The n_TOF Collaboration, www.cern.ch/n_TOF

From Nuclear Astrophysics to Fundamental Nuclear Physics: challenging experimental approaches at *n_TOF* (CERN)

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for the n_TOF collaboration

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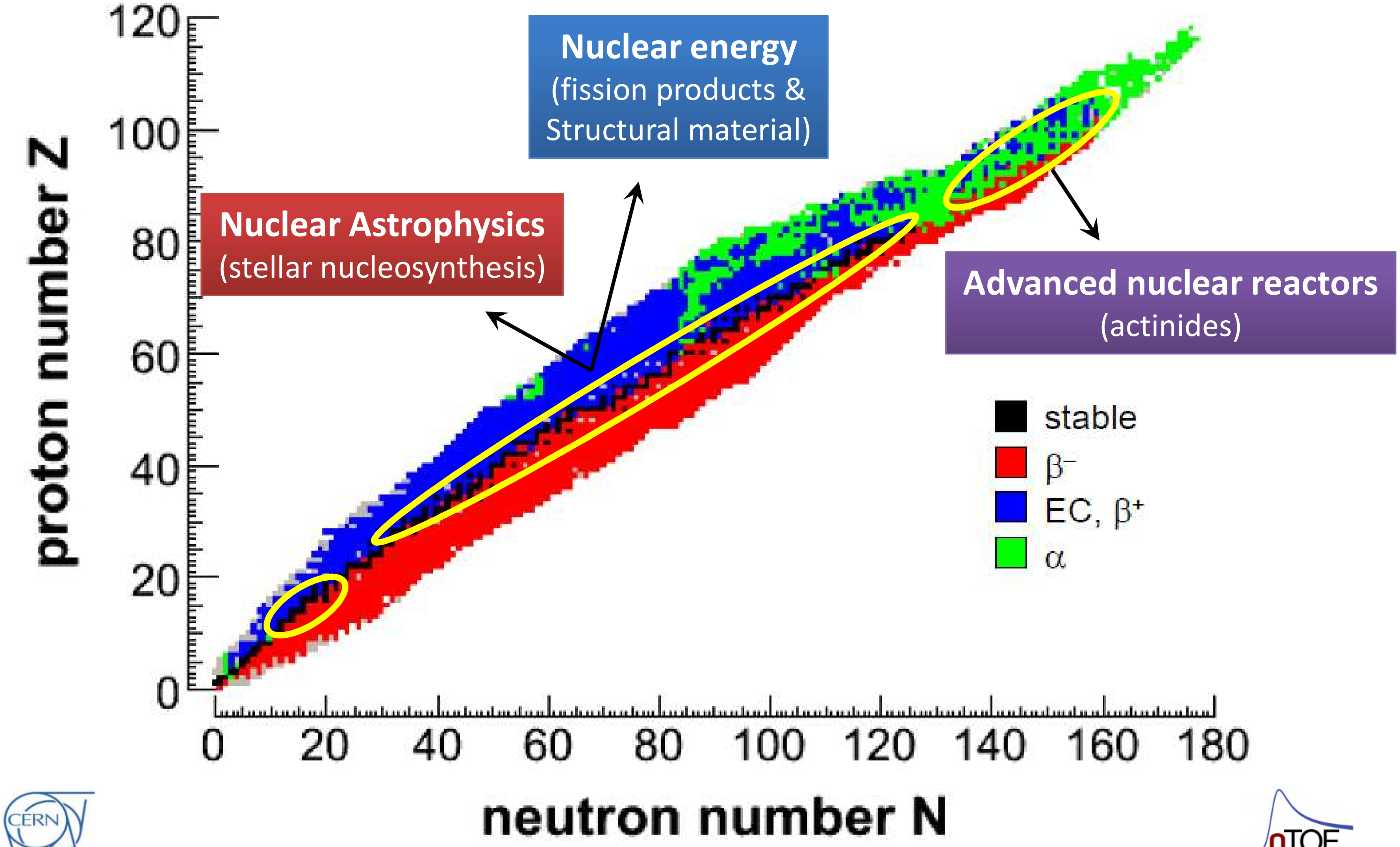
Outline

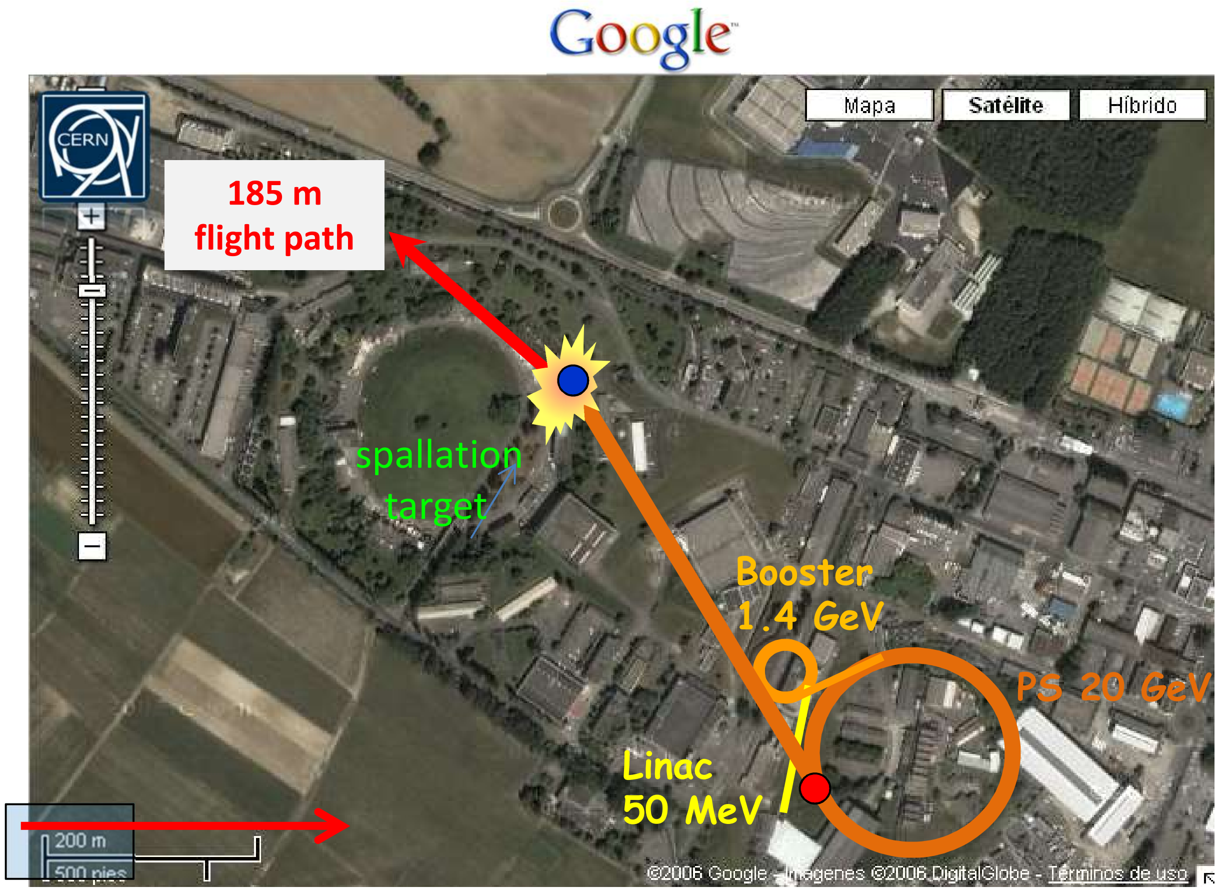
- ***Brief description of the n_TOF facility***
- ***Nuclear Astrophysics $^{7}Be(n,\alpha)$***
- ***Nuclear Physics the $^{2}H(n,p)nn$ (proposal)***
- ***Perspectives***

The story of the n_TOF facility goes back to 1998, when *Carlo Rubbia* and colleagues proposed the idea of building a neutron facility to measure neutron-reaction data needed for the development of an "energy amplifier"

Neutron cross sections



The n_TOF facility at CERN - first generation

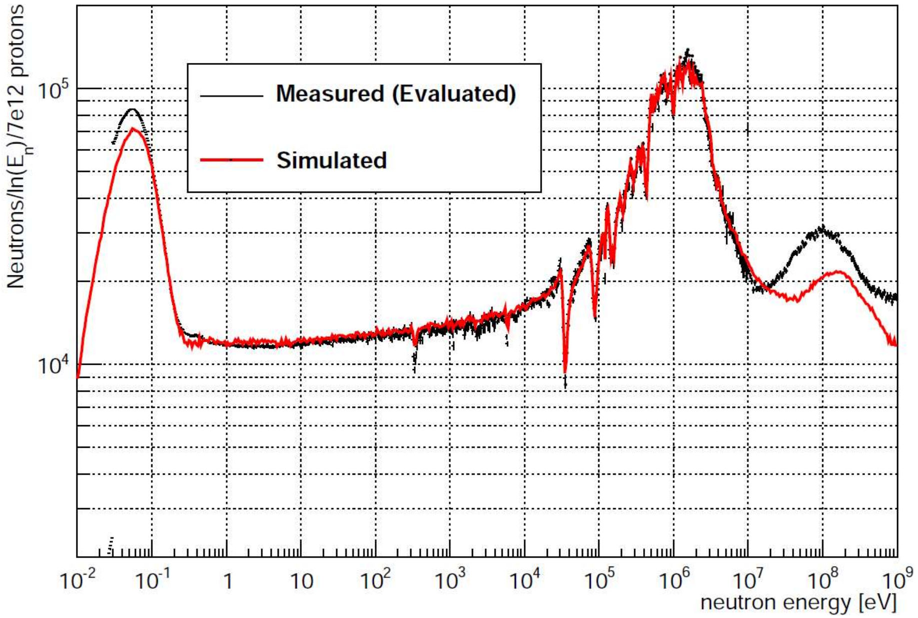


n_TOF is a **spallation** neutron source based on **20 GeV/c protons** from the CERN PS hitting a **Pb block** (~360 neutrons per proton).

Experimental area at **185 m**.

The n_TOF facility

Advantages of the **PS proton beam**: **high energy, high peak current, low duty cycle.**



Main feature: **high instantaneous neutron flux** (*10^6 n/pulse).*

- very convenient for measurements of **radioactive isotopes** (maximizes signal-to-background ratio)
- ideal facility for **actinides** (nuclear technology)

Other features of the neutron beam:

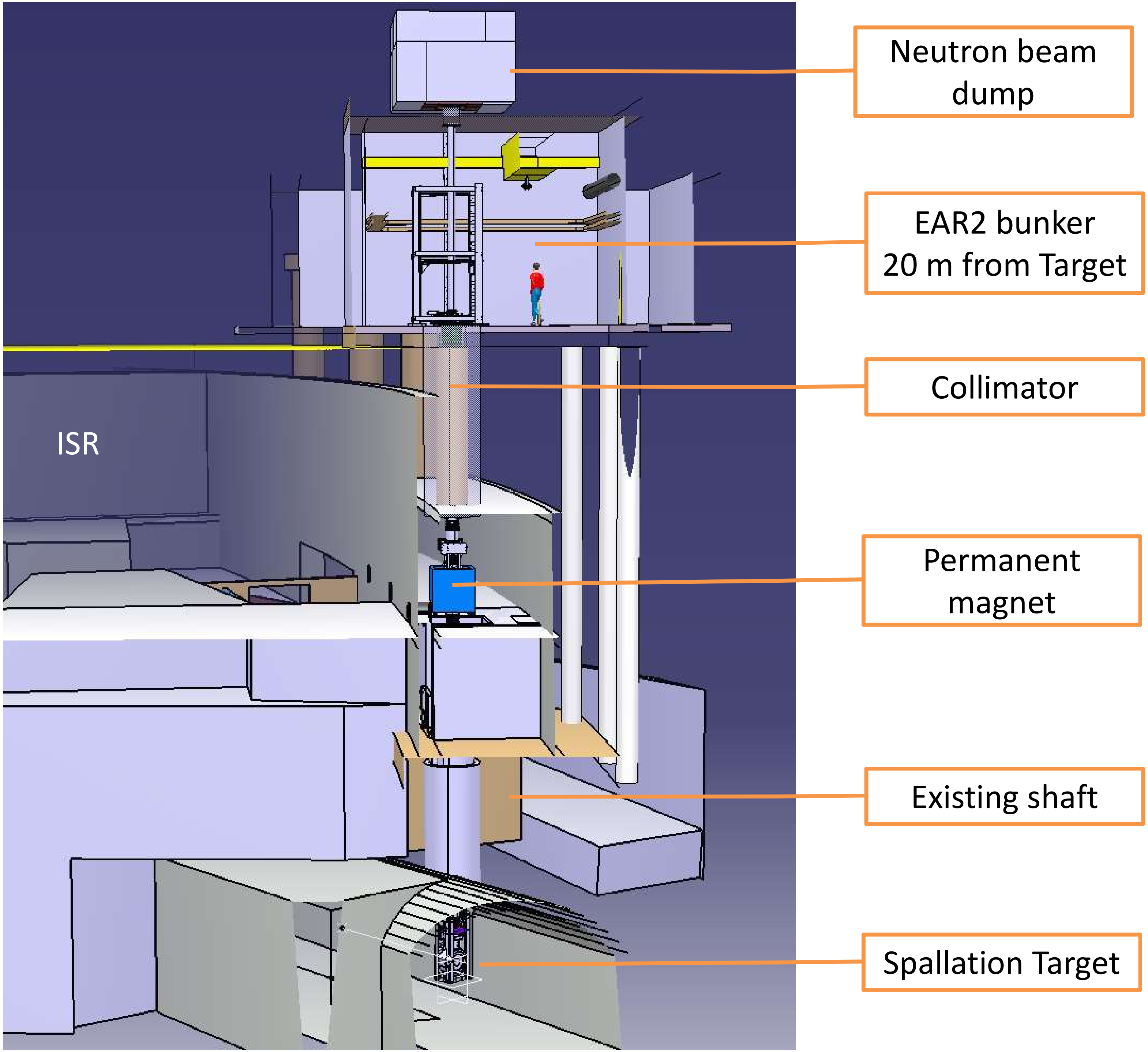
- high **resolution in energy** (*$\Delta E/E = 10^{-4}$*) .... study **resonances**
- wide **energy range** (*25 meV<E_n<1GeV*) .... measure **fission** from thermal to GeV
- low **repetition** rate (*< 0.8 Hz*) .... no **wrap-around**

How to get more intensity

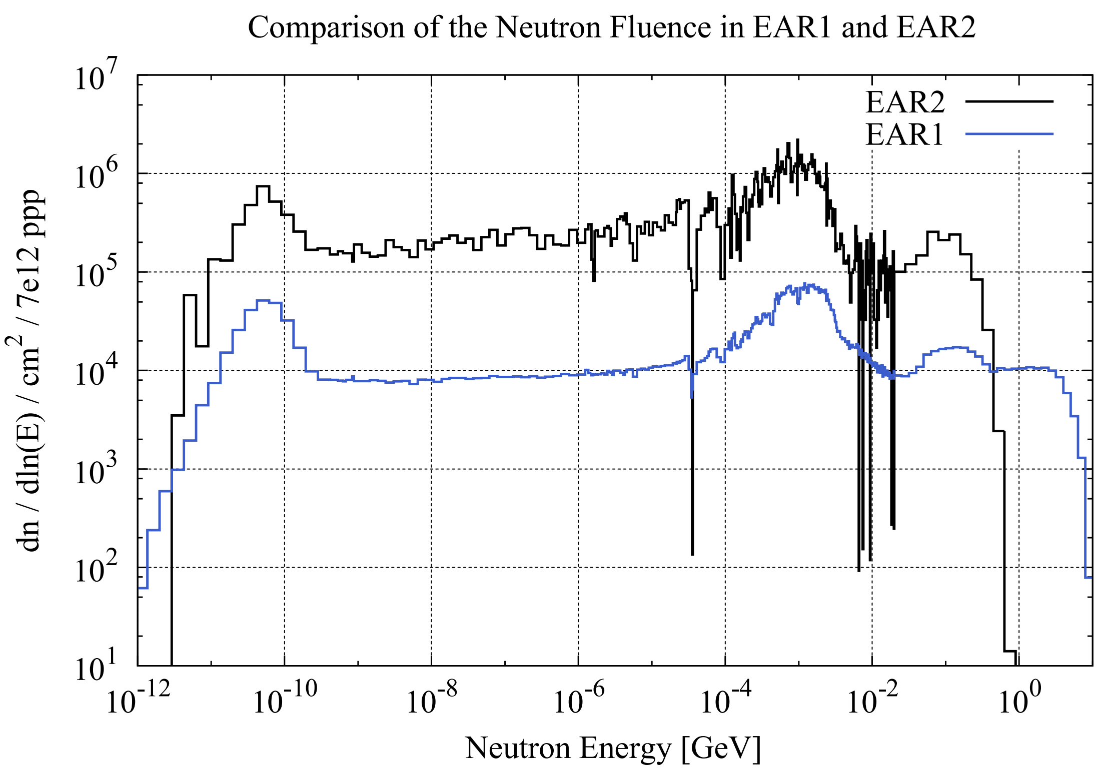
for an huge gain in signal-to-background ratio ?

Make the neutron flight-path shorter

The second experimental area at n_TOF


Neutron beam dump
EAR2 bunker 20 m from Target
Collimator
ISR
Permanent magnet
Existing shaft
Spallation Target

Main features of EAR 2



Higher fluence, by a factor of 25,(*30 exp*) relative to EAR1.

The **shorter flight path** implies a factor of 10 smaller time-of-flight.

Global gain by a factor of **250 in the signal/background ratio** for radioactive isotopes!

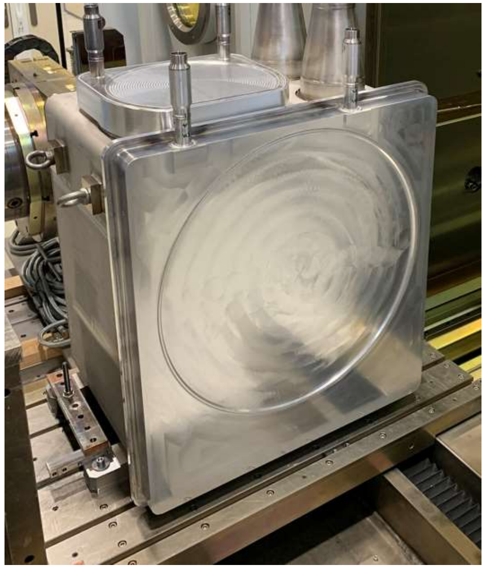
The gain in signal-to-background ratio in EAR2 allows to measure radioactive isotopes with **half lives as low as a few years.**

^{7}Be(n,α) and ^{7}Be(n,p) measurements (Big-Bang Nucleosynthesis)

spokesperson A. Musumarra, M. Barbagallo

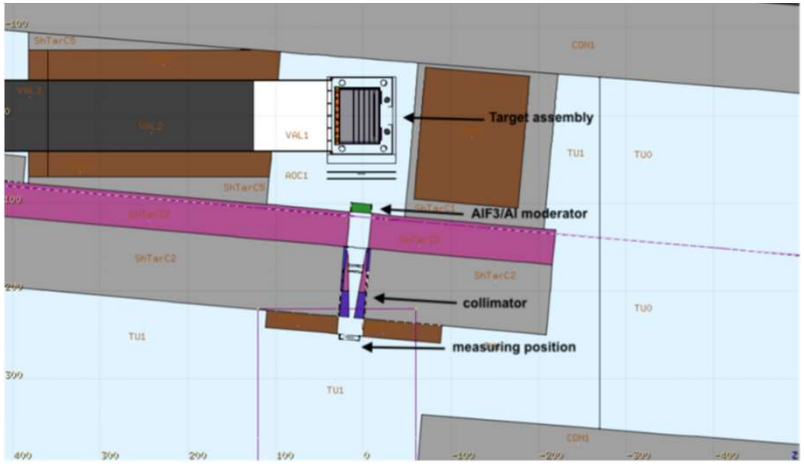
After ten years of service

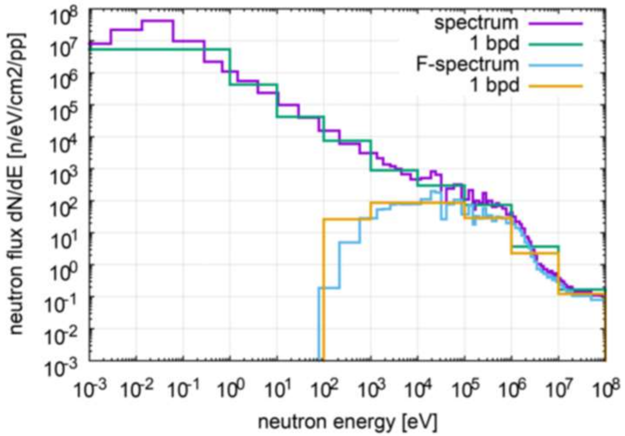
The new spallation source and the NEAR station



3rd generation n_TOF spallation target
work of Marco Calviani and coll.

The new target houses an additional water moderator tank on its top, that will improve the resolution of the measurements of a neutron's time of flight in the vertical flight path. Overall it further improves the physics performance of the facility.





Activation measurements are now possible by a quasi-maxwellian *n*-spectrum

The *Cosmological Lithium Problem* and the Measurement of the ^{7}*Be(n,alpha)* Reaction at *n_TOF*-CERN.

Agatino Musumarra and Massimo Barbagallo

for the n_TOF@CERN Collaboration

DFA-University of Catania, INFN-Laboratori Nazionali del Sud
INFN-Bari

Bing Bang Nucleosynthesis

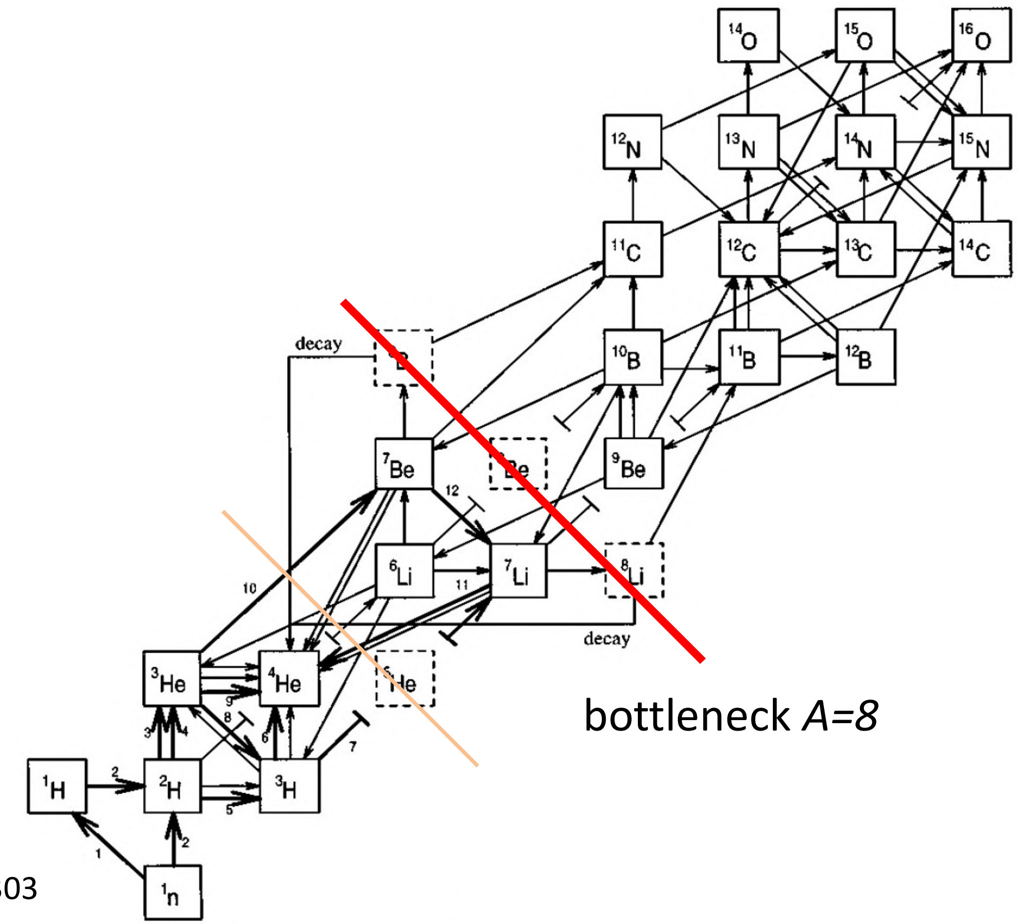
Bing Bang Nucleosynthesis (BBN), together with Hubble expansion and Cosmic Microwave Background Radiation is one of the cornerstones for Bing Bang Theory.

BBN gives the sequence of nuclear reactions leading to the synthesis of light elements up to Na* in the early stage of Universe (0.01-1000 sec)

At his first formulation, it depended on 3 parameters:

- -the baryon-to-photon ratio η,
- -the number of species of neutrino ν,
- -the lifetime of neutron τ.

Nowadays **BBN is a parameter free theory****, being the **cross-sections** of reactions involved the only input to the theory.



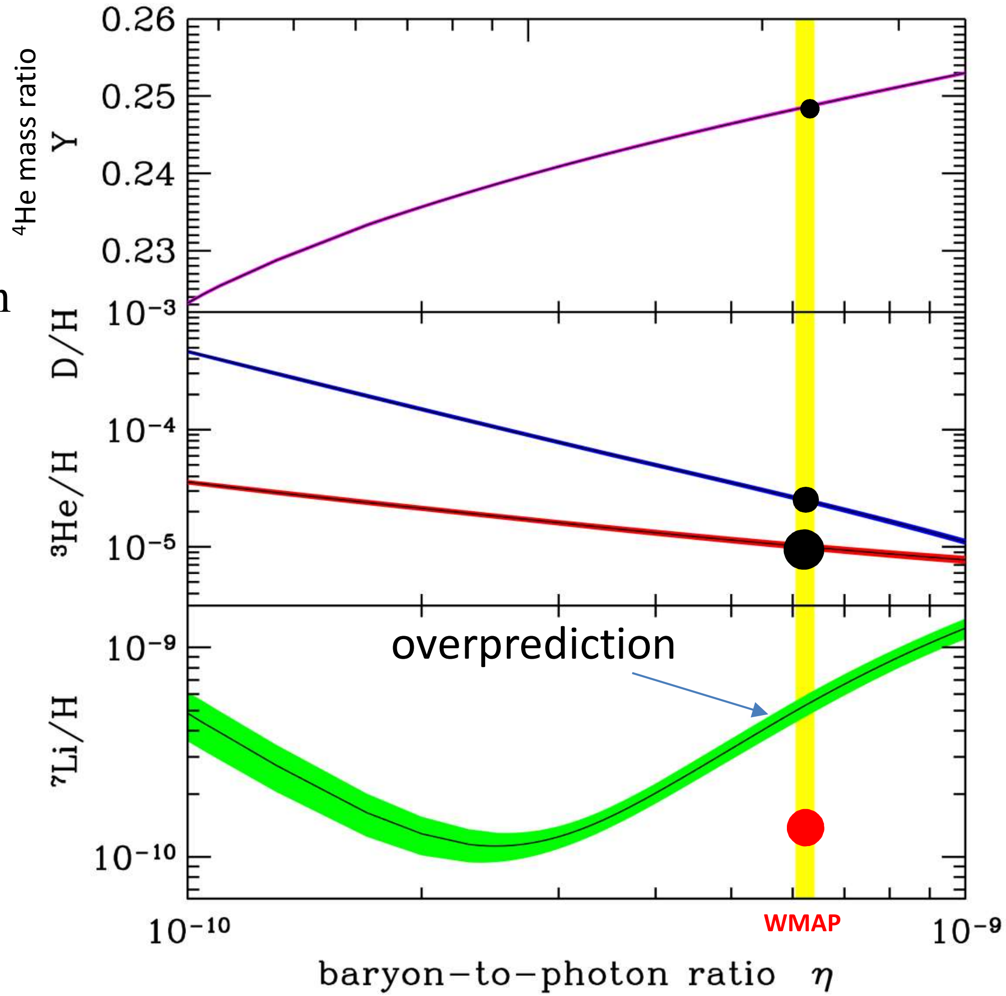
* A.Coc et al., The Astrophysical Journal, 744:158 (2012)
**D.N. Schramm and T.S Turner, Rev. Mod. Phys 70 (1998) 303

The Cosmological Lithium Problem

BBN successfully predicts the abundances of primordial elements such as ^{4}He, D and ^{3}He.

A serious discrepancy (factor 2-4) between the predicted abundance of **^{7}Li** and the value inferred by measurements (Spite et al, many others.)

Cosmological Lithium Problem (CLiP)



* R.H.Cyburt et al., Journal of Cosmology and Astroparticle Physics 11 (2008) 012

** A.Coc et al., The Astrophysical Journal, 744:158 (2012)

Solution to CLiP?

Approximately 95% of primordial ^{7}**Li** is produced from the Electron Capture *decay* of ^{7}***Be*** ($T_{1/2}$=53.2 d ?).

A higher destruction rate of ^{7}Be can solve or at least partially explain the **CLiP.**

^{7}Be is destroyed via **(n,p)** **(~97%)** and **(n,α)** **(~2.5%)** reactions

$n + {}^{7}Be \longrightarrow p + {}^{7}Li \quad Q = 1.644\ MeV$

$n + {}^{7}Be \longrightarrow \alpha + \alpha \quad Q = 19\ MeV$

150 mb @ 25 meV (Bassi 1963)

^{7}Be(n,p)^{7}Li total cross section from 25 meV to 13.5 keV

P. E. Koehler, C. D. Bowman, F. J. Steinkruger, D. C. Moody, G. M. Hale,
J. W. Starner, S. A. Wender, R. C. Haight, P. W. Lisowski, and W. L. Talbert
Los Alamos National Laboratory, Los Alamos, New Mexico 87545
(Received 17 August 1987)

The total ^{7}Be(n,p)^{7}Li cross section has been measured from 25 meV to 13.5 keV. These energies correspond to temperatures of $T=2.9\times10^{-7}$ to 0.16 GK. For thermal neutrons the cross sections to the ground state (p_0) and the first excited state (p_1) of ^{7}Li are 38 400±800 b and 420±120 b, respectively. This result for the total ^{7}Be(n,p)^{7}Li thermal cross section is about 25% lower, and is approximately a factor of 10 more precise than previous published measurements. For energies above 100 eV, a significant departure from a $1/v$ shape for the total cross section is observed. The data were analyzed using a single-level approximation, and were also analyzed together with other data using multilevel-multichannel R-matrix theory. Results are presented for the properties of the 2^- threshold state and for a possible nearby 2^- state. The astrophysical reaction rate, $N_A\langle\sigma v\rangle$, was calculated from the measured cross sections for the combined p_0 and p_1 transitions. The resulting reaction rate is approximately 60–80% of the rate currently in use. This reduction in the ^{7}Be(n,p)^{7}Li reaction rate could result in a calculated increase in the production of ^{7}Li during the big bang by as much as 20%.

Phys. Rev. C 37(1988) 917

The Reaction ^{7}Be(n, α)^{4}He and Parity Conservation in Strong Interactions (*).

P. Bassi, B. Ferretti and G. Venturini
Istituto di Fisica dell'Università - Bologna
Istituto Nazionale di Fisica Nucleare - Sezione di Bologna

G. C. Bertolini, F. Cappellani, V. Mandl, G. B. Restelli and A. Rota
C. C. R. EURATOM - Ispra

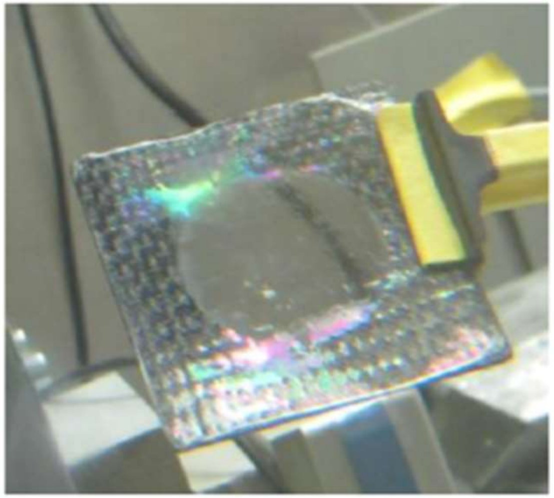
Summary. — We have studied experimentally the reactions ^{7}Be(n, α)^{4}He and ^{7}Be(n, γα)^{4}He, produced by thermal neutrons. We have established an upper limit for the first of the two: $\sigma_1\leqslant0.1$ mb. For the second one we have found $\sigma_2=155$ mb. The limit for σ_1, in the hypothesis of (2^-) attribution to the 18.9 MeV level of ^{8}Be, corresponds to $F^2\leqslant4.10^{-10}$, where F is the ratio of the amplitudes of the opposite parity wave functions. This result is used to put an upper limit to the strength of a possible parity-violating interaction involving strange particles.

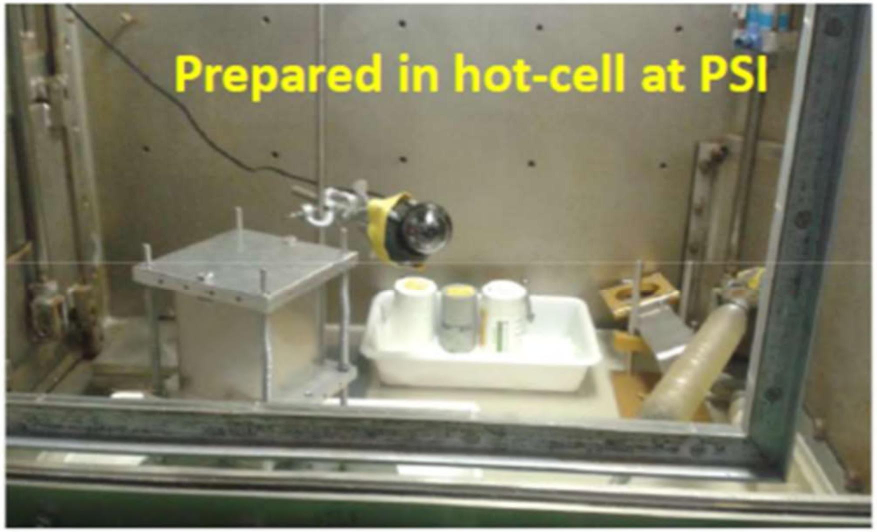
Il Nuovo Cimento XXVIII (1963)1049

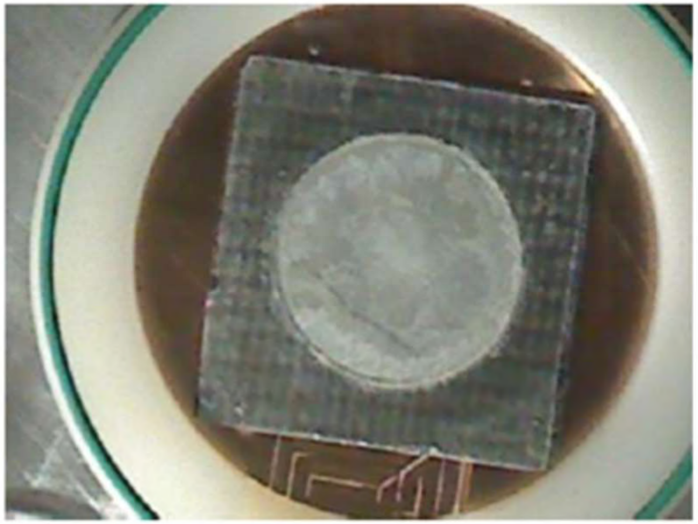
^{7}Be available at PSI-Zurich !

2 different samples: Molecular plating
(3.5 μg total mass) Vaporization of droplets

	Vaporization	Molecular Plating
Backing	Stretched PE (0.6 μm)	Aluminum (5 μm)
Activity	20 GBq	19 GBq
Diameter	30 mm	31.6 mm







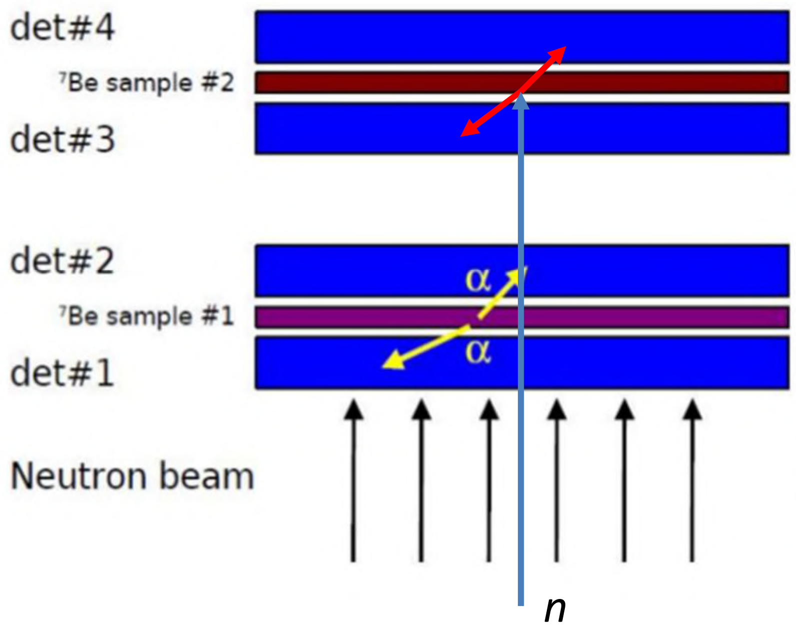
Thanks to E. Maugeri, S. Heinitz, D. Schumann (PSI Villigen)

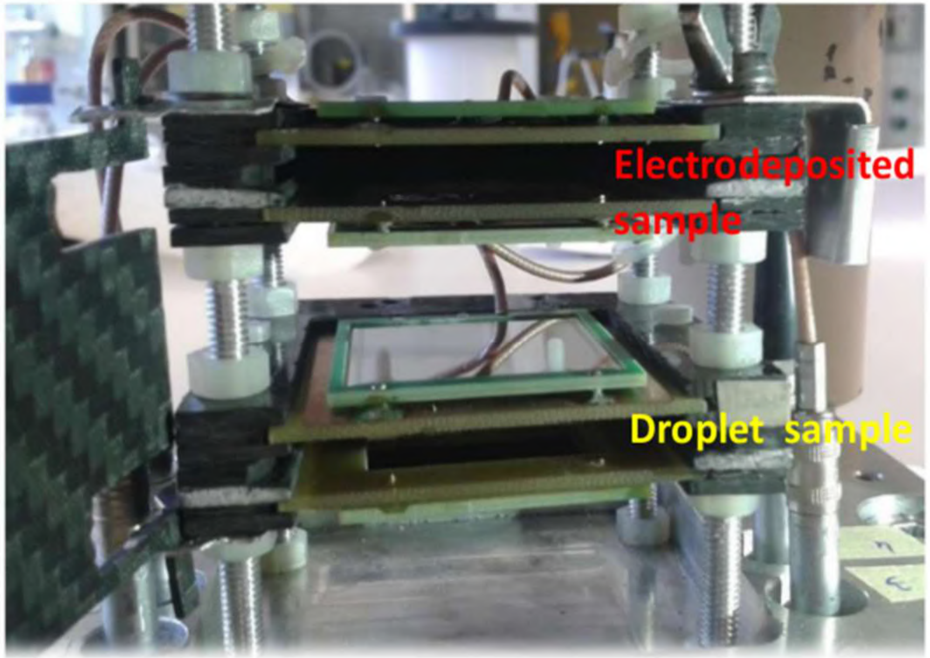
Experimental setup

Silicon detectors directly inserted in the beam (3x3 cm^2 active area, 140 μm thickness)

Detection of high energy α-particles

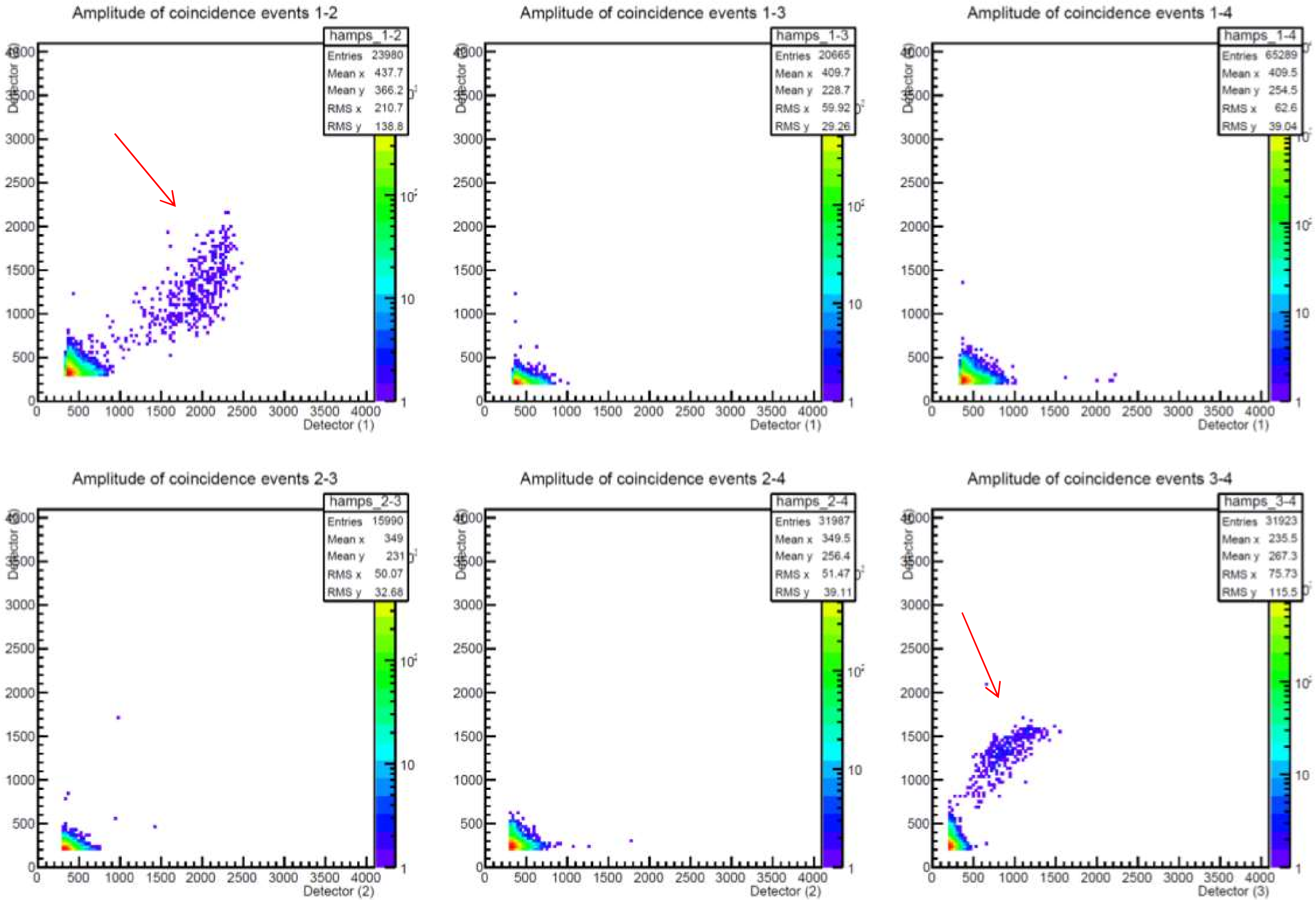
Strong rejection of background (sample preparation)





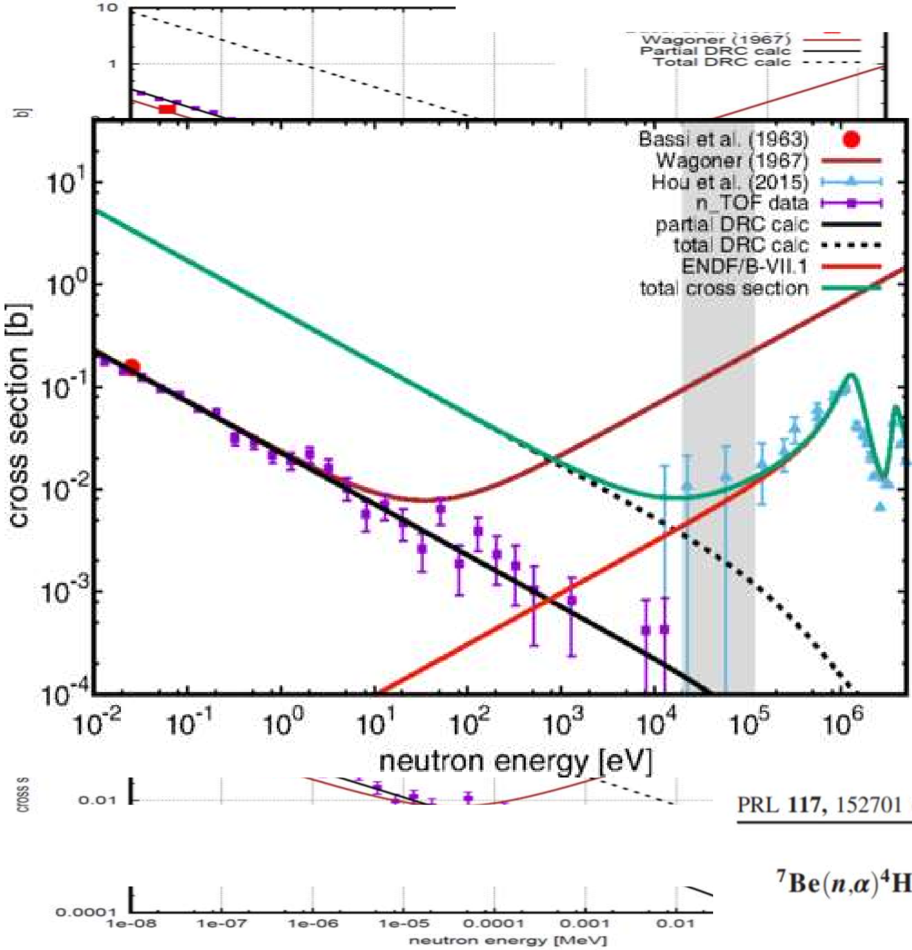
The double alpha signature is the key ***capability of the Si-detector to survive***

^{7}Be(n,α) data analysis



Possible to evaluate random coincidences comparing uncorrelated couples of detectors

Impact on Cosmological Lithium Problem



the cross section in a wide energy range at n_TOF (CERN)

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(The n_TOF Collaboration (www.cern.ch/ntof))
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[2] Dipartimento di Fisica e Astronomia DFA, Università di Catania and INFN-Laboratori Nazionali del Sud, Catania, Italy
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[5] Karlsruhe Institute of Technology (KIT), Institut für Kernphysik, Karlsruhe, Germany
[6] ENEA, Bologna, Italy
[7] CERN, Geneva, Switzerland

for submission to PRL

BBN calculations. Although new measurements at present results hint to a minor role of this reaction Lithium problem unsolved.

mological Lithium Problem

The ^{7}Be$(n,\alpha)^4$He reaction and the Cosmological Lithium Problem: measurement of the cross section in a wide energy range at n_TOF (CERN)

M. Barbagallo,[1] A. Musumarra,[2] L. Cosentino,[3] E. Maugeri,[4] S. Heinitz,[4] N. Colonna,[1,*] F. Käppeler,[5] P. Finocchiaro,[3] A. Mengoni,[6] D. Schumann,[4] L. Damone,[1] O. Aberle,[7] S. Altstadt,[8] J. Andrzejewski,[9] L. Audouin,[10] M. Bacak,[11] S. Barros,[12] V. Bécares,[13] F. Bečvář,[14] F. Belloni,[15] E. Berthoumieux,[16] J. Billowes,[17] V. Boccone,[7] D. Bosnar,[18] M. Brugger,[7] M. Calviani,[7] F. Calviño,[19] D. Cano-Ott,[13] C. Carrapiço,[12] F. Cerutti,[7] E. Chiaveri,[7] M. Chin,[7] G. Cortés,[19] M.A. Cortés-Giraldo,[20] M. Diakaki,[21] C. Domingo-Pardo,[22] R. Dressler,[4] I. Duran,[23] C. Eleftheriadis,[24] A. Ferrari,[7] K. Fraval,[16] S. Ganesan,[25] A.R. García,[13] G. Giubrone,[22] M.B. Gómez-Hornillos,[19] I.F. Gonçalves,[12] E. González-Romero,[13] E. Griesmayer,[11] C. Guerrero,[7] F. Gunsing,[16] P. Gurusamy,[25]

PRL 117, 152701 (2016) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2016

^{7}Be$(n,\alpha)^4$He Reaction and the Cosmological Lithium Problem: Measurement of the Cross Section in a Wide Energy Range at n_TOF at CERN

Paper sent to Editorial Board to get approval for submission to PRL

of the cross section estimates currently used in BBN calculations. Although new measurements at higher neutron energy may still be needed, the present results hint to a minor role of this reaction in BBN, leaving the long-standing Cosmological Lithium problem unsolved.

The n-n scattering lenght

CERN-INTC-2020-051 / INTC-I-220
21/09/2020

Measurement of the neutron-neutron scattering length at the CERN n_TOF facility

September 21, 2020

D.M. Castelluccio[1,2], P. Console Camprini[1,2], M. Diakaki[3], Z. Eleme[4], P. Finelli[1,5], A. Junghans[6], M. Kokkoris[3], A. Manna[1,5], C. Massimi[1,5], P. Mastinu[1], M. Mastromarco[1], P.M. Milazzo[1], A. Musumarra[1,7], N. Patronis[4], M.G. Pellegriti[1], E. Stamati[4], N. Terranova[1,2], G. Vannini[1], R. Vlastou[3], R. Zannoni[5], and the n_TOF Collaboration[8]

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[7] *Dipartimento di Fisica ed Astronomia, Università di Catania, Catania, Italy*
[8] *www.cern.ch/n_TOF*

Spokespersons: C. Massimi (massimi@bo.infn.it), A. Musumarra (musumarra@lns.infn.it), N. Patronis (npatronis@uoi.gr)
Technical coordinator: O. Aberle (oliver.aberle@cern.ch)

The n-n scattering length

Charge symmetry breaking and Nucleon-Nucleon force investigation

n + n cross section, cannot be measured due to the unavailability of a free neutron target.

It has been long realised that the neutron-neutron (*nn*) cross section, or more generally the *nn* interaction, as a function of energy can be studied only through reactions with two neutrons in the final state, such as:

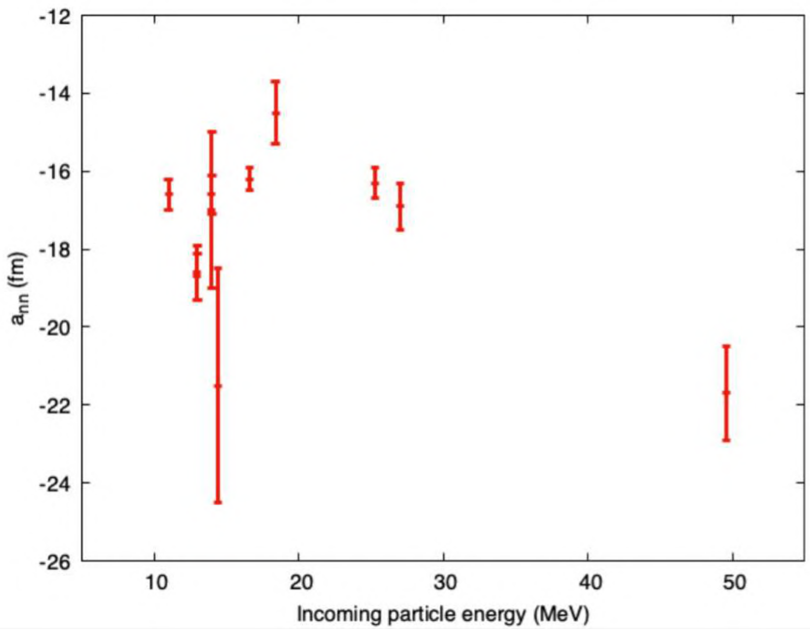
$$\pi^- + {}^2H \rightarrow n + n + \gamma$$

$$n + {}^2H \rightarrow n + n + p$$

n_TOF proposal

- determination of the *n-n* scattering length in a wide energy range *10-100 MeV*

-contextual *n-p* scattering length measurement



The new experiment proposal will be based on:

detection of the three outgoing particles in kinematic coincidence, leading to a full three-body kinematic reconstruction

Proton trigger in an **active target** to suppress random, providing also a time reference

Challenging measurement

- ***Experimental technique:*** ***detection efficiency and n-momentum reconstruction***
- ***low cross-section at high n-energies***

-But high-gain: **first wide energy range *n-n* scattering-length measurement (1-100 MeV) after five decades of efforts**

In 2006 the *n-TOF* Collaboration already submitted a proposal (INTC-P-204) for a measurement of the neutron-neutron scattering length.

Scientific Committee Paper

CERN-INTC-2006-006 ; INTC-P-204

Proposed study of the neutron-neutron interaction at the CERN nTOF facility

Assimakopoulos, Panayotis

Assimakopoulos, P A (spokesperson) (Univ. Ioannina) ; Vlachoudis, V (resp.) (CERN) ; Eleftheriadis, C ; Galanopoulos, S ; Harissopoulos, S V ; Ioannides, K G ; Karadimos, D ; Karamanis, D ; Kokkoris, M ; Lagoyannis, A ; Lamboudis, C ; Papachristodoulou, C ; Papadopoulos, C T ; Patronis, N ; Perdikakis, G ; Savvidis, E ; Vlastou, R

Work in progress (LoI and experimental set-up)

Active Target Scintillators (Stilbene) and SiPM sensors already under test:

1) *Experimental task: LoI*

setup and test of the first *n*-TOF Active target

- *Information on γ-flash response and related determination of the highest neutron energy that can be reached*
- *background characterization rate induced by the neutron beam in the active target and detectors (very high rate)*

2) *Experimental task: final proposal*

new detection technique for *n*-momentum reconstruction with high efficiency → «Blended» Spin-Off *Bologna & Catania* ***Joining HEP + NP skills***

several application fields

«RIPTIDE»
***R**eco**I**l-**P**roton **T**rack **I**maging **DE**tector*

C. Massimi(UNIBO)
M. Villa (UNIBO) ***PI***
R. Spighi (INFN-BO)
F. Romano(INFN-CT)
M.G. Pellegriti(INFN-CT)
A.Musumarra(UNICT)
F. Leone(UNICT)

Monthly *mini-workshop* in progress from November 2020

Two congress contributions submitted in 2021

C. Massimi (22nd International Workshop on Radiation Imaging Detectors) Ghent June-July
A. Musumarra (The 12th International Conference on Position Sensitive Detectors) Birmingham September

New Active Target developments

Experimental task: LoI
setup and test of the *first*
n-TOF Active target (*n-n* & *n-p*)

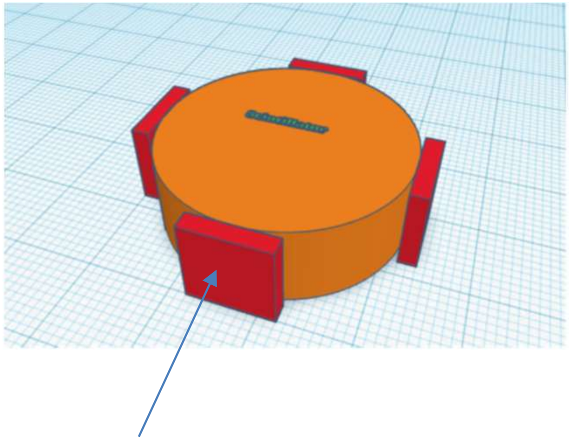
- *Cristian and Nikolas* (Riccardo Mucciola - GEANT4 simulations)
- *Agatino and Maria Grazia* (Experimental setup)

First test planned
at NCSR Demokritos

Preliminary
deuterated scintillator:
Stilbene Disk
32mm diameter, 5 & 10 mm thick

NE-232 liquid scintillator — Used at TUNL
BC-436 plastic scintillator — Loading ?

Scintillators
INRADoptics



n-point SiPM readout
(4x4 and <u>6x6 mm^2</u>)

SiPM readout
(two options)

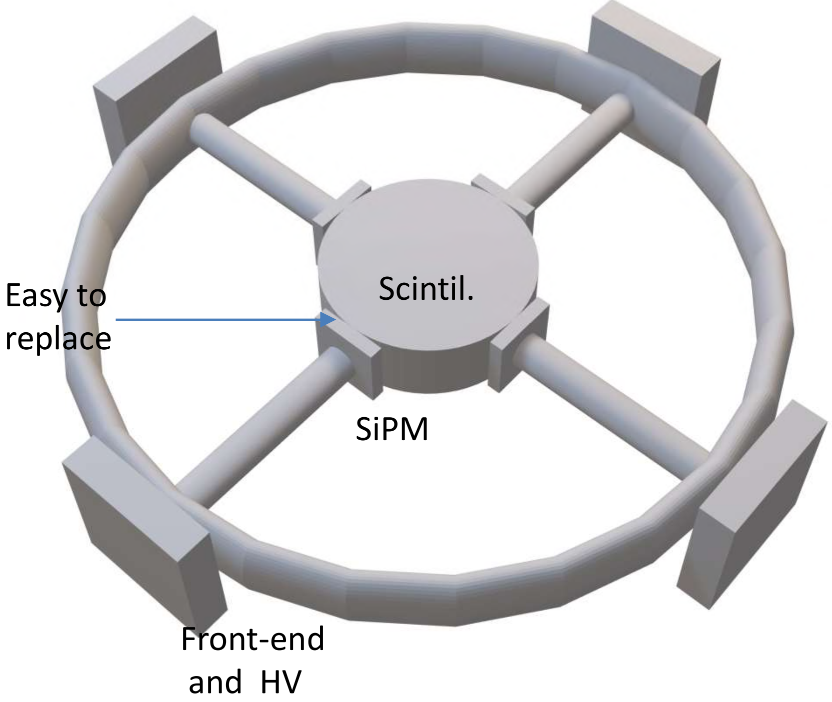
AdvanSid
ASD-NUV4S-P (4x4) and
Standard *RC* + fast pre-amp

Hamamatsu evaluation kit
and 2xS13360-6050CS (6x6)

- Fast (scintillator and readout)
- Improved light collection (multi point)
- PS capabilities by light sharing (primary vertex)
- Reduced amount of in-beam material
- γ-n discrimination

Active Target (Frame and front-end)

Setup and engineering



Symmetry allows rescaling
(number of sensors and diameters)

3D MSLA printing for fast prototyping
Masked StereoLithogrAphy
cheap and reliable technology

Tested and working (*3D*-objects in-vacuum $2 \cdot 10^{-5}$ mbar)

- *50 μm* tolerance (x-y)
- *Real-time* machining (***FAST***)
- Mechanical structure impossible or hard-to-design by ‘standard’ approach
- No workshop required
- *COVID free*

The final design (if necessary) can be implemented by any material (Aluminum)

Final remarks

Concluding:

- The updated *n_TOF* spallation target offer new possibilities at the NEAR station
- Commissioning will take place starting from *summer 2021*
- The setup for the *n-n* scattering length measurement is in progress
  Development:
  - First n_TOF Active Target
  - New *n*-detectors with tracking capabilities and high efficiency
- New ideas are welcome in order to support a «*white paper*» for the new campaign

Thank you