Nuclear Physics for WIMPs

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SDSU & UCI
Joint Doctoral Program in
Computational Science

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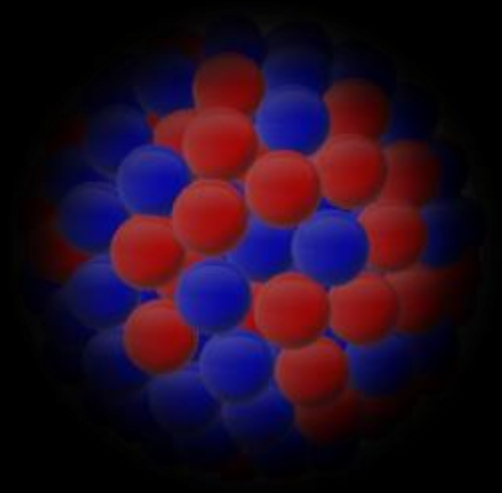

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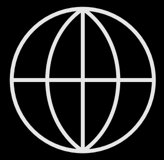
Disclaimer

Much of the introductory material in this presentation does not belong to me!

 = Not my work

What is dark matter?

Evidence for the 'silent' 85%

- Galaxy rotation curves
- Gravitational lensing
- Cosmic microwave background

…

[1] ESO https://www.eso.org/public/videos/eso1217a/

Annual Rev. Astron. Astrophys., Vol. 25, p. 425-472 (1987)

What is dark matter?

Candidates for dark matter

- Weakly Interacting Massive Particles (WIMPs)
- Primordial black holes
- Modified gravity
- Sterile neutrinos

…

[1] ESO https://www.eso.org/public/videos/eso1217a/

LUX-Zeplin (LZ): direct detection experiment for WIMPS @ Sanford Underground Research Facility in South Dakota

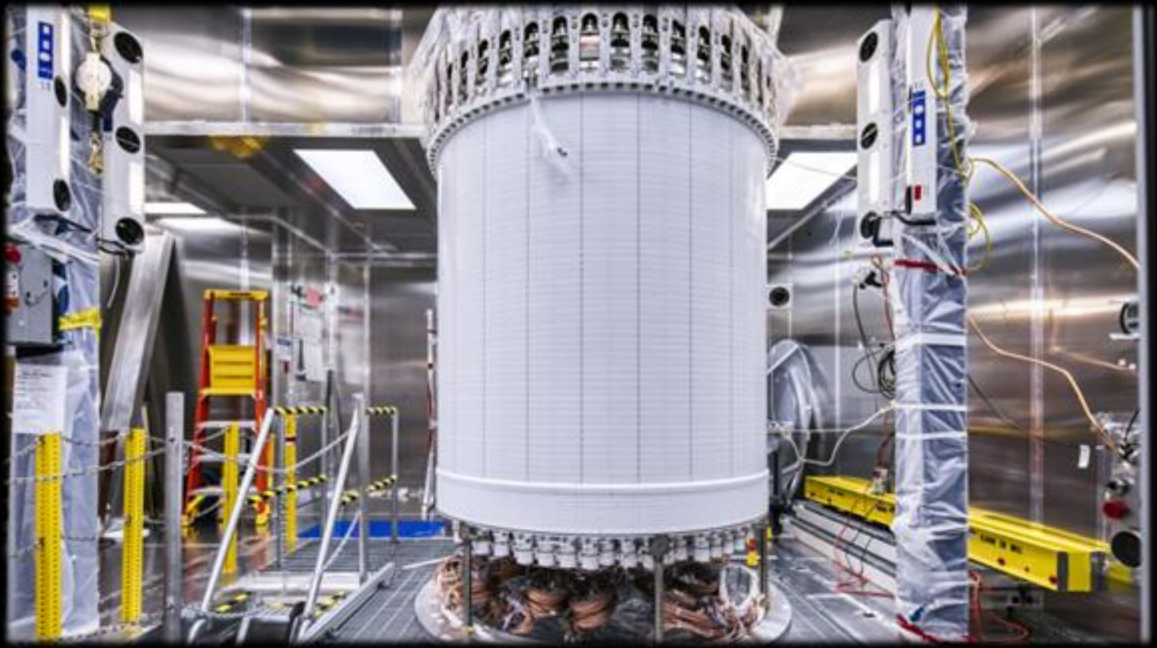
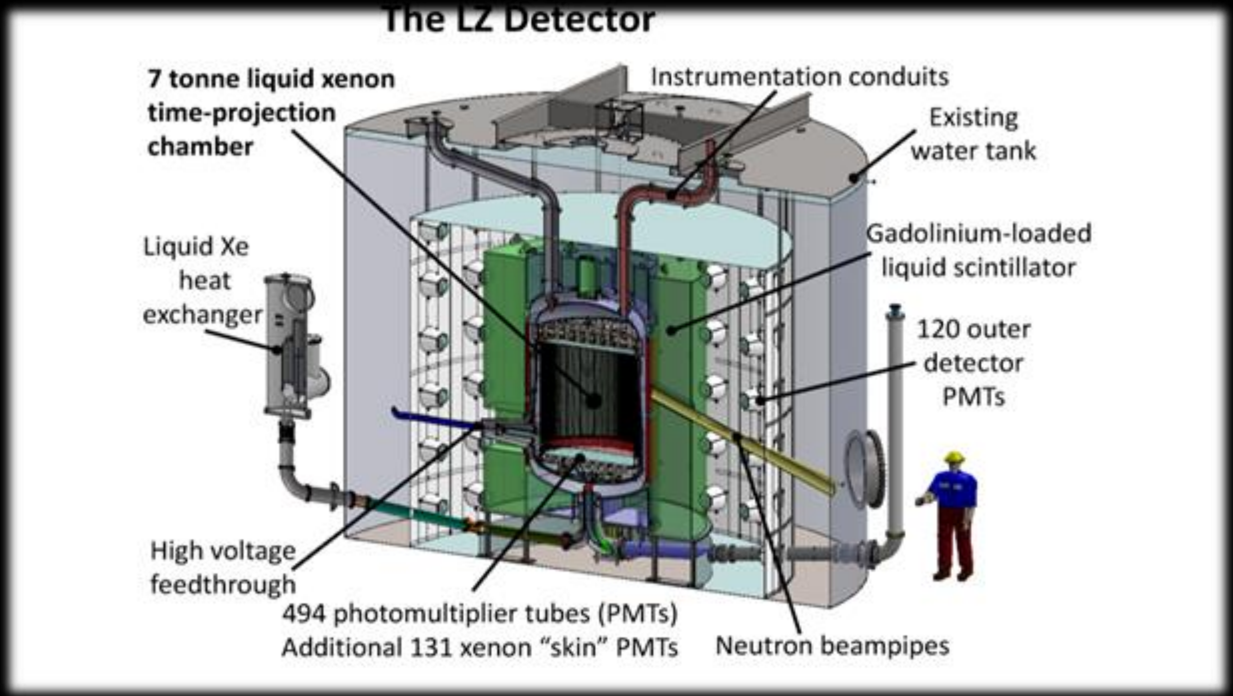


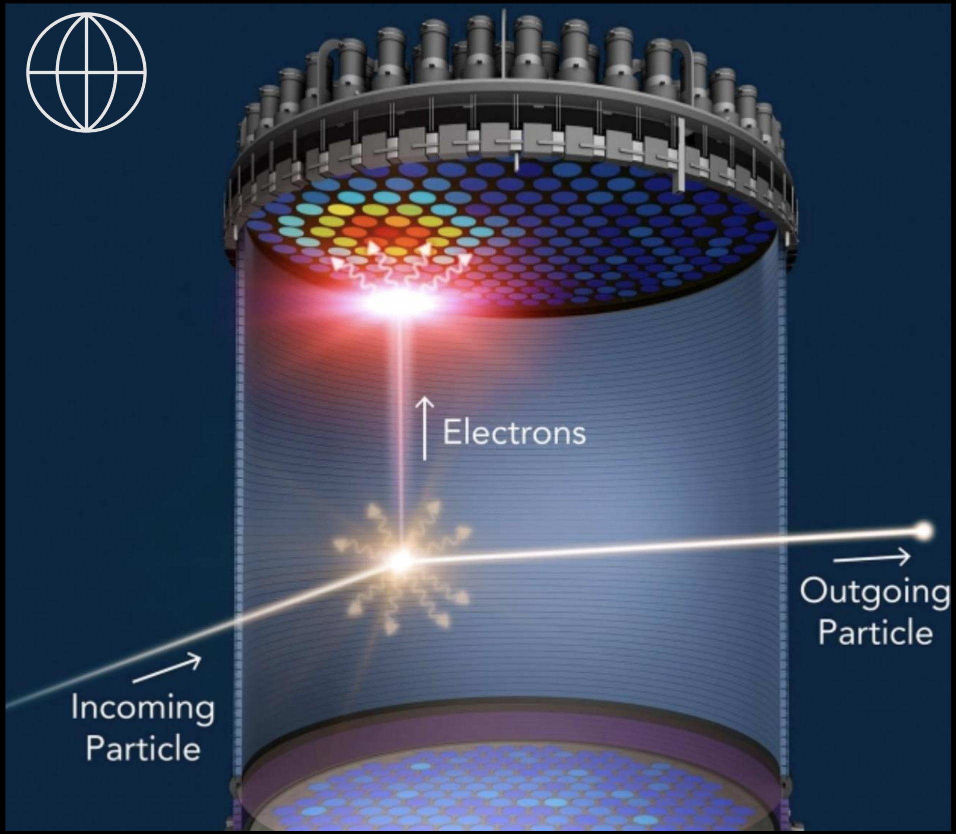
Photo by Matthew Kapust Sanford Underground Research Facility. https://www.sanfordlab.org/article/lz-time-projection-chamber-assembly-completed



DOE LZ detector in SD, USA https://lz.lbl.gov/detector/

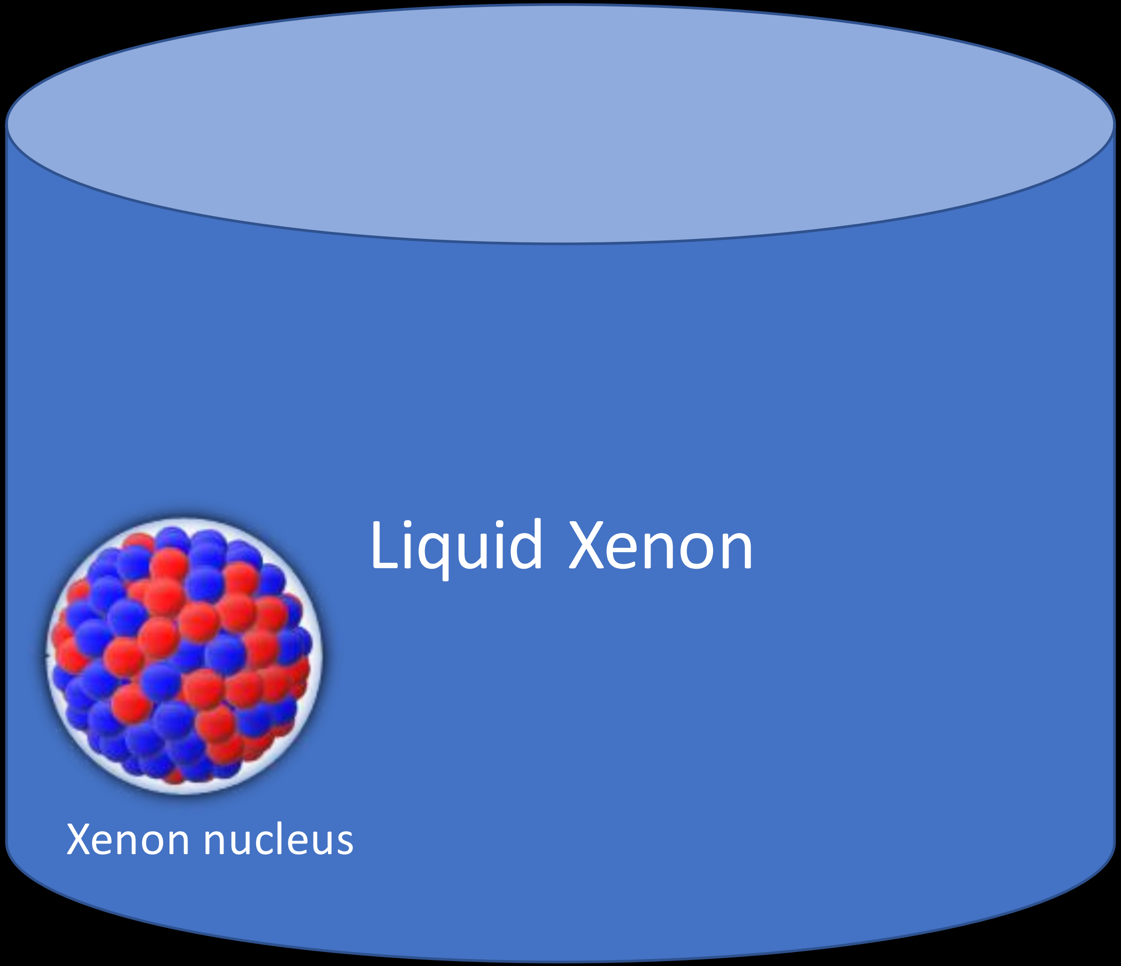
From the Sanford Underground Research Facility
https://www.sanfordlab.org/article/lz-time-projection-chamber-assembly-completed

A Xenon nucleus recoils from an unseen projectile



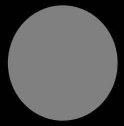
https://www.sanfordlab.org/experiment/lux-zeplin

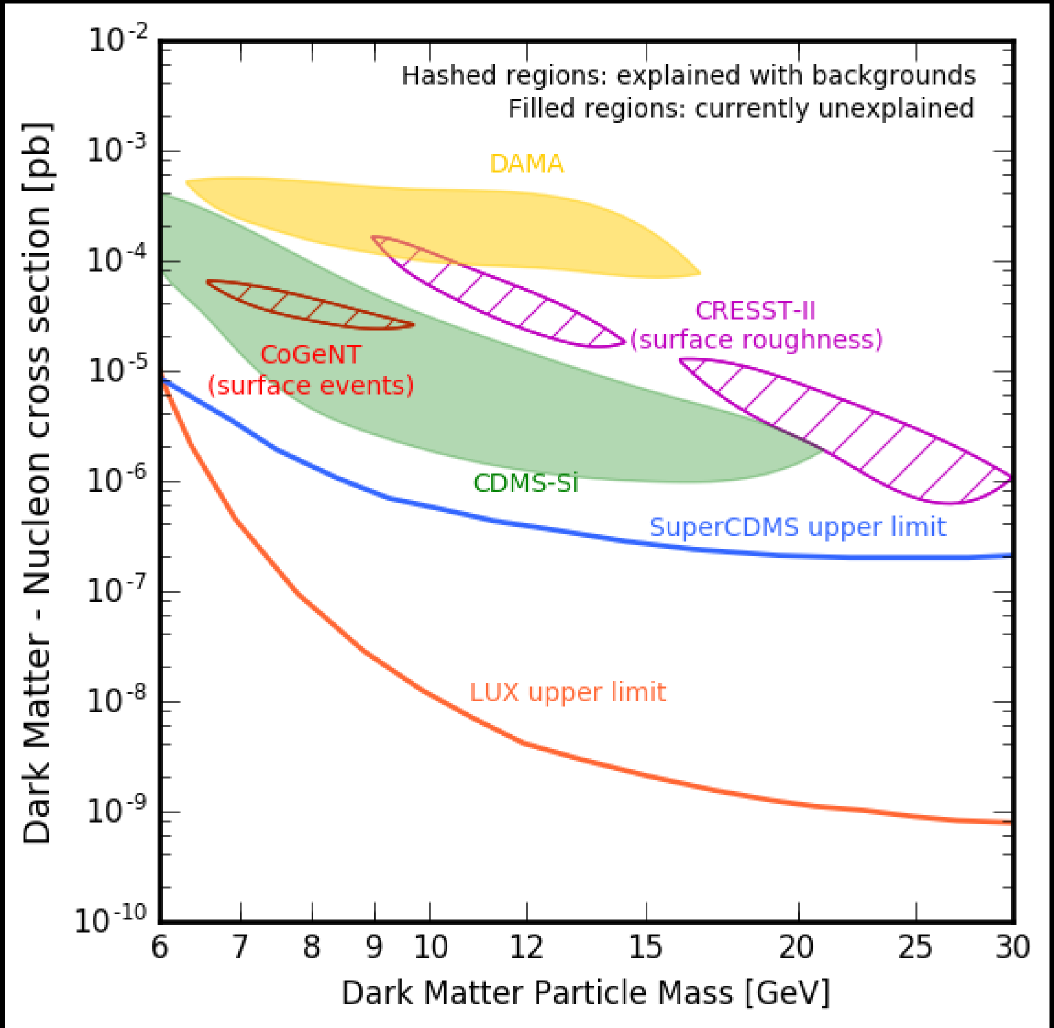
“Scintillation light is produced by the self-trapping of excited xenon atoms” 1802.06162



What would we learn from a detection event?

What would we learn from no detection?

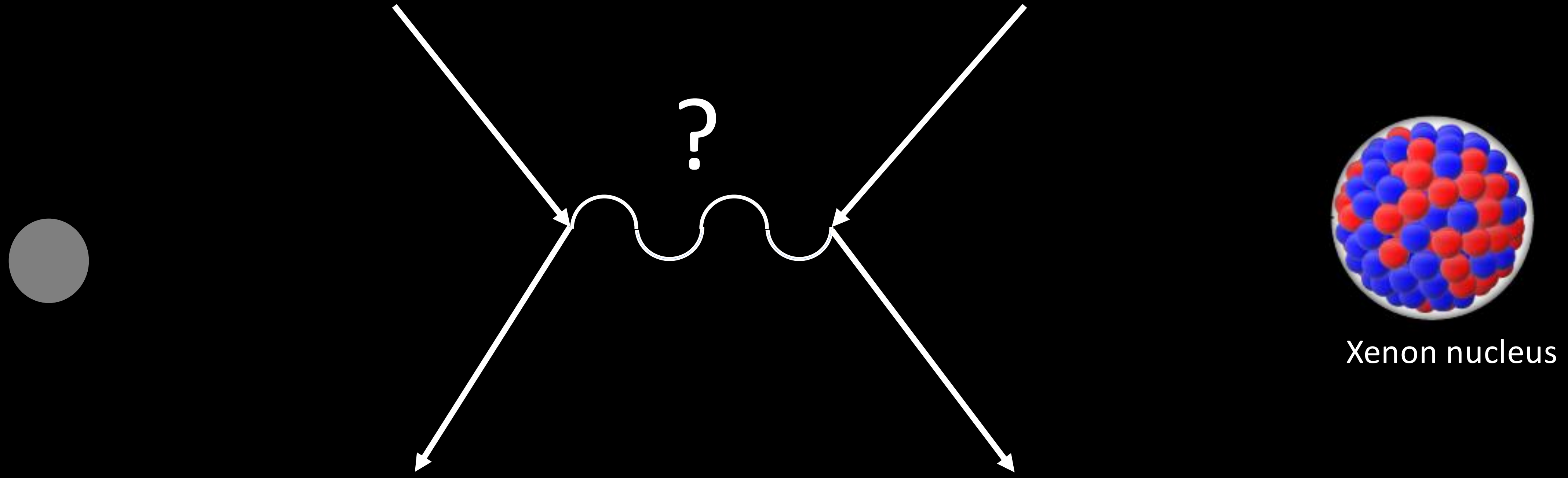




Xenon nucleus

What would we learn from a detection event?

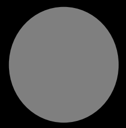
How can we describe an unknown interaction?



What would we learn from a detection event?

How can we describe an unknown interaction?

?



$$\mathcal{L}_{EFT} = a_1 1 + a_2 \vec{v}^\perp \cdot \vec{v}^\perp + a_3 \vec{S}_N \cdot (\vec{q} \times \vec{v}^\perp) + a_4 \vec{S}_\chi \cdot \vec{S}_N + i a_5 \vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp) + a_6 \vec{S}_\chi \cdot \vec{q} \vec{S}_N \cdot \vec{q}$$
$$+ a_7 \vec{S}_N \cdot \vec{v}^\perp + a_8 \vec{S}_\chi \cdot \vec{v}^\perp + i a_9 \vec{S}_\chi \cdot (\vec{S}_N \times \vec{q}) + i a_{10} \vec{S}_N \cdot \vec{q} + i a_{11} \vec{S}_\chi \cdot \vec{q}$$

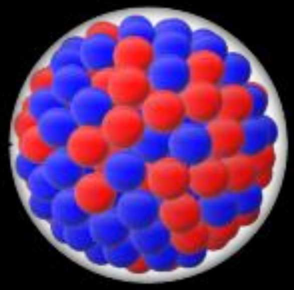
Xenon nucleus

Standard Model Formalism: provides a framework for writing down an arbitrary interaction

- Effective field theory
- Non-relativistic
- Elastic collision
- Leading orders in momentum and energy

This work has been done

- DMFormFactor (Mathematica)
  https://www.ocf.berkeley.edu/~nanand/software/dmformfactor/
- WimPyDD (Python)
  https://wimpydd.hepforge.org/



$|\Psi\rangle$

→

$$\mathcal{L}_{EFT} = a_1 1 + a_2 \vec{v}^{\perp}\cdot\vec{v}^{\perp} + a_3 \vec{S}_N\cdot(\vec{q}\times\vec{v}^{\perp}) + a_4 \vec{S}_\chi\cdot\vec{S}_N + i a_5 \vec{S}_\chi\cdot(\vec{q}\times\vec{v}^{\perp}) + a_6 \vec{S}_\chi\cdot\vec{q}\vec{S}_N\cdot\vec{q}$$
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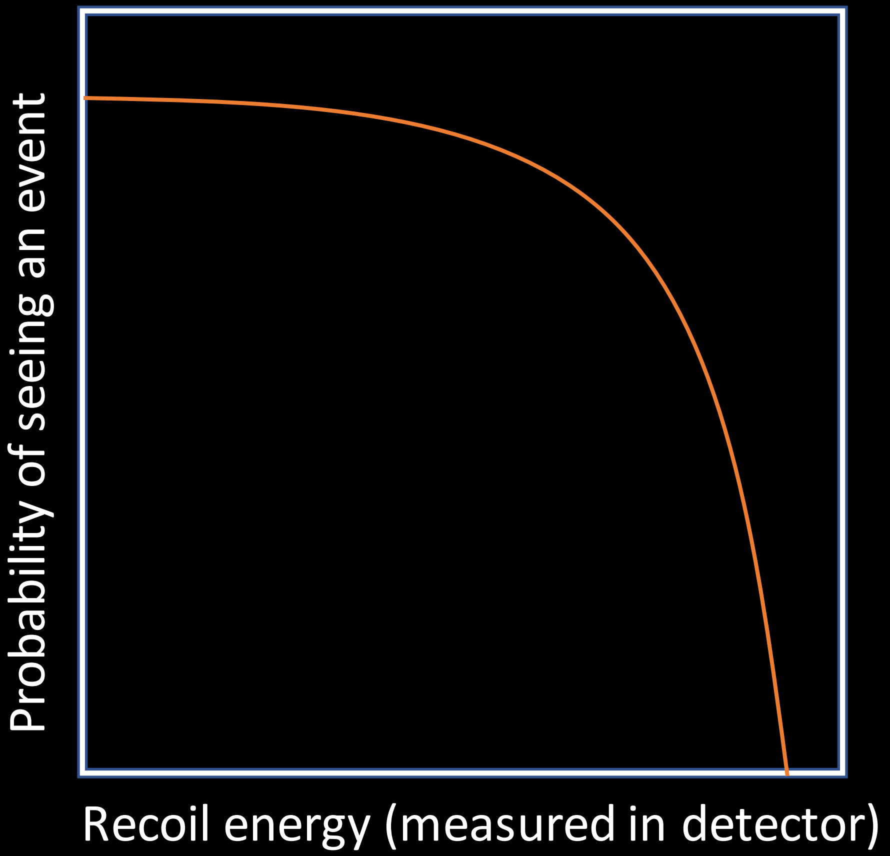
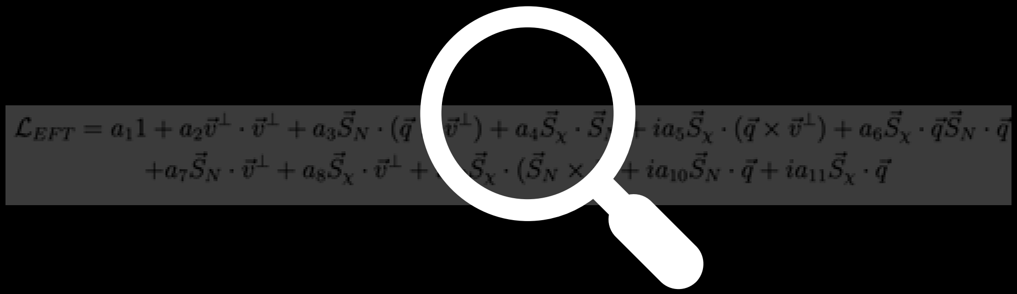
→



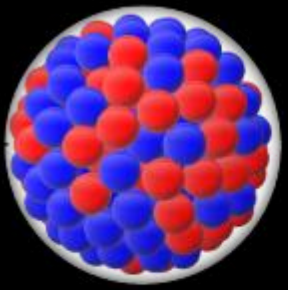
How do we <u>compute</u> this interaction with a nucleus?



$$\longrightarrow \sum_i c_i |\langle \Psi | O_i | \Psi \rangle|^2$$

$c_i =$ QFT Interaction Parameters

$$|\Psi\rangle =$$

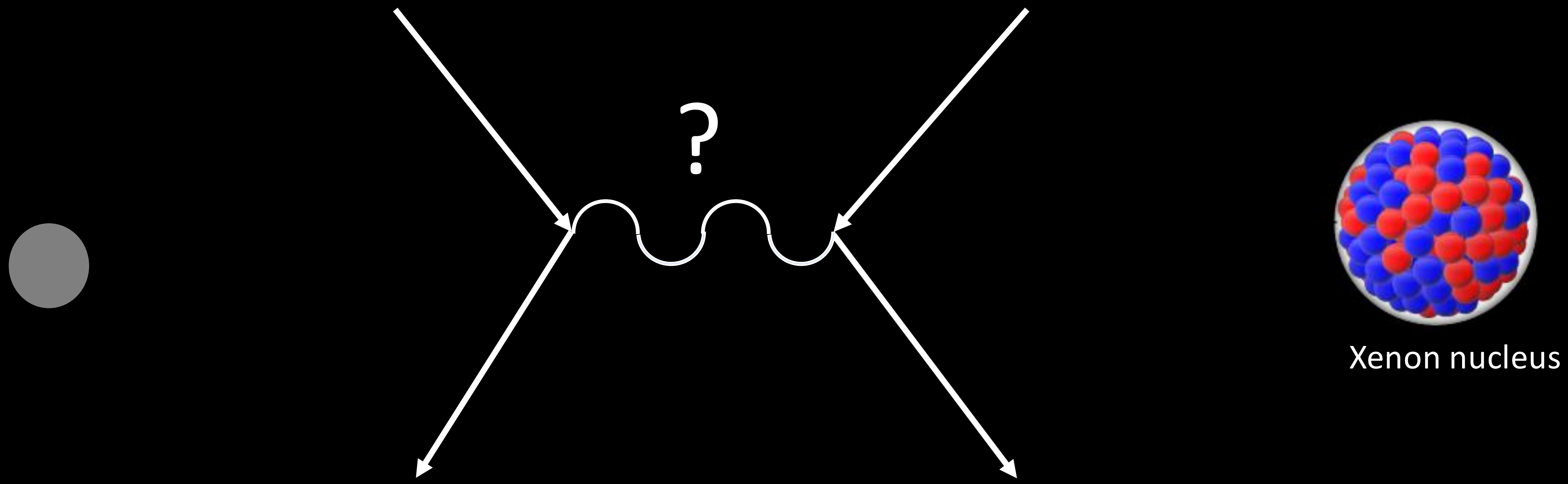


$$= \sum_{ij} a_{ij} \, det \begin{bmatrix} \phi_1(r_1) & \cdots & \phi_1(r_A) \\ \vdots & \ddots & \vdots \\ \phi_A(r_1) & \cdots & \phi_A(r_A) \end{bmatrix}$$

$\phi_i(r_j) =$ 

$O_i =$ Single-nucleon operators for simple basis states ϕ; have closed forms

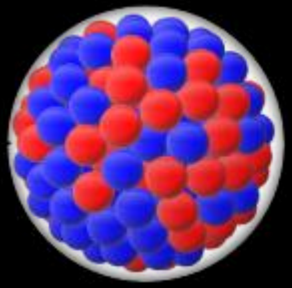
What would we learn from a detection event… and from a no event



Constraints on the coupling strengths in the EFT model

What’s left to do?

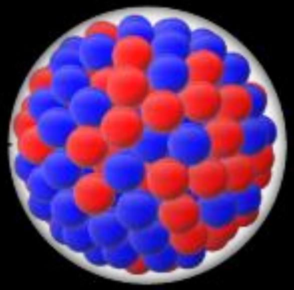
$$|\Psi\rangle =$$



Nuclear physics
- How can we provide wave functions for complex nuclei?
- How accurate are observables computed with these wave functions?

Particle physics
- Wait for an event
- How sensitive are the constraints to the underlying nuclear physics?
- What nuclei will make the best targets for detection?

Computing large nuclear wave functions

$$|\Psi\rangle =$$ 

$$\hat{H}\,|\Psi\rangle = E|\Psi\rangle$$

$$\hat{H}\,\vec{\Psi} = E\vec{\Psi}$$

Many-body Schrödinger equation

$$1 = \sum_a |a\rangle\langle a|$$

Choose an orthonormal basis

$$H_{ab} = \langle a|\hat{H}|b\rangle$$

Compute the matrix elements of the Hamiltonian

$$\sum_b H_{ab}\,\Psi_b = E\,\Psi_a$$

Solve the matrix-eigenvalue problem

What makes this hard: VERY large basis dimensions. 10^9 - 10^{10}

Computing large nuclear wave functions

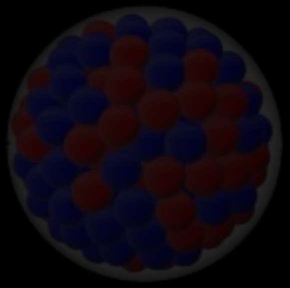
- Master's thesis work: physics-based importance basis-truncation scheme to reduce the model space size
- Further optimized using on-the-fly block-Lanczos iterations (iterative extremal eigenvalue solver)

Dimension	Reference Time	Improved Time
$2 * 10^3$	9.0 s	1.7 s
$2 * 10^4$	960 s	320 s
$5 * 10^4$	?	1800 s
$1 * 10^5$	?	?

Reference Memory	Improved Memory
0.02 GB	0.01 GB
2.2 GB	0.1 GB
11 GB	0.4 GB
47 GB	0.9 GB

What's left to do?

$$|\Psi\rangle =$$



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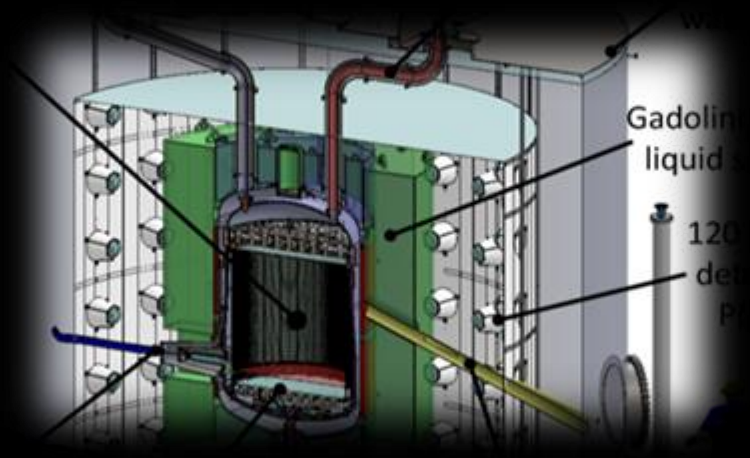

Particle physics
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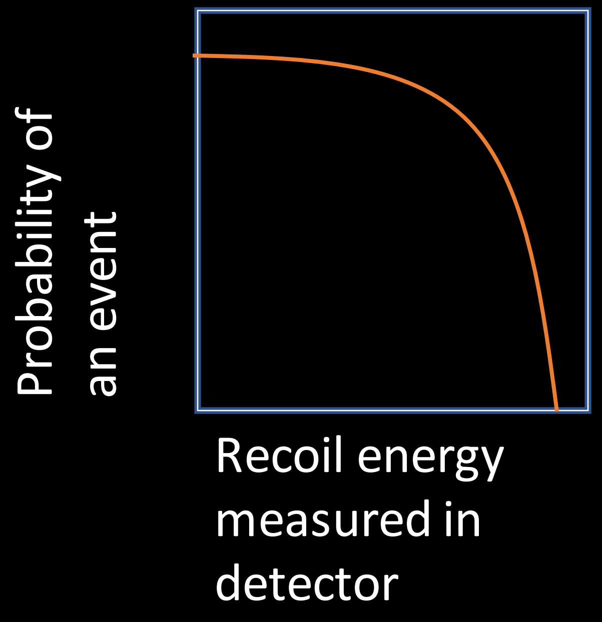
Speeding up WIMP calculations

$$Detection\ Rate = \int dv\, f(v) \sum_i c_i |\langle \Psi | O_i | \Psi \rangle|^2$$

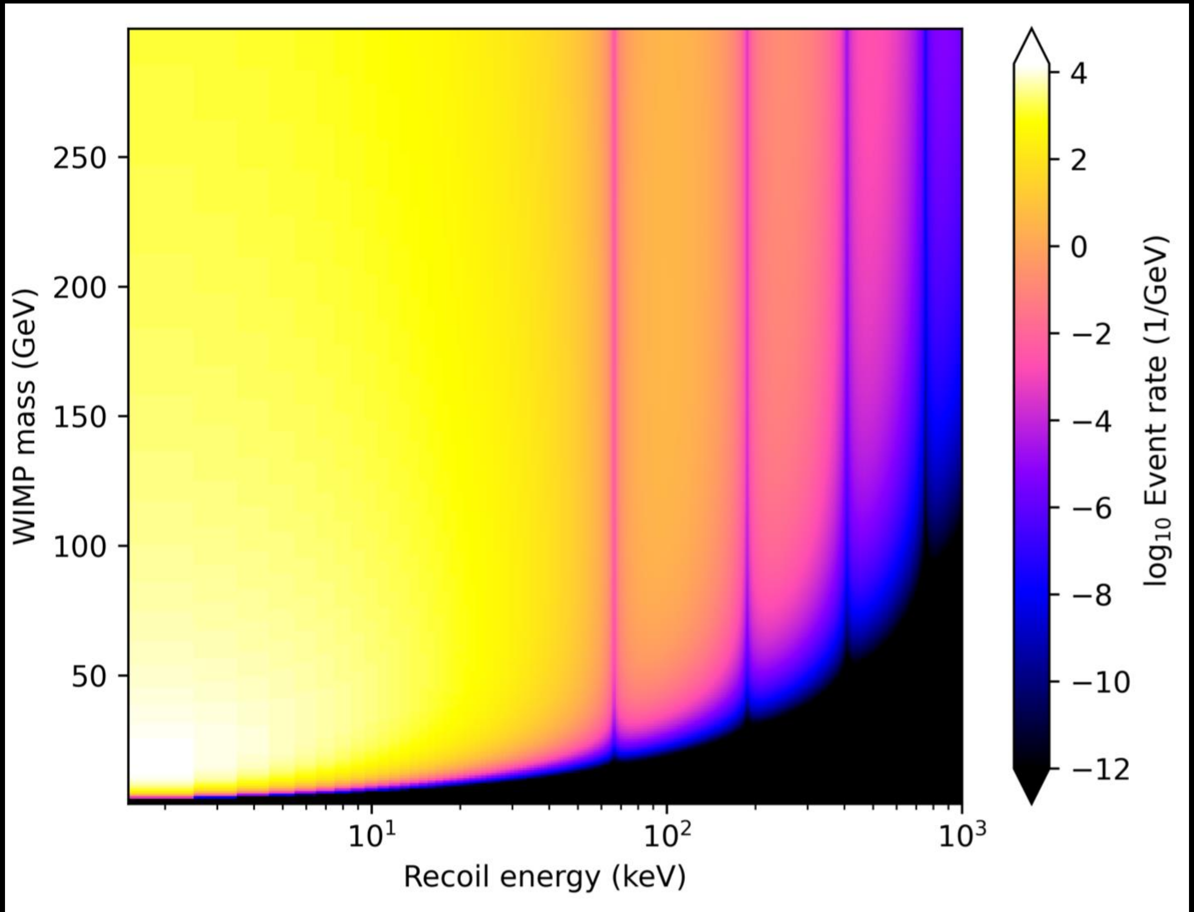


Timing Data (runtime in seconds)

Test	Most used code
^{29}Si (23 matrix elements)	
c_1^n	3800
c_3^n	3800
c_4^n	3700
c_5^n	3700
c_6^n	3700
^{131}Xe (67 matrix elements)	
c_1^n	20 000

New code enables rapid parameter space exploration

- Figure runtime (this work): 30 minutes
- Estimated runtime with public code: 70 days

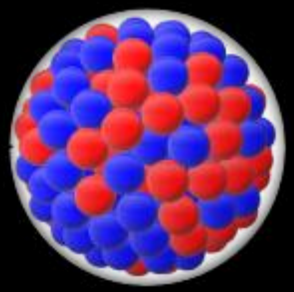


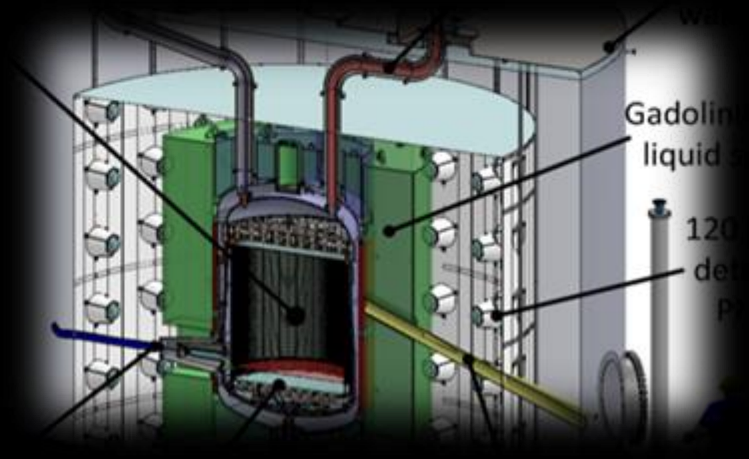
Will be able to conduct Monte Carlo parameter sampling to:

Examine sensitivity to nuclear physics inputs
Explore sensitivity to different regions of parameter space
Compare potential targets for future experiments

What’s next?

$$|\Psi\rangle =$$





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Acknowledgements and more

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- Thanks to our collaborators:
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  - Dr. A. Baha Balantekin, UW Madison
  - Dr. Kimberly Palladino, UW Madison
  - Jonathan Nikoleyczik, UW Madison

For more on direct dark matter detection:
lz.lbl.gov
sanfordlab.org

For more on computational nuclear physics:
http://sci.sdsu.edu/johnson/