Dark Matter Direct Detection (XENON1T world best sensitivity)

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What Dark Matter it not

➔Barnard 68 : cold molecular cloud ~ 500 ly.
Transparent in infrared

Definition

By « Dark Matter » we mean non-luminous matter :
no associated emission of light (visible, UV, IR, radio, etc...)

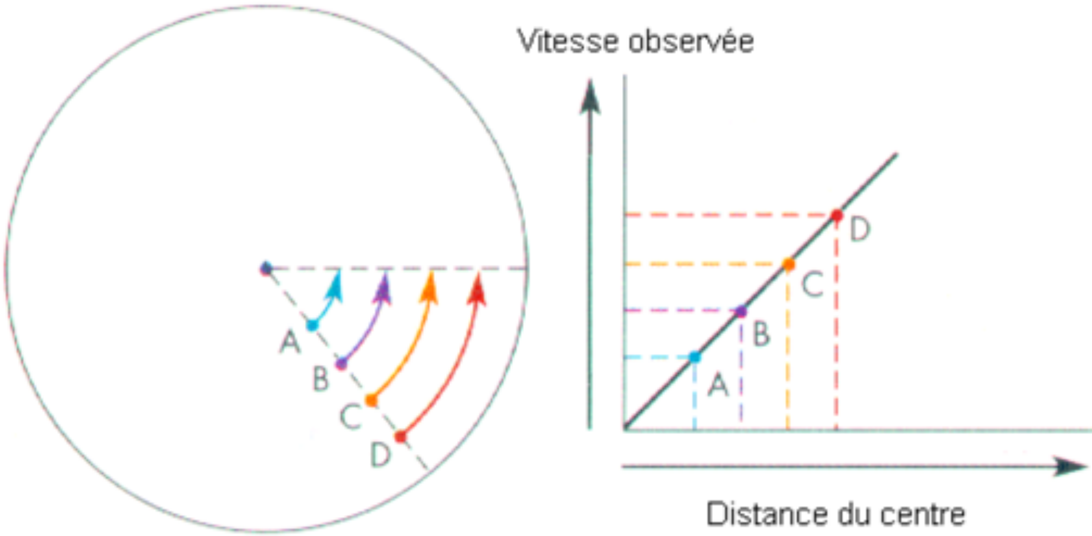
... But we assume its existence by its gravitational effect in:

1) Galaxies
2) Galaxy clusters
3) Cosmology

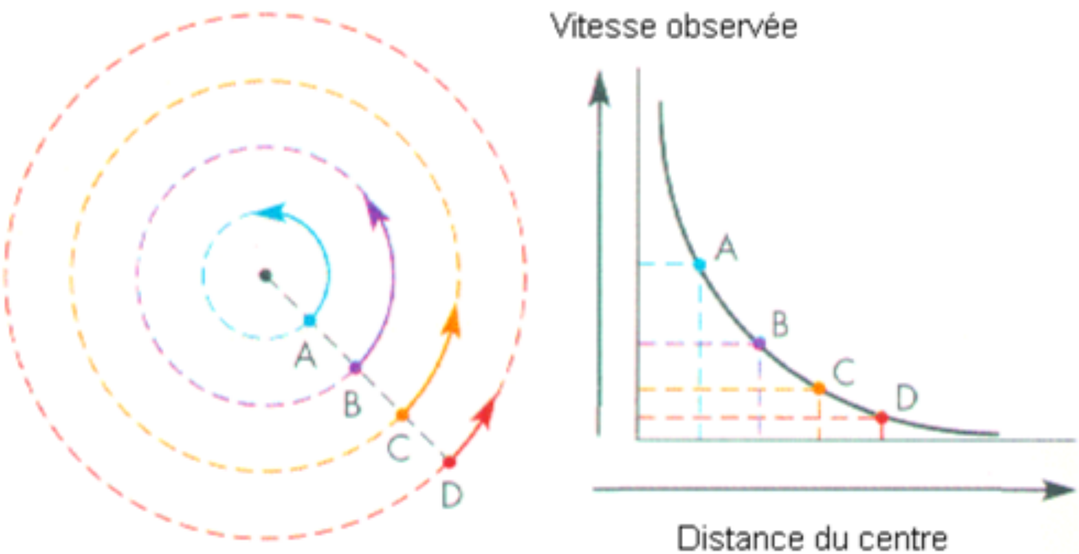
Galaxies

In galaxies, stars are not statics but turns around the galactic center. Thanks to the rotation, the centrifugal force compensates the gravitational force, which prevents stars to collapse in the core.

Galaxies

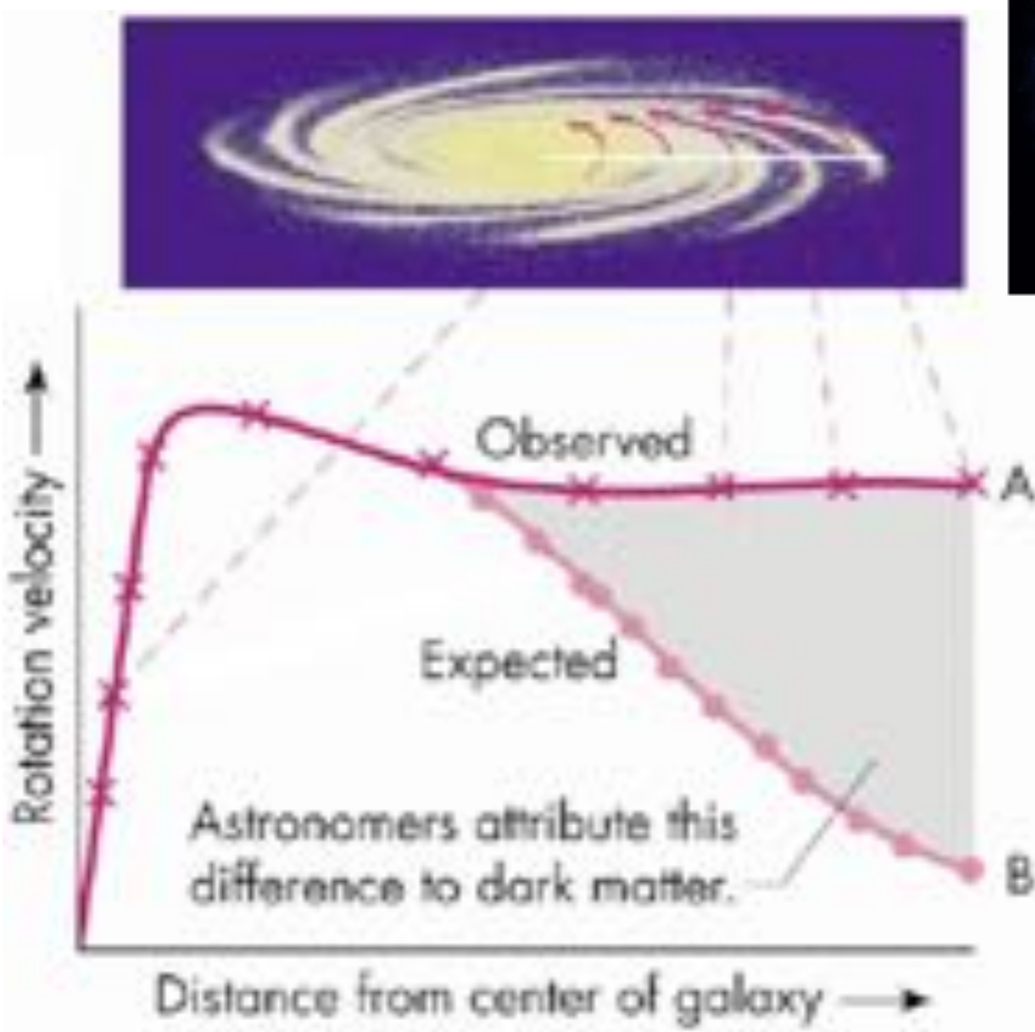


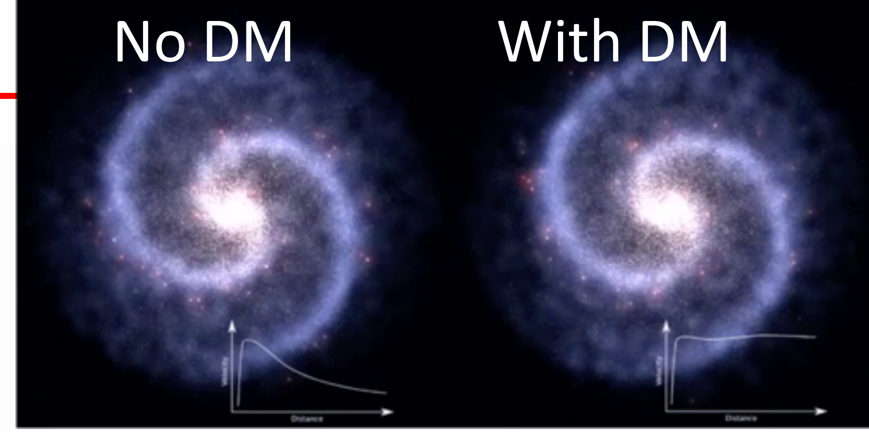
Solid rotation



Planetary rotation

Galaxies



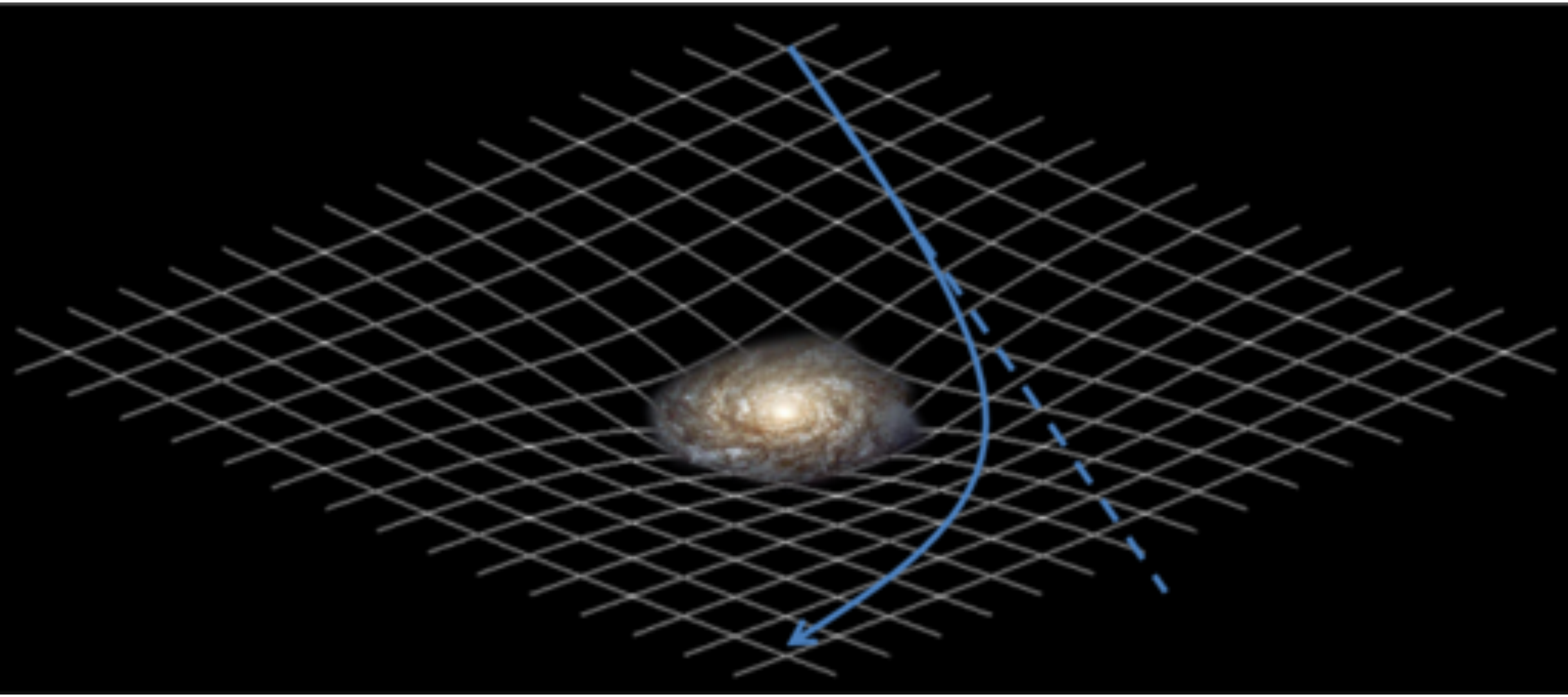


Rotation velocity almost constant at all radius !

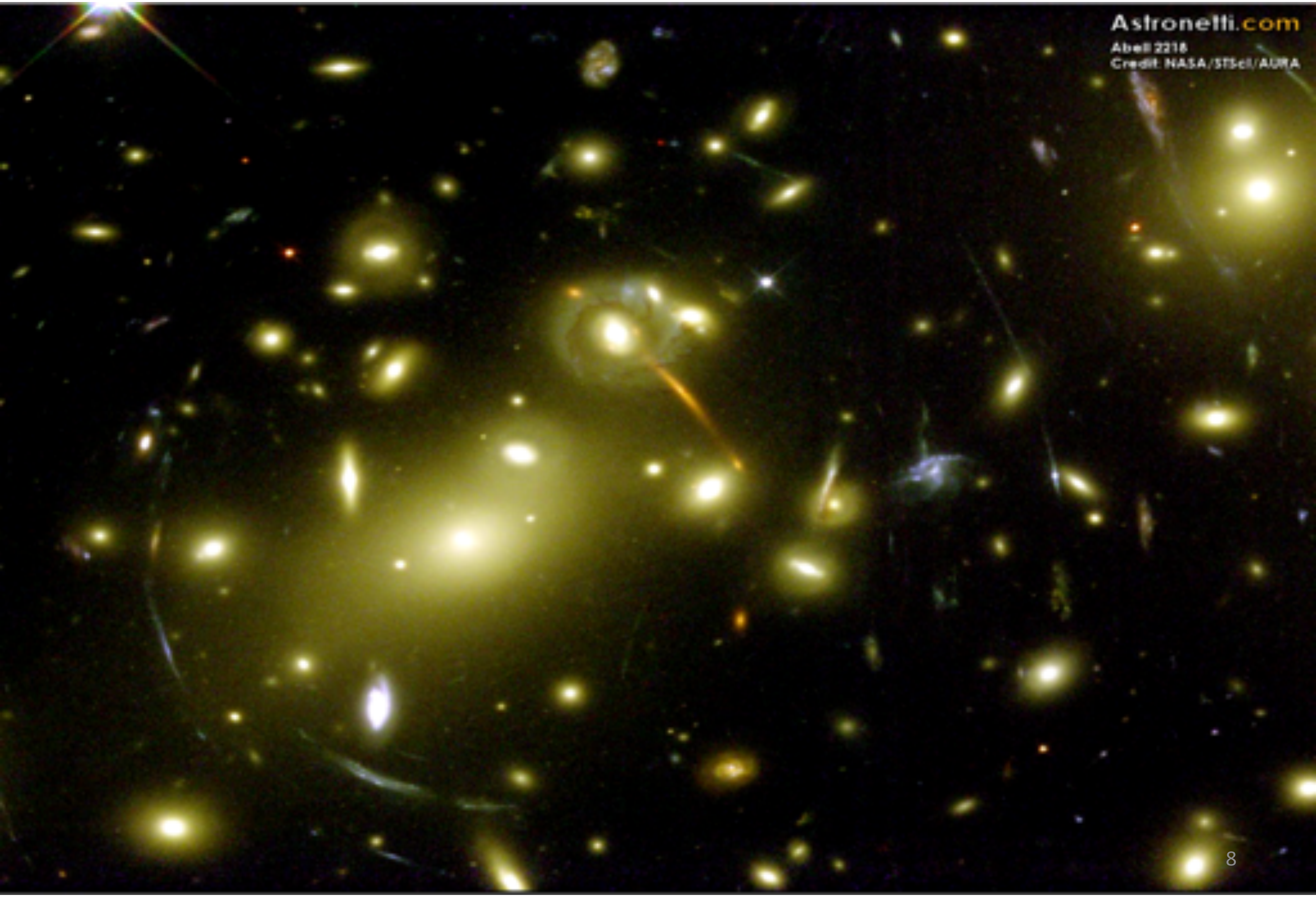
➔ Presence of a halo of invisible matter, 5-10 times heavier than standard matter

Vera Rubin ~1970

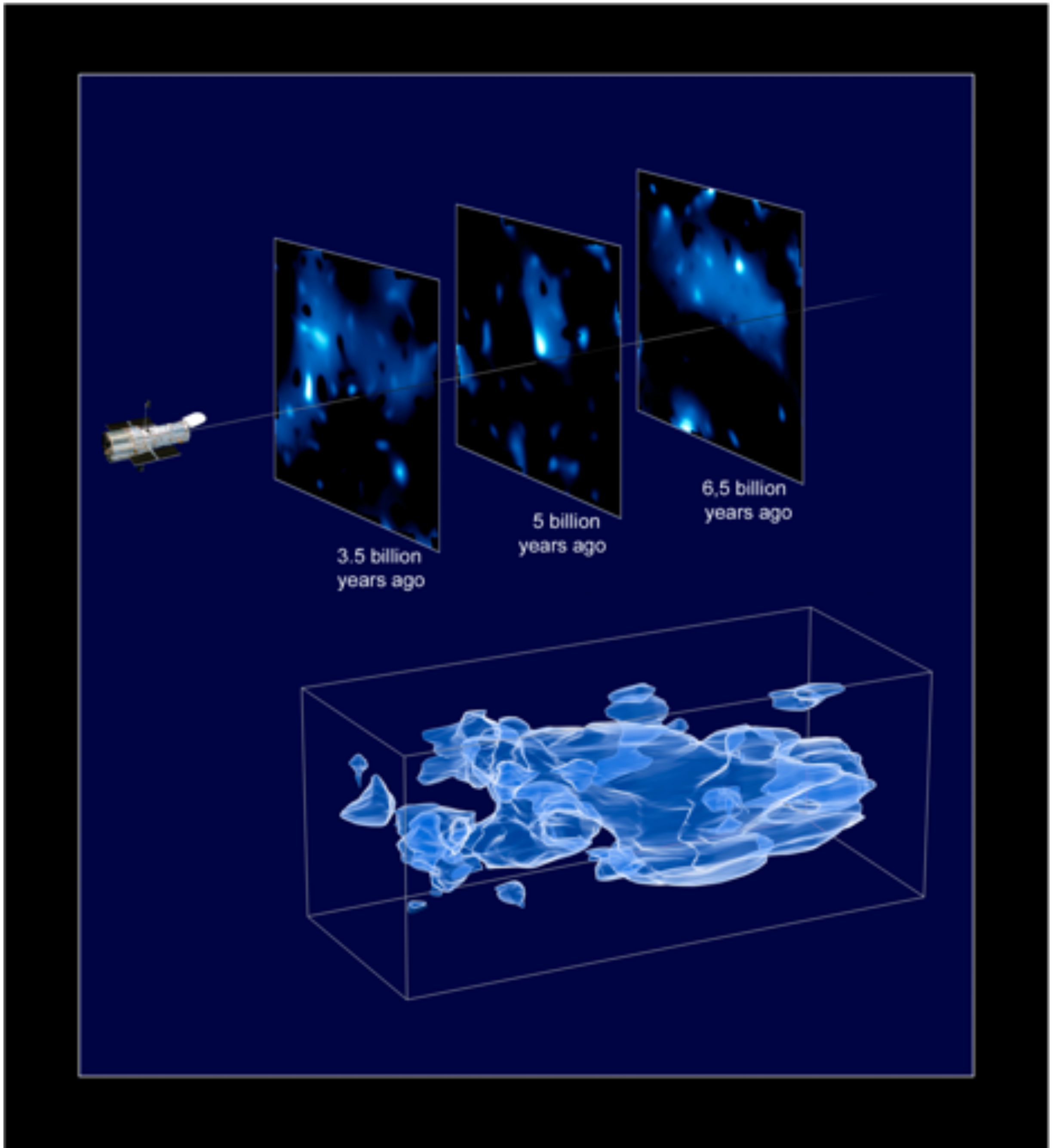
Gravitational lenses



Gravitational lenses

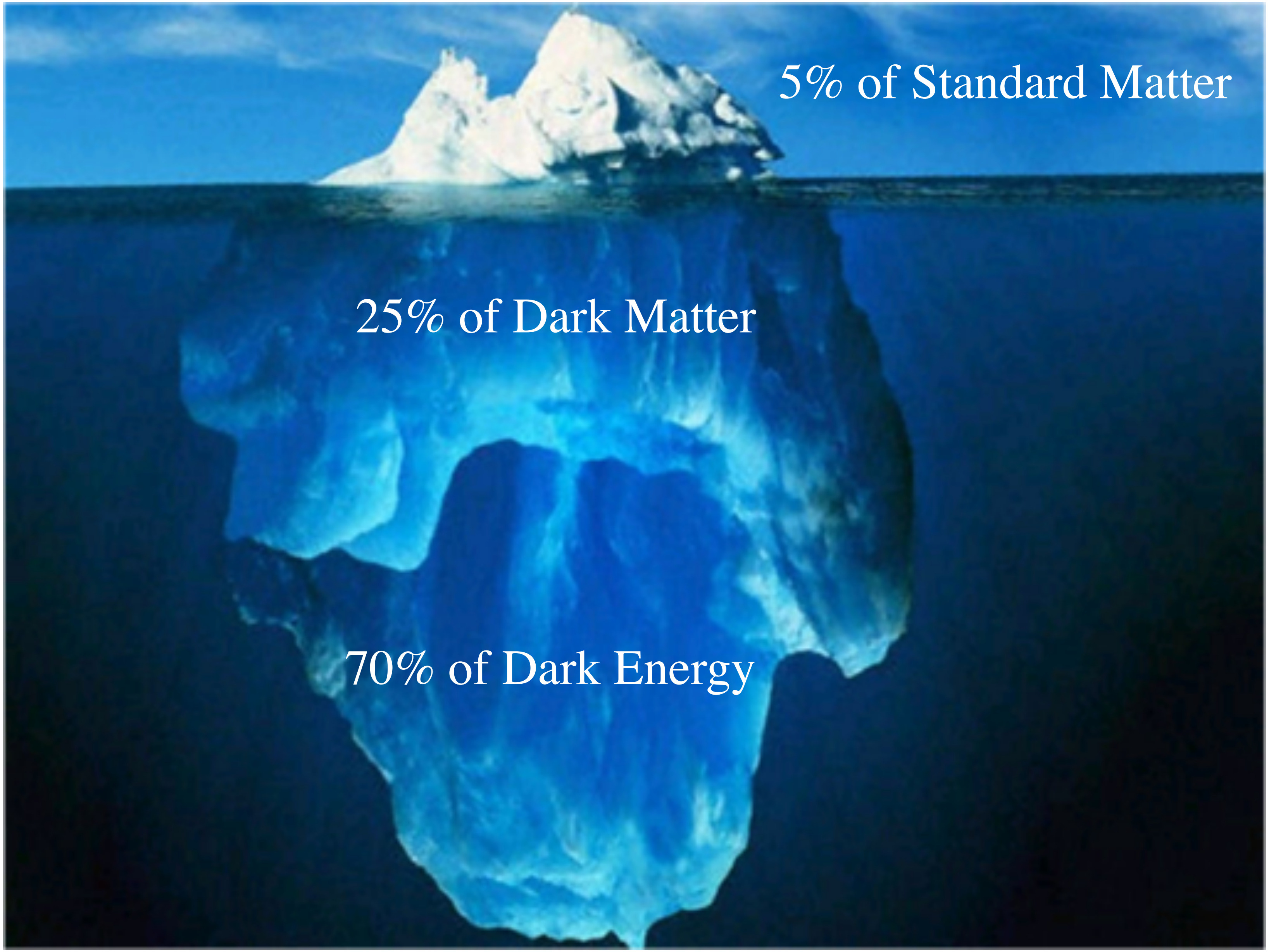


Dark Matter 3D-map



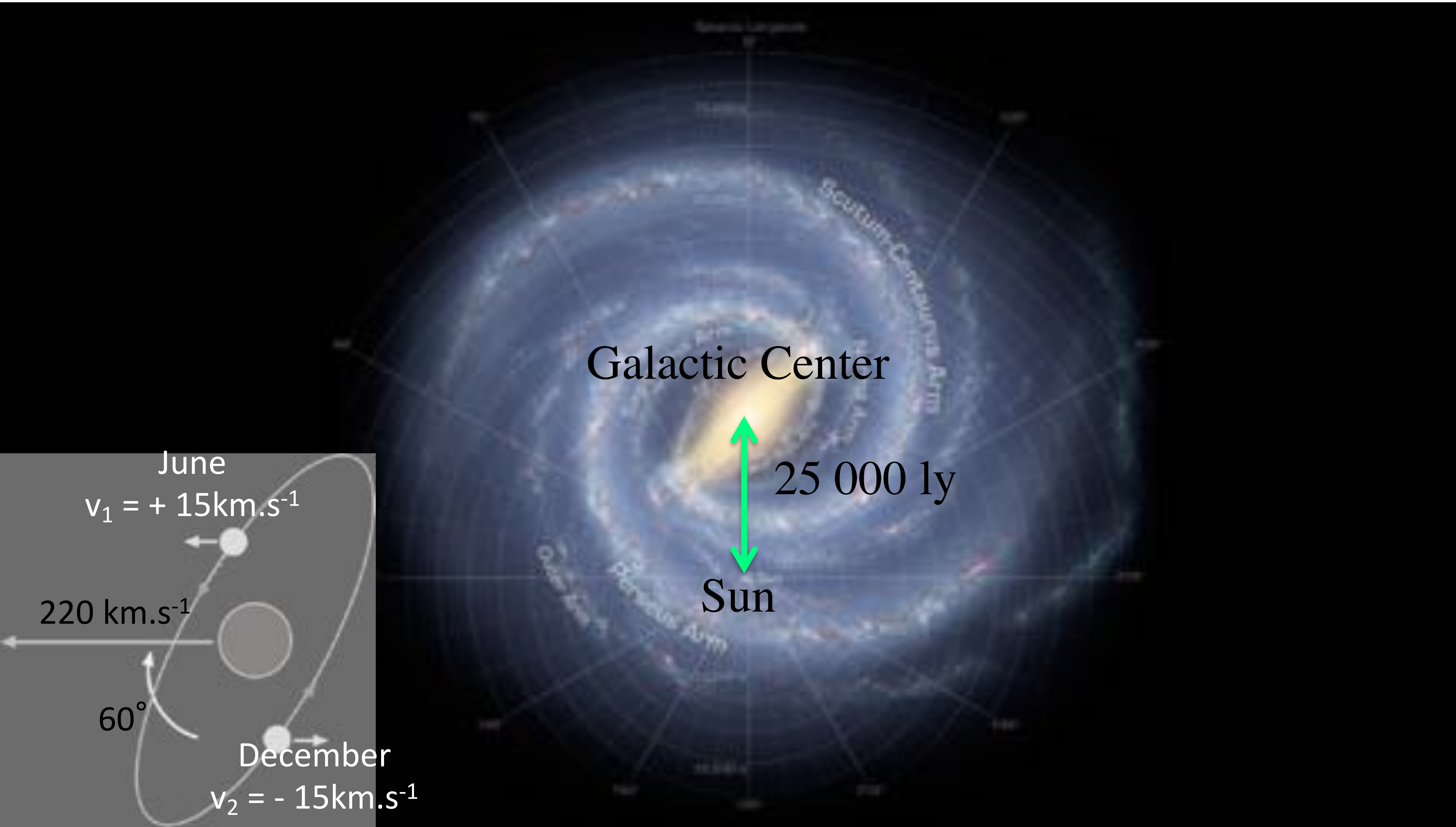
Colliding clusters

Energy composition of the universe



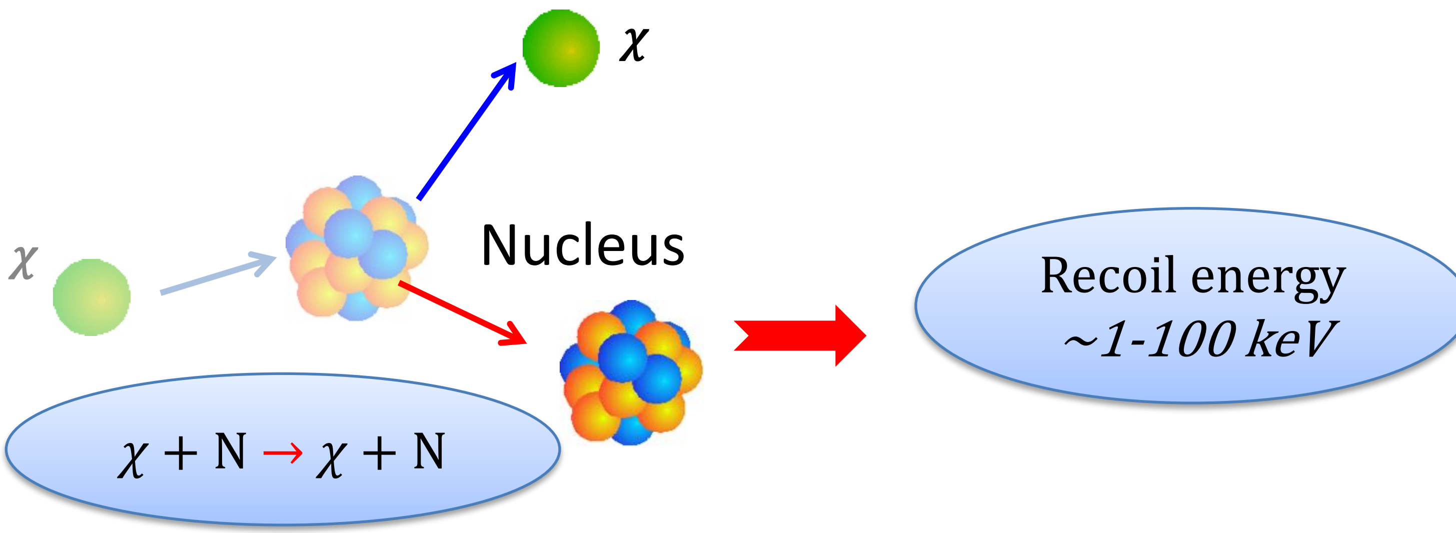
Characteristics of Dark Matter Particles

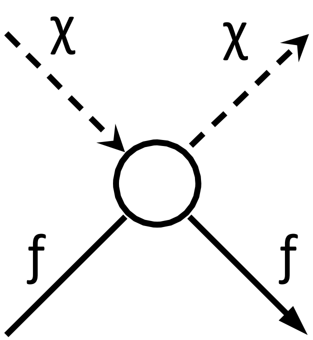
- Weak interaction
- Stable
- Non-baryonic Matter
- Non relativistic



Direct dark matter detection principle

Nuclear Recoil (NR)

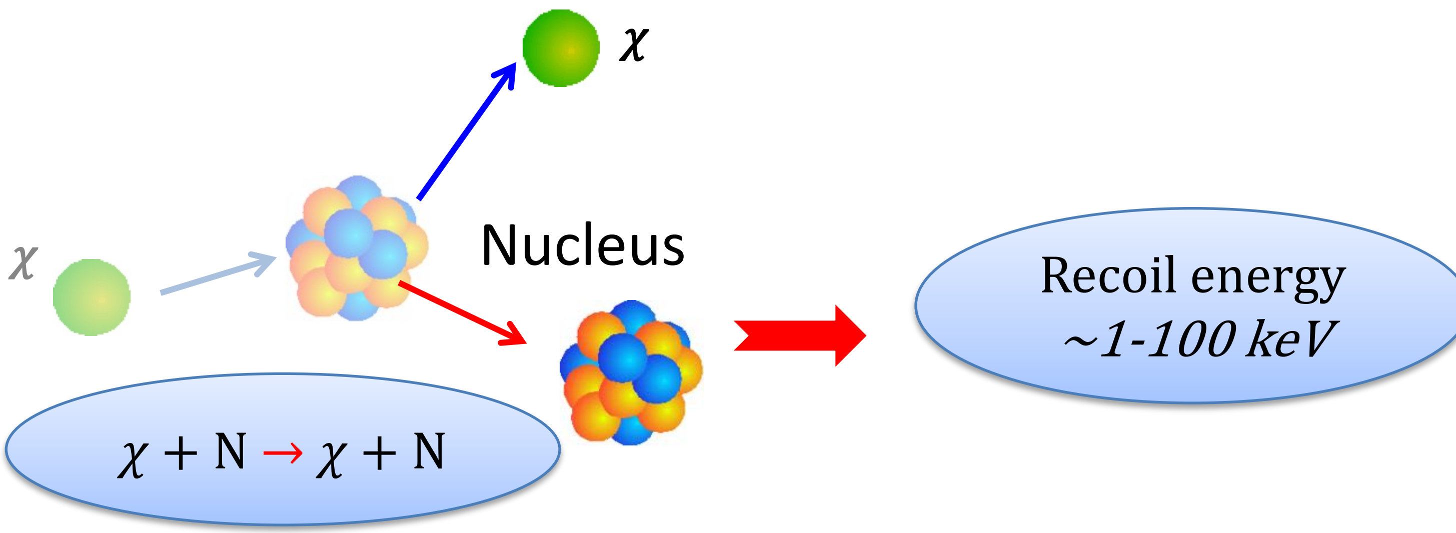


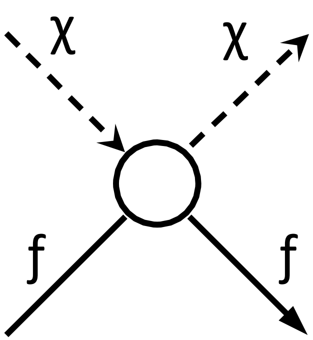


- **Direct detection**
- Indirect detection
- Production

Direct dark matter detection principle

Nuclear Recoil (NR)

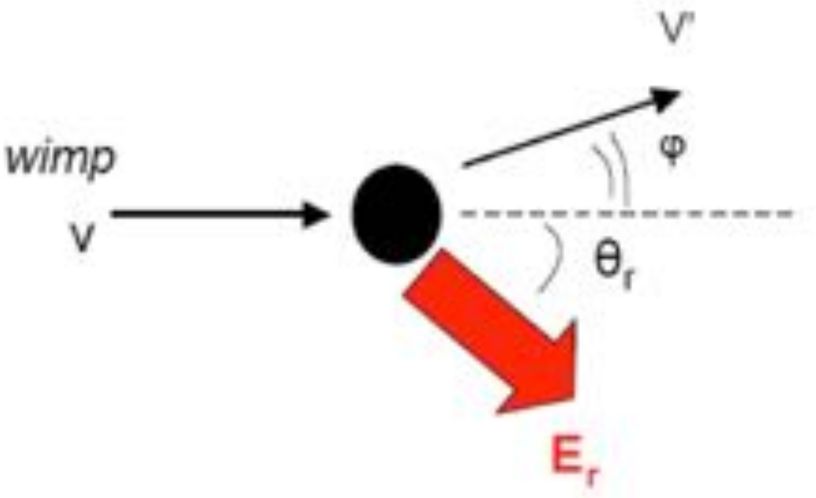




Electronic Recoil (ER)

γ and β particles interact with the atomic electrons
→ background

Cinematic



$$\frac{m_\chi}{2} v^2 = \frac{m_\chi}{2} v'^2 + E_r \qquad \left(E_r = \frac{1}{2} m_N w^2 \right)$$

$$m_\chi v = m_\chi v' \cos\varphi + m_N w \cos\theta_r$$

$$m_\chi v' \sin\varphi = m_N w \sin\theta_r$$

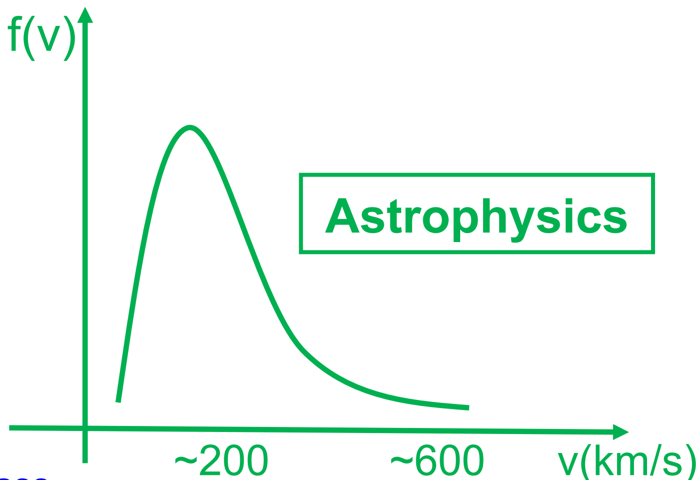
$$\Rightarrow \boxed{E_r = \left(\frac{m_\chi}{2} v^2\right) \times \frac{4 m_N m_\chi}{(m_N + m_\chi)^2} \times \cos^2\vartheta_r}$$

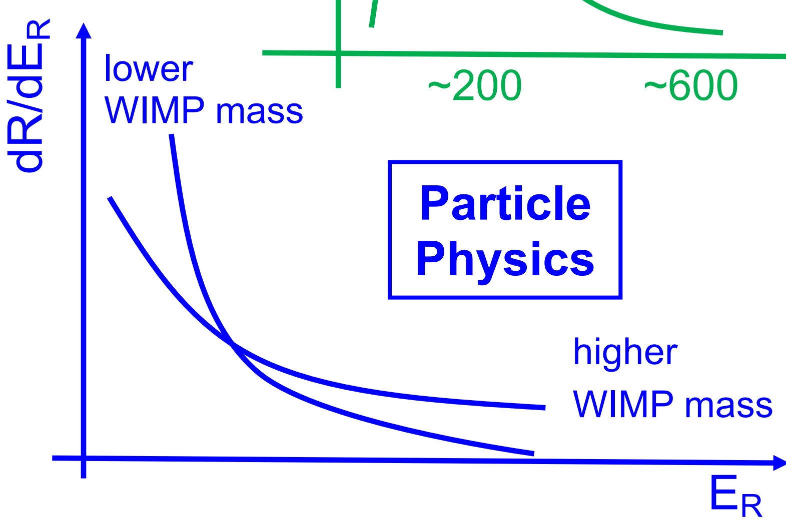
~ 1 - 100 keV

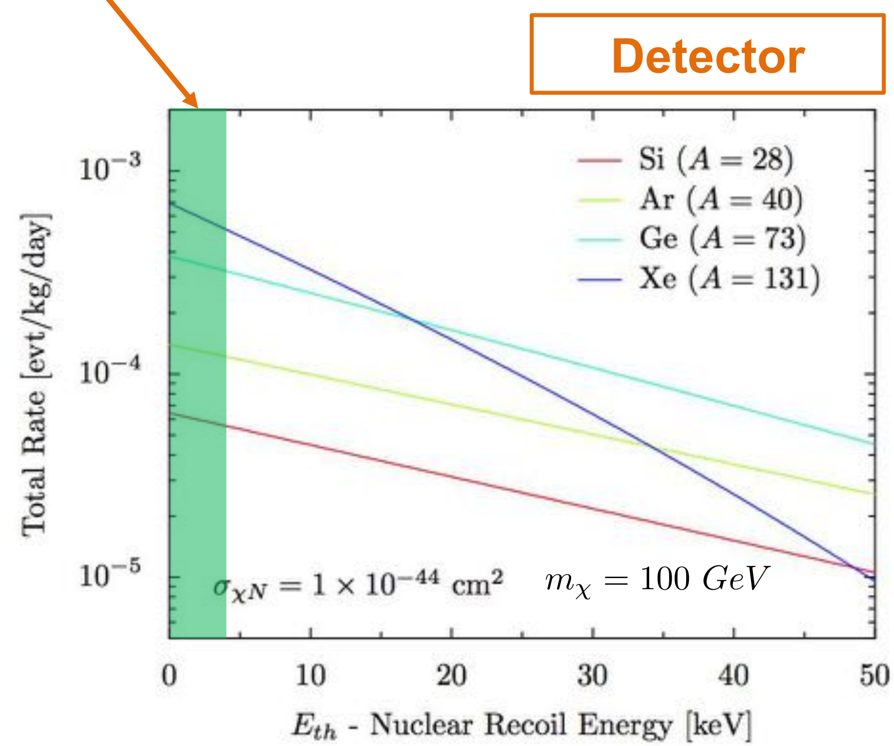
Expected rate for terrestrial detector

$$\frac{dR}{dE_R} = N_N \frac{\rho_\odot}{m_\chi} \int_{v_{min}}^{v_{max}} f(v) v \frac{d\sigma}{dE_R} dv$$

$$v_{min} = \sqrt{\frac{m_N E_{th}}{2\mu}}$$

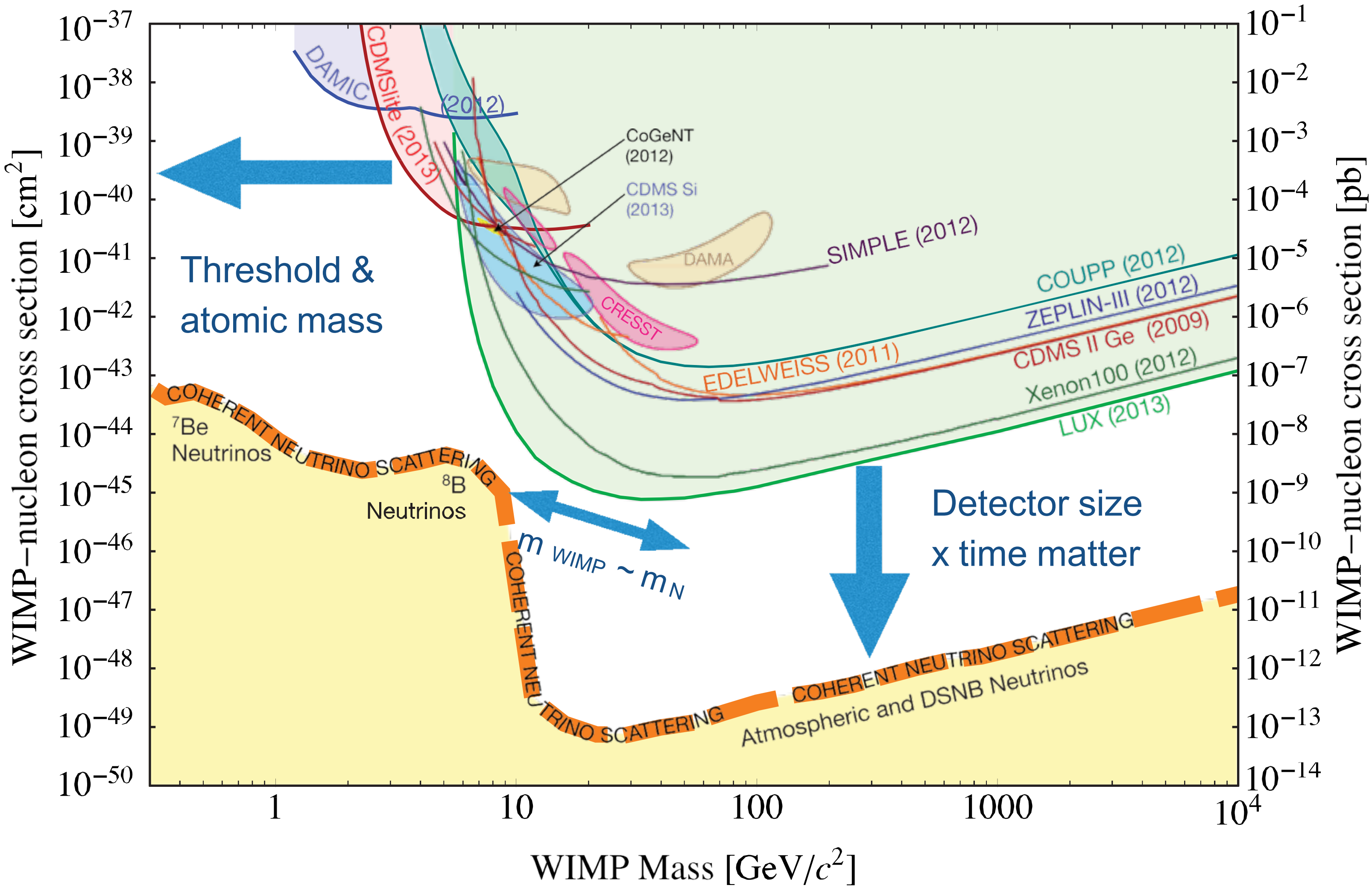




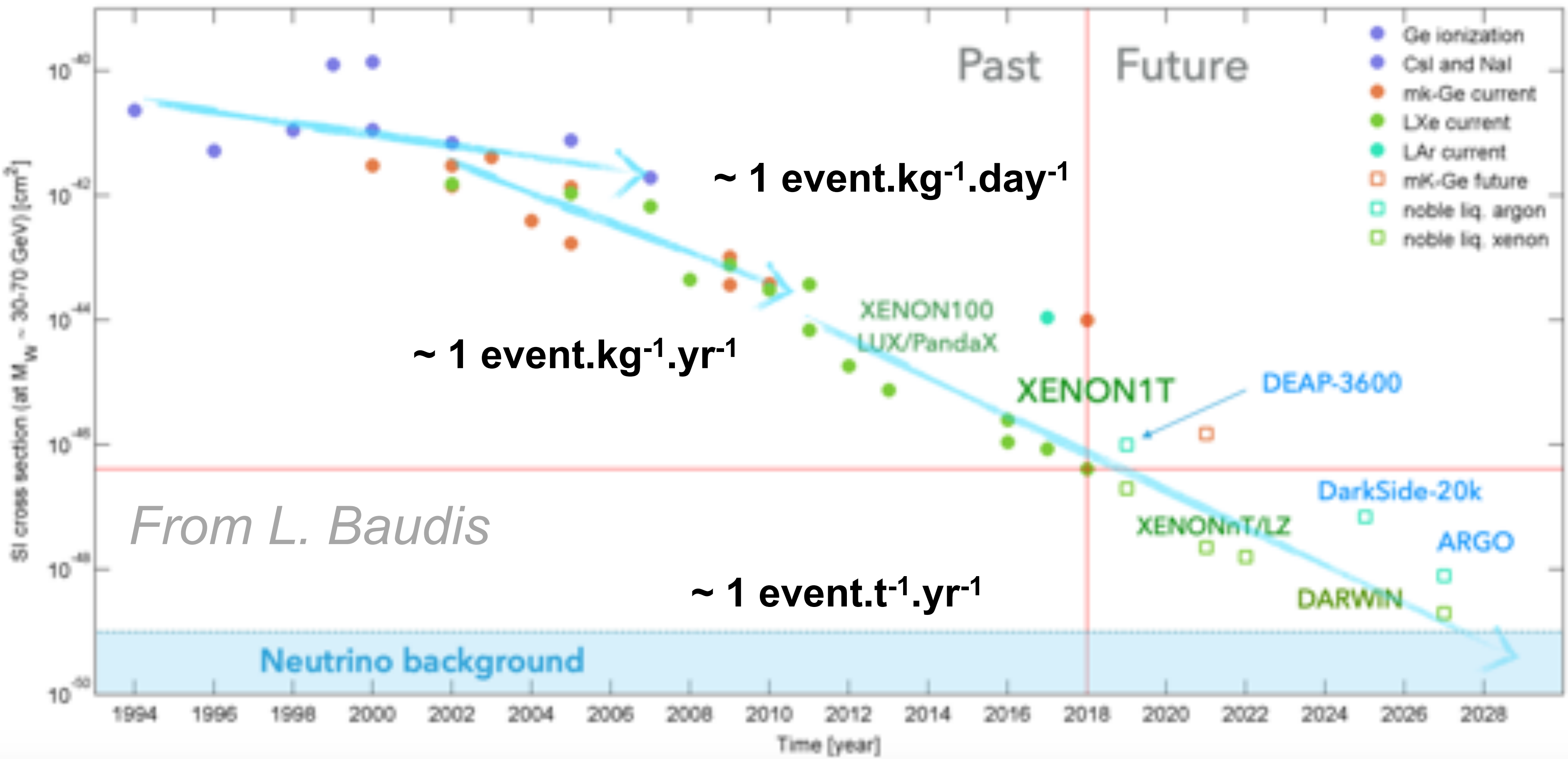


How is evolving the field of Direct Detection ?

$$R \sim 0.13 \frac{\text{events}}{\text{kg . year}} \left[\frac{A}{100} \times \frac{\sigma_{\chi N}}{10^{-38}\ \text{cm}^2} \times \frac{\langle v \rangle}{220\ \text{km.s}^{-1}} \times \frac{\rho_\odot}{0.3\ \text{GeV.cm}^{-3}} \right]$$



Direct detection : progress over time



Detectors needs

- ultra-low background experimental environment
- low energy threshold to detect small recoil energy signals
- good discrimination power against particle that might mimic WIMP collision
- large detector mass to enhance the interaction probability inside the target


Hunts Needle in a Haystack

The fight against the background

- **Avoid background**

- **External γ's** from natural radioactivity

- Material screening
- Self shielding (fiducialization)

- **External neutrons**
  muon-induced (α,n) and fission reaction

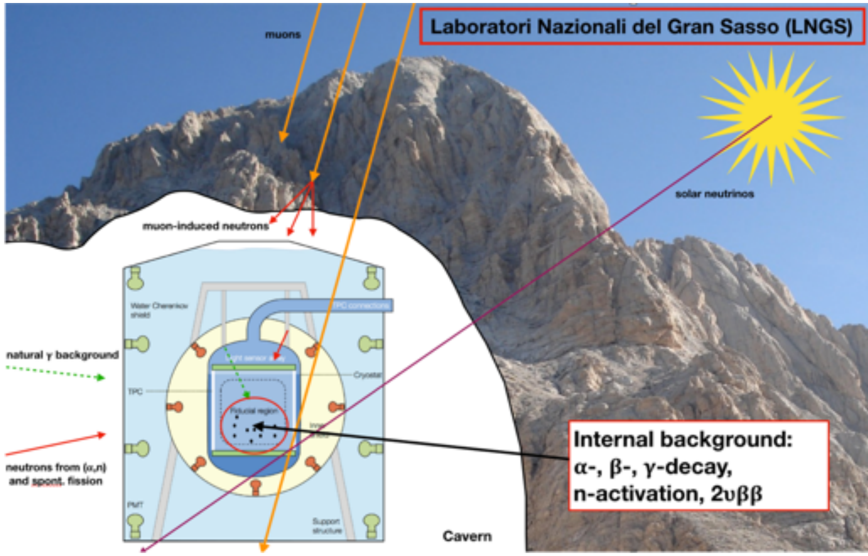
- Material screening (low U and Th)
- Underground experiments
- Shield & active veto

- **Internal contamination**

- ^{85}Kr : removed by cryogenic distillation
- ^{222}Rn : removed by cryogenic distillation
- ^{136}Xe : ββ decay, long lifetime ($T_{1/2} = 2.2 \times 10^{21}$ years)

- **Use WIMP properties**

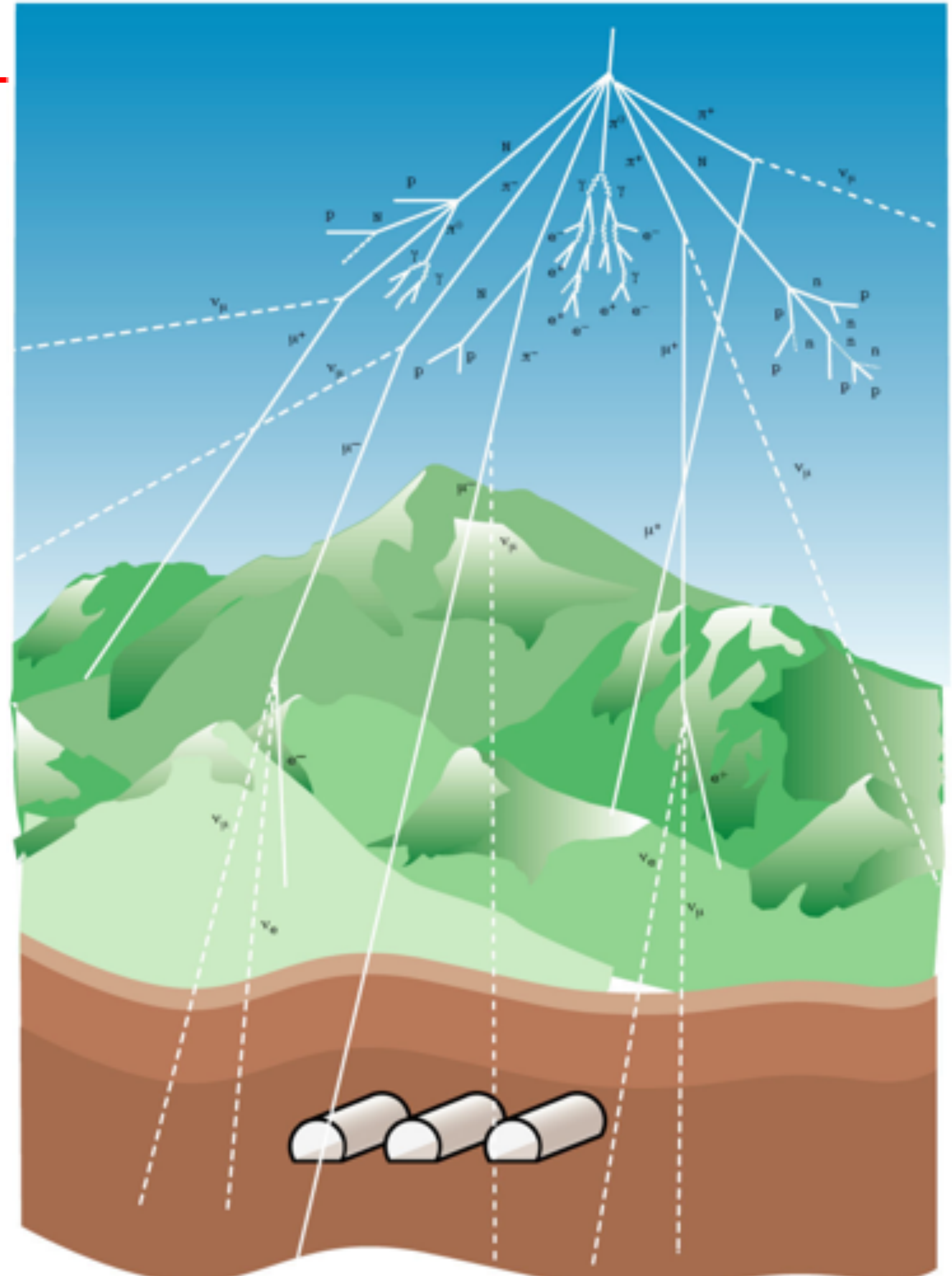
  - No double scatter
  - Homogeneously distributed
    → *Position reconstruction*
  - Nuclear recoils
    → *ER/NR Discrimination*



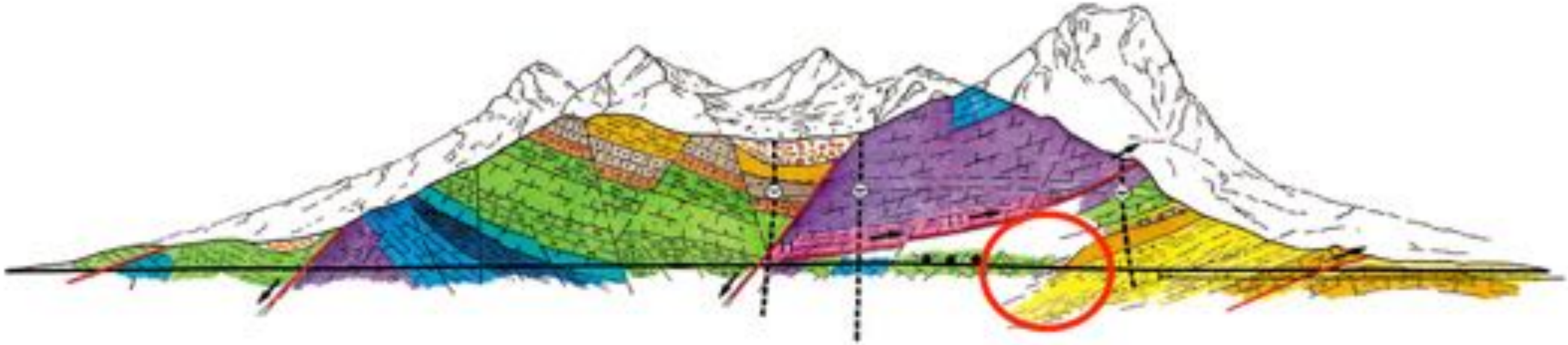
Cosmic Rays

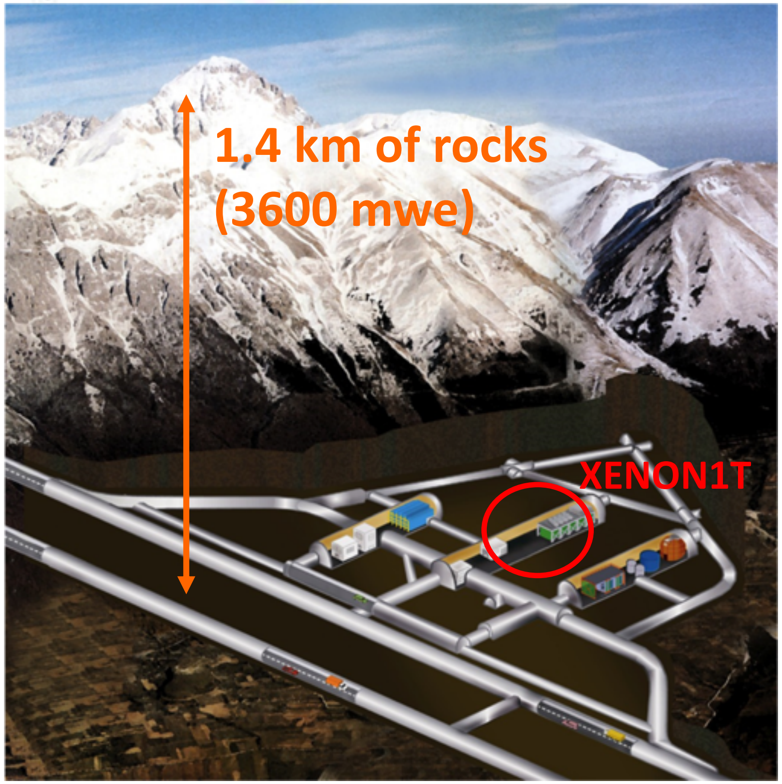
To increase the sensitivity of the experiments, we need:

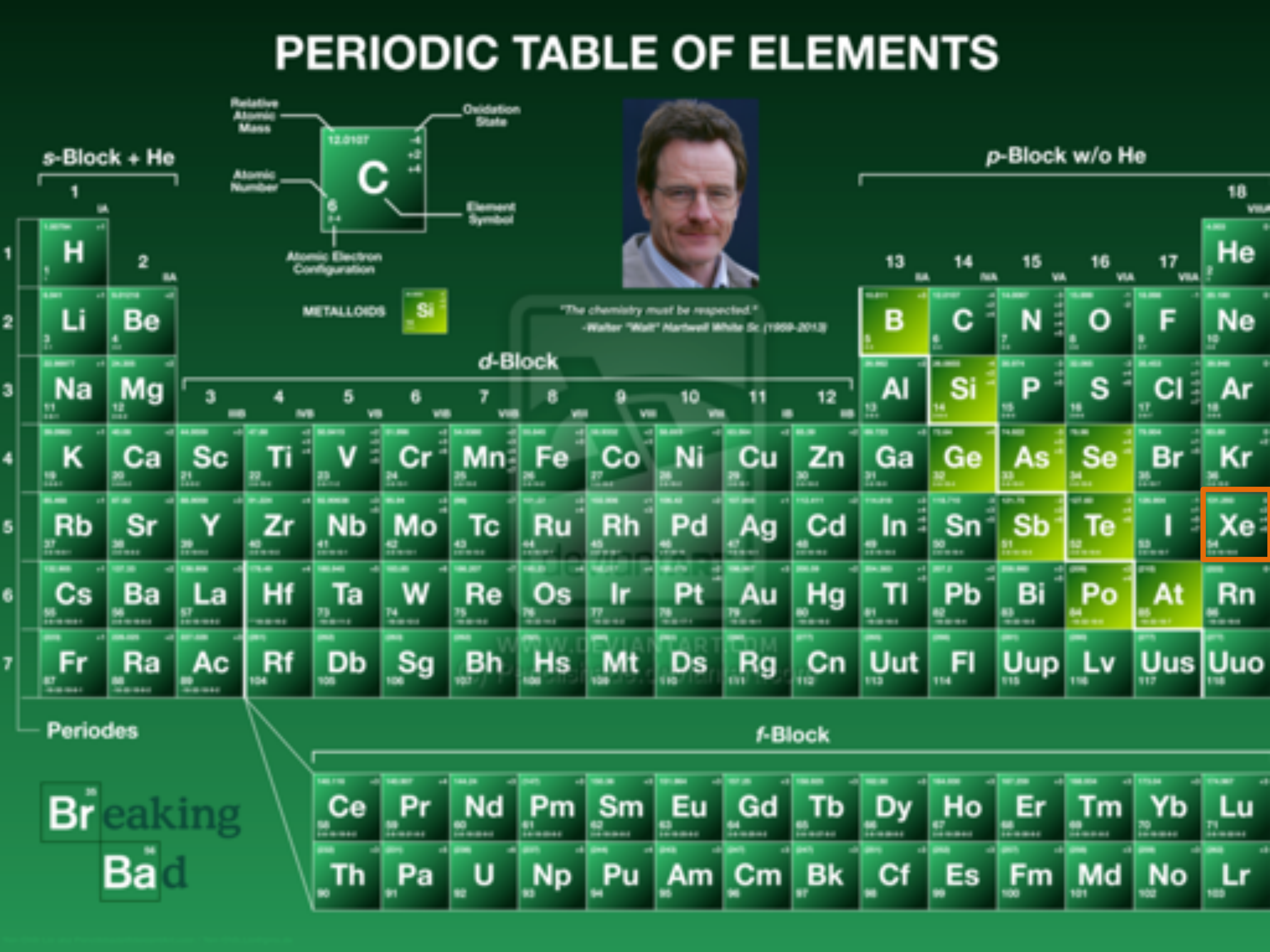
- To hide under a mountain to be protected from cosmic rays (100 per second across ou body),
- To be protected from natural radioactivity from rocks
- To purify from materials of the detector



XENON1T experiment site

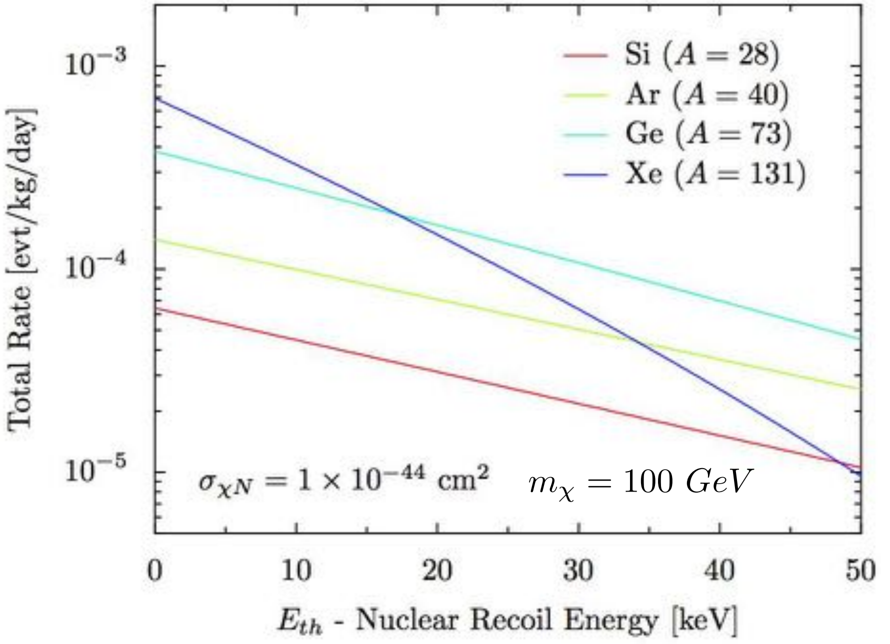





PERIODIC TABLE OF ELEMENTS
Relative Atomic Mass
Oxidation State
Atomic Number
Element Symbol
Atomic Electron Configuration
12.0107
C
6
s-Block + He
p-Block w/o He
d-Block
f-Block
METALLOIDS
Si
"The chemistry must be respected."
-Walter "Walt" Hartwell White Sr. (1959-2013)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba La Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Ac Rf Db Sg Bh Hs Mt Ds Rg Cn Uut Fl Uup Lv Uus Uuo
Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr
Periodes
Breaking
Bad

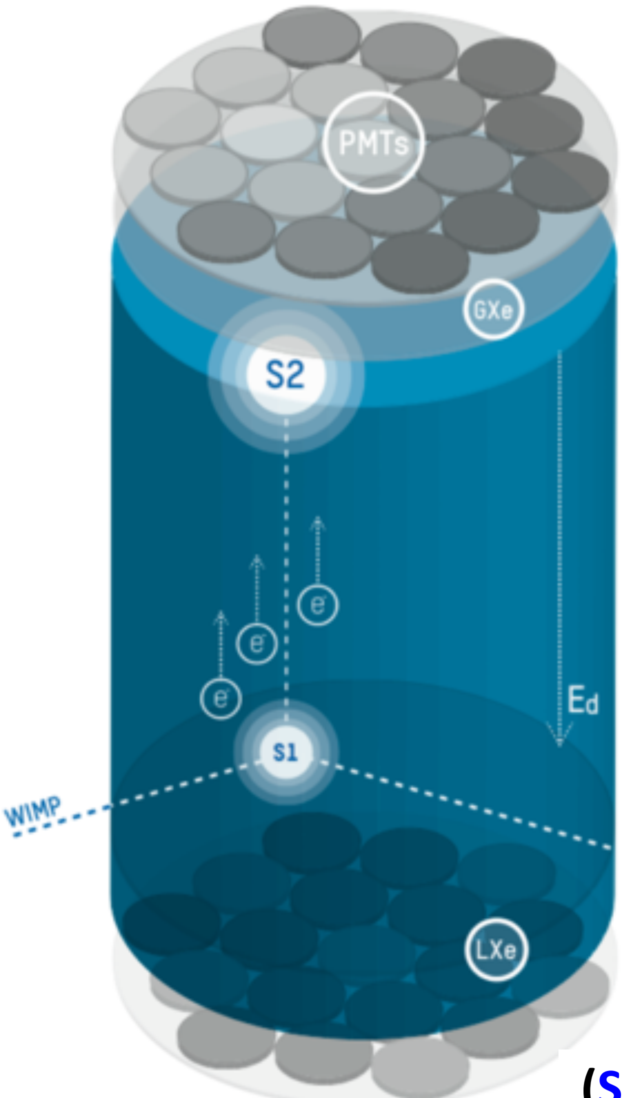
Why Xenon ?

- Large mass number A (131) (Interaction cross section ∝ A^2)
- 50% odd isotopes (^{129}Xe, ^{131}Xe) for Spin-Dependent interactions
- Kr can be reduced to ppt levels
- High stopping power, i.e. active volume is self-shielding
- Efficient scintillator (178 nm)
- Scalable to large target masses
- Electronic recoil discrimination with simultaneous measurement of scintillation and ionization



Dual phase TPC: principle

TPC = Time Projection Chamber



<u>S1:</u>

→ Photon (λ = 178 nm) from Scintillation process → Dectected by PMTs (mainly botton array)

<u>S2:</u>

→ Electrons drift

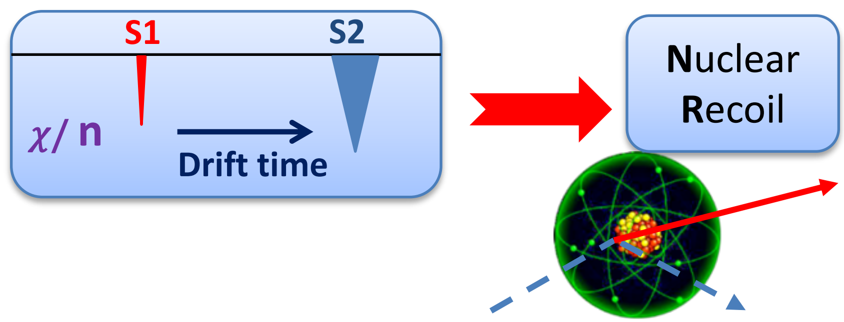
→ Extraction in gaseous phase

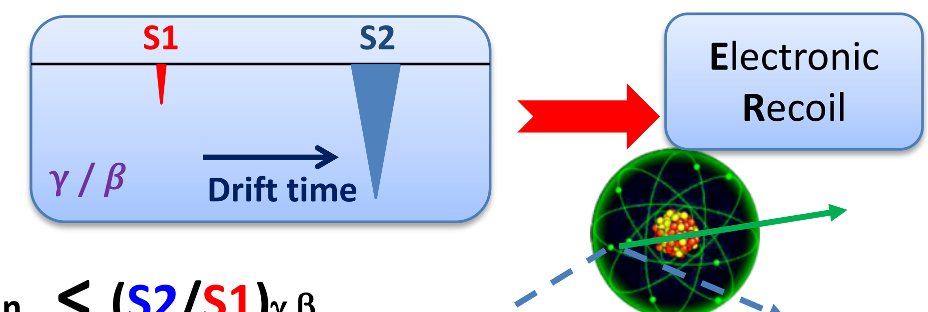
→ Proportional scintillation light

<u>3D reconstruction :</u>

→ X,Y from top array

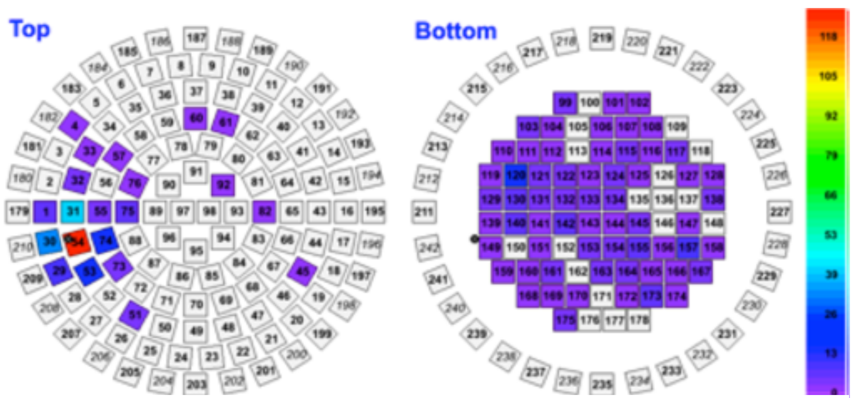
→ Z from Drift time



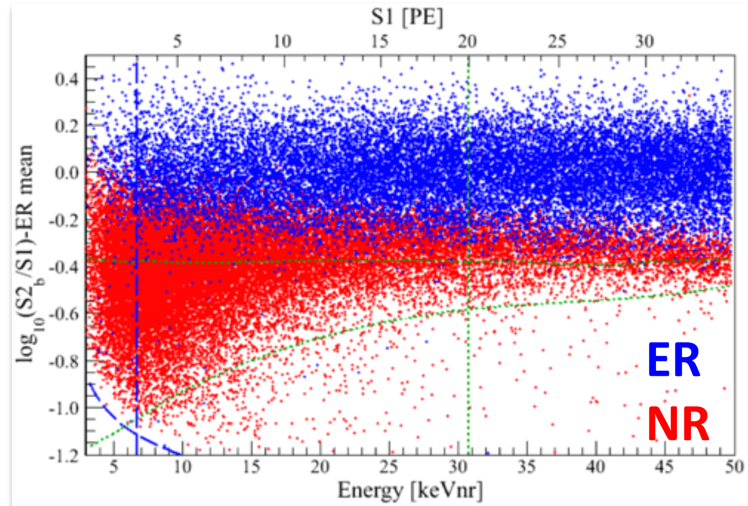


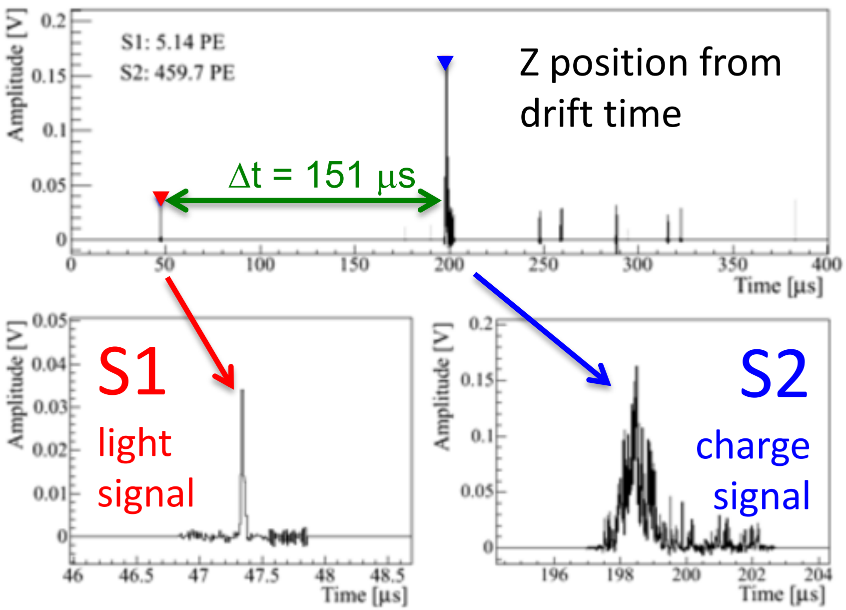
$(S2/S1)_{WIMP,n} < (S2/S1)_{\gamma,\beta}$

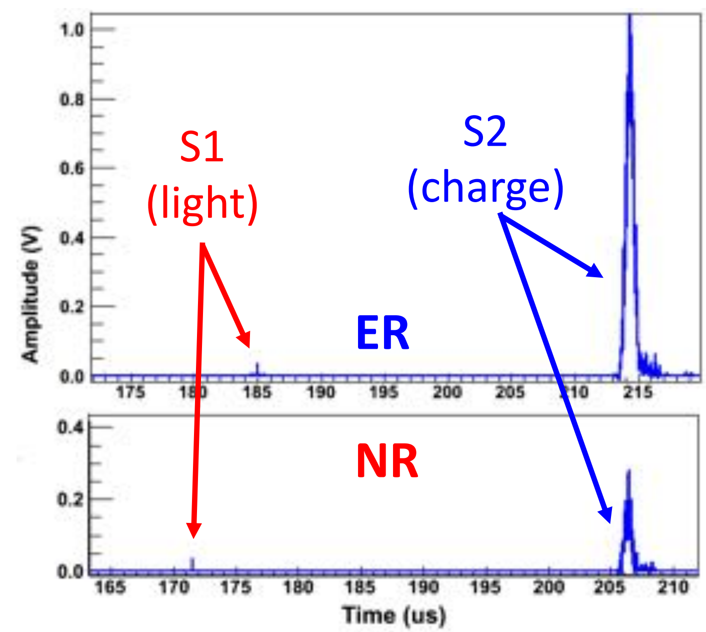
Dual phase TPC: real life



X and Y position from S2 hit pattern on the top PMTs







XENON World

25 Institutions
11 Countries
165 Scientists

XENON1T facility

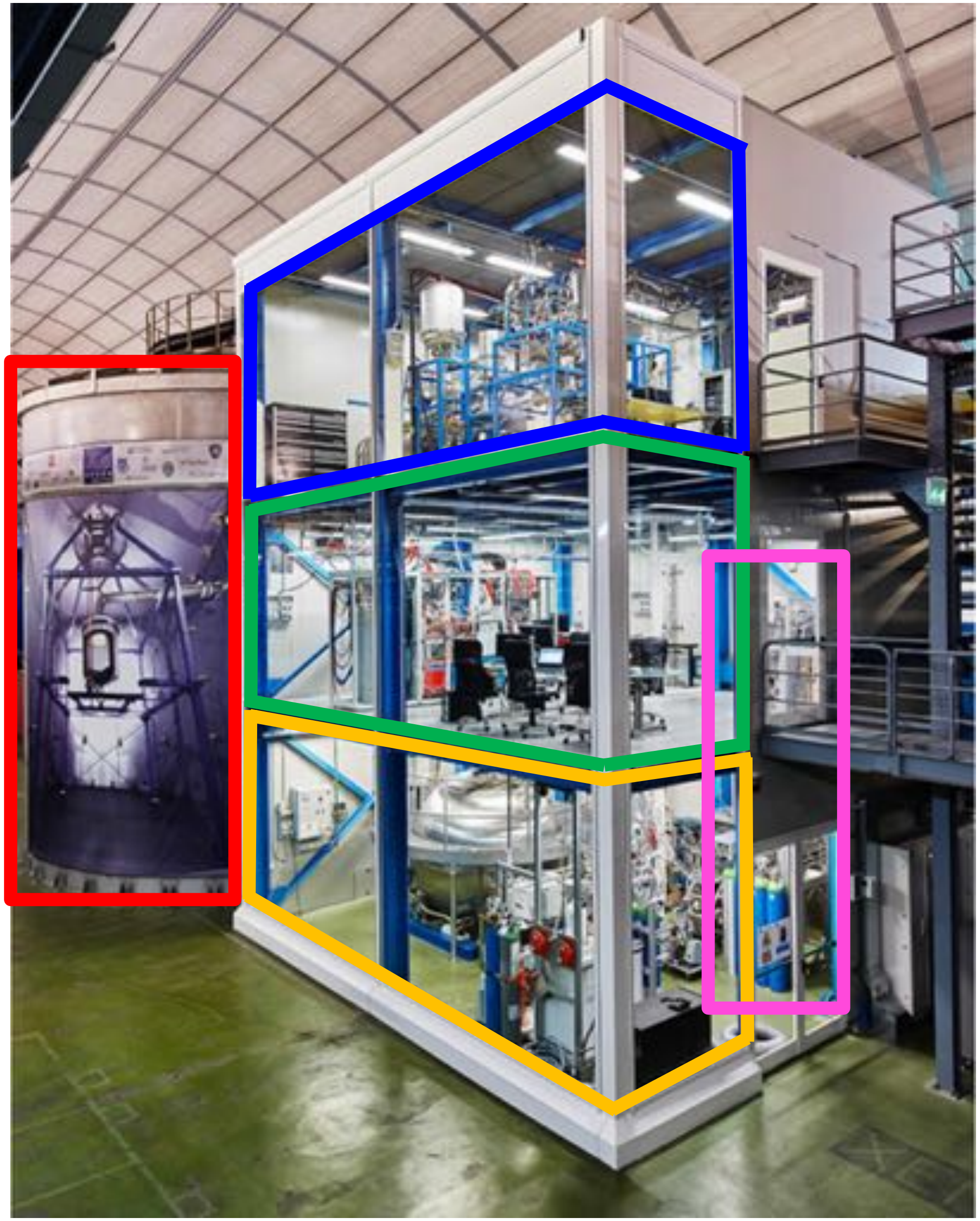
Water shield: deionized water as passive radiation shield
Muon veto: Active muon veto against muon induced neutrons (84 PMTs)

Cryogenics: Stable conditions(3.2t LXe)
Purification: LXe flow through getters, remove impurities

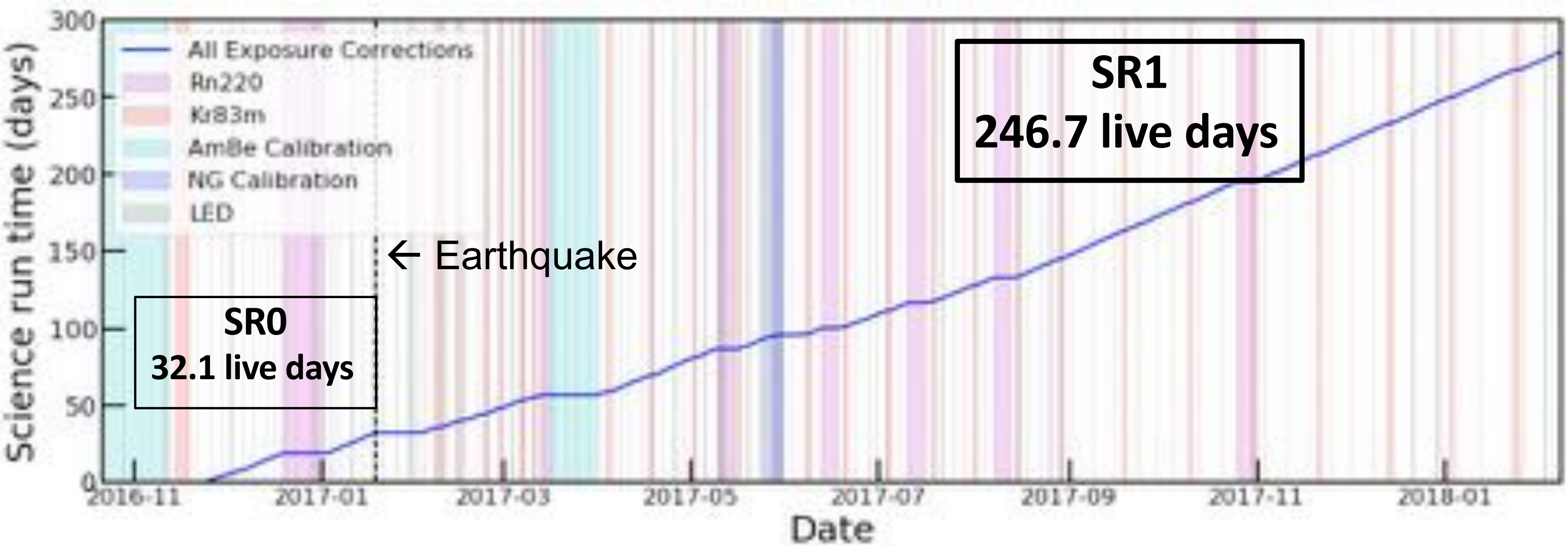
DAQ: Each channel has its own threshold, Flexible software algorithms
Readout: Up to 300MB/s for high rate calibrations

ReStoX: Emergency recovery up to 7.6 tons of LXe
Passive: No active cooling required to keep Xe contained

Kr Distillation: Remove Kr from system during fill or online
Rn Distillation: Initial tests show promising reduction for Rn



XENON1T Data Taking



- DM total exposure SR0+SR1: 278.8 Live days
  ➔ Largest exposure reported to-date with this type of detector

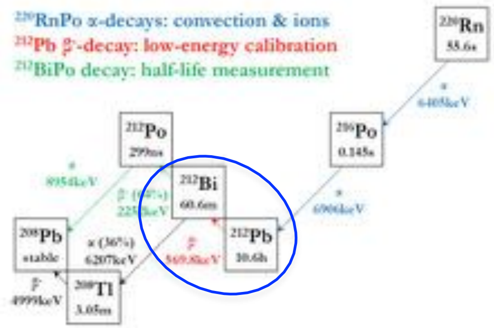
- Calibration Data:
  - 83mKr ➔ Spacial Response (electron lifetime,…)
  - 220Rn ➔ ER-Band
  - 241AmBe & NG➔ NR-Band
  - LED ➔ PMT gain monitoring

Calibrations

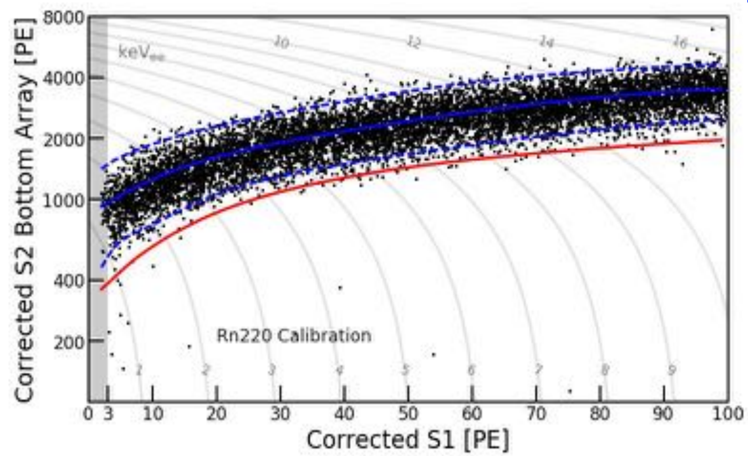
Electronic Recoils

Internal source

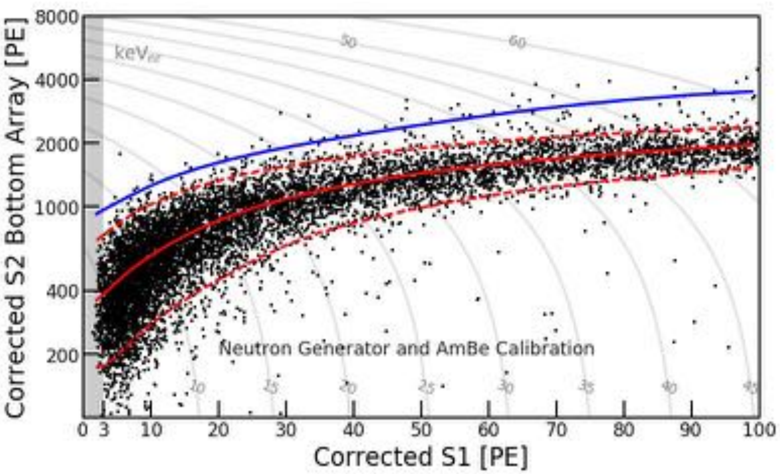
- ^{228}Th source emanates ^{220}Rn into LXe
- β-**decay** of ^{212}Pb to ^{212}Bi
  → **low energy** events (2–20 keV)
- Decay of activity dominated by ^{212}Pb half-life (10.6 h)



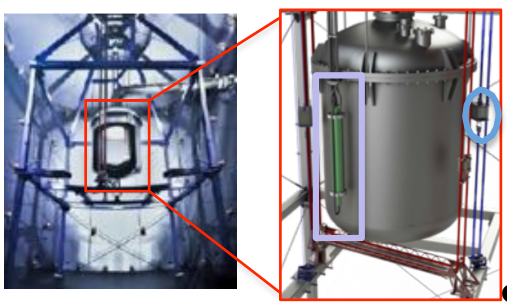
Blue: ER, Red: NR; ——: median, ▪▪▪▪▪ : $\pm 2\sigma$



Blue: ER, Red: NR; ——: median, ▪▪▪▪▪ : $\pm 2\sigma$



External source

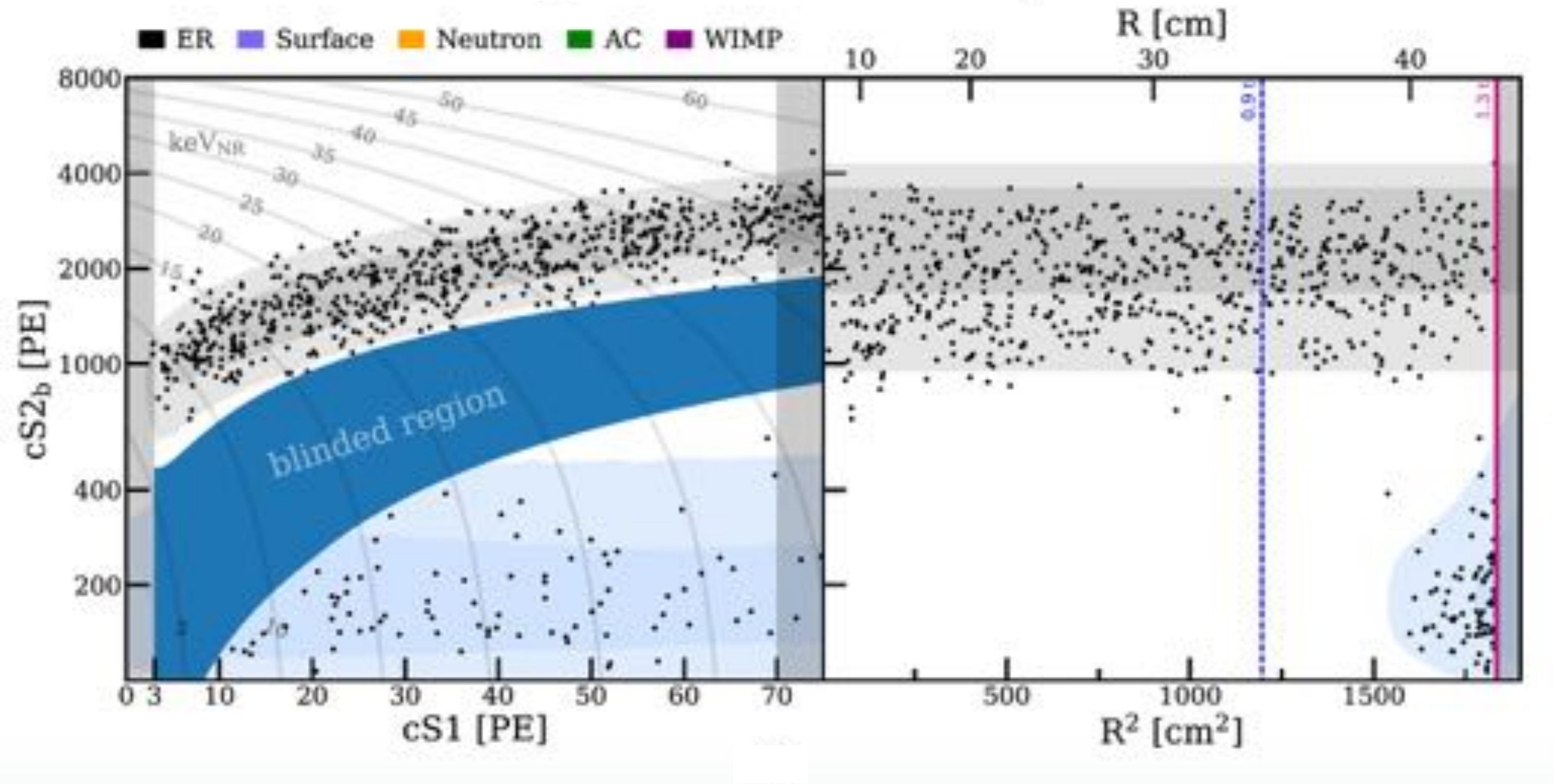


Nuclear Recoils

- External ^{241}**AmBe** source mounted on a belt
  - The α particles emitted by the decay of the Am collide with the light Be nuclei producing fast neutrons
- **Neutron Generator**

Dark Matter Search Data

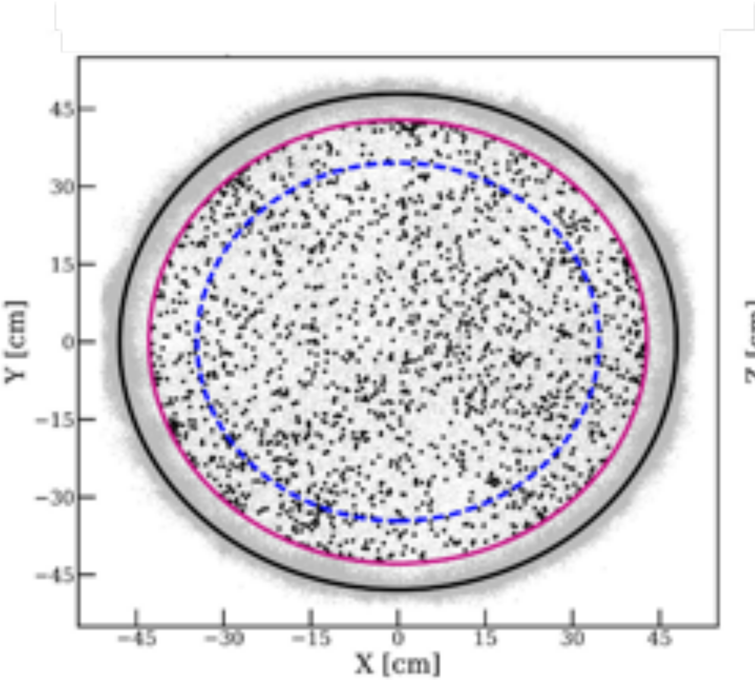
- **Blinding ➔** to avoid biases in event selection and signal/background modeling
- **Salting** (addition of fake events) ➔ to protect against post-unbliding tuning of the cuts and background models

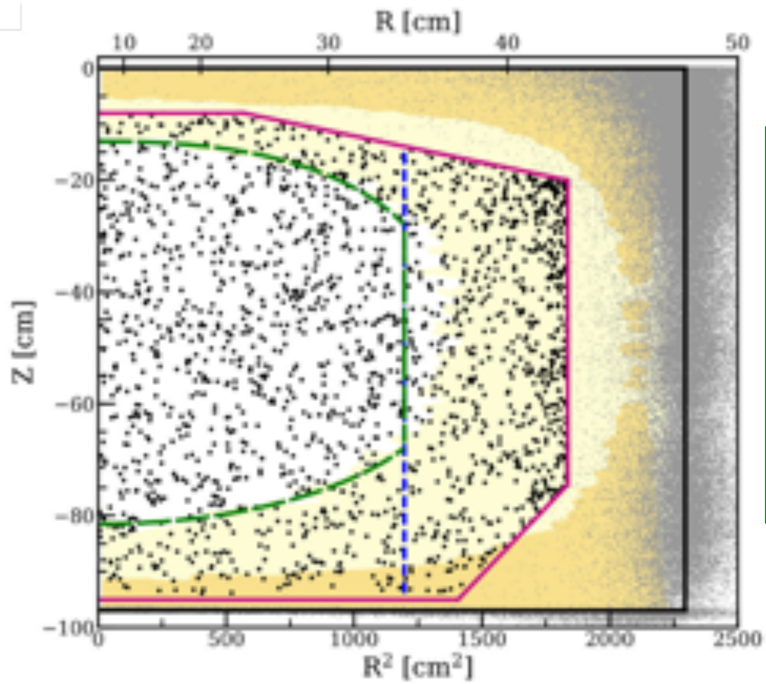


Fiducial Volume Optimization

Optimize fiducial volume before unblinding by using improved understanding

- position reconstruction
- detector response
- correlations between spectral and spacial distribution
- include knowledge on background distributions in statistical framework
- MC simulations



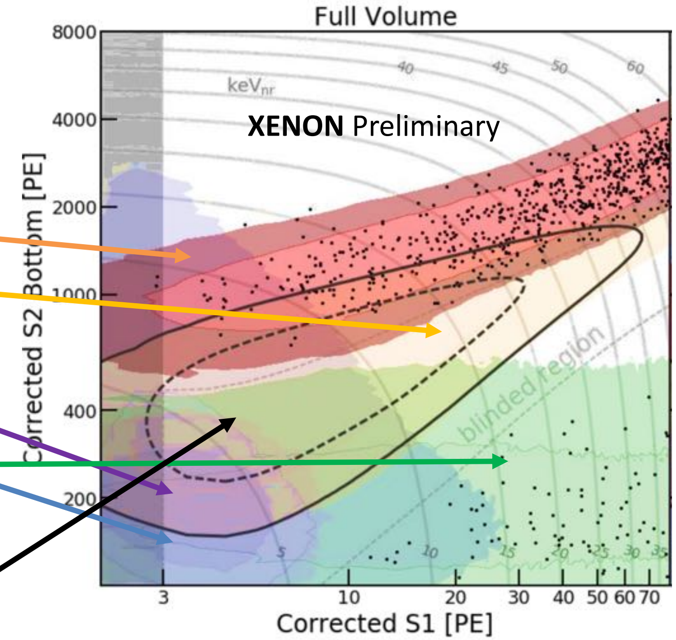


Aim at optimal S/B

larger FV
1 t → 1.3 t

XENON1T Expectations

278.8 days live-time	1.3 t Full ROI	0.65 t NR Reference	Mass (S2,S1) region
ER	627 ± 18	0.60 ± 0.13	
neutron	1.43 ± 0.66	0.14 ± 0.07	
CEνNS	0.05 ± 0.01	0.01	
AC	$0.47^{+0.27}$	$0.04^{+0.02}$	
Surface	106 ± 8	0.01	
TOTAL BKG	**735 ± 20**	**0.80 ± 0.14**	



WIMP
50 GeV/c^2

Background models

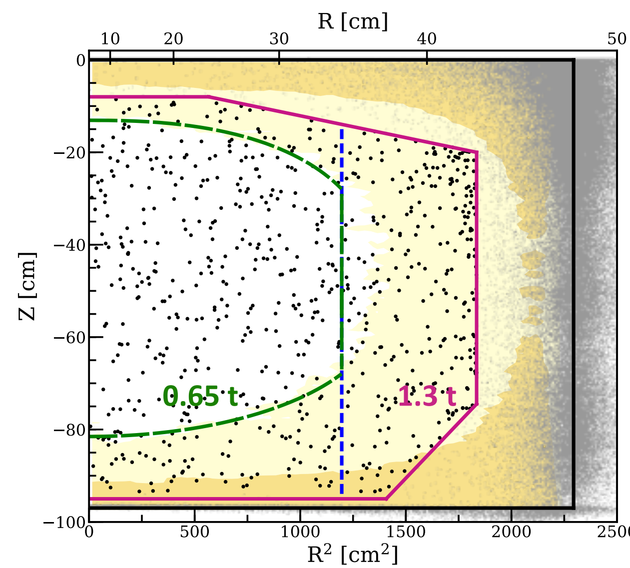
In 4-dimensional space: S1, S2, r, z

Statistical inference

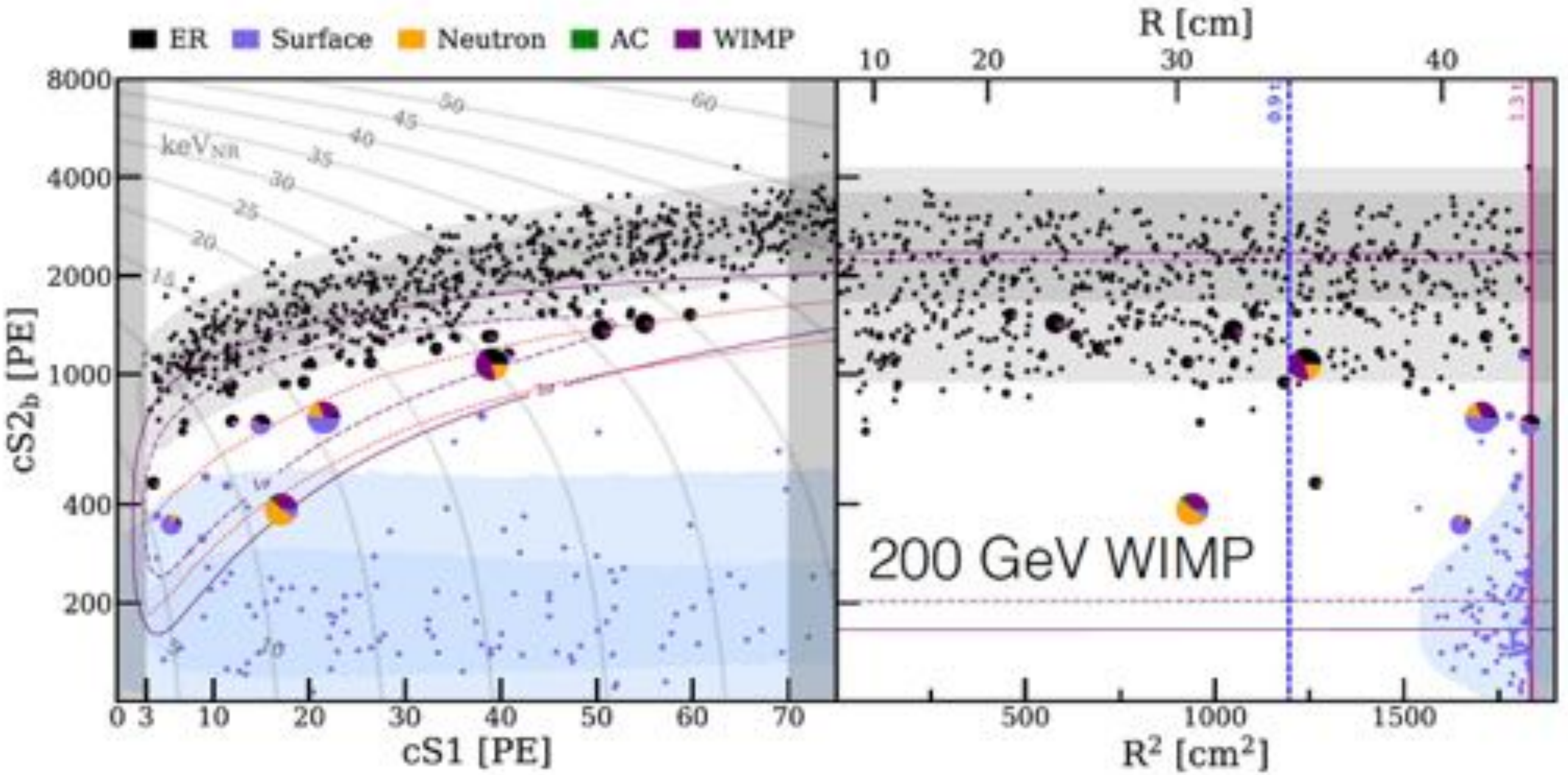
Done with PLR analysis in 1.3 t fiducial volume and full (S1,S2) space, corresponding to [4.9, 40.9] keV$_{nr}$ and [1.4, 10.6] keV$_{ee}$.

NR reference region

Between NR median and -2σ quantile. Numbers in table are for illustration; final results from complete PLR statistical inference.

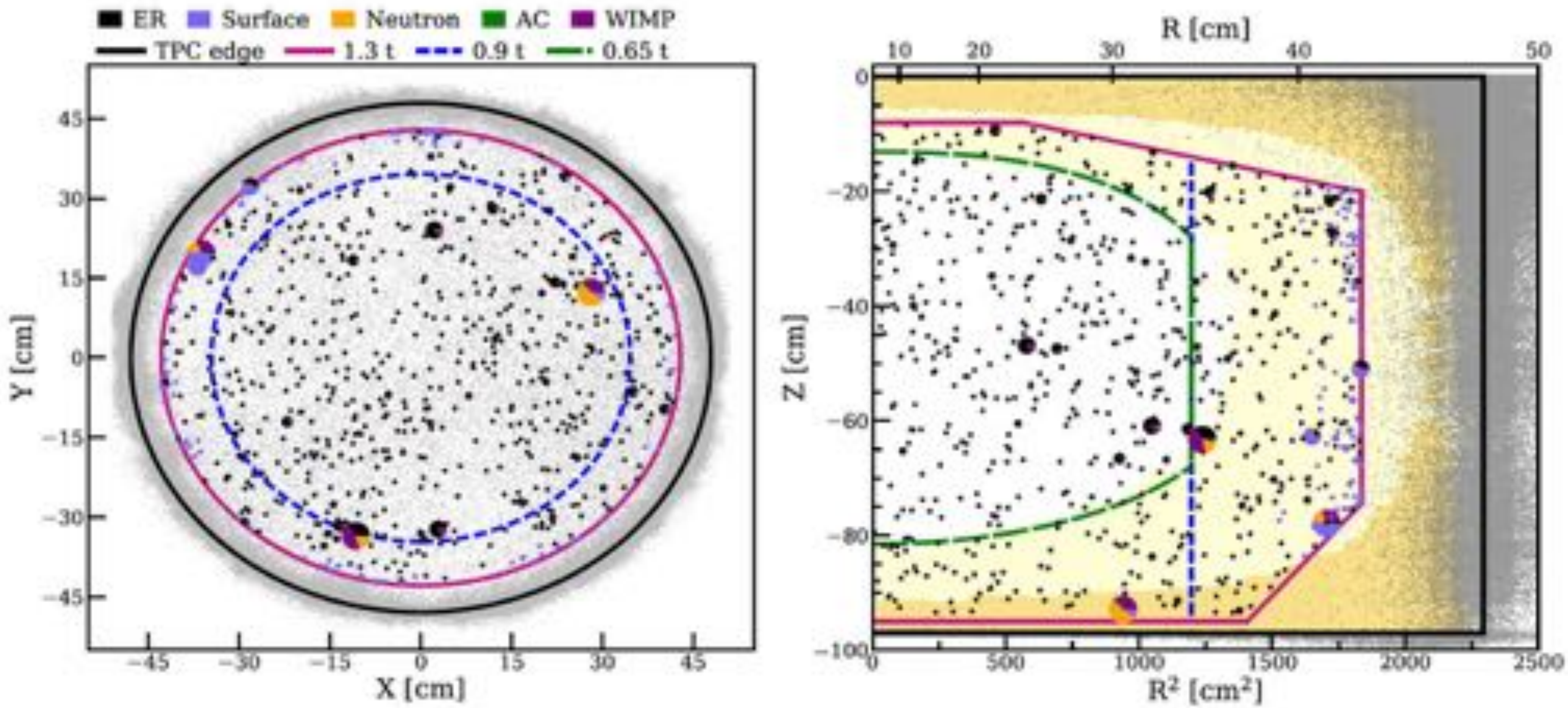


Dark Matter Search Results



- Results interpreted with unbinned profile likelihood analysis in cs1, cs2, R space
- Piechart indicate the relative probabilities of this event to be of a certain class for a best fit to a 200 GeV/c^2 WIMPs with a cross-secI on of 4.6 x 10^{-47} cm2

Spacial Distribution of Dark Matter Search Results

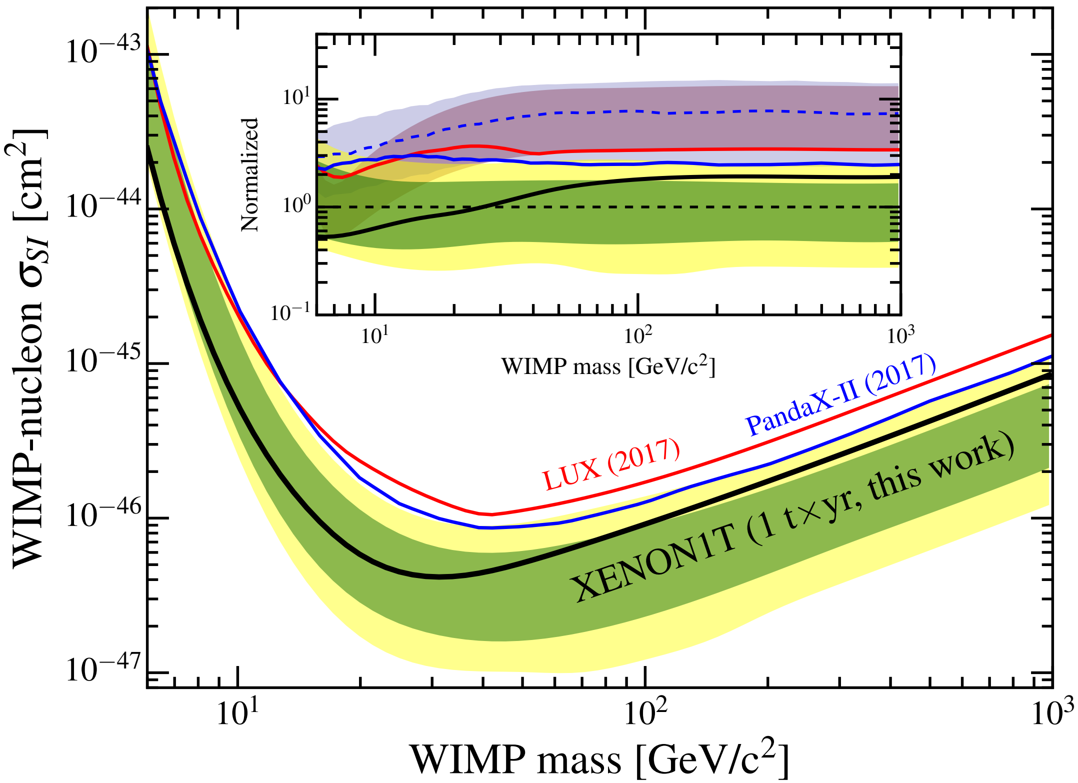


- Core volume to distinguish WIMPs over neutron background
- Yellow shaded regions display the 1σ (dark), and 2σ (light) probability density percentiles of the radiogenic neutron background component

XENON1T Results

- **Spin-independent WIMP-nucleon cross section**

Strongest exclusion limits (at 90% CL) on WIMPs > 6 GeV/c^2.



7 times better sensitivity compared to previous experiments (LUX, PANDAX-II)

World best limit:
First 1 ton x years exposure !

σ_{SI} < 4.1.10^{-47} cm^2 at 30 GeV/c^2

- **1 sigma upper fluctuation at higher WIMP masses**

No significant excess (>3 sigma) is observed.

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Phases of the XENON Program

XENON10
2005 – 2007
15 cm drift TPC
Total: 25 kg
Target: **14** kg
Fiducial: 5.4 kg

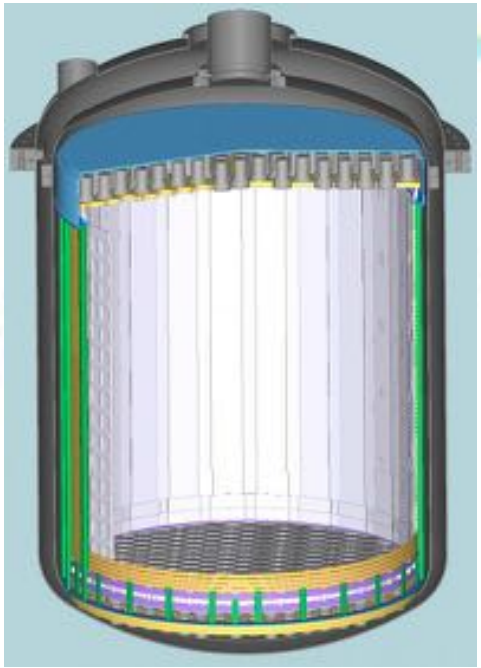
Achieved (2007)
$\sigma_{SI} = 8.8 \cdot 10^{-44}$ cm^2
@ 100 GeV/c^2

XENON100
2008 – 2016
30 cm drift TPC
Total: 161 kg
Target: **62** kg
Fiducial: 34/48 kg

Achieved (2016)
$\sigma_{SI} = 1.1 \cdot 10^{-45}$ cm^2
@ 55 GeV/c^2

XENON1T
2012 – 2019
100 cm drift TPC
Total: 3 200 kg
Target: **2 000** kg
Fiducial: 1 000 kg

Achieved (2018)
$\sigma_{SI} = 4.1 \cdot 10^{-47}$ cm^2
@ 30 GeV/c^2



XENONnT
2017 (R&D) – 2023
144 cm drift TPC
Total: 8 000 kg
Target: **6 000** kg
Fiducial: 4 500 kg

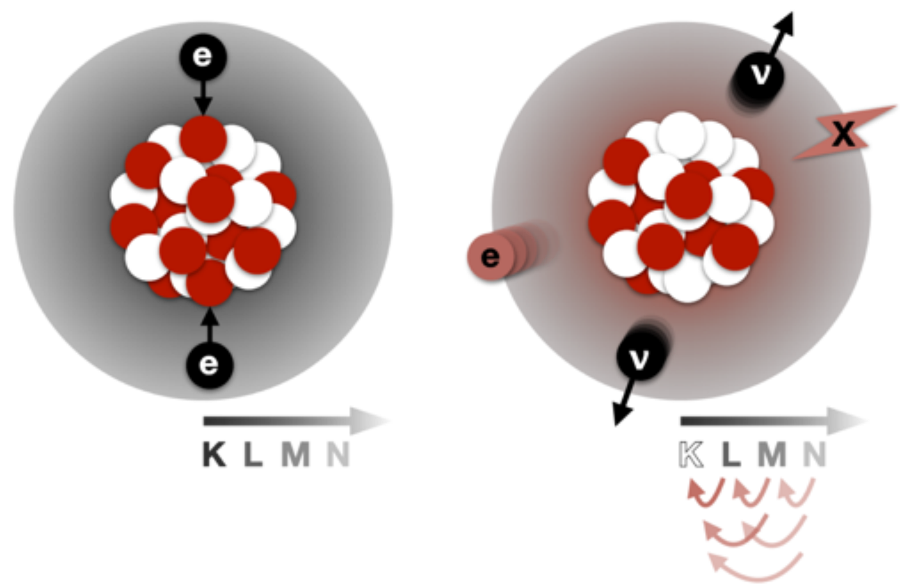
Projected (2022)
$\sigma_{SI} = 1.6 \times 10^{-48}$ cm^2
@ 50 GeV/c^2

Double electron capture (DEC) with ^{124}Xe

- $^{124}Xe + 2e^- \rightarrow {}^{124}Te + 2\nu_e$
- Vacancies on the K shell : Detectable cascade of X-rays and Auger electrons in the **keV-range (64.3 keV)**
- Large half-lives : $> 10^{12} . T_{univers}$
- Needs very **low background** experiment

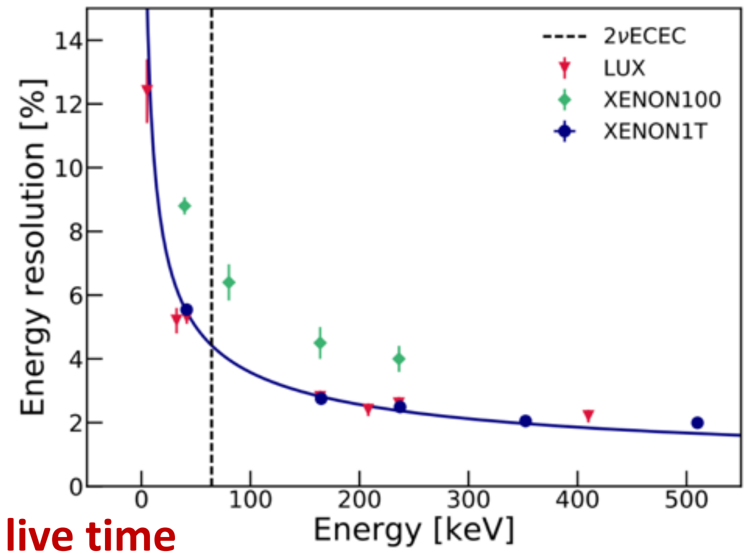
XENON1T

$^{124}Xe \sim 1$ kg / t



Double electron capture (DEC) with XENON1T

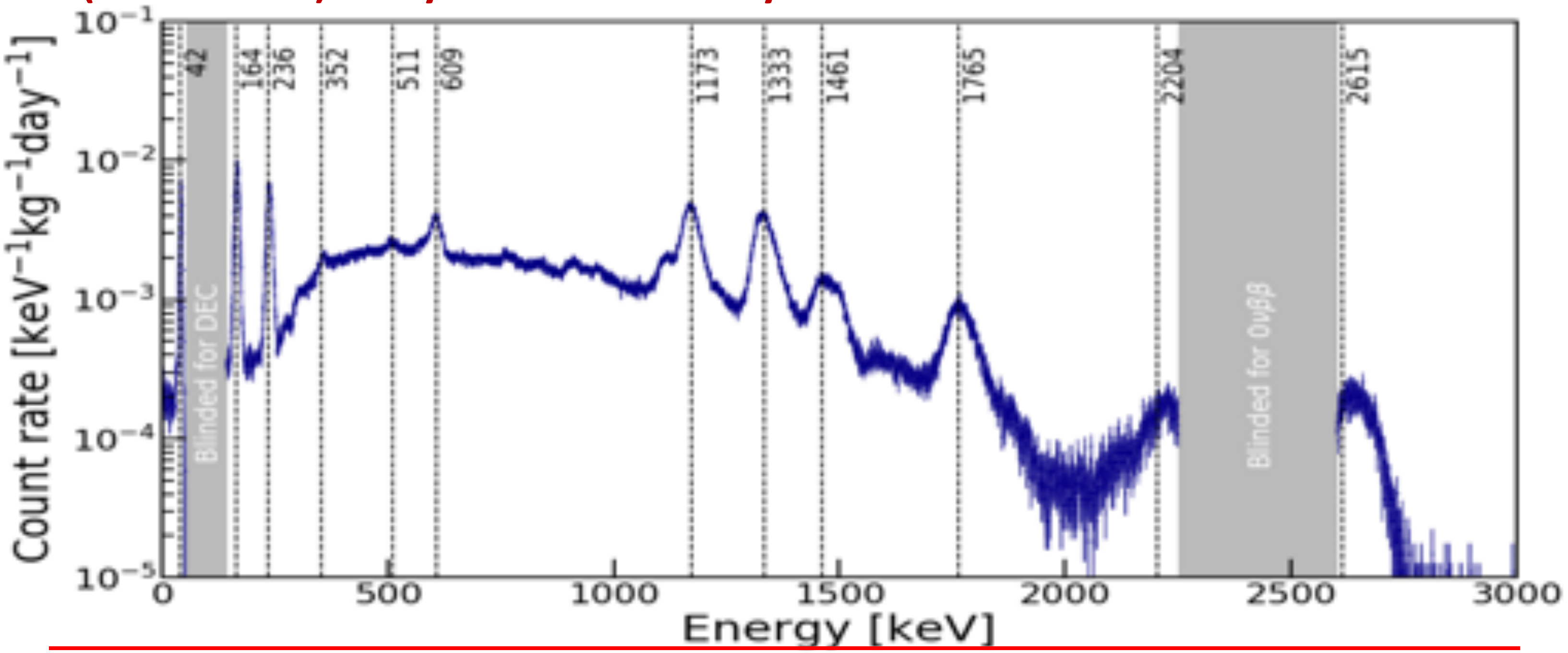
^{124}Xe ⇔ Double K-shell capture :
X-rays and Auger electrons
Single peak @64.3 keV



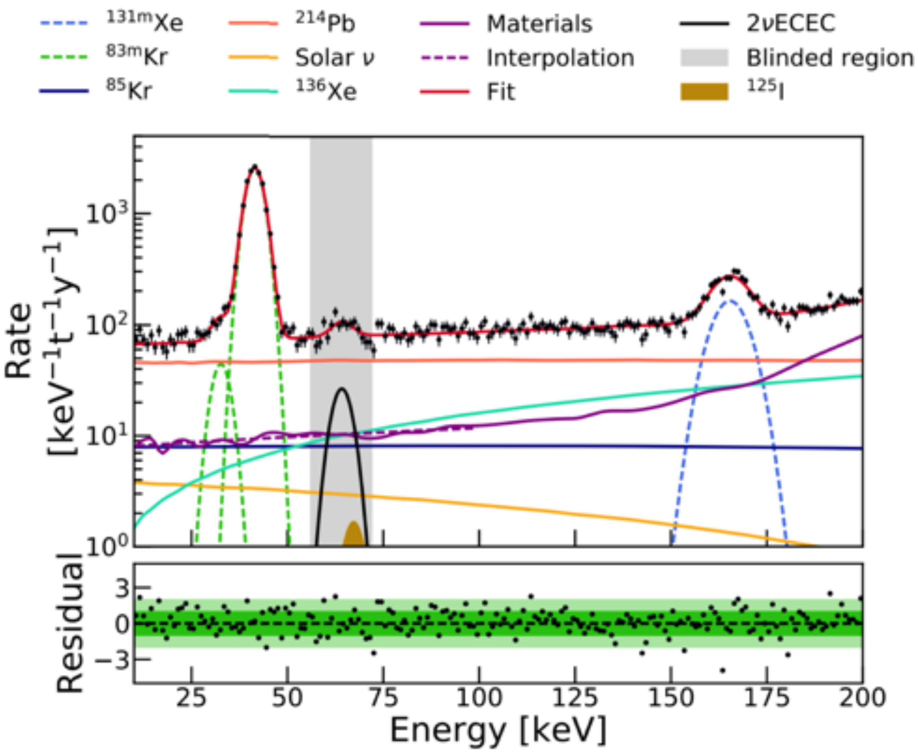
Energy resolution @64.3 keV:

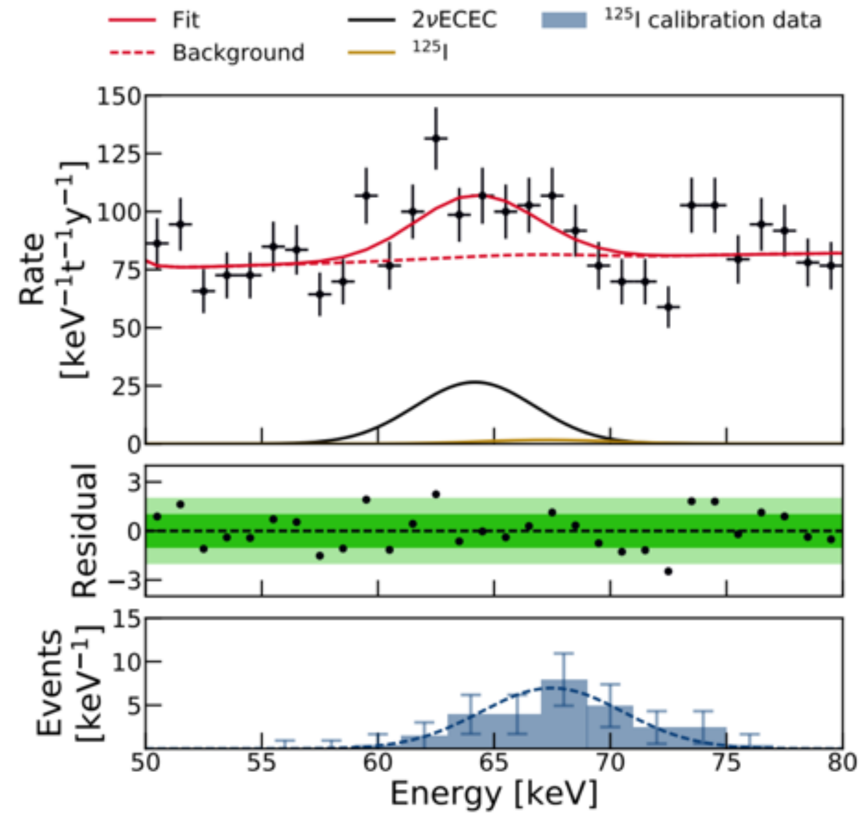
$$\frac{\sigma}{\mu} = (4.1 \pm 0.4)\ \%$$

Blinded (56 – 72 keV) analysis with 177.7 days of live time



Double electron capture (DEC) Results



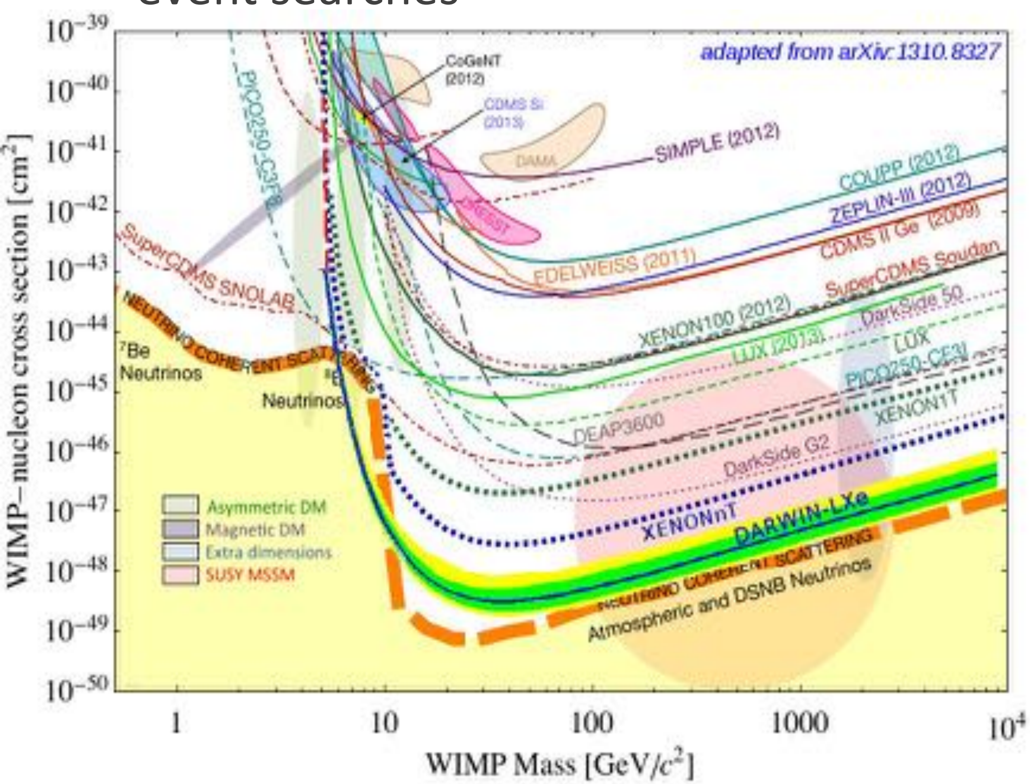


- Blinded region from 56 keV to 72 keV
- Ellipsoidal 1.5 t inner fiducial volume
- Peak at E = (64.2±0.5) keV and
  σ = (2.6±0.3) keV
- Significance 4.4σ

Half-life $T_{1/2}$ =
$(1.8 \pm 0.5_{stat} \pm 0.1_{sys}) \times 10^{22}$ y

Conclusions

- **Liquid Xenon is the world leading technique of DM searches**
- First multi-ton scale LXe-TPC successfully operated for more than 1 year
- **Strongest limit** on WIMP-nucleon SI cross-section above 6 GeV/c^2: minimum at $4.1 \cdot 10^{-47}$ cm^2 for a WIMP of 30 GeV/c^2
- Double Electron Capture detection : longest half-life ever measured directly
- Proof that xenon-based Dark Mater search experiments are sensitive for rare event searches



- ***Dark matter is highly searched***
- *Solution to an astrophysics / particle physics / Cosmological problem*

Other XENON1T analysis:

- S2 only analysis channel
- Annual modulation
- Migdal effect
- Light dark matter searches
- $0\nu\beta\beta$ of ^{136}Xe

Stay Tuned!