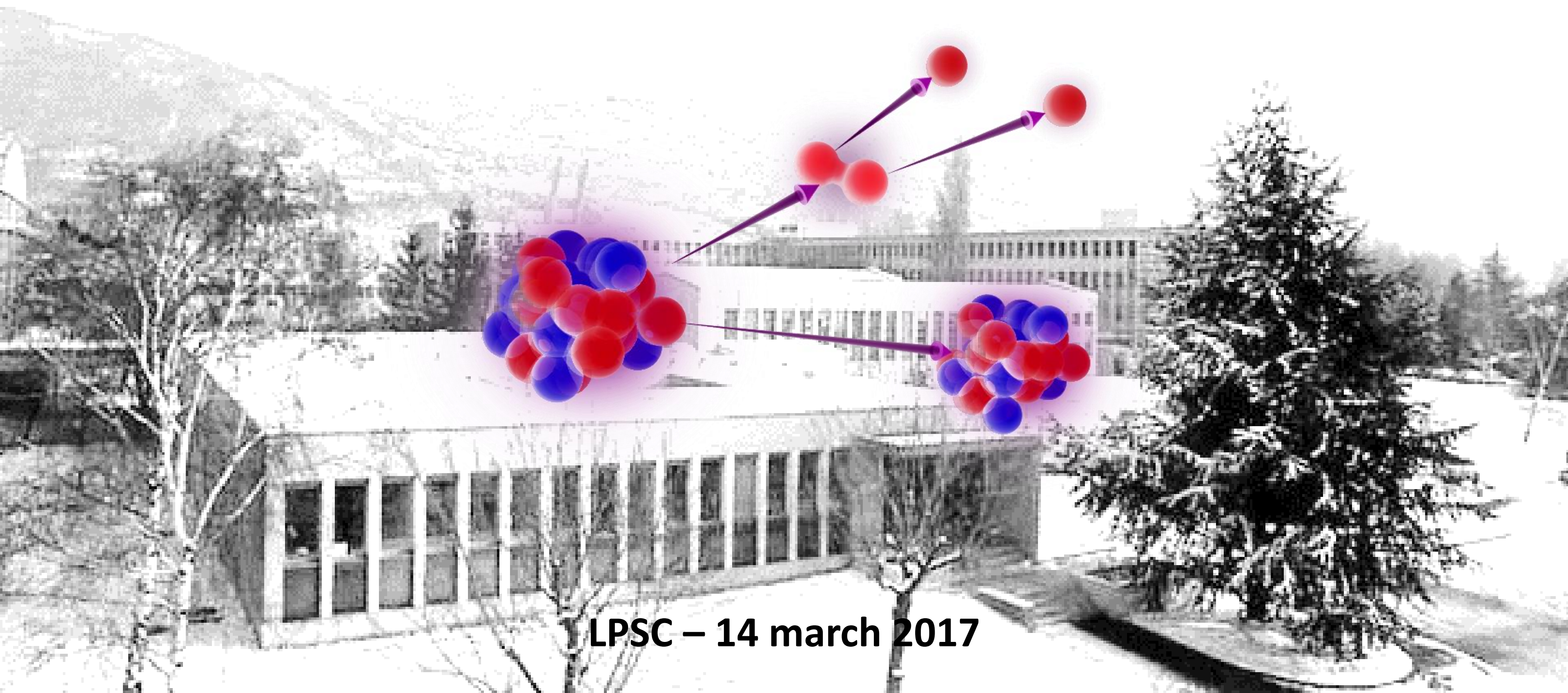
J. Giovinazzo – CENBG / IN2P3

2-proton radioactivity

from theoretical prediction to experimental exploration



LPSC – 14 march 2017

presentation summary

- ▷ nuclear landscape
  - ○ stability and radioactivity
  - ○ exotic decays modes at the proton drip-line
  - ○ 2-proton radioactivity theoretical frameworks

- ▷ discovery experiments
  - ○ indirect observation
  - ○ recent results

- ▷ tracking experiments
  - ○ indirect observation
  - ○ experimental studies status

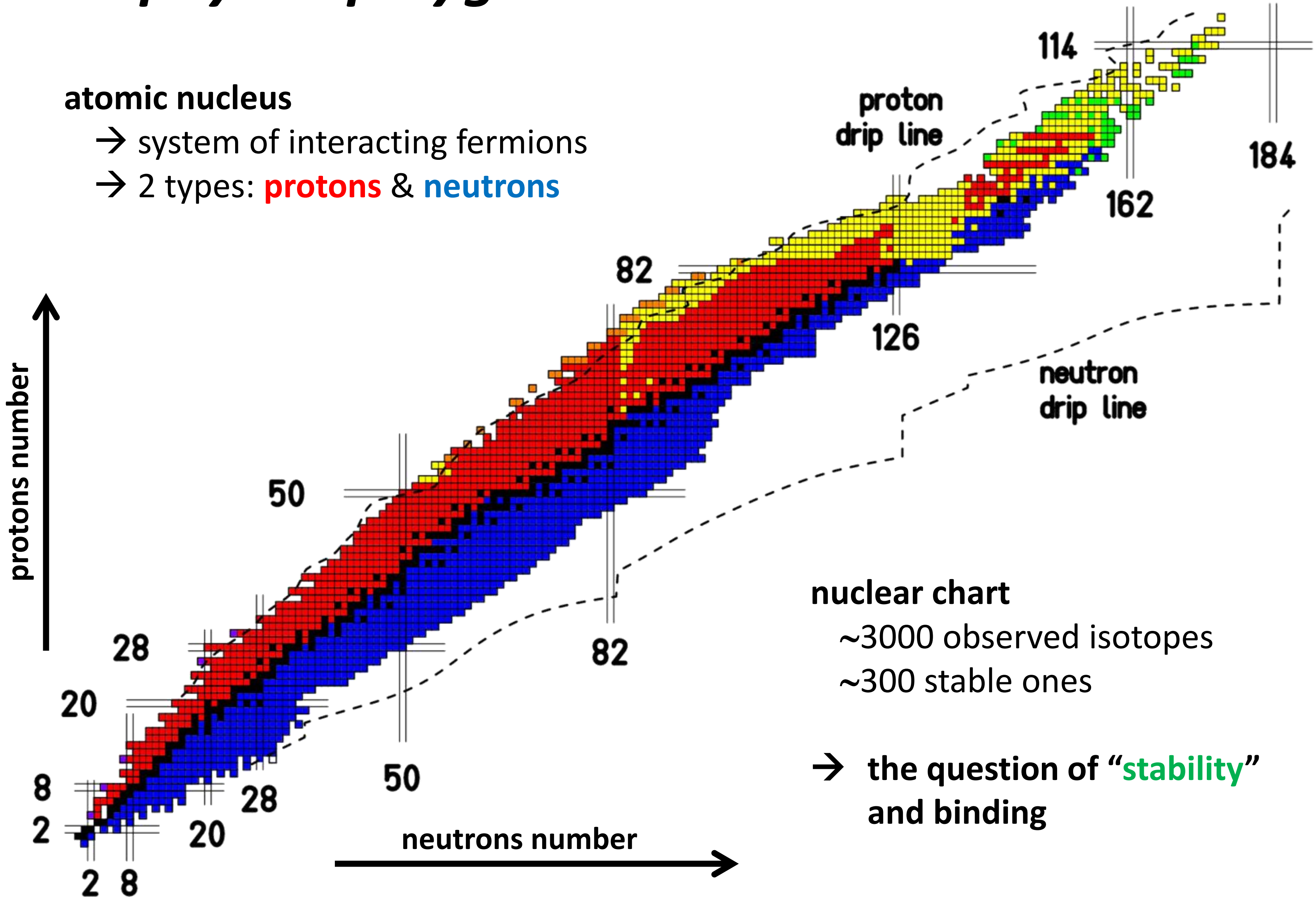
- ▷ ongoing developments and outlook

nuclear physics playground

atomic nucleus

→ system of interacting fermions

→ 2 types: **protons** & **neutrons**



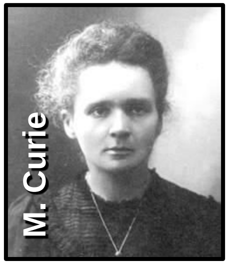
nuclear chart

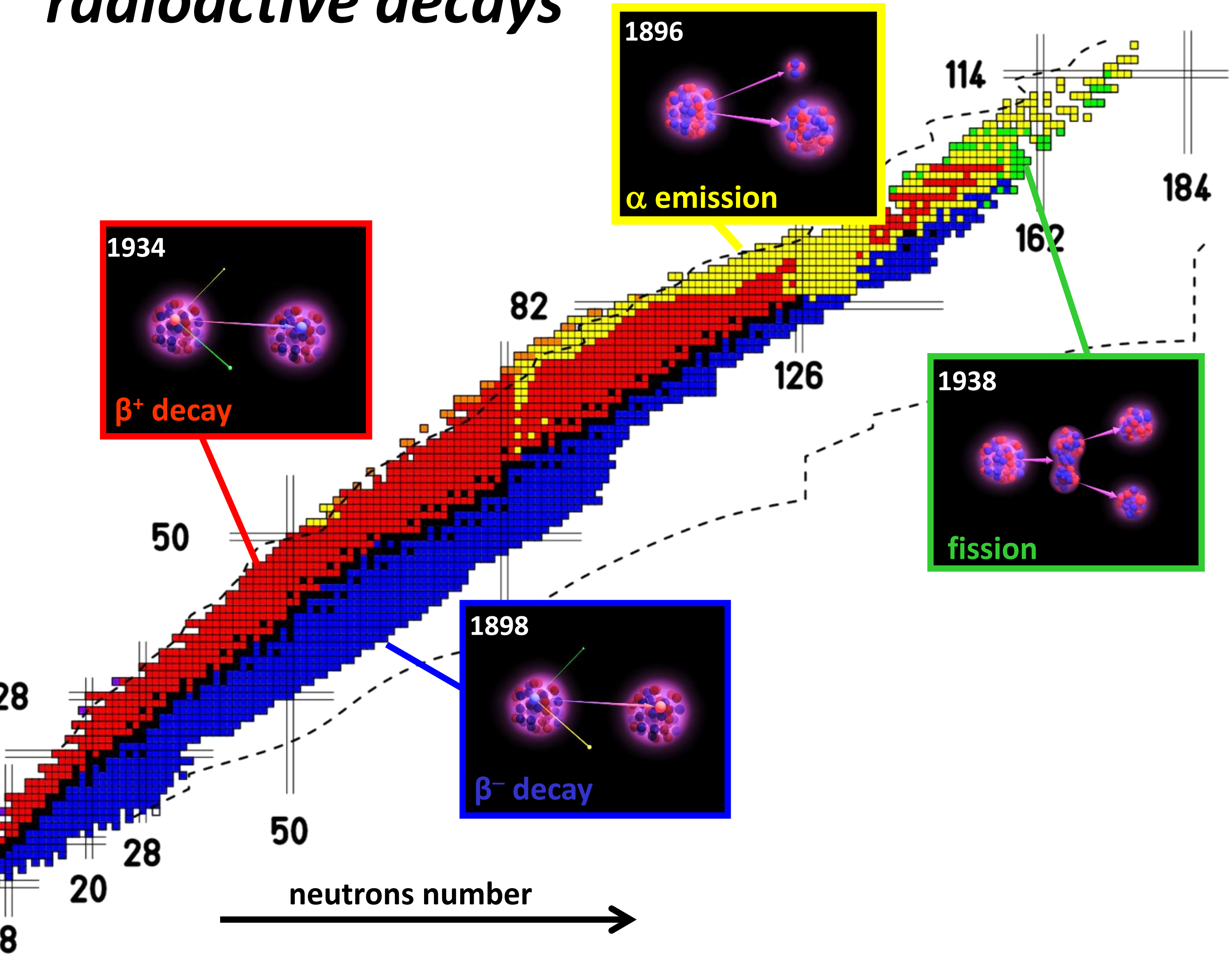
~3000 observed isotopes

~300 stable ones

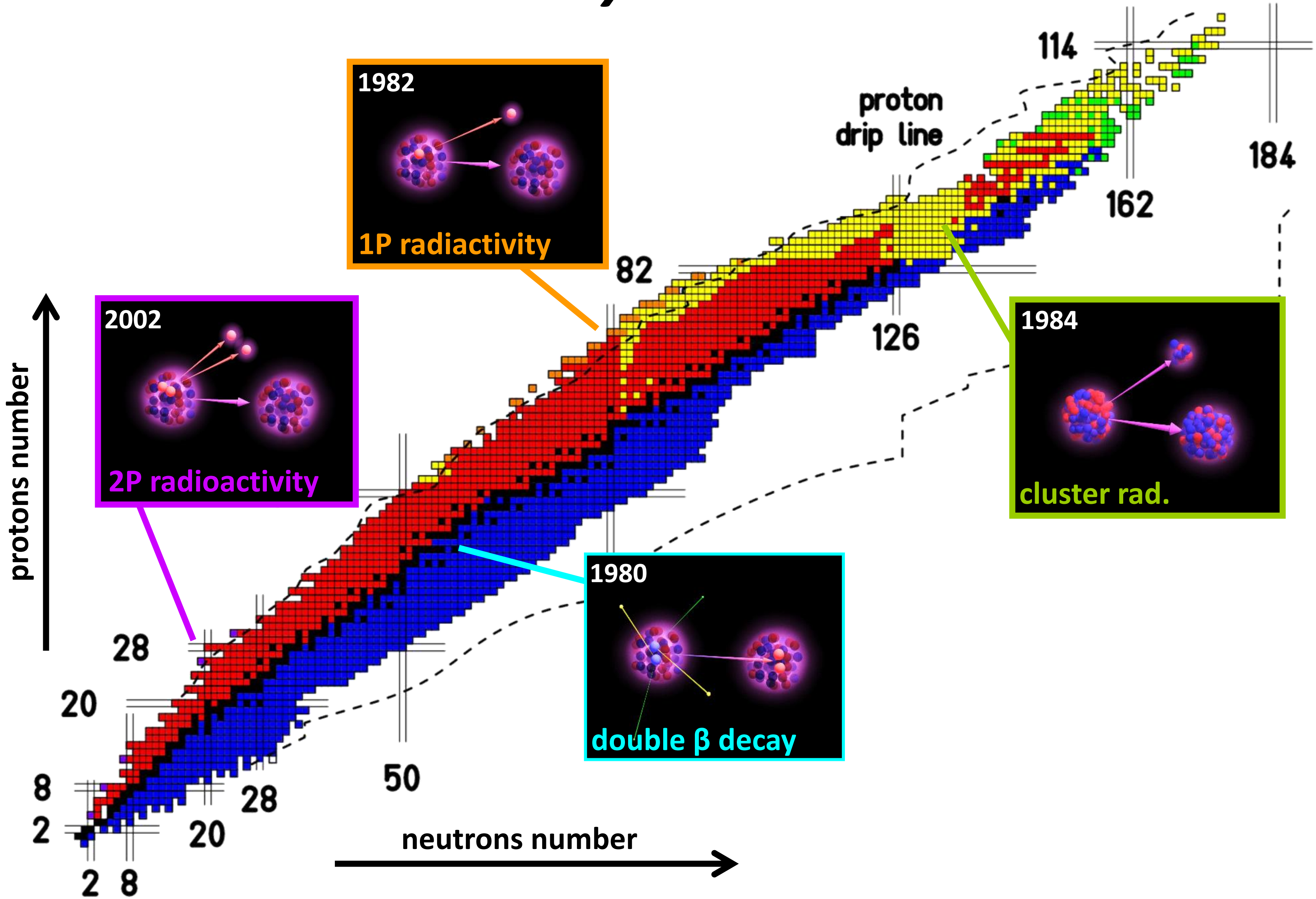
→ **the question of "stability" and binding**

"classic" radioactive decays





"exotic" radioactive decays



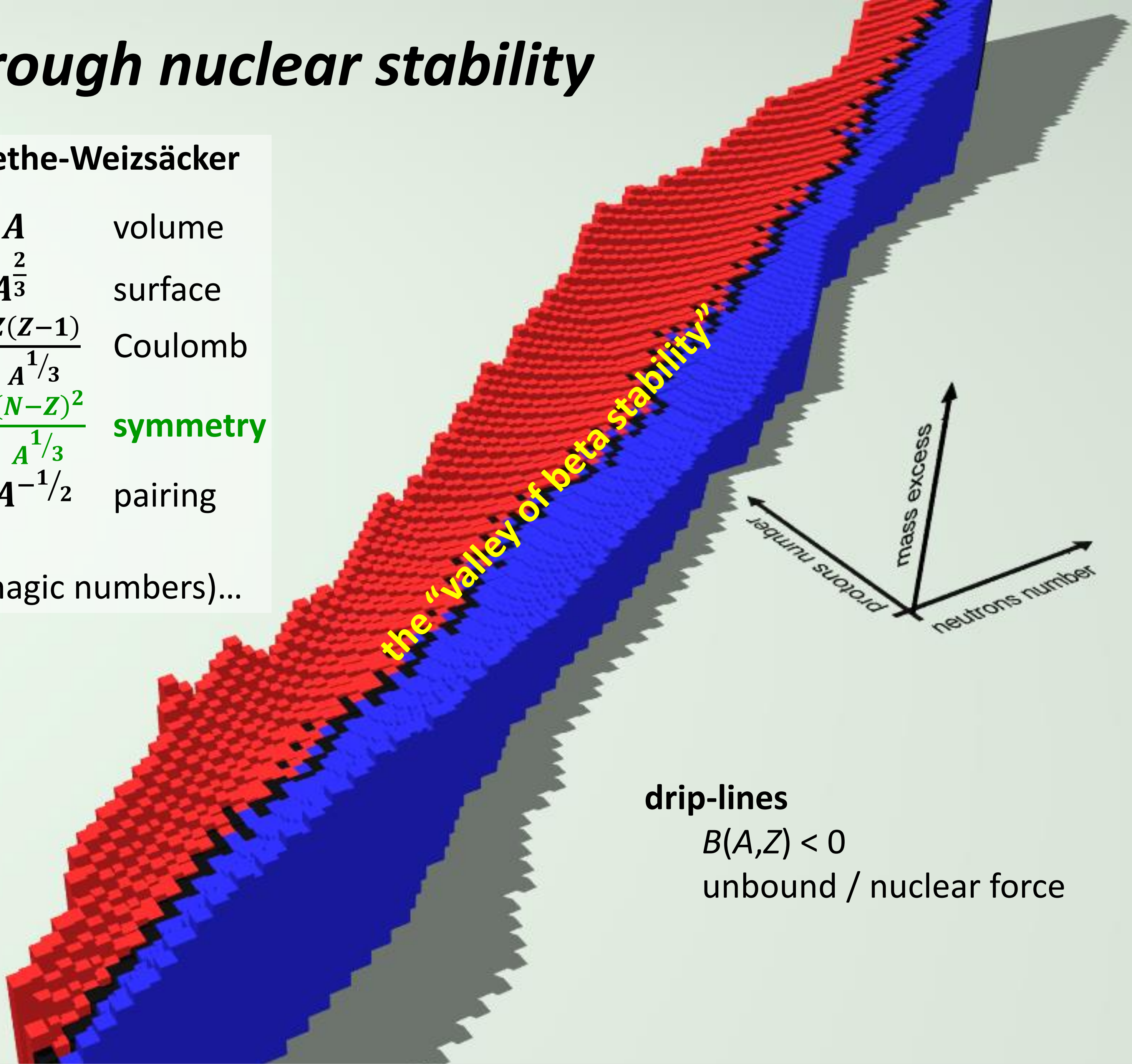
a detour through nuclear stability

binding energy: Bethe-Weizsäcker

$$\begin{aligned}
B(A,Z) &= a_v \cdot A && \text{volume}\\
&- a_s \cdot A^{\frac{2}{3}} && \text{surface}\\
&- a_c \cdot \frac{Z(Z-1)}{A^{1/3}} && \text{Coulomb}\\
&- a_a \cdot \frac{(N-Z)^2}{A^{1/3}} && \textbf{symmetry}\\
&\pm a_p \cdot A^{-1/2} && \text{pairing}
\end{aligned}$$

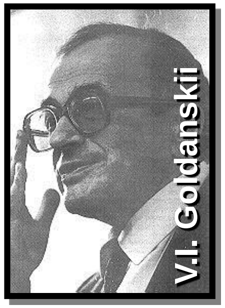
+ shell effects (magic numbers)…

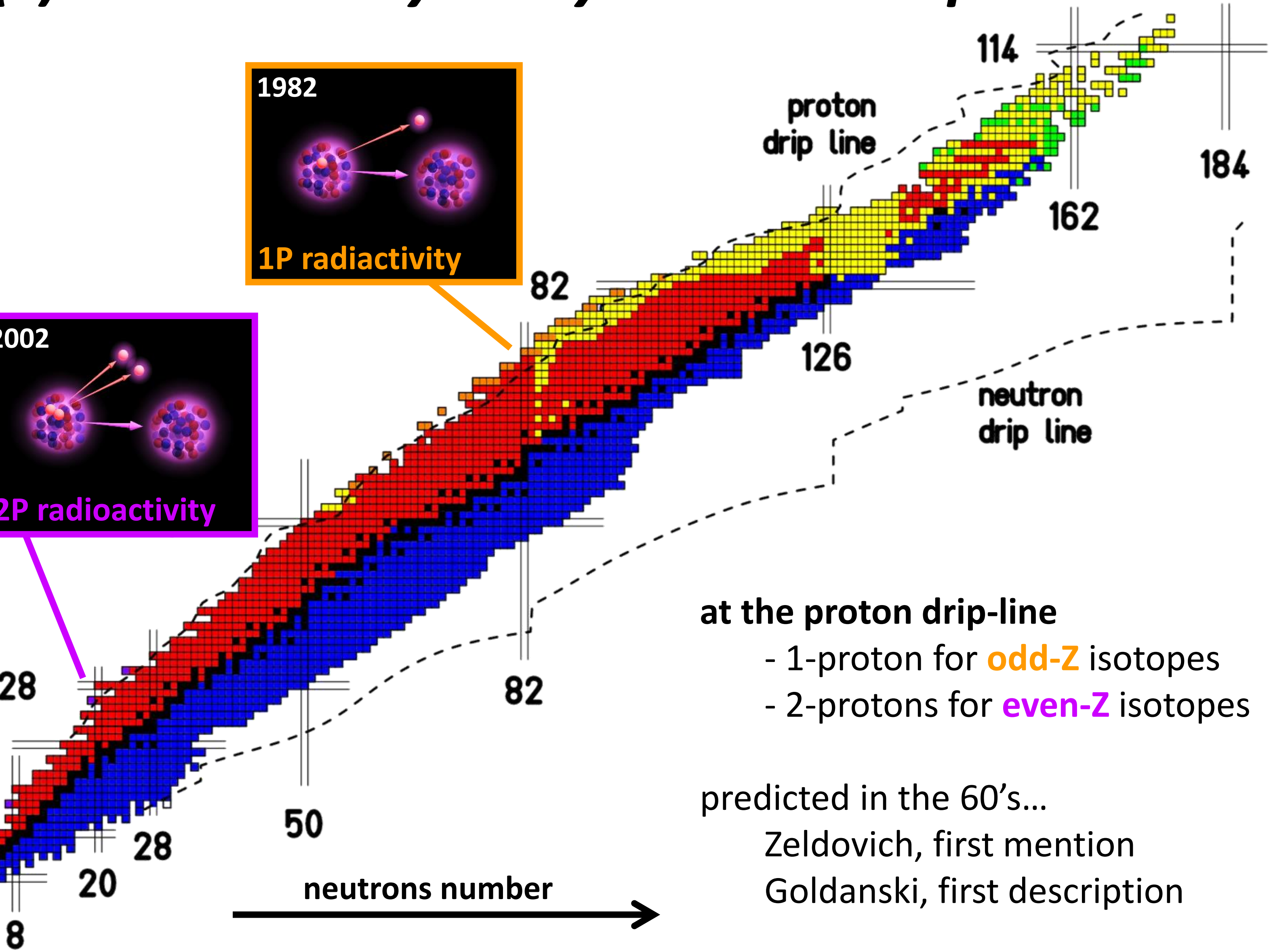
mass (excess)
⇳
binding energy



drip-lines
$B(A,Z) < 0$
unbound / nuclear force

proton(s) radioactivity: “beyond” the drip-line





at the proton drip-line

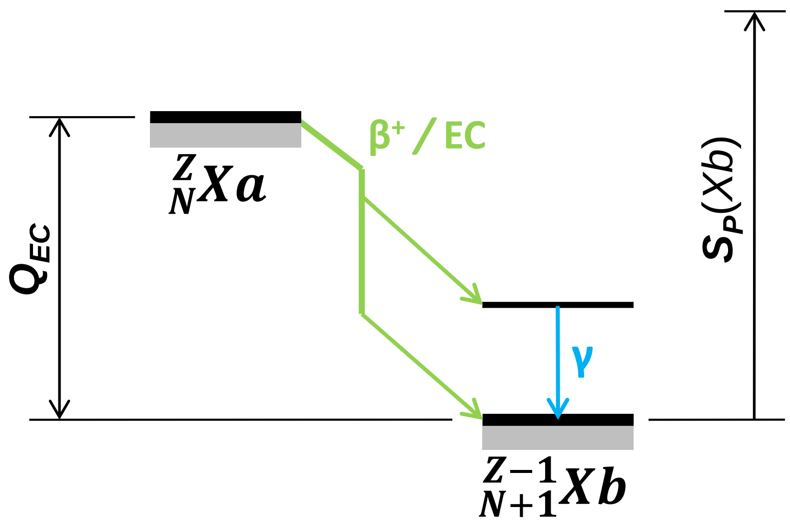
- 1-proton for **odd-Z** isotopes
- 2-protons for **even-Z** isotopes

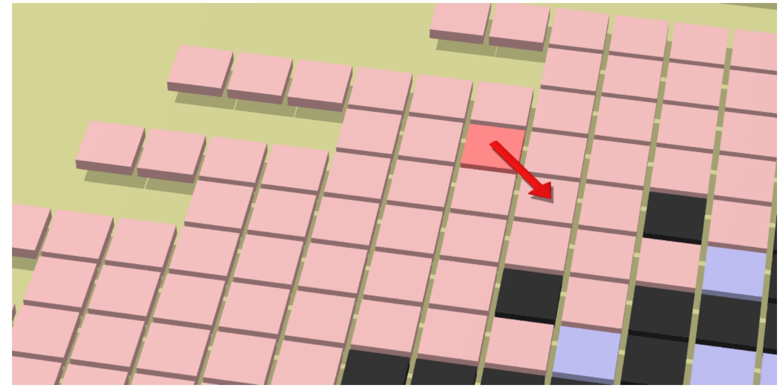
predicted in the 60’s…

Zeldovich, first mention

Goldanski, first description

towards the proton drip-line





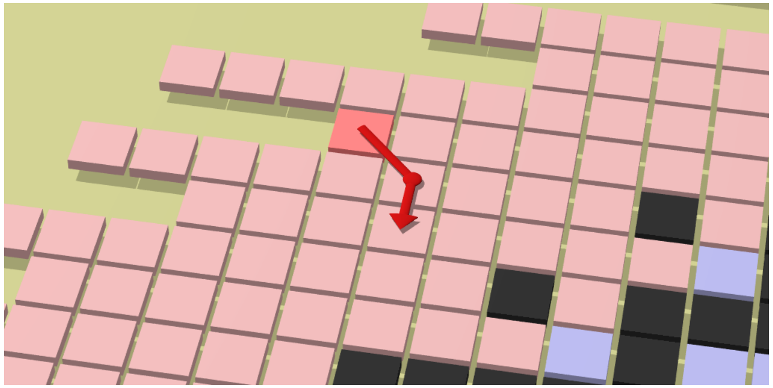
β and β-γ decays:

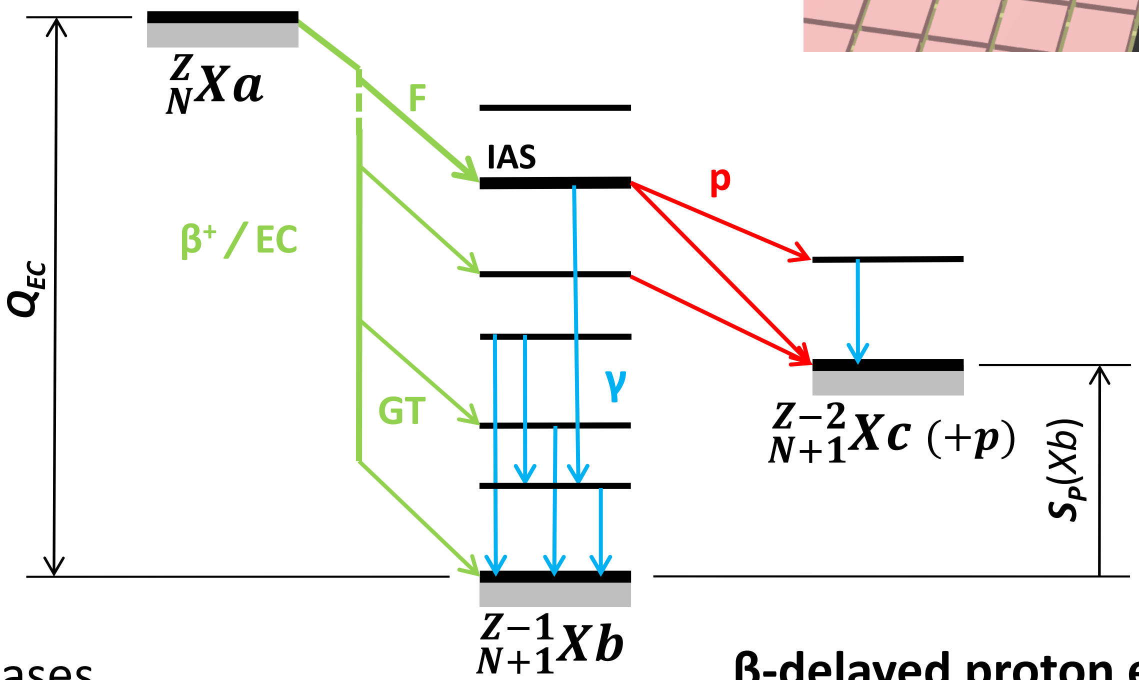
- spectroscopy and nuclear structure
- precision tests of weak interaction

β⁺/EC decay energy: $Q_{EC} \sim$ few *MeV*

proton separation: $S_P(Xb) > Q_{EC}$ (*B/A* ~8 *MeV*)

towards the proton drip-line





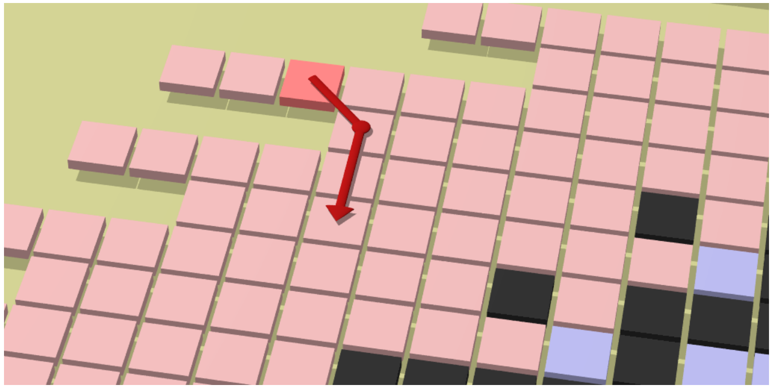
Q_{EC} increases
S_P (Xb) decreases

β-delayed proton emission:

- nuclear astrophysics
- gamma / proton competition

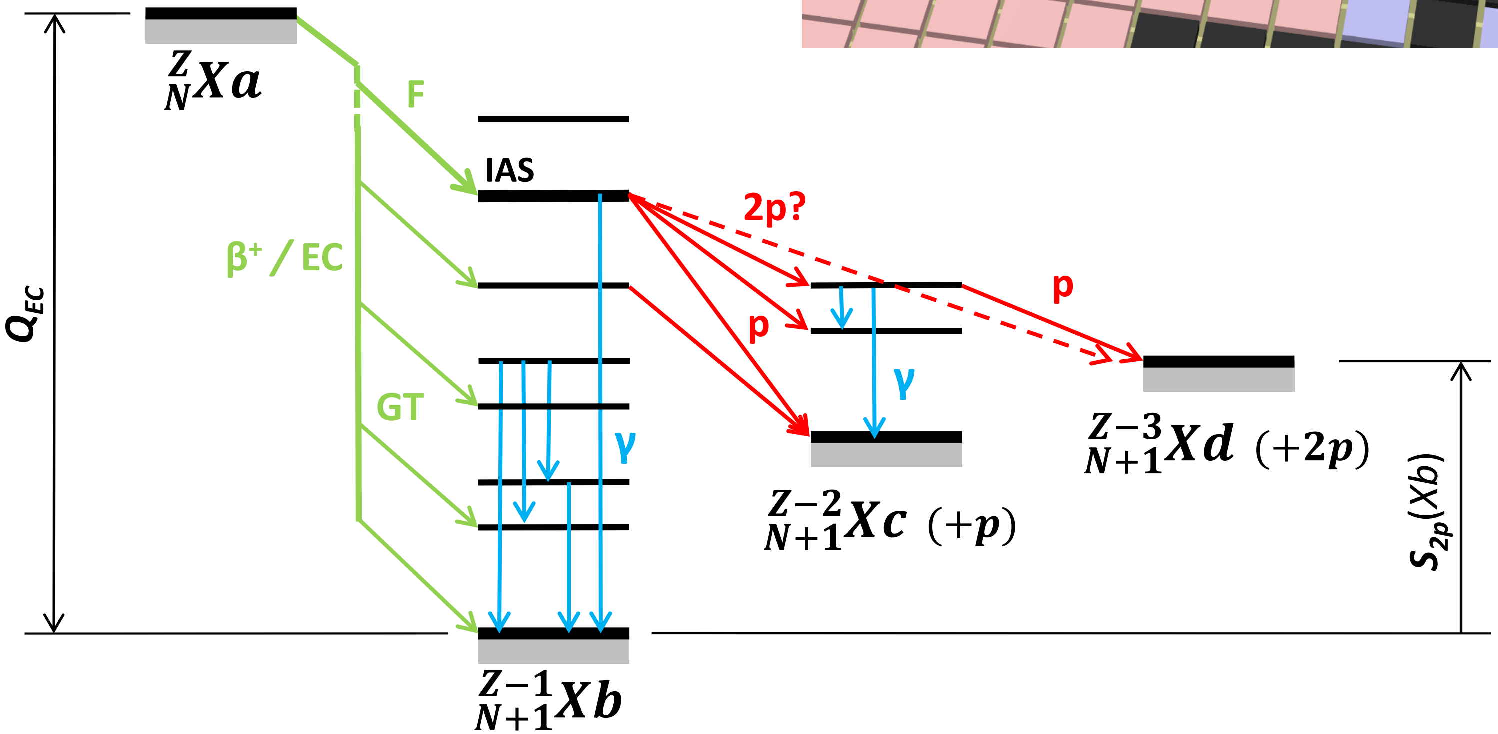
proton transitions: precise probe

towards the proton drip-line



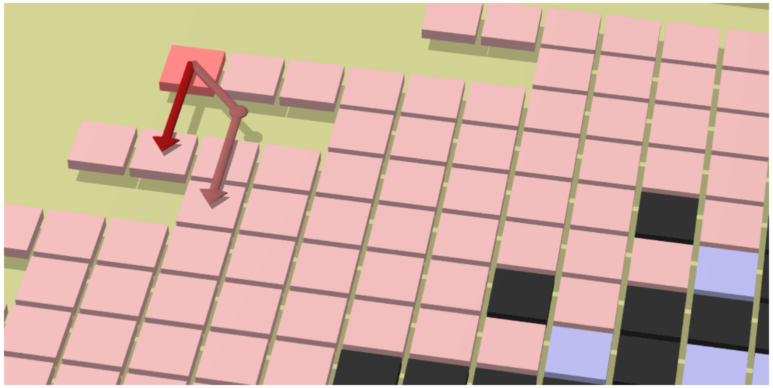
β-delayed multi- proton emission:

- *rp*-process waiting points
- search for direct 2P emission

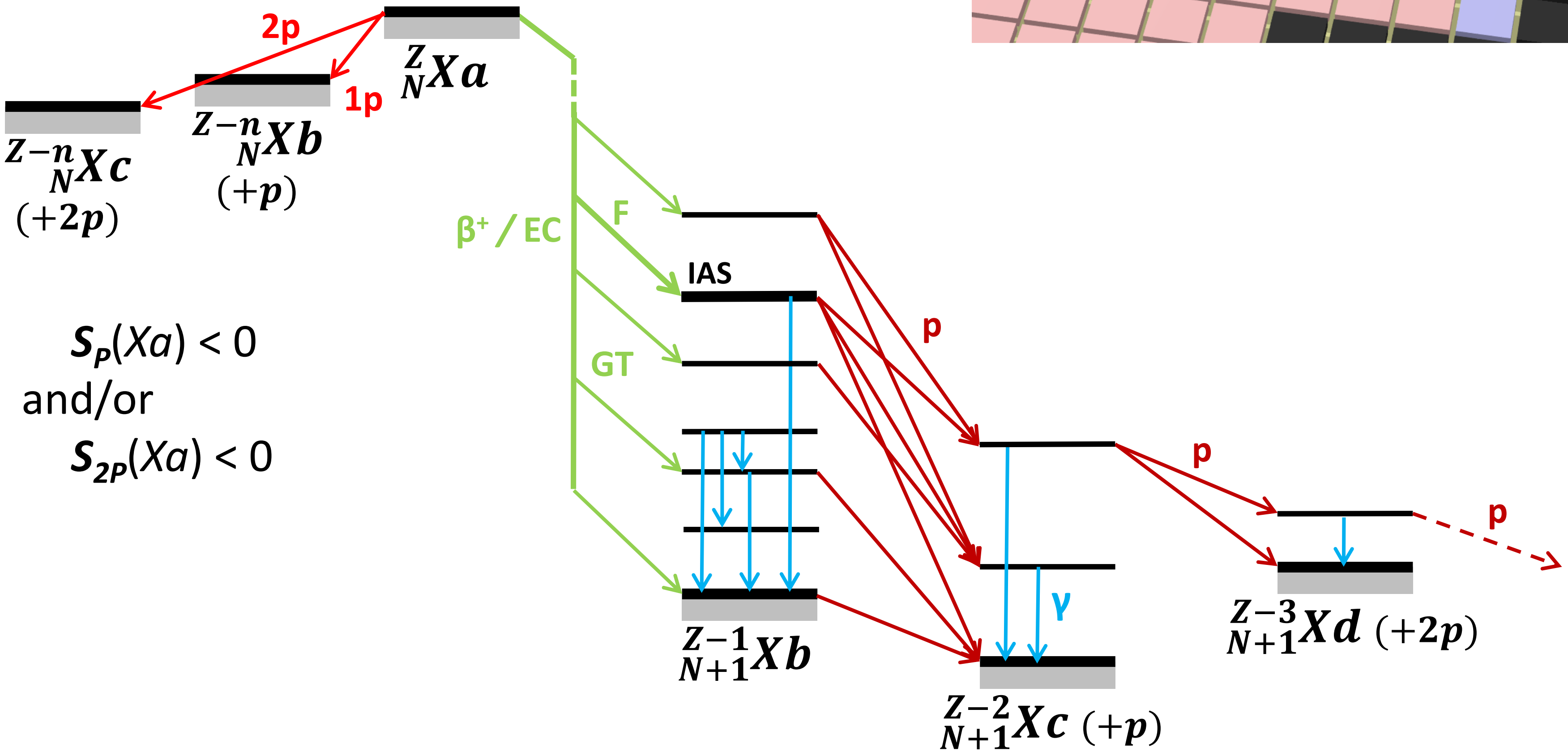


- often the only access to very exotic isotopes
- complex proton emission patterns: level densities & statistical aspects

towards the proton drip-line



unbound with respect to proton(s) emission

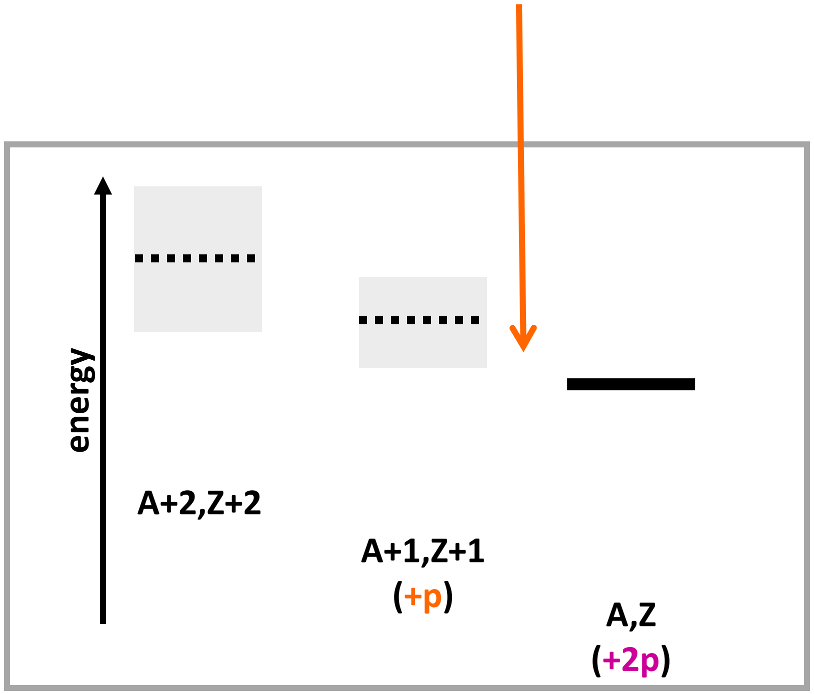


$S_P(Xa) < 0$
and/or
$S_{2P}(Xa) < 0$

proton(s) radioactivity

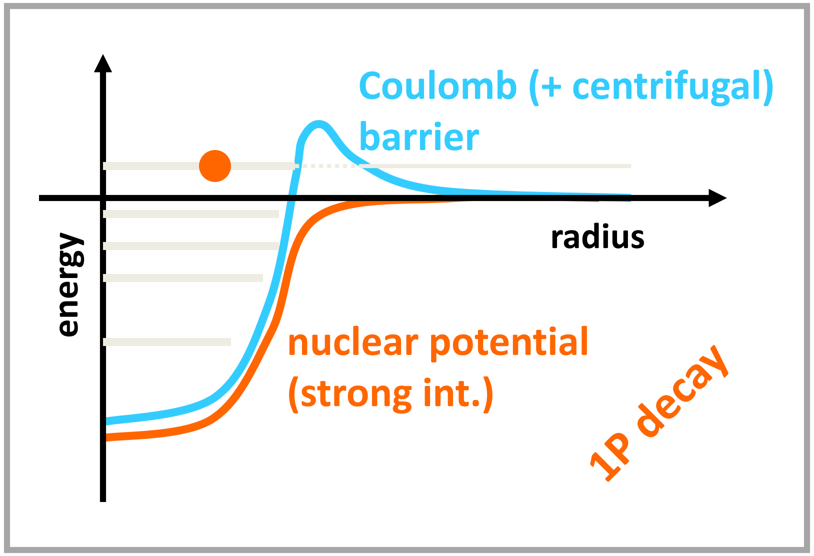
quasi-(un)bound ground state

proton drip line
(w/r nuclear interaction)

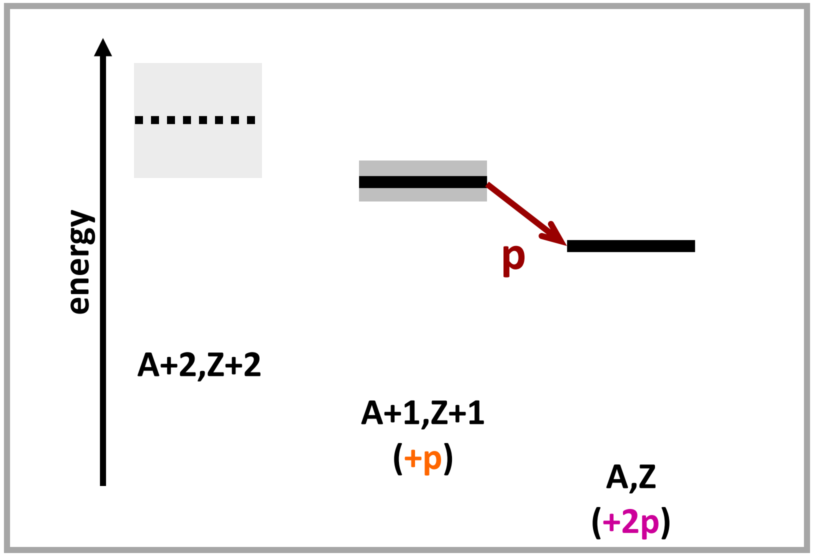


time scale of nucleons motion **~10^{-20} s**

quasi-(un)bound ground state



odd-Z isotope



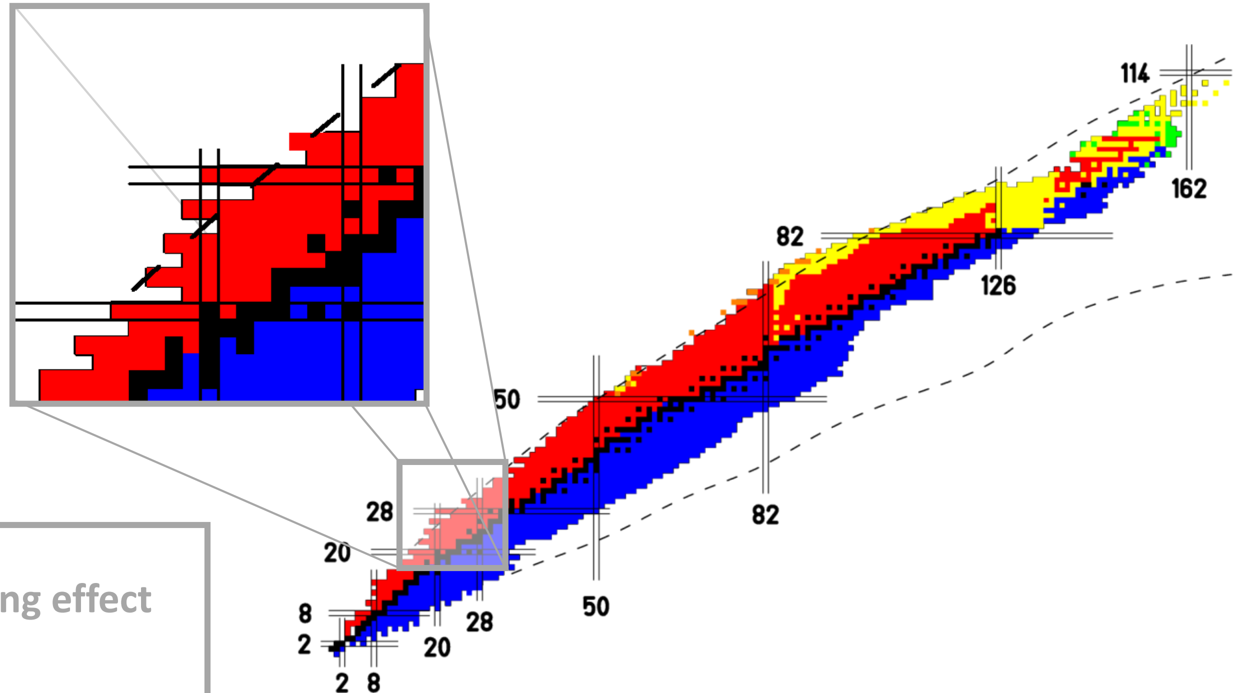
if Coulomb barrier is larger than proton separation energy
→ metastable state

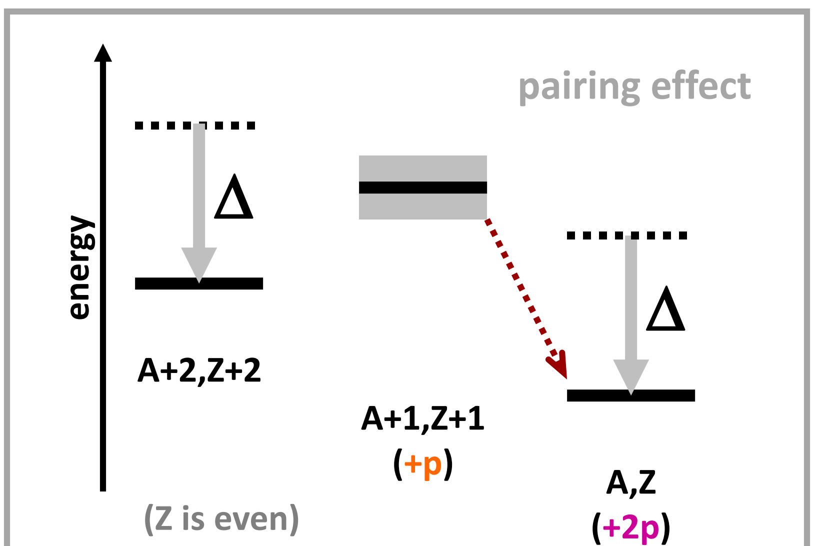
then tunnel effect
→ **1-proton radioactivity**

quasi-(un)bound ground state

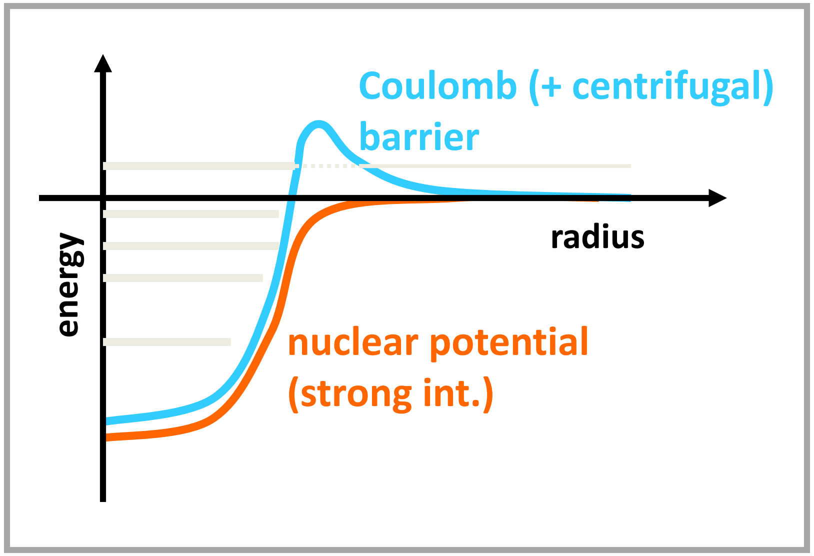
illustration of odd – even effect:

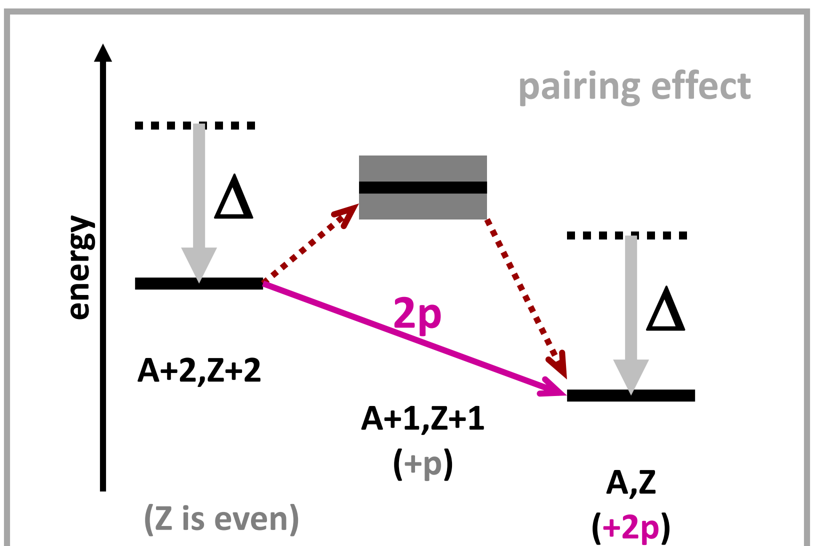
- **stable isotopes**
- **drip-lines**

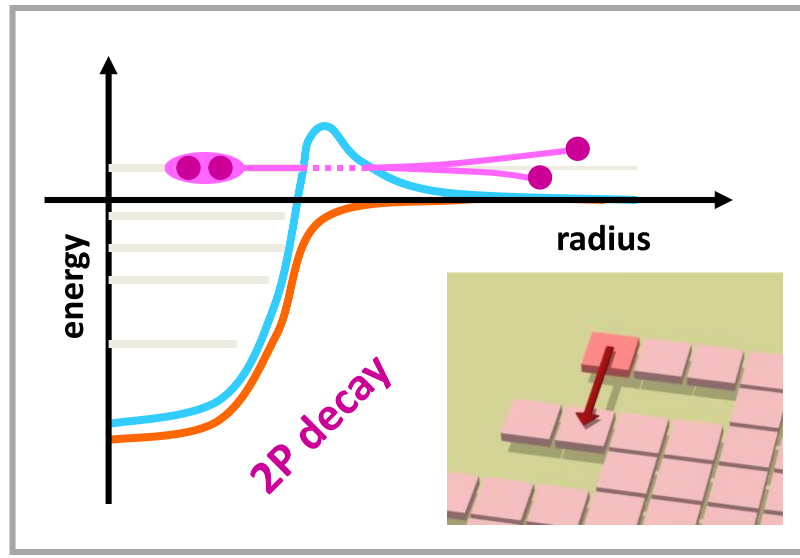




quasi-(un)bound ground state







even-Z isotope

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

physics case (motivation)

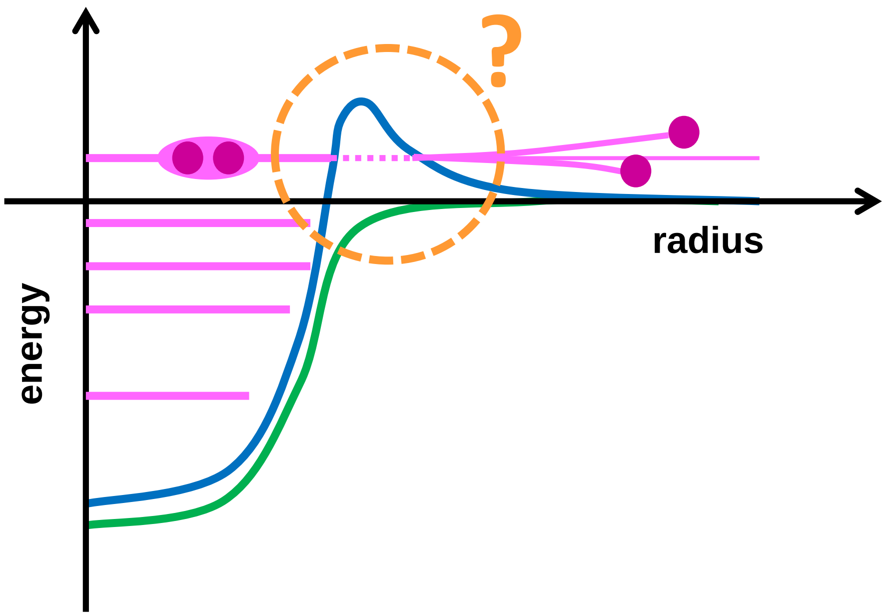
ground-state 2-proton radioactivity

→ **drip-line and masses** (beyond the « drip-line »)
transition Q-values

→ **nuclear structure**
energies, half-life, levels configuration

→ **pairing**
correlations in energy and angle of emitted protons

→ **tunnel effect**
theoretical descriptions

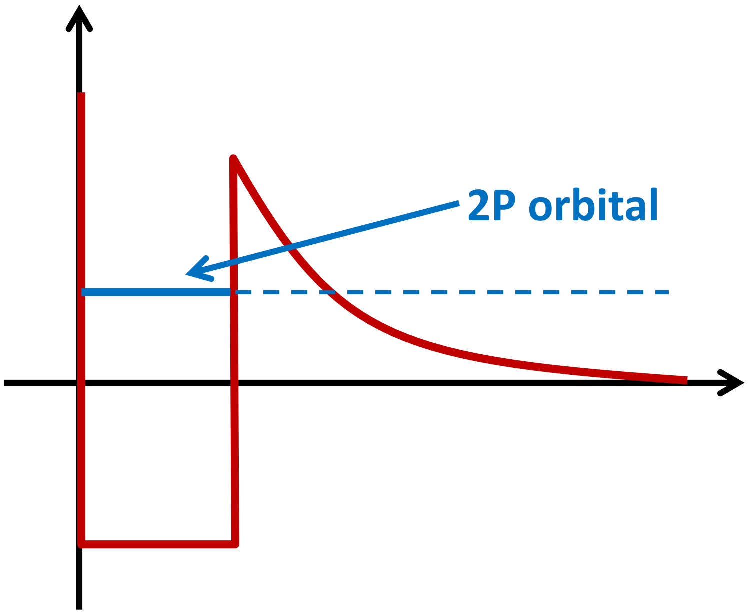


the emitted protons carry information on what's going on inside the nucleus

the 2-proton radioactivity mixes
the **structure** (wave functions)
and the (decay) **dynamics**

predictions and theoretical frameworks

initial predictions



First calculation by V.I. Goldanskii (1960)

→ **simple potential model**

→ **based on masses differences**
(mass predictions)

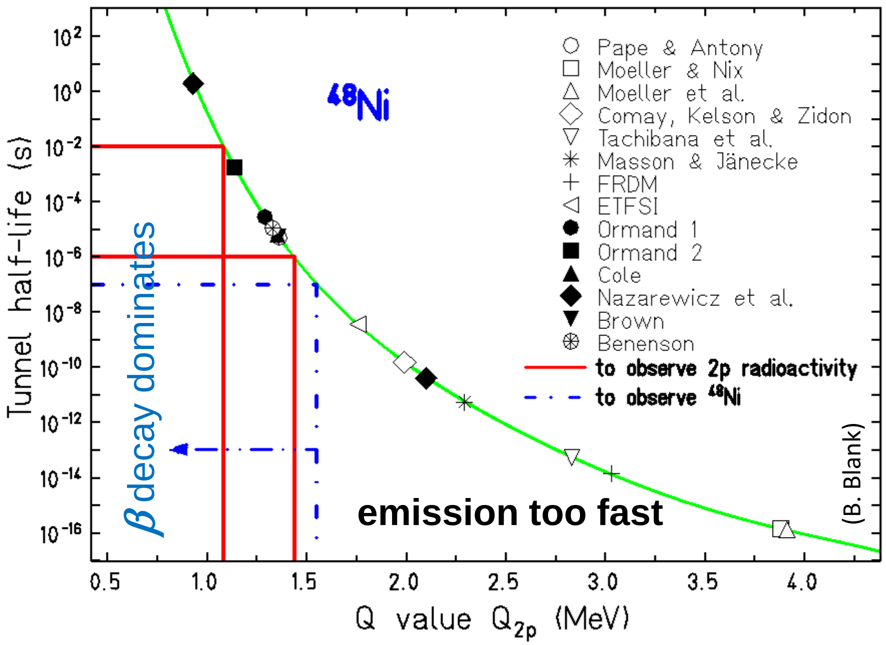
→ **tunnel effect**
barrier penetration of a ^{2}He particle vs. simultaneous emission of 2 protons

energy sharing
→ equal sharing between protons

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

Mass region A ≈ 50 already foreseen as the most promising

simple ^{2}He tunneling model



⇨ $T_{1/2} = f(Q_{2P})$

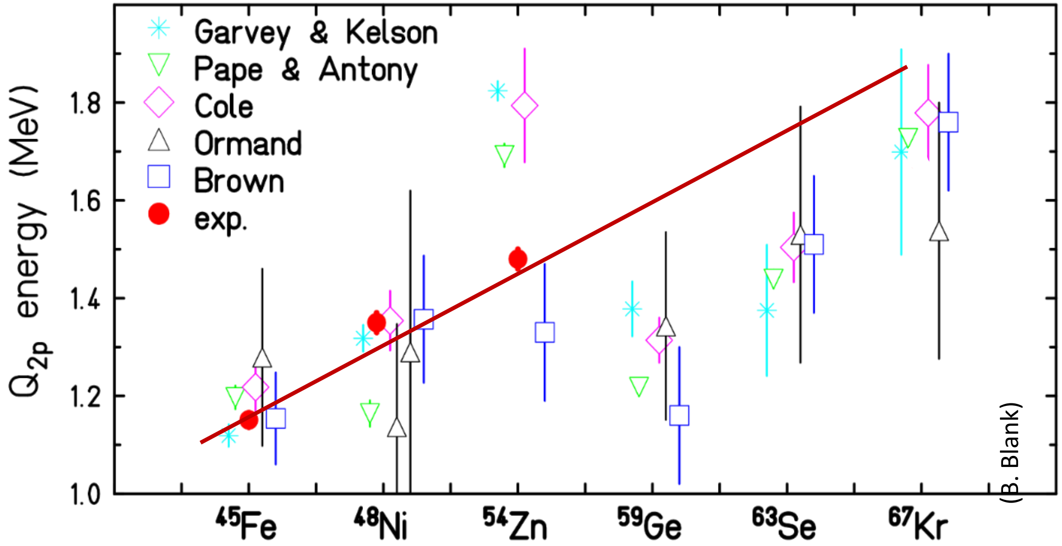
if Q_{2P} too high ⇨ too short $T_{1/2}$

if Q_{2P} too small ⇨ tunneling too slow: β^+ dominates the decay

mass region A~50
(already foreseen by Goldanskii)

- **Coulomb barrier high enough (Z ≈ 20 to 30)**
- **half-life 1 μs ~ 10 ms**

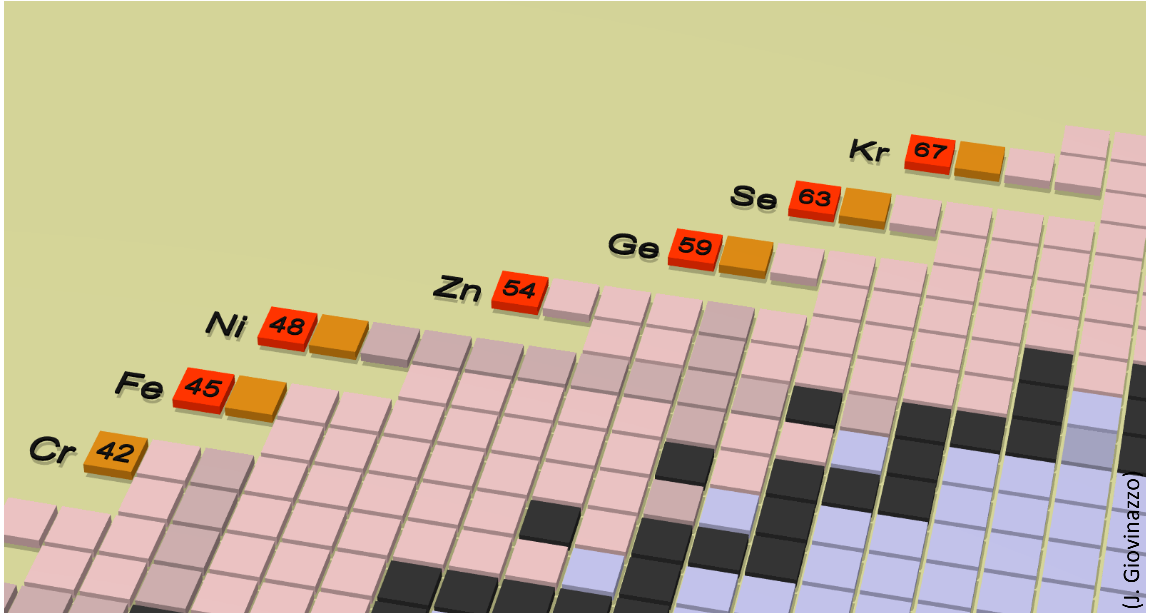
search for candidates: mass models



candidates
$(Q_{2P} > 0)$ & $(Q_{1P} < 0)$

local mass models

- **microscopic**
- **IMME**
- **Garvey-Kelson**



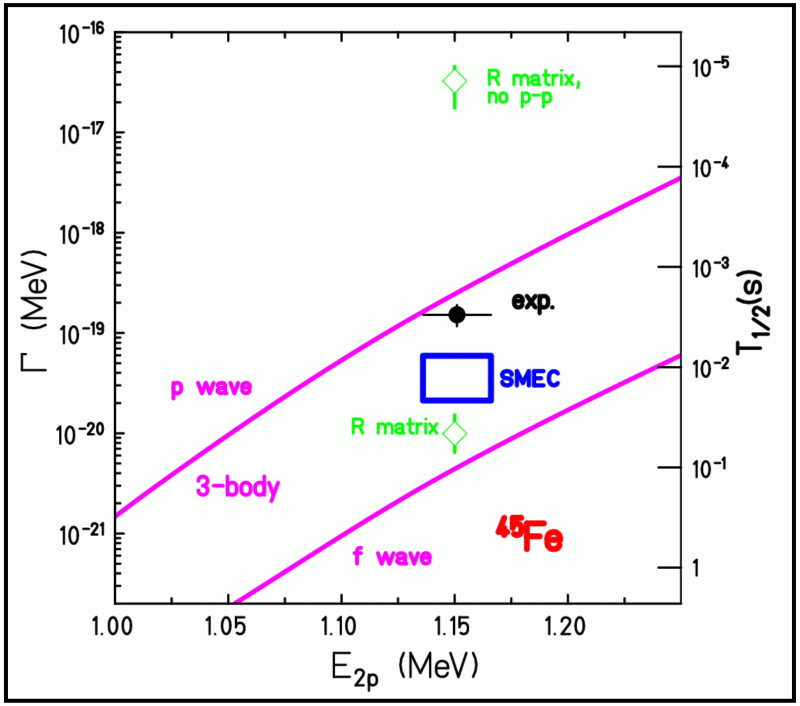
theoretical models interpretation

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

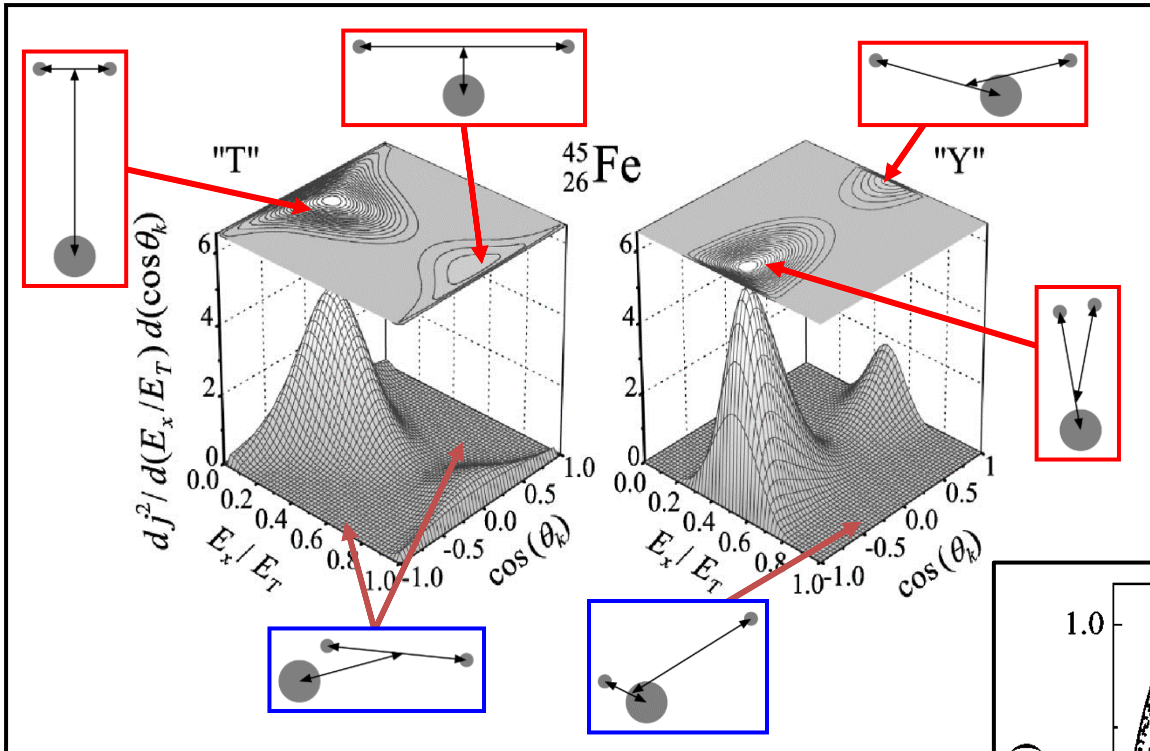
⇨ **no dynamics**
limited comparison: $T_{1/2}(Q_{2P})$
(with Q_{2P} taken from experiments !)



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

3-body model

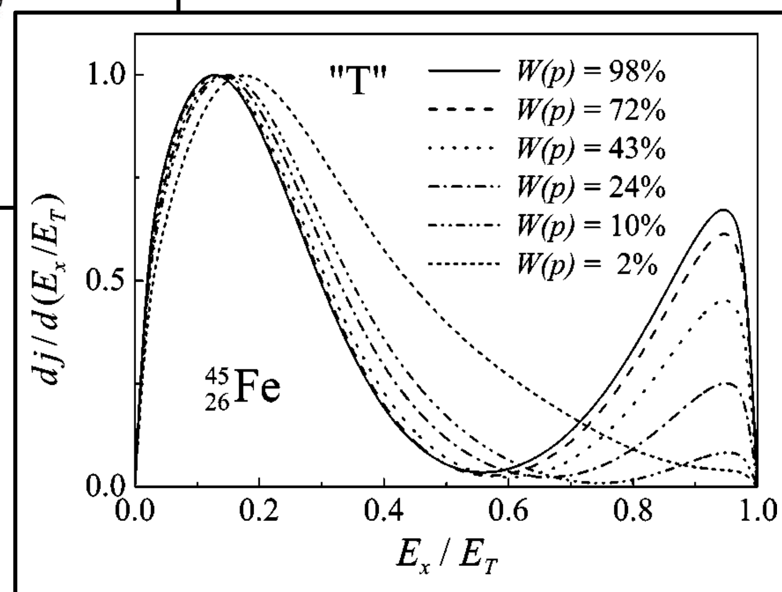
developed by M.V. Zhukov & L.V. Grigorenko



L.V. Grigorenko

3-body Schrödinger equation

solved in *hyper-spherical harmonics* basis



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

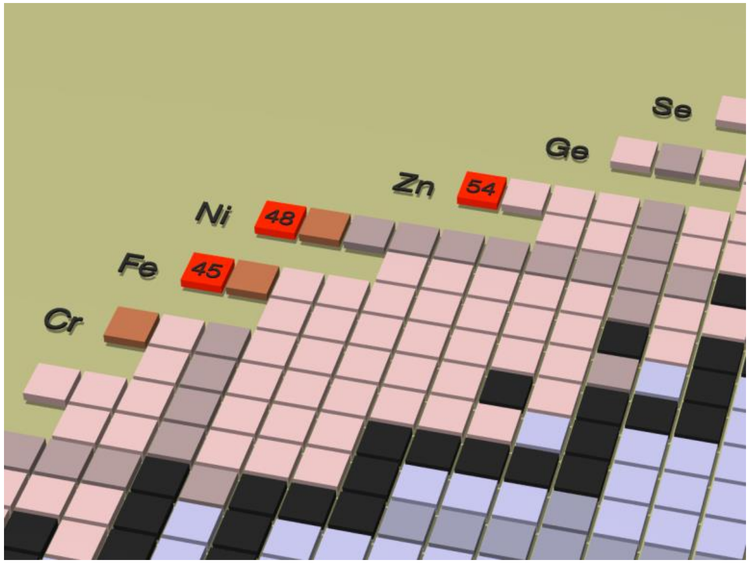
sensitive to involved orbitals

discovery experiments

(beyond) drip-line nuclei: fragmentation experiments

projectile fragmentation facilities
only way to produce such exotic nuclei

available facilities: **GANIL, GSI, NSCL, RIKEN**



(beyond) drip-line nuclei: fragmentation experiments

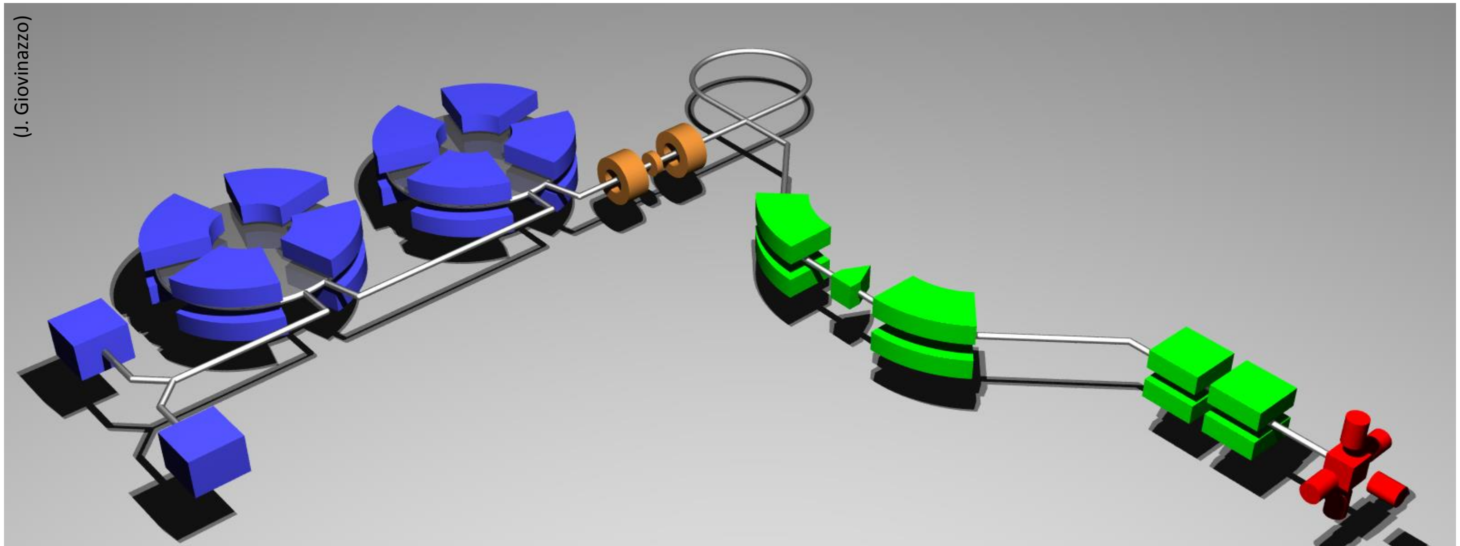
projectile fragmentation facilities

only way to produce such exotic nuclei

available facilities: **GANIL, GSI, NSCL, RIKEN**

basic ingredients

- ⇨ **primary beam**
  high intensity & high energy
- ⇨ **thin target**
  fragments coming out the target with almost the projectile speed
- ⇨ **fragments separator**
- ⇨ fragments stopping in **thick detectors**
  implantation / decay correlations

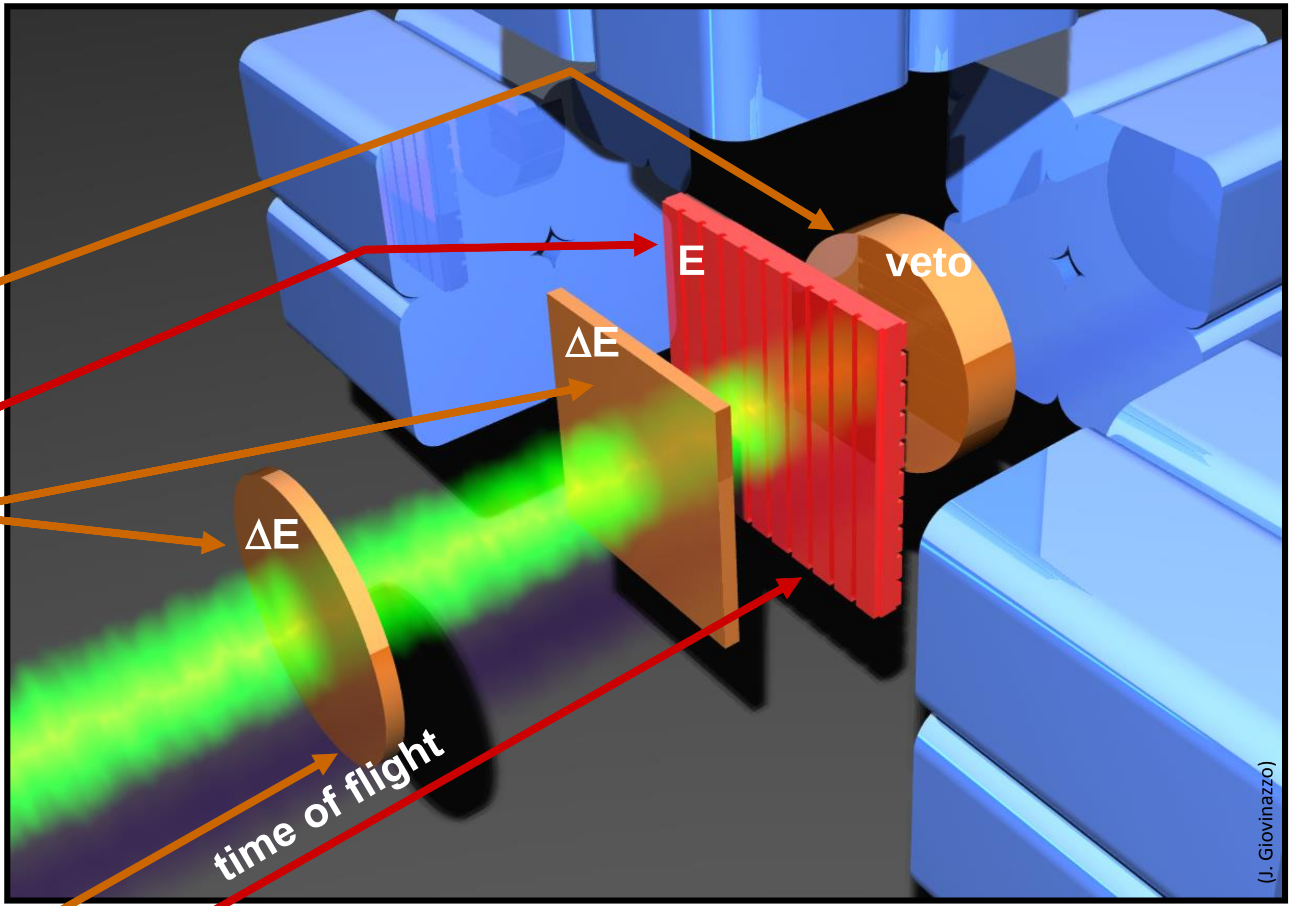


GANIL / LISE3 facility

fragments implantation & identification

fragments energy

- impl. veto (light particles)
- residual energy
- energy losses



time of flight

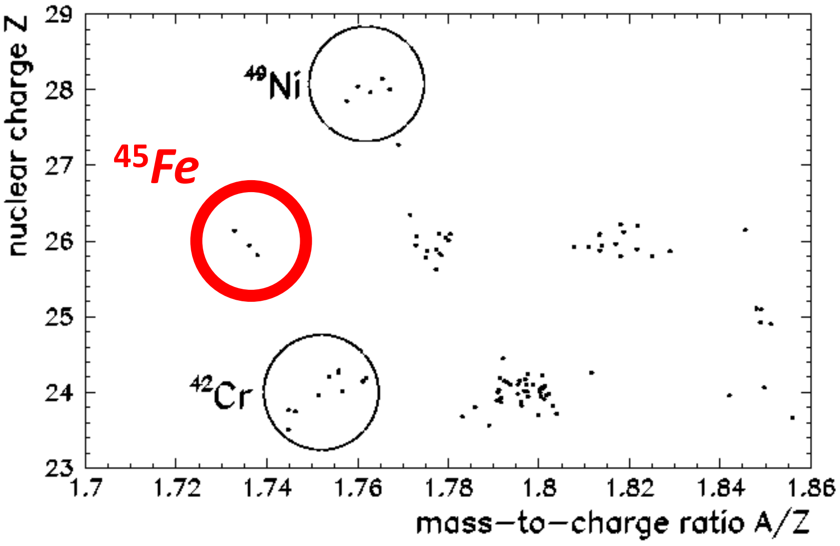
- micro-channel plates
- cyclotrons HF

silicon telescope

implantation: DSSSD (X-Y) 16 x 3 mm

ion by ion identification of implanted fragments
redundant measurements (E, ΔE, ToF)
⇨ background reduction in identification matrices

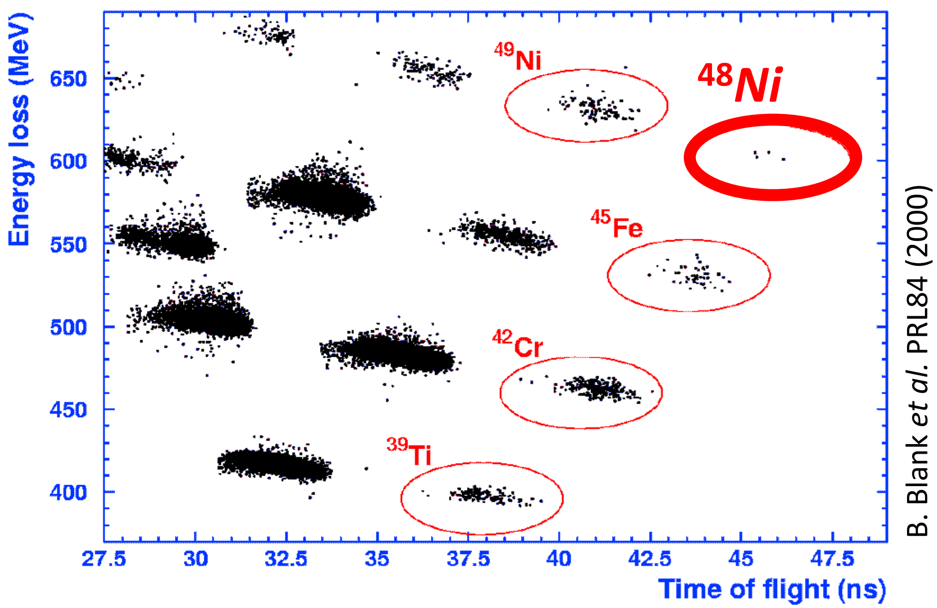
previous attempts



first observation of ***^{45}Fe***

GSI experiment (1996)

3 events



first observation of ***^{48}Ni***

GANIL experiment (1999)

4 events

no measurement of the decay modes…

radioactive decay measurement

decay information

particle energy in the impl. detector (protons total energy)

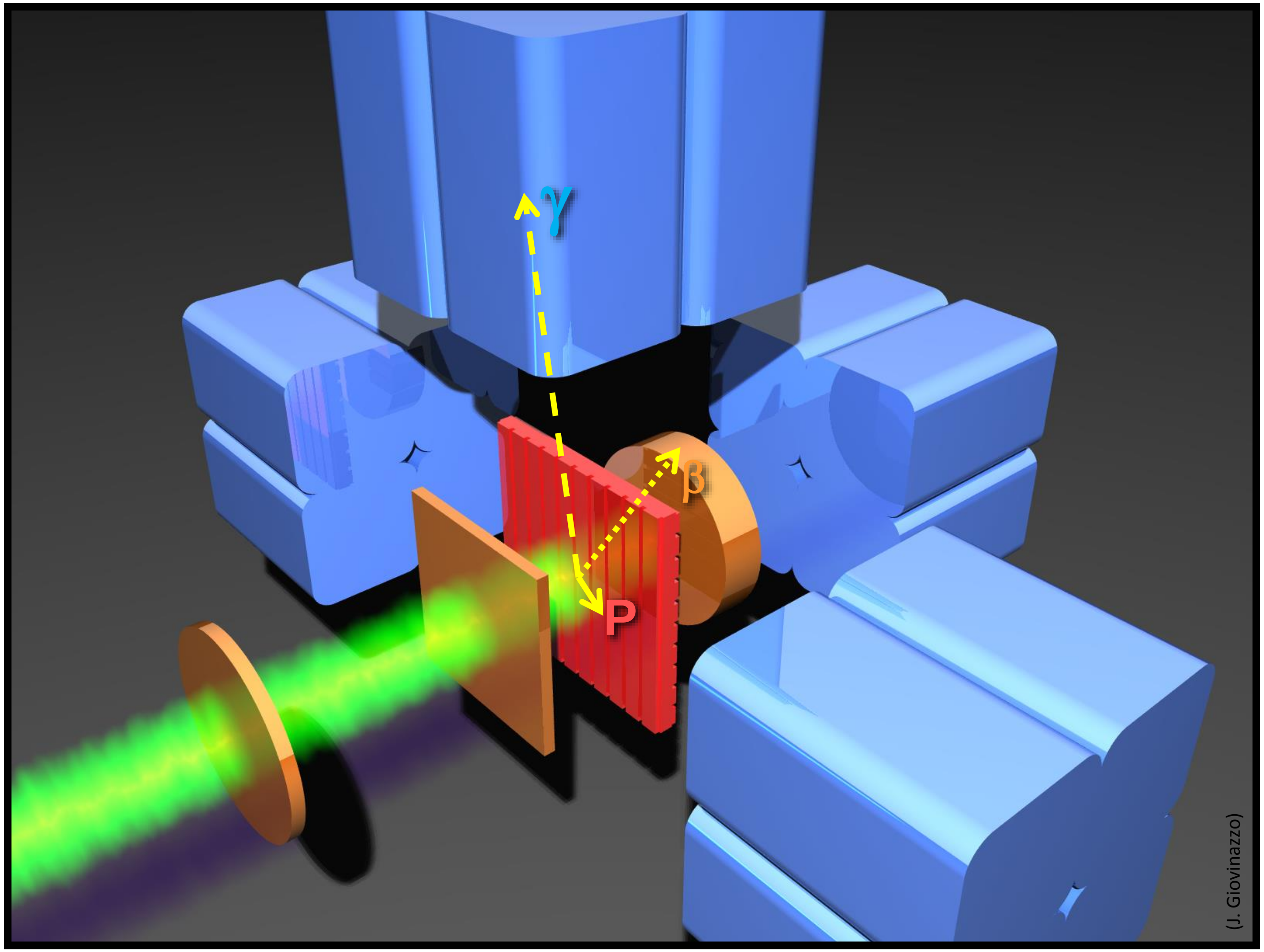
beta coincidences (other silicon)

gamma energy (germanium array)

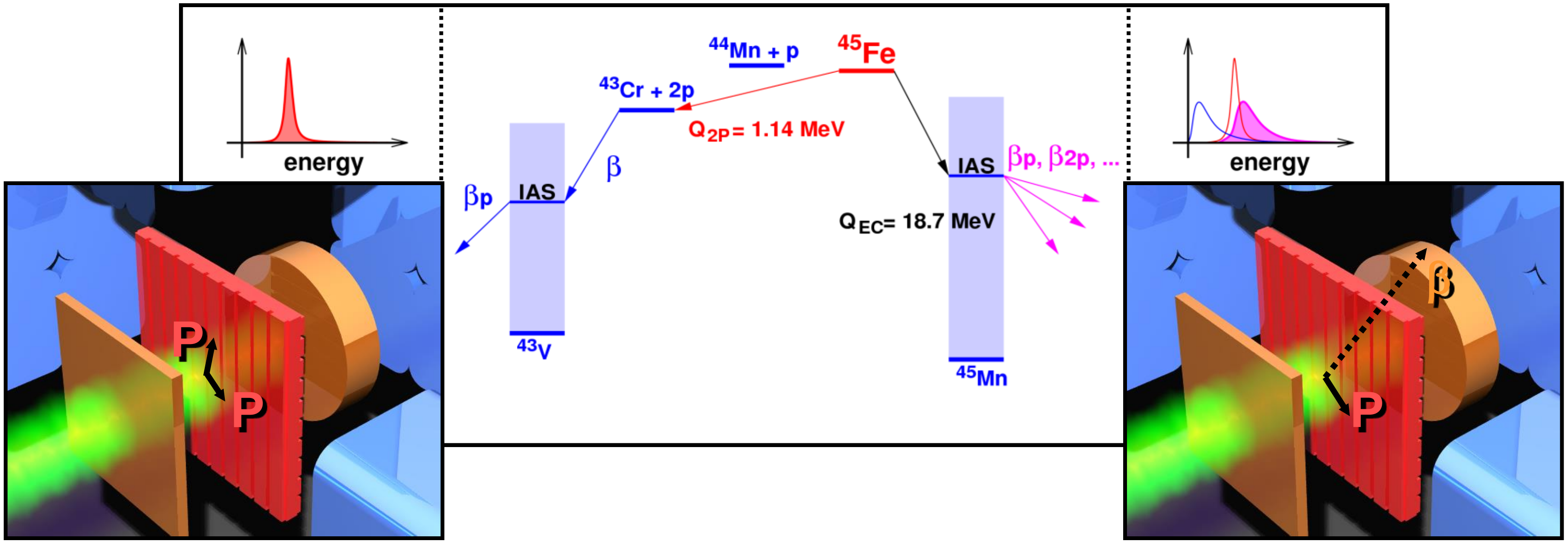
implantation / decay

decay time (half-life)

pixel correlation (decay background reduction)



indirect signature of the 2-proton radioactivity



2-proton transition

β-p (2p, pα,…) decay

detection efficiency
- protons **ϵ ~ 99 %**
- betas **ϵ ~ 40 %**

→ **no β coincidence**
→ **narrow peak (no ΔE_β pile-up)**

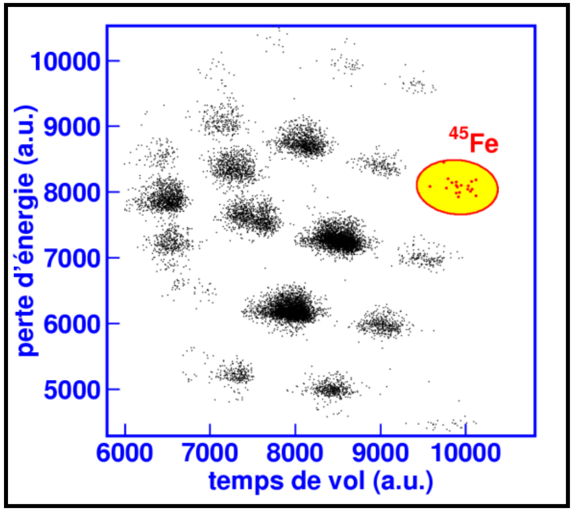
→ **daughter decay identification**
(β–delayed particle(s) emitter)

→ **coincidences with β (nor γ)**
→ **peak broadening (ΔE_β pile-up)**

^{45}Fe decay: first experiment (GANIL)

identification matrix

→ 22 events for ^{45}Fe



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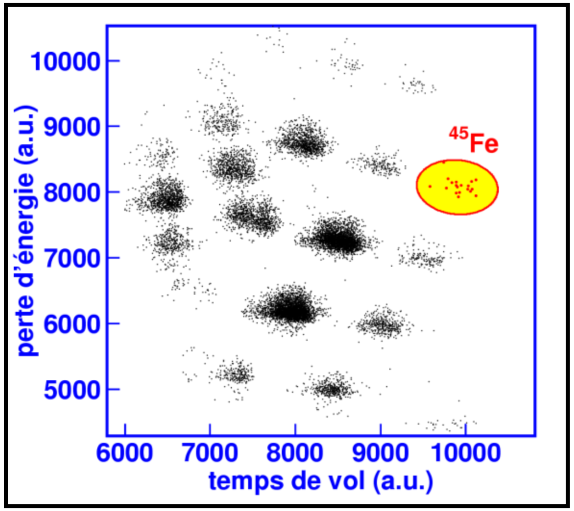
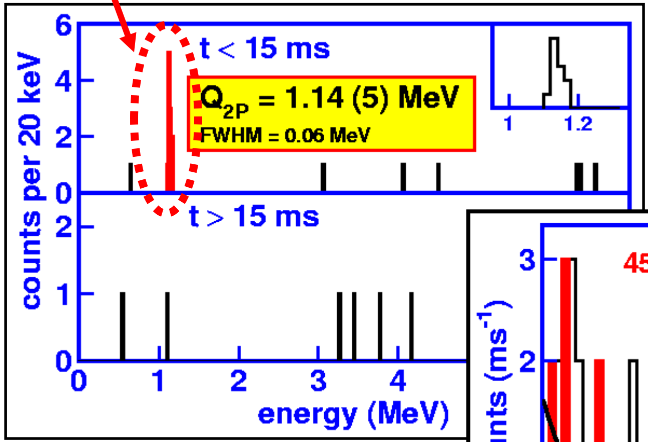


2-proton transition

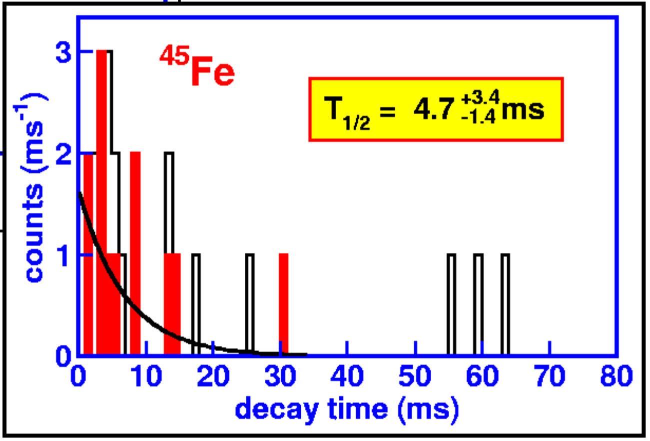
experimental information: Q_{2P}, $T_{1/2}$

→ **no β coincidence** (>99% C.L.)

→ **no ΔE_β pile-up** (peak 30% narrower than bp)



J.G. *et al.* (PRL 2002)



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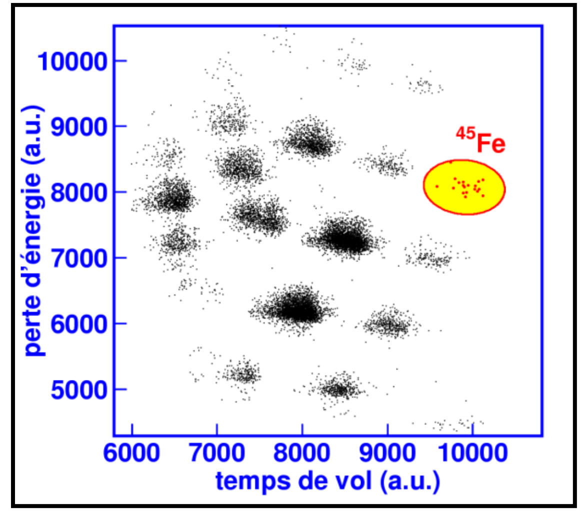


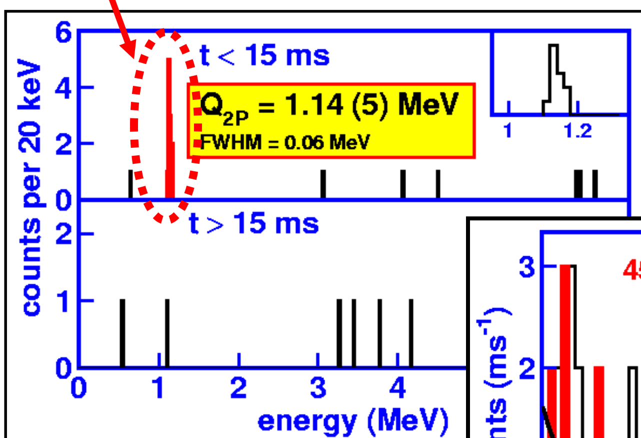
2-proton transition

experimental information: **Q_{2P}, $T_{1/2}$**

→ **no β coincidence** (>99% C.L.)

→ **no ΔE_β pile-up** (peak 30% narrower than bp)

→ **daughter decay half-life : ^{43}Cr**



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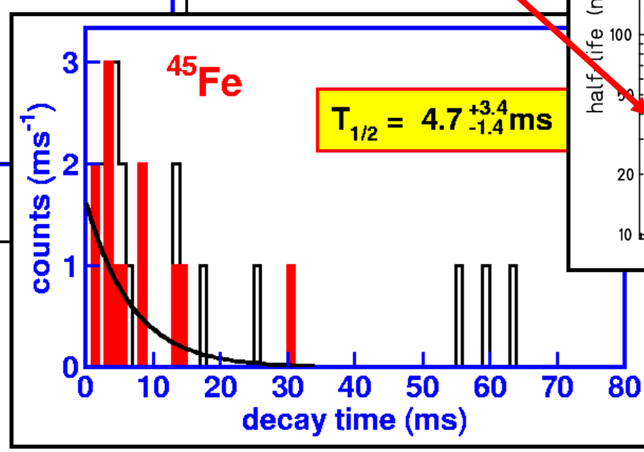
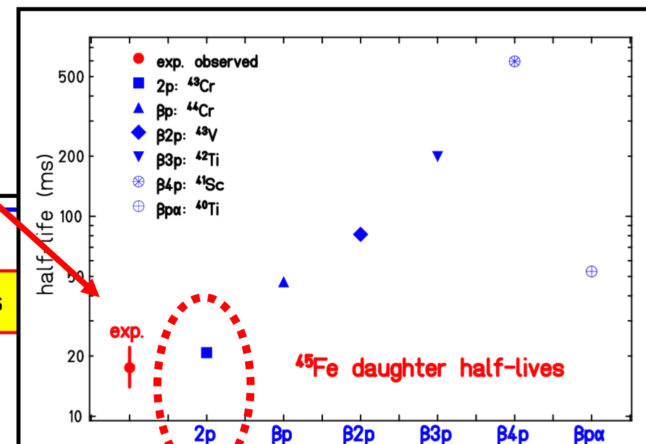
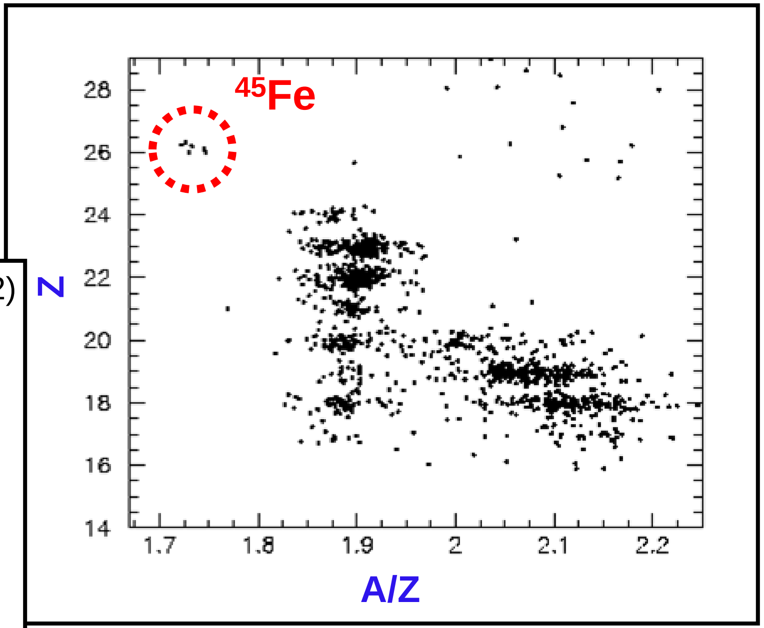




^{45}Fe decay: GSI data

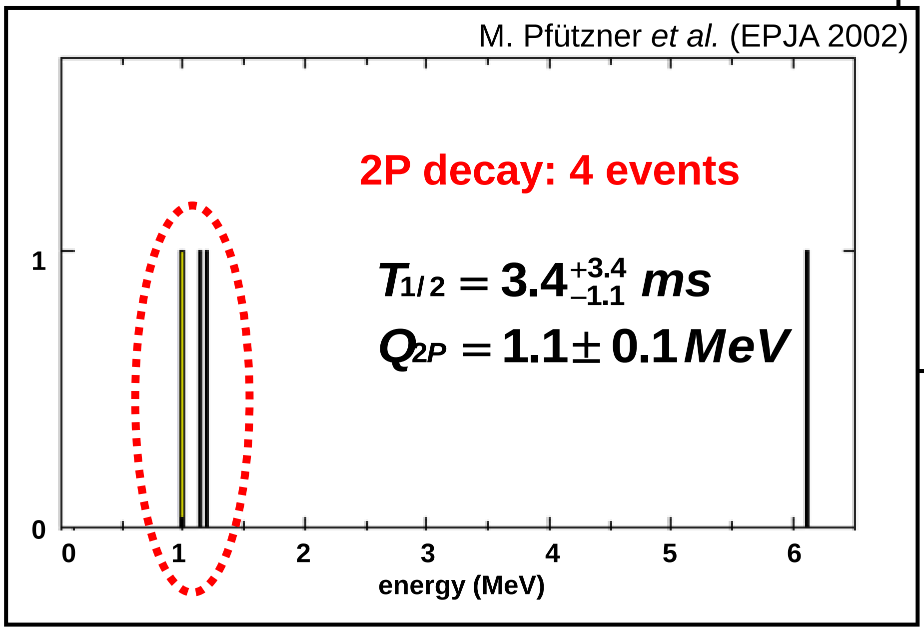
identification plot (6 events)



decay analysis

β^+ ➔ positron ➔ 2x511 keV annihilation γ

2P ⇨ γ anti-coincidence



Good agreement with GANIL experiment for Q_{2P} and $T_{1/2}$

^{48}Ni and ^{54}Zn decay (GANIL)

^{54}Zn

peak:

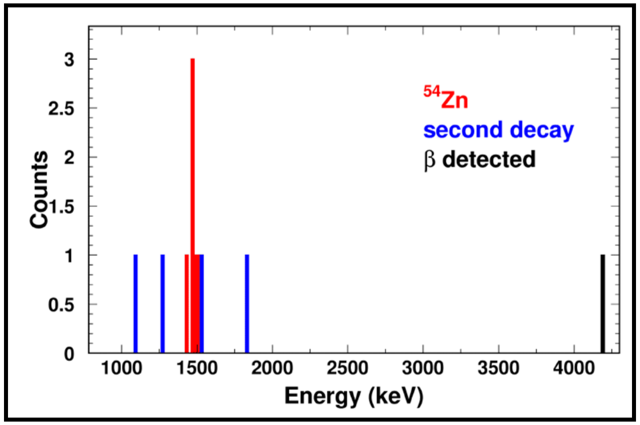
$$T_{1/2} = 3.2^{+1.8}_{-0.8}\ ms$$

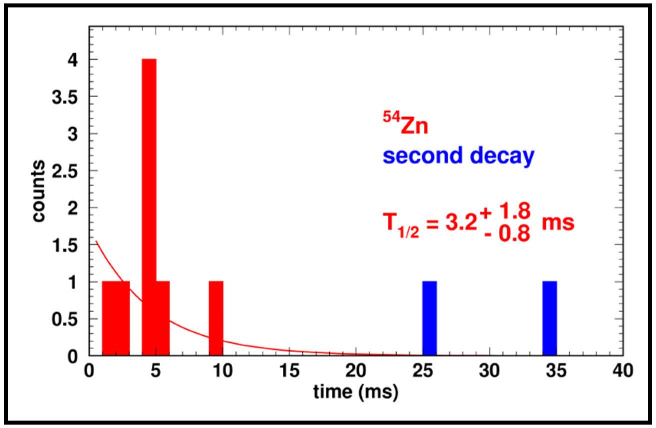
daughter (^{52}Ni):

$$T_{1/2} = 30 \pm 20\ ms$$

(C. Dossat, PhD:

39.9 ± 0.7 ms)





Blank *et al.* (PRL 2005)

2-proton emitter !

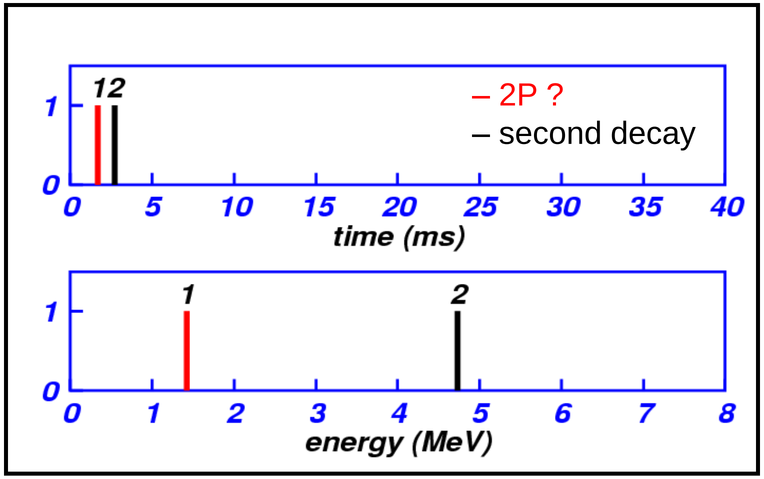
^{48}Ni

3 decay events: ***$T_{1/2}$ ~ 1-2 ms***

- 2 are compatible with β-delayed particle emission (β coinc. and high part. energy)

- 1 is compatible with ***2-proton decay***

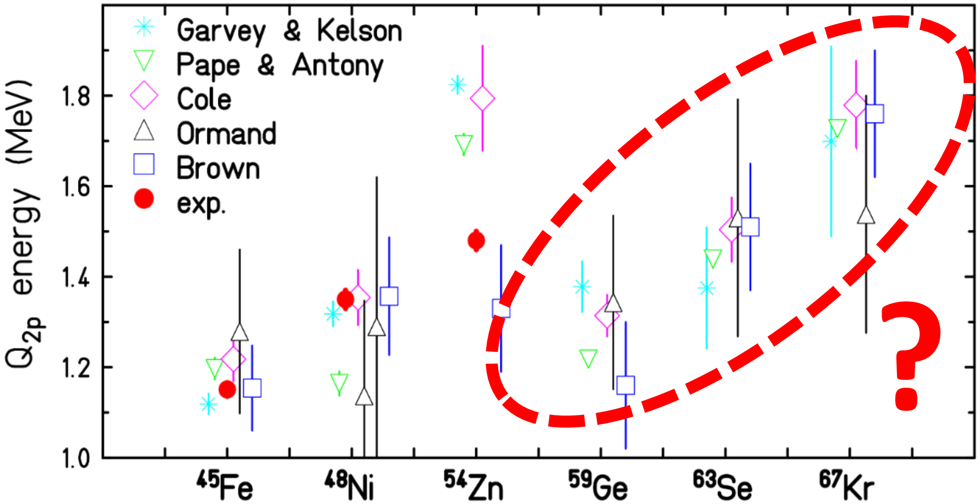
not enough to conclude…



Dossat *et al.* (PRC 2005)

recent result for ^{67}Kr

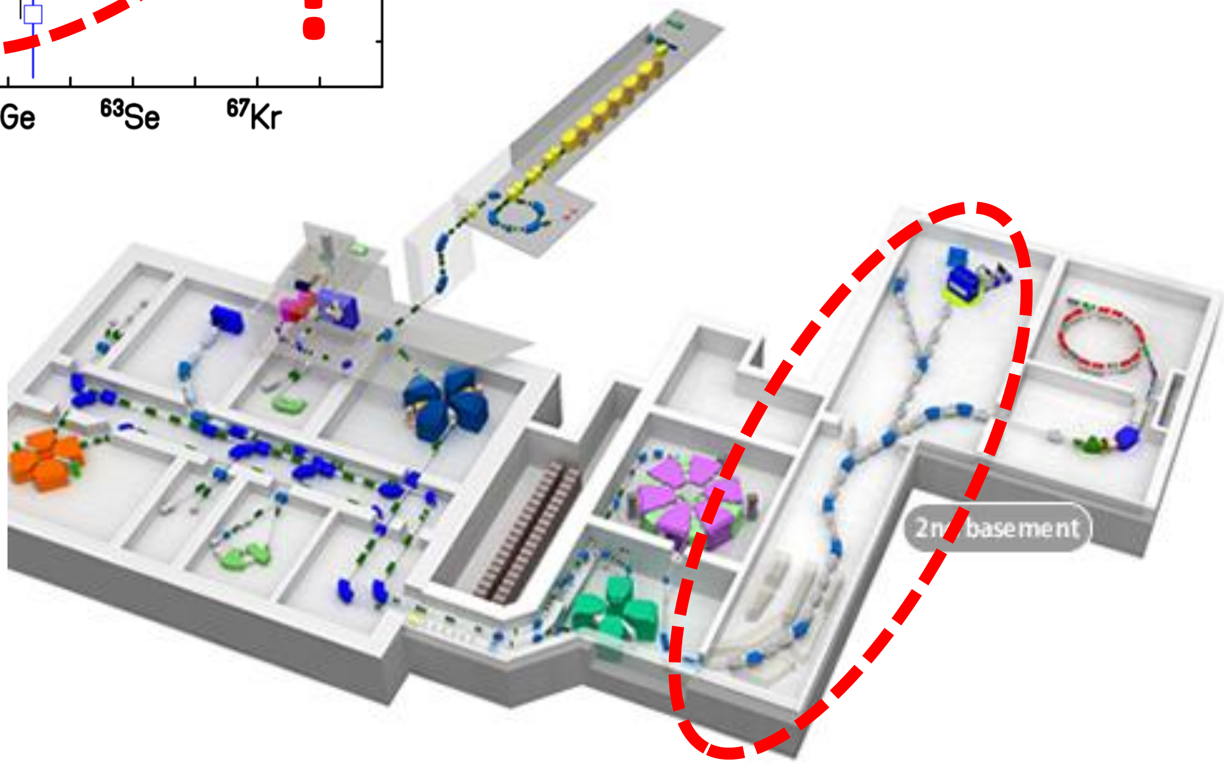
2015 experiment @ RIKEN



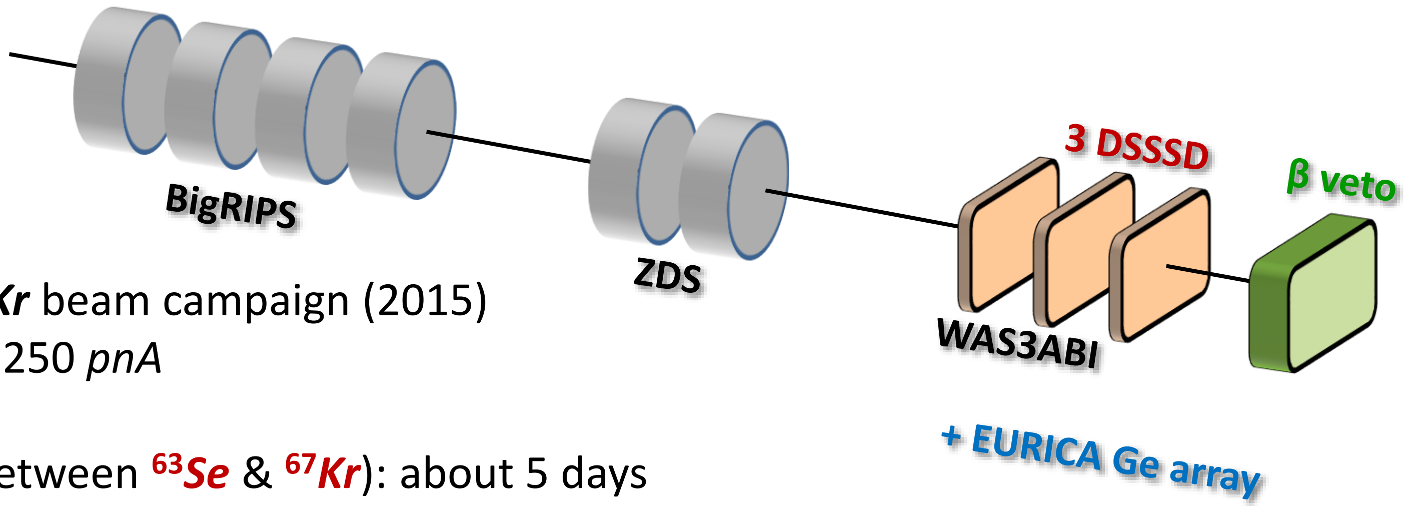
search for other candidates

only facility where the production is possible

- **^{78}Kr primary beam**
- **BigRIPS + ZDS spectro**

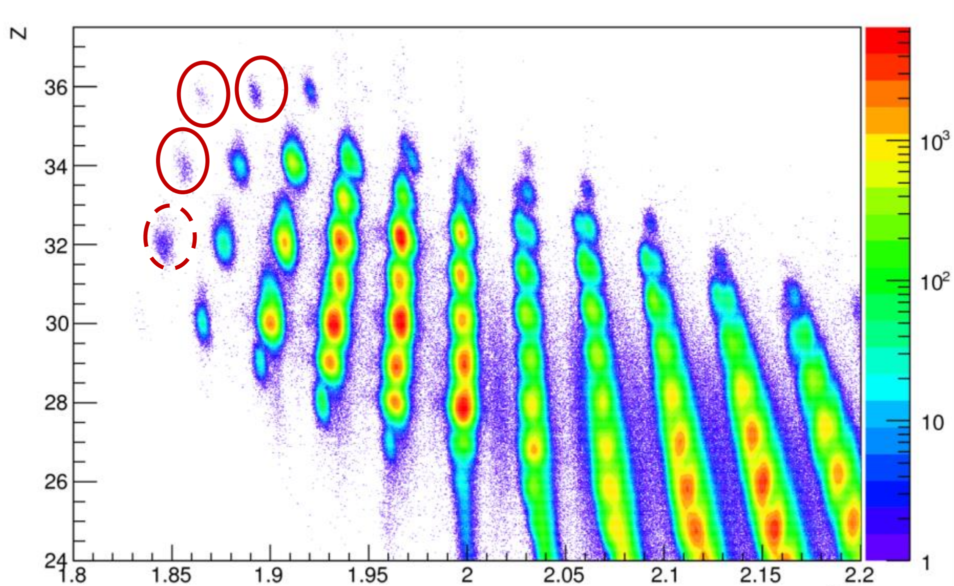


new isotopes identification



BigRIPS (+ZDS) ^{78}***Kr*** beam campaign (2015)
350 *MeV*/A – 250 *pnA*

setting on ^{65}***Br*** (between ^{63}***Se*** & ^{67}***Kr***): about 5 days



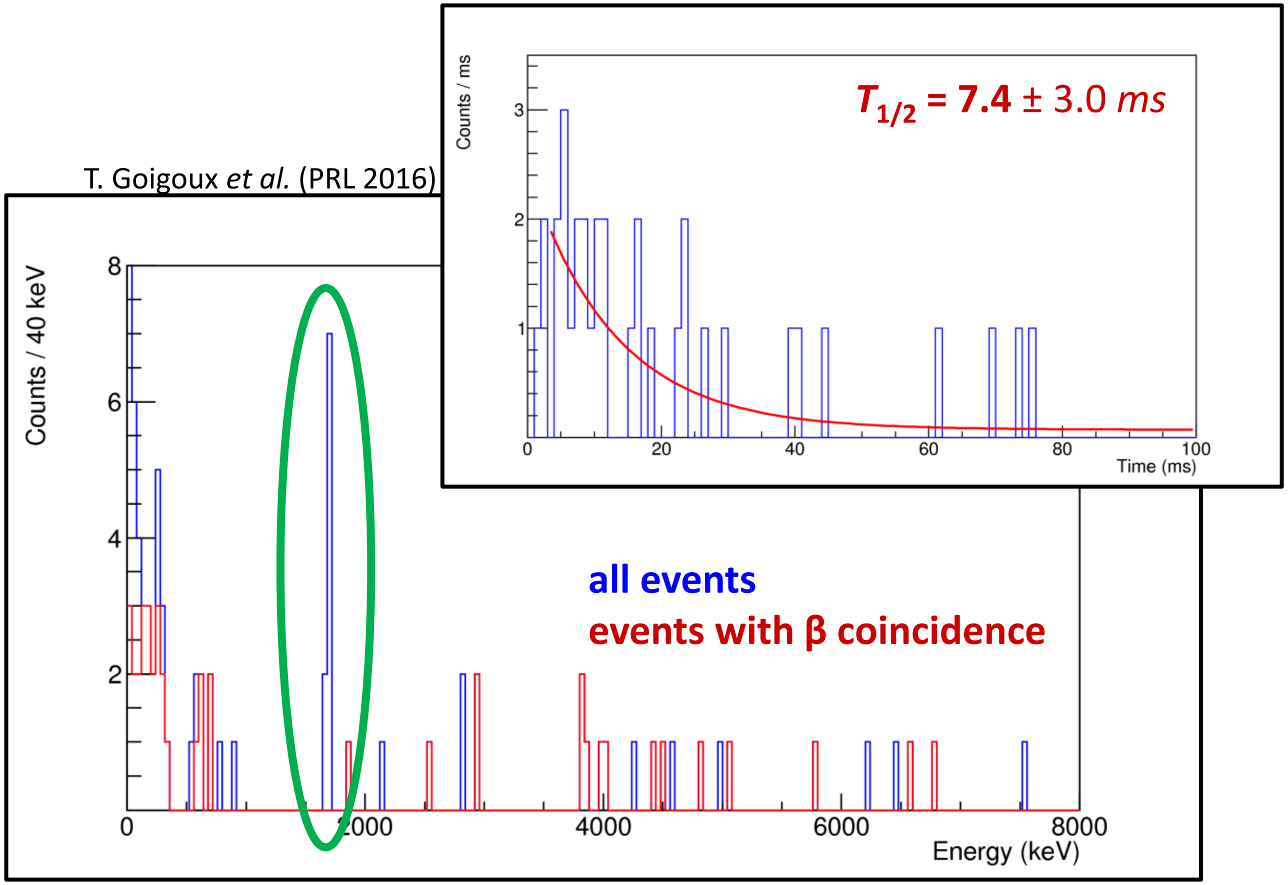
B. Blank *et al.* (PRC 2016)

observed production

	BigRIPS (F7)	ZDS (F11)	WAS3ABI
^{59}***Ge***	1170	**979**	563
^{63}***Se***	336	**258**	193
^{67}***Kr***	80	**79**	49

^{67}Kr decay

T. Goigoux *et al.* (PRL 2016)



observed peak: 9 events

Q_{2P} = **1.69** ± 0.02 *MeV*

no beta coincidence

ε_β = **67** %

prob. to miss all ≈ **5×10^{-6}**

no annihilation 511 *keV*

ε_γ ≈ **8** %

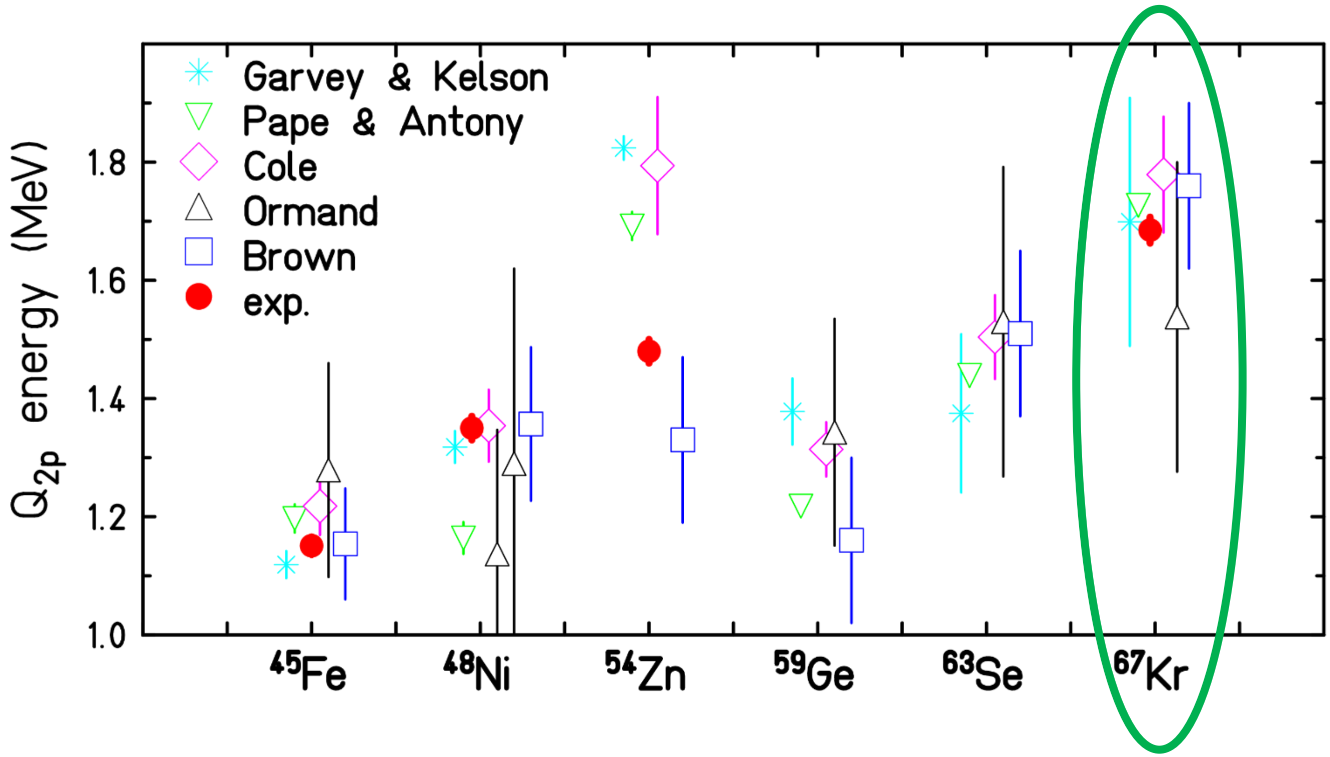
prob. to miss all ≈ **45 %**

Q_{2P} = **1.69** ± 0.02 *MeV*

$T_{1/2}$ = **7.4** ± 3.0 *ms*

BR_{2P} = **37** ± 14 **%**

^{67}Kr: a new ground-state 2-proton emitter



tracking experiments

motivation for tracking experiment

standard (silicon) experiments

- **limited experimental information: $T_{1/2}$, Q_{2P} & BR_{2P}**
- **limited comparison with theoretical interpretations**

purpose of tracking experiments

- **measure proton-proton correlations**
  angular distribution and energy sharing
- **compare with 3-body model** (kinematics)
- **extract structure information**

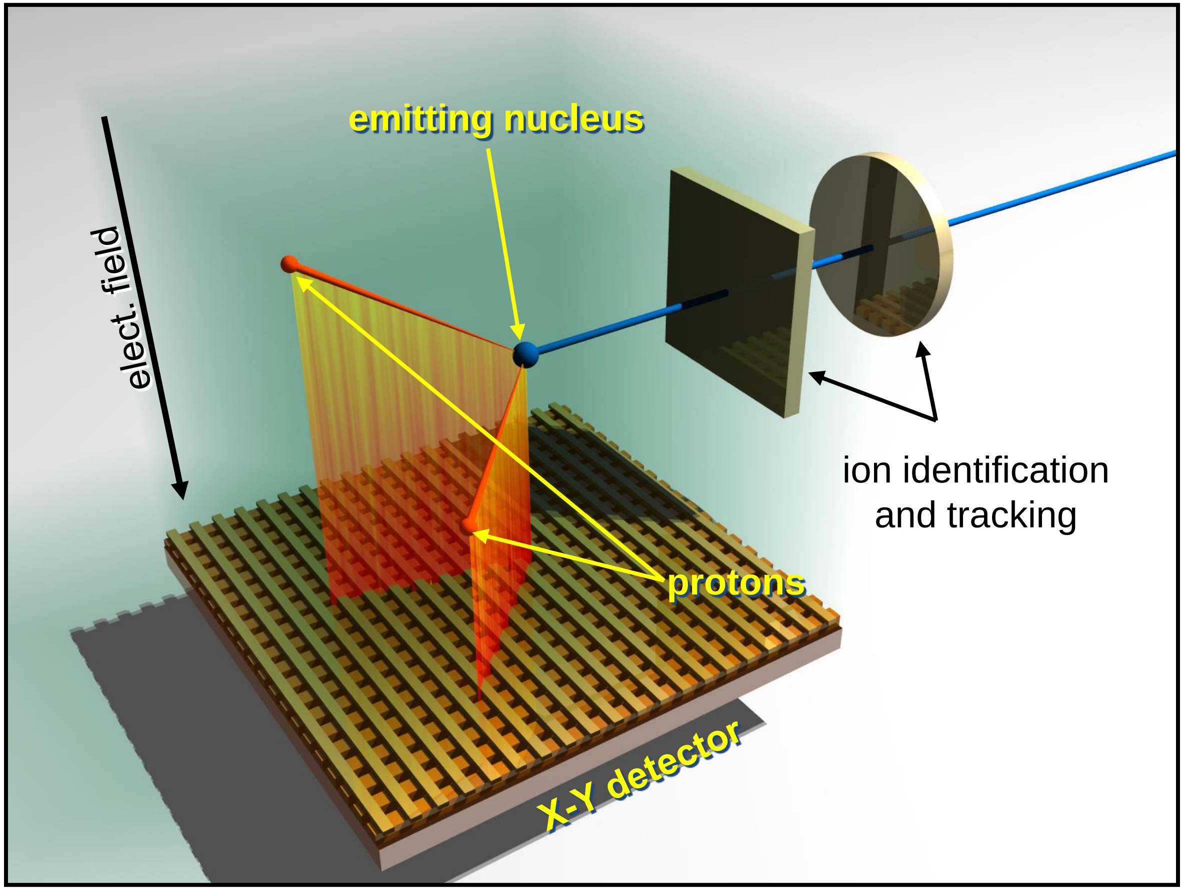
first TPC at CENBG

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

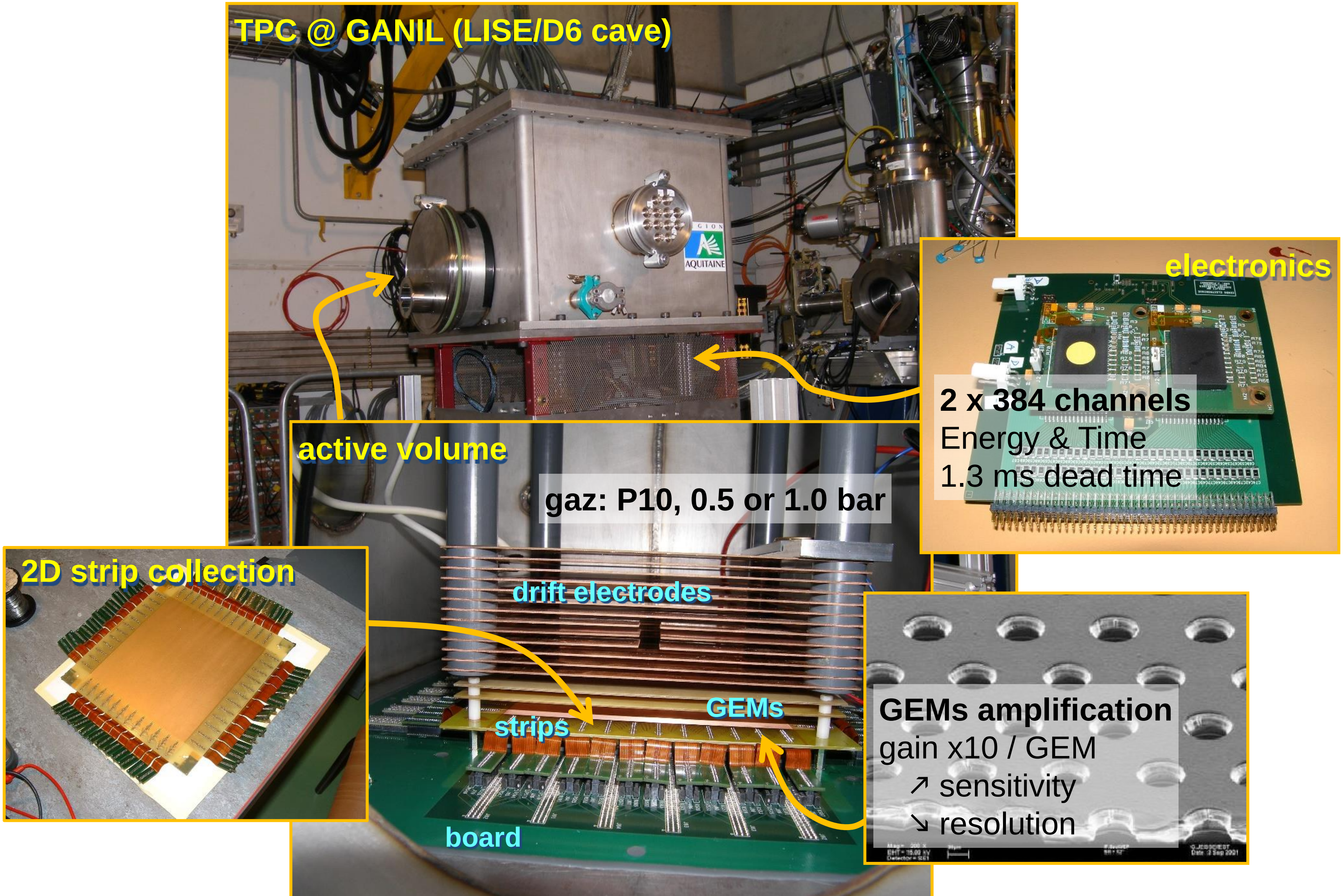
ionisation electrons drift to a 2D detector

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

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

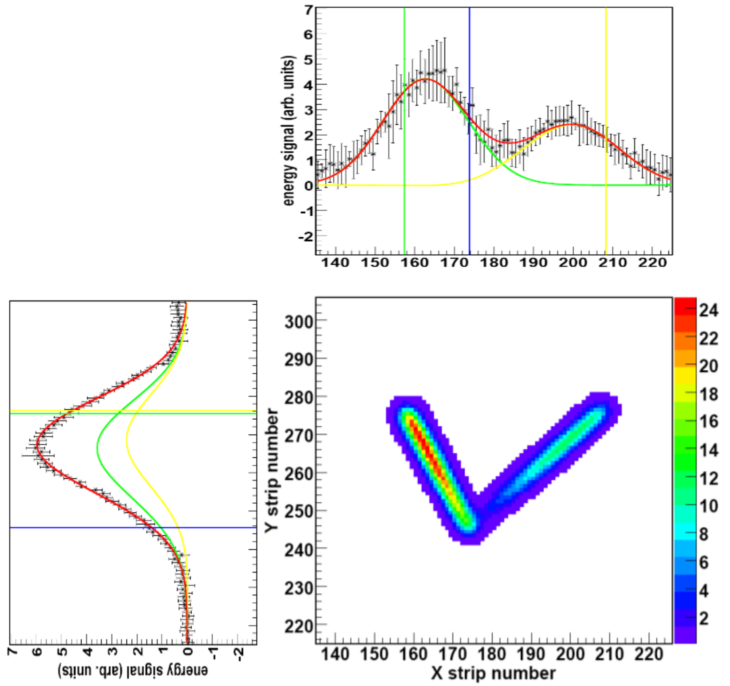


CENBG TPC layout



^{45}Fe @ GANIL: first direct observation (2006)

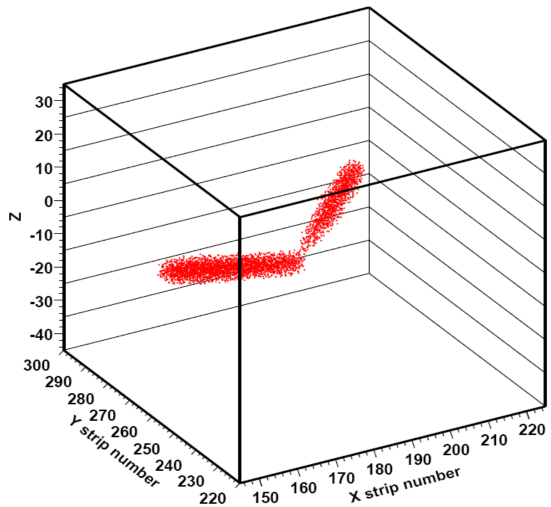
J. Giovinazzo et al., PRL 2007



overall agreement with standard exp.

few counts only

poor angular distribution



^{54}Zn @ GANIL (2008)

P. Ascher et al., PRL 2011

few events: rough correlation distributions

experiment by-products

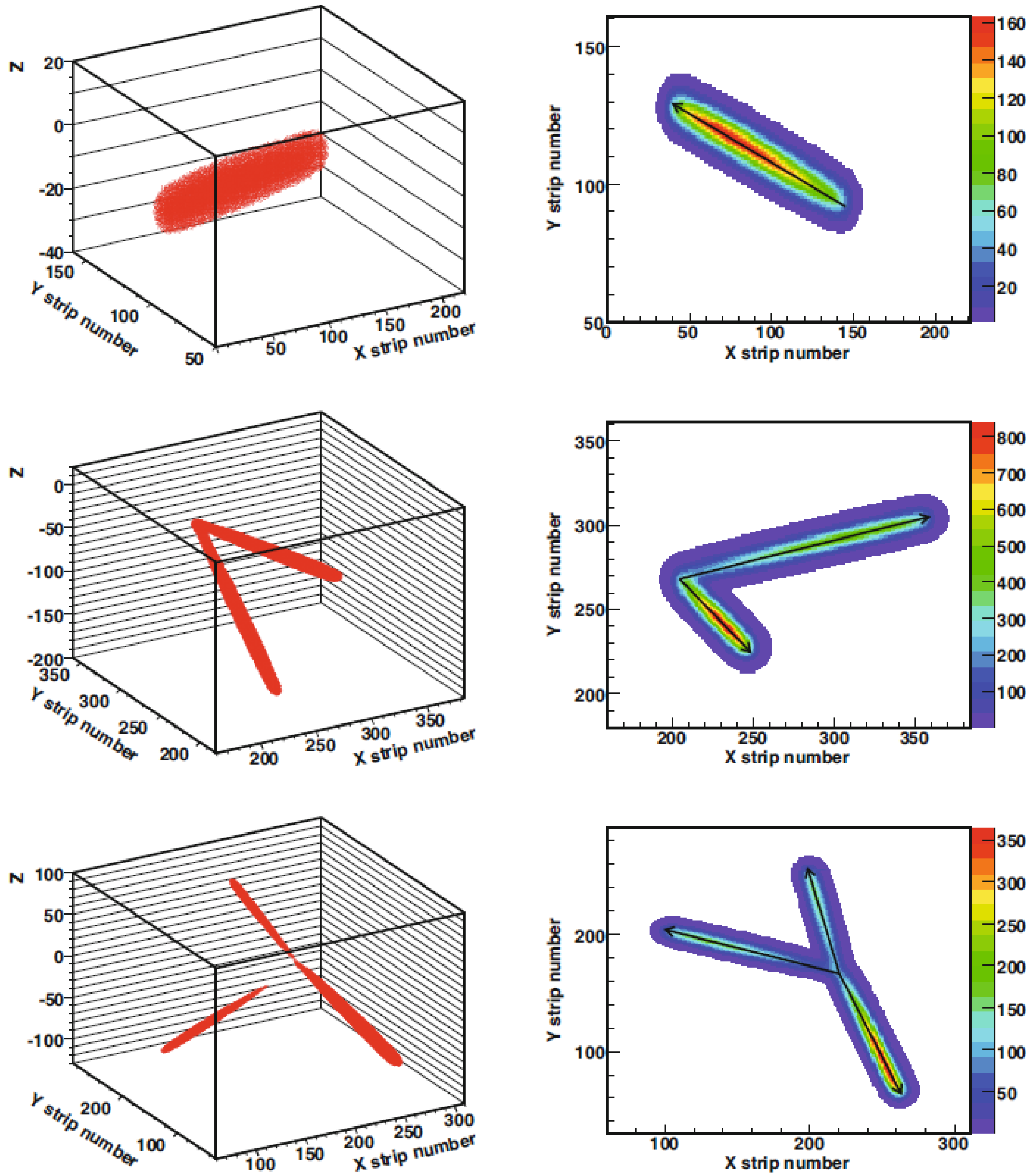
beta-delayed multi-proton emission

β-p

^{43}Cr

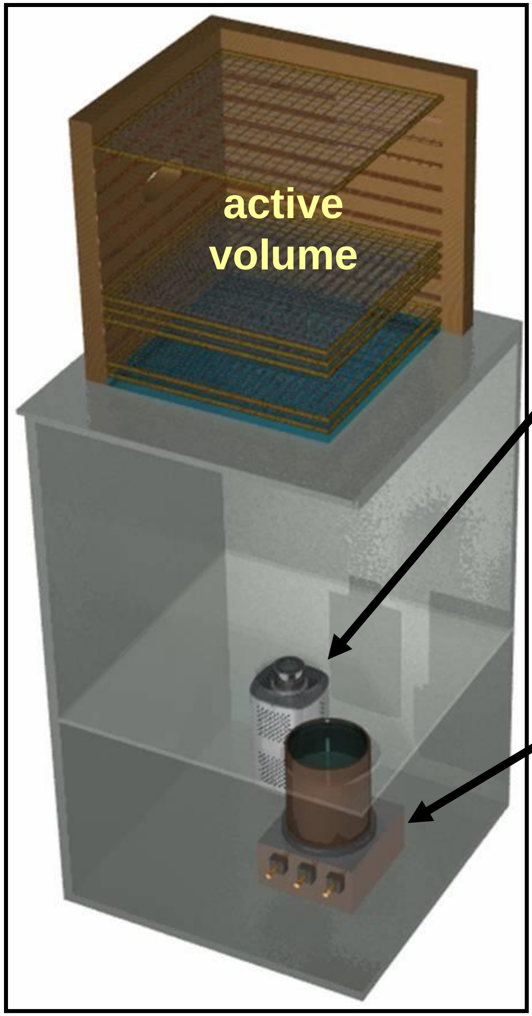
β-2p

β-3p



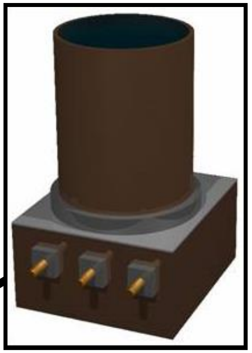
L. Audirac et al., EPJA 2012

optical TPC from Warsaw team



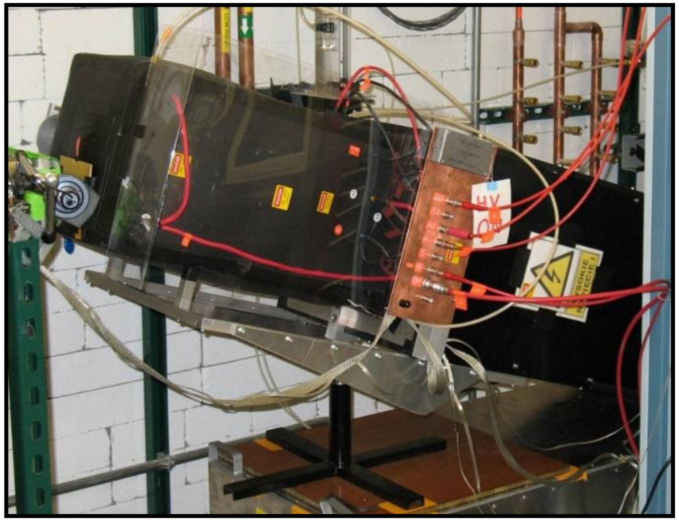
M. Pfützner, K. Miermik, et al., 2007

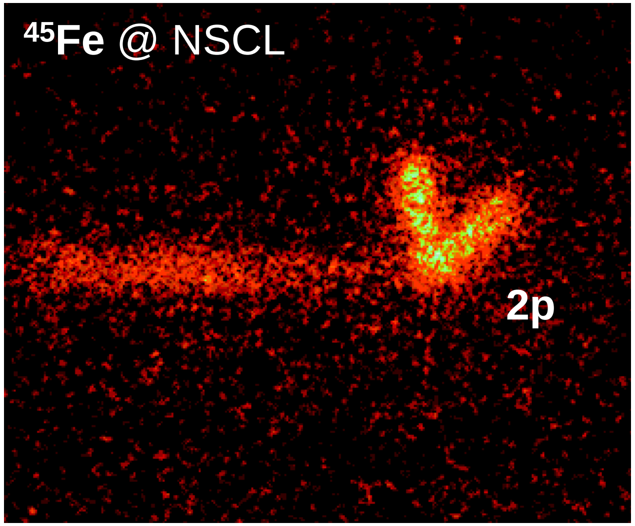
CCD camera
cumulated light



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

K. Miernik *et al.*



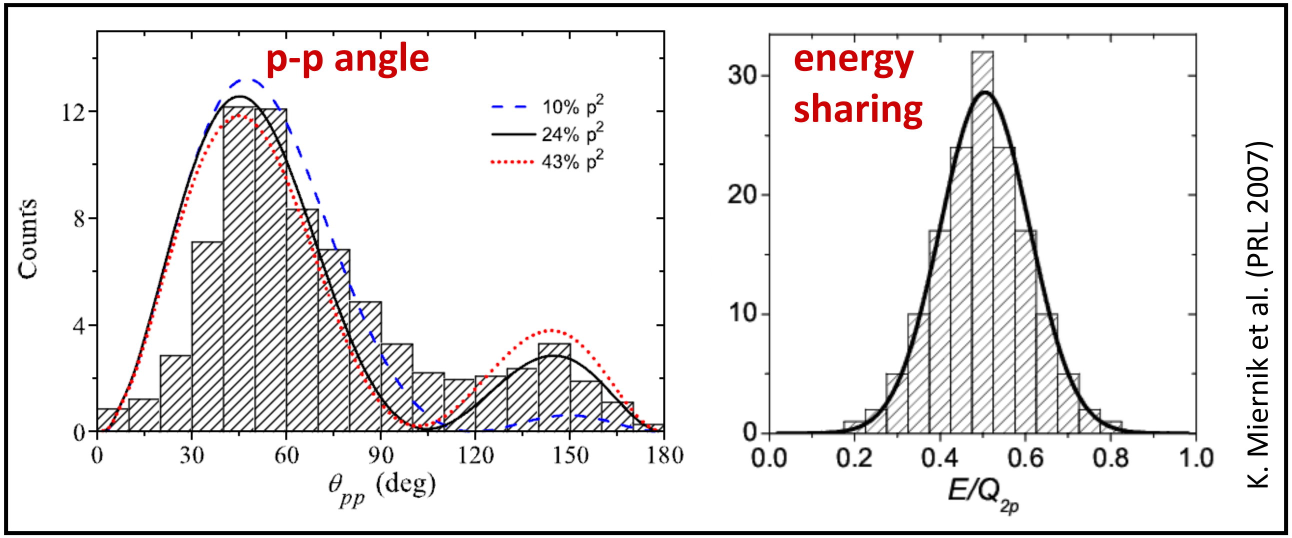


2-proton studies status

tracking experiments results

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

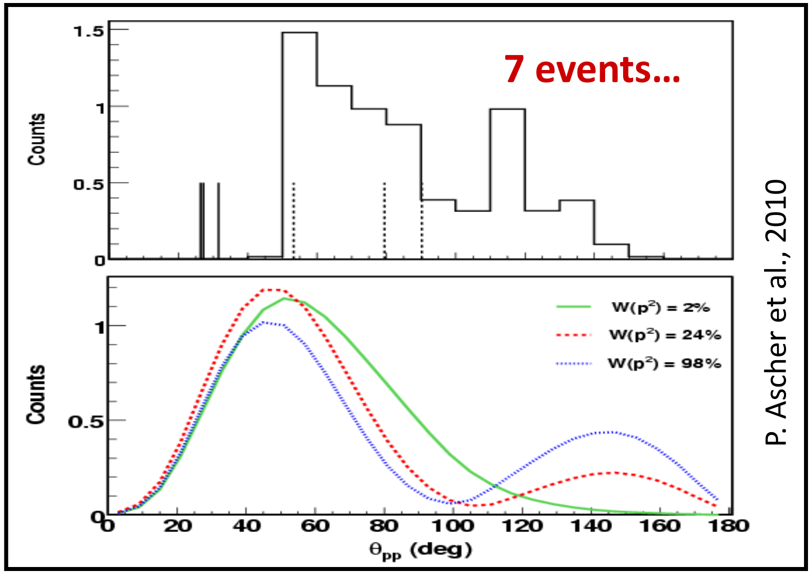
^{45}Fe (MSU)



pioneering experiments

→ **opening structure studies** at the drip-line
→ angular distribution probes the **wave function** content (single particle states)

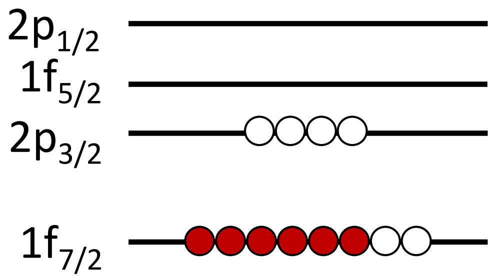
requires more statistics
other cases to test the models descriptions

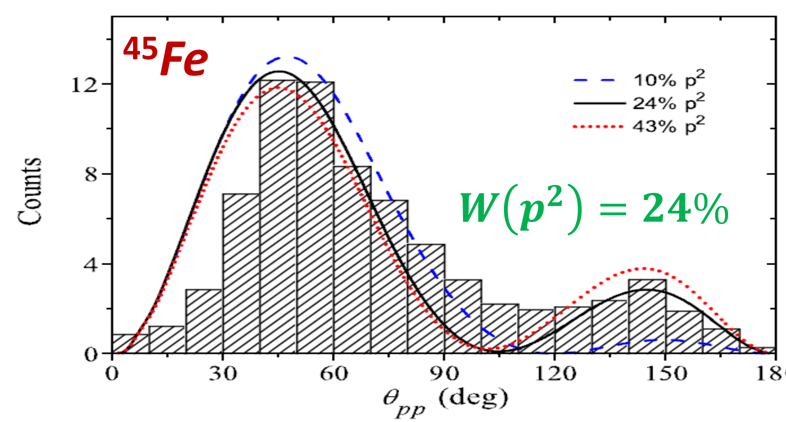


^{54}Zn (GANIL)

probing structure beyond the drip-line

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

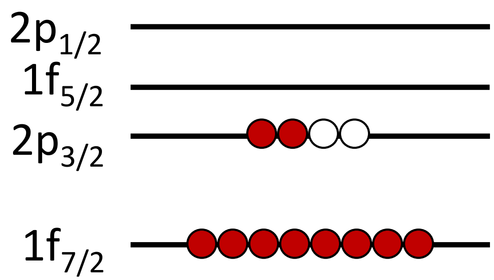


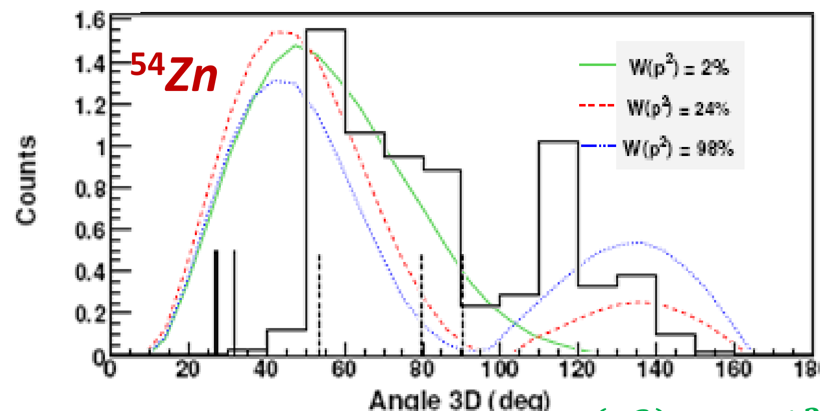


K. Miernik *et al.*, EPJA (2009)

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

proton-proton angular distribution → orbitals configuration

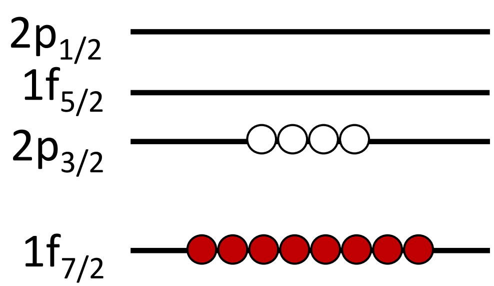




P. Ascher *et al.*, PRL (2011)

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

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



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

doubly magic → pure configuration ?

mixing structure and dynamics: half-lives

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

B.A. Brown: good 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)

	calculation	experiment(s)	
^{45}Fe	2.7 *ms*	$3,76 \pm 0,26$ *ms*	OK
^{54}Zn	1.6 *ms*	$1.98^{+0.73}_{-0.41}$ *ms*	OK
^{67}Kr	660 *ms*	21 ± 12 *ms*	**!?**

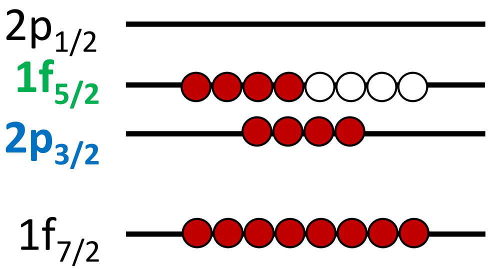
^{67}Kr correlation pattern

On the structure side: region of **deformation**

Ongoing work by L.V. Grigorenko *et al*. (revised calculation)

- semi-analytical R-matrix direct decay model
- 3-body model

→ consistent results



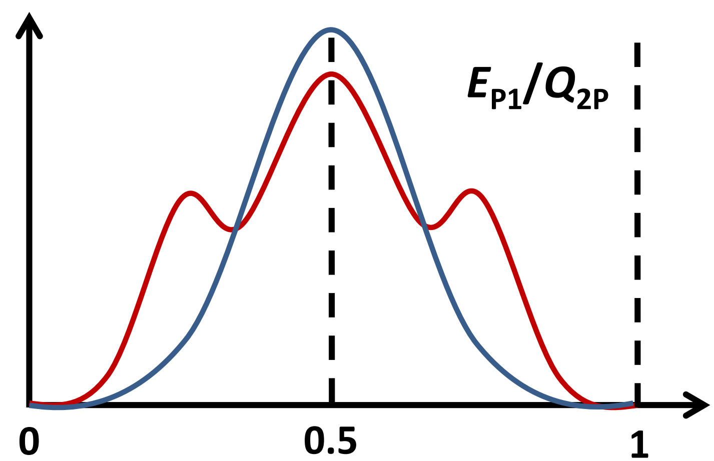
(1) pure $(p_{3/2})^2$ configuration → compatible with exp.
but expected only 18% $(p_{3/2})^2$ config. from shell model

(2) possible interpretation
- possible transition from **2P** to **sequential** decay
- depends on the resonance energy (intermediate state)
- based on S_P ($-400 < S_P < 200$ *keV*) and S_{2P} analysis

→ **proton-proton correlations**

- no indication available concerning angular correlations
- different **energy sharing** distribution

→ **clarify the decay process !!!**



experimental studies summary

in the 60's first predictions by Goldanskii

late 90's candidates can be produced at fragmentation facilities (discovery of ^{45}**Fe**, ^{48}**Ni**)

Discovery experiments

indirect measurements: global quantities only

2002 2-proton radioactivity of ^{45}**Fe** at GANIL (Caen)
another experiment at GSI (Darmstadt)

2004 2-proton radioactivity of ^{54}**Zn** (GANIL)
indication of a possible 2P-decay for ^{48}**Ni** (1 event)

2016 2-proton radioactivity of ^{67}**Kr** (RIKEN)

Tracking experiments

direct observation of 2 protons (individually)

2007 decay of ^{45}**Fe** at GANIL (few events)

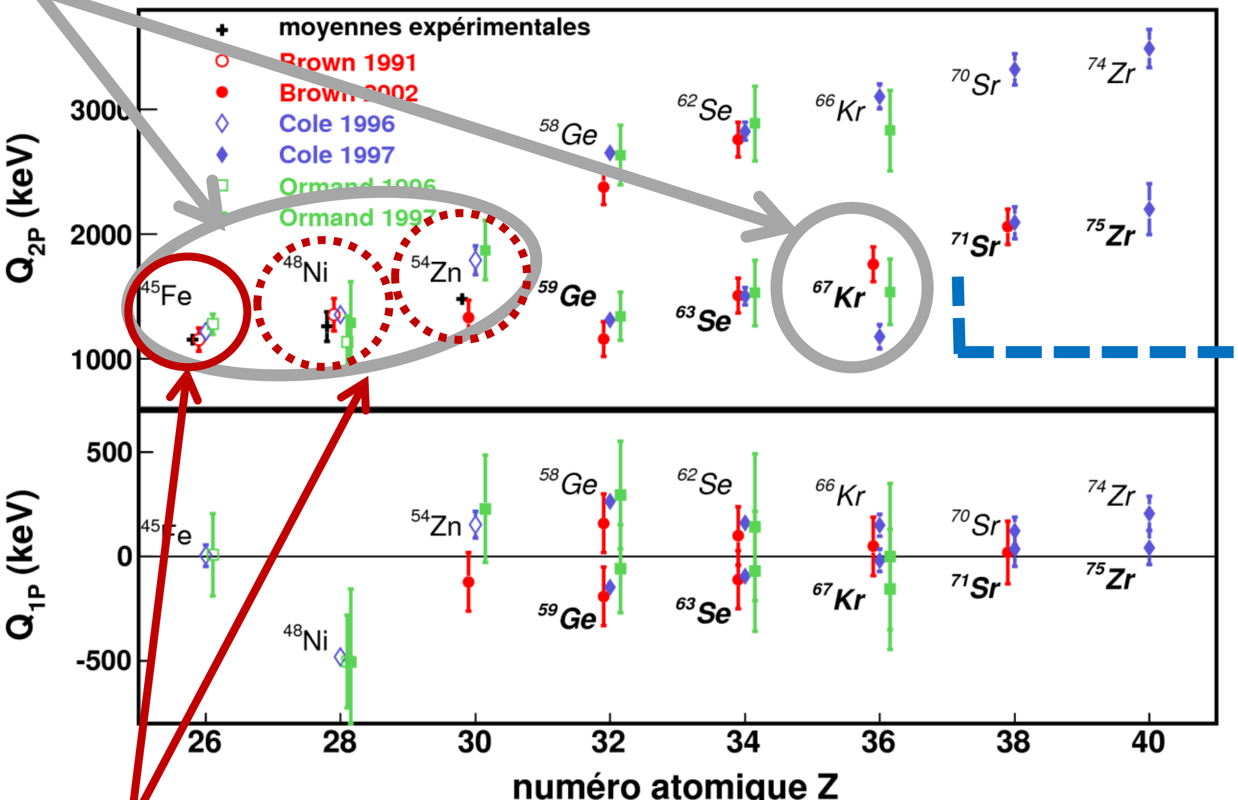
2008 decay of ^{45}**Fe** at MSU (1st correlations, structure)

2010 decay of ^{54}**Zn** (GANIL, few events, structure)

2011 decay of ^{48}**Ni** at MSU (4 events)

further studies

known cases



search for new emitters ?

direct observations

→ future (short term) tracking / correlation experiments: ^{48}***Ni***, ^{54}***Zn***, ^{67}***Kr***

ACTAR TPC development

TPC development for future studies

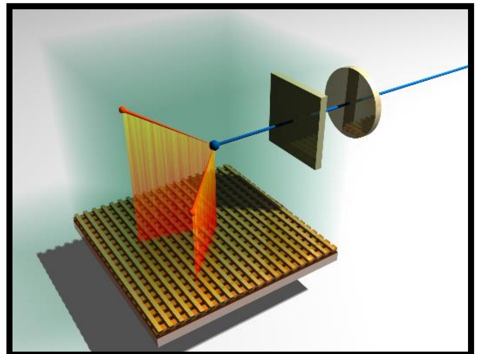
GANIL experiment: milestone of the ACTAR TPC collaboration

- **2-proton radioactivity is part of the ACTAR TPC physics case (ERC)**
- **accepted experiment: ^{48}*Ni* or ^{54}*Zn***
  will depend on the context:
  accepted ^{54}Zn O-TPC experiment at RIKEN
  ^{48}*Ni* doubly magic configuration / unknown / less statistics
  ^{54}*Zn* more statistics / if not already done

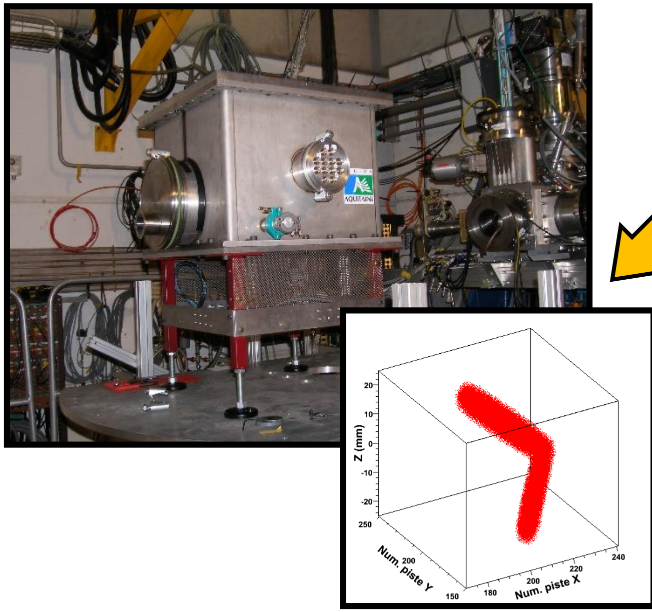
RIKEN experiment: ^{67}*Kr*

- **half-life theory / experiment discrepancy**
  deformation / structure issues ?
- **first proton-proton correlations measurement**
  angular distribution and energy sharing
  relation with $T_{1/2}$ question ?

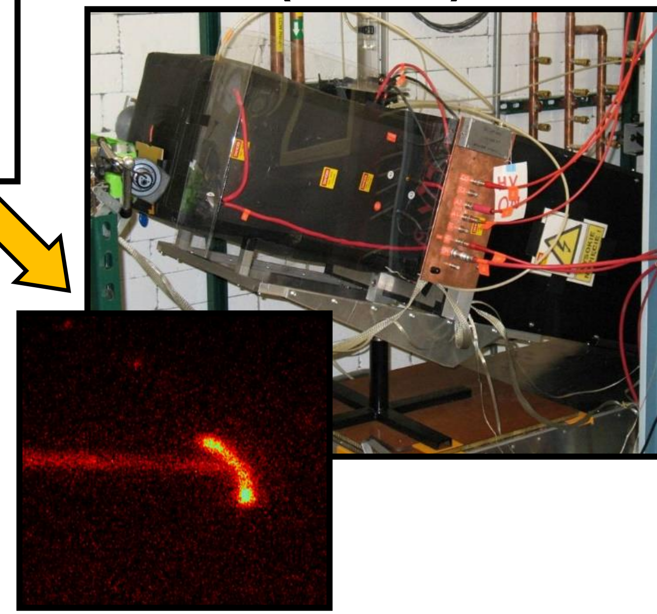
current instruments limitations



TPC Bordeaux (CENBG)



Optical TPC (Warsaw)



charges measurement (projection) :

2 series of strips (X and Y)

→ 2 x (1D) energy measurements

→ 2 x (1D) time measurements correlated T and E signals

charges to light conversion

CCD camera + photo-multiplier

→ "true" 2D projection

→ 1 time dist. for total charge (PM + sampling)

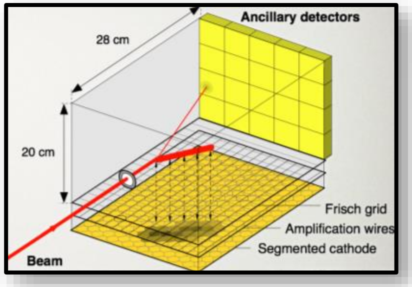
instrumental limitations

vertical tracks or in the same vertical plane

angles close to 0 or 180 degrees, dead-time, …

ACTAR TPC collaboration

time projection chambers for (fundamental) nuclear physics

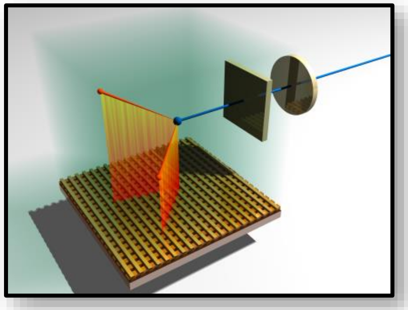


MAYA

(GANIL and coll.)

nuclear reactions

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



CENBG TPC

ions stopping and decay

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

development of a new TPC
for a large (nuclear) physics case

actar TPC

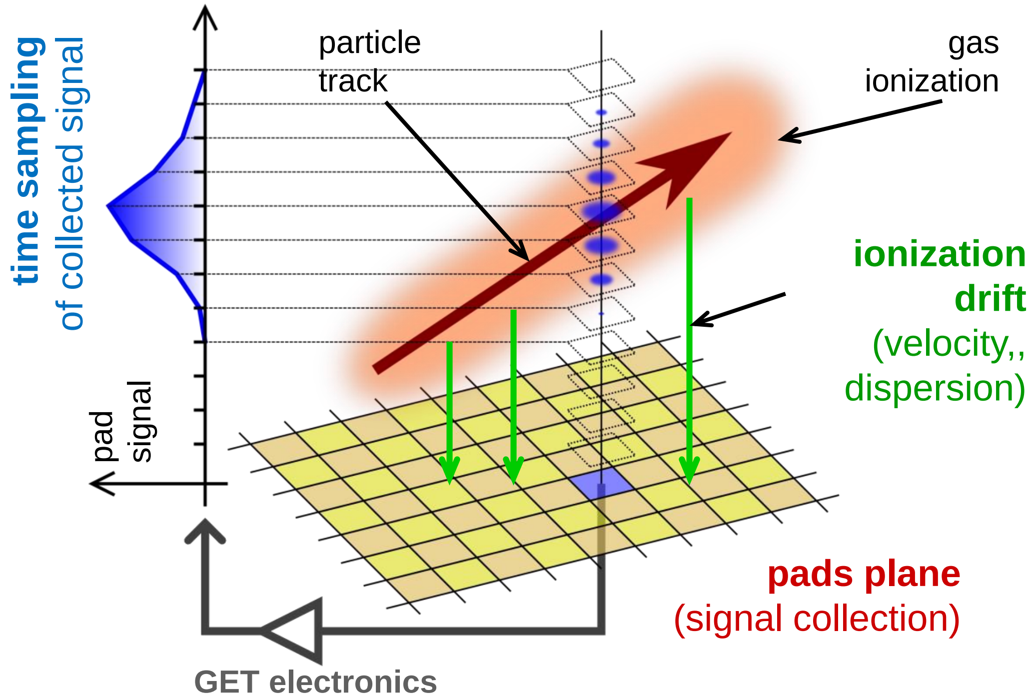
erc

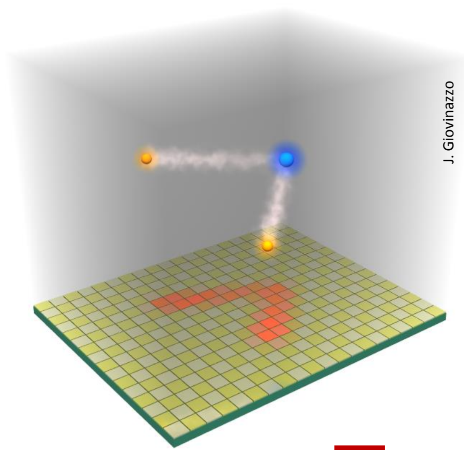
GANIL, CENBG, IPNO
Leuven, Santiago de C.

ACTAR TPC principle: full 3D + energy

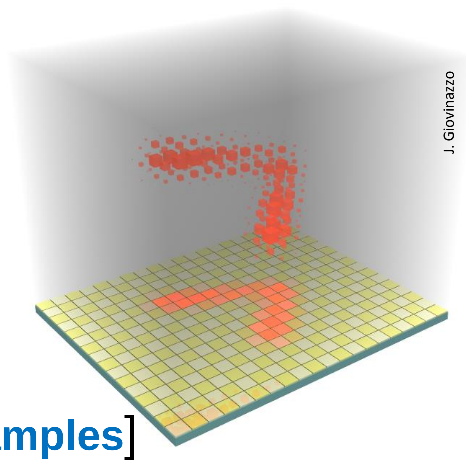
pads plane (signal collection)	TPC principle	time sampling of signal
2D digitization	$z \Leftrightarrow t$	3D digitization

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





3D reconstruction of ionizations charges along the particles trajectories



ΔE[16384 pads × 512 time samples]

ACTAR TPC technical issues

electronics

16384 channels with 100 Hz sampling

pad plane

high density pads

electric field

large gas volume (use of the whole 3D volume)

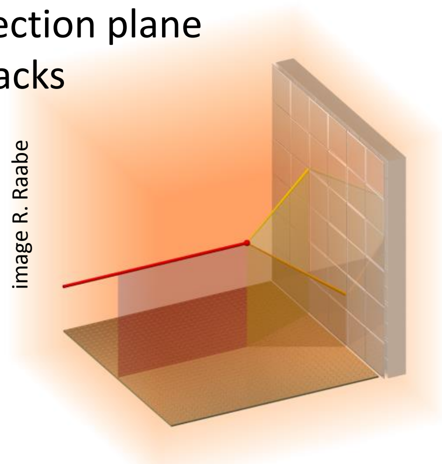
mechanics

gas chamber, detector interface, readout boards occupancy, …

1 development, 2 detectors

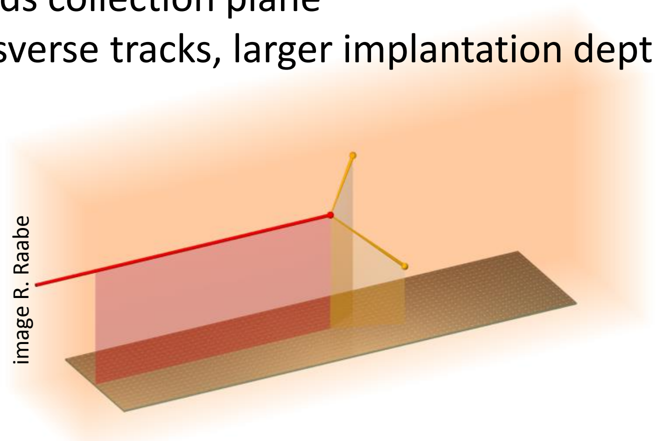
“reaction” chamber

128x128 pads collection plane
large transverse tracks



“decay” chamber

256x64 pads collection plane
short transverse tracks, larger implantation depth



shared design and technology

16384 pads, 2x2 mm^2
2 geometries

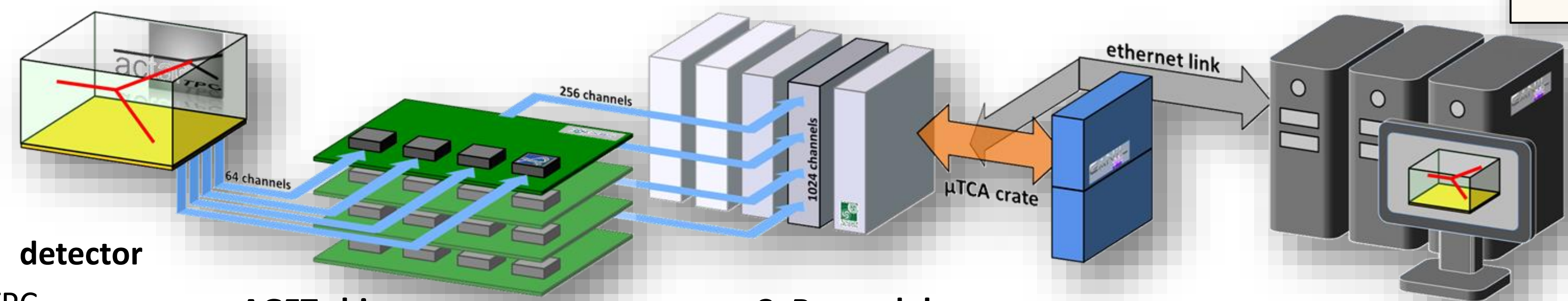
→ main funding: ERC
(J.F. Grinyer, GANIL)

→ decay chamber: Region
pad plane R&D
(J. Giovinazzo, CENBG)

GET electronics
technical solution
for channels readout

GET: General Electronics for TPC

IRFU, CENBG, GANIL, MSU
ANR 2011-2015



detector
TPC
16384 pads

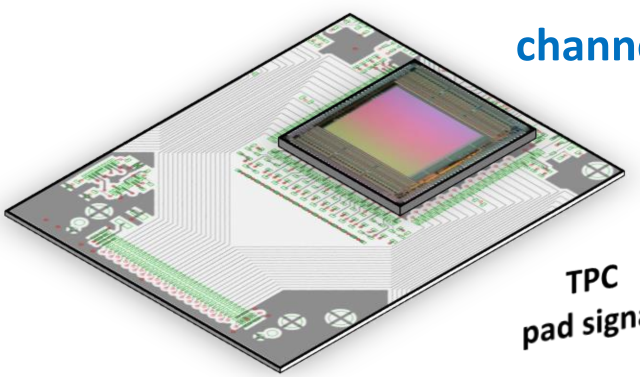
AGET chip
64 channels
signal processing
(CSA + shaper),
analog memory,
discriminator

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

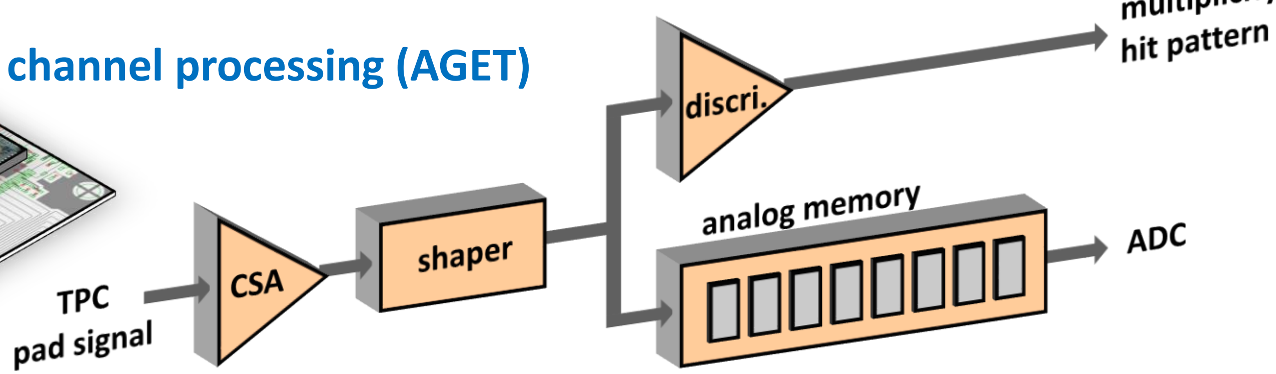
CoBo module
4 AsAd boards
digital data
management

MuTAnT
clock distrib.,
trigger management
(3 levels)

control / acquisition



channel processing (AGET)

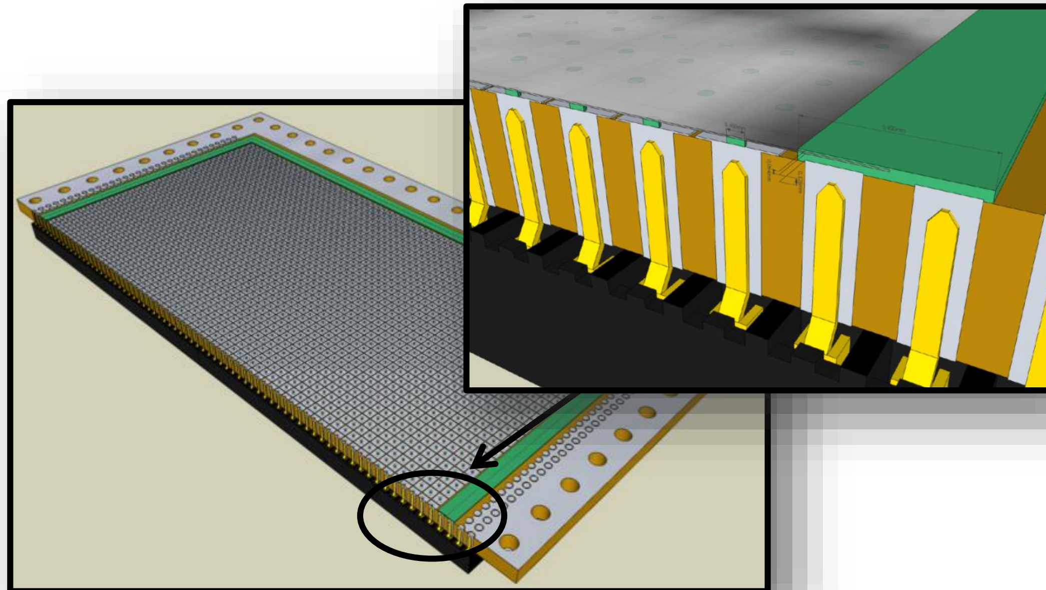


some boards sent to ~20 projects around the world !!!

pad-plane development: the "Fakir" option

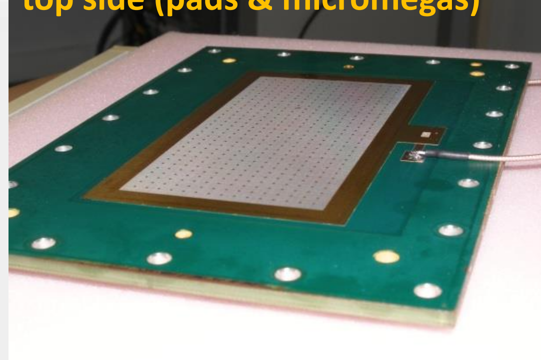
original design: **CENBG** (J. Pibernat)

realization:
collaboration **CERN PCB workshop**
(R. de Oliveira)



principle: **metal-core PCB** (Alu-HR)
- metal plate drilling
- holes isolation (resin)
- PCB layers
- drilling & metallization
- connectors soldering
  (coll. **FeDD** company)
- micromegas

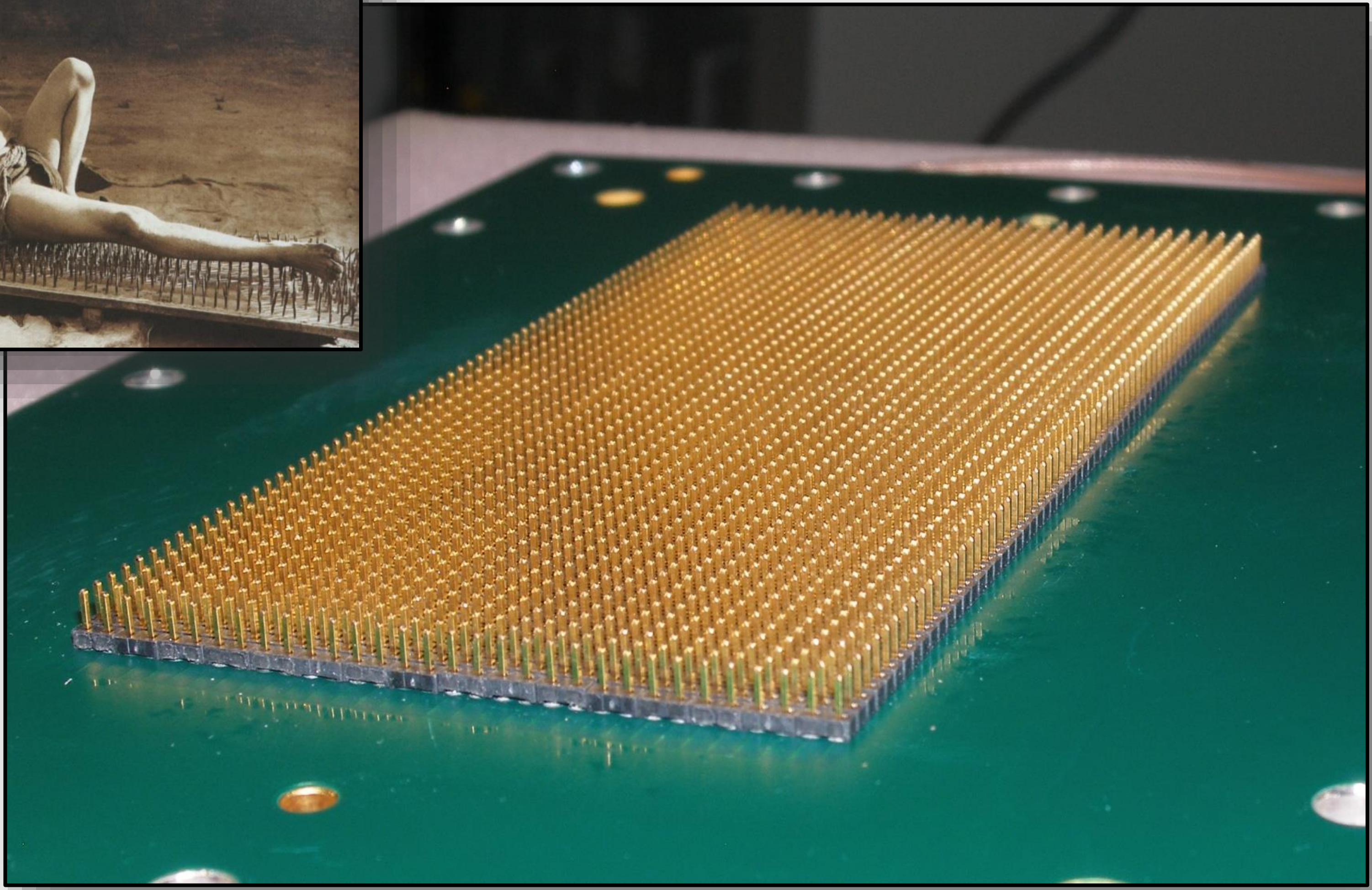
prototype:
for ACTAR TPC demonstrator
reduced size: 2048 pads



top side (pads & micromegas)

bottom side (connectors)

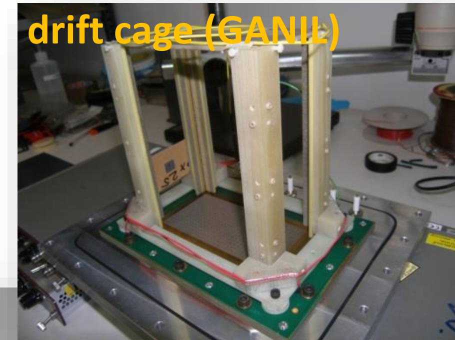
why "Fakir"?...

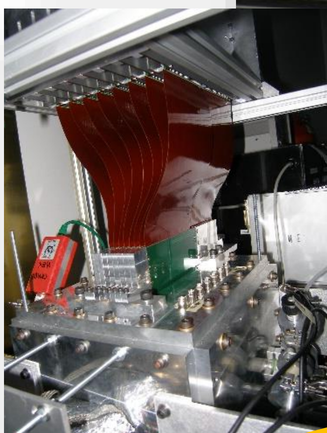


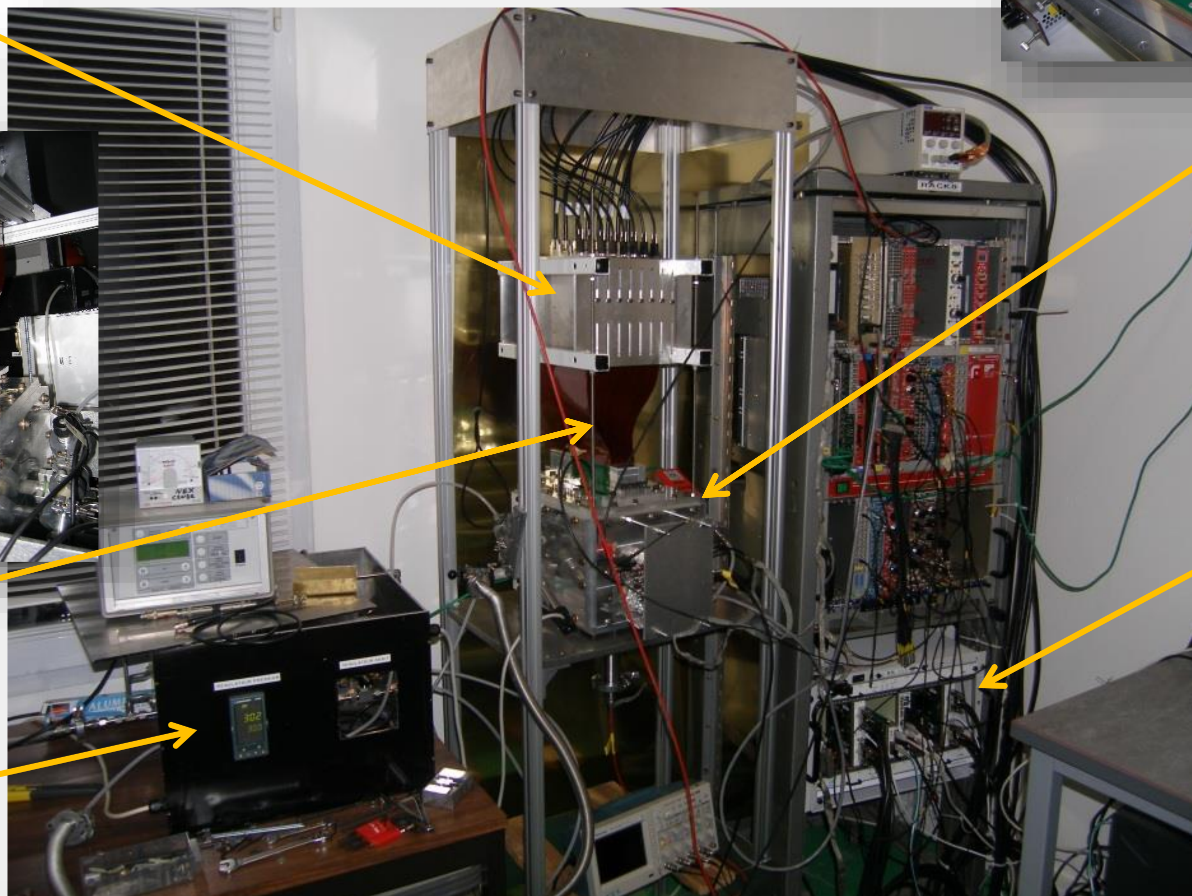
ACTAR TPC demonstrator

(CENBG version)

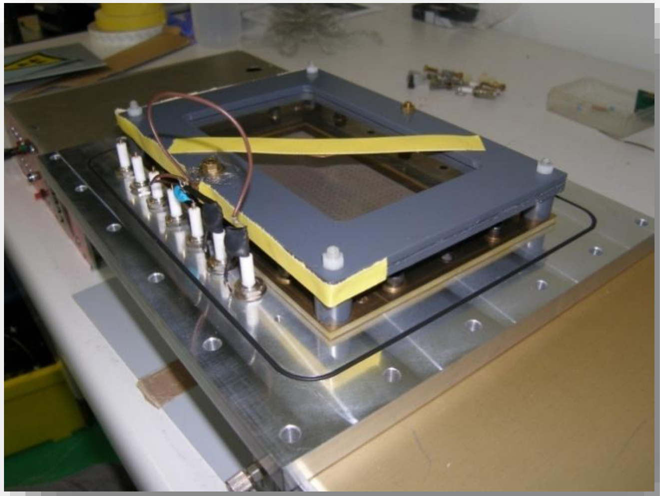
full electronics (march 2016) → 2048 pads signal





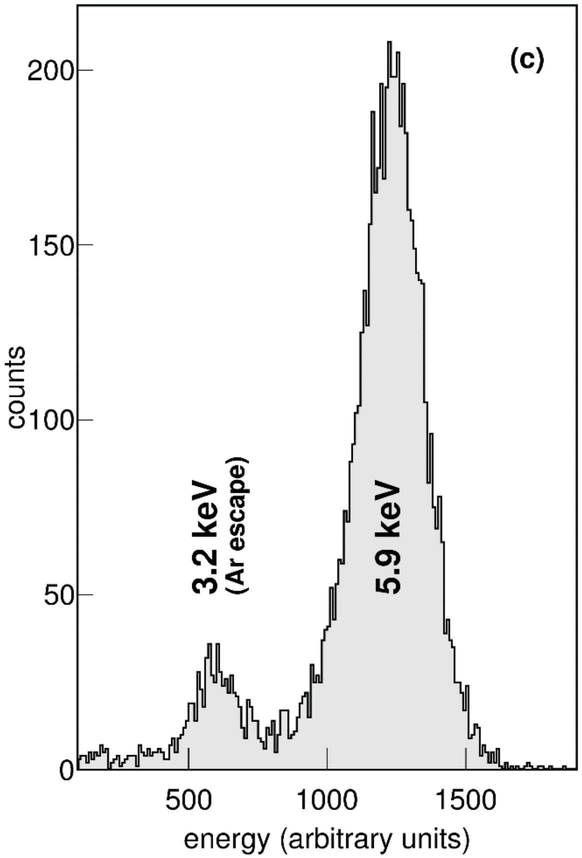


^{55}Fe X-rays source tests



drift volume thickness: **2.5 *cm***
HV$_{mesh}$* = –570 *V
HV$_{drift}$* = –1000 *V

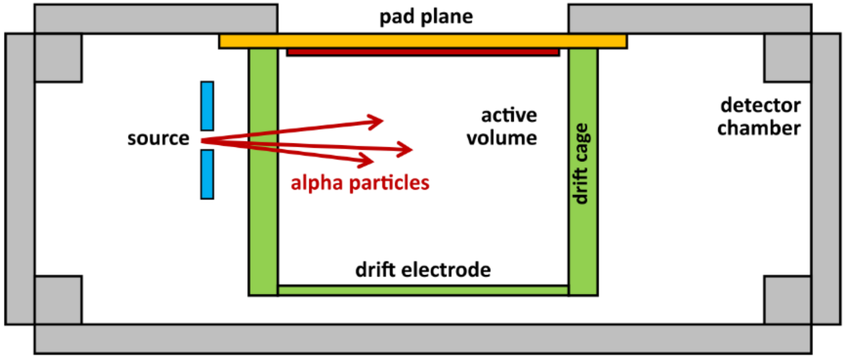
P10 gas (Ar-CH_4), 1 atm

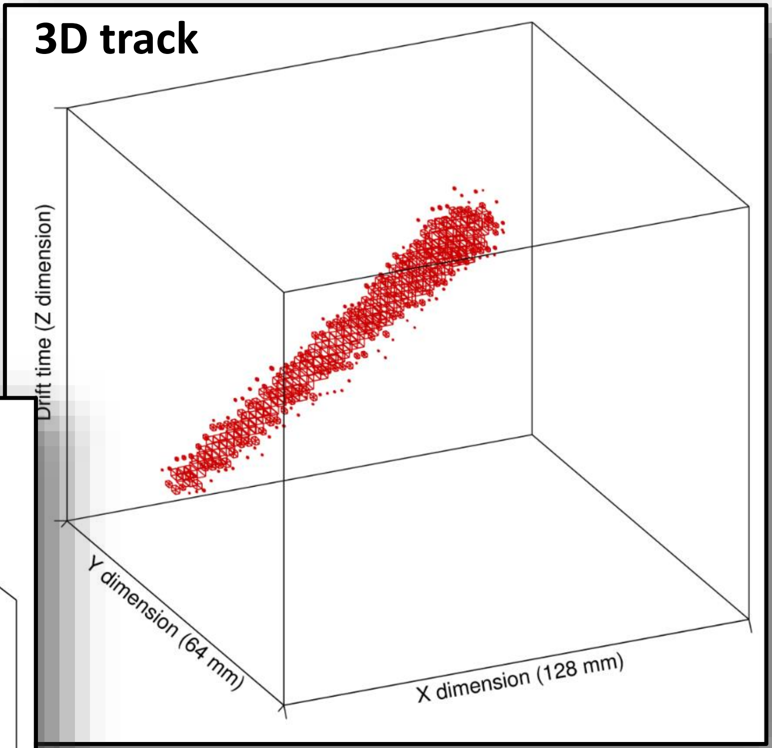


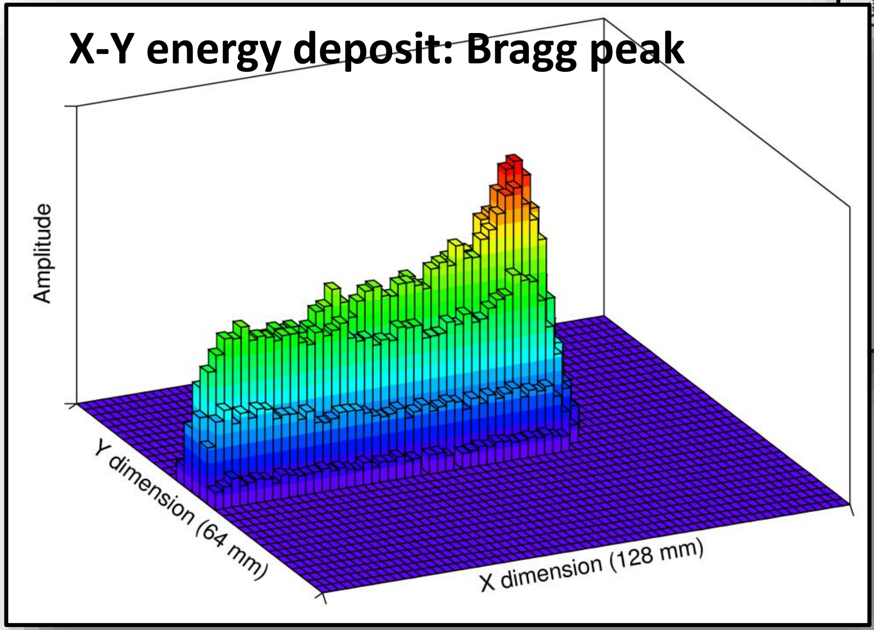
energy resolution (FWHM)
@ **6** *keV*: ~**21 %**

signal from *micromegas* **mesh**
or from **pads**

alpha source tests

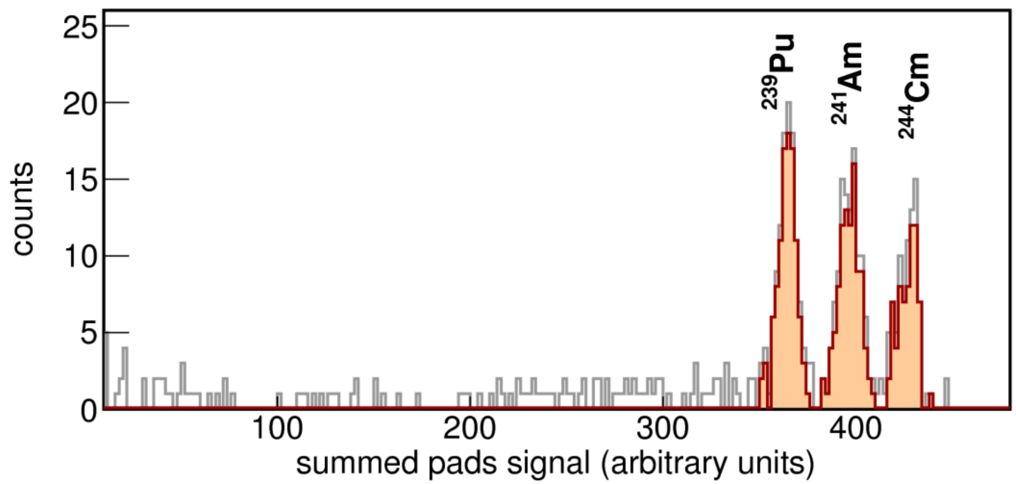






P10 gas (Ar-CH_4), 400 *mbar*

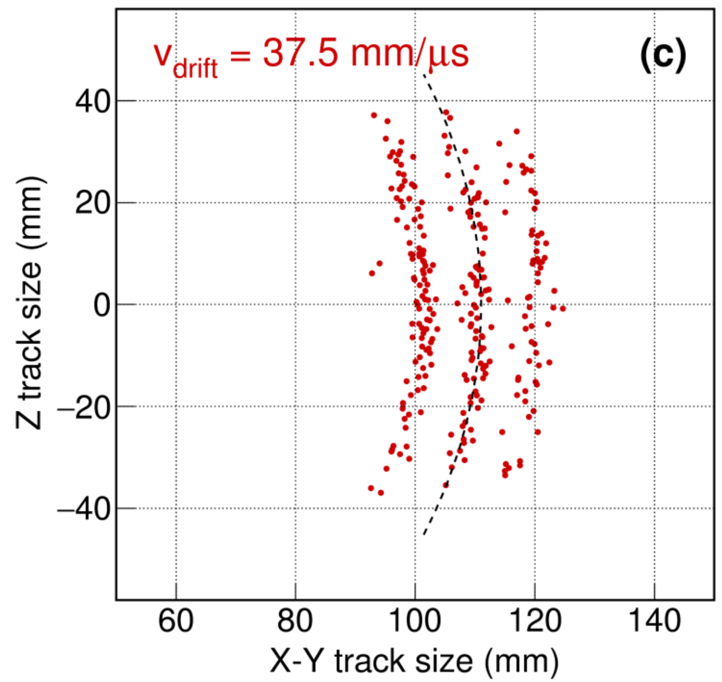
particles tracks analysis



energy resolution (FWHM)

100 *keV* @ 4.8 *MeV*

(corrected for dead volume)



Bragg peak fitting along track

simple model

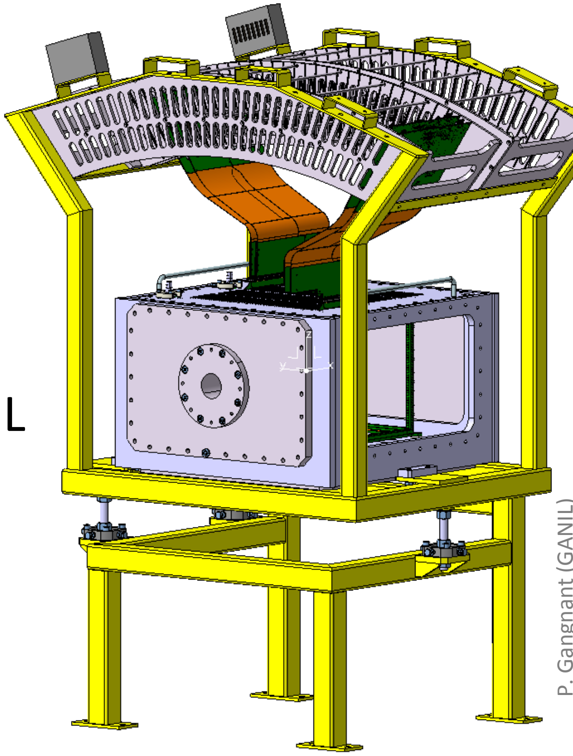
based on Geant4 simul.

angular and position/length estimates in the order of particles intrinsic limitations (from Geant4)

ACTAR TPC current status

pad plane: "CENBG" option selected

electronics: almost ready (few adjustments)

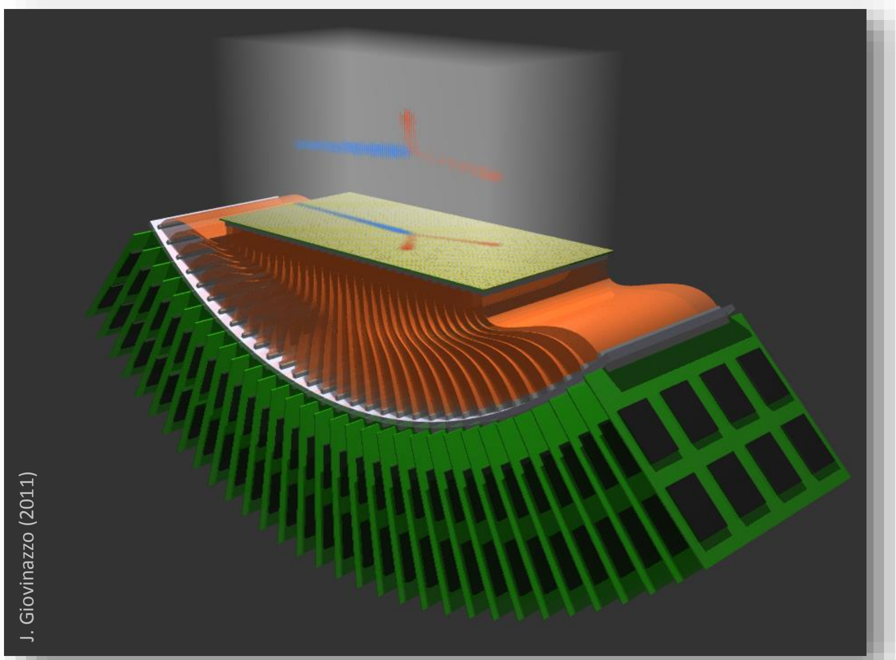


"reaction" detector

under construction at GANIL

→ ready mid 2017

→ first experiment 2018



"decay" detector

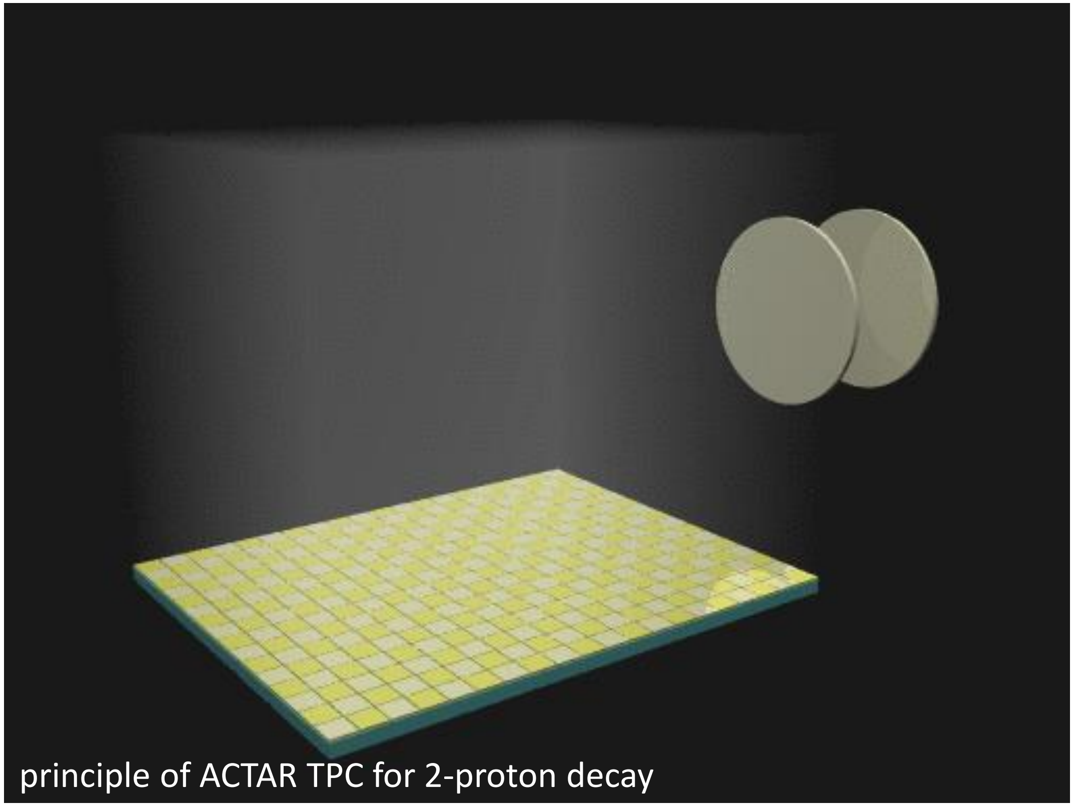
final design under study (CENBG)

→ ready mid 2017

→ exp.: GANIL 2018 / RIKEN 2018-2019

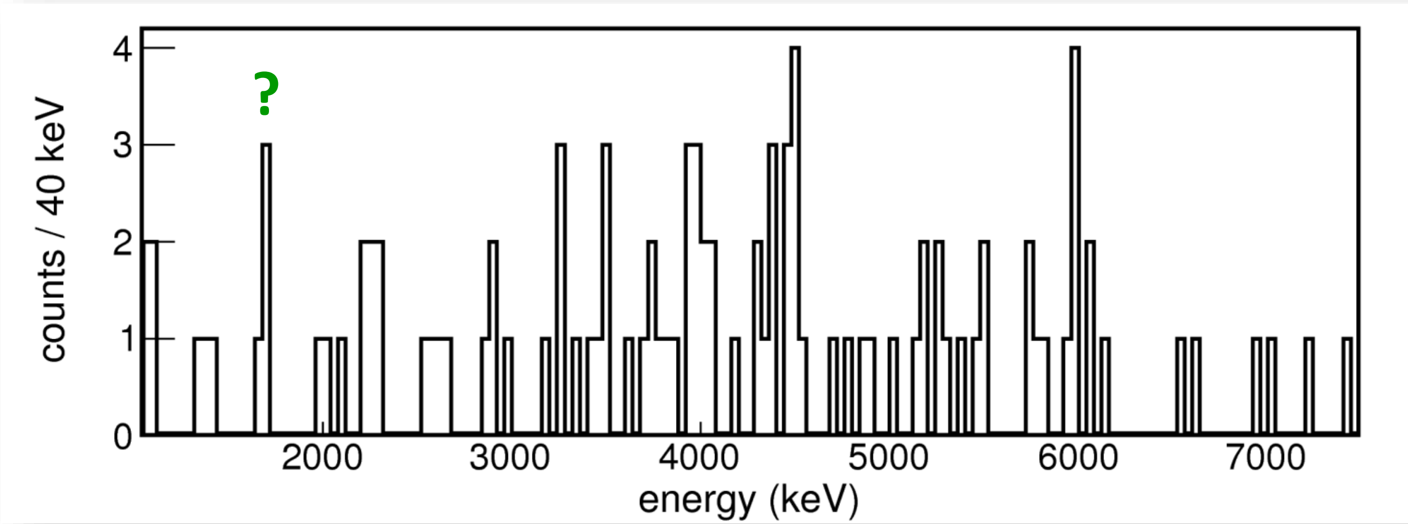
Conclusion

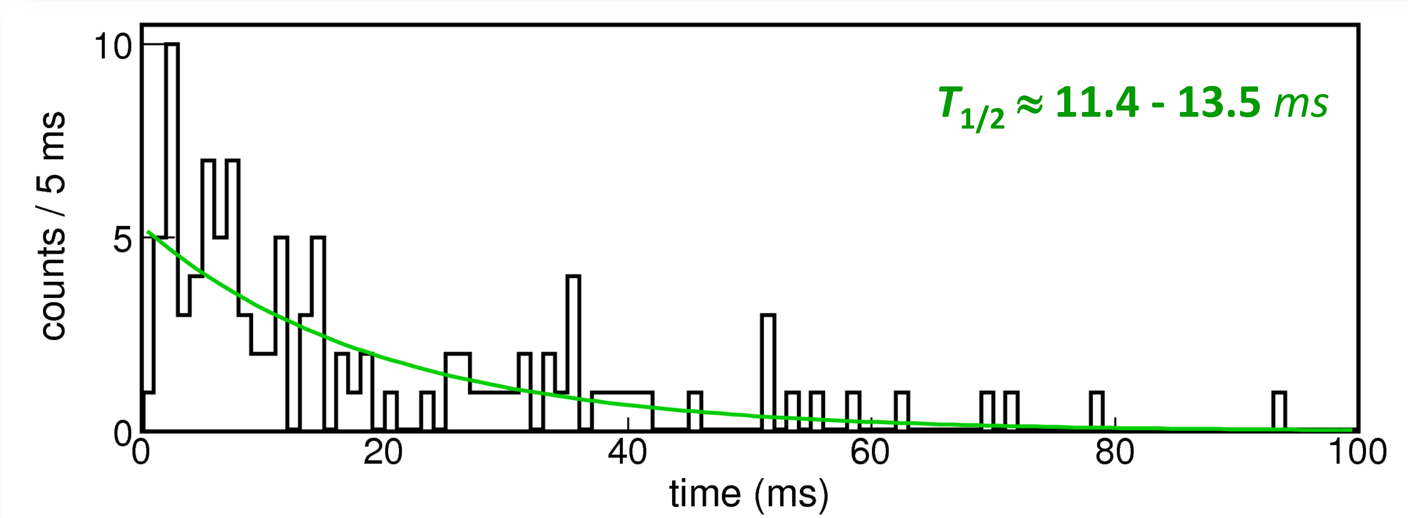
→ **Ongoing program (TPC)**
→ **Opportunities at GSI / FAIR**
→ **Need for theory developments**



extra slides

the decay of ^{63}*Se* (preliminary results): decay energy & time

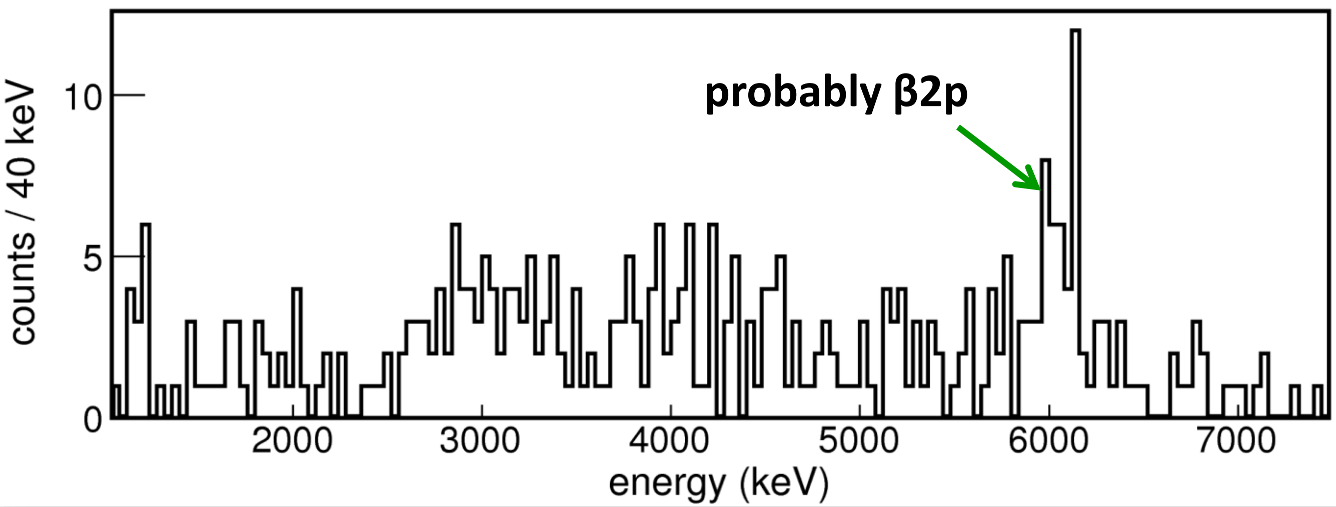


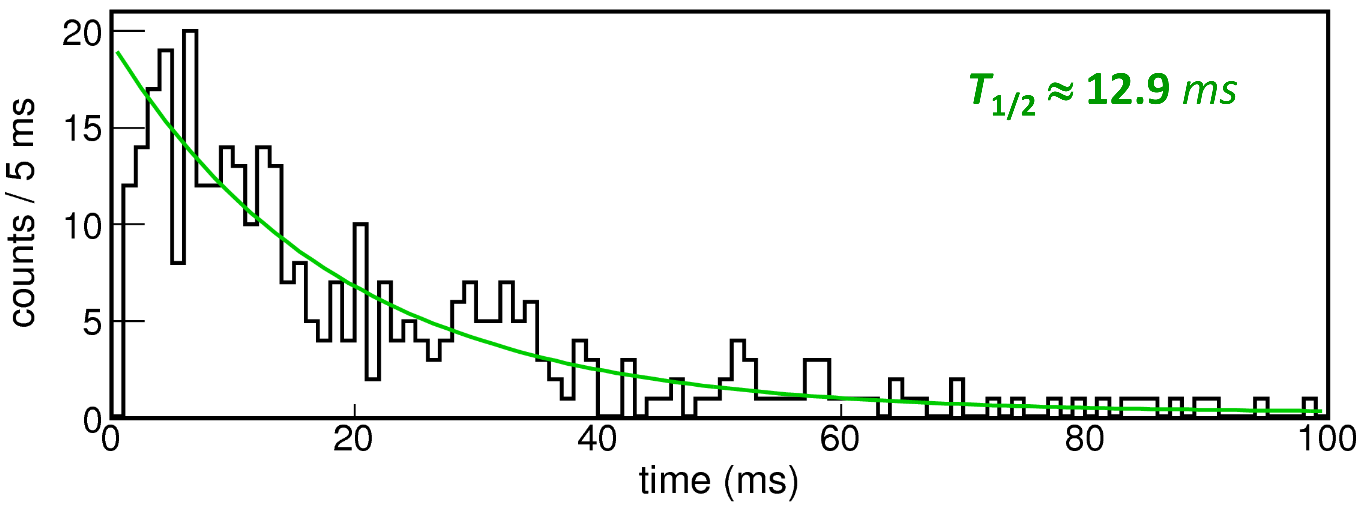


mainly β-delayed proton(s) emitter

if 2P, weak B.R.

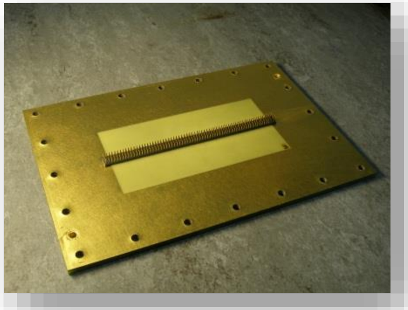
the decay of ^{59}*Ge* (preliminary results): decay energy & time



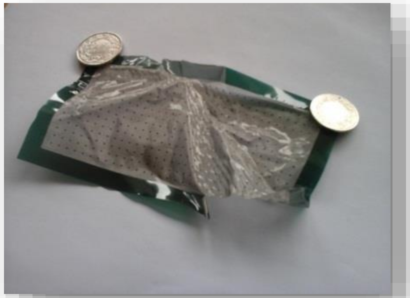


"FAKIR" pad plane prototypes

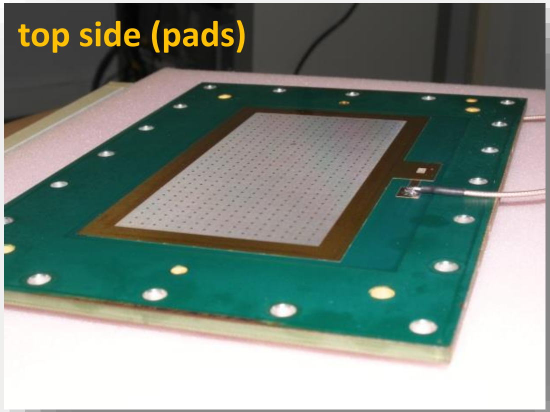
1st prototype: feasibility test (limited pads number)
coll. CERN / R de Oliveira
PCB realization issues
soldering issues

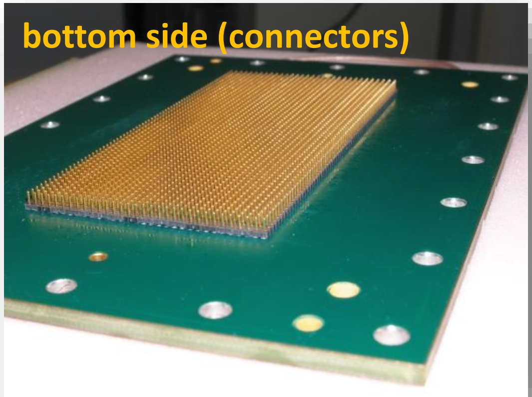


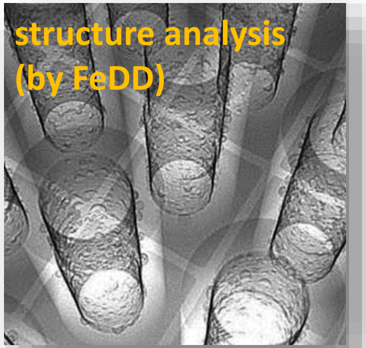
2nd prototype: response characterization
coll. CERN / R de Oliveira
problems with micromegas



3rd prototype: ACTAR TPCdemonstrator equipment
coll. CERN / R de Oliveira (PCB + micromegas)
& FeDD company (connectors soldering)







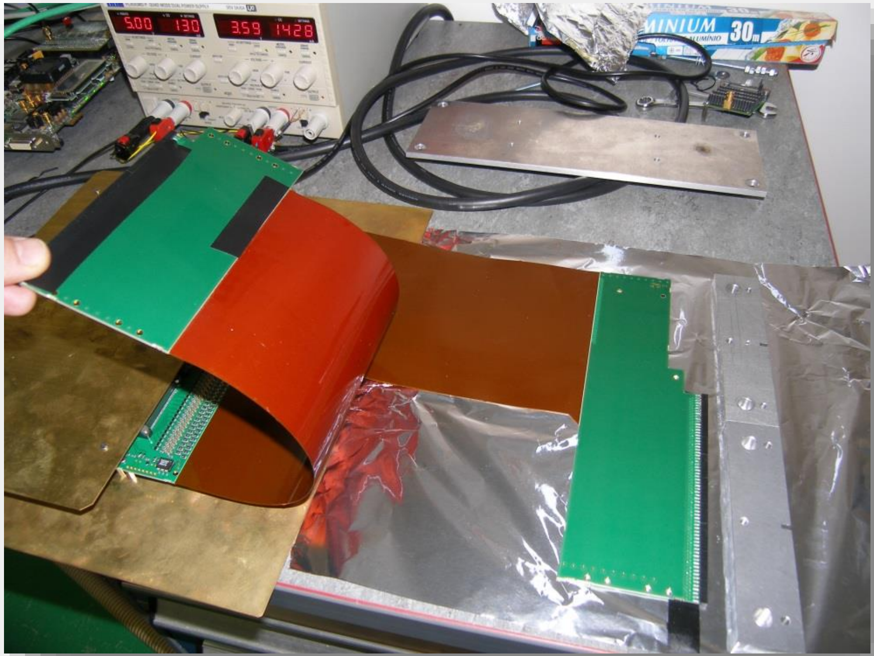
ZAP connectors: flex design

signal readout

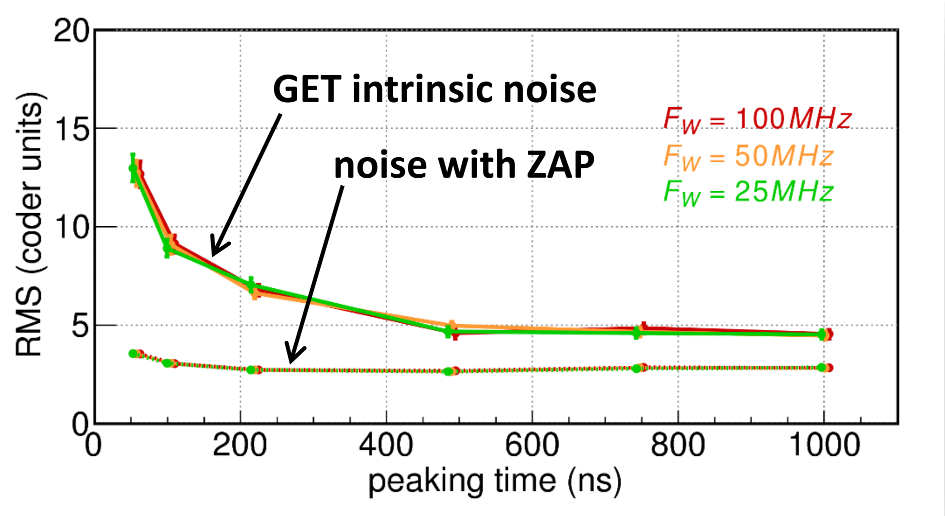
limited noise (capacitor)

shielding

electronics channels protection



noise from ZAP



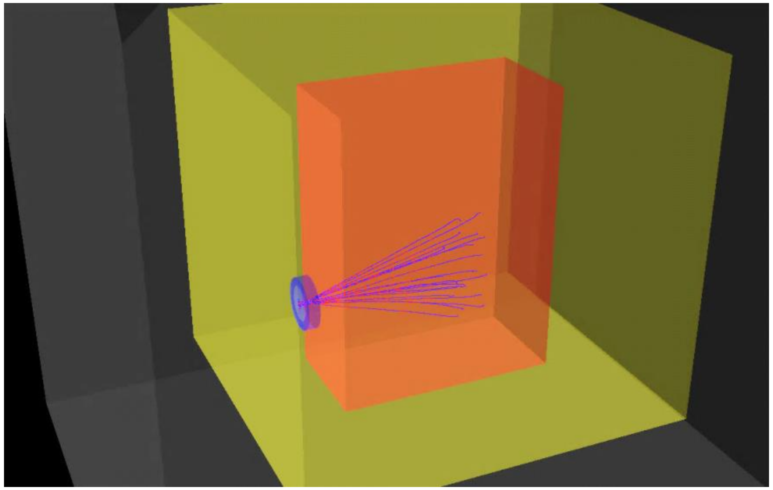
design for both final chambers

1 x 64 AsAd boards (decay)

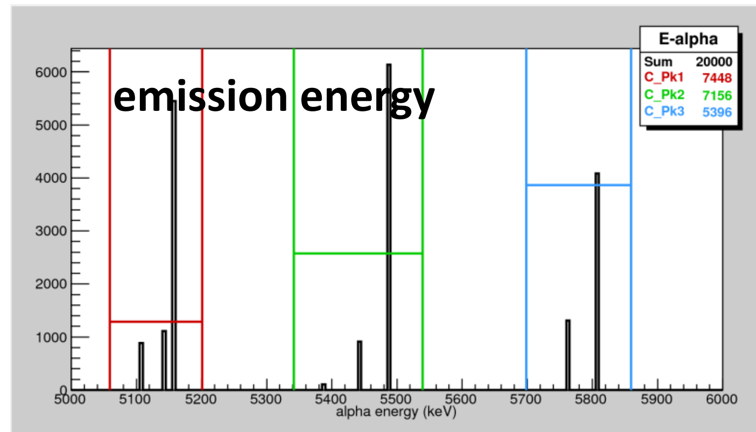
2 x 32 AsAd boards (reaction)

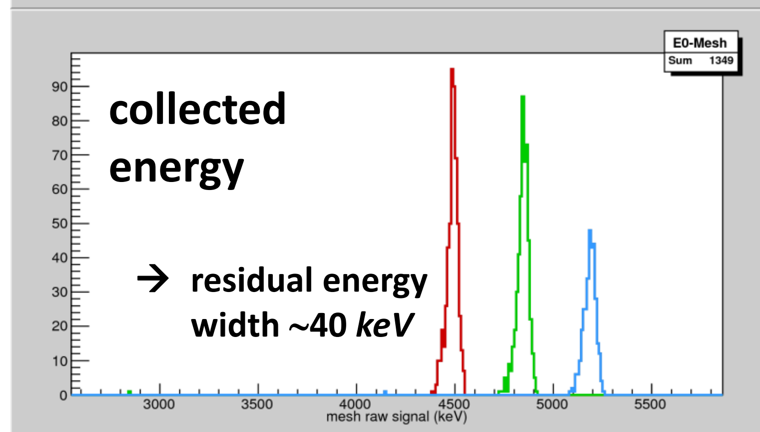
3-alpha source: alpha effective energies

from Geant4 simulations

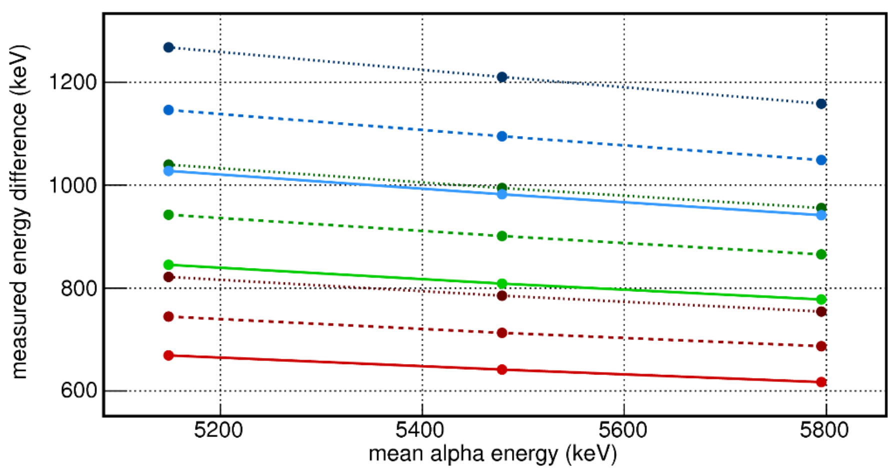


effective energy collected
in the active area of the detector
(energy loss before entering the volume)
→ gas pressure
→ source position





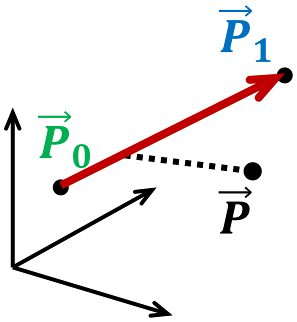
P = 400 *mbar* —— **d = 18 *mm***
P = 500 *mbar* ---- **d = 20 *mm***
P = 600 *mbar* ········ **d = 22 *mm***



tracks fit function: energy loss

track initial point: $\vec{P}_0 = (x_0, y_0, z_0)$

track final point: $\vec{P}_1 = (x_1, y_1, z_1)$



energy loss along the track $L = \|\overrightarrow{P_0P_1}\|$

track length: $L = \|\overrightarrow{P_0P_1}\|$

track path coordinate: $\varepsilon \in [0; 1]$

$\varepsilon = 0 \Leftrightarrow \vec{P} = \vec{P}_0$

$\varepsilon = 1 \Leftrightarrow \vec{P} = \vec{P}_1$

energy loss function: $f_E(\varepsilon) = \frac{dE}{dx}(\varepsilon \cdot L)$ → Bragg peak

total energy: $E = \int_{\varepsilon=0}^{1} f_E(\varepsilon) \cdot d\varepsilon$

tracks fit function: Bragg peak model

simulated energy deposit along the track

normalized function from simulation: $f_{Bragg}(\lambda_L)$

estimated at energy E_0 and gas pressure P_0

→ track length $L_0(E_0, P_0)$

energy loss along the track: $f_E(\varepsilon) = A \cdot f_{Bragg}(\lambda_L + (1 - \lambda_L) \cdot \varepsilon)$

λ_L fraction of the track length for a particle with energy $E \neq E_0$

A normalization for total energy loss

- at $\vec{P}_0$ $(\varepsilon = 0)$:

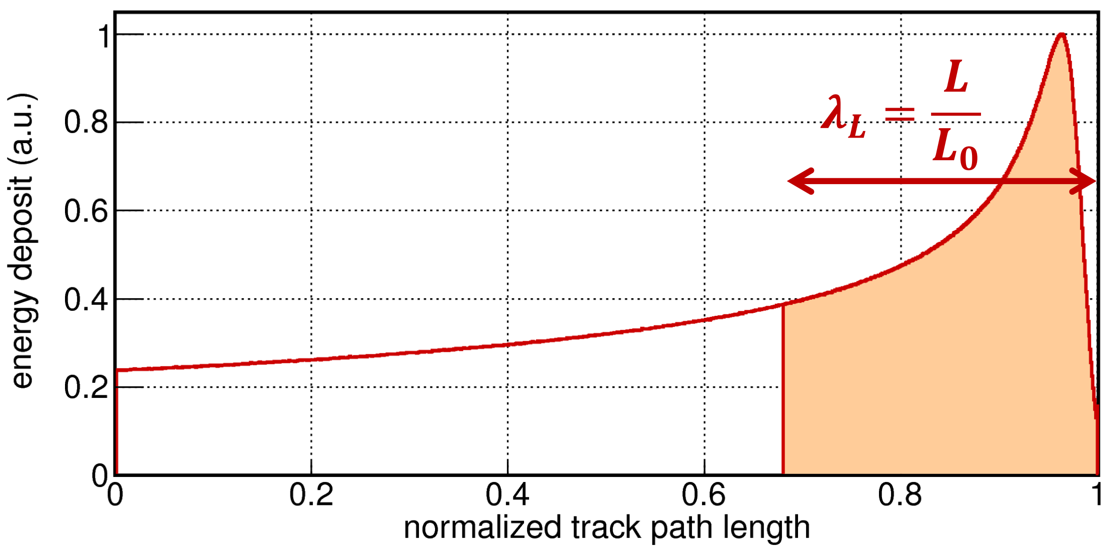
$$f_E(0) = A \cdot f_{Bragg}(\lambda_L)$$

- at $\vec{P}_1$ $(\varepsilon = 1)$:

$$f_E(1) = A \cdot f_{Bragg}(1)$$

energy from track length:

$$E_{sim}(\lambda) = E_0 \frac{\int_{1-\lambda}^{1} f_{Bragg}(\lambda) \cdot d\lambda}{\int_0^1 f_{Bragg}(\lambda) \cdot d\lambda}$$



tracks fit function: signal dispersion

2D (X-Y) signal projection + T dimension

$$S_{XY}(x,y) = \int_{\varepsilon=0}^{1} f_E(\varepsilon|A,\lambda) \cdot \frac{1}{2\pi \cdot \sigma_X(\varepsilon) \cdot \sigma_Y(\varepsilon)} \cdot e^{-\left[\frac{r(x|x_0,x_1,\varepsilon)^2}{2\sigma_X(\varepsilon)^2} + \frac{r(y|y_0,y_1,\varepsilon)^2}{2\sigma_Y(\varepsilon)^2}\right]} \cdot d\varepsilon$$

parameters

track start & stop positions: (x_0, y_0, t_0) and (x_1, y_1, t_1)

energy loss along the track: $f_E(\varepsilon|A,\lambda)$ ← peak shape from simulation

distance to track point $\vec{P}_\varepsilon$:
(linear track segment)

$$r(x|x_0,x_1,\varepsilon) = x - [x_0 + \varepsilon \cdot (x_1 - x_0)]$$
$$r(y|y_0,y_1,\varepsilon) = y - [y_0 + \varepsilon \cdot (y_1 - y_0)]$$

dispersion:
(linear variation along track)

$$\sigma_{X,Y}(\varepsilon) = \sigma_0^{(X,Y)} + \epsilon \cdot \sigma_1^{(X,Y)}$$