INFN
Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Experiment Heavy DM
(Liquid Noble Detectors)

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Theory Meets Experiments 2025:
Direct Detection Across Dark Matter Mass Ranges
GGI (Florence), 10-21 November 2025

Outline

General Characteristics of Signal and Backgrounds:

- WIMP signal features
- Main backgrounds (Natural Radioactivity, Cosmic Rays, Neutrinos, …)
- Techniques to mitigate backgrounds (screening, passive and active shield, distillation, ER/NR discrimination, pulse shape discrimination,…)
- Generalities on DM detectors

Properties of Noble liquids (Xenon e Argon) as particle detectors:

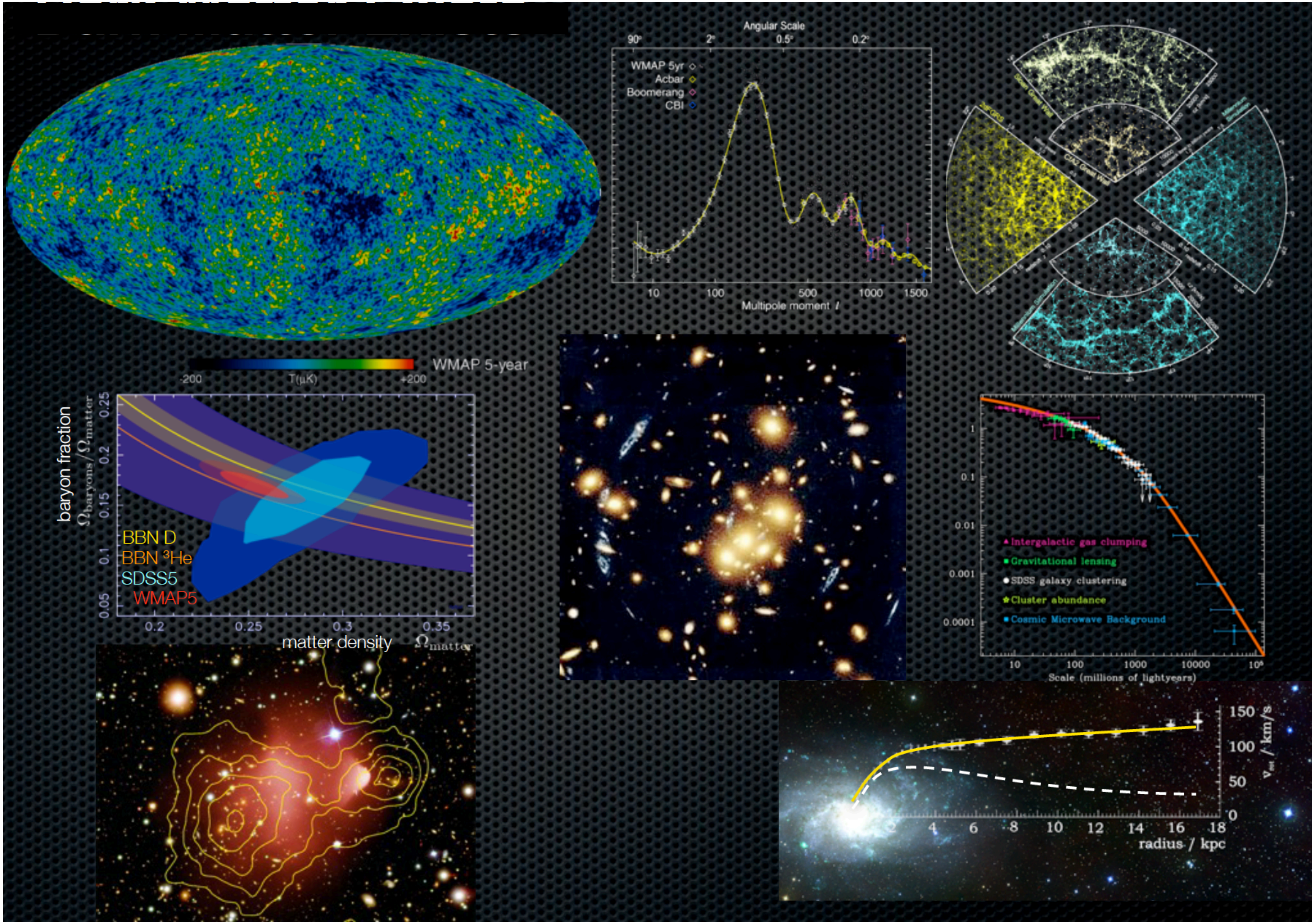
- Mechanism of scintillation, ionization, impact of impurities
- Different response in light and charge for different kind of particles: electron e nuclear recoil discrimination
- (Single and) Double Phase Time Projection Chambers
- Examples from state-of-the-art detectors

Suggested review papers:

- Dark matter direct-detection experiments (T. Marrodan et al.) https://arxiv.org/abs/1509.08767
- Dark matter direct-detection of classical WIMPs (J. Cooley) https://arxiv.org/pdf/2110.02359.pdf
- PDG Chapter on DM https://pdg.lbl.gov/2025/reviews/astro-cosmo.html
- APPEC Committee report (2021) https://arxiv.org/abs/2104.07634

* many thanks to
E. Aprile, L. Baudis, G. Bertone, G. Fiorillo, T. Marrodan, K. Palladino, K. Ni, M. Schumann
for useful materials used in these lectures

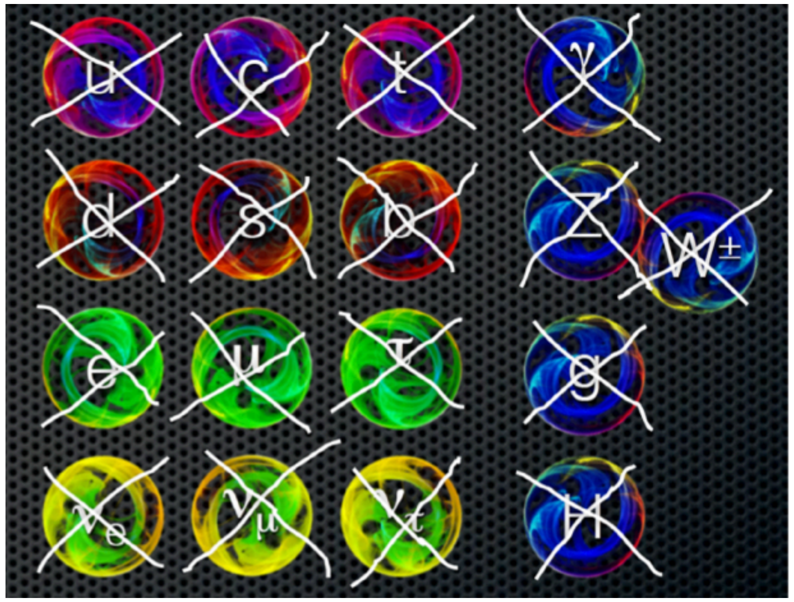
Dark Matter exists



What is Dark Matter made of ?

An elementary particle?

- Massive → explain gravitational effects
- Neutral → no EM interaction & Weakly interacting at most
- Stable or long-lived → not to have decayed by now
- Cold (moving non-relativistically) or warm → structure formation



In the standard model of particle physics:
Neutrino fulfil most
but it is a hot dark matter candidate

→ Models beyond SM typically predict NEW particles

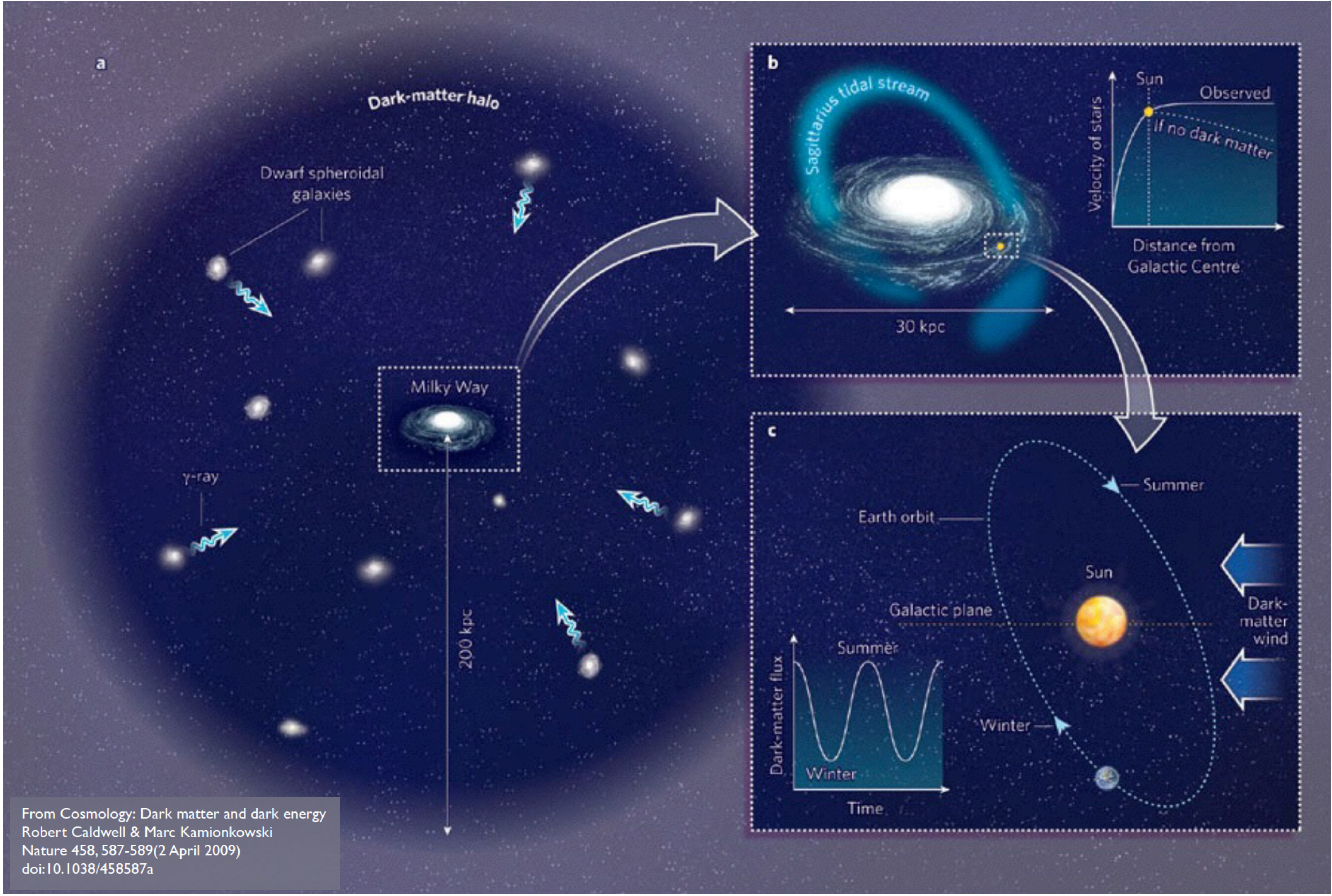
Neutralino in Supersymmetry, gravitino, Axion, LKP in extra dimensions, Sterile neutrino, Super-heavy dark matter and many others

WIMP

(**W**eakly **I**nteracting **M**assive **P**article)

Characteristics of DM Signal & Backgrounds

We live in a dark matter halo

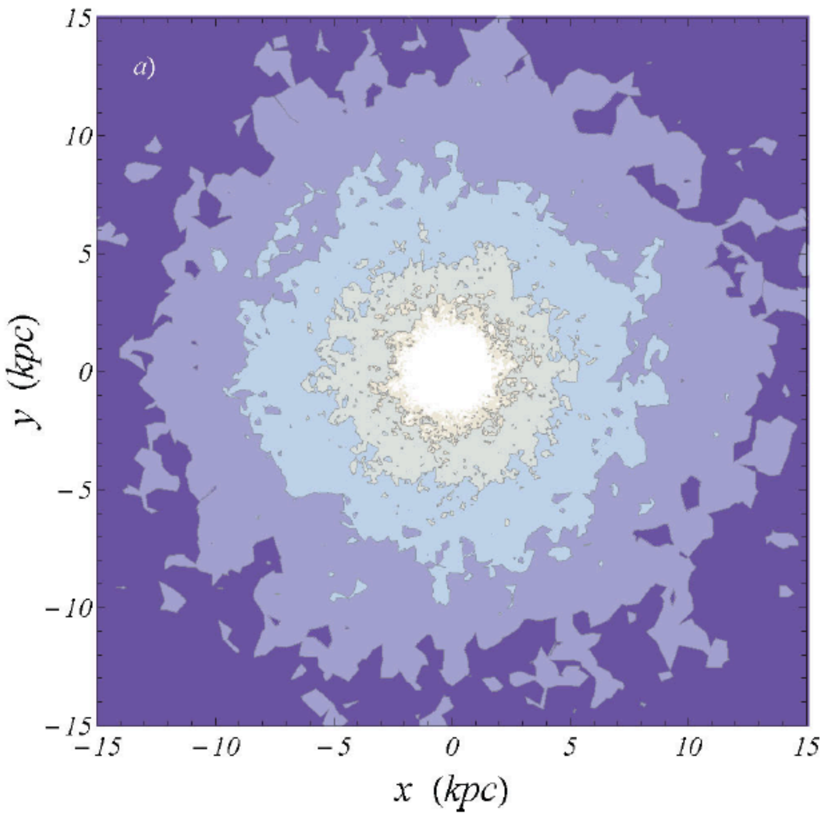


From Cosmology: Dark matter and dark energy
Robert Caldwell & Marc Kamionkowski
Nature 458, 587-589(2 April 2009)
doi:10.1038/458587a

WIMP density and velocity distribution

WIMPs in the galactic halo

Density map of the dark matter halo
rho = [0.1, 0.3, 1.0, 3.0] GeV cm^{-3}

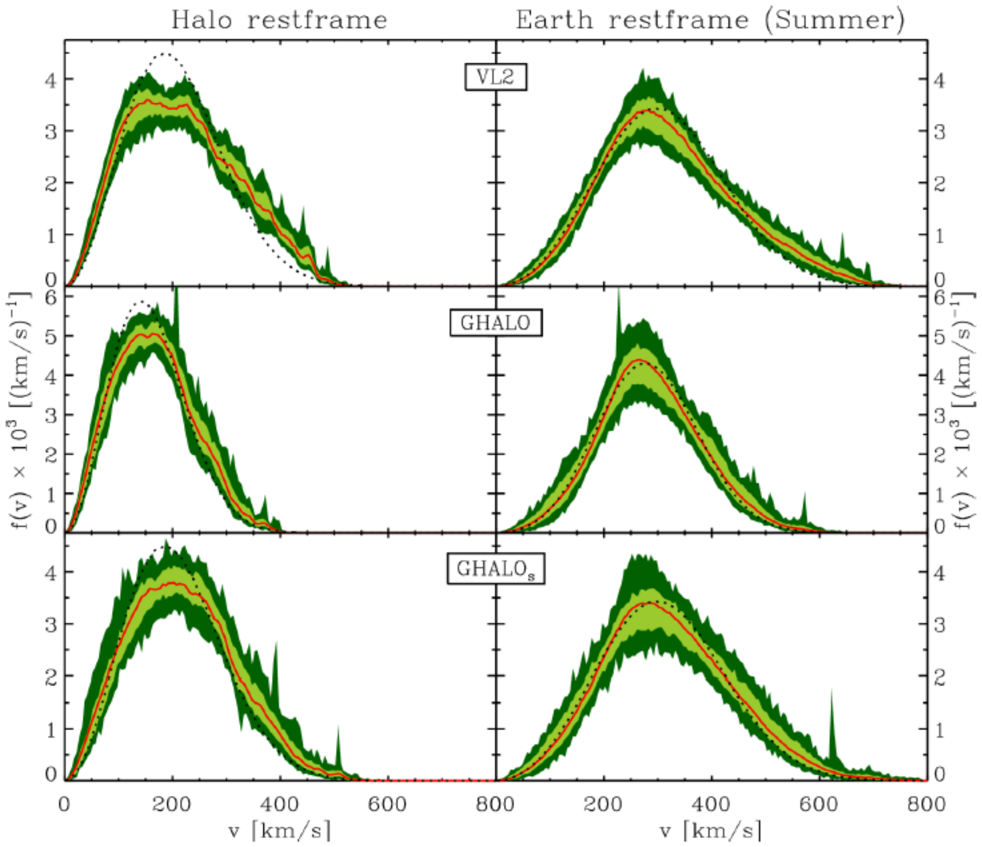


High-resolution cosmological simulation with baryons: F.S. Ling et al, JCAP02 (2010) 012

$$\rho_{local} \sim \cancel{0.3}\,\mathrm{GeV}\cdot\mathrm{cm}^{-3}$$

0.47

Velocity distribution of WIMPs in the galaxy

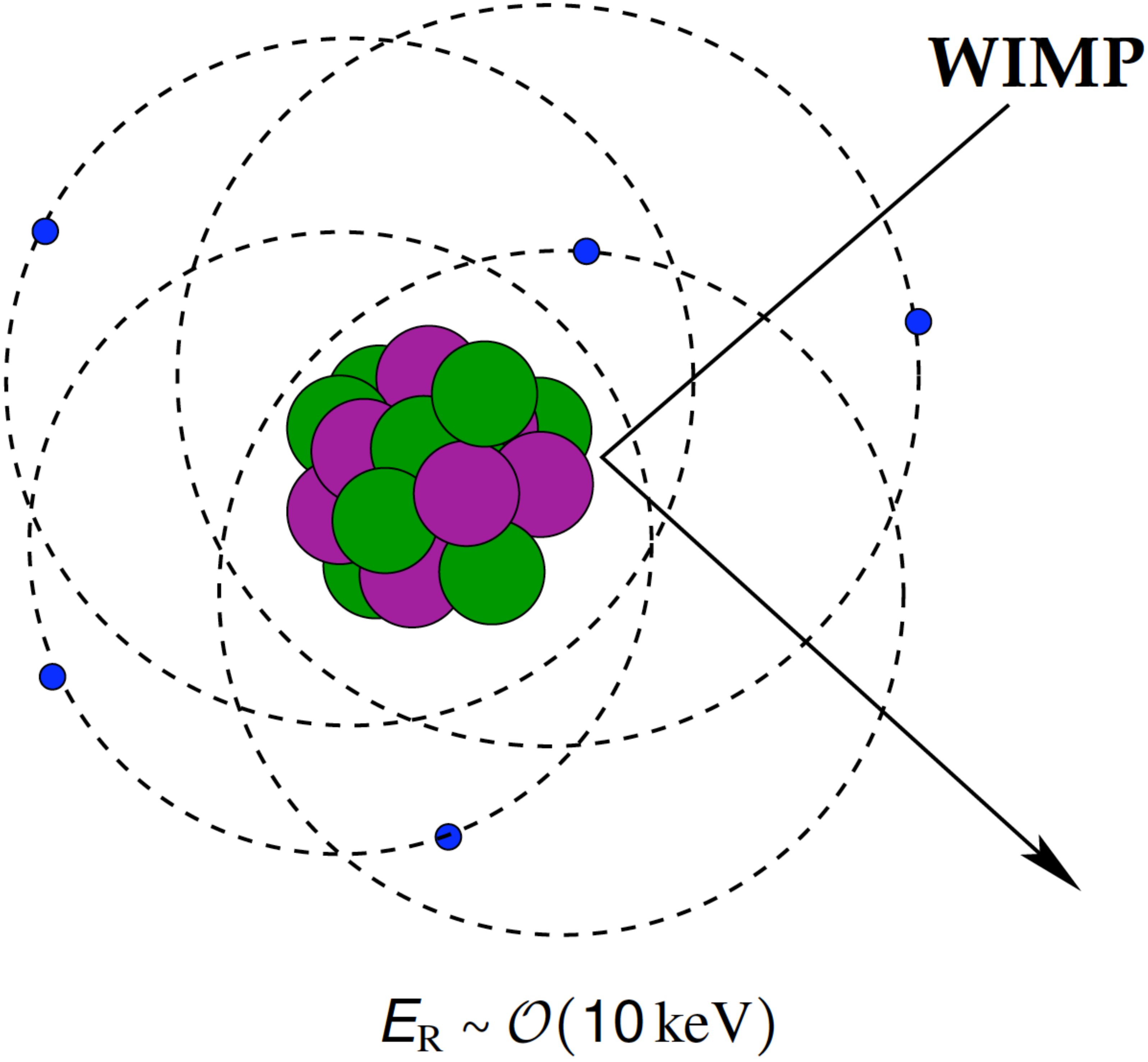


M. Kuhlen et al, JCAP02 (2010) 030

From cosmological simulations of galaxy formation: departures from the simplest case of a Maxwell-Boltzmann distribution

In direct detection experiments, mostly a simple MB distribution, truncated at v_{esc}, is used in the sensitivity calculation

Direct Dark Matter Detection



$$R \propto N_T \frac{\rho_0}{m_X} \sigma \langle v \rangle$$

$E_R \sim \mathcal{O}(10\,\mathrm{keV})$

Expected Rates

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v},t) \cdot \frac{d\sigma}{dE}(E,v)\, \mathrm{d}^3 v$$

Astrophysical parameters:

- ρ_0 = local density of the dark matter in the Milky Way
- $f(\mathbf{v},t)$ = WIMP velocity distribution

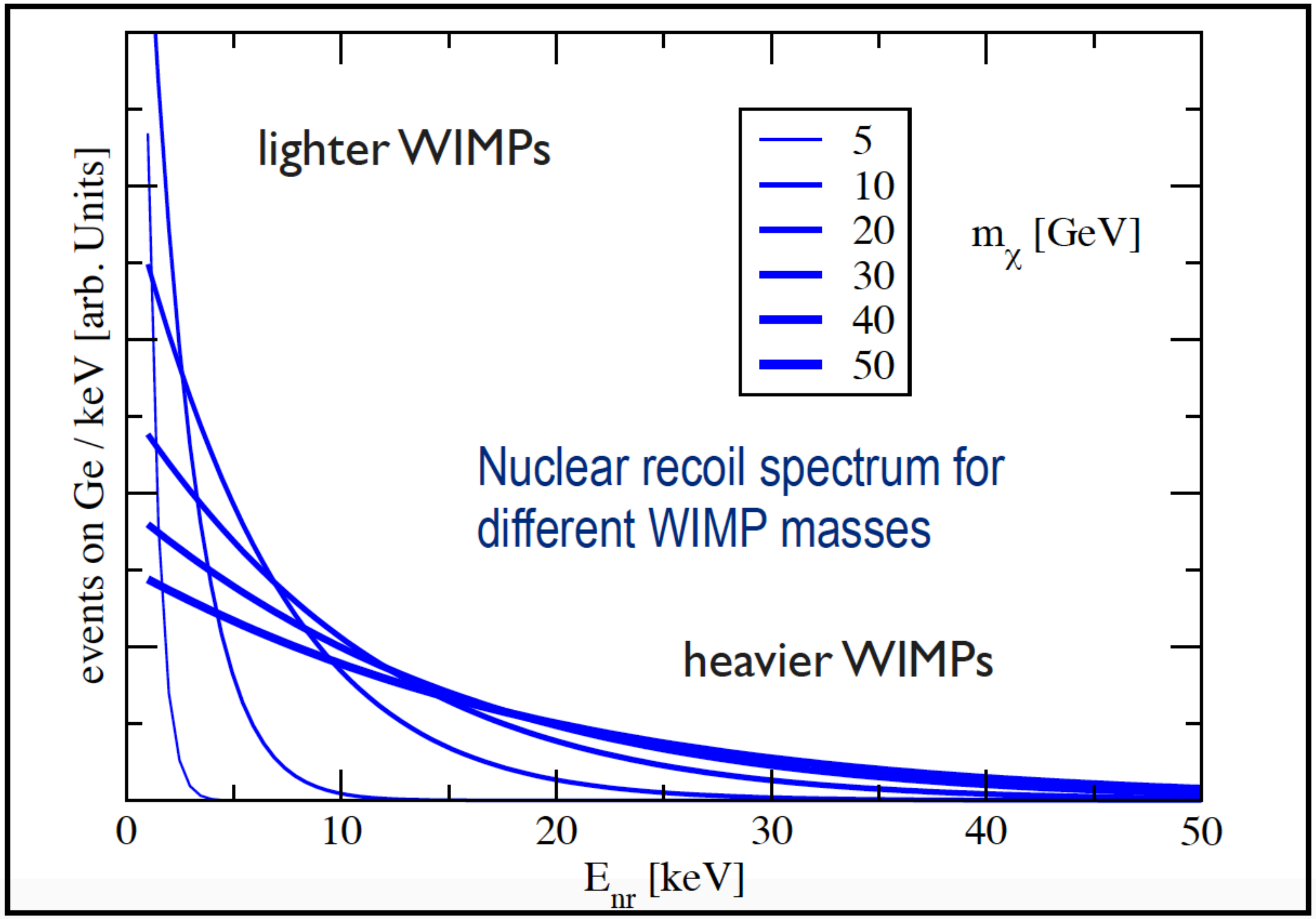
Parameters of interest:

- m_χ = WIMP mass ($\sim 100\,\mathrm{GeV}/c^2$)
- σ = WIMP-nucleus elastic scattering cross section
  - Spin-independent interactions: coupling to nuclear mass
  - Spin-dependent interactions: coupling to nuclear spin

Nuclear Recoil Energy Spectrum

Rate after integration over WIMP velocity distribution

$$R \sim 0.13 \, \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$



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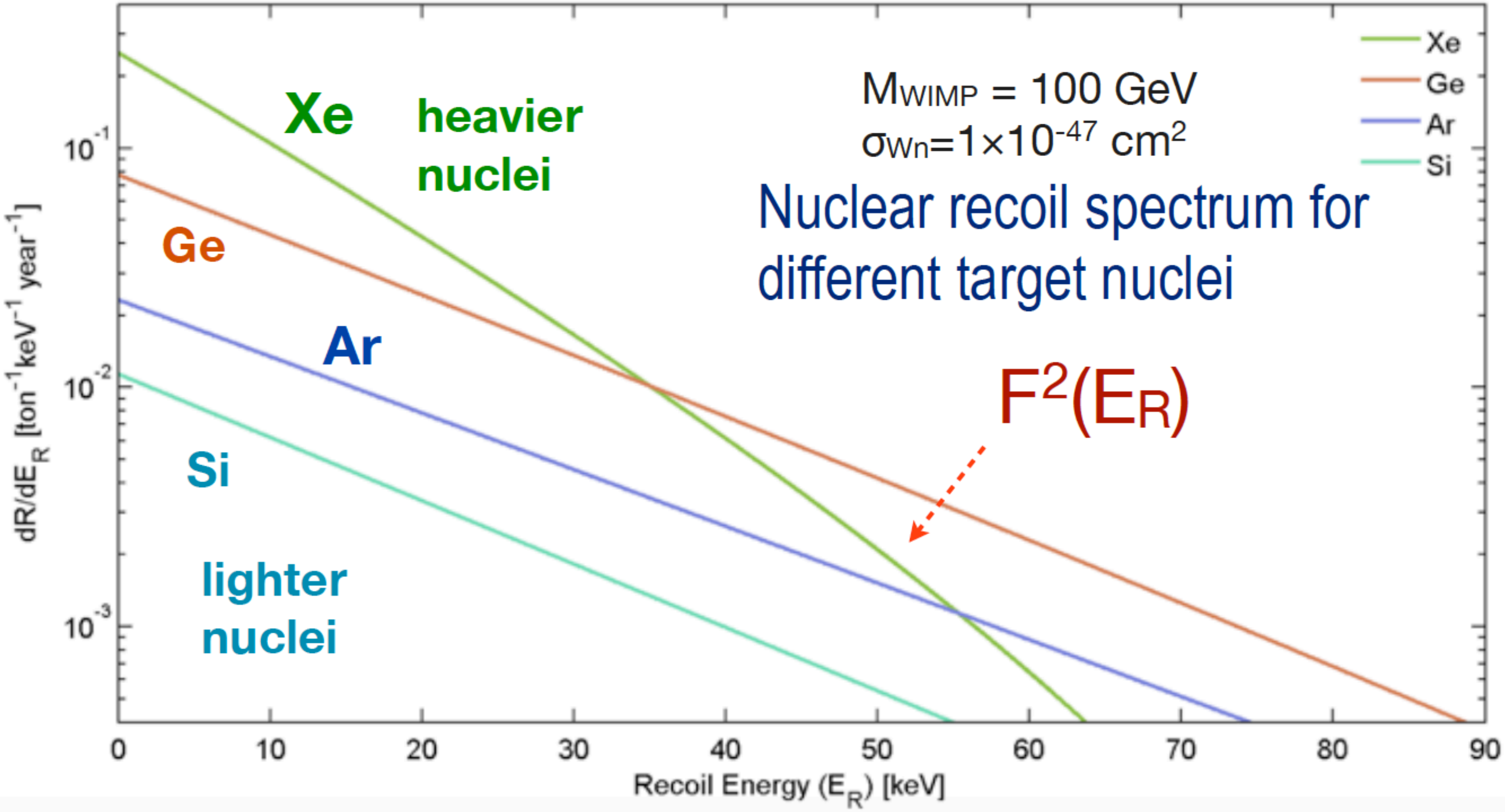
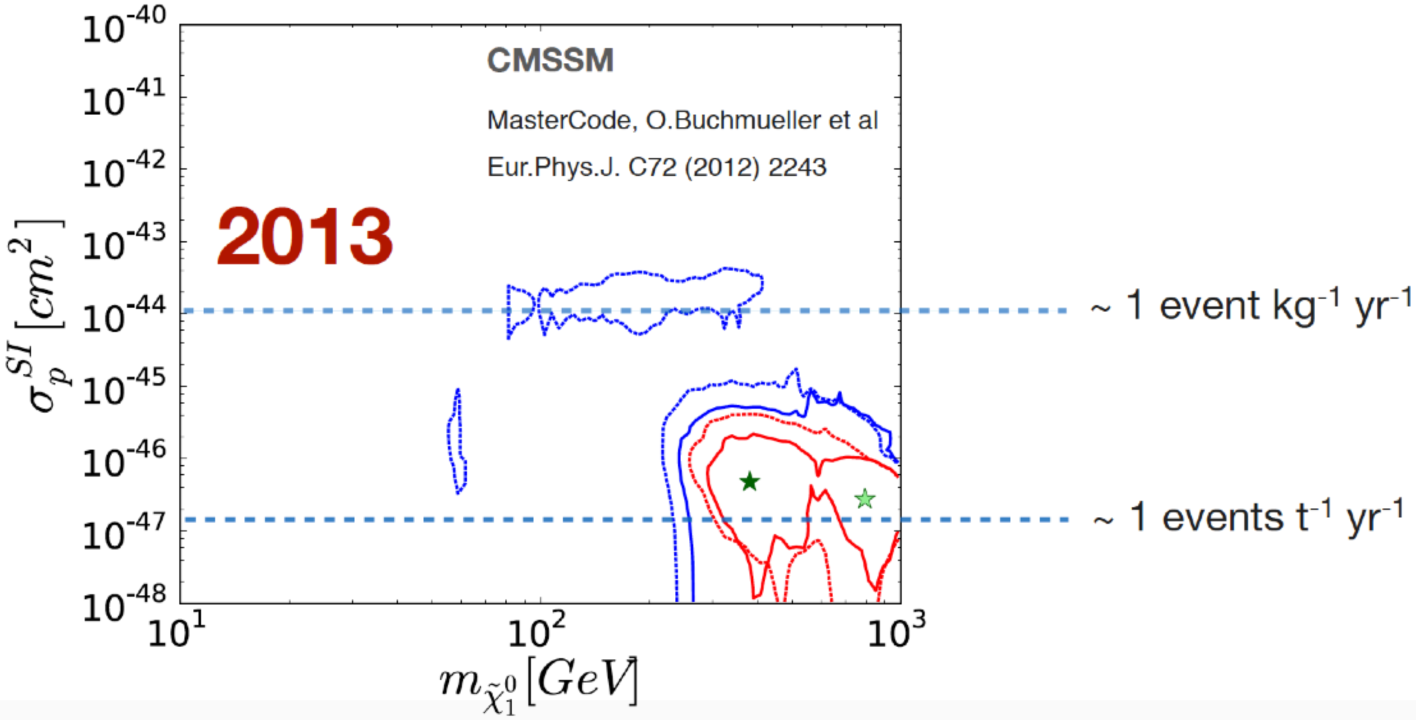


Nuclear recoil spectrum for different target nuclei

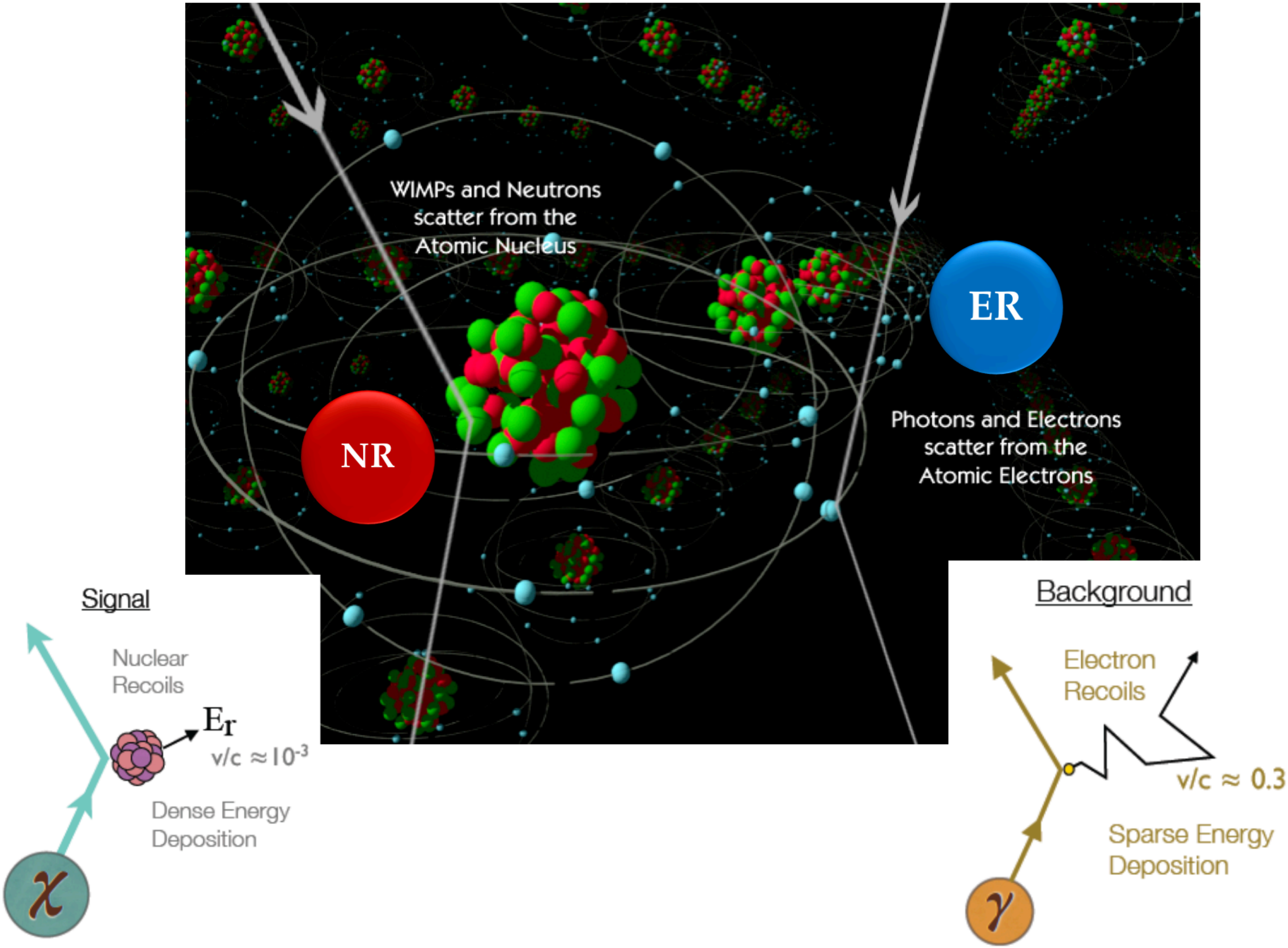
Detector requirements and signatures

- Requirements for a dark matter detector
  - Large detector mass
  - Low energy threshold ~ sub-keV to few keV's
  - Very low background and/or background discrimination
  - Long term stability

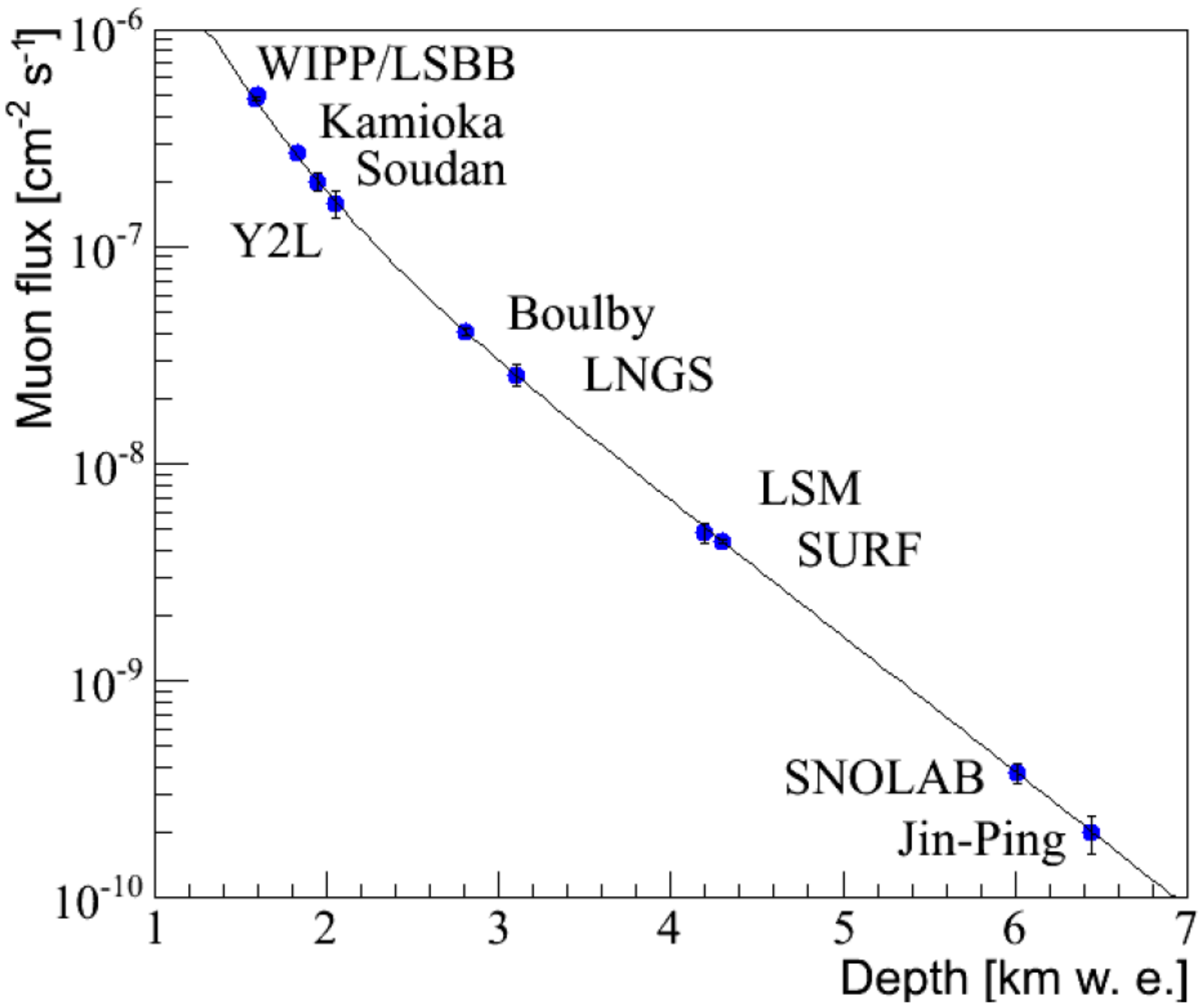
…a needle in a haystack



Backgrounds: Electron & Nuclear Recoils



Underground laboratories



- WIPP in USA (DMTPC)
- LSBB in France (SIMPLE)
- Kamioka in Japan (XMASS, NEWAGE)
- Soudan in USA (SuperCDMS, GoGeNT)
- Y2L in Corea (KIMS)
- Boulby in UK (DRIFT, ZEPLIN)
- LNGS in Italy (XENON, DAMA, Cresst, DarkSide)
- LSM in France (Edelweiss, MIMAC)
- SURF in USA (LUX)
- SNOLAB in Canada (DEAP/CLEAN, PICASSO, COUPP)
- Jin-Ping in China (PandaX, CDEX)

Underground laboratories

courtesy of Laura Baudis

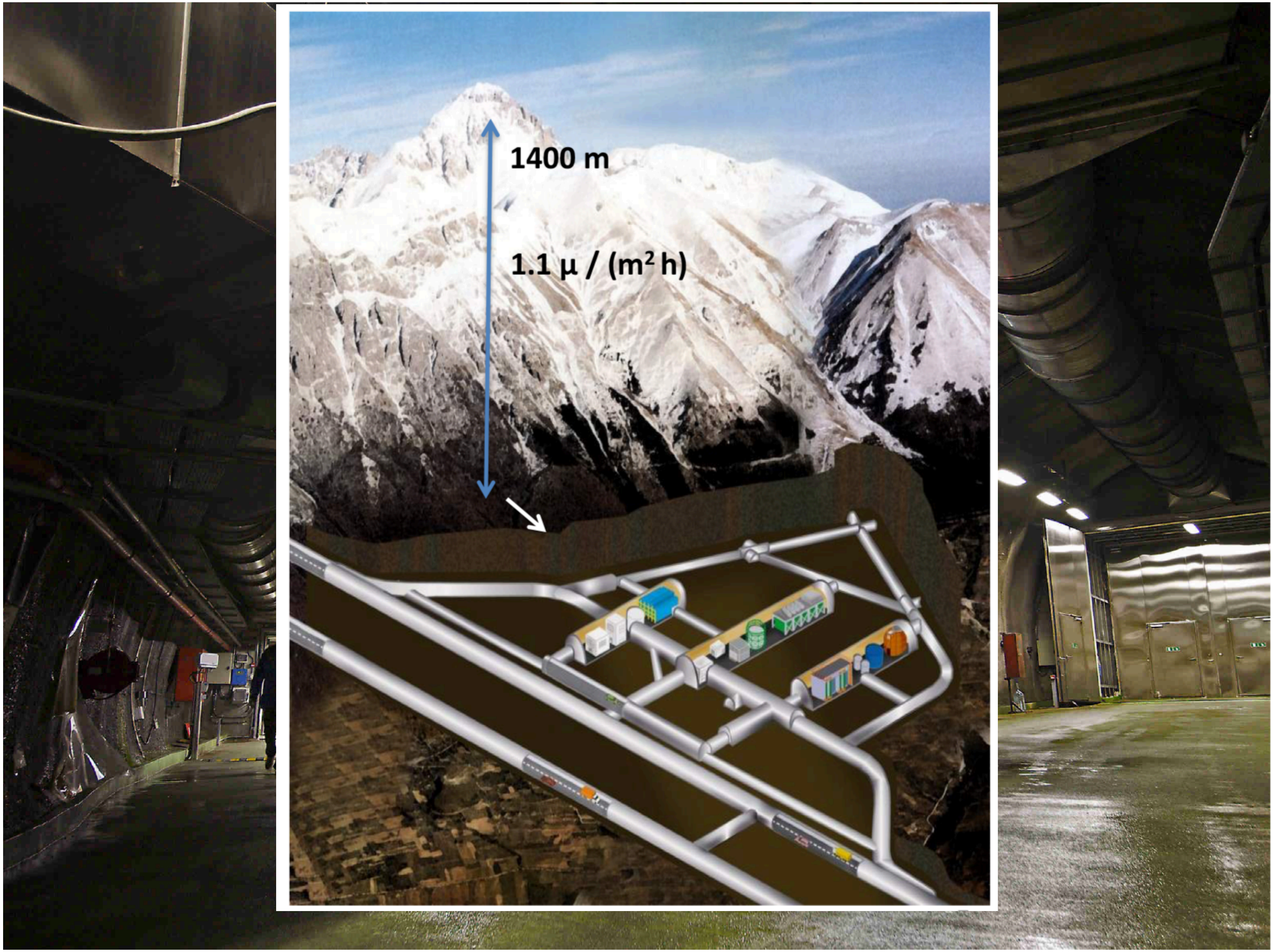
Laboratori Nazionali del Gran Sasso

LNGS


Laboratori Nazionali del Gran Sasso

LNGS

LNGS



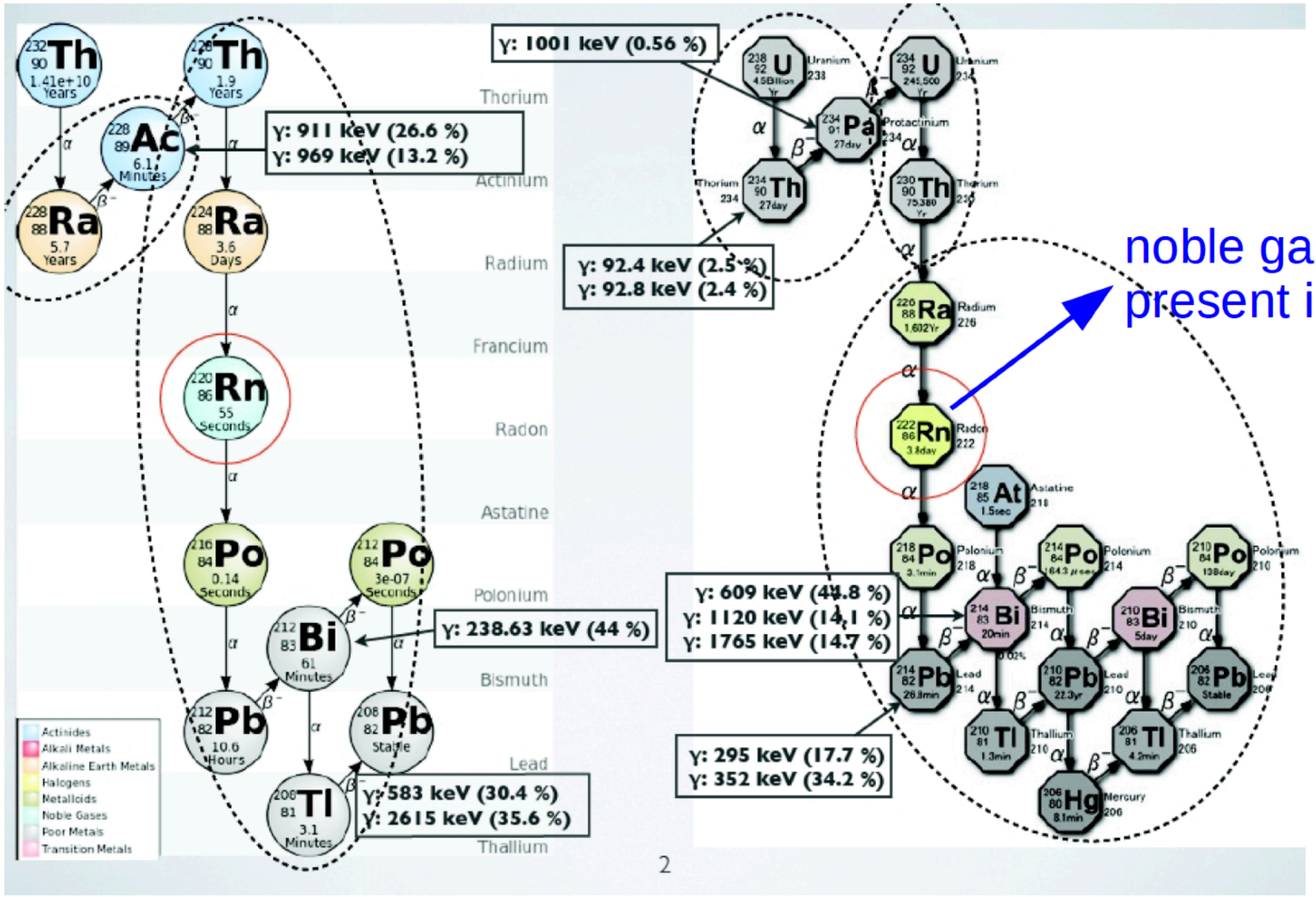
Natural Radioactivity

- Radioactivity is everywhere:

  Q: Radioactivity of a human body?
  → 4 kBq (C-14), 4 kBq (K-40: e^- + 400 γ [1.4 MeV], +8000ν)

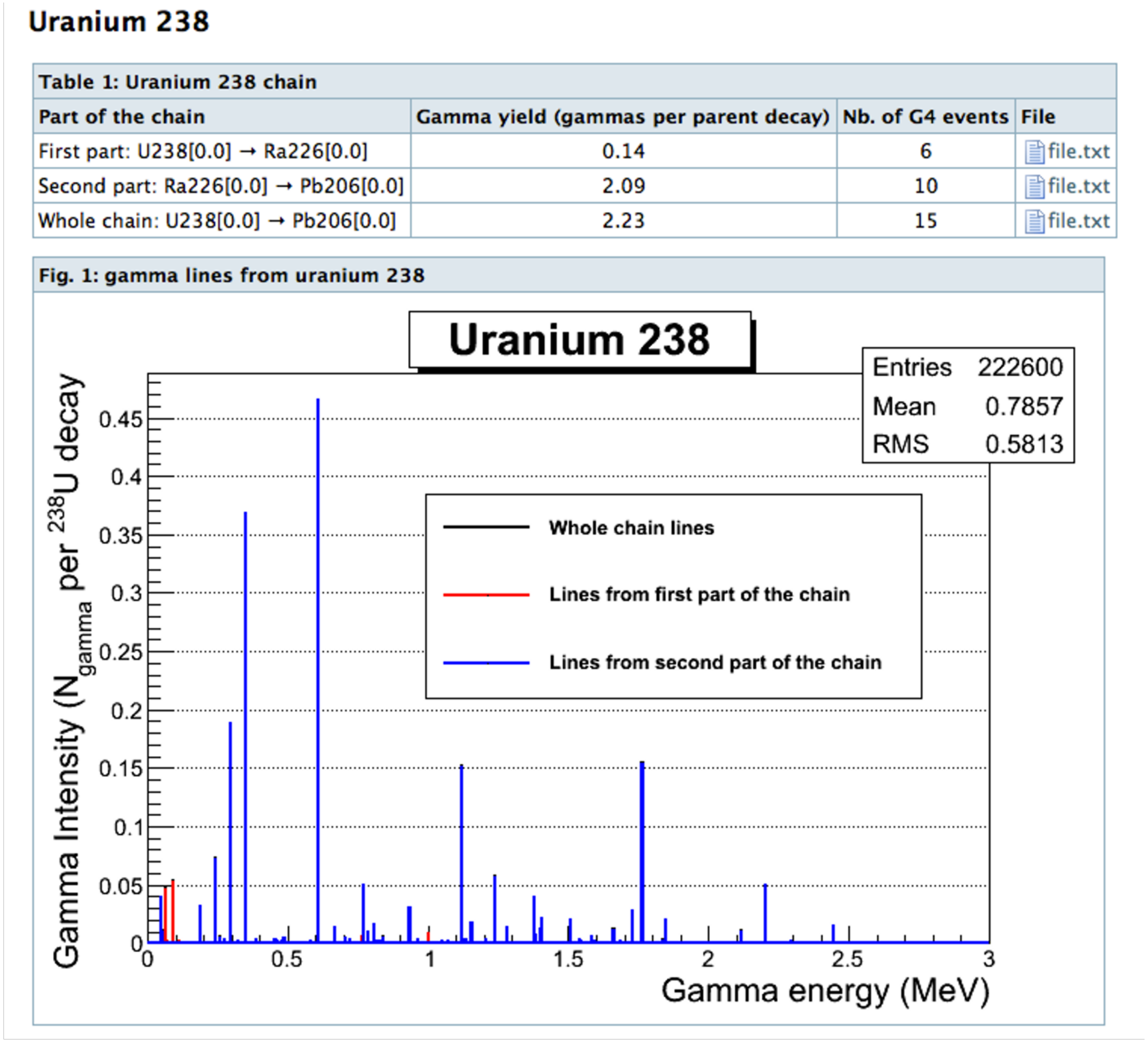
  Q: Rn atoms escaping the ground?
  → 7000 s^{-1} m^{-2}

Q: Number of Pu atoms in 1kg of soil?
→ 10 million (transmutation of U-238 by CR neutrons)



noble gas, present in air

Natural Radioactivity



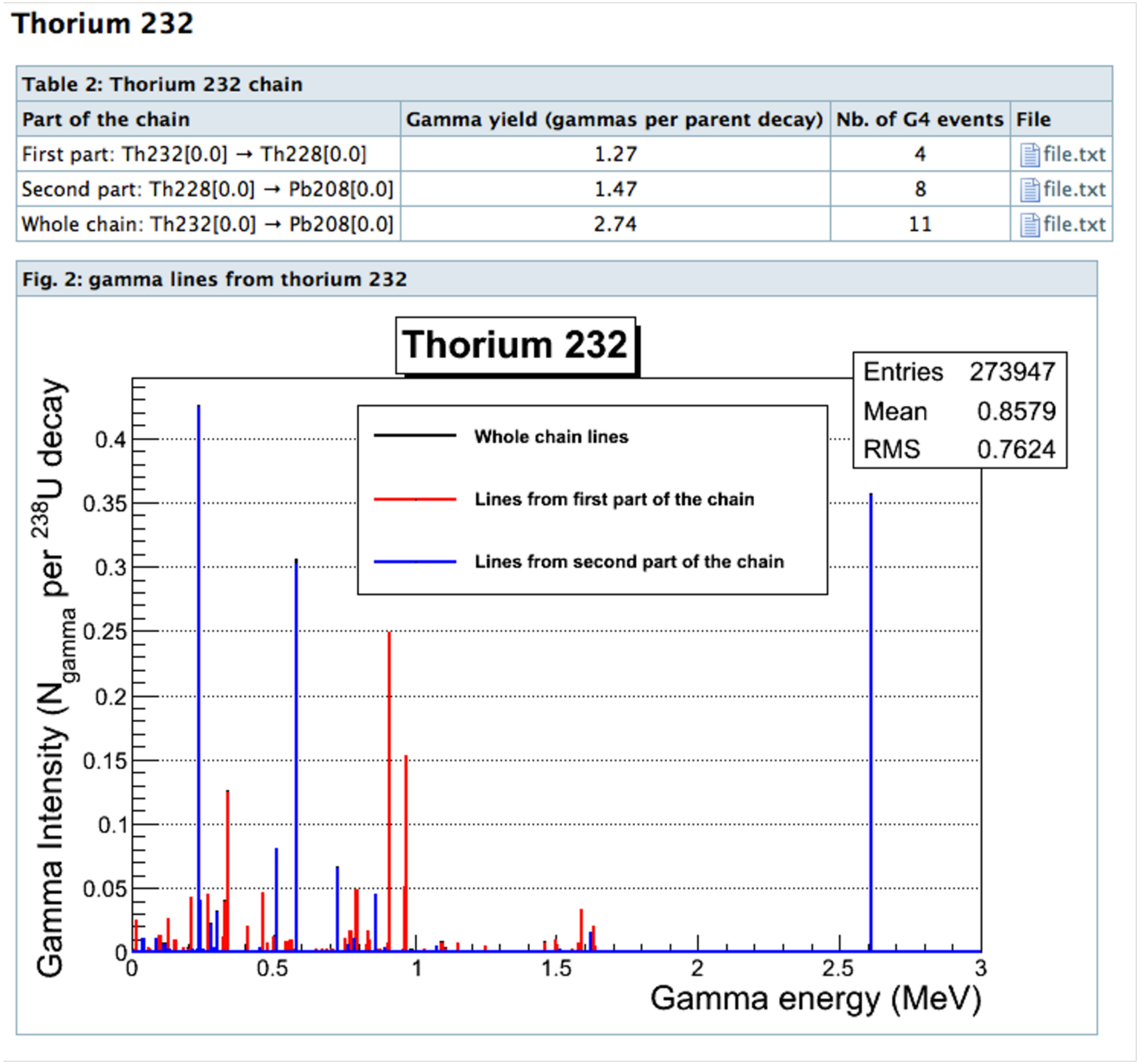
Uranium 238

Table 1: Uranium 238 chain

Part of the chain	Gamma yield (gammas per parent decay)	Nb. of G4 events	File
First part: U238[0.0] → Ra226[0.0]	0.14	6	file.txt
Second part: Ra226[0.0] → Pb206[0.0]	2.09	10	file.txt
Whole chain: U238[0.0] → Pb206[0.0]	2.23	15	file.txt

Fig. 1: gamma lines from uranium 238

Natural Radioactivity



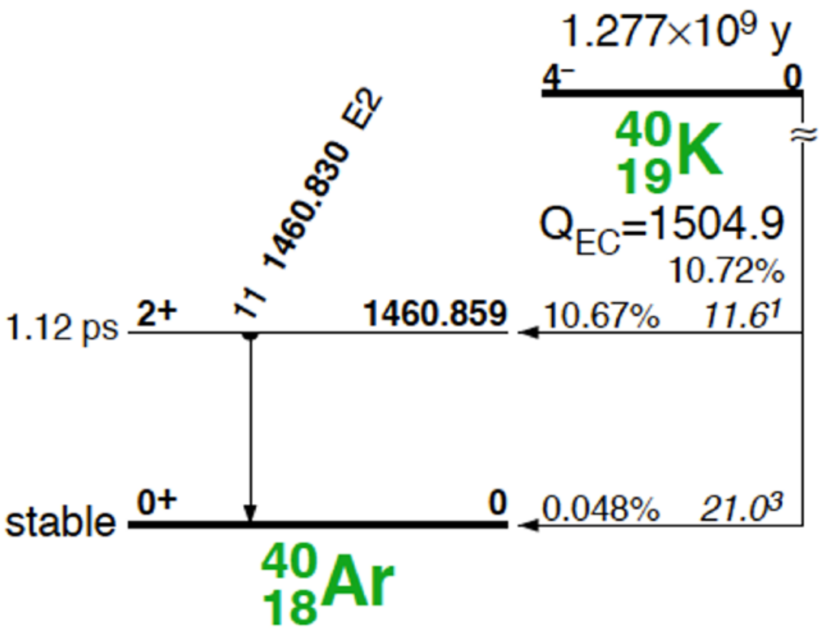
Thorium 232

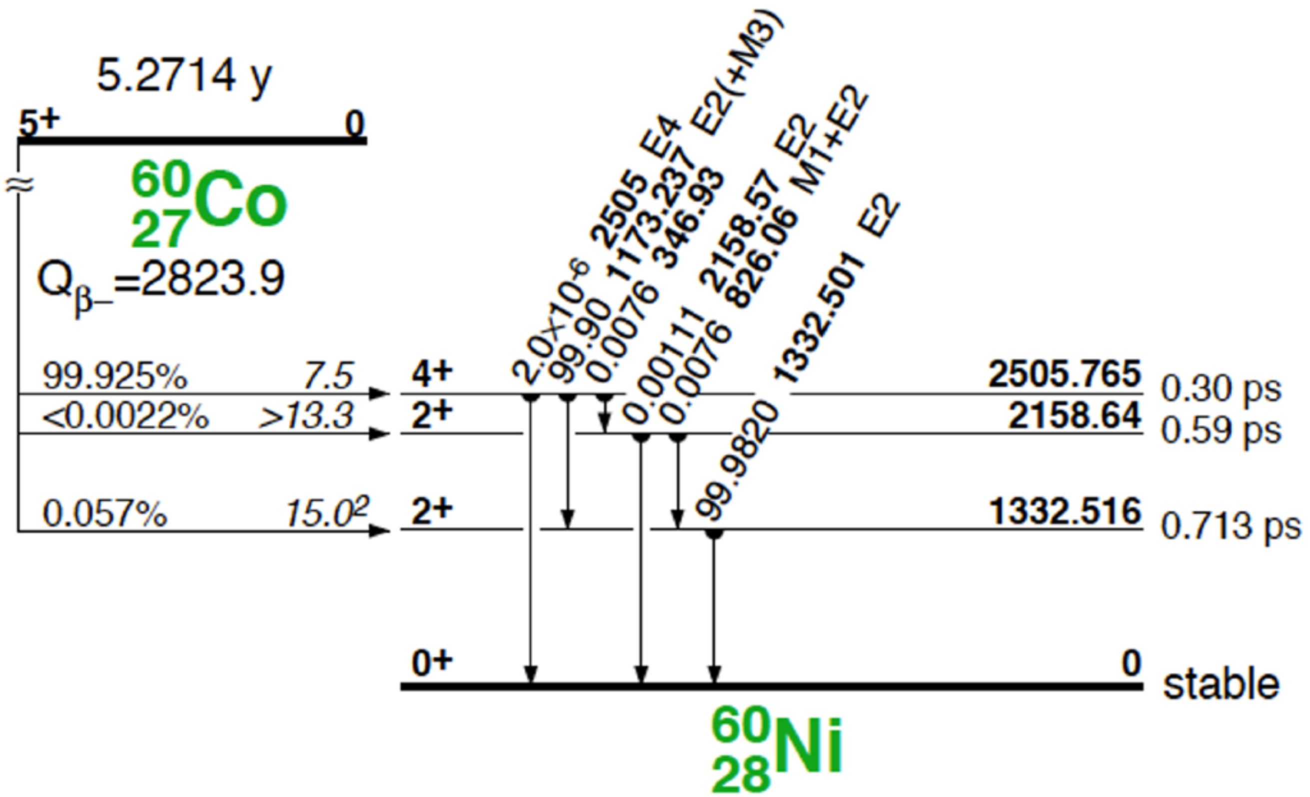
Table 2: Thorium 232 chain

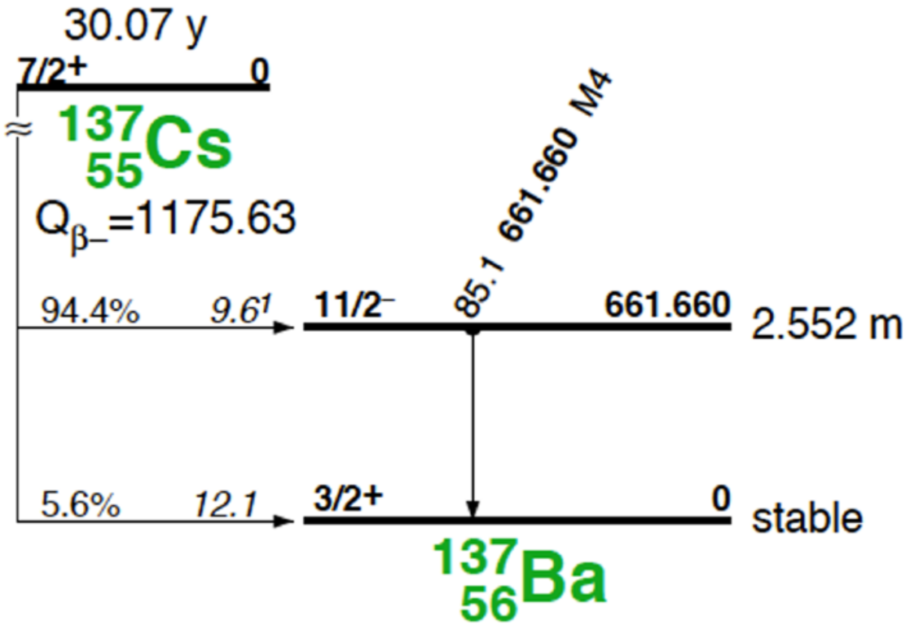
Part of the chain	Gamma yield (gammas per parent decay)	Nb. of G4 events	File
First part: Th232[0.0] → Th228[0.0]	1.27	4	file.txt
Second part: Th228[0.0] → Pb208[0.0]	1.47	8	file.txt
Whole chain: Th232[0.0] → Pb208[0.0]	2.74	11	file.txt

Fig. 2: gamma lines from thorium 232

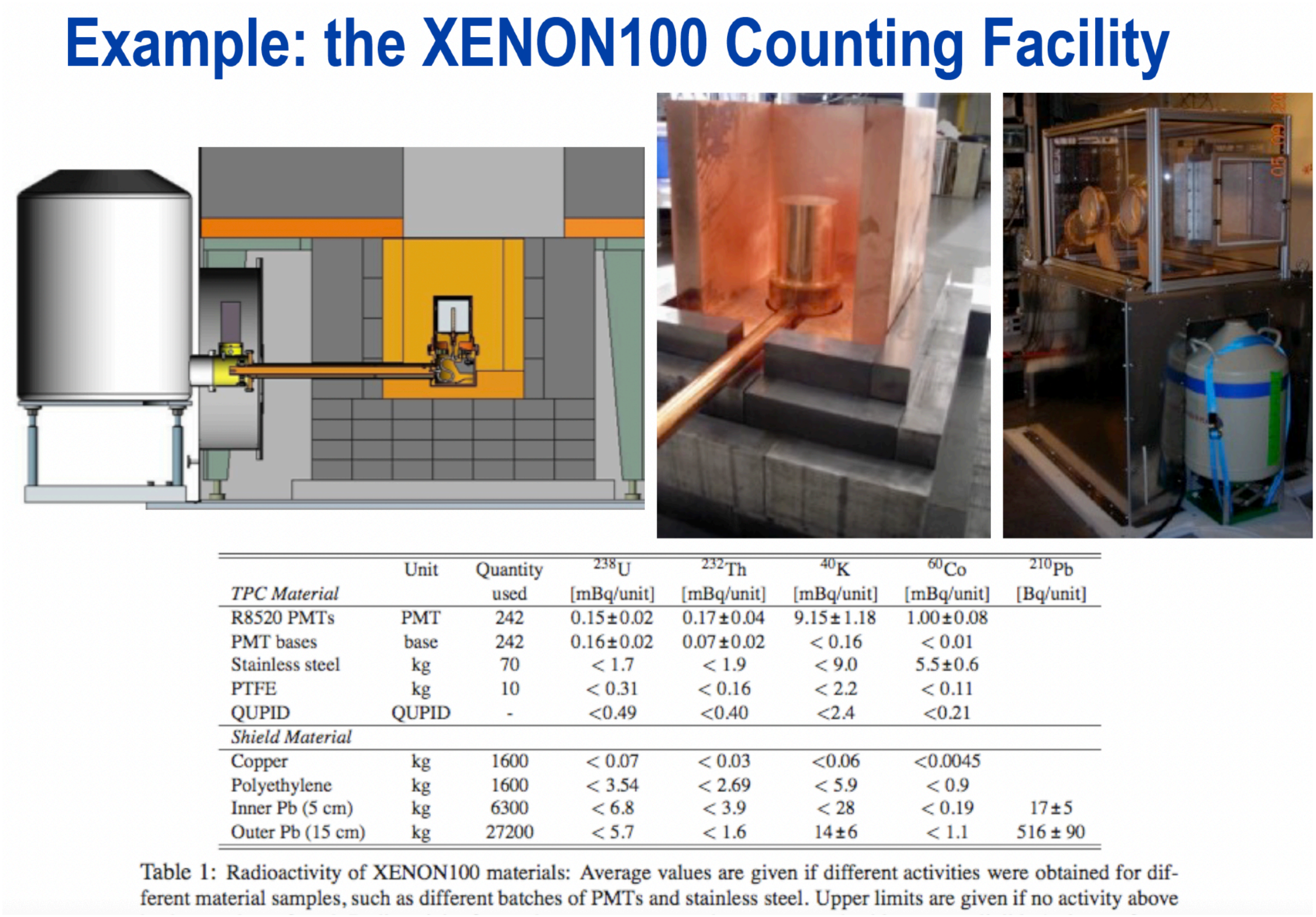
Natural Radioactivity







Material Screening



Example: the XENON100 Counting Facility

TPC Material	Unit	Quantity used	^{238}U [mBq/unit]	^{232}Th [mBq/unit]	^{40}K [mBq/unit]	^{60}Co [mBq/unit]	^{210}Pb [Bq/unit]
R8520 PMTs	PMT	242	0.15±0.02	0.17±0.04	9.15±1.18	1.00±0.08	
PMT bases	base	242	0.16±0.02	0.07±0.02	< 0.16	< 0.01	
Stainless steel	kg	70	< 1.7	< 1.9	< 9.0	5.5±0.6	
PTFE	kg	10	< 0.31	< 0.16	< 2.2	< 0.11	
QUPID	QUPID	-	<0.49	<0.40	<2.4	<0.21	
Shield Material							
Copper	kg	1600	< 0.07	< 0.03	<0.06	<0.0045	
Polyethylene	kg	1600	< 3.54	< 2.69	< 5.9	< 0.9	
Inner Pb (5 cm)	kg	6300	< 6.8	< 3.9	< 28	< 0.19	17±5
Outer Pb (15 cm)	kg	27200	< 5.7	< 1.6	14±6	< 1.1	516 ± 90

Table 1: Radioactivity of XENON100 materials: Average values are given if different activities were obtained for different material samples, such as different batches of PMTs and stainless steel. Upper limits are given if no activity above

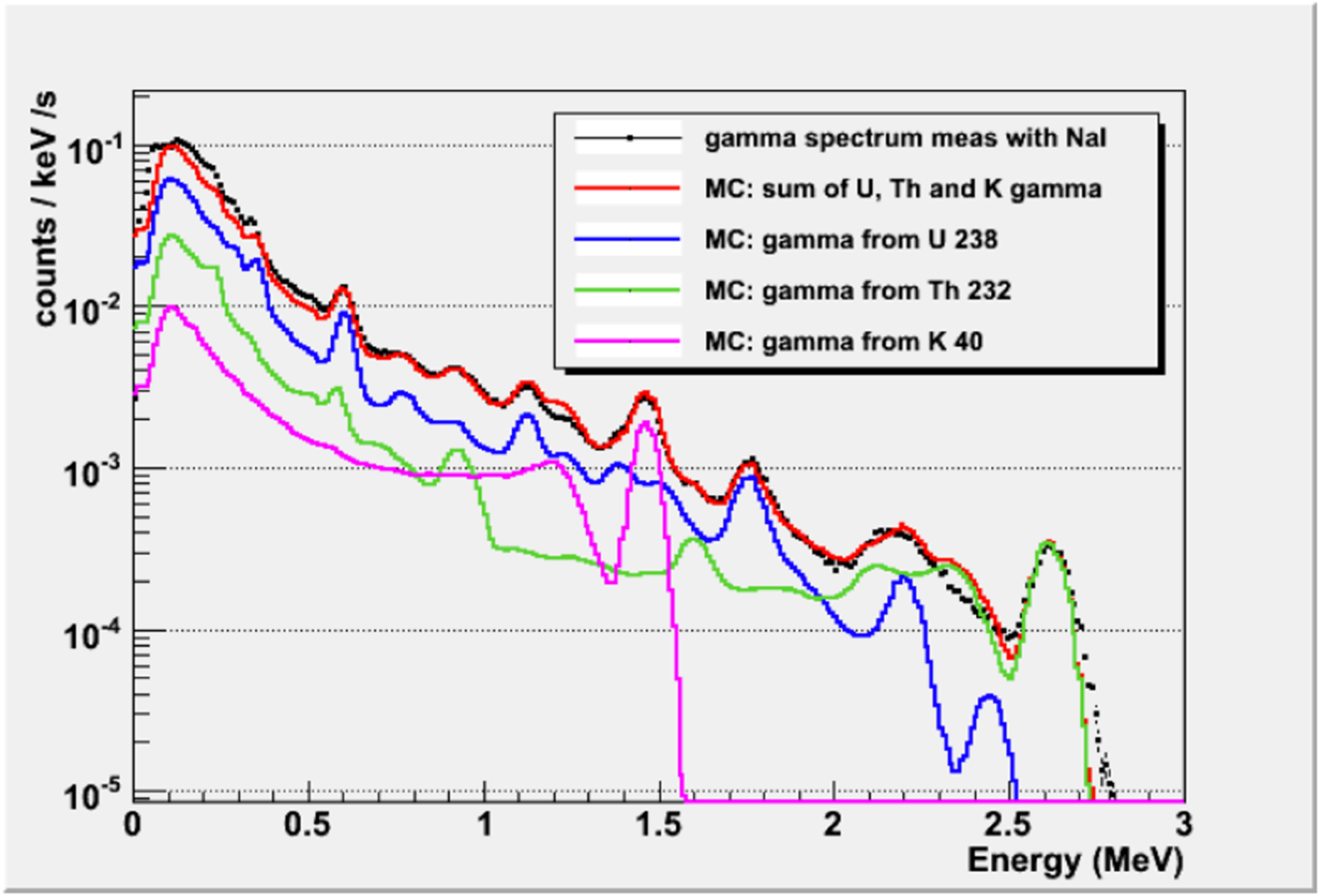
Material Screening

Gamma spectrum @ LNGS

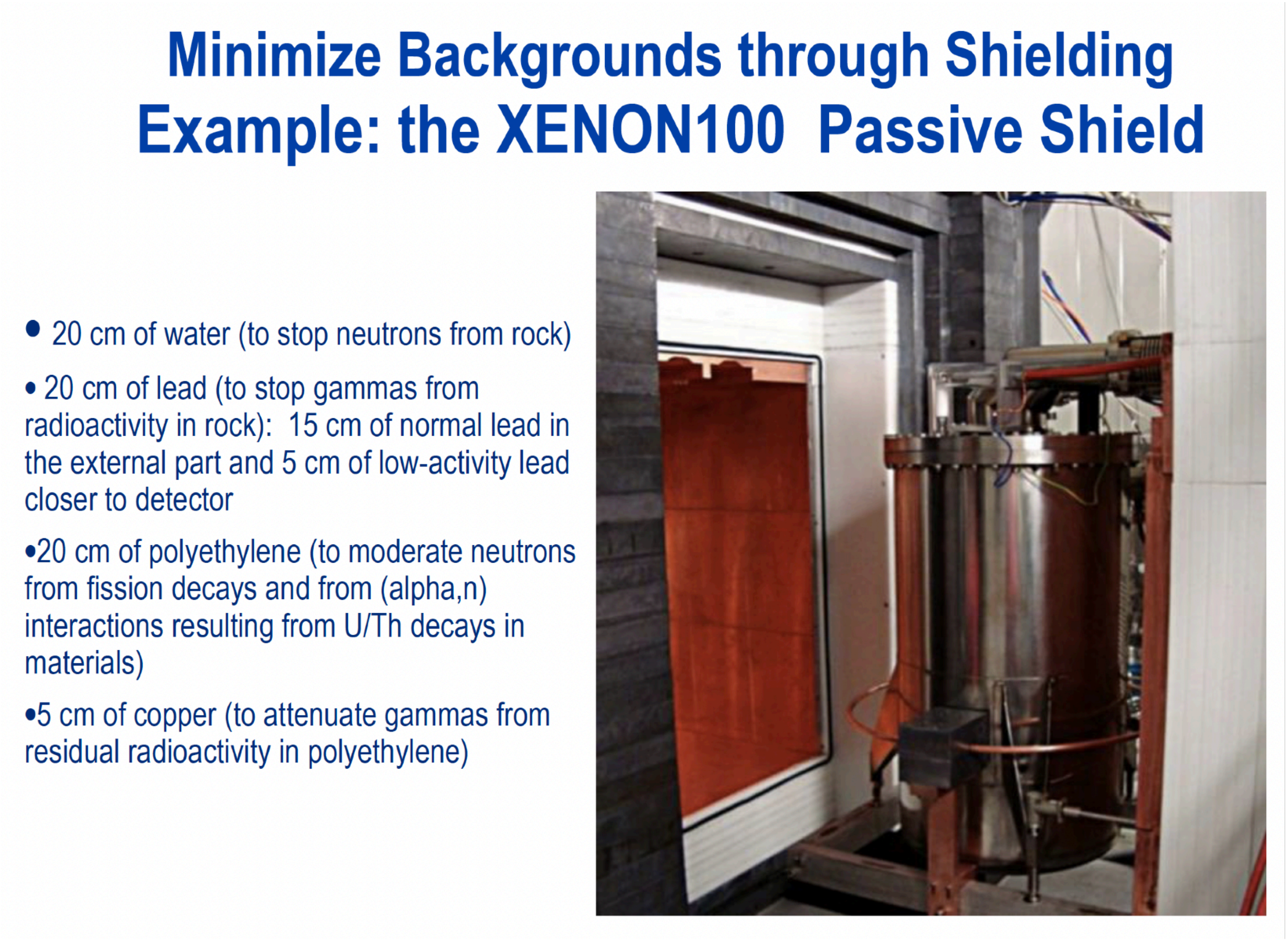
Gamma background at LNGS measured in 2008 in hall B with a 2” NaI detector, by G. Bruno (LVD) and S. Fattori (Xenon).

The MC is done generating U, Th and K gammas isotropically inside LNGS concrete (30 cm thick), and simulating the response of a 2” NaI detector, smeared with its energy resolution.

Then the weight of the 3 contributions are chosen to match best their sum (red histo) with the measured spectrum (black dots).



Passive Shielding



Minimize Backgrounds through Shielding
Example: the XENON100 Passive Shield

- 20 cm of water (to stop neutrons from rock)
- 20 cm of lead (to stop gammas from radioactivity in rock): 15 cm of normal lead in the external part and 5 cm of low-activity lead closer to detector
- 20 cm of polyethylene (to moderate neutrons from fission decays and from (alpha,n) interactions resulting from U/Th decays in materials)
- 5 cm of copper (to attenuate gammas from residual radioactivity in polyethylene)

Screening and MC-DATA matching

XENON100

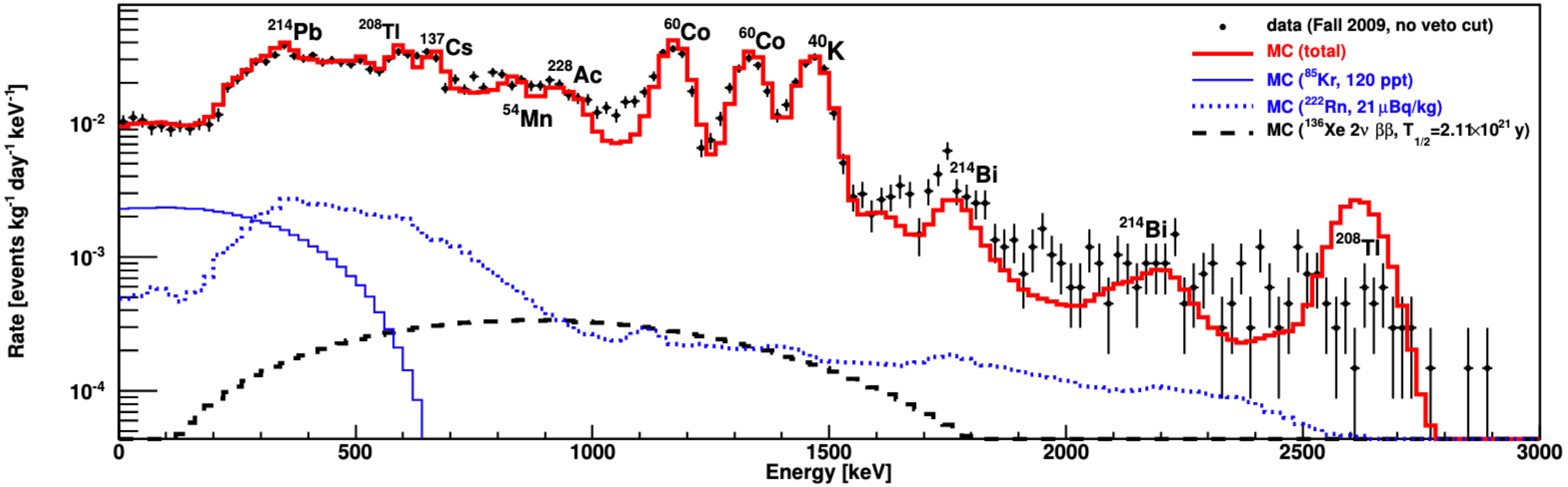
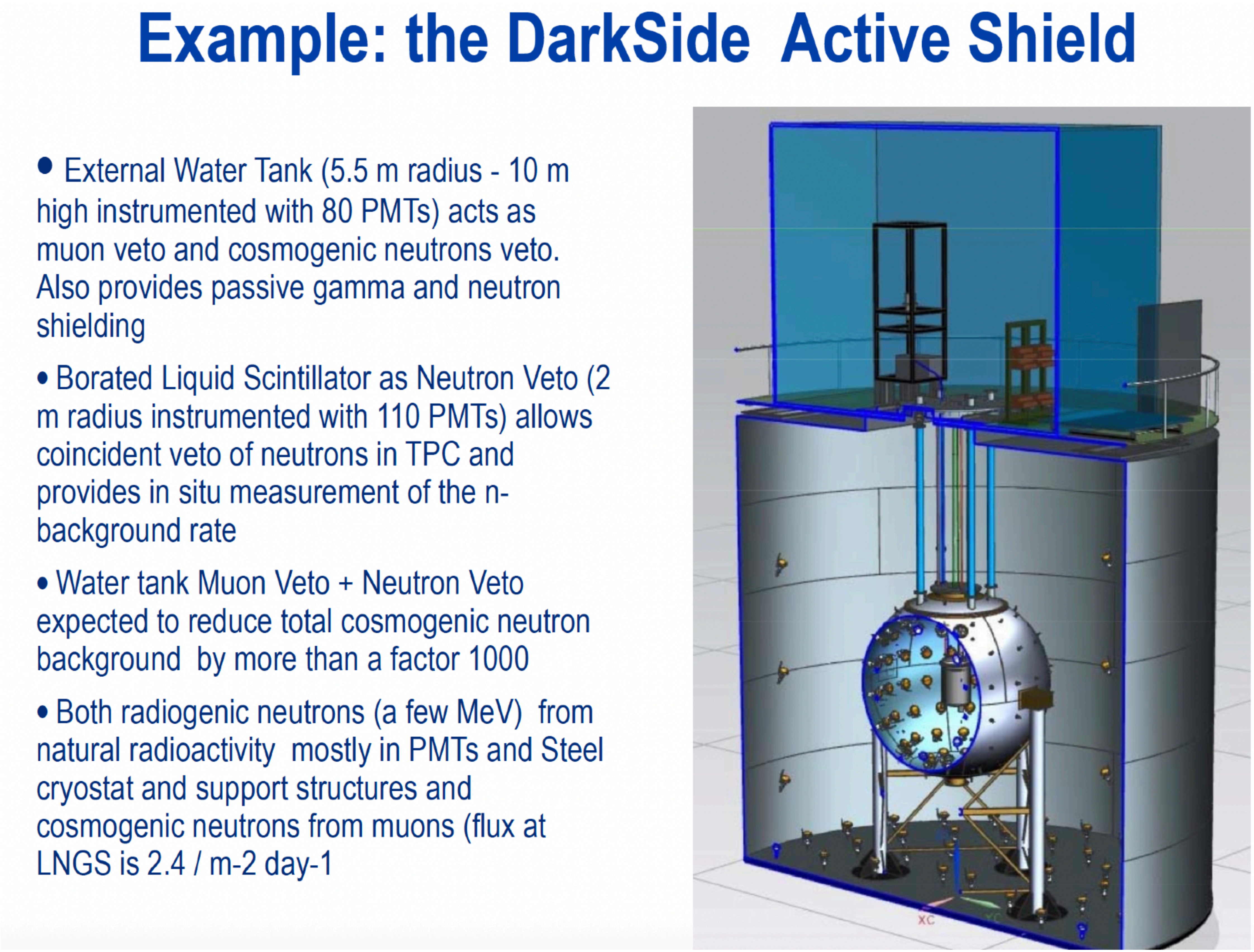


FIG. 11: (Color online) Energy spectra of the background from measured data (commissioning run in Fall 2009 [5]) and Monte Carlo simulations in the 30 kg fiducial volume without veto cut (thick red solid line). Cosmogenic activation of LXe is not included. The energy spectra of ^{85}Kr and ^{222}Rn decays in LXe are shown with the thin blue solid and dotted lines, respectively. The thin black dashed histogram shows the theoretical spectrum of the 2ν double beta decay of ^{136}Xe, assuming half-life of 2.11×10^{21} years [22].

TABLE IV: Summary of the predicted electronic recoil background: rate of single scatter events in the energy region below 100 keV, before S2/S1 discrimination. The veto cut with an average energy threshold of 100 keV has been applied.

	Predicted rate [$\times10^{-3}$ events$\cdot$kg$^{-1}\cdot$day$^{-1}\cdot$keV^{-1}]					
Volume	62 kg target		40 kg fiducial		30 kg fiducial	
Veto cut	none	active	none	active	none	active
Detector and shield materials	137.22	75.30	12.89	3.42	7.22	2.02
^{222}Rn in the shield (1 Bq/m^3)	5.95	1.72	0.92	0.16	0.16	0.02
^{85}Kr in LXe (150 ppt of ^{nat}Kr)	2.90	2.90	2.90	2.90	2.90	2.90
^{222}Rn in LXe (21 μBq/kg)	1.04	0.51	0.56	0.38	0.53	0.37
All sources	147.11	80.43	17.27	6.86	10.81	5.31

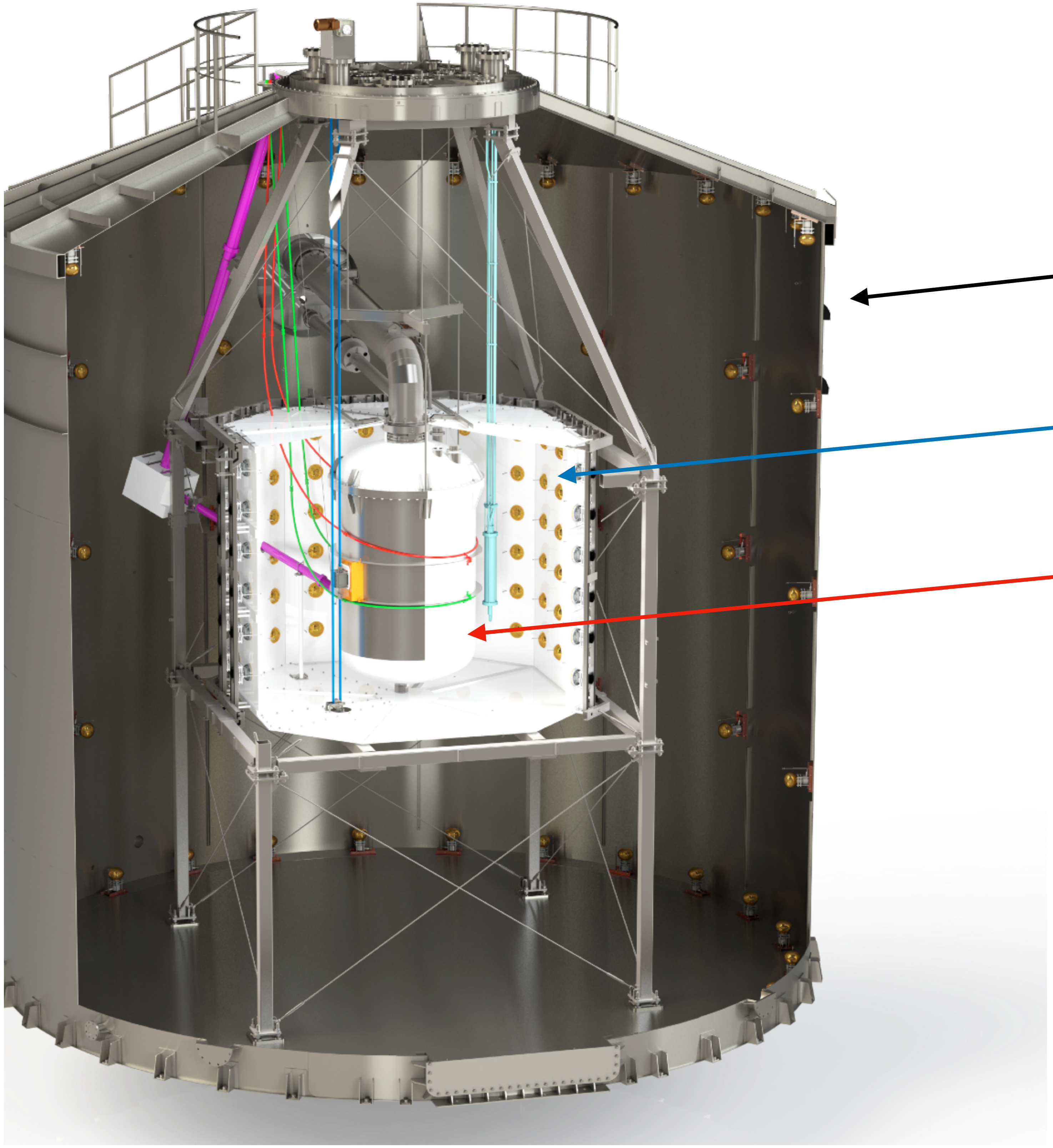
Active Shielding



Example: the DarkSide Active Shield

- External Water Tank (5.5 m radius - 10 m high instrumented with 80 PMTs) acts as muon veto and cosmogenic neutrons veto. Also provides passive gamma and neutron shielding
- Borated Liquid Scintillator as Neutron Veto (2 m radius instrumented with 110 PMTs) allows coincident veto of neutrons in TPC and provides in situ measurement of the n-background rate
- Water tank Muon Veto + Neutron Veto expected to reduce total cosmogenic neutron background by more than a factor 1000
- Both radiogenic neutrons (a few MeV) from natural radioactivity mostly in PMTs and Steel cryostat and support structures and cosmogenic neutrons from muons (flux at LNGS is 2.4 / m-2 day-1

Active Shielding



XENONnT:

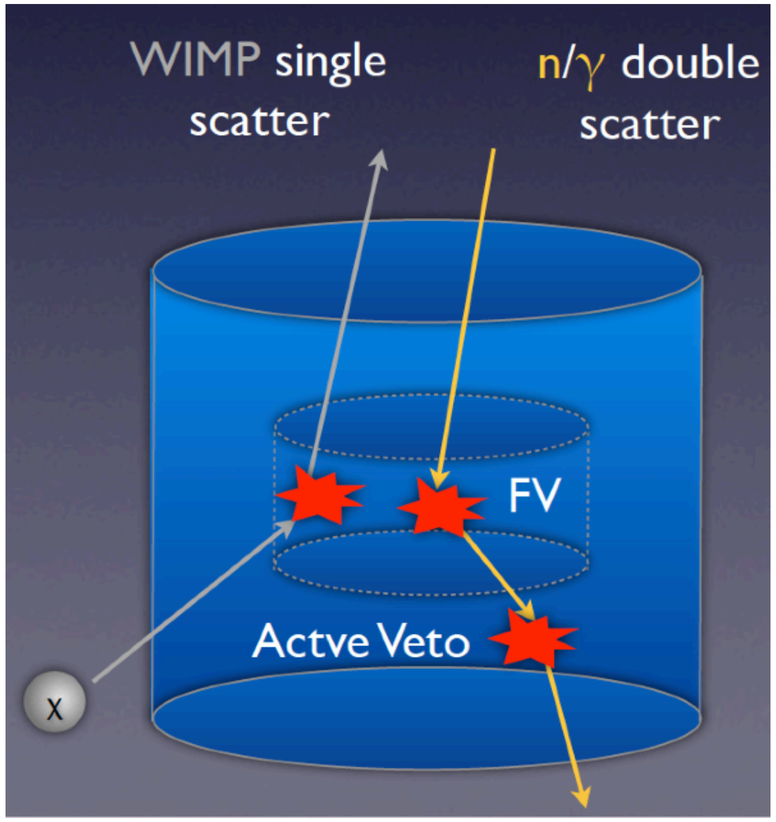
Muon Veto

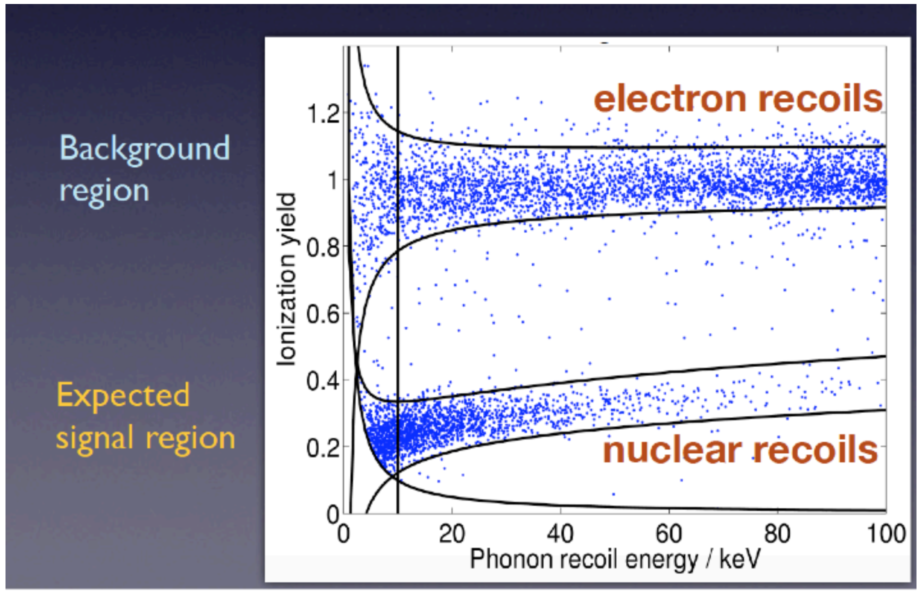
Neutron Veto

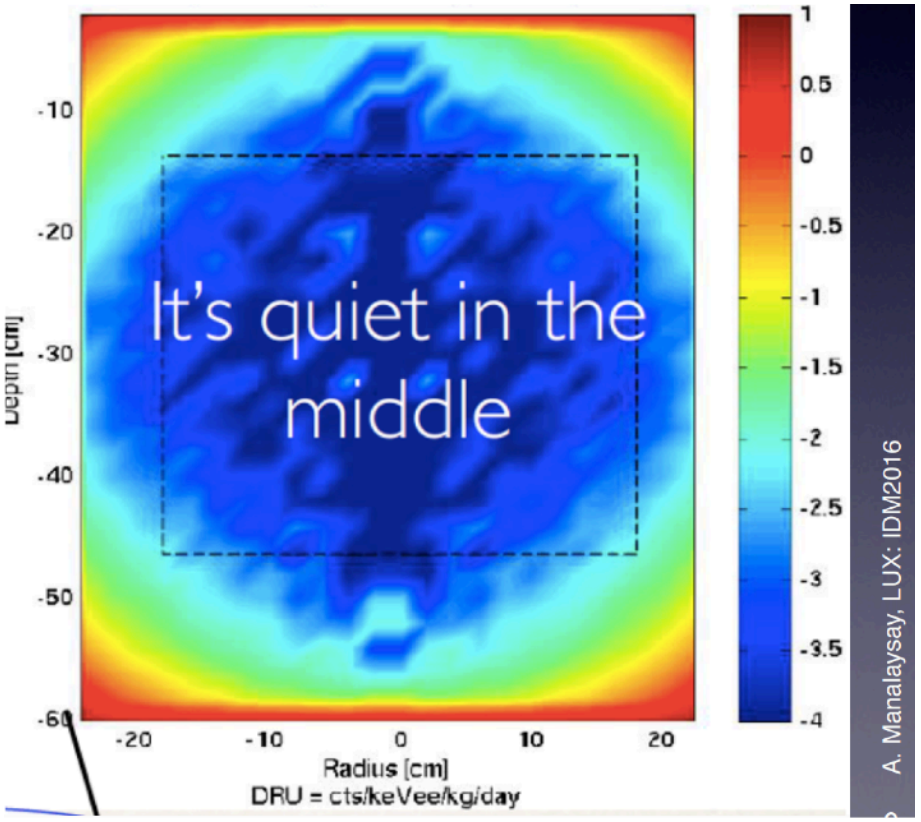
TPC inside the Cryostat

Backgrounds: external sources

- External γ's from natural radioactivity:
    - Suppression via self-shielding of the target
    - Material screening and selection
    - Rejection of multiple scatters & discrimination
- External neutrons:
  muon-induced, (α, n) and from fission reactions
    - Go underground!
    - Shield: passive (polyethylene) or active (water/scintillator vetoes)
    - material selection for low U and Th contaminations







A. Manalaysay, LUX: IDM2016

Backgrounds: internal sources

- Internal contamination in liquids:
  - ^{85}Kr: removal by cryogenic distillation/chromatography/centrifuges
  - Rn: removal using activated carbon , distillation, dust removal
  - Argon: ^{39}Ar (565 keV endpoint, 1 Bq/kg), ^{42}Ar
  - Xenon: ^{136}Xe $\beta\beta$ decay ($T_{1/2} = 2.2 \times 10^{21}$ y) *long lifetime!*

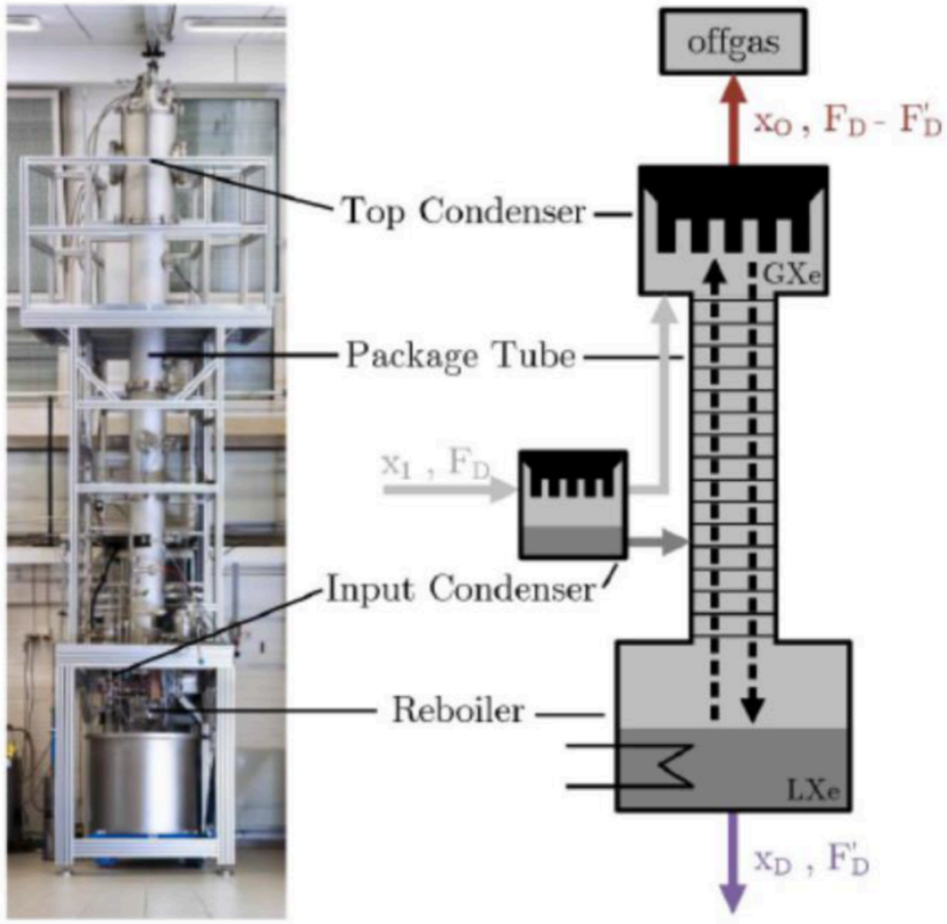
Decreasing Internal Backgrounds

Cryogenic Distillation to remove Kr and Rn from Xe

Application and modeling of an online distillation method to reduce krypton and argon in XENON1T

Krypton distillation

- Kr/Ar distillation based on their higher vapor pressure compared to Xe at -96 °C (goal 100 ppq)
- Inherited from XENON1T



Underground Ar

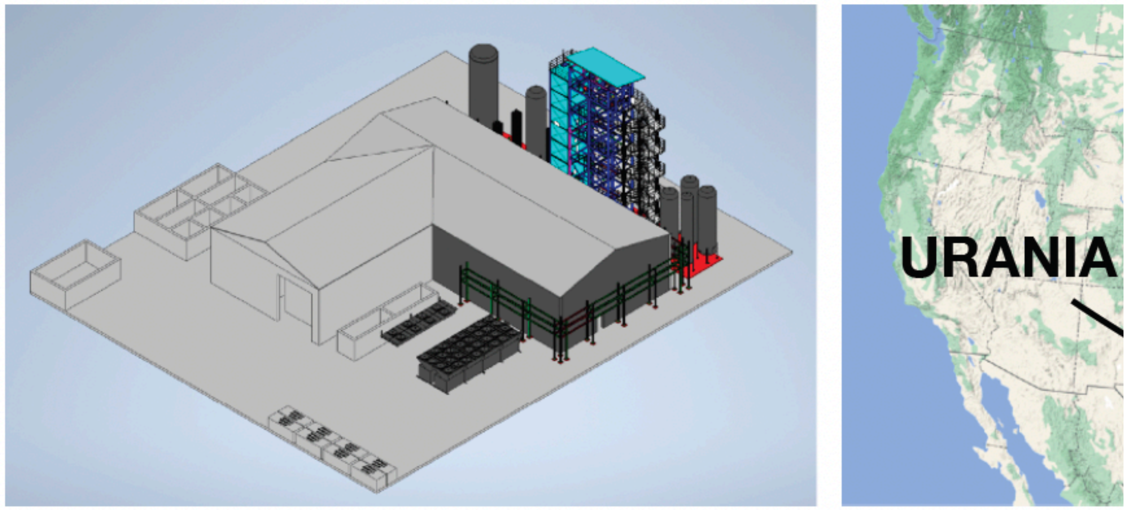
1) UAr extraction at the URANIA plant.

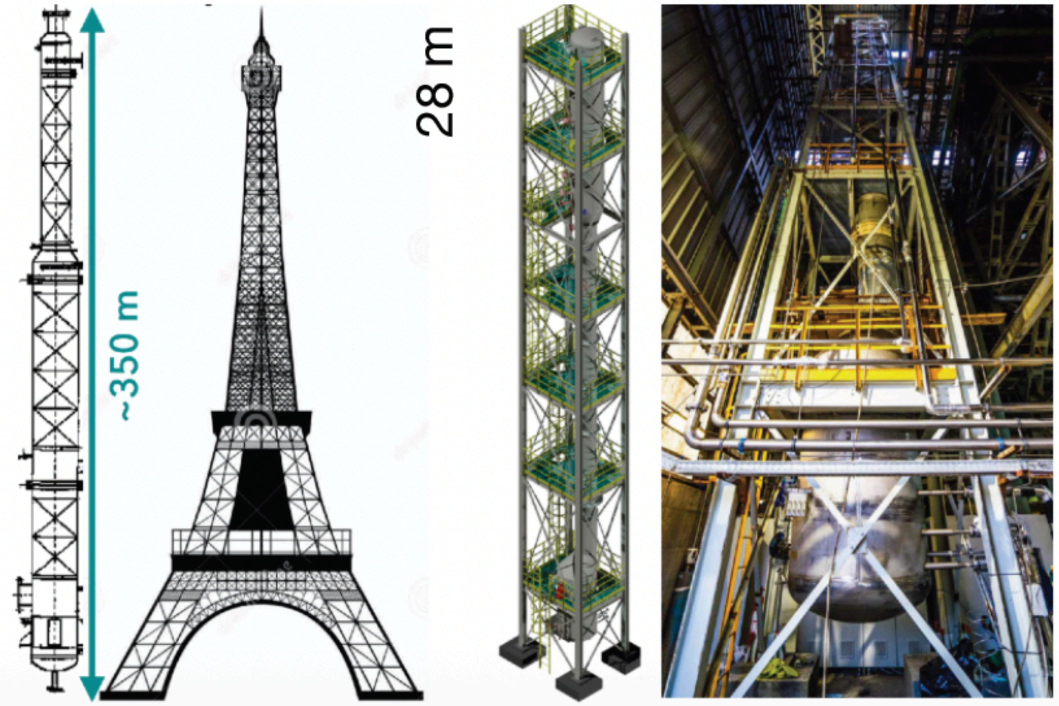
^{39}Ar (β-decay) suppressed by $\sim 10^3$ in undergrc

CO2 reservoir in Cortez, Colorado

UAr extraction rate: 250-330 kg/day

Expected argon purity at outlet: 99.99%

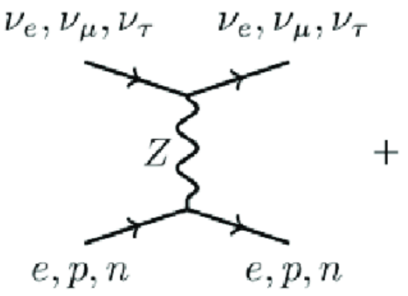


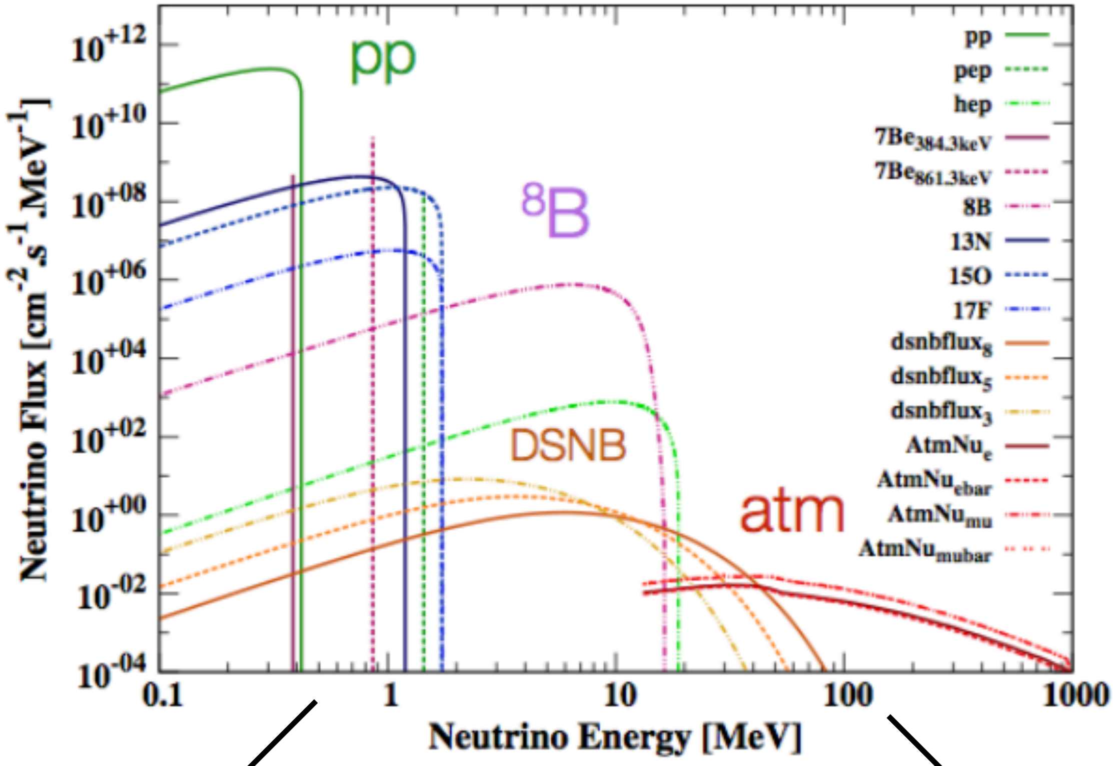


Eur. Phys. J. C (2021) 81:359

The ultimate background from neutrinos

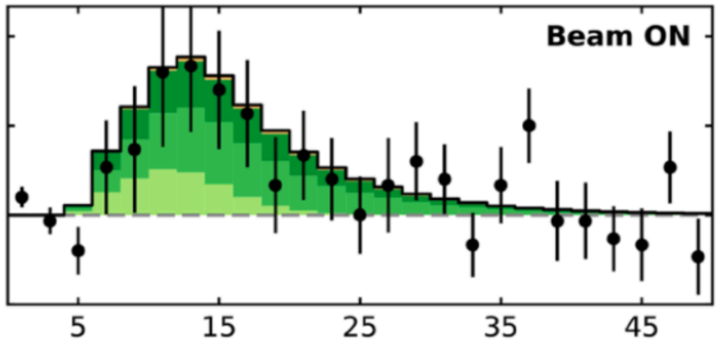
Background of today
can be the signal
of tomorrow !

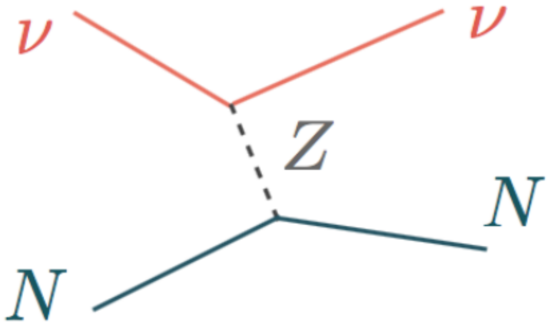




F. Ruppin et al., 1408.

COHERENT, Science, 2017

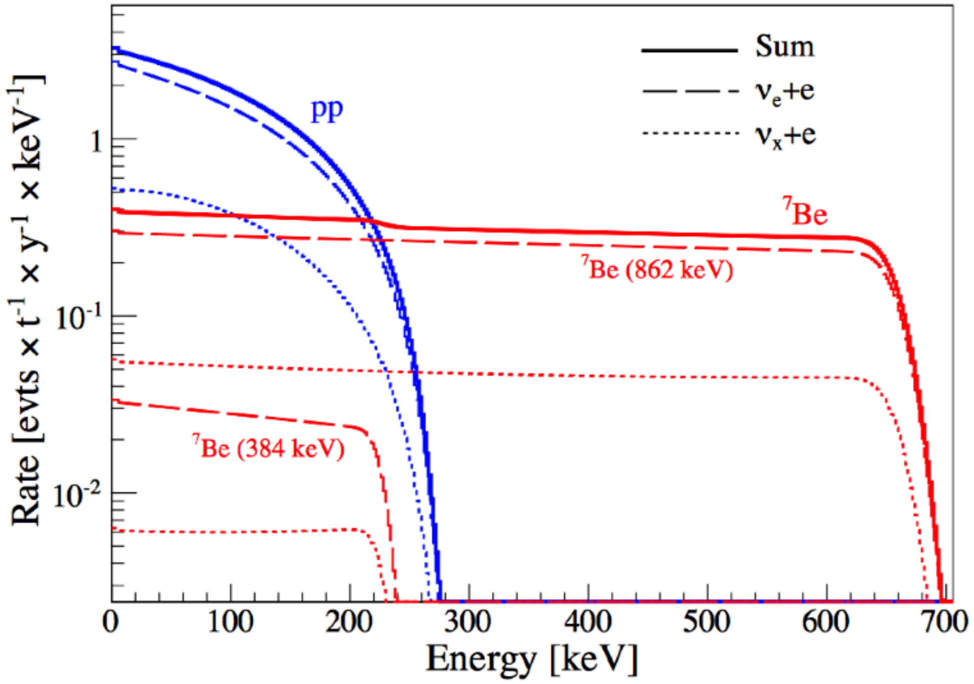


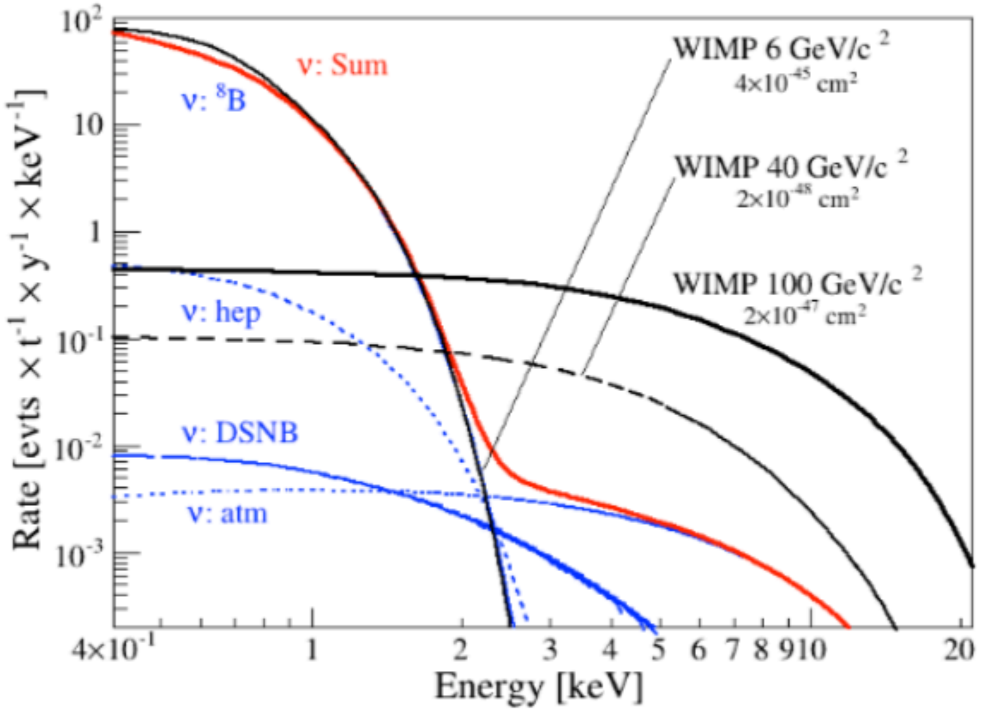


ER

NR

$\nu + N \longrightarrow \nu + N$





LB et al., JCAP01 (2014) 044

Summary of main backgrounds

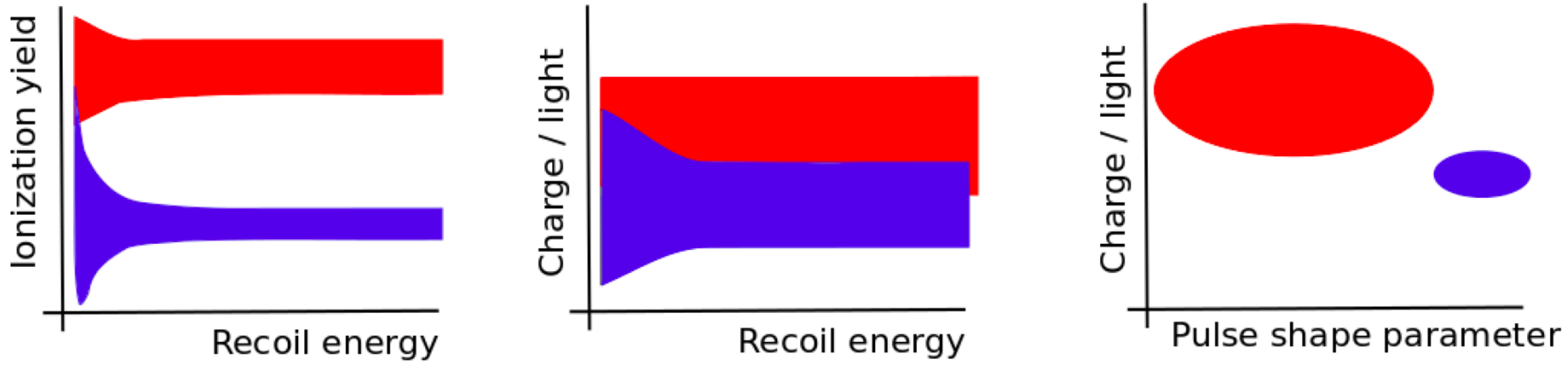
	WIMPs	Gammas	Internal Beta	Neutrons	Neutrinos
Single/	SS	SS/MS	SS	SS/MS	SS
Fiducial	Uniform	Mostly outer	Uniform	Mostly outer	Uniform
ER/NR	NR	ER	ER	NR	ER/NR

Detector Calibration

Purposes of detector calibration:

- Data stability:
  monitoring of detector parameters (amplification of signals, slow control parameters, ..) and of the related electronics
- Determination of energy scale:
  detector signals are photoelectrons, charges or heat
  → need to convert to keV_{nr}
- Determination of signal and background regions:
  description of nuclear and electronic recoil regions

Detector Calibration: Signal & Background

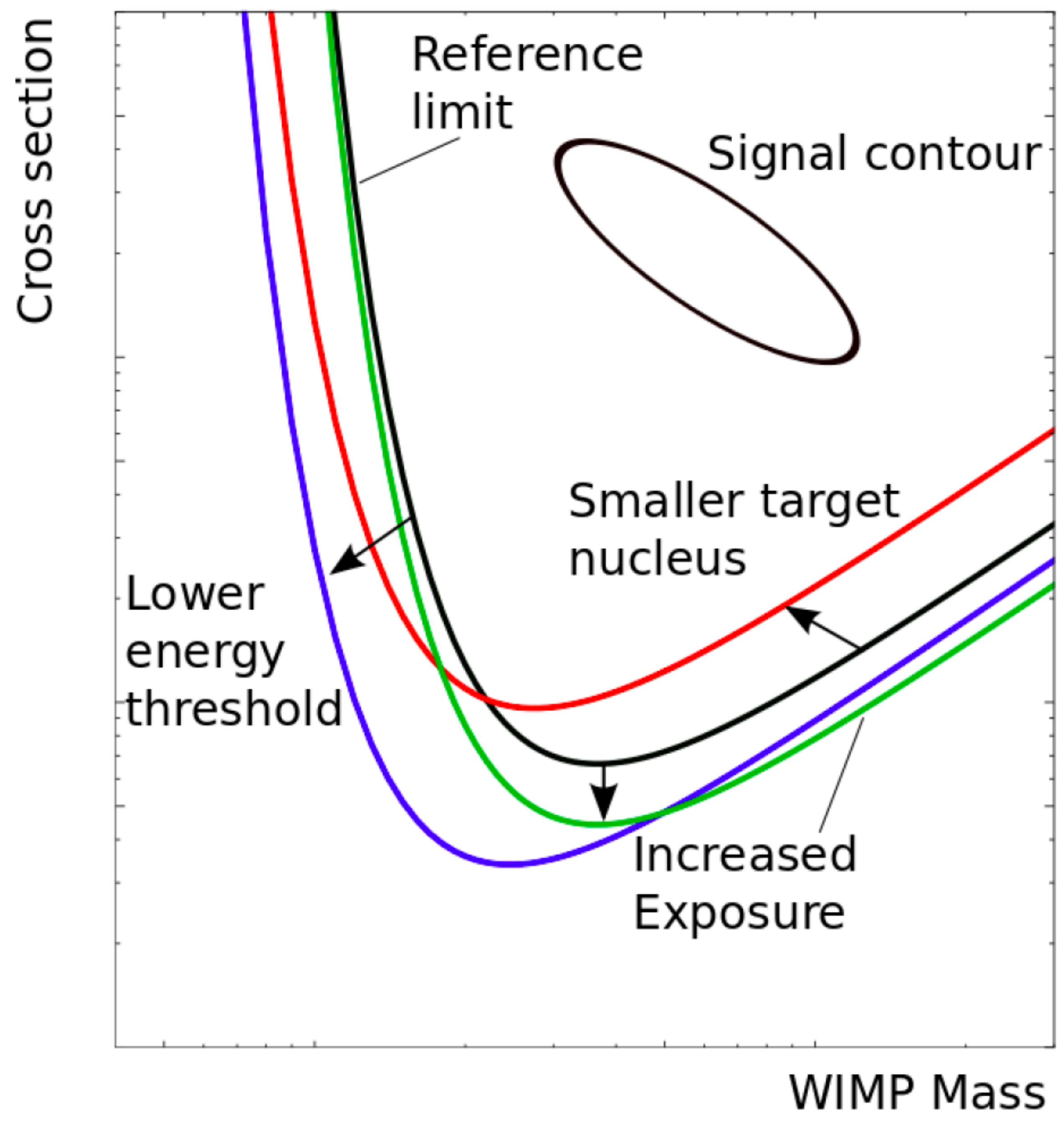


- Discrimination in a cryogenic germanium detector (left)
  No surface events included!
- Discrimination in a liquid xenon detector (middle)
- Discrimination in a liquid argon detector (right)
  Two parameters available for discrimination

Sensitivity plot in direct DM experiments

→ Statistical significance of signal over expected background?

J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

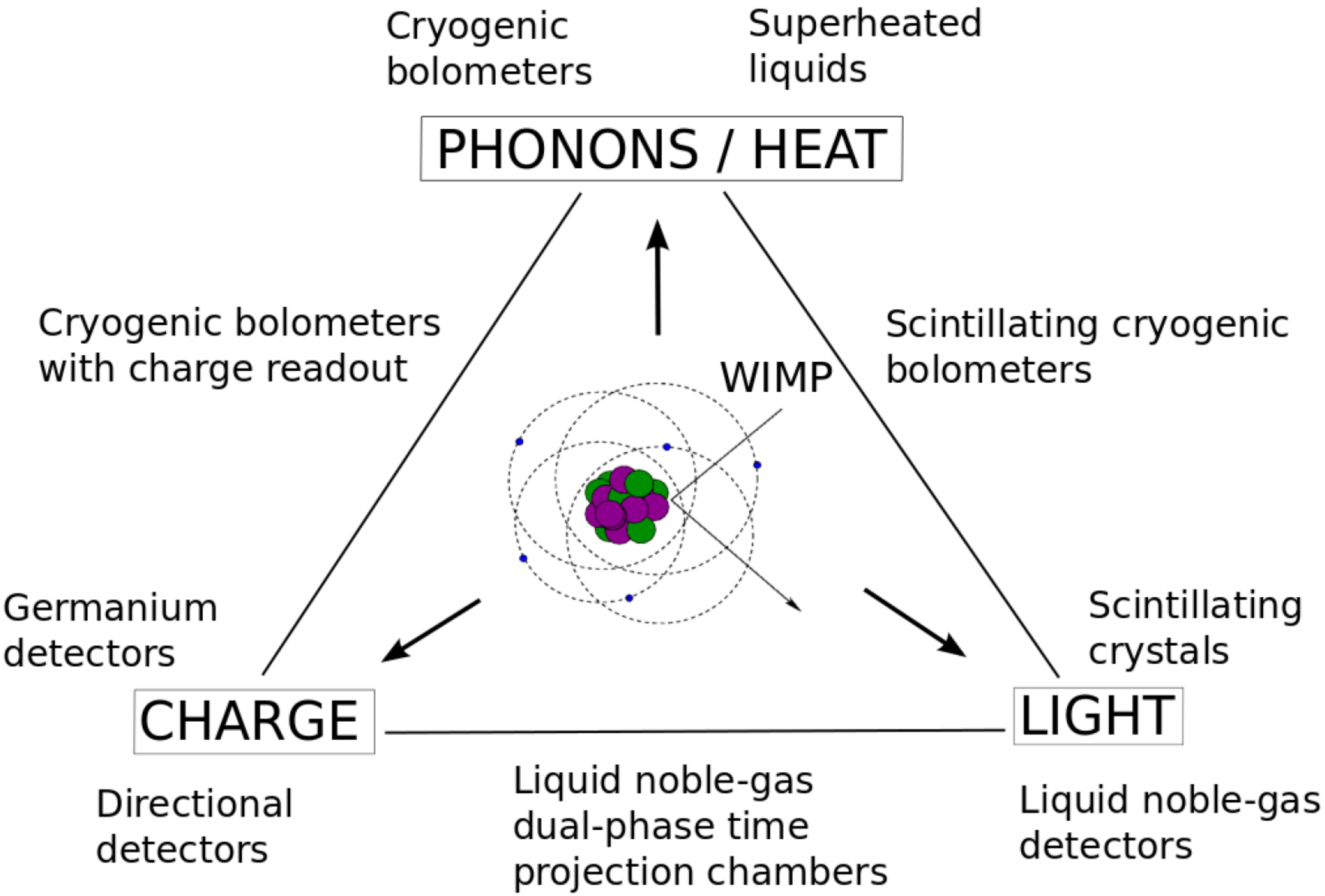


- Positive signal
  - Region in σ_χ versus m_χ
- Zero signal
  - Exclusion of a parameter region

- Low WIMP masses: detector threshold matters
- Minimum of the curve: depends on target nuclei
- High WIMP masses: exposure matters $\epsilon = m \times t$

$$R \propto N_T \frac{\rho_0}{m_X} \sigma \langle v \rangle$$

Direct detection Techniques



Cryogenic bolometers

Superheated liquids

PHONONS / HEAT

Cryogenic bolometers with charge readout

WIMP

Scintillating cryogenic bolometers

Germanium detectors

Scintillating crystals

CHARGE

LIGHT

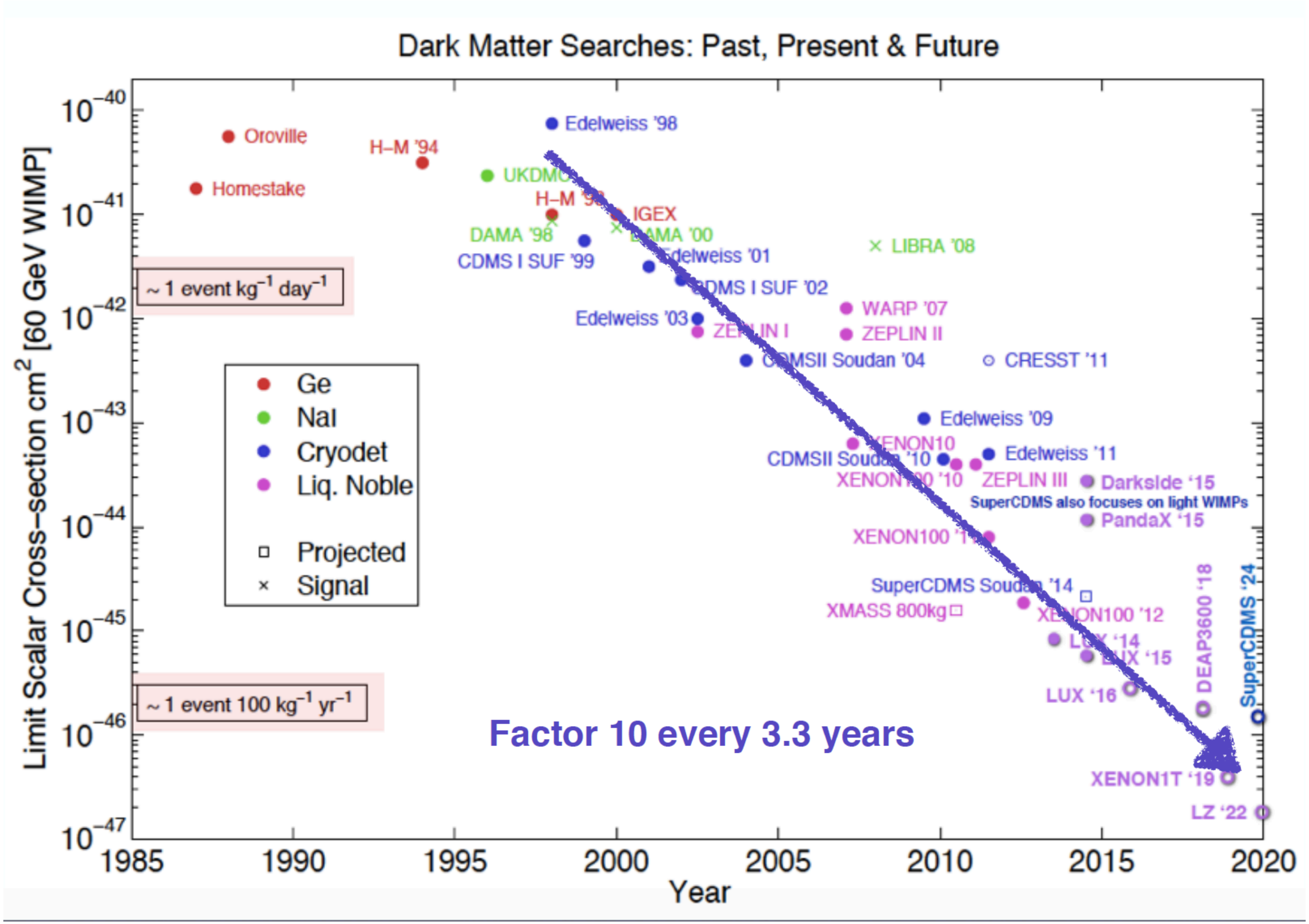
Directional detectors

Liquid noble-gas dual-phase time projection chambers

Liquid noble-gas detectors

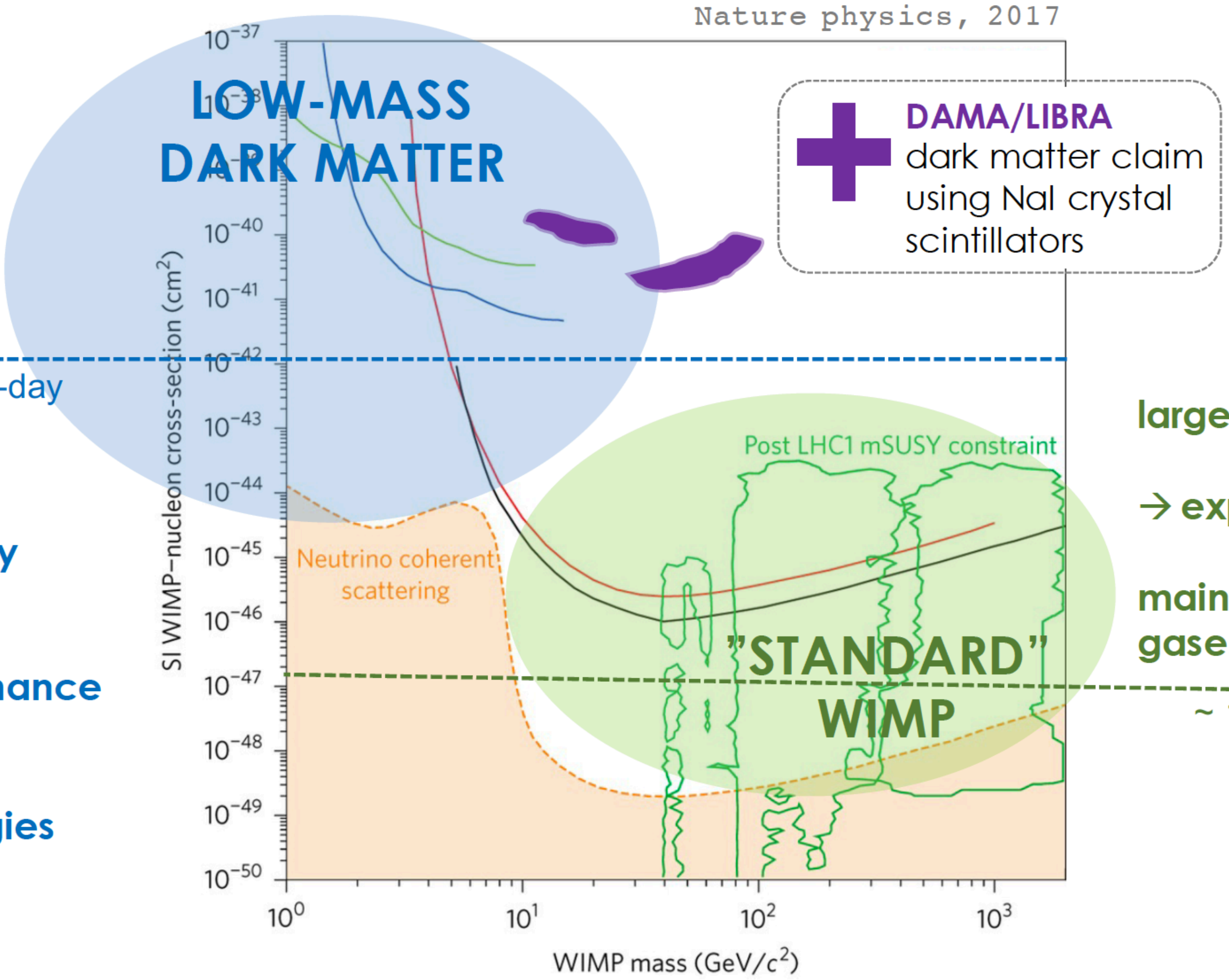
J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

Competitive field, rapid progress



detector sensitivity improved by ~5 orders of magnitude in the last 20 years

Two main lines of improvements



DAMA/LIBRA dark matter claim using NaI crystal scintillators

~ 1 event/ kg-day

~ 1 event/ tonne-year

low energy threshold

→ performance

diverse technologies

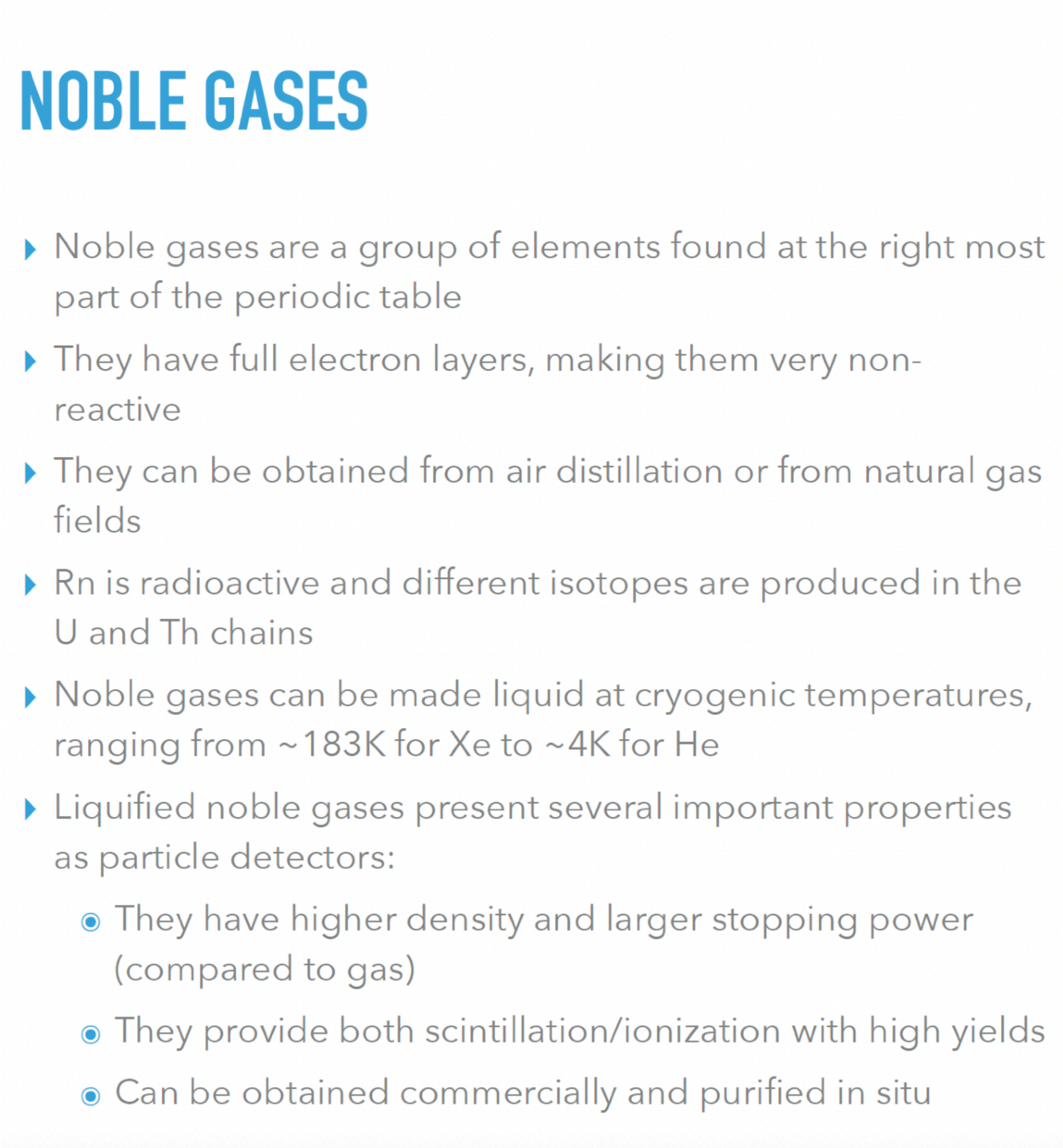
large target

→ exposure

mainly liquid noble gases

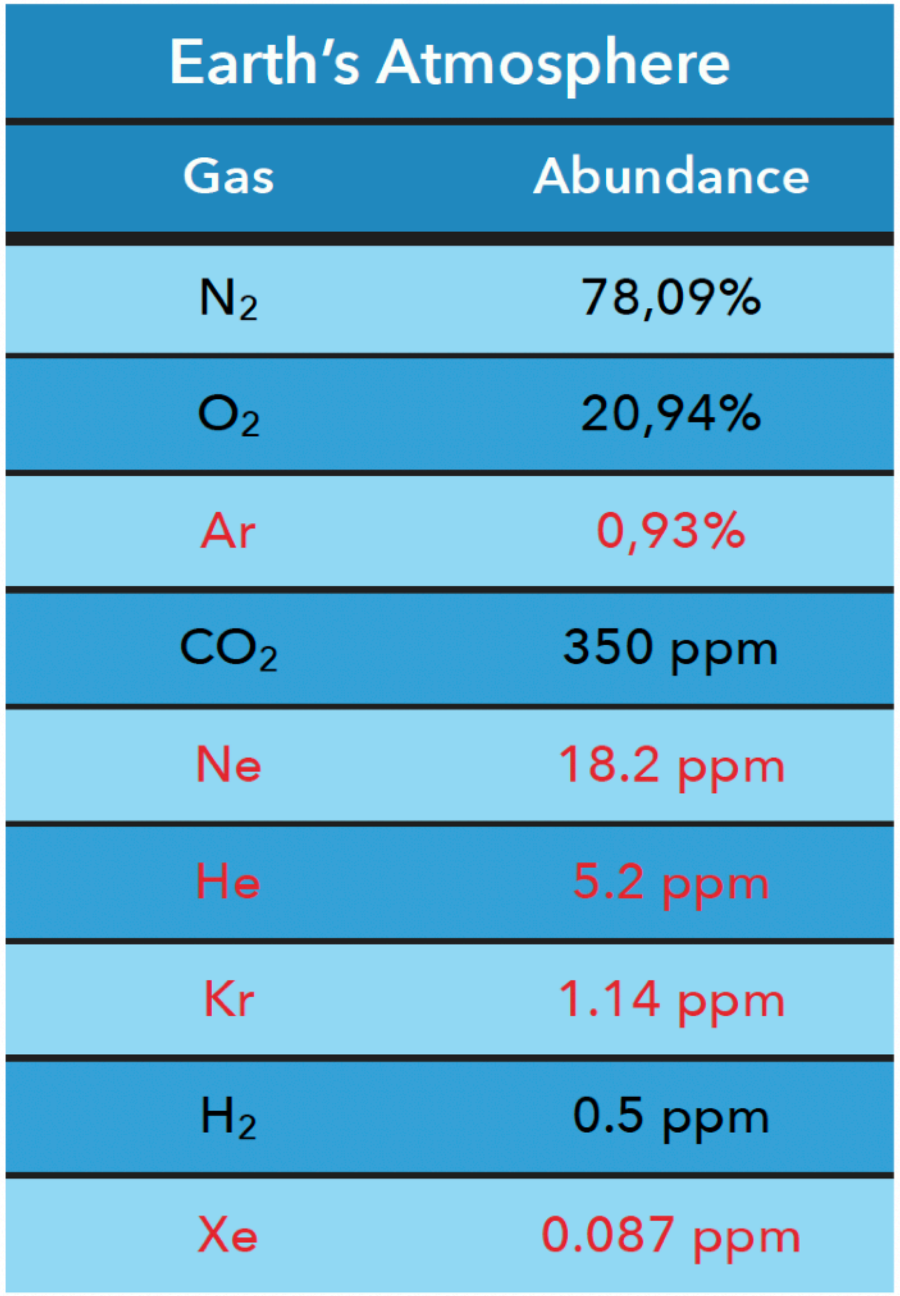
Noble liquid properties as particle detectors

Noble Liquids as Particle Detectors



NOBLE GASES

- Noble gases are a group of elements found at the right most part of the periodic table
- They have full electron layers, making them very non-reactive
- They can be obtained from air distillation or from natural gas fields
- Rn is radioactive and different isotopes are produced in the U and Th chains
- Noble gases can be made liquid at cryogenic temperatures, ranging from ~183K for Xe to ~4K for He
- Liquified noble gases present several important properties as particle detectors:
  - They have higher density and larger stopping power (compared to gas)
  - They provide both scintillation/ionization with high yields
  - Can be obtained commercially and purified in situ

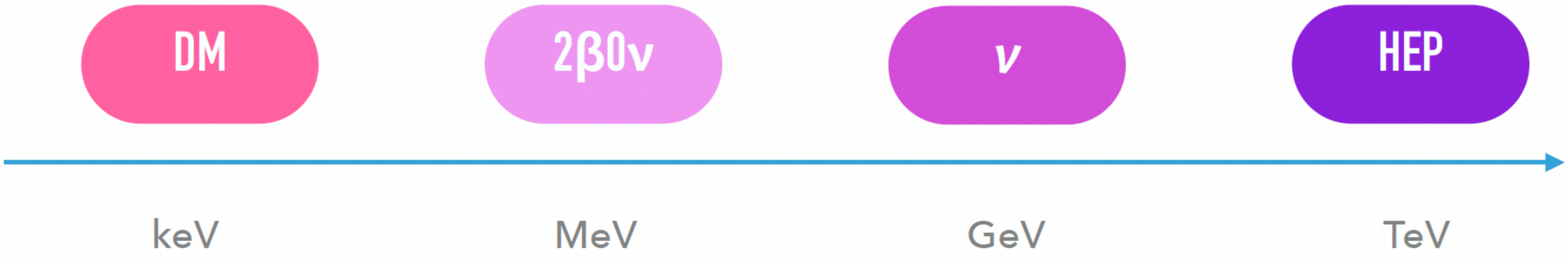


Earth's Atmosphere

Gas	Abundance
N_2	78,09%
O_2	20,94%
Ar	0,93%
CO_2	350 ppm
Ne	18.2 ppm
He	5.2 ppm
Kr	1.14 ppm
H_2	0.5 ppm
Xe	0.087 ppm

Noble Liquids as Particle Detectors

- Because of their ability to produce light and electrons following particle interactions liquefied noble gases are used in very different branches of physics:
  - High Energy Particle Physics (GeV-TeV)
  - Neutrino Detection and Proton Decay (MeV-GeV)
  - Neutrinoless Double Beta Decay (MeV)
  - Dark Matter Detection (~10-100 keV)



Noble Liquids as Particle Detectors

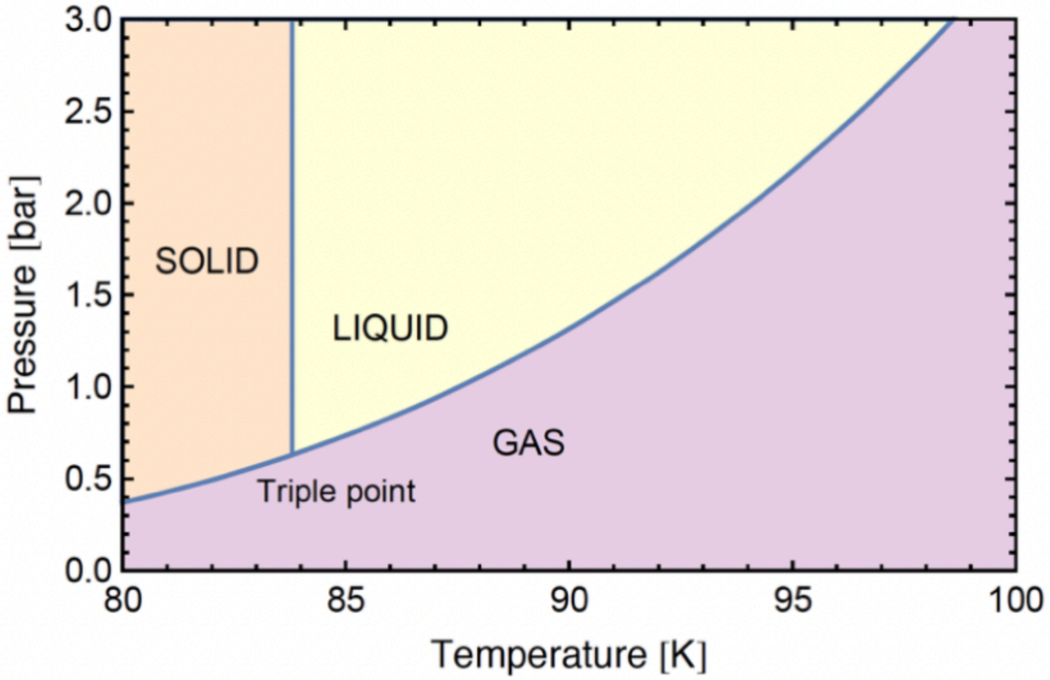
Suitable materials for detecting ionization tracks:

- high charge and light yields
  - Calorimetry, excellent energy resolution
  - Particle identification
  - Precise timing
- no e- attachment, which allows for long drift distance
  - Tracking, 3D reconstruction
- inert, non flammable, very good dielectrics which allows for high voltages to drift over long distances
- transparent to their own scintillation light, which can be collected in large volumes

Element	Z(A)	BP @ 1 atm [K]	Liquid density @ BP [g/cc]	Dielectric constant	Ionisation [e$^-$/keV]	Scintillation [photon/keV]
He	2 (4)	4,2	0,13	1,06	39	15
Ne	10 (20)	27,1	1,21	1,53	46	7
Ar	18 (40)	87,3	1,40	1,51	42	40
Kr	36 (84)	119,8	2,41	1,66	49	25
Xe	54 (131)	165	2,95	1,95	64	46

Noble Liquids as Particle Detectors

- Most underground experiments use **argon** and **xenon** (helium and neon detectors are proposed)
  - Dense, homogeneous targets for rare event searches
  - Detectors with self-shielding and fiducialisation
  - Large detector masses with ultra-low levels of radioactivity

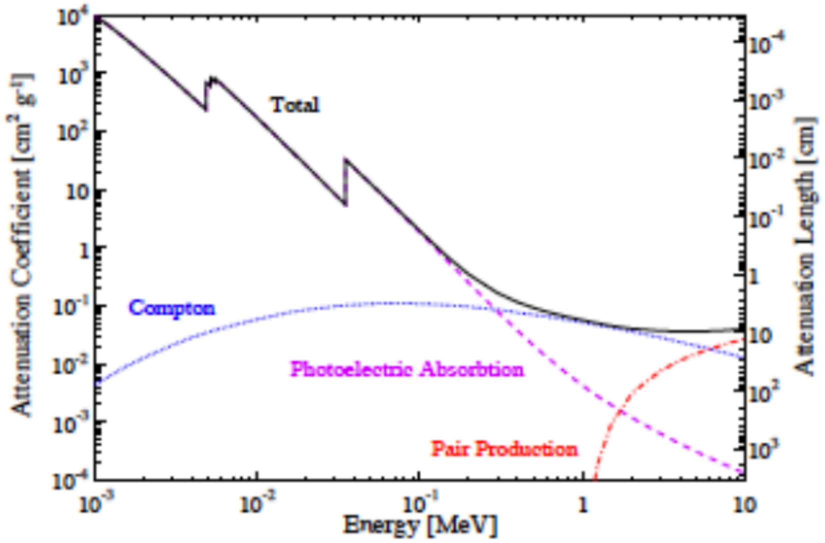


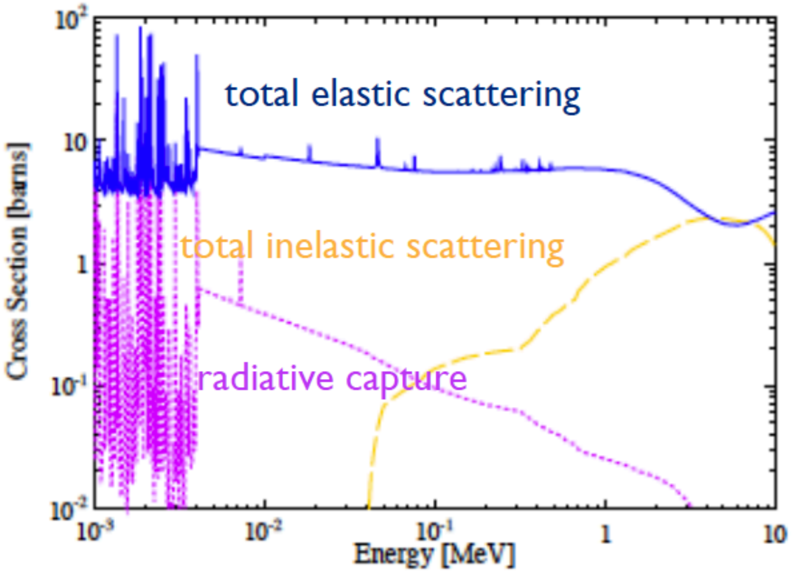
Properties	Xe	Ar
Atomic number	54	18
Mean relative atomic mass	131,3	40,0
Boiling point (BP) @ 1 atm [K]	165,0	87,3
Melting point @ 1 atm [K]	161,4	83,8
Gas density @ 1 atm and 298 K [g/l]	5,40	1,63
Gas density @ 1 atm and BP [g/l]	9,99	5,77
Liquid density @ BP [g/cm^3]	2,94	1,40
Dielectric constant of liquid	1,95	1,51
Volume fraction in Earth's atmosphere [ppm]	0,09	9340

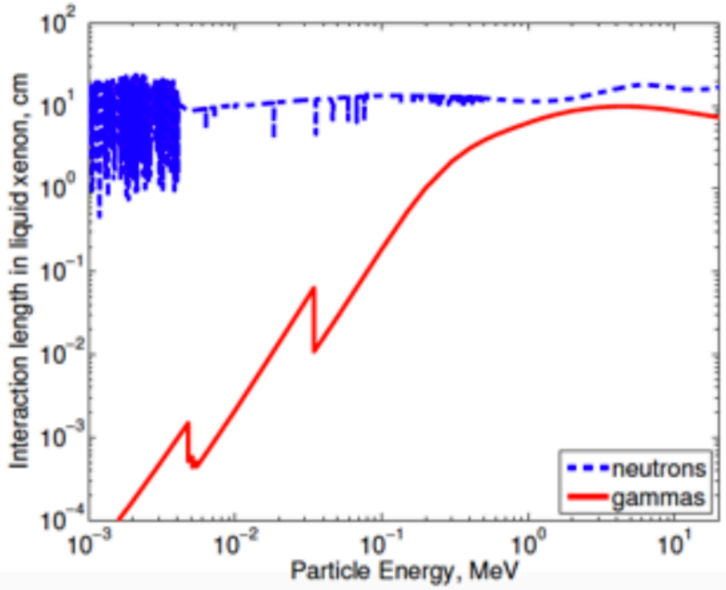
Gamma and Neutron Interactions in LXe

- Electrons (and positrons) produced in PE/Compton and pair production processes will loose energy through electronic excitation resulting in charge and light signals in LXe. At the energies of interest to DM search, ERs from low energy single Compton scatters are the main external background. The high stopping power of LXe is such that most gammas are absorbed in the outer layers (self-shielding)

- Fast neutron interact in LXe primarily via elastic scattering producing NRs (irreducible background for DM search). At MeV inelastic interactions (see table) excite nucleus which then decays with gamma emission. For the Xe-129 and Xe-131 isotopes, excited states are long-lived (metastable states) and decays are observed days after n-irradiation. These provide a uniform source of gammas for calibration, as neutrons penetrate deeper than gamma-rays of same energy (roughly 12 cm vs 6 cm for 1 MeV). The multiplicity of fast neutrons scatters provides a way to discriminate neutrons from WIMPs. For 100 keV neutrons, elastic and radiative capture occur.







Reaction	Cross Section[a] (barns)	Decay Half Life	γ Energy (keV)
$^{129}\mathrm{Xe}(n,n')^{129}\mathrm{Xe}$	0.28	0.97 ns	39.58
$^{131}\mathrm{Xe}(n,n')^{131}\mathrm{Xe}$	0.15	0.48 ns	80.19
$^{129}\mathrm{Xe}(n,n')^{129m}\mathrm{Xe}$	0.011	8.88 d	236.14
$^{131}\mathrm{Xe}(n,n')^{131m}\mathrm{Xe}$	0.054	11.84 d	163.93

[a] Cross section at 1 MeV.

Energy Loss in Noble Liquid

- Energy loss (E_0) of an incident particle in noble liquids: shared between ionization, excitation, and sub-excitation electrons (E_{kin} < energy of first excited level) freed in the ionization process

$$E_0 = N_i E_i + N_{ex} E_{ex} + N_i \epsilon$$

Platzmann equation

- N_i, N_{ex} are the mean number of ionized and excited atoms; E_i, E_{ex} are the mean energies to ionize and excite the atoms; ϵ is the average kinetic energy of sub-excitation electrons (energy eventually goes into heat)

- In their condensed states: noble liquids exhibit a band-like structure of electronic states

- We divide all terms by the band gap energy E_g and define the W_i-value as the energy required to produce an electron-ion pair

$$W_i \equiv \frac{E_0}{N_i}$$

- To obtain: $$\frac{W_i}{E_g} = \frac{E_i}{E_g} + \frac{N_{ex}}{N_i} \times \frac{E_{ex}}{E_g} + \frac{\epsilon}{E_g}$$

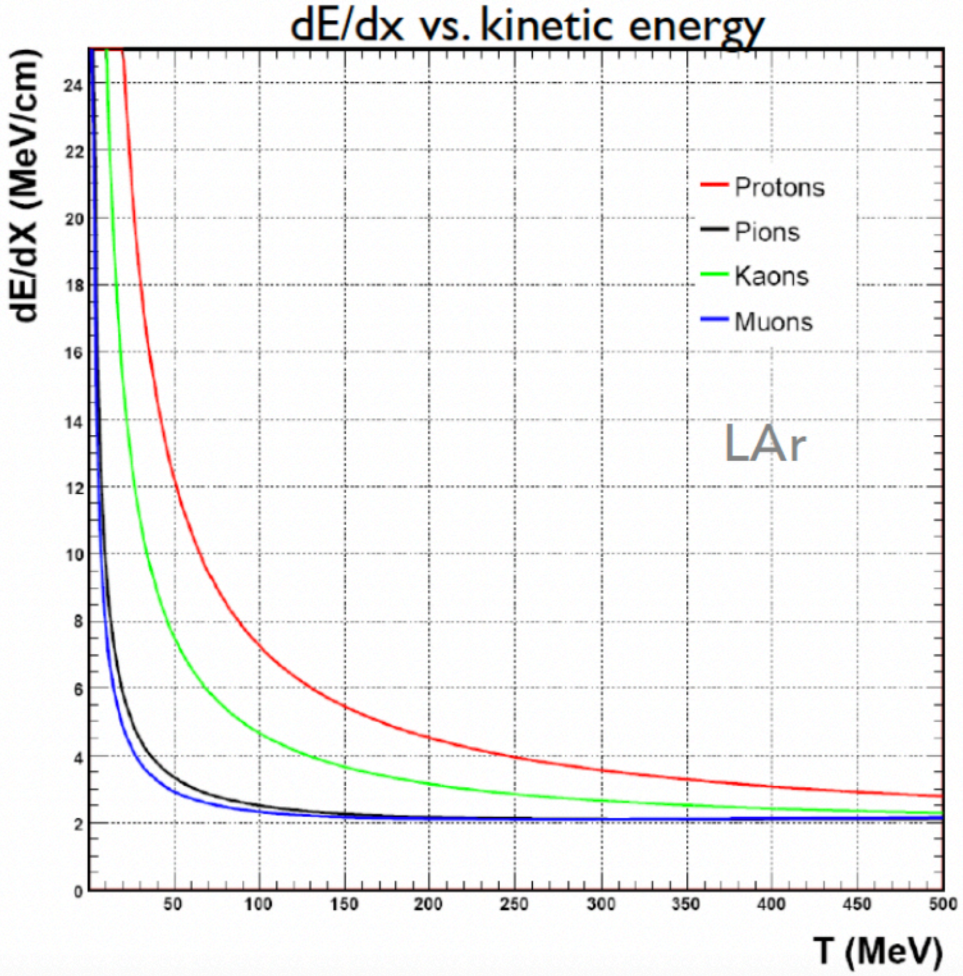
Ionization electrons

THE IONIZATION PROCESS IN NOBLE LIQUIDS

- The average energy loss in ionization is slightly larger than the ionization potential or the band gap Energy E_g, because it includes multiple ionization processes
  - As result, the ratio of the W_i-value to the ionization potential or band gap energy is:

$$\frac{W_i}{E_g} = 1.6 - 1.7$$

Material	LAr	LKr	LXe
Gap energy [eV]	14,3	11,6	9,3
W-value [eV]	23,6	20,5	15,6
dE/dx for a MIP (βγ=3.5)	2.2	3.5	4



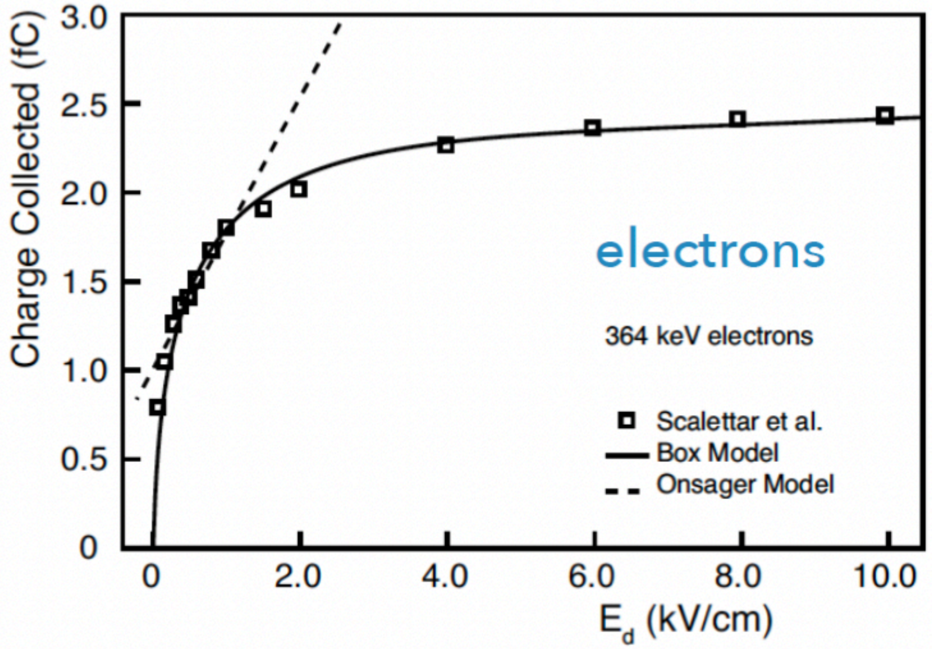
Ionization electrons

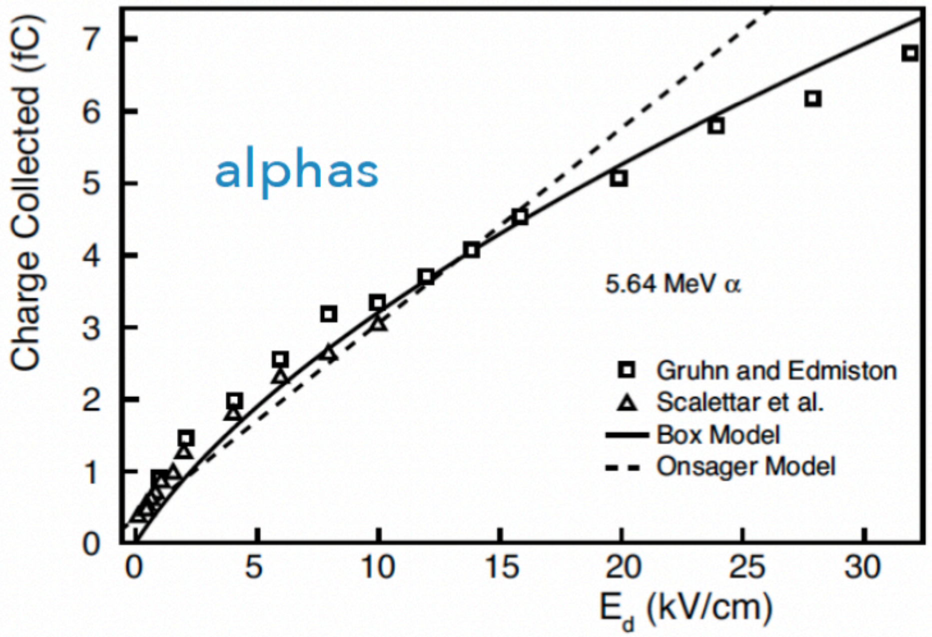
IONIZATION RECOMBINATION PROCESS

- After being created electron and ion can recombine
- The recombination process is strongly dependent
  - on the external applied electric field,
  - on the nature and on the kinematical properties of the ionizing particle (dE/dx)
- Many theoretical and phenomenological models to fit the data

Birk's Model: $$\frac{Q}{Q_0} = \frac{A}{1 + \frac{k}{\mathscr{E}}\frac{dE}{dx}}$$

Box Model: $$\frac{Q}{Q_0} = \frac{1}{\xi} ln(1+\xi) \text{ with } \xi = \alpha Q_0/\mathscr{E}$$





Scintillation photons

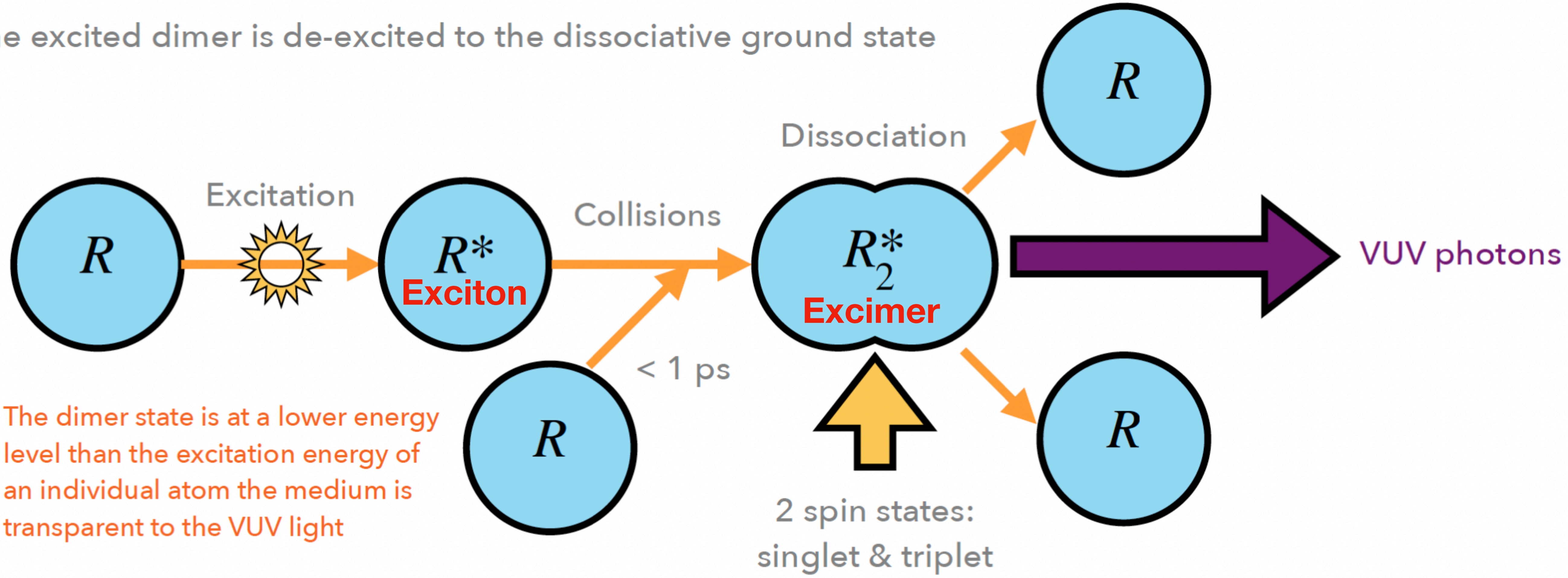
THE SCINTILLATION PROCESS IN NOBLE LIQUIDS

Two distinct processes: *excitation luminescence* and *recombination luminescence*

Excitation luminescence

less than 1 ps after the excitation, the excited atom (exciton, R^*) forms a bound state with a stable atom (R): *a bound dimer state, called excimer*

the excited dimer is de-excited to the dissociative ground state



R

Excitation

R^*

Exciton

Collisions

R

< 1 ps

R^*_2

Excimer

Dissociation

R

R

VUV photons

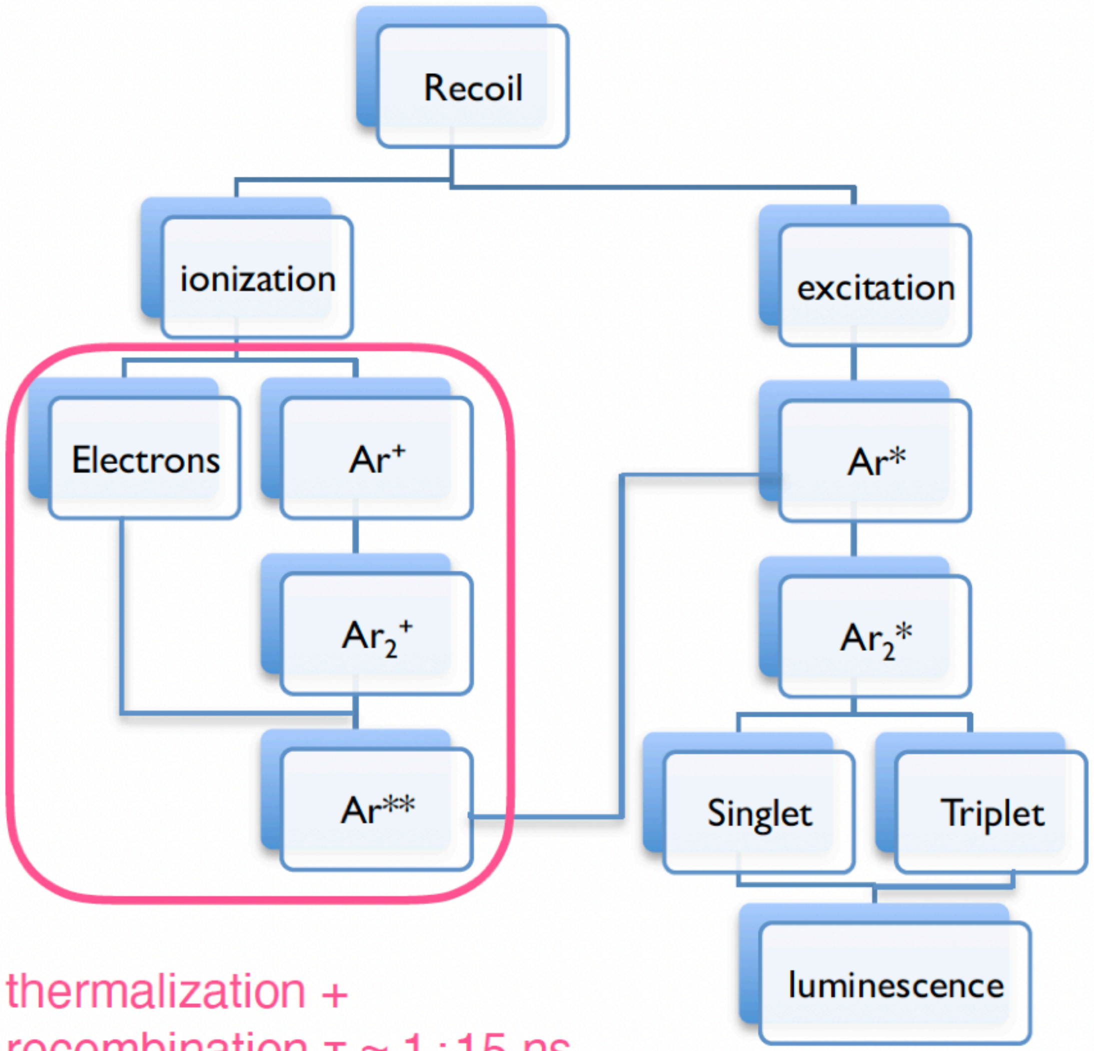
2 spin states:
singlet & triplet

- The dimer state is at a lower energy level than the excitation energy of an individual atom the medium is transparent to the VUV light

- The 2 spin states refer to the combined spin state of the electron and the angular momentum due to the molecular orbit

Scintillation photons

THE SCINTILLATION PROCESS IN NOBLE LIQUIDS



thermalization +
recombination τ ≈ 1÷15 ns

Recombination luminescence:

A fraction of the ionization electrons will recombine with ions and produce a scintillation photon in the following processes

$$R^+ + R \to R_2^+$$

$$R_2^+ + e^- \to R^{**} + R$$

$$R^{**} \to R^* + \text{heat}$$

$$R^* + R + R \to R_2^* + R$$

$$R_2^* \to 2R + h\nu$$

- ✳ Electrons that thermalize far from their parent ion may escape recombination
- ✳ A mechanism called “bi-excitonic quenching” can also reduce the scintillation yield in very dense tracks

$$R^* + R^* \to R_2^{**} \to R + R^+ + e^-$$

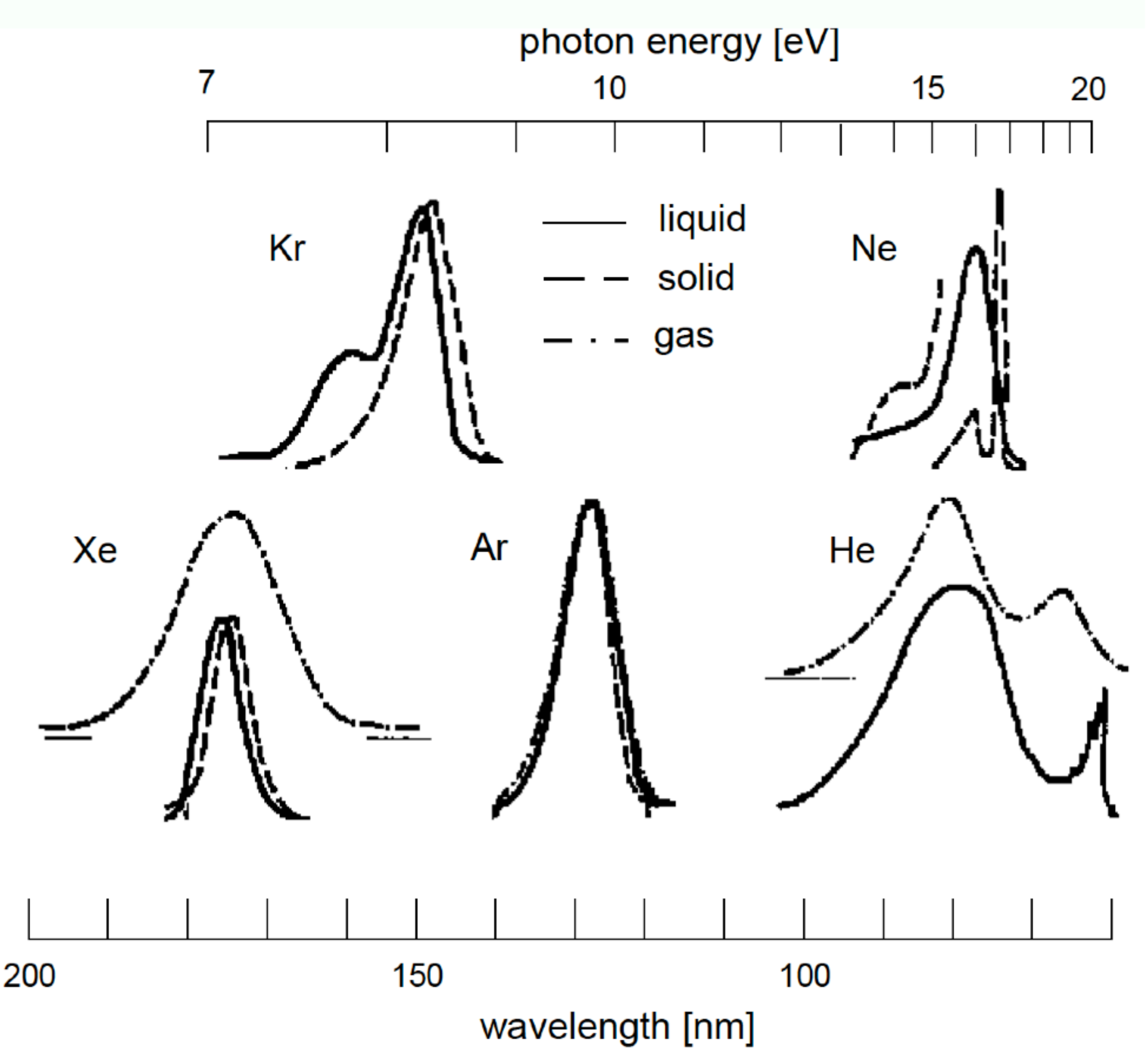
Bi-excitonic quenching (or Penning Quenching): two excitons combine to form an electron-ion pair and a ground -state atom. Hence only a single electron or photon (in case of recombination) is produced instead of two

Scintillation photons

$$\lambda_{LNe} \sim 78\,\mathrm{nm}$$

$$\lambda_{LAr} \sim 128\,\mathrm{nm}$$

$$\lambda_{LXe} \sim 178\,\mathrm{nm}$$



Scintillation photons

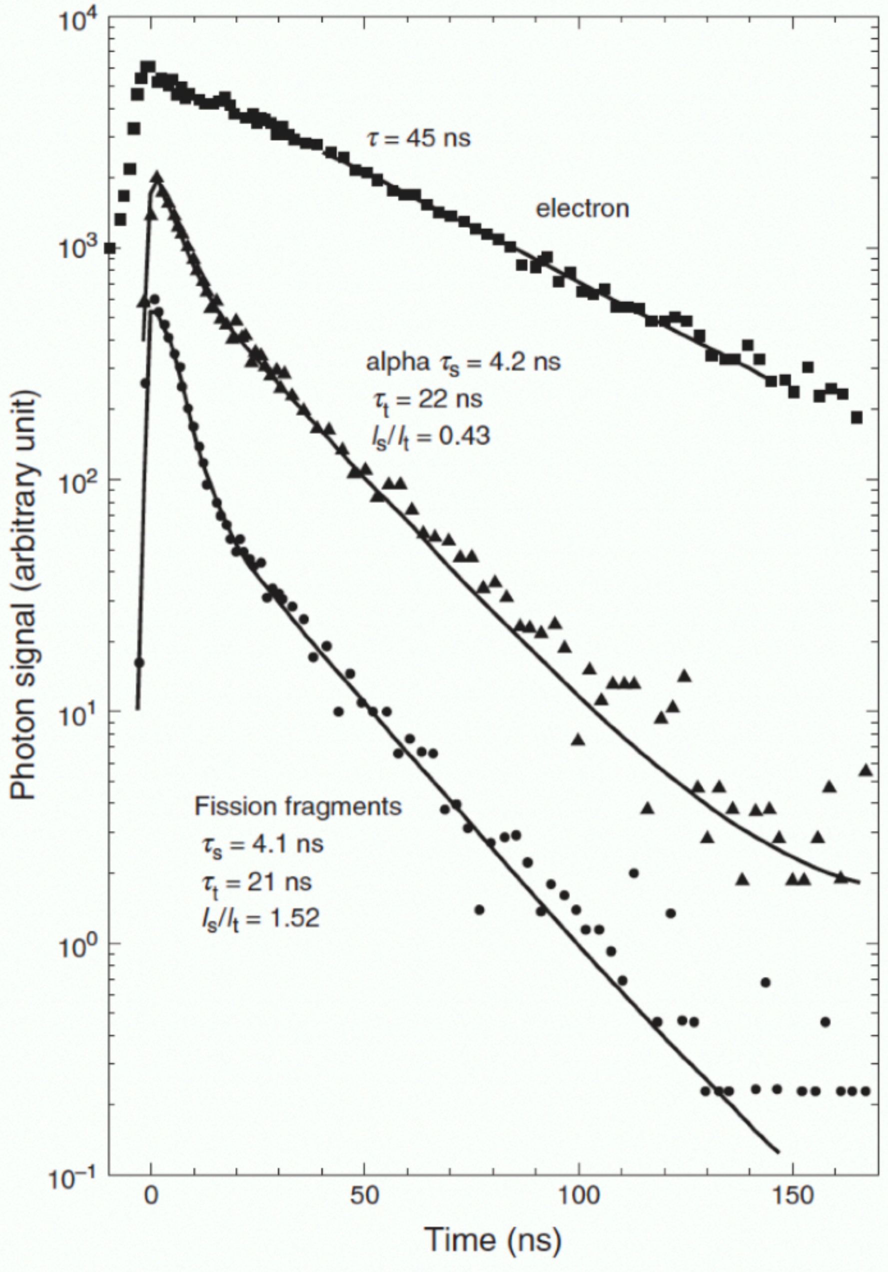
THE SCINTILLATION PULSE SHAPE

The scintillation light from pure noble liquids has two decay components due to the de-excitation of the singlet and triplet states of the excited dimer:

$$R_2^* \rightarrow 2R + h\nu$$

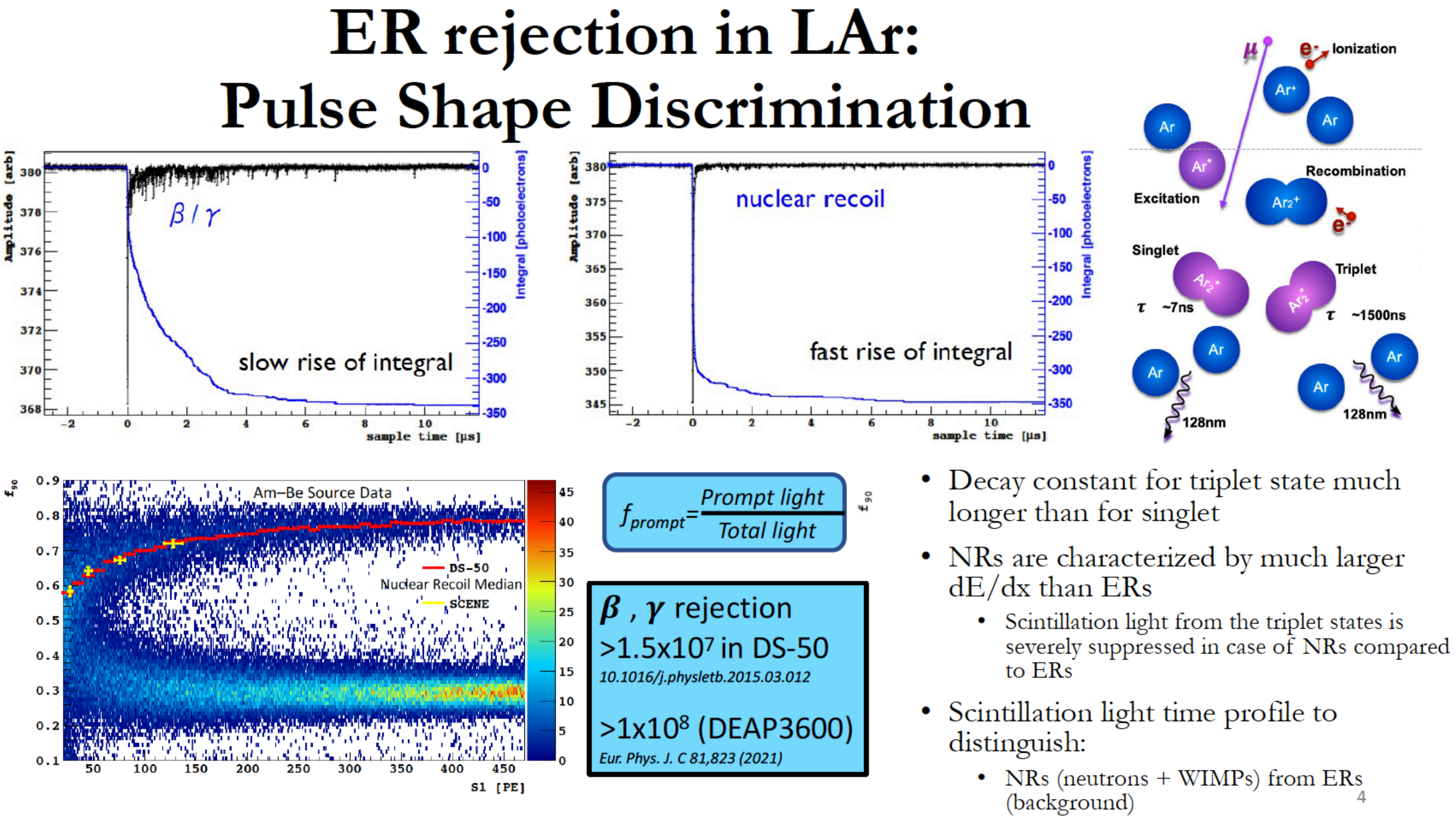
- The figure shows
  - α and fission fragments: the shorter decay time comes from the de-excitation of singlet states, the longer from triplet states
  - Relativistic electrons: only one decay component
- As we shall see later, the difference in pulse shape between different type of particle interactions is used to discriminate among the various particles via PSD

Specie	Time constants
Ne	Few ns vs 15.4 μs
Ar	7 ns vs 1.5 μs
Xe	4 ns vs 27 ns



Decay curves of luminescence from liquid xenon excited by electrons, alpha-particles and fission fragments, without an external electric field

Pulse Shape Discrimination in Ar



ER rejection in LAr: Pulse Shape Discrimination

$$f_{prompt} = \frac{\text{Prompt light}}{\text{Total light}}$$

β, γ rejection

>1.5x10^7 in DS-50

10.1016/j.physletb.2015.03.012

>1x10^8 (DEAP3600)

Eur. Phys. J. C 81,823 (2021)

- Decay constant for triplet state much longer than for singlet
- NRs are characterized by much larger dE/dx than ERs
  - Scintillation light from the triplet states is severely suppressed in case of NRs compared to ERs
- Scintillation light time profile to distinguish:
  - NRs (neutrons + WIMPs) from ERs (background)

4

Scintillation&Ionization mechanism

- An ER or NR in LXe will create a track of excited atoms or free excitons,Xe*, and e-ion pairs, $Xe^+ + e^-$
- Scintillation signal is produced after the creation of the excitons and the e-ion pairs
- Excitons can form excited molecular states, Xe*2 (excimers) by colliding with near Xe atoms.
- Ionized atoms can also form excimers through the process

$$Xe^+ + Xe \rightarrow Xe_2^+,$$

$$Xe_2^+ + e^- \rightarrow Xe^{**} + Xe,$$

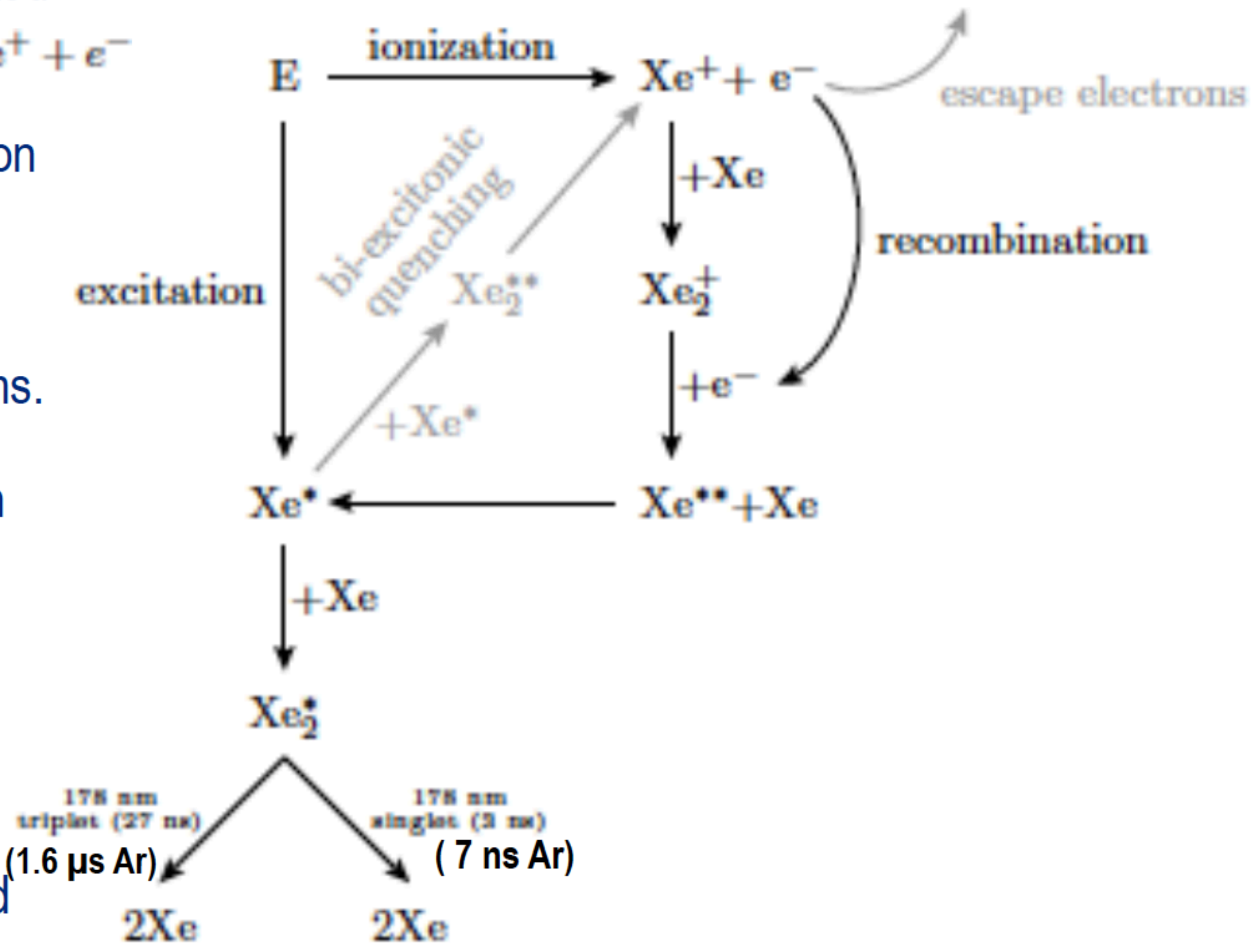
$$Xe^{**} \rightarrow Xe^* + \text{heat},$$

$$Xe^* + Xe \rightarrow Xe_2^*.$$

- The excimers decay to the dissociative ground sate by emission of one scintillation photon

$$Xe_2^* \rightarrow 2Xe + h\nu.$$

- Scintillation with two components due to de-excitation of singlet and triplet state of excimers



- For highly ionizing tracks, such as alphas, quenching of the light can occur before creation of excitons, though “bi-excitonic” mechanism: electron may later recombine producing one photon (whereas two excitons would $Xe^* + Xe^* \rightarrow Xe_2^{**} \rightarrow Xe + Xe^+ + e^-$

Scintillation VS Ionisation

- We define as W_{ph} as the average energy required to produce a single photon:

$$W_{ph} = \frac{E_0}{N_{ex} + N_i} = \frac{W_i}{1 + N_{ex}/N_i} = \frac{W_i}{1 + \alpha}$$

Doke et al, 2002

- E_0 is the energy loss, N_{ex}, N_i are the mean number of excitons and electron-ion pairs, E_i, E_{ex} are the mean energies to ionize and excite the atoms, and $\alpha = N_{ex}/N_i$ (~ 0.2 for LAr, and LXe)

- We assume the efficiency for exciton and electron-ion pair creation are unity, namely

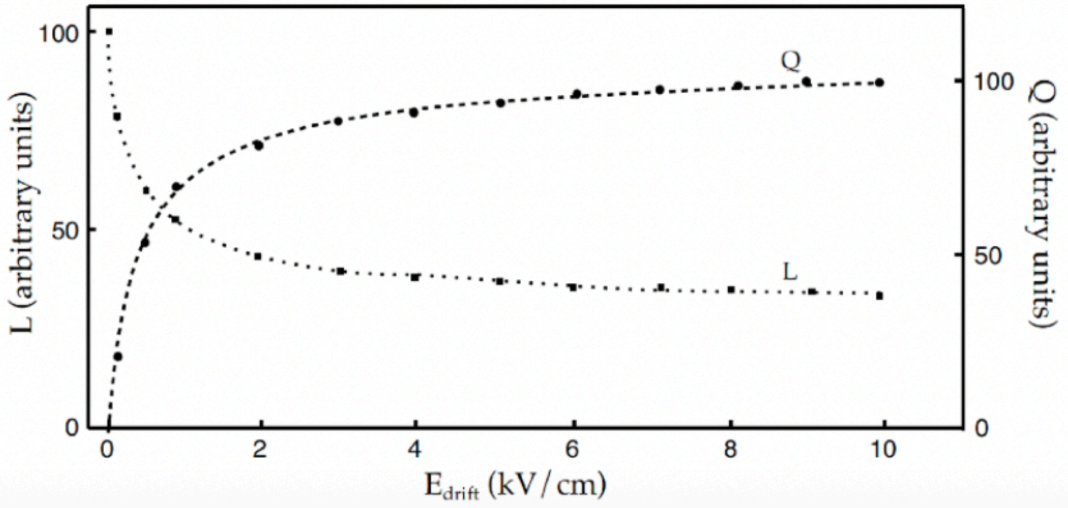
$$N_{ph} = N_{ex} + r \cdot N_i$$

- Where r is the recombination fraction

- If an electric field is applied, one can measure the electrons which do not recombine, **with the amount of extracted charge defined as**

$$N_q = (1 - r) \cdot N_i$$

Charge and light are complementary!

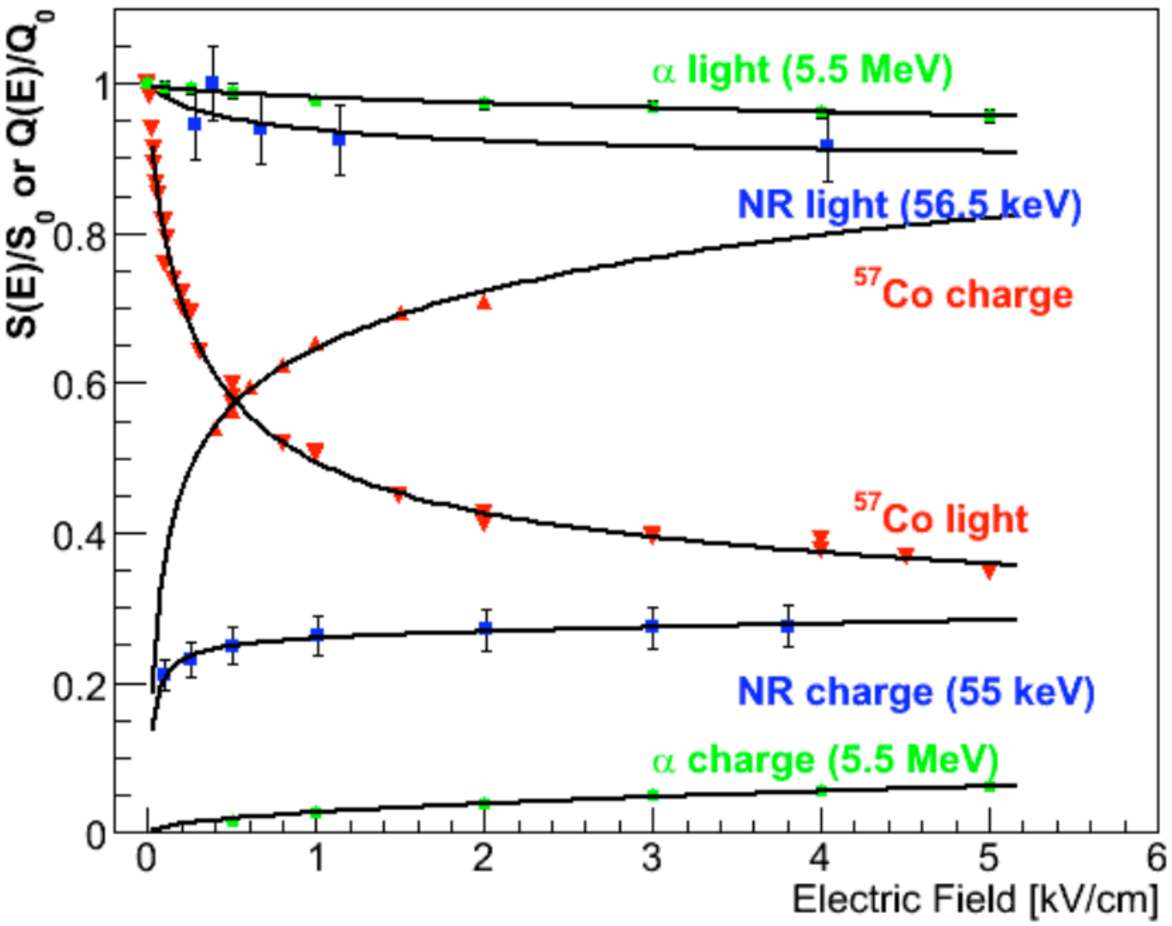


Scintillation/Ionization vs Electric Field

Non-relativistic heavy charged particles, such recoiling nuclei produced in DM particle interactions, in addition loose a substantial amount of energy through elastic collisions with atomic nuclei. Since the signals detected in LXe are from electronic excitation, the amount of energy spent in elastic collisions leads to a quenching of the signal (nuclear quenching)

Along the particle track, excited atoms or excitons, rapidly form excited dimers or excimers, which decay emitting scintillation photons. Without an E-field, electron recombination also leads to excimers and thus to scintillation. Thus the scintillation signal is reduced by the field

The different charge and light ratio for relativistic electrons and non-relativistic particles in LXe provides the basis for discrimination between these two classes and thus between EM background (gamma and electrons) and signal (NRs from DM)



Aprile et al., Phys. Rev. D 72 (2005) 072006

Charge/Light (electron) >> Charge/Light (non relativistic particle)