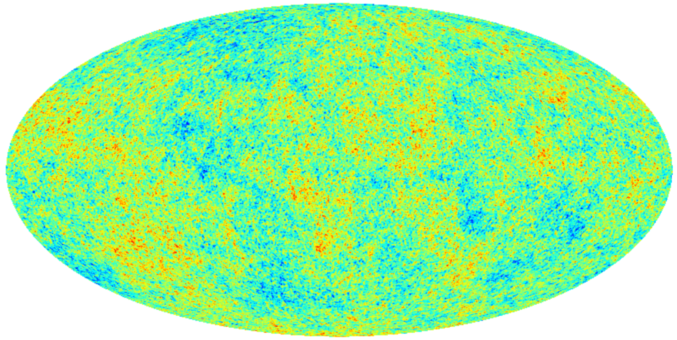
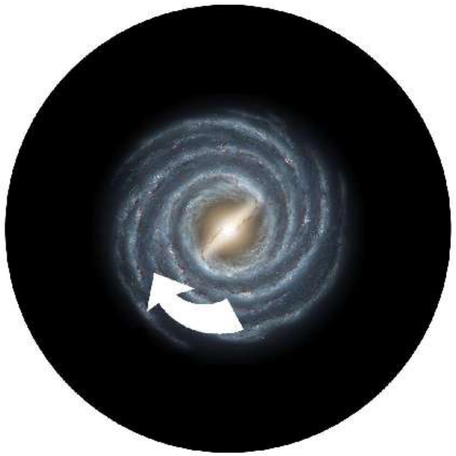


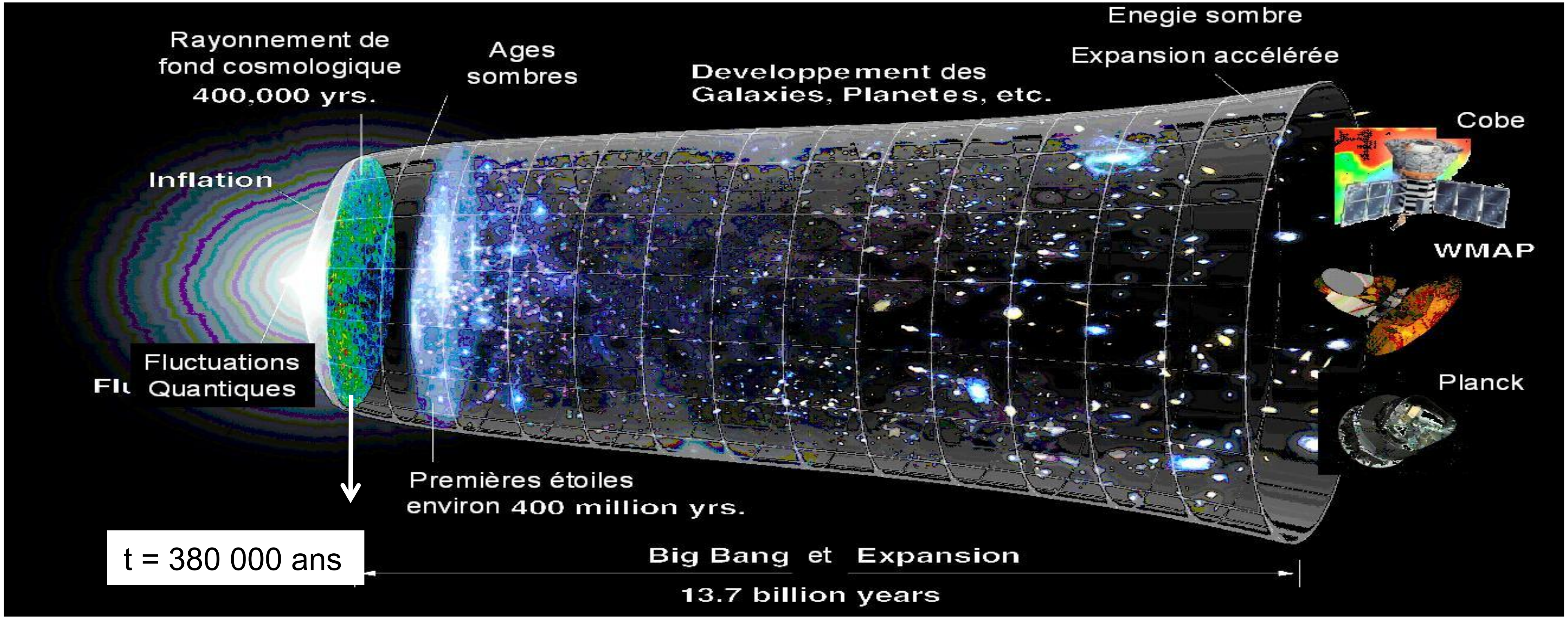
CMB et Détection Directionnelle de Matière Sombre

Daniel Santos
Laboratoire de Physique Subatomique et de Cosmologie
(LPSC-Grenoble)(UJF Grenoble 1 -CNRS/IN2P3-INPG)



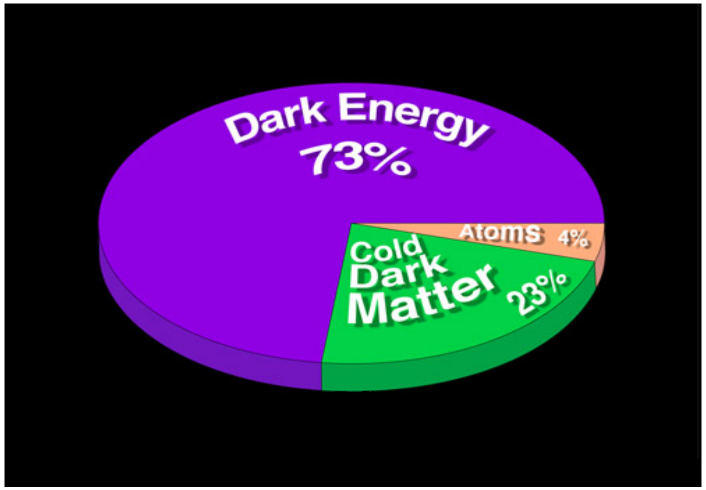
LPNHE – Paris, 10 Novembre 2011

« Thermal History » of our Universe…



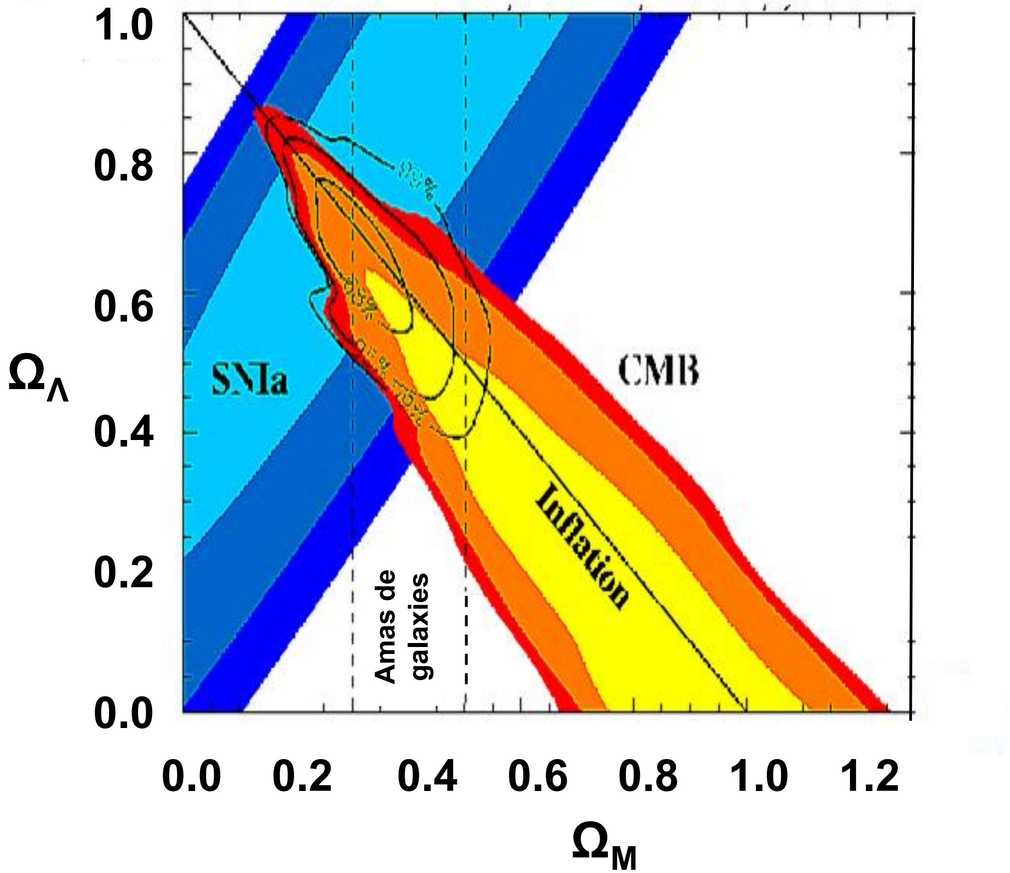
WMAP 7 ans (E. Komatsu *et al.* 2010) :

- Energie noire : $\Omega_\Lambda = 0,734 \pm 0,029$
- Matière non baryonique $\Omega_{CDM} = 0,222 \pm 0,026$
- Matière baryonique $\Omega_B = 0,0449 \pm 0,0028$

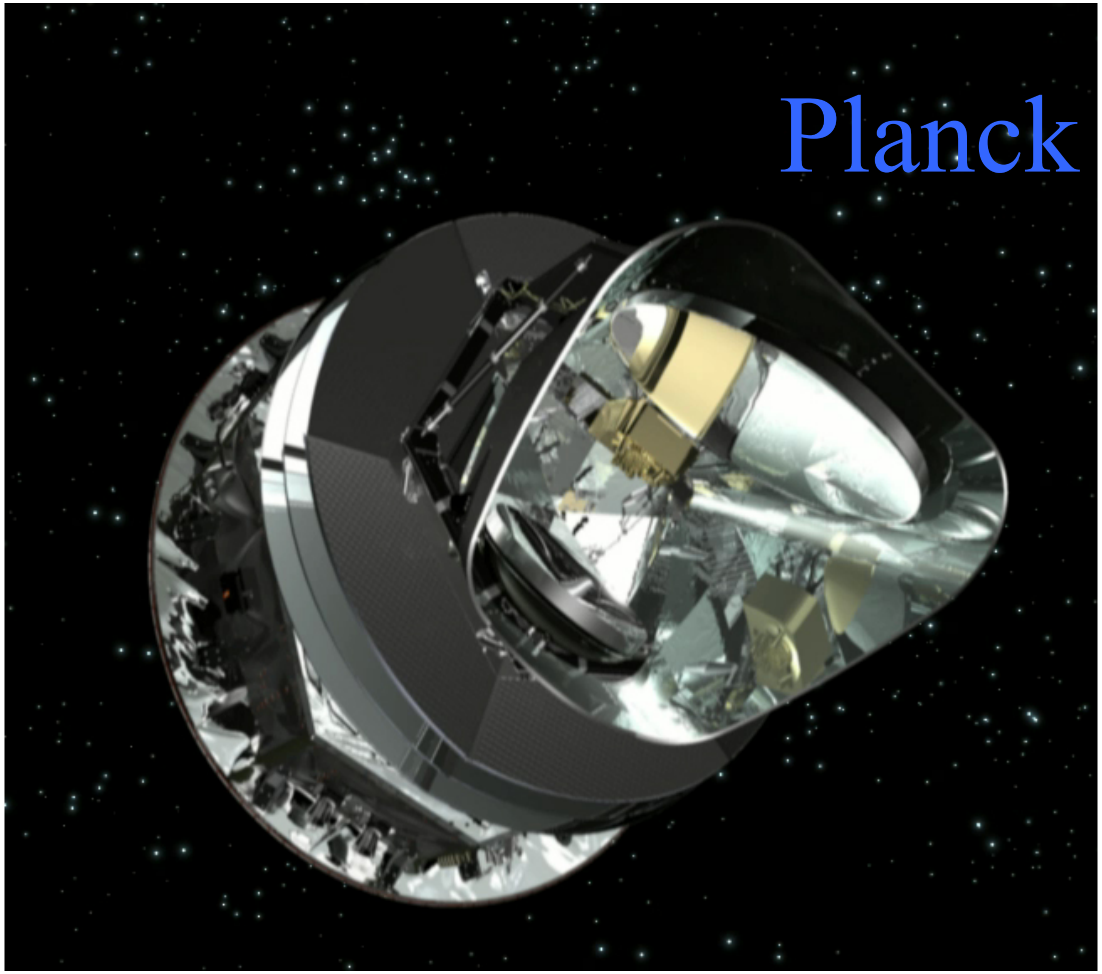


$\Omega_{tot} = \Omega_r + \Omega_\Lambda + \Omega_M$

- **densité de matière $\Omega_M = \Omega_B + \Omega_{NB}$**
- déterminée par CMB
  SNIa
  « clusters » de galaxies



Planck mission



1m50 ø telescope
→ up to 5' resolution

2 instruments :

Low Frequency Instrument
30 to 70 GHz @ 18 K

High Frequency Instrument
100 to 857 GHz @ 0.1 K

ESA mission : first European satellite dedicated to CMB study
launched: May 14th 2009
HFI PI : J.-L. Puget (France)
LFI PI : R. Mandolesi (Italy)

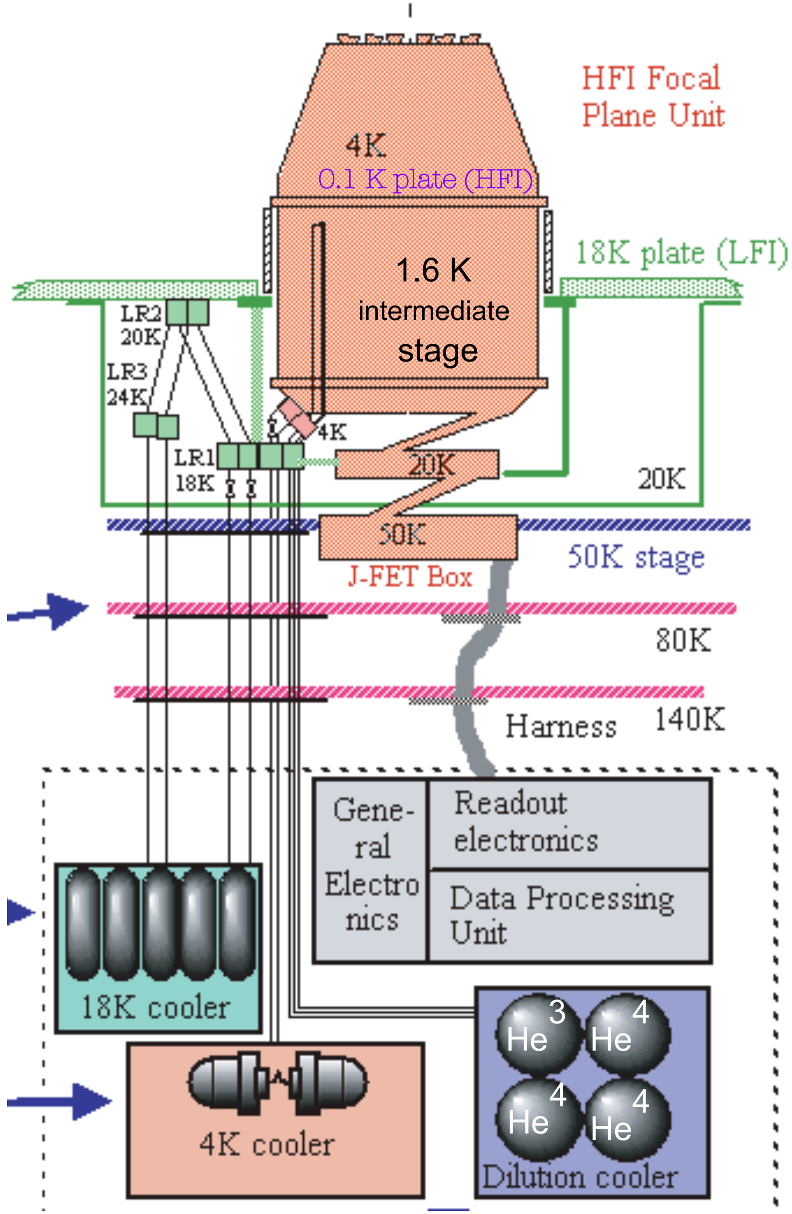
The cryogenic system

Main mirror
50 K

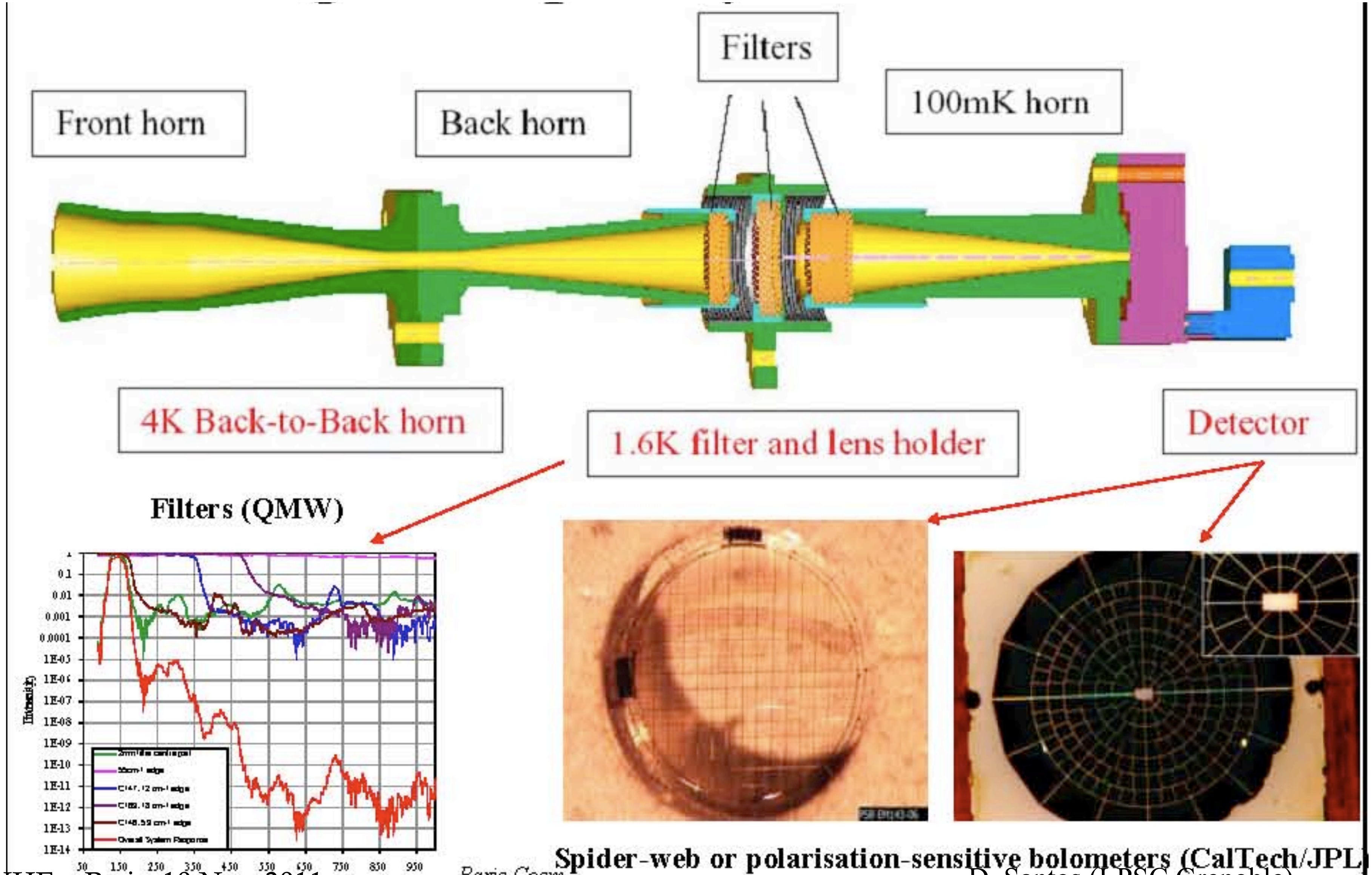
Instruments
18 & 0.1 K

shields
50-60 K
(passive cooling)

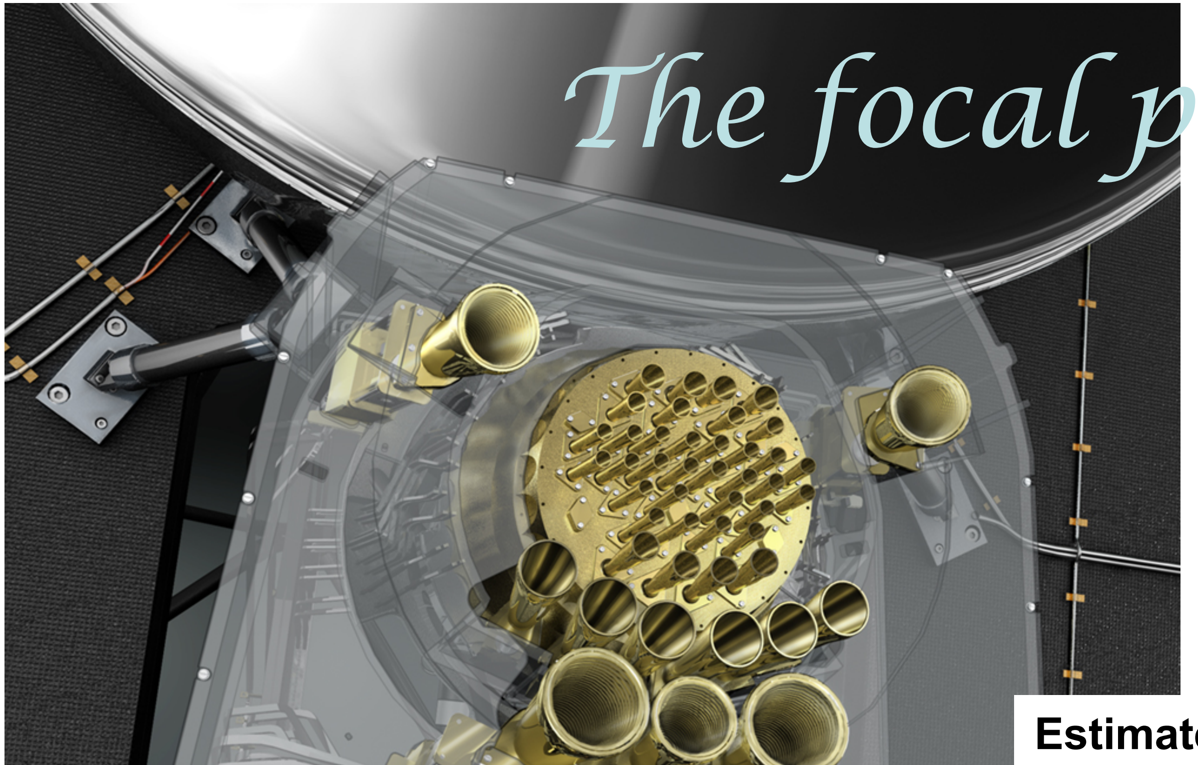
Service module
300 K



High Frequency Instrument



The focal plane

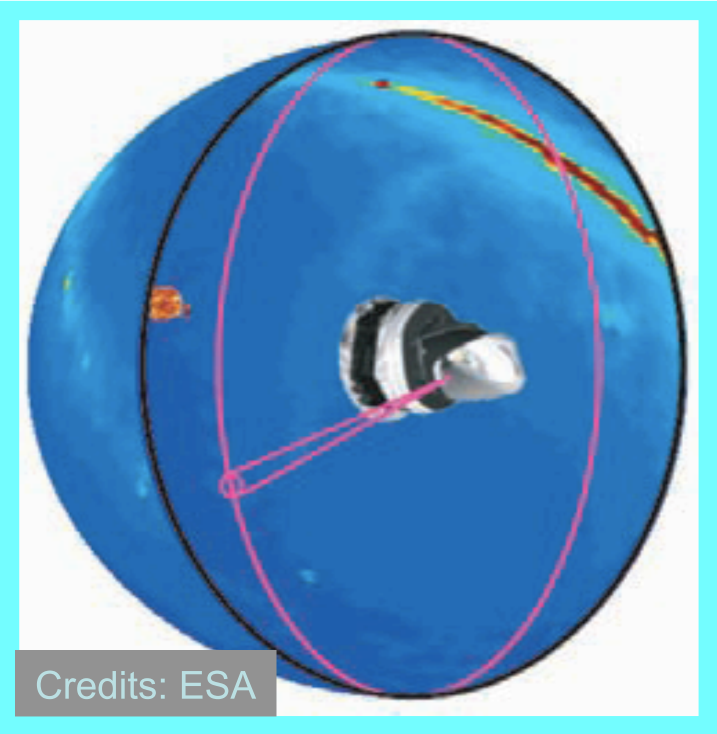


The HFI plate (100 to 857 GHz) is surrounded by
LFI horns (30 to 70 GHz)

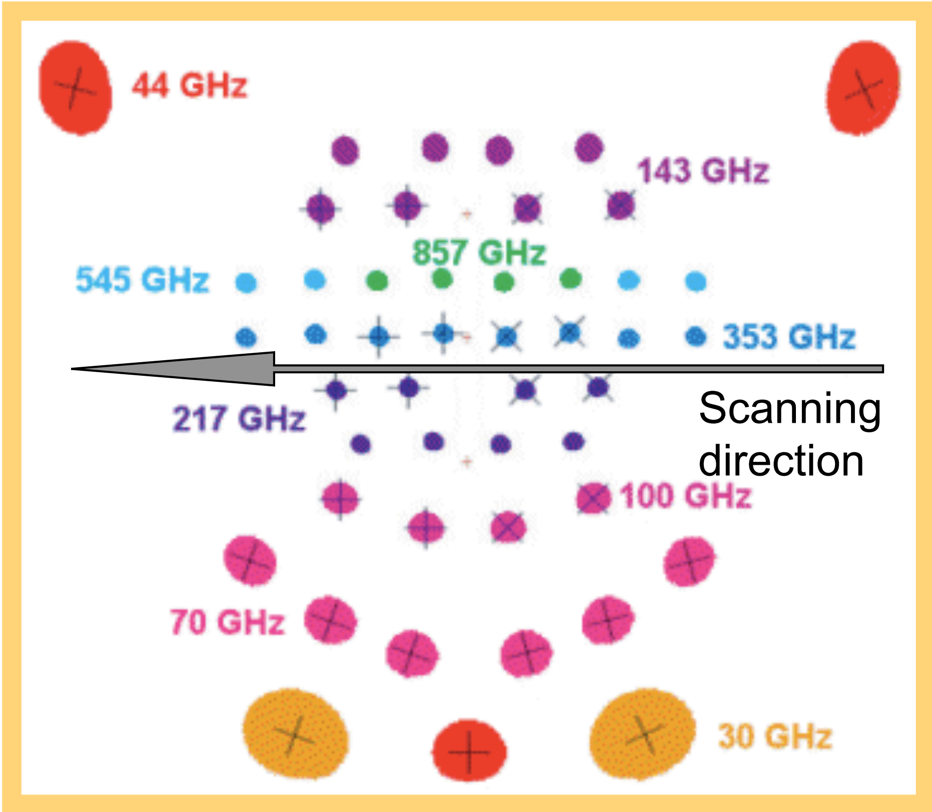
Estimated Instrument Performance Goals

Instrument	LFI			HFI					
Center Freq. (GHz)	30	44	70	100	143	217	353	545	857
Detector Technology	HEMT LNA arrays			Bolometer arrays					
Detector Temperature	~20 K			0.1 K					
Cooling Requirements	H_2 sorption cooler			H_2 sorption + 4 K J-T stage + Dilution cooler					
Number of Unpol. Detectors	0	0	0	0	4	4	4	4	4
Number of Linearly Polarised Detectors	4	6	12	8	8	8	8	0	0
Angular Resolution (FWHM, arcmin)	33	24	14	9.5	7.1	5	5	5	5
Bandwidth (GHz)	6	8.8	14	33	47	72	116	180	283
Average $\Delta T/T_I{}^*$ per pixel[#] In 10^{-6}	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
Average $\Delta T/T_{U,Q}{}^*$ per pixel[#] In 10^{-6}	2.8	3.9	6.7	4.0	4.2	9.8	29.8		

The scanning strategy



From the L2 Lagrange point
30 to 50 times the same circle,
then shift of a third of the smallest beam
→ full sky survey in 7 months



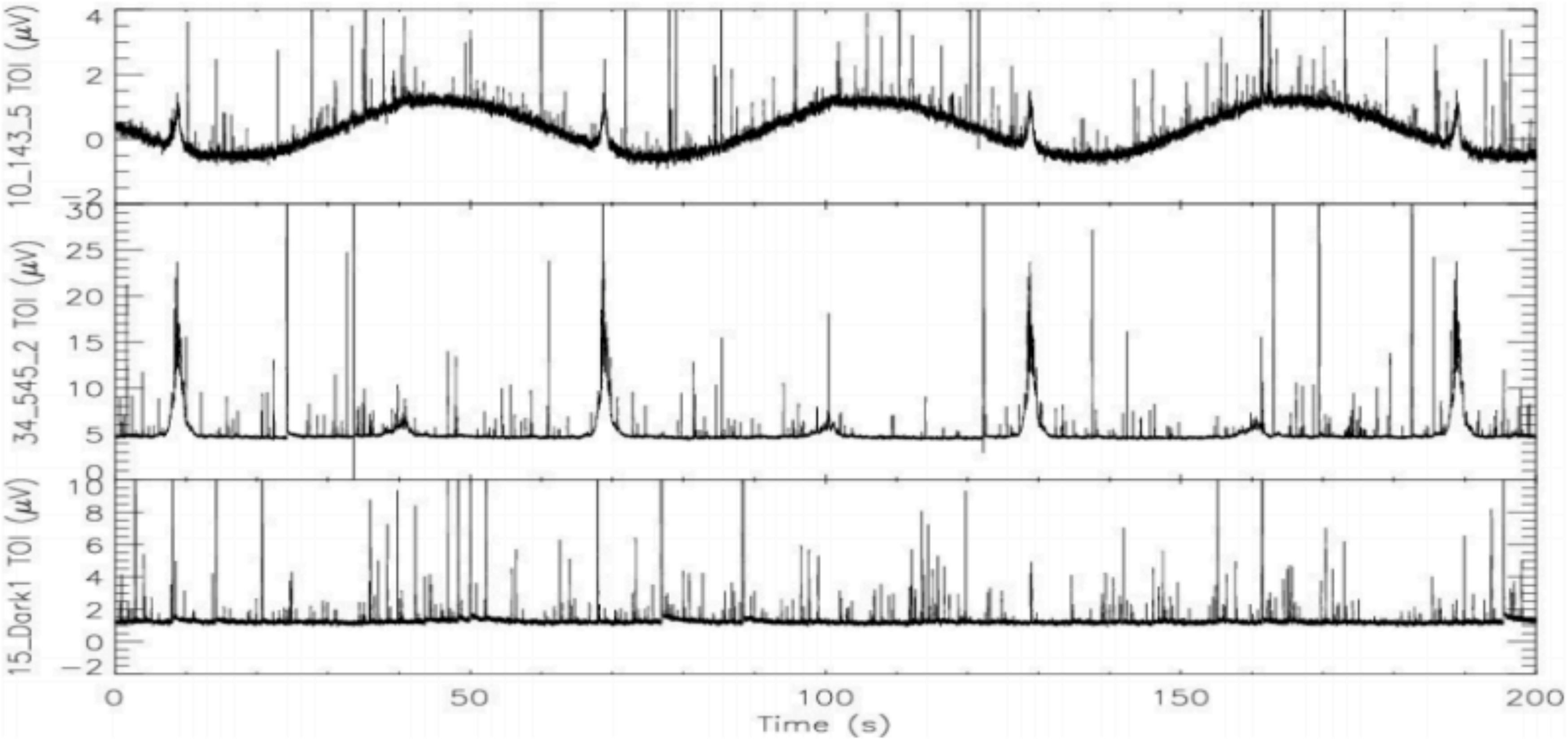


Figure 4. Raw TOIs for three bolometers, the '143-5' (top), '545-2' (middle), and 'Dark1' (bottom) illustrating the typical behaviour of a detector at 143 GHz, 545 GHz, and a blind detector over the course of three rotations of the spacecraft at 1 rpm. At 143 GHz, one clearly sees the CMB dipole with a 60 s period. The 143 and 545 GHz bolometers show vividly the two Galactic Plane crossings, also with 60 s periodicity. The dark bolometer exhibits a nearly constant baseline together with a population of glitches from cosmic rays similar to those seen in the two upper panels.

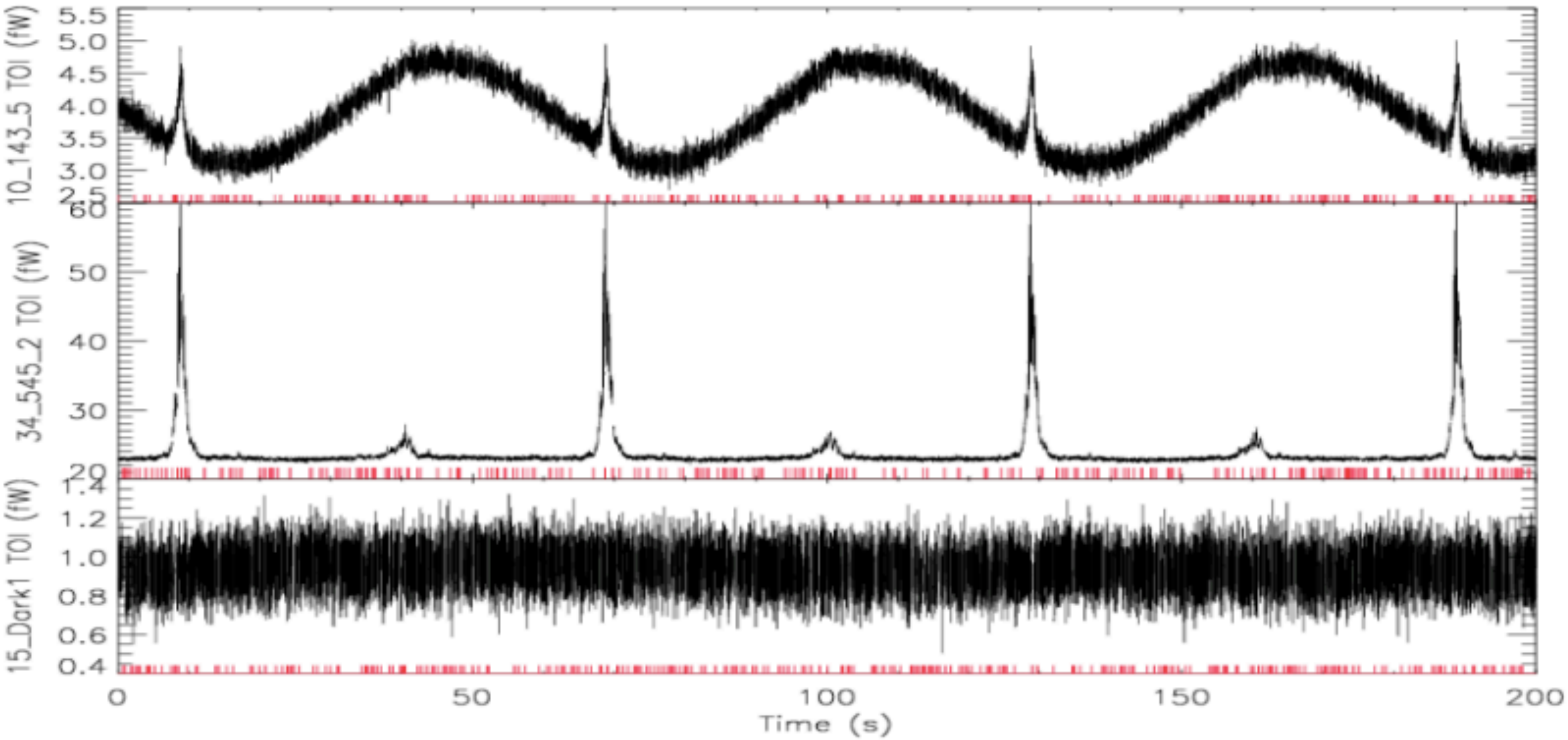
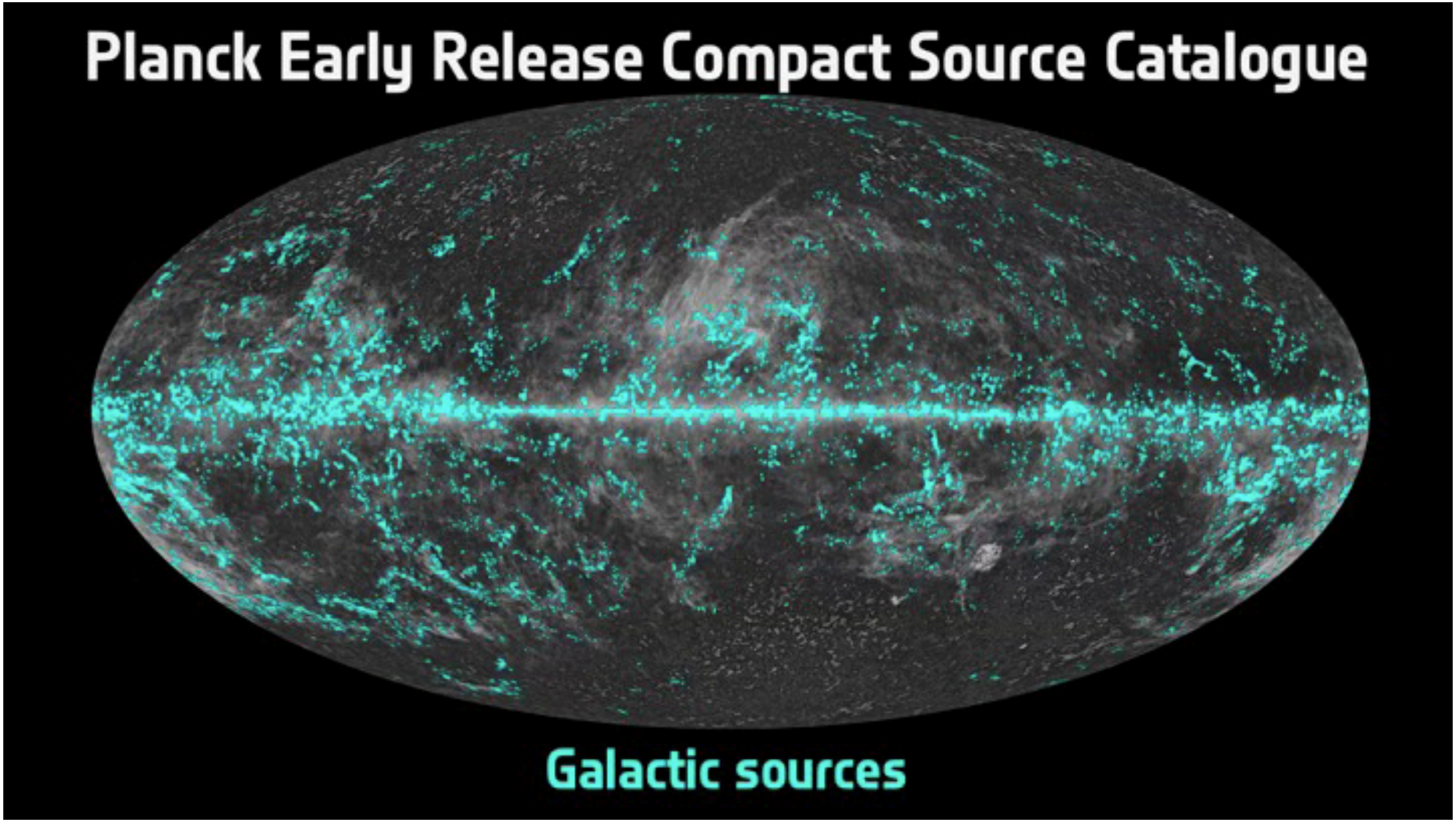
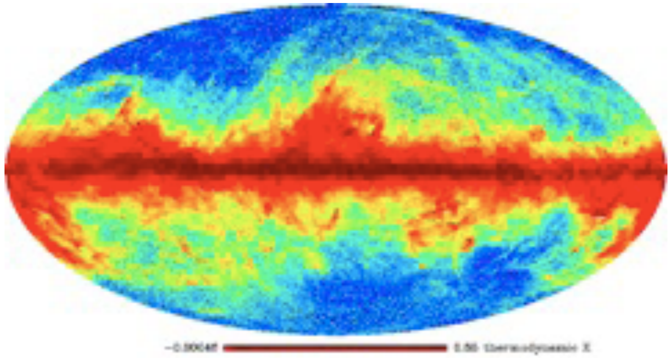
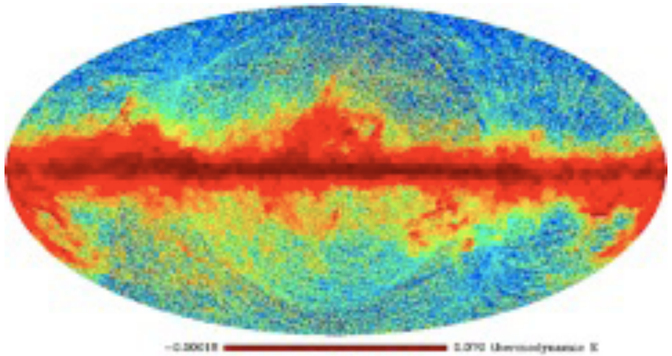


Figure 19. Processed TOI for the same bolometers and time range as shown in Fig. 4. Red samples are considered valid. Times where data are flagged, are indicated by the purple ticks at the bottom of each plot.

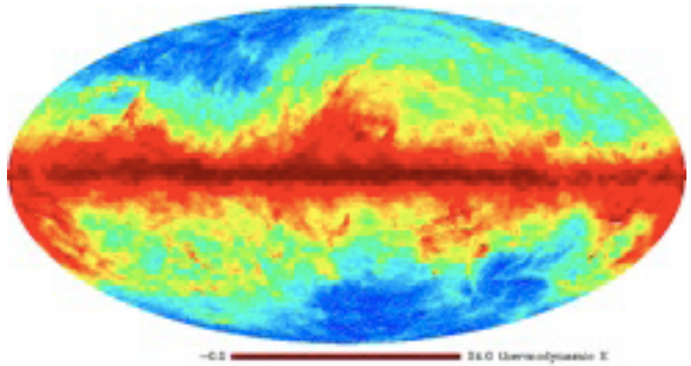

Planck Early Release Compact Source Catalogue
Galactic sources



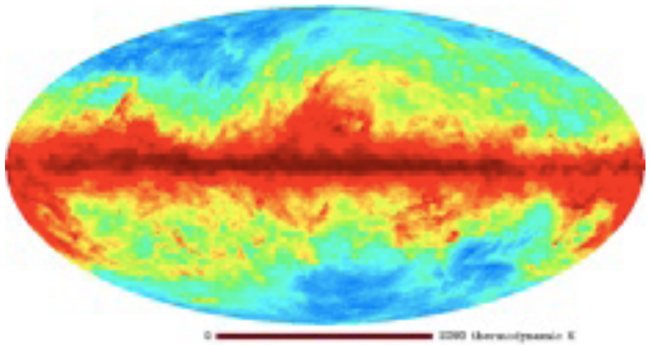
353 GHz



143 GHz



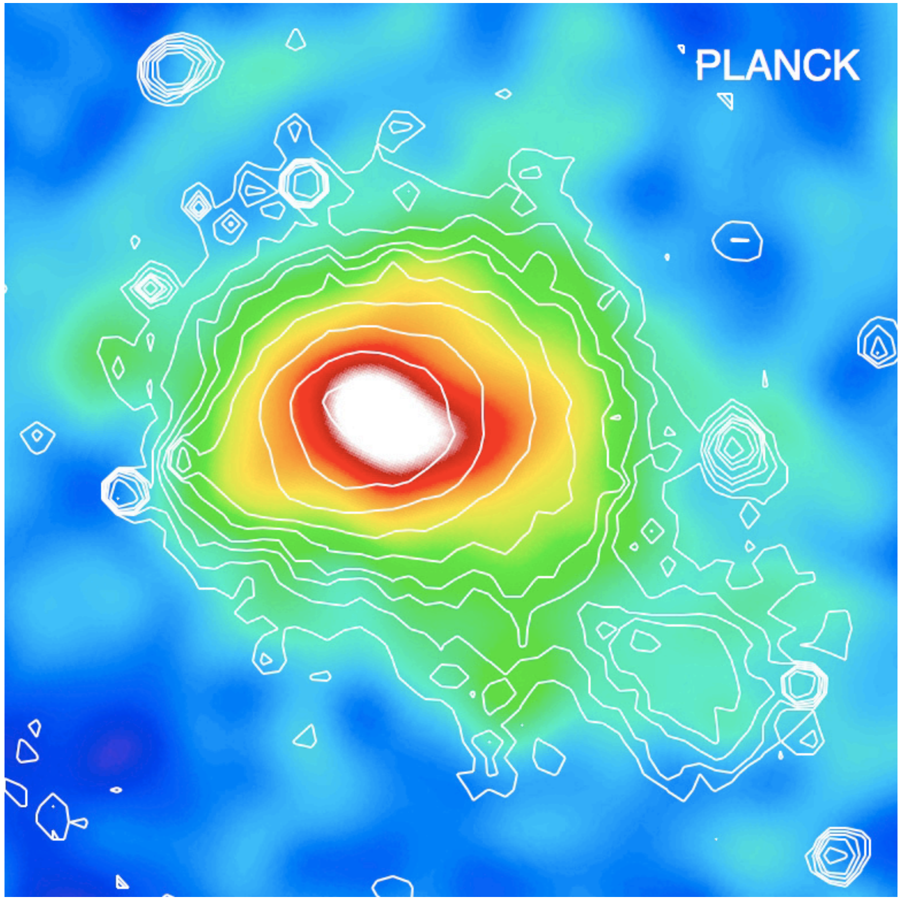
545 GHz



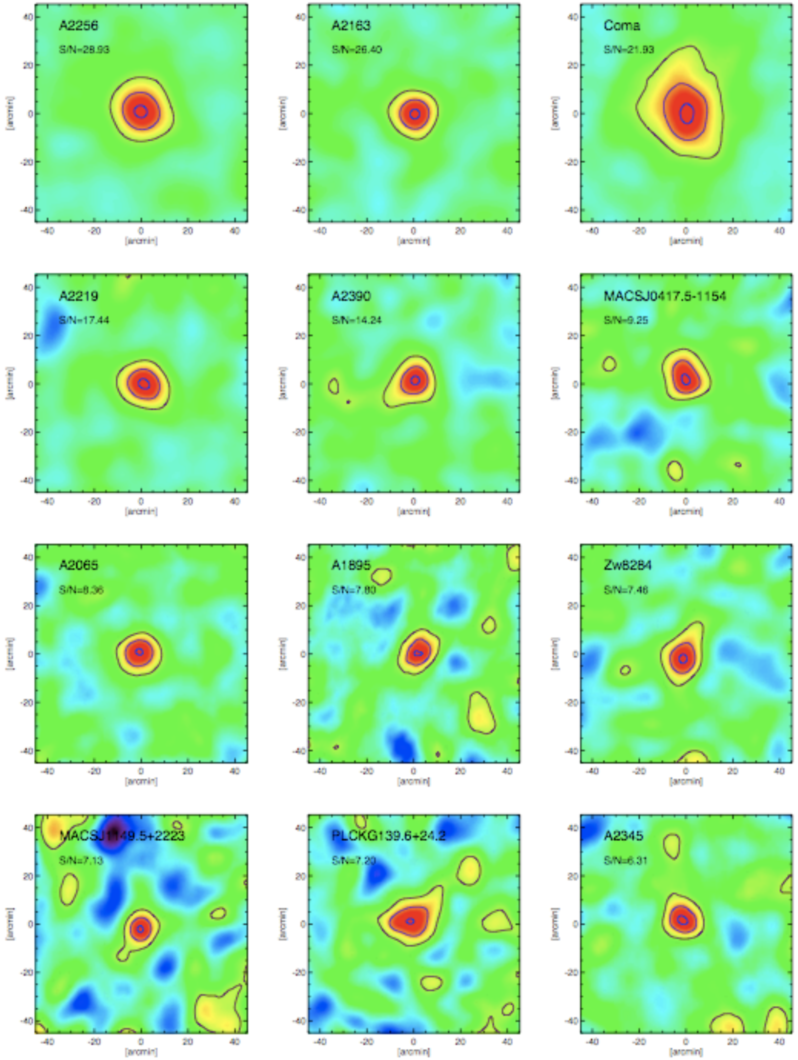
857 GHz

Effet SZ thermique avec Planck

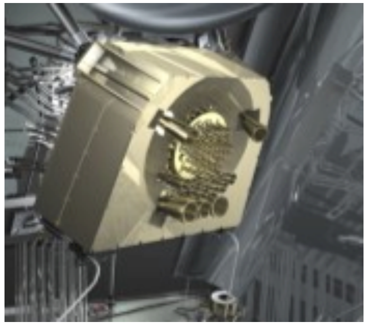
189 détections robustes des amas, dont 30 nouvelles…

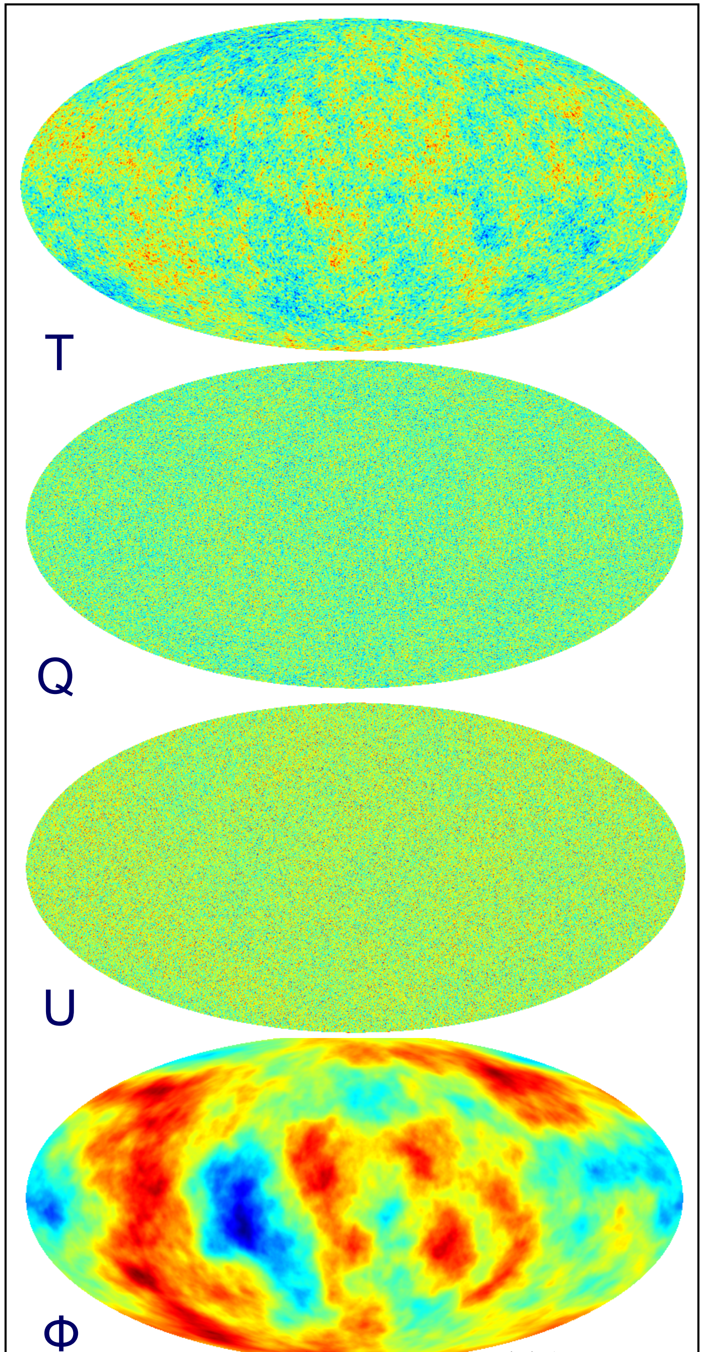


Coma: Planck (couleurs)
XMM (contours)



D. Santos (LPSC Grenoble)

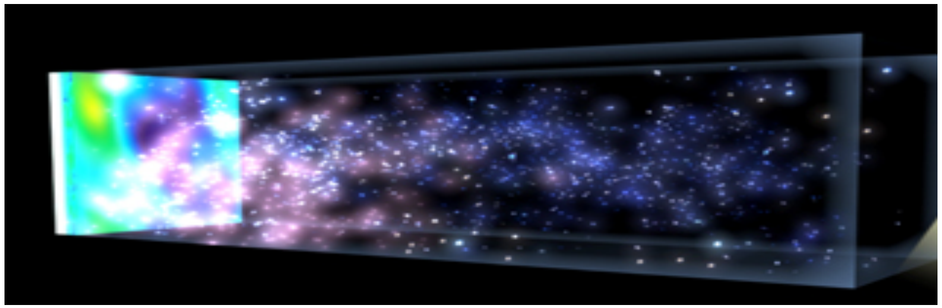




D. Santos (LPSC Grenoble)

Polarisation linéaire : (Q,U) Stokes par.

Mesurer le potentiel gravitationnel intégré :



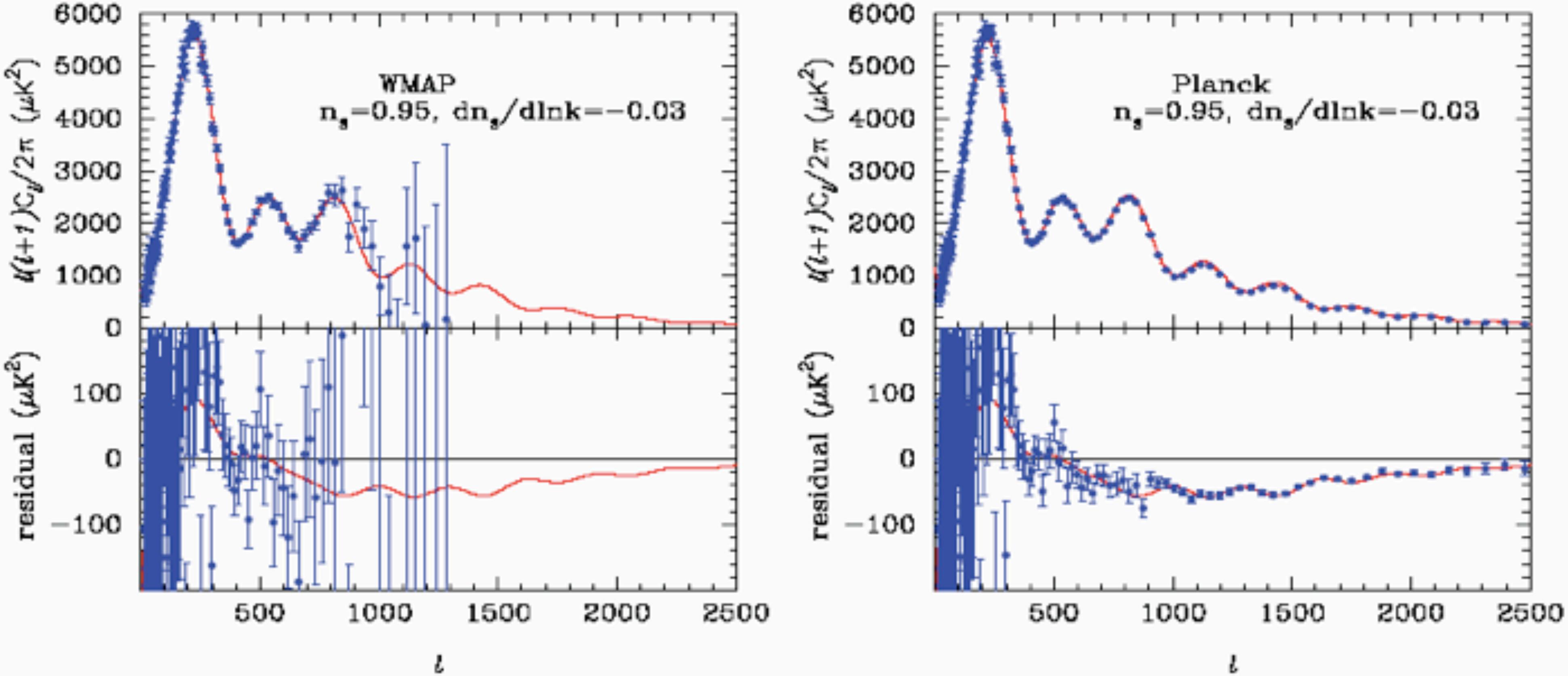
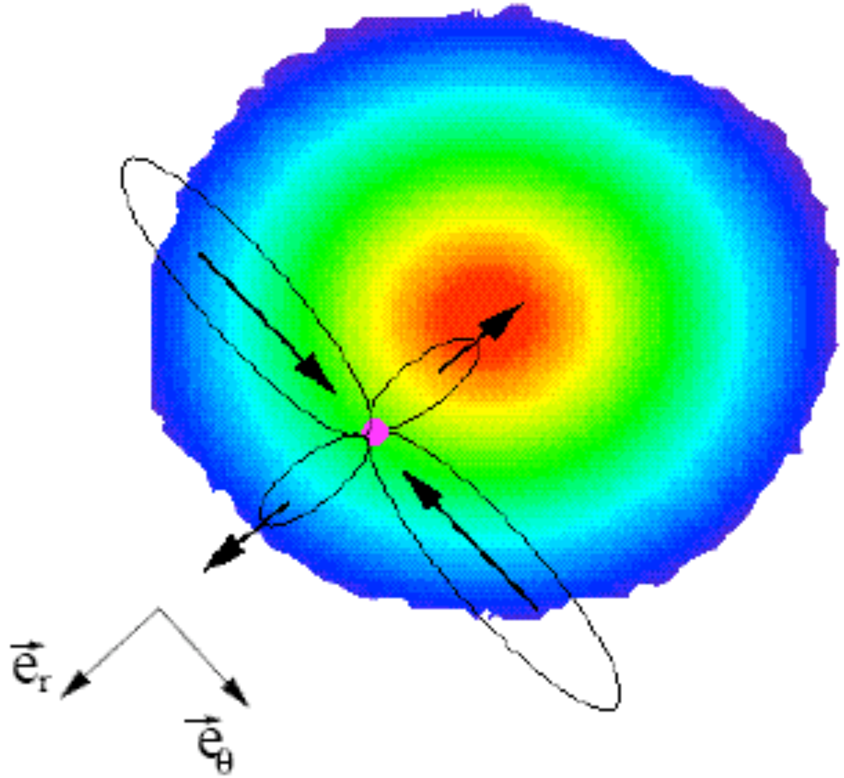
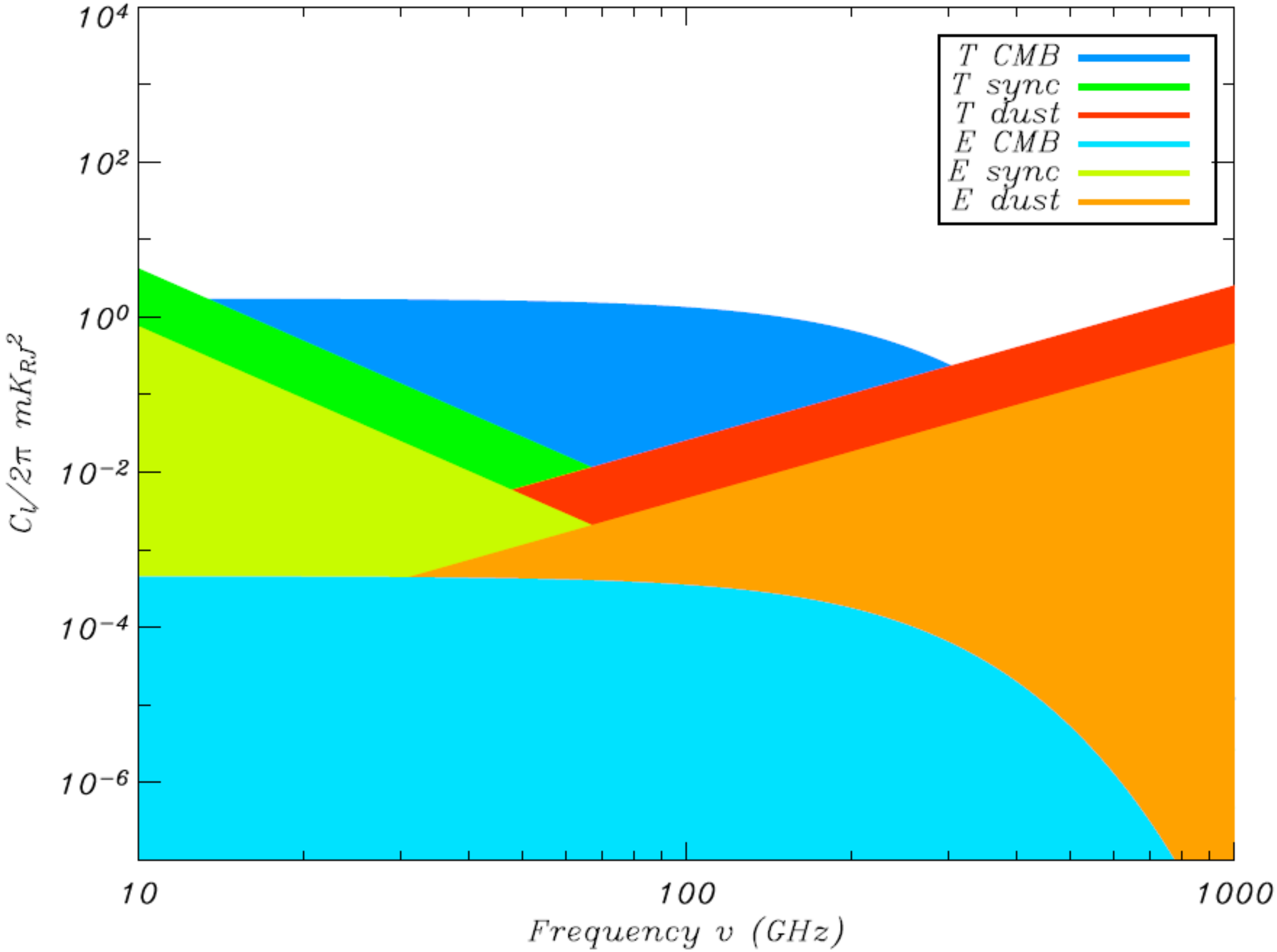


FIG 2.12.—Same as Figure 2.11, but now comparing the concordance ΛCDM model, having $n_S = 0.95$ and zero run (solid line), with a realisation of a model having with $n_S = 0.95$ (at a fiducial wavenumber of $k_0 = 0.05$ Mpc^{-1}) and a run of $dn_S/d\ln k = -0.03$.

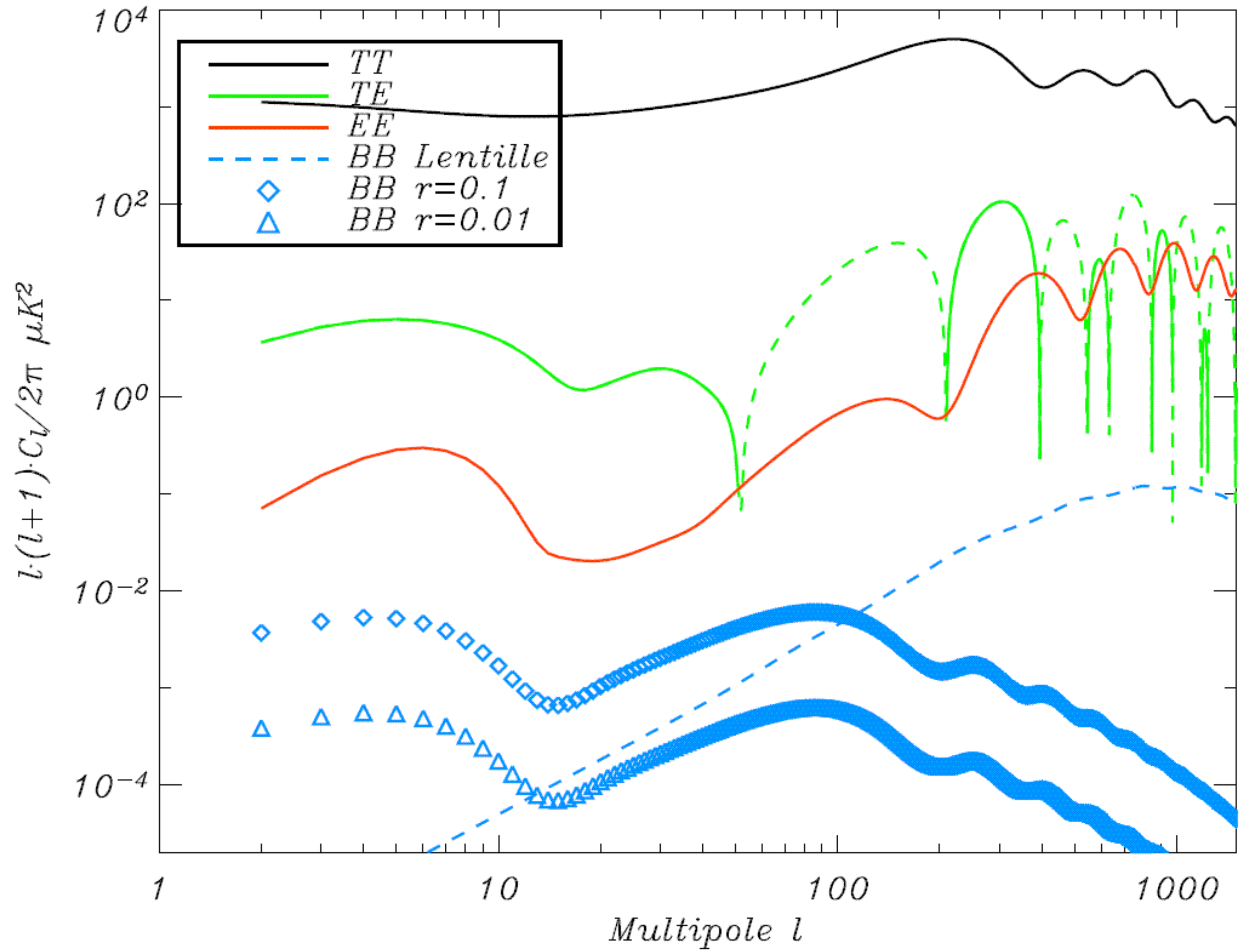


$$(Q \pm iU)(\hat{\mathbf{n}}) = \sum_{\ell,m} a_{\pm 2,\ell m} \cdot_{\pm 2} Y_{\ell m}(\hat{\mathbf{n}})$$

$$E(\hat{\mathbf{n}}) = -\sum_{\ell,m} \frac{1}{2}\left[a_{2,\ell m} + a_{-2,\ell m}\right] Y_{\ell m}(\hat{\mathbf{n}}) \ , \quad B(\hat{\mathbf{n}}) = \sum_{\ell,m} \frac{i}{2}\left[a_{2,\ell m} - a_{-2,\ell m}\right] Y_{\ell m}(\hat{\mathbf{n}})$$



T CMB
T sync
T dust
E CMB
E sync
E dust
$C_l/2\pi\ mK_{RJ}^2$
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10
100
1000
Frequency ν (GHz)


TT
TE
EE
BB Lentille
BB r=0.1
BB r=0.01
10^4
10^2
10^0
10^{-2}
10^{-4}
$l\cdot(l+1)\cdot C_l/2\pi\ \mu K^2$
1
10
100
1000
Multipole l

Prédiction des contraintes sur les paramètres cosmologiques

Méthodologie: Exploration de l'espace des paramètres par MCMC

➡ Estimation de $\mathcal{L}$ (paramètres)

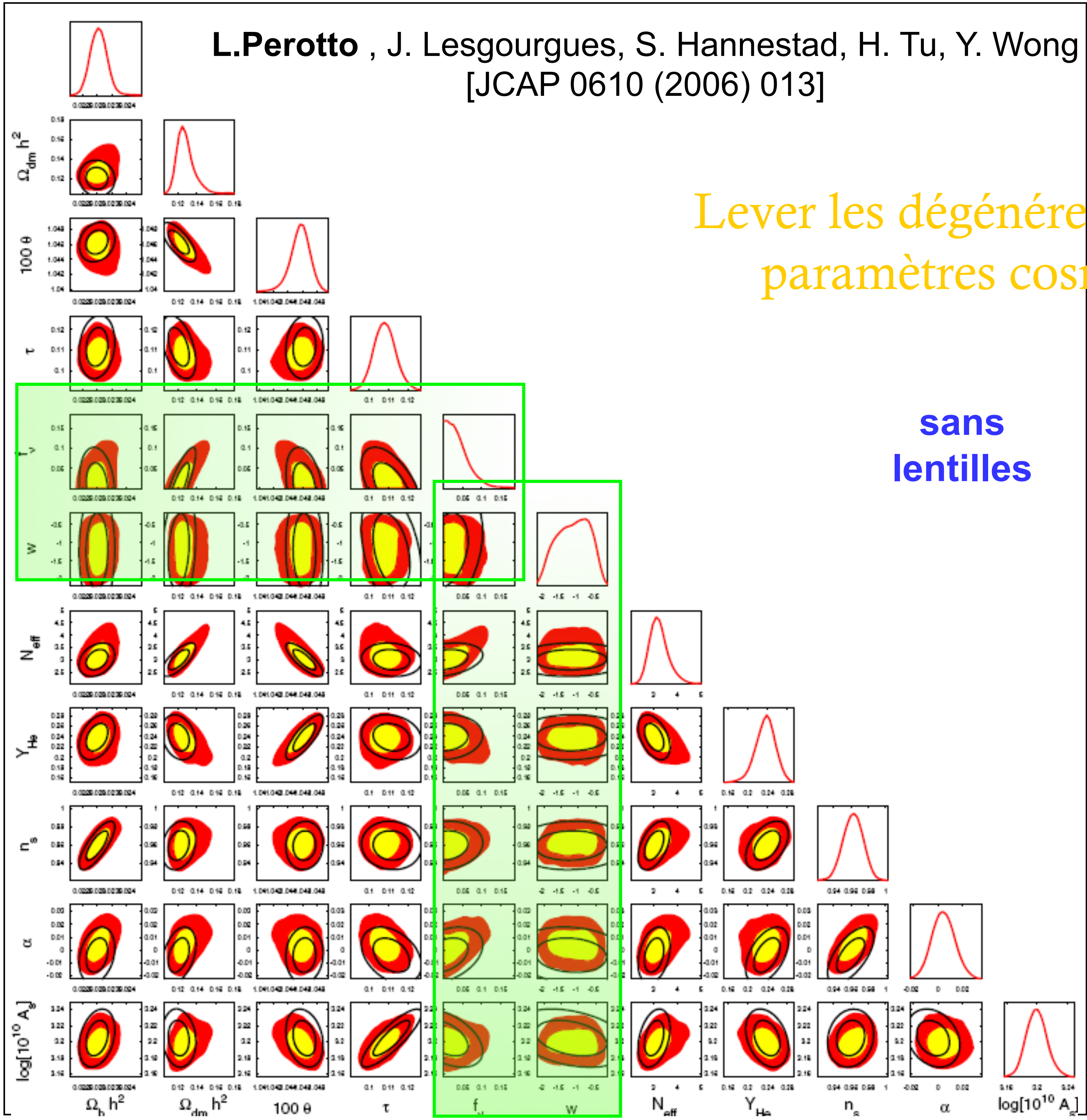
Choix du modèle cosmologique sous-jacent :

$$(\Omega_b h^2 , \Omega_m h^2 , \Omega_\Lambda , A_s , n_s , \tau , Y_{He} , \Sigma m_\nu , w, \alpha, N_{eff}) =$$
$$(0.022 , 0.134 , 0.73 , 0.8 , 0.98 , 0.12 , 0.24 , 0.1 , -1 , 0 , 3.04)$$

Modèle minimal

paramètre potentiellement détectable

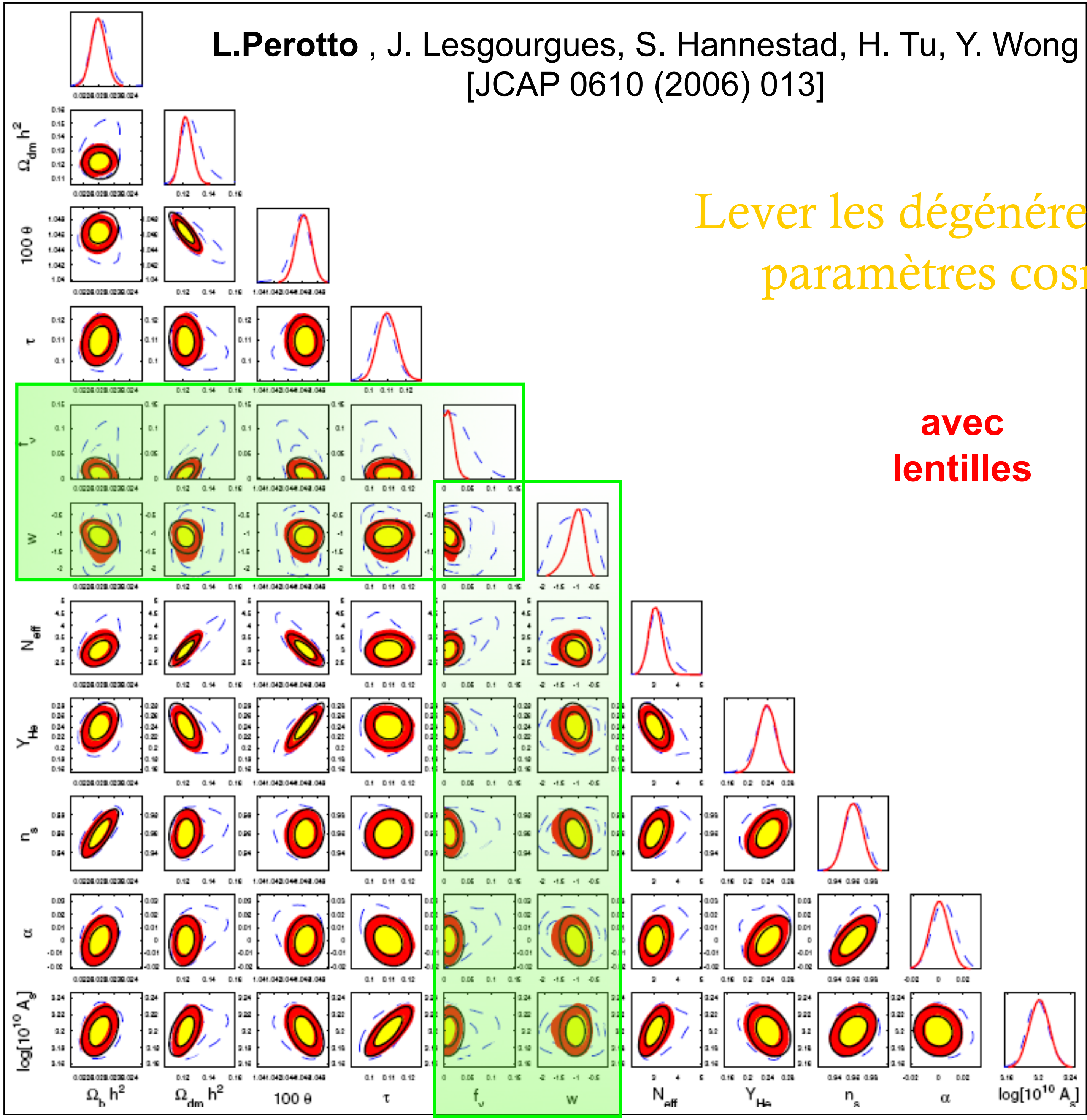
paramètres supplémentaires test des dégénérescences



Lever les dégénérescences sur les paramètres cosmologiques

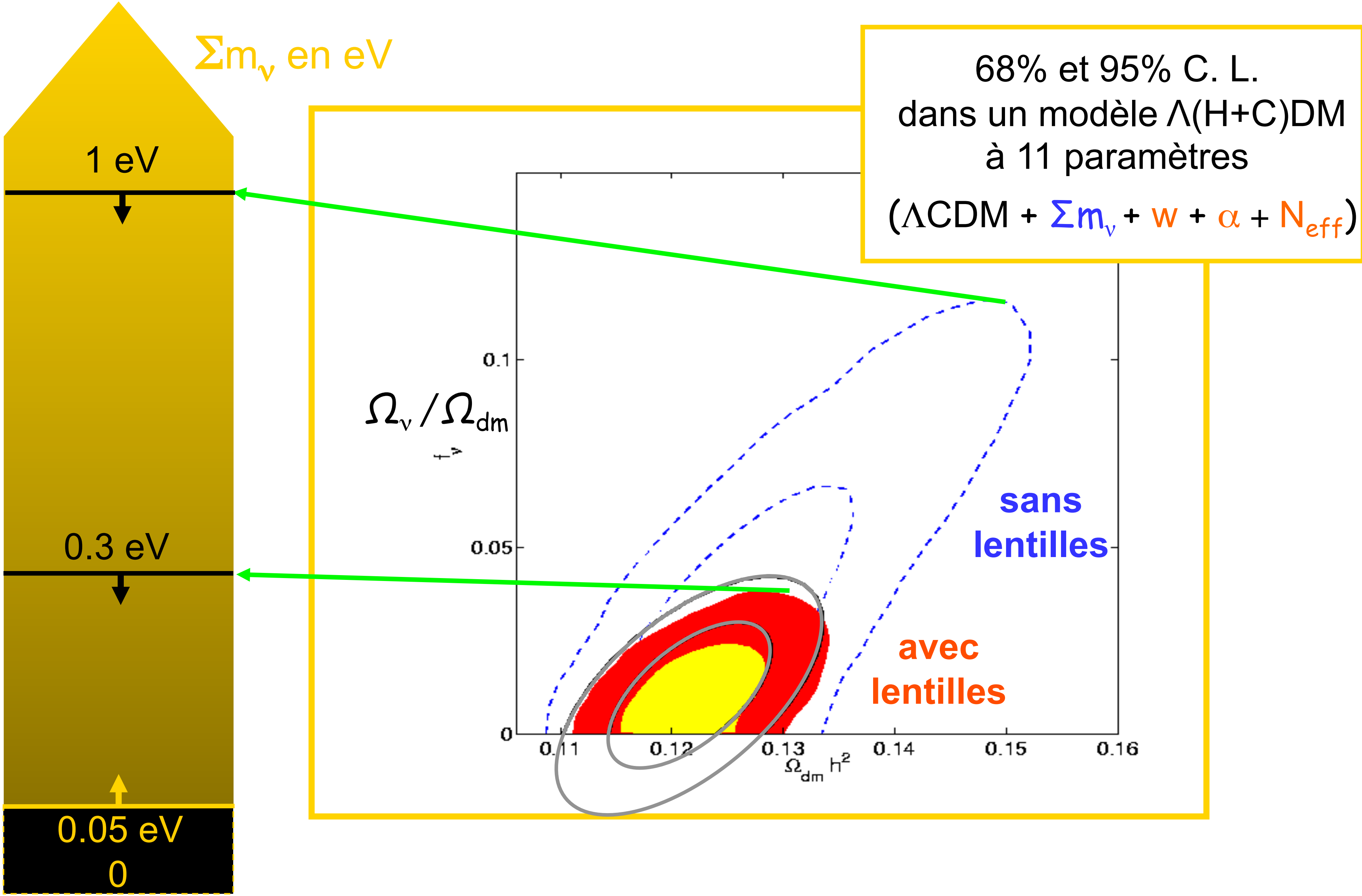
sans lentilles

Lever les dégénérescences sur les paramètres cosmologiques



avec lentilles

Contraindre la masse des neutrinos avec PLANCK



Non-baryonic Dark Matter

- DM hot (relativistic) : neutrinos **$\Omega_\nu h2 < 0.0067$ (95% CL)** (WMAP+2dFGRS)

- DM cold (not relativistic) : WIMPs, $M\chi \sim O(GeV)$

For WIMPs :

$$\Omega_\chi h^2 = \frac{O\left(10^{-9}\ GeV^{-2}\right)}{<\sigma_A v>}$$

avec $M\chi$ **= O(100 GeV)**

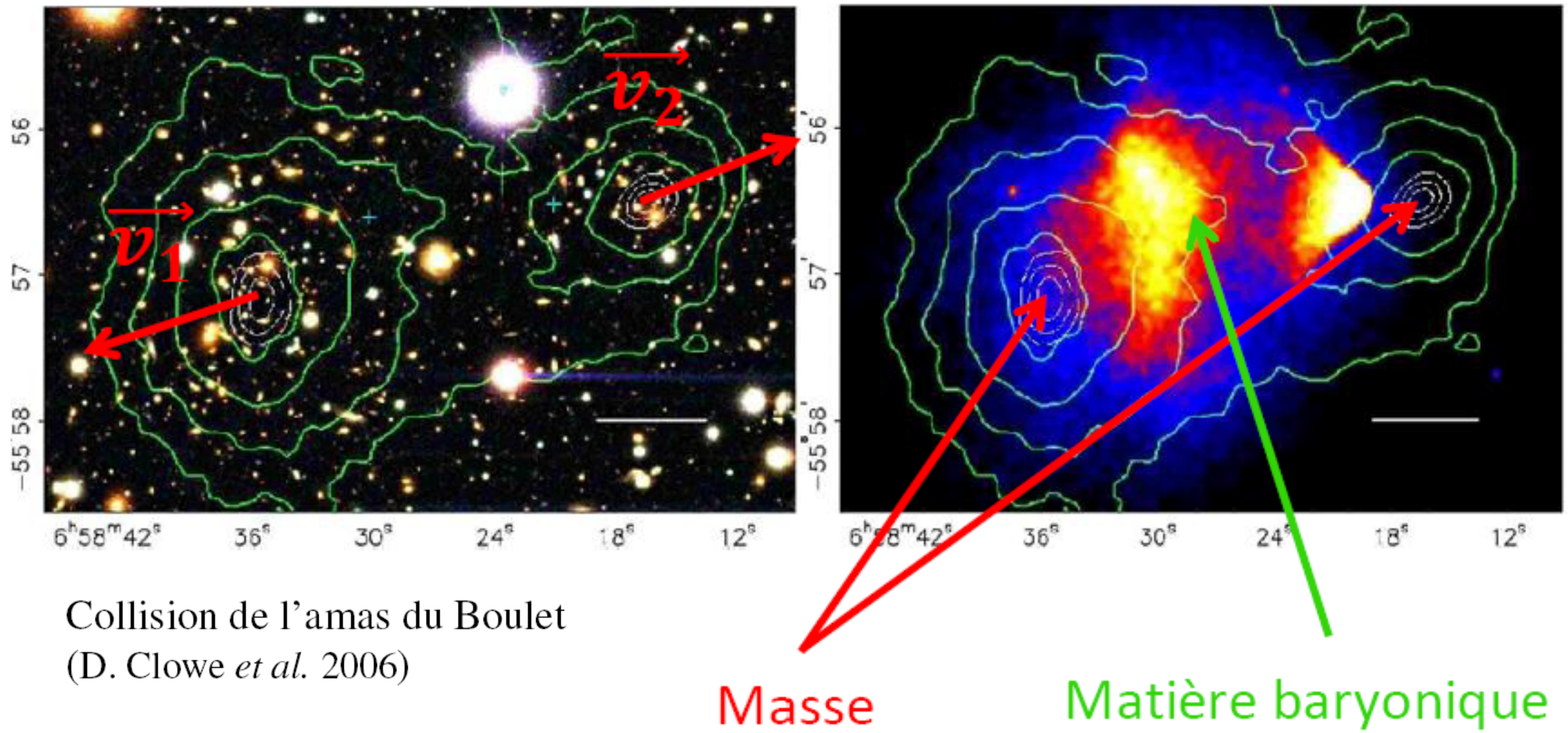
$\Rightarrow$ **$\Omega\chi h2 = O(0.1)$**

Most favorable candidate :

- **heavy : from 1 GeV to 1 TeV**
- **stable**
- **neutral**

À l'échelle des amas

(1E0657-558) Z= 0.296



Collision de l'amas du Boulet
(D. Clowe *et al.* 2006)

La matière non-baryonique est 6 fois plus importante que la baryonique

MIMAC

MIcro-tpc MAtrix of Chambers

A Large TPC for directional non baryonic Dark Matter detection

3rd International Workshop on Directional Detection of Dark Matter
June 7th-10th, 2011
Aussois (FRANCE)

LPSC Grenoble

CNRS IN2P3 Les deux infinis

MIMAC

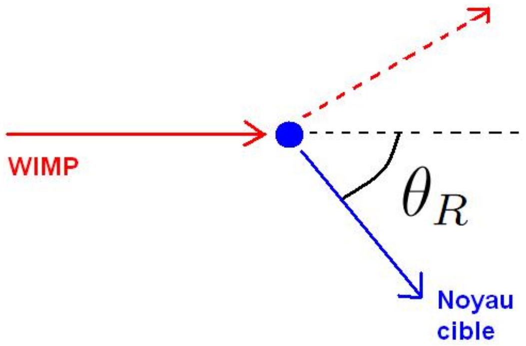
LPSC (Grenoble) : F. Mayet , J. Lamblin (starting 10/2011), D. Santos
J. Billard (Ph.D), C. Grignon (post-doc:10/08-10/10)
Technical Coordination : O. Guillaudin
- Electronics : G. Bosson, J-L. Bouly, O.Bourrion, J-P. Richer, J-P. Scordilis
- Gas detector : O. Guillaudin, A. Pellisier, M. Marton
- Data Acquisition: O. Bourrion
- Mechanical Structure: Ch. Fourel, S. Roudier, J-C. Malacour, D. Fombaron, S. Roni
- Ion source : P. Sortais, T. Lamy, J. Angot

CEA-Saclay (IRFU): I. Giomataris, E. Ferrer, F.J. Iguaz, J-P. Mols

IRSN (Cadarache): L. Lebreton, C. Golabek (leaving 10/2011)
(**CCPM (Marseille):** J. Busto , Ch. Tao (Tsinghua Univ.**)) (starting 06/2011)**

Fundings: ANR-Blanc (10/2007 – 10/2010) (IRSN contract (11/2010 – 11/2015)

Direct detection



Elastic collision of a Wimp with a gas target nucleus :

$$E_r = E_{\tilde{\chi}} r \cos^2 \theta_R$$

r : reduced mass

$$\frac{dR}{dE_r} = \frac{\sigma(E_r)\rho_0}{2 m_{\tilde{\chi}} m_r^2} F^2(E_r) \int_{v_{\min}}^{\infty} \frac{f_1(v)}{v} dv$$

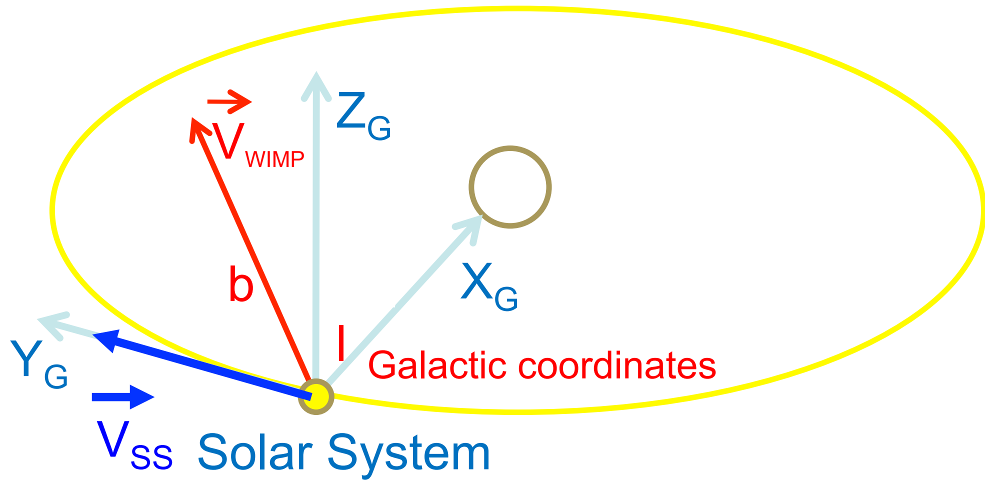
Differential rate as a function of the recoil energy

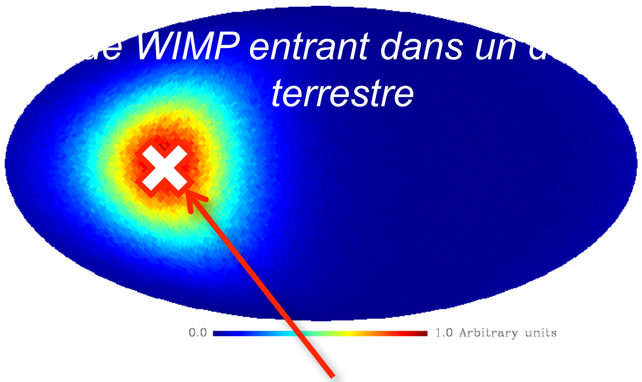
Galactic halo

Particle Physics

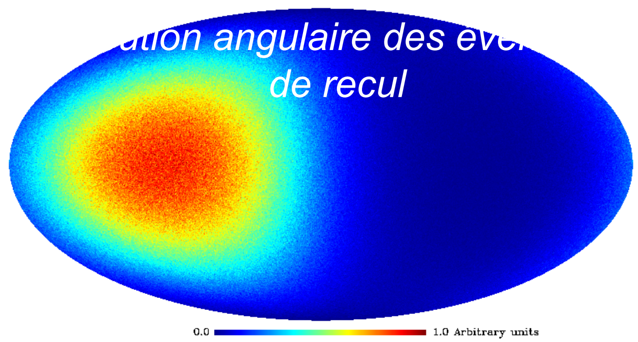
Nuclear Physics

Signal WIMP





Après collision



Cygnus Constellation (l = 90°,b = 0°)

Signal WIMP attendu

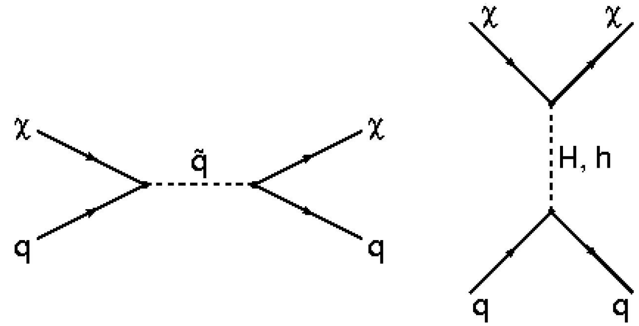
Direct detection : scalar vs axial

WIMP-quark interaction :

Scalar Interaction :

$$\sigma_{SI}(^{A}X) \propto \sigma_{SI}(p) \times A^{4}$$

Heavy nuclei : Ge, Xe, …

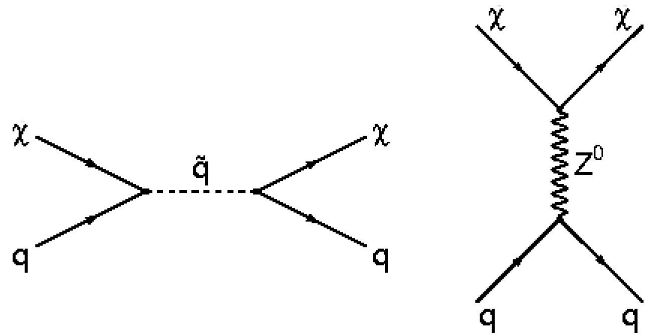


Axial Interaction : (spin coupling)

$$\sigma_{SD}(^{A}X) \propto \sigma_{SD}(p) \times A^{2}$$

Odd nuclei : ^{1}H, ^{3}He, ^{19}F,

Or… (^{73}Ge, ^{129}Xe)



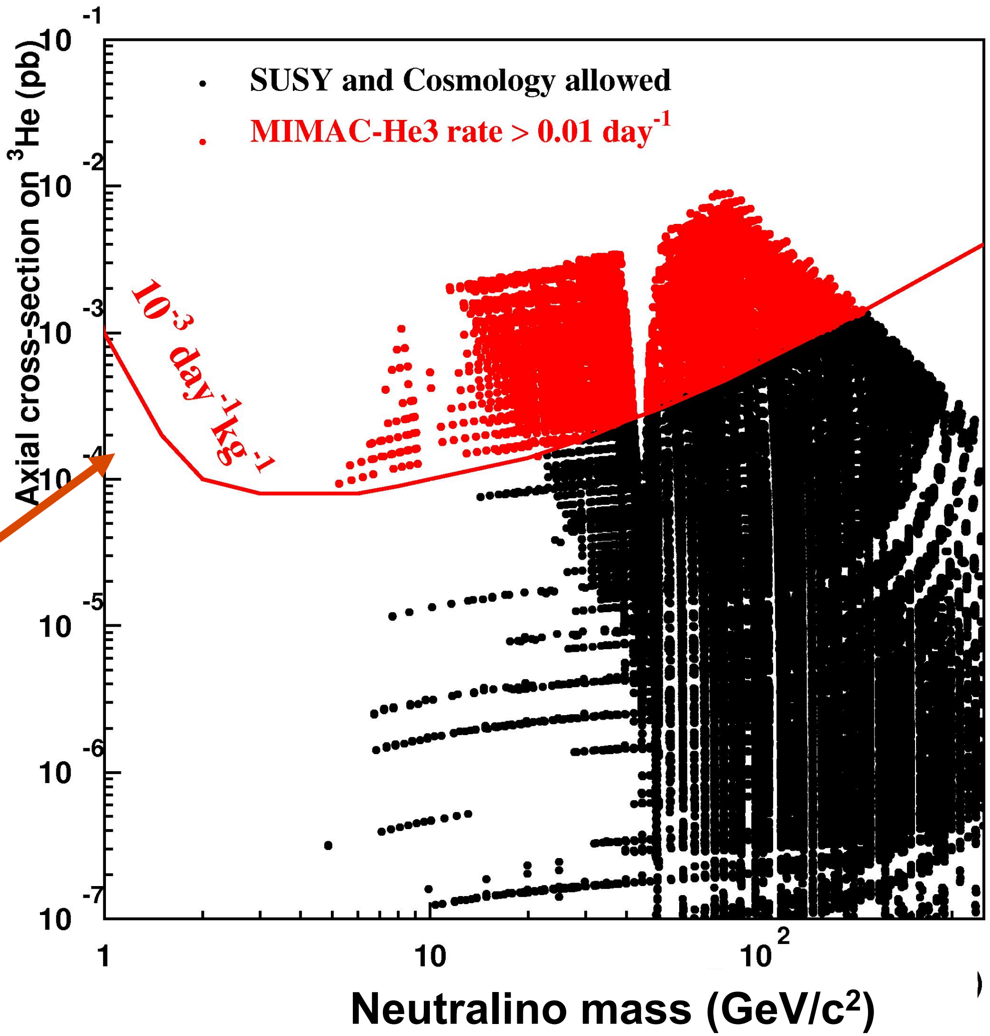
Complementary searches…

Very weakly correlated…

Axial cross section and event rate in MIMAC-^{3}He (10kg)

- $0.02 < \Omega_{\chi} h^2 < 0.15$
- Accelerator constrains

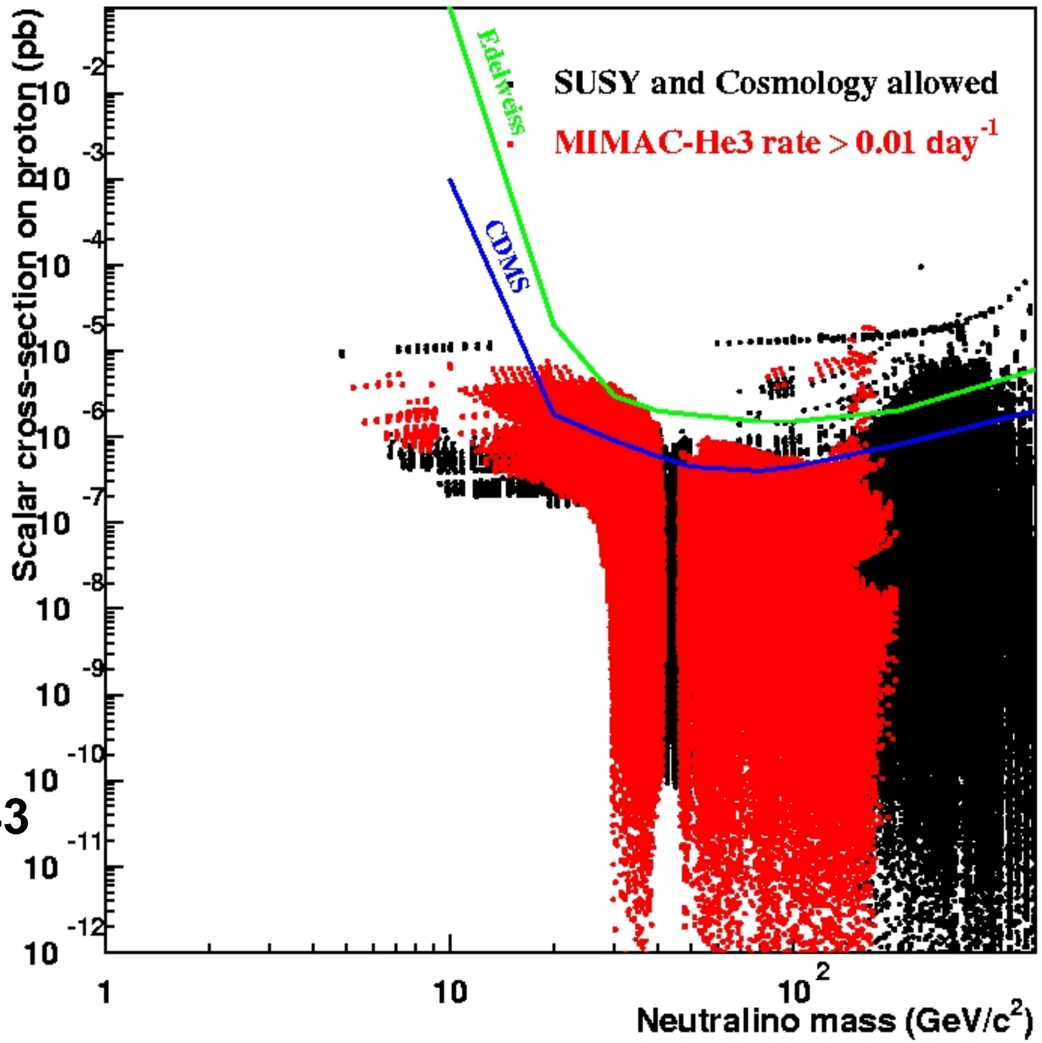
Exclusion curve for background 10^{-3} kg^{-1}jour^{-1}



D. Santos (LPSC Grenoble)

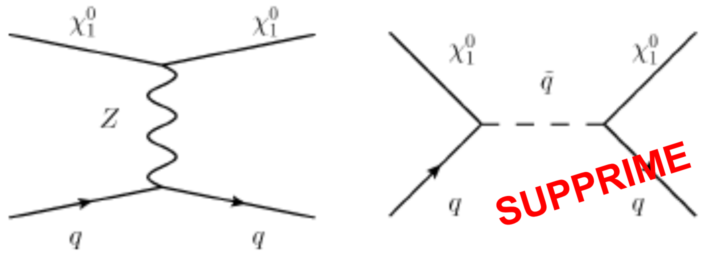
Complementarity with scalar detection

σ_{SD} and σ_{SI} not correlated



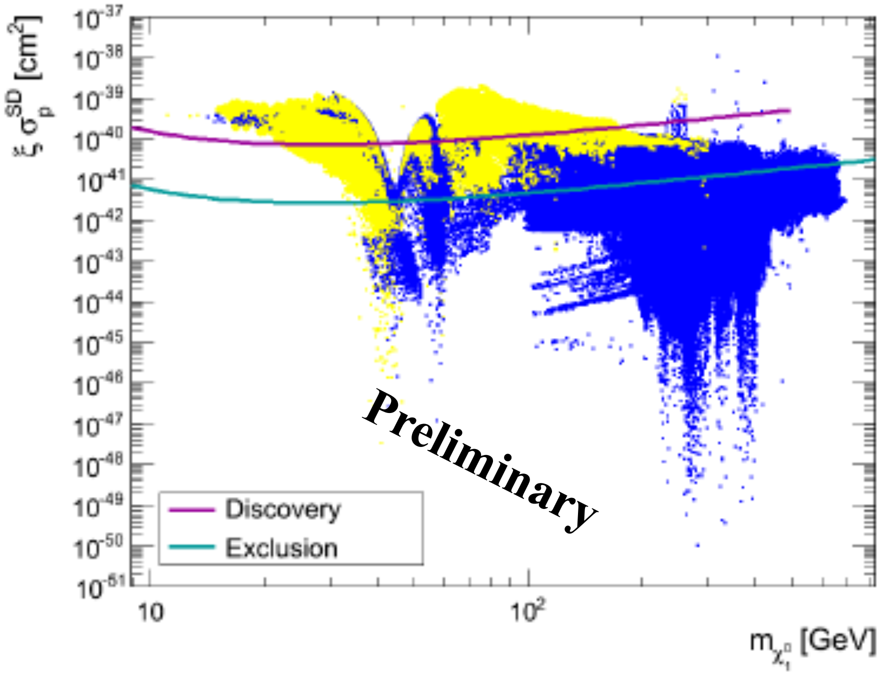
E. Moulin et al, PLB 614 (2005)143

Directionalité et SUSY



→ Squarks légers exclus au LHC (>1 TeV/c^2)

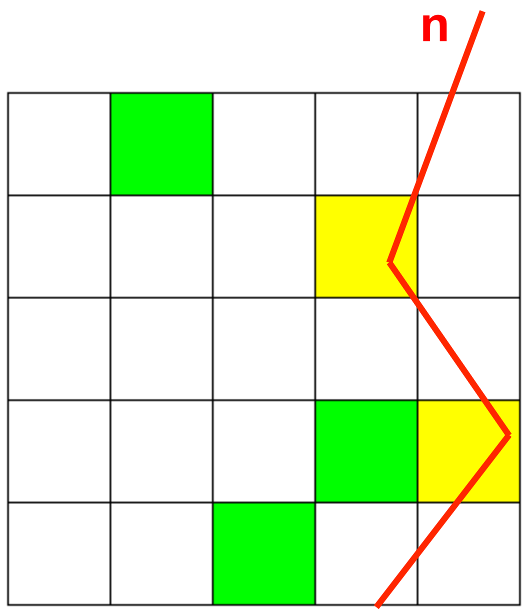
arXiV:1109.6572 (ATLAS col.)



→ de nombreux modèles accessibles (MSSM, NMSSM)

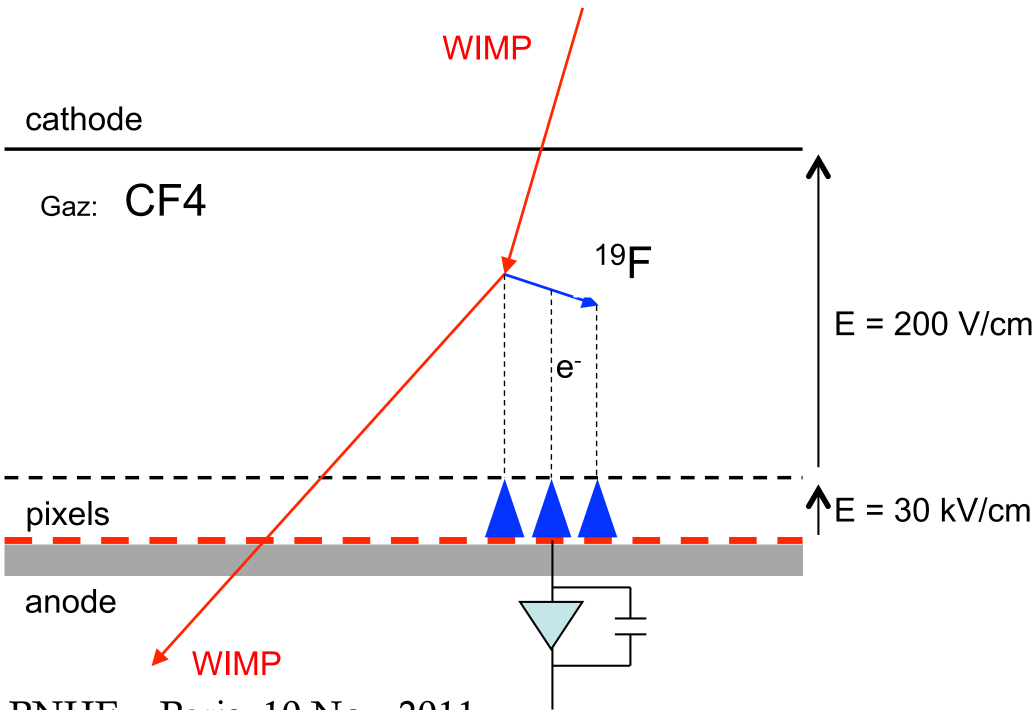
Collaboration : D. Albornoz Vasquez & G. Bélanger (LAPTH) (publication en cours)

MIMAC



Strategy :

- Matrix of micro-TPC
- Directional detection (energy and 3D track)
- Multi-targets (1H,^{3}He, ^{19}F) ➡ σ(A)
- Axial interaction
- ^{3}He, CH_4, C_4H_{10}, CF_4 ➡ Tested !

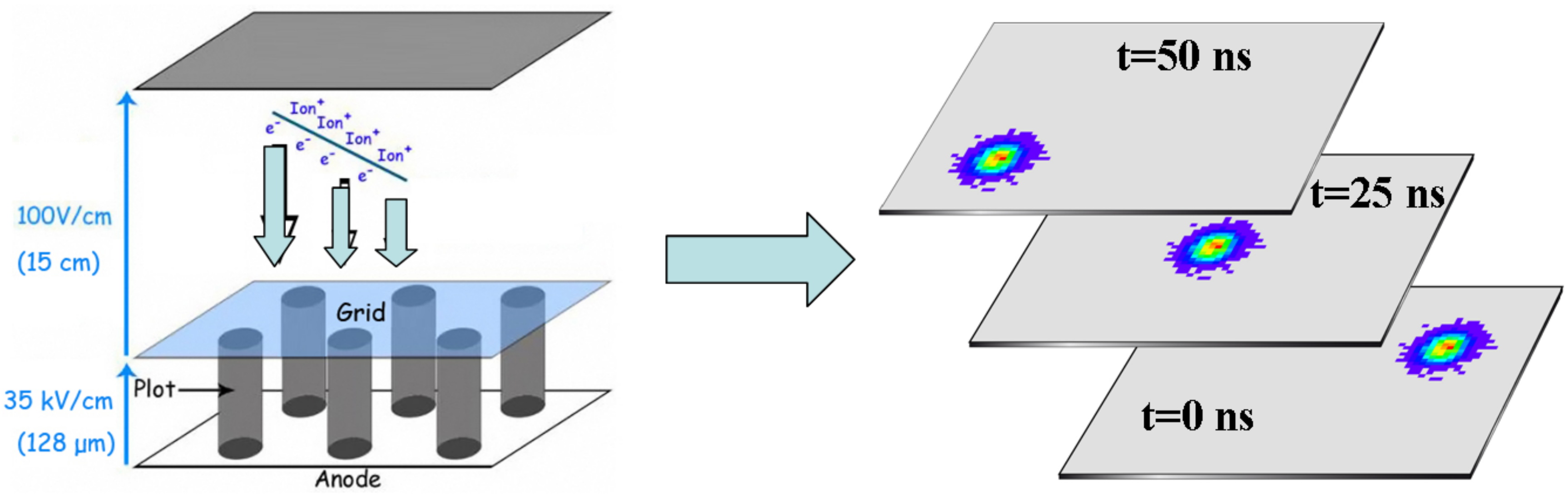


- TPC low pressure (~50 mbar)
- Micromegas (CEA Saclay)
- Tracks of a few mm and keV

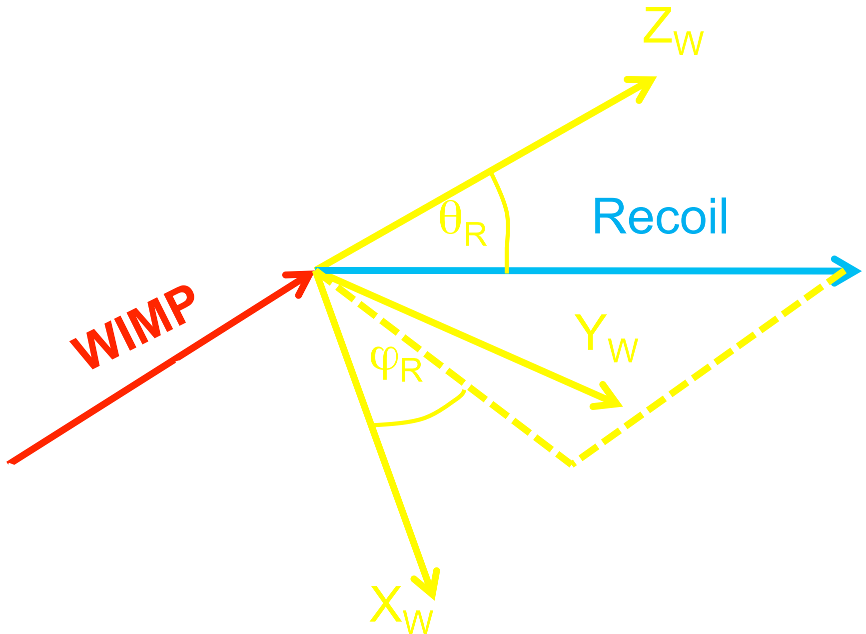
Rejection based on :

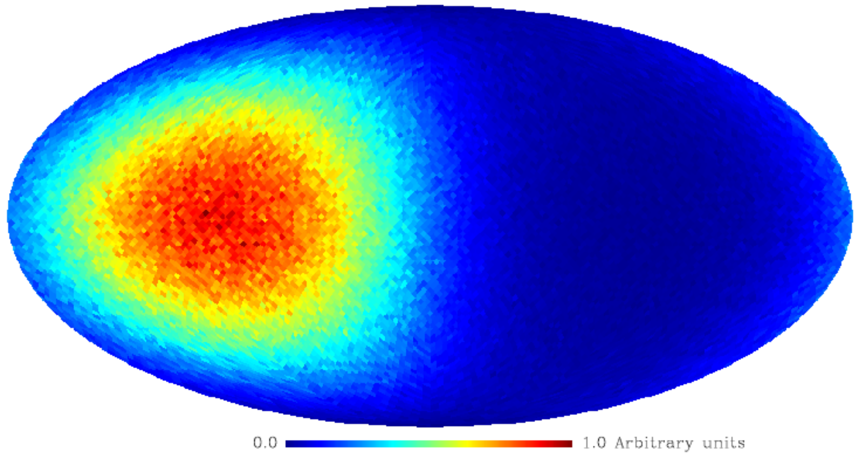
- Energy and 3D-track : e-/nuclei
- Correlation of μTPCs (neutrons)

3D Detection principle



Directional Detection

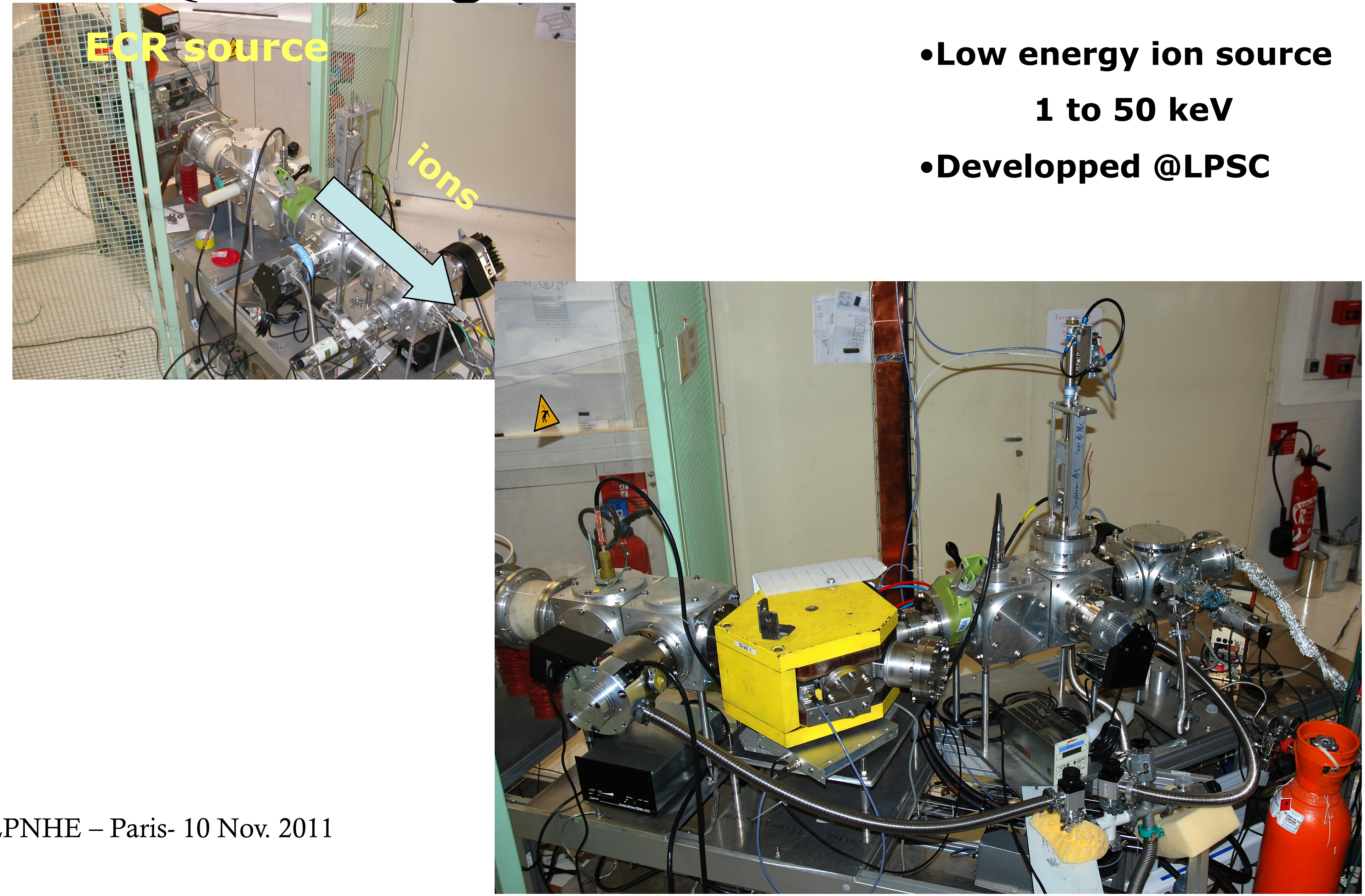




Map of recoils in galactic coordinates (HealPix)

10^8 Events with E_R = [5,50] keV

Quenching factor measurement

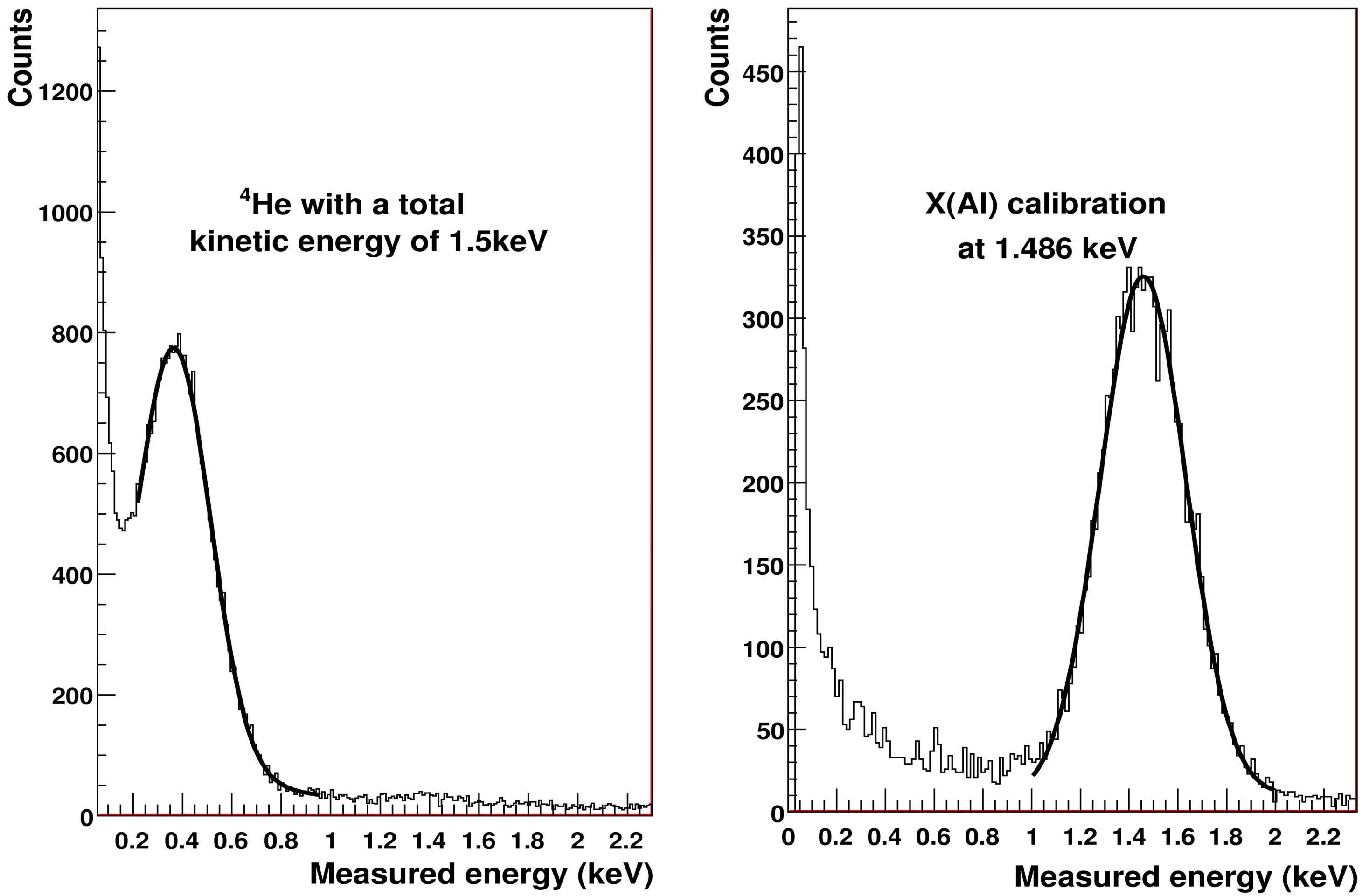


- Low energy ion source

  1 to 50 keV

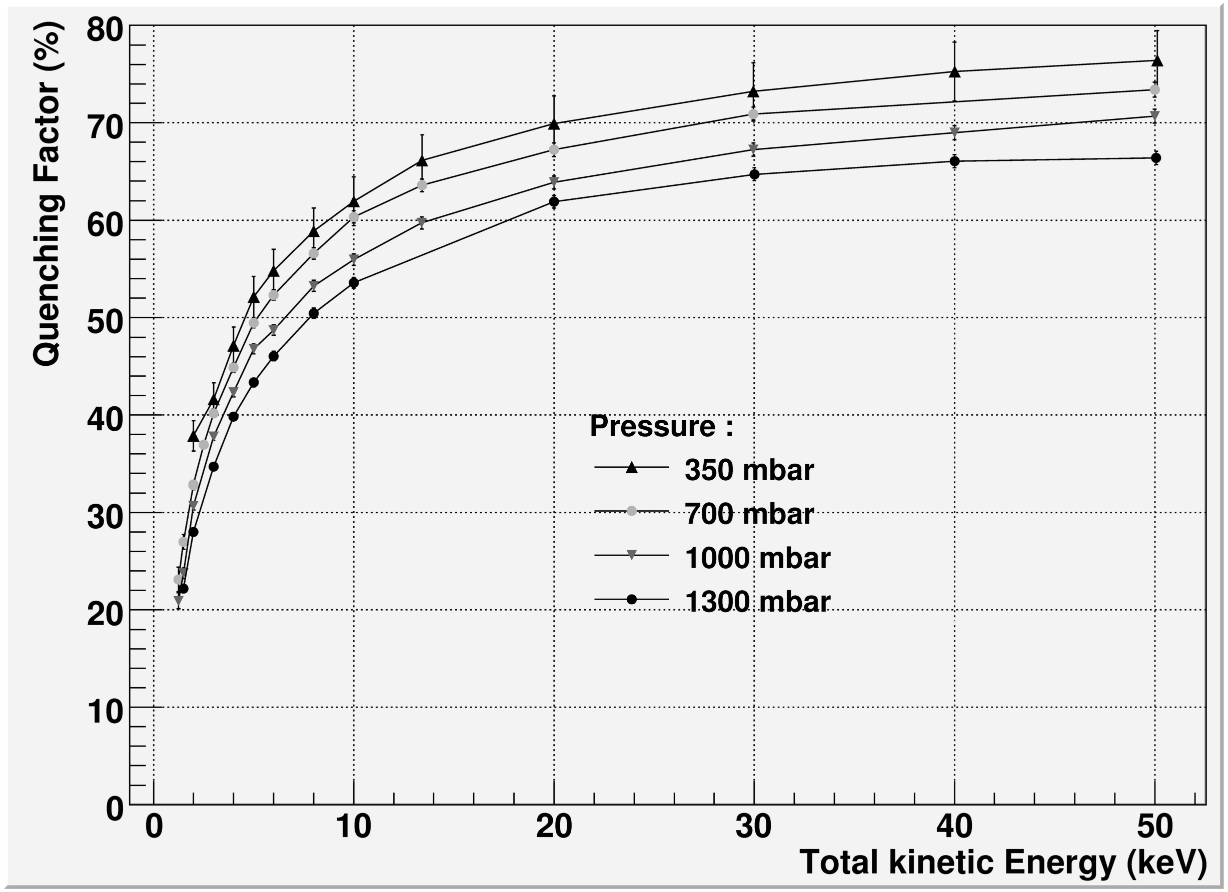
- Developped @LPSC

Detection of ^{4}He (recoils) of 1.5 keV !!
(95% ^{4}He + 5% iso) at 700mbars



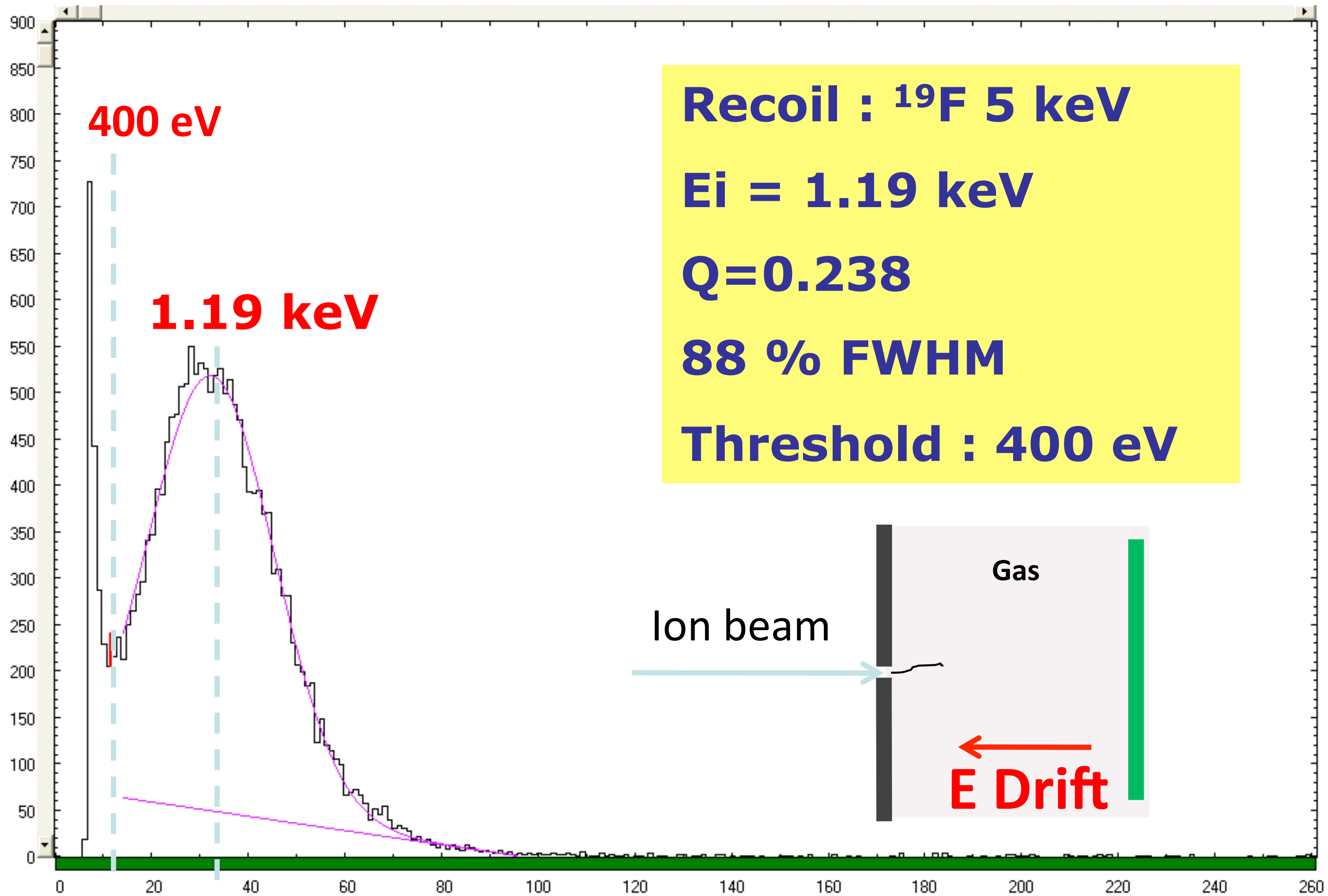
IQF Measurement of ^{4}He in 95% ^{4}He + 5% C_4H_{10} as a function of the pressure

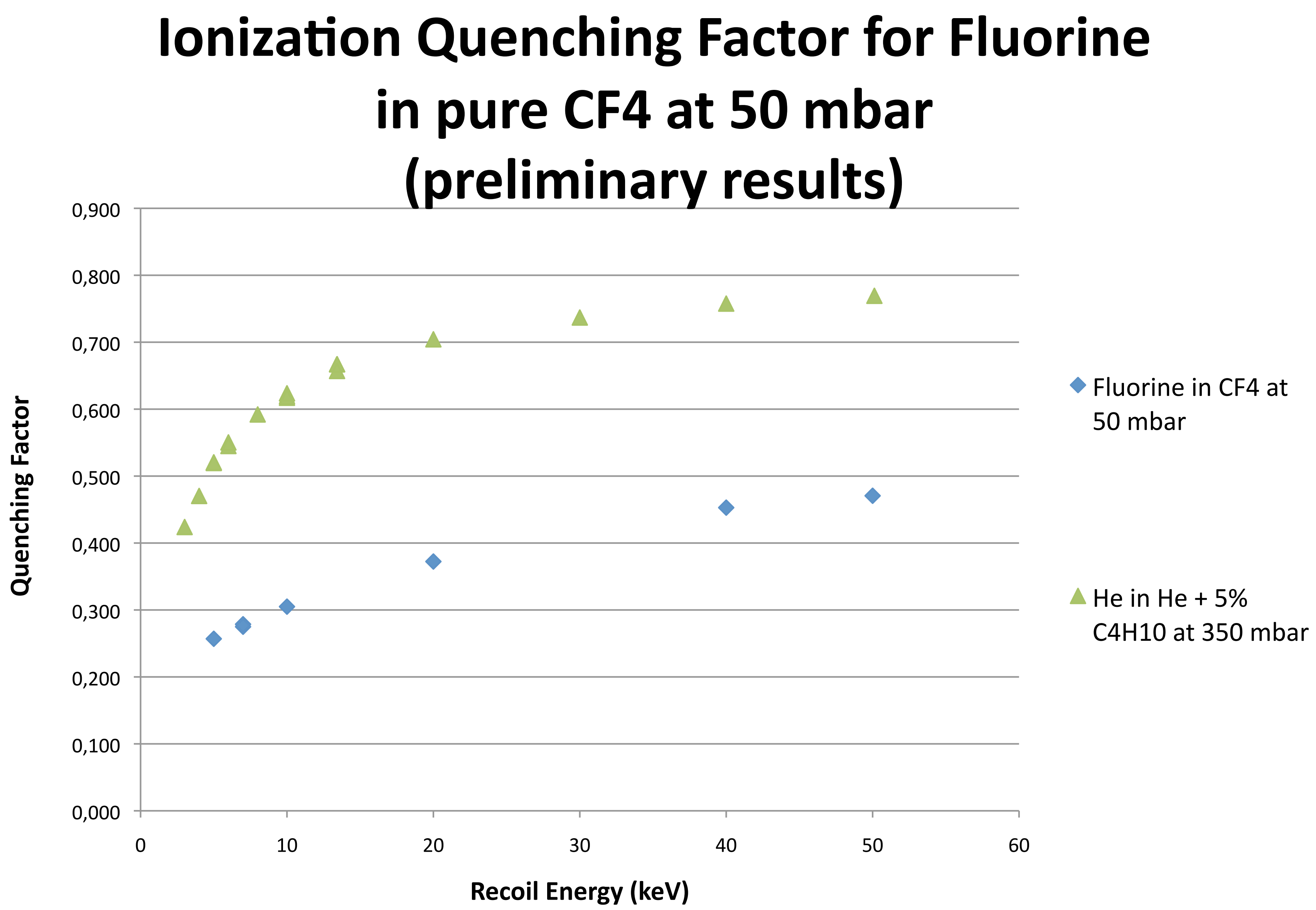
D. Santos et al. arXiv:astro-ph0810.1137



5keV ^{19}F Recoil in 60 mbar

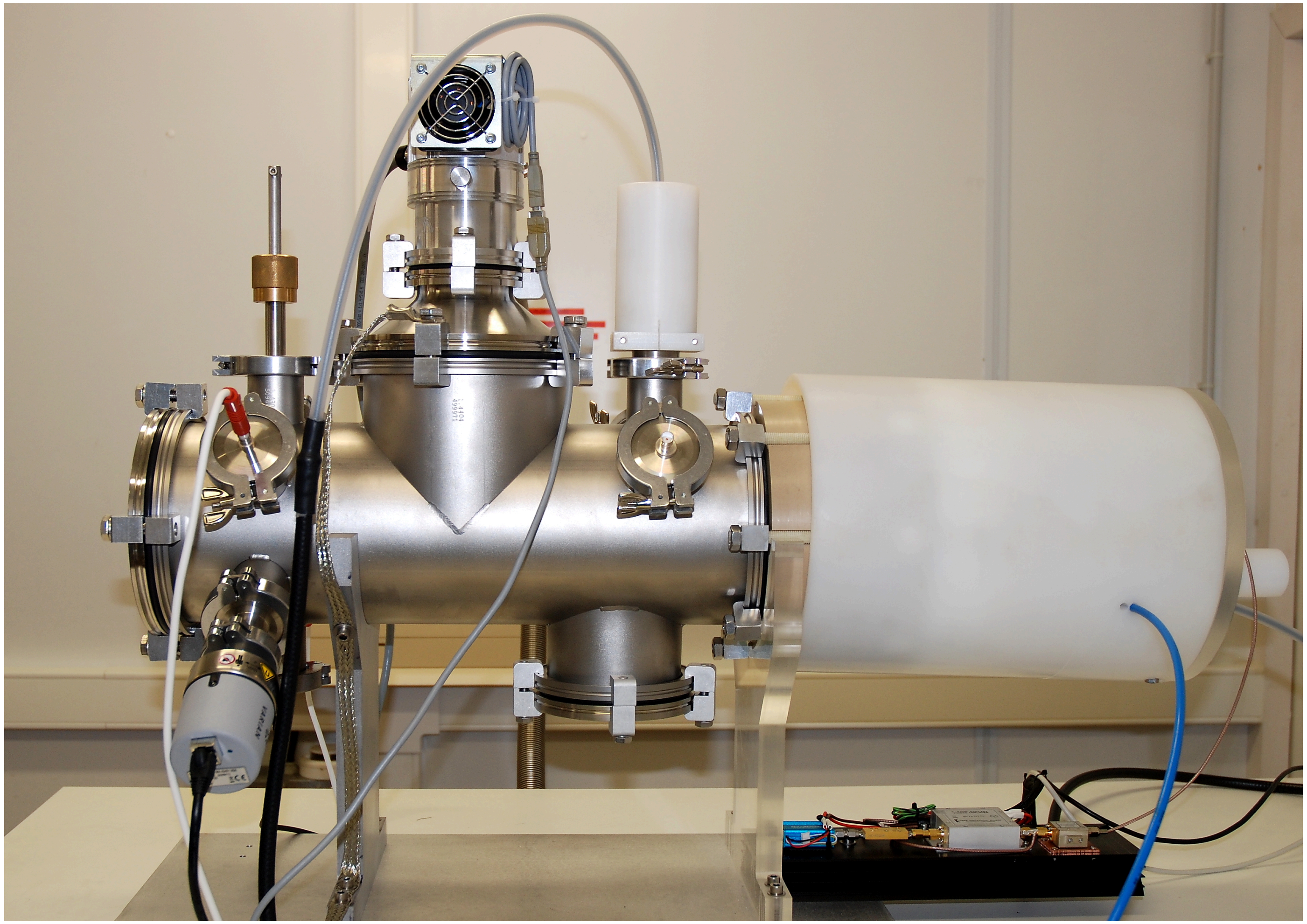
40mbar CF4+16.8mbar CHF3+1.2 mbar Isobutane





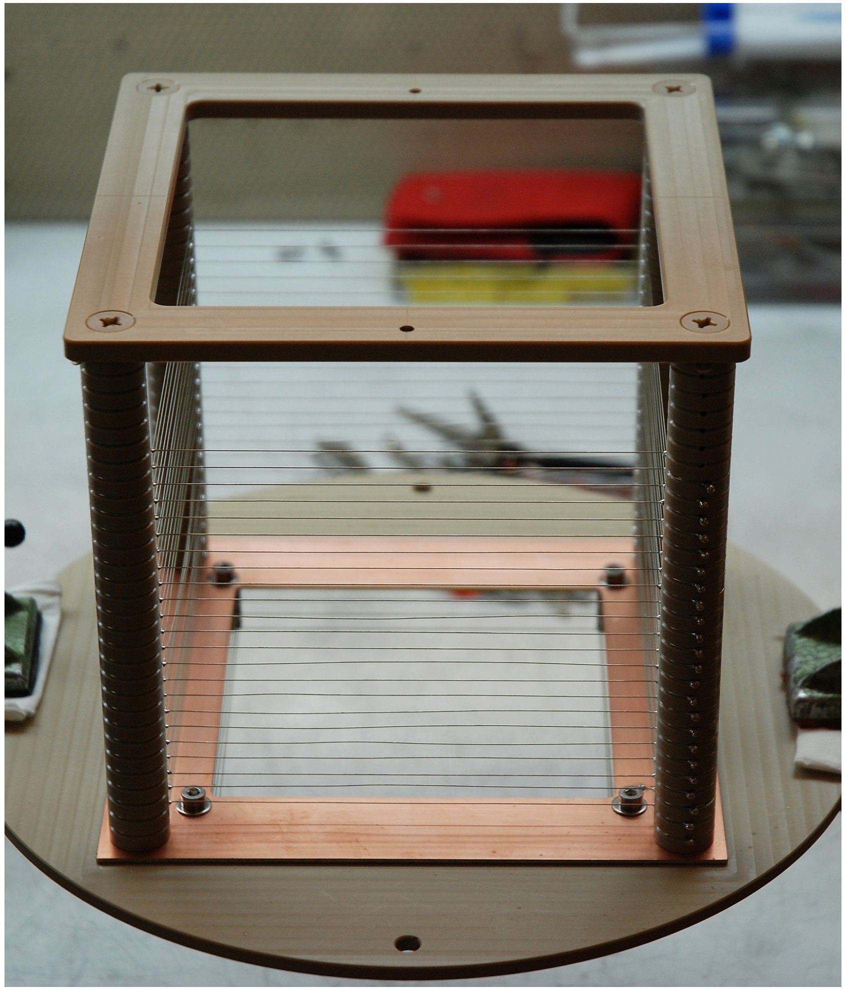
Ionization Quenching Factor for Fluorine
in pure CF4 at 50 mbar
(preliminary results)
Quenching Factor
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0
10
20
30
40
50
60
Recoil Energy (keV)
Fluorine in CF4 at 50 mbar
He in He + 5% C4H10 at 350 mbar

New Ion Source for calibration (quenching) purposes (COMIMAC)

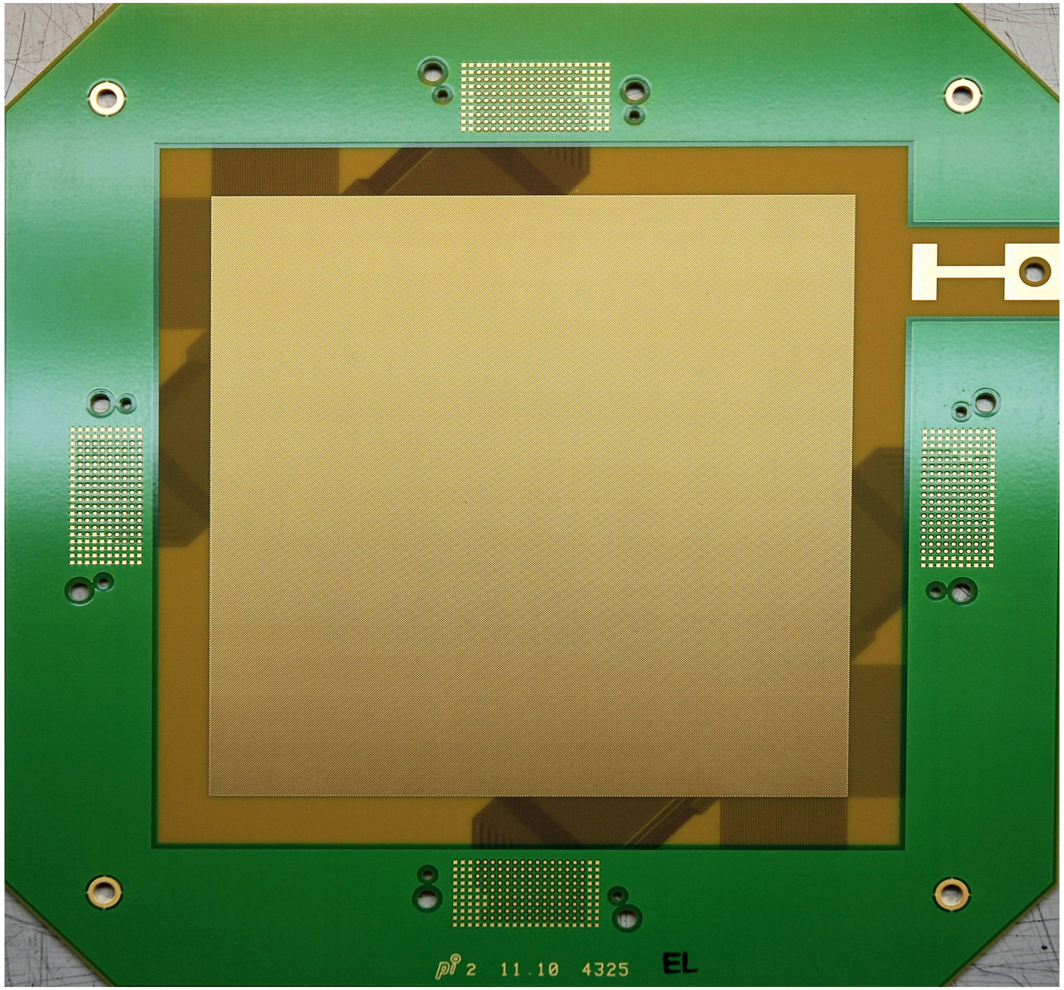


D. Santos (LPSC Grenoble)

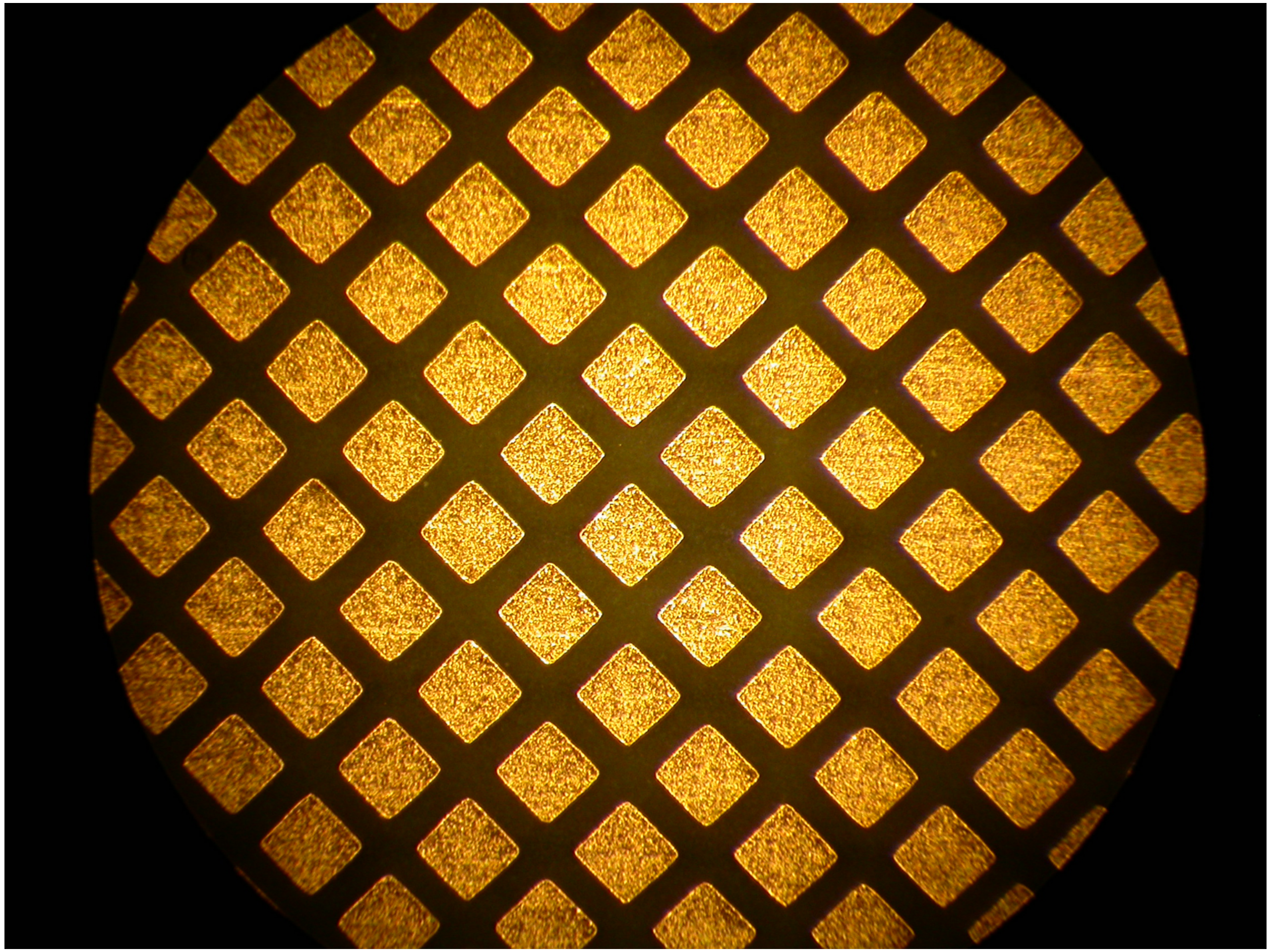
Drift volume – charge collection



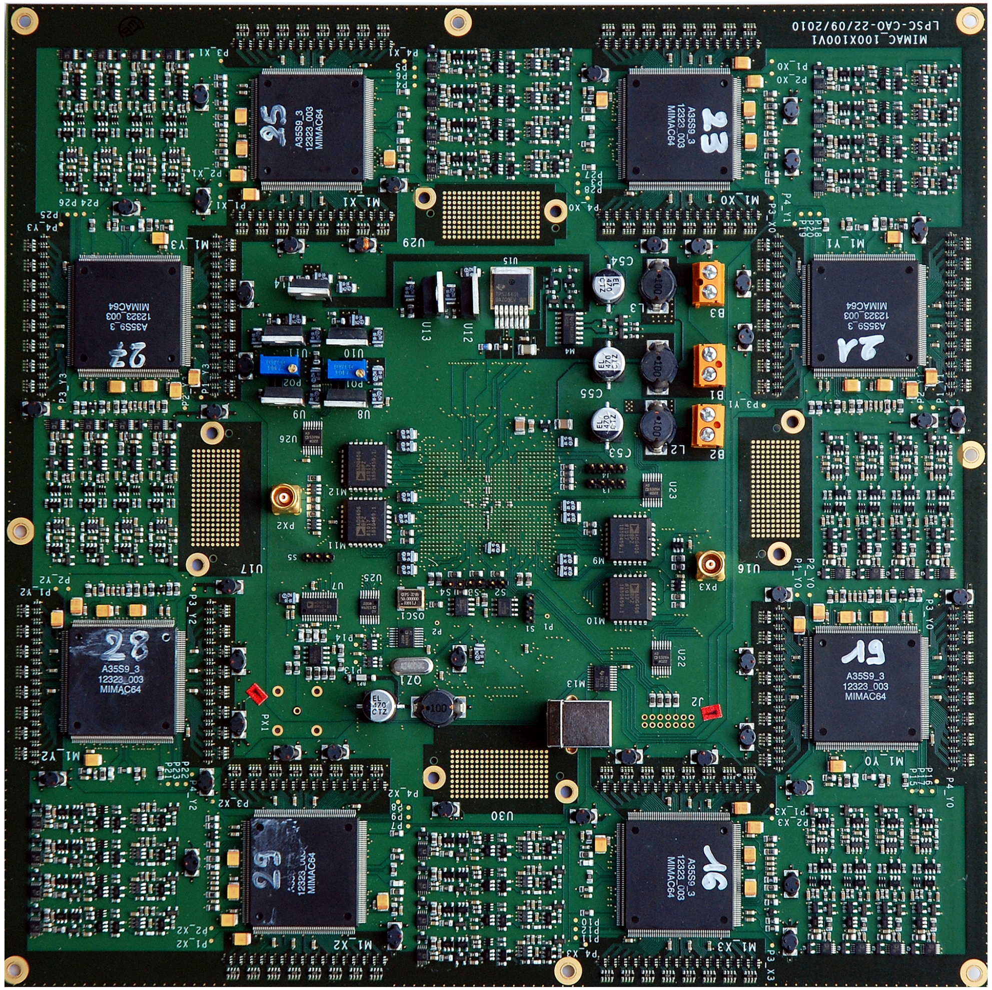
The MIMAC-micromegas 100x100 (bulk)



MIMAC 100x100 (v2)

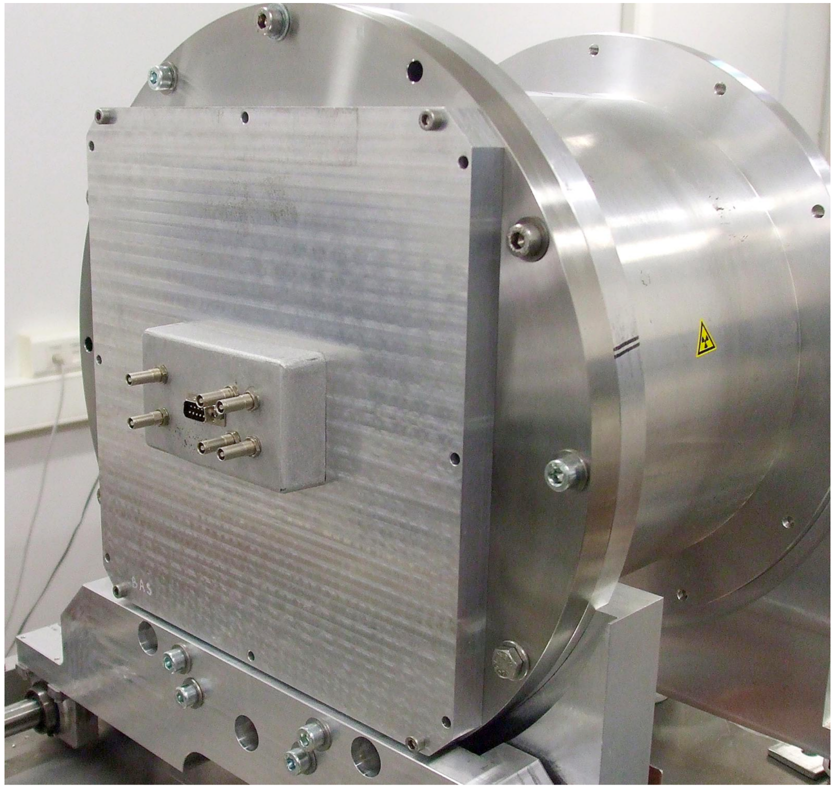


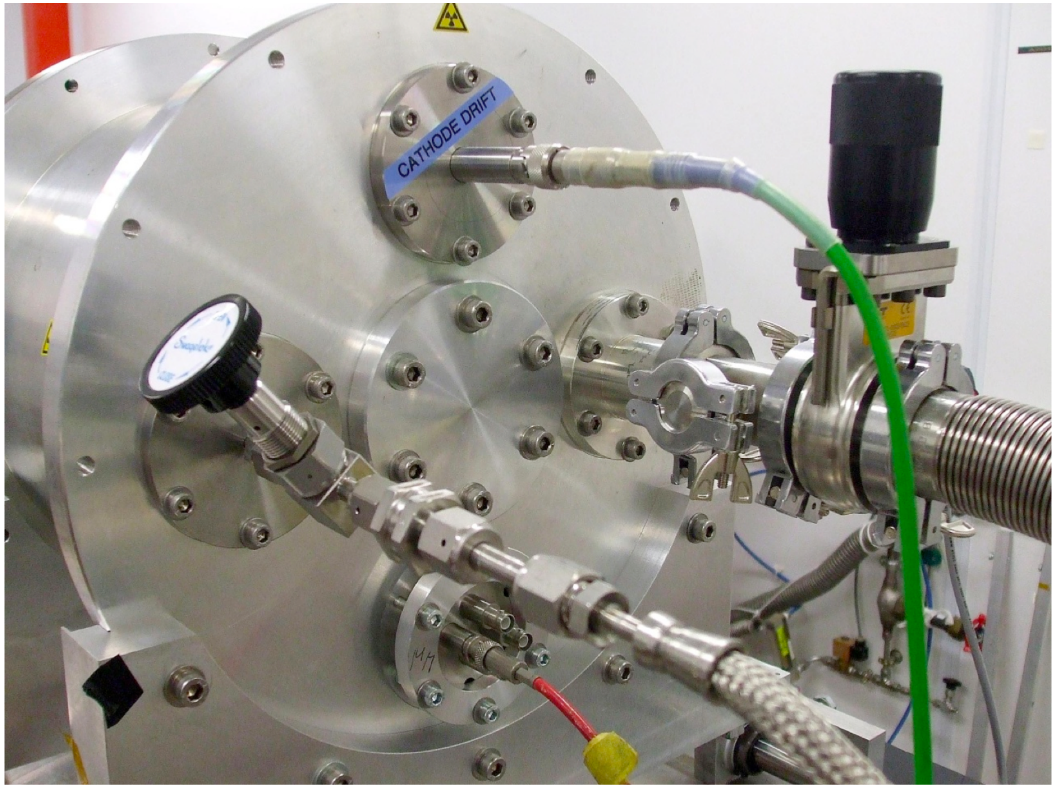
MIMAC electronics (v2.0) (512 channels)



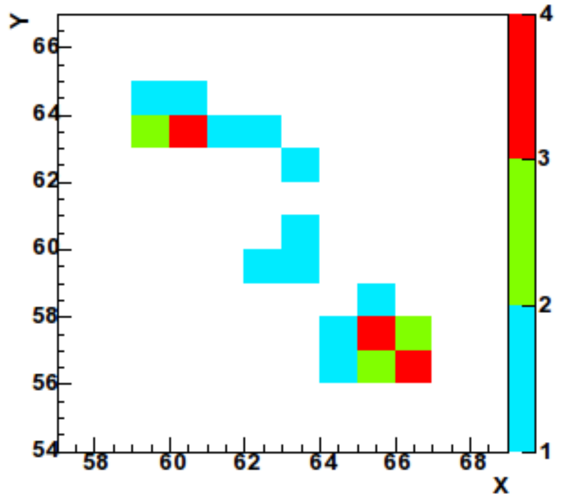
D. Santos (LPSC Grenoble)

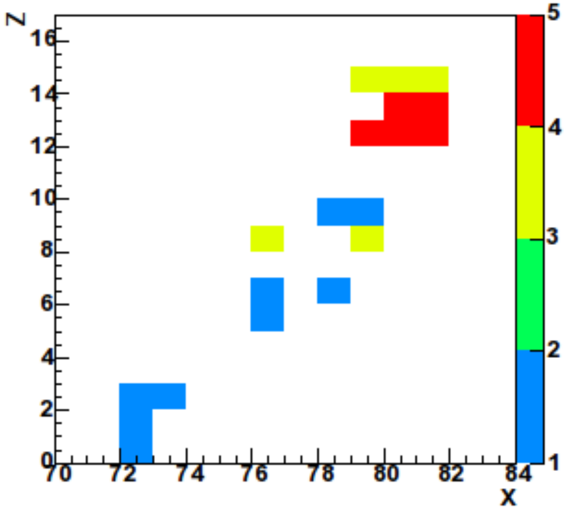
MIMAC prototype (v2.0) – 10x10x18 cm^3





3D Track : 5.9 keV electron (^{55}Fe)

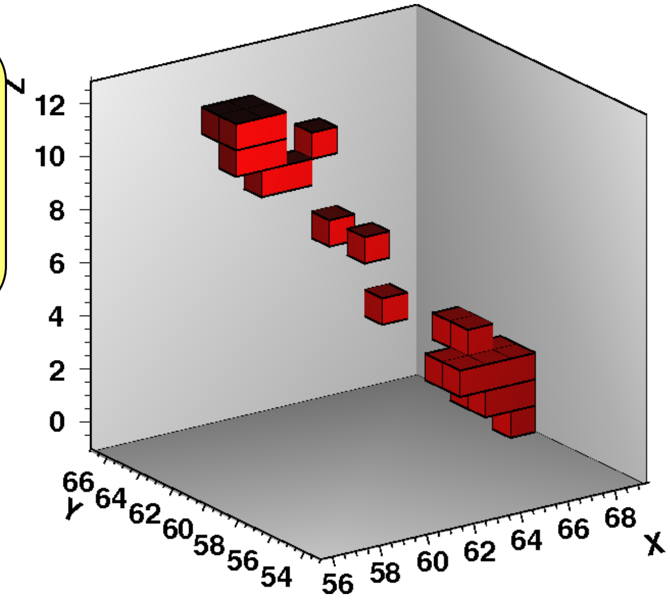




He + 5% iC_4H_{10}

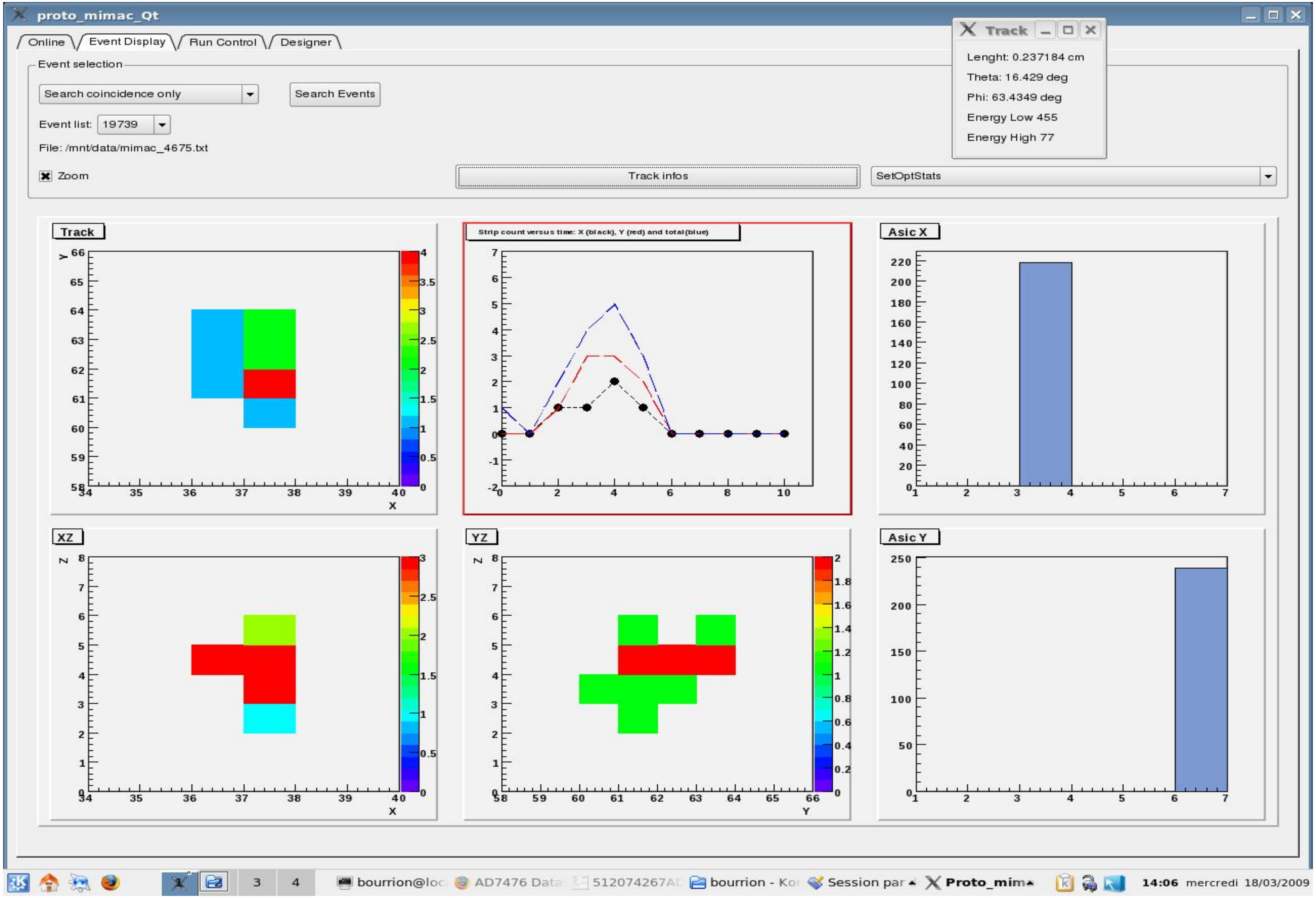
350 mbar,

150 V/cm



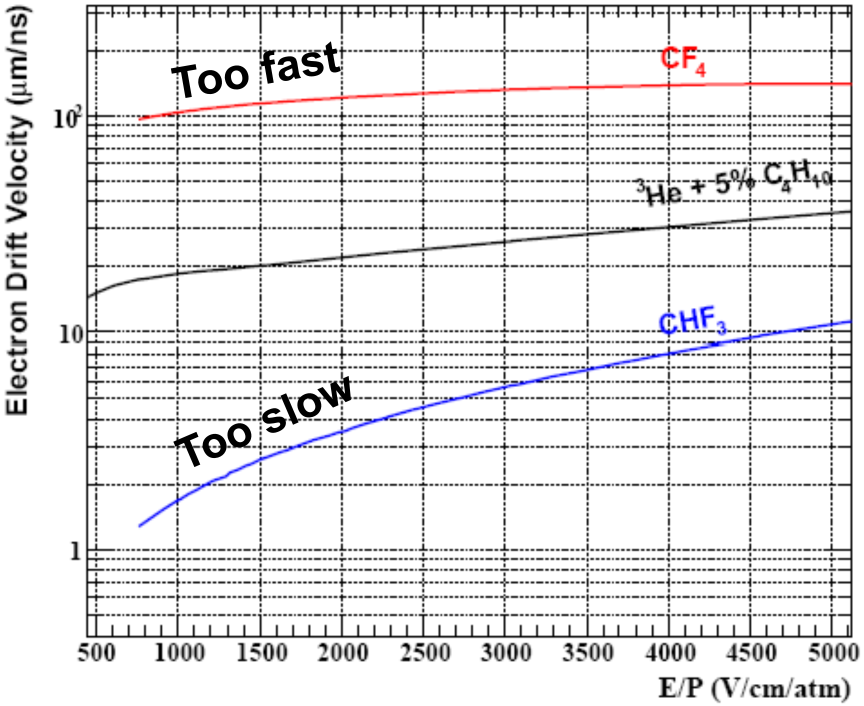
Typical background in DM detection

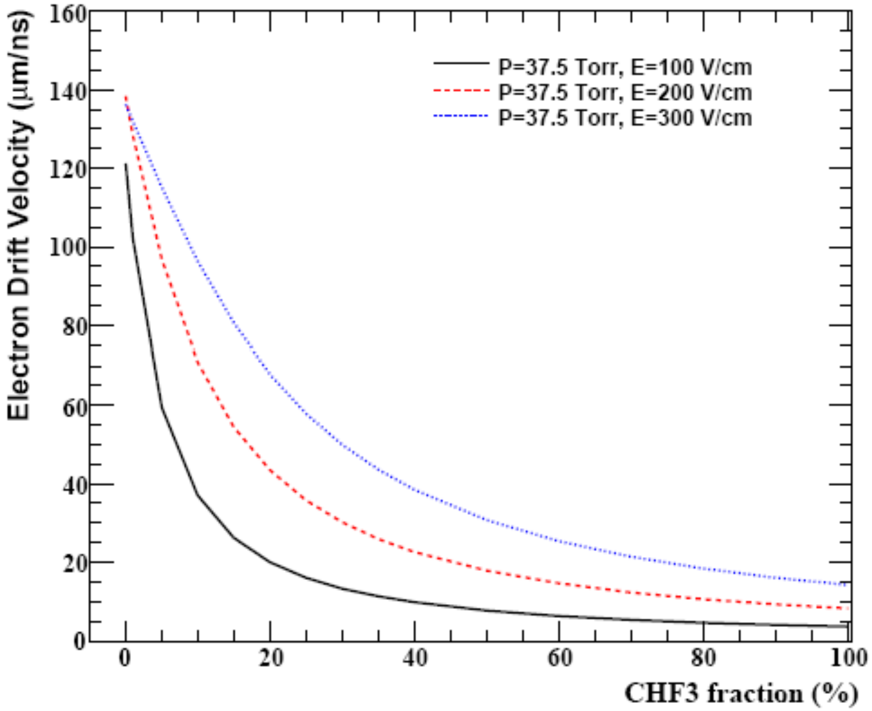
3D track measurement of an electron of 1.5 keV (X(Al))



3D Tracks: Drift velocity

Magboltz Simulation





- New mixed gas MIMAC target : CF_4 + x% CHF_3 (x=30)

MIMAC : recoil track measurements

April 2009

@ IRSN Cadarache

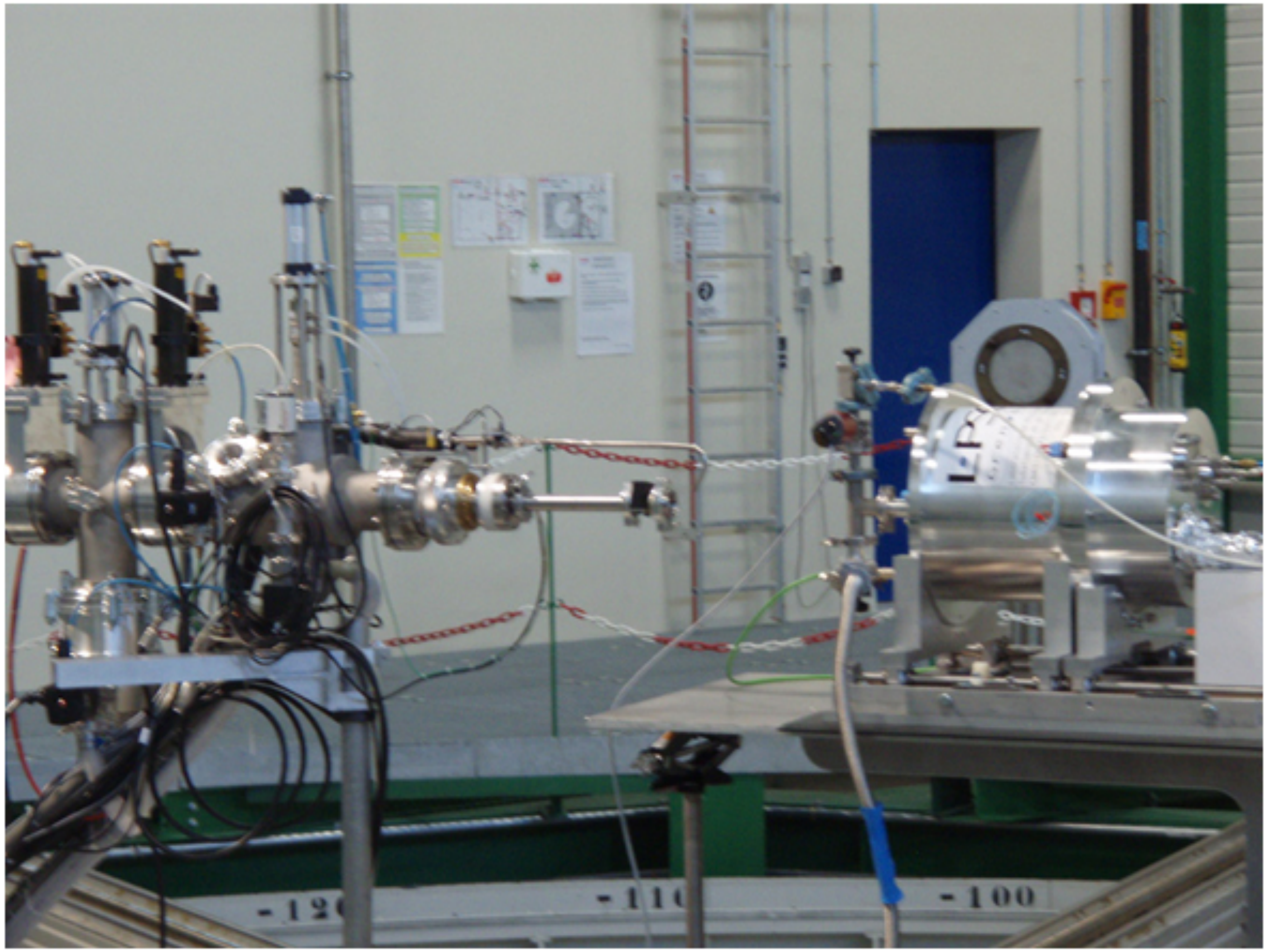
and May 16th, 2011 !!

Amande facility :

•Neutron field with energies down to a few keV

D. Santos (LPSC Grenoble)

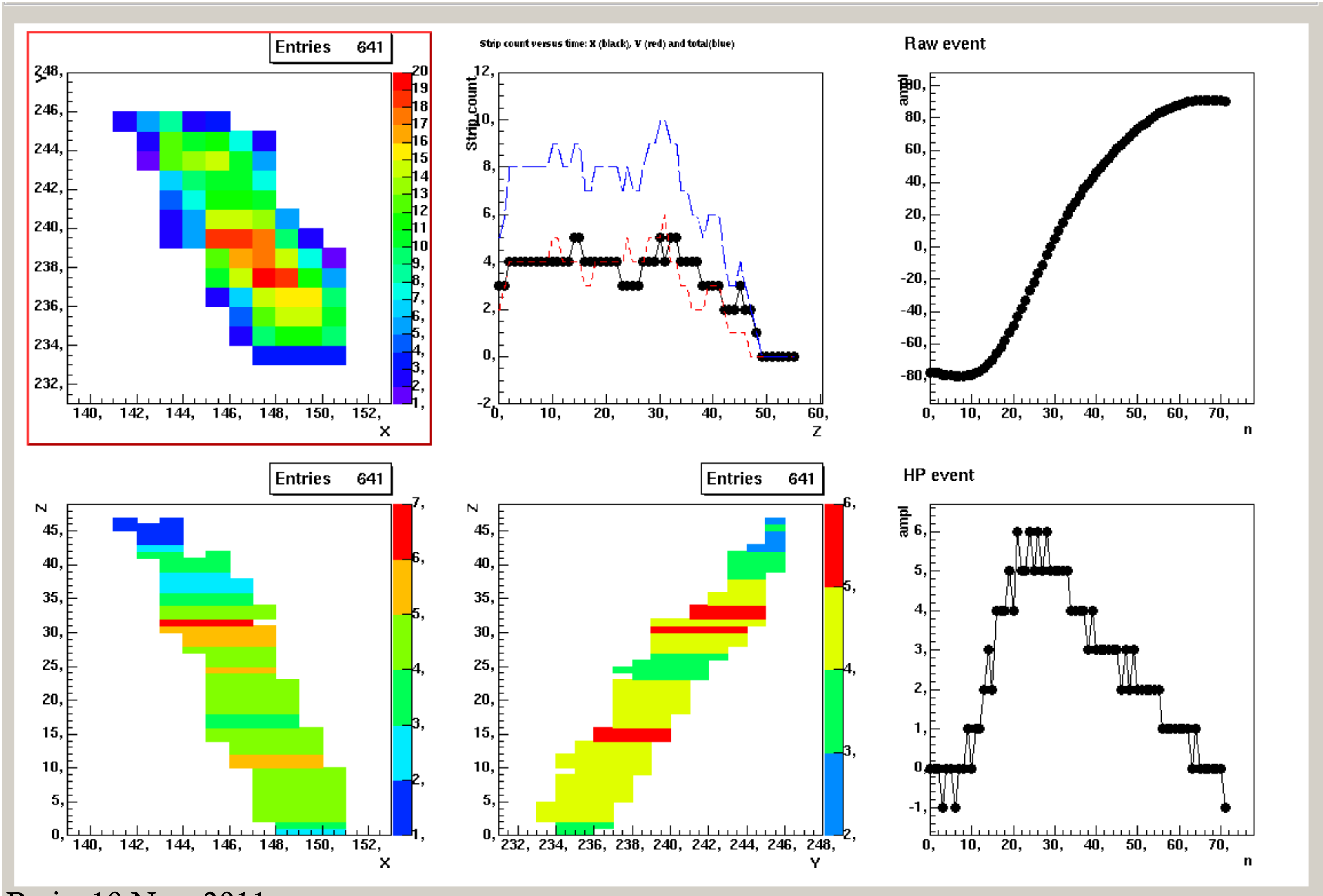
MIMAC prototype at Cadarache (detecting neutrons by nuclear recoil)



MIMAC – (512 channels) 10x 10 x18 cm^3

X-Y, X-Z and Y-Z projections, of a ^{1}H (60 keVee) 3D-recoil track produced by a neutron (565keV)(Amande-Cadarache). Flash-ADC (sampled every 20ns) giving its stoping power dE/dx

X-Y

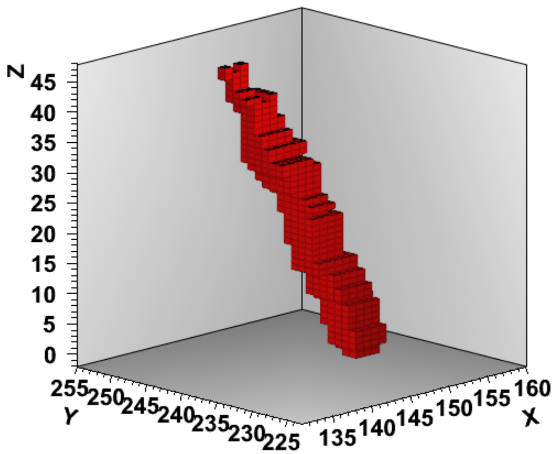


FADC

dE/dx

X-Z

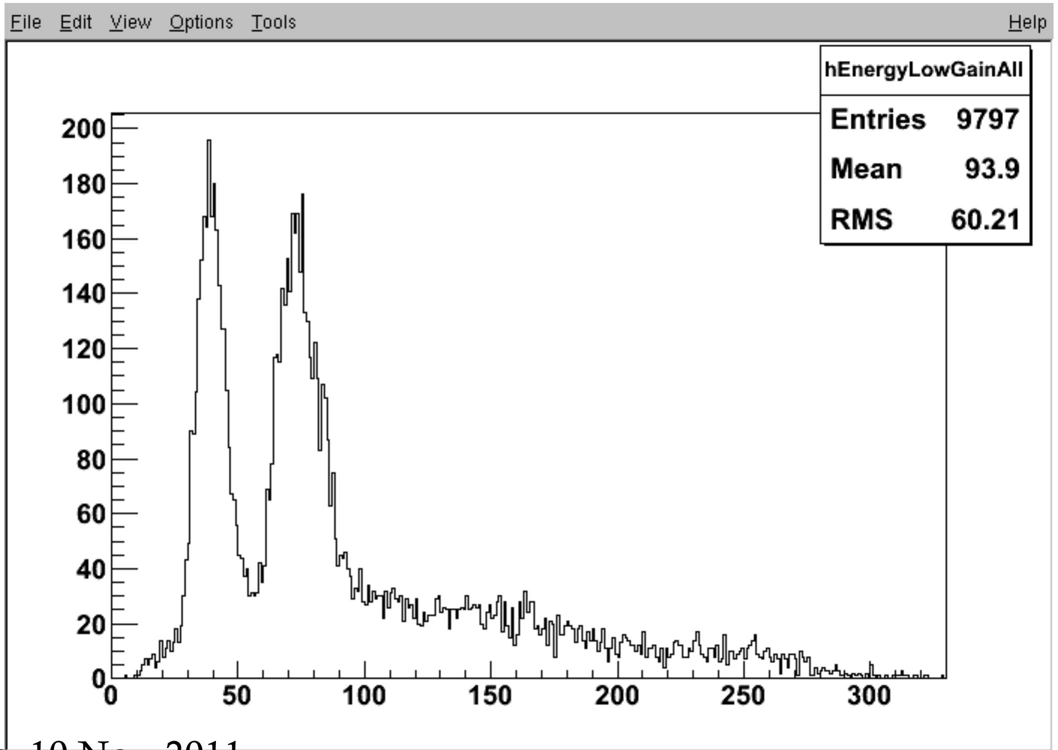
Y-Z



Trace en 3D : ^{1}H en 50mbar : 35mbar CF_4 + 14 of CHF_3 + 1mbar of C_4H_{10} !!!

~57 keV (ionization), ~3 cm

Calibration from X rays: 3.05 keV (^{109}Cd) et 5.96 keV (^{55}Fe)



Each event has its associated track…

Recoils from 144 keV neutrons

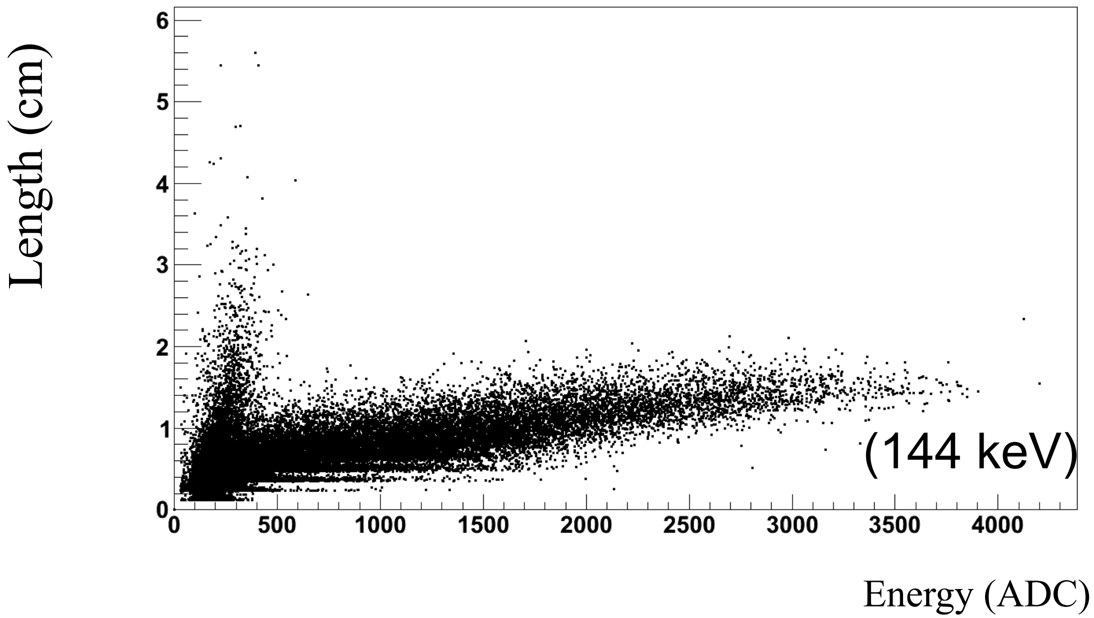
Pure isobutane

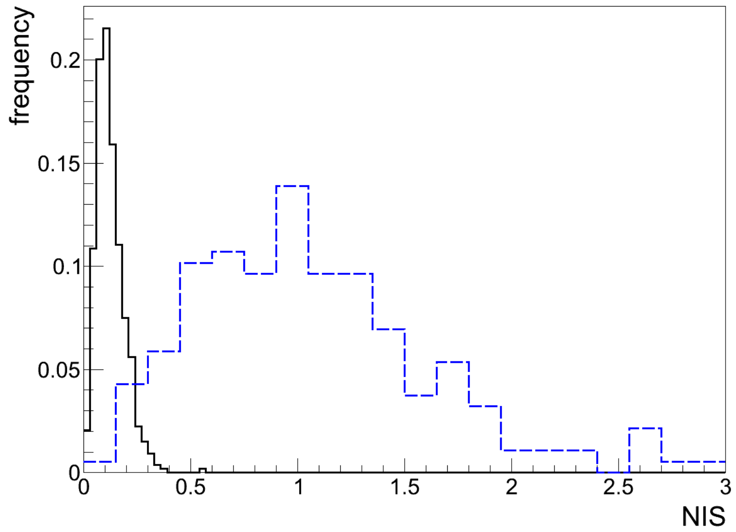
100 mbar

150 V/cm

<u>Amande facility</u> @ IRSN Cadarache

-> Neutron field with energies down to a few keV





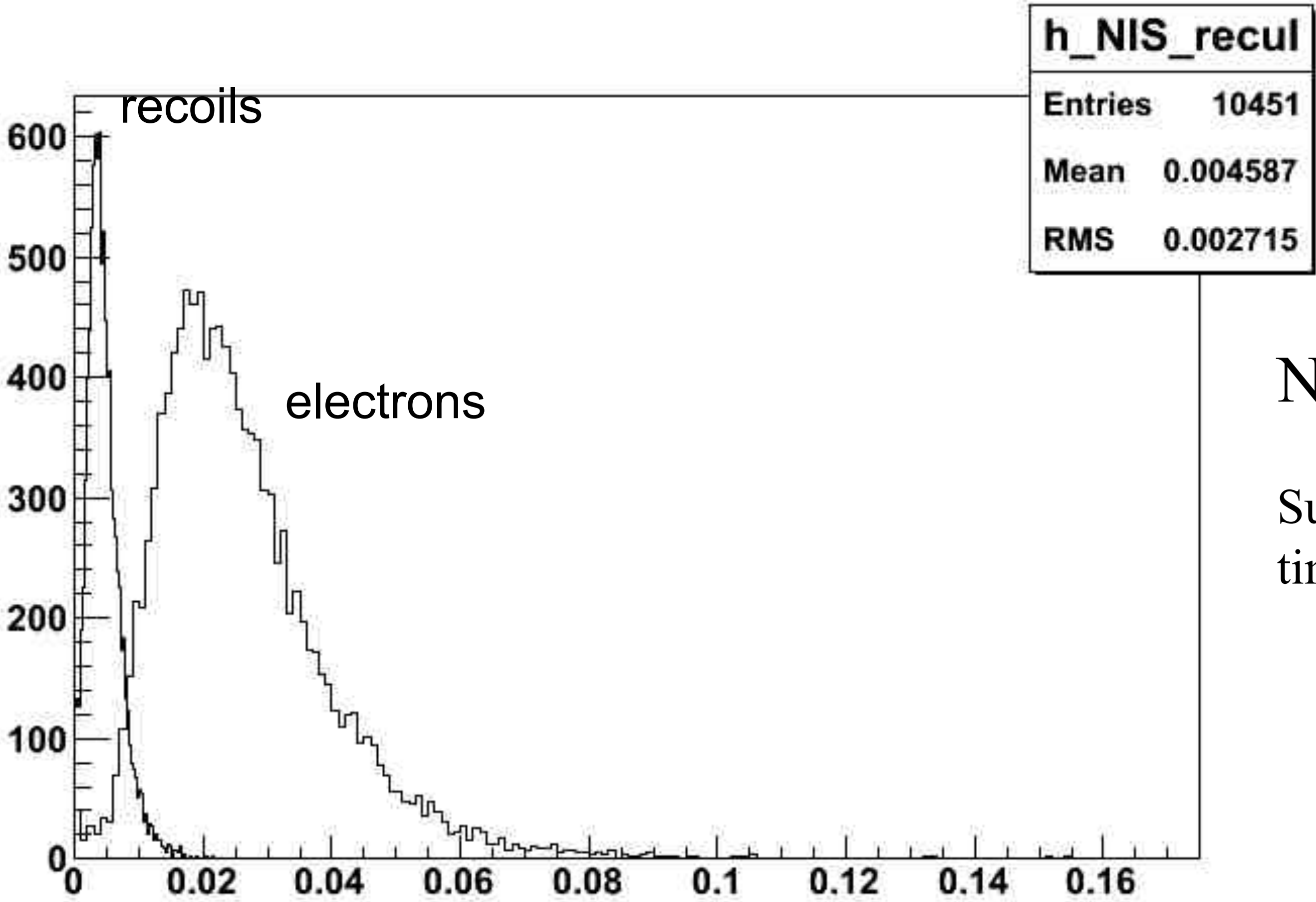
Background discrimination from recoils

NIS (Normalized Integrated Straggling) degree of freedom

Normalized Integrated Straggling (NIS)

(a new degree of freedom for e-recoil discrimination)

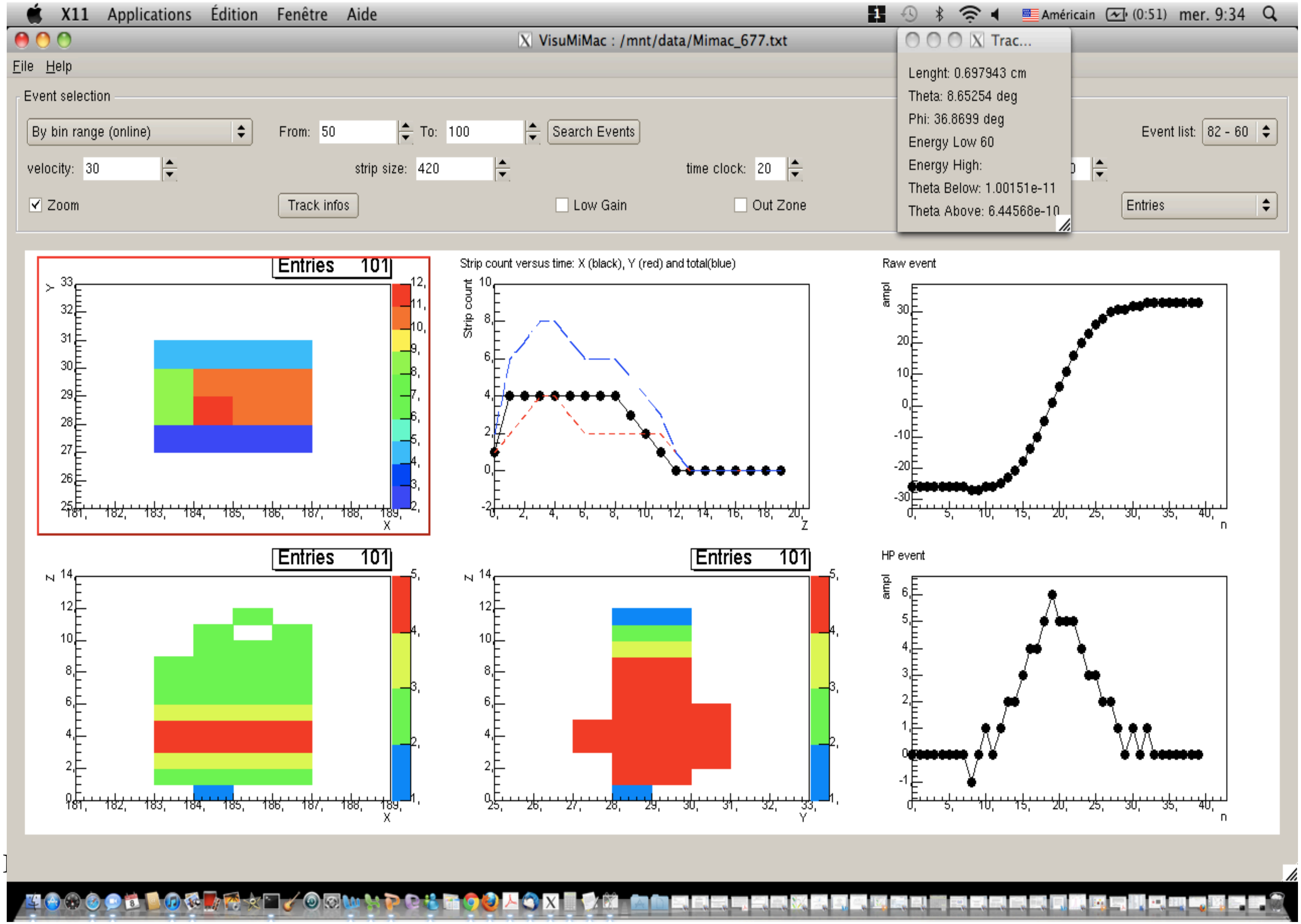
(The adition of partial deflections along the measured track, normalized by its total energy)



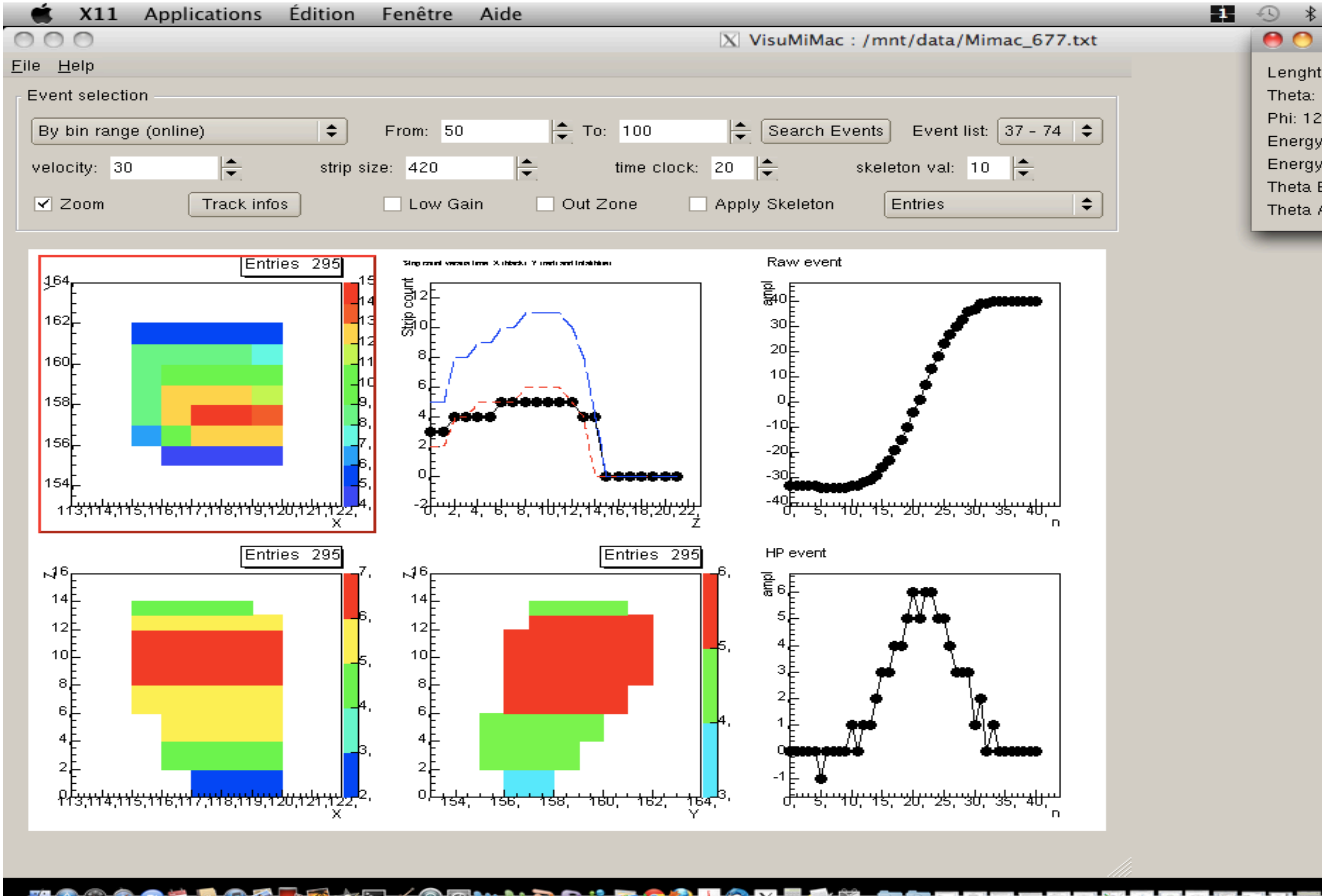
$$NIS = \Sigma\ (\Delta\theta_i)\ /\ E$$

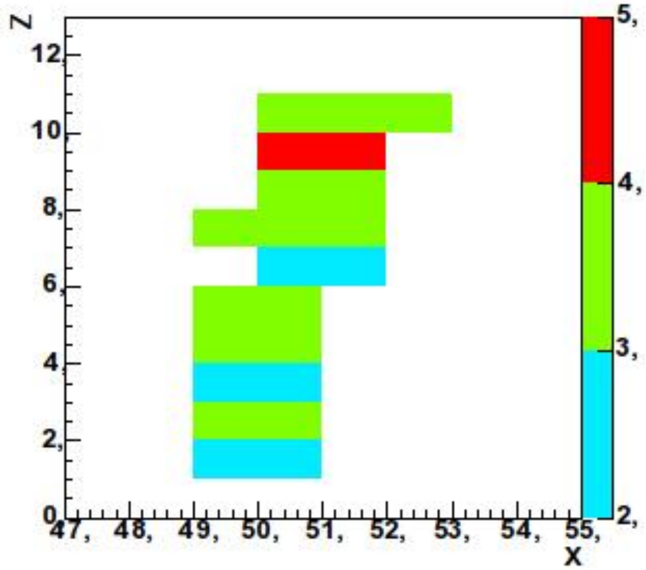
Summed over all the time samples of a track

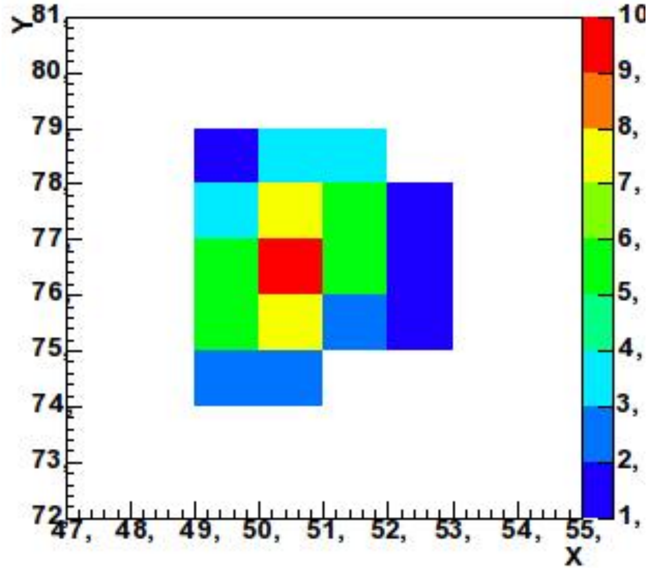
X-Y, X-Z and Y-Z projections, of a ^{19}F (~40 keVee) 3D-recoil track in CF_4+CHF_3



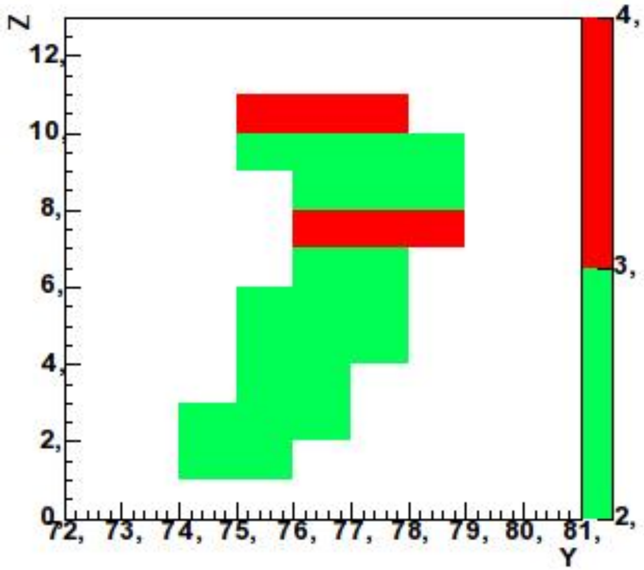
X-Y, X-Z and Y-Z projections, of a ^{19}F (~50 keVee) 3D-recoil track in CF_4+CHF_3

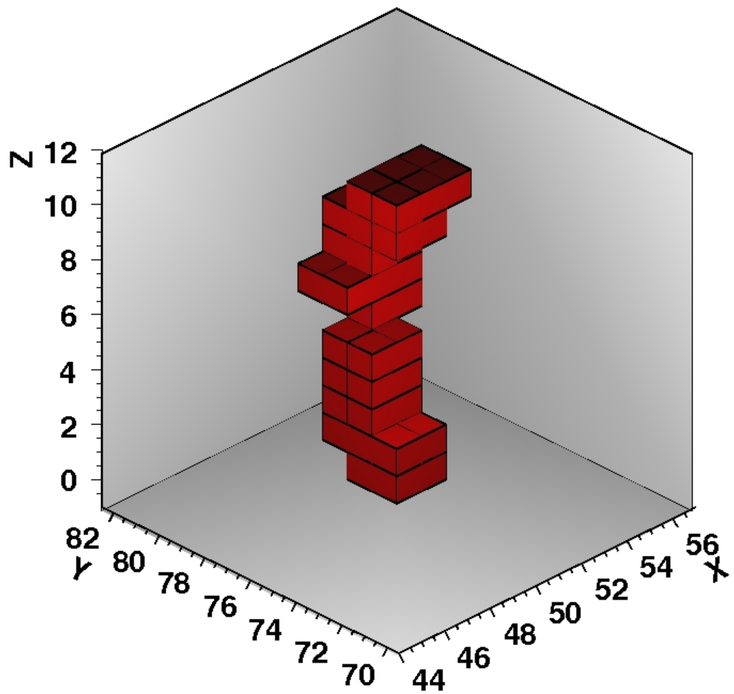




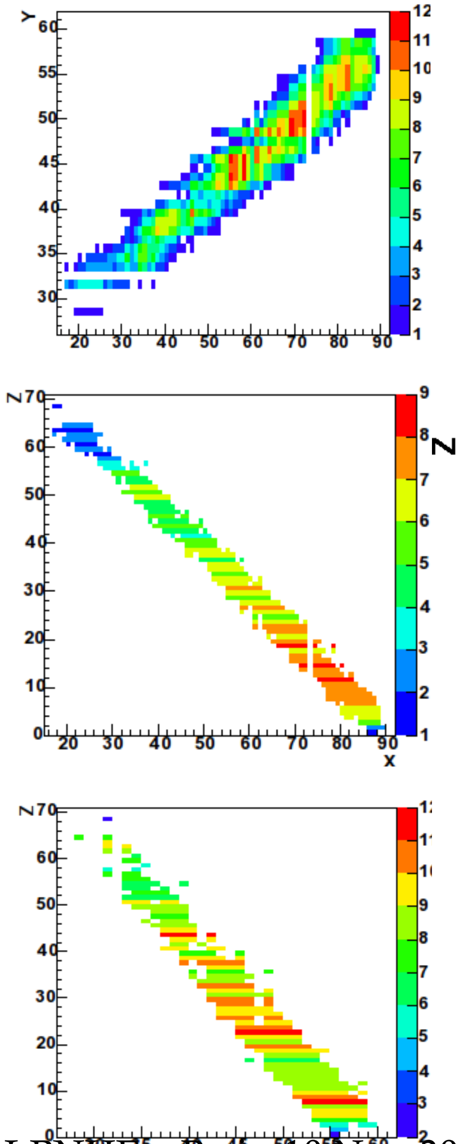


Recoil of 19F
(E_{ion}~40 keV)
in 50 mbar of
CF4 + CHF3 (30%)





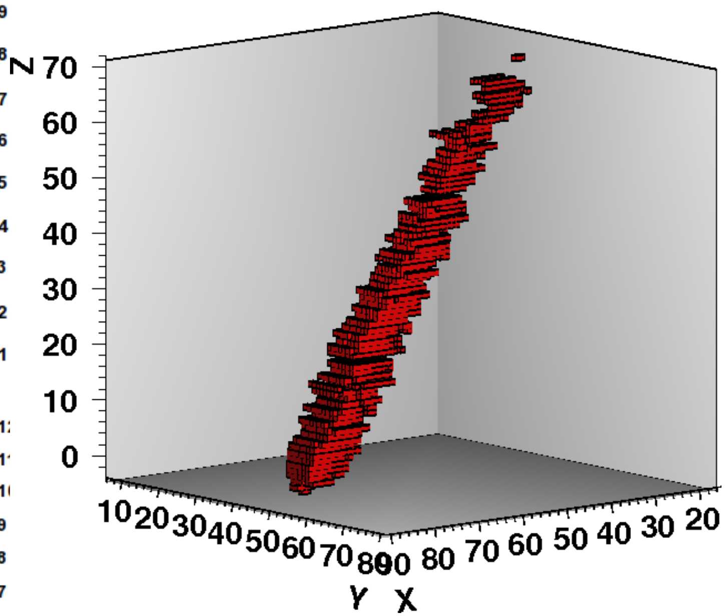
3D track : **Alpha 5,5 MeV** (^{222}Rn)

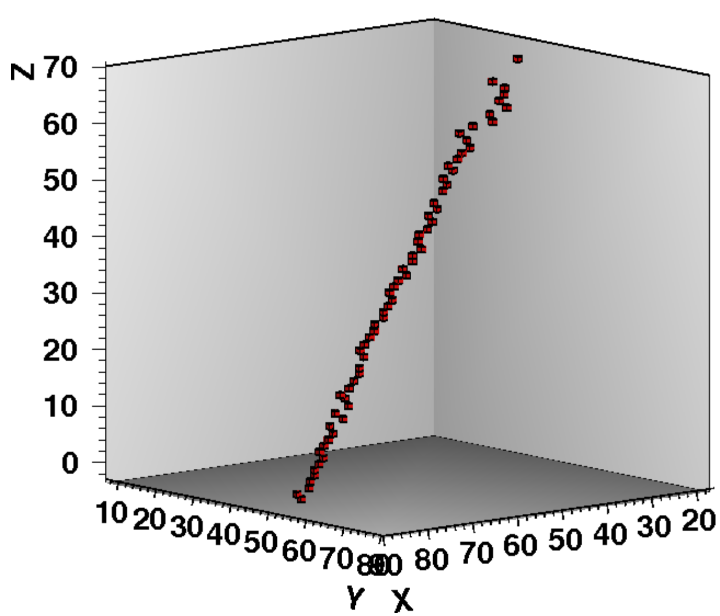


He + 5% iC_4H_{10}

350 mbar,

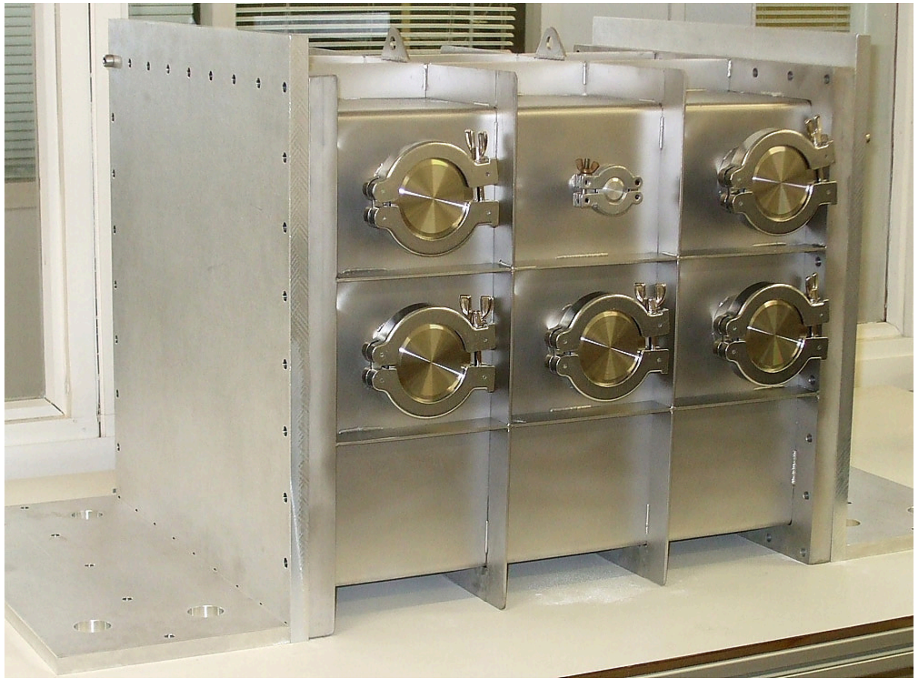
150 V/cm





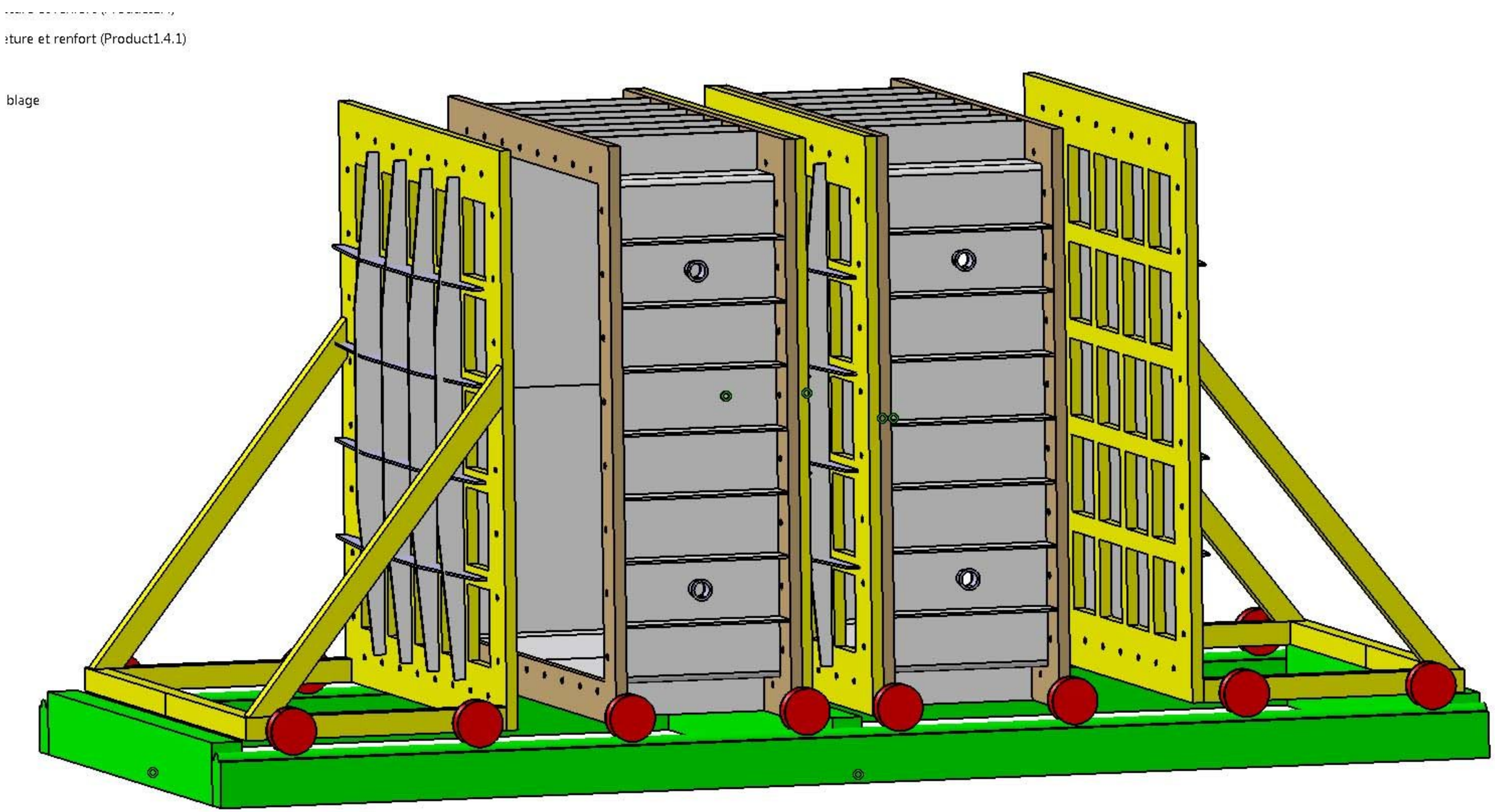
D. Santos (LPSC Grenoble)

Bi-chamber module (Modane)
2x (10x10x25 cm^3)
(March 2012 !)



D. Santos (LPSC Grenoble)

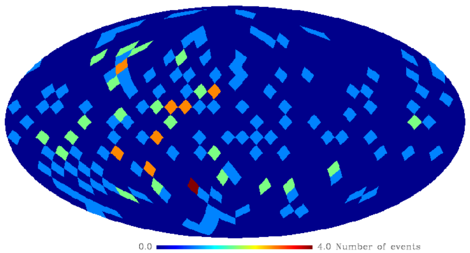
MIMAC – 1m^3



MIMAC : Dark Matter discovery/exclusion

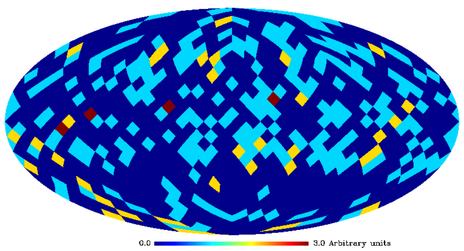
J. Billard *et al.*, PLB 2010
J. Billard *et al.*, PRD 2010

- ***discovery (5σ)***
  Up to 10^{-4} pb

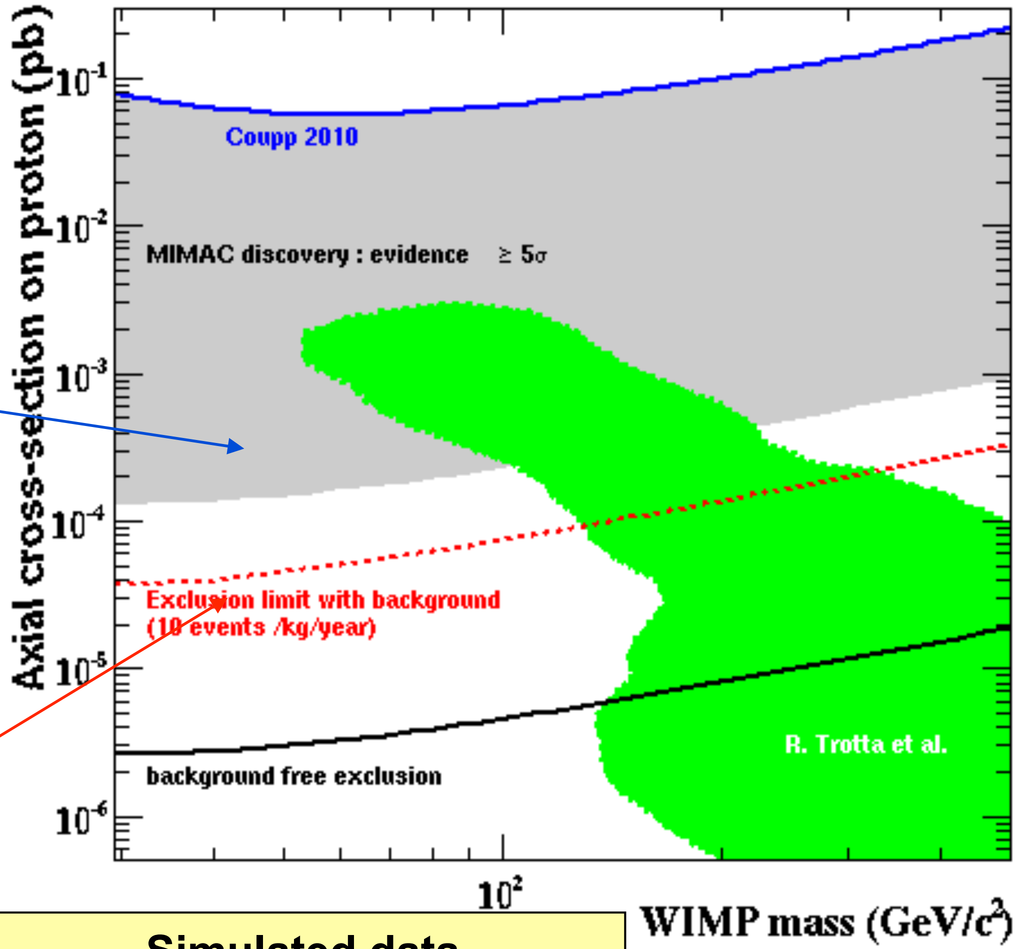


100 WIMP, 100 bkg

- **exclusion**
  Up to 10^{-6} pb



0 WIMP, 300 bkg

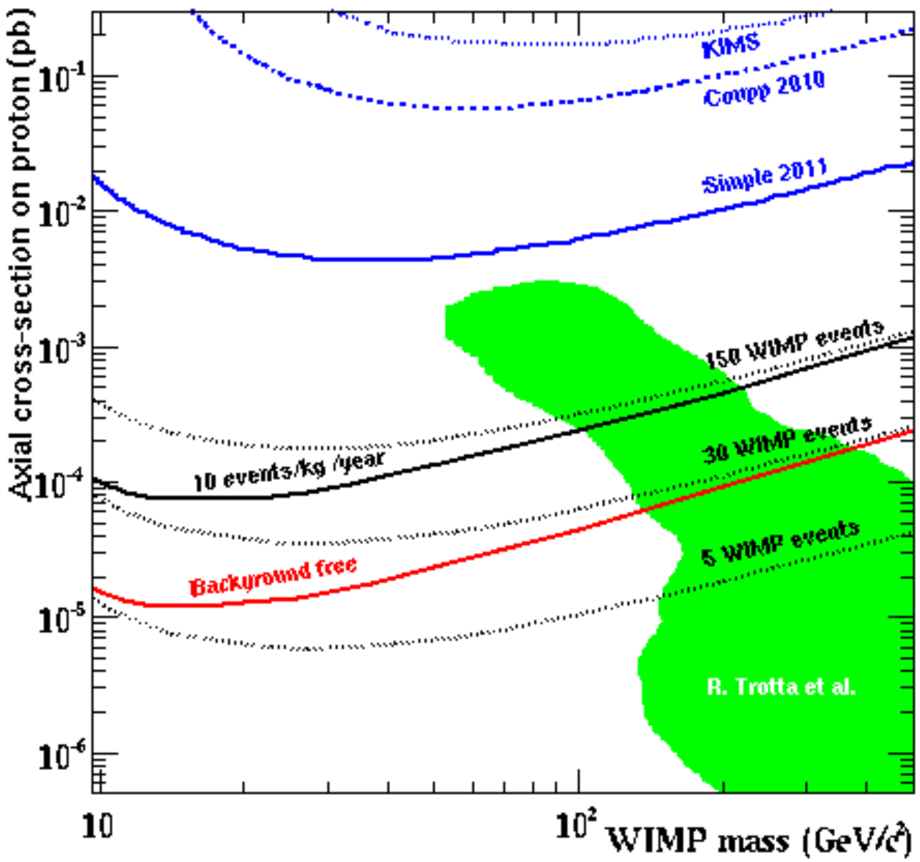


Simulated data
- 30 kg.year CF_4
- Recoil energy [5, 50] keV
- Angular resolution : 15°

Détection directionnelle : découverte

J. Billard *et al.*, PLB 2010
J. Billard *et al.*, arXiv:1110.6079

Découverte à 3σ
- avec BDF
- sans BDF



→ La découverte reste possible même en présence de bruit de fond résiduel

→ Blindage léger ?

→ Limiter le BDF permet de gagner un ordre de grandeur.

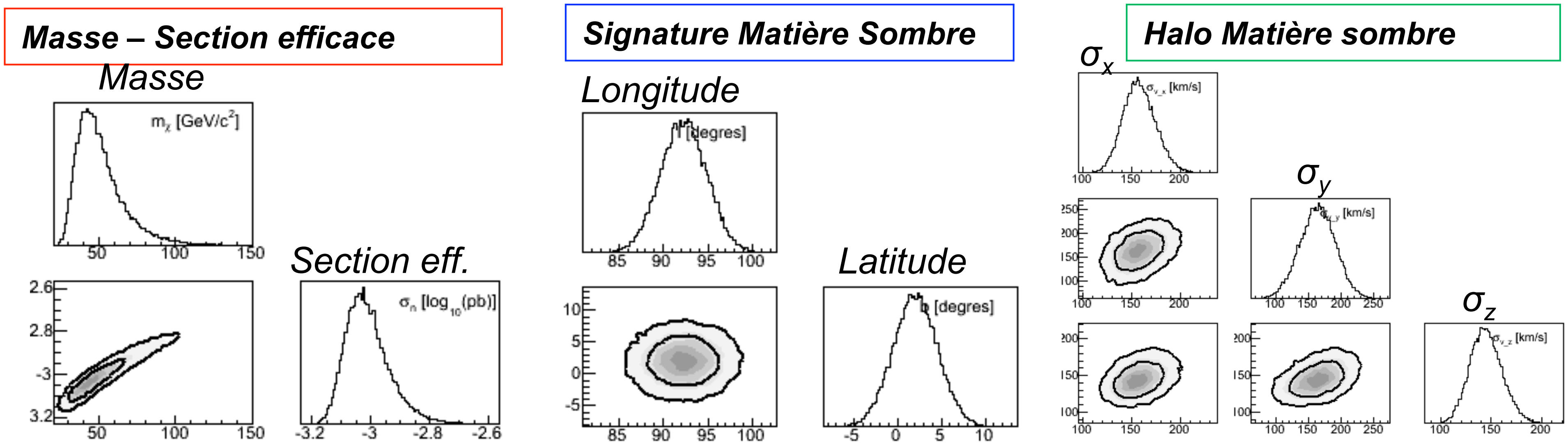
→faible nombre de WIMPs nécessaires

→ Une découverte (>3σ @90%CL) **avec BDF** est possible jusqu'à **10^{-3}-10^{-4} pb**

Détection directionnelle : identification

J. Billard *et al.*, PRD 2011

Contrainte simultanée des 8 paramètres avec une seule expérience



	m_χ (GeV/c^2)	$\log_{10}(\sigma_n$ (pb))	$\ell_\odot$ (°)	$b_\odot$ (°)	σ_x (km.s^{-1})	σ_y (km.s^{-1})	σ_z (km.s^{-1})	β	R_b (kg^{-1}year^{-1})
Input	50	-3	90	0	155	155	155	0	10
Output	$51.8^{+5.6}_{-19.4}$	$-3.01^{+0.05}_{-0.08}$	$92.2^{+2.5}_{-2.5}$	$2.0^{+2.5}_{-2.5}$	158^{+15}_{-17}	164^{+27}_{-26}	145^{+14}_{-17}	$-0.073^{+0.29}_{-0.18}$	10.97 ± 1.2

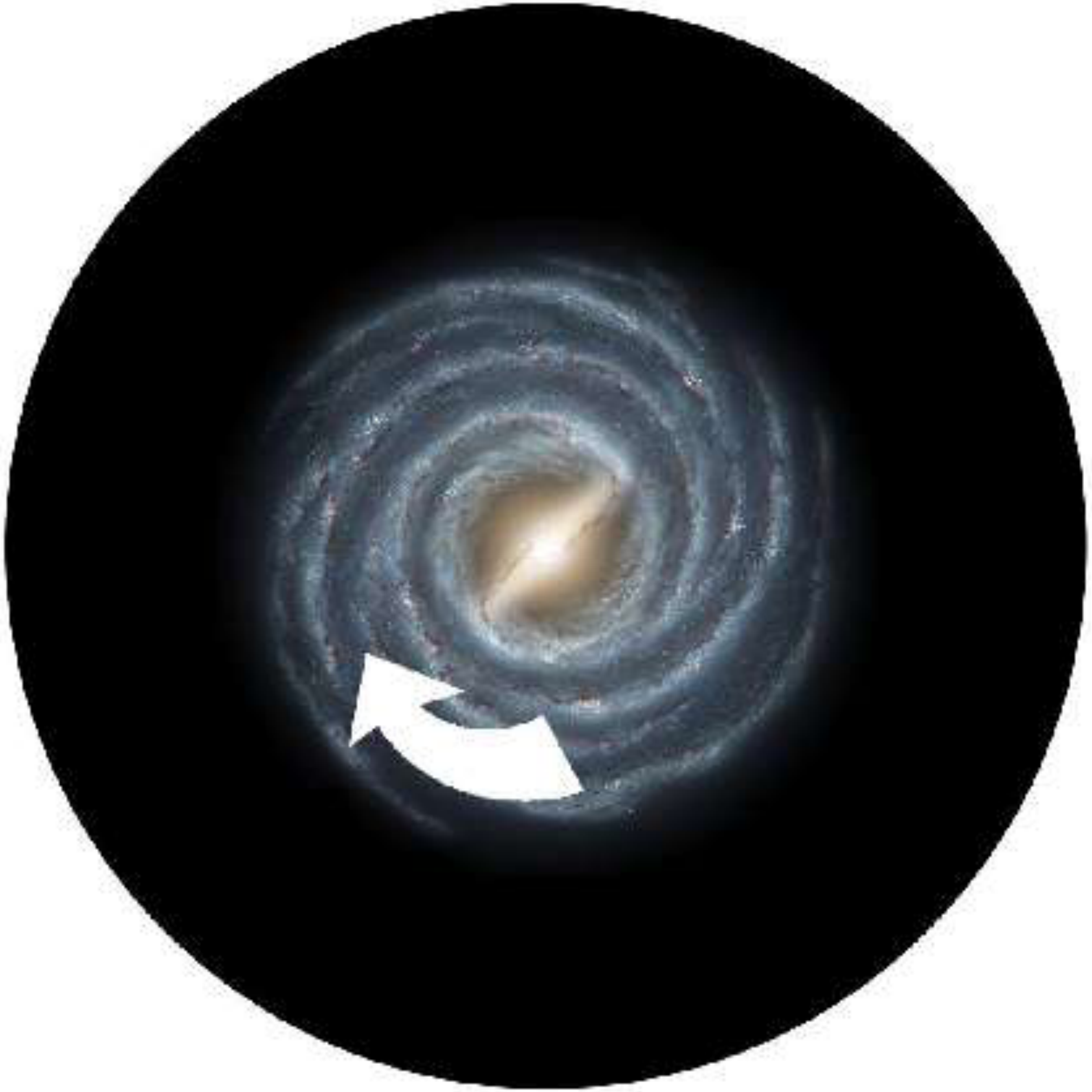


Table 1
Summary of the Cosmological Parameters of ΛCDM Model[a]

Class	Parameter	*WMAP* Seven-year ML[b]	*WMAP*+BAO+H_0 ML	*WMAP* Seven-year Mean[c]	*WMAP*+BAO+H_0 Mean
Primary	$100\Omega_b h^2$	2.227	2.253	$2.249^{+0.056}_{-0.057}$	2.255 ± 0.054
	$\Omega_c h^2$	0.1116	0.1122	0.1120 ± 0.0056	0.1126 ± 0.0036
	Ω_Λ	0.729	0.728	$0.727^{+0.030}_{-0.029}$	0.725 ± 0.016
	n_s	0.966	0.967	0.967 ± 0.014	0.968 ± 0.012
	τ	0.085	0.085	0.088 ± 0.015	0.088 ± 0.014
	$\Delta^2_{\mathcal{R}}(k_0)$[d]	2.42×10^{-9}	2.42×10^{-9}	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.430 \pm 0.091) \times 10^{-9}$
Derived	σ_8	0.809	0.810	$0.811^{+0.030}_{-0.031}$	0.816 ± 0.024
	H_0	$70.3\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$	$70.4\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$	$70.4 \pm 2.5\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$	$70.2 \pm 1.4\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$
	Ω_b	0.0451	0.0455	0.0455 ± 0.0028	0.0458 ± 0.0016
	Ω_c	0.226	0.226	0.228 ± 0.027	0.229 ± 0.015
	$\Omega_m h^2$	0.1338	0.1347	$0.1345^{+0.0056}_{-0.0055}$	0.1352 ± 0.0036
	z_{reion}[e]	10.4	10.3	10.6 ± 1.2	10.6 ± 1.2
	t_0[f]	13.79 Gyr	13.76 Gyr	13.77 ± 0.13 Gyr	13.76 ± 0.11 Gyr

Notes.
[a] The parameters listed here are derived using the RECFAST 1.5 and version 4.1 of the *WMAP* likelihood code. All the other parameters in the other tables are derived using the RECFAST 1.4.2 and version 4.0 of the *WMAP* likelihood code, unless stated otherwise. The difference is small. See Appendix A for comparison.
[b] Larson et al. (2011). "ML" refers to the maximum likelihood parameters.
[c] Larson et al. (2011). "Mean" refers to the mean of the posterior distribution of each parameter. The quoted errors show the 68% confidence levels (CLs).
[d] $\Delta^2_{\mathcal{R}}(k) = k^3 P_{\mathcal{R}}(k)/(2\pi^2)$ and $k_0 = 0.002\ \mathrm{Mpc}^{-1}$.
[e] "Redshift of reionization," if the universe was reionized instantaneously from the neutral state to the fully ionized state at z_{reion}. Note that these values are somewhat different from those in Table 1 of Komatsu et al. (2009a), largely because of the changes in the treatment of reionization history in the Boltzmann code CAMB (Lewis 2008).
[f] The present-day age of the universe.