Modeling of Electron Recoils in XENON100 with Monte Carlo Simulations

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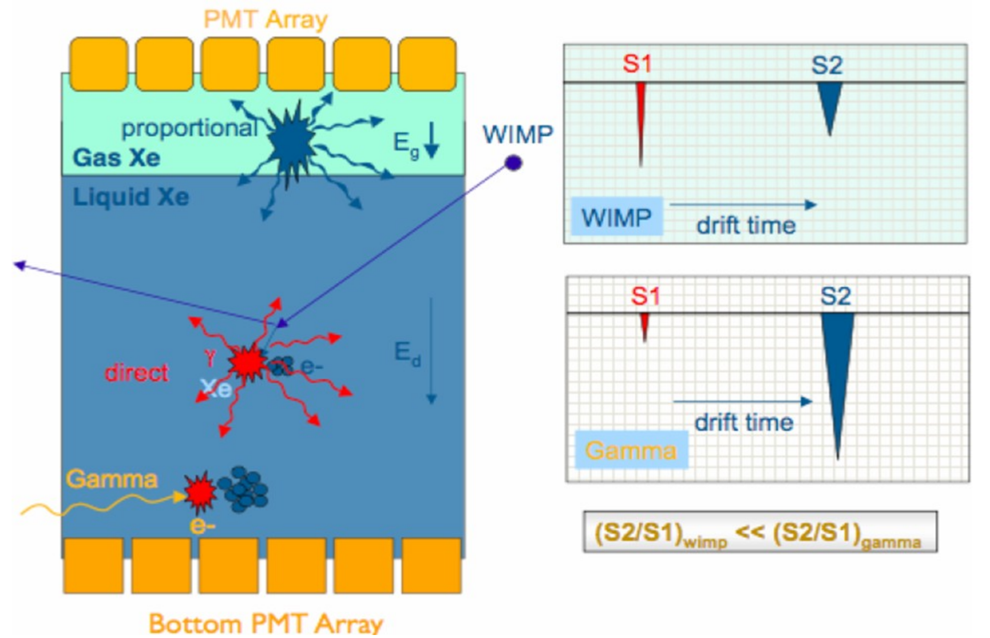
The XENON project

See talk by F.V. Massoli



- Low event rate expected
- Necessity to reduce the background
  - Nuclear Recoil (NR) background
    → spontaneous fission, (α,n) reactions, μ-induced neutrons, ν coherent scatterings
  - Electron Recoil (ER) background
    → material contaminations, intrinsic sources
- Why do we want to model the ERs?
  - discrimination between ER/NR bands
  - use the MC as calibrating system in XENON1T

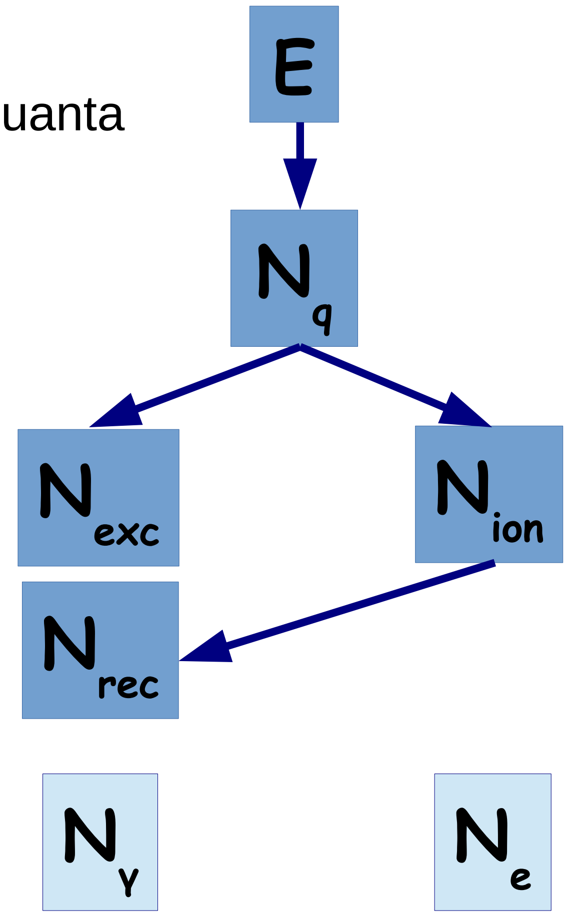
Modeling ERs with NEST

Noble Element Simulation Technique:

- collection of constants obtained by fitting experimental up-to-date results
- converts the energy deposited by a particle hitting a LXe detector, into light and charge

How does it work?

- energy E released in the detector converts itself into quanta
  $N_q=N_{exc}+N_{ion}$
- N_q~Gauss(73 E, √0.03 73 E)
  μ=73 quanta/keV, Fano factor F=0.03
  - N_{exc}~Binom(N_q,N_{exc}/N_q)
    N_{exc}/N_{ion}=0.055
  - $N_{ion}=N_q-N_{exc}$
  - N_{rec}: part of N_{ion} recombines itself (*Doke-Birks* model); for short tracks the *Thomas-Imel* model is used
- light: $N_\gamma=N_{exc}+N_{rec}$
- charge: $N_e=N_{ion}-N_{rec}$

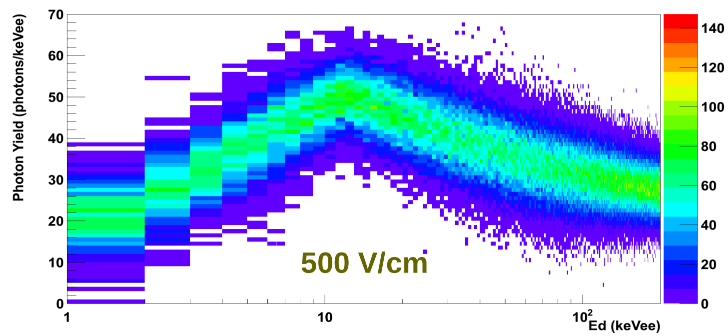


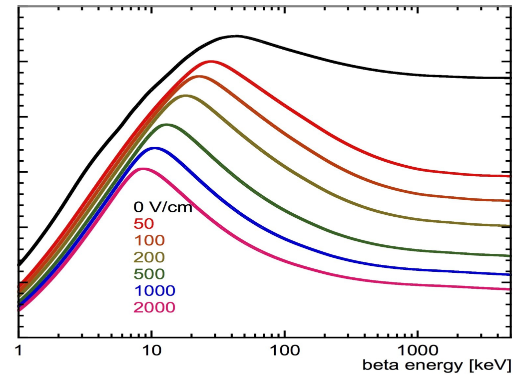
Monte Carlo simulation

- NEST has been implemented in the XENON100 Monte Carlo code

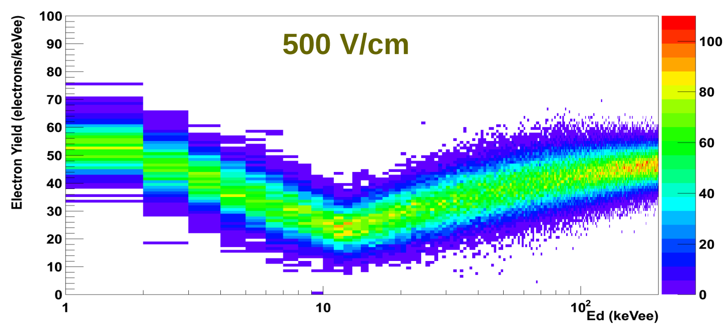
XENON100 | 2011 JINST 6 P10002

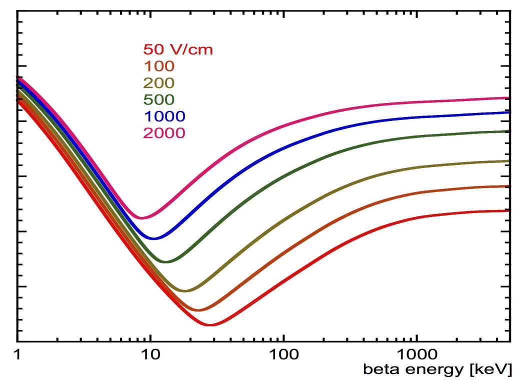
Light yield (photons/keV)





Charge yield (electrons/keV)





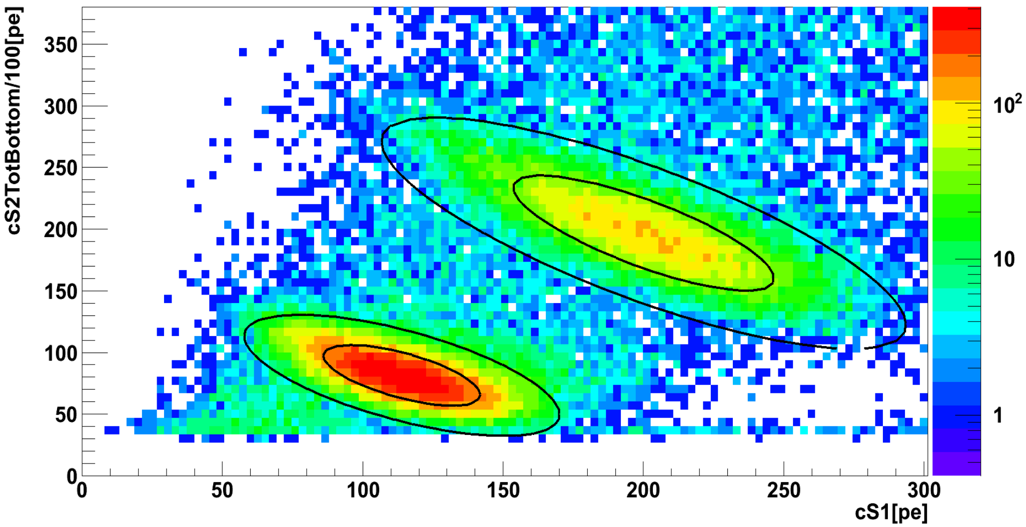
- conversion of light/charge from NEST into S1 and S2 signal: pdf related to the detector
- we want to validate NEST by comparing the MC products with the data from XENON100 calibrations

AmBe calibration: MC-Data matching

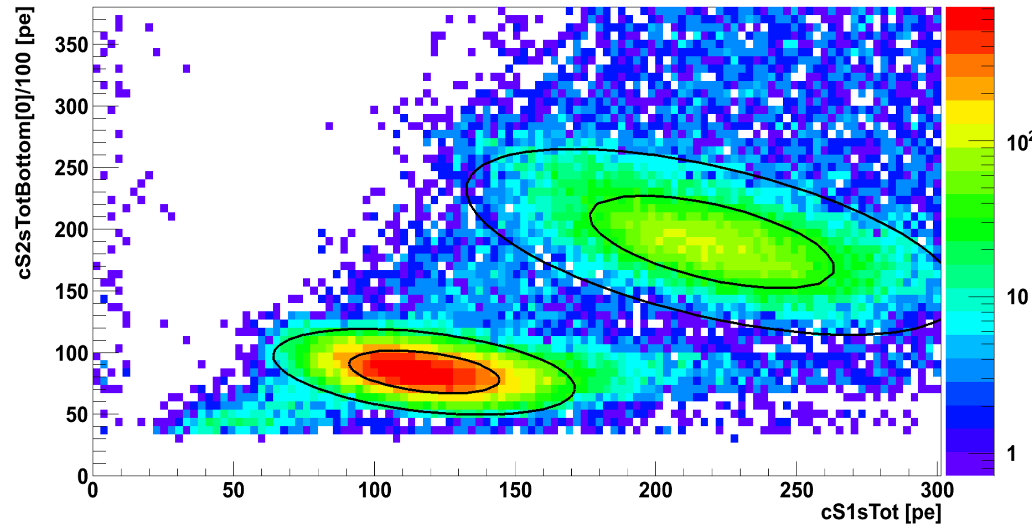
- ^{129}Xe and ^{131}Xe isotopes: part of target mass
- a neutron from AmBe source can interact via inelastic scattering with the LXe target, which in turn activates itself and emits
  - 39.6 keV line –> from ^{129}Xe isotope
  - 80.2 keV line –> from ^{131}Xe isotope
- the detector responds with S1 and S2 signals, anti-correlated and Gaussian distributed
- same cuts to select the lines in both MC and Data

  → single scatter, 40 kg fiducial volume, S2 threshold
- analysis of ~5 live days

Monte Carlo simulation

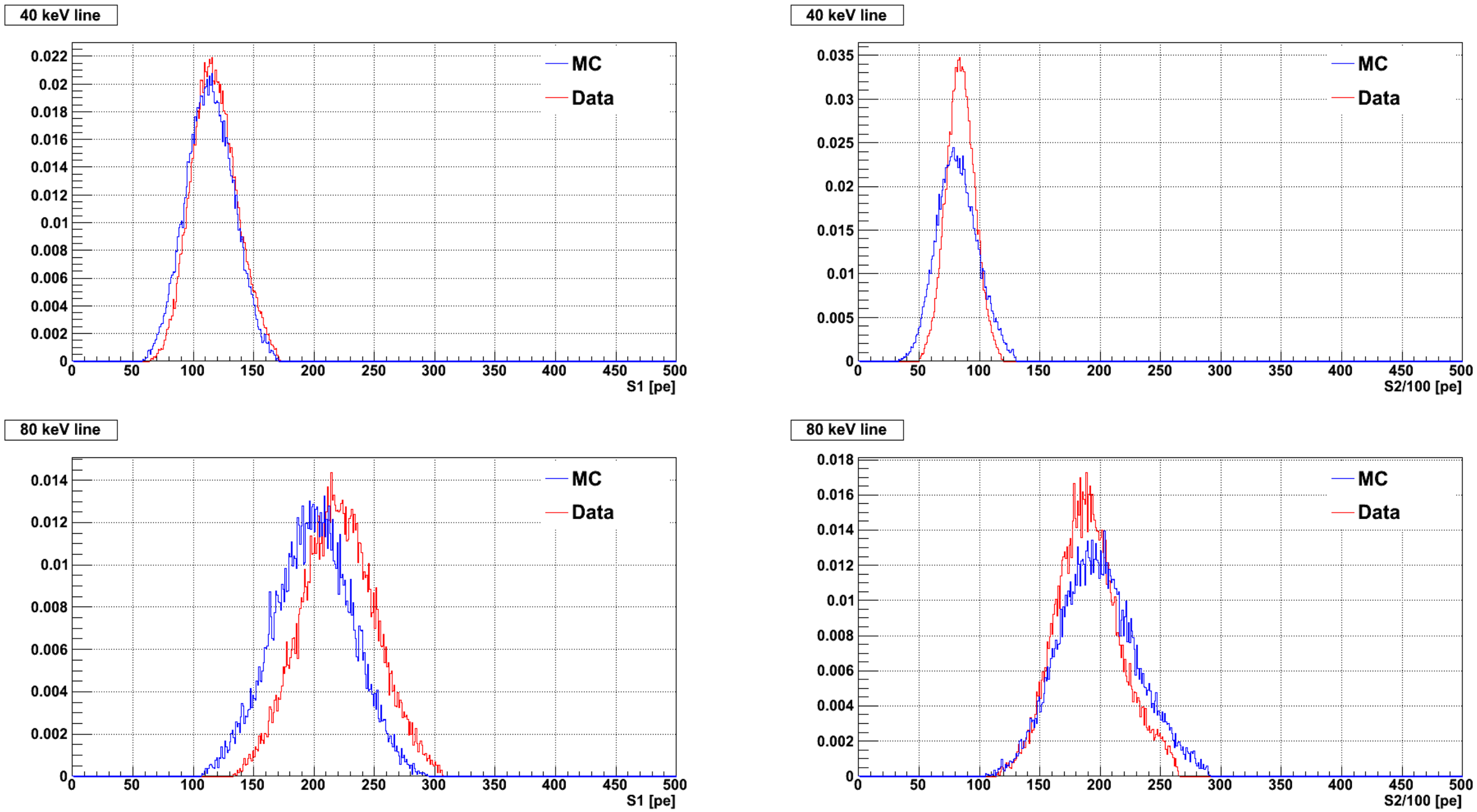


XENON100 data



		μ_{Fit} S1 (pe)	σ_{Fit} S1 (pe)	μ_{Fit} S2/100 (pe)	σ_{Fit} S2/100 (pe)	θ_{Fit} (deg)	Rate (x10^{-3} n/s)
40 keV	**MC**	113.91±0.11	24.05±0.10	81.47±0.10	10.95±0.05	140.8±0.2	116±5
	Data	117.66±0.09	19.81±0.07	84.30±0.06	10.91±0.04	159.7±0.2	116.2±1.6
	Discrepancy	-3%	21%	-3%	0.4%	-12%	0.3%
80 keV	**MC**	200.1±0.3	44.4±0.4	196.7±0.3	15.06±0.10	134.9±0.2	73±4
	Data	220.0±0.2	36.3±0.3	189.6±0.2	18.75±0.13	142.4±0.4	48.6±1.2
	Discrepancy	-9%	22%	4%	-20%	-5%	50%

- good agreement for the S1 and S2 average
- for the MC case the rotation angle is almost constant in both the lines, as expected in absence of further interactions
- the rate of inelastic scattering with ^{129}Xe isotope shows a very good match



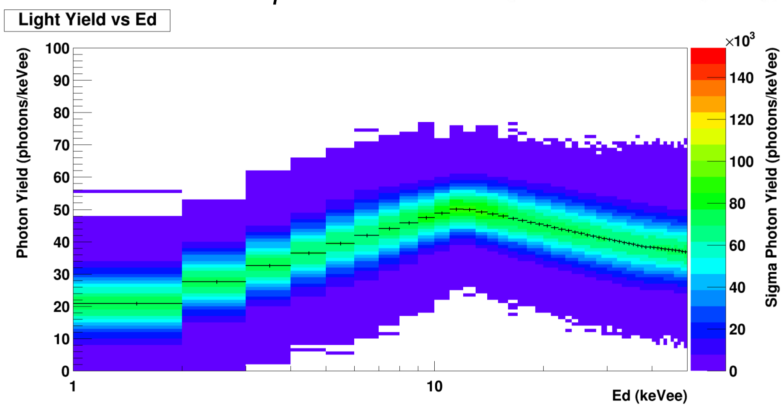
S1 and S2 projections inside the 2-sigma contour

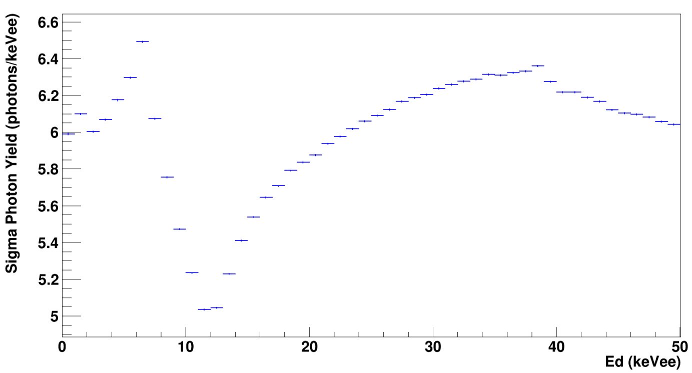
		S1 (pe)		S2/100 (pe)	
		Mean	RMS	Mean	RMS
40 keV	MC	113.77±0.10	19.43±0.07	81.64±0.09	16.75±0.06
	Data	117.56±0.08	18.55±0.06	84.30±0.05	11.69±0.04
	Discrepancy	-3%	5%	-3%	43%
80 keV	MC	199.0±0.2	32.13±0.15	198.2±0.2	32.13±0.15
	Data	220.0±0.2	30.71±0.15	190.19±0.18	26.64±0.13
	Discrepancy	-10%	5%	4%	21%

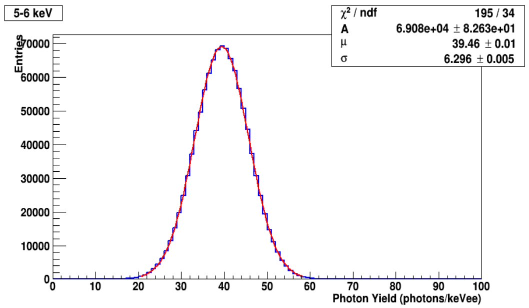
very good agreement between MC and Data

Bayesian approach

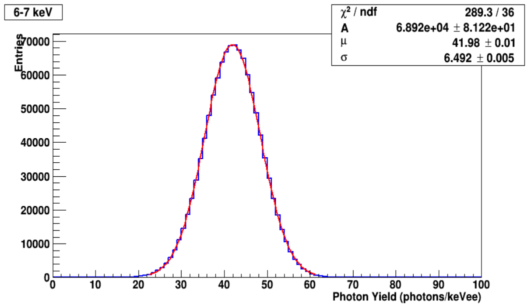
- ER background reconstruction using known parameters Ξ
  → $\mathcal{L}(\Xi) = p(\{S1^{\rm obs}, S2^{\rm obs}\}|\Xi) = p(S1^{\rm obs}|\Xi)p(S2^{\rm obs}|\Xi)$
- *photon yield* (m_j and s_j) per unit of energy E_j as input parameter, from NEST
  → draw N_γ from $p(N_\gamma|\Xi) = \mathcal{N}_{N_\gamma}(m_j E, s_j E)$

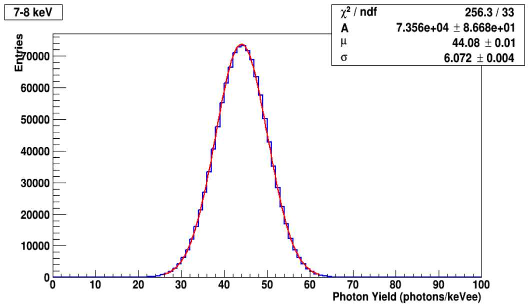






- draw N_q from $\mathcal{N}_{N_q}(73E, \sqrt{0.03 \cdot 73E})$
- get the anti-correlated N_e from N_q-N_γ
- then we want to use as much as possible the physics of the detector
  → same pdf as previously





- final likelihood: $\mathcal{L}_{S1}(\Xi) = \sum_{N_{\rm PE}} \mathcal{N}_{S1}(N_{\rm PE}, 0.5\sqrt{N_{\rm PE}}) {\rm Binom}_{N_{\rm PE}}(N_\gamma^{\rm corr}, \langle\mu\rangle) N_\gamma^{\rm corr}$

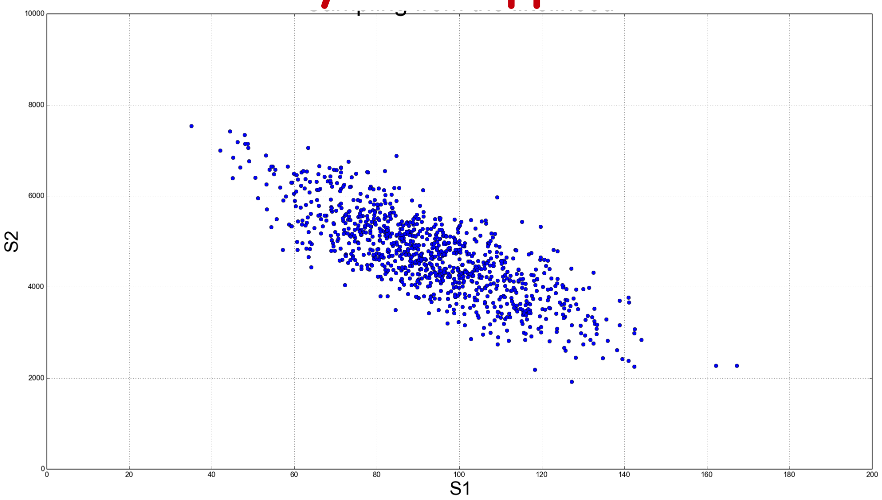
$$\mathcal{L}_{S2}(\Xi) = \sum_{N_g} \mathcal{N}_{S2}(\mu_0 N_g, \sigma_0\sqrt{N_g}) {\rm Binom}_{N_g}(N_e^{\rm corr}, e^{-t_d/\tau_e}) N_e^{\rm corr}$$

- why Bayesian approach? test the low energy region of interest (E< 50 keV)
- we firstly have to validate the method
  → comparison with known results

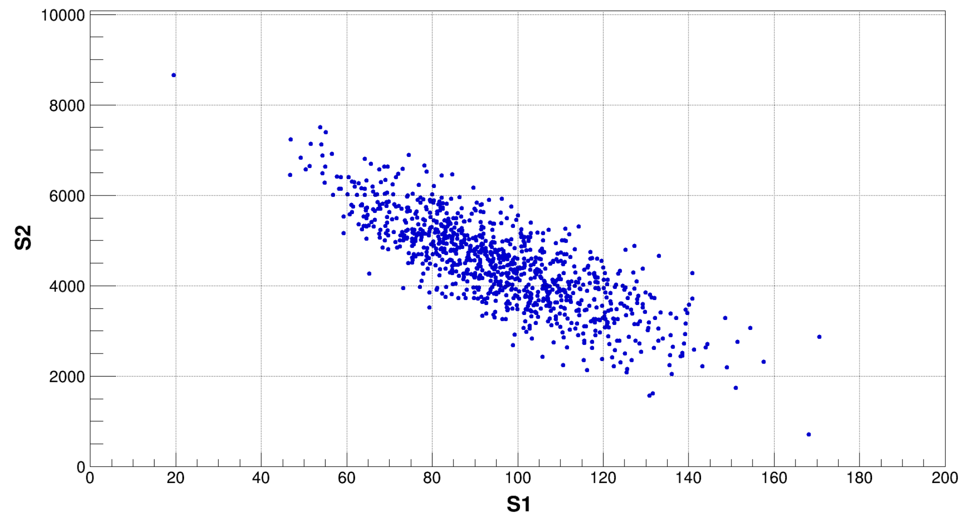
Testing the Bayesian approach

- test on 1000 events of 40 keV ERs

Bayesian approach



MC simulation



very good agreement between the S1 and S2 average values, their spread and the anti-correlation
→ we can consider the procedure properly validated

Conclusions

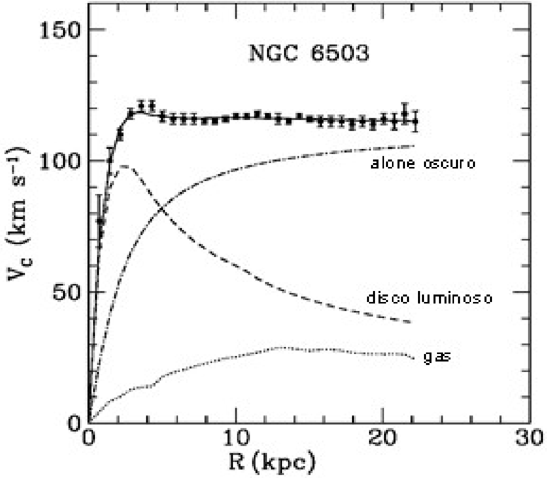
- XENON is a low event rate experiment, thus the background (ER and NR) needs to be under control
- MC description of ERs using NEST
  - comparison with AmBe calibrations
  - good agreement for the S1 and S2 average
  - the rate of inelastic scattering with ^{129}Xe isotope shows a perfect matching
- statistical description of ERs with Bayesian approach
  - comparison with 40 keV ERs from the above MC
  - very good agreement between S1 and S2 average, spread and anti-correlation

Backup slides

Dark Matter

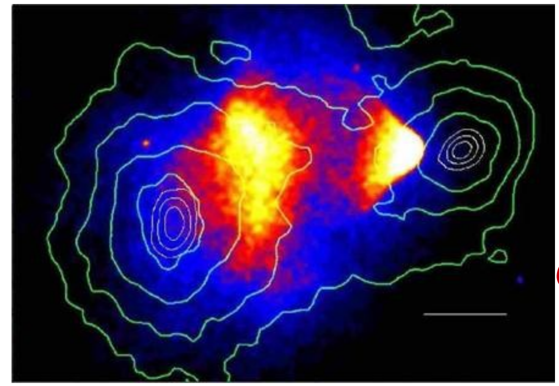
Evidences of Dark Matter

Rotational curves

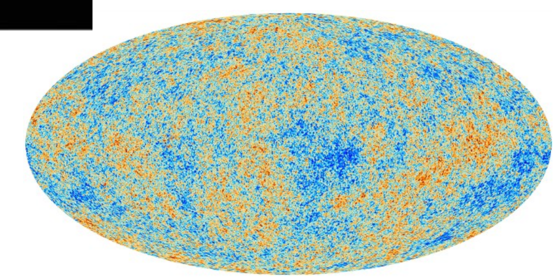


Gravitational lensing

Bullet cluster

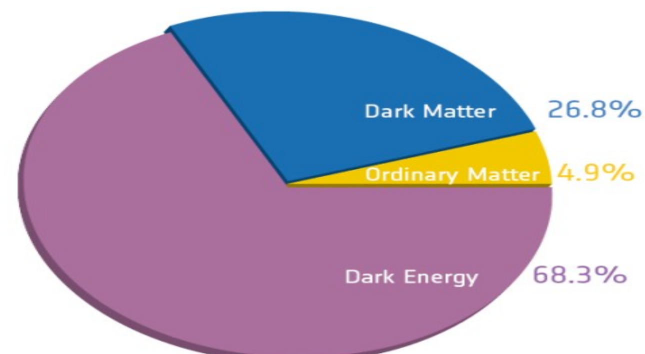


CMB anisotropies



What does Dark Matter mean:

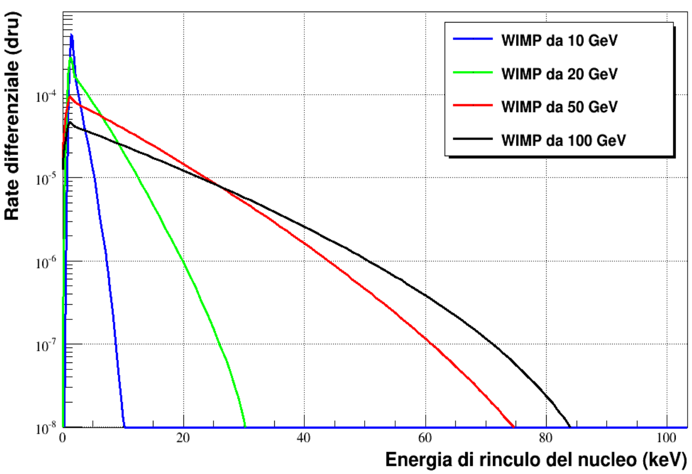
- only gravitational and weakly interacting matter
- it constitutes about 27% of the universe
- best candidate: WIMP (*Weakly Interacting Massive Particle*)

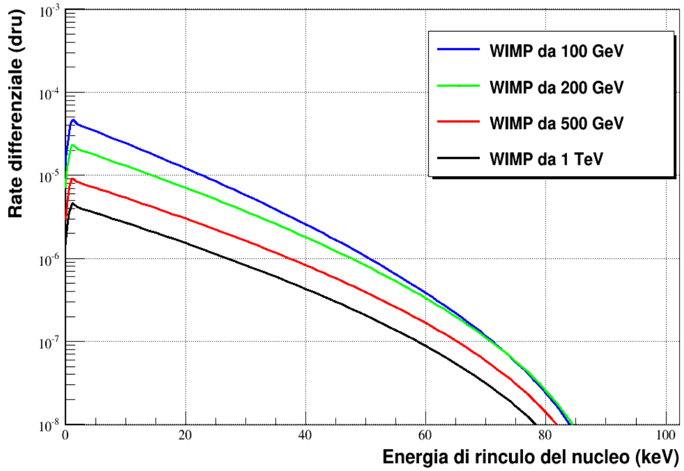


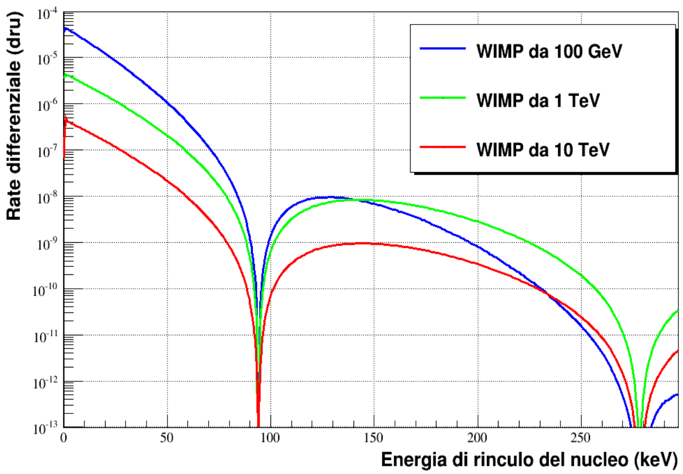
Plank Collaboration, Astron.Astrophys. 571 (2014) A1

Expected Dark Matter rate

$$\frac{dR}{dE_R} = \frac{\rho_0 \sigma^p_{teor}}{2\mu_p^2 m_\chi} A^2 F(q)^2 \int_{v_{min}}^{v_{fuga}} \frac{\rho(\overrightarrow{v} + \overrightarrow{v}_{Sole})}{v} d\overrightarrow{v}$$





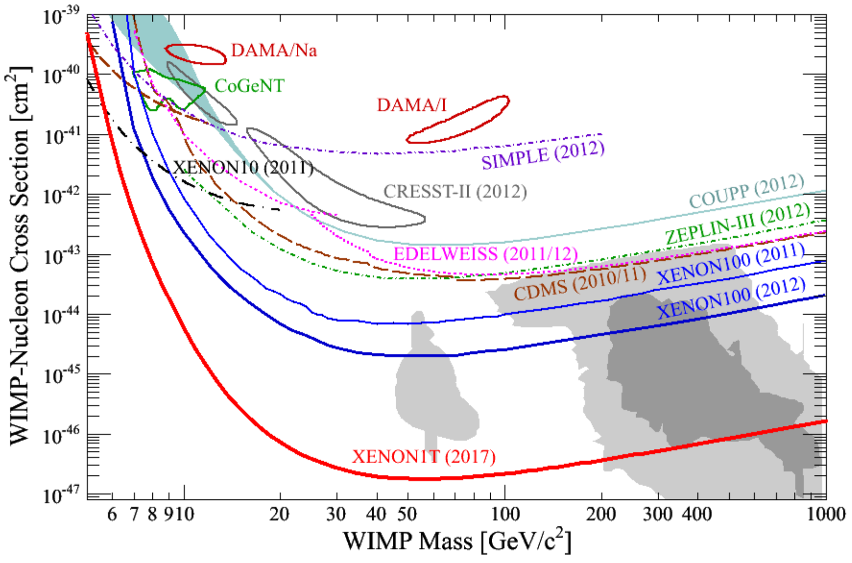


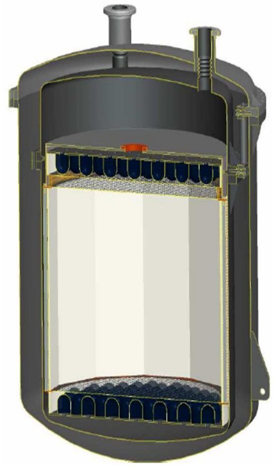
	Rate totale $(\cdot 10^{-4}\ \frac{\text{n° di eventi}}{\text{giorno}\cdot\text{kg}})$							
	m_χ(GeV)							
	10	**20**	**50**	**100**	**200**	**500**	**1000**	**10000**
0 – 100keV	2.3	7.2	8.8	6.50	3.3	1.39	0.77	0.078
10 – 50keV	0	0.59	3.63	3.09	1.83	0.789	0.402	0.041
30 – 50keV	0	10^4	0.38	0.55	0.38	0.173	0.089	0.0092

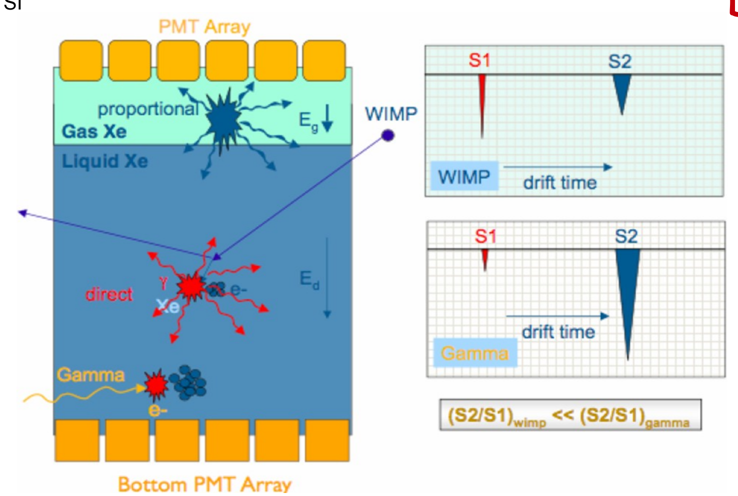
XENON: dark matter experiment

The XENON project

- **XENON10**
  - activity: 2005-2007
  - 25 kg fiducial mass
  - results: $\sigma_{SI} < 8.8\ 10^{-44}\ cm^2\ (m_\chi = 100\ GeV)$
- **XENON100**
  - activity: 2008-now
  - 161 kg fiducial mass
  - results: $\sigma_{SI} < 2\ 10^{-45}\ cm^2\ (m_\chi = 55\ GeV)$ and $\sigma_{SD} < 3.5\ 10^{-40}\ cm^2\ (m_\chi = 45\ GeV)$
- **XENON1T**
  - activity: under construction
  - 3300 kg fiducial mass
  - goal: $\sigma_{SI} < 1.2\ 10^{-47}\ cm^2$



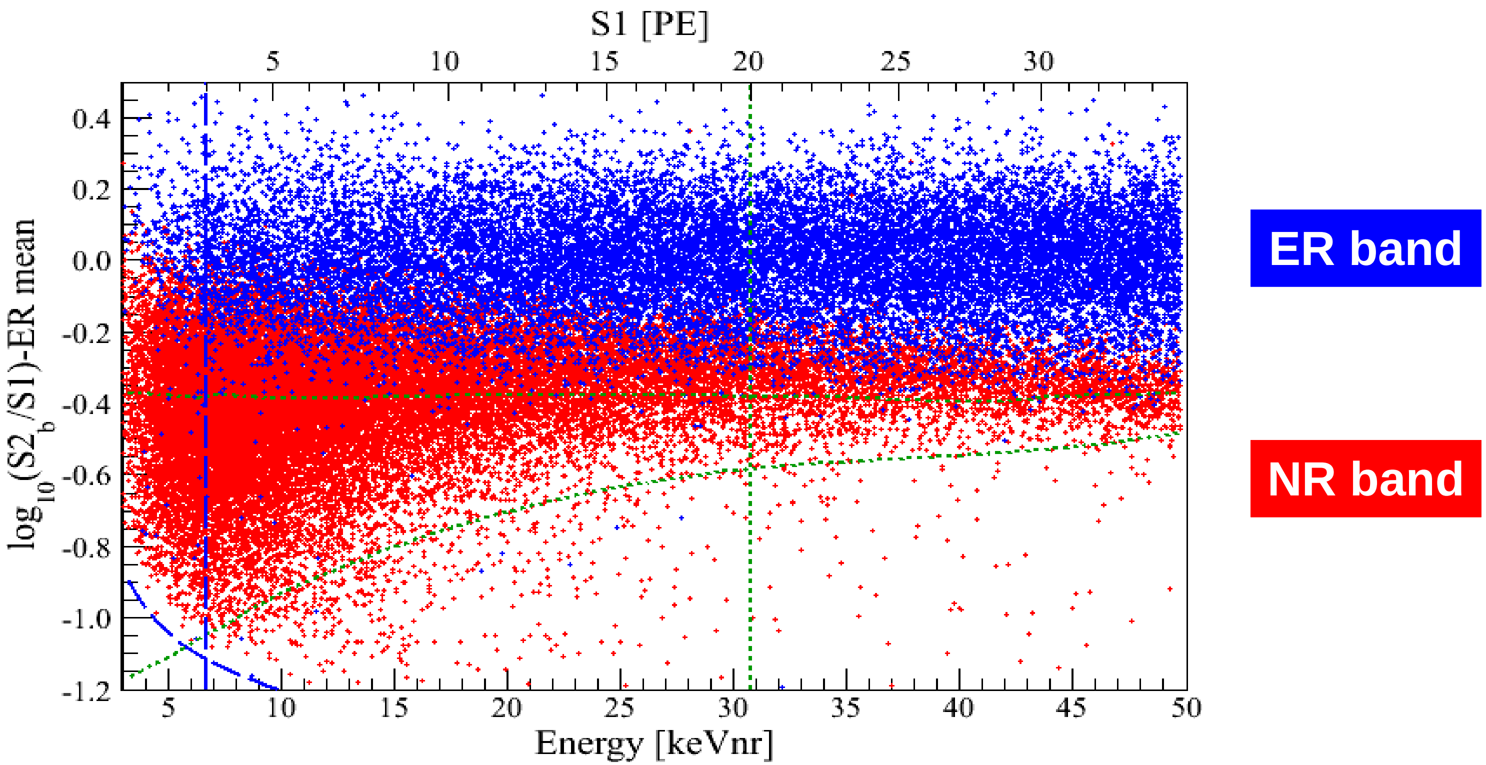




Detection technique

- dual phase Time Projection Chamber (TPC)
  - S1: primary scintillation in LXe
  - S2: secondary scintillation in Gxe
- impinging particles:
  - WIMPs (or n) scattering off Xe nuclei → NRs
  - e^-, γ scattering off electrons → ERs
    → $S2/S1_{NR} << S2/S1_{ER}$

ER/NR discrimination



$S2/S1_{NR} << S2/S1_{ER}$

99.75% discrimination for ER, 40% acceptance for NR

MC estimation of the background in XENON1T:

- 130±10 ev/year → ER
- 1.1±0.2 ev/year → NR

Detector response – details

Once known (from NEST) N_γ – and N_e:

S1

$L(S1|N_\gamma)=\Sigma_{Npe}p(S1|N_{PE})p(N_{PE}|N_\gamma)$

- $p(S1|N_{PE})=p_{PMT}(S1|N_{PE})=Gauss_{S1}(N_{PE},0.5\sqrt{N_{PE}})$
  0.5 is the average single PE resolution of the PMTs
- $p(N_{PE}|N_\gamma)=Binom_{Npe}(N_\gamma,<\mu>)$
  μ = LCE x QE is the photon detection efficiency

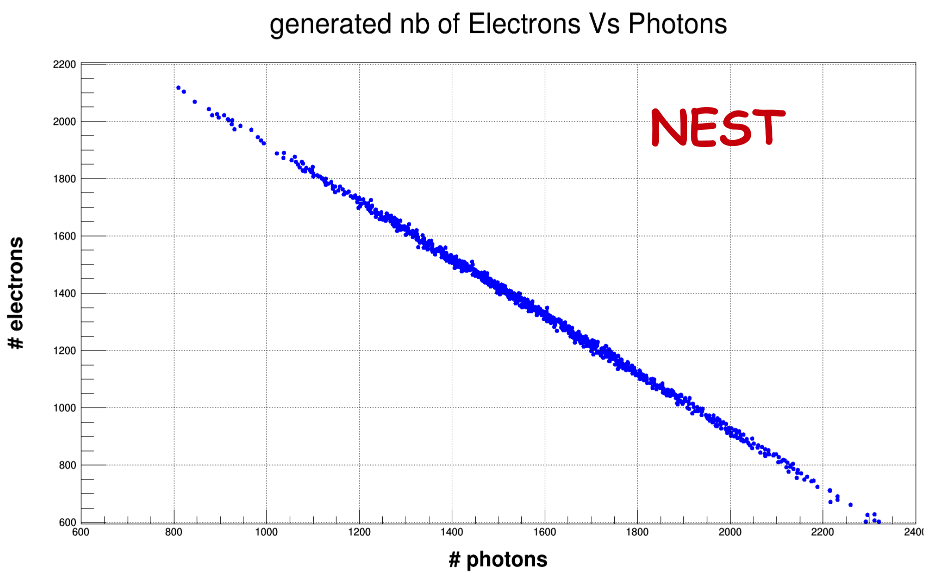
S2

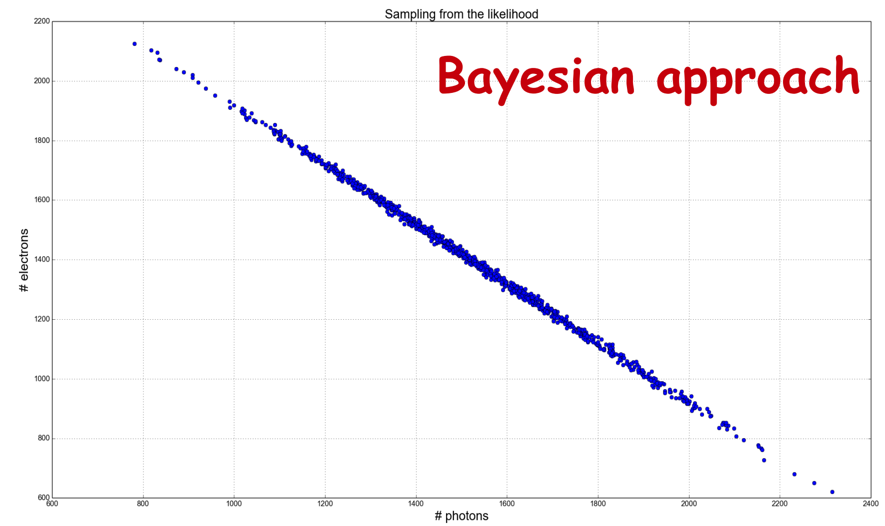
$L(S2|N_e)=\Sigma_{Ng}p(S2|N_g)p(N_g|N_e)$

- $p(S2|N_g)=p_{PMT}(S2|N_g)=Gauss_{S2}(\mu_0 N_g,\sigma_0\sqrt{N_g})$
  μ_0 (σ_0) is the average (spread) of the secondary scintillation gain
- $p(N_g|N_e)=Binom_{Ng}(N_e,\exp\{-t_d/\tau_e\})$
  t_d is the drift time and τ_e the electron lifetime

Bayesian approach

Checking the anti-correlation





Detector response: values used

$\langle\mu\rangle$	0.0607	QE x LCE – spatially average photon detection efficiency
μ_0	19.7	secondary scintillation gain: mean
σ_0	7	secondary scintillation gain: sigma
t_d	1500/1.7	drift time (Δz/vd)
τ_e	500	electron lifetime