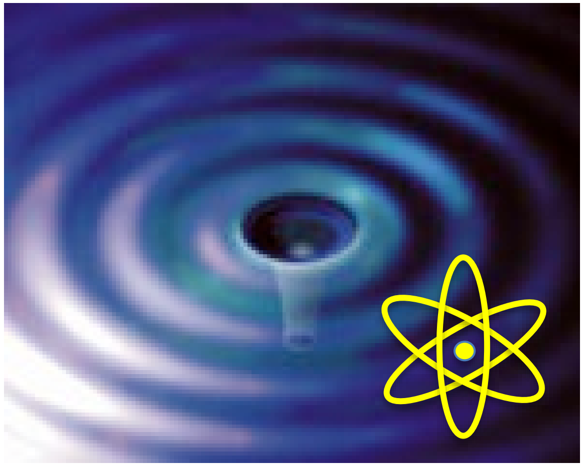
Drag-free Atomic Acceleration Reference for LISA Disturbance Reduction System

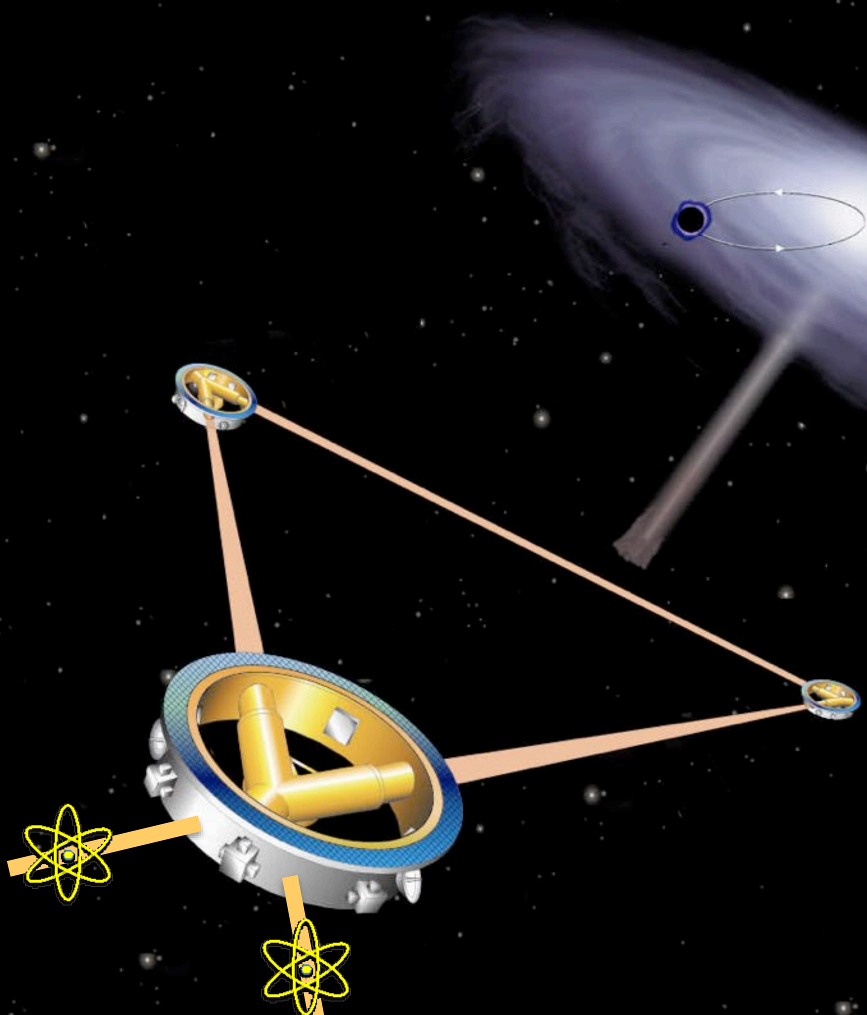
POC: Nan Yu
Email: nan.yu@jpl.nasa.gov
Phone: 818-354-4093

Jet Propulsion Laboratory
California Institute of Technology



This presentation has been reviewed not containing ITAR controlled materials.

Atom Interferometers for LISA DRS (aDRS)



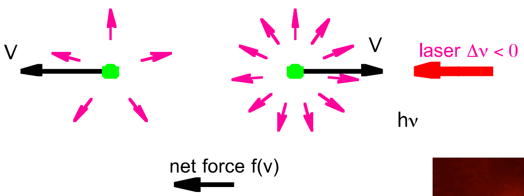
Big Idea: Truly drag-free atomic proof masses for LISA's Disturbance Reduction System (DRS).

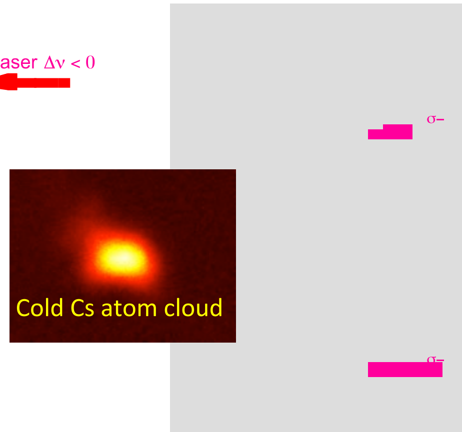
Approach: Atomic acceleration reference based atom-wave interferometry using laser-cooled free fall atoms.

Concept: Use atomic inertial sensors to replace the LISA accelerometers by measuring relative acceleration-induced displacements between ideal drag-free atoms and spacecraft accelerometers.

Goal: Reduce/eliminate spacecraft drag-free requirement and the associated complexity, risk, and cost, while potentially increase measurement bandwidth and higher science returns.

Light forces are used for cooling and trapping atoms

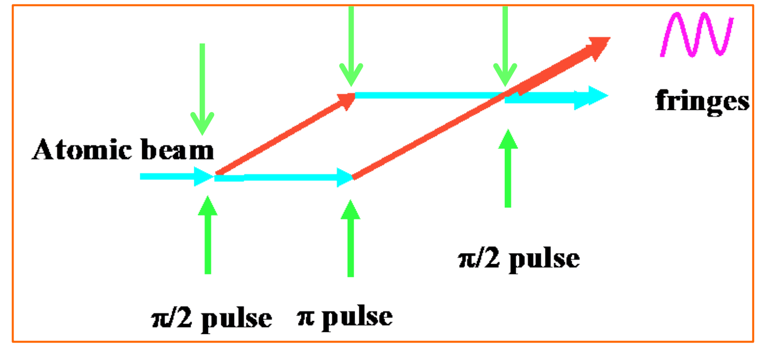




Cooling by Doppler (velocity)-dependent viscous force (top) and trapping by magnetic (spatial)-dependent light force (left).

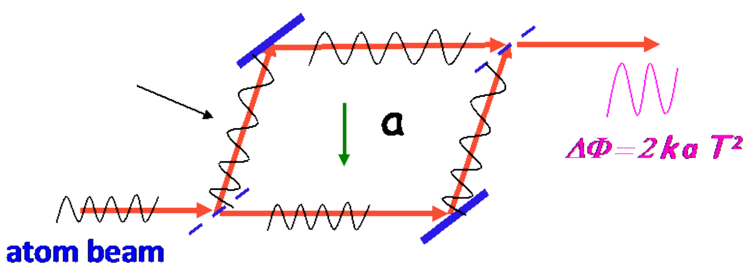
Magneto-optical trap (MOT)

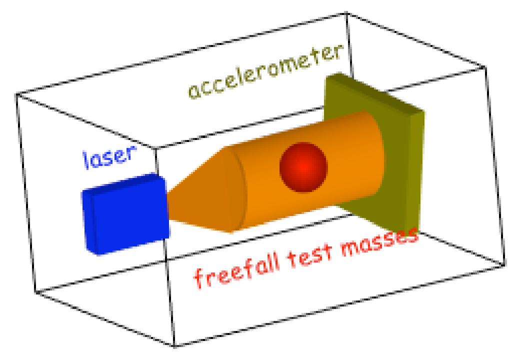
Light-atom interaction creates atom-wave optics



Acceleration/gravity sensing [Kasevich, 1991]

Phase shift due to acceleration $\Delta\Phi = 2kaT^2$

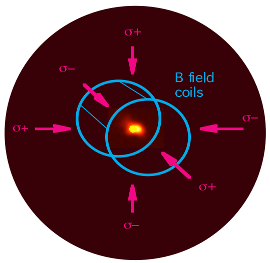




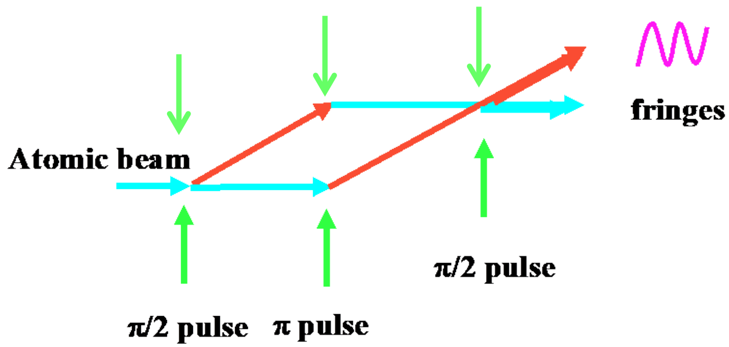
AI referenced accelerometer [Yu 2006]
(laser + atoms + retro-reflector)

Atom Interferometers – Salient Features and Benefits

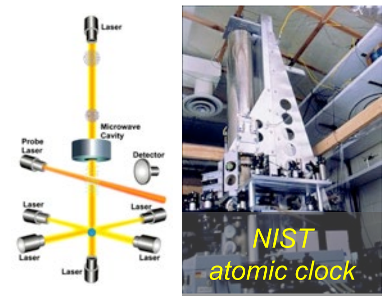
Free fall test mass + **Displacement Detection** + **Atomic system stability**



Laser-cooled Cs atom cloud at μK [Metcalf 1990]



atom-wave interferometer [Kasevich 1991]



Atoms are stable clocks [Jefferts, 2011]

- Use totally freefall atomic particles as ideal test masses

  , *identical atomic particles are collected, cooled, and set in free fall in vacuum with no external perturbation other than gravity/inertial forces; laser-cooling and trapping are used to produce the atomic test masses at μK and nK; no cryogenics and no mechanical moving parts.*

- Matter-wave interference for displacement measurements

  displacement measurements through interaction of lasers and atoms, pm/Hz$^{1/2}$ when in space; laser control and manipulation of atoms with opto-atomic optics.

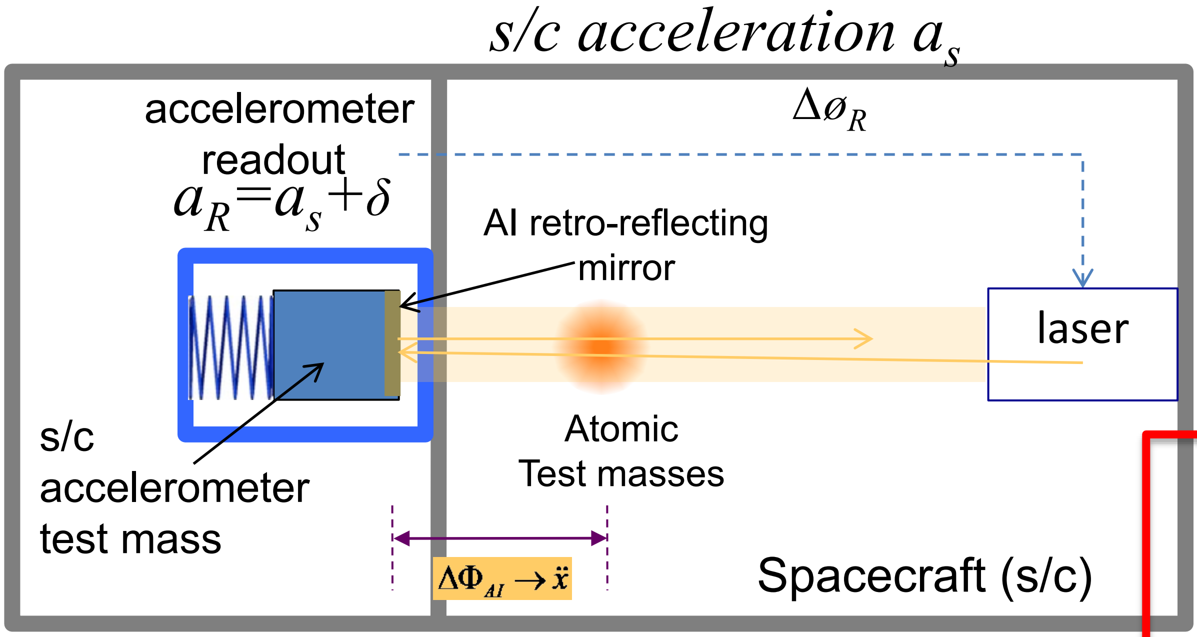
- Intrinsic high stability of atomic system

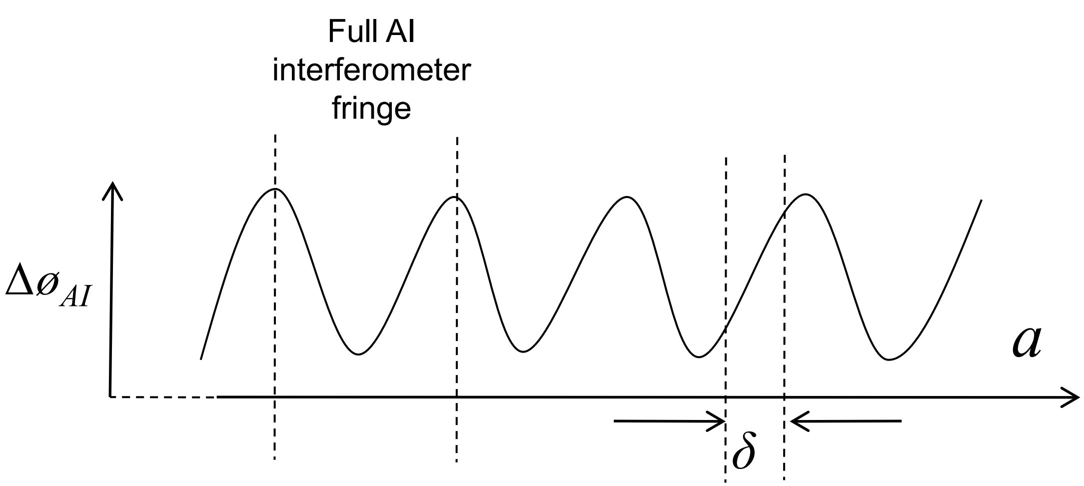
  use the very same atoms and measurement schemes as those for the most precise atomic clocks, allowing high measurement stabilities.

- Enable orders of magnitude sensitivity gain when in space

  microgravity environment in space offers long interrogation times with atoms, resulting orders of magnitude higher sensitivity compared terrestrial operations [Yu 2002].

What does an atom interferometer measure in Raman Pulse scheme?

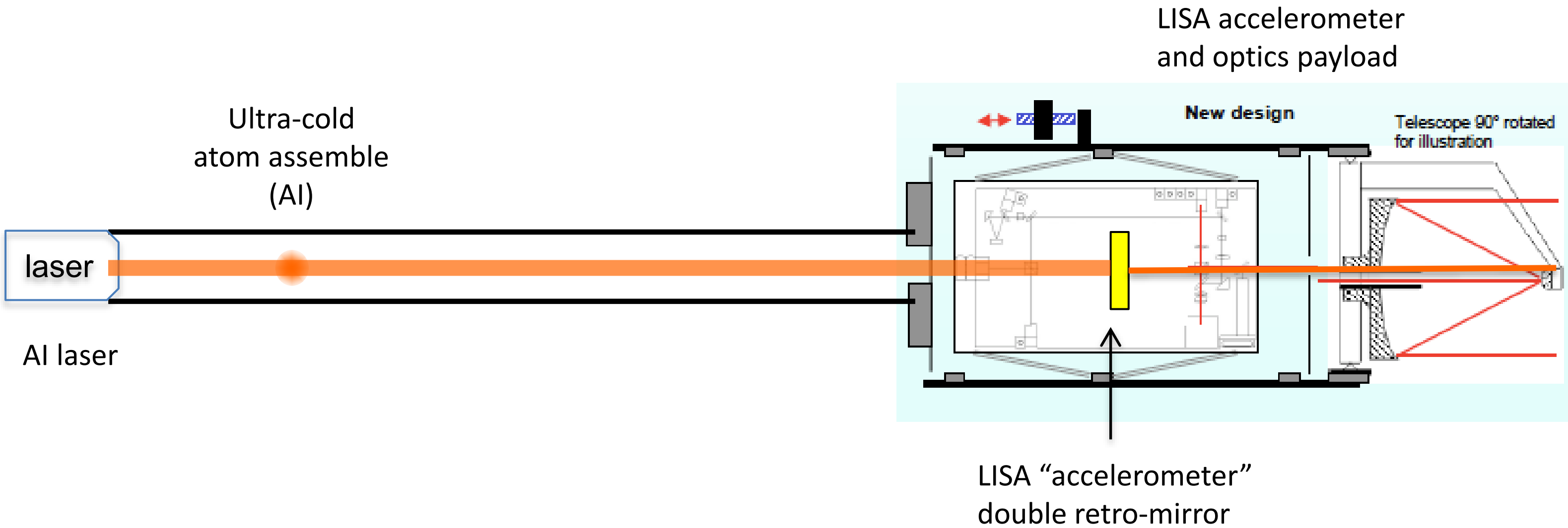


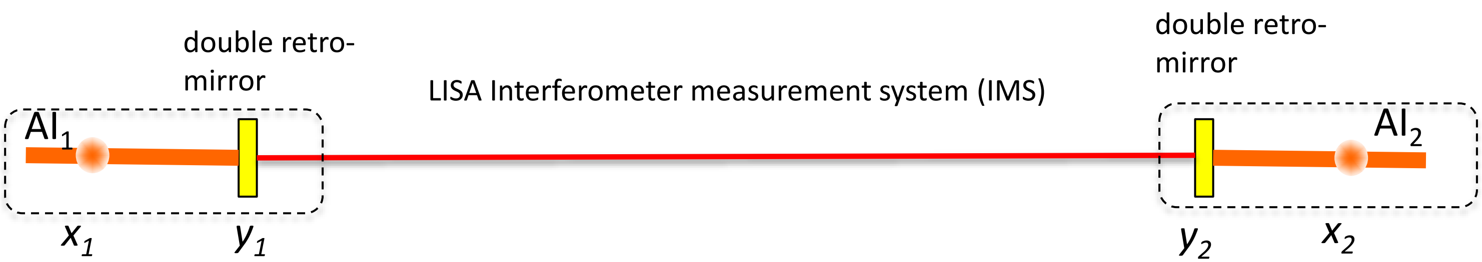


$$\Delta\Phi_{AI} = N\mathbf{k}\,a\,T^2 + \Delta\Phi_{laser}$$

- An AI phase shift measures the relative acceleration (corresponding displacement change) between the drag-free atomic masses and the optical retro-reflecting mirror.
- The phase measurement is modulo 2π, but can be resolved by the s/c accelerometer measurements if necessary. Ideally (but not necessarily), the acceleration of the retro-mirror should be controlled within one AI fringe range. Otherwise the phase feedforward scheme can be used, or at reduced data rate without it.
- AI phase shift is not sensitive to the laser linear motion in the measurement direction.
- AI laser beam tilt jitter must be tightly controlled.

Concept of Drag-free Atomic Referenced DRS





$$\Delta X = x_2(t) - x_1(t) = \underbrace{[x_2(t) - y_2(t)]}_{\text{Measured by } AI_1} + \underbrace{[y_2(t) - y_1(t)]}_{\text{Measured by IMS}} + \underbrace{[y_1(t) - x_1(t)]}_{\text{Measured by } AI_2}$$

Measured by AI_1 Measured by IMS   Measured by AI_2

Note: ideally, the displacement jitters of the mirrors are completely cancelled out, therefore, reducing the spacecraft "accelerometer" drag-free requirements.

Atom interferometer phase shift due to an acceleration *a*:

$$\Delta\Phi_{AI} = NkaT^2$$

Where $\Delta\Phi_{AI}$ is the AI phase measurement, λ AI laser wavelength, *N* is the number of photon momentum transfer in AI, and *T* the AI interrogation time (about half of the measurement time).

- *N*=2 is most common [Kasevich 1991].
- *N*=24 has been demonstrated [Mueller 2008].
- *N*=1 allows one-legged bandit interferometer concept [Yu 2010].
- T can be long in microgravity for LISA mission, to be determined by the upper frequency of the LISA measurement bandwidth.

"Acceleration-integrating" displacement measurement concept

$$\Delta x_a = \frac{1}{2} a T^2 \longrightarrow \Delta x_a = \frac{\lambda}{4\pi N} \Delta\Phi_{AI}$$

where Δx_a is the "integrated" atomic proof mass displacement due to an acceleration a. With λ=1 μm and a phase resolution of 100 μrad, *pm* displacement resolution can be reached.

- Assuming a quantum projection noise limited detection, SNR=1x10^4 with 1x10^8 atoms in a single measurement. We then have $S_{\Phi}(f) = SNR^{-1} \cdot \sqrt{2T} = 1.4x10^{-4}\sqrt{T}$ if the small measurement dead time is neglected.

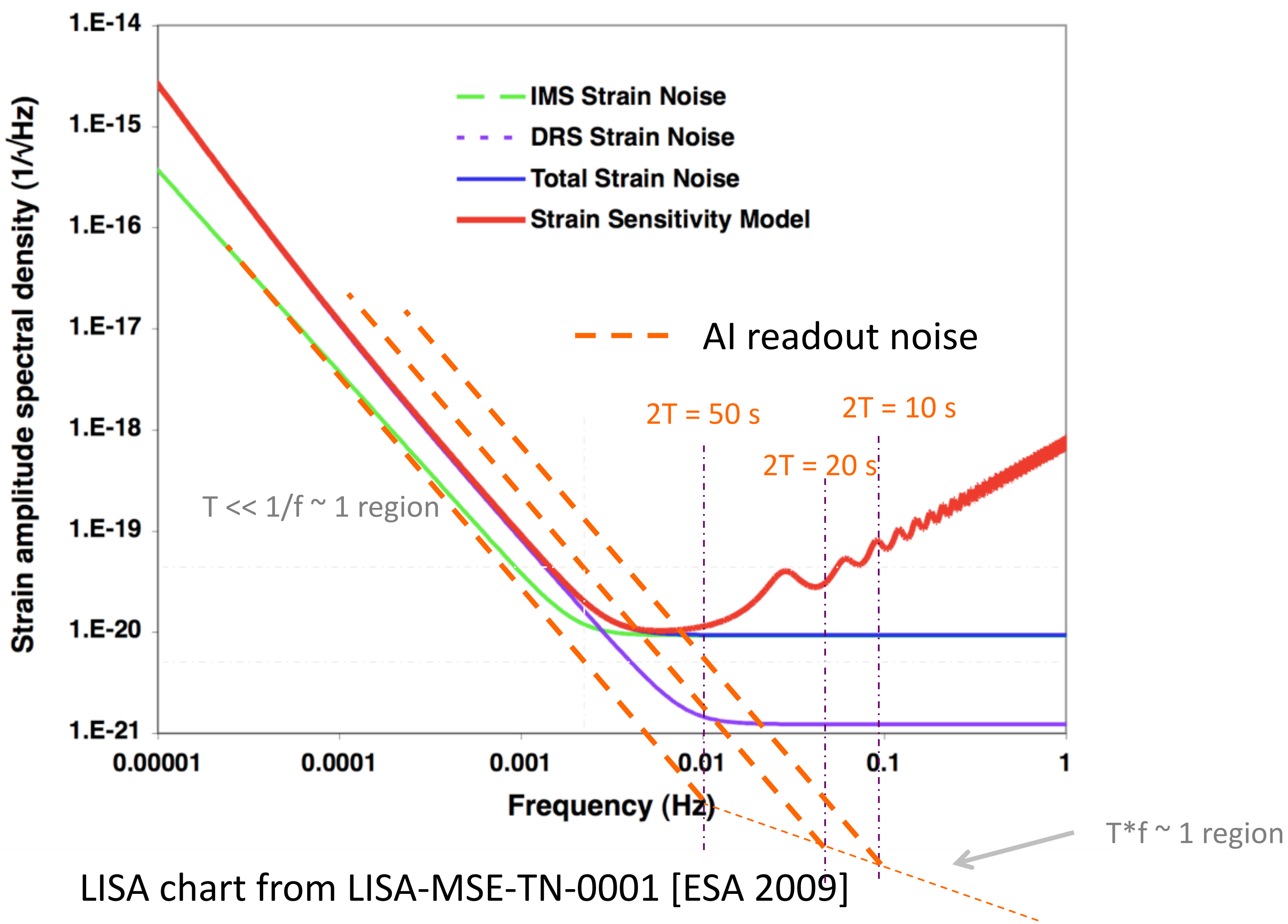
- Recall: $a = \Delta\ddot{x} = \omega^2 \Delta x$

- Putting all together, we have: $S_h(f) = \left(\frac{1}{L}\right) \cdot S_{\Delta x}(f) = \frac{1}{L} \cdot \frac{\lambda}{(2\pi)^3 N}\left(\frac{1}{f^2 T^2}\right) S_{\Delta\Phi}$

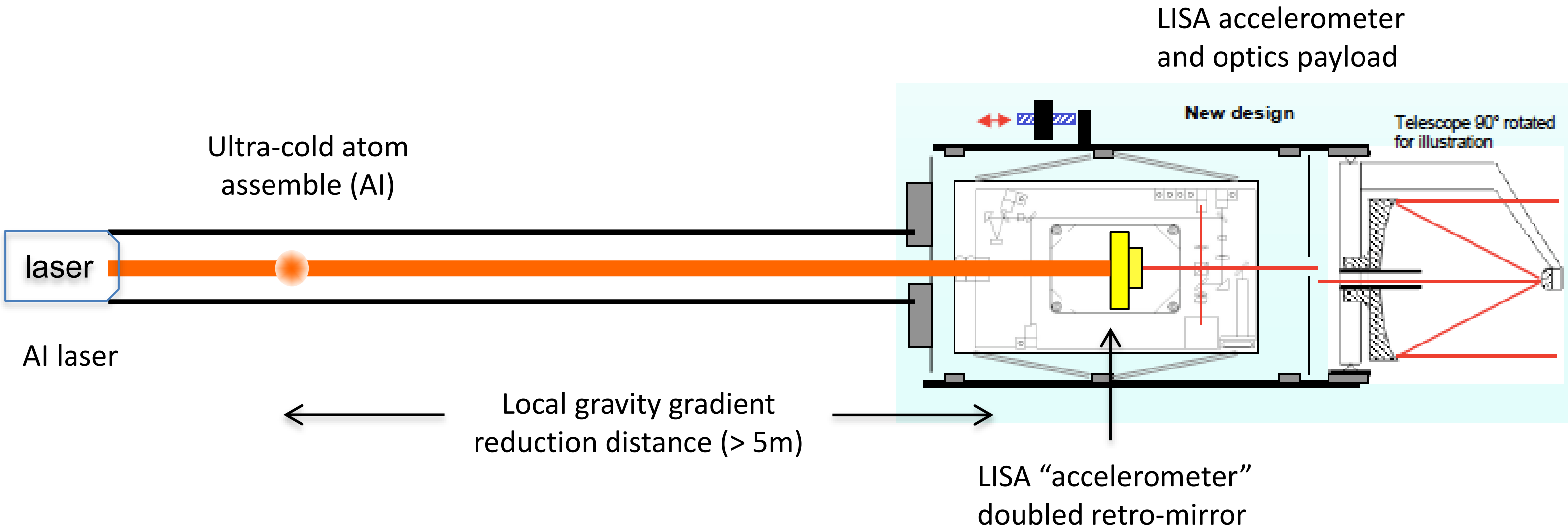
$$S_h(f) = \frac{\sqrt{2}}{(2\pi)^3 N} \cdot \frac{\lambda}{L} \cdot \left(\frac{1}{f^2 T^{3/2}}\right) \frac{1}{SNR}$$

Example in LISA*: N*=20, *SNR*=1x10^4, *λ*=1 *µm, L*=5x10^9 *m, we will have* $S_h(f)$=5.6x10^{-24}T$^{-3/2}$f^{-2}. This yields S_h(2mHz)=4x10^{-20} for T=10 s, indeed comparable to the current LISA DRS and IMS error budget.

Notional Strain Readout Sensitivity Spectrum Using AI



LISA chart from LISA-MSE-TN-0001 [ESA 2009]



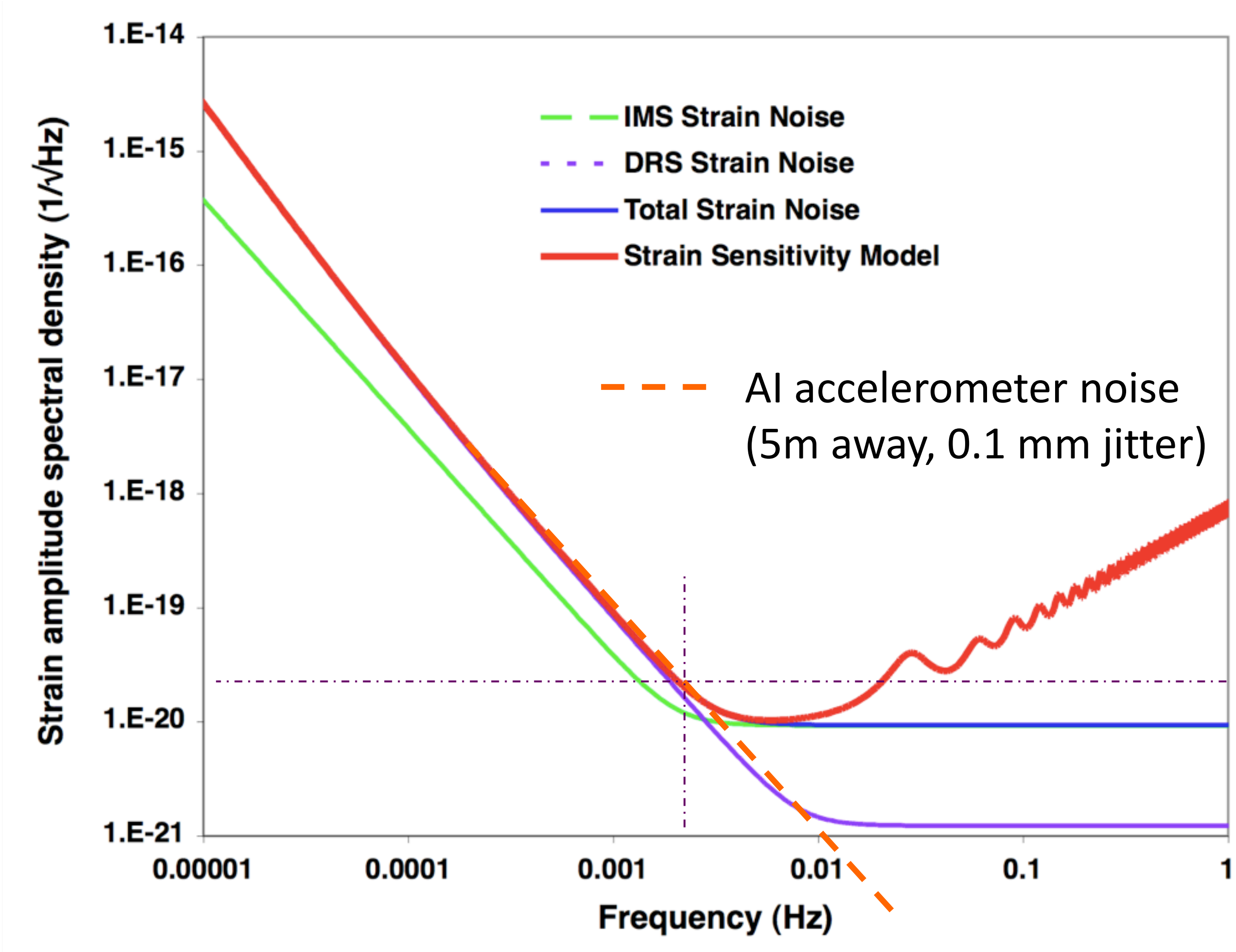
Atom position jitters in the residual s/c gravity field gradient results in error.
Mitigation – By moving atoms away from main spacecraft mass [Hogan, 2011]:

$$\Delta x_a = \iint (\Delta f / m) dt = \iint \Delta\left(\frac{GM_{sc}}{r^2}\right) dt = -\iint \frac{2GM_{sc}}{r_0^3} \Delta r(t)\, dt$$

$$S_x(f) = \left(\frac{2GM_{sc}}{r^3 \omega^2}\right) S_r(f) = \frac{8.1\times 10^{-12}}{f^2} S_r(f)$$

Assuming a 5-m distance away from a 300 kg spacecraft, < 100 μm/Hz$^{1/2}$ atomic position jitter and < 10 μm/s launch velocity stability would be sufficient to meet the LISA accelerometer noise budget requirement.
(Specific s/c mass distribution design can reduce this requirement further.)

Notional Local Acceleration Noise Spectrum Using AI



LISA chart from LISA-MSE-TN-0001 [ESA 2009]

Three major types of atomic reference error source

- *Fundamental noise* – white phase noise
  - Atomic state projection noise (or atom shot noise), $n^{1/2}$, determined by the total number of atoms, n.

  Mitigation: increased number of cold atoms.

- *AI phase noise* – Random phase noise and drifts
  - Due to laser phase noise
  - Due to various field effects on atoms, magnetic Zeeman shift, electric field Stark shifts
  - Due to optical wave front
  - Due to atomic assemble inhomogeneity

  Mitigation: reduced various field effects, can be well controlled as in atomic clocks.

- *Parasitic force noise* – $1/f^2$ noise
  - Coriolis force due to rotation disturbances
  - Random residual local gravity gradient noise

  Mitigation: atomic test mass far away from spacecraft.

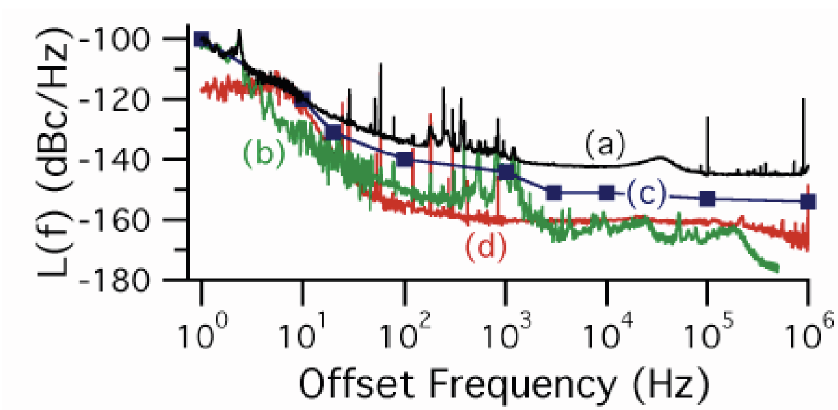
Laser phase noises are critical in all AI-based schemes.

$$\Delta\Phi_{AI} = N\,k\,a\,T^2 + \Delta\phi_{laser} \quad \Longrightarrow \quad S_{\Phi_{laser}}(f) \le S_{\Phi_{AI}}(f)$$

The form of the laser noise $\Delta\phi_{laser}$ depends on specific schemes. For a simple illustration here, we use (N/2) Raman pulses, $\Delta\phi_{laser}$ ~ $N^{1/2}$ ™ϕ_{Ram}, where ™ϕ_{Ram} is Raman laser phase noise at the laser difference frequencies (~10 GHz).

$$S_{\Phi_{laser}}(f) \le S_{\Phi_{AI}}(f) = 1\times10^{-4} / \sqrt{Hz}$$

for N=20. This is -80 dBc/Hz at 10 GHz. This is not difficult at high frequencies (at the bandwidth of Raman pulses). It is somewhat challenging at the time scale of 2T (20 sec), but certainly realizable, especially with recent optical frequency comb microwave generation technique [Quinlan, 2011].



Single-sideband phase noise on a 10 GHz carrier [Quinlan, 2011].

1. Vacuum package
a) Non-magnetic housing
b) Large aperture high quality optical windows
c) Sealed vacuum package without active pump

2. Laser and optics
a) Master lasers
b) Amplifiers
c) Agile laser frequency and intensity switching
d) Beam alignments

3. Environmental control
a) Magnetic field management
b) Vibration reduction
c) Platform rotation
d) Drag-free systematics reduction

4. Microgravity operation
a) Ultra cold high flux atom source
b) Atomic ensemble dynamics

AI development activities

- Maintain overall LISA mission concept
  - Replace LISA DRS with atomic DRS (aDRS)
  - Address the LISA Disturbance Reduction System (DRS), the most challenging part of the LISA mission
- Using truly drag-free atomic proof masses
  - Quantum inertial sensor technology of atom interferometry
  - Ground-proven atom interferometer measurement technique is sufficient for LISA mission application
- Reduction of the DRS test mass requirements
  - Reduced spacecraft drag-free requirement by 10,000
  - Significantly reduce the complexity, likely risk and cost of the current LISA DRS
- Key risk assessment
  - Atom interferometer technology validation in microgravity at long measurement time

References:

1. Kasevich M. and Chu, S. (1991) , *Phys. Rev. Lett*., 67, 181.
2. Hogan et al. (2011)``An atomic gravitational wave interferometric sensor in low earth orbit (AGIS-LEO)", *GENERAL RELATIVITY AND GRAVITATION,* Volume 43, Number 7, 1953-2009.
3. Mueller,H. et al. (2008) *Phys. Rev. Lett*. 100, 180405.
4. Mueller, H. et al. (2009) *Phys. Rev. Lett*. 102, 240403.
5. ESA (2009) ''Laser Interferometer Space Antenna (LISA) Measurement Requirements Flowdown Guide" *LISA-MSE-TN-0001*.
6. Yu N. and Tinto, M. (2011) "Gravitational wave detection with single-laser atom interferometers ," *General Relativity And Gravitation*, V. 43 Issue: 7 Special Issue: Sp. Iss. SI Pages: 1943-1952 (2011); arXiv:1003.4218v1 [gr-qc] 22 Mar 2010.
7. Yu, N. et al., (2006) "Development of a Quantum Gravity Gradiometer for Gravity Measurement from Space," J. Appl. Phys. B. **84**, 647 (2006)..
8. Yu, N. et al. (2002) "Quantum Gravity Gradiometer Sensor for Earth Science Applications," NASA Earth Science and Technology Conference 2002. Paper B3P5. Pasadena, California. June 2002.
9. Yu, N. and Maleki L. (2006) "High precision atomic reference for acceleration measurement," JPL NTR No. 43776, April, 2006.
10. Jefferts, S. et al. (2011) NIST http://www.nist.gov/pml/div688/grp50/primary-frequency-standards.cfm.
11. Peters, A. (2001) et al. Metrologia, v.38, 25, 2001.
12. McGuirk J. M. (2002) et al. Phys. Rev. A, V65, 033608, 2002.
13. Sorrentito F. et al. (2009) New J. of Phys. B.V12, 095009 2009.
14. Wu, X., (2009) Ph.D. Thesis, Stanford, March 2009.
15. P. R. Berman, *Atom Interferometry,* Academic Press (December 30, 1996)
16. Harold J. Metcalf and Peter van der Straten, *Laser Cooling and Trapping*, Springer, New York, NY, 1990.
17. F. Quinlan et al, "Ultralow phase noise microwave generation with an Er:fiber-based optical frequency divider," ArXiv1105, 2011.