Present and future of direct dark matter searches

S. Moriyama, ICRR, University of Tokyo

Physics in LHC and the Early Universe

@University of Tokyo, January 9-11, 2017

Birth of the WIMP detection exp.

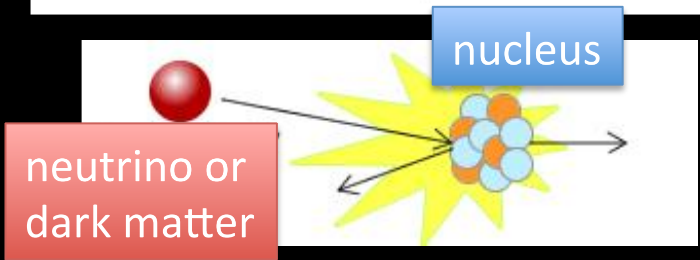
PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
...ry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

890 citations

...sider the possibility that the neutral-current neutrino detector recently proposed by ...ier 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.



- Expect nuclear recoils by DM.
- Leading candidate: SUSY WIMPs

Experimental source	Event rate in $kg^{-1}\,day^{-1}$	Recoil energy range
Spallation source	10^2—10^3	10—100 keV
Reactor	10	50—500 eV
Solar neutrinos		
pp cycle	10^{-3}—10^{-2}	1—10 eV
^{7}Be	10^{-2}—5×10^{-2}	5—50 eV
^{8}B	10^{-3}—10^{-2}	100 eV—3 keV
Galactic halo		
coherent $m\sim2$ GeV	50—1000	10—100 eV
$m\gtrsim100$ GeV	up to 10^4	10—100 keV

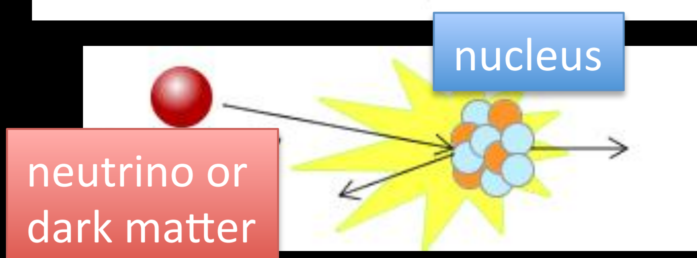
Birth of the WIMP detection exp.

The first experimental result

Volume 195, number 4 PHYSICS LETTERS B 17 September 1987

LIMITS ON COLD DARK MATTER CANDIDATES FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

S.P. AHLEN [a], F.T. AVIGNONE III [b], R.L. BRODZINSKI [c], A.K. DRUKIER [d,e], G. GELMINI [f,g,1] and D.N. SPERGEL [d,h]



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Galactic halo		
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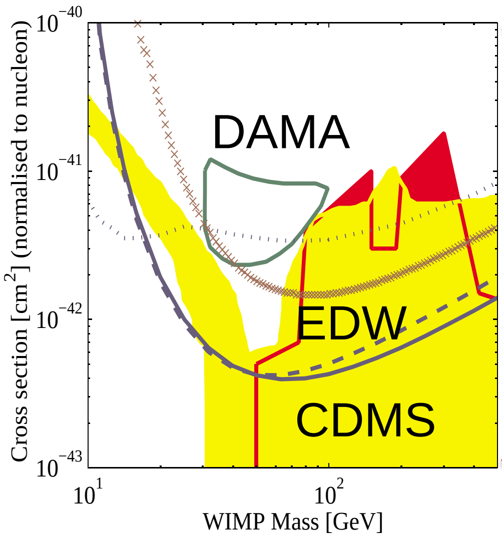
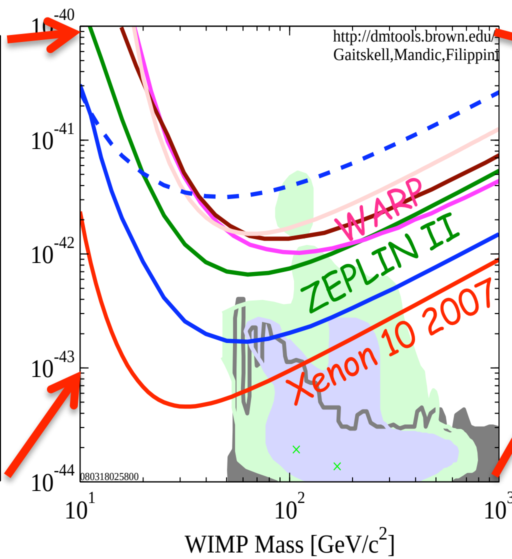
20-30 yrs later: unexpected (expected) difficulty

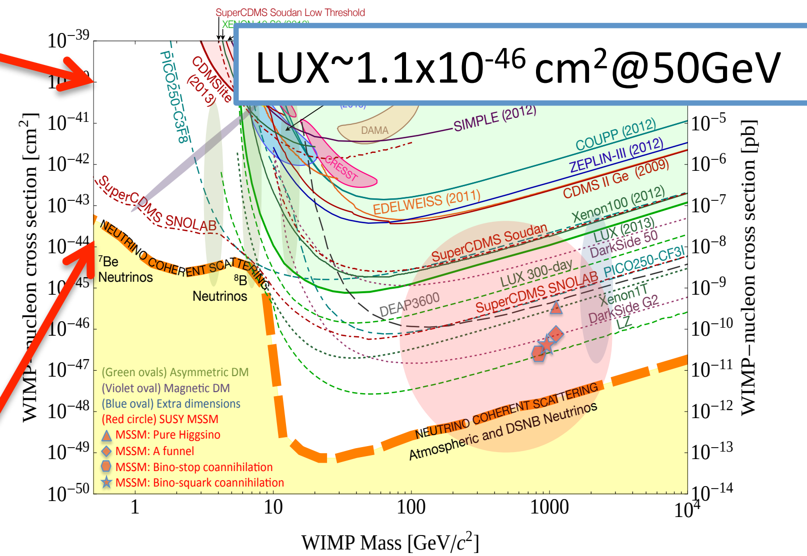
2004, CDMS
~0.1ev/kg/d



2008, B. Sadoulet
at neutrino conf.
~0.03ev/kg/d



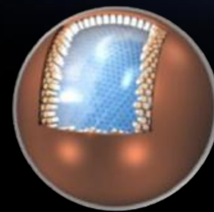
2016 LUX combined
best limit ~0.06ev/ton/d
down to ~0.00006ev/ton/d

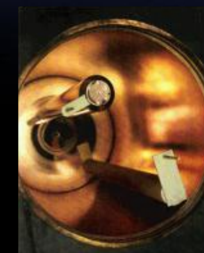


- Searches over 8 orders of mag. of xsec range did not show any evidence. No signal from LHC either.
- Consider stories different from the WIMP miracle.

Multiple paths toward positive detection

Liquid noble
>10GeV WIMPs





axion
cavity etc.

semiconductor/crystals
<10GeV WIMPs
and lighter mass

DM direct detection

Weakly
Interacting
Slim Particles
(WISPs) <<eV

Electron recoils

Sub-GeV, MeV dark matter

modulation, directional, threshold type…

- In parallel to search for conventional heavy WIMPs, various approaches started: beyond G2.
- DAMA annual modulation still remain: Run 2 results (lower threshold) are expected to be public this year.

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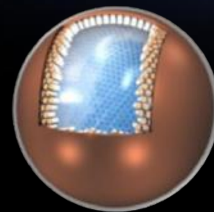
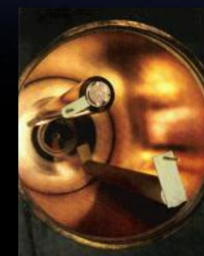
>10GeV WIMPs





axion
cavity etc.

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DM direct detection

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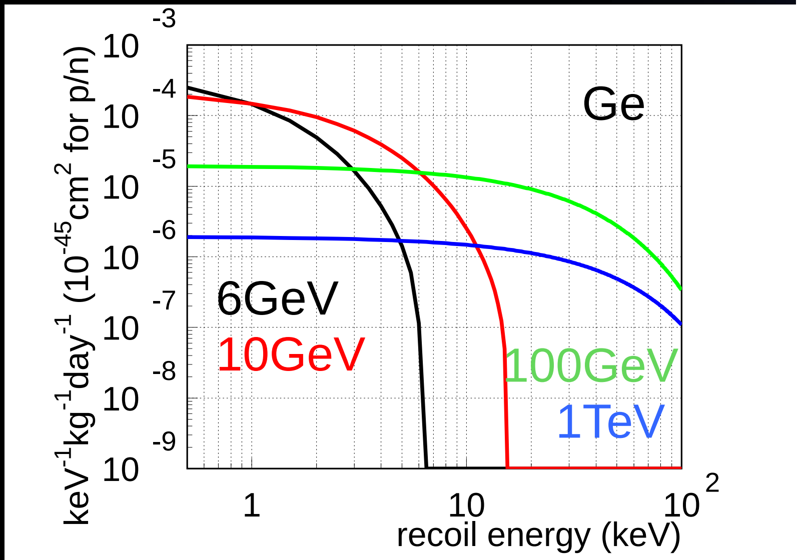
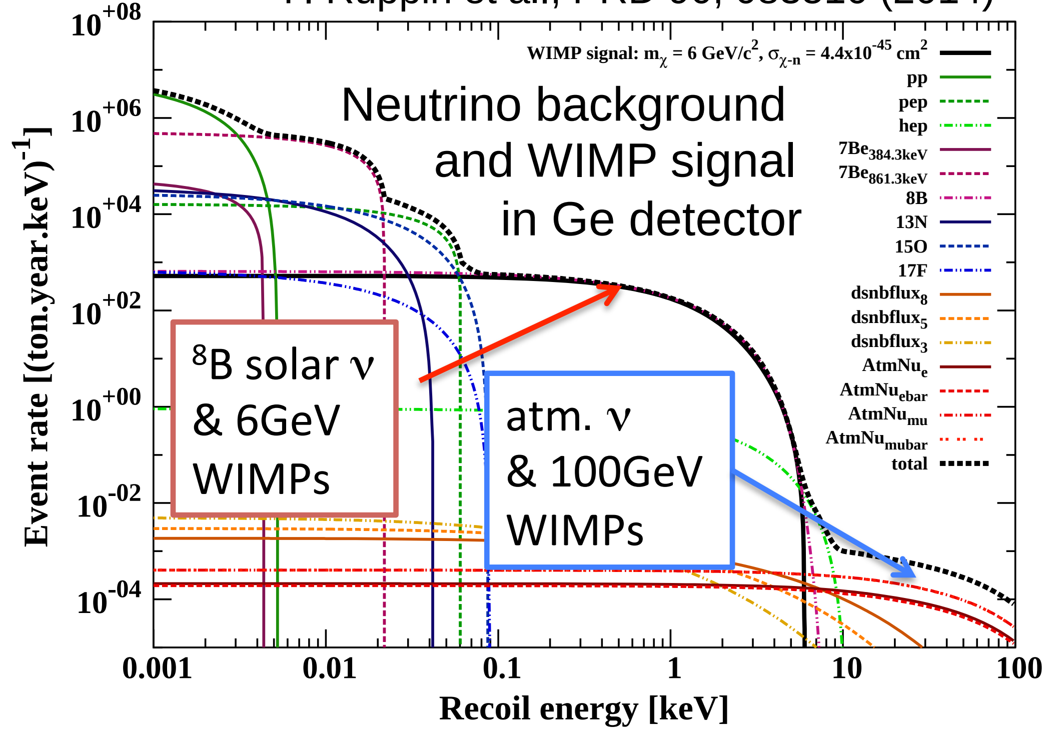
Larger detector: solar ν and atm. ν



F. Ruppin et al., PRD 90, 083510 (2014)

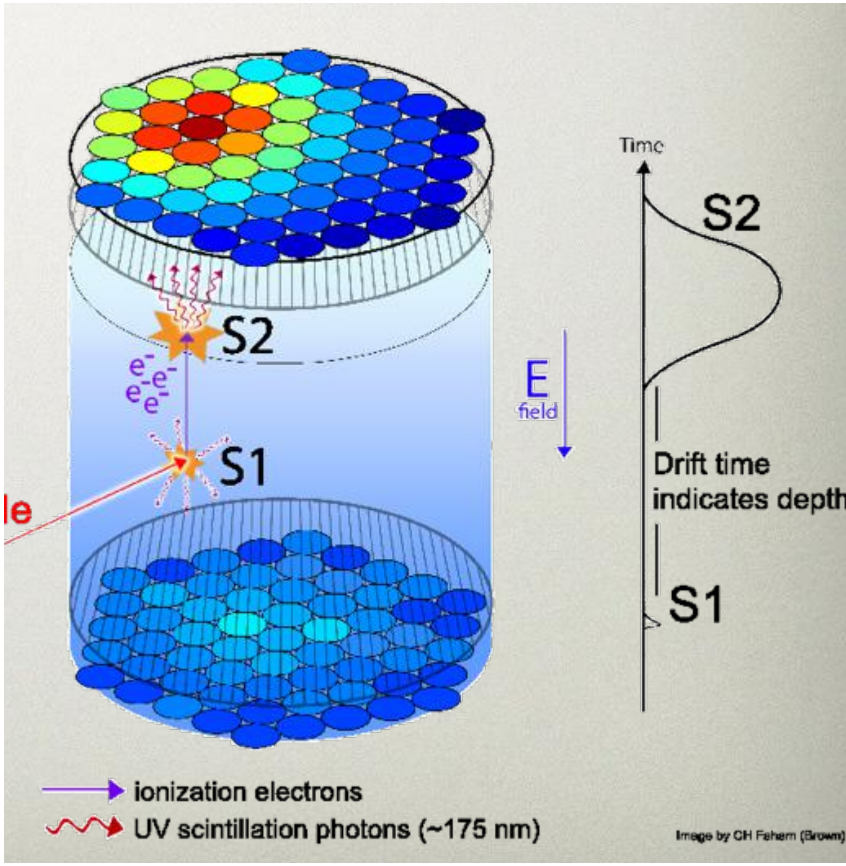


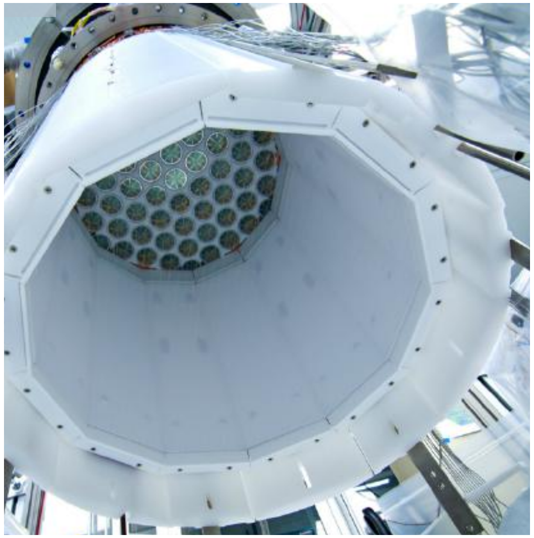
- Coherent ν–nucleus scattering will be observed soon!
- High mass WIMPs >10GeV: atm. ν ~ 1ev/30 ton yr (>4keV)
- Low mass WIMPs <10GeV: solar ^{8}B ν ~ 1ev/1 kg yr (>3eV)
- Directional information is useful if technology available.
- Precise determination of atm. ν flux <<20% important.
  - Precise study on CR flux, interactions, experimental site important!

Recent direct searches for heavy WIMPs

LUX ($^{124-136}Xe$)

- Dual phase Liquid xenon detector.
- 0.37 t of LXe, 0.1 t of fiducial mass.
- Nuclear recoil/electron BG discrimination possible (difference in S1/S2 ratio).
- 50% selection efficiency @4keV nuclear recoil energy (~2/3 signal above for 100GeV WIMPs): $1.1 \times 10^{-46} cm^2$@50 GeV
- 95 + 332 live days
- Already completed.

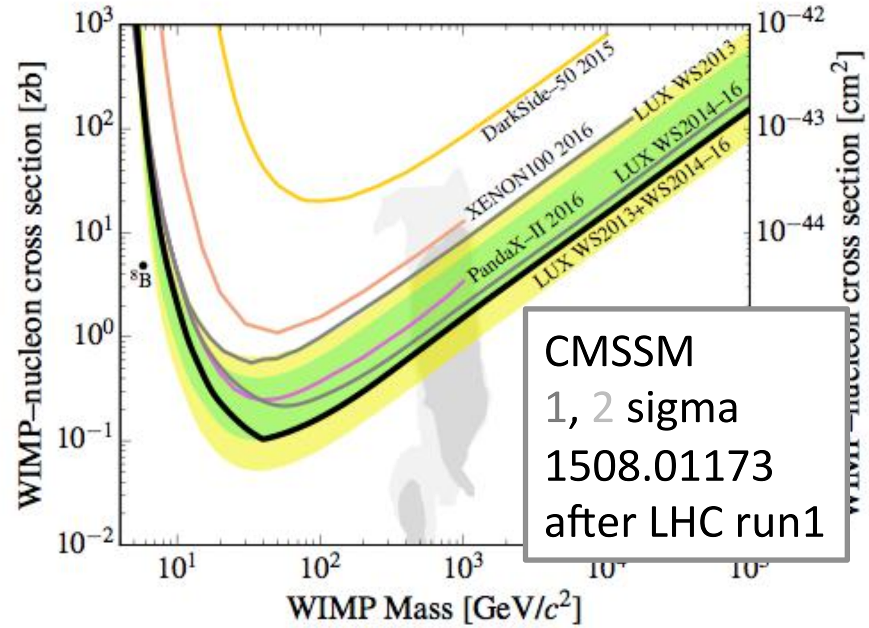


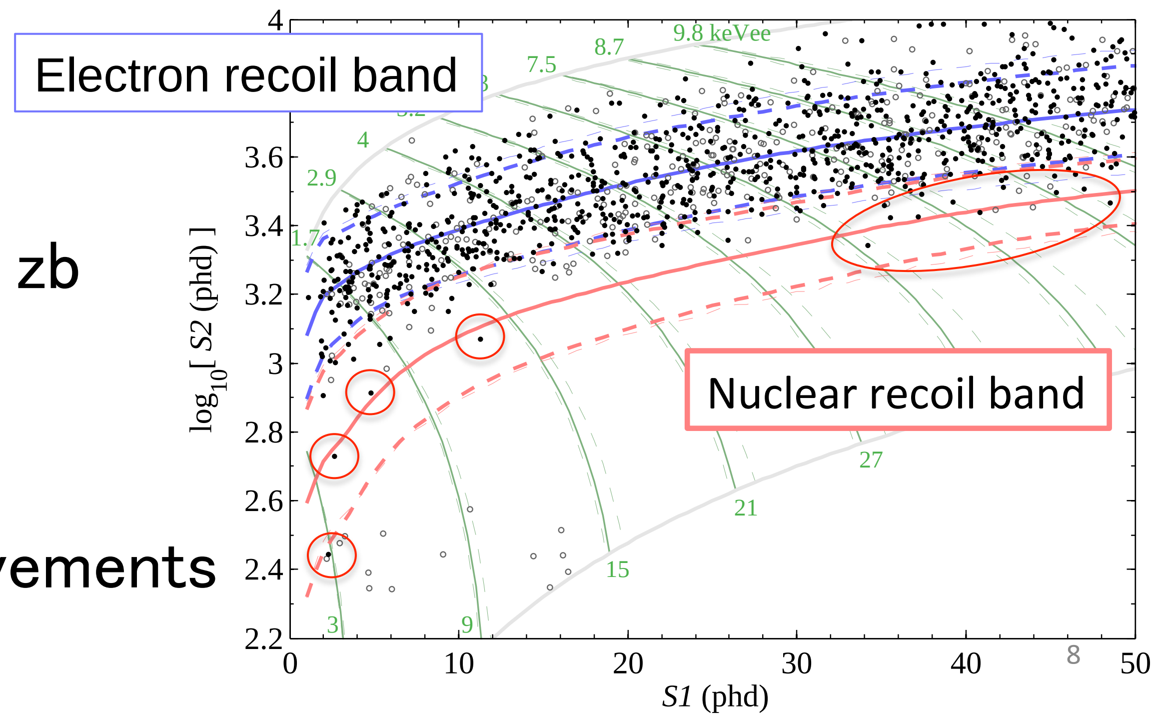


LUX ($^{124-136}Xe$)

Background source	Expected number below NR median	
External gamma rays	1.51 ± 0.19	PMT γ etc.
Internal betas	1.2 ± 0.06	Rn, Kr ..
Rn plate out (wall background)	8.7 ± 3.5	Rn daugther
Accidental S1-S2 coincidences	0.34 ± 0.10	
Solar ^8B neutrinos (CNNS)	0.15 ± 0.02	
Neutrons	0.3 ± 0.03	

arXiv: 1608.07648

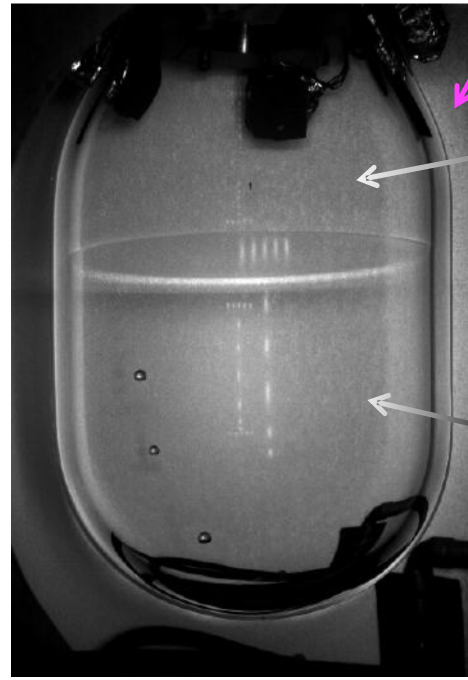




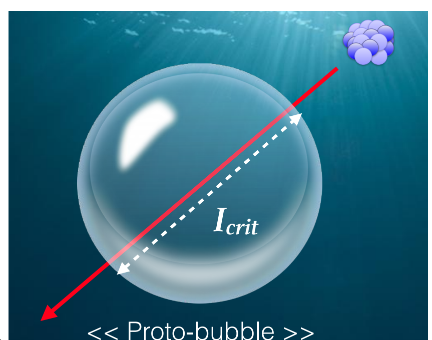
- World-best limit, sub zb
- Rn beta decay BG
- Rn daughters BG
- BG limited ➔ improvements necessary!

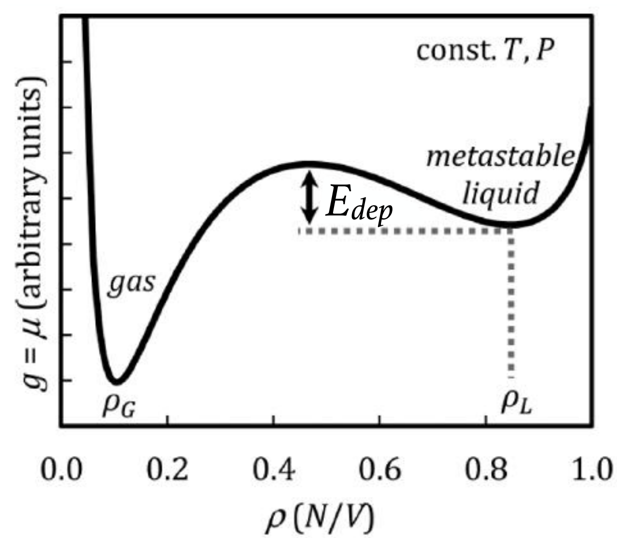
PICO-60/2L (spin dependent, ^{19}F proton)

- Bubble chamber
  - Acoustic signal
  - visual image
  - Threshold type
  - Fluorine: proton SD
  - $CF_3I \rightarrow C_3F_8$
- BG suppression due to dE/dx difference.
- 36.8kg/2.9kg
- 92.8/66.3 live days
- BG understood/improved.



M. B. Crisler and C. Amole IDM2016

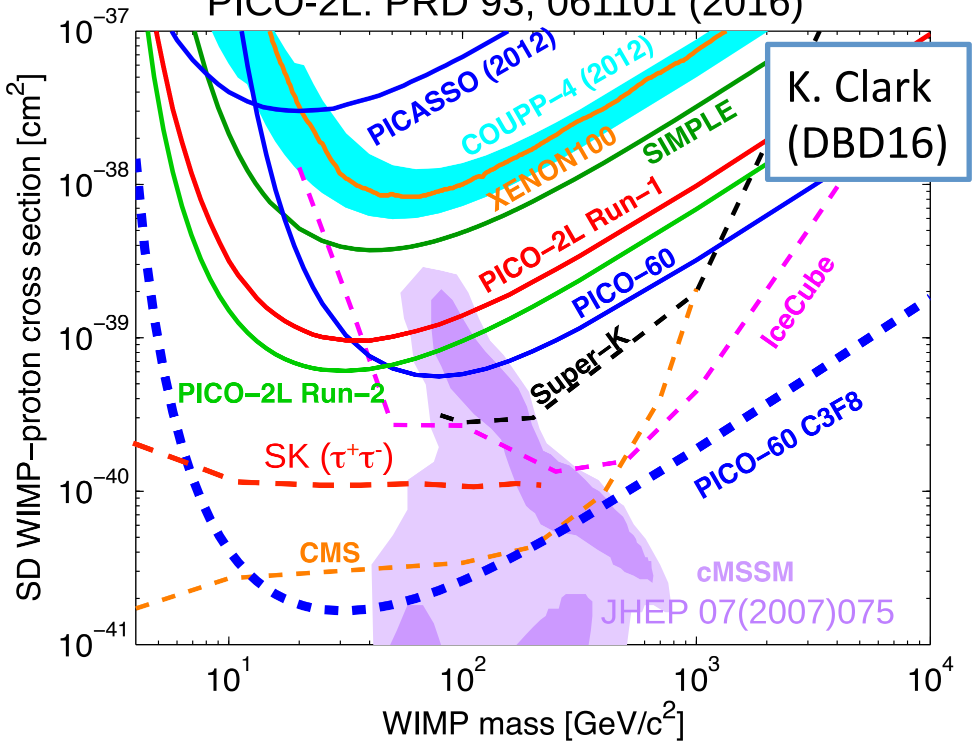


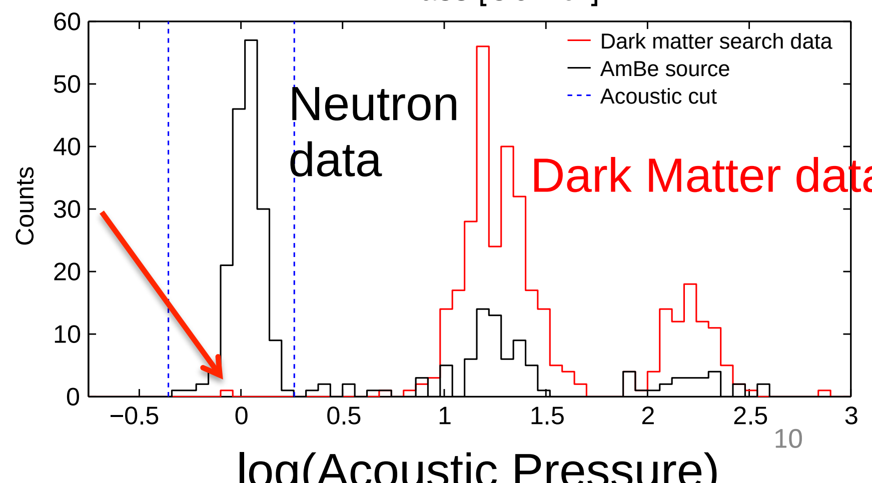


PICO-60/2L (spin dependent, ^{19}F proton)

- Selection based on acoustic pressure.
- BG caused by particulates.
- The world-best limit on WIMP-proton xsec.
- Entering SUSY region
- PICO-60 run 2 started with C_3F_8 and better filtering. Expected to overcome LHC results >10 GeV.

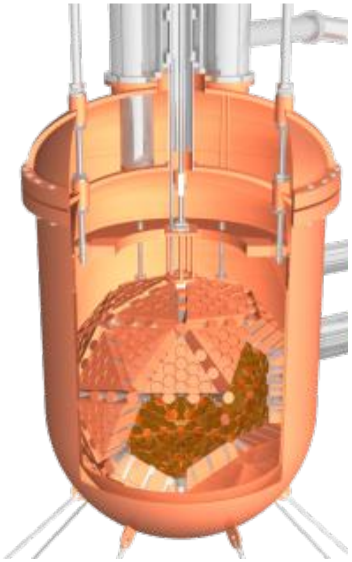
PICO-60: PRD 93, 052014 (2016)
PICO-2L: PRD 93, 061101 (2016)





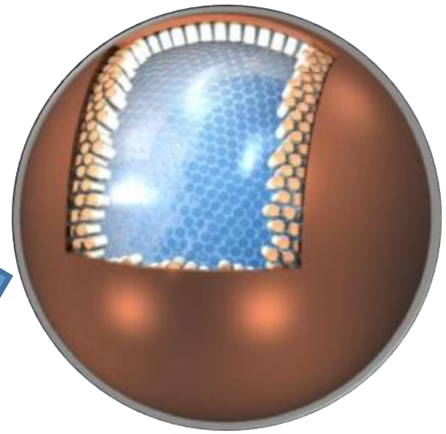
XMASS-I/1.5/II: 1 phase LXe @Kamioka

XMASS-I



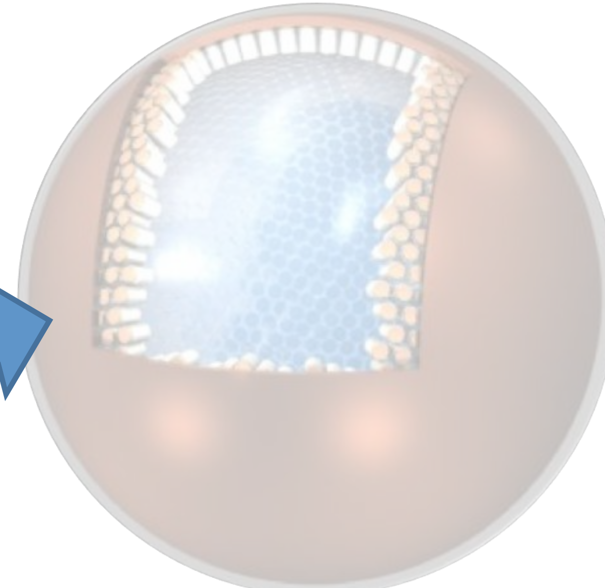
DM
100kg fid. (800kg)
0.8mϕ, 642 PMTs
2010-
DM search

XMASS-1.5



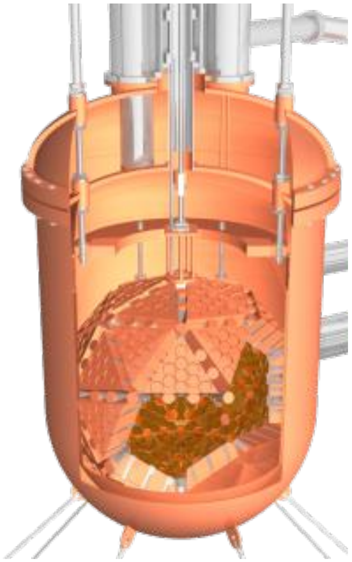
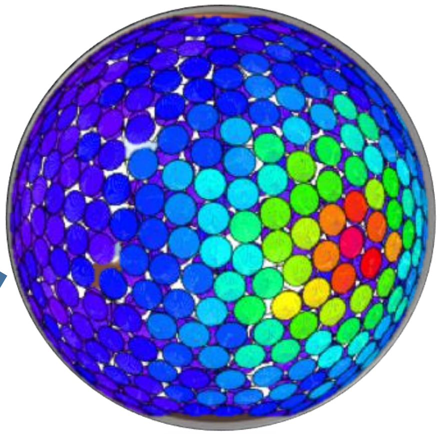
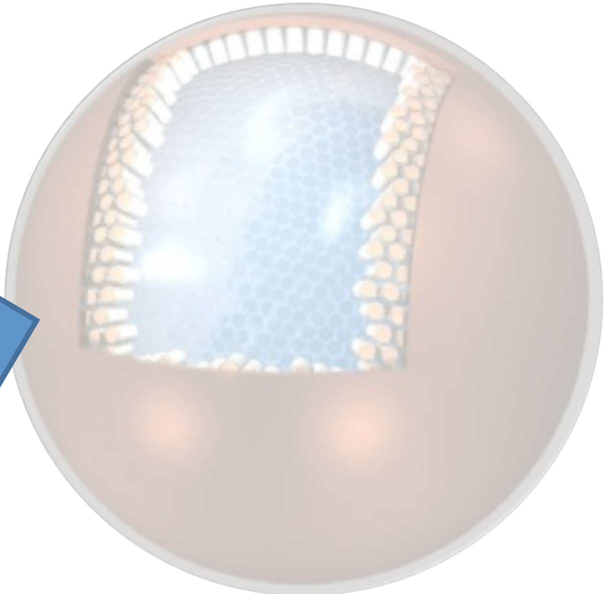
DM
3 ton fid. (6 ton)
1.5mϕ, ~1000 PMTs
pp solar ν limited
Ultimate BG for elec.
2x10^{-47}cm^2
Annual/spectral info.

XMASS-II



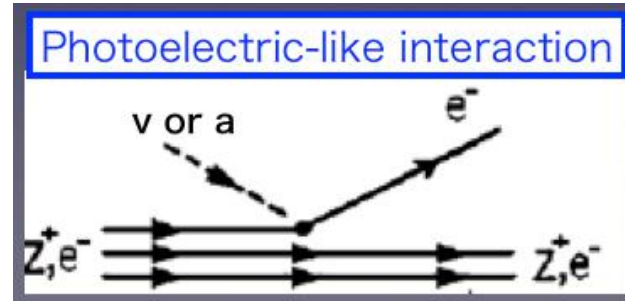
DM, solar, $\beta\beta$
10ton fid. (25ton)
Detailed study of DM
including e channel
pp Solar nu
$\beta\beta$ ~30meV(IH)

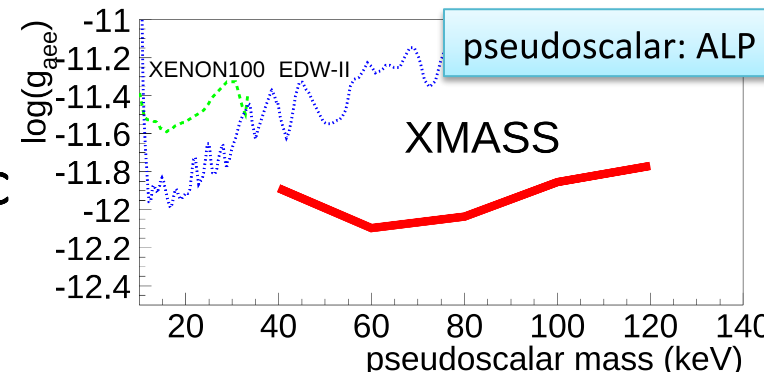
XMASS-I/1.5/II: 1 phase LXe @Kamioka

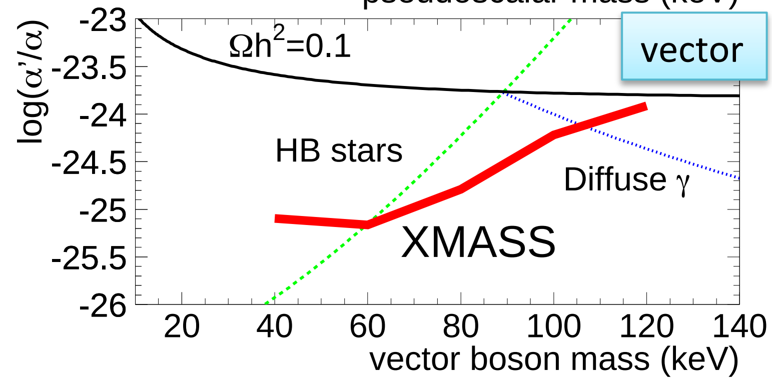
XMASS-I	XMASS-1.5	XMASS-II
		
DM 100kg fid. (800kg) 0.8mϕ, 642 PMTs 2010- DM search	DM 3 ton fid. (6 ton) 1.5mϕ, ~1000 PMTs pp solar ν limited Ultimate BG for elec. 2x10^{-47}cm^2 Annual/spectral info.	DM, solar, $\beta\beta$ 10ton fid. (25ton) Detailed study of DM including e channel pp Solar nu $\beta\beta$ ~30meV(IH)

Results from XMASS-I

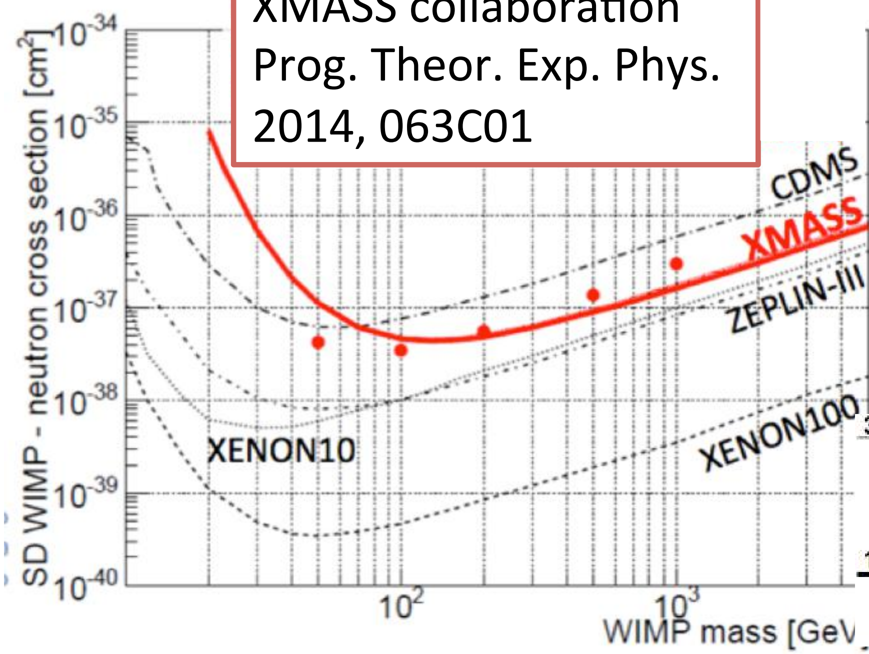
- Large mass (835kg), low thre. (0.8keVee), <u>world best BG including electron events.</u>
- Inelastic scattering off ^{129}Xe (SD).
- First experimental search for bosonic Super-WIMPs as DM.

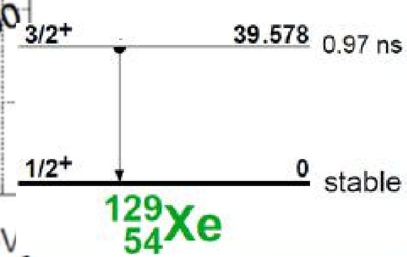






XMASS collaboration
Prog. Theor. Exp. Phys.
2014, 063C01

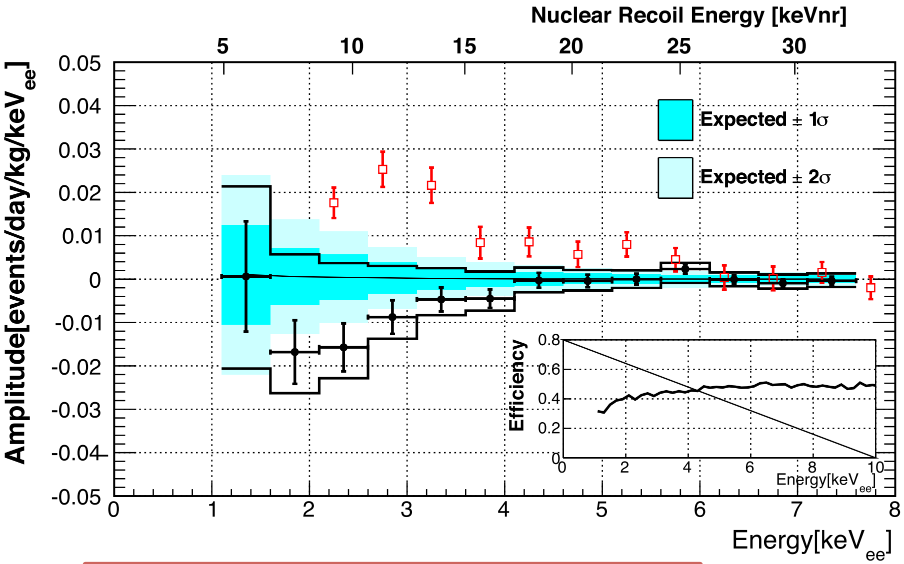




XMASS collaboration
Phys. Rev. Lett
113, 121301 (2014)

Results from XMASS-I

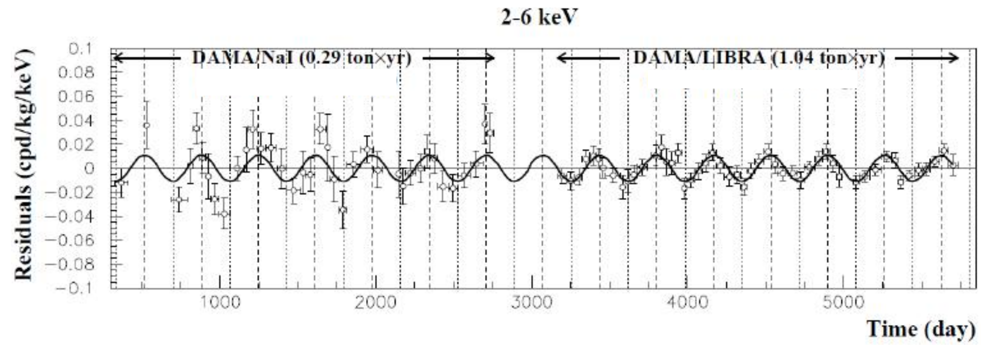
- Modulation analysis ~1yr



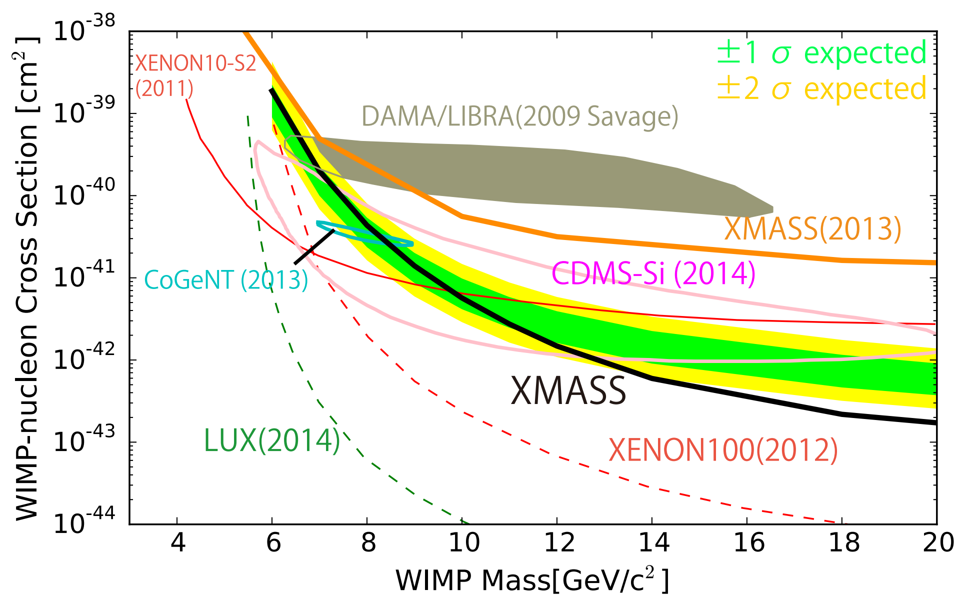
XMASS collaboration
Phys. Lett B. 759 (2016) 272

The first extensive search against the DAMA region, including electron recoils.

DAMA 100-250kgx14yr



XMASS 832kg x ~1yr

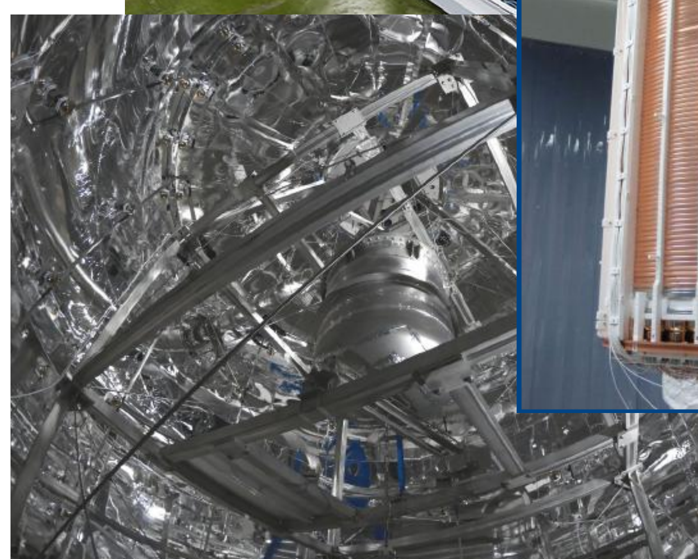


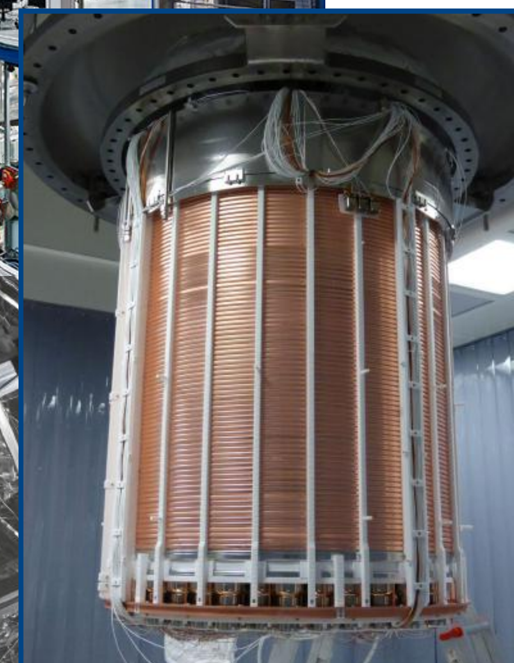
Future direct searches for heavy WIMPs

XENON1T ($^{124-136}Xe$)

H. Simgen (TPC2016)

- Dual phase liquid xenon detector.
- 3.2 ton of LXe, 1 ton of fiducial mass.
- Data taking started.
- Factor 2 improved light yield wrt XENON100.
- Purification ongoing.
- Expected sensitivity $1.6\text{x}10^{-47}\text{cm}^2$ @50 GeV (2 ton years exposure)





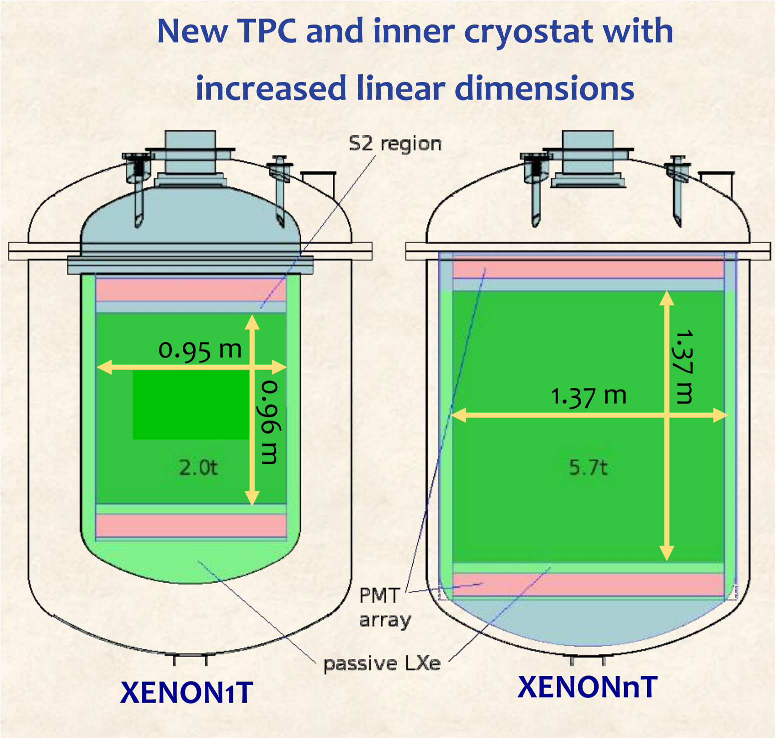
XENONnT ($^{124-136}Xe$)

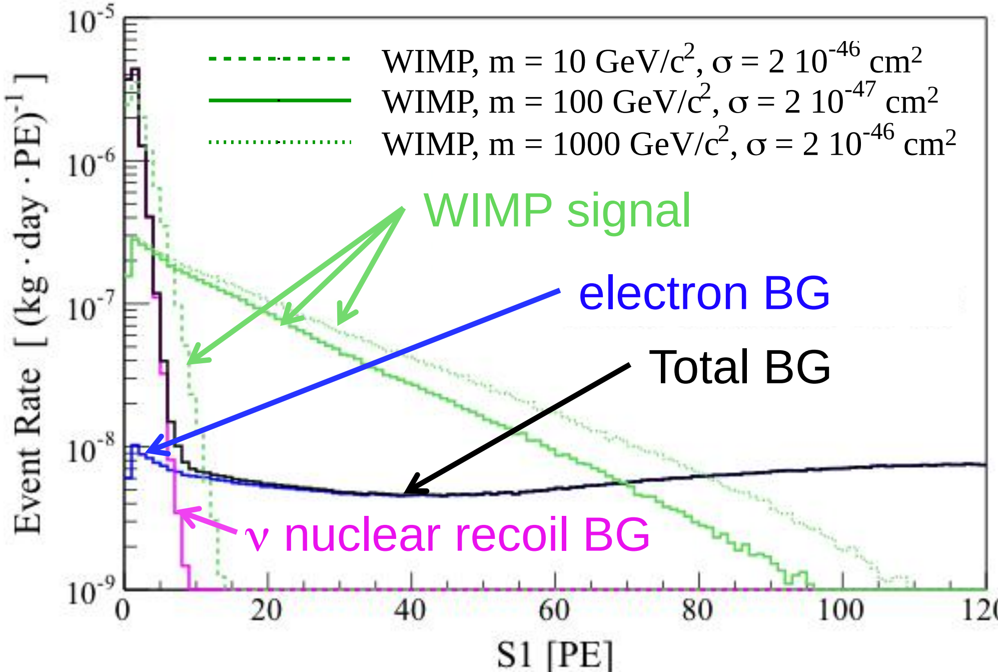
- Replace the inner cryostat of XENON1T to a larger one: rapid upgrade possible.
- 8 t of LXe, 6 t of target
- construction 2018
- $1.6 \times 10^{-48} cm^2$ @50GeV (20 t yrs) from 2019?
- Background reduction

1/100 of Radon

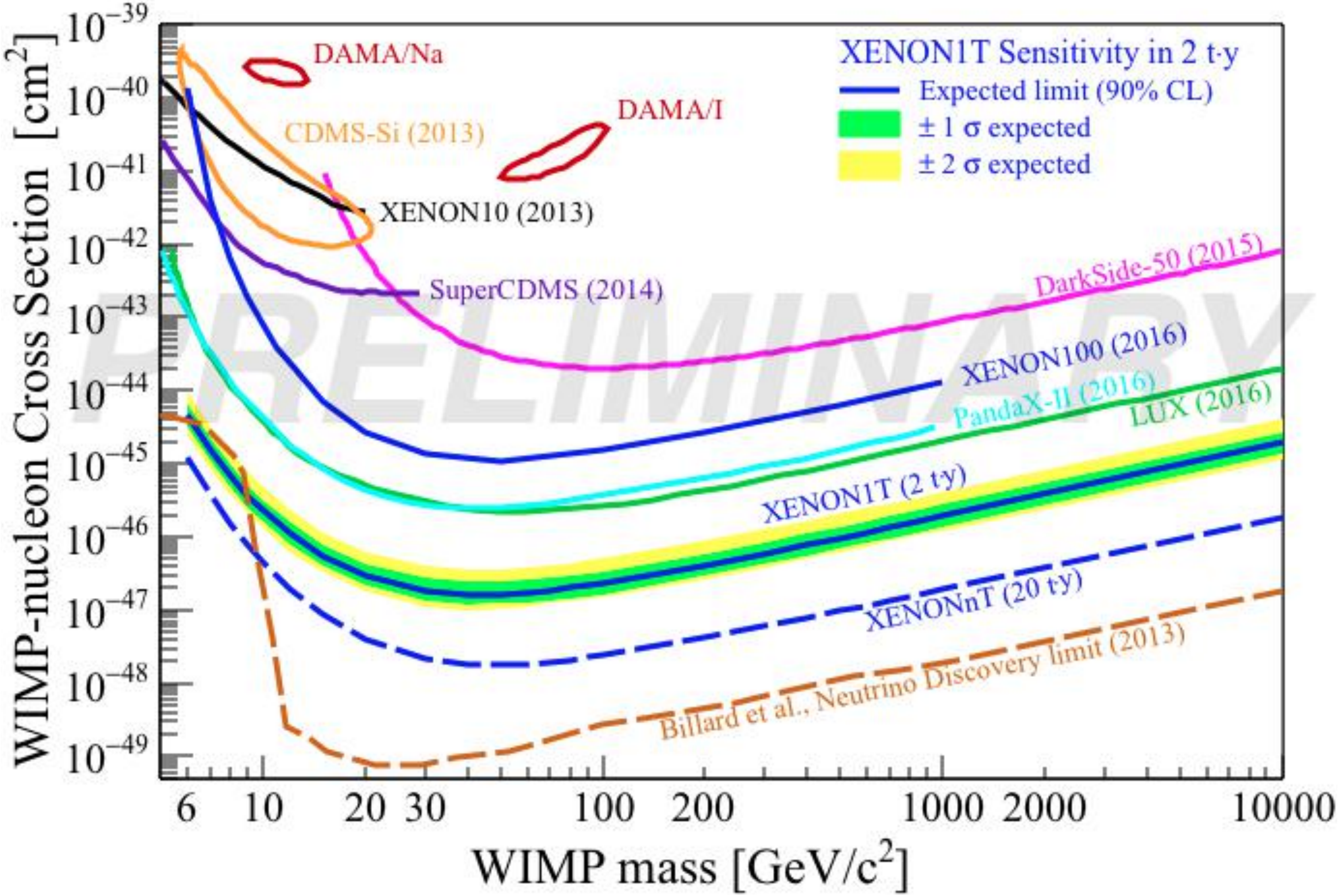
1/10 of Krypton

from XENON1T





XENON1T/nT ($^{124-136}Xe$)

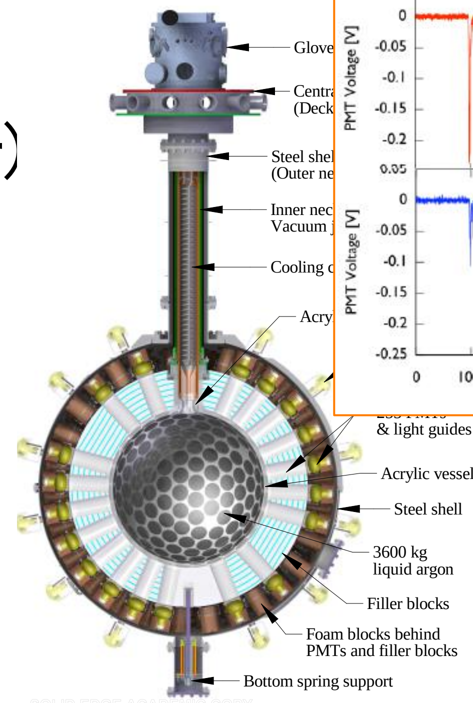


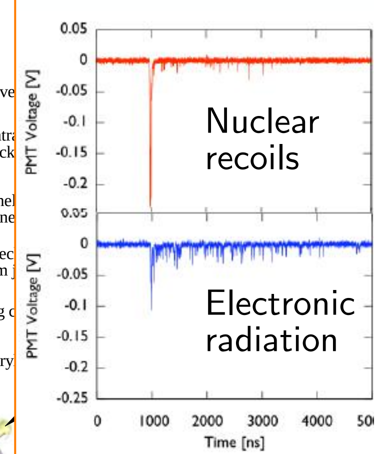
- BG@XENON1T: 5 events (3.25 events ~ Radon)

JCAP 04 (2016) 027

DEAP3600 (^{40}Ar)

- Single phase (pure scintillator) liquid argon detector.
- 3.6 ton of liquid argon, 1 ton of fiducial mass
- Nuclear recoil/electron BG discrimination possible
- Large BG due to ^{39}Ar necessary to be rejected.
- ~1×10^{-46} cm^2@100GeV
- Started operation and normal data collection.
- DEAP–50T: $2 \times 10^{-48} cm^2$

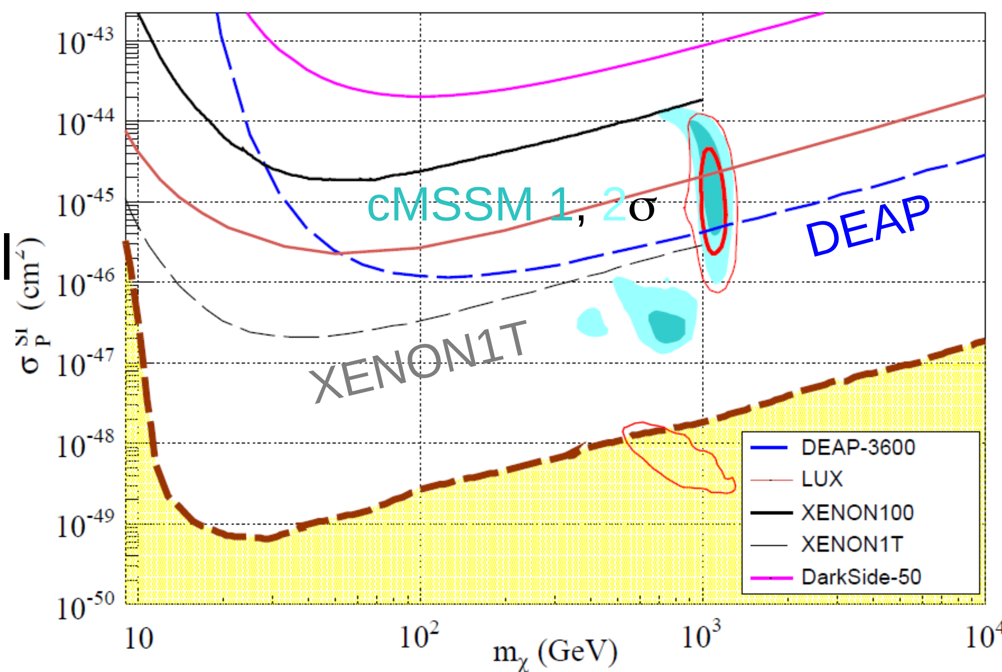




$$\frac{\text{Singlets}}{\text{Triplets}} = 3$$

$$\frac{\text{Singlets}}{\text{Triplets}} = 0.3$$

particle identification by waveform

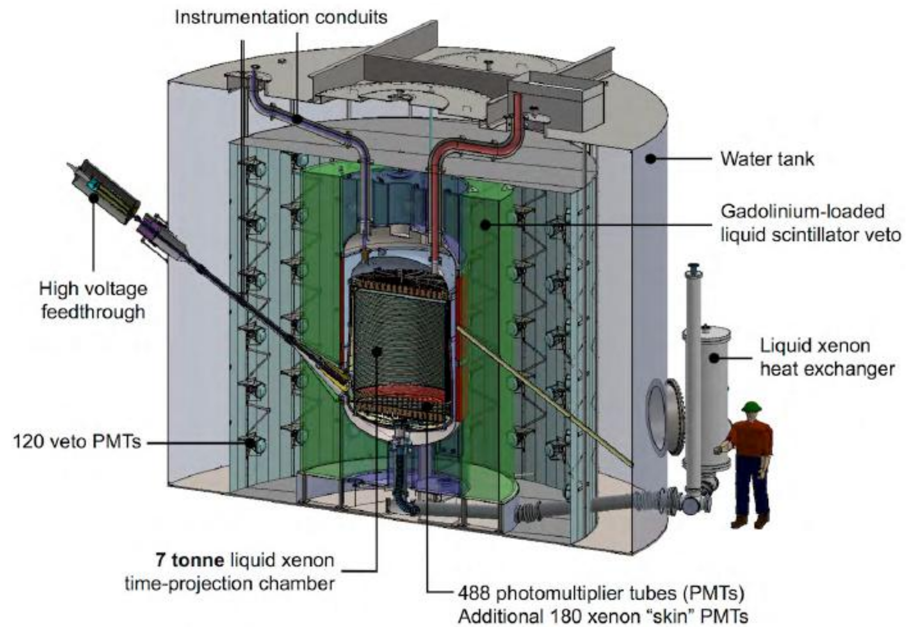


LZ ($^{124-136}Xe$)

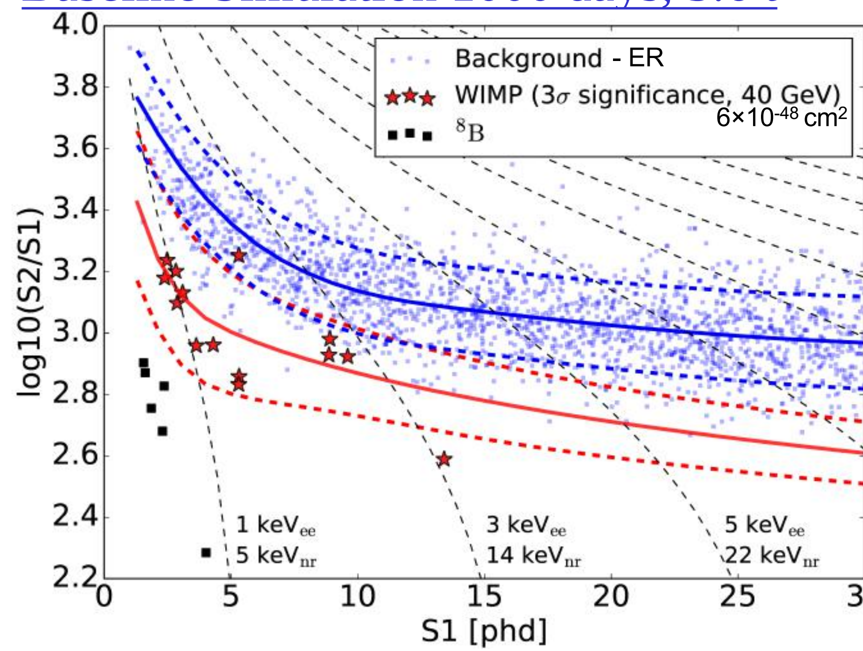
- Dual phase LXe detector.
- 10 t of LXe, 7 t of target,
  5.6 t of fiducial mass.
- CD3 review this month
- Operation: 2020 April
- Goal $1.1 \times 10^{-48} cm^2$
  Baseline $2.3 \times 10^{-48} cm^2$
  @50 GeV (1000days)
- Dominant background

Rn: 72(goal)–1000(baseline)
before 99.5% rejection

LZ conceptual design report



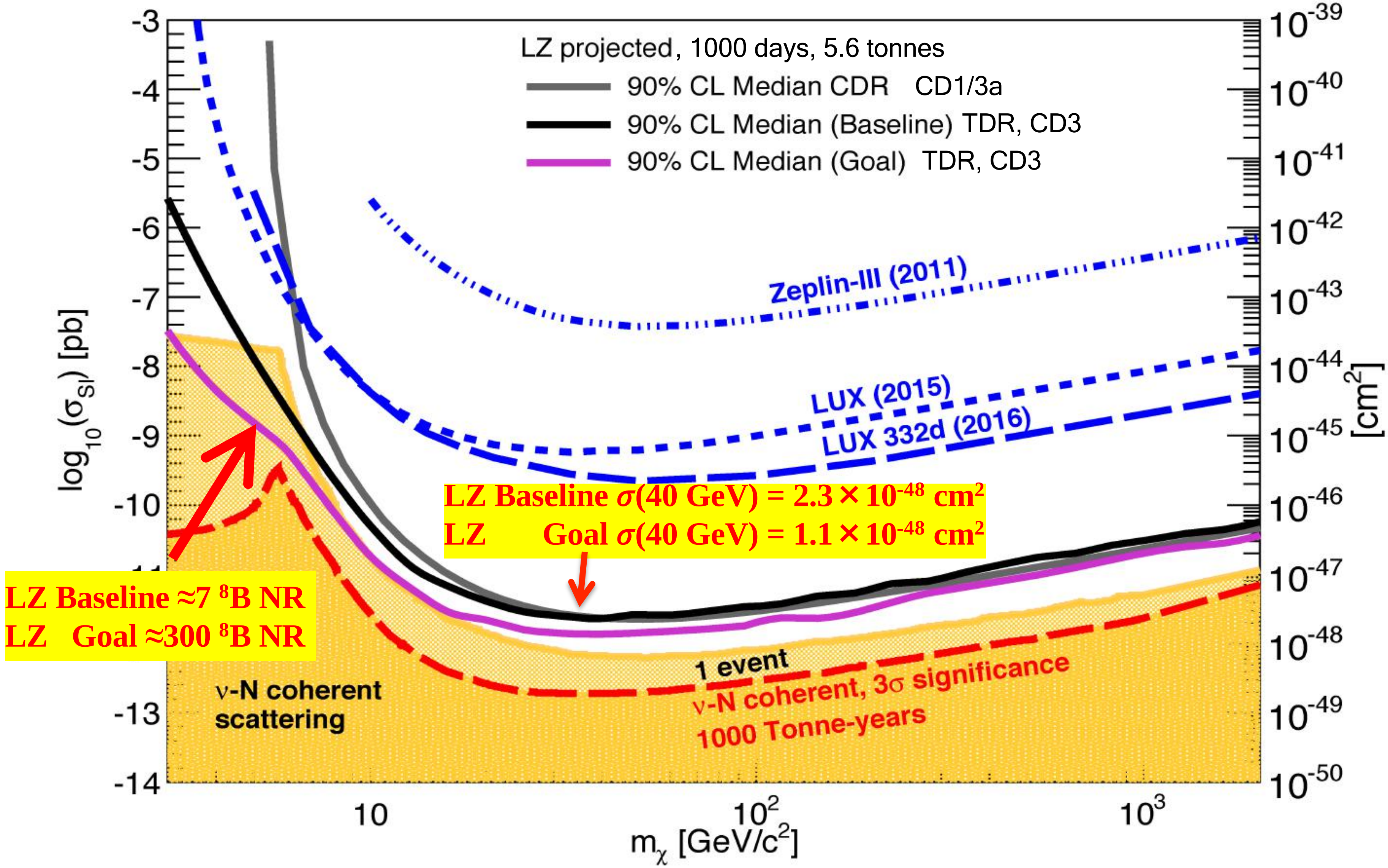
Baseline Simulation 1000 days, 5.6 t



LZ ($^{124-136}Xe$)

H. Nelson, DBD16

Projected Sensitivity (Spin Independent)

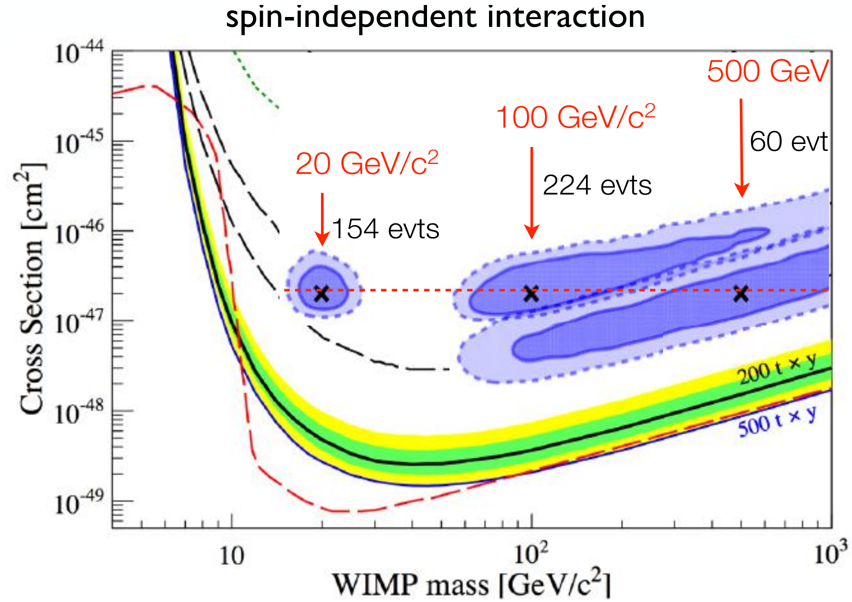


DARWIN ($^{124-136}Xe$)

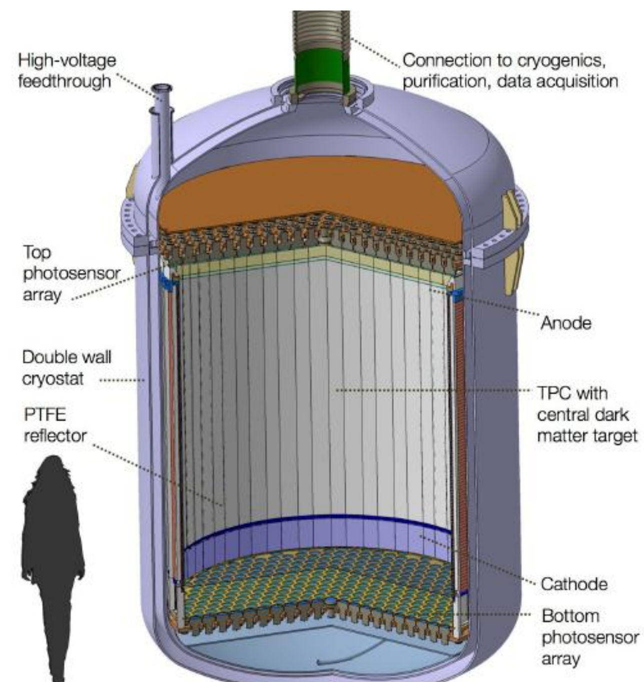
- 50 t of LXe, 40 t of target

30 t of fidicial mass, sub yoctob!

- Required Improvements
  - Radon reduction ~1/100
  - Discrimination: 99.98% reduction, 30% signal eff. (XENON100: 99.75%, 50% eff.)
  - 130kV HV
- Physics channels with a large detector
  - ν: pp solar, double beta decay, coherent scattering, supernova
  - axion like particles
- 2025~?



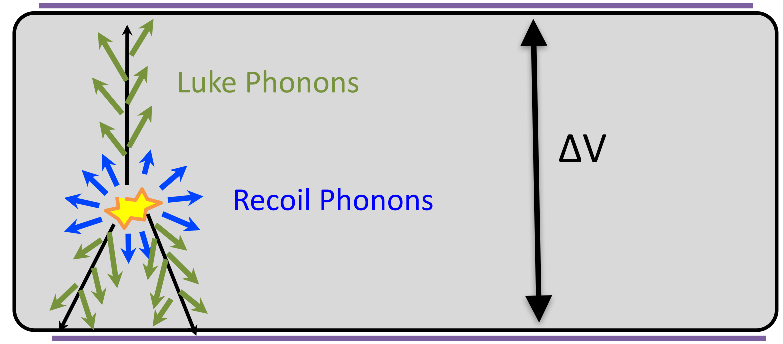
→ minimum sensitivity: 2.5×10^{-49} cm² @ 40 GeV/c²



~2.6m diameter and height

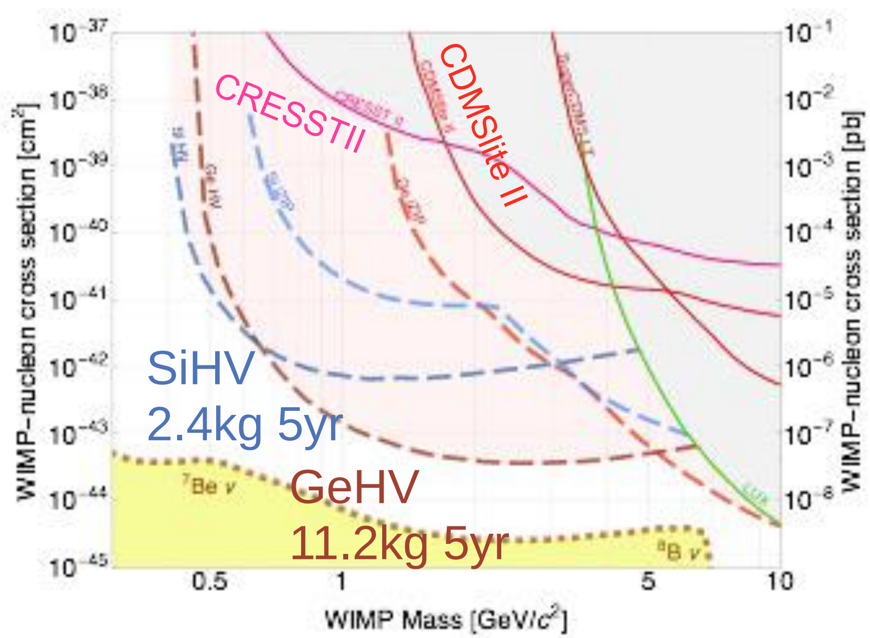
SuperCDMS ($^{70-76}Ge$)

- target: Light WIMPs
- ~10kg size, semiconductor
- Ionized electrons produce additional phonons due to high electric field ➔ low thre.
- Sacrificing discrimination btw nuclear/e recoils.
- R&D by March 2017
- CD2/CD3 Nov. 2017
- Operation expected @2020



$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + Qe\Delta V$$

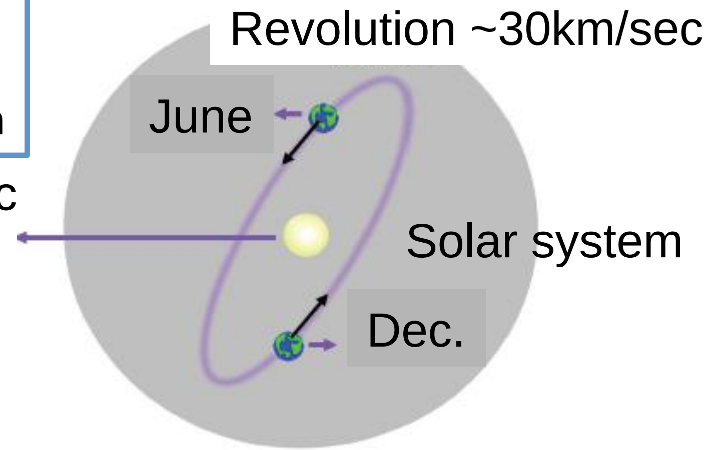
SuperCDMS Sensitivity
arXiv:1610.00006



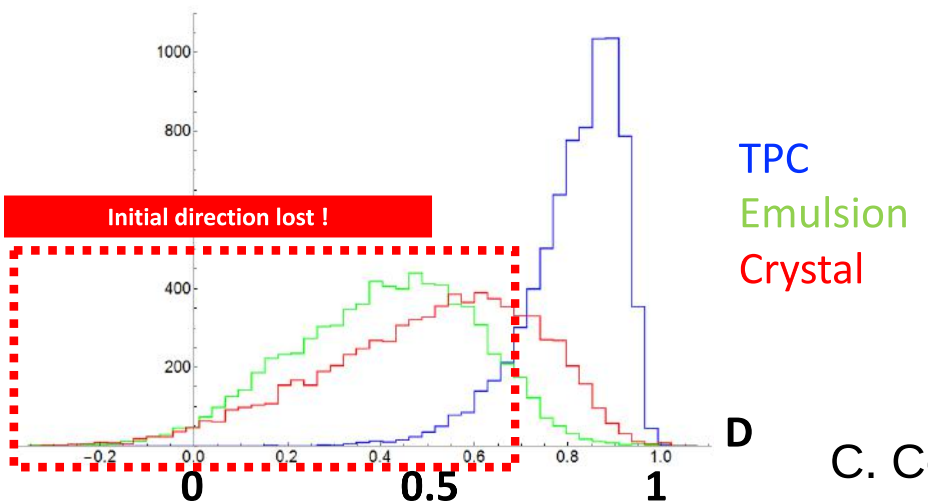
Directionality

- Smoking gun evidence
- Better once we hit to the neutrino floor.
- Gas seems to be better than solid and liquid.
- All depend on BG!
  - If any, sensitivity ~sqrt(BG)

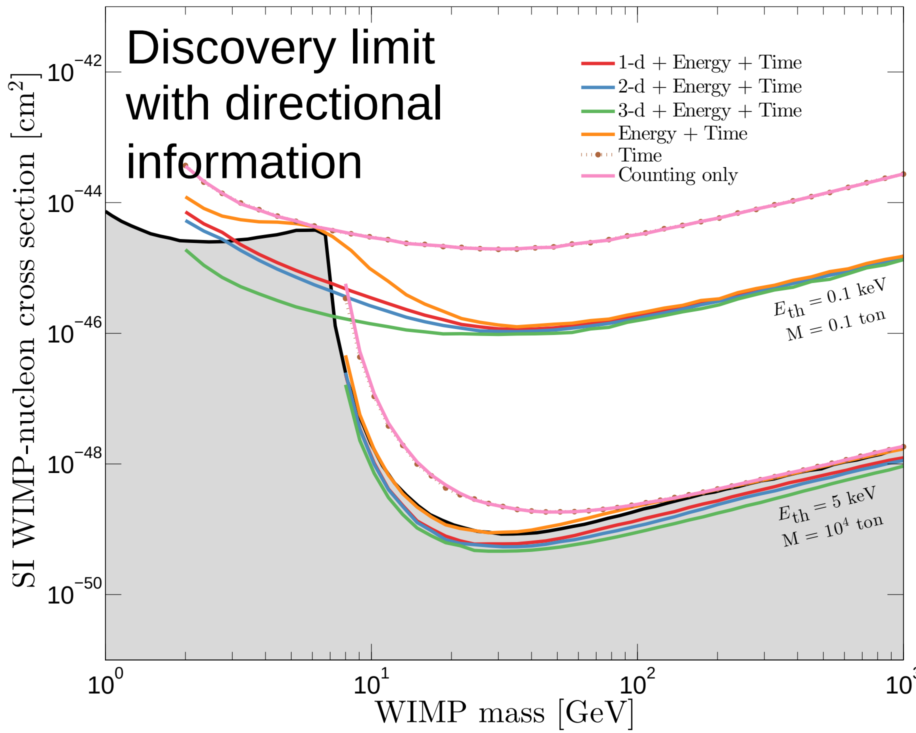
See
K. Miuchi
this afternnon



recoils induced by a **1000 GeV WIMP**



C. Couturier, IDM2016

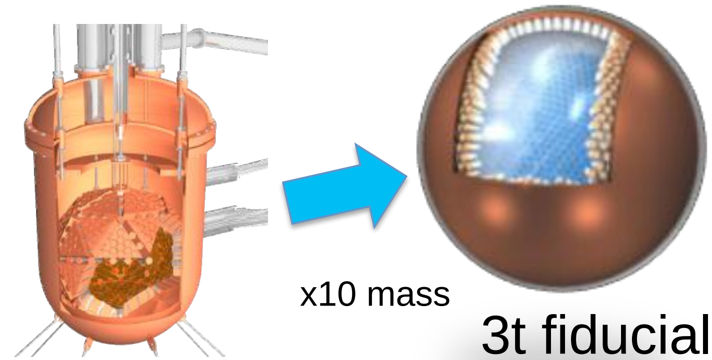


O'Hare et al., PRD 92, 063518 (2015)

XMASS−1.5 ($^{124-136}Xe$)

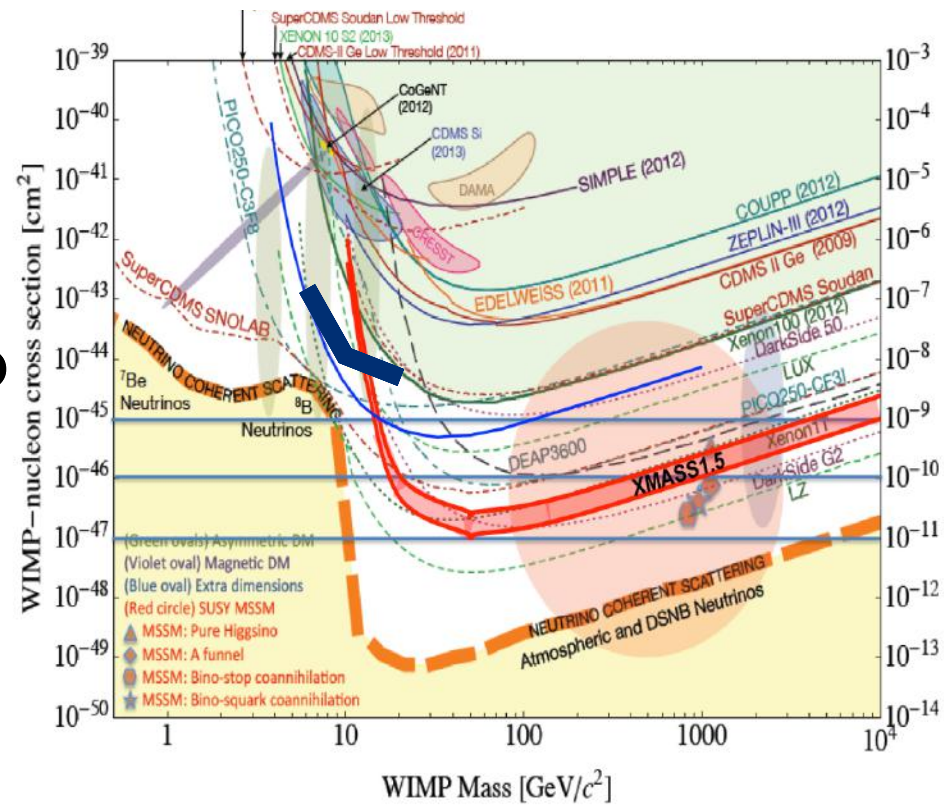
- Single phase liquid xenon detectors
- XMASS−1.5: 6 ton of LXe and 3 ton of fiducial mass
- Low background in electron channel as well.
- $2\times10^{-47}cm^2$@50GeV
- e−scat. pp solar neutrino observation (not nuclear recoils) ⇔ background
- Next step: need particle identification method

XMASS-I **XMASS-1.5**

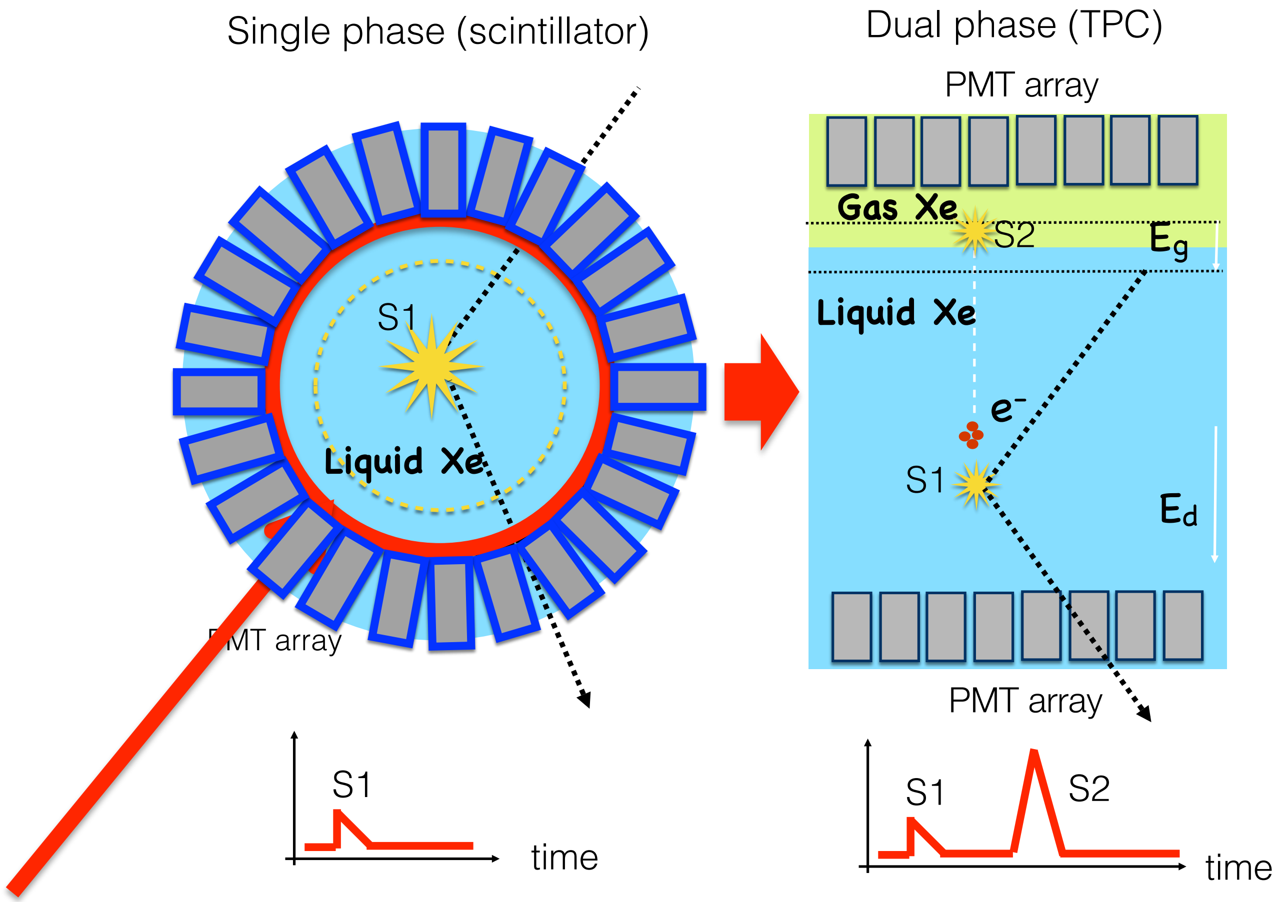


Phase I: 0.1t fiducial mass (Total 835kg)

3t fiducial (total 6t) ~$10^{-47}cm^2$



XMASS future: applying merits of single phase detectors to dual phase detectors?



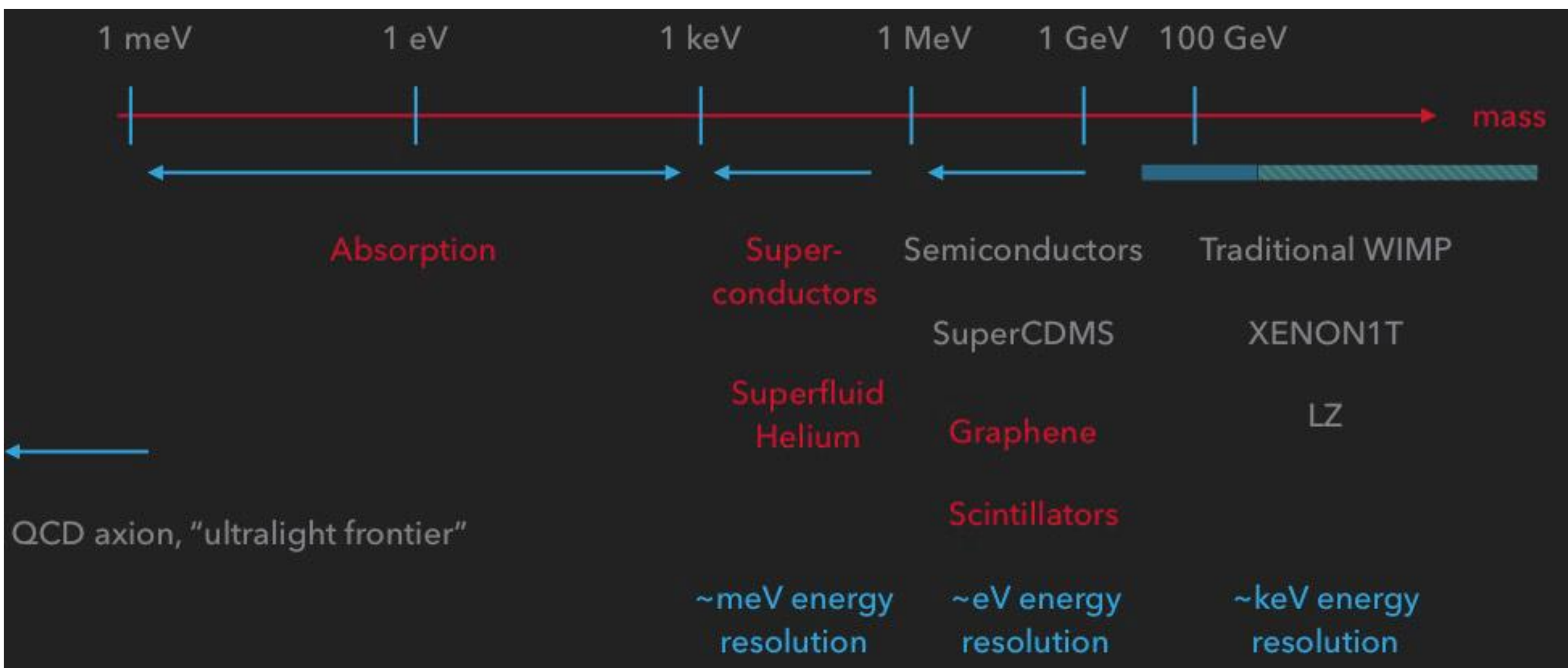
- Low Radon/Krypton background: separated target volume
- Improvements of light yield (discr. power): larger coverage by PMTs
- by-products: Light WIMPs search?

Lighter WIMPs

Light dark matter (<GeV)

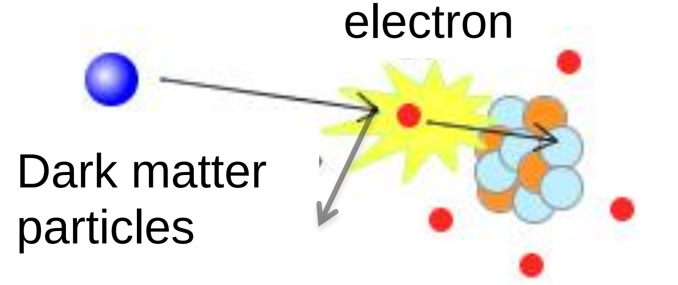
- Wider interests in a new paradigm of DM theories.
- Many, many new technical ideas.
  - Heat, single e detection, small gap material, cooper pairs, multi-excitation, superfluid He, spin avalanche, and ...
  - Input for 2017 June US DOE whitepaper.

K. Zurek, Sub-eV 2016

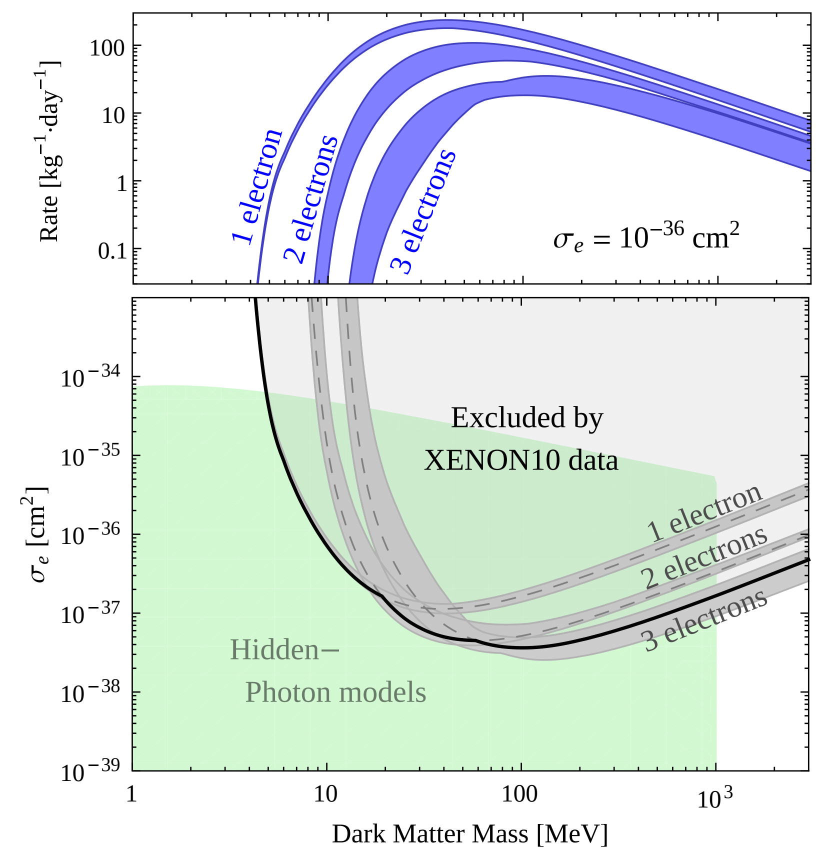


Single electron detection for <GeV DM

R. Essig, T. Volansky et al., PRL 109, 021301 (2012)



- DM-nucleus scattering << threshold of a DM detector
- DM-electron scattering: $\frac{1}{2}m_e\beta^2 \sim O(\mathrm{eV})$ may cause excitation of shallow atomic electrons.
- 2 phase LXe detector is able to see single electron (+ a few associated electrons).
- BG prediction difficult: modulation signal?



Summary

- Heavy WIMPs
  - DM detectors are going to achieve original goal: coherent neutrino-nucleon scattering. It will be major background of DM searches.
  - With large liquid noble gas detectors heavy WIMPs ~10^{-48}cm^2 are expected to be covered ~ 5 years.
    - XENON1T:1.6×10^{-47}cm^2, nT: 1.6×10^{-48}cm^2, LZ: 1-2×10^{-48}cm^2
  - Further future, precise determination of atm. ν flux and site selection are important.
- Other ways
  - Missing any observational evidence motivates people to investigate wider range of dark matter particles.
  - New technologies for the new territory (light WIMPs, non-WIMPs) are being proposed/investigated.