Quantum Tools to Explore the Universe

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Harvard University, Department of Physics
Harvard University, Center for Brain Science

Three examples

- Past

  Maser atomic clocks => tests of Lorentz & CPT symmetry ~ 10^{-31} GeV

  => Tech spin-off to portable, low-cost medical MRI

- Present

  Laser frequency combs => 100x improved astrophysical spectroscopy

  => search for Earth-like planets around other stars

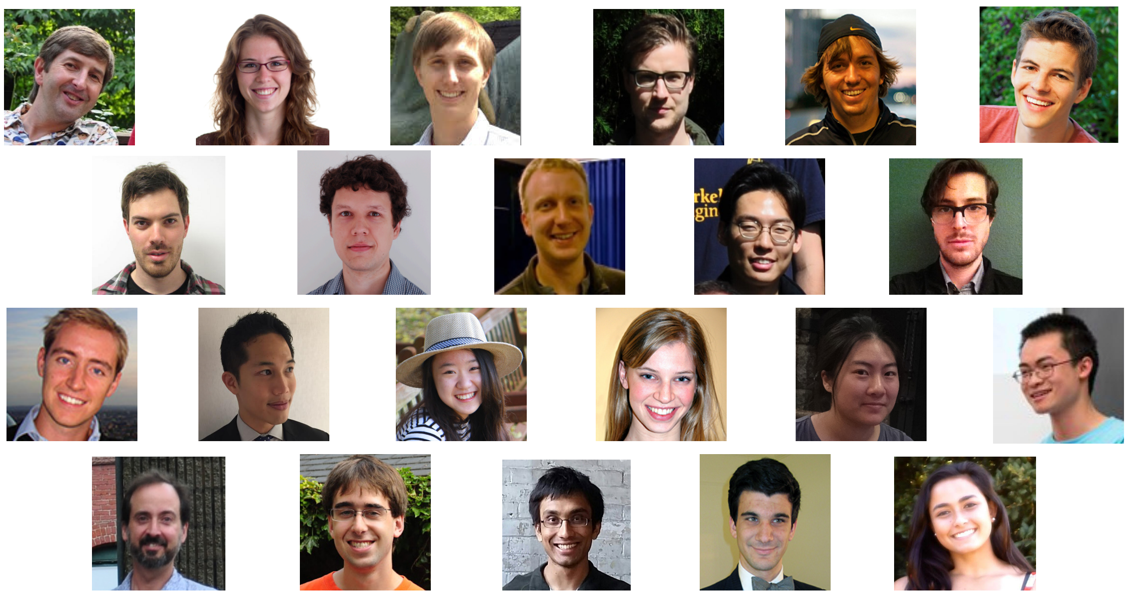
  => cosmology applications, e.g., measure Hubble drift?

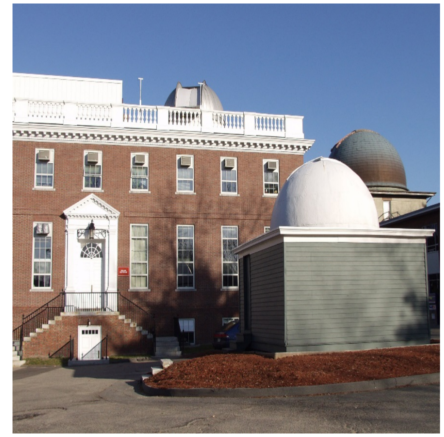
- Future

  Directional detection of dark matter with quantum defects in diamond

  => detect WIMPs below "neutrino floor"

Walsworth Group



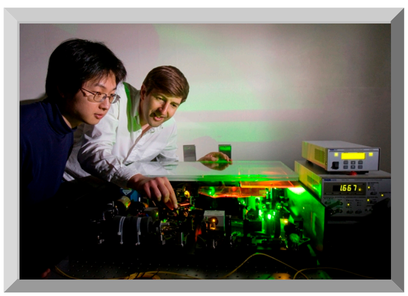


Center for Astrophysics

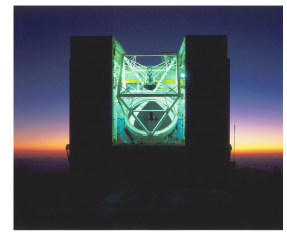
Harvard Physics &
Center for Brain Science

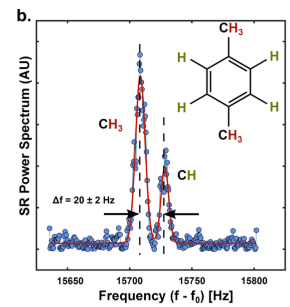
Building bridges…

Quantum tools for
precision measurement

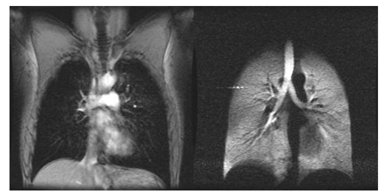


High-impact(?)
applications

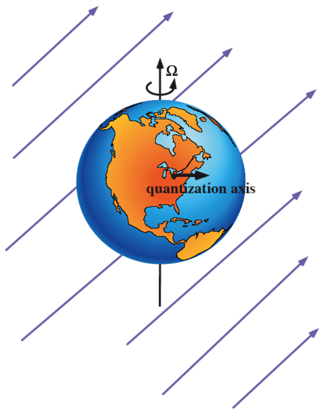




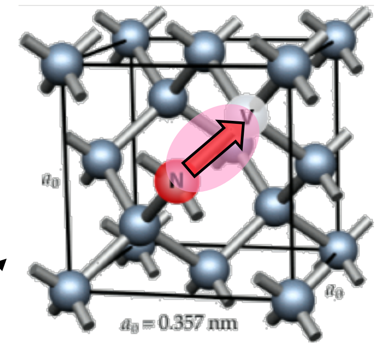
What we do



novel NMR & MRI methods

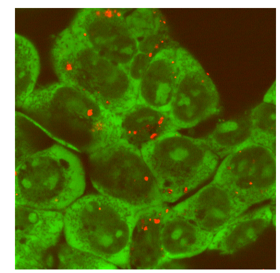


fundamental physics
& cosmology



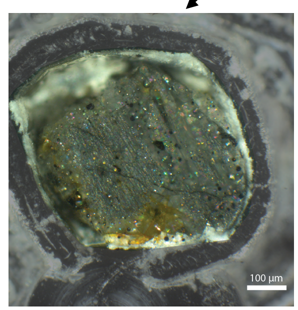
quantum sensors

Develop & apply tools for precision measurement

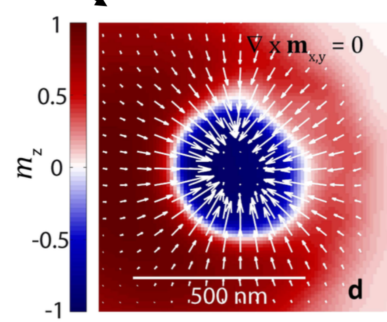


neuroscience
& cell biology

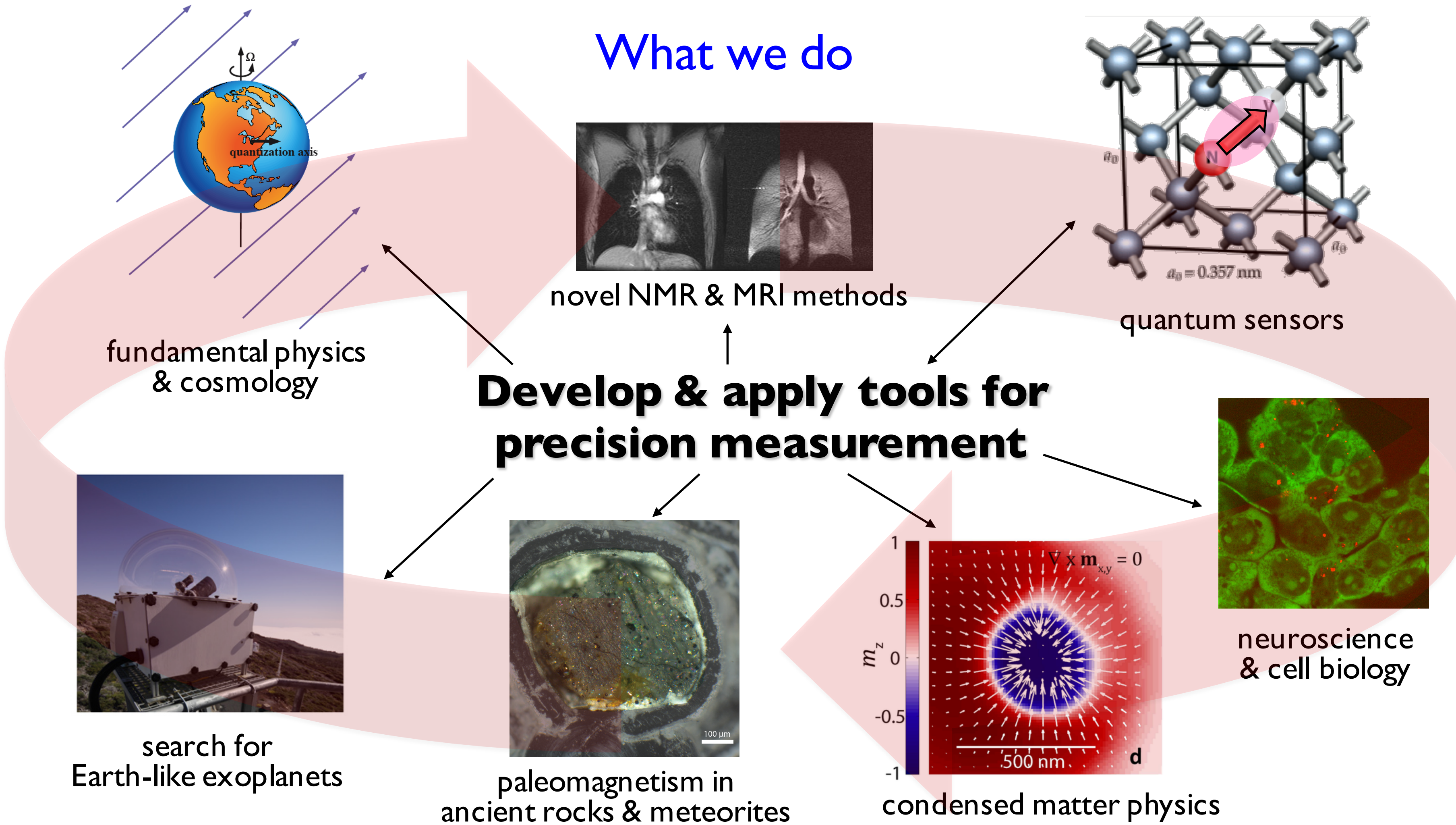
search for
Earth-like exoplanets



paleomagnetism in
ancient rocks & meteorites



condensed matter physics

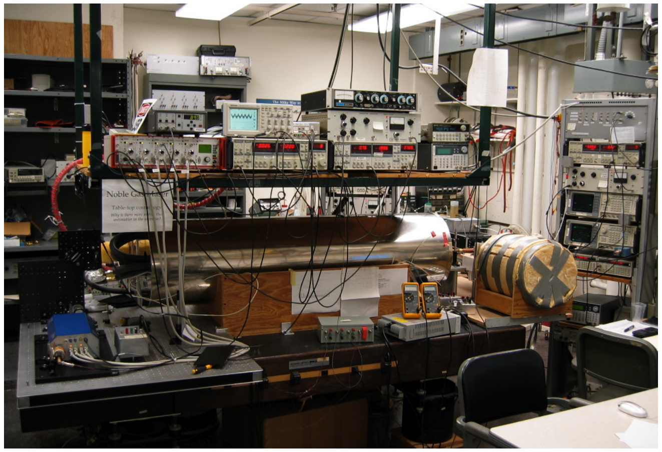

What we do
Develop & apply tools for precision measurement
novel NMR & MRI methods
quantum sensors
$a_0 = 0.357$ nm
neuroscience & cell biology
condensed matter physics
$\nabla \times \mathbf{m}_{x,y} = 0$
m_z
500 nm
paleomagnetism in ancient rocks & meteorites
100 μm
search for Earth-like exoplanets
fundamental physics & cosmology
quantization axis

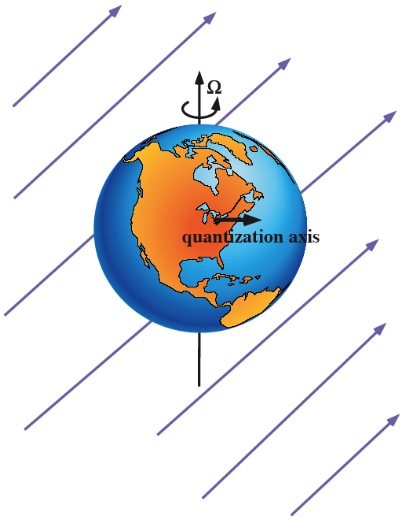
Past

Atomic clocks

=> Lorentz/CPT symmetry tests

1990 - 2008





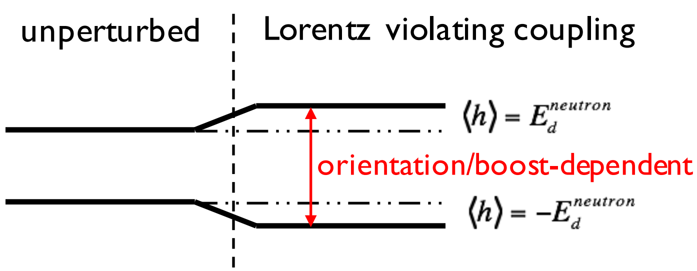
^{3}He & ^{129}Xe masers:
low-magnetic-field NMR, active oscillators
10^{-3} Hz linewidth, 10^{-8} Hz precision

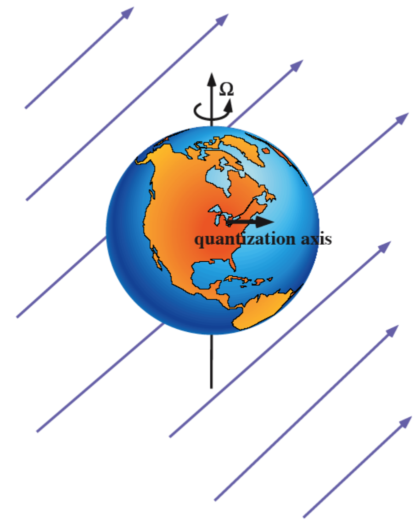
Atomic clocks

=> Lorentz/CPT symmetry tests

1990 - 2008

Nuclear Zeeman masers, spin 1/2





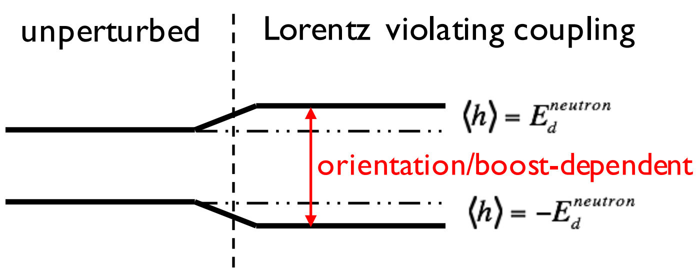
^3He & ^{129}Xe masers:
low-magnetic-field NMR, active oscillators
10^{-3} Hz linewidth, 10^{-8} Hz precision

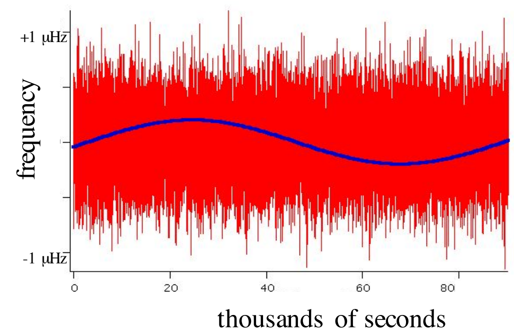
Atomic clocks
=> Lorentz/CPT symmetry tests

1990 - 2008

Bear et al., *PRL* (2000)
Phillips et al., *PRL* (2001)
Cane et al., *PRL* (2004)

Nuclear Zeeman masers, spin 1/2





^{3}He & ^{129}Xe masers:
low-magnetic-field NMR, active oscillators
10^{-3} Hz linewidth, 10^{-8} Hz precision

Best laboratory tests (till 2010) of Lorentz/CPT symmetry:
=> neutron limit ~10^{-31} GeV
proton limit ~10^{-27} GeV (H maser)

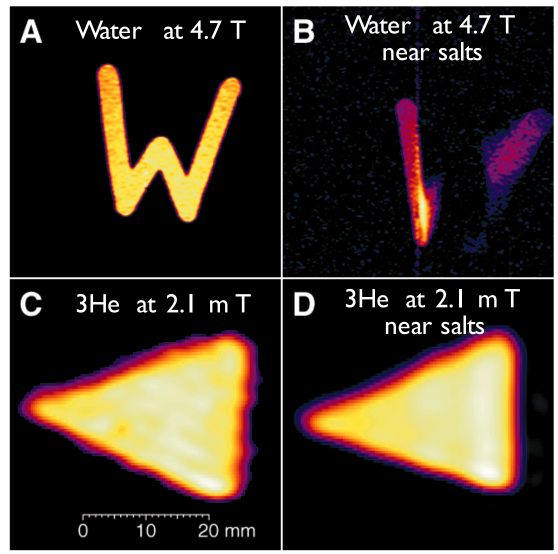
Low-field, low-cost MRI
=> spin-off of Lorentz/CPT symmetry test

2.1 mT electromagnet MRI at CfA
(repurposed noble gas maser)

1998

(first idea in 1995)

Tseng et al., *PRL* (1998)



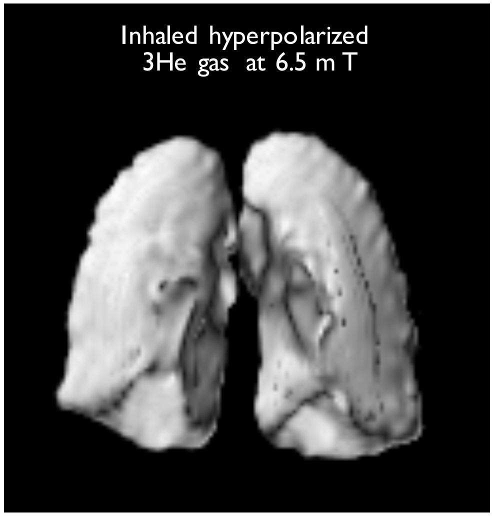
Low-field, low-cost MRI
=> spin-off of Lorentz/CPT symmetry test

2008

6.5 mT MRI in physics lab:
walk-in human lung imager

Tsai et al., *JMR* (2008)

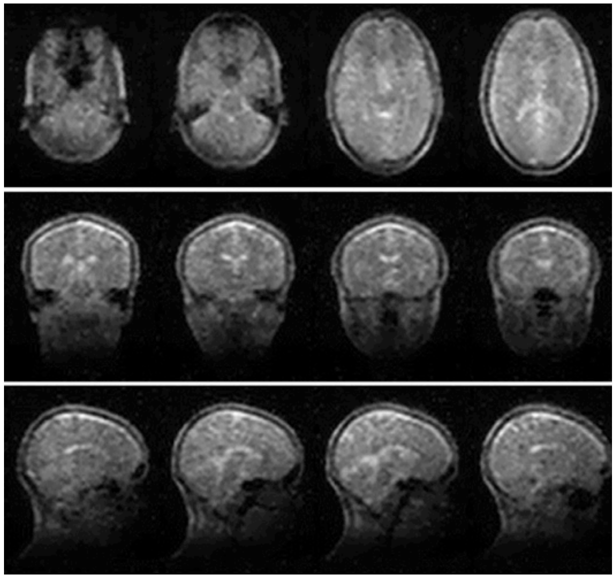
First system to allow lung imaging in both horizontal & vertical orientations



Low-field, low-cost MRI
=> spin-off of Lorentz/CPT symmetry test

Matt Rosen

2014

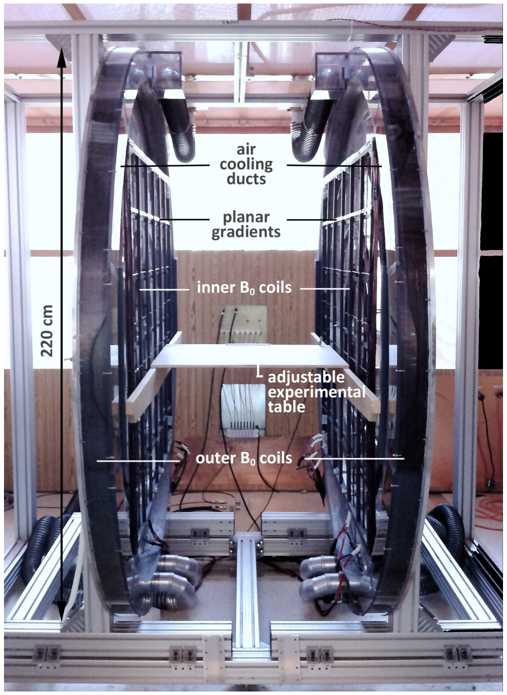


Human brain imaging
in low-field, low-cost system
resolution ~2 mm

1) Physics:
Optimized data rate (like maser)

2) Compute:
- Pattern matching of dynamics
- Deep learning image reconstruction

Nature (2018)



6.5 mT human MRI
at Mass General Hospital

Present

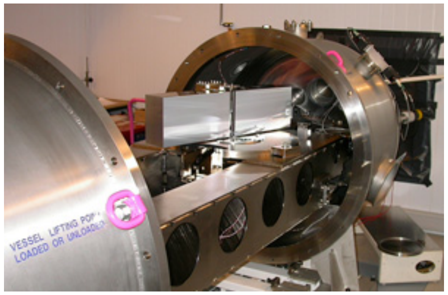
Discovery of exo-Earths

Two big problems:

1) “Non-quantum” wavelength calibrator => RV ~1 m/s
   But Earth & Venus RV ~10 cm/s

2) “Stellar jitter”
   => RV noise ~ 1 m/s

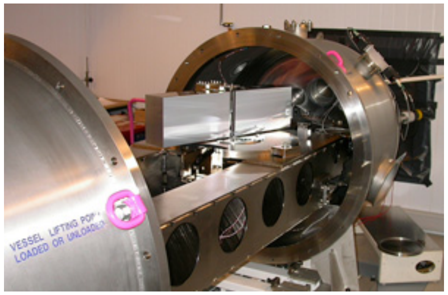
HARPS-N spectrograph



TNG telescope
Canary Islands

Discovery of exo-Earths

HARPS-N spectrograph



TNG telescope
Canary Islands

Astro-comb wavelength calibrator
=> RV ~1 cm/s

2008-2014:
technology maturation
=> ~1 cm/s RV calibration

Facility instrument at TNG telescope

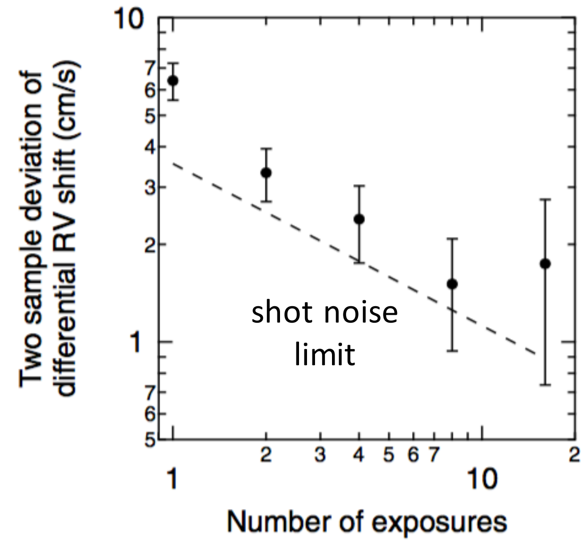
Research Article Vol. 2, No. 3 / March 2015 / *Optica* 250

optica

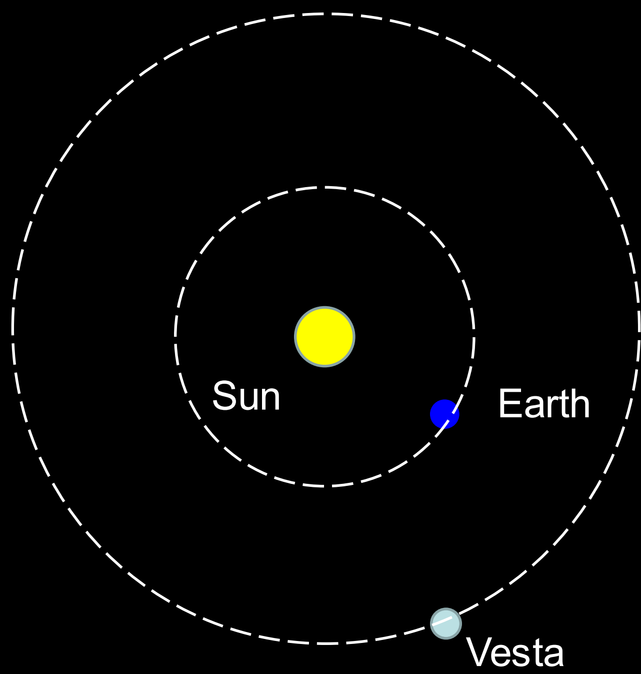
Operation of a broadband visible-wavelength astro-comb with a high-resolution astrophysical spectrograph

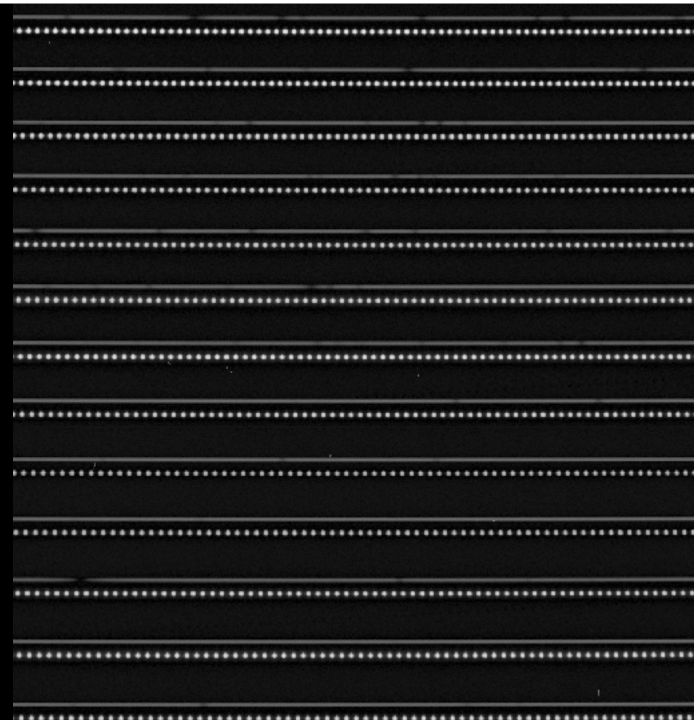
Alexander G. Glenday,[1,†] Chih-Hao Li,[1,†] Nicholas Langellier,[2] Guoqing Chang,[3,5] Li-Jin Chen,[4] Gabor Furesz,[1] Alexander A. Zibrov,[1] Franz Kärtner,[3,5] David F. Phillips,[1] Dimitar Sasselov,[1] Andrew Szentgyorgyi,[1] and Ronald L. Walsworth[1,2,*]

HARPS-N astro-comb
internal calibration ~1 cm/s

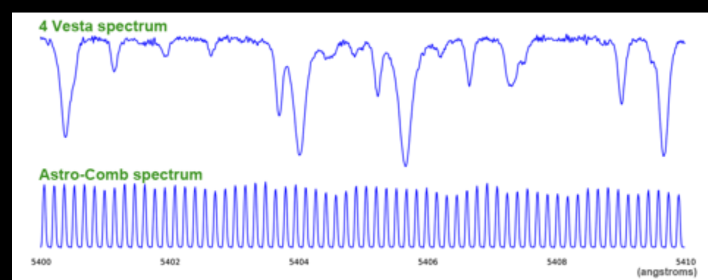


2014-2018: On sky with astro-comb





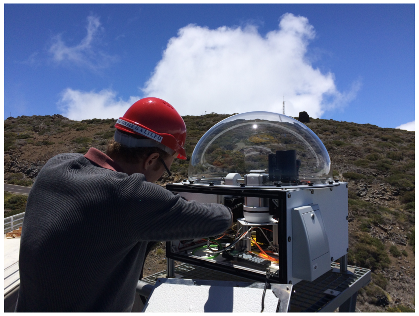
HARPS-N spectra



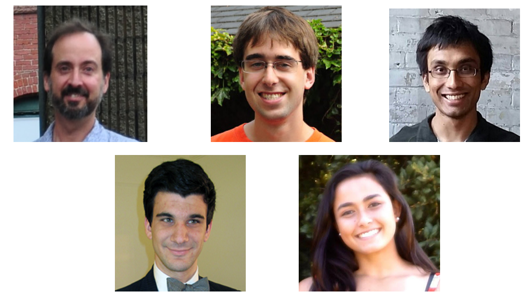
Small section of extracted 1D science & calibration spectra

Sun-as-a-Star => Discovery of exo-Earths

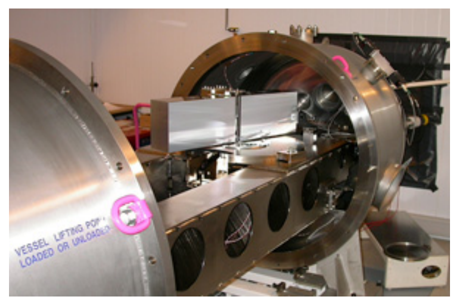
Small solar telescope mounted on TNG exterior



1) Characterize stellar jitter of Sun
2) RV detection of Venus
3) Apply to other Sun-like stars



HARPS-N spectrograph



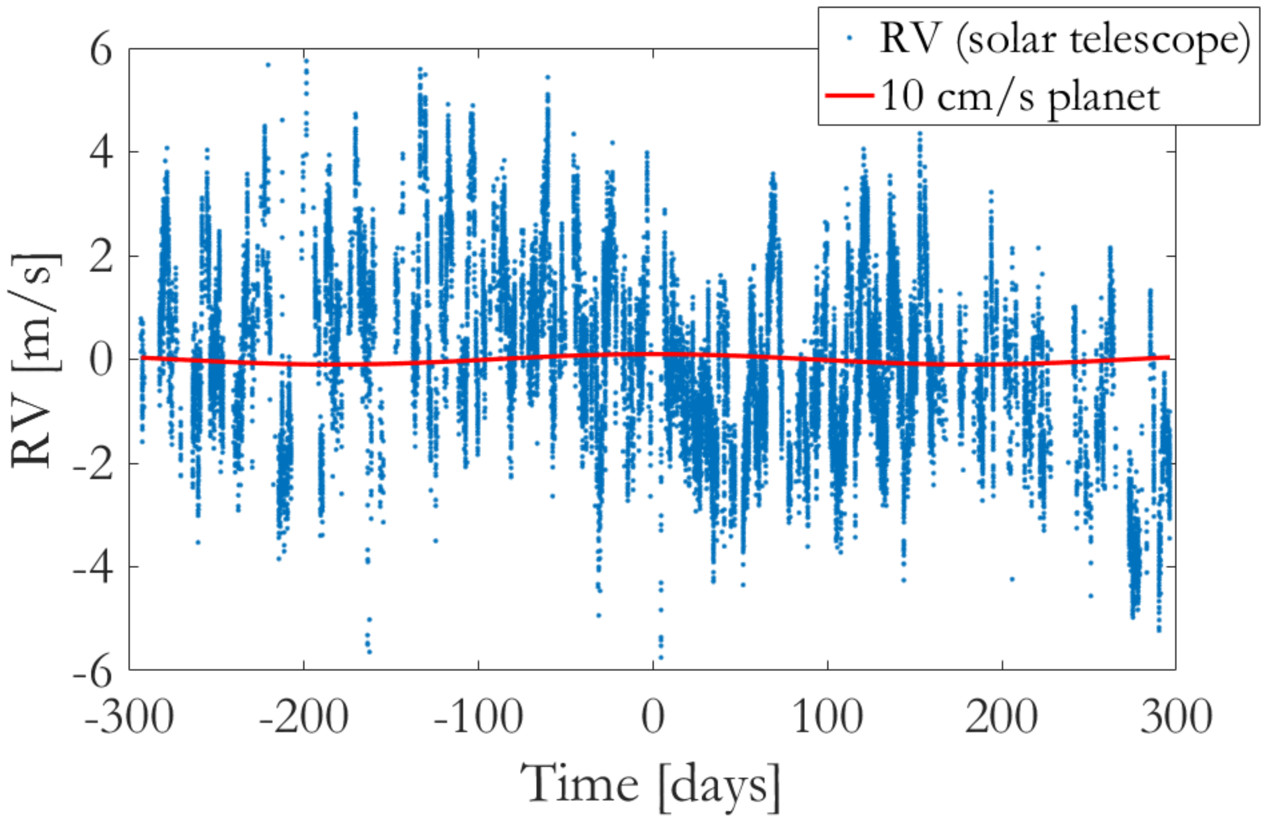
Astro-comb wavelength calibrator
=> RV ~1 cm/s

TNG telescope
Canary Islands

Solar telescope

- Solar telescope operating at TNG/HARPS-N since July 2015
- 3” refracting telescope
- Feeds integrating sphere to scramble the full disk of Sun
- Housed in weather-proof enclosure on TNG dome
- Fiber-coupled to calibration unit of HARPS-N
- Operates during the day - HARPS-N is otherwise unused

2+ years of data…work in progress…



Precision astrophysical spectroscopy
=> applications to cosmology & fundamental physics?

Assume we can apply RV ~1 cm/s instrumental precision & stability to astrophysical sources of interest over 3 years
=> measure accelerations ~10^{-8} cm/s^2

?

- Change of cosmic expansion rate over time
  ~1 cm/s per year ~3×10^{-8} cm/s^2
  => real-time measure of cosmological dynamics => direct measure of H(z)
  => determine total matter content + independent measure of dark energy

Sandage-Loeb test

?

?

- Galactic rotation acceleration ~10^{-8} cm/s^2
  => map stellar motion dynamics => direct map of dark matter?

'beyond Gaia'

- Dark matter perturbations of 'hi-Q' periodic astro phenomena,
  e.g., binary stars, hypervelocity stars in Milky Way halo
  => dark matter density variations, total dark matter content in Milky Way

?

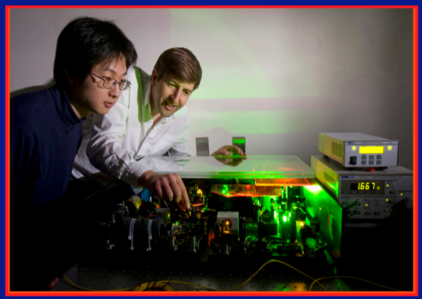
?

- Your idea here…

?

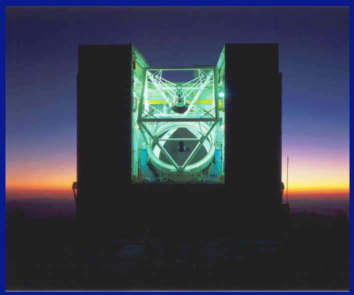
Measuring Cosmological Dynamics in Real Time (Hubble drift): Sandage-Loeb Test

- Change in galaxy redshifts – impractical (Sandage 1962)
- Shift in Lya forest (Loeb 1998) – measurable in ~ 100 years
- Astro-comb => 10 years with next-gen (20+ m) telescope



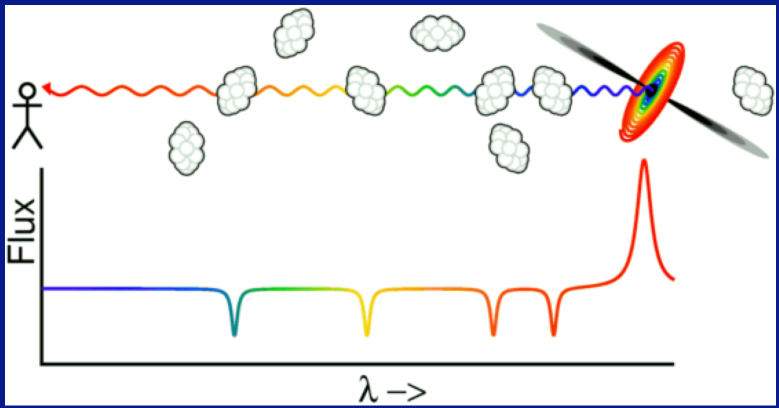
astro-comb

+

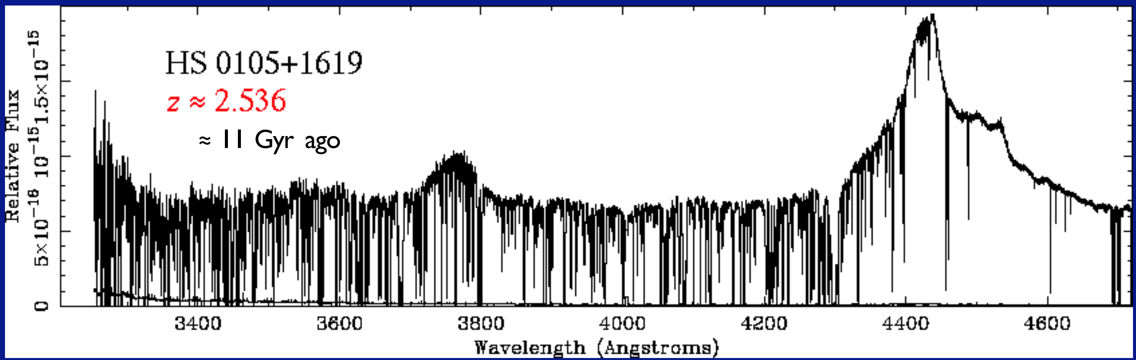


next-gen telescope

Measuring Cosmological Dynamics in Real Time (Hubble drift):
Sandage-Loeb Test

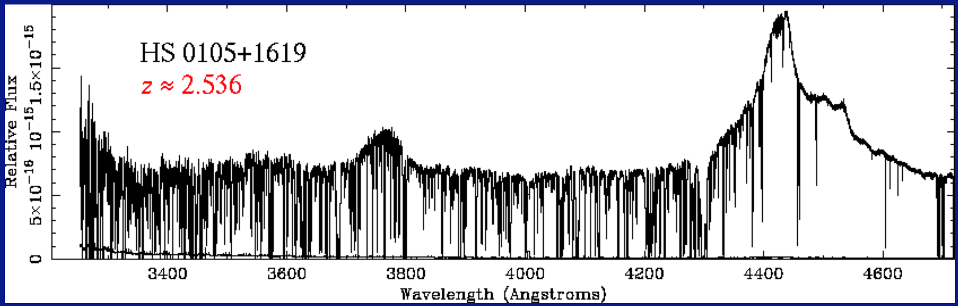


Quasars in early universe illuminate intervening H clouds



Lyman-α forest of spectral lines

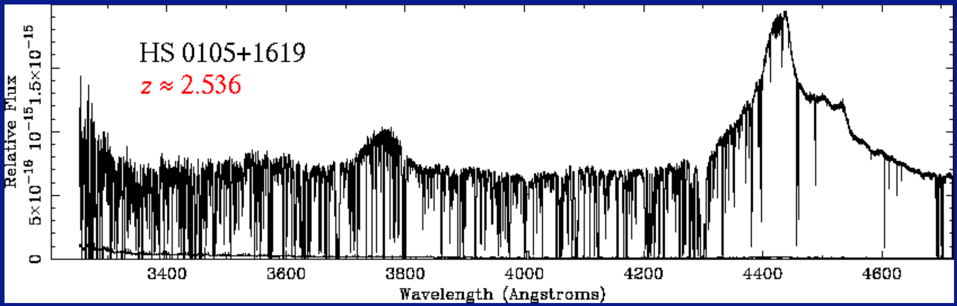
Measuring Cosmological Dynamics in Real Time (Hubble drift):
Sandage-Loeb Test



today

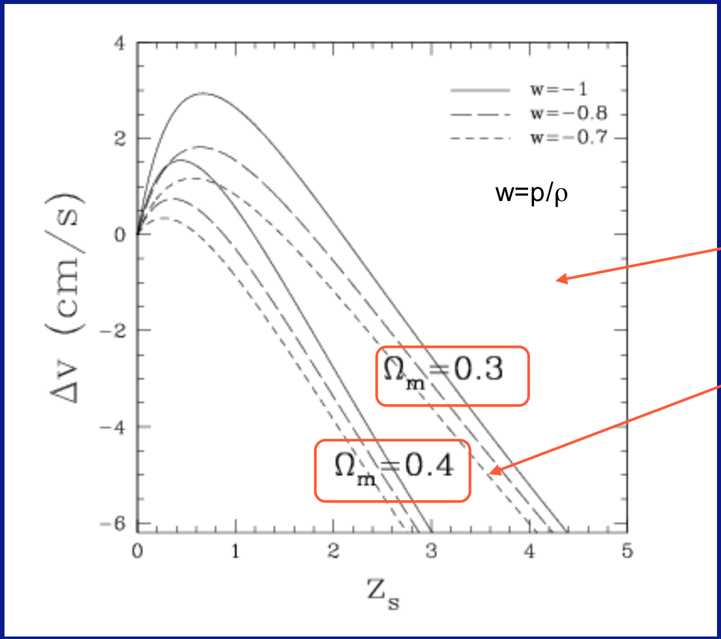
<= blueshift (less redshift) due to deceleration of the universe <=

~1 cm/s per year measurable only with astro-comb



measure a few years later

Measuring Cosmological Dynamics in Real Time (Hubble drift): Sandage-Loeb Test



- Directly determine H(z)
- Determine total matter content of universe
- Unique sensitivity to dark energy effects at z ≈ 2 – 5

Corasaniti, Huterer, & Melchiorri 2007

Future

PHYSICAL REVIEW D **94**, 124043 (2016)

Gravitational wave detection with optical lattice atomic clocks

S. Kolkowitz,[1,*] I. Pikovski,[2,3] N. Langellier,[2] M. D. Lukin,[2] R. L. Walsworth,[2,4] and J. Ye[1,†]

Shimon Kolkowitz
U Wisconsin

NV color centers in diamond

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]

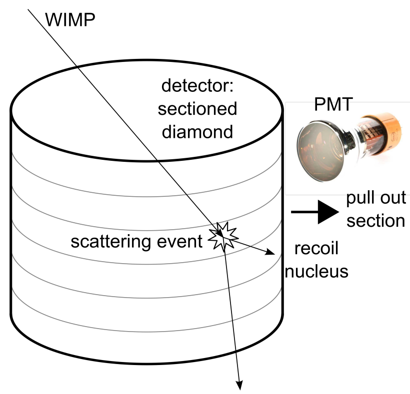
High energy theorists

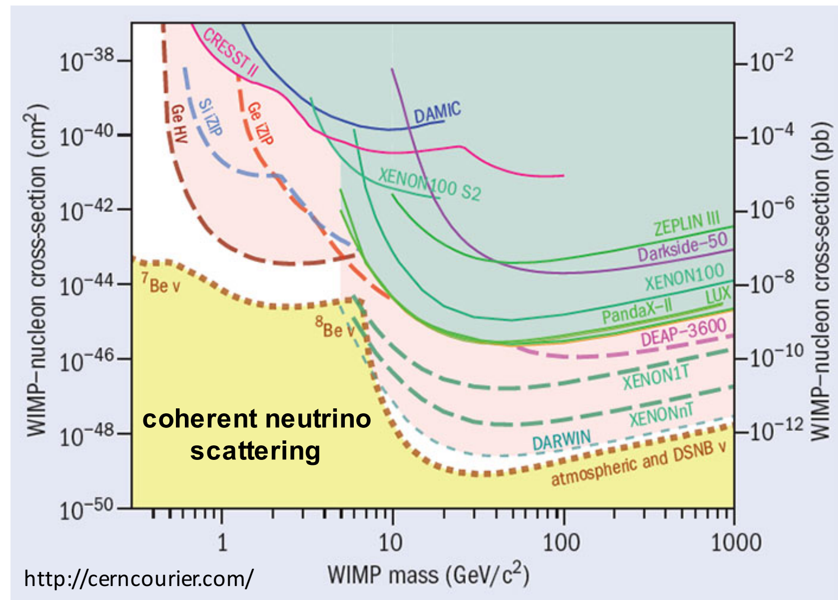
AMO/quantum types

James Battat, Wellesley
DRIFT experiment
(directional WIMP
gas-phase detector)

Directional detection of small x-section WIMPs

a “bubble chamber” in diamond



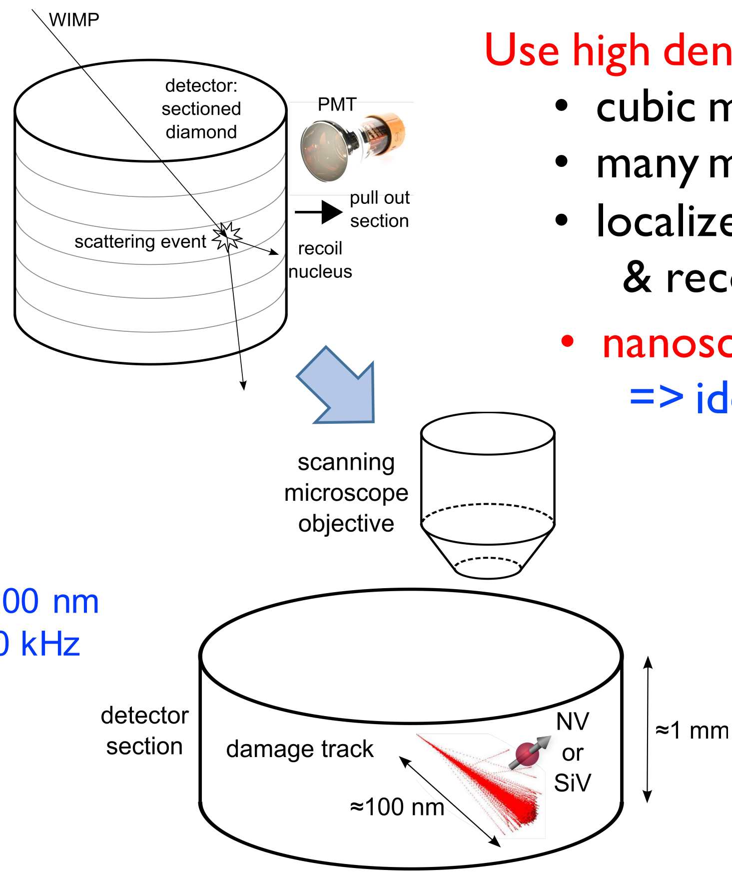


Next-gen WIMP searches limited by neutrino floor

Our method: distinguish WIMPs from neutrinos with directional detector

Directional detection of small x-section WIMPs

a "bubble chamber" in diamond



Use high density of NVs in diamond

- cubic meter
- many millimeter-scale sections
- localize section with scintillation & record event time
- nanoscale strain imaging w/ NVs
  => identify damage track due to WIMP

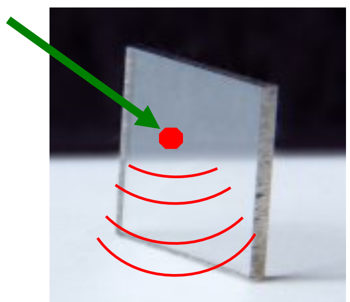
WIMP interaction with carbon nuclei (~10 keV)

=> stable damage track ~ 100 nm
=> NV frequency shifts ~ 30 kHz
easily observable

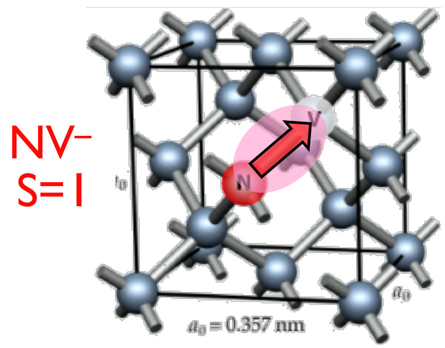
What is an NV color center?

Atom-like defect in diamond:

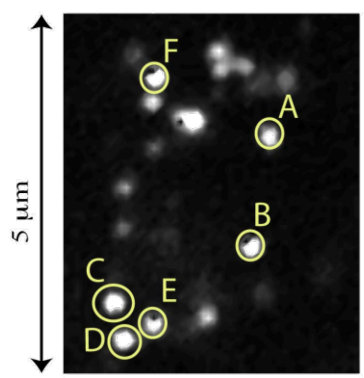
- Fluorescent point quantum defect
- Stable, single photon emitter
- Electronic spin (S=1) with long coherence time ~1 ms at room temp
- Optically detected magnetic resonance (ODMR) => B, E, T sensor



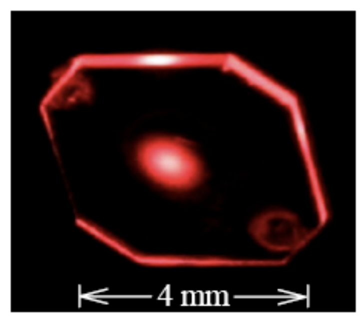
red fluorescence



4 crystal axes

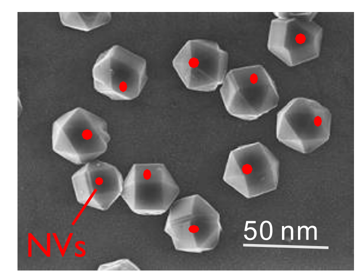


Confocal: individual NVs in diamond



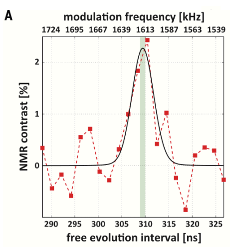
Dense NV ensemble in bulk diamond

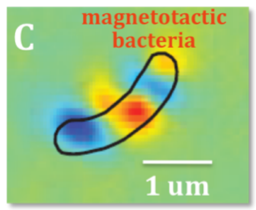
Nanodiamonds



NV-diamond sensing highlights (at Harvard)

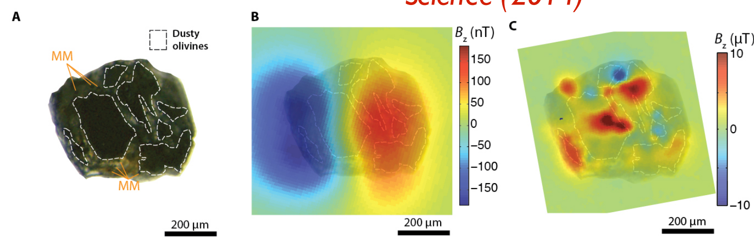
Single protein NMR
Science (2016)



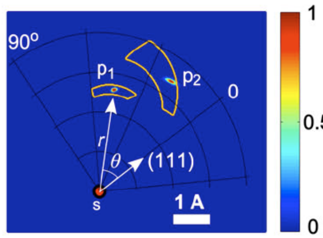


Live cell
magnetic imaging
Nature (2013)

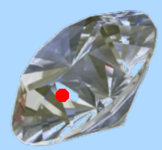
Magnetic fields in early solar system
Science (2014)



Single proton MRI
PRL (2014)

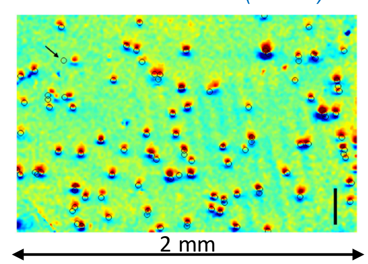


Nitrogen vacancy (NV)
quantum defect in diamond

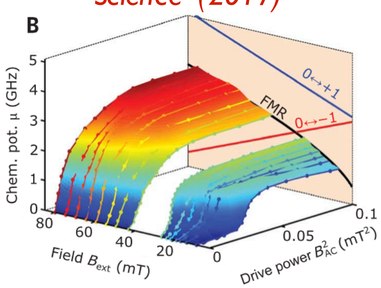


Nanoscale sensor of B, E, T

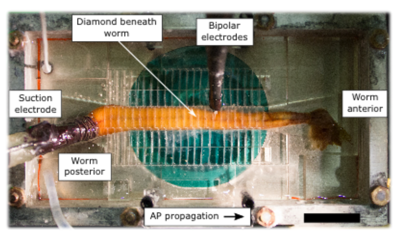
High-fidelity bioassay
Nature Methods (2015)

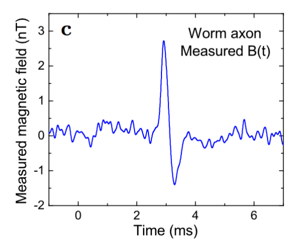


Spin chemical potential in magnetic insulator
Science (2017)

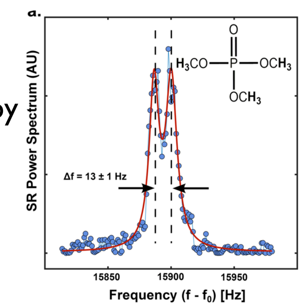


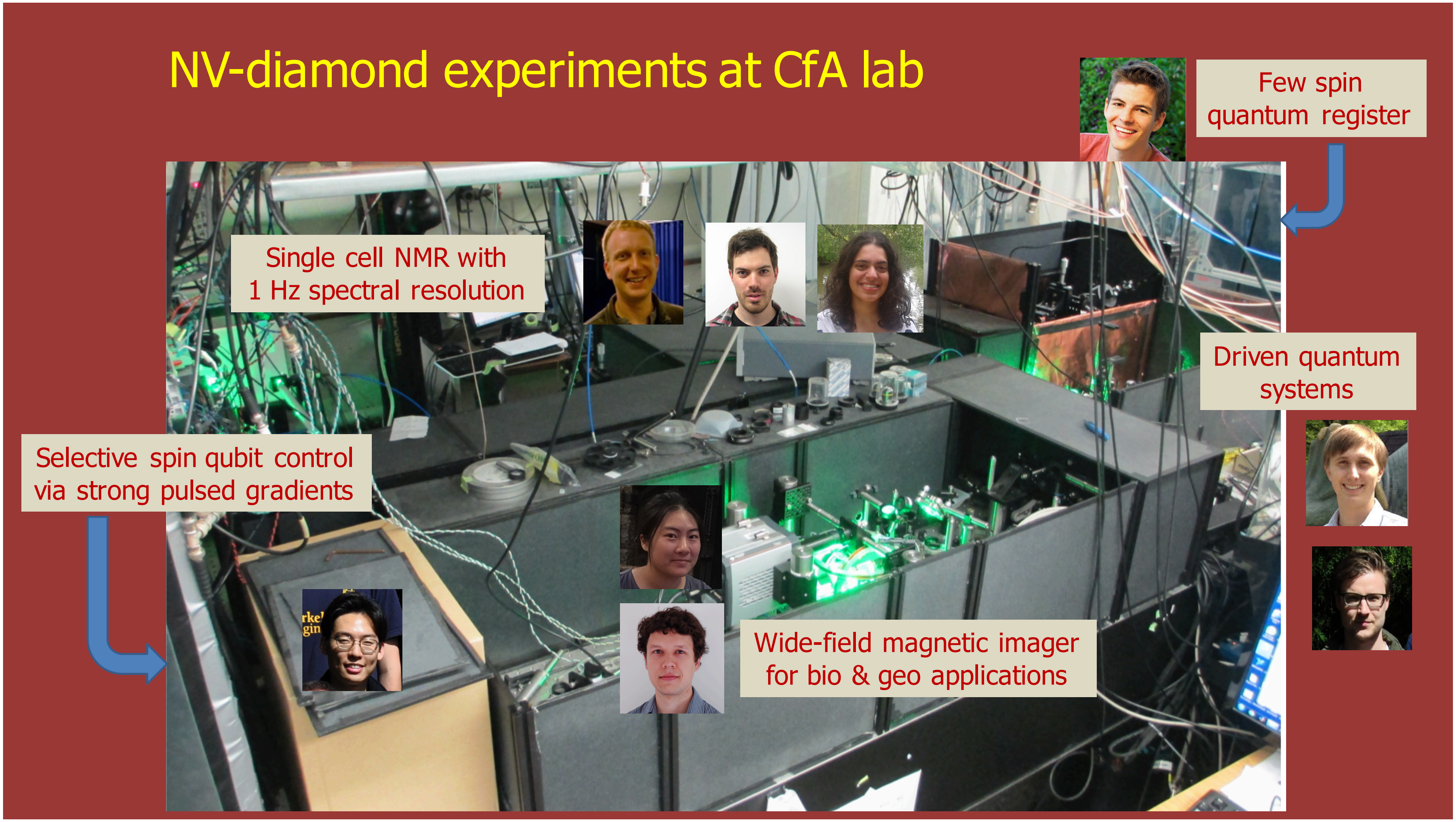
Neuroscience
PNAS (2016)





Single-cell-scale
NMR spectroscopy
Nature (2018)

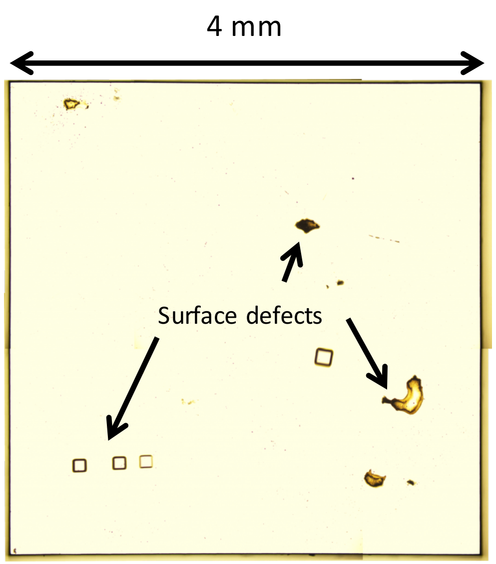



NV-diamond experiments at CfA lab
Few spin quantum register
Single cell NMR with 1 Hz spectral resolution
Driven quantum systems
Selective spin qubit control via strong pulsed gradients
Wide-field magnetic imager for bio & geo applications

Preliminary work #1: NV strain mapping, 400 nm resolution, 4 mm field-of-view

~100 kHz strain-induced NV frequency shifts typical

Macroscopic diamond chip
with dense NV surface layer
& many induced strain features

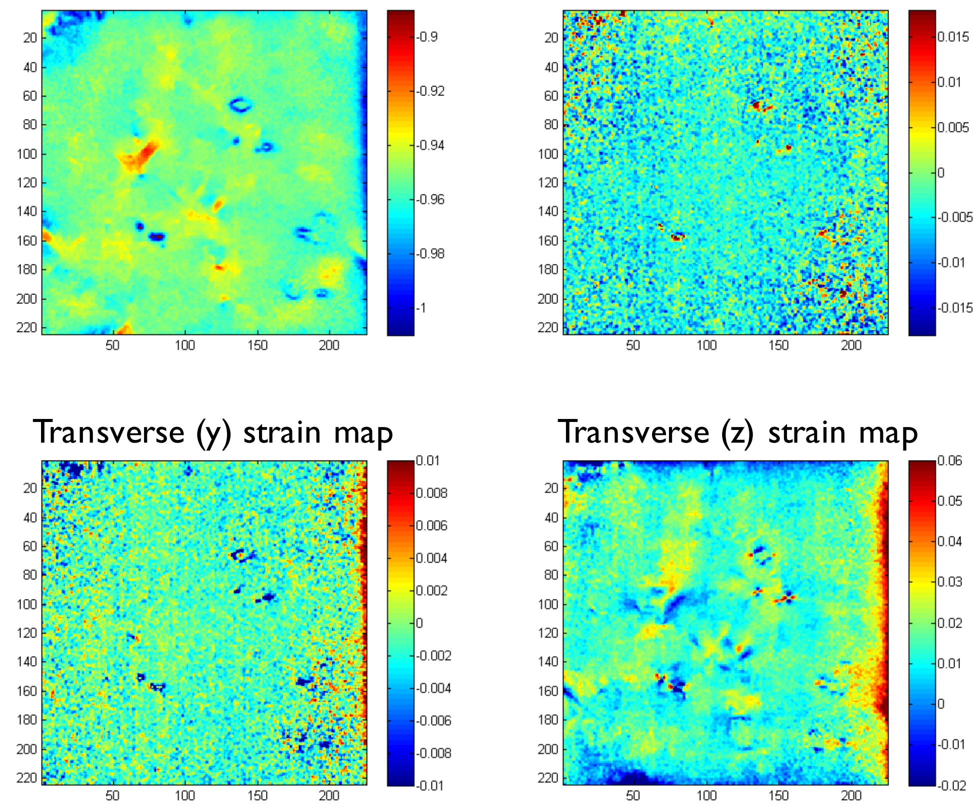


Longitudinal strain map

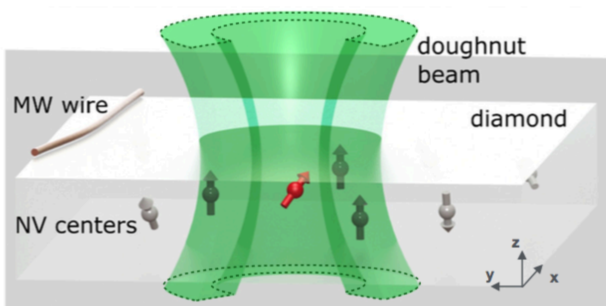
Transverse (x) strain map

Transverse (y) strain map

Transverse (z) strain map



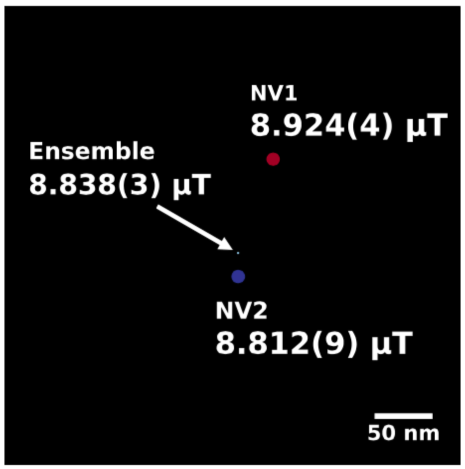
Preliminary work #2: NV nanoscale magnetic sensing

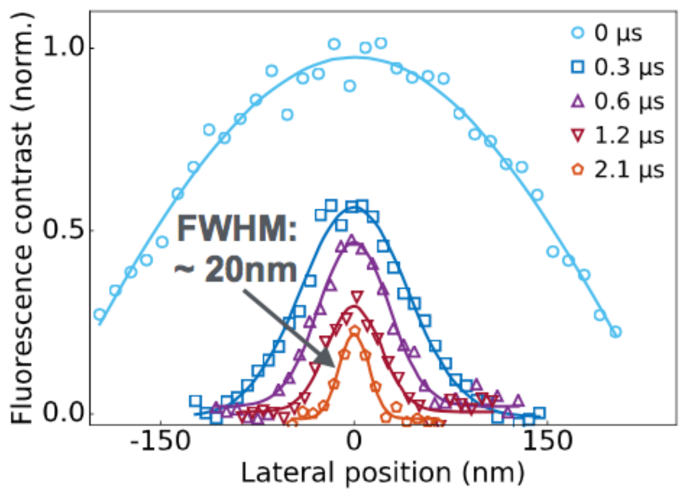


spin-RESOLFT using scanned doughnut laser beam

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

Jaskula et al.,
Optics Express (2017)

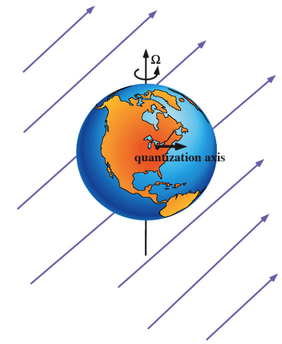




Challenges — from near to long term

- Nanoscale strain imaging with high density of NVs
- Identify strain tracks & reconstruct incoming particle direction in mm-scale diamond
- Make scintillation work in segmented diamond (surfaces?)
- Localize events to < 1 mm^3 via scintillation, etc.
- Shield external backgrounds
- Reduce internal backgrounds (from ^{14}C, etc.)
- Do everything efficiently
- Scale up

Thank you



- Past

  Atomic clocks

  => tests of Lorentz & CPT symmetry ~ 10^{-31} GeV

- Present

  Laser frequency combs

  => detect exo-Earths & measure Hubble drift?

- Future

  Detect WIMPs below "neutrino floor" with NV-diamond?