Title: Detecting Nanometer-Scale New Forces with Coherent Neutron Scattering

Speakers: Zachary Bogorad

Series: Particle Physics

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Abstract: Significant effort has been devoted to searching for new fundamental forces of nature. At short length scales (below approximately 10 nm), many of the strongest experimental constraints come from neutron scattering from individual nuclei in gases. The leading experiments at longer length scales instead measure forces between macroscopic test masses. I will present a proposal that combines these two approaches: scattering neutrons off of a target that has spatial structure at nanoscopic length scales. Such structures will give a coherent enhancement to small-angle scattering, where the new force is most significant. This can considerably improve the sensitivity of neutron scattering experiments for new forces in the 0.1 - 100 nm range. I will discuss the backgrounds due to Standard Model interactions and a variety of potential target structures that could be used, estimating the resulting sensitivities. I will show that, using only one day of beam time at a modern neutron scattering facility, our proposal has the potential to detect new forces as much as four orders of magnitude beyond current laboratory constraints at the appropriate length scales.

Zoom link https://pitp.zoom.us/j/98201041537?pwd=MS9weFpNcHVFTVIwMTVoYmpxeTd6Zz09

Detecting New Nanometer-Range Forces Using Coherent Neutron Scattering

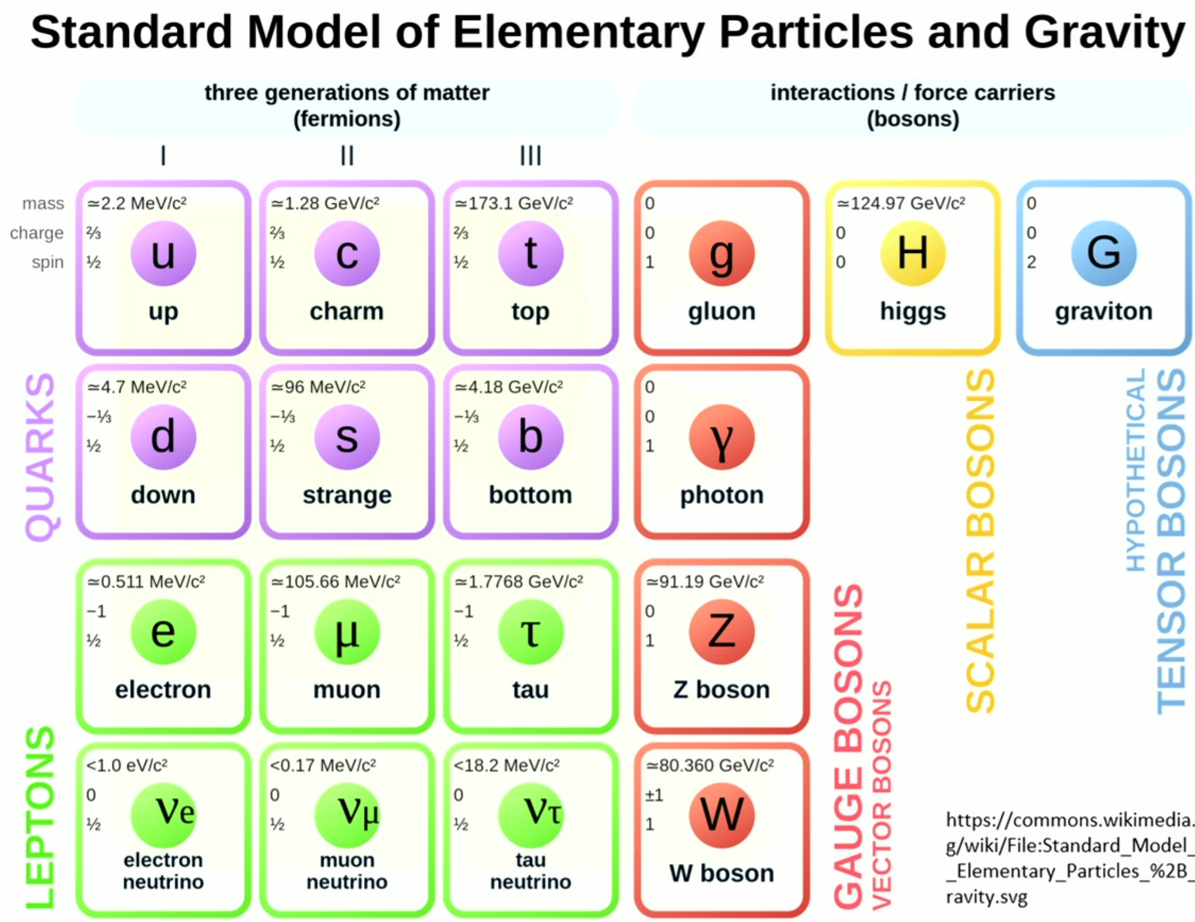
Zach Bogorad

Based on arXiv:2303.17744, with Peter Graham and Giorgio Gratta

Outline

- New forces: motivation and previous experiments
- Single-material targets: how they work and possible implementation
- Two-material targets: challenges and possible implementation

Four fundamental forces are known



https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles_%2B_Gravity.svg

New scalars can mediate macroscopic forces

- Two possible fermion vertices:

$$\begin{array}{ll} \text{Scalar:} & \phi\bar{\psi}\psi \\ \text{Pseudoscalar:} & \phi\bar{\psi}i\gamma^5\psi \end{array}$$

- In this talk we'll only care about the scalar-scalar potential:

$$V_{ss}(r) = -\frac{g_{s,1}g_{s,2}}{4\pi}\left(\frac{1}{r}\right)e^{-\mu r}$$

Background

Single-Material

Two-Material

New scalars can mediate macroscopic forces

- Two possible fermion vertices:

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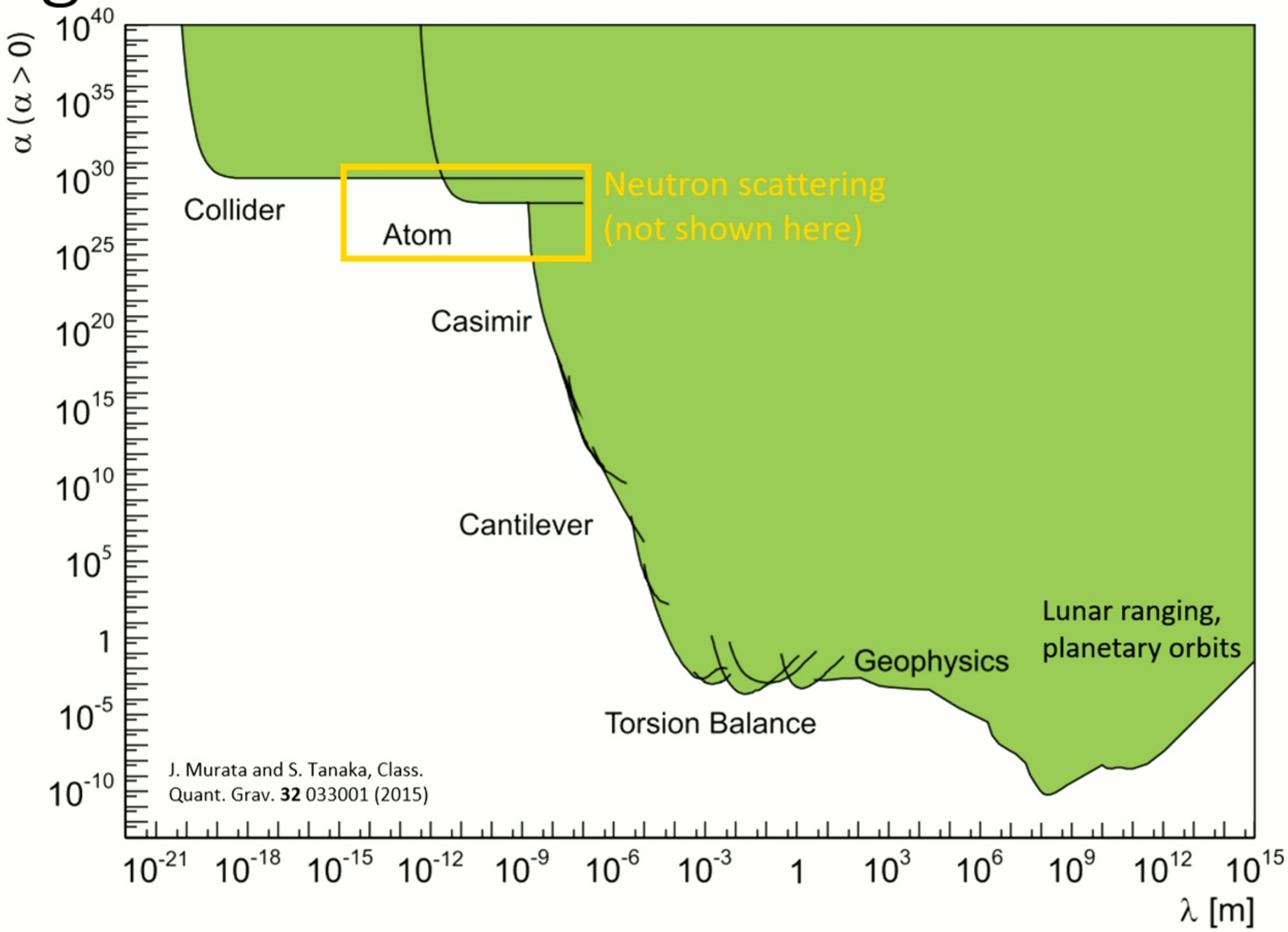
Existing limits on new forces



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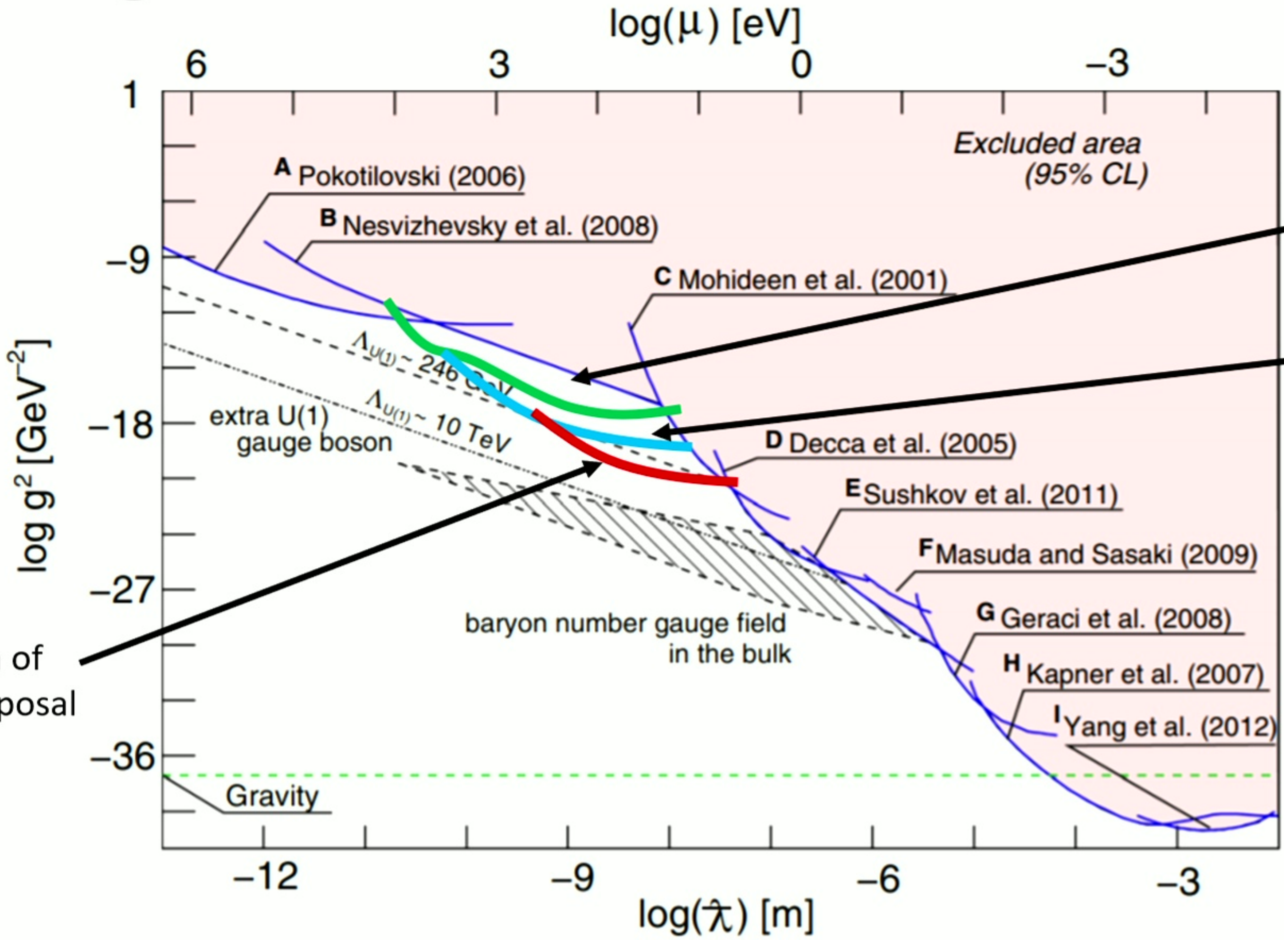
Existing limits on new forces



(Relatively) recent limits using neutron scattering from xenon

Recent limits from neutron interferometry

Potential reach of this work's proposal

Y. Kamiya *et al.*, PRL **114**, 161101 (2015)

Y. Kamiya *et al.*, AIP Conf. Proc. **2319**, 040017 (2021)

Heacock *et al.*, Science **373**, 1239 (2021)

Background

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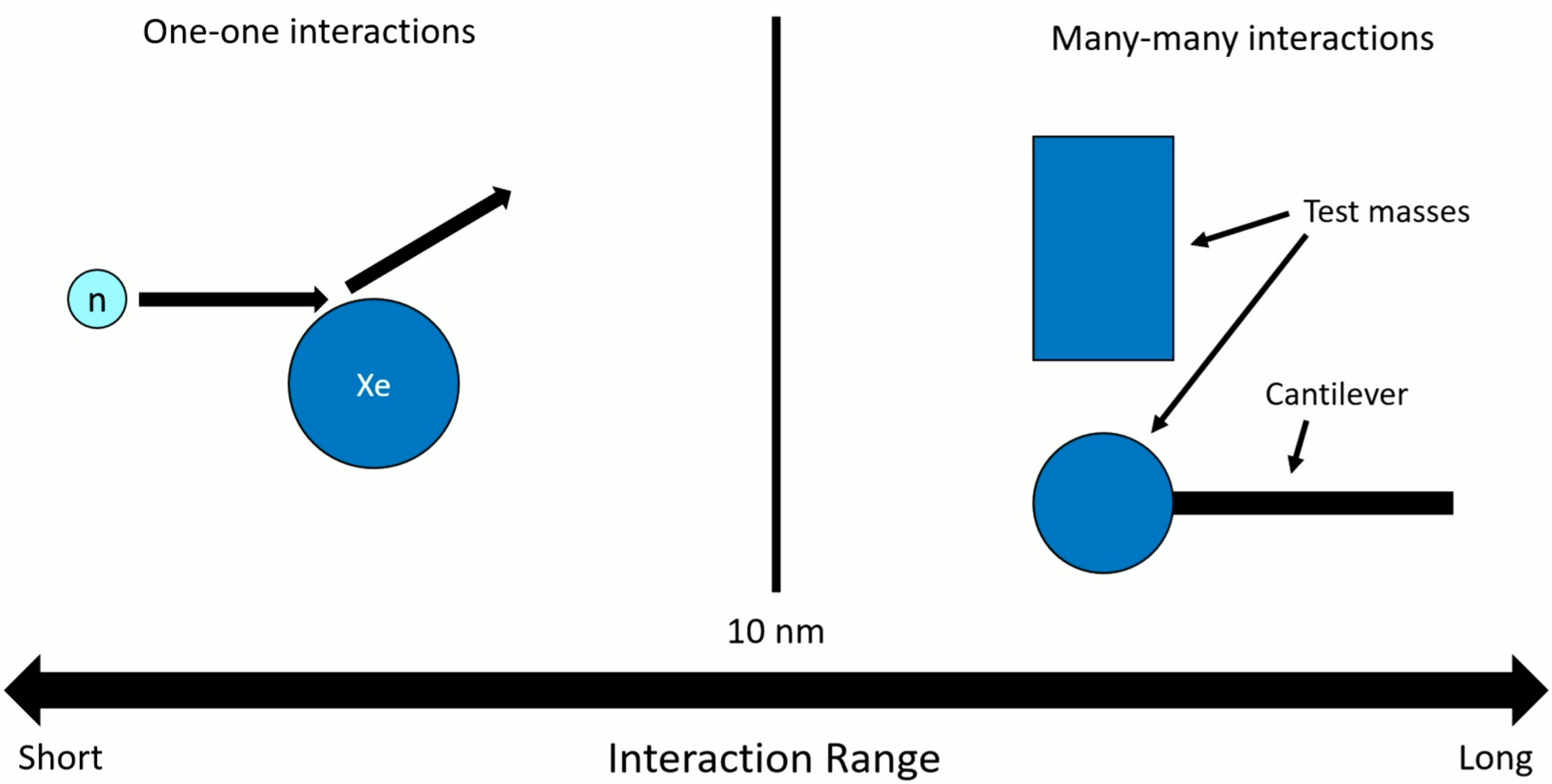
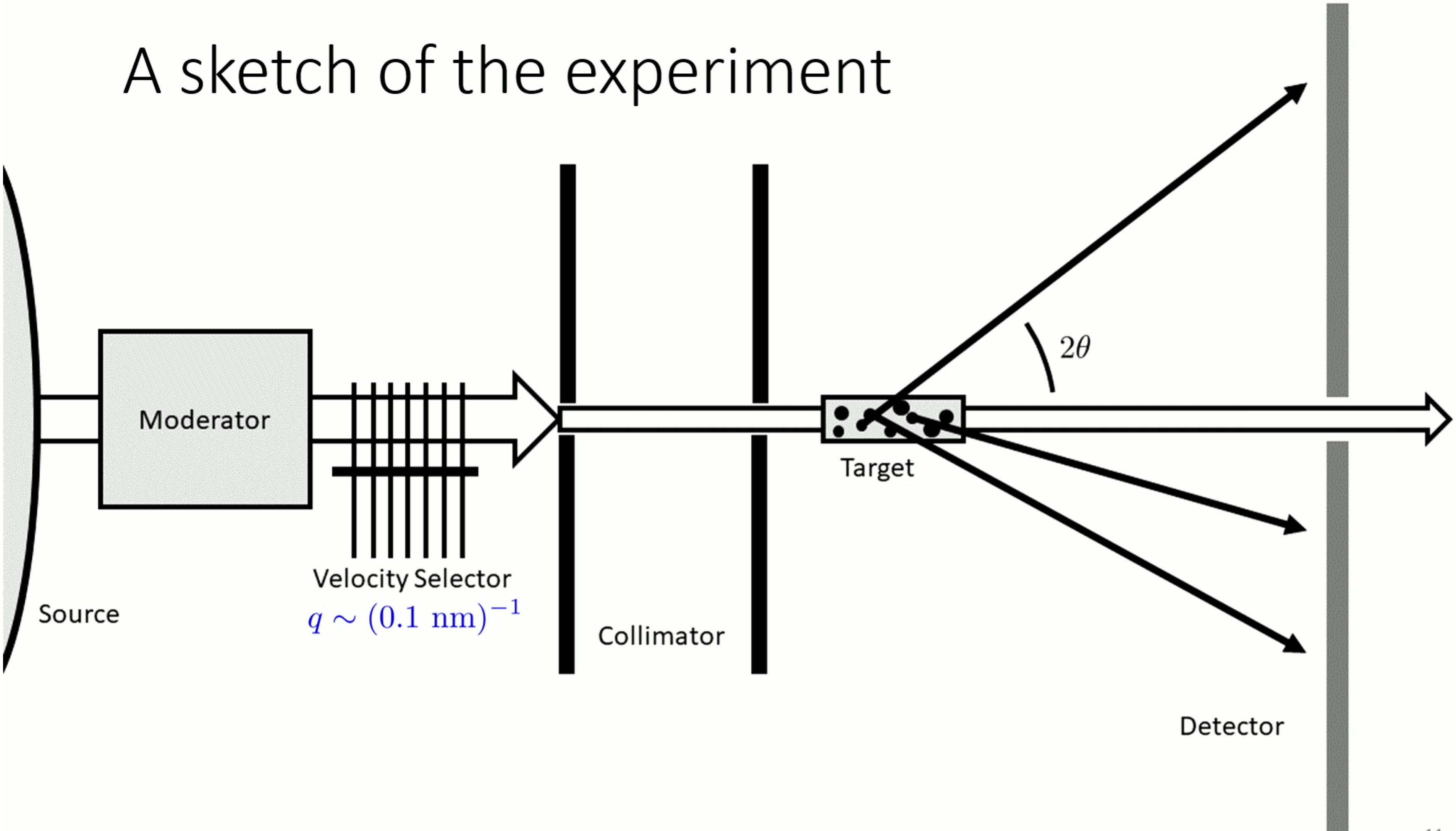
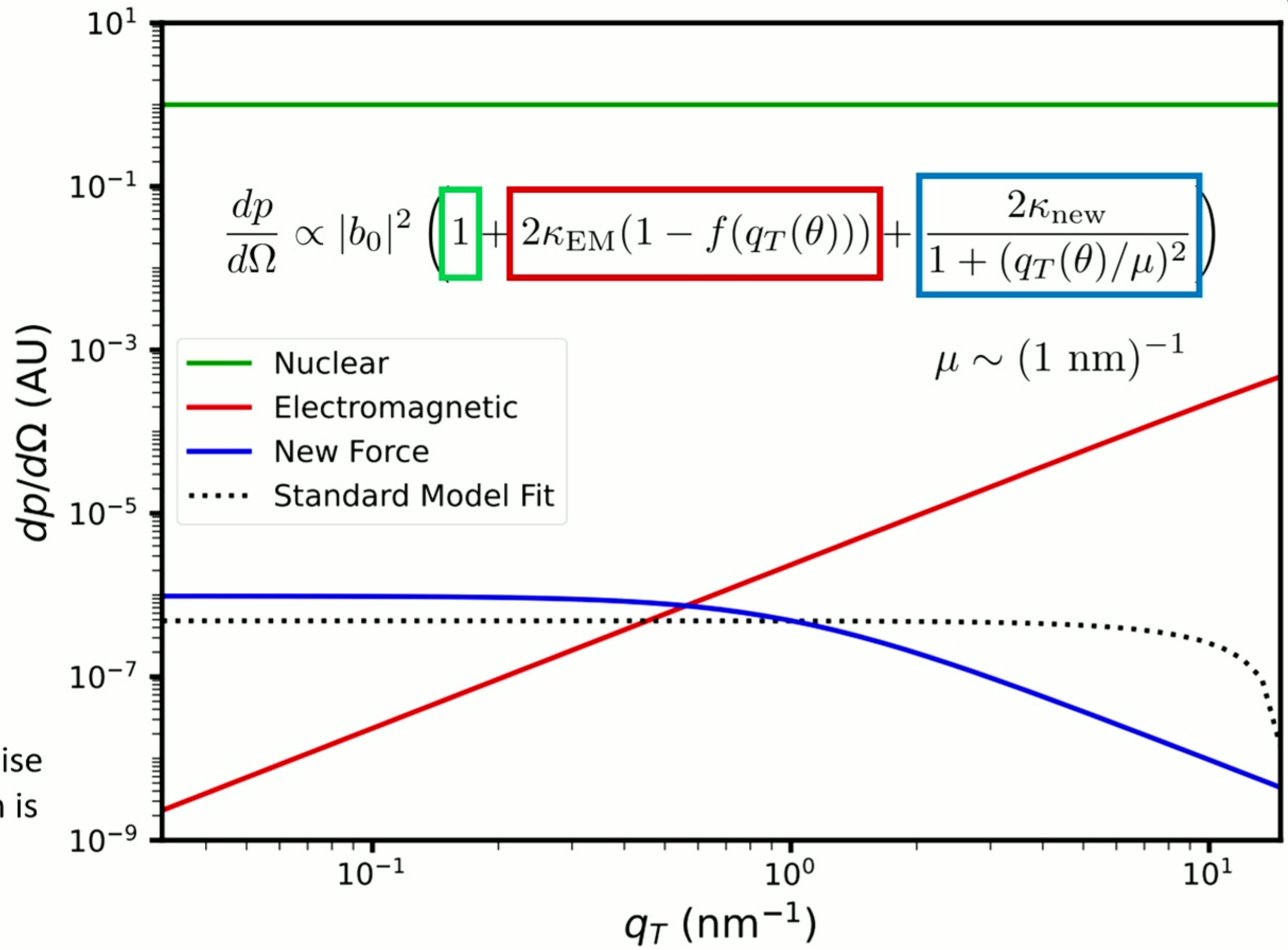
Single-particle versus collective interactions



A sketch of the experiment

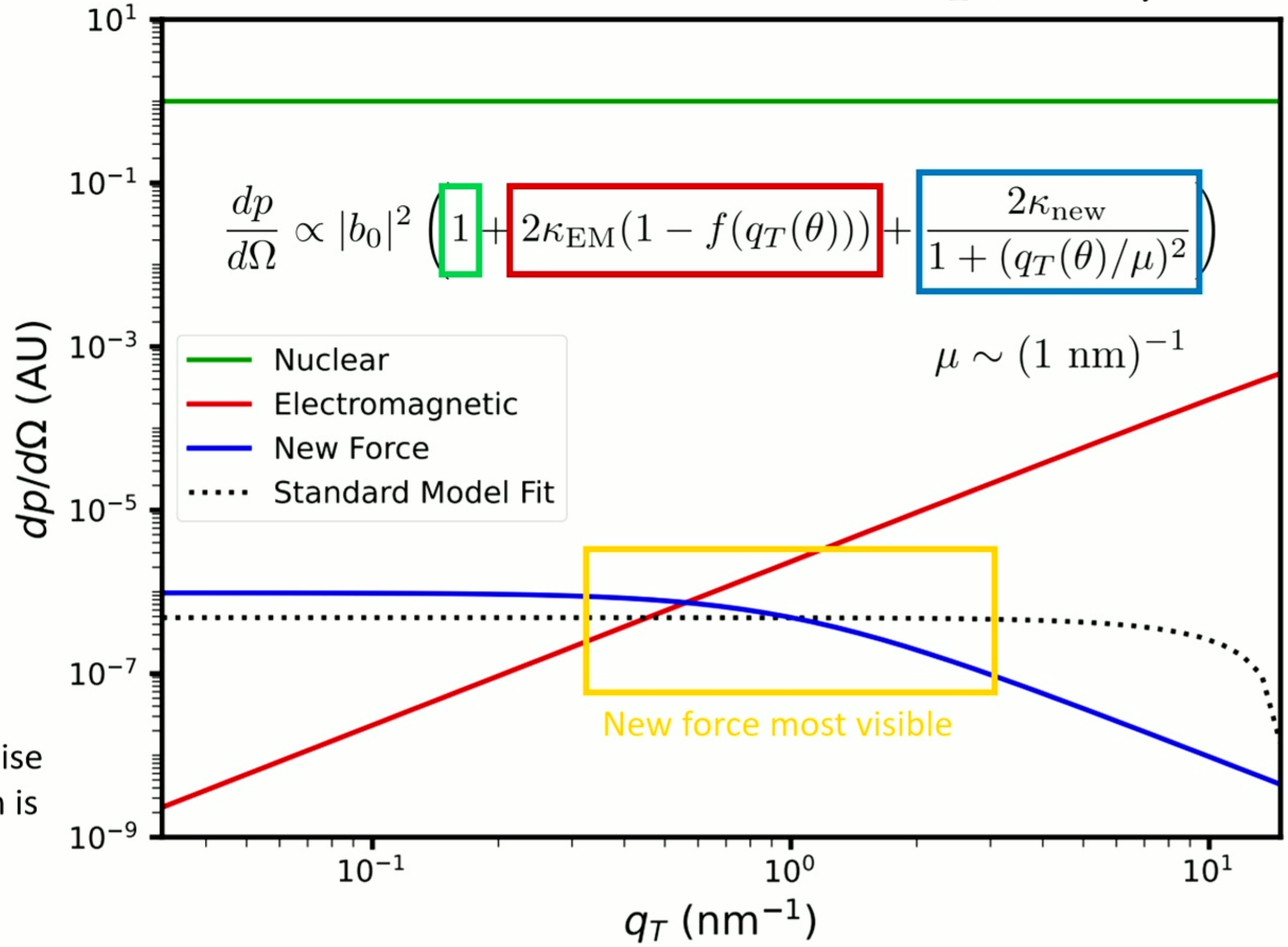


Three main sources of neutron scattering



Plot is for noble elements: otherwise electromagnetism is much more complicated

New forces are most visible at $q_T \sim \mu$



Plot is for noble elements: otherwise electromagnetism is much more complicated

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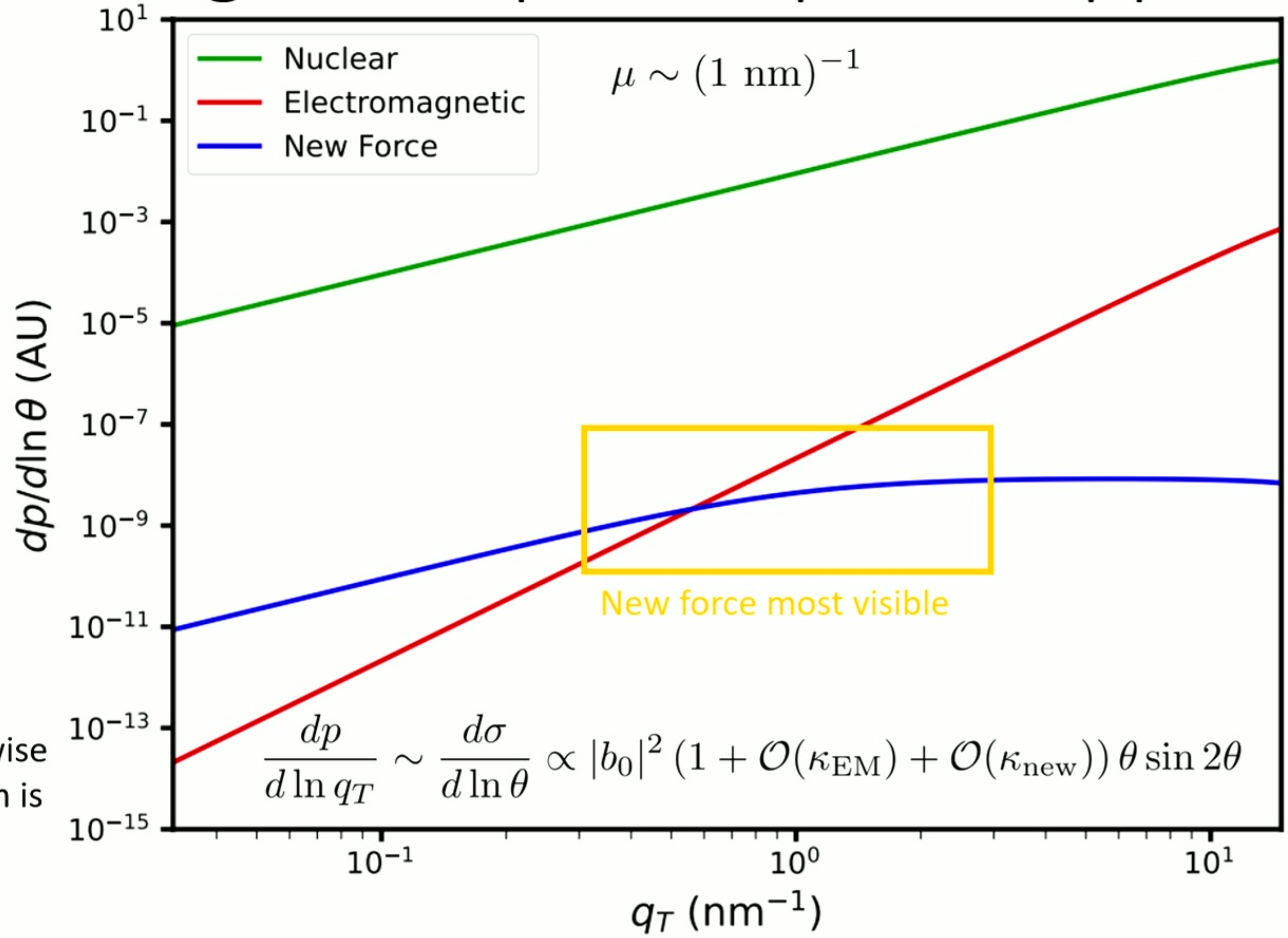
Optimal angles are phase space-suppressed



Plot is for noble elements: otherwise electromagnetism is much more complicated

Background
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Target structure can change scattering distributions

- Each scatterer in the target comes in with a factor of

$$e^{i\mathbf{q}_T\cdot\mathbf{r}}$$

  due to different path lengths

- The total scattering cross-section from a collection of identical scatterers is then proportional to

$$N S(q_T) = \left|\sum_{j=1}^{N} e^{i\mathbf{q}_T\cdot\mathbf{r}_j}\right|^2$$

The "structure factor"

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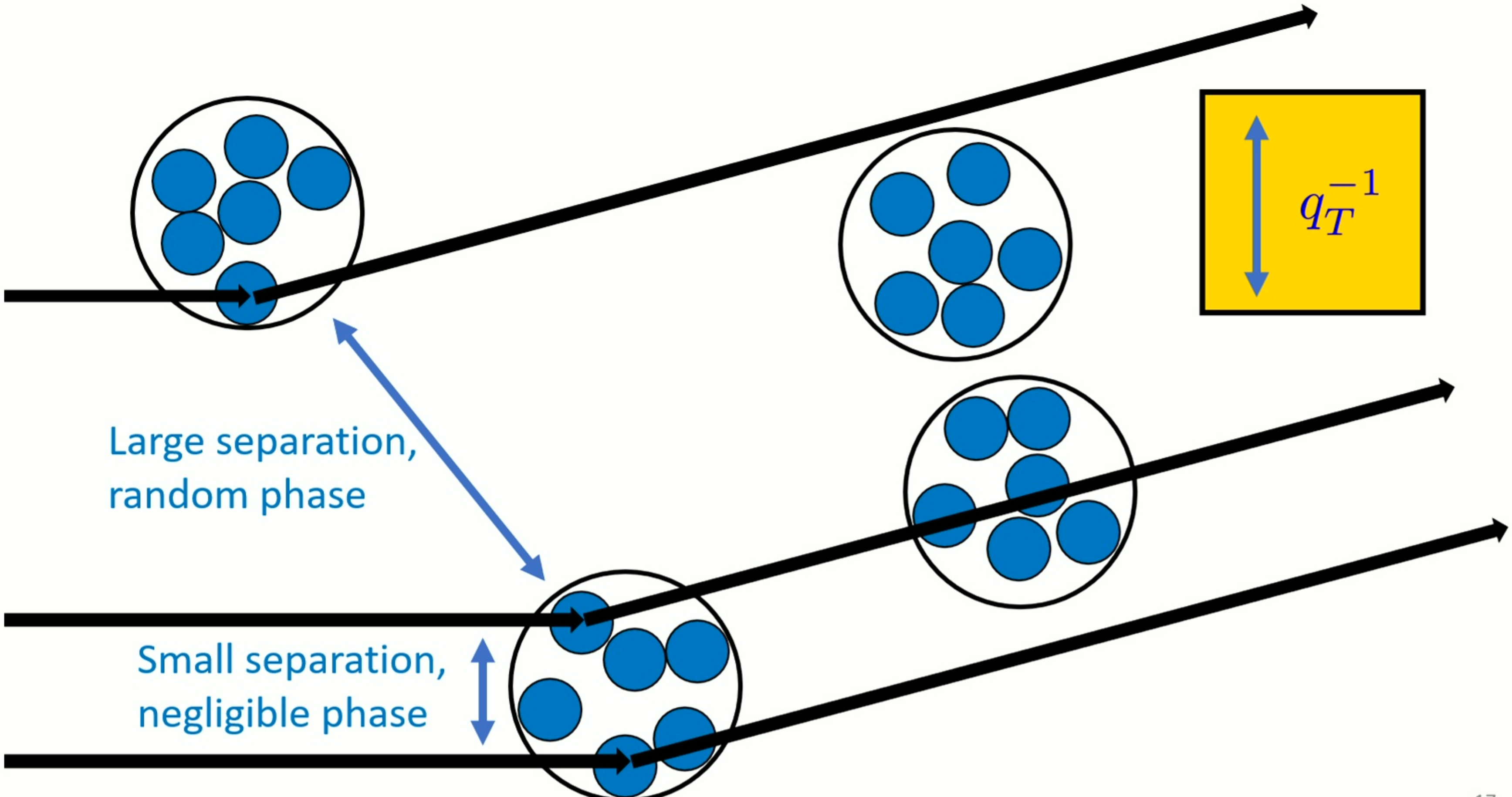
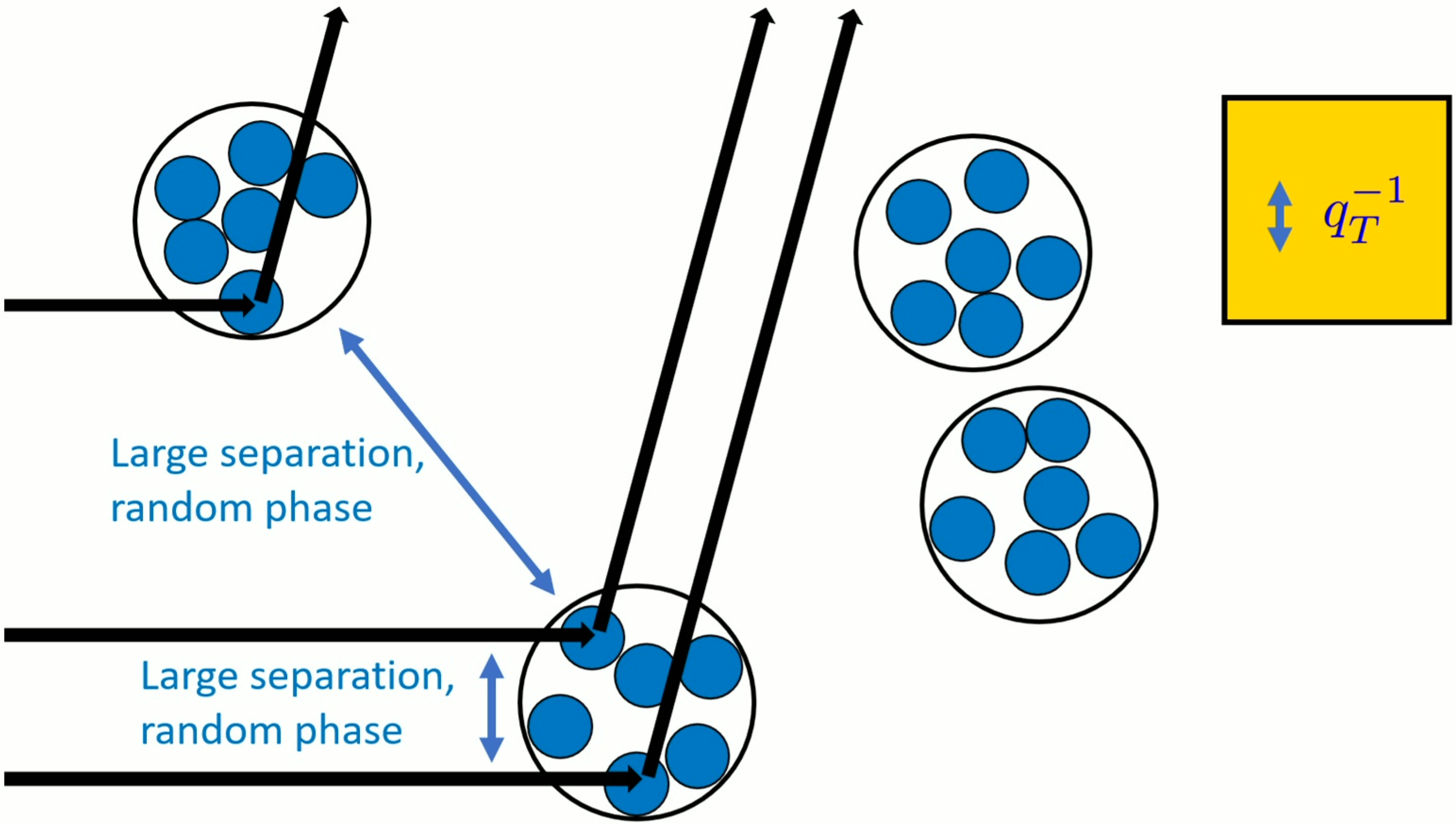
Coherence from separated lengthscales



Coherence from separated lengthscales



Structure factors for uniform spheres: exact form

- The structure factor of a sphere of radius R with number density n is

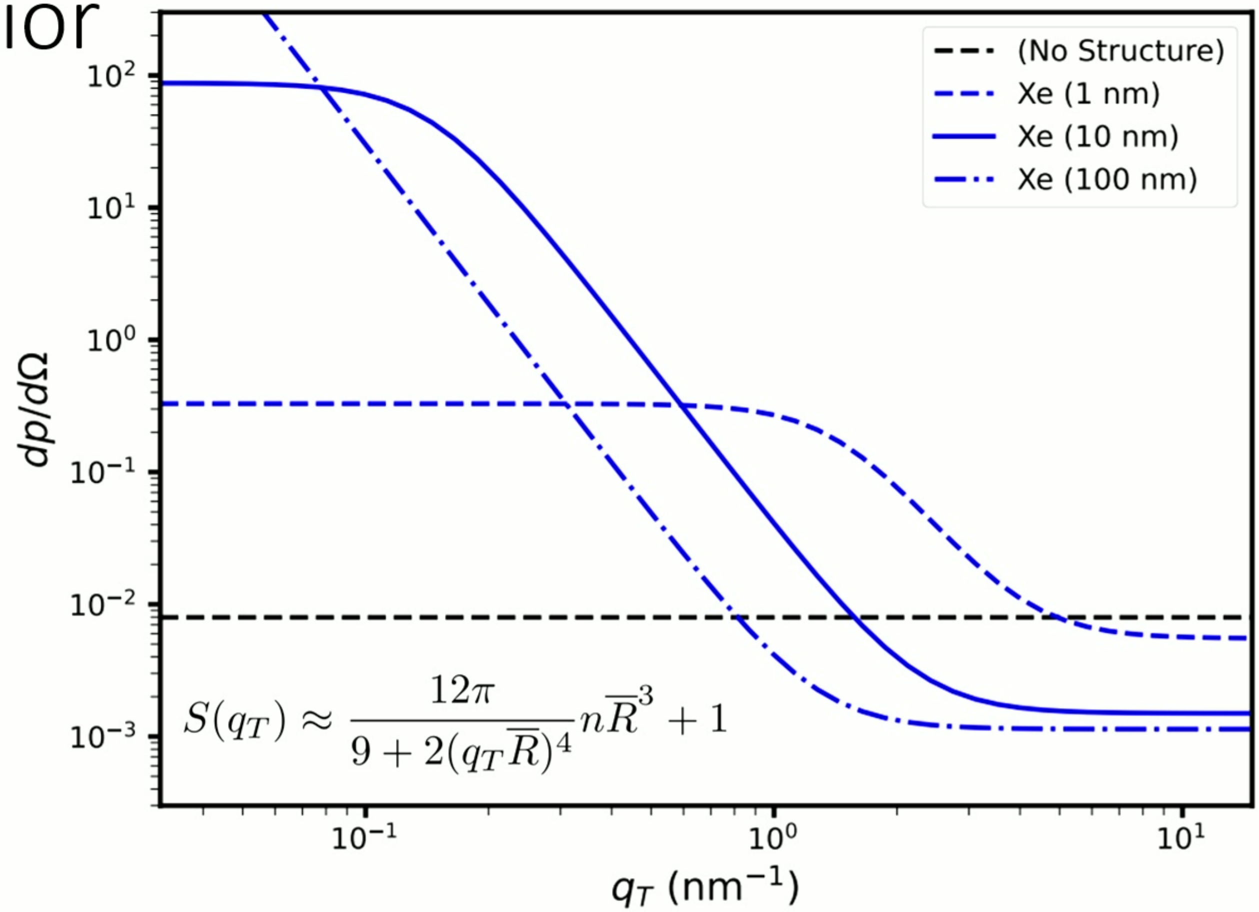
$$S(q_T) = \left(\frac{3(\sin(q_T R) - q_T R \cos(q_T R))}{(q_T R)^3} \right)^2 n R^3 + 1$$

Incoherent scattering

- Averaging over a small spread in radii smooths this to

$$S(q_T) \approx \frac{12\pi}{9 + 2(q_T \overline{R})^4} n \overline{R}^3 + 1$$

Structure factors for uniform spheres: scaling behavior



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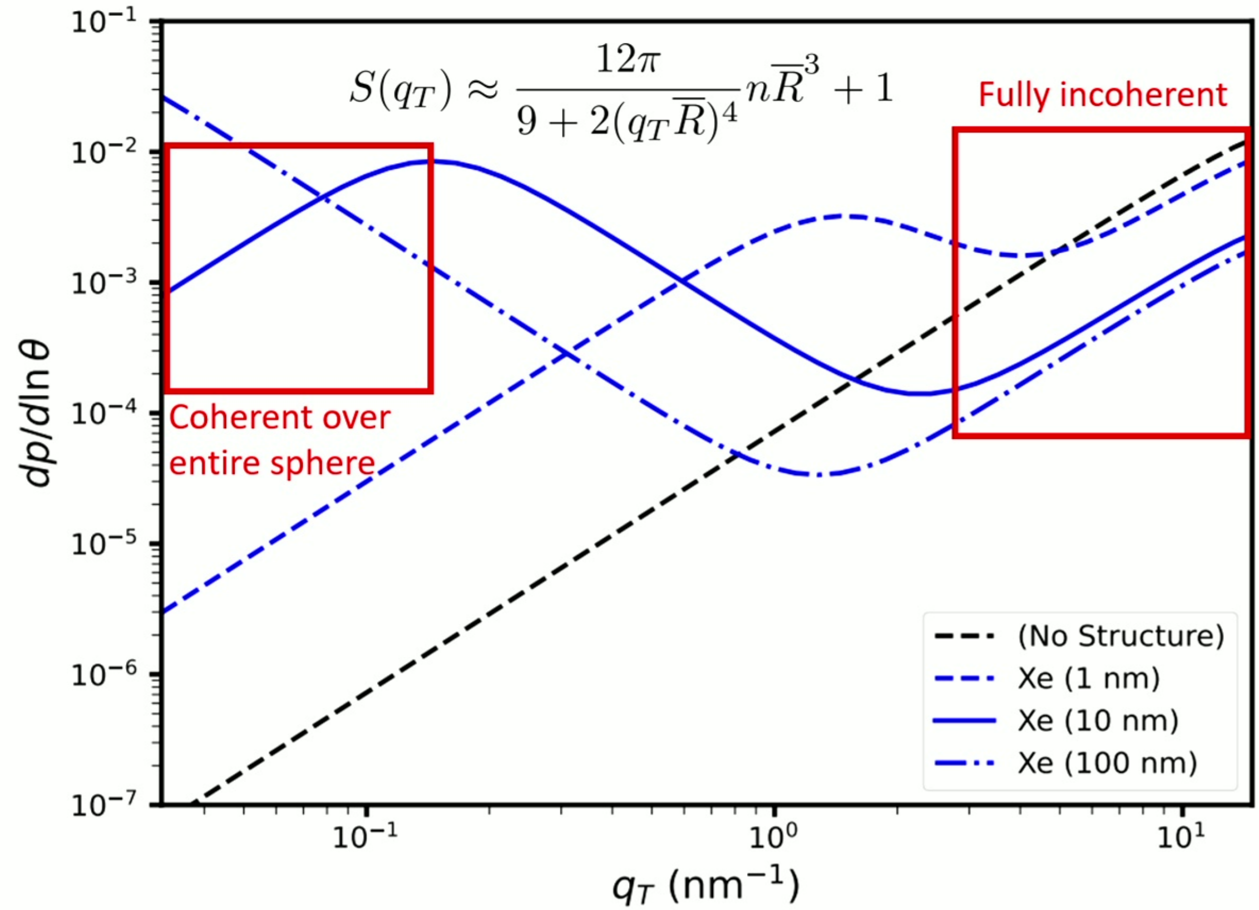
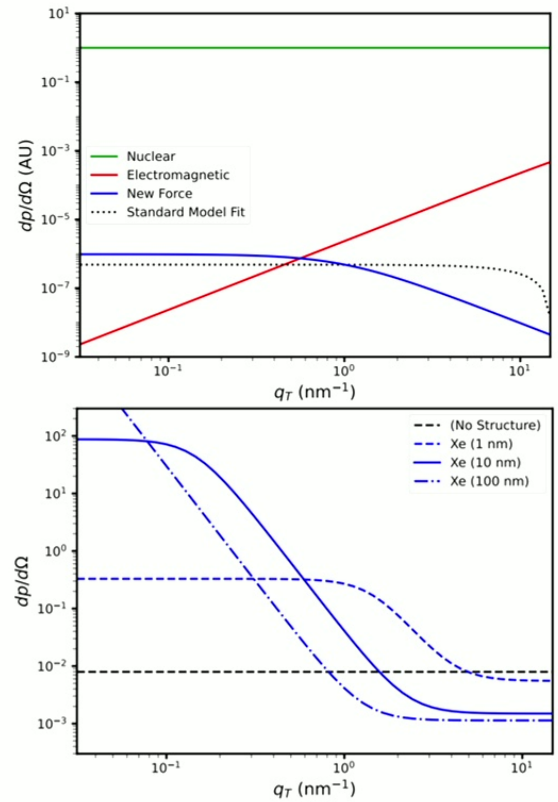
Structure enhances low-angle scattering



The problem: how do you distinguish a new force from a change in the structure factor?

- Both new forces and structure factors look like low-angle bumps
- No way to know the structure factor *a priori*
  - In fact, a typical use of neutron scattering is to measure structure factors



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The solution: X-ray scattering

- Can perform the same measurements with X-rays
- X-ray scattering distributions will be proportional to the same structure factor
  - Structure factors are a property of geometry alone
- Then look at

$$\underbrace{\frac{dp_{n,s}}{dq_T}\left(\frac{dp_{X,u}/dq_T}{dp_{X,s}/dq_T}\right)}_{\text{Measurable}} = \frac{dp_{n,u}}{dq_T}$$

Compare to prediction

Background

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Two-Material

Single-material target candidates

- Noble "snow"
- Aerosols
- Boiling liquids

Image from https://www.youtube.com/watch?v=QtDPv637KHY&ab_channel=AttilaDobi , from Carter Hall's group at UMD

Background

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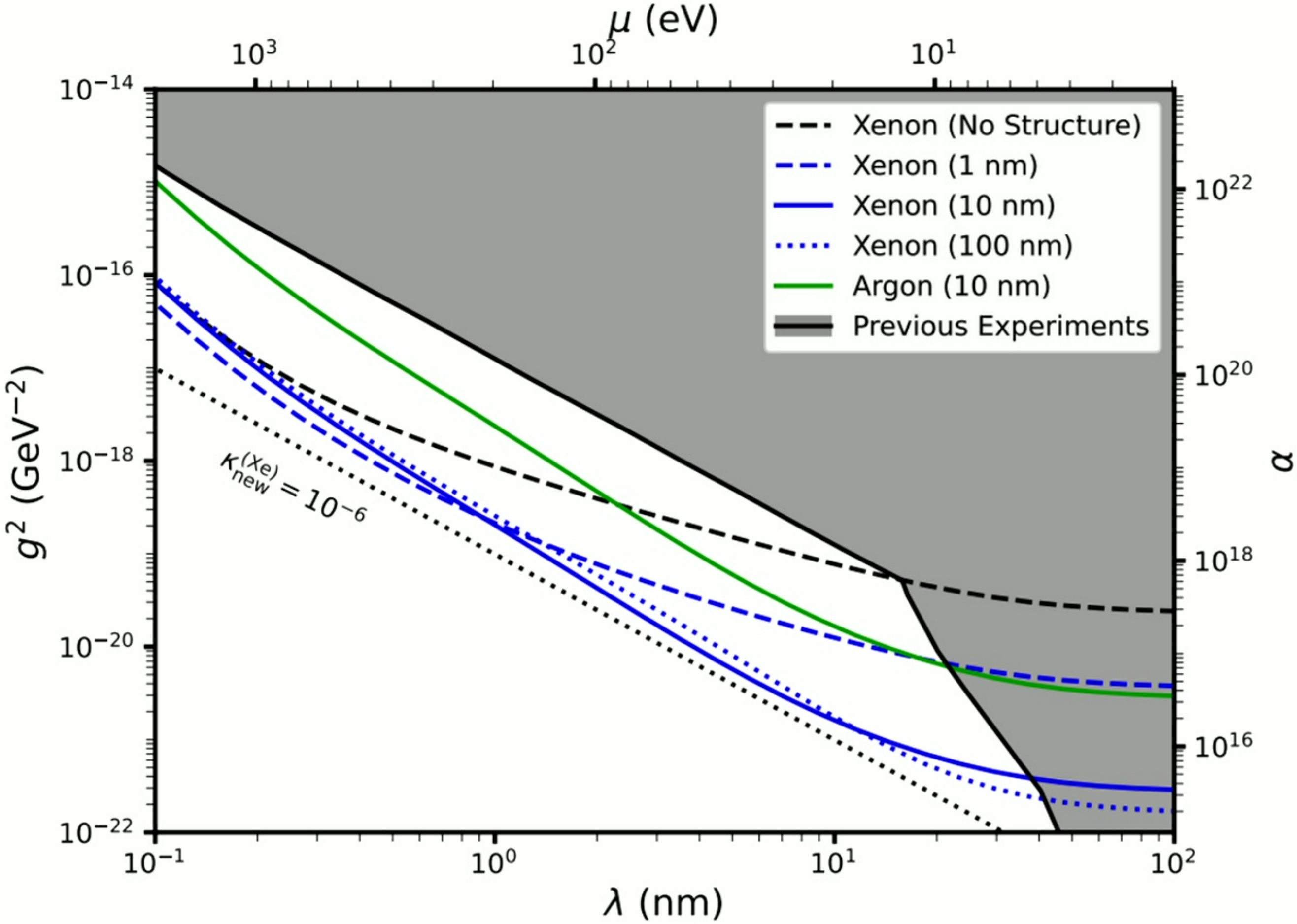
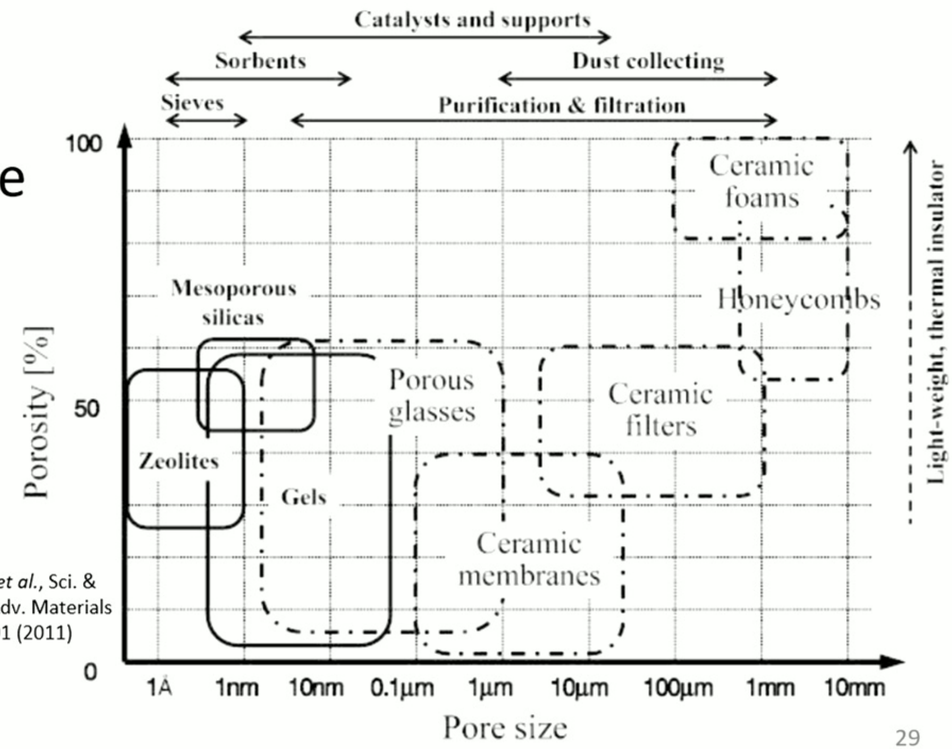
Two-Material

Projected sensitivity: single-material targets



Two-material targets: less effective but more certain

- Noble elements have simpler electromagnetic scattering, but giving them structure is hard
- However, many other solids have structures of the right size; can then add noble gas to them
- Two broad categories:
  - Porous
  - Granular



K. Okada *et al.*, Sci. & Tech. of Adv. Materials **12**, 064701 (2011)

Background

Single-Material

Two-Material

Structure factors for two-material targets: contrast dependence

- Coherent scattering depends only on the "scattering length density," or "SLD" of a material:

$$\mathcal{S}(q_T) := \sum_j n_j b_j(q_T)$$

- Structure factors thus depend only on the contrast between the SLD of different regions:

$$S(q_T) \approx \frac{12\pi\overline{R}^3}{9 + 2(q_T\overline{R})^4} \left(\frac{f\,|\Delta\mathcal{S}|^2}{f n_g |b_g(\mathbf{q}_T)|^2 + (1-f)\sum_j n_{s,j} |b_{s,j}(\mathbf{q}_T)|^2} \right) + 1$$

Two-material target candidates

Material	b_c (fm)	n_{liquid} (nm^{-3})	$\text{SLD}_{\text{liquid}}$ (fm nm^{-3})
He-4	3.3	22	72
Ne-20	4.6	37	170
Ar-36	25	21	530
Kr-86	8.1	18	140
Xe-136	9.0	14	120
Material	b_c^{unit} (fm)	n^{unit} (nm^{-3})	SLD_{max} (fm nm^{-3})
SiO_2	16	27	420
Al_2O_3	24	24	580
$Al_2Ti_3O_9$	49	5.6	275
$BaTiO_3$	19	15	290
CeO_2	16	25	410
CNTs	6.7	100	670

Background

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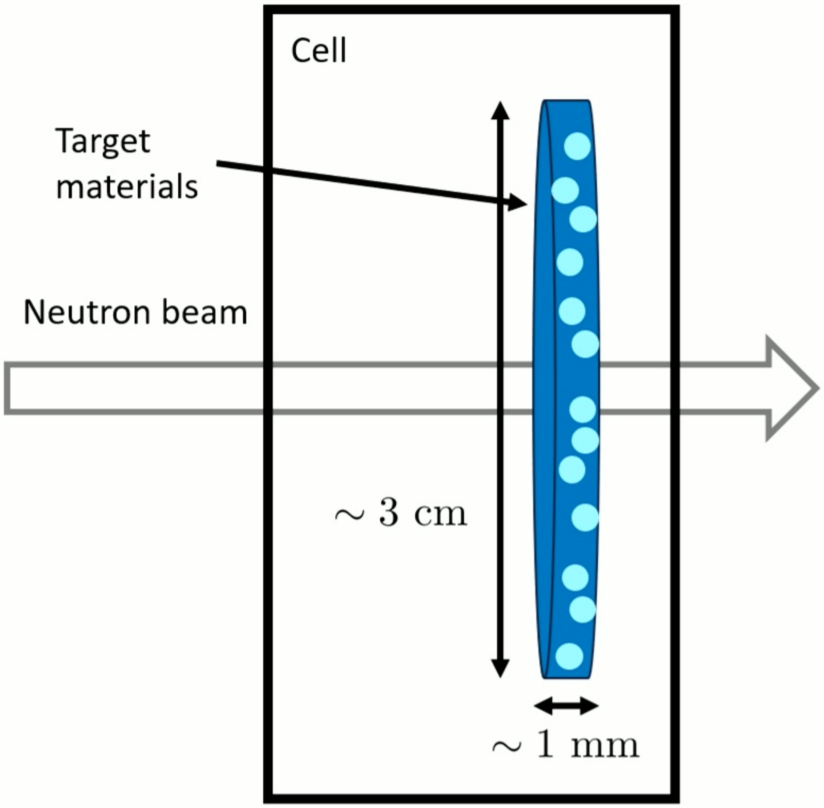
Two-material target geometry



- Liquid xenon: $-110^{\circ}\mathrm{C},\ 1\ \mathrm{atm}$
- Liquid argon: $-190^{\circ}\mathrm{C},\ 1\ \mathrm{atm}$

- Both dense: $-100^{\circ}\mathrm{C},\ \ \sim 100\ \mathrm{atm}$
  - (e.g. $< 1\ \mathrm{cm}$-thick aluminum)

- Cell windows need to have no structure at 10 nm scales.

Distinguishing new forces from two-material structure factors is difficult…

- Tempting to simply subtract solid-only scattering from combined target scattering

- This doesn't work: can only measure scattering *probabilities* of different targets, but there's interference between *amplitudes*

$$\frac{d\sigma}{d\Omega} = \left|\sum_g b_g(\theta)e^{i\mathbf{q}\cdot\mathbf{r}} + \sum_s b_s(\theta)e^{i\mathbf{q}\cdot\mathbf{r}}\right|^2$$
$$\neq \left|\sum_g b_g(\theta)e^{i\mathbf{q}\cdot\mathbf{r}}\right|^2 + \left|\sum_s b_s(\theta)e^{i\mathbf{q}\cdot\mathbf{r}}\right|^2$$

Background

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Distinguishing new forces from two-material structure factors is difficult… but possible

- Can still obtain noble element scattering distribution through a combination of measurements using two different noble gases

	Neutrons	X-Rays
Xenon Alone	✗	✓
Argon Alone	✗	✓
Solid Alone	✓	✓
Solid + Xenon	✓	✓
Solid + Argon	✓	✓

<table>
<tr><th></th><th>Neutrons</th><th>X-Rays</th></tr>
<tr><td>Xenon Alone</td><td colspan="2" rowspan="2">2x Atomic Form Factor</td></tr>
<tr><td>Argon Alone</td></tr>
<tr><td>Solid Alone</td><td colspan="2">2x Scatter Len.</td></tr>
<tr><td>Solid + Xenon</td><td colspan="2" rowspan="2">1x Struct. Fact., 2x Phase</td></tr>
<tr><td>Solid + Argon</td></tr>
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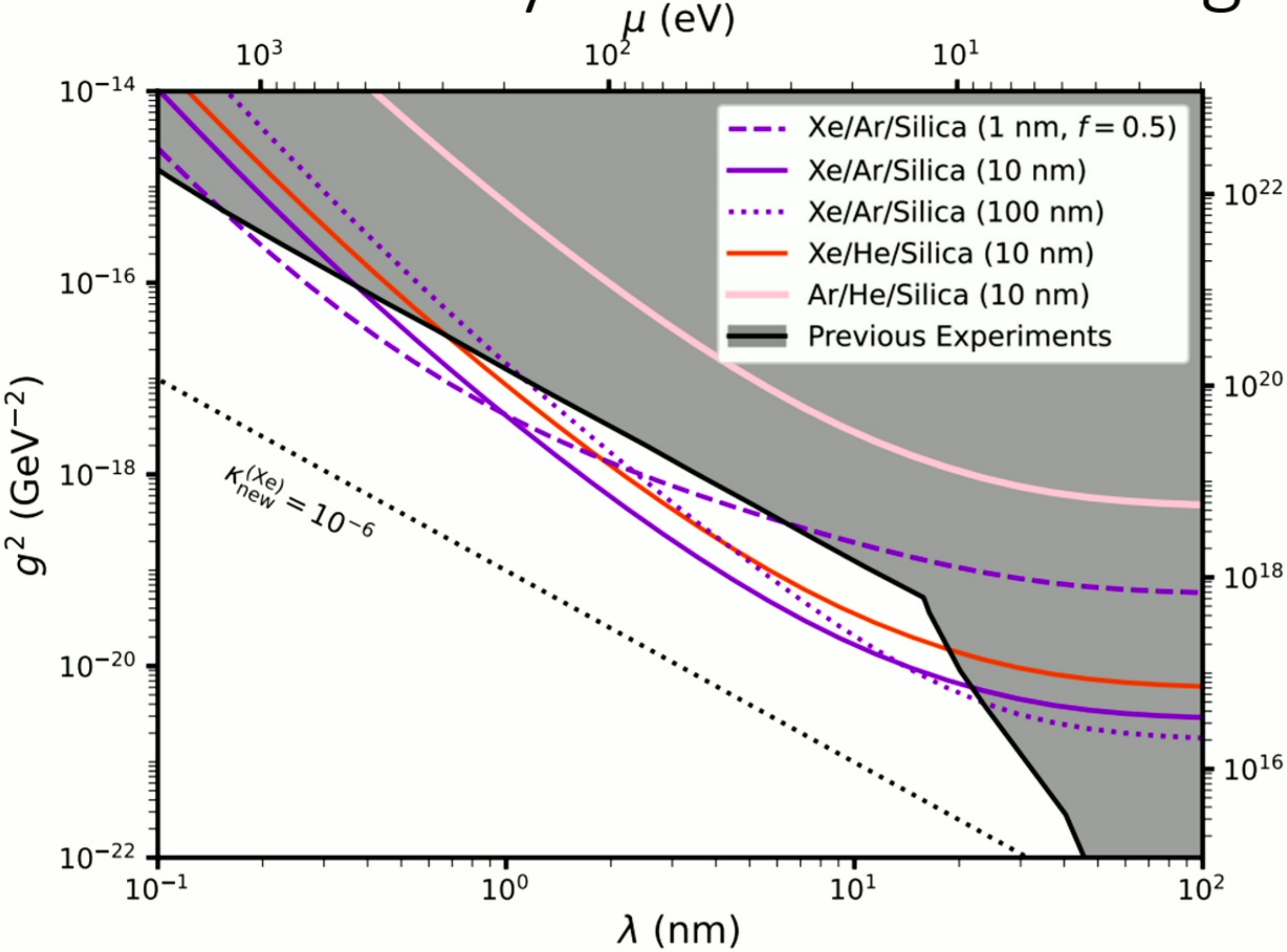
Projected sensitivity: two-material targets



Background

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Astrophysical constraints on new forces

- New scalars could radiate from stars, increasing their cooling rates
- Relevant for masses $\mu \lesssim T_{\text{core}} \sim 10^4\ \text{eV}$
- Model-dependent:
  - B-coupled scalars $g^2 \lesssim 10^{-24}$
  - (B-L)-coupled scalars $g^2 \lesssim 10^{-30}$
  - Extra dimensions not constrained
  - Etc.

Background
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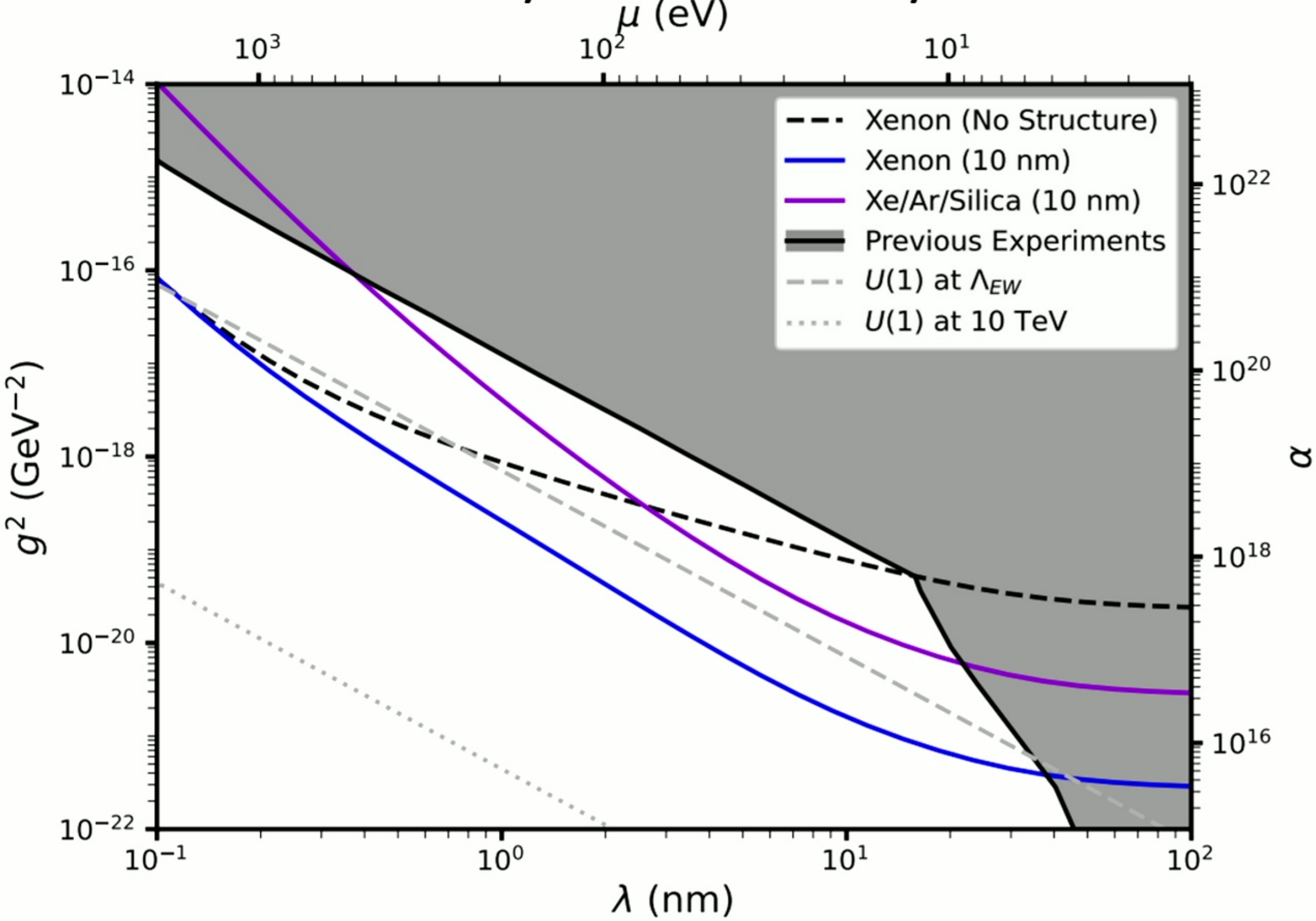
Two-Material

Projected sensitivity: summary



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