CYGNUS-TPC Australia Meeting
University of Melbourne, Australia

UNDER
Underground Neutron DEtection through nuclear Recoils @ LNGS

Elisabetta Baracchini
Istituto Nazionale di Fisica Nucleare INFN, Laboratori Nazionali di Frascati, Italy

Natural Neutron Background

- **Neutron background limits the maximum achievable sensitivity in most deep underground nuclear, astroparticle and double-beta decay experiments**
  - Fast neutrons background to current experiments
  - Thermal neutrons: able to activate detector material, background for future large volume experiments

- **At a typical depth of 3000-4000 m.w.e. neutron flux from the environment is about 2-3 order of magnitude larger than from cosmogenic muon activation**
  - Dominant source from ^{238}U fission from rocks, (alpha,n) reaction on light nuclei and experimental setup activity

Motivations

Fast neutron measurements at LNGS

Measurement of fast neutron flux are more than 20 years old!

Fast neutrons are 100 keV - 50 MeV

[5] Aleksan 1989 — Hall A
[6] Arneodo 1999 — Hall C
[2] Belli 1989 — Hall A
[1] Bellotti 1985 — Hall A
[7] Cribier 1995 — Hall A
[8] Rindi 1988 — Hall A

NONE of this is a low radioactivity detector

	Li6 liquid scintillator	liquid scintillator	BF_3	^3He	radio chemical techinque	^3He
E interval (MeV)	Fast Neutron Flux ($10^{-6}cm^{-2}s^{-1}$)					
	Ref. [5]	Ref. [6]	Ref. [2]	Ref. [1]	Ref. [7]	Ref. [8]
$0.1-1$			0.54 ± 0.01			
$1-2.5$		0.14 ± 0.12	(0.53 ± 0.08)			
$2.5-3$		0.13 ± 0.04	0.27 ± 0.14			
$3-5$			(0.18 ± 0.04)			2.56 ± 0.27
$5-10$		0.15 ± 0.04	0.05 ± 0.01 (0.04 ± 0.01)	3.0 ± 0.8	0.09 ± 0.06 UL	
$10-15$	0.78 ± 0.3 UL	$(0.4\pm0.4)\cdot10^{-3}$	$(0.6\pm0.2)\cdot10^{-3}$ $((0.7\pm0.2)\cdot10^{-3})$			
$15-25$			$(0.5\pm0.3)\cdot10^{-6}$ $((0.1\pm0.3)\cdot10^{-6})$			

Measurements varying widely

Thermal neutron measurements at LNGS

[1] Bellotti 1985
[2] Belli 1989
[3] Debicki 2009
[4] Best 2015

E interval (eV)	Thermal Neutron Flux ($10^{-6}cm^{-2}s^{-1}$)			
	Ref. [1] (^3He)	Ref. [2] (BF_3)	Ref. [3] (^3He)	Ref. [4] (^3He)
0 - 0.05	5.3 ± 0.9	1.08 ± 0.02 (1.07 ± 0.05)	0.54 ± 0.13	0.32 ± 0.09
0.05 - 1000		1.84 ± 0.20 (1.99 ± 0.05)		

NONE of this is a low radioactivity detector

Measurements varying widely

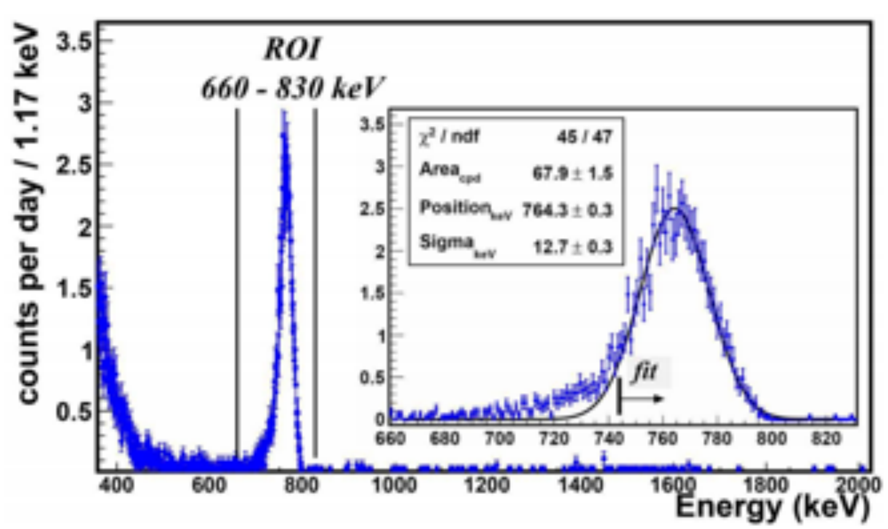
Thermal neutrons are below 1 keV

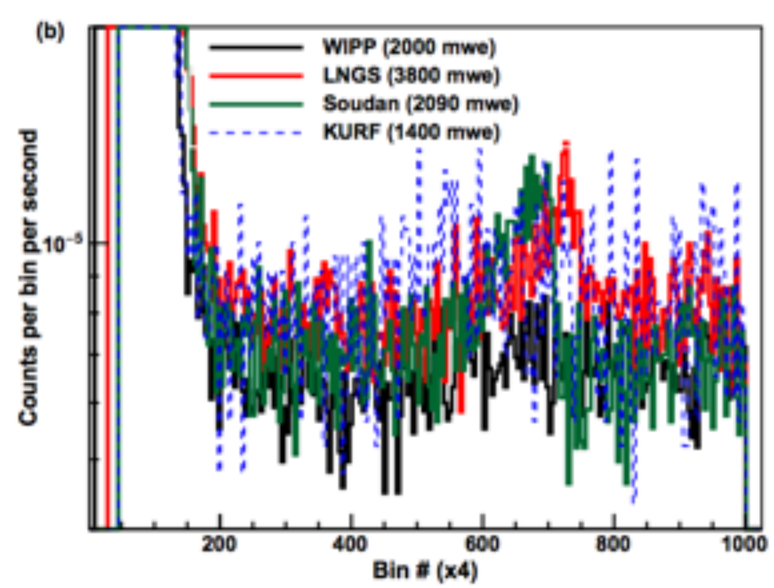
^{3}He and BF_3 counters technique

- **^{3}He and BF_3 measurements**
  - Thermal neutron through capture: a peak over a large background of internal radioactivity (alphas mainly), to be estimated and subtracted to obtain the final result
    - NOTE that several other laboratories felt the need to perform ^{3}He measurements with low-radioactivity background detectors
  - Fast neutron (Belli, Bellotti): only through Cadmium and Polyethylene moderators, complicating detector efficiency and introducing additional uncertainty on yield and energy range

Best et al., ^{3}He at LNGS (2016) (only thermal neutrons)

Edelweiss He3 at LMS (2012)





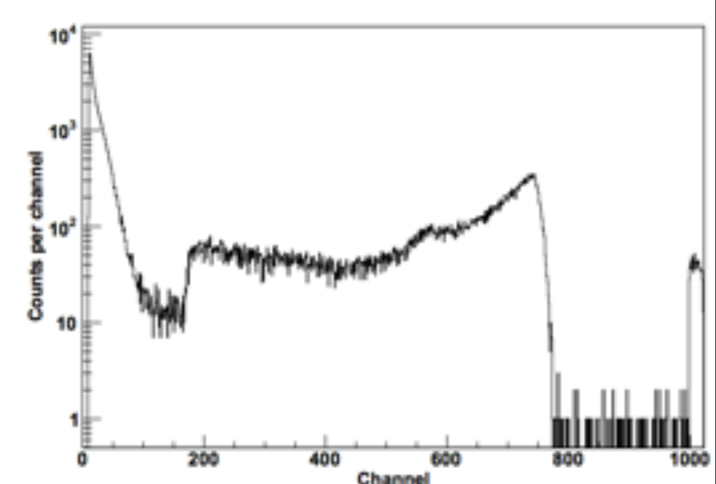
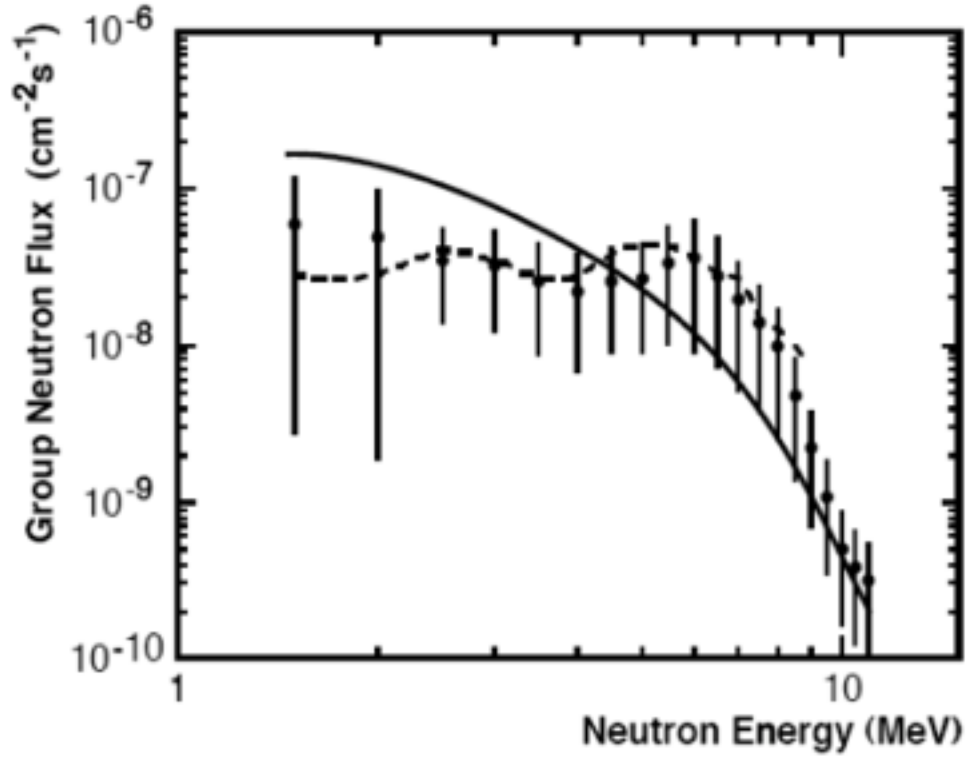


Figure 1: Typical spectrum from a ^{3}He counter (1 channel ≈ 1 keV). A neutro[n] generates a signal between channels ~200 and 800. Signals above and belo[w] this region are due to alpha particles and electronic noise, respectively.

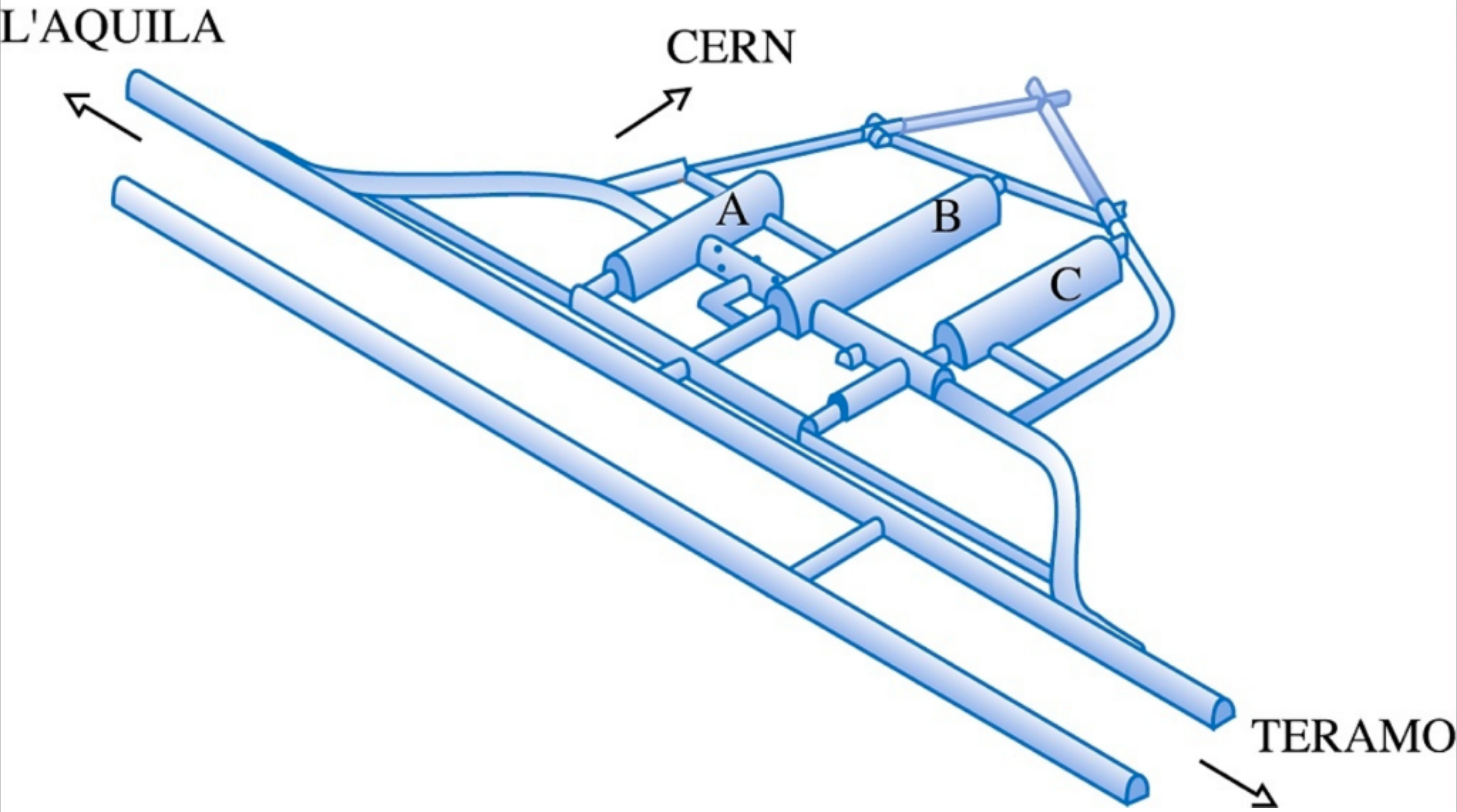
Proton recoil technique

- **Scintillator with proton recoil technique [6] (1999)**
  - Proton recoil technique is similar to nuclear recoil
  - Authors recognize energy calibration with external gamma source was complicated and used internal alpha particles from internal radioactivity but had to estimate the contaminants from simulation (unable to resolve alpha lines)
  - Alphas were also background to proton recoils

Neutron spectrum at Gran Sasso - Arneodo et al. Nuovo Cimento, A112 (1999) 819.



LNGS halls and tunnels map



LNGS Hall A, Hall B and Hall C

Wulandari et. al.,
Astropart.Phys. 22 (2004) 313-322

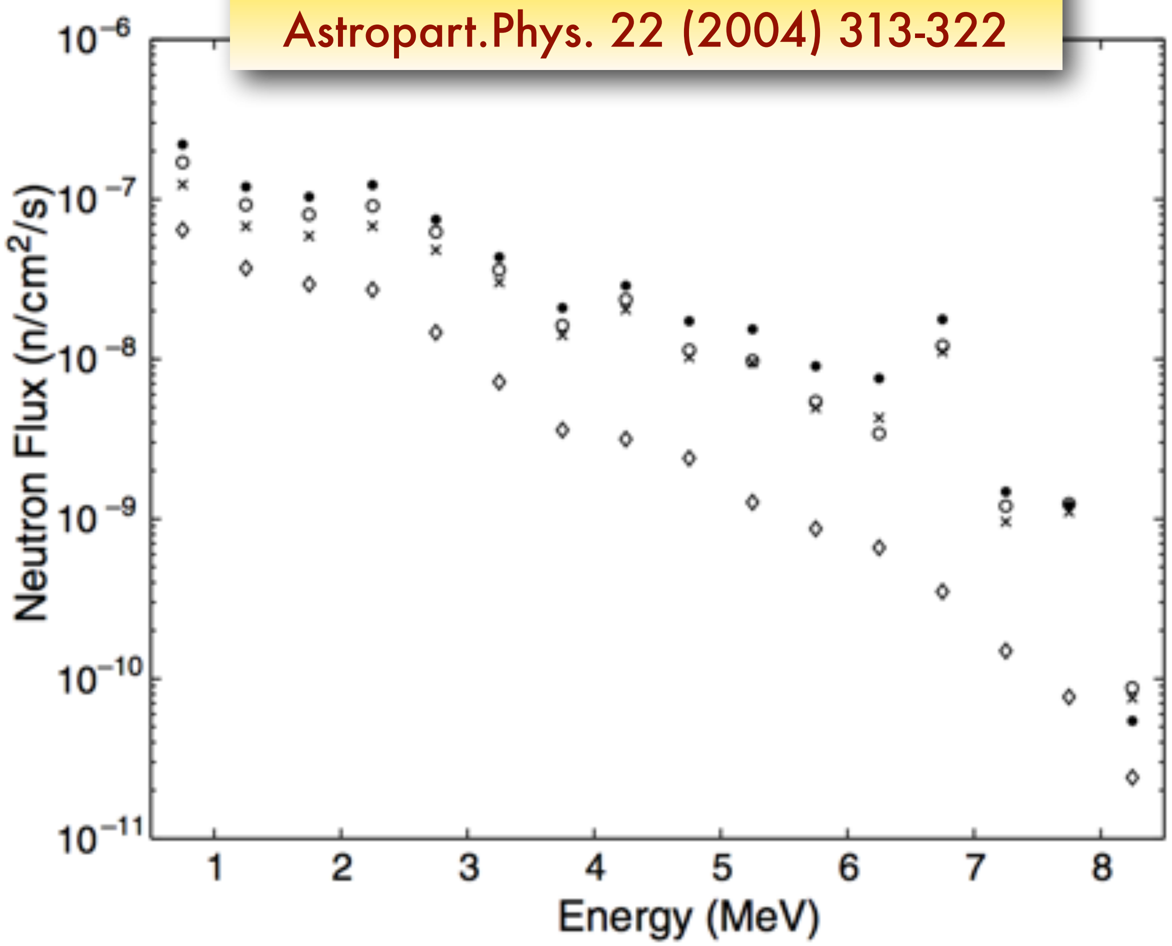


Fig. 3. Neutron flux at the Gran Sasso laboratory, ●: hall A, dry concrete, ×: hall A, wet concrete, ◇: hall A, dry concrete, fission reactions only and ○: hall C, dry concrete. Each point shows the integral flux in a 0.5 MeV energy bin.

NEUTRON BACKGROUND HIGHLY DEPENDENT ON CONCRETE WATER CONTENT!!!

..something that can change over a year...

The flux is dominated by neutrons produced in the concrete layer and therefore does not vary much from hall to hall

At higher energies, the contribution of (alpha,n) reaction becomes larger introducing the difference

emitted per fission [11]. The total number of neutrons produced by fission and (α,n) in the rock/concrete at the Gran Sasso laboratory depends eventually on the ^{238}U and ^{232}Th contamination.

Table 3
^{238}U and ^{232}Th activities in LNGS rock

Hall	Activities (ppm)	
	^{238}U	^{232}Th
A	6.80 ± 0.67	2.167 ± 0.074
B	0.42 ± 0.10	0.062 ± 0.020
C	0.66 ± 0.14	0.066 ± 0.025

	Hall A	Hall B	Hall C
rock	3.54	0.22	0.34
concrete	0.55	0.55	0.55

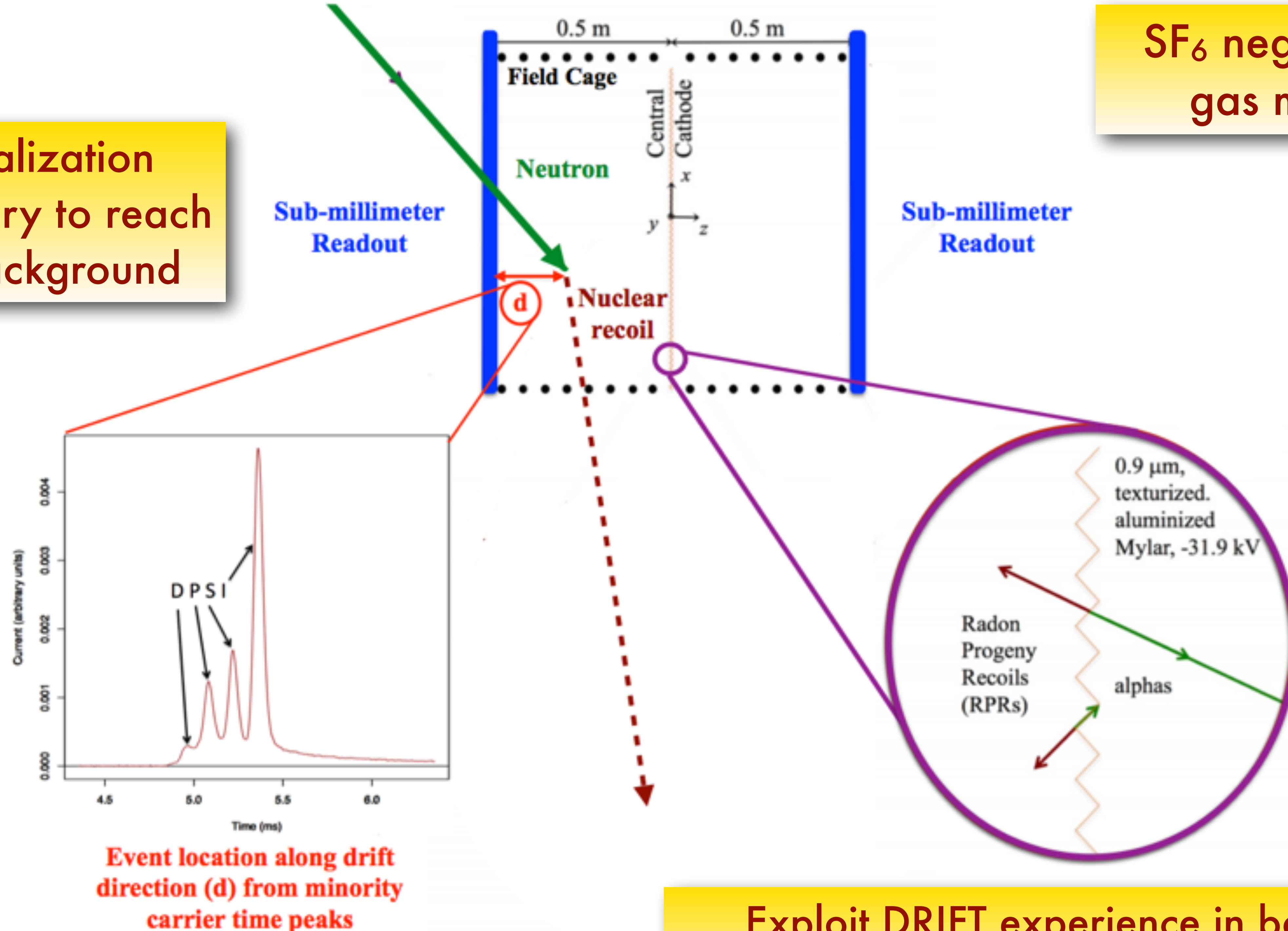
n/year/g

The proposed detector

UNDER detector concept

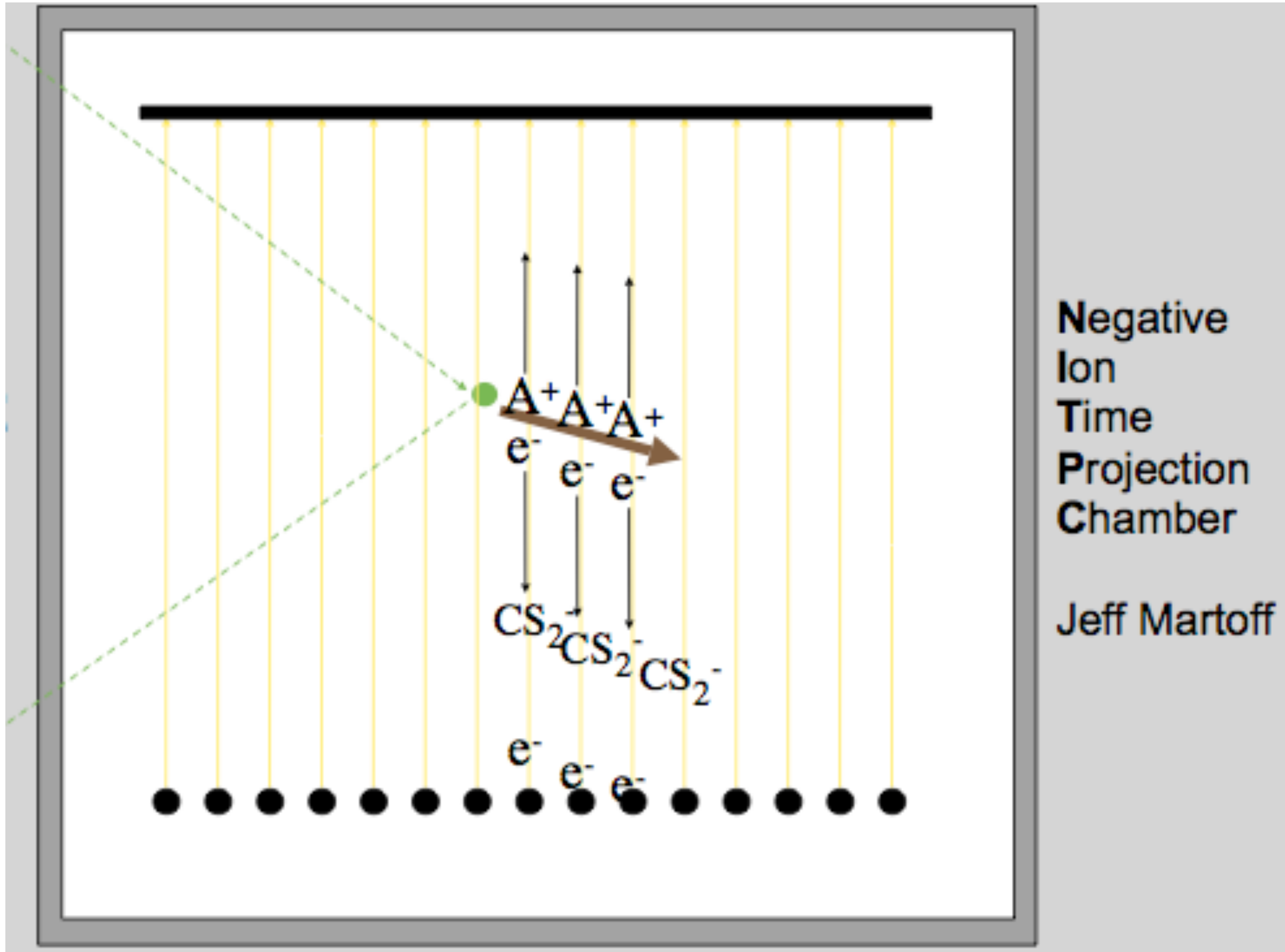
SF$_6$ negative ion gas mixture

Fiducialization compulsory to reach zero background



Exploit DRIFT experience in background minimization (also for vessel manufacturing)

Negative Ion drift



< 0.5 mm diffusion achieved over 0.5 m drift length w.r.t. 10 mm obtained with electrons (no magnetic field)

J. Martoff et al., NIM A 440 355

T. Ohnuki et al., NIM A 463

- Mixture of target gas + electronegative gas
- Primary ionization electrons are captured by the electronegative molecules at O(100) um
- Anions drift to the anode acting as the effective image carrier instead of the electrons
- Thanks to the much higher anions mass w.r.t. electrons, longitudinal and transversal diffusion is reduced to thermal limit w/out any magnetic field
- At the anode, the electron is stripped from the anion and normal electron avalanche occurs

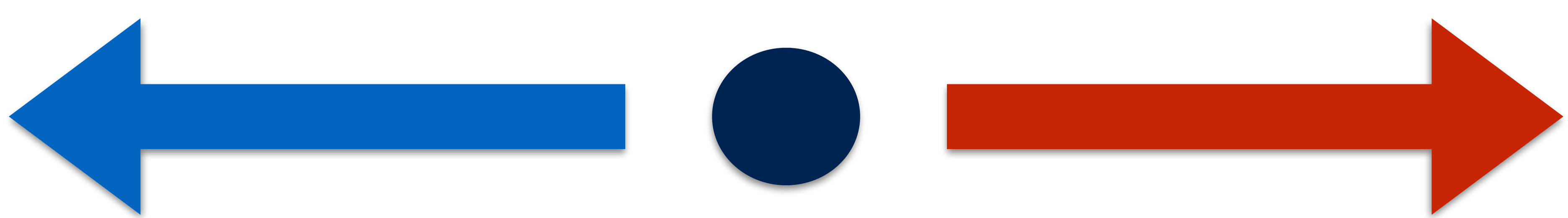
Address TPC typical volume limitations

UNDER: thermal and fast neutron flux measurement in LNGS Hall B with a CYGNUS demonstrator

J. Battat et al., arXiv: 1701.00171

- **Idea born after DRIFT neutron flux measurement in Boulby**
  - A 1 m^3 active volume with 2 back-to-back 50 cm drift NITPC with low radioactive content can measure a $O(10^{-6})$ fast neutron flux
- **He:^{3}He:SF_6 gas mixture (at atmospheric pressure?)**
  - Fast neutron flux through usual nuclear recoil technique
  - Thermal neutron flux through ^{3}He capture with energy measurement plus tracking of tritium and proton recoil

$$n + {}^3He \longrightarrow p + {}^3H + 764keV$$



Proton 573 keV

Tritium 191 keV

Very clear signature in a (NI)TPC

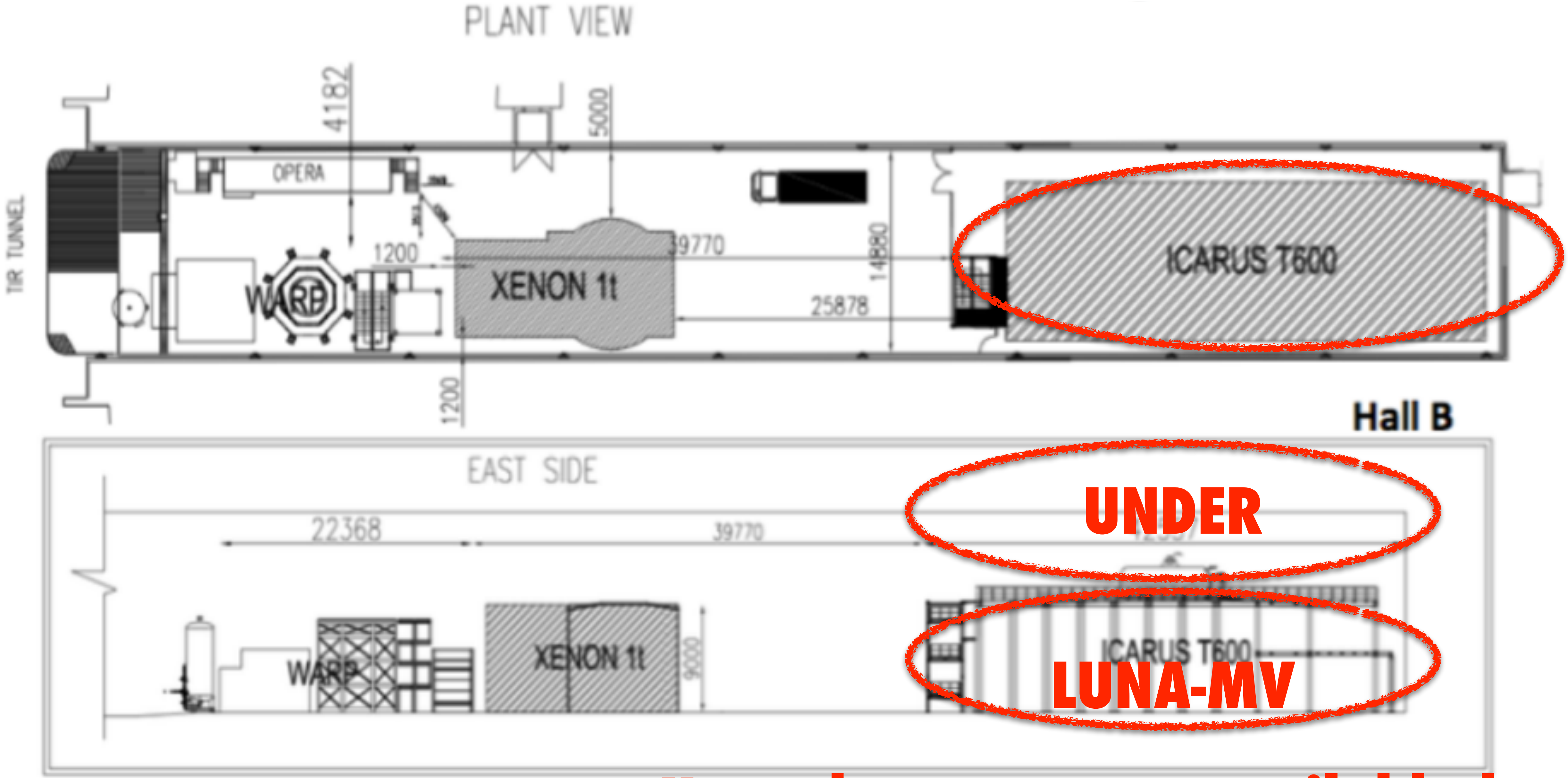
UNDER: thermal and fast neutron flux measurement in LNGS Hall B with a CYGNUS demonstrator

- **Nicely fit into CYGNUS-TPC effort**
  - Readout choice to come from CYGNUS-TPC simulation studies, optimization and R&D

- **Two-stage measurements**
  - One year (directional i.e. lower pressure?) measurement in Hall B above LUNA-MV
  - Shorter (non-directional i.e. higher pressure?) measurements in different location of the laboratories

LNGS free space and upgrades

- Icarus, Opera gone
- Free areas in Hall B:
    - "Icarus" 65 m x15 m
    - "Warp" 22 m x 10 m

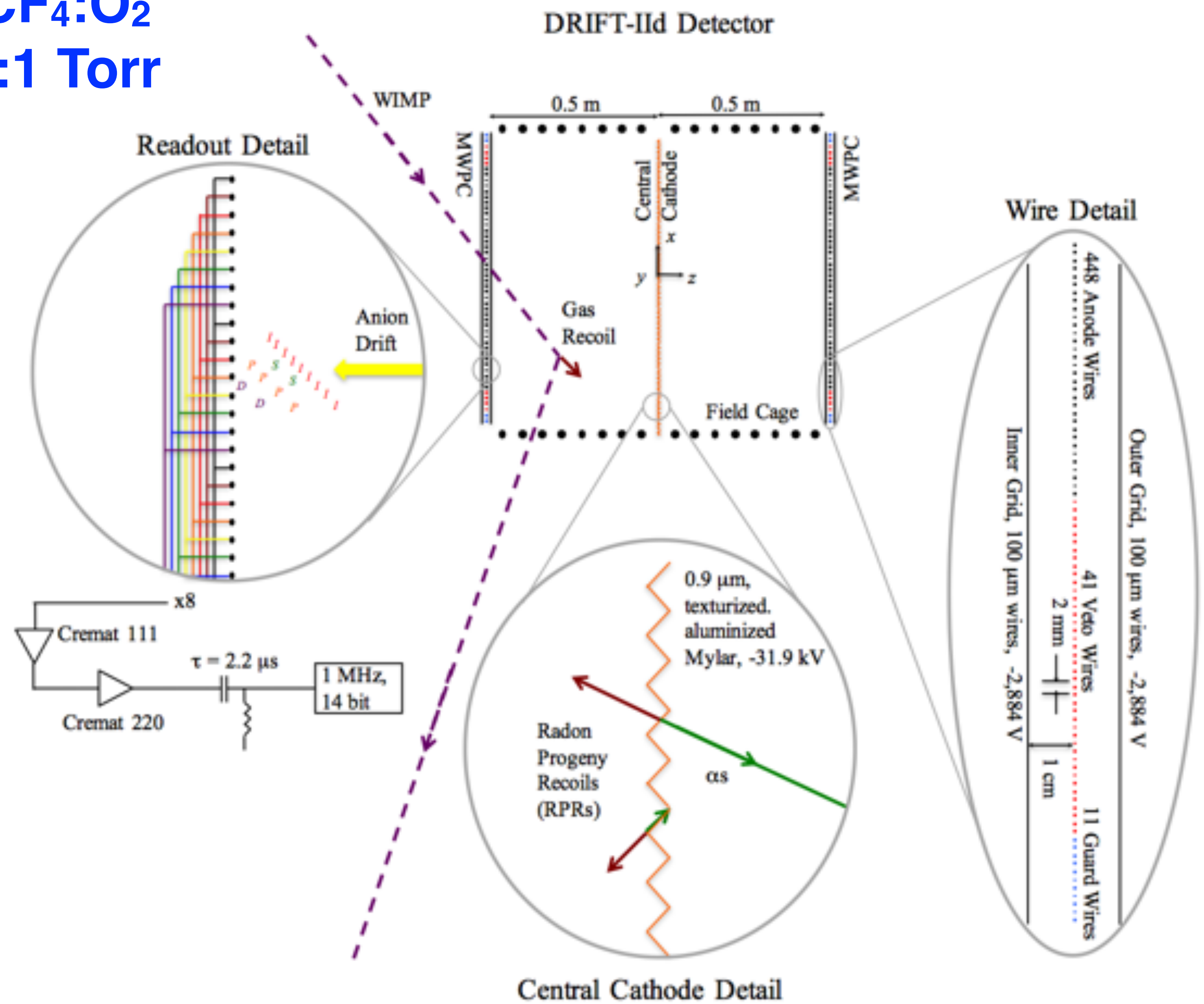


Here there are two available levels

DRIFT neutron flux measurement @ Boulby

J. Battat et al., arXiv: 1701.00171

CS_2:CF_4:O_2
30:10:1 Torr



Boulby measured neutron flux
$\sim 0.7 \times 10^{-6}$ cm^{-2} s^{-1}

45 live days of unshielded data (in a total time period of ~ 400 days with high stability)

14 neutron scattering events in 45 live days

What we can learn from DRIFT

- **Fiducialization is compulsory to reach zero background**
    - Need to understand how much we can lower the threshold and still be able to fiducialize in SF_6
    - Remember, minority carriers peak in SF_6 much smaller than with $CS_2:O_2$
- **DRIFT is a low-pressure 41 Torr NITPC to allow enough track length for O(keV) nuclear recoil to determine direction**
- **You don't need directionality to fiducialize**
- **Hence, you don't need to go to low pressure if you don't care about direction**
    - CAVEAT: need to verify gamma rejection ability at higher pressures

Back-of-the-envelope number of events estimation

- **Let's assume a He:^{3}He:SF_6 600:1:10 Torr gas mixture**
  - He:CF_4:SF_6 360:240:10 shown to work
  - Neutron capture cross section is ~ 600 times neutron scattering cross section
  - Proposed gas only 16% more dense than DRIFT mixture but at nearly atmospheric pressure!
    - Can assume (nearly) same potentialities on directionality in terms of recoil length?
    - With 749:1:10 Torr 34% more dense than DRIFT

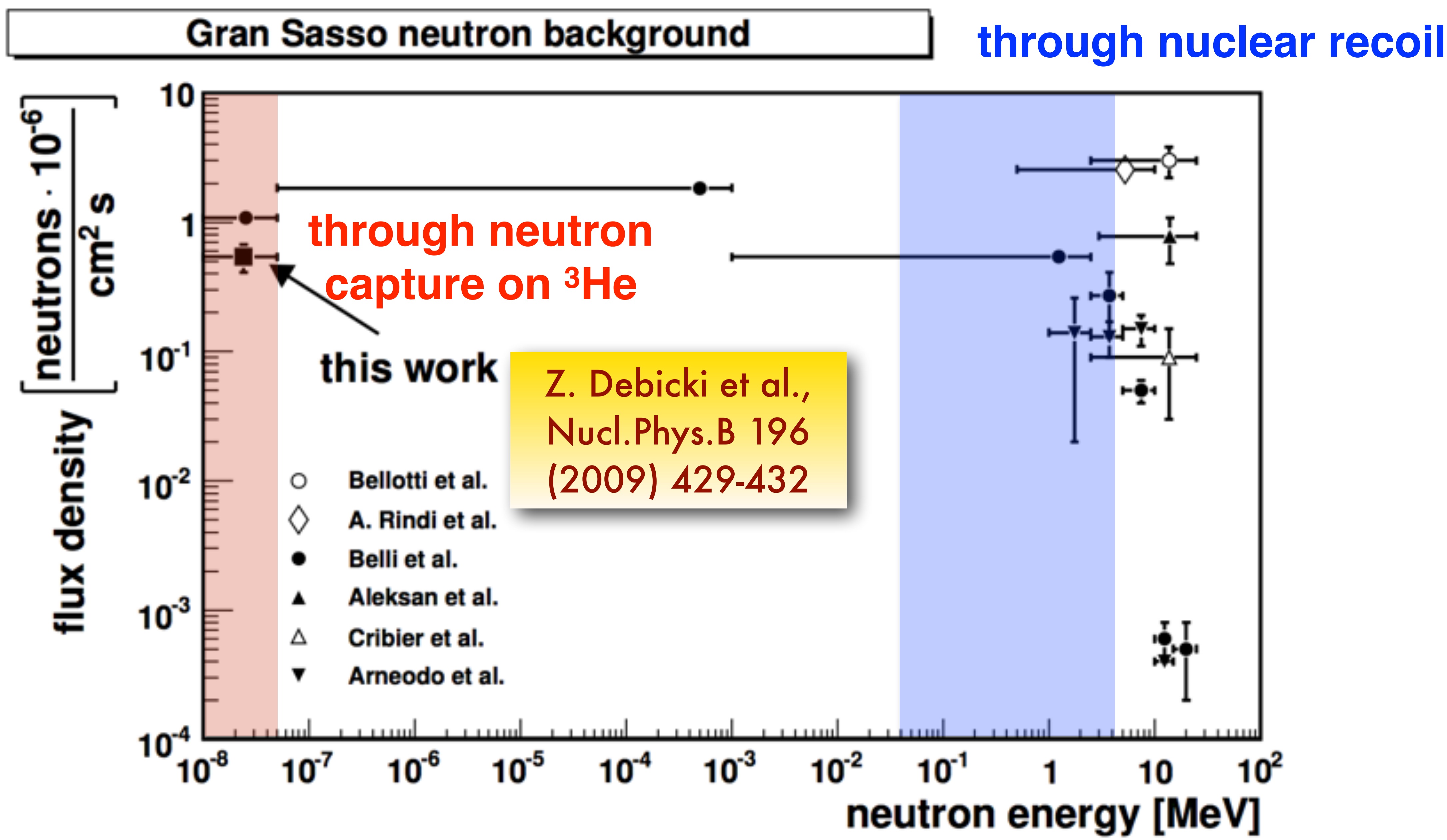
assuming we still want to keep gas density low to be as much as similar to DRIFT

- **Assuming a LNGS flux of fast neutrons in Hall B of 0.5 x 10^{-6} n/s/cm^2 and same performances and efficiencies as DRIFT:**
  - ~100 nuclear recoil events/year
  - At least 100 thermal neutron capture (assuming same efficiency, very pessimistic)
- **Higher SF_6 content run with He:^{3}He:SF_6 600:1:100 Torr**
  - Probably loose directionality (to be confirmed)
  - ~50 events/month
- **Could go even higher? Thin GEMs shown to be able to get gain up to 370 Torr of pure SF_6**

UNDER: thermal and fast neutron flux measurement in LNGS Hall B with a CYGNUS demonstrator

- **Improvements w.r.t. available measurements:**
  - First background-free measurement
  - One year measurement to see <u>if flux changes with season</u>
  - First measurement in Hall B
  - (First measurement with directionality?)
  - First measurement with a (low pressure?) NITPC at LNGS
  - Cross-check of LUNA-MV induced background in the environment
  - Demonstrator for CYGNUS-TPC

VERY VERY TENTATIVE estimation of neutrons energy range



Next steps

- **Perform simulation of expected neutrons flux inside a $1m^3$ DRIFT-like vessel at LNGS starting from DRIFT experience (thanks to F. Mouton)**

Example of UNDER synergy with CYGNUS-TPC

- **Attached to the talk is a 2-pages description of the project and a tentative more detailed LOI**
    - If the proto-collaboration agrees on these basic points, send the shortest version signed by the ISG to LNGS Scientific Committee to ask for a talk at the next SC in April
    - Finalize together the longer LOI (with flux simulation)
    - Have the LOI signed by proto-collaborators (as support for now, not as a commitment to work on the experiment, i.e. like CYGNUS-TPC agreement)
    - Send the LOI to LNGS SC a couple of weeks before April
    - In 2018, with CYGNUS-TPC white paper, LNGS SC recommendation and all the results from our R&D, start to ask for fundings (INFN & others)

LNGS measurements references

[1] E. Bellotti et al., INFN/TC-85/19, October 1985.
[2] P. Belli et al., Il Nuovo Cim. 101A (1989) 959.
[3] Z. Debicki *et al.*, Nucl. Phys. Proc. Suppl. **196** (2009) 429.
[4] A. Best *et al.*, Nucl. Instrum. Meth. A **812** (2016) 1
[5] R. Aleksan et al., Nucl. Instrum. Meth. in Phys. Res. A 274 (1989) 203.
[6] F. Arneodo et al., Il Nuovo Cim. 112A (1999) 819.
[7] M. Cribier et al., Astropart. Phys. 4 (1995) 23.
[8] A. Rindi, F. Celani, M. Lindozzi and S. Miozzi, Nucl. Instrum. Meth. A 272 (1988) 871.

Backup

LNGS flux from LUNA-MV studies

The LNGS Underground Laboratory

- Rock coverage of 3800m

Underground laboratory		Depth m.w.e.	Cosmic Rays Muon flux [cm^{-2} s^{-1}]	Mean specific gamma activity ^{40}K [Bq/kg]	^{238}U [Bq/kg]	^{232} Th [Bq/kg]	Neutrons Neutron energy	Neutron flux 10^{-6}[cm^{-2} s^{-1}]	Radon [Bq/m3]
LNGS	Hall A Rock	3800	2.87E-008	224.0	84.7	8.8	(0 ÷ 1*10^{-7}) eV	1.08	26
							(50*10^{-3} ÷ 1*10^{3}) eV	1.98	
							1 keV< E_{neut}< 2.5 MeV	0.54	
							E_{neut} > 2.5 MeV	0.23	
	Hall B Rock			5.1	5.2	0.25			21
	Hall C Rock			2.9	8.2	0.27	1 < Eneut< 10 MeV	0.42	87
Modane		4800	4.86E-009	210.0	10.4	9.95			
Boulby		2805	3.79E-008	34.9	0.83	0.52	Eneut> 0.5 MeV	1.72	
Canfranc		2500	3.94E-007	169.0	41.4	34.4			66.2
Pyhäsalmi		3960	1.10E-008						
Felsenkeller		112							

What's LUNA-MV?

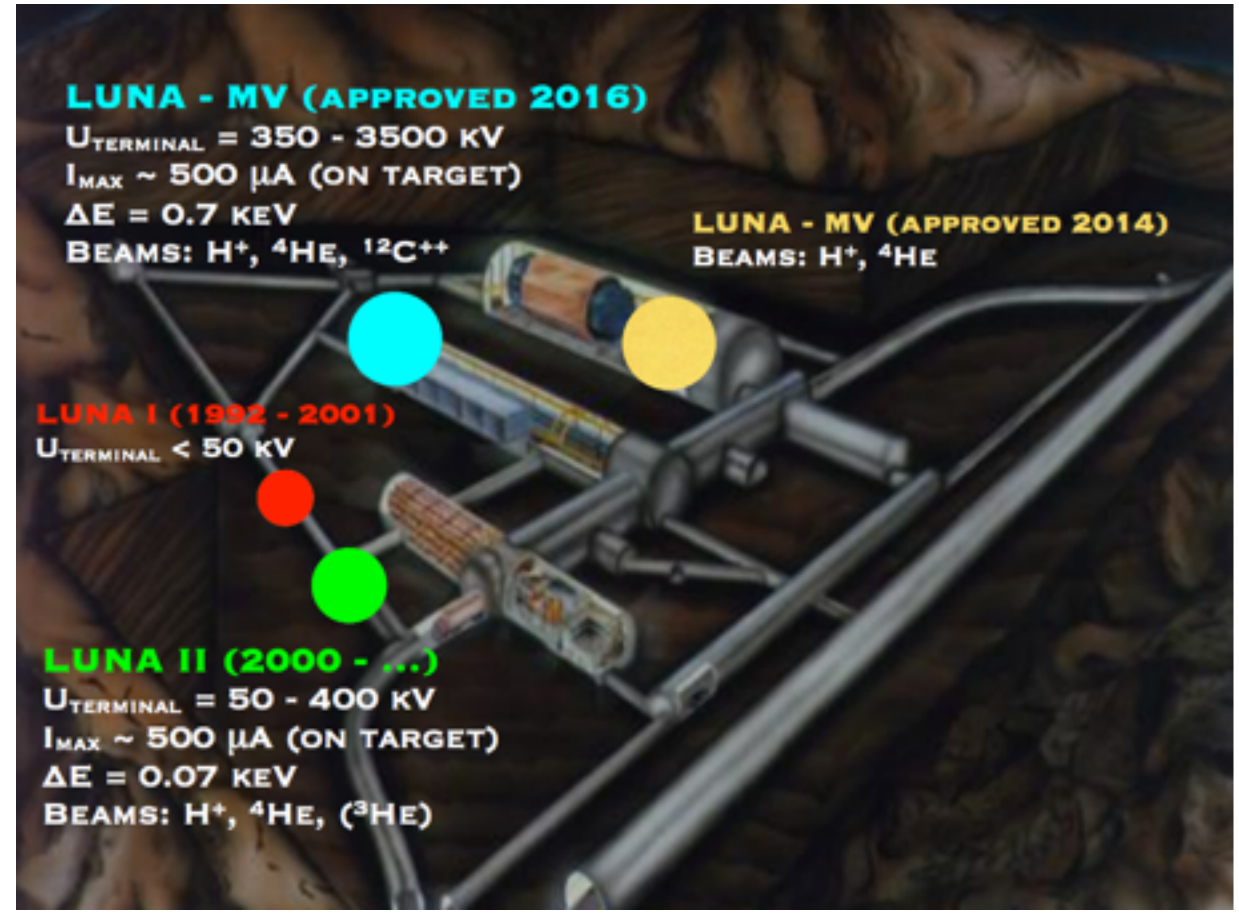
- **The LUNA 400 kV Accelerator**
  - **The Sun**: p-p chain, CNO cycle and solar neutrinos
  - **Nucleosynthesis at work**: ^{26}Al
  - **Hot environment**: BBN and Novae
- **Target preparation and analysis**: a tough job
- **The LUNA-MV project**: a big step forward

Limits of a 400 kV accelerator

- Solar fusion reactions
- Stellar Helium and Carbon burning
- Neutron sources for astrophysical s-processes

A new, higher energy underground accelerator is needed !

Single ended 3.5 MV positive ion accelerator



From FLUKA+GEANT4 simulation

In Hall B, the control room will be widened to 50 m². Concrete shielding 80 cm are enough to have a neutron flow outside the LUNA-MV building ≲ 10^{-6} n /(cm² s)

LUNA-MV induced background