Precision Measurements with Large Quantum Systems

Michael Romalis

Princeton University

Outline

- Precision Frontier
- LIGO - the largest quantum-limited experiment
  - ⇒Practical lessons
- Future precision measurements
  - ⇒Scaling-up existing table-top systems
  - ⇒Noise!
  - ⇒Organizational and funding issues
- Possible approaches
  - ⇒Small → medium-scale experiments
  - ⇒University-based research facilities
  - ⇒National lab technical expertise

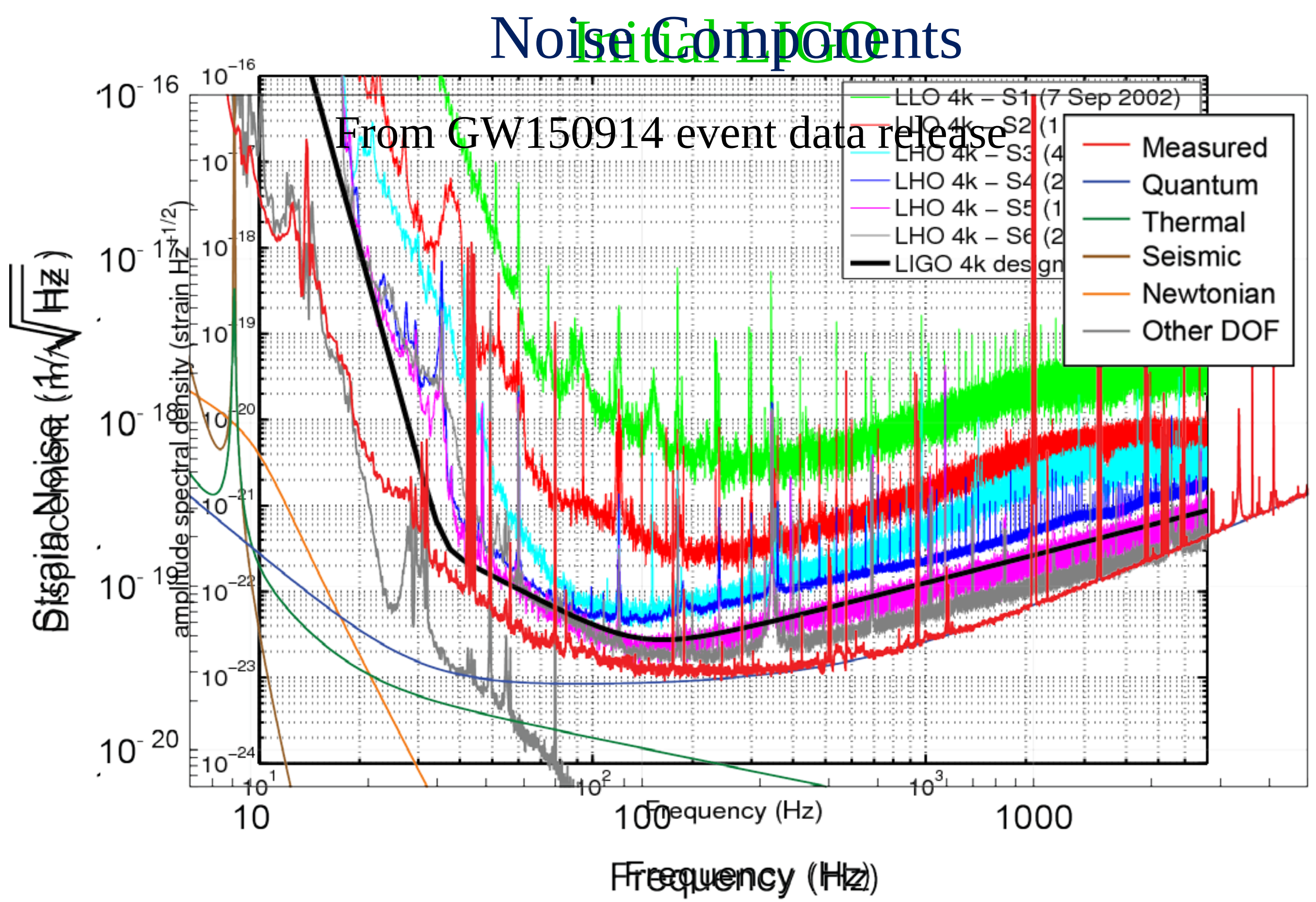
Precision Frontier

- How can we scale-up precision quantum measurement techniques beyond table-top setups?
- Many old and new ideas for precision measurements and searches for new physics require much higher sensitivity than presently achievable
- Signal increases as N, quantum noise increases as $\sqrt{N}$, but classical noise increases also as N.

  $\Rightarrow$ *Need to work harder to beat classical noise for larger N.*

LIGO

- A table-top experiment scaled up to do something great!
  - ⇒A 20 year effort dedicated to beating down the noise



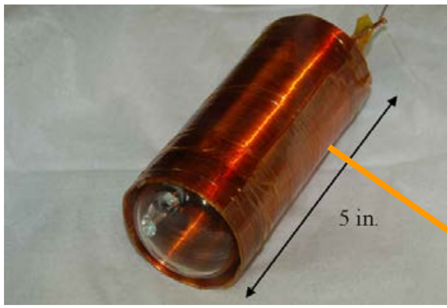
LIGO

- Examples of technical challenges
  - ⇒Vibration isolation by 10 orders of magnitude
  - ⇒Dissipation in materials
    - *Fluctuation-dissipation theorem* $\rightarrow$ *material losses = noise*
  - ⇒Precision manufacturing
  - ⇒Classical feedback and control systems

- Applicable to all precision measurements
  - ⇒Not very glamorous technical issues that require many years of dedicated efforts

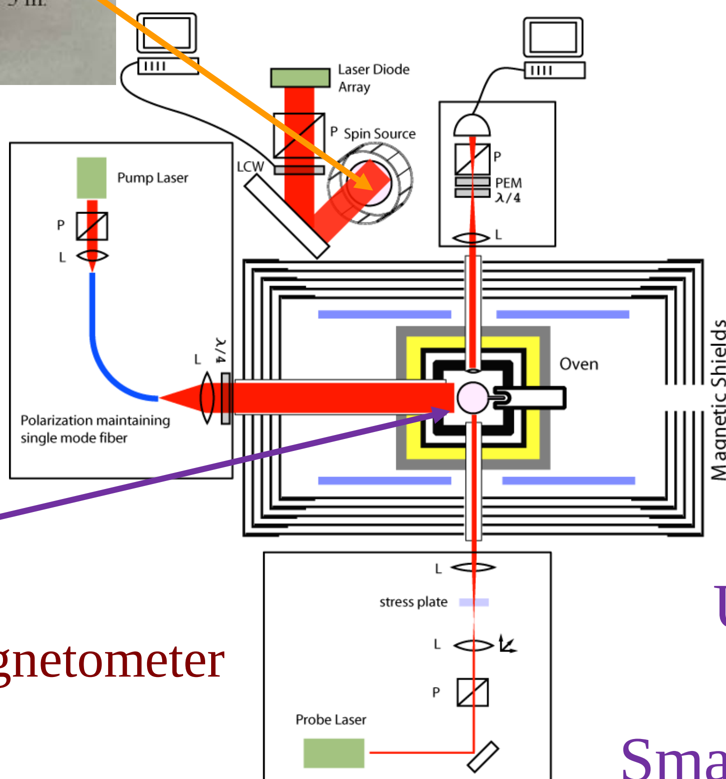
Precision measurements with a large number of atoms

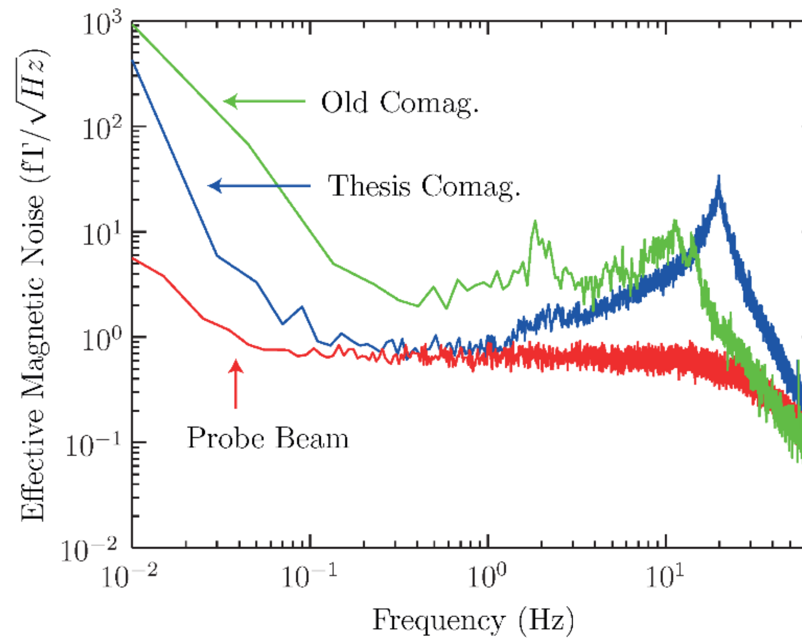
Search for new, nuclear spin-dependent forces

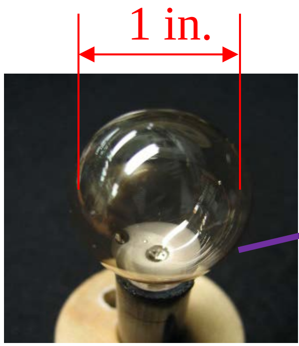


Spin Source:

10^{22} Polarized ^{3}He spins







K-^{3}He co-magnetometer

10^{14} K atoms

10^{21} ^{3}He atoms

Uncertainty (1σ) = 18 pHz =

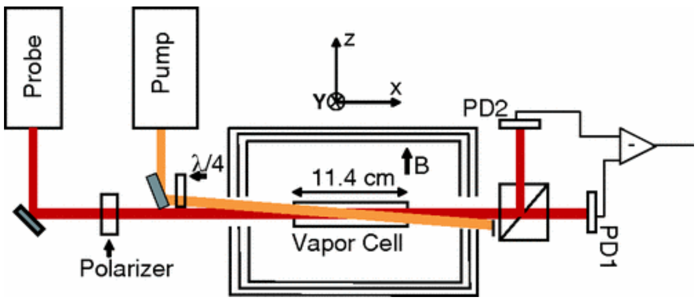
$4.3 \cdot 10^{-35}$ GeV = 0.5 aT

Smallest energy shift ever measured

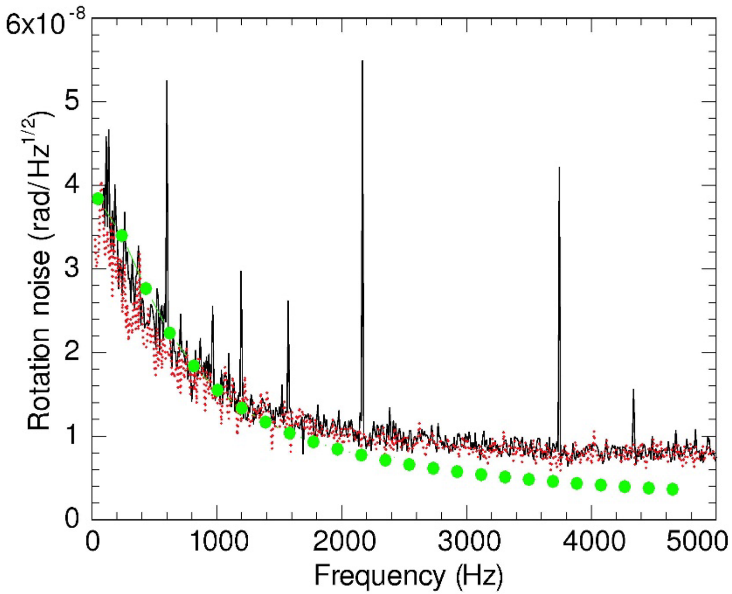
G. Vasilakis, J. M. Brown, T. W. Kornack, MVR, Phys. Rev. Lett. **103**, 261801 (2009)

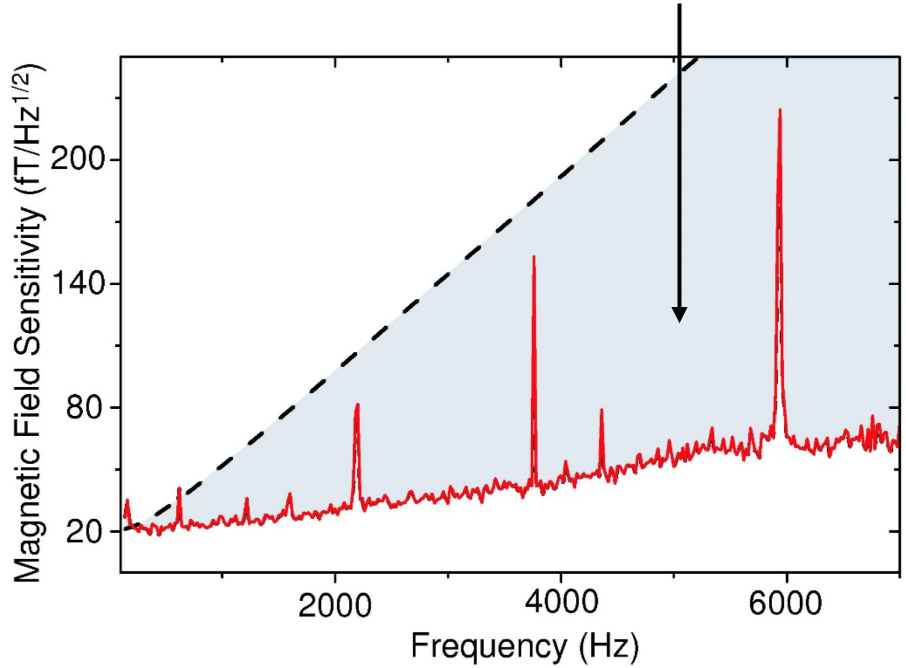
Quantum measurements with a large number of atoms

- Quantum non-demolition measurements of spin noise on $N = 2\times10^{13}$ Rb atoms.



⇒Used to increase the bandwidth of an atomic magnetometer



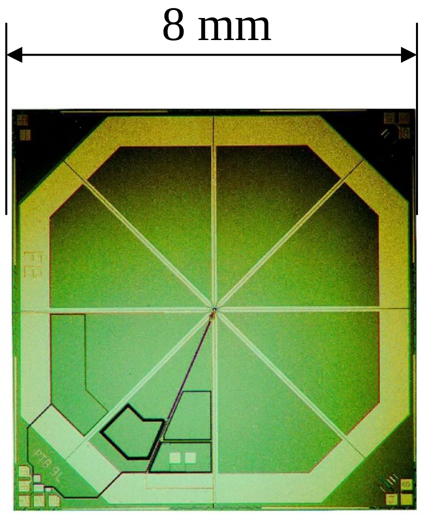


V. Shah, G. Vasilakis, and MVR, Phys. Rev. Lett. **104**, 013601 (2010)

Can we scale up these experiments?

- Yes, there are no fundamental or steep practical limits
  - ⇒Laser power used typically is tens of mW (vs. tens of W in LIGO)
  - ⇒Main impediments are classical sources of noise: laser noise, magnetic noise, vibration noise
  - ⇒Costs and engineering

- Another example: A SQUID from PTB:



  - ⇒SQUID with pick-up coil is typically < 1 cm^2
  - ⇒Can one fabricate a pick-up coil 1000 cm^2 or more in area and still be limited by fundamental noise?

Challenges

- Picking target experiments and techniques
  - ⇒While gravitational waves were pretty certain to exist, we have a number of possible, but uncertain targets:
    - * Symmetry violations (EDMs, etc)
    - * Dark matter candidates (Axions, WIMPS, etc)
    - * Other possible new particles or interactions

- Development of new precision measurement techniques is slow and can be expensive
  - ⇒Need the right mechanism for funding development work and scaling things up.
  - ⇒Need the right balance between Universities/graduate students vs. National Labs/permanent staff

Possible models

- University labs with DOE-supported research infrastructure facilities (e.g. CENPA at U. of Washington, home to ADMX and Project 8)
  - ⇒ Maintains key technical expertise
  - ⇒ Most physicists employed by the university

- Small targeted collaborations between universities and national labs focused on specific technical issues
  - ⇒ Avoid big collaborations and project management structure until technical issues are resolved.

Conclusions

LIGO uses ~10^{24} photons/sec.

Can we develop other quantum-limited systems that use that many particles?

Can we use them to find something new?