Status of DM Direct Detection

Ranny Budnik
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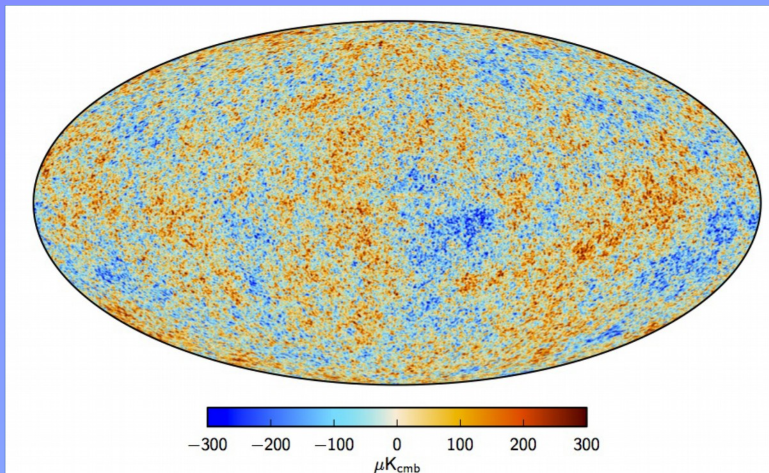
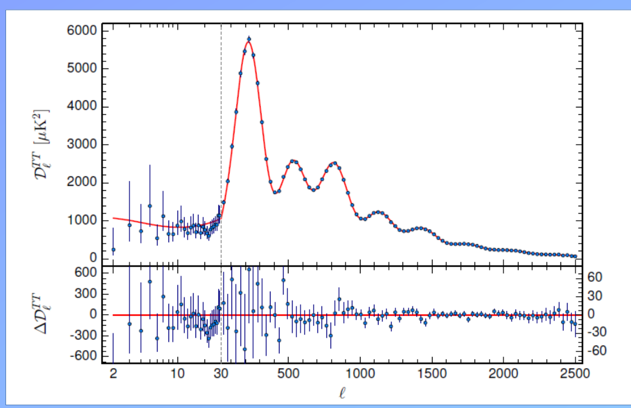
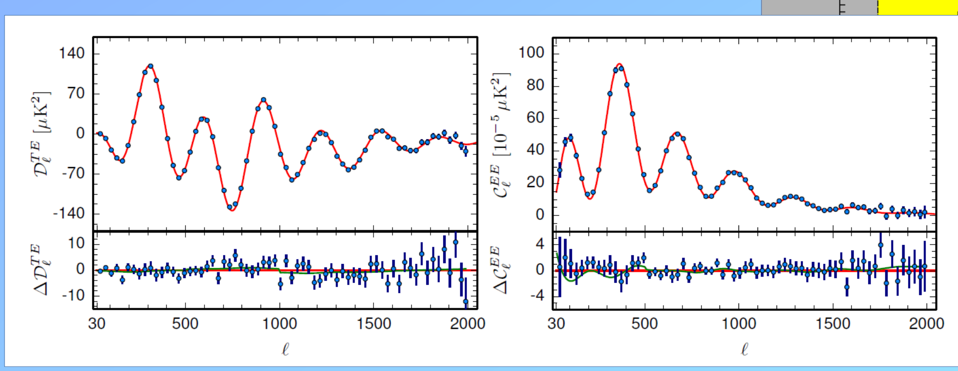
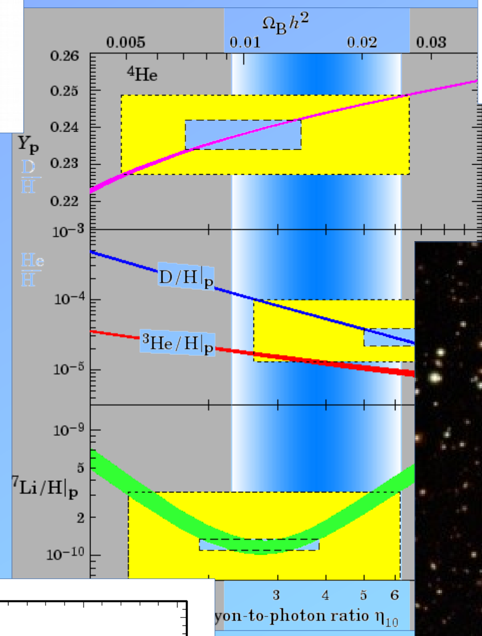
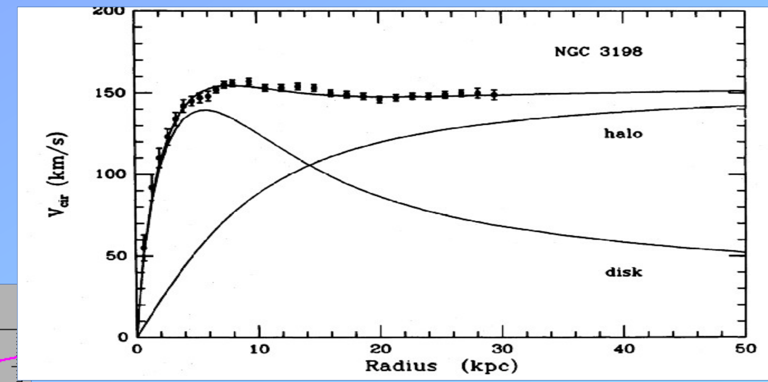
DM evidence on one slide











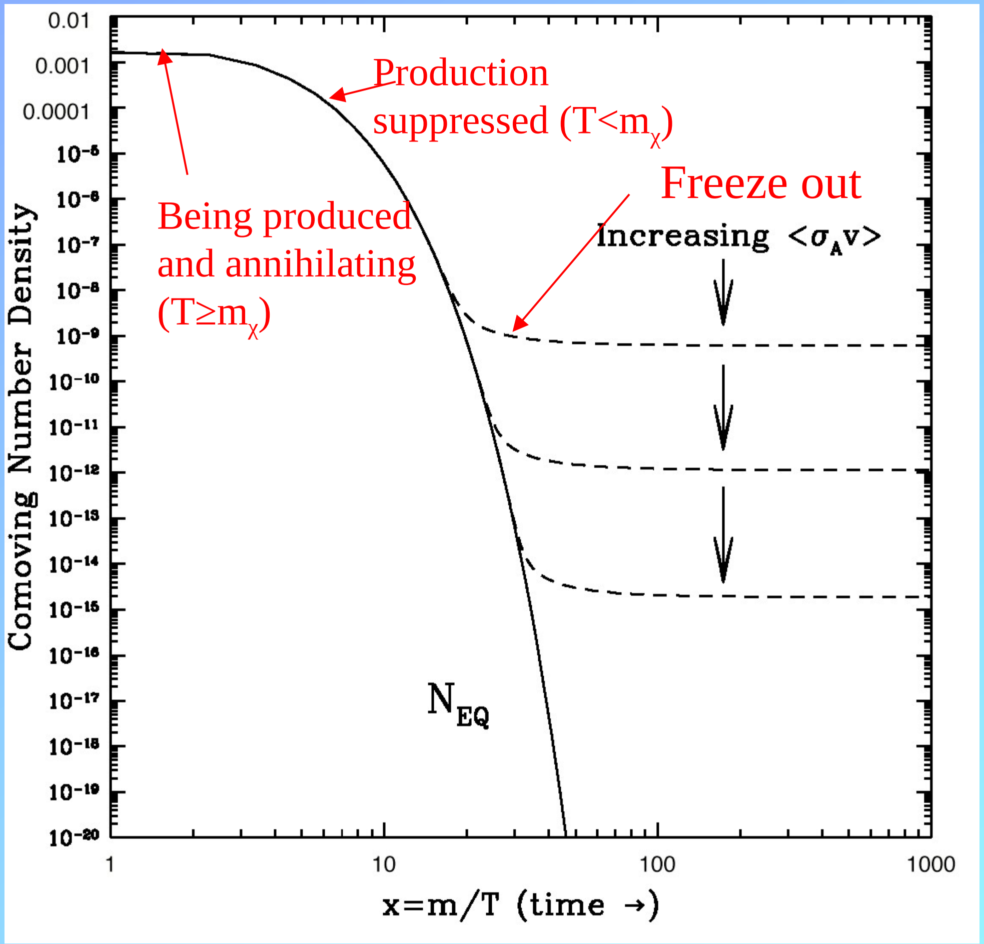
R. Budnik, LP2017

Thermal freeze out of dark matter in the standard cosmological model

- Weakly Interacting Massive Particles (WIMPs) were produced in Big Bang
- The equilibrium abundance is maintained by pair annihilation and vice versa
- Due to the expansion of the Universe, the rate of the annihilation goes down and freezes.

$$\Omega_\chi h^2 \propto <\sigma_A v>^{-1}$$
$$\sim \left(\frac{3\cdot 10^{-27}\mathrm{cm}^3\mathrm{s}}{<\sigma_A v>}\right)$$

e.g. Bertone, Hooper, Silk (2005)



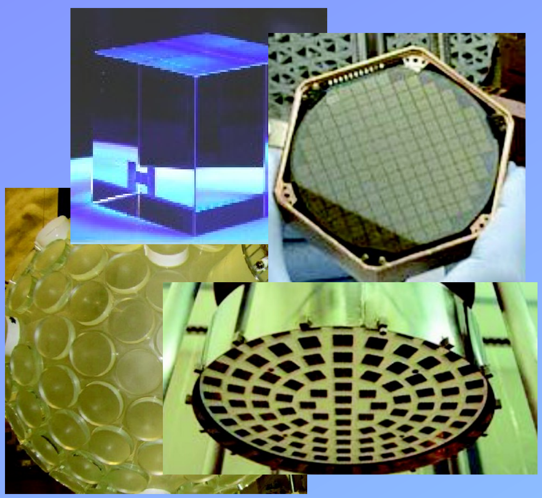
Timeline of Universe since big bang

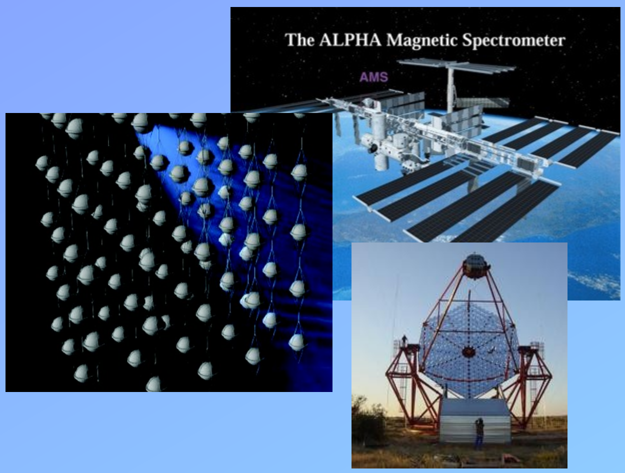
But there are other ways as well

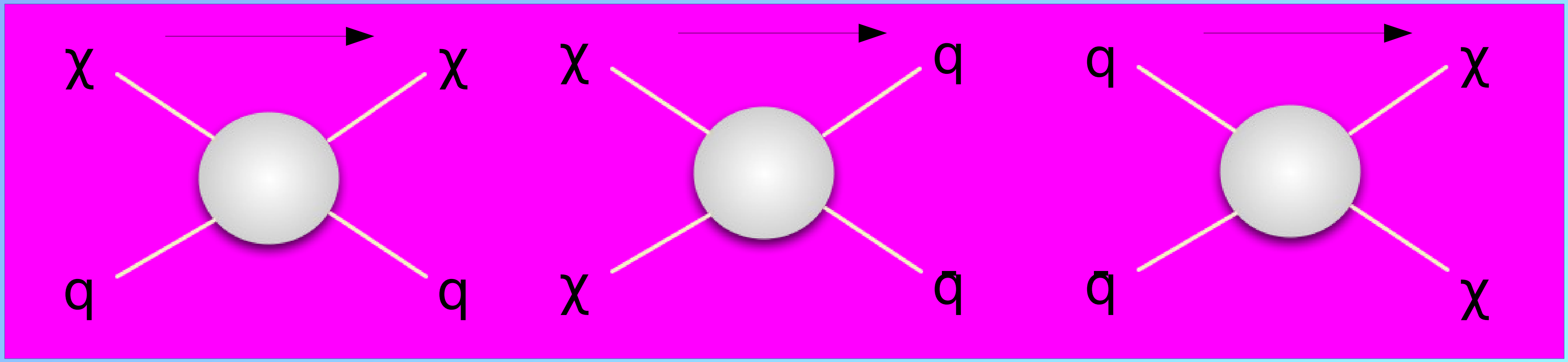
Fig.: Jungman, Kamionkowski & Griest, PR'96

A short reminder, how to look for WIMPs

Directly | **Indirectly** | **Accelerators**







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A complementary approach

Directly

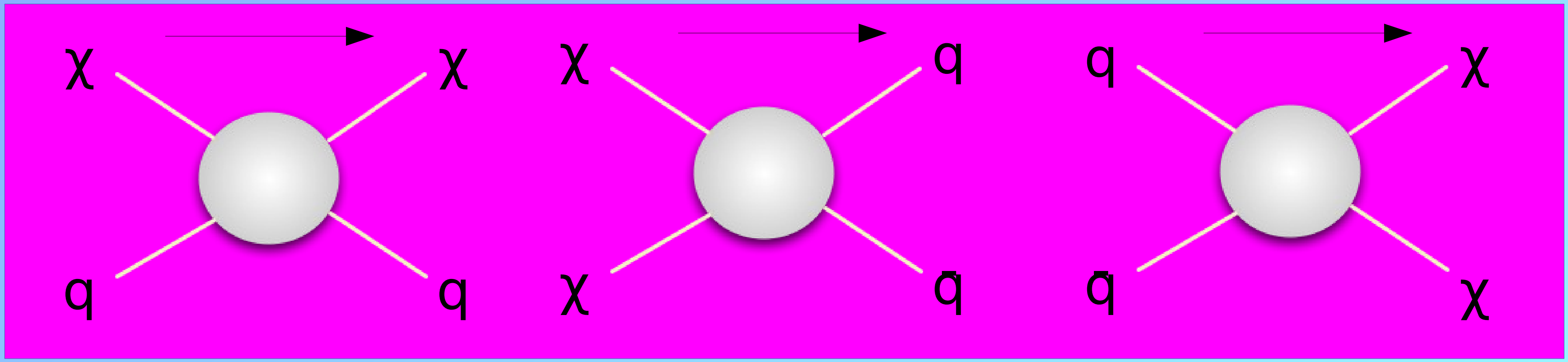
- Local DM distribution
- Backgrounds
- Limited mass range

Indirectly

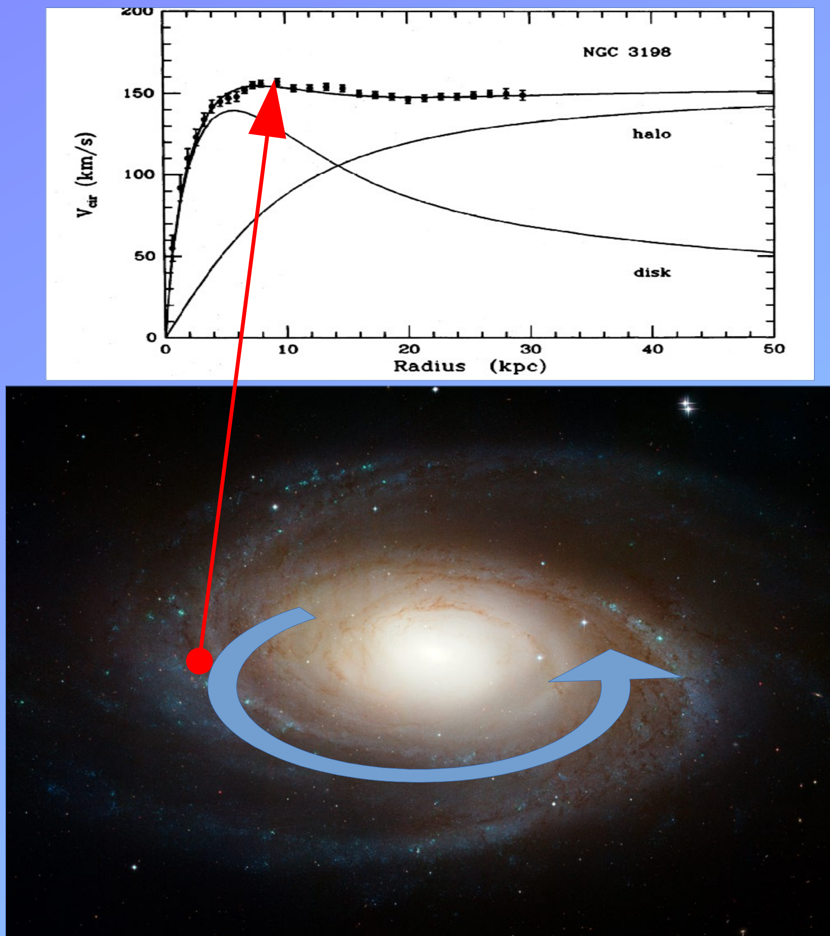
- Strong astrophysical uncertainties
- Distribution in centers of halos
- Product propagation

Accelerators

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



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)

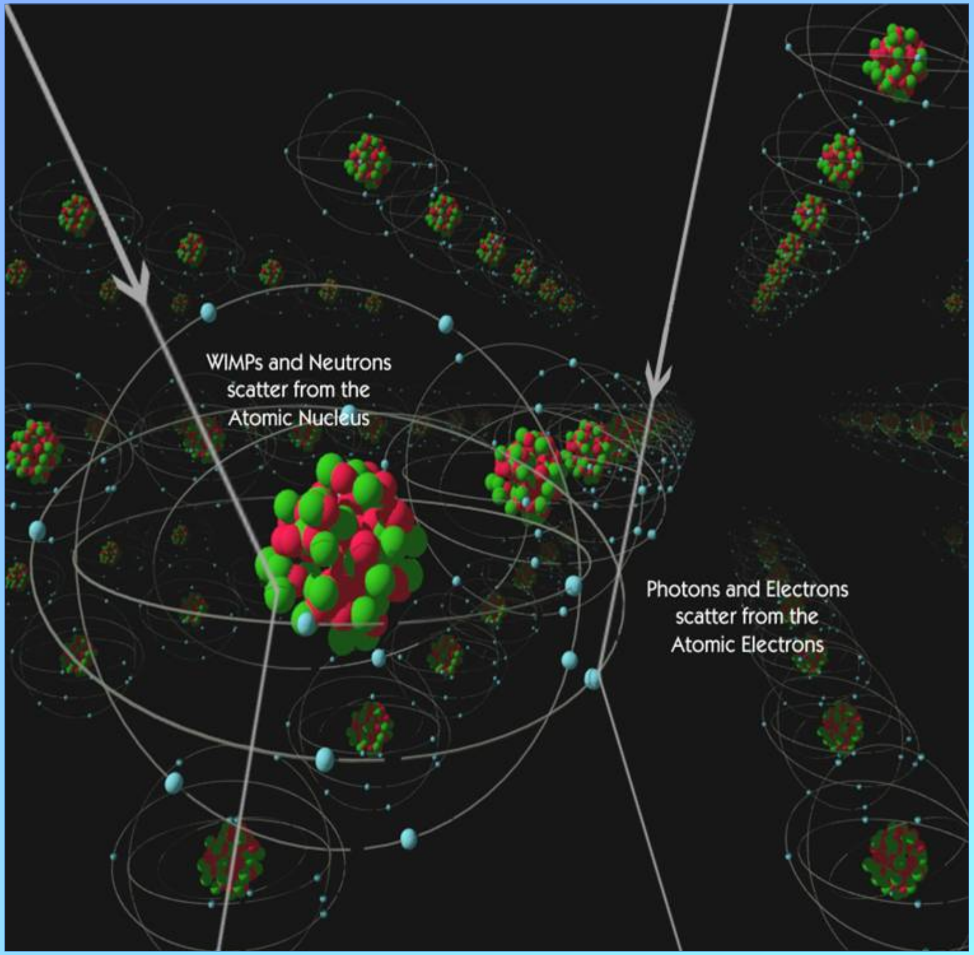
Principles of Direct Detection

- Movement with respect to the galactic frame imply 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.

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.

Dark Matter Direct Detection

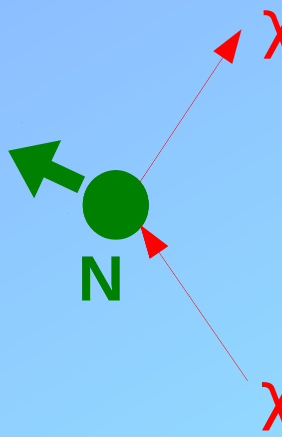
Goal: Observe WIMP interactions with some target material

Expected interaction rate

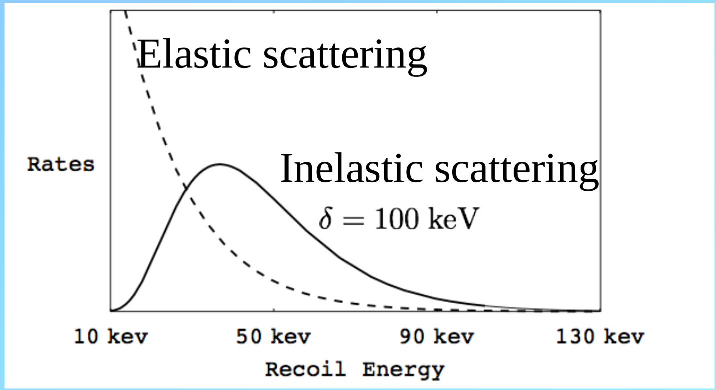
Number of targets — **WIMP density** — **Nuclear Form factor**

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

WIMP mass — **Interaction cross section** — **WIMP velocity distribution**



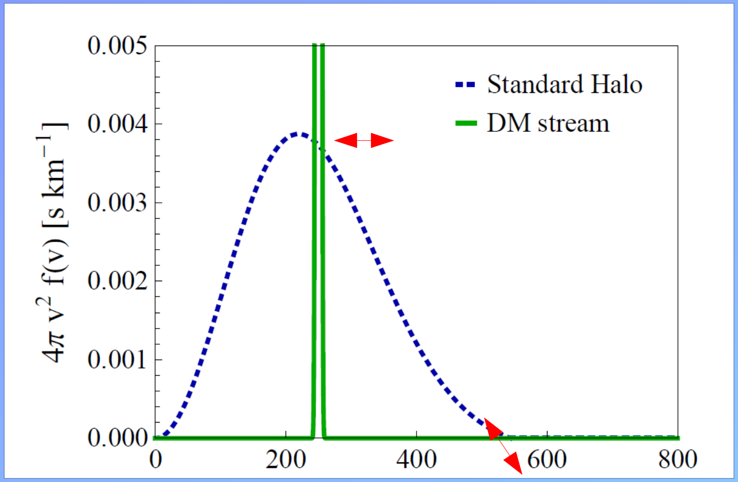
$$v_{min} = \sqrt{\frac{m_N E_{nr}}{2\,\mu^2}}$$

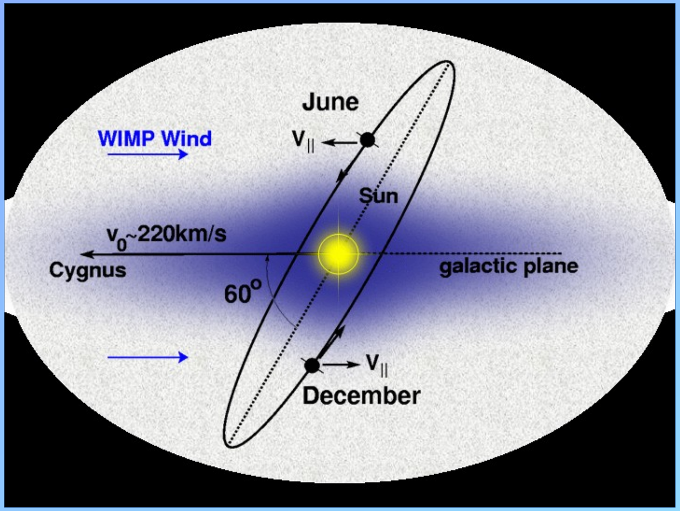


- Only those WIMPs with velocity above threshold will contribute to that energy
- For Spin Independent interactions the cross section is enhanced by a factor A^2 (coherent scattering)

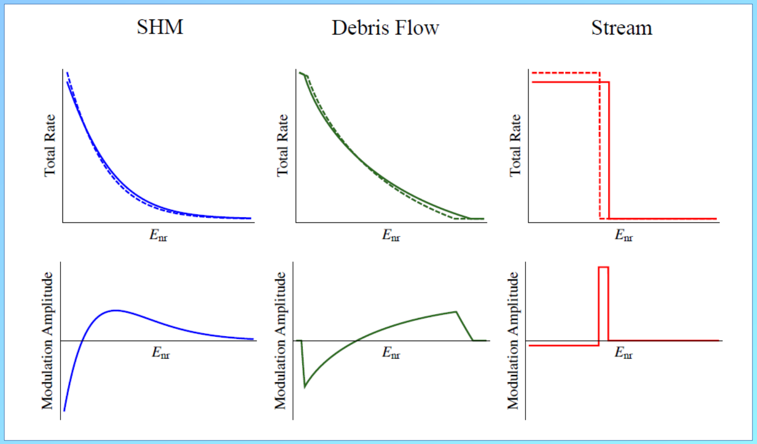
Dark matter and Earth dynamics: Annual modulation

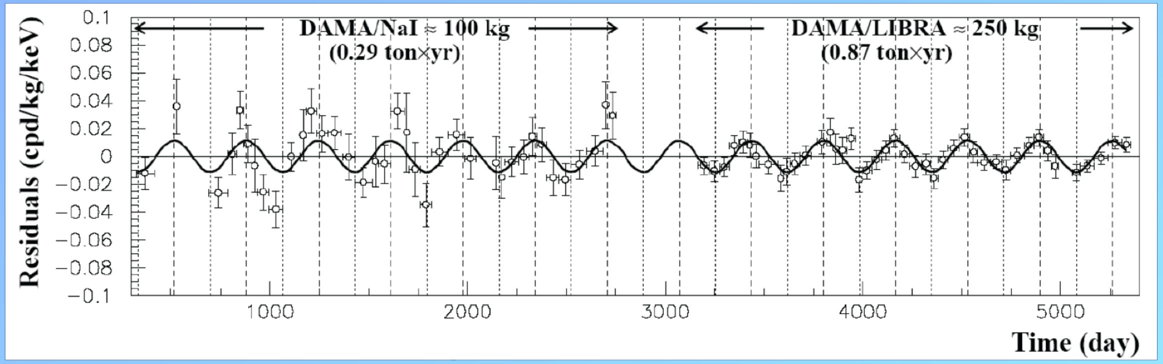
- In general, the higher v_{min}, the stronger the relative modulation, but...





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





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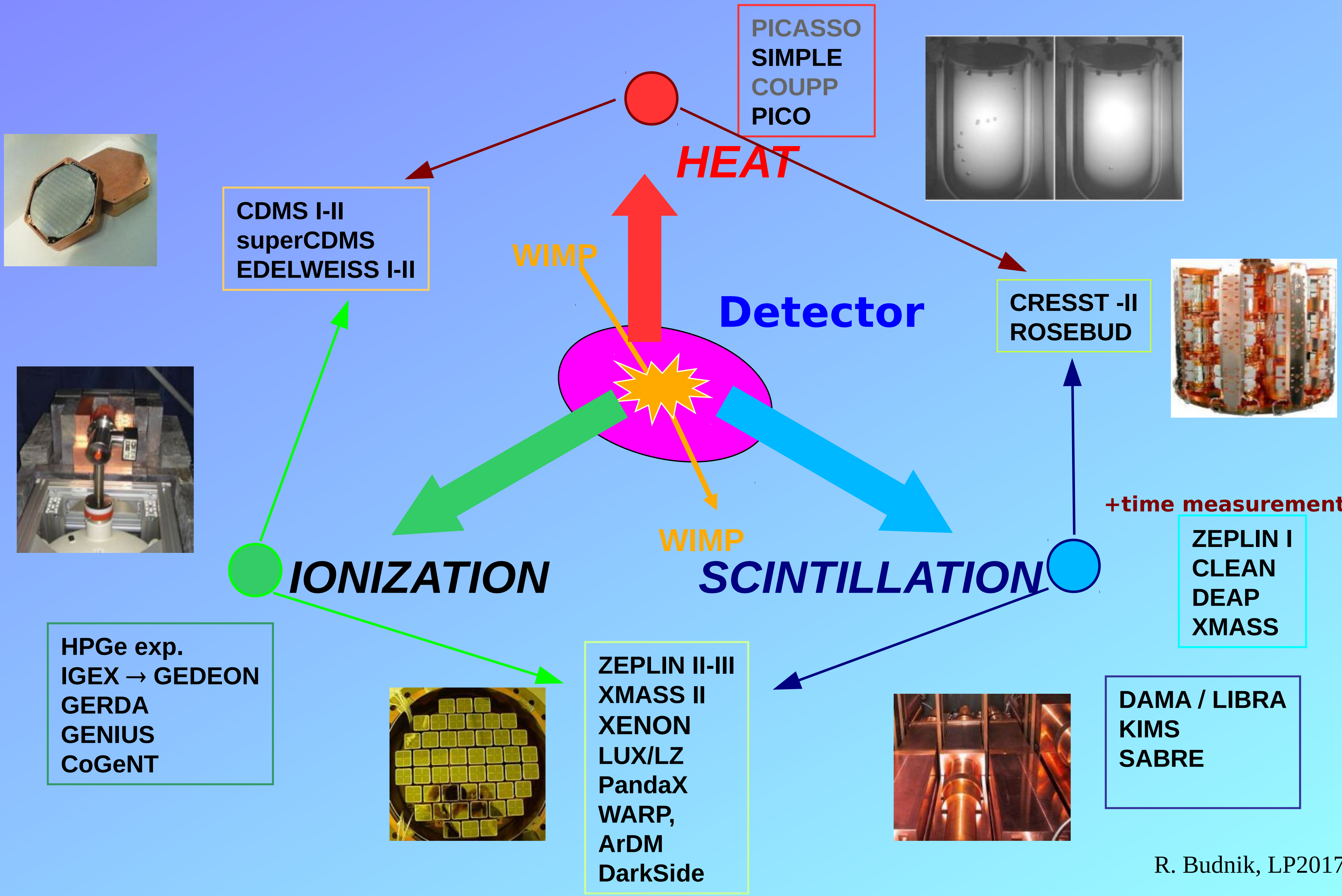
Direct Detection Techniques



R. Budnik, LP2017

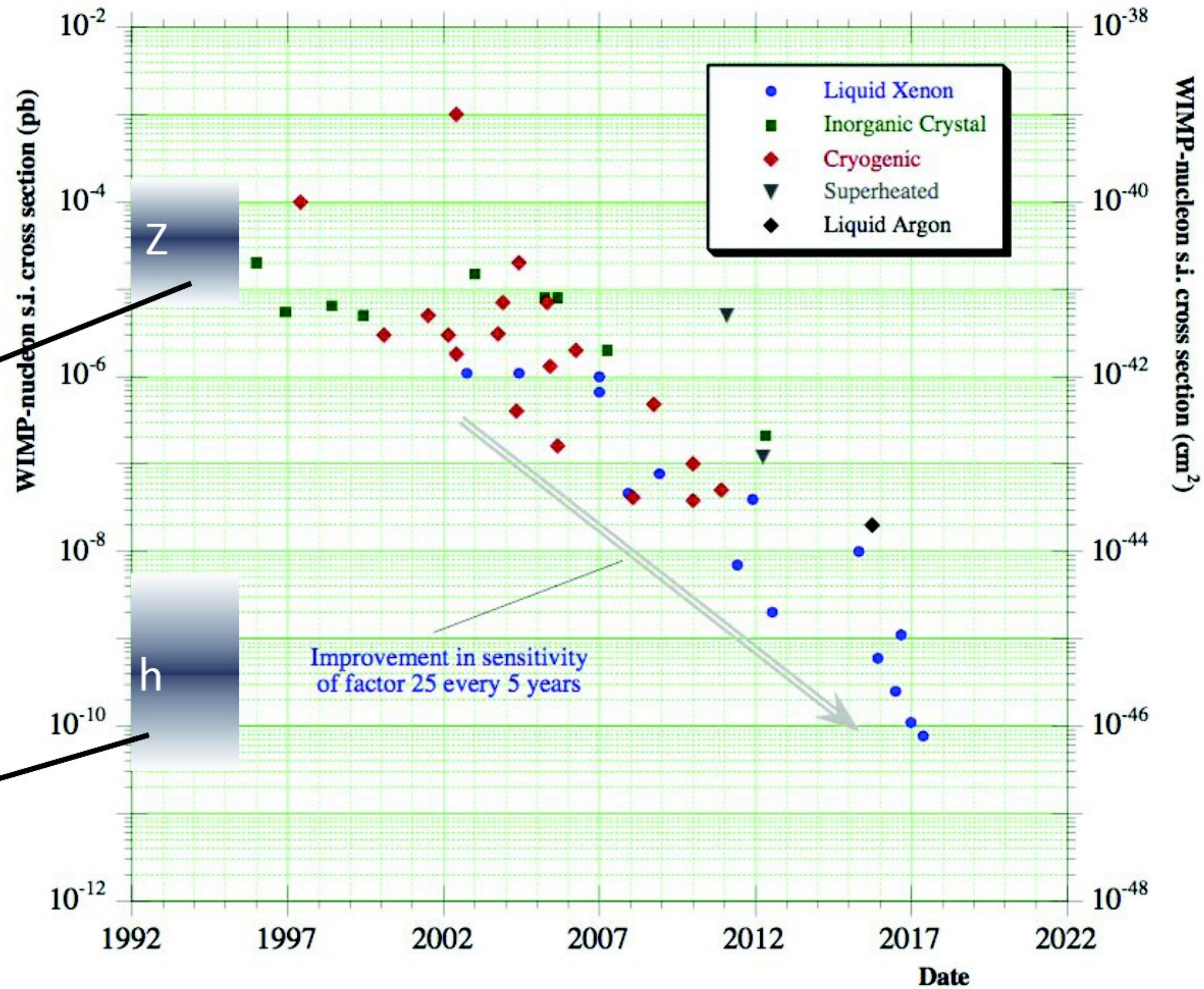
Underground facilities: A must

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: Don't know yet...
- Plus, each detector carries extra unique backgrounds (instrumental, unknown source)

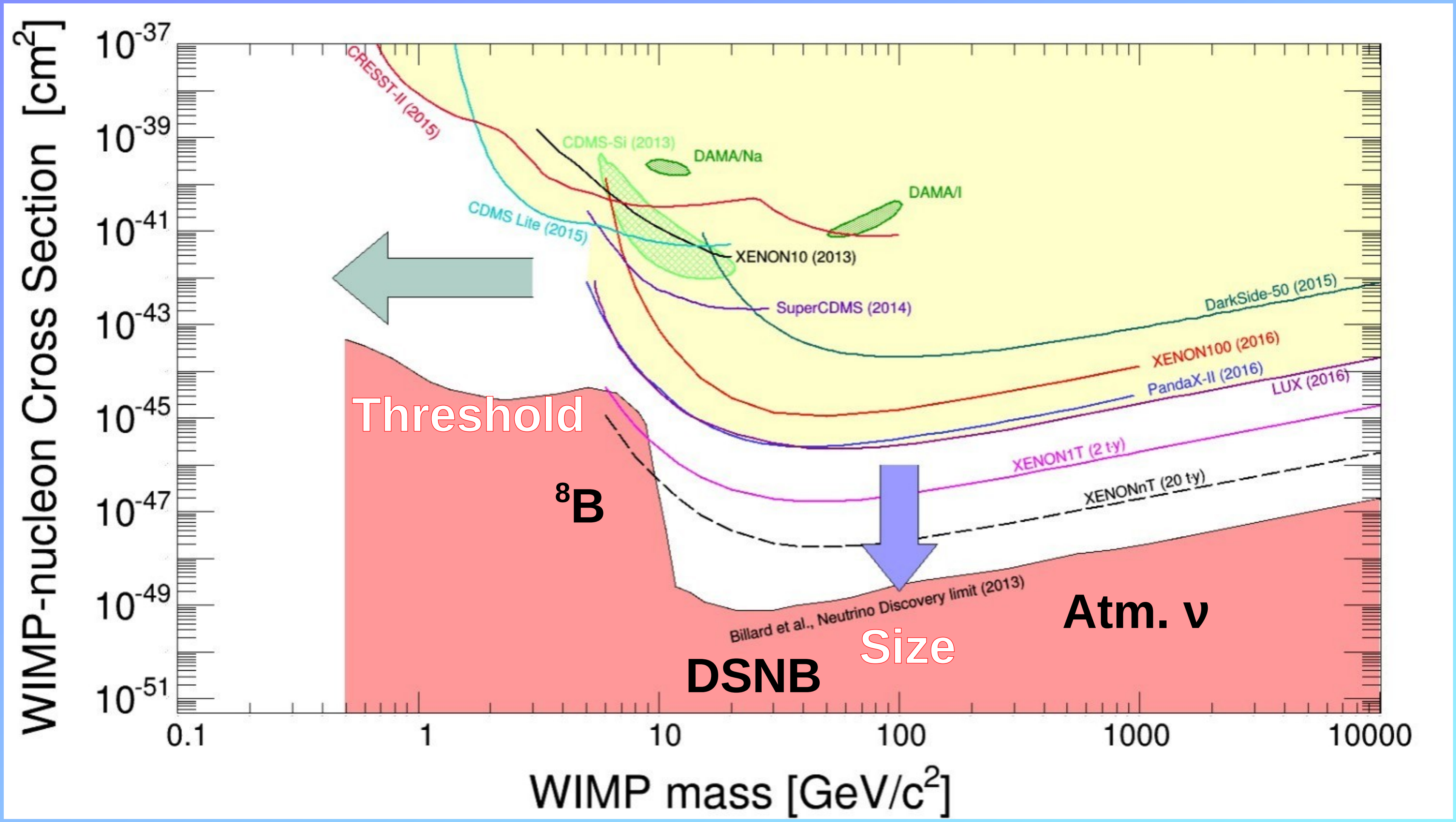
Fast progress over ~2 decades

- 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

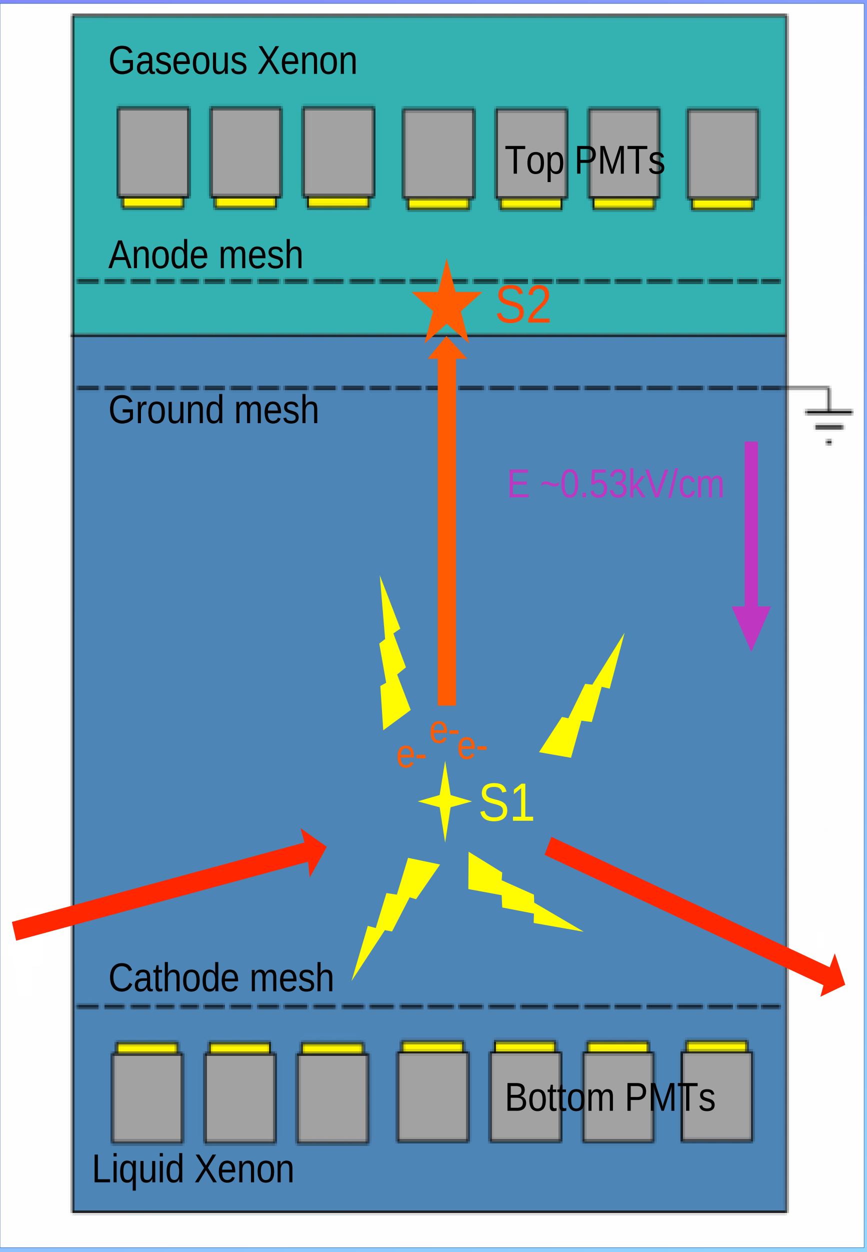
Let neutrinos set the stage!



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)

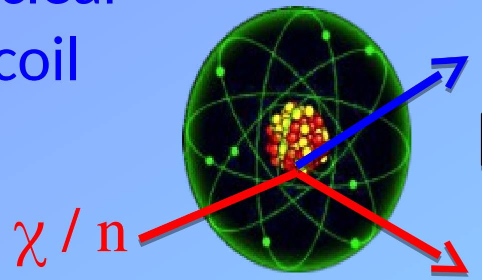
The leading tech: Dual Phase Xenon TPC

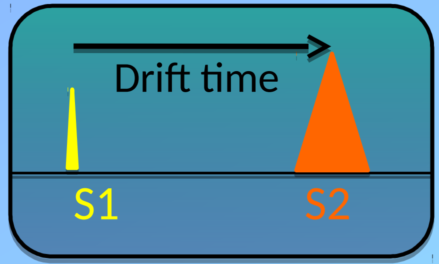


S1: Prompt scintillation

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

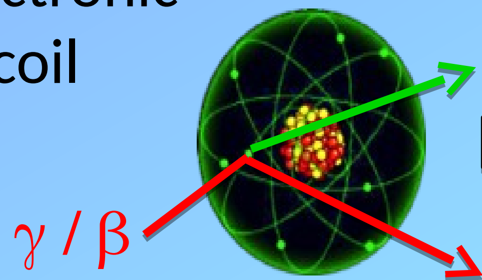
Nuclear Recoil

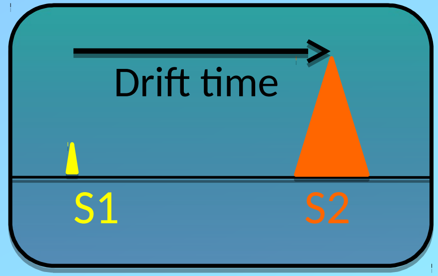




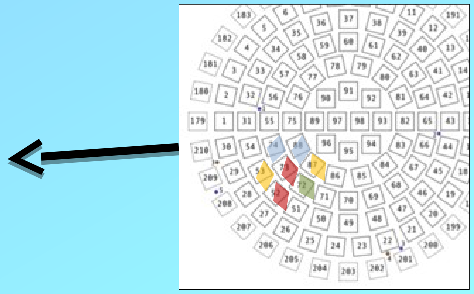
Discrimination by S2/S1

Electronic Recoil



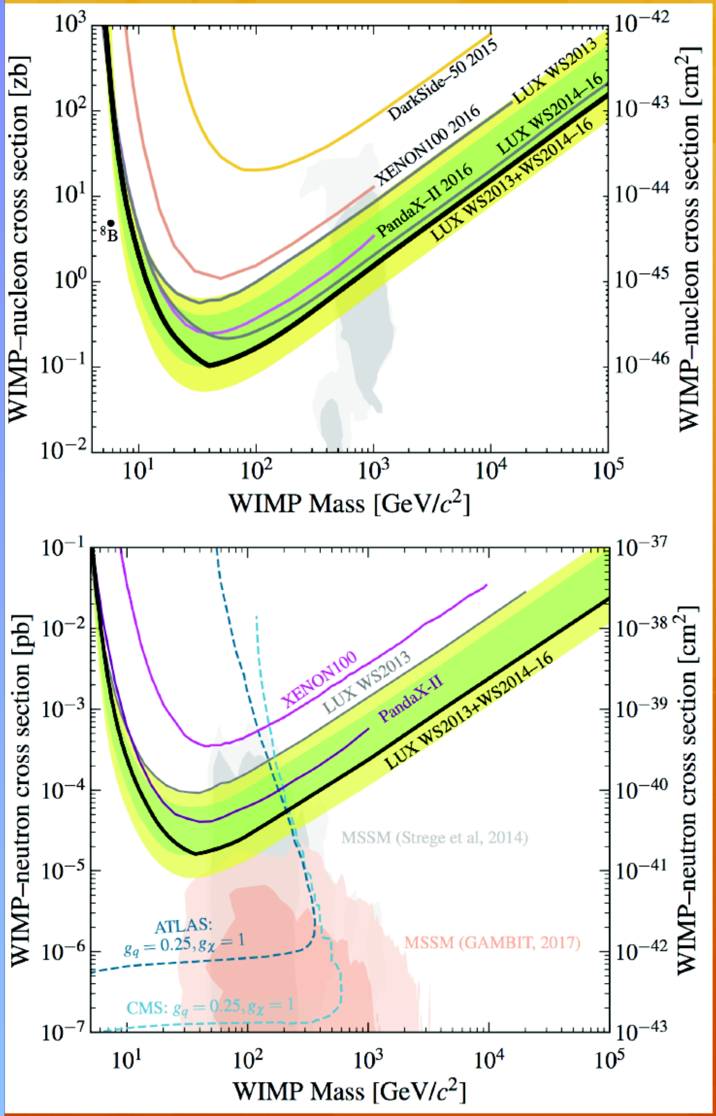


Interaction vertex reconstruction:
- Horizontal from top PMT array
- Vertical from drift time



LUX – Forerunner Summer 2016

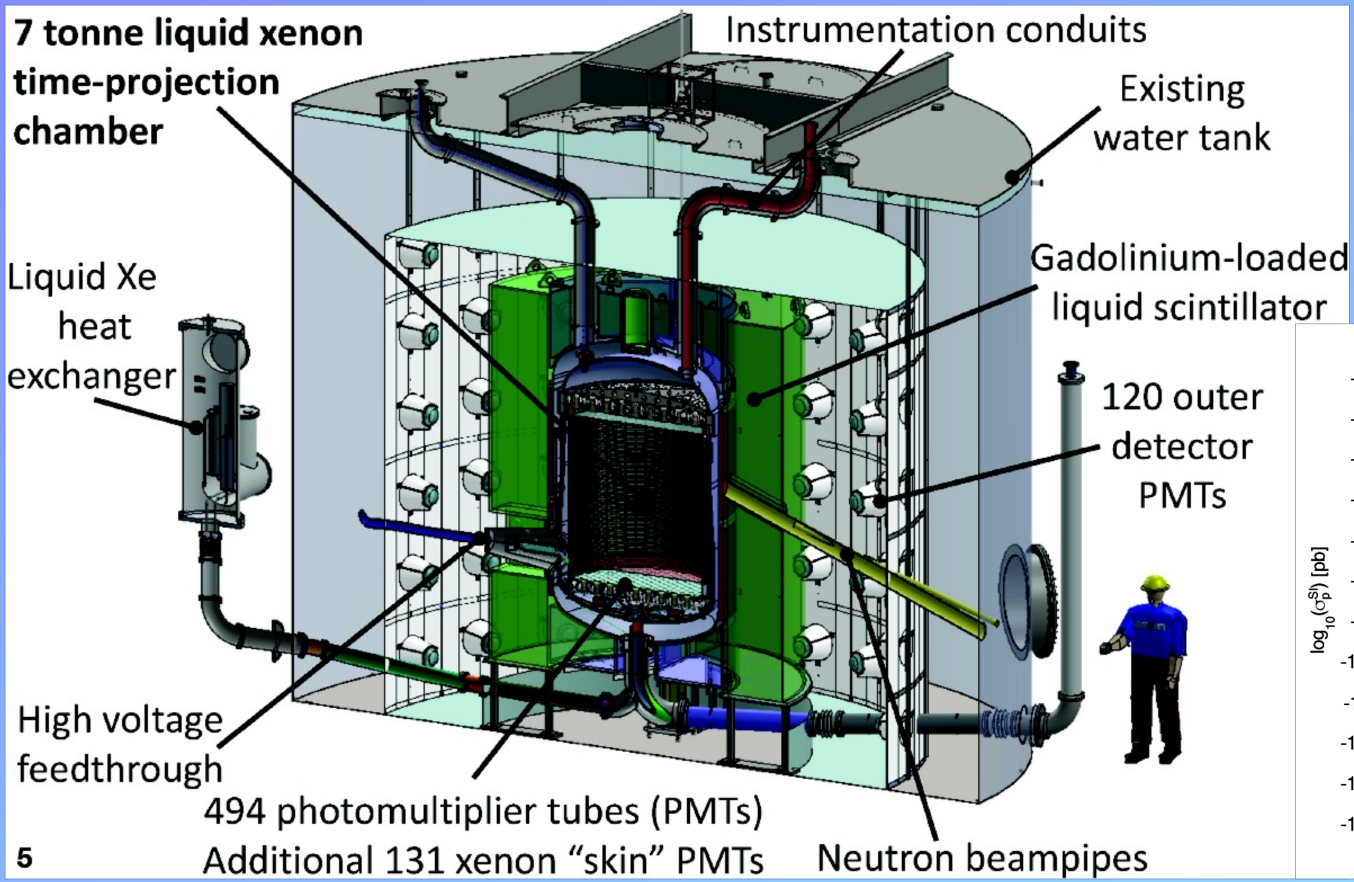
LUX Impact 2013/17

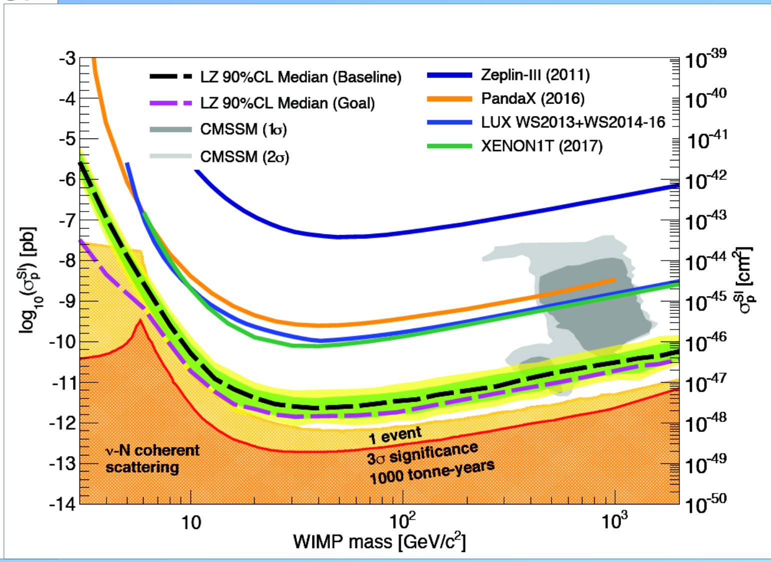


- LUX First Science Run in 2013
  Second Science Run 2014-2016
  Full exposure: 47.5 tonne.days
  (427 live-days)
- Improved Spin-Indep. WIMP Sensitivity by Factor 20x since state prior to 2013.
  Also Neutron Spin-Dep. Sensitivity.
- Axion/ALP Search
- Full self-consistent models for all backgrounds events and detector response
- In parallel: Major program improving LXe ER and NR calibration over wide energy range (including sub keV) with high statistics and low systematics.
  Allowed significant improvement in accuracy of Xe response models.
  Also clearly establishes sensitivity to 8B coh. scattering.
- LZ: Kim Palladino Tues 15:30
  LZ: Christine Ignarra, Tues 15:45
  LUX: Rick Gaitskell Wed 14:00

From Gaitskell, TAUP

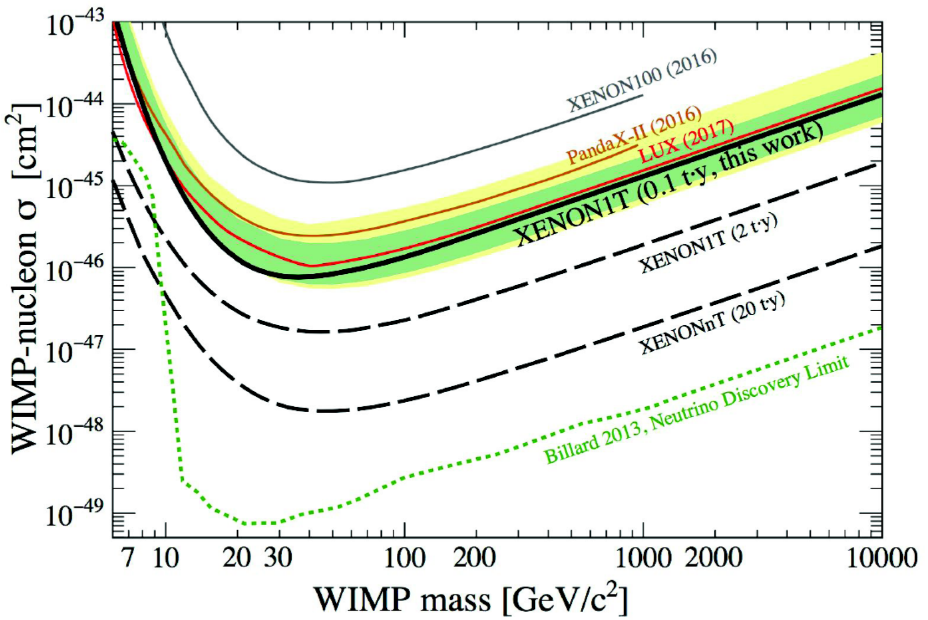
LZ- LUX+Zeplin





- To start 2020 @SURF
- Use of n-veto, 7-ton TPC, 5 year run

XENON1T/nT

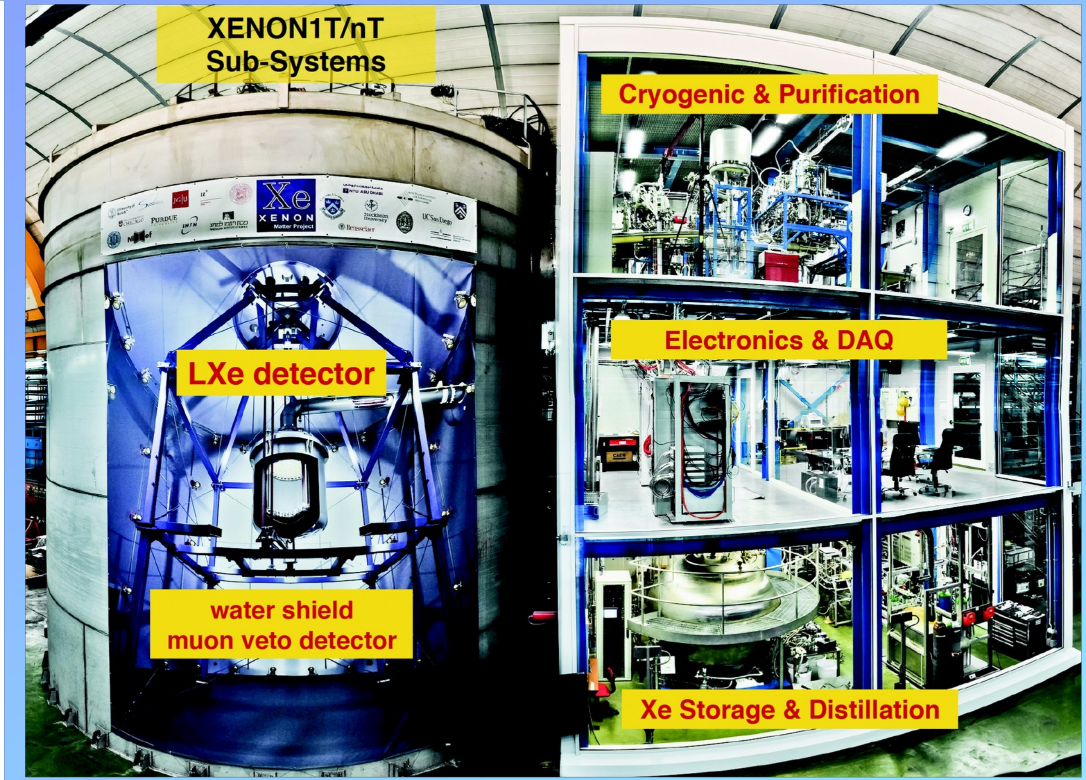


First science run: 34.2 live-days

- Largest ever Xe fiducial mass: 1042 kg
- Lowest ever low-E ER bg.: (0.193 ± 0.025) mDRU
- Most stringent SI-WIMP limit

Still running, >100 live-days taken

XENONnT upgrade planned for 2019



- Swift upgrade to XENONnT within 18 months, equivalent to LZ

Arxiv:1705:06655

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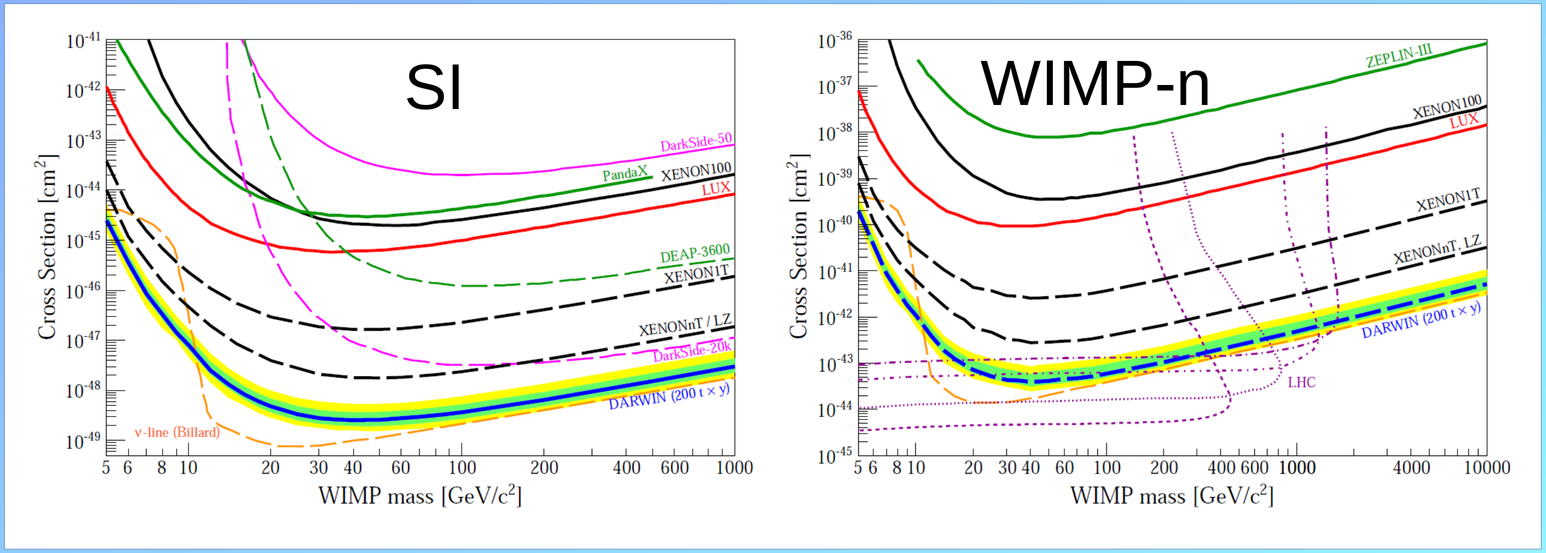
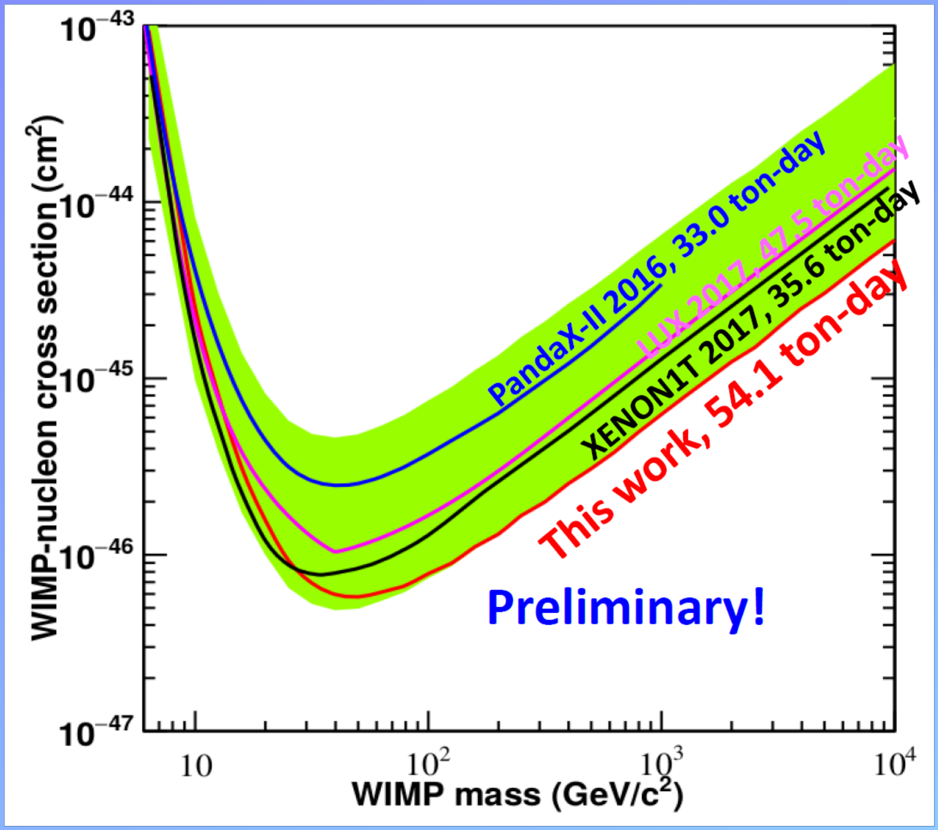
DARWIN – The ultimate LXe exp?

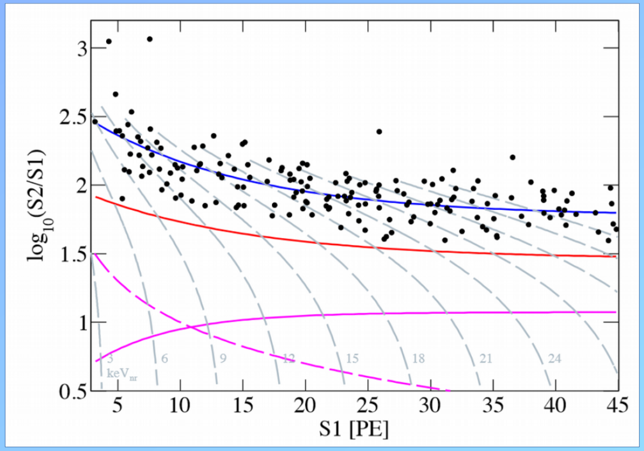
- Can we reach the ν floor?
  - Would require O(50t) Xe
  - **Backgrounds** at unprecedented levels
  - Technology stretching to the end: HV, purity, calibration, stability…
  - Probably means cooperation between long-time competitors



1606:07001

PandaX-II – hot from the oven – 3 days ago





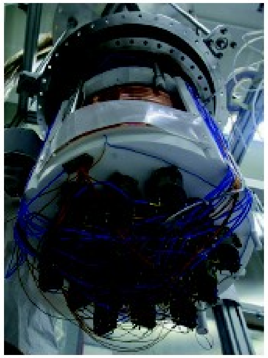
- Combining all runs, 54 ton-day
- Reduced Kr background, plus under-fluctuation
- Future plans for PandaX-4t and PabdaX-III (2ν0β)

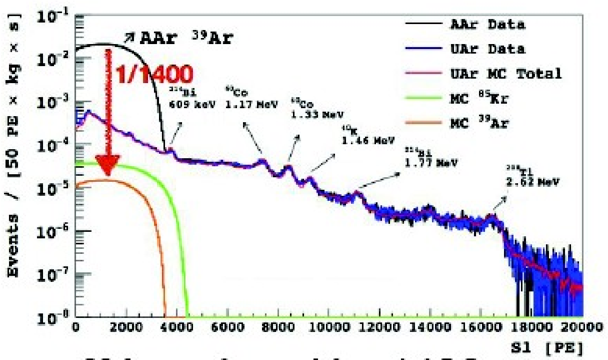
DarkSide50 and 20k

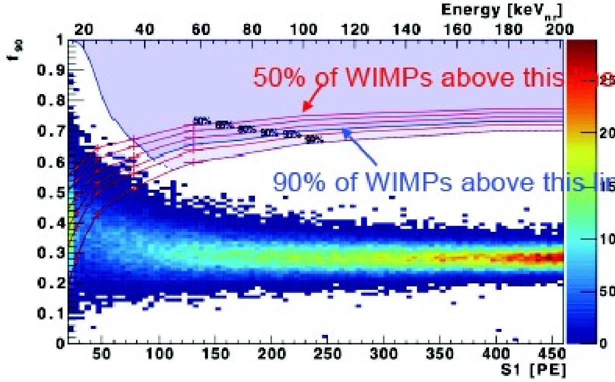
- High light yield: LAr Pulse Shape Discrimination $>10^7$
- Underground Argon: low ^{39}Ar
- TPC 3D event reconstruction
- High-efficiency neutron vetoing

DarkSide-50

150/50/30 kg
total/active/fiducial
Sensitivity<10^{-44} cm^2
Data: 2013-present







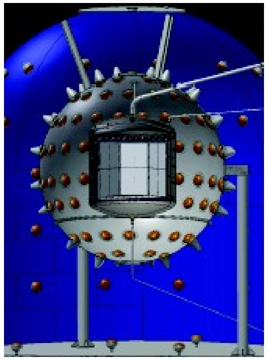
^{39}Ar reduced by 1400

70-d of Underground Ar

Blind analysis of 500-d underway

DarkSide-20k

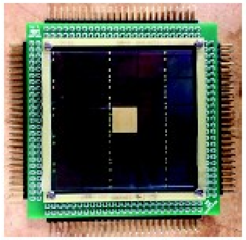
30/23/20 T
tot/act/fiducial
Sensitivity<10^{-47} cm^2
Data: ~2021



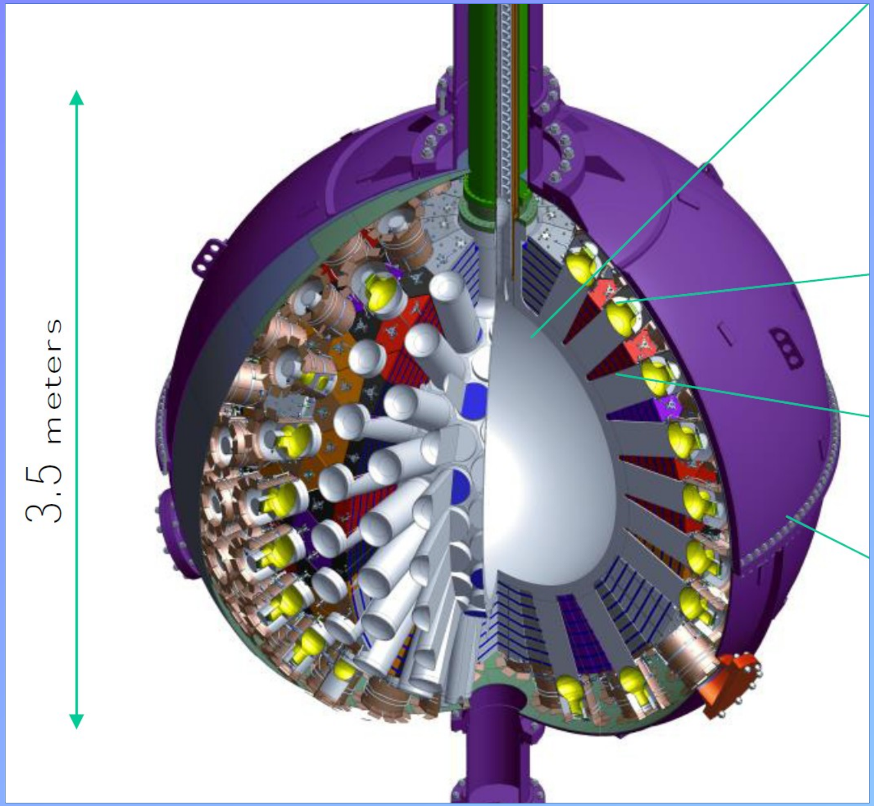
New Argon Collaboration
DarkSide
DEAP
MiniCLEAN
ArDM
} DS-20k⟶ Multi-100 ton

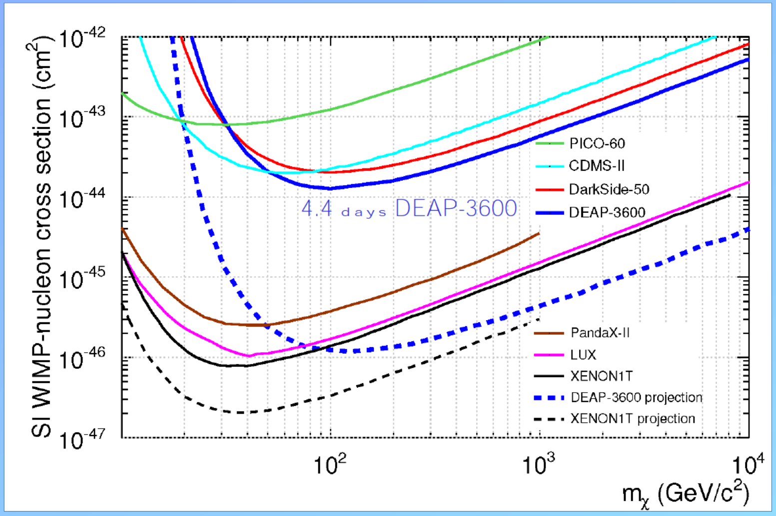
← Massive effort to extract and purify UAr

SiPMs replace → PMTs



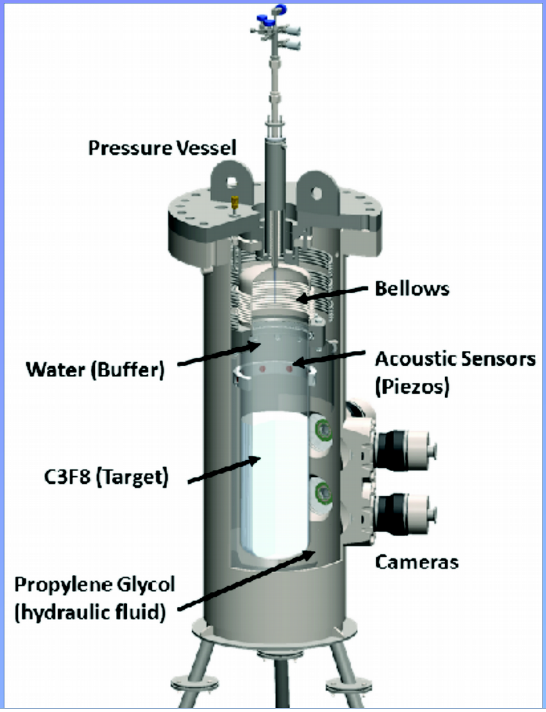
Single phase - DEAP3600



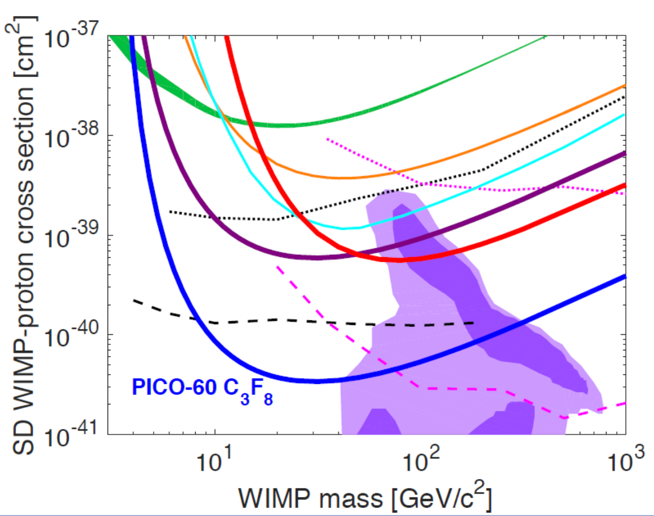


- 3.6t of LAr
- Low radioactivity underground Ar
- Great discrimination, LY, purity
- Has great potential at high masses
- Future prospects for >100t global experiment (with DS, ArDM, CLEAN)

PICO – Bubble chambers back in the biz



WIMP - Proton Exclusion

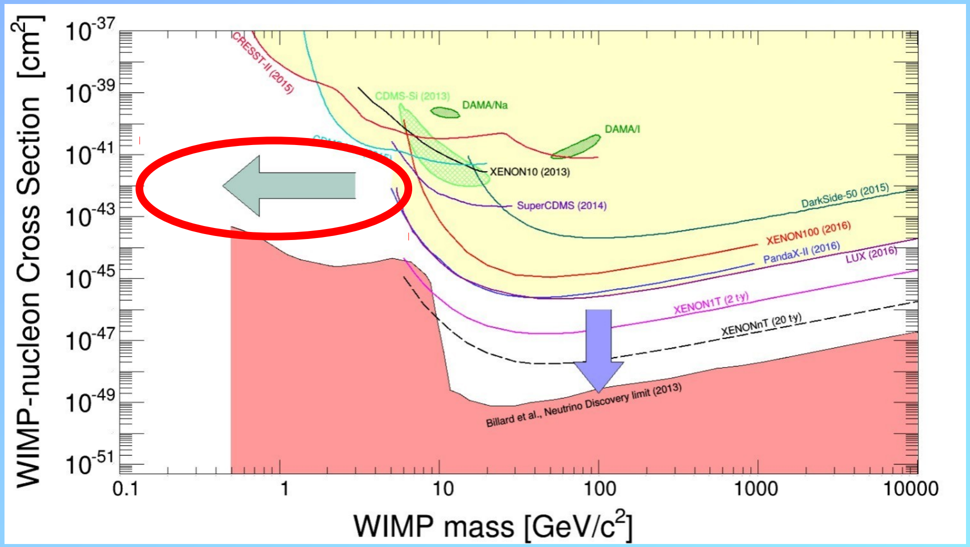


The 90% C.L. limit on the SD WIMP-proton cross section from PICO-60 C_3F_8 blue, along with limits from PICO-60 CF3I (red), PICO-2L (purple), PICASSO (green), SIMPLE (orange), PandaX-II (cyan), IceCube (dashed and dotted pink), and Super-K (dashed and dotted black)

- Using bubble nucleation plus acoustic (to reject α's)
- PICO60 best in proton cross section
- PICO500 to begin construction 2018
- Fight with n-background, water background

The “Low Mass Frontier”

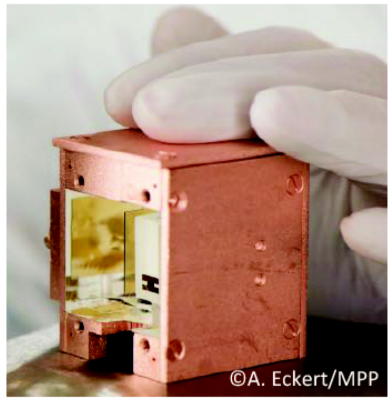
- Name of the game – Lower threshold, control backgrounds
- Main competitors: Crystals with all channels
- Ongoing R&D efforts for low noise, low T, low background, low threshold

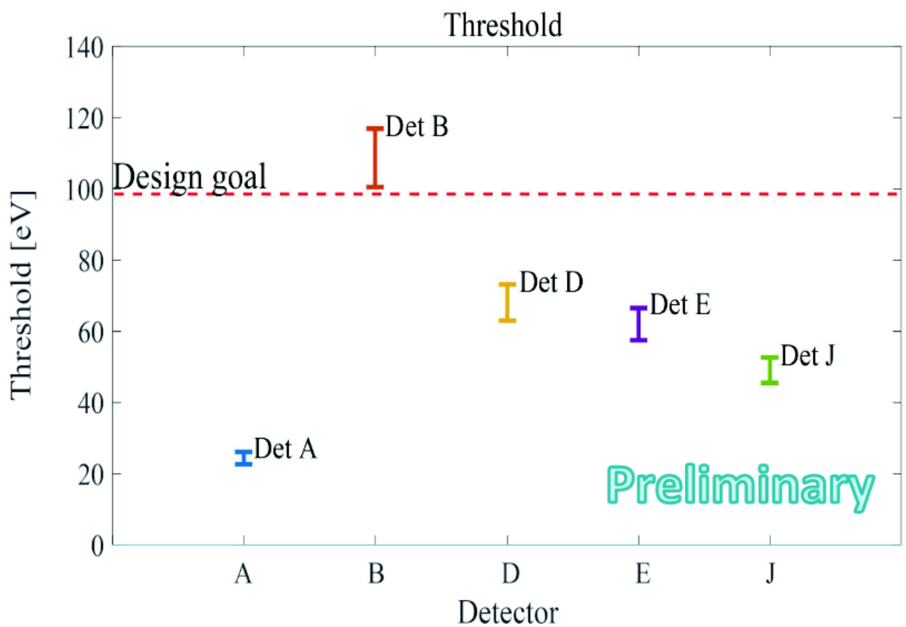


CRESST-III: Lowest achieved threshold

Detectors optimized for low mass dark matter

- Absorber volume reduced by a factor ~10 (≈24g)
- 100 eV threshold goal
- Veto surface related background

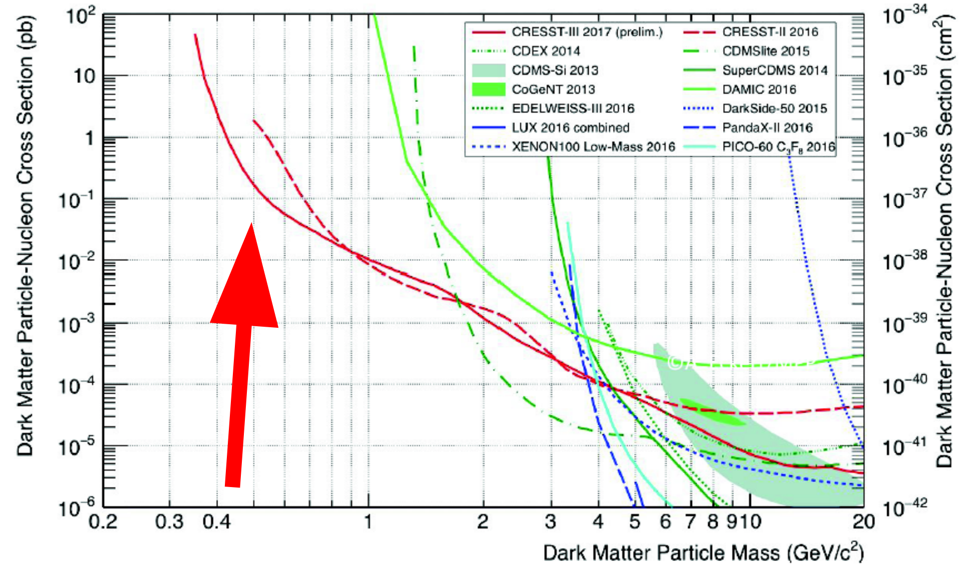




5 detectors reach/exceed threshold design goal

Analysis of one detector

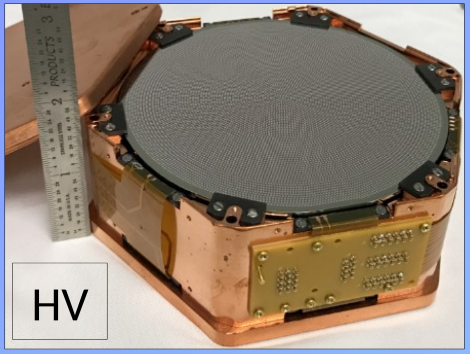
- Analysis threshold 100eV
- Net exposure 2.21 kg days

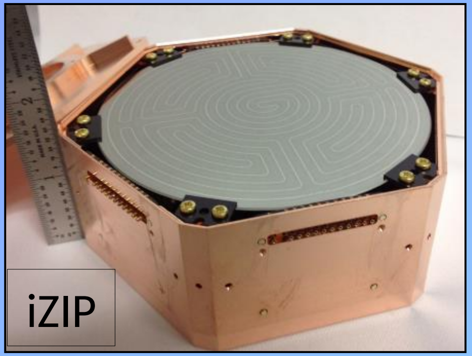


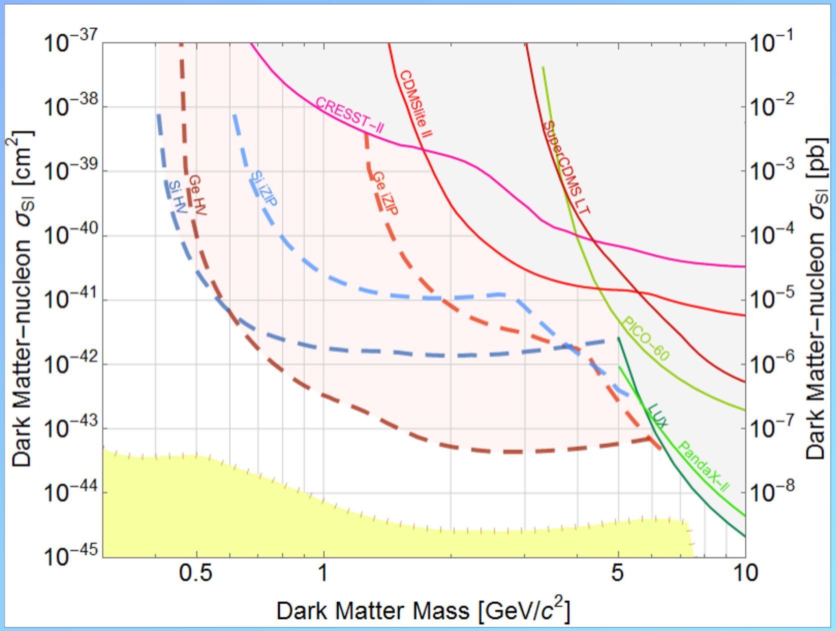
- One order of magnitude improvement at 0.5 GeV/c^2
- Reach of direct dark matter experiments extended to 0.35 GeV/c^2

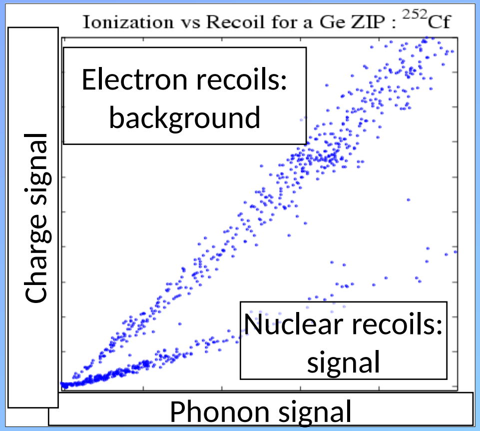
SuperCDMS

- Ge and Si crystals at 10s of mK – using TES for phonons, plus ionization
- The old-time leader, re-invented to lead in the low mass range
- Will start data taking 2020 @SNOLAB









HV may come at the expense of backgrounds and discrimination

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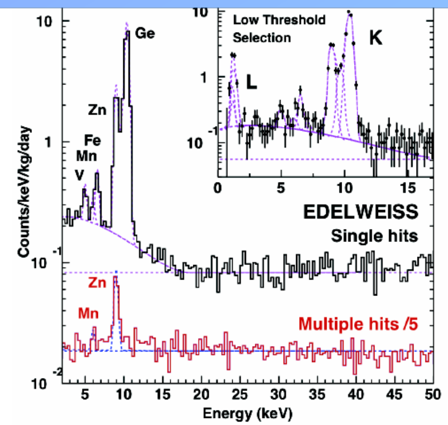
EDELWEISS-III

EDELWEISS-III

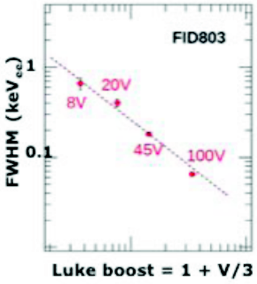
- Robust design, good reproducibility of performances *[arXiv:1706.01070]*
- Detailed description of backgrounds; first measurement of cosmogenic ^{3}H in Ge *[AstroPart. 91 (2017) 51]*
- Improved ionization resolution & thresholds lead to x40 improvement of WIMP sensitivity at ~5-10 GeV wrt EDELWEISS-II. *[JCAP05 (2016) 019] [EPJC 76 (2016) 548]*

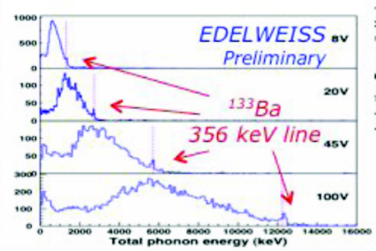


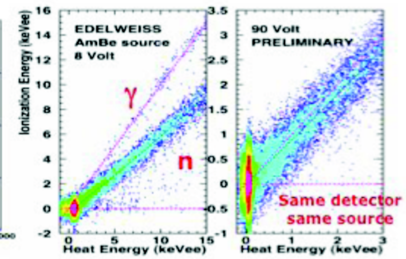
Prospects: *[arXiv:1707.04309]*

→ in the GeV-WIMP range: EDELWEISS-LT

- Improve thresholds x10 using boost 8 to 100V (achieved)
- 10^{-41} cm^{2} achievable at LSM with 4 detectors with present levels of backgrounds

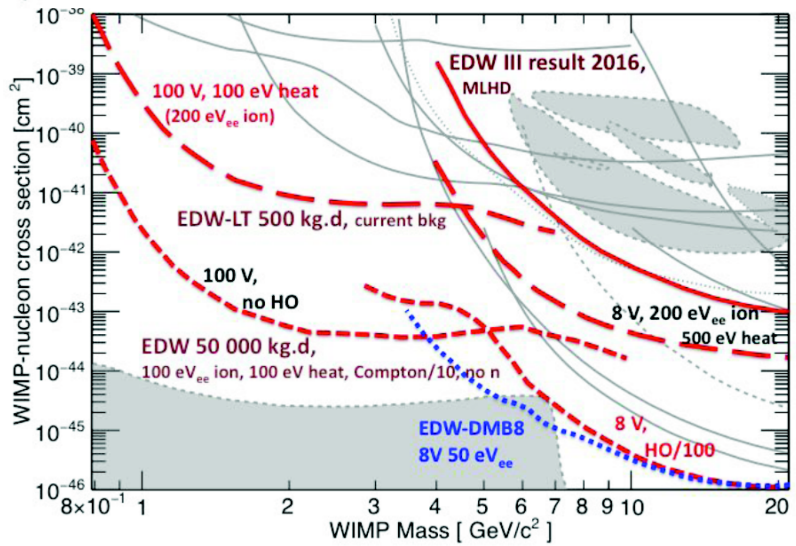




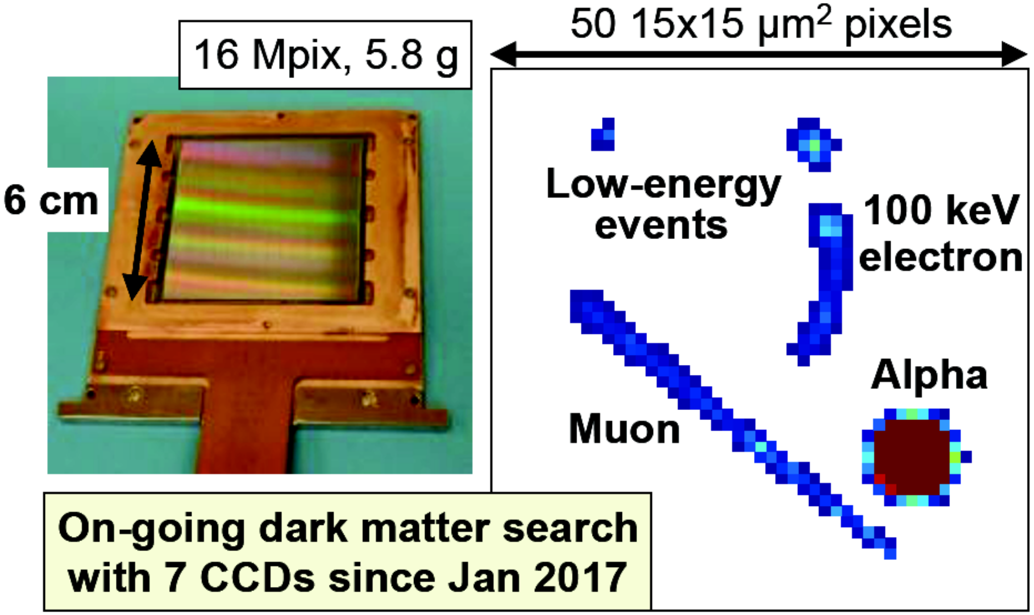


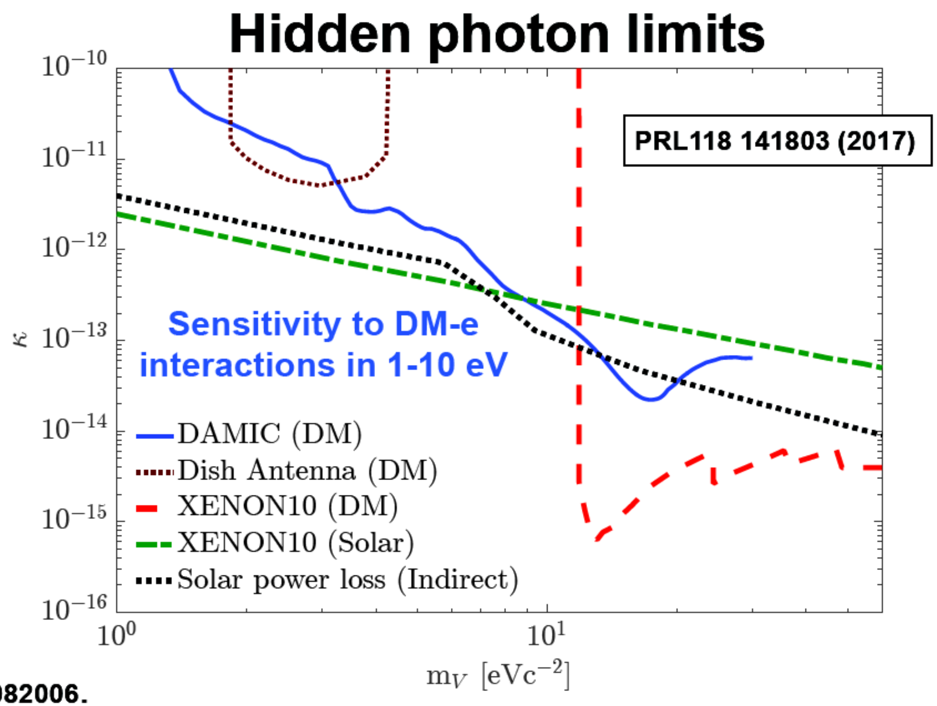
→ in the ^{8}B region: EDELWEISS-DMB8

- 50 eV ionization resolution to obtain pure nuclear recoil sample + 10% resolution on recoil energy: clear spectral identification of ^{8}B ν
- Use HEMT preamplifier + reduce electrode capacitance (reduction by a factor of 2 of number of electrodes achieved)
- ~200 kg FIDs at SNOLAB to complement nicely the SuperCDMS-SNOLAB reach

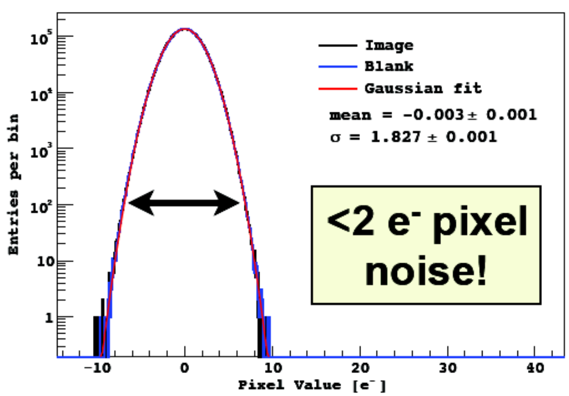


DAMIC – e^- recoil



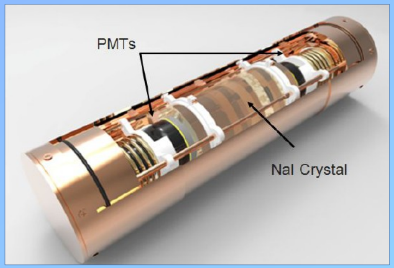


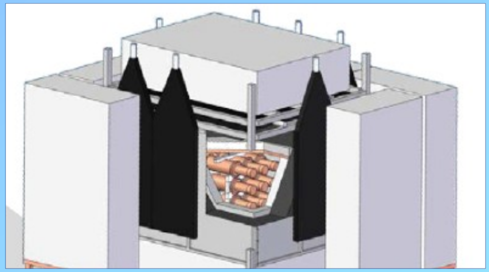
- Low-mass WIMP limits with 0.6 kg d exposure **PRD94 082006.**
- Nuclear / electron recoil response characterized down to 60 eV_{ee} threshold **PRD94 082007, JINST12 P06014, arXiv:1706.06053.**
- High-spatial resolution for powerful background rejection **JINST 10 P08014.**
- Lowest leakage current ever achieved in a silicon device **PRL118 141803.**
- Demonstrated single e^- detection with "skipper" technology for next generation **arXiv:1706.00028.**



Can someone finally solve the DAMA/LIBRA conundrum?

- Can we resolve a two decade old puzzle of disagreement with so many experiments?
  - SABRE
  - ANAIS
  - DM-ICE
  - PICOLON
  - COSINE-100
  - COSINUS





- Efforts should yield an answer is a few years...

And more,

- Off the mainstream:
  - SD, EFT, axions, inelastic, e- scattering...
  - Annual modulation
- Crazy technologies for future detectors
  - Ptolemy, Sensei
- Experiments skipped today, but not forgotten – XMASS, KIMS, CDEX, CUORE...
- How to battle the backgrounds? New ideas are required!

Conclusions

- The direct detection field keeps growing in sensitivity is both major directions: **size** and **threshold**
- Competitiveness is **very high**, backgrounds are low but should be **lower**!
- Search for crazier technologies ongoing
- **Many windows still closed**, and the “neutrino floor” is coming for us! What is the step beyond?
  - How about directionality?