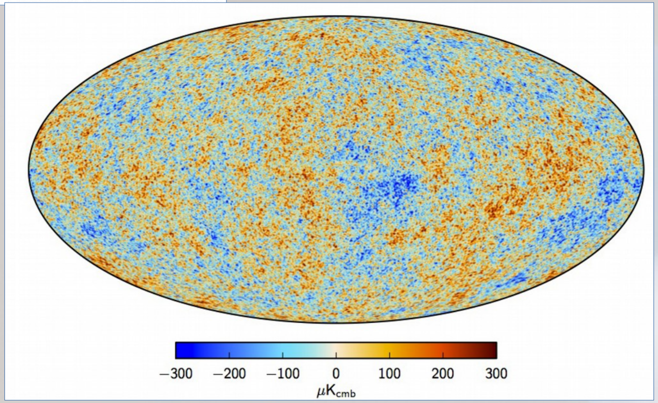
Dark Matter Direct Detection Experiments
I. Concepts

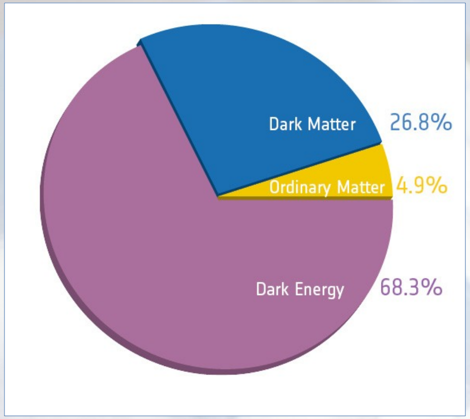
Ranny Budnik

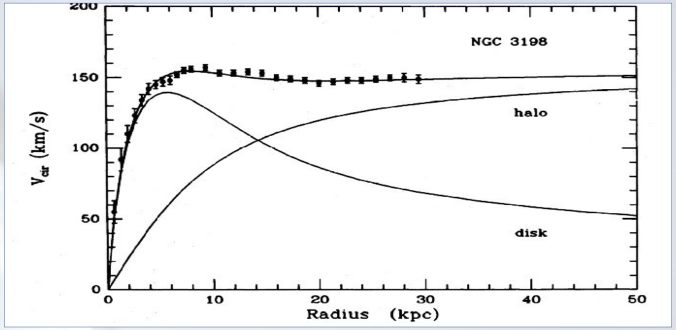
Department of Particle Physics and Astrophysics
Weizmann Institute of Science

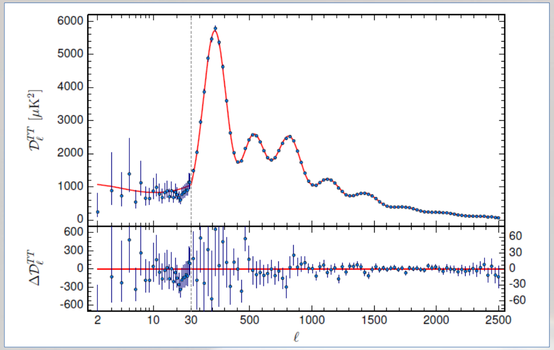
מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

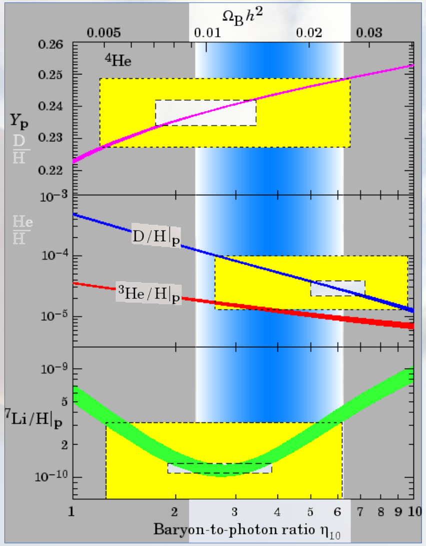
DM evidence on one slide

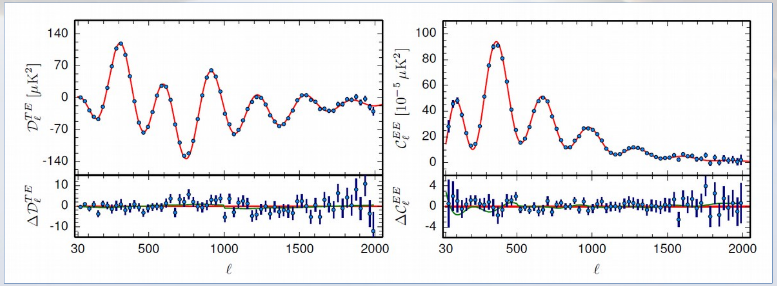








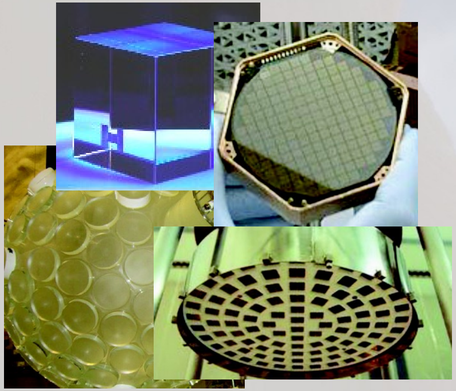




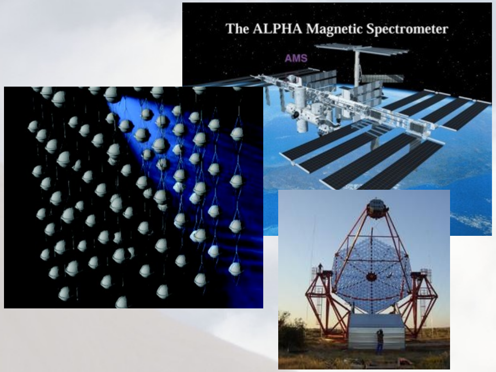
R. Budnik, ISAPP 2019

A short reminder, how to look for WIMPs

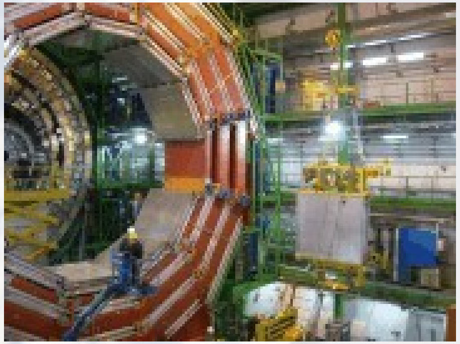
Directly



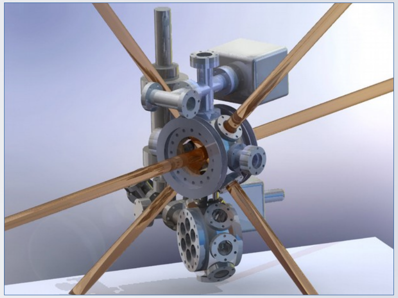
Indirectly

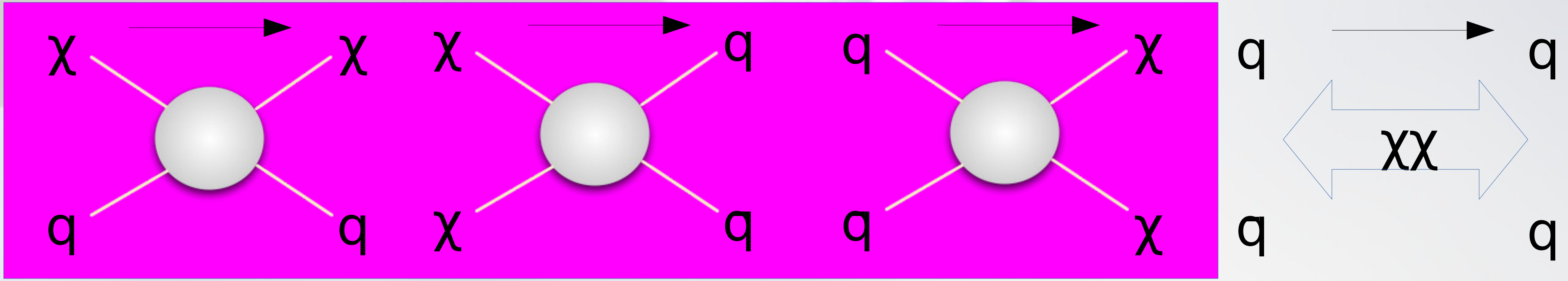


Accelerators



Precision!





A short reminder, how to look for WIMPs

Directly

- Local DM distribution
- Backgrounds
- Limited mass range

Indirectly

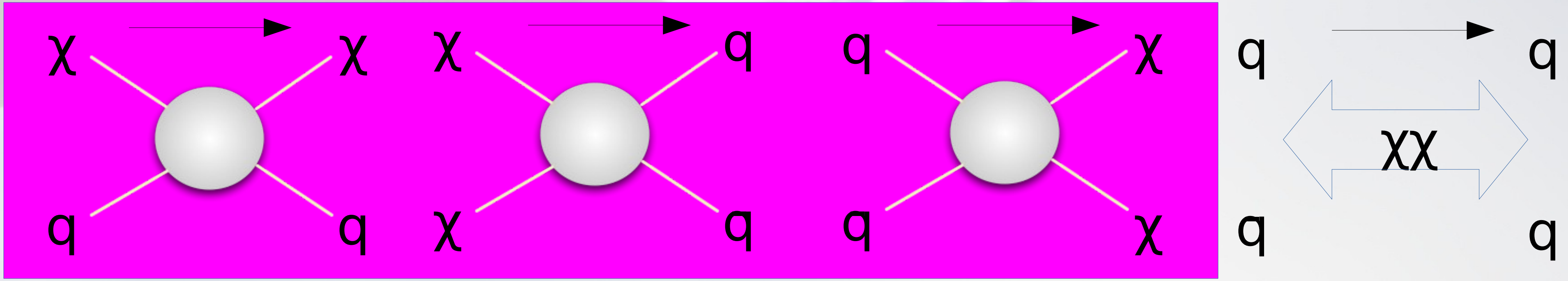
- Strong astrophysical uncertainties
- DM Distribution in halos
- Product propagation

Accelerators

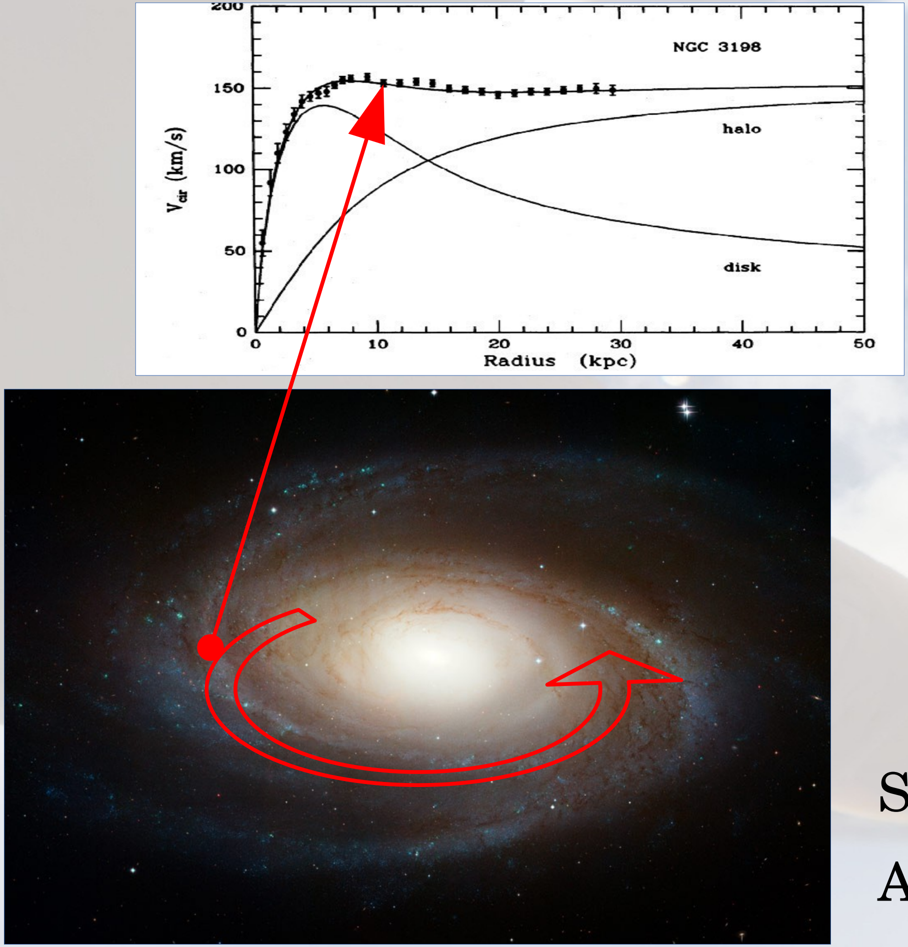
- Can only produce candidates
- Model dependence: p-p and operators

Precision!

- At its infancy
- Promising in some sectors (e.g. axions)



Direct Detection of Galactic DM



- Our Galaxy is rotating at ~200 km/s at the Sun's orbit
- DM is "standing still"
- Hence, there is a "constant" flux of DM through Earth
- Velocities are non-relativistic, $\beta \sim 10^{-3}$
- $\langle v^2_{DM} \rangle \approx v^2_{SUN}$ (or close to it)

Search for an interaction with the **nucleus**!

Almost all backgrounds interact with **electrons**

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

Principles of Direct Detection

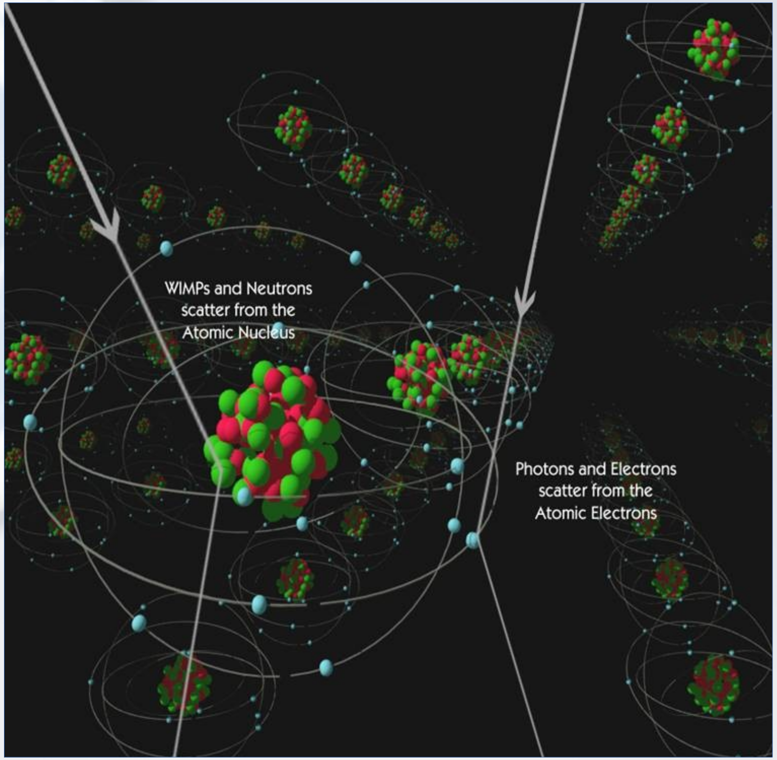
- Movement with respect to the galactic frame implies DM flux,

$$\Phi \simeq 7.5 \times 10^4 \text{ particles/cm}^2\text{/sec}$$ (for ~100 GeV particle)

- DM recoils off a target material, leaving some energy in the form of:
  - Ionized electrons.
  - Scintillation light.
  - Heat/phonons.

Signal is collected and the recoil energy is extracted, in the **KeV range**.

- A^2 enhancement for the simplest (SI) models



REVIEW D VOLUME 31, NUMBER 12

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.

Some thumb rules for the interaction

- Assuming an isothermal halo $\rho_{DM} \approx 0.3\ \mathrm{GeV/cm^3}$
- Velocity of the sun around the Galaxy "rest frame" $v_0 \sim 230\ \mathrm{km/s}$, escape velocity $\sim 550\ \mathrm{km/s}$
- Recoil energy of a nucleus by elastic scattering:
  $E_{r,\max} = \frac{p_\chi}{2m_N} \sim \frac{(100\mathrm{GeV/c^2} \times 10^{-3} c)^2}{2 \times 100\mathrm{GeV/c^2}} \approx 50\ \mathrm{keV} \Rightarrow$ Low energy detectors
- Coherent scattering
  $\frac{\lambda_{\mathrm{DeBroglie}}}{2\pi} = \frac{\hbar}{p} \approx 1\mathrm{fm} \approx r_{\mathrm{nuc}} \Rightarrow \sigma_{SI} \propto A^2$
- Rate of interactions:
  $\Gamma = \Phi \sigma_{\chi,N} N_{\mathrm{Detector}} A^2$, for $\sigma_{\chi,N} = 10^{-45}\ \mathrm{cm}^2, m_\chi = 100\ \mathrm{GeV}$
  $\Gamma \sim 100$ events/ton/yr

True for elastic recoils only!

Dark Matter Direct Detection Rates

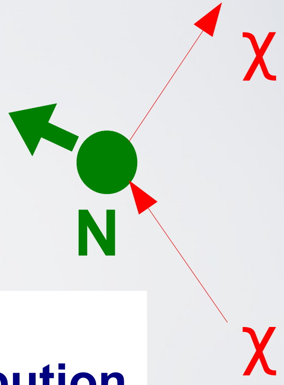
Goal: Observe WIMP interactions with some target material

Expected interaction rate

Number of targets | WIMP density | Nuclear Form factor

$$\frac{dR}{dE_{NR}} \propto N \frac{\rho_\chi}{2 m_\chi \mu^2} \sigma_N |F^2(E_{NR})| \int_{v_{min}}^{v_{esc}} \frac{f(\vec{v})}{v} d^3 v$$

WIMP mass | Interaction cross section | WIMP velocity distribution

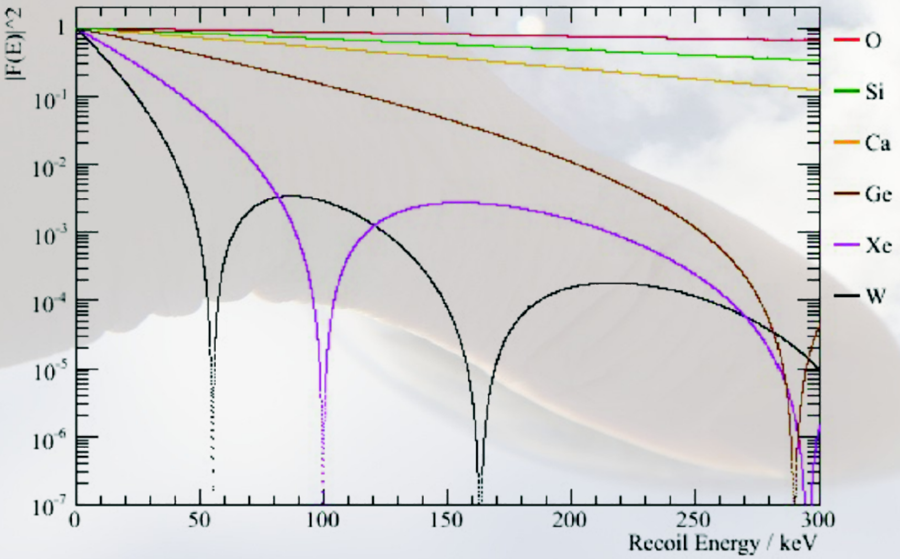


- Only those WIMPs with velocity above threshold will contribute to that energy
- For Spin Independent interactions the cross section is enhanced by a factor A^2 (coherent scattering)

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

Nuclear Form Factor

- When the inverse momentum transfer is large relative to the size of the nucleus, the coherence is reduced
- Nuclear excitations reduce dramatically the cross section, so each isotope has its own nuclear Form Factor



"Helm" form factor:

$$F(qr_n) = \underbrace{\frac{3[\sin(qr_n) - qr_n\cos(qr_n)]}{(qr_n)^3}}_{j_1(qr_n)} e^{-(qs)^2/2}$$

r_n = nuclear radius, $r_n \approx 1.2\ A^{1/3}$ fm, s = 1fm (skin thickness)

Spin Independent and Spin Dependent

- Simplified picture for the interactions DM $\leftrightarrow$ Nucleon
  - SI: Scalar interactions (coupling to χ through scalar, vector, tensor part of $\mathscr{L}$)

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

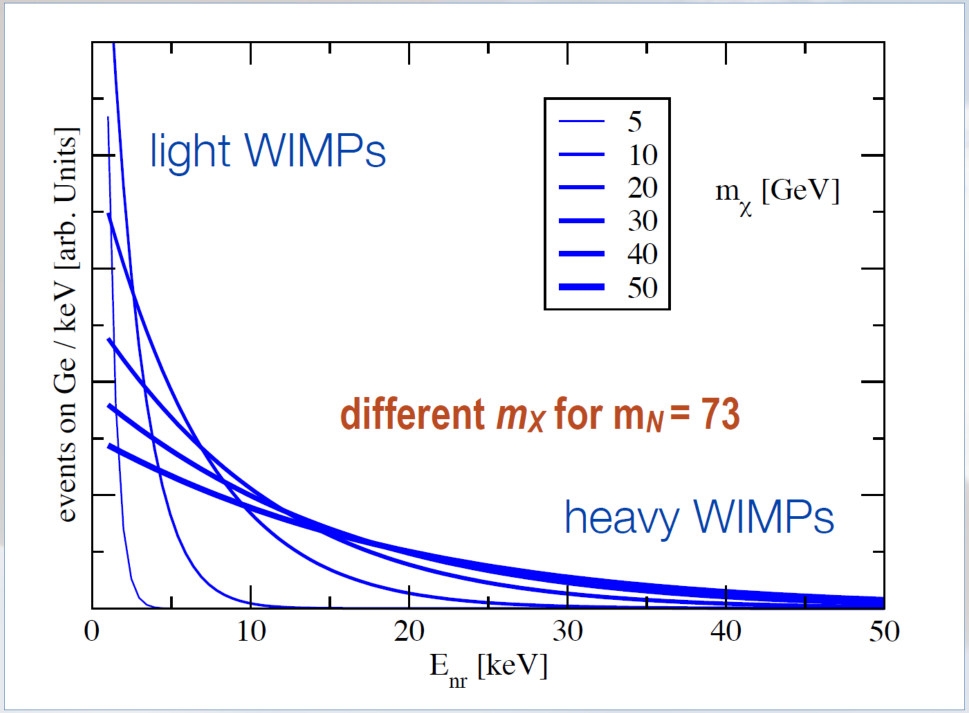
    - Nuclei with high A favorable (mostly if $f_p \approx f_n$)
  - SD: Spin-spin, coupling spin of χ to the nuclear spin from axial vecor part of $\mathscr{L}$

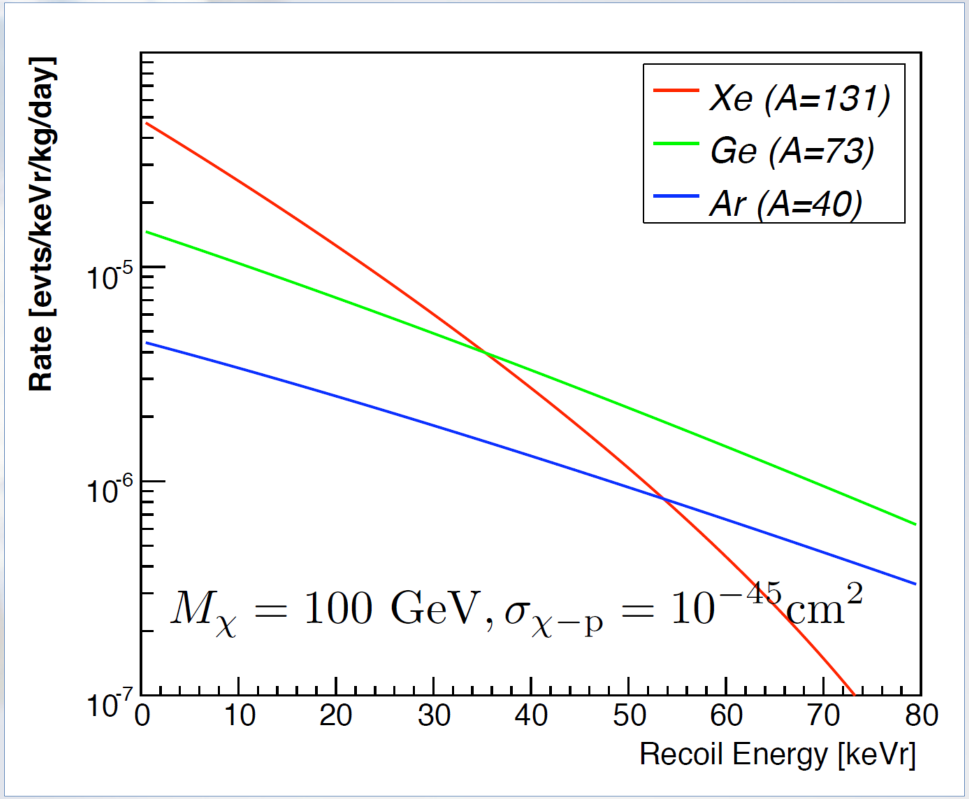
$$\sigma_{SD} \sim \mu^2 \frac{J_N+1}{J_N}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2$$

$$\langle S_{p,n}\rangle = \langle N | S_{p,n} | N\rangle$$

    - Targets with large nuclear spin are preferable (odd A)

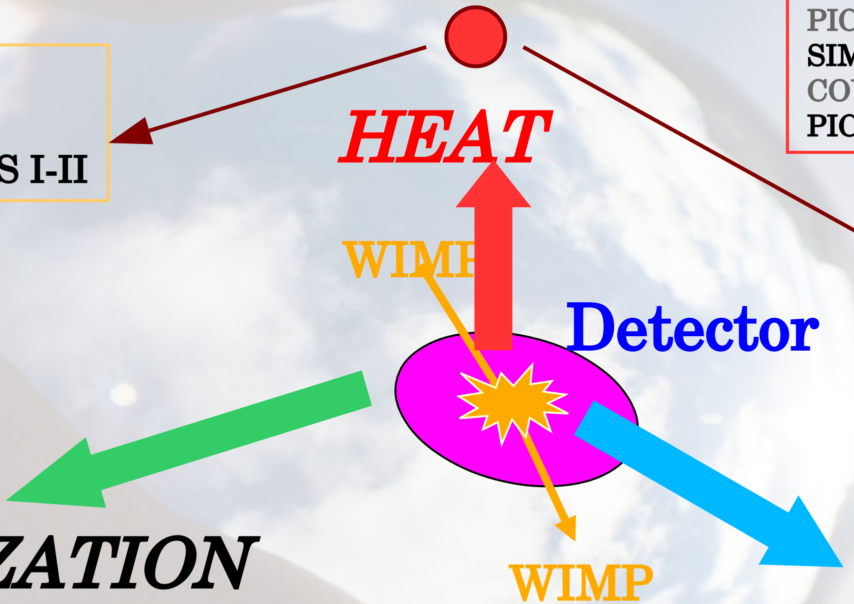
Recoil Spectrum



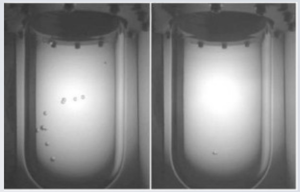


R. Budnik, ISAPP 2019

Direct Detection Techniques



CDMS I-II
superCDMS
EDELWEISS I-II



PICASSO
SIMPLE
COUPP
PICO

CRESST -II/III
ROSEBUD

IONIZATION

HPGe exp.
IGEX
GEDEON
GERDA
GENIUS
CoGeNT
CDEX

SCINTILLATION

+time measurement

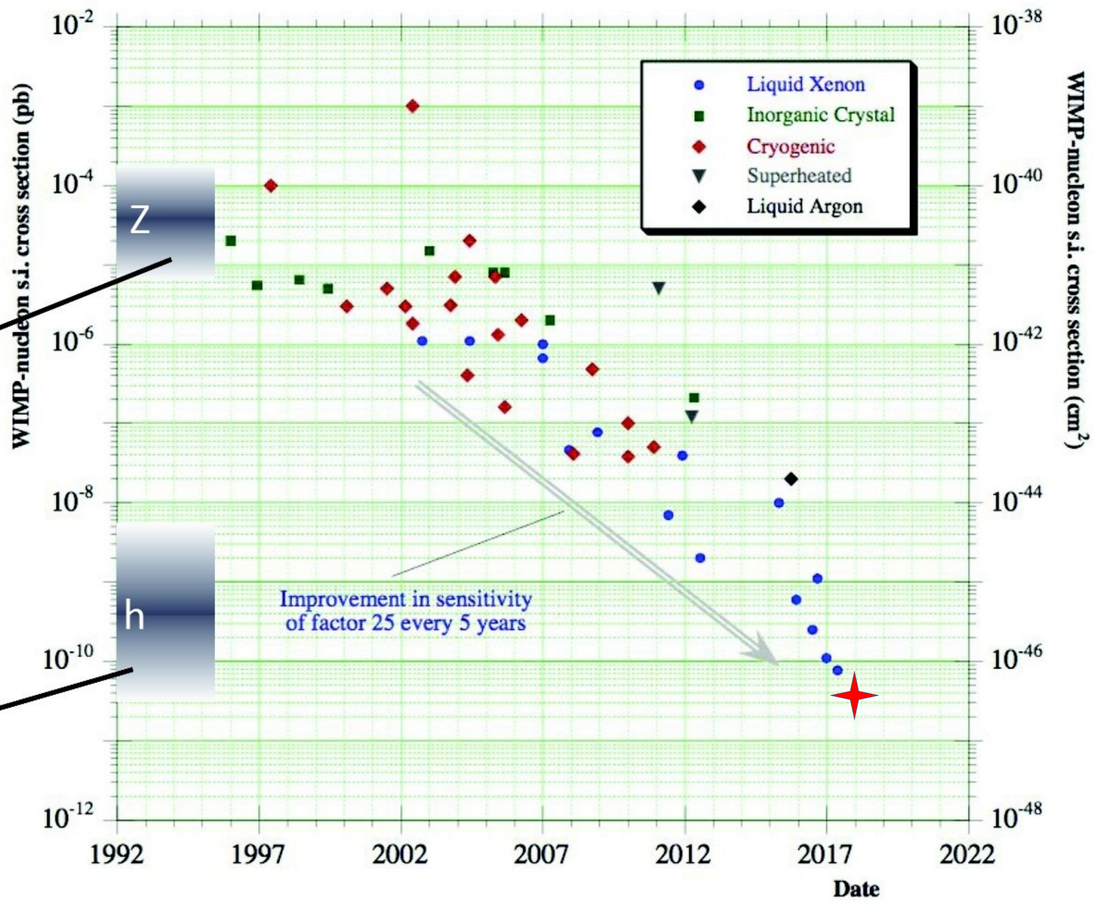
ZEPLIN I
CLEAN
DEAP
XMASS

ZEPLIN II-III
XMASS II
XENON
LUX/LZ
PandaX
WARP,
ArDM
DarkSide

DAMA / LIBRA
KIMS
SABRE
COSINE
COSINUS
DM-ICE

Fast progress over ~2 decades

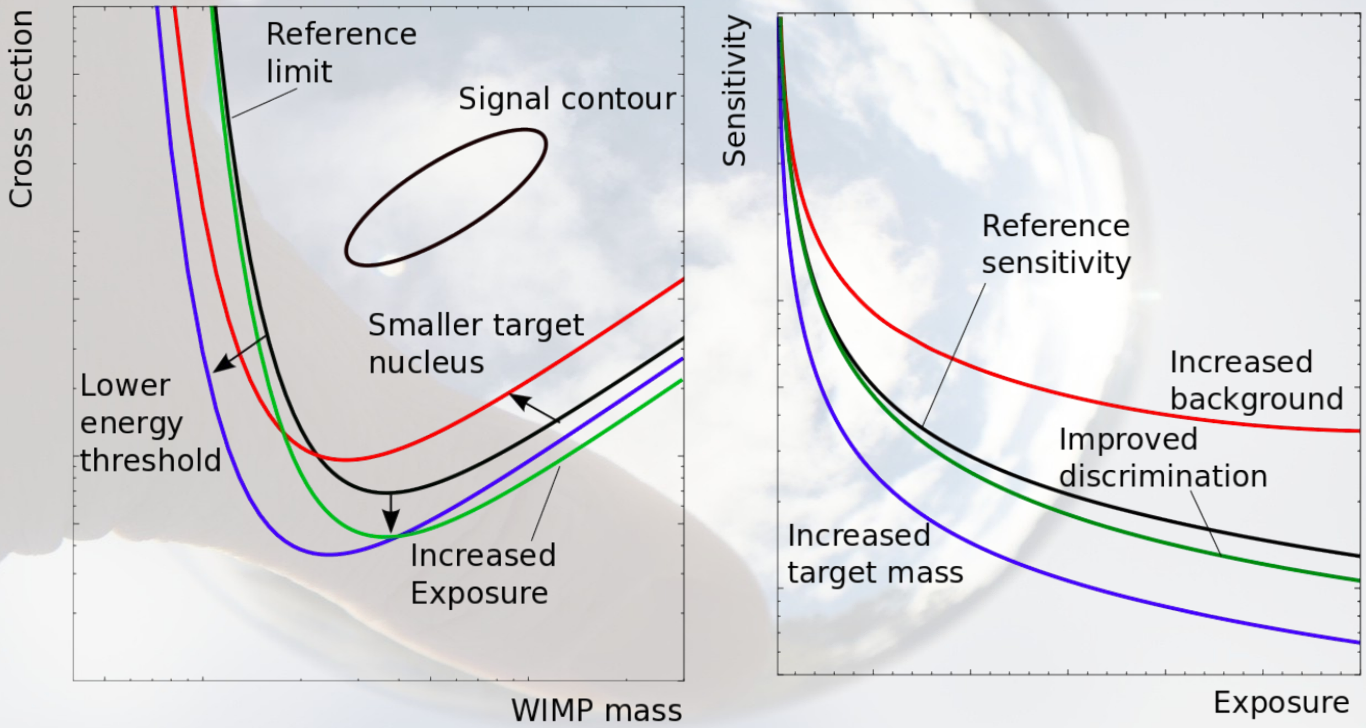
- Direct detection sensitivities improving factor 25 every 5 years
- Already (1990's) excluded Z-mediated exchanges (e.g. heavy neutrinos)
- Now into higgs-mediated cross sections



After Gaitskell

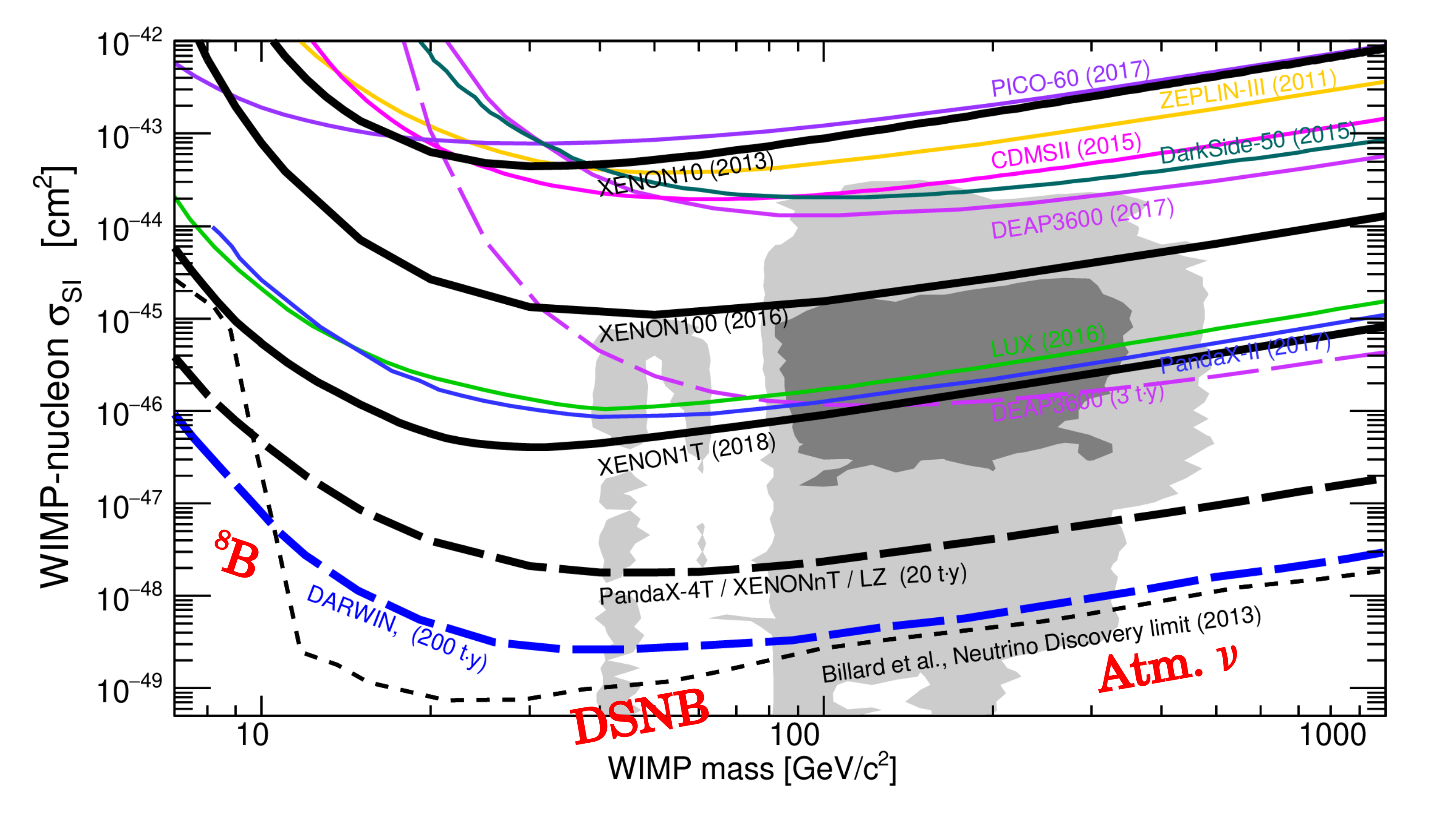
R. Budnik, ISAPP 2019

Exclusion/Discovery plots



J. Phys. G43 (2016) 1, 013001, 1509.08767

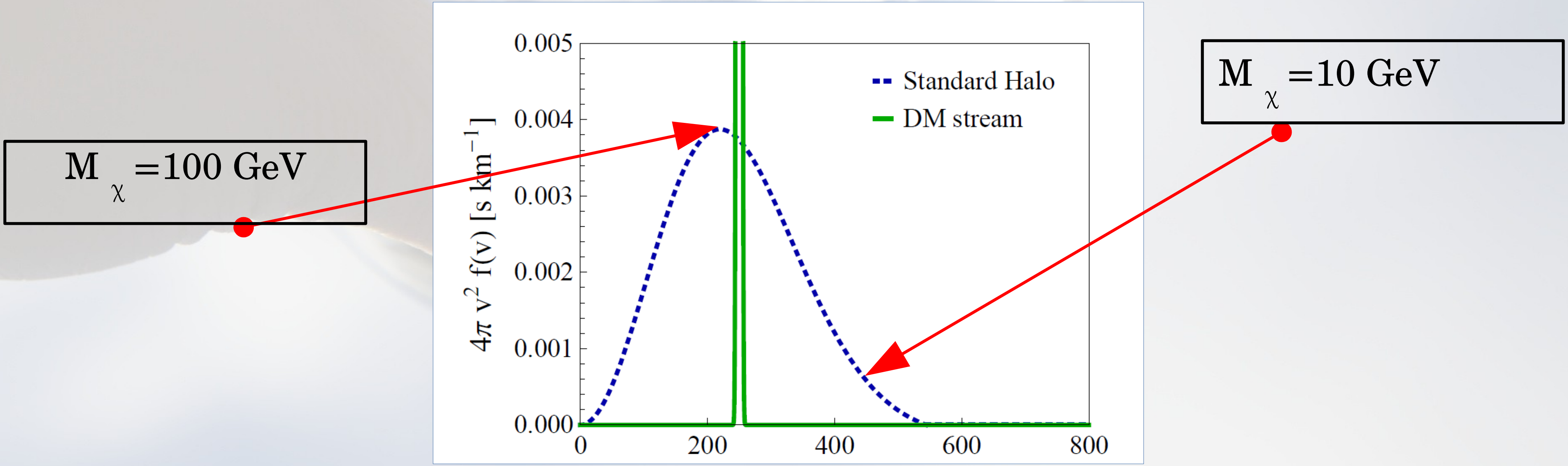
Exclusion Curves, “ν floor”



Minimum velocity

- Each combination of **DM mass**, **target nucleus mass** and detector **threshold** determines v_{min}, under which no recoil can be detected
- As an example,

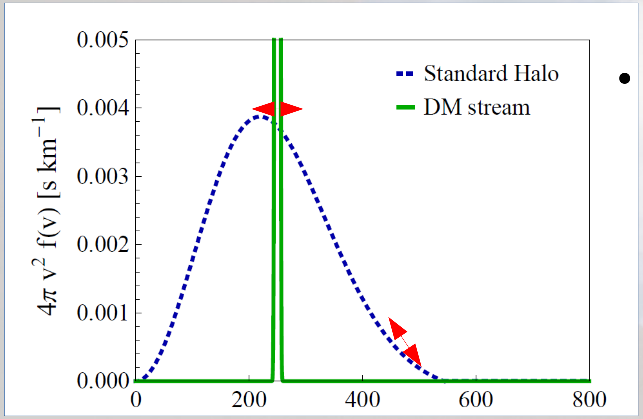
  For Xe target and threshold of 5 keV:



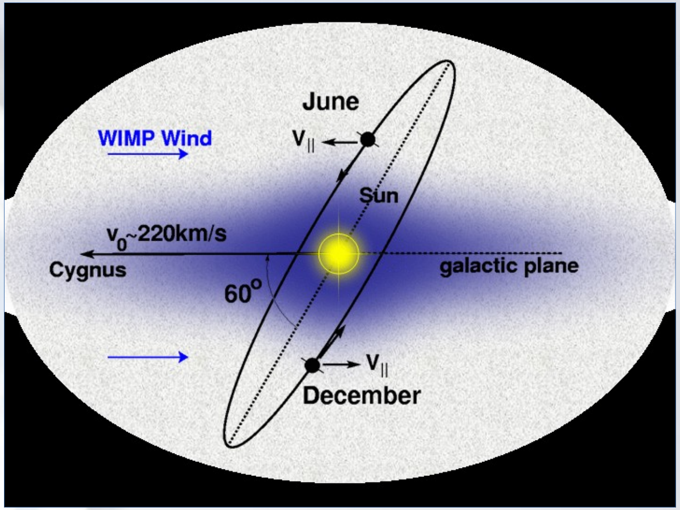
R. Budnik, ISAPP 2019

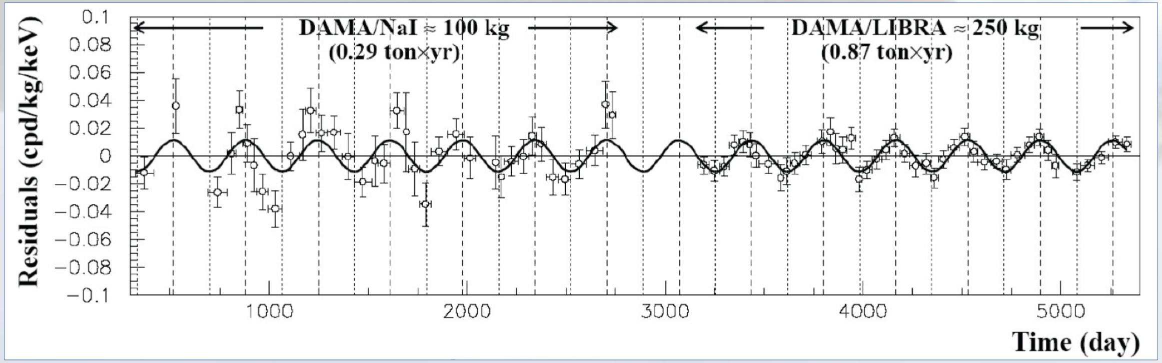
Dark matter and Earth dynamics: Annual modulation

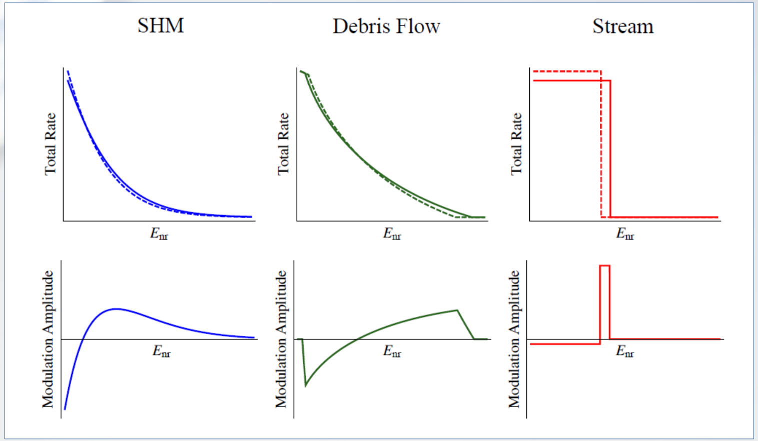
- In general, the higher v_{min}, the stronger the relative modulation, but…



- About 7% modulation on <>, can be much higher in signal



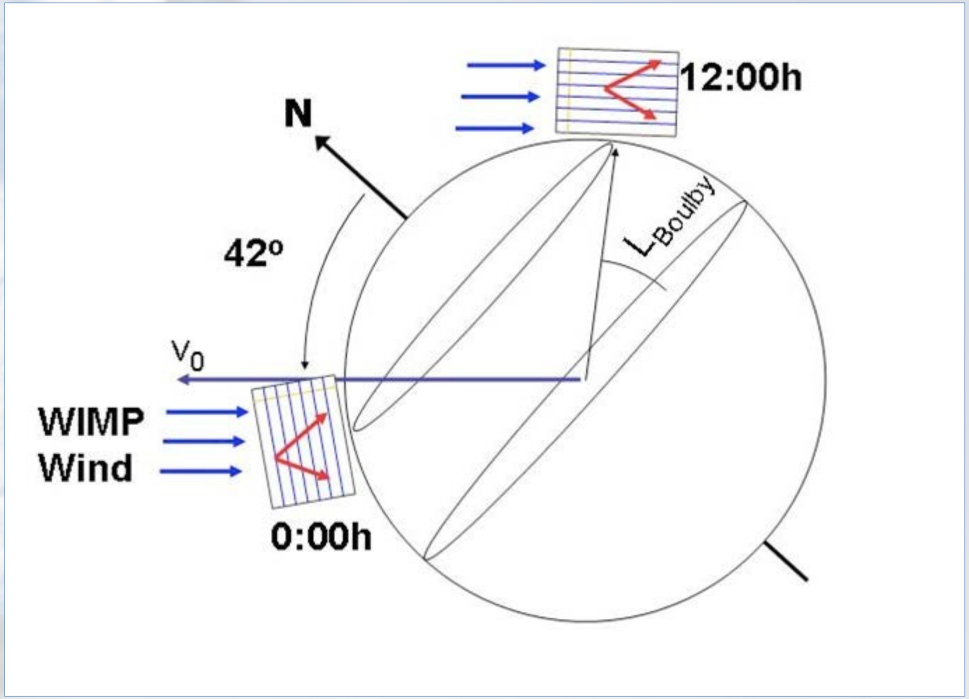




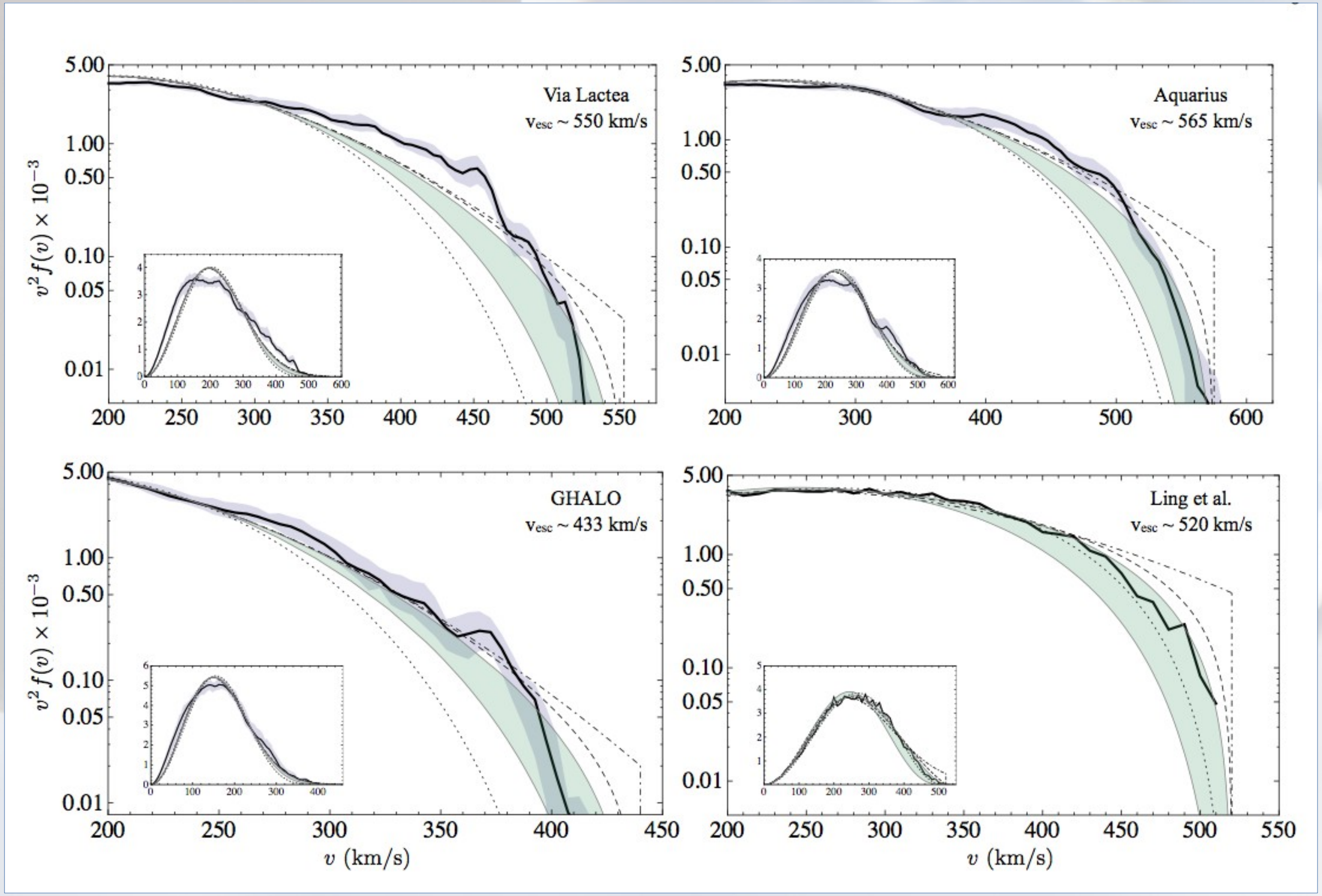
R. Budnik, ISAPP 2019

Daily modulation

- During the day the direction of the lab changes, and the direction of the WIMP wind is fixed
- If e.g. particles are partially blocked by Earth, one expects daily modulation
- Modulation moves with 25h56' - why??



Uncertainties in Velocity Distributions



[Lisanti et al., 2010]

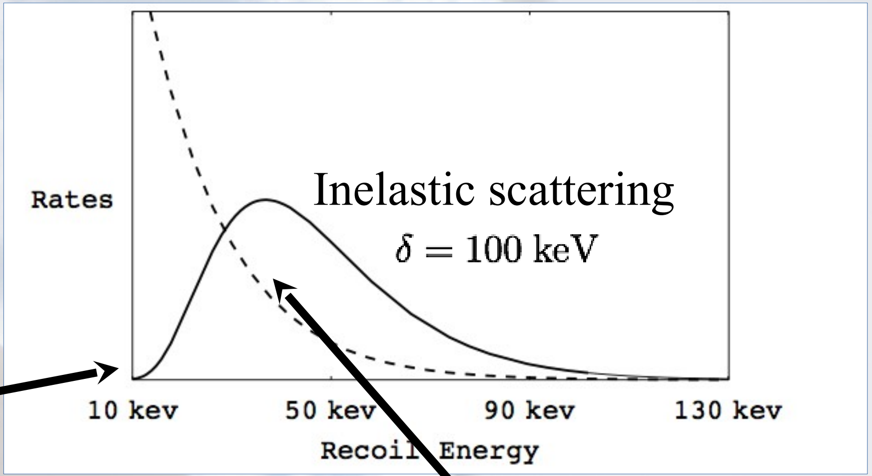
- Halo density around our position is relatively solid
- Escape velocity affects "perfect" velocity distribution, and depends on the assumed halo profile
- High velocities suffer greatest uncertainties

Recoil Energy Spectrum – beyond vanilla

- Exponentially falling for simple scenarios, however there are complications

Elastic scattering

$$v_{\min} = \frac{1}{\sqrt{2m_N E_R}} \left| \frac{m_N E_R}{\mu} + \delta \right| .$$



Drop at low energy for inelastic scattering

Exponential fall due to nucleus form-factor and velocity distribution

Backgrounds in Dark Matter Detectors

- **Most problematic: muons and muon induced neutrons. MeV neutrons can mimic WIMPs**
- **Cosmic rays and secondary/tertiary particles:** **deep underground** laboratories
- **Hadronic component (n, p)**: reduced by few meter water equivalent (m.w.e.)

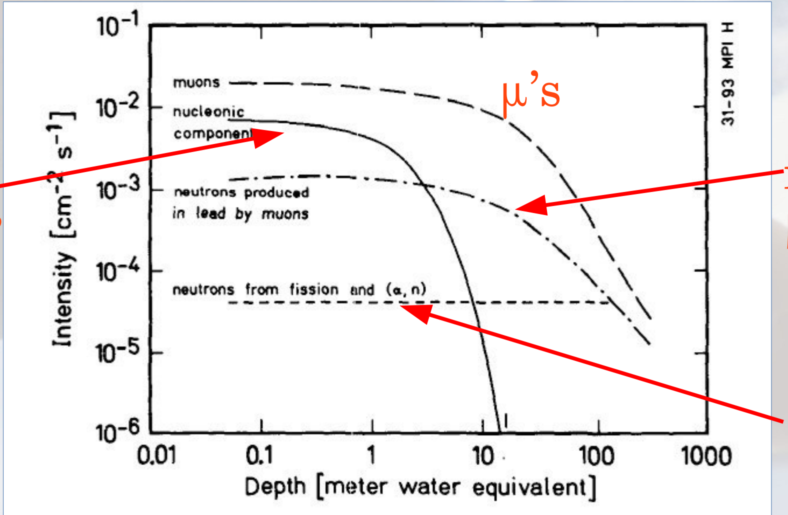
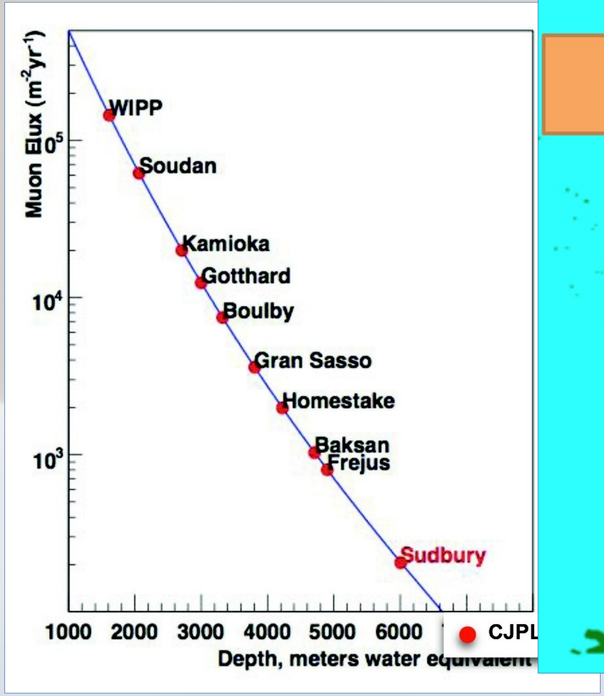


Figure 2 Flux of cosmic ray secondaries and tertiary-produced neutrons in a typical Pb shield vs shielding depth. Neutron flux from natural fission and (α, n) reactions is also shown. The nucleonic component is more than 97% neutrons.

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

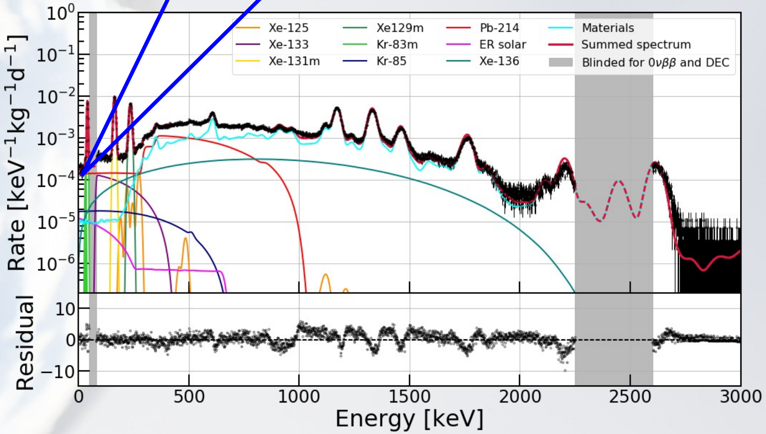
Underground facilities: A must



Fighting backgrounds - UG

- External γ
  - Shielding and self shielding
  - Multiple scattering
  - Discrimination ER/NR
- Internal α, β
  - Cleaning, discrimination
- Neutrons: Fission, μ-generated, α-n
  - Multiple scattering, moderators, n-veto
- ν's: Solar and Atmospheric
- Plus, each detector carries extra unique backgrounds (instrumental, unknown source)

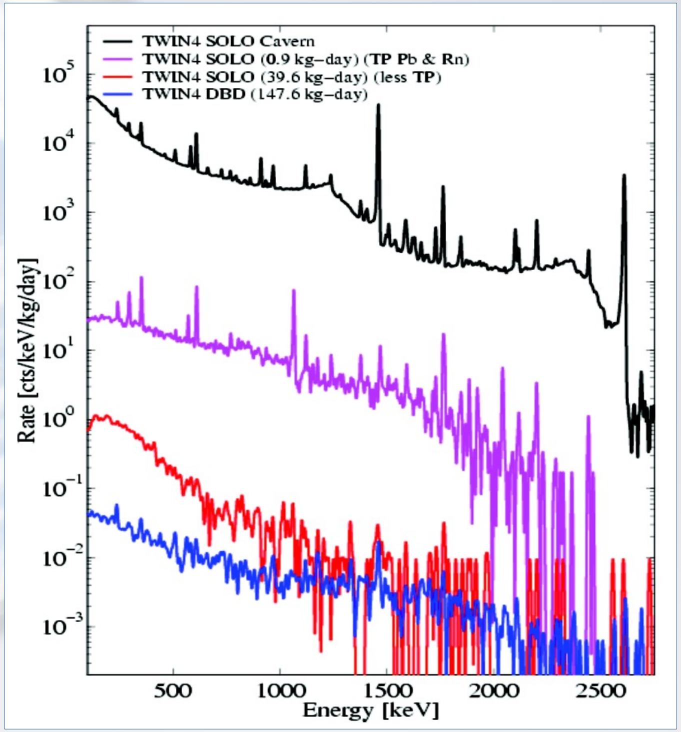
The least radioactive place in the known universe



Backgrounds – External EM

- External, natural radioactivity: ^{238}U, ^{232}Th, ^{40}K decays in rock and concrete walls of the laboratory => mostly gammas and neutrons from (α,n) and fission reactions
- Radon decays in air
  - passive shields: Pb against the gammas, polyethylene/water against neutrons
  - active shields: large water Cherenkov detectors or scintillators for gammas and neutrons

Ge detector underground

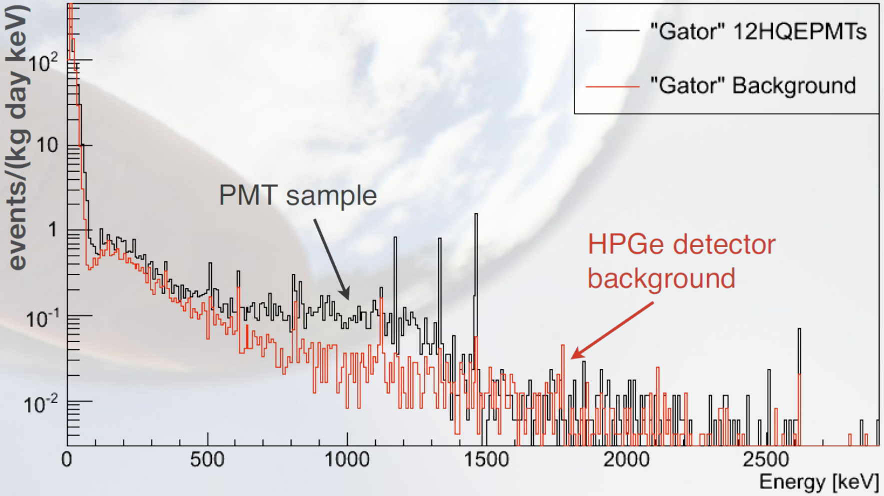


Without and WITH Pb shield and Rn purging

R. Budnik, ISAPP 2019

Backgrounds – Internal EM

- Detector materials contain trace amounts of radioactive elements
- Usual suspects: ^{238}U, ^{232}Th, ^{40}K, ^{137}Cs, ^{60}Co, ^{39}Ar, ^{85}Kr, ^{222}Rn … 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



R. Budnik, ISAPP 2019

A Game of numbers

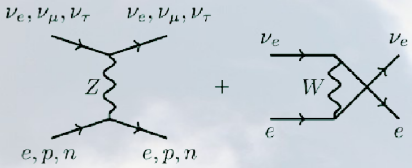
- how much radioactivity (in Bq) is in your body? where from?
  - 4000 Bq from ^{14}C, 4000 Bq from ^{40}K (e^- + 400×1.4 MeV γ + 8000×ν_e)
- how many radon atoms escape per 1 m2 of ground, per s?
  - 7000 atoms/m^2 s
- how many plutonium atoms you find in 1 kg of soil?
  - 10 millions (transmutation of ^{238}U by fast CR neutrons), soil: 1 - 3 mg U per kg

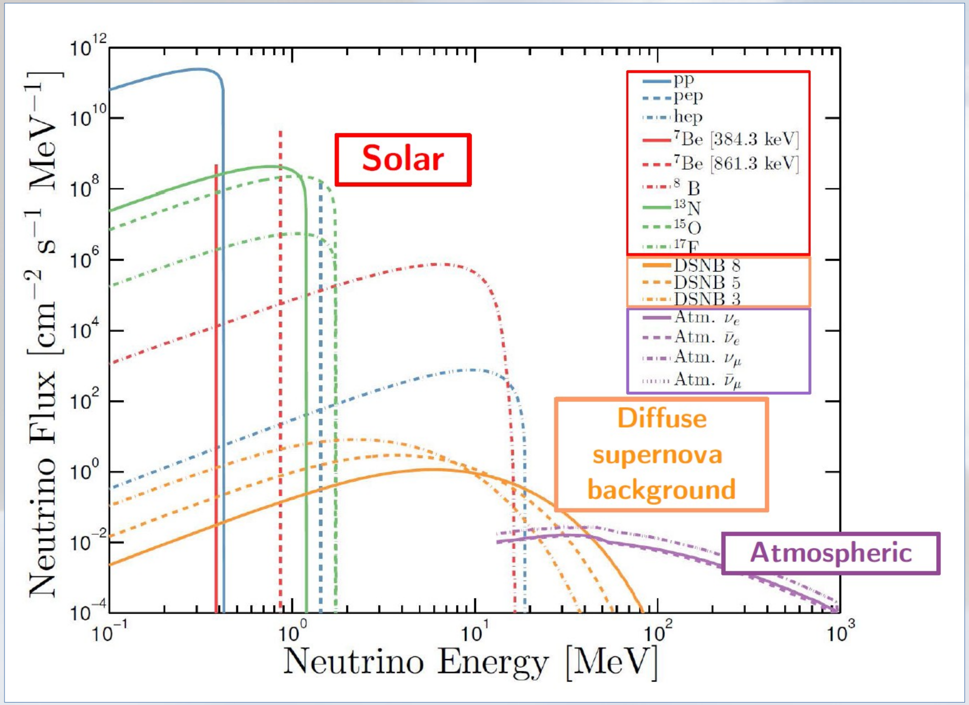
Backgrounds – Neutrons

- MeV+ neutrons mimic DM elastic scattering!
- Sources:
  - Cosmogenic – μ induced shower, high E neutrons
  - Radiogenic:
    - U, Th spontaneous fission
    - (α,n) from plate out of actinides on walls
- Solutions:
  - Shielding
  - Size (for multiple scattering)
  - Active neutron veto

Backgrounds – Neutrinos e⁻ recoil

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



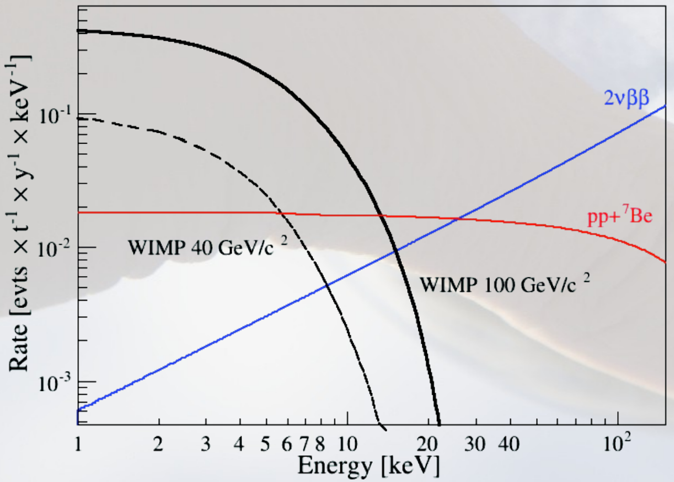


- Practically all neutrinos have enough energy to be relevant
- pp dominate in most scenarios
- “Irreducible” background – single scatter, homogeneous

Backgrounds – Neutrinos e⁻ recoil

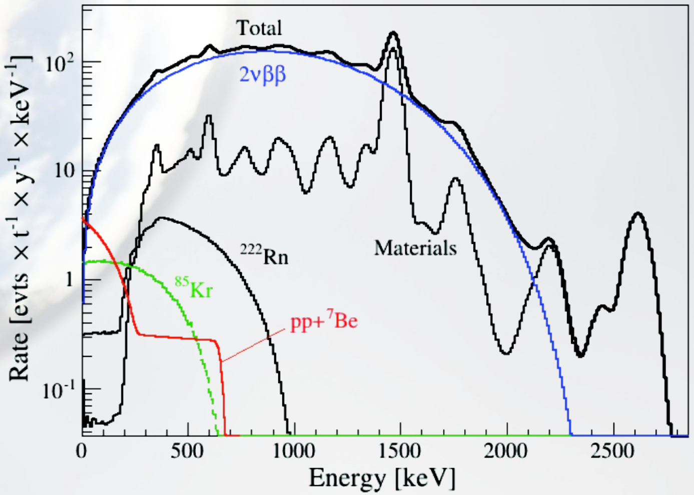
- Electron will recoil, producing a broad spectrum, uniform in the detector
- Some will pass the discrimination and look like signal!
- Taking LXe as an example

After discrimination (99.5%)



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

Before discrimination

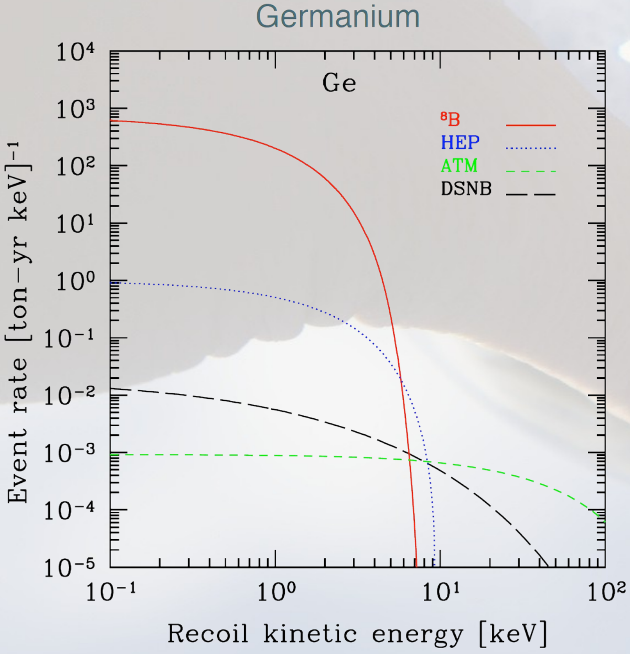


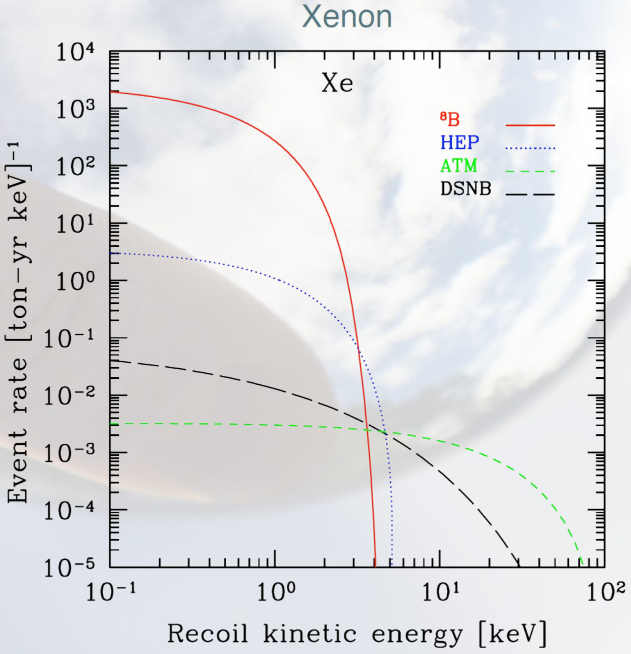
R. Budnik, ISAPP 2019

Baudis et. al., JCAP01 (2014) 044

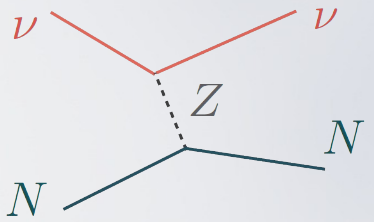
Backgrounds – Neutrino-Nucleus recoil

- ^{8}B dominate νs at low energy/low mass (<4 keV heavy targets, somewhat higher for light targets)
- DSNB and Atmospheric νs dominate at higher E, but still out of reach of current experiments





R. Budnik, ISAPP 2019



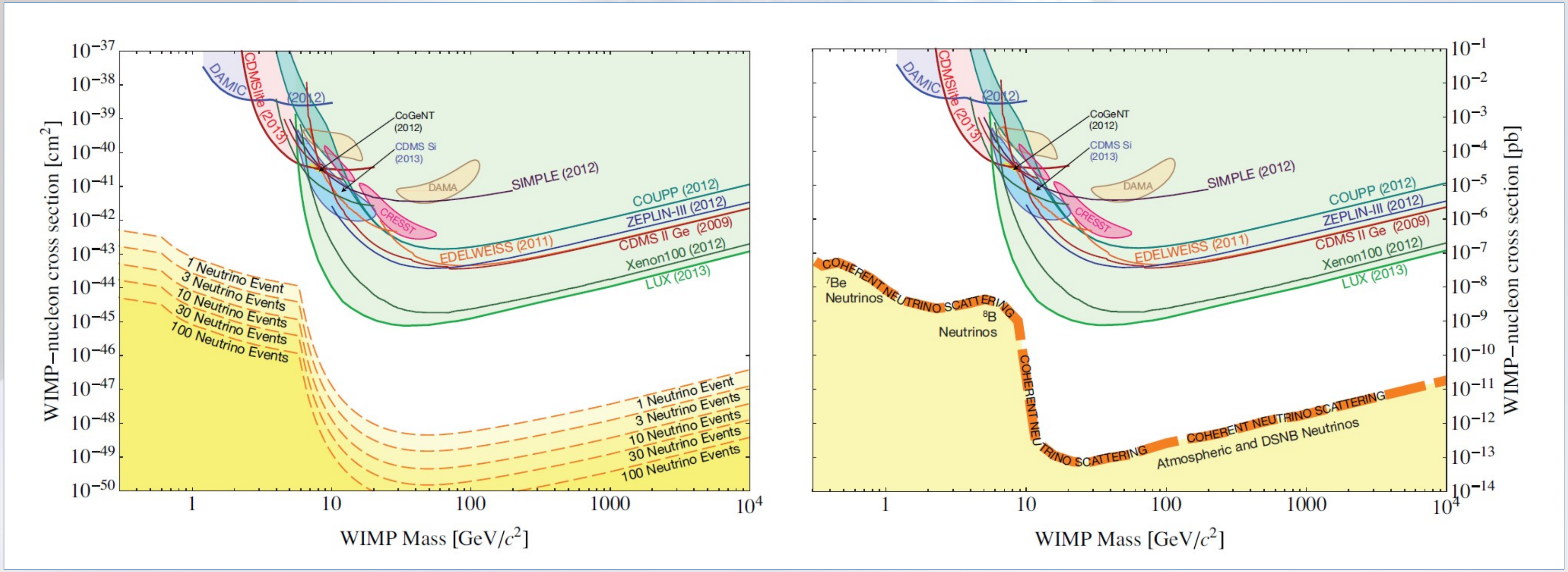
$$\frac{d\sigma(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_\omega^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F_{SI}^2(E_r)$$

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

Stigari, New J. Phys. 11 (2009) 105011

“ν Floor”

- Coherent ν-Nucleus scattering looks like WIMPS
- The uncertainty on that rate puts a pretty hard limitation
- The “floor” has target dependence in the translation to DM cross section

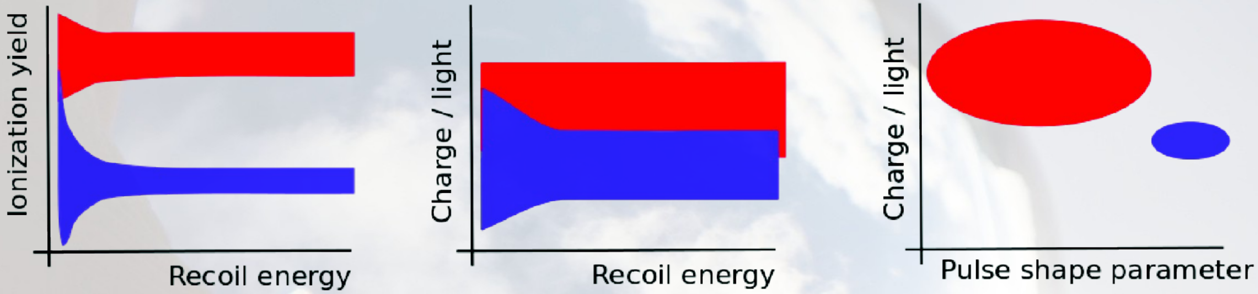


Billard et. al. (2013)

Calibration – Never leave home without it

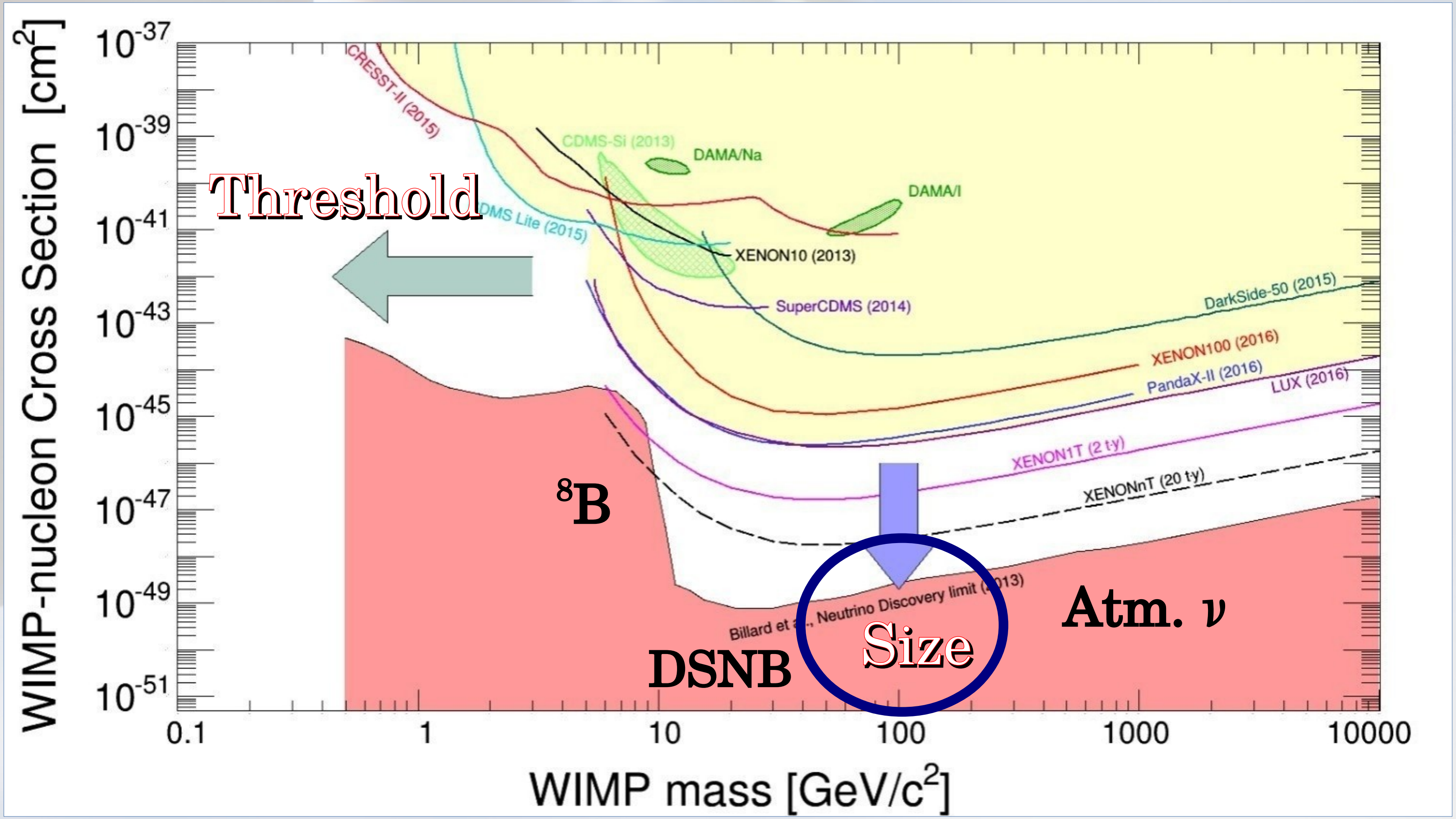
- Calibrating the energy scale: From detectors signals (PMTs readout → Photoelectrons → Energy; Ionization signal → Energy; etc.
- Determining signal and background signal shape and distributions (and discrimination when relevant)
- Following detector stability over long periods of time

Discrimination



- (Left) Discrimination in a cryogenic Germanium detector
- (Center) Discrimination in a liquid xenon detector
- (Right) Discrimination in a liquid argon detector (two discriminating parameters)

The Road Map

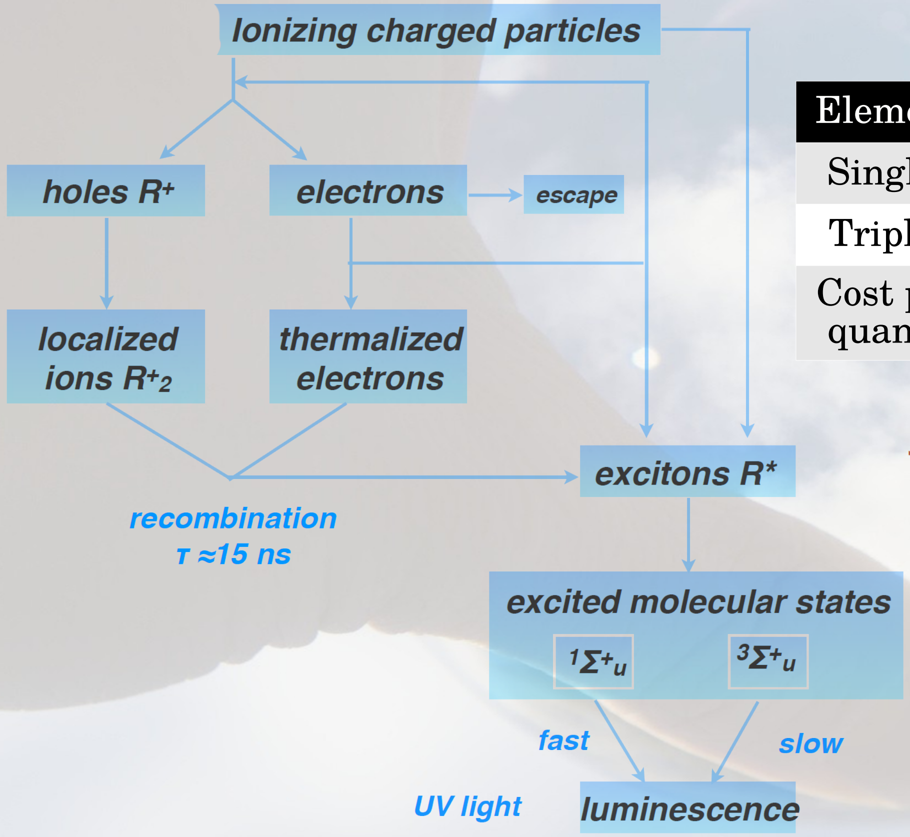


R. Budnik, ISAPP 2019

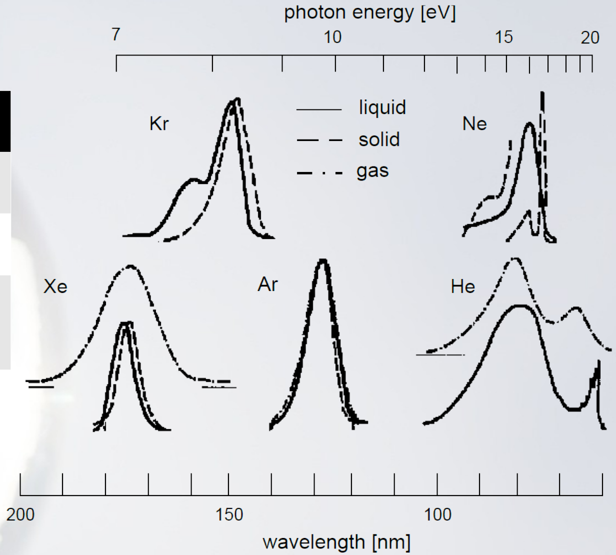
The "Size Frontier"

- Target mass is #1 priority
  - However: **backgrounds**, threshold play a role
- Currently led by **liquid noble elements**:
  - **Xenon**: LUX/LZ, PandaX-II, XENON1T/nT
  - **Argon**: DEAP3600, DarkSide, ArDM...
- If looking at non-trivial interaction (e.g. Spin-Dependent), other targets get the lead (e.g. PICO, ^{19}F)

Scintillation of LXe, LAr



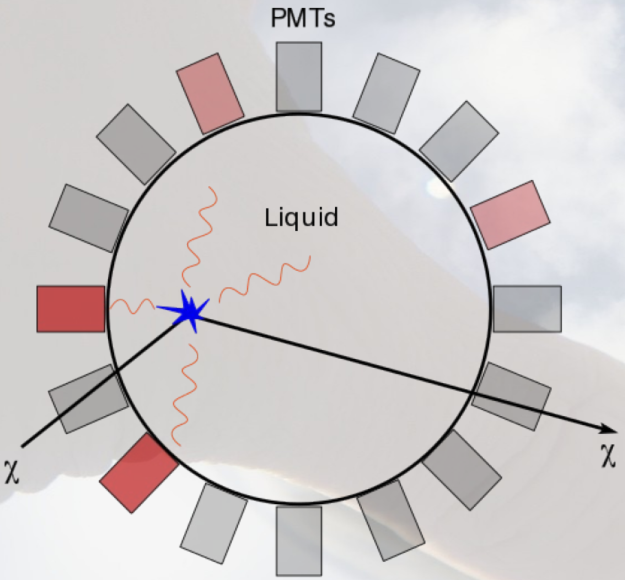
Element	Xe	Ar
Singlet	4-5 ns	7 ns
Triplet	22-25 ns	1500 ns
Cost per quanta	~~9.4~~ ~13 eV	~~12.2~~ ~18 eV



Take home:

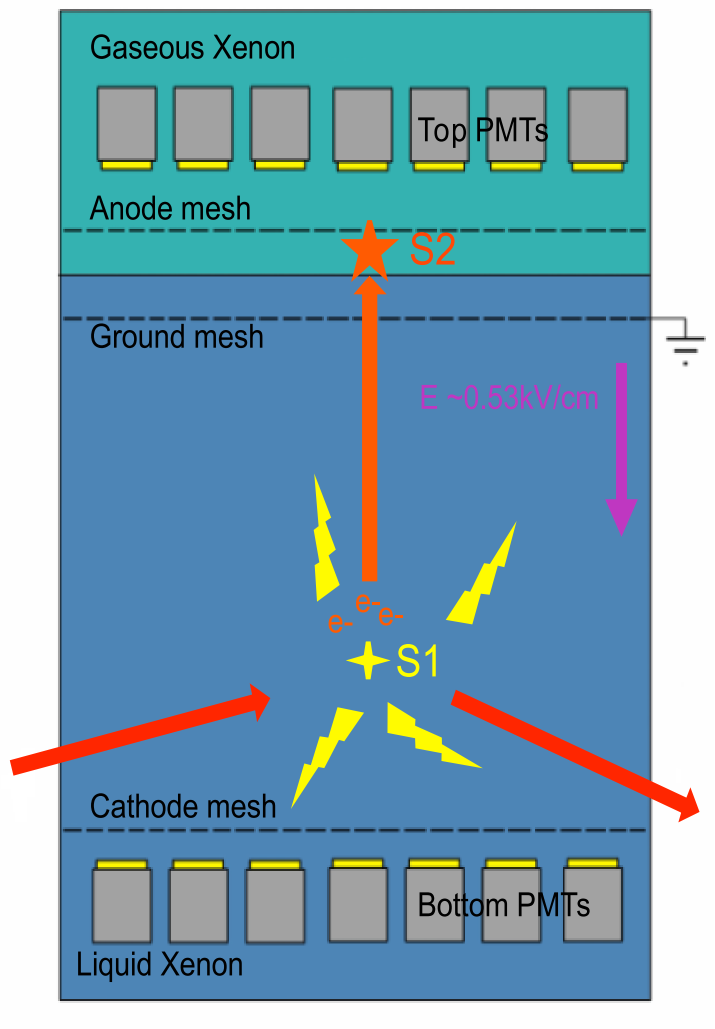
1. Detectibility
2. Discrimination
3. Yield

Single Phase Liquid Noble Element



- Uses positioning from hit pattern, allows fiducialization
- Possible discrimination through Pulse Shape
- Simplicity helps

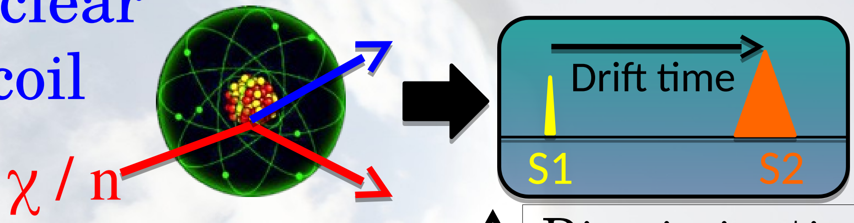
The leading tech: Dual Phase Xenon TPC



S1: Prompt scintillation

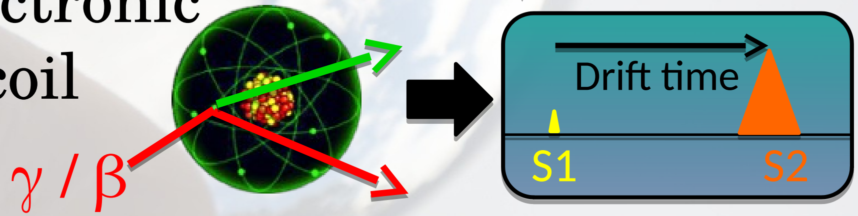
S2: Proportional scintillation after *e-* drift and extraction into gas

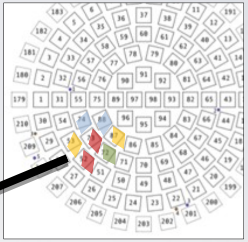
Nuclear Recoil



Discrimination by S2/S1

Electronic Recoil





Interaction vertex reconstruction:

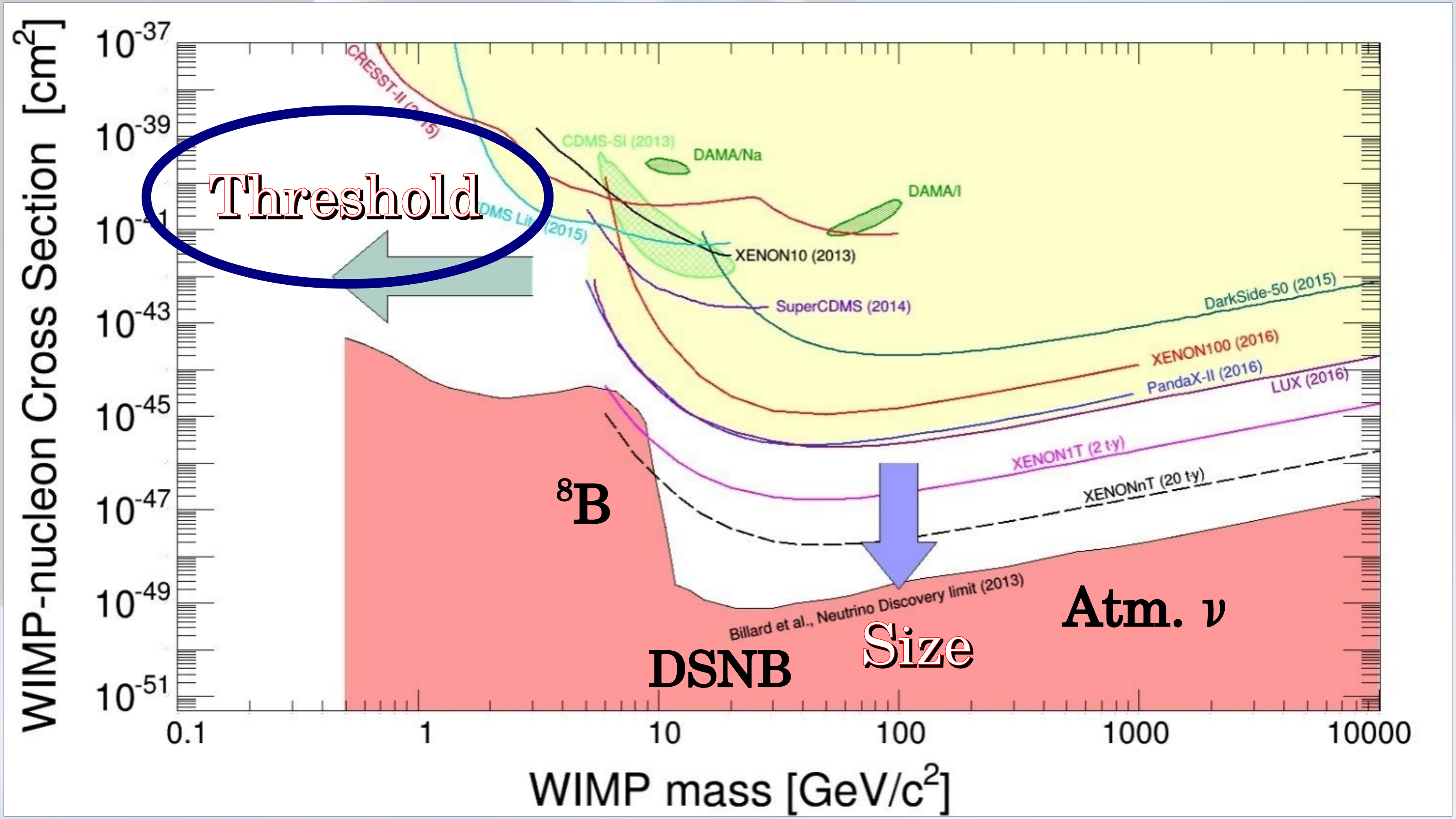
- Horizontal from top PMT array
- Vertical from drift time

R. Budnik, ISAPP 2019

Liquid Noble Elements Detectors

- Pros
  - Large mass attainable
  - Low Background (LXe) or amazing discrimination (LAr)
  - Self Shielding
  - Single and Dual phase shown to be successful
  - "Cheap"
- Cons
  - "High" threshold
    - LXe - O(keV)
    - LAr – O(10 keV)

The Road Map



R. Budnik, ISAPP 2019

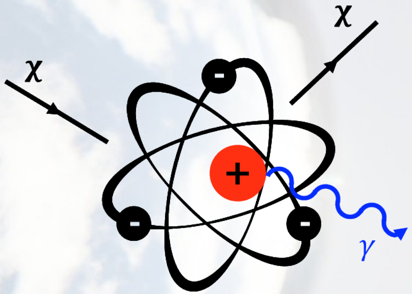
Low mass DM

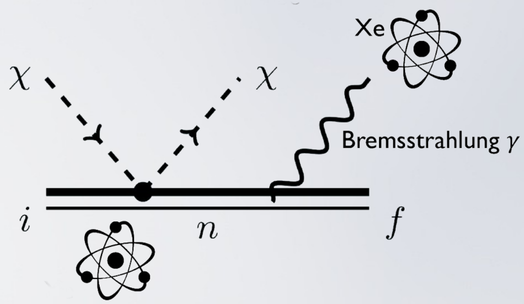
- For masses below a few GeV, the "classical" NR and discrimination fails, owing to the small energy deposit
- Lowering the threshold is key
- Some novel ideas may open the gate for "high threshold" experiments as well (but at a cost):
  - Bremmstrahlung
  - Migdal effect

Bremsstrahlung and Migdal:
Lowering the threshold for NRs

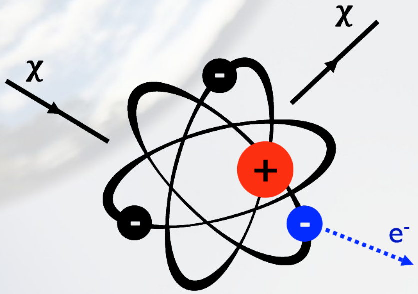
- Two proposed processes can "translate" a NR into a low energy ER through inelasticity of the interaction

Bremsstrahlung: Kouvaris & Pradler (2017), McCabe (2017)





Migdal effect: Ibe et. al. (2018), Dolan et. al. (2017)

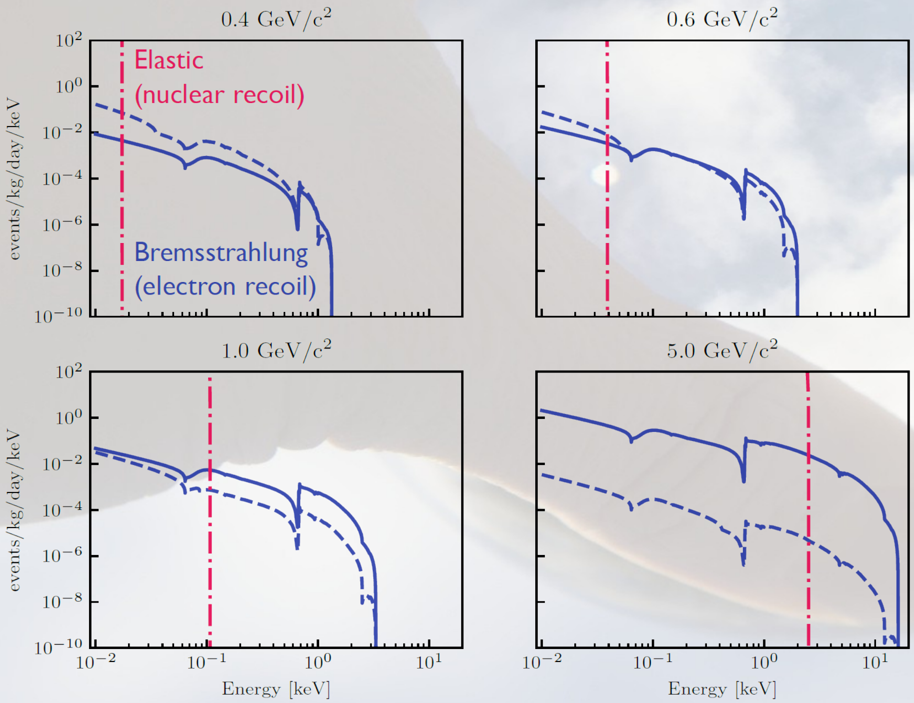


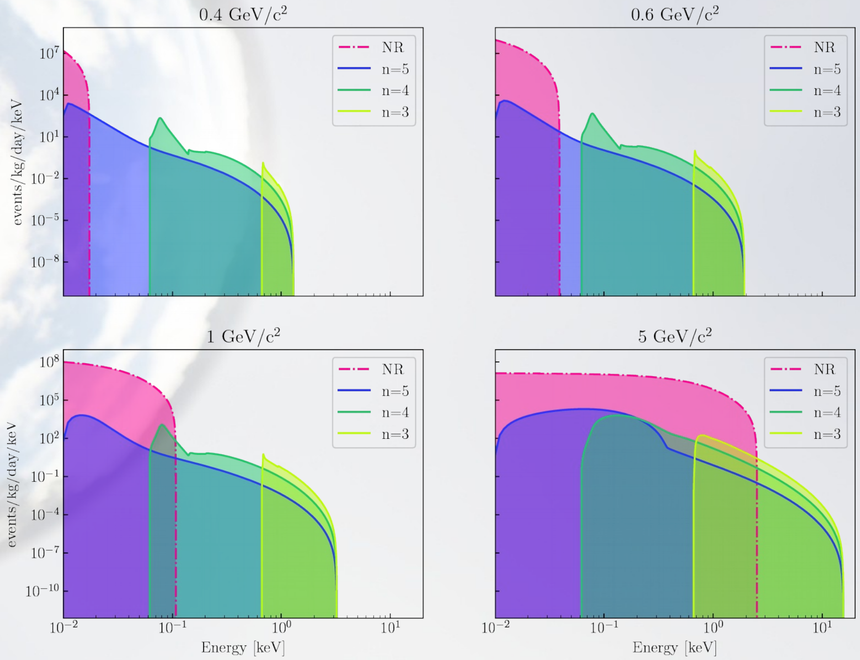
$$|\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle$$

$$\mathcal{P} = |\langle\Phi^*_{ec}|\Phi'_{ec}\rangle|^2$$

Brem & Migdal observables

- Brem (left) and Migdal (right) @ $\sigma = 10^{-35}$ cm²





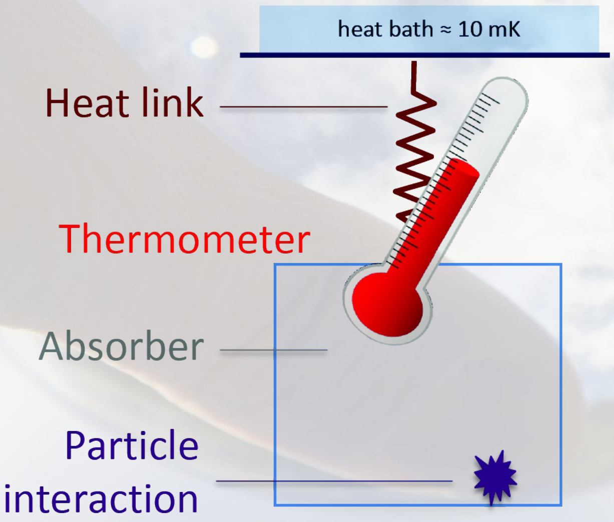
R. Budnik, ISAPP 2019

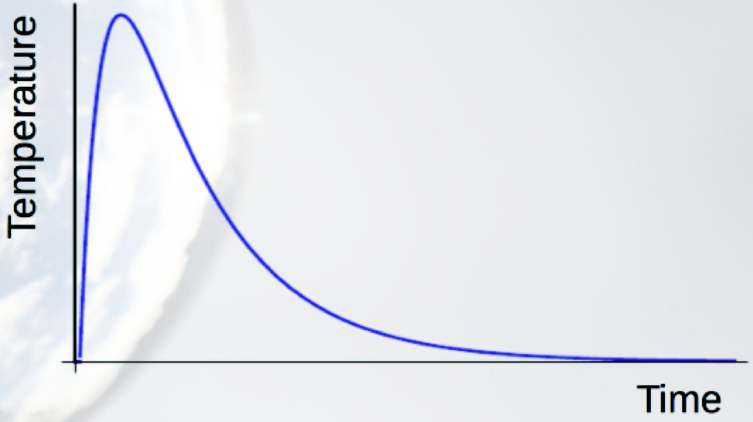
e^- scattering: New access to LDM

- Kinematics of a free electron gives O(1 eV) recoil
- Approaches:
  - Very low gap (i.e. many quantas for the <1 eV): Superconductors
  - Bound electrons - “violate” momentum conservation by inelasticity
  - Amplify a single electron
- Main problem: backgrounds are the same as the signal…
  - (BUT) the rates are “low”: small ΔE, small exposure.

Crystals for LDM - Calorimeters

- Low threshold
- Can be combined with other channels (ionization, scintillation)
- Hard to reach large target mass



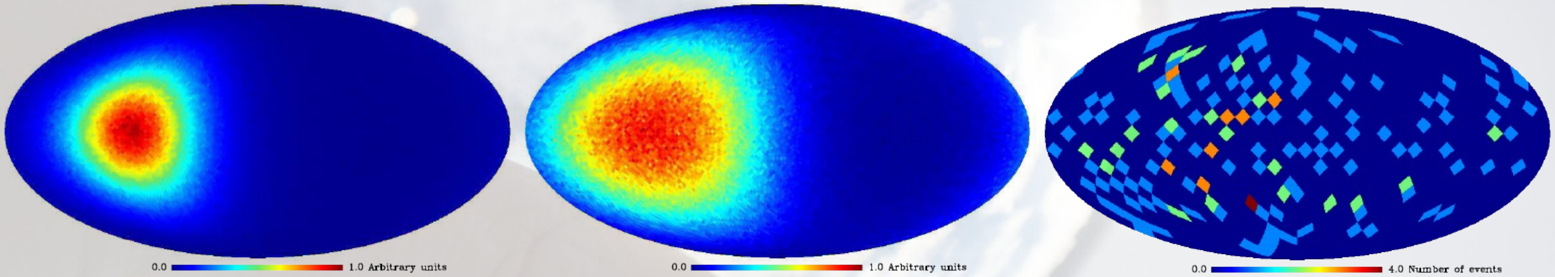


$\Delta T = \Delta E/C$

- Direct measurement of the full energy deposition
- Cryogenic temperatures

Directional Detection

- Signal preferrably arrives from Cygnus direction
- If a detector can tell the direction of recoiled particle, one can try to pinpoint “Galactic Origin” which is a smoking gun



100 GeV WIMP | NR | Simulated events

$$\frac{dR}{dE\, d\cos\gamma} \propto \exp\left[\frac{-[(v_E + v_\odot)\cos\gamma - v_{min}]^2}{v_c^2}\right]$$

γ: NR direction relative to the mean direction of solar motion

v_E and $v_\odot$: the Earth and Sun motions

$v_c = \sqrt{3/2 v_\odot}$: halo circular velocity

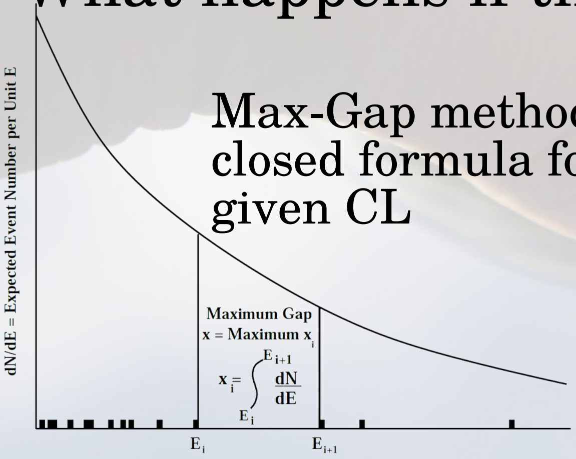
Billard et. al. 2010

Directional Detectors

- Pros
  - Can pinpoint Galactic origin
  - Can remove “irreducible” backgrounds
  - Can give direct access to properties of DM
- Cons
  - DILUTE: not competitive with mass
  - “High” threshold

Word About Statistics

- The easiest way: Set a “box” where signal (or part of it) is expected, and find the mean expected background count
  - Simple Poisson statistics gives discovery/limit
  - Limit set at 90% CL
  - No agreed “discovery” threshold
- What happens if the background is unknown? (Yellin, 2002)

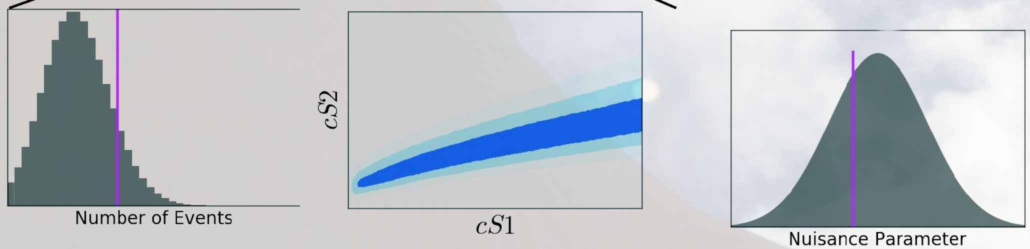


Max-Gap method, closed formula for a given CL

Optimum Interval method: When there are “many” events it is more beneficial to choose Max Gap of n events

Profile Likelihood

$$\mathcal{L}_{\mathrm{SR}}(\sigma,\theta\neq\sigma,M)=\mathcal{L}_{\mathrm{sci\ SR}}\cdot\mathcal{L}_{\mathrm{cal\ SR}}\cdot\mathcal{L}_{\mathrm{meas\ CNNS}}\mathcal{L}_{\mathrm{meas\ eff}}\cdot\mathcal{L}_{\mathrm{meas\ AC}}\cdot\mathcal{L}_{\mathrm{meas\ AC\ cal}}$$



Poisson term

S1/S2/r shapes

Nuisance parameter constraints

+run combination:

$$\mathcal{L}_{\mathrm{tot}}(\sigma,\theta\neq\sigma,M)=\prod_{\mathrm{SR}}\left(\mathcal{L}_{\mathrm{SR}}(\sigma,\theta\neq\sigma,M)\right)\cdot\mathcal{L}_{\mathrm{meas\ Radiogenic}}$$

- Taking into account shapes increases the sensitivity significantly
- Bringing unknowns and uncertainties in a mathematically correct way into the inference through nuisance parameters
- Adopting HEP methods but adapting for DM needs: Low statistics, calibrations vs. “known” response

Cowan et. al. Eur.Phys.J. C71 (2011) 1554 (2011);
Priel et. al. JCAP 1705 (2017) no.05, 013