Direct WIMP searches with the LUX-ZEPLIN experiment

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Outline

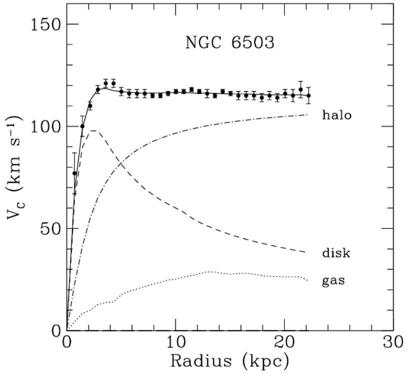
1. The dark matter puzzle
2. Direct detection of WIMPs
3. The LZ experiment
   - Sensitivity to WIMP interactions
   - WIMP parameter reconstruction
4. Summary

The dark matter puzzle

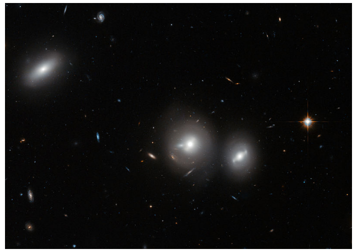
Gravitational mass is missing at all scales (and all times…)

Astrophysical evidence

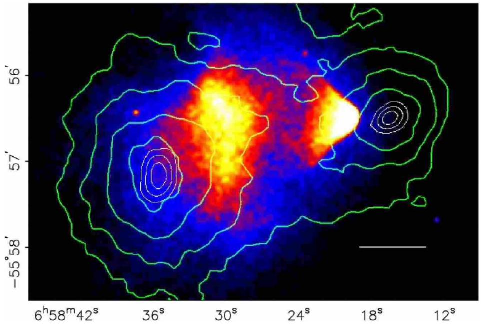
- ❖ **Rotation curves** of spiral galaxies



- ❖ **Virial theorem** applied to gravitational bound systems: galaxies in some clusters move far too fast to be held by the amount of luminous matter (e.g. the Coma Cluster)

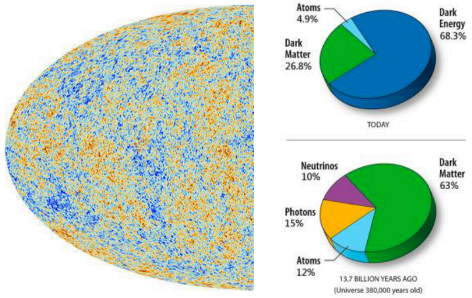


- ❖ **X-ray emission** and **gravitational lensing** techniques: mismatch between the position of intergalactic gas and the regions with the highest gravitational fields (e.g. Bullet Cluster)

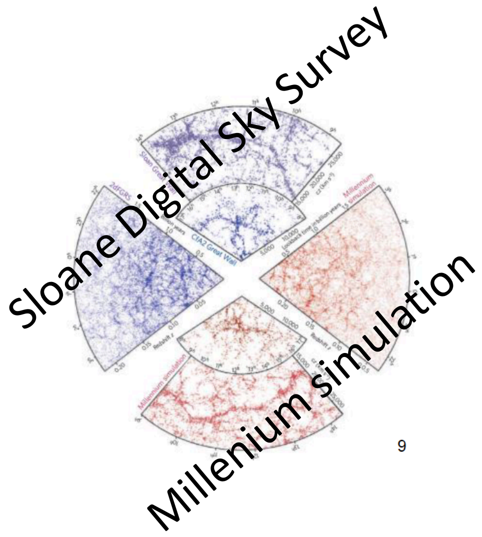


Cosmological evidence

- ❖ We can estimate the value of some cosmological parameters from the temperature anisotropies in the **CMB radiation**

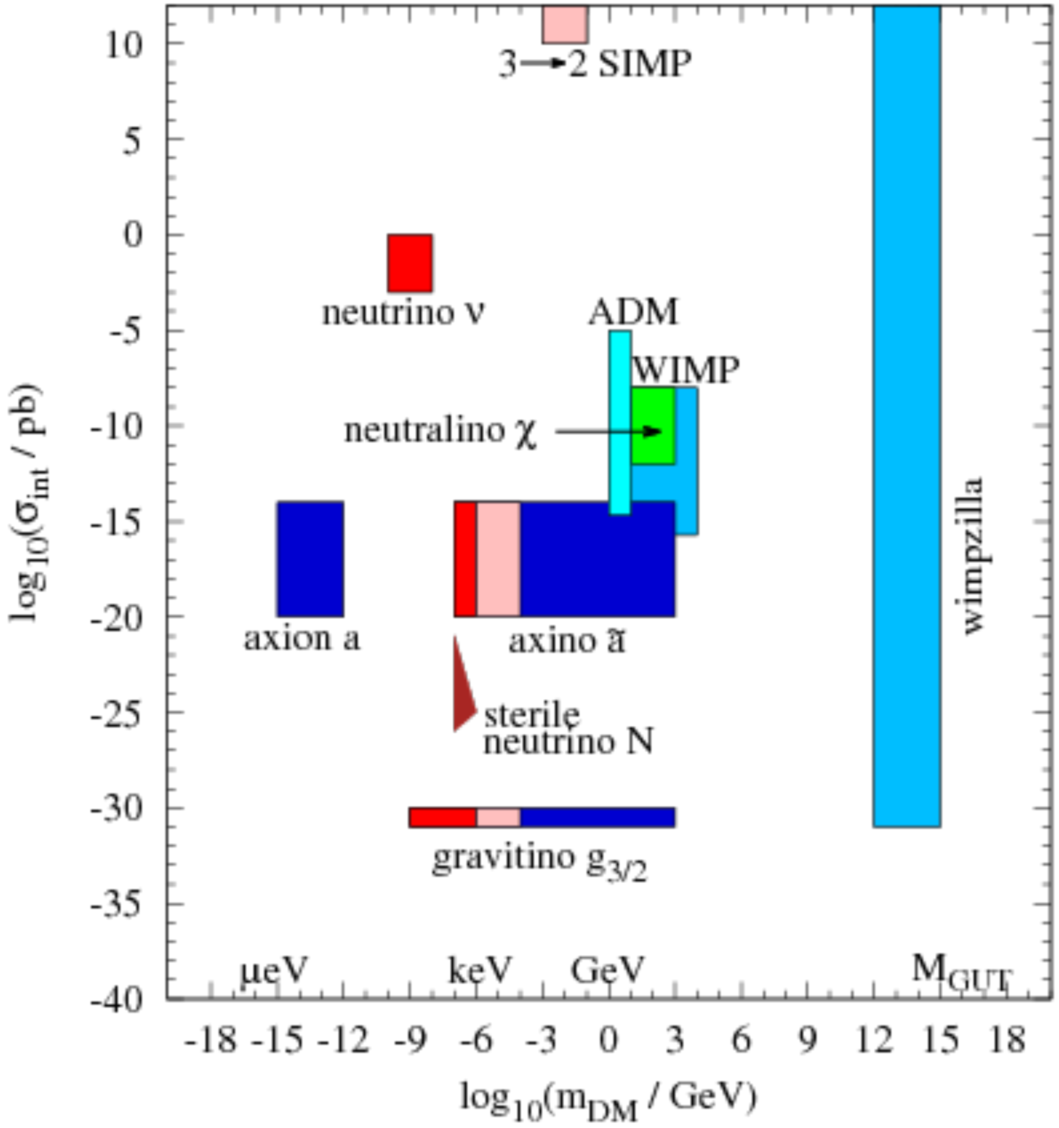


- ❖ **Large Scale Simulations (LLS)** of the evolution of the universe favour the Λ-CDM



Checklist for a good dark matter candidate

- ❑ **No EM or strong interaction:** otherwise we would have "seen" it or "found" it in atoms
- ❑ **Non-baryonic:** no more room for baryons (BBN, LLS)
- ❑ **Stable:** its lifetime should be comparable to the age of the Universe
- ❑ **Cold relic** (non-relativistic at freeze out): hot matter is ruled out from N-body simulations



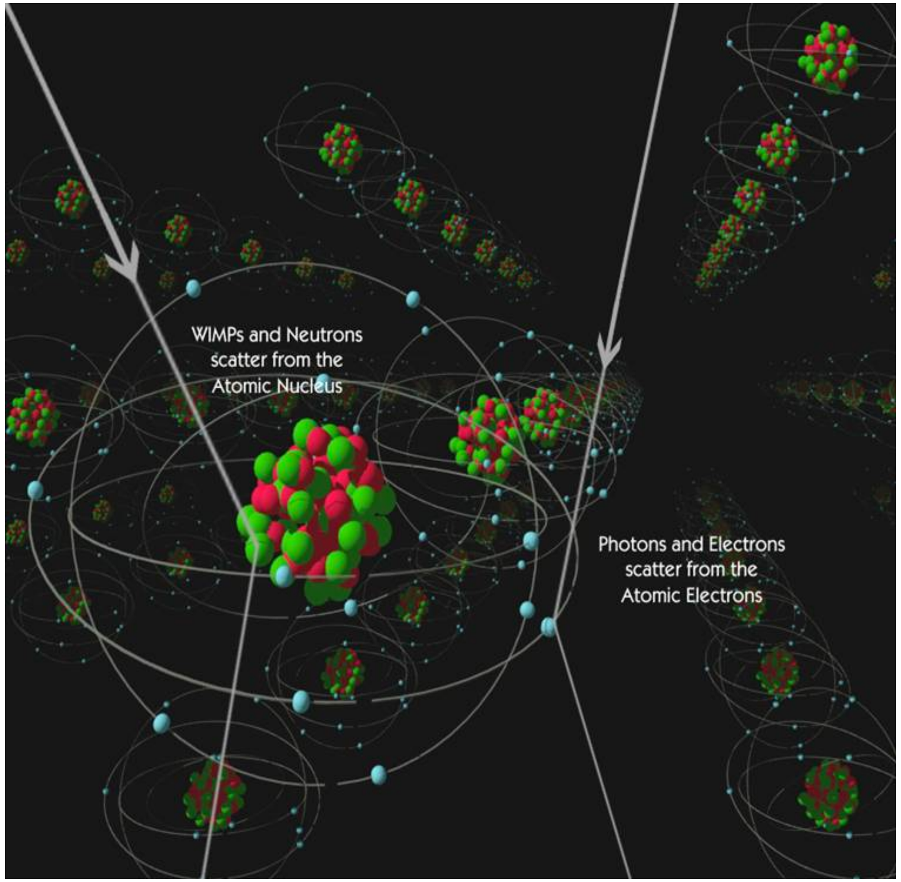
Favoured candidates

- ❖ **WIMPs:** mass in the GeV-TeV range. If weakly interacting, they would be thermally produced in the early Universe with the correct relic density (*WIMP miracle*)
- ❖ **Axions:** very light particles ($m_a < 0.01$ eV). They could be detected through their coupling to photons
- ❖ **Sterile neutrinos:** RH neutrinos that only interact gravitationally. Their mass is constraint to be less than 10 keV

Direct detection of WIMPs

Strategy

The Milky Way is embedded in a halo of dark matter
→ A continuous WIMP flux should be crossing the Earth as the Solar system moves around the halo
→ Hence, look for nuclear recoils from elastic scatterings of WIMPs from atomic nuclei using terrestrial detectors
→ Expected signal rate is of the order of < 1 event/kg/year



Background sources must be understood in exquisite detail to be successful in the search:

- **Nuclear Recoil (NR) background:** elastic neutron scatters, ν-N coherent scattering, daughter nuclei from radioactive decay
- **Electron Recoil (ER) background:** gamma rays, beta and conversion electrons, ν-e scattering

~ tens to hundreds counts/kg/day

Differential WIMP recoil rate

$$\frac{dR}{dE_R} = \frac{\rho_0 \sigma_A}{2 m_{WIMP} \mu_A^2} F^2(E_R) \int_{v_{min}(E_R)}^{\infty} \frac{f_{\oplus}(v)}{v} d^3 v$$

Differential WIMP recoil rate

Astrophysics
Particle physics

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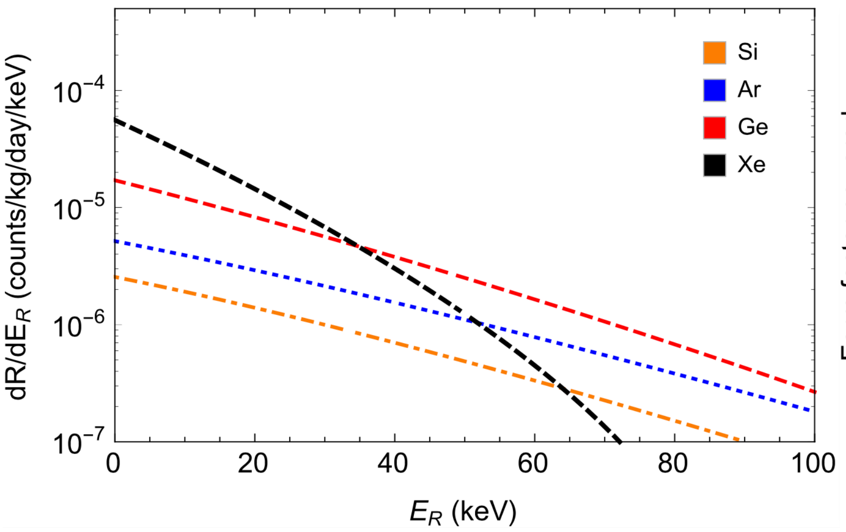
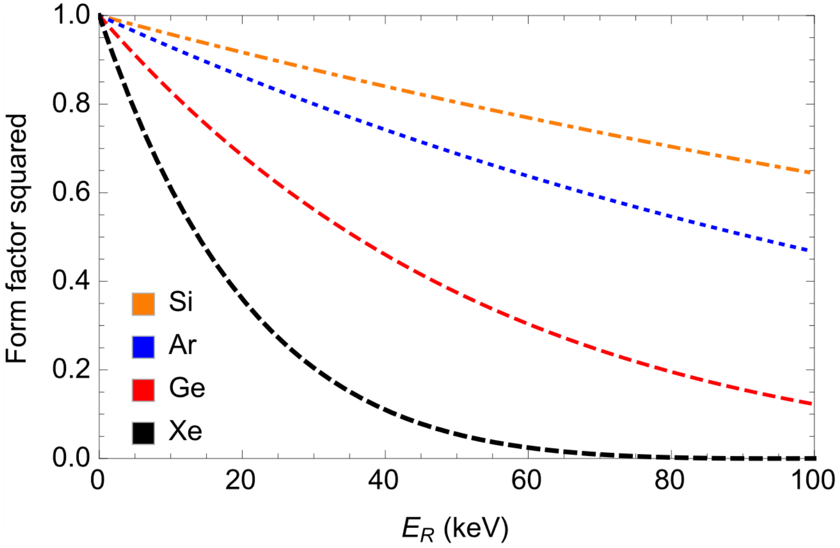
Nuclear to *nucleon* interaction:

$$\sigma_A \propto \begin{cases} A^2 \sigma_p^{SI} & \text{SI (scalar) interaction} \\ \left(\frac{J+1}{J}\right) \sigma_{p,n}^{SD} & \text{SD (axial-vector) interaction} \end{cases}$$

For a SI interaction and $m_{WIMP} = 100$ GeV, $\sigma_p^{SI} = 10^{-45}$ cm²:





The "spherical cow" galactic model

- Stationary and isothermal DM halo with $\rho_0 = 0.3$ GeV/cm³
- Maxwell-Boltzmann WIMP velocity distribution

Differential WIMP recoil rate

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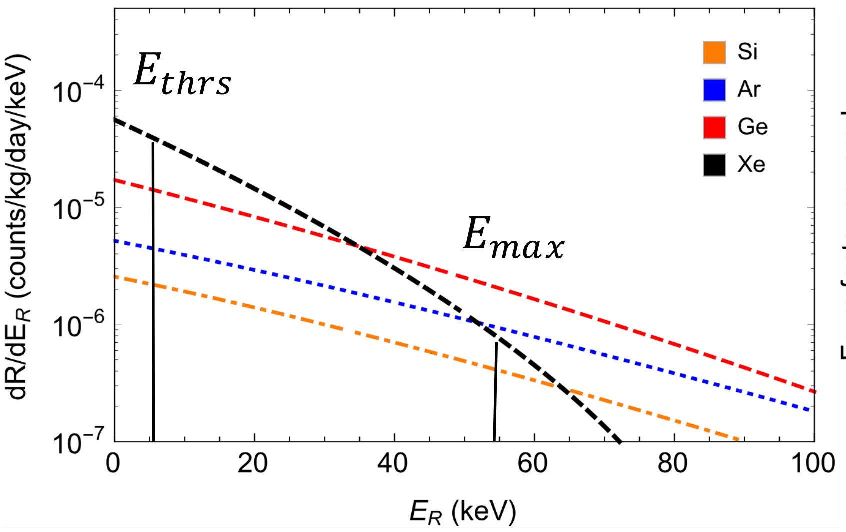
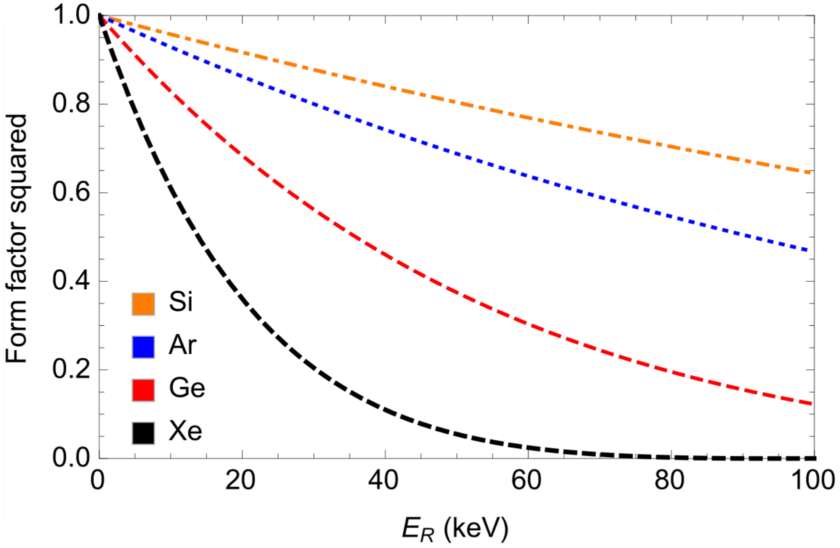


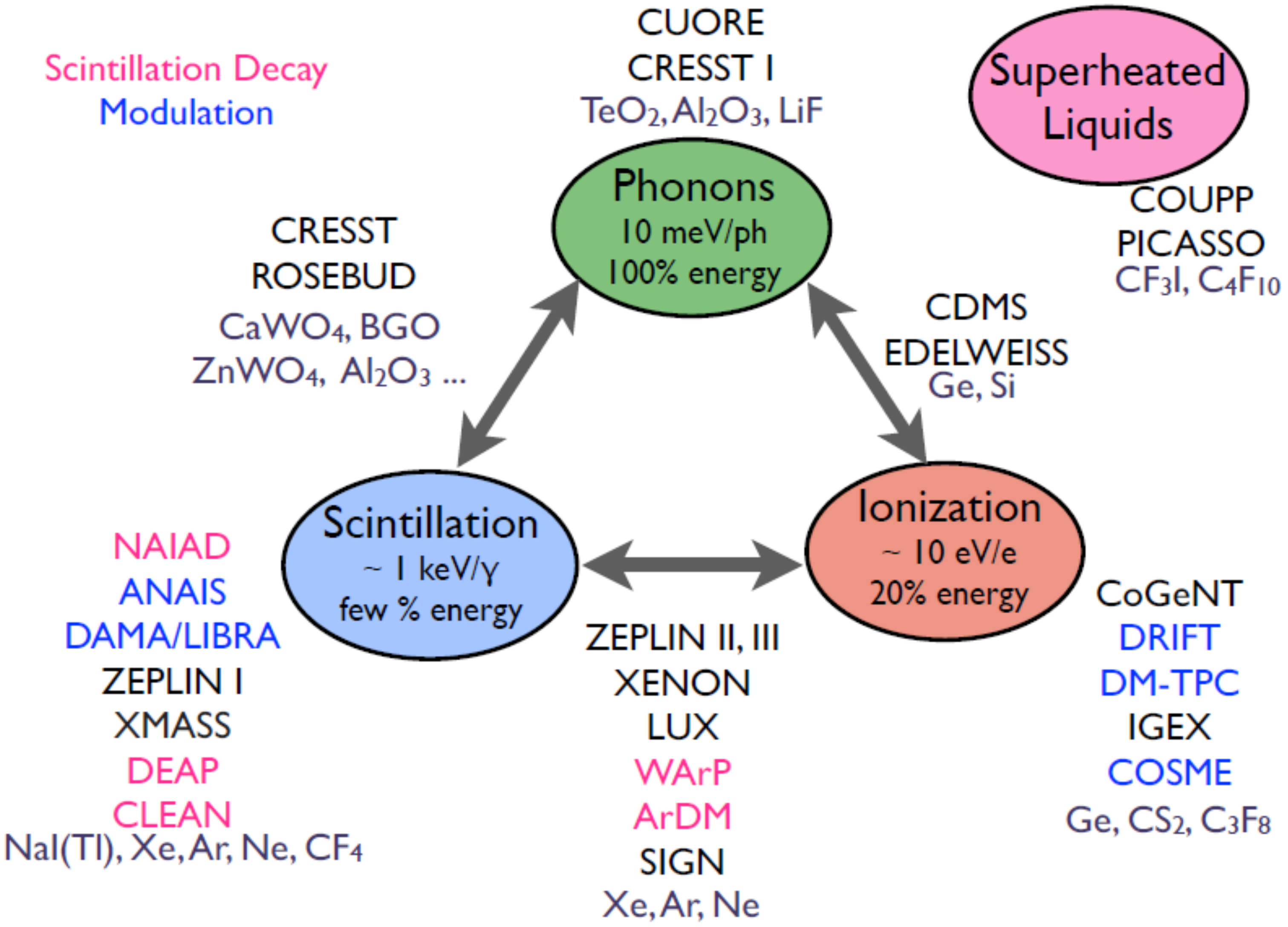


The "spherical cow" galactic model

- ❖ Stationary and isothermal DM halo with $\rho_0 = 0.3$ GeV/cm^3
- ❖ Maxwell-Boltzmann WIMP velocity distribution

Easy! Build the detector, measure a WIMP energy spectrum and infer mass and cross section from it

No so easy...



Ideally, any direct detection experiment would like to:

1. Discriminate between electron and nuclear recoils
2. Reconstruct the energy of each interaction accurately

The LZ experiment

Two-phase Xenon detector

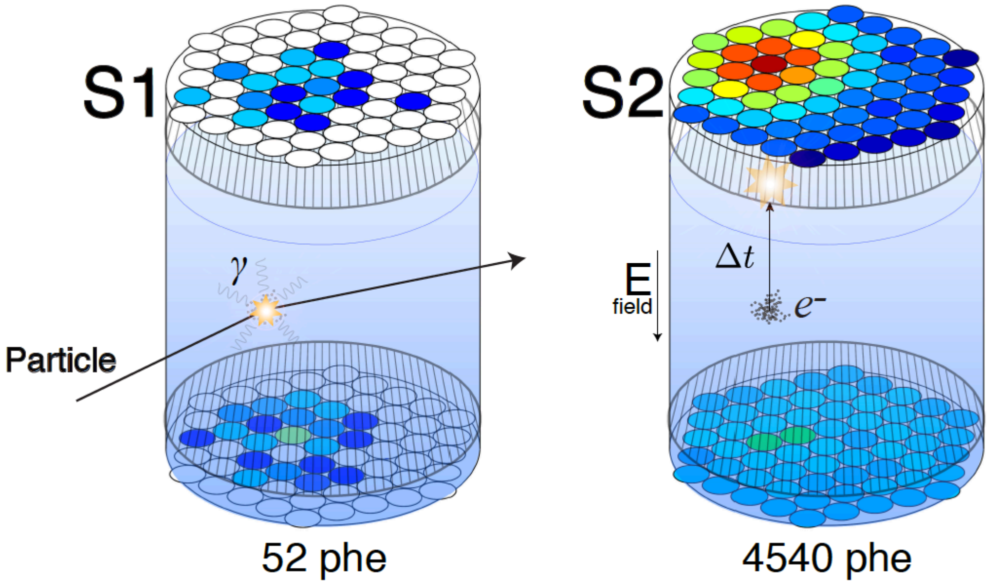
Any particle interacting with the detector will produce UV scintillation photons (S1 signal) and ionization electrons (S2 signal)

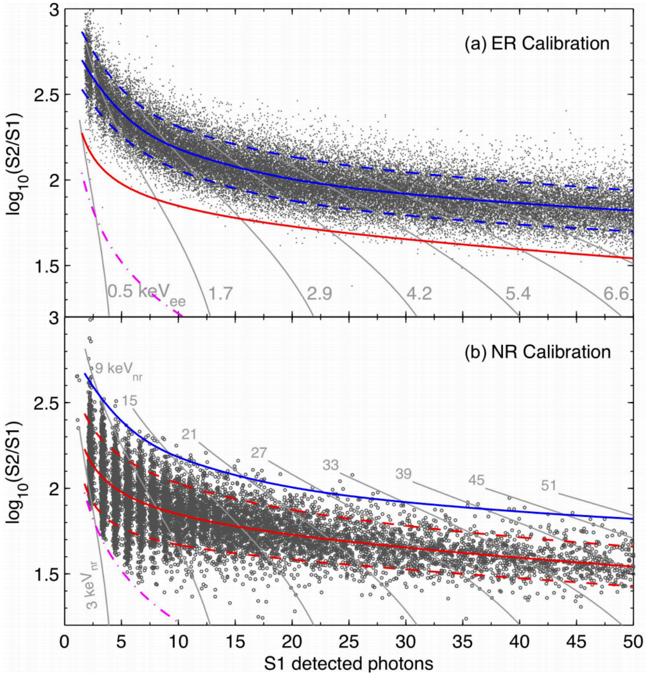
- Position reconstruction: S2 signal in the top PMT array determines (x,y) and z-position is calculated from time difference between S1 and S2

- Energy reconstruction: $E_{nr} = W(n_\gamma + n_e)/L$

W : work function (average energy/quantum)
n_γ, n_e: calculated from pulse areas of S1 and S2 signals
L: Linhard factor, to account for heat energy loss

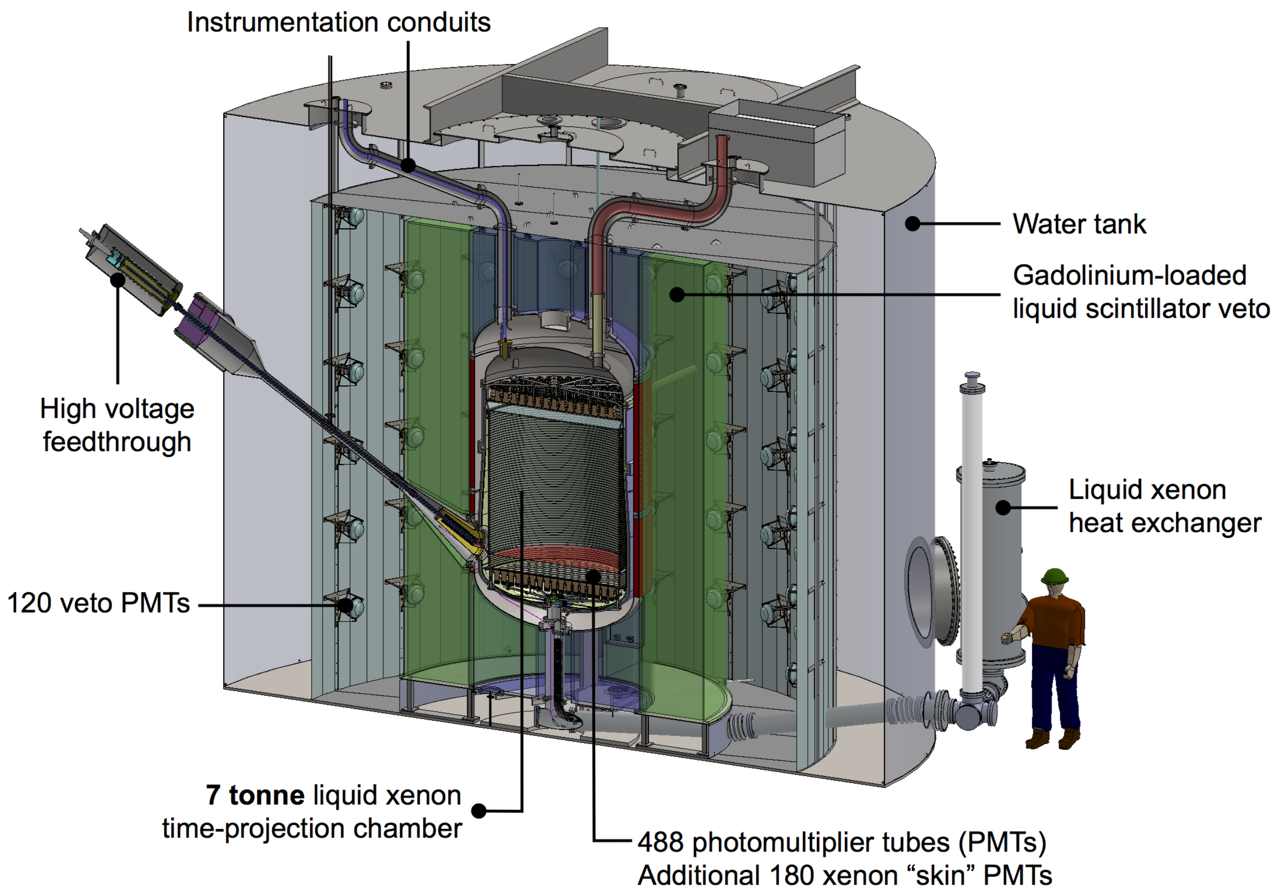
- Particle discrimination: ER and NR events are distributed along separate bands in the S2-S1 plane



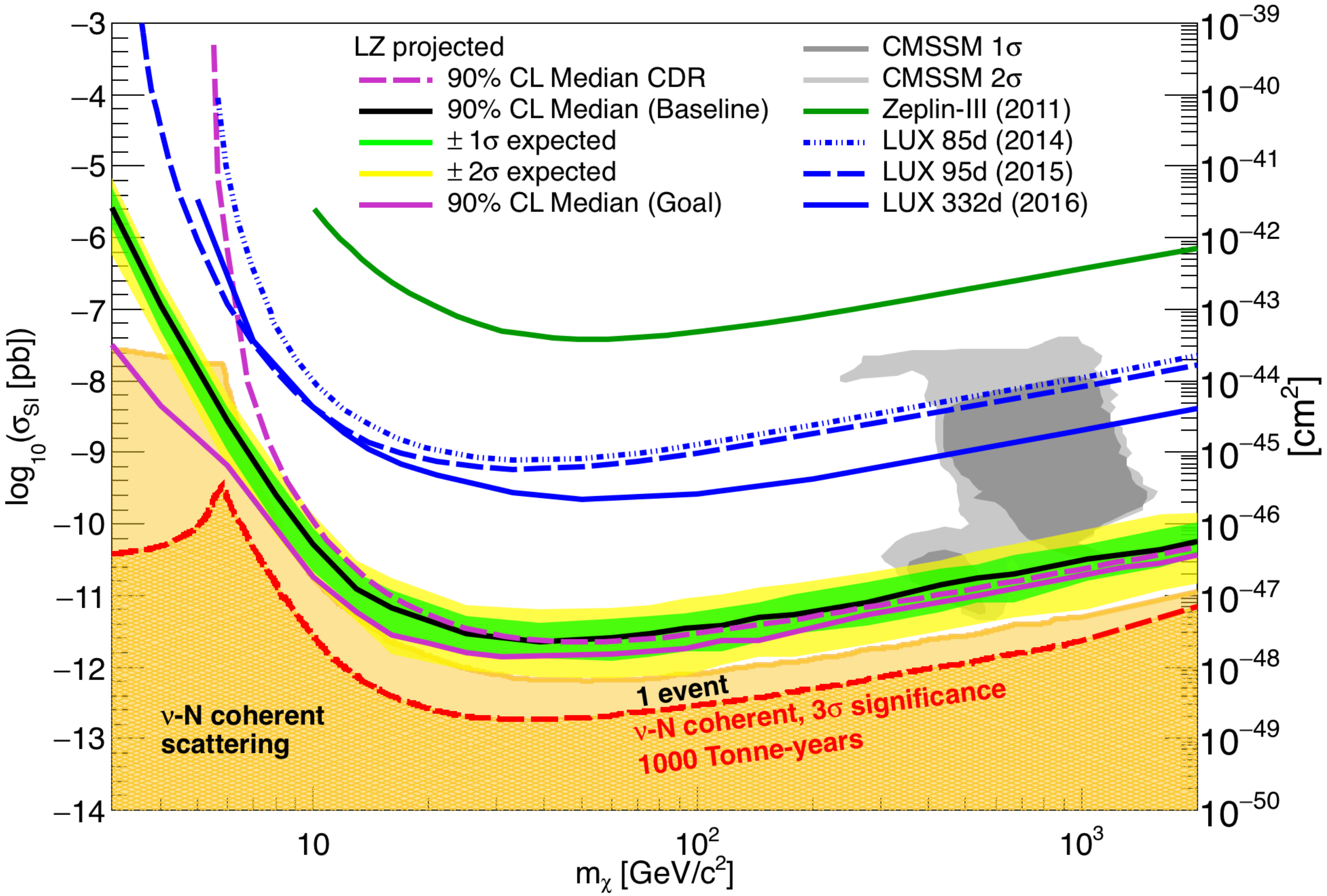


The LZ detector

- The inner vessel is about 1.5m in diameter and 2.6m in height and contains 7 tonnes of active liquid Xe
- It incorporates two monitored veto systems to reject gammas and neutrons:
  - Xe skin surrounding the TPC
  - Liquid scintillator outer tank with enhanced neutron capture rate
- Located at the Sandford Underground Research Facility (SURF) in Lead, South Dakota (US)
- Installation is expected to start in mid-2018 and commissioning by beginning of 2019



LZ sensitivity to WIMP SI interactions



Exposure

Running time: 1000 live days

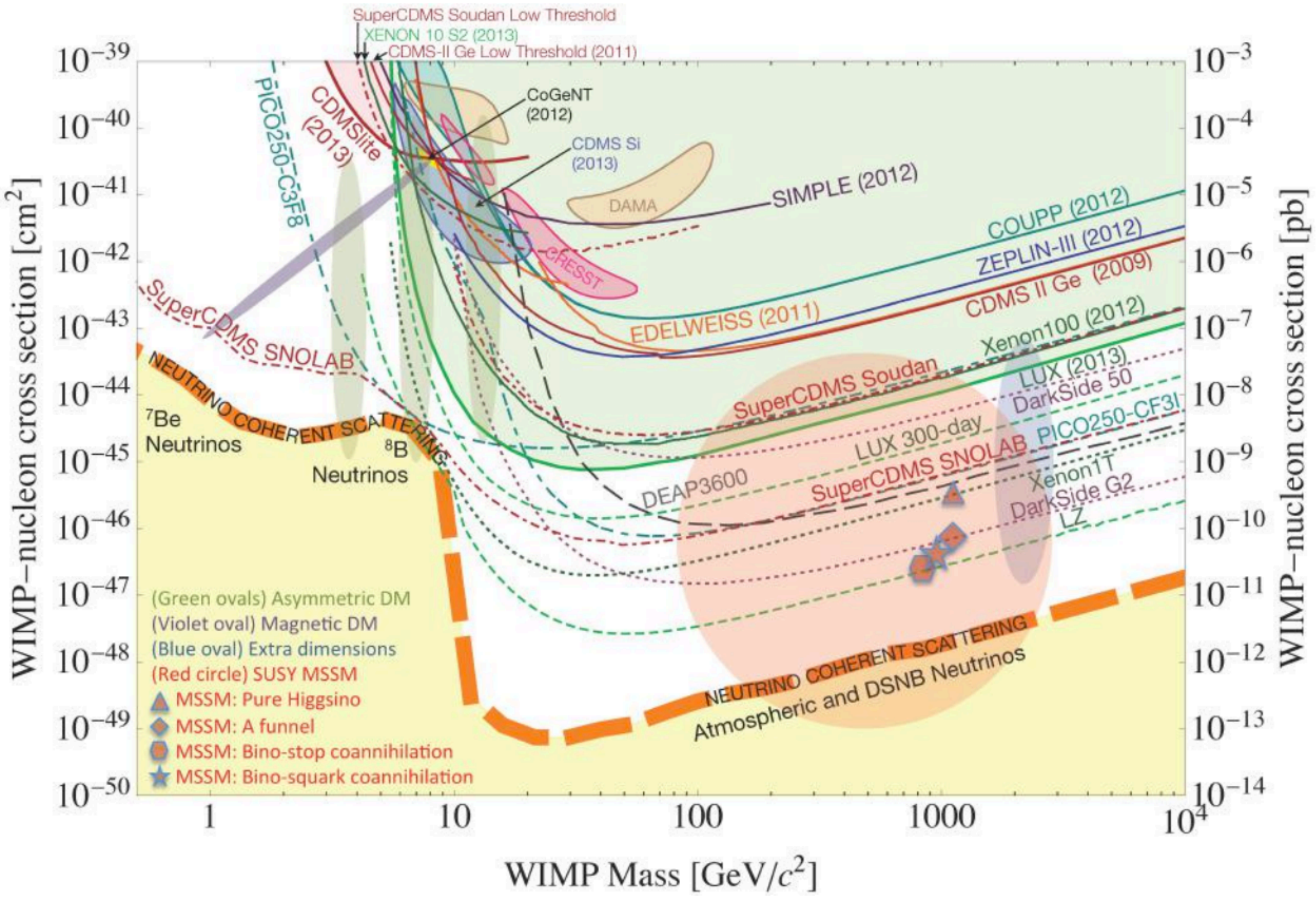
Target mass: 5.6 tonnes

Best sensitivity

Baseline: 2.3e-48 cm^2

Goal: 1.1e-48 cm^2

LZ sensitivity to WIMP SI interactions



We can proudly say that we are the best at not finding dark matter...

WIMP parameter reconstruction

In the case of discovery, we would like to estimate the value of the most relevant WIMP parameters.
For that, we need to construct a precise likelihood function:

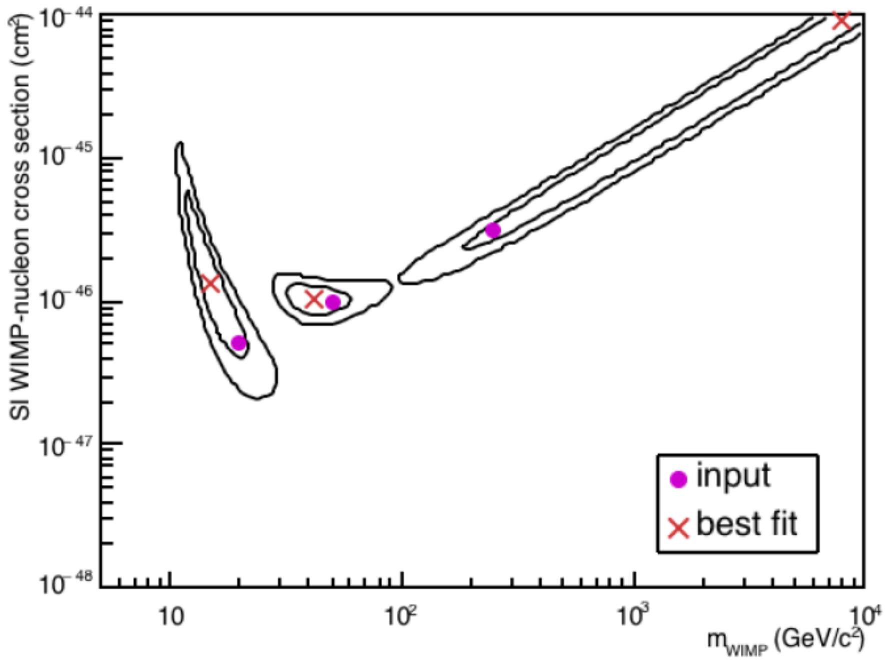
$$\mathcal{L}(\boldsymbol{\theta}, \boldsymbol{\nu}, \mu) = \underbrace{\frac{\mu^n}{n!} e^{-\mu}}_{} \prod_{i=1}^{n} f(\boldsymbol{x_i} | \boldsymbol{\theta}, \boldsymbol{\nu})$$

Poisson probability of measuring n events if mean is μ

$\boldsymbol{x}$: data
$\boldsymbol{\theta}$: parameters of interest
$\boldsymbol{\nu}$: nuisance parameters

$$\boldsymbol{\nu} = \boldsymbol{\nu_s} \cup \boldsymbol{\nu_b}$$

$$\mu = \mu_s + \mu_b$$

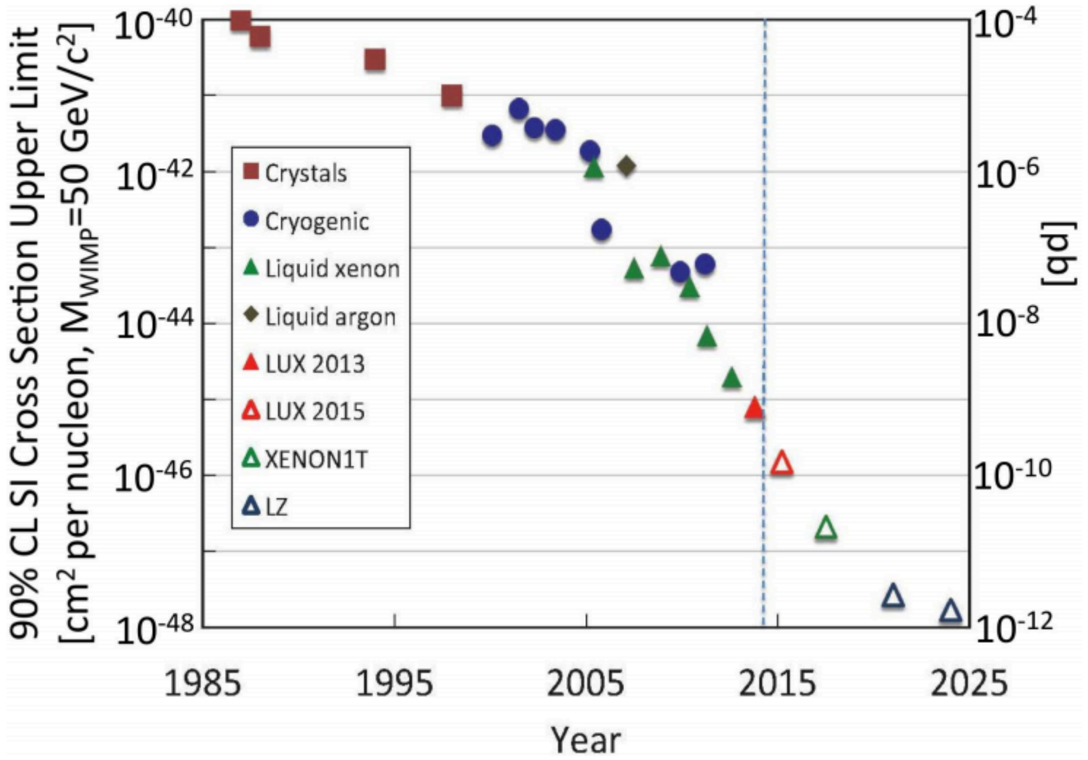


Model PDF : $f(\boldsymbol{x}|\boldsymbol{\theta}, \boldsymbol{\nu}) = \frac{\mu_s(\boldsymbol{\theta}, \boldsymbol{\nu}_s)}{\mu} f_s(\boldsymbol{x}|\boldsymbol{\theta}, \boldsymbol{\nu}_s) + \frac{\mu_b(\boldsymbol{\nu}_b)}{\mu} f_b(\boldsymbol{x}|\boldsymbol{\nu}_b)$

- $\boldsymbol{x} = \{S1, S2\}$, $\boldsymbol{\theta} = \{m_{WIMP}, \sigma_p^{SI}\}$
- $f_s(\boldsymbol{x}|\boldsymbol{\theta}, \boldsymbol{\nu}_s)$: signal PDF
- $f_b(\boldsymbol{x}|\boldsymbol{\nu}_b)$: background PDF, which is broken into the different background components

Summary

- There has been an impressive increase in sensitivity in direct dark matter experiments over the past two decades. How far we can push this limit?
- The LZ experiment will probe WIMP interactions practically as far as it is allowed by new neutrino backgrounds and many theoretical models will be tested
- In the case of discovery, most likely a combination of results from different experiments will be necessary to completely characterise the new particle



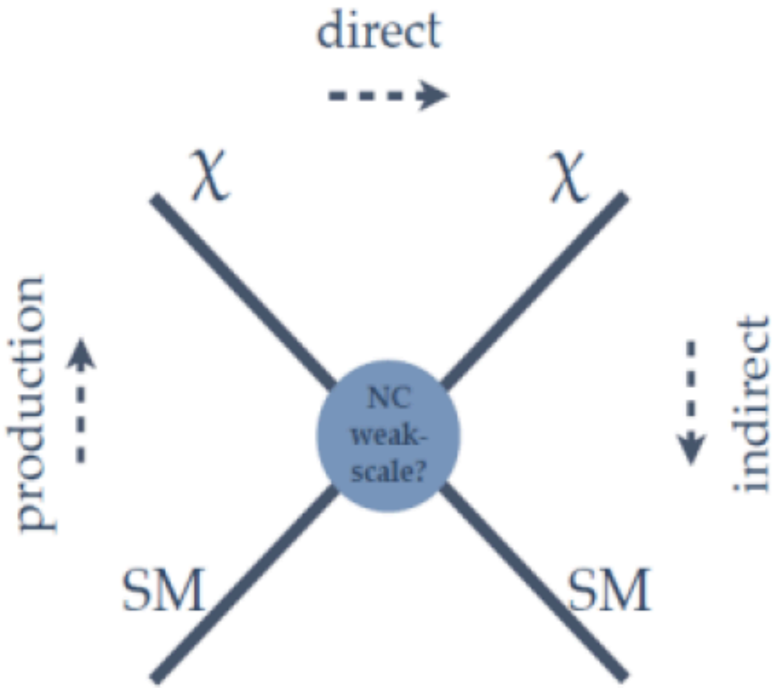
BACKUP

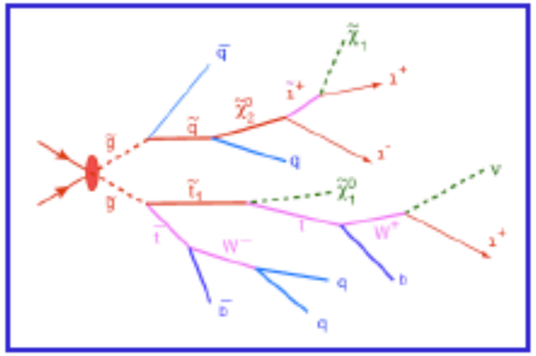
Dark matter searches

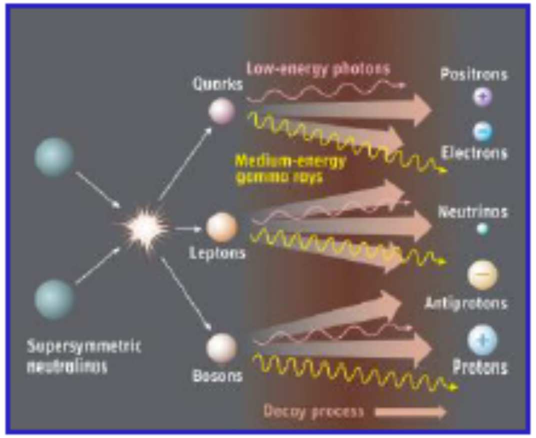
Production
- Missing energy at accelerators
- LHC, ...

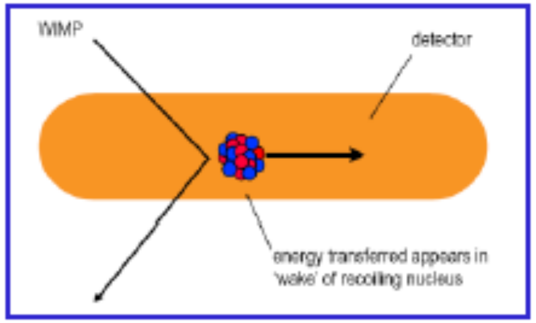
Annihilation
- Into fermion pairs, photons, neutrinos, ...
- FERMI, AMS, ...

Scattering
- Nuclear recoils at terrestrial underground labs
- XENON, LUX, PICO, CDMS, ...









Total background rate for the LZ exposure

Item	ER cts	NR cts
Detector Componenents	6.20	0.07
Dispersed radionuclides (Rn, Kr, Ar)	911	-
Laboratory and cosmogenic	4.3	0.06
Fixed surface contamination	0.19	0.37
^{136}Xe $2\nu\beta\beta$	67.0	-
Neutrinos (ν-e, ν-A)	255	0.72
Total	1240	1.22
Total (with 99.5% ER discrimination, 50% NR efficiency)	6.22	0.61
Total ER+NR background events	6.82	