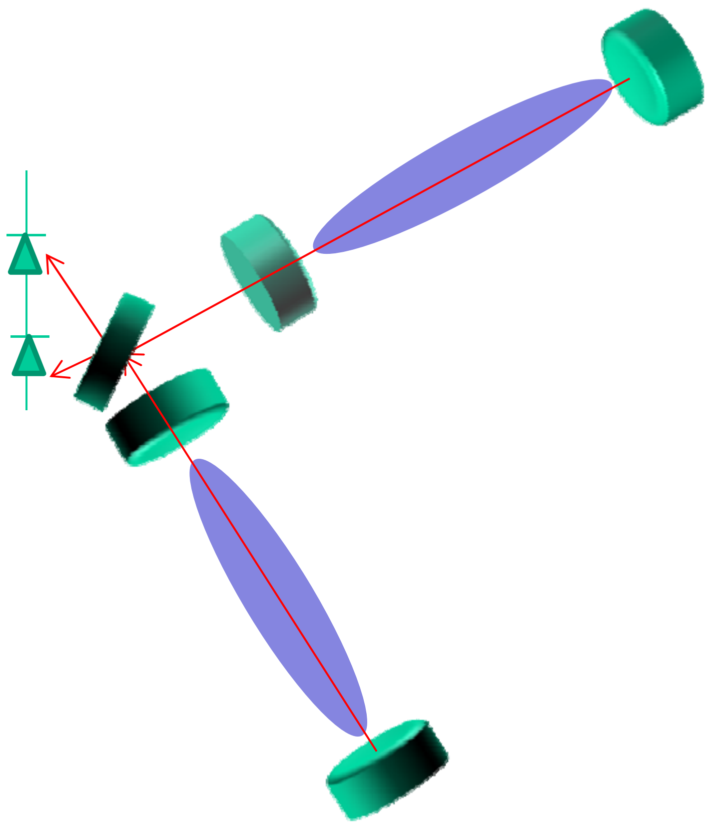
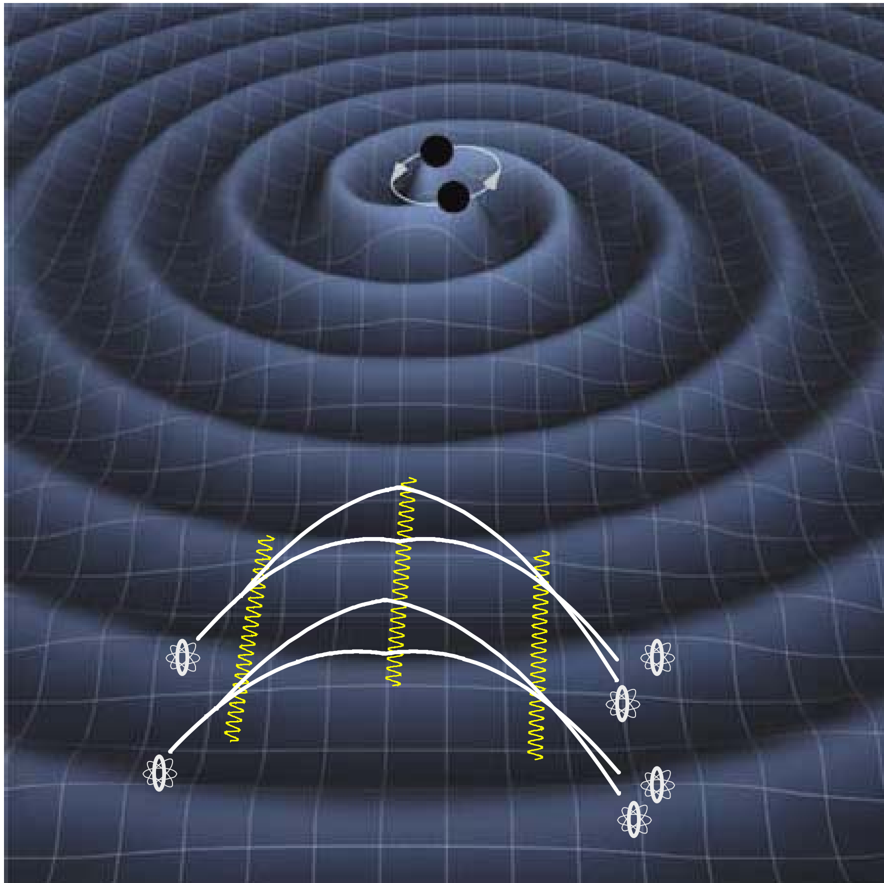
Gravitational wave detection with light and atoms





Holger Müller, UC Berkeley

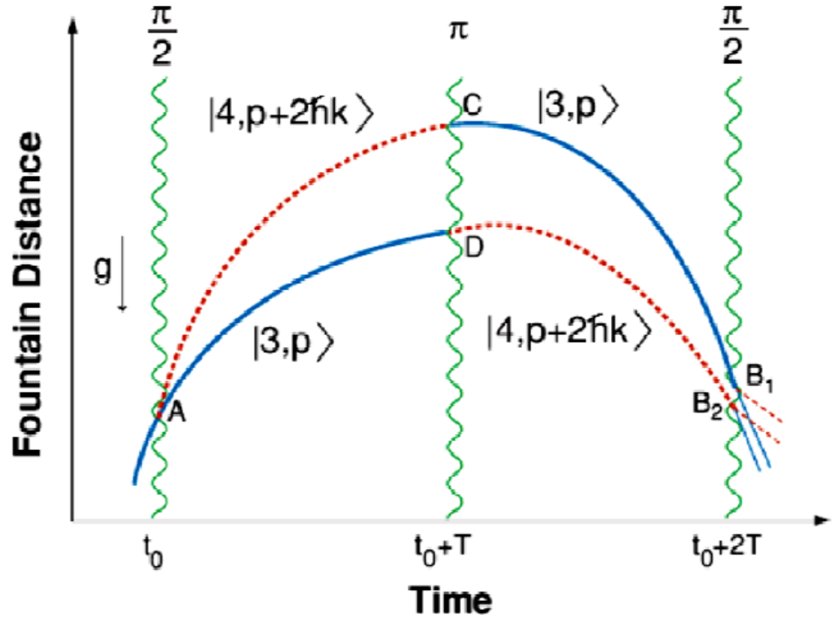
Light pulse atom interferometer

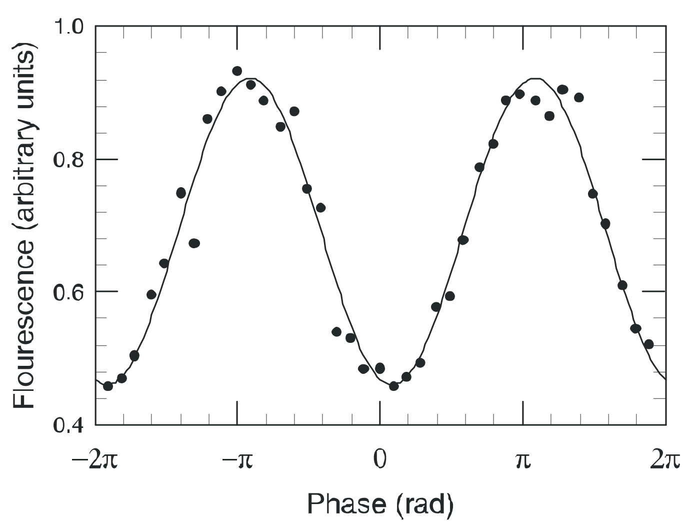
- Light pulses exchange momentum with matter waves
- Single atom interference

$$\Delta\varphi = -\frac{mc^2}{\hbar}\oint d\tau + \Delta\varphi_{\text{laser}}$$

$$= 2T^2\vec{\Omega}\cdot[\vec{k}\times(\vec{v}_0 + \vec{a}T)] + \vec{k}\vec{a}T^2$$

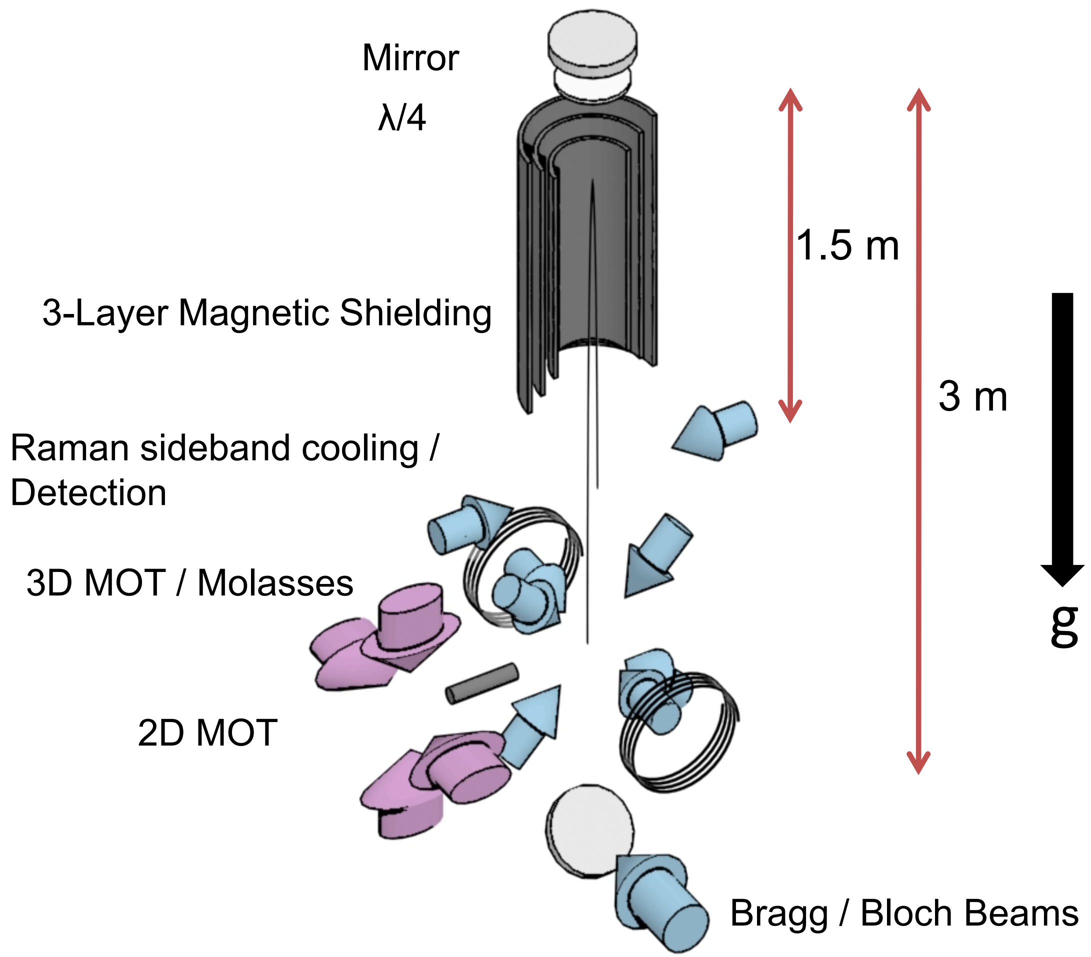
$$+ O(1/c^4)$$



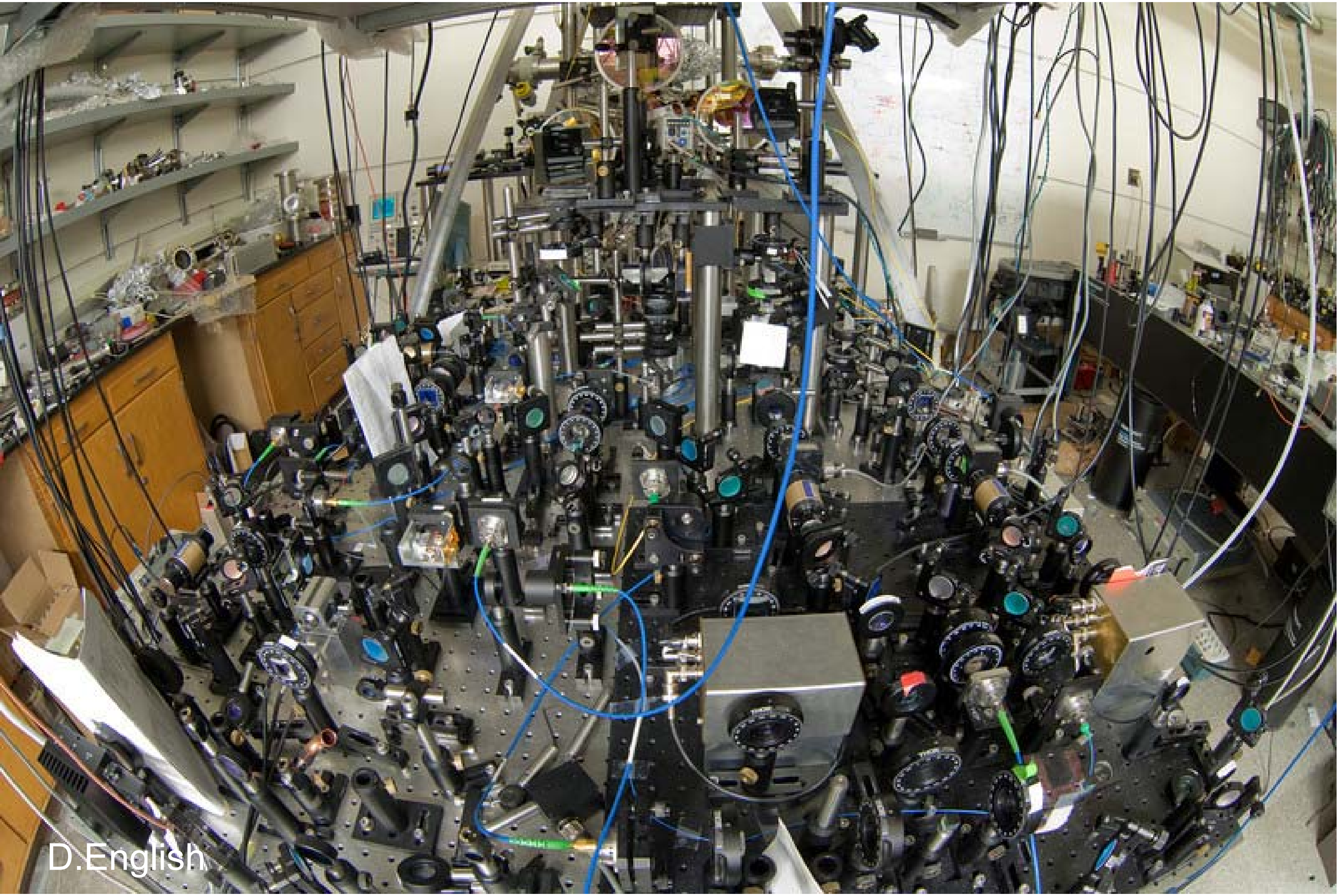


Experimental Setup

Atomic Fountain : Cs de Broglie Wave Source

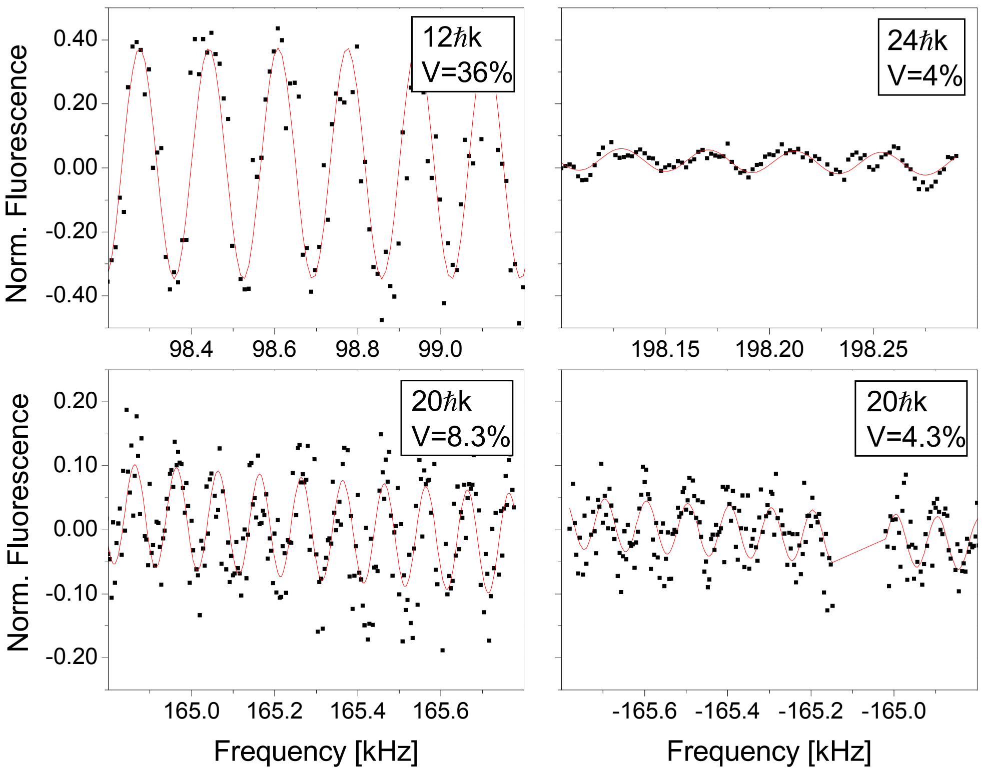


- 3D magneto-optical trap
- Molasses cooling
- Adiabatic cooling
- Launch
- Raman sideband cooling
- Adiabatic microwave transfer
- F= 3, m=0 state selection
- Velocity selection
- Interferometer sequence
- Florescence detection

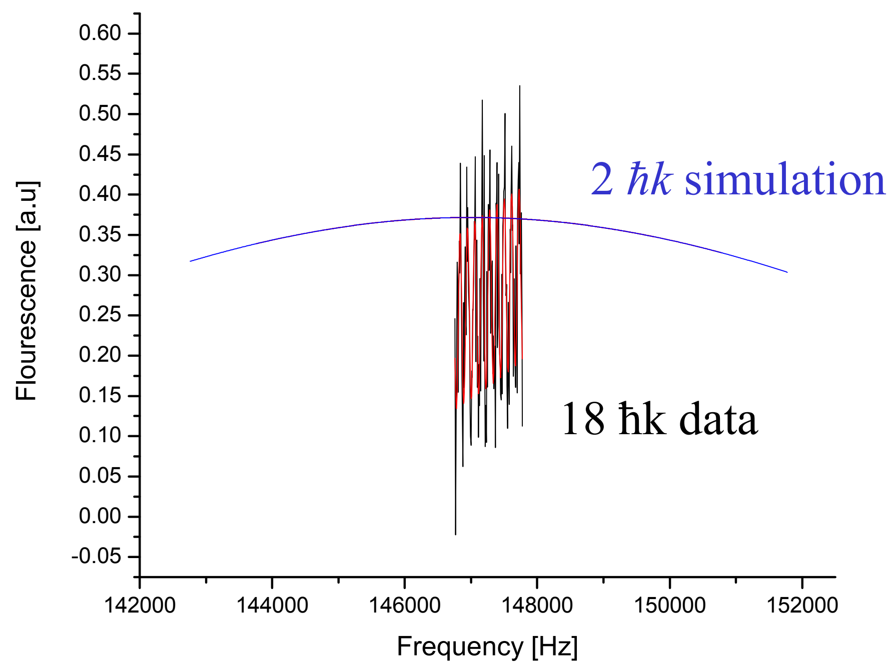

D.English

Large momentum transfer

12-24 *ħk* interferometers

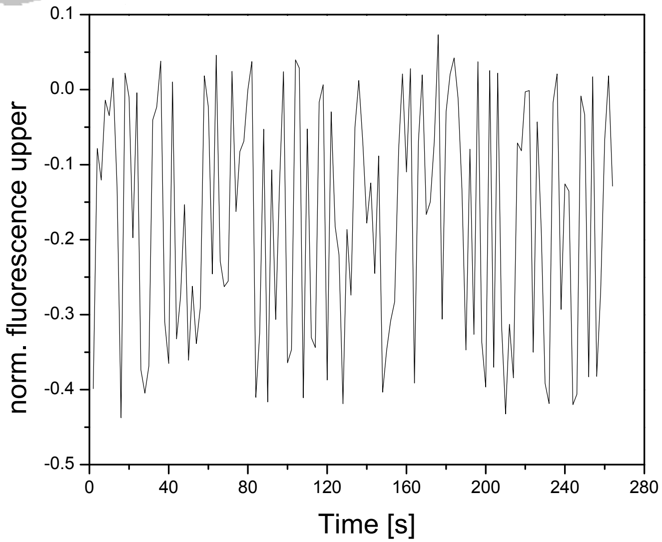


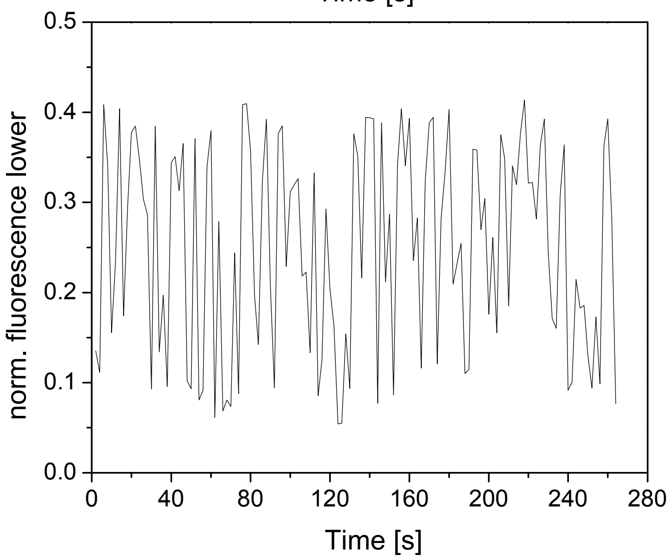
Comparison to 2 *ħk*



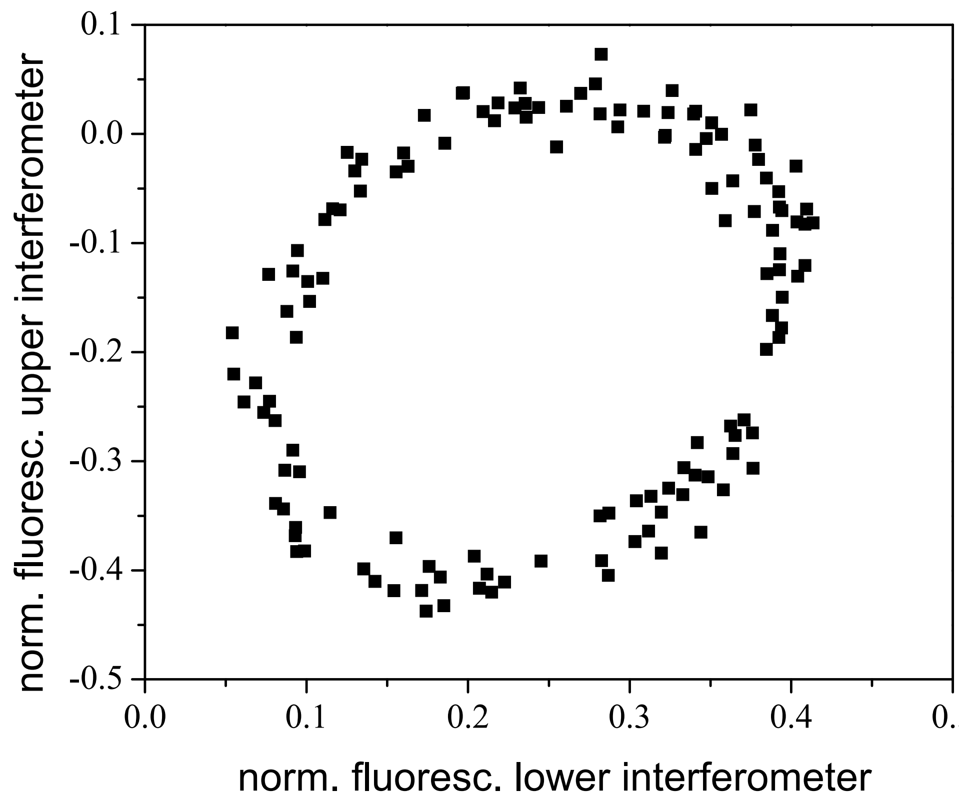
H. M. *et al.*, PRL 100 (2009): Chiow et al, PRL 2009

Noise cancellation



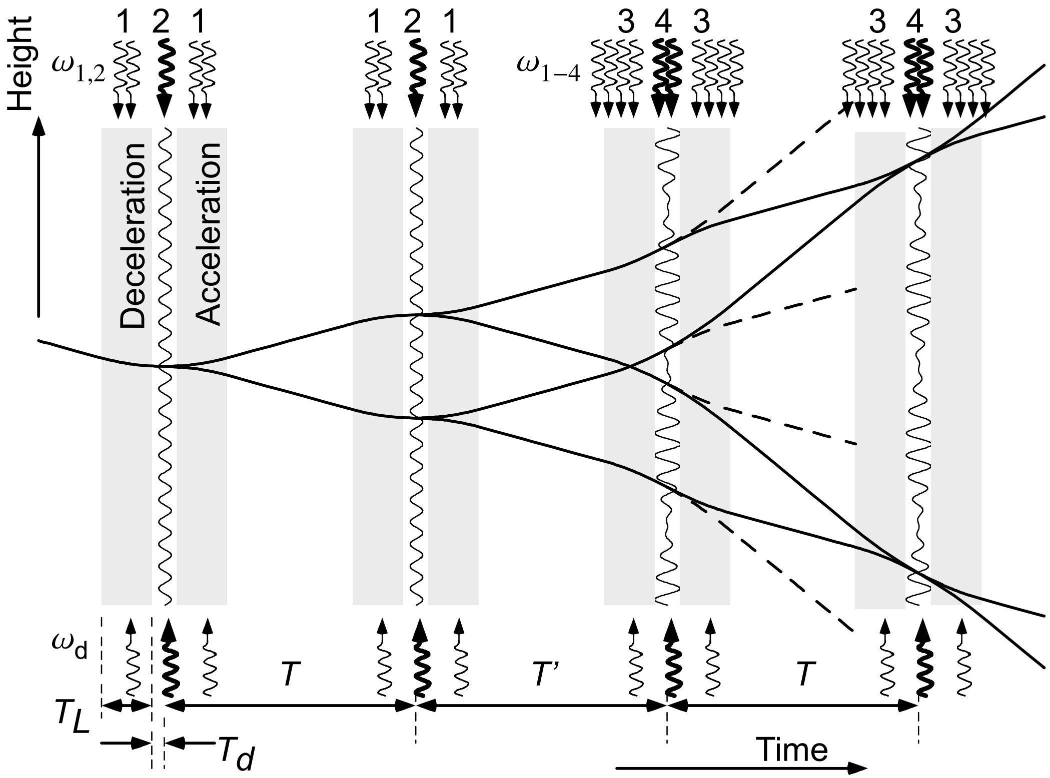


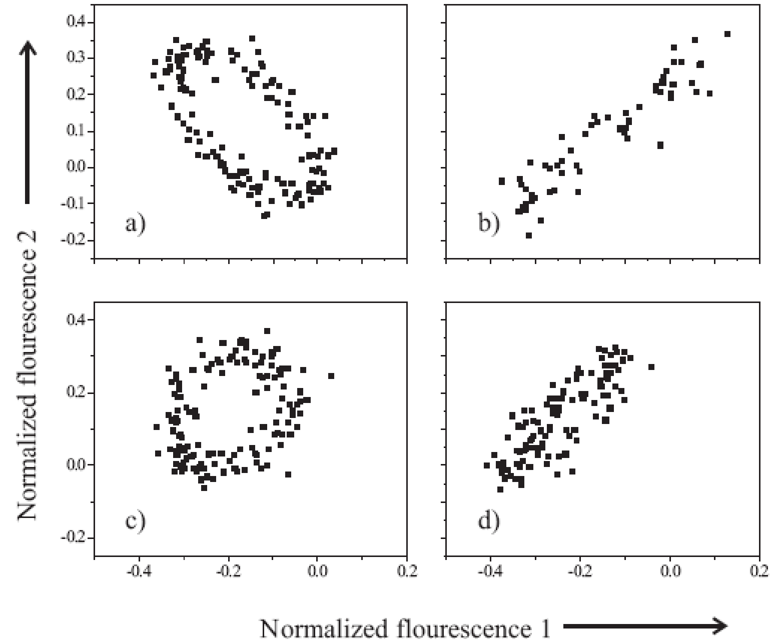
6^{th} order Bragg diffraction, T =1 ms



H. M. *et al.,* PRL 102, 240403 (2009)

BBB interferometers





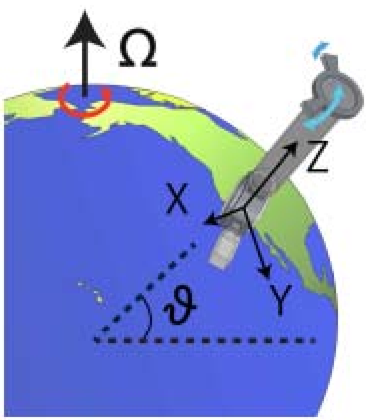
1: dual lattice (Matter wave accelerator)
2: single Bragg
3: quadruple lattice
4: dual Bragg

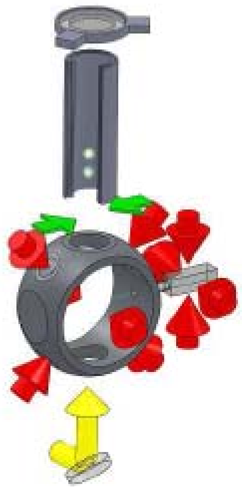
Large velocity difference can be used test PNO(4) while cancelling PNO(2)

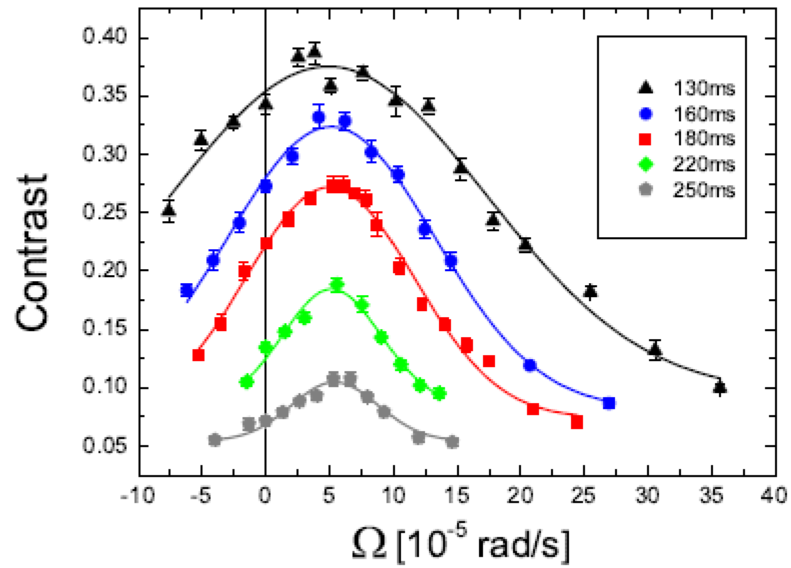
H. M. *et al.,* PRL 100 (2009)

Coriolis force

$$\vec{\delta} = 4nv_r\Omega_{\oplus}T(T+T')\cos\vartheta(1,0,0).$$







- Interferometer does not close
- Cancellation improves contrast (350%), T
- World's most sensitive atom interferometer (10 ħk, 250 ms)

Lan *et al., PRL* 108, 090402 (2012)

REPORTS

Science AAAS

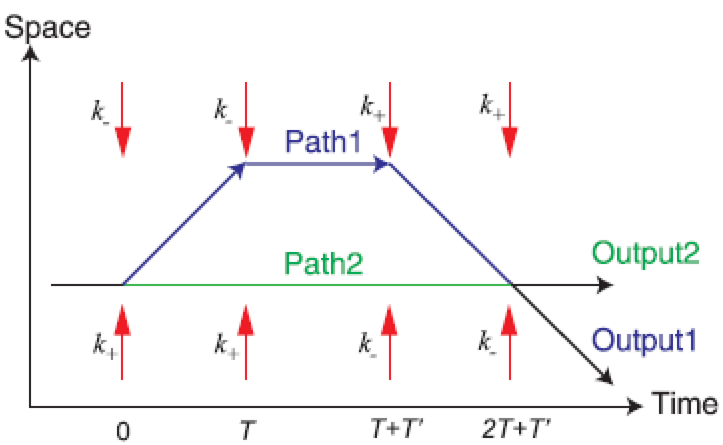
A Clock Directly Linking Time to a Particle's Mass

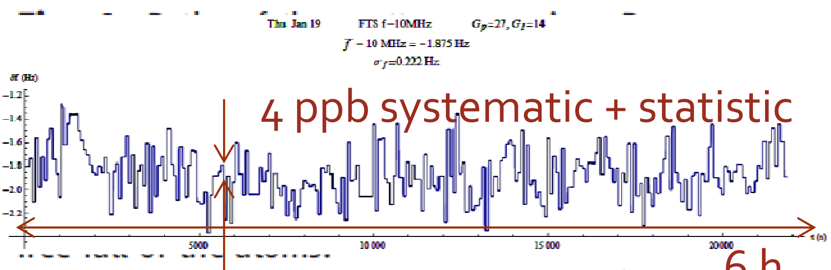
Shau-Yu Lan,[1] Pei-Chen Kuan,[1] Brian Estey,[1] Damon English,[1] Justin M. Brown,[1] Michael A. Hohensee,[1] Holger Müller[1,2*]

states is given by wave equations whose plane-wave solutions are proportional to

$$e^{-i\phi} = \exp(-ip_\mu x^\mu/\hbar) = \exp(-i\omega_0\tau) \qquad (1)$$

where $p_\mu = (-m\gamma, m\gamma\mathbf{v})$ and x^μ are the momentum and position four-vector, $\tau = t/\gamma$ is the proper time, γ is the Lorentz factor, and $\mathbf{v}$ and t are the





$$\omega_m = \frac{1}{2nN^2}\frac{mc^2}{\hbar}$$

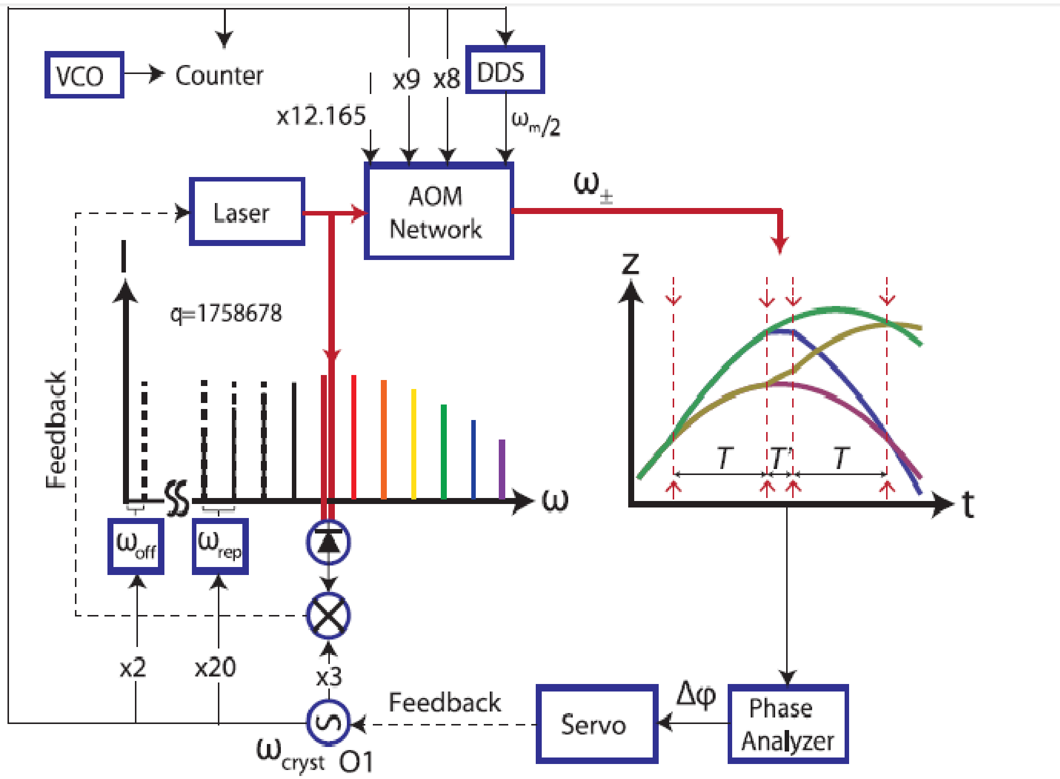


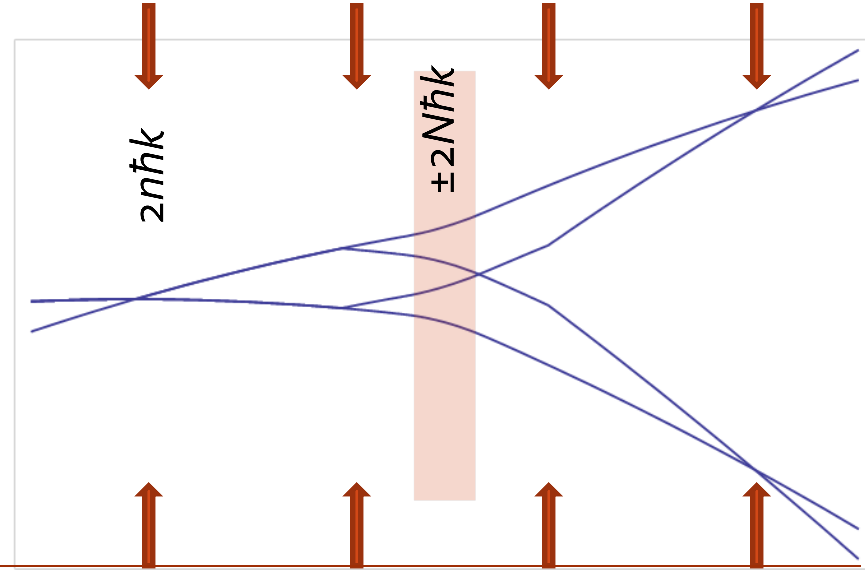
Fig. 2. Schematic. Oscillator O1 is the frequency reference for all signal generators and the optical frequency comb. The laser used to address the atom interferometer is phase-locked to the comb. Shown in the diagram is the freely falling atomic trajectories versus time for the simultaneous conjugate interferometers (the lower of which being shown in Fig. 1) used to cancel the gravity-induced phase. The phase measurement from the atom interferometer provides an error signal to O1 in order to close

Further improvements

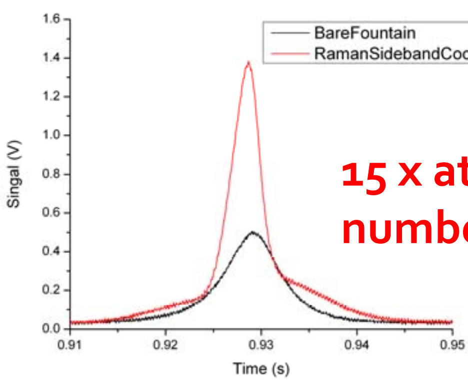
Bloch oscillations

- Split interferometers by $\pm 2N\hbar k$
- Increases signal $(n+N)/n \sim 4$ fold

$$\Phi_1 - \Phi_2 = 16n^2(N+1)\omega_r T$$

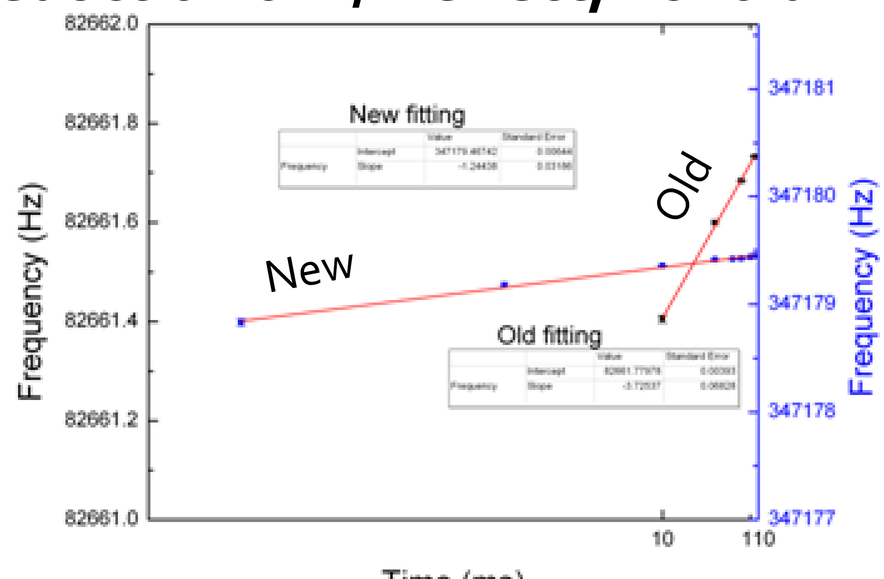


3D Raman Sideband Cooling

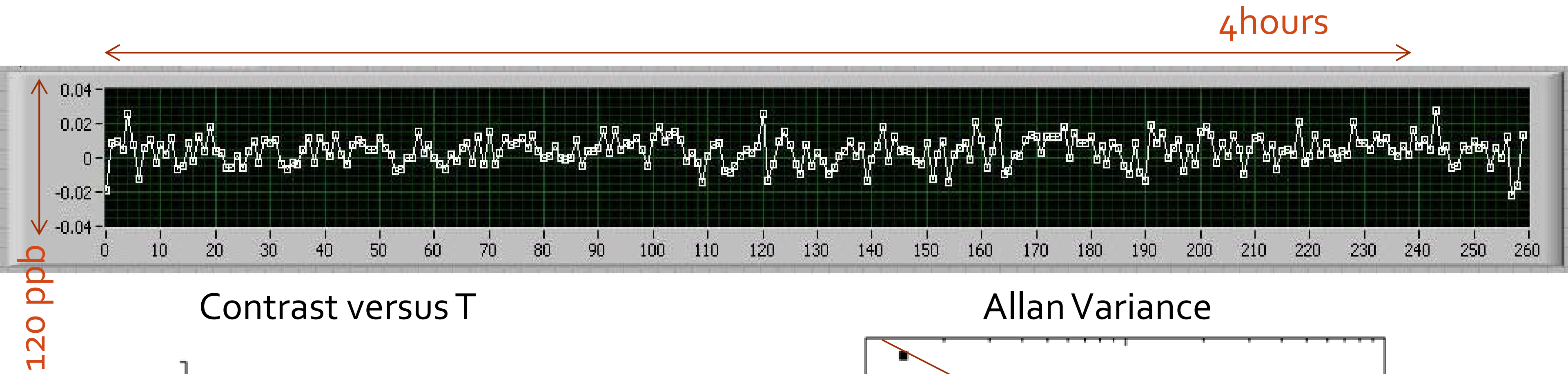


15 x atom number

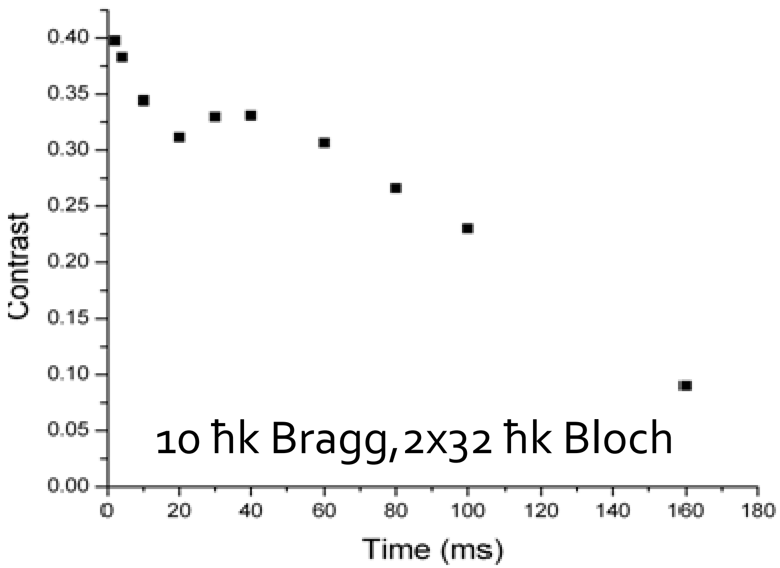
Reduction of 1/T-effect, ~8 fold



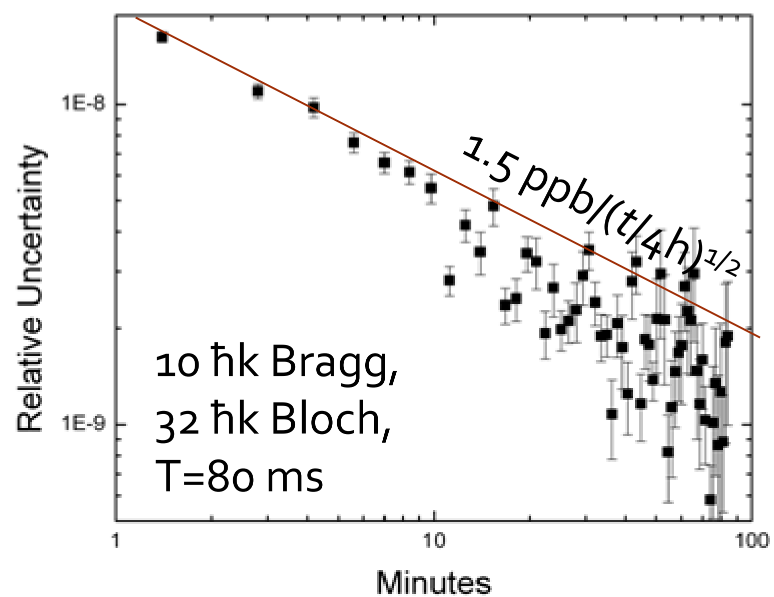
High-sensitivity RB interferometer



Contrast versus T



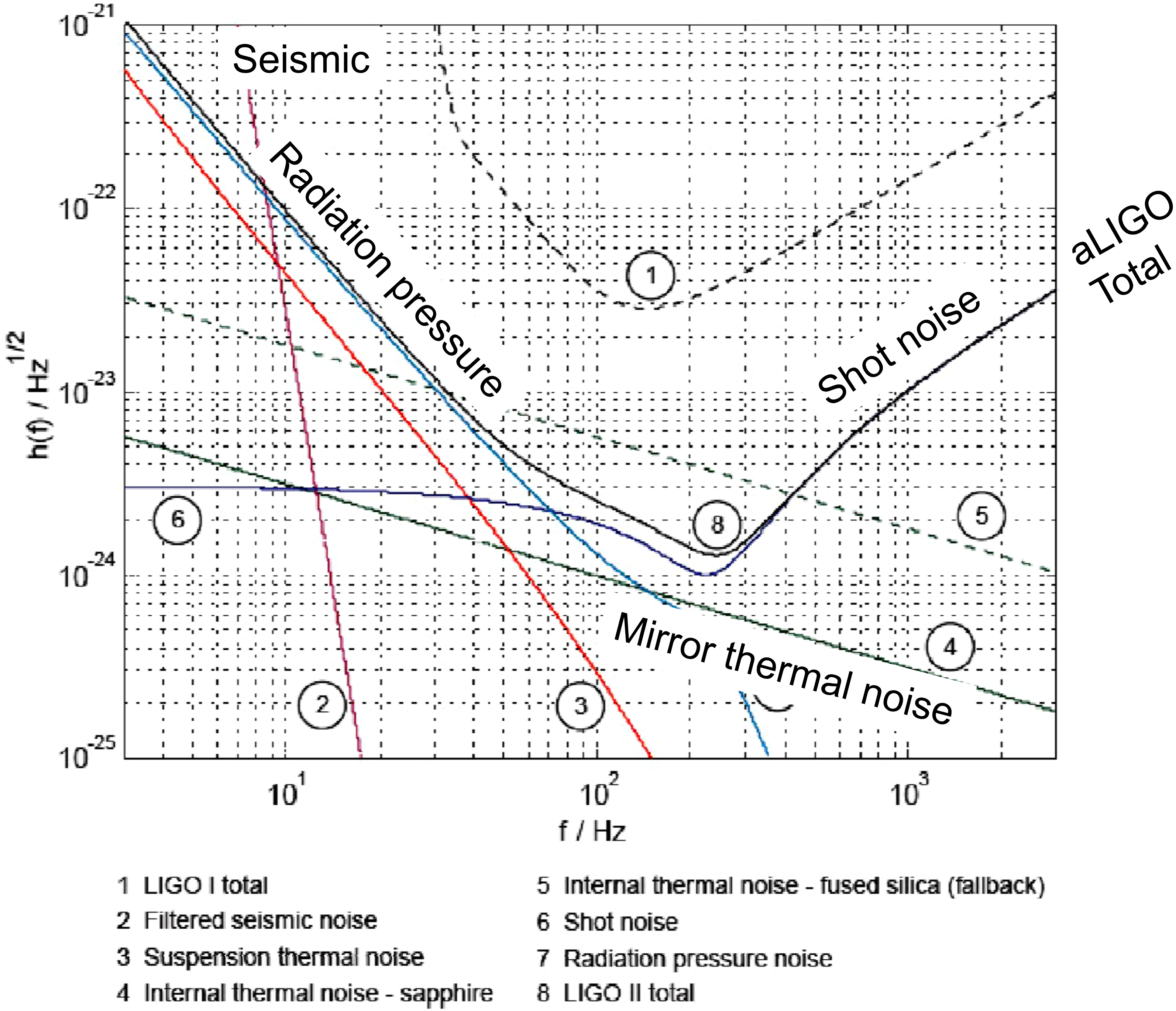
Allan Variance



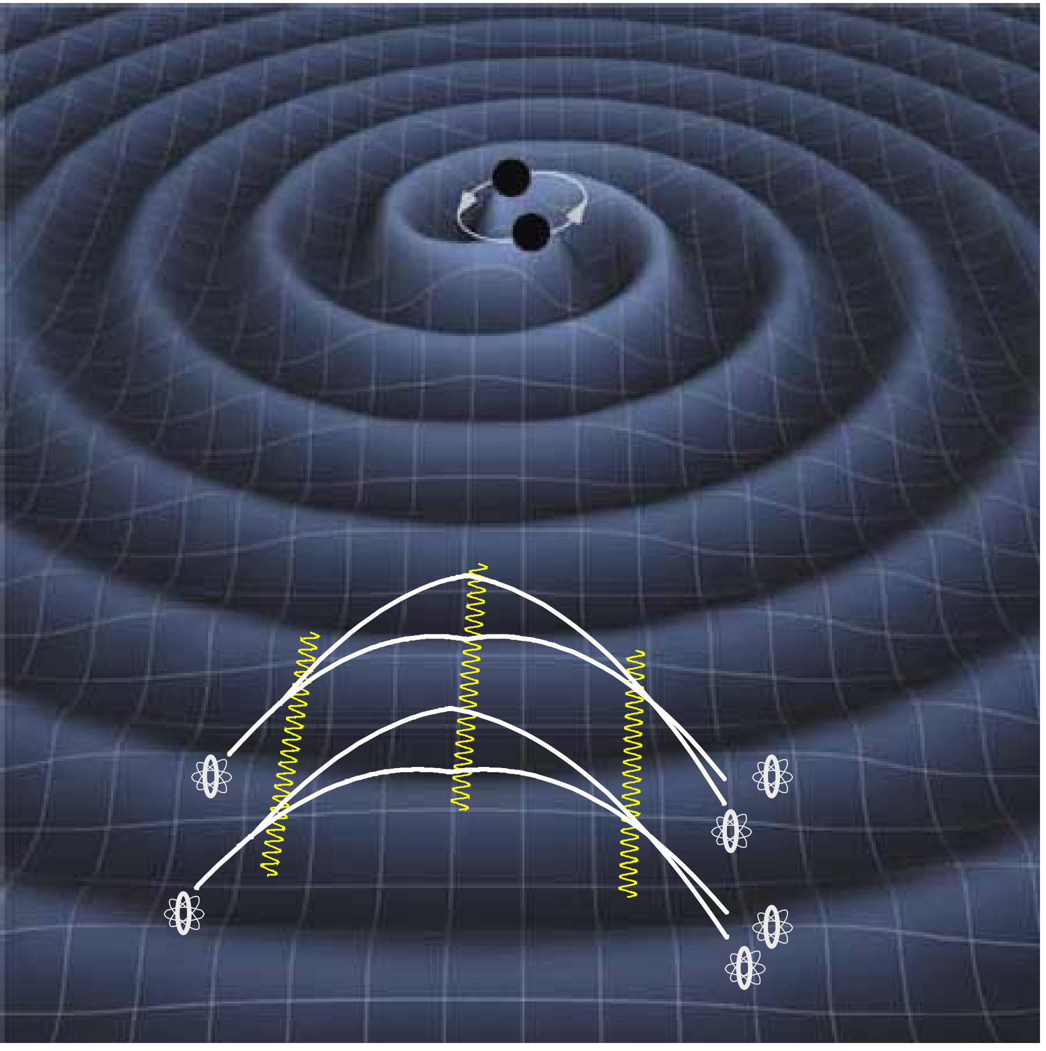
0.45 ppb x (4 hours)$^{1/2}$ resolution in α …still Improving

No discernible drift after ~100 minutes

Contents

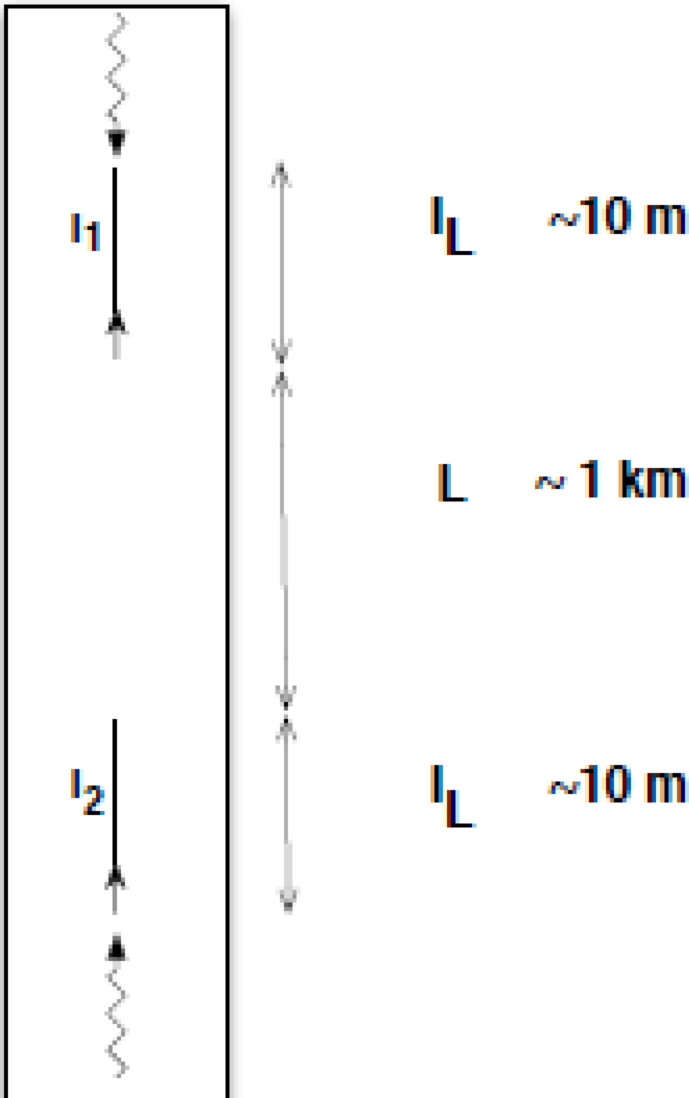

Seismic
Radiation pressure
Shot noise
aLIGO Total
Mirror thermal noise
1
2
3
4
5
6
8
h(f) / Hz^1/2
f / Hz
1 LIGO I total
2 Filtered seismic noise
3 Suspension thermal noise
4 Internal thermal noise - sapphire
5 Internal thermal noise - fused silica (fallback)
6 Shot noise
7 Radiation pressure noise
8 LIGO II total

Atomic gravitational wave interferometric sensor (AGIS)



- "Mirrors" are atoms
- no thermal noise,
- no radiation pressure noise
- Almost perfect free fall, no vibration isolation
- Much higher atom shot noise

“Old” AGIS



$$\Phi_1 = 2nk_{eff}hL\sin^2\left(\frac{\omega T}{2}\right)\sin\varphi_0$$

Examples:
k=2π/1μ,
h=10^{-17},
ω=2π*1Hz

⇒Φ~3*10^{-7}

n=100

=>Φ~3*10^{-5}

Dimopoulos, Graham, Hogan, Kasevich & Rajendran, PR D **78,** 122002 (2008)

Optimization

Sensitivity

$$h_{\rm rms} = \frac{1}{2nkL\sin^2(\omega T/2)\sqrt{\eta}},$$

Low-frequency limit

$$h_{\rm rms}^{\rm LF} = \frac{2}{nkL\omega^2 T^2\sqrt{\eta}}.$$

Optimizing T, n

$$T_{\rm opt} = \sqrt{\frac{2L_{\rm Tube}}{5g}},$$

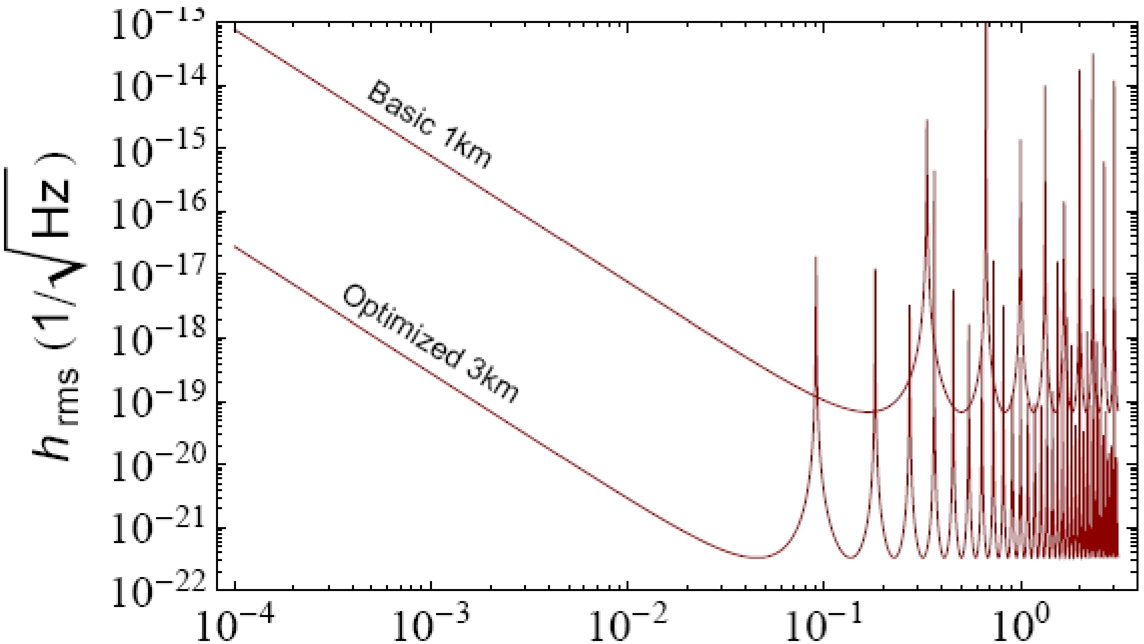
$$n_{\rm opt} = \frac{2L_{\rm Tube} - gT^2}{4Tv_r},$$

$$h_{\rm rms}^{\rm LF,opt} = \frac{25v_r\sqrt{5g}}{2kL_{\rm Tube}^{5/2}\omega^2\sqrt{2\eta}}.$$

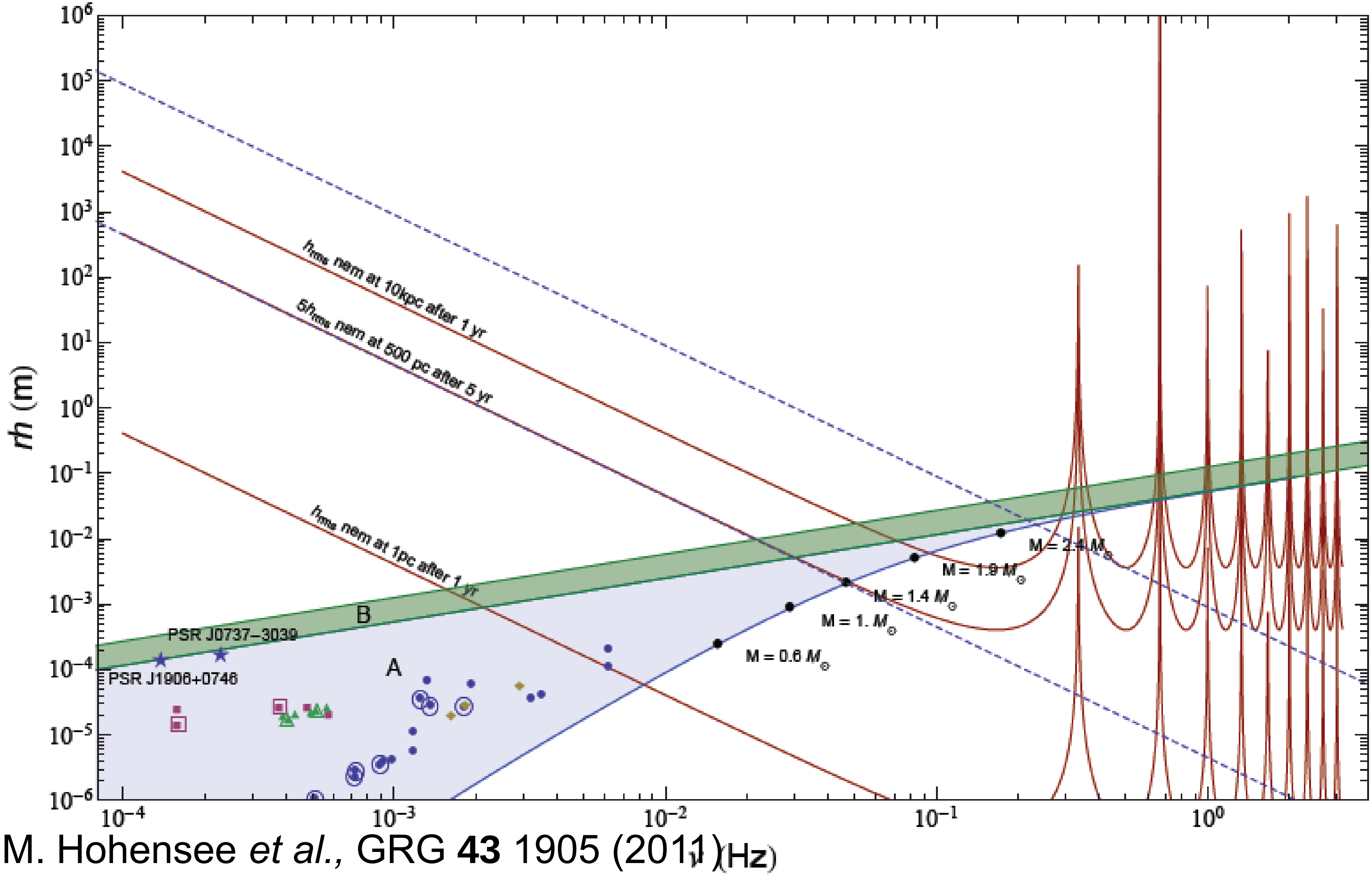
M. Hohensee *et al.*, GRG **43** 1905 (2011)

AGIS sensitivity

Parameter	Symbol	Basic	Optimized
Wavenumber	k	$2\pi/852\,\mathrm{nm}$	$2\pi/852\,\mathrm{nm}$
Momentum transfer/$(\hbar k)$	n	1,000	31,000
Pulse separation time	T	$3\,\mathrm{s}$	$11\,\mathrm{s}$
Tube length	L_{Tube}	$1{,}000\,\mathrm{m}$	$3{,}000\,\mathrm{m}$
Separation	L	$\approx L_{\mathrm{Tube}}$	$1{,}200\,\mathrm{m}$
Atom throughput	η	$10^{12}/\mathrm{s}$	$3\times10^{13}/\mathrm{s}$
Peak sensitivity	h_{rms}	$7\times10^{-20}/\sqrt{\mathrm{Hz}}$	$1.3\times10^{-22}/\sqrt{\mathrm{Hz}}$
Low freq. sensitivity	$h_{\mathrm{rms}}^{\mathrm{LF,opt}}$	$3\times10^{-20}(\frac{\mathrm{Hz}}{\omega})^2\frac{1}{\sqrt{\mathrm{Hz}}}$	$1.1\times10^{-23}(\frac{\mathrm{Hz}}{\omega})^2\frac{1}{\sqrt{\mathrm{Hz}}}$

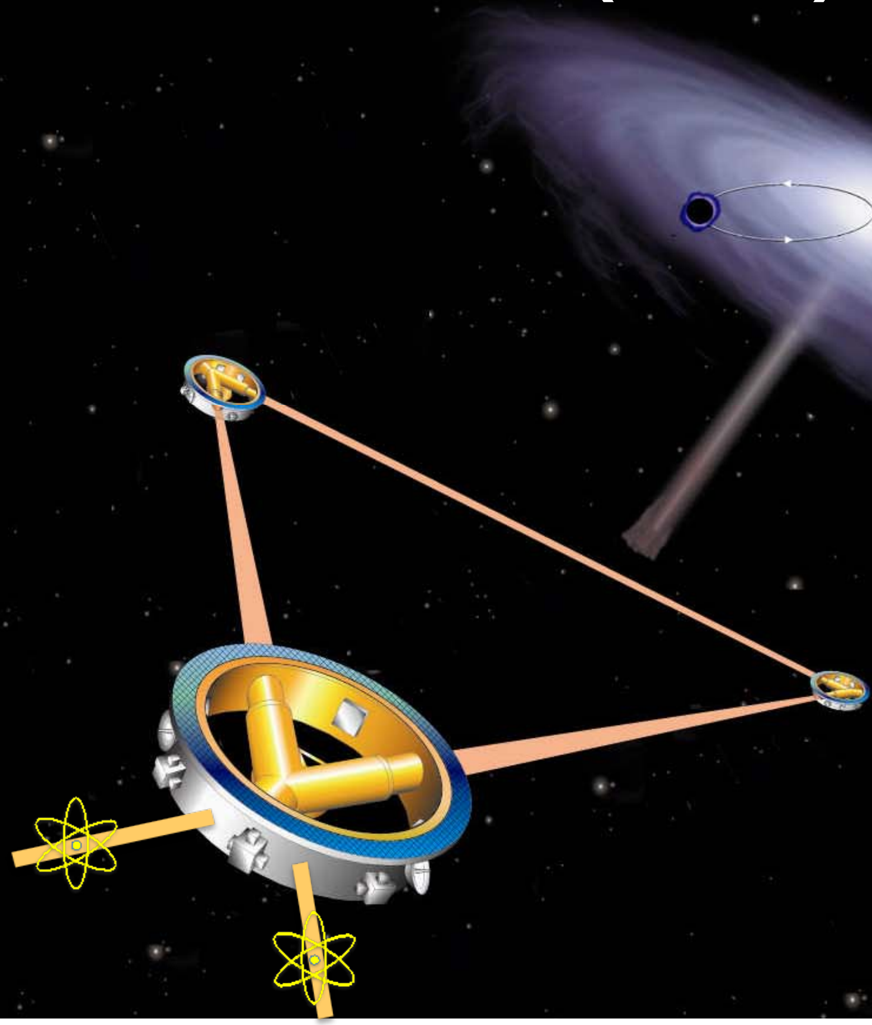


Galactic Binaries



M. Hohensee *et al.*, GRG **43** 1905 (2011)

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

Concept: Use atomic inertial sensors to replace LISA accelerometers

Goal: Reduce/eliminate spacecraft drag-free requirement

Nan Ju, James Kohel, Massimo Tinto

AGIS vs LIGO

Large momentum transfer: 100s-1000s of hk

Pulsed operation:

- Sensitive at all frequencies, but aliasing
- Low-frequency sensitivity has to be given up for high-frequency detection

Atom sources

Suppresses mirror seismic/thermal noise, radiation pressure noise

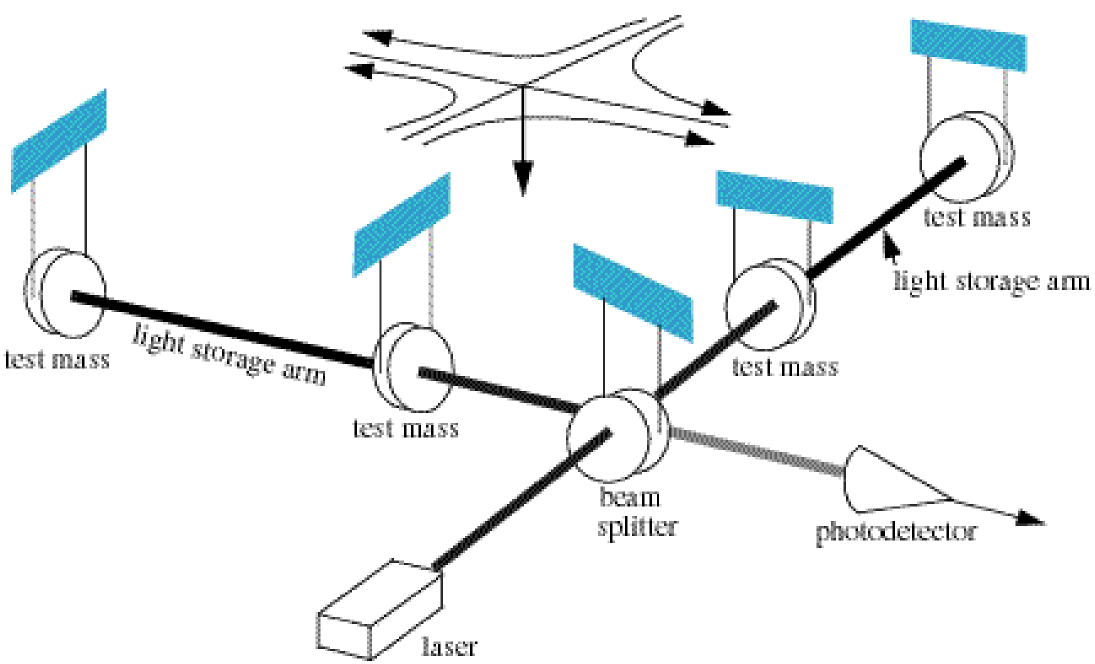
Laser noise cancellation requires two arms or a laser-noise immune scheme [1,2]

Other noise sources similar as LIGO

[1] Yu & Tinto, GRG **43,** 1943 (2011); [2] Graham *et al.,* PRL **110**, 171102 (2013).

Laser noise / mirror motion

• Laser noise: nearly same influence as in LIGO
• Small differences due to aliasing favor LIGO
• AI less sensitive to mirror motion ~ as LIGO with arm length = gravitational wave length



Superradiant Laser Interferometer GW detector

Michael Hohensee and Holger Müller

SUPER RADIANCE MONDAY

Come to the Golden Domes and Maharishi Vedic City to create a Large Number of Yogic Flyers (AM or PM or Both)

BE PART OF THIS GREAT WAVE OF BLISS

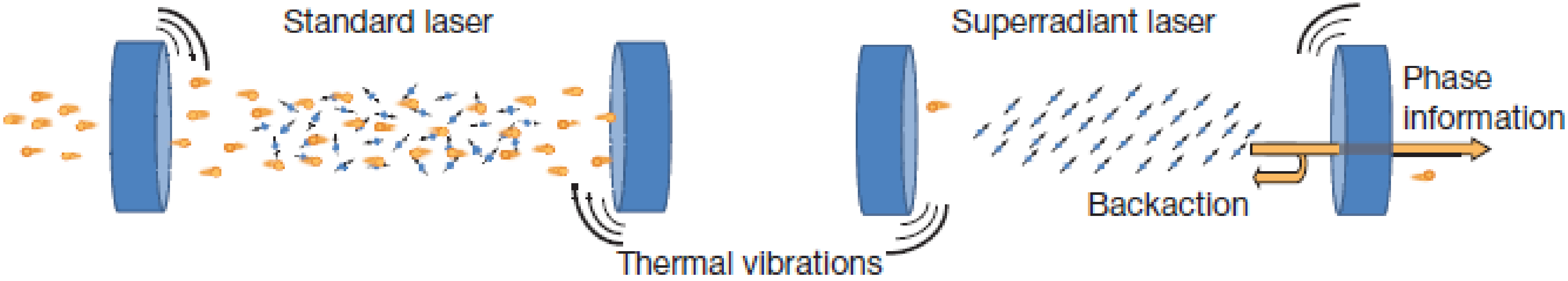
Sidhas Warmly Invited

PLEASE BRING YOUR CURRENT DOME BADGE

Badge renewals: Call 472-1212

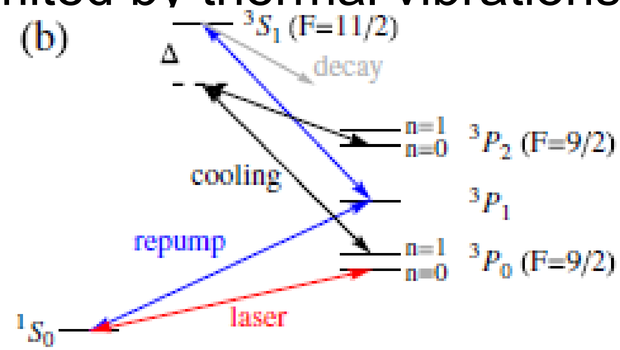
Cookies after program

Superradiance



- Cavity linewidth << Gain medium linewidth, κ<<γ
- Laser frequency determined by cavity
- Best performance ~10^{-16}
- Limited by thermal vibrations

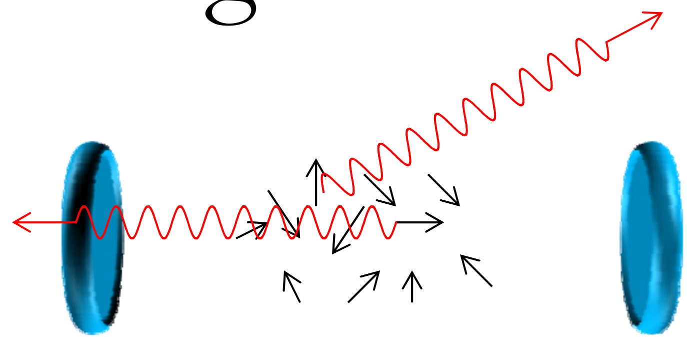
- κ>>γ
- Laser frequency determined by atom, linewidth ~$\kappa^3/(g^2N^2)$
- Predicted performance ~10^{-18}
- Limited by thermal vibrations



R. H. Dicke, Phys. Rev. **93,** 99 (1954)

Phase matching

- Thermal equilibrium
- Individual emission

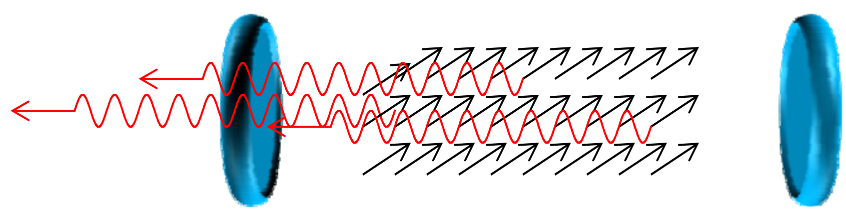


Superradiant

- Coherent sample
- Quantum amplitude for

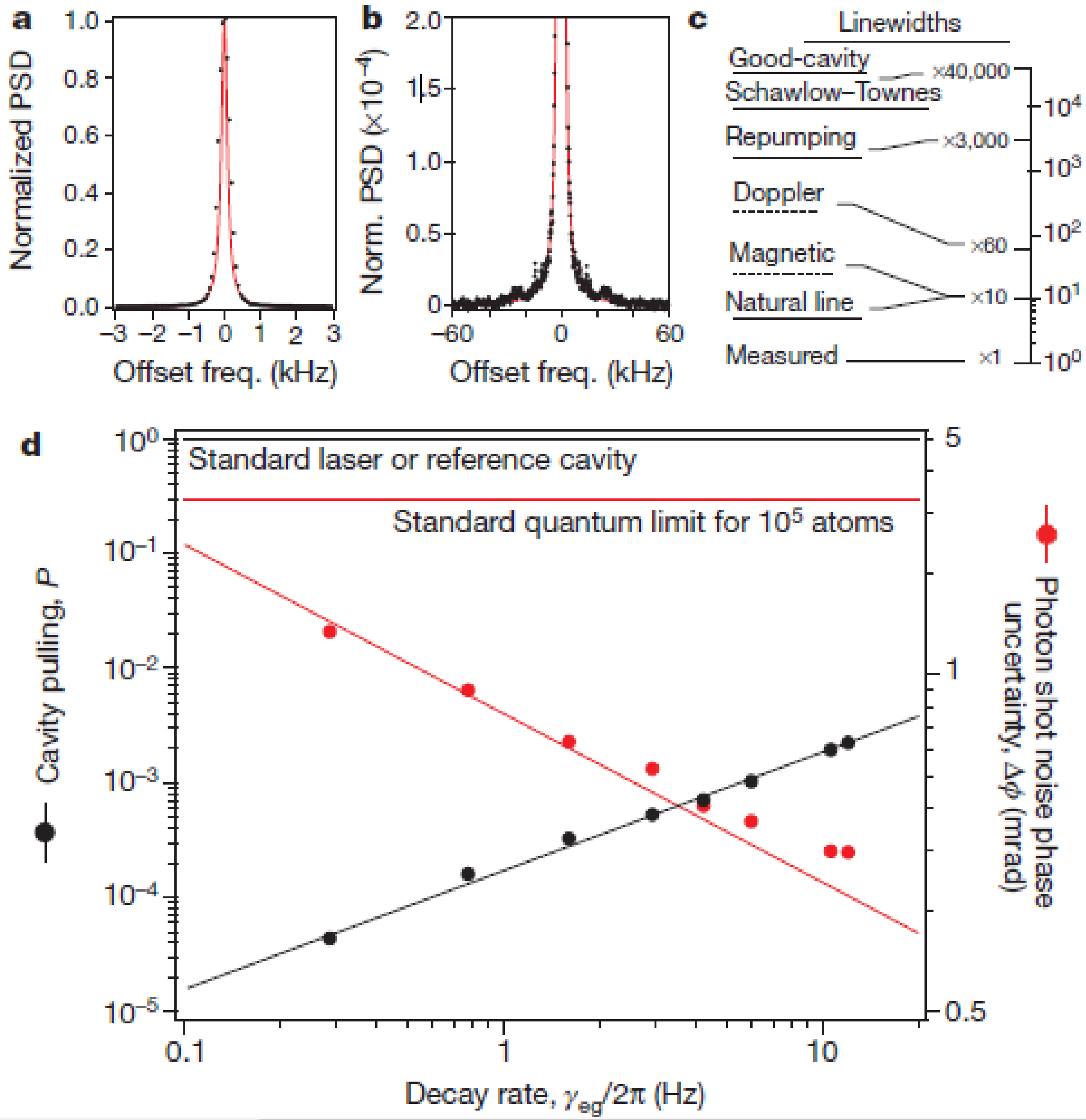
Emissions can add coherently

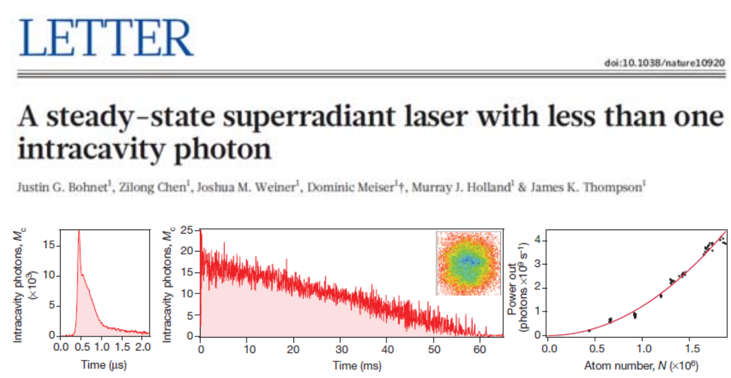
- Phase matching



$$\left(\mathbf{k}(0)-\mathbf{k}(t)\right)\mathbf{r}_1 = \left(\mathbf{k}(0)-\mathbf{k}(t)\right)\mathbf{r}_2 = \ldots$$

Bad-cavity Superradiant laser




LETTER

doi:10.1038/nature10920

A steady-state superradiant laser with less than one intracavity photon

Justin G. Bohnet[1], Zilong Chen[1], Joshua M. Weiner[1], Dominic Meiser[1]†, Murray J. Holland[1] & James K. Thompson[1]

Linewidth **less than**

- Cavity linewidth
- Good cavity Schawlow-Townes limit
- Repump rate
- Doppler limit
- Natural linewidth

Bohnet, Chen, Weiner, Meiser, Holland & Thompson, Nature **484,** 78 (2012).

TT gauge metric

TT gauge metric

$$g_{\mu\nu} = \eta_{\mu\nu} + \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & h_+ \cos\Omega t & h_\times \sin\Omega t \\ 0 & 0 & h_\times \sin\Omega t & -h_+ \cos\Omega t \end{pmatrix}$$

Coordinates constant

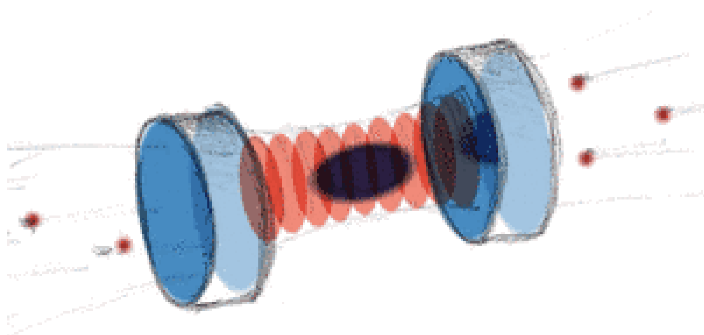
$$\frac{dx^\mu}{d\tau} = 0$$

Proper distance

$$d_{AB}^2 = \left[\delta_{ij} + h_{ij}(t)\right] d^i d^j$$

Superradiant ensemble

ETH Zurich



$$H = H_0(\mathbf{r}_1,\ldots\mathbf{r}_N) + \frac{\hbar\omega_0}{2}\sum_{j=1}^{N}(\sigma_3)_j$$

$$\psi_{gm} = \psi_g(\mathbf{r}_1,\ldots\mathbf{r}_N)\left|\uparrow\uparrow\downarrow\uparrow\ldots\right\rangle$$

$$E_{gm} = E_g + m\hbar\omega_0$$

Sum operators

$$S_{1,2,3} = \sum_j (\sigma_{1,2,3})_j$$

Interaction

$$H_{\text{int}} = -\frac{1}{2}\mathbf{A}(\mathbf{r})\left[\mathbf{e}_1(\sigma_1)_j + \mathbf{e}_2(\sigma_2)_j\right]$$

$$\mathbf{A}(\mathbf{r}) = \sum_k a_{\mathbf{k}} e^{ik^i r^j g_{ij}} + a_{\mathbf{k}}^{+} e^{-ik^i r^j g_{ij}}$$

Rewriting…

Collective operators

$$S_{1,\mathbf{k}}(t) = \sum_j \left[(\sigma_1)_j \cos\left(k^i r^j g_{ij}\right) - (\sigma_2)_j \sin\left(k^i r^j g_{ij}\right) \right],$$

$$S_{2,\mathbf{k}}(t) = \sum_j \left[(\sigma_1)_j \sin\left(k^i r^j g_{ij}\right) + (\sigma_2)_j \cos\left(k^i r^j g_{ij}\right) \right],$$

$$S_{\pm,\mathbf{k}}(t) = S_{1,\mathbf{k}}(t) \pm i S_{2,\mathbf{k}}(t)$$

Interaction Hamiltonian

$$H_{\text{int}} = -\frac{1}{4} \sum_{\mathbf{k}} \left(a_{\mathbf{k}} \mathbf{e} S_{+,\mathbf{k}}(t) + a_{\mathbf{k}}^{+} \mathbf{e} S_{+,\mathbf{k}}(t) \right)$$

A model for the emission process

1. Establish coherence

$$\psi(0) \to \psi(t) = e^{i\omega_0 t S_3} T \psi(0)$$

$$T(t_0) = \exp\left\{ i\frac{\theta}{2}\left(S_{+,\mathbf{k}}(t) e^{i\phi} + S_{-,\mathbf{k}}(t) e^{-i\phi} \right) \right\} e^{i\theta' S_3}$$

$$\rho(t) = e^{-i\omega_0 t S_3} T(t_0) \rho_0 T^{-1}(t_0) e^{i\omega_0 t S_3}$$

1. Intensity of emitted radiation

$$I(\mathbf{k}') = I_0 \mathrm{Tr} S_{-,\mathbf{k}'}(t) \rho(t) S_{+,\mathbf{k}'}(t)$$

2. Evaluate assuming intial sample in thermal equilibrium

$$I(\mathbf{k}') = I_0 \frac{N}{2}\left[1 - \cos\theta \tanh\left(\frac{\hbar\omega_0}{k_B T} \right) \right.$$

$$\left. + \frac{1}{2}\sin^2\theta \tanh\left(\frac{\hbar\omega_0}{k_B T} \right) \times \left(N \left| \left\langle e^{i\left[k^i r^j g_{ij}(t_0) - k'^i r^j g_{ij}(t) \right]} \right\rangle_{\mathrm{ens}} \right|^2 - 1 \right) \right]$$

Gravity wave modulates superradiant frequency

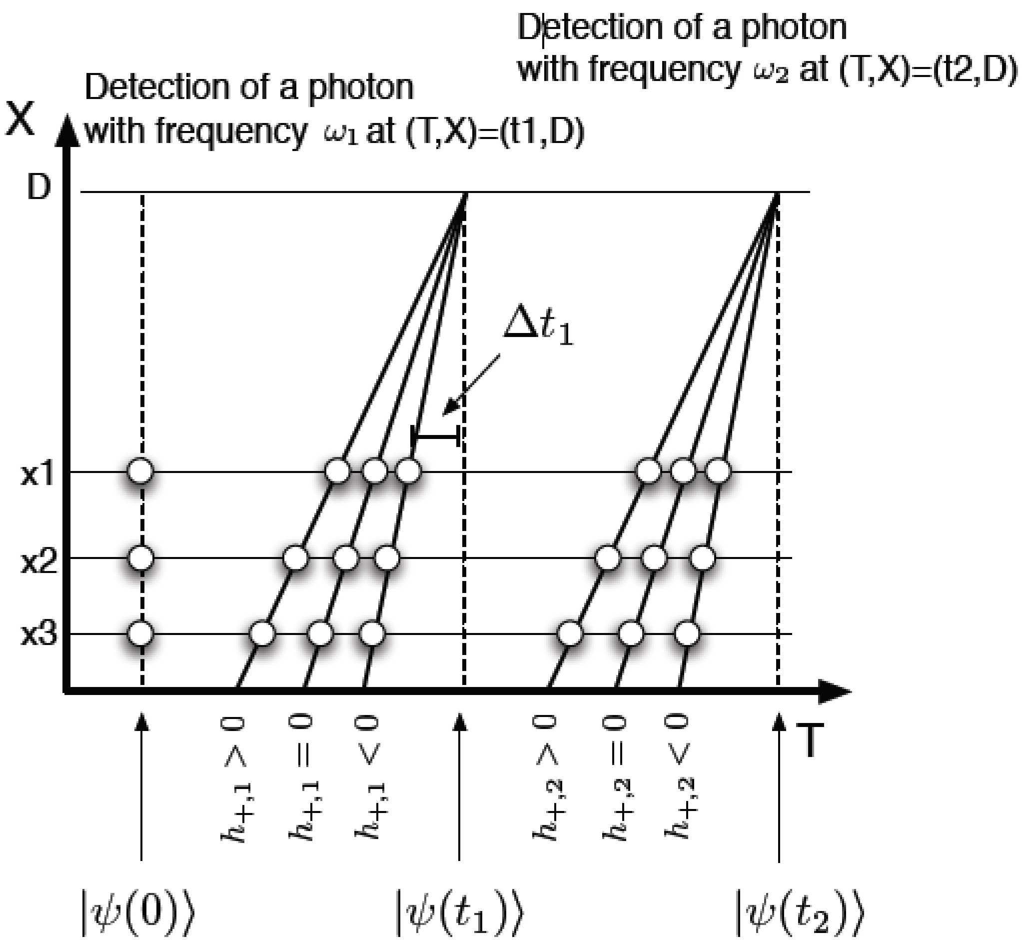
Emission strongly peaked

$$\left\langle e^{i\left[k^i r^j g_{ij}(t_0) - k'^i r^j g_{ij}(t)\right]} \right\rangle$$

$$\sim \delta\left(\left[k^i g_{ij}(t_0) - k'^i g_{ij}(t)\right]\right)$$

Dispersion relation

$$k^\mu k^\nu g_{\mu\nu} = 0$$



Gravity wave modulates superradiant frequency

Frequency emitted by z-arm

$$\omega_z(t) = \omega_0\left(1 + \frac{1}{2}h_+ \cos\Omega t\right)$$

Difference to y-arm

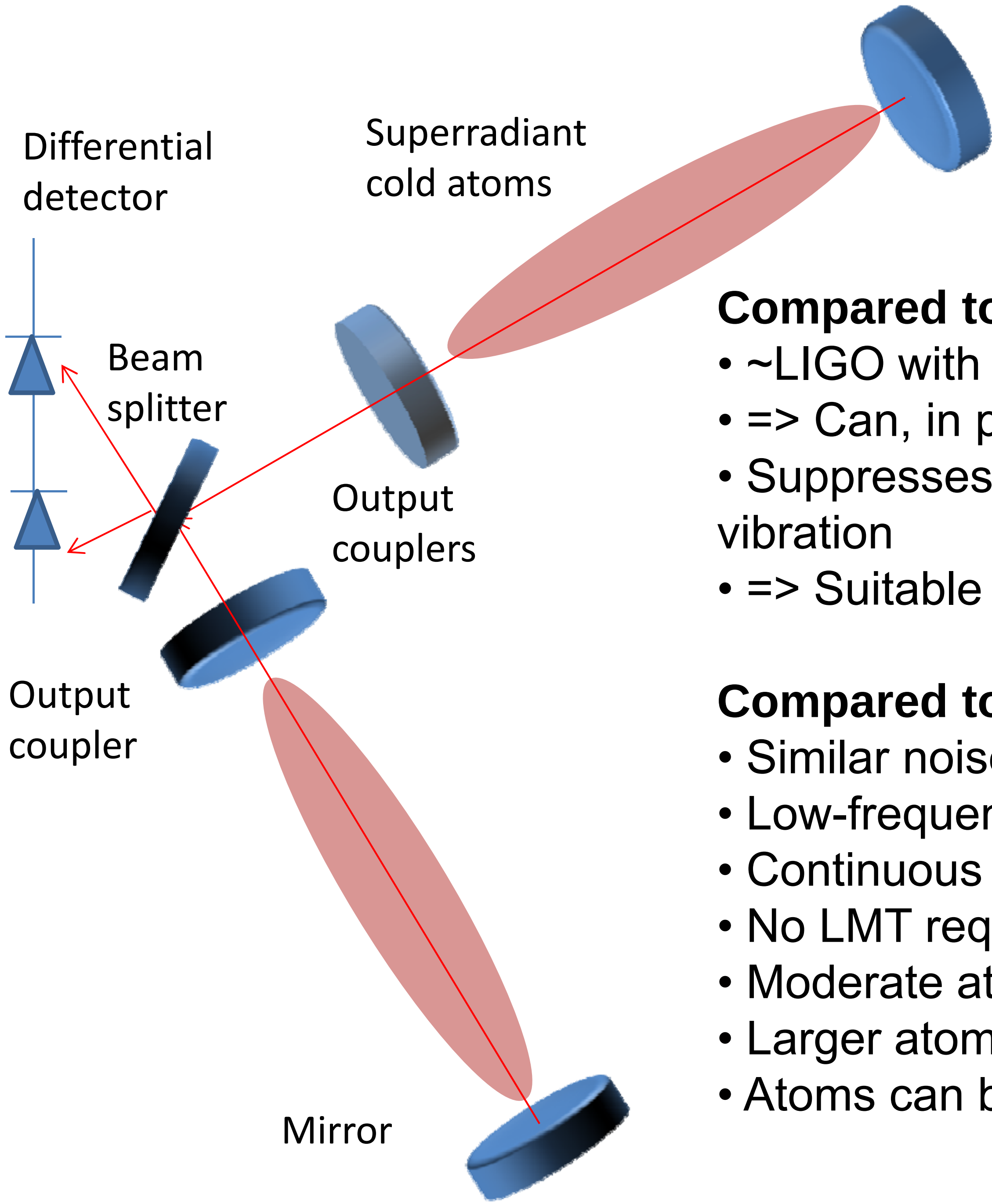
$$\omega_z - \omega_y = \omega_0 h_+ \cos\Omega t$$

Phase detected

$$\varphi = \frac{\omega_0 h_+}{\Omega}\sin\Omega t$$

Assumptions used:

- Short arms, low linewidth $\gamma \ll c/L$
- Low-frequency waves: $L \ll c/\Omega$
- Dilute samples no reabsorption of photons
  This assumption is (fortunately) not true
  =>Need more theory



Compared to LIGO

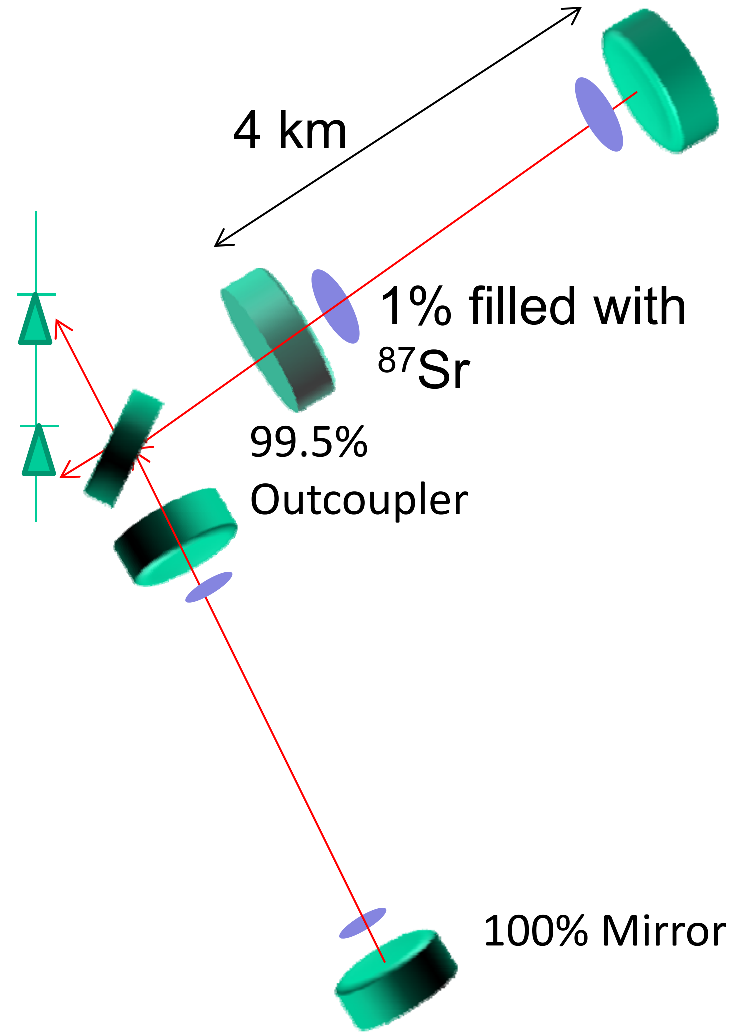
- ~LIGO with infinitely good (r=1) cavities
- => Can, in principle, be compact
- Suppresses beamsplitter and mirror vibration
- => Suitable for low frequencies

Compared to atom interferometers

- Similar noise sources, no laser noise
- Low-frequency sensitivity
- Continuous operation
- No LMT required
- Moderate atom temperature requirement
- Larger atom number -> lower noise
- Atoms can be continuously replaced

A scenario

Quantity	
Cavity linewidth	30 Hz
Natural linewidth	1 mHz
Decoherence rate	10/s
Coupling	5×10^{-6} Hz
Collective coupling	3×10^{4}
Atomic density	$10^{8}/cm^{3}$
Cavity Pulling	0.1
Atom Doppler linewidth	50 Hz
Photons/second	3×10^{6}
Sensitivity	$2\times10^{-21}[f_{GW}/10$ mHz]



Conclusion

- LMT, Simultaneous, BBB, Coriolis compensation
- α, inertial sensors, tests of GR, Compton clock
- Basic GW sensor: principles, comparison to LIGO
- Proposals on Earth and in Space
- SuperLIGO:
  - LIGO optics
  - No laser noise
  - Continuous operation
  - No LMT, moderate temperature
  - Larger atom number, lower noise

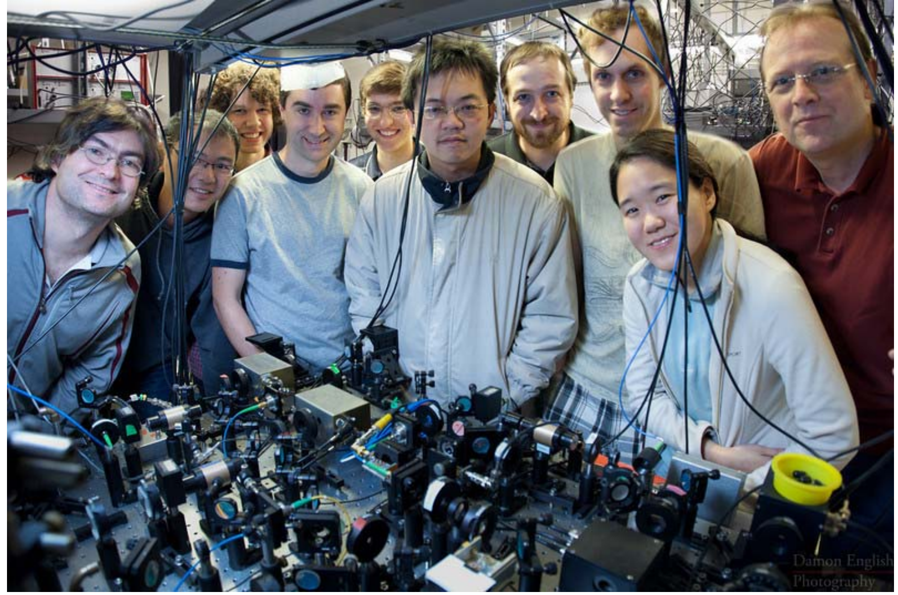
Compton clock
Postdocs: S.-y. Lan,
M. Hohensee,
D. English
Grad students:
P.-C. Kuan, B. Estey,

EEP
Postdocs: P. Hamilton
Grad student: G. Kim,

Lorentz invariance
Postodc: M. Hohensee
Grad student: F. Monsalve

Phase contrast TEM
Postdoc: M. Xu
Grad Student: E. Sohr

Cavity, AB effect
Postdoc :J. M. Brown
Grad student: B. Estey



XUV atom interferometer
Postdoc :Paul Hamilton

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NASA