WIMP Dark Matter Direct-Detection Searches in Noble Gases

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Direct WIMP detection: principle

Goodman and Witten, PRD31, 1985

- Elastic collision with atomic nuclei in ultra-low background detectors
- Energy of recoiling nucleus: few keV to tens of keV

Astrophysics

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{min}} d\mathbf{v} f(\mathbf{v}) v \frac{d\sigma}{dE_R}$$

Particle+nuclear physics

N_N = number of target nuclei in a detector

ρ_0 = local density of the dark matter in the Milky Way

$f(v)$ = WIMP velocity distribution in lab frame

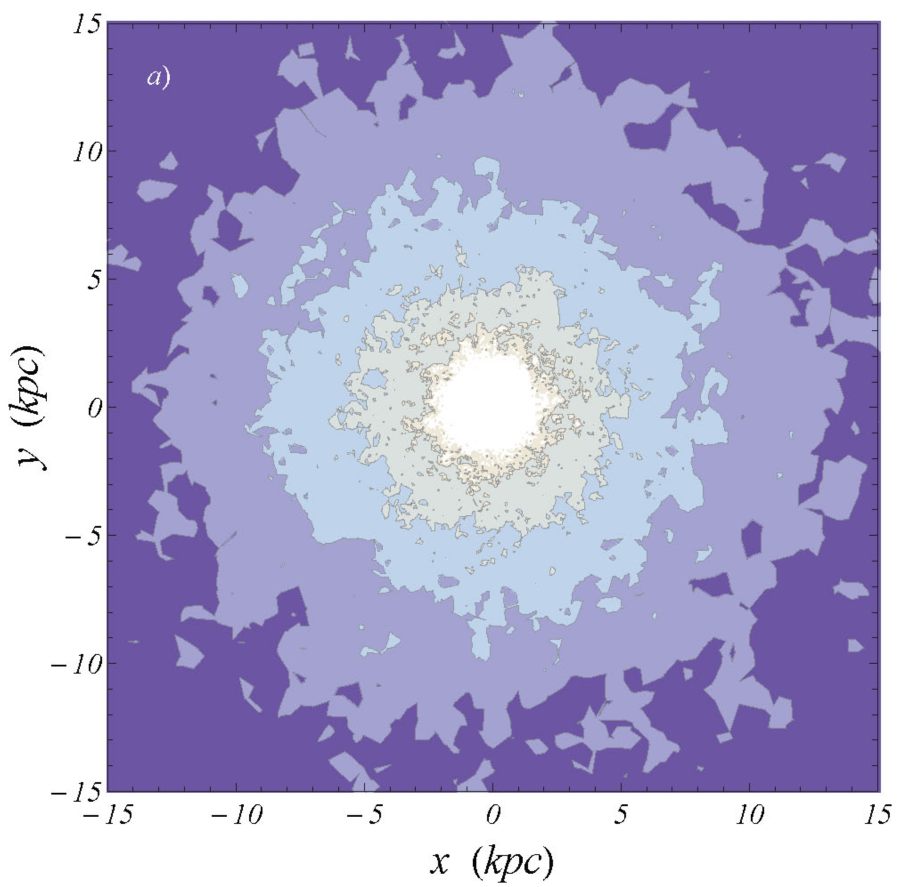
m_W = WIMP-mass

σ =cross section for WIMP-nucleus elastic scattering

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

WIMPs in the galactic halo

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

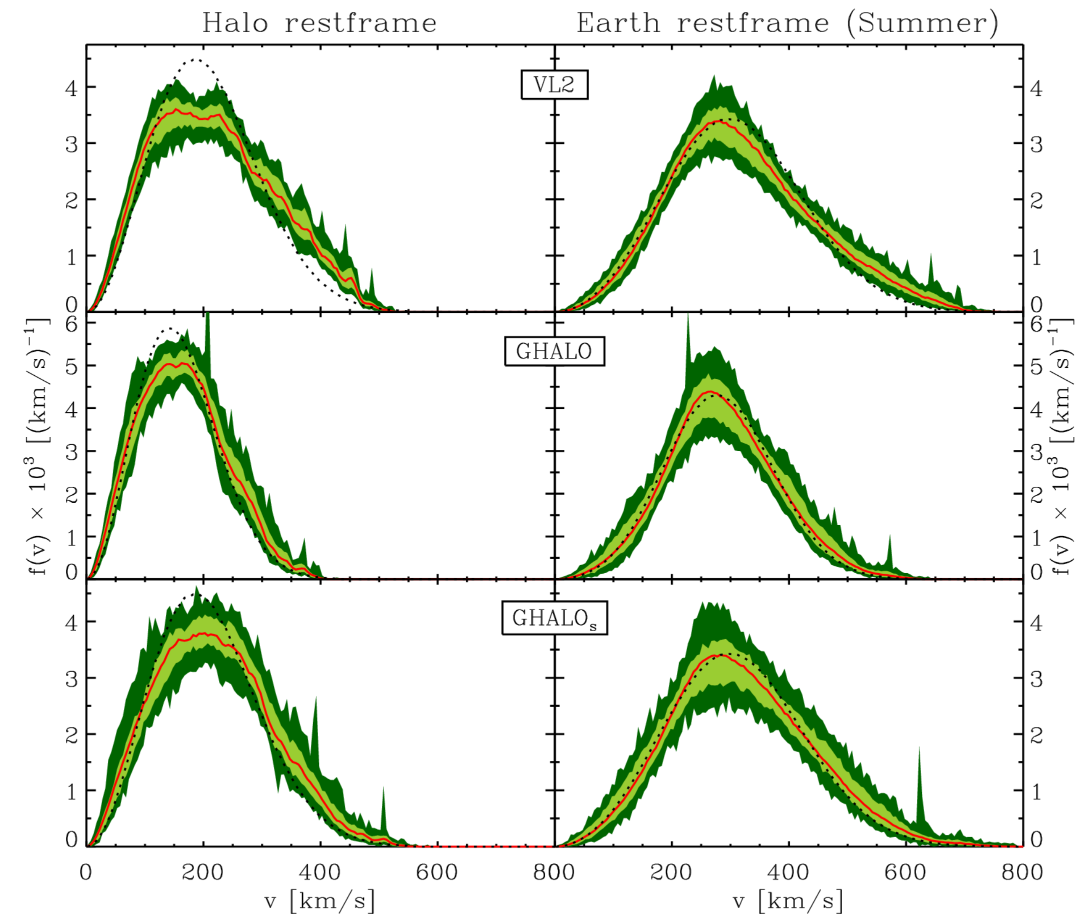


High-resolution cosmological simulation with baryons: F.S. Ling et al, JCAP02 (2010) 012

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

=> WIMP flux on Earth:
$\sim 10^5\ cm^{-2}s^{-1}$ (M_W=100 GeV)

Velocity distribution of WIMPs in the galaxy



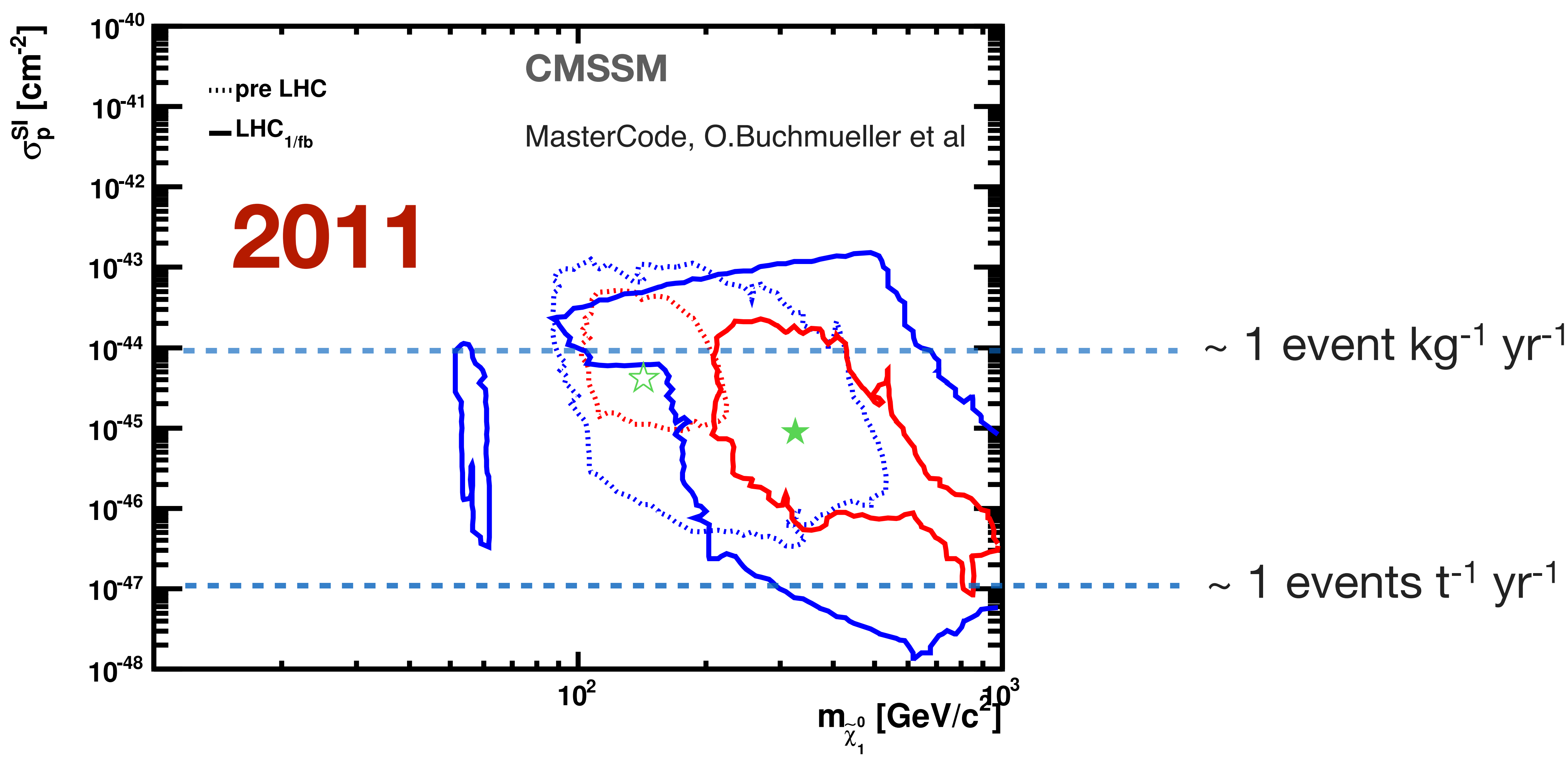
M. Kuhlen et al, JCAP02 (2010) 030

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

WIMP masses and scattering cross sections

- Example for theoretical predictions from supersymmetry
- Scattering cross sections on protons/neutrons down to 10^{-48} cm^2



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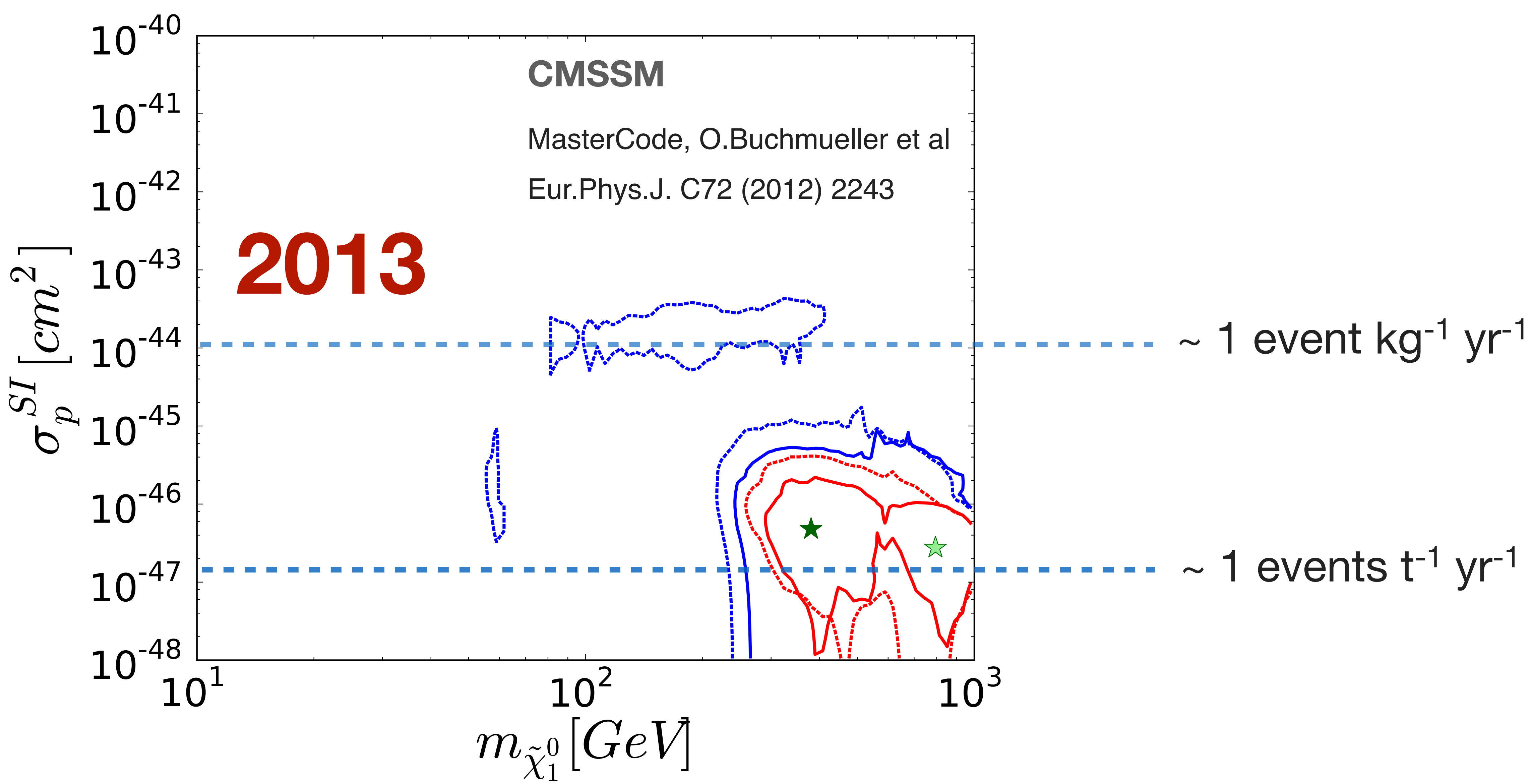
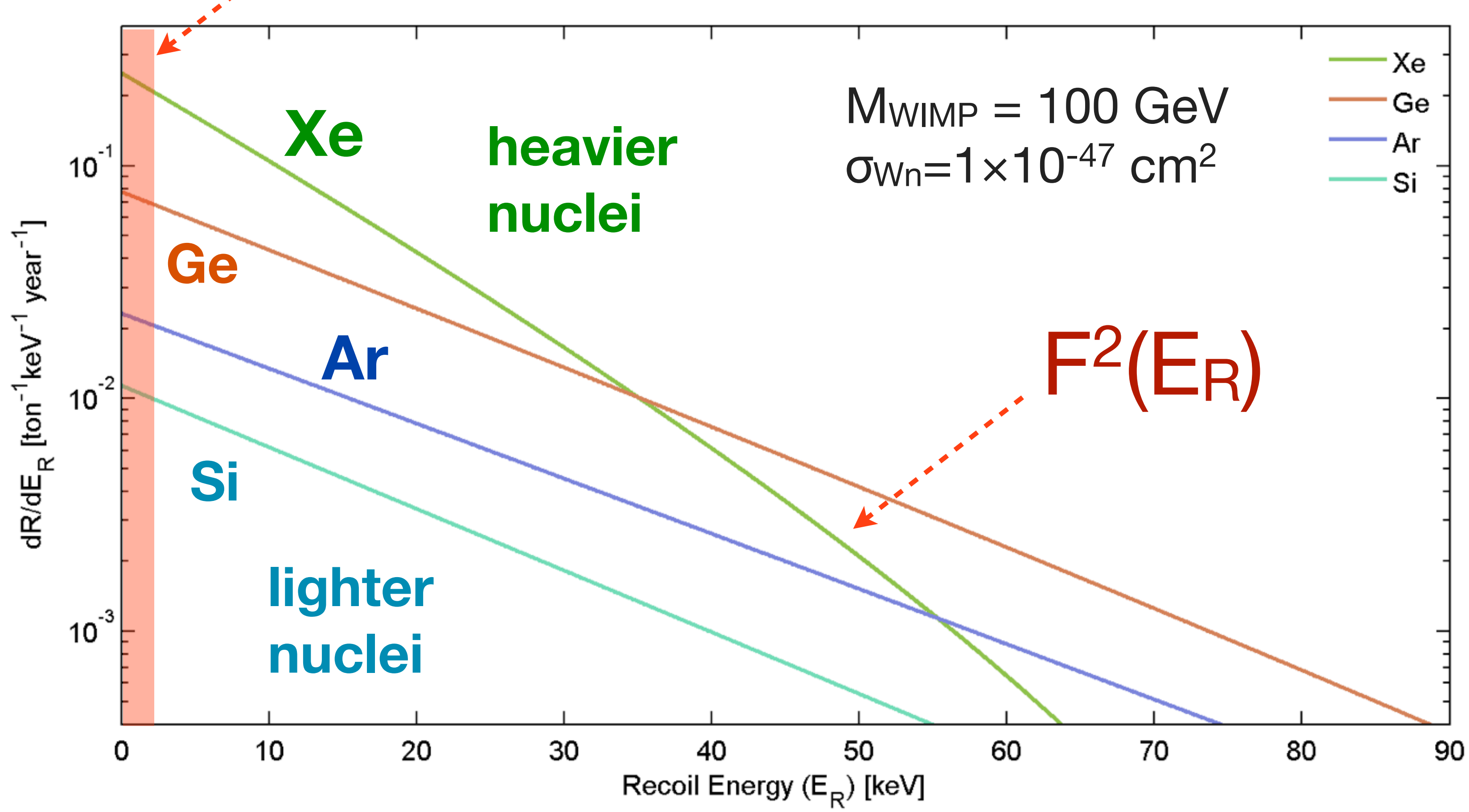


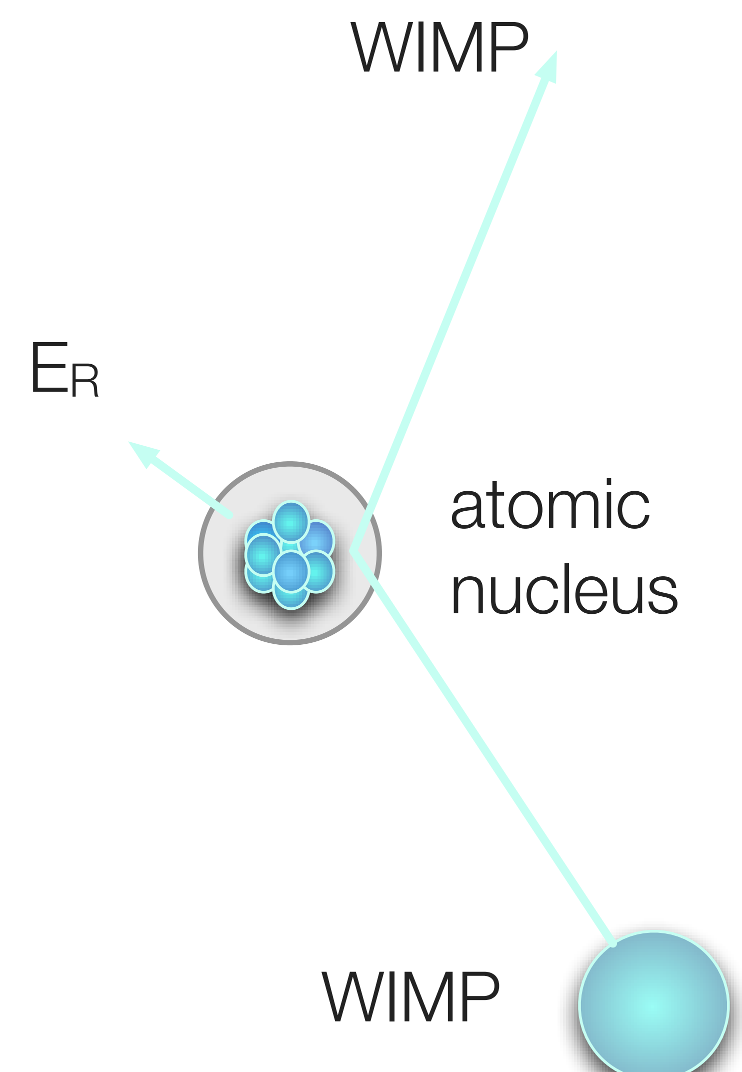
Interaction rates for elastic scattering

- Recoil rate after integration over WIMP velocity distribution

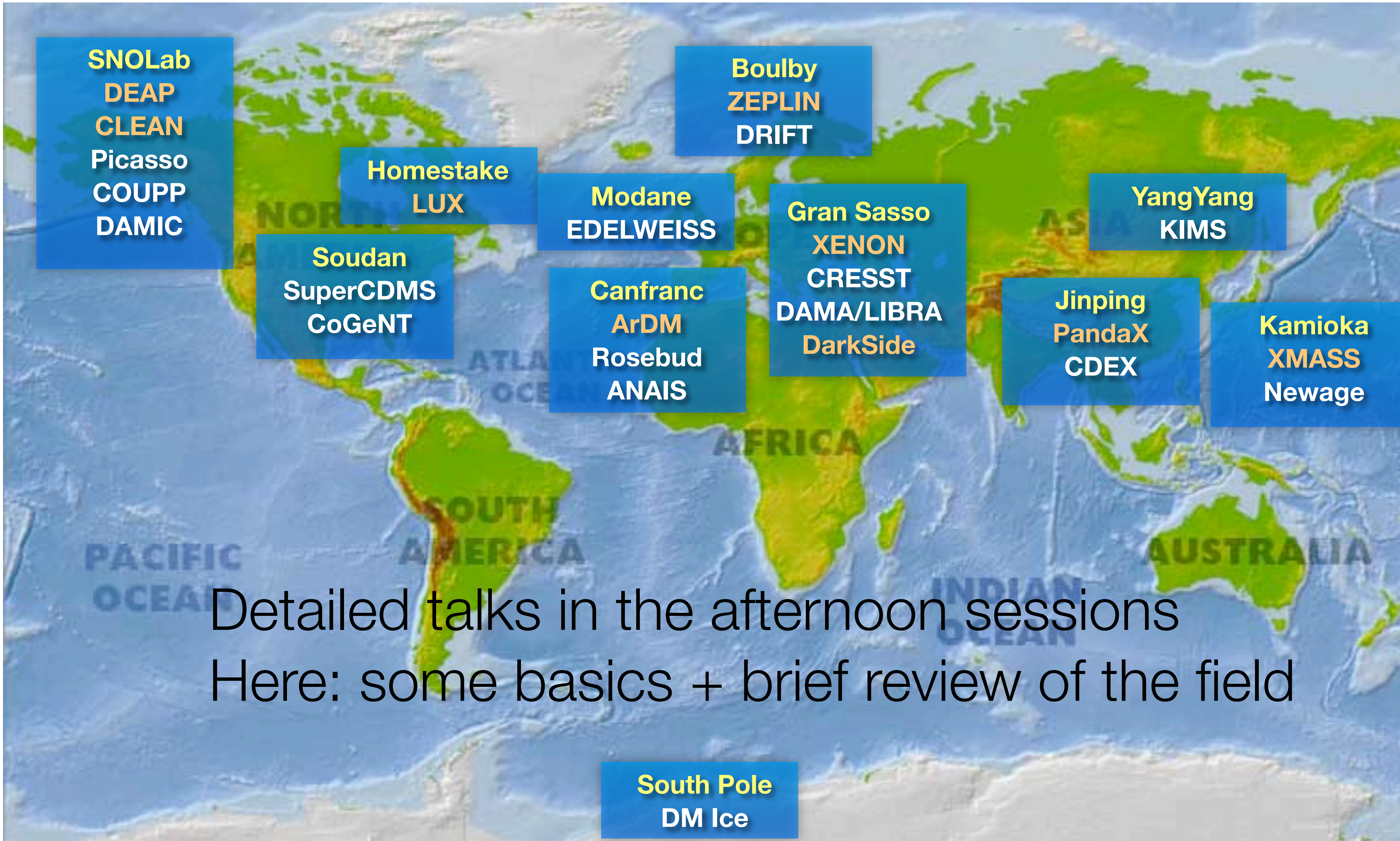
$$R \sim 0.13 \, \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$

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



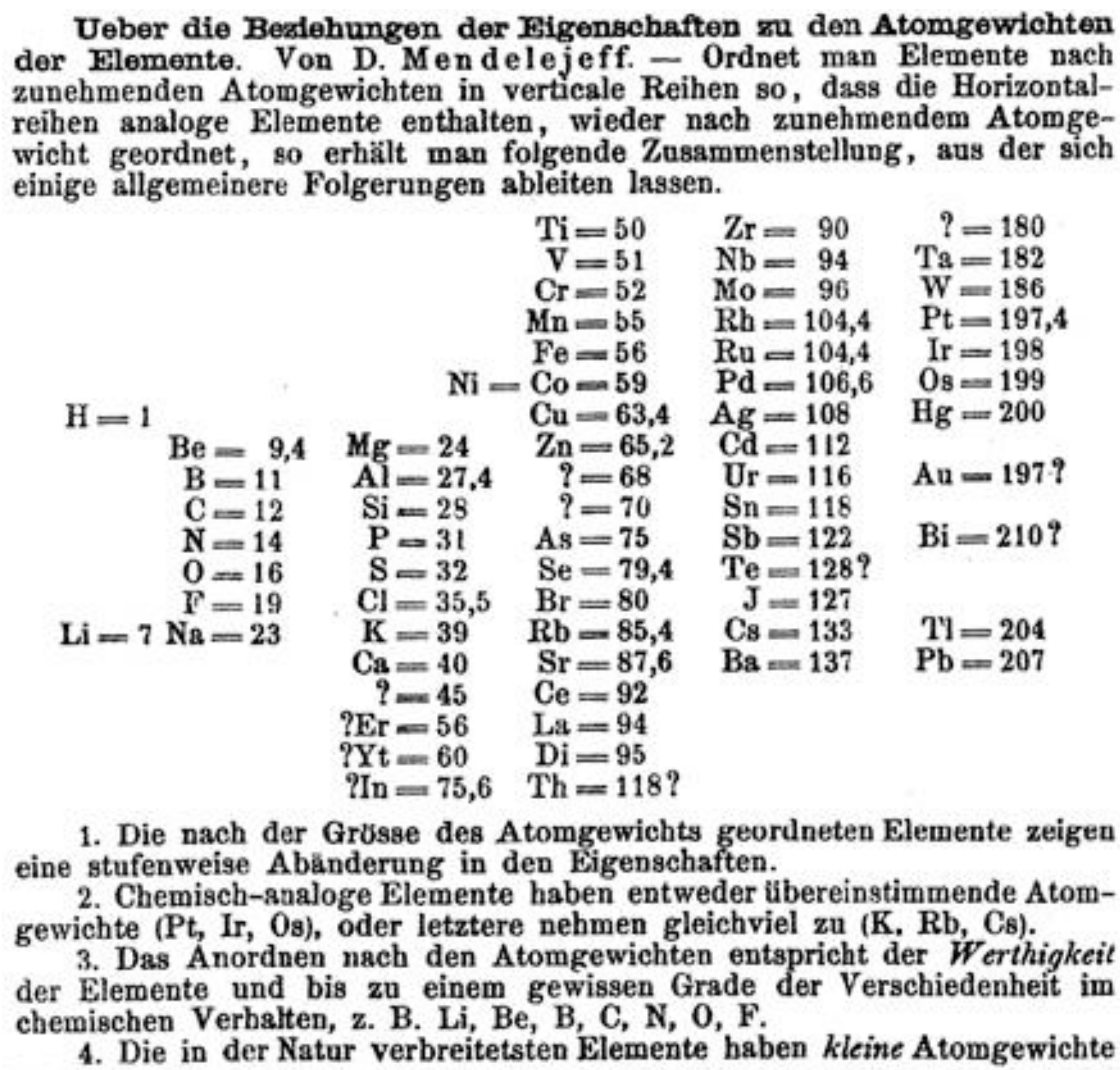


A world-wide effort to search for WIMPs



Detailed talks in the afternoon sessions
Here: some basics + brief review of the field

Noble gases in Mendeleev's Periodic Table

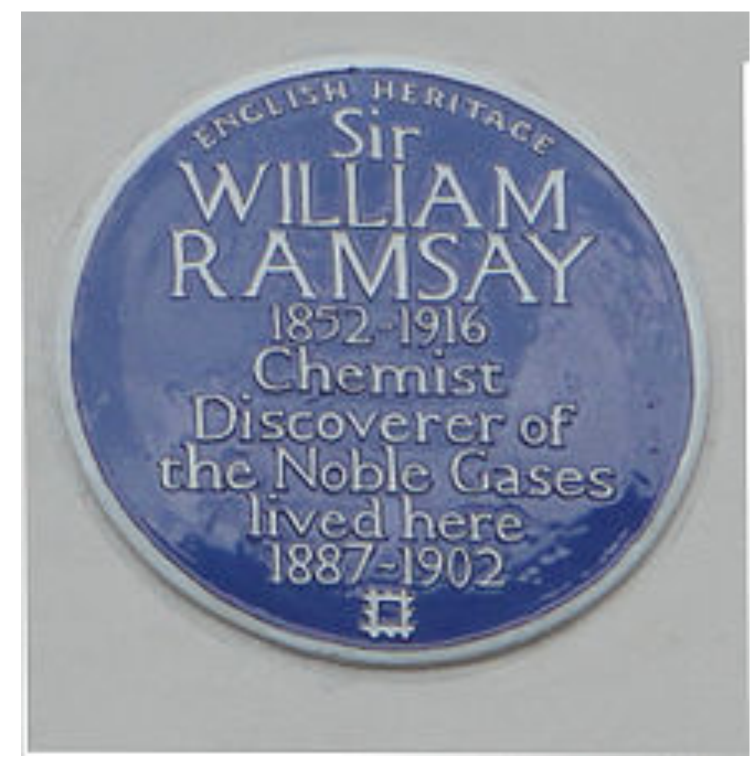


Ueber die Beziehungen der Eigenschaften zu den Atomgewichten der Elemente. Von D. Mendelejeff. — Ordnet man Elemente nach zunehmenden Atomgewichten in verticale Reihen so, dass die Horizontalreihen analoge Elemente enthalten, wieder nach zunehmendem Atomgewicht geordnet, so erhält man folgende Zusammenstellung, aus der sich einige allgemeinere Folgerungen ableiten lassen.

			Ti = 50	Zr = 90	? = 180
			V = 51	Nb = 94	Ta = 182
			Cr = 52	Mo = 96	W = 186
			Mn = 55	Rh = 104,4	Pt = 197,4
			Fe = 56	Ru = 104,4	Ir = 198
			Ni = Co = 59	Pd = 106,6	Os = 199
H = 1			Cu = 63,4	Ag = 108	Hg = 200
	Be = 9,4	Mg = 24	Zn = 65,2	Cd = 112	
	B = 11	Al = 27,4	? = 68	Ur = 116	Au = 197?
	C = 12	Si = 28	? = 70	Sn = 118	
	N = 14	P = 31	As = 75	Sb = 122	Bi = 210?
	O = 16	S = 32	Se = 79,4	Te = 128?	
	F = 19	Cl = 35,5	Br = 80	J = 127	
Li = 7	Na = 23	K = 39	Rb = 85,4	Cs = 133	Tl = 204
		Ca = 40	Sr = 87,6	Ba = 137	Pb = 207
		? = 45	Ce = 92		
		?Er = 56	La = 94		
		?Yt = 60	Di = 95		
		?In = 75,6	Th = 118?		

1. Die nach der Grösse des Atomgewichts geordneten Elemente zeigen eine stufenweise Abänderung in den Eigenschaften.
2. Chemisch-analoge Elemente haben entweder übereinstimmende Atomgewichte (Pt, Ir, Os), oder letztere nehmen gleichviel zu (K, Rb, Cs).
3. Das Anordnen nach den Atomgewichten entspricht der *Werthigkeit* der Elemente und bis zu einem gewissen Grade der Verschiedenheit im chemischen Verhalten, z. B. Li, Be, B, C, N, O, F.
4. Die in der Natur verbreitetsten Elemente haben *kleine* Atomgewichte

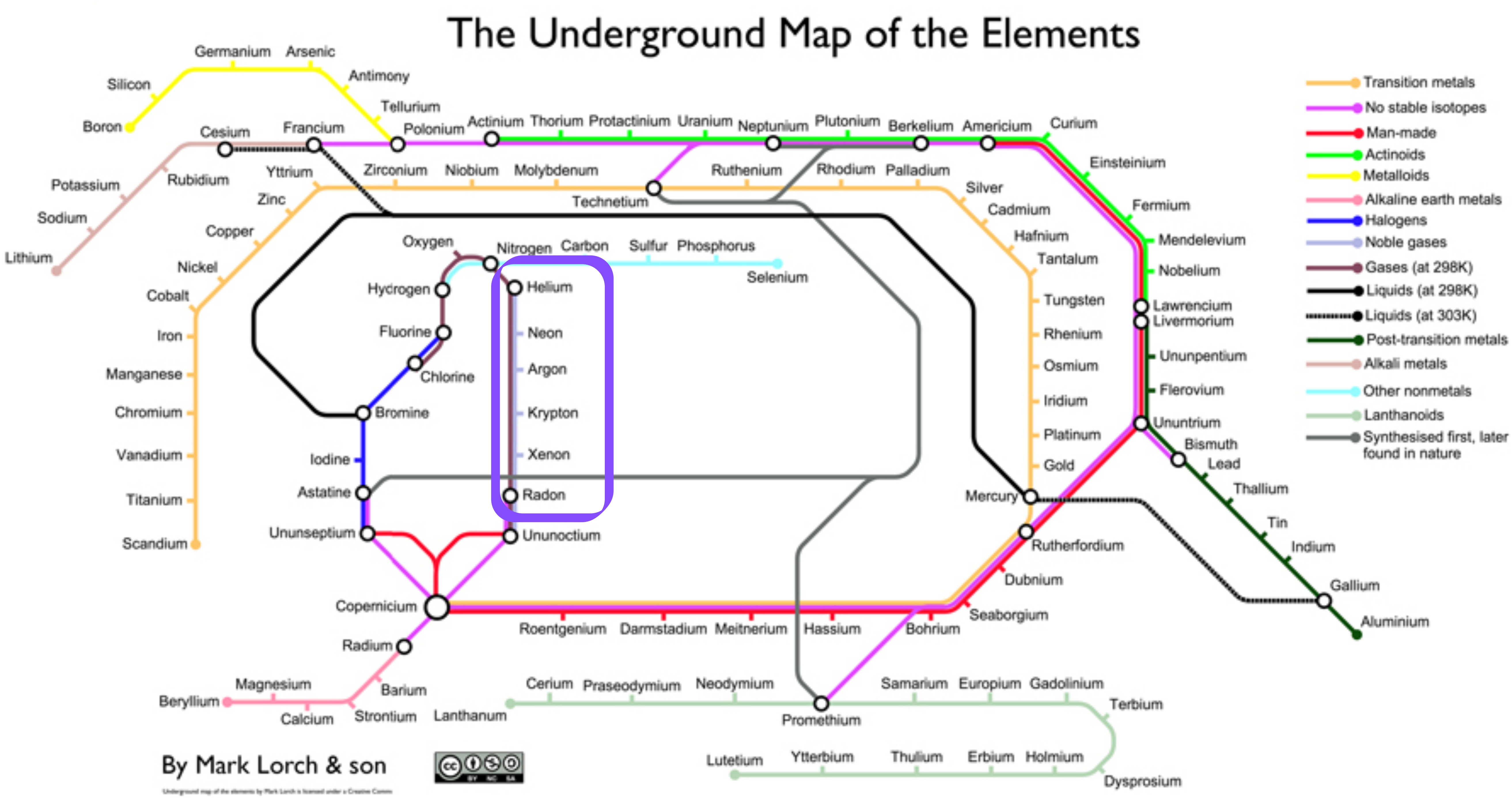
Discovered later by William Ramsay, student of Bunsen and professor at UC London
1904 Nobel Prize in Chemistry



"in recognition of his services in the discovery of the inert gaseous elements in air, and his determination of their place in the periodic system".

Argon: "the inactive one", neon: "the new one", krypton: "the hidden one", xenon: "the strange one"

Noble gases underground



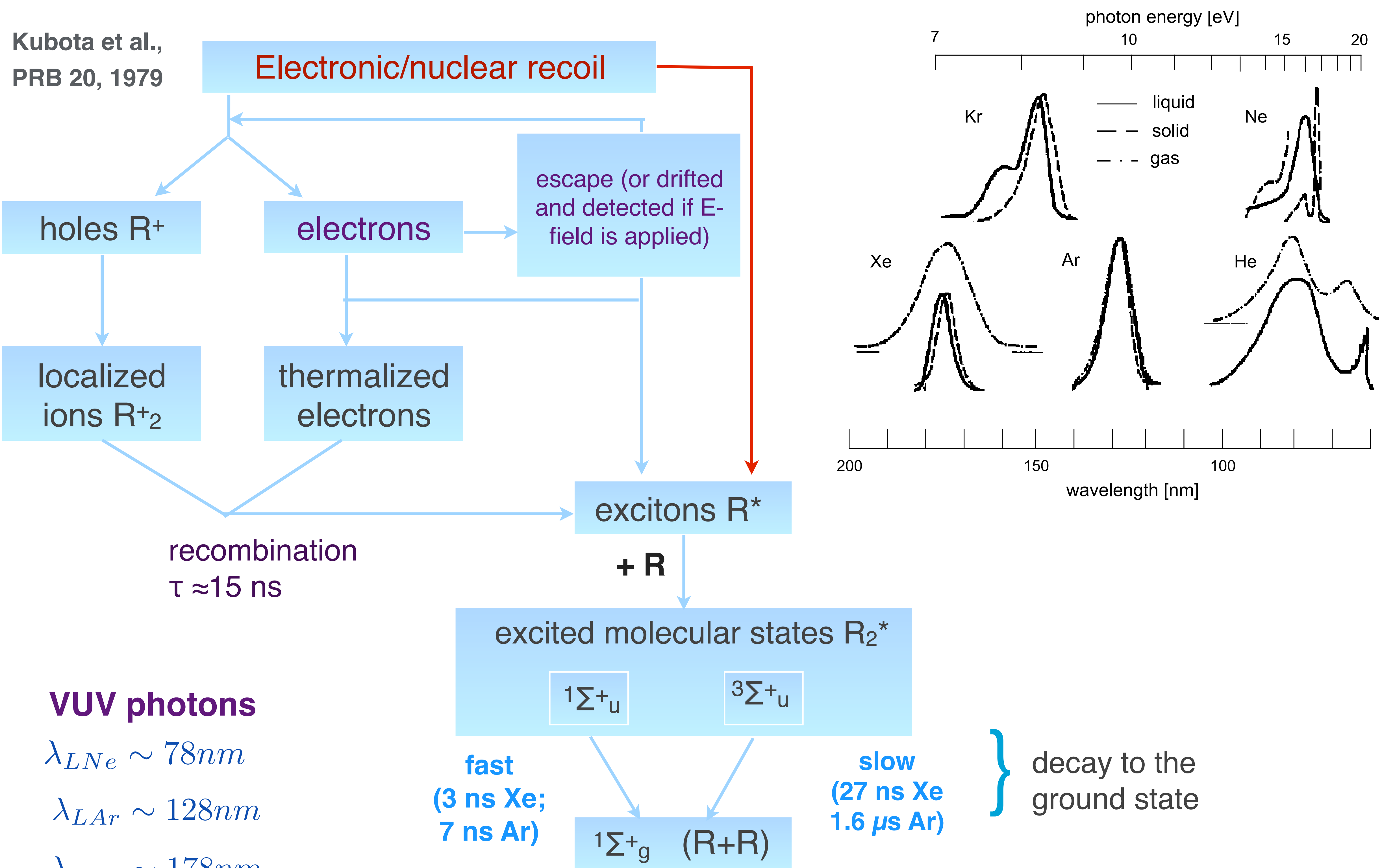
Liquefied noble gases as WIMP targets

- Dense, homogeneous target with self-shielding; fiducialization
- Large detector masses feasible at moderate costs
- High light (40 photons/keV) and charge (W_{LAr} = 24 eV, W_{LXe} = 15 eV) yields

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 [$g\,l^{-1}$]	5.40	1.63	0.82
Gas density at 1 atm & T_b [$g\,l^{-1}$]	9.99	5.77	9.56
Liquid density at T_b [$g\,cm^{-3}$]	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

W. Ramsay: "These gases occur in the air but sparingly as a rule, for while argon forms nearly 1 hundredth of the volume of the air, neon occurs only as 1 to 2 hundred-thousandth, helium as 1 to 2 millionth, krypton as 1 millionth and xenon only as about 1 twenty-millionth part per volume. *This more than anything else will enable us to form an idea of the vast difficulties which attend these investigations*."

Scintillation/ionization process in noble liquids



VUV photons

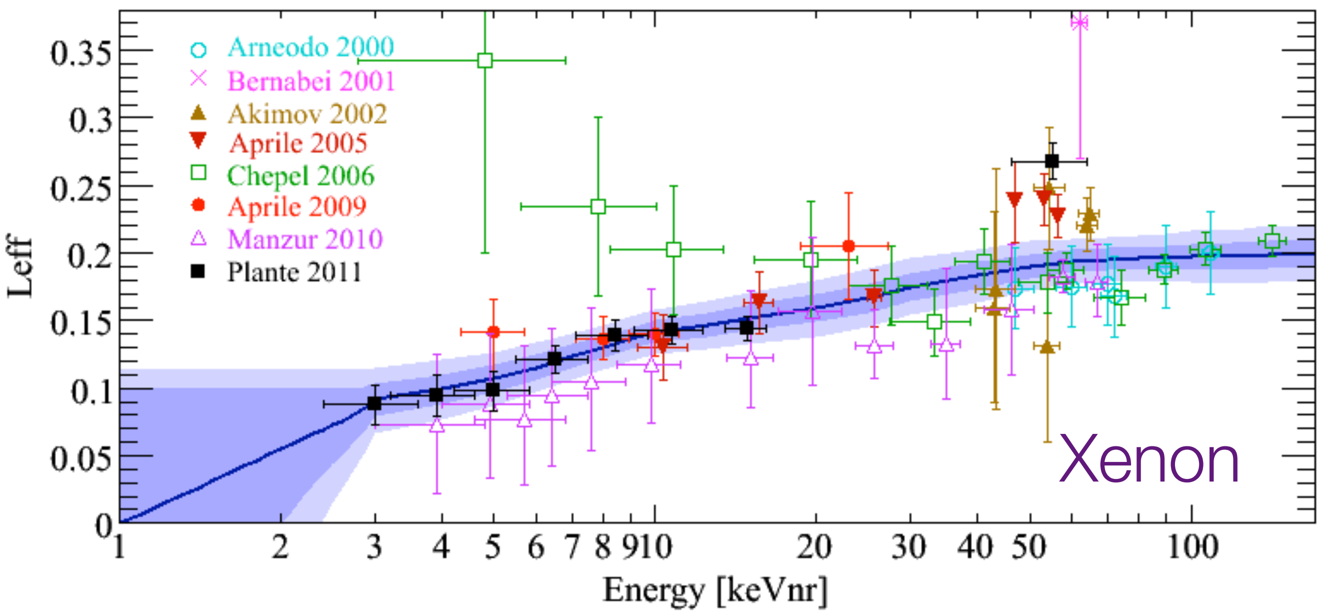
$\lambda_{LNe} \sim 78nm$

$\lambda_{LAr} \sim 128nm$

$\lambda_{LXe} \sim 178nm$

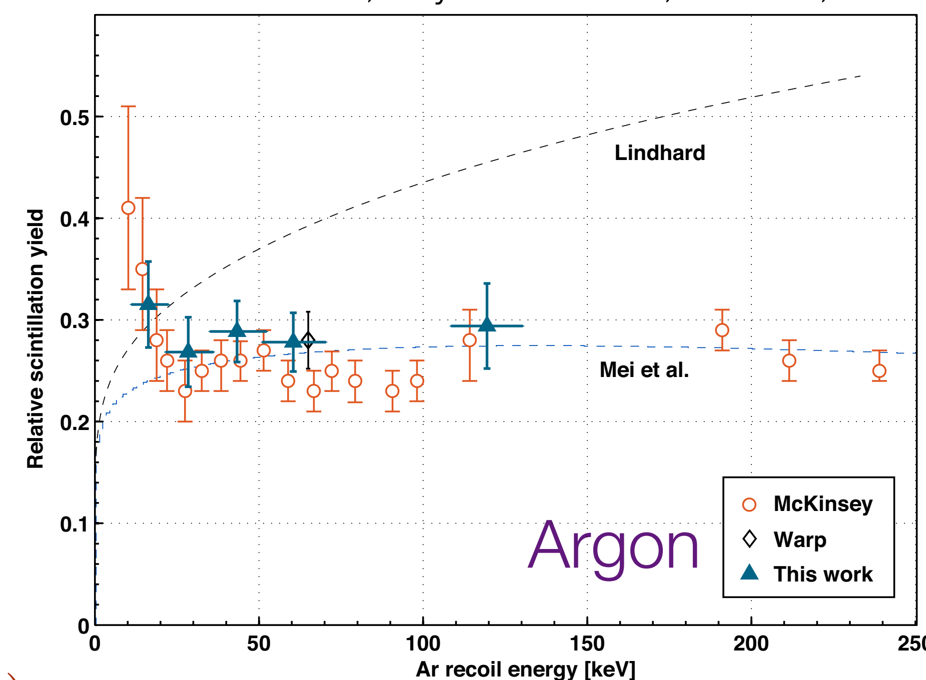
Energy scale for nuclear recoils: light yield

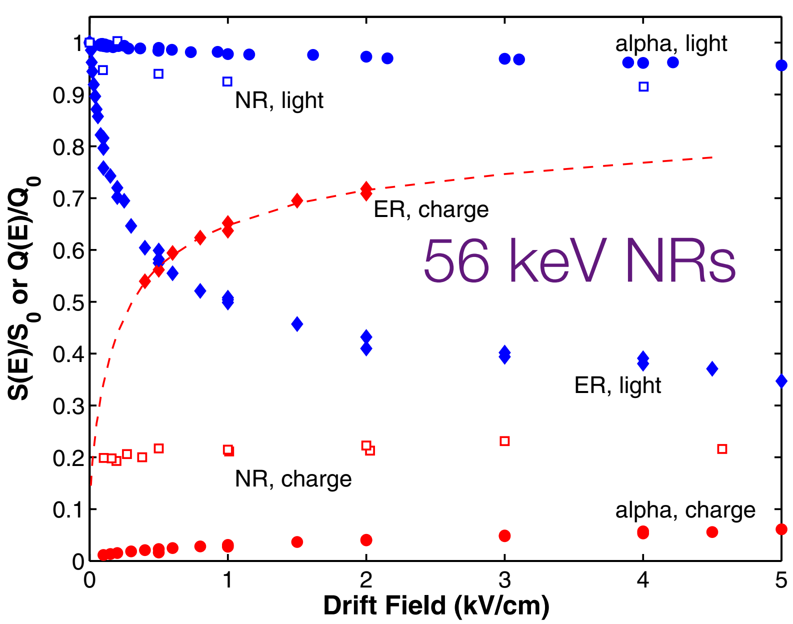
G. Plante *et al.*, Phys. Rev. C **84**, 045805, 2011



C. Regenfus *et al.*, JoP Conf. Series 375, 01219, 2012

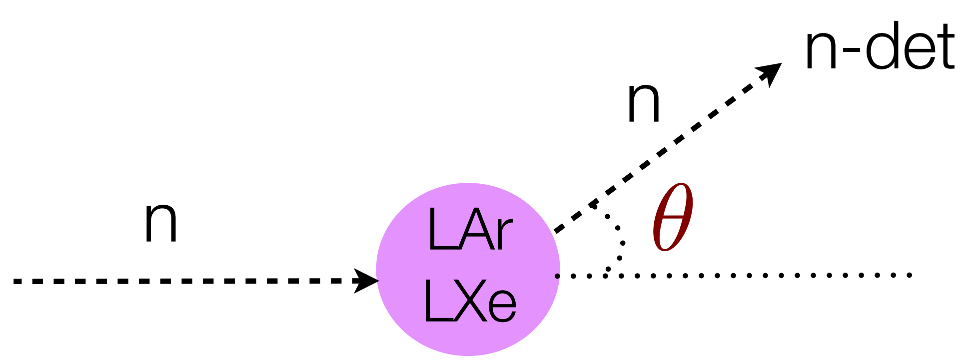
D. Gastler *et al.*, Phys. Rev. C **85**, 065811, 2012

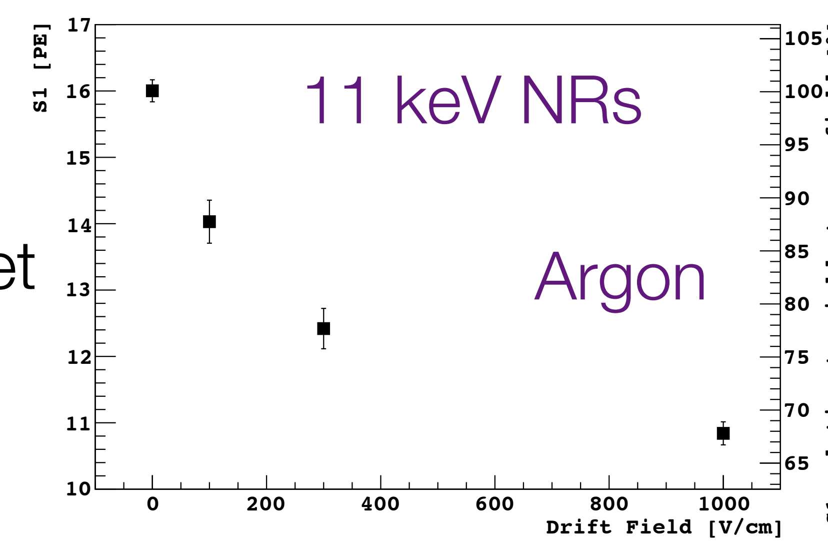




E. Aprile et al, PRL 97, 2006

$$\mathcal{L}_{\text{eff}}(E_{\text{nr}}) = \frac{L_{y,er}(E_{\text{nr}})}{L_{y,er}(E_{\text{ee}} = 122\,\text{keV})}$$





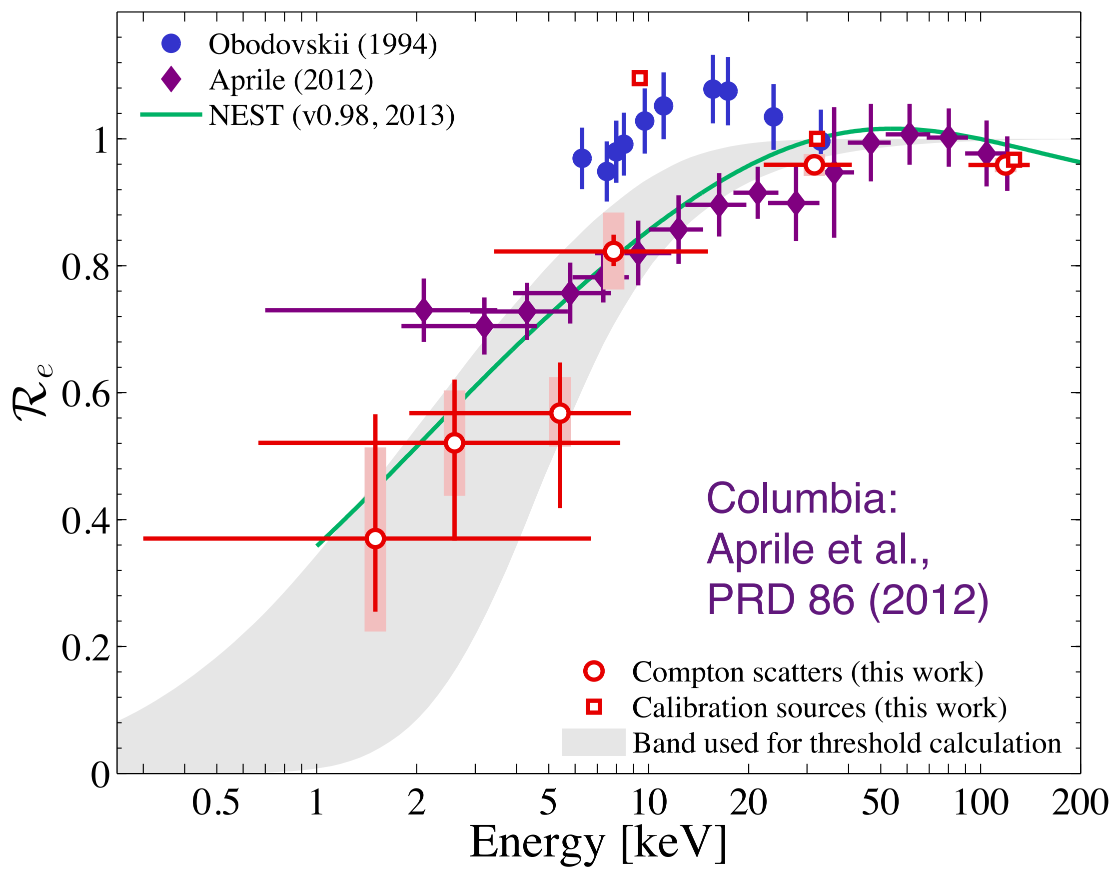
T. Alexander et al., arXiv:1306.5675

Field dependance: LXe, also measured by Manzur et al down to 4 keVnr, no significant quenching of the light yield was observed

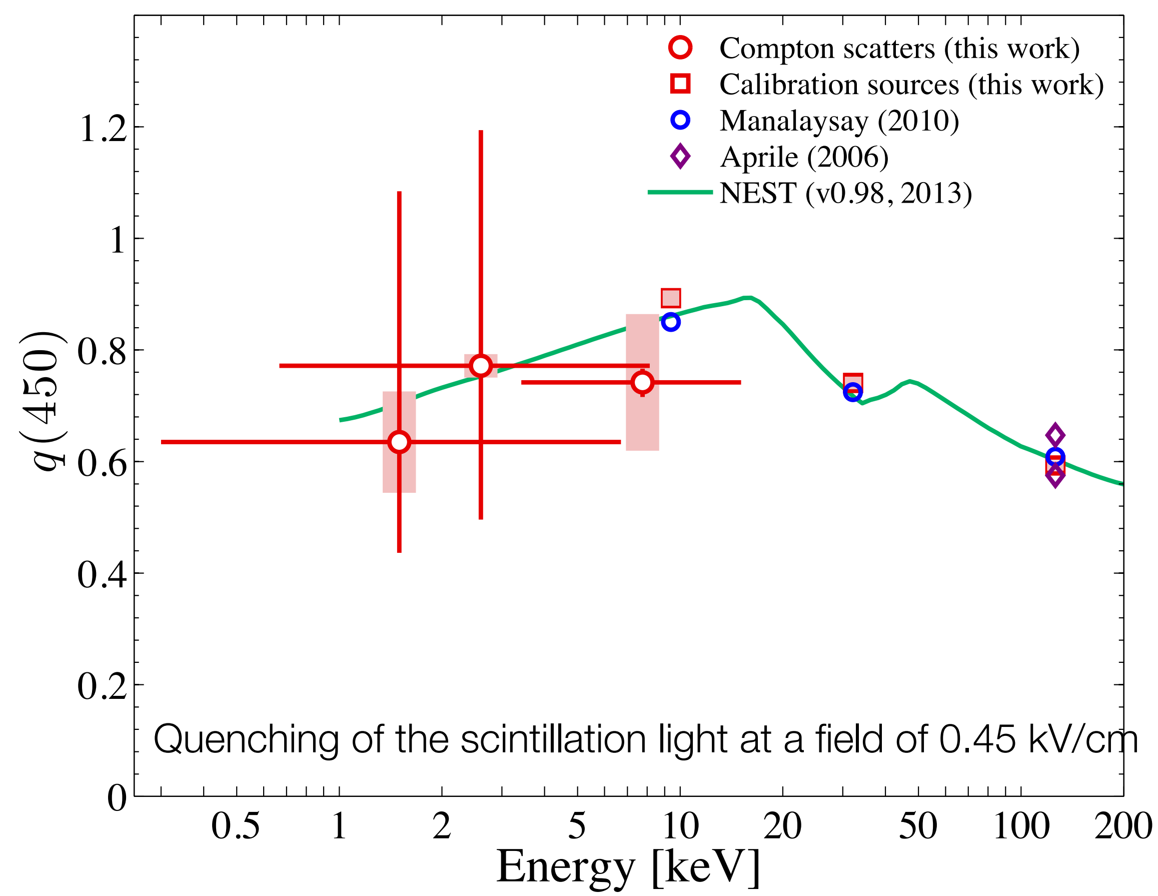
Energy scale for electronic recoils: light yield

- The light yield decreases with lower deposited energies in the LXe; field quenching is ~ 75%, only weak field-dependance
- The energy threshold of XENON100 is 2.3 keV => can test DAMA/LIBRA

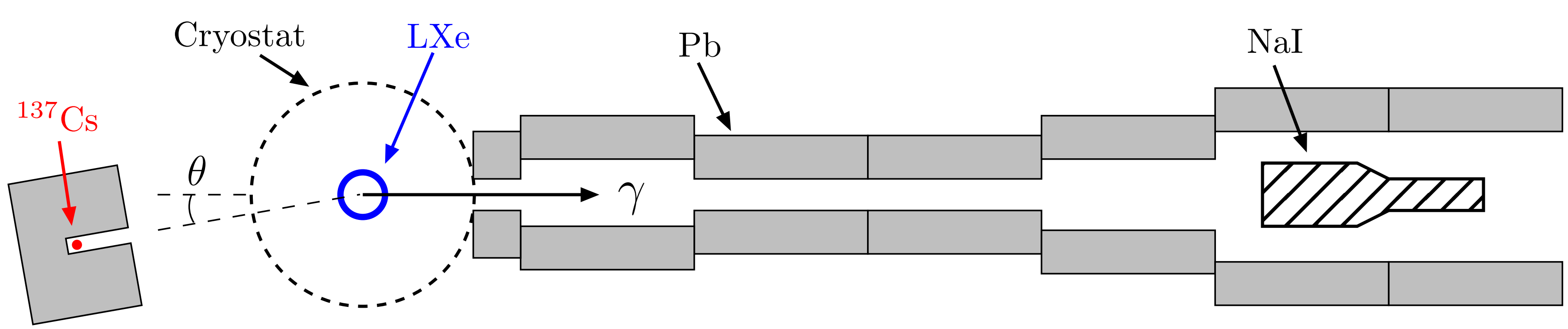
Relative light yield to 32.1 keV of ^{83m}Kr



LB et al., PRD 87, 2013; arXiv:1303.6891



17.3 MBq

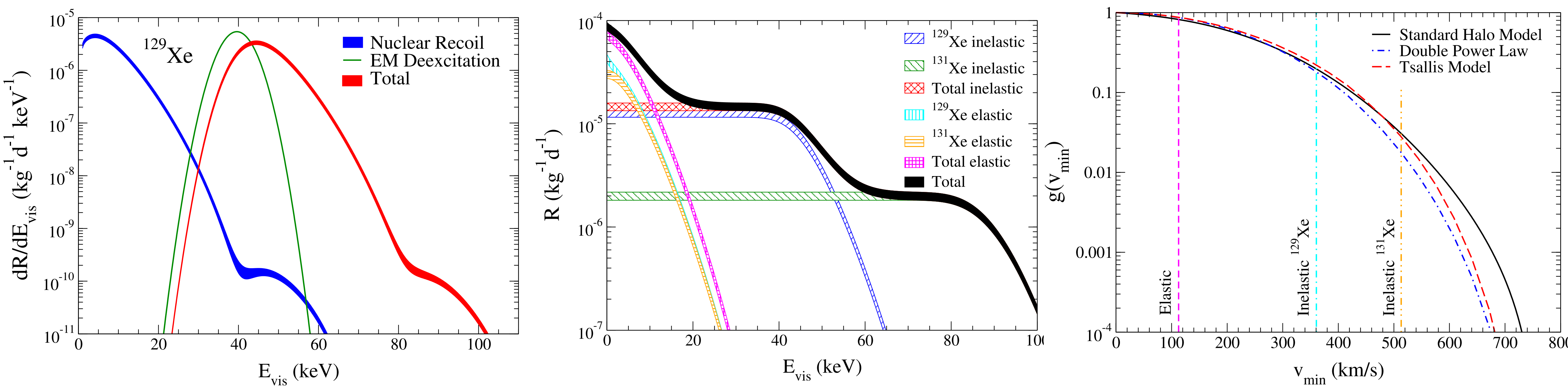


Xenon: an additional WIMP channel

- Spin-dependent WIMP-nucleus *inelastic scattering*
  - ➡ new, promising structure factors
  - ➡ shifts ROI to higher energies
  - ➡ integrated rate dominates at moderate energies, depending on the WIMP mass
  - ➡ probes the high-tail of the galactic WIMP velocity distribution

Theory: Ellis, Flores, Lewin,1988
Searches: Ejiri et al, 1993, Belli et al, 1996, Avignone et al, 2000

LB, G. Kessler, P. Klos, J. Menendez, S. Reichard, A. Schwenk, arXiv:1309.0825



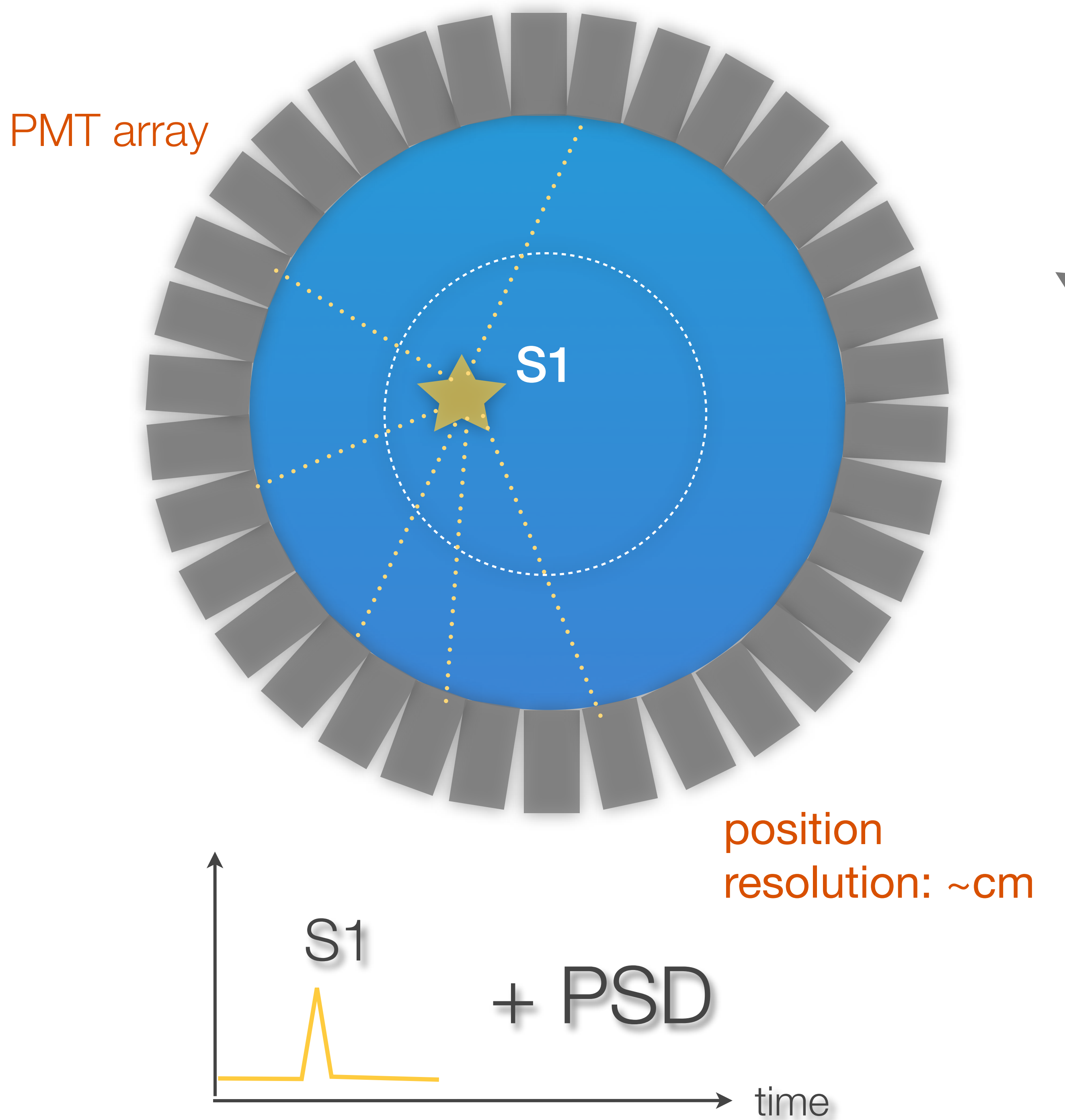
$$\chi + ^{129,131}Xe \rightarrow \chi + ^{129,131}Xe^* \rightarrow \chi + ^{129,131}Xe + \gamma$$

1 ns, 0.5 ns

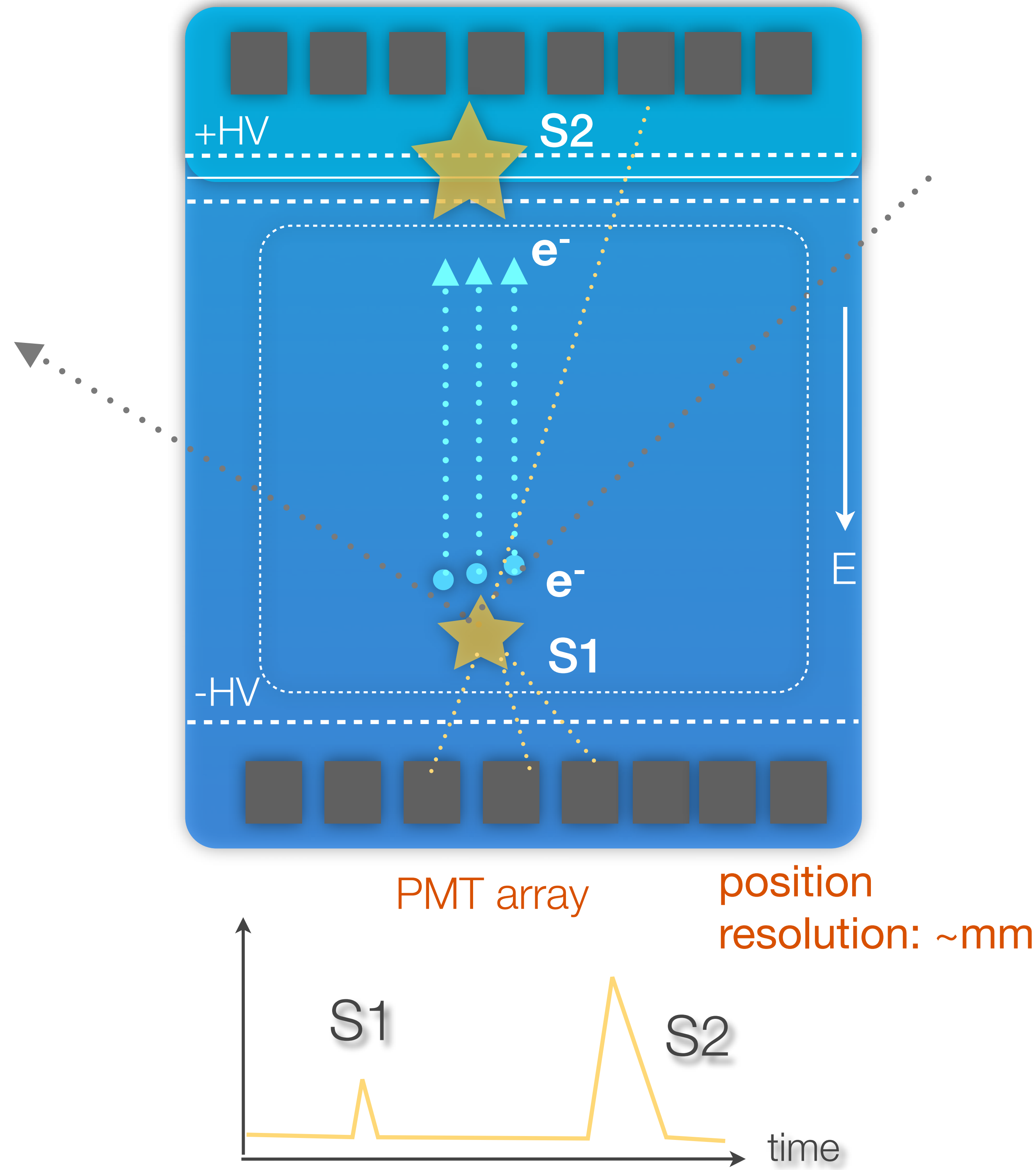
40 keV, 80 keV

Two detector concepts

Single phase

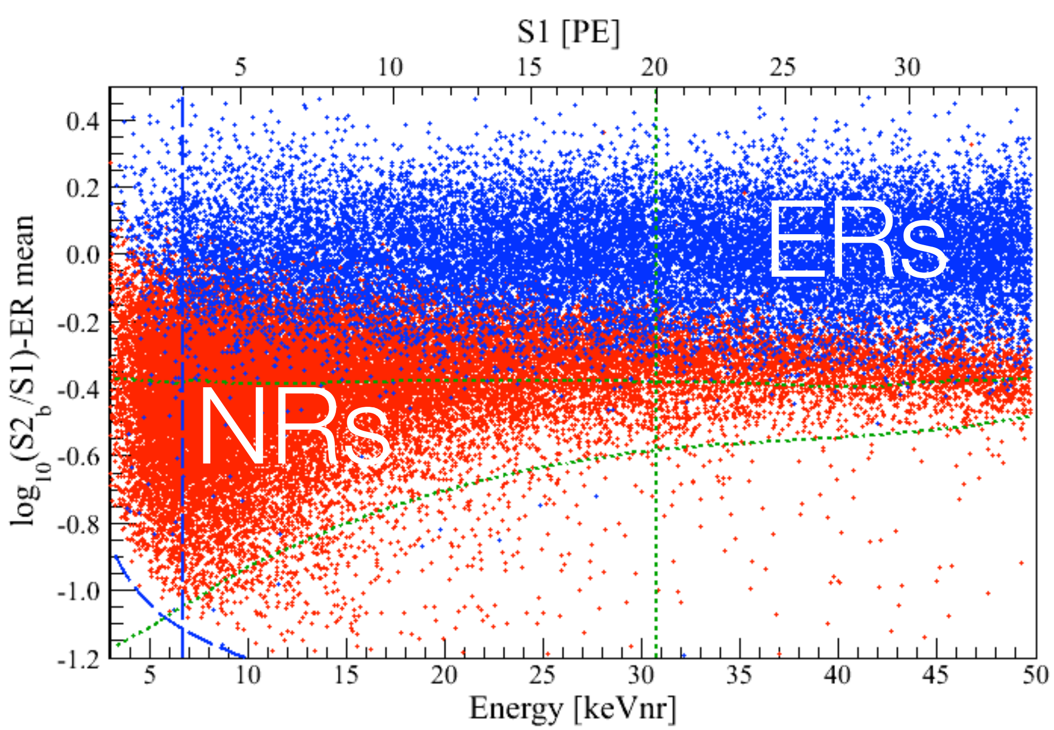


Double phase (TPC)

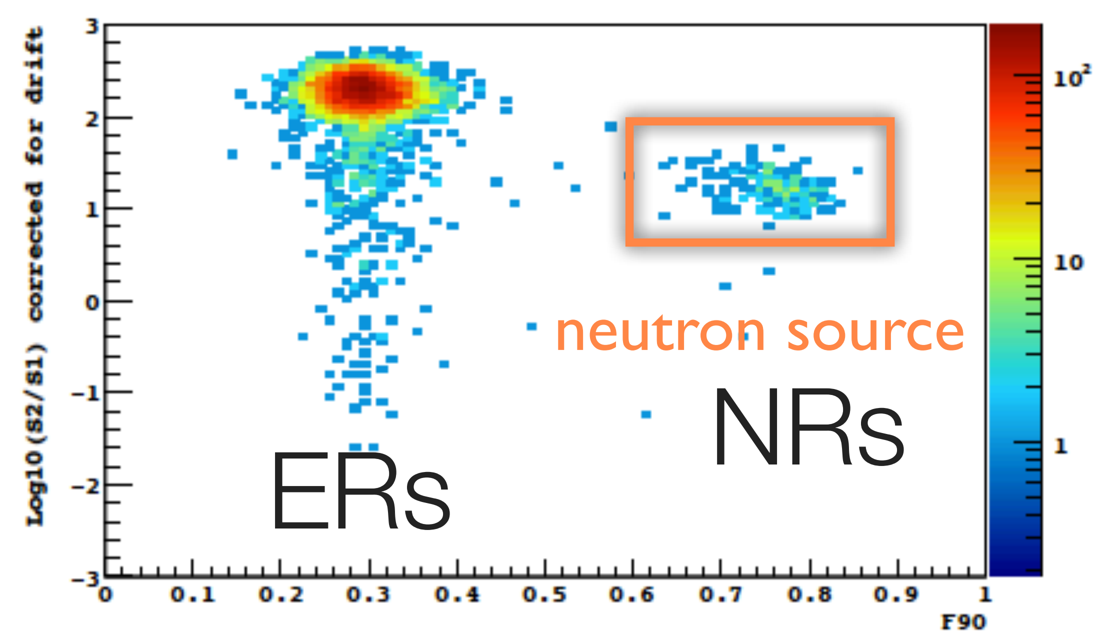


Particle discrimination

- Pulse shape of prompt scintillation signal (LAr)
  - ➡ the ratio of light from singlet and triplet depends on dE/dx (~ 10:1 for NRs:ERs)
- Charge versus light (LAr and LXe)
  - ➡ the recombination probability, and thus the S2-to-S1 ratio depends on dE/dx



LXe (XENON100)



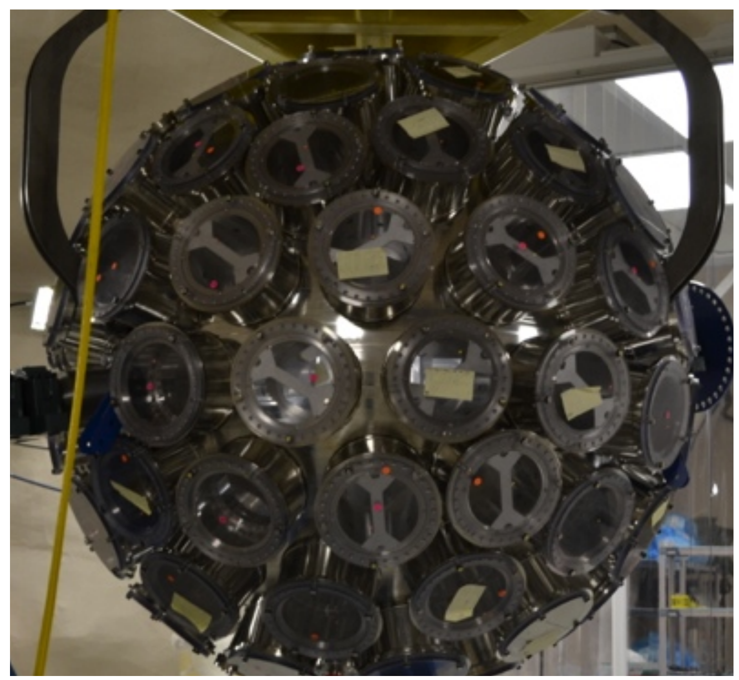
LAr (DarkSide-10)

Single-phase detectors

- Challenge: ultra-low absolute backgrounds
- LAr: pulse shape discrimination, factor 10^9-10^{10} for gammas/betas

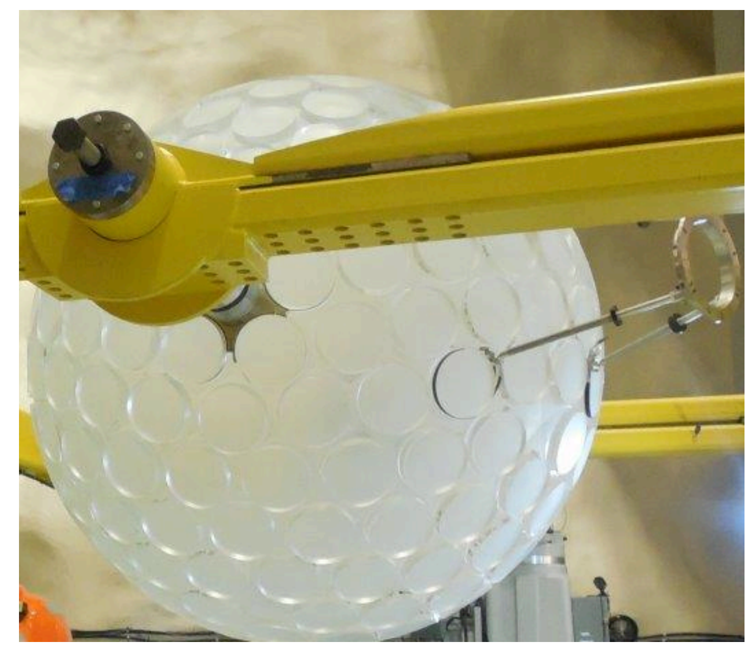
XMASS-RFB at Kamioka:

835 kg LXe (100 kg fiducial),
single-phase, 642 PMTs
unexpected background found
detector refurbished (RFB)
new run this fall -> 2013



CLEAN at SNOLab:

500 kg LAr (150 kg fiducial)
single-phase open volume
under construction
to run in 2014



DEAP at SNOLab:

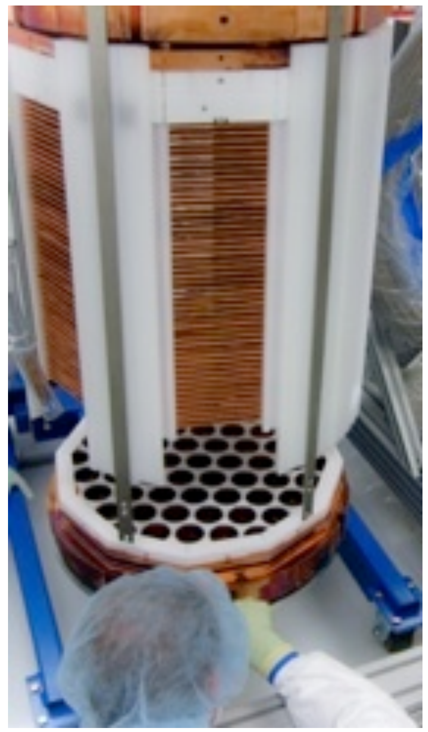
3600 kg LAr (1t fiducial)
single-phase detector
under construction
to run in 2014

Time projection chambers

XENON100 at LNGS:

161 kg LXe
(~50 kg fiducial)

242 1-inch PMTs
taking new science data



LUX at SURF:

350 kg LXe
(100 kg fiducial)

122 2-inch PMTs
physics run since spring 2013
first result by the end of this year

PandaX at CJPL:

125 kg LXe
(25 kg fiducial)

143 1-inch PMTs
37 3-inch PMTs
started in 2013

ArDM at Canfranc:

850 kg LAr
(100 kg fiducial)

28 3-inch PMTs
in commissioning
to run 2014

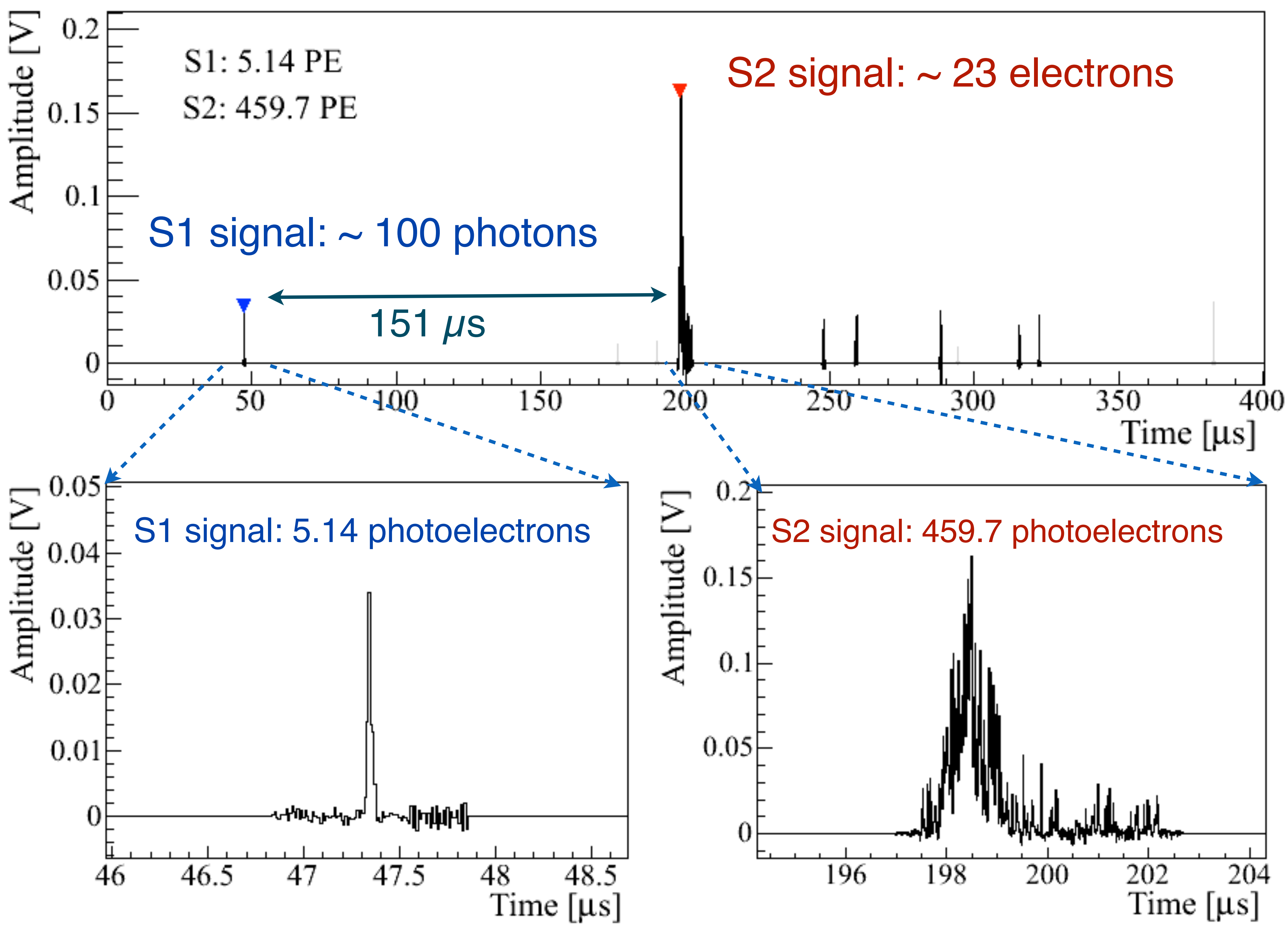
DarkSide at LNGS

50 kg LAr (dep in ^{39}Ar)
(33 kg fiducial)

38 3-inch PMTs
in commissioning
since May 2013
to run in fall 2013

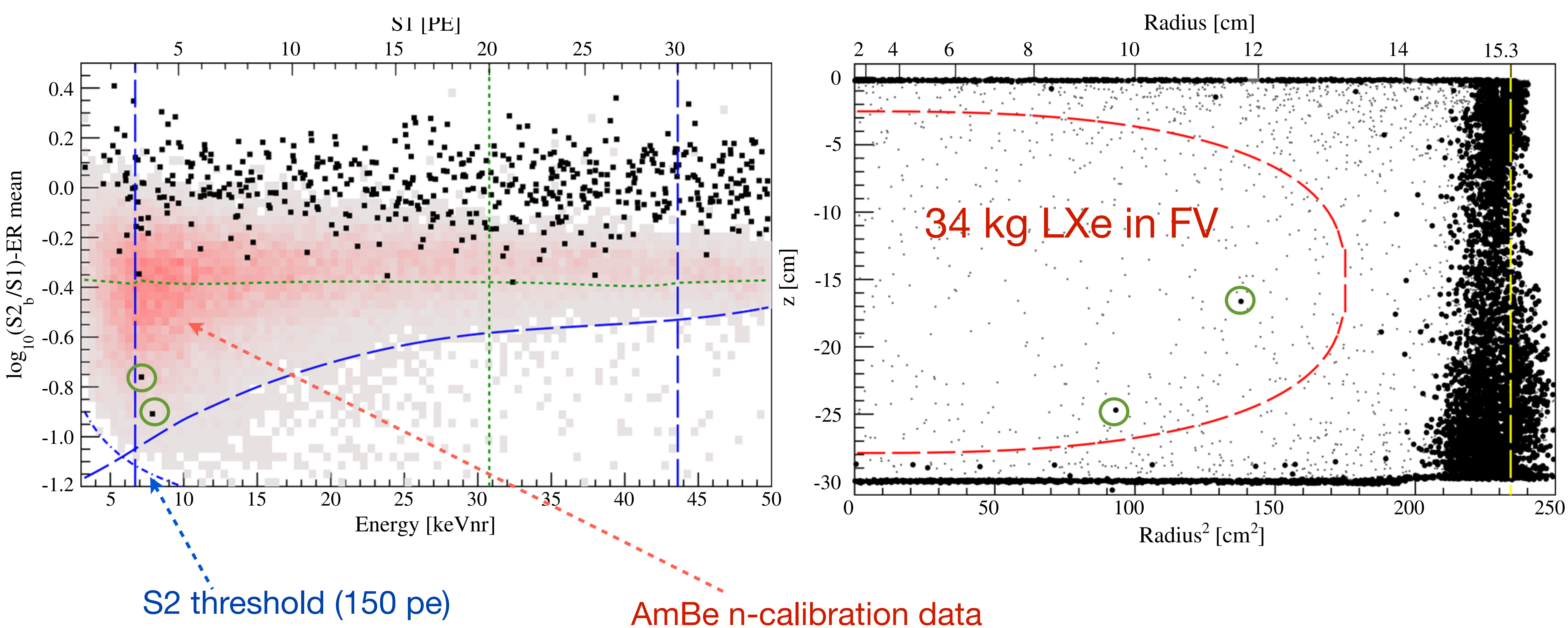
Example of a low-energy event in XENON100

The maximum electron drift time at 0.53 kV/cm is 176 μs



Example: XENON100 dark matter data

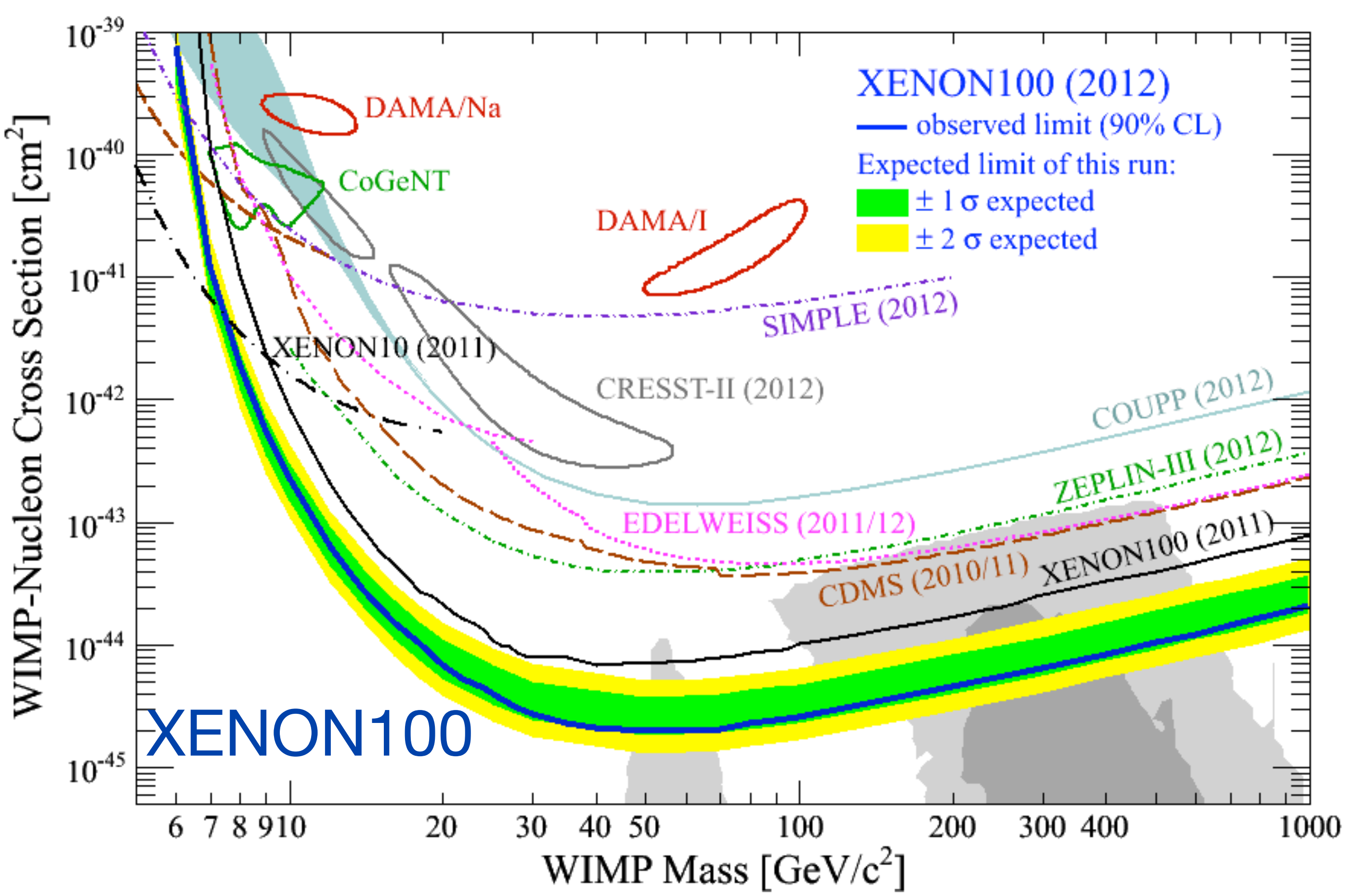
- Exposure: 225 days x 34 kg fiducial LXe mass
- Two events observed in signal region (1 BG event expected; there is a 26.4 % chance for upward fluctuation): at 7.1 keV_{nr} (3.3 pe) and at 7.8 keV_{nr} (3.8 pe) (note: zero events below 3 pe)



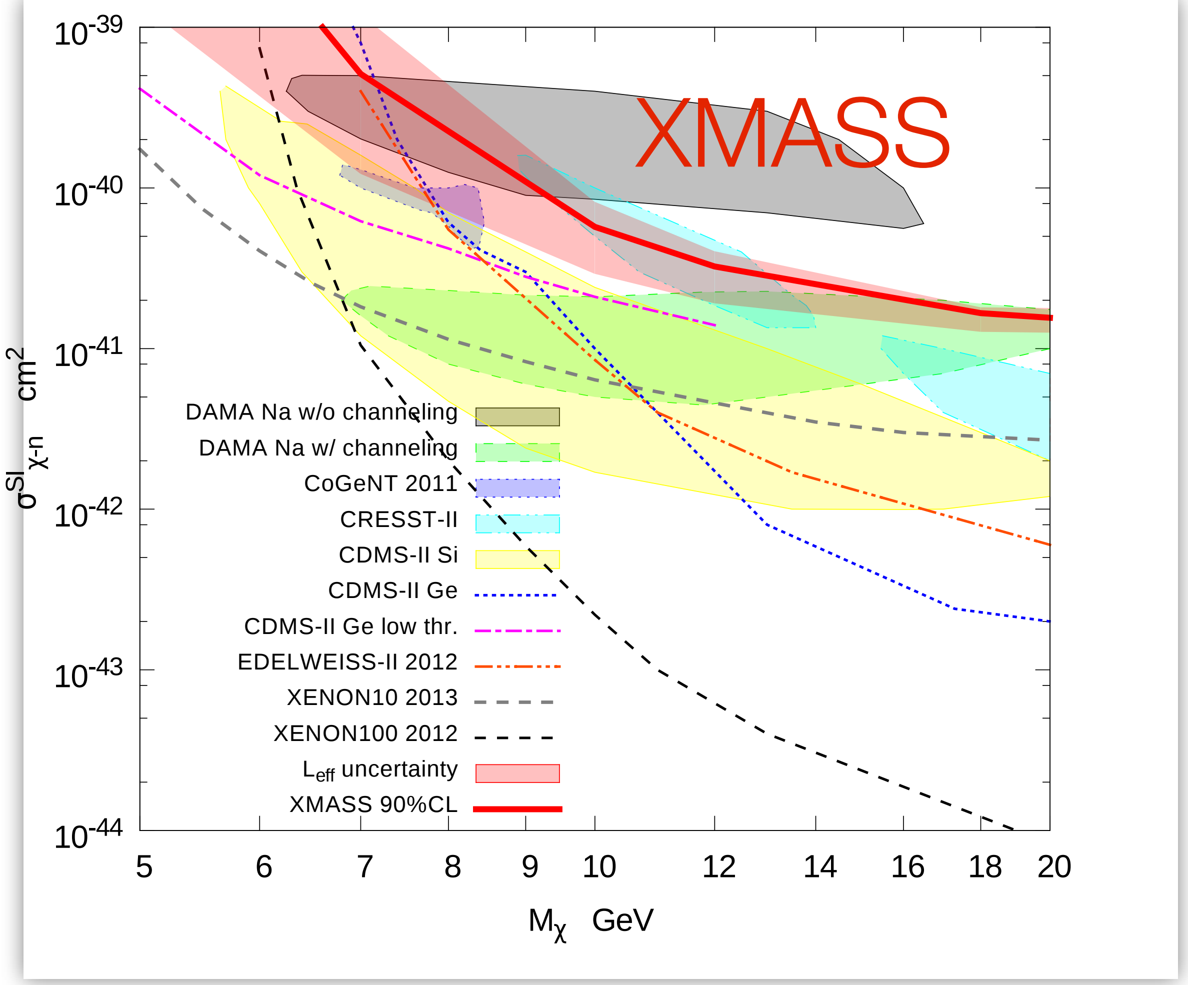
Noble liquid recent results: spin-independent

- No evidence for WIMPs
- Upper limit on WIMP-nucleon cross section is 2×10^{-45} cm^2 at M_W = 55 GeV

XENON100: Phys. Rev. Lett. 109 (2012)



XMASS: Phys. Lett. B 719 (2013)

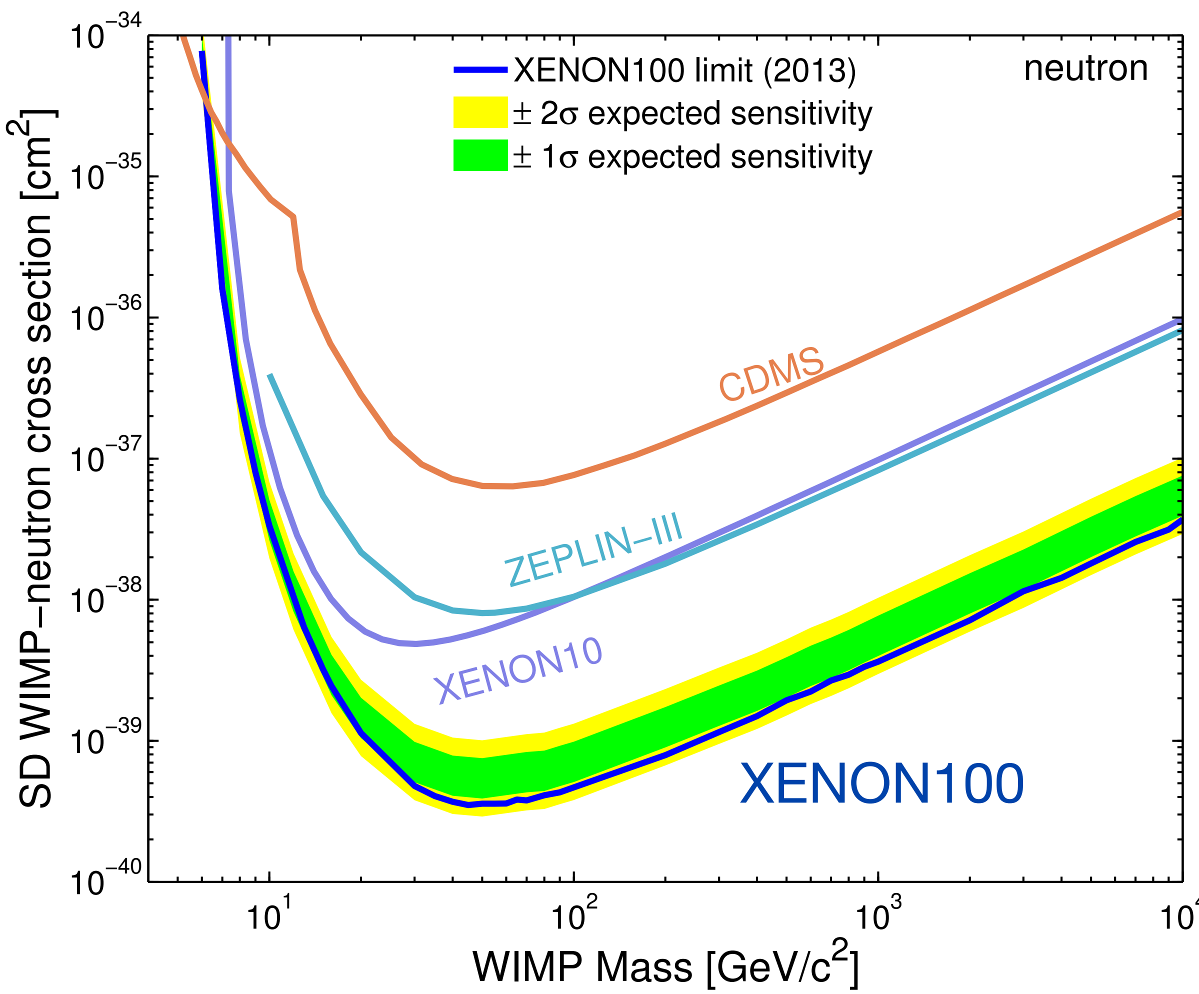


Noble liquid recent results: spin-dependent

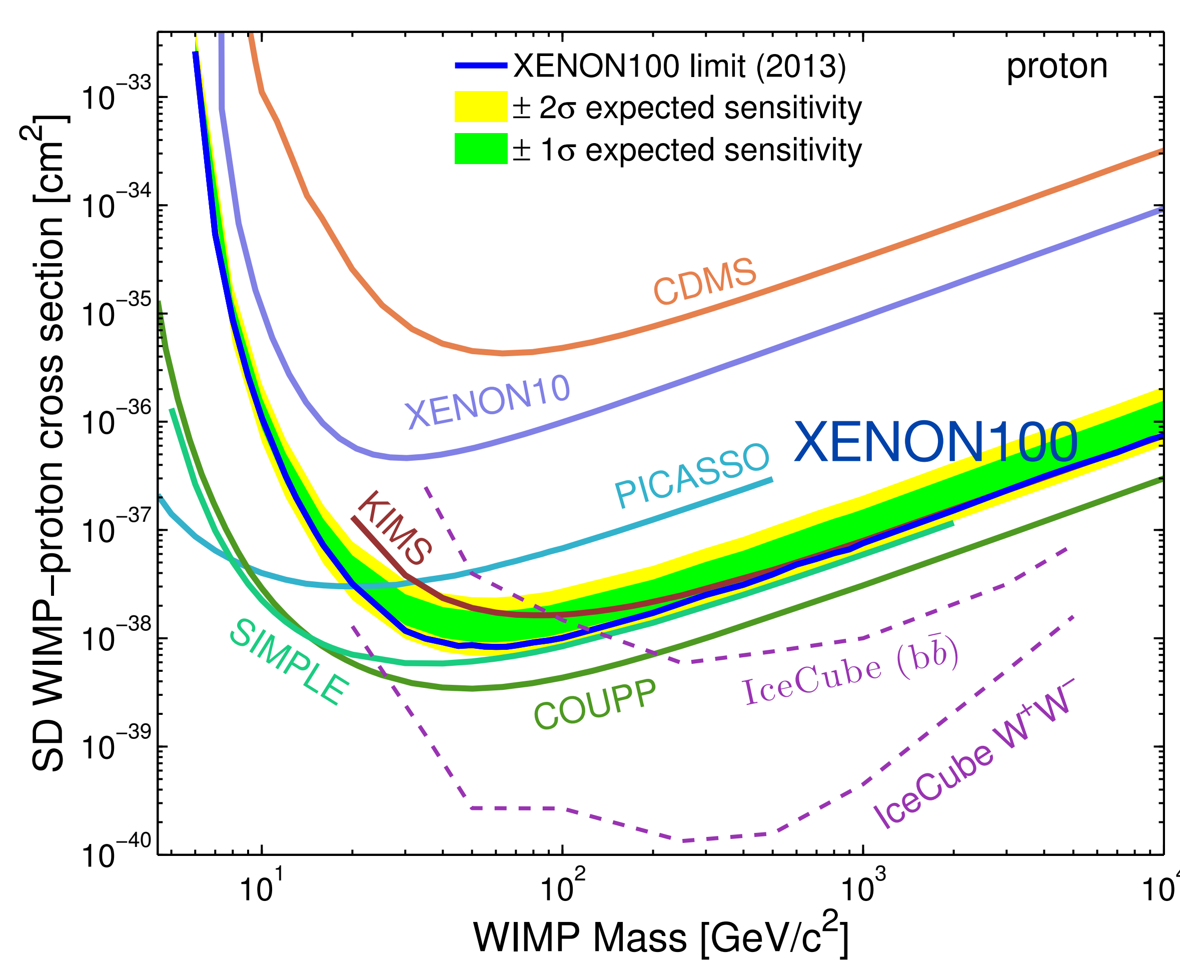
- ^{129}Xe (spin-1/2) and ^{131}Xe (spin-3/2), two isotopes with J ≠ 0 and abundance of 26.2% and 21.8% in XENON100

$$\frac{d\sigma_{SD}(q)}{dq^2} = \frac{8G_F^2}{(2J+1)v^2} S_A(q) \qquad S_A(0) = \frac{(2J+1)(J+1)}{\pi J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2$$

WIMP-neutron coupling



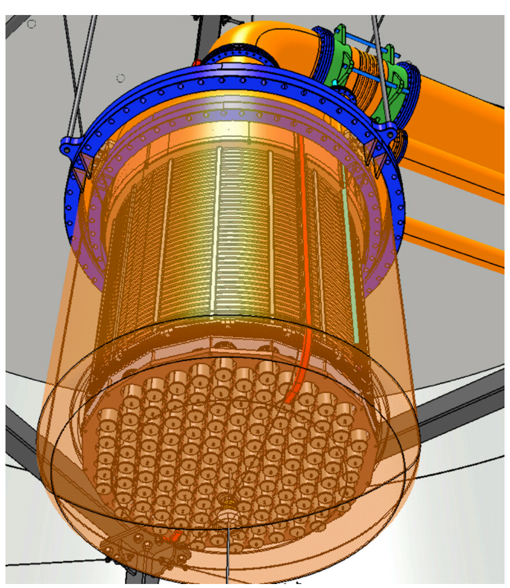
WIMP-proton coupling



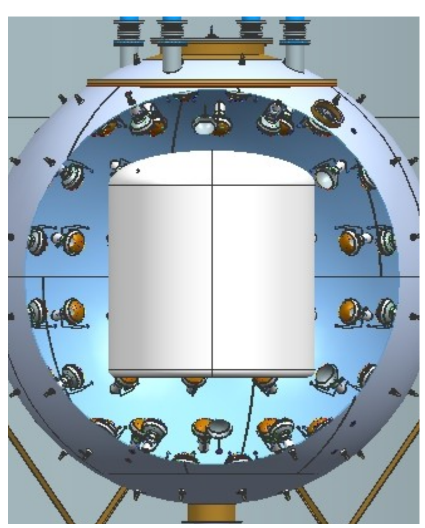
Phys. Rev. Lett. 111 (2013)

Future argon and xenon detectors

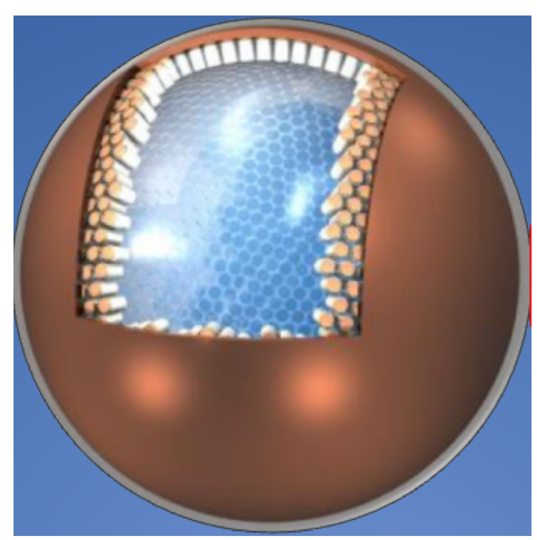
- Under construction: XENON1T at LNGS, 3.5 t LXe in total
    - ➡ commissioning in 2014, first run in 2015, goal 2 x 10^{-47} cm^2
- Near future + design and R&D: XENONnT (n t LXe), XMASS-1.5 (5 t LXe), DarkSide-5000 (5 t LAr), LZ (7 t LXe), DARWIN (20 t LXe)



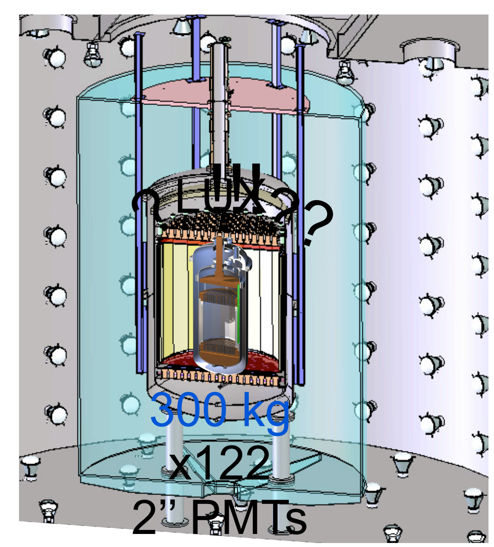
XENON1T: 3.5 t LXe



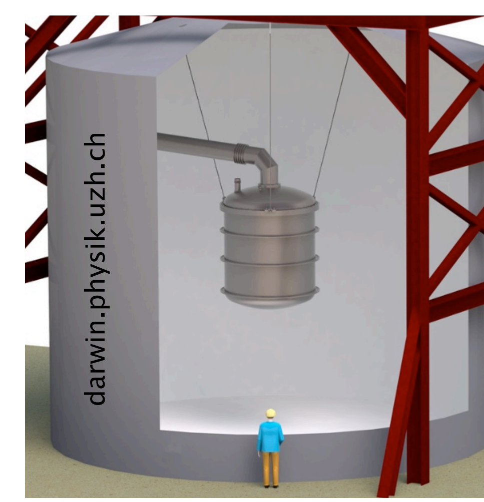
DarkSide: 5 t LAr



XMASS: 5t LXe



LZ: 7t LXe



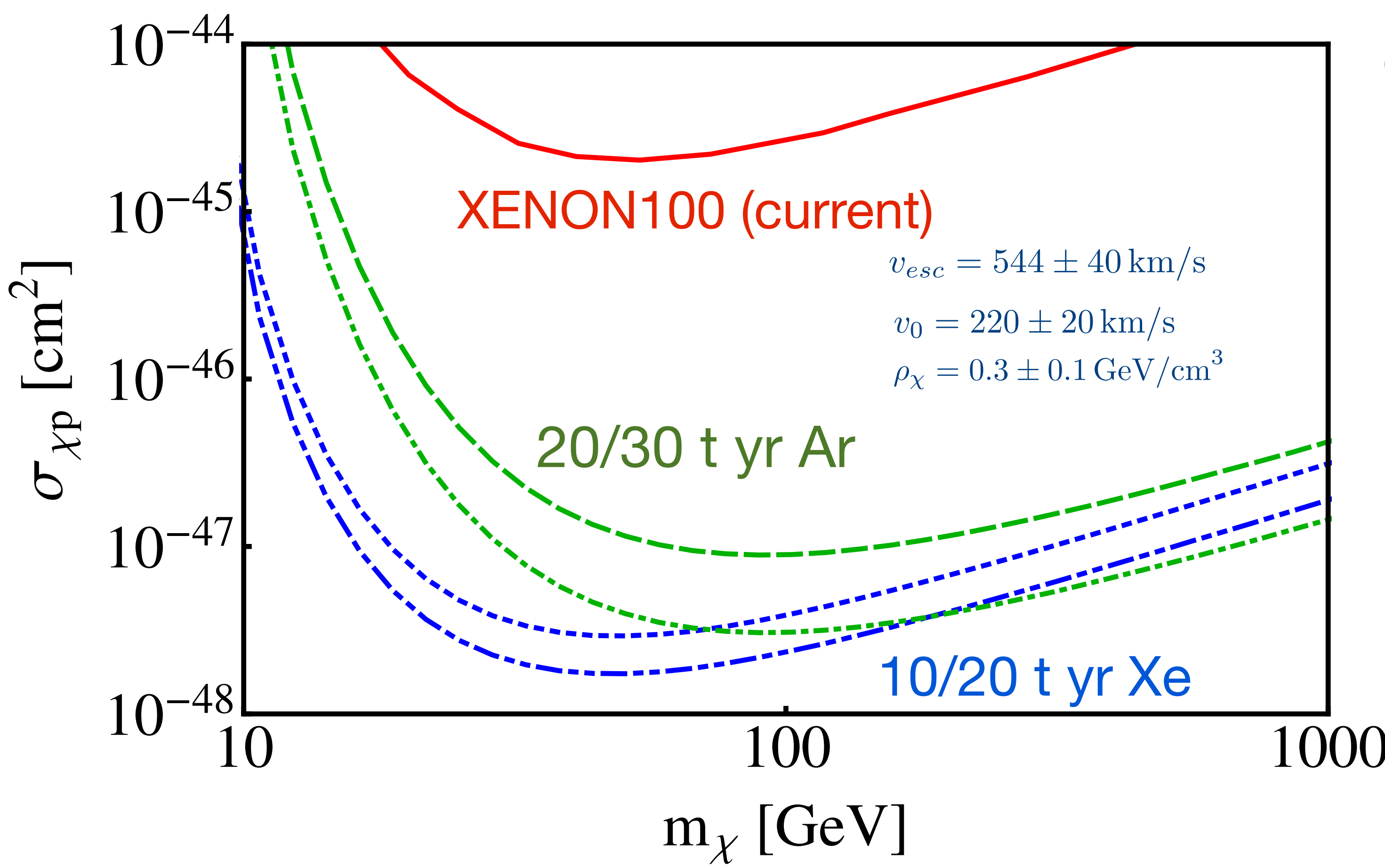
DARWIN: 20 t LXe/LAr

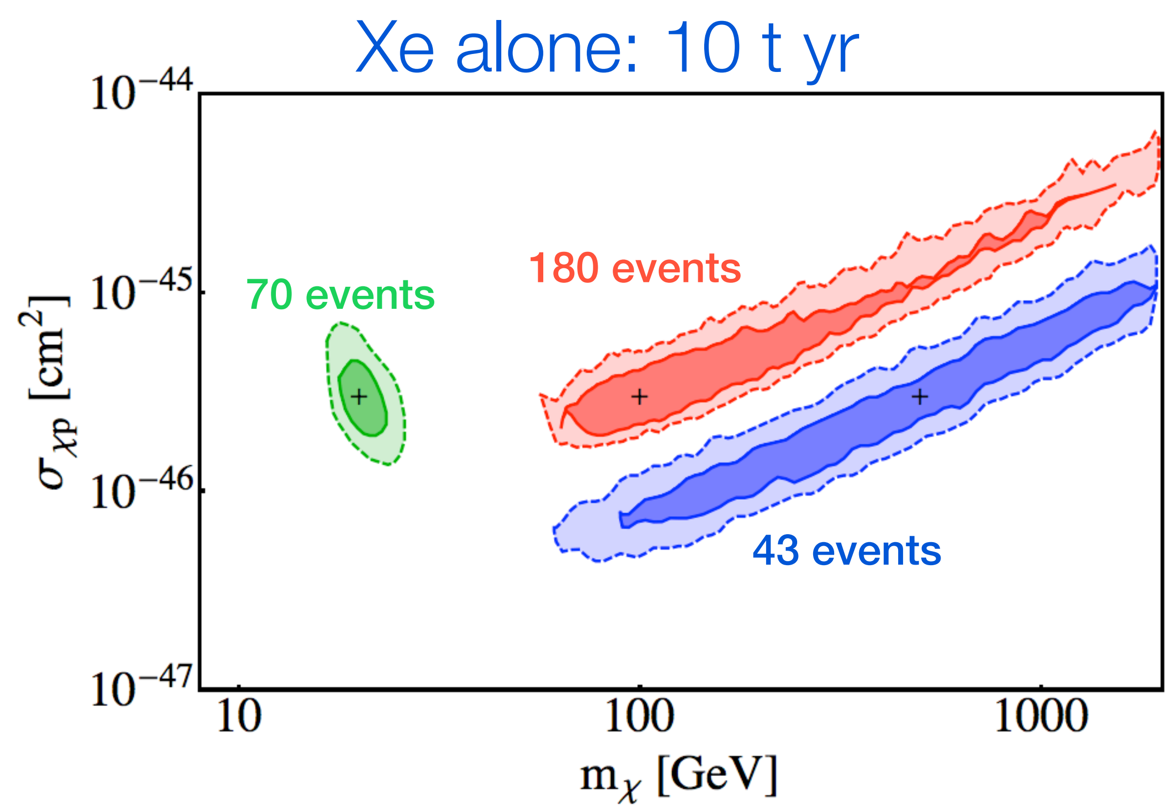
Argon and xenon complementarity

The Scientific Reach of Multi-Ton Scale Dark Matter Direct Detection Experiments

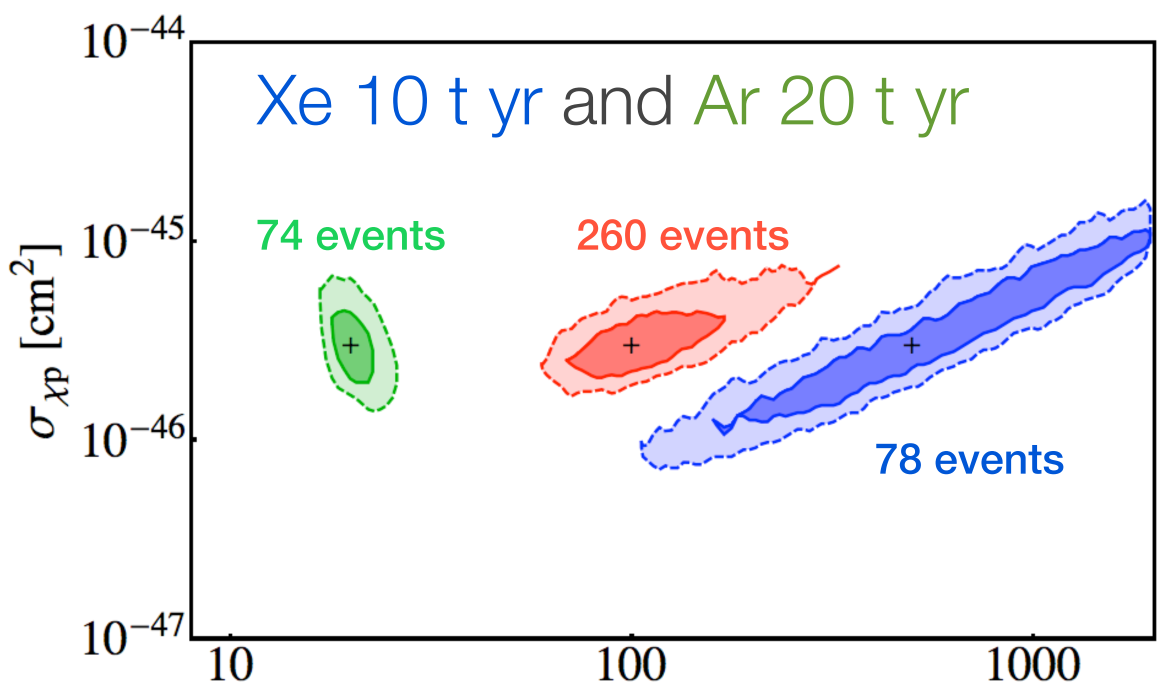
Jayden L. Newstead[a], Thomas D. Jacques[a], Lawrence M. Krauss[a,b], James B. Dent[c], and Francesc Ferrer[d]

arXiv:1306.3244





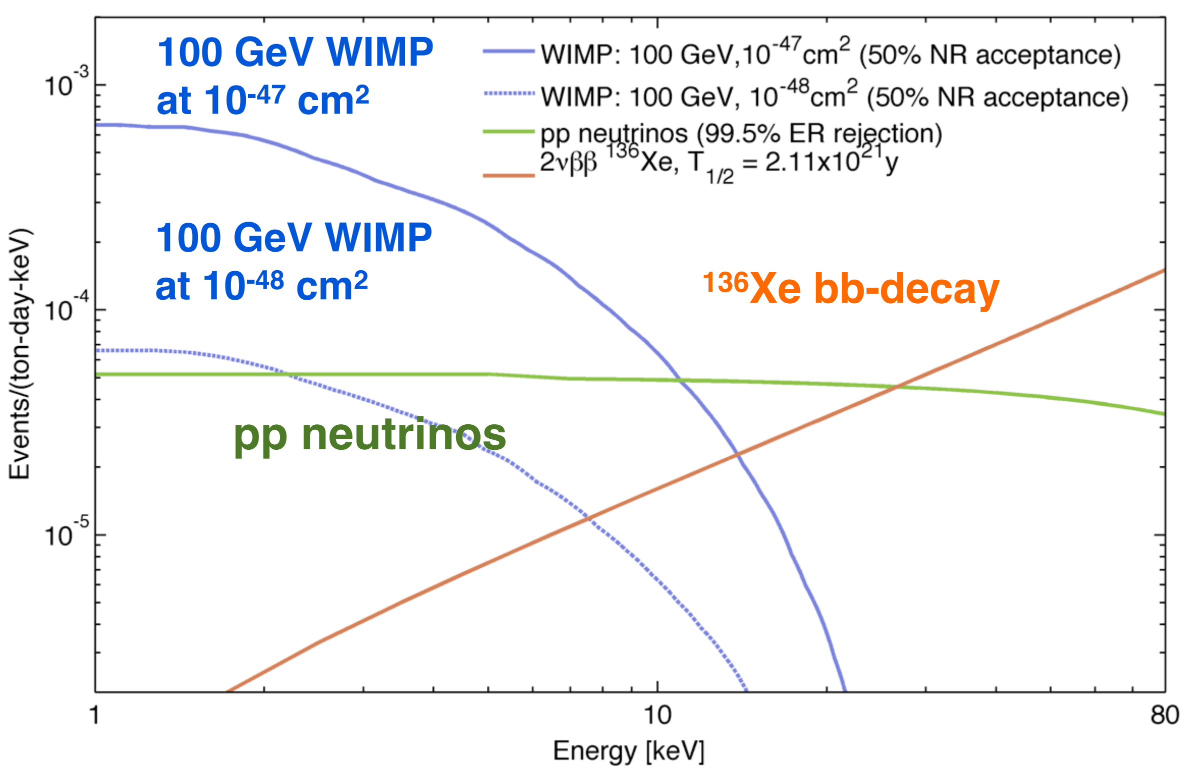
	Xenon	Argon
Nuclear recoil acceptance	40%	50% at 35keV, 100% >60 keV
Total background (post-discrimination)	6×10^{-9} dru	2.3×10^{-9} dru
WIMP search region	6.6-43 keV	20-150 keV



Neutrinos as backgrounds

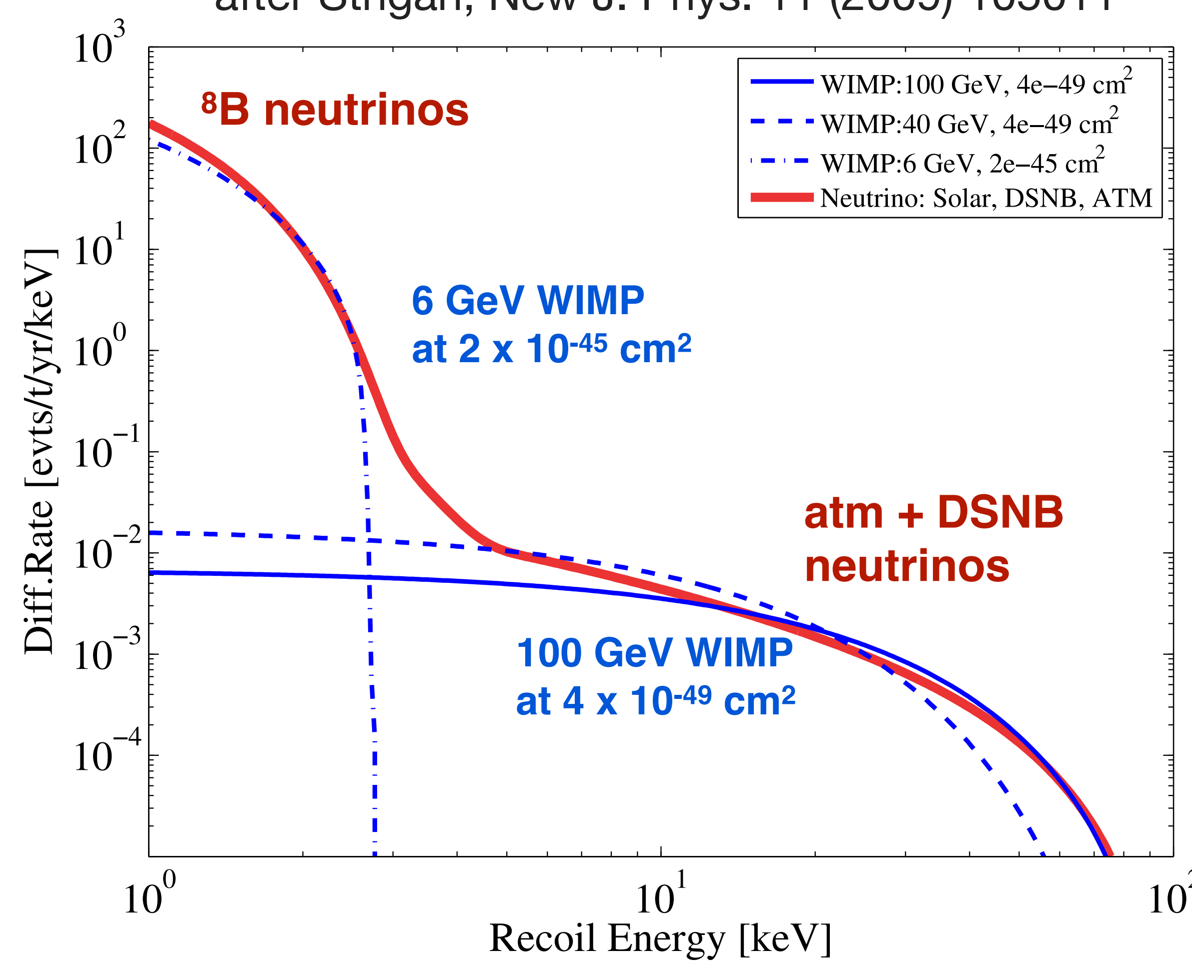
- Electronic recoils from pp solar neutrinos: ~ 10^{-48} cm^2
- Nuclear recoils from ^{8}B solar neutrinos: below ~10^{-45} cm^2 for low-mass WIMPs
- Nuclear recoils from atmospheric + DSNB: below ~10^{-48} cm^2

LB, Physics of the Dark Universe 1, 94 (2012)



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

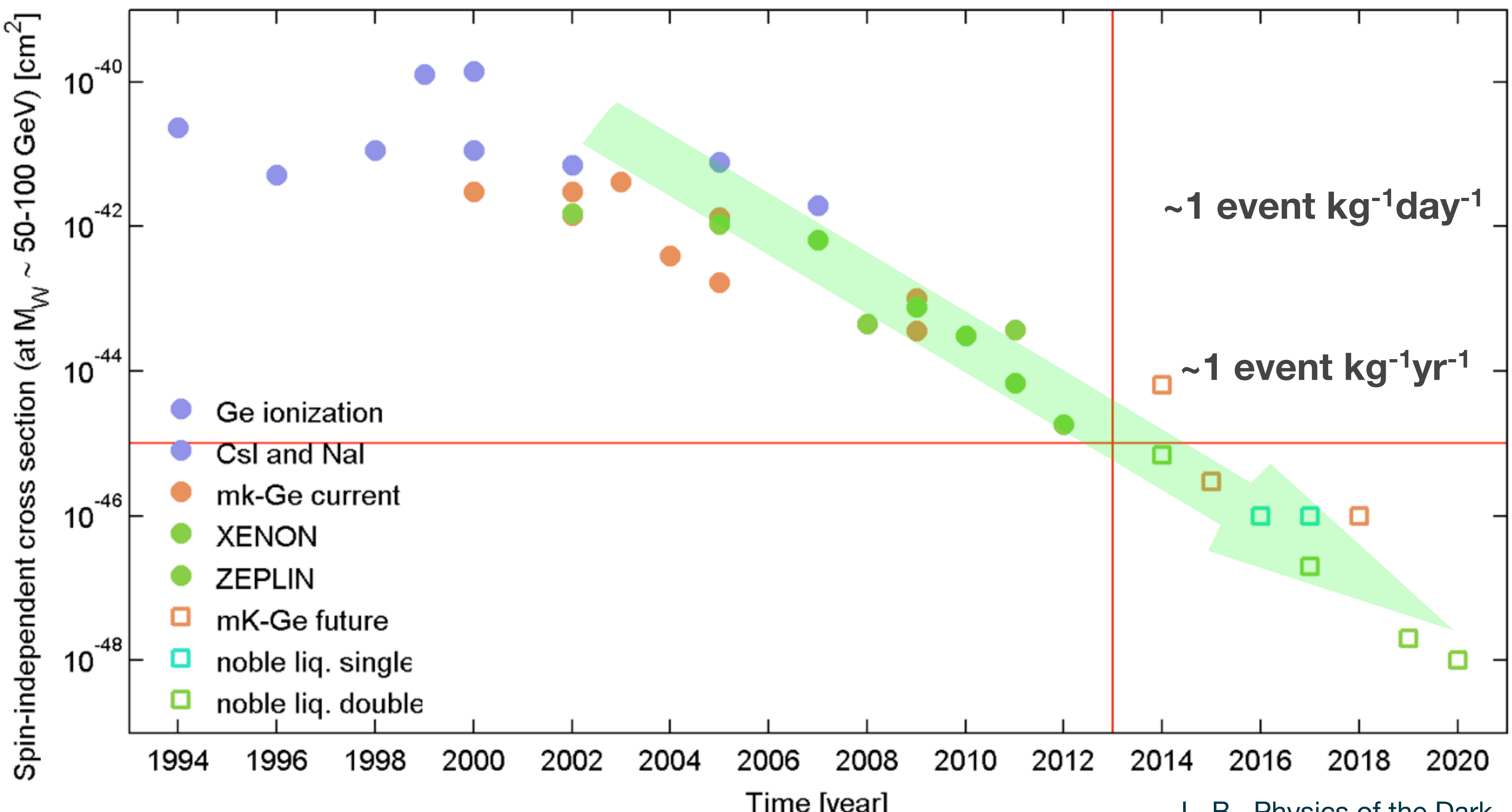
after Strigari, New J. Phys. 11 (2009) 105011



$$\nu + N \rightarrow \nu + N$$

Direct detection: sensitivity versus time

Factor ~ 10 every two years!



L. B., Physics of the Dark Universe 1, 94 (2012)

End