101° CONGRESSO NAZIONALE
SOCIETÀ ITALIANA DI FISICA
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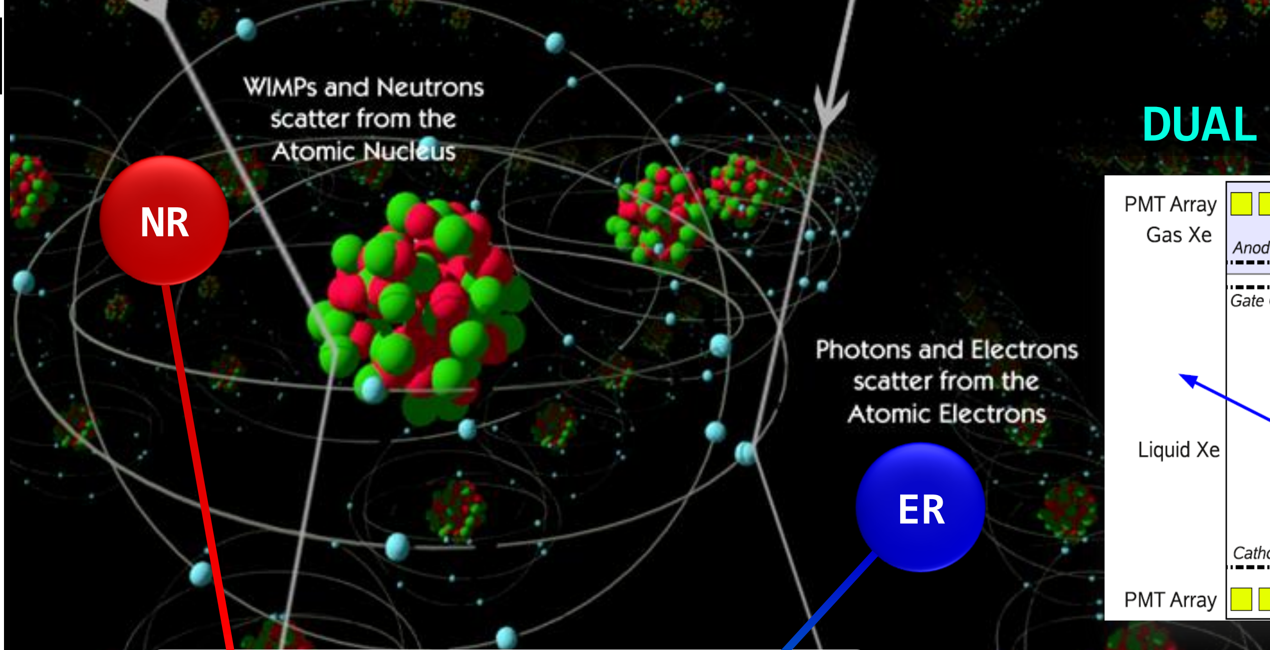
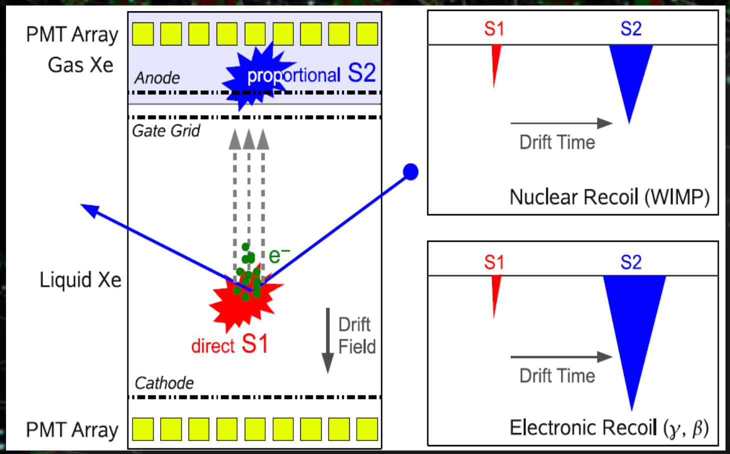
On behalf of the XENON Collaboration
University of Bologna - INFN

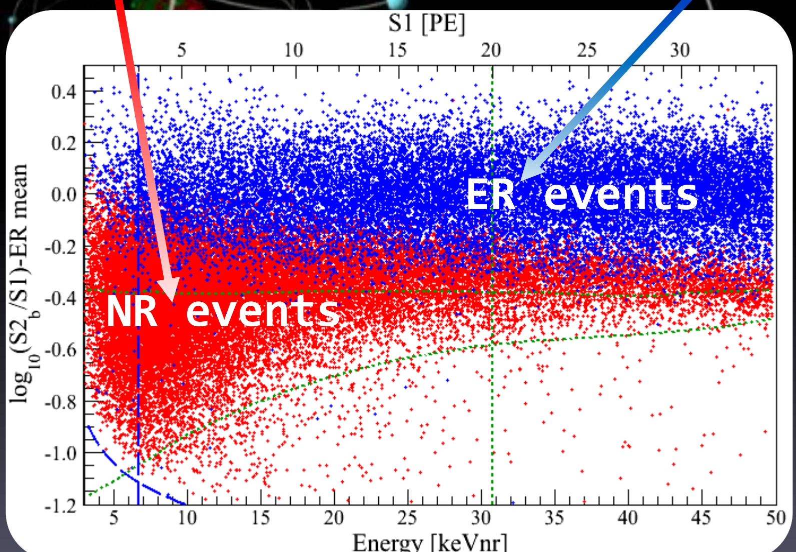
STUDY OF THE SENSITIVITY OF THE XENON1T EXPERIMENT WITH THE PROFILE LIKELIHOOD METHOD

XENON Detection Technique



DUAL PHASE LXe/GXe TPC





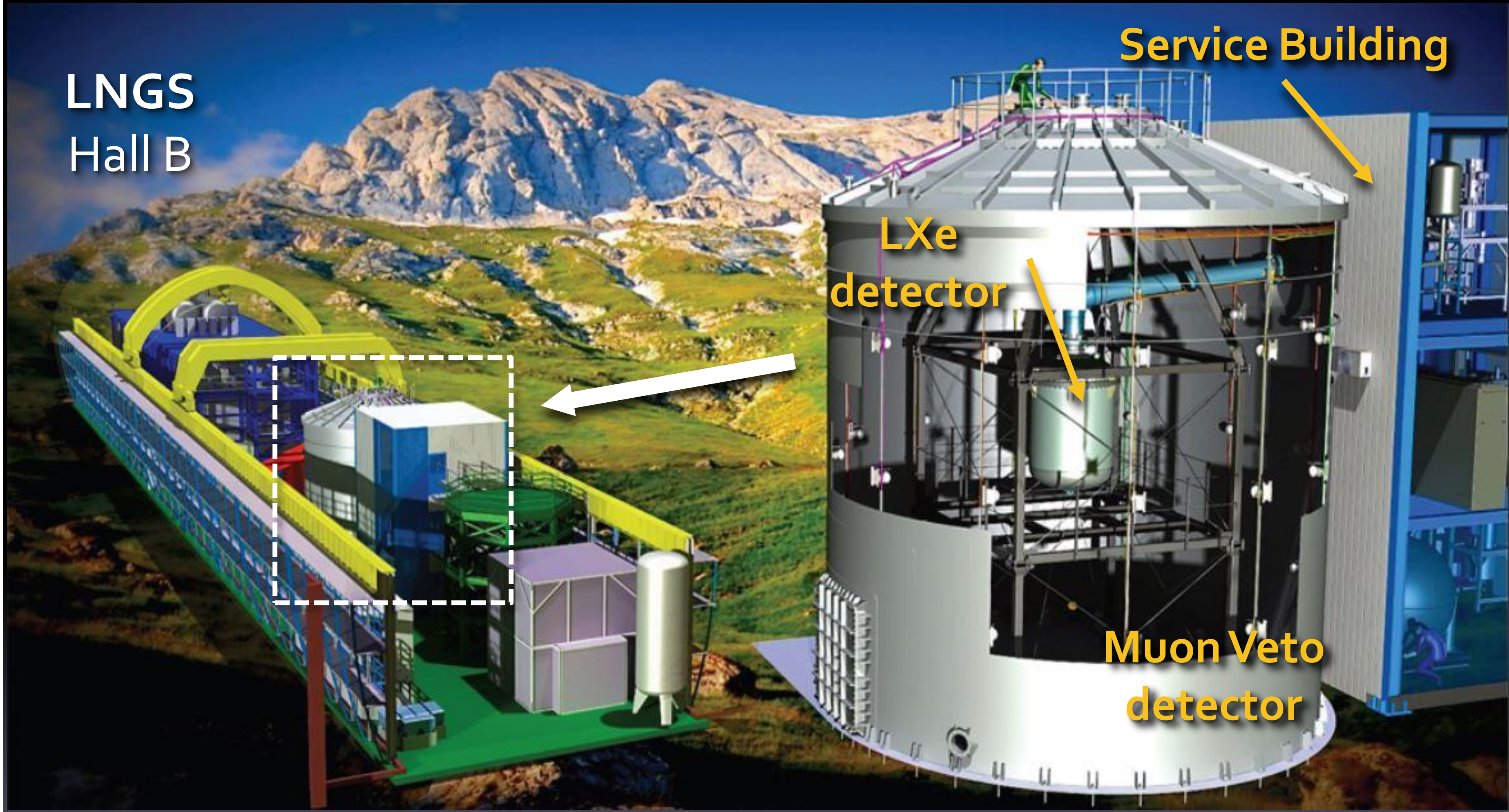
$(S2/S1)_{ER} >> (S2/S1)_{NR}$

ER/NR DISCRIMINATION

XENON100 performance

- **99.5%** **ER** discrimination, **50%** **NR** acceptance
- **99.75%** **ER** discrimination, **40%** **NR** acceptance

The XENON1T experiment



XENON1T Sensitivity

Bi-dimensional statistical model

SIGNAL WIMP-nucleon elastic scattering

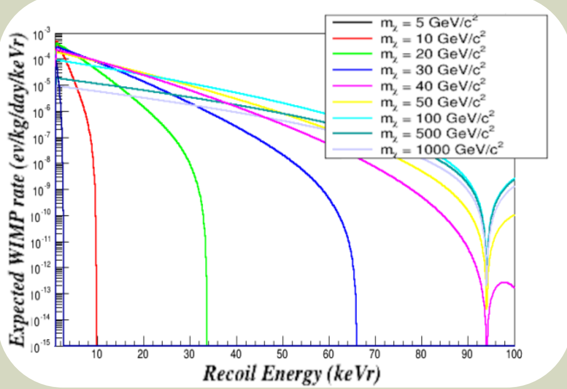
BACKGROUND ERs and NRs

Criteria of event selection

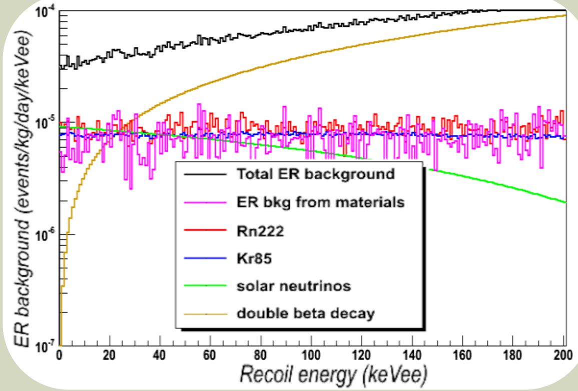
- **Single scatter** interaction
- Vertex of interaction inside the **Fiducial Volume (1 ton)**
- Deposited energy in the **experimental search window [3,70] PE**

SIGNAL and BACKGROUND models

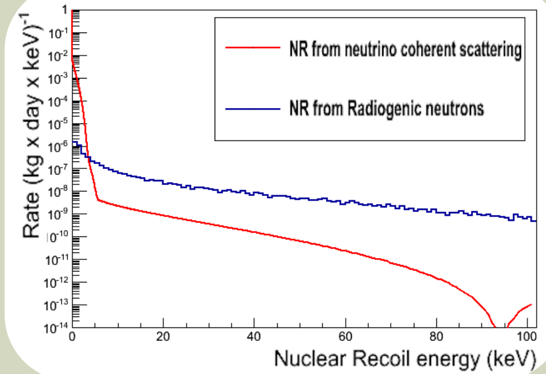
WIMP signal



ER background



NR background



Expectation value μ_s

Differential rate
WIMP-nucleon elastic scattering [1]

$$\frac{dR}{E_R} = \frac{\rho_0\,\sigma\,A^2}{2\mu_p^2\,m_\chi} F^2(q) \int_{v_{min}}^{v_{max}} \frac{f(|\vec{v} + \overrightarrow{v_{Sun}}|)}{v}\,\mathrm{d}v$$

- σ Spin-Independent cross section
- m_χ WIMP mass
- $F(q)$ Nuclear form factor
- v WIMP velocity
- v_{Sun} Rotational velocity of the Solar System in the galactic frame

[1] J. Lewin and P. Smith, *Astropart. Phys.* 6(1), 1996

Expectation value μ_{bER}

Monte Carlo estimation[2]

DETECTOR MATERIALS
27 ± 3 ev/yr
XENON CONTAMINANTS
^{222}**Rn** (1μBq/kg)
32 ± 6 ev/yr
^{85}**Kr** (0.2 ppt)
28 ± 6 ev/yr
^{136}**Xe**
9 ± 5 ev/yr
ER SOLAR NEUTRINOS
(elastic scattering)
32 ± 1 ev/yr

NO ER/NR Discrimantion Cut

TOTAL ER BKG
130 ± 10 ev/yr

Expectation value μ_{bNR}

Monte Carlo estimation[2]

RADIOGENIC NEUTRONS
0.5 ± 0.1 ev/yr

COSMOGENIC NEUTRONS
<0.01 ev/yr (Muon Veto)

CNNS NEUTRINOS
0.6 ± 0.1 ev/yr

TOTAL NR BKG
1.1 ± 0.2 ev/yr

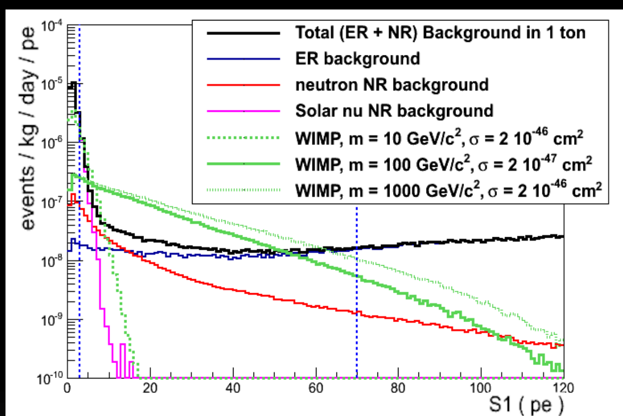
[2] F. V. Massoli, *PhD thesis*, 2015

2D statistical model

S1 distributions f_s, f_{bER}, f_{bNR}

Recoil energy spectra **converted into S1 distributions** (n° PE detected) through

- **Light Yield L_Y** (n° γ produced/keV)
- **Charge Yield Q_Y** (n° e^- produced/keV)
- **Detector performance** (**LCE**, PMTs **QE** and **CE**)



Y distributions

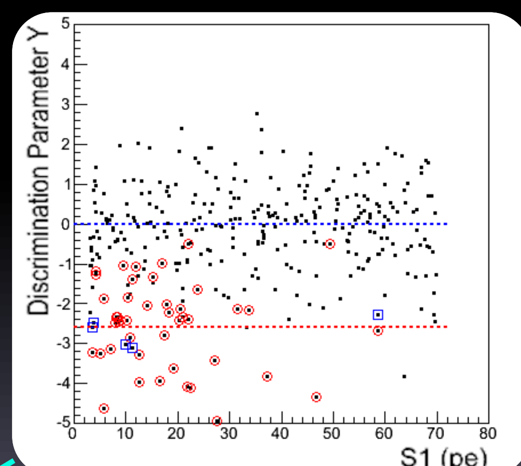
Y is an idealized version of the **discrimination parameter** $\log_{10}(S2/S1)$

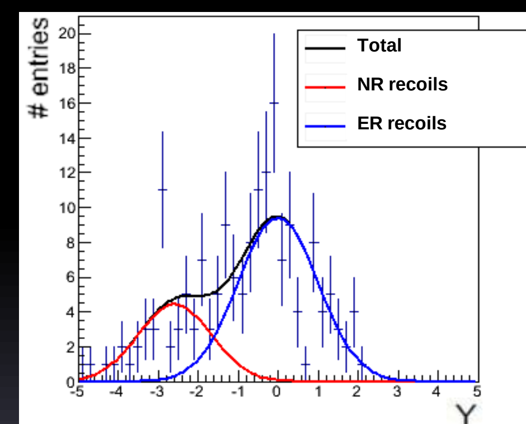
- g_{ER} **ER** events ***Gauss(0,1)***
- g_{NR} **NR** events ***Gauss(-2.58,0.92)***

These distributions reproduce the XENON100 **ER/NR discrimination** and **NR acceptance** performance

NO discrimination cut on ER events (full data set used)

A simulated data set



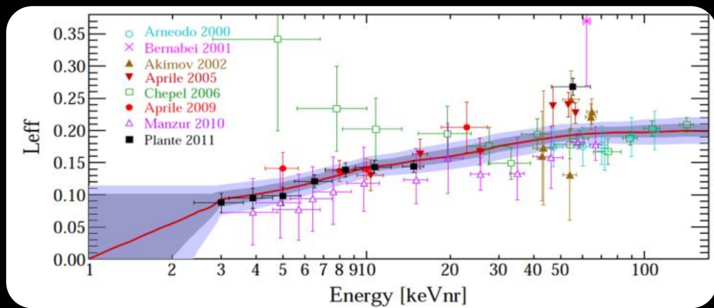


- **2 t·yr** exposure
- m_χ**=100 GeV/c²**
- μ_s**=50** (enhanced)
- μ_{bER}**=258**
- μ_{bNR}**=3.9**

- **ER Background** events
- **NR Background** events
- (NR) **Signal** events

Systematic uncertainty on $\mathcal{L}_{eff}$

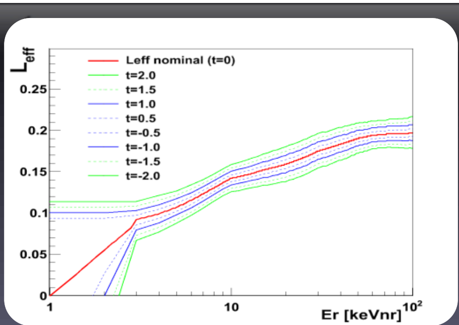
- The **RELATIVE SCINTILLATION EFFICIENCY for NR** $\mathcal{L}_{eff}$ rules the light output of nuclear recoils in Xenon
- $\mathcal{L}_{eff}$ is the major **systematic uncertainty** for XENON1T; no experimental measurements below 3 keV



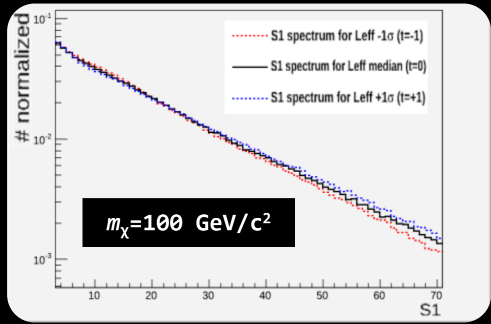
Parameterization of the uncertainty on $\mathcal{L}_{eff}$

Gaussian nuisance parameter ***t***

$$\mathcal{L}_{eff} = \begin{cases} \mathcal{L}_{eff}(\text{median}) + t \cdot \Delta\mathcal{L}_{eff}(+1\sigma) & \text{if } t \geq 0 \\ \mathcal{L}_{eff}(\text{median}) + t \cdot \Delta\mathcal{L}_{eff}(-1\sigma) & \text{if } t < 0 \end{cases}$$

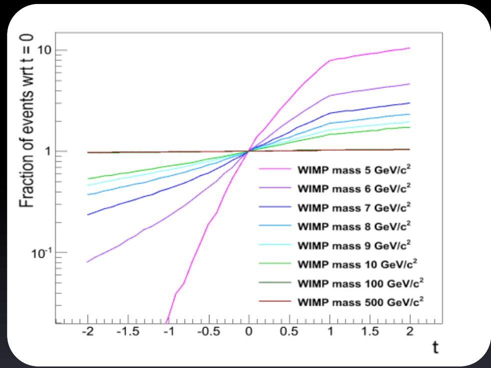


IMPACT OF $\mathcal{L}_{eff}$ VARIATIONS



S1 SPECTRAL SHAPES of signal and backgrounds change very slightly under different $\mathcal{L}_{eff}$

➡ **We keep fixed the shape of S1 spectra**



NUMBER of EXPECTED EVENTS in [3,70] PE

CNNS neutrinos behave like 6 GeV/c² WIMP

Neutrons behave like 30 GeV/c² WIMP

The **number of expected events** from **CNNS** and **low mass WIMPs** is highly affected by $\mathcal{L}_{eff}$ variations ➡

$\mu_s = \mu_s(t)$ and $\mu_{bNR} = \mu_{bNR}(t)$

Sensitivity evaluation with the Profile Likelihood method

Likelihood function
(unbinned, extended)
Parameter of interest μ_s

$$-2\ln L(\mu_s,t) = 2\left[\mu_s(t) + \mu_{bER} + \mu_{bNR}(t)\right] - 2\sum_{i=1}^{N_{obs}}\left[\mu_s(t)\, f_s(S1_i)\, g_{NR}(Y_i) + \mu_{bER}\, f_{bER}(S1_i)\, g_{ER}(Y_i) + \mu_{bNR}(t)\, f_{bNR}(S1_i)\, g_{NR}(Y_i)\right] + t^2$$

Exclusion test statistic
Profile Likelihood ratio

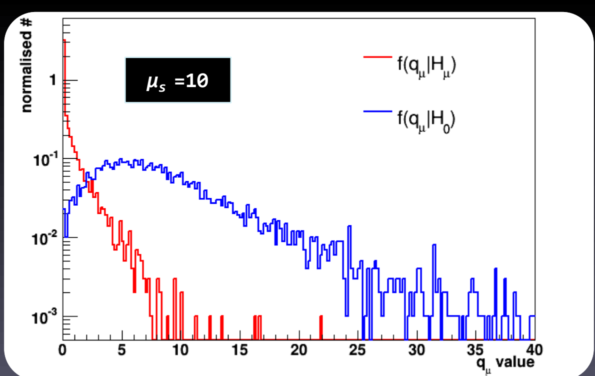
$L(\mu_s,\hat{\hat{t}})$ is the *conditional* maximized likelihood

$L(\hat{\mu}_s,\hat{t})$ is the *unconditional* maximized likelihood

$$q_\mu = \begin{cases} -2\ln\frac{L(\mu_s,\hat{\hat{t}})}{L(\hat{\mu}_s,\hat{t})} & \text{if } \hat{\mu}_s \le \mu_s \\ 0 & \text{if } \hat{\mu}_s > \mu_s \end{cases}$$

Compute test statistic P.D.F.

$f(q_\mu|H_\mu)$ under **signal hypothesis H_μ**
$f(q_\mu|H_0)$ under **bkg-only hypothesis H_o**

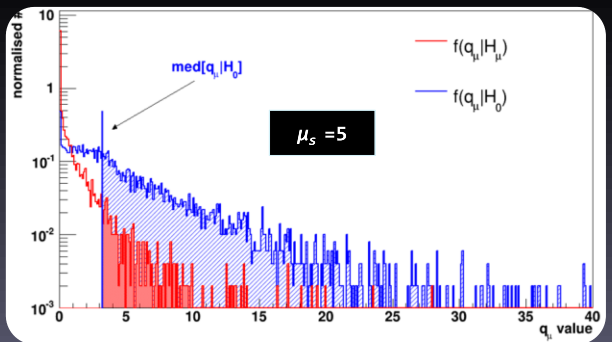


Run hypotheses tests

- Generated **10^4 MC toy experiments** under H_o
- **Rejection test** of each signal hypothesis H_μ (different μ_s) using ***med[q_μ|H_μ]*** as observed test statistic q_μ^{obs}
- The **significance** of each test is given by the ***p-value***

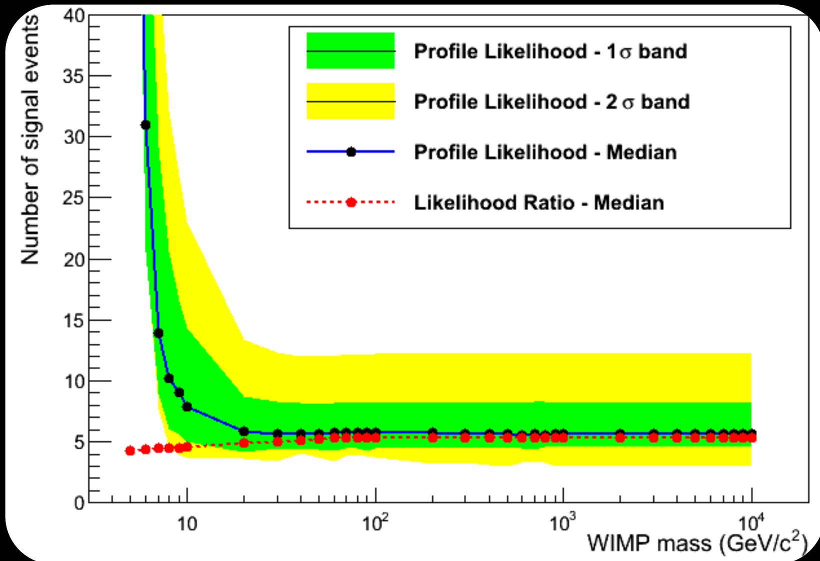
$$p'_s = \frac{\int_{q_\mu^{obs}}^{\infty} f(q_\mu|0)\, dq_\mu}{\int_{q_\mu^{obs}}^{\infty} f(q_\mu|\mu)\, dq_\mu}$$

Modified p-value
CL_s method

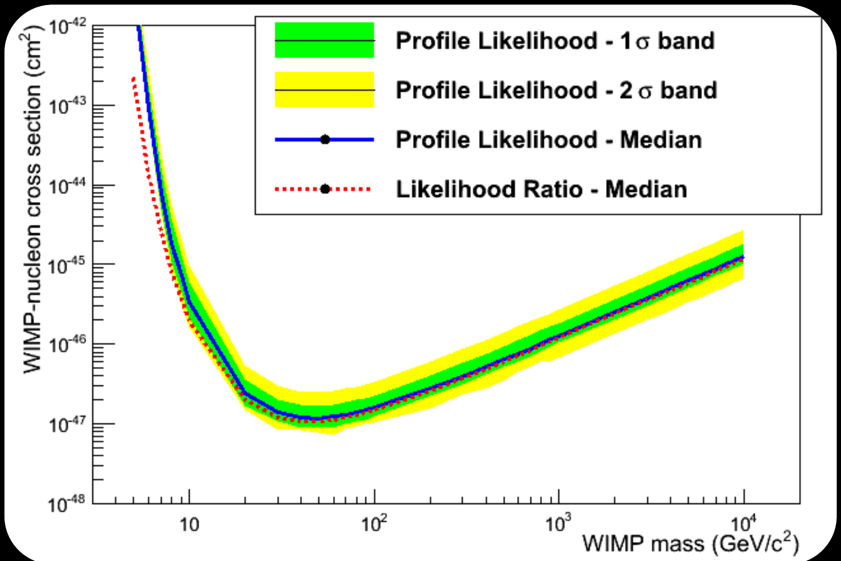


Sensitivity results PL vs LR

XENON1T SENSITIVITY CURVE
in terms of **number of signal events μ_s**
90% CL with CL_s

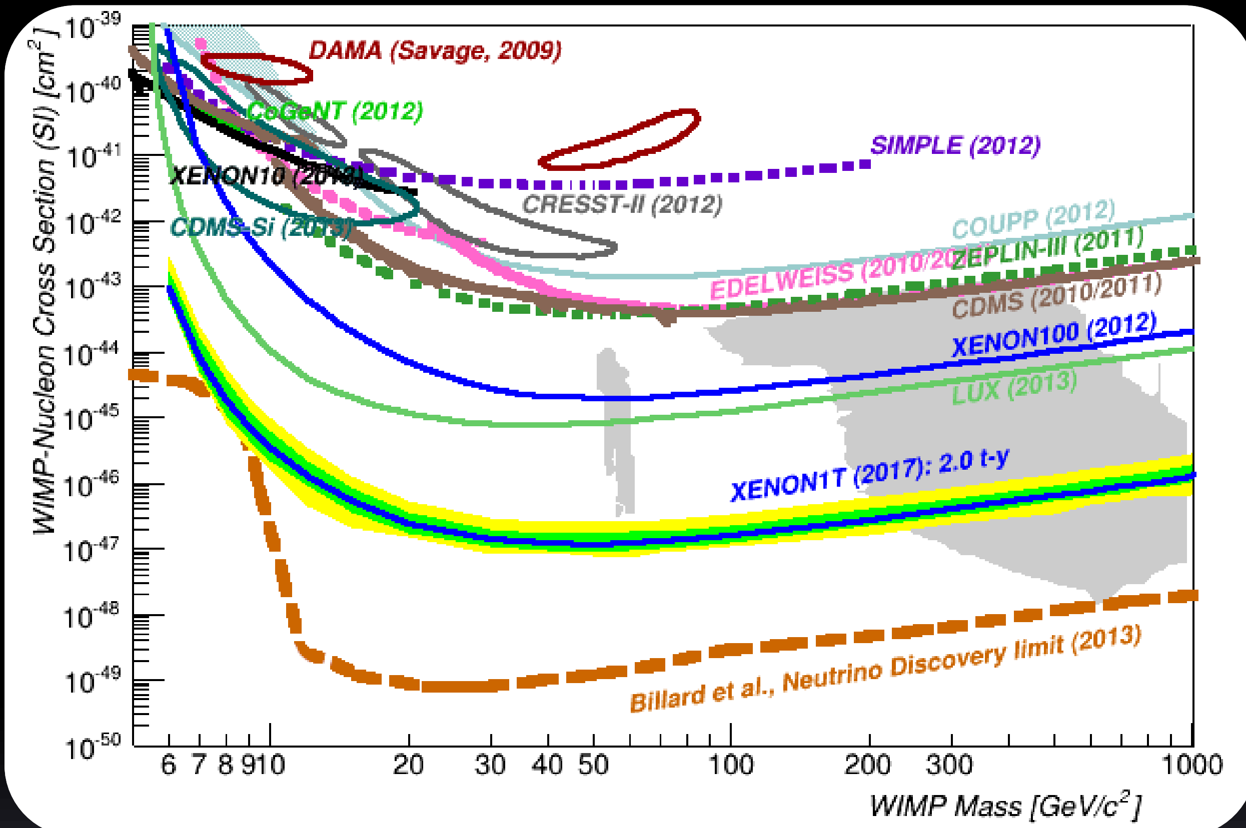


XENON1T SENSITIVITY CURVE
in terms of **WIMP-nucleon cross section σ**
90% CL with CL_s



- The **exclusion upper limit** is the value of μ_s for which **p'_s=10%** (90% CL)
- Scan of the **WIMP mass range [5,1000] GeV/c²**
- The **Likelihood Ratio method** (no systematics) gives **stronger limits**, especially at low WIMP masses (huge impact of $\mathcal{L}_{eff}$ uncertainty)

Expected sensitivity of XENON1T



XENON1T Sensitivity

in the nominal exposure

2 t·yr

Minimum at m_χ=50 GeV/c^2

σ = 1.2·10^{-47} cm^2

XENON100 limit (2012)

2·10^{-45} cm^2

at m_χ=55 GeV/c^2

[3] E. Aprile et al., *Phys. Rev. Lett.*, 109(181301), 2012

LUX limit (2013)

7.6·10^{-46} cm^2

at m_χ=33 GeV/c^2

[4] D. Akerib et al., *Phys. Rev. Lett.*, 112(091303), 2013

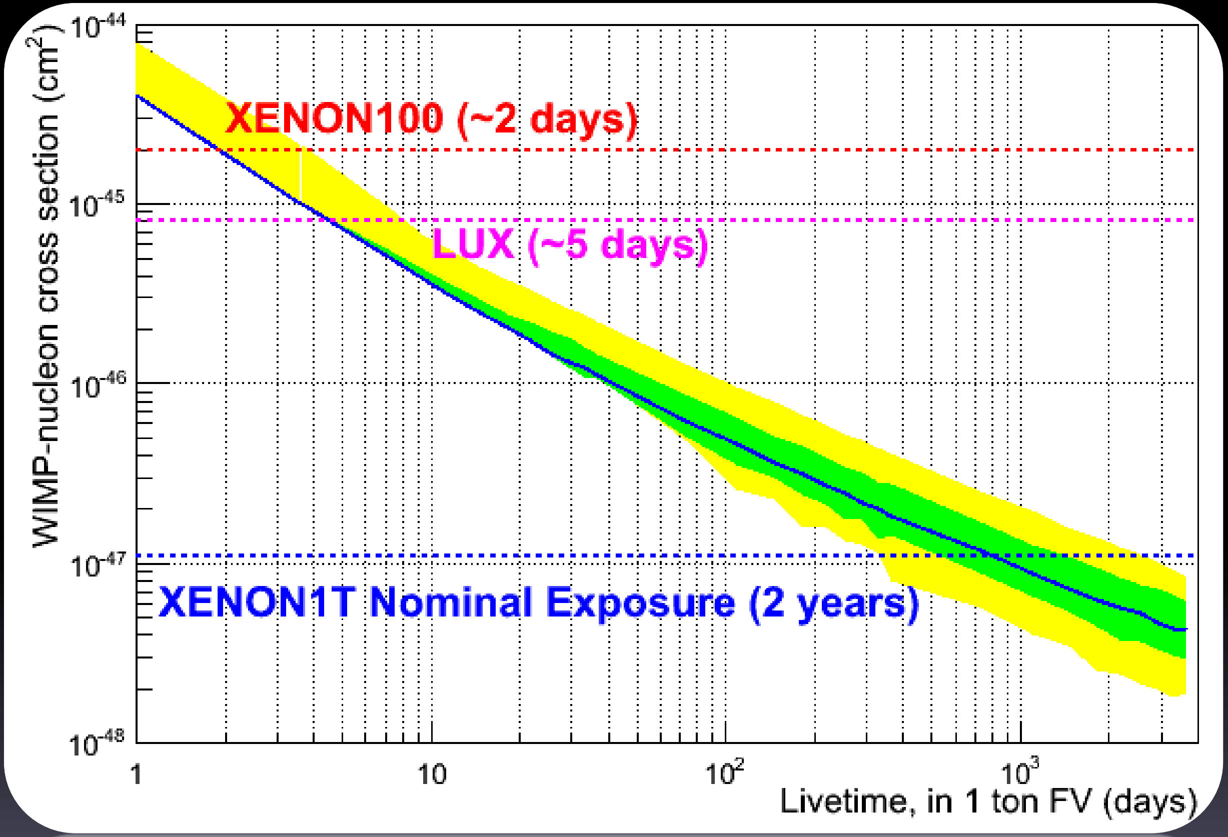
Sensitivity as a function of the exposure time

XENON1T WILL IMPROVE UPON THE CURRENT LIMITS IN A WHILE!

Fixing
1 ton
FIDUCIAL VOLUME

5 live-days
of data acquisition
to reach the
current
best limits

$7.6 \cdot 10^{-46}$ cm^2



Summary and conclusions

- The **PROFILE LIKELIHOOD METHOD** allows to use the full data set (no hard cuts) and to naturally include systematics.
- **XENON1T EXPECTED SENSITIVITY**: minimum at $\mathbf{1.2 \cdot 10^{-47}\ cm^2}$ for $\boldsymbol{m_\chi}$**=50 GeV/c^2 at 90% confidence level (using CL_s)**
- With **1 t fiducial volume**, XENON1T is expected to reach the **WORLD'S BEST SENSITIVITY to SI WIMP-nucleon scattering** in **~5 days** of data taking.

THANKS FOR YOUR ATTENTION!

BACKUP SLIDES

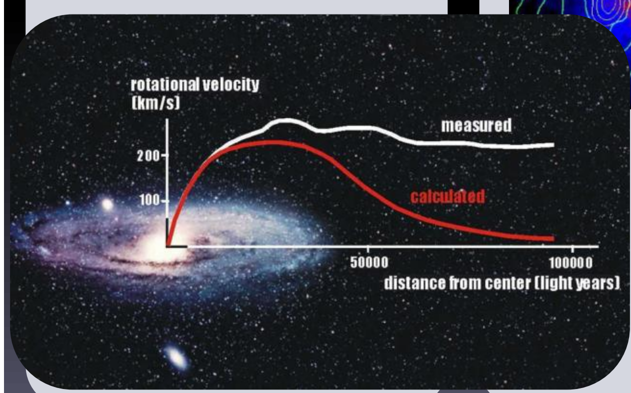
Dark Matter evidences

First hint for Dark Matter existence:

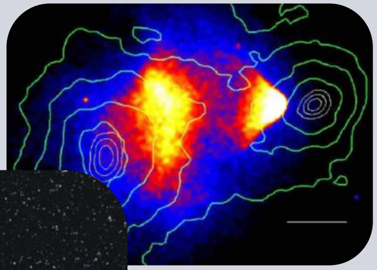
Zwicky's study of the **Coma cluster** of galaxies (1933)

Total mass >> Mass of luminous matter

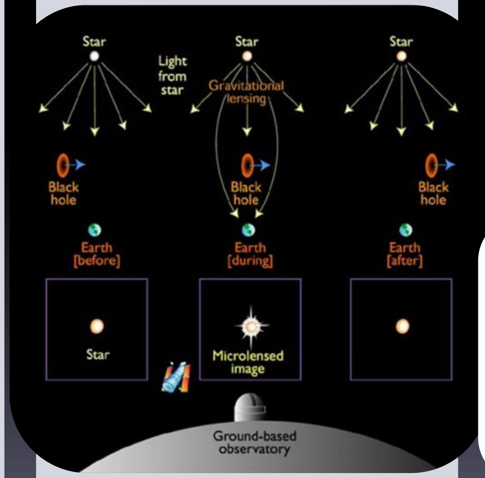
Rotational velocity of spiral galaxies



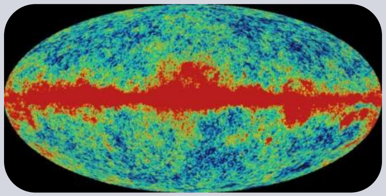
Bullet Cluster

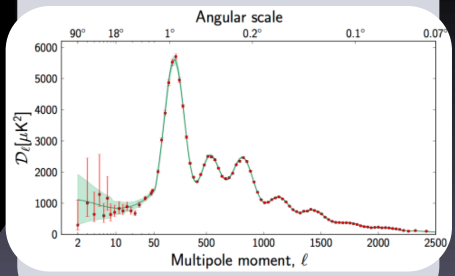


Microlensing studies



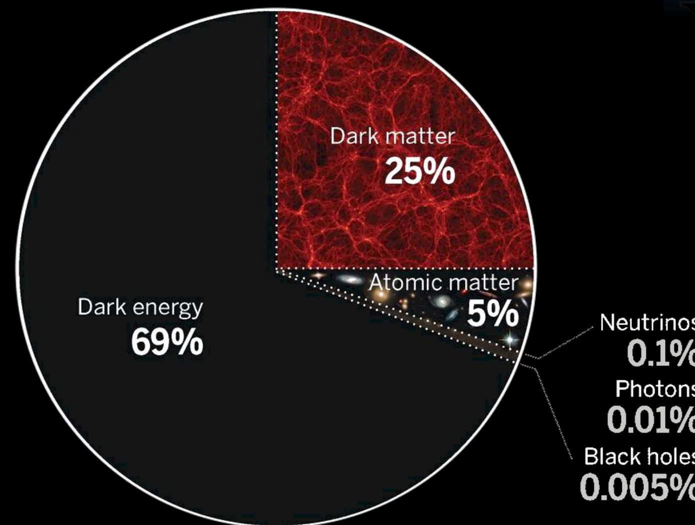
CMB anisotropies





DARK MATTER is among us

MATTER in the Universe
- **~15%** Baryonic matter
- **~85%** Dark matter



DARK MATTER properties
- Very long-lived $\tau > 2 \cdot 10^{11}$ yr
- Neutral
- Only gravitational and **weak(?)** interactions
- Non-relativistic **COLD DARK MATTER scenario**
- Non-baryonic
- Beyond Standard Model particles

WIMP Weakly Interacting Massive Particle

DM candidates naturally arise in theories **beyond SM**

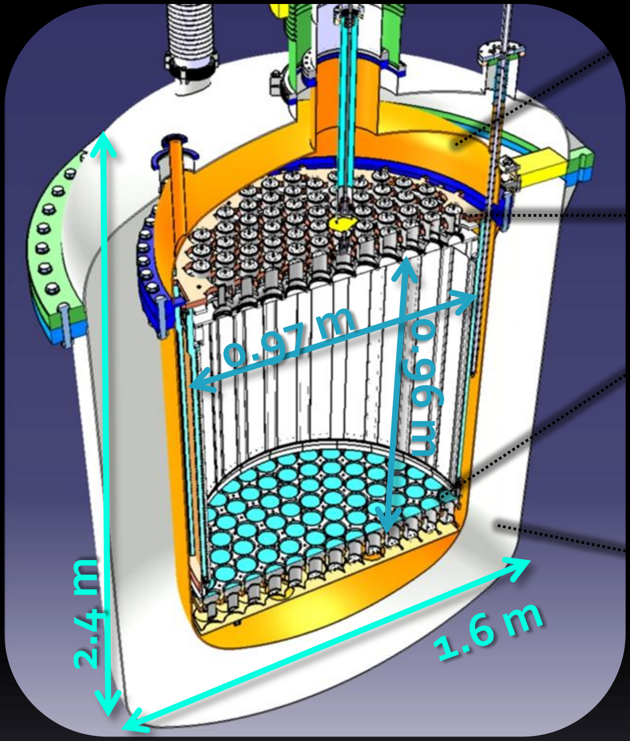
SUSY, Extra Dimensions, ...

XENON1T overview

- **3.3 t total LXe**: ~2 t as active volume (inside TPC);
- ~1 t as shield; ~1 t Fiducial Volume
- ~1 m drift **electric field** (~500 V/cm); **HV field** (~50 kV)
- 248 low radioactivity 3″ **PMTs**
- ~720 m^3 Water Cherenkov **Muon Veto** (84 8″ PMTs)

Status: Commissioning and first science run by the end of 2015

XENON1T TPC

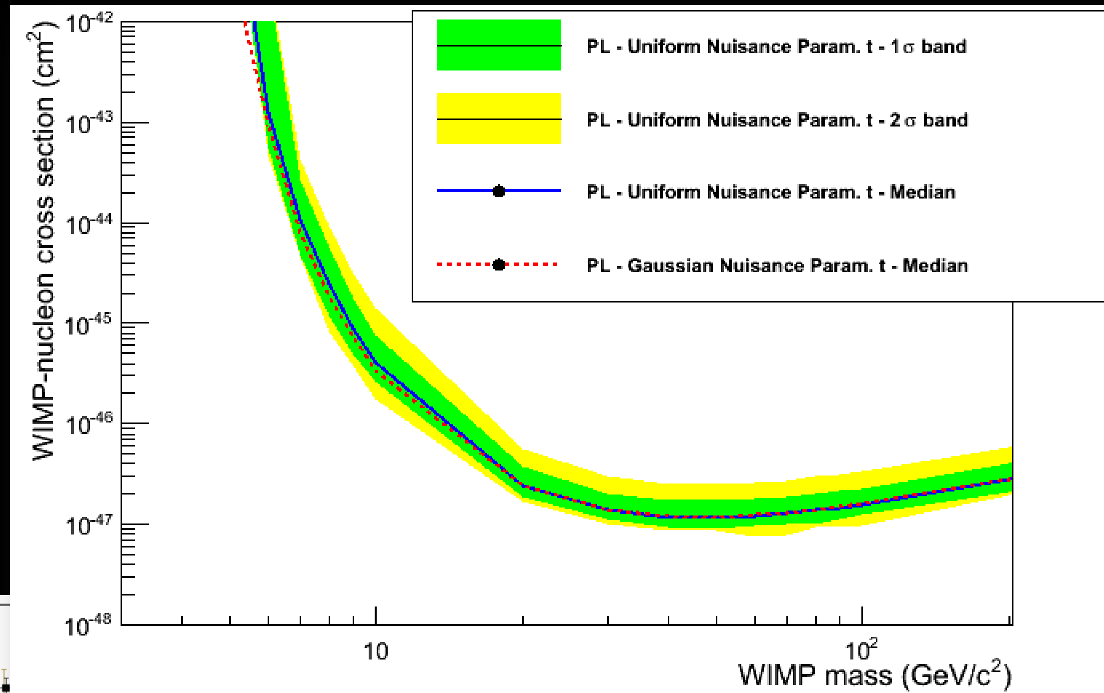


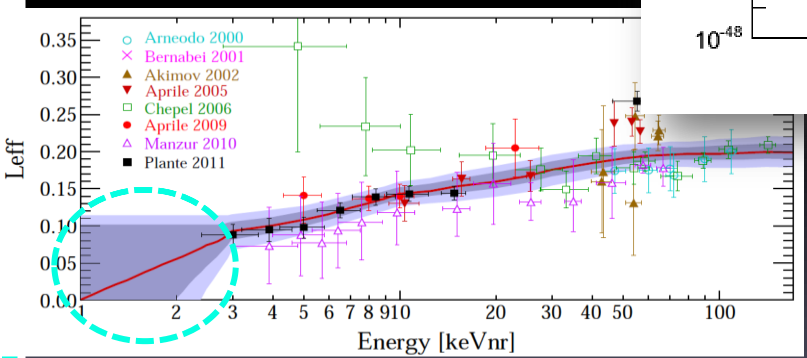
- **Sensitivity goal**: $\sigma \sim 10^{-47}$ cm^2

A different parameterization of $\mathcal{L}_{eff}$

- Sensitivity curve with **uniform uncertainty** on $\mathcal{L}_{eff}$

Complete lack of knowledge below 3 keV.
Uniform distribution of the nuisance parameter *t between the 2σ contours* (the most conservative assumption!)





For m_χ>10 GeV/c²: **same limits** as gaussian assumption;

For m_χ<10 GeV/c²: **weaker limits**. **The low energy range (<3keV) of $\mathcal{L}_{eff}$ affects the sensitivity.**