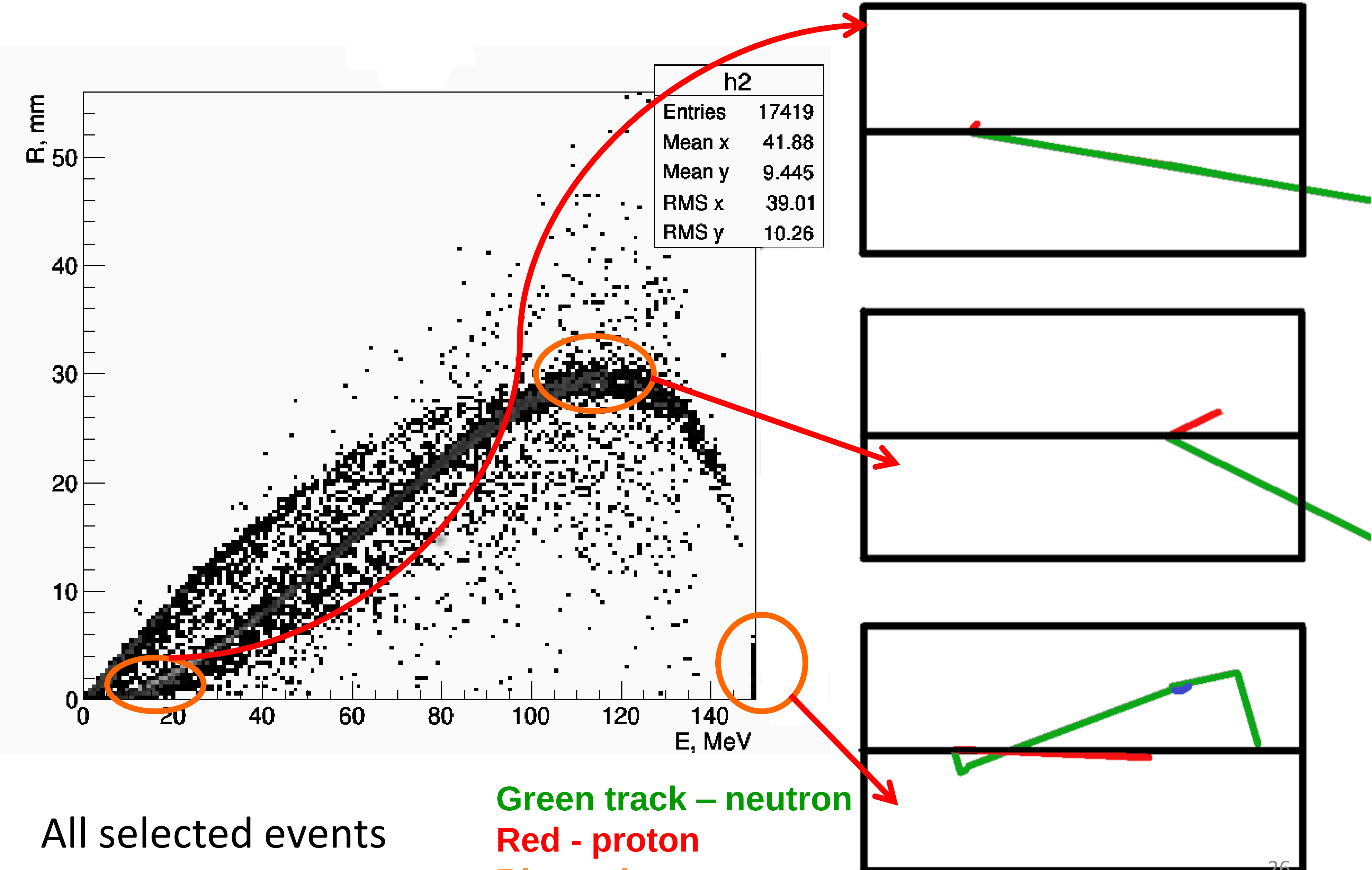


300MeV



Distribution of secondary protons in the transverse coordinates

Dependence of maximum deviation protons from deposit energies (neutron energy 150 MeV)



All selected events

Green track – neutron
Red - proton
Blue - electron

Results of the simulations

Neutron energy, MeV	50	100	150	200	300
mean deviation of protons track, mm	0,6	2,4	4,8	7,5	12,2

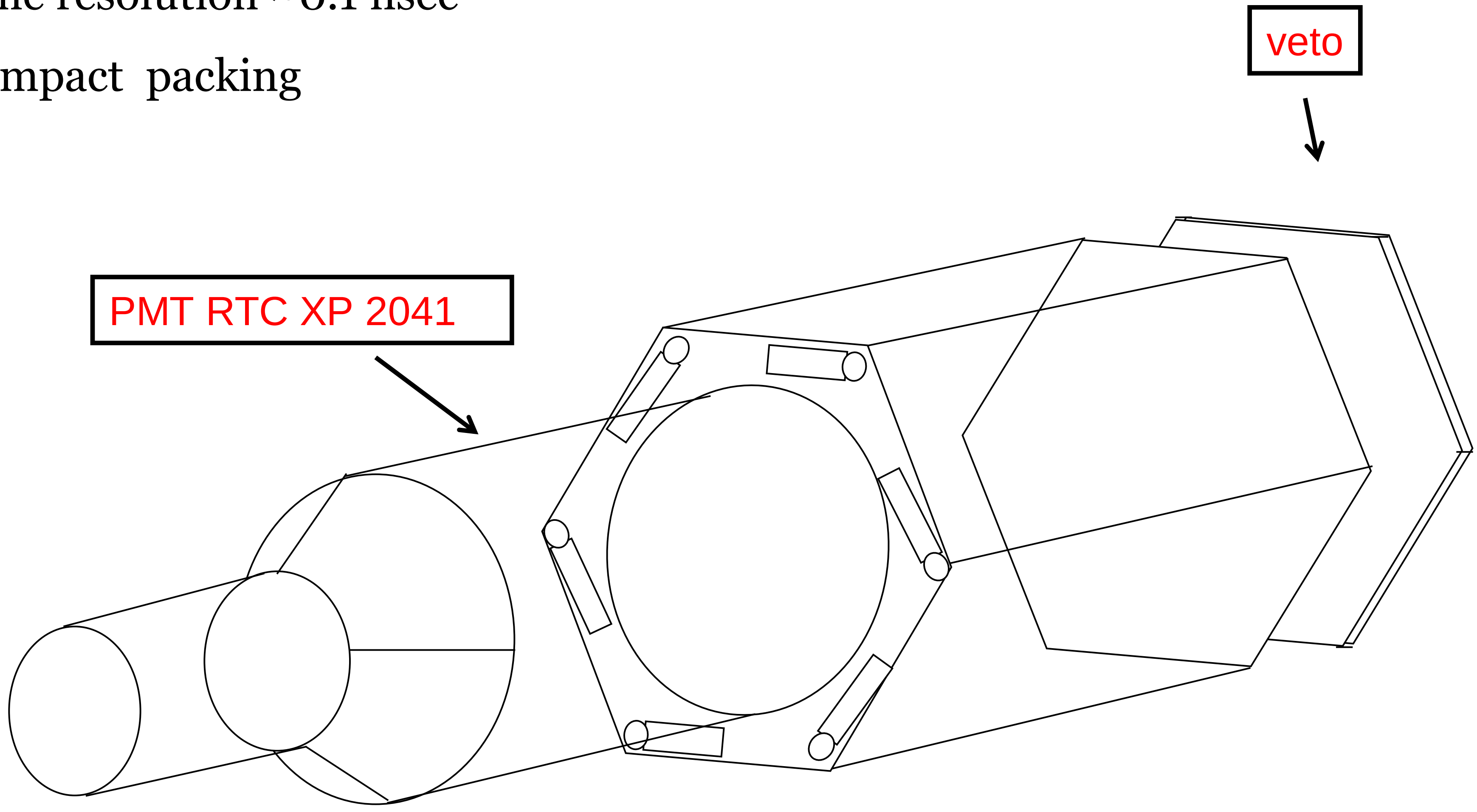
Detector module with PMT and VETO

-neutrons energies range 2-200 MeV

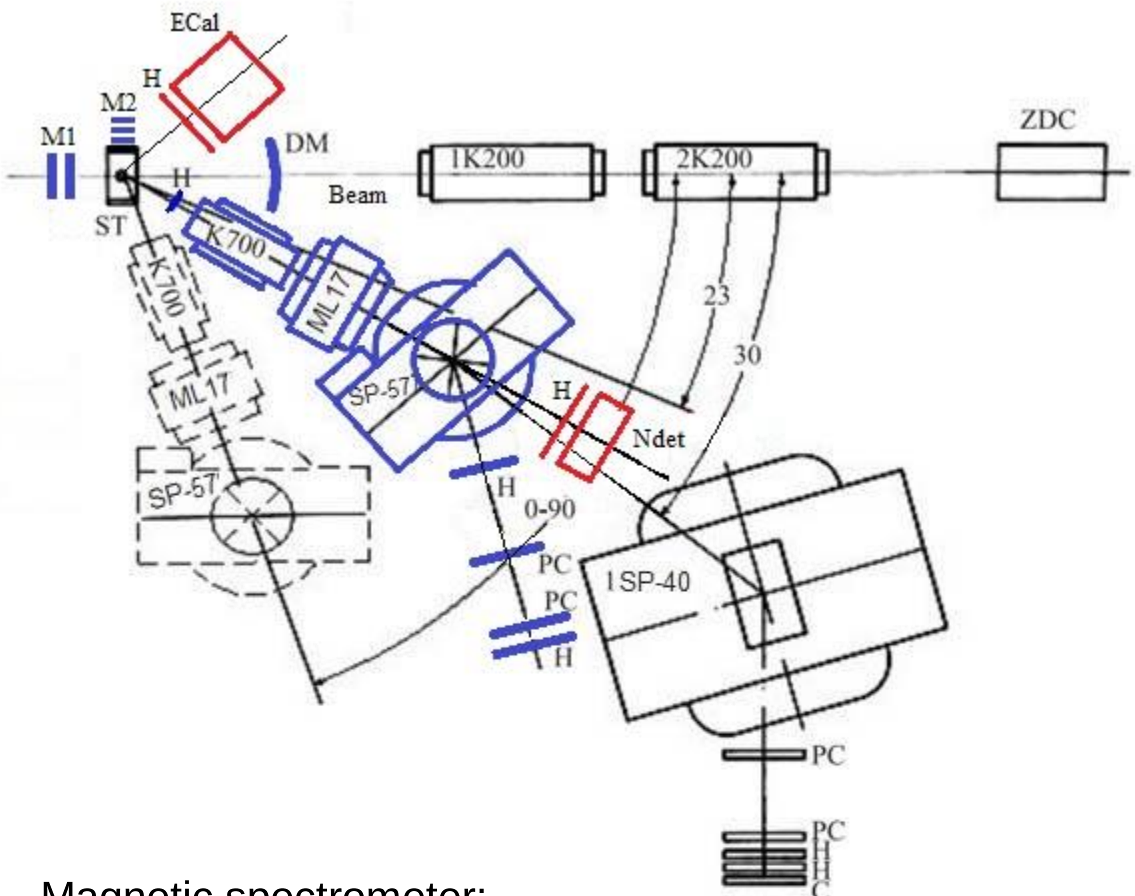
-space resolution ~ 1 sm

-time resolution ~0.1 nsec

-compact packing



MARUSYA-FLINT set-up at NUCLOTRON



Scheme of experimental set-up MARUSYA-FLINT:

- ST - cryogenic target station,
- M1, M2- scintillation monitors,
- DM- multiplicity detectors,
- H- scintillation hodoscopes,
- PC - proportional chambers,
- ML17, K700 - quadrupole lens,
- SP-57, SP-40 - dipole magnets,
- ECal - electromagnetic calorimeter,
- Ndet – neutron detector

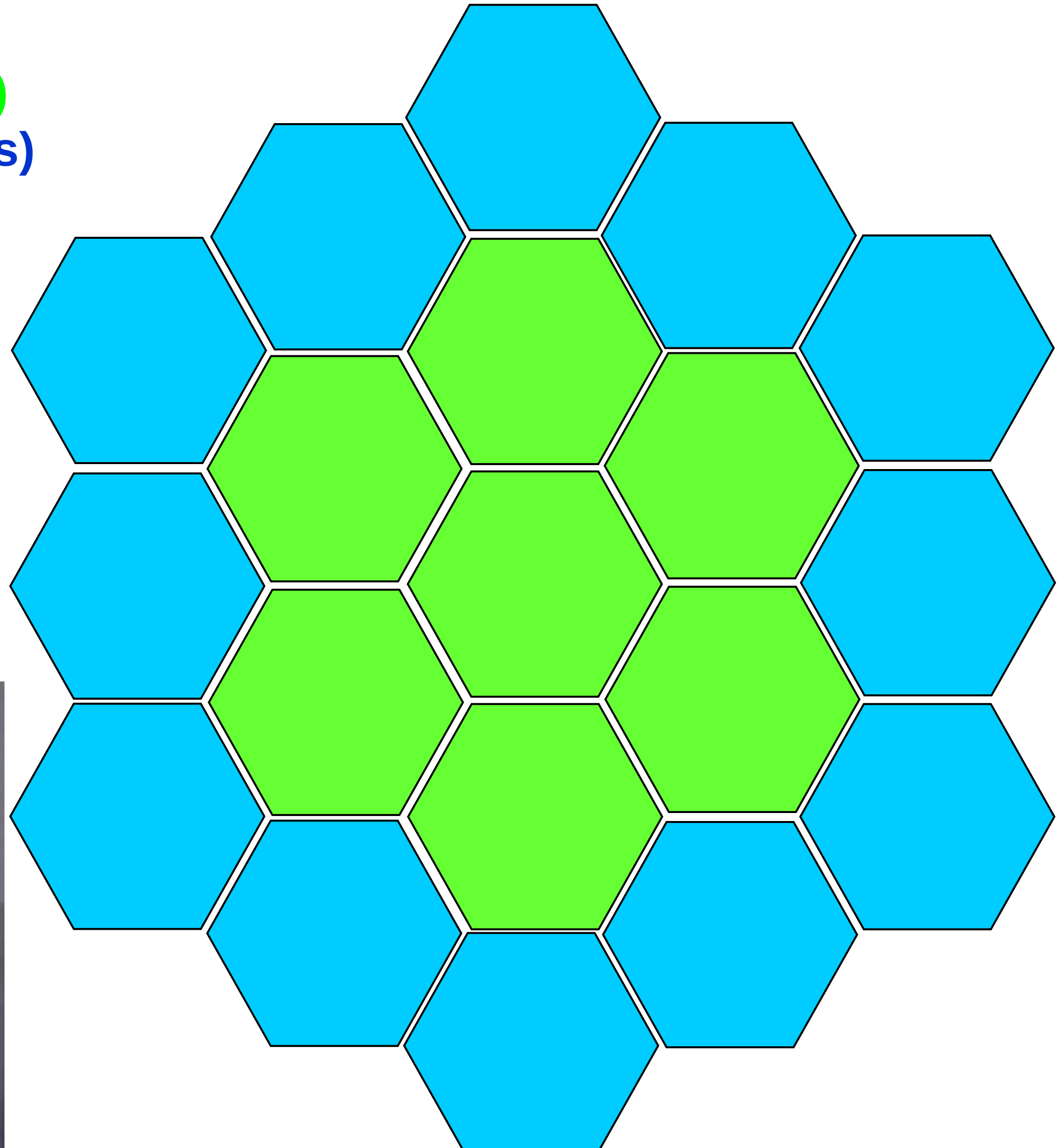
Magnetic spectrometer:
For P_t = 0,3-0,8 GeV/c used magnet SP-57
Coordinate system on scintillation hodoscopes provide resolution 2-5% in area 0,3-0,8 GeV/c

POsitionSEnsitiveIDentificationOfNeutrons = POSEIDON

Neutron detector for MARUSYA-FLINT

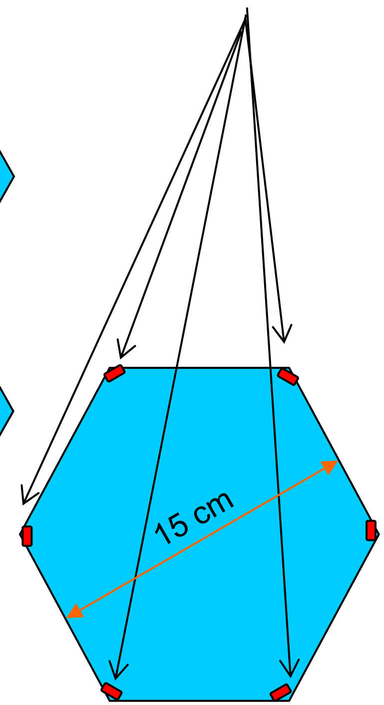
Stage 1(7modules)
Stage 2(19modules)

Next step to improve spatial resolution from 2,5 to 1,5 cm.
Prototype1 4 diodes * 1 mm^2
Prototype2 6 diodes * 4 mm^2



Distance from the target 240cm; Detector thickness 20cm

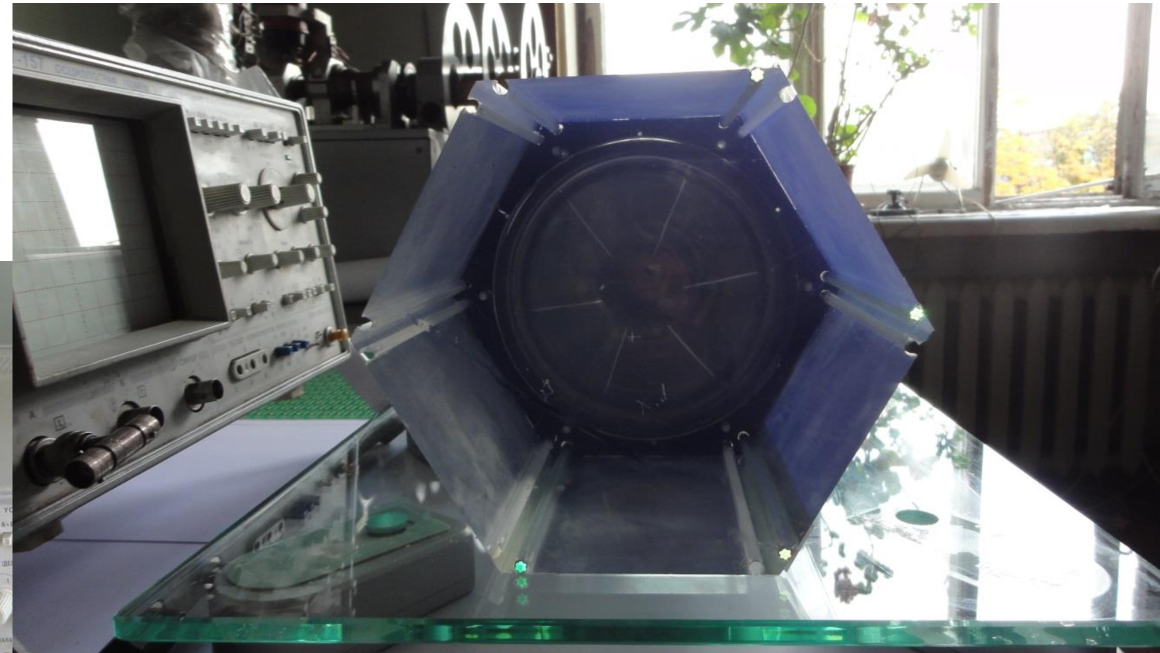
Fiber + SiPM

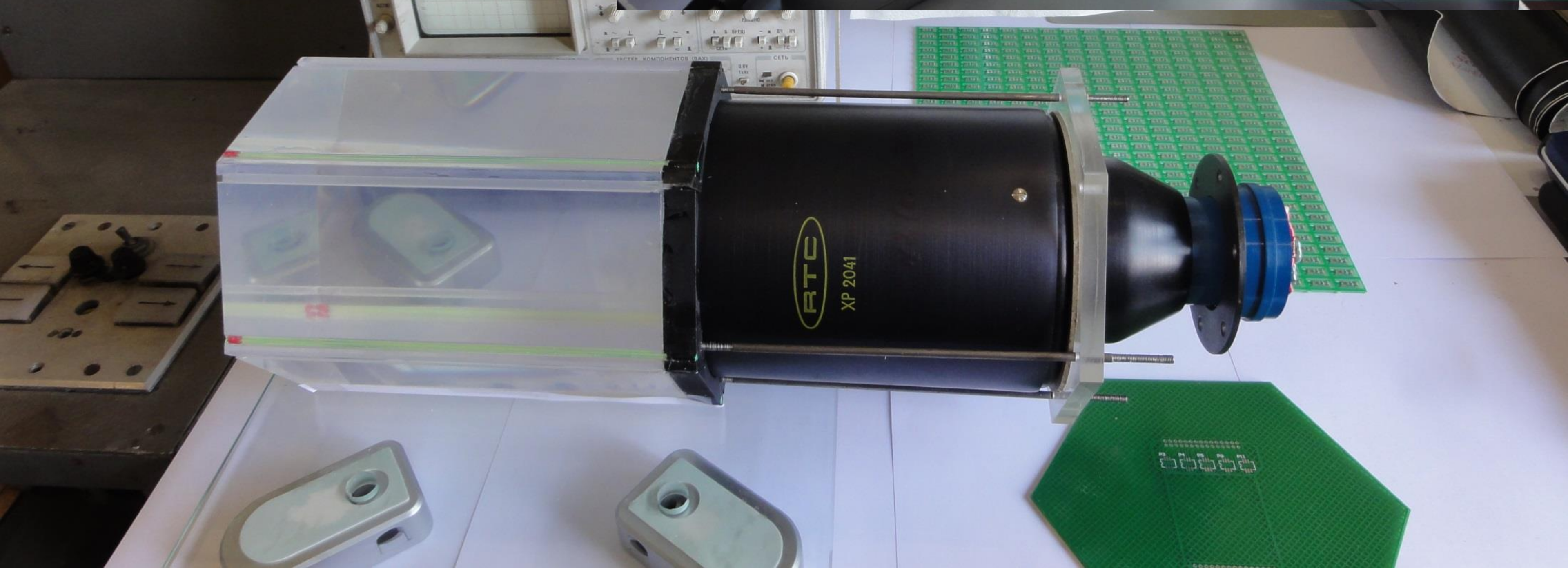


POsitionSEnsitiveIDentificationOfNeutrons = POSEIDON

Detector module

in consctruction





Conclusions

1. Cold and dense part of phase diagram is important to study for: QCD check, color superconductivity, neutron stars

2. It is accessible in the lab using high P_T trigger ($P_T \approx P_{beam}$)

3. Experimental program for cold dense matter study is proposed

4. The phase is neutrons-rich. A dedicated neutron detector is needed

5. A position sensitive neutron detector is proposed, prototype is tested on protons and neutrons

Thank you for attention!

Conclusions for POSEIDON

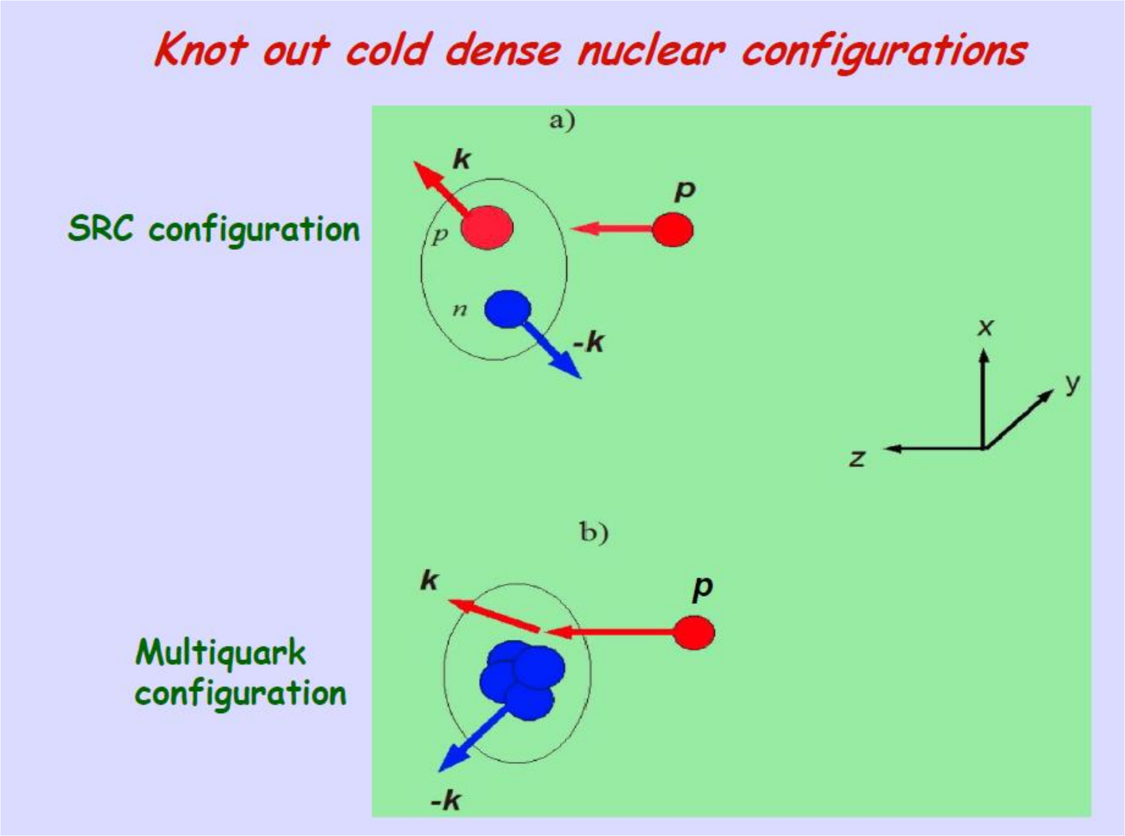
1. The prototype 1 was designed, constructed and tested. Beam tests was made at ITEP(2011) and JINR(2012-2013).
2. The results of beam tests was used in simulations of the prototype 2.
3. All characteristics of the prototype 2, obtained from this simulations, are in accordance with designed goals.
4. Prototype 2 is constructed and ready for the beam test

Experimental program:

2) Dense cold matter contribution in ordinary nuclear matter and its nature SRC,flucton,…

- **hard scattering**

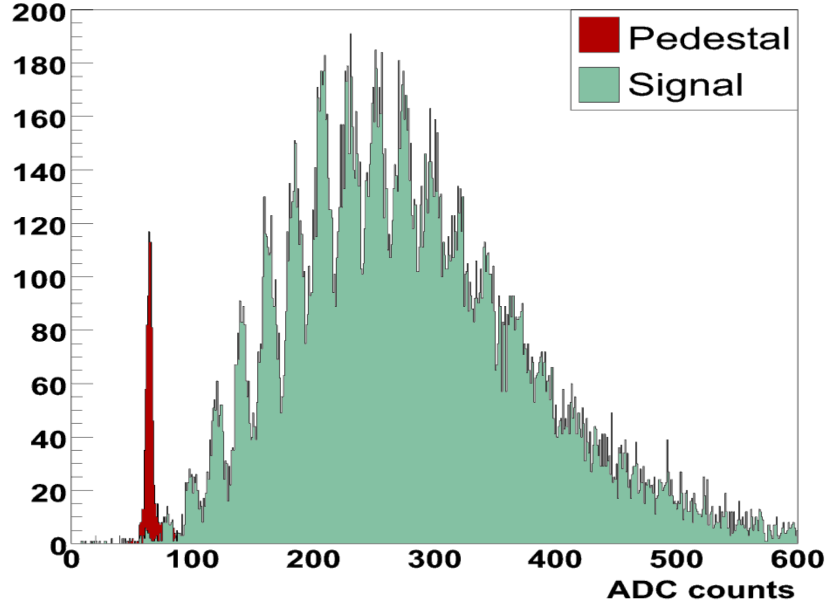
p+A→ p + <mN>, where m is an average number of nucleons
m~1 for SRC model and
m~cumulative number for multiquark system knockout
(see also S.S.Shimanskiy proposal for future PANDA experiment at FAIR)

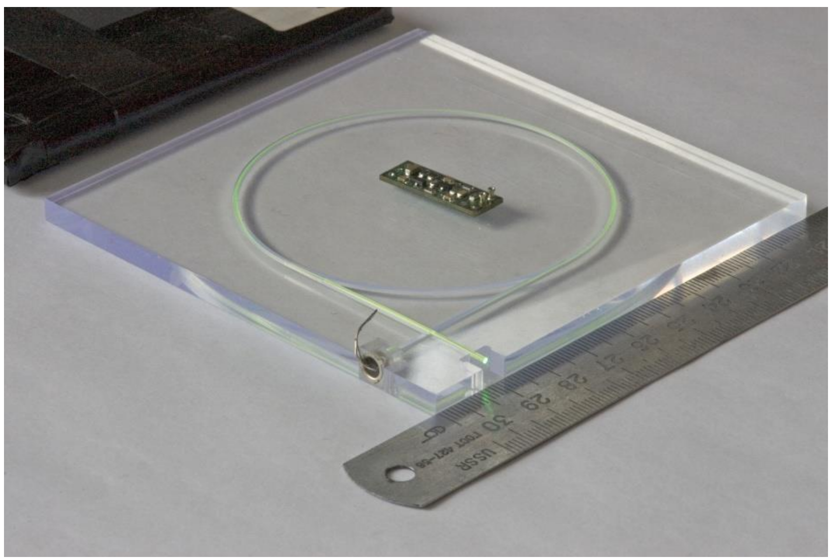


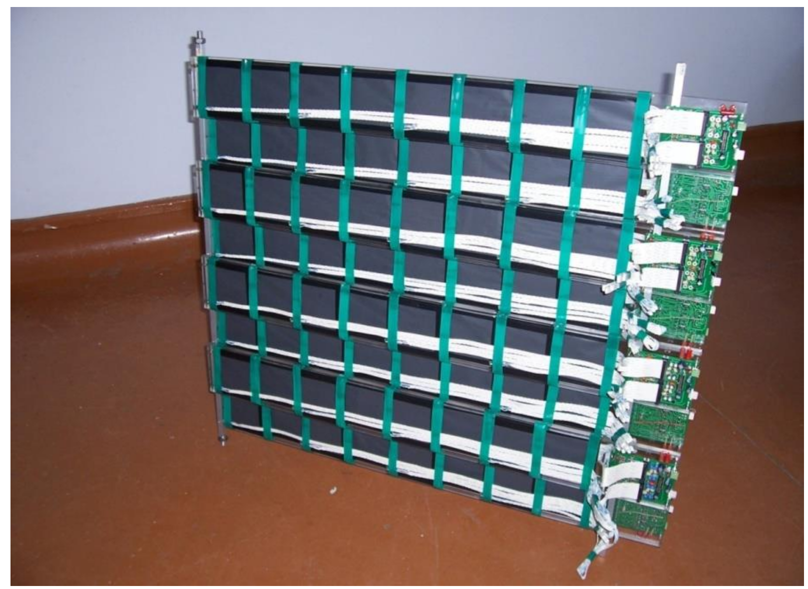
Plastic Scintillator 105*100*5 mm^3

Fiber: KYRARAY, Y-11,d =1mm, wavelength shift

MRS APD & Amplifier - CPTA(Golovin)







Dense Cold Matter with fluctons

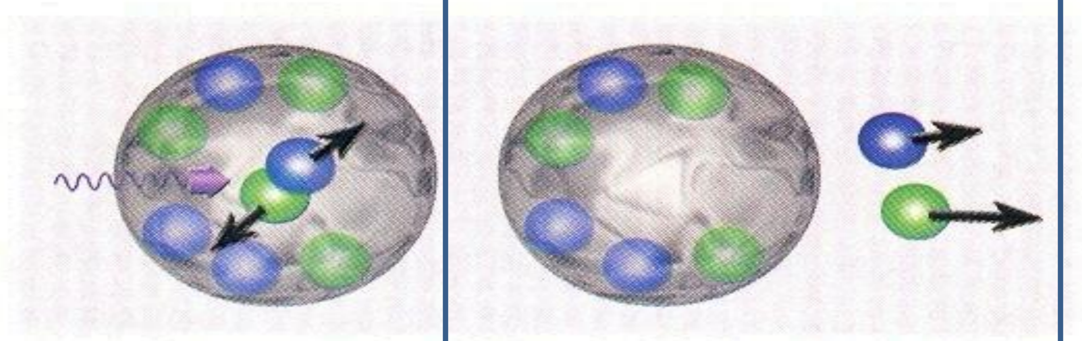


Fig. 1. Scattering of a virtual photon off a two-nucleon correlation, $x > 1.5$, before (left) and after (right) absorption of the photon.

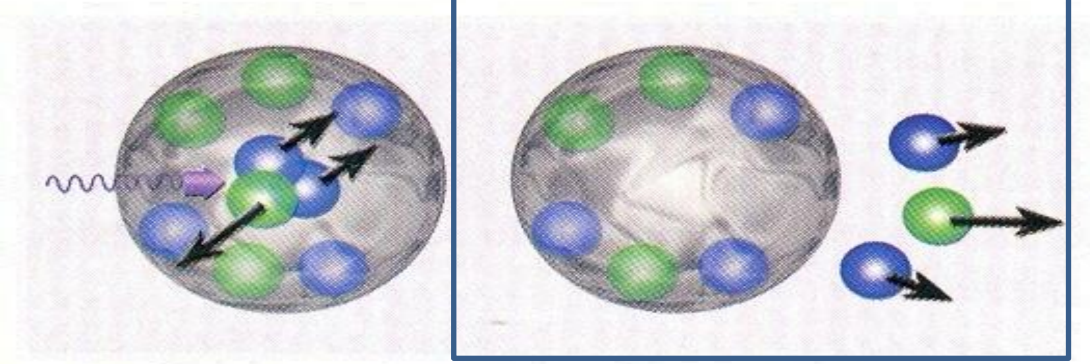
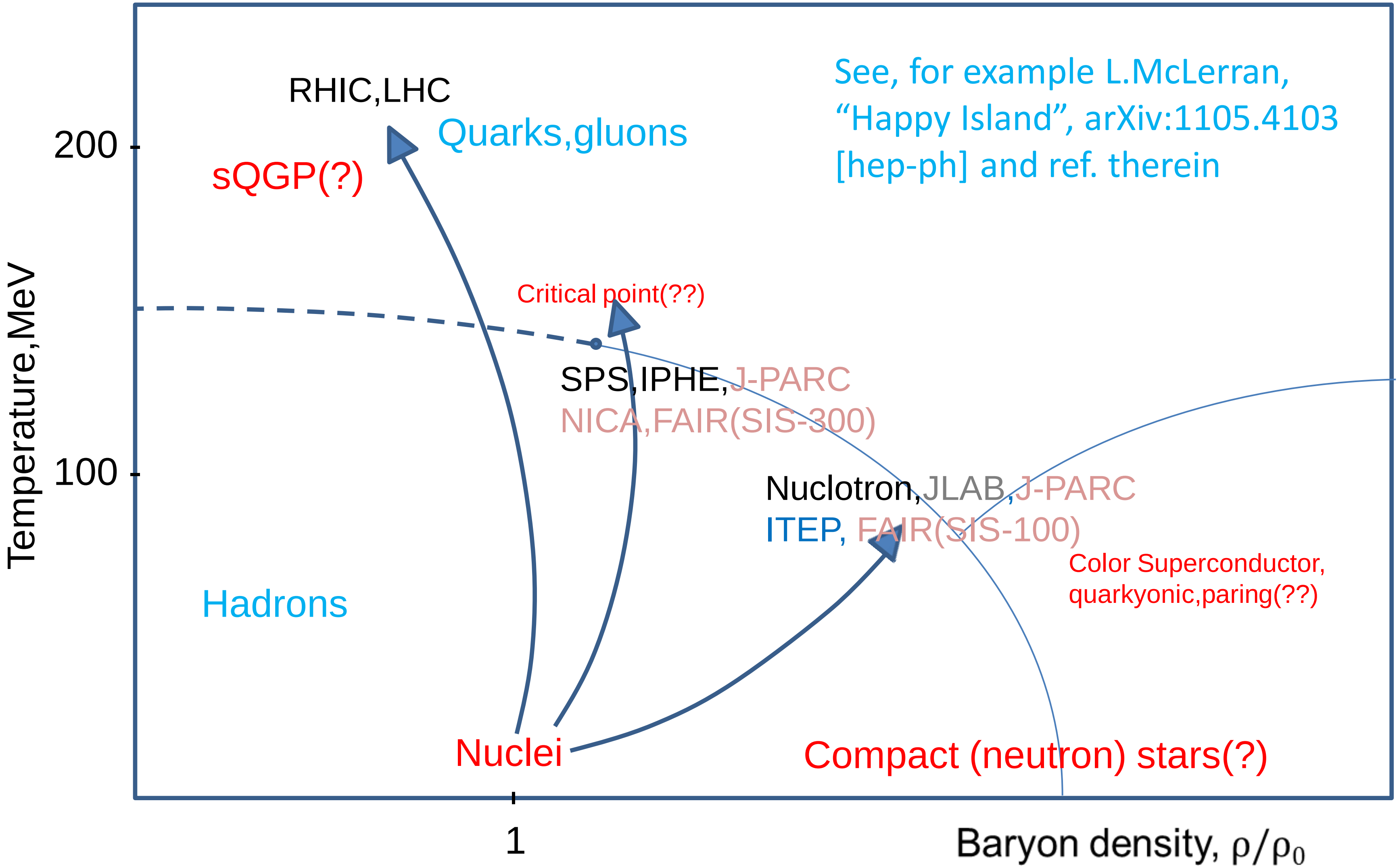


Fig. 2. Scattering of a virtual photon off a three-nucleon correlation, $x > 2$, before (left) and after (right) absorption of the photon.

1).Special final state selection
2) Correlation measurements

Figure from: M.Strikman, CERN Courier Nov.2,2005

Phase diagram of nuclear matter



arXiv:0908.1514v1 [nucl-ex] 11 Aug 2009

Probing Cold Dense Nuclear Matter

R. Subedi,[1] R. Shneor,[2] P. Monaghan,[3] B. D. Anderson,[1] K. Aniol,[4] J. Annand,[5] J. Arrington,[6] H. Benaoum,[7,8] F. Benmokhtar,[9] W. Bertozzi,[3] W. Boeglin,[10] J.-P. Chen,[11] Seonho Choi,[12] E. Cisbani,[13] B. Craver,[14] S. Frullani,[13] F. Garibaldi,[13] S. Gilad,[3] R. Gilman,[11,15] O. Glamazdin,[16] J.-O. Hansen,[11] D. W. Higinbotham,[11*] T. Holmstrom,[17] H. Ibrahim,[18] R. Igarashi,[19] C.W. de Jager,[11] E. Jans,[20] X. Jiang,[15] L.J. Kaufman,[9,22] A. Kelleher,[17] A. Kolarkar,[23] G. Kumbartzki,[15] J. J. LeRose,[11] R. Lindgren,[14] N. Liyanage,[14] D. J. Margaziotis,[4] P. Markowitz,[10] S. Marrone,[24] M. Mazouz,[25] D. Meekins,[11] R. Michaels,[11] B. Moffit,[17] C. F. Perdrisat,[17] E. Piasetzky,[2] M. Potokar,[26] V. Punjabi,[27] Y. Qiang,[3] J. Reinhold,[10] G. Ron,[2] G. Rosner,[28] A. Saha,[11] B. Sawatzky,[14,29] A. Shahinyan,[30] S. Širca,[26,31] K. Slifer,[14] P. Solvignon,[29] V. Sulkosky,[17] G. M. Urciuoli,[13] E. Voutier,[25] J. W. Watson,[1] L.B. Weinstein,[18] B. Wojtsekhowski,[11] S. Wood,[11] X.-C. Zheng,[3,6,14] and L. Zhu[32]

The protons and neutrons in a nucleus can form strongly correlated nucleon pairs. Scattering experiments, where a proton is knocked-out of the nucleus with high momentum transfer and high missing momentum, show that in ^{12}C the neutron-proton pairs are nearly twenty times as prevalent as proton-proton pairs and, by inference, neutron-neutron pairs. This difference between the types of pairs is due to the nature of the strong force and has implications for understanding cold dense nuclear systems such as neutron stars.

CLAS $e^-A \rightarrow e^-X$ @~4 AGeV

JLAB Phys Seminar Dec05 K. Egiyan

Having these data, we know almost full (≈99%) nucleonic picture of nuclei with $A \leq 56$

Fractions / Nucleus	Single particle (%)	2N SRC (%)	3N SRC (%)
^{56}Fe	**76** ± 0.2 ± 4.7	**23.0** ± 0.2 ± 4.7	**0.79** ± 0.03 ± 0.25
^{12}C	**80** ± 02 ± 4.1	**19.3** ± 0.2 ± 4.1	**0.55** ± 0.03 ± 0.18
^{4}He	**86** ± 0.2 ± 3.3	**15.4** ± 0.2 ± 3.3	**0.42** ± 0.02 ± 0.14
^{3}He	**92** ± 1.6	**8.0** ± 1.6	**0.18** ± 0.06
^{2}H	**96** ± 0.8	**4.0** ± 0.8	-----

Using the published data on (p,2p+n) [PRL,90 (2003) 042301] estimate the isotopic composition of 2N SRC in ^{12}C

$a_{2N}(^{12}C) \approx 20 \pm 0.2 \pm 4.1\ \%$ →

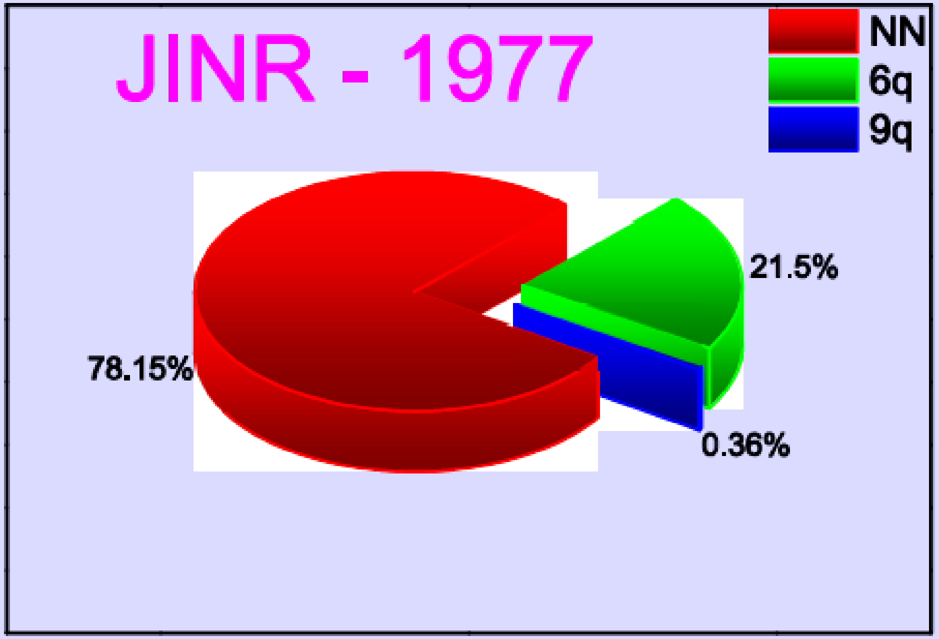
$a_{pp}(^{12}C) \approx 4 \pm 2\ \%$

$a_{pn}(^{12}C) \approx 12 \pm 4\ \%$

$a_{nn}(^{12}C) \approx 4 \pm 2\ \%$

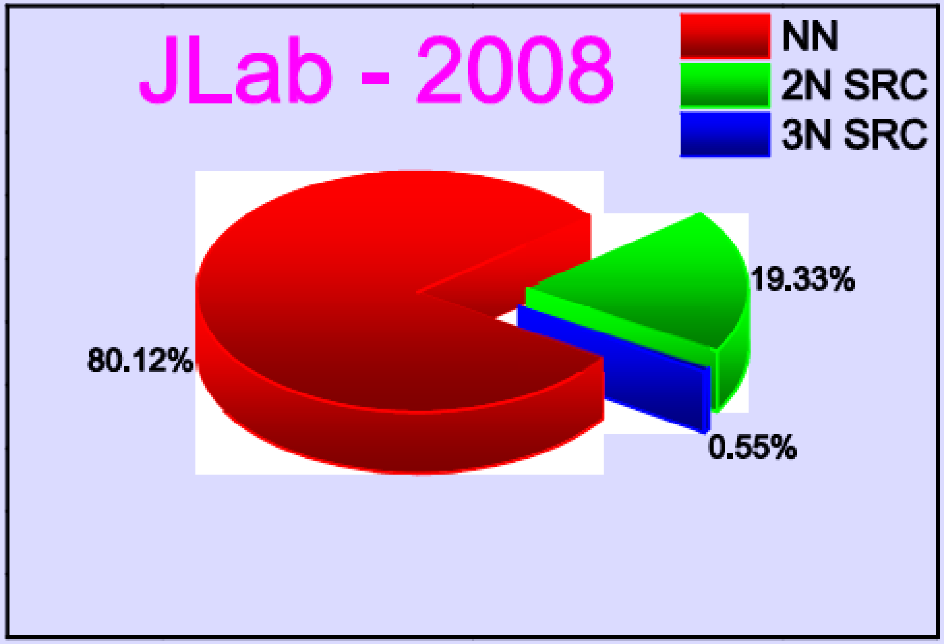
RNP - program at JINR

V.V.B., V.K.Lukyanov, A.I.Titov, PLB, 67, 46(1977)

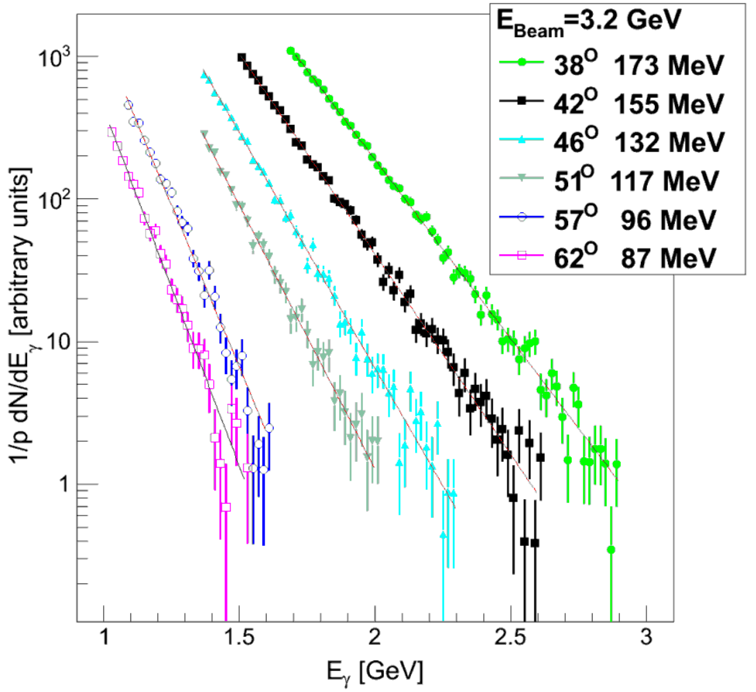


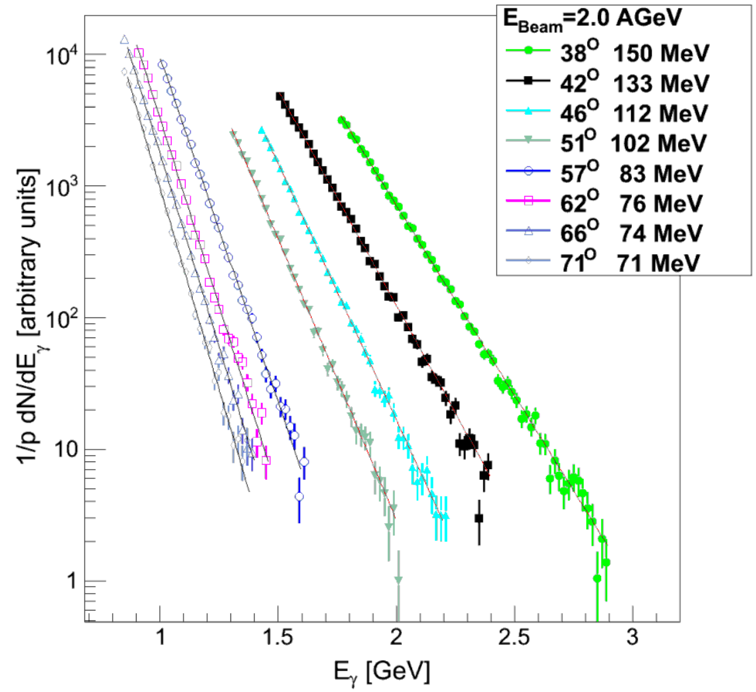
eA - program at JLab

R.Subedi et al., Science 320 (2008) 1476-1478
e-Print: arXiv:0908.1514 [nucl-ex]



FLINT DATA: Photon spectra
CBe→γX

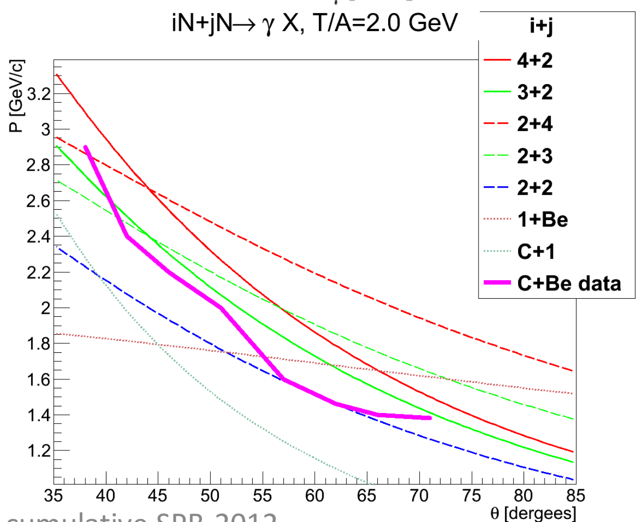




FLINT have got data for flucton-flucton interaction up to 6 nucleons kinematical region, which cannot be explained neither p+Be nor C+p interactions

Six nucleons system: n!n¡p!p¡+??

Does we already see phase transition?



An estimate of baryon density

$r_f \sim 1.5 fm$