Shining light on the DarkSide of the Standard Model:
Expanding the search for dark matter with liquid argon detectors

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Brookhaven National Lab
Particle Physics Seminar

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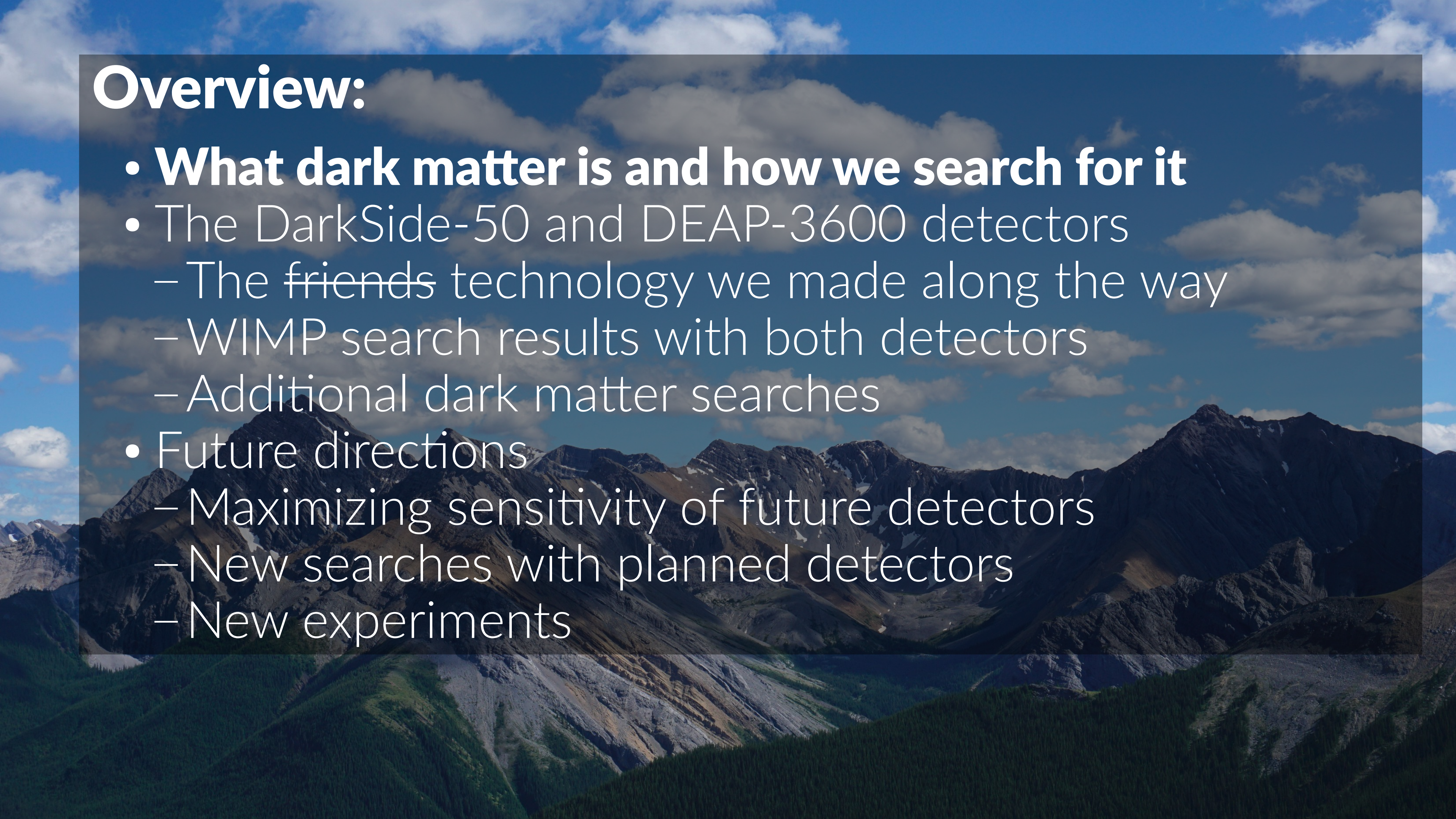
Canfranc Underground Laboratory
Canfranc-Estación, Spain

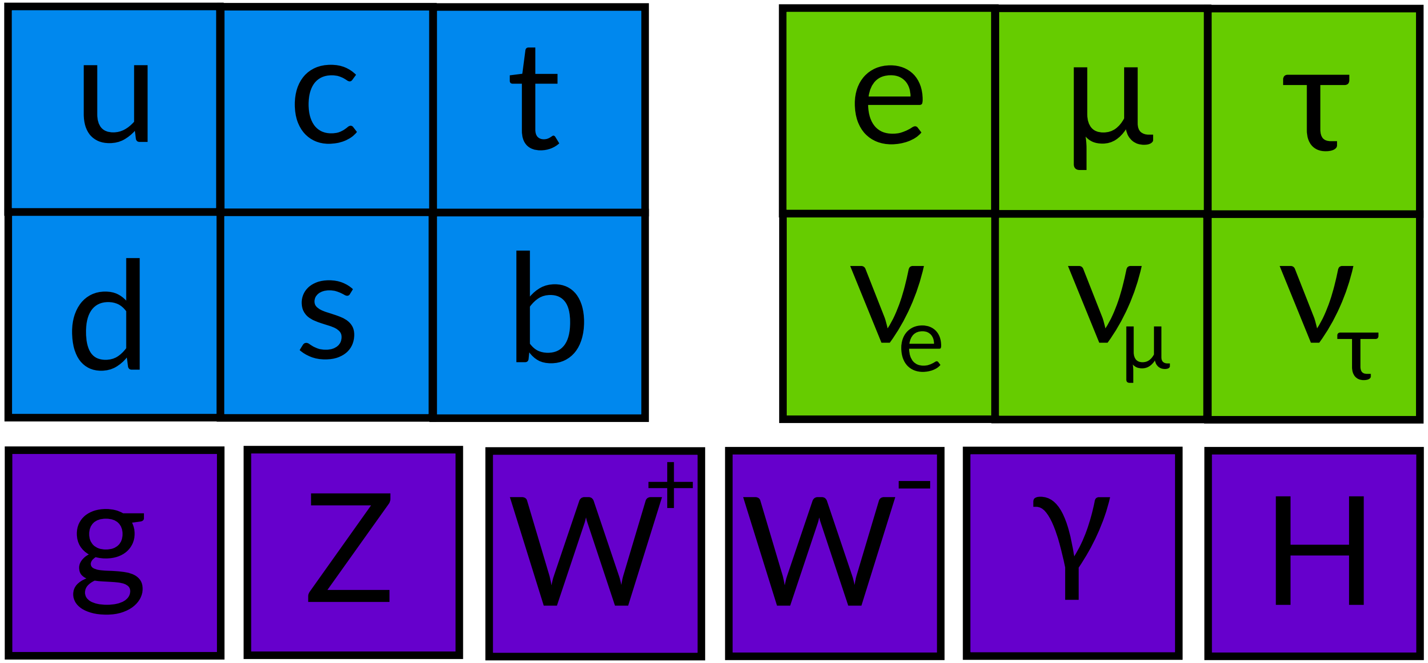
Overview:



Overview:

- **What dark matter is and how we search for it**
- The DarkSide-50 and DEAP-3600 detectors
  - The ~~friends~~ technology we made along the way
  - WIMP search results with both detectors
  - Additional dark matter searches
- Future directions
  - Maximizing sensitivity of future detectors
  - New searches with planned detectors
  - New experiments

quarks leptons



u	c	t
d	s	b

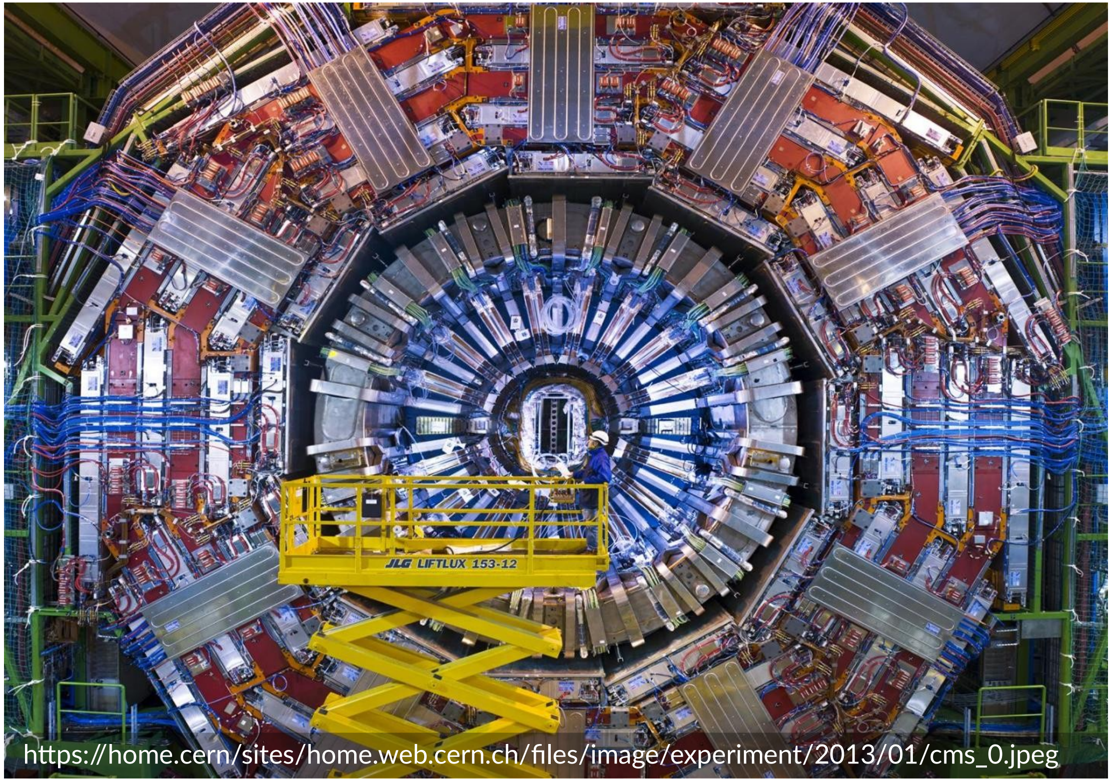
e	μ	τ
ν_e	ν_μ	ν_τ

g	Z	W^+	W^-	γ	H

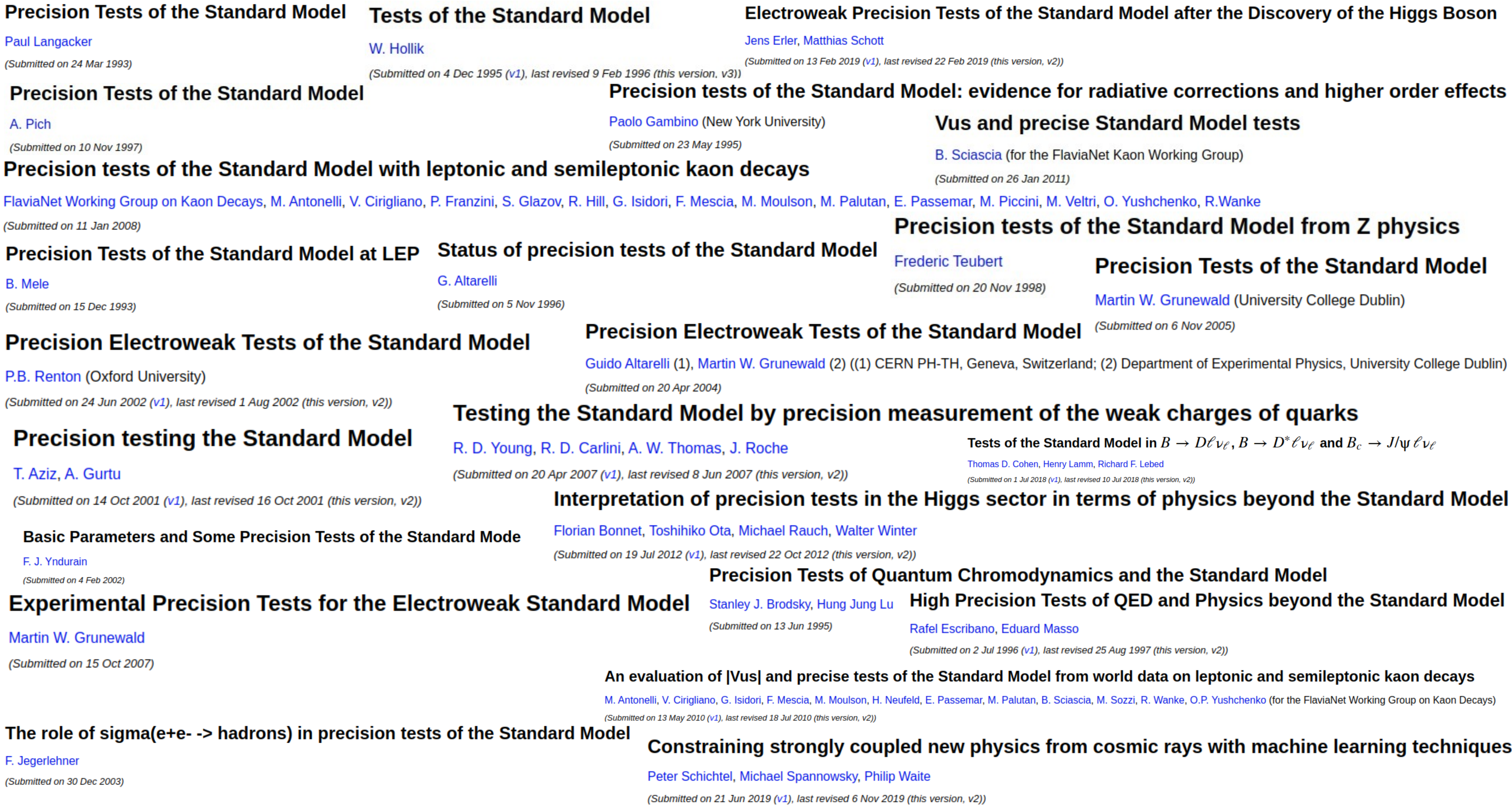
bosons

$$\mathcal{L}_{SM} =$$
$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu -$$
$$\frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a +$$
$$g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu -$$
$$\frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu -$$
$$\frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- -$$
$$M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 -$$
$$\frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \frac{2M}{g}H +$$
$$\frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h -$$
$$igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) -$$
$$Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) +$$
$$Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] -$$
$$igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) -$$
$$A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) +$$
$$A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] -$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu +$$
$$g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu -$$
$$A_\mu A_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) -$$
$$2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 +$$
$$2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 +$$
$$4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- +$$
$$2(\phi^0)^2 H^2] - gMW^+_\mu W^-_\mu H -$$
$$\frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- -$$
$$\phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- -$$
$$\phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] +$$
$$\frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) -$$
$$ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) -$$
$$ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$
$$\frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 -$$
$$1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda -$$
$$\bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial +$$
$$m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) +$$
$$\frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 -$$
$$1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - 1 -$$
$$\gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] +$$
$$\frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1 +$$
$$\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1 +$$
$$\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] +$$
$$\frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) +$$
$$\phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) +$$
$$i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] +$$
$$\frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] +$$
$$\frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) -$$
$$m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) -$$
$$\frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$
$$\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ +$$
$$\bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 +$$
$$\bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- -$$
$$\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 -$$
$$\partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H +$$
$$\bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H] +$$
$$\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] +$$
$$\frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$
$$igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$
$$\frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

Heavily tested by many experiments…



https://home.cern/sites/home.web.cern.ch/files/image/experiment/2013/01/cms_0.jpeg



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(Submitted on 24 Mar 1993)

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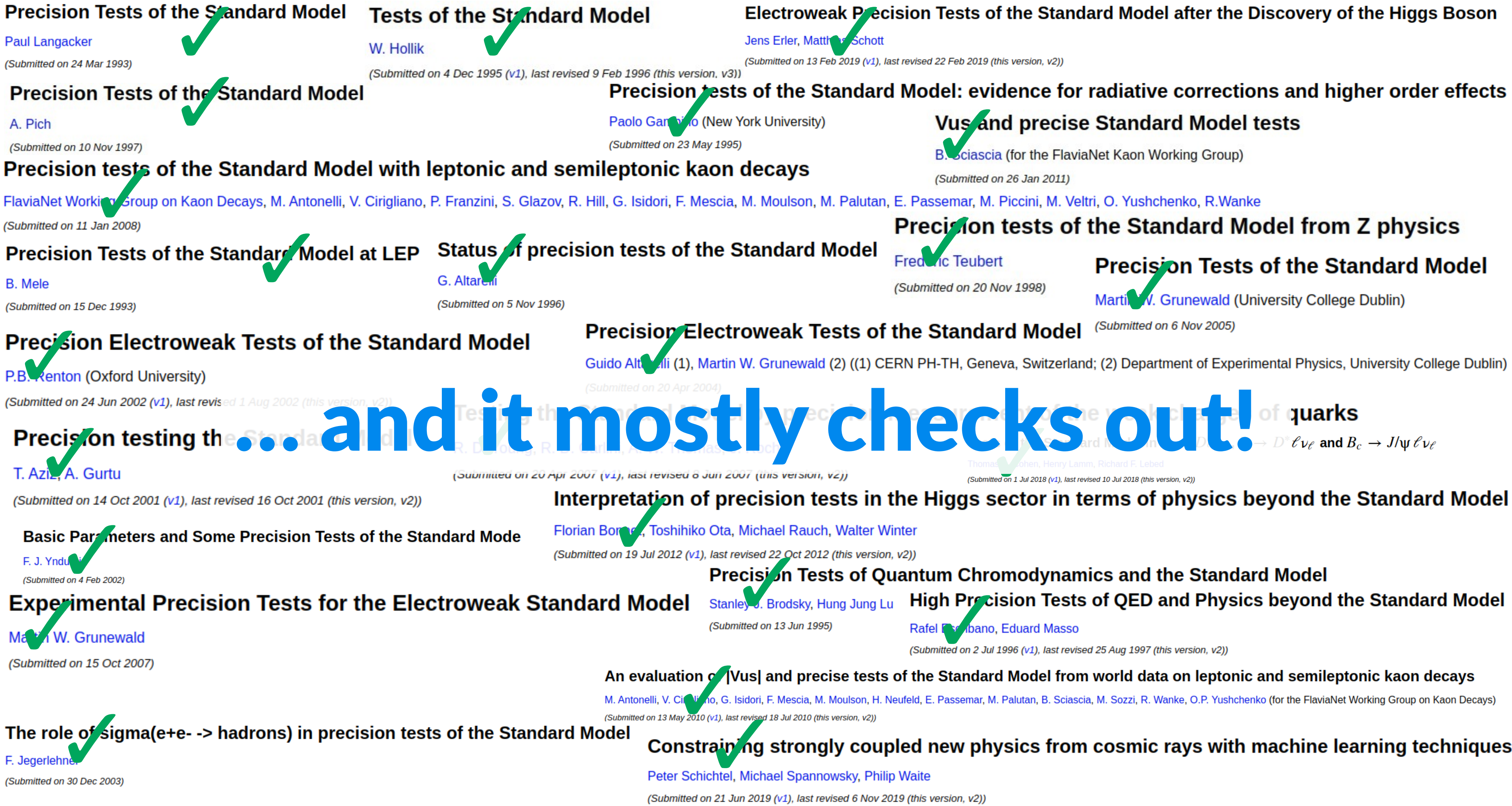

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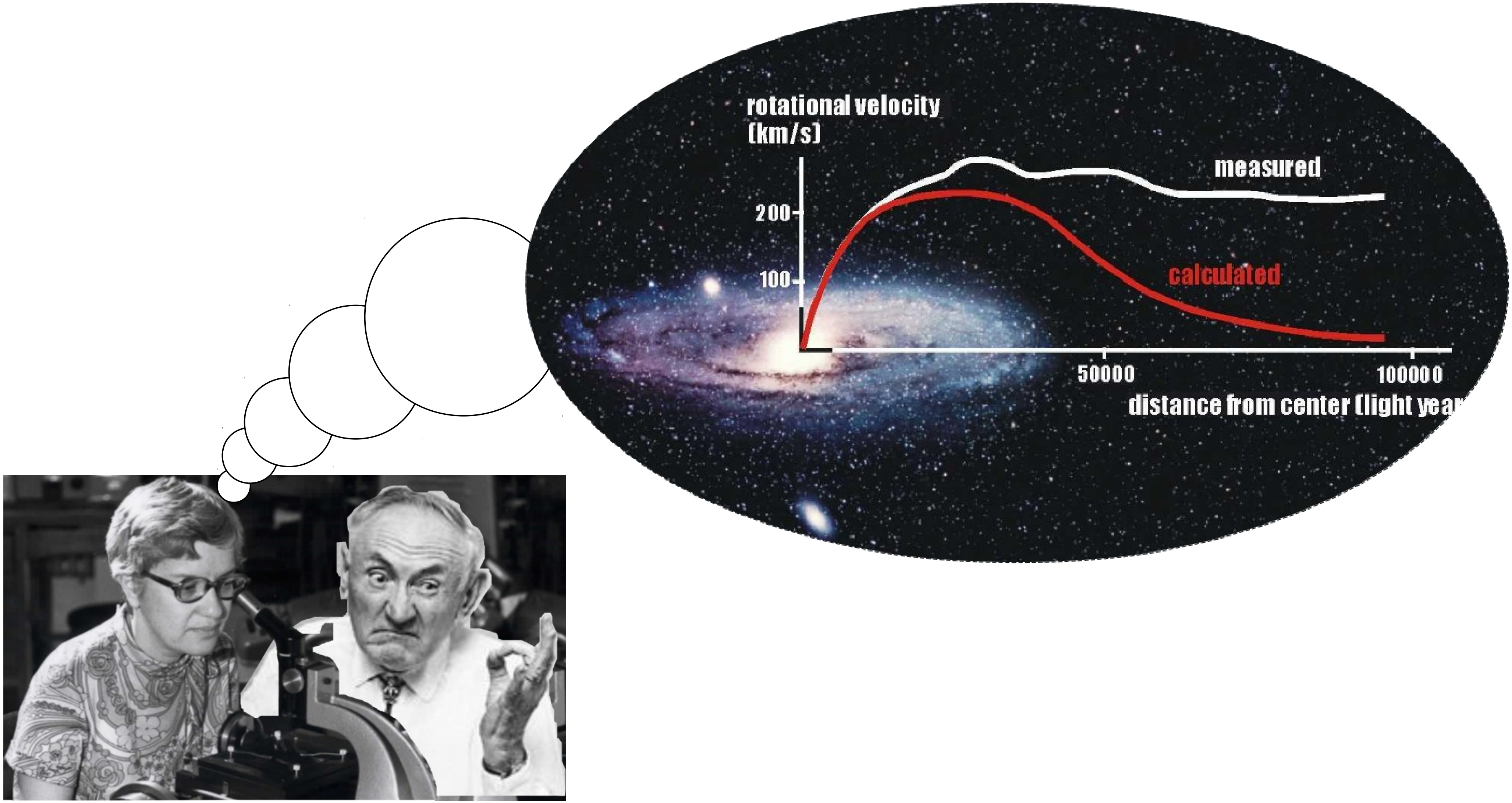
rotational velocity
(km/s)
200
100
measured
calculated
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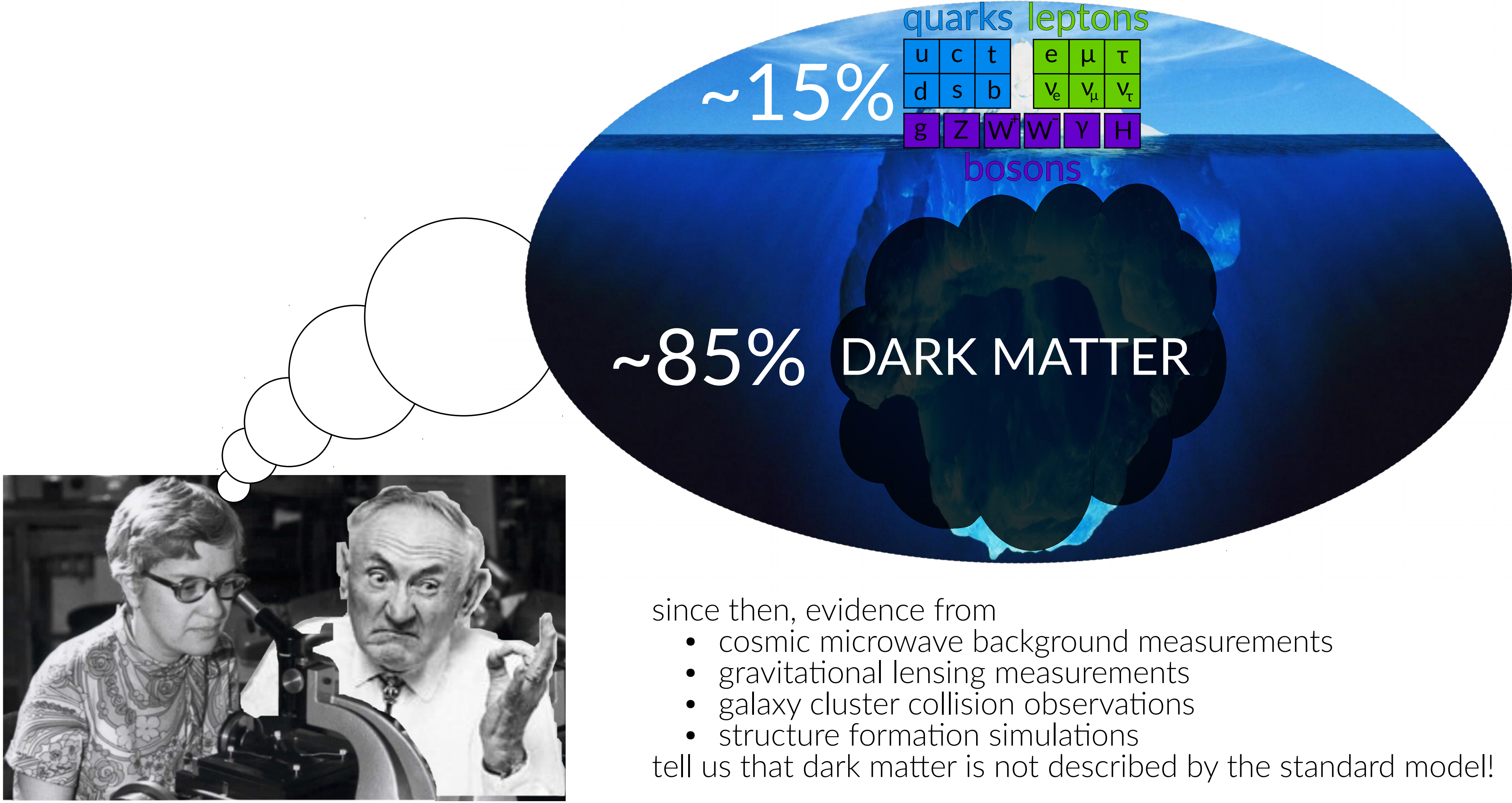
100000
distance from center (light yea

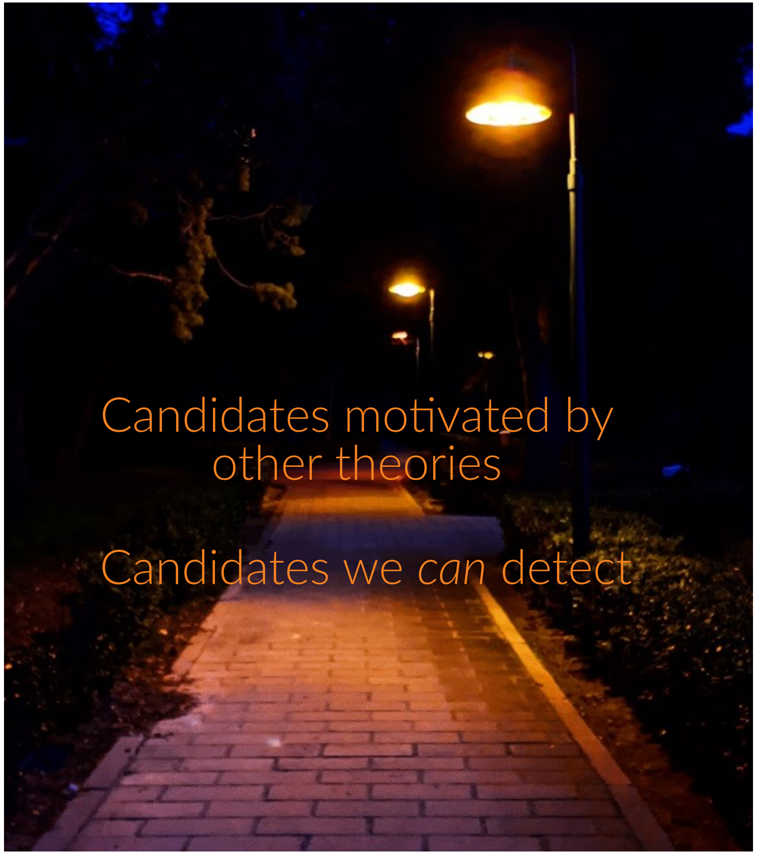


since then, evidence from

- cosmic microwave background measurements
- gravitational lensing measurements
- galaxy cluster collision observations
- structure formation simulations

tell us that dark matter is not described by the standard model!

Where to start: Looking under the light posts



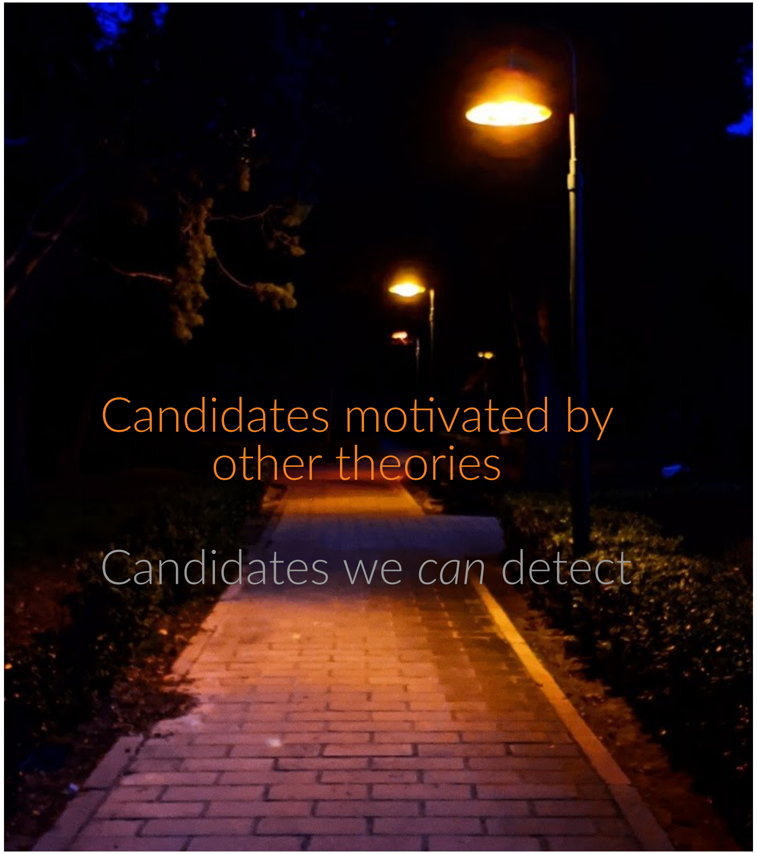
Candidates motivated by other theories

Candidates we *can* detect

We want…

- **Depth:** Perform the most sensitive search we can
- **Breadth:** Search for as many candidates as possible

Where to start: Looking under the light posts



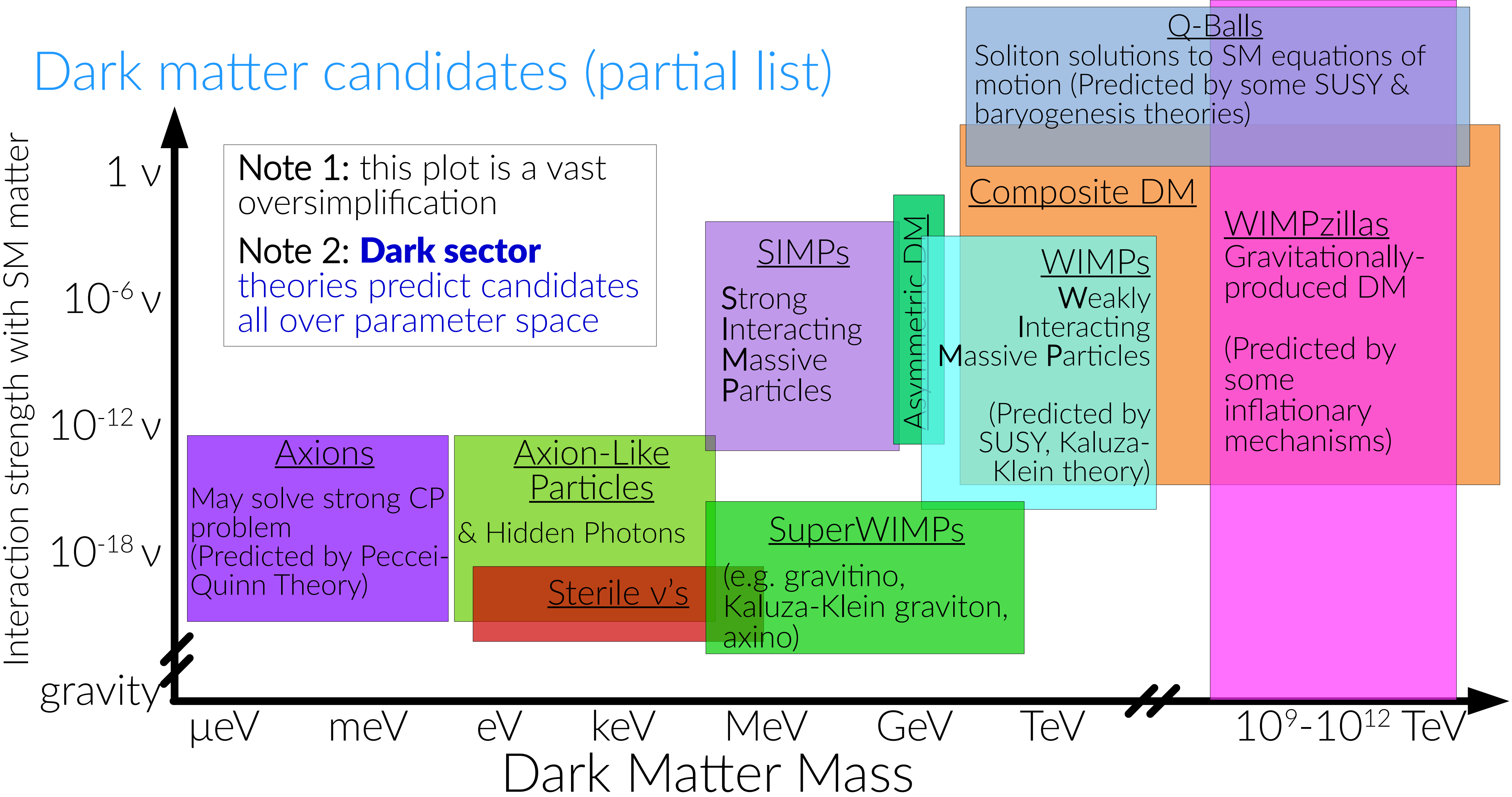
Candidates motivated by other theories

Candidates we *can* detect

Dark matter candidates (partial list)

Note 1: this plot is a vast oversimplification

Note 2: Dark sector theories predict candidates all over parameter space



Axions

May solve strong CP problem (Predicted by Peccei-Quinn Theory)

Axion-Like Particles

& Hidden Photons

Sterile ν's

SIMPs

Strong Interacting Massive Particles

Asymmetric DM

SuperWIMPs

(e.g. gravitino, Kaluza-Klein graviton, axino)

WIMPs

Weakly Interacting Massive Particles

(Predicted by SUSY, Kaluza-Klein theory)

Composite DM

Q-Balls

Soliton solutions to SM equations of motion (Predicted by some SUSY & baryogenesis theories)

WIMPzillas

Gravitationally-produced DM

(Predicted by some inflationary mechanisms)

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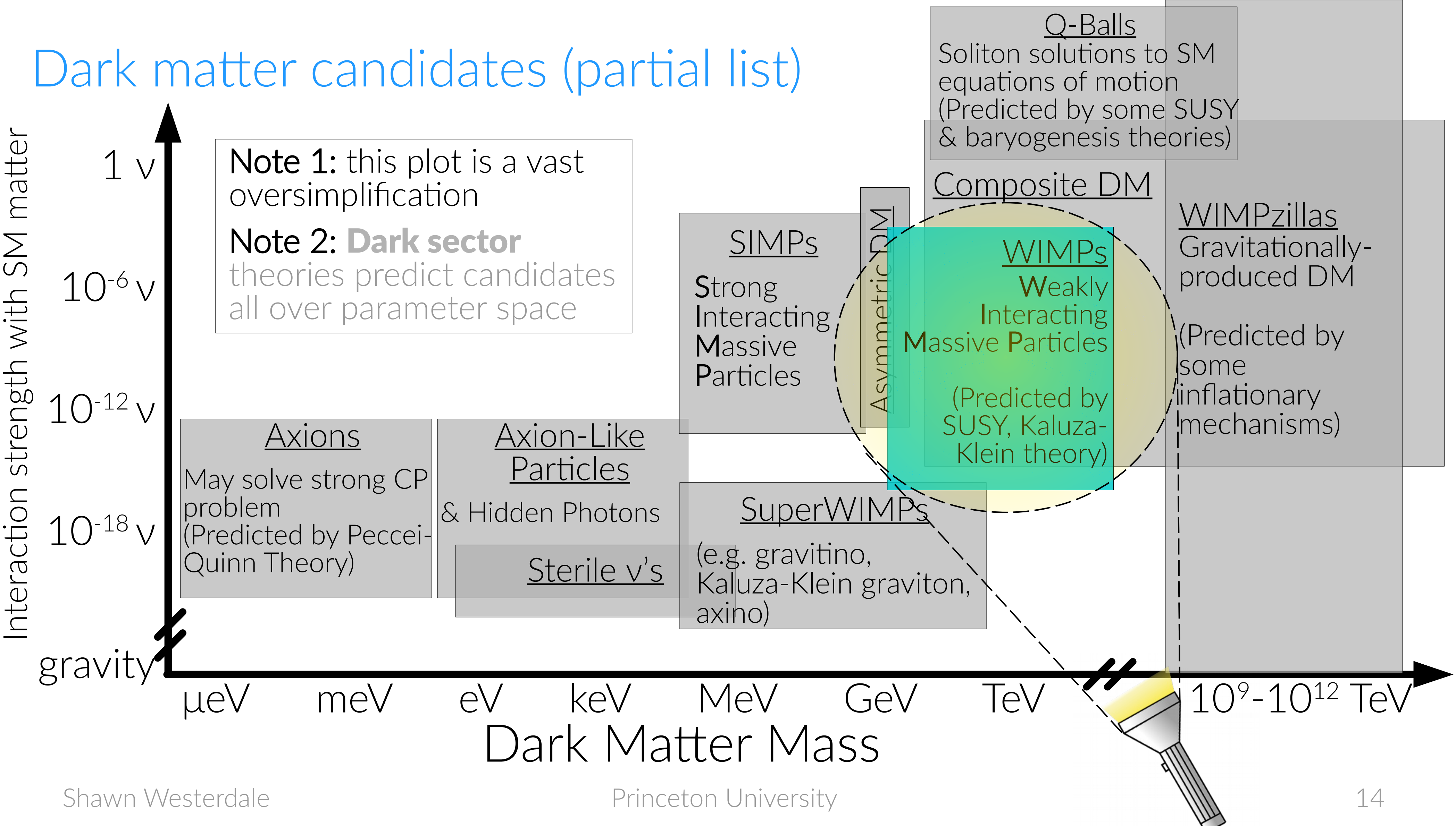

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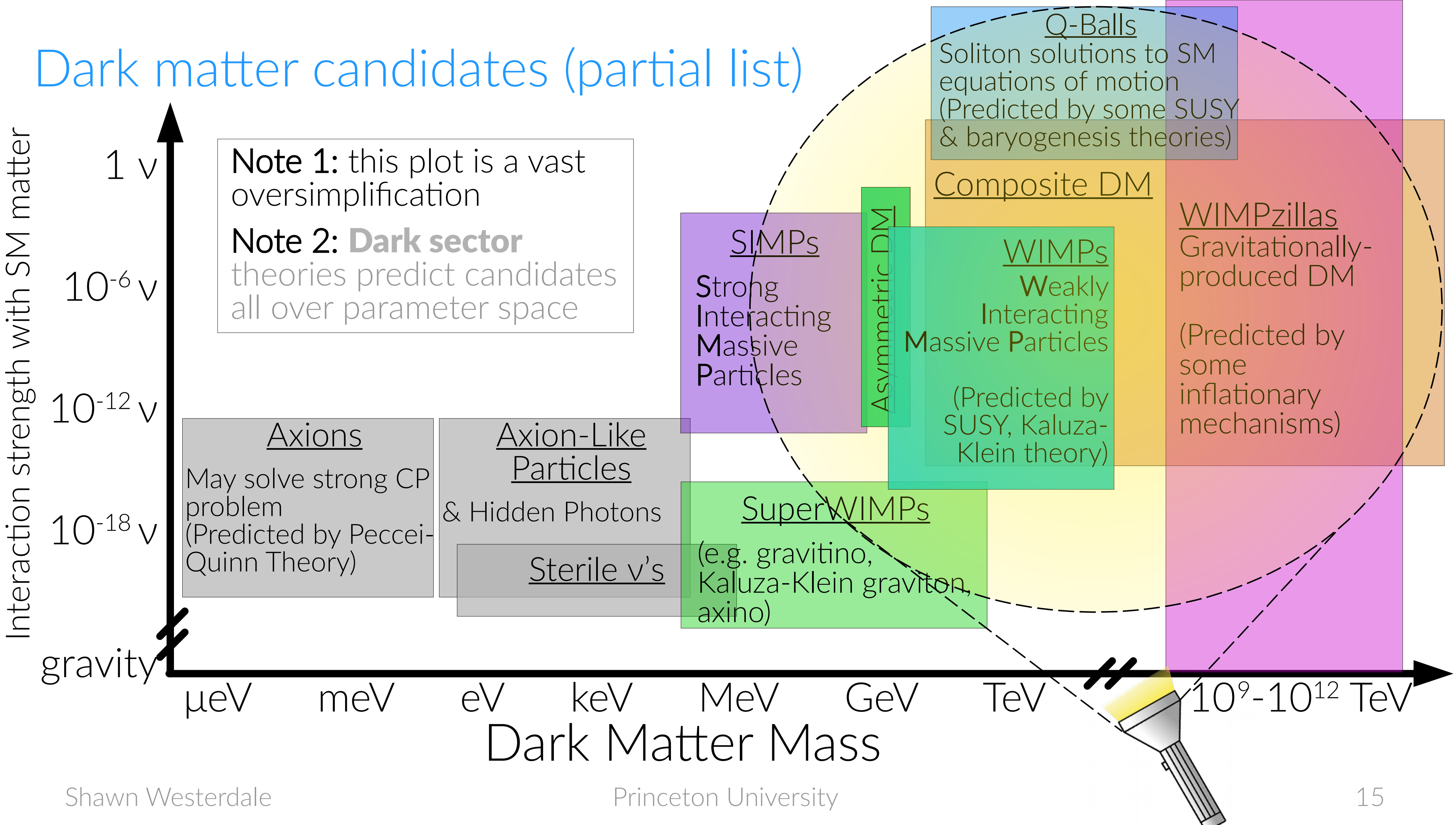

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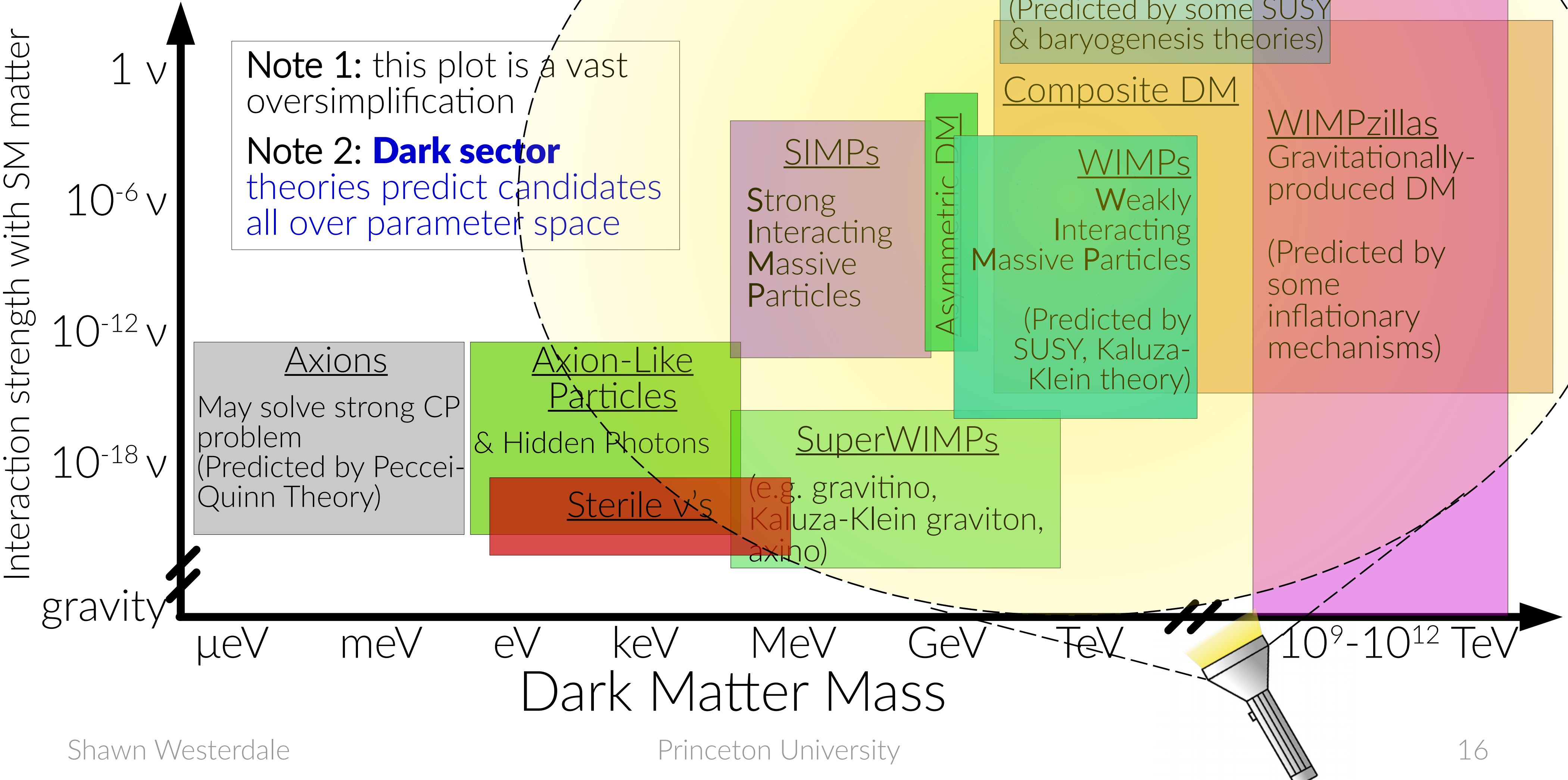

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SIMPs

Strong **I**nteracting **M**assive **P**articles

Asymmetric DM

WIMPs

Weakly **I**nteracting **M**assive **P**articles

(Predicted by SUSY, Kaluza-Klein theory)

SuperWIMPs

(e.g. gravitino, Kaluza-Klein graviton, axino)

Q-Balls

Soliton solutions to SM equations of motion (Predicted by some SUSY & baryogenesis theories)

Composite DM

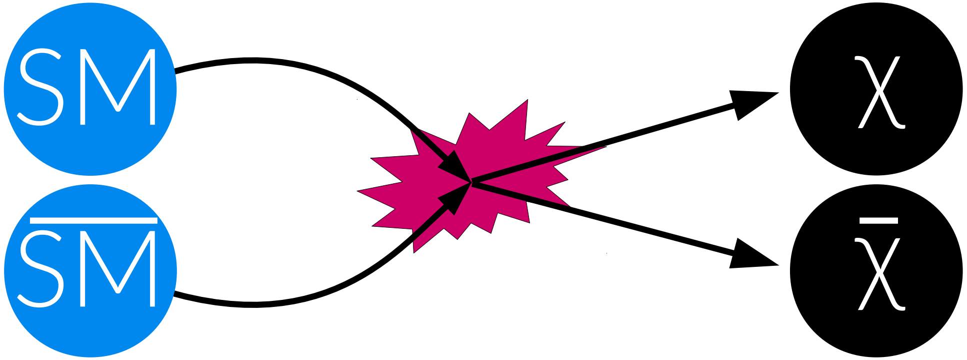
WIMPzillas

Gravitationally-produced DM

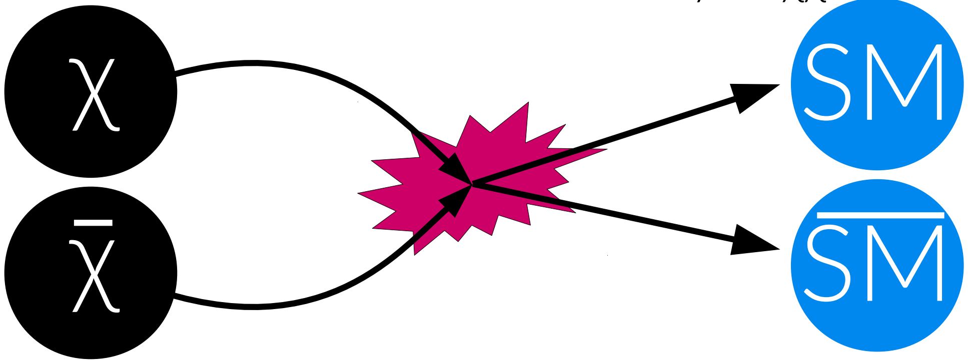
(Predicted by some inflationary mechanisms)

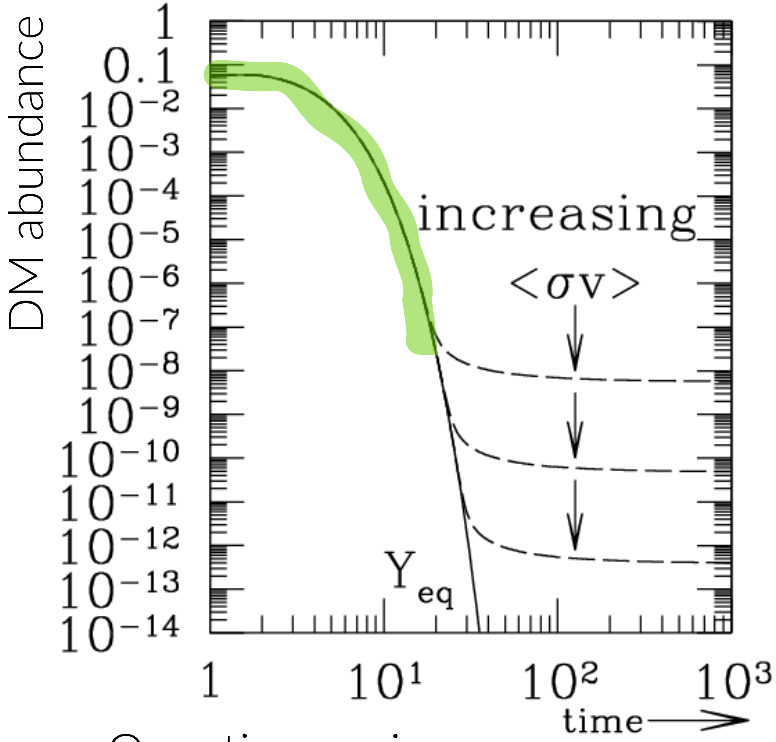
WIMP in thermal equilibrium with universe

WIMP production ∝ density of SM hot enough to produce $\chi\bar{\chi}$



WIMP annihilation ∝ density of $\chi\bar{\chi}$

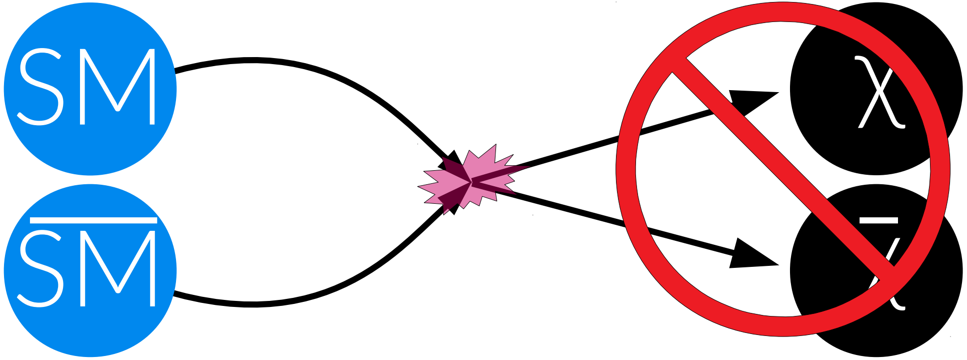




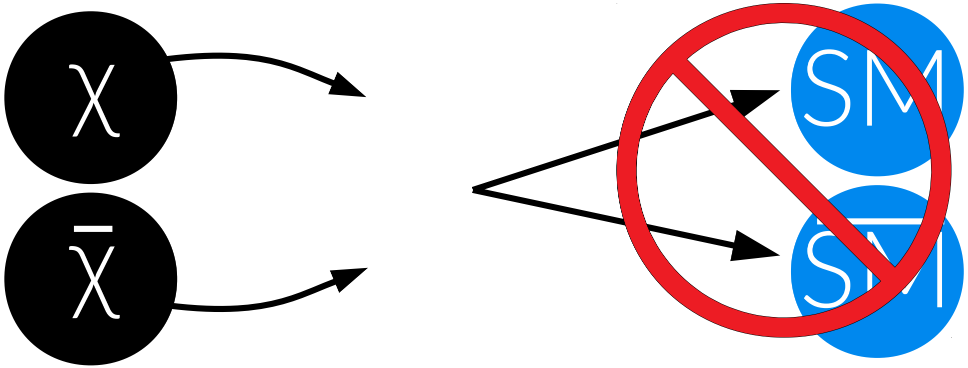
Over time, universe expands and cools

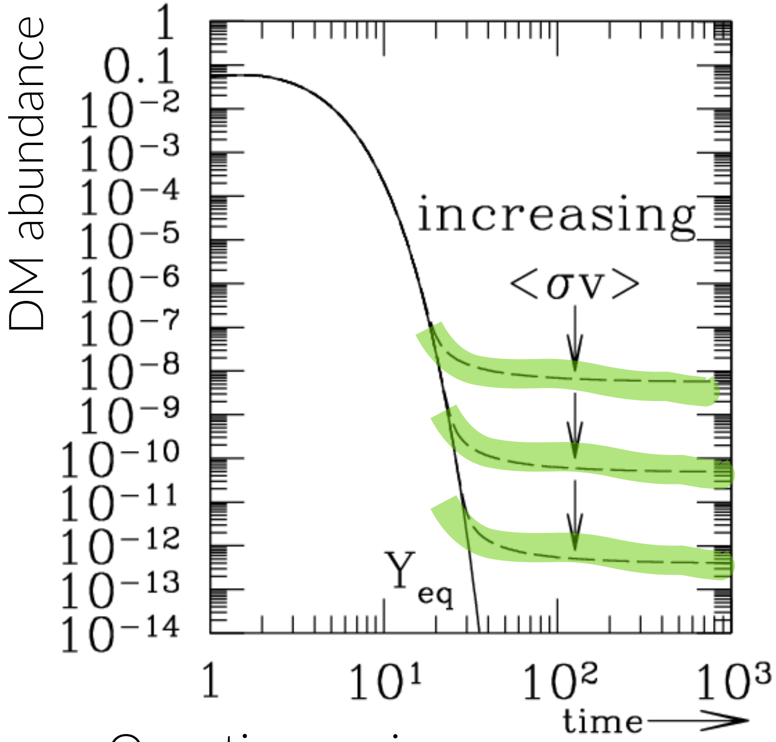
WIMPs thermally freezing-out

SM particles have too little kinetic energy to produce $\chi\bar{\chi}$



WIMP too dilute to find each other and annihilate





Over time, universe expands and cools

WIMPs: Thermal relics

To get the dark matter density we see today, we need

- $\langle \sigma v \rangle \sim 10^{-26}\ \mathrm{cm^3/s}$
- Mass ~ 100 GeV/c^2

WIMPs: Thermal relics

To get the dark matter density we see today, we need

$$\left.\begin{array}{l} \bullet\ \langle\sigma v\rangle \sim 10^{-26}\ \mathrm{cm}^3/\mathrm{s} \\ \bullet\ \text{Mass} \sim 100\ \mathrm{GeV}/c^2 \end{array}\right\}\ \text{Weak interaction scale}$$

WIMPs: Thermal relics

To get the dark matter density we see today, we need

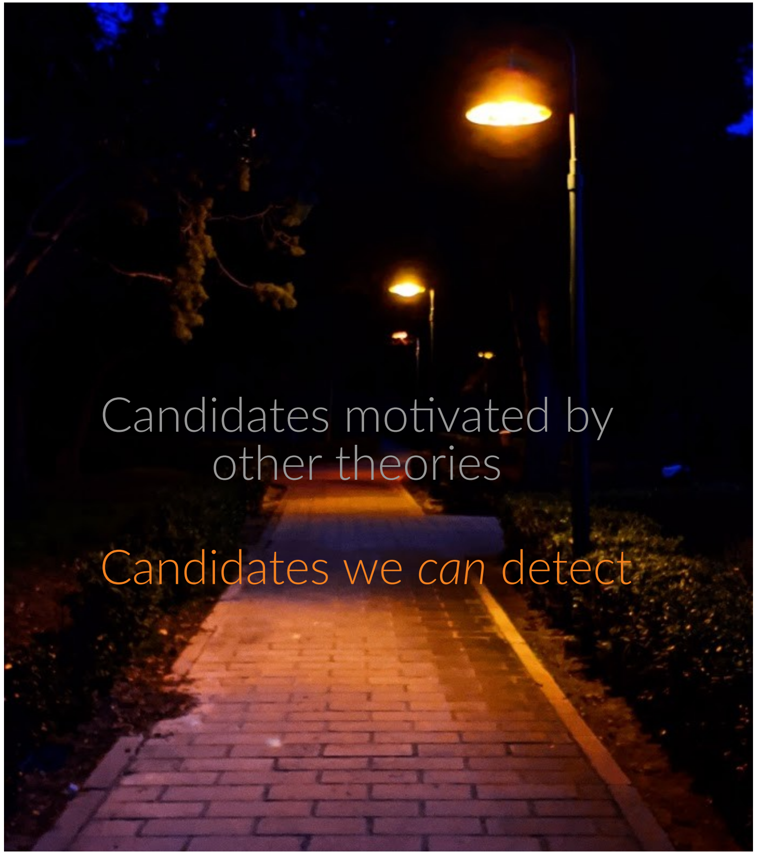
- $\langle \sigma v \rangle \sim 10^{-26}\ \mathrm{cm^3/s}$
- Mass ~ $100\ \mathrm{GeV/c^2}$

Weak interaction scale

Many theories predict such particles
Most couple to nuclei
Interactions will be rare, and < 100 keV

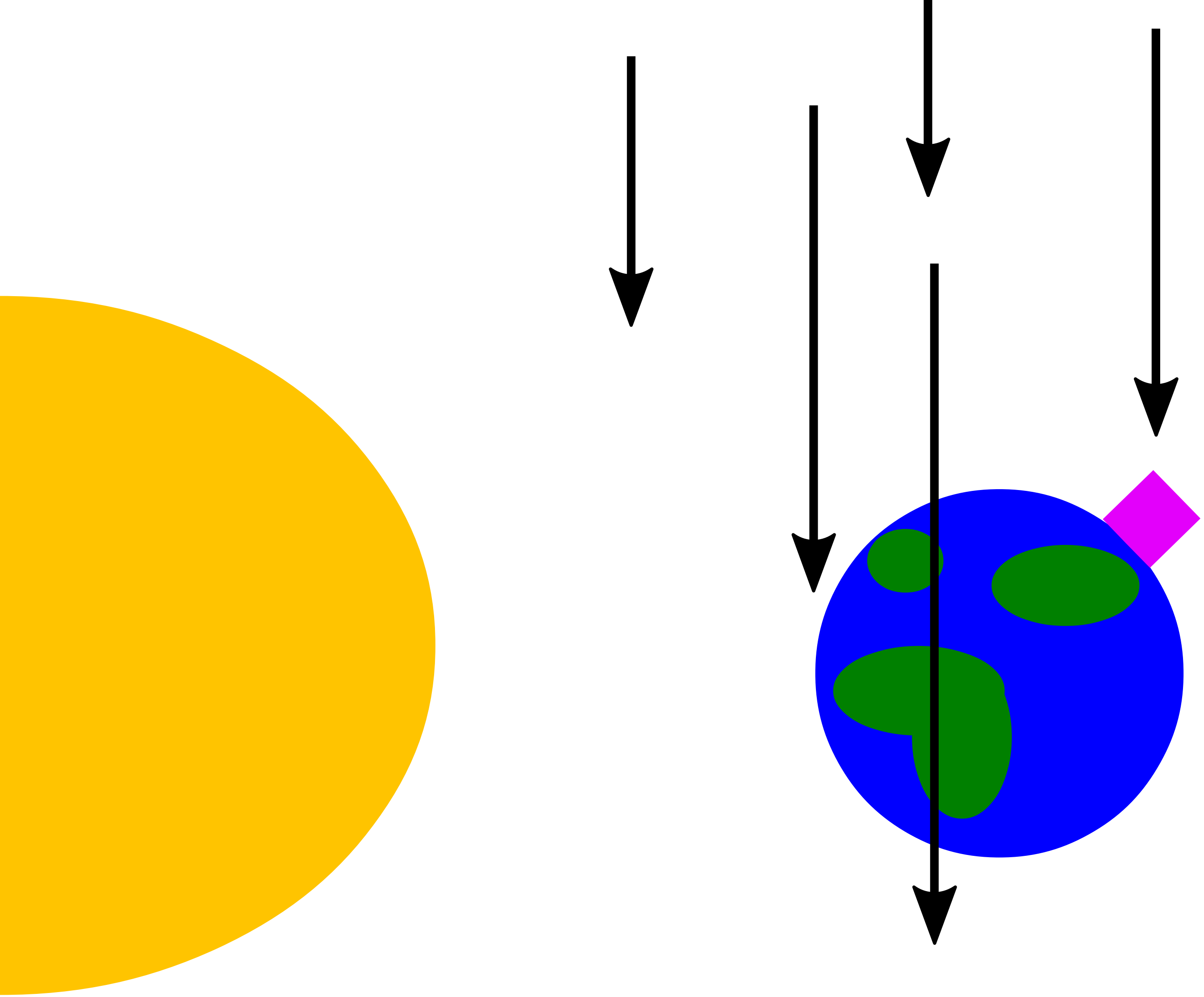
But they may be detectable

Where to start: Looking under the light posts

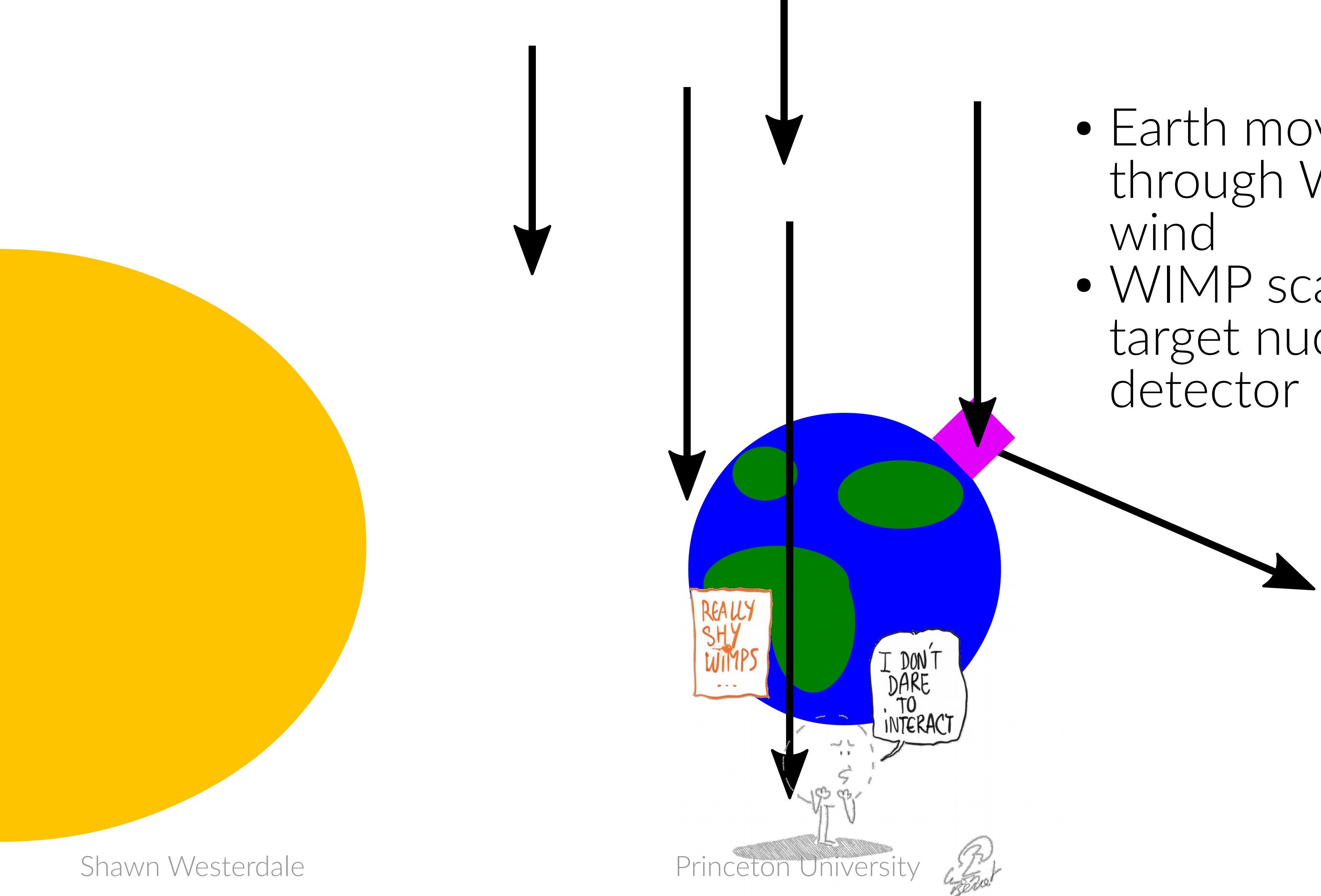


Candidates motivated by other theories

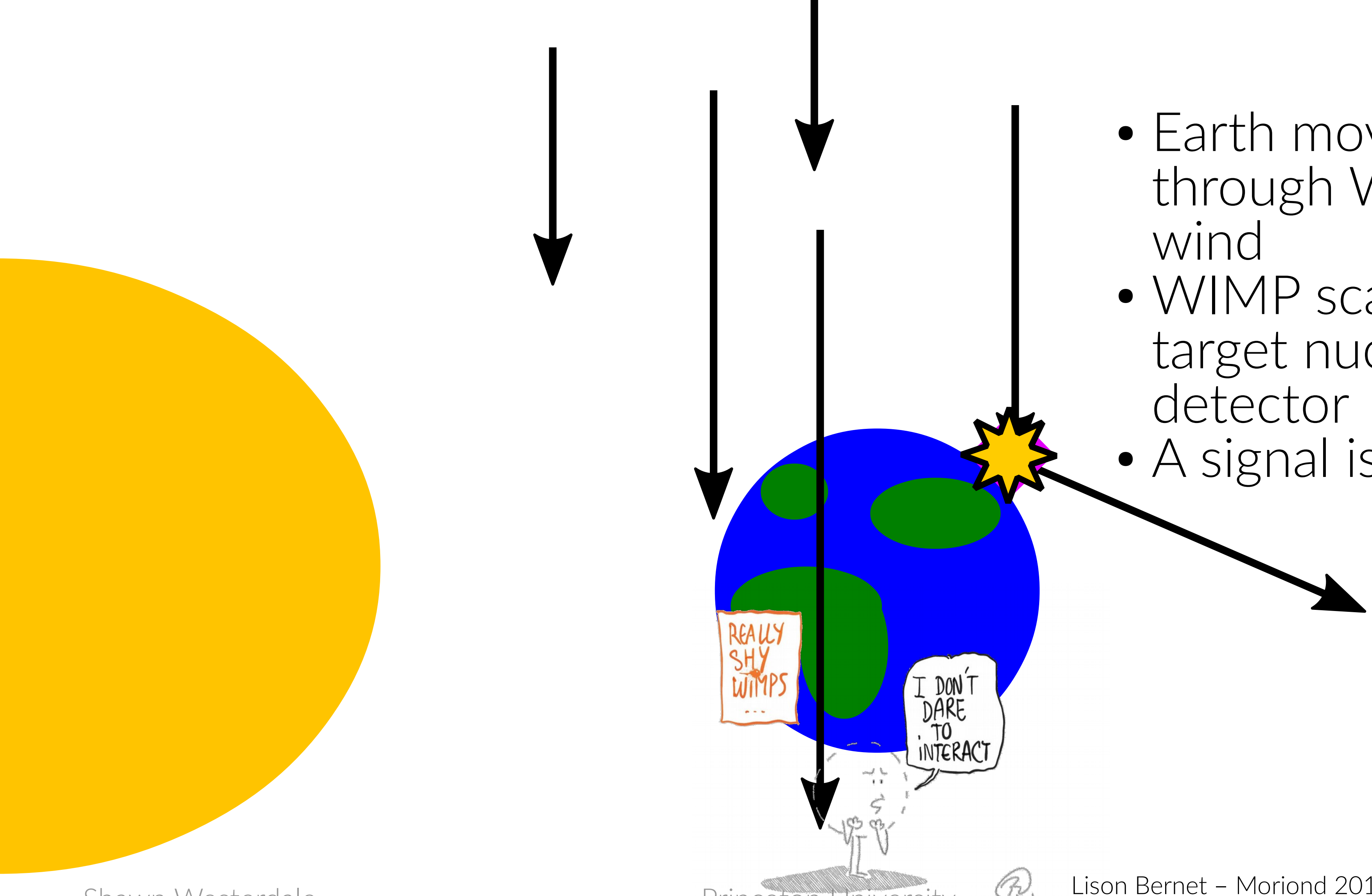
Candidates we *can* detect



- Earth moves through WIMP wind



- Earth moves through WIMP wind
- WIMP scatters on target nucleus in detector



- Earth moves through WIMP wind
- WIMP scatters on target nucleus in detector
- A signal is produced

Lison Bernet – Moriond 2019
http://lisonbernet.ultra-book.com/

DarkSide-50

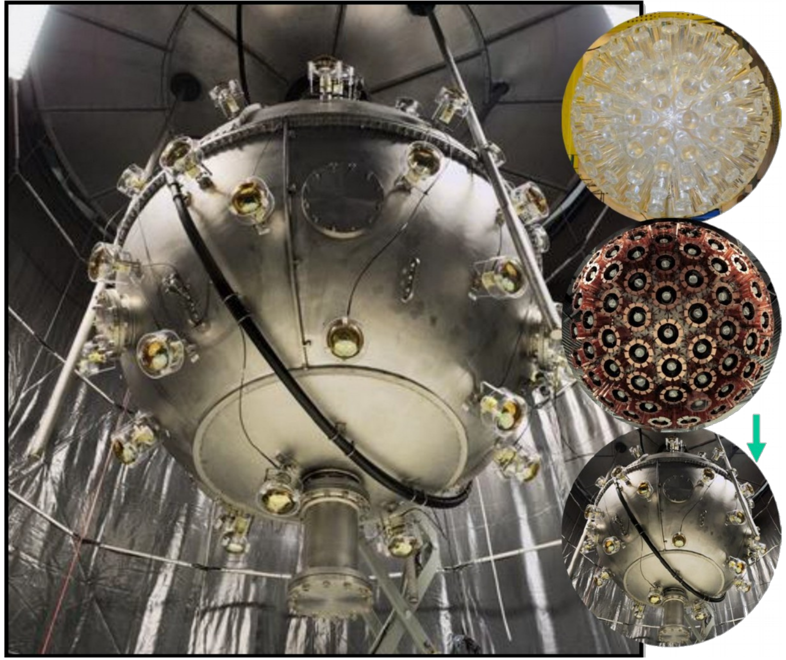
Laboratori Nazionali del Gran Sasso
Abruzzo, Italy

DarkSide Collaboration. "The electronics, trigger and data acquisition system for the liquid argon time projection chamber of the DarkSide-50 search for dark matter". J. Instrum. 12, P12011 (2017).

DarkSide Collaboration. "The electronics and data acquisition system for the DarkSide-50 veto detectors". J. Instrum. 11, P12007 (2016).

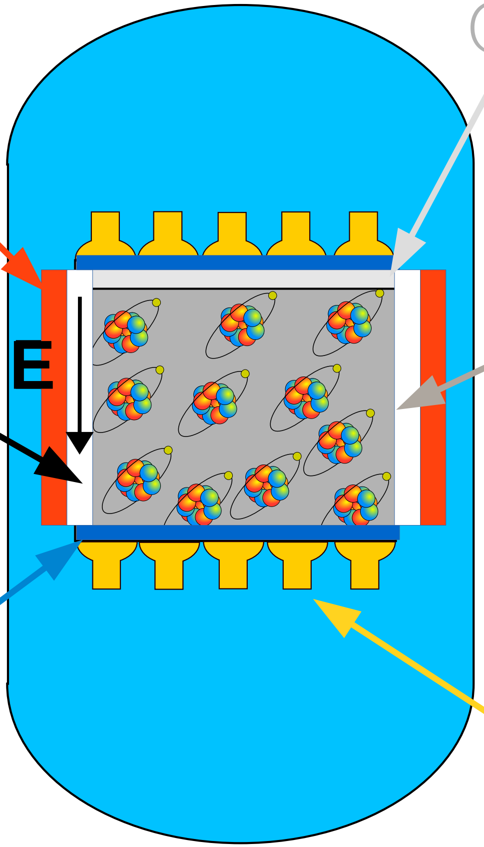
DEAP-3600

SNOLAB
Sudbury, Canada



DEAP Collaboration. "Design and construction of the DEAP-3600 dark matter detector". Astropart. Phys. 108, pp. 1–23 (2019).

DarkSide-50



Copper field cage

GAr

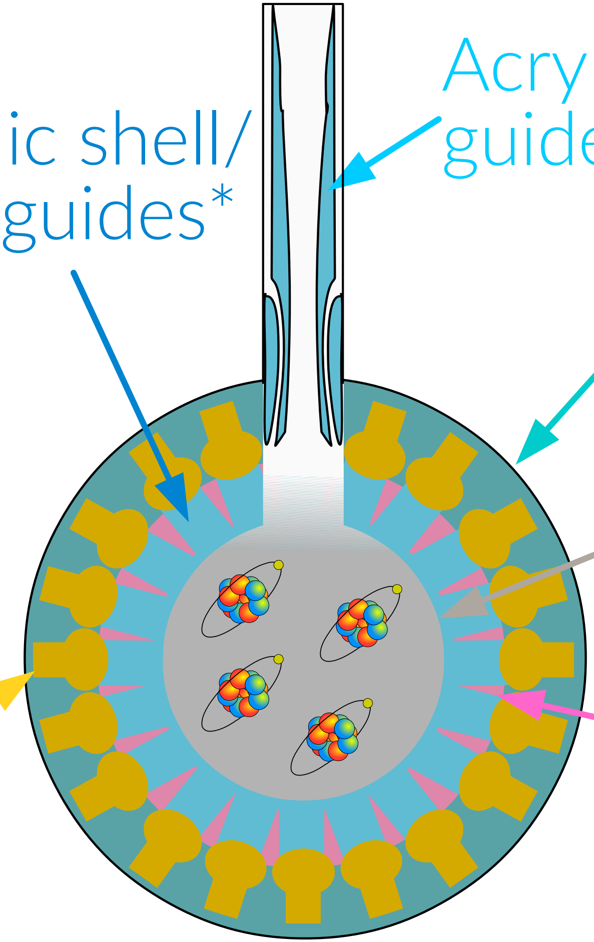
PTFE reflector*

50 kg LAr

Quartz windows*

Photo Multiplier Tubes

DEAP-3600



Acrylic shell/ light guides*

Acrylic flow guides

Steel shell

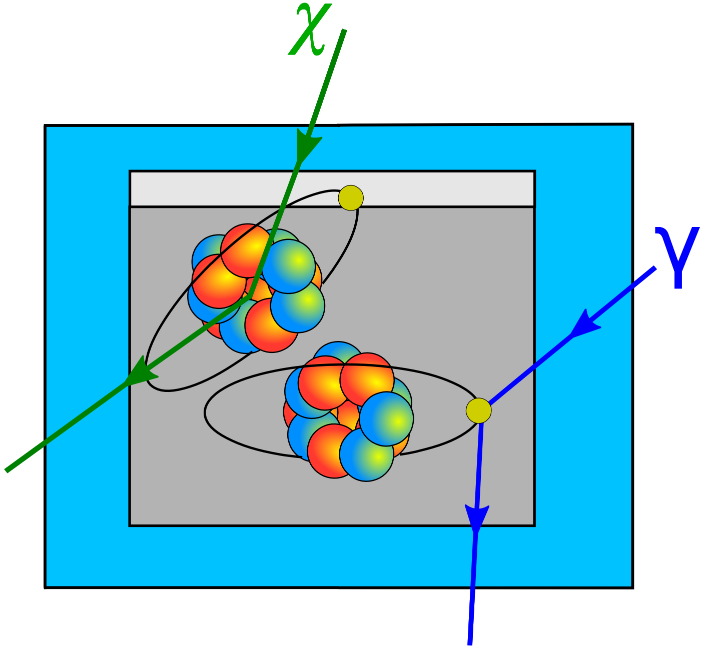
3.3 t LAr

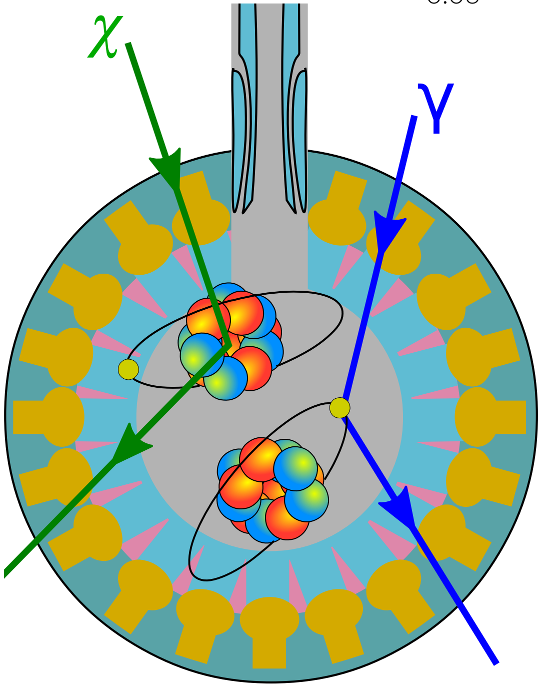
Filler foam

* Coated in TPB wavelength shifter

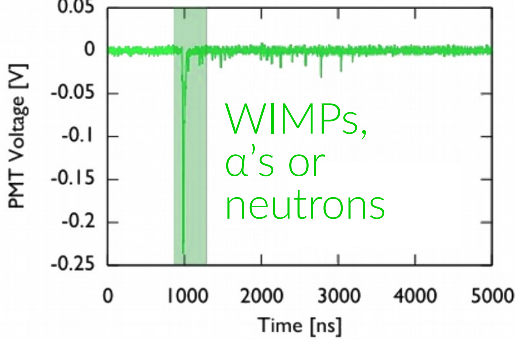
Energy depositions produce 128 nm scintillation with two time constants, photons shifted to 420 nm by TPB

Singlet component (dominates nuclear recoils): τ ~ 8 ns
Triplet component (dominates electronic recoils): τ = $1.44^{+0.10}_{-0.06}$ µs

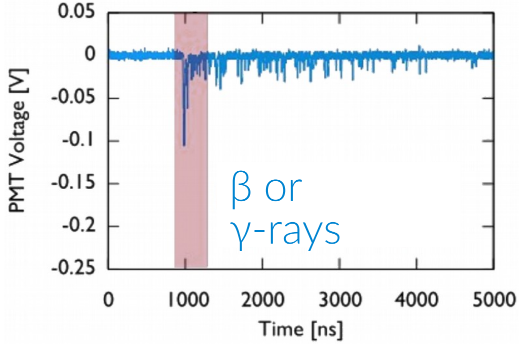




Nuclear recoils



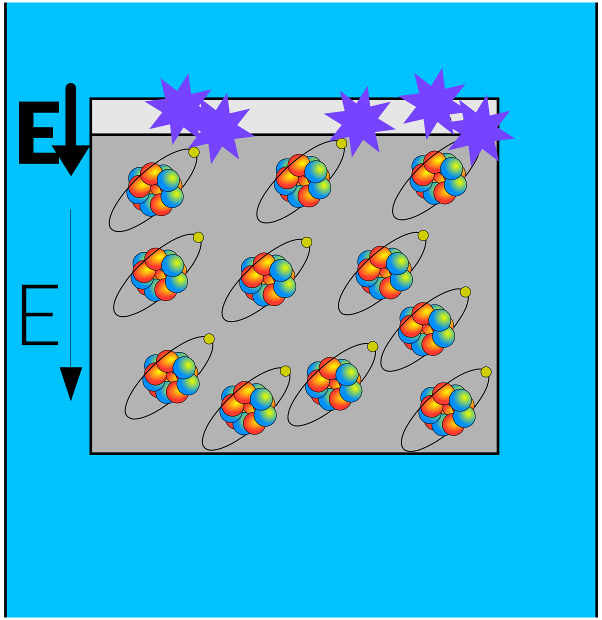
Electron recoils

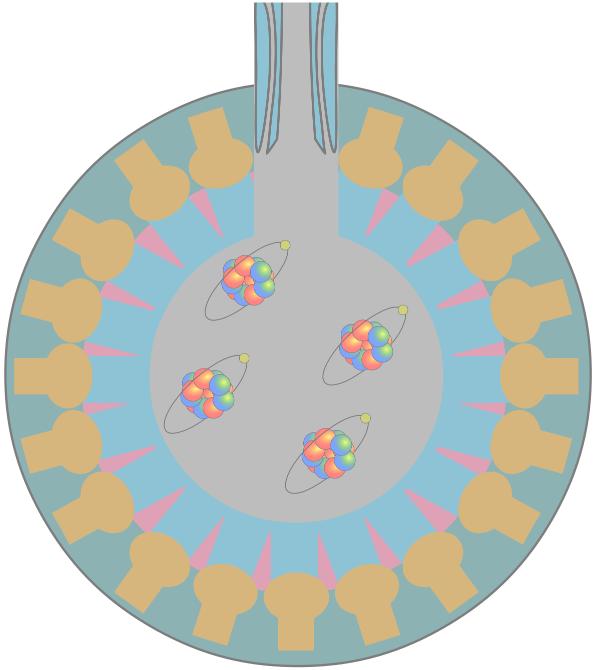


DEAP Collaboration, "The liquid-argon scintillation pulseshape in DEAP-3600". Eur. Phys. J. C 80, 303 (2020)

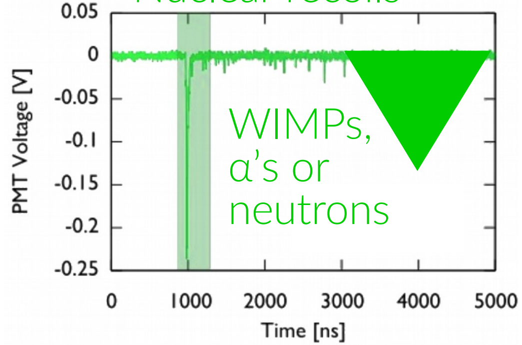
(DarkSide-50 only) S2: Ionized electrons drifted to gas pocket and accelerated through GAr to produce 2nd pulse

S2 proportion to number of extracted electrons, tells event position and number of scatters

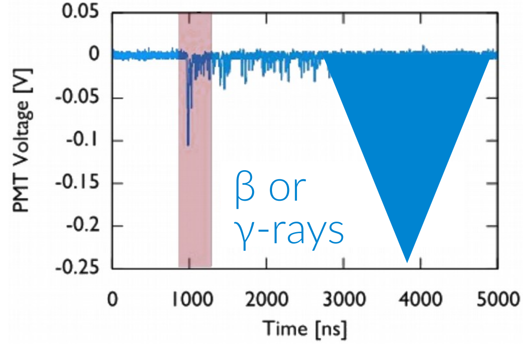


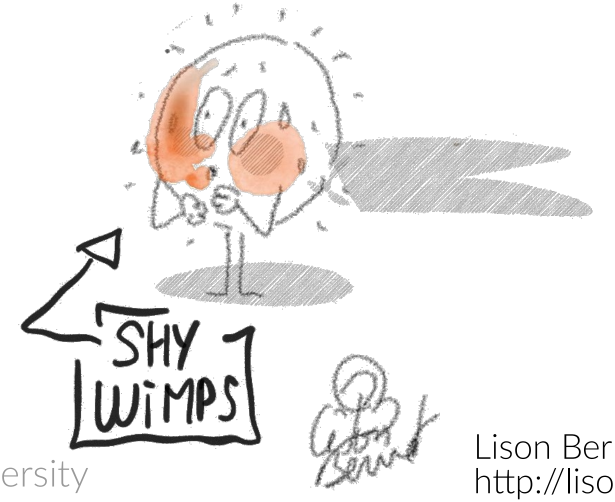


Nuclear recoils



Electron recoils





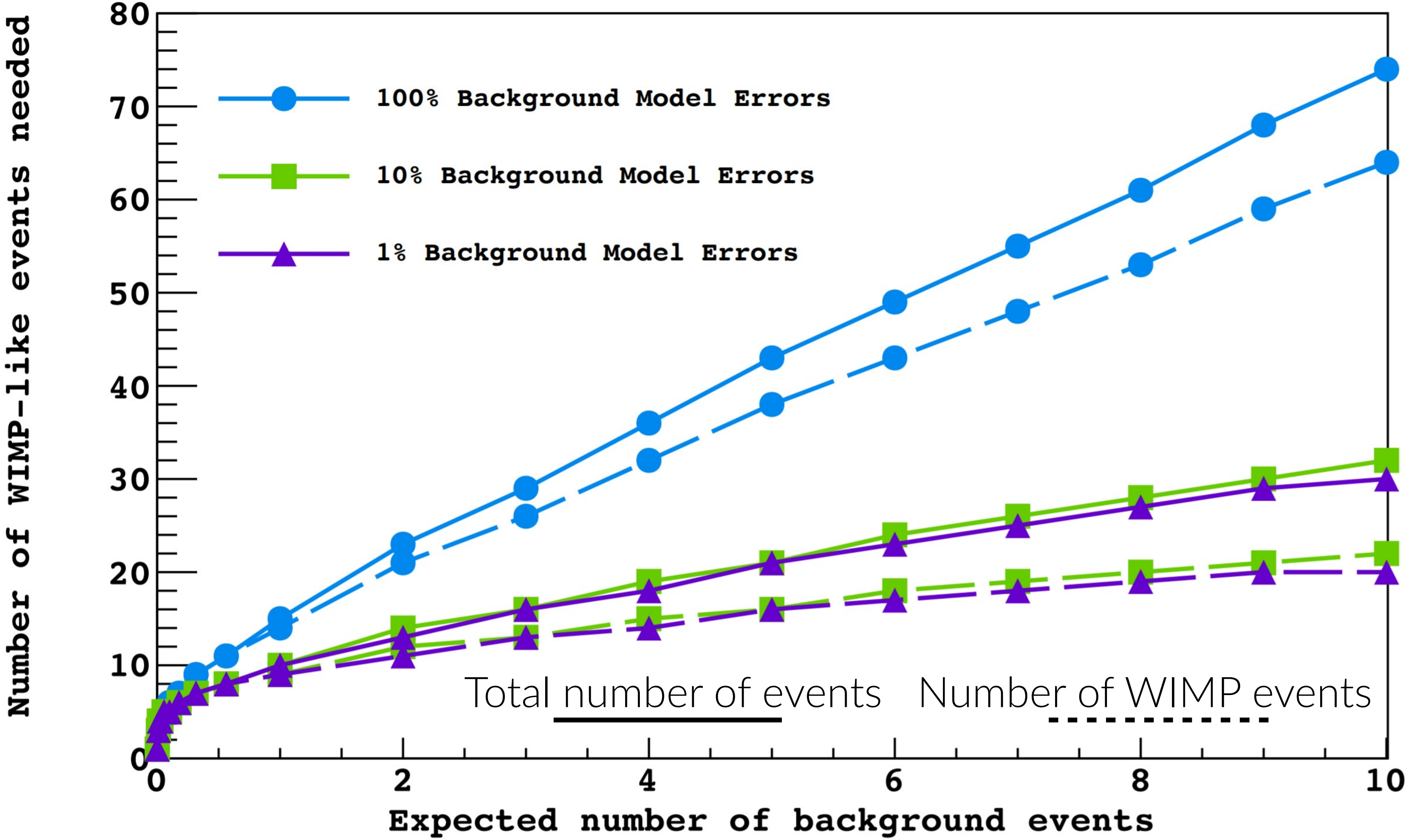
Lison Bernet – Moriond 2019
http://lisonbernet.ultra-book.com/

To discover dark matter, we must:

- Minimize backgrounds
- Accurately model what remains

Lison Bernet – Moriond 2019
http://lisonbernet.ultra-book.com/

(for a 5σ discovery)



Total number of events ▬▬▬ Number of WIMP events - - - - -

β-decays and γ-rays

- Decays of radioactive contaminants

Neutrons

- Cosmogenic origin
- Radiogenic origin

α-decays

- Rn progeny decaying on detector inner surfaces

Neutrinos

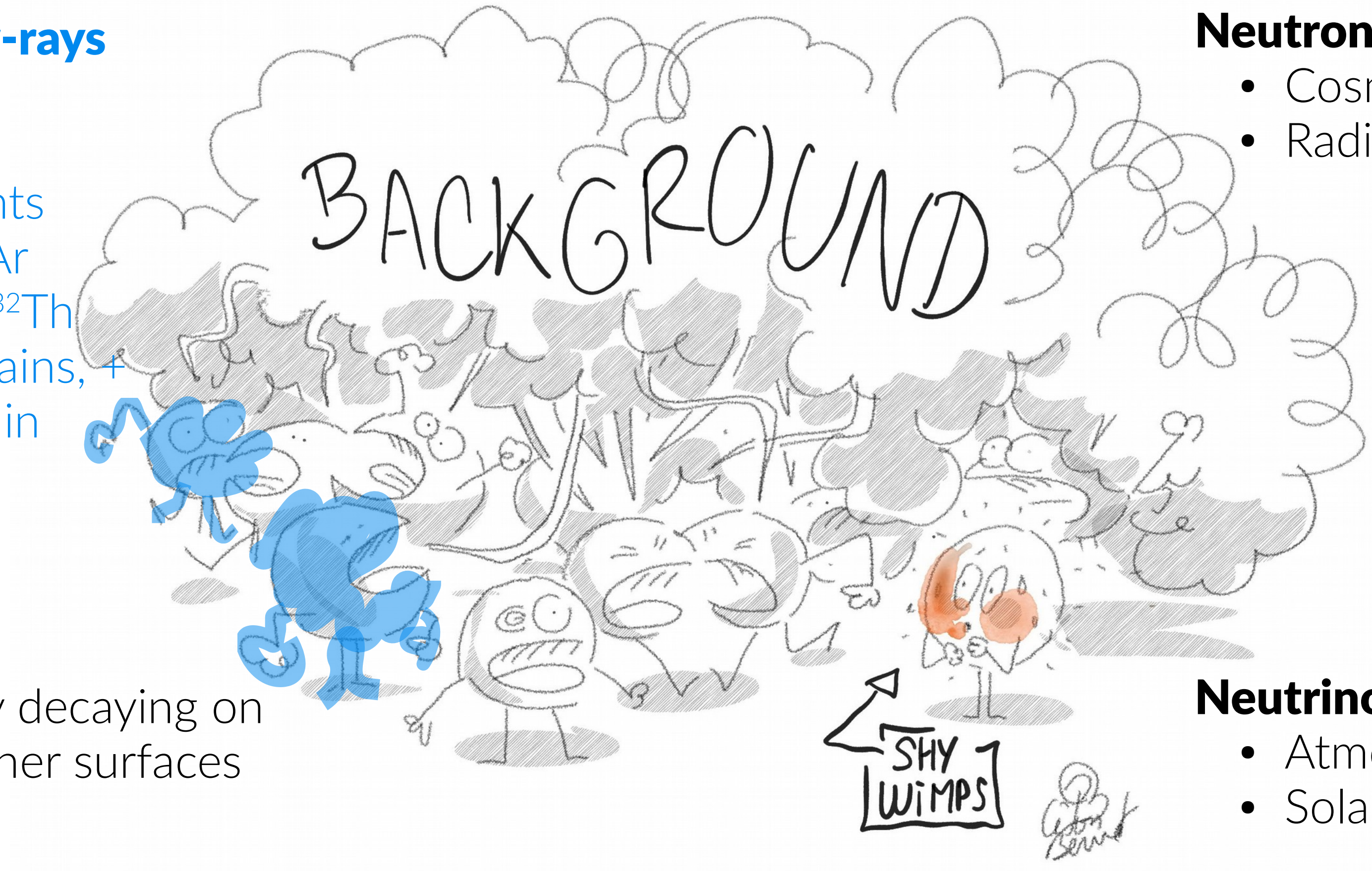
- Atmospheric origin
- Solar origin

β-decays and γ-rays

- Decays of radioactive contaminants
  - ^{39}Ar in LAr
  - ^{235,238}U, ^{232}Th decay chains, + ^{40}K, ^{60}Co in materials

α-decays

- Rn progeny decaying on detector inner surfaces



Neutrons

- Cosmogenic origin
- Radiogenic origin

Neutrinos

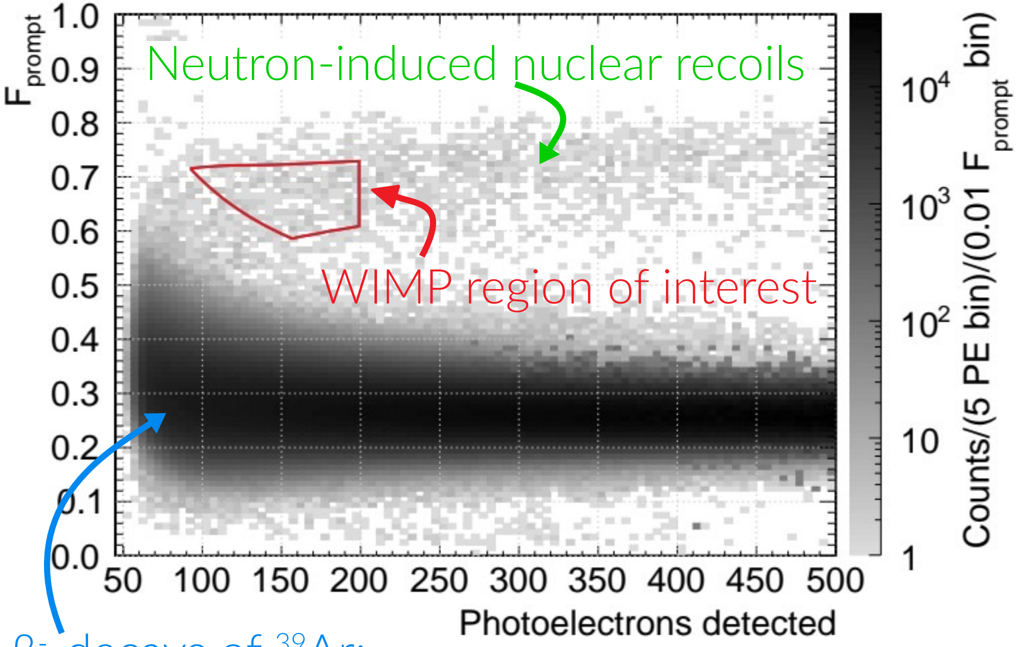
- Atmospheric origin
- Solar origin

β-decays and γ-rays: Pulse shape discrimination

Dominant source: ^{39}Ar in LAr, produced by cosmic ray ^{40}Ar(n,2n)^{39}Ar interactions in atmosphere

Currently developing software for cosmogenic activation calculations with student

AmBe neutron calibration data



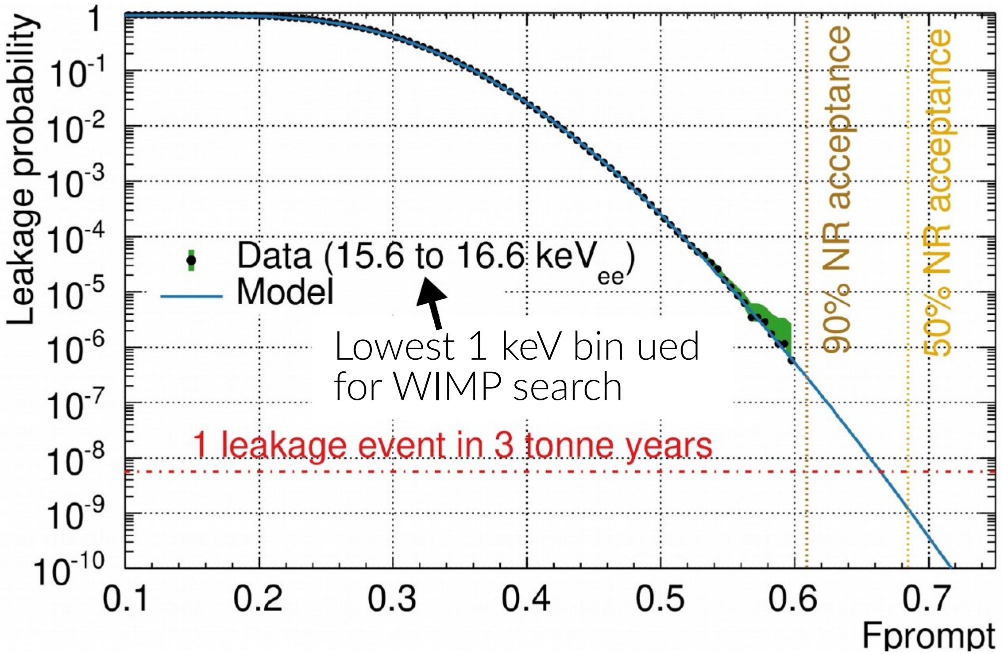
Neutron-induced nuclear recoils

WIMP region of interest

β$^-$-decays of ^{39}Ar:

- Endpoint = 565±5 keV, $t_{1/2}$ = 268±8 years
- Activity in DEAP ~ 3.3 kBq

Strongest demonstration of PSD in LAr



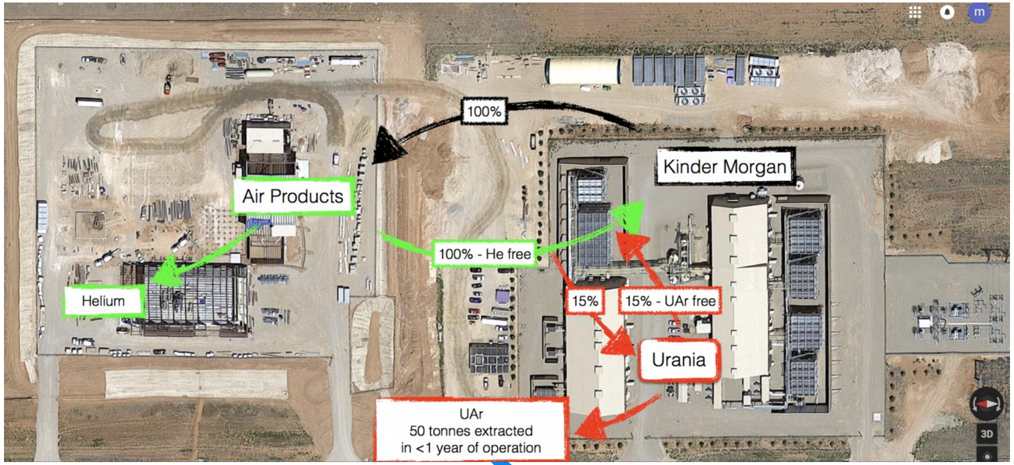
Lowest 1 keV bin ued for WIMP search

1 leakage event in 3 tonne years

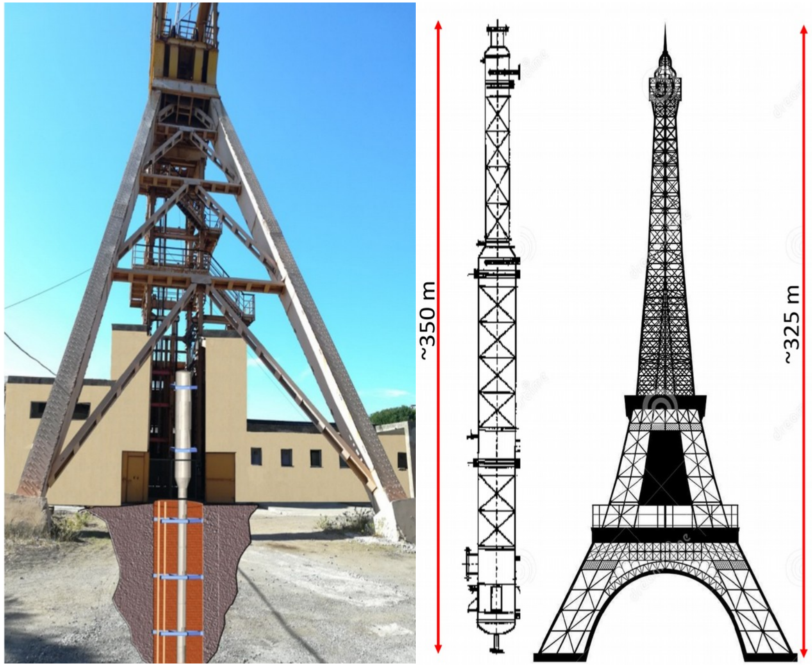
DEAP Collab.. "Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB". Phys. Rev. D 100, 022004 (2019)

β-decays and γ-rays: Further reduction with isotopically purified argon

Urania: Underground Ar extraction in Cortez, CO



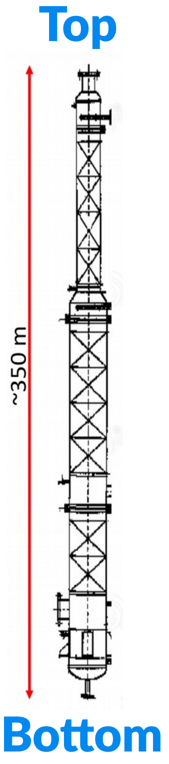
Aria: Chemical and isotopic ^{40}Ar distillation in Sardinia, Italy

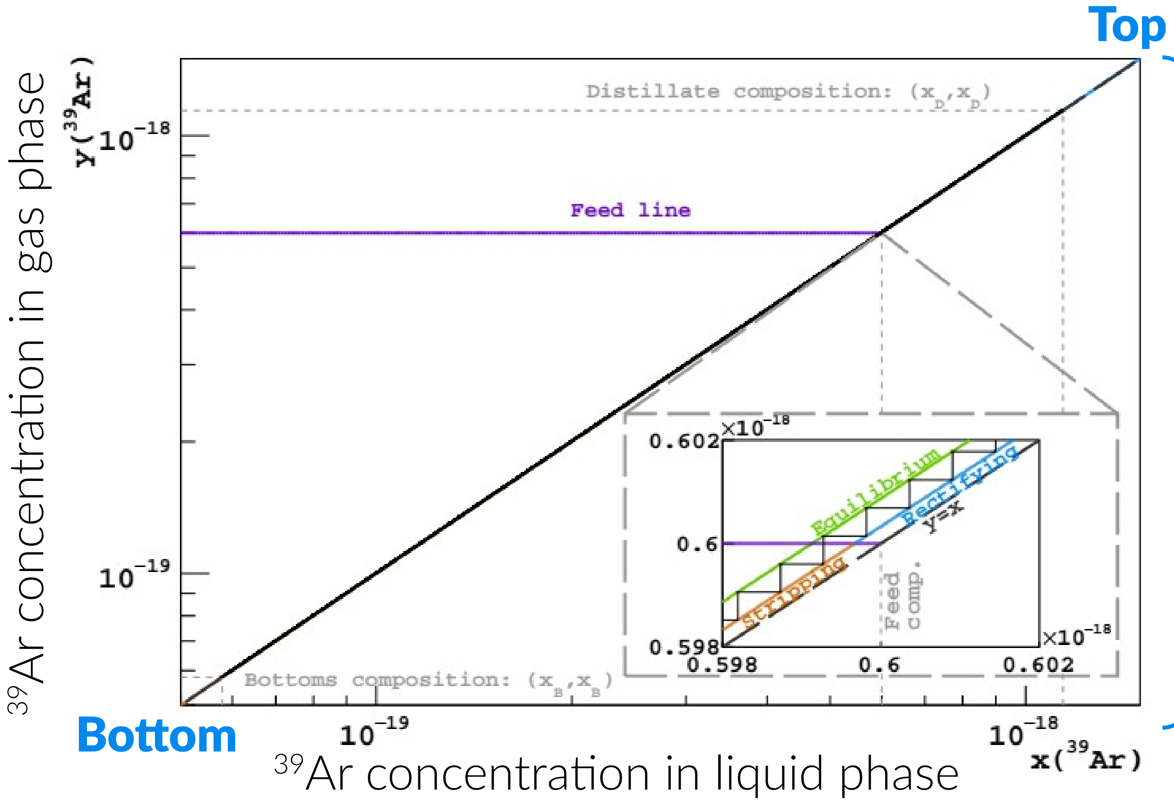


^{39}Ar activity in underground Ar is at least 1400x lower than in atmospheric Ar!

DarkSide Collaboration. “Results from the first use of low radioactivity argon in a dark matter search”. Phys. Rev. D 93, 081101(R) (2016).

β-decays and γ-rays: With 2870 stages, the Aria column can deplete ^{39}Ar by 10x, at rate 8.1 kg/day





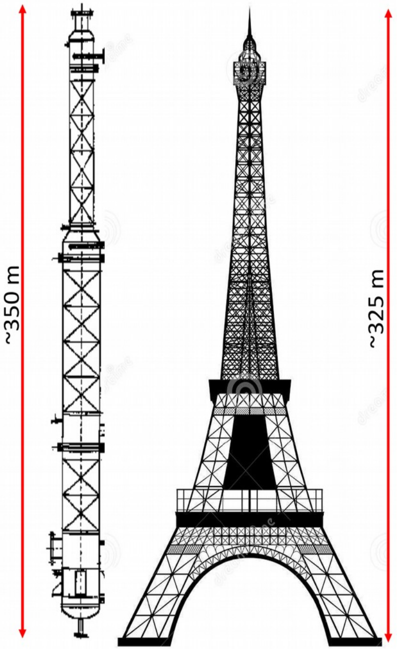
McCabe-Thiele calculation, modified to account for the change in temperature and ^{39}Ar-^{40}Ar relative volatility with height

This plot shows the depletion of ^{39}Ar in liquid and gas phases at higher points in the column

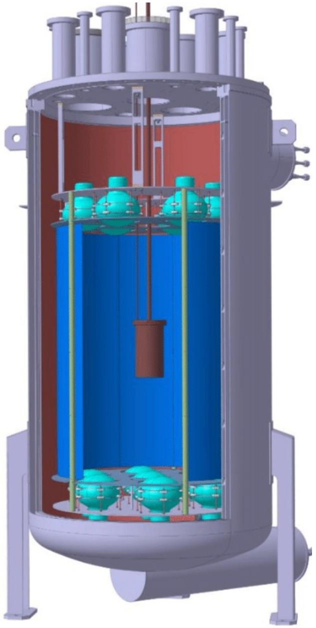
DarkSide Collaboration
"Separating ^{39}Ar from ^{40}Ar by cryogenic distillation with Aria for dark matter searches".
arXiv:2101.08686 (2021)
[submitted to Eur. Phys. J. C]

β-decays and γ-rays: Assay distilled argon with DArT in ArDM to measure ^{39}Ar content

Aria: Chemical and isotopic ^{40}Ar distillation in Sardinia, Italy



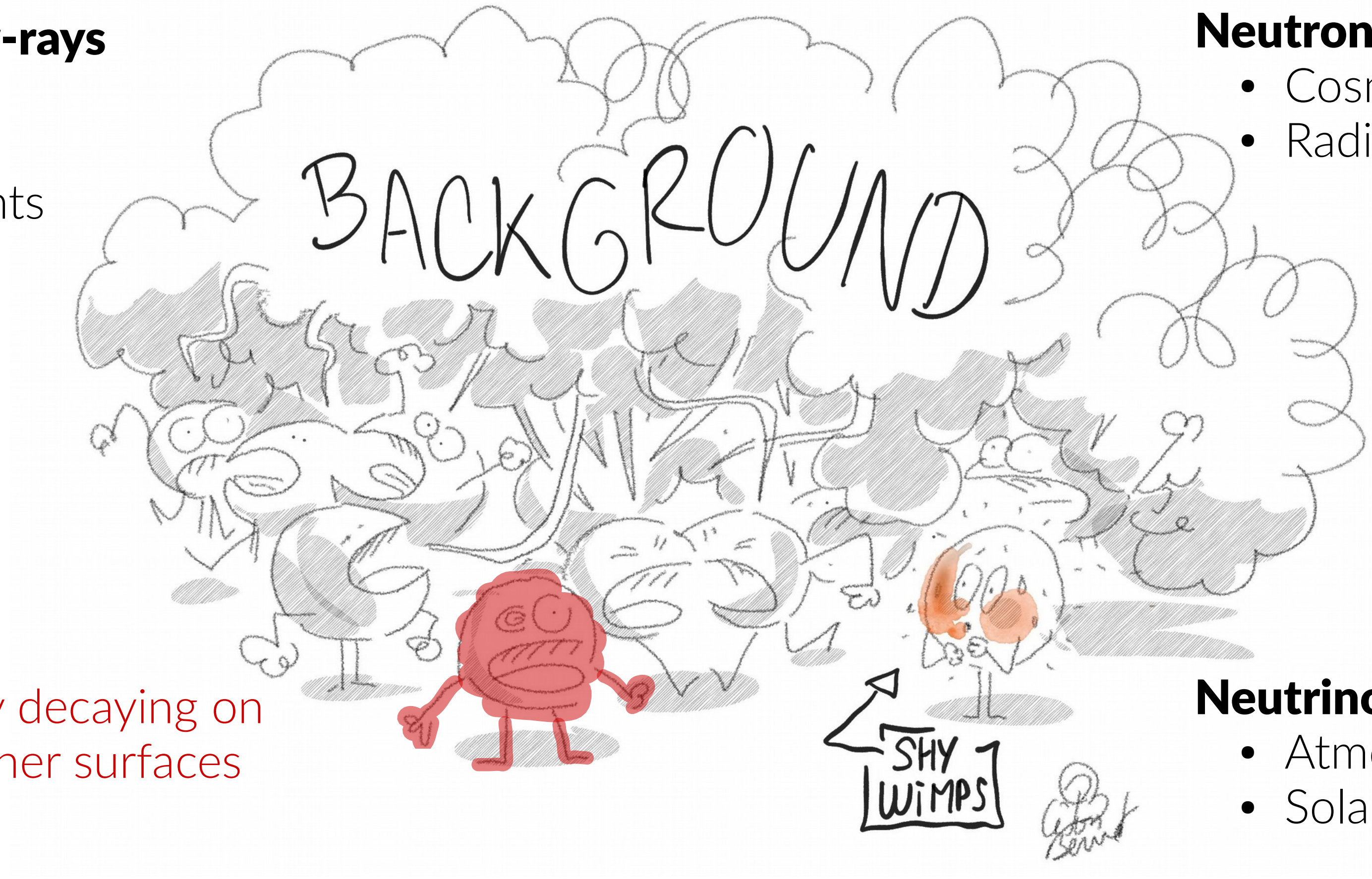
DArT in ArDM: Depleted Ar radio-assay-facility



DarkSide Collaboration. "Design and construction of a new detector to measure ultra-low radioactive-isotope contamination of argon". J. Instrum. 15, P02024 (2020).

β-decays and γ-rays
- Decays of radioactive contaminants

Neutrons
- Cosmogenic origin
- Radiogenic origin



α-decays
- Rn progeny decaying on detector inner surfaces

Neutrinos
- Atmospheric origin
- Solar origin

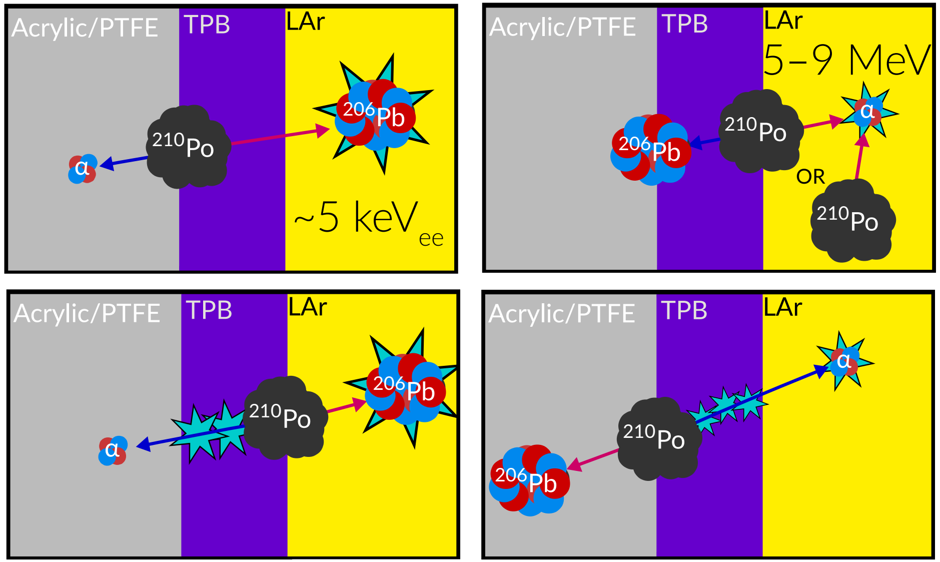
α-decays: Characterization of attenuated α signals enables more effective modeling

Too low energy: Pb nucleus quenched below ROI

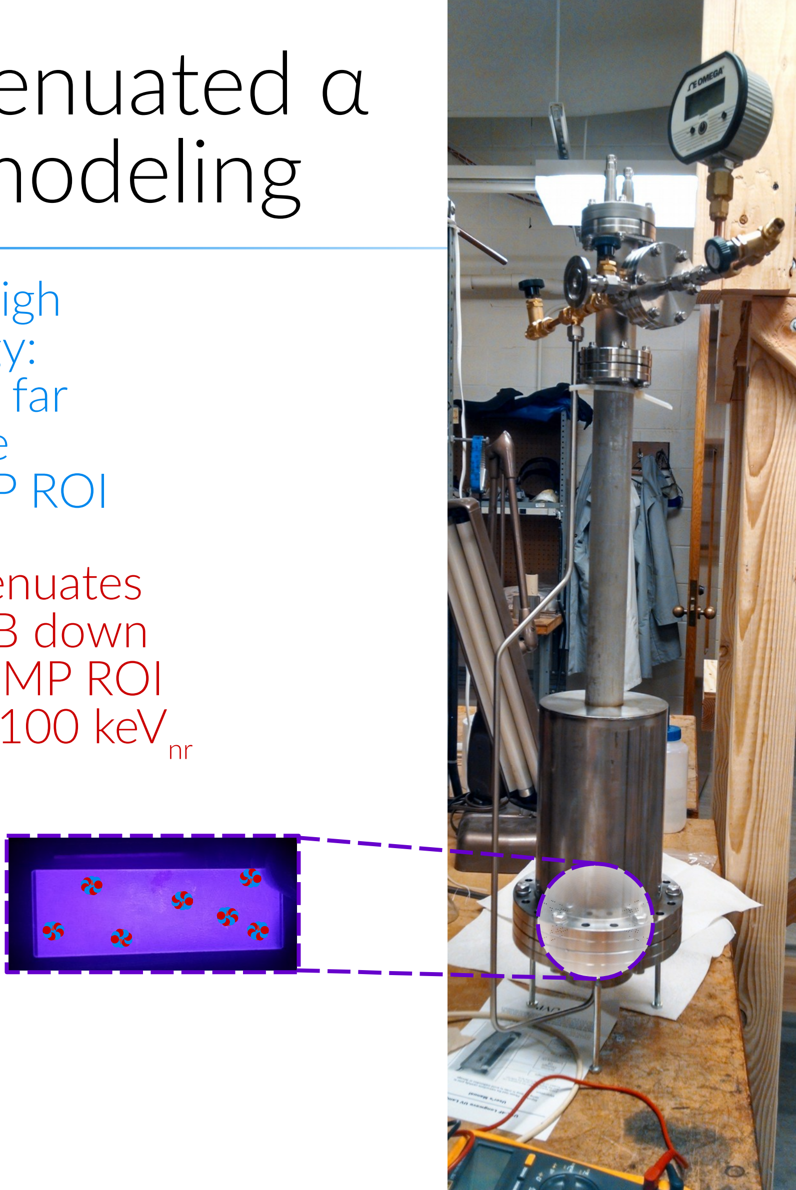
Too high energy: Full α far above WIMP ROI

α scintillation in TPB pushes Pb into ROI

α attenuates in TPB down to WIMP ROI ~10–100 keV_{nr}



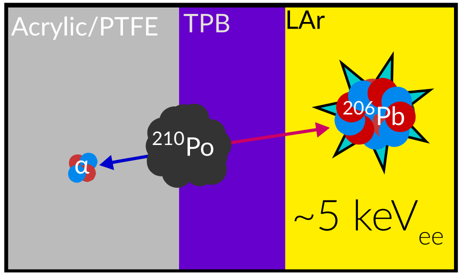
Wavelength shifter

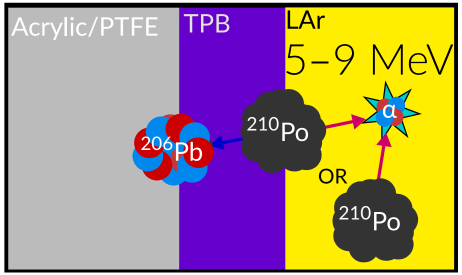


J. Xu, C. Stanford, **S. Westerdale**, F. Calaprice, A. Wright, Z. Shi. *"First measurement of surface nuclear recoil background for argon dark matter searches". Phys. Rev. D 96, 061101(R) (2017)*

α-decays: α scintillation in TPB provides a powerful veto for surface backgrounds

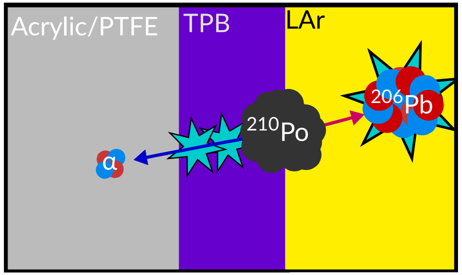
Too low energy: Pb nucleus quenched below ROI

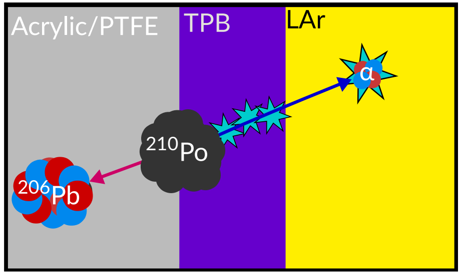




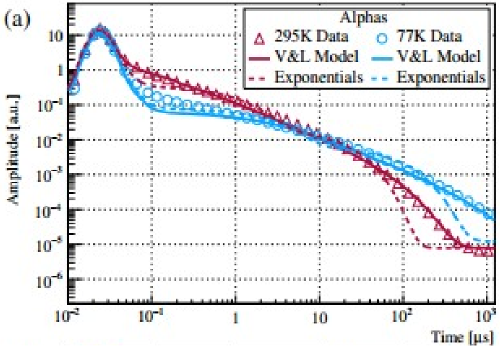
Too high energy: Full α far above WIMP ROI

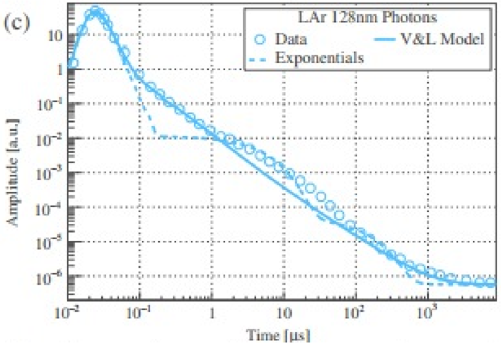
α scintillation in TPB pushes Pb into ROI

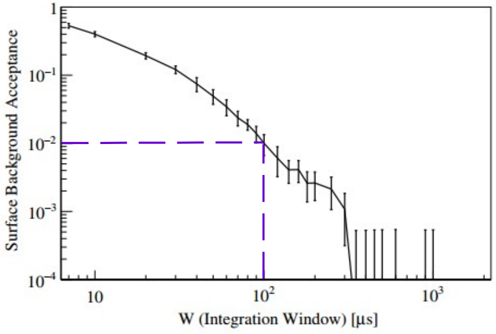




α attenuates in TPB down to WIMP ROI $\sim$10–100 keV$_{nr}$







C. Stanford, **S. Westerdale**, J. Xu, and F. Calaprice. "Surface background suppression in liquid argon dark matter detectors using a newly discovered time component of tetraphenyl-butadiene scintillation". Phys. Rev. D 98, 062002 (2018).

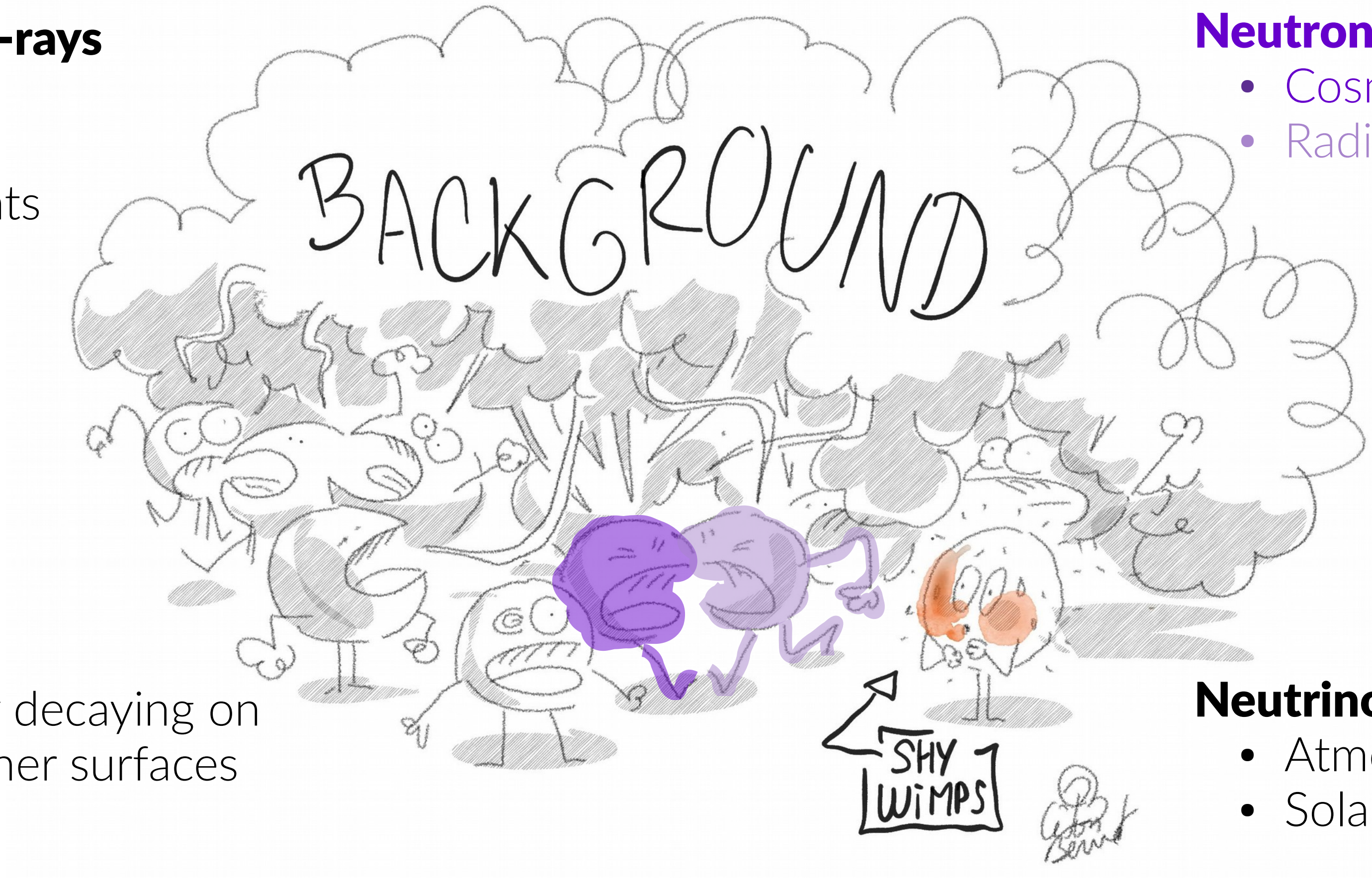
TPB pulse shape in a 100 μs window provides a surface α discriminant, robust to position mis-reconstruction

β-decays and γ-rays

- Decays of radioactive contaminants

Neutrons

- Cosmogenic origin
- Radiogenic origin



α-decays

- Rn progeny decaying on detector inner surfaces

Neutrinos

- Atmospheric origin
- Solar origin

Cosmogenic neutrons: Cosmic rays

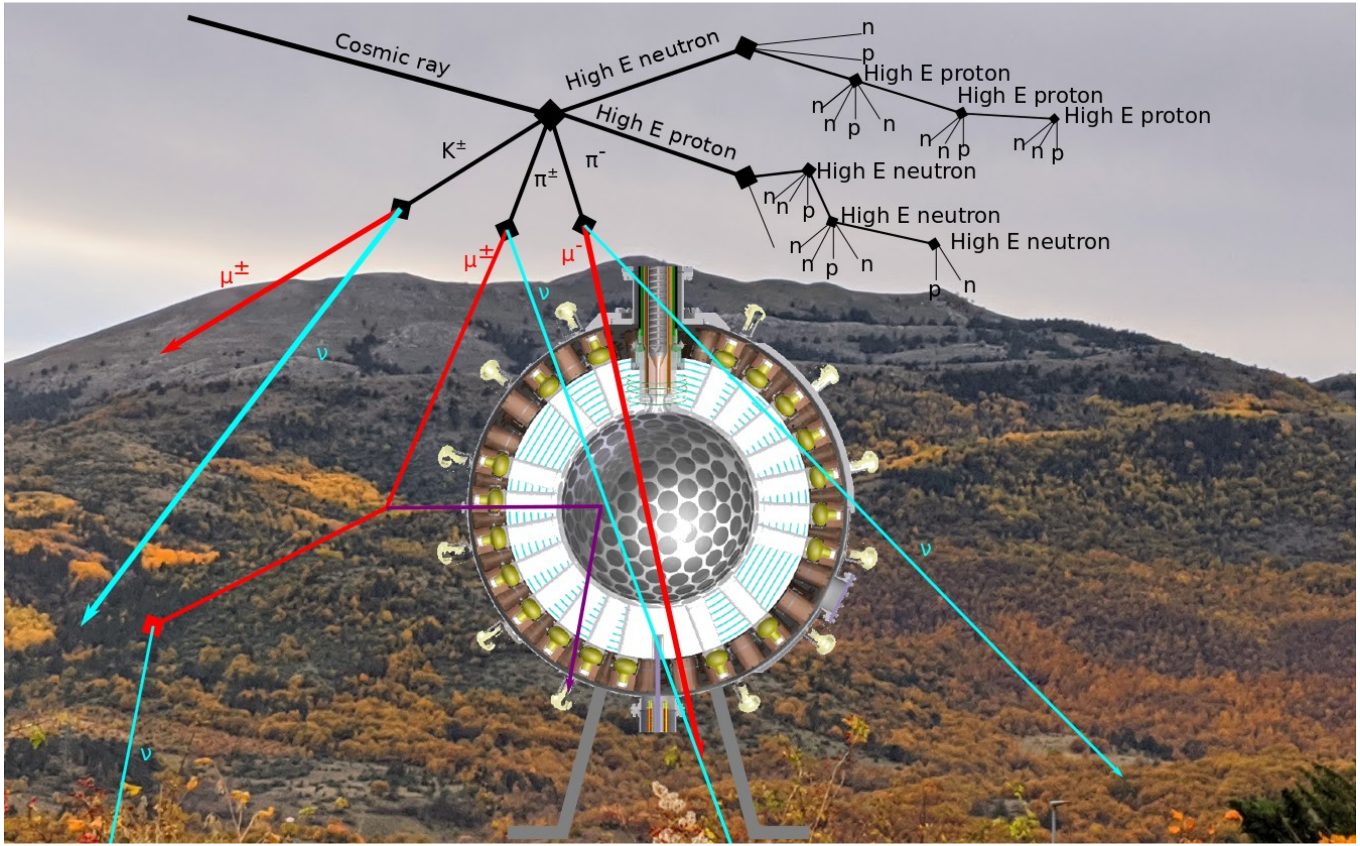
Cosmic rays produce nucleonic and mesonic showers, which may activate detector materials.

High energy nucleons and mesons also induce a prohibitively high trigger rate on surface.

High energy neutrons produced in shower (especially from μ±) can produce nuclear recoils in the LAr.

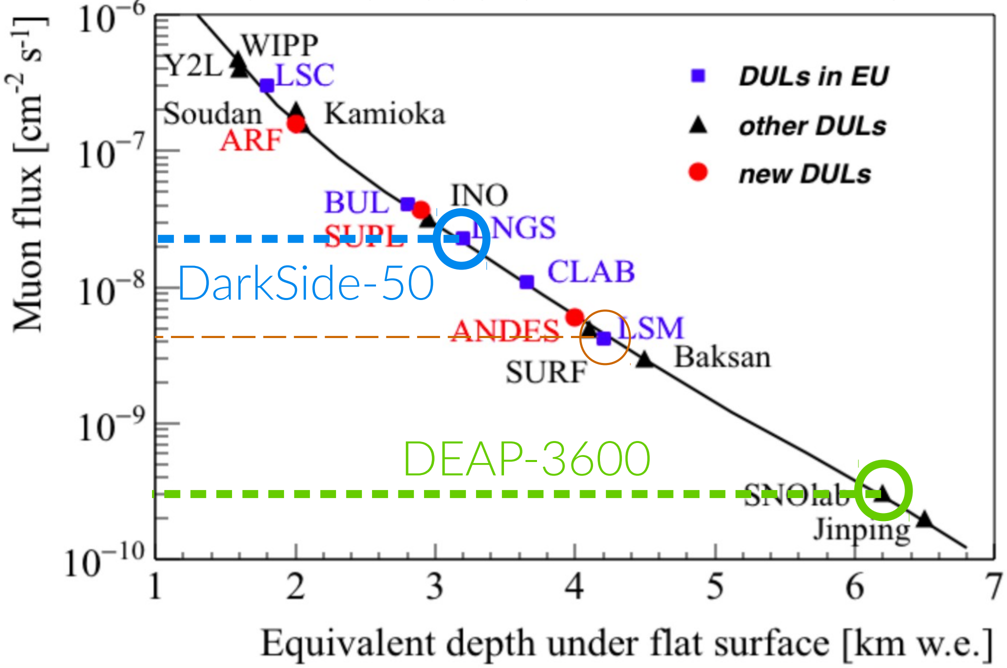
Interactions produce atmospheric neutrinos

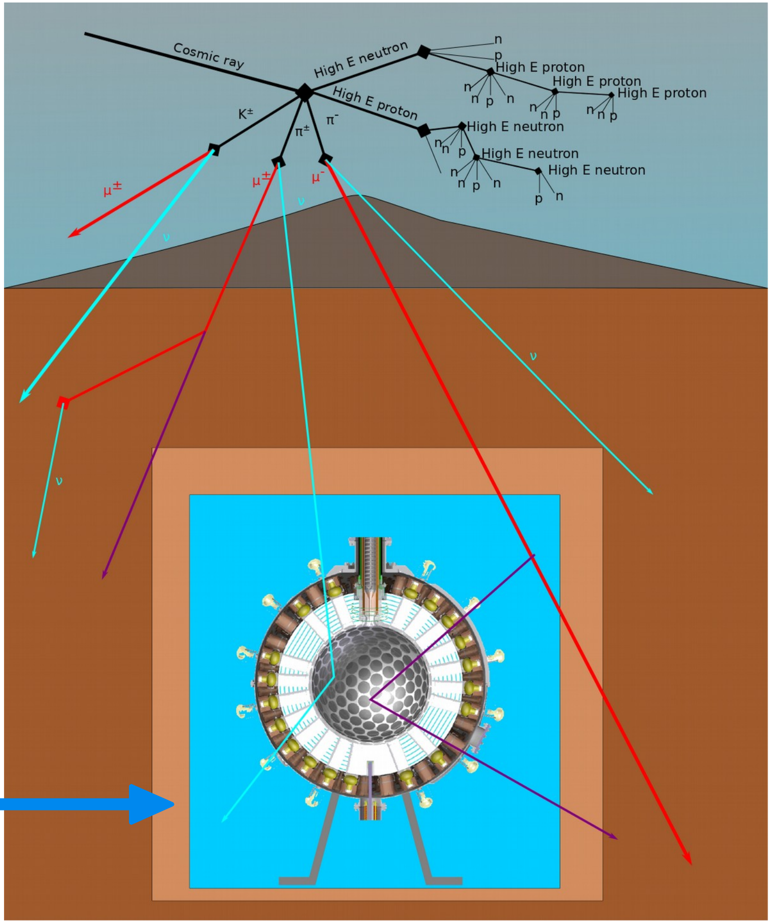
μ flux at sea level: ~10^{-2} $cm^{-2}s^{-1}$



Cosmogenic neutrons: DEAP underground

Muon flux at sea level: ~10^{-2} cm^{-2}s^{-1}





Water-based muon veto tags muons by Cherenkov light muons and their electromagnetic showers produce

DarkSide-50

Laboratori Nazionali del Gran Sasso
Abruzzo, Italy

1.4 km overburden
[3.4 km water equivalent]

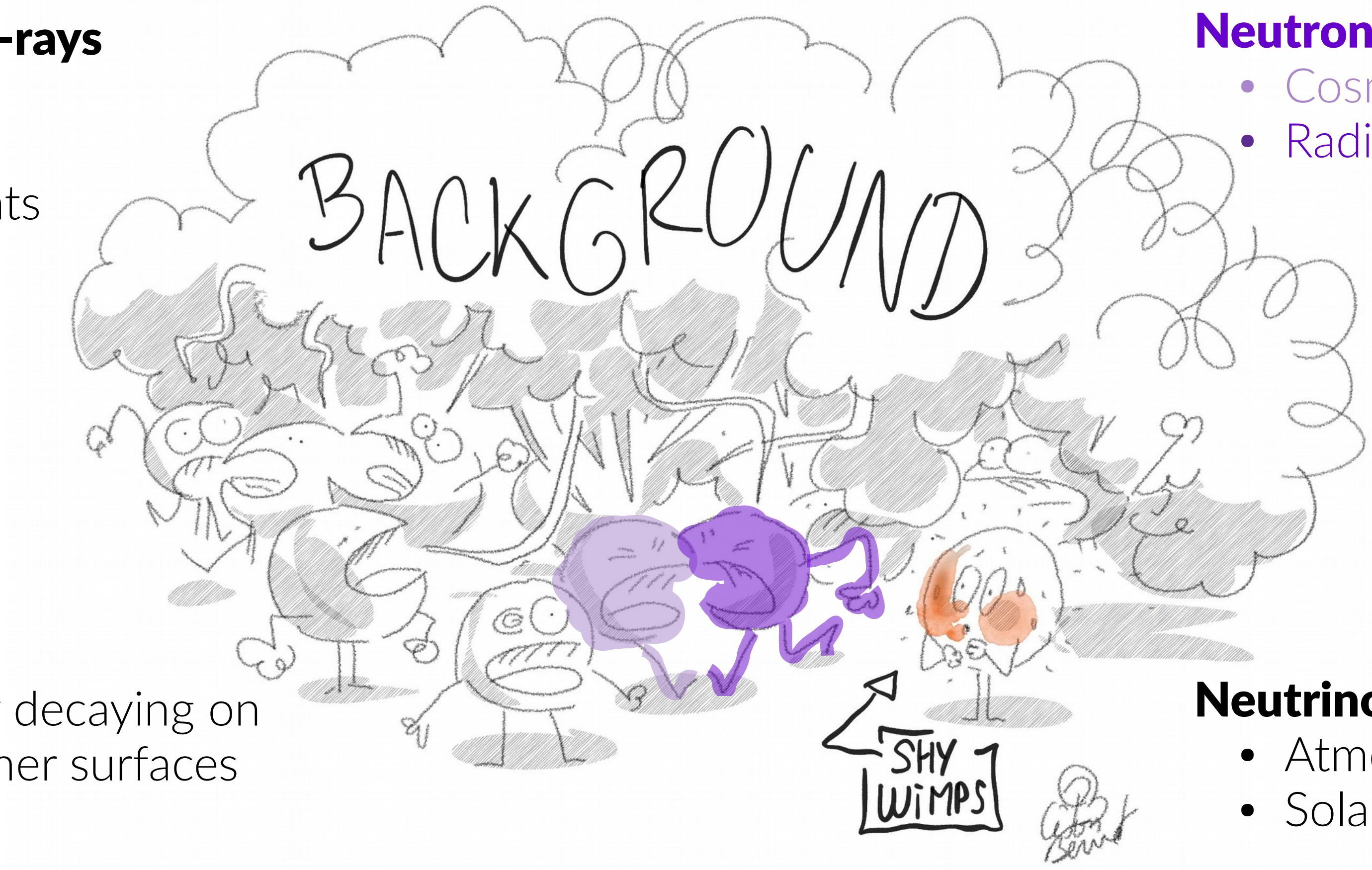
DEAP-3600

SNOLAB
Sudbury, Canada

2 km underground
[6 km water equivalent]

β-decays and γ-rays

- Decays of radioactive contaminants



Neutrons

- Cosmogenic origin
- Radiogenic origin

α-decays

- Rn progeny decaying on detector inner surfaces

Neutrinos

- Atmospheric origin
- Solar origin

Radiogenic neutrons: A new (α,n) yield calculator

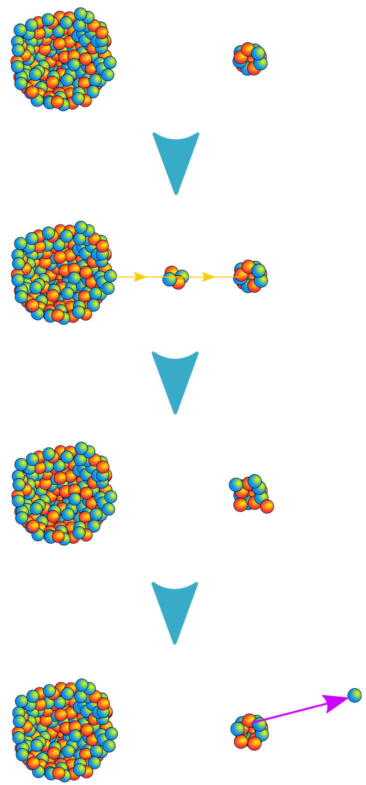
$$Y(T_n) = \sum_{\alpha} P_{\alpha} \sum_{m} \frac{N_A C_m}{A_m} \sum_{T'_{\alpha} \in \{T_{\alpha}, T_{\alpha} - \Delta T'_{\alpha}, \ldots, 0\}} \frac{\sigma_m(T'_{\alpha}, T_n)}{S(T'_{\alpha})} \Delta T'_{\alpha}$$

Calculate (α,n) yields using NeuCBOT

- ENSDF nuclear decay libraries
- SRIM stopping power calculations
- TALYS nuclear reaction simulations

Download at: https://github.com/shawest/neucbot

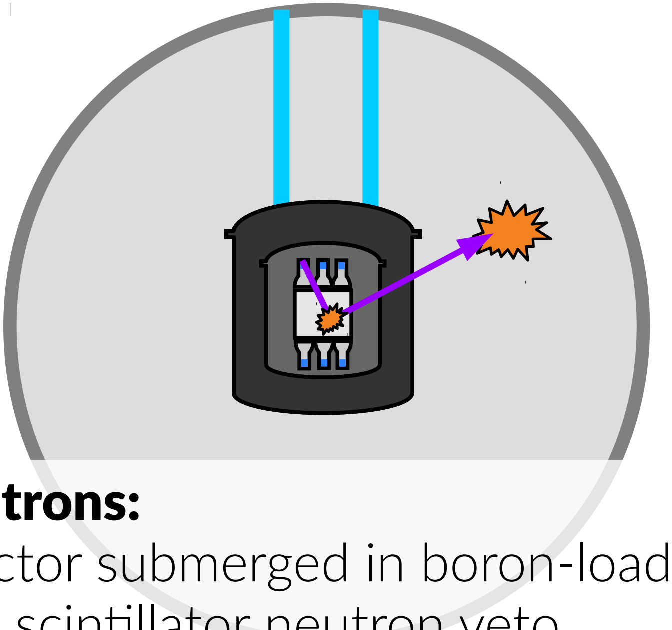
S. Westerdale and P.D. Meyers, “Radiogenic Neutron Yield Calculations for Low-Background Experiments“. NIM A (Dec. 2017) Vol 875, pp. 57-64



(α,n) reactions

Radiogenic neutrons: Mitigation and measurement

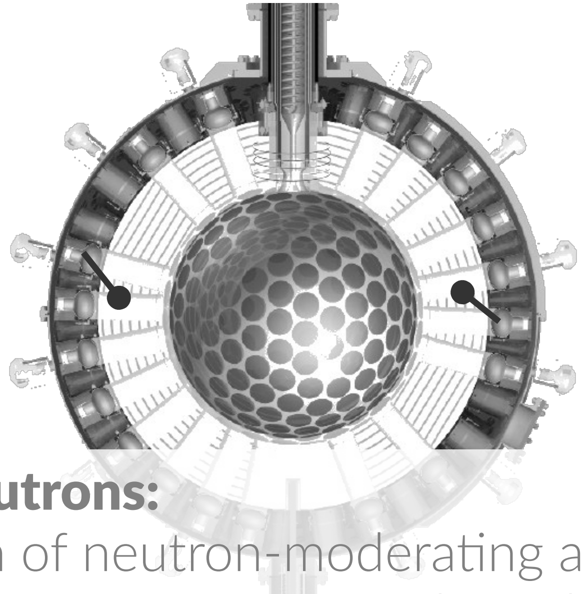
DarkSide-50



Veto neutrons:

- Detector submerged in boron-loaded liquid scintillator neutron veto
- Minimize mass between detector & veto

DEAP-3600

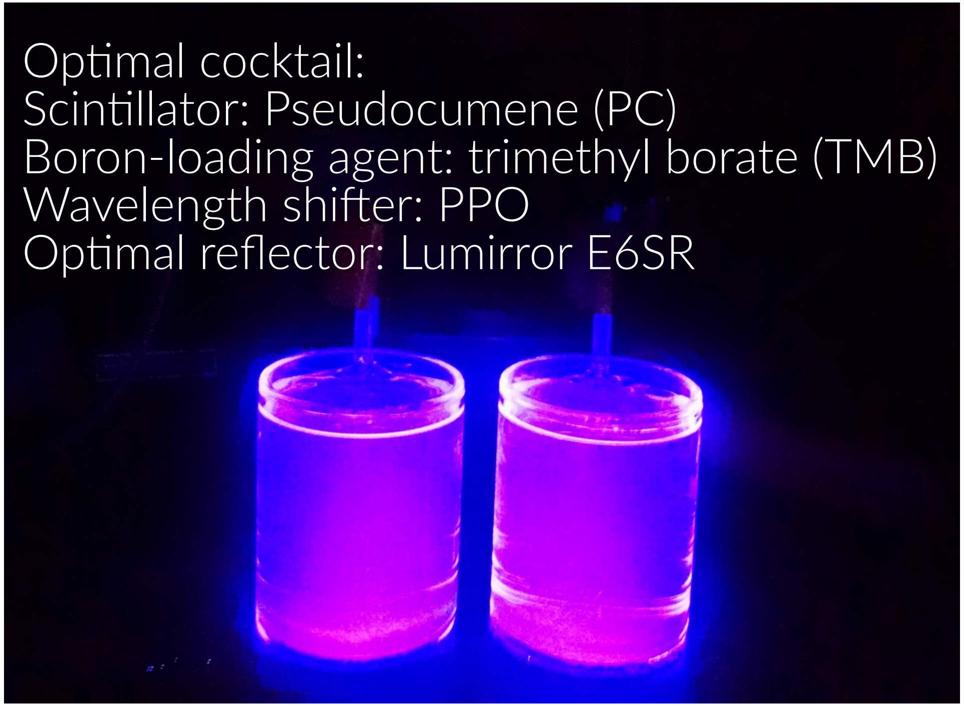


Shield neutrons:

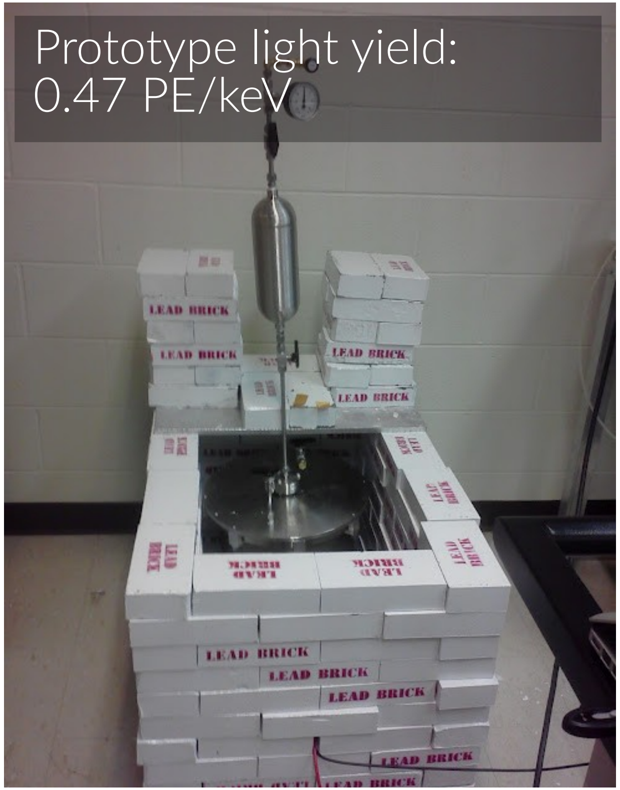
- 50 cm of neutron-moderating acrylic block neutrons from reaching the LAr
- Position & energy cuts reduce residuals

Radiogenic neutrons: The DarkSide-50 veto

R&D to optimize design



Optimal cocktail:
Scintillator: Pseudocumene (PC)
Boron-loading agent: trimethyl borate (TMB)
Wavelength shifter: PPO
Optimal reflector: Lumirror E6SR

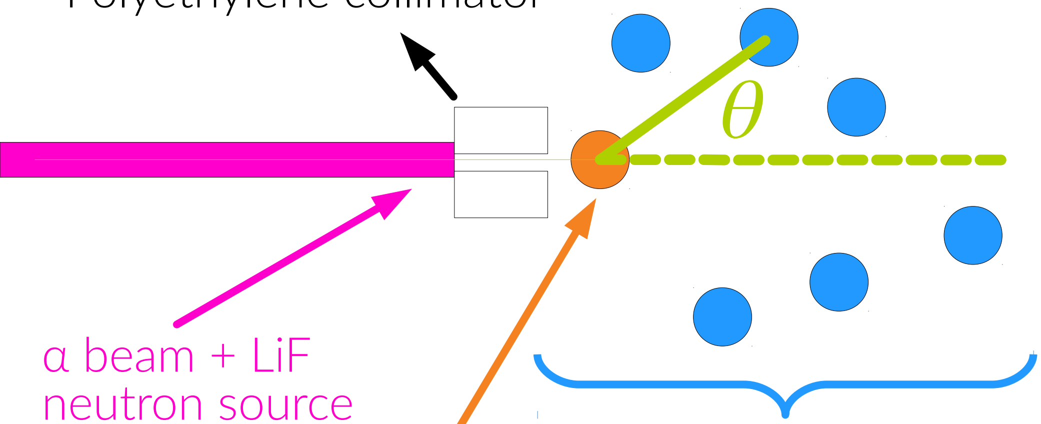


Prototype light yield:
0.47 PE/keV

S. Westerdale, E. Shields, F. Calaprice, "A Prototype Neutron Veto for Dark Matter Detectors". Astropart. Phys., 79, 10 (2016)

Radiogenic neutrons: The DarkSide-50 veto

Nuclear recoil quenching measurements

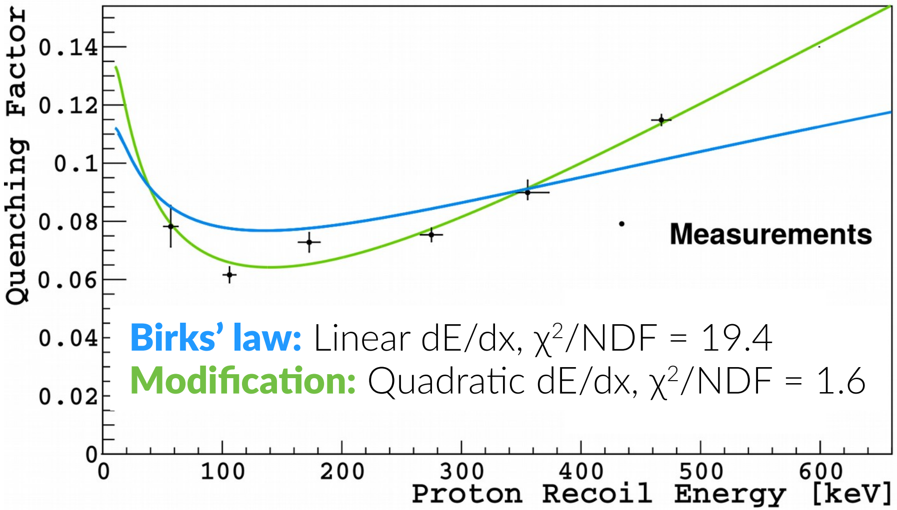


Polyethylene collimator

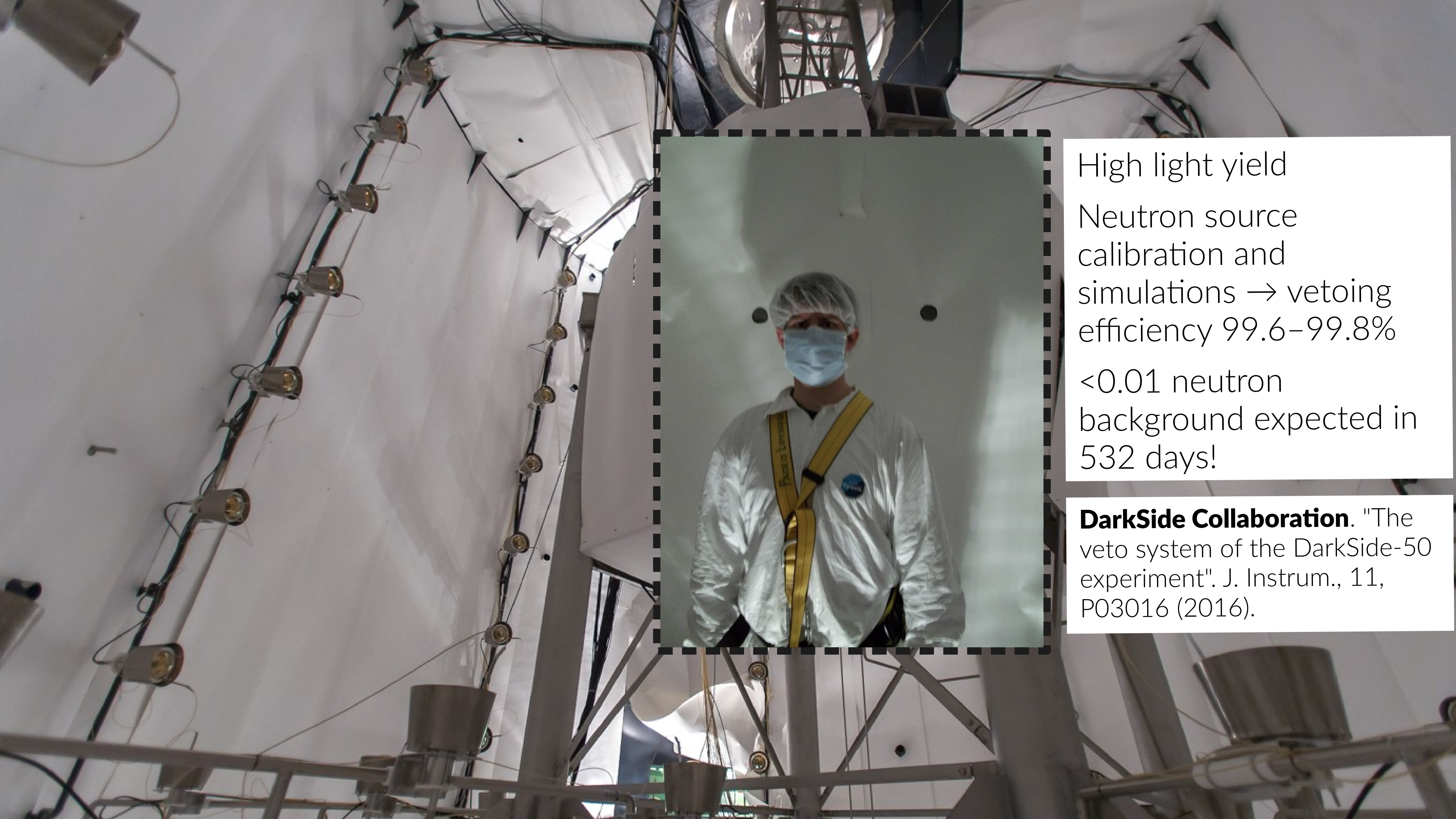
α beam + LiF
neutron source

Liquid scintillator
detector

Coincidence detectors



S. Westerdale *et al.*, "Quenching Measurements and Modeling of a Boron-Loaded Organic Liquid Scintillator". J. Instrum. 12 (2017)



High light yield

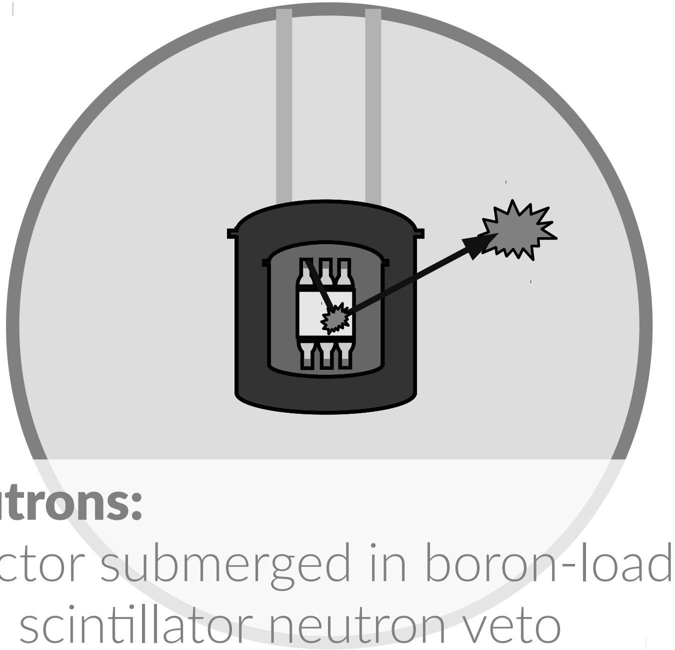
Neutron source calibration and simulations → vetoing efficiency 99.6–99.8%

<0.01 neutron background expected in 532 days!

DarkSide Collaboration. "The veto system of the DarkSide-50 experiment". J. Instrum., 11, P03016 (2016).

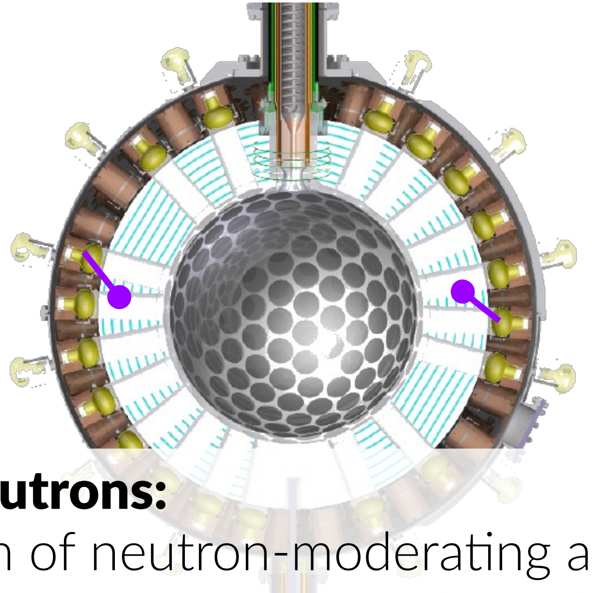
Radiogenic neutrons: Mitigation and measurement

DarkSide-50



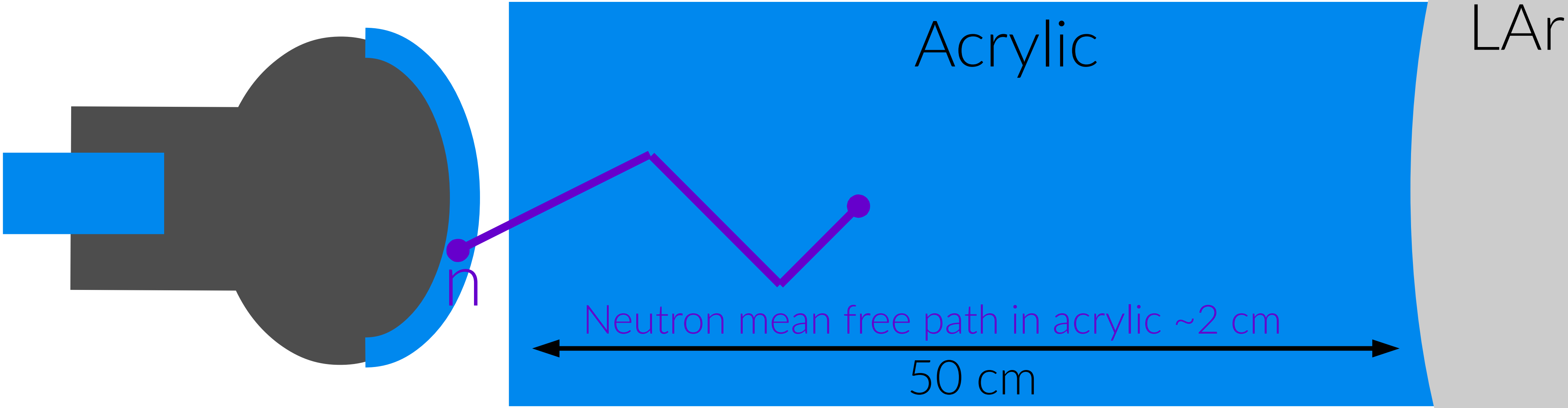
Veto neutrons:
- Detector submerged in boron-loaded liquid scintillator neutron veto
- Minimize mass between detector & veto

DEAP-3600



Shield neutrons:
- 50 cm of neutron-moderating acrylic block neutrons from reaching the LAr
- Position & energy cuts reduce residuals

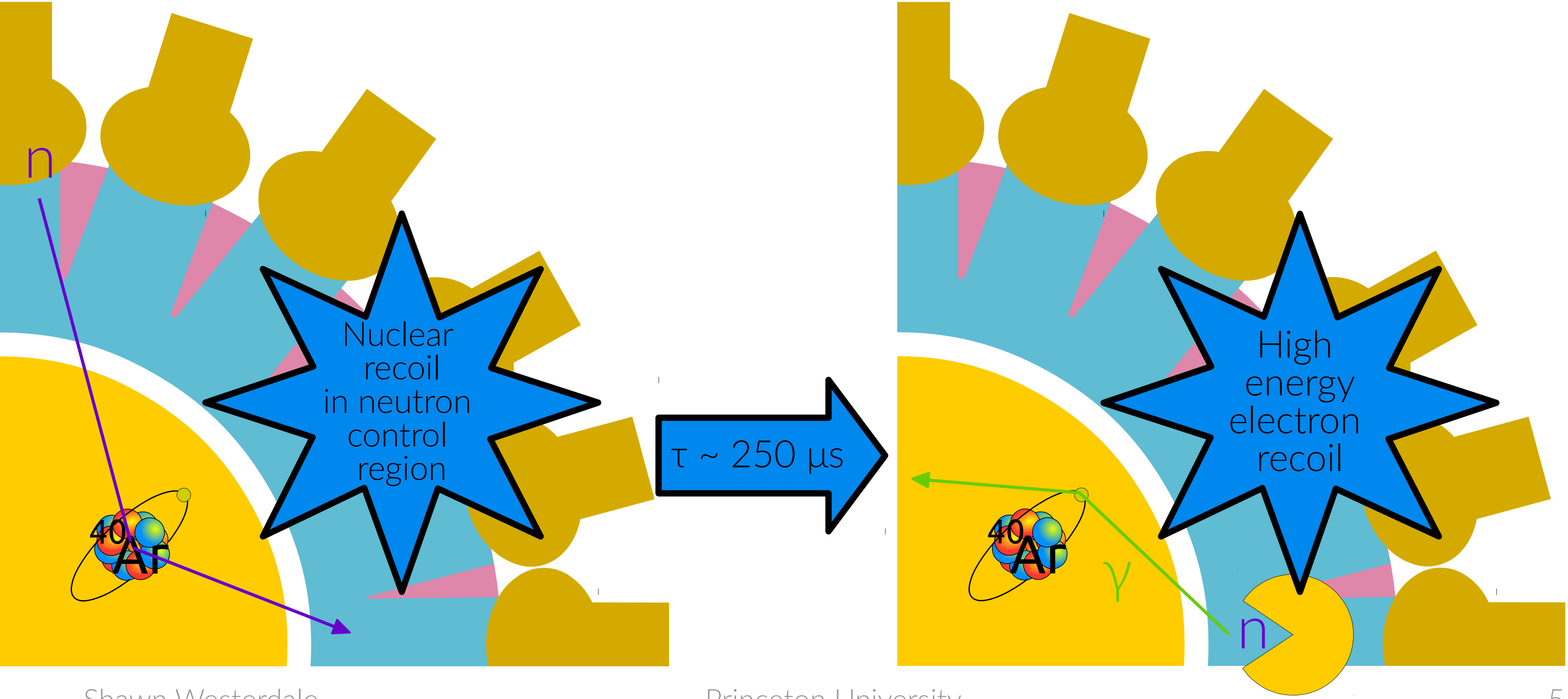
Radiogenic neutrons: DEAP-3600 shielding and measurements



From Monte Carlo simulations:

- 1 out of ~10^4 neutrons will make it into LAr with enough energy to produce a visible signal
- Simulations predict $0.073^{+0.119}_{-0.048}$ neutrons in the WIMP region of interest in 231 live days

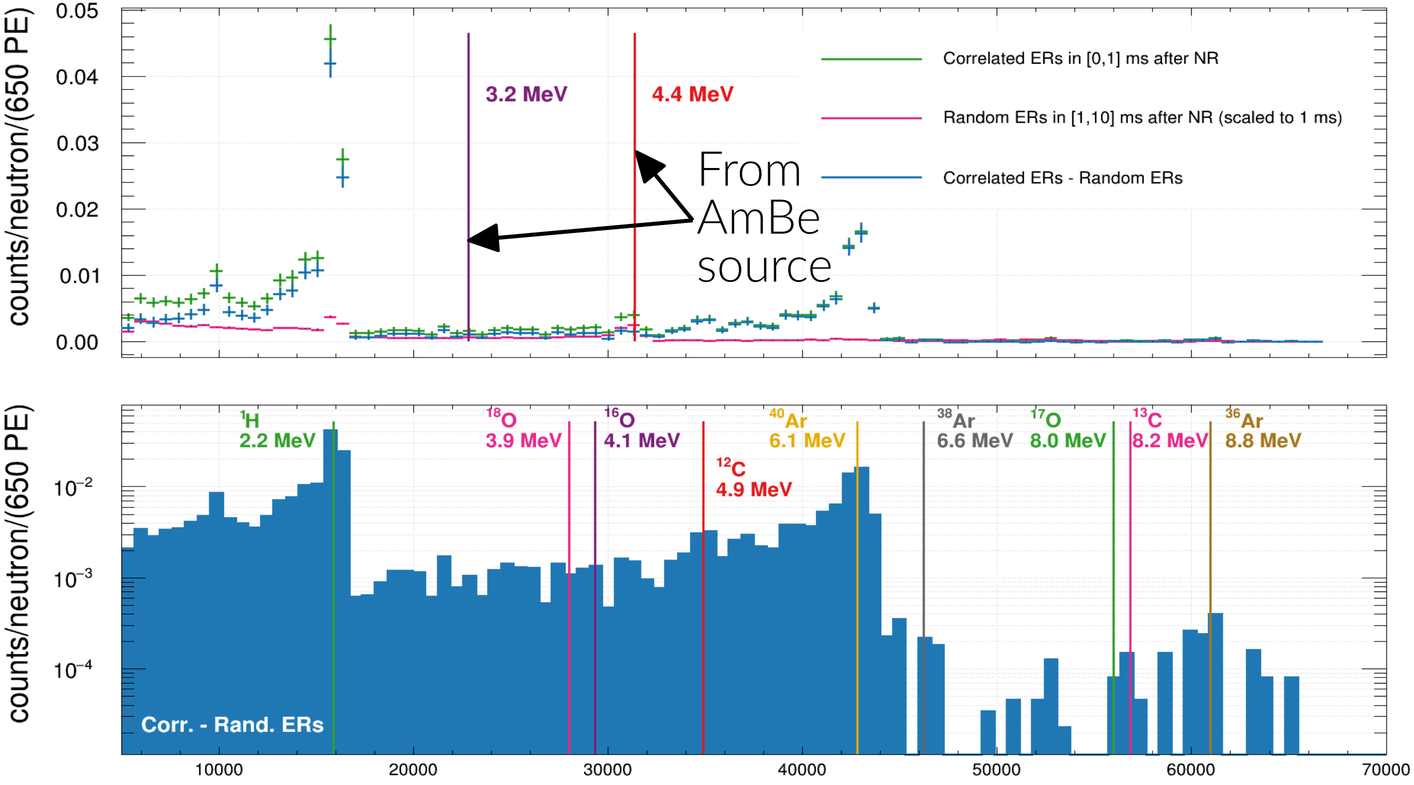
Radiogenic neutrons: DEAP-3600 predictions in 231 live days, *in situ* validation in data



Radiogenic neutrons: DEAP-3600 predictions in 231 live days, *in situ* validation in data

Calibration with AmBe neutron source data:

- Tagging efficiency = 22.5±0.5%



From AmBe source

Photoelectrons Detected

DEAP Collaboration. "Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB". Phys. Rev. D 100, 022004 (2019)

Radiogenic neutrons: DEAP-3600 predictions in 231 live days, *in situ* validation in data

	Control Region	ROI
From assays and MC (NeuCBOT)	$13.6^{+9.4}_{-7.8}$	$0.073^{+0.119}_{-0.052}$
From assays and MC (SOURCES-4C)	$10.6^{+8.3}_{-7.1}$	$0.060^{+0.104}_{-0.045}$
From capture analysis	$23.1^{+16.9}_{-14.3}$	$0.10^{+0.10}_{-0.09}$

Agrees with *ex-situ* simulation-based prediction

Radiogenic neutron-induced backgrounds are primarily mitigated with radial position cut

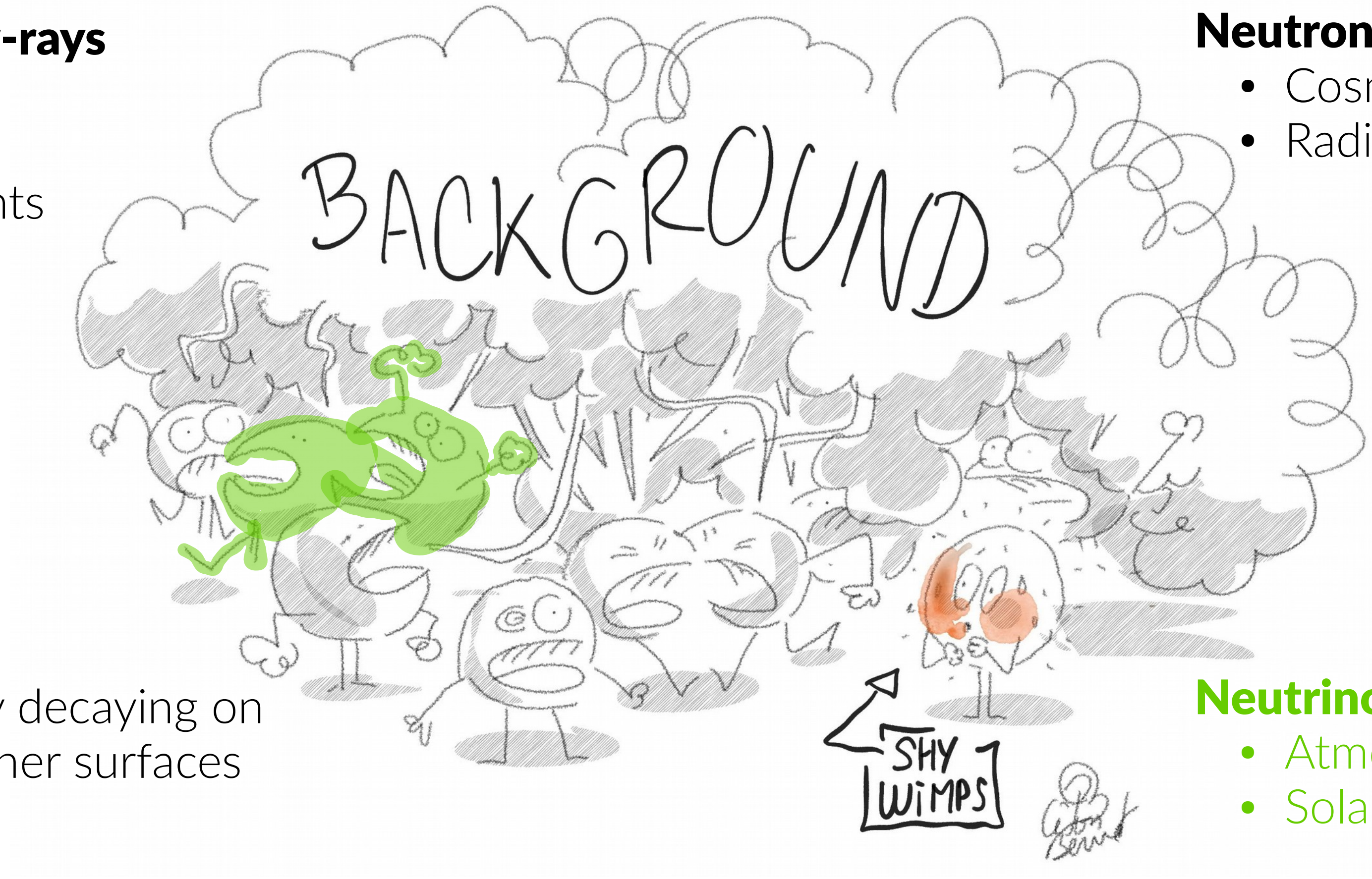
DEAP Collaboration. “Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB”. Phys. Rev. D 100, 022004 (2019)

β-decays and γ-rays

- Decays of radioactive contaminants

Neutrons

- Cosmogenic origin
- Radiogenic origin



α-decays

- Rn progeny decaying on detector inner surfaces

Neutrinos

- Atmospheric origin
- Solar origin

Neutrinos: Visible through mutliple channels

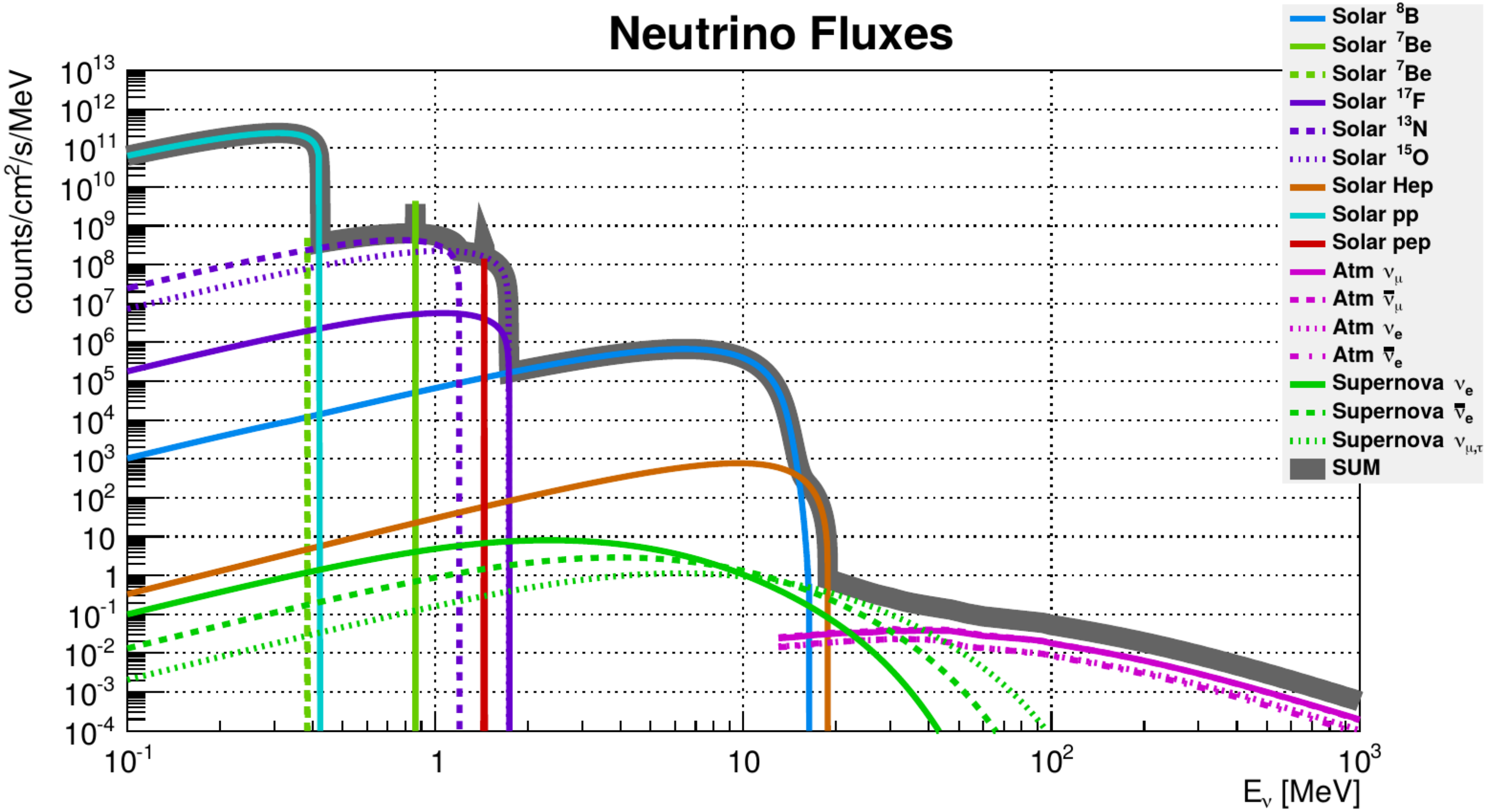
Three sensitive channels:

1. Neutrino-electron elastic scattering
$^{40}\text{Ar}+\nu/\bar{\nu}\rightarrow{}^{40}\text{Ar}^{+}+e^{-}+\nu/\bar{\nu}$

2. Neutrino absorption
$^{40}\text{Ar}+\nu_e\rightarrow{}^{40}\text{K}+e^{-}$

3. Coherent elastic neutrino-nucleus scattering (CEνNS)
$^{40}\text{Ar}+\nu/\bar{\nu}\rightarrow{}^{40}\text{Ar}+\nu/\bar{\nu}$

Future large LAr detectors will be sensitive to supernova and solar ν physics



Neutrinos: Coherent Elastic v-Nucleus Scattering (CEvNS) eventually produces WIMP-like background

Solar ^{8}B neutrinos

CEvNS on ^{40}Ar can below WIMP energies:

10^4 counts/(100 t·year)

Atmospheric neutrinos

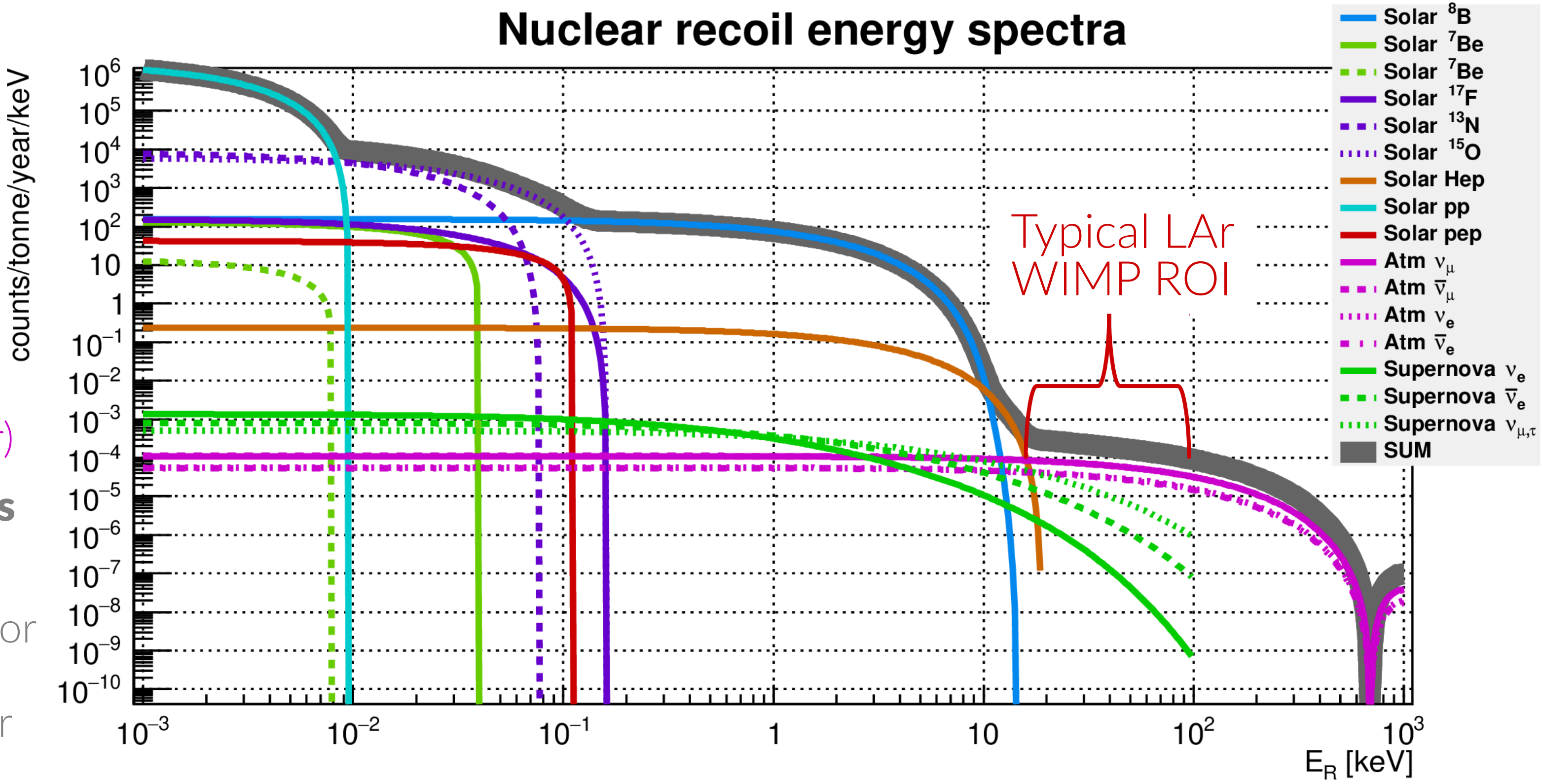
CEvNS on ^{40}Ar can exactly mimic WIMPs:

1.5 ROI counts/(100 t·year)

Supernova burst neutrinos

(not shown)

O(10^2-10^3) events in 10 s for M_{SN}>11 M_{Sun} within galaxy for a 50 tonne LAr detector



DarkSide Collaboration. "Sensitivity of future liquid argon dark matter search experiments to core-collapse supernova neutrinos". J. Cosmol. Astropart. Phys. 03, 043 (2021)

Neutrinos: Coherent Elastic ν-Nucleus Scattering (CEνNS) eventually produces WIMP-like background

Solar ^{8}B neutrinos

CEνNS on ^{40}Ar can b
WIMP energies:

10^4 counts/(100 t·ye

Atmospheric neutri

CEνNS on ^{40}Ar can e
mimic WIMPs:

1.5 ROI counts/(100

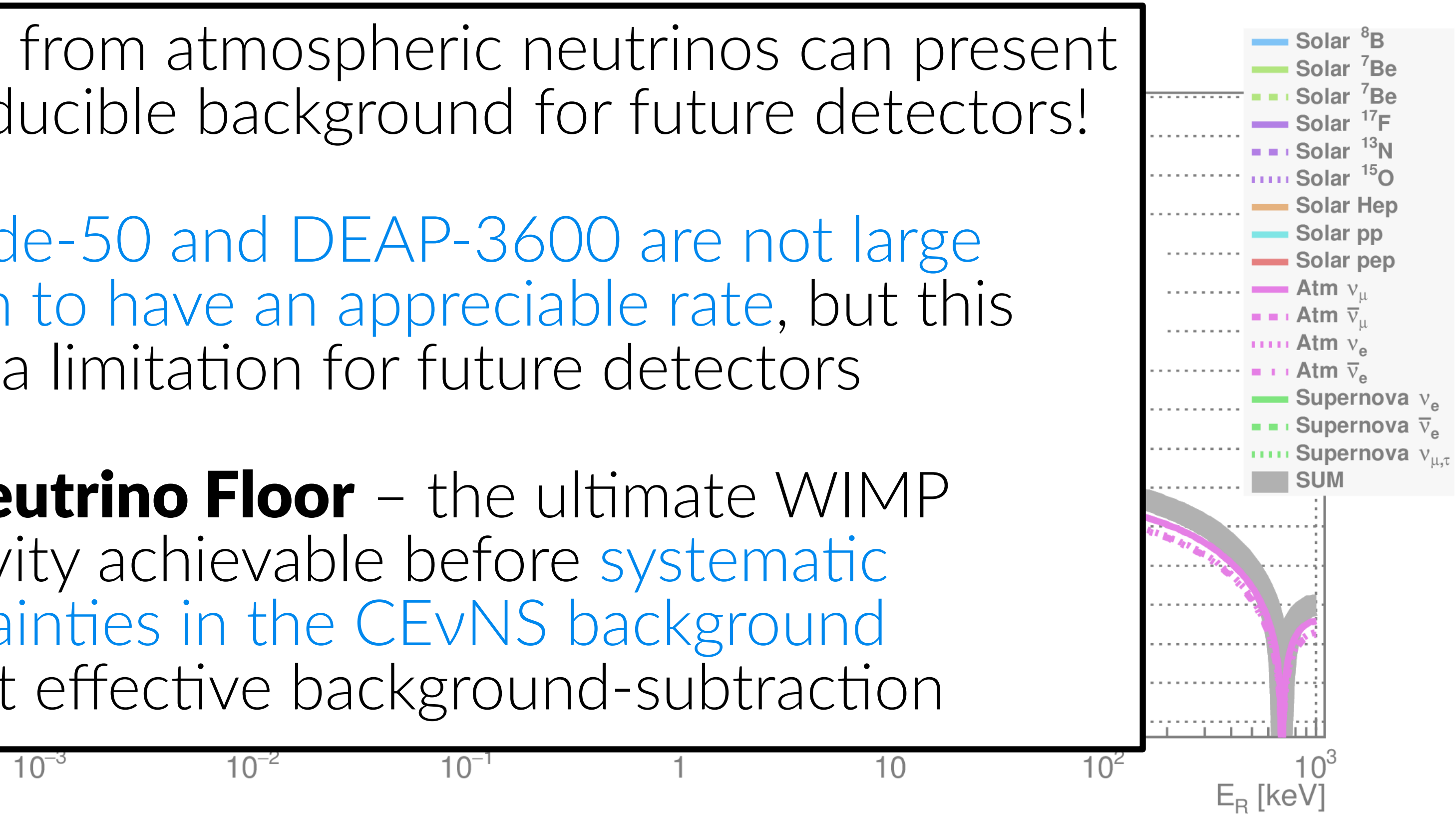
Supernova burst neu
(not shown)

O(10^2-10^3) events in
M_{SN}>11 M_{Sun} within
for a 50 tonne LAr detector

CEνNS from atmospheric neutrinos can present an irreducible background for future detectors!

DarkSide-50 and DEAP-3600 are not large enough to have an appreciable rate, but this will be a limitation for future detectors

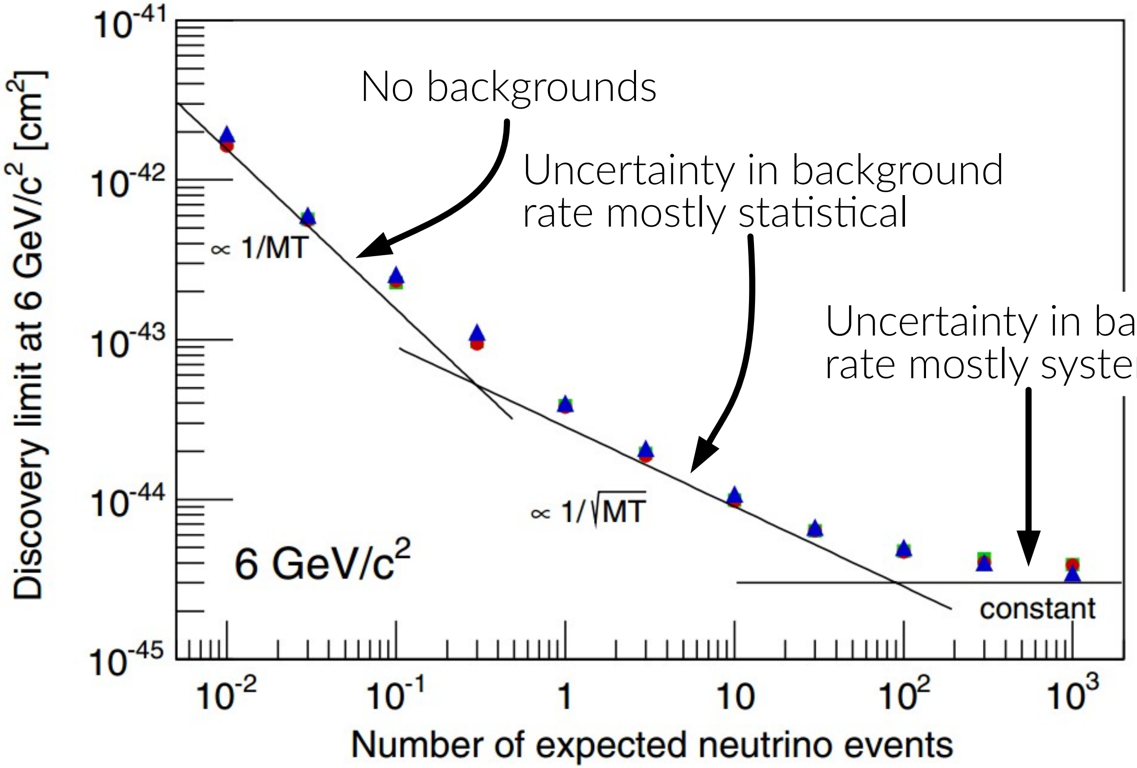
The Neutrino Floor – the ultimate WIMP sensitivity achievable before systematic uncertainties in the CEνNS background prevent effective background-subtraction



DarkSide Collaboration. “Sensitivity of future liquid argon dark matter search experiments to core-collapse supernova neutrinos”. J. Cosmol. Astropart. Phys. 03, 043 (2021)

Neutrinos: The Floor

J. Billard, E. Figueroa-Feliciano, L. Strigari. “Implication of neutrino backgrounds on the reach of next generation dark matter direct detection experiments”. Phys. Rev. D 89, 023524 (2014).



No backgrounds

Uncertainty in background rate mostly statistical

Uncertainty in background rate mostly systematic

MT = exposure
= Mass × Time

Neutrinos: ~~Raise the Roof~~ Lower the Floor

Ideas I'll discuss

- Cross-target comparisons
- Decreasing background rate uncertainty

Other ideas:

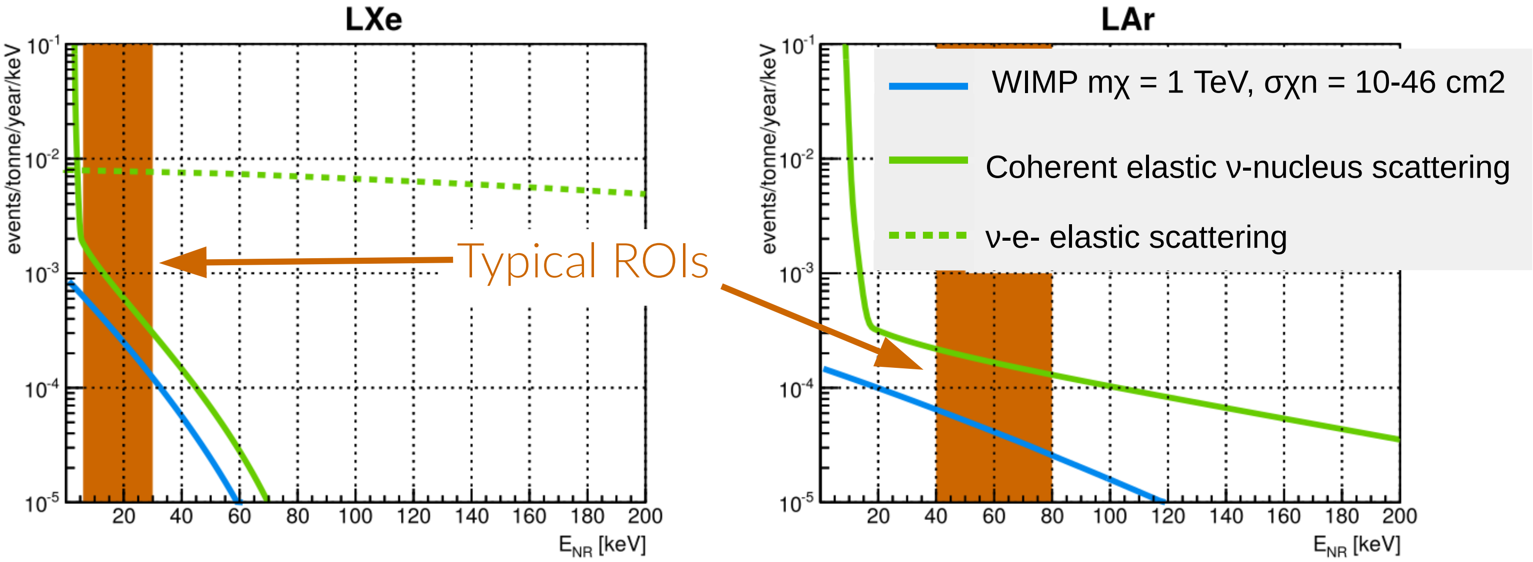
- Annular modulation
- Direction-sensitivity

These comparisons require a unified set of conventions across experiments:

D. Baxter **et al.** "Recommended conventions for reporting results from direct dark matter searches." EPJ C **81**: 907 (2021)

Is there anything we can do about neutrinos once we hit the floor?

Neutrinos: Differences in ν bkgd → joint analyses can achieve better sensitivity than one target alone



Factor of 200 ER suppression

WIMPs (1 TeV): 0.0078 events/tonne/year
CEvNS: 0.020 events/tonne/year
ν-e$^-$ ES: 0.13 events/tonne/year

Factor of 10^8 ER suppression

WIMPs (1 TeV): 0.0017 events/tonne/year
CEvNS: 0.0063 events/tonne/year
ν-e$^-$ ES: ~0 events/tonne/year

Key differences:

ν's most closely mimic different WIMP masses with both targets.

LAr has higher signal-to-background ratio, but LXe is dominated by electron recoils

Considering only CEvNS:
$(N_\chi/N_{bkgd})_{LAr}$ / $(N_\chi/N_{bkgd})_{LXe}$ = 0.7
Considering CEvNS and ν-e$^-$ ES:
$(N_\chi/N_{bkgd})_{LAr}$ / $(N_\chi/N_{bkgd})_{LXe}$ = 5.2

Neutrinos: ~~Raise the Roof~~ Lower the Floor

Ideas I'll discuss
- Cross-target comparisons
- Decreasing background rate uncertainty

Other ideas:
- Annular modulation
- Direction-sensitivity

Atmospheric ν-flux varies with time and location, making it hard to constrain.

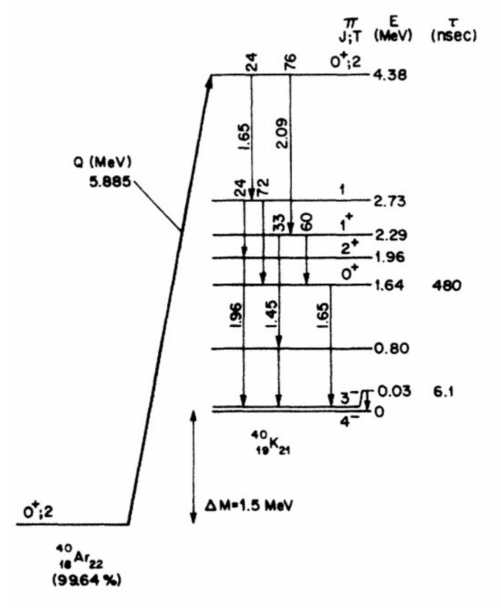
This can be improved by *in-situ* measurements of correlated muon flux and atmospheric conditions from NOAA

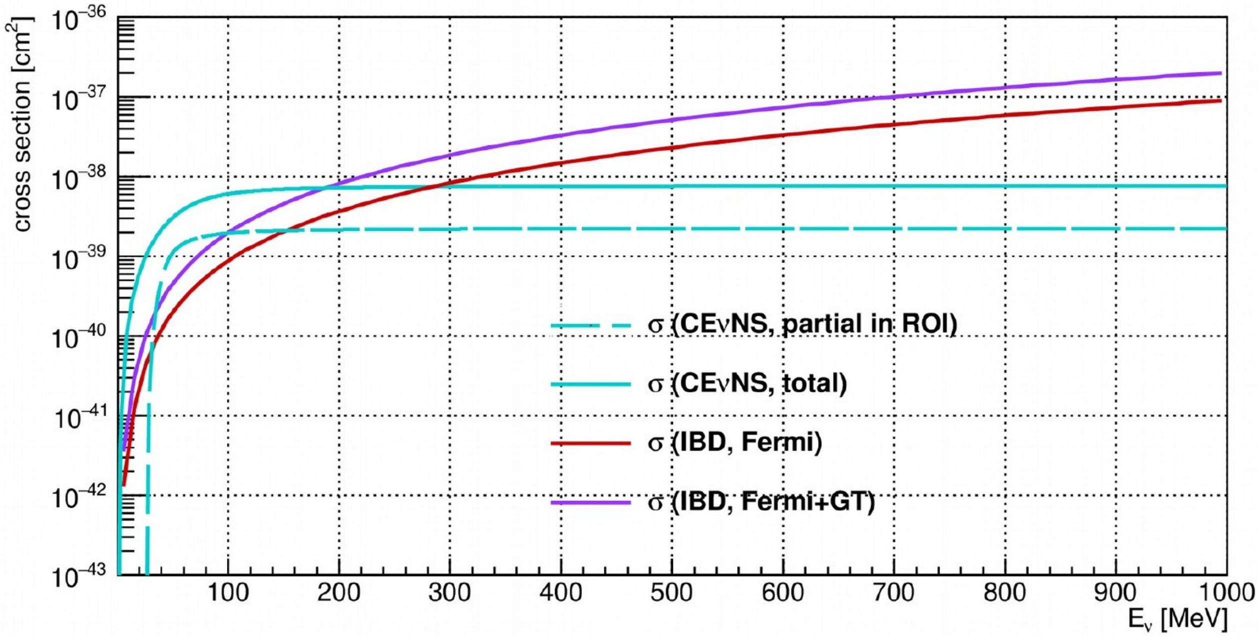
Is there anything we can do about neutrinos once we hit the floor?

Neutrinos: Neutrino absorption

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + \beta^-$$

Signal: Electron recoils summing to E_ν-1.5 MeV, ~2/3 passing through 480 ns metastable state





This provides an independent side band measurement of the atmospheric neutrino flux, to constrain the uncertainty better than can be done with *ex situ* measurements

Neutrinos: Neutrino absorption
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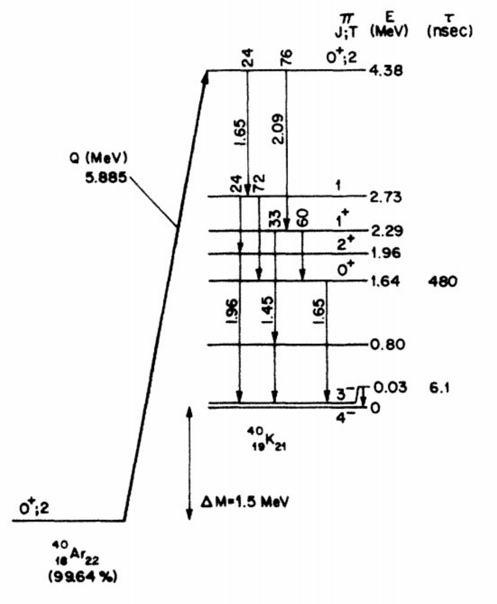

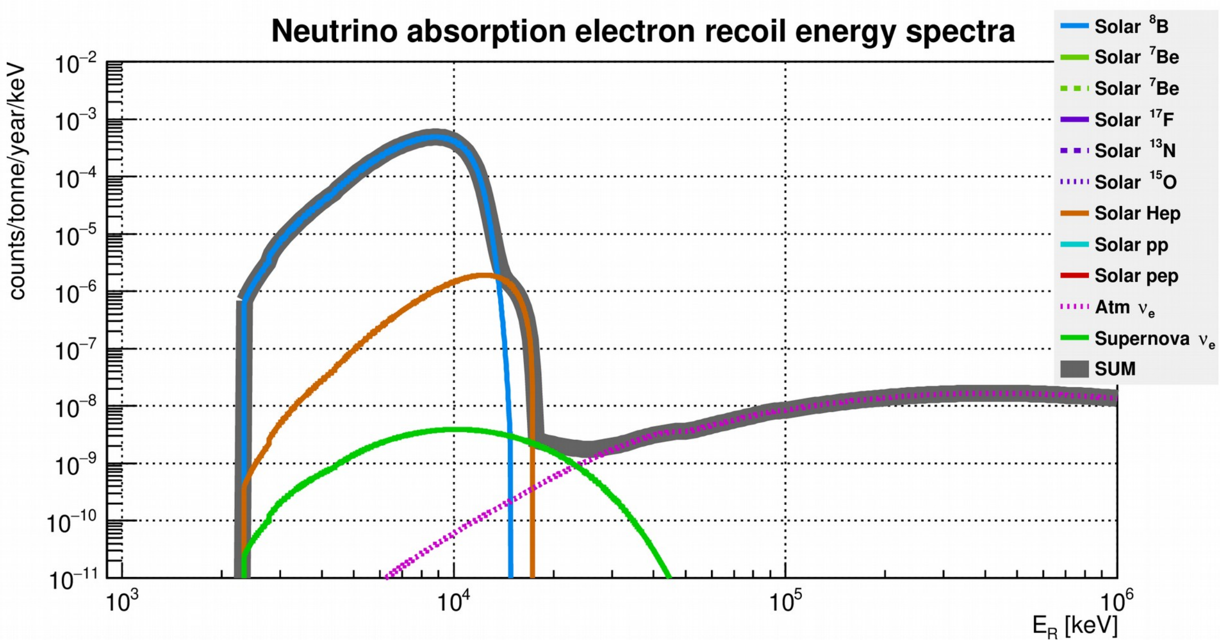

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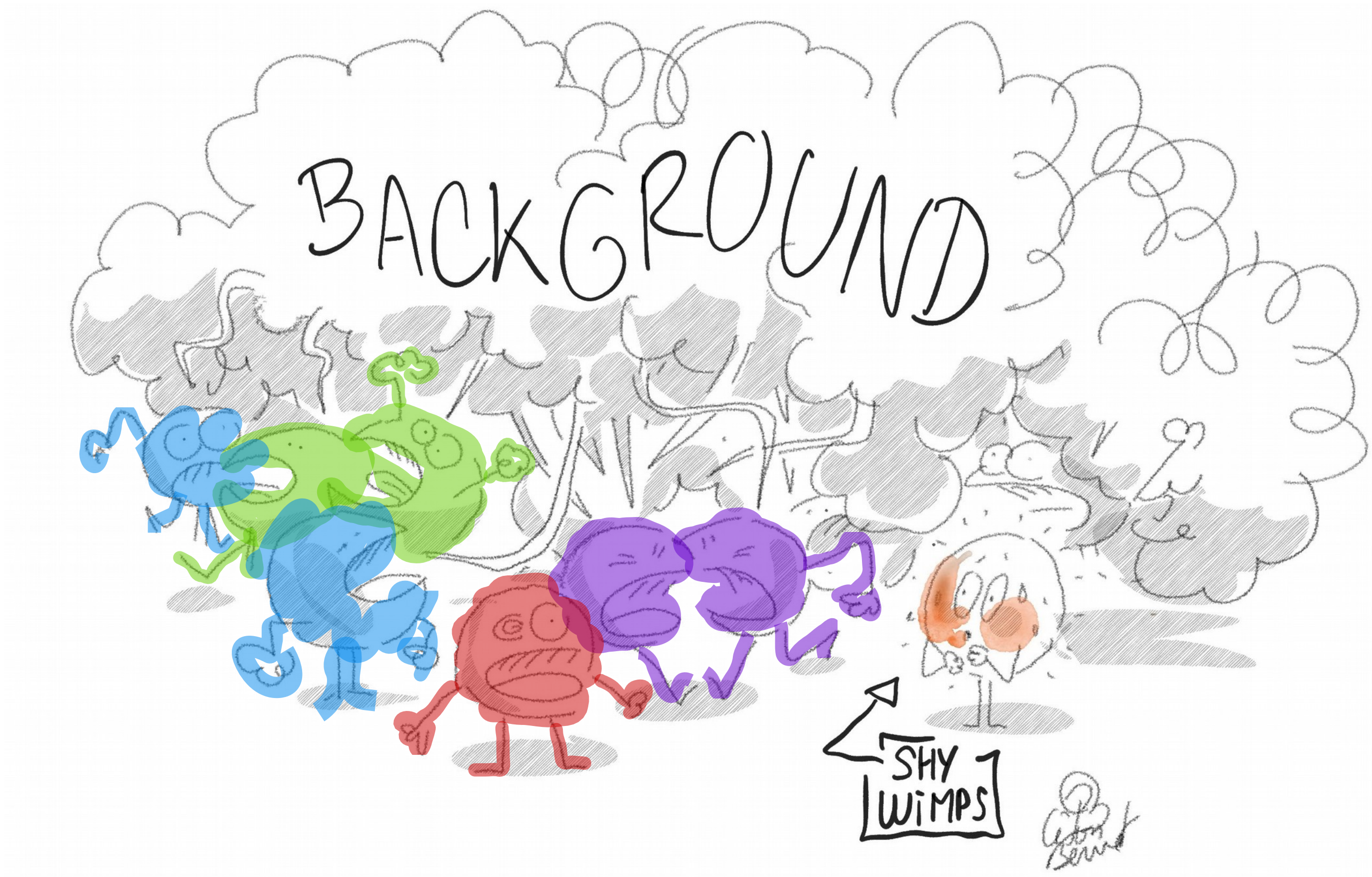
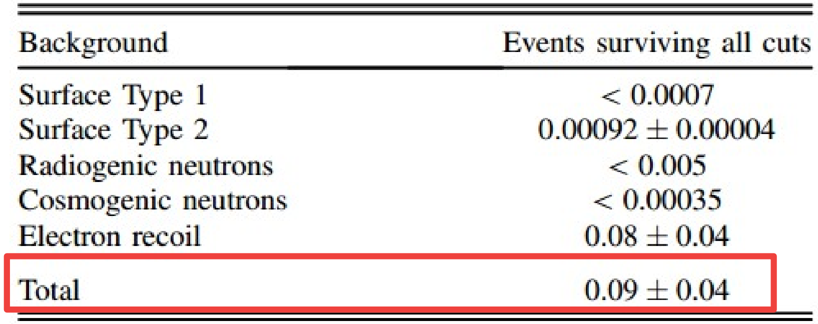

BACKGROUND
SHY WiMPS

The WIMP searches

DarkSide-50: 532 live-days, 31.3±0.5 kg

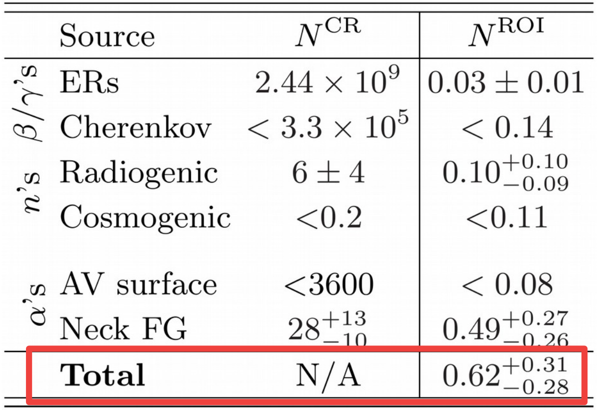


Background	Events surviving all cuts
Surface Type 1	< 0.0007
Surface Type 2	0.00092 ± 0.00004
Radiogenic neutrons	< 0.005
Cosmogenic neutrons	< 0.00035
Electron recoil	0.08 ± 0.04
Total	0.09 ± 0.04

Total WIMP acceptance: 72.5±0.5%

DarkSide Collaboration. “DarkSide-50 532-day Dark Matter Search with Low-Radioactivity Argon”. Phys. Rev. D 98, 102006 (2018)

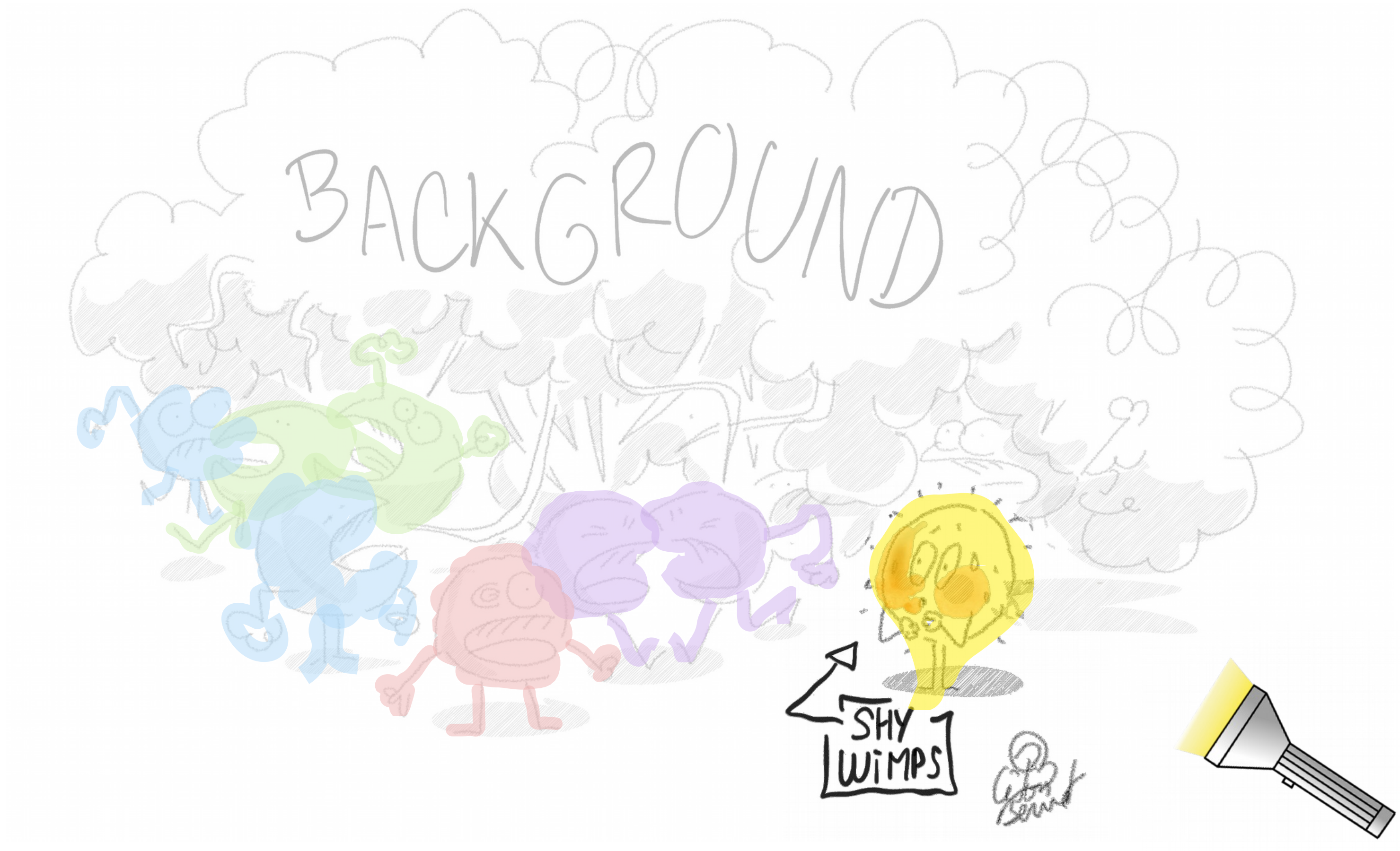
DEAP-3600: 231 live-days, 824±25 kg



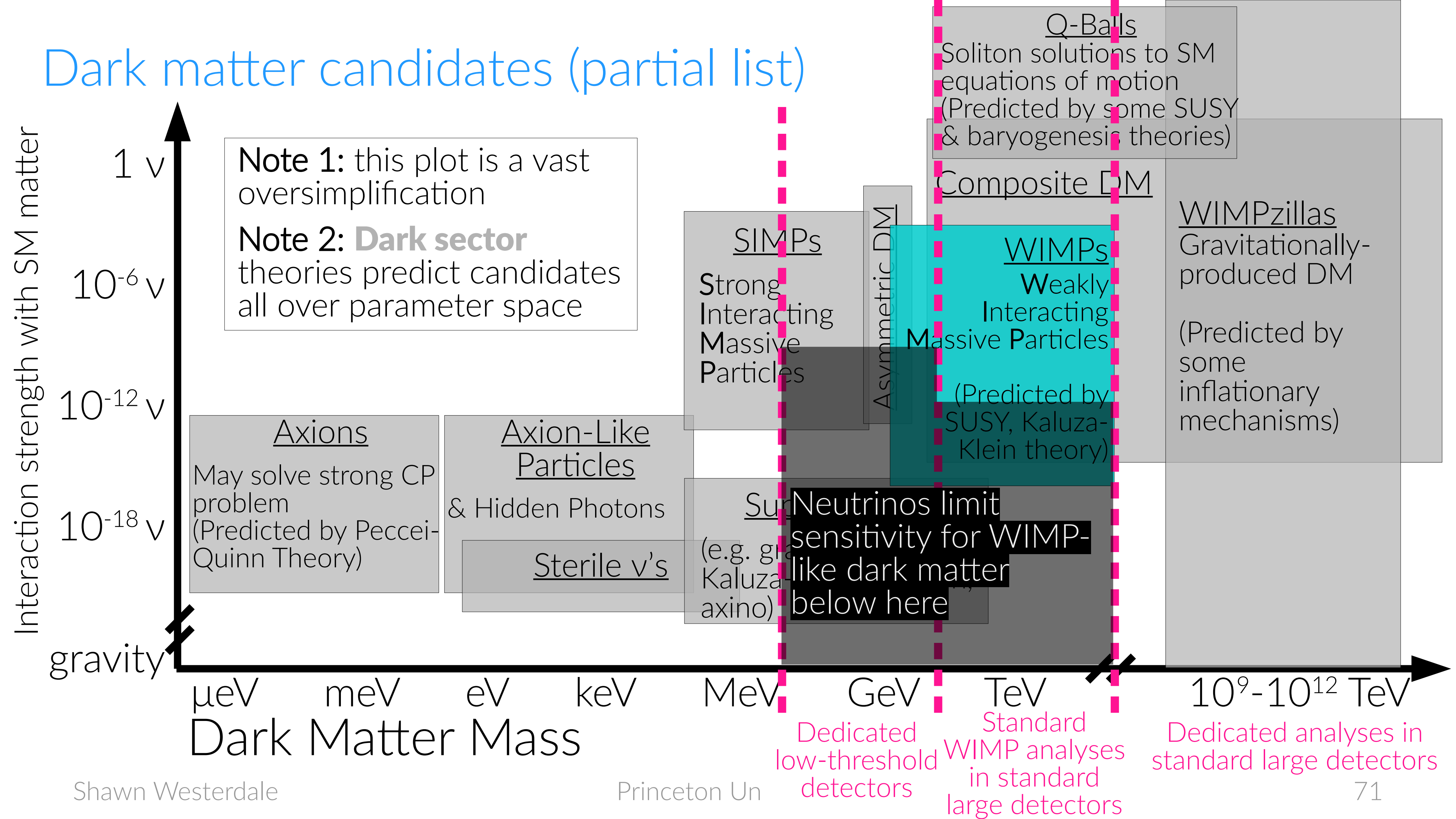
	Source	N^{CR}	N^{ROI}
β/γ's	ERs	2.44×10^9	0.03 ± 0.01
	Cherenkov	$< 3.3 \times 10^5$	< 0.14
n's	Radiogenic	6 ± 4	$0.10^{+0.10}_{-0.09}$
	Cosmogenic	<0.2	<0.11
α's	AV surface	<3600	< 0.08
	Neck FG	28^{+13}_{-10}	$0.49^{+0.27}_{-0.26}$
	Total	N/A	$0.62^{+0.31}_{-0.28}$

Total WIMP acceptance: $35.4^{+2.5}_{-0.1}$ %

DEAP Collaboration. “Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB”. Phys. Rev. D 100, 022004 (2019)


BACKGROUND
SHY WIMPS

Dark matter candidates (partial list)



Note 1: this plot is a vast oversimplification

Note 2: **Dark sector** theories predict candidates all over parameter space

Interaction strength with SM matter

1 ν

10^{-6} ν

10^{-12} ν

10^{-18} ν

gravity

Dark Matter Mass

µeV meV eV keV MeV GeV TeV 10^9-10^{12} TeV

Axions

May solve strong CP problem (Predicted by Peccei-Quinn Theory)

Axion-Like Particles

& Hidden Photons

Sterile ν's

SIMPs

Strong **I**nteracting **M**assive **P**articles

Asymmetric DM

Su

(e.g. gr

Kaluza

axino)

Neutrinos limit sensitivity for WIMP-like dark matter below here

Q-Balls

Soliton solutions to SM equations of motion (Predicted by some SUSY & baryogenesis theories)

Composite DM

WIMPs

Weakly **I**nteracting **M**assive **P**articles

(Predicted by SUSY, Kaluza-Klein theory)

WIMPzillas

Gravitationally-produced DM

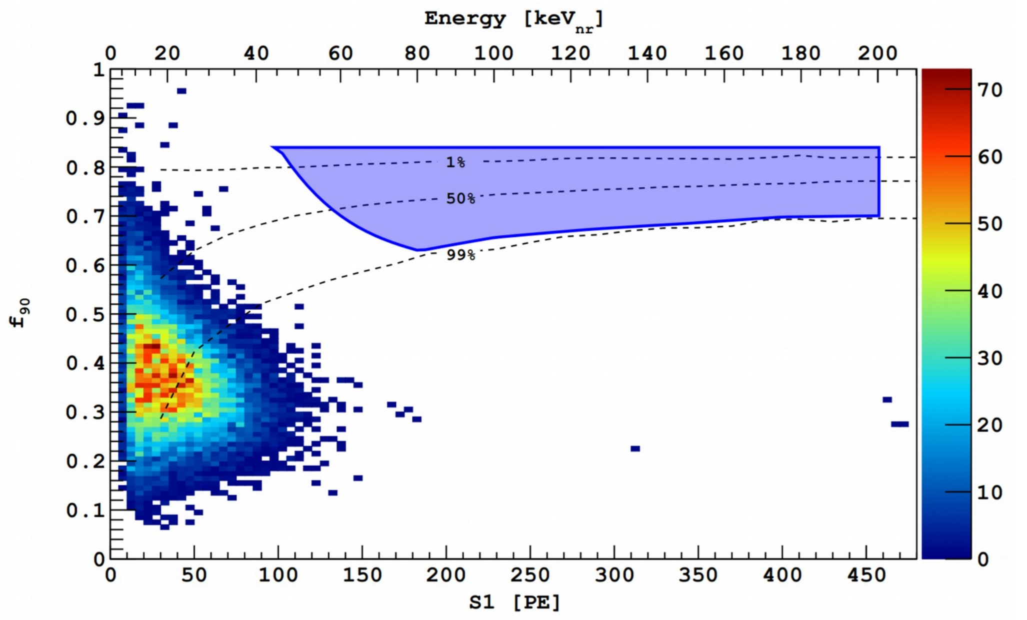
(Predicted by some inflationary mechanisms)

Dedicated low-threshold detectors

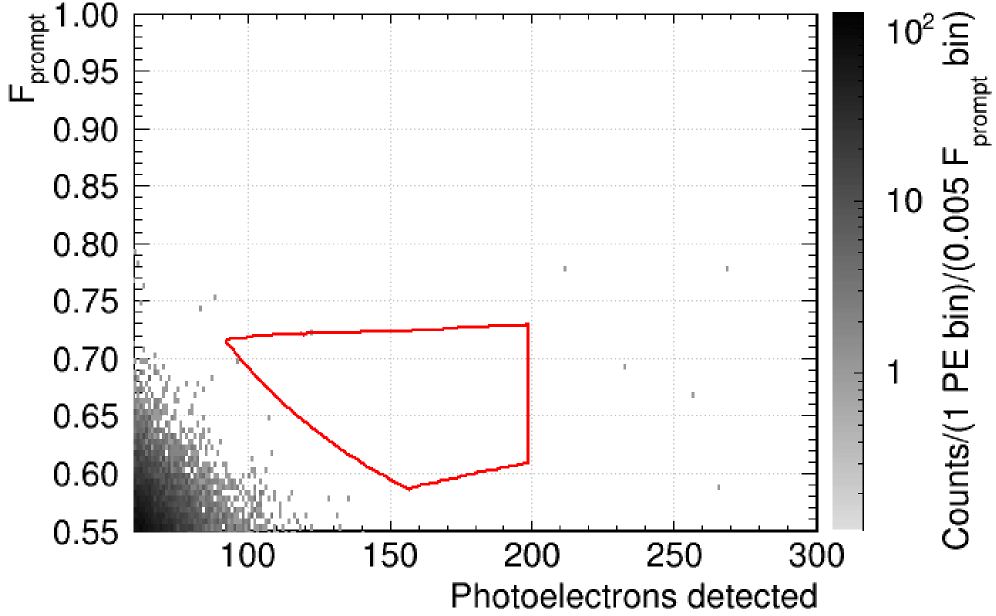
Standard WIMP analyses in standard large detectors

Dedicated analyses in standard large detectors

No WIMPs found yet



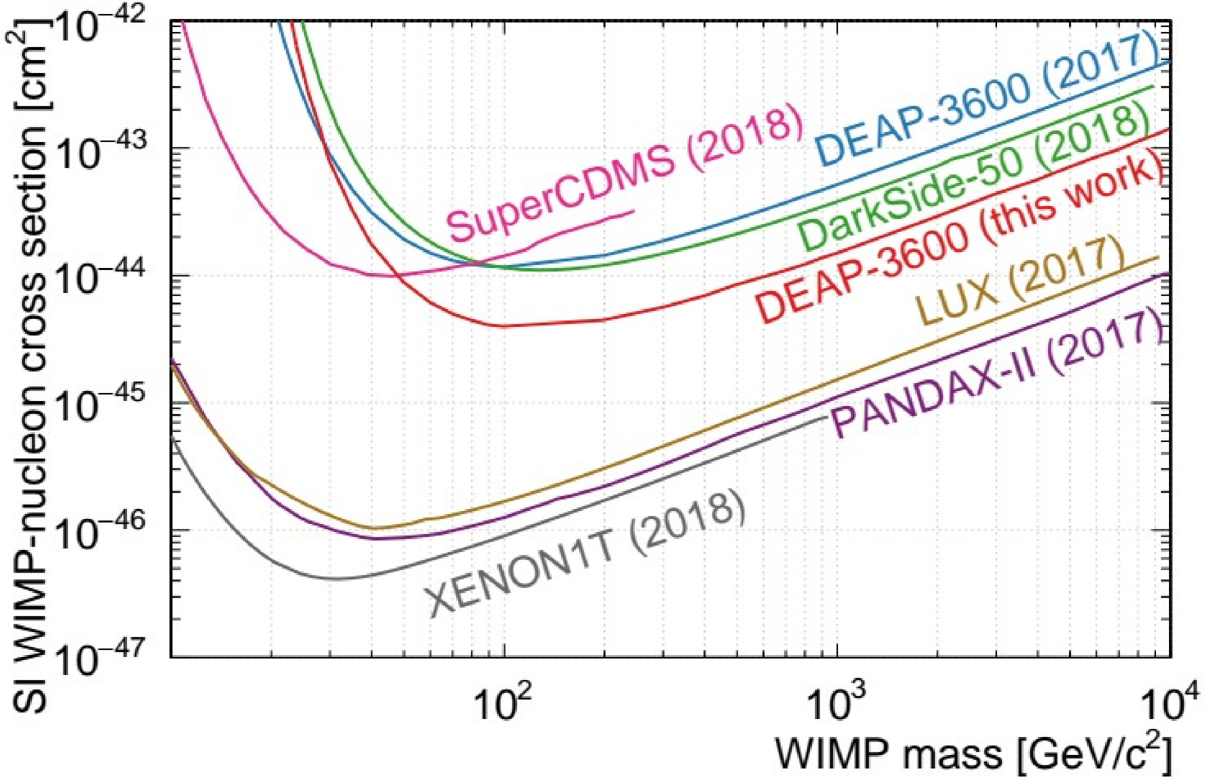
DarkSide Collaboration. "DarkSide-50 532-day Dark Matter Search with Low-Radioactivity Argon". Phys. Rev. D 98, 102006 (2018)



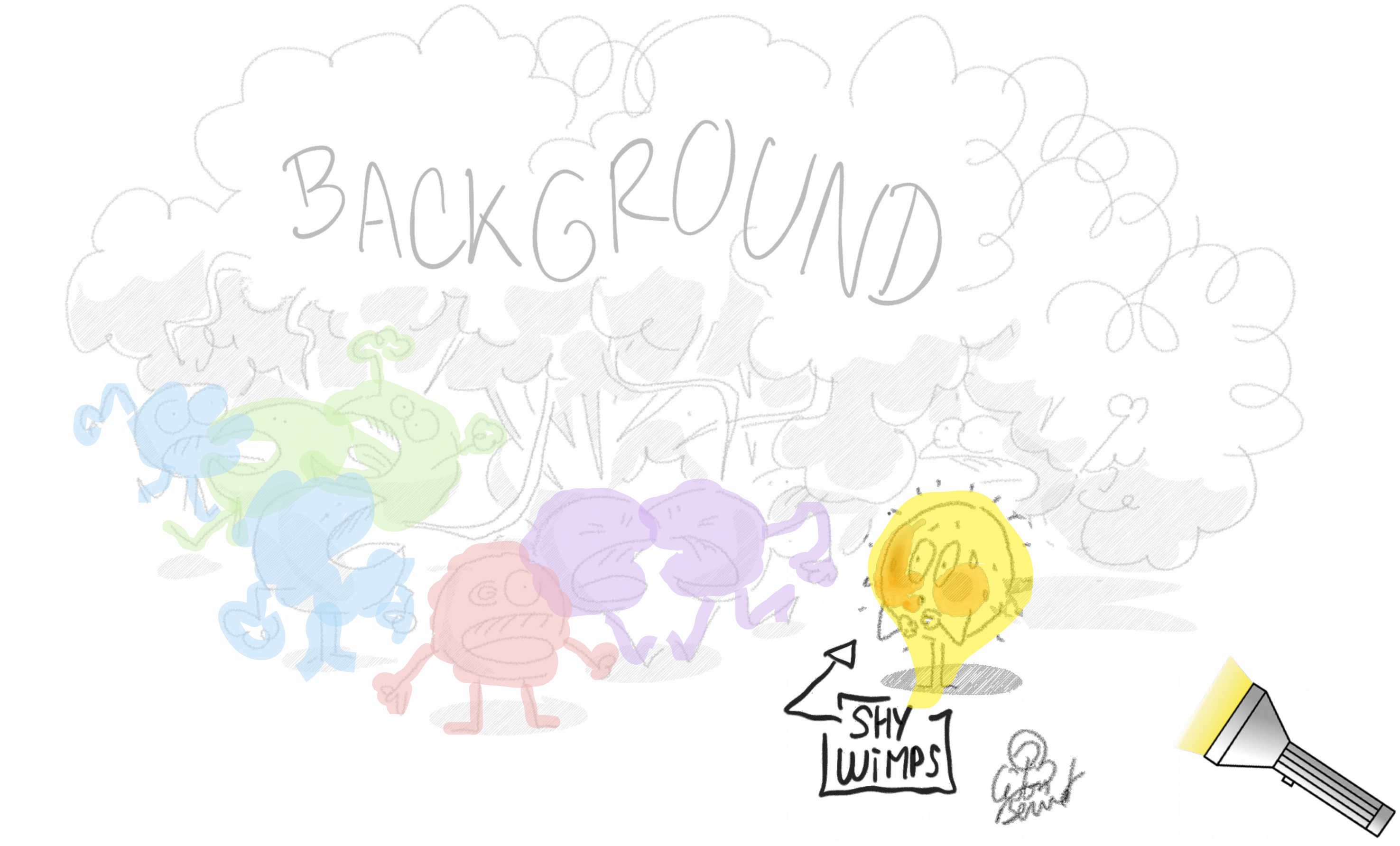
DEAP Collaboration. "Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB". Phys. Rev. D 100, 022004 (2019)

Where we know dark matter isn’t, for standard interaction and halo models

DEAP Collaboration. “Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB”. Phys. Rev. D 100, 022004 (2019)



Ruling out more specific WIMP models will require comparisons of results across several different targets


BACKGROUND
SHY WIMPS

$$\frac{dR}{dE_R} = \frac{\rho_T}{m_T}\frac{\rho_\chi}{m_\chi}\varepsilon(E_R)\int_{v_{\min}}^{\infty} v f_\chi^{\oplus}(\vec{v})\frac{d\sigma}{dE_R}d^3\vec{v}$$

Rate of DM-nucleus recoils of energy E_R

Target nucleus number density

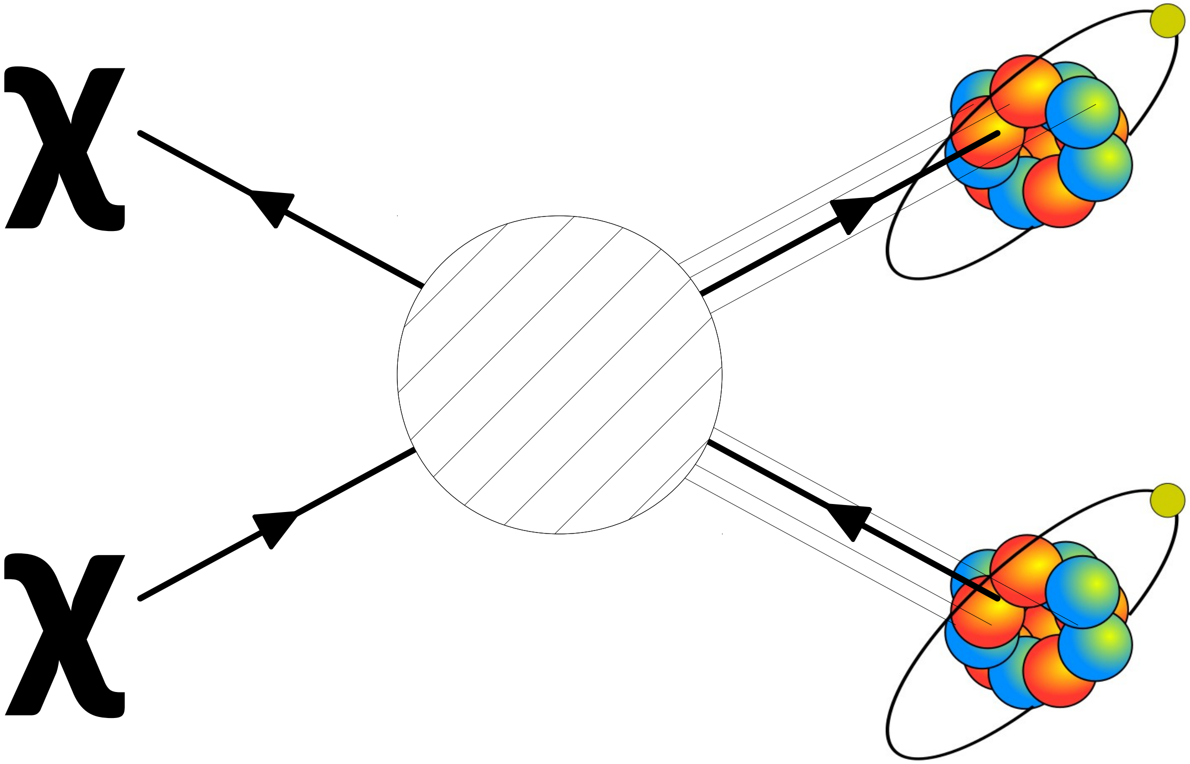
DM number density

Efficiency

DM velocity distribution

DM-nucleus differential cross section

Within a non-relativistic effective field theory, several DM-nucleon operators can be written



Operators describing DM-nucleon couplings detectable with ^{40}Ar:

$$\mathcal{O}_1 = 1_\chi 1_N$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_\perp\right)$$

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_\perp\right)$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}_\perp$$

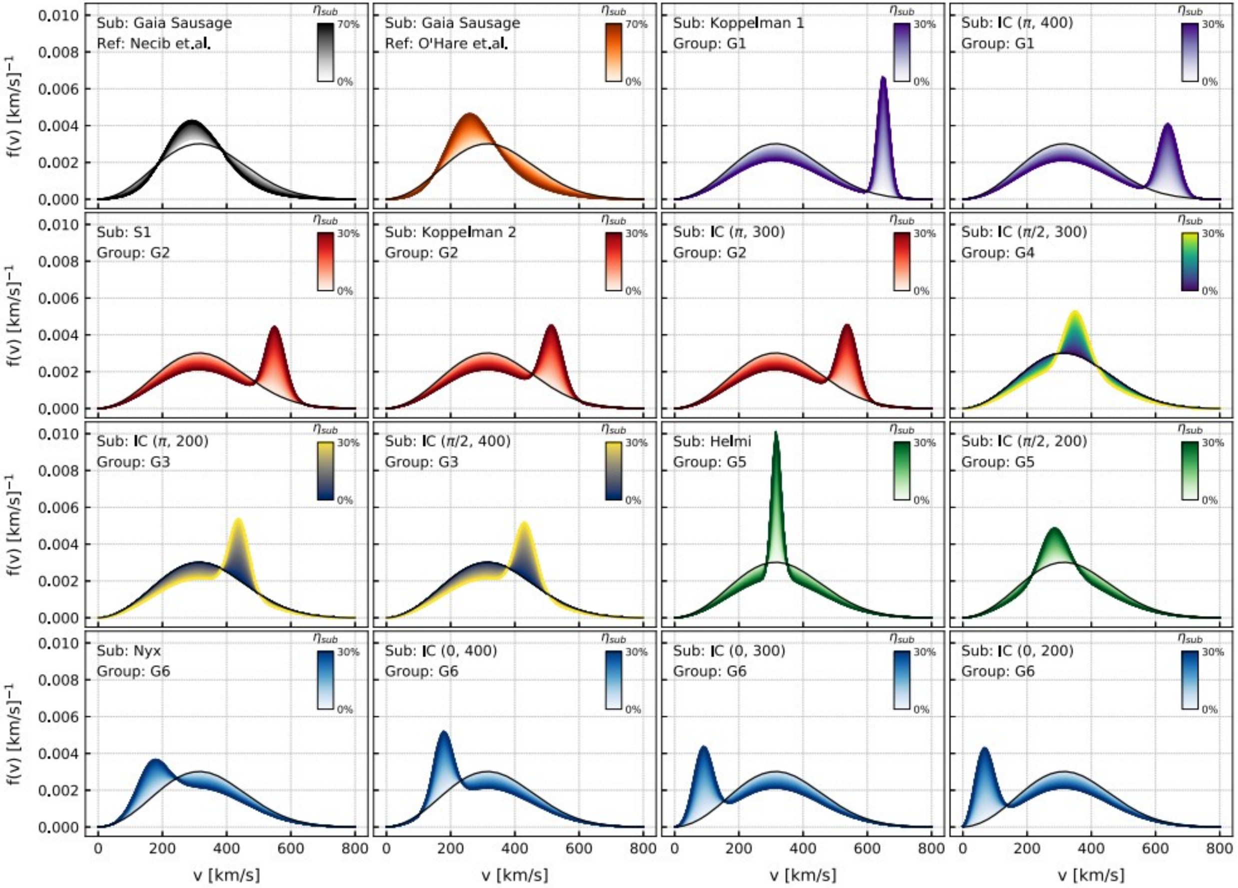
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

Isoscalar: equal proton & neutron couplings

Isovector: opposite proton & neutron couplings

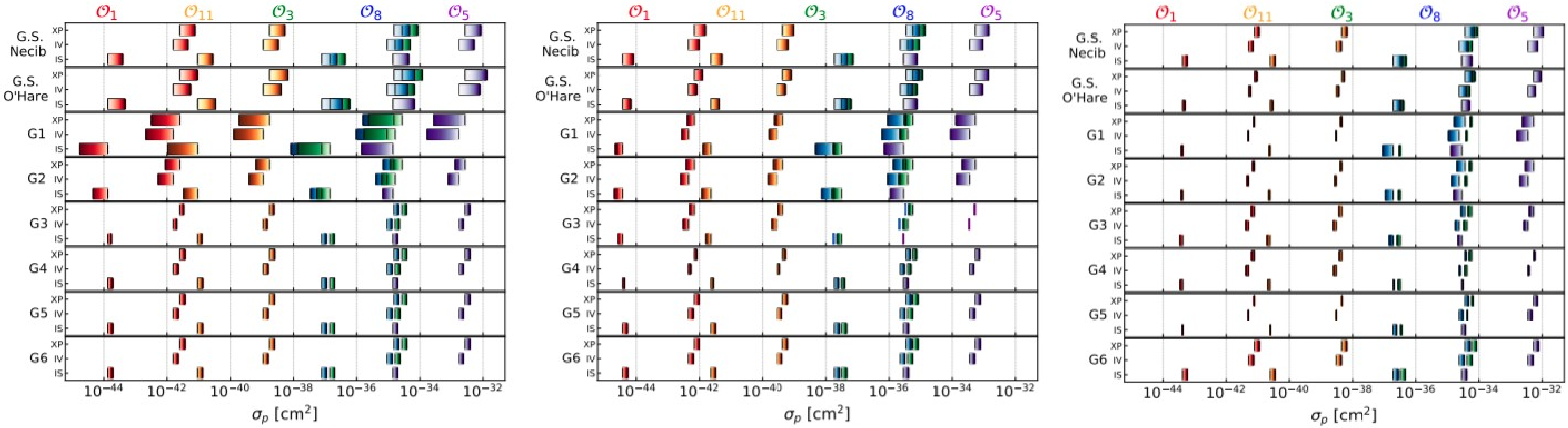
Xenonphobic: cancellation for Xe

Potential DM halo substructures, motivated by observed stellar substrutures



DEAP Collaboration. "Constraints on dark matter-nucleon effective couplings in the presence of kinematically distinct halo substructures using the DEAP-3600 detector". Phys. Rev. D 102, 082001 (2020)

Re-interpreted DEAP limits considering WIMP-nucleon effective interactions with halo substructure



(a) m_χ=40 GeV/c^2 (b) m_χ=100 GeV/c^2 (c) m_χ=3 TeV/c^2

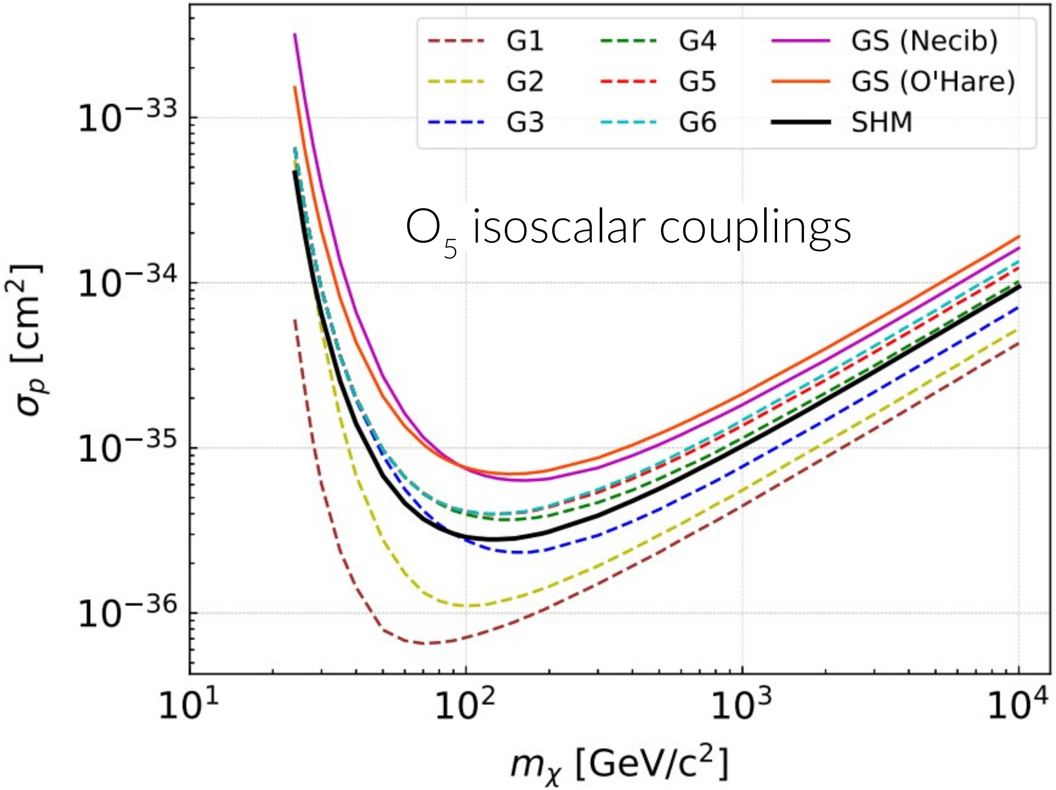
G.S.: Two *Gaia* Sausage models
G1: Fastest stellar streams (*e.g.* S1) …to…
G6: Slowest stellar streams (*e.g.* Nyx)

$$\mathcal{O}_1 = 1_\chi 1_N, \qquad \mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_\perp\right) \qquad \mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

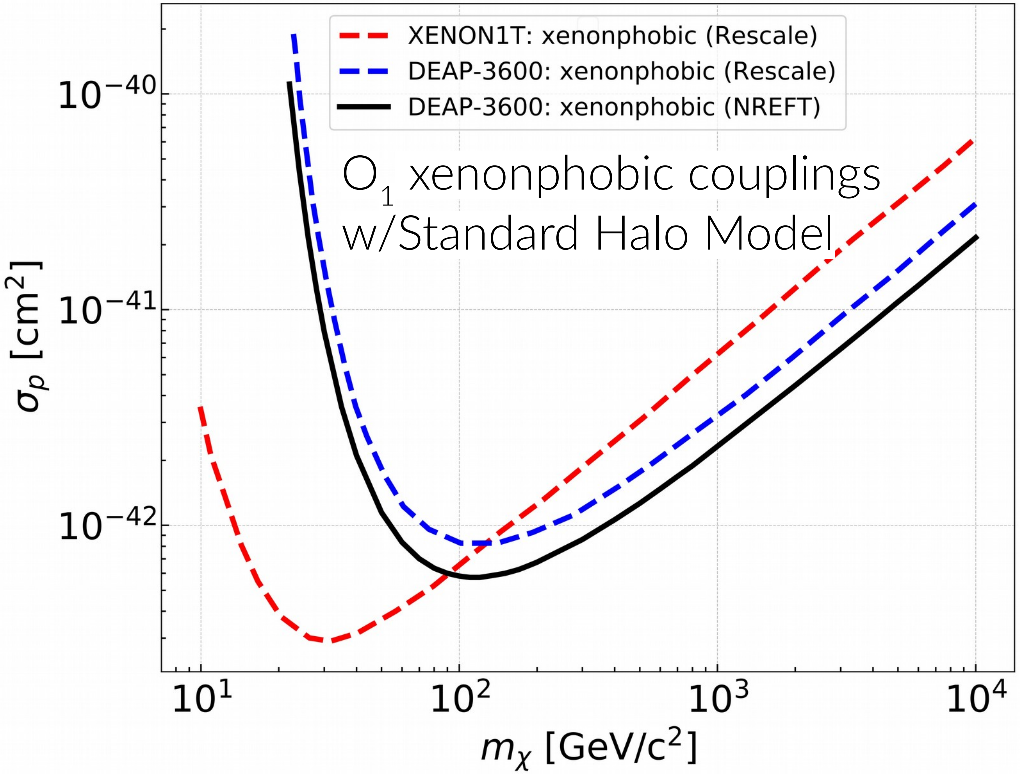
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_\perp\right) \qquad \mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}_\perp$$

DEAP Collaboration. "Constraints on dark matter-nucleon effective couplings in the presence of kinematically distinct halo substructures using the DEAP-3600 detector". Phys. Rev. D 102, 082001 (2020)

Significant model-dependencies in DM constraints must be resolved with cross-target comparisons



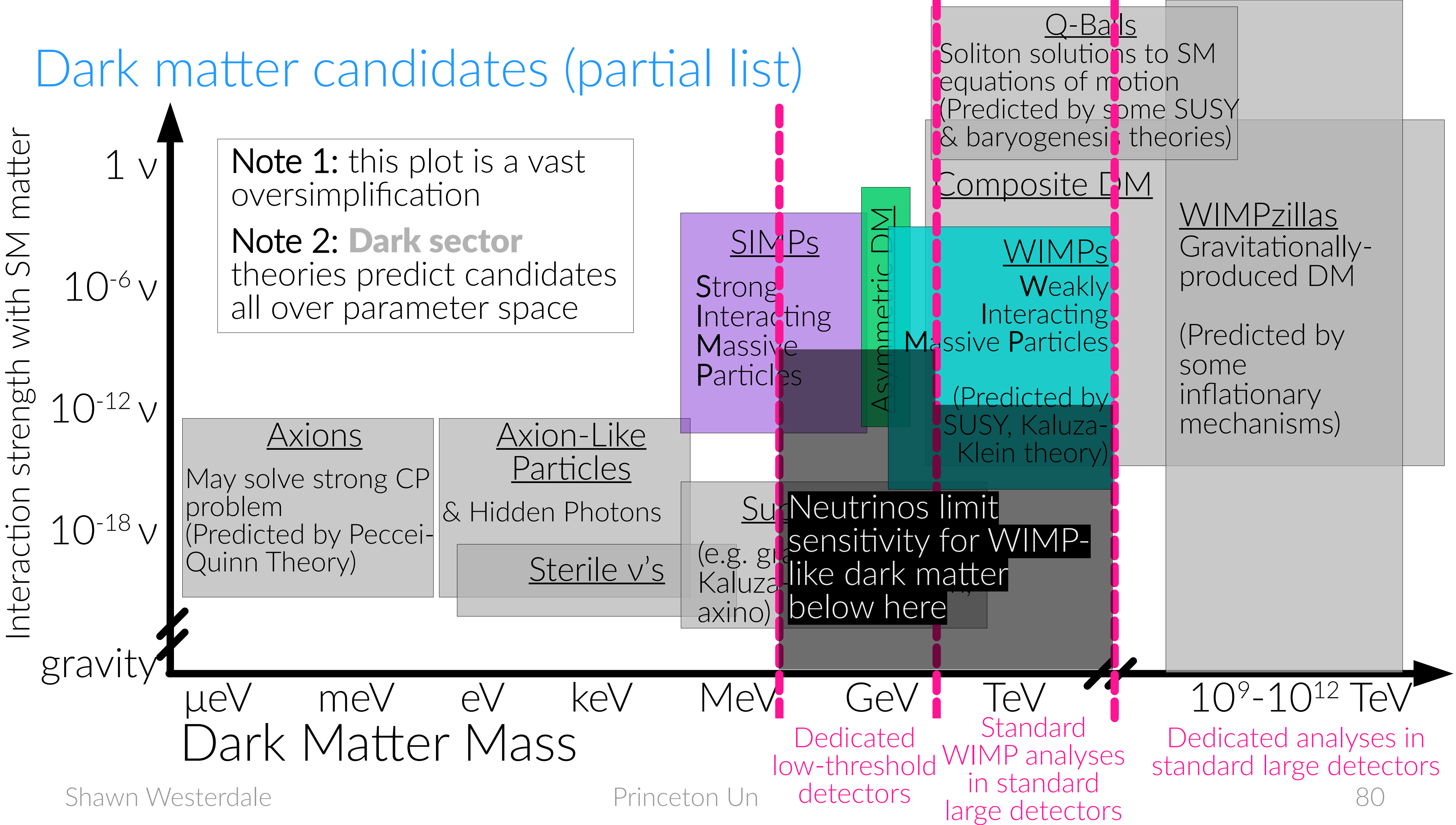
O_5 isoscalar couplings



O_1 xenonphobic couplings
w/Standard Halo Model

DEAP Collaboration. "Constraints on dark matter-nucleon effective couplings in the presence of kinematically distinct halo substructures using the DEAP-3600 detector". Phys. Rev. D 102, 082001 (2020)

Dark matter candidates (partial list)



Note 1: this plot is a vast oversimplification

Note 2: **Dark sector** theories predict candidates all over parameter space

Axions

May solve strong CP problem (Predicted by Peccei-Quinn Theory)

Axion-Like Particles

& Hidden Photons

Sterile ν's

Su

(e.g. gr Kaluza- axino)

SIMPs

Strong **I**nteracting **M**assive **P**articles

Asymmetric DM

WIMPs

Weakly **I**nteracting **M**assive **P**articles

(Predicted by SUSY, Kaluza-Klein theory)

Neutrinos limit sensitivity for WIMP-like dark matter below here

Q-Balls

Soliton solutions to SM equations of motion (Predicted by some SUSY & baryogenesis theories)

Composite DM

WIMPzillas

Gravitationally-produced DM

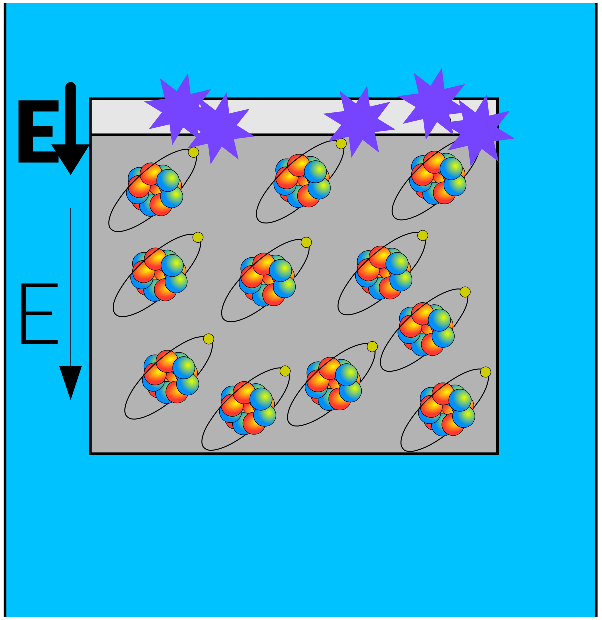
(Predicted by some inflationary mechanisms)

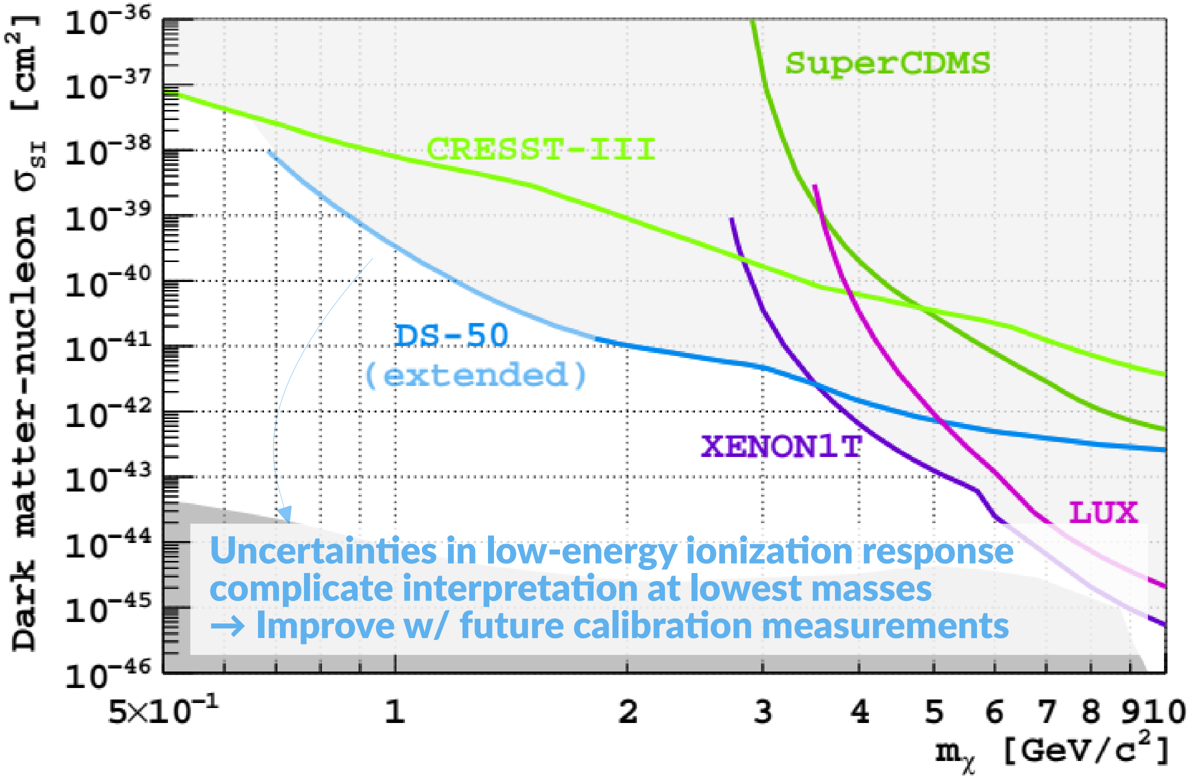
Dedicated low-threshold detectors

Standard WIMP analyses in standard large detectors

Dedicated analyses in standard large detectors

DS-50's constraints on light DM w/ nuclear couplings

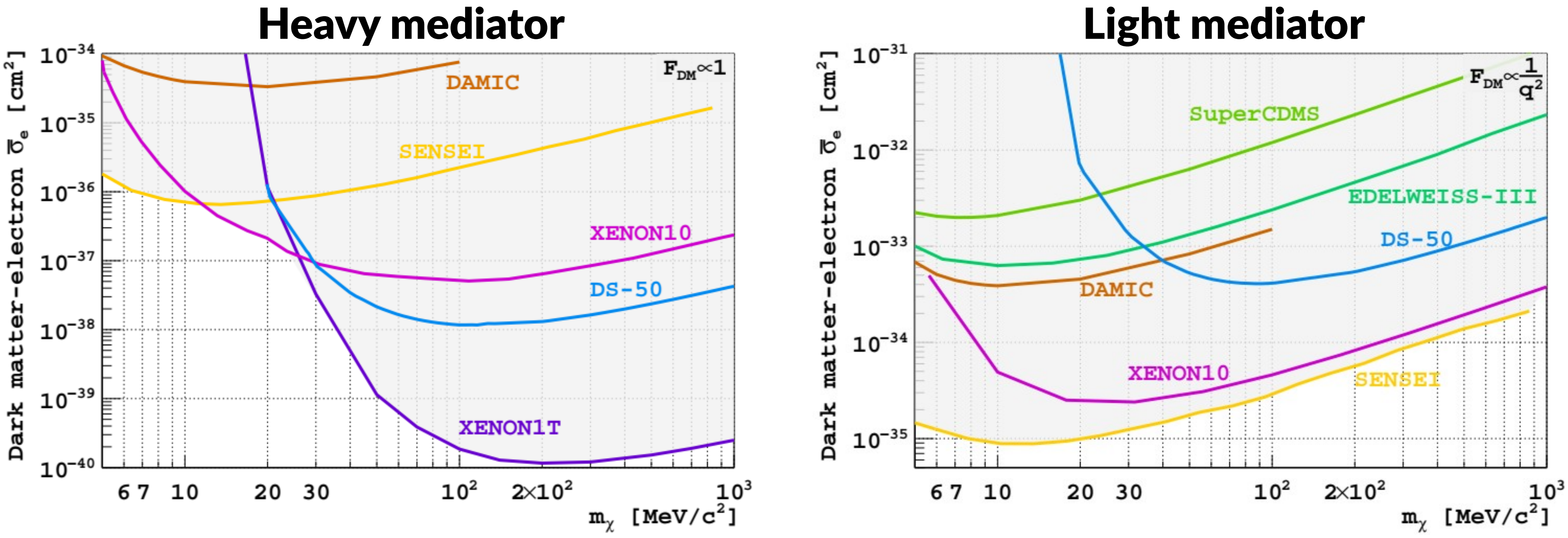




Uncertainties in low-energy ionization response complicate interpretation at lowest masses
→ Improve w/ future calibration measurements

DarkSide Collaboration. "Low-mass Dark Matter Search with the DarkSide-50 Experiment". Phys. Rev. Lett. 121, 081307 (2018)

DS-50 constraints on light DM w/ electronic couplings

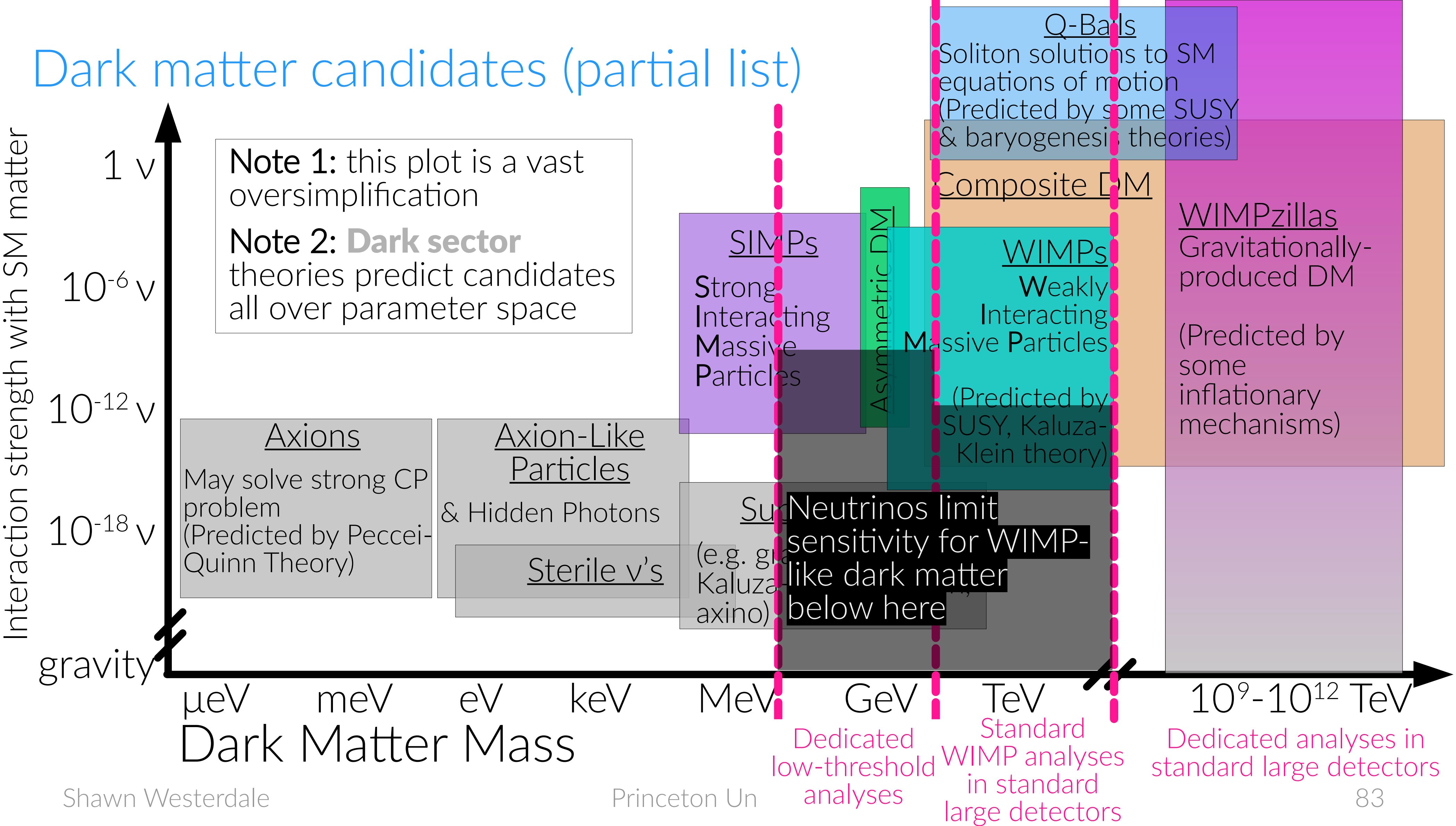


DarkSide Collaboration. "Constraints on Sub-GeV Dark Matter-Electron Scattering from the DarkSide-50 Experiment". Phys. Rev. Lett. 121, 111303 (2018).

Dark matter candidates (partial list)

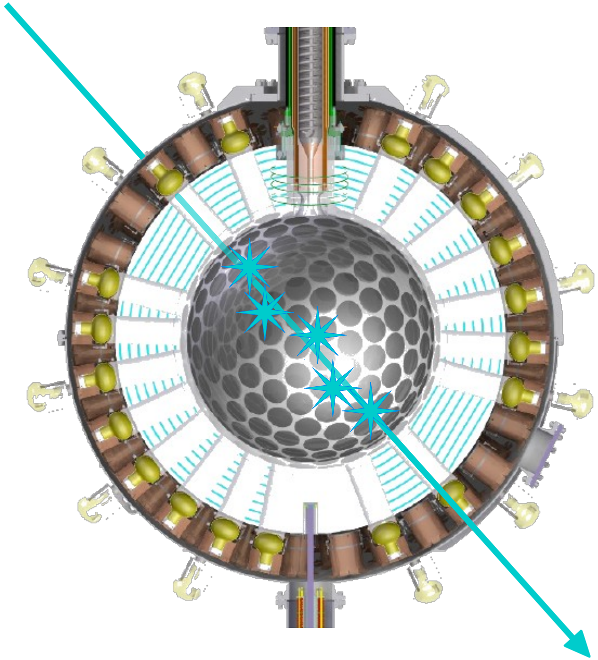
Note 1: this plot is a vast oversimplification

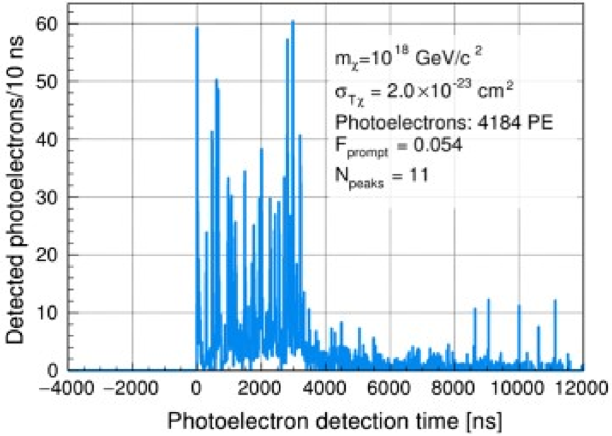
Note 2: **Dark sector** theories predict candidates all over parameter space

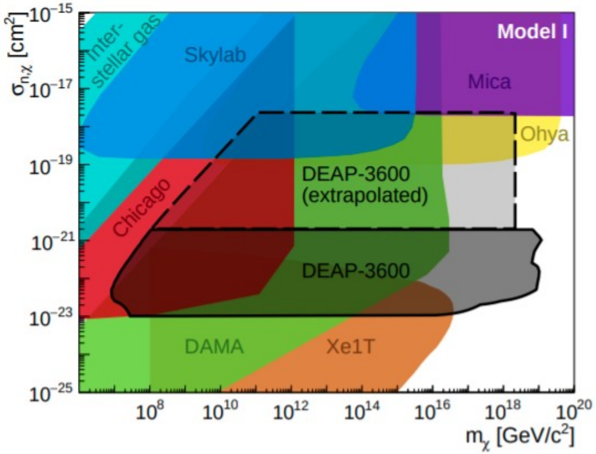


Ultraheavy Dark Matter Search Results

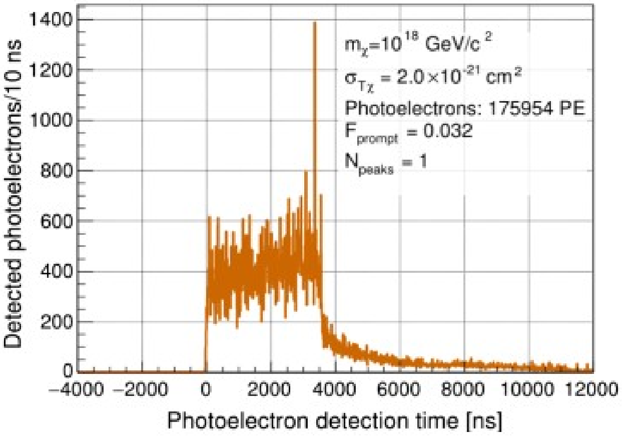
DEAP Collaboration. “First Direct Detection Constraints on Planck-Scale Mass Dark Matter with Multiple-Scatter Signatures Using the DEAP-3600 Detector”. Phys. Rev. Lett. 128, 011801 (2022)

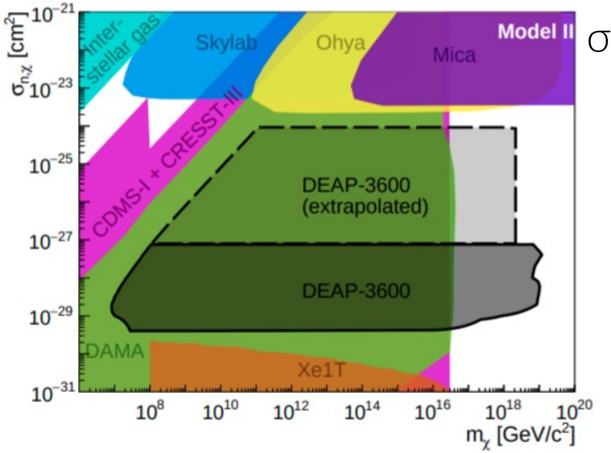






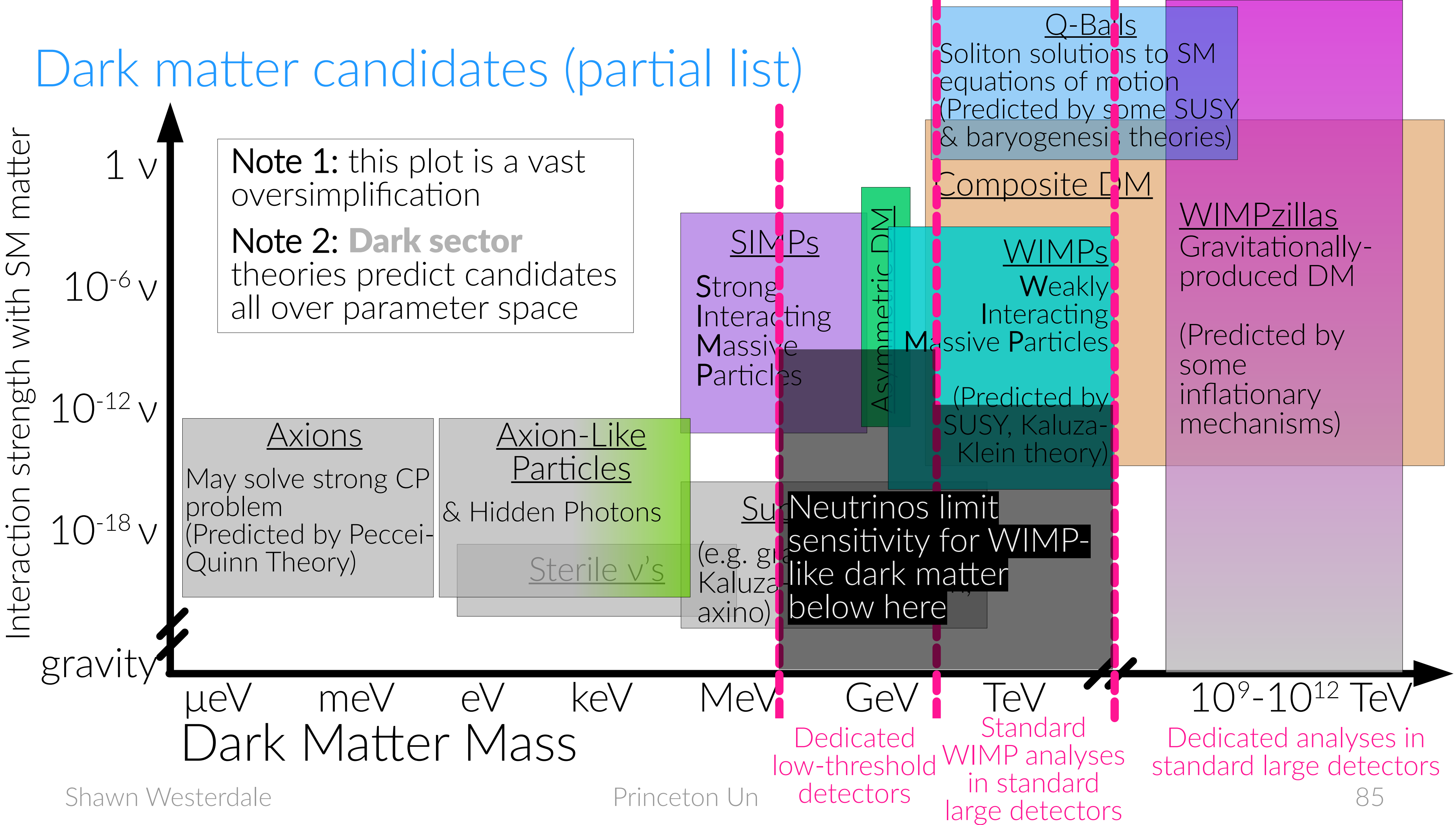
$\sigma_{T\chi}=\sigma_{n\chi}\ F^2(q)$





$\sigma_{T\chi}=A^4\sigma_{n\chi}\ F^2(q)$

Dark matter candidates (partial list)



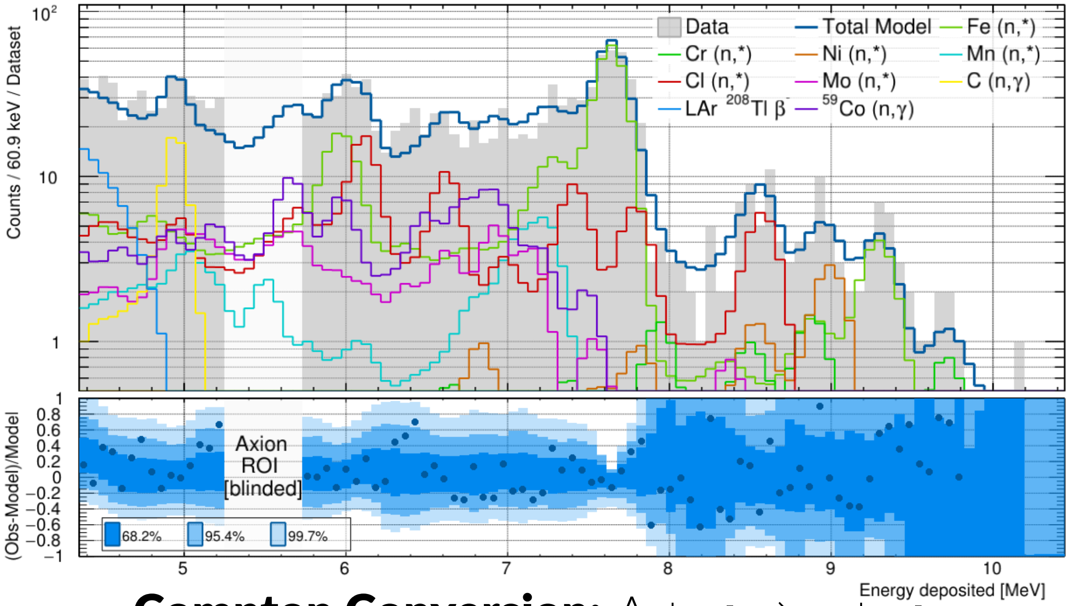
Note 1: this plot is a vast oversimplification

Note 2: **Dark sector** theories predict candidates all over parameter space

Search for axion-like particles from 5.5 MeV solar $p(d,{}^3He)A$

PhD thesis of Carl Rethmeier (2021). Blind analysis + publication coming soon

Preliminary fit to blinded data

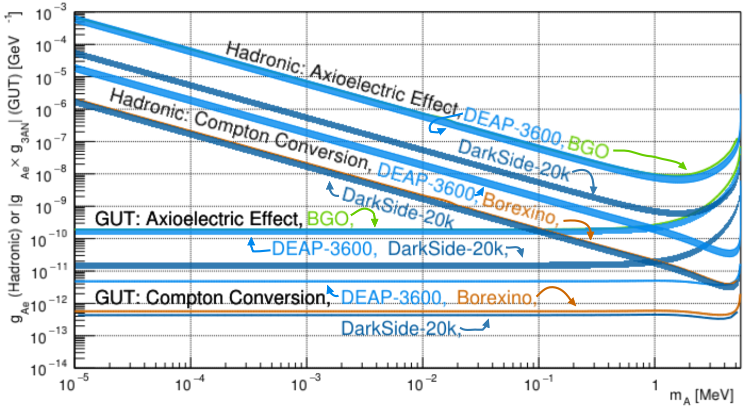


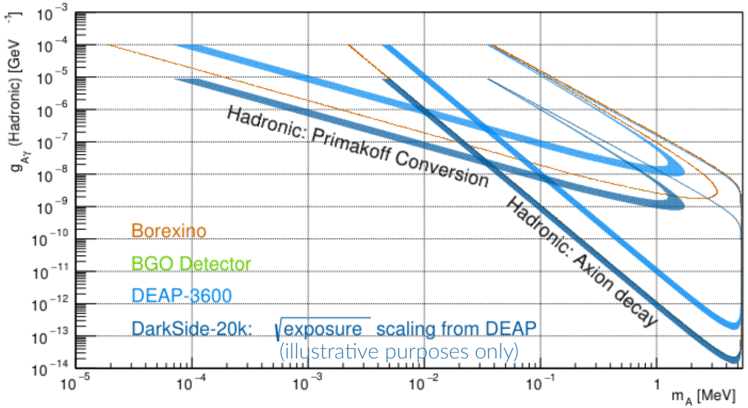
Compton Conversion: $A + e^- \rightarrow \gamma + e^-$

Axioelectric Effect: $A + e^- + Z \rightarrow e^- + Z$

Axion Decay: $A \rightarrow 2\gamma$

Primakoff Conversion: $A + Z \rightarrow \gamma + Z$

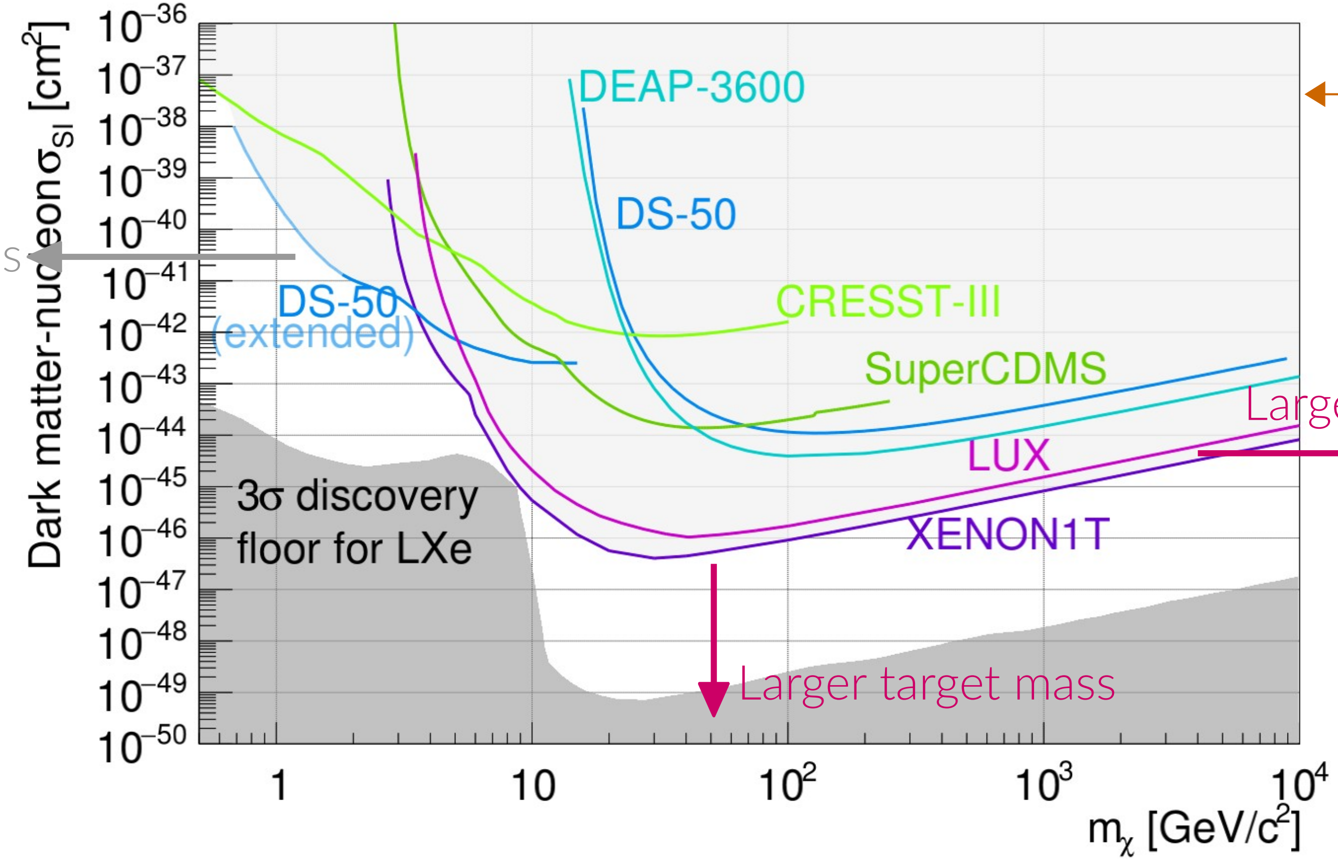




Conservative 90% exclusion curve projections

Two ALP models: GUT is generic, Hadronic relates nuclear & electromagnetic couplings

Expanding the search



Lower thresholds

All directions:
Lower backgrounds

Larger target area

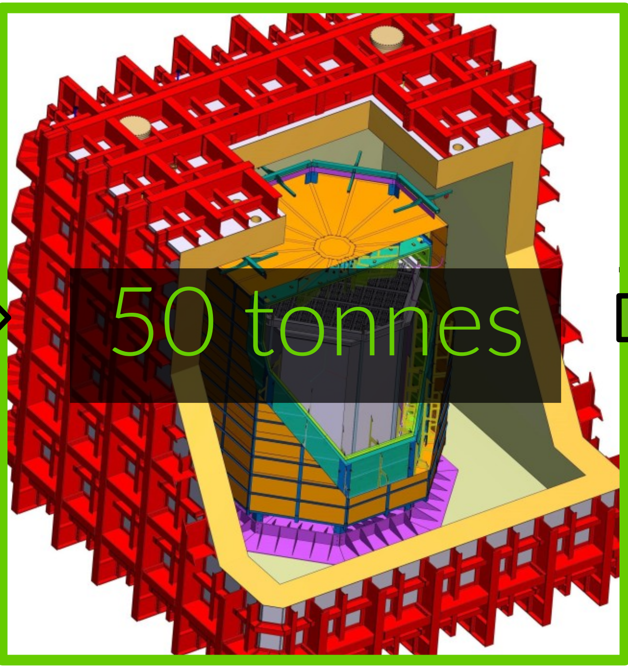
Larger target mass

Future experiments: High-mass DM detection

50 kg to 3.3 tonnes

Now

DarkSide-20k



50 tonnes

2025

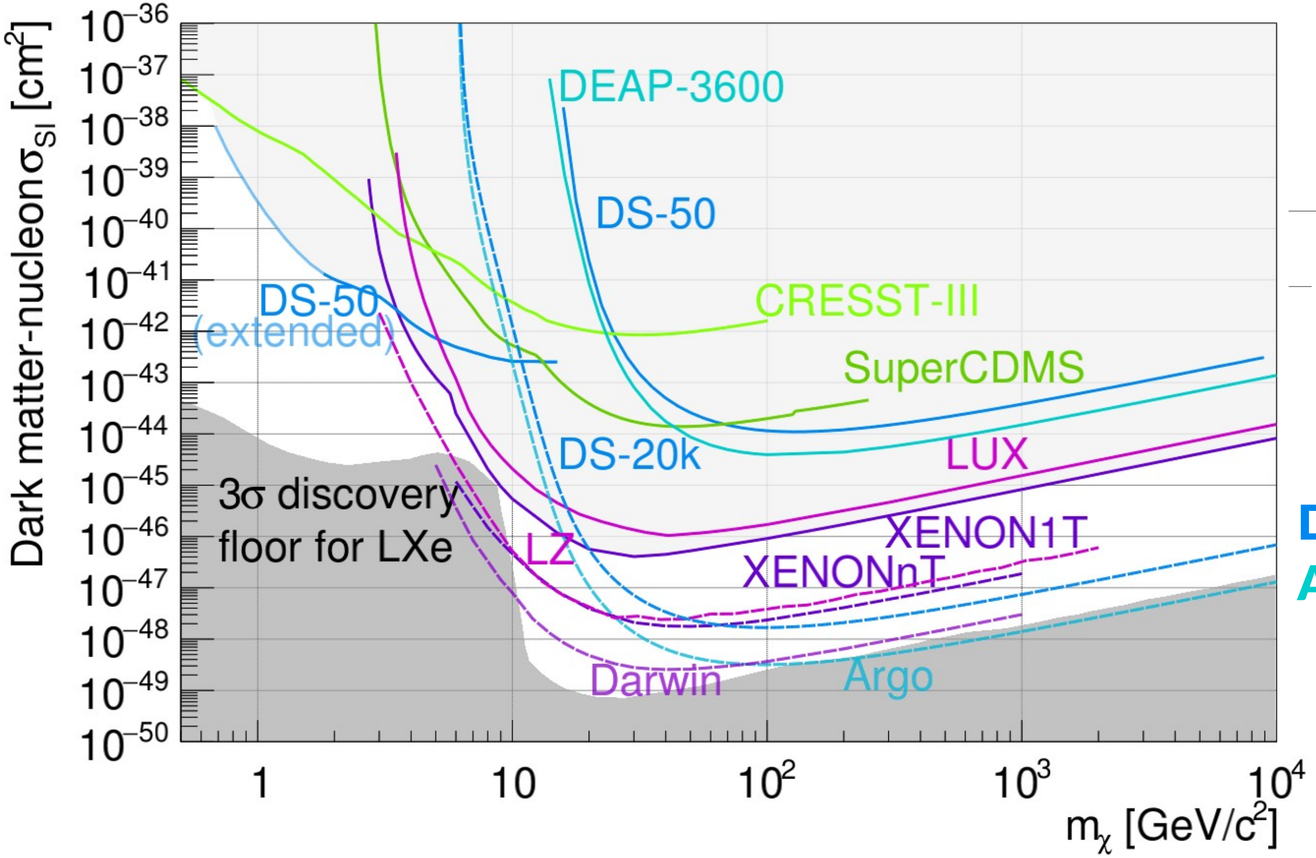
Argo

?

300 tonnes

~2030

Pursing the atmospheric neutrino floor



90% C.L. exclusion curves

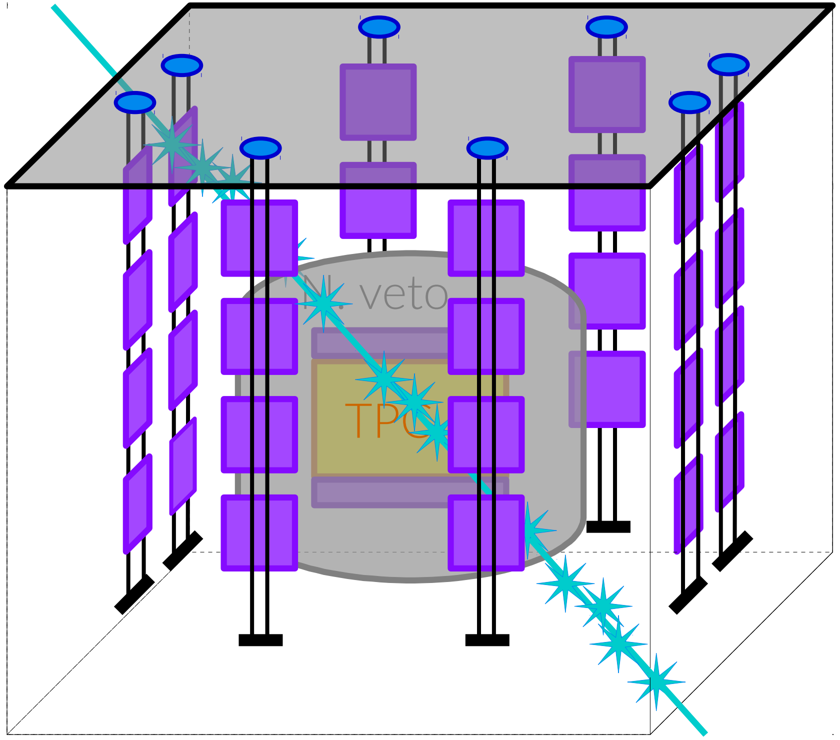
—— Excluded

- - - Projected

DS-20k: 3 atm ν's

Argo: atm ν floor

Maximizing DS-20k's sensitivity



Low-background cryostat based on ProtoDUNE design

Goal: Bkgd expectation << 1, excluding ν's

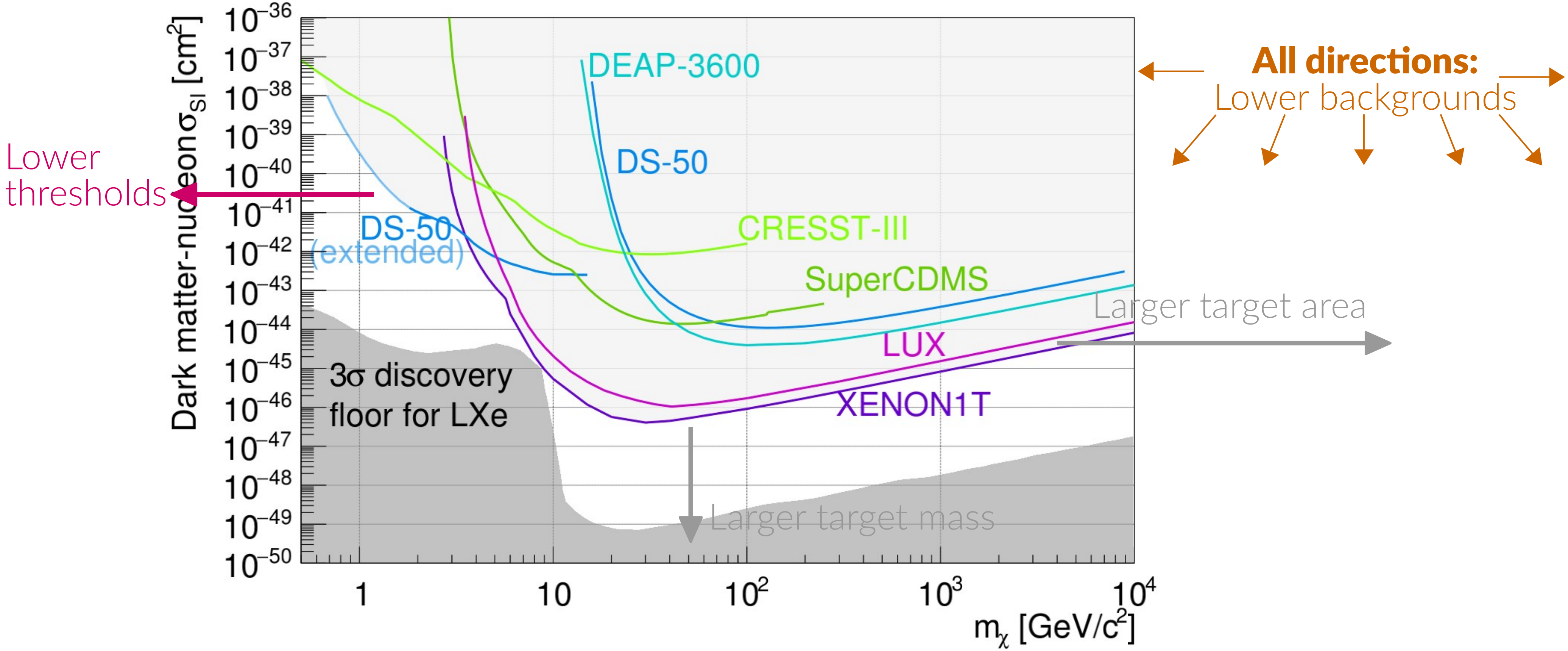
To obtain goal:

- Decrease radiogenic & cosmogenic bkgd uncertainties
  - → Data enabling calculations is limited
- Design cosmogenic veto to eliminate muon-induced backgrounds

Additional sensitivity to:

- Ultra-heavy DM:
  - Masses up to 10^{21} GeV
  - Lower cross sections
  - Dark nuclei with SM-like form factors
- Axions/Axion-like particles (ALPs):
  - 5.5 MeV p(d,3He)A solar ALPs
  - High-flux, O(keV) solar & cosmic ALPs
- Baryonic dark matter via excess (n,γ)
- Sterile ν's with O(1–100 keV) masses from sun

Expanding the search



Lower thresholds

All directions:
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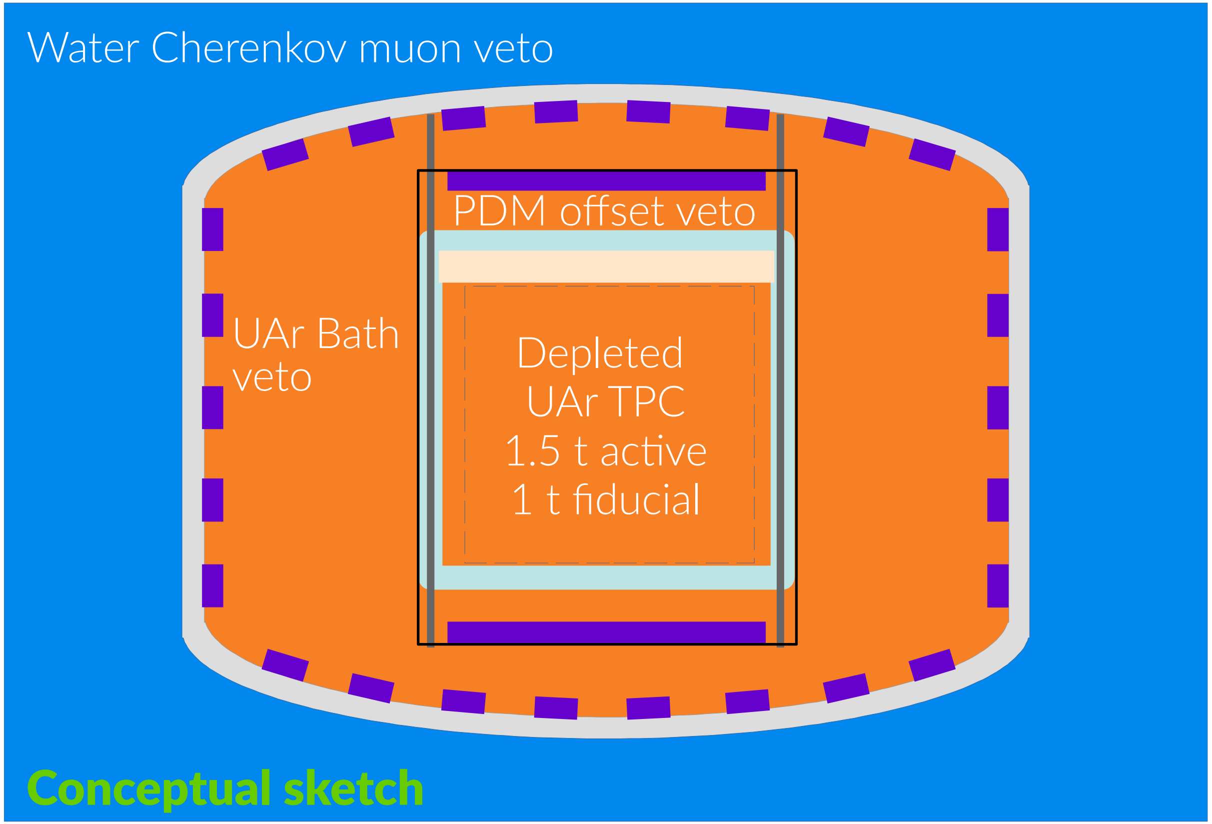
Larger target area

Larger target mass

DarkSide-LowMass



Low energy threshold

^{40}Ar has a light nucleus

→ Stronger kinematic coupling to low-mass DM

Low backgrounds

Depleted ^{39}Ar with UAr and Aria

Low temperature and small nucleus

→ More readily purified of
- Electronegative impurities
- Radon

Low dielectric constant

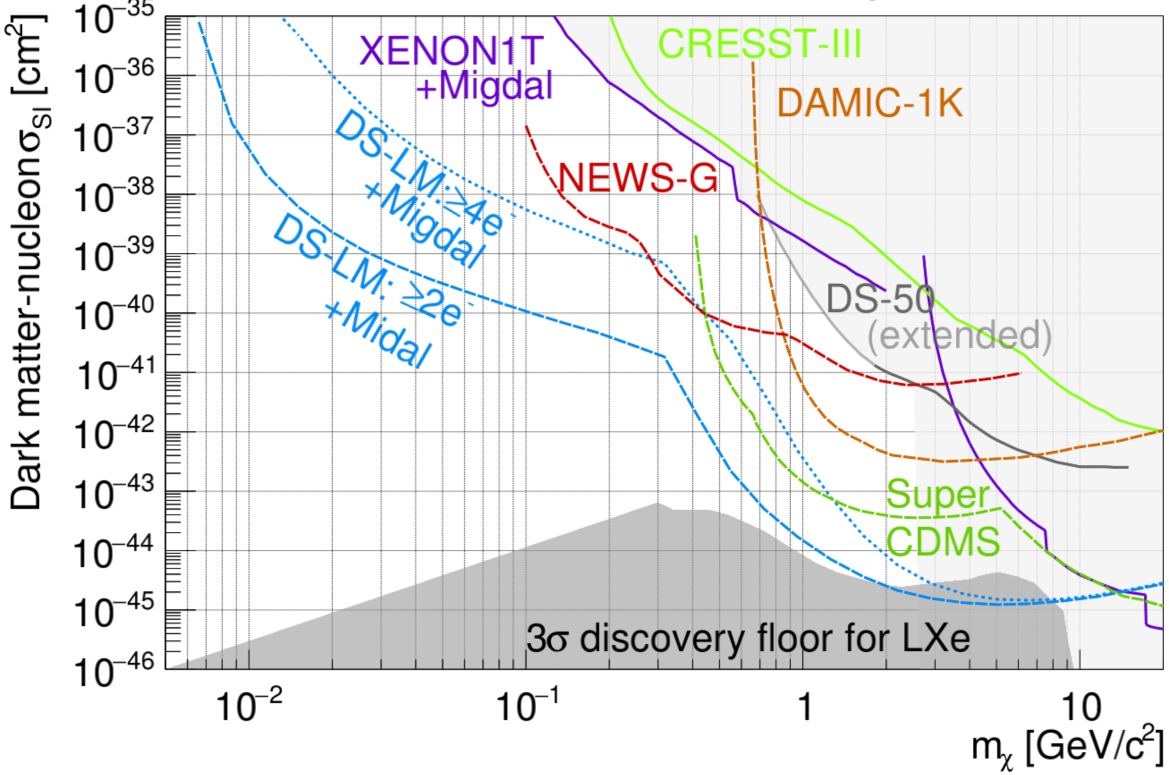
→ Efficient e$^-$ extraction from LAr surface

Sensitivity limitations:

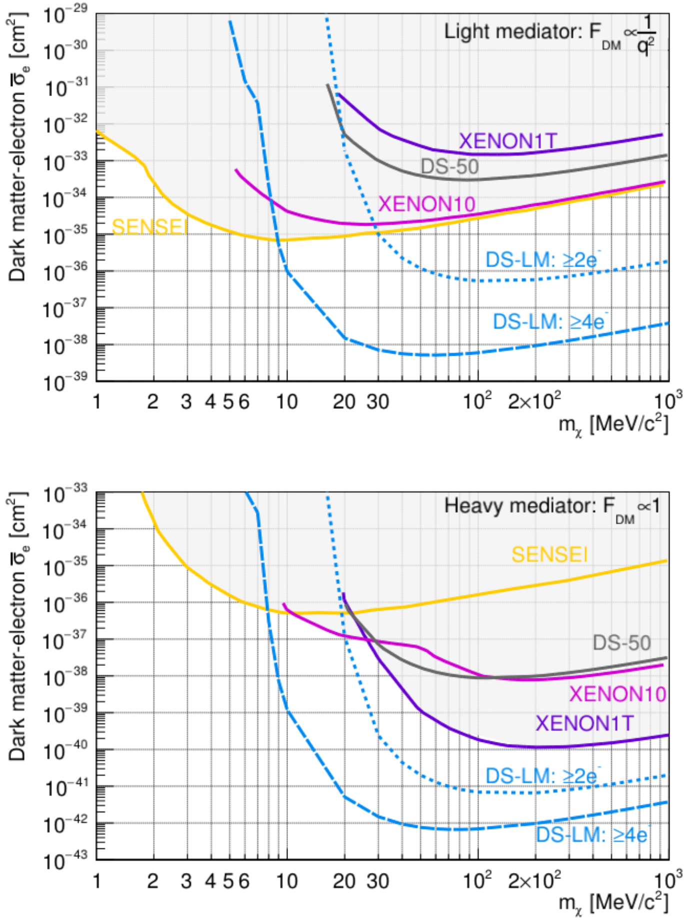
- Single e$^-$ backgrounds
- β-decays and γ-rays
- Uncertainties in the LAr ionization yield at low energies

DarkSide-LowMass sensitivity

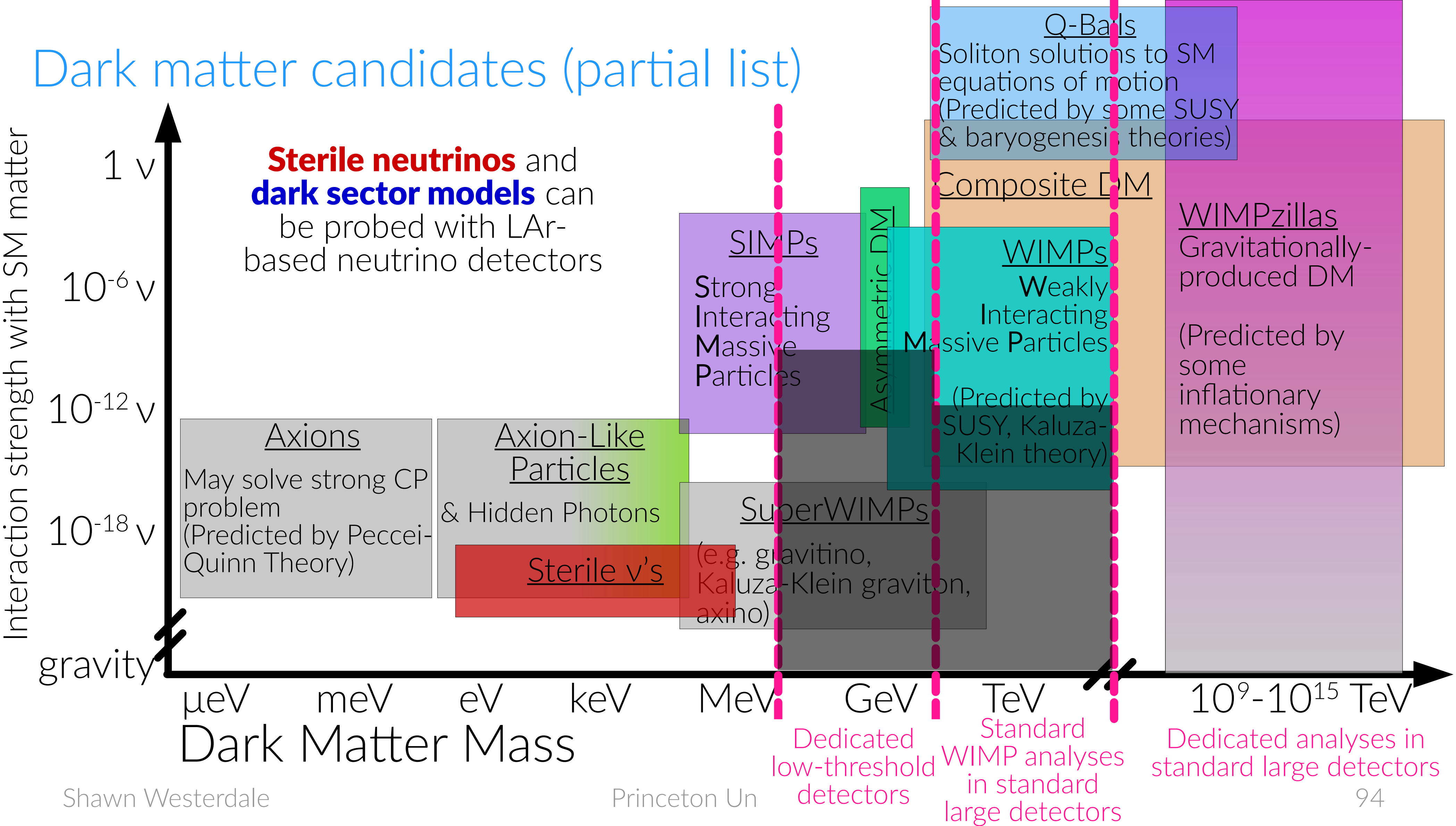
DM-nucleon couplings



DM-electron couplings



Dark matter candidates (partial list)



Sterile neutrinos and **dark sector models** can be probed with LAr-based neutrino detectors

Axions

May solve strong CP problem (Predicted by Peccei-Quinn Theory)

Axion-Like Particles

& Hidden Photons

Sterile ν's

SIMPs

Strong **I**nteracting **M**assive **P**articles

Asymmetric DM

SuperWIMPs

(e.g. gravitino, Kaluza-Klein graviton, axino)

Q-Balls

Soliton solutions to SM equations of motion (Predicted by some SUSY & baryogenesis theories)

Composite DM

WIMPs

Weakly **I**nteracting **M**assive **P**articles

(Predicted by SUSY, Kaluza-Klein theory)

WIMPzillas

Gravitationally-produced DM

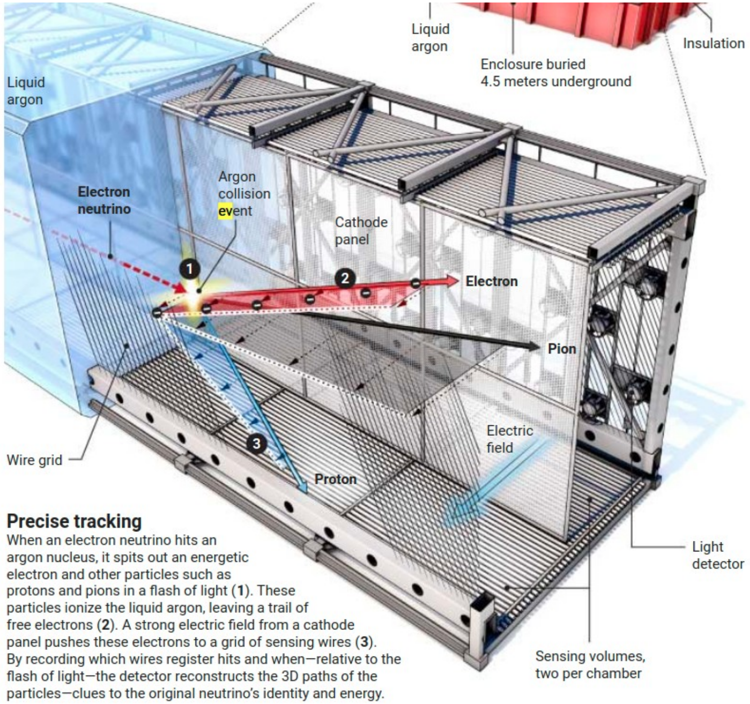
(Predicted by some inflationary mechanisms)

Dedicated low-threshold detectors

Standard WIMP analyses in standard large detectors

Dedicated analyses in standard large detectors

Sterile neutrino search with ICARUS



Precise tracking

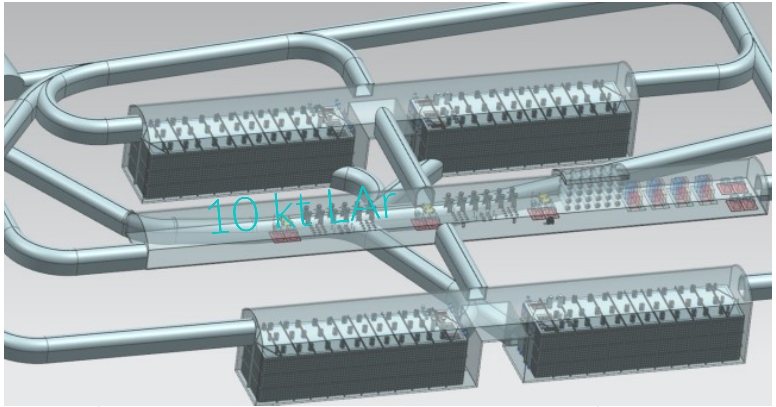
When an electron neutrino hits an argon nucleus, it spits out an energetic electron and other particles such as protons and pions in a flash of light (**1**). These particles ionize the liquid argon, leaving a trail of free electrons (**2**). A strong electric field from a cathode panel pushes these electrons to a grid of sensing wires (**3**). By recording which wires register hits and when—relative to the flash of light—the detector reconstructs the 3D paths of the particles—clues to the original neutrino's identity and energy.

https://www.science.org/content/article/resurrected-detector-will-hunt-some-strangest-particles-universe

Sterile neutrino search in a ν_μ beam

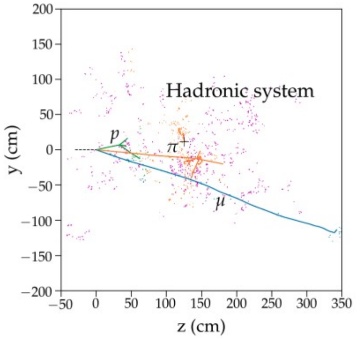
- Signals in ν_e appearance channel
  - Detected through ${}^{40}Ar+\nu_e \rightarrow {}^{40}K^*+e^-$ etc. (CC chans)
  - $E_\nu = E_e + E_{K^* \text{ de-excitation cascade}}$ (or others products)
  - Precise reconstruction requires accurately summing together many MeV-scale signals, and differentiating between them and backgrounds
  - MeV-scale reconstruction + background discrimination techniques from DM detection naturally lend themselves to this task!
    - (n,γ) signals, cosmogenic, and dirt backgrounds are all important here
- Signals in ν_μ spectrum
  - Require understanding of cosmogenic backgrounds

Dark sector probes in a DUNE low-background, Xe-doped far detector



Module of Opportunity → Chance to design a far detector for more physics

D. Caratelli **et al.** “Low-Energy Physics in Neutrino LArTPCs”. arXiv:2203.00740 (2022)



A low-threshold, Xe-doped far detector can

- Study stellar and supernova mechanisms by observing solar and core-collapse supernova neutrinos → constrain dark sector theories
- Search for bayonic DM by looking for excess (n,γ) signals
- Search for 0νββ, linked to sterile neutrinos
- Indirectly search for DM with ν-couplings and primordial black holes
- Neutrino-nucleus event reconstruction, more precise event reconstruction in general
  - e.g. “blip” reconstruction

Significant synergy with event reconstruction work at BNL

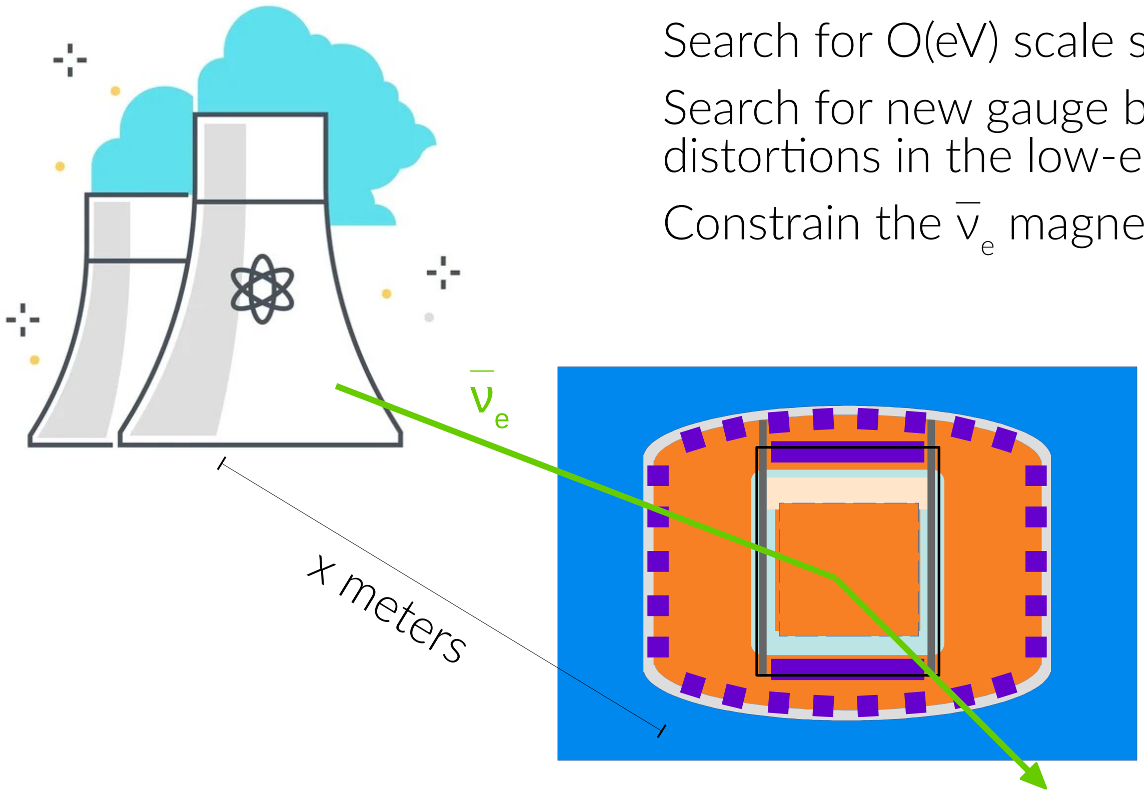
νDEAL for sterile neutrinos and dark sector

By measuring CEνNS from reactor neutrinos, νDEAL will

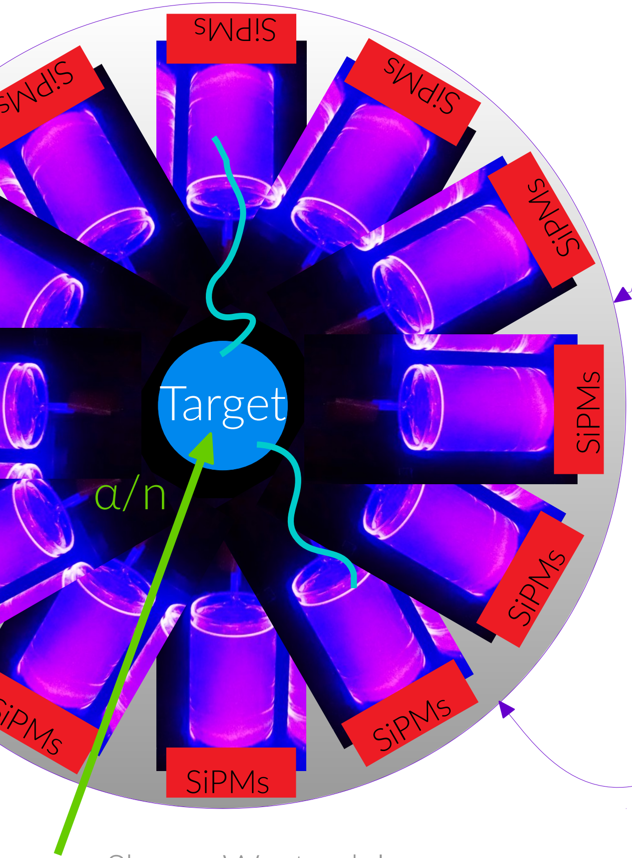
Search for O(eV) scale sterile neutrinos using varying baselines

Search for new gauge bosons in the dark sector by looking for distortions in the low-energy CEνNS signal

Constrain the $\bar{\nu}_e$ magnetic moment



What we need to achieve these goals



n/γ detector array for nuclear measurements

- Low-energy n-induced nuclear recoil backgrounds
- MeV-scale (n,γ) and (α,γ) backgrounds
- Cosmogenic background & material activation
- Machine learning background discriminators
- Atmospheric ν models
- Better reactor ν flux models
- Stellar and supernova mechanisms

Low-threshold LArTPC R&D

- Load w/ impurities → characterize & reduce spurious electron backgrounds
- Dope w/ Xe, allene → develop techniques & quantify effects for lowering threshold
- Calibrate low-energy recoils in pure & doped LAr

Thank you