Highlights from direct dark matter detection

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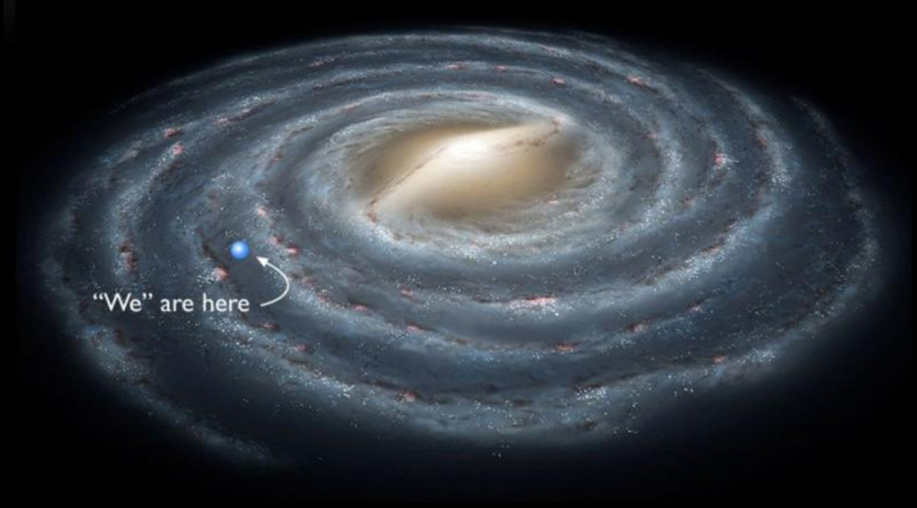
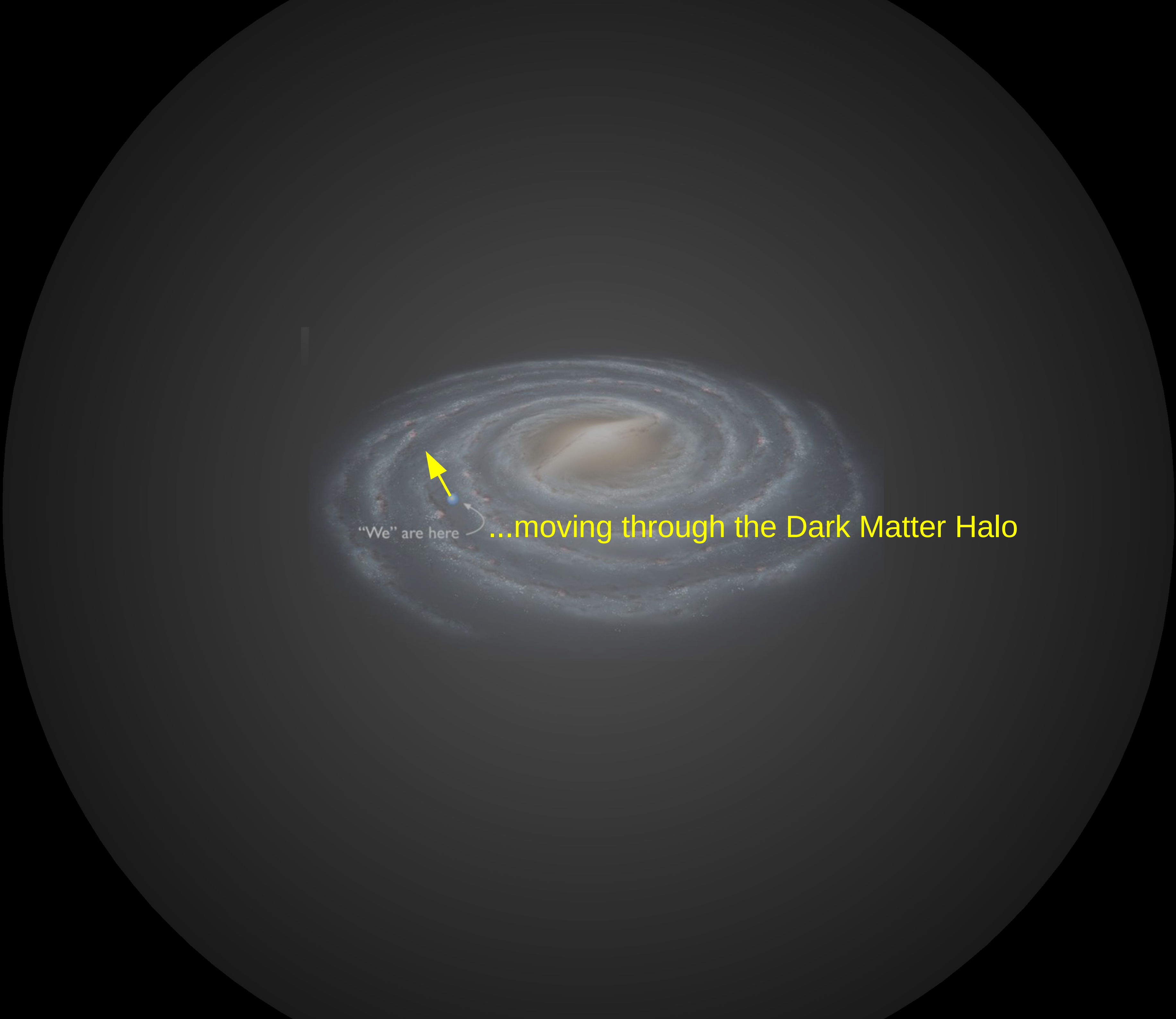
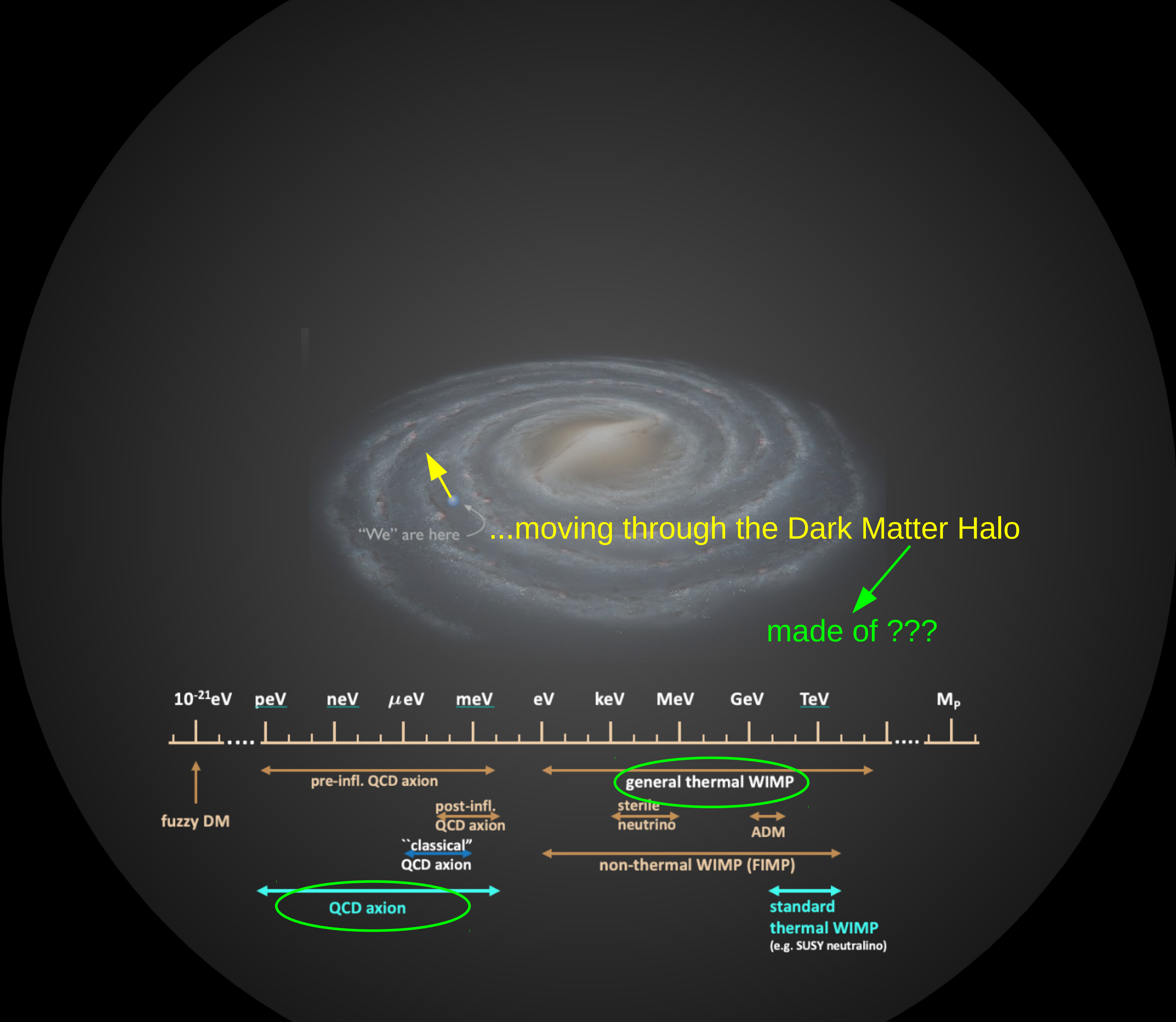

"We" are here



"We" are here
...moving through the Dark Matter Halo

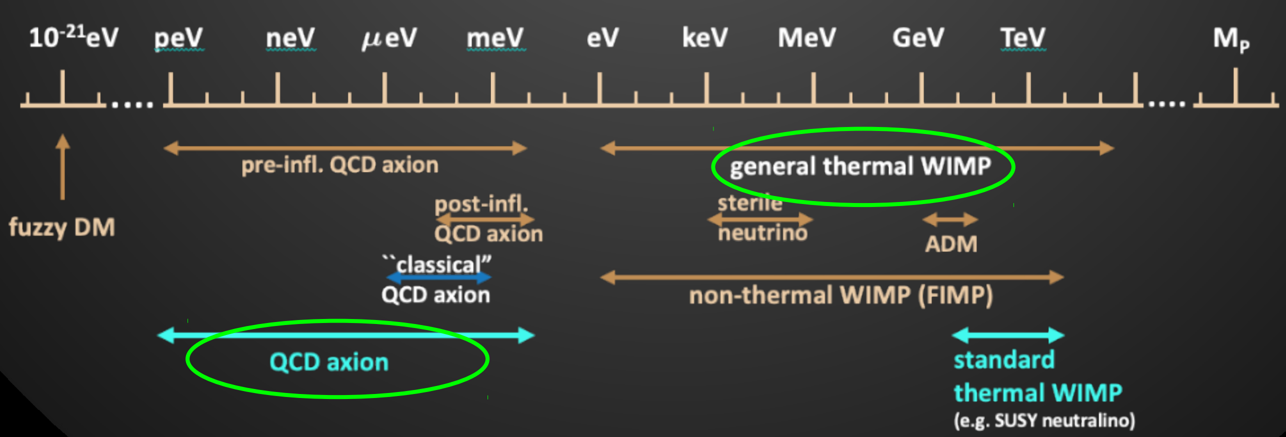


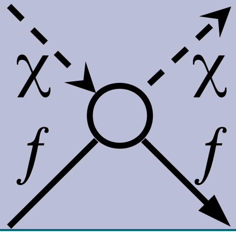
"We" are here
...moving through the Dark Matter Halo
made of ???
10-21eV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
Mp
fuzzy DM
pre-infl. QCD axion
post-infl. QCD axion
``classical" QCD axion
QCD axion
general thermal WIMP
sterile neutrino
ADM
non-thermal WIMP (FIMP)
standard thermal WIMP
(e.g. SUSY neutralino)

Disclaimer: very little time for a very rich field.
→ focus on general status of field and recent results
→ biased selection of topics!

...moving through the Dark Matter Halo

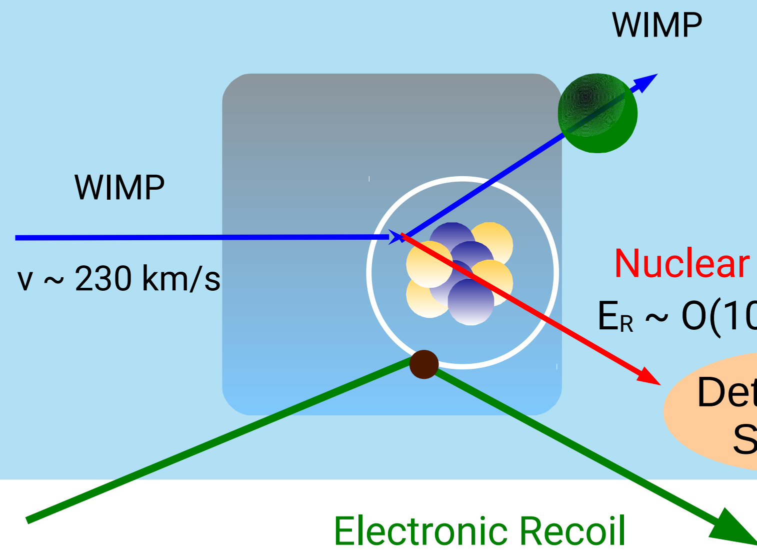
made of ???



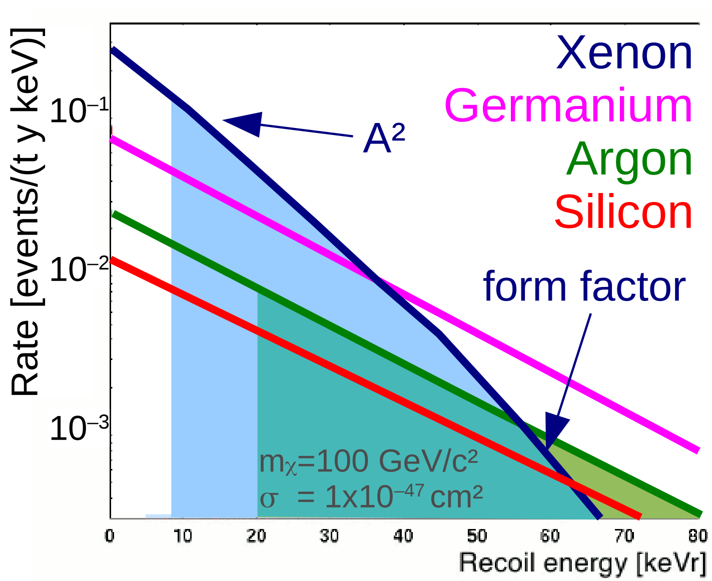


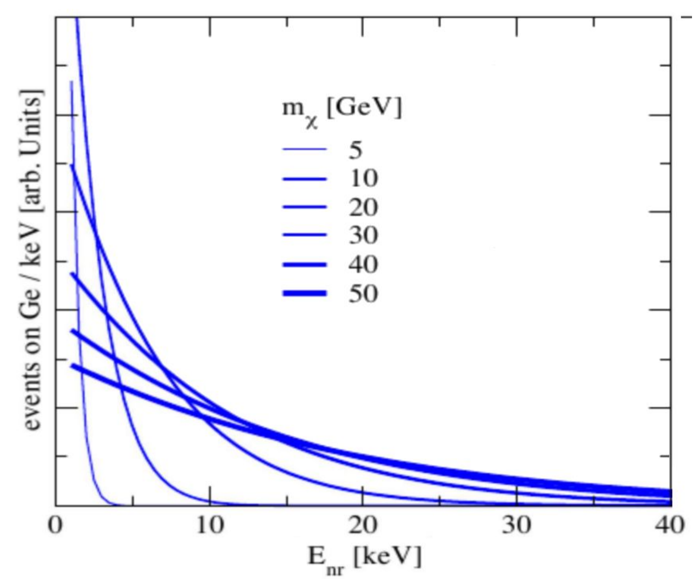
Direct WIMP Search

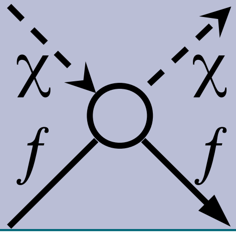
Elastic Scattering of WIMPs off target nuclei
→ nuclear recoil



Recoil Spectra:







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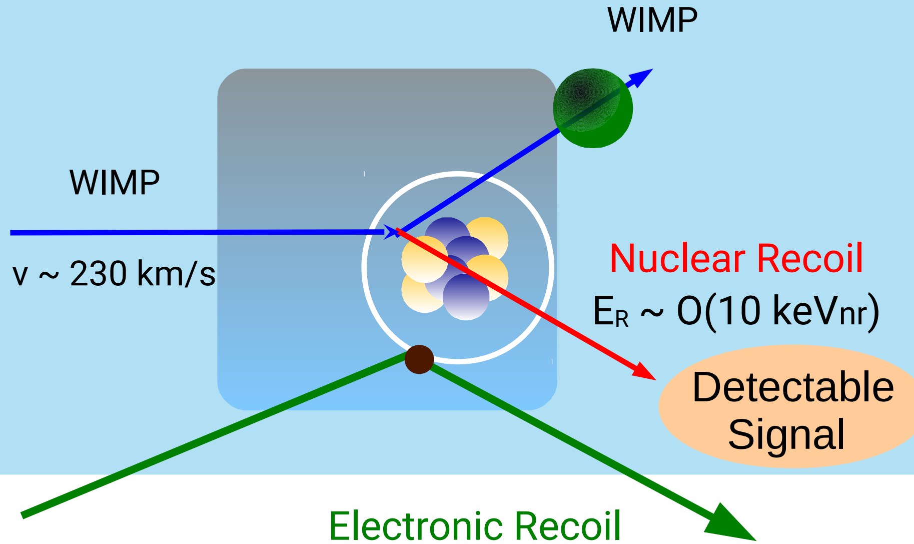
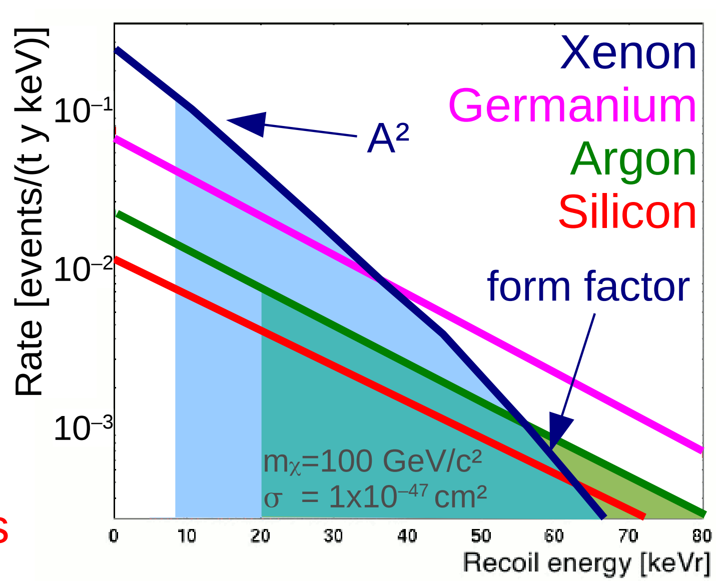
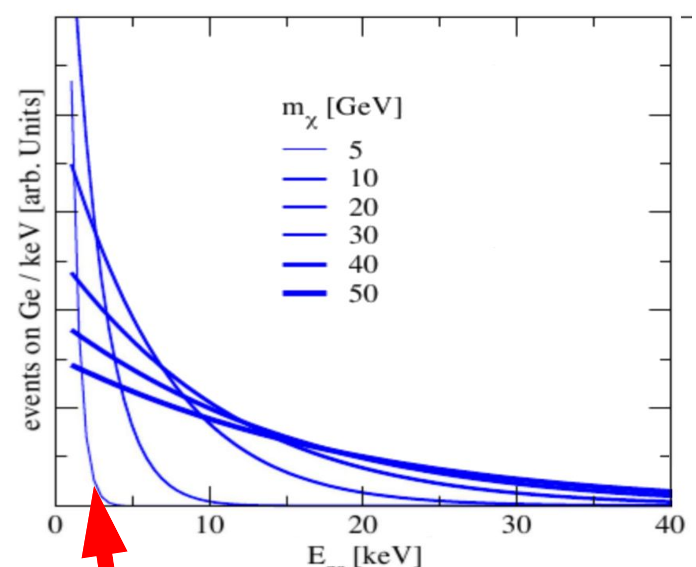


Recoil Spectra:





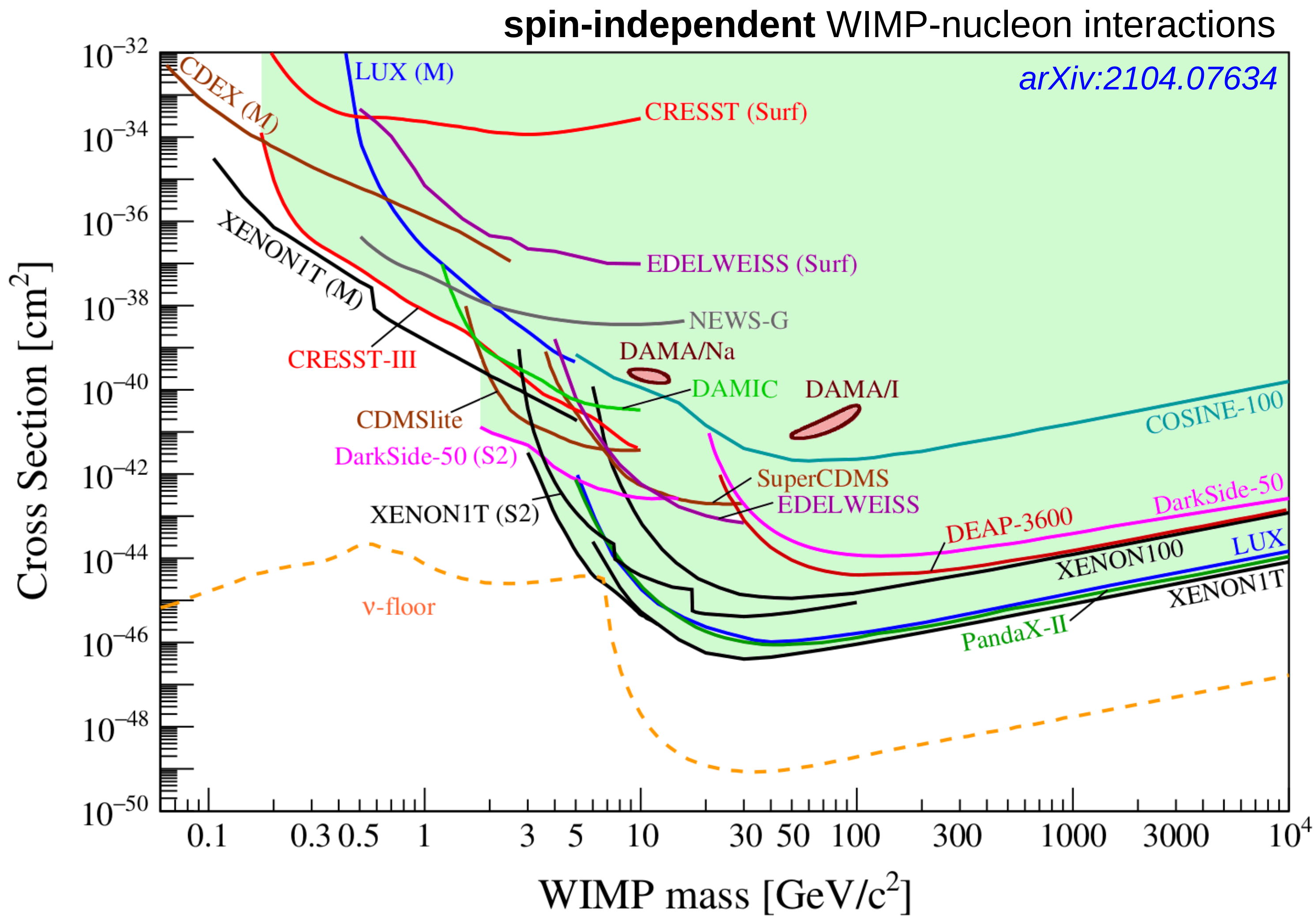
tiny!

→ low backgrounds
→ large exposures

tiny!

low mass → low threshold

Current Status

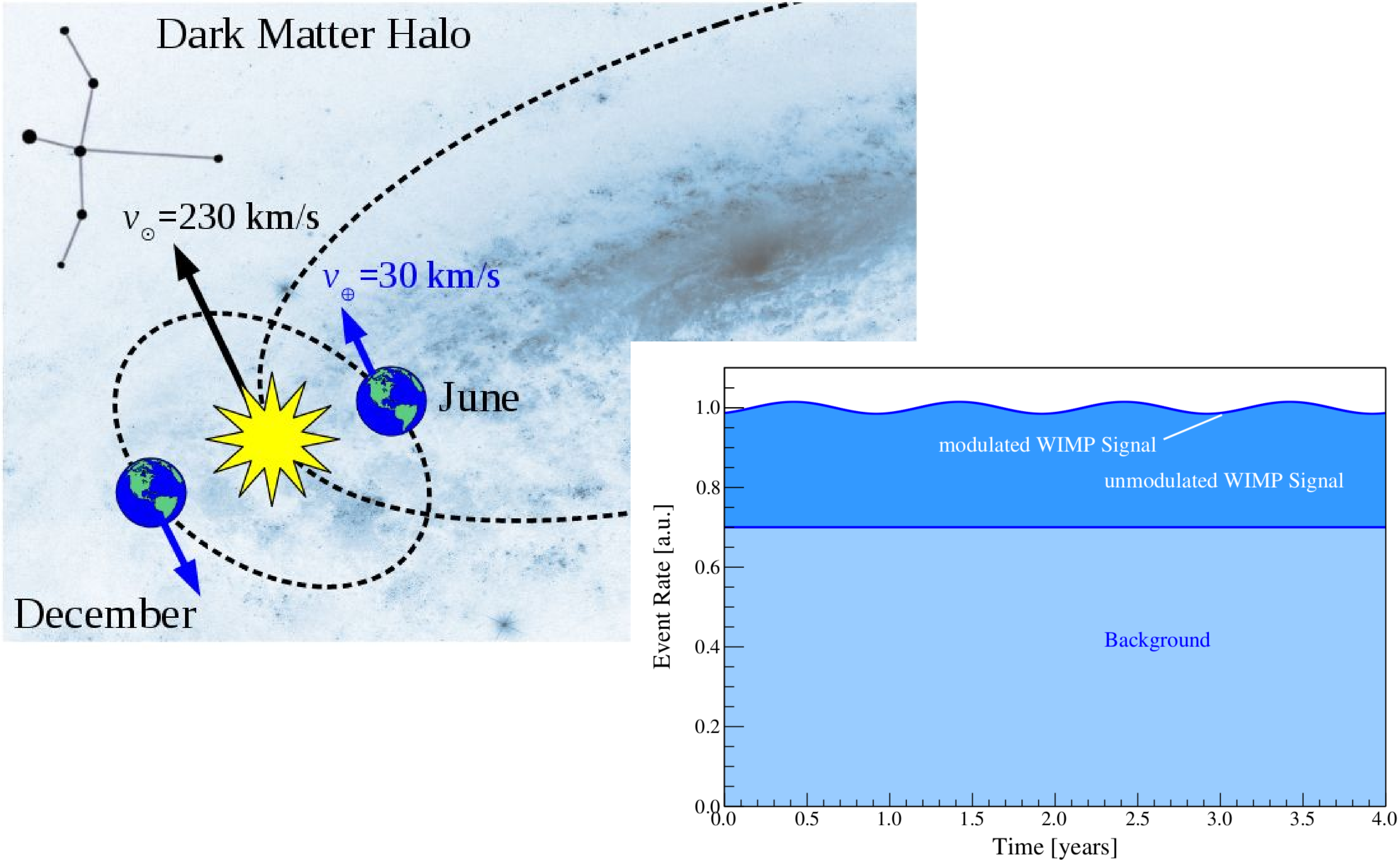


10^{14}

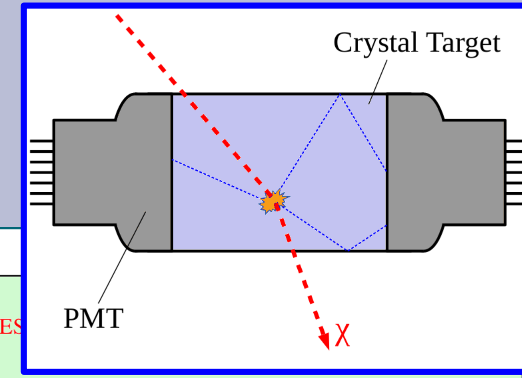
Exposure+ Background

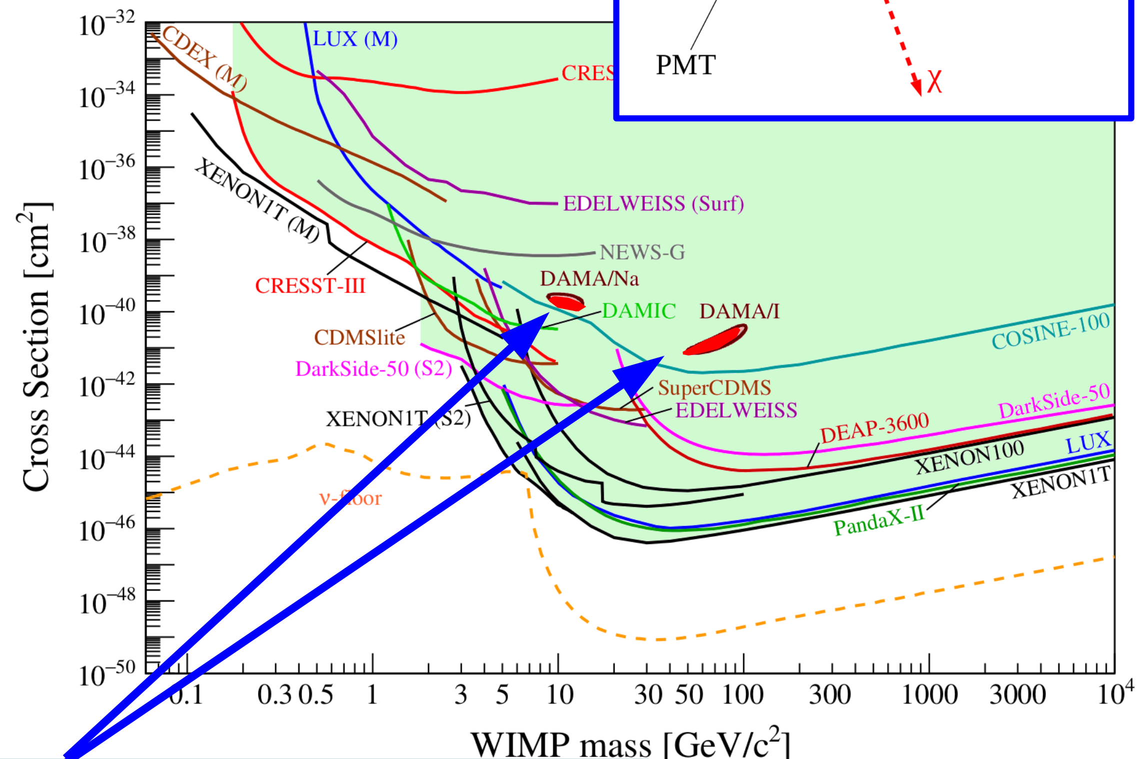
Threshold

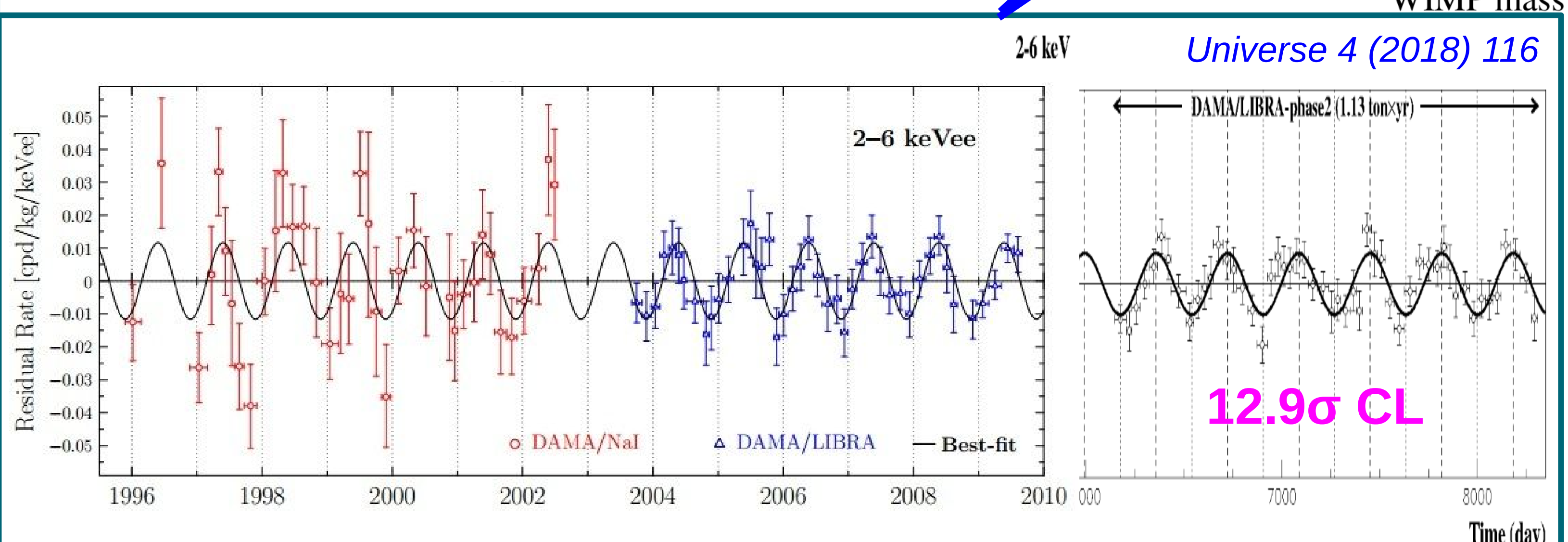
Annual Modulation



DAMA/LIBRA



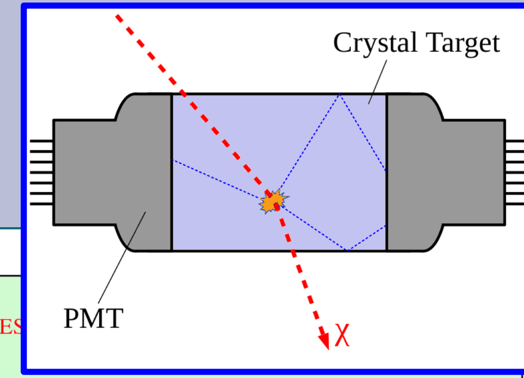




~250 kg NaI(Tl)

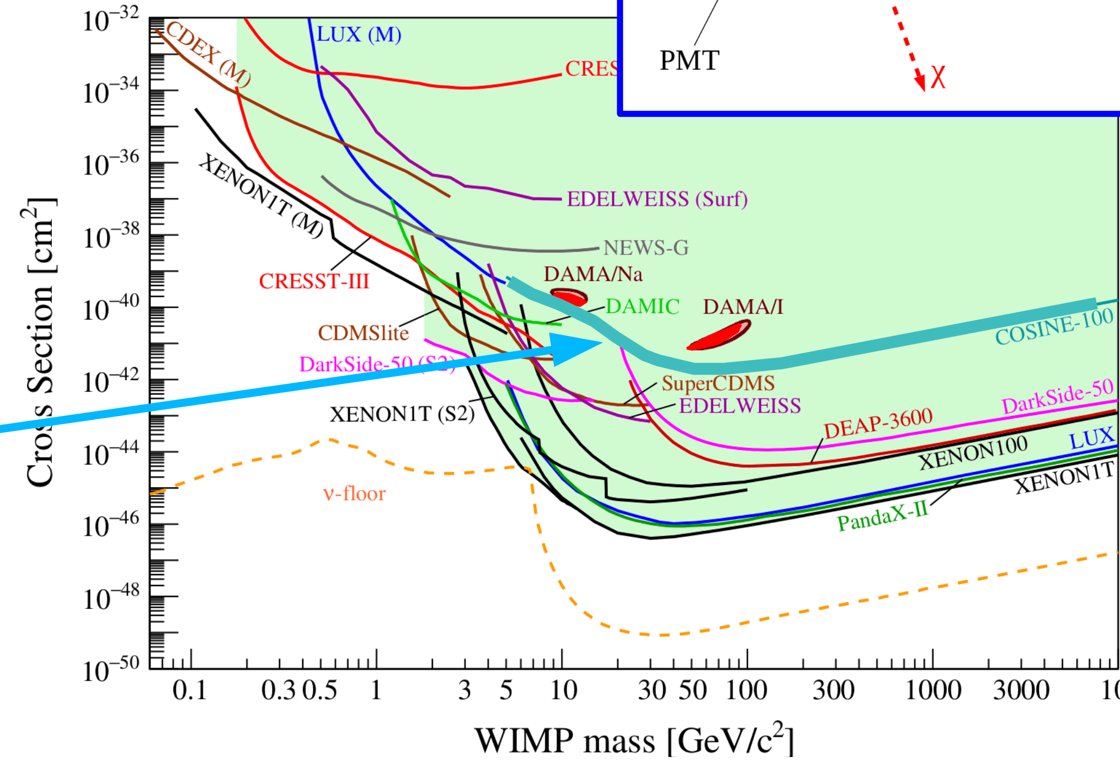
New data:
– 1 keVee threshold
– 6 annual cycles

DAMA vs Others



Challenged by

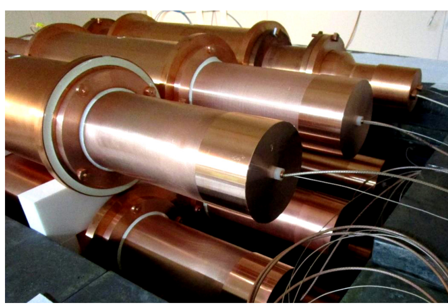
- SI-induced NRs ruled out by many experiments with lower backgrounds (and NR identification)
- Modulation from DM-e scattering challenged by **LXe TPCs**
- **COSINE100** (NaI)
  Nature 564, 83 (2018), PRL 123, 031302 (2019)
  excludes DAMA interpreted as SI interaction with standard halo model



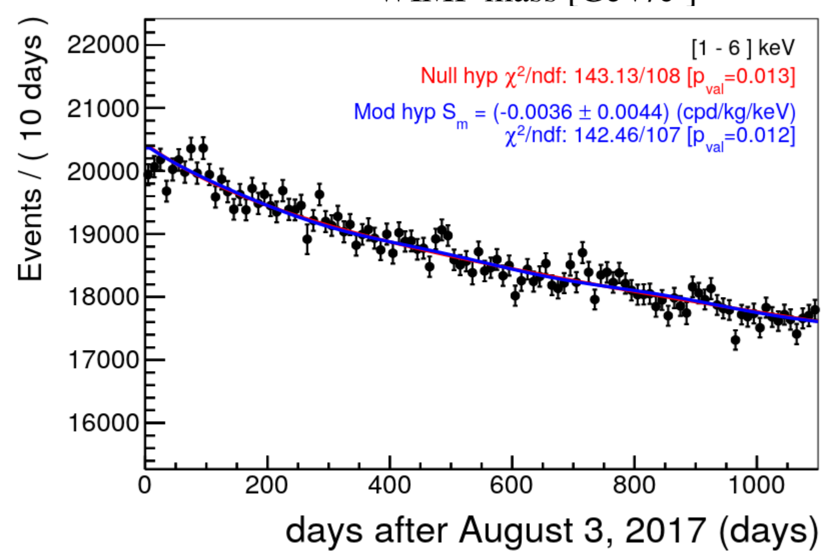
NEW!

ANAIS (NaI)

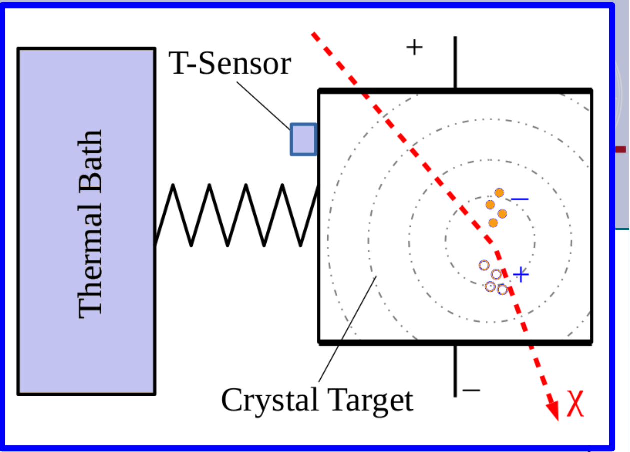
PRD 103, 102005 (2021)



- 3 year data: 314 kg x y exposure
  same threshold but ~3x higher background
- data consistent with no modulation;
  incompatible with DAMA at 3.3σ [1-6 keV]



Cryogenic Bolometers



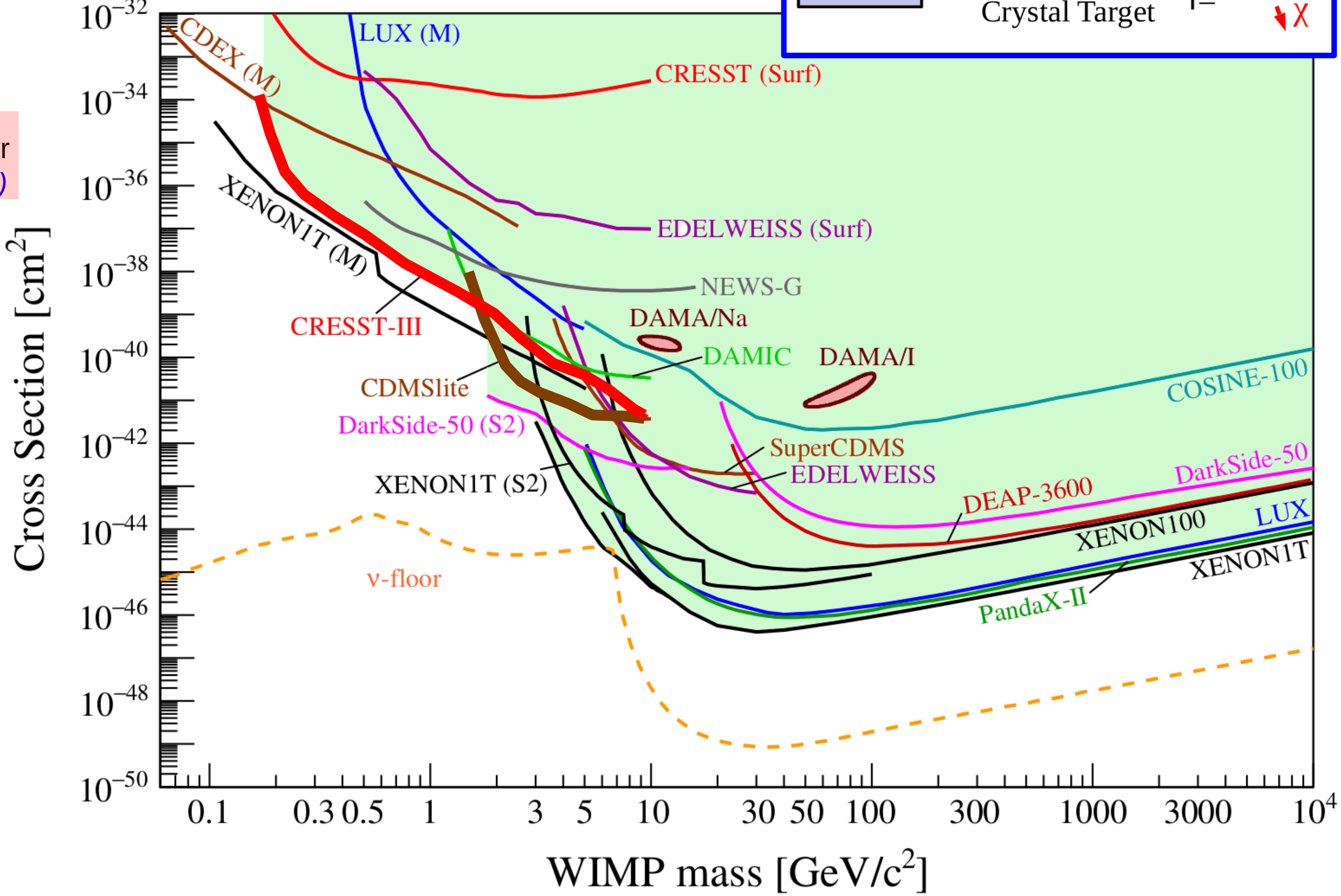
CRESST
Scintillating Bolometer

24g $CaWO_4$, E_{thresh}=30 eV_{nr}
PRD 100, 102002 (2019)

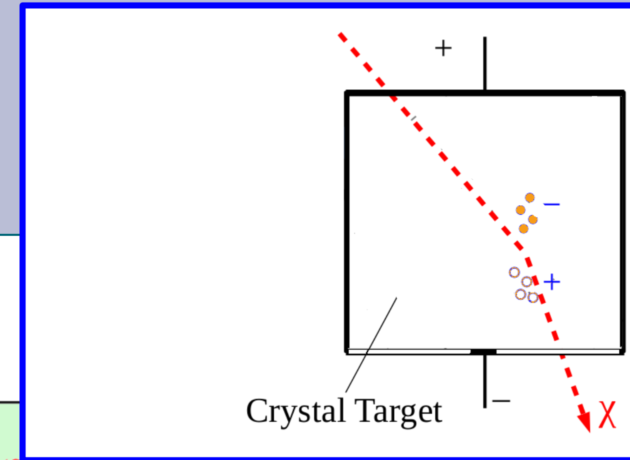
CDMS / EDELWEISS
Ge Bolometers

„Lite“-Mode: convert charge into heat → reduce threshold but no ER rejection

CDMSLite
600g Ge, E_{thresh}=70 eV
PRD 99, 062001 (2019)



P-type Point Contact Ge



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24g $CaWO_4$, E_{thresh}=30 eV_{nr}

PRD 100, 102002 (2019)

CDMS / EDELWEISS

Ge Bolometers

„Lite"-Mode: convert charge into heat → reduce threshold but no ER rejection

CDMSLite

600g Ge, E_{thresh}=70 eV

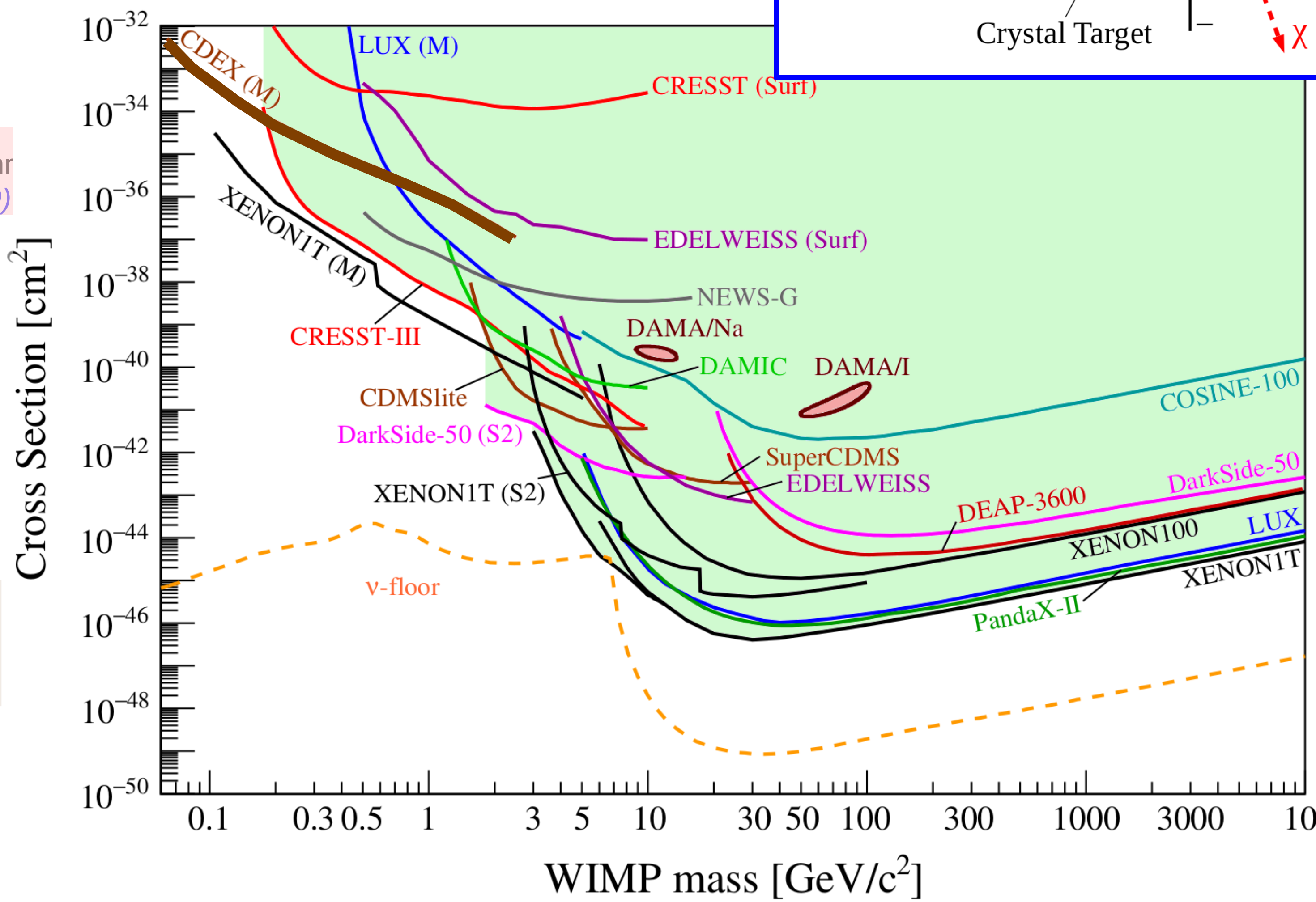
PRD 99, 062001 (2019)

CDEX

p-type point contact Ge

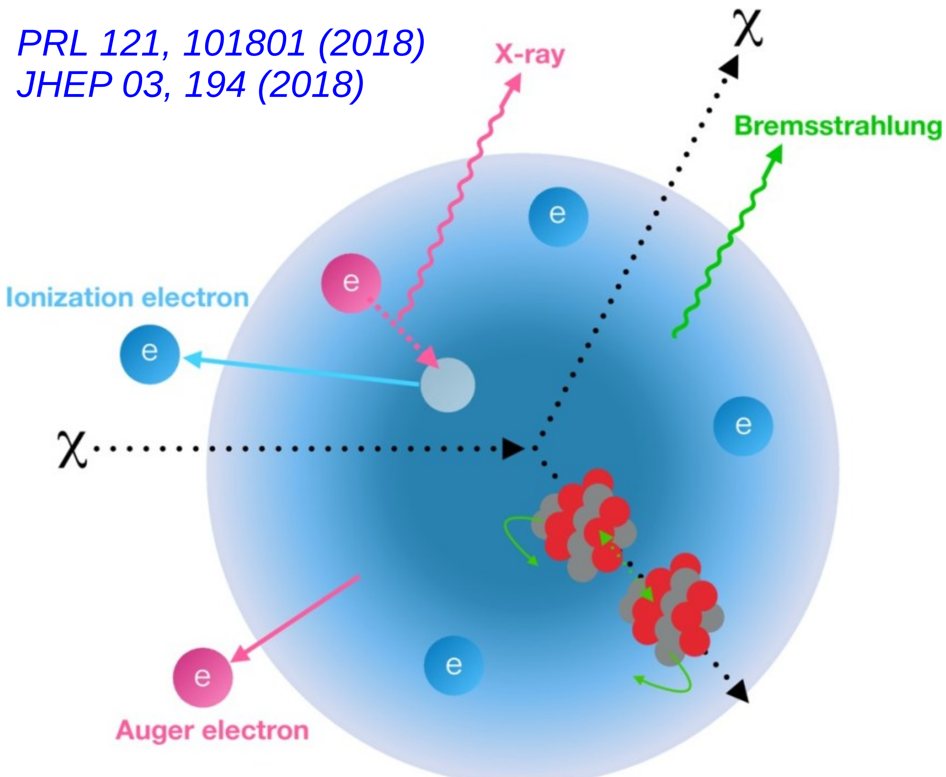
939g Ge, E_{thresh}=160 eV

PRL 123, 161301 (2019)

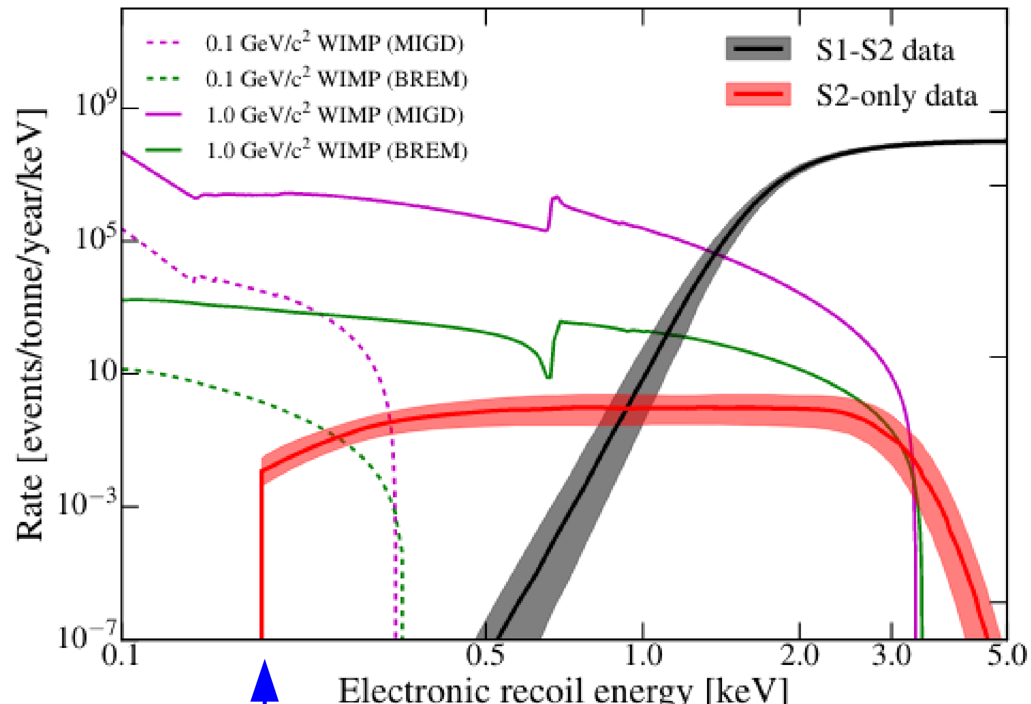


Migdal Effect

PRL 121, 101801 (2018)
JHEP 03, 194 (2018)



XENON1T: PRL 123, 241803 (2019)

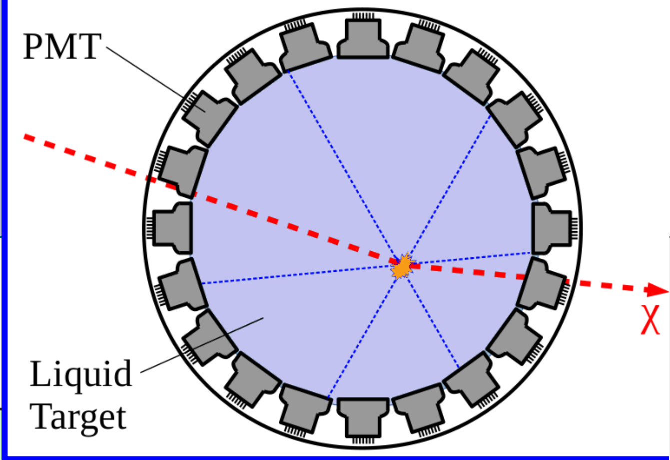


~180 eV (~4.5 electrons)

– exploit expected effects after nuclear recoil
→ very low threshold

– caveat: effect not yet observed in calibration

Noble Liquids: Single Phase



Xenon and Argon are excellent szintillators
→ realize large target masses in liquid state

XMASS

832kg Xe

PLB 789, 45 (2019)

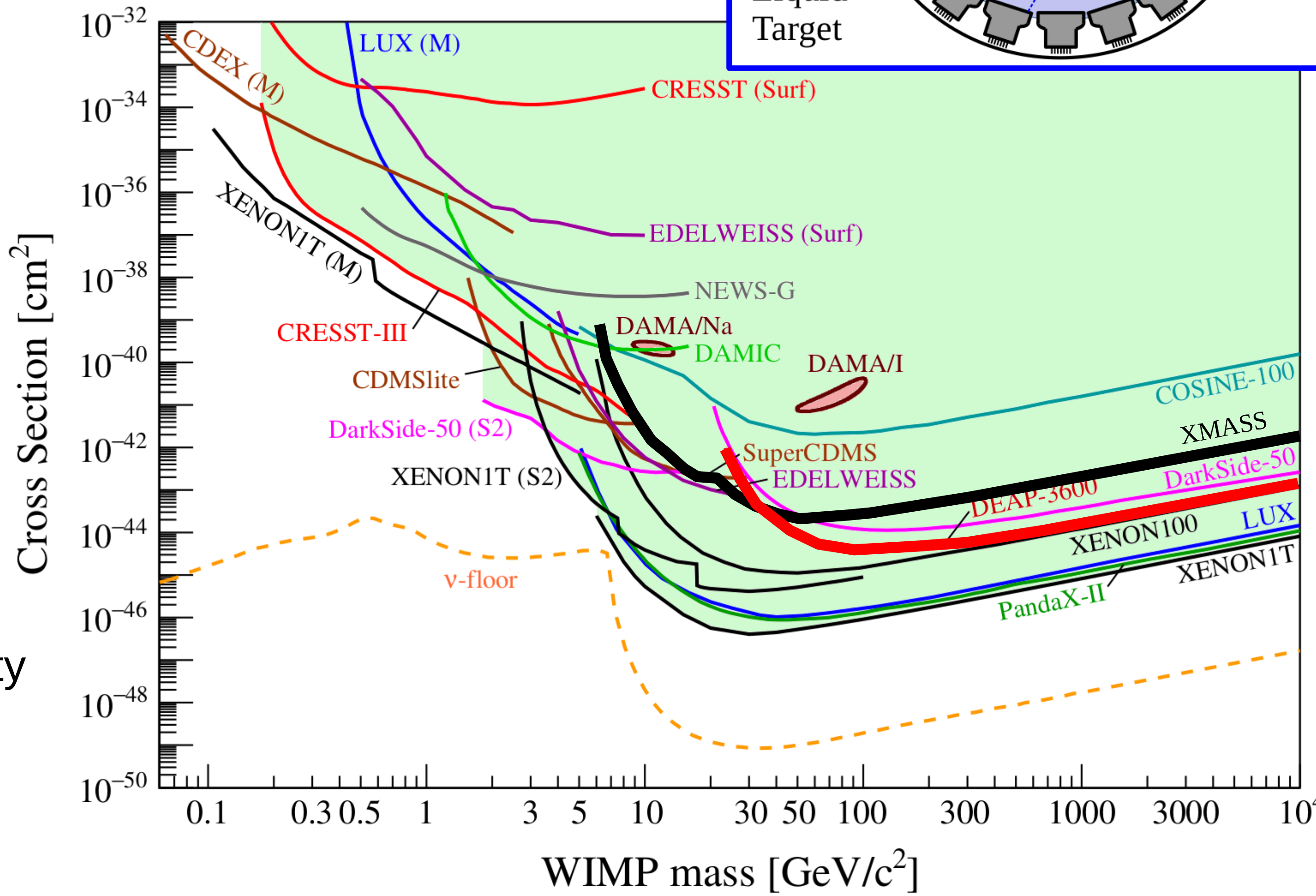
DEAP-3600

3280kg Ar

PRD 100, 022004 (2019)

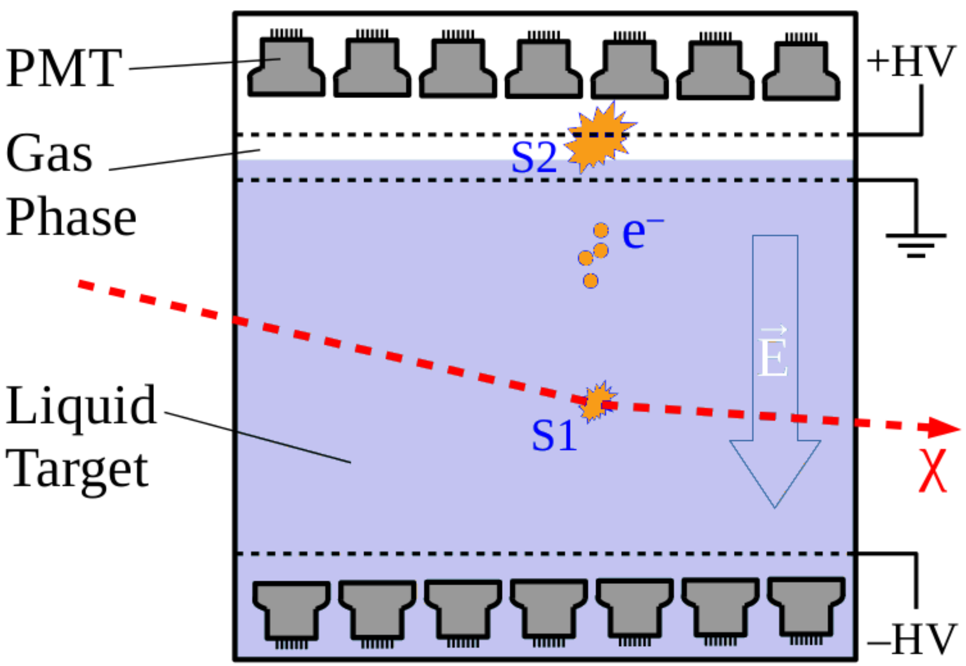
→ despite large target masses, both projects have no leading sensitivity

→ consolidation of field:
DEAP joined DarkSide
XMASS joined XENON



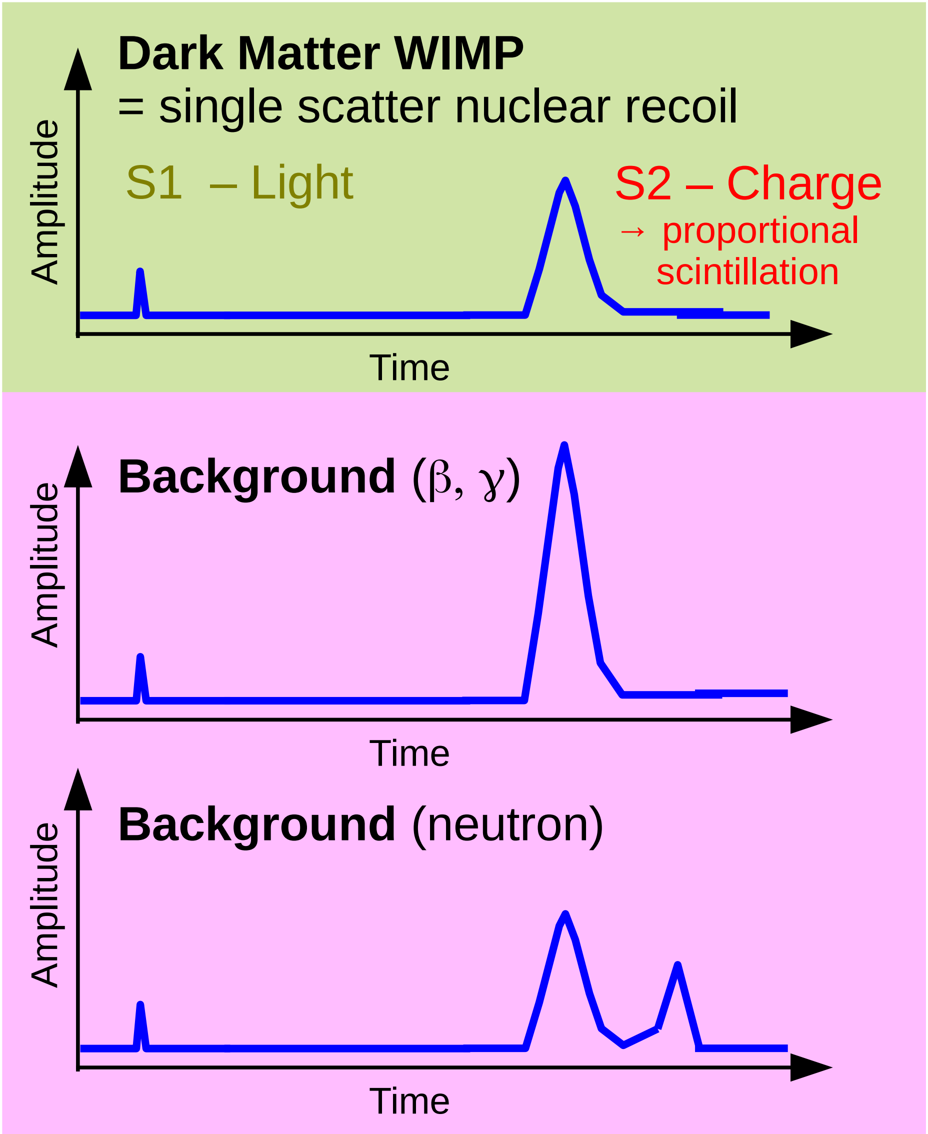
Dual-Phase TPC

Xenon and Argon are excellent **szintillators** and can be **ionized** easily



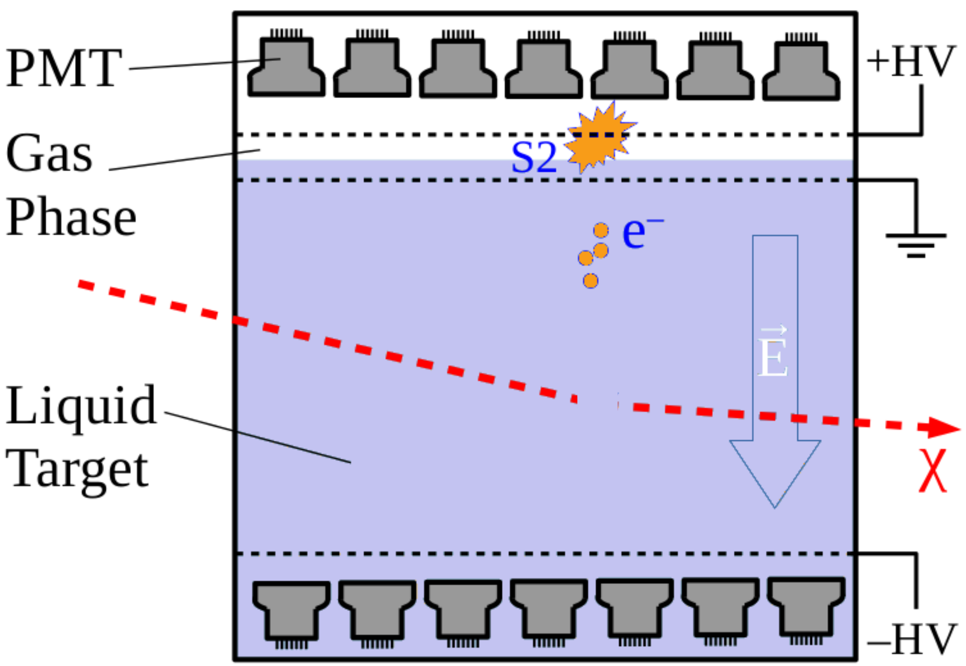
- 3d position reconstruction
  → target fiducialization
- background rejection

TPC = time projection chamber



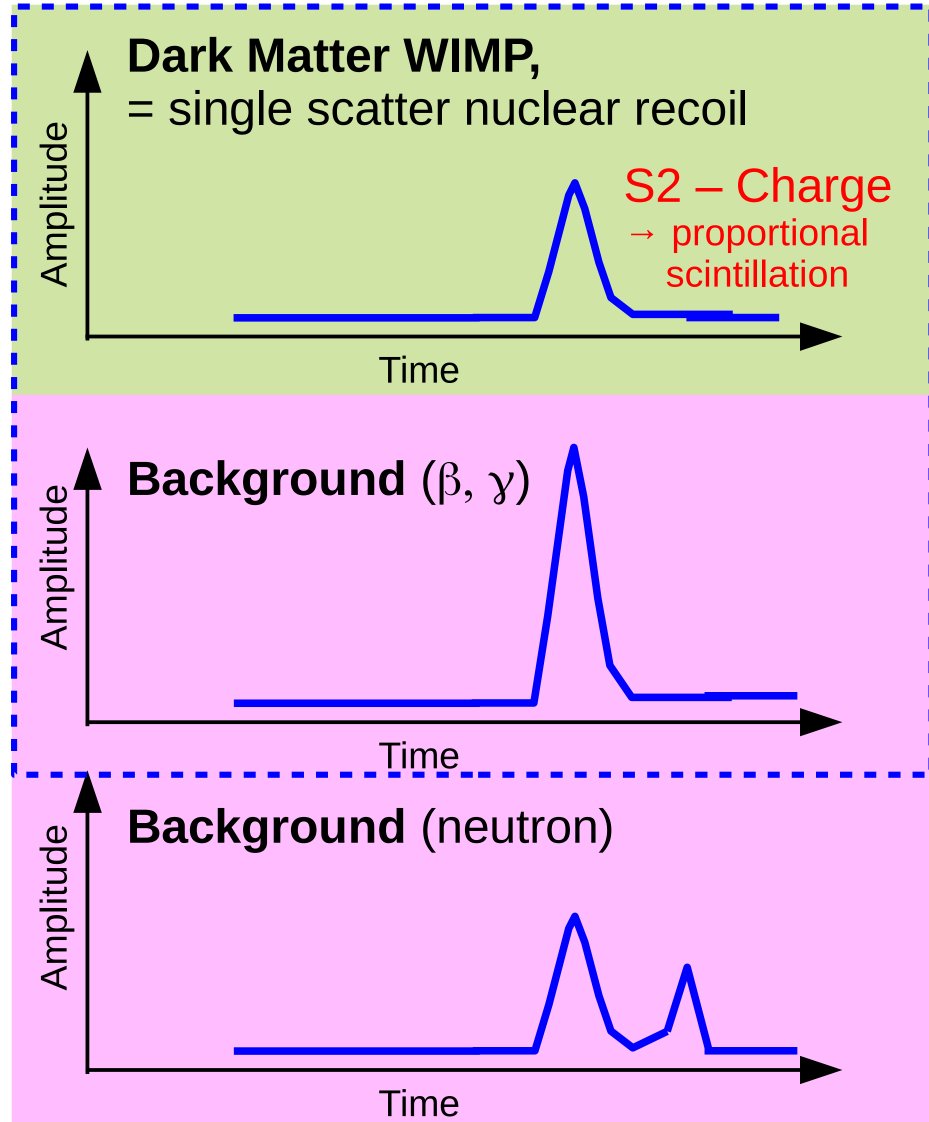
Dual-Phase TPC – Charge Only

Xenon and Argon ~~are excellent **szintillators** and~~ can be **ionized** easily

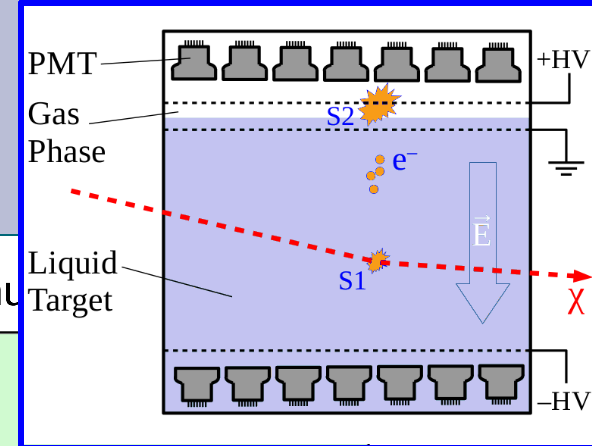


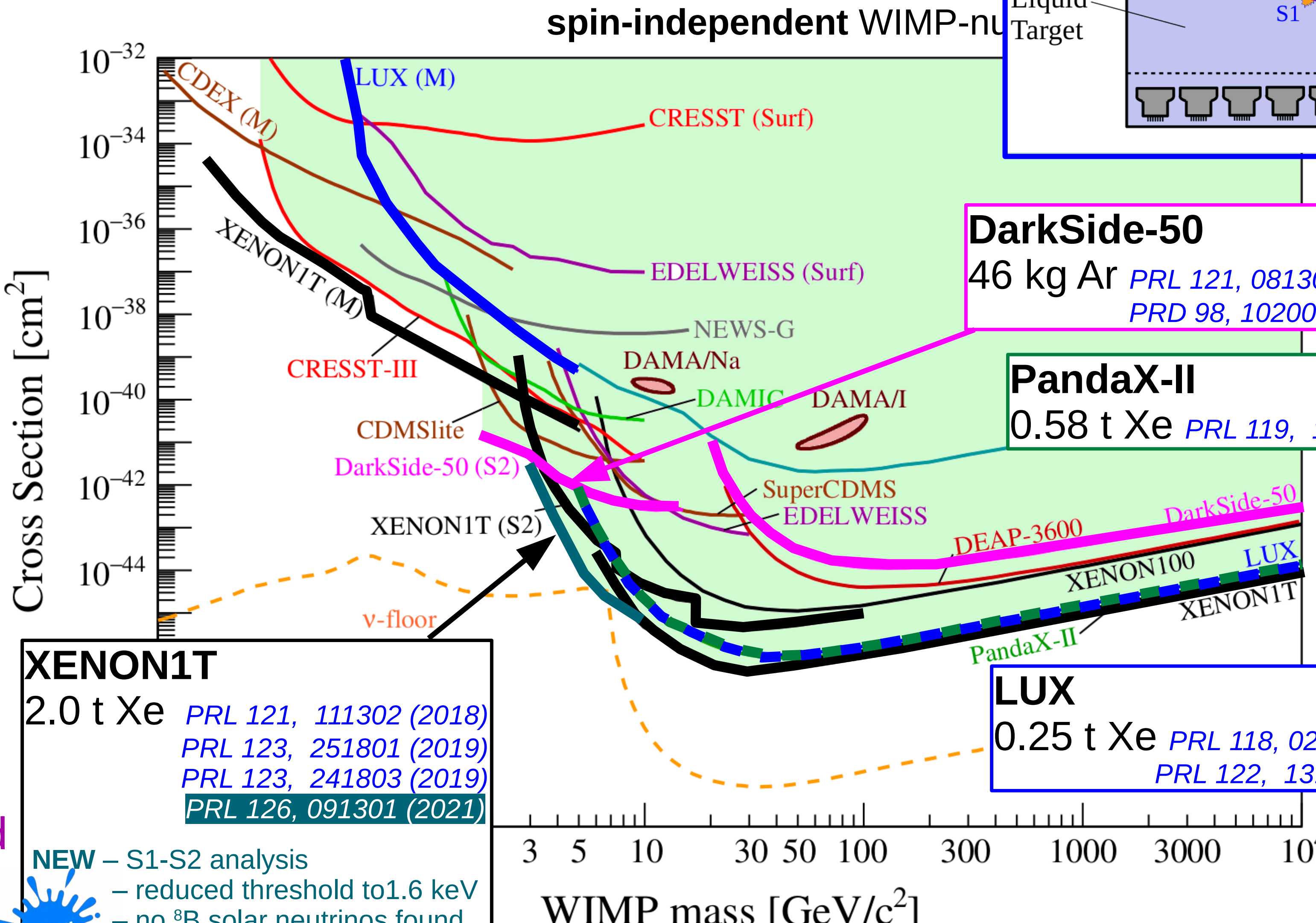
- **2d** position reconstruction
  → **limited** target fiducialization
- ~~background rejection~~
- reduced threshold

TPC = time projection chamber



Noble Liquids: Dual Phase





DarkSide-50
46 kg Ar *PRL 121, 081307 (2018)*
PRD 98, 102006 (2018)

PandaX-II
0.58 t Xe *PRL 119, 181302 (2017)*

XENON1T
2.0 t Xe *PRL 121, 111302 (2018)*
PRL 123, 251801 (2019)
PRL 123, 241803 (2019)
PRL 126, 091301 (2021)

NEW – S1-S2 analysis
– reduced threshold to1.6 keV
– no ^{8}B solar neutrinos found

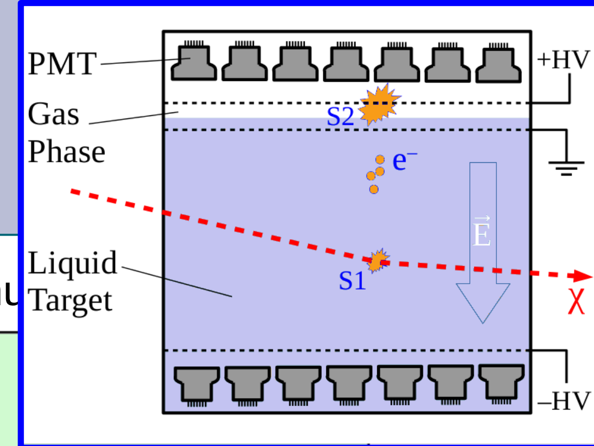
NEW!

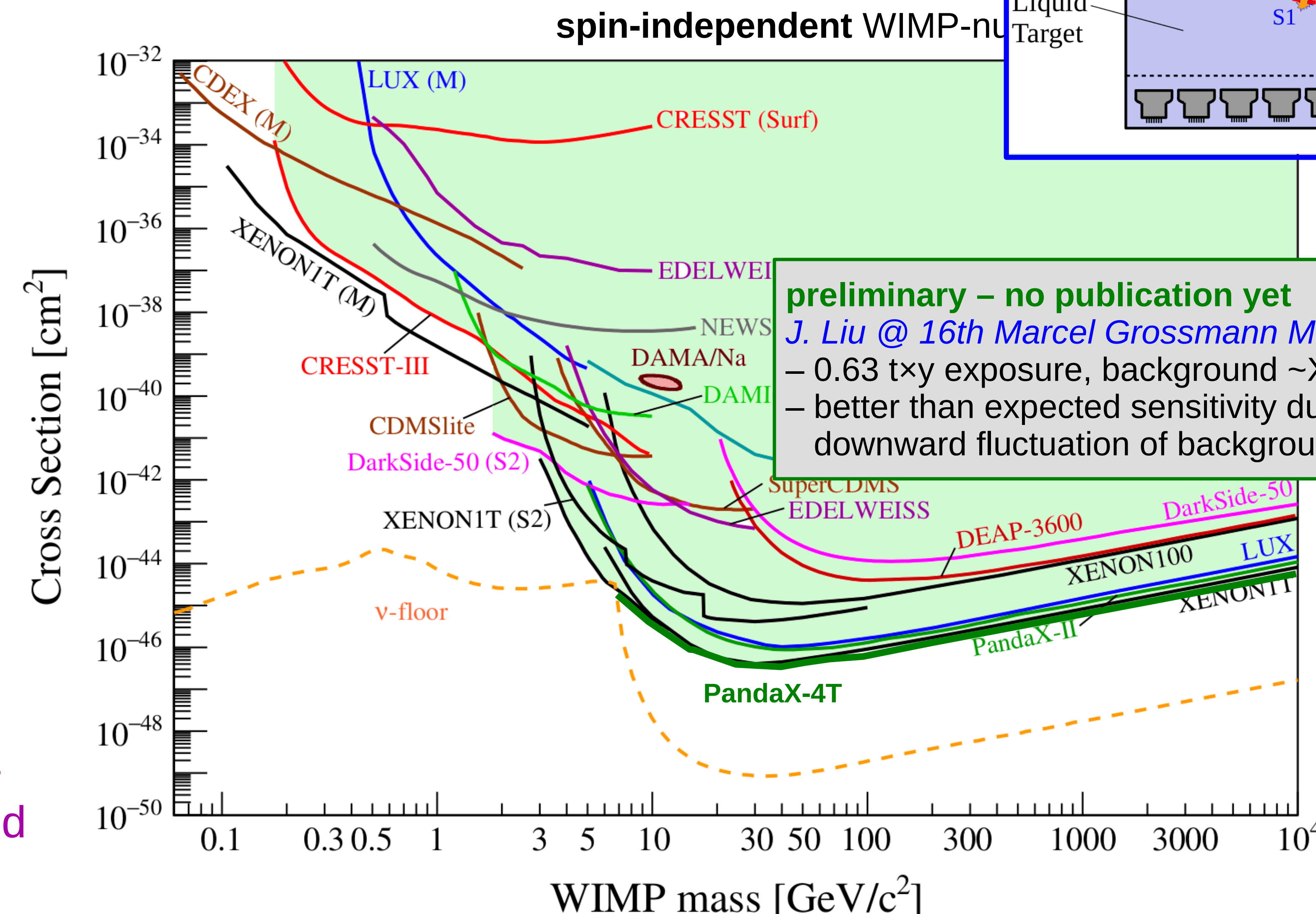
LUX
0.25 t Xe *PRL 118, 021303 (2017)*
PRL 122, 131301 (2019)

Exposure+ Background

Threshold

PandaX-4T – New Result?





preliminary – no publication yet

J. Liu @ 16th Marcel Grossmann Meeting

– 0.63 t×y exposure, background ~XENON1T

– better than expected sensitivity due to downward fluctuation of background

NEW!

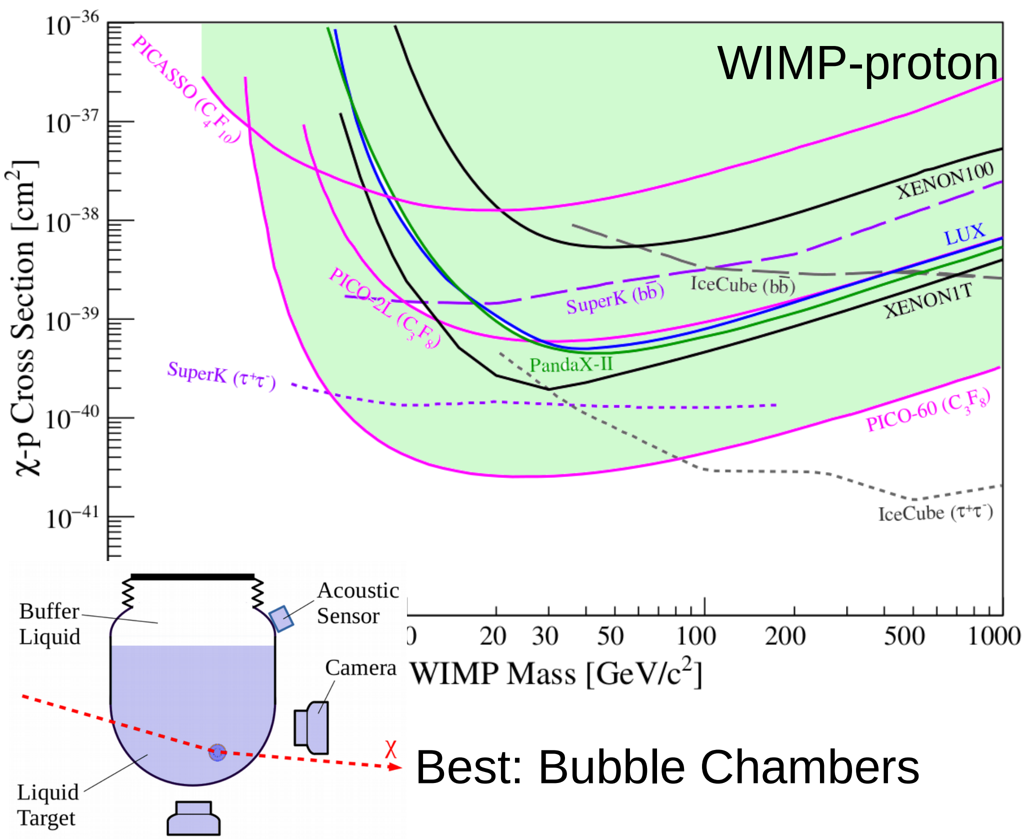
Exposure+ Background

Threshold

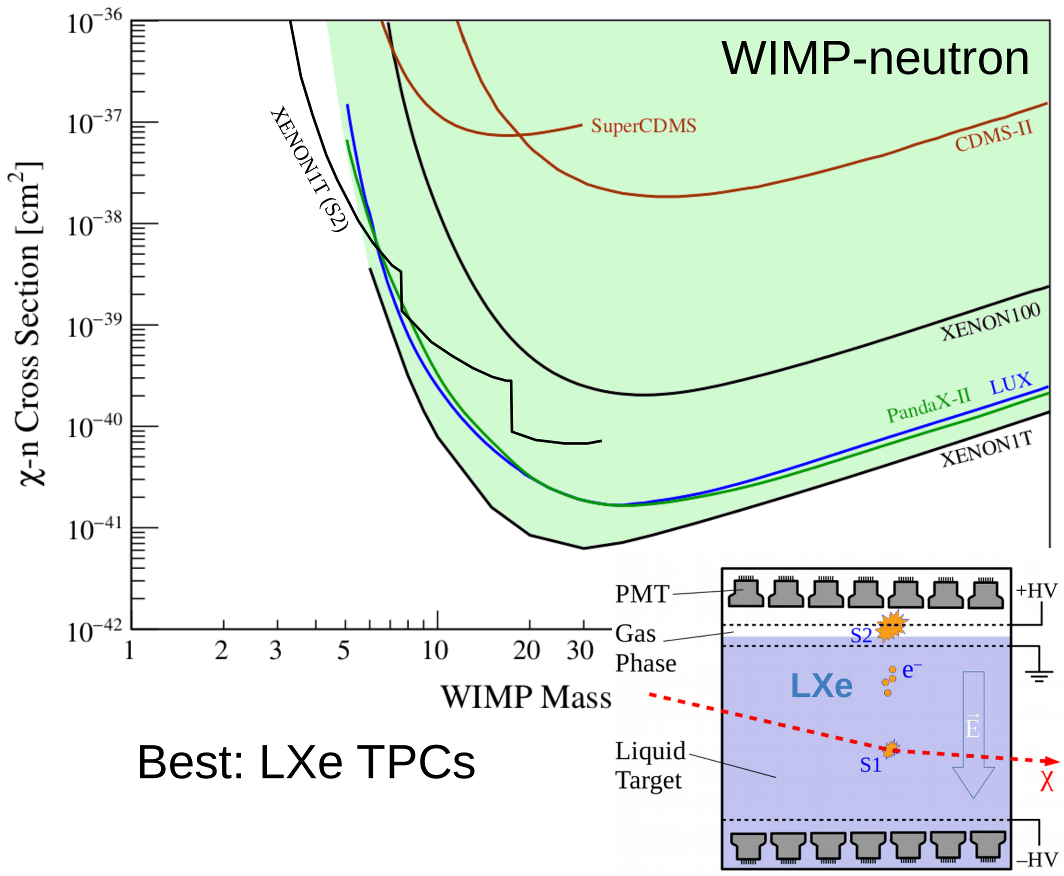
Status Spin-Dependent Couplings

- coupling of WIMP to unpaired nucleon spins
- traditionally separated in proton-only and neutron-only
- same parameter space explored by indirect and collider searches

Isotope	Abundance	Spin	Unpaired Nucleon	Relative Strength
^{7}Li	92.6%	3/2	proton	12.8
^{19}F	100.0%	1/2	proton	100.0
^{23}Na	100.0%	3/2	proton	1.3
^{29}Si	4.7%	1/2	neutron	9.7
^{73}Ge	7.7%	9/2	neutron	0.3
^{127}I	100.0%	5/2	proton	0.3
^{131}Xe	21.3%	3/2	neutron	1.7



Best: Bubble Chambers



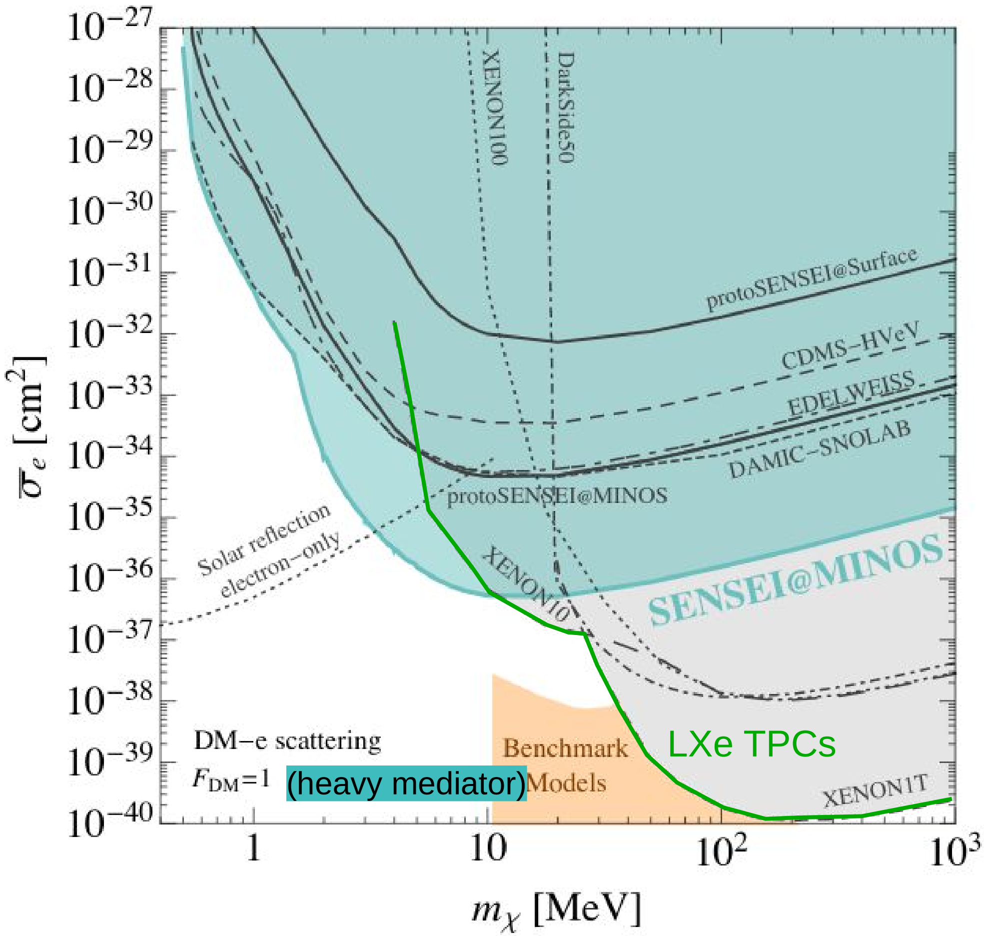
Best: LXe TPCs

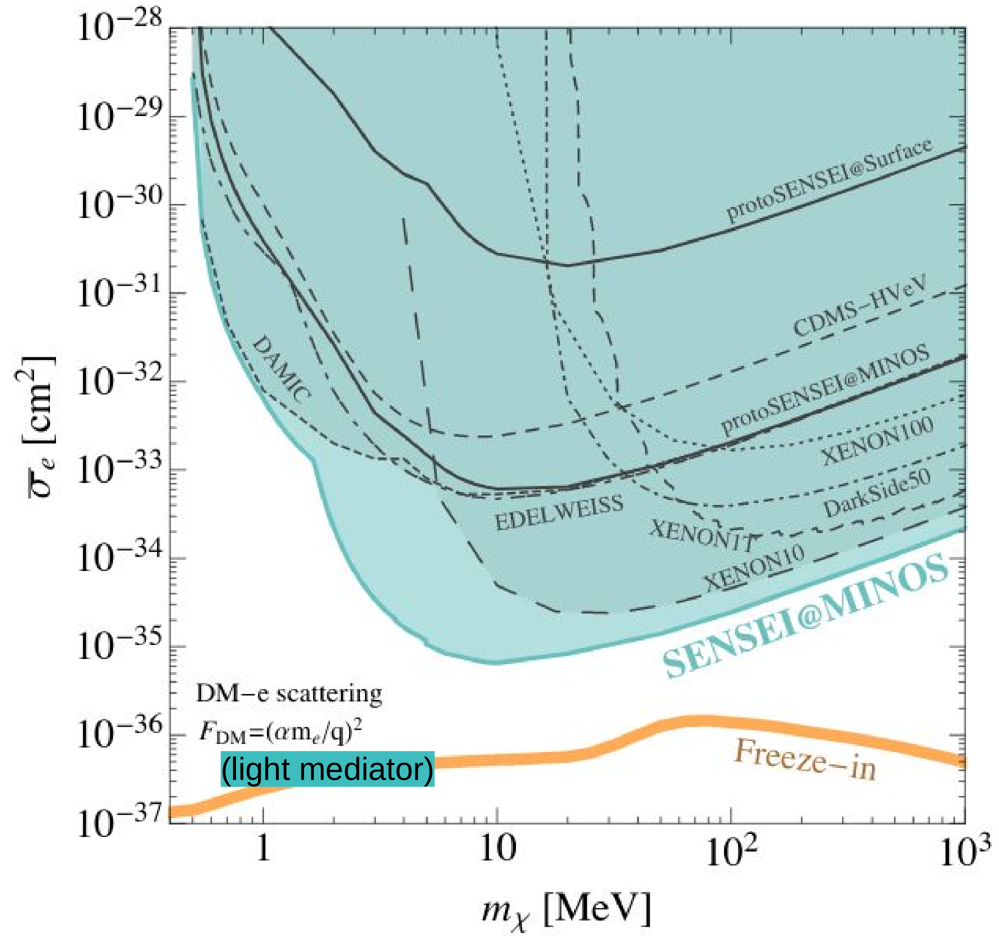
Status: WIMP-e⁻ Scattering

- Detectors with single-e⁻ sensitivity required
- **SENSEI**: ~2g Si-CCD provides best limits >500 keV/c²

PRL 125, 171802 (2020)

NEW!

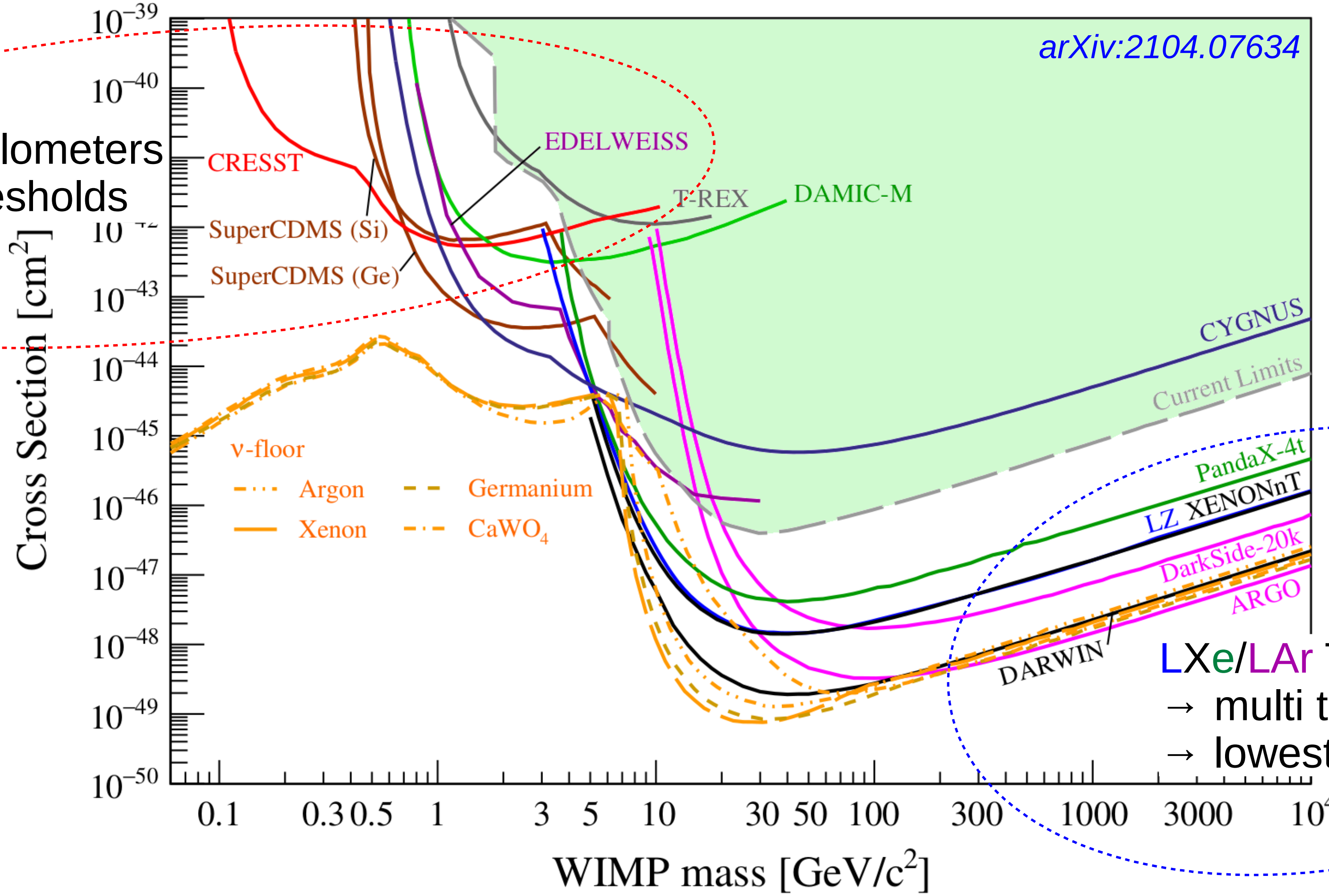




Upcoming Projects

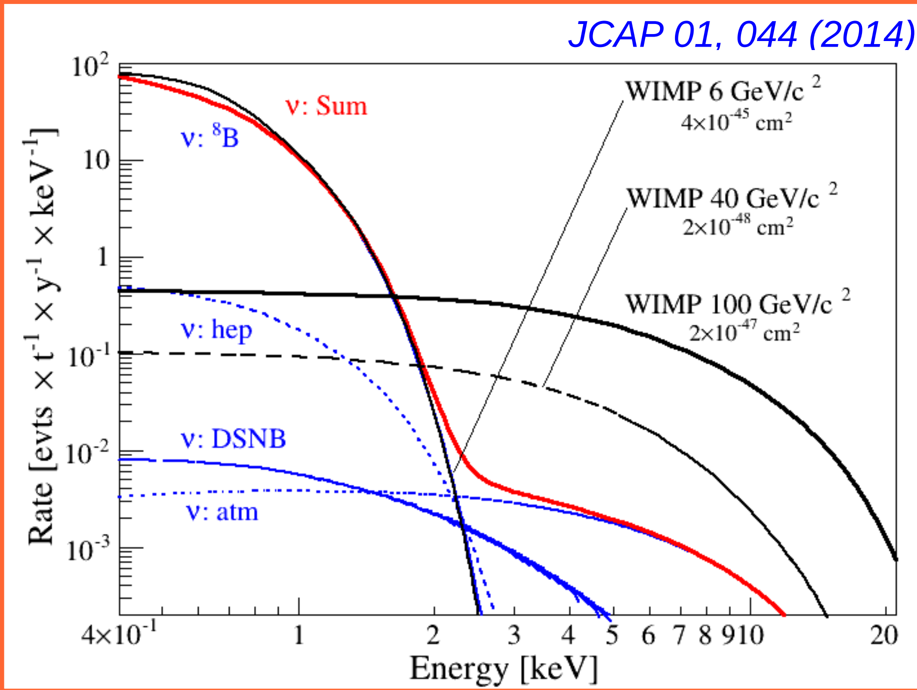
spin-independent WIMP-nucleon interactions – **projections**

Cryogenic Bolometers
→ lowest thresholds

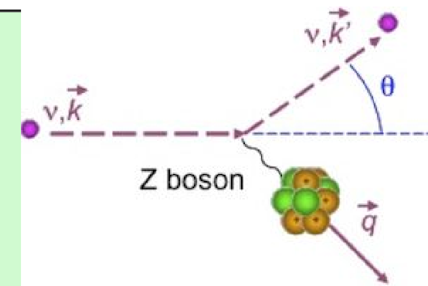


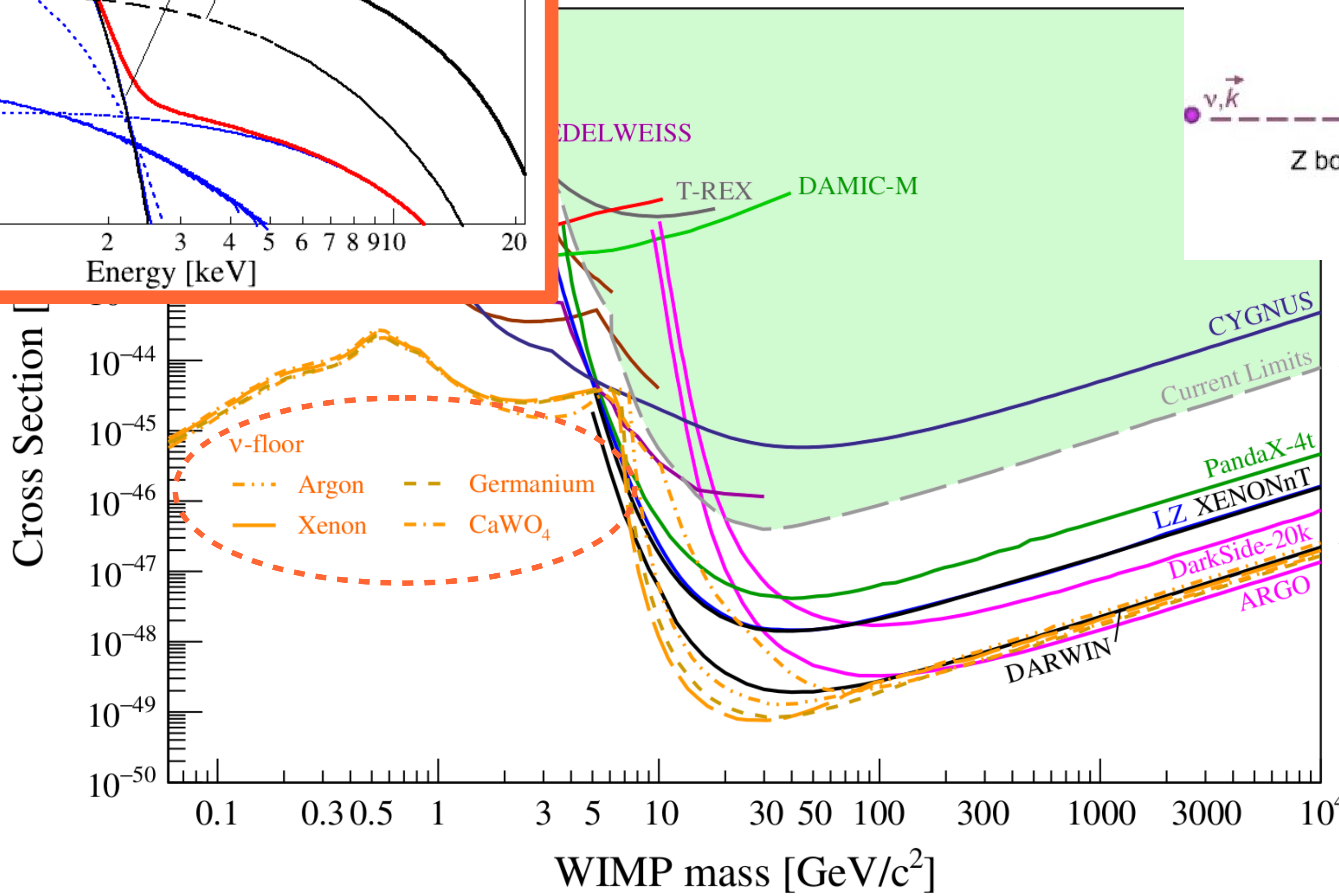
LXe/LAr TPCs
→ multi ton-scale
→ lowest backgrounds

The Limit



Coherent neutrino-nucleus scattering will dominate
→ **ultimate background** for direct detection





◄ 1 t×y (LXe)

◄ 200 t×y (LXe)

Exposures of ~200 t×y (LXe), ~1000 t×y (LAr) needed to „reach" atm-ν ~~floor~~ *fog*

DARWIN+LZ join forces towards common future detector

NEW!

Direct Axion Detection

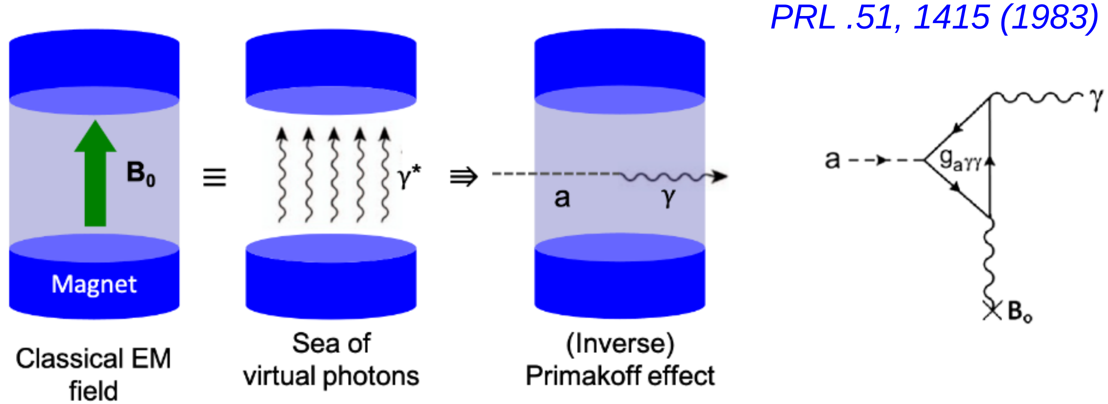
- Presence of axions modify Maxwell‘s eq.

$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma} \nabla a \cdot \mathbf{B}$$
$$\nabla \times \mathbf{B} - \dot{\mathbf{E}} = j + g_{a\gamma\gamma} \left(\dot{a}\mathbf{B} + \nabla a \times \mathbf{E} \right)$$

axion-induced charge and current densities
nb: $\nabla a \approx 0$ for DM axions

- Axion-Photon Conversion

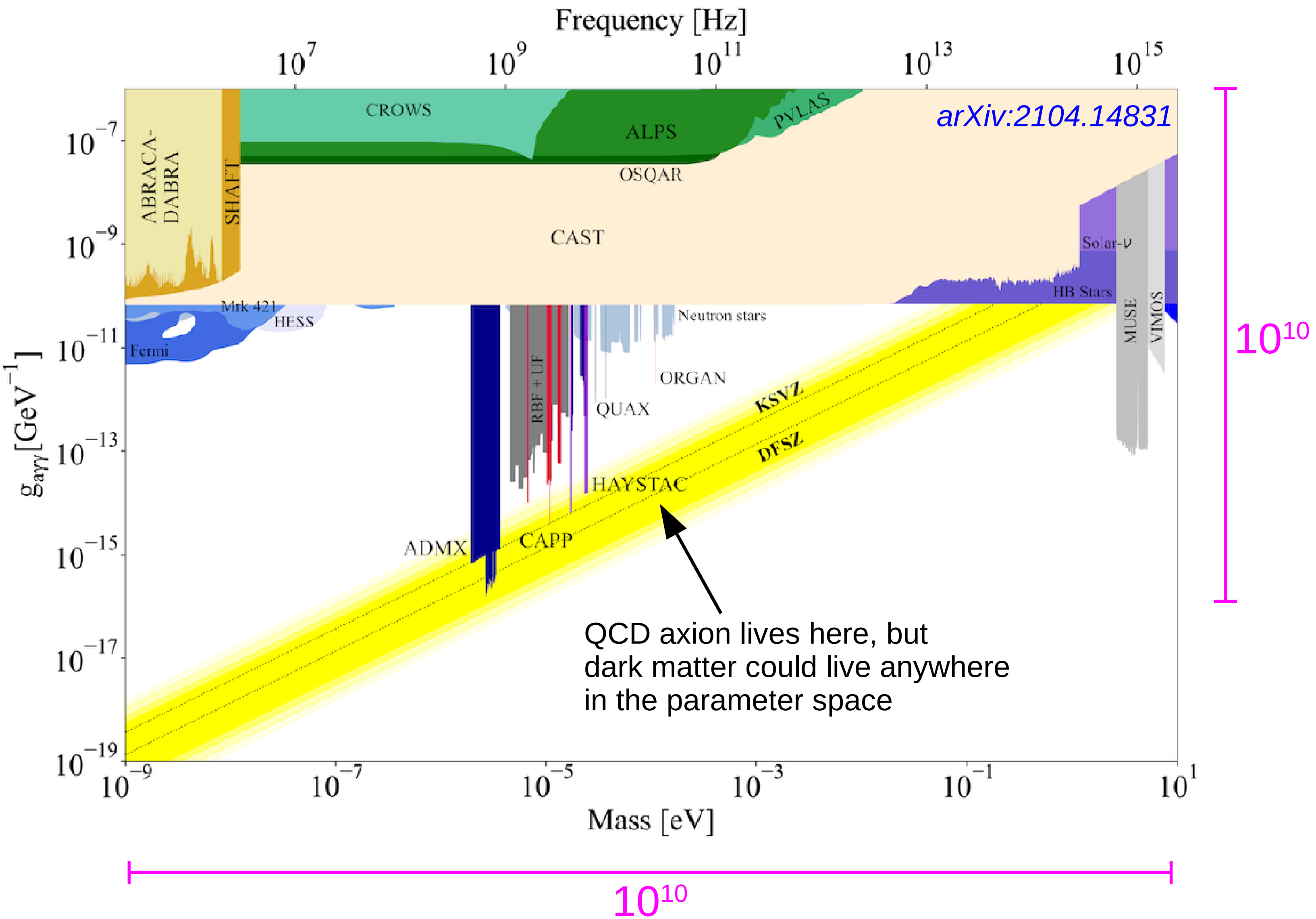
PRL .51, 1415 (1983)



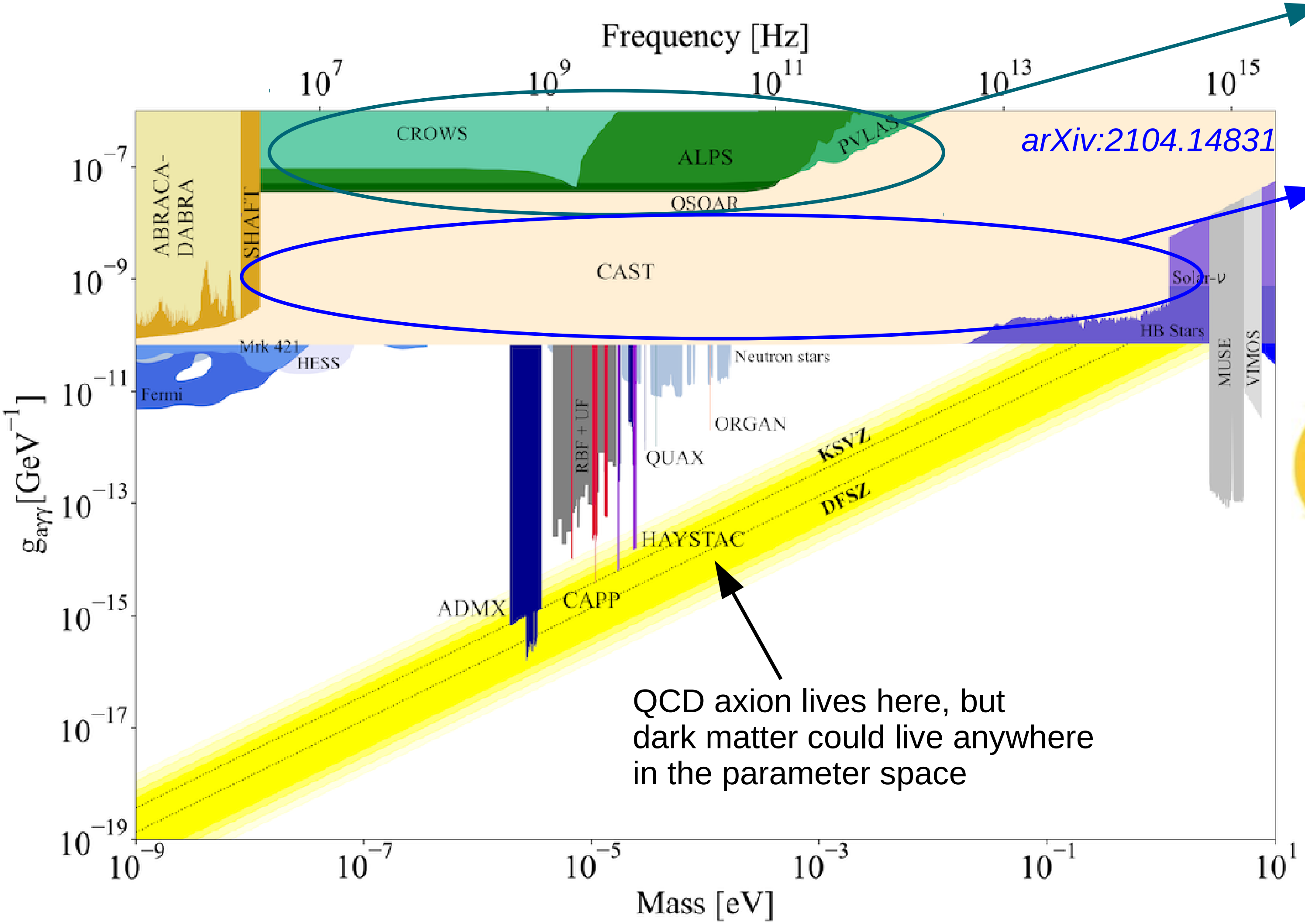
- EM interaction mediates axion-photon coupling

→ too many experimental approaches and projects to cover properly

Status and Search Strategies



Status and Search Strategies

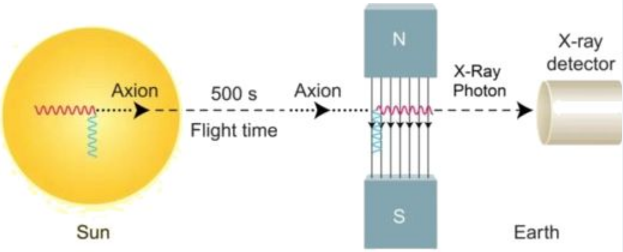


arXiv:2104.14831

QCD axion lives here, but
dark matter could live anywhere
in the parameter space

Lab Experiments
→ produce and
detect axions

Helioscopes
solar photons (keV)
covert to axions in B-field
→ detection via Primakoff



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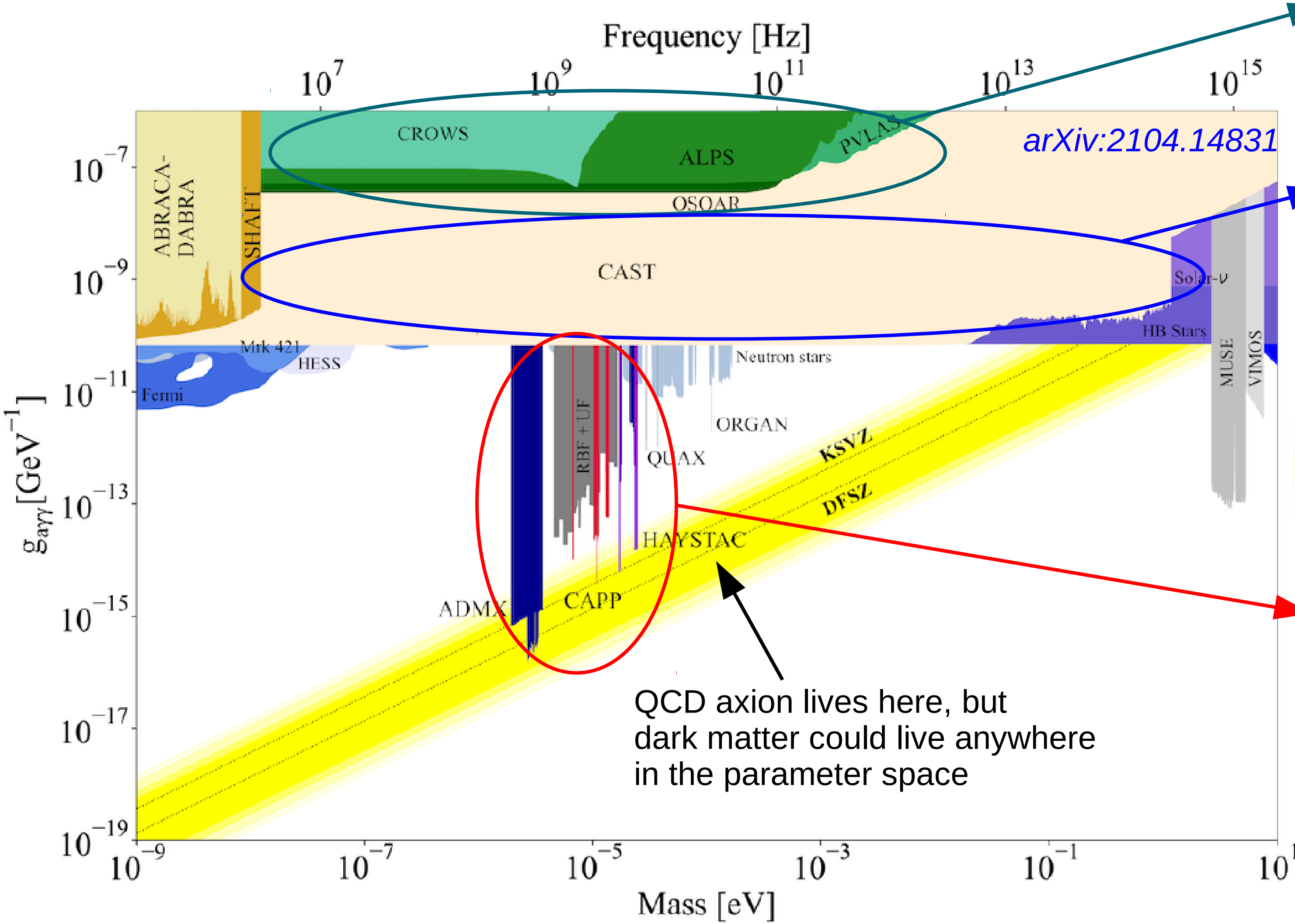

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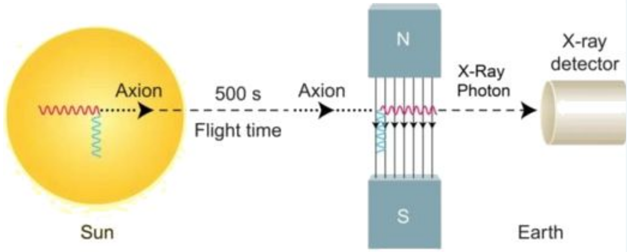
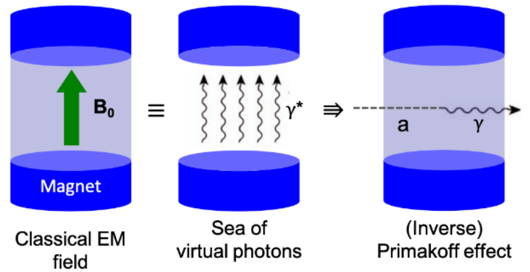


Haloscopes
dark matter axions
convert to microwave
photons in cavity



Haloscopes: Figure of Merit

- axion mass unknown → scan all masses (~frequencies ν_a)

- FoM: search rate („time needed to explore a mass range at a given sensitivity“)

$$\frac{df}{dt} = 1.2\,\frac{\mathrm{GHz}}{\mathrm{year}}\left(\frac{5}{snr}\right)^2\left(\frac{0.15\,\mathrm{K}}{T_{\mathrm{sys}}}\right)^2\left(\frac{C_\gamma}{0.75}\right)^4\left(\frac{\rho_a}{0.45\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}}\right)^2\left(\frac{\nu_a}{1\,\mathrm{GHz}}\right)^2\left(\frac{B_0}{10\,\mathrm{T}}\right)^4\left(\frac{V}{30\,\mathrm{L}}\right)^2\left(\frac{G}{0.5}\right)^2\left(\frac{Q_c}{10^5}\right)$$

Minimize
- system noise T_{sys}:
  - temperature of cavity
  - amplifier/receiver noise

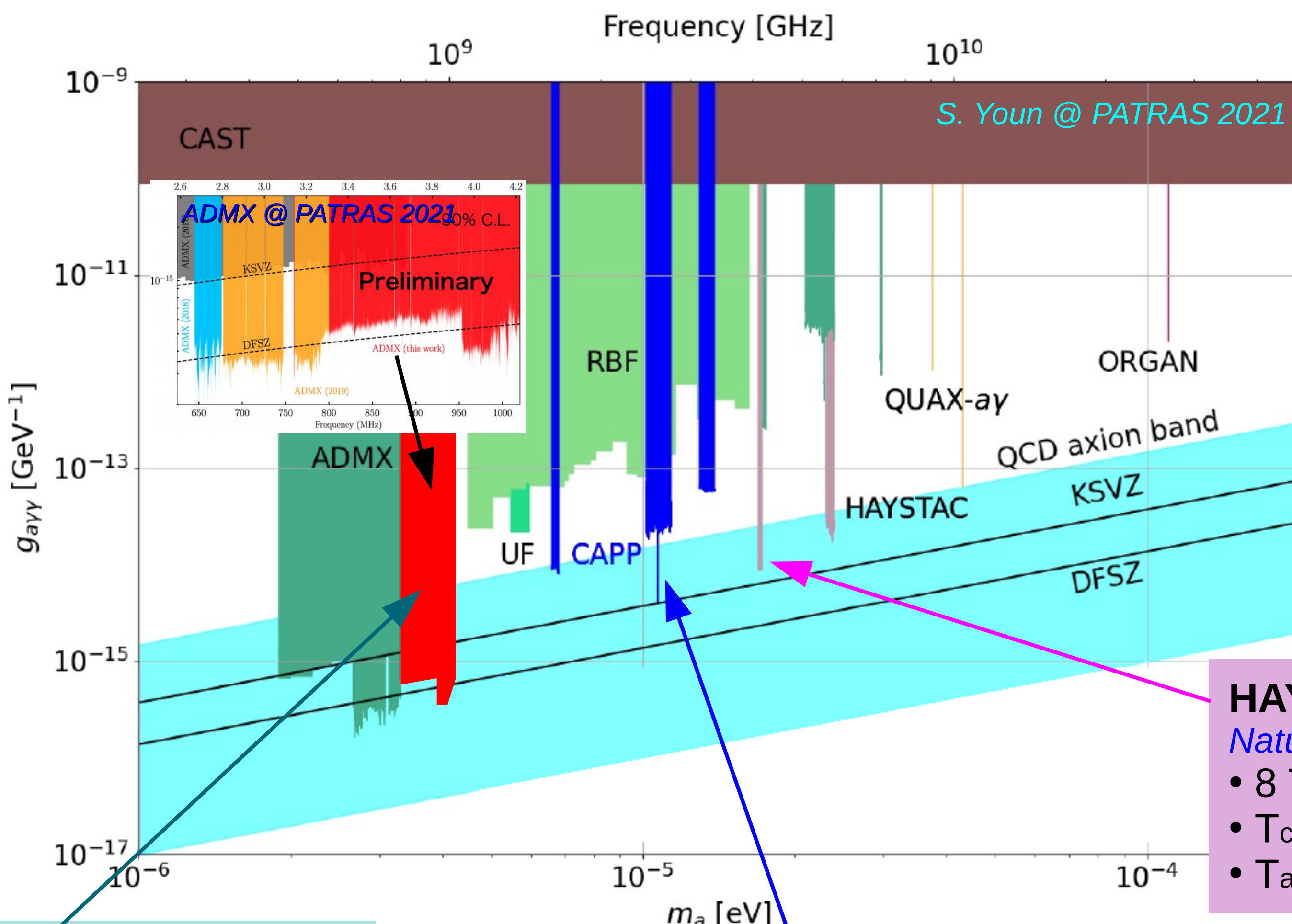
Set by Physics
- Local axion density ρ_a
- Frequency to be scanned ν_a
- Coupling constant C_γ
  –1.29 (KSVZ), 0.75 (DFSZ)

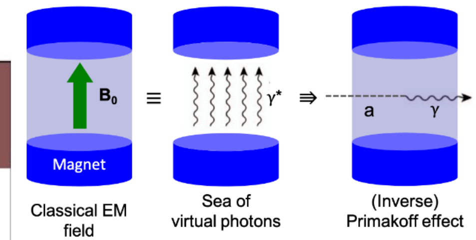
Maximize
- B Field B_0
- Cavity Volume V
- Cavity Quality Factor Q_c
- Geometrical Form Factor G

→ many „knobs“ to optimize for a given frequency range and sensitivity

- Nb: – resonance frequency of cavity is inversely proportional to size
  → scanning higher frequency requires smaller cavities
  – quantum noise in RF amplifiers increases with frequency

New Haloscope Results





HAYSTAC
Nature 590, 238 (2021)
- 8 T, V=1.5L
- T_{cav}=127mK
- T_{amp}~500 mK

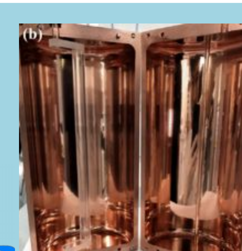
NEW!

ADMX
C. Bartram @ PATRAS 2021
- 7.6 T, V=150L
- T_{cav}=100mK
- T_{amp}=200mK

NEW!

CAPP-PACE
PRL 126, 191802 (2021)
- 8 T, 1.9L
- T_{cav}=38mK
- T_{amp}~1K

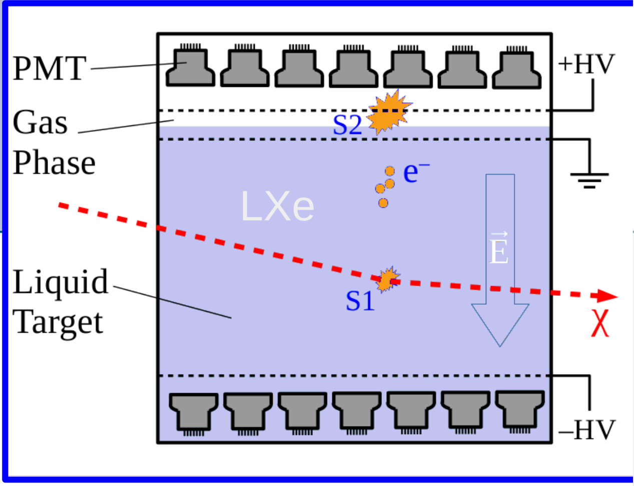
NEW!



The XENON1T „Excess“

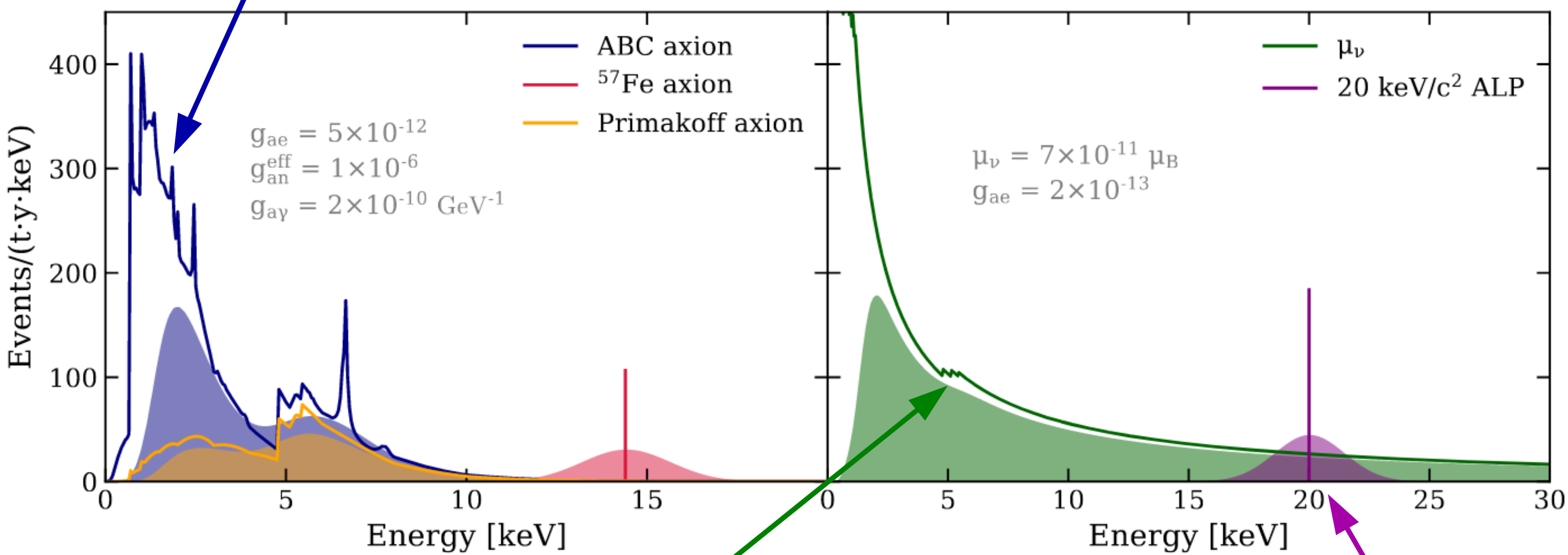
NEW!

PRD 102, 072004 (2020)



New Physics signatures in low-E ER data.
The XENON1T selection:

Solar Axions
- if axions exist, production in Sun with E_{kin} ~ keV
- low-background WIMP detector as **helioscope**



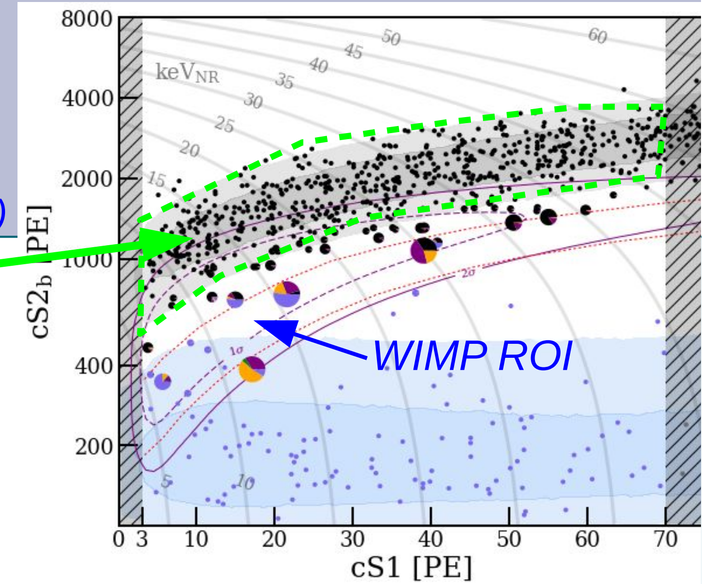
Enhanced Neutrino magn. Moment
- BSM physics could enhance μ_ν;
- i/a cross-section increases with μ_ν^2/E_ν

Axion-like Particle (Bosonic ALPs)
- assume all DM is made of non-relativistic ALPs
- expect mono-energetic peak at unknown m_a

The XENON1T „Excess“

NEW!

PRD 102, 072004 (2020)



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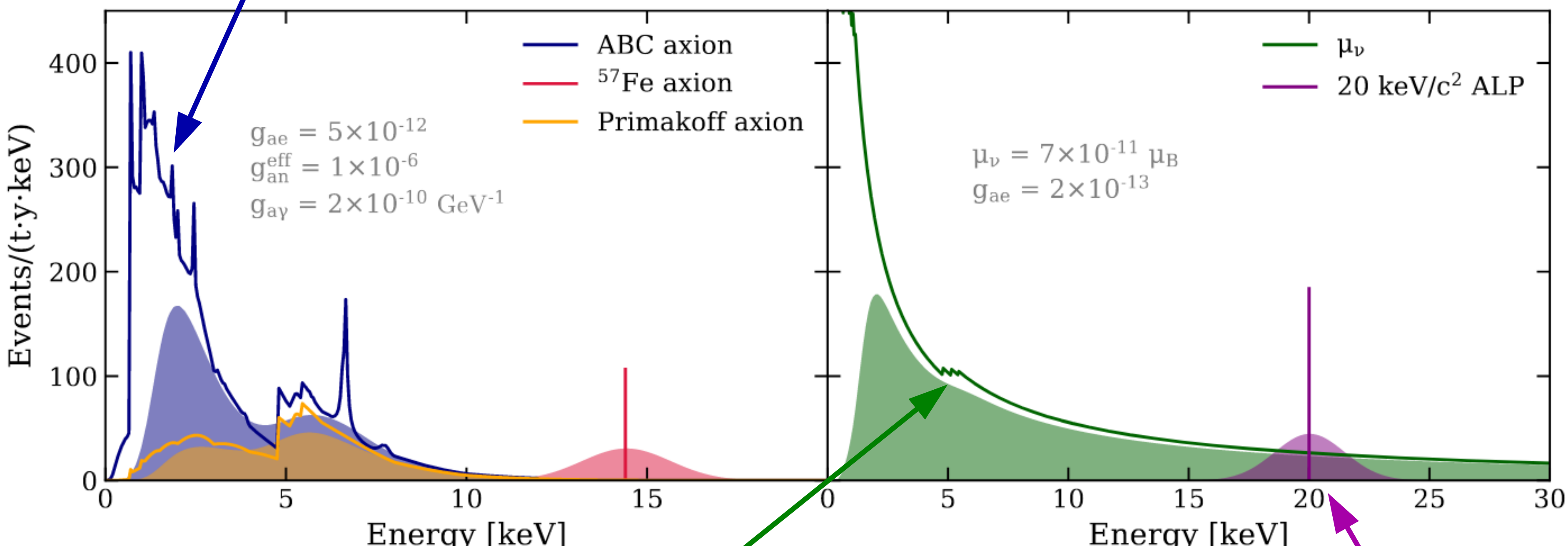

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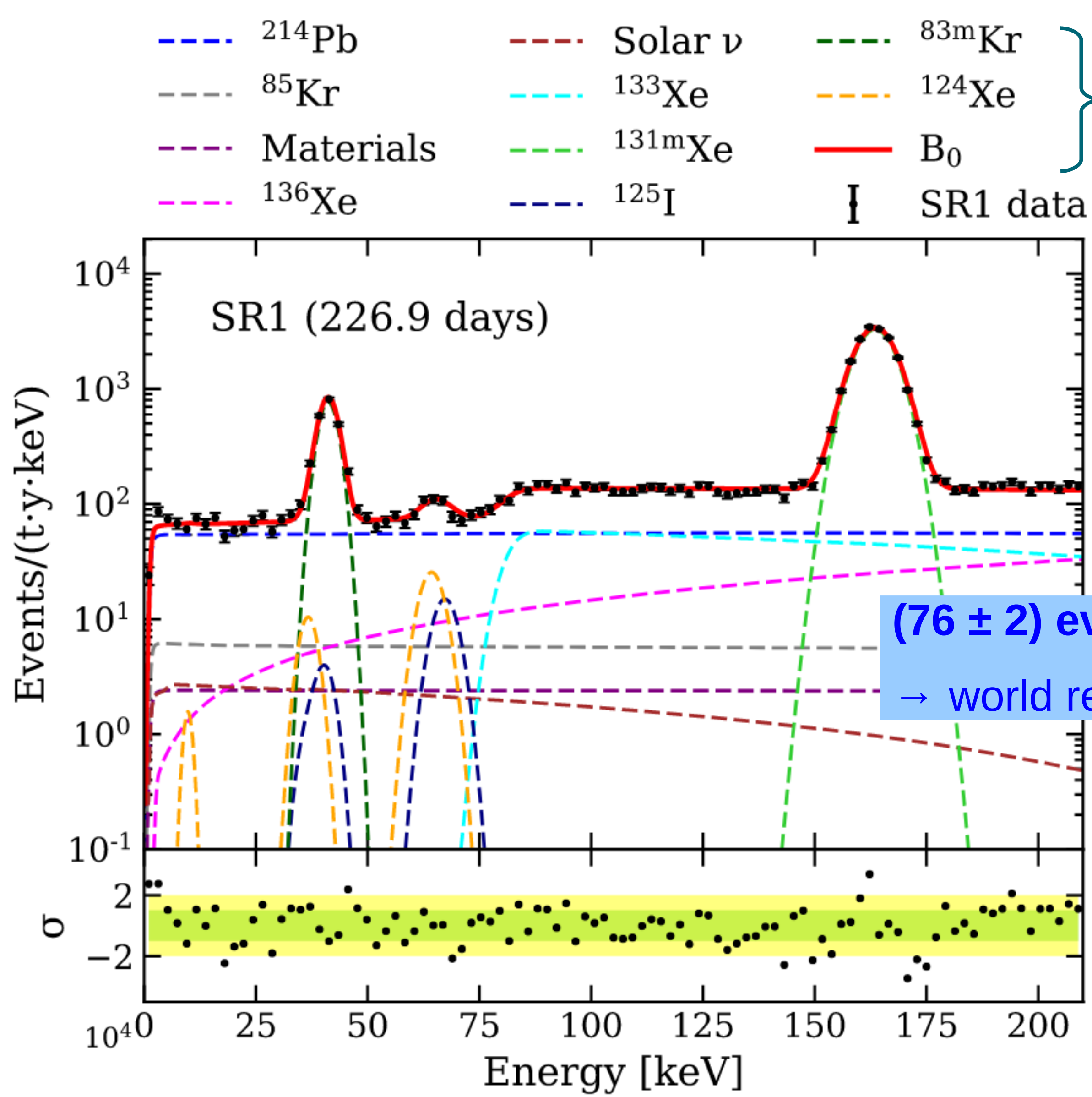
Background Fit

PRD 102, 072004 (2020)



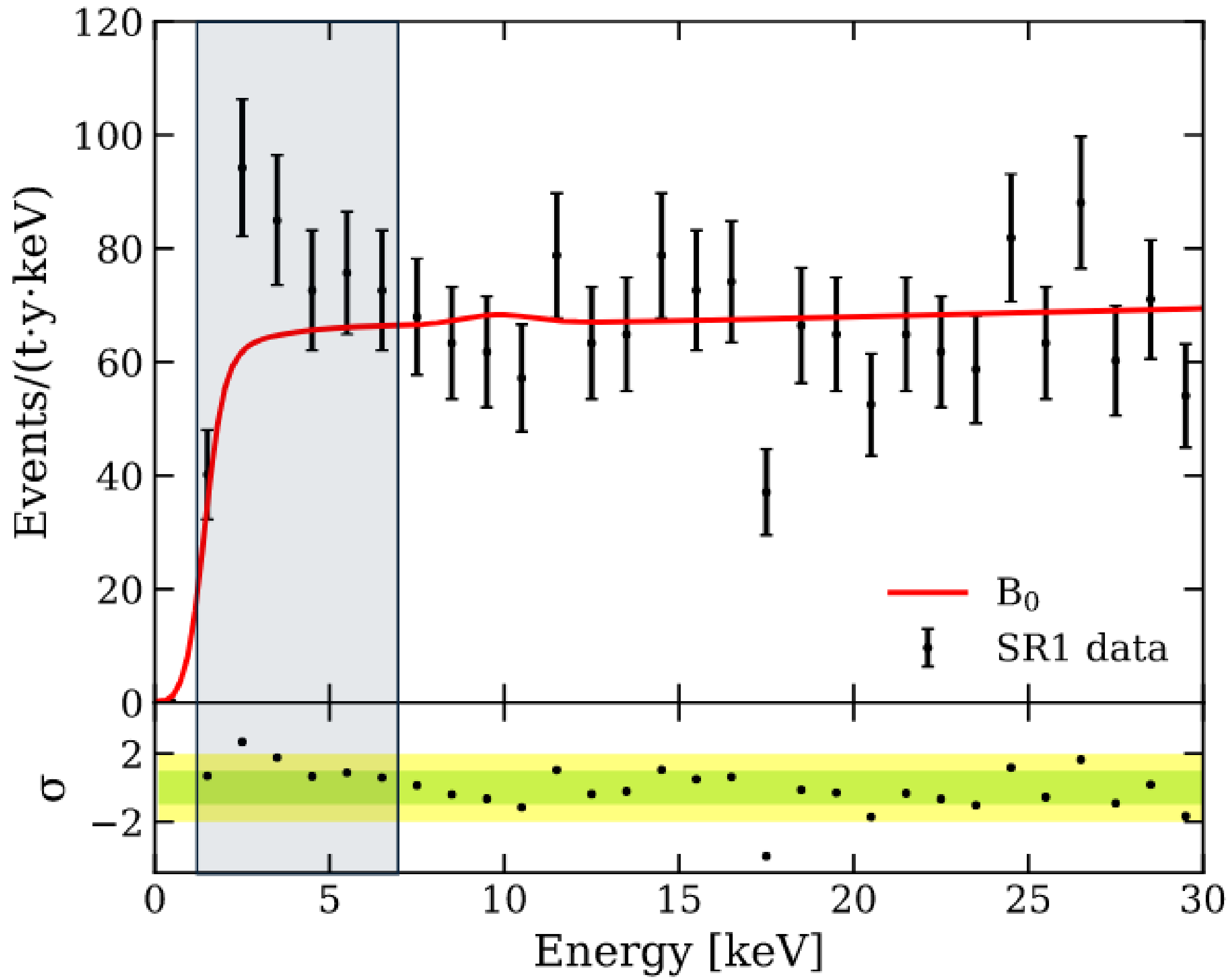
detailed background model

(76 ± 2) evts/(t y keV) in 1-30 keV

→ world record background level!

Excess of Events

PRD 102, 072004 (2020)



- **excess in 1-7 keV range**
  285 evts observed vs
  232 ± 15 expected
  → **(naive) 3.3σ fluctuation**

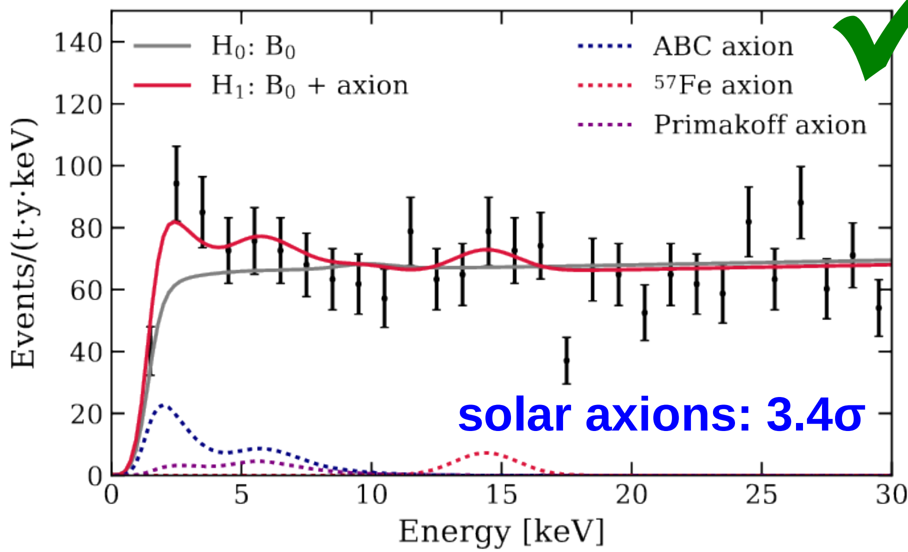
- events uniformly distributed
  – in space
  – in time (but low stats)

- far away from typical WIMP artefact backgrounds
  – accidental coincidences
  – surface background

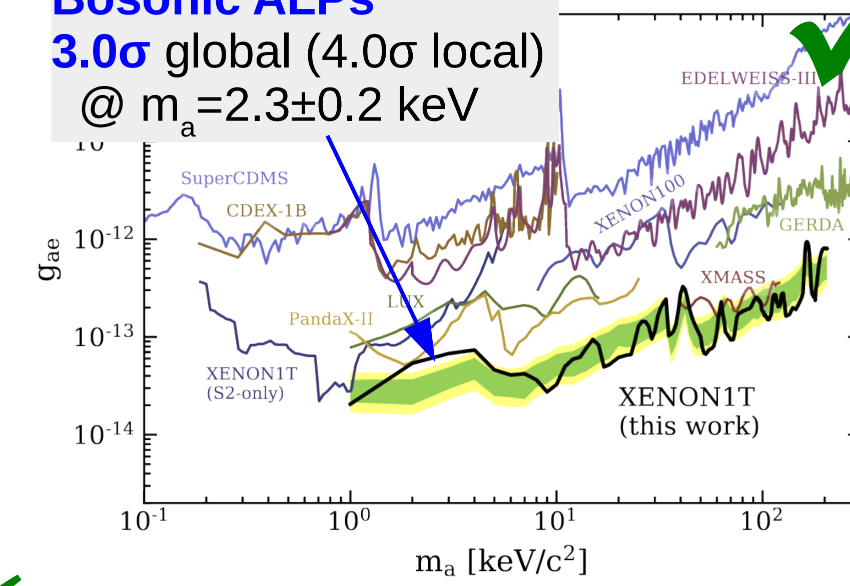
- efficiency and reconstruction validated down to threshold via calibration

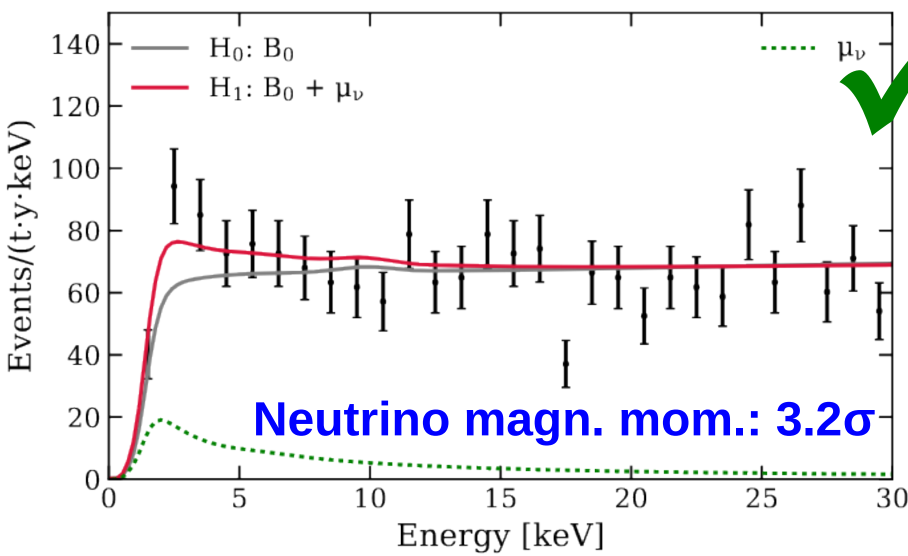
Possible Explanations

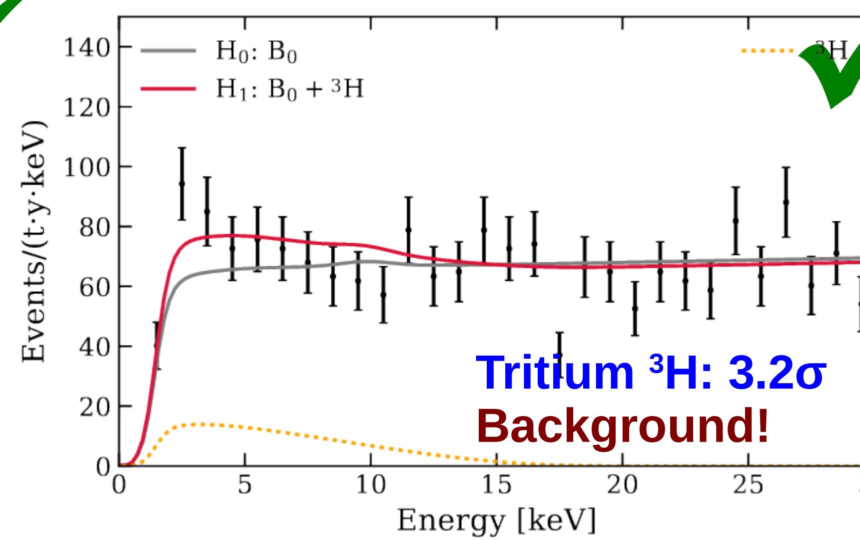
PRD 102, 072004 (2020)



Bosonic ALPs
3.0σ global (4.0σ local)
@ m_a=2.3±0.2 keV



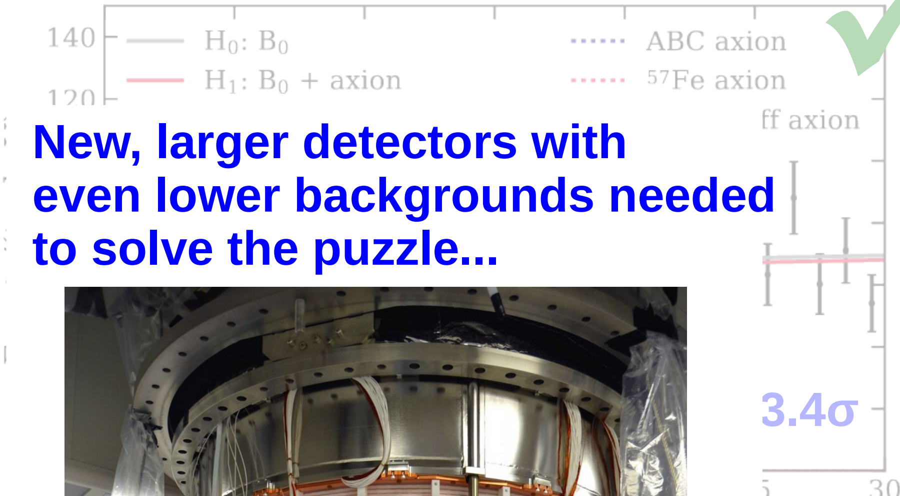




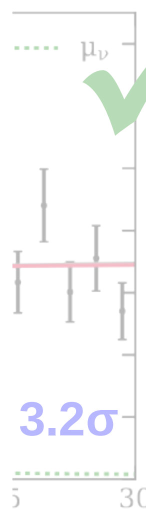
… and many others since XENON made result public.

Possible Explanations

PRD 102, 072004 (2020)



New, larger detectors with even lower backgrounds needed to solve the puzzle...



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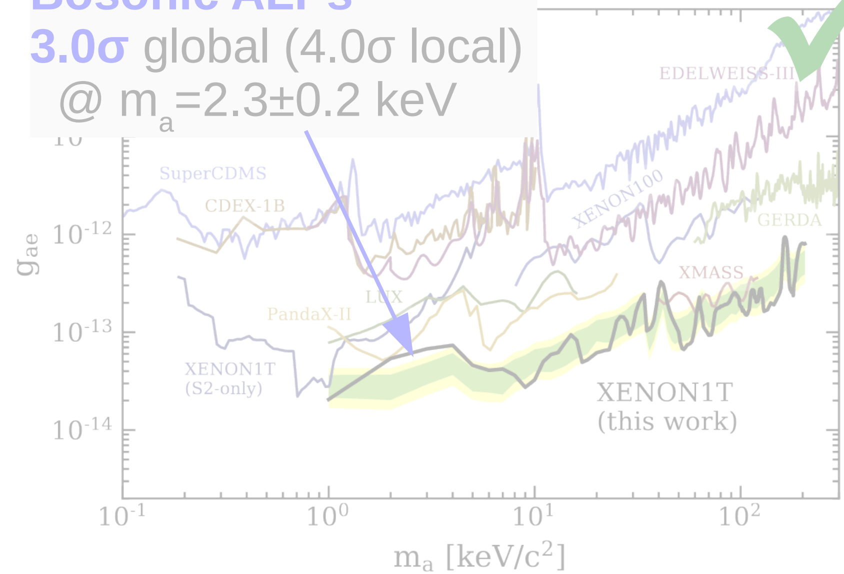
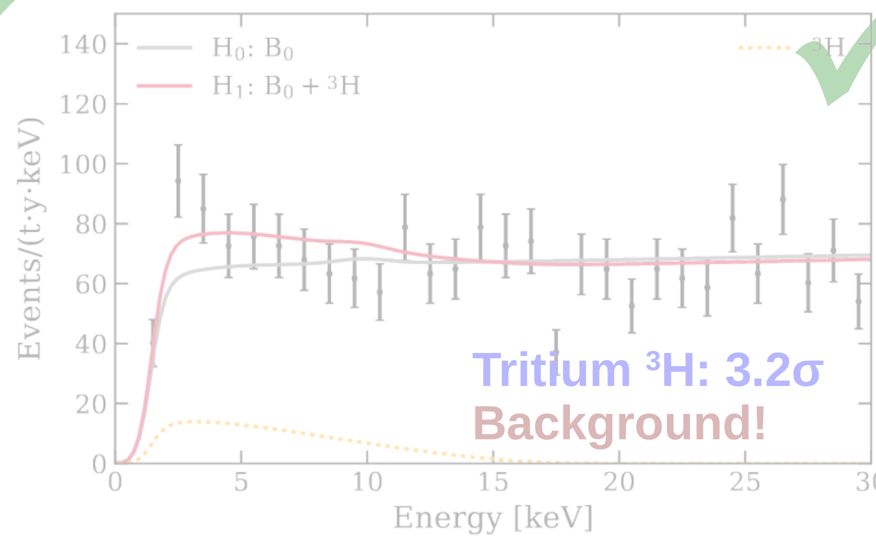


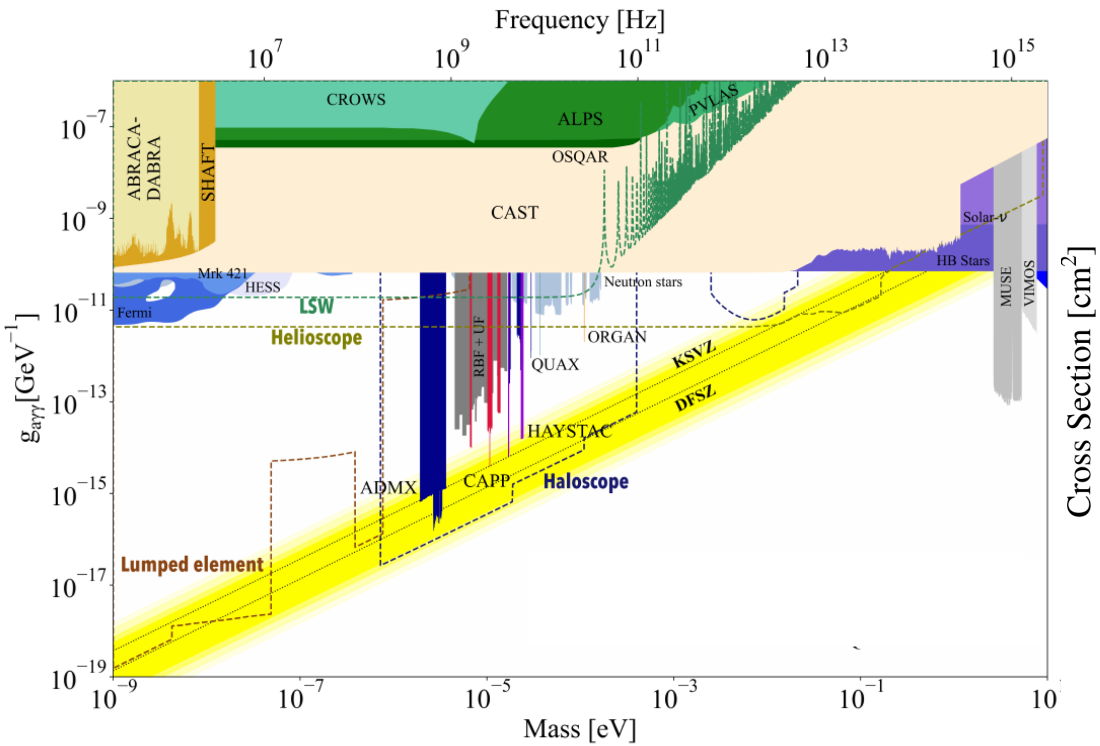


Tritium ^{3}H: 3.2σ
Background!

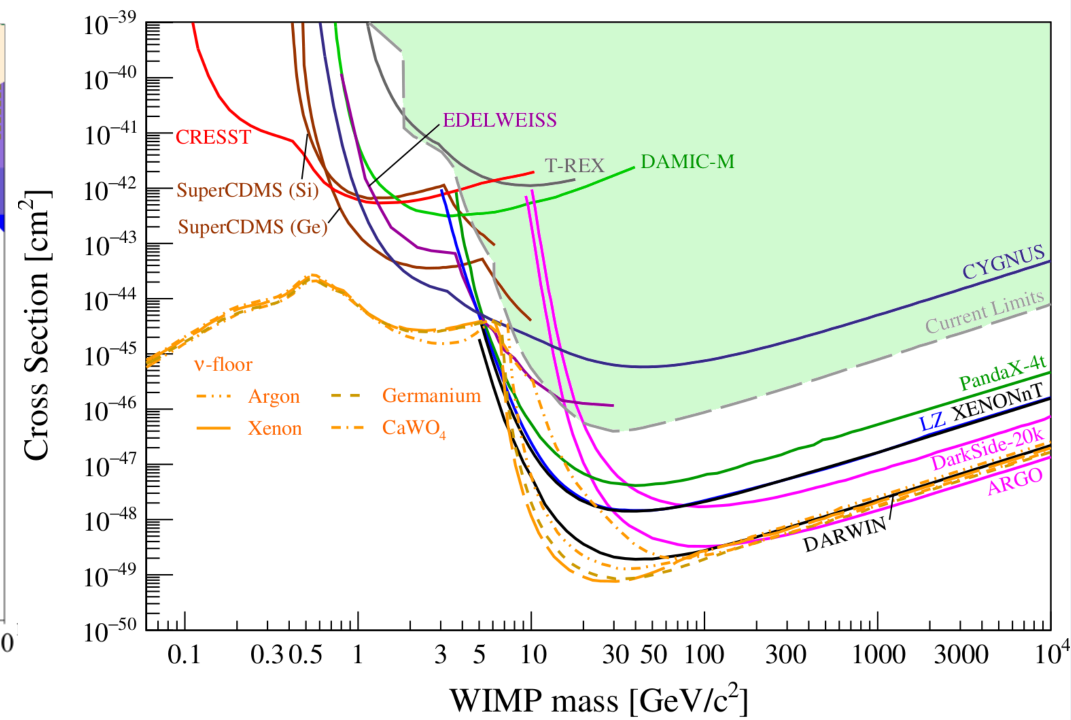
… and many others since XENON made result public.

Exciting Future for Direct Detection

Axions



WIMPs



- very diverse experimental landscape – many different projects
- both, WIMP and axion communities aim at closing most interesting paramer space in the next decade(s)