Quantum tools to explore the Universe

Ronald Walsworth

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Quantum Technology Center, University of Maryland

Two hard problems

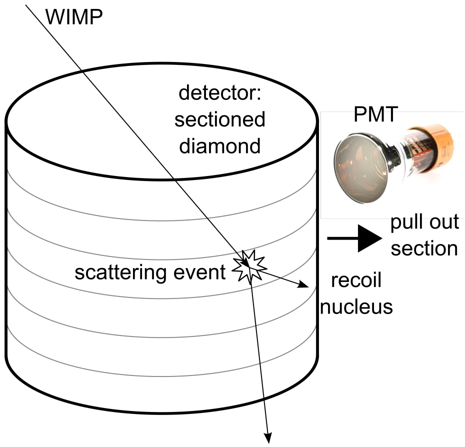
Detect dark matter on Earth

Measure dark matter in galaxy directly

Two hard problems — Two ‘crazy’ ideas

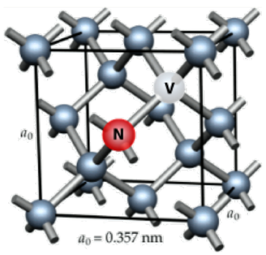
10+ years

Detect dark matter on Earth

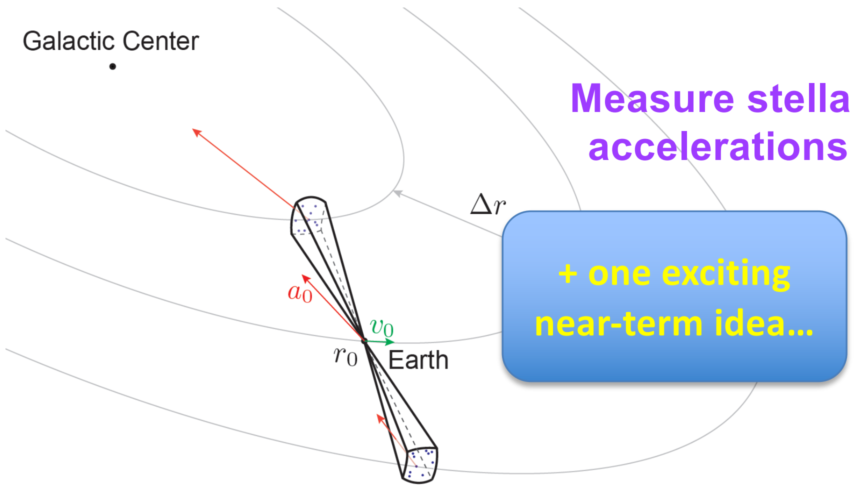


WIMP tracks in diamond

Nitrogen vacancy (NV) quantum defect in diamond



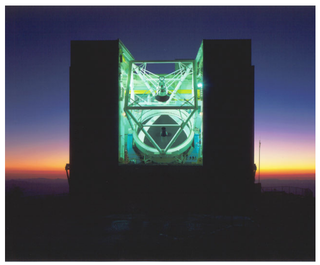
Measure dark matter in galaxy directly



Measure stellar accelerations

+ one exciting near-term idea…

Astro-comb wavelength calibrator

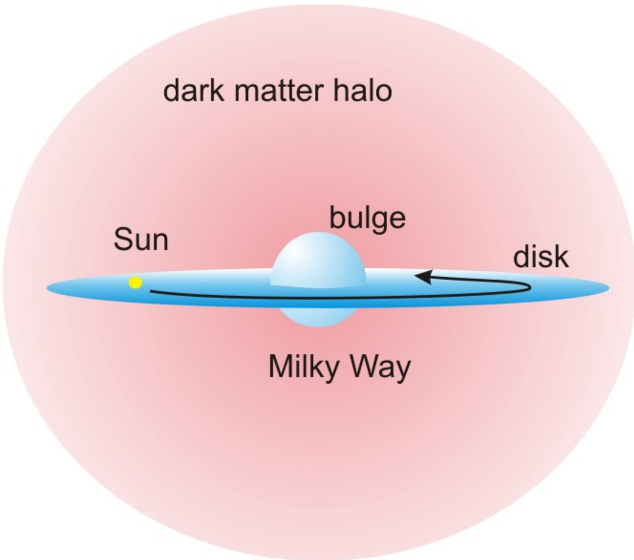


Why directly (i.e., dynamically) measure DM density in galaxy?

- Reduce systematics from assumptions & models in indirect (static) methods

  => Improve accuracy

- Observe DM density sub-structure
- Probe Milky Way history
- Inform direct detection experiments



Are we in a region of DM under- or over-density?

Detect WIMP dark matter on Earth

PHYSICAL REVIEW D **96,** 035009 (2017)

A method for directional detection of dark matter using spectroscopy of crystal defects

Surjeet Rajendran,[1] Nicholas Zobrist,[2] Alexander O. Sushkov,[3,4] Ronald Walsworth,[5] and Mikhail Lukin[6]

High energy theorists

AMO types

2 year pilot project supported by US Dept. of Energy

ScienceNews
MAGAZINE OF THE SOCIETY FOR SCIENCE & THE PUBLIC

News in Brief: Particle Physics

Dark matter particles elude scientists in the biggest search of its kind

But XENON1T's results narrow where to search for hypothetical particles called WIMPS

By Emily Conover 5:00am, May 28, 2018

WIMPS =
Weakly Interacting
Massive Particles

WIMPING OUT The XENON1T experiment (contained inside the large tank above, at left) reports no hint of any interactions from particles of dark matter within, despite a yearlong search.

Roberto Corrieri and Patrick De Perio

Challenges

1) small WIMP-nucleon x-section

2) neutrino "floor"

Neutrino event rate (solar ^{8}B)

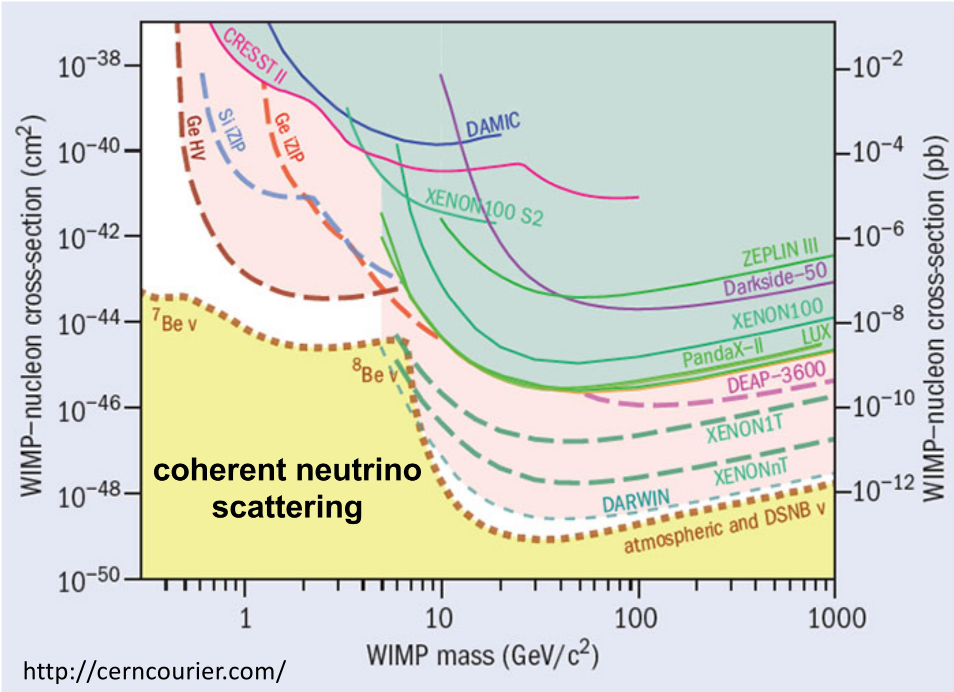
~ 10 / ton-year

L. E. Stringari, *New J. Phys.* **11**, 105011 (2009).

WIMP event rate (σ ~ 10^{-46} cm^2)

~ 10 / ton-year

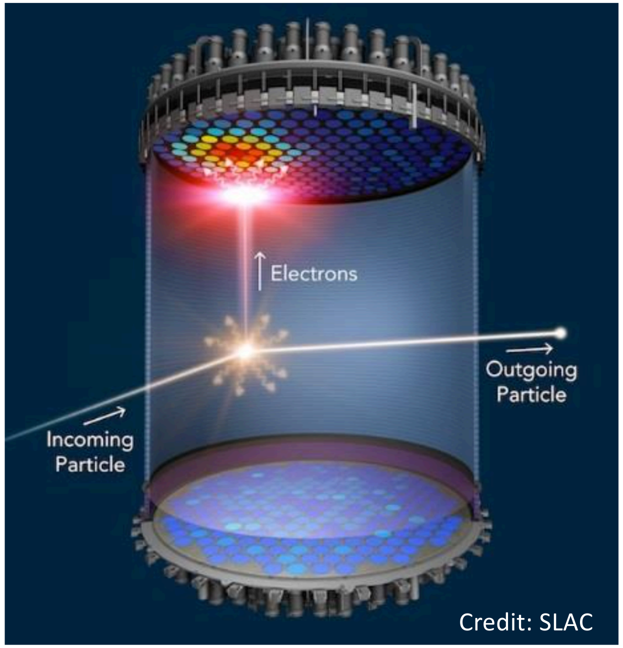
J. Monroe, *J. Phys.: Conf. Ser.* **136**, 022037 (2008).

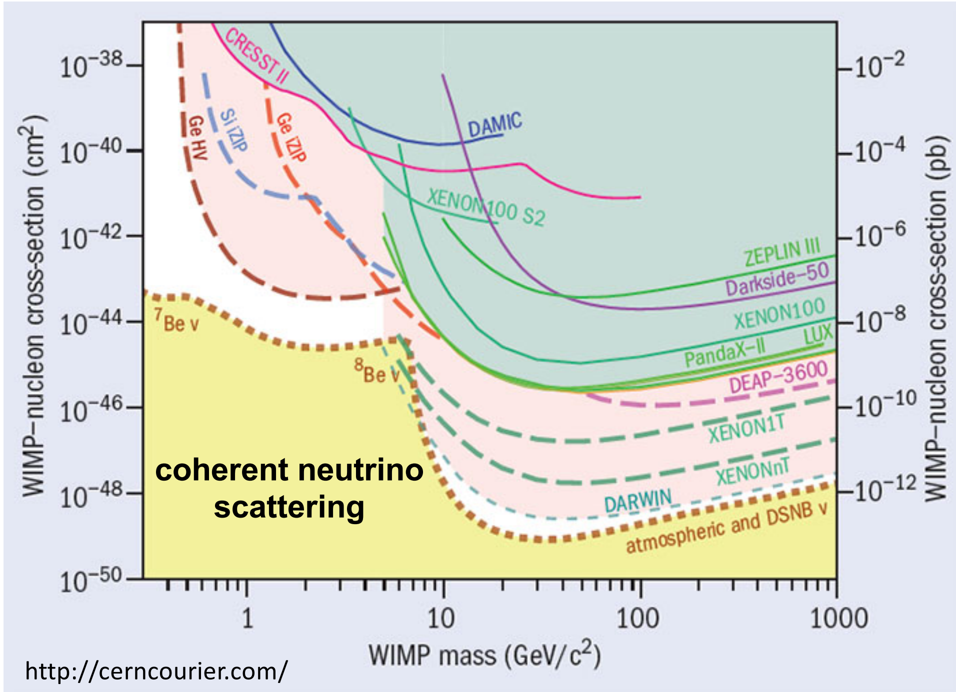


Challenge #1: small WIMP-nucleon x-section => large mass detector

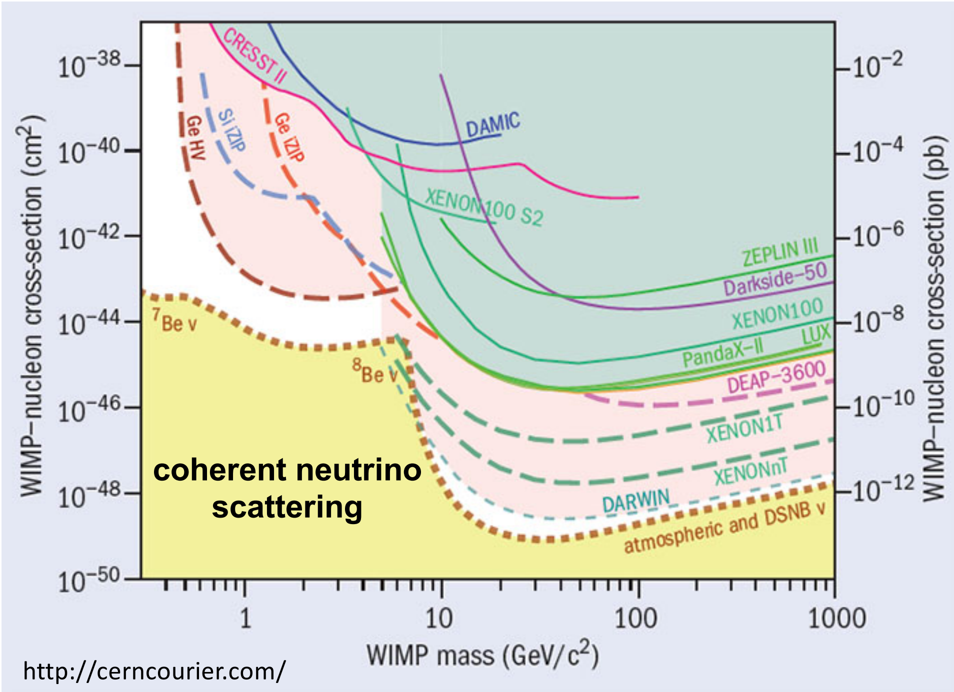
e.g., liquid Xe

~10^4 kg = 3 m^3





Challenge #2: neutrino "floor" => directional detection of WIMPs



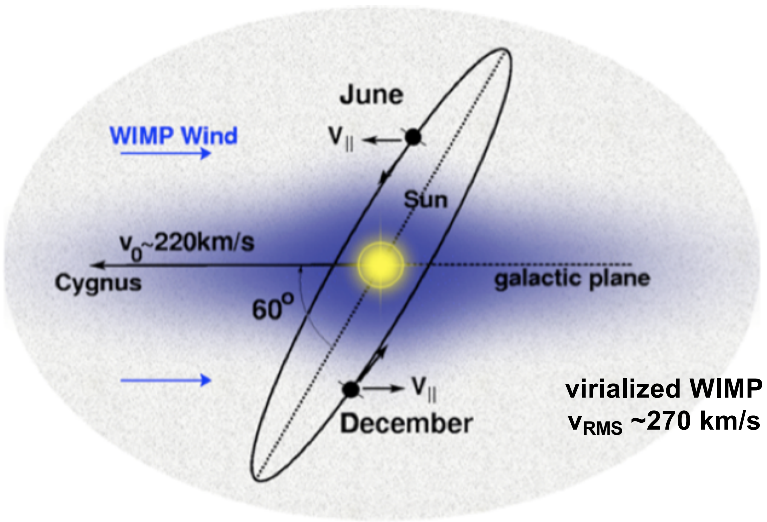
Motion of the Earth and the detection of weakly interacting massive particles

David N. Spergel*
Institute for Advanced Study, Princeton, New Jersey 08540

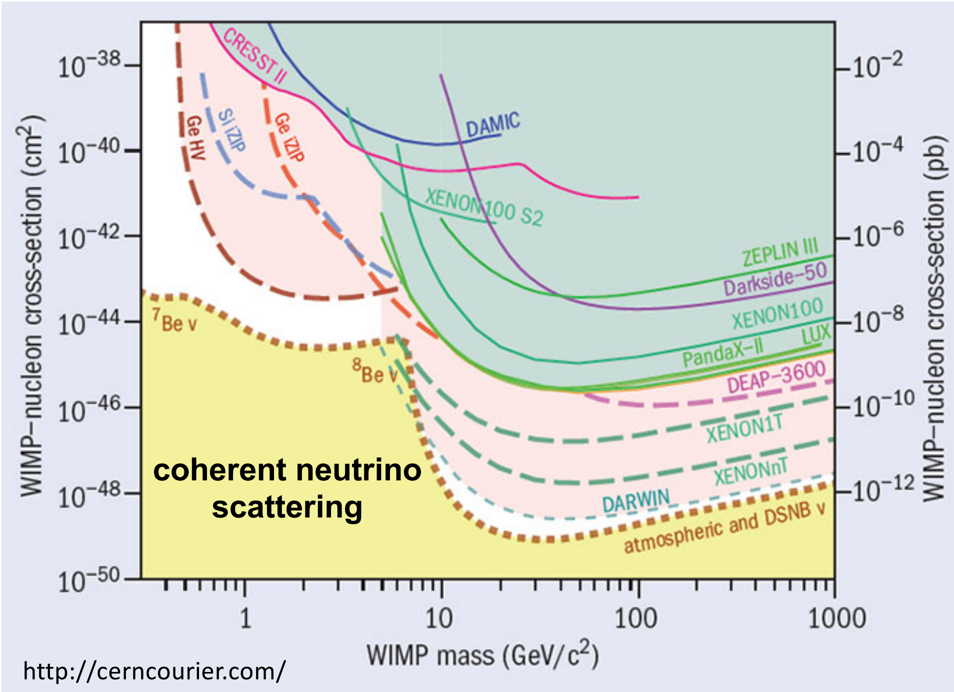
(Received 21 September 1987)

Challenge #2: neutrino "floor" => directional detection of WIMPs

WIMP flux in Sun frame



https://www.hep.shef.ac.uk/research/dm/drift.php



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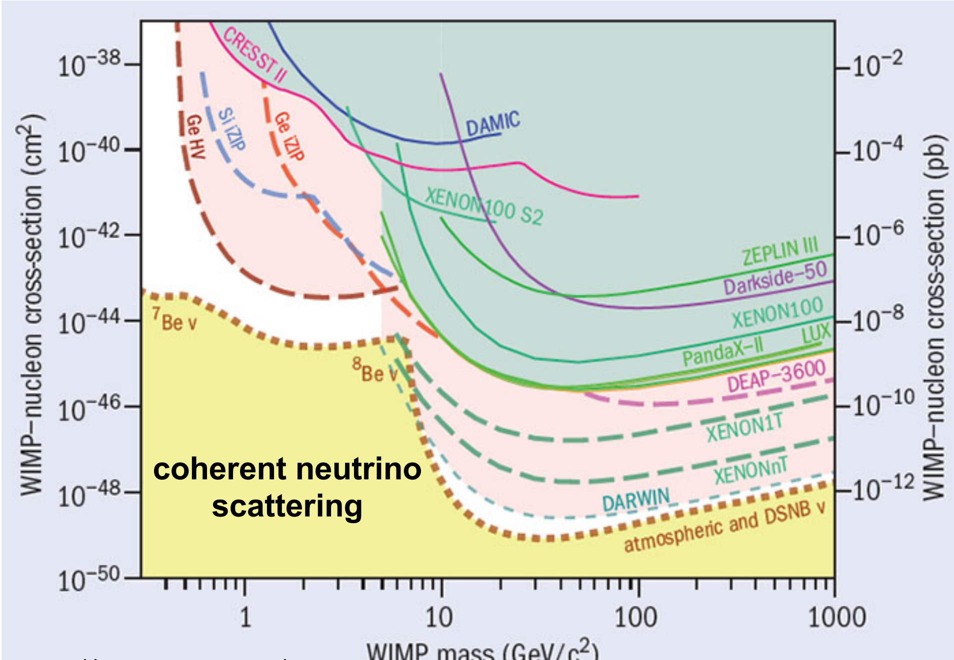
Challenge #2: neutrino "floor" => directional detection of WIMPs

DRIFT detector
CYGNUS collaboration

Time projection chamber
Ionization tracks in ~10 torr gas ~0.1 kg

https://web.infn.it/cygnus/



http://cerncourier.com/

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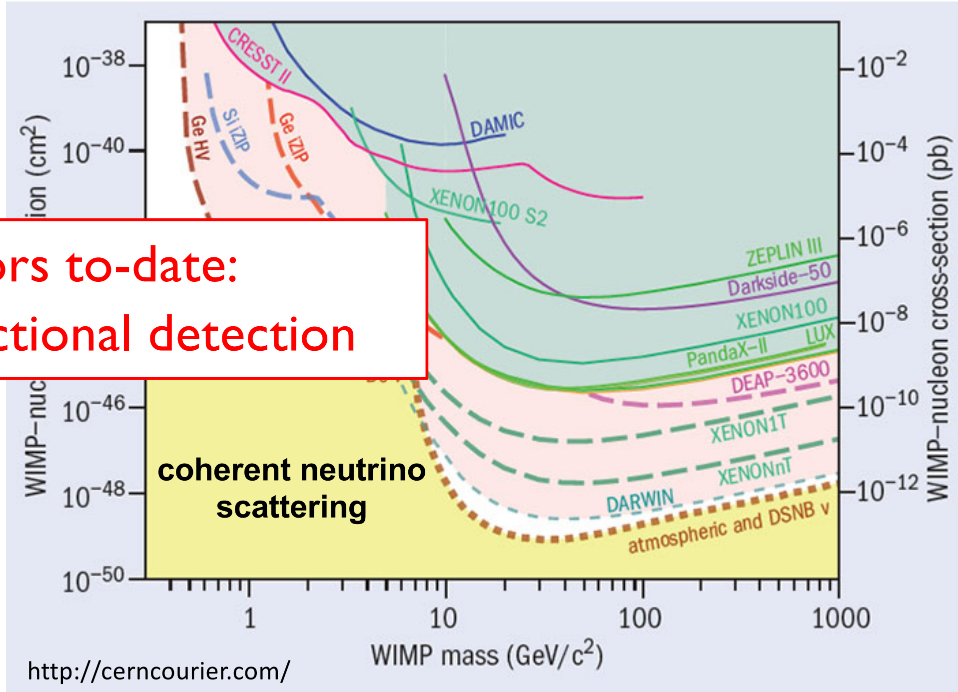
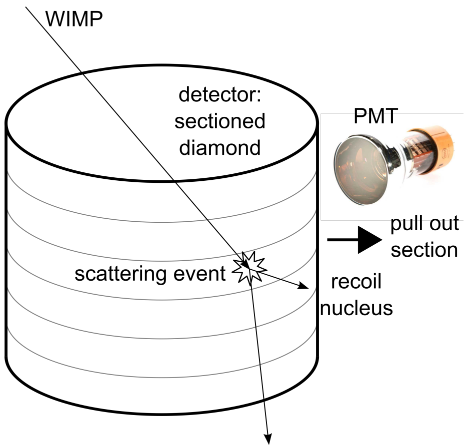


WIMP detectors to-date:
large mass OR directional detection

Our approach: a "bubble chamber" in diamond

Cubic meter of diamond with high NV-density



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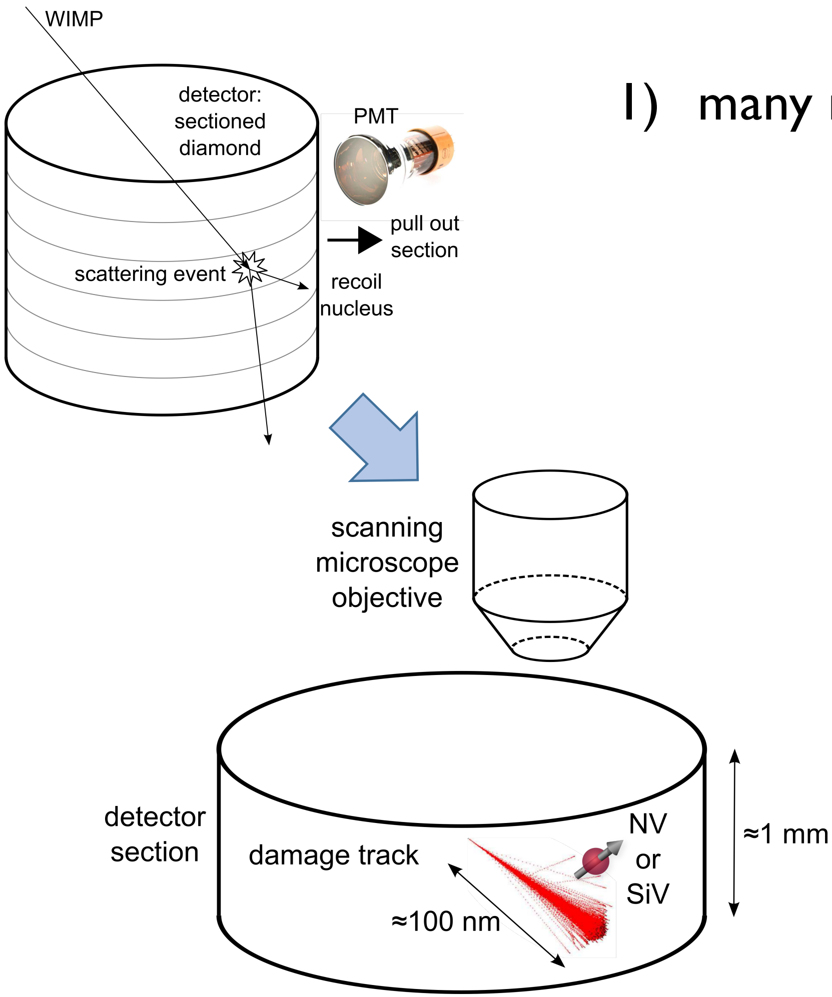
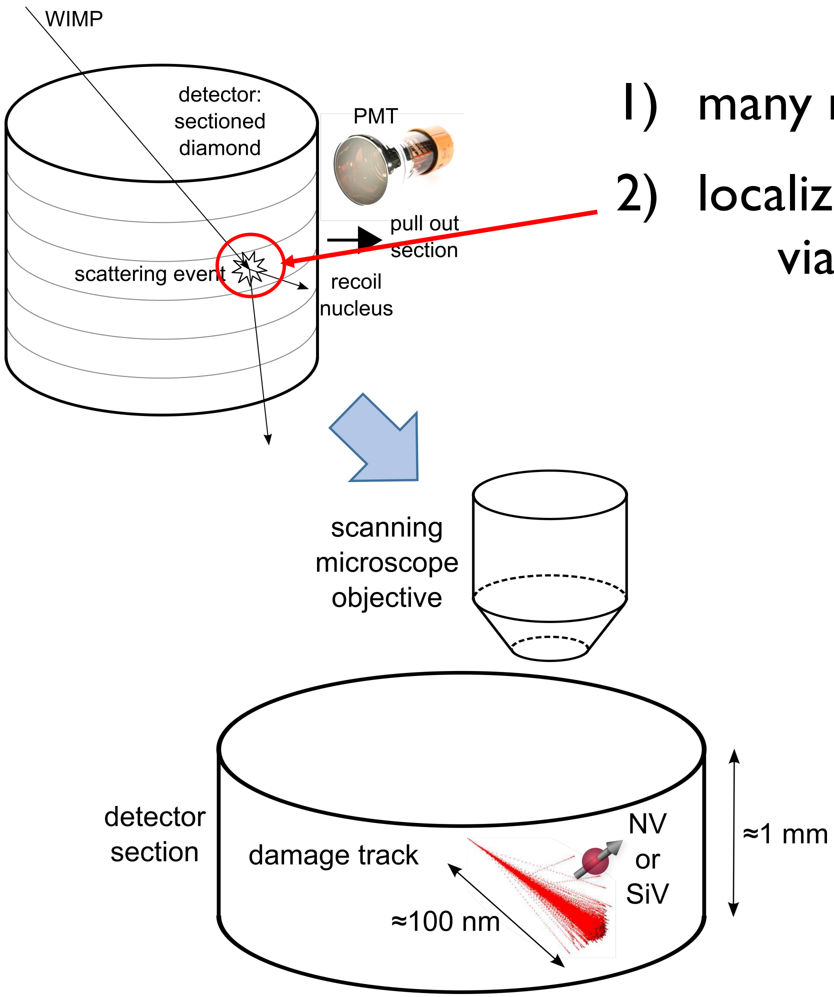


1) many millimeter-scale sections

Our approach: a "bubble chamber" in diamond

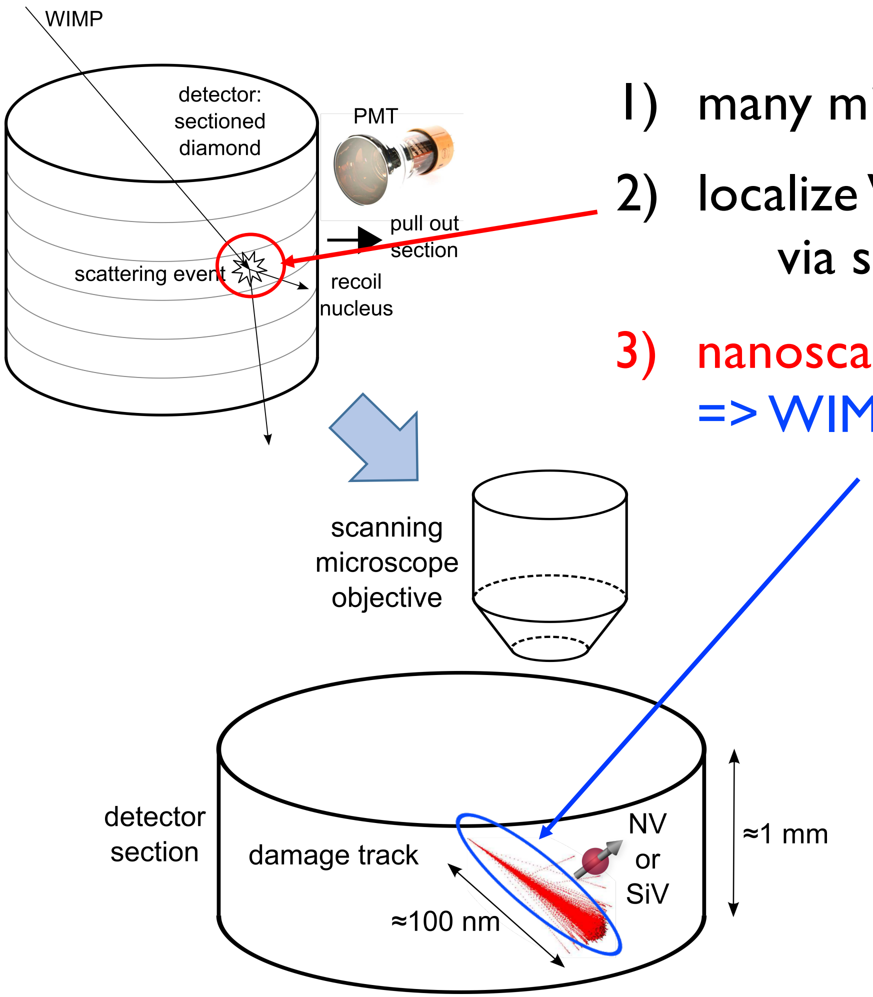
Cubic meter of diamond with high NV-density



1) many millimeter-scale sections
2) localize WIMP scattering to section via scintillation & record event time

Our approach: a "bubble chamber" in diamond

Cubic meter of diamond with high NV-density



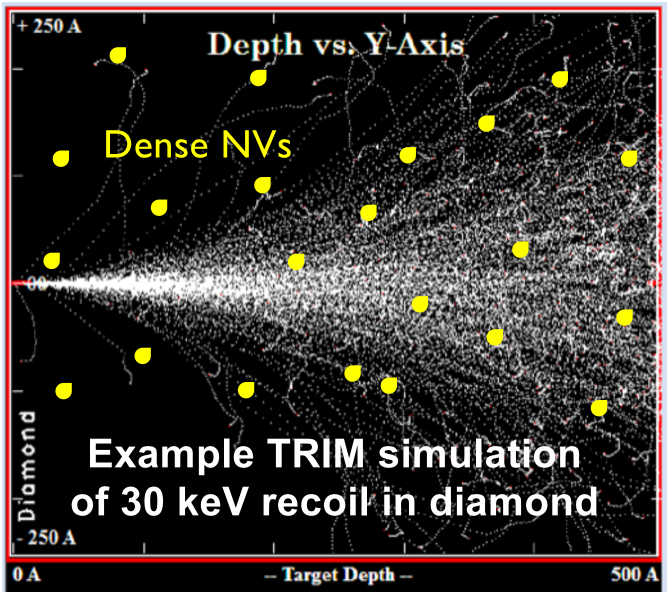
1) many millimeter-scale sections
2) localize WIMP scattering to section via scintillation & record event time
3) nanoscale imaging of damage track => WIMP direction

i) Strain imaging with dense NVs
ii) Induced NV track in diamond
iii) X-ray nano-tomography

May combine techniques

Our approach: a "bubble chamber" in diamond

WIMP or neutrino
=> C nucleus



Stable damage track ~ 100 nm

>100 interstitials & vacancies

asymmetric
shape

i) Strain imaging with dense NVs

NV frequency shifts > 100 kHz
=> easily observable

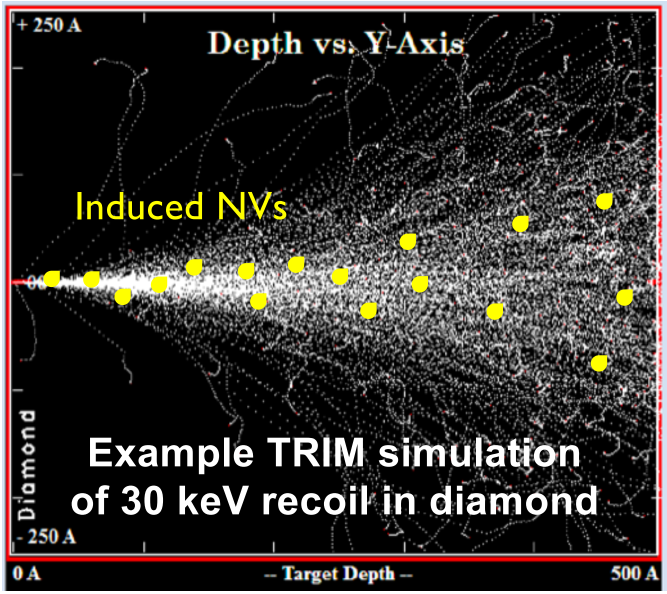
NV spin Hamiltonian

$$H_\kappa = (D + M_{z,\kappa}) S_{z,\kappa}^2 + \gamma \vec{B} \cdot \vec{S}_\kappa$$

Strain-induced shift for kth crystal axis

Our approach: a "bubble chamber" in diamond

WIMP or neutrino
=> C nucleus



Stable damage track ~ 100 nm

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asymmetric
shape

ii) Induced NV track in diamond

Low background signal

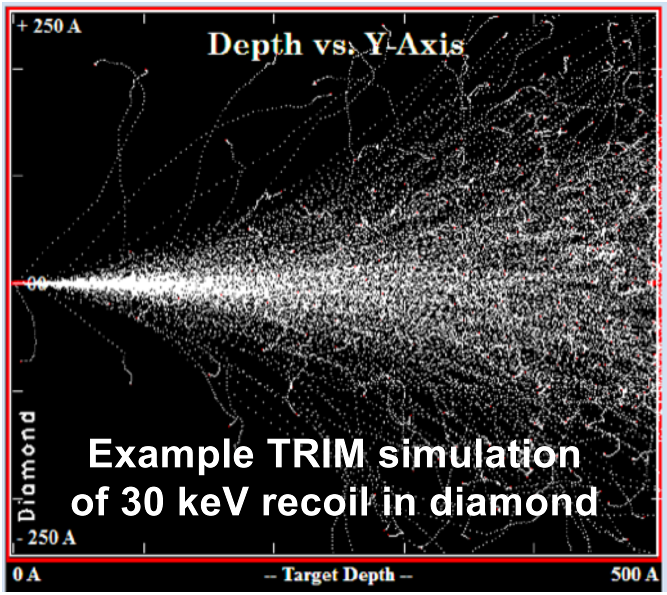
NV spin Hamiltonian

$$H_\kappa = (D + M_{z,\kappa})S_{z,\kappa}^2 + \gamma \vec{B} \cdot \vec{S}_\kappa$$

Strain-induced shift for kth crystal axis

Our approach: a "bubble chamber" in diamond

WIMP or neutrino
=> C nucleus



Stable damage track ~ 100 nm

>100 interstitials & vacancies

asymmetric shape

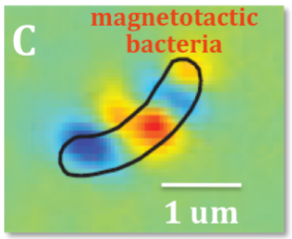
iii) X-ray nano-tomography

Track resolution ~ 30 nm
Requires diamond slices <10 μm

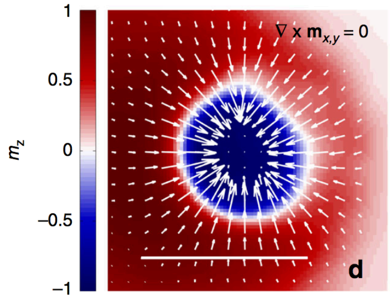
Collaboration with Argonne National Lab
Advanced Photon Source

NV-diamond sensing highlights

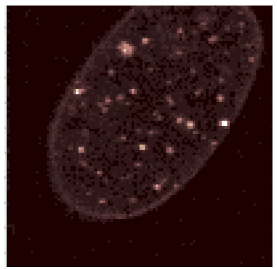
Live cell magnetic imaging



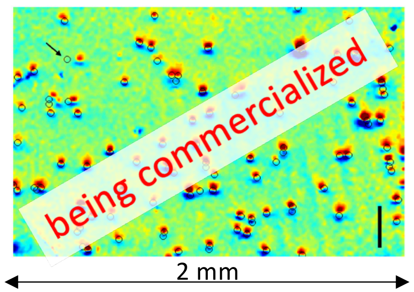
Condensed matter physics



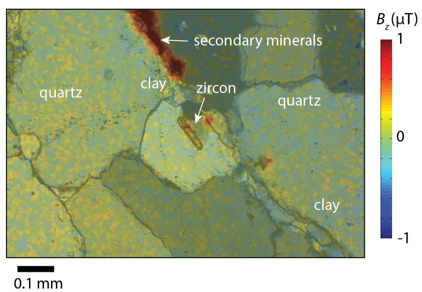
Nanodiamond thermometry for developmental biology



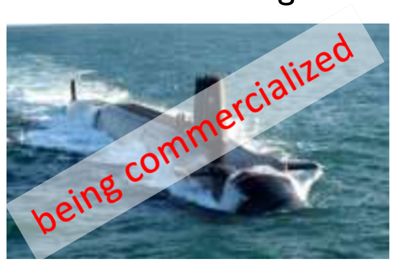
Clinical bioassay

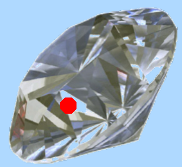


Paleomagnetism of rocks & meteorites



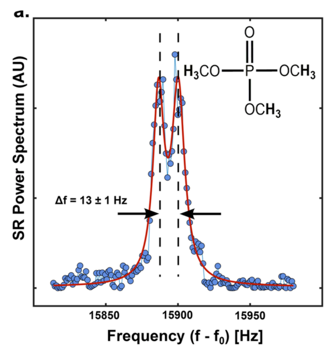
Anomaly detection & GPS-denied navigation



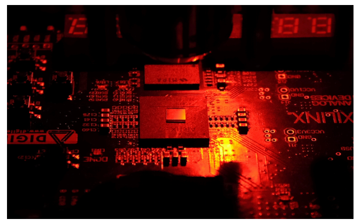


Platform quantum sensor

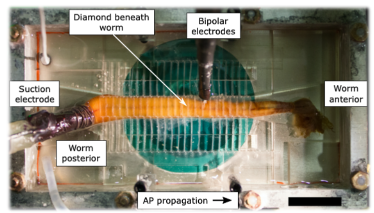
NMR of single cells and proteins

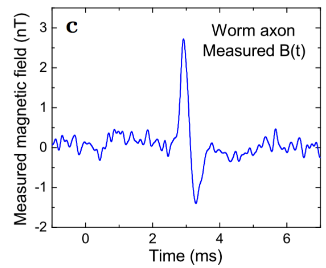


Monitor electronic activity

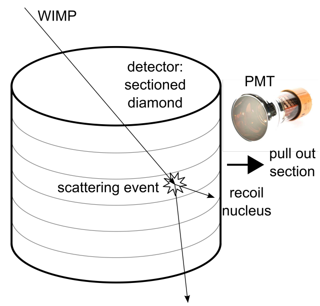


Neuroscience

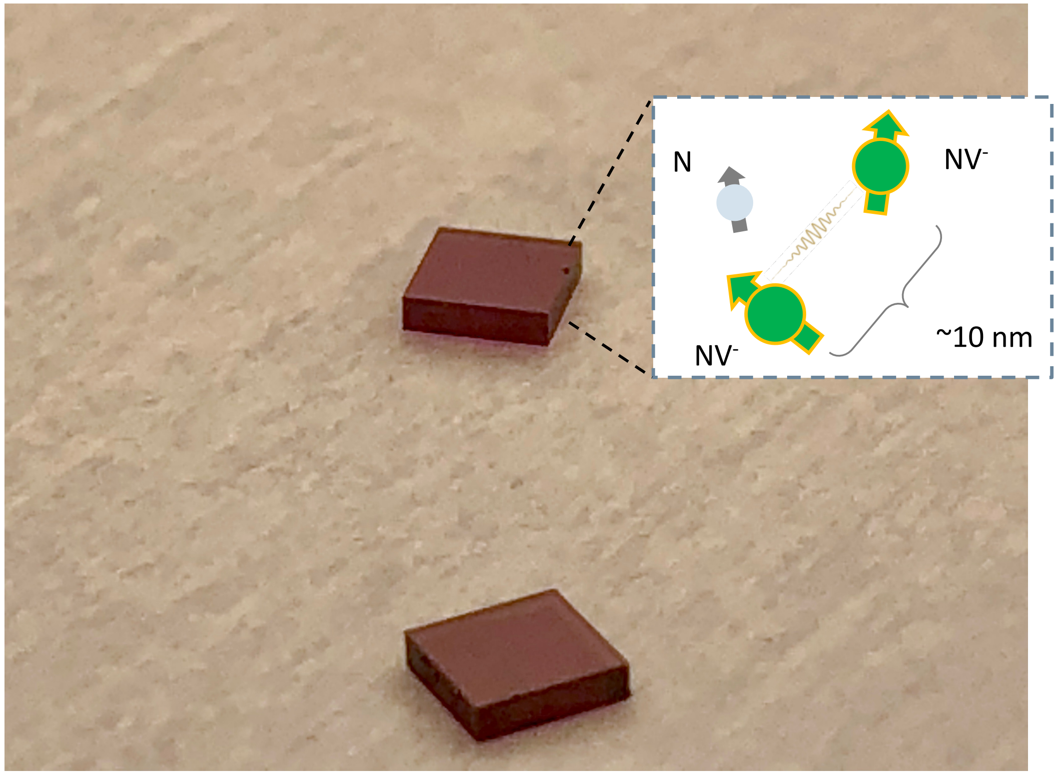




Dark matter detection



Preliminary work #1: Purple diamonds (dense NVs)



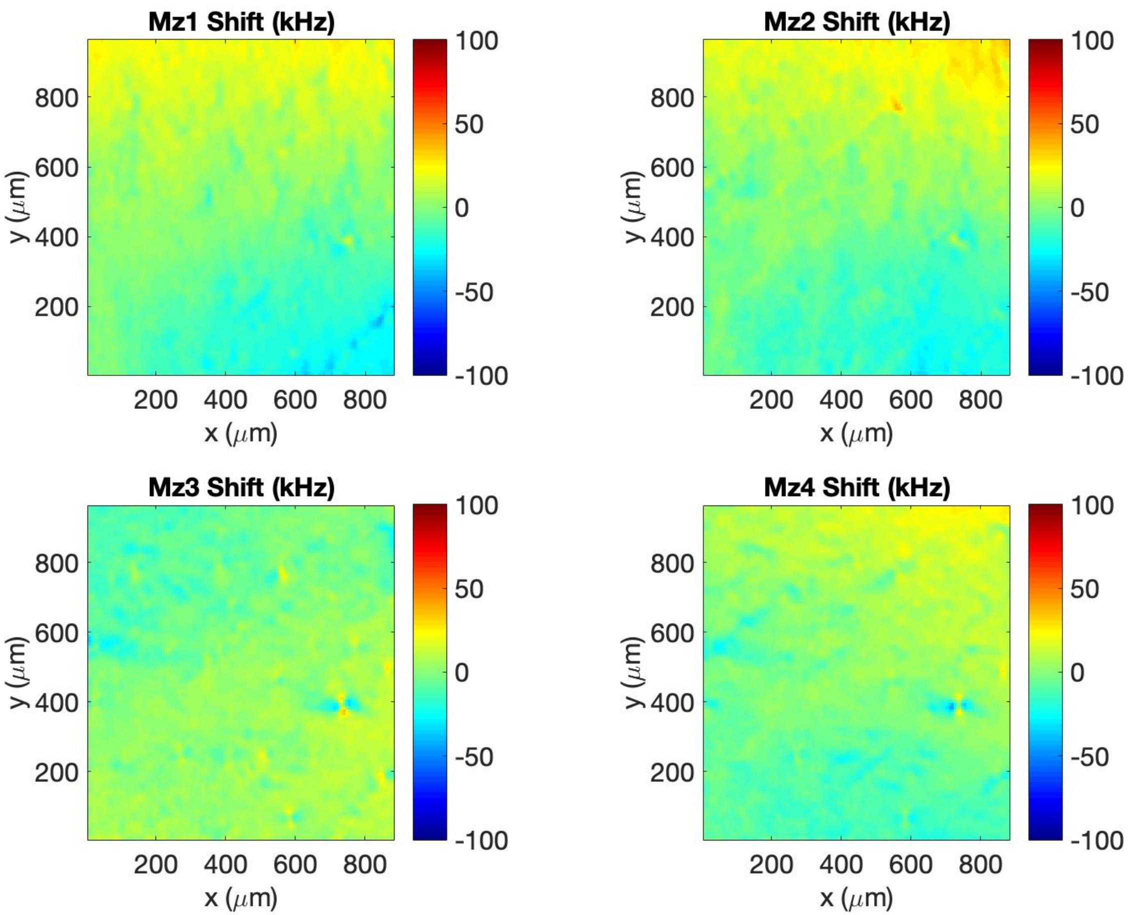
~10 ppm [N]
~5 ppm [NV]
99.999% ^{12}C

Birefringence => low strain, homogeneous NV properties over mm

Measurements in progress…

Preliminary work #2: NV strain mapping, 1 micron resolution, mm field-of-view, homogeneous strain

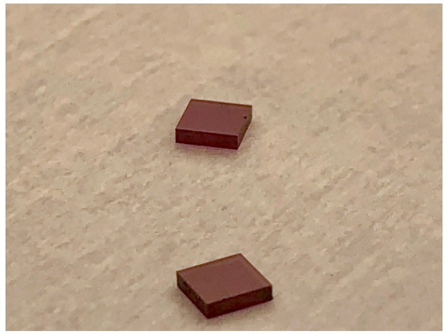
40 μm dense NV surface layer



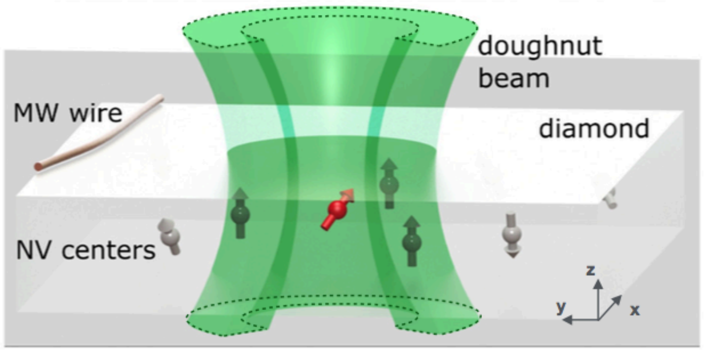
Strain-induced NV frequency shift along each crystal axis (kHz)

~30 kHz NV freq deviation over mm field-of-view

Purple diamonds should be better + 3D homogeneous NV distribution



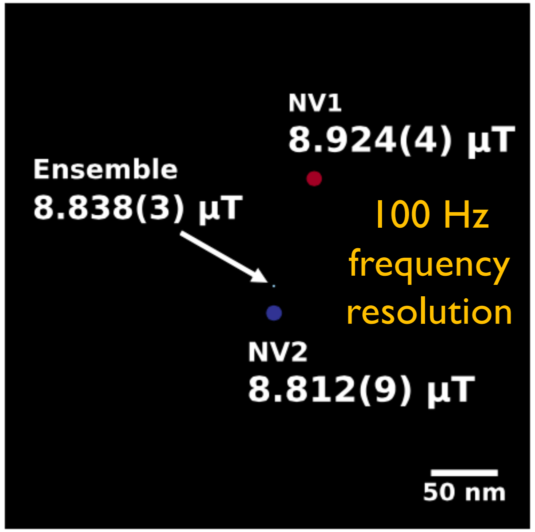
<u>Preliminary work #3</u>: NV nanoscale magnetic sensing

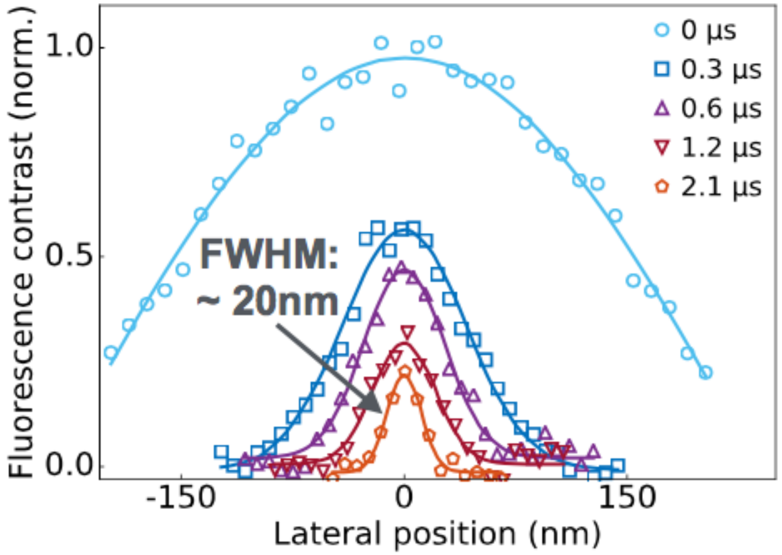


spin-RESOLFT using scanned doughnut laser beam

=> localize individual NV centers to ~20 nm
measure local magnetic field at multiple NVs

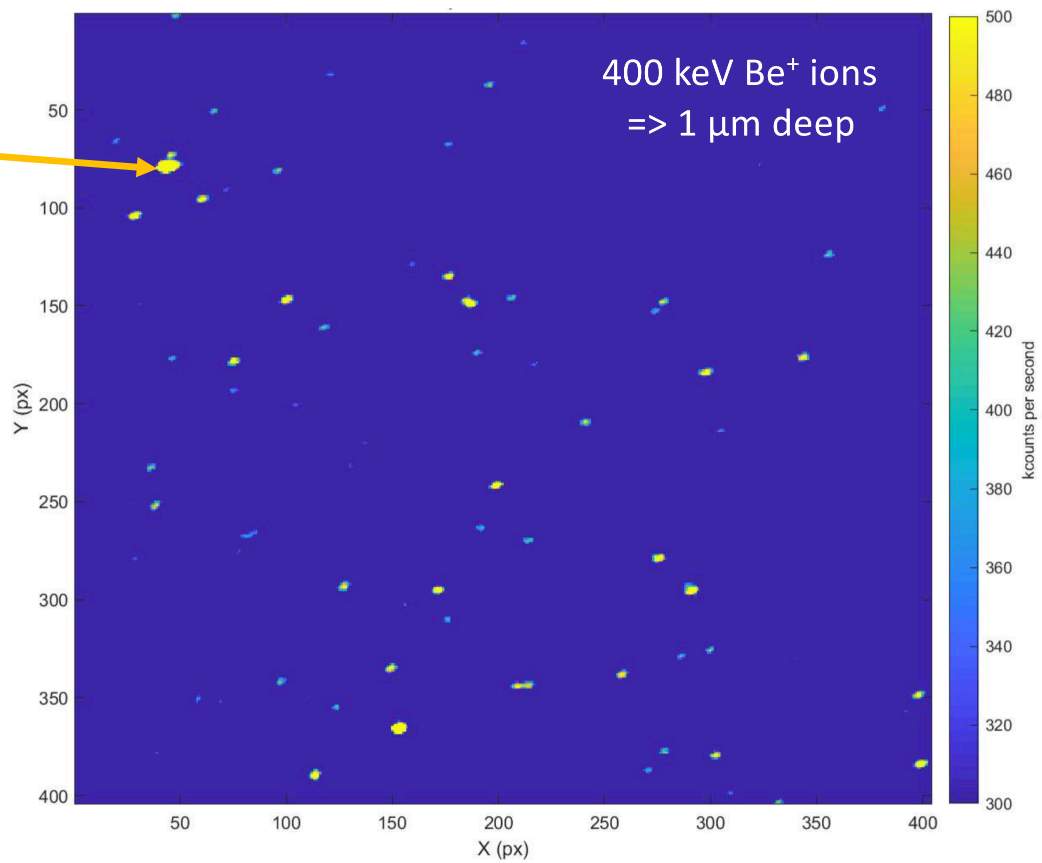
Optics Express (2017)





Preliminary work #4: Induced NVs in low [NV] diamond

500 kc/s => 5 NVs



40 μm

In progress:
X-ray tomography correlated with NV imaging

Challenges — from near to long term

2 year pilot project

- 3D nanoscale strain imaging with high NV density
- Demonstrate nanoscale x-ray & induced NV track measurements
- Identify strain tracks & reconstruct incoming particle direction in mm-scale diamond
- Fully model WIMP, neutrino, background angular distributions
- Make scintillation work in segmented diamond (surfaces?)
- Shield external backgrounds (e.g., neutrons, α)
- Reduce internal backgrounds (from ^{14}C, etc.)
- Do everything efficiently
- Scale up

Cost for cubic meter of diamond?

Measure dark matter in galaxy directly

PHYSICAL REVIEW LETTERS **123,** 091101 (2019)

Probing Dark Matter Using Precision Measurements of Stellar Accelerations

Aakash Ravi,[1,2] Nicholas Langellier,[1,2] David F. Phillips,[2] Malte Buschmann,[3]
Benjamin R. Safdi,[3] and Ronald L. Walsworth[1,2,*]

High energy,
cosmology theorists

AMO/quantum types

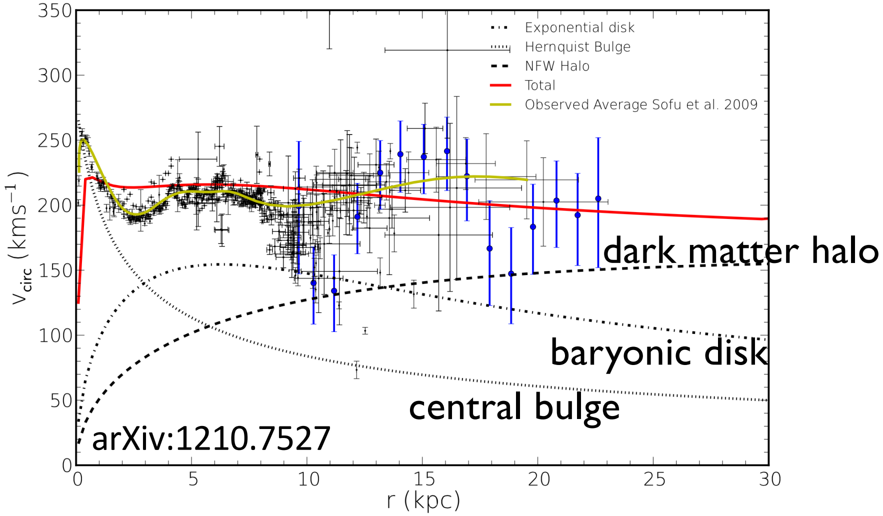
Technology supported by NASA, NSF

To date: local dark matter density determined indirectly

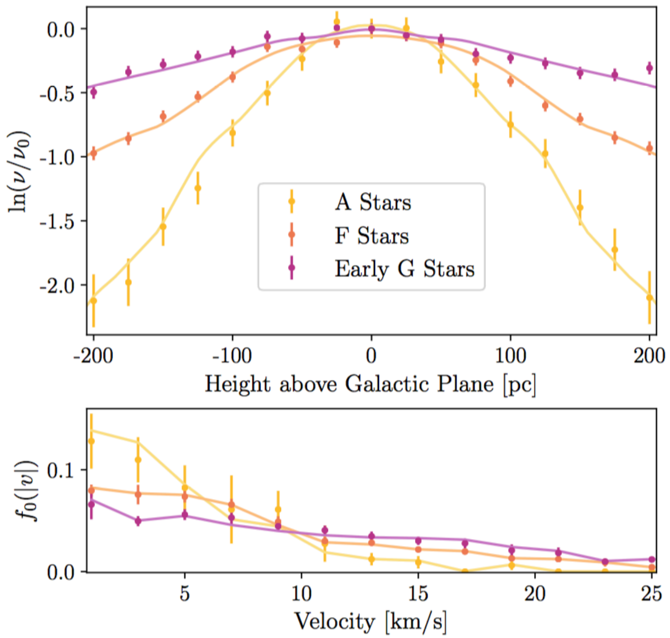
No dynamics

To date: local dark matter density determined indirectly

Method 1: Milky Way rotation curve stellar velocities vs. radius



Method 2: stellar velocity dispersion perpendicular to disk



arXiv:1711.03103

Downsides

(1) assumes equilibrium (known to be wrong)

(2) requires modeling Milky Way bulge and disk

(3) assumes DM halo spherical symmetry

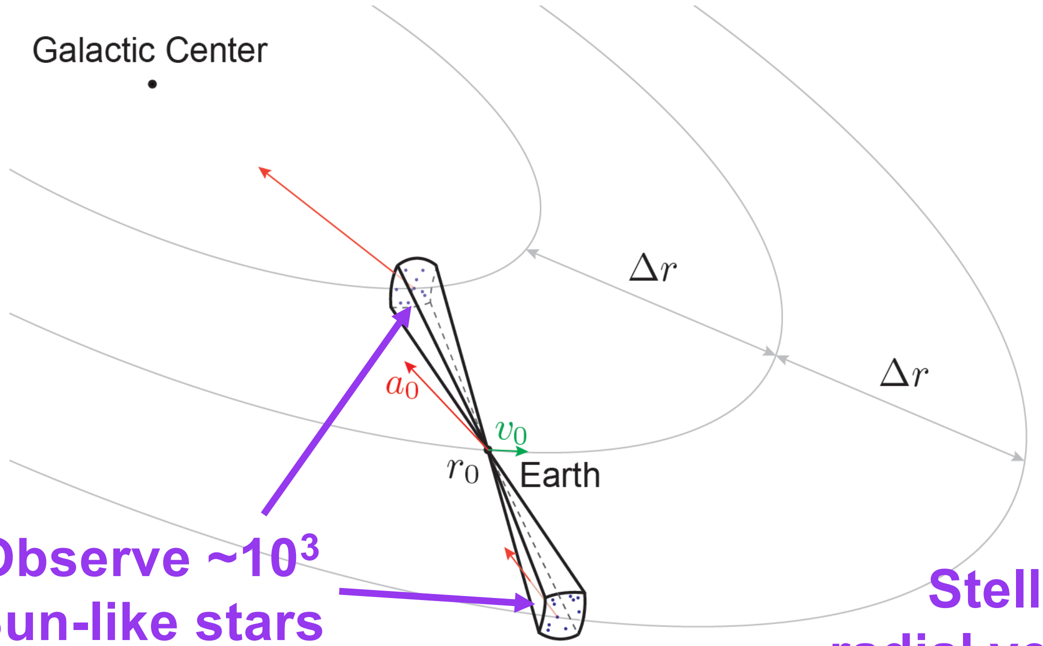
(4) **insensitive to DM density variation ~1 kpc**

Our approach: measure stellar radial accelerations

=> direct measure of galaxy grav. potential gradient

=> local dark matter density

'complement Gaia'



Observe ~10^3 Sun-like stars in ~0.1 kpc regions ~3 kpc away

$$\rho_{DM} \sim -\frac{1}{4\pi G}\frac{\partial a_r}{\partial r}$$

$$a_r \sim 10^{-8}\ \mathrm{cm/s^2}$$

Crazy?

Stellar radial velocity change $\sim \dfrac{1\ \mathrm{cm/s}}{3\ \mathrm{years}}$



Search for Earth-like exoplanets

2008

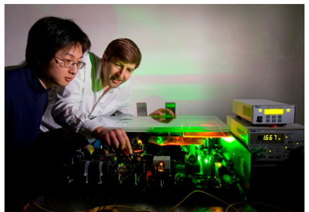
nature Vol 452|3 April 2008|doi:10.1038/nature06854

LETTERS

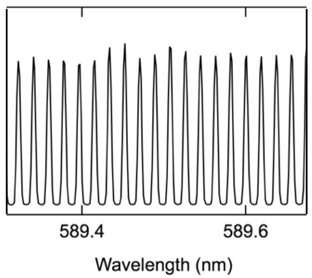
In the lab, not at the telescope…

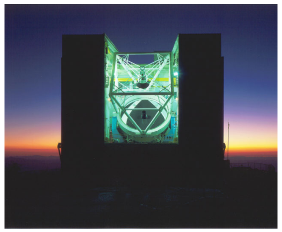
A laser frequency comb that enables radial velocity measurements with a precision of 1 cm s^{-1}

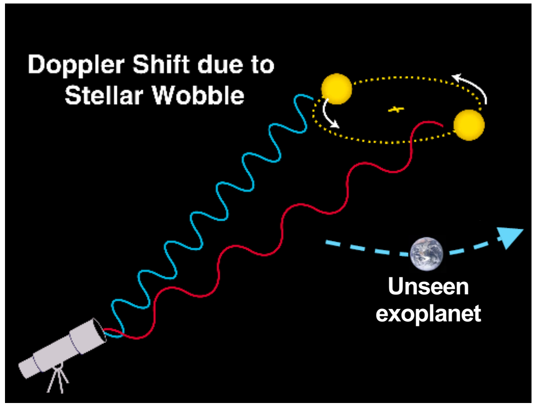
Chih-Hao Li[1,2], Andrew J. Benedick[3], Peter Fendel[3,4], Alexander G. Glenday[1,2], Franz X. Kärtner[3], David F. Phillips[1], Dimitar Sasselov[1], Andrew Szentgyorgyi[1] & Ronald L. Walsworth[1,2]



Atomic clock





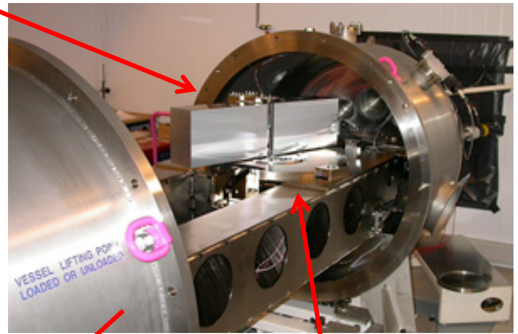


2015

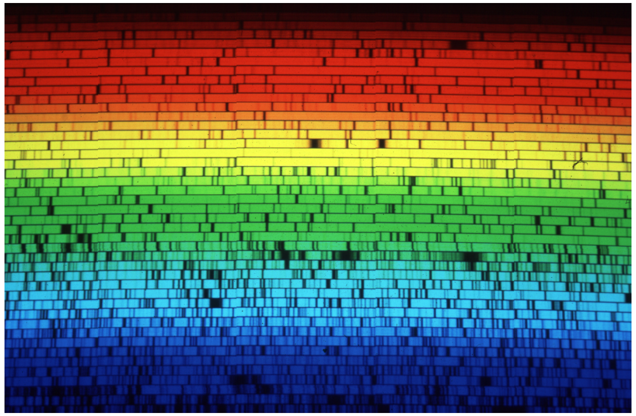
Operating at TNG telescope...

Astro-comb

HARPS-N spectrograph



Stellar spectrum => radial velocity



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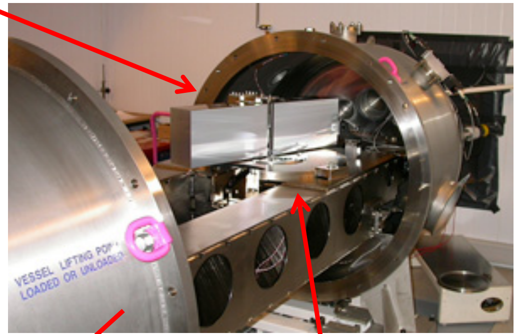
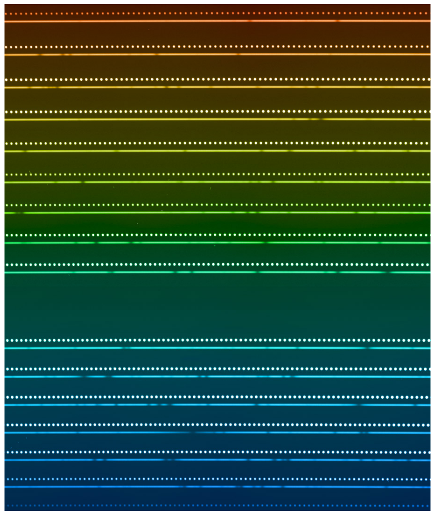
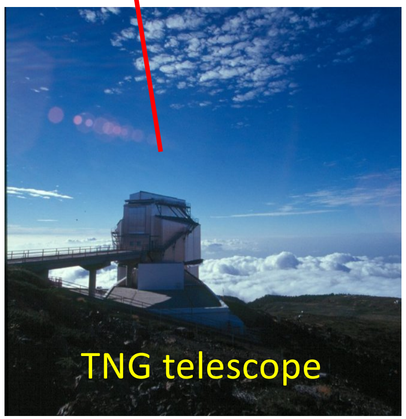
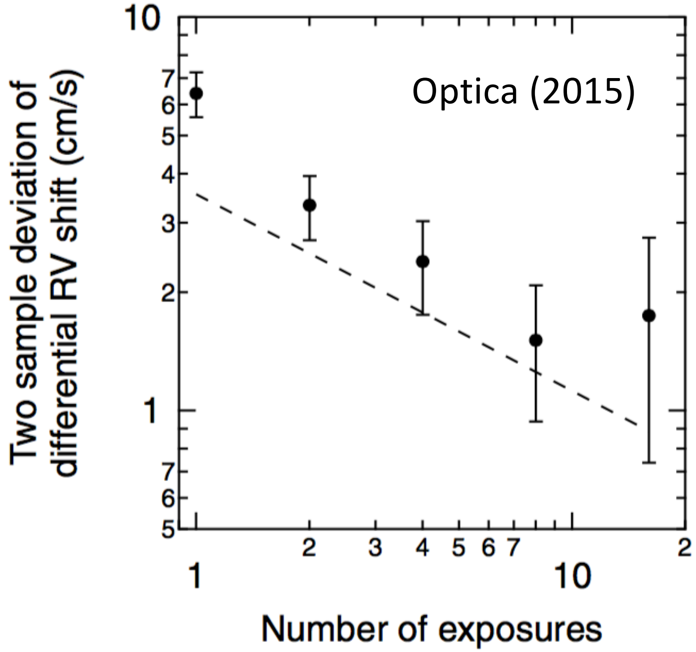
HARPS-N spectrograph



Stellar spectrum => radial velocity

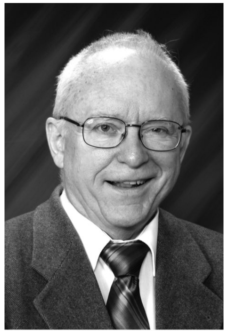






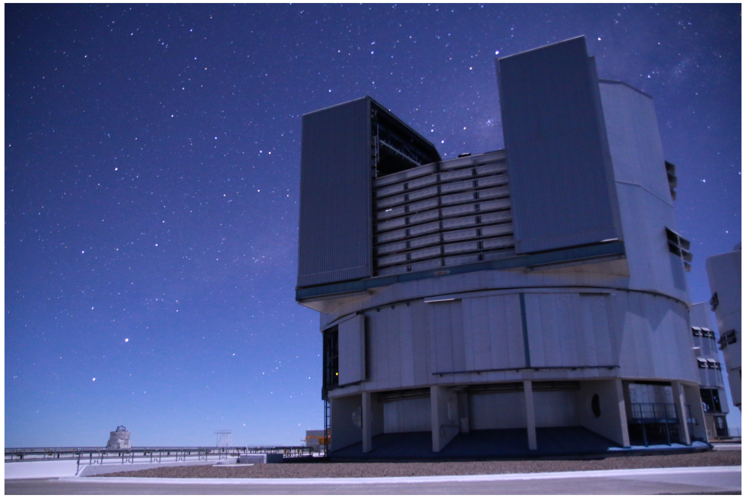
Stellar acceleration ~10^{-8} cm/s^2 practical?

MenloSystems



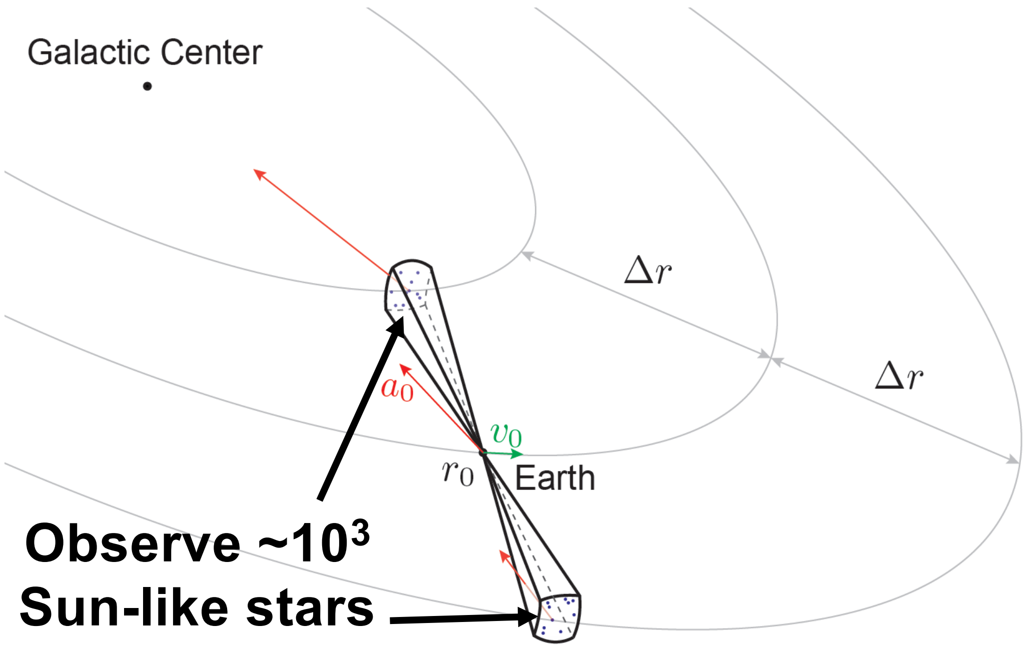
Menlo Systems frequency comb helps analyze combined light from four telescopes in the VLT

ESO's Very Large Telescope has four main telescopes; their light, combined in a single spectrograph, is analyzed using the 'AstroComb.'



Goal: measure stellar accelerations ~10^{-8} cm/s^2 ~10-20 yrs

=> direct measure of local dark matter density

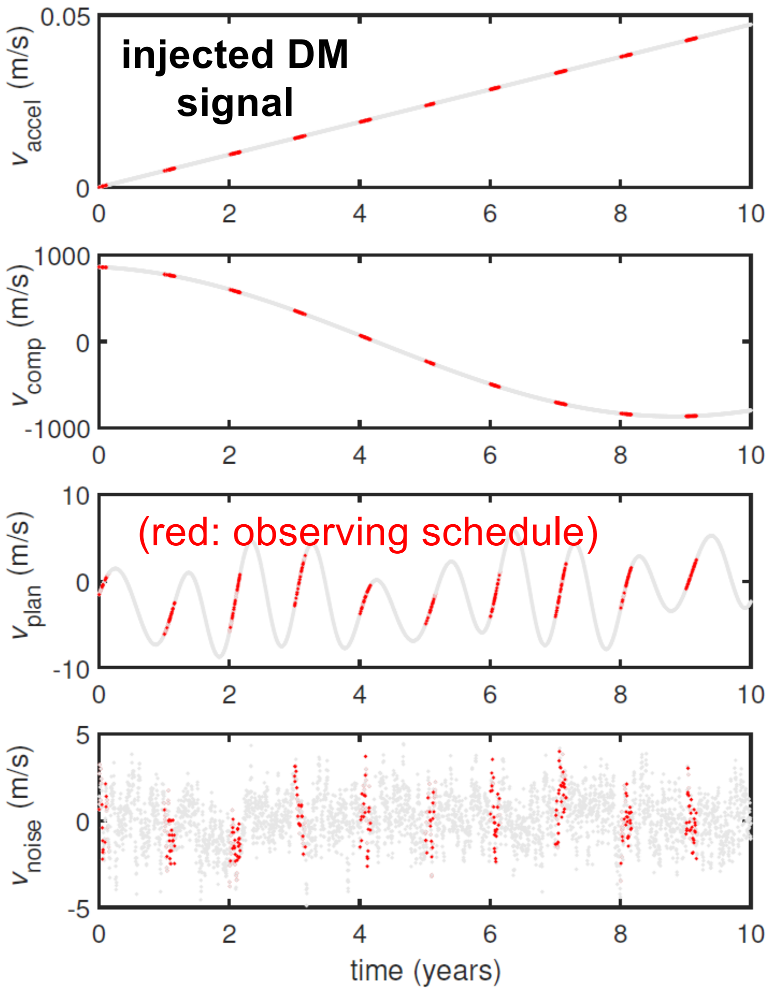


Observe ~10^3
Sun-like stars
in ~0.1 kpc regions
~3 kpc away
for a decade

- Next-gen telescope (~30 m)
  => shot-noise
  $$$$$
- Account for companions & planets
- Understand stellar activity
- Astro-comb provides long-term spectroscopic stability over years

Simulate observing campaign (10 yrs)

$$v_{\text{total}}(t) = v_{\text{accel}}(t) + v_{\text{comp}}(t) + v_{\text{plan}}(t) + v_{\text{noise}}(t)$$



1. DM diffl. acceleration (~5 cm/s/decade)
2. Stellar companions (~1 km/s amplitude)
3. Planets (~1-10 m/s amplitude)
4. Stellar activity (~1-10 m/s amplitude)

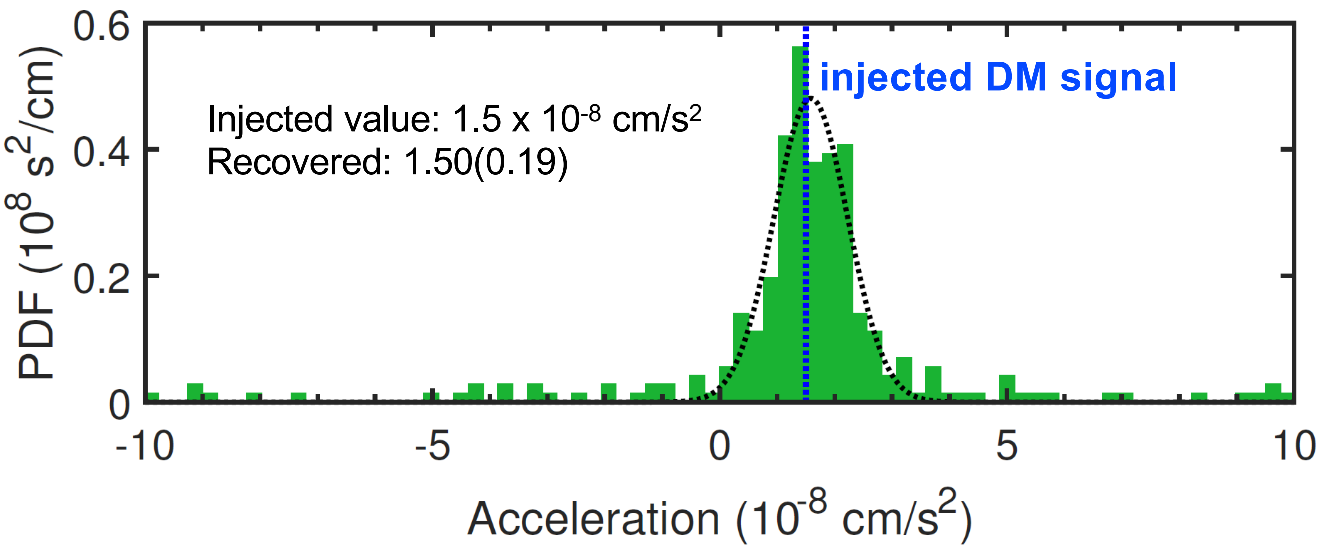
Common for all stars in cohort

Different for each star in cohort

Simulation uses distribution of observed behavior for 1,000 Sun-like stars

Stellar acceleration precision for stellar activity ~10 cm/s

Small solar telescope
on TNG exterior



Need to solve stellar activity problem!

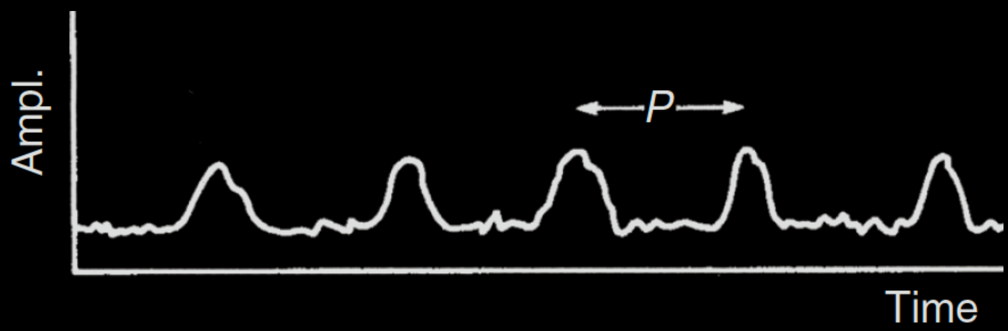
Today ~1 m/s

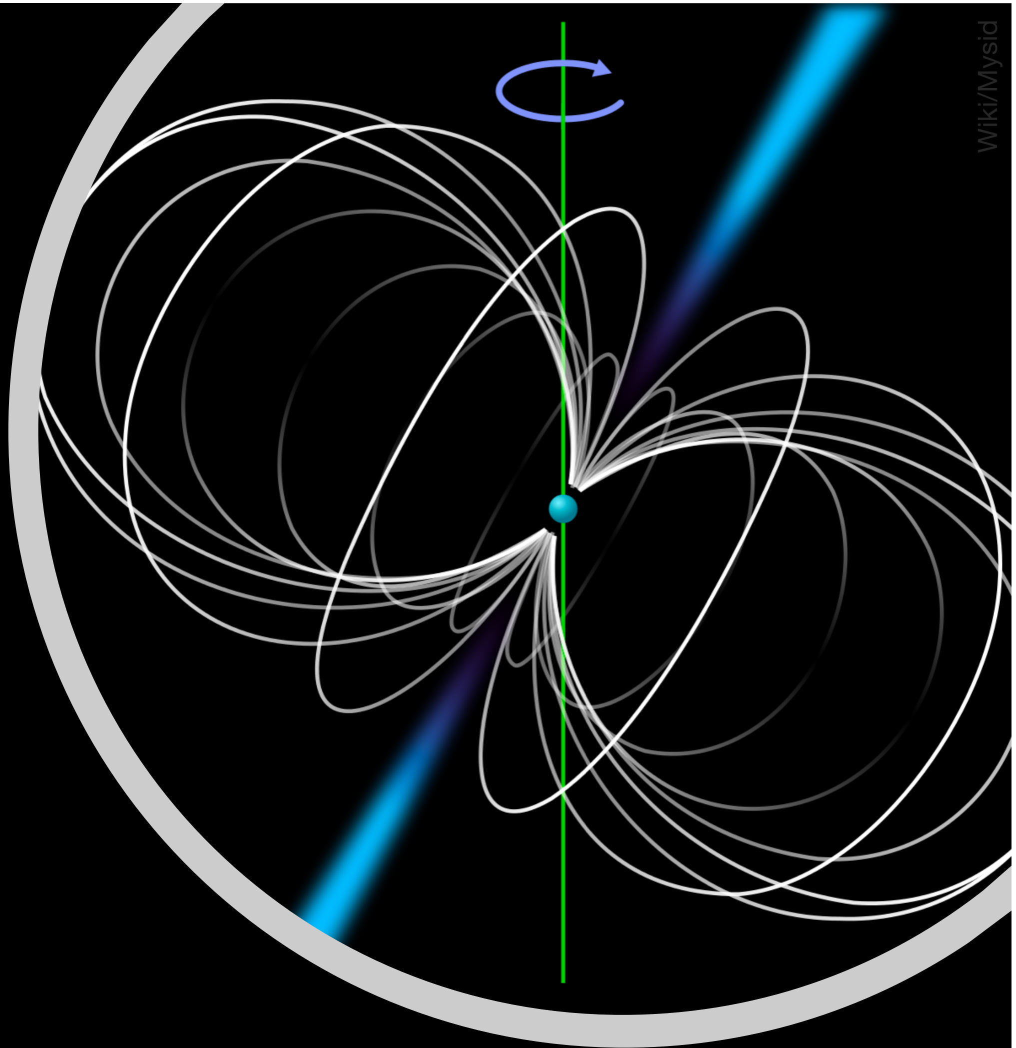
5σ detection possible with 1,000 stars

Find Earth-like planets	⟺	Directly measure local dark matter density

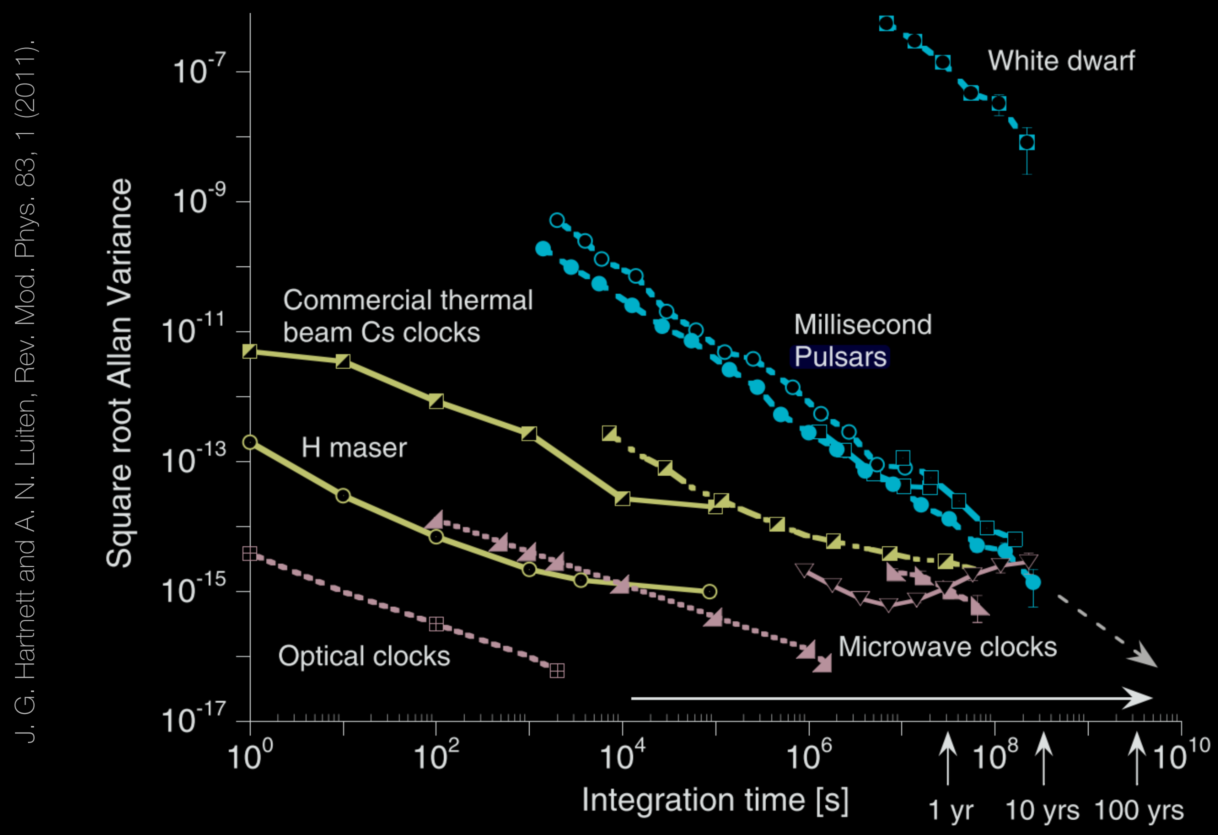
Future directions

Can we do similar acceleration surveys with pulsars? (David Phillips)





Pulsars are stable long-term astro-clocks



Pulsar acceleration from DM => frequency chirp

For a pulse frequency ν,

$$\dot{\nu}_{\rm accel} = a\nu/c$$

For a millisecond pulsar ($\nu = 300\ {\rm Hz}$) and typical galactic acceleration ($a = 10^{-10}\ {\rm m/s^2}$):

$$\dot{\nu}_{\rm accel} = 10^{-16}\ {\rm Hz/s} \approx 3 \times 10^{-9}\ {\rm Hz/yr}$$

Should be detectable with current pulsar timing arrays! (existing data)

Pulsar braking and astrometry requirements

$$\dot{\nu}_{\rm accel} = 10^{-16}\ {\rm Hz/s}$$

DM signal indistinguishable from natural braking of pulsar as a consequence of radiative loss.

$$\dot{\nu}_{\rm braking} \sim 10^{-16}\ {\rm Hz/s}$$

=> Need to average over pulsars as acceleration is common-mode but braking rate has a broad distribution.

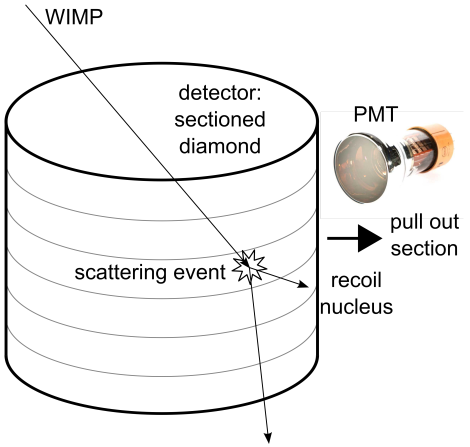
few kpc length-scale

In addition, analysis needs to correct for proper motion using high-precision astrometric surveys (e.g., Gaia).

Stay tuned….

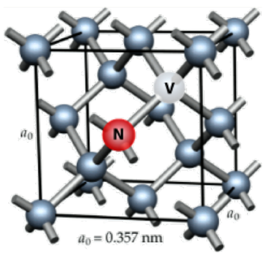
Two hard problems — Two ‘crazy’ ideas

Detect dark matter on Earth

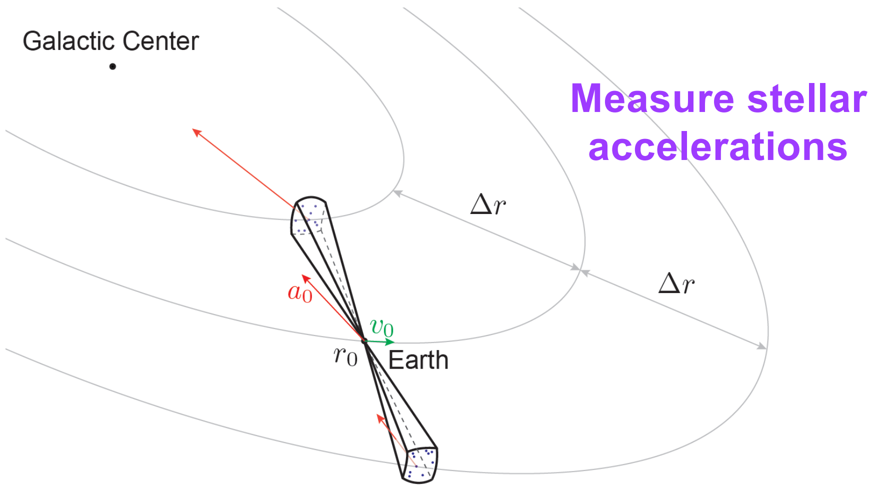


WIMP tracks in diamond

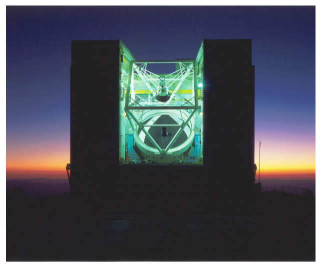
Nitrogen vacancy (NV) quantum defect in diamond



Measure dark matter in galaxy directly



Astro-comb wavelength calibrator

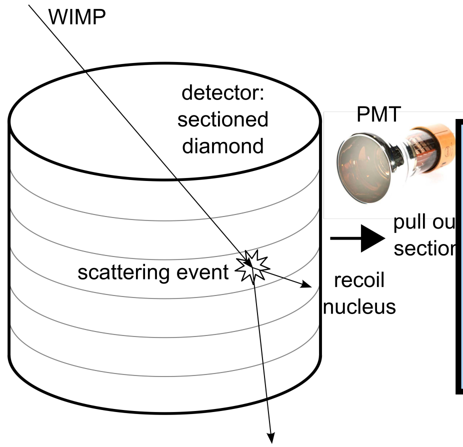


+ one not-so crazy idea

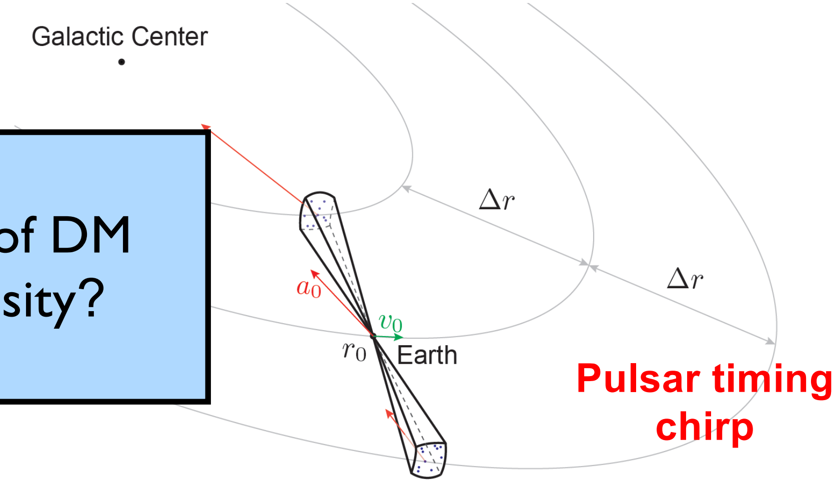
Two hard problems — Two ‘crazy’ ideas

<u>Detect dark matter on Earth</u>

<u>Measure dark matter in galaxy directly</u>

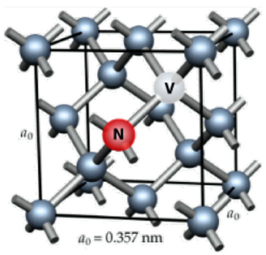


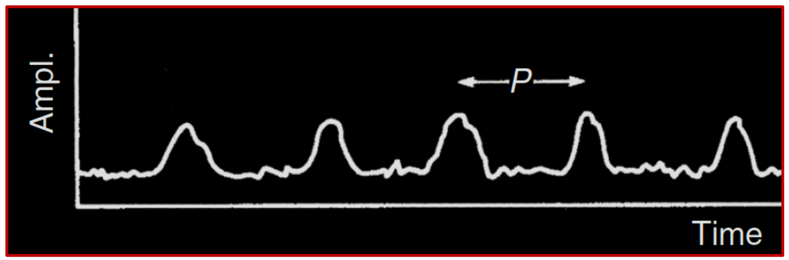
Are we in a region of DM under or over-density?



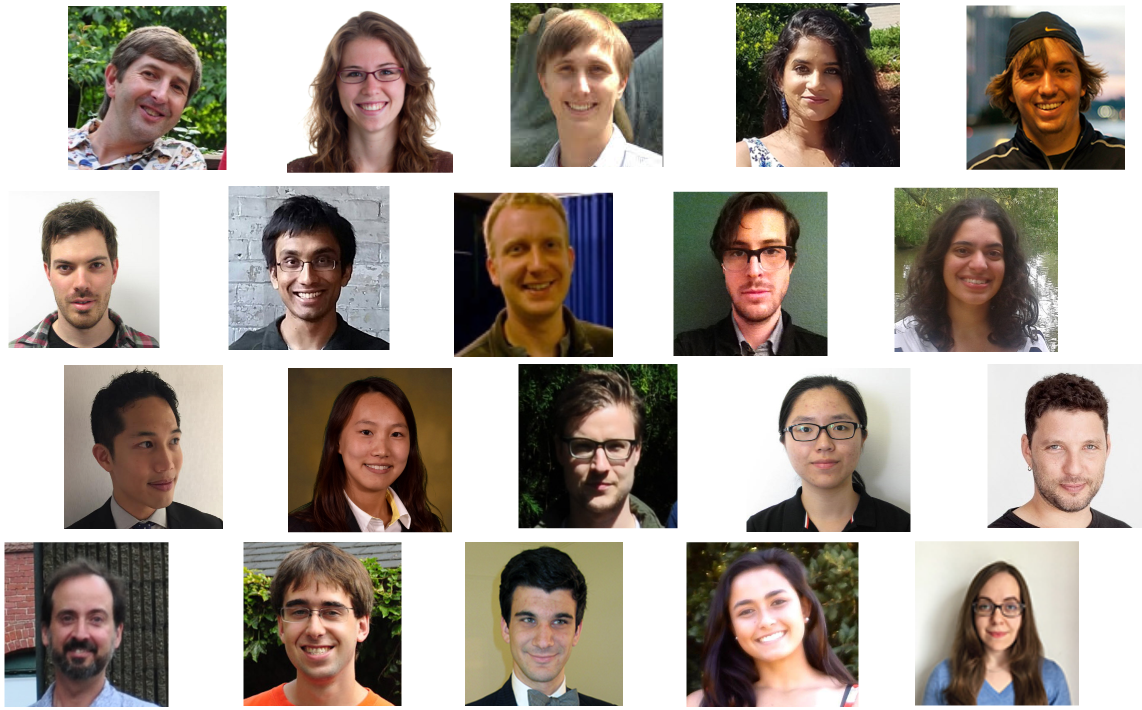
Pulsar timing chirp

Nitrogen vacancy (NV) quantum defect in diamond





Thank you



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