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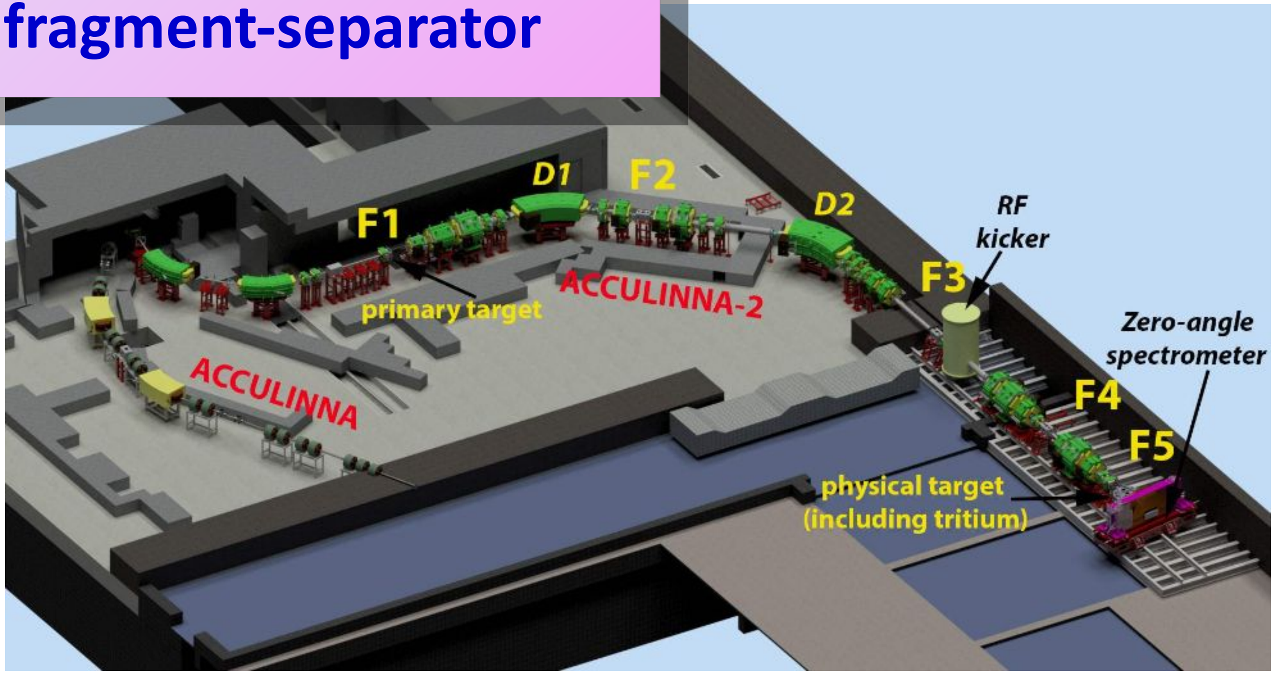
# The prospective scientific program of the ACCULINNA-2 fragment-separator

http://aculina.jinr.ru/




New Trends in Nuclear Physics Detectors (NTNPD-2021), 25-27 October, 2021,
Heavy Ion Laboratory, University of Warsaw, Warsaw, Poland

# Flerov Laboratory of Nuclear Reactions (FLNR)
at
Joint Institute for Nuclear Research (JINR)

# Flerov Laboratory of Nuclear Reactions (FLNR)

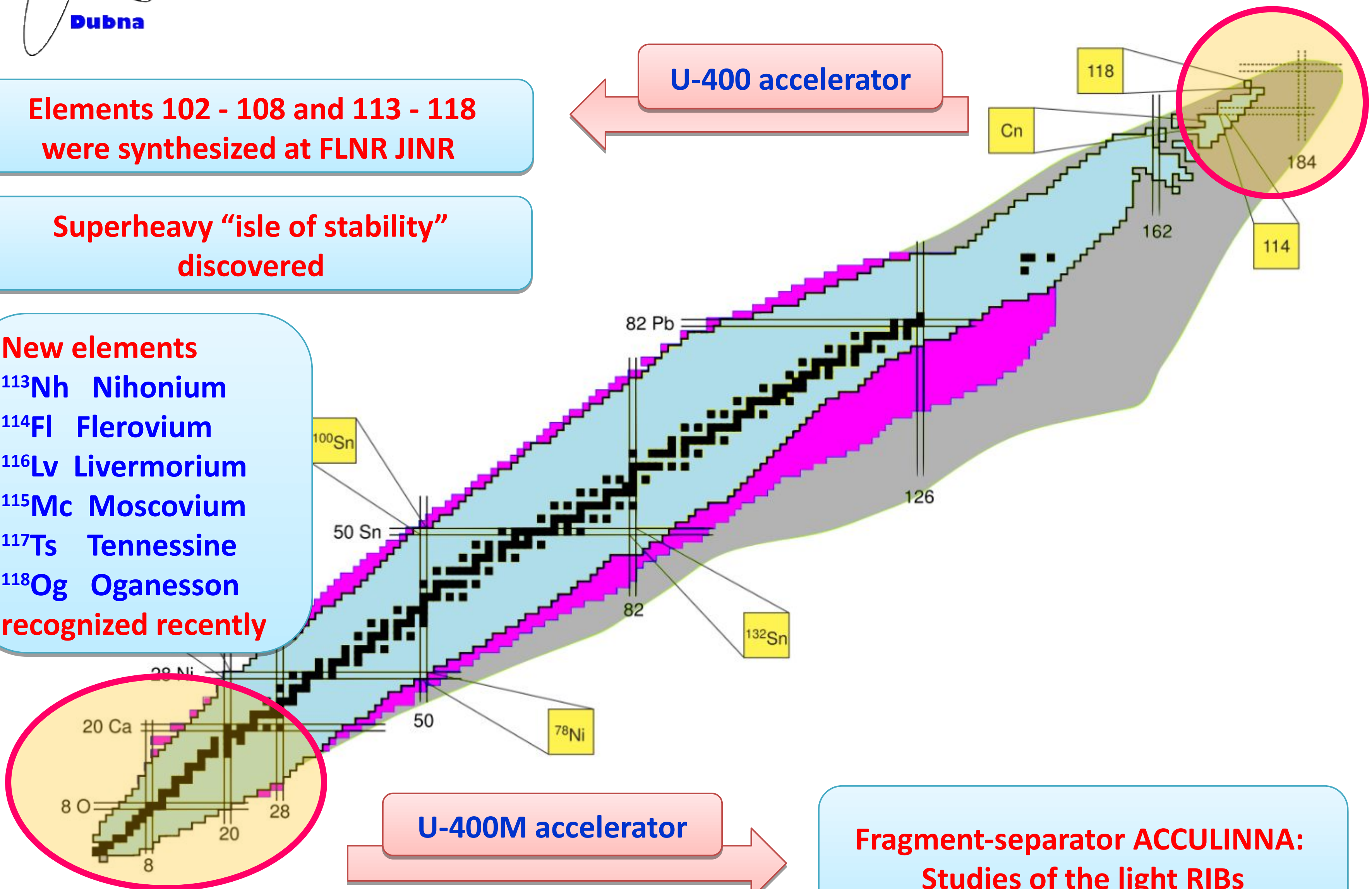
# FLNR history

Elements 102 - 108 and 113 - 118 were synthesized at FLNR JINR

Superheavy "isle of stability" discovered

New elements
$^{113}$Nh Nihonium
$^{114}$Fl Flerovium
$^{116}$Lv Livermorium
$^{115}$Mc Moscovium
$^{117}$Ts Tennessine
$^{118}$Og Oganesson
recognized recently

U-400 accelerator




U-400M accelerator

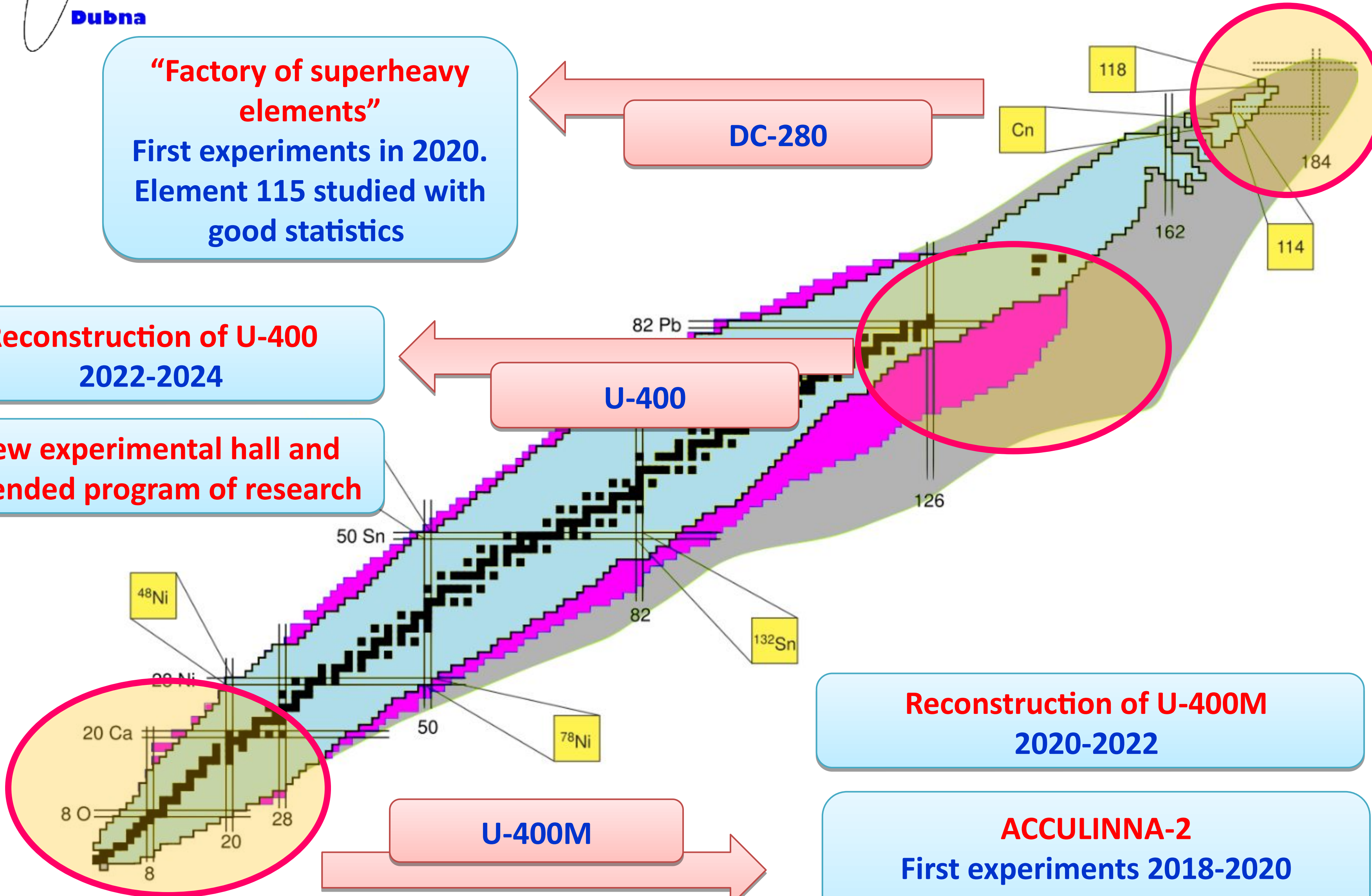
Fragment-separator ACCULINNA: Studies of the light RIBs

# FLNR prospects

“Factory of superheavy elements”
First experiments in 2020.
Element 115 studied with good statistics

Reconstruction of U-400
2022-2024

New experimental hall and extended program of research

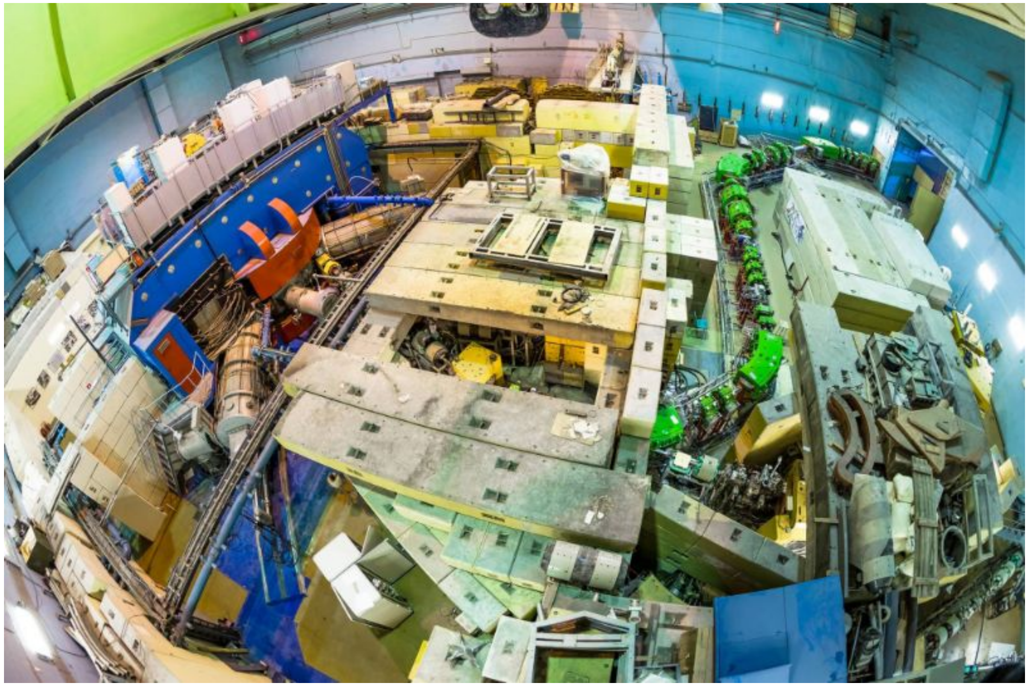



Reconstruction of U-400M
2020-2022

ACCULINNA-2
First experiments 2018-2020
Instrumentation upgrade 2020-2022

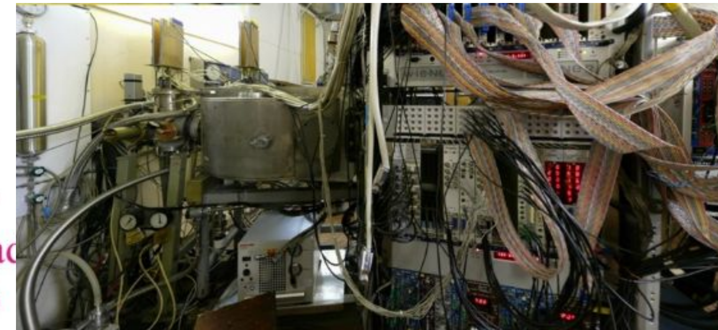
# New facilities at FLNR

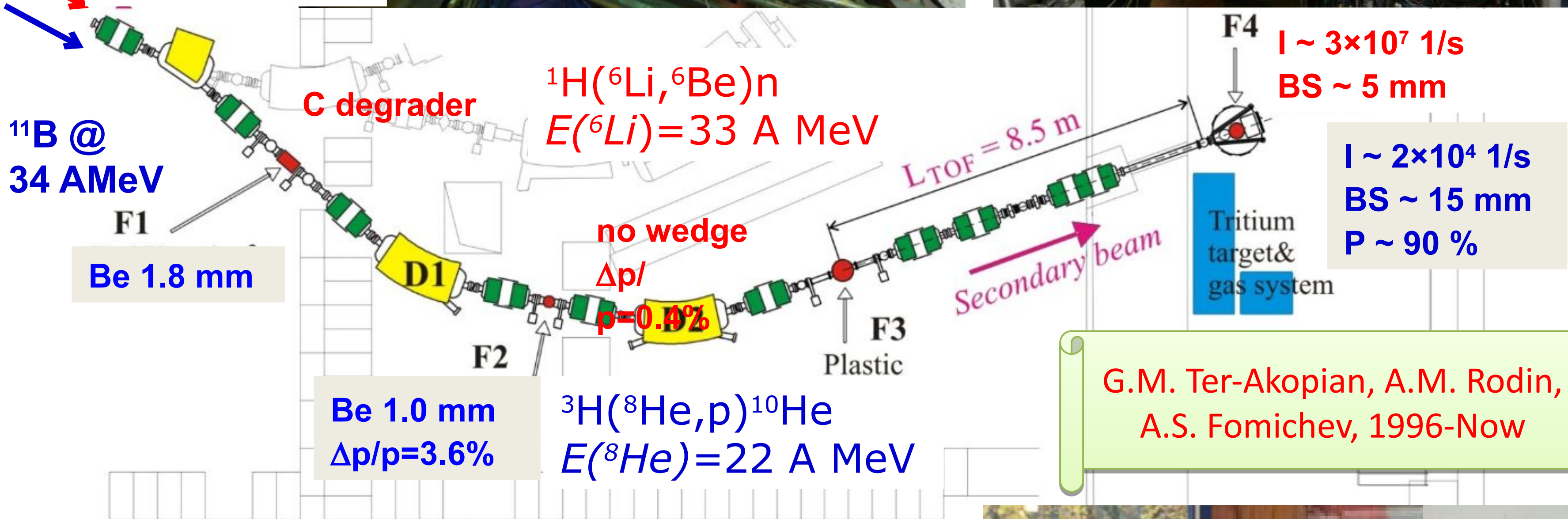
ACCULINNA-2 fragment-separator



# Light RIB studies at FLNR

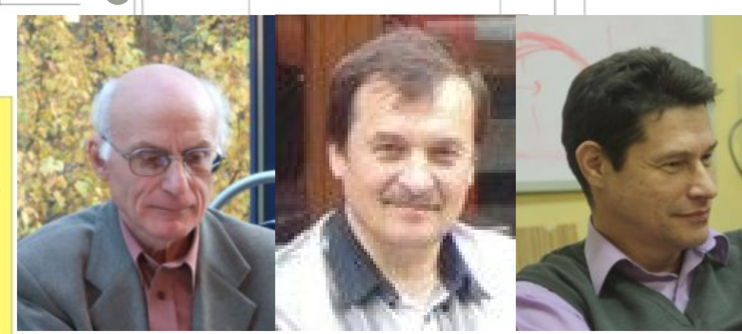
# Flerov Lab: “Superlights” – fragment separator ACCULINNA



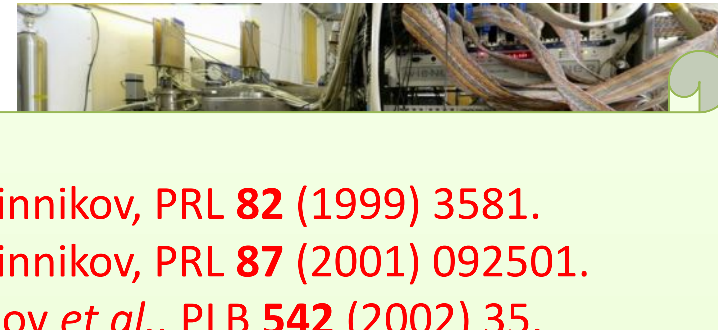



G.M. Ter-Akopian, A.M. Rodin, A.S. Fomichev, 1996-Now

| | F2 | F3 | F4 |
|---|---|---|---|
| H/V magnification | 0.5/2.0 | 1.0/1.0 | 2.25/1.6 |
| Mom. dispersion, mm/% | 4.0-18.0 | – | – |
| Mom. resolution | 0.003 | | |
| H/V RIB size, mm | | 8/10 | 20/16 |

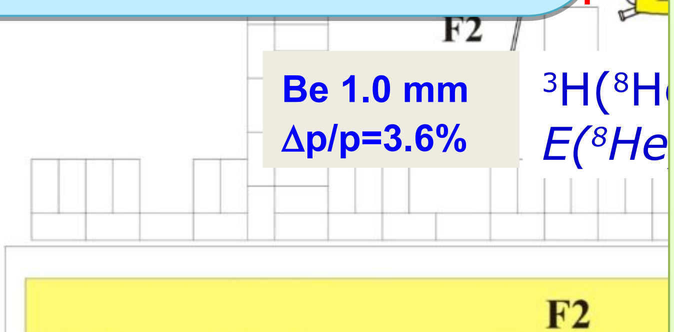


# Flerov Lab: Superlights – fragment separator  ACCULINNA



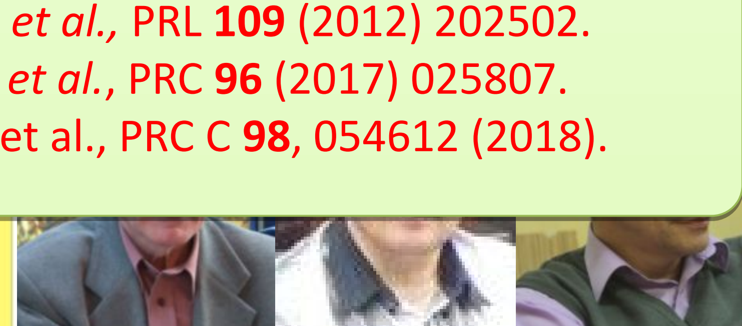
U-400M :

Transfer, charge-exchange and QFS reaction studies of $^{4,5}$H, $^{5,6,8,9,10}$He, $^{9}$Li, $^{6}$Be, $^{26,27}$S, $^{17}$Ne




| | F2 | | |
|---|---|---|---|
| H/V magnification | 0.5/2.0 | | |
| Mom. dispersion, mm/% | 4.0-18.0 | – | – |
| Mom. resolution | 0.003 | | |
| H/V RIB size, mm | | 8/10 | 20/16 |


A.A.Korsheninnikov, PRL **82** (1999) 3581.
A.A.Korsheninnikov, PRL **87** (2001) 092501.
S.V. Stepantsov *et al.*, PLB **542** (2002) 35.
M.S. Golovkov *et al.*, PLB **566** (2003) 70.
G.V. Rogachev *et al.* PRC **67** (2003) 041603(R).
M.S. Golovkov *et al.*, PRL **93** (2004) 262501.
M.S. Golovkov *et al.*, PLB **588** (2004) 163.
M.S. Golovkov *et al.*, PRC **76** (2007) 021605(R).
M.S. Golovkov *et al.*, PLB **672** (2009) 22.
L.V. Grigorenko *et. al.*, PLB **677** (2009) 30.
S.I. Sidorchuk *et al.*, PRL **108** (2012) 202502.
A.S. Fomichev *et al.*, PLB **708** (2012) 6.
I.A. Egorova *et al.*, PRL **109** (2012) 202502.
P. G. Sharov *et al.*, PRC **96** (2017) 025807.
V. Chudoba et al., PRC C **98**, 054612 (2018).

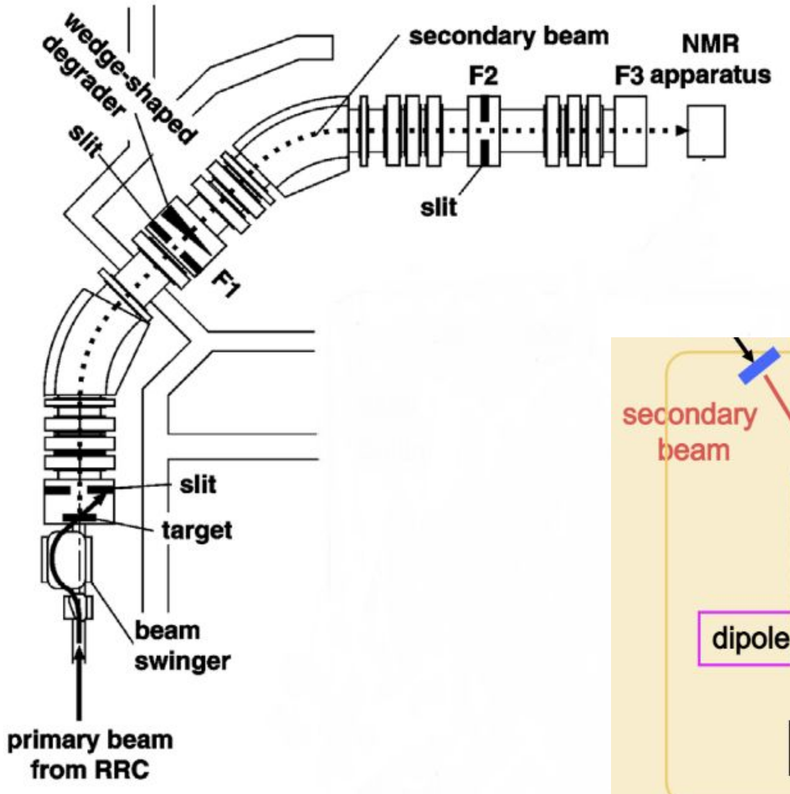



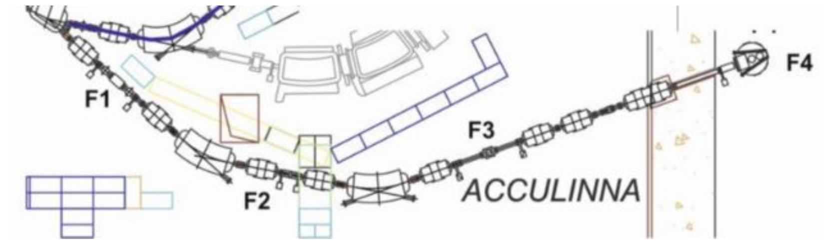
# Predecessors

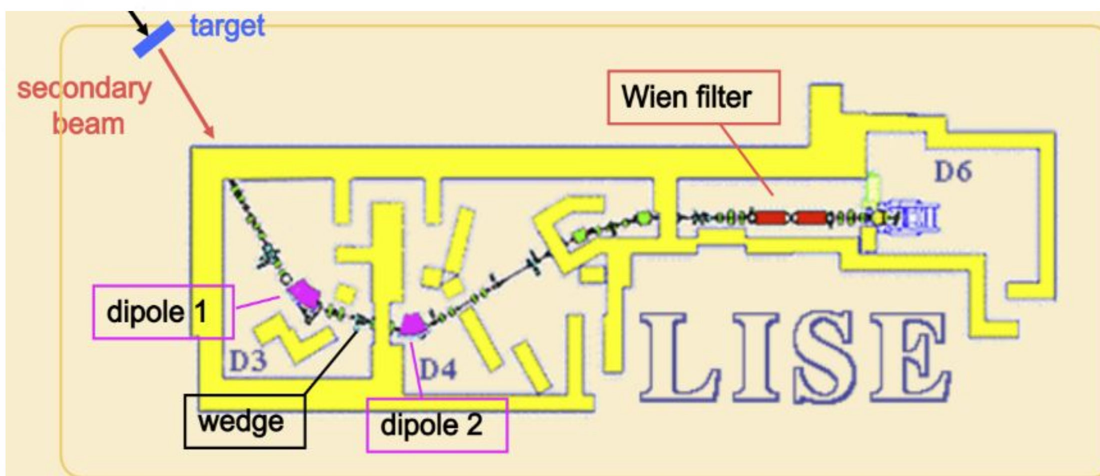
**RIPS (RIKEN)**

**LISE (GANIL)**

**ACCULINNA (Flerov lab)**



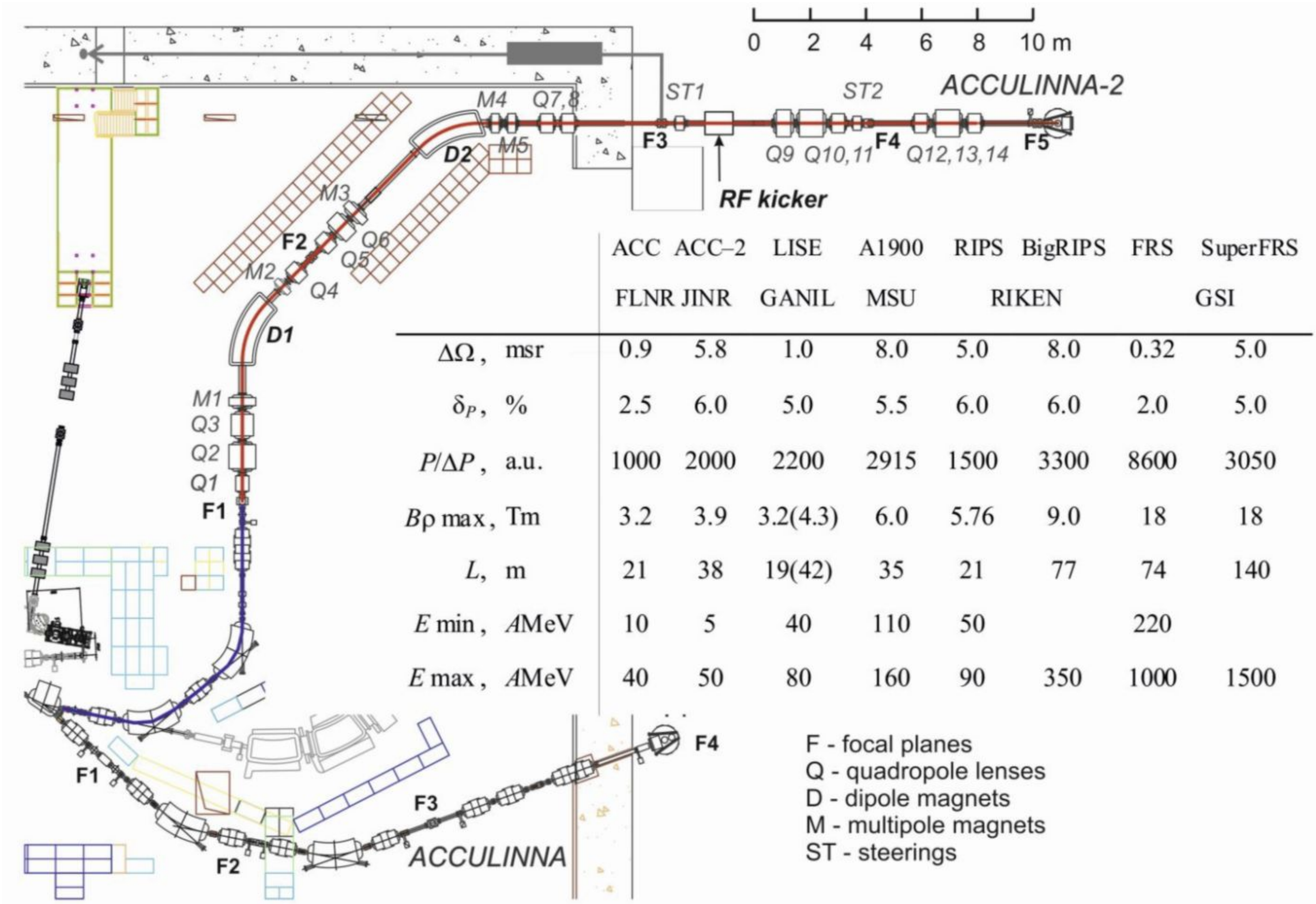




**Single achromatic spectrometers**

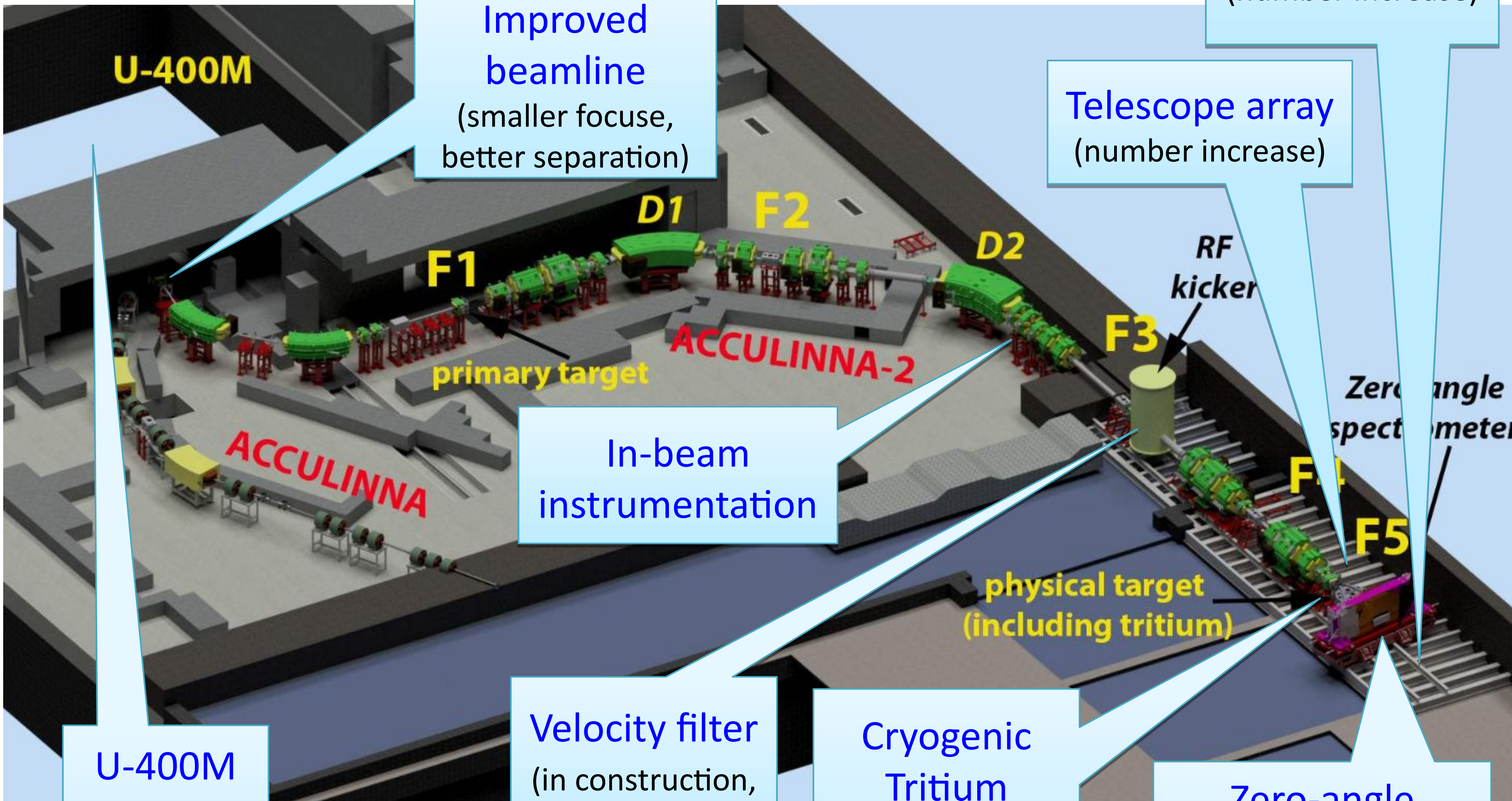
**C-type**

# Acculinna-2 layout




| | ACC | ACC–2 | LISE | A1900 | RIPS | BigRIPS | FRS | SuperFRS |
|---|---|---|---|---|---|---|---|---|
| | FLNR JINR | | GANIL | MSU | RIKEN | | GSI | |
| $\Delta\Omega$, msr | 0.9 | 5.8 | 1.0 | 8.0 | 5.0 | 8.0 | 0.32 | 5.0 |
| $\delta_P$, % | 2.5 | 6.0 | 5.0 | 5.5 | 6.0 | 6.0 | 2.0 | 5.0 |
| $P/\Delta P$, a.u. | 1000 | 2000 | 2200 | 2915 | 1500 | 3300 | 8600 | 3050 |
| $B\rho$ max, Tm | 3.2 | 3.9 | 3.2(4.3) | 6.0 | 5.76 | 9.0 | 18 | 18 |
| $L$, m | 21 | 38 | 19(42) | 35 | 21 | 77 | 74 | 140 |
| $E$ min, $A$MeV | 10 | 5 | 40 | 110 | 50 | | 220 | |
| $E$ max, $A$MeV | 40 | 50 | 80 | 160 | 90 | 350 | 1000 | 1500 |

# 2021-2022: upgrade program




**Neutron array** (number increase)

**Improved beamline** (smaller focuse, better separation)

**Telescope array** (number increase)

**In-beam instrumentation**

**U-400M upgrade** (stability, beams, intencities)

**Velocity filter** (in construction, SigmaPhi)

**Cryogenic Tritium system** (ordered, R&D)

**Zero-angle spectrometer hodoscope** (in development)

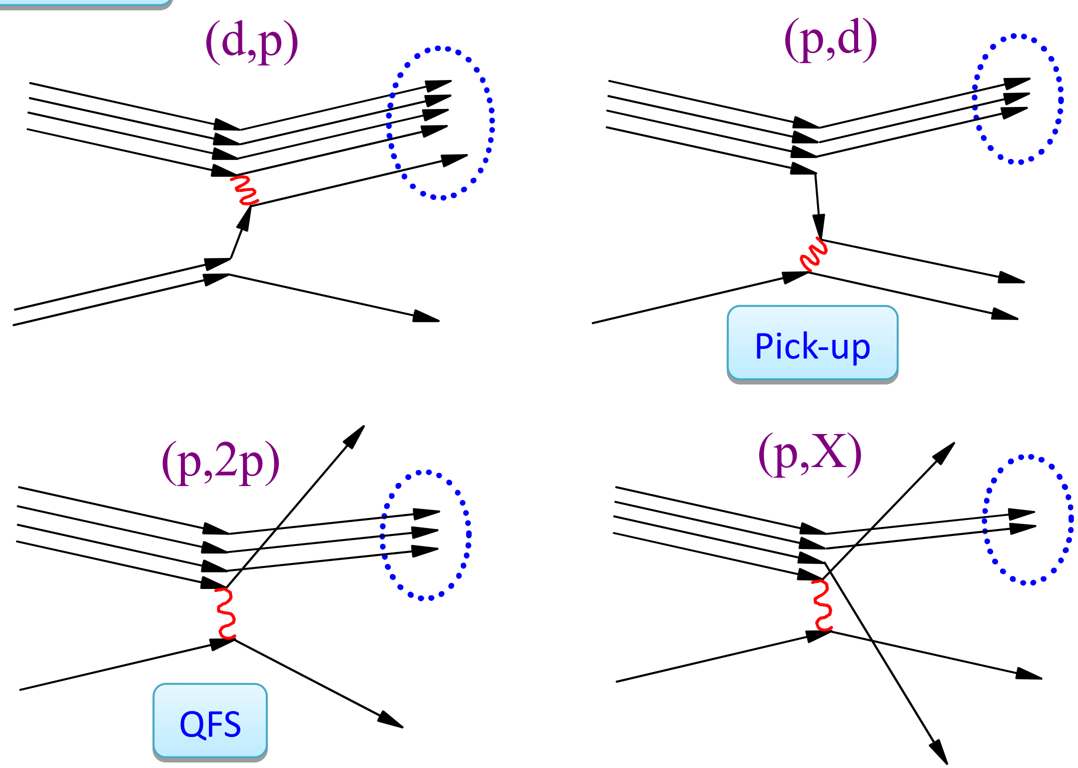
# Direct reactions

# Direct reactions

**Very few degrees of freedom are involved**

**The reaction mechanism is well approximated by a single-pole picture: one vertex, one interaction**

**Transfer**




**Knockout**

**Bunch of robust theoretical approximations:**
- **DWIA**
- **DWBA**
- **FRESCO**
- **CCDC**
- **"Troyan Horse"**
- **ANC**

**Certain model-independent results are available. Example - correlations**

# Competitive light nuclei RIB program at FLNR
# 1. Field of studies

**Intermediate energy reactions (20-70 MeV/nucleon)**

**Transfer reactions**

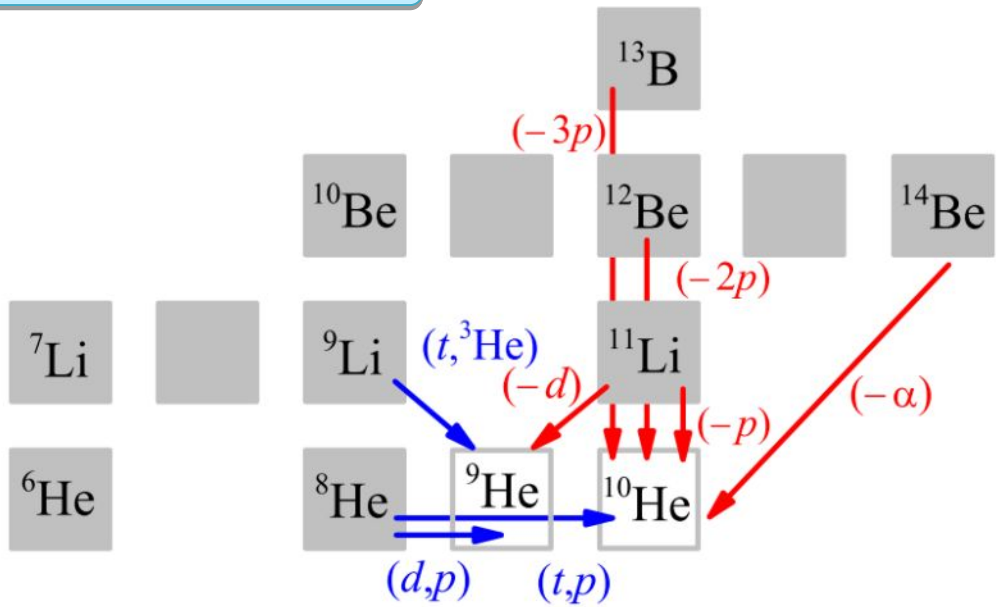
**Missing mass, invariant mass, combination**

**Lower energy – better resolution**

**High energy reactions (>70-100 MeV/nucleon)**

**Knockout reactions**

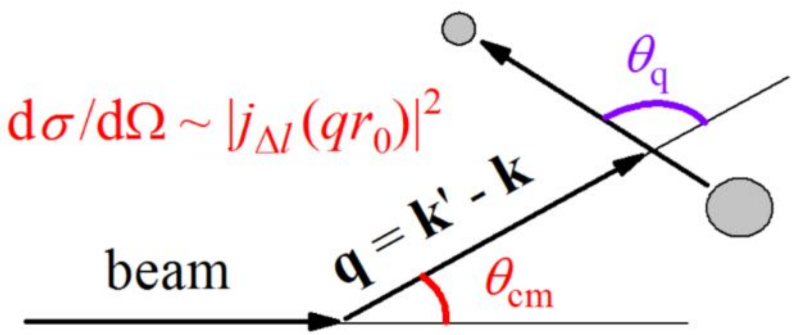
**Only invariant mass (exclusion (p,2p) reactions**




**Importance of complementary reaction studies**

# Competitive light nuclei RIB program at FLNR
# 2. Correlations and few-body dynamics studies

**Correlations for aligned continuum states populated in the direct reactions**

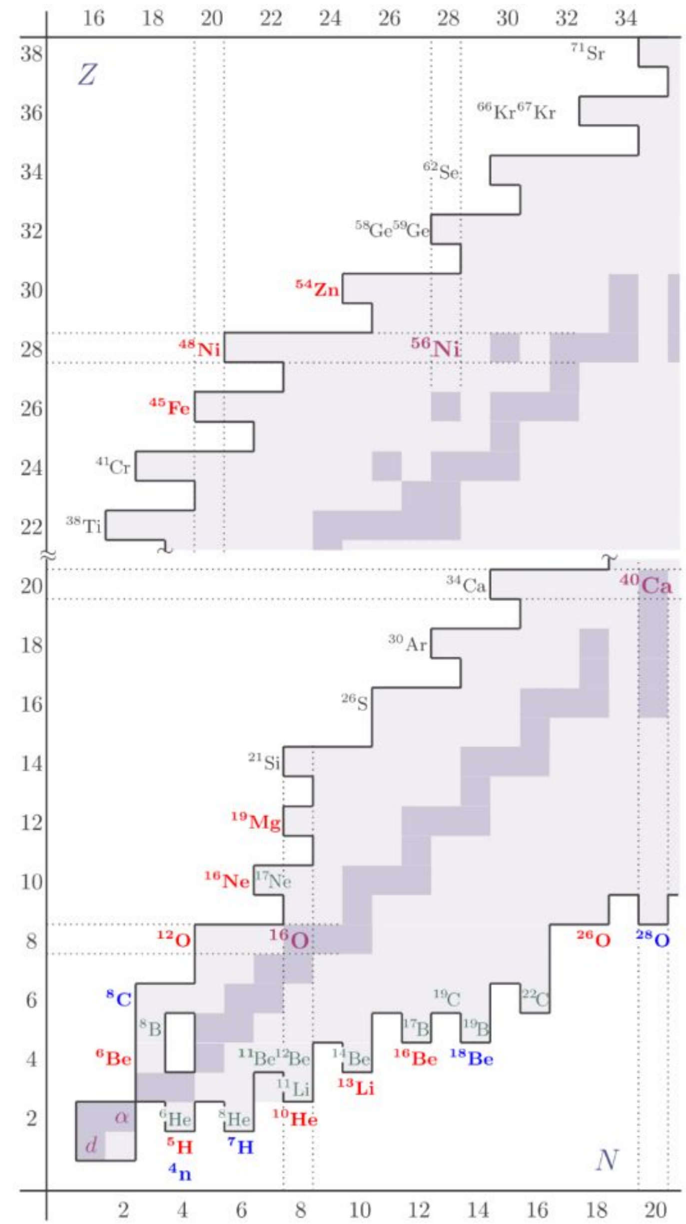



**Few-body dynamics near the driplines, Correlations in the few-body decays: additional degrees of freedom**

**Few-body dynamics at the driplines is consequence of (i) clusterization and (ii) paring**

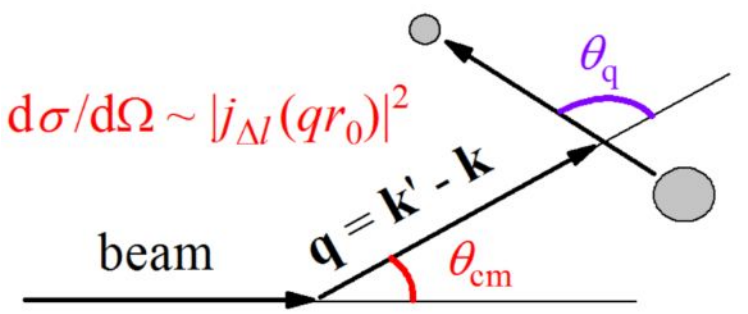
**Exotic phenomena near driplines: Haloes (green) True 2p/2n decays (red) 4p/4n emitters (blue) NOT INVESTIGATED (gray)**

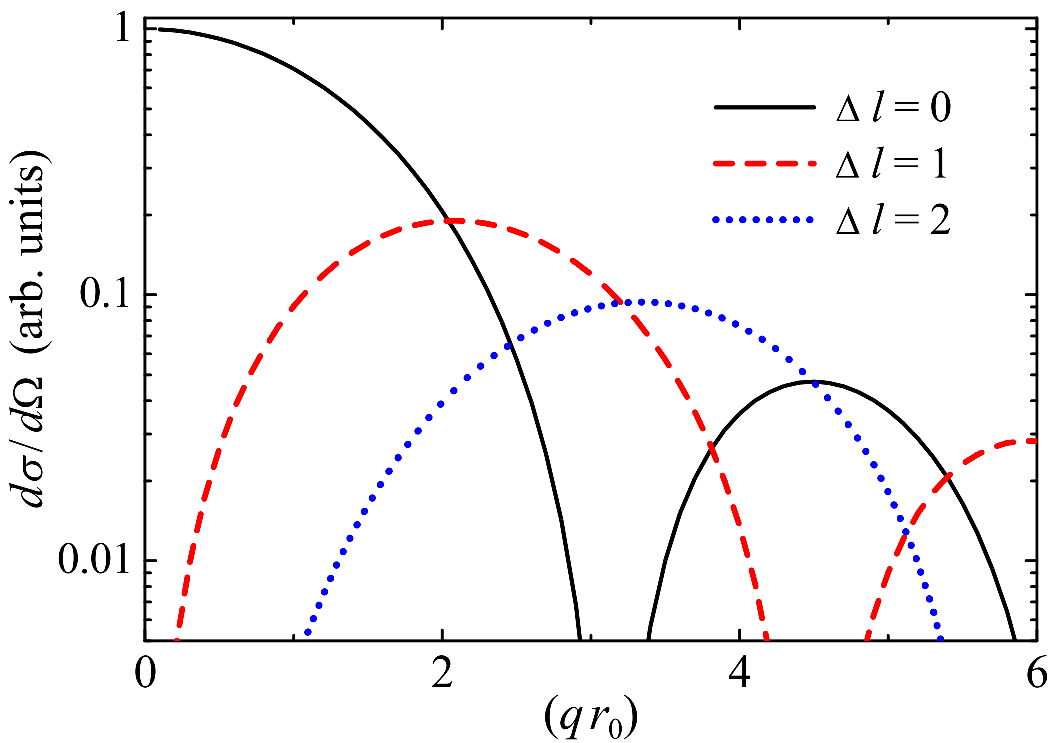
**NOT SO EXOTIC: More or less every second isotope in vicinity of the driplines has features connected to few-body dynamics**



# CM angular distributions for the direct reactions

# CMS correlations of the recoils or products



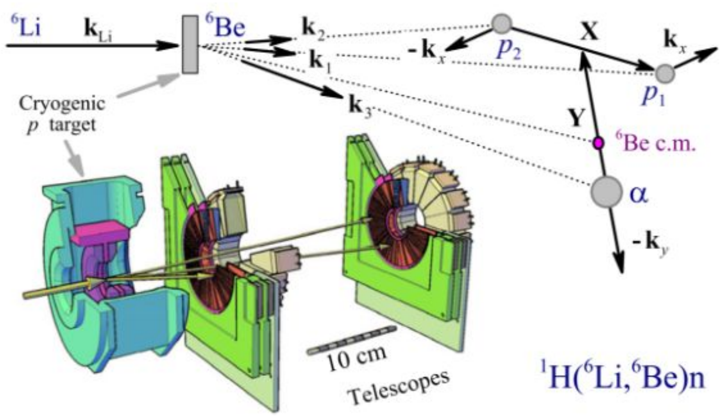

For fixed energy of the product transferred momentum q and cms angle are trivially connected

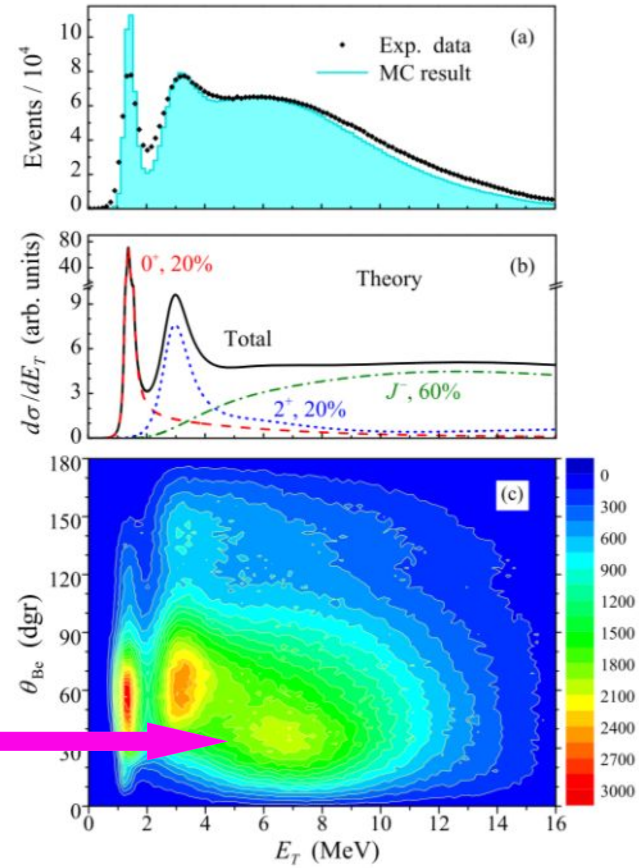
Simple systematics of diffraction minima and maxima as function of the momentum transfer

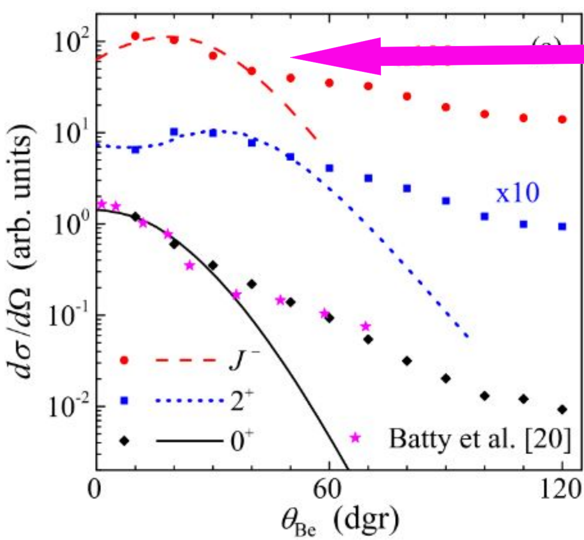
Opportunity of spin-parity identification

# Example: $^6$Be studied in the $^6$Li(p,n)$^6$Be -> α+p+p reaction

A. Fomichev *et al.*, PLB **708** (2012) 6

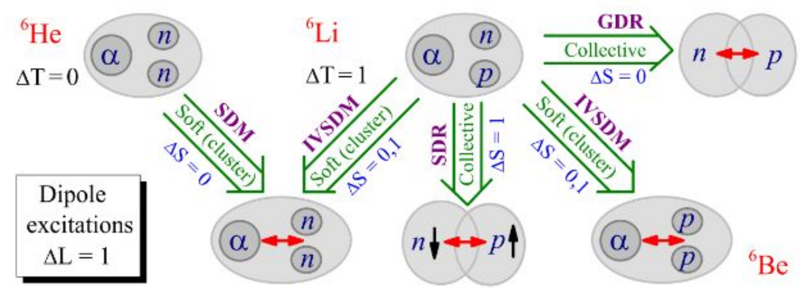


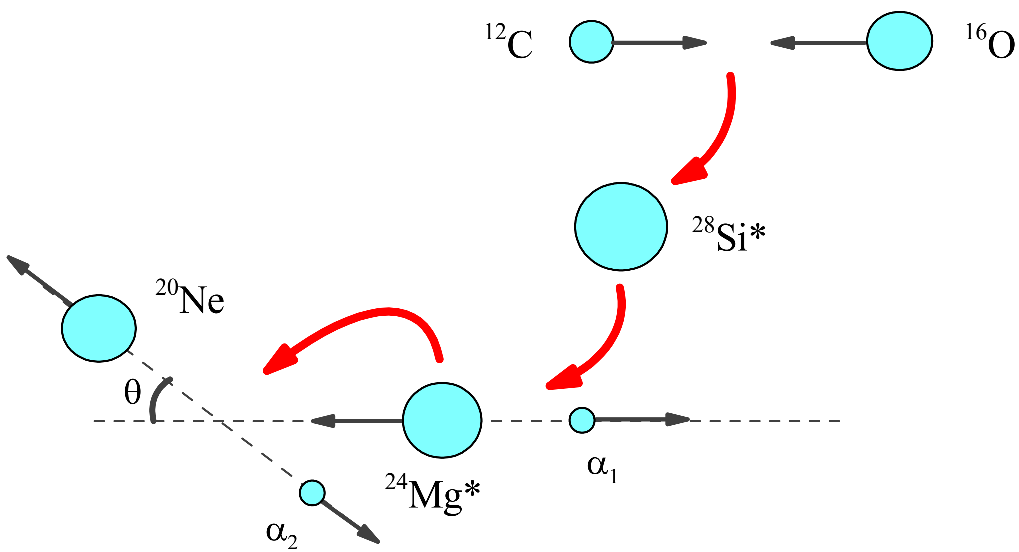

**Δ *l* = 1**

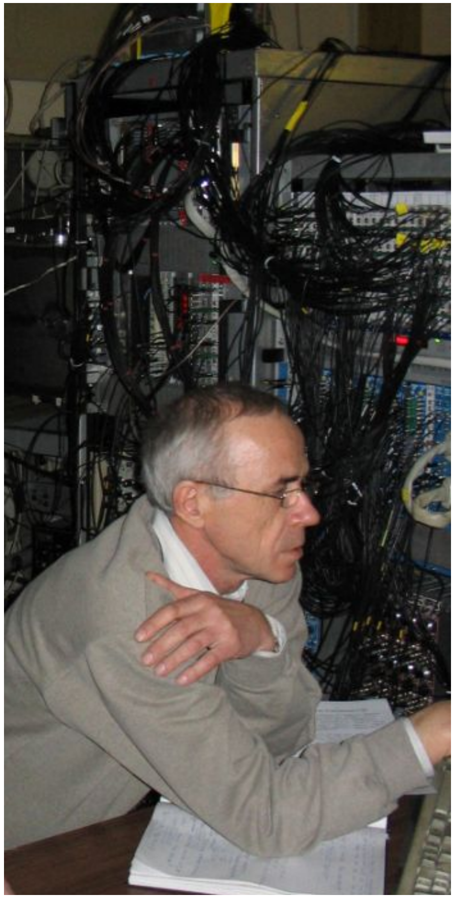
**Isovector Soft Dipole Mode identification**



# Correlations in the momentum transfer frame for direct reactions

# Correlations in the “zero geometry” reactions populating continuum states

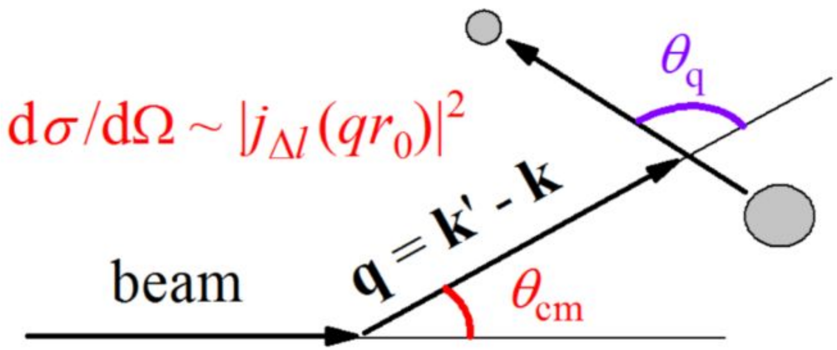


- Correlations in the zero geometry transfer reactions.
- Classics of alpha-cluster state studies
- First alpha-particle is measured at zero angle.
- Then completely aligned intermediate state is populated.
- Then for second alpha-particle the angular distribution is $|P_L^0(\cos\theta)|^2$ where $L$ is angular momentum of intermediate state.

Prof. M. Golovkov pioneered this approach for RIB research

# Correlations in direct reactions populating continuum states




$$\{[\Delta \mathbf{L} \times \mathbf{q}] \equiv 0\,,\; z \parallel \mathbf{q}\} \quad \rightarrow \quad M_{\Delta L} \equiv 0\,.$$

L.V. Grigorenko *et al.*, Physics-Uspekhi 59 (2016) 321
Experimental review, 60-th anyversary of FLNR

**Experimental bias:**
**Acceptance +**
**Resolution +**
**Physical backgrounds**

**MC simulations in density matrix formalism**

**Selected direction in reactions – beam axis**

**There is extra selected direction in direct reactions – momentum transfer**

**There is typically large alignment of the final state in most direct reactions**

**Works well for (i) one-step (single-pole approximation) direct reactions and (ii) small spin transfer**

**If we have continuum state we have alternative way to identify spin-parity**

$$\frac{d\sigma}{dq_{\parallel}\, dq_{\perp}\, dE_{\mathrm{T}}\, d\Omega} \sim \sum_{SM_S} \sum_{JM,J'M'} \rho^{J'M'}_{JM}(q_{\parallel}, q_{\perp}, E_{\mathrm{T}}) \times$$

$$\times\; A^{\dagger}_{J'M'SM_S}(E_{\mathrm{T}}, \Omega)\, A_{JMSM_S}(E_{\mathrm{T}}, \Omega)\,.$$

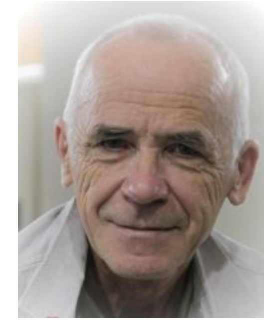
$$\Omega \rightarrow \Omega_2 = \{\theta, \phi\}\,,$$

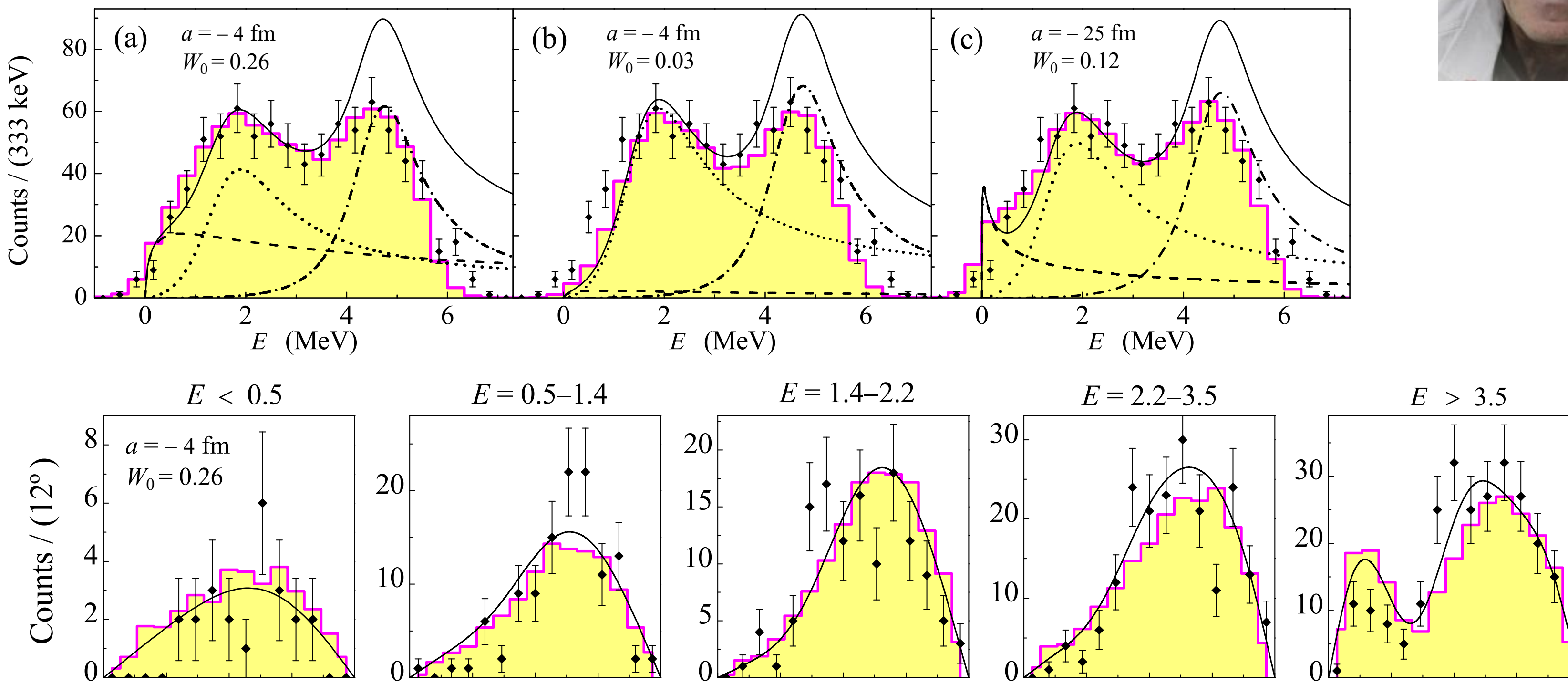
$$\Omega \rightarrow \Omega_5 = \{\varepsilon, \Omega_{kx}, \Omega_{ky}\} = \{\varepsilon, \theta_k, \alpha, \beta, \gamma\}\,.$$

# Example: of $^{9}$H studied in $^{2}$H($^{8}$He,p)$^{9}$H -> $^{8}$He+n reaction:

## From correlations to spin-parity identification

M.S. Golovkov et al. PRC **76** (2007) 021605(R)






- Due to M = ± 1/2 population the interference leading to backward-forward asymmetry is possible only for { $s_{1/2}$ - $p_{1/2}$ , $p_{1/2}$ - $d_{5/2}$ , $p_{3/2}$ - $d_{3/2}$ } interference patterns
- Low energy distributions $s_{1/2}$ - $p_{1/2}$ interference → $p_{1/2}$
- Distribution $E > 3.5$ MeV: higher polinomial → d-wave. Asymmetry → $d_{5/2}$
- Set of states is uniquely identified as {$s_{1/2}$ $p_{1/2}$ $d_{5/2}$}

Recent $^{7}He \rightarrow {}^{6}He + n$ experiment at ACCULINNA-2, (d,p) reaction, see report of P. Sharov

Prospects of analogous studies in the other neutron and proton emitters

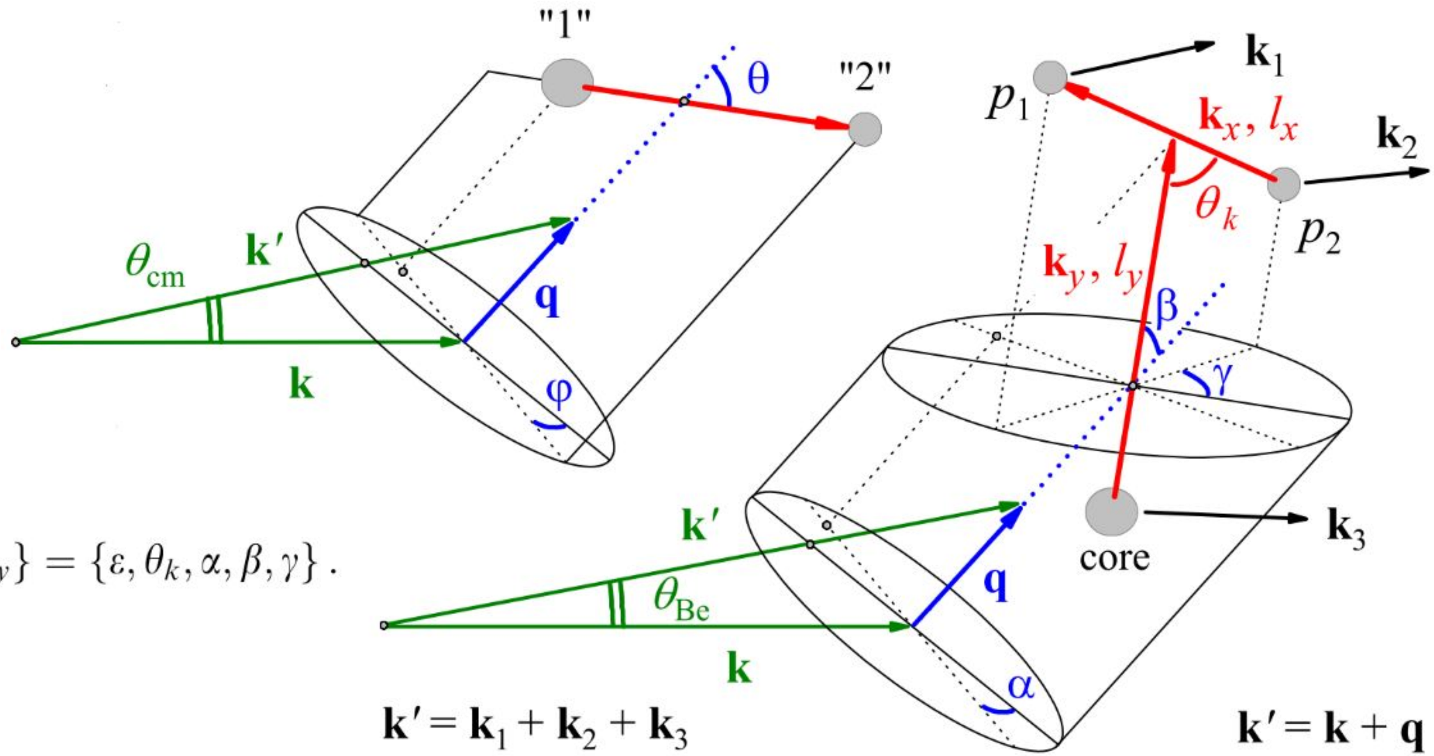
# Correlations in the direct reactions populating continuum

**2-body decays: are defined by 2 parameters - energy and width**

**3-body decays: 2-dimensional "internal" 3-body correlations: $\{k_x/k_y,\ \theta_k\}$**

**2-body reactions: additional "external" correlation angle $\theta$**

**3-body reactions: additional 3-dimensional "external" correlations described by Euler $\{\alpha, \beta, \gamma\}$**




$$\Omega \rightarrow \Omega_2 = \{\theta, \phi\}\,,$$

$$\Omega \rightarrow \Omega_5 = \{\varepsilon, \Omega_{kx}, \Omega_{ky}\} = \{\varepsilon, \theta_k, \alpha, \beta, \gamma\}\,.$$

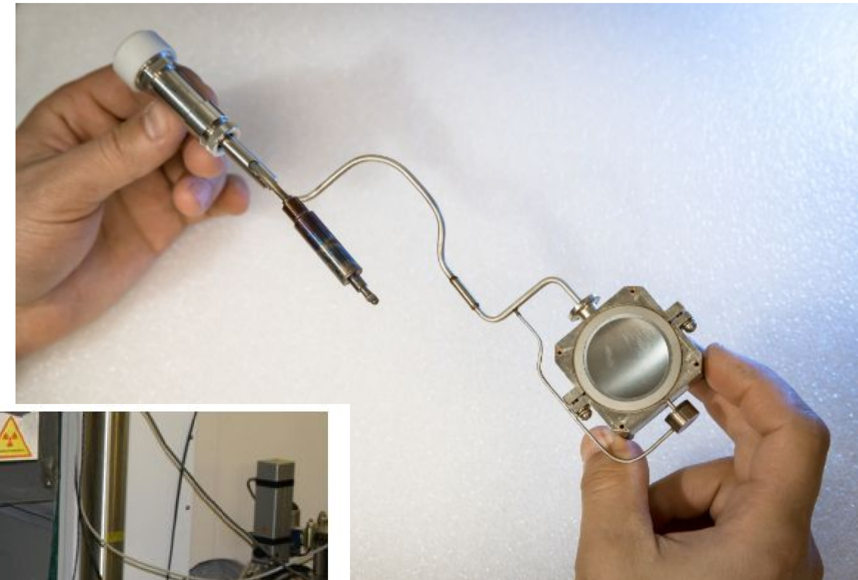
# Three-body correlations in the momentum transfer frame for direct reactions:

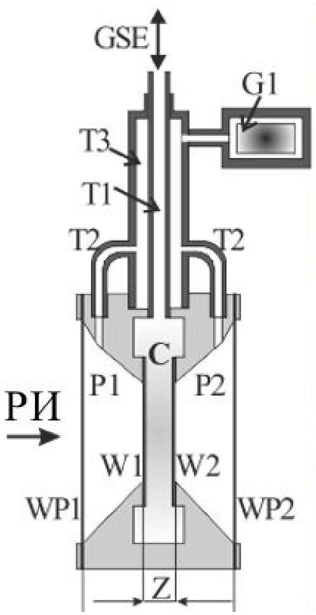
# «External correlations»

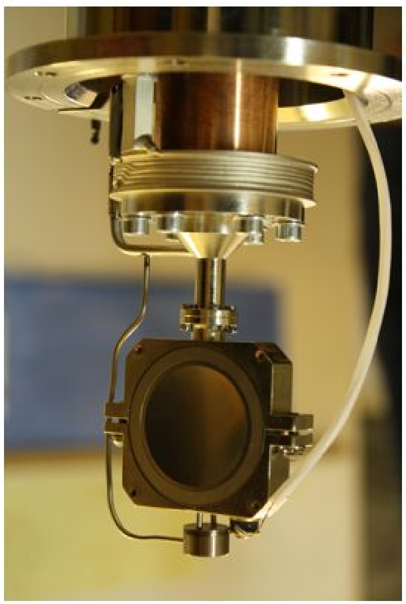
# Cryogenic tritium gas system at ACCULINNA

Two units move to the neutron-rich region in (t,p) reaction

Background free experiments, easy variation of target thickness





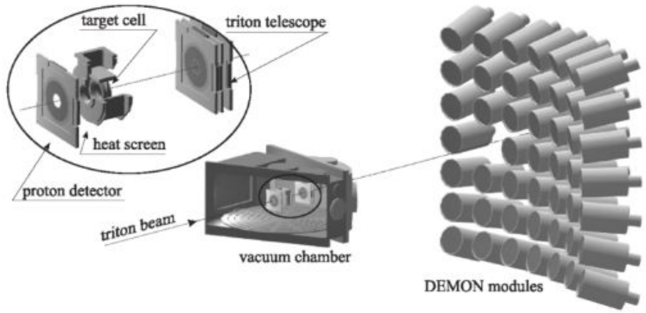



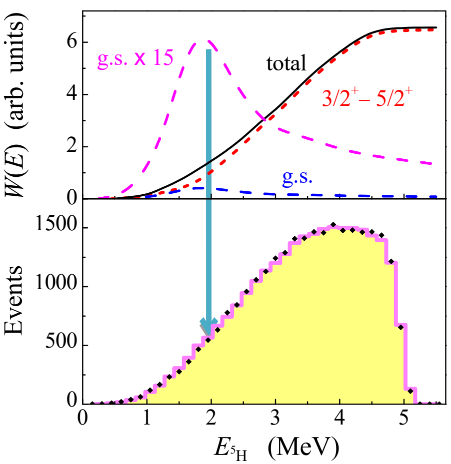
Available only in military laboratories

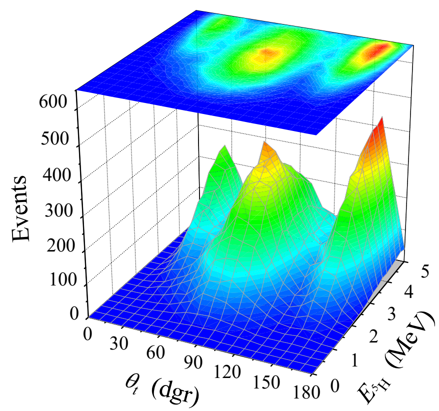
Nice example of military technology conversion for fundamental science conversion

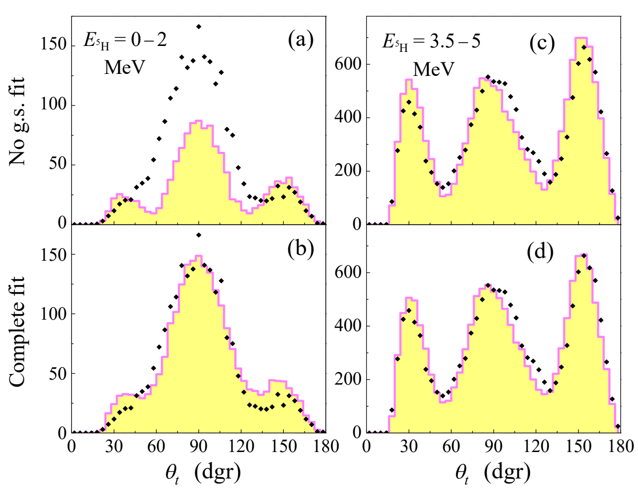
Truly unique item providing important scientific opportunities

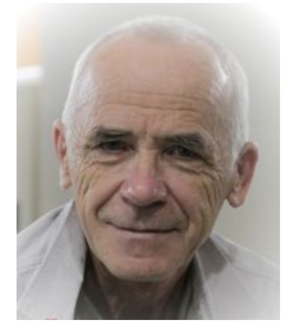
# Example: $^5$H studied in the $^3$H(t,p)$^5$H -> t+n+n reaction



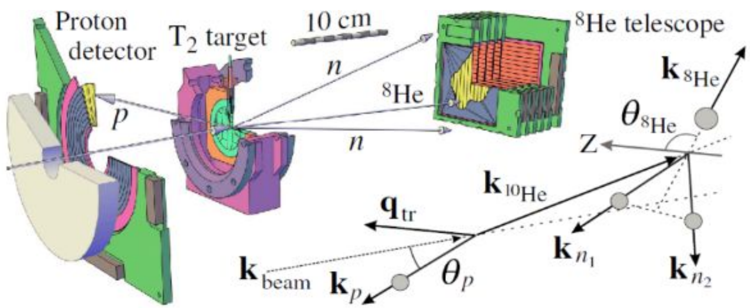
A.A. Korsheninnikov, 2001, $^6$He(p,2p)$^5$H
Discovery of $^5$H at FLNR

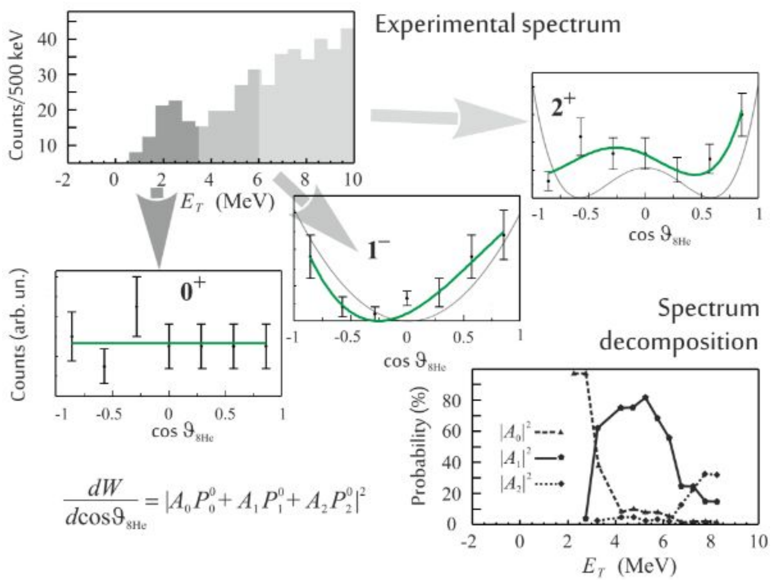
M.S. Golovkov, 2004,
Pioneering correlation studies

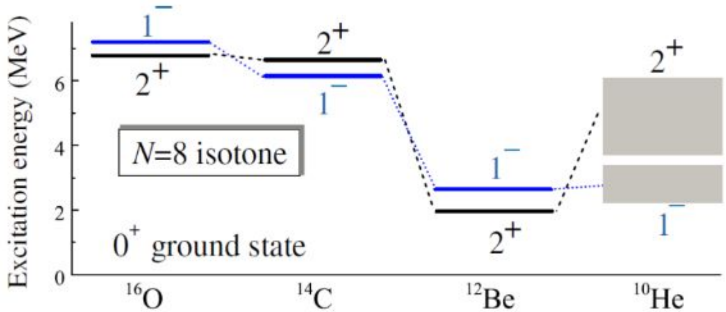
A.A. Korsheninnikov et al., PRL **87** (2001) 92501.
M.S.Golovkov et al., PLB **566** (2003) 70.
M.S.Golovkov et al., PRL **93** (2004) 262501.
S.V. Stepantsov et al., NPA **738** (2004) 436.
M.S.Golovkov et al., PRC **72** (2005) 064612.

- Poor population of ground state. However, correlations provide enough selectivity: quantum amplification
- $^5$H ground state position is finally established; the excited state is established as $3/2^+$-$5/2^+$ degenerate mixture

# Example: $^{10}$He studied in the $^{8}$He(t,p)$^{10}$He -> $^{8}$He+n+n reaction

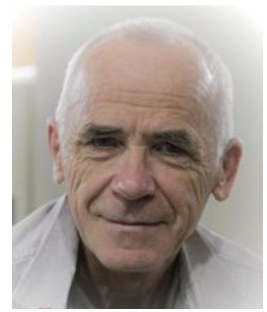



**"Conundrum nucleis" second double magic in nuclide chart**

**Discovered by Korsheninnikov et al. in 1994 in RIKEN giving $E_T$=1.2 MeV**



M.S. Golovkov *et al.*, PLB **672** (2009) 22
S.I. Sidorchuk *et al.*, PRL **108** (2012) 202502

- Three-body correlations were studied in $^{5}$H basing on outstanding statistics. Can be something useful done with really exotic systems and limited statistics?

**New ground state energy for $^{10}$He: $E_T$=2.0-2.5 MeV**

**Shell structure breakdown in $^{10}$He**

New cryogenic tritium gas system under construction; commissioning in the end of 2022 expected

Prospects of analogous studies for $^{10}He$, $^{13}Li$, $^{16}Be$

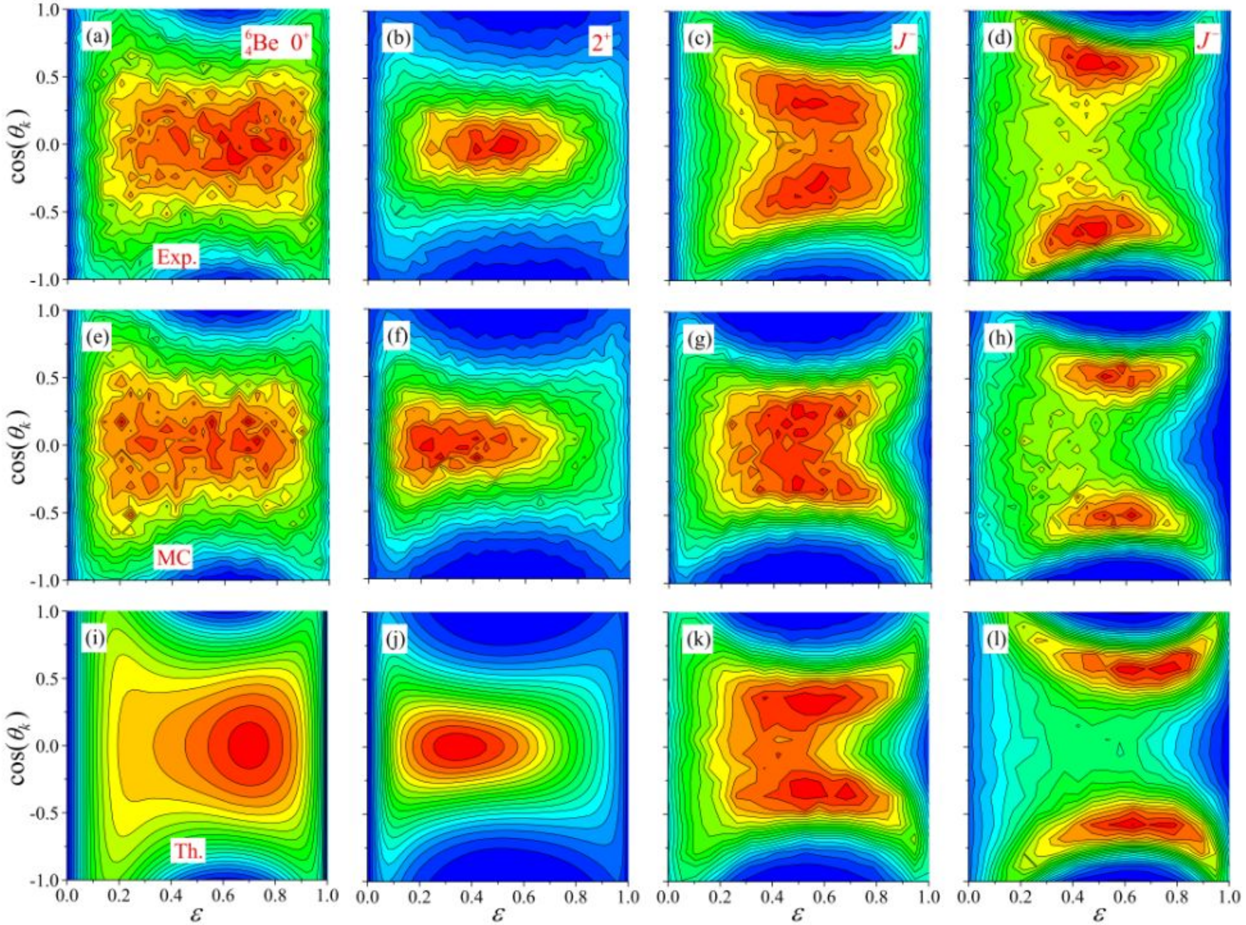
# Three-body correlations in the direct reactions:

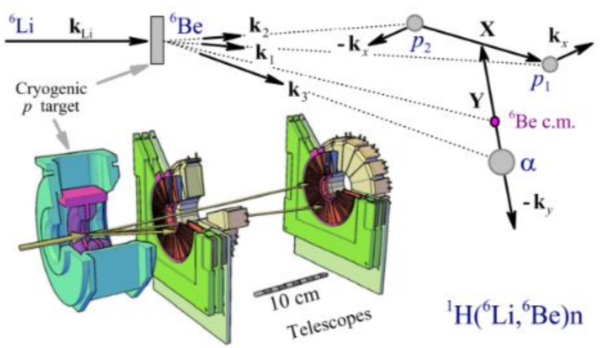
# “External” vs “Internal” correlations

# Example: $^6$Be studied in the $^6$Li(p,n)$^6$Be -> α+p+p reaction

A. Fomichev *et al.*, PLB **708** (2012) 6

**Isovector Soft Dipole Mode identification**




**For positive parity states perfect agreement with theoretical predictions**

**The three-body correlations for soft dipole excitations observed for the first time**

**Δ $l$ = 0 → 0$^+$**

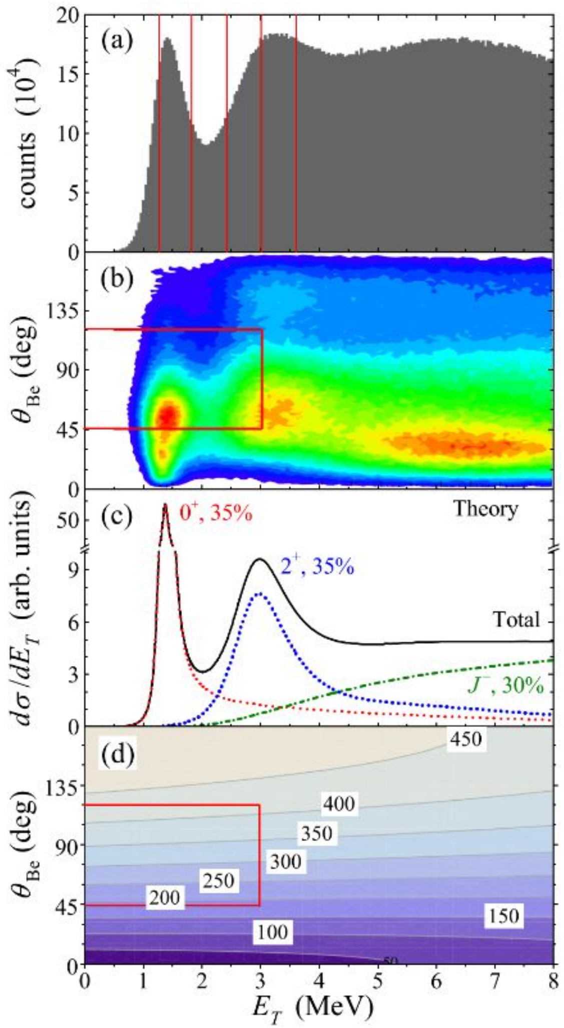
**Δ $l$ = 2 → 2$^+$**

**Δ $l$ = 1 → $J^-$**

# Example: $^6$Be studied in the $^6$Li(p,n)$^6$Be -> $\alpha$+p+p

V. Chudoba *et al.*, PRC C **98**, 054612 (2018)

**From known level scheme to complete quantum mechanical information (density matrix parameters as function of energy and cm angle)**



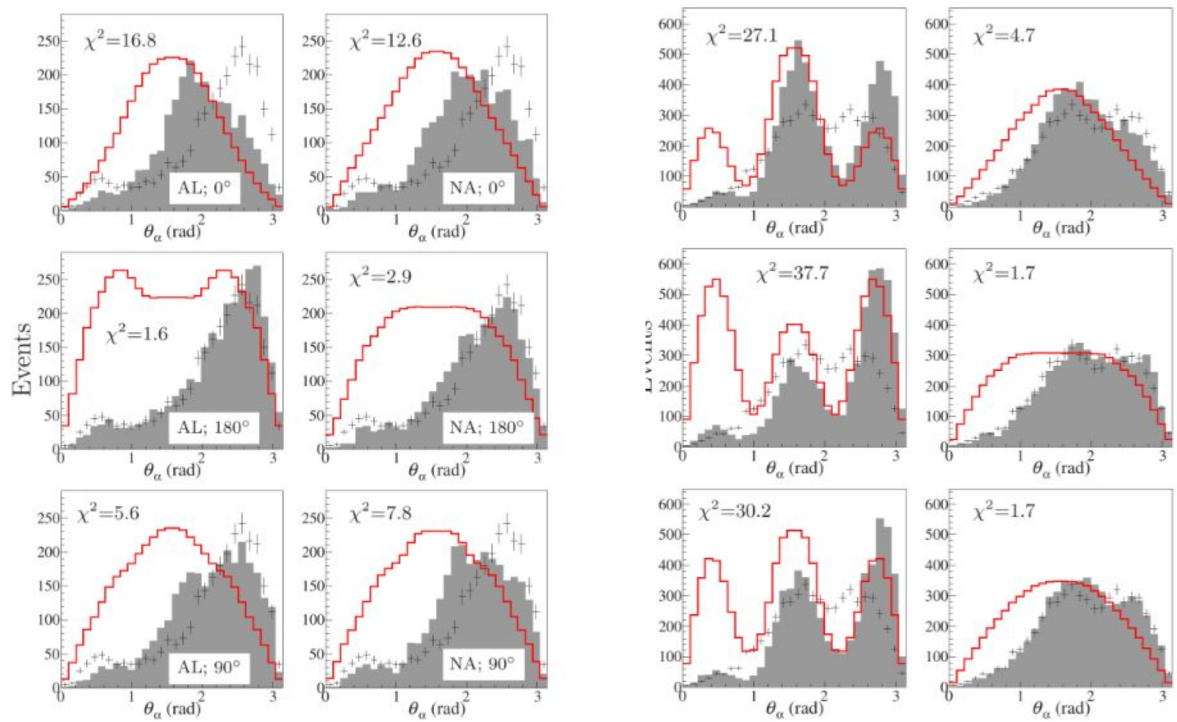




TABLE I. The best fit to experimental data of density matrix parameters for different $\{E_T, \theta_{\text{Be}}\}$ ranges. The fits were found using the figures with $\theta_\alpha$ distribution for all six configurations of the theoretical model.

| $E_T$ (MeV) | $\theta_{\text{Be}}\in(45,60)^\circ$ | $\theta_{\text{Be}}\in(60,75)^\circ$ | $\theta_{\text{Be}}\in(75,90)^\circ$ | $\theta_{\text{Be}}\in(90,120)^\circ$ |
|---|---|---|---|---|
| 1.4–1.9 | AL; $\varphi_{02}=135^\circ$ | AL + 50% NA; $\varphi_{02}=180^\circ$ | AL; $\varphi_{02}=180^\circ$ | AL + 20% NA; $\varphi_{02}=180^\circ$ |
| 1.9–2.5 | AL + 50% NA; $\varphi_{02}=135^\circ$ | NA + 10% AL; $\varphi_{02}=180^\circ$ | NA; $\varphi_{02}=180^\circ$ | AL + 10% NA; $\varphi_{02}=90^\circ$ |
| 2.5–3.1 | NA + 10% AL; $\varphi_{02}=180^\circ$ | AL + 10% NA; $\varphi_{02}=180^\circ$ | NA + 30% AL; $\varphi_{02}=90^\circ$ | NA; $\varphi_{02}=135^\circ$ |

3He target available with new cryogenic gas system under construction

Transfer and charge exchange reaction campaign exploring the isobaric symmetry aspect on $^{3}He$ vs $^{3}H$ target

Prospective $^{7}Be \rightarrow {}^{7}B \rightarrow {}^{4}He+3n$ experiment at ACCULINNA-2, ($^{3}He$,$^{3}H$) reaction, see report of V. Chudoba

# Extreme exotic systems at ACCULINNA-2:

## $^{7}H$ and $^{6}H$

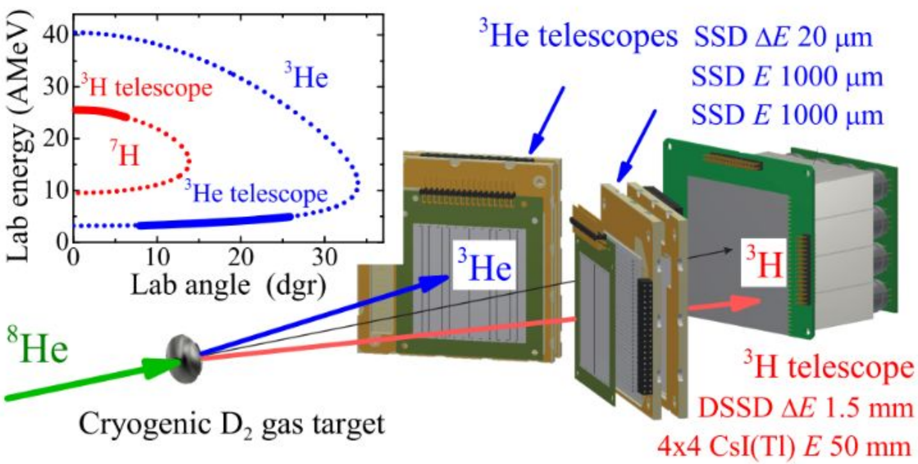
## Is the problem of $^{7}H$ and $^{6}H$ solved?

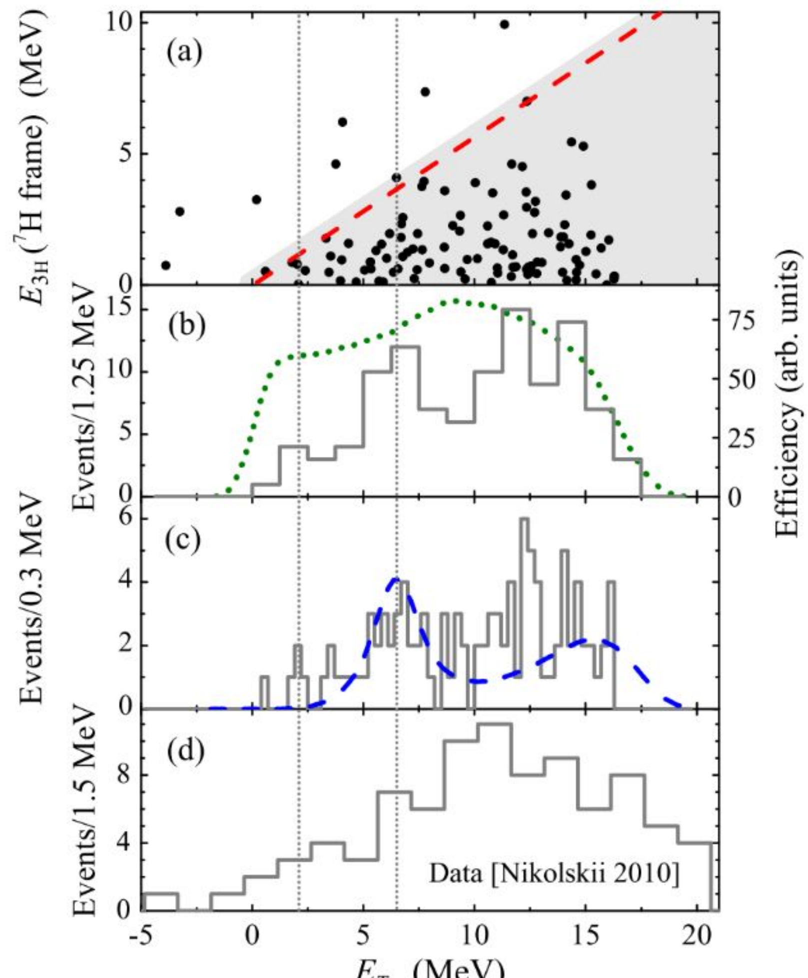
# $^{2}H(^{8}He, ^{3}He)^{7}H$ reaction

PHYSICAL REVIEW LETTERS **124**, 022502 (2020)

**Evidence for the First Excited State of $^{7}H$**

A. A. Bezbakh,[1,2] V. Chudoba,[1,2,*] S. A. Krupko,[1,3] S. G. Belogurov,[1,4] D. Biare,[1] A. S. Fomichev,[1,5] E. M. Gazeeva,[1] A. V. Gorshkov,[1] L. V. Grigorenko,[1,4,6] G. Kaminski,[1,7] O. A. Kiselev,[8] D. A. Kostyleva,[8,9] M. Yu. Kozlov,[10] B. Mauyey,[1,11] I. Mukha,[8] I. A. Muzalevskii,[1,2] E. Yu. Nikolskii,[6,1] Yu. L. Parfenova,[1] W. Piatek,[1,7] A. M. Quynh,[1,12] V. N. Schetinin,[10] A. Serikov,[1] S. I. Sidorchuk,[1] P. G. Sharov,[1,2] R. S. Slepnev,[1] S. V. Stepantsov,[1] A. Swiercz,[1,13] P. Szymkiewicz,[1,13] G. M. Ter-Akopian,[1,5] R. Wolski,[1,14] B. Zalewski,[1,7] and M. V. Zhukov[15]




$^{8}$He beam 26 AMeV, $10^{5}$ pps 2018, two weeks

- Excited state at 6.5 MeV
- Indication of ground state at 1.8 MeV
- May be something at 12 MeV

# $^{7}$H studied in the $^{2}$H($^{8}$He, $^{3}$He)$^{7}$H reaction. Second run.



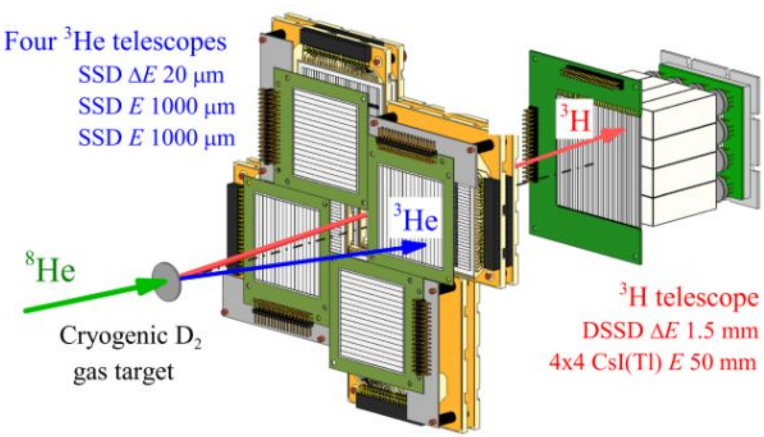
PHYSICAL REVIEW C **103**, 044313 (2021)

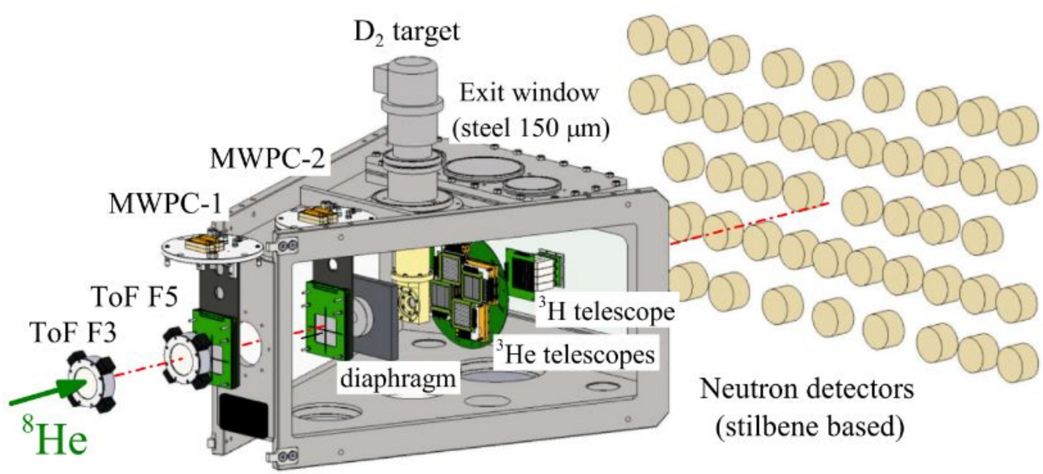
**Resonant states in $^{7}$H: Experimental studies of the $^{2}$H($^{8}$He, $^{3}$He) reaction**

I. A. Muzalevskii,[1,2,*] A. A. Bezbakh,[1,2] E. Yu. Nikolskii,[3,1] V. Chudoba,[1,2] S. A. Krupko,[1] S. G. Belogurov,[1,4] D. Biare,[1] A. S. Fomichev,[1,5] E. M. Gazeeva,[1] A. V. Gorshkov,[1] L. V. Grigorenko,[1,4,3] G. Kaminski,[1,6] O. Kiselev,[7] D. A. Kostyleva,[7,8] M. Yu. Kozlov,[9] B. Mauyey,[1,10] I. Mukha,[7] Yu. L. Parfenova,[1] W. Piatek,[1,6] A. M. Quynh,[1,11] V. N. Schetinin,[9] A. Serikov,[1] S. I. Sidorchuk,[1] P. G. Sharov,[1,2] N. B. Shulgina,[3,12] R. S. Slepnev,[1] S. V. Stepantsov,[1] A. Swiercz,[1,13] P. Szymkiewicz,[1,13] G. M. Ter-Akopian,[1,5] R. Wolski,[1,14] B. Zalewski,[1,6] and M. V. Zhukov[15]

$^{8}$He beam 26 AMeV, $10^{5}$ pps
2019, 3 weeks

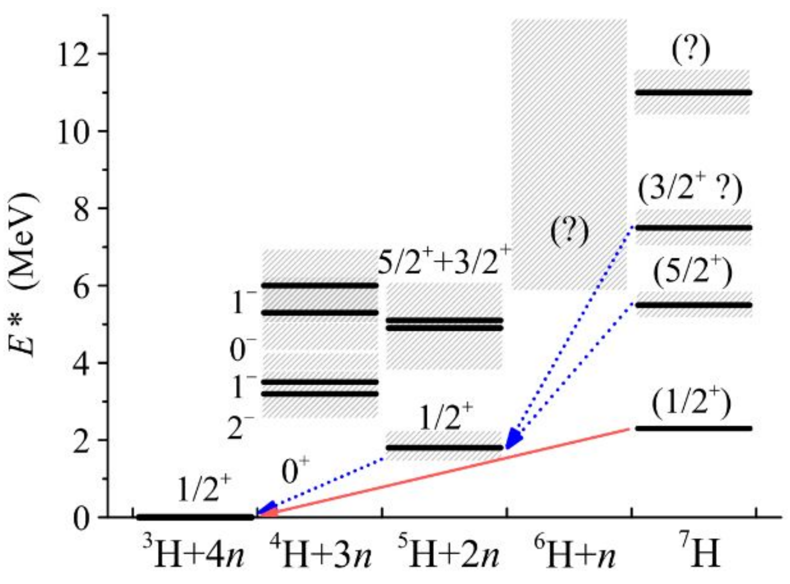
**"Comming out party" for the neutron wall**

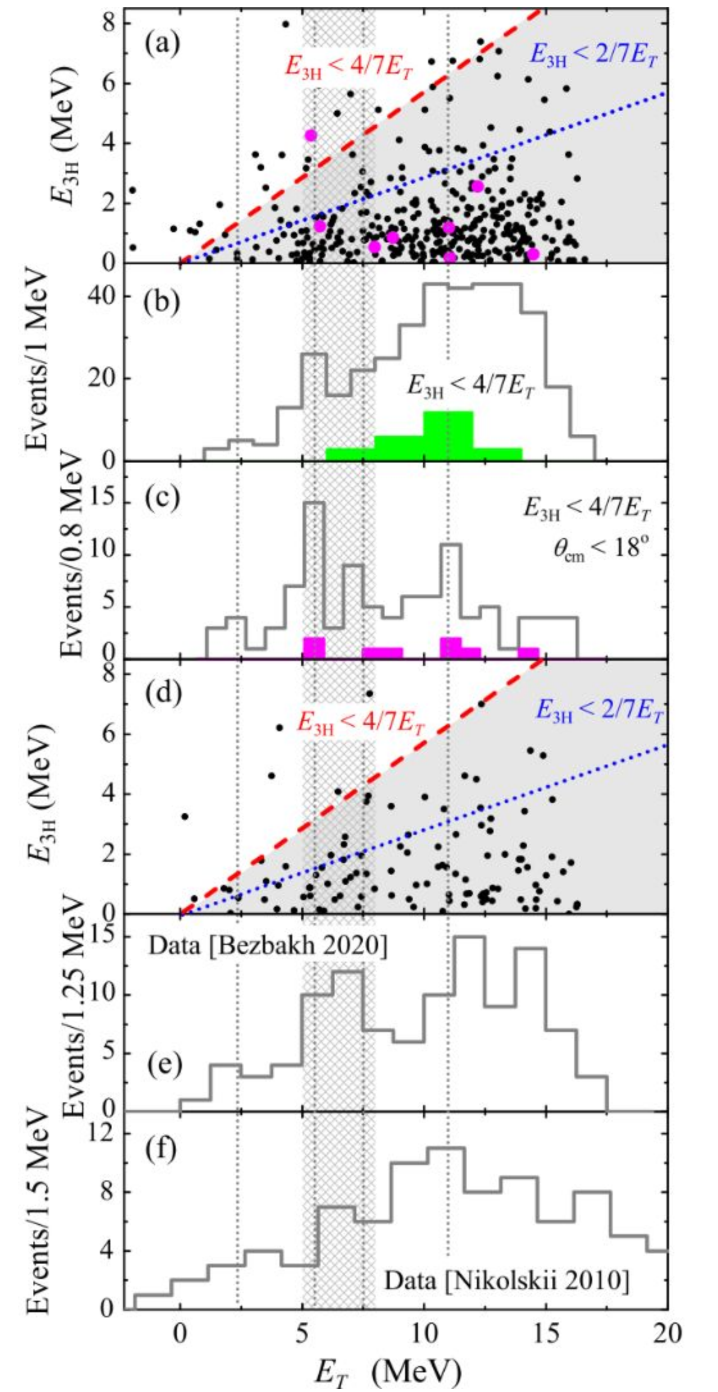


# MM spectra and “kinemtical triangles”

- $^7$H ground state at 2.2 MeV
- $^7$H excited state at 5.5 MeV. Could be 5.5-7.5 MeV doublet
- Some evidence for $^7$H excited state at 11 MeV
- “Triangle” cuts reduce the backgrounds.
- Reaction cm angle cutoff $\theta_{cm}$ < 18 dgr provides especially safe result for the $^7$H g.s.
- Consistent results in 2 independent JINR experiments.
- Consistent with data of [Nikolskii 2010] obtained in the same reaction within resolution and statistics of older data.

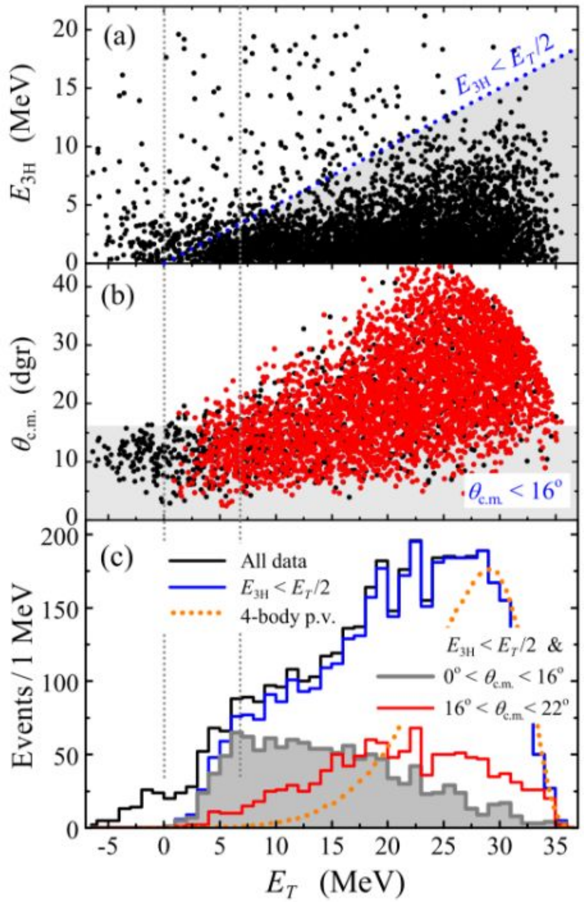


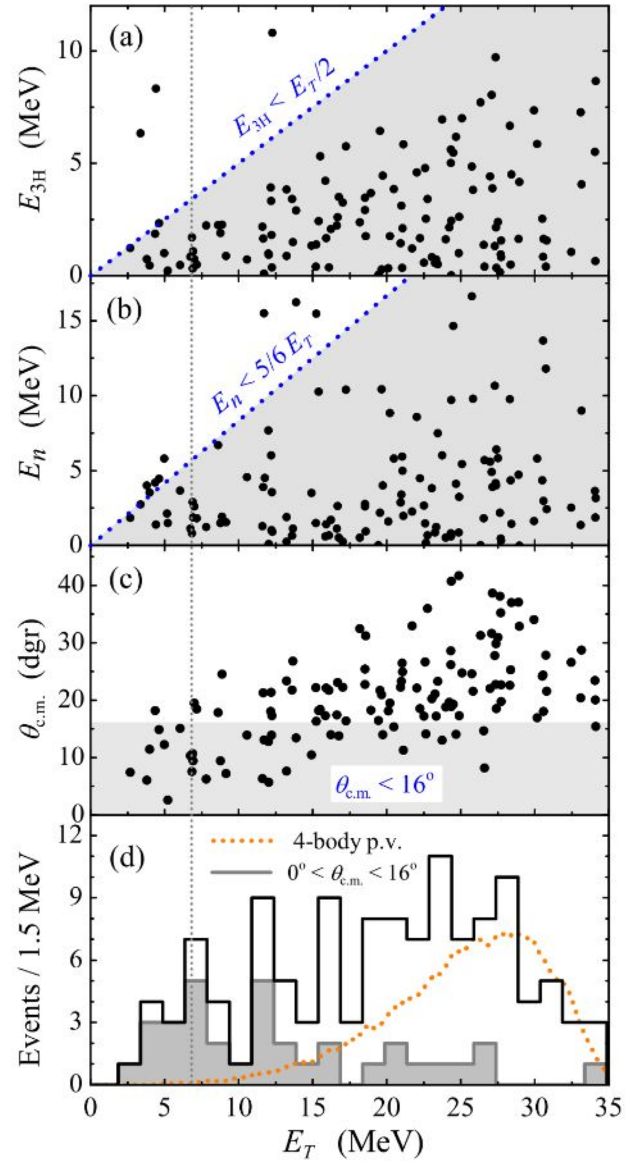
# “Satellite” experimental data on $^6$H from $^2$H($^8$He,$^4$He)$^6$H

Nikolskii *et al.*,
arXiv:2105.04435

Double coincidences $^4$He-$^3$H



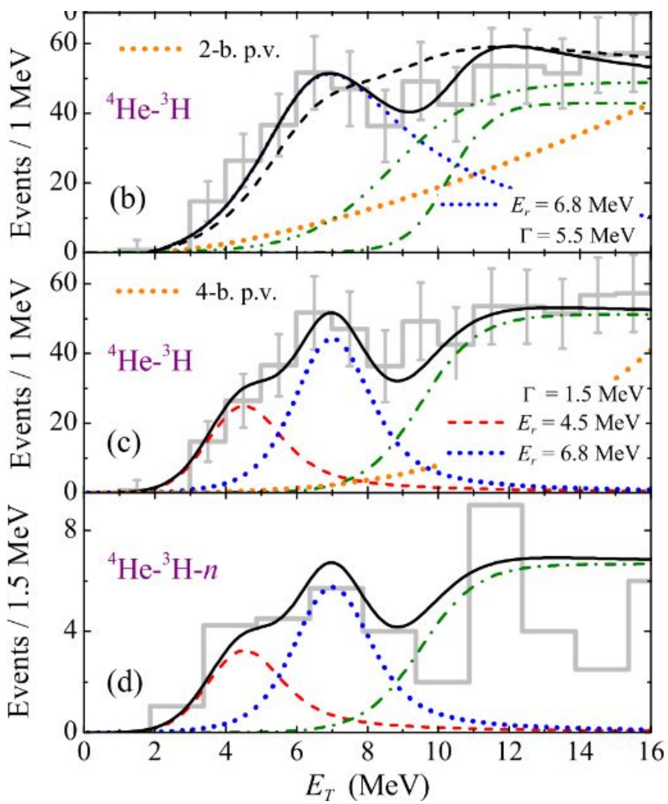

Triple coincidences $^4$He-$^3$H-n




– Setup is not specially suited for this experiment
– Higher cross section and high statistics (factor 10)
– Large backgrounds (accidental alphas)
– Neutron coincidence data

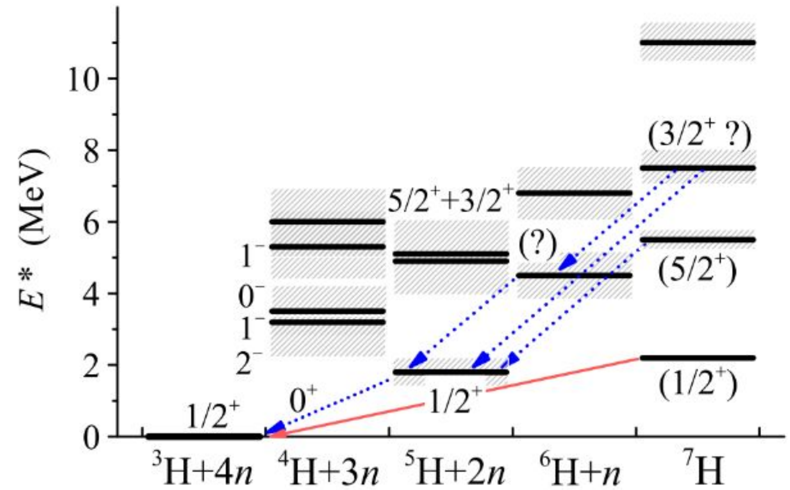
# Preliminary results

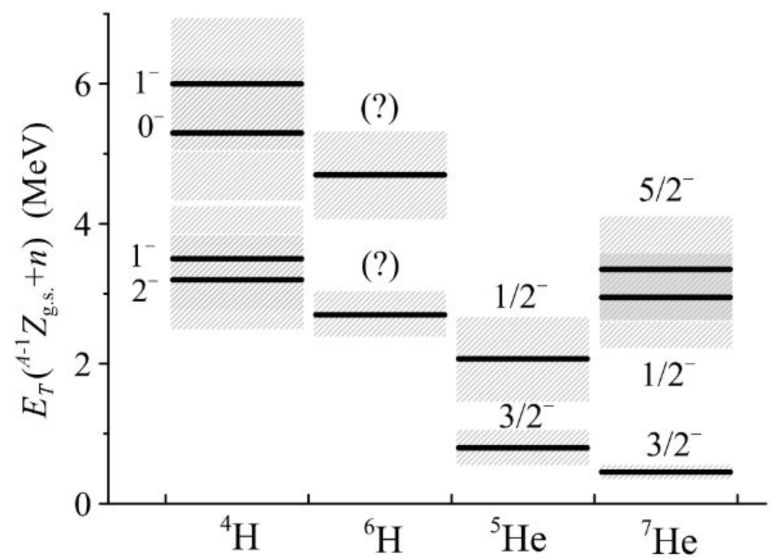
Background-subtracted, efficiency corrected




- No $^6$H g.s. at 2.6-2-7 MeV
- Resonant state at 6.5 MeV
- Possible resonant state at 4.5 MeV

**Excitation spectra relative $^3$H ground state**




**Analogies in the excitation spectra relative $^3$H and $^5$H, $^4$He and $^6$He ground states**

For $^{7}H$ and $^{6}H$ experiment details see report of V. Chudoba

It seem that it is a good idea to repeat $^{7}H$ studies in the (d,3He) reaction with somewhat improved setup and for $^{6}H$ in strongly revised setup

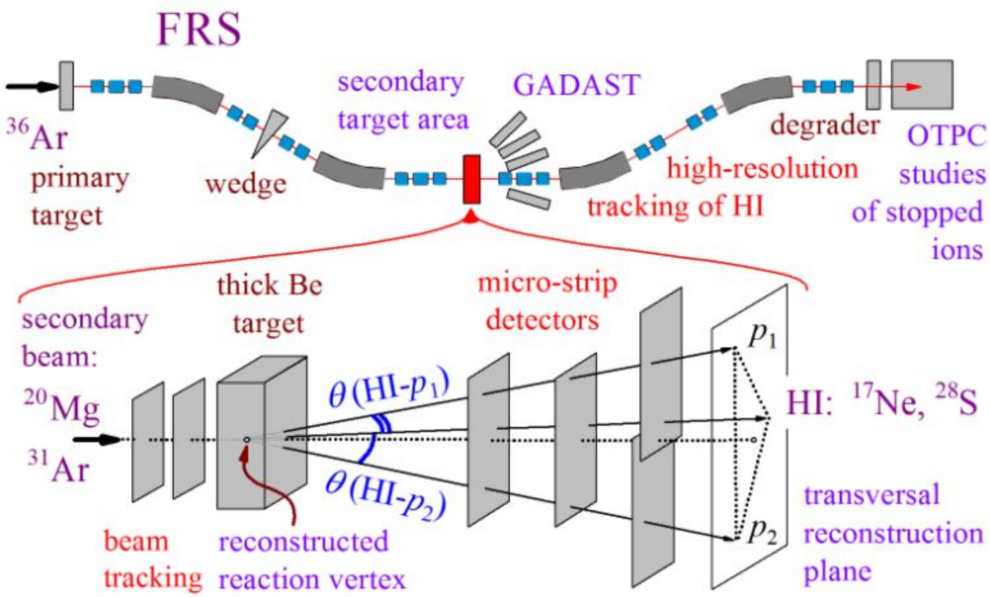
# EXPERT@FRS/SuperFRS

# EXPERT@FRS/SuperFRS

**EXPERT = Exotic Particle Emission and Radioactivity by Tracking**

**Example of specific use for double achromatic FS**

A.S. Fomichev,
Russian coordinator of
NUSTAR program at FAIR




**EXPERT pilot experiments in 2012: studies of systems beyond the proton dripline at FRS**

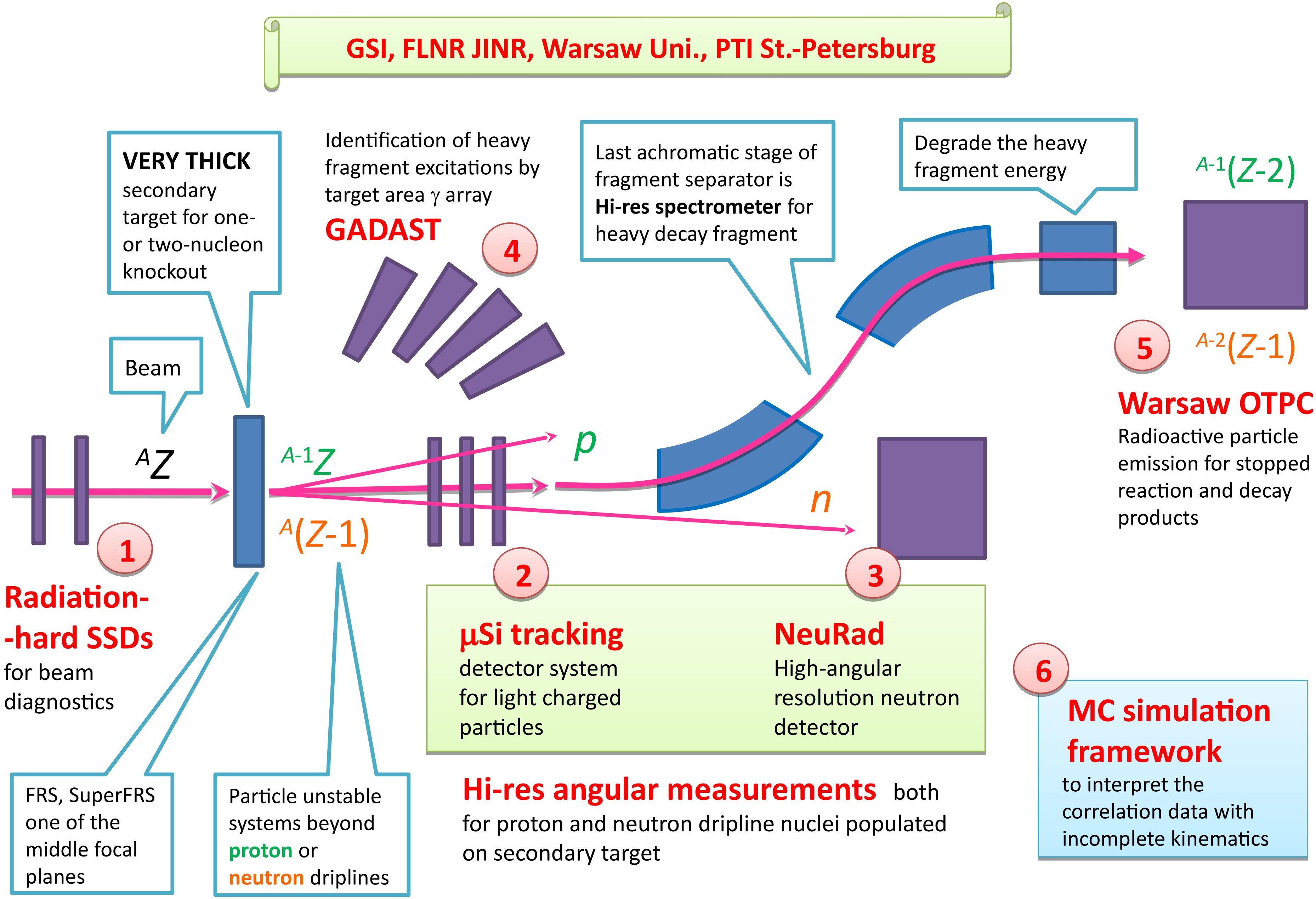
**Instrumentation development: (i) silicon microstrip detectors (µSSD), (ii) GADAST, (iii) NEURAD, (iv) OTPC**

**«Superefficient» experiemnts with superthick targets (up to 50 mm berillium)**

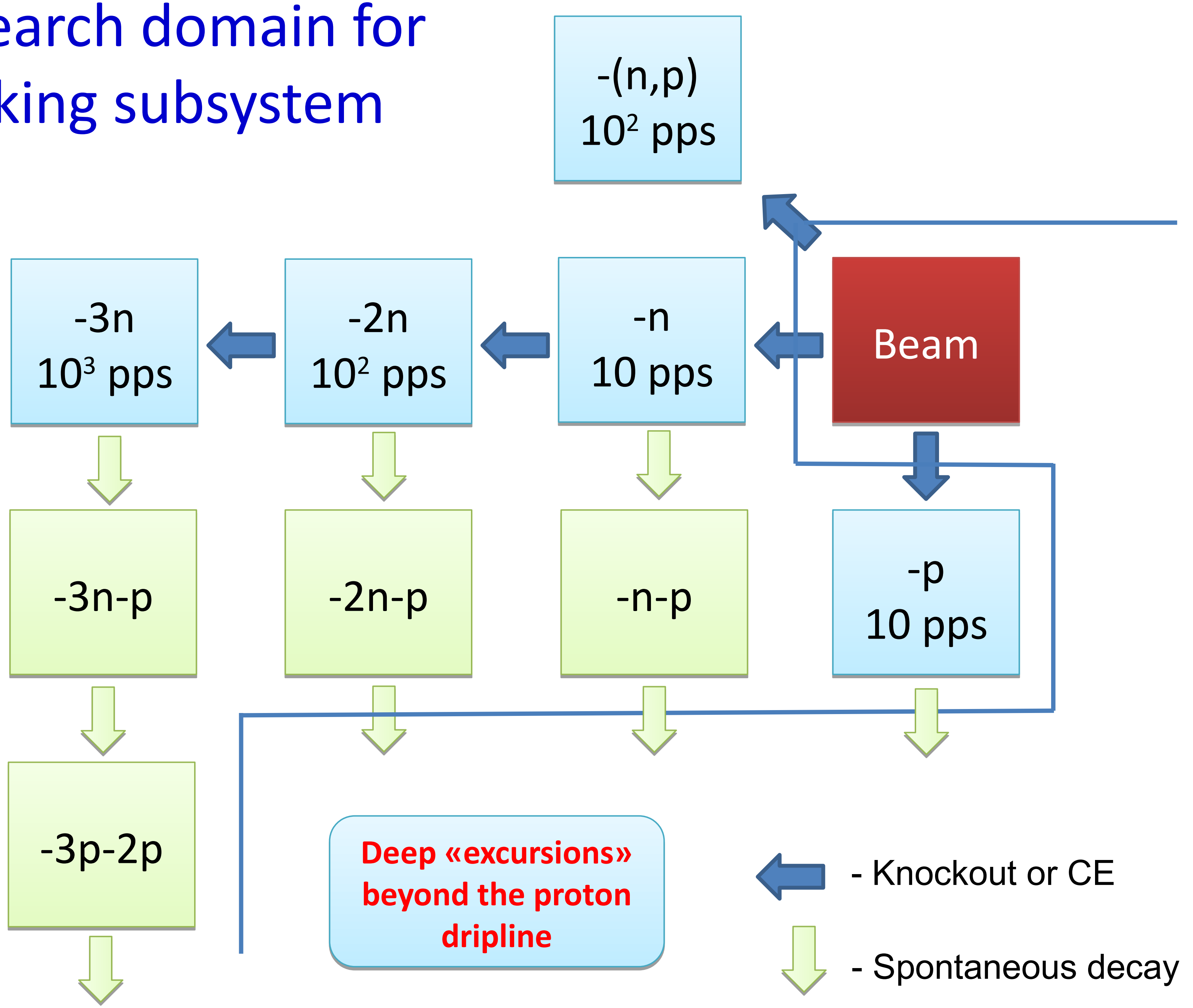
**Second achromat is used as high-resolution spectrometer for HI identification**

**http://aculina.jinr.ru/expert.html**

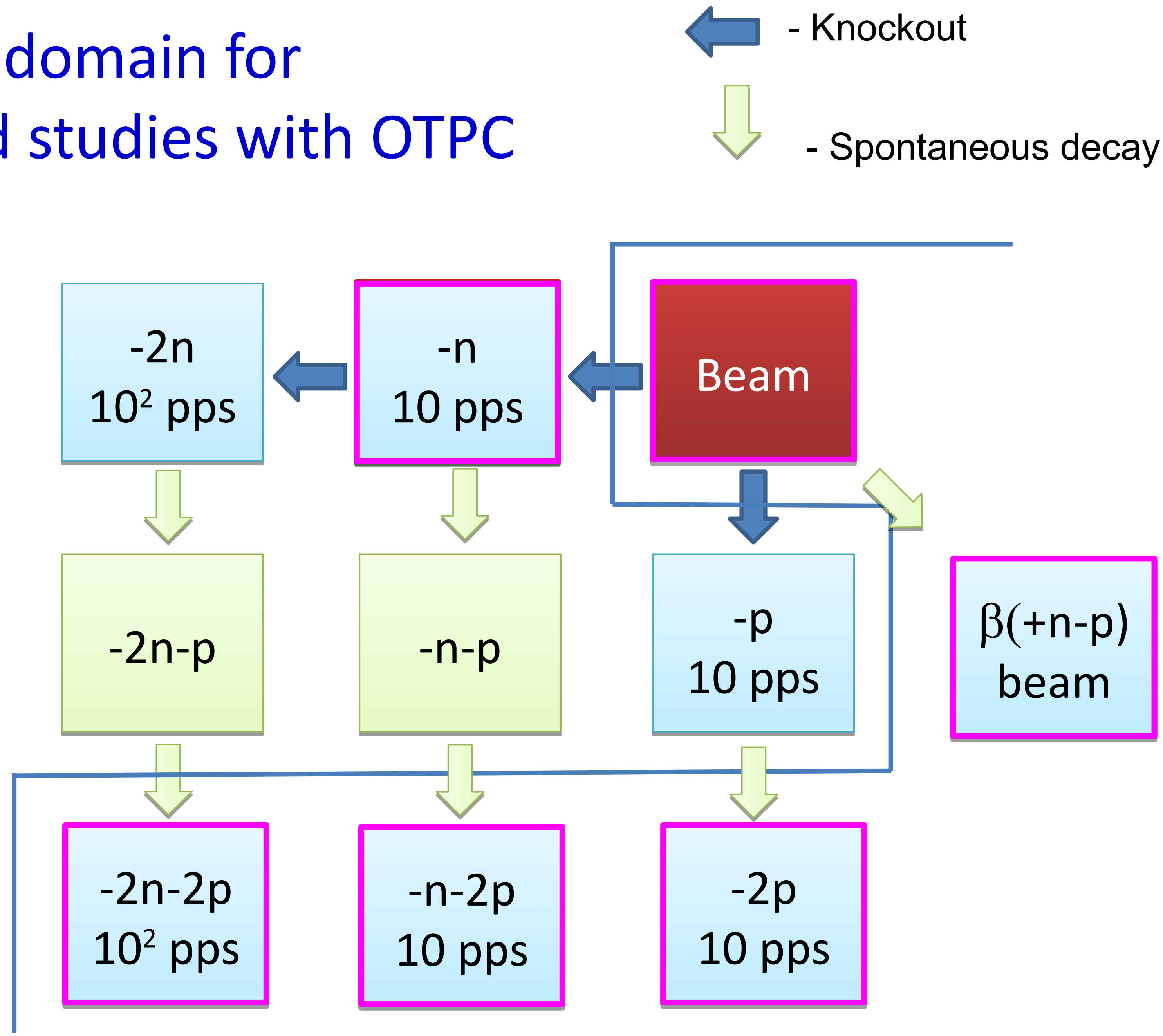
# EXPERT: EXotic Particle Emission and Radioactivity by Tracking



# Research domain for tracking subsystem



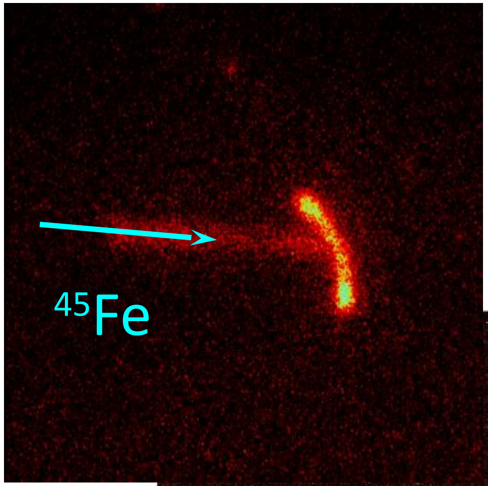
# Research domain for β-delayed studies with OTPC

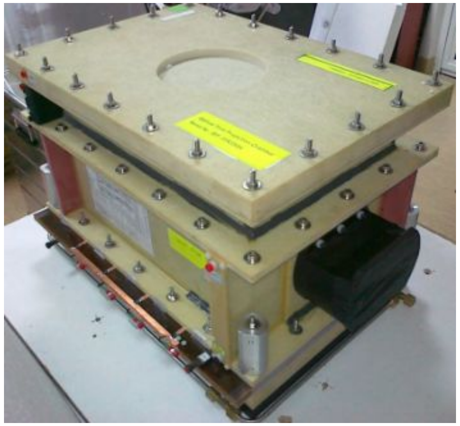


# Studies of exotic decays by OTPC

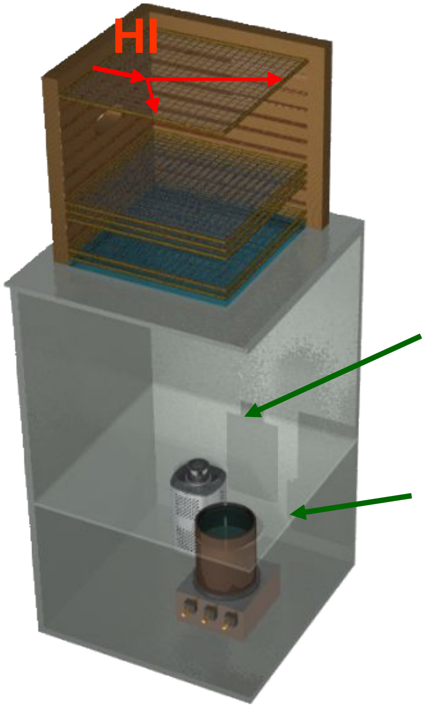
Prof. M. Pfutzner: new vision of extreme rare processes

**MSU 2007: $^{45}Fe$, 2p-radioactivity**



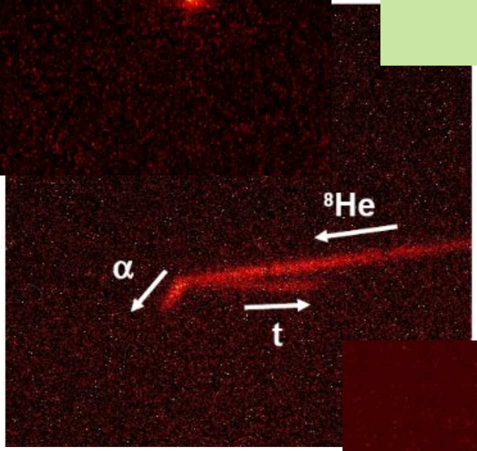
**New OTPC at ACCULINNA in 2011**



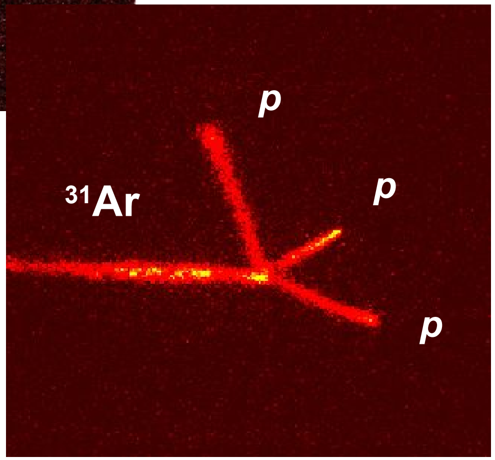

**CCD 2/3"**

- **1000 × 1000 pix**
- **12-bits**
- **image ampl. (× 2000)**

**ACCULINNA 2011: $^{8}He$, β-delayed α-t-n**




**GSI 2012: S388, $^{31}Ar$, β-delayed 3p**



# Major results

PRL 115, 202501 (2015) PHYSICAL REVIEW LETTERS week ending 13 NOVEMBER 2015

## Observation and Spectroscopy of New Proton-Unbound Isotopes $^{30}$Ar and $^{29}$Cl: An Interplay of Prompt Two-Proton and Sequential Decay

I. Mukha,[1,2] L. V. Grigorenko,[3,4,2] X. Xu,[5,1,6] L. Acosta,[7,8] E. Casarejos,[9] A. A. Ciemny,[10] W. Dominik,[10] J. Duénas-Díaz,[11] V. Dunin,[12] J. M. Espino,[13] A. Estradé,[14] F. Farinon,[1] A. Fomichev,[3] H. Geissel,[1,5] T. A. Golubkova,[15] A. Gorshkov,[3] Z. Janas,[10] G. Kamiński,[16,3] O. Kiselev,[1] R. Knöbel,[1,5] S. Krupko,[3] M. Kuich,[17,10] Yu. A. Litvinov,[1] G. Marquinez-Durán,[11] I. Martel,[11] C. Mazzocchi,[10] C. Nociforo,[1] A. K. Ordúz,[11] M. Pfützner,[10,1] S. Pietri,[1] M. Pomorski,[10] A. Prochazka,[1] S. Rymzhanova,[3] A. M. Sánchez-Benítez,[11] C. Scheidenberger,[1,5] P. Sharov,[3] H. Simon,[1] B. Sitar,[18] R. Slepnev,[3] M. Stanoiu,[19] P. Strmen,[18] I. Szarka,[18] M. Takechi,[1] Y. K. Tanaka,[1,20] H. Weick,[1] M. Winkler,[1] J. S. Winfield,[1] and M. V. Zhukov[21]

PHYSICAL REVIEW C 91, 064309 (2015)

## $\beta$-delayed three-proton decay of $^{31}$Ar

A. A. Lis,[1] C. Mazzocchi,[1,*] W. Dominik,[1] Z. Janas,[1] M. Pfützner,[1,2] M. Pomorski,[1] L. Acosta,[3,4] S. Baraeva,[5] E. Casarejos,[6] J. Duénas-Díaz,[7] V. Dunin,[5] J. M. Espino,[8] A. Estrade,[9] F. Farinon,[2] A. Fomichev,[5] H. Geissel,[2] A. Gorshkov,[5] G. Kamiński,[10,11] O. Kiselev,[2] R. Knöbel,[2] S. Krupko,[5] M. Kuich,[1,12] Yu. A. Litvinov,[2] G. Marquinez-Durán,[7] I. Martel,[7] I. Mukha,[2] C. Nociforo,[2] A. K. Ordúz,[7] S. Pietri,[2] A. Prochazka,[2] A. M. Sánchez-Benítez,[7,13] H. Simon,[2] B. Sitar,[14] R. Slepnev,[5] M. Stanoiu,[15] P. Strmen,[14] I. Szarka,[14] M. Takechi,[2] Y. Tanaka,[2,16] H. Weick,[2] and J. S. Winfield[2]

Physics Letters B 762 (2016) 263–270

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ELSEVIER

## Transition from direct to sequential two-proton decay in *s–d* shell nuclei

CrossMark

T.A. Golubkova[a], X.-D. Xu[b,c,d], L.V. Grigorenko[e,f,g,*], I.G. Mukha[c,g], C. Scheidenberger[b,c], M.V. Zhukov[h]

# Major results

PHYSICAL REVIEW C **97**, 034305 (2018)

## Spectroscopy of excited states of unbound nuclei $^{30}$Ar and $^{29}$Cl

X.-D. Xu,[1,2,3] I. Mukha,[3] L. V. Grigorenko,[4,5,6] C. Scheidenberger,[2,3,*] L. Acosta,[7,8] E. Casarejos,[9] V. Chudoba,[4]
A. A. Ciemny,[10] W. Dominik,[10] J. Duénas-Díaz,[11] V. Dunin,[12] J. M. Espino,[13] A. Estradé,[14] F. Farinon,[3] A. Fomichev,[4]
H. Geissel,[2,3] T. A. Golubkova,[15] A. Gorshkov,[4,16] Z. Janas,[10] G. Kamiński,[4,17] O. Kiselev,[3] R. Knöbel,[2,3] S. Krupko,[4,16]
M. Kuich,[10,18] Yu. A. Litvinov,[3] G. Marquinez-Durán,[11] I. Martel,[11] C. Mazzocchi,[10] C. Nociforo,[3] A. K. Ordúz,[11]
M. Pfützner,[3,10] S. Pietri,[3] M. Pomorski,[10] A. Prochazka,[3] S. Rymzhanova,[4] A. M. Sánchez-Benítez,[19] P. Sharov,[4]
...rmen,[20] I. Szarka,[20] M. Takechi,[3]
... and J. S. Winfield[3]

PHYSICAL REVIEW C **98**, 064308 (2018)

## Deep excursion beyond the proton dripline. I. Argon and chlorine isotope chains

I. Mukha,[1] L. V. Grigorenko,[2,3,4] D. Kostyleva,[5,1,*] L. Acosta,[6,7] E. Casarejos,[8] A. A. Ciemny,[9] W. Dominik,[9] J. A. Dueñas,[10]
V. Dunin,[11] J. M. Espino,[12] A. Estradé,[13] F. Farinon,[1] A. Fomichev,[2] H. Geissel,[1,5] A. Gorshkov,[2] Z. Janas,[9] G. Kamiński,[14,2]
O. Kiselev,[1] R. Knöbel,[1,5] S. Krupko,[2] M. Kuich,[15,9] Yu. A. Litvinov,[1] G. Marquinez-Durán,[16] I. Martel,[16] C. Mazzocchi,[9]
C. Nociforo,[1] A. K. Ordúz,[16] M. Pfützner,[9,1] S. Pietri,[1] M. Pomorski,[9] A. Prochazka,[1] S. Rymzhanova,[2]
A. M. Sánchez-Benítez,[17] C. Scheidenberger,[1,5] P. Sharov,[2] H. Simon,[1] B. Sitar,[18] R. Slepnev,[2] M. Stanoiu,[19] P. Strmen,[18]
I. Szarka,[18] M. Takechi,[1] Y. K. Tanaka,[1,20] H...

PHYSICAL REVIEW C **98**, 064309 (2018)

## Deep excursion beyond the proton dripline. II. Toward the limits of existence of nuclear structure

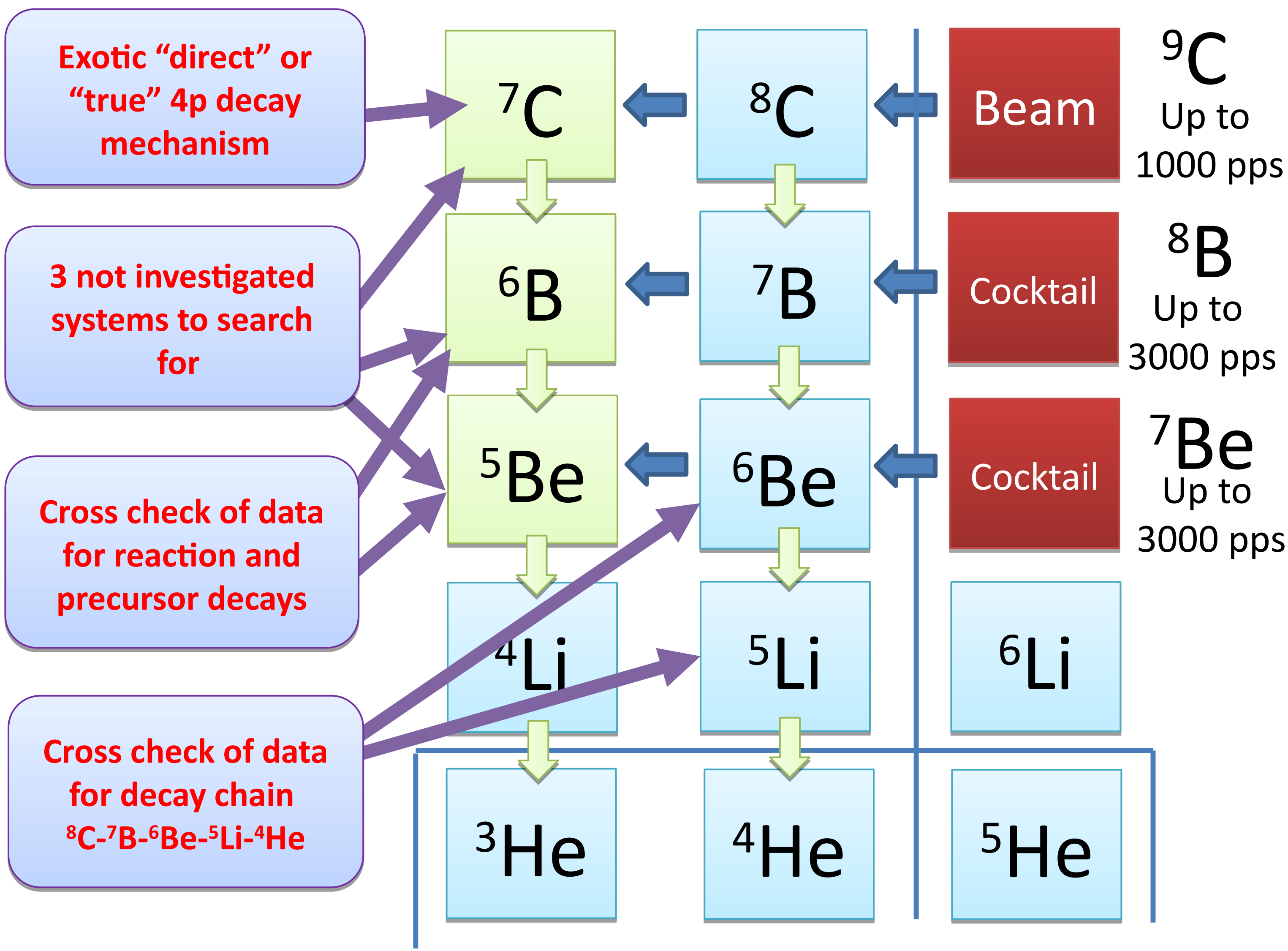
L. V. Grigorenko,[1,2,3] I. Mukha,[4] D. Kostyleva,[5,4,*] C. Scheidenberger,[4,5] L. Acosta,[6,7] E. Casarejos,[8] V. Chudoba,[1,9]
A. A. Ciemny,[10] W. Dominik,[10] J. A. Dueñas,[11] V. Dunin,[12] J. M. Espino,[13] A. Estradé,[14] F. Farinon,[4] A. Fomichev,[1]
...iński,[15,1] O. Kiselev,[4] R. Knöbel,[4,5] S. Krupko,[1] M. Kuich,[16,10]
...[17] C. Mazzocchi,[10] E. Yu. Nikolskii,[3,1] C. Nociforo,[4] A. K. Ordúz,[17]
...a,[4] S. Rymzhanova,[1] A. M. Sánchez-Benítez,[18] P. Sharov,[1] H. Simon,[4]
... Szarka,[19] M. Takechi,[4] Y. K. Tanaka,[4,21] H. Weick,[4] M. Winkler,[4]
X. Xu,[22,5,4] and M. V. Zhukov[23]

PHYSICAL REVIEW LETTERS **123**, 092502 (2019)

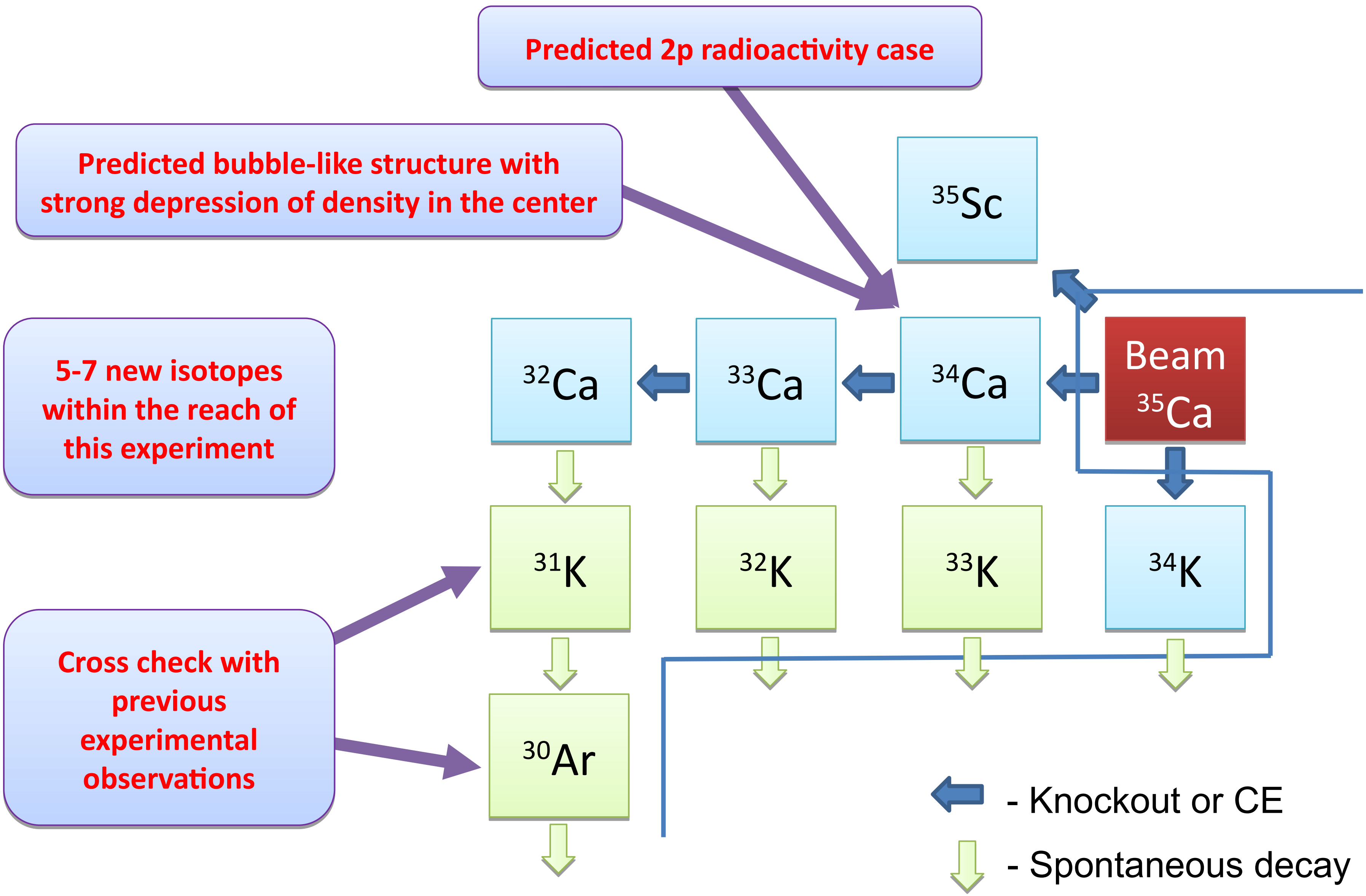
## Towards the Limits of Existence of Nuclear Structure: Observation and First Spectroscopy of the Isotope $^{31}$K by Measuring Its Three-Proton Decay

D. Kostyleva,[1,2,*] I. Mukha,[1] L. Acosta,[3,4] E. Casarejos,[5] V. Chudoba,[6,7] A. A. Ciemny,[8] W. Dominik,[8] J. A. Dueñas,[9]
V. Dunin,[10] J. M. Espino,[11] A. Estradé,[12] F. Farinon,[1] A. Fomichev,[6] H. Geissel,[1,2] A. Gorshkov,[6] L. V. Grigorenko,[6,13,14]
Z. Janas,[8] G. Kamiński,[15,6] O. Kiselev,[1] R. Knöbel,[1,2] S. Krupko,[6] M. Kuich,[16,8] Yu. A. Litvinov,[1] G. Marquinez-Durán,[17]
I. Martel,[18] C. Mazzocchi,[8] C. Nociforo,[1] A. K. Ordúz,[25] M. Pfützner,[8,1] S. Pietri,[1] M. Pomorski,[8] A. Prochazka,[1]
S. Rymzhanova,[6] A. M. Sánchez-Benítez,[19] C. Scheidenberger,[1,2] H. Simon,[1] B. Sitar,[20] R. Slepnev,[6] M. Stanoiu,[21]
P. Strmen,[20] I. Szarka,[20] M. Takechi,[1] Y. K. Tanaka,[1,22] H. Weick,[1] M. Winkler,[1]
J. S. Winfield,[1] X. Xu,[23,2,1] and M. V. Zhukov[24]

# $^{12}$Ca → $^{9}$Ca → $^{34}$Ca → $^{32}$Ar+2p experiment



# $^{40}Ca \rightarrow {}^{35}Ca \rightarrow {}^{34}Ca \rightarrow {}^{32}Ar+2p$ experiment

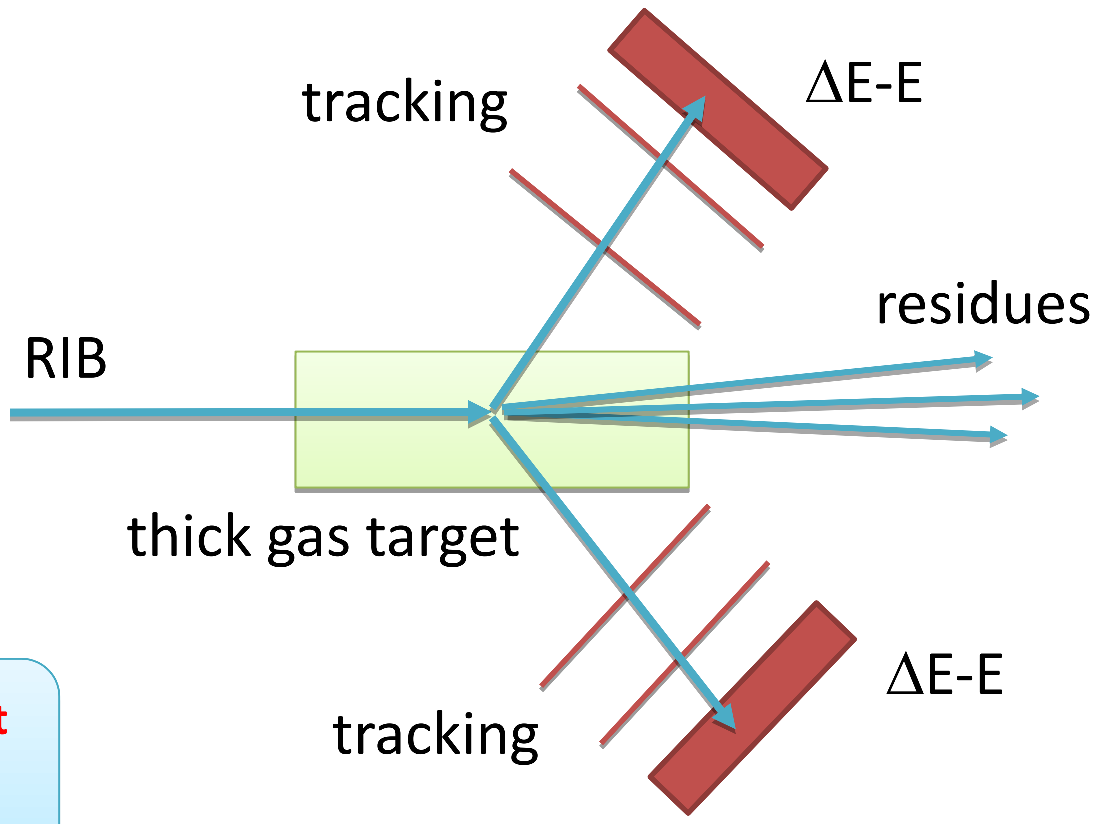


# New experimental ideas for QFS experiements at ACCULINNA-2 with EXPERT technologies

**Basic problem of QFS at low energies – resolution vs target thickness**

**Thin target is needed. Large QFS cross sections but thin targets**

**New type of QFS experiment at low (20-40 AMeV) energy with extreme thick targets**




RIB(p,2p), RIB(α,2α), etc.

Look forward for new experoiements at

ACCULINNA-2 and EXPERT@FRS!