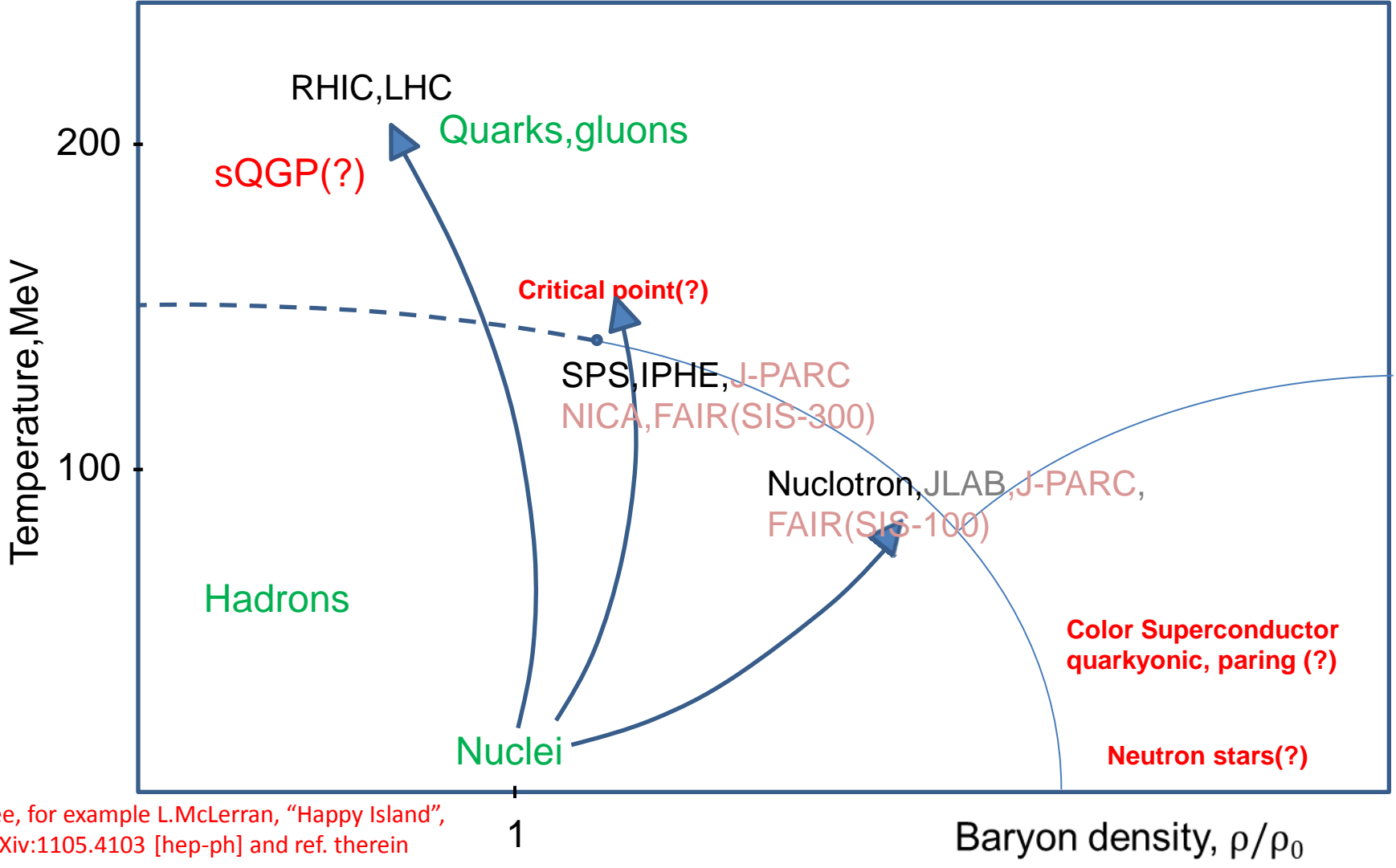


Cold dense baryonic matter

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

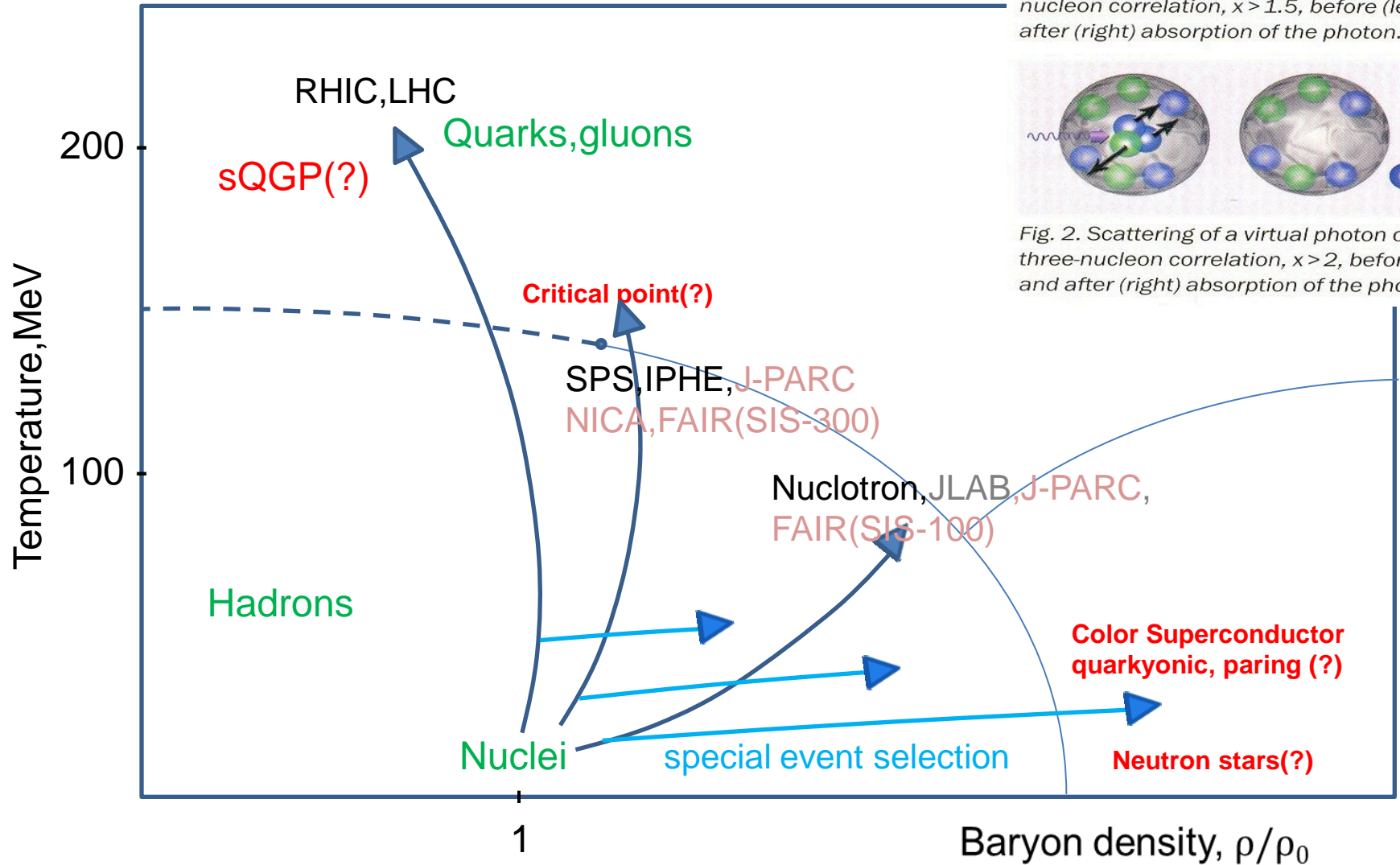


Figure from: M.Strikman, CERN Courier Nov.2,2005

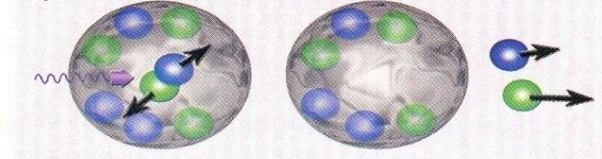


Fig. 1. Scattering of a virtual photon off a two-nucleon correlation, $x > 1.5$, before (left) and after (right) absorption of the photon.

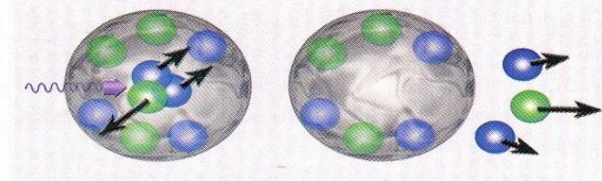


Fig. 2. Scattering of a virtual photon off a three-nucleon correlation, $x > 2$, before (left) and after (right) absorption of the photon.

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

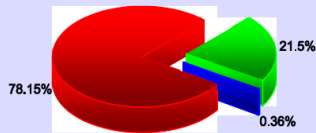
eA - program at JLab

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

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

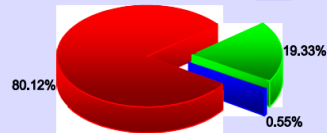
JINR - 1977

NN
6q
9q



JLab - 2008

NN
2N SRC
3N SRC

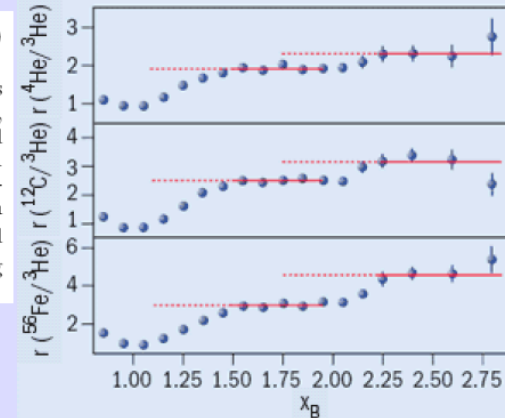


$$r(A, {}^3\text{He}) = \frac{A(2\sigma_{ep} + \sigma_{en})}{3(Z\sigma_{ep} + N\sigma_{en})} \frac{3\mathcal{Y}(A)}{A\mathcal{Y}({}^3\text{He})} C_{\text{rad}}^A \quad (2)$$

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_{rad}^A is the ratio of the radiative correction factors for A and ${}^3\text{He}$ ($C_{\text{rad}}^A = 0.95$ and 0.92 for ${}^{12}\text{C}$ and ${}^{56}\text{Fe}$ 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 ${}^4\text{He}$ and 1.18 ± 0.02 for ${}^{56}\text{Fe}$. Fig. 1 shows the resulting ratios integrated over $1.4 < Q^2 < 2.6 \text{ GeV}^2$.

•No rescattering

$$\mathbf{x}_B = Q^2/2m_N U$$



20.09.2014 ISHEPP XXII
2014 Shimanskiy S.S.

32

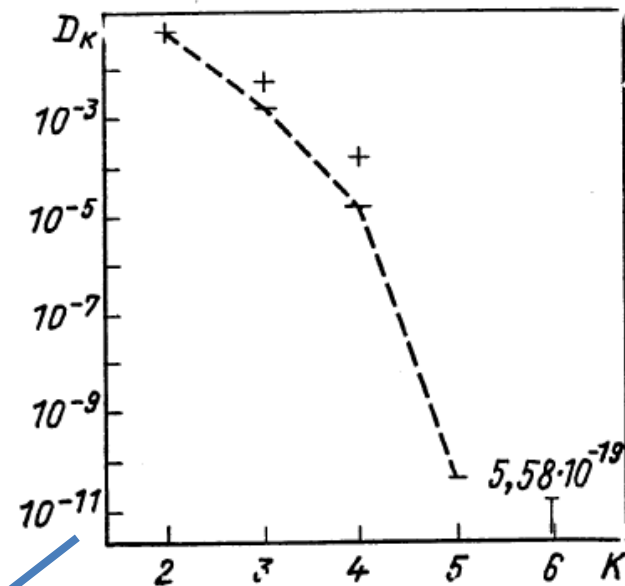
Probing Cold Dense Nuclear Matter,

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

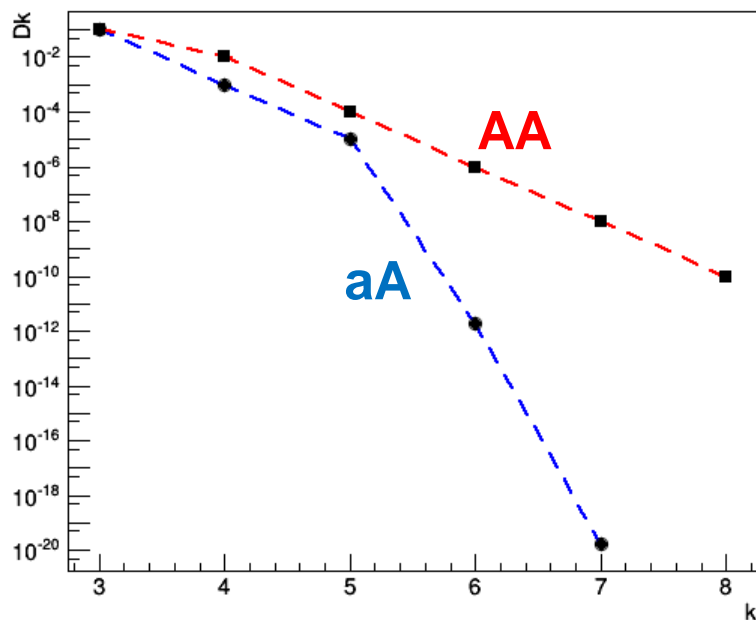
The protons and neutrons in a nucleus can form strongly correlated nucleon pairs. Scattering experiments, where a proton is knocked-out of the nucleus with high momentum transfer and high missing momentum, show that in ${}^{12}\text{C}$ the neutron-proton pairs are nearly twenty times as prevalent as 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 ?

	$a_{2N},$ %	$a_{3N},$ %	$(a_{2N})^2,$ %
${}^3\text{He}$	8.0 ± 1.6	0.18 ± 0.06	0.64
${}^4\text{He}$	15.4 ± 3.3	0.42 ± 0.14	2.4
${}^{12}\text{C}$	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



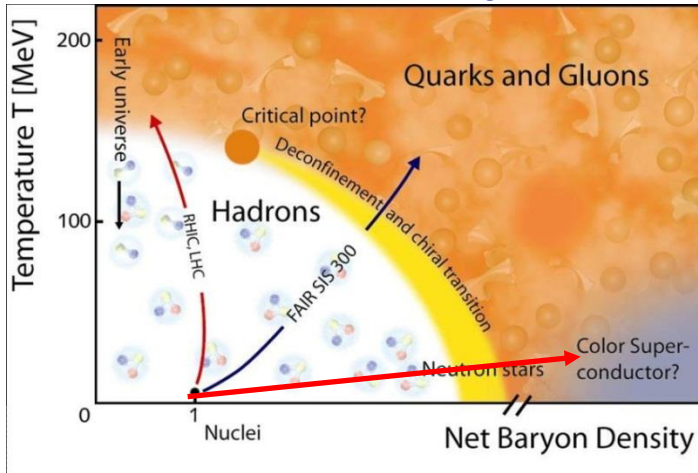
dramatic decreasing
of the cross sections with N:
----> max N~4

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

FLINT experiment @ ITEP

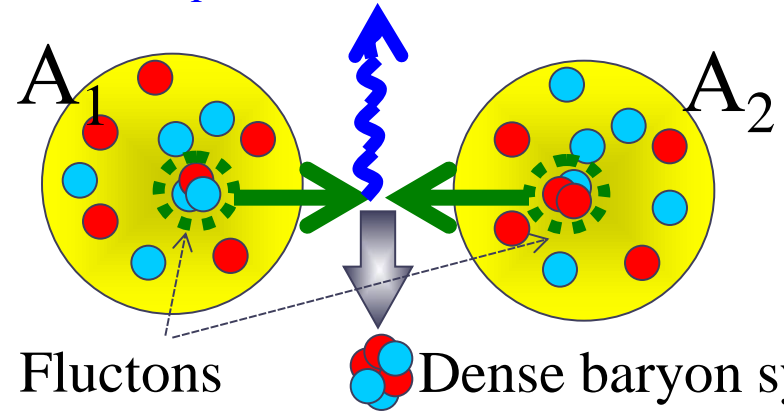


Phase diagram*



Scheme of process

High p_T trigger $\gamma, \gamma(\pi^0), \dots$



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

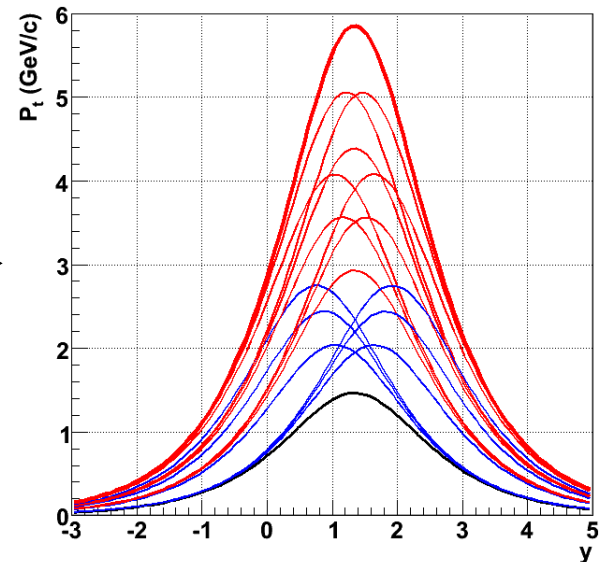
Kinematical limits for different subprocesses:

1N+1N(black line)

1N+Flucton(2N,3N,4N)&Flucton+1N(blue lines)

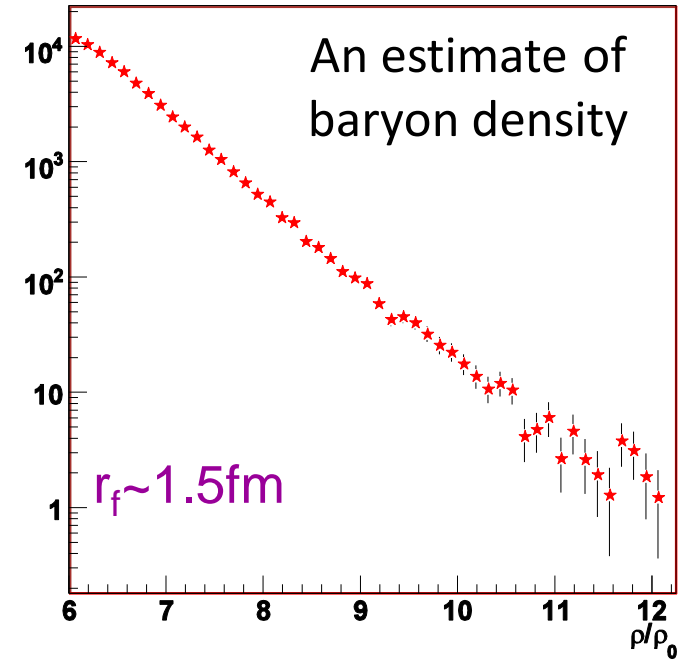
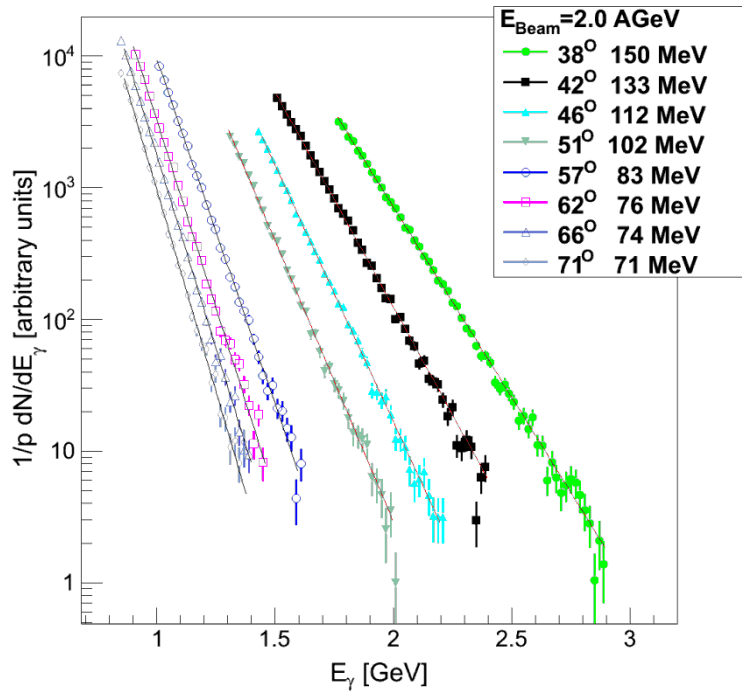
Flucton+Flucton(red lines)

He+He @ 6 AGeV



FLINT DATA: Photon spectra

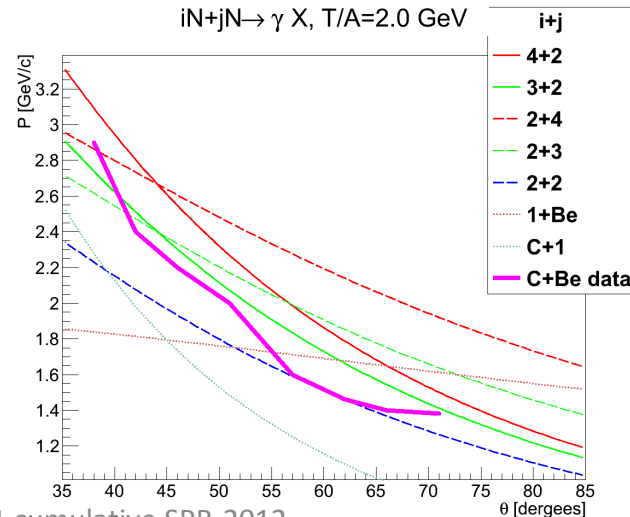
CBe → γX



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?



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
- isotopic properties of the droplet
- strangeness production in the droplet
- fluctuations
- search for an exotic in the droplet

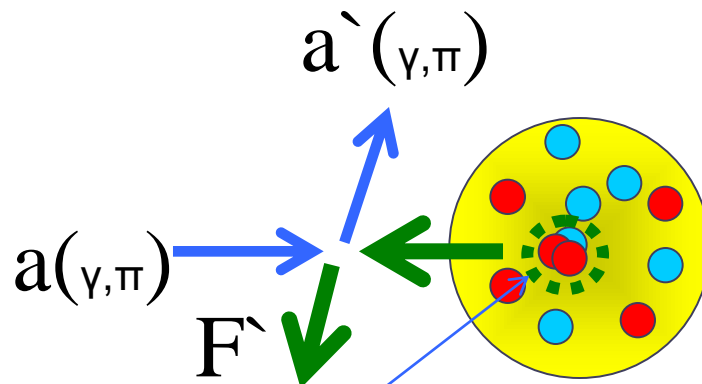
2) Dense cold matter contribution in ordinary nuclear matter and its nature SRC, flucton,...

- nuclear fragmentation
- hard scattering

Proposed measurements:

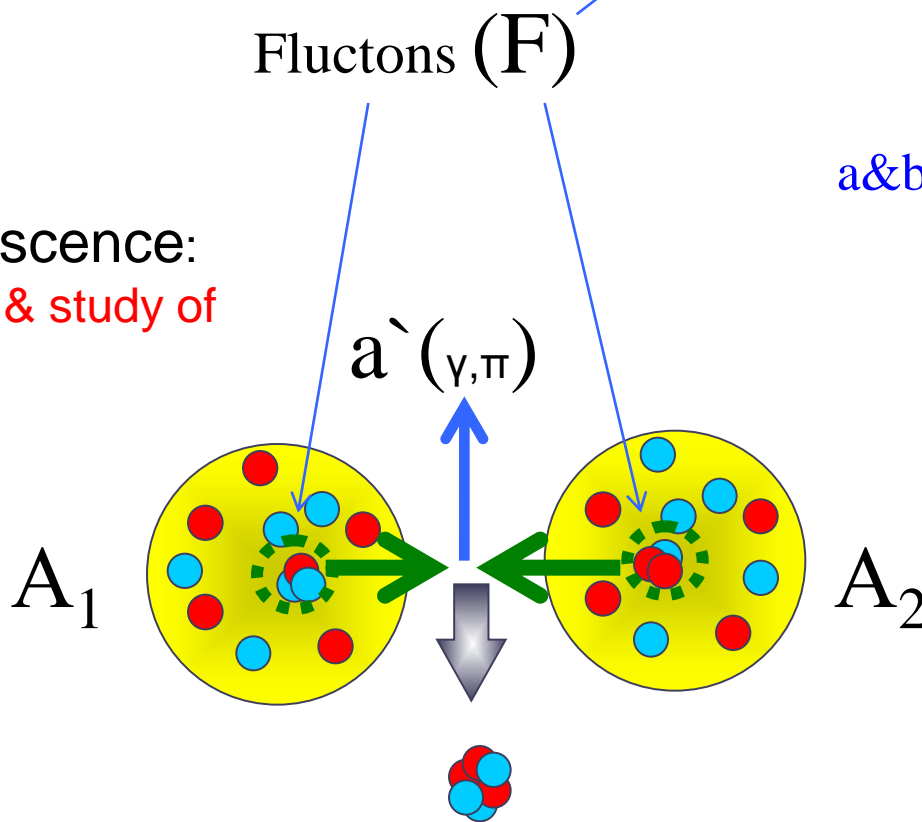
1. Beams and targets: $A_1(p(\text{anti } p), d, {}^3\text{He}, {}^4\text{He}, \text{C})$; $A_2({}^3\text{He}, {}^4\text{He}, \text{C}, \text{Pb})$;
2. Beam energy(for fix target): $\sim 1-10$ GeV/nucleon
3. Trigger's particles: $\gamma, \pi, K^-, K^+, p, d, \dots (p_t/E_0 \sim 1)$
4. Recoil particles: nucleon, multinucleon systems, nuclear fragments, exotic states
5. Measurement values: $\langle N(p_t, y) \rangle$ vs X_{trig} and E_0 (2-6 GeV/nucleon);
-ratios($p/n, {}^3\text{He}/t, \dots$); correlations between recoil particles

a) Knockout:
 the study of the
 structure of
 flucton in knockout
 process



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.

b) Coalescence:
 search for & study of
 DCM



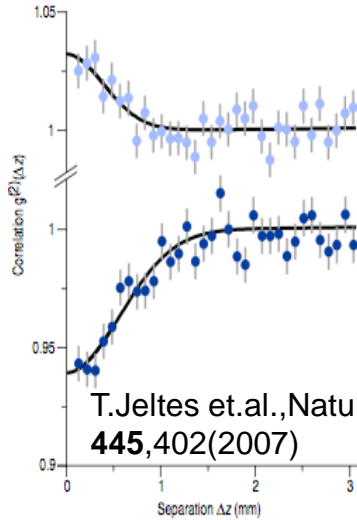
a&b: in both cases high p_T trigger
 $(\pi, \gamma, \gamma(\pi^0), \dots)$

A_1, A_2 : He, Be, C, ...

Dense baryon system

– femtoscopy measurements for the dense baryonic droplet

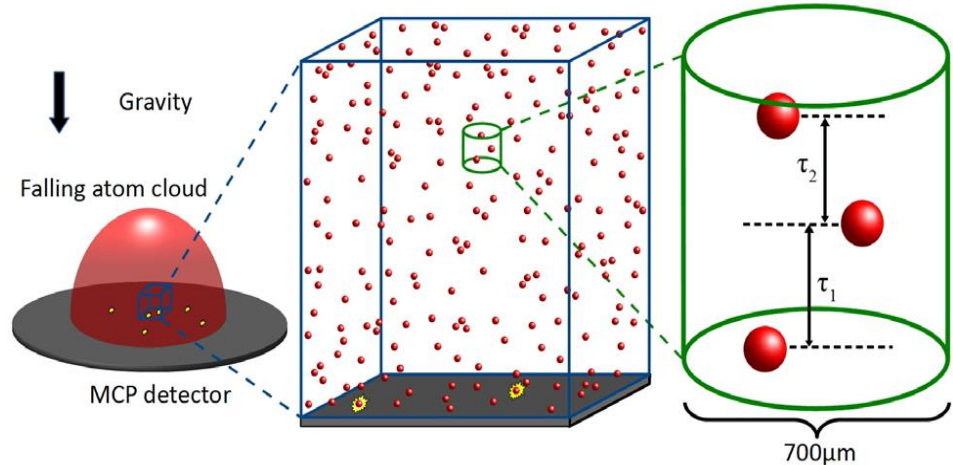
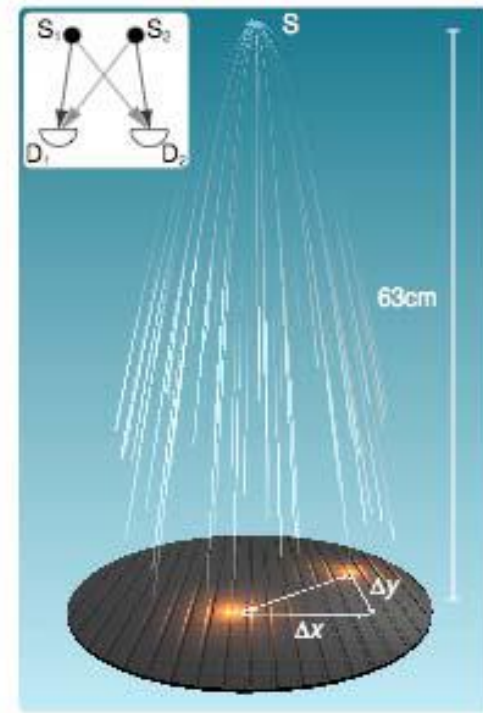
Condensed matter(not an analog in the state of matter but for the statistical properties of the system):Advances in atom cooling and detection have led to the observation and full characterisation of the atomic analogue of the HBT effect



Caption for figure 1: Normalised correlation function for 4He^* (bosons) in the upper graph, and 3He^* (fermions) in the lower graph. Both functions are measured at the same cloud temperature ($0.5\ \mu\text{K}$), 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 $0.75 \pm 0.07\ \text{mm}$ and $0.56 \pm 0.08\ \text{mm}$ for fermions and bosons respectively!

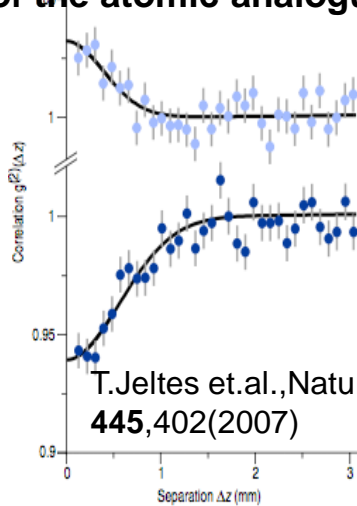
T.Jeltes et.al., Nature, 445,402(2007)

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: S_1 and S_2 refer to the initial positions of two identical atoms jointly detected at D_1 and D_2 .



– 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)

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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]

Bose-Einstein Condensation(BEC)

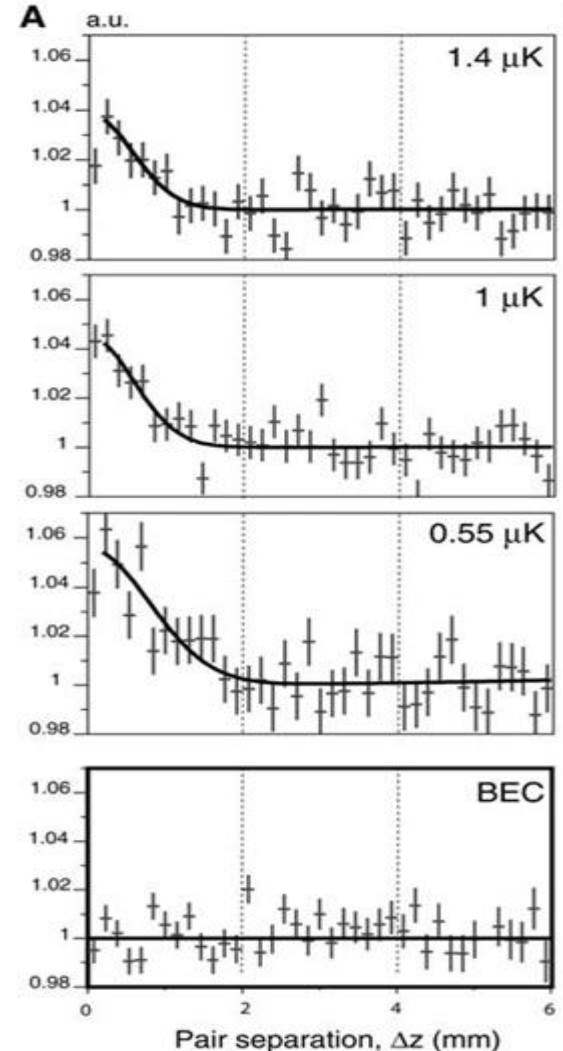


Fig. 2. (A) Normalized correlation functions along the vertical (z) axis for thermal gases at three different temperatures and for a BEC.

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

Experimental program:

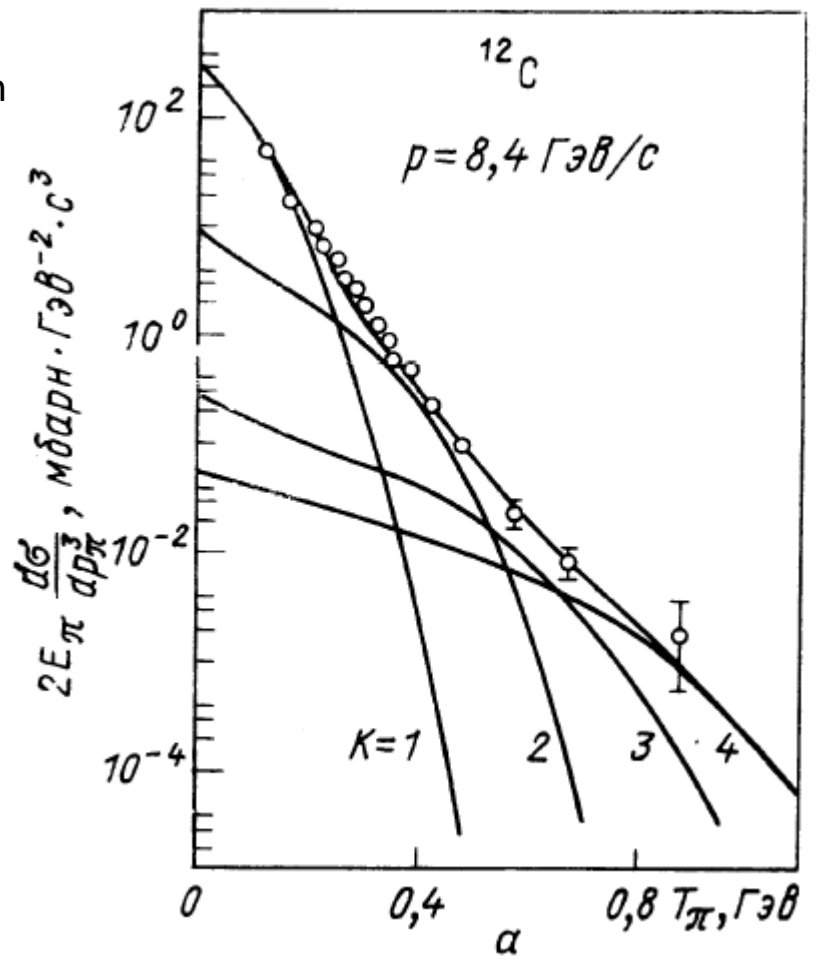
1). Search for and the study of new state of matter at high density and low temperature corner of phase diagram

– **fluctuations**

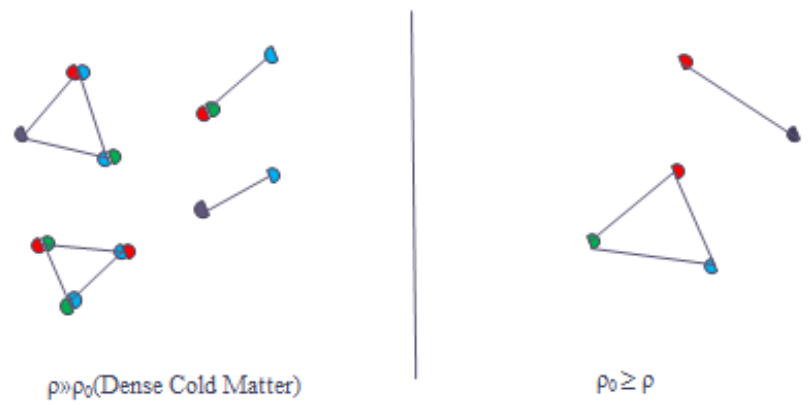
Phase space volume vs flucton probability ->
 Baryon system temperature fluctuations
 from event to event

– **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

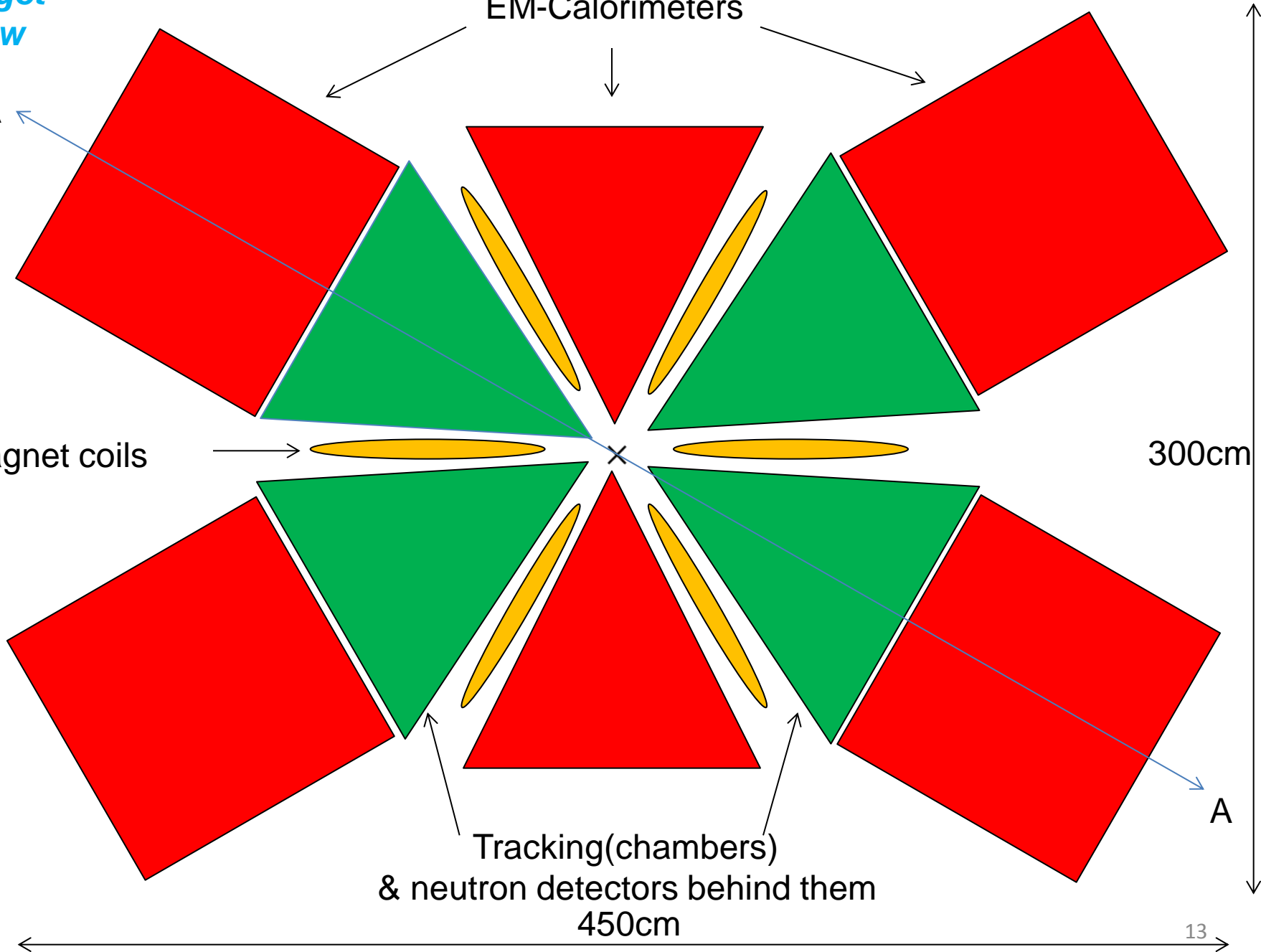
magnet coils

300cm

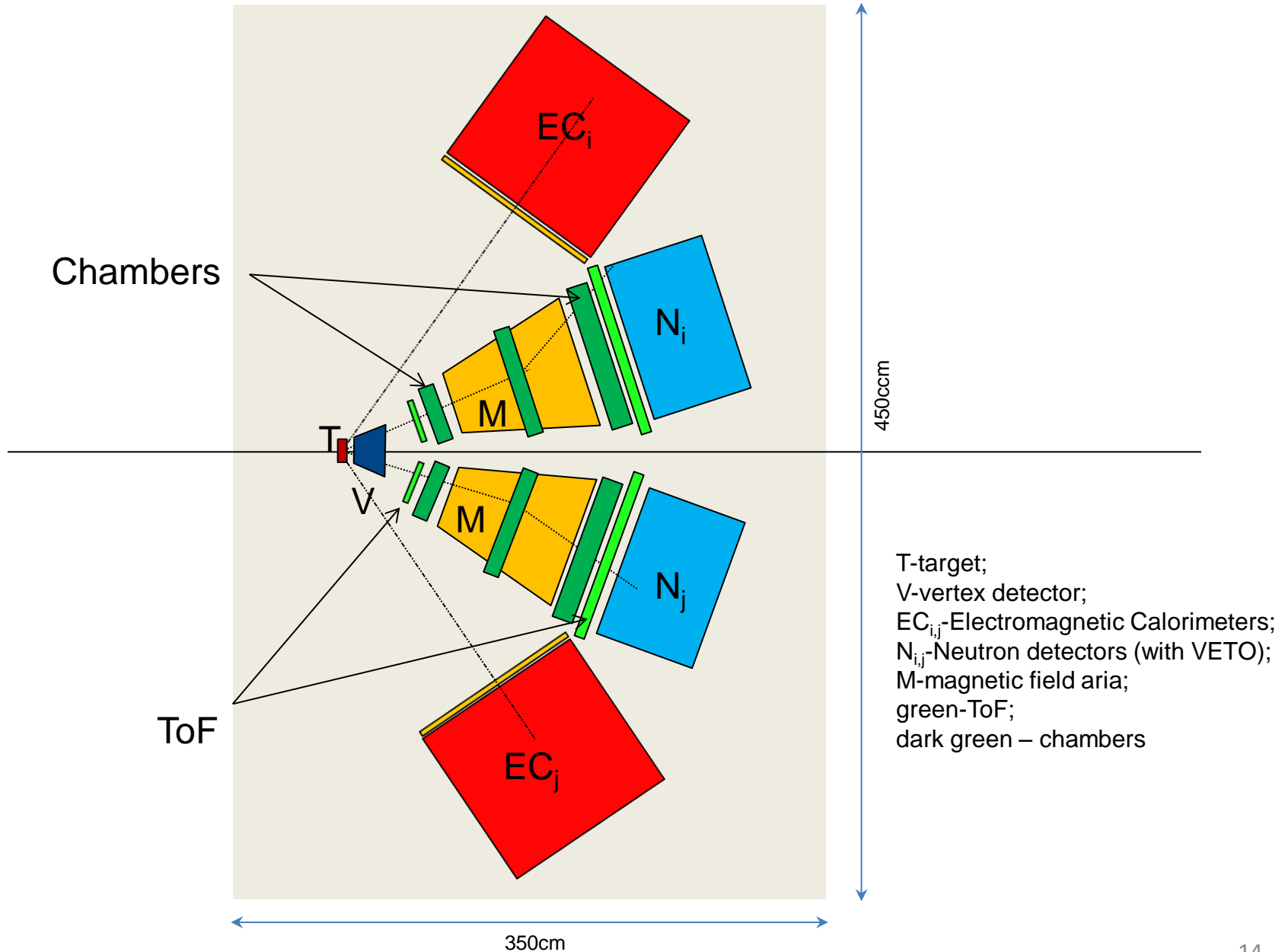
A

Tracking(chambers)
& neutron detectors behind them
450cm

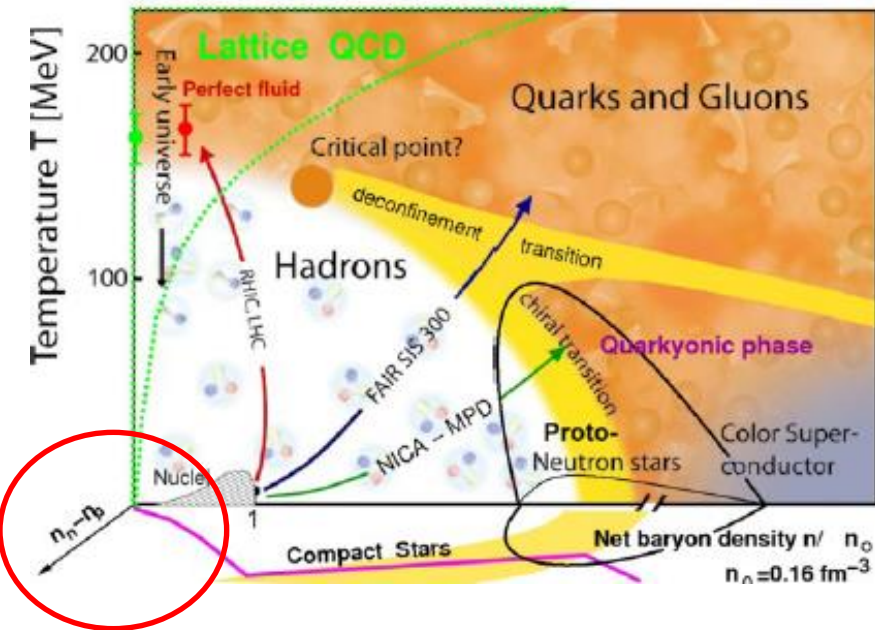
13



DCM detector(project version), AA plane



Neutron detector. Motivation



1. Neutron is one of the main particle species 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 needs to 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

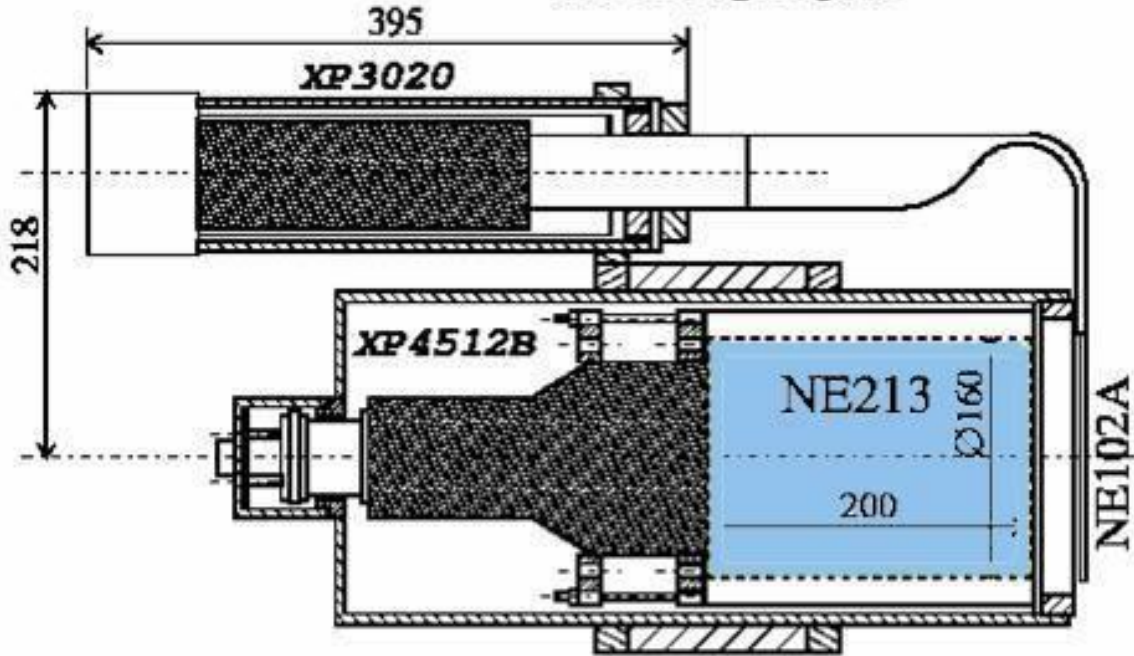
$E_{kin} \sim 10(1?) - 200 \text{ MeV}$

Femtoscopy : the **width** of the effect

$\sim 30 \text{ MeV}/c \Rightarrow \Delta p \sim 10 \text{ MeV}/c,$
cross-talk problem

Neutron detectors

SYREP DETECTOR



DEMON DETECTOR

$\epsilon_n = 20-30\%$ for neutrons of $T_n = 60-250 \text{ MeV}$

Time resolution ~ 250psec

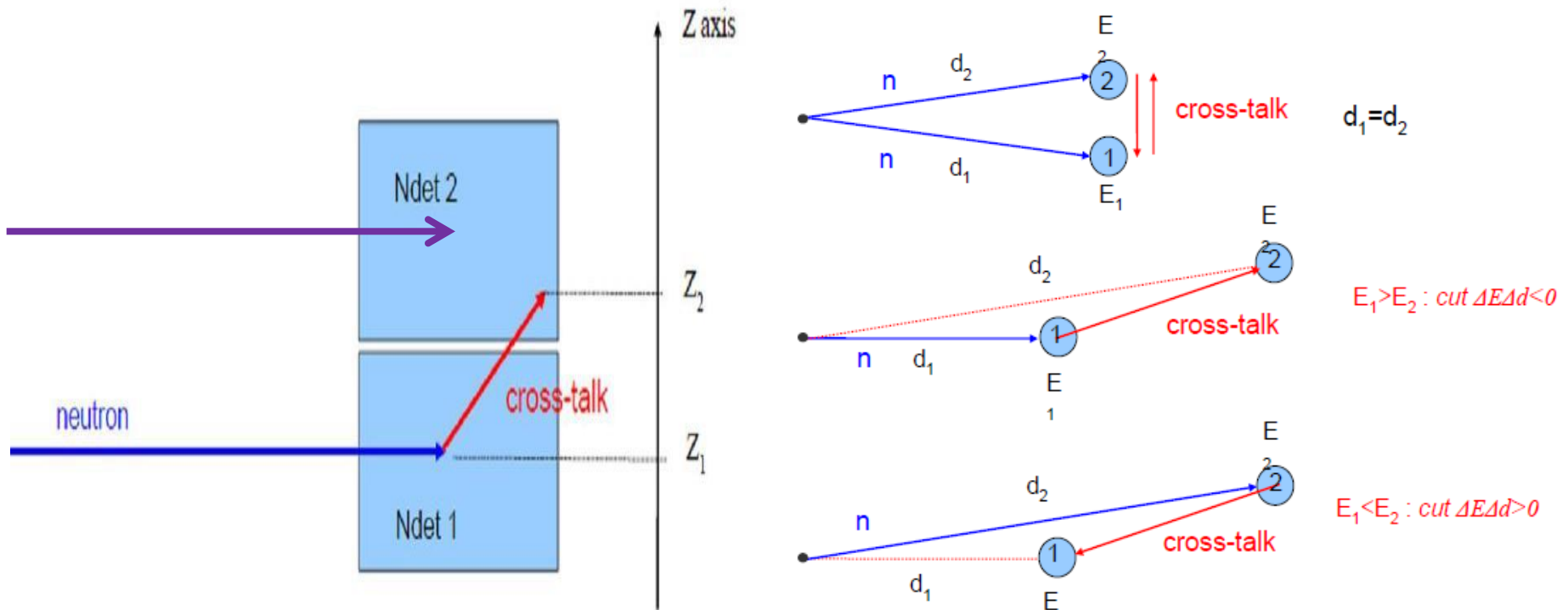
Liquid scintillator -> different signal shape for n/ γ
Large total volume $V \sim 50 \text{ dm}^3$ and small sensitive volume $V \sim 4 \text{ dm}^3$

[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.

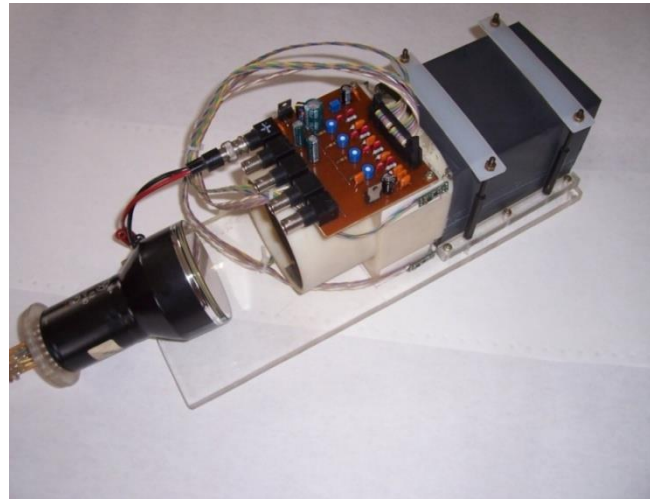
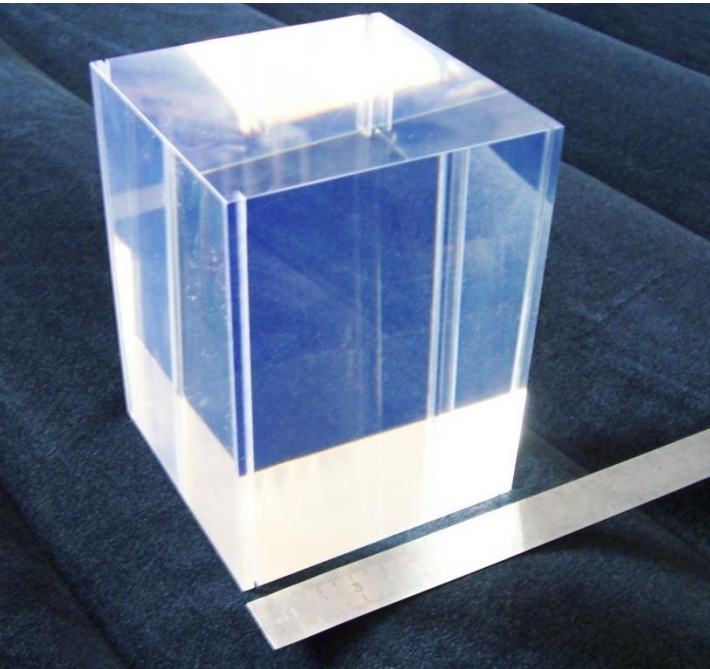


Solution: position sensitive detector

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 correlation 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



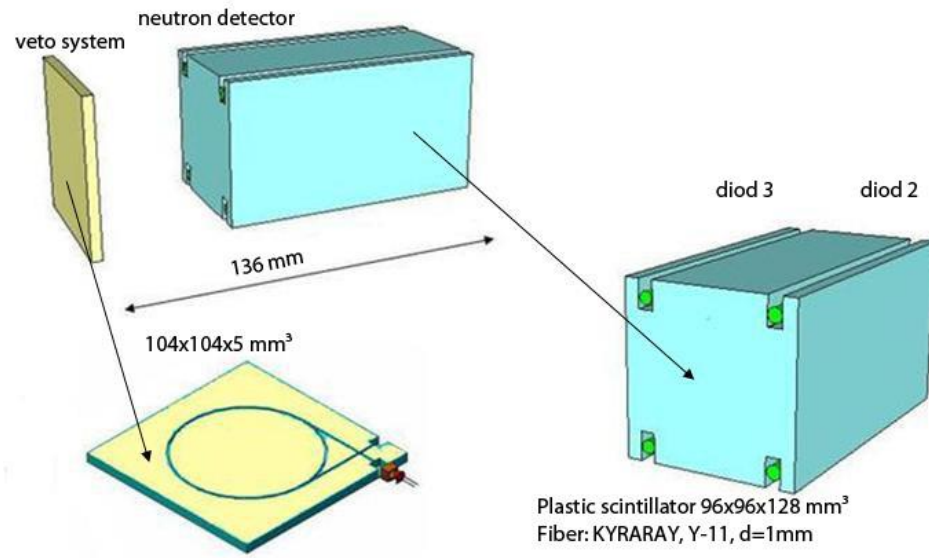
Plastic Scintillator $96 * 96 * 128 \text{ mm}^3$

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

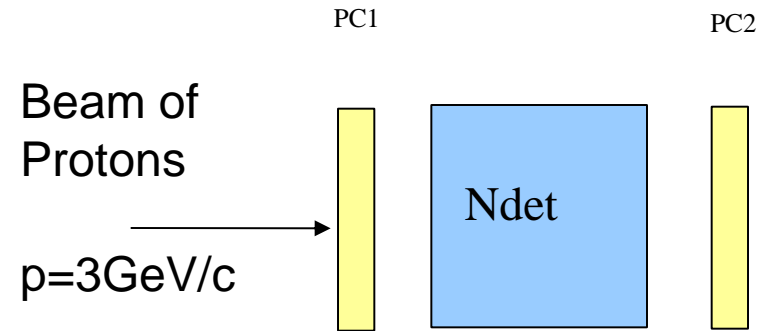
wavelength shift

4 SiPM & Amplifier - CPTA(Golovin)

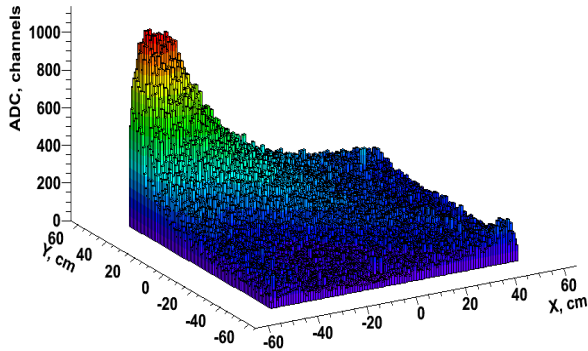
Efficiency (estimate) 15%



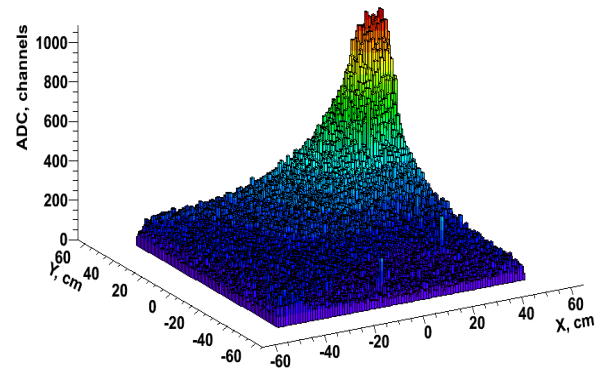
Tests of prototype 1 with proton beam(ITEP)



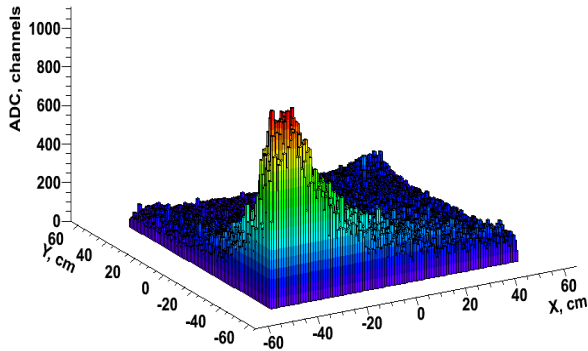
AmpDiod 3



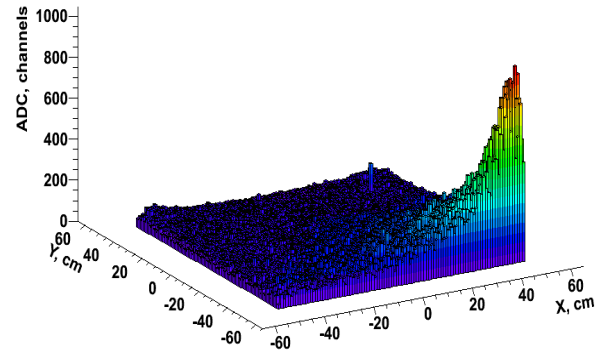
AmpDiod 2



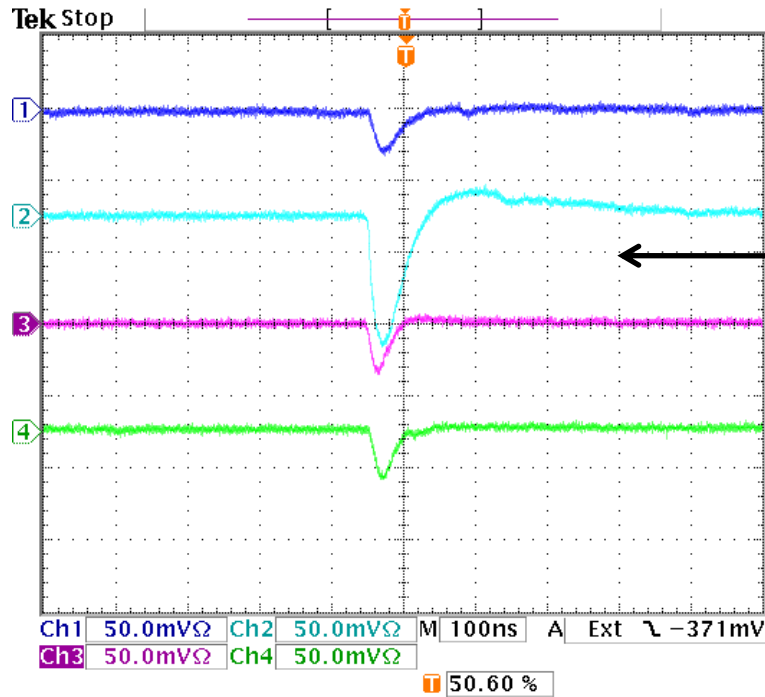
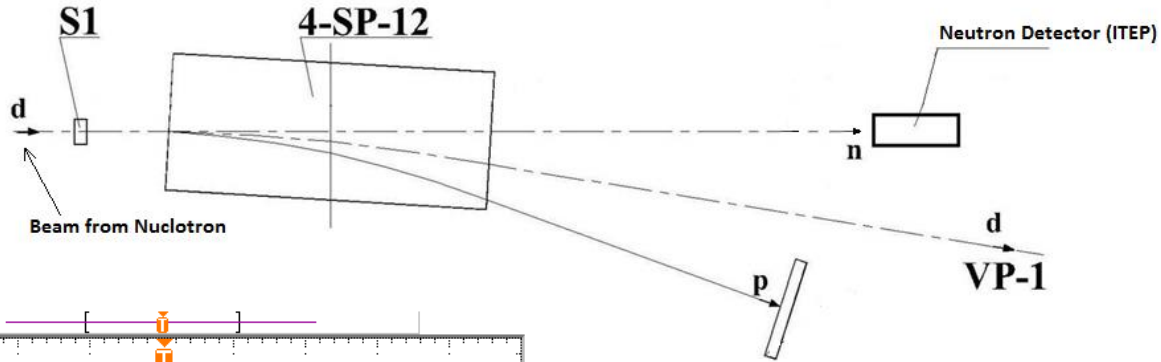
AmpDiod 4



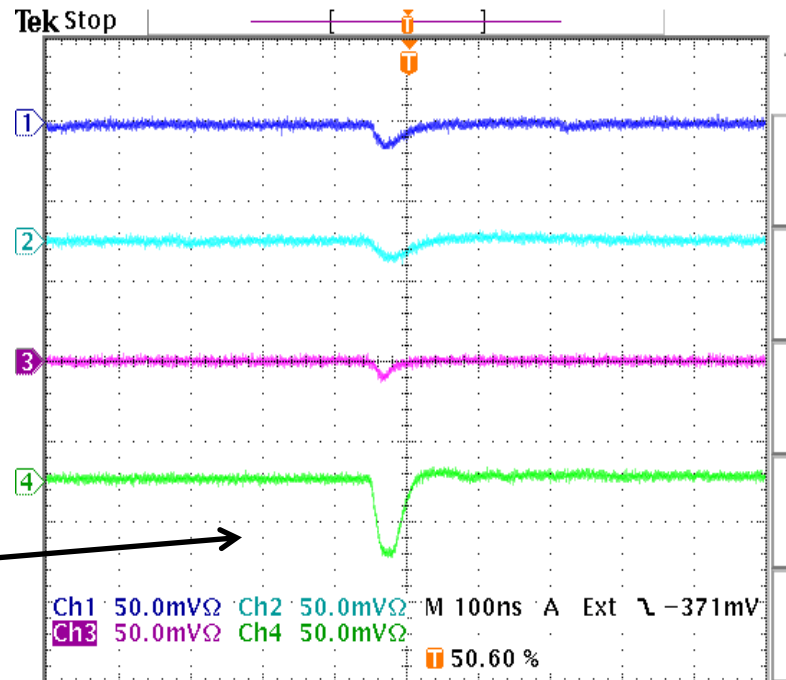
AmpDiod 1



Tests of prototype 1 with neutron beam (MARUSYA)

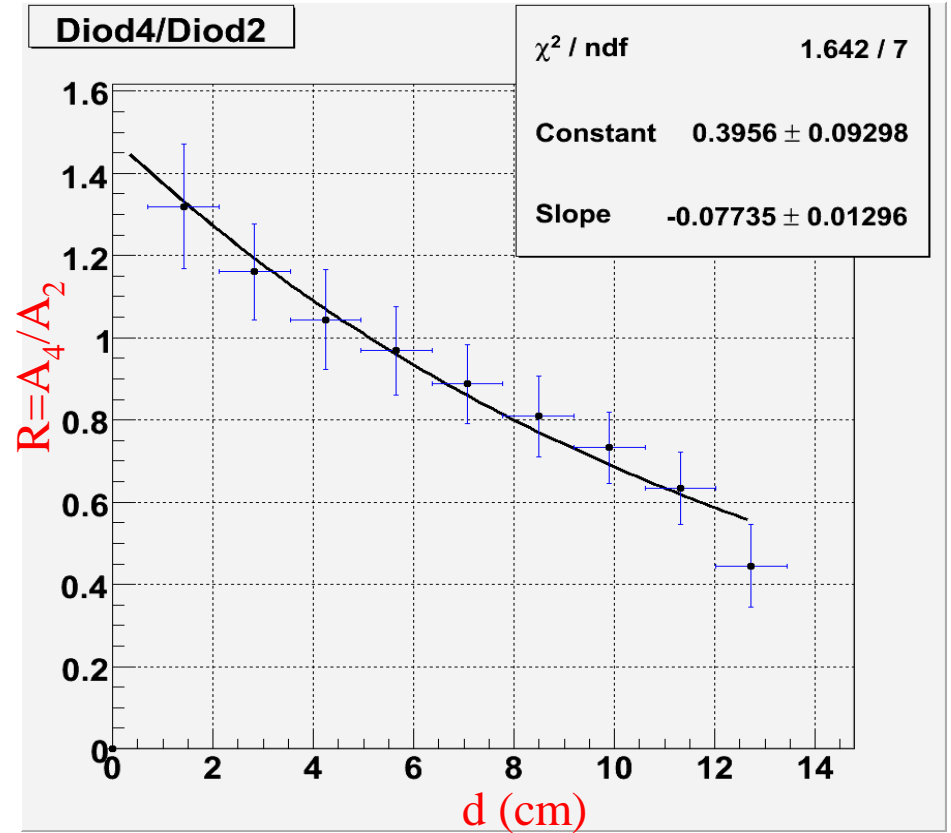
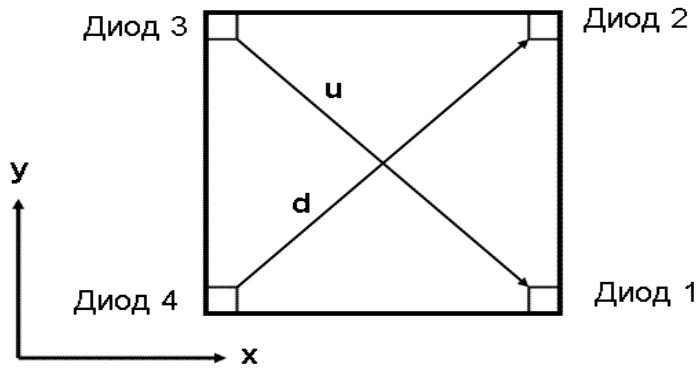


Neutron near 2 diode

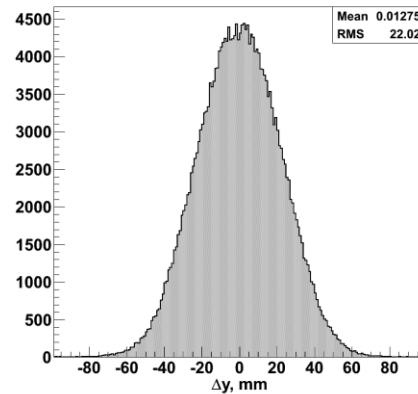
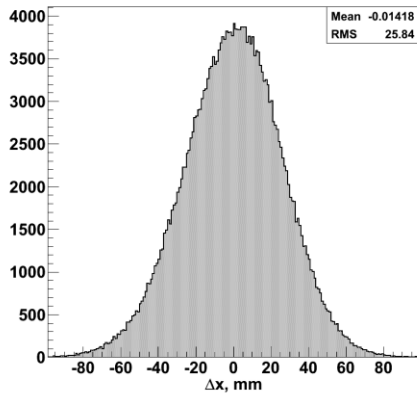


Neutron near 4 diode

Neutron detector (prototype 1)



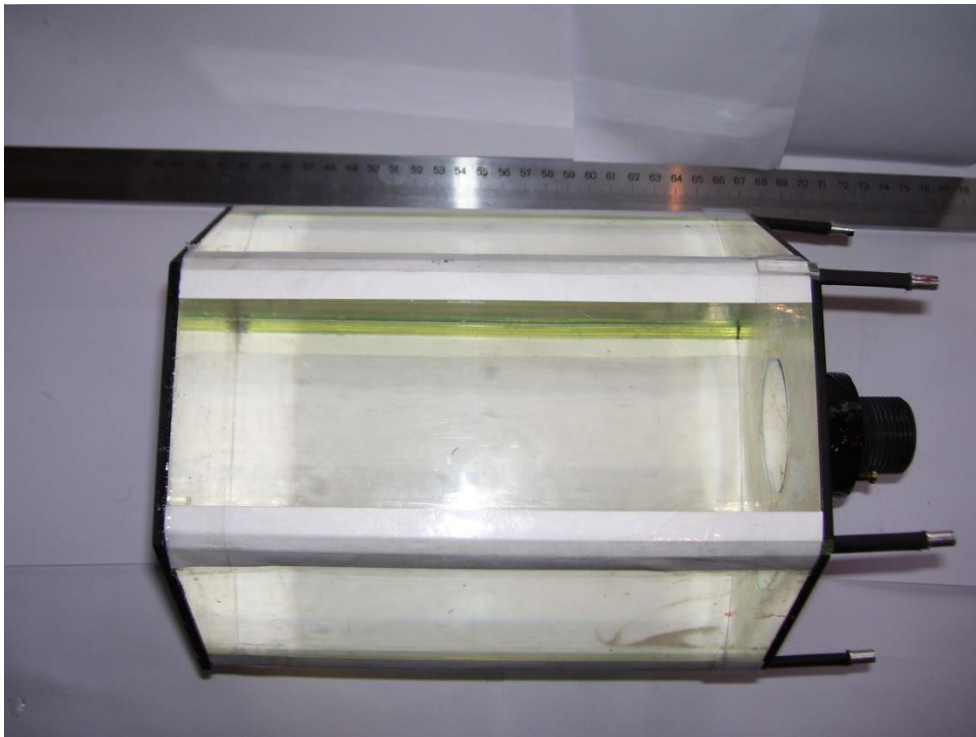
spatial resolution for the first prototype ~ 2.5 cm



Next step to improve spatial resolution from 2,5 to ~1 cm.

Prototype1 4 diodes * 1 mm² → Prototype2 6 diodes * 4 mm²

- 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

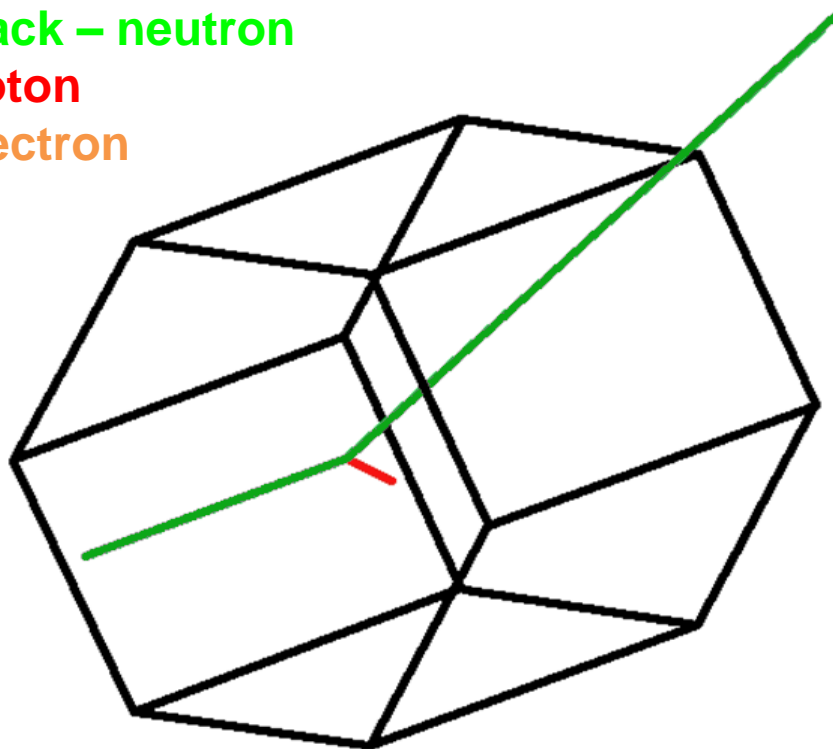


version without PMT

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.

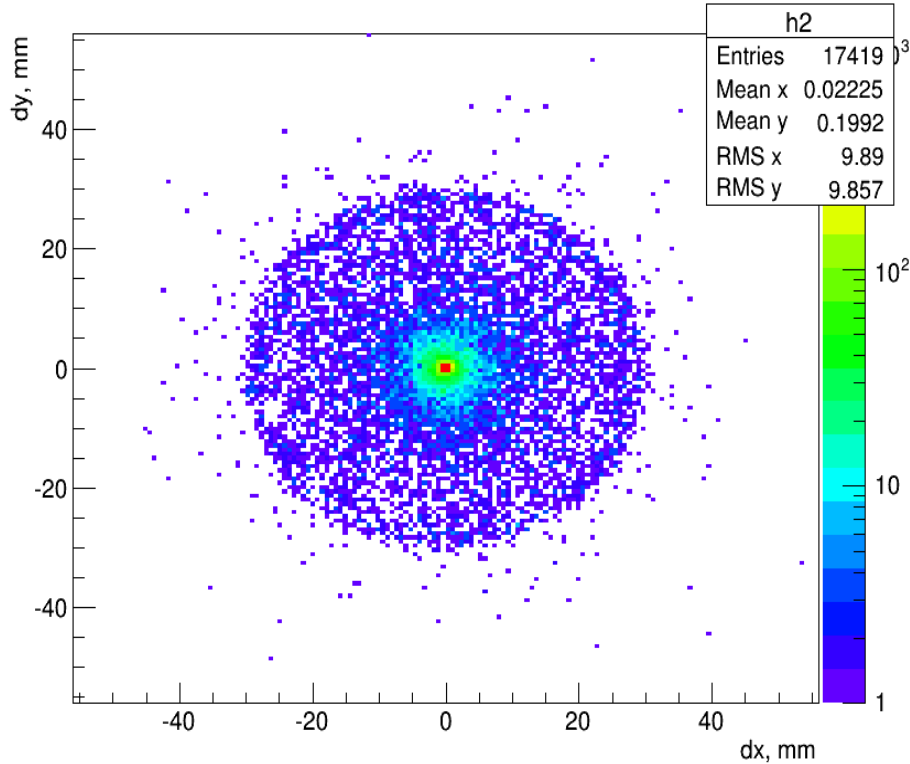
Green track – neutron
Red - proton
Blue - electron



Simulation neutron detector (prototype 2)-ITEP

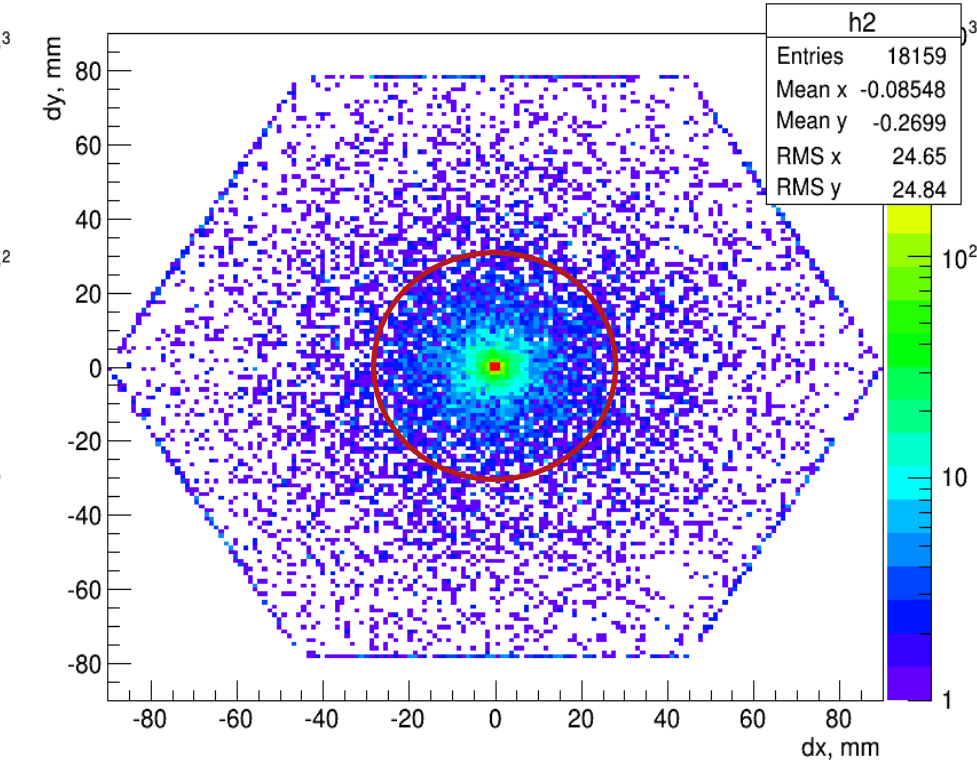
150MeV

Hist with dx dy



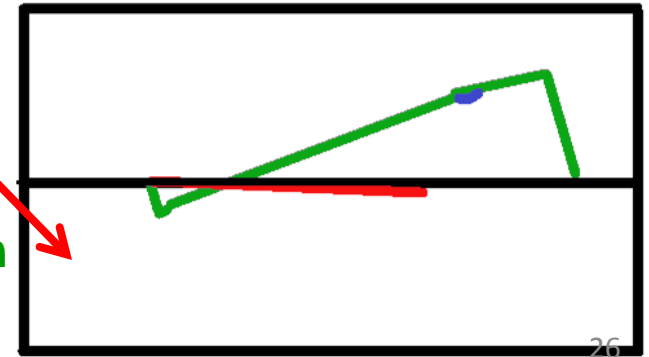
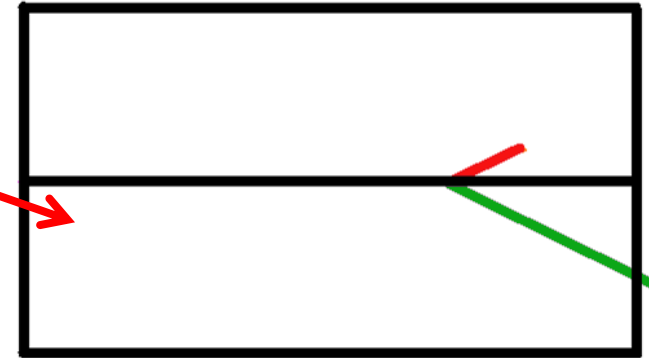
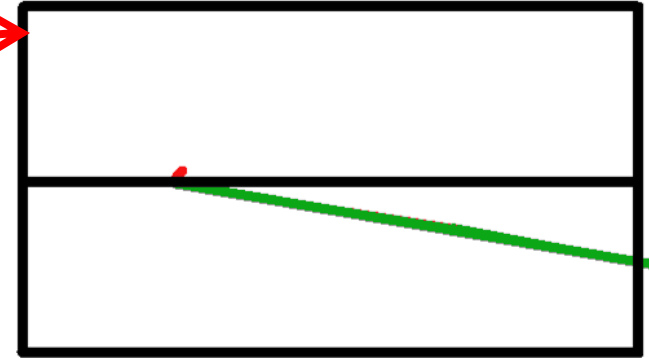
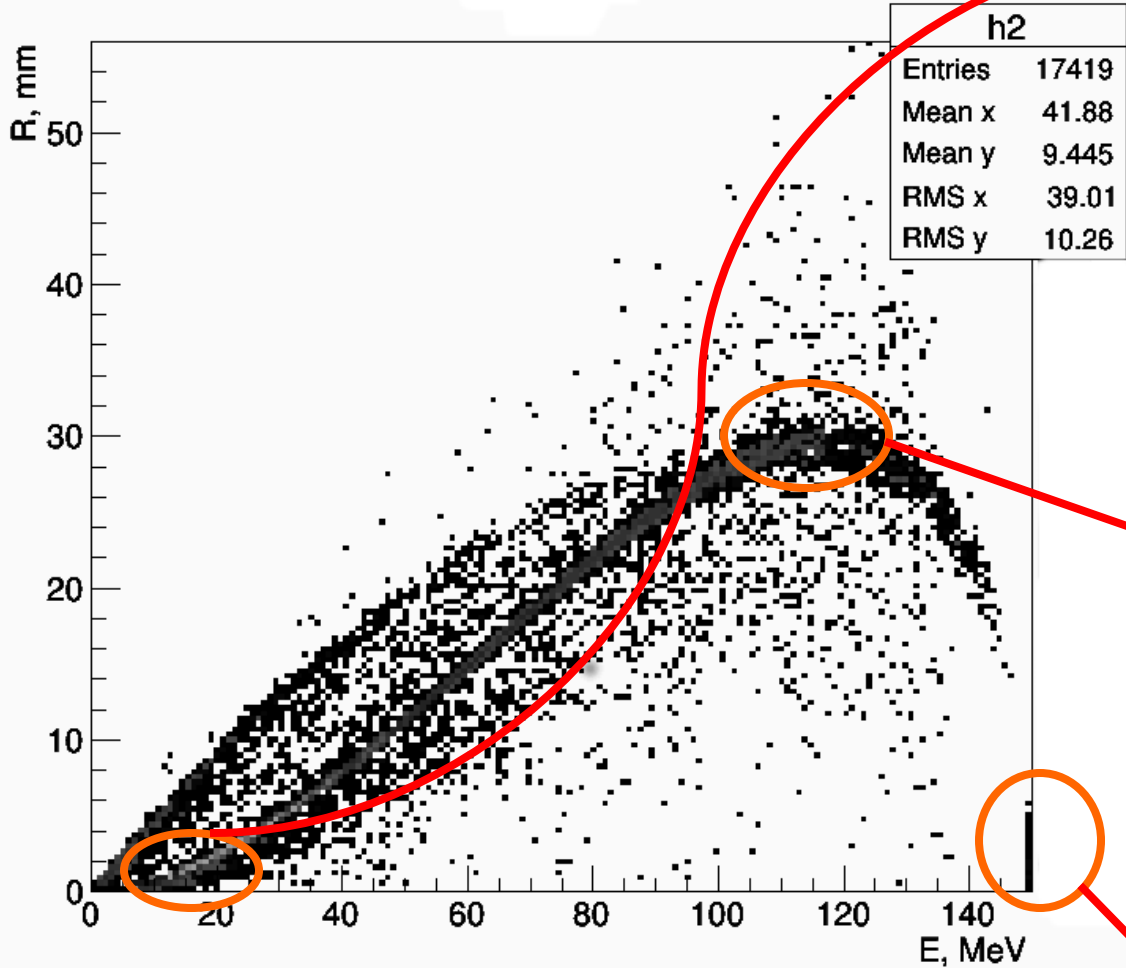
300MeV

Hist with dx dy



Distribution of secondary protons in the transverse coordinates

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



All selected events

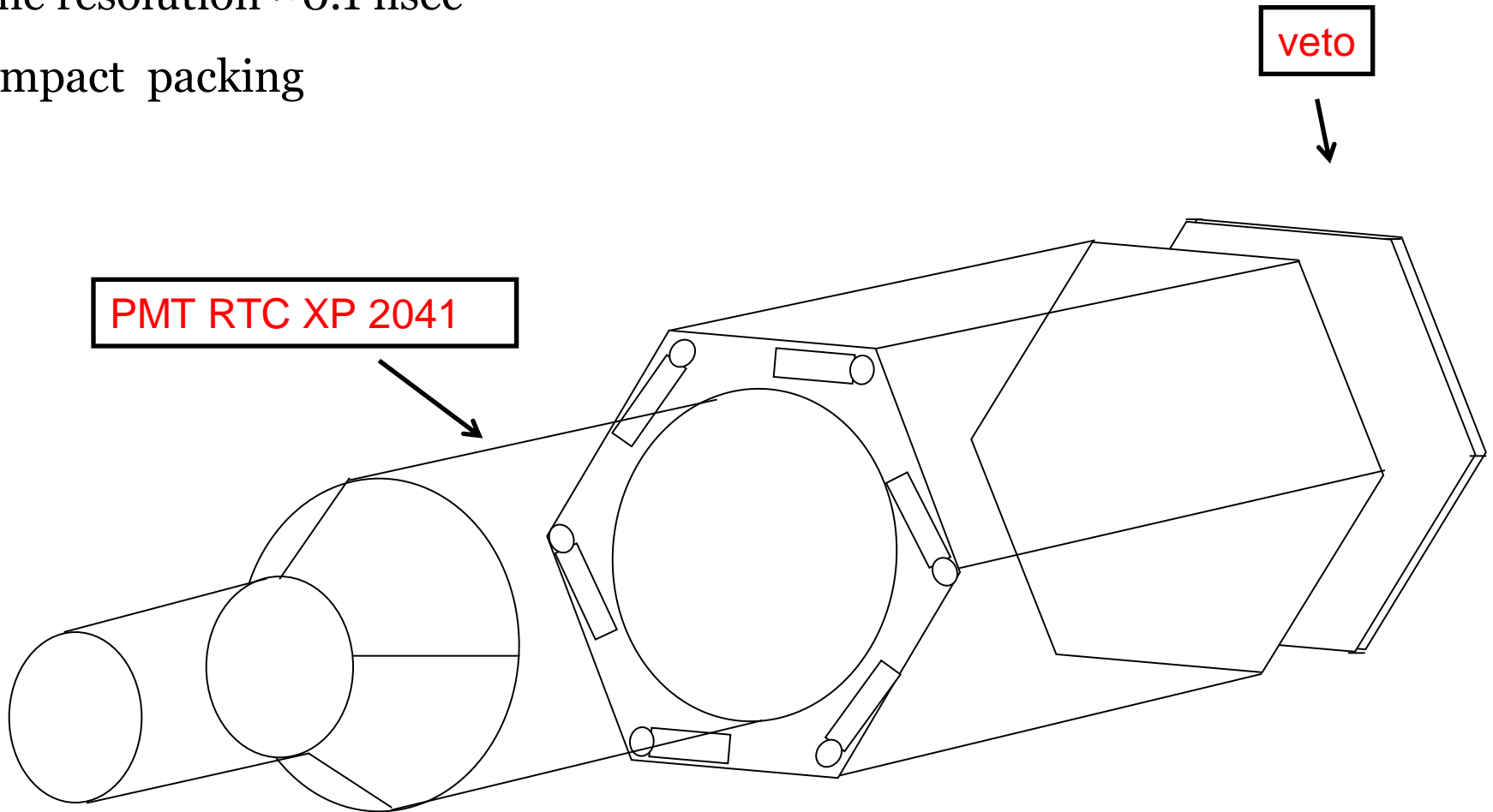
Green track – neutron
Red - proton
Blue - electron

Results of the simulations

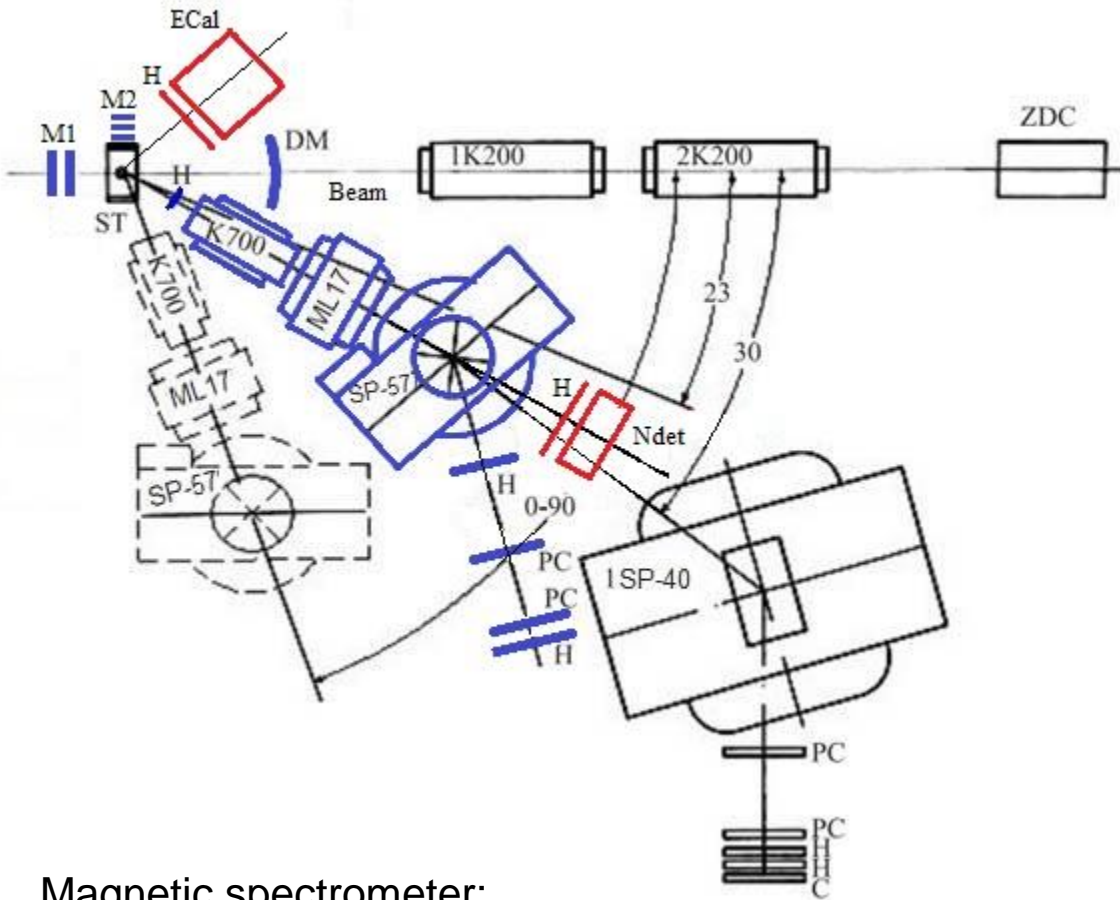
Neutron energy, MeV	50	100	150	200	300
mean deviation of protons track, mm	0,6	2,4	4,8	7,5	12,2

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

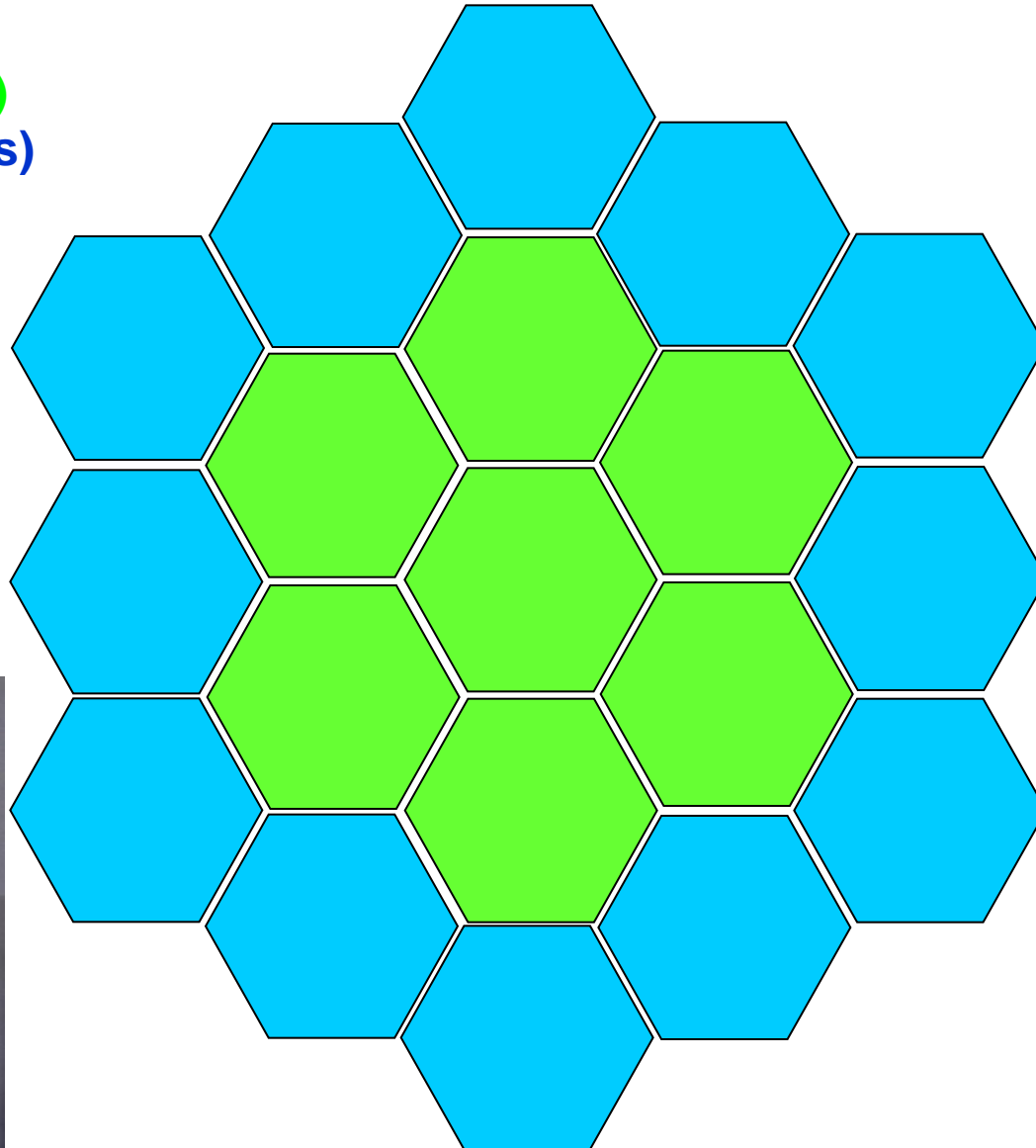
Neutron detector for MARUSYA-FLINT

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

Next step to improve spatial resolution from 2,5 to 1,5 cm.

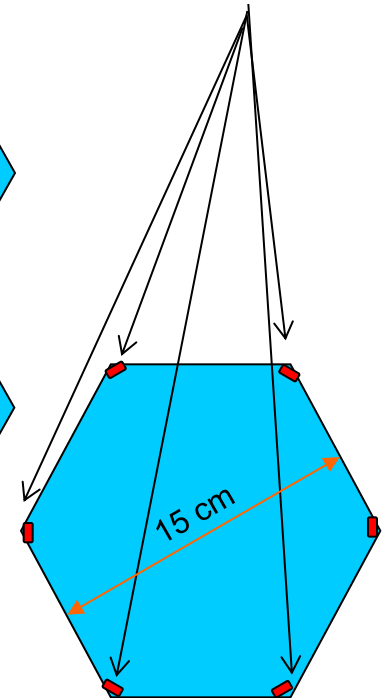
Prototype1 4 diodes * 1 mm²

Prototype2 6 diodes * 4 mm²



Distance from the target 240cm;
Detector thickness 20cm

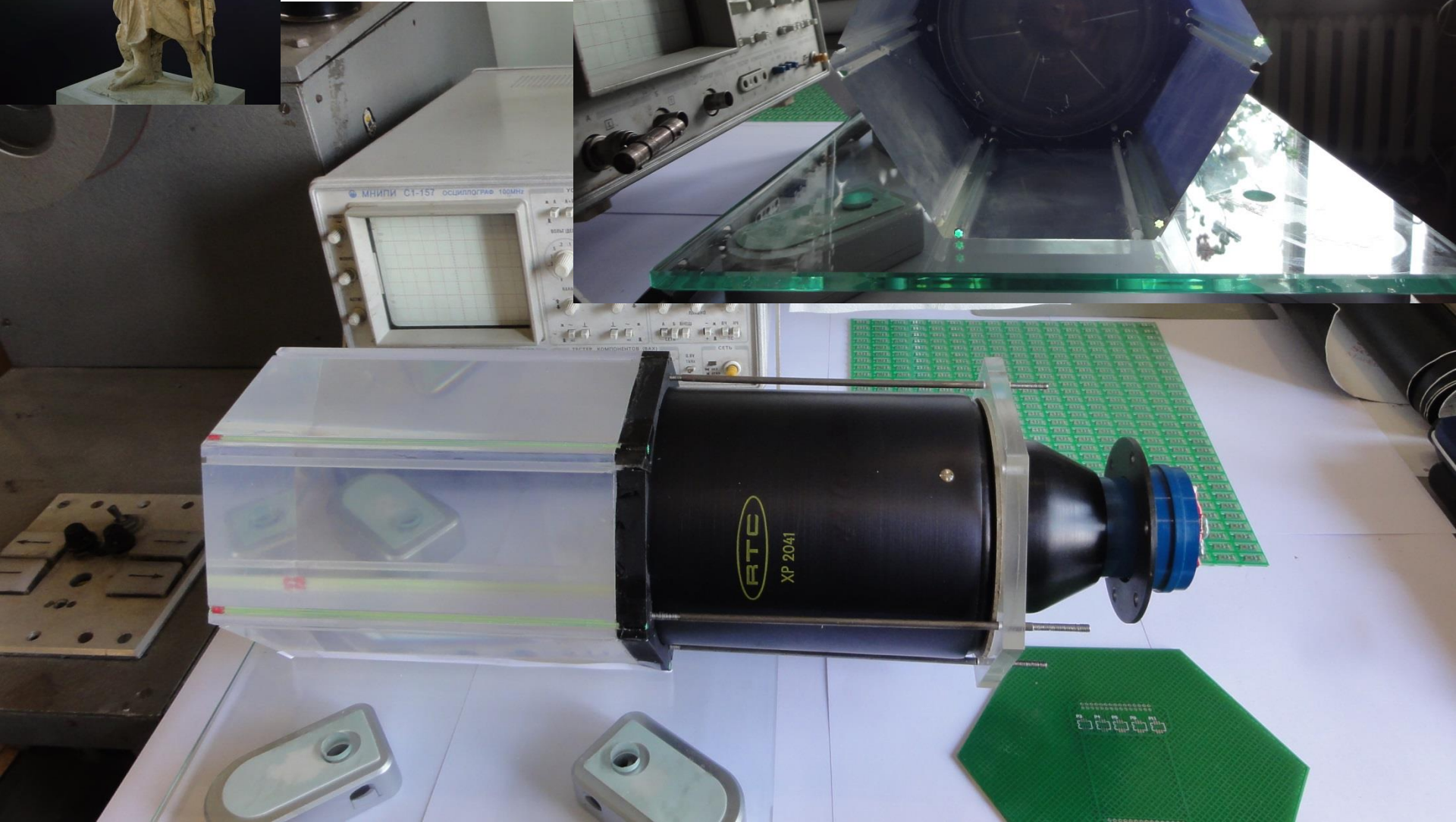
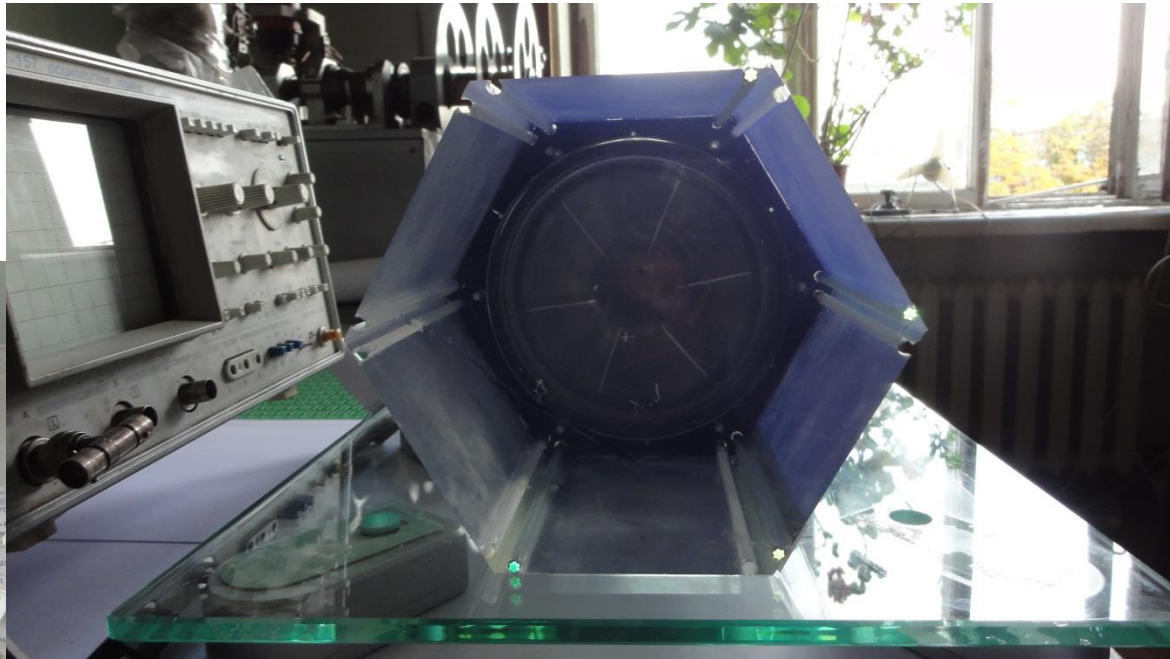
Fiber + SiPM



Position Sensitive Identification of Neutrons = POSEIDON



Detector module
in construction



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 ($P_T \approx P_{\text{beam}}$)
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:

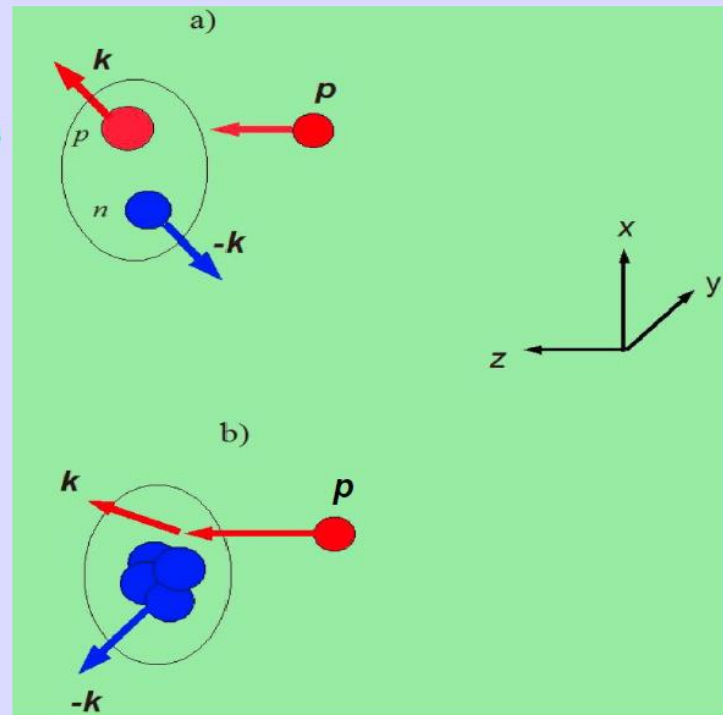
2) Dense cold matter contribution in ordinary nuclear matter and its nature SRC,flucton,...

– **hard scattering**

$p+A \rightarrow p + \langle mN \rangle$,
where m is an
average number of
nucleons
 $m \sim 1$ for SRC model
and
 $m \sim$ cumulative
number for
multiquark system
knockout
(see also S.S.Shimanskiy
proposal for future PANDA
experiment at FAIR)

Knot out cold dense nuclear configurations

SRC configuration



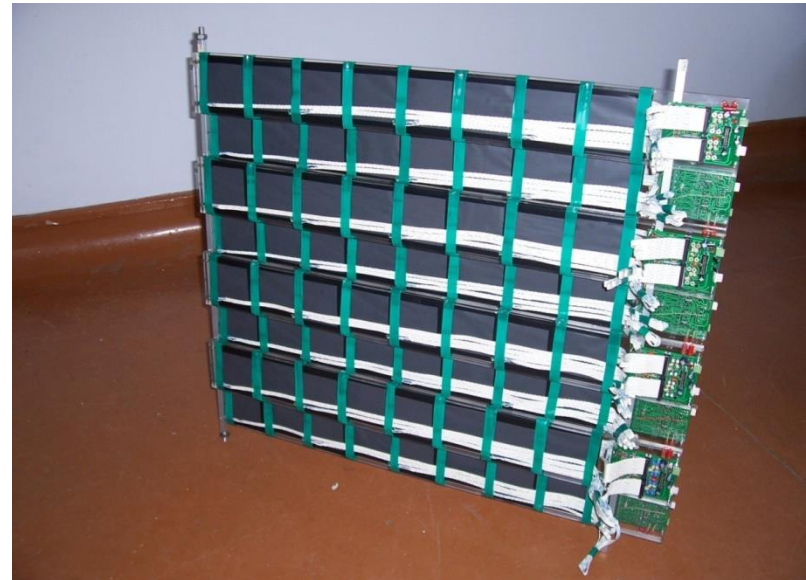
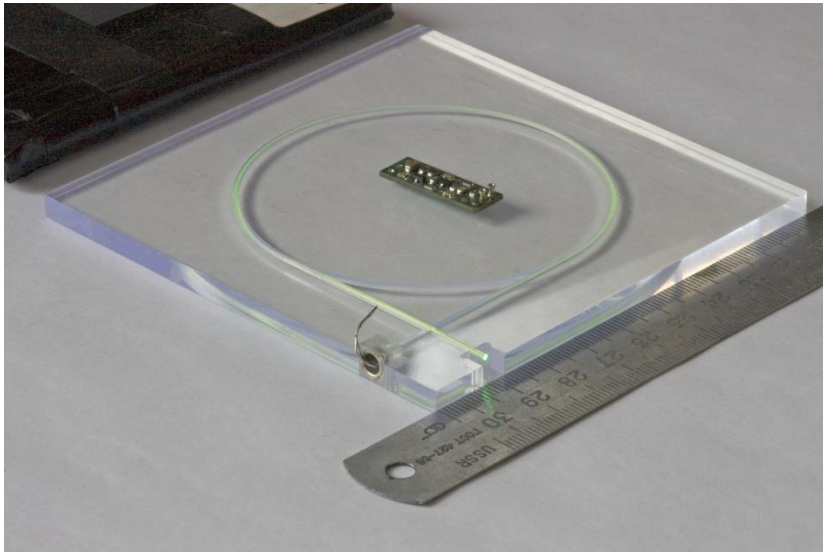
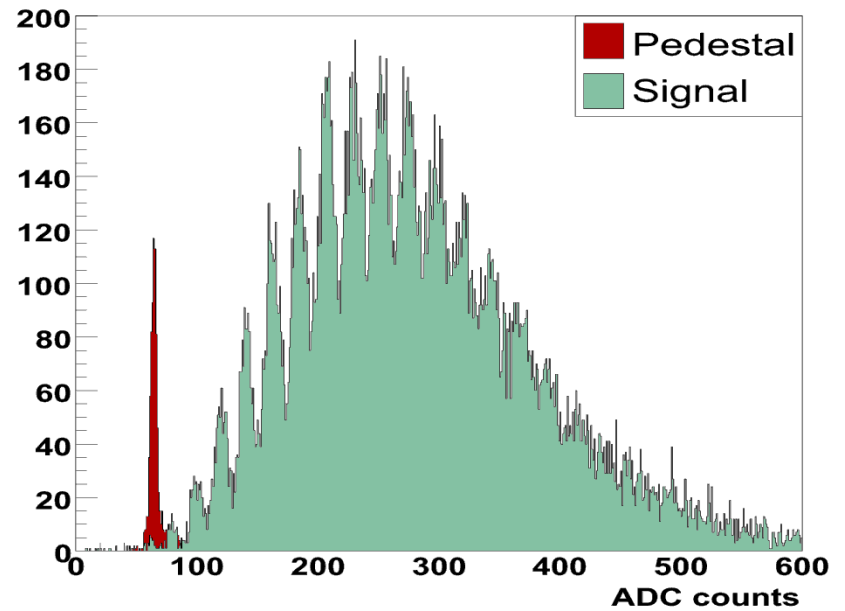
Multiquark
configuration



Plastic Scintillator
105*100*5 mm³

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

MRS APD &
Amplifier -
CPTA(Golovin)



Dense Cold Matter with fluctons

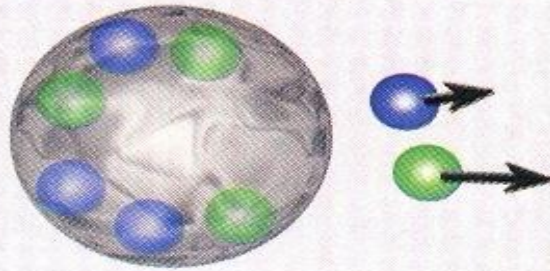
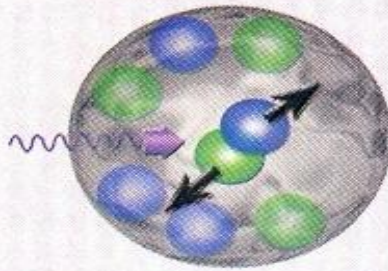


Fig. 1. Scattering of a virtual photon off a two-nucleon correlation, $x > 1.5$, before (left) and after (right) absorption of the photon.

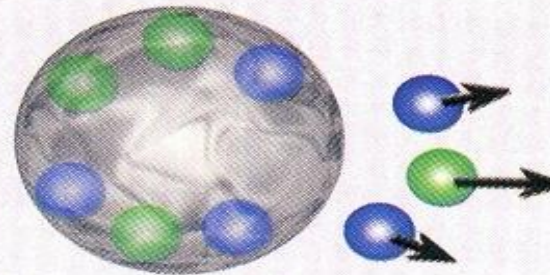
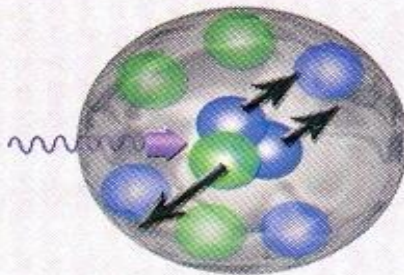
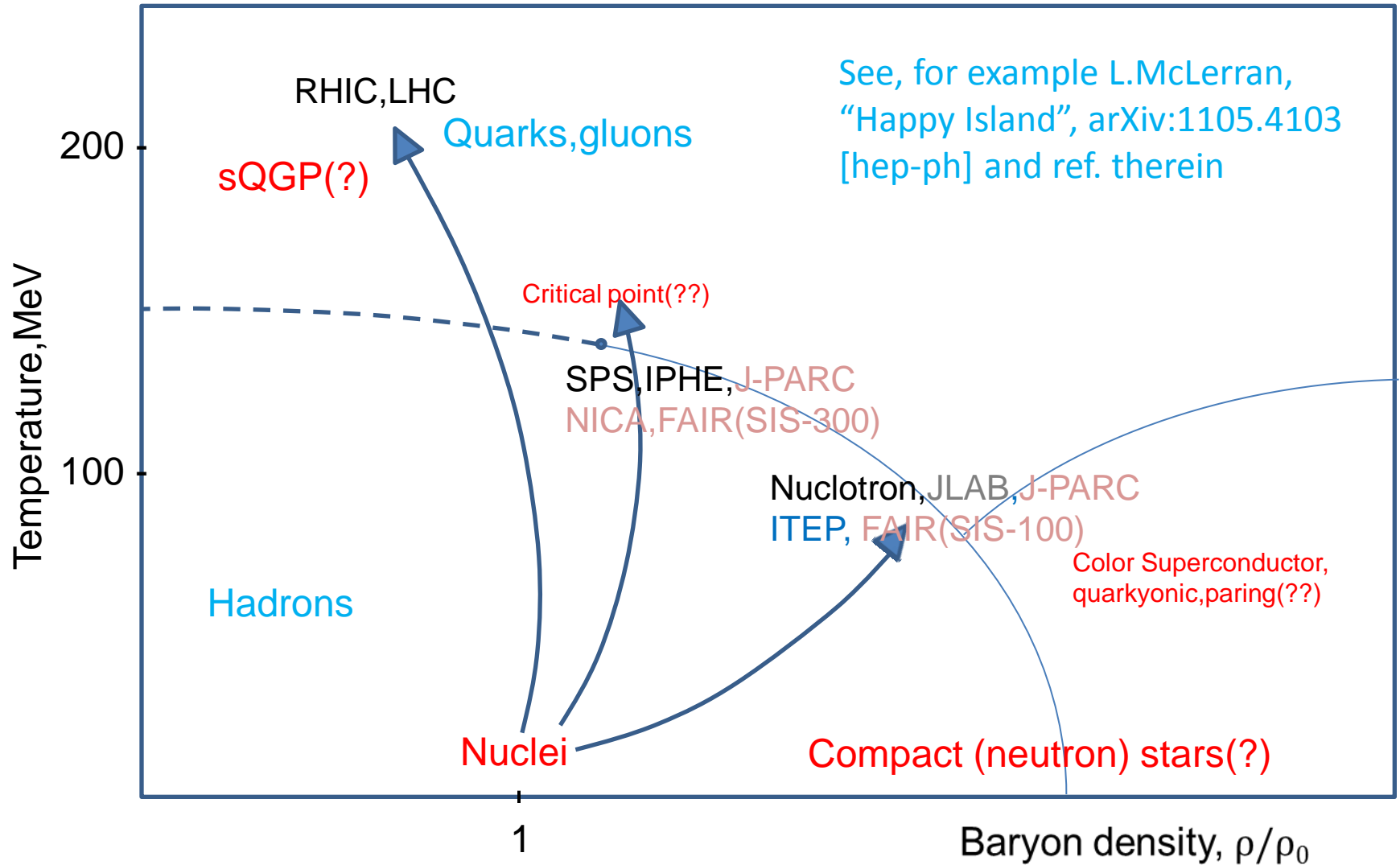


Fig. 2. Scattering of a virtual photon off a three-nucleon correlation, $x > 2$, before (left) and after (right) absorption of the photon.

- 1). Special final state selection
- 2) Correlation measurements

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

Phase diagram of nuclear matter



Probing Cold Dense Nuclear Matter

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 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
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 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. Piassetzky,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. Zhu³²

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 ($\approx 99\%$) nucleonic picture of nuclei with $A \leq 56$

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

$$\begin{aligned}
 a_{pp}(^{12}\text{C}) &\approx 4 \pm 2 \% \\
 a_{2N}(^{12}\text{C}) &\approx 20 \pm 0.2 \pm 4.1 \% \quad \longrightarrow \quad a_{pn}(^{12}\text{C}) \approx 12 \pm 4 \% \\
 a_{nn}(^{12}\text{C}) &\approx 4 \pm 2 \%
 \end{aligned}$$

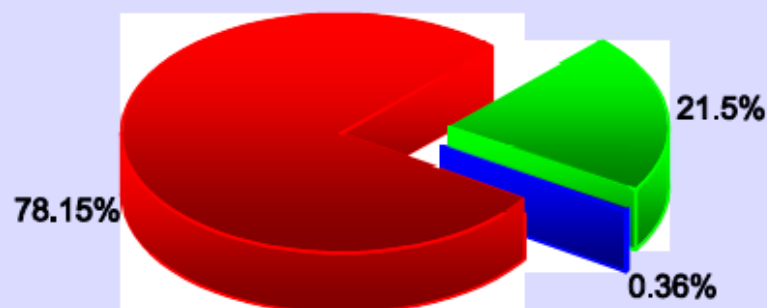
RNP - program at JINR

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

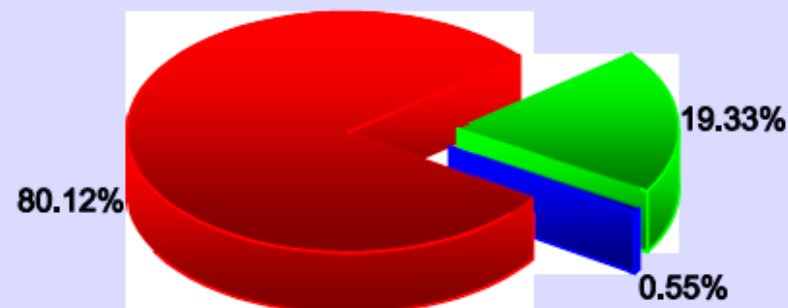
eA - program at JLab

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

JINR - 1977

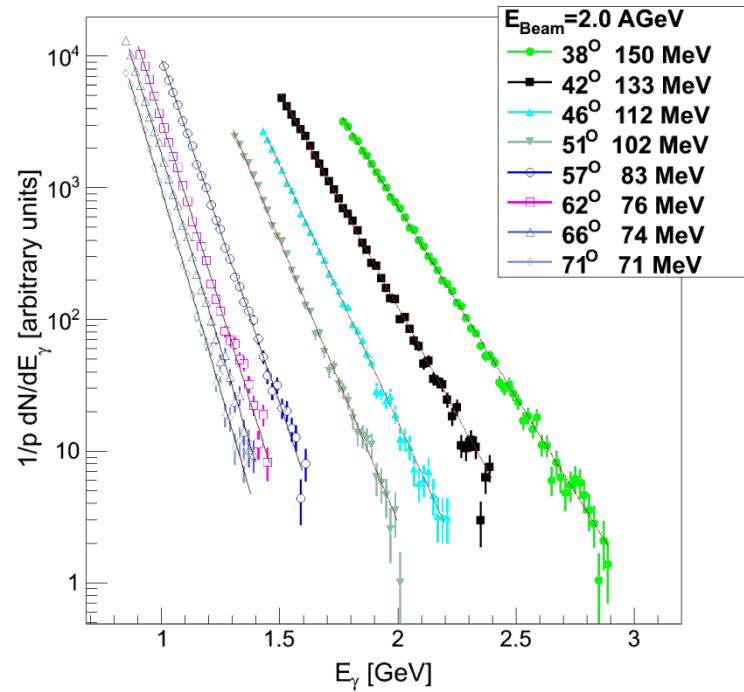
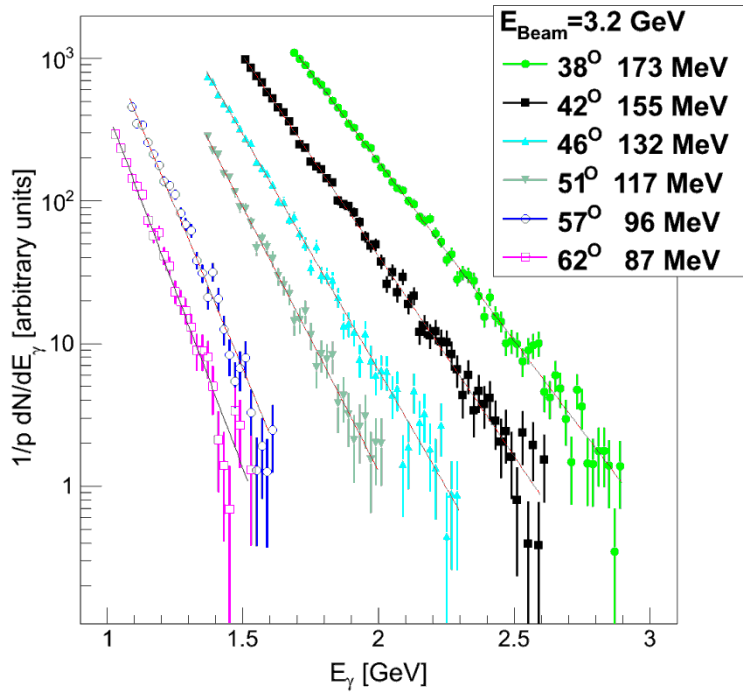


JLab - 2008

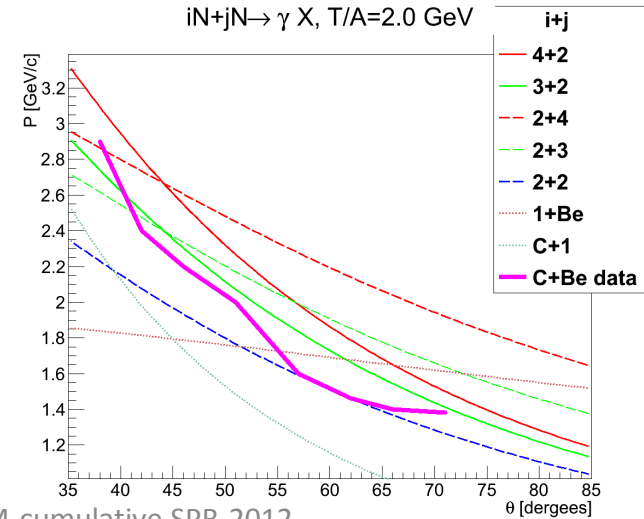


FLINT DATA: Photon spectra

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

$r_f \sim 1.5 \text{ fm}$

