*He recoils in CYGNO
10 L prototype

CYGNO/INITIUM: physics cases & measurements

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European Research Council
Established by the European Commission

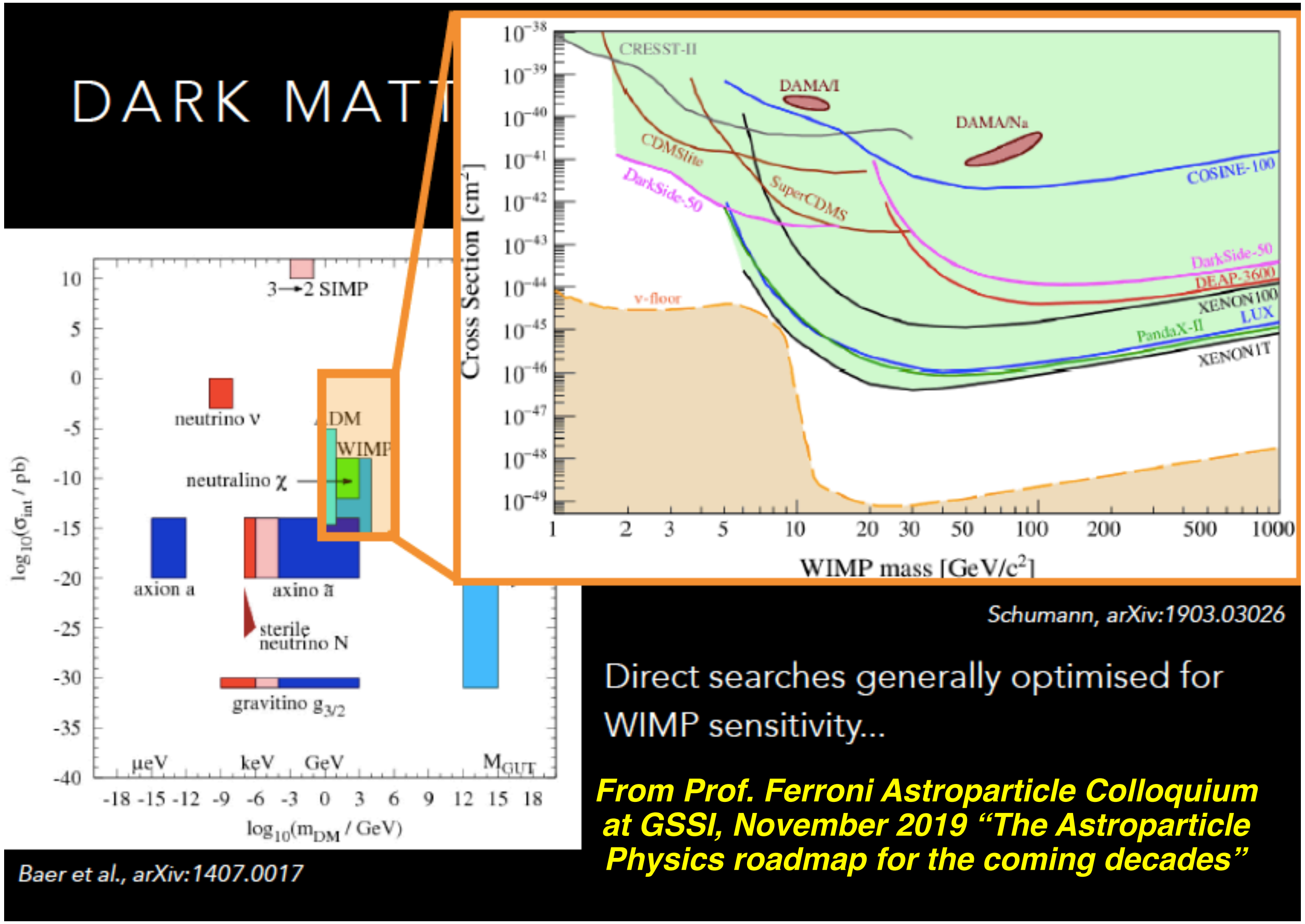
Physics cases & foreseen measurement

- Classical WIMP searches: 3 σ sensitivity in frequentist approach with and without presence of background
- Solar neutrino measurement with elastic scattering on electrons
- LIME underground LNGS neutron flux measurement

CYGNO WIMP searches:

3 sigma sensitivity

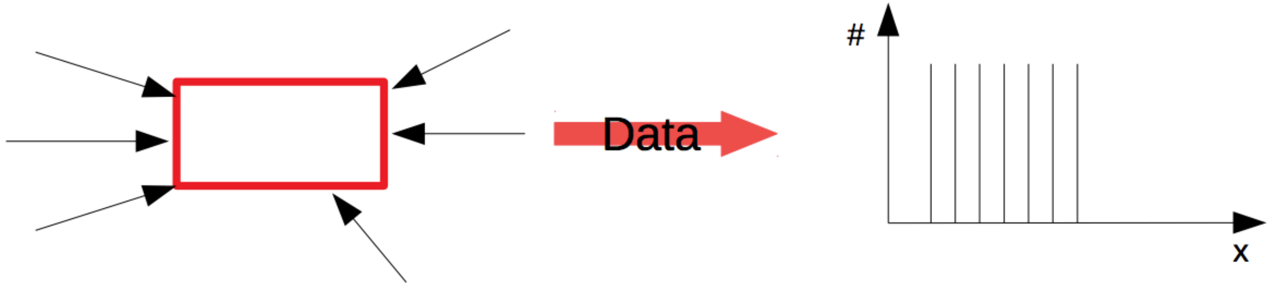
What do we mean with WIMP



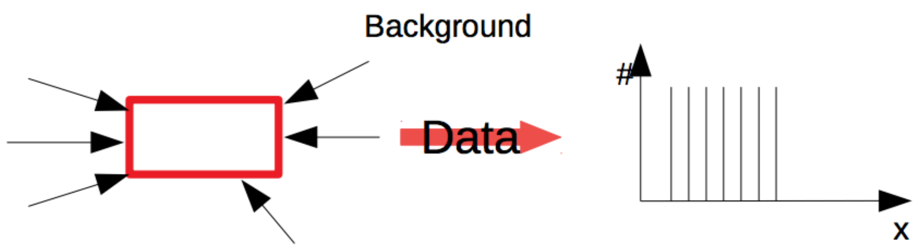
From Prof. Ferroni Astroparticle Colloquium at GSSI, November 2019 "The Astroparticle Physics roadmap for the coming decades"

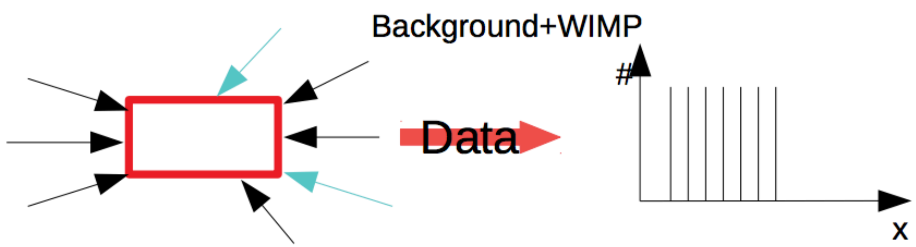
How to

- The MC procedure consists in the repetition of fake experiments



- Experiments with pure background or background +WIMP





- The extended profile likelihood ratio method will be used to find the 3 σ significance

G. Dho

Background & signal modelling

Background

Energy

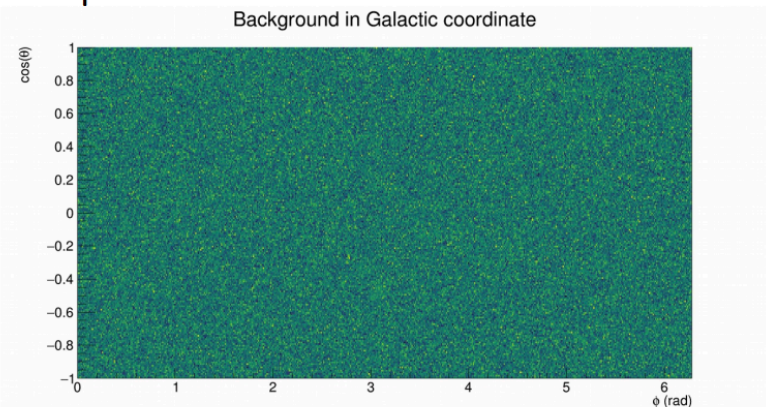
– Unknown shape (similar to an exponential)

– Less discriminative power than angle

2D angle

– Unknown shape

– At first order, in Galactic coordinates most of the background should dilute and look isotropic

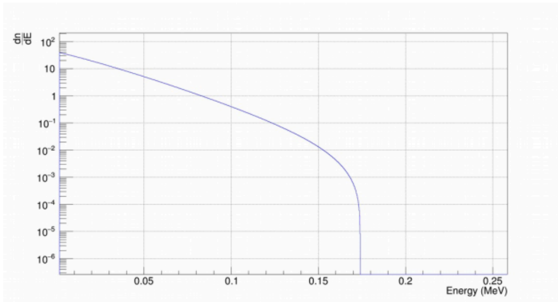


n,

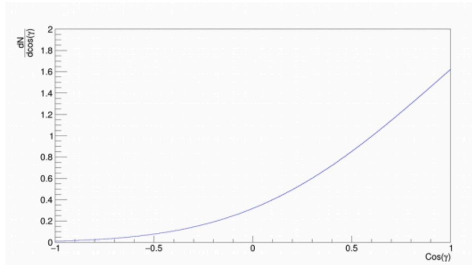
Being easier to model and more powerful in discrimination, the angular information will be used

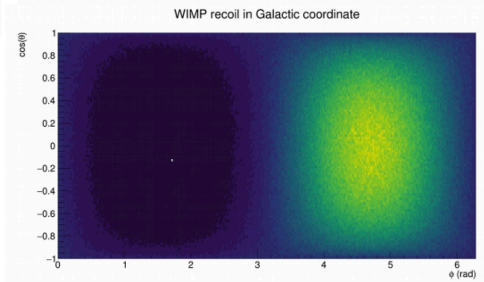
Signal from WIMP theory

Energy spectrum



Angular spectrum





Probability of hitting an element

Important during simulation to extract

the element hit by the DM particle

G. Dho

Angular spectrum in galactic coordinates

- To have the angular spectrum in the lab RF, the integration must be modified to include the angle between recoil and Sun direction. I adapted the calculation from *DOI:10.1103/PhysRevD.66.103513*

$$\frac{dR}{dE_R\, d\cos\gamma} = \left(e^{-\frac{(v_{min}-v_E\cos\gamma)^2}{v_0^2}} - e^{-\frac{v_{esc}^2}{v_0^2}}\right)\Theta\left(\cos\gamma - \frac{v_{min}-v_{esc}}{v_E}\right)$$

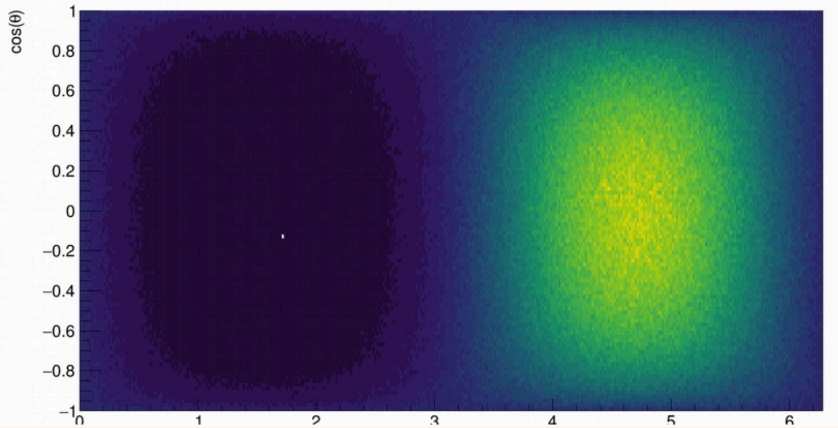
- And rearranging

$$\frac{dR}{d\cos\gamma} = \int_{E_{thr}}^{\frac{1}{2}m_\chi r(v_E\cos\gamma+v_{esc})^2} \left(e^{-\frac{(v_{min}-v_E\cos\gamma)^2}{v_0^2}} - e^{-\frac{v_{esc}^2}{v_0^2}}\right) dE_R$$

If low integral extreme is less than high integral extreme

According to the angle, not all the energies can contribute, with v_{esc} different than 0

- Assuming the detector in the centre of the Sun, the spectra can be transformed in the Galactic coordinates



G. Dho

Fake experiments for signal & background

- The experiment data will consist in a 2D angular histogram with the values obtained from the simulated events

- Background experiment

1. Expecting μ_b background events
2. Extract x events from Poisson(x,μ_b)
3. For each event the 2D coordinates are extracted from background distribution

- Procedure for background+WIMP experiment

1. Same for background
2. Extract y events from Poisson(y,μ_s,m_χ), with μ_s the expected WIMP events
3. For each event the 2D coordinates are extracted from signal distribution

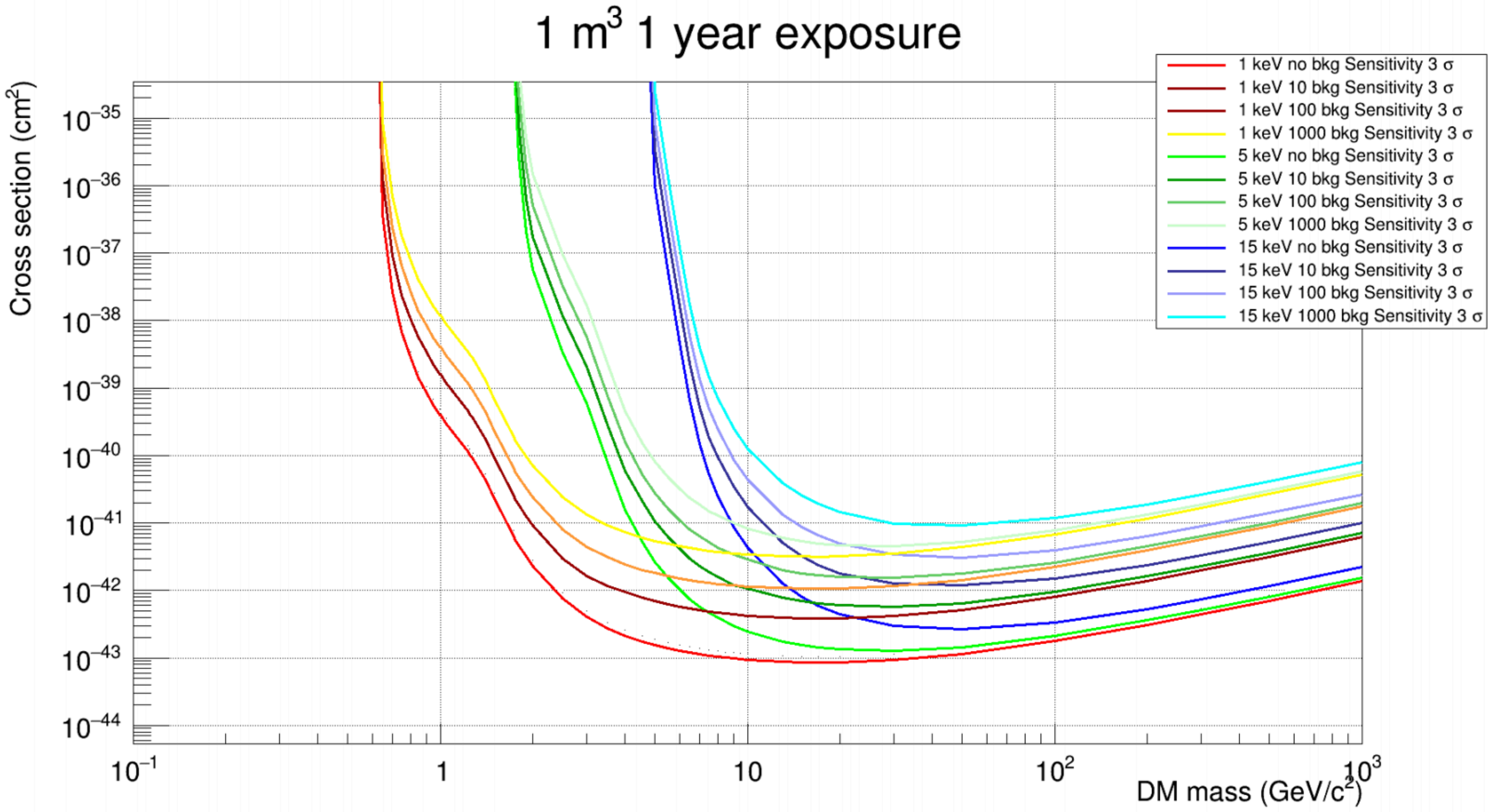
G. Dho

Experimental assumptions

- Angular resolution σ_a is taken as 30x30 deg^2 and is independent on the energy of the recoil
- The histogram containing the data in binned so that each bin is $\pm 1\sigma_a$ (so twice as resolution)
- The angular resolution effect is applied to the simulation with a gaussian smear centred in zero and with σ_a as standard deviation
- Perfect head-tail recognition is considered
- Low energy threshold determines the minimum energy detectable, thus the angular spectrum shape
- High energy threshold determines is up to the end of the spectrum (200 keV recoils are expected to be visible and contained)
- The probability of hitting a specific element is considered in the simulation, taking into account the gas mixture

G. Dho

Results

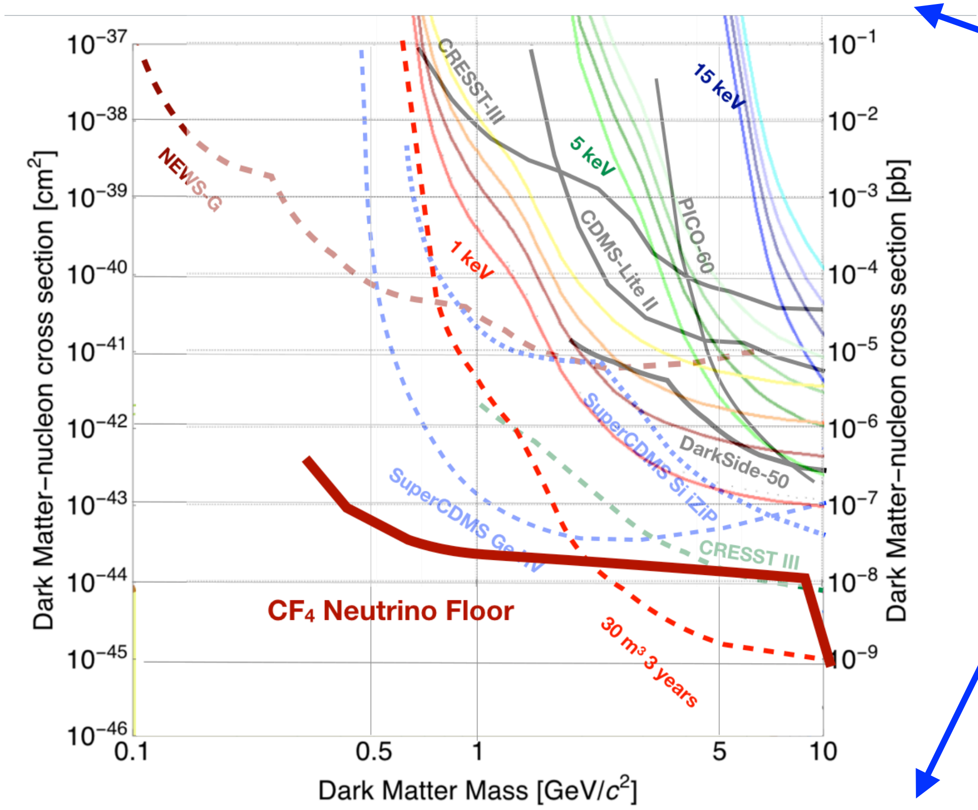


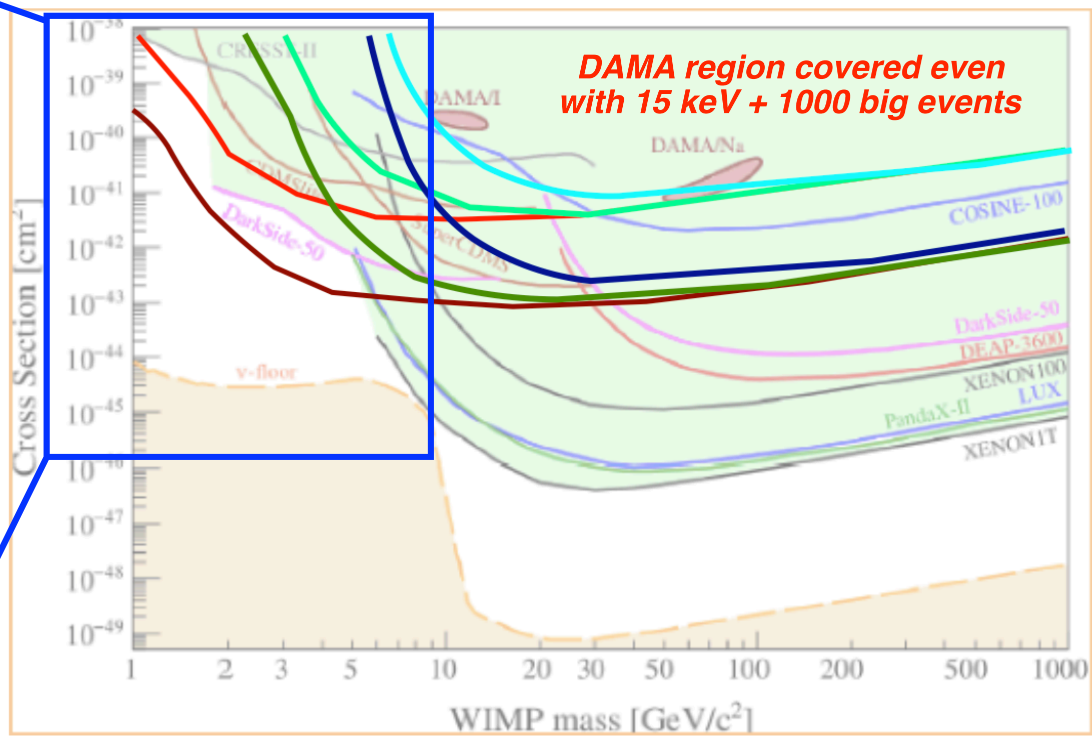
PRELIMINARY

G. Dho

Comparison with other experiments

Please, keep in mind that only 1 m³ year exposure is shown for CYGNO



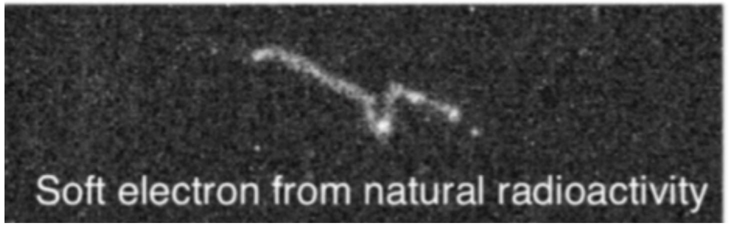


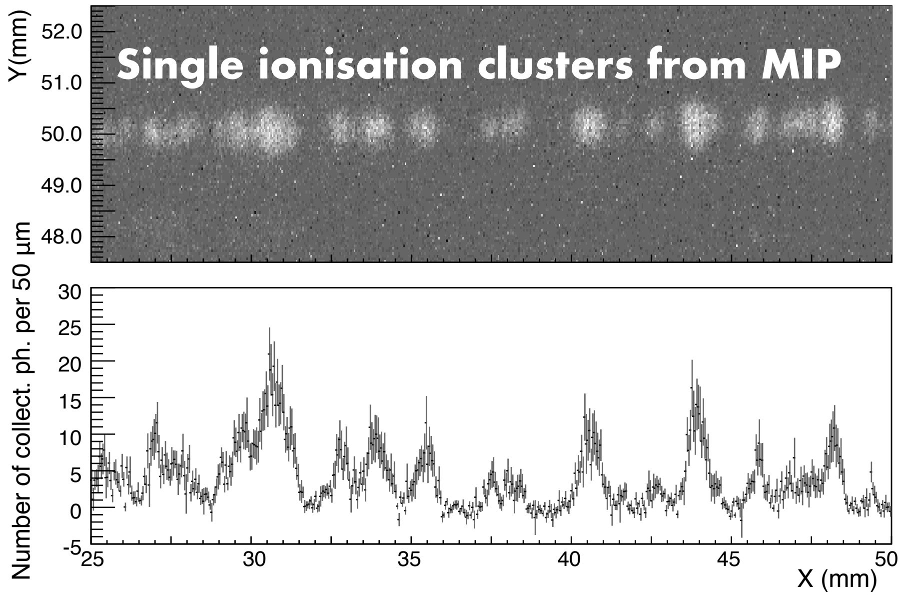
get up to ± 100 kg year exposure with 30 m³ 3 years

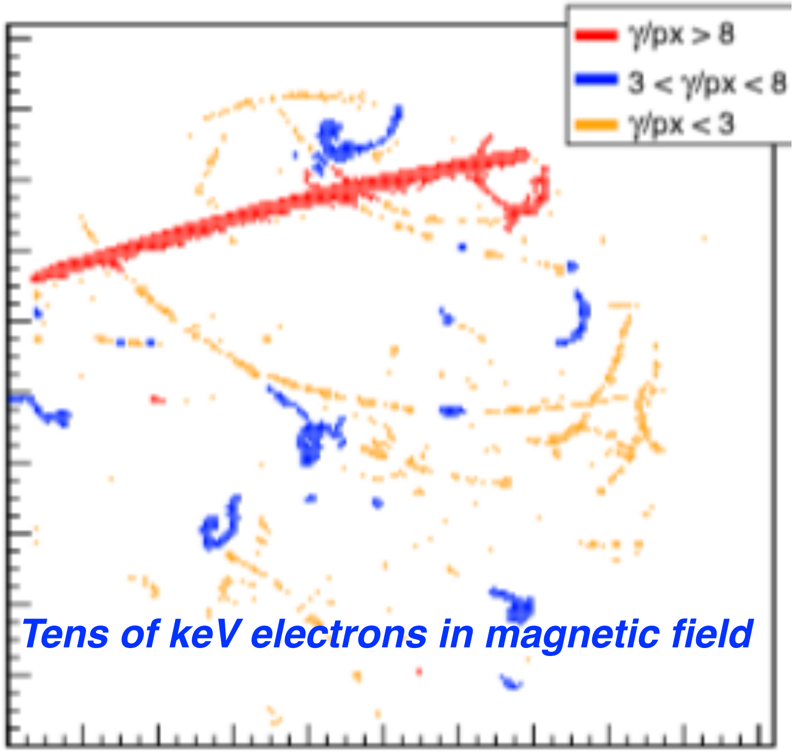
0 bkg & 1000 bkg shown for each threshold

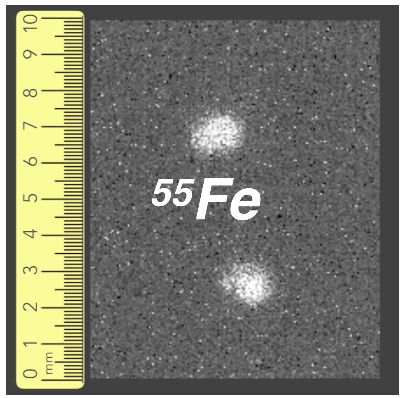
CYGNO/INITIUM beyond WIMP searches:
electron recoils from Neutrinos

Electron recoil thresholds









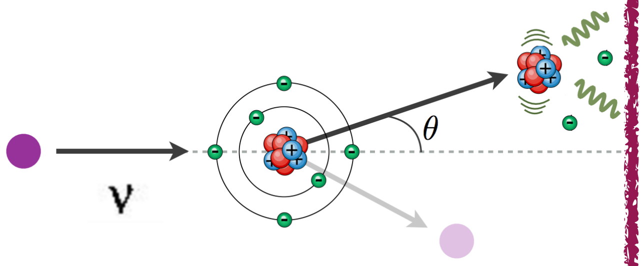
Tentative detection threshold: 1-2 ionisation clusters > 100 eV

Tentative directional detection threshold: >20-30 keV

Directionality as a new window on neutrino physics

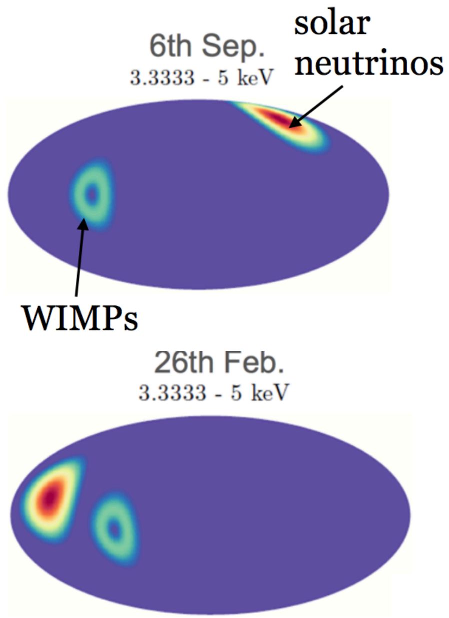
Neutrinos: an opportunity for directional DM detectors, rather than an inconvenience

Coherent Neutrino-Nucleus scattering



NOTE: only a directional DM detector can distinguish from WIMP signal

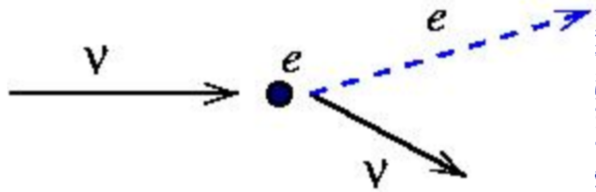
C. O'Hare et al, Phys. Rev. D 92 063518 (2015)



NEW! Physics reach under study

Elastic Neutrino-Electron scattering

with event by event precise neutrino energy measurement



NOTE: only a directional DM detector can distinguish from ER background

Message from back on the envelope evaluations & old published papers: O(50 kg) directional detector can measure neutrinos through elastic scattering using directionality to reject electromagnetic backgrounds (CYGNO PHASE 2 ok!)

Elastic neutrino - electron scattering with gaseous TPC: revitalising old ideas

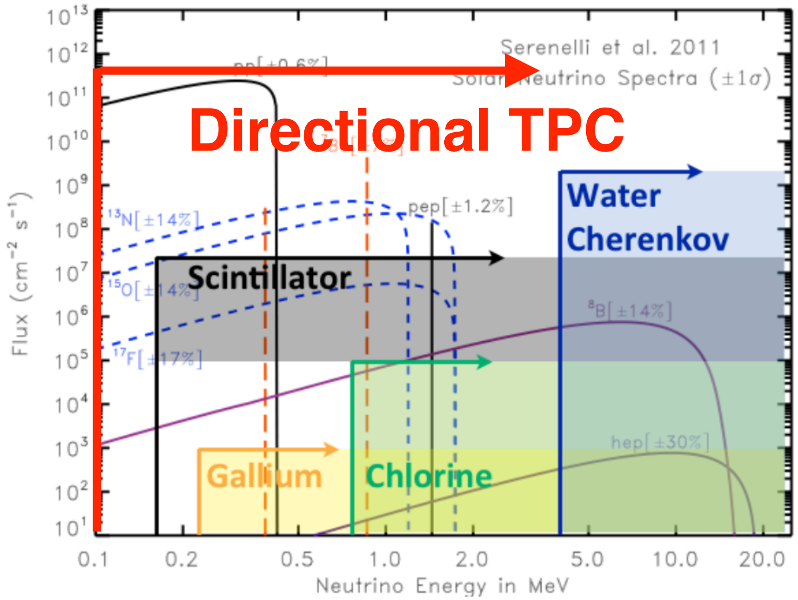
A HIGH RATE SOLAR NEUTRINO DETECTOR
WITH ENERGY DETERMINATION

1992 **He**

J. Séguinot, T. Ypsilantis
Collège de France, IN2P3 - CNRS
et CERN, Genève, Suisse

A. Zichichi
CERN, Genève, Suisse
et INFN-Laboratoire national du Gran Sasso, Italie

1994 HELLAZ: A HIGH RATE SOLAR NEUTRINO DETECTOR WITH NEUTRINO ENERGY DETERMINATION



1996 **CF_4**

A possible gas for solar neutrino spectroscopy

C. Arpesella [a], C. Broggini [b], C. Cattadori [c]
[a] I.N.F.N. Laboratori Nazionali del Gran Sasso, I-67010 Assergi (AQ), Italy
[b] I.N.F.N. Sezione di Padova, via Marzolo 8, I-35131 Padova, Italy
[c] I.N.F.N. Sezione di Milano, via Celoria 16, I-20133 Milano, Italy

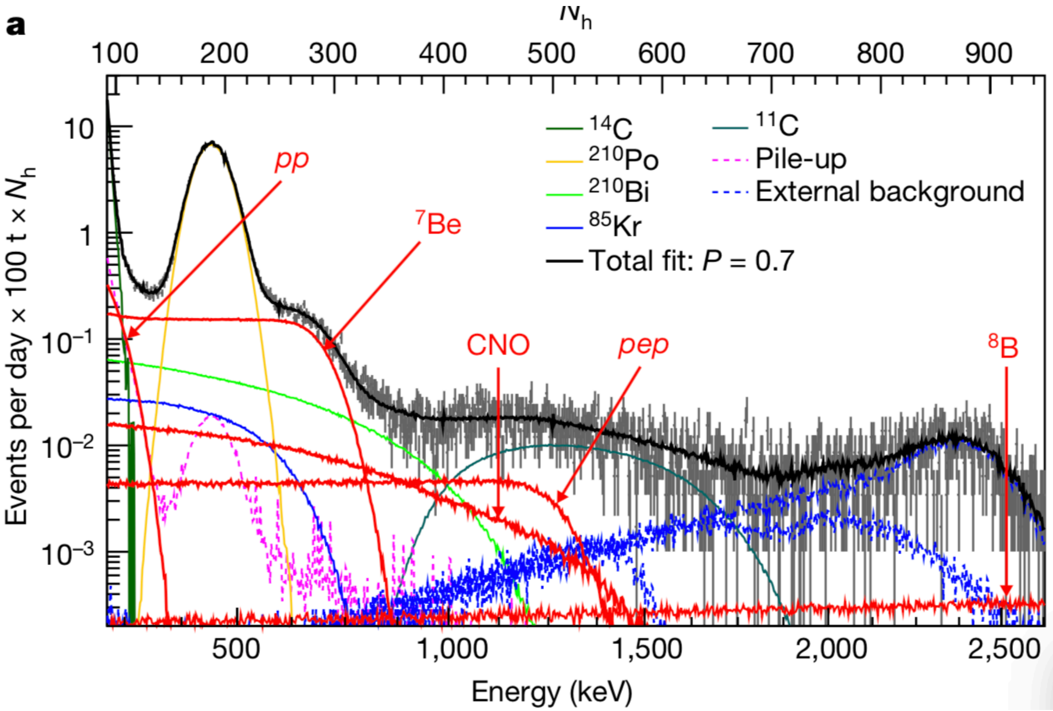
Received 25 July 1995; revised 24 October 1995

Tetrafluoromethane appears very attractive for low energy neutrino spectroscopy because it has a high density of 3.7 g ℓ^{-1} (at normal pressure and 15°C temperature), which maximizes the number of target electrons, and it contains low Z nuclei, which minimizes the multiple scattering and allows for the reconstruction of the electron direction.

Typical spatial resolution: 1-2 mm
Energy threshold: 100 keV

The detector has two new outstanding features:
– it can give the spectrum of the low energy neutrinos from the Sun;
– it is sensitive to and it can identify solar neutrinos of different origin: *pp*, ^{7}Be, and, eventually, ^{8}B.

Borexino Sun neutrino measurement



Solar neutrino	Rate (counts per day per 100 t)
pp	$134 \pm 10^{+6}_{-10}$
^{7}Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$
pep (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$
$^{8}B_{HER-I}$	$0.136^{+0.013+0.003}_{-0.013-0.003}$
$^{8}B_{HER-II}$	$0.087^{+0.080+0.005}_{-0.010-0.005}$
$^{8}B_{HER}$	$0.223^{+0.015+0.006}_{-0.016-0.006}$
CNO	<8.1 (95% C.L.)
hep	<0.002 (90% C.L.)

total LER exposure is 1,291.51 days × 71.3 t.

- **CYGNO has O(100) um tracking** *Borexino interaction position resolution:12 cm*
- **CYGNO has 20-30 keV DIRECTIONAL threshold** *Borexino E_{thr}: 160 keV*
- **CYGNO directionality provides background discrimination**

Solar neutrino measurements with directionality

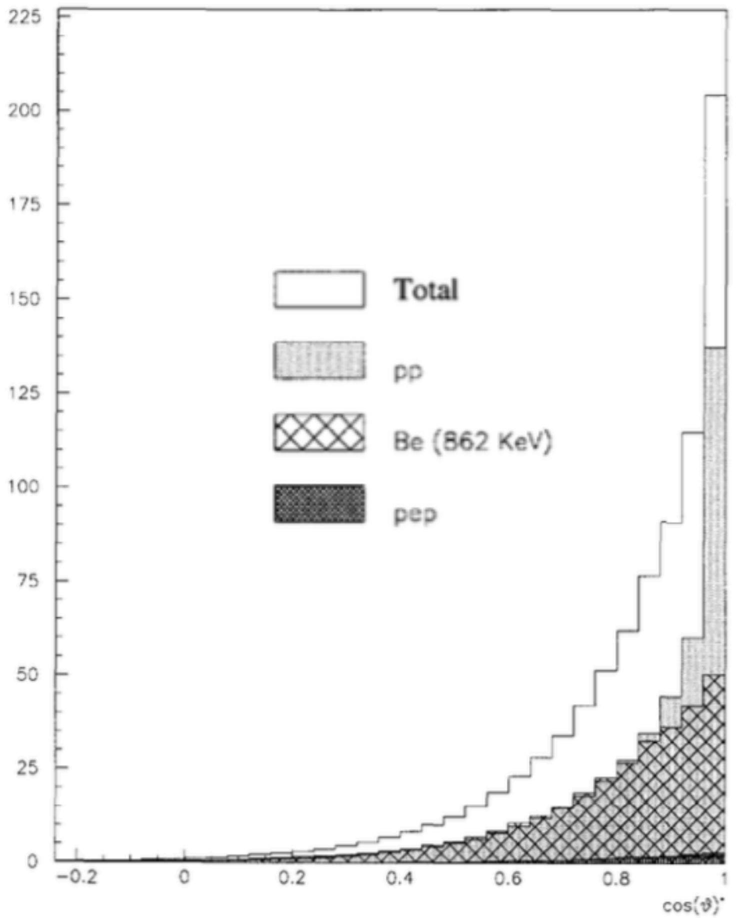


Fig. 4. The events of one year as a function of the reconstructed scattering angle.

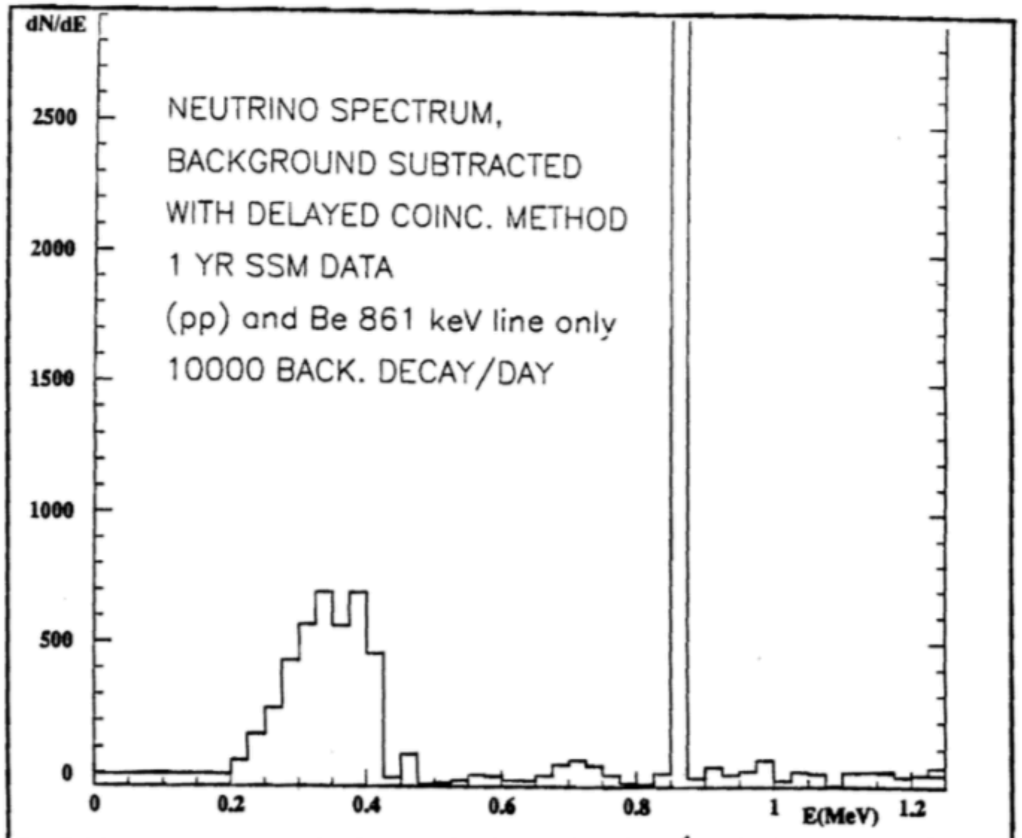
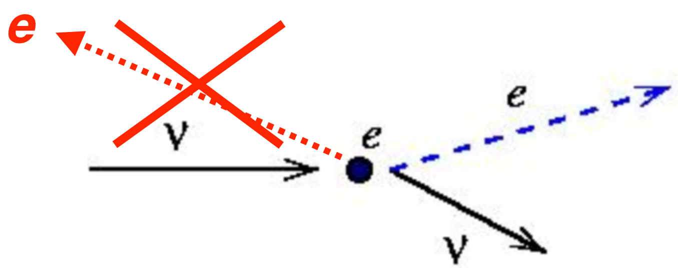


Fig.7. Neutrino spectrum background subtacted with 10^4 γs/d from the TPC cage.

Given the Sun position, recoils in opposite direction are kinematically forbidden



Differently from WIMPs, background can be measured on sidebands data

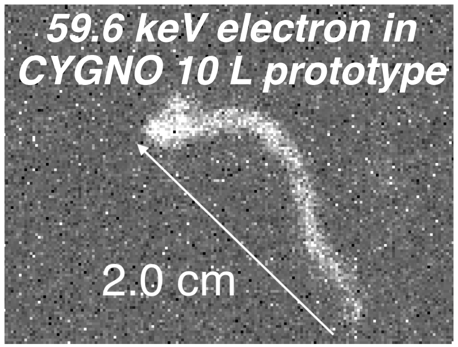
CYGNO as an innovative detector for low energy, precision solar neutrino spectroscopy

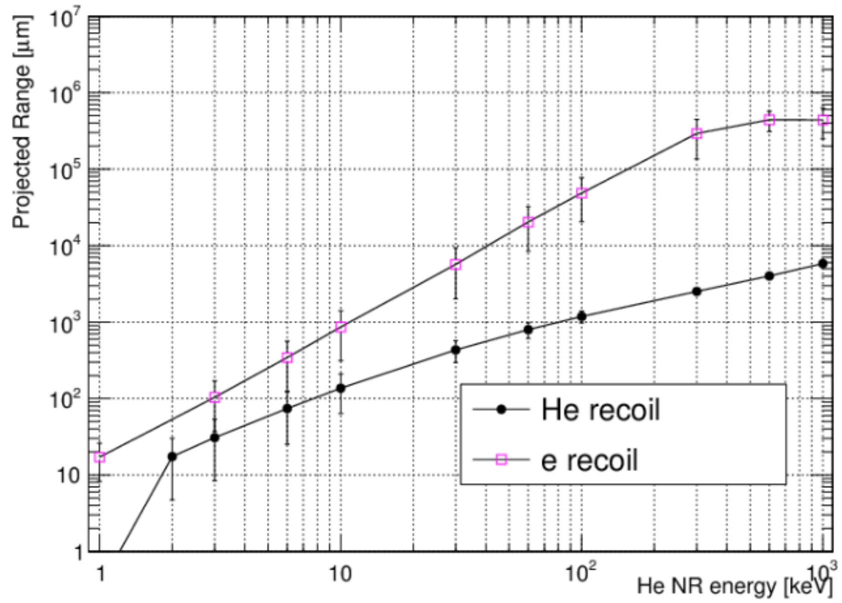
- **He:CF4 allows a lot of electron, with a low density gas**

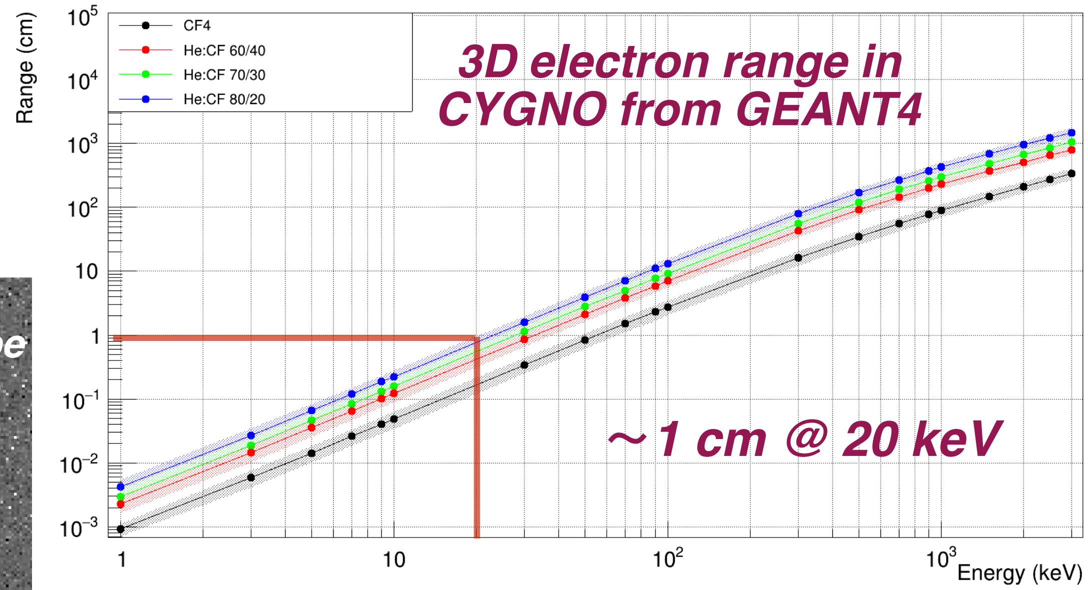
  Good target/density ratio

- **CYGNO readout approach has O(100) um track resolution**
- **CYGNO can aim at 20 keV DIRECTIONAL threshold for electrons (i.e. 80 keV neutrinos)**
- **CYGNO is sensitive to single ionisation cluster for MeV electrons (i.e. calorimetry)**

Question to answer: upper energy threshold.
Obvious: contained track
But: if track not on dE/dx plateau, could measure E through dE/dx?





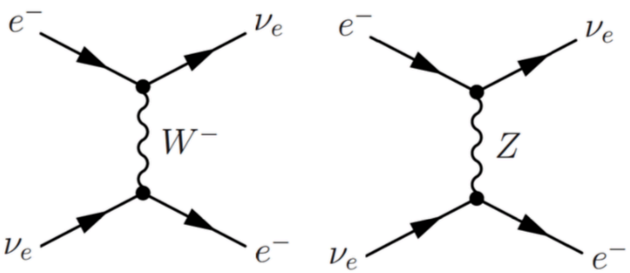


Expected # of events

Interaction rate of solar neutrino from the *ppI* cycle with electrons in the prototype of the INITIUM project

Samuele Torelli

PRELIMINARY



$$d\sigma = \frac{1}{s_0}\frac{1}{s_1}\ldots\frac{1}{s_N}\frac{1}{\varphi}|M_{i\to f}|^2(2\pi)^4\delta^4\left(P_A + P_B - \sum_{i=0}^{i=N} P_i\right)\cdot\prod_{i=0}^{i=N}\left(\frac{d^3P_i}{2E_i(2\pi)^3}\right) \quad (1)$$

$$|M_{i\to f}|^2 = 64\frac{G_F^2E_\nu^2m_e^2}{2}\left\{(V+A)^2 + (V-A)^2\left(1-\frac{T'_e}{E_\nu}\right)^2 - (V^2-A^2)\left(\frac{m_eT'_2}{E_\nu^2}\right)\right\} \quad (13)$$

$$\frac{d\sigma(E_\nu, T'_e)}{dT'_e} = \frac{G_F^2m_e}{2\pi}\left\{(2+g_V+g_A)^2 + (g_V-g_A)^2\left(1-\frac{T'_e}{E_\nu}\right)^2 - (g_V-g_A)(g_V+g_A+2)\frac{m_eT'_e}{E_\nu^2}\right\} \quad (20)$$

$$T'_e(\theta) = \frac{2E_\nu^2m_e cos^2(\theta)}{(E_\nu+m_e)^2 - E_\nu^2cos^2(\theta)}$$

$$\sigma(E_\nu) = \frac{G_F^2m_e}{2\pi}\left\{(g_V+g_A+2)^2\left[\frac{2E_\nu^2}{(m_e+2E_\nu)} - T'_{e,Thr}\right] + \right.$$
$$- (g_V-g_A)^2\frac{E_\nu}{3}\left[\left(1-\frac{2E_\nu}{m_e+2E_\nu}\right)^3 - \left(1-\frac{T'_{e,Thr}}{E_\nu}\right)^3\right] +$$
$$\left. - (g_V-g_A)(g_V+g_A+2)\frac{m_e}{2}\left[\frac{4E_\nu^2}{(m_e+2E_\nu)^2} - \frac{T'^2_{e,Thr}}{E_\nu^2}\right] \right. \quad (23)$$

Including neutrino oscillations

For 1 m^3 of He:CF_4 60:40 with 20 keV threshold

$$R = N_e \cdot \int_{E_{min}}^{E_{max}} w(E)\varphi_{ppI}(E)\sigma(E)dE \qquad R = 2.9\cdot 10^{-8}\,\frac{events}{s\cdot m^3} = 0.9\,\frac{events}{y\cdot m^3}$$

Neutrino energy resolution from expected electron resolutions

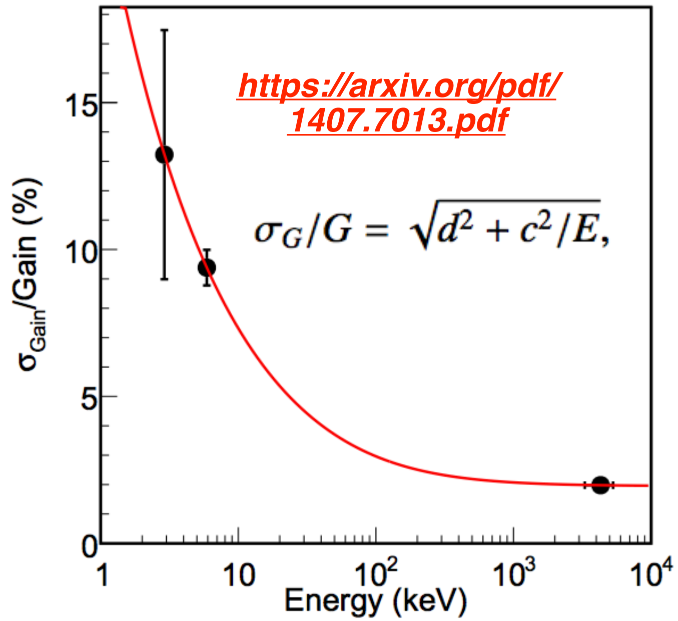
The neutrino energy resolution $\sigma_{E\nu}/E_\nu$ is obtained from the derivatives of eq. (2) i.e.

$$\sigma_{E\nu}/E_\nu=\sqrt{\{D_\theta^2\sigma_\theta^2+D_T^2(\sigma_T/T)^2\}} \quad (11)$$

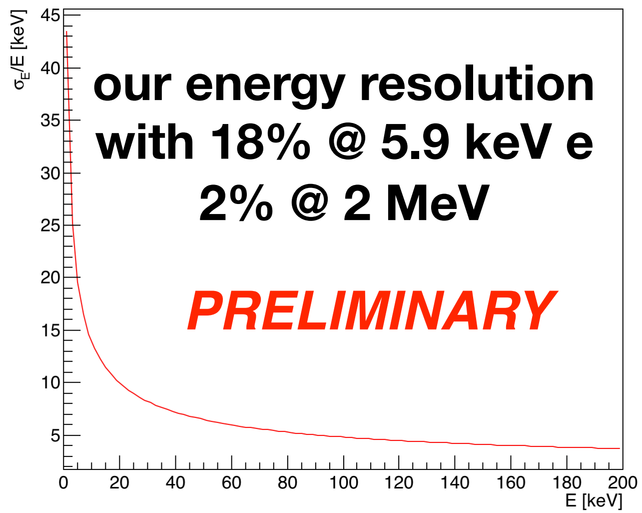
ere the dimensionless logarithmic derivatives

$$D_\theta=(1/E_\nu)(\partial E_\nu/\partial\theta)=(E_\nu/m_e)\sqrt{\{1+(2m_e/T)-[1+(m_e/E_\nu)]^2\}} \quad (12)$$
$$D_T=(T/E_\nu)(\partial E_\nu/\partial T)=(E_\nu+m_e)/(T+2m_e)$$

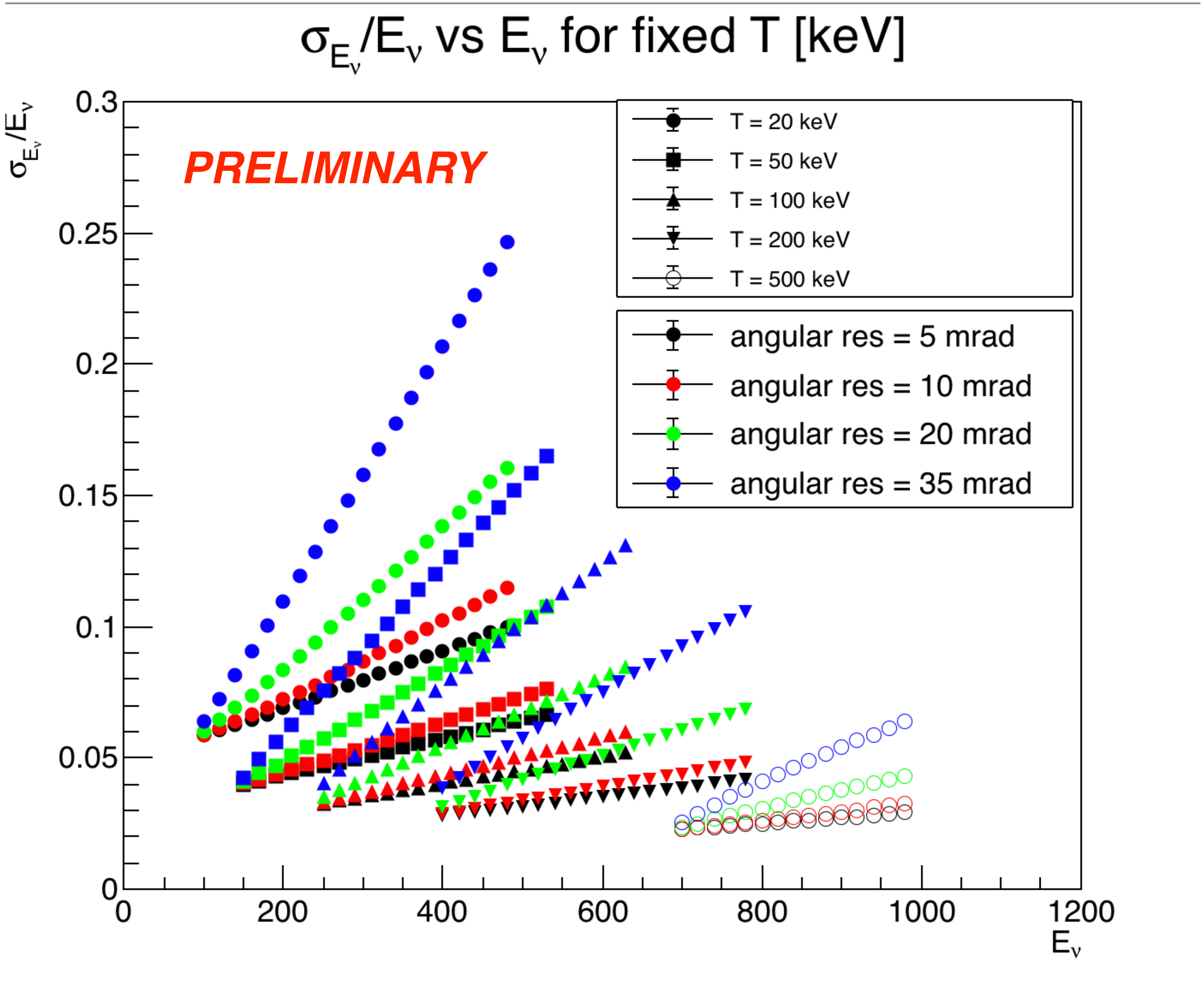
Input parameters: energy & angular resolution



TMath::Sqrt(4.33 + 1890.0/x)

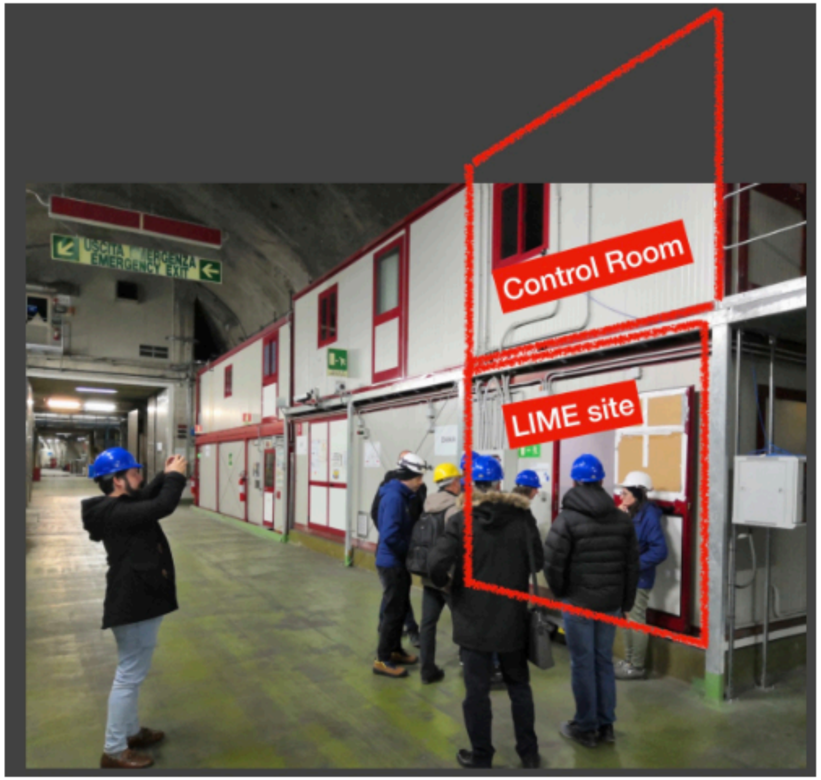


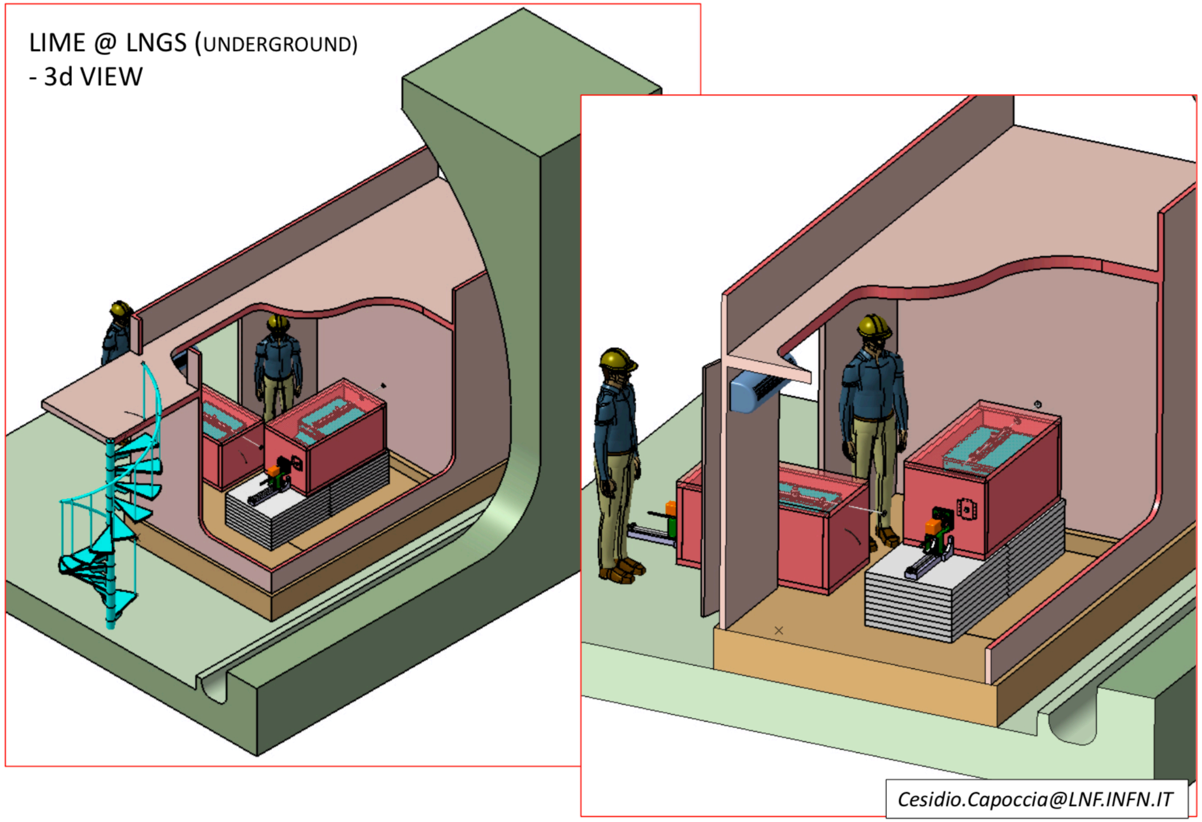
Neutrino energy resolution



Measurements with LIME: underground LNGS neutron flux

LIME @ underground LNGS





Neutron flux measurement @ LNGS with LIME

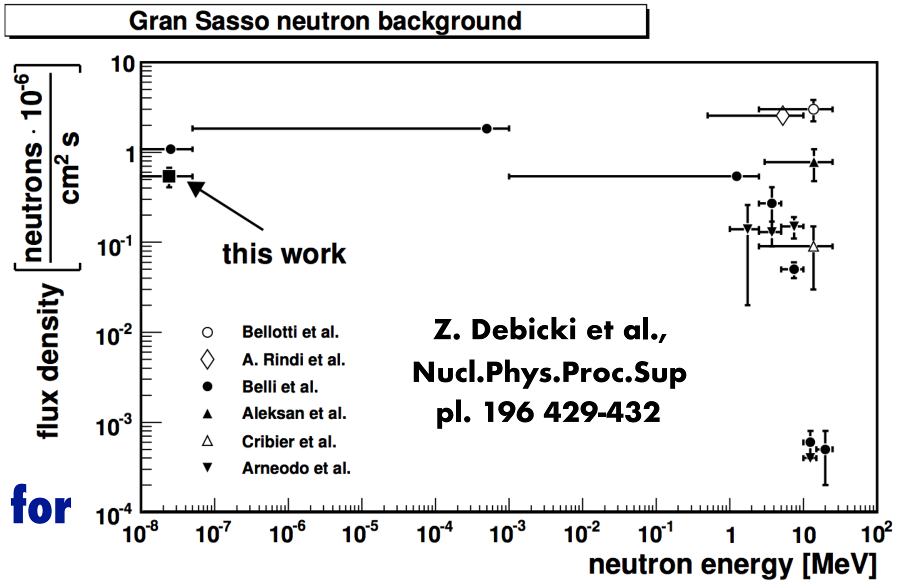
Environmental neutrons in underground halls are background to all current & future experiments: their precise knowledge is fundamental

- **Simultaneous sensitivity to thermal and fast neutron flux with $^3He:He:CF_4:SF_6$ at atmospheric pressure**
  - Fast neutron through nuclear recoil
  - Thermal neutron through capture on ^{3}He (0.5% is enough thanks to the large capture cross section).
- **O(10 keV) or lower threshold on fast neutrons**
- **Precise spectral measurement**
- **Directional measurement**
- **Seasonal measurement**
- **LIME location in front of DAMA setup**
- **Possibility to optimize pressure and gases content for higher yield or lower directional threshold**
- **Demonstrator for CYGNO PHASE-1**

Proton 573 keV

Tritium 191 keV

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



PRELIMINARY

± 250 detected nuclear recoils induced by fast neutrons/year

± 250 detected thermal neutrons through capture/year