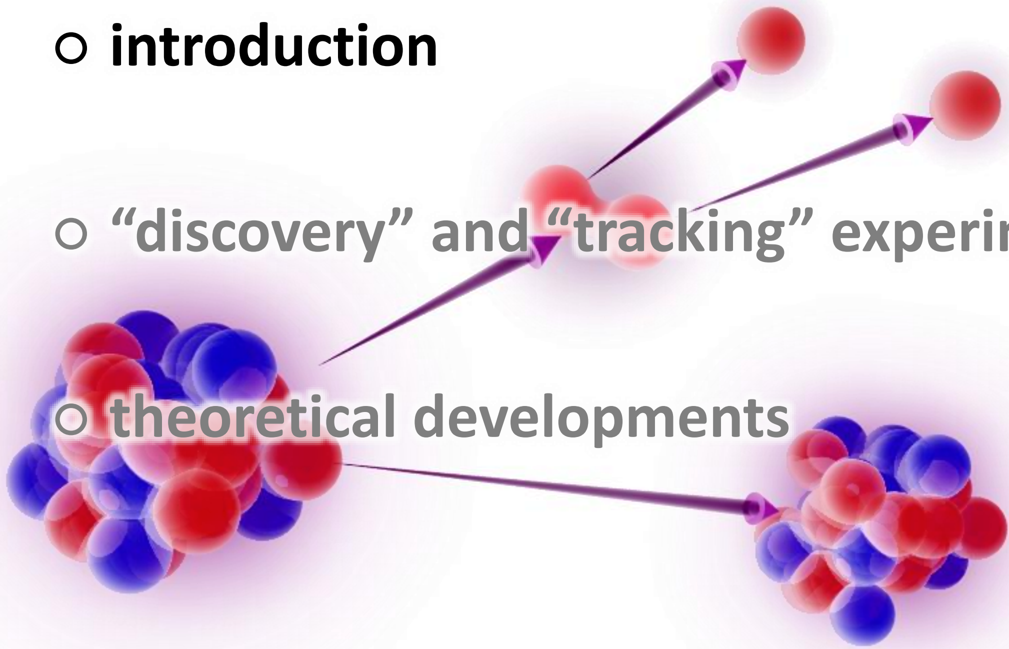
2-proton radioactivity opportunities at FAIR

J. Giovinazzo - CENBG

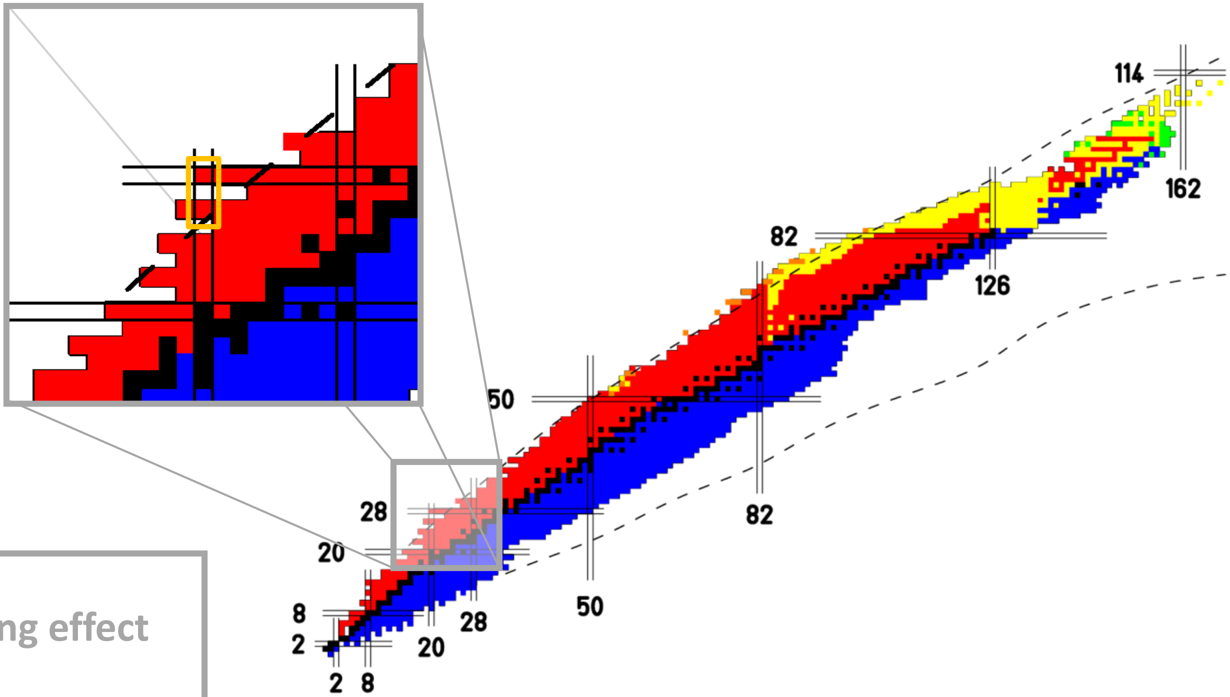
- status of 2P radioactivity studies
- ACTAR TPC: a new tracking device
- perspectives… at FAIR / (Super)FRS

2-proton radioactivity

- **introduction**
- **“discovery” and “tracking” experiments**
- **theoretical developments**



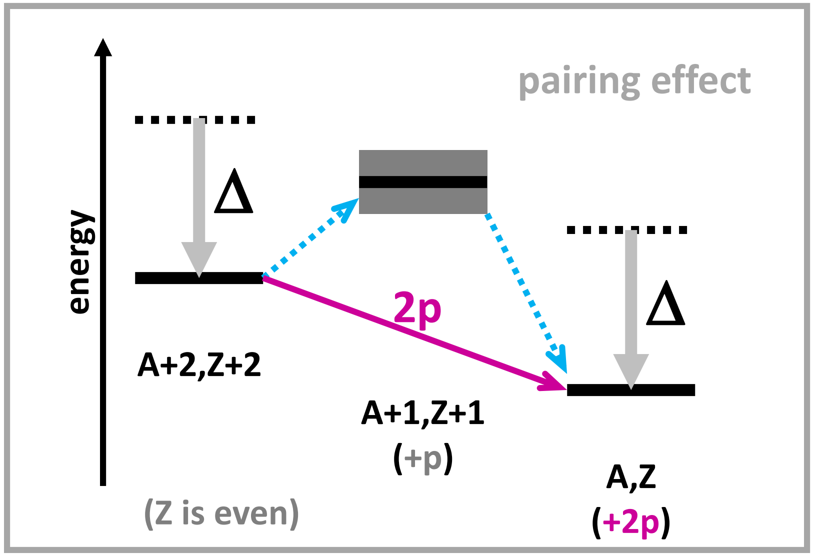
two-proton radioactivity: drip-line & pairing



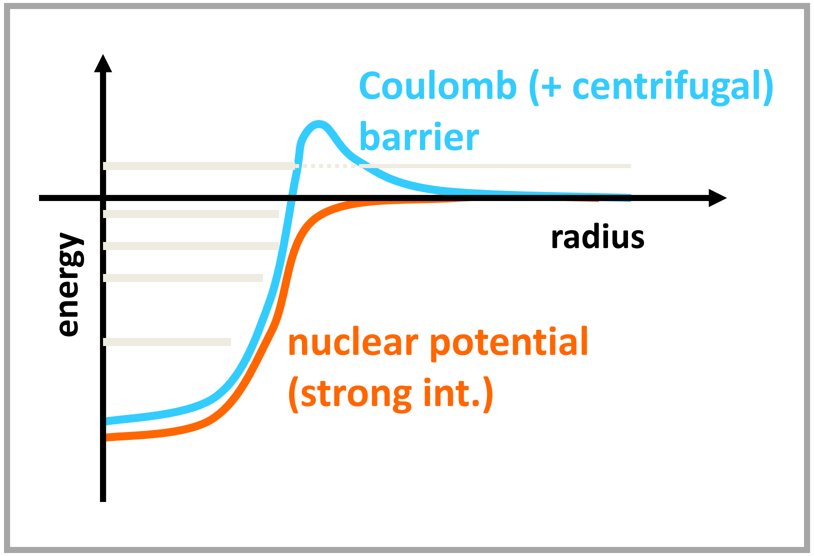
drip-line odd-even staggering

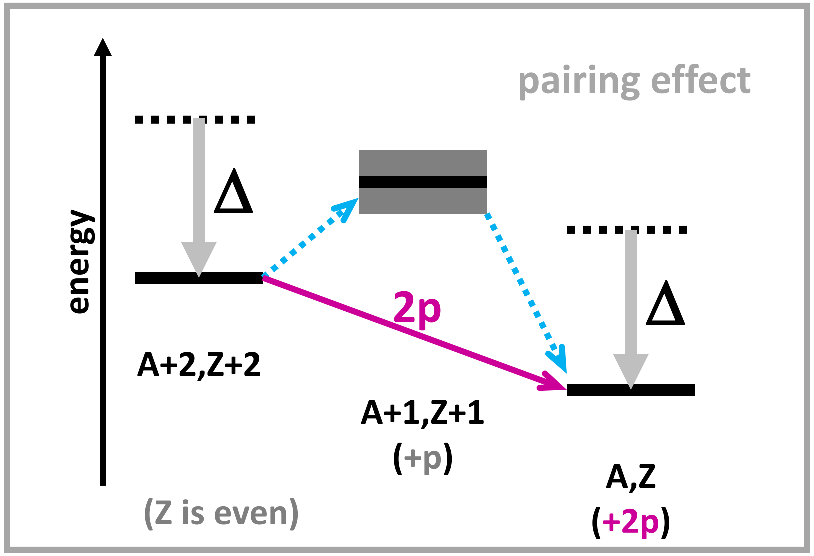
→ (quasi) **bound even Z**

→ **unbound odd Z**



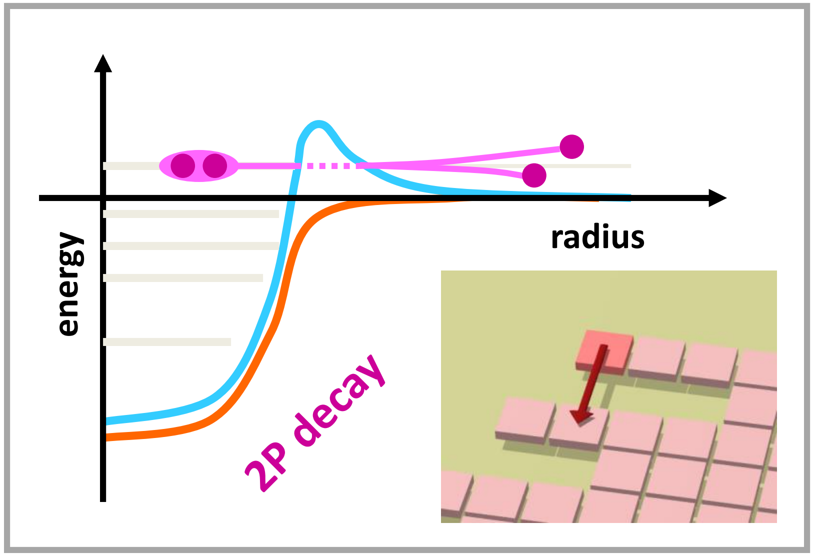
two-proton radioactivity: pairing & Coulomb barrier





even-Z isotope

1 proton emission forbidden
(so called "***true***" 2P radioactivity)



two-proton radioactivity

« exotic » radioactive decays

- 1-proton for **odd-Z** isotopes
- 2-protons for **even-Z** isotopes

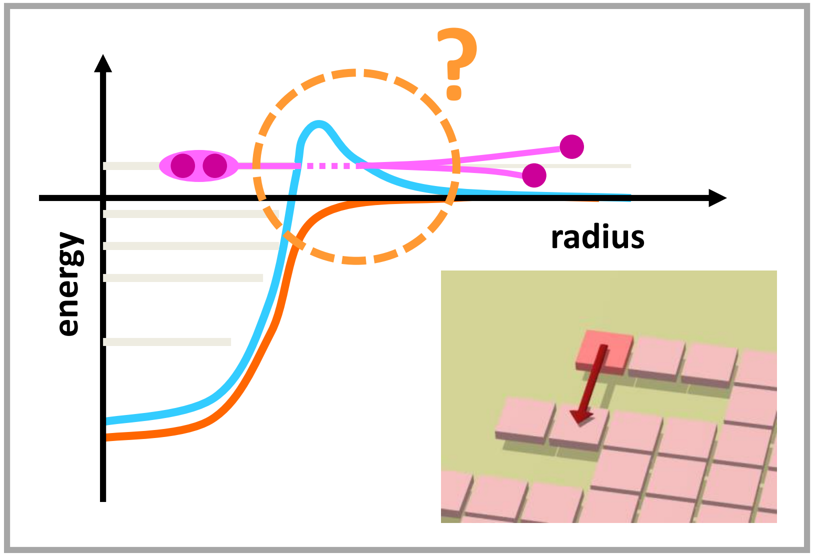
predicted in the 60's…

Zeldovich, first mention

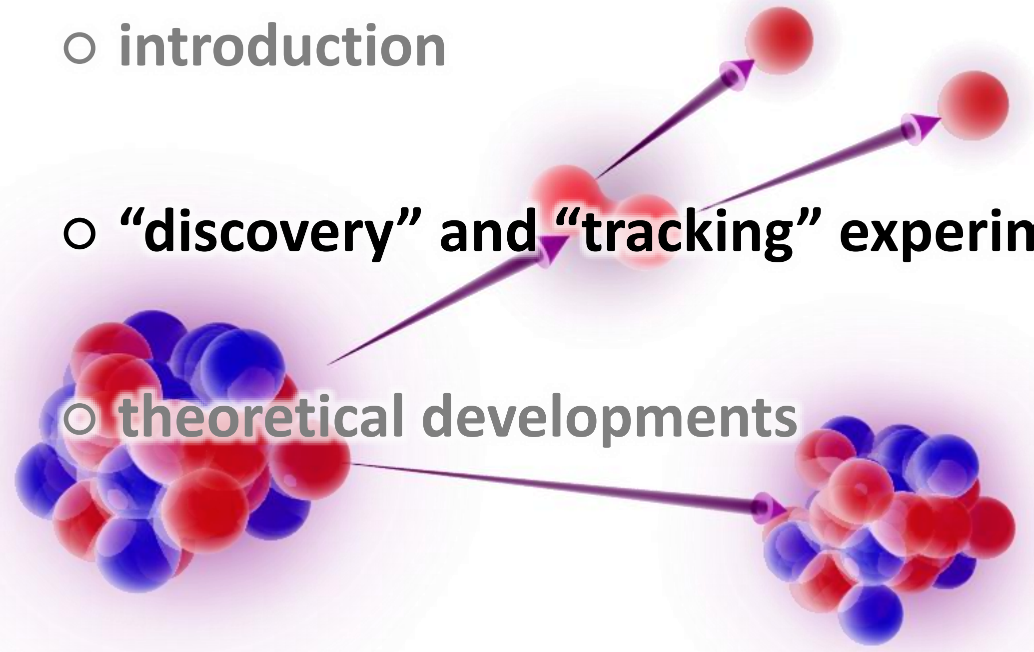
Goldanski, first description

physics motivation

- **drip-line and masses**
  transition Q-values
- **nuclear structure beyond drip-line**
  energies, half-life,
  levels configuration…
- **pairing**
  correlations in energy and angle of emitted protons
- **decay dynamics & tunnel effect**
  through **theoretical descriptions**



2-proton radioactivity



- introduction
- **“discovery” and “tracking” experiments**
- theoretical developments

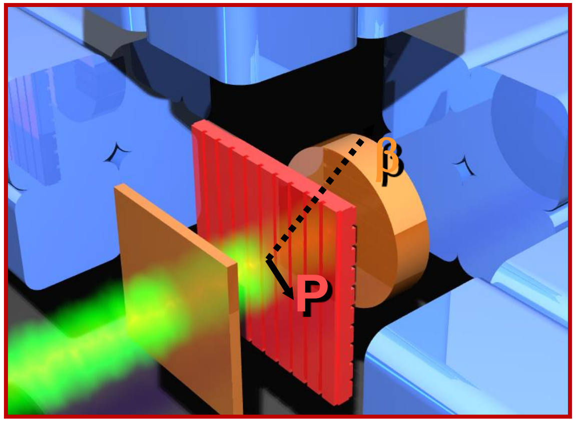
"discovery" experiment: indirect evidence

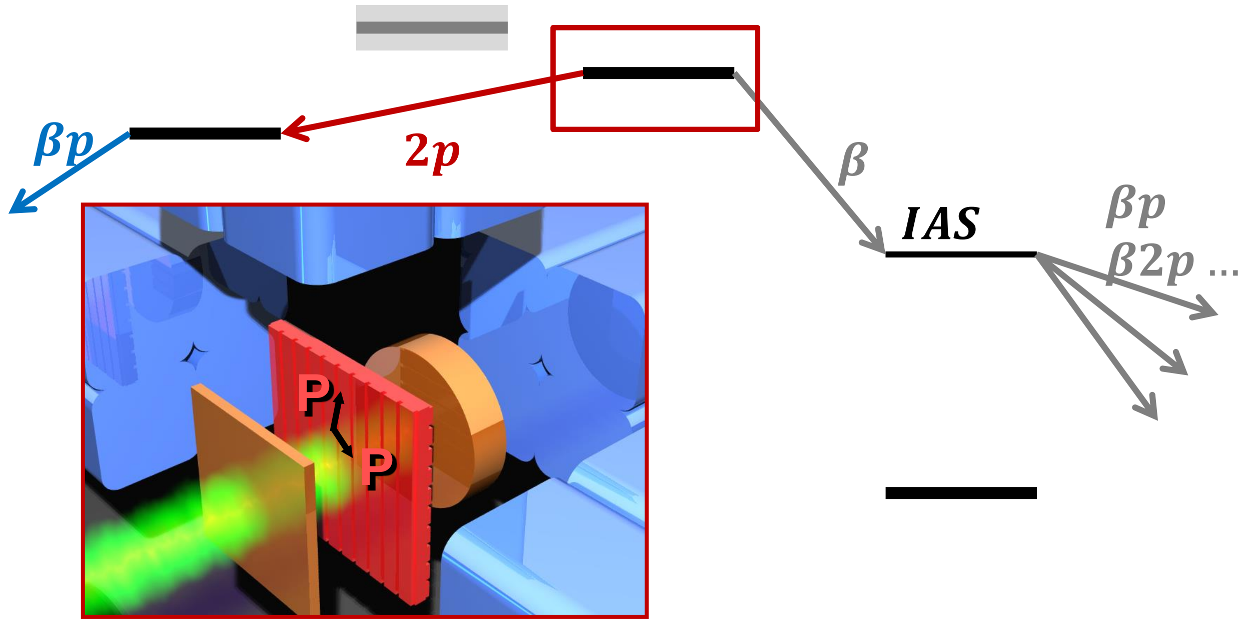
indirect observation of the process

- **projectile fragmentation** experiments
- implantation / decay in **thick detectors** (DSSSD)
- **global quantities**: $T_{1/2}$, Q_{2P} & BR_{2P}

  no β coinc., no γ (511 keV)

  daughter decay





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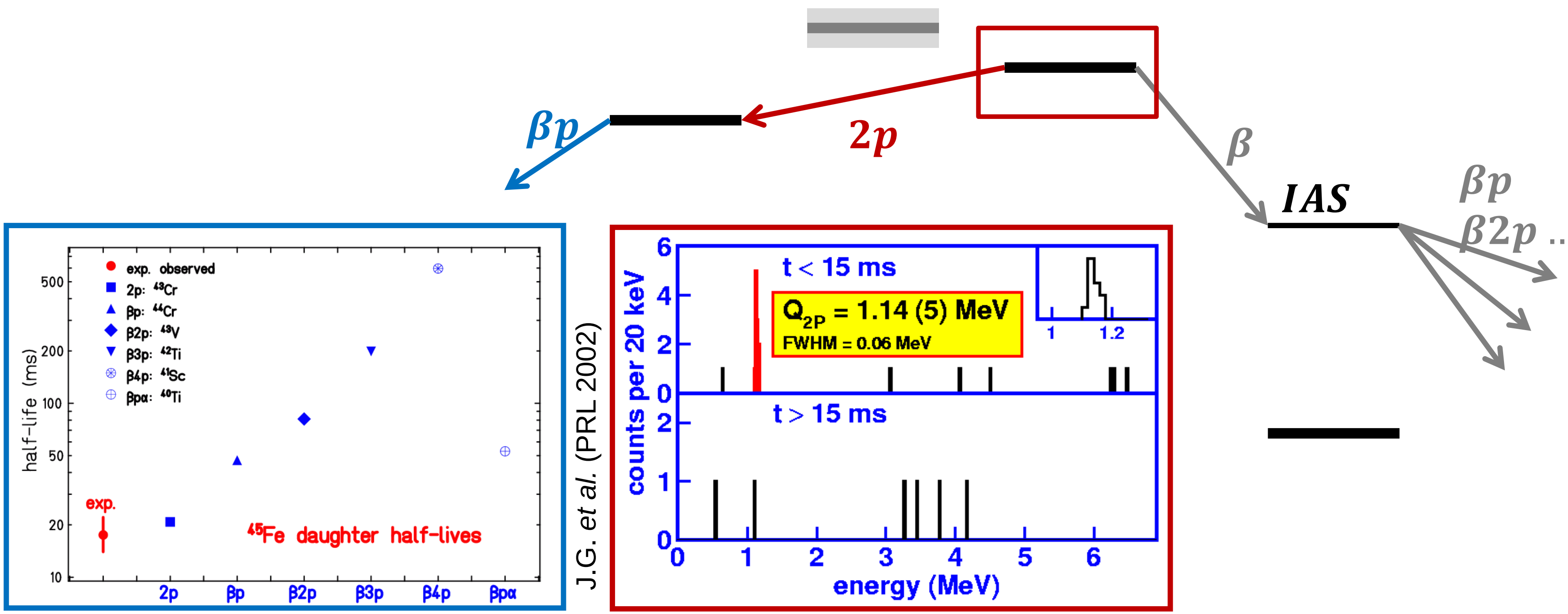

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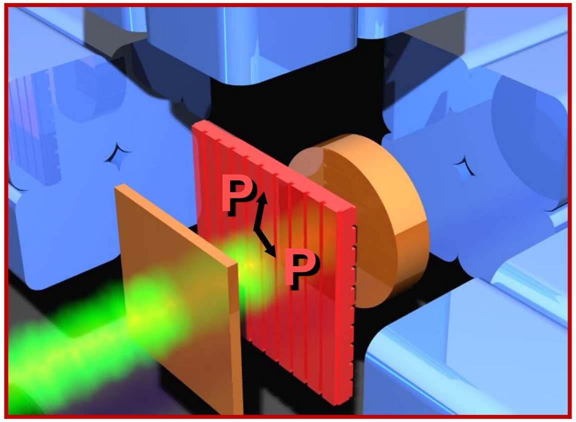

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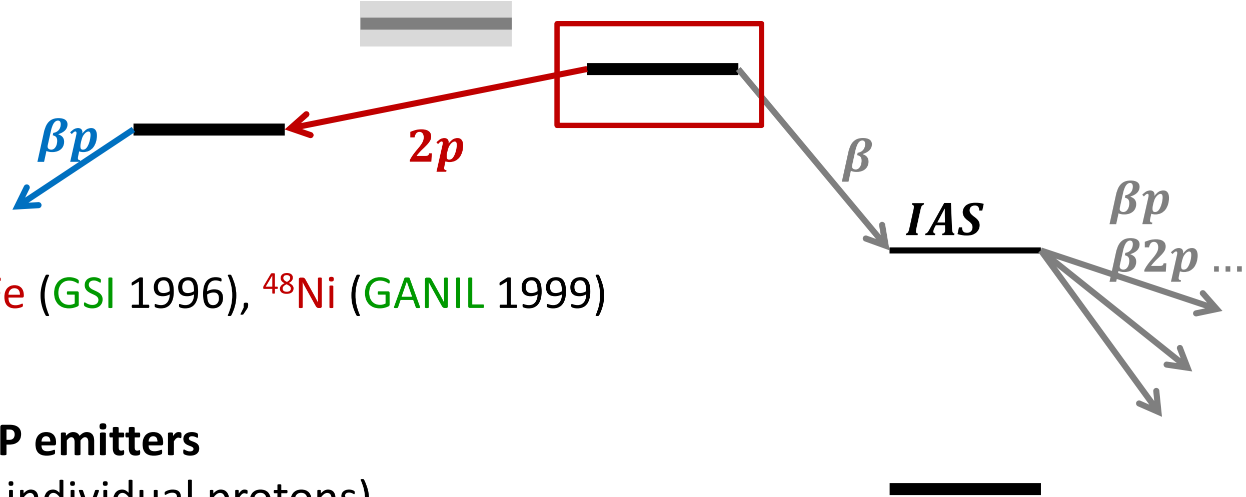


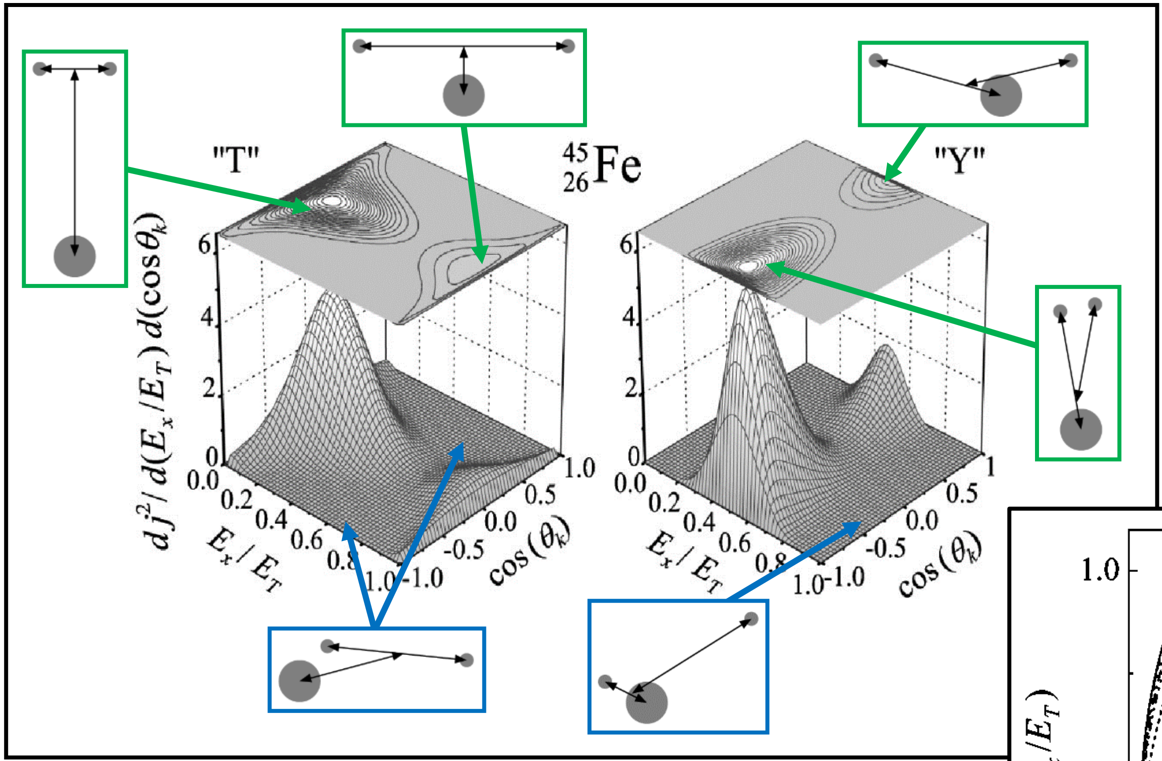
known emitters

- isotopes **discovery**: ^{45}Fe (GSI 1996), ^{48}Ni (GANIL 1999)
  (no decay data)

- **indirect signature of 2P emitters**
  (no information about individual protons)
  ▷ **first observation: ^{45}Fe (GANIL** 2002, **GSI** 2002)
  ▷ **other emitters ^{54}Zn (GANIL** 2005), (^{48}Ni (GANIL 2005) ?)

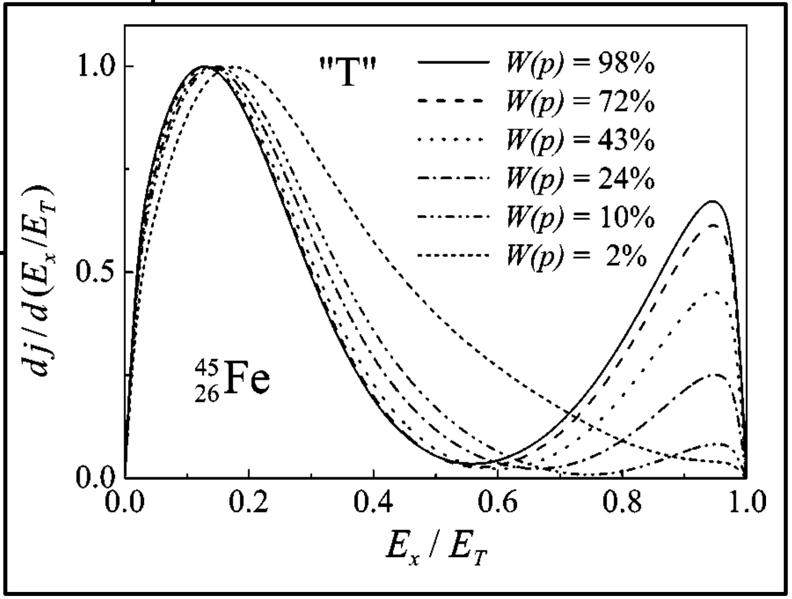
  ▷ **recent result: ^{67}Kr (RIKEN** 2016)

need for proton-proton correlations information



3-body model
developed by
L.V. Grigorenko

L.V. Grigorenko



prediction of distributions for
- **energy sharing between protons**
- **proton-proton angular correlations**

sensitive to involved orbitals

→ requires different experimental technique to measure correlations

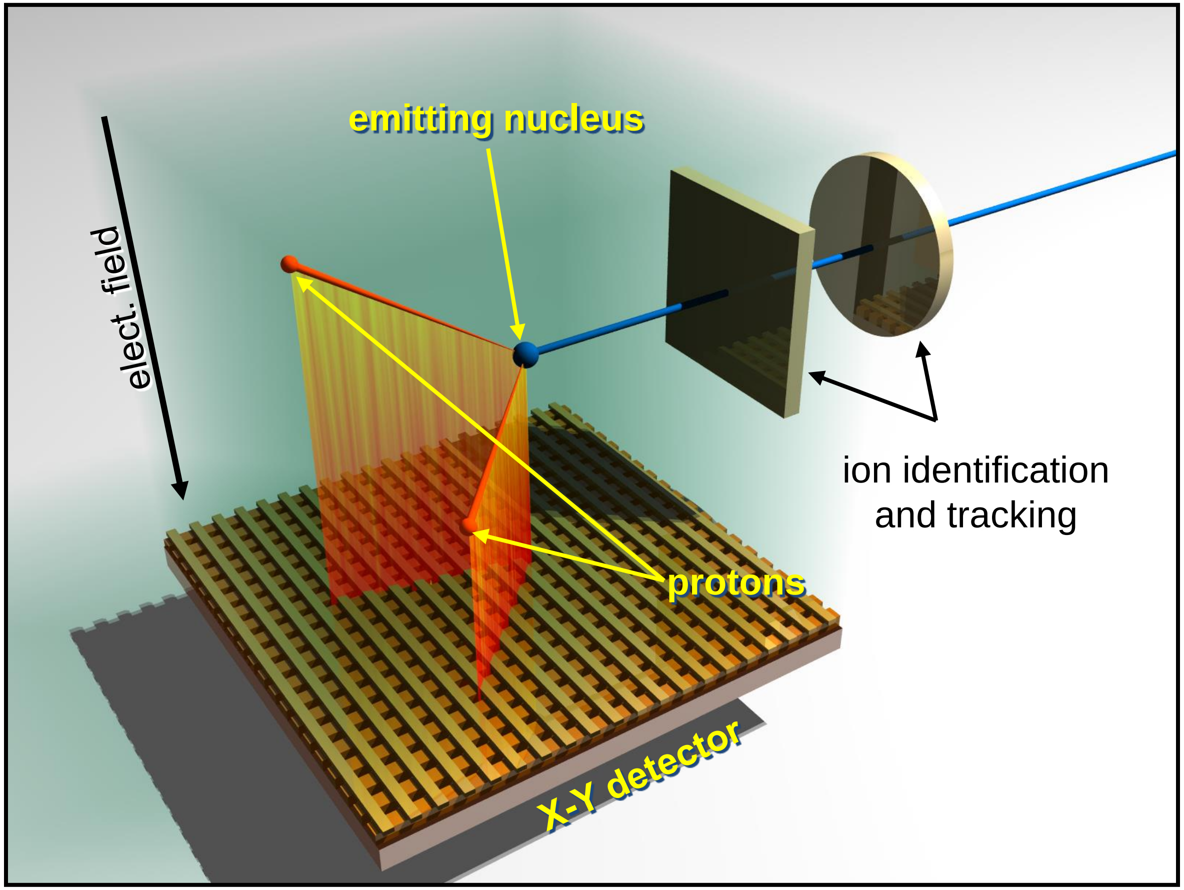
experiments with time projection chambers

charged particles slow down in a **gas volume**

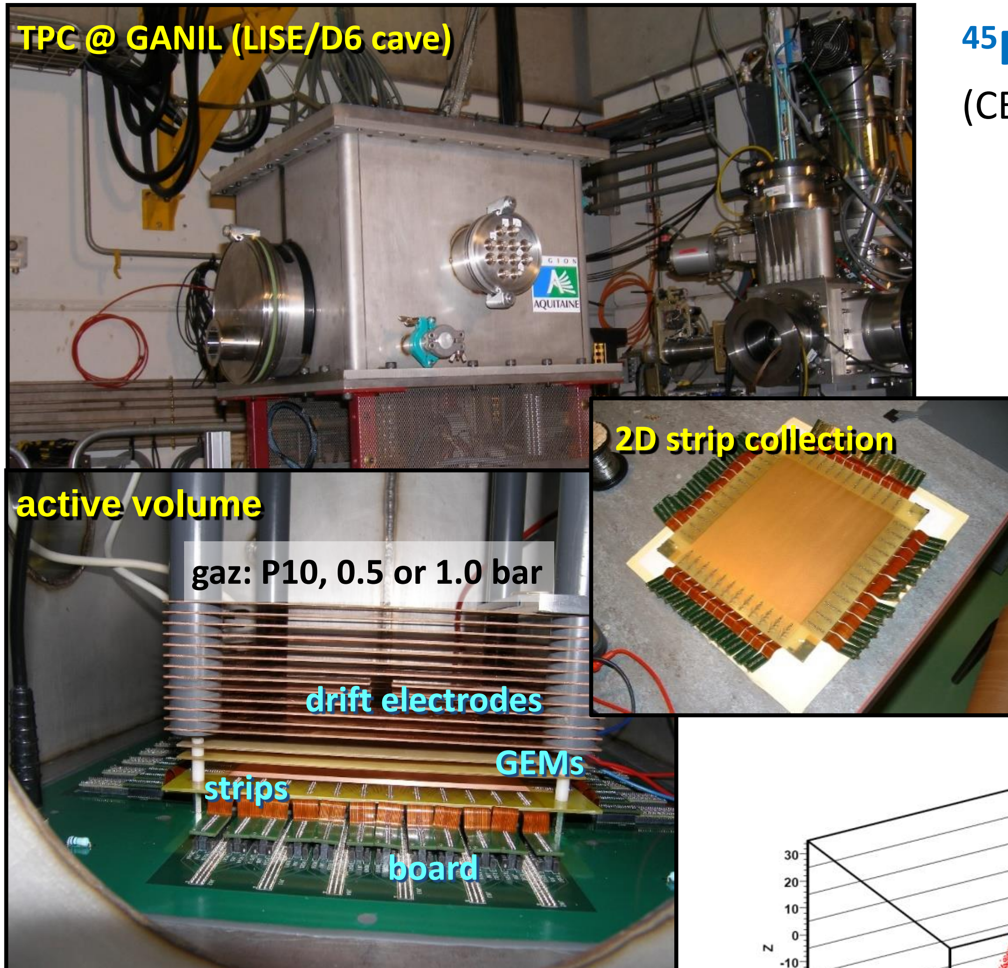
ionisation electrons drift to a 2D detector (uniform **elect. field**)

the **2D detector** registers the **tracks projection**

the **drift time** measures the **3rd dimension**

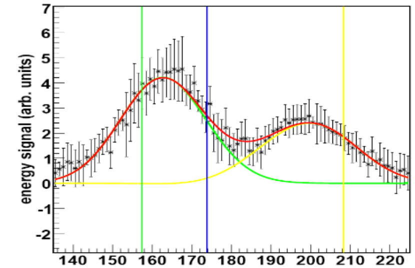


first direct observations

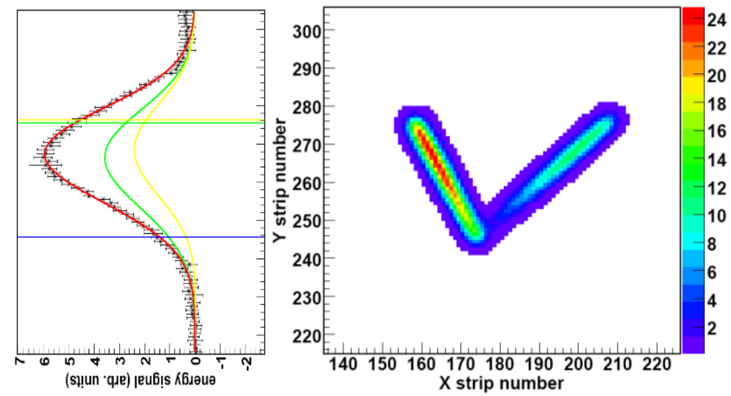


CENBG TPC

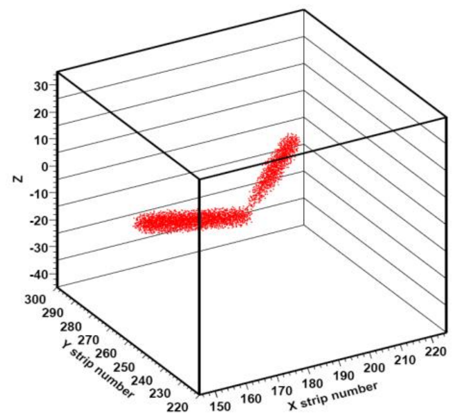
^{45}Fe @ LISE/GANIL
(CENBG-TPC 2006)



J.G. et al., PRL 2006



overall agreement with standard exp.
few counts only

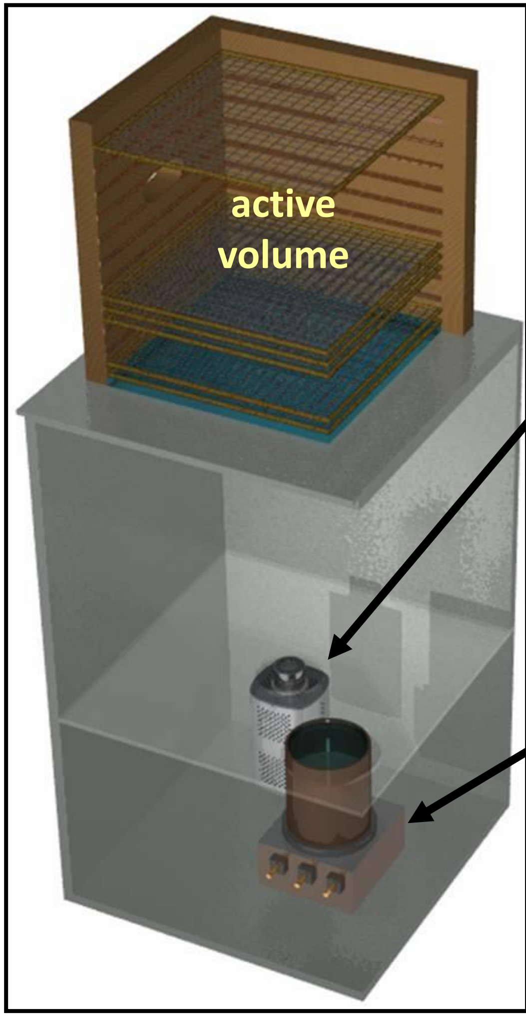


P. Ascher et al., PRL 2011

^{54}Zn @ LISE/GANIL
(CENBG-TPC 2011)

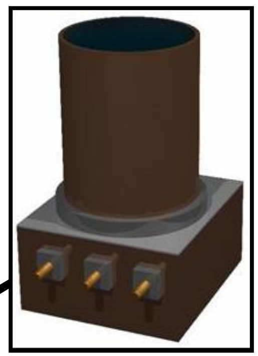
first correlation distributions

Warsaw O-TPC



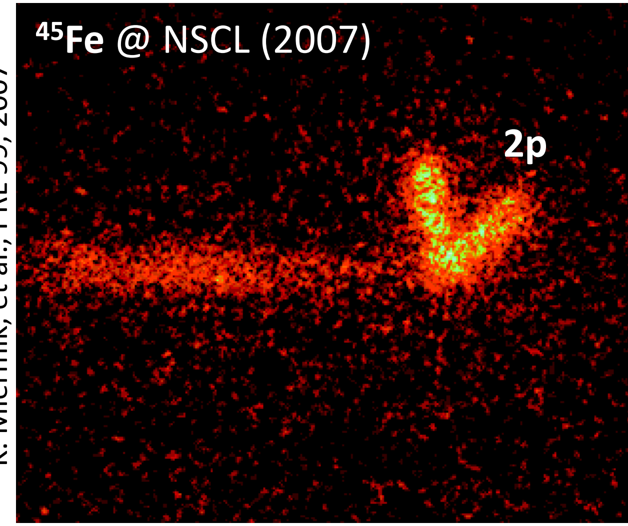
M. Pfützner, K. Miermik, et al., 2007

CCD camera
cumulated light



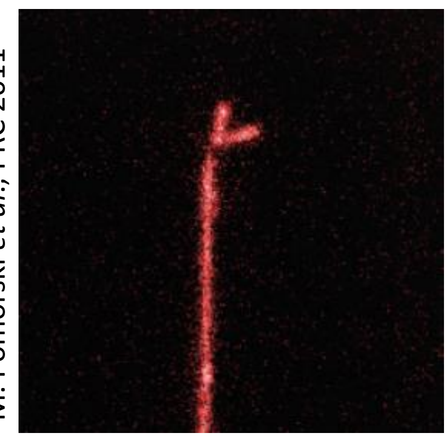
Photomultiplier
with sampling ADC
→ **time** distribution
of signal

K. Miermik, et al., PRL 99, 2007

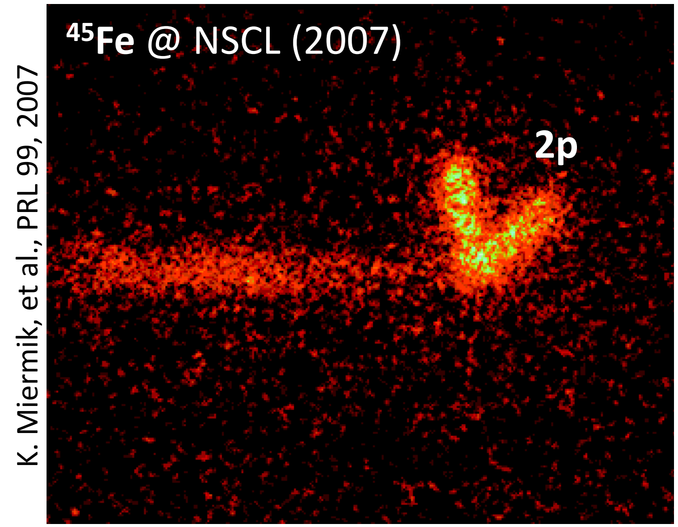


^{48}**Ni** @ NSCL (2011)

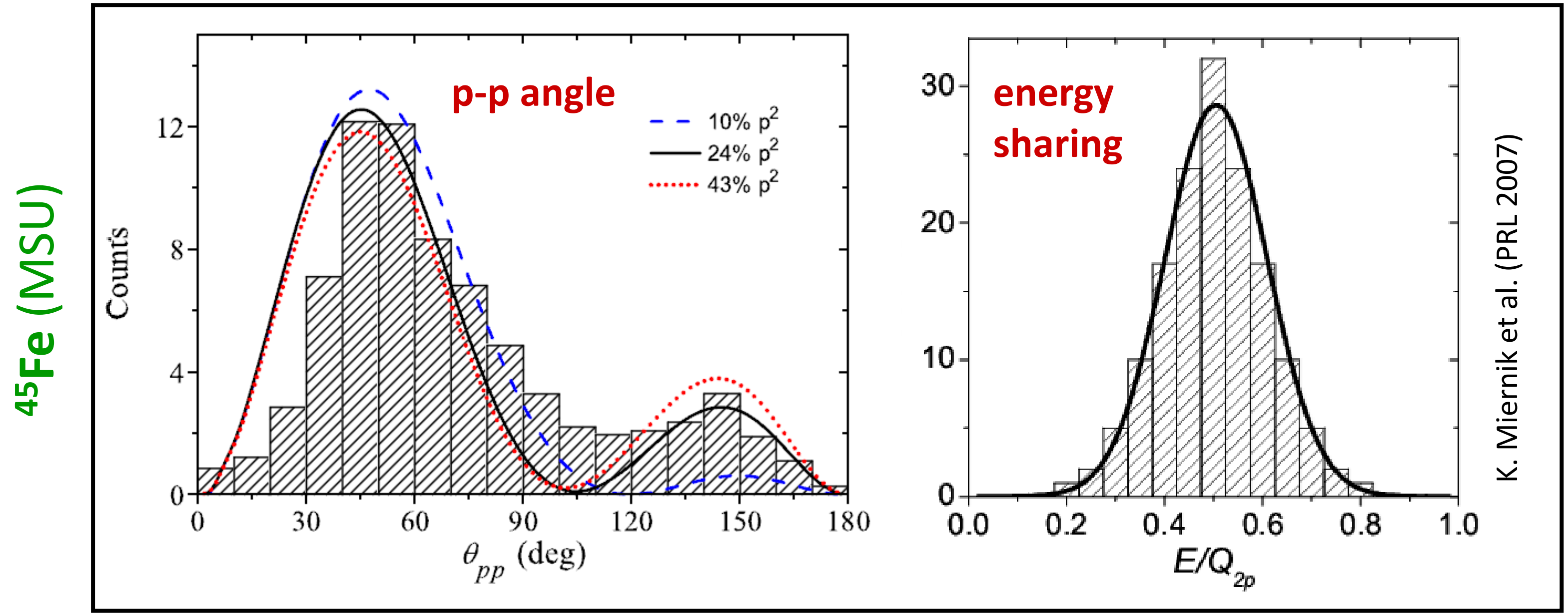
M. Pomorski *et al.*, PRC 2011



first correlation distributions



first angular distribution: good agreement with **predictions** from the 3-body model



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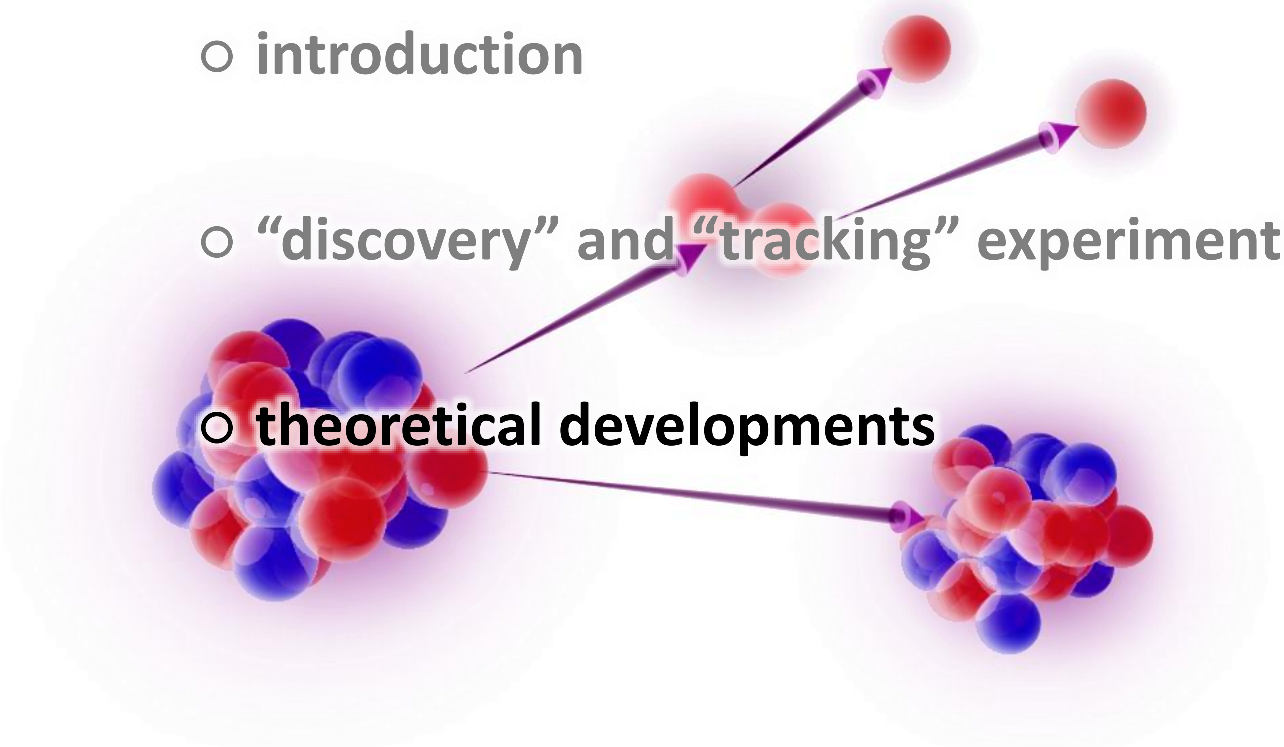
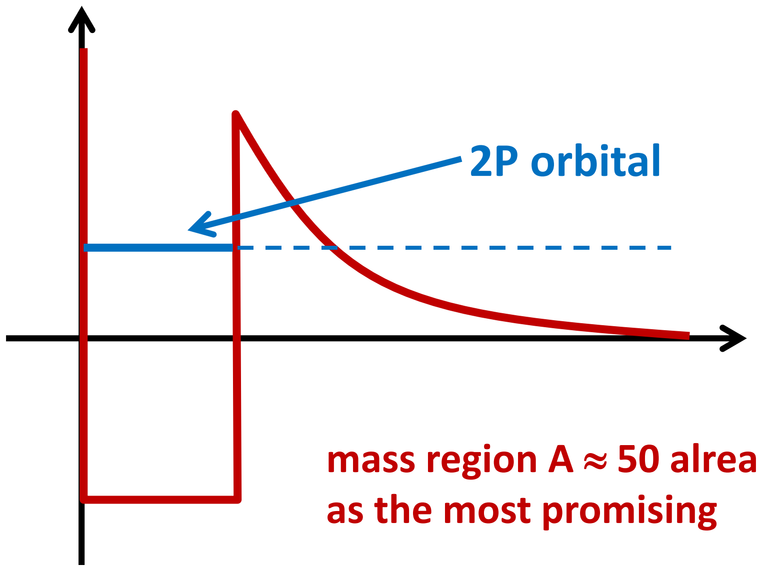
- **theoretical developments**



mass models (Q_{2P})



mass region A ≈ 50 already foreseen as the most promising

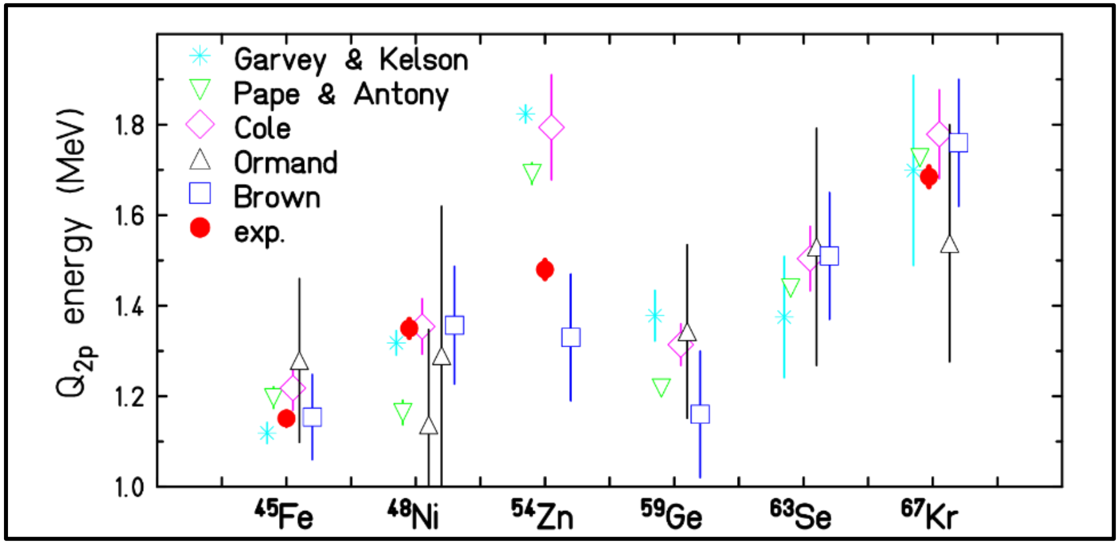
First calculation by V.I. Goldanskii (1960)

- → **simple potential model**
- → **based on masses differences** (mass predictions)
- → **tunnel effect**
  barrier penetration of a ^{2}***He*** particle vs. simultaneous emission of 2 protons

energy sharing
→ equal sharing between protons

discussion of the splitting of ^{2}***He*** into 2 protons along ***r*** axis

local mass models
- **microscopic**
- **IMME**
- **Garvey-Kelson**



courtesy of B. Blank

test of mass predictions at the proton drip-line

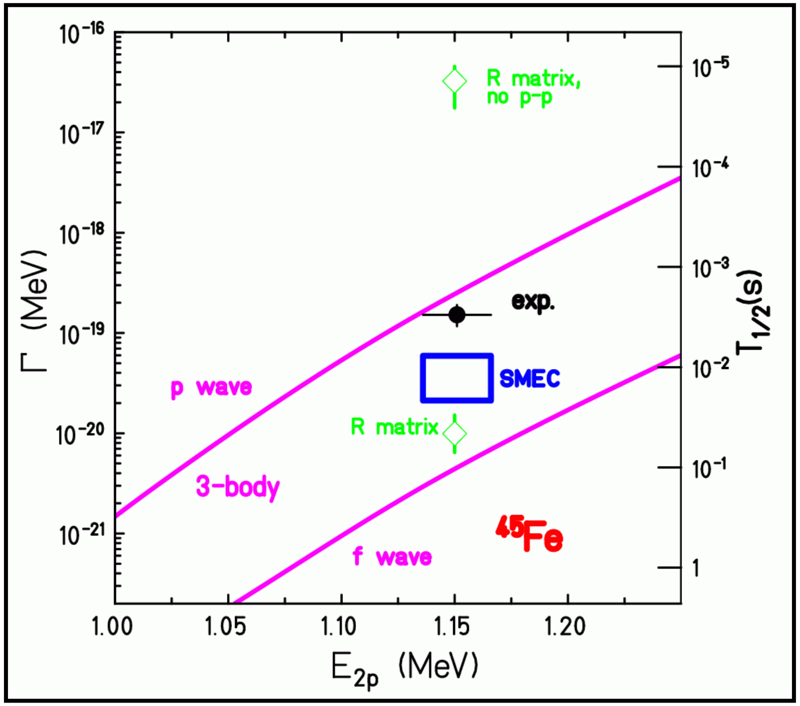
theoretical interpretations attempts

models based on nuclear structure

R-matrix formalism
- Barker & Brown approach
- include ***p-p*** resonance
- shell model wave functions

shell Model embedded in the continuum (SMEC)
- tentative approach from Ploszajczak & Rotureau

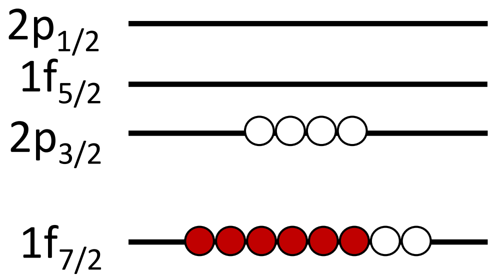
⇨ **no dynamics**
limited comparison: $T_{1/2}(Q_{2P})$
(with Q_{2P} taken from experiments !)



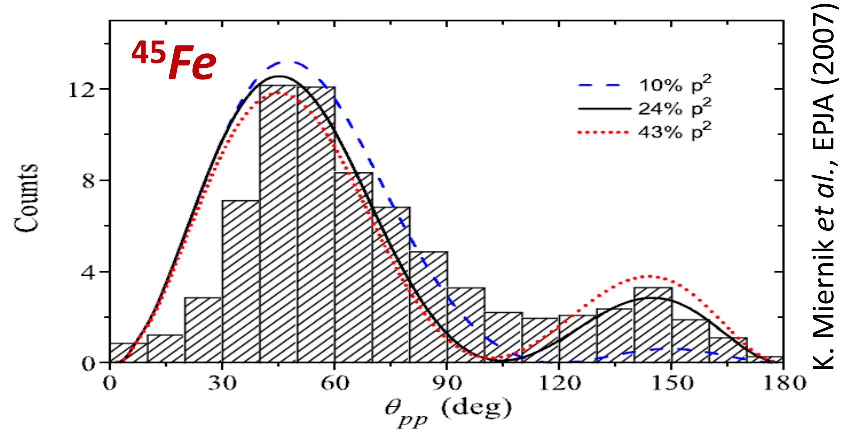
3-body model
- **core+p+p** system (hyperspherical harmonics)
- good dynamical description
- no intrinsic structure prediction

3-body model and angular correlations

^{45}***Fe*** : 26 protons

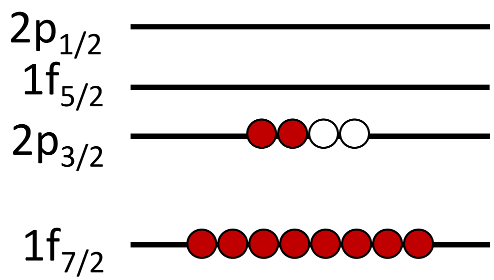


$W(p^2) = 24\%$

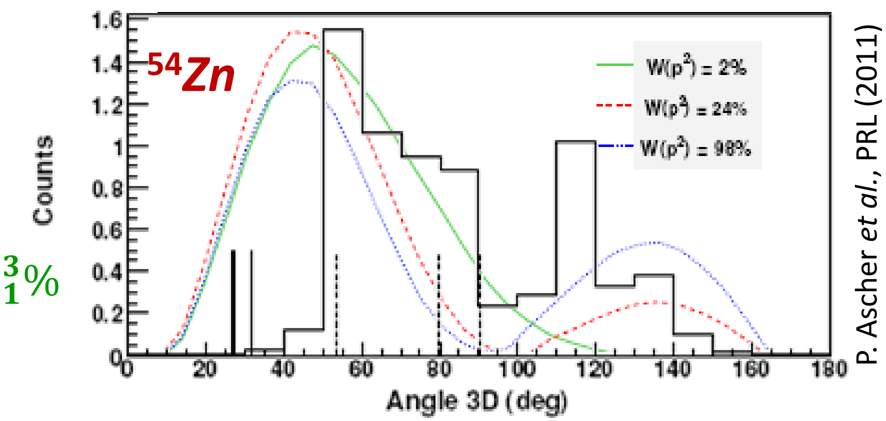


proton-proton angular distribution → orbitals configuration

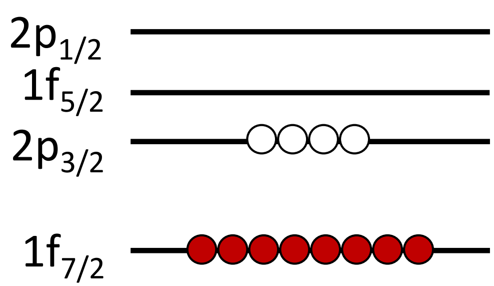
^{54}***Zn*** : 30 protons



$W(p^2) = 30^{+33}_{-21}\%$



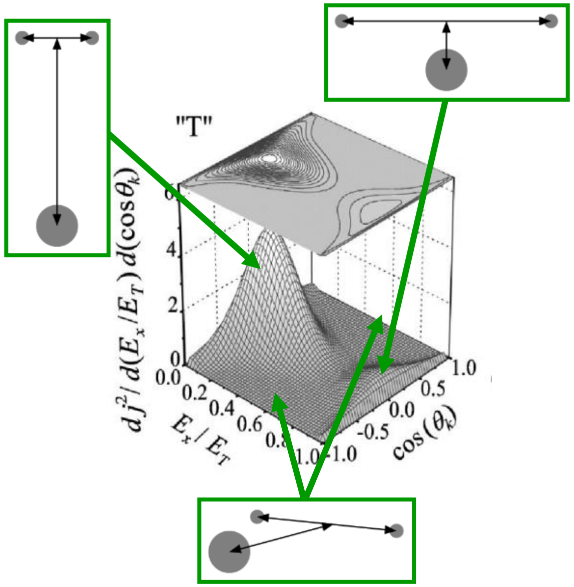
^{48}***Ni*** : 28 protons

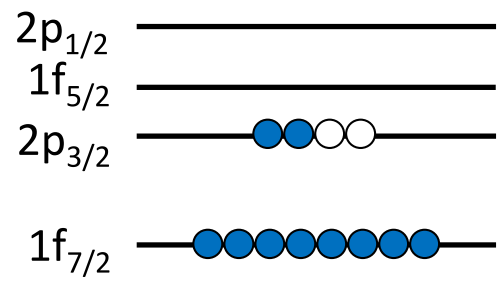


^{48}***Ni ??***

doubly magic → pure configuration ?

half-lives from hybrid model





L.V. Grigorenko: dynamics
half-lives:
$T_{1/2}$ for pure (s^2,) p^2 and f^2 config.

B.A. Brown: structure
2-proton amplitudes:
for pure (s^2,) p^2 and f^2 config

"Shell model corrected half-lives"

$A = A(f^2) + A(p^2)$ ⇒ $T_{1/2}$**(2P)**

B.A. Brown, B. Blank

half-lives from hybrid model

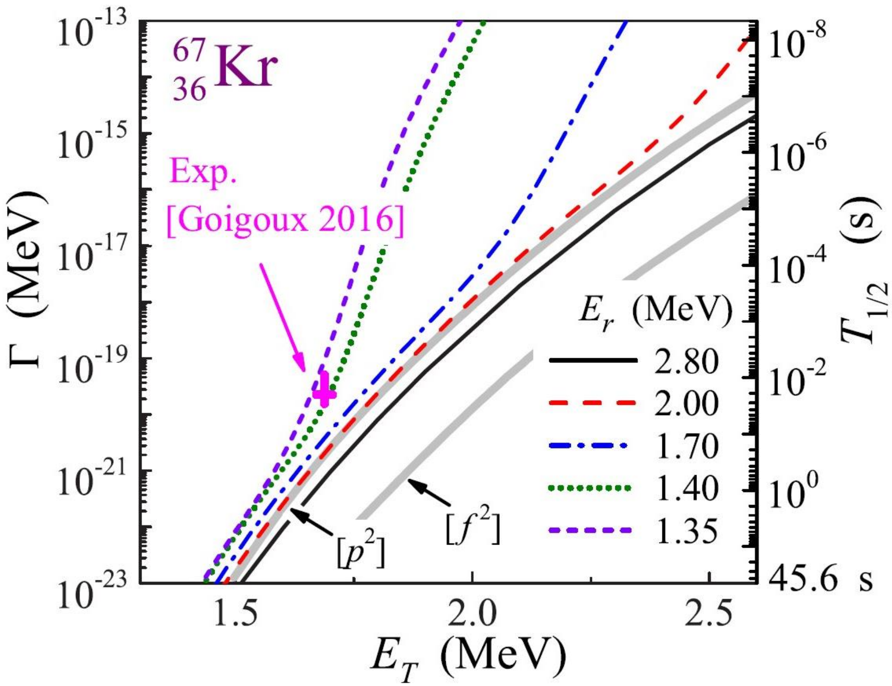
^{45}Fe	
3-body half-lives	**Shell-model 2p removal amplitudes**
$T_{1/2}(s^2) = 0.24$ ms $T_{1/2}(p^2) = 1.8$ ms $T_{1/2}(f^2) = 99.2$ ms	$A(s^2) = 0.140$ $A(p^2) = 0.283$ $A(f^2) = 1.039$
exp. 2p half-life: $T_{1/2}(2p) = 3.6$ ± 4 ms	**hybrid-model half-life: $T_{1/2}(2p) = 2.7$** ms
^{48}Ni	
3-body half-lives	**Shell-model 2p removal amplitudes**
$T_{1/2}(p^2) = 0.3$ *ms* $T_{1/2}(f^2) = 10$ ms	$A(p^2) = 0.0161$ $A(f^2) = 1.0263$
exp. 2p half-life: $T_{1/2}(2p) = 4.1^{+2.9}_{-1.8}$ ms	**hybrid-model half-life: $T_{1/2}(2p) = 8.0$** ms
^{54}Zn	
3-body half-lives	**Shell-model 2p removal amplitudes**
$T_{1/2}(p^2) = 0.91$ ms $T_{1/2}(f^2) = 45$ ms	$A(p^2) = 0.686$ $A(f^2) = 0.443$
exp. 2p half-life: $T_{1/2}(2p) = 2.0^{+0.7}_{-0.5}$ ms	**hybrid-model half-life: $T_{1/2}(2p) = 1.6$** ms
^{67}Kr	
3-body half-lives	**Shell-model 2p removal amplitudes**
$T_{1/2}(p^2) = 0.28$ s $T_{1/2}(f^2) = 13.5$ s	$A(p^2) = 0.556$ $A(f^2) = 0.655$
exp. 2p half-life: $T_{1/2}(2p) = 20$ ± 11 ms	**hybrid-model half-life: $T_{1/2}(2p) = 660$** ms

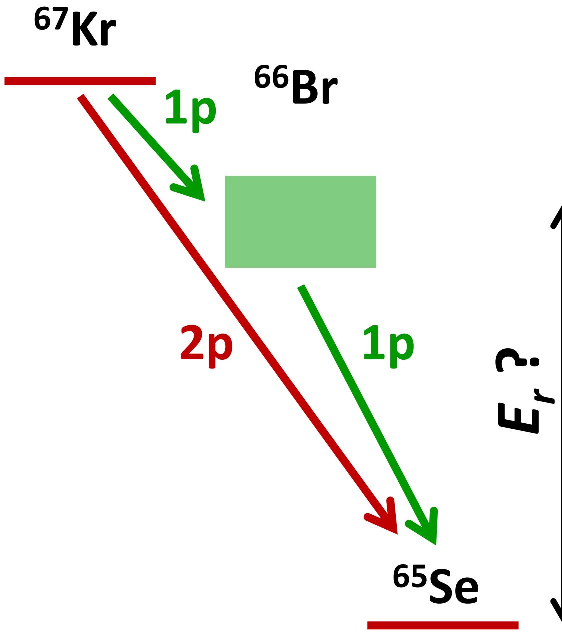
agreement within a factor <2

factor 20 difference !

transition from 2P to sequential decay ?

L. Grigorenko et al., PRC 95 (2017) 021601(R)



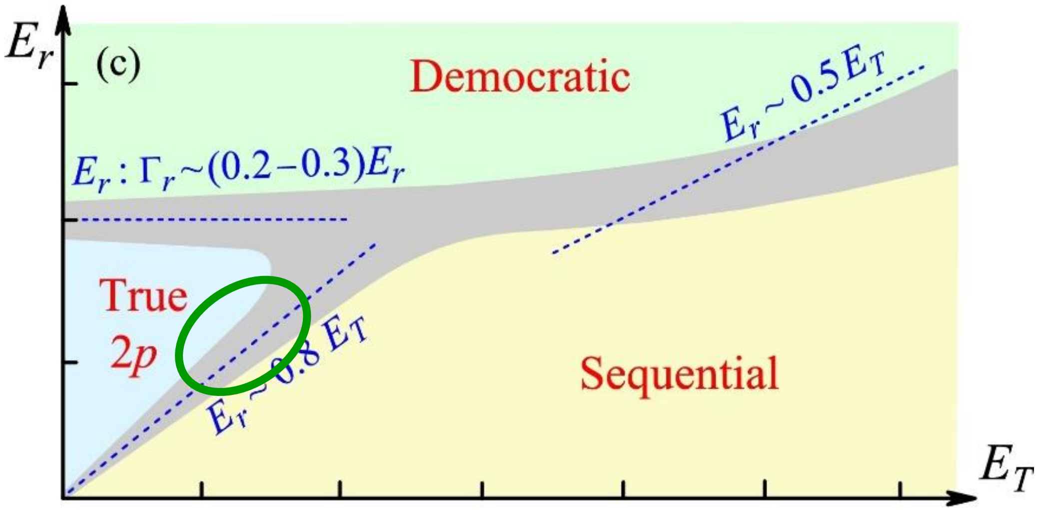


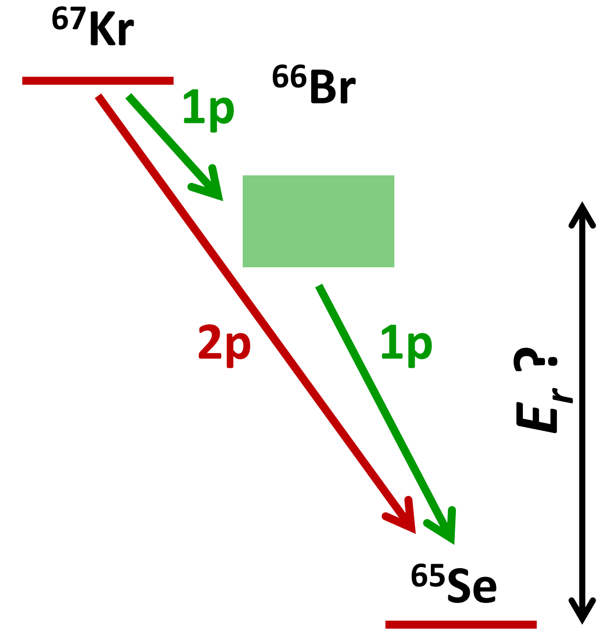
(semi-analytical R-matrix calculation)

- indication of a 1p channel opening ?
- possible transition from 2P to seq. emission

transition from 2P to sequential decay ?

L. Grigorenko et al., PRC 95 (2017) 021601(R)

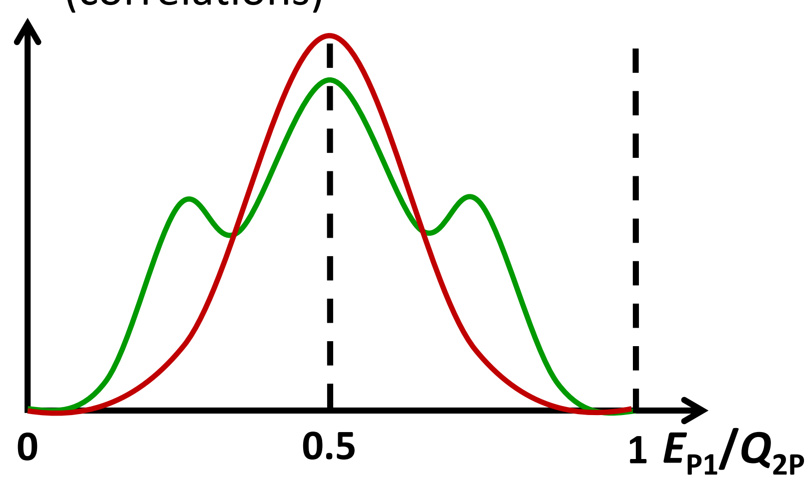




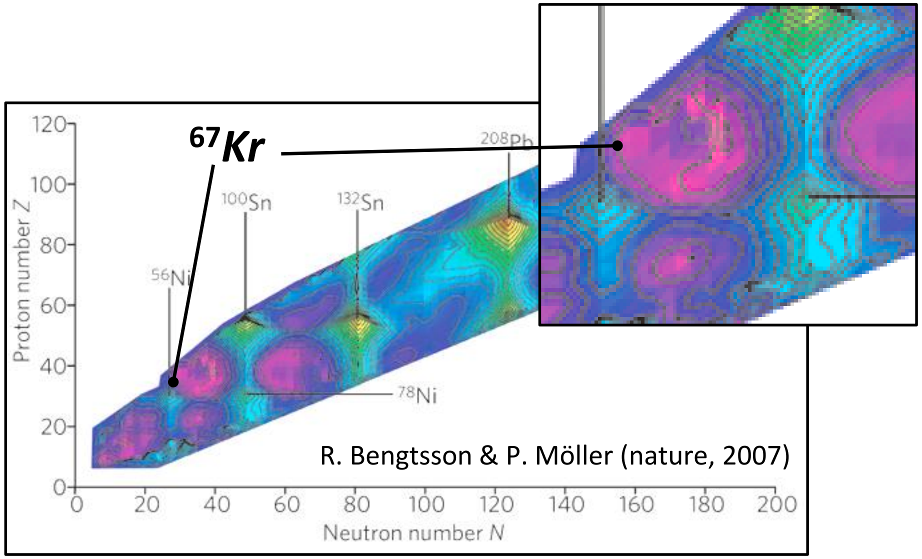
(semi-analytical R-matrix calculation)

- indication of a 1p channel opening ?
- possible transition from 2P to seq. emission
  transition region: S_p = [−340 ; −270] *keV*

energy sharing pattern
(correlations)



^{67}Kr in a region of deformation

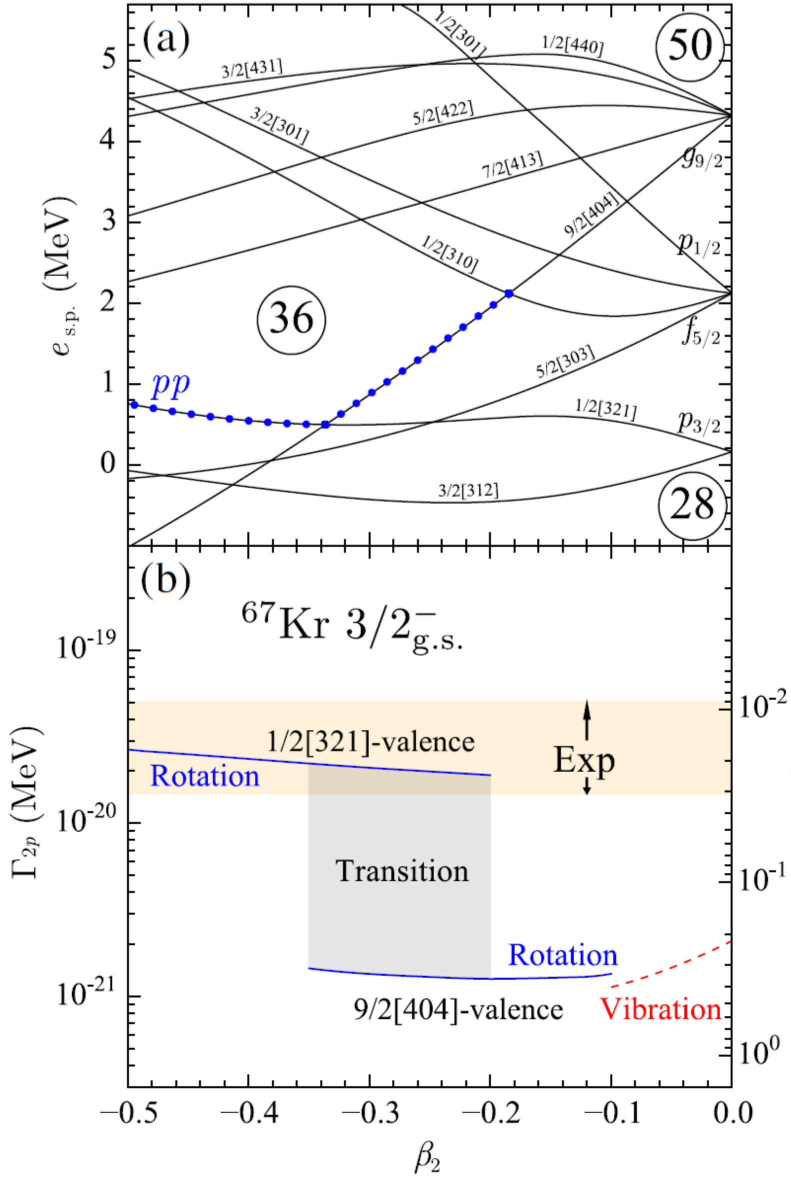


recent work by Wang & Nazarewicz, PRL 120 (2018)
(Gamow Coupled Channels + coupling to core exc.)

with $|\beta_2| < 0.1$ → $T_{1/2}^{2P} > 220$ *ms*

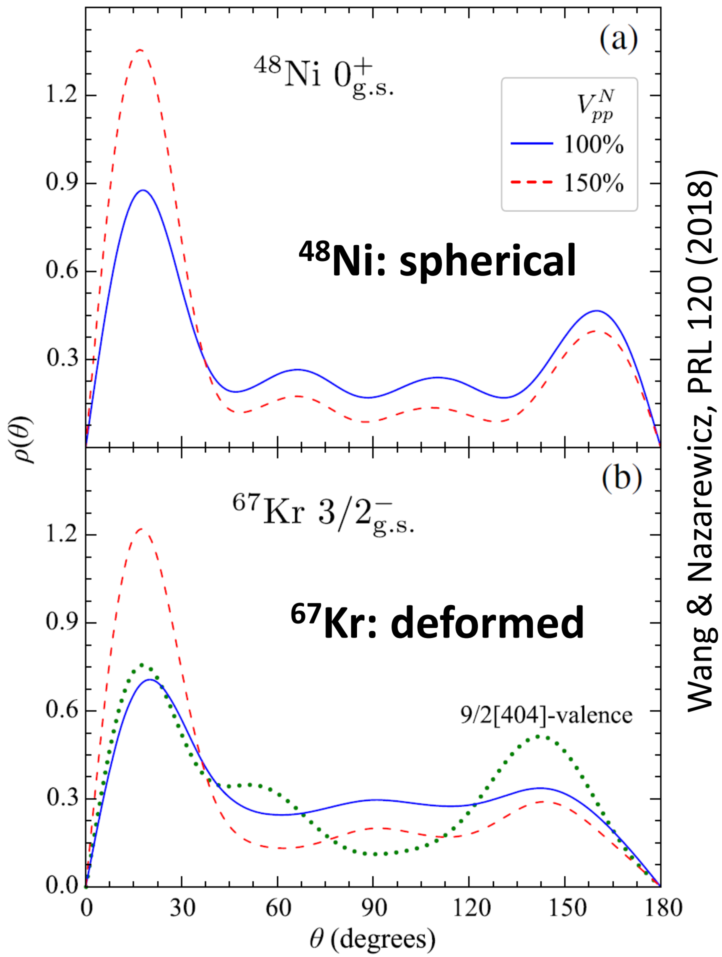
with $\beta_2 = -0.3$ → $T_{1/2}^{2P} = 24^{+10}_{-7}$ *ms*

agreement with exp. !



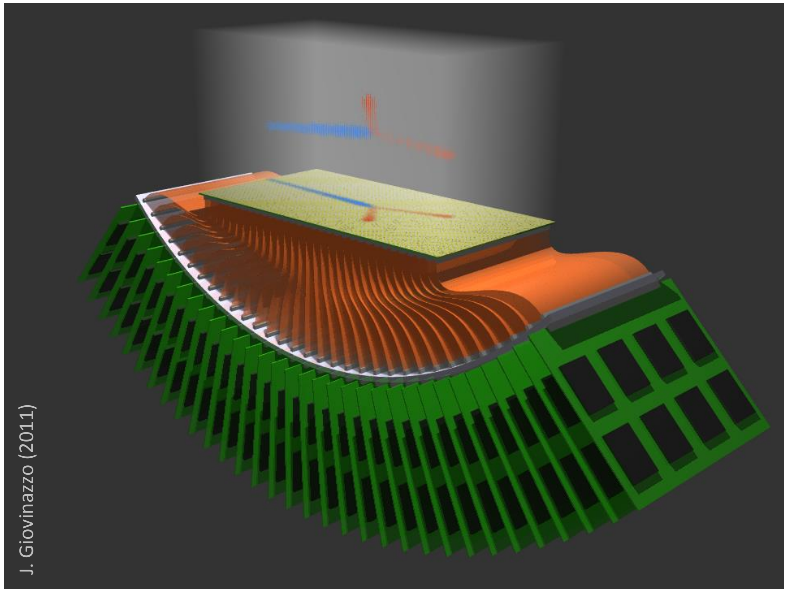
^{67}Kr & ^{48}Ni in GCC framework

new theoretical development
with angular distributions !

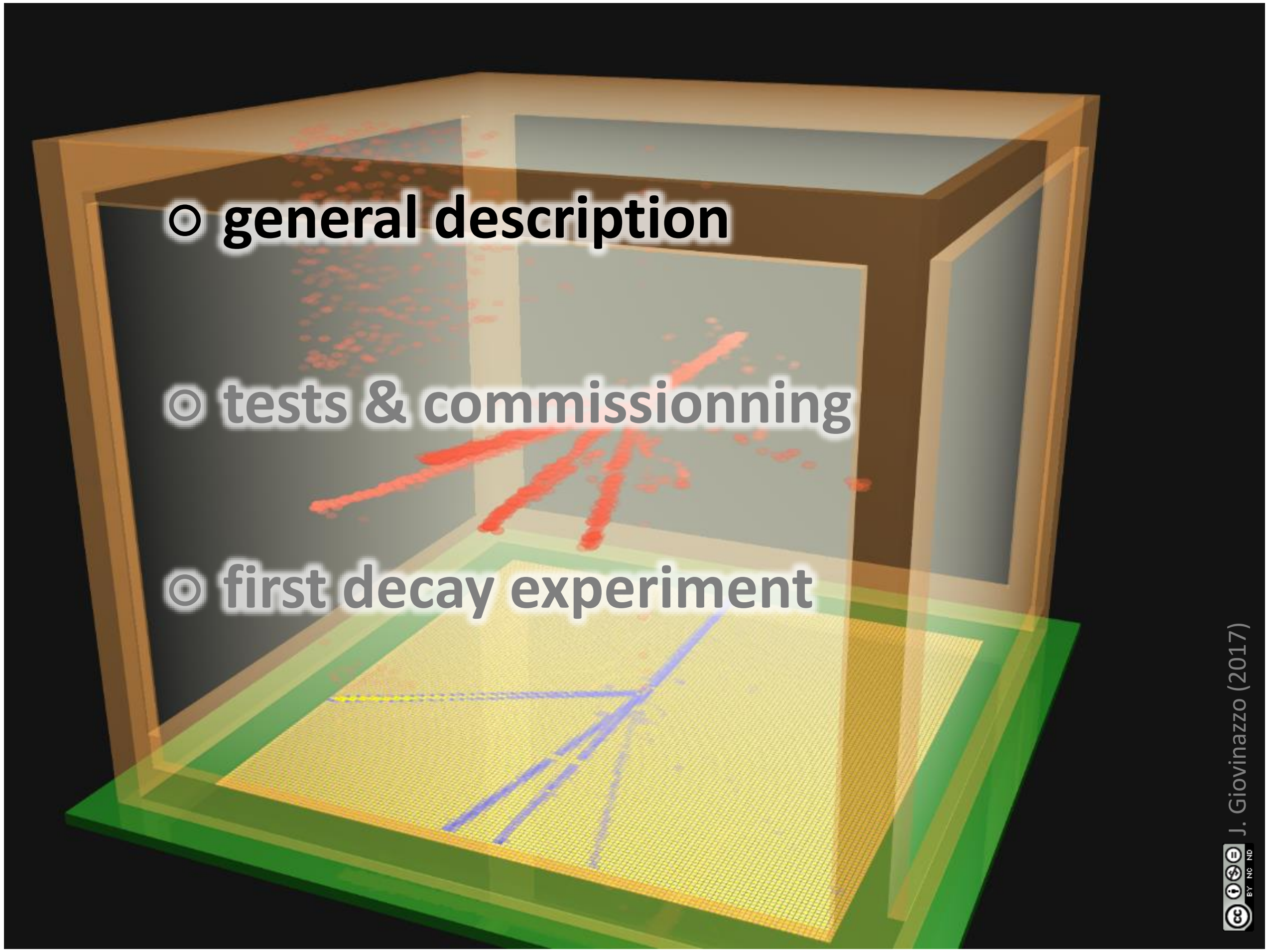


improved
tracking experiments
(ACTAR TPC)

- *angular correlations*
- *energy sharing*

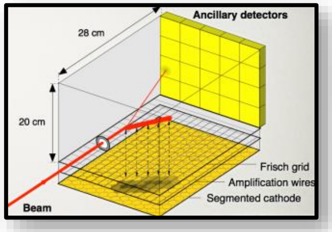


ACTAR TPC: a new tracking device



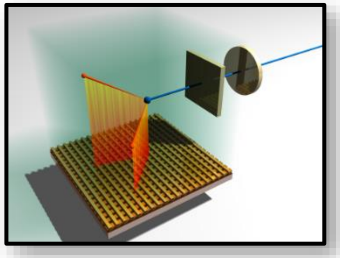
time projection chambers for nuclear physics

previous TPC devices



MAYA (GANIL & coll.)

pads (hex): 2D proj.
wires: drift time

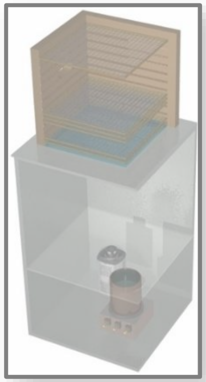


CENBG TPC

X-Y strips
energy
& time:
2x 1D proj.

^{45}Fe, ^{54}Zn,…

image Warsaw coll.



Optical TPC
(Warsaw)

CCD cam.: 2D proj.
PM + sampling:
global time dist.

^{45}Fe, ^{48}Ni,…

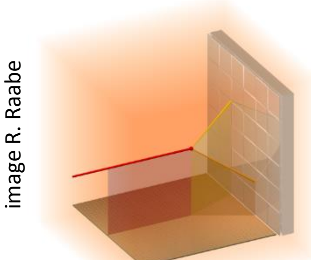
nuclear reactions — ions stopping and decay

development of a new device: ACTAR TPC

a versatile instrument
for nuclear structure/reaction
and decay studies

GANIL, **CENBG**, IPNO (F)
Leuven (B), Santiago de C. (S)
+ Legnaro (I)

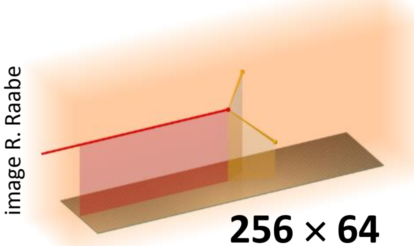
image R. Raabe



128 × 128

16384 pads
(2×2 mm^2)

image R. Raabe

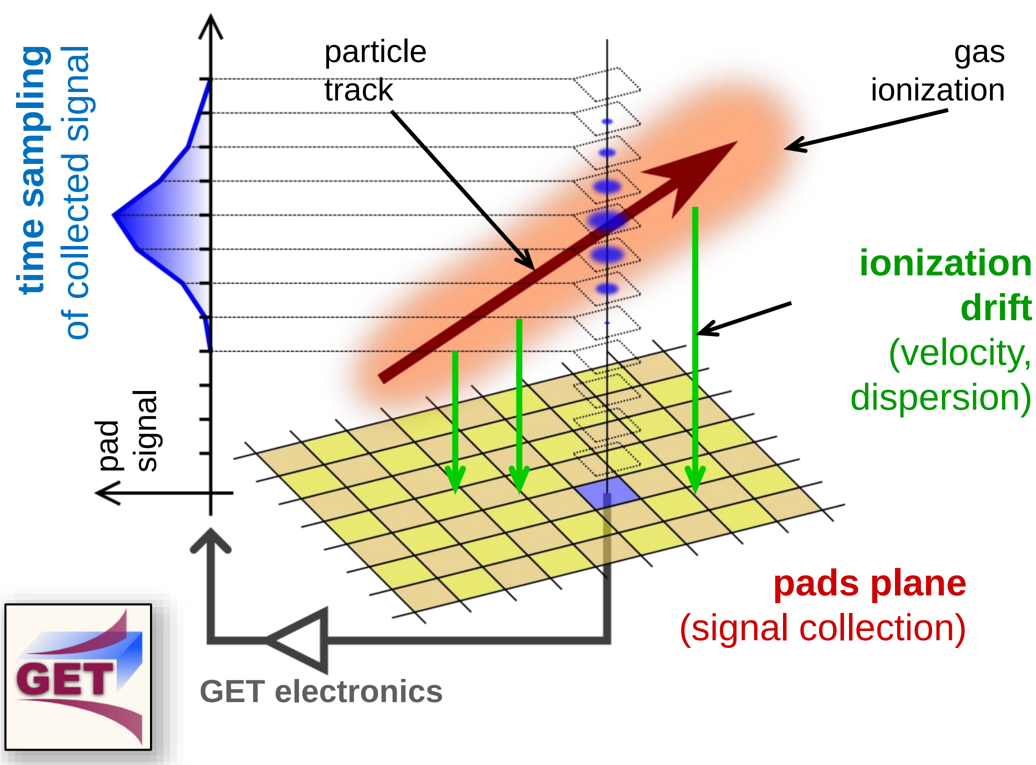


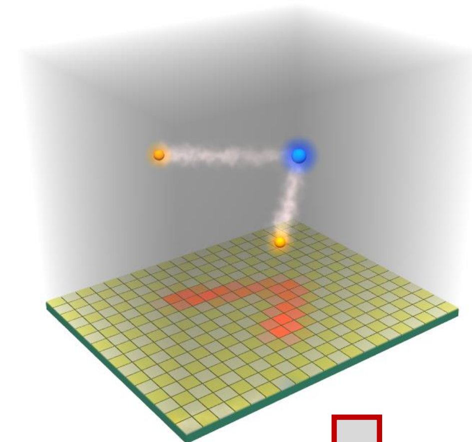
256 × 64

a 4D detector: tracking and energy

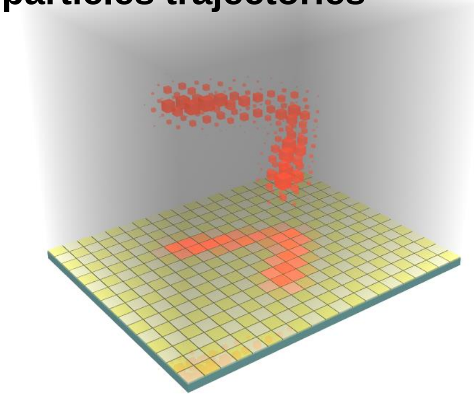
pads plane (signal collection)	TPC principle	time sampling of signal
2D digitization	$z \Leftrightarrow t$	3D digitization

$\Delta E(x,y,z) \Longleftrightarrow \Delta E[x_i,y_j](z) \Longleftrightarrow \Delta E[x_i,y_j](t) \Longleftrightarrow \Delta E[x_i,y_j,$





3D reconstruction of ionizations charges along the particles trajectories



ACTAR TPC: global design

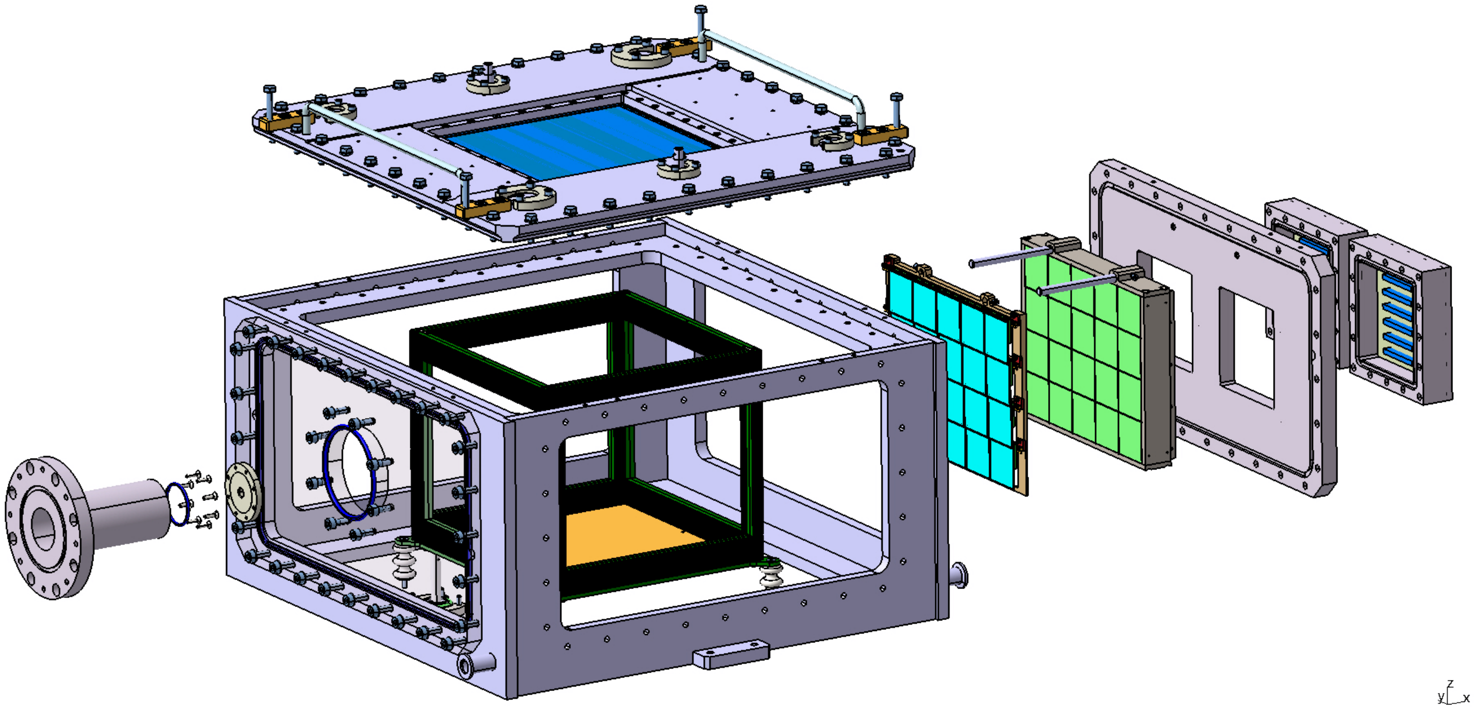
T. Roger *et al.*, NIM A 895 (2018)

- 2 demonstrators (R&D)
  (32x64 pads: **2048 channels**)
  at GANIL & CENBG
- 2 final detector geometries
  (**16384 channels**)

→ **"reaction"** (GANIL) chamber (128x128 pads)

→ **"decay"** (CENBG) chamber (64x256 pads)

- **active volume (drift region)**
- **collection plane (pads) & amplification**
- **electronics**
- additional detectors

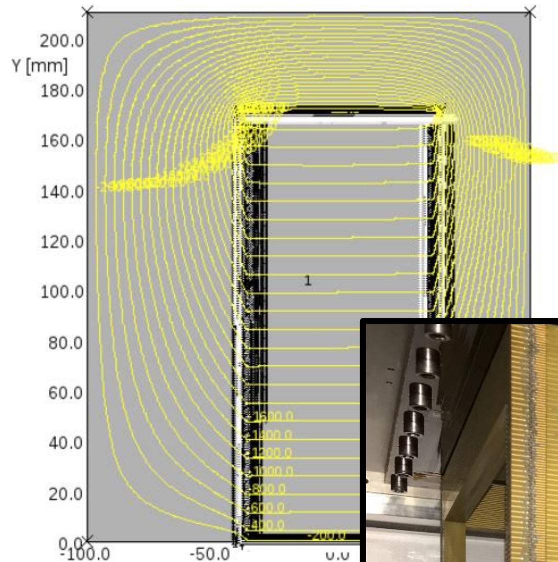


ACTAR TPC: active volume & drift cage

electric field **uniformity**

transparent to particles

→ **double wires frames**
- 1 and 2 mm pitch (inside/outside)
- 98 % transparency



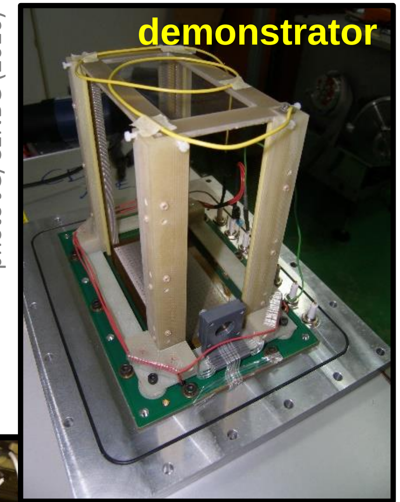


photo JG/CENBG (2016)

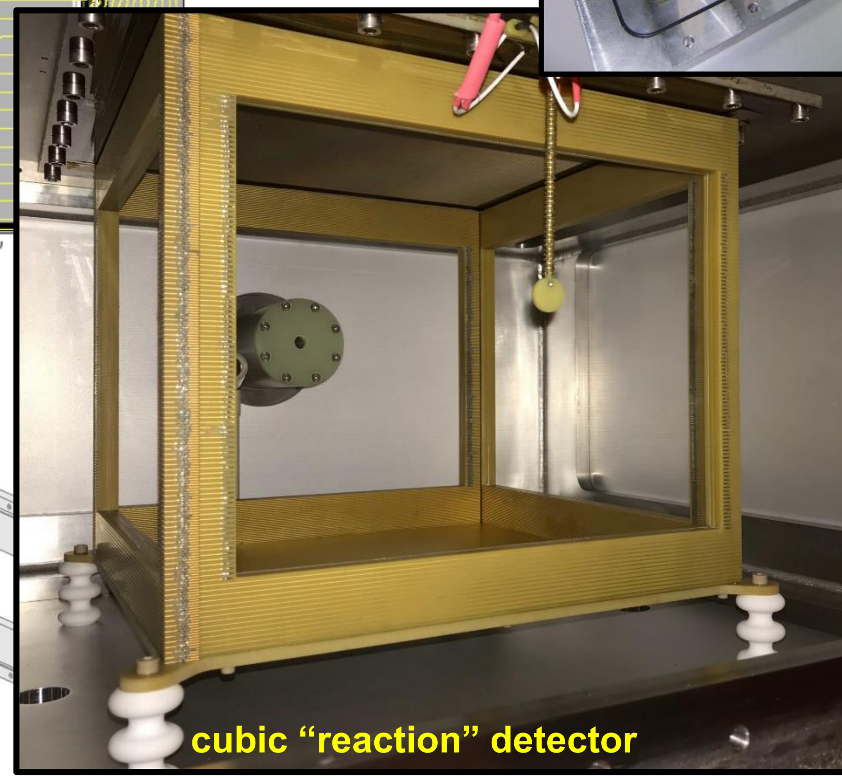
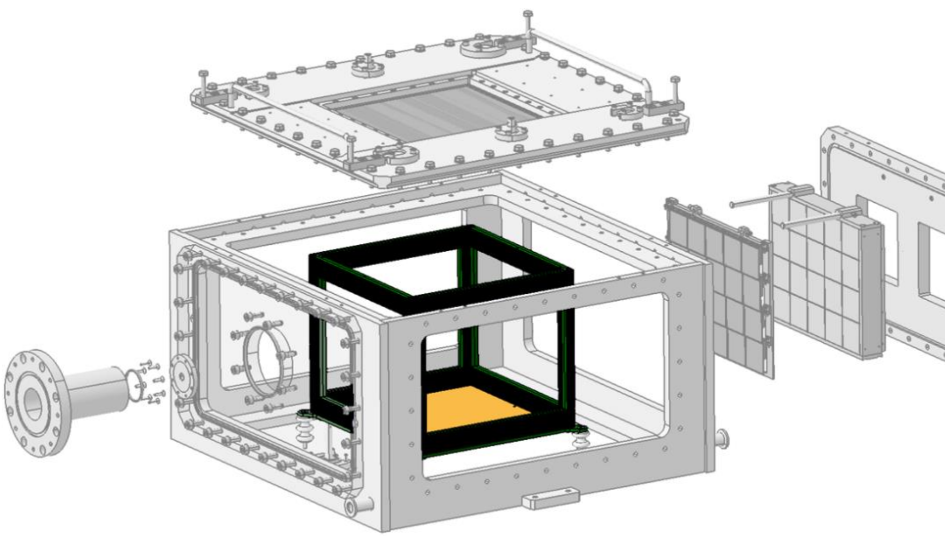


photo O. Poleshchuk (2017)

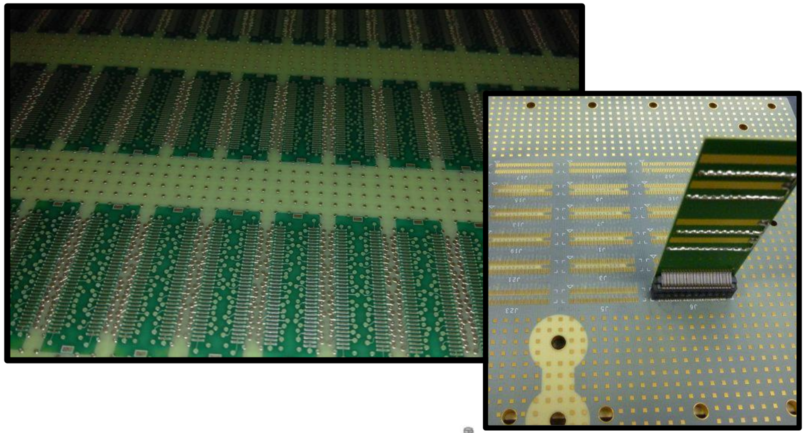


GANIL design

ACTAR TPC: collection (pads) plane

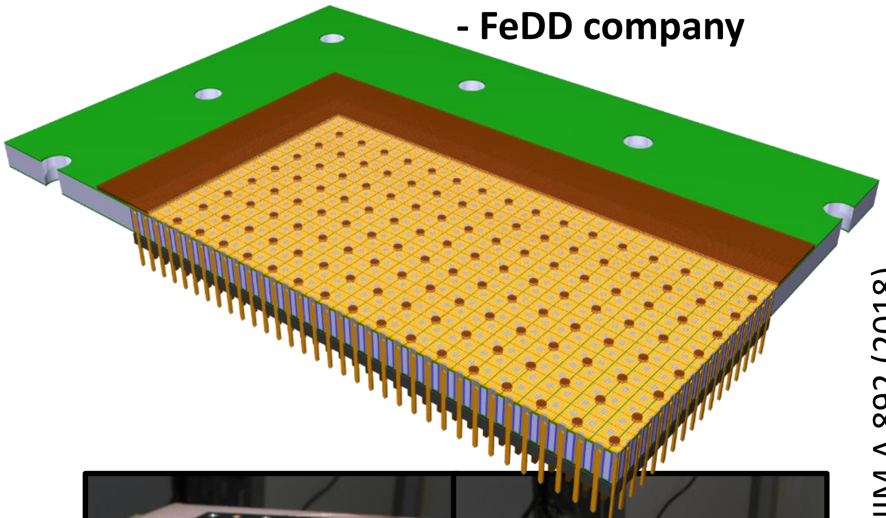
high density of pads
mechanical constraints

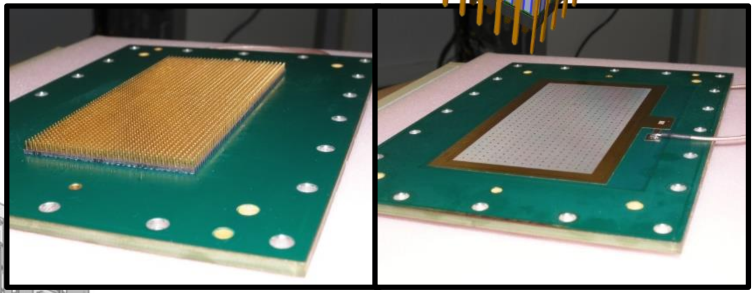
multi-layer PCB (GANIL version)



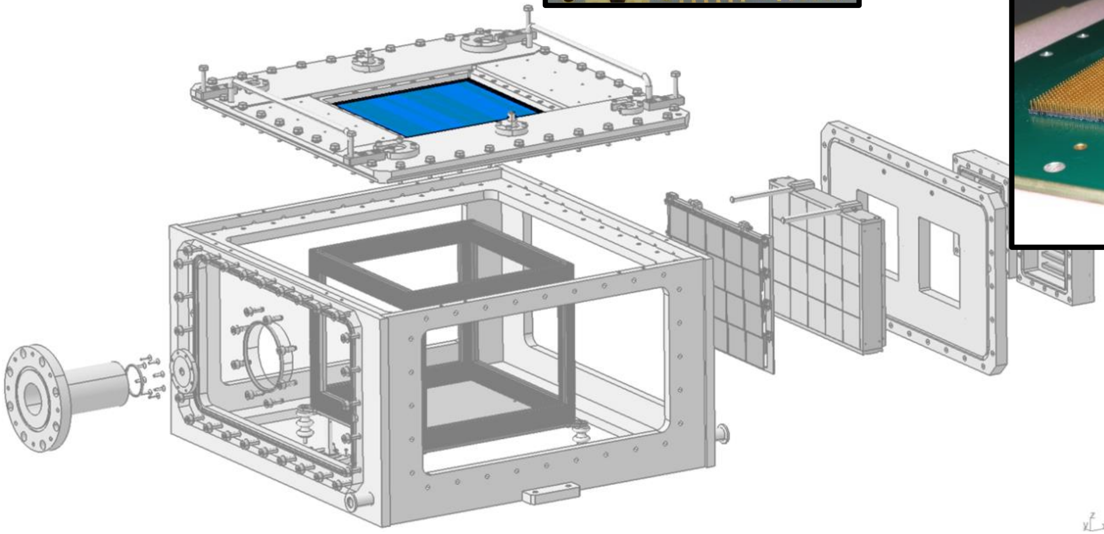
metal-core PCB
(CENBG version)

developed with
- CERN PCB workshop
- FeDD company





J.G. *et al.*, NIM A 892 (2018)



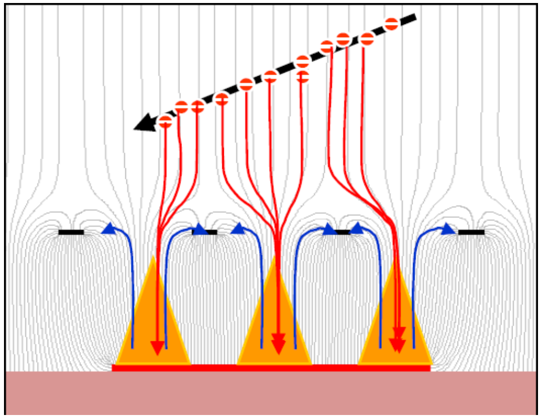
both tested on demonstrators

→ specific the connection to readout electronics

ACTAR TPC: signal amplification

bulk micromegas
(CERN)

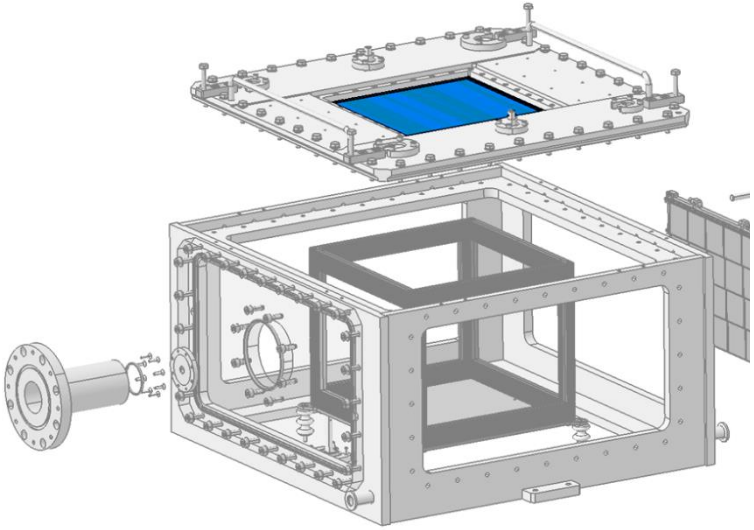
possible use of GEMs

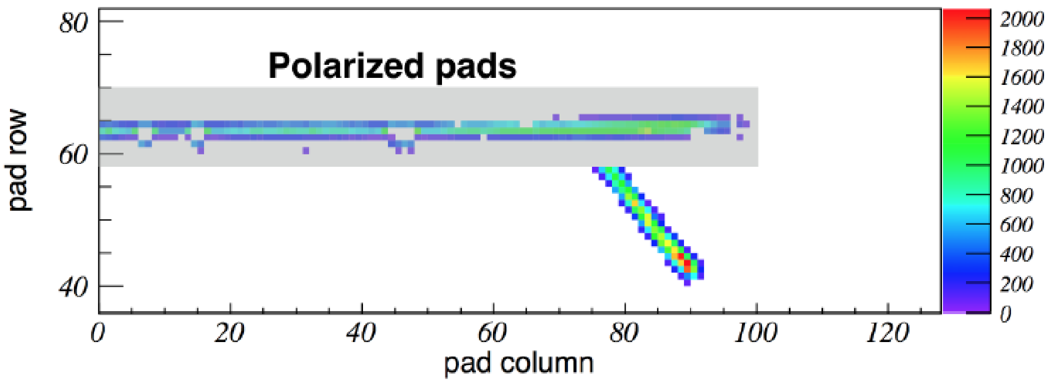


selected pads polarization

- **local reduction of the gain**
- **"active target" mode:**
  - **- high intensity beam**
  - **- few interactions**

→ avoid saturation





ACTAR TPC: signal extraction, spark protection, pads polarization

high density of pads: FEE larger than pad plane

connectors for multi-layer PCB

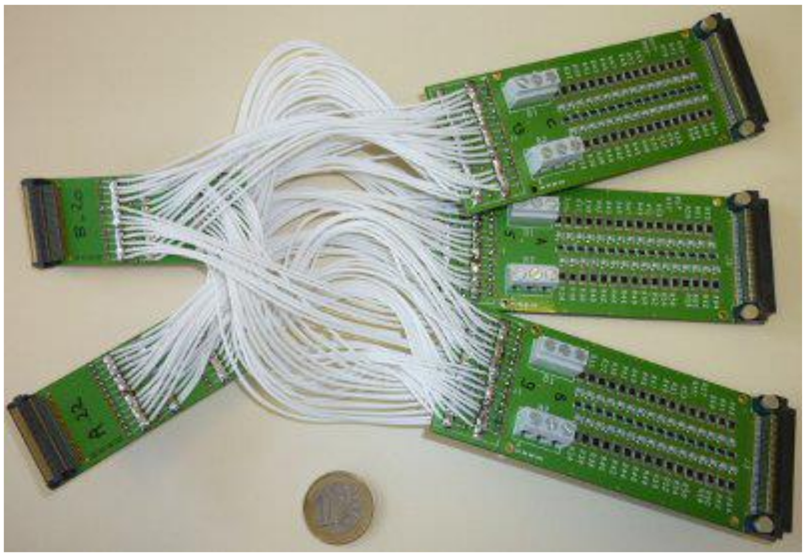


photo GANIL (2015)

with µ-coax cables
problem for 16384 pads…

connectors for metal-core PCB

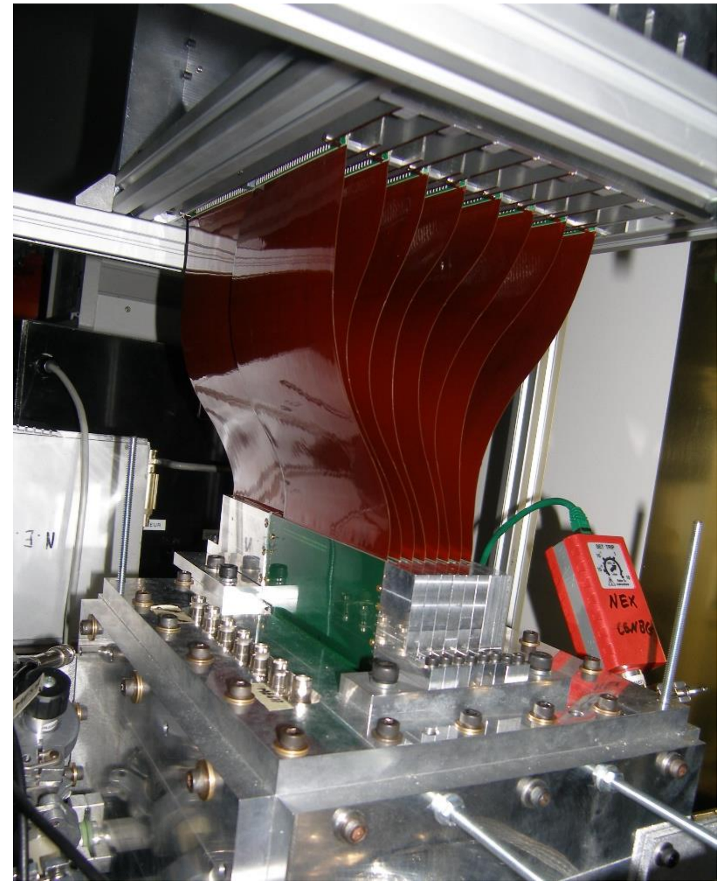


photo JG/CENBG (2016)

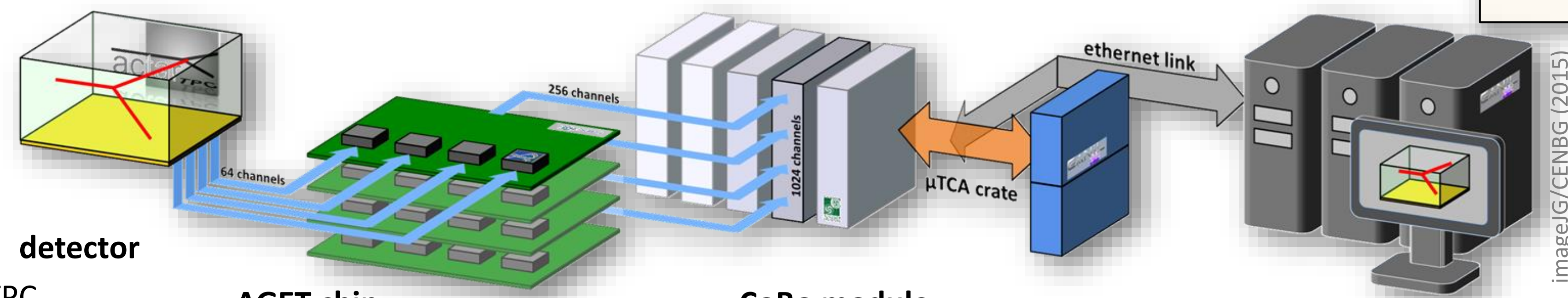
with flex (shielded) PCB

comparable noise (test measurements)

pads polarization for both geometries

ACTAR TPC: readout electronics

IRFU, CENBG,
GANIL, MSU
ANR 2011-2015



detector
TPC
16384 pads

AGET chip
64 channels
signal processing
(CSA + shaper),
analog memory,
discriminator

AsAd board
4 chips
(+ config.)
signal & mult.
coding (ADC)

CoBo module
4 AsAd boards
digital data
management

MuTAnT
clock distrib.,
trigger management
(3 levels)

control / acquisition

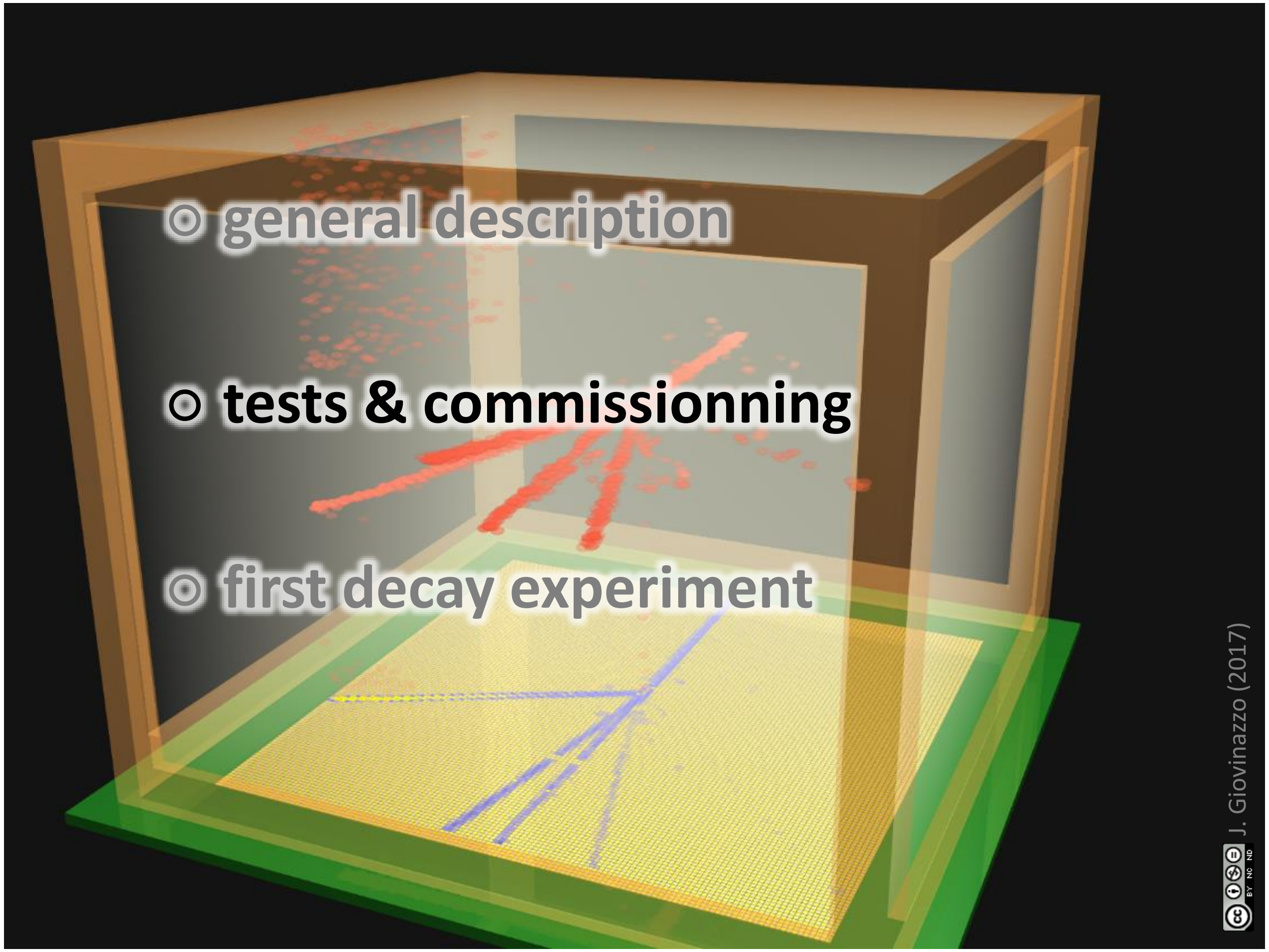
for each channel:

- **time sampling** (max. 512, freq. 1-100 *MHz*): analog mem. + ADC
- **discriminator → internal multiplicity trigger**
- **(**no DSP**)**

designed to handle 1 *kHz* count rate for 10% of channels hit (~1600 channels)

E.C. Pollaco *et al.*, NIM A 887 (2018)
J.G. et al., NIM A 840 (2016)

ACTAR TPC: a new tracking device



- general description
- **tests & commissionning**
- first decay experiment

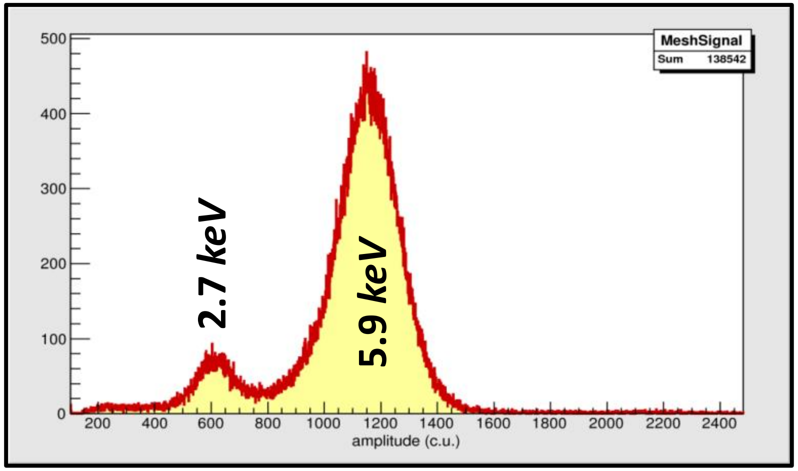
demonstrator test: R&D validation

^{55}*Fe* source X-rays

drift volume thickness: **2.5 *cm***

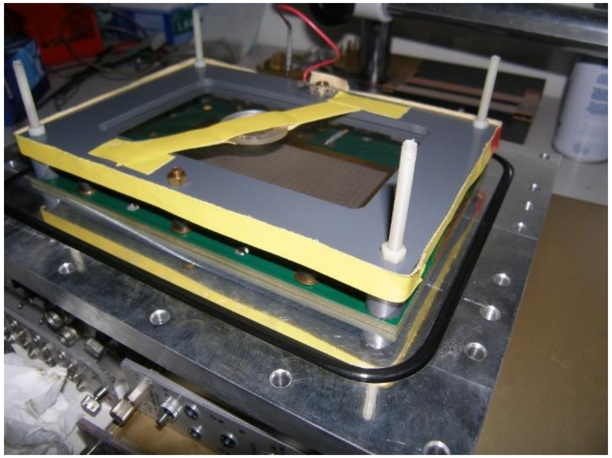
HV_{mesh} = **–570** *V*

HV_{drift} = **–1000** *V*



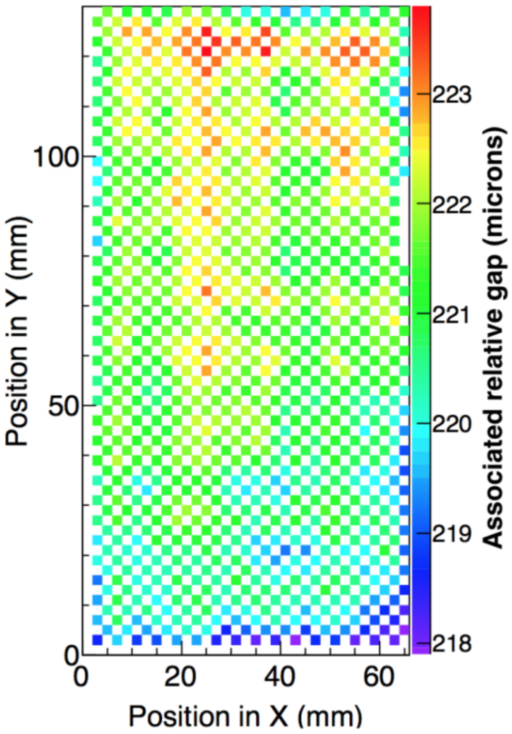
resolution (FWHM) @ **6** *keV*: ~**21 %**

mesh signal & **pads** signal



GANIL scanning table

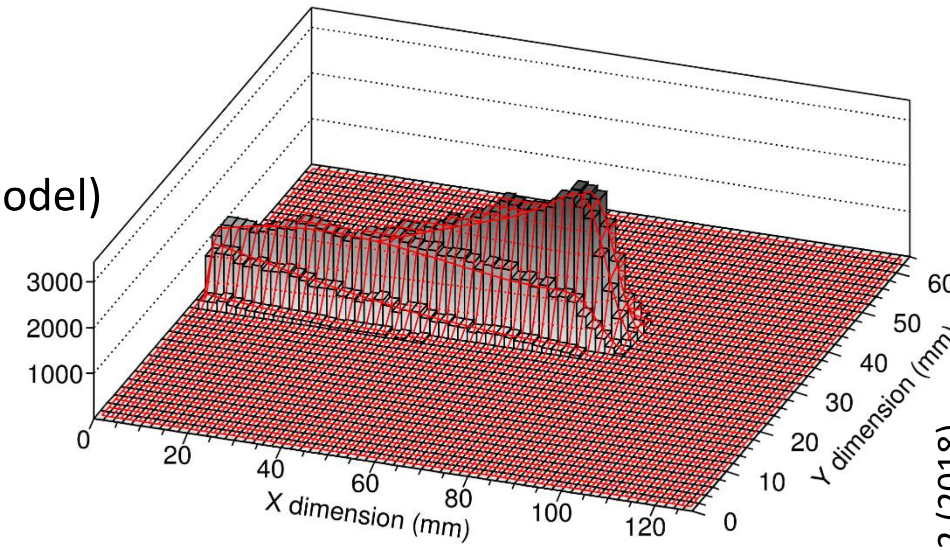
- amplification gap homogeneity
- gain matching



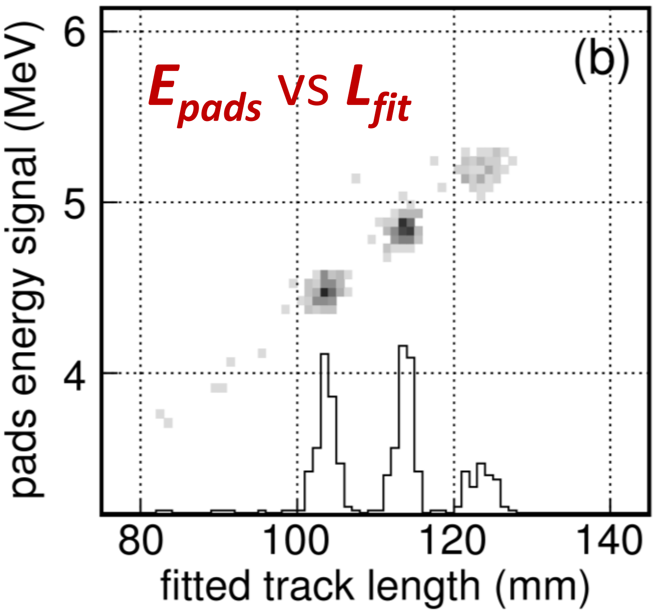
demonstrator test: stopped tracks analysis

3-alpha source tests

2D projection of Bragg peak:
- energy deposit along track (Bragg peak model)
- X & Y dispersion
- no time (Z) distribution of signal



J.G. *et al.*, NIM A 892 (2018)



independent precision of
energy estimate (pads signal)
& **track length** (fit)

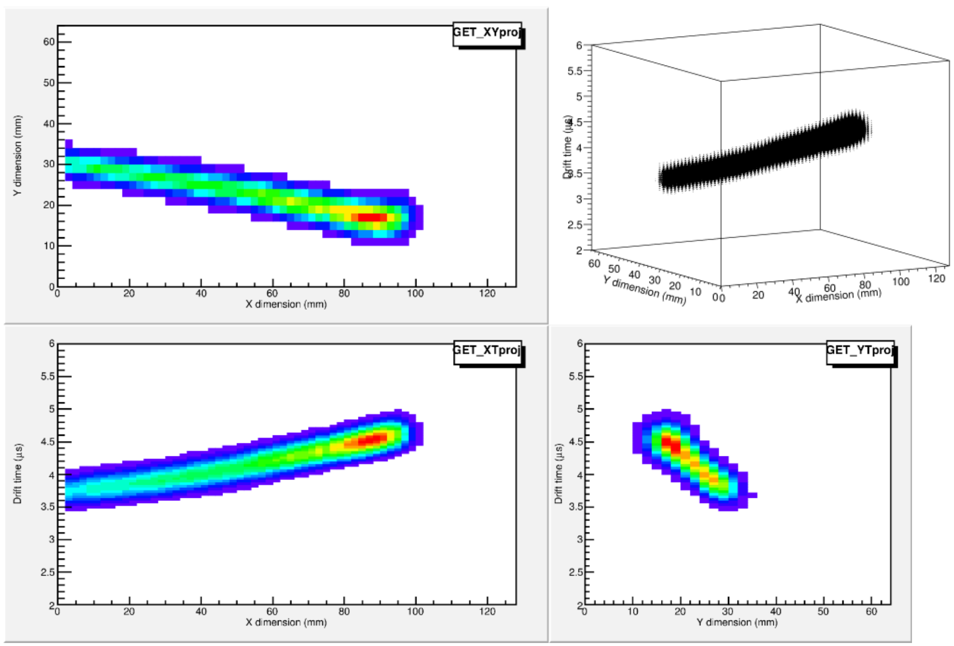
energy resolution: $\sigma_E^{pads} \sim 85\ keV$ at 5 *MeV*

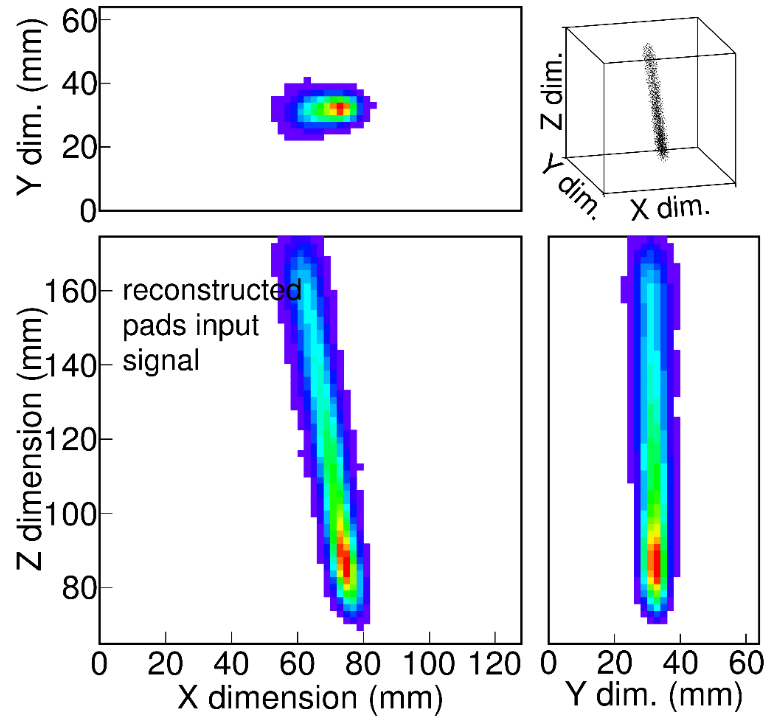
fitted length dispersion: $\sigma_L^{rec} \sim 3.2\ mm$
(particles dispersion from simulation)

demonstrator test: full 3D tracks reconstruction

with response function de-convolution
→ effective Z charge distribution

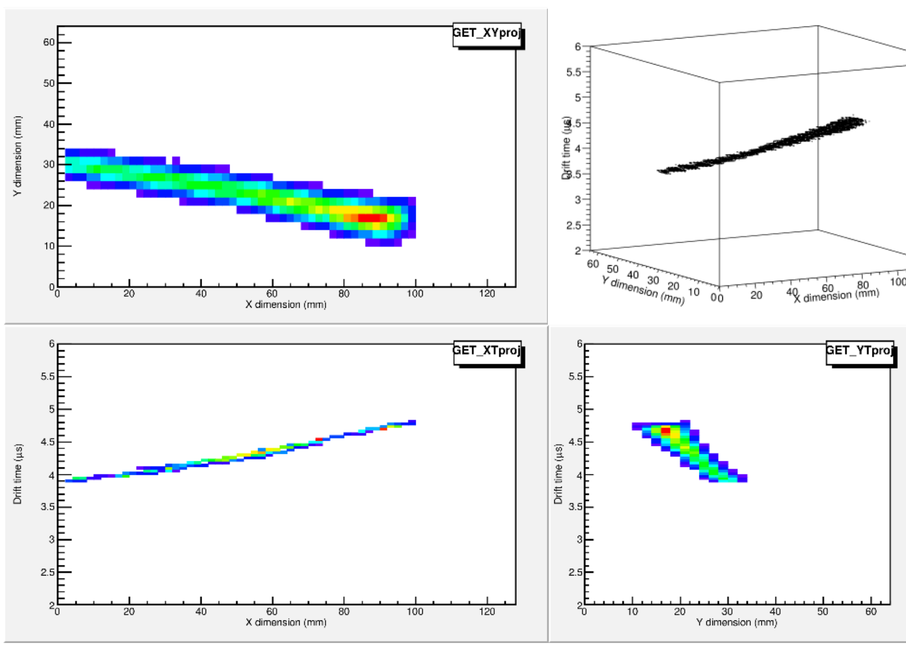
energy resolution from rec. signal
equiv. to output signal

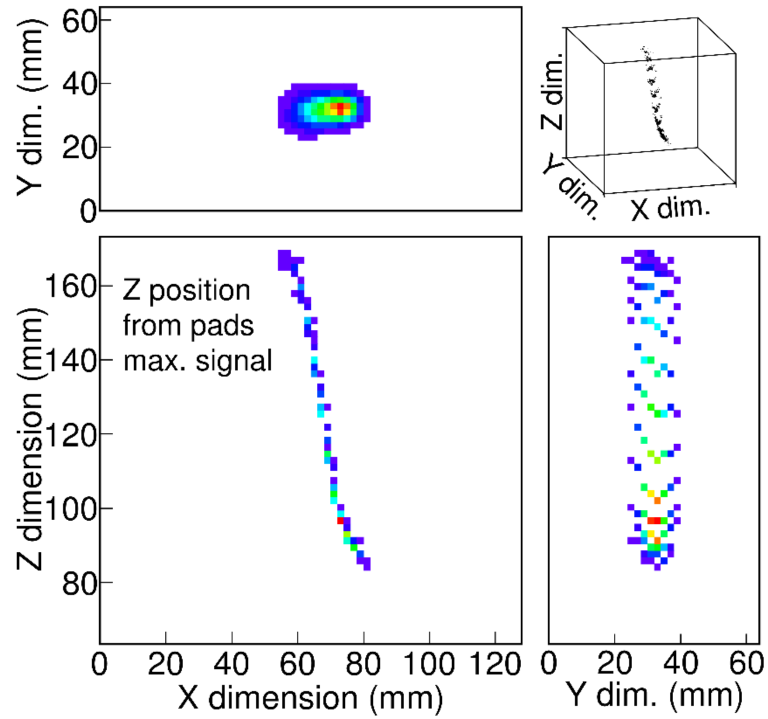




demonstrator test: full 3D tracks reconstruction

raw signal projection

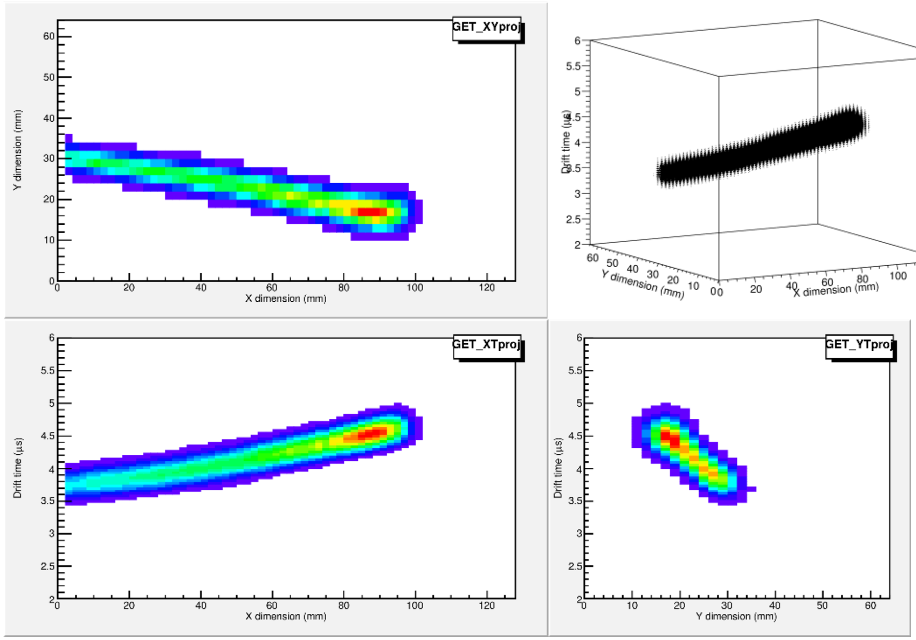


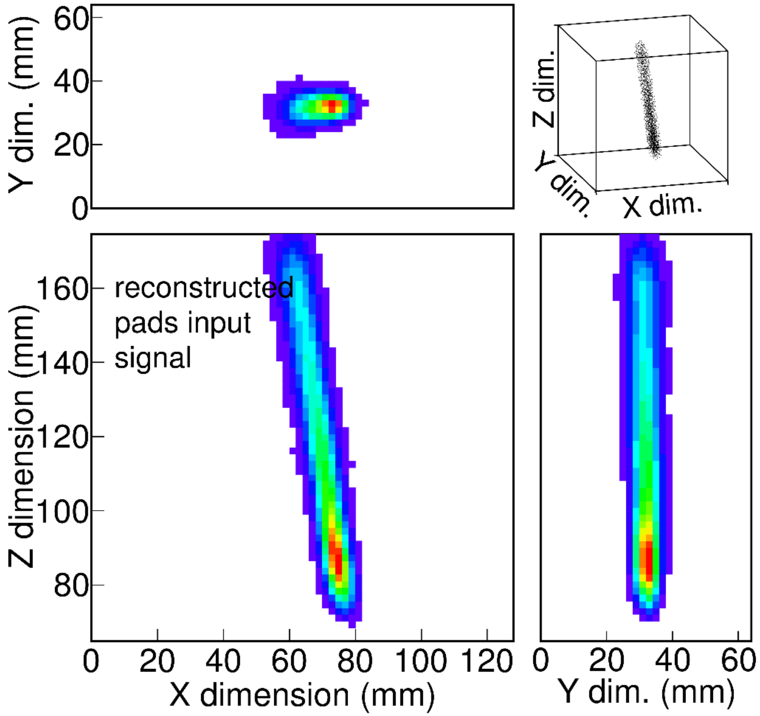


demonstrator test: full 3D tracks reconstruction

with response function de-convolution
→ effective Z charge distribution

energy resolution from rec. signal equiv. to output signal





commissioning experiment (active target mode)

tests @ GANIL
(11/2017 & 04/2018)
Commissioning of the
128x128 pads
full detector

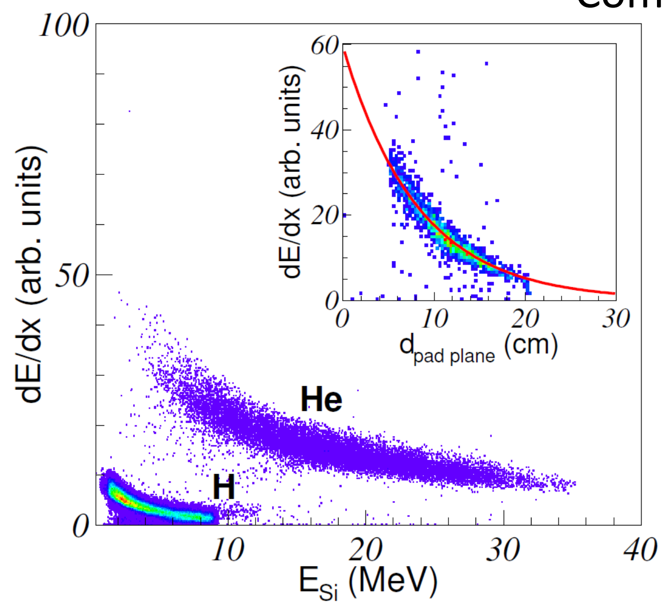
$^{18}O(p,p)$ and $^{18}O(p,\alpha)$ excitation functions

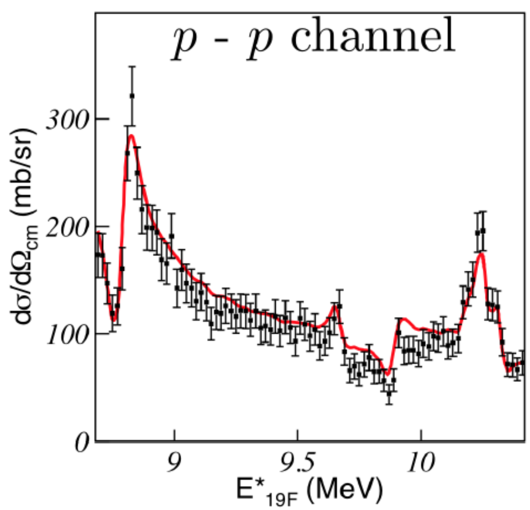
→ scattered particles identification
channel selection

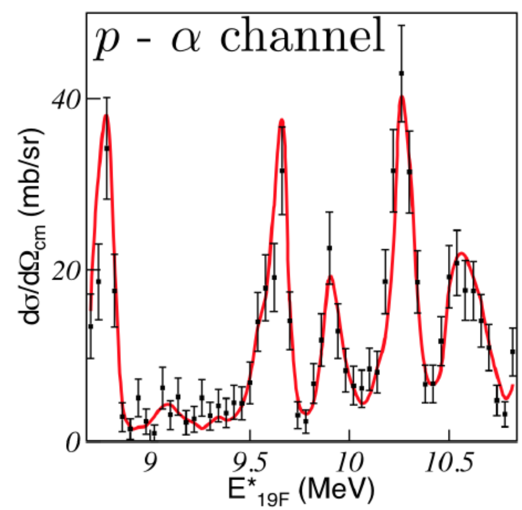
→ reaction kinematics
part. tracks & energy

→ absolute cross section

energy resolution 50~100 *keV*

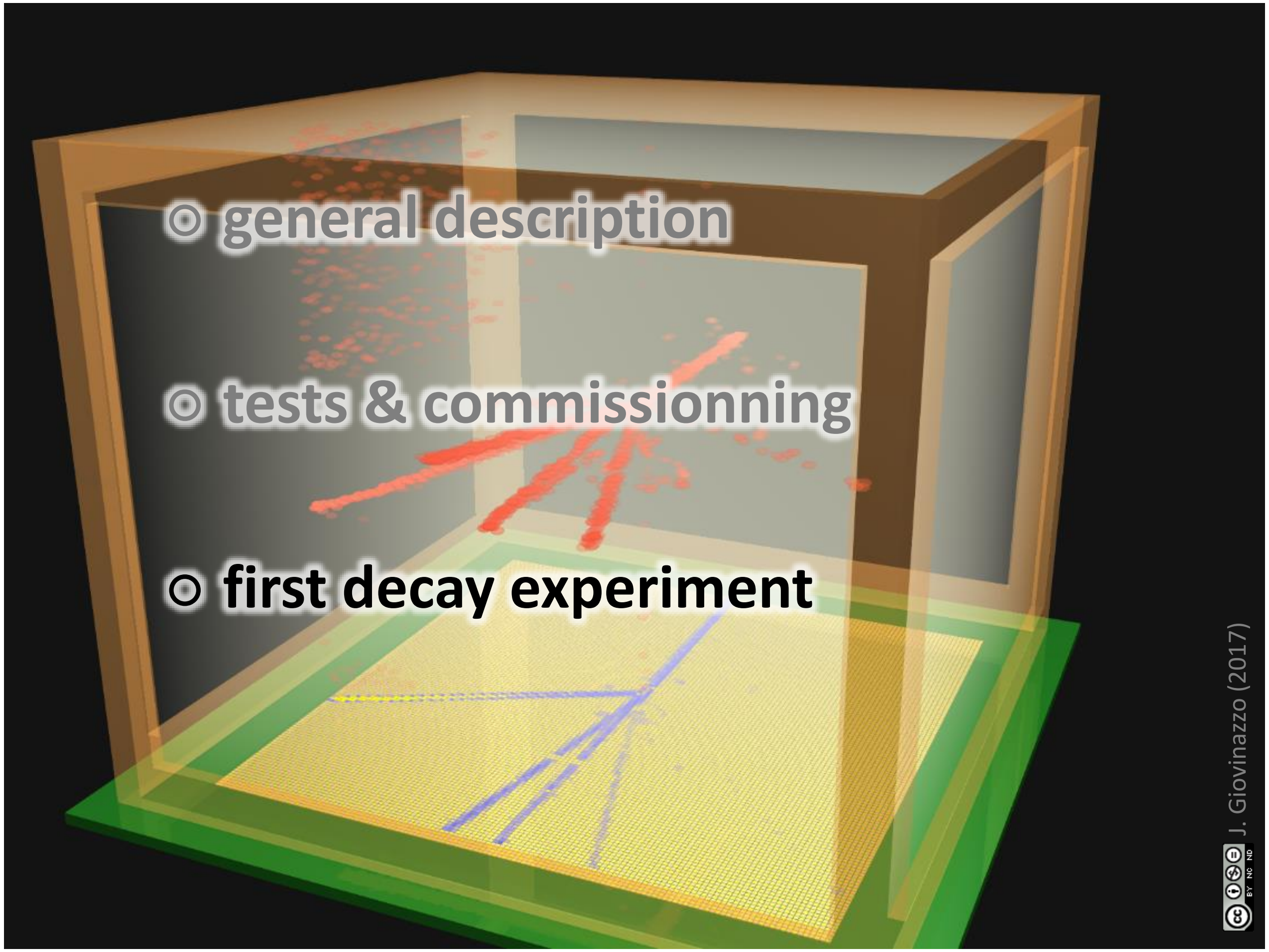






B. Mauss, PhD thesis (GANIL)
B. Mauss et al., NIM A940 (2019)

ACTAR TPC: a new tracking device



- general description
- tests & commissionning
- first decay experiment

first decay experiment (may 2019 @ GANIL/LISE)

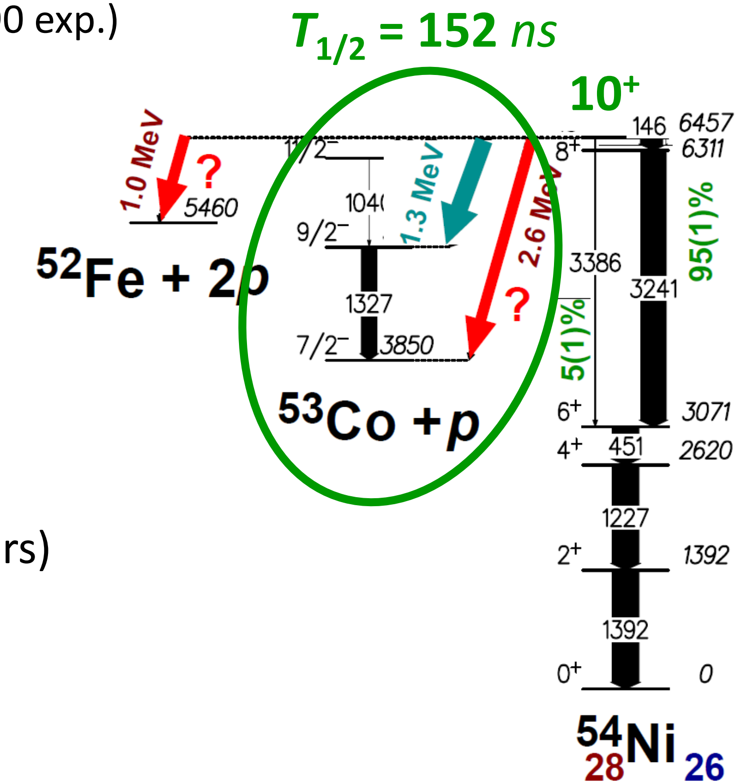
proton decay of ^{54}Ni 10^+ isomer
(D. Rudolph et al., E690 exp.)

RISING campaign
D. Rudolph et al., PRC78 (2008)

(passive stopper,
protons cannot be observed in Si detectors)

1.3 MeV deduced from 1327 gamma line

2.6 MeV proton should be there
(2p branch ?)



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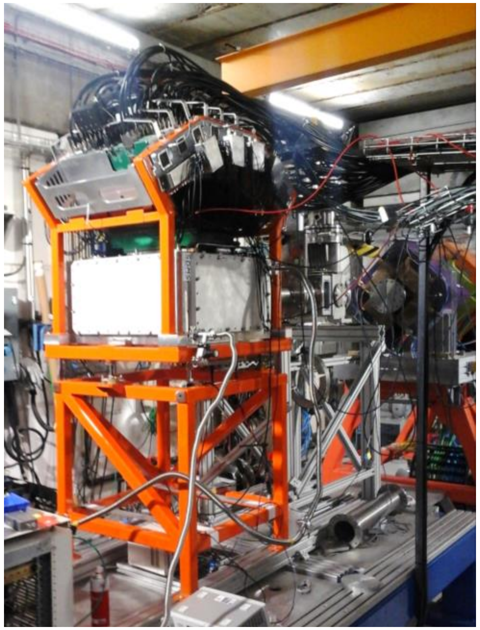
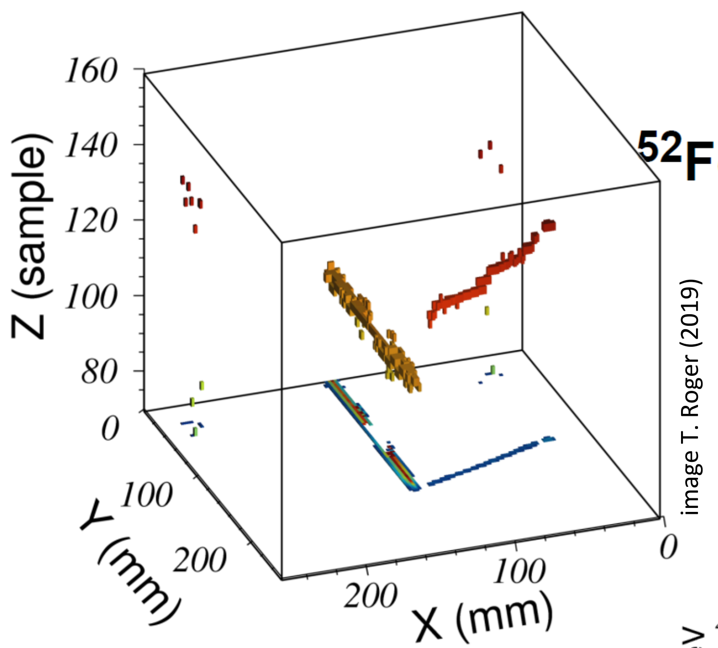
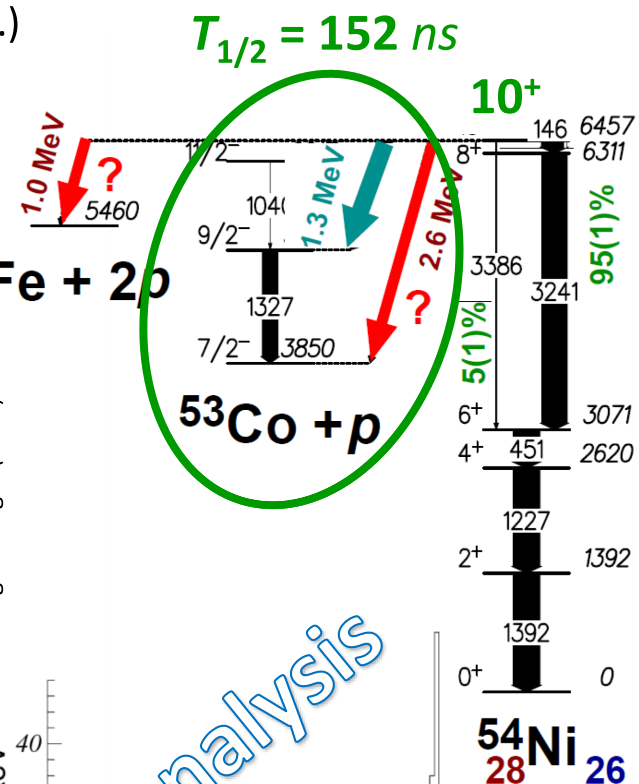
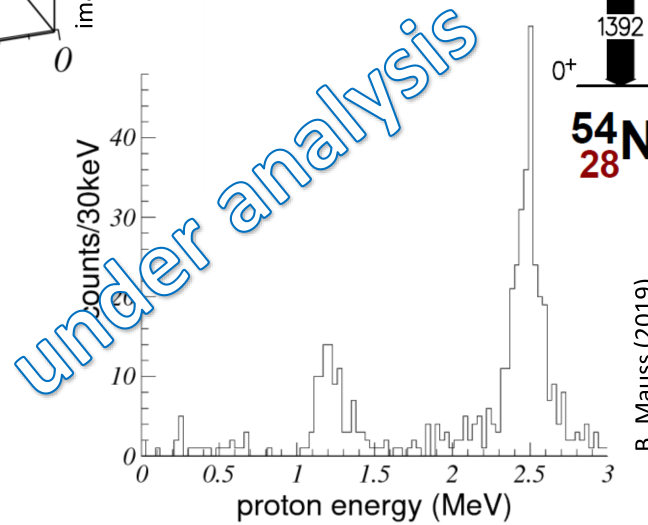


proton decay of ^{54}Ni 10^+ isomer

(D. Rudolph et al., E690 exp.)







similar result for the decay of ^{53}Co isomer

($T_{1/2}$ = 240 ms ; E_{proton} = 0.6 & 1.5 MeV)

perspectives…

short term... existing facilities

GANIL /LISE3 high intensity ^{56}Ni beam (5 μA)

limited energy (75 *AMeV*)

^{48}*Ni* doubly magic → pure configuration ?

→ influence on angular distribution ?

test-bench in Wang/Nazarewicz calculation

(planned 2020)

RIKEN/BigRIPS good ^{78}Kr beam (450 *nA*)

energy (350 *AMeV*)

^{67}*Kr* understand half-life problem

→ emission process / deformation ?

(accepted exp.)

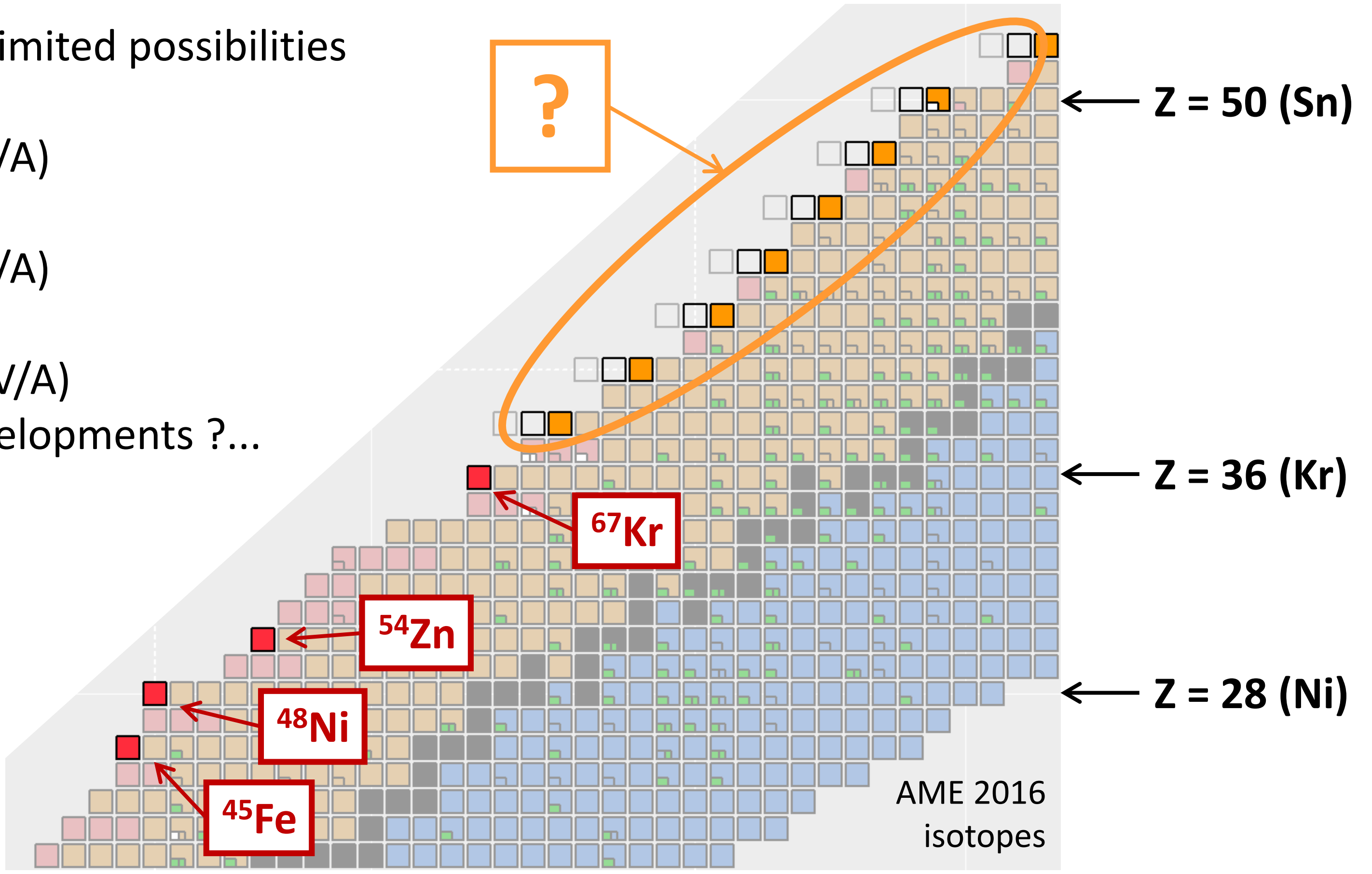
^{54}*Zn* (M. Pfützner et al.)

exp. in **2019**: only few counts... (Ni beam)

further studies, new candidates ?

larger set of nuclei with different structure configurations
between closed shells Z = 28 and Z = 50

- **current facilities** – limited possibilities
  - **GANIL** (95 MeV/A)
  - **NSCL** (160 MeV/A)
  - **RIKEN** (350 MeV/A)
    ...beam developments ?...



further studies, new candidates ?

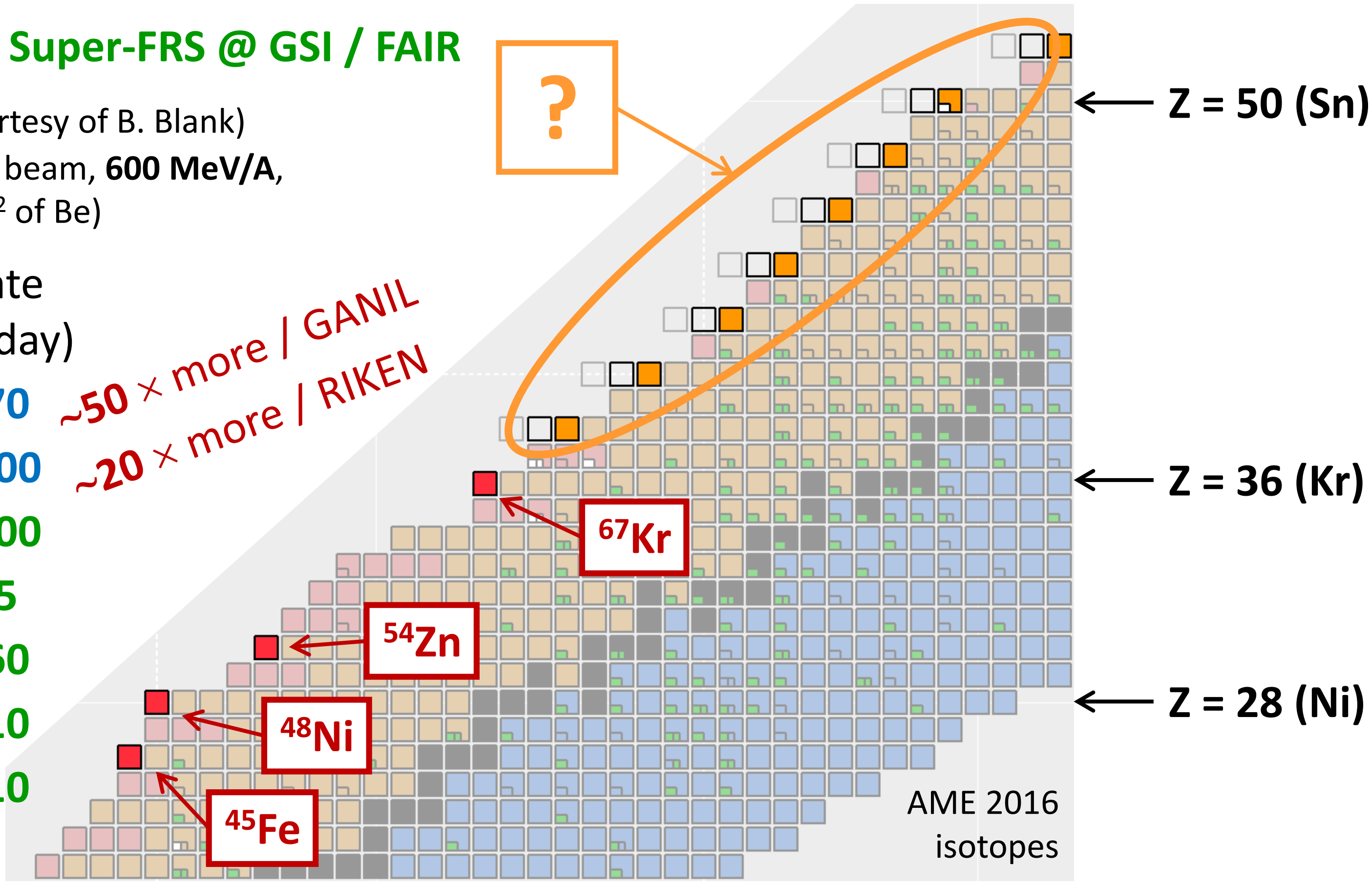
larger set of nuclei with different structure configurations
between closed shells Z = 28 and Z = 50

- opportunities **FRS / Super-FRS @ GSI / FAIR**

rate estimates (courtesy of B. Blank)
(**5 × 10^{11} pps** of primary beam, **600 MeV/A**,
4 sec per pulse, 4 g/cm^2 of Be)

beam	frag.	rate (1/day)
^{58}Ni	^{48}Ni	70
^{78}Kr	^{67}Kr	200
^{92}Mo	^{71}Sr	100
	^{70}Sr	5
	^{75}Zr	60
	^{79}Mo	10
^{124}Xe	^{98}Sn	10

~50 × more / GANIL
~20 × more / RIKEN



further studies, new candidates ?

larger set of nuclei with different structure configurations
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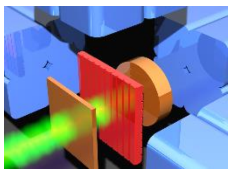
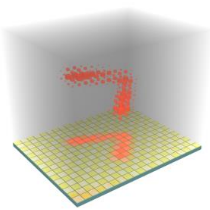
▶ opportunities **FRS / Super-FRS @ GSI / FAIR**

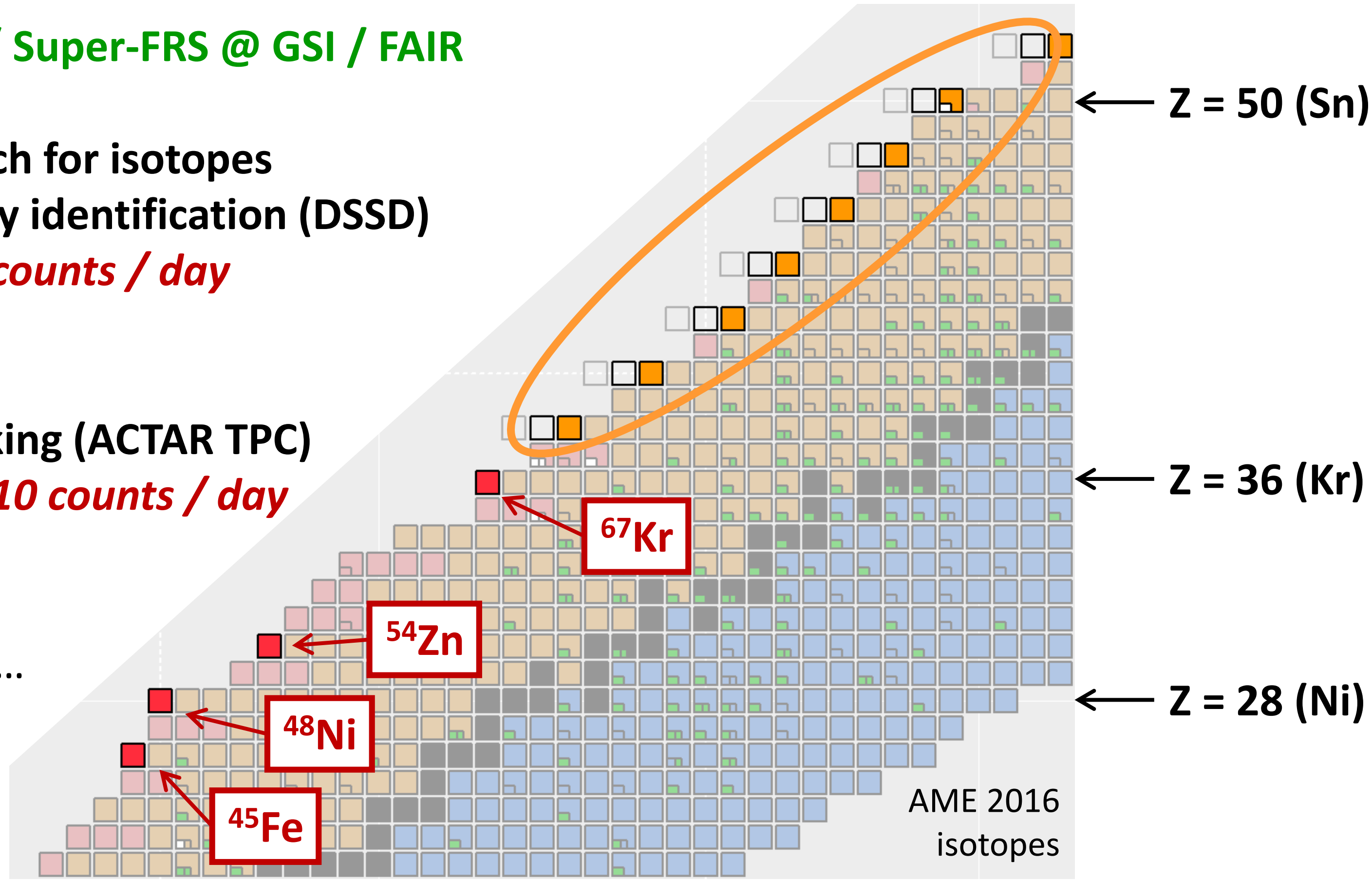


▷ **search for isotopes**
decay identification (DSSD)
few counts / day



▷ **tracking (ACTAR TPC)**
few 10 counts / day

depends on beams…
availability ?
intensities ?



thank you for your attention !