DIRECT DETECTION OF CLASSICALLY UNDETECTABLE DARK MATTER THROUGH QUANTUM DECOHERENCE

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Material from arXiv:1212.3061, forthcoming PRD
Slides will be made available at jessriedel.com
Bowling balls and ping-pong balls

- Suppose everything in the universe—including us—were made of bowling balls
- Now suppose we were surrounded by a sea of slow-moving ping-pong balls
  - Could we ever tell?
- Is it possible to influence without being influenced?
What are the limits on experimental physicists for identifying “sectors” of the universe to which we are weakly coupled?

- Dark matter
- Supersymmetry
- New neutrinos
- Mirror matter
- Fifth forces
- …
Outline

Decoherence without classical influence
  Intro to low-mass dark matter
Collisional decoherence by dark matter
  Feasibility and contributing effects
  Dark matter search potential
Conclusions and outlook
Outline

**Decoherence without classical influence**

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- Conclusions and outlook
Collisional Decoherence Observed in Matter Wave Interferometry

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We study the loss of spatial coherence in the extended wave function of fullerenes due to collisions with background gases. From the gradual suppression of quantum interference with increasing gas pressure we are able to support quantitatively both the predictions of decoherence theory and our picture of the interaction process. We thus explore the practical limits of matter wave interferometry at finite gas pressures and estimate the required experimental vacuum conditions for interferometry with even larger objects.

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Matter wave interferometers are based on quantum superpositions of spatially separated states of a single particle. However, as is well known, the concept of wave-particle duality does not apply to a classical object which by definition never occupies macroscopically distinct states simultaneously. By performing interference decoherence effects were not observed in these experiments, since the detected atoms did not change the state of the colliding gas sufficiently to leave behind the required path information for decoherence. In contrast to that, our experiment uses massive C$_{70}$-fullerene molecules, and is based on a Talbot-Lau interferometer
Collisional decoherence in experiment

- **Molecule being interfered:**
  - Carbon fullerene ($C_{70}$)
  - 840 amu

- **Molecule causing decoherence:**
  - Methane ($CH_4$)
  - 16 amu

- **Deflection of much heavier fullerenes is small**
Collisional decoherence in experiment

Key idea: varying gas pressure in experiment controls interference fringe visibility

Collisional decoherence in experiment

Visibility and count rate fall exponentially

- Visibility *and* count rate fall exponentially
- Sufficiently dense methane knocks fullerenes out of experiment

Visibility = \frac{amplitude}{average}

Limits of detection

- But what if we dial down the mass of methane molecules while holding their velocity constant?
  - Increasing methane density still suppresses interference visibility
  - Fullerenes are undeflected
  - Count rate remains constant
- This naturally suggests the massless limit
- Apparently, we can detect the presence of arbitrarily light particles transferring arbitrarily little momentum and energy
- Quantum measurements can detect particles which are classically undetectable
Bowling-ball interferometry
Outline

Decoherence without classical influence

**Intro to low-mass dark matter**

Collisional decoherence by dark matter

Feasibility and contributing effects

Dark matter search potential

Conclusions and outlook
Basic dark matter

- Many observations suggest new, non-baryonic form of gravitating matter
- Evidence comes from sub-galactic scales and above, e.g.
  - Galactic rotation curves
Basic dark matter

- Many observations suggest new, non-baryonic form of gravitating matter
- Evidence comes from sub-galactic scales and above, e.g.
  - Galactic rotation curves
  - Bullet cluster
X-ray emissions [Interstellar hydrogen: normal matter (90%)]
Gravitational lensing [Mass density: dark matter]

Basic dark matter

- Many observations suggest new, non-baryonic form of gravitating matter
- Evidence comes from sub-galactic scales and above, e.g.
  - Galactic rotation curves
  - Bullet cluster
  - Large-scale structure
Basic dark matter

- All evidence is essentially gravitational
- Many, many competing ideas
- Candidate explanations must satisfy a wide range of experiments and observations stretching back decades
  - Many indirect, model-dependent restrictions
- Relatively few model-independent results
The dark matter halo

- But we have a **generic** local prediction: roughly spherical, virialized halo of dark matter enveloping the Milky Way
  - Isotropic in galactic rest frame
  - Maxwellian velocity distribution
  - Local density $\sim 0.4$ GeV/cm$^3$
  - Typical velocity $\sim 230$ km/s
- Assumed for limits set by underground detectors
- Based only on local, present-day observation
  - (no cosmology necessary)

Image source: European Southern Observatory (artist impression, duh)
Conventional direct dark matter detection

- Preferred method...
  - Get a big container full of normal matter (e.g. liquid xenon)
  - Squint your eyes and look really closely at it
  - Witness dramatic nuclear recoil!
  - Enjoy wild fame and accolades

- More often: establish new exclusion limits
  - $\rho_{DM}$ and distribution of $\nu_{DM}$ fixed
  - Any choice of $m_{DM}$ sets number density and flux
  - Count number of nucleons in container and exposure time without scattering event
  - Sets limit on the nucleon-dark matter cross-section $\sigma$
  - Usually spin-independent, elastic scattering
  - Key plot: $m_{DM}$ vs. $\sigma$
Limits evaporate for dark matter masses below a GeV.
Limits of conventional direct detection

- Conventional experiments are blind below 1 GeV
- Lee-Weinberg bounds WIMPs as $m_{DM} \gtrsim 2$ GeV
- But experimental exclusions on traditional WIMPs are becoming uncomfortable
  - See recent LUX results
- Many proposed sub-GeV models are not constrained by Lee-Weinberg bound
- Can we look for lighter masses?
Detecting low-mass dark matter

- Nucleons masses are $M \sim 1$ GeV
- Energy transfer goes like $\sim \frac{m_{DM}^2 v_{DM}^2}{M}$

- Minimum sensitivity of experiments $\sim 1$ keV energy transfer
- Corresponds to $M \sim m_{DM}$
- A 1 MeV dark matter candidate deposits $10^{-3}$ eV
- A 1 keV dark matter candidate deposits $10^{-9}$ eV
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Alternative: detection through decoherence

- Initial state: \[ |N_L N_R⟩ |N_R⟩ |D_{in}⟩ \]
- Final state: \[ |N_L⟩ |D_{out}^{(L)}⟩ + |N_R⟩ |D_{out}^{(R)}⟩ \]
- Measurement: \( \{ |N_{\pm}⟩ = |N_L⟩ ± |N_R⟩ \} \)

\[ \langle D_{out}^{(L)} | D_{out}^{(R)} \rangle \approx 0 \]
Collisional decoherence by dark matter

- Strength of suppression depends on quality of “which-path” information recorded in the dark matter out states

- **Full information:** \( \langle D^{(L)}_{\text{out}} | D^{(R)}_{\text{out}} \rangle \approx 0 \)
  - Complete decoherence
  - Short-wavelength dark matter
  - Zero interference visibility
  - One scattering event required

- **Minimal information:** \( \langle D^{(L)}_{\text{out}} | D^{(R)}_{\text{out}} \rangle \approx e^{-\epsilon N} \)
  - Minimal decoherence
  - Long-wavelength dark matter
  - Slight suppression of interference visibility
  - Many scattering events required
Collisional decoherence

- We consider a single nucleon placed in a superposition of two localized wavepackets
  - Separated by a distance $\Delta x$
  - Exposed to dark matter for a time $T$
Collisional decoherence

- Collisional decoherence is well-known
- Final state in \(|\mathcal{N}_L\rangle, |\mathcal{N}_R\rangle\) basis will be

\[
\rho_N = \frac{1}{2} \begin{pmatrix} 1 & \gamma \\ \gamma^* & 1 \end{pmatrix} \text{ where } \gamma = \exp \left[ - \int_0^T dt F(\Delta \vec{x}) \right]
\]

and

\[
F(\Delta \vec{x}) = \int d\vec{q} \, n(\vec{q}) \frac{q}{m_{DM}} \int d\vec{\hat{r}} \left\{ 1 - \exp[i(\vec{q} - q\vec{\hat{r}}) \cdot \Delta \vec{x}] \right\} |f(\vec{q}, q\vec{\hat{r}})|^2
\]

“Decoherence rate” (Hz)
“Decoherence factor” (dimensionless)
Differential cross-section

Dark matter momentum
Momentum out states
Set by overlap of out states

Dark matter phase space density
Calculating strength of decoherence

- Decoherence is effective when

\[ \text{Re } F(\Delta x) \gg 1/T \]

- Must assume form of scattering cross-section to calculate

- Assume s-wave scattering, no strong momentum dependence
  - S-wave expected to dominate partial-wave expansion unless dark matter interacts through long-range force
  - Modifying angular cross section gives only order-unity correction (see paper for details)
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Feasibility

- Obvious problem #1: How to tell anomalous decoherence is really dark matter?
  - Let’s postpone this question for a few slides

- Obvious problem #2: Dark matter collisions are very rare
  - Conventional experiments looks for handful of collisions amongst $10^{28}$ nucleons exposed for $10^6$ seconds!
  - Is it really feasible to look at $10^0$ nucleons exposed for $10^0$ seconds?
  - For 10 eV - 100 MeV, existing experimental limits are between $10^{21}$ and $10^{29}$ times weaker than for 10 GeV - 1000 GeV!

- Still not enough...
Massive superpositions

- Profound property of decoherence: it only takes a single environmental particle to decohere an \textit{arbitrarily} large object
- If you can put a large object into a superposition, the dark matter can scatter off of \textit{any} of the nucleons
- Effective decoherence factor is raised to the power $N$ (number of particles)
  - Decoherence rate increases proportional to $N$
  - Sensitivity increases proportional to $N$
- But creating large superpositions is too hard, right? Won’t $N$ always be small, or unity?

(Teaser: this is an example of the “decoherent Heisenberg limit” of matter interferometry!)
Matter interferometry

- No! Modern matter interferometry is incredible!
- Experiments in Vienna have superposed molecules of almost $10^4$ amu
- The next generation of interferometers should tickle $10^7$ amu
- That’s not all...

Coherent elastic scattering

- When the de Broglie wavelength of the dark matter is larger than distance between nucleons, it scatters coherently
  - Well known from X-ray and neutron small-angle scattering and (futile) investigation of relic neutrino detection
- Dark matter doesn’t scatter off of any single nucleon, it scatters off of all of them
- This decreases energy transfer but increases scattering rate
- Yields additional boost of factor $N$
Coherent elastic scattering

- For $m_{DM} < \text{GeV}$, dark matter is always scattering coherently within nucleus
- For $m_{DM} \sim \text{MeV}$, starts scattering coherently across *multiple* nuclei
- For $m_{DM} < \text{keV}$, scatters coherently over most objects we will ever be able to superpose anytime soon
- In intermediate region, there are complicated interference effects (constructive and destructive)
- Good approximation: boost is proportional to number of nucleons in “coherent scattering volume” $\lambda^3$
  - See paper for details
Dark matter wind

- Dark matter velocity distribution is roughly thermal and isotropic in galactic rest frame
- Typical speed of dark matter particle and Earth’s speed as the Sun orbits the galaxy are about the same: 230 km/s
- Observers on Earth experience apparent dark matter “wind” opposite Earth’s motion in galaxy
- This leads to phase shift in interferometer

(Teaser: smooth link between “decoherent quantum enhanced measurement” and conventional, unitary QEM!)
Anomalous decoherence

- There are many possible sources of decoherence
- Massive challenge of interferometry is identifying and defeating one level of decoherence after another
- Anomalous decoherence does not imply dark matter
- However, the inverse statement is true: a successful interferometer implies all sources of decoherence have been eliminated
- This establishes robust dark matter exclusion limits
- But if we think anomalous decoherence might be due to dark matter, how could we be sure?
Establishing convincing evidence

- Try varying experimental parameters, e.g.
  - Spatial extent of the superposition (distance between arms)
  - Exposure time (length of arms, or speed)
  - Elemental composition object
  - Isotopic composition of elements

- General sources of decoherence will not have same dependence on these parameters
Establishing convincing evidence

- Try varying expected dark matter flux
  - Shield experiment from dark matter (concrete, lead, underground)
  - Strength of dark matter wind will vary by several percentage points over the year due to Earth’s motion around the sun

- When dark matter wavelength isn’t too short, the orientation of the interferometer arms will give order-unity change
  - Interferometers are naturally *directional* dark matter detectors!
  - They can unambiguously identify a signal possessing a fixed direction in the galaxy!
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Low-mass dark matter

- Concentrate on $m_{DM}$-$\sigma$ plane
- Lower bound: $10 \text{ eV} < m_{DM}$
  - Any lower and occupation number approaches unity
  - Would have to be bosonic, and coherent wave effects would become important
- Upper bound: $m_{DM} < 100 \text{ MeV}$
  - Any higher and conventional detection methods will be more effective
- Above 1 GeV, cross-section experimentally constrained to be very low
- But for low-mass dark matter, constraints are very weak
Existing generic constraints

- Only direct detection constraints below 100 MeV come from the X-ray Quantum Calorimetry (XQC) experiment
  - Flew on sounding rocket to ~ 200 km
  - Measures energy from multiple collisions, so lower threshold
- The other generic constraint arises from requiring...
  - Stability of the dark matter halo from collisions with the Milky Way disk and
  - Consistency with temperature of interstellar hydrogen
Existing thermal-scenario constraints

- “Thermal” dark matter is a popular property for many dark matter models (e.g. WIMPs)
  - Dark matter particle was in thermal equilibrium with rest of universe at early cosmological times
  - As universe expands, density of dark matter drops low enough that interactions become rare
  - Dark matter streams around and clumps into galaxies today

- Thermal dark matter influences many cosmological and astrophysical parameters, giving constraints:
  - Lyman-α forest
  - Large scale structure (LSS)
  - Cosmic microwave background (CMB)
Low-mass dark matter models

- Very little theoretical attention paid to low-mass possibility
  - Generally assumed to be depressingly undetectable
  - Recent increase in model-building, probably due to negative WIMP results

- Best-known toy models are the so-called Strongly Interacting Massive Particles (SIMPs)
  - Characterized by $m_{\text{DM}}/\sigma$ ratio which could help explain so-called “cusp” problem (among others)
  - Not very attractive these days for large masses ($m_{\text{DM}} > \text{GeV}$)
  - Provides good landmark for Not-Totally-Crazy theories
Robustly excluded

Excluded for thermal models

Typical E&M cross section (big)

Plausible landmark
Proposed experiments as benchmarks

- Consider proposals for three next-generation matter interferometers in order to estimate sensitivity to dark matter

- Atomic Gravitational-wave Interferometric Sensor (AGIS) satellite experiment proposal
  - Single atoms (so minimal coherence boost) interfered in open vacuum of space (so no atmospheric shielding)
  - J. Hogan et al. General Rel. Grav. 43, 1953 (2011)
Proposed experiments as benchmarks

- Optical Time-domain Ionizing Matter-wave (OTIMA) Interferometer proposal
  - Improved technology applied to previously mentioned matter interferometry experiment
Atmospheric shielding

- Problem: Atmospheric shielding is a real concern at sea level (~$10^{-27}$ cm$^2$)
  - Can’t look for dark matter if it is stopped by atmosphere

- Alternatives:
  - High-altitude balloon (~30 km, $10^{-25}$ cm$^2$)
  - Sounding rocket (~200 km, $10^{-18}$ cm$^2$)
  - Satellite

- Or, create a superposition so large it’s sensitive to smaller dark matter
  - Not possible for terrestrial experiments in foreseeable future

- For now: assume sounding rocket platform (200 km)
Proposed experiments as benchmarks

- Optically trapped 40 nm silica ‘Nanosphere’ proposal
  - Nanometer sized ball of silicon suspended and brought into superposition optically; very different than traditional interferometry
DECIDE satellite experiment (speculative)

- “Macroscopic quantum experiments in space using massive mechanical resonators”

**Timespan**: $10^3$

**Mass**: $[10^2]^2 = 10^4$

**Displacement**: $[1 - 10^{1.5}]^2 = 1 - 10^3$

**Total**: 7 to 10 orders of magnitude

* Compared to terrestrial ‘Nanosphere’ experiment
DECIDE satellite experiment

“Macroscopic quantum experiments in space using massive mechanical resonators”

- Timespan*: $10^3$
- Mass*: $[10^2]^2 = 10^4$
- Displacement*: $[1 - 10^{1.5}]^2 = 1 - 10^3$
- Total*: 7 to 10 orders of magnitude

* Compared to terrestrial ‘Nanosphere’ experiment
Progress in masses

- Compare to some existing interferometers:
  - Neutron
  - Helium
  - C\textsubscript{70} fullerene
  - PFNS10 (C\textsubscript{60}[C\textsubscript{12}F\textsubscript{25}]\textsubscript{10}; a fullerene derivative)

- Also consider three OTIMA masses:
  - 10\textsuperscript{4} amu (done)
  - 10\textsuperscript{6} amu (hard but likely to be achieved in next few years)
  - 10\textsuperscript{8} amu (not possible on Earth because of gravity; same techniques may work in orbit)
Typical WIMP exclusions

\( \sigma (\text{cm}^2) \)

\( m_{\text{DM}} \) (eV)

(Very preliminary)
Dark matter conclusions

- Next generation of matter interferometers will probably need to get above the atmosphere to see dark matter.
- Rapid improvement in masses superposed translates to squared increases in sensitivity.
- Satellite experiments can open up 5 orders of magnitude in previously inaccessible dark matter masses.
- What if we relax requirement for complete decoherence?
  - Can pick up orders of magnitude with statistics: $\sqrt{M}$ scaling.
**Statistical enhancements:**
- **AGIS:** $\sim 10^{6.3}$
- **OTIMA:** $\sim 10^{4.7}$
- **Nanosphere:** $\sim 10^{3.2}$
- **DECIDE:** $\sim 10^{1.8}$

Typical WIMP exclusions:

![Diagram showing solar neutrino and statistical enhancements](image)
(Super duper preliminary)

Statistical enhancements:
- AGIS: $\sim 10^{6.3}$
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Thomson

Typical WIMP exclusions

$\sigma (\text{cm}^2)$

$m_{DM} (\text{eV})$
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Other types of superpositions

- These are all *free* results from experiments with existing, unrelated motivations
- What happens if experiment were designed explicitly for dark matter?
- What about superconducting qubits?
  - Electron-dark matter scattering cross-section
- Or massive superposed oscillators?
  - Much more mass, but not separated on scale of object
- Normal BEC interferometers don’t work well
  - Not entangled, so no coherence boost
  - Could squeezed states or NOON states?
Other types of searches

- What about axion dark matter?
  - Or other coherent waves of bosons?
- Relic neutrinos?
  - Notoriously tiny momentum transfer
- Graviton existence?
  - Well, not any time soon
  - Relativistic Planck mass superpositions decohere through gravitational bremsstrahlung
  - See arXiv:1310.6347 or bonus slide
Detection through decoherence

• Claim: detecting new particles or forces through decoherence is a fundamentally different technique for detection

• Can detect *classically undetectable* phenomena

• Stability in the presence of decoherence can be used to define the “classicality” of quantum states

• The most “non-classical” states will be the most sensitive to decoherence, and therefore the most sensitive to weak phenomena

• **New motivation for pursuing macroscopic quantum superpositions of all kinds**
Historical lesson: CMB Discovery

- Arno Penzias and Robert Wilson weren’t looking for the cosmic microwave background when they discovered it with the Holmdel horn antenna in 1965
- Thought it was just an unknown source of noise
- They saw it first for one reason: because they built the world’s most sensitive detector of its type
- Progress in interferometry is very rapid, producing the world’s most sensitive detectors of decoherence
- Keep your eyes open!
The End

ArXiv:1212.3061
Slides: jessriedel.com
Generalized framework

- Decoherence detection can be put in same mathematical framework as well-known Aharonov-Bohm effect and the “quantum-enhanced measurements”:
  - Beating standard quantum limit for weak-force detection with test-mass
  - Beating shot-noise limit with interferometers
- Quantum-enhanced measurements and AB effect model the to-be-detected phenomena as classical
  - Action on the probe system is unitary
- Detection through decoherence is the complimentary, *non*-unitary process
  - Weak phenomenon becomes entangled: distinctly quantum
  - Can only be modeled as non-unitary CP map on probe system
  - Generalizes unitary case

See arXiv:1205.3195 for further discussion
Graviton detection is argued to be infeasible even in distant future
- Jupiter-sized detector in orbit around neutron star absorbs 1 graviton per decade
- Background is likely irreducible

Massive superpositions decohere through gravitational bremsstrahlung
- Decoherence factor goes like
  \[ \gamma \sim \exp \left( -\frac{Gm^2\beta^4}{\hbar c} \right) \]

Planck-mass superpositions accelerated relativistically enables detection of gravitons

See arXiv:1310.6347 for further discussion