Direct Search of Dark Matter with Noble Liquid Detectors

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Lecture 1&2

Lecture 1 & 2

- *the DM problem*
- *DM direct detection*
- *signal and backgrounds*
- *noble liquids characteristics*

References and Additional Readings

- *Rate/Signal Definition*

J. D. Lewin and P. F. Smith, Astropart. Phys. 6, (1996) 87.

F. Donato, N. Fornengo, and S. Scopel, Astropart. Phys. 9,(1998) 247.

- *Backgrounds and more*

G. Heusser, Ann. Rev. Nucl. Part. Sci., 45, (1995) 543.

R. J. Gaiskell, Ann. Rev. Nucl. Part. Sci., 54, (2004) 315.

- *Detectors and experimental methods*

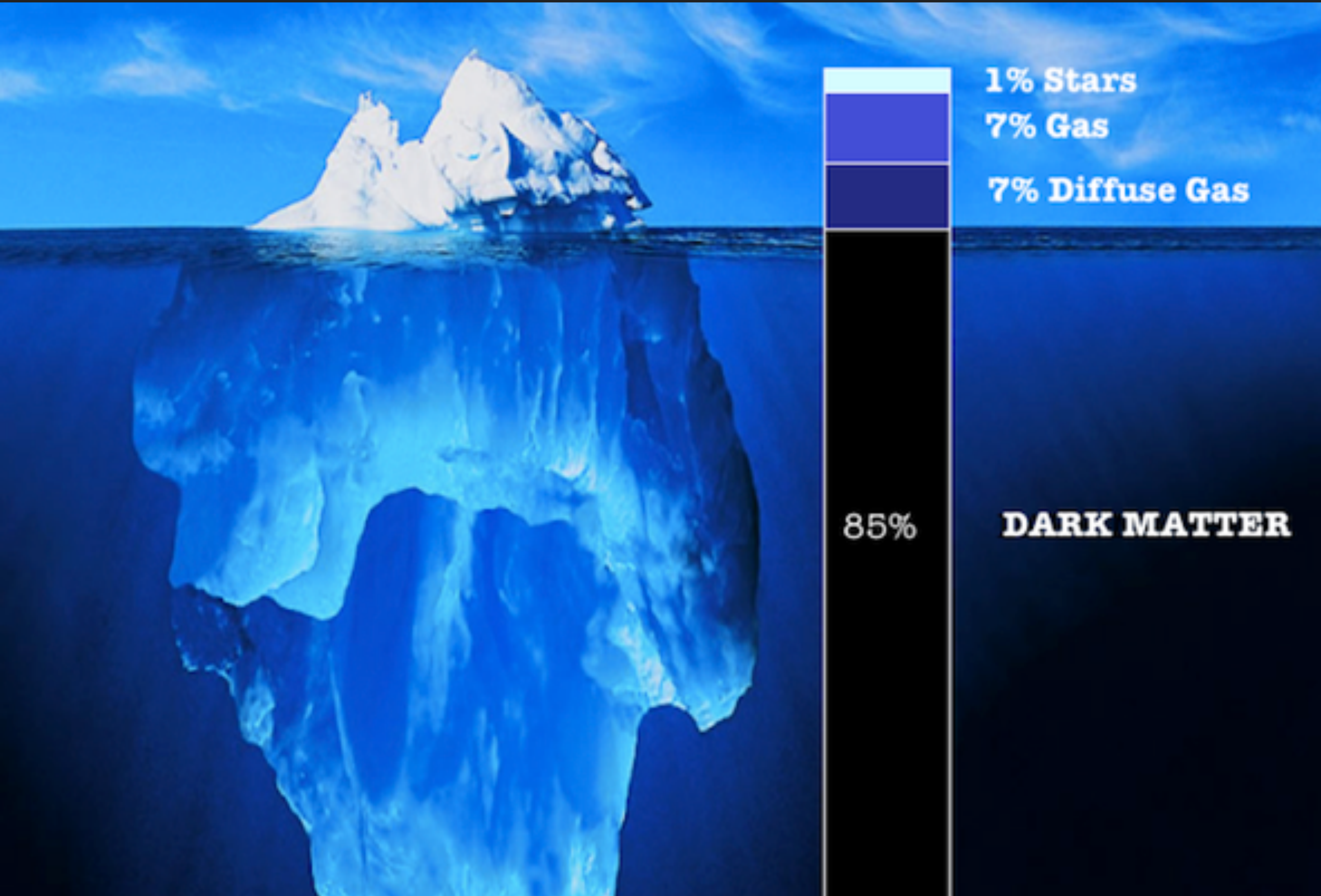
W. R. Leo, *Techniques for nuclear and particle physics experiments*, Springer, (1994)

G. F. Knoll, *Radiation Detection and Measurement*, Wiley, (2000).

- *LXe Detectors and Applications*

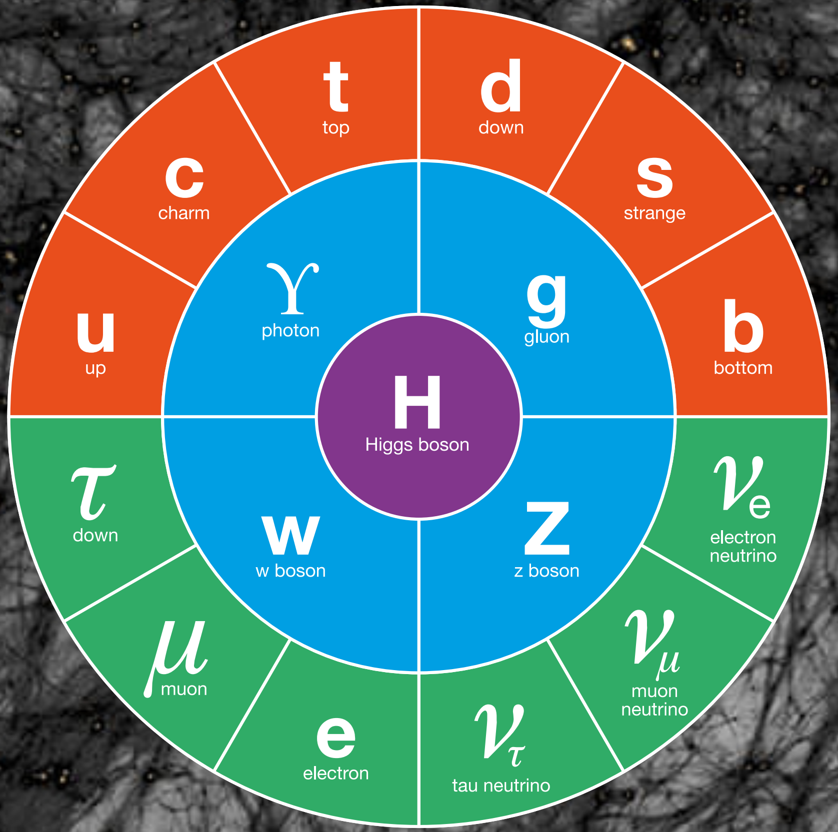
E. Aprile and T. Doke, Review of Modern Physics (2010).

The Dark Matter Problem



What do we know about Dark Matter?

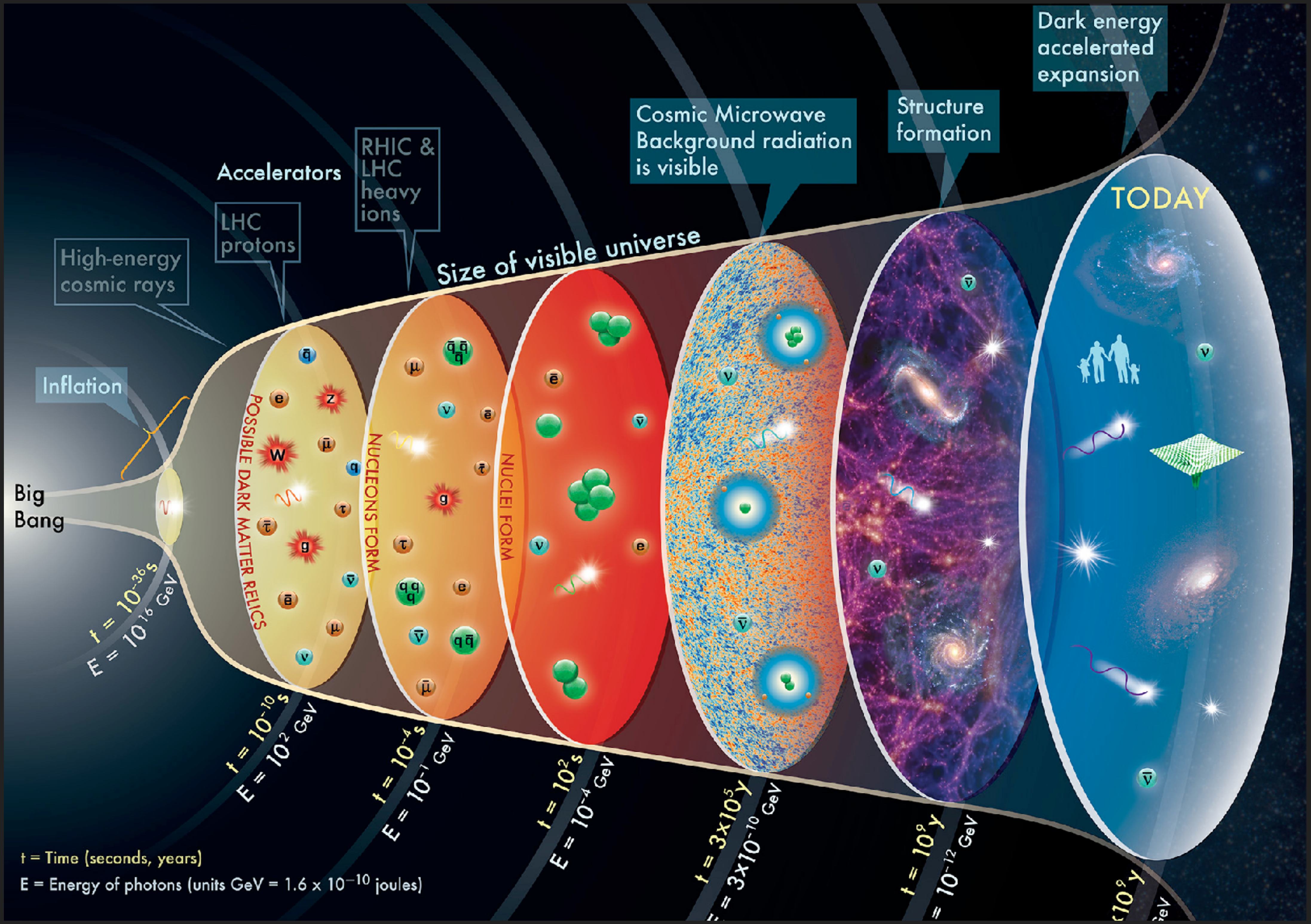
We know how much there is
We know it is cold
We know it is neutral
We know it is non-baryonic
We know it is stable



Pandora's Galaxienhaufen; nasa.gov

Not a Standard Model Particle

Leading Hypothesis: a new particle created in the early Universe

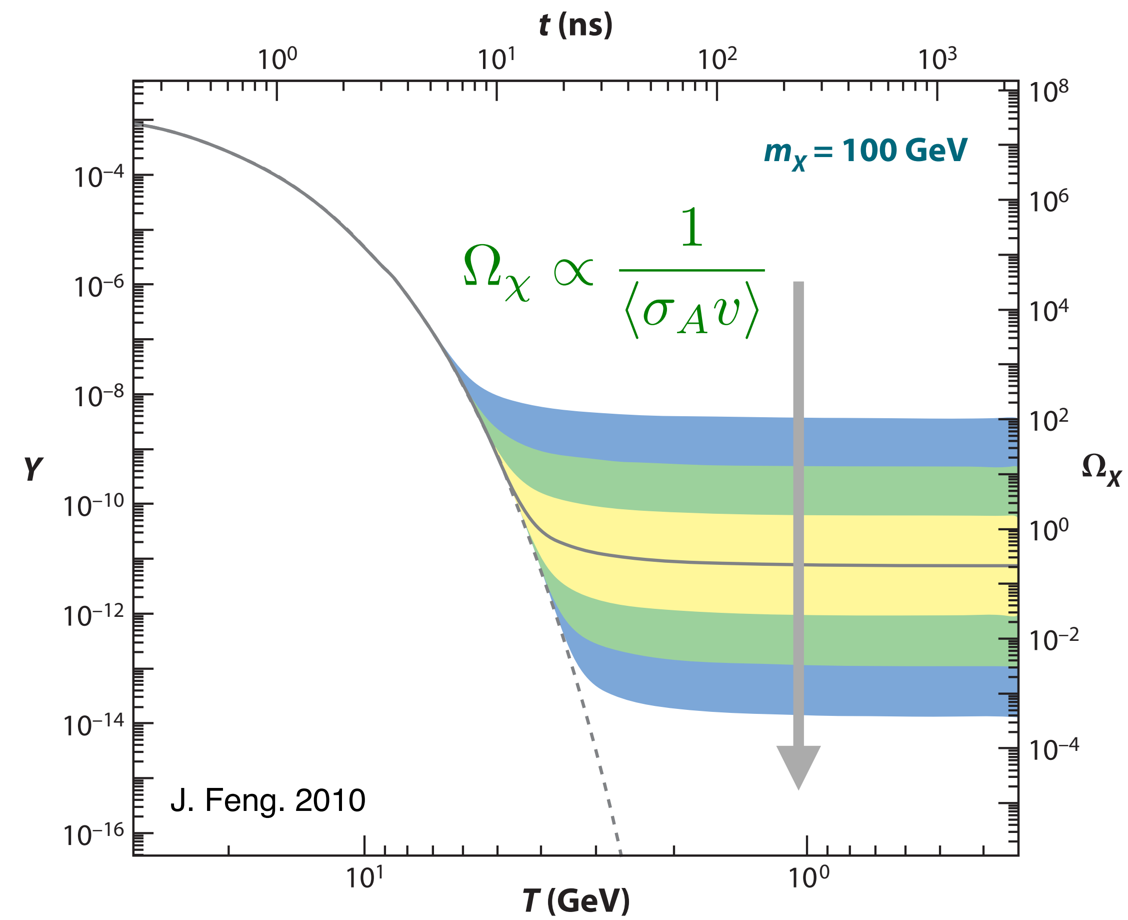


Weakly Interacting Massive Particles

- **In thermal equilibrium in the early Universe**

- Freeze-out: *when annihilation rate drops below expansion rate and M_{WIMP} > T ('cold')*

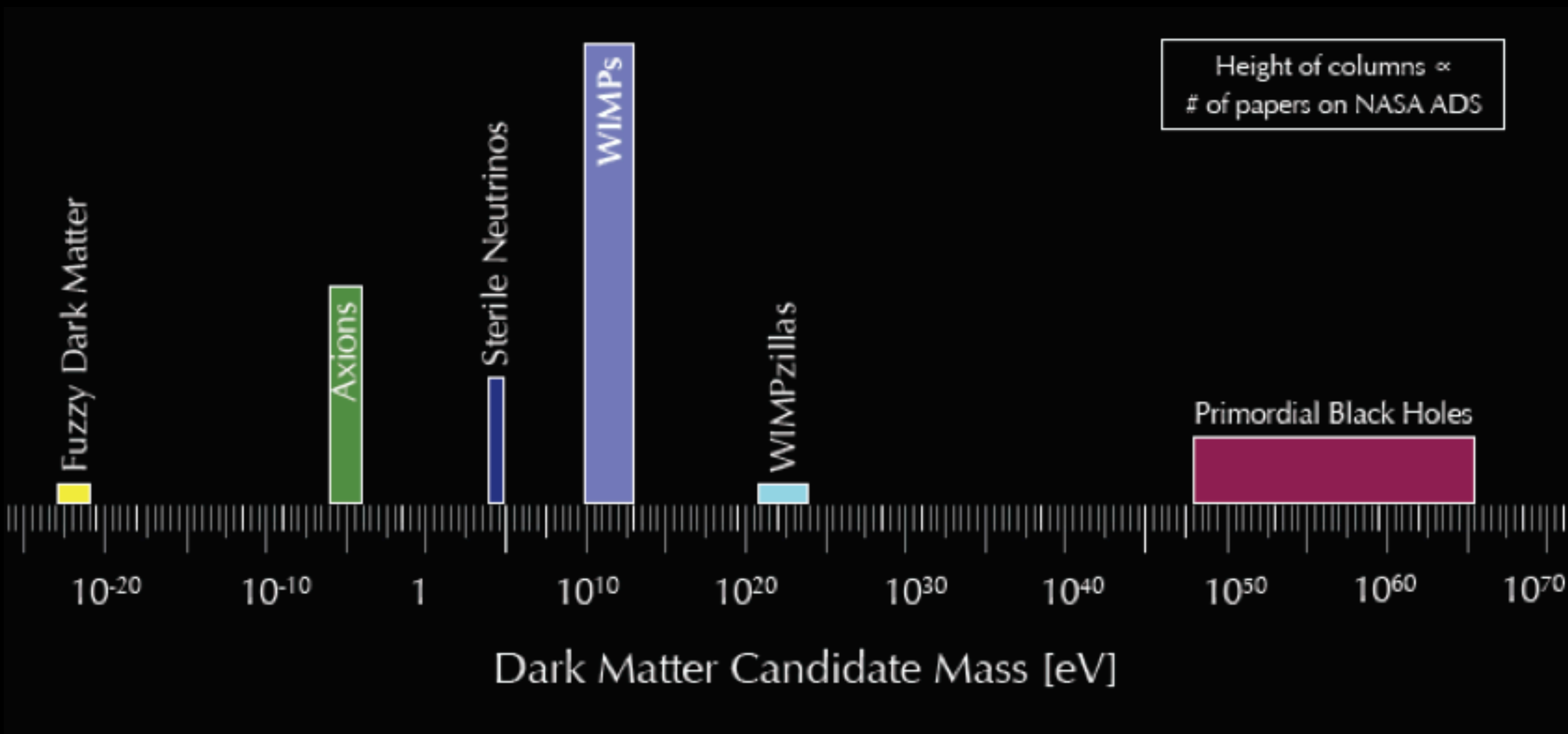
- Their relic density can account for the dark matter *if the annihilation cross section is weak (pb range)*



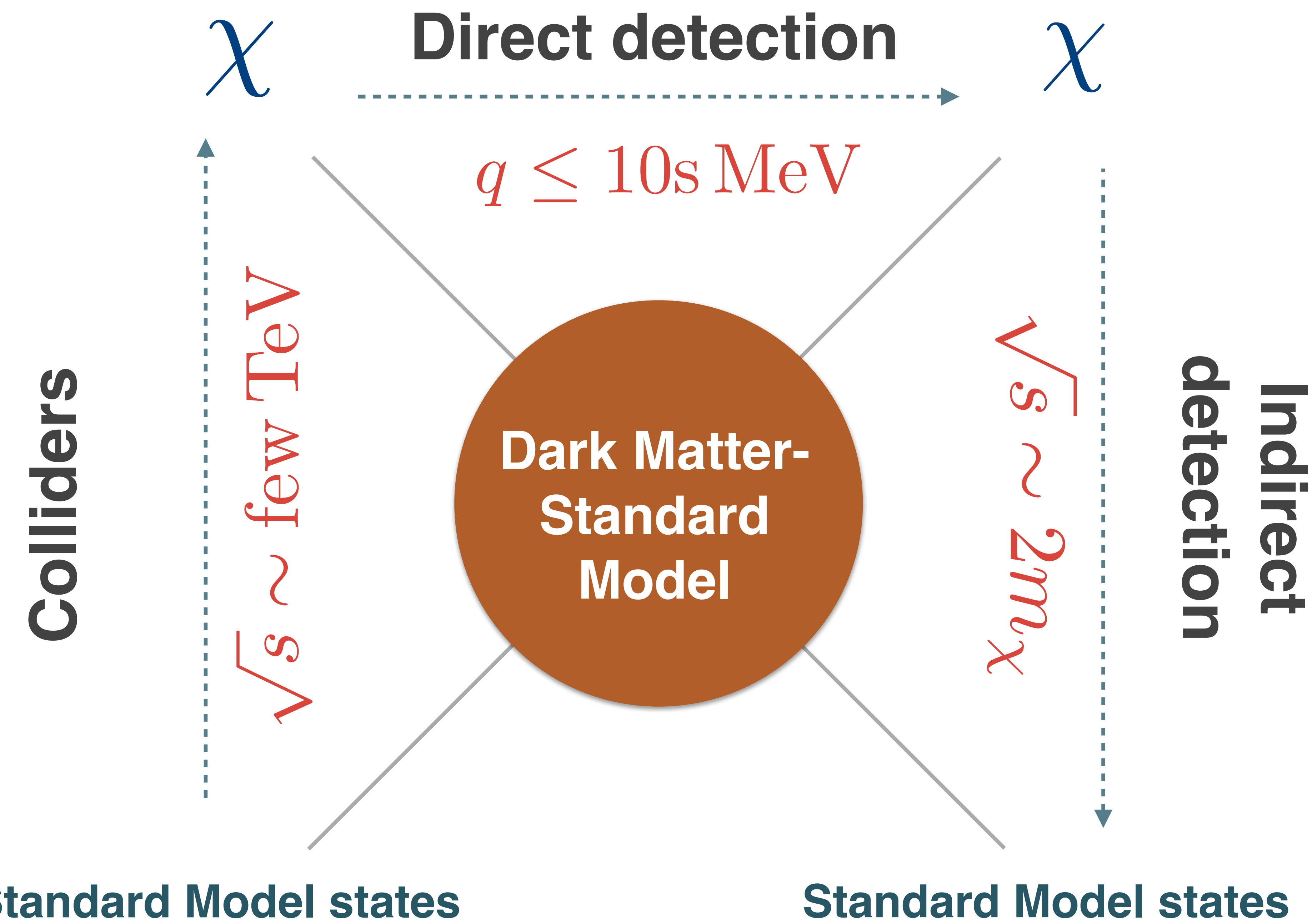
$$\Omega_\chi h^2 \simeq 3 \times 10^{-27} cm^3 s^{-1} \frac{1}{\langle \sigma_A v \rangle}$$

$$\Omega_\chi h^2 = \Omega_{cdm} h^2 \simeq 0.1141 \Rightarrow \langle \sigma_A v \rangle \simeq 3 \times 10^{-26} cm^3 s^{-1}$$

Dark Matter Particle Candidates



Search for Weakly Interacting Massive Particles



Dark Matter Direct Detection

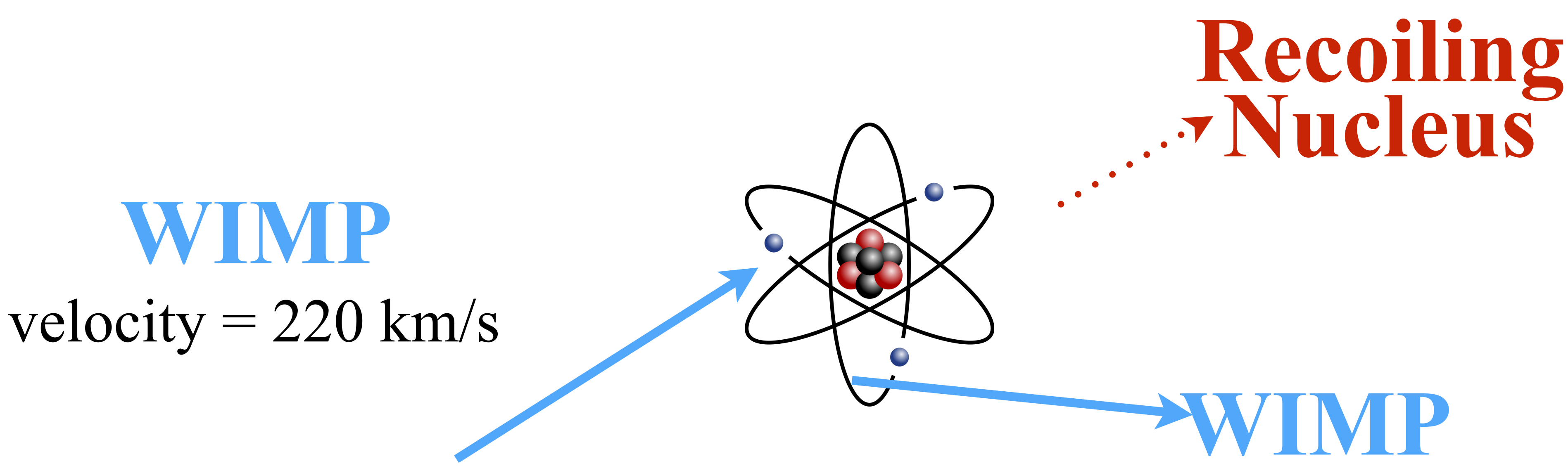
PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.



Direct Detection of WIMPs

- With the WIMP-nucleus speed being of the order of 100 km s^{-1}, the average momentum transfer

$$\langle q \rangle \simeq \mu \langle v \rangle$$

- will be in the range between 3 MeV/c - 30 MeV/c for WIMP and nucleus masses in the range 10 GeV/c^2 - 100 GeV/c^2. Thus the elastic scattering occurs in the extreme non-relativistic limit and the scattering will be isotropic in the center of mass frame

- The *de Broglie wavelength* corresponding to a momentum transfer of q = 10 MeV/c

$$\lambda = \frac{\hbar}{q} \simeq 20\,\mathrm{fm} > r_0 A^{1/3} = 1.25\,\mathrm{fm}\,A^{1/3}$$

- is larger than the size of most nuclei, thus the scattering amplitudes on individual nucleons will add coherently (coherence loss will be important for heavy nuclei and/or WIMPs, and WIMPs in the tail of the velocity distribution)

Scattering cross section on nuclei

- In general, interactions leading to WIMP-nucleus scattering are parameterized as:
  - **scalar interactions** (coupling to WIMP mass, from scalar, vector, tensor part of L)

$$\sigma_{SI} \sim \frac{\mu^2}{m_\chi^2}[Zf_p + (A-Z)f_n]^2$$

f_p, f_n: scalar 4-fermion couplings to p and n

=> nuclei with large A favourable (but nuclear form factor corrections)

  - **spin-spin interactions** (coupling to the nuclear spin J_N, from axial-vector part of L)

$$\sigma_{SD} \sim \mu^2 \frac{J_N+1}{J_N}(a_p\langle S_p\rangle + a_n\langle S_n\rangle)^2$$

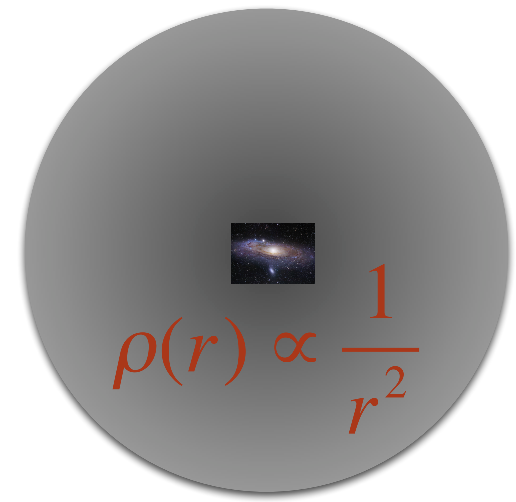
a_p, a_n: effective couplings to p and n; $\langle S_p\rangle$ and $\langle S_n\rangle$ expectation values of the p and n spins within the nucleus

=> nuclei with non-zero angular momentum (corrections due to spin structure functions)

WIMP flux on Earth

- For a typical WIMP mass of 100 GeV/c^2, the expected WIMP flux on Earth (for the 'standard local density' value of 0.3 GeVcm-3) is:

$$\phi_\chi = \frac{\rho_\chi}{m_\chi} \times \langle v \rangle = 6.6 \times 10^4 \,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$



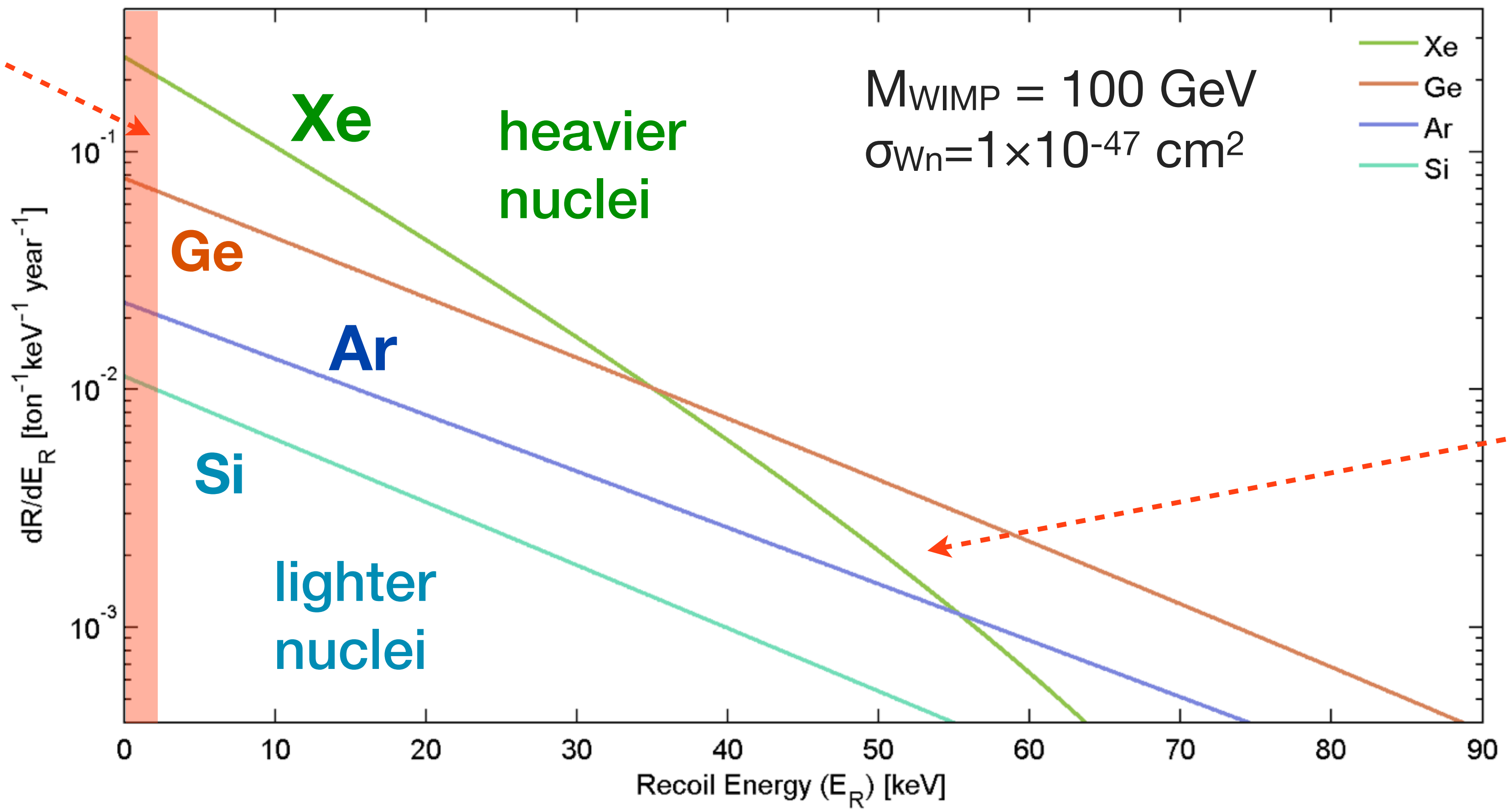
- This flux is sufficiently large that, even though WIMPs are weakly interacting, a small but potentially measurable fraction will elastically scatter off nuclei in an Earth-bound detector
- Direct dark matter detection experiments aim to detect WIMPs via nuclear recoils which are caused by WIMP-nucleus elastic scattering
- Assuming a scattering cross section of 10^{-38} cm^2, the expected rate (for a nucleus with atomic mass A = 100) would be:

$$R = \frac{N_A}{A} \times \phi_\chi \times \sigma \sim 0.13 \,\mathrm{events\,kg}^{-1}\mathrm{yr}^{-1}$$

Expected Rate in a Detector

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

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



F²(E_R)

Expected Rate in a Detector

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{\sqrt{(m_N E_{th})/(2\mu^2)}}^{v_{max}} dv\, f(v) v \frac{d\sigma}{dE_R}$$

Detector physics

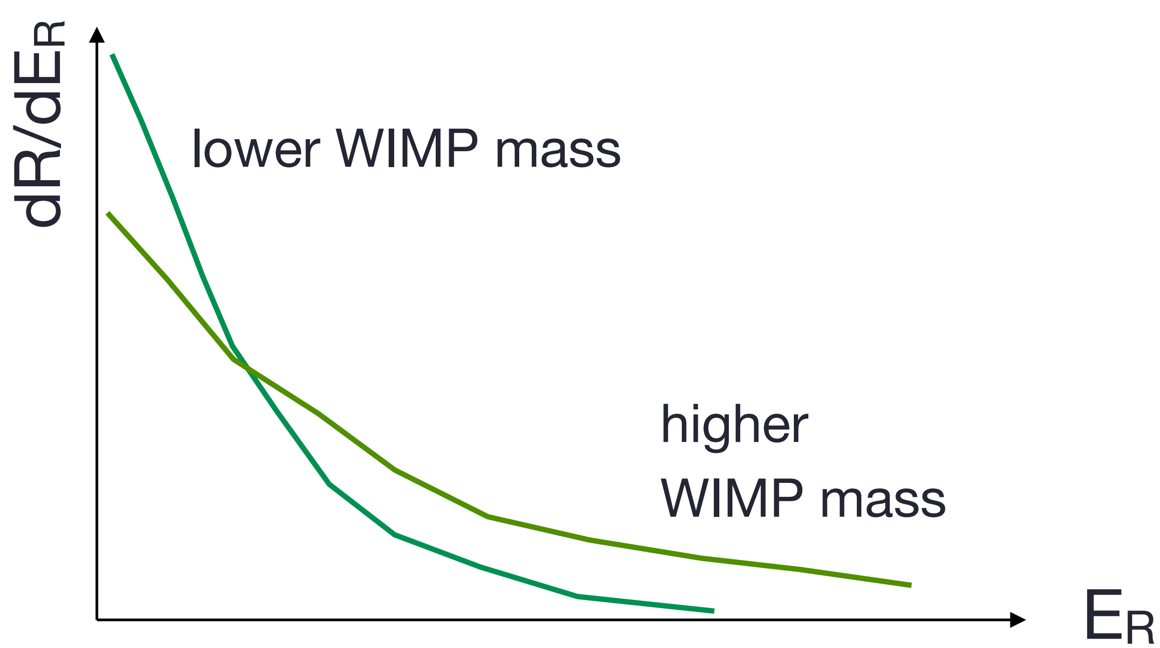
N_N, E_{th}

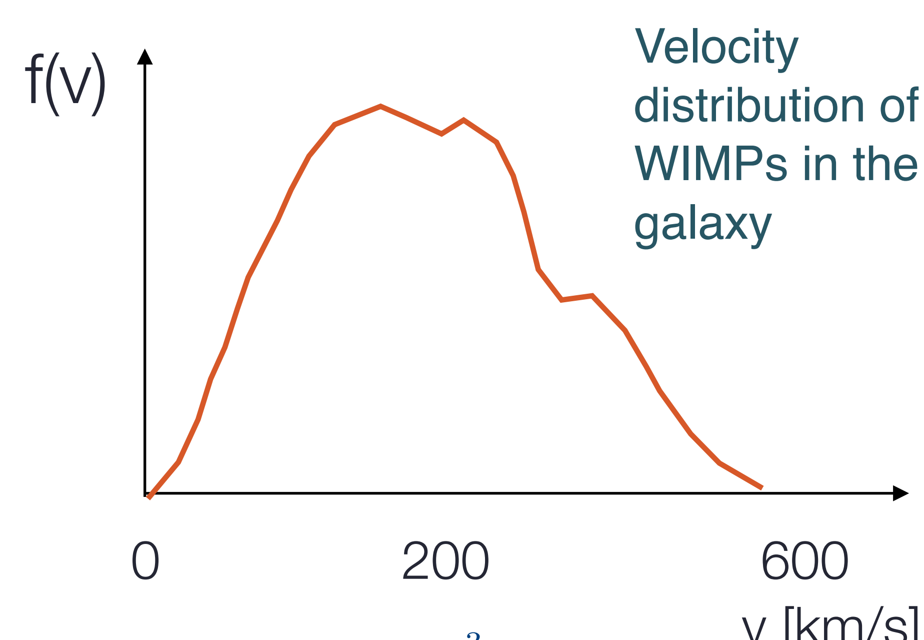
Particle/nuclear physics

$m_W, d\sigma/dE_R$

Astrophysics

$\rho_0, f(v)$

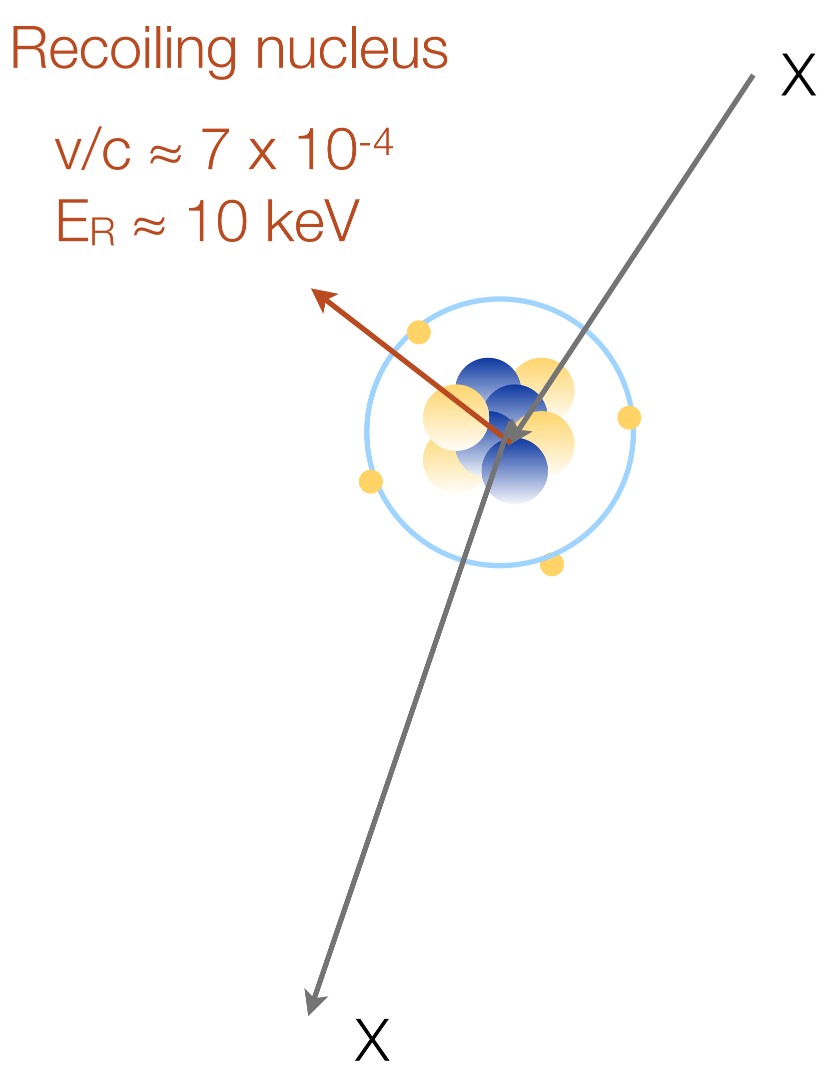




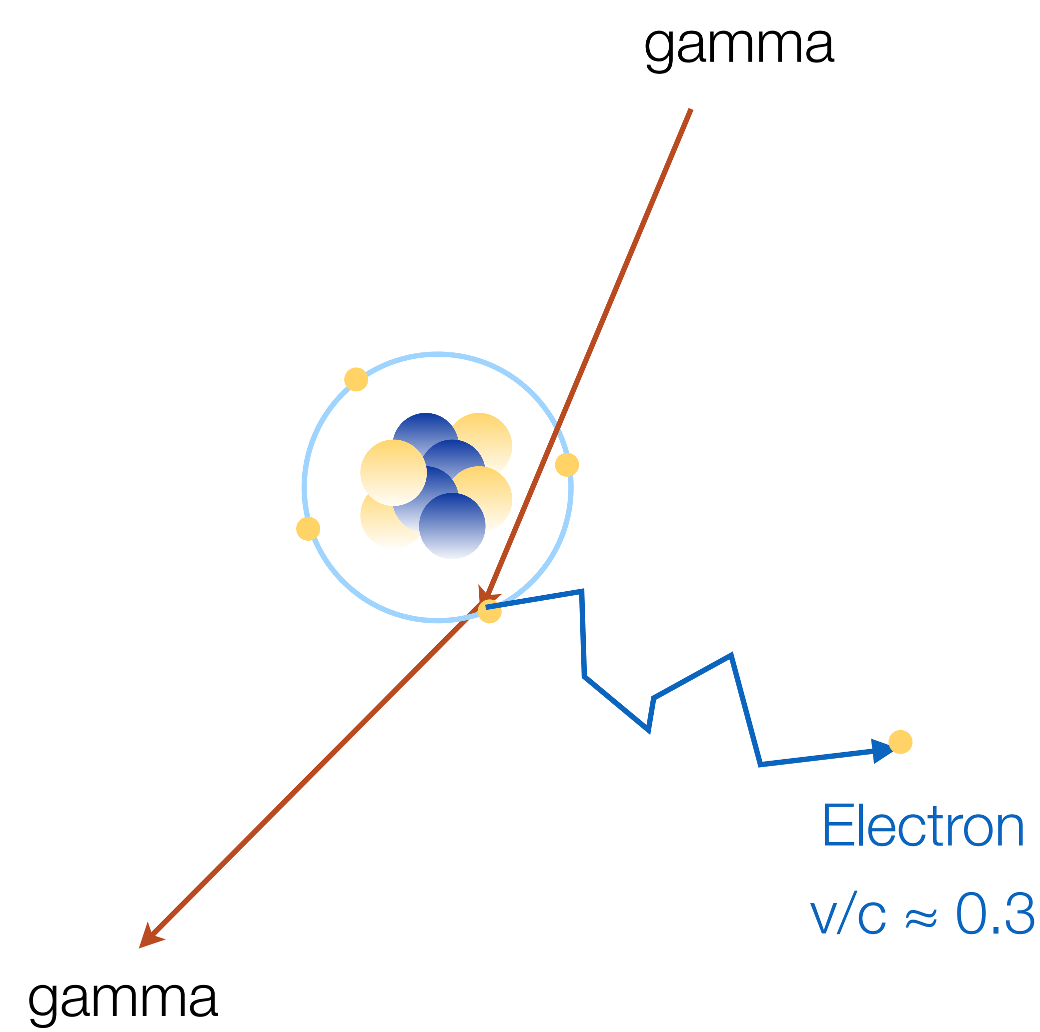
$\rho(R_0) = 0.2 - 0.56\,\mathrm{GeV\,cm^{-3}} = 0.005 - 0.015\,\mathrm{M_\odot\,pc^{-3}}$

Detection of WIMPs: Signal and Backgrounds

Signal (WIMPs)



Background (gamma-, beta-radiation)



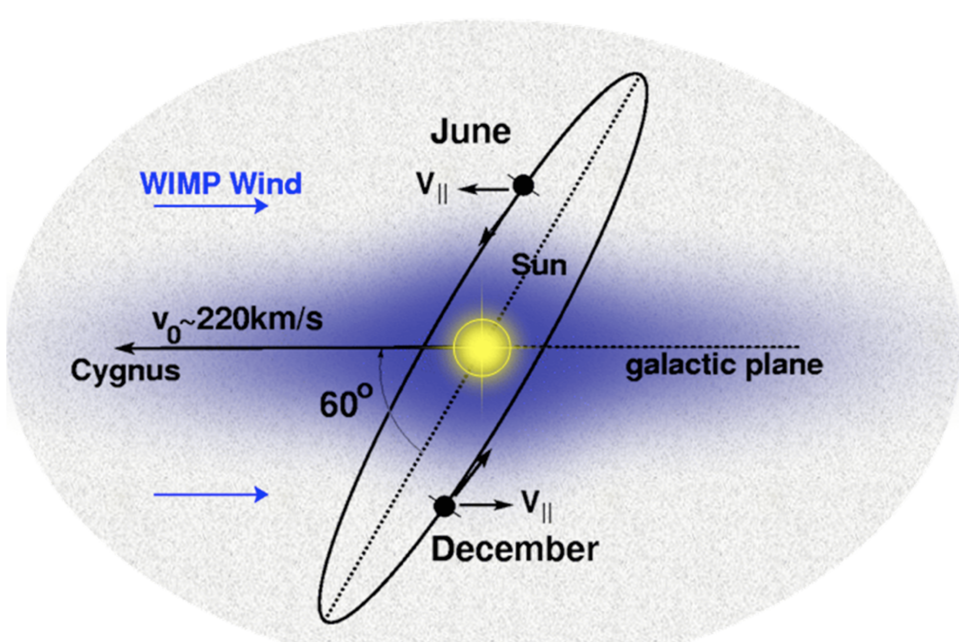
WIMP Signatures

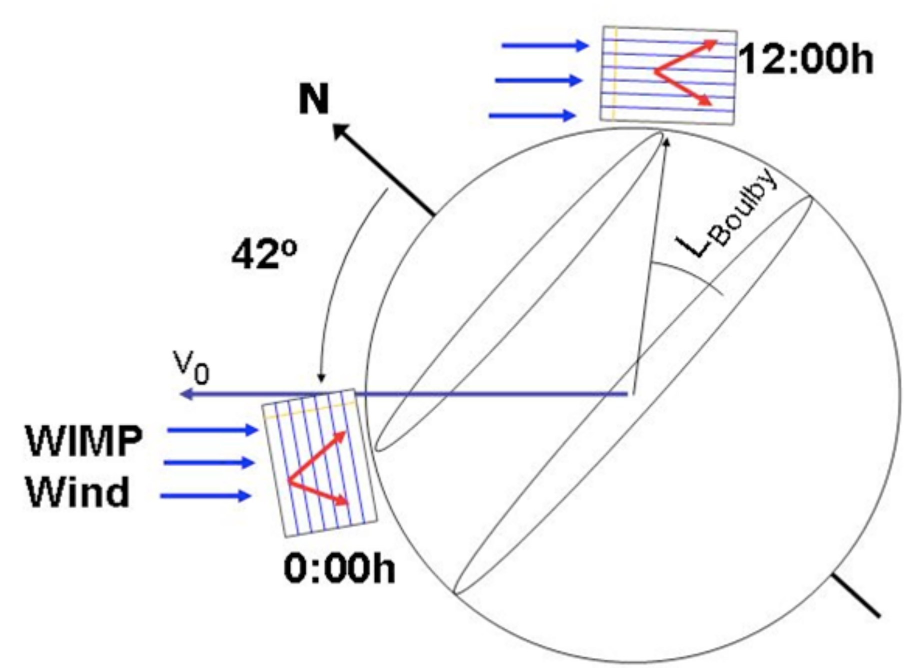
- Nuclear recoils: single scatters with uniform distribution in target volume

- A^2 & $F^2(Q)$ Dependence: recoil rate is energy dependent due to kinematics and WIMP velocity distribution. Hence we can test consistency of signal with different targets (SI and SD)

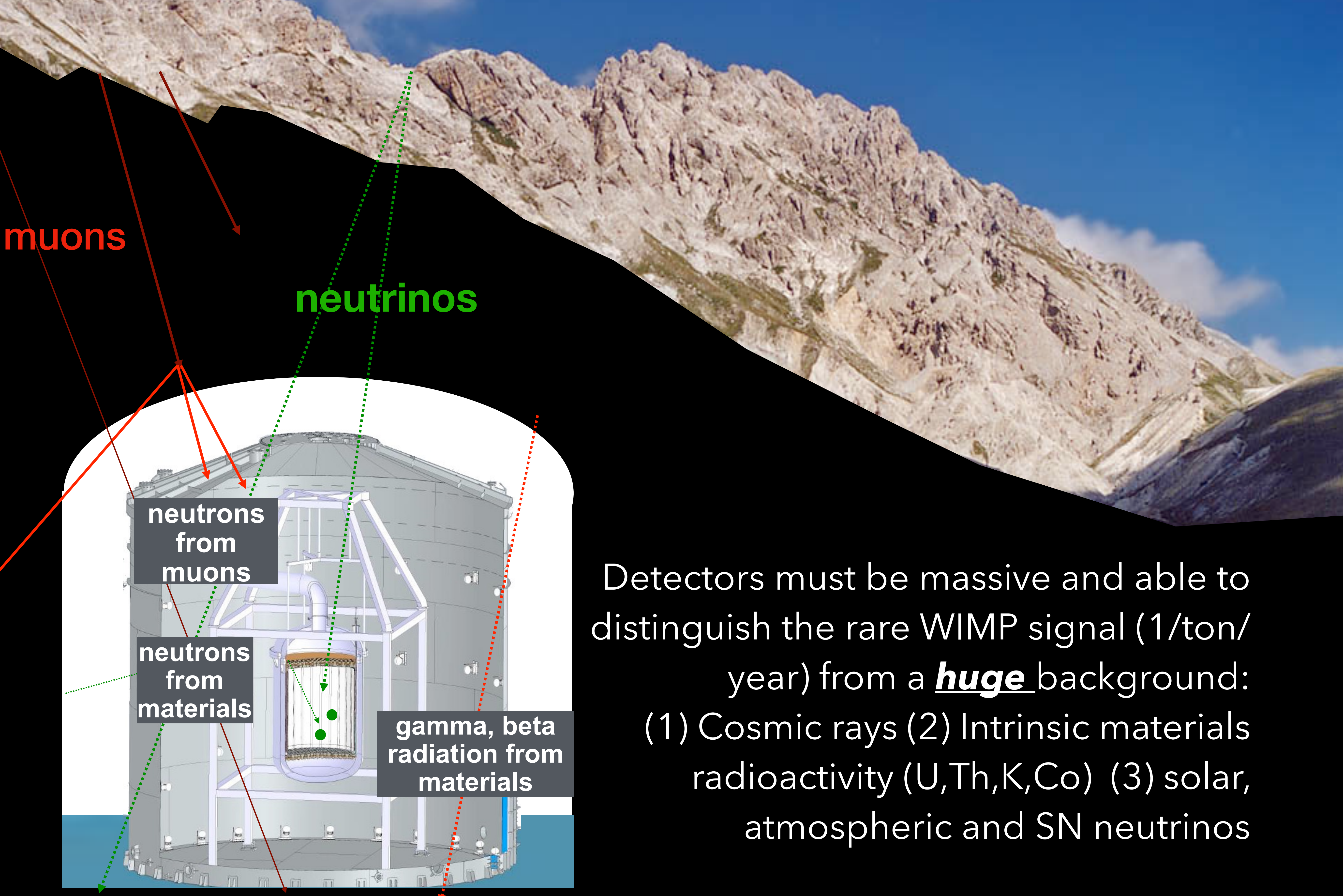
- Annual Modulation: Earth annual rotation around Sun: orbital velocity has a component that is anti-parallel to WIMP wind in summer and parallel to it in winter. So apparent WIMP velocity (and hence the rate) will increase (decrease) with season: rate modulation with a period of 1 year and phase ~2 June; small effect (few %) among other effects which also have seasonal dependence

- Diurnal Direction Modulation: Earth rotation about its axis, oriented at angle w/respect to WIMP "wind" , change the signal direction by 90 degree every 12 hrs. 30% effect.





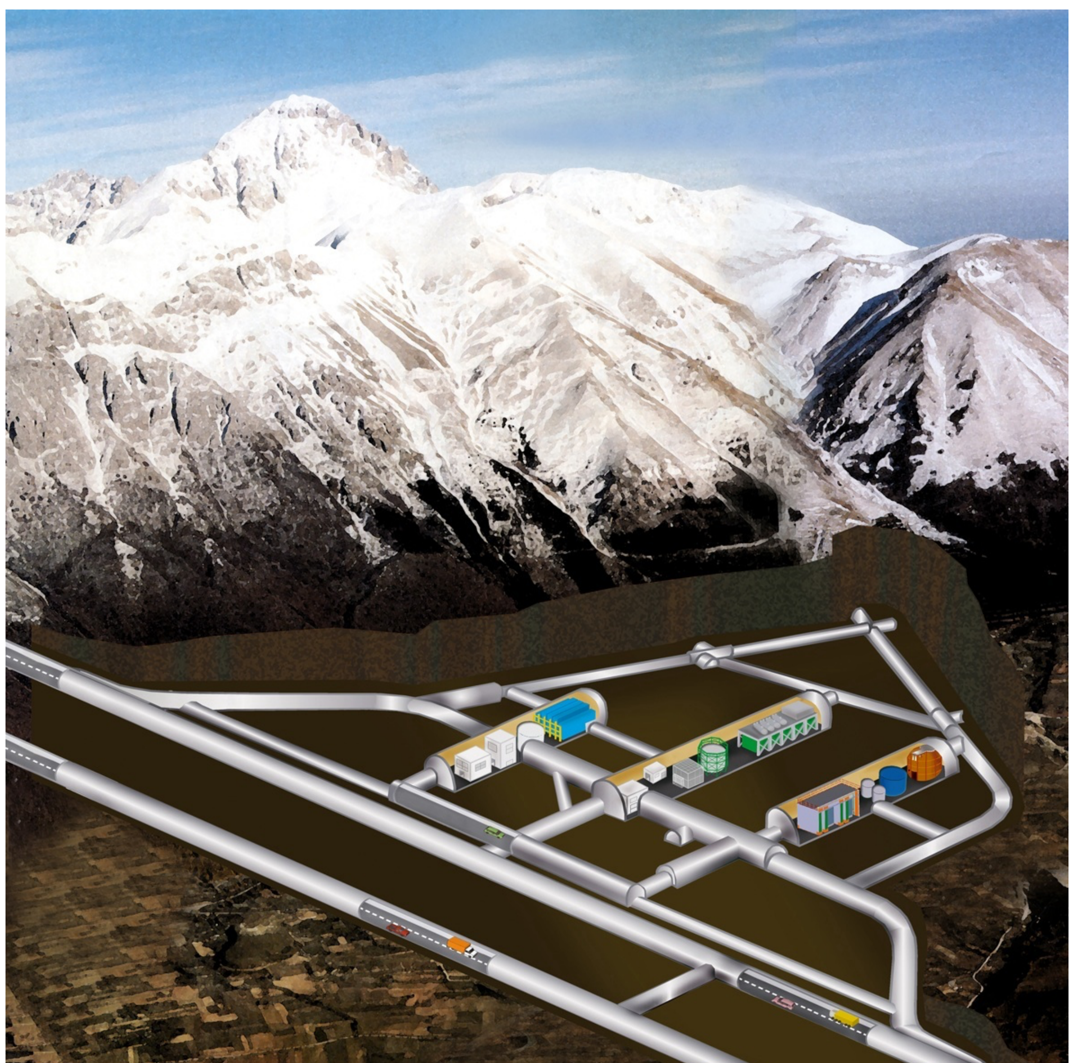
an experimental challenge



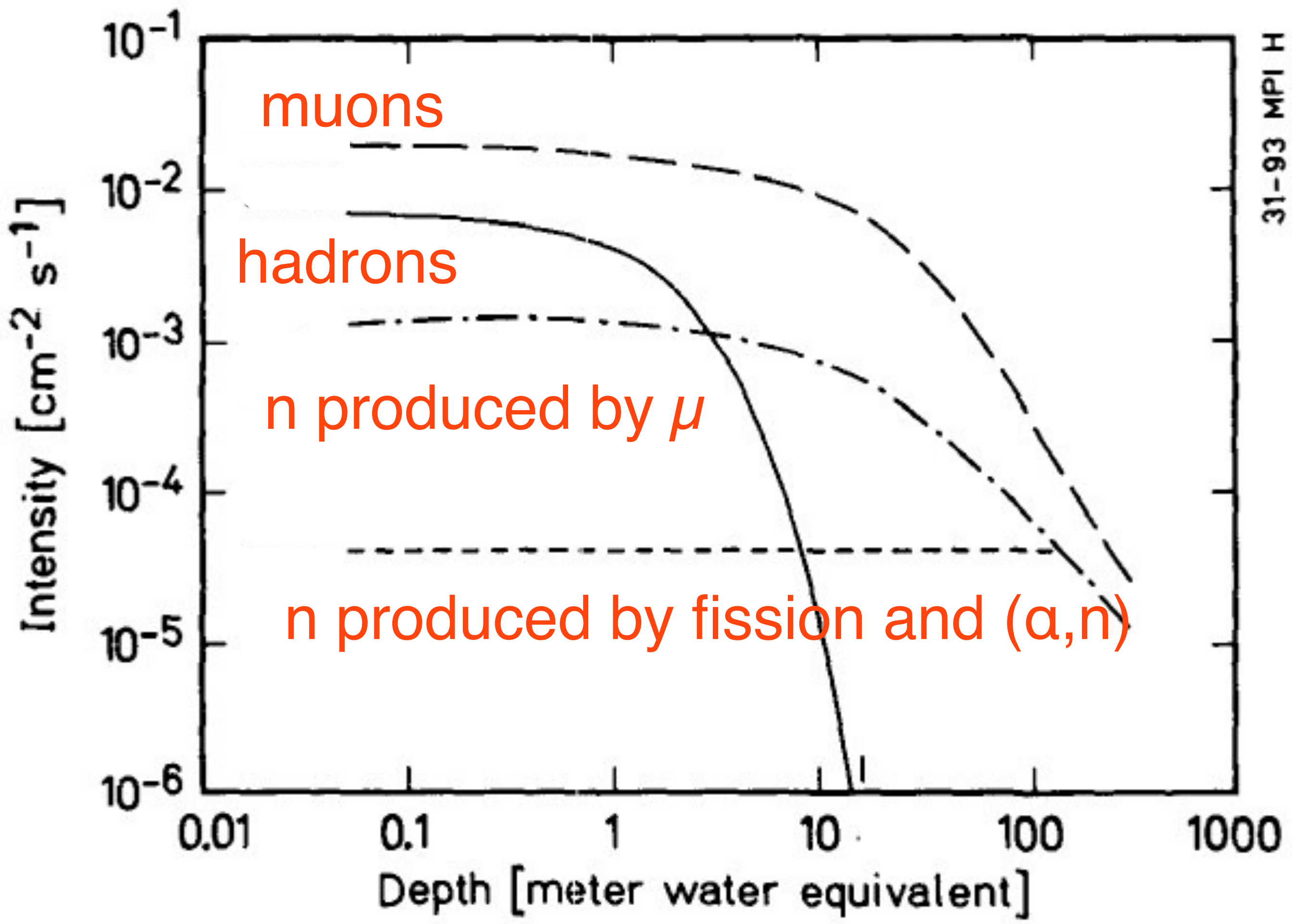
Detectors must be massive and able to distinguish the rare WIMP signal (1/ton/year) from a ***huge*** background:
(1) Cosmic rays (2) Intrinsic materials radioactivity (U,Th,K,Co) (3) solar, atmospheric and SN neutrinos

Backgrounds in Dark Matter Detectors

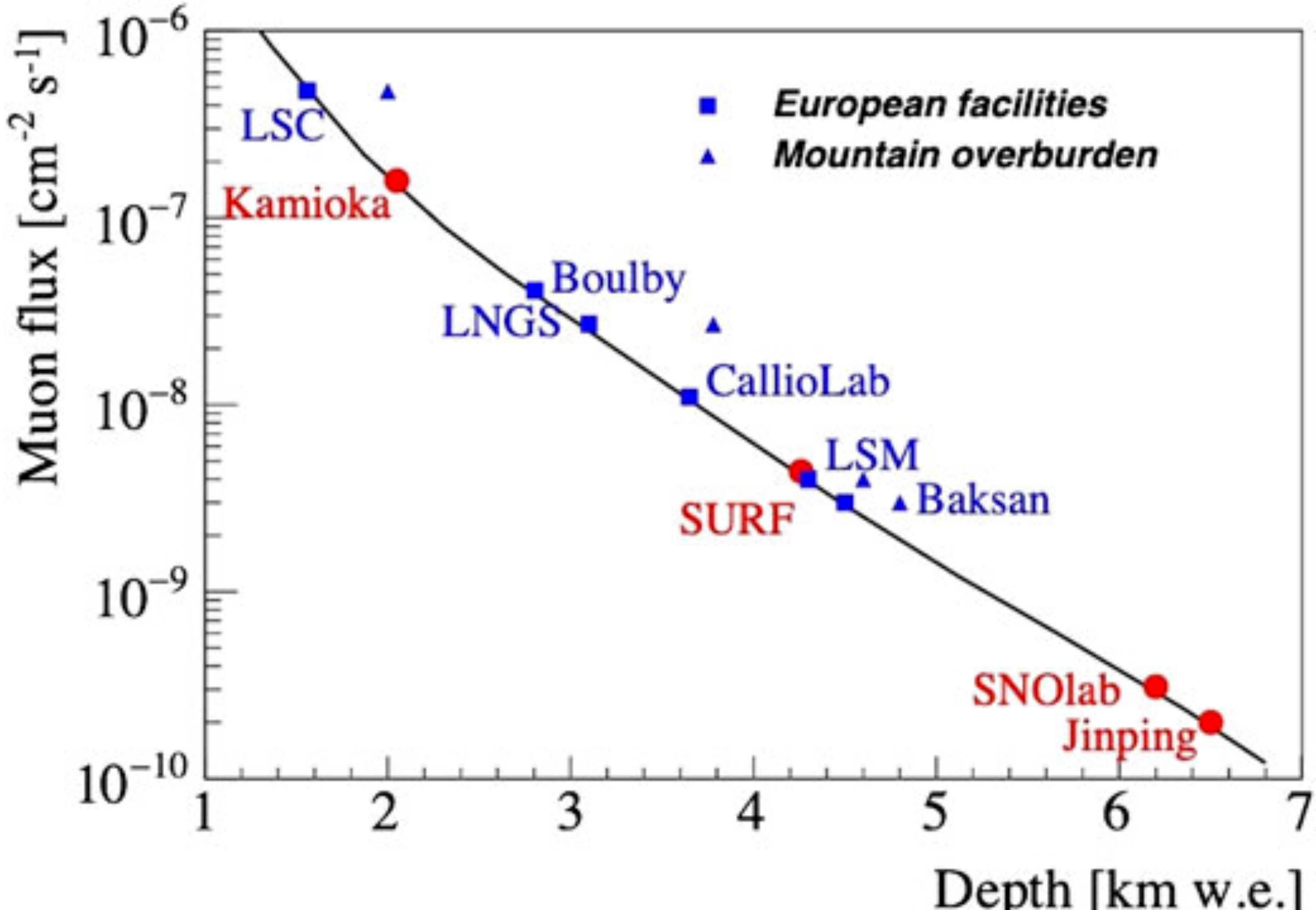
- **Cosmic rays and secondary/tertiary particles: go underground**
- Cosmogenic neutrons and cosmogenic activation are proportional to muon flux
- Hadronic component (n, p): reduced by few meter water equivalent (m w. e.)



Flux of cosmic ray secondaries and tertiary-produced neutrons in a typical Pb shield vs shielding depth
Gerd Heusser, 1995

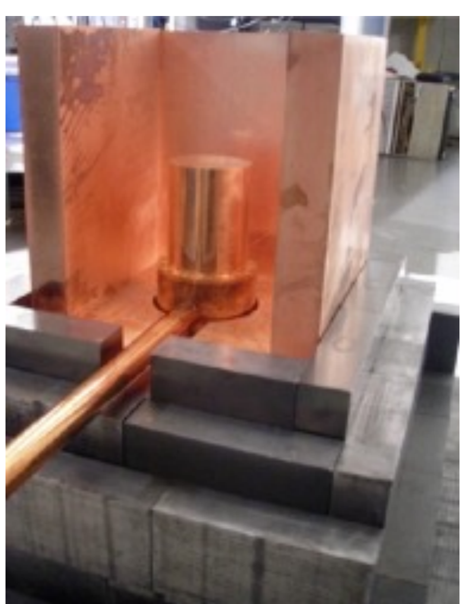


Worldwide Laboratories



Backgrounds in Dark Matter Detectors

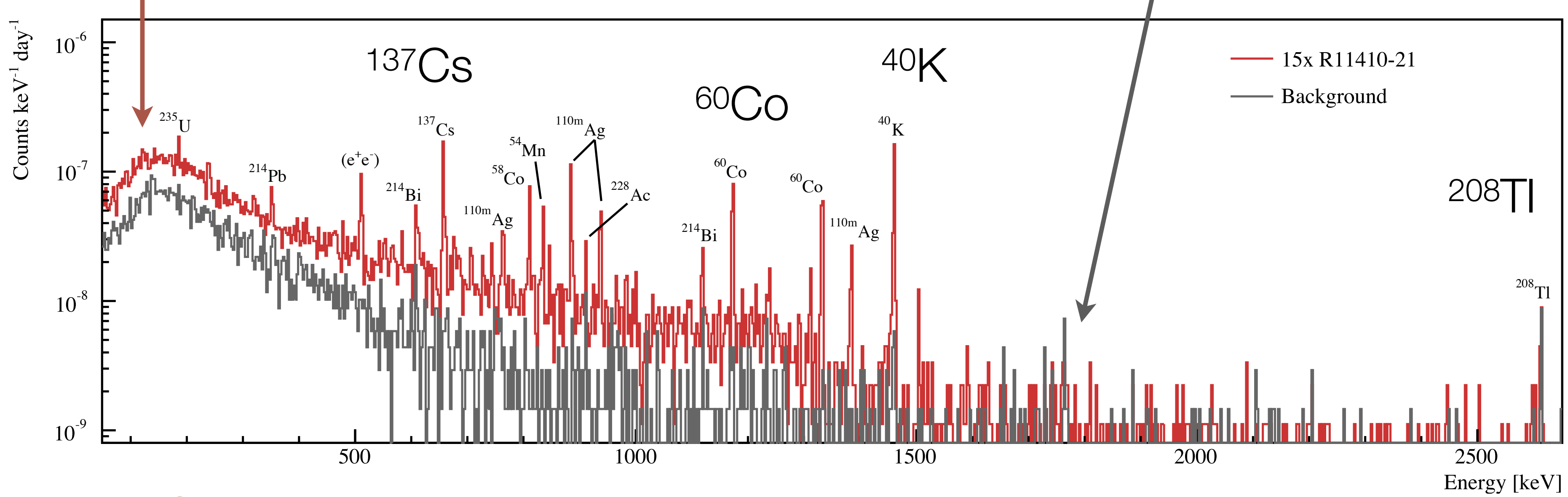
- **Internal radioactivity:**
- ^{238}U, ^{238}Th, ^{40}K, ^{137}Cs, ^{60}Co, ^{39}Ar, ^{85}Kr, ... decays in the detector materials, target medium and shields
- Ultra-pure Ge spectrometers (as well as other methods) are used to screen the materials before using them in a detector, down to parts-per-billion (ppb) (or lower) levels



PMT sample

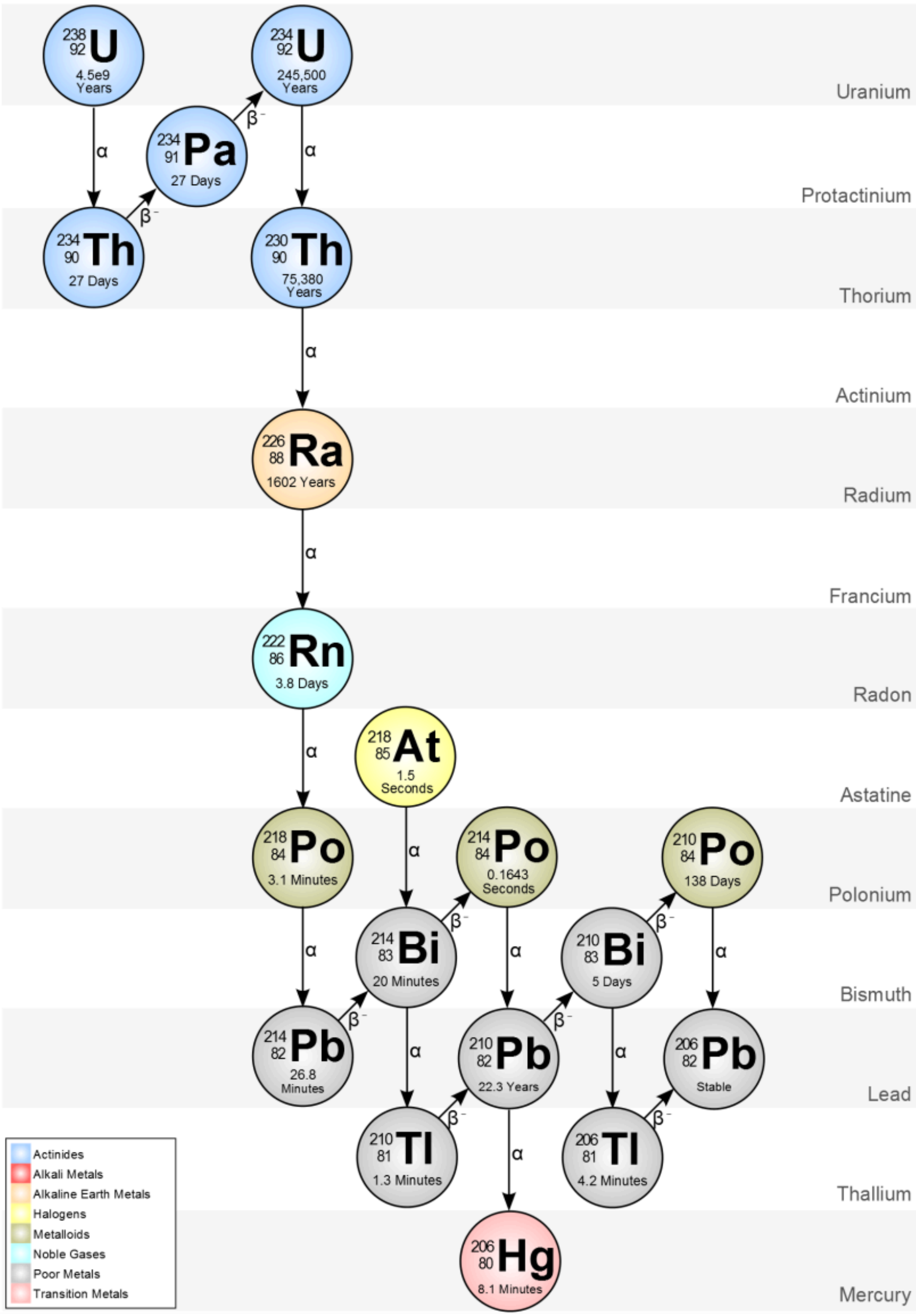
^{226}Ra/^{228}Th:
~1 mBq/PMT

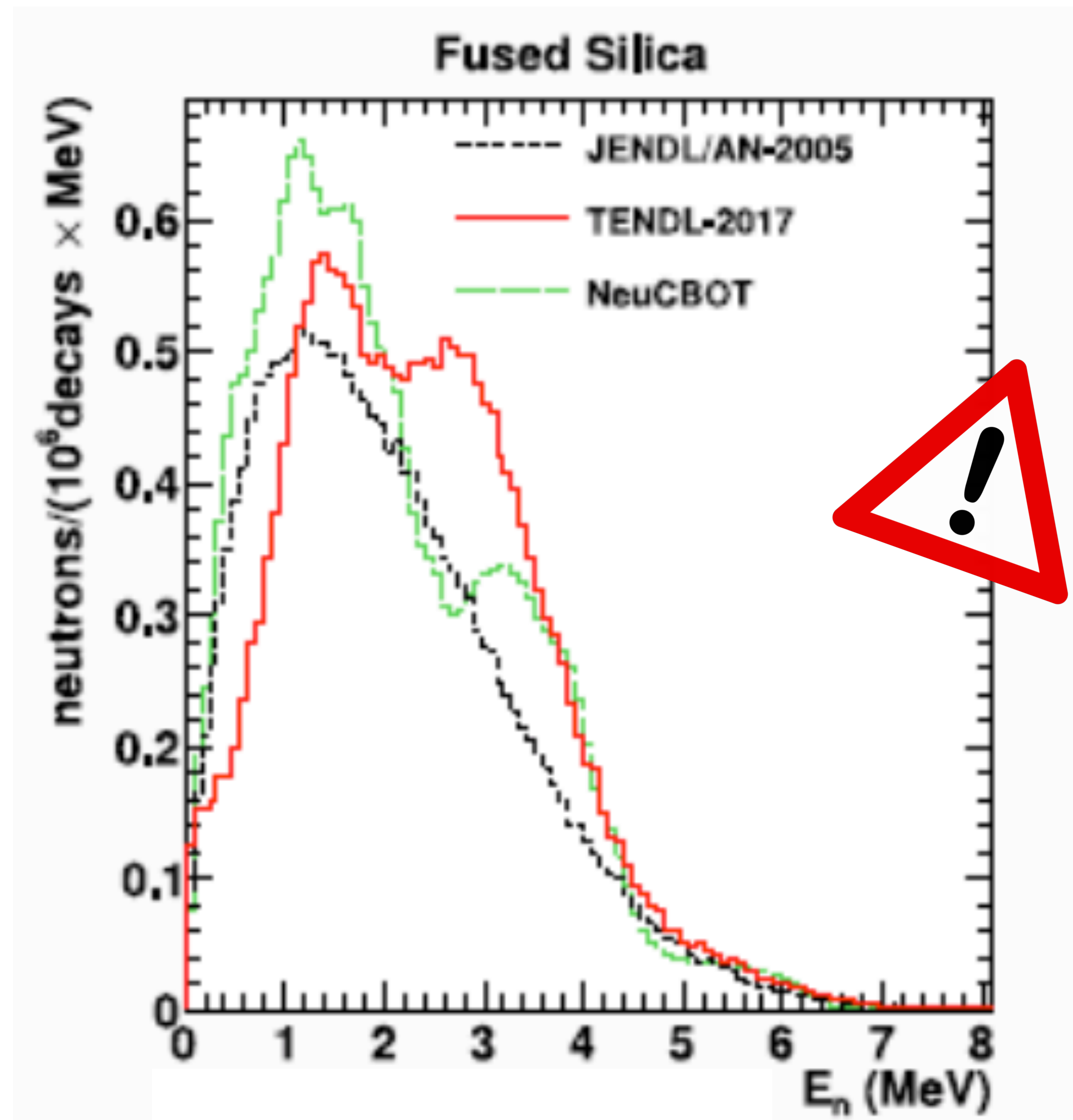
HPGe detector
background



XENON collaboration, arXiv:1503.07698v1

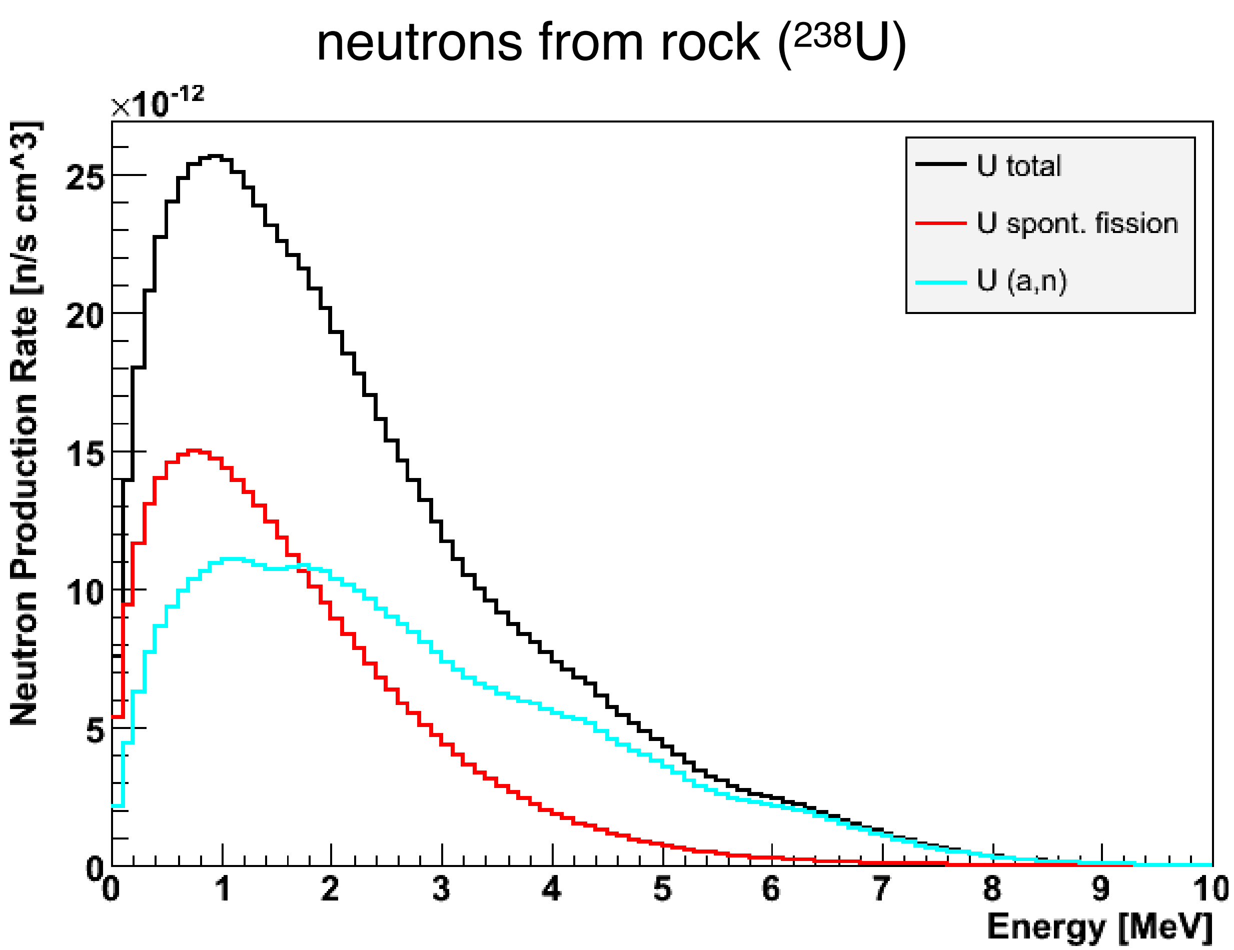
U and Th decay chains are particularly relevant <u>for neutrons too</u>, via (a,n) reactions

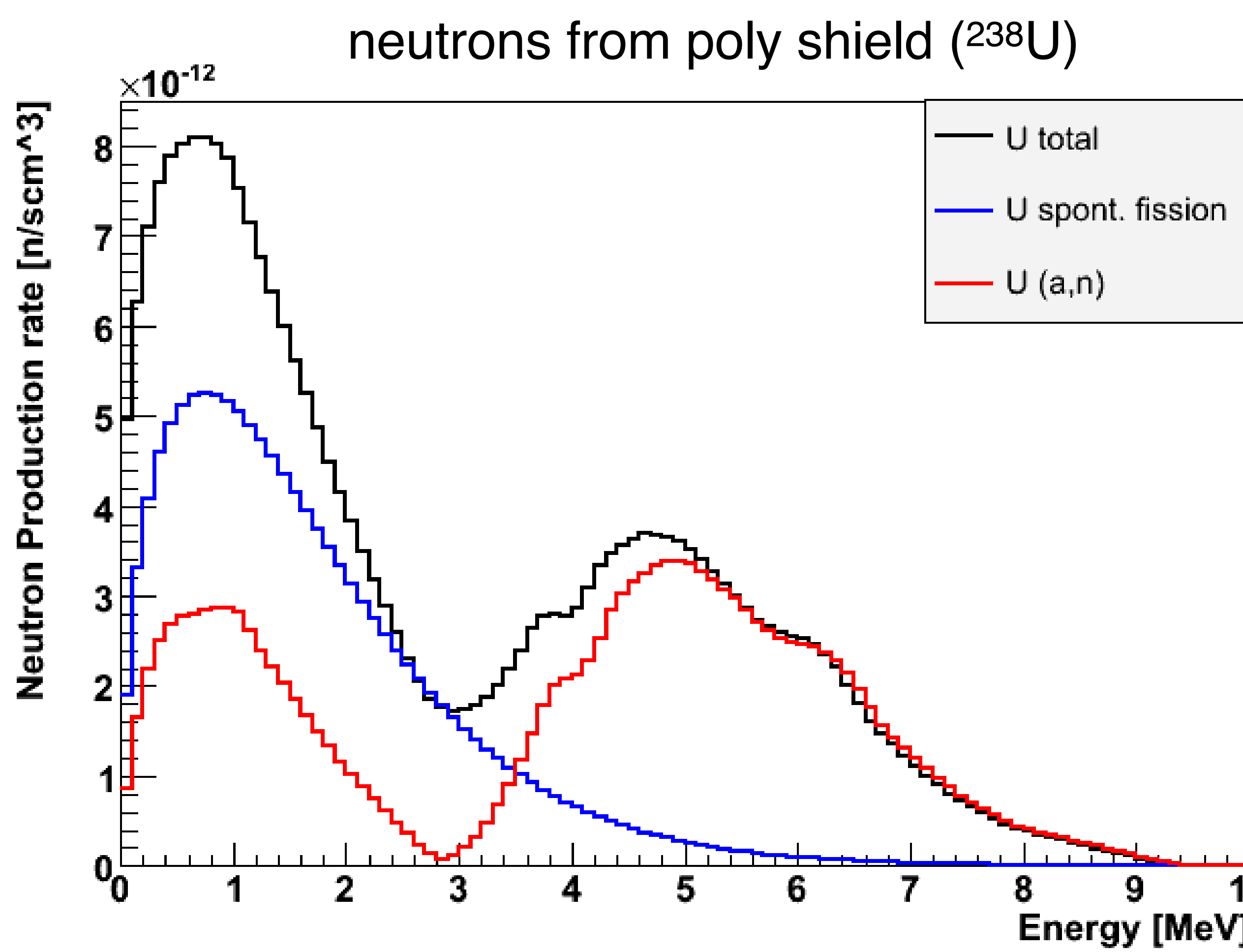




Backgrounds in Dark Matter Detectors

- **MeV neutrons can mimic WIMPs** by elastically scattering from the target nuclei
  ➡the rates of neutrons from detector materials and rock are calculated taking into account the exact material composition, the α energies and cross sections for (α,n) and fission reactions and the measured U/Th contents





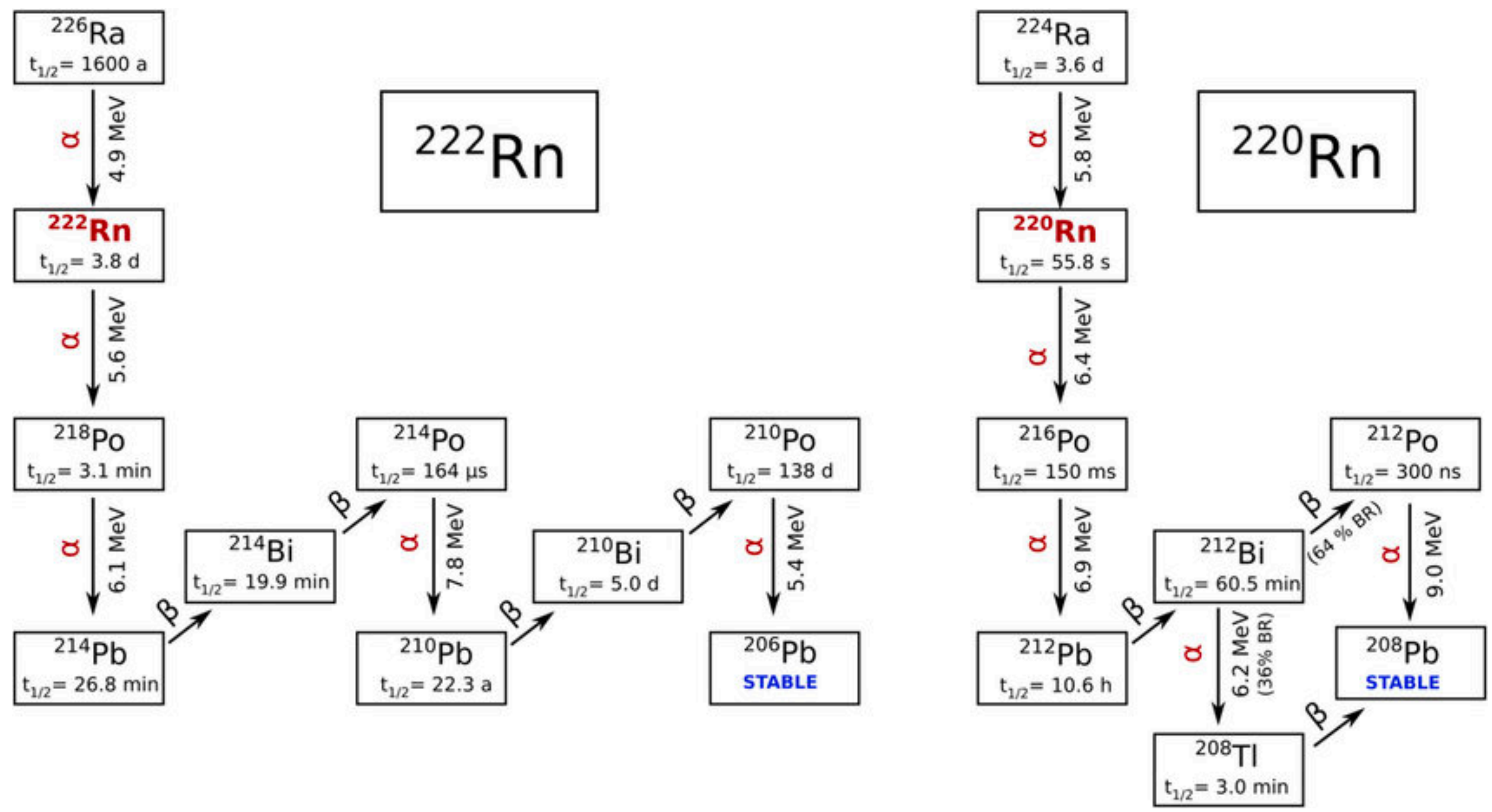
The problem with Radon contamination

Radon escapes both solids and liquids

^{220}Rn, ^{219}Rn, and especially ^{222}Rn and their daughters release several high-energy γ's and α's

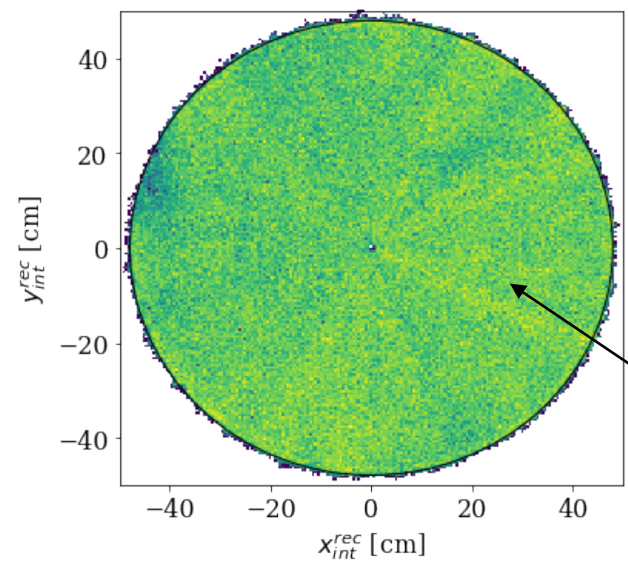
— underground Rn contamination is larger than surface (~10 vs ~100 Bq/m^3)
— Rn daughters plate-out on surfaces

—> Screen/clean materials. Avoid long term exposure to air. Assemble detectors in Rn-free clean rooms. Ultimately remove Rn continuously with systems based on charcoal absorption or with cryogenic distillation

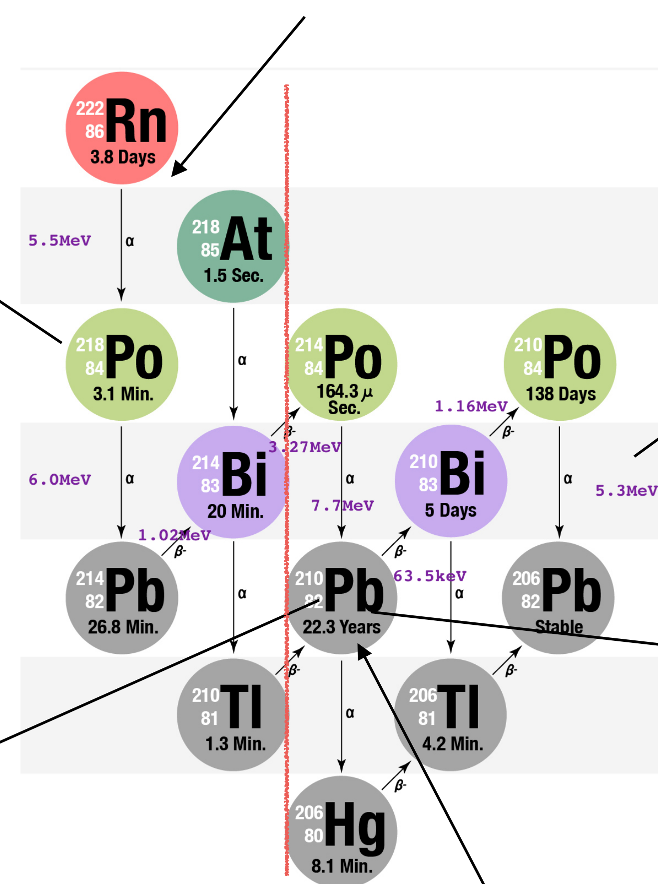


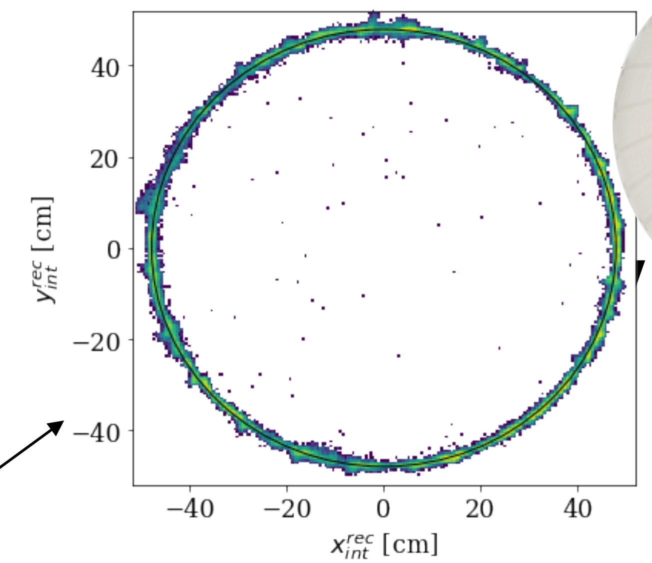
Radon background is the main challenge for next generation DM experiments

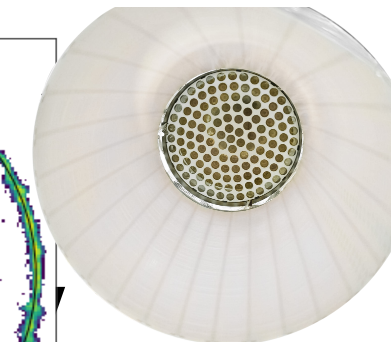
Seeing Rn-222 decay chain in the XENON1T TPC

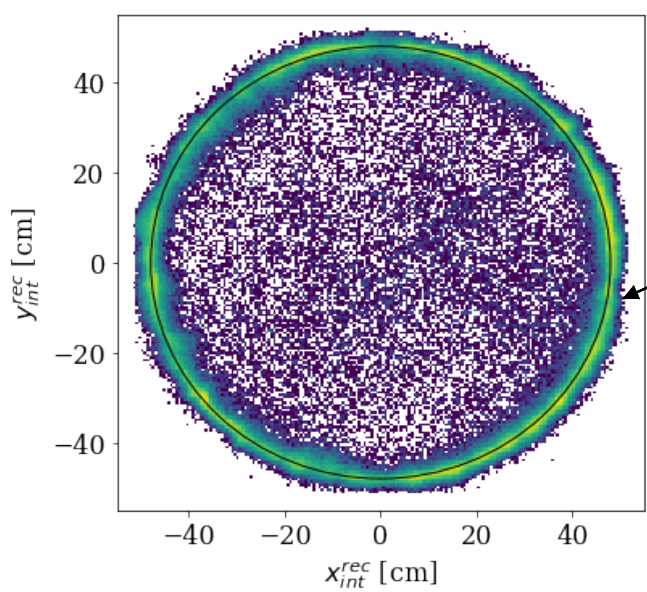


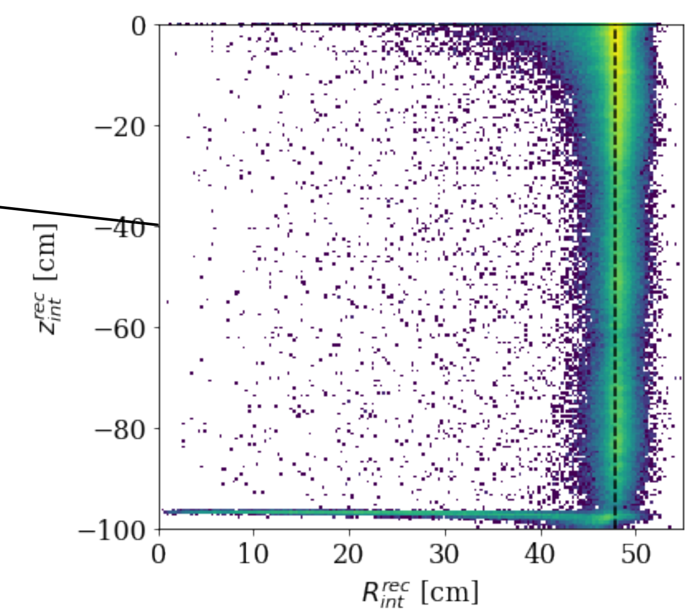
Radon-222 concentration in LXe











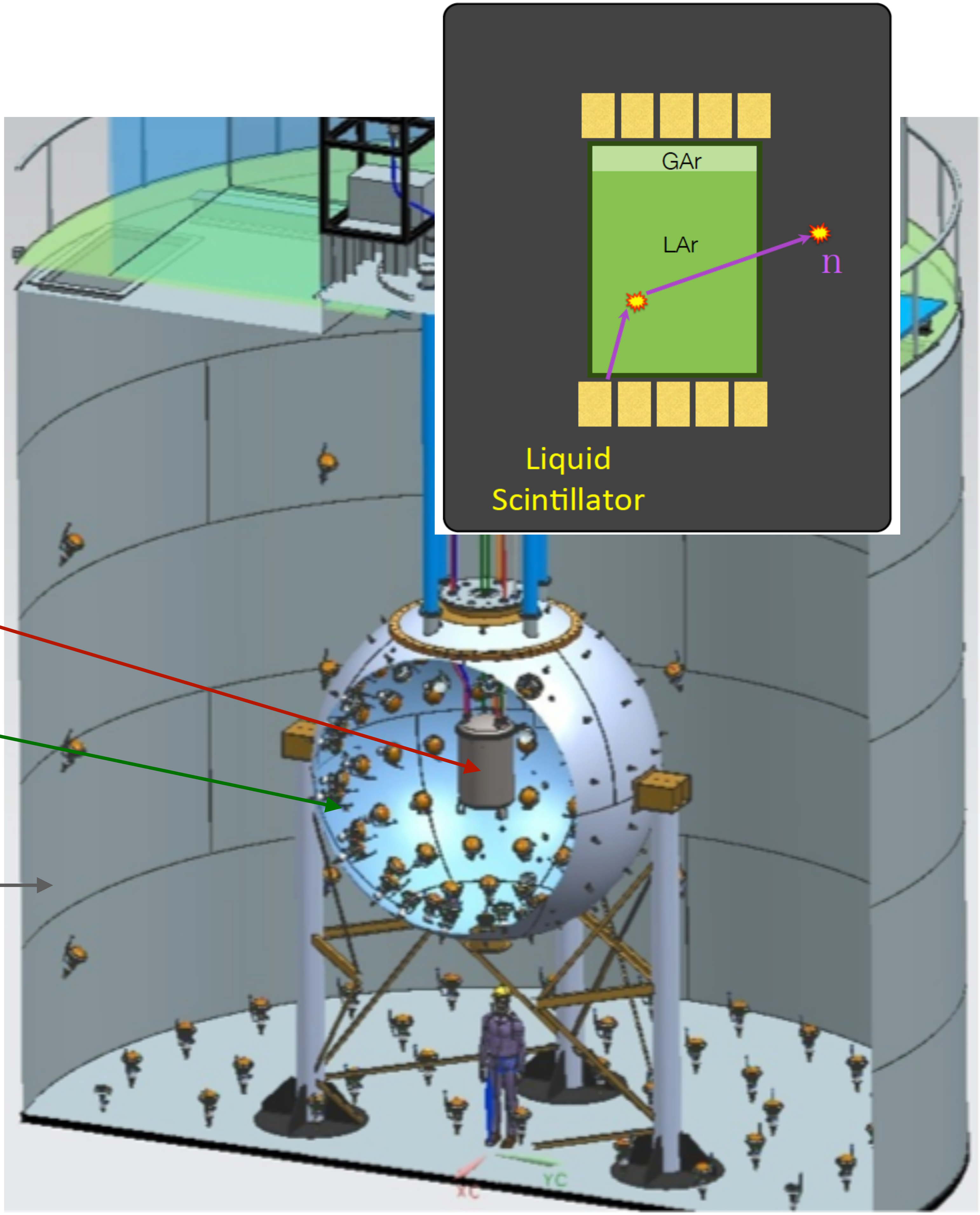
Pb210 and Po210 on TPC surfaces during construction/ assembly give reduced-S2 events

Use Shield(s), better if active
Example: DarkSide -50

Liquid argon TPC
50 kg LAr

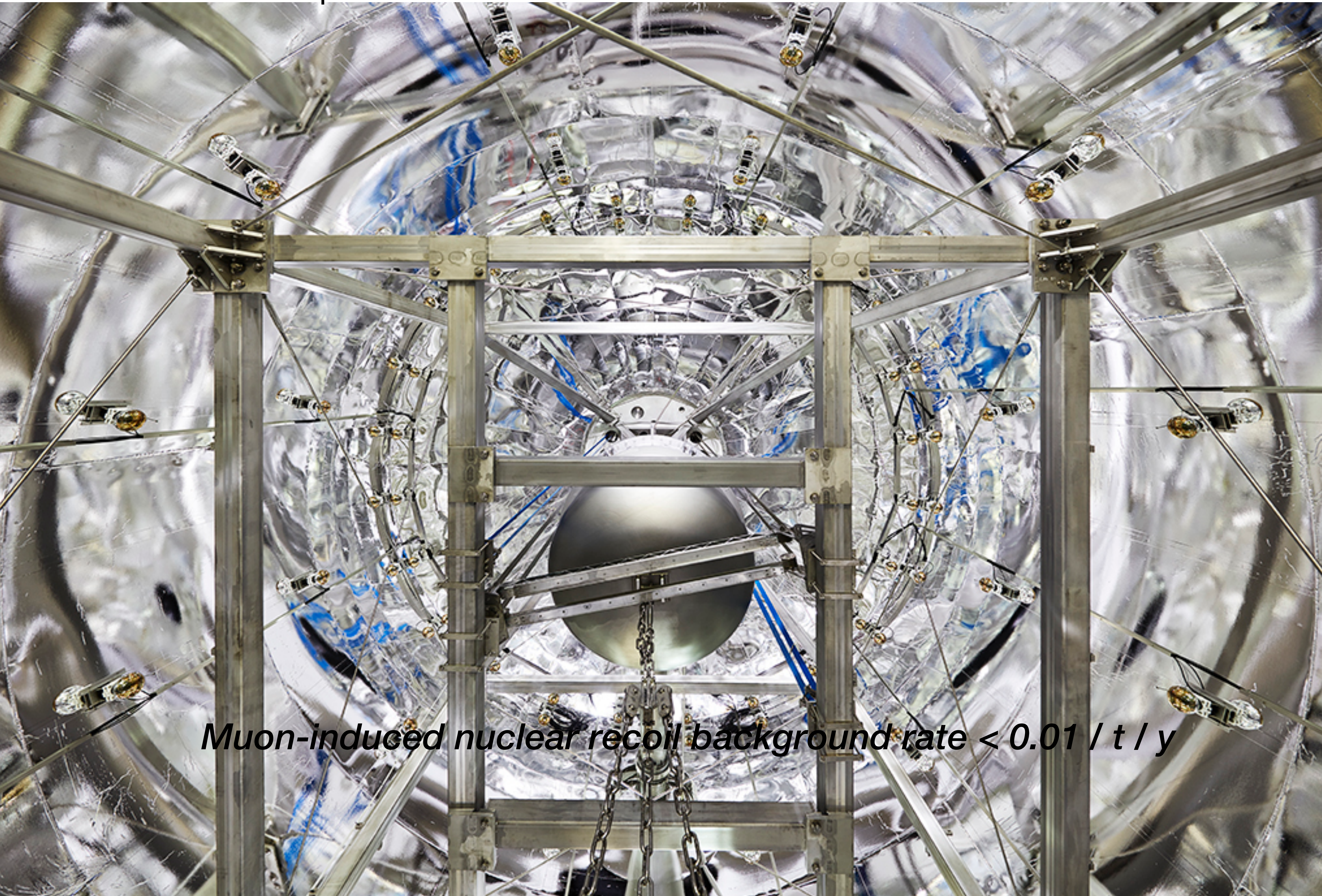
Liquid Scintillator Veto (LSV)
30 tons, 2 m radius
110 PMTs (LY = 0.5 pe/keV)

Water Cherenkov Detector (WCD)
1 kt water, 5.5 m radius
80 PMTs



Active Veto:
- suppresses bg rates from outside
- measures bg rate *in-situ*! and reduce systematics

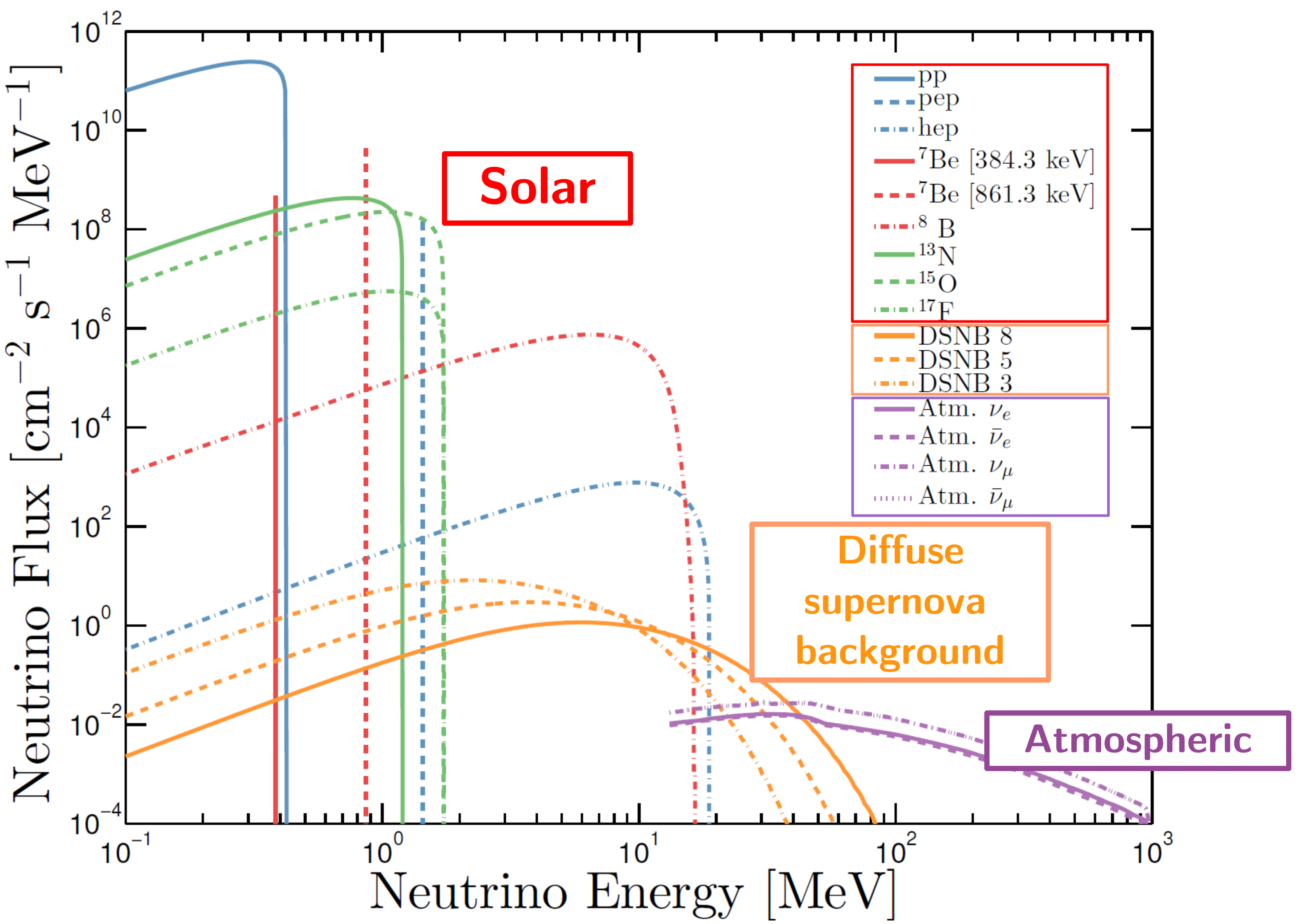
Example: XENON1T Water Cherenkov Muon Veto
700 tons pure water instrumented with 84 x 8 " PMTs

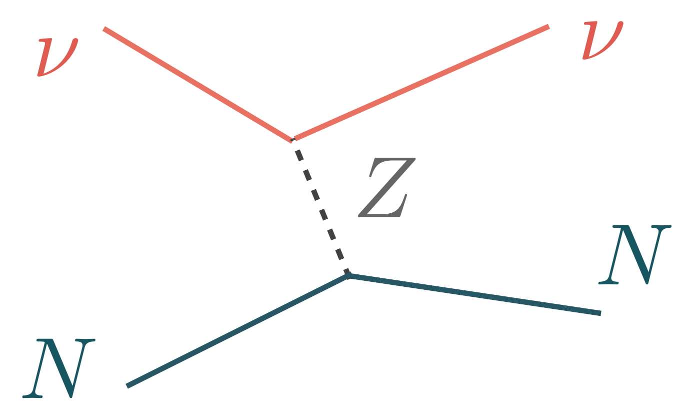


Neutrino backgrounds

- Neutrino-electron and neutrino-nucleus scatters

$$\nu + e^{-} \longrightarrow \nu + e^{-}$$





$$\frac{d\sigma(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_\omega^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F_{SI}^2(E_r)$$

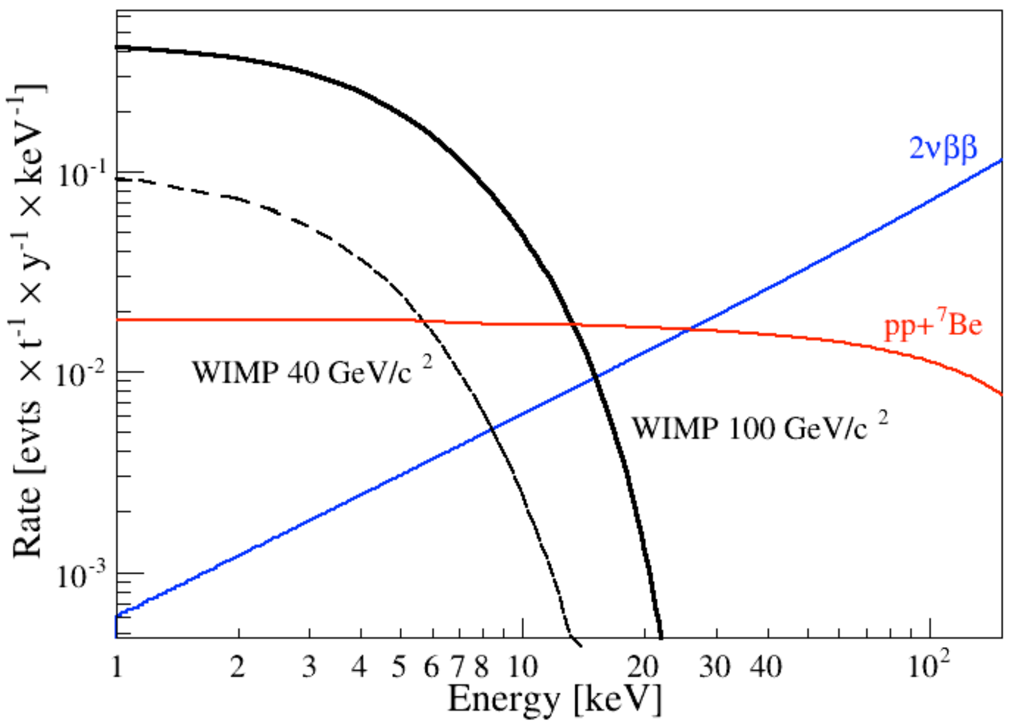
$$Q_\omega = N - (1 - 4\sin^2\theta_\omega) Z$$

F. Ruppin et al., 1408.3581, PRD 90, 2015

Neutrino-electron scatters

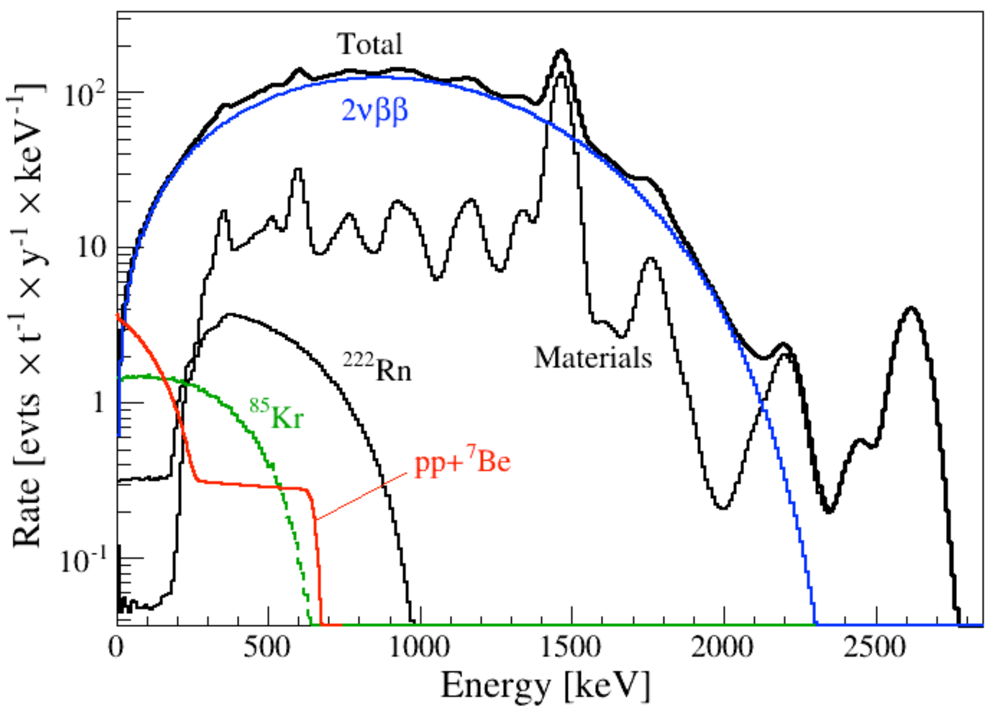
- Will generate electron recoils, uniformly distributed in the detector
- In spite of various background discrimination techniques, such events can potentially "leak" into the signal region
- Example (in liquid xenon) for spectra expected from WIMPs and solar neutrinos

After discrimination (99.5%)



$$\nu + e^{-} \rightarrow \nu + e^{-}$$

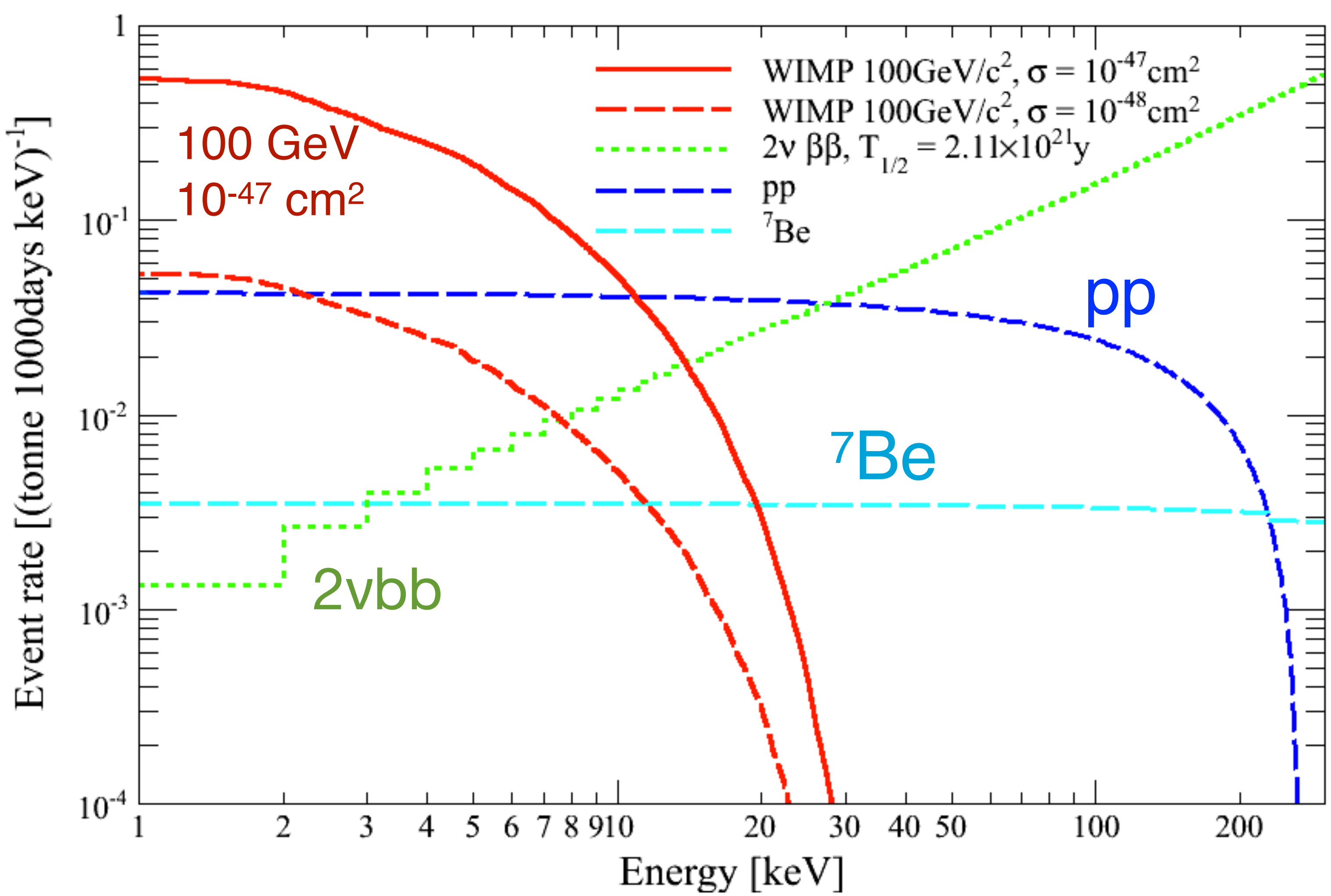
Before discrimination



LB et al., JCAP01 (2014) 044

Neutrino backgrounds

- Neutrinos may be the ‘ultimate’ backgrounds (also: a new physics channel)
- ^{85}Kr (^{nat}Kr < 0.1 ppt) and 222Rn < 1 µBq/kg required



2vbb: EXO measurement of ^{136}Xe $T_{1/2}$
Assumptions: 50% NR acceptance, 99.5% ER discrimination
Contribution of 2vbb background can be reduced by depletion

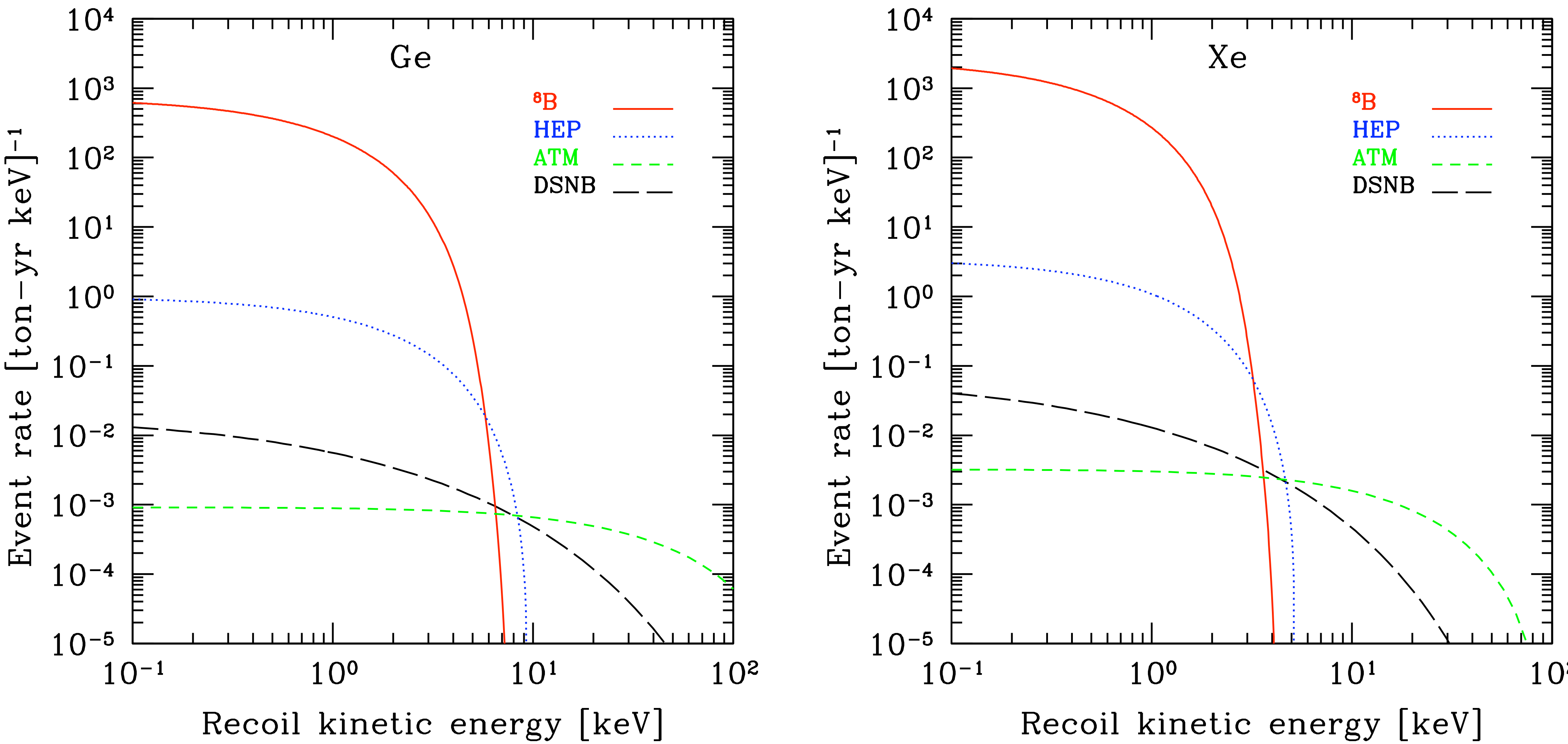
Neutrino-nucleus scatters

- ^{8}B neutrinos dominate: serious background if the WIMP-nucleon cross section < 10^{-10} pb
- But: energy of nuclear recoils: <4 keV (heavy targets, Xe, I etc) to <30 keV in light targets (F, C)
- Non-^{8}B neutrinos: impact on WIMP detectors at much lower WIMP-nucleon cross sections

L. E. Strigari, New J. Phys. 11 (2009) 105011

Germanium

Xenon

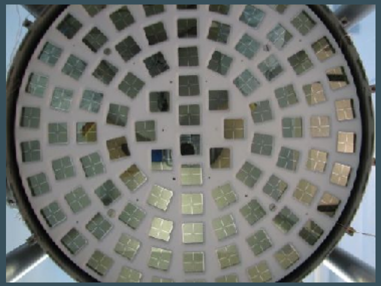


MANY DETECTOR TECHNOLOGIES AND EXPERIMENTS

Ge, Si:
SuperCDMS
EDELWEISS

$CaWO_4$:
CRESST

LXe: XENON, LUX,
LZ, PandaX, DARWIN
LAr: ArDM, DarkSide,



Detector strategies

Aggressively reduce the absolute background & pulse shape analysis	Background reduction by pulse shape analysis and/or self-shielding	Background rejection based on simultaneous detection of two signals	Other detector strategies
State of the art: (primary goal is $0\nu\beta\beta$ decay): Past experiments: Heidelberg-Moscow HDMS IGEX Current and near-future projects: GERDA MAJORANA	Large mass, simple detectors: NaI (DAMA/LIBRA, ANAIS, SABRE, DM-Ice) CsI (KIMS) Large liquid noble gas detectors: XMASS, CLEAN, DEAP-3600	**Charge/phonon** (CDMS, EDELWEISS, SuperCDMS) **Light/phonon** (CRESST) **Charge/light** (XENON, LUX-LZ, PandaX DarkSide)	Large bubble chambers - insensitive to electromagnetic background: COUPP, PICASSO, SIMPLE, PICO Low-pressure gas detectors, sensitive to the direction of the nuclear recoil: DRIFT, DMTPC, NEWAGE, MIMAC,DAMIC

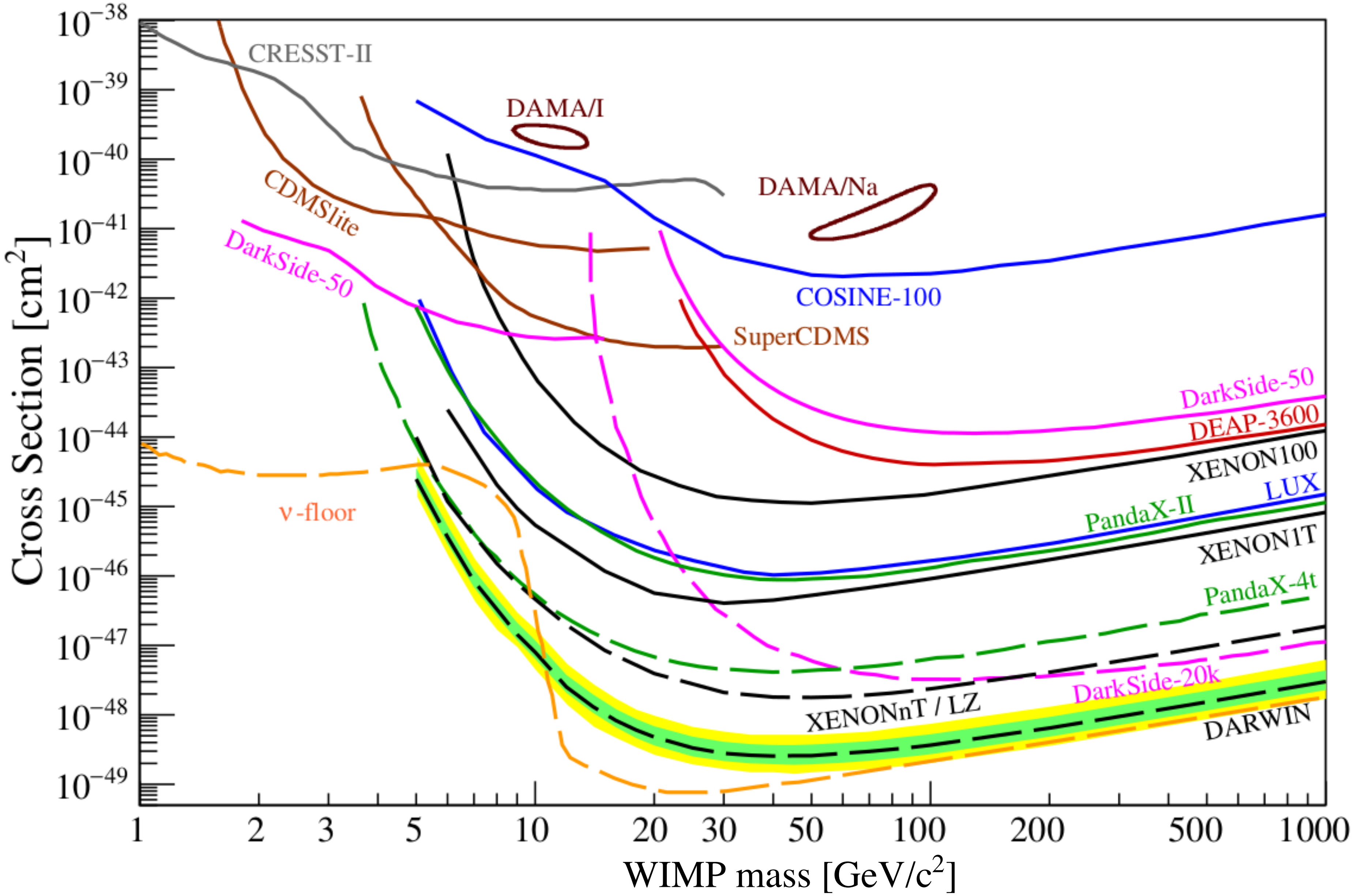
In addition:

→ reject multiple scattered events and events close to detector boundaries

→ look for an annual and a diurnal modulation in the event rate

World Wide Dark Matter Searches: ~50% use Noble Liquids

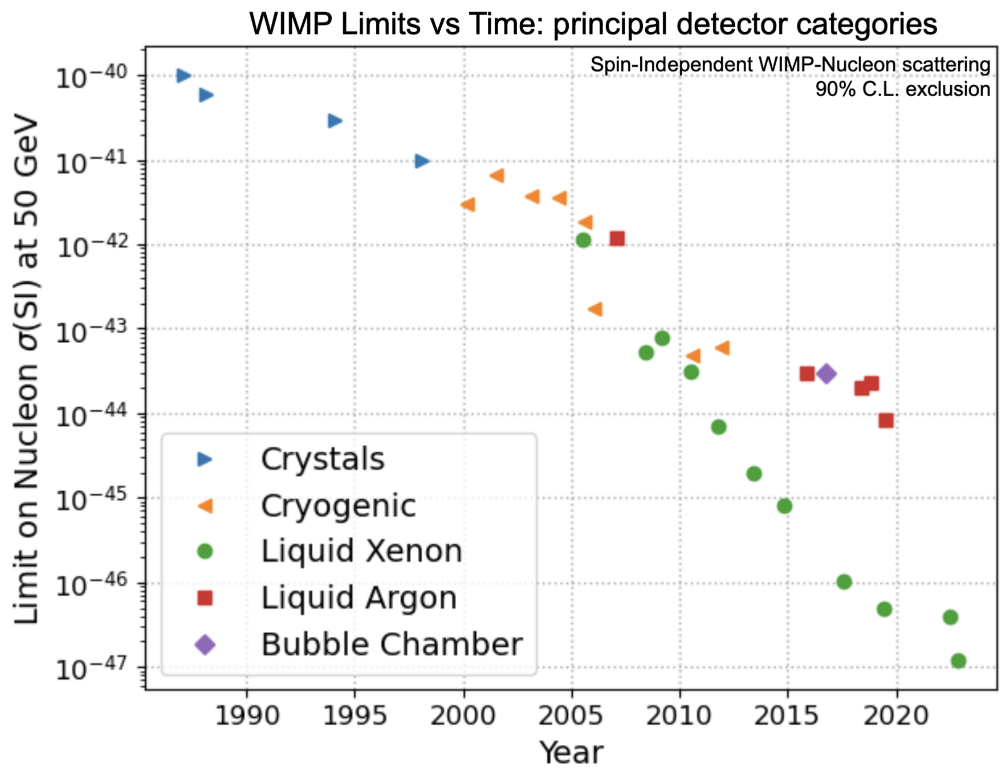
Where do we stand?

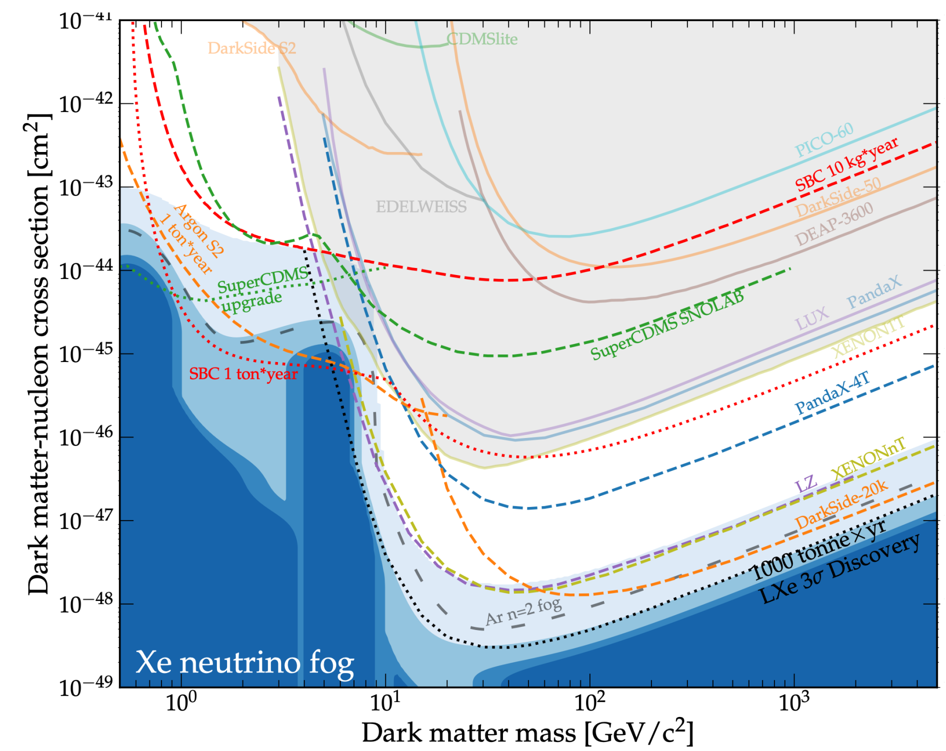


1 event/ kg-day

1 event/ tonne-year

XeTPC Technology: leading sensitivity since 2007





Snowmass 2021 Whitepaper on particle dark matter
arXiv:2203.08084

Cryogenic Noble Liquids: Properties

- Dense and homogenous; excellent insulators; chemically inert; non-toxic; non-flammable
- do not attach electrons; high electron mobility; small electron diffusion
- Very good ionization and scintillation response to radiation
- commercially available as gases with ppm level of electronegative impurities
- different purification methods remove impurities to ppb level for radiation detection
- different cooling methods enable operation of cryogenic liquid detectors of ton-scale

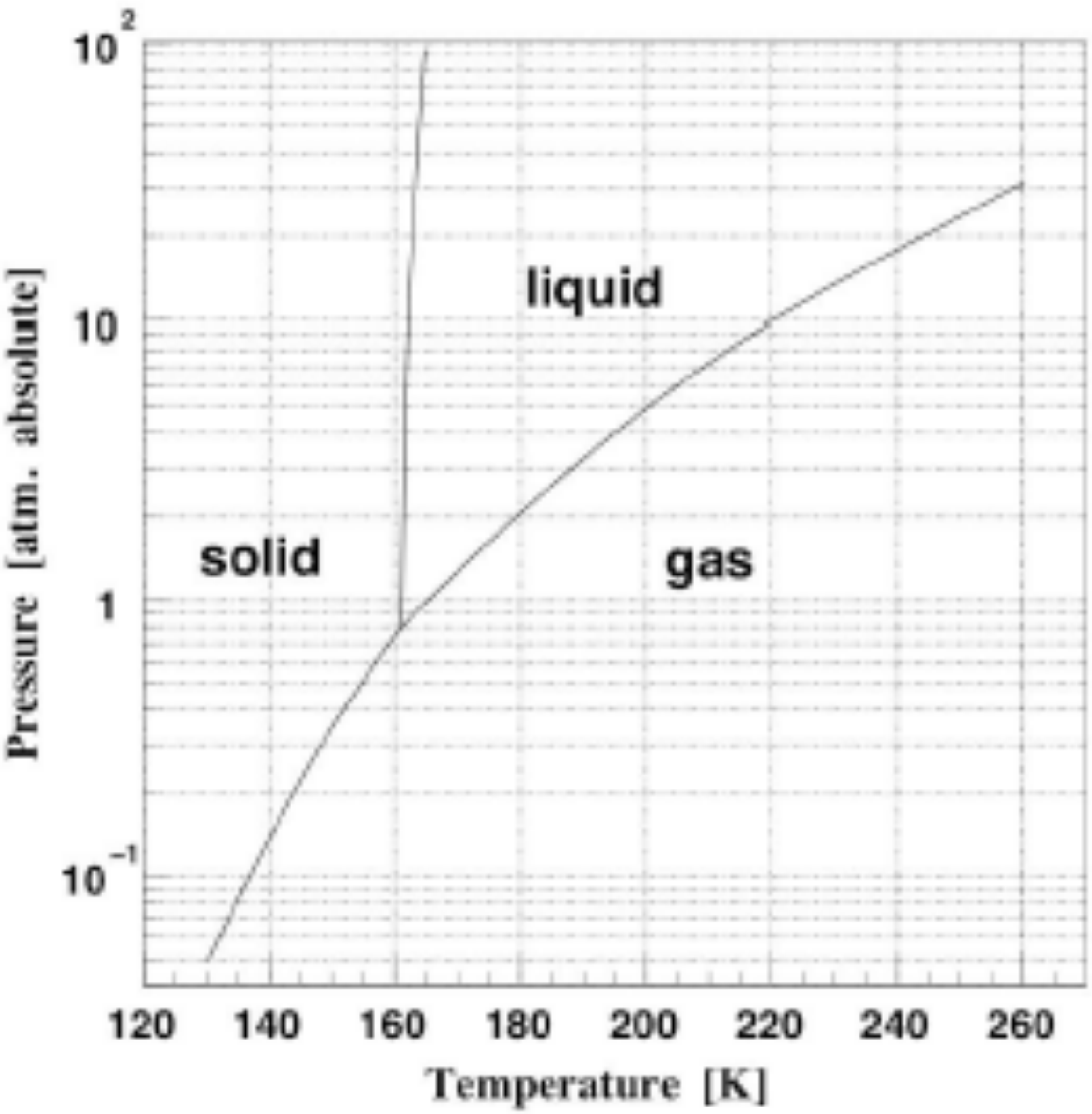
Element	Z (A)	BP (T_b) at 1 atm [K]	liquid density at T_b [g/cc]	ionization [e^-/ keV]	scintillation [photon/keV]
He	2 (4)	4.2	0.13	39	15
Ne	10 (20)	27.1	1.21	46	7
Ar	18 (40)	87.3	1.40	42	40
Kr	36 (84)	119.8	2.41	49	25
Xe	54 (131)	165.0	3.06	64	46

Properties [unit]	**Xe**	**Ar**	**Ne**
Atomic number:	54	18	10
Mean relative atomic mass:	131.3	40.0	20.2
Boiling point T_b at 1 atm [K]	165.0	87.3	27.1
Melting point T_m at 1 atm [K]	161.4	83.8	24.6
Gas density at 1 atm & 298 K [$\mathrm{g\,l^{-1}}$]	5.40	1.63	0.82
Gas density at 1 atm & T_b [$\mathrm{g\,l^{-1}}$]	9.99	5.77	9.56
Liquid density at T_b [$\mathrm{g\,cm^{-3}}$]	2.94	1.40	1.21
Dielectric constant of liquid	1.95	1.51	1.53
Volume fraction in Earth's atmosphere [ppm]	0.09	9340	18.2

Noble Liquids for Dark Matter Search

- ✦ scalability : relatively inexpensive for large scale (multi-ton) detectors
- ✦ easy cryogenics : 170 K (LXe), 87 K (LAr)
- ✦ self-shielding : very effective (especially for LXe case) for external background reduction
- ✦ low threshold : high scintillation yield (similar to NaI(Tl) but much faster timing)
- ✦ n-recoil discrimination: by charge-to-light ratio and pulse shape discrimination
- ✦ Xe nucleus (A~131) : good for SI plus SD sensitivity (~50% odd isotopes)
- ✦ For Xe: no long-lived radioactive isotopes (Kr-85 can be removed)
- ✦ For Ar: radioactive Ar-39 is an issue but there are ways to overcome it

A closer look at Liquid Xenon



Liquid Density (1 bar at boiling point): ~ 3 times that of water

High boiling point of Xe requires modest cooling compared to Ar

Correspondence Liquid/ Gas: 1 L liquid --> 519 L Gas (STP)

Thermal conductivity similar to that of an insulator, i.e. teflon at 300K; 1000 times less than Cu

Property	Value
Atomic number Z	54
Isotopes	^{124}Xe(0.09%), ^{126}Xe(0.09%), ^{128}Xe(1.92%), ^{129}Xe(26.44%) ^{130}Xe(4.08%), ^{131}Xe(21.18%) ^{132}Xe(26.89%), ^{134}Xe(10.44%) ^{136}Xe(8.87%)
Mean atomic weight A	131.30
Density	$3\ \mathrm{g{\cdot}cm^{-3}}$
Boiling point	$T_b = 165.05$ K, $P_b = 1$ atm $\rho_b = 3.057\ \mathrm{g{\cdot}cm^{-3}}$
Critical point	$T_c = 289.72$ K, $P_c = 58.4$ bar $\rho_c = 1.11\ \mathrm{g{\cdot}cm^{-3}}$
Triple point	$T_t = 161.3$ K, $P_t = 0.805$ bar $\rho_t = 2.96\ \mathrm{g{\cdot}cm^{-3}}$
Volume ratio (ρ_{liquid}/ρ_{gas})	519
Thermal properties	
Heat capacity	$10.65\ \mathrm{cal{\cdot}g{\cdot}mol^{-1}{\cdot}K^{-1}}$ for 163 – 166 K
Thermal conductivity	$16.8 \times 10^{-3}\ \mathrm{cal{\cdot}s^{-1}{\cdot}cm^{-1}{\cdot}K^{-1}}$
Latent heat of a) evaporation at triple point	$3048\ \mathrm{cal{\cdot}g{\cdot}mol^{-1}}$
b) fusion at triple point	$548.5\ \mathrm{cal{\cdot}g{\cdot}mol^{-1}}$
Electronic properties	
Dieletric constant	$\epsilon_r = 1.95$

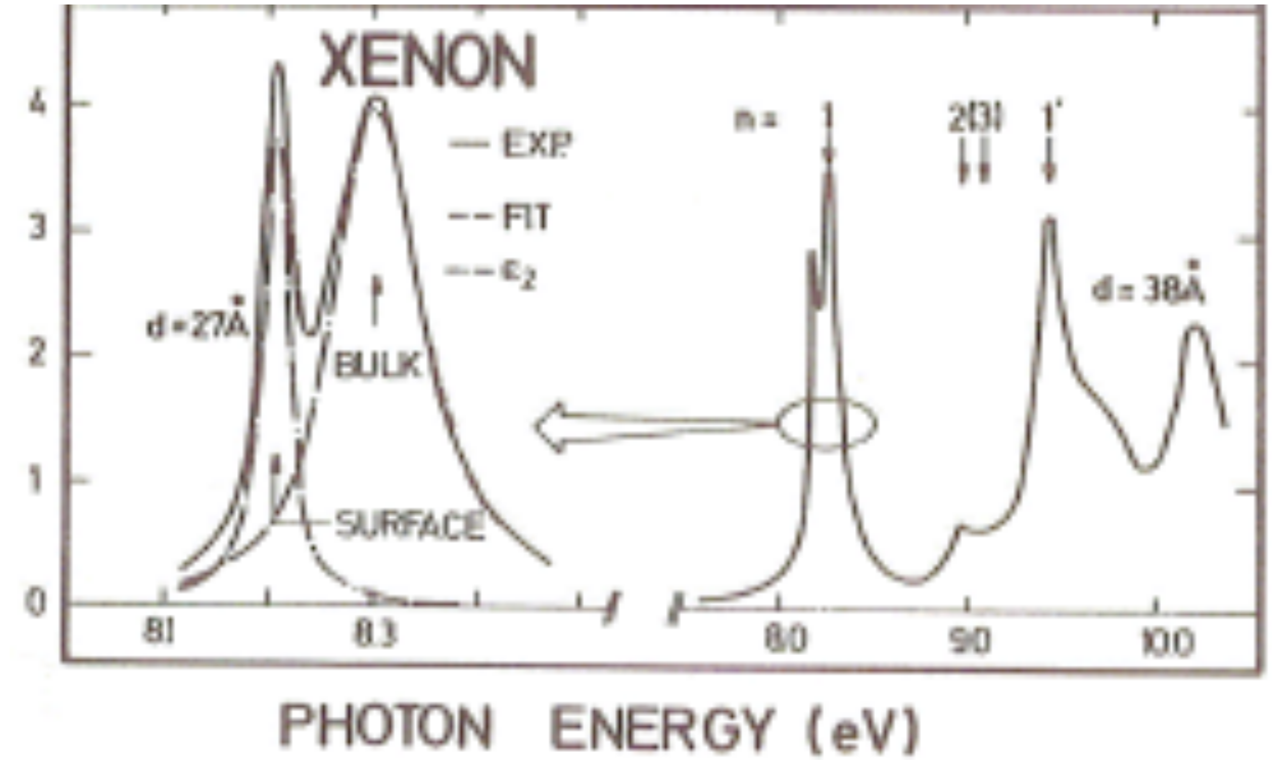
a word about Xe production and market

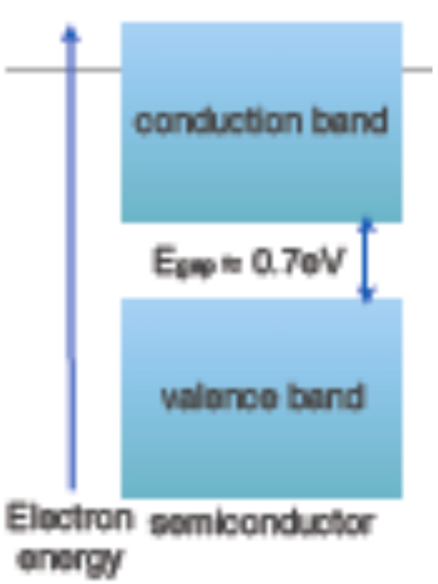
- very rare: content in the air is 0.09 ppm. Compare to Ar at 9340 ppm
- Byproduct of air liquefaction and separation into O_2 and N_2. Liquid O_2 contains Xe and Kr which can be extracted by cryogenic distillation
- World Wide Production: less than 1000 kg/year
- Historically a very cyclic and speculative market
  - alternating shortage and oversupply situations
  - large price fluctuations from $30/L to $3/L
  - market difficult to anticipate. Currently lighting industry leads demand
- Specific Applications:
  - Lighting Industry (general and speciality lighting products)
  - Electronic industry (semiconductors and LCD makers)
  - Satellites industry (ion propulsion)
  - Medical (Xe as anesthetic being patented in Europe)
  - Research: Dark Matter/Neutrinoless Double Beta decay/ Medical Imaging

Air composition	
N_2	78 %
O_2	21 %
Ar	9,340 ppm
CO_2	330 ppm
Ne	18.18 ppm
He	5.24 ppm
CH_4	2.00 ppm
Kr	1.14 ppm
H_2	0.50 ppm
Xe	0.09 ppm

Noble Liquids: Electronic Band Structure

- Solid and Liquid rare gases have an electronic band structure (like semiconductors or insulators)
- Evidence of electronic band structure from absorption spectra (see example for solid Xe) with clear volume and surface exciton peaks
- Band gap energy (between bottom of conduction band and top of valence band) measured for LXe/LAr and LKr (see Table)
- Compare Eg = 9.28 eV for LXe with Eg = 0.7 eV for Ge





Material	Ar	Kr	Xe
Gas			
Ionization potential I (eV)	15.75	14.00	12.13
W-values (eV)	26.4[a]	24.2[a]	22.0[a]
Liquid			
Gap energy (eV)	14.3	11.7	9.28
W-value (eV)	23.6±0.3[b]	18.4±0.3[c]	15.6±0.3[d]

Ionization and Excitation in Noble Liquids

- In noble liquids, the energy E0 deposited by radiation is expended in three processes: Atomic ionization; Atomic excitation; Heat. Both electron-ion pairs, Ni, and free electrons with kinetic energy lower than the energy of 1st excited level (sub-excitation electrons) are produced in ionization process
- Platzman energy balance equation: $$E_0 = N_i E_i + N_{ex} E_x + N_i \epsilon$$
- The average energy lost in ionization is a bit larger than the ionization potential or gap energy because it includes multiple ionization processes. The average energy lost in excitation is comparatively small
- LXe has the smallest W-value (E0/Ni) = average energy to produce one electron-ion pair hence the largest ionization yield among all noble liquids. $$W = E_0/N_i = E_i + E_x\,(N_{ex}/N_i) + \epsilon$$

Material	Ar	Kr	Xe
Gas			
Ionization potential I (eV)	15.75	14.00	12.13
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Liquid			
Gap energy (eV)	14.3	11.7	9.28
W-value (eV)	23.6±0.3[b]	18.4±0.3[c]	15.6±0.3[d]

Energy Resolution of LXe (ionization)

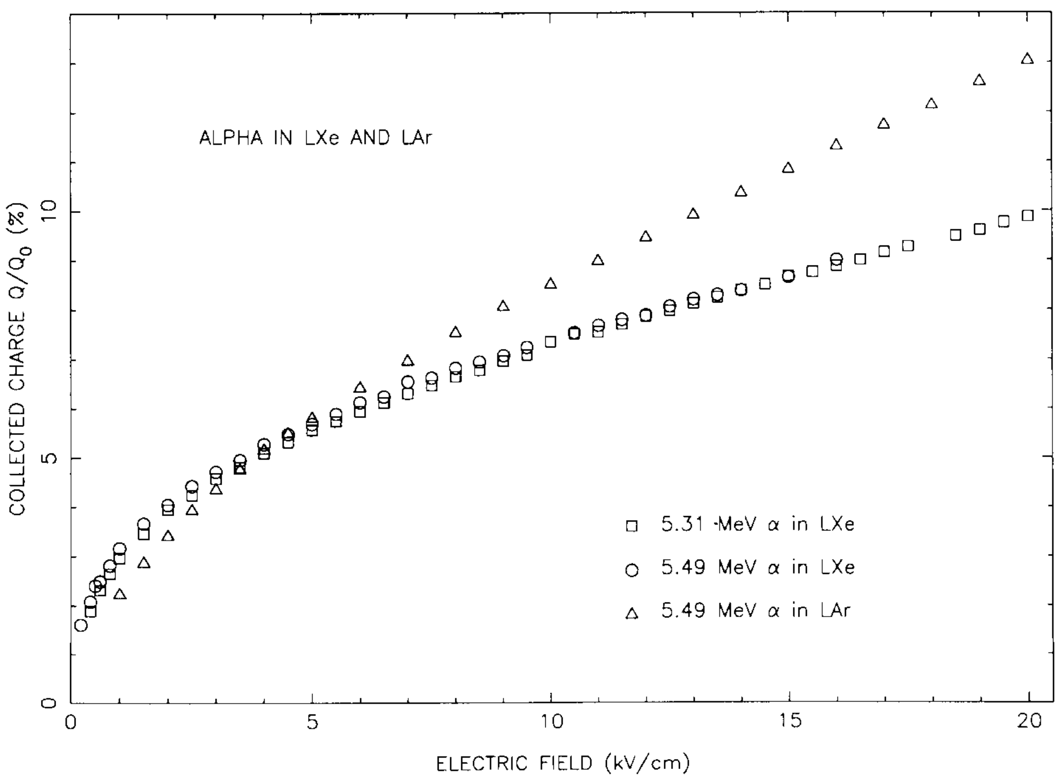


FIG. 3 Collected charge (Q/Q_0 %) as a function of electric field for ^{210}Po in liquid xenon (squares) and ^{241}Am in liquid xenon (circles) and liquid argon (triangles)(Aprile, 1991b).

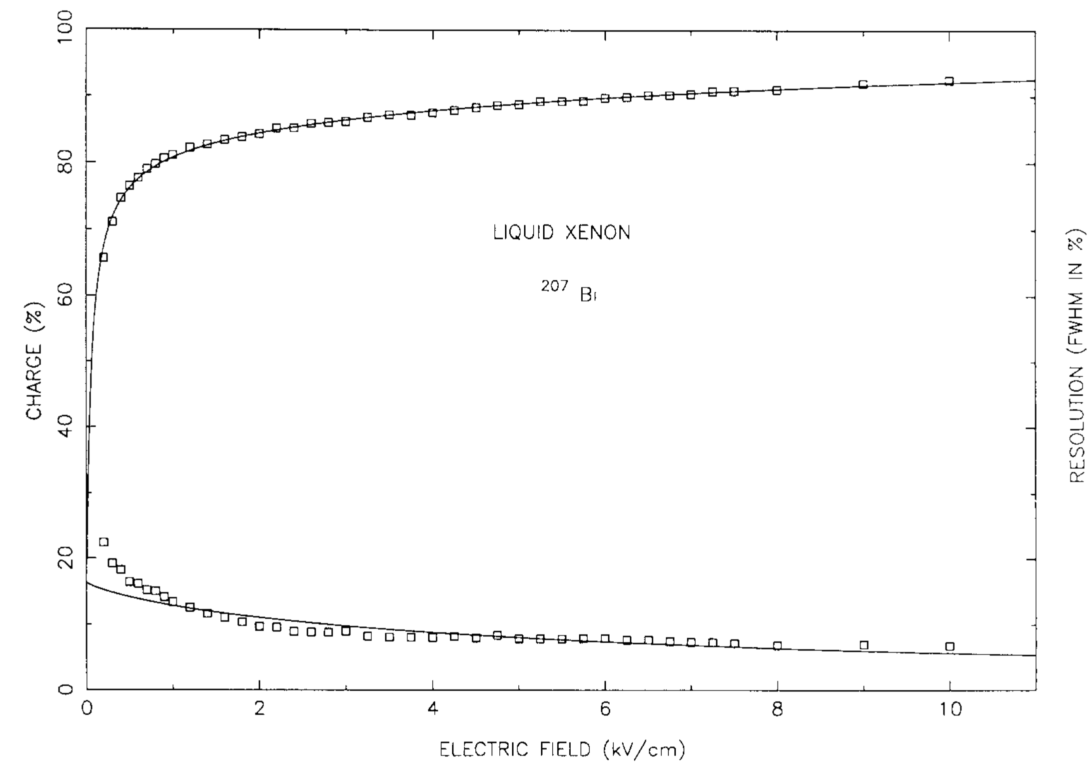


FIG. 4 Collected charge and energy resolution of 570 keV gamma-rays in LXe as a function of electric field (Aprile, 1991a).

- The Fano factor is small $F(LAr) \sim .11$
  $F(LXe) \sim .04$

→ Good energy resolution

$\frac{\Delta E}{E}$ better than $\frac{1}{\sqrt{N}}$

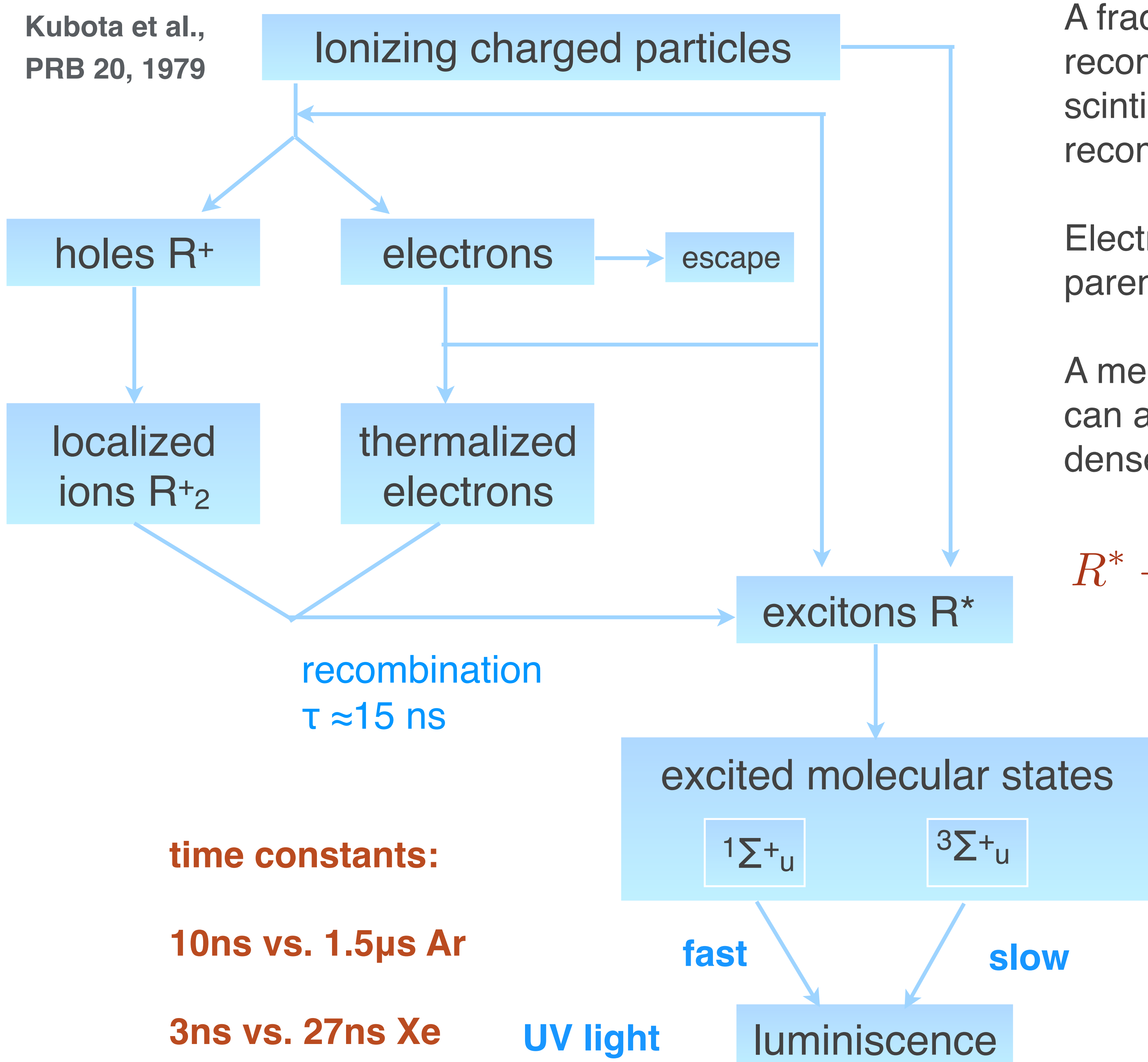
$$\frac{\Delta E}{E}(FWHM) = 2.35\sqrt{\frac{F}{N}} = 2.35\sqrt{\frac{FW}{E}}$$

$\Delta E(LAr) \sim 4\ keV$ at $1\ MeV$

$\Delta E(LXe) \sim 2\ keV$ at $1\ MeV$

Scintillation in Noble Liquids

Kubota et al., PRB 20, 1979



time constants:

10ns vs. 1.5μs Ar

3ns vs. 27ns Xe

A fraction of the ionization electrons will recombine with ions and produce a scintillation photon in the process called recombination

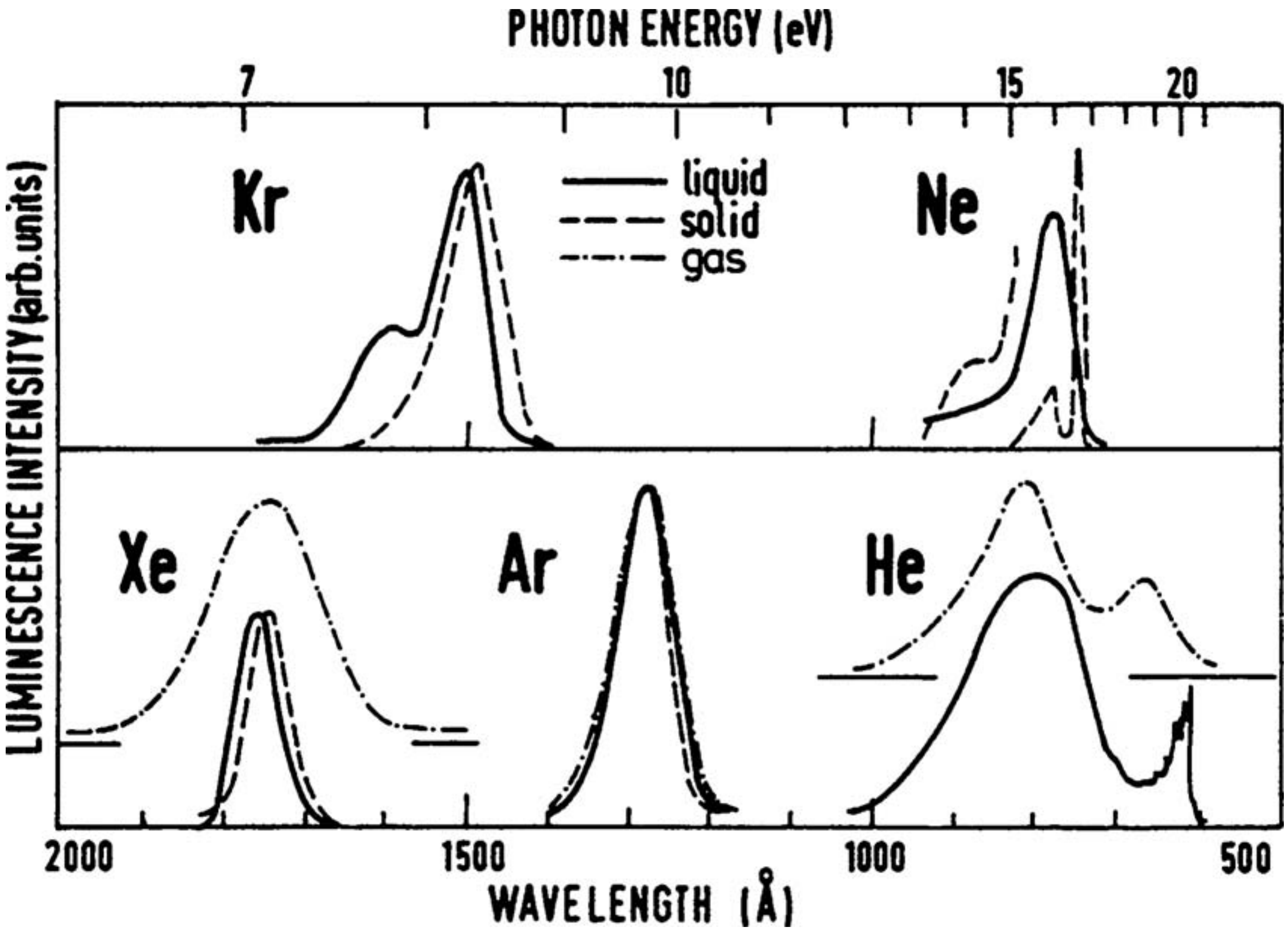
Electrons that thermalize far from their parent ion may escape recombination

A mechanism called “bi-excitonic quenching” can also reduce the scintillation yield in very dense tracks:

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

Scintillation Spectra in Noble Liquids

- The spectrum of scintillation photons is in the vacuum ultraviolet range, centered at 178 nm for LXe (7 eV) and with a width of 13 nm.



$\lambda_{LNe} \sim 78nm$

$\lambda_{LAr} \sim 128nm$

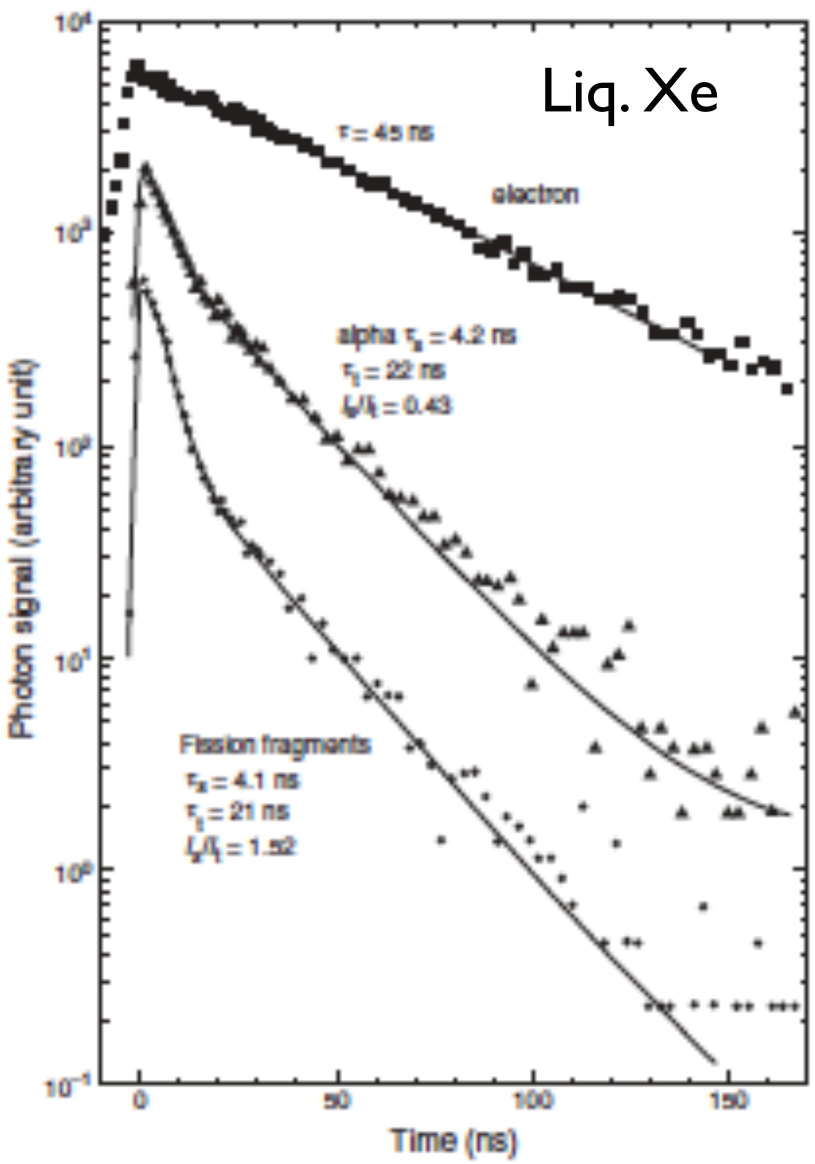
$\lambda_{LXe} \sim 178nm$

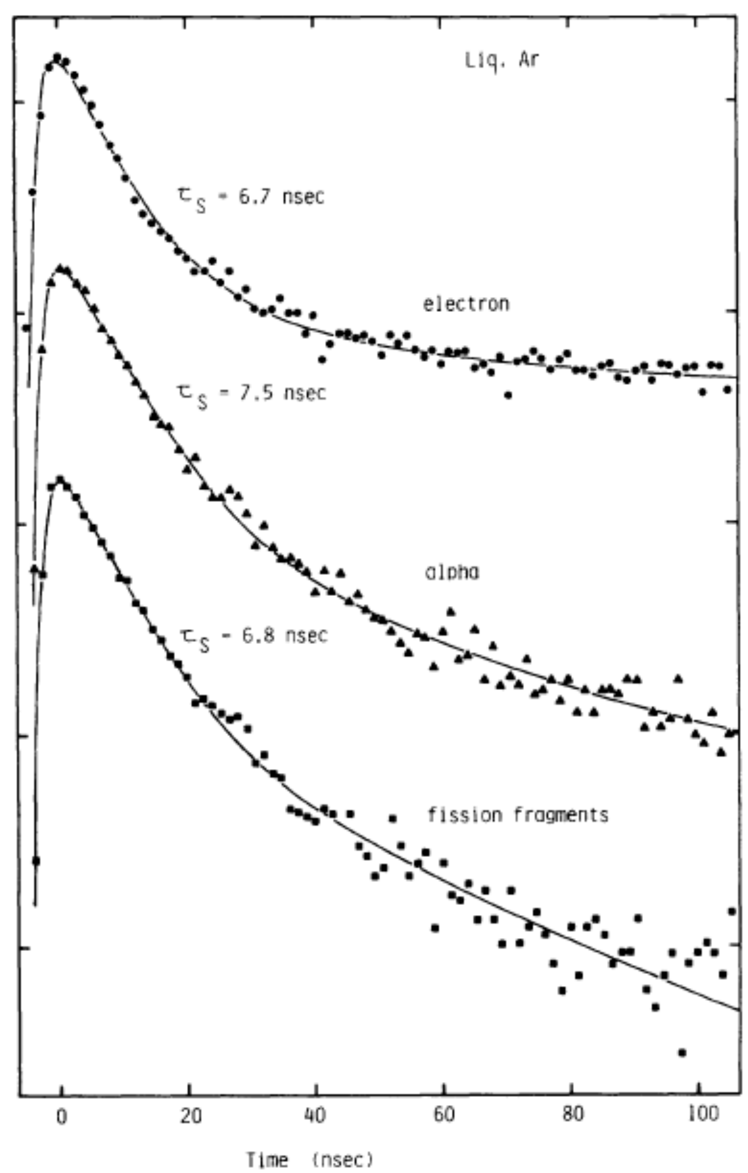
Scintillation Pulse Shape in Noble Liquids

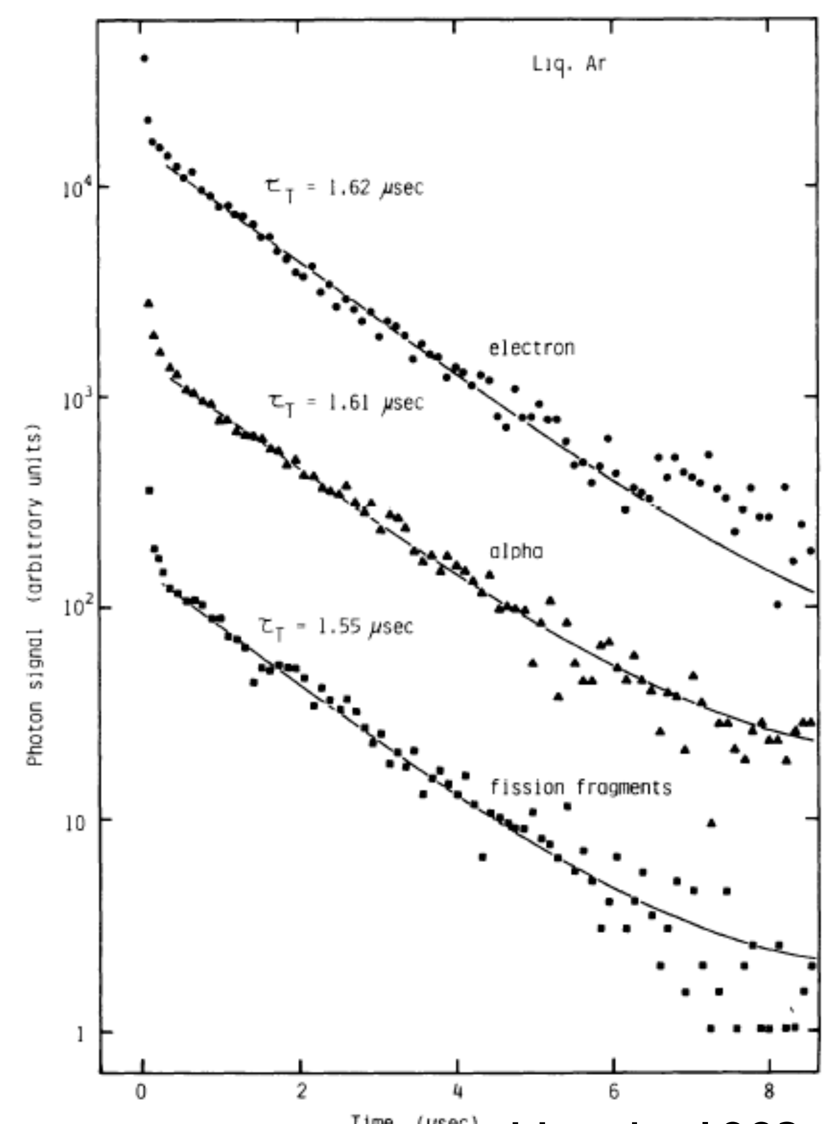
- The light has two components from decay of singlet and triplet states of the excimers. For relativistic electrons with an external field, singlet and triplet states have decay times of 2.2 and 27 ns in LXe, making it one of the fastest scintillators. Without field, recombination time dominates and a single decay time of 45 ns is observed. For alpha particles decay times are 4.2 and 22 ns.

- While decay times depend only weakly on the ionization density of the particle, the ratio of singlet to triplet states is higher at higher ionization density

- The large separation between singlet (~10ns) and triplet (~1.5 microsec) decay times for LAr enables effective PSD

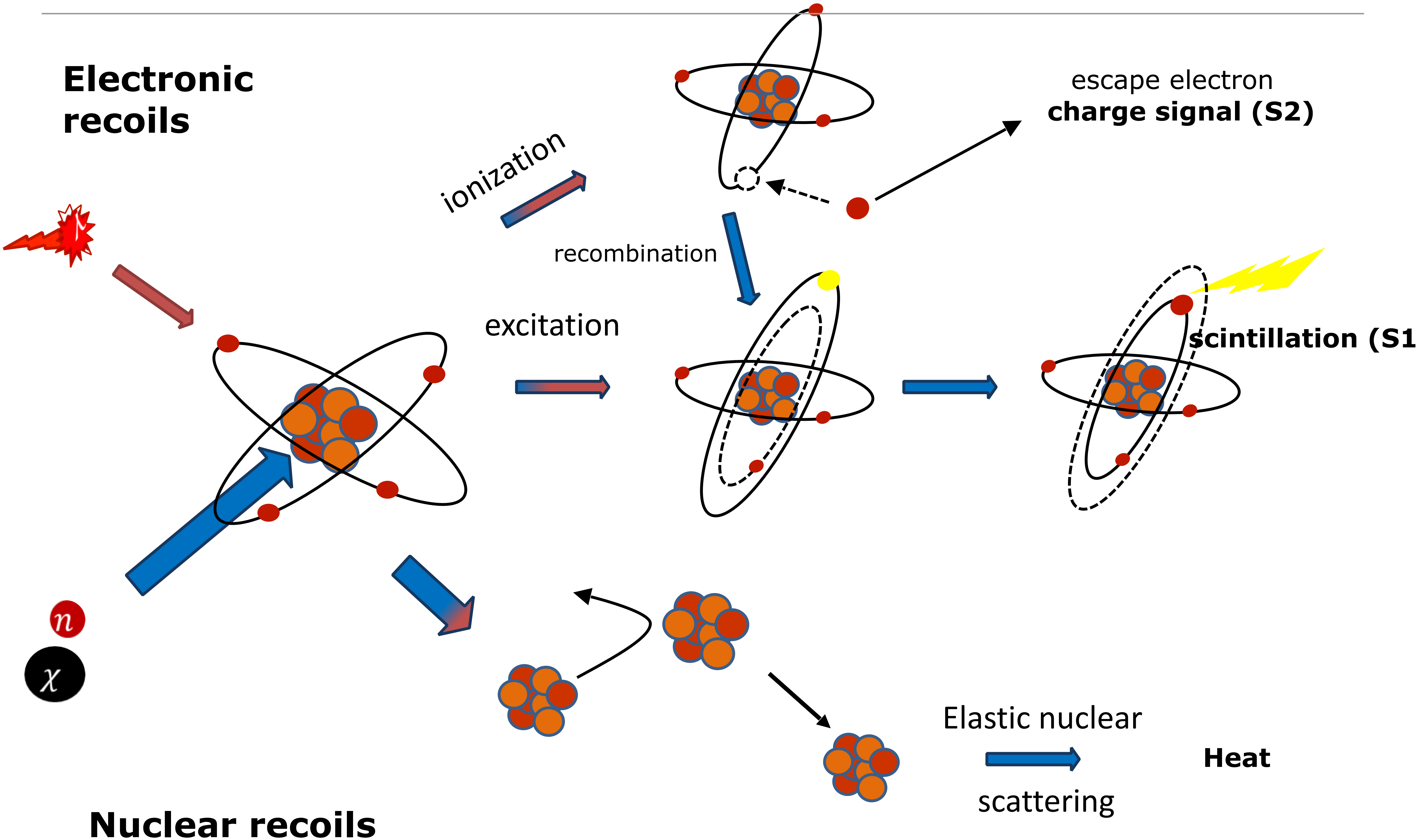






Hitachi, 1983

Ionization and Scintillation Signals in Noble Liquids

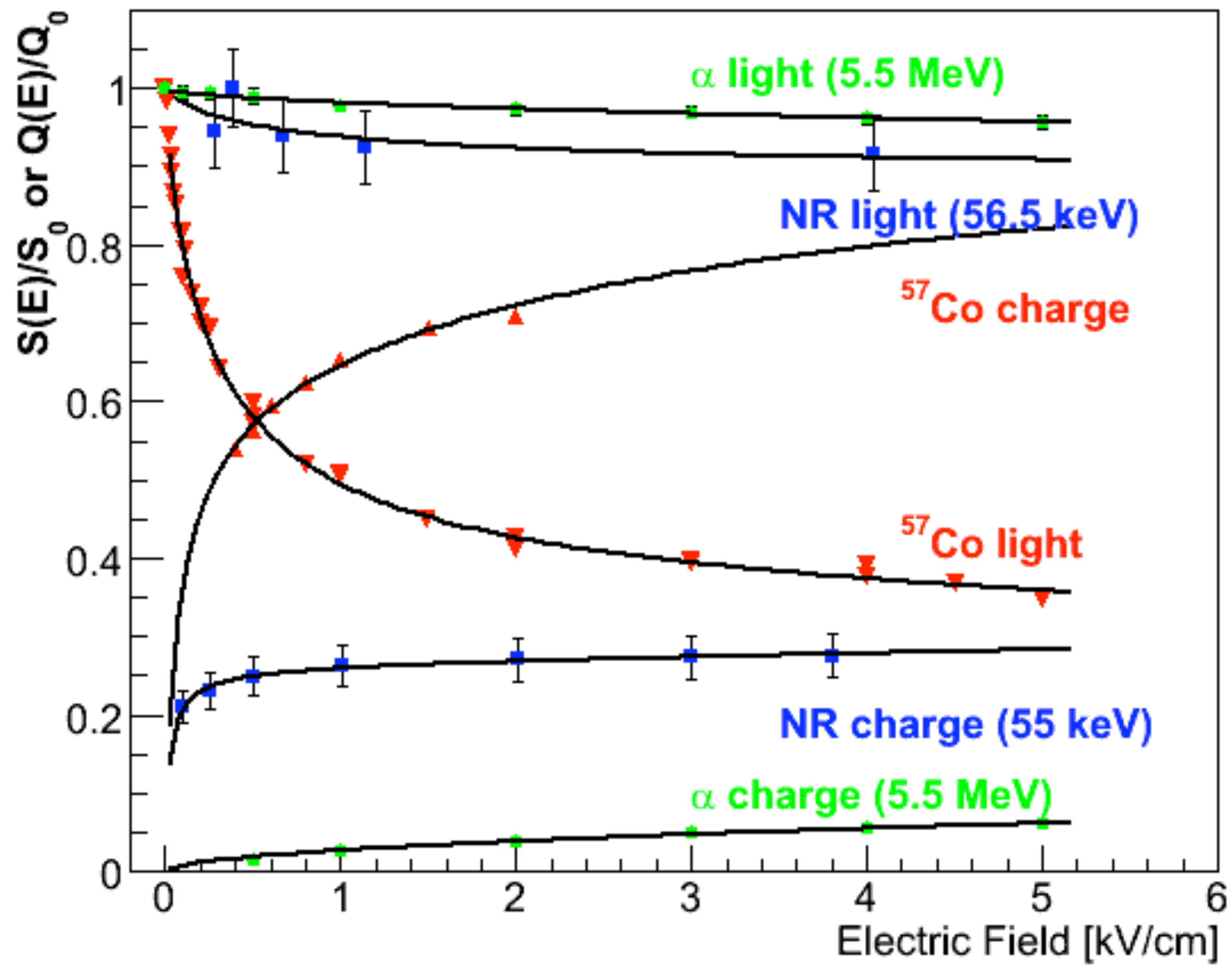


Ionization & Scintillation Yield of Nuclear Recoils in LXe

- 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 quickly 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)



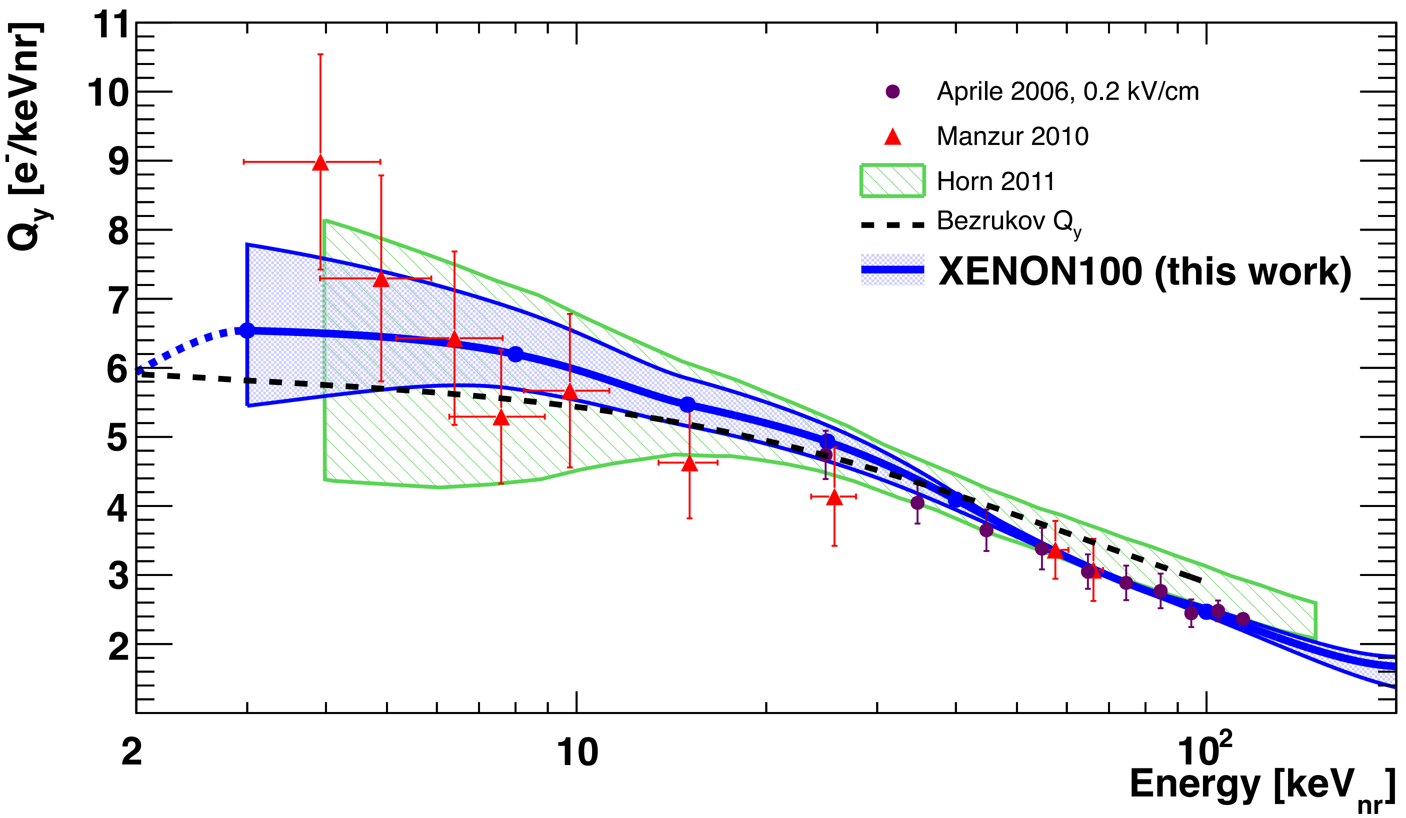
Aprile et al., Phys. Rev. D 72 (2005) 072006

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

Ionization Yield of Nuclear Recoils in LXe

- Nuclear recoils have denser tracks, and are assumed to have larger electron-ion recombination than electronic recoils
  - ➡ in consequence, the collection of ionization electrons becomes more difficult for nuclear than electronic recoils
- The ionization yield of nuclear recoils is defined as the number of observed electrons per unit recoil energy:

$$Q_{y,nr} = \frac{n_{e,nr}}{E_{nr}}$$

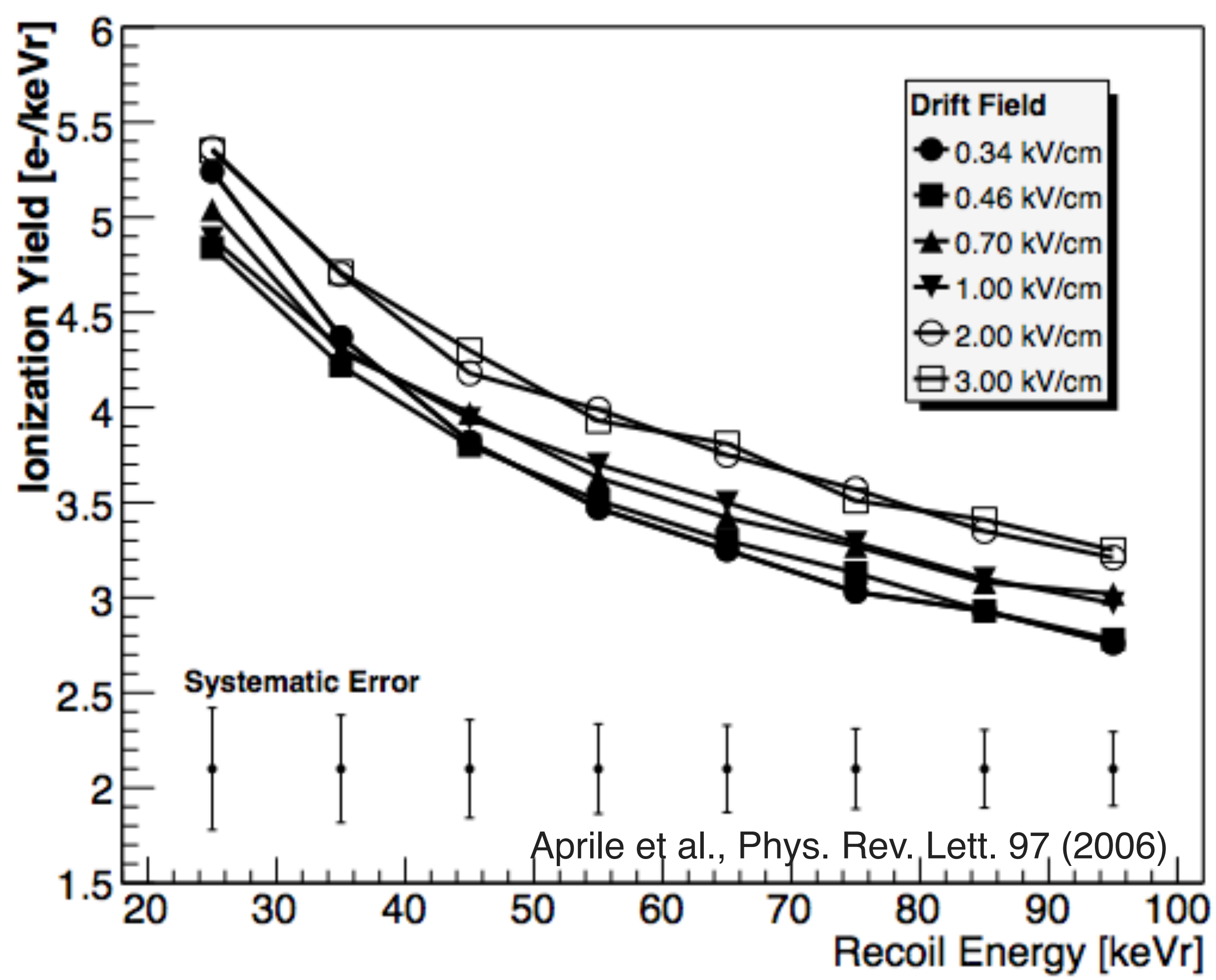


arXiv:1304.1427
blue: indirect measurement, by data/MC comparison of AmBe neutron calibration data

- It has been measured mostly in LXe, with two-phase detectors

Ionization Yield of Nuclear Recoils in LXe

- Charge yield as a function of the applied field
  - ➡ the dependance on the field is weak
  - ➡ the yield increases at low recoil energies - it is argued that this is due to the lower recombination rate expected from the drop in electronic stopping power at low energies
  - ➡ the increase allows the observation of xenon nuclear recoils down to a few keVr, improving the sensitivity for WIMP detection



Aprile et al., Phys. Rev. Lett. 97 (2006)

Relative Scintillation Efficiency of Nuclear Recoils, Leff

- We have seen that the scintillation light yield of nuclear recoils in noble liquids is different than the one produced by electron recoils of the same energy
- The ratio of the two = *relative scintillation efficiency (L_{eff})* is important for the determination of the sensitivity of noble liquids as dark matter detection media
- Experimentally this quantity is defined as the *zero-field value of light yield of nuclear recoils* (generated with n-sources) and *electronic recoils* (generated with γ-sources):

$$\mathcal{L}_{eff} = \frac{L_{y,nr}}{L_{y,er}} = \frac{E_{er}}{n_{\gamma,er}} \frac{n_{\gamma,nr}}{E_{nr}} = \frac{1}{L_y} \frac{n_{pe,nr}}{E_{nr}} = \frac{E_{ee}}{E_{nr}}$$

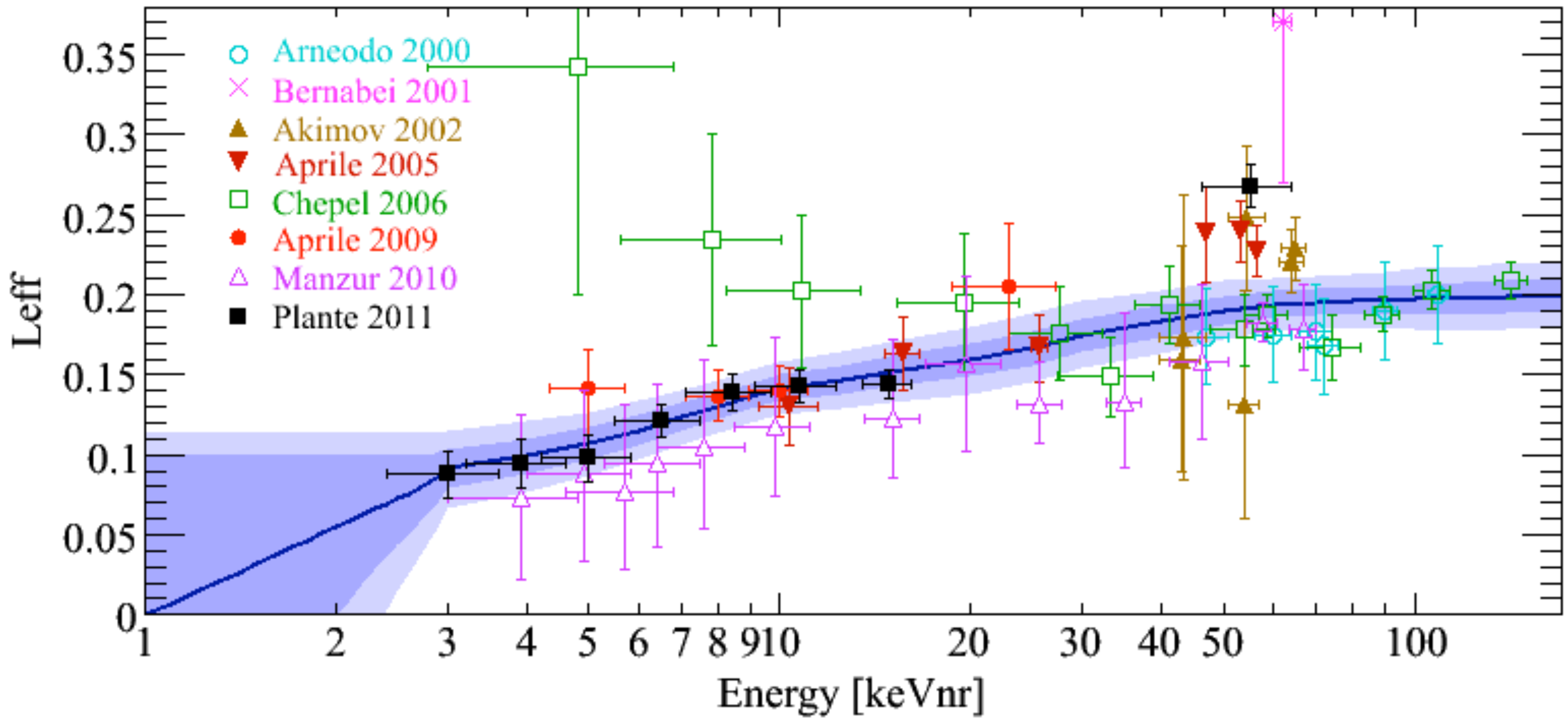
$n_{\gamma,er}$ = nr. of primary photons from electronic recoils
$n_{\gamma,nr}$ = nr of primary photons from nuclear recoils
$n_{pe,nr}$ = nr of primary photoelectrons from nuclear recoils

E_{ee} = “electron-equivalent” energy
L_y = the light yield of 122 keV gamma rays (^{57}Co source) as “standard calibration candle”

Measurements of Leff in LXe

- In general, two methods are used:
  - ➡ a direct method using mono-energetic neutrons scatters which are tagged with a n-detector
  - ➡ an indirect method by comparing measured energy spectra in LXe from n-sources (AmBe) with Monte Carlo predictions

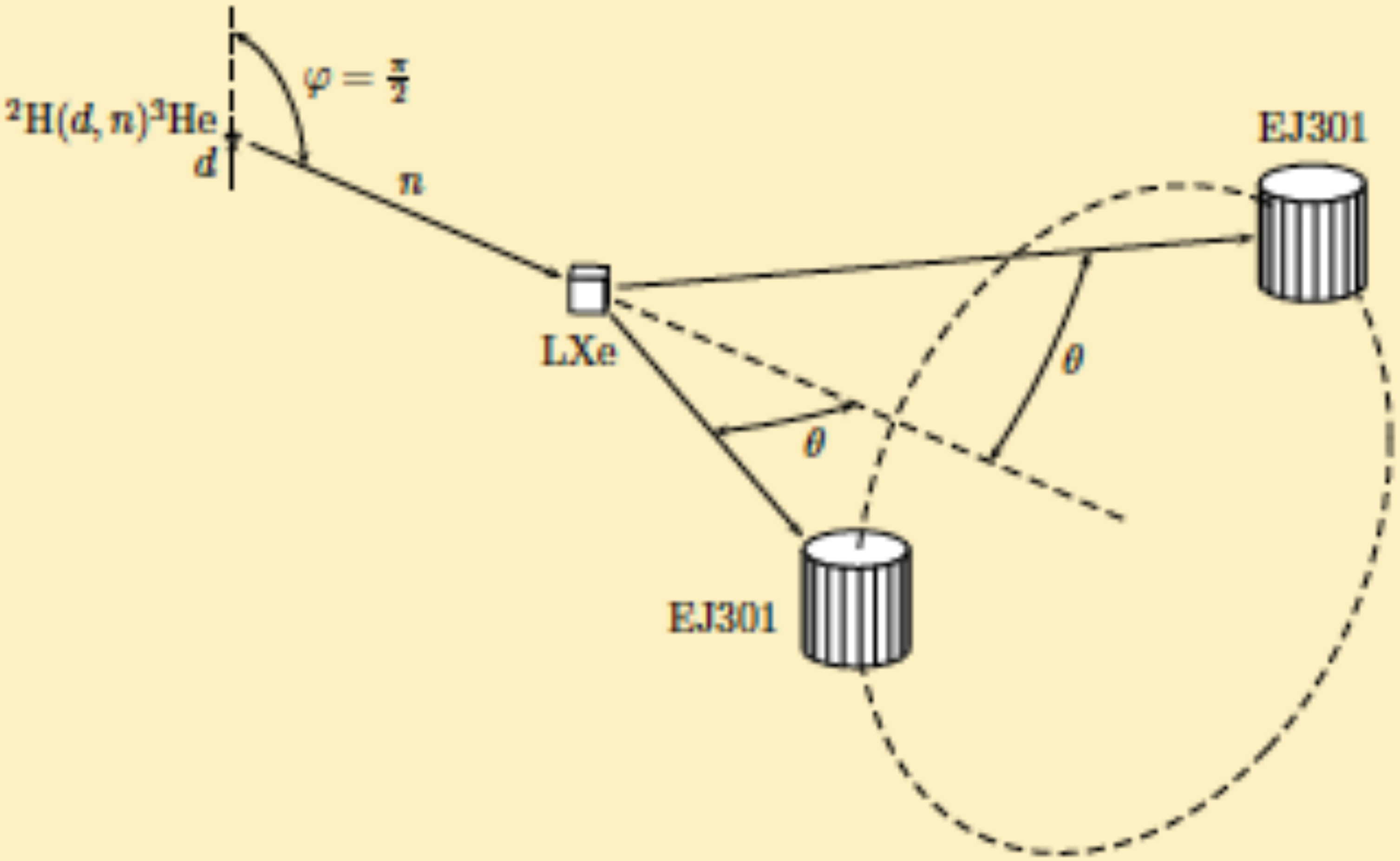
Plante *et al.*, Phys. Rev. C **84**, 045805, 2011



mean (solid) and 1-, 2-sigma uncertainties (blue bands)

Leff Measurement at Columbia (LXe)

- DD neutron generator, $\sim 2 \times 10^6$ n/s in 4π
- 6 PMT channels digitized
- 2-fold LXe coincidence trigger
- 2 liquid scintillators with n/γ discrimination
- Time of flight



- Recoil energy is fixed by kinematics

$$E_r \approx 2E_n \frac{m_n M_{Xe}}{(m_n + M_{Xe})^2}(1 - \cos\theta)$$

Design of the Leff Detector System

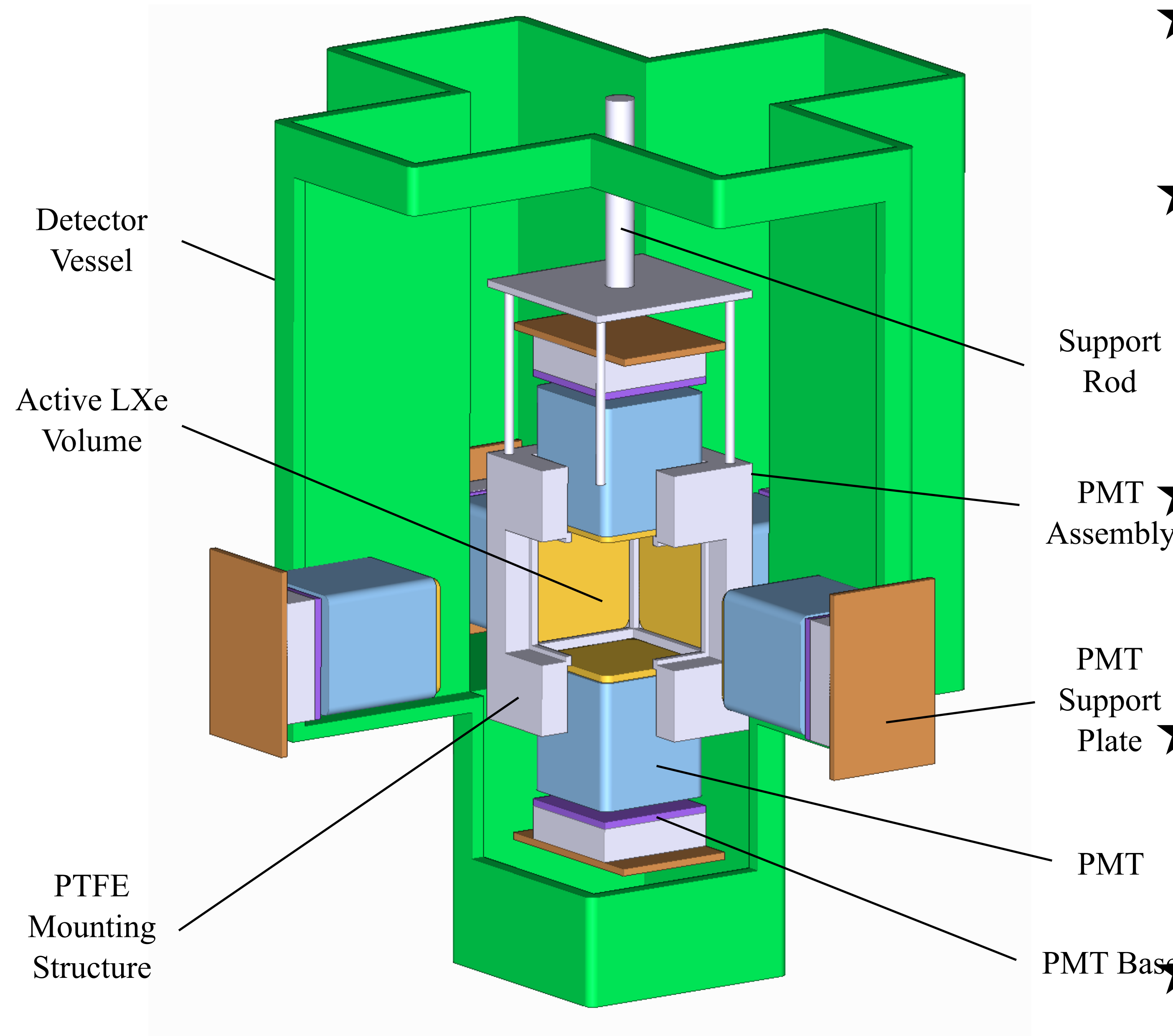


FIG. 2: LXe Detector schematic.

★Maximize the scintillation light detection efficiency.

★Minimize background from multiple scattered neutrons with a vessel design which reduces non-active materials near sensitive LXe volume.

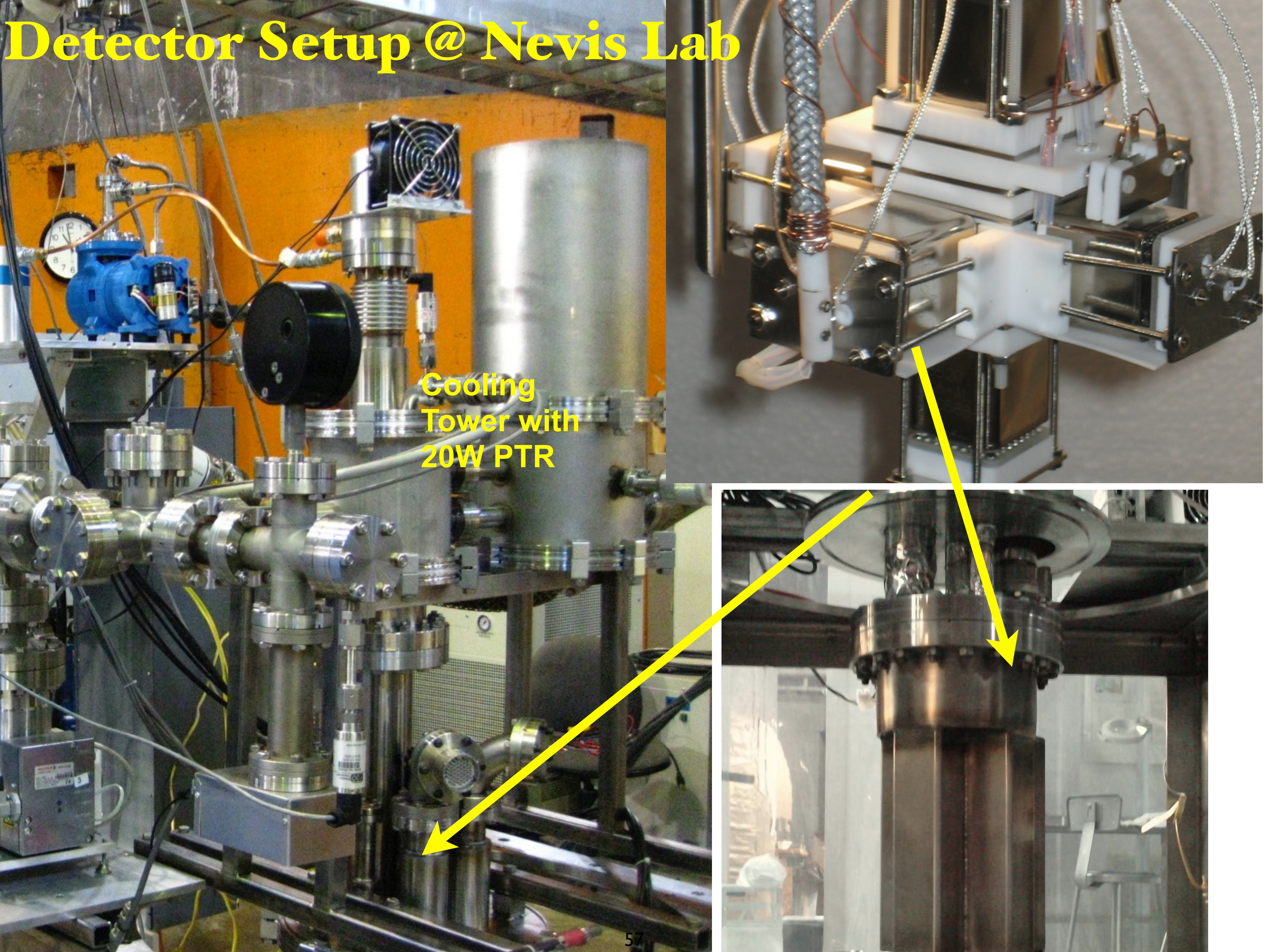
★Cubic LXe sensitive volume with six 2.5 x 2.5 cm Hamamatsu R8520-406 SEL High QE PMTs

★2-fold coincidence trigger on LXe PMTs with single channel thresholds at 0.3 PE for very low trigger threshold

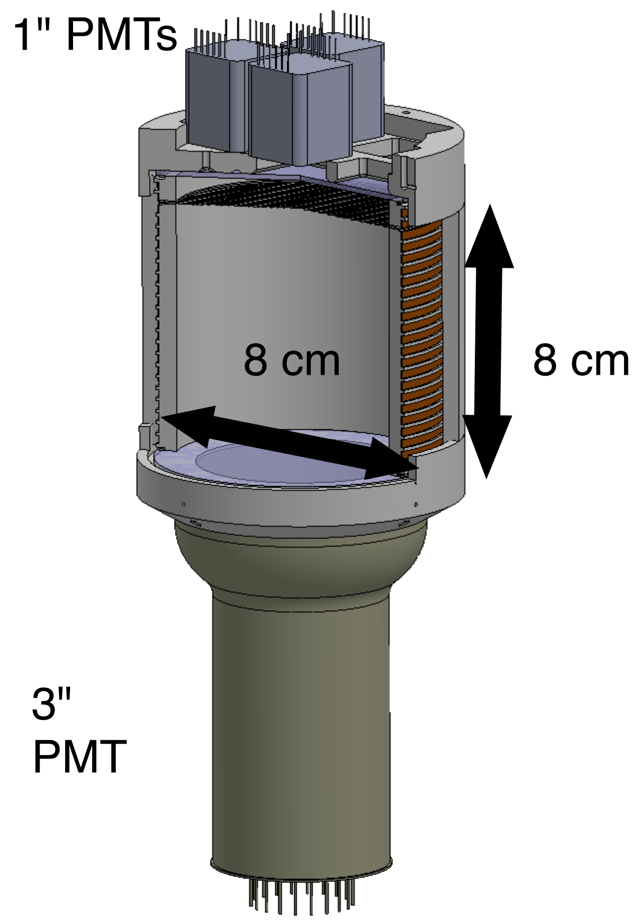
★Cooling with a Pulse Tube Refrigerator for reliable long term operation

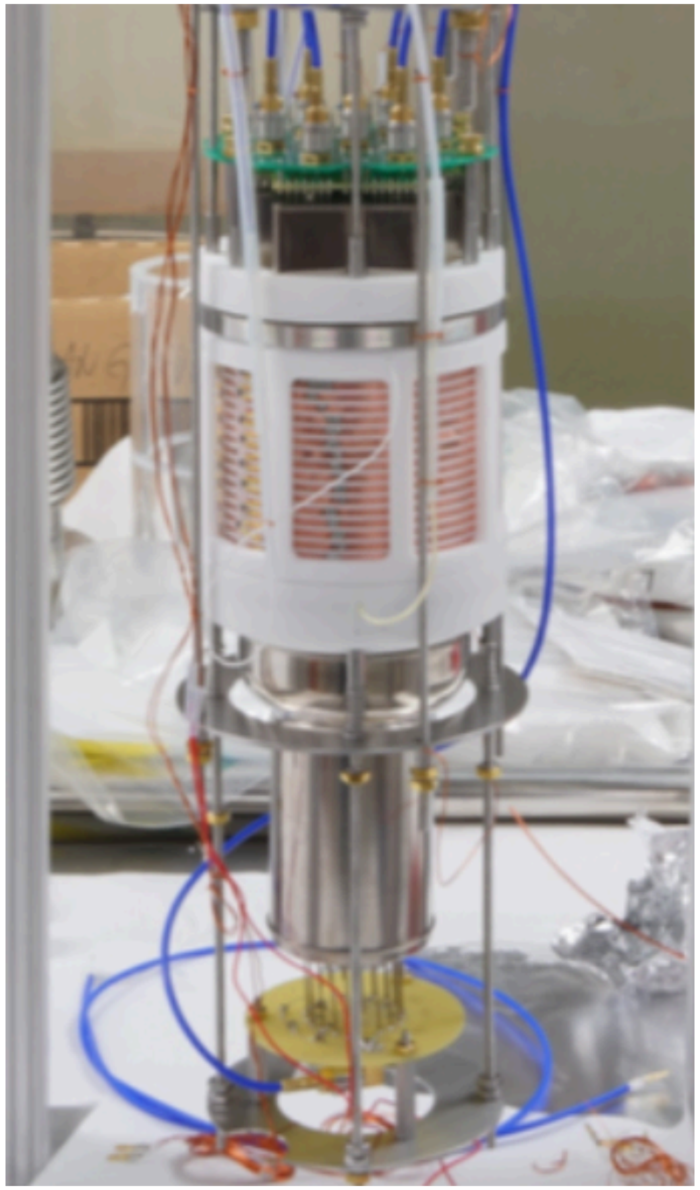
★2.5 MeV neutrons from a miniature DD generator (Schlumberger Minitron)

Detector Setup @ Nevis Lab



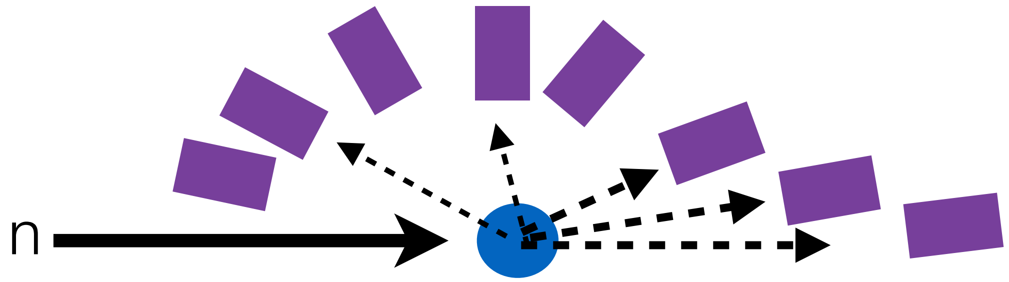
Leff Measurement at LICORNE @IPNO, Paris (LAr)





Measure L_{eff} down < 10 keV_{NR}
Small size to minimize multiple scatters

Collimated and mono-energetic neutron beam coupled with a set of neutron detectors



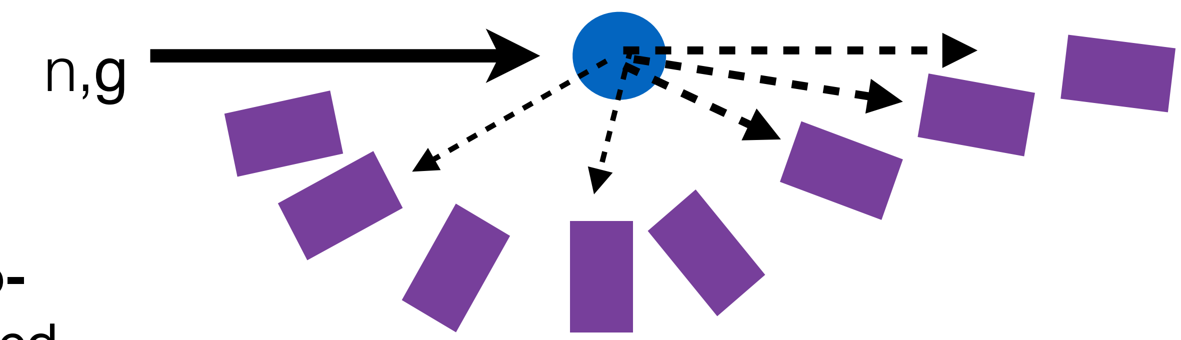
TPC:

- ~0.5 kg of LAr
- PTFE reflector with TPB coated surface
- 7 Hamamatsu 1" PMTs on top, one 3" PMT on bottom
- Anode/Cathode created with ITO plated fused-silica windows
- Grid 1 cm below the anode (extraction field)
- Ability to create a gas pocket for dual-phase running
- Operated in SINGLE PHASE

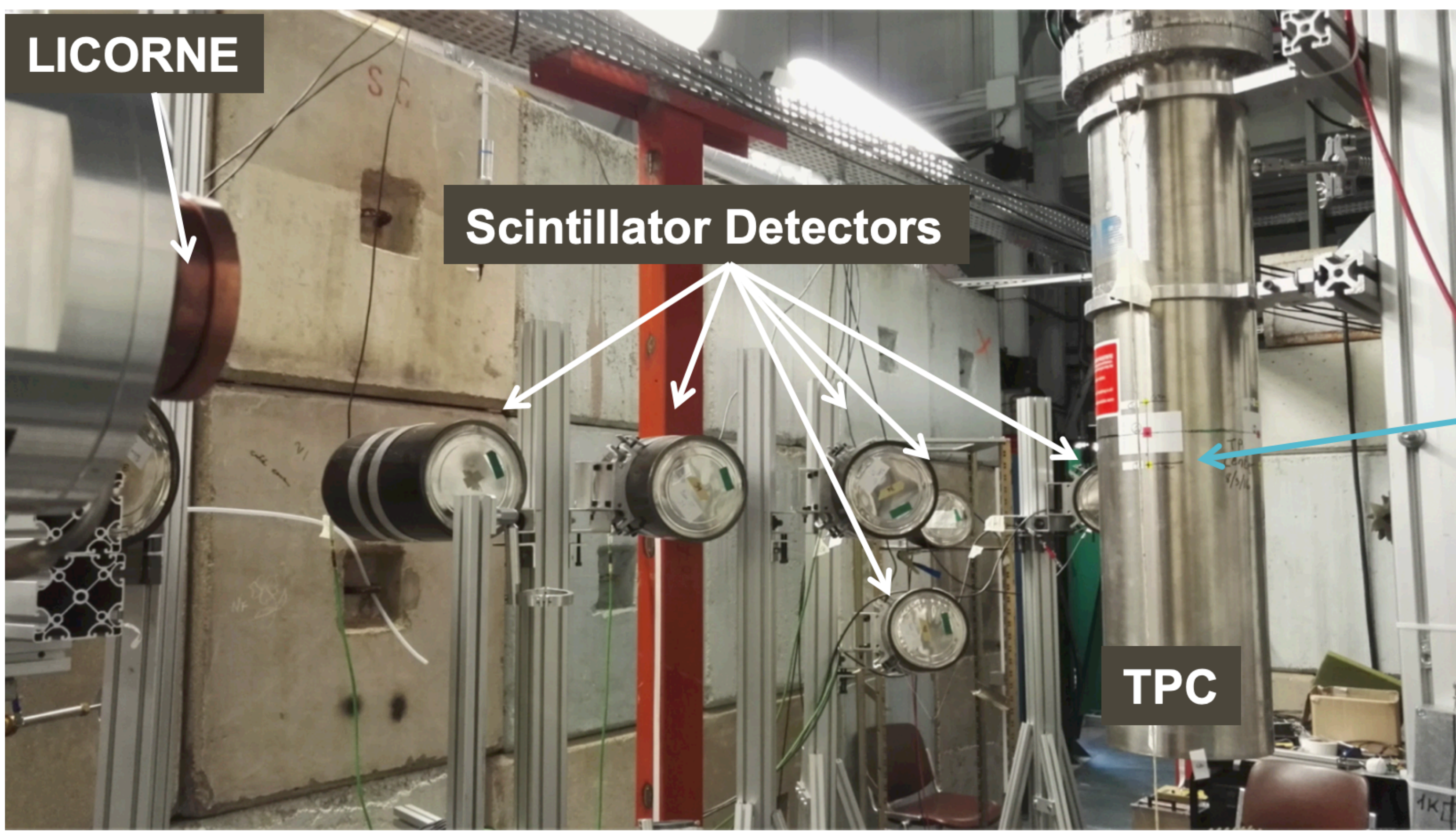
8 neutron detectors:

- NE213 liquid scintillator
- 20 cm diameter
- 5 cm height
- Signal pulse shape discrimination available

Main goal: L_{eff} at low energy
(scintillation efficiency of NR's)



Expose a small scale TPC to a **pulsed**, **collimated**, **mono-chromatic** neutron beam (LICORNE @IPNO, Paris), coupled with 8 neutron detectors, to fix NR energy by kinematics.



D1 neutrons selected by TOF and ND PSD cuts.

D2 gammas, correlated to the beam.

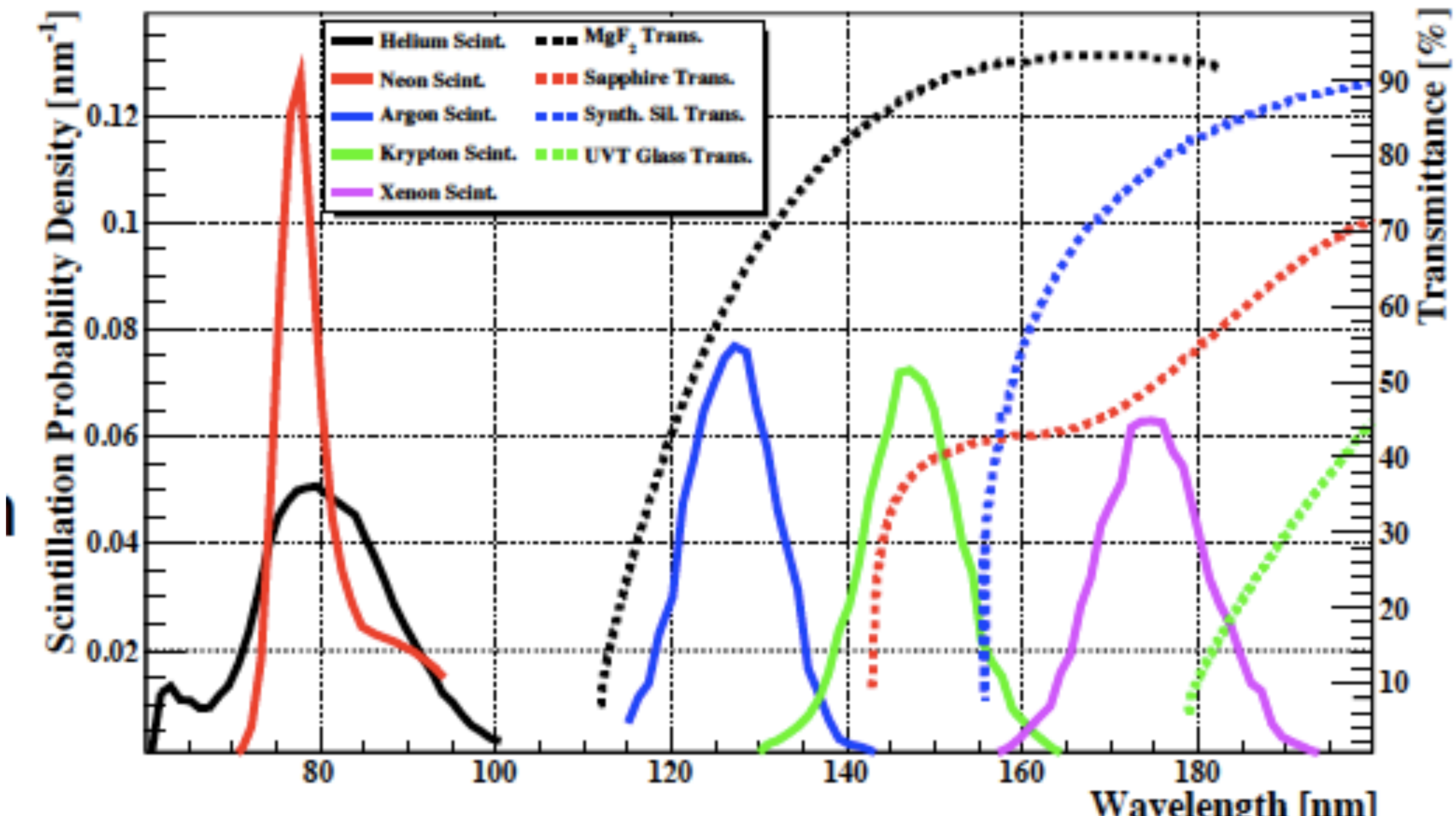
Cryogenic Noble Liquids: some challenges

- Cryogenics: efficient, reliable and cost effective cooling systems
- Detector materials: compatible with low-radioactivity and purity requirements
- Intrinsic radioactivity: ^{39}Ar and ^{42}Ar in LAr, ^{85}Kr in LXe, radon emanation/diffusion

- **Light detection:**
  - ➡ efficient VUV PMTs, directly coupled to liquid (low T and high P capability, high purity), effective UV reflectors (also solid state Si devices are under study)
  - ➡ light can be absorbed by H_2O and O_2: continuous recirculation and purification
- **Charge detection:**
  - ➡ requires << 1ppb (O_2 equivalent) for e^--lifetime > 1 ms (commercial purifiers and continuous circulation)
  - ➡ electric fields ≥ 1 kV/cm required for maximum yield for MIPs; for alphas and NRs the field dependence is much weaker, challenge to detect a small charge in presence of HV

Challenges to detect VUV Light from Noble Liquids

- The VUV light of noble liquids is challenging to detect as most transmission windows stop working at these wavelengths.
- Photomultipliers with quartz windows and bialkali photocathides which can be operated at cryogenic temperatures and high pressure have been developed for LXe.
- For LAr, wavelength shifters must be used. Tetra-Phenyl-Butadiene (TPB) tyically used to shift 128 nm to 430 nm.



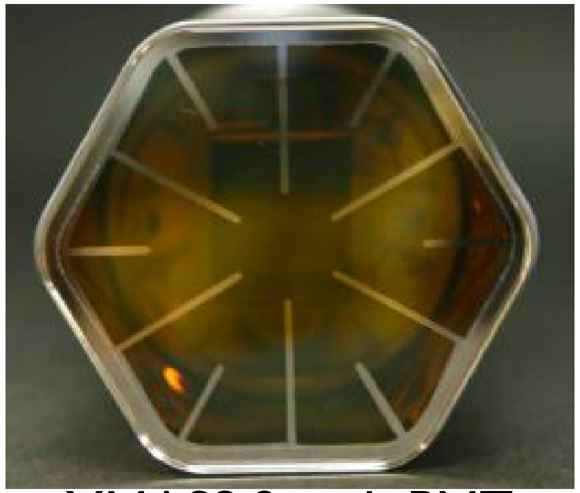
Photomultipliers for Noble Liquids

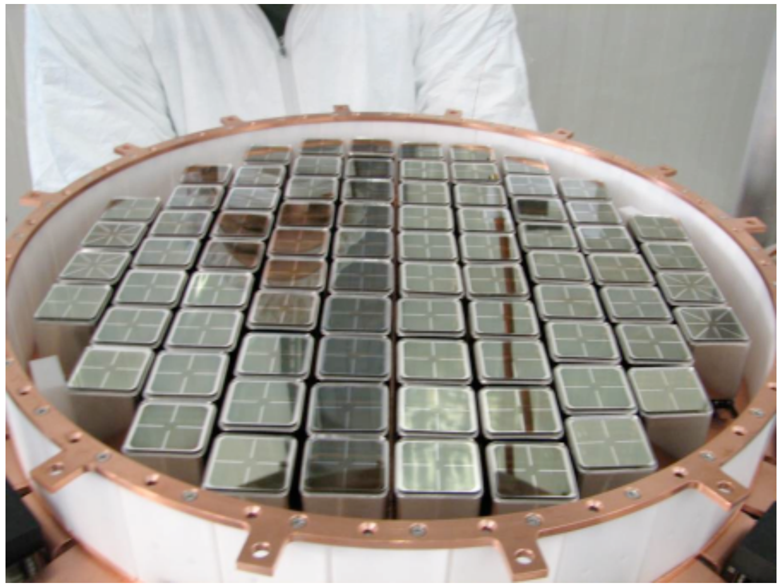
- LT bialkali photocathodes: high QE (~30-40%), all metal body, Al seal (up to 5 bar and -100C)
- Ultra-low radioactivity: < 1 mBq/PMT (U/Th/K/Co/Cs)
- Quartz (sapphire under development) window: transparent to the Xe 178 nm scintillation light
- For LAr shifted light, PMTs directly operating in the cold liquid have also been developed


XENON100 1-inch PMT


XENON1T 3-inch PMT


LUX 2-inch PMT


XMASS 2-inch PMT


XENON100 array


LUX array


XMASS array

Light Absorption and Electron Attachment due to Impurities

Impurities dissolved in the liquid absorb UV photons, reducing the light yield. Light attenuation described as

$$I(x) = I(0)\exp(-x/\lambda_{att})$$

Strong absorption by H2O, even stronger at 128 nm of LAr

Electronegative impurities dissolved in the liquid also trap electrons reducing the charge yield

$$[e(t)] = e(0)exp(-k_S[S]t)$$

We define electron lifetime in terms of the impurity concentration [S] and an attachment rate constant k

$$\tau = (k_S[S])^{-1}$$

The electron attenuation length is related to the lifetime via the electron mobility and the electric field

$$\lambda_{att} = \mu E \tau$$

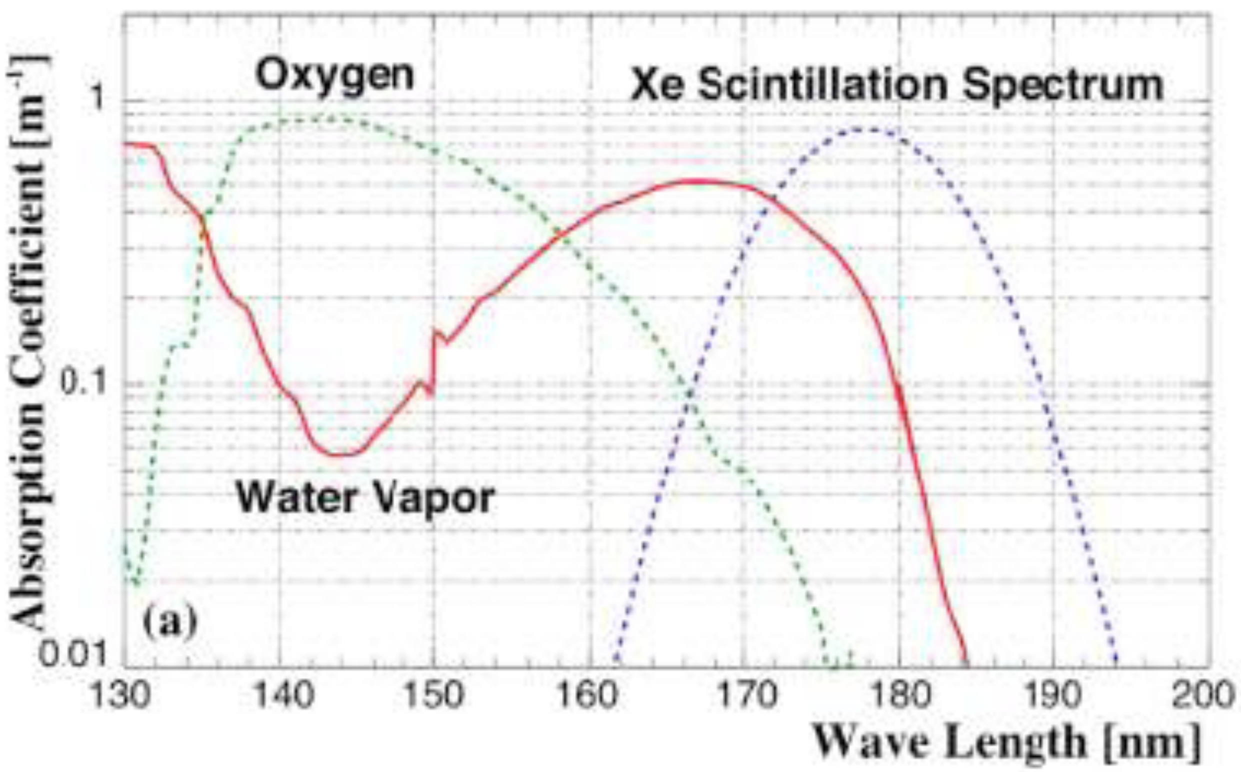


FIG. 25 Absorption coefficient for VUV photons in 1 ppm water vapor and oxygen and superimposed Xe emission spectrum (Ozone, 2005).

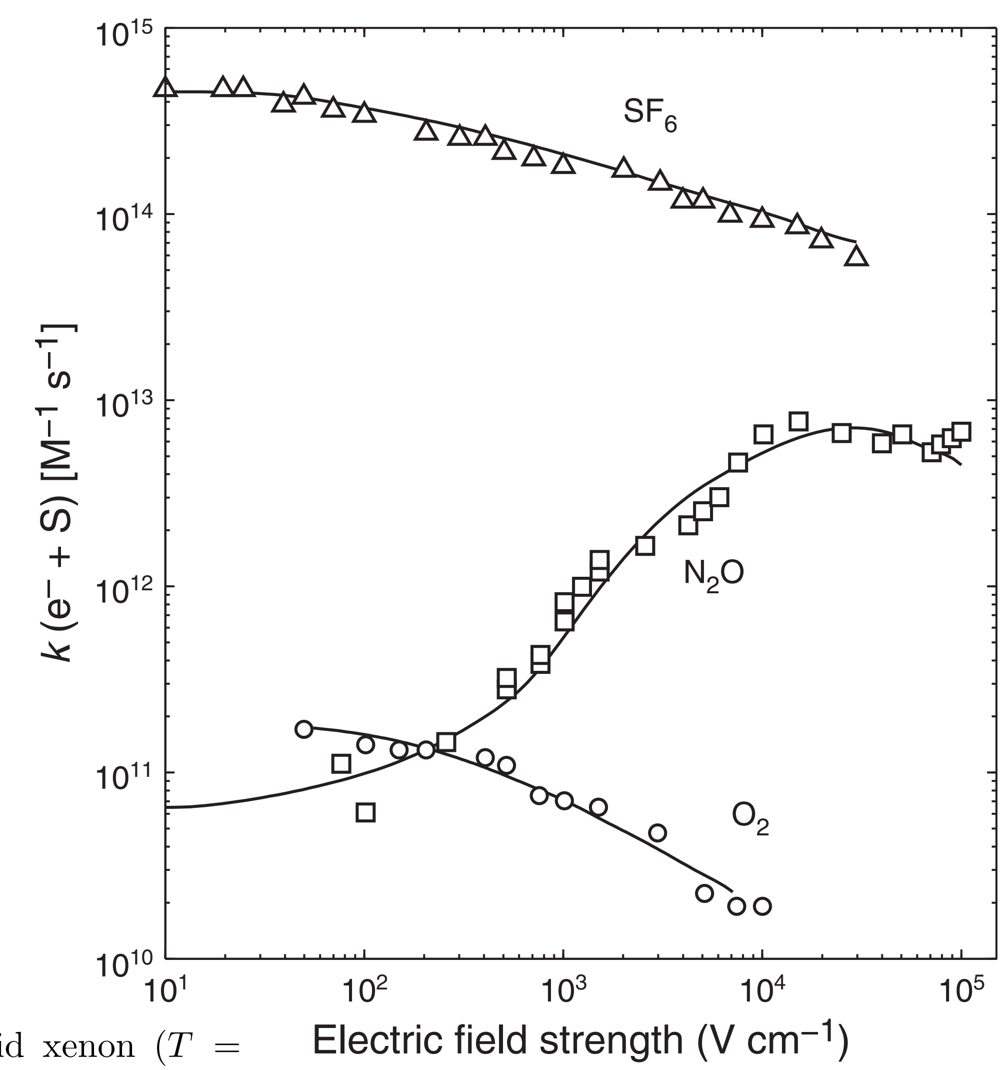


Fig. 21.4. Rate constant for the attachment of electrons in liquid xenon (T = 167 °K) to several solutes: (△) SF_6, (□) N_2O, (○) O_2 [174].

What level of liquid purity is required?

Light: 1 ppm of H_2O would result in strong absorption hence water vapor must be well below ppm level for efficient light detection

$$\lambda_{\mathrm{abs},\mathrm{H_2O}} = \frac{1}{10^{-6}\cdot n_{\mathrm{Xe}}\sigma_{\mathrm{H_2O}}} = \frac{131\,\mathrm{g\,mol^{-1}}}{10^{-6}N_A\cdot 2.83\,\mathrm{g\,cm^{-3}}\cdot 2\times 10^{-18}\,\mathrm{cm^2}} \approx 38\,\mathrm{cm}$$

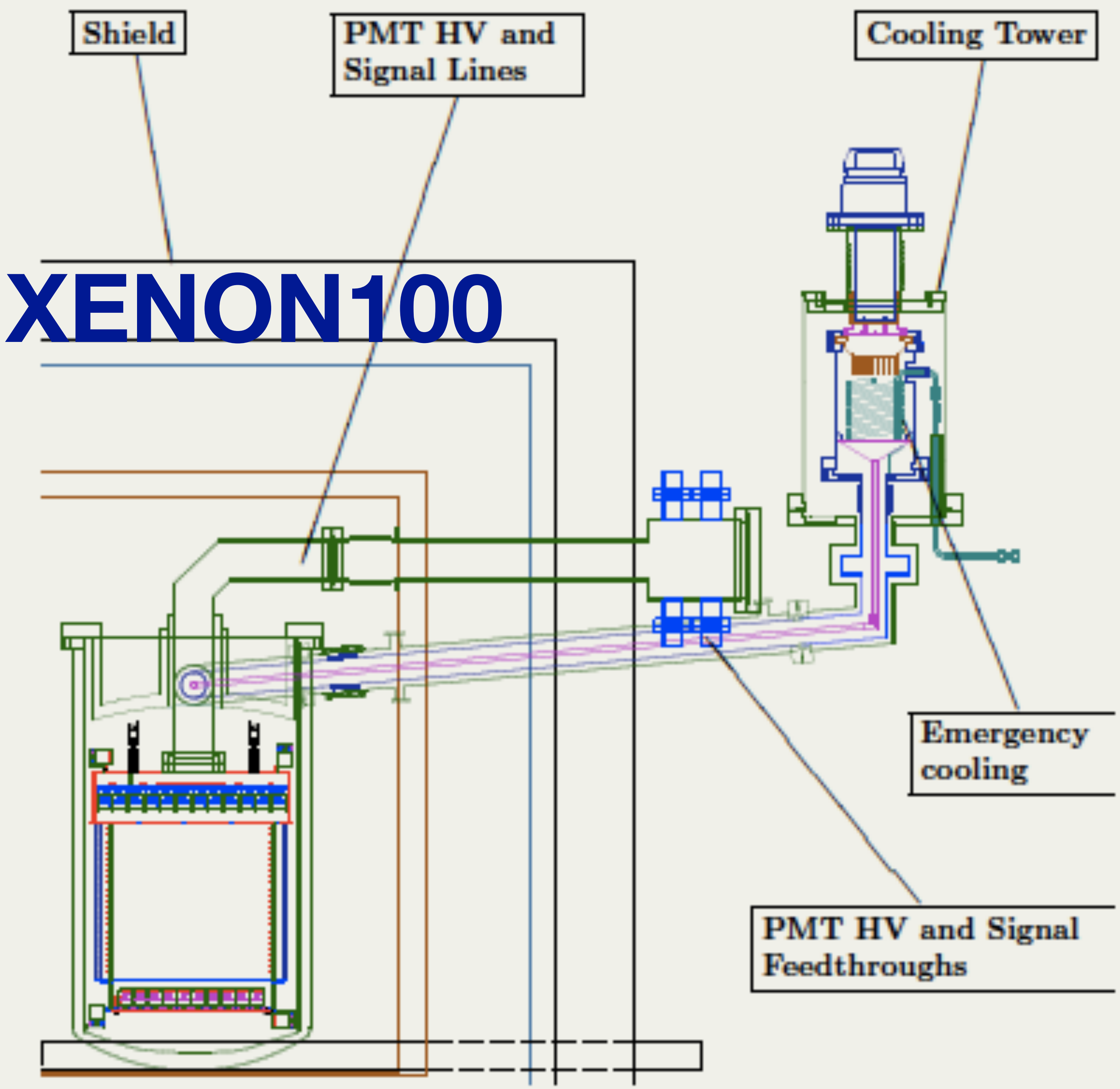
Charge: 1 ppb of O_2 equivalent impurities would result in a reasonable electron lifetime,taking the attachment rate constant value at a field of 0.5 kV/cm from Bakale et al.

$$\tau_e = \frac{1}{10^{-9}\cdot n_{\mathrm{Xe}}k_{\mathrm{O_2}}} = \frac{131\,\mathrm{g\,mol^{-1}}}{10^{-9}\cdot 2.83\,\mathrm{g\,cm^{-3}}\cdot 1\times 10^{11}\,\mathrm{mol^{-1}\,L\,s^{-1}}} \approx 463\,\mu\mathrm{s}$$

Other Challenges for Cryogenic Noble Liquids

- Reliable and efficient cooling systems are required for long term operation
- Detector construction materials and components in contact with the liquid must be compatible with both ultra-high purity and ultra-low radioactivity requirements
- The target gas itself must have no intrinsic radioactive contaminants: special purification plants are needed to remove the Kr85 from natural Xe and the Ar39 from natural Ar
- Radon emanation and diffusion from construction materials and Rn in commercial gas itself must be reduced to ultra-low levels (<1 microBq/m2). Background due to Pb206 recoils from Po210 decays on most materials surfaces. Reduce by proper surfaces treatment and nearly Rn-free assembly plus Rn trapping via charcoals
- For noble liquid detectors using both light and charge (TPCs) the required HV for a drift field can get as high as 100 kV for a meter drift detector and a nominal 1kV/cm field. Commercial HV feedthroughs (FT) are too radioactive hence the need to develop custom-made FTs with radio-pure materials and of special design to operate in dual phase TPCs

Example of Cooling System for Xe



- PC150 PTR 200 W in a "cooling tower" outside passive shield.
- Copper cold finger in thermal contact with the PTR coldhead seals the top of the inner vessel. Copper "cup" with resistive heaters between the PTR coldhead and the cold finger.
- The temperature of the cold finger is regulated via a PID control loop that adjusts the heater power.
- LXe flows back from the cooling tower to the cryostat vessel through an inclined double-wall pipe.
- Recirculation takes LXe from the bottom of the vessel and pushes back GXe in the bell.
- Emergency cooling provided by LN_2 flowing through a stainless steel coil inside the cooling tower.