A trip to FRIB with FAZIA

A. Camaiani
G. Casini
for the NUCLEX Collaboration

FAZIA
FRIB
UNIVERSITÀ DEGLI STUDI FIRENZE
INFN
NUCLEX

The NUSDAF "Yellow Brick Road"

See G. Verde talk

ReAccelerate beams (<10 AMeV)

Energy degraded fragmentation beams (30-100 AMeV)

Primary fragmentation beams (>150 AMeV)

GASPEC – GAmma and charged particle SPEctroscopy and Collective excitations

SYMEOS – SYMmetry energy and Equation Of State

RIBDCE – Radioactive Ion Beam induced Double-Charge Exchange reactions

NUSYC – NUcleo-SYnthesis and Clustering

SYSTERSE - SYnergic Stategy for fuTure ElectRonics and Streaming rEadout solutions

The FAZIA "Yellow Brick Road"

ReAccelerate beams (<10 AMeV)	Energy degraded fragmentation beams (30-100 AMeV)	Primary fragmentation beams (>150 AMeV)

SYMEOS

Investigation of the nuclear equation of state at supra-saturation densities

Coupled with local HIRA, LANA, FROG
Coupled with other INFN detectors

What FAZIA can offer?
Are we ready for that?

FAZIAEXPLORER

Exploring the limit of the drip lines

Possible coupling with GAMMA arrays

How? What FAZIA can offer?
Are we ready for that?

FAZIAEXOTIC

Exploring exotic clustering configurations

Coupled with OSCAR-like
Coupled with FROG-like

How? What FAZIA can offer?
Are we ready for that?

The FAZIA ''Yellow Brick Road''

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FAZIAEX

Explorin
configur

Coupled
Coupled

How? W
Are we r

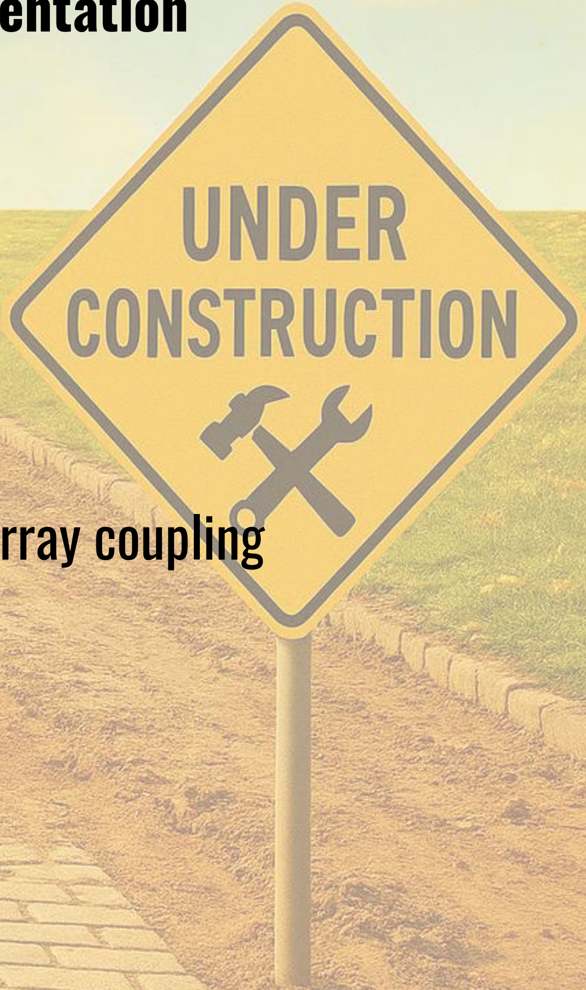
Conditions and hypotheses at the base of this presentation

1. Not a precise experiment proposals
   but a brain-storming idea

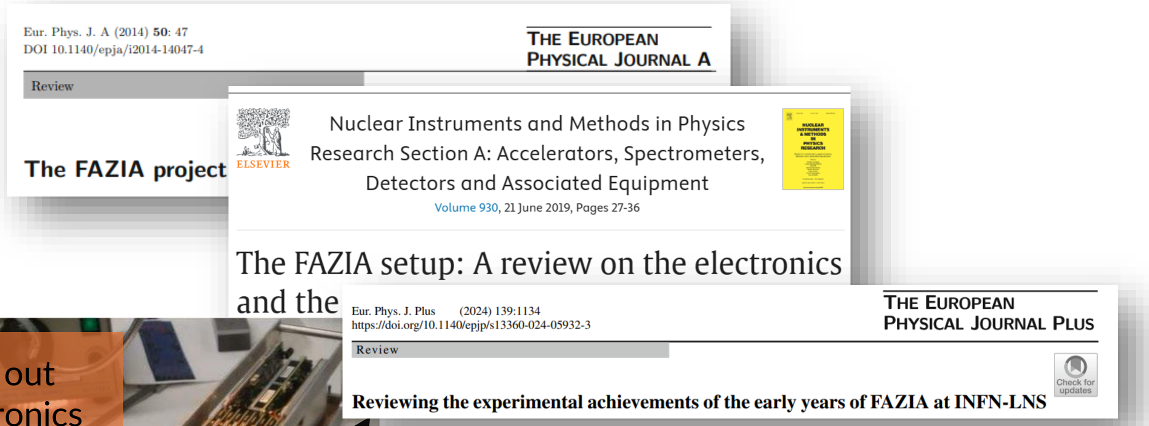
2. Needs of a specific reaction chamber

3. Large increase of scientific potential
   in case of complementary charge particle / gamma-array coupling

4. Help of theorists is strongly recommended
   mainly to strengthen/define the physics cases



The FAZIA actual status



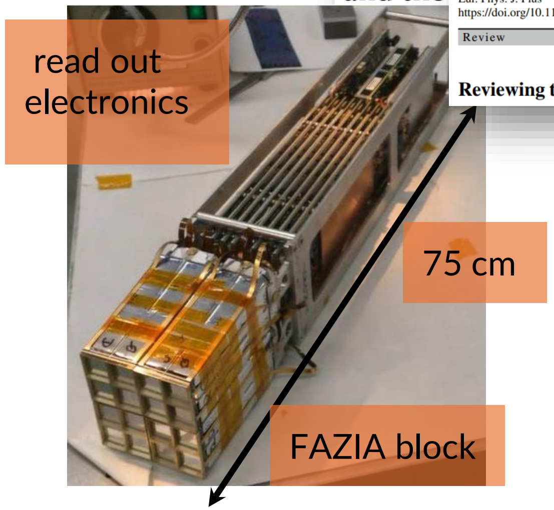
The state of the art of ion identification in the Fermi energy domain

1 BLK = 16 telescope

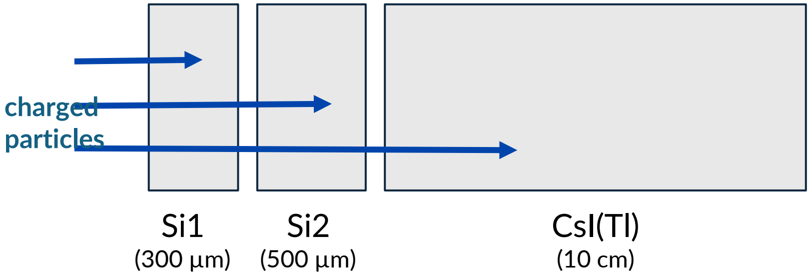
Telescope (area 2x2 cm^2):

Si1, 300um + Si2, 500 um + CsI 10 cm – since 2015 ...
Si1, 300um + Si2, 750 um + CsI 10 cm – since 2022 ...

- ✓ Doping uniformity within ± 3%
- ✓ Thickness uniformity within ±1 μm
- ✓ Random cut to avoid channeling
- ✓ "reverse mounting" configuration
- ✓ Reverse current monitor and compensation
- ✓ FEE electronics on "block"



The combination of PSA and ΔE-E allows for an excellent identification from protons to Z=25 in a broad energy range with low thresholds.



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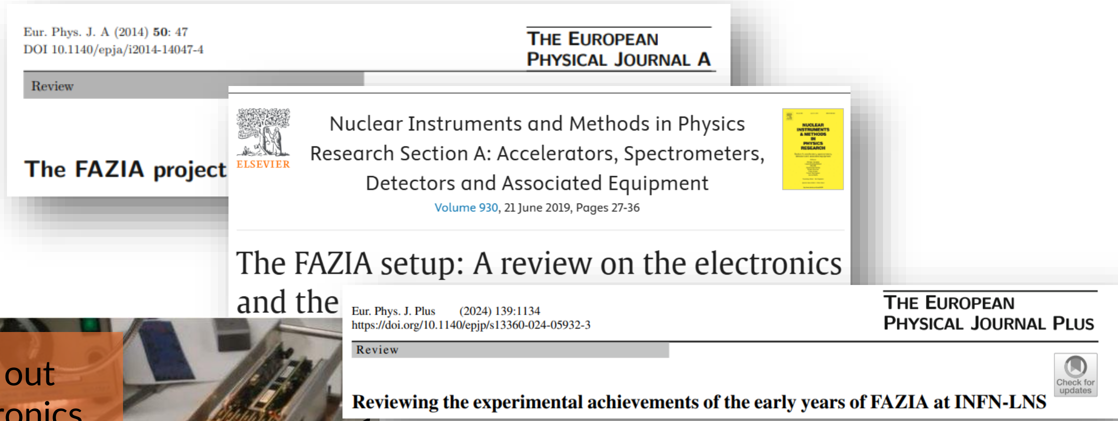
Eur. Phys. J. A (2014) 50: 47
DOI 10.1140/epja/i2014-14047-4
THE EUROPEAN PHYSICAL JOURNAL A
Review
The FAZIA project

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
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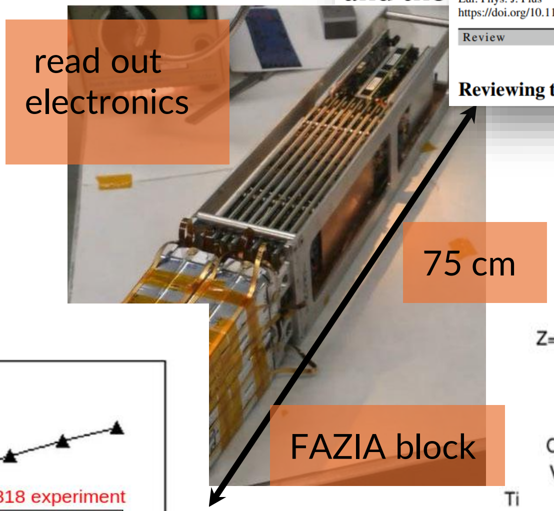

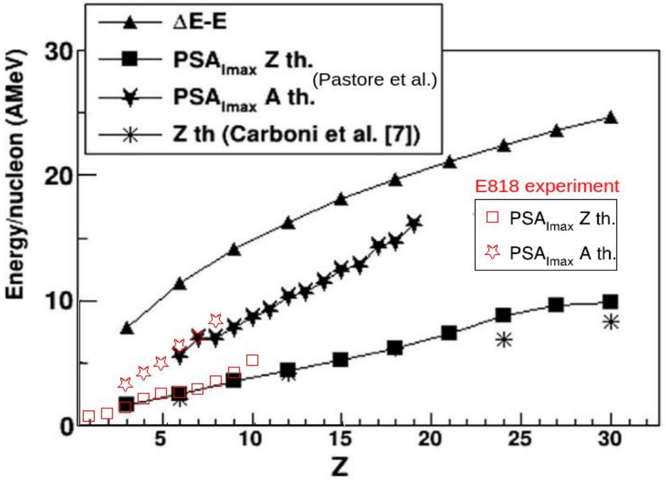

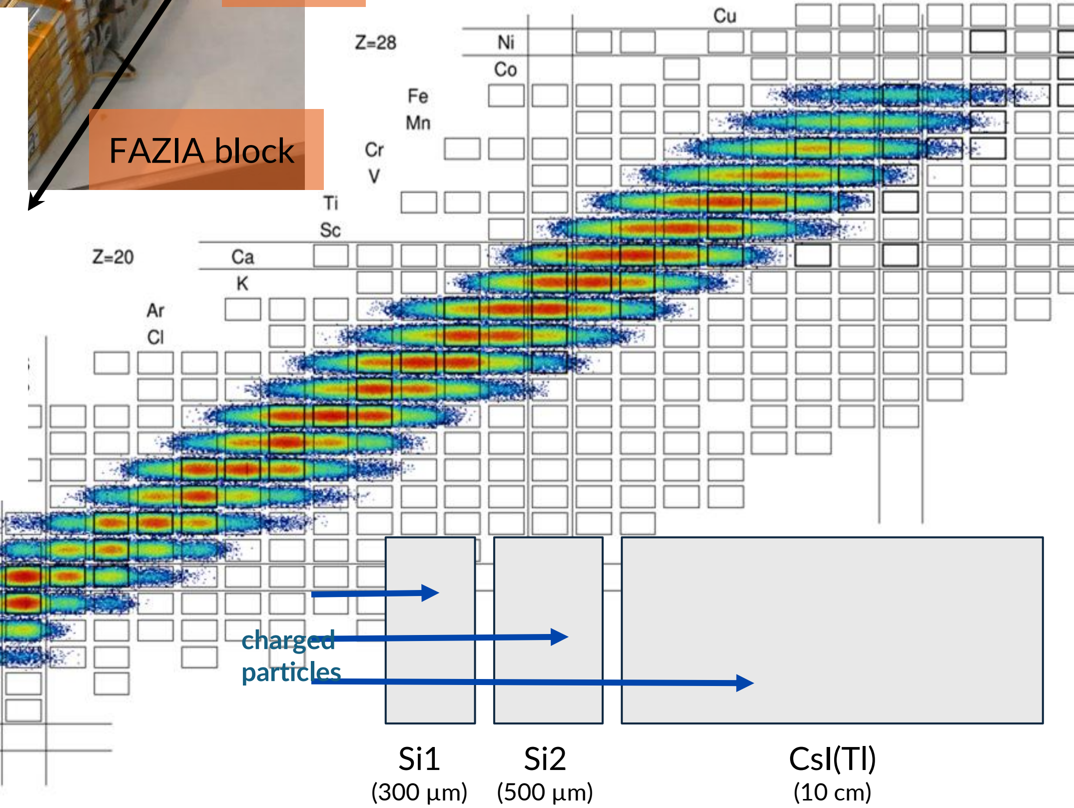

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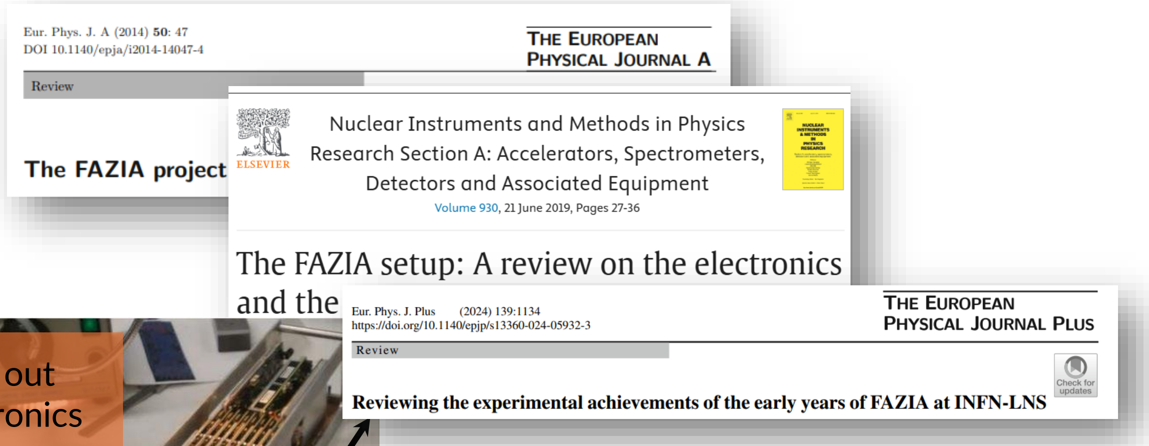
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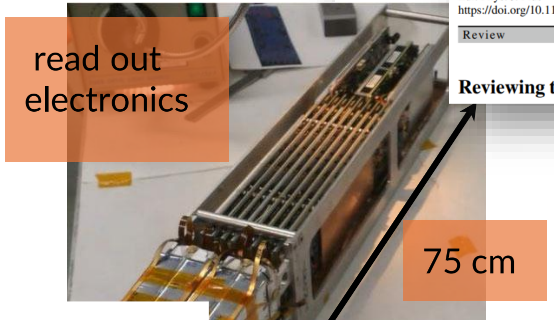
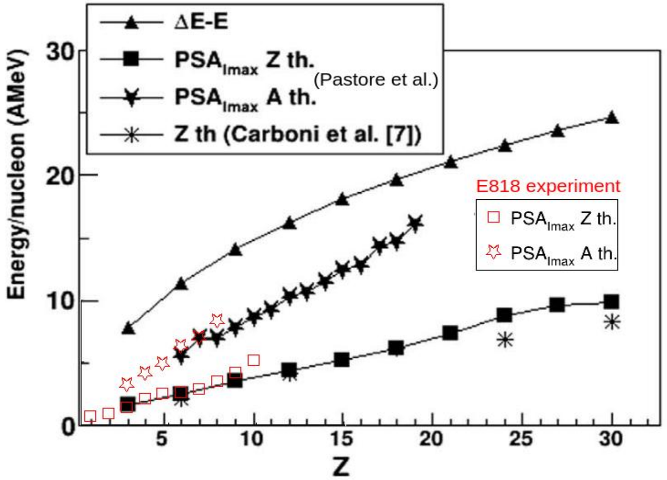
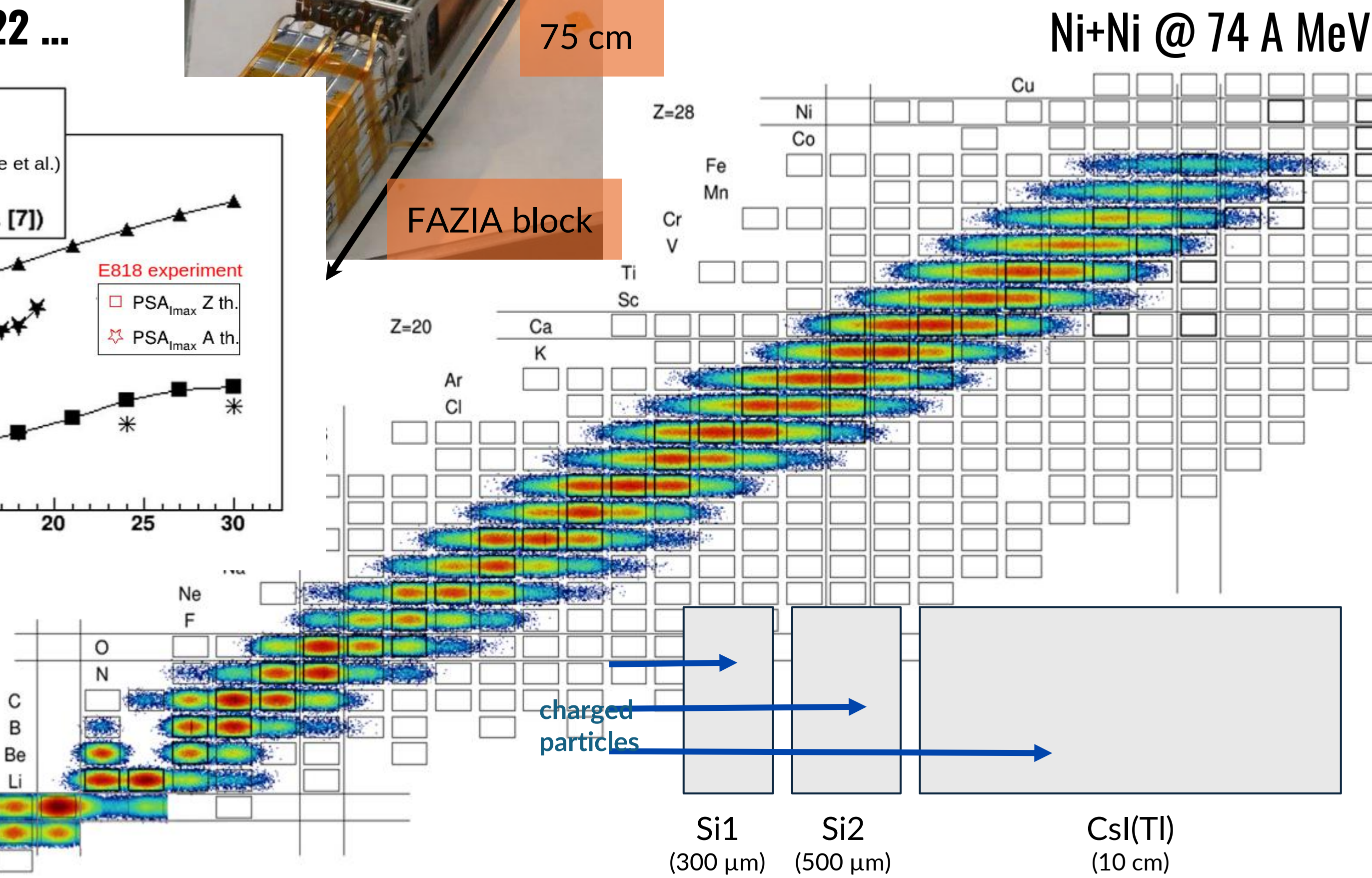


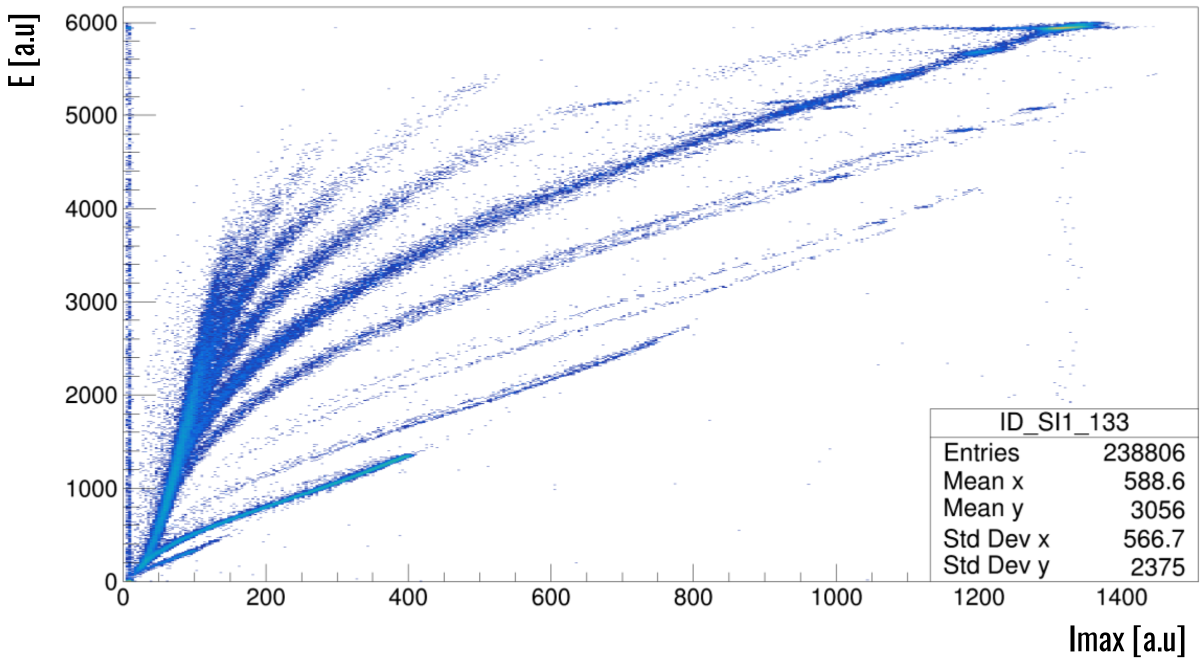




- Is the (Z,A) identification still possibile at 200 AMeV?
- Are the E thresholds a limit for ReA beams?

FAZIA performances below 10 A MeV

12C+12C @ 8.5 AMeV – E881 GANIL experiment



From FAZIADAYS 25
Ilham Dekhissi & Andrea DeRosa

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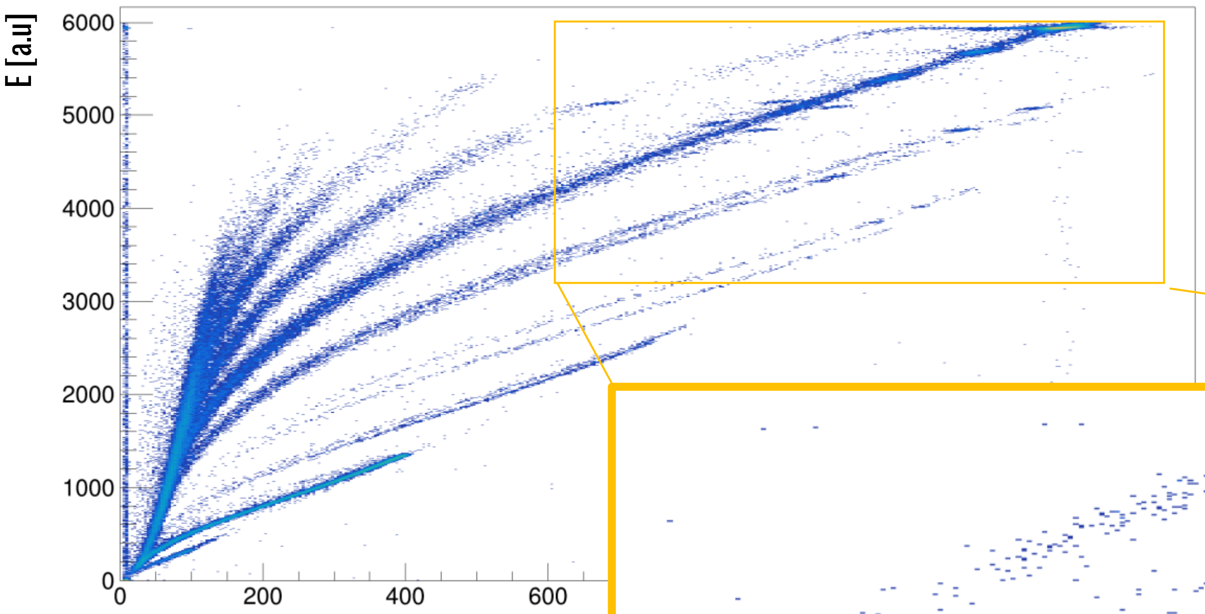

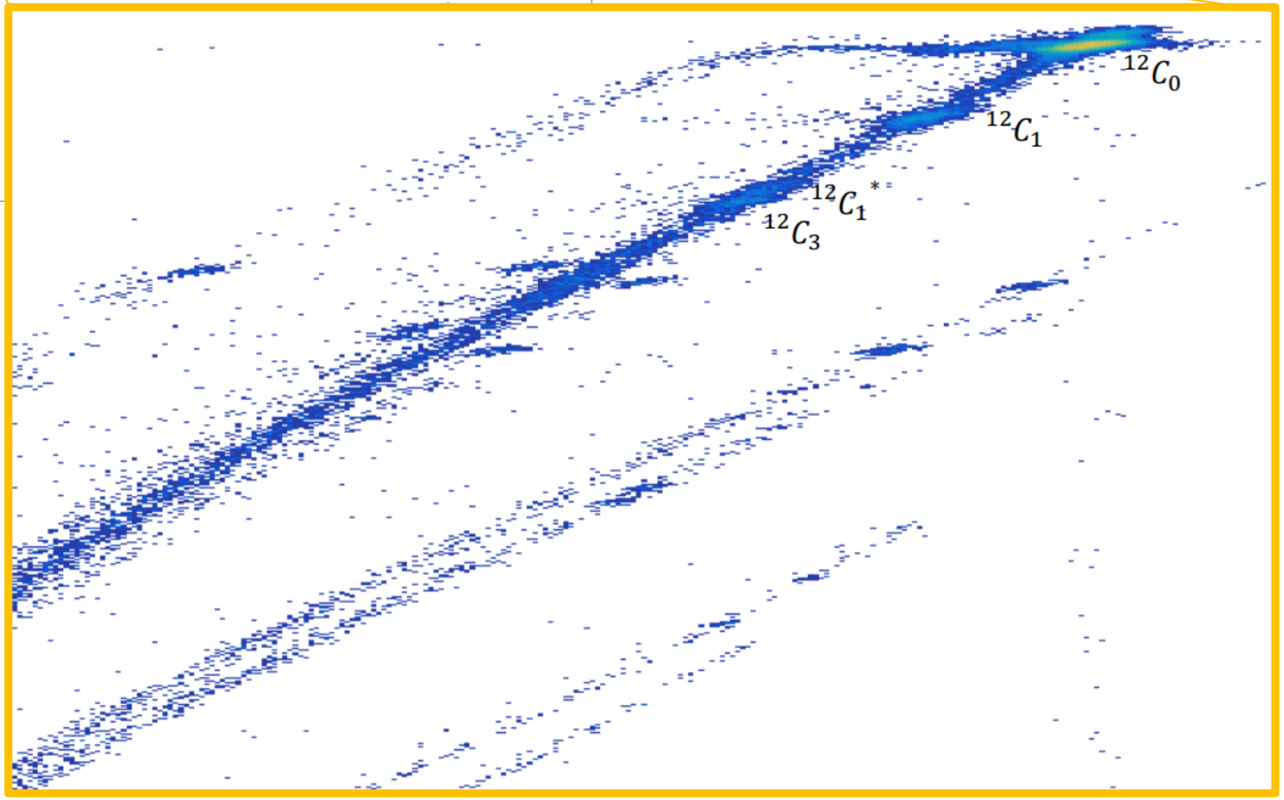

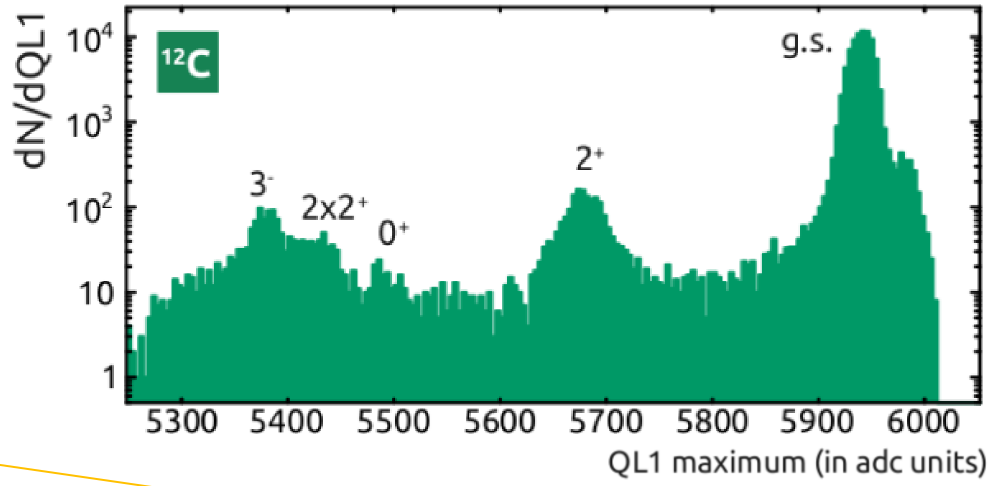

Elastic and inelastic:

- $12C_0$ elastic
- $12C_1$ – 4.4 MeV
- $12C_1{}^*$ - 2 x 4.4 MeV
- $12C_3$ – 9.6 MeV

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Ilham Dekhissi & Andrea DeRosa

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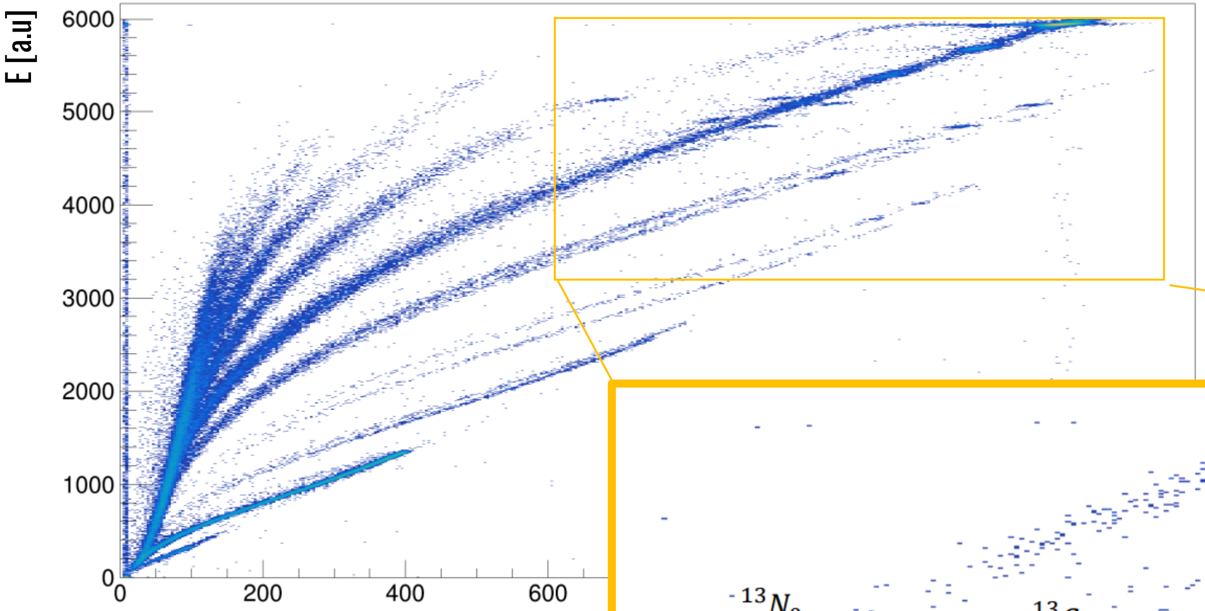
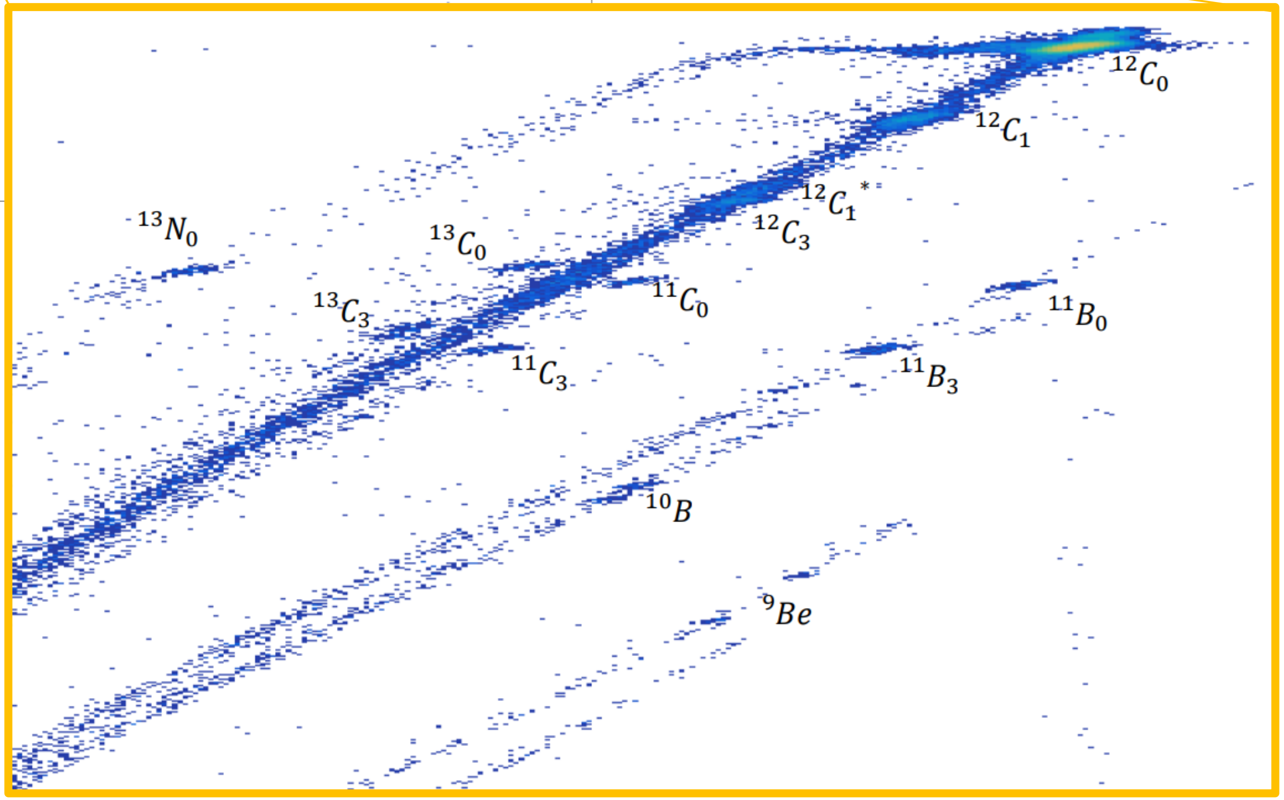
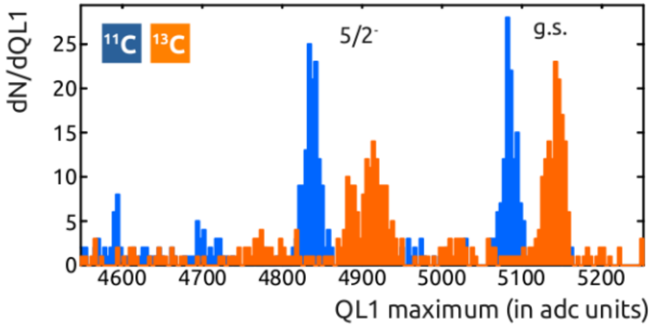
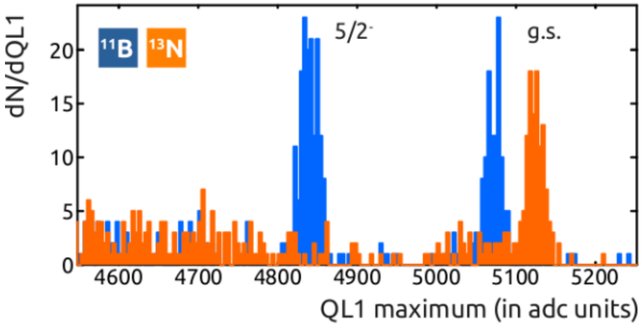








One Nucleon transfer
:

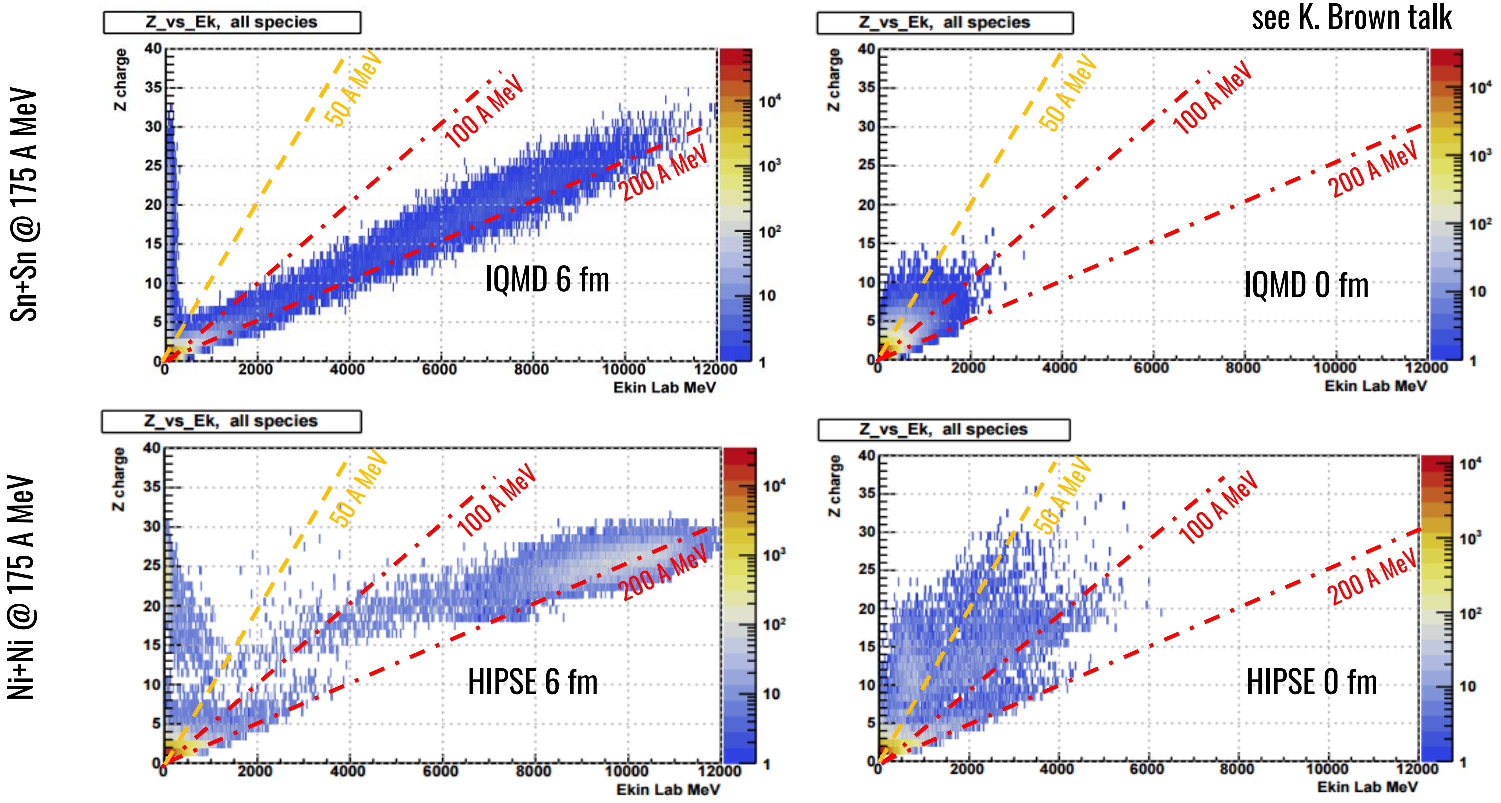
- $11C_0$, $11C_3$ – n removal
- $13C_0$, $13C_1$ - n transfer
- $11B_0$, $11B_3$ - p removal
- $13N_0$ p transfer

From FAZIADAYS 25
Ilham Dekhissi & Andrea DeRosa

FAZIA above 150 A MeV

- The kinematic phase space of an HIC at SYMEOS energies is outside the typical FAZIA energy range

see K. Brown talk



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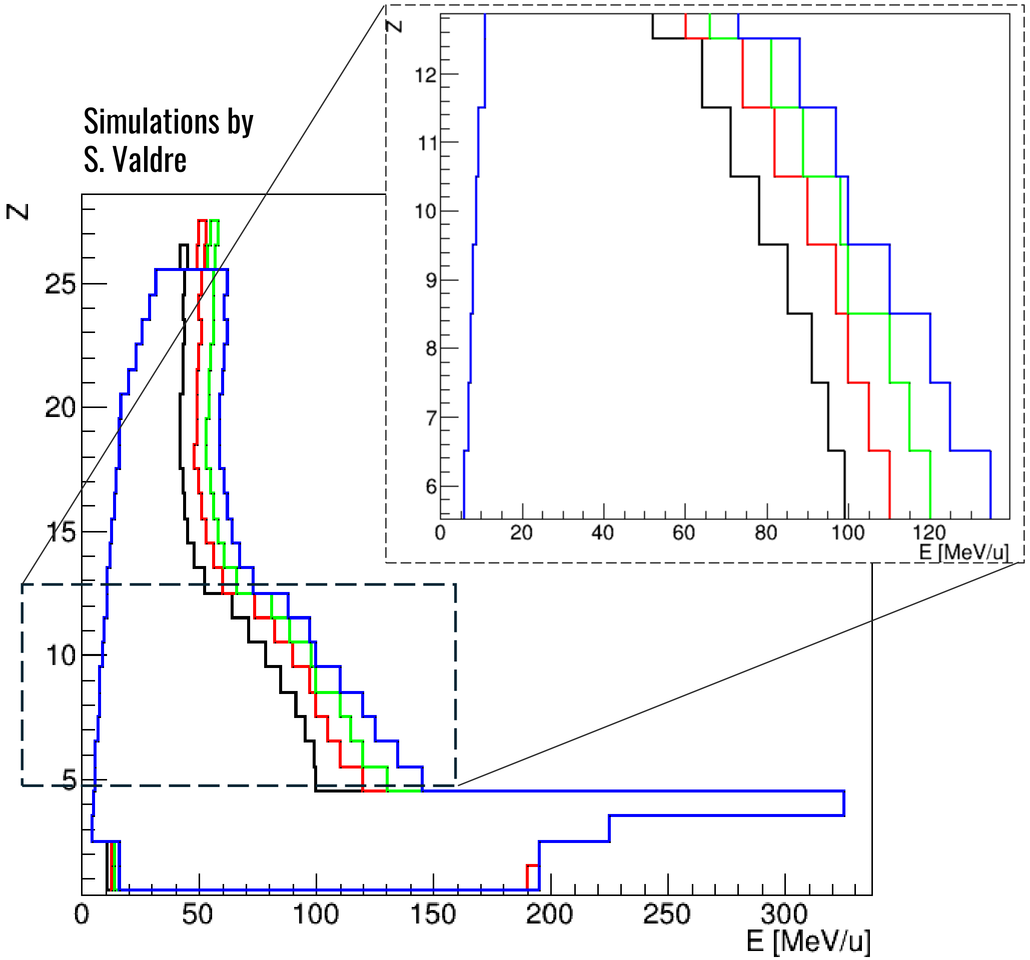
Simulations by
S. Valdre



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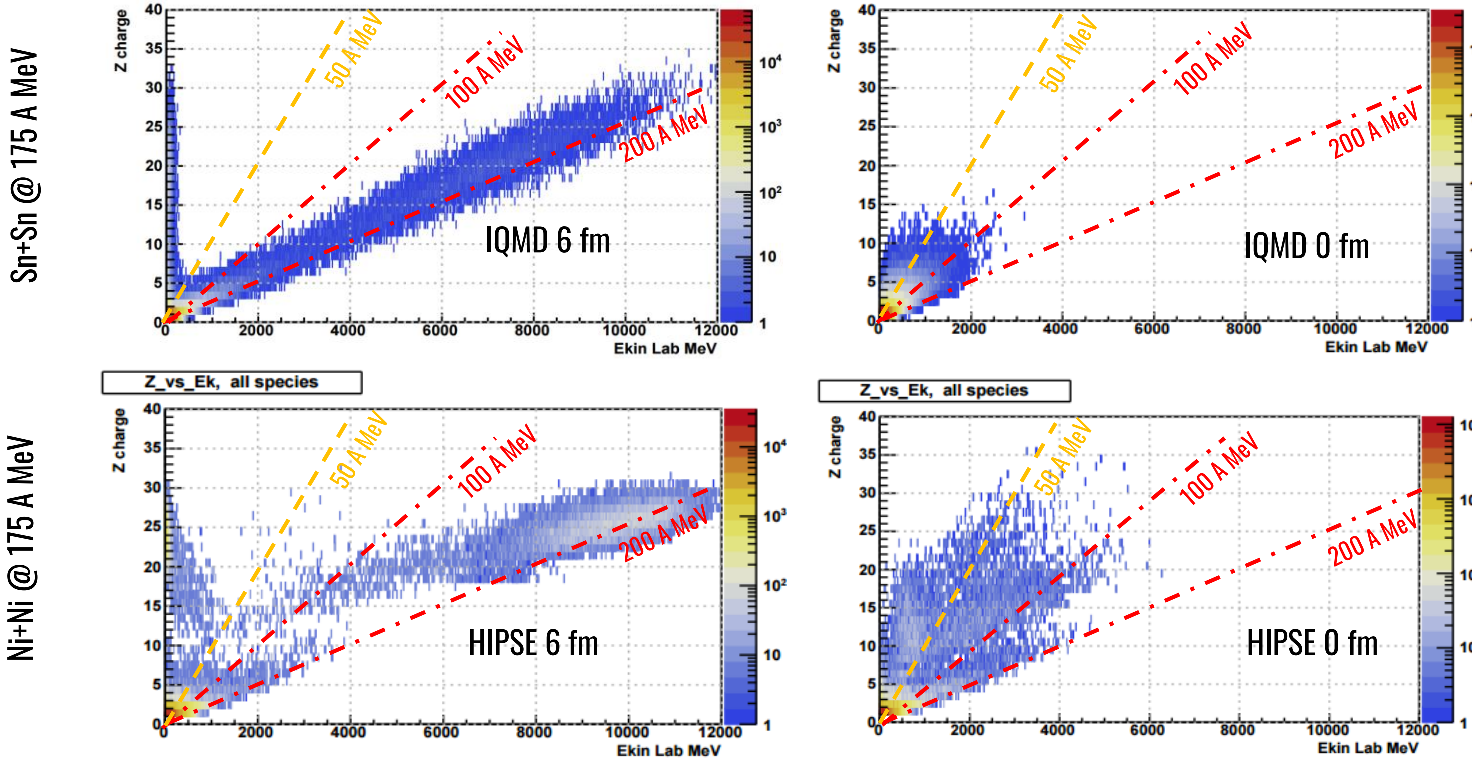


- FAZIA Identification capabilities for different telescopes thicknesses

  - 300um + 500um + 10cm
  - 300um + 750um + 10cm
  - 500um + 750um + 10cm
  - 750um + 750um + 10cm

The FAZIA "Yellow Brick Road"

ReAccelerate beams (<10 AMeV)	Energy degraded fragmentation beams (20-100 AMeV)	Primary fragmentation beams (>150 AMeV)

SYMEOS

Investigation of the nuclear equation of state at supra-saturation densities

Coupled with local HIRA, LANA, FROG
Coupled with other INFN detectors

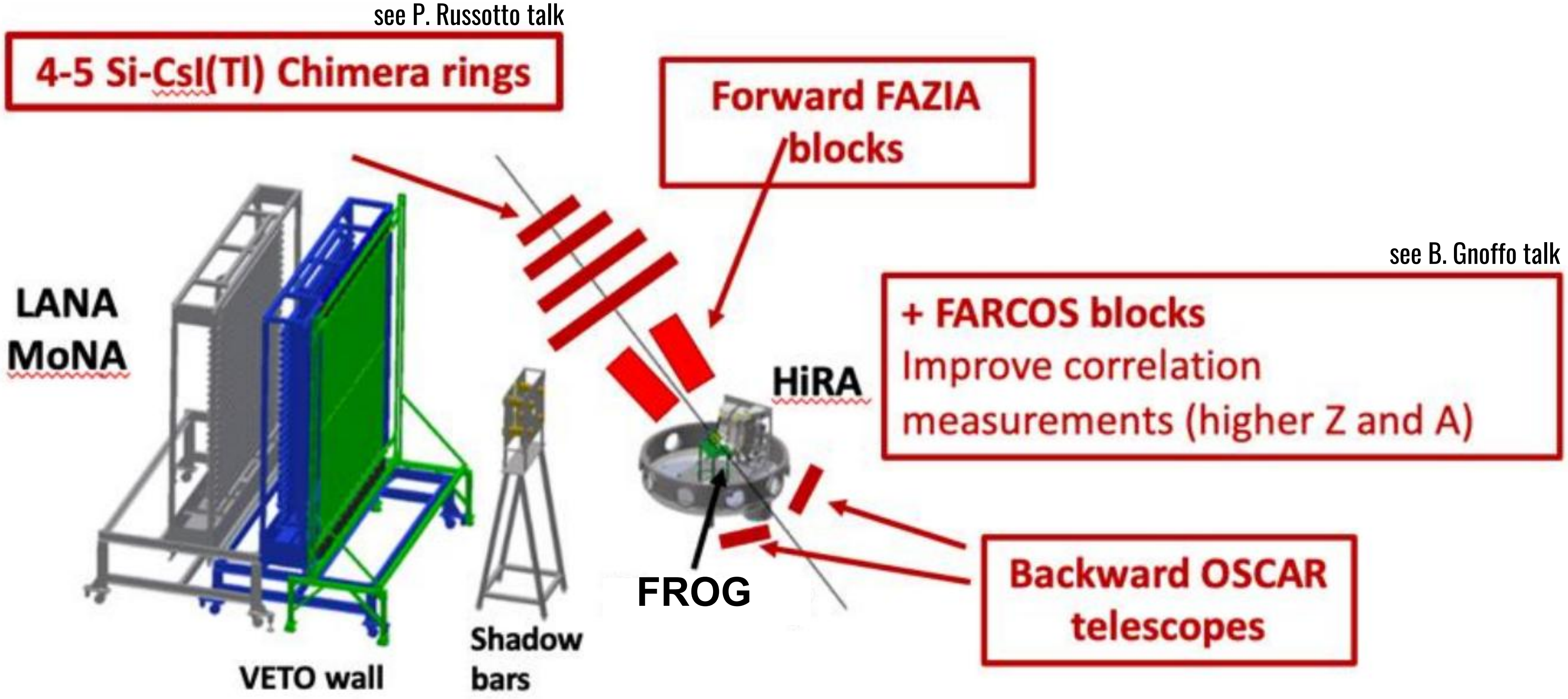
What FAZIA can offer?
Are we ready for that?

SYMEOS synergy

Letter of Intent

INFN-NUSDAF (INFN - Nuclear Structure, Dynamics and Astrophysics at FRIB)

From the Letter of Intent ....



SYMEOS synergy

Letter of Intent

INFN-NUSDAF (INFN ... FRIB)

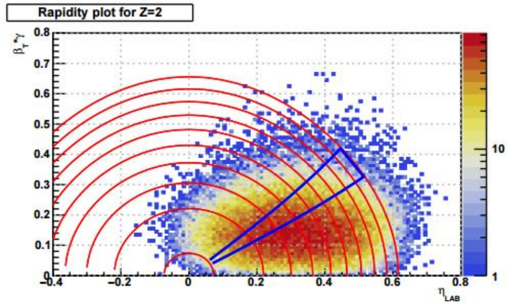
From the Letter of Intent ....

see P. Russotto talk

4-5 Si-CsI(Tl) Chimera rings

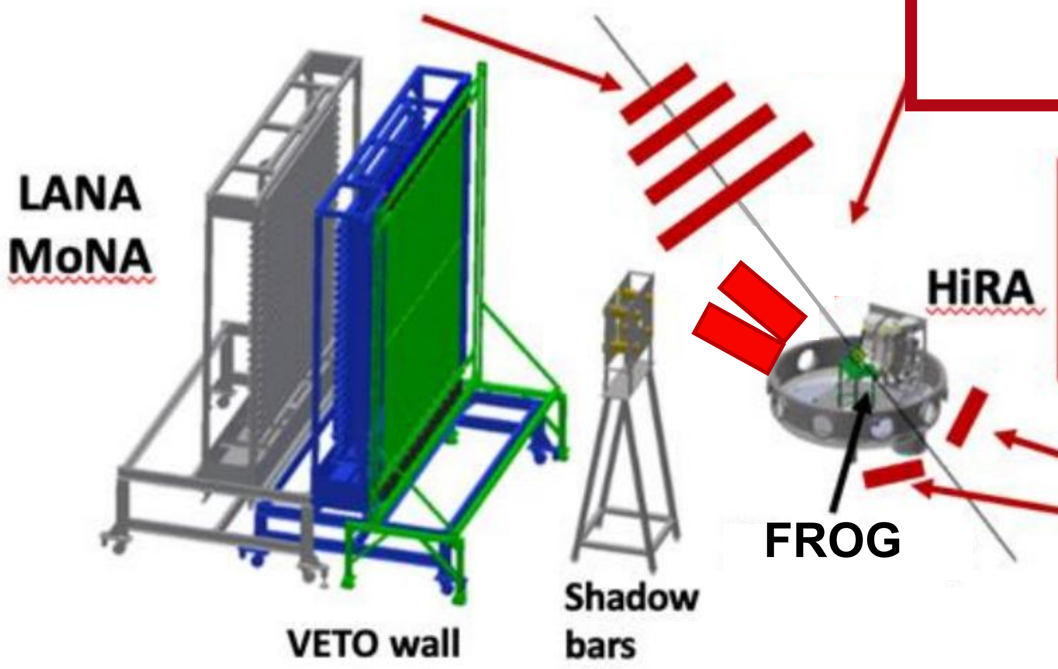
Sideward FAZIA blocks

- 0.8 - 1m from the target
- Under vacuum
- Lab. Coverage 15-40 deg



see B. Gnoffo talk

+ FARCOS blocks
Improve correlation measurements (higher Z and A)



Backward OSCAR telescopes

to a more realistic FAZIANS view!

What FAZIA can do for SYMEOS

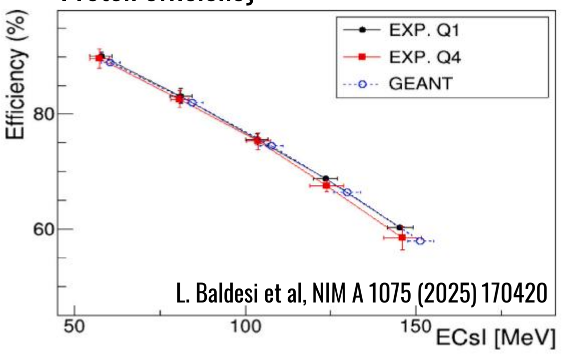
- Blocks of FAZIA can be placed between 15-40° in the lab. frame, extending the acceptance provided by HiRA
- We can cover mid-rapity regions accessing (similar to HiRA)

A. Sorensen et al, PPNP 134, 2024, 104080

- Protons up to 197 MeV
  - ✓ p flow
  - ✓ p kinematics

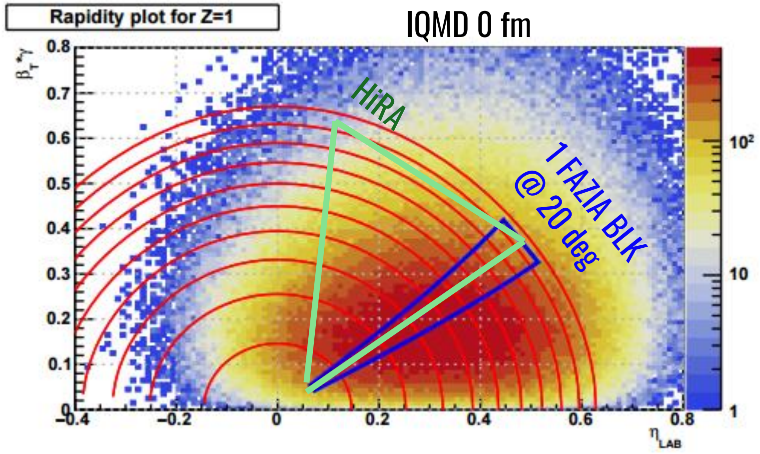
Observables aiming at symmetry energy and effective masses

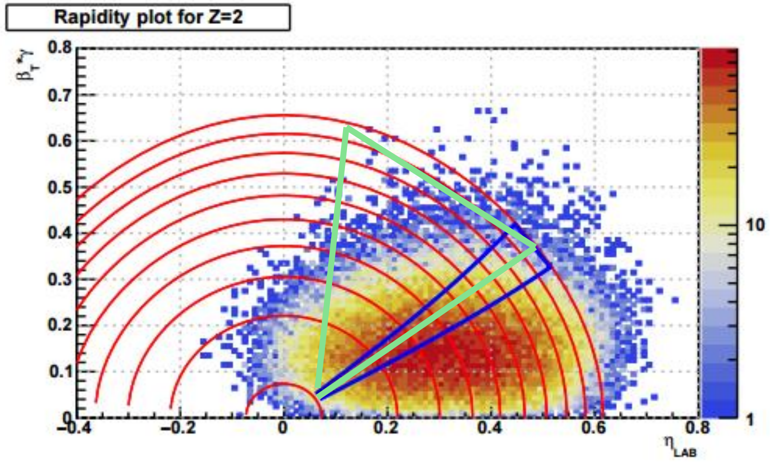
Proton efficiency



L. Baldesi et al, NIM A 1075 (2025) 170420

Sn+Sn @ 175 A MeV
IQMD 0 fm





- Light and heavy clusters
  - ✓ multiplicity
  - ✓ kinematics in the whole production range
  - ✓ Coalescence Invariant Flow
  - ✓ Particle-particle and Particle-fragment correlation

see G. Verde talk

Completementary/auxiliary observable for n/p flow

Observables to shed lights on clusterization processes in hot and compressed medium

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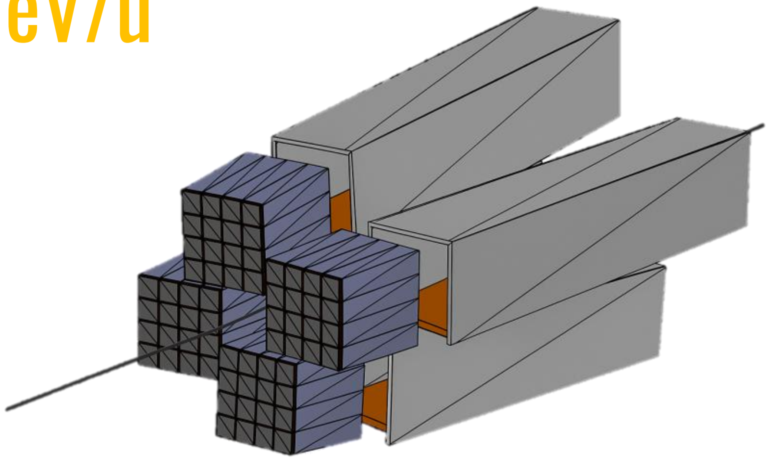
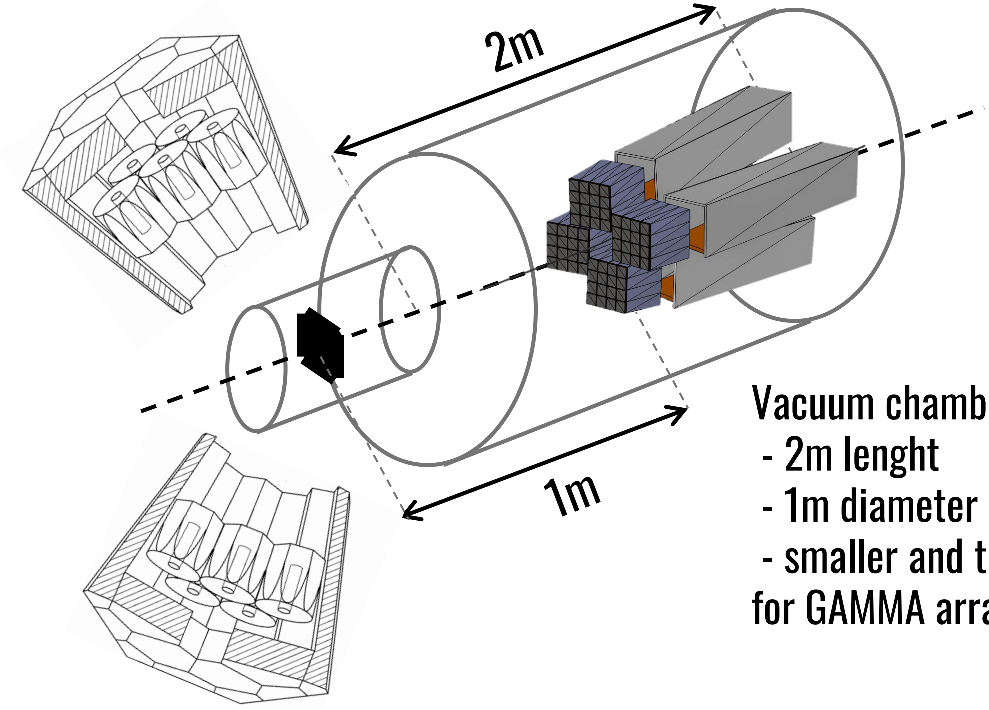
FAZIAEXPLORER: a possibile research line at 30-80 MeV/u

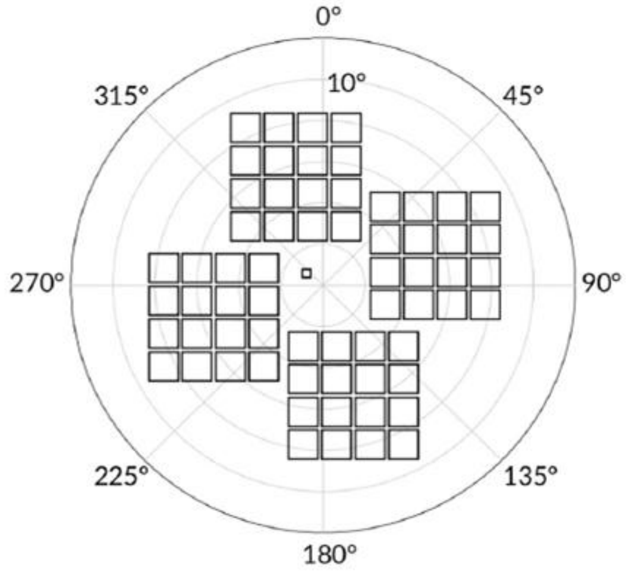
- Beam range: 30-80 MeV/u by degrading the primary fragmentation beams
- 4 FAZIA blocks in stand-alone mode mounted in a wall configuration at forward angles, 1m distance from target
- Polar range: about 2 to 9 degrees with a geometric efficiency in this range about 70%
- Additional Gamma Detector may be placed around the target. Is such configuration suitable for GRETA/GRETINA?





Vacuum chamber requirements:
- 2m lenght
- 1m diameter
- smaller and thinner volume around the target for GAMMA array coupling

4 FAZIA Block polar plot at 1m



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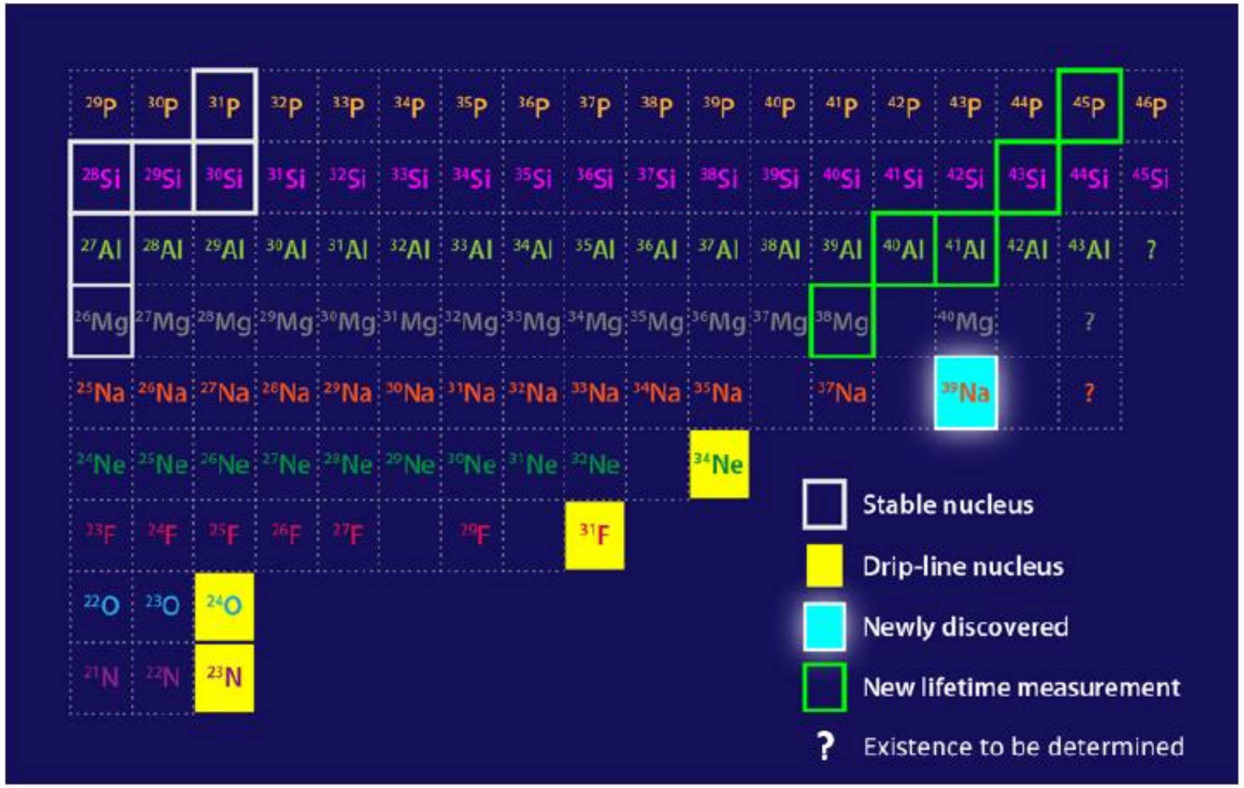
- The idea is to perform experiments with very exotic ions at 40-70MeV/u kinetic energies
- Both directions, towards p-drip and n-drip can be explored
- FAZIA can explore part of this region and also heavier ions up to around Z=20

Y. Blumenfeld et al. Physics 15, 177 (2022)



The region of n-rich nuclei from N to P as it is known today.
The yellow nuclei are at the n-drip

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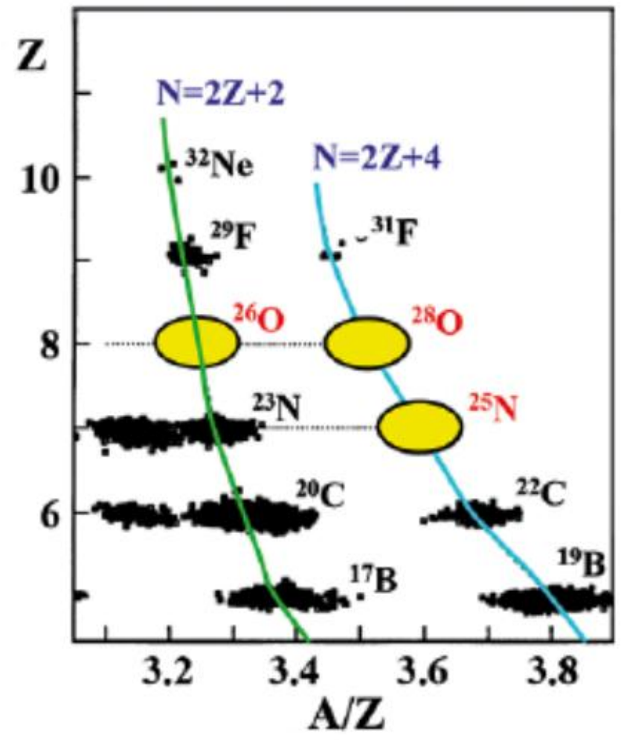
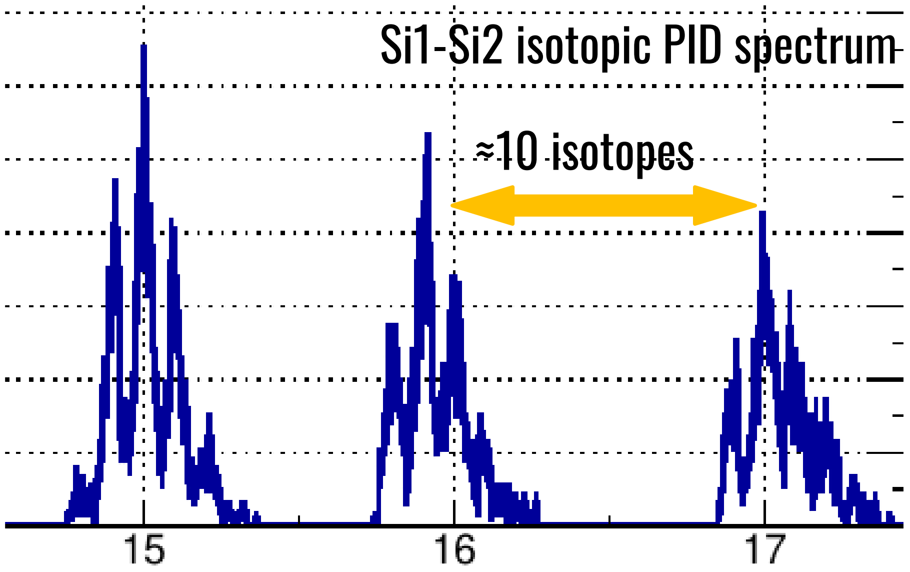
Most experiments towards the drip lines
(either to assess the drip nuclei either to inform on exotic species properties)
have been made with mass spectrometers

The FAZIA structure (+-0.6deg granularity)
will allow to detect and identify the main QP species up to Z=20
but also, LCP and cluster in coincidence
to attempt correlation and reconstruction studies

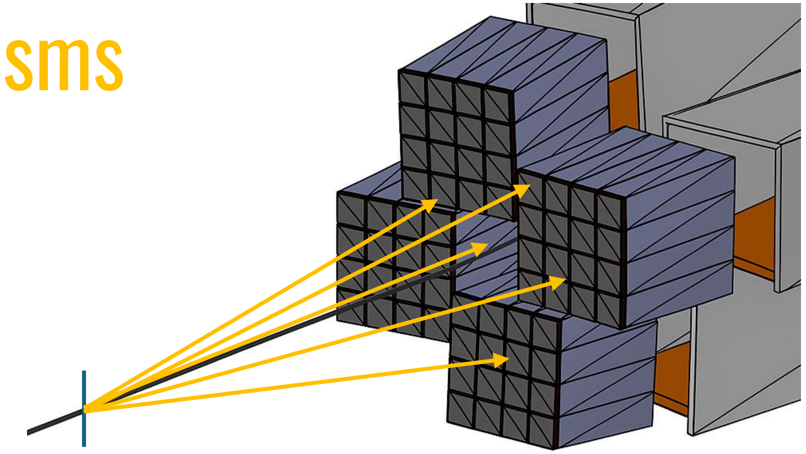
M. Notani et al. Phys.Rev.C 76 044605 (2007)





FAZIAEXPLORER: foreseen reaction mechanisms

- QP fragmentation: e.g. 53Ti, 70Ni+12C – Wall configuration
  Relatively light neutron-rich beams in reverse kinematics
  Detection of the light and exotic charge produced



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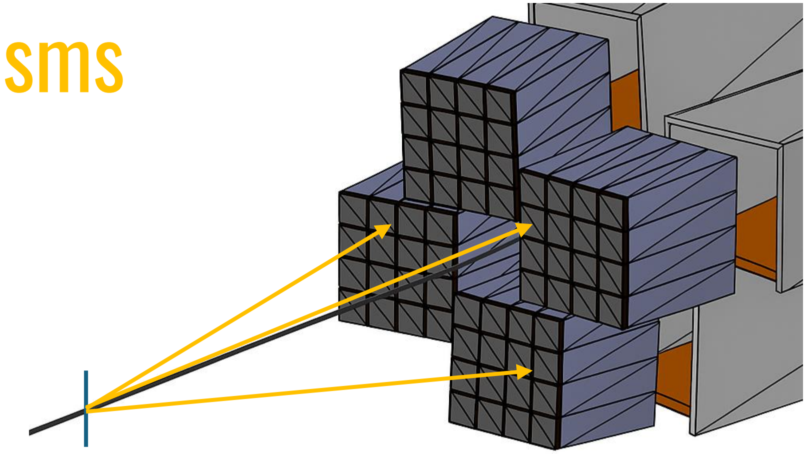

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- MNT reactions: e.g. 53Ti+124Sn, 209Bi – Wall configuration
  starting from very exotic beams, exploit the MNT reactions to populate even more exotic QP ions.
  Detection of the heavy exotic scattered nucleus and accompanying particles

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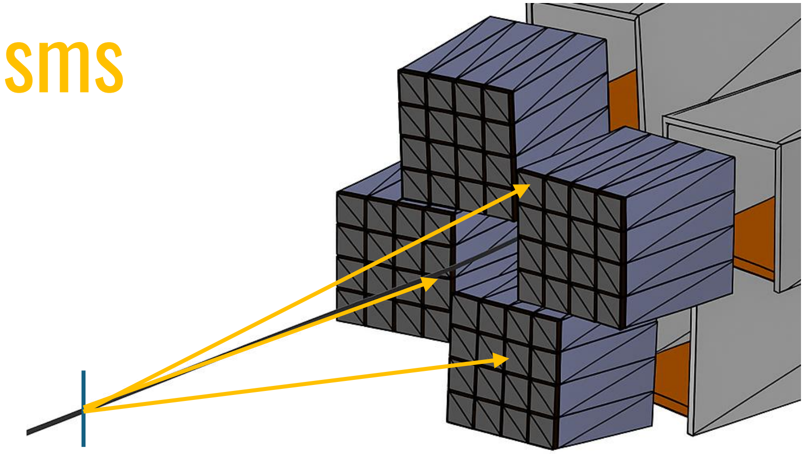

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- Fast fission: e.g. 130Sn,106Sn+12C – Wall configuration
  Heavy exotic beams on light targets to study in a complete way the fast fission channel far from stability

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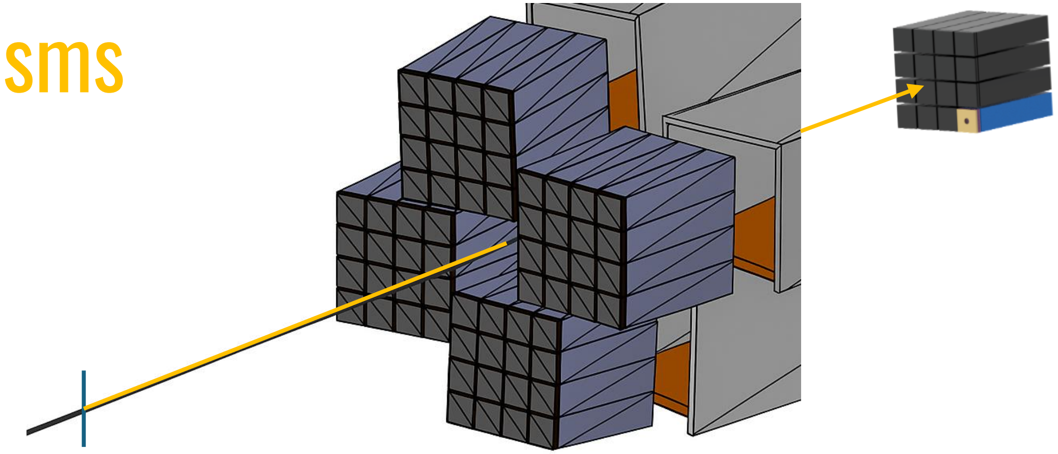

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- Not reacted beam: e.g. . 35Ca,53Ca – ZeroDegree configuration
  For ions available only with very low currents some cross sections (interaction, charge exchange) could be measured with the transmission method

FAZIAEXPLORER: some possible beams

From https://frib.msu.edu/user-facilities/frib/calculator

- QP fragmentation
- MNT reactions
- Fast fission
- Not reacted beam

beam isotope energy (MeV/nucl.)	target species (thickness mg/cm^2)	θ_g deg	current 10^6(pps)	prod rate (cps) with 1μbarn D)	time for 10 hits	method E)
^{68}Ni 60	^{12}C (1)	0.4	58	2.8 10^{-3}	5 h A)	fragm
^{70}Ni 60	^{12}C (1)	0.4	1	5 10^{-5}	11.5 d A)	fragm
^{70}Ni 60	Al (1)	0.7	1	4.4 10^{-5}	26.5 d A	fragm
^{70}Ni 60	^{124}Sn (1)	2.2	1	4.6 10^{-6}	125 d A)	fragm
^{56}Ni 60	^{12}C (1)	0.5	400 C)	2 10^{-2}	2500 s A)	fragm
^{53}Ti 60	^{12}C (1)	0.4	4.8	2.4 10^{-4}	2.5 d A)	fragm
^{53}Ti 60	^{124}Sn (1)	3	4.8	2.4 10^{-5}	24 d A)	fragm
^{52}Ti 60	^{12}C (1)	0.4	20	1 10^{-4}	14 h A)	fragm
^{43}Ti 60	^{12}C (1)	0.5	10	5 10^{-4}	28 h A)	fragm
^{130}Sn 60	^{12}C (1)	0.3	1.4	7 10^{-5}	33 d B)	fragm
^{106}Sn 60	^{12}C (1)	0.4	6	3 10^{-4}	7.5 d B)	fragm
^{53}Ca 60	^{12}C (1)	–	$<$ 0.001	—	—	transm
^{35}Ca 60	^{12}C (1)	–	$<$ 0.001	—	—	transm

Some ingredients

- Primary current:
  FRIB online culculator & factor 5 (conservely) for energy-degrade beams
- Target thickness:
  fixed at 1mg/cm2 & pencil beam (beam dimension not an issue for energy degraded beams)
- Production rate: for a channel at 1ubarn level
- Time for 10hits:
  assuming 20% efficiency for 2b
  5% efficiency for 3b channels

The FAZIA "Yellow Brick Road"

ReAccelerate beams (<10 AMeV)

Energy degraded fragmentation beams (20-100 AMeV)

Primary fragmentation beams (>150 AMeV)

FAZIAEXOTIC

Exploring exotic clustering configurations

Coupled with OSCAR-like
Coupled with FROG-like

How? What FAZIA can offer?
Are we ready for that?

FAZIAEXPLORER

Exploring the limit of the drip lines

Possible coupling with GAMMA arrays

How? What FAZIA can offer?
Are we ready for that?

SYMEOS

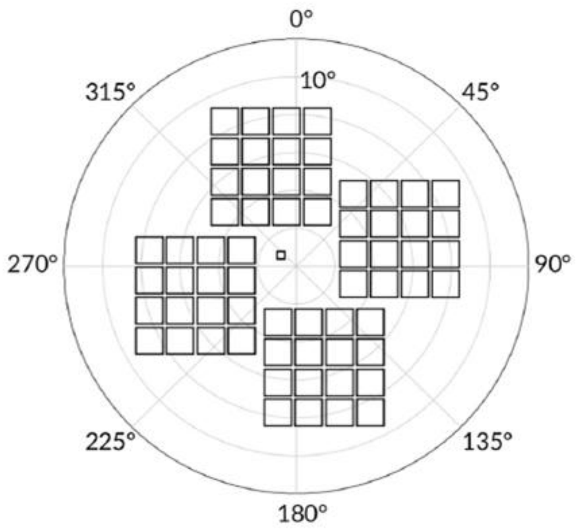
Investigation of the nuclear equation of state at supra-saturation densities

Coupled with local HIRA, LANA, FROG
Coupled with other INFN detectors

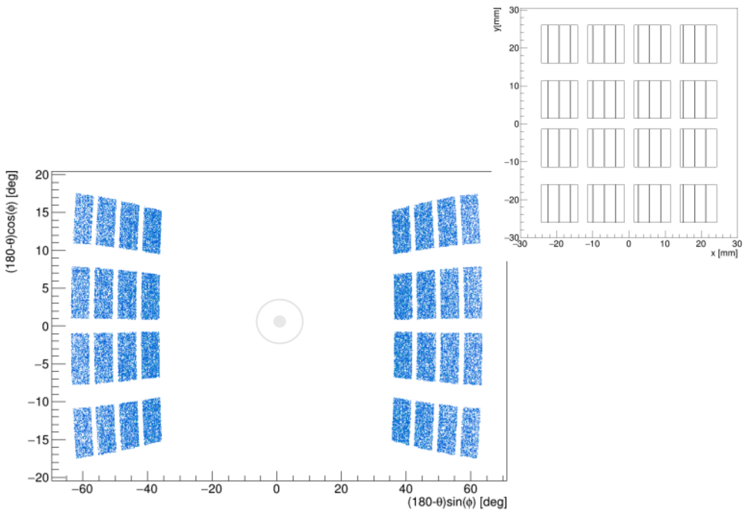
What FAZIA can offer?
Are we ready for that?

FAZIAEXOTIC: for ReA and primary E degraded beams

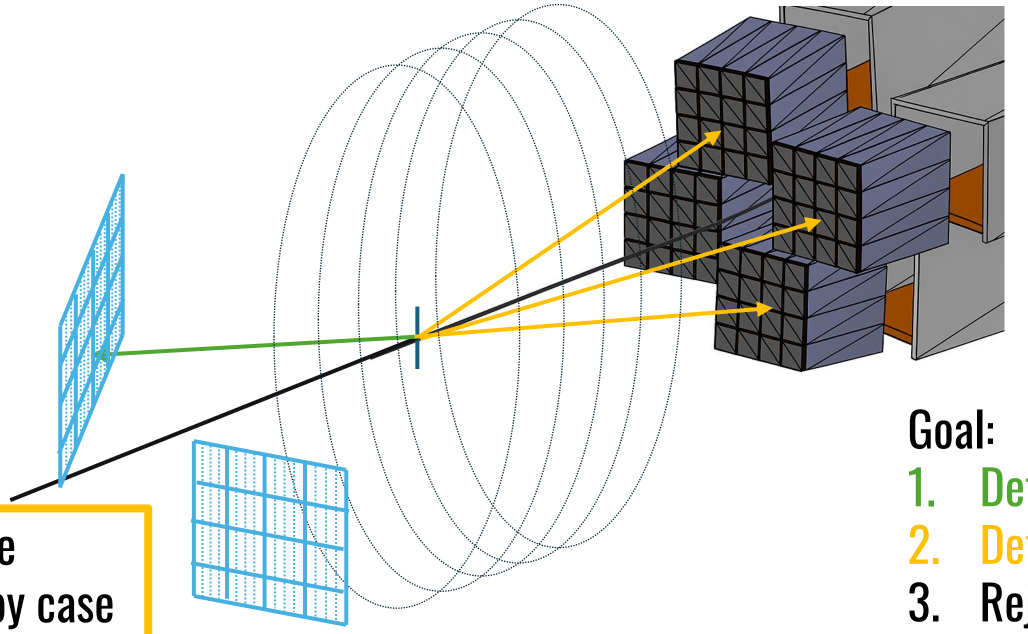
- Beam range: <10 MeV/u but also 30-80 MeV/u
- Same 4 FAZIA block configuration plus
  1. Position sensitive detector with low energy thresholds placed at backwards/forward angles. e.g. OSCAR modules
     D. Dell'Aquila et al., NIM A 877 (2018) 227-237
  2. Large acceptance detector e.g FROG-like or MicroBall
     D. G. Sarantites et al, NIM A 381, 418 (1996)



4 FAZIA Block polar plot



2 OSCAR modules polar plot
d = 100 mm
θ_c = 130 deg
ϕ_c = 90 deg



Geometry to be decided case by case

Goal:
1. Detect target recoil
2. Detect projectile decay product(s)
3. Reject fusion-evaporation events

FAZIAEXOTIC: for ReA and primary E degraded beams

- Beam range: <10 MeV/u but also 30-80 MeV/u

- Same 4 FAZIA block configuration plus

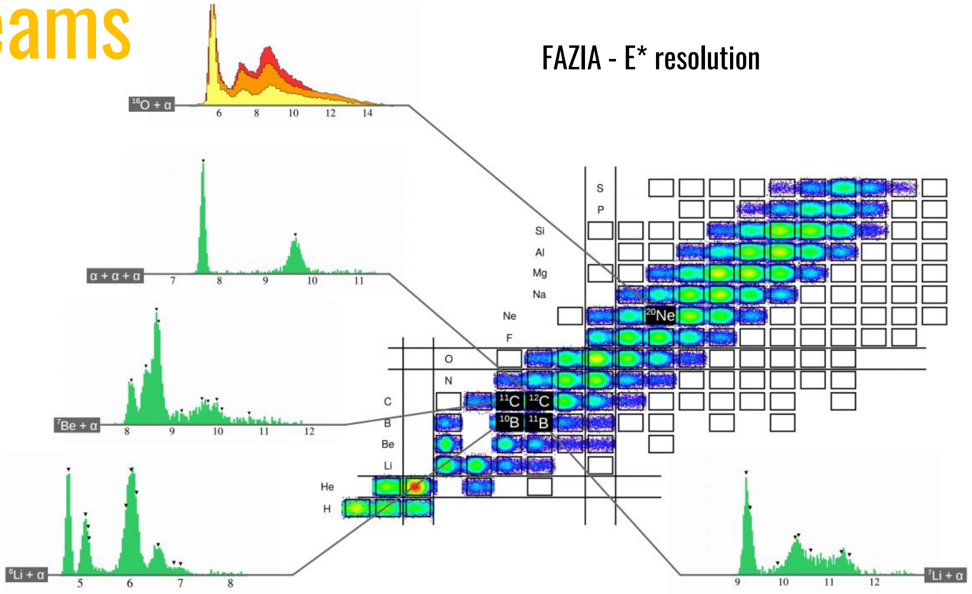
    1. Position sensitive detector with low energy thresholds placed at backwards/forward angles. e.g. OSCAR modules
    D. Dell'Aquila et al., NIM A 877 (2018) 227-237

    2. Large acceptance detector e.g FROG-like or MicroBall
    D. G. Sarantites et al, NIM A 381, 418 (1996)

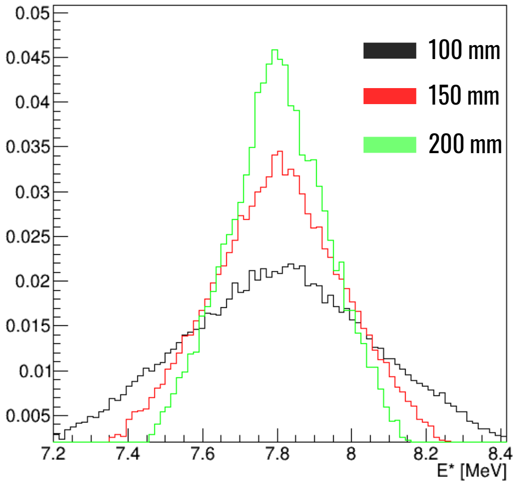
- Combination of *missing-mass* and *invariant-mass* methods B. Yang et al., Phys. Rev. C 99, 064315 (2019)
    1. Access E* nuclei of interest
    2. Access J:
        a. from recoil target nuclei
        b. from decay products (if $M_{riv}>2$) M. Freer, NIM A 383 (1996) 463-472

    3. Estimate decay branching ratio

FAZIA - E* resolution



OSCAR-like E* resolution

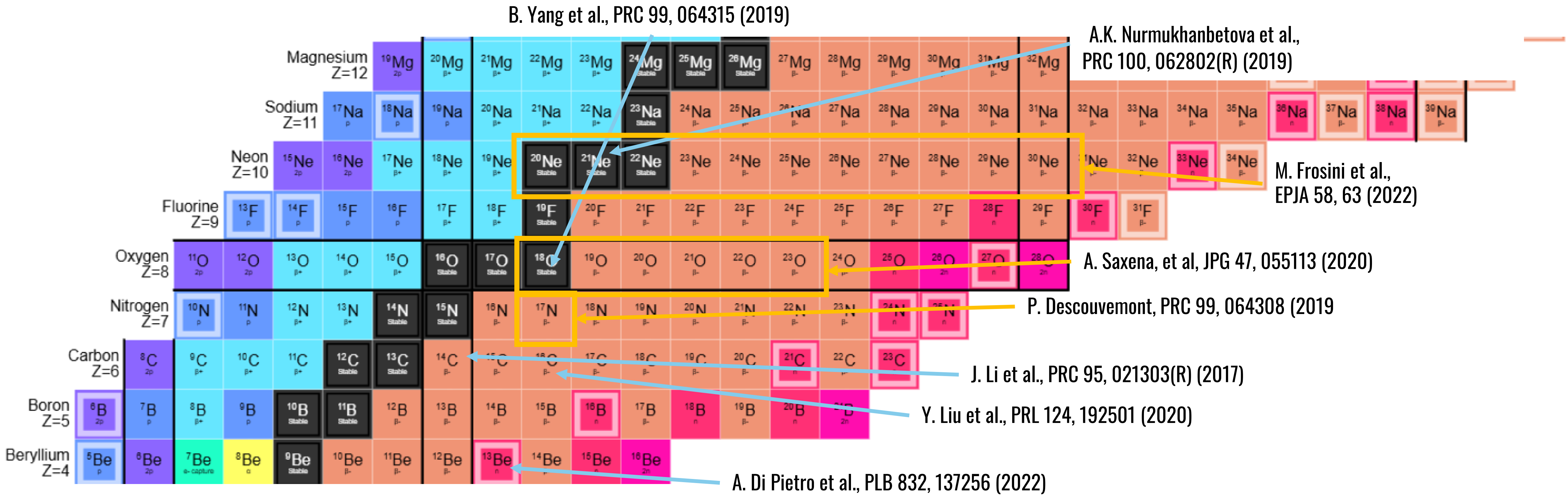


FAZIAEXOTIC: searching for exotic configurations

see A. di Pietro Talk

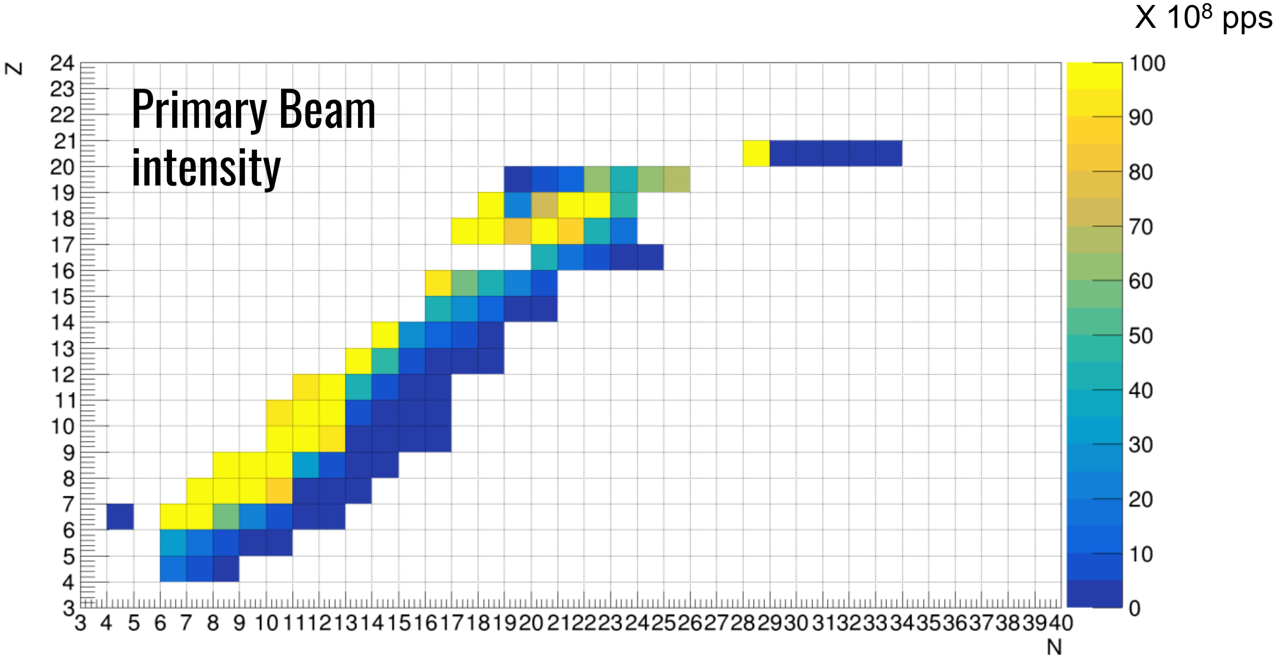
- Such a technique may be applied to search for the occurrence of exotic (alpha-)cluster configuration moving towards the n-drip line
- Even if some studies on dedicated even Z nuclei exist in the vicinity of the valley of stability, we are still in front of a quite-unexplored landscape
- Some (non-exhausting) recent available experimental information:

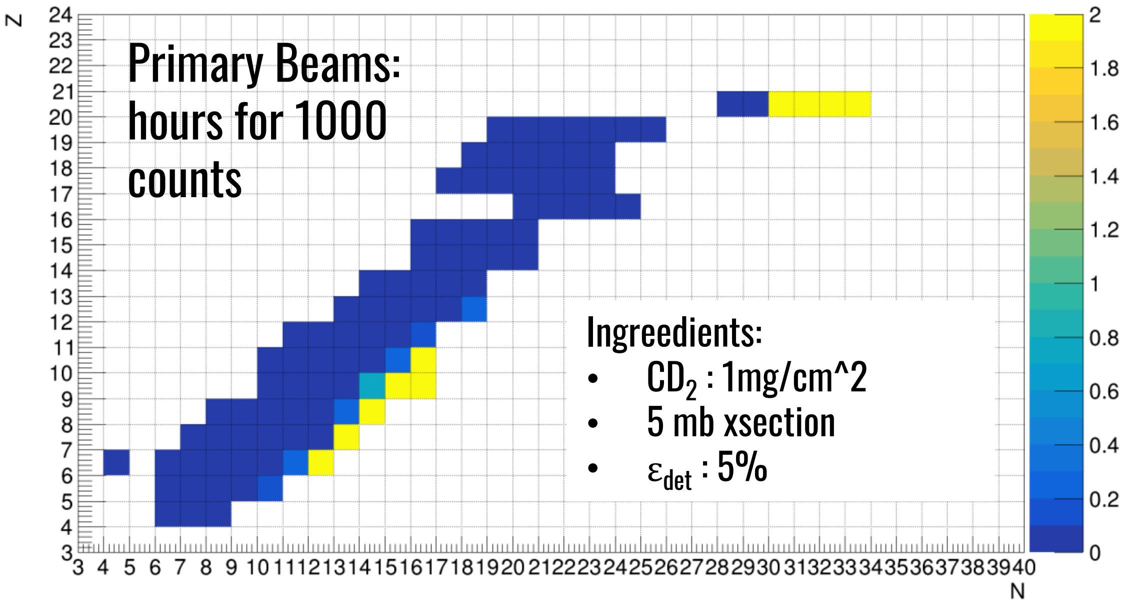
I. Lombardo, D. Dell'Aquila,
La Rivista del Nuovo Cimento 46, 521–618, 2023

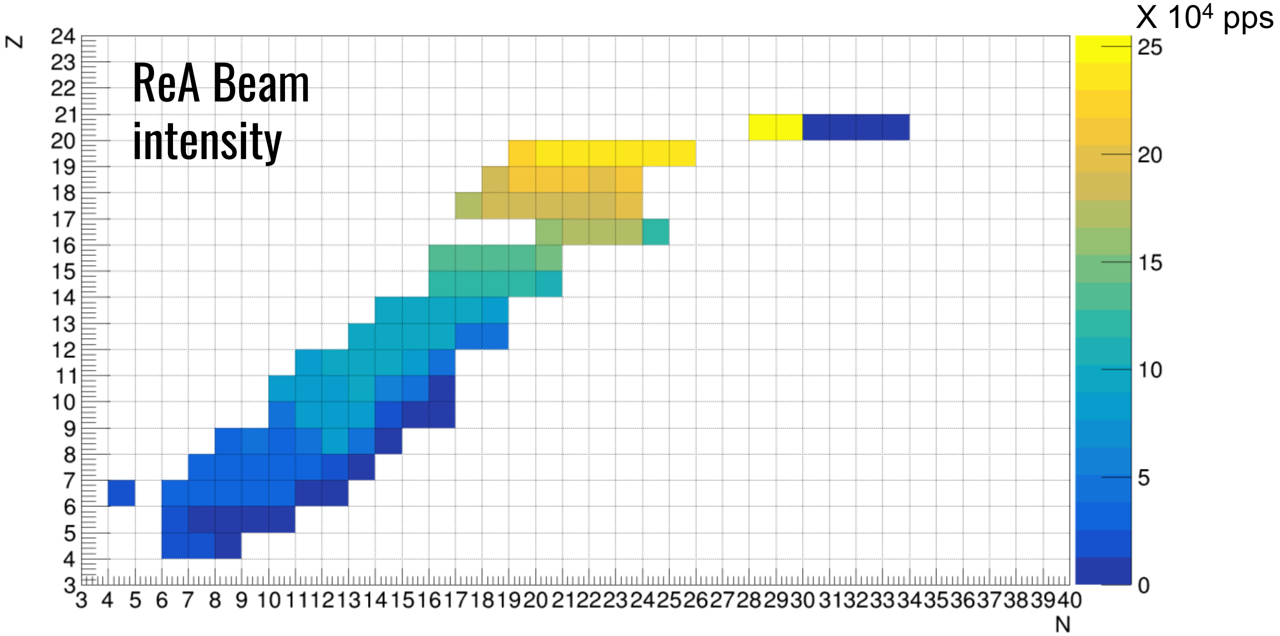


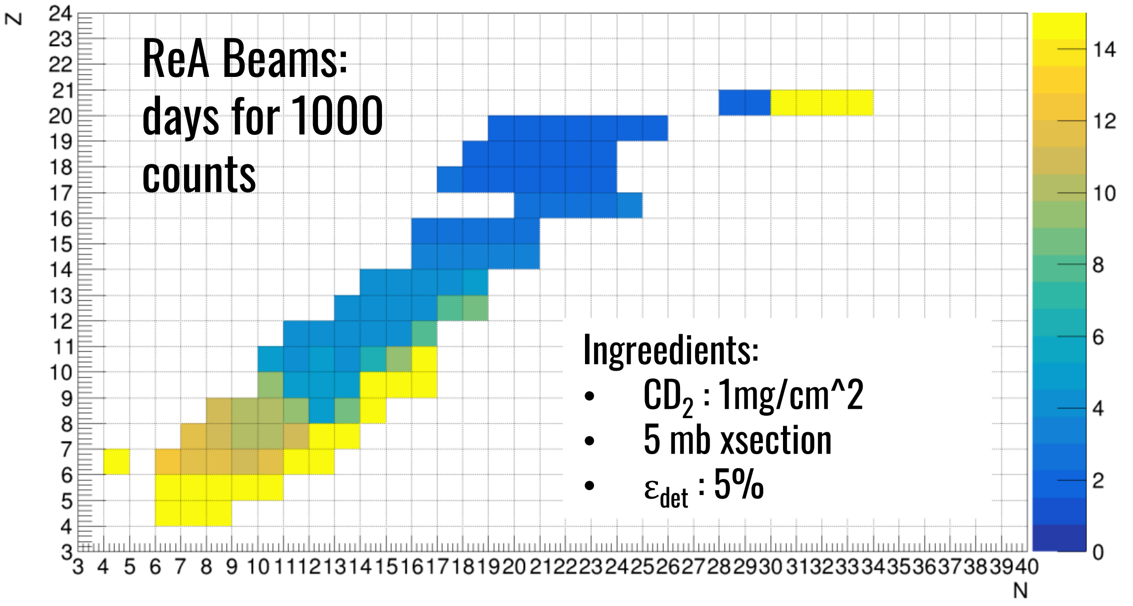
FAZIAEXOTIC: beams and rates

From https://frib.msu.edu/user-facilities/frib/calculator









Conclusions

ReAccelerate beams (<10 AMeV)	Energy degraded fragmentation beams (30-100 AMeV)	Primary fragmentation beams (>150 AMeV)

~~Conclusions~~ → Starting Point

ReAccelerate beams (<10 AMeV)

Energy degraded fragmentation beams (30-100 AMeV)

Primary fragmentation beams (>150 AMeV)

FAZIAEXOTIC

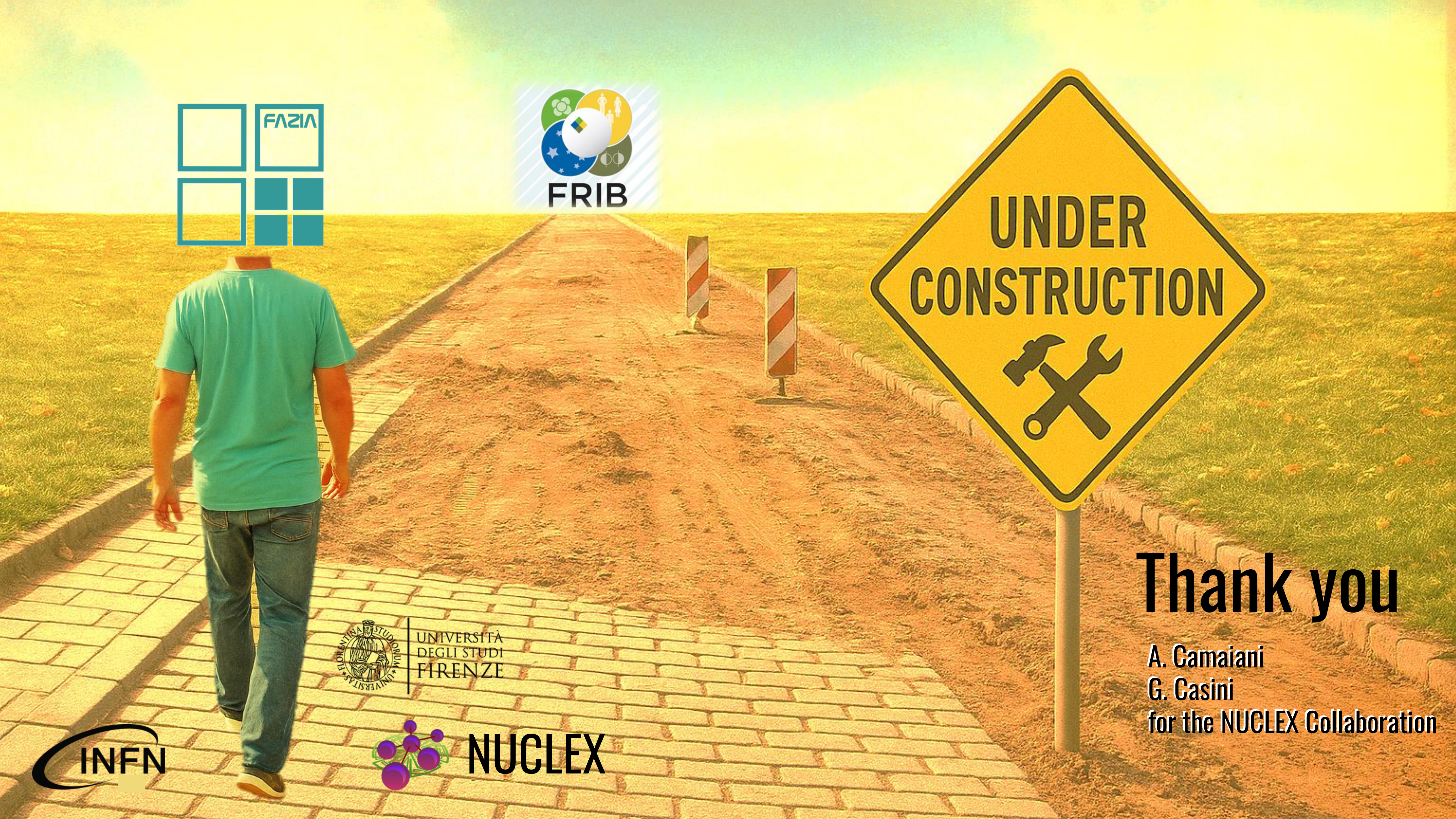
- Multi-particle detection from exotic nuclei
- To be coupled to other detector to tag the reaction
- FAZIA is ready
- Are the rates a limit?

FAZIAEXPLORER

- FAZIA as a surrogate of mass spectrometer (Z<20) exploring the n-drip lines
- FAZIA is ready
- Are the rates a limit?

SYMEOS

- We can extend the phase space covered
- Completementary/auxiliary observable for n/p
- Observables to shed lights on clusterization processes in hot and compressed medium
- FAZIA is ‘’ready’’ but thicker Si stages are usefull. Work is on going

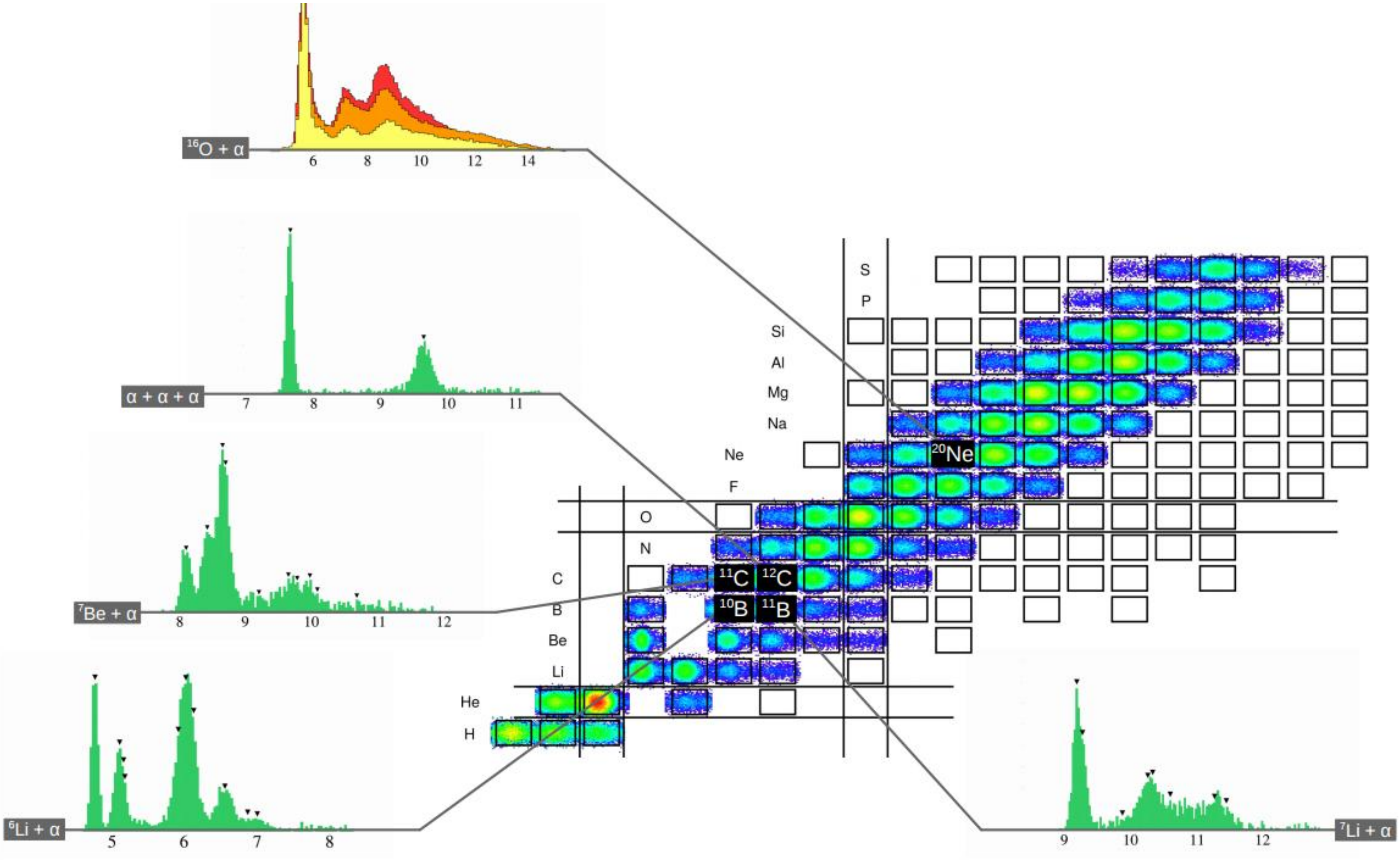

FAZIA
FRIB
UNDER CONSTRUCTION
Thank you
A. Camaiani
G. Casini
for the NUCLEX Collaboration
UNIVERSITÀ DEGLI STUDI FIRENZE
INFN
NUCLEX

Stopped Beams

Beam rates for experiments in the stopped beam areas and for delivery to ReAccelerator (ReA) have been estimated based on observed performance of the Advanced Cryogenic Gas Stopper (ACGS). The estimates assume optimal conditions and are only intended to provide a rough indication of experiment feasibility. Actual rates will likely be less. The rate estimates take into account the transport efficiency for fast beams from the ARIS separator to the gas stoppers and the stopping efficiency, calculated with LISE++ assuming optimum fast beam momentum compression settings. Also included is a parametrization of the extraction efficiency from the gas stopper as a function of the ion mass and the incoming fast beam rate. Stopping efficiency range from a maximum of 95% for heavy ions to 10% for low atomic numbers. Extraction efficiency vary from 20% for mass numbers A > 6 to near unity for A > 70. Decay losses are considered using measured extraction times that vary from 15 ms for light ions to 60 ms for heavy ions. The possible effect of radio-molecule formation that can lead to lower delivered beam rates is not taken into account. Atomic numbers lower than four were excluded from rate estimates.

Reaccelerated beams

Beam intensities in the reaccelerated beam areas have been estimated using the stopped beam intensities multiplied by efficiencies for the Beam-Cooler-Buncher (BCB), the Electron Beam Ion Trap (EBIT) charge breeder, and the ReA-linac. The efficiencies are based on data from experiment runs and beam tests. The BCB efficiency ranges from 15% for ions with A50. Decay losses in the EBIT are considered assuming an average breeding time of 100 ms. The ReAlinac and beamline transport efficiencies are assumed to be 60%.



$^{16}O + \alpha$
6 8 10 12 14
$\alpha + \alpha + \alpha$
7 8 9 10 11
$^{7}Be + \alpha$
8 9 10 11 12
$^{6}Li + \alpha$
5 6 7 8
$^{7}Li + \alpha$
9 10 11 12
S
P
Si
Al
Mg
Na
Ne
F
O
N
C
B
Be
Li
He
H
^{20}Ne
^{11}C
^{12}C
^{10}B
^{11}B

FAZIAEXOTIC: possible beams and reactions .... To be fineshed

Z	A	Fast	Stopped	Reaccelerated [pps]
4	10	8.17e+9	7.50e+5	2.02e+4
4	11	2.56e+9	8.06e+5	2.17e+4
5	11	1.73e+10	8.07e+5	1.45e+4
6	12	5.13e+10	8.59e+5	3.09e+4
6	13	4.82e+10	9.07e+5	3.26e+4
6	14	2.90e+10	9.51e+5	3.42e+4
6	15	1.10e+10	9.88e+5	3.46e+4
6	16	3.60e+9	1.02e+6	3.33e+4
6	17	3.95e+7	4.98e+5	1.25e+4
7	14	1.04e+11	9.51e+5	3.42e+4
7	15	8.83e+10	9.92e+5	3.57e+4
7	16	9.01e+10	1.03e+6	3.67e+4
7	17	4.38e+10	1.06e+6	3.77e+4
7	18	1.24e+9	1.08e+6	3.48e+4
7	19	1.79e+8	6.08e+5	1.78e+4
8	16	3.57e+13	9.66e+5	3.48e+4
8	17	1.32e+11	1.07e+6	3.84e+4
8	18	3.12e+13	1.03e+6	3.72e+4
8	19	1.57e+10	1.13e+6	4.07e+4
8	20	4.62e+9	1.16e+6	8.33e+4
8	21	4.31e+7	6.19e+5	4.37e+4
9	19	8.75e+10	1.13e+6	4.08e+4
9	20	9.50e+10	1.16e+6	8.32e+4
9	21	4.52e+10	1.19e+6	8.43e+4
9	22	5.80e+8	1.14e+6	8.09e+4
9	23	1.59e+7	3.13e+5	2.19e+4
10	20	4.64e+10	1.16e+6	8.38e+4
10	21	1.27e+11	1.19e+6	8.59e+4
10	22	2.24e+13	1.14e+6	8.24e+4
10	23	2.91e+9	1.25e+6	8.97e+4
10	24	3.44e+8	8.75e+5	6.30e+4
10	25	3.90e+7	6.24e+5	4.00e+4
10	26	5.25e+6	1.15e+5	5.81e+4