Neutron-induced reaction measurements in Europe

René Reifarth
Goethe-University Frankfurt

Nuclear Astrophysics Town meeting
Feb16, 2016, GSI, Darmstadt, Germany

The nucleosynthesis of the elements

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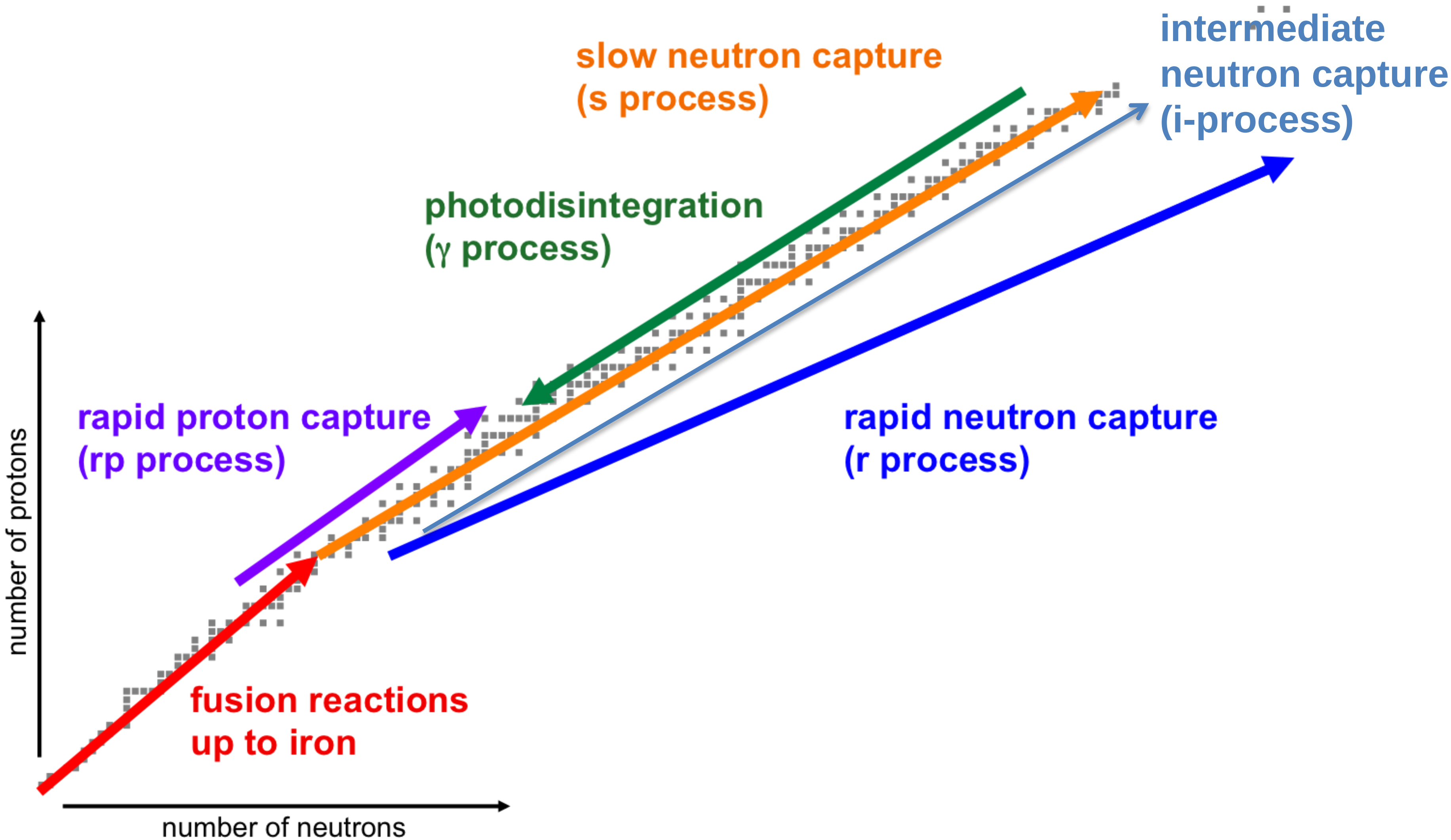
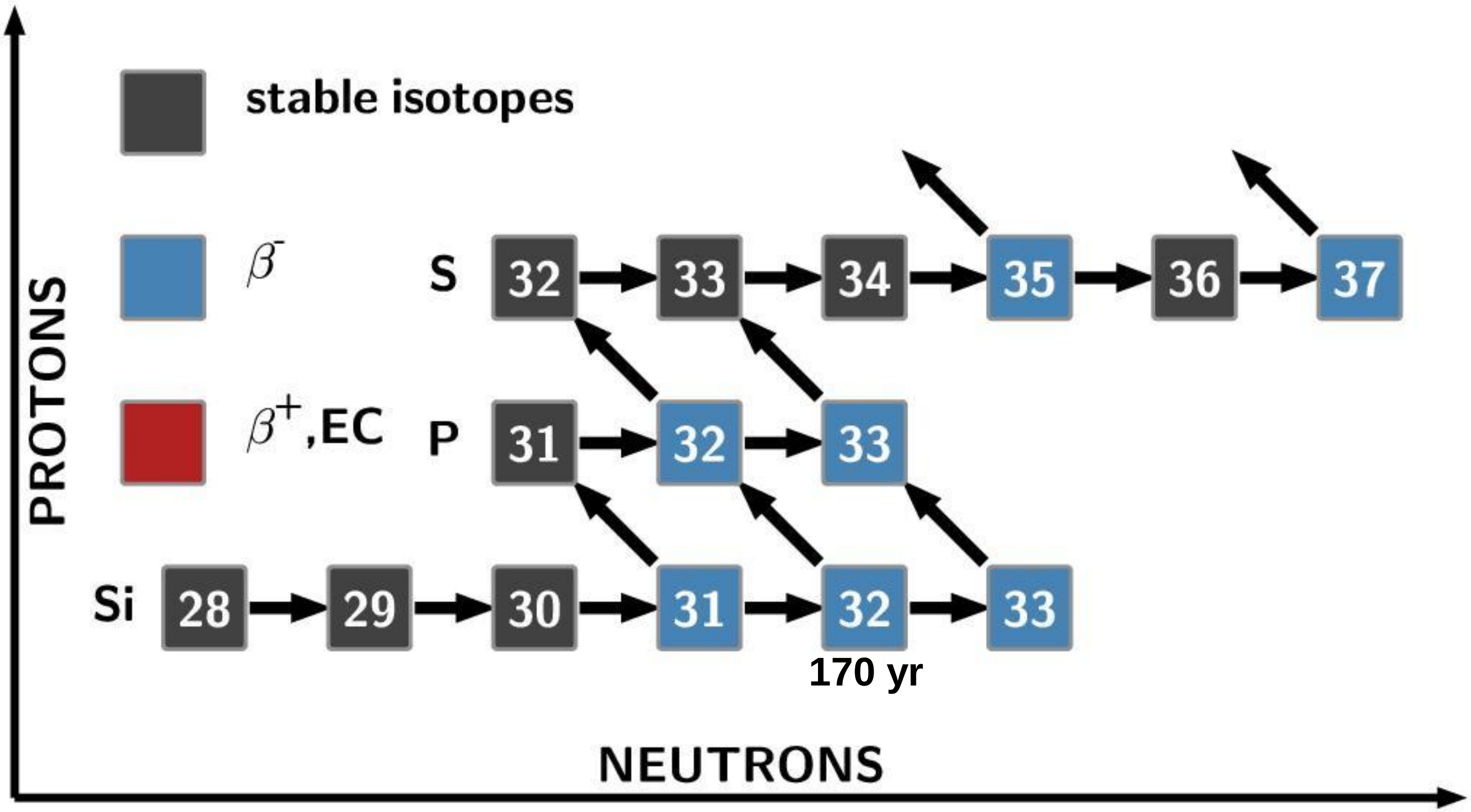
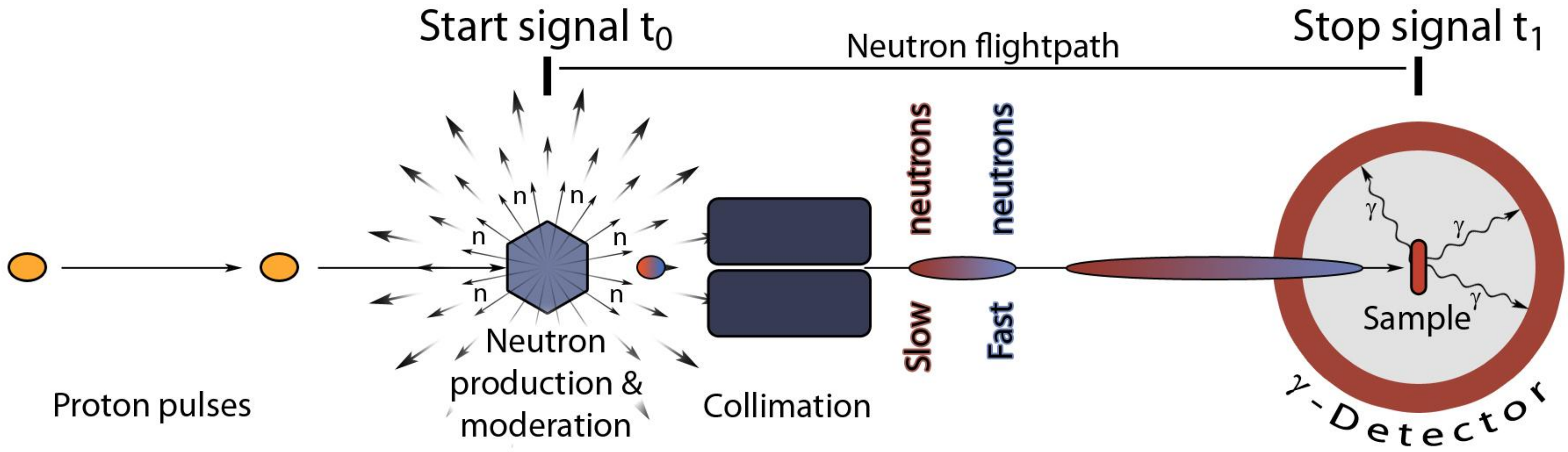


Origin of ^{32}S: neutron captures



Pignatari et al, ApJL 771:L7 (2015)

Neutron Captures – time-of-flight technique



- the TOF-technique is the only generally applicable method the determine energy-dependent neutron capture cross sections
- beam pulsing & distance to the neutron production site significantly reduce the number of neutrons available on the sample

nTOF @ CERN - spallation neutron source

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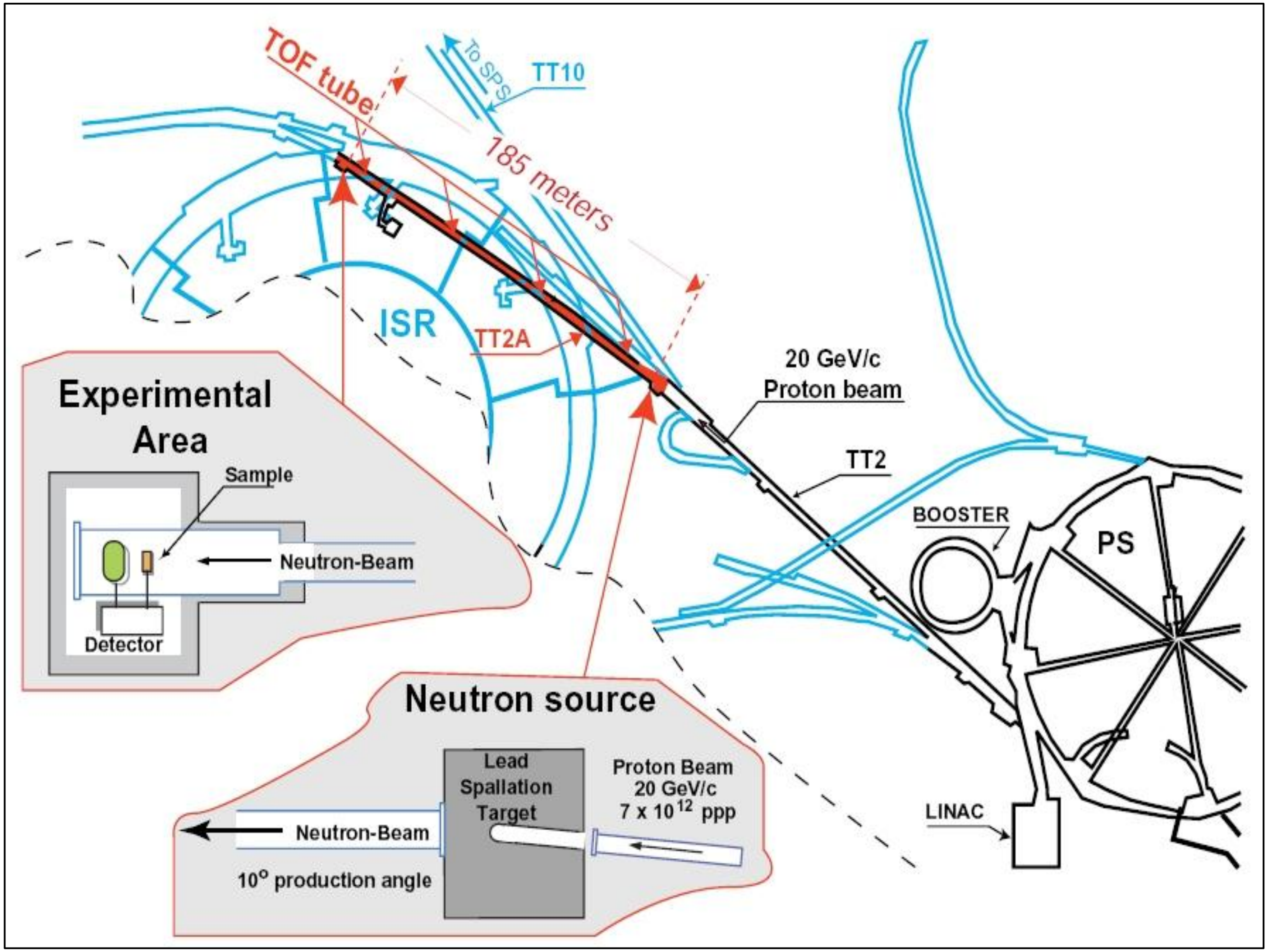
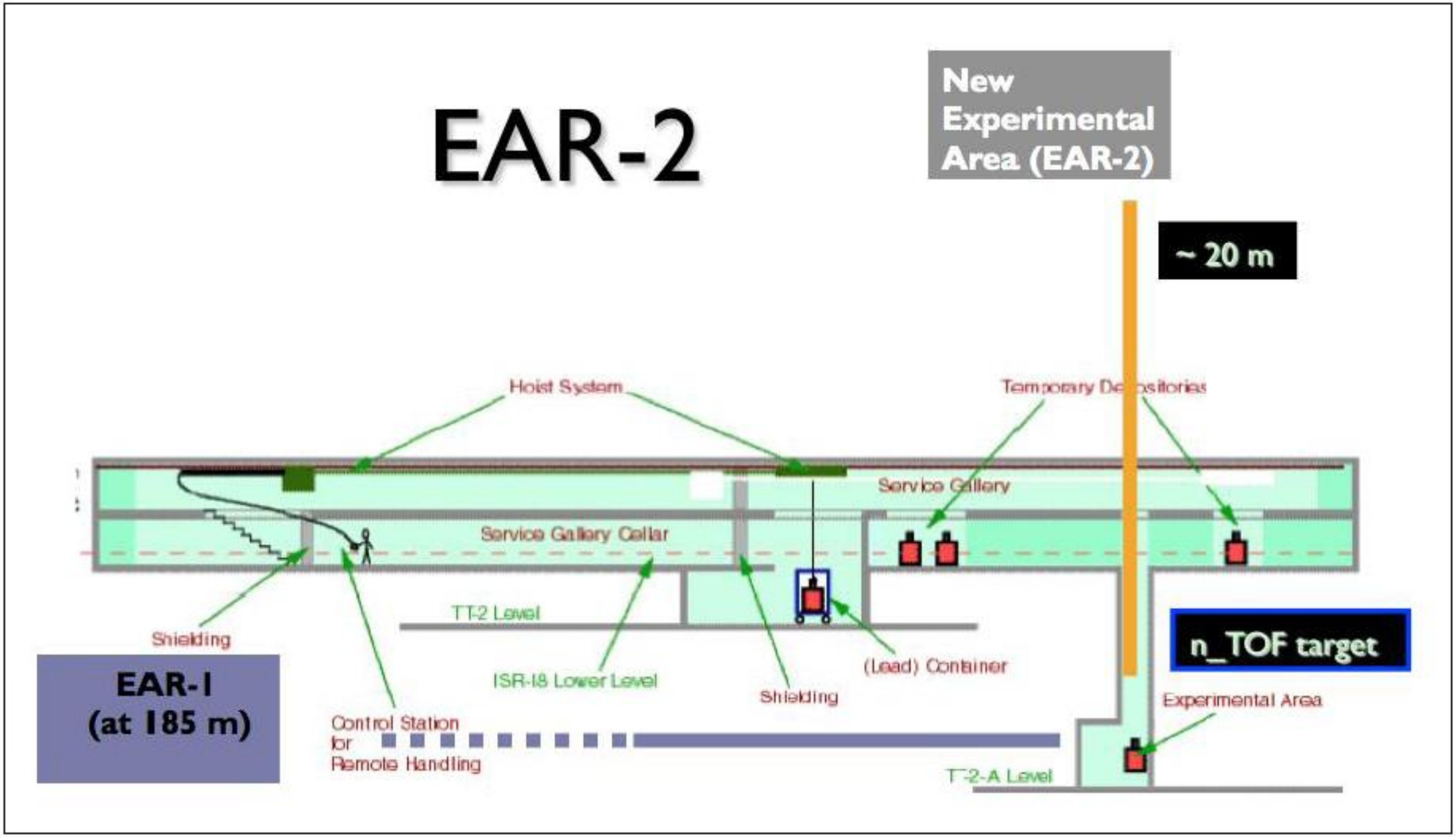
- **Δt = 7 ns**
- **1-10 s between pulses**



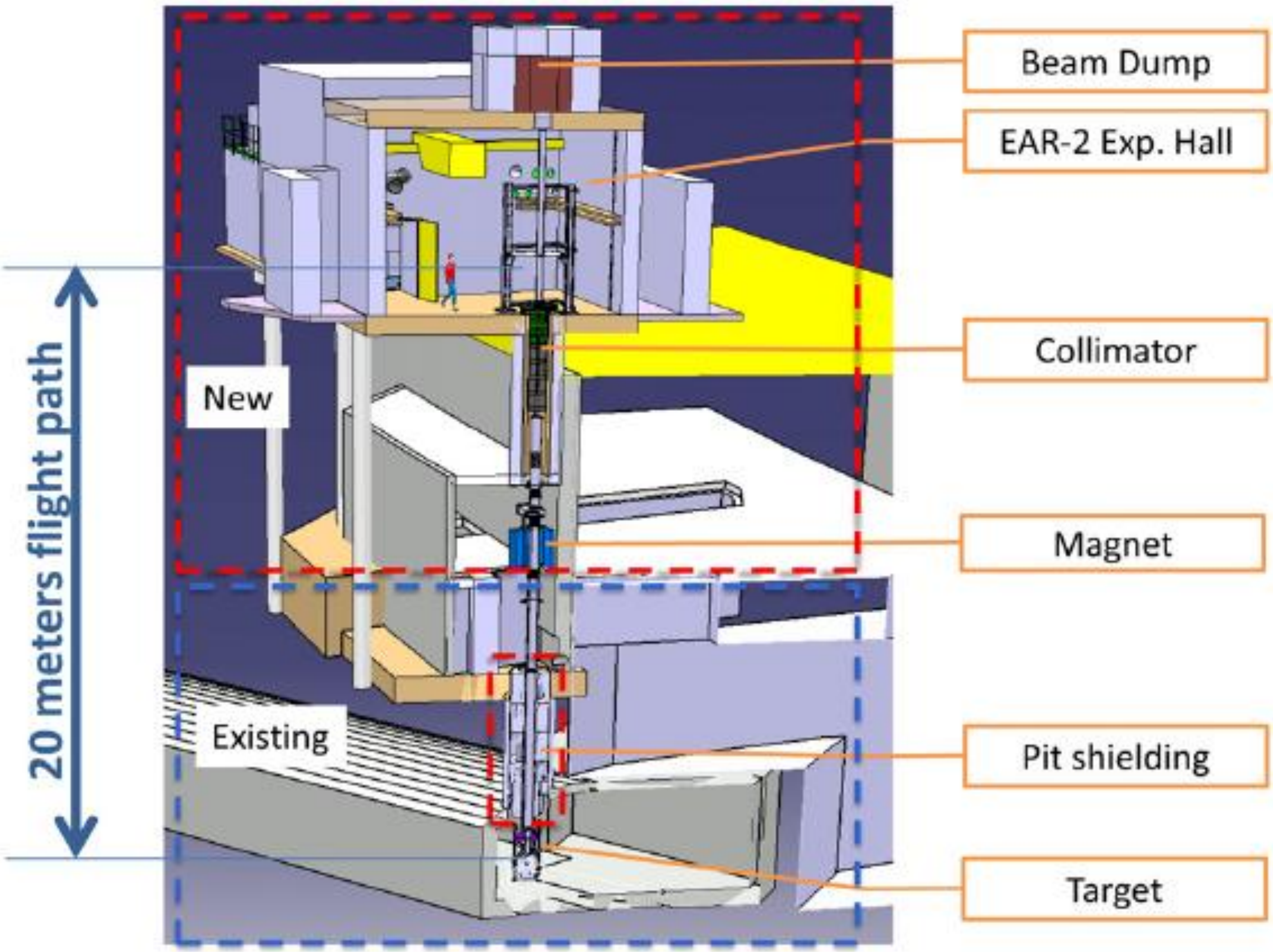
C. Guerrero et al, Eur. Phys. J. A (2013) 49: 27

nTOF @ CERN : 20 m & 200 m

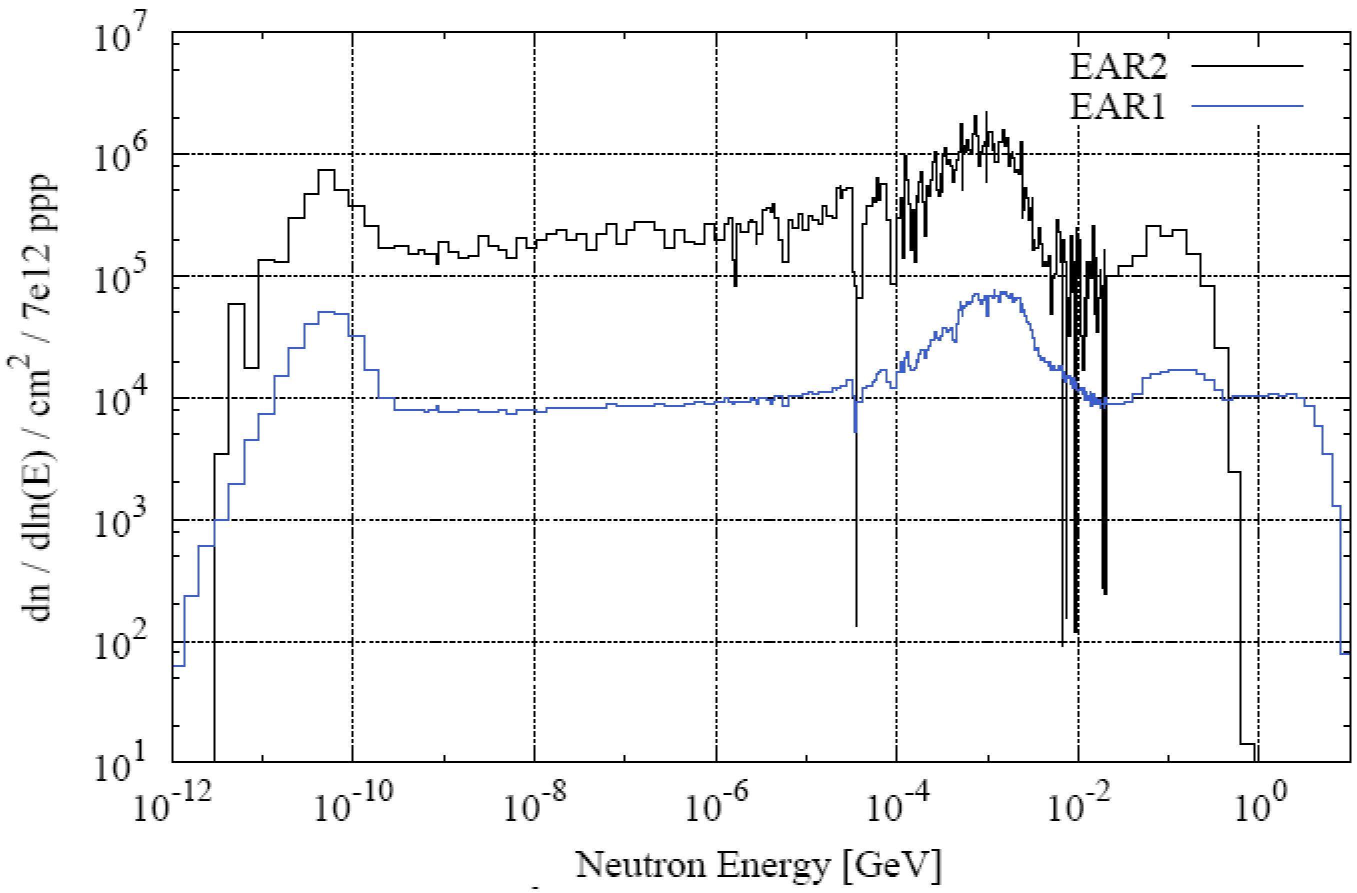


nTOF @ CERN -> EAR2

- commissioning 2014/2015
- 20 m
- 90° direction



nTOF @ CERN – neutron flux



(n,γ) of branching points@CERN

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Three new s-process branching-points have been measured at CERN:

Irradiation of stable pellets at ILL → target prep. at PSI → irradiation at CERN n_TOF (& LiLiT)

UNIVERSIDAD DE SEVILLA

CERN nTOF

ill NEUTRONS FOR SCIENCE

PAUL SCHERRER INSTITUT PSI

REVIEW OF MODERN PHYSICS, VOLUME 83, JANUARY–MARCH 2011

Sample	Half-life (yr)	Q value (MeV)	Comment
^{63}Ni	100.1	β^-, 0.066	TOF work in progress (Couture, 2009), sample with low enrichment
^{79}Se	2.95×10^5	β^-, 0.159	Important branching, consti…
^{81}Kr	2.29×10^5	EC, 0.322	Part of ^{79}Se branching
^{85}Kr	10.73	β^-, 0.687	Important branching, constr…
^{95}Zr	64.02 d	β^-, 1.125	Not feasible in near future, but important for neutron density low-mass AGB stars
^{134}Cs	2.0652	β^-, 2.059	Important branching at $A = 134, 135$, sensitive to s-process temperature in low-mass AGB stars, measurement not feasible in near future
^{135}Cs	2.3×10^6	β^-, 0.269	So far only activation measurement at $kT = 25$ keV by P…
^{147}Nd	10.981 d	β^-, 0.896	Important branching at $A = 147/148$, constrains neutron … AGB stars
^{147}Pm	2.6234	β^-, 0.225	Part of branching at $A = 147/148$
^{148}Pm	5.368 d	β^-, 2.464	Not feasible in the near future
^{151}Sm	90	β^-, 0.076	Existing TOF measurements, full set of MACS data available (Abbondanno *et al.*, 2004a; Wisshak *et al.*, 2006c)
^{154}Eu	8.593	β^-, 1.978	Complex branching at … density
^{155}Eu	4.753	β^-, 0.246	So far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1995)
^{153}Gd	0.658	EC, 0.244	Part of branching at $A = 154, 155$
^{160}Tb	0.198	β^-, 1.833	Weak temperature-sensitive branching, very challenging experiment
^{163}Ho	4570	EC, 0.0026	Branching at $A = 163$ sensitive to mass density during s… activation measurement at $kT = 25$ keV by Jaag and K…
^{170}Tm	0.352	β^-, 0.968	Important branching, constrains neutron density in low-mass AGB stars
^{171}Tm	1.921	β^-, 0.098	Part of branching at $A = 170, 171$
^{179}Ta	1.82	EC, 0.115	Crucial for s-process contribution to ^{180}Ta, nature's rarest stable isotope
^{185}W	0.206	β^-, 0.432	Important branching, sensitive to neutron density and s-process temperature in low-mass AGB stars
^{204}Tl	3.78	β^-, 0.763	Determines ^{205}Pb/^{205}Tl clock for dating of early Solar System

n_TOF→ PRL 93, 161103 (2004)

n_TOF 2015

n_TOF→ PRL 110, 022501 (2013)

n_TOF 2014

n_TOF 2015

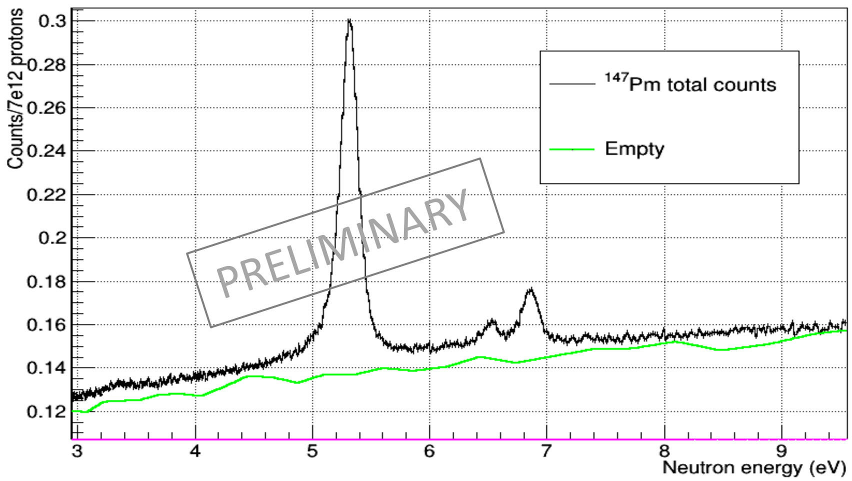
(n,γ) of branching points@CERN

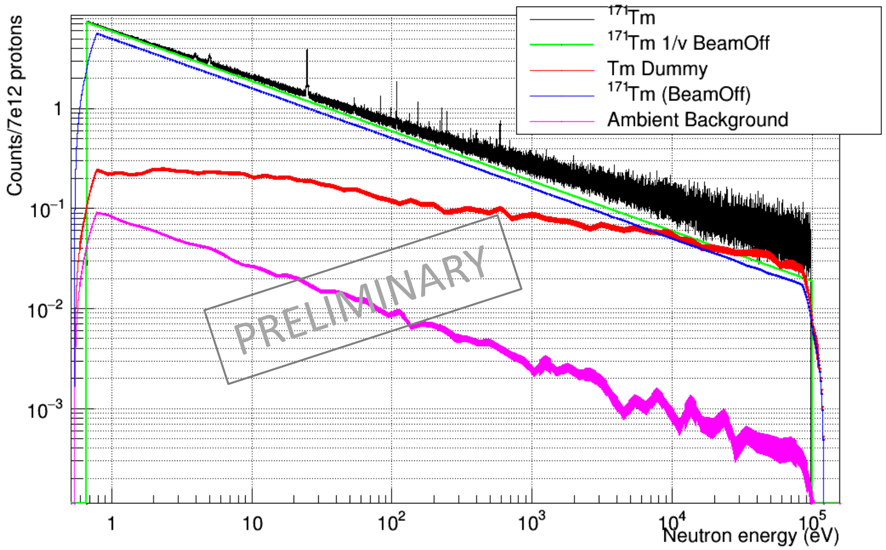
Limited statistics, but good prospects.

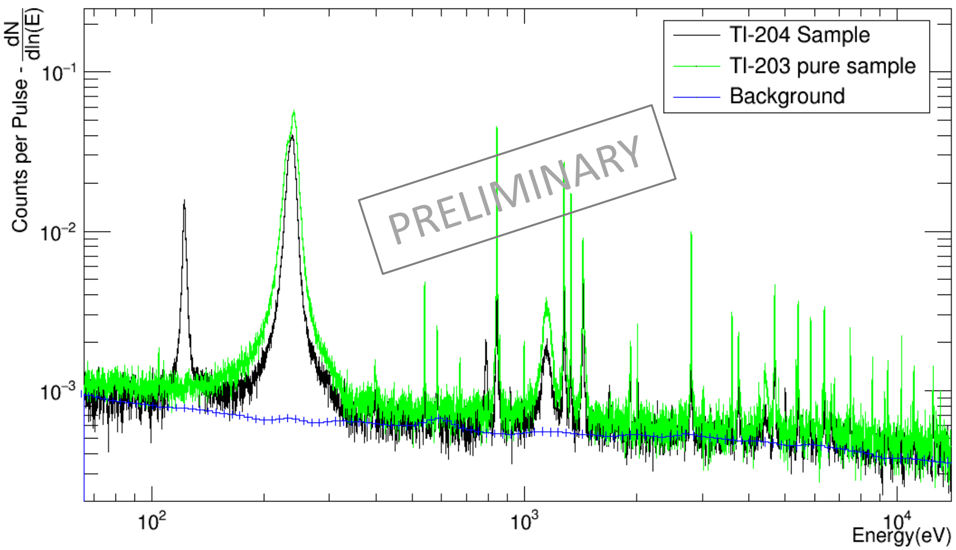
Analysis ongoing at U. Sevilla and UPC/IFIC.

Upcoming MACS measurements at LiLiT.

Targets available for possible future experiments (but ~2 years half life).

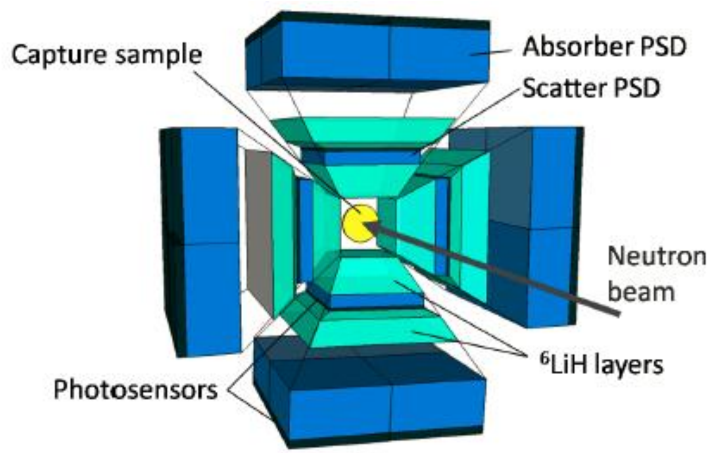




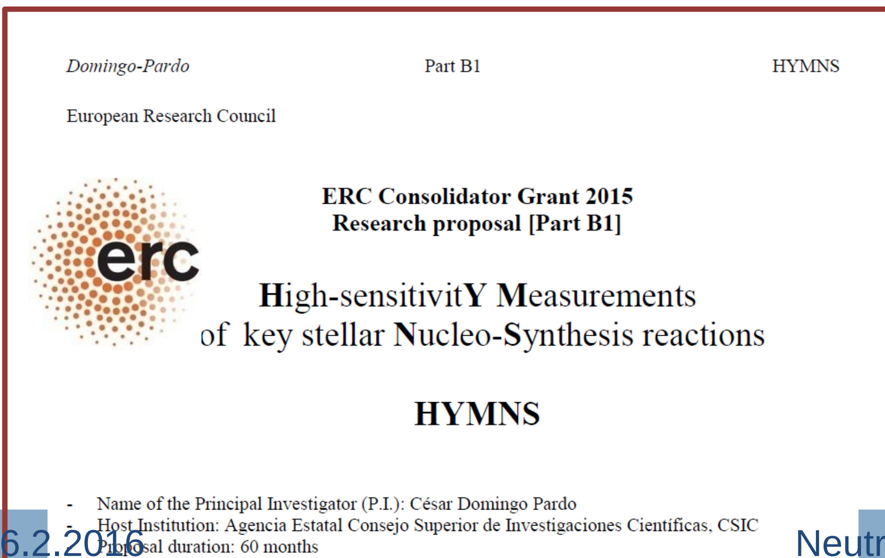


HYMNS: High-sensitivitY Measurements of key stellar Nucleo-Synthesis reactions

The aim of HYMNS is to develop and apply a novel detection system in the field of (n,γ) measurements, i-TED, which enables the first measurement of key s-process branching nuclei over the full stellar enegy range, such as ^{79}Se, which can be interpreted as a nuclear thermometer for massive stars.



i-TED: Total Energy Detector with γ-imaging


Domingo-Pardo Part B1 HYMNS

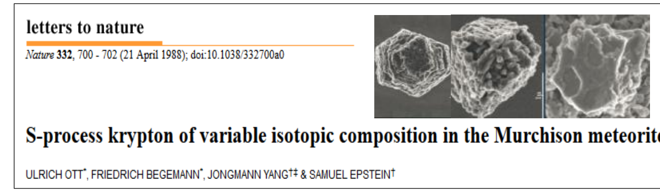
European Research Council

ERC Consolidator Grant 2015
Research proposal [Part B1]

High-sensitivitY Measurements of key stellar Nucleo-Synthesis reactions

HYMNS

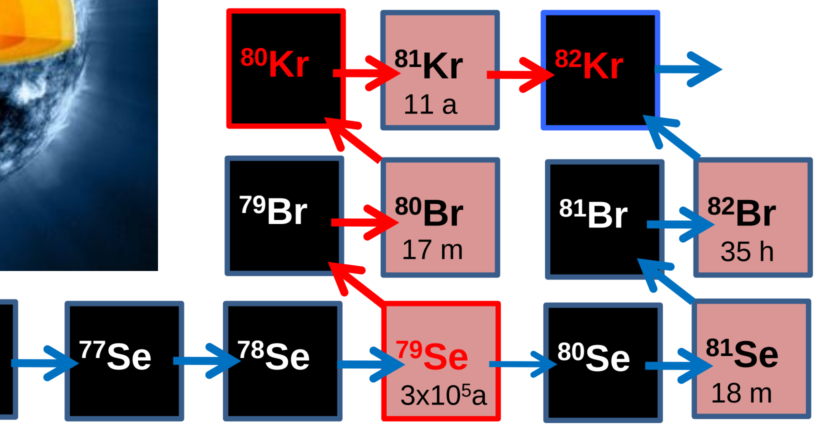
- Name of the Principal Investigator (P.I.): César Domingo Pardo
- Host Institution: Agencia Estatal Consejo Superior de Investigaciones Científicas, CSIC
- Proposal duration: 60 months

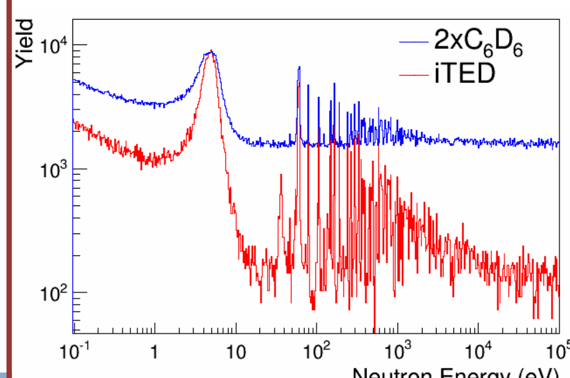

letters to nature

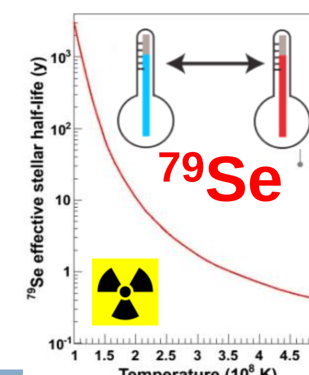
Nature 332, 700 - 702 (21 April 1988); doi:10.1038/332700a0

S-process krypton of variable isotopic composition in the Murchison meteorite

ULRICH OTT*, FRIEDRICH BEGEMANN*, JONGMANN YANG†‡ & SAMUEL EPSTEIN†



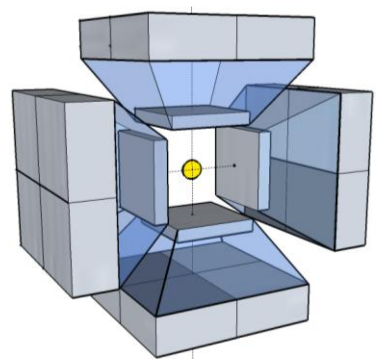




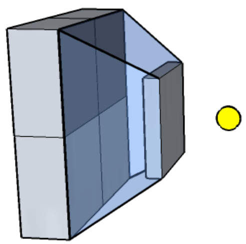
Expected results, contribution to the field and long-term impact

HYMNS

i-TED



Demonstrator



Conceptual MC design

GRID CSIC

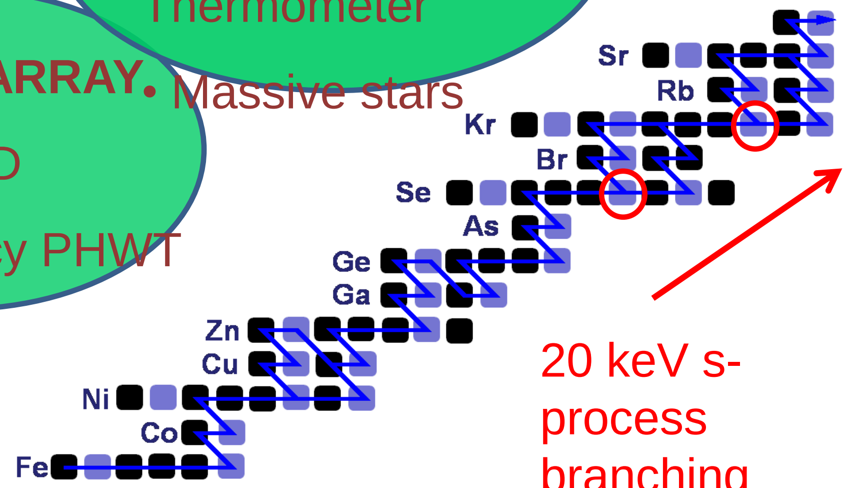
- MC Design
- Neutron ints.

- DEMONSTRATOR
- Proof-of-principle
- PHWT Validation

- FULL ARRAY
- 4π i-TED
- Accuracy PHWT

- First ^{79}Se(n,γ)
- Nuclear Thermometer
- Massive stars

- s-branchings
- i-process & RIBs (FAIR, HIE, SPIRAL2, NFS)
- Hadron-Therapy
- Molecular imaging
- GenIV, ADS



20 keV s-process branching nuclei

ERC-Consolidator Grant

2016 2017 2018 2019 2020 2021

CERN-LS2

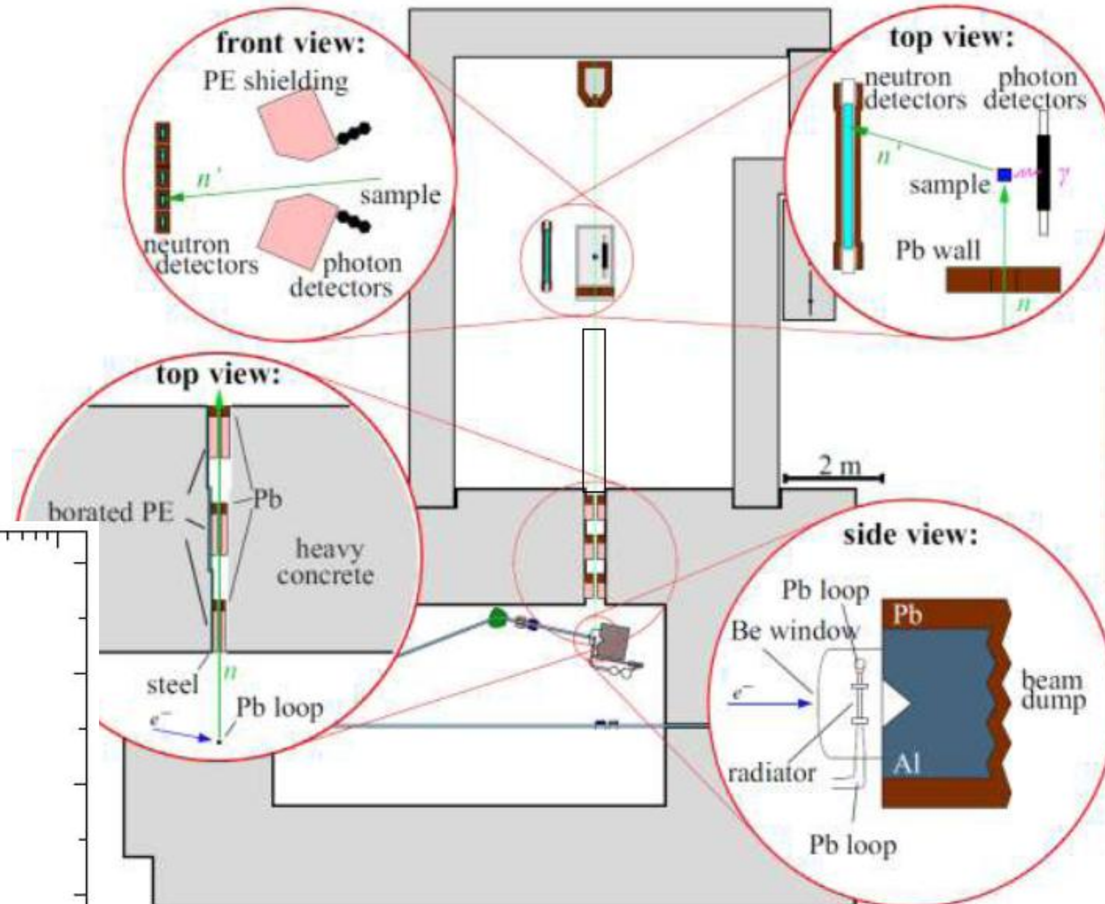
GELINA @ IRMM

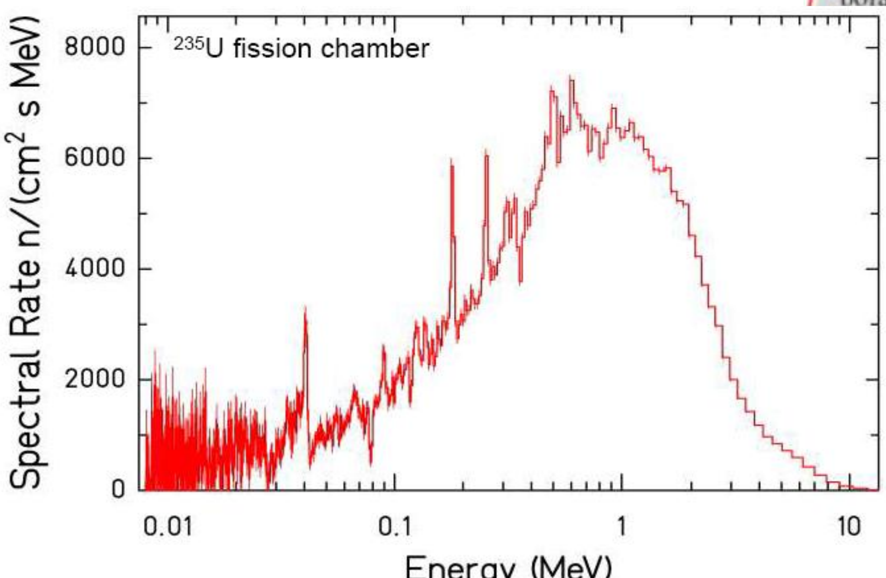
- 140 MeV electron energy
- Δt = 1 ns
- Several flight paths ~ 10 m
- Moderated

F. Corvi et al, BgNS Transactions (2000) 5: 41

nELBE @ FZDR

- 40 MeV electron energy
- Δt = 5 ps
- Fligth path ~ 10 m
- Liquid lead loop

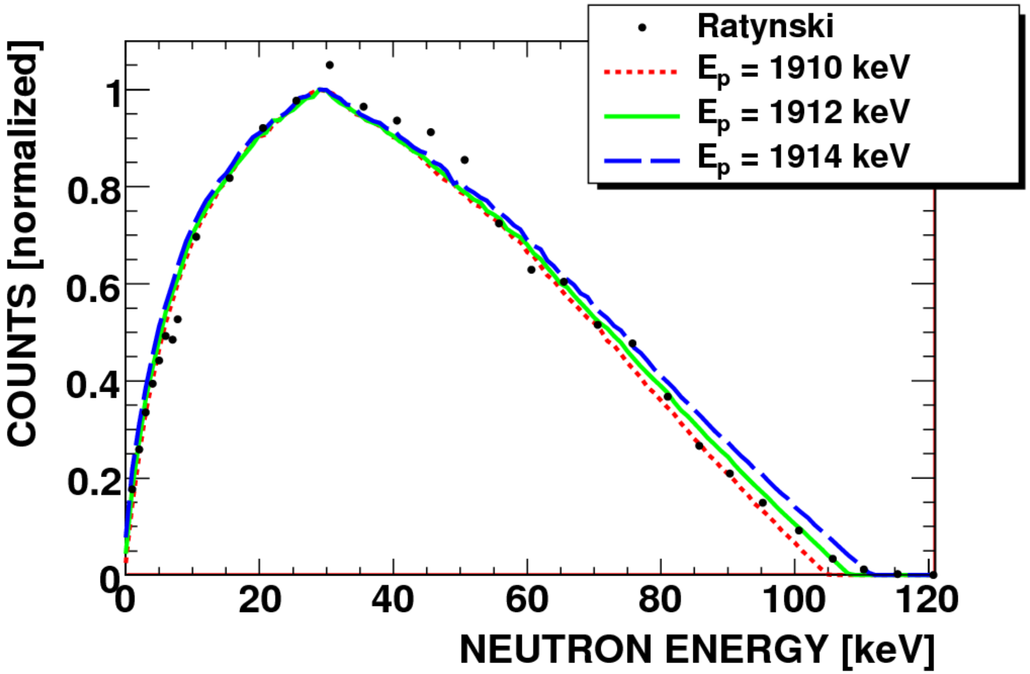


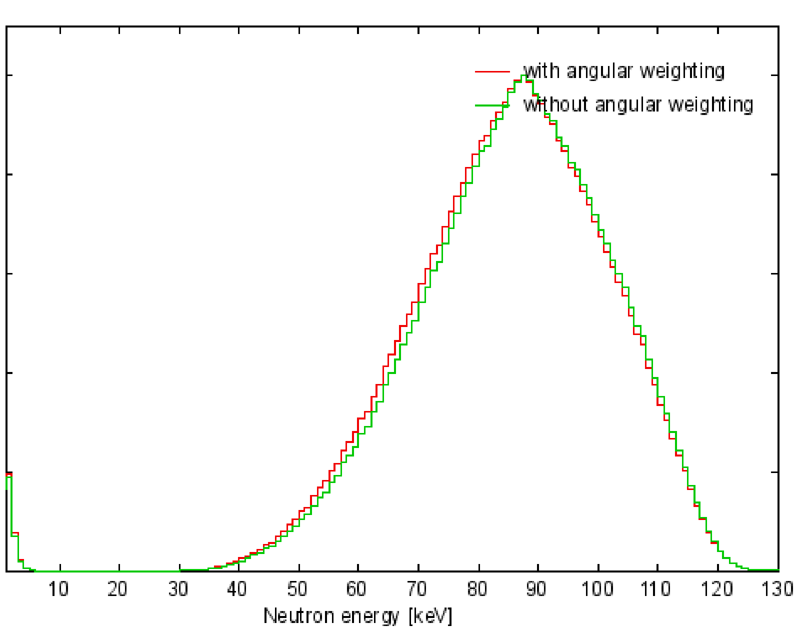


R. Beyer et al, Nucl. Instrum. Methods Phys. Rev. A (2013) 723 151

VdG @ IRMM – $^{7}Li(p,n)$, $^{3}H(p,n)$

- 4 MeV max. proton energy
- Δt = 1 ns
- flight path ~ 1 m





FRANZ @ GUF – ^{7}Li(p,n)

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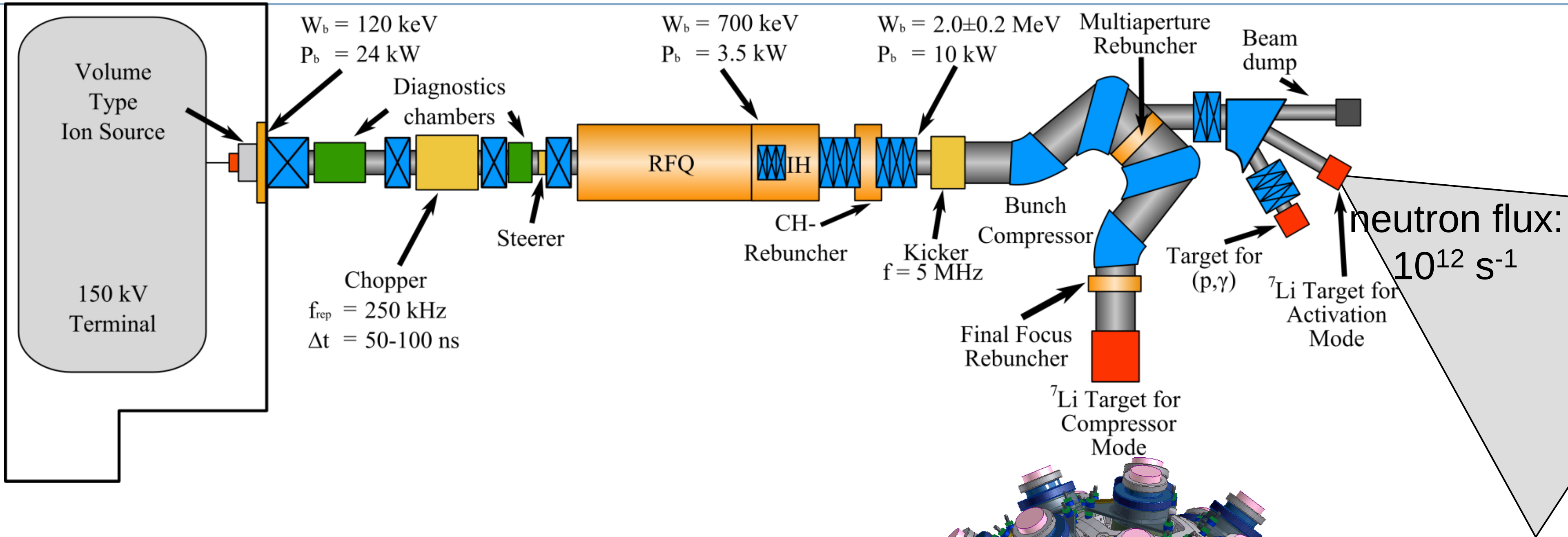
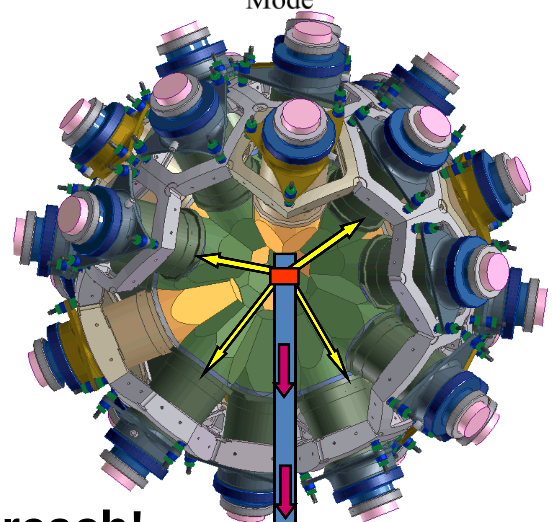
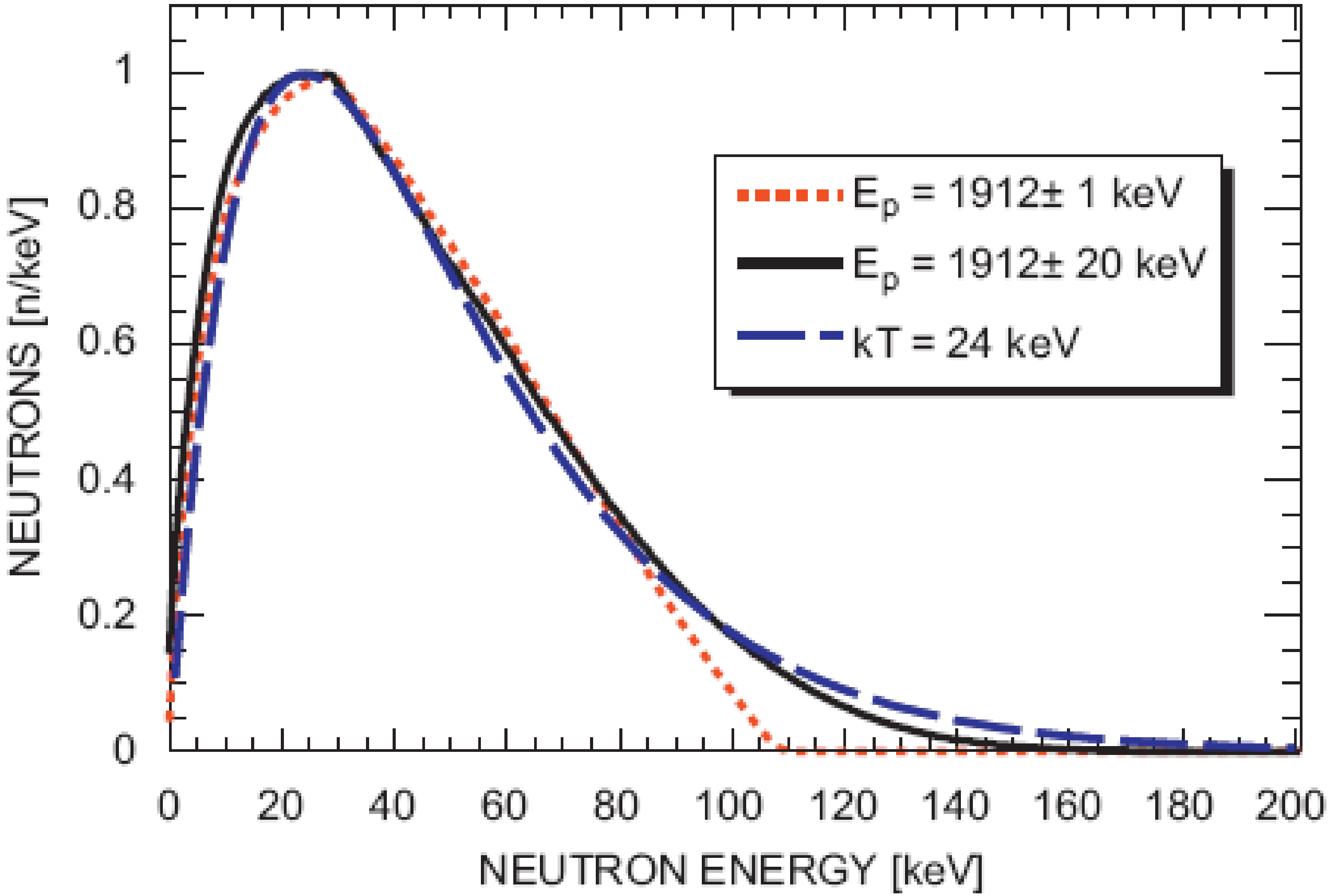




2 mA proton beam (8 A peak current)
250 kHz
< 1ns pulse width
neutron flux at 1 m: 10^7 s^{-1} cm^{-2}
neutron flux at 0.1m: 10^9 s^{-1} cm^{-2}

Isotopes with half-lives down to months are in reach!

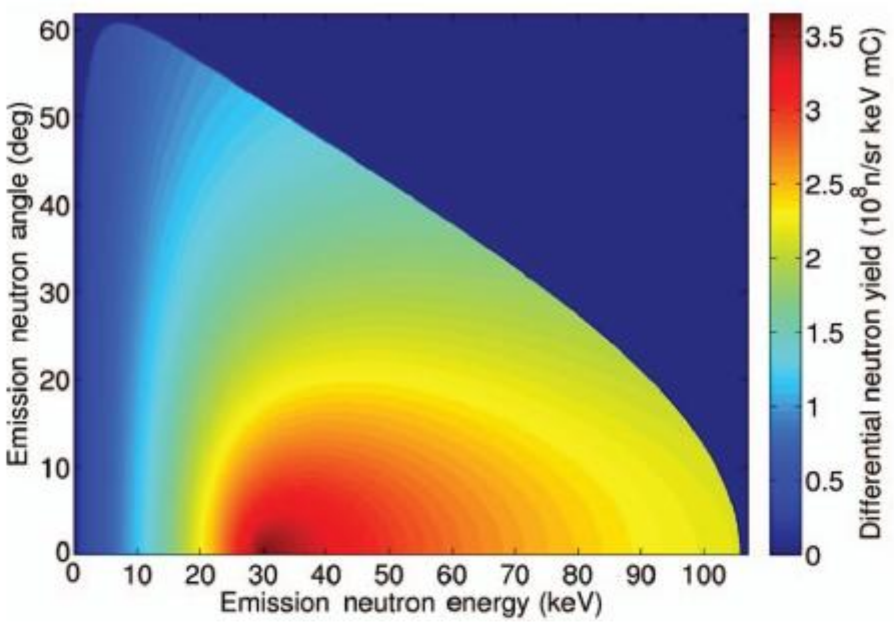
Impact broader proton energy

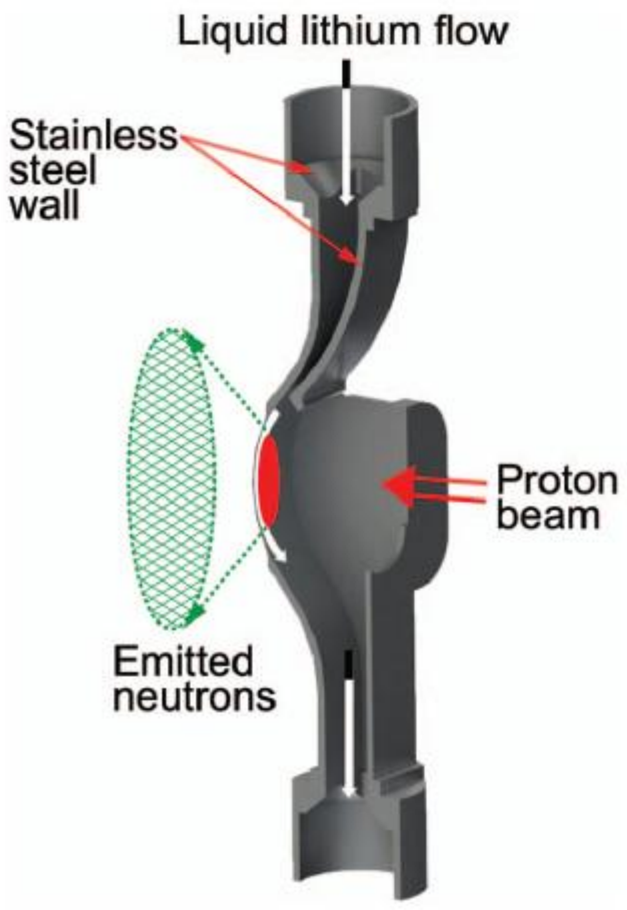


R. Reifarth et al, NIM A 608 (2009) 139

SARAF @ SOREQ

- **no pulsed mode**
- **Liquid lithium loop**
- **2 kW beam power on 6 mm diameter Li target**





S. Halfon et al, REVIEW OF SCIENTIFIC INSTRUMENTS 84, 123507 (2013)

Liquid-Lithium Target (LiLiT): a high-intensity 30-keV quasi-Maxwellian neutron source used for activation measurements

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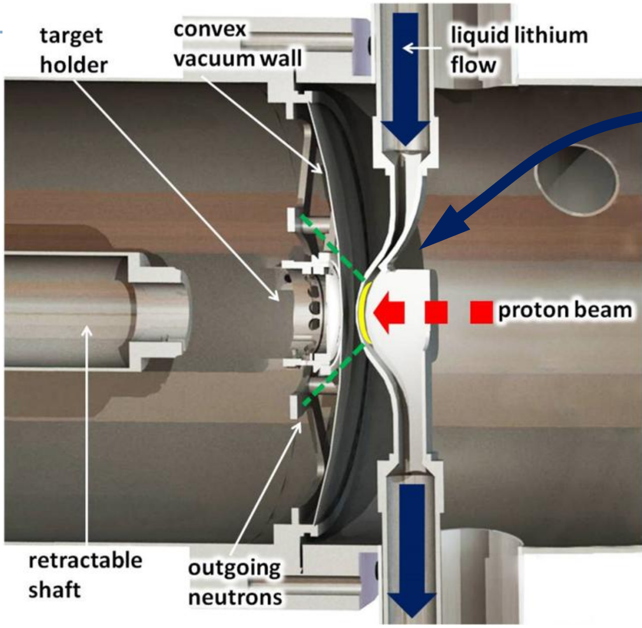
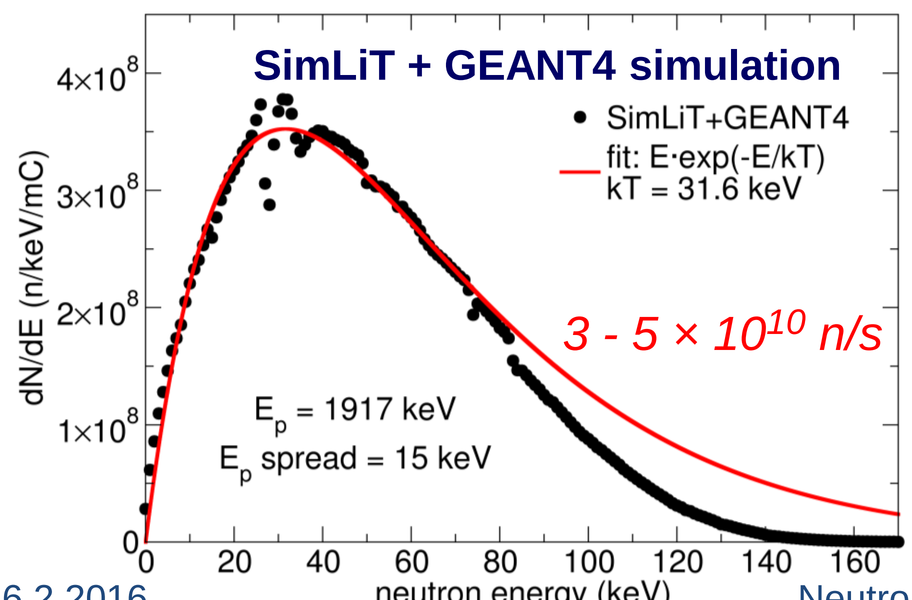
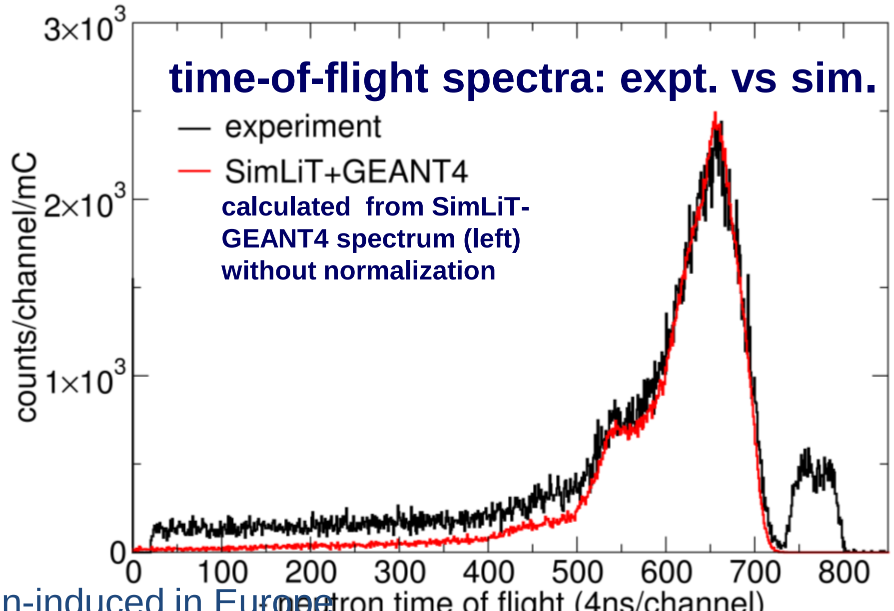


free-surface
liquid lithium target
I_p = 1-2 mA, 1.92 MeV
~ 2-4 kW

S. Halfon *et al.*,
Rev. Sci. Instr. (2013, 2014)

M. Tessler *et al.*
Phys. Lett. B (2015)

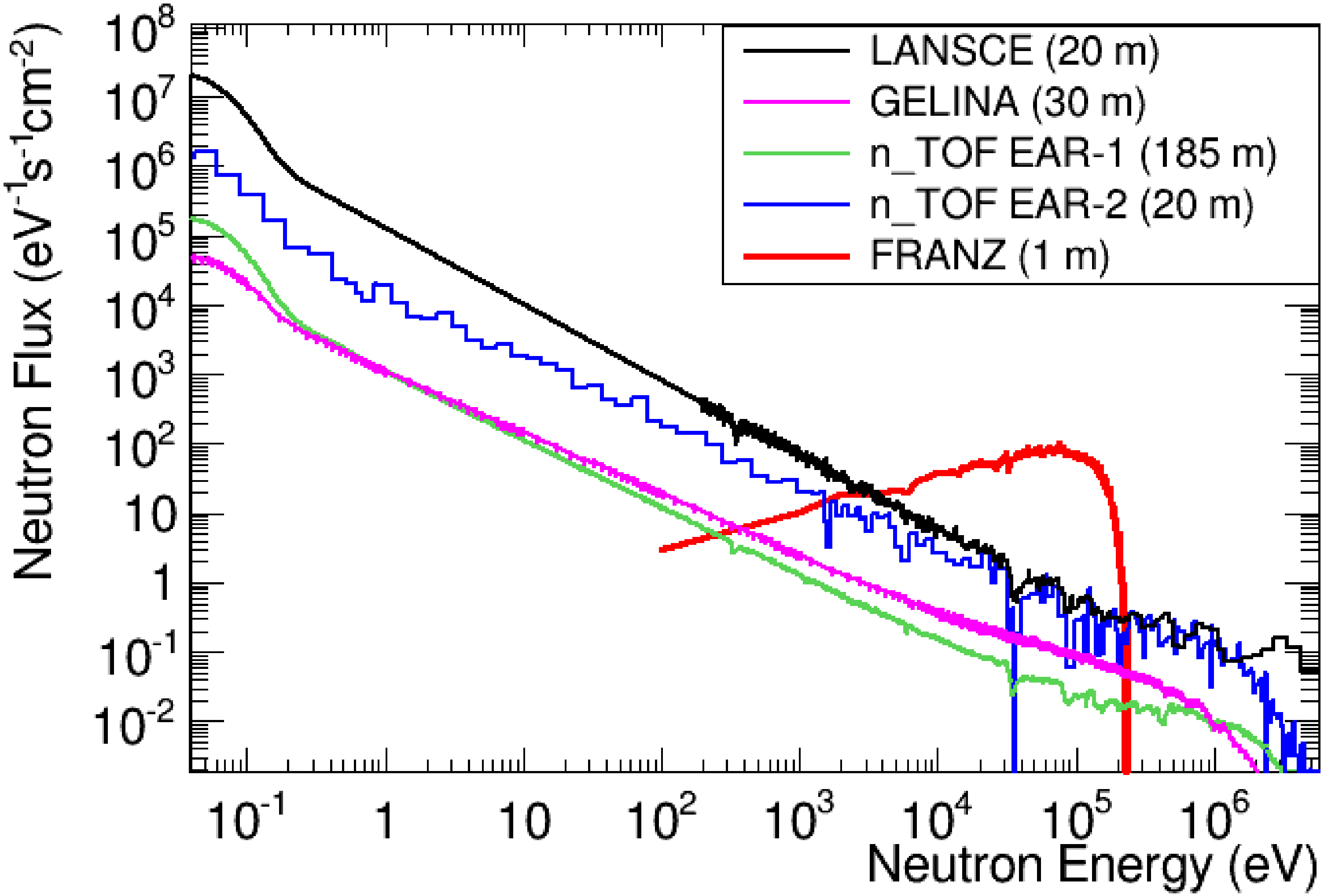




Measurements at SARAF-LiLiT

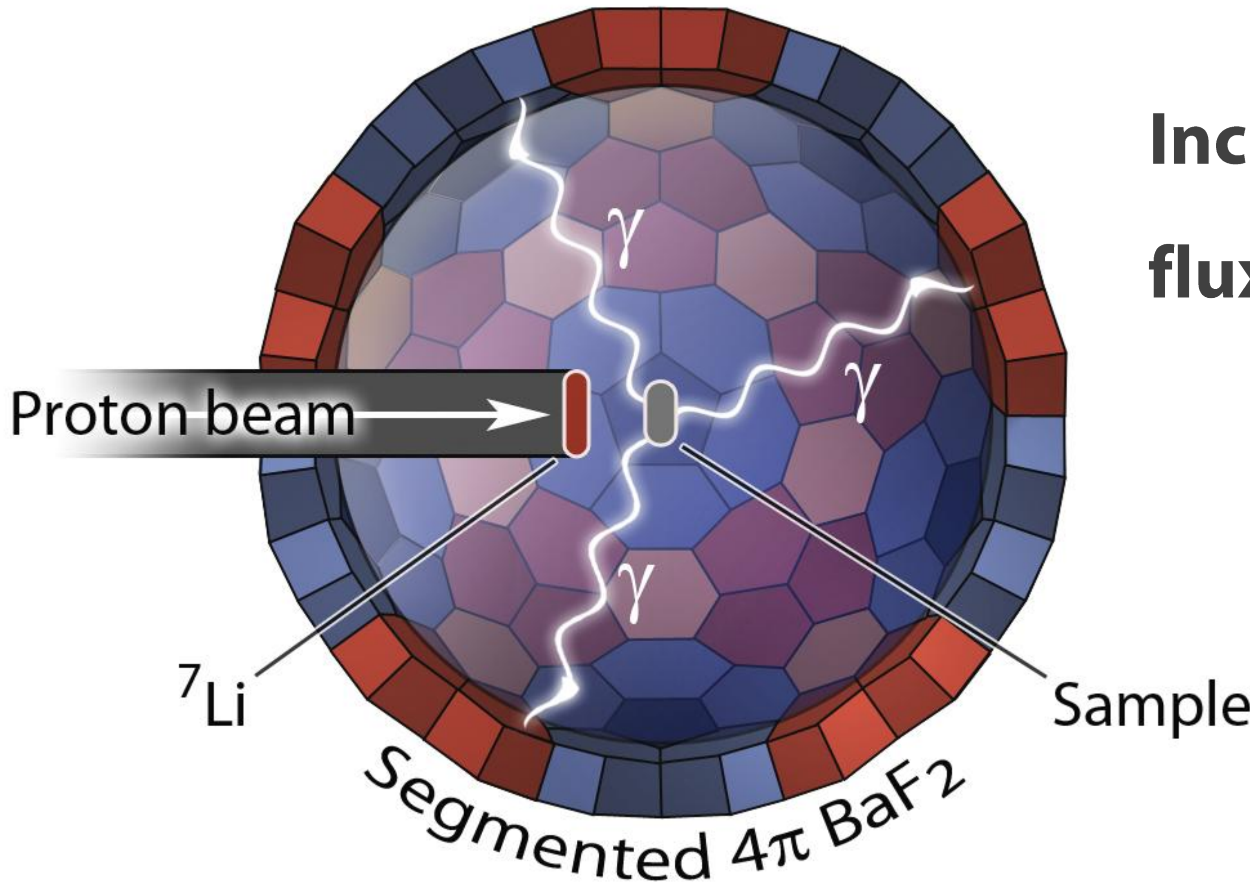
Target	Detection technique	Collaboration HU-SARAF-	status
$^{nat}Zr(n,\gamma)$	γ spec	-	✓
$^{23}Na^{35,37}Cl$ (n,γ)	γ spec + AMS	Goethe U – Rossendorf - ANU	✓
$^{nat}Ce(n,\gamma)$	γ spec	-	in progress
^{nat}Ga	γ spec	-	
^{nat}Se	γ spec	-	
$^{92}Zr(n,\gamma)$	AMS	ANU-ANL	
$^{nat}Kr(n,\gamma)$	γ spec+ β spec + MOT atom trap	ANL - Goethe U - U. Bern	
^{36}Ar, ^{38}Ar, ^{40}Ar (n,γ)	AMS + γ spec	ANL - Goethe U	
^{nat}Xe (n,γ)	γ spec	Goethe U	
$^{209}Bi(n,\gamma)$	α spec + β spec + γ spec	JRC IRMM Geel	
$^{7}Be(n,\alpha)$	CR-39	UConn- PSI–CERN-Weizmann	
$^{147}Pm(n,\gamma)$	γ spec	n-TOF	in plan
$^{171}Tm(n,\gamma)$	γ spec	n-TOF	
$^{nat}Zr(\gamma,n)$	γ spec	-	✓
$^{nat}Mo(\gamma,n)$	γ spec	-	✓

Comparison of fluxes



R. Reifarth et al, J. Phys. G: Nucl. Part. Phys. 41 (2014) 053101

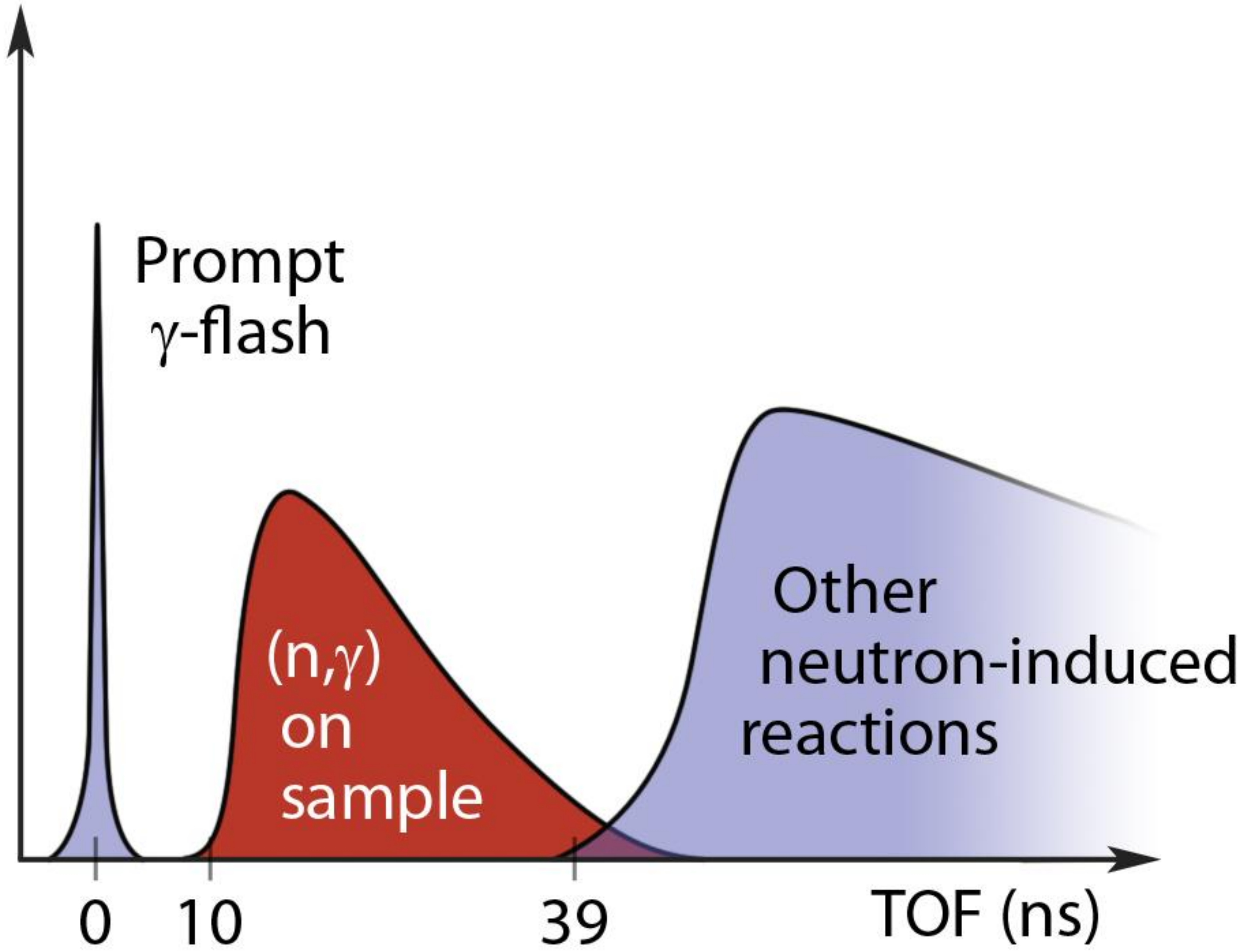
Short flightpath @ FRANZ



Increase neutron flux by factor 100

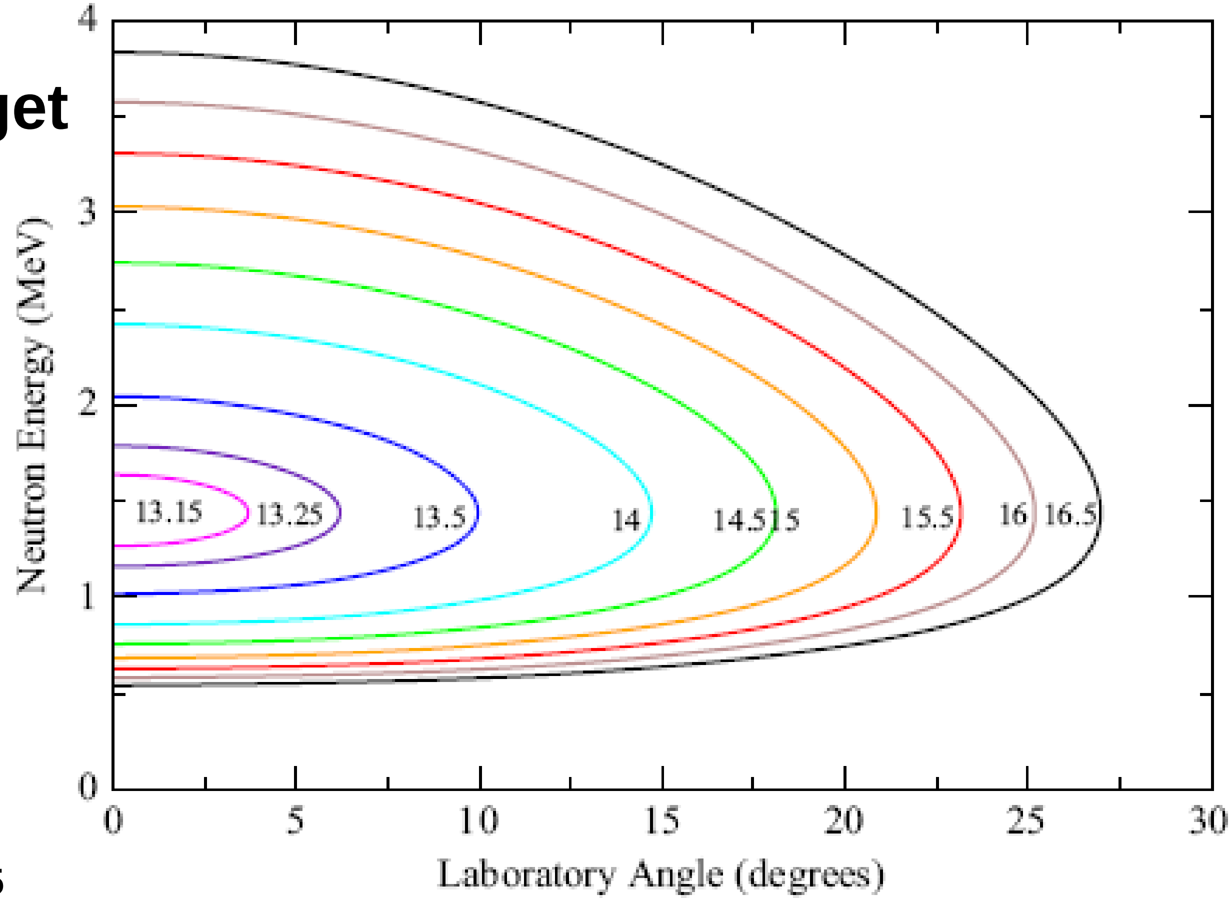
R. Reifarth et al, NIM A 524 (2004) 215

Expected Time-Of-Flight spectrum



LICORN @ Orsay

- $p(^7Li,^7Be)n$
- kinematically focused neutron beam
- under development
- Organic or TiH_2 target



M. Lebois et al, NIM A 735 (2014) 145