Atom Interferometers

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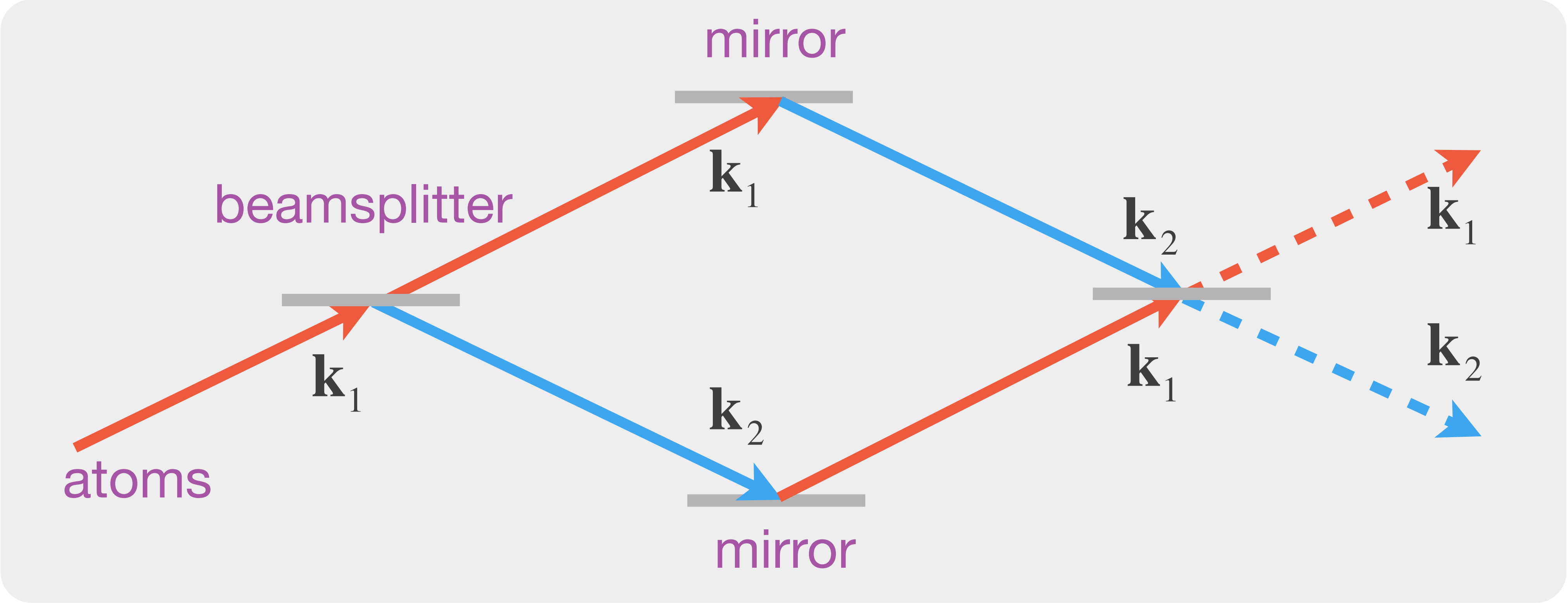
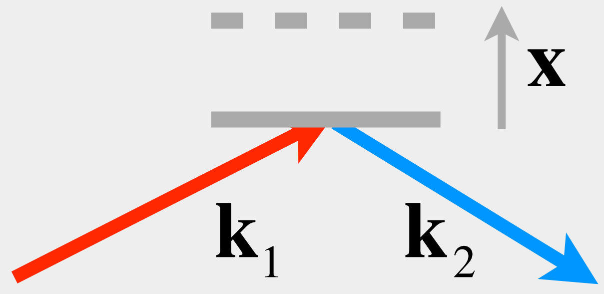
Why Atom Interferometers?

- Not because atoms have short de Broglie wavelength.
- But because atom clouds could be used as test masses for low frequency detection.
- Some recent proposals
  - R. Chiao et al.
  - S. Dimopoulos, P.W. Graham, J.M. Hogan, M.A. Kasevich and S. Rajendran, Phys. Rev. D **78**, 122002, (2008).
- Paper on how atom interferometers respond to gravitational waves
  - A. Roura, D.R. Brill, B.L. Hu, C.W. Misner, and W.D. Phillips, Phys. Rev. D **73**, 084018 (2006)

How does an atom interferometer work?



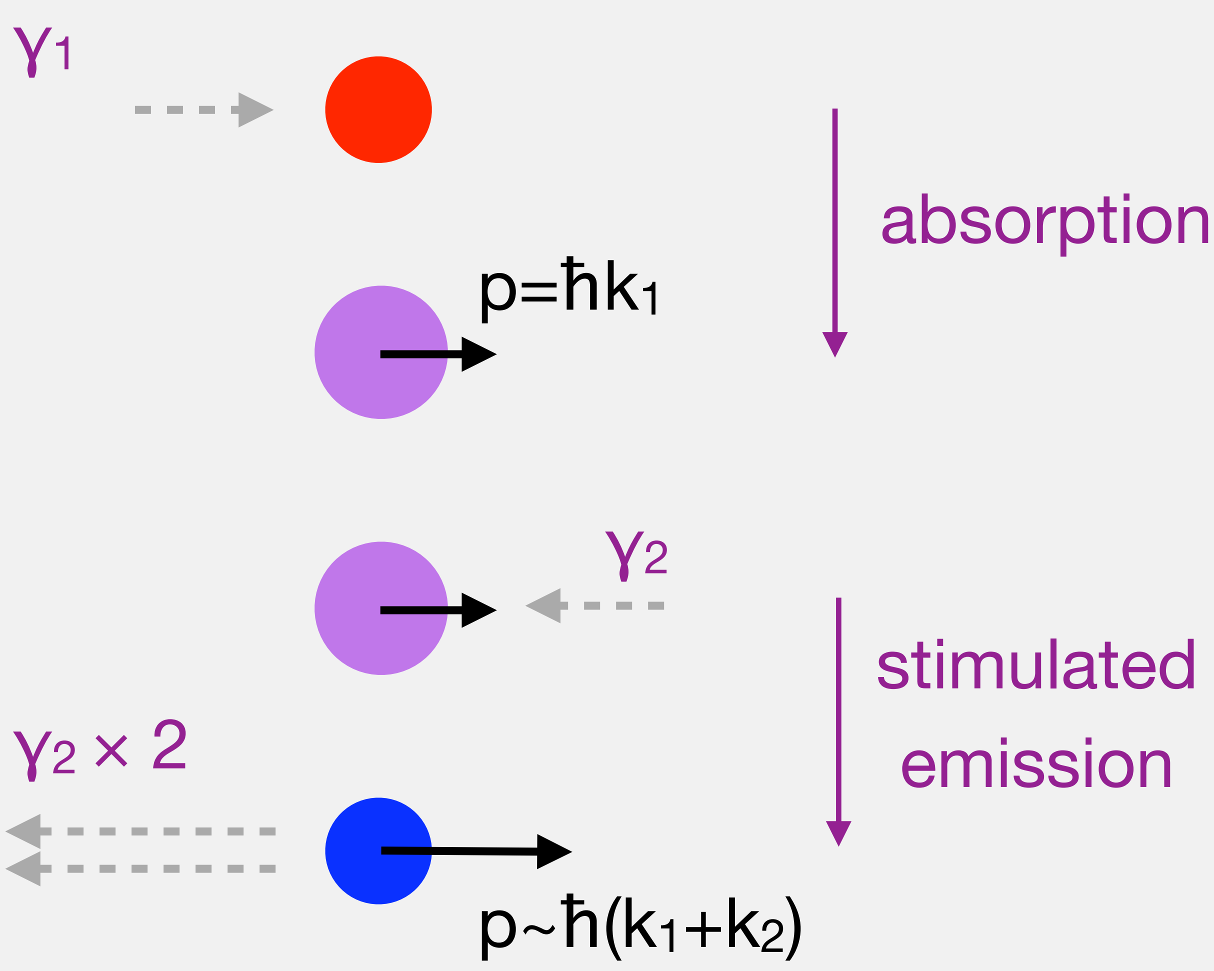
- Similar to optical interferometer
- Phaseshift depends on momentum transfer at mirror
- De Broglie wavelength $\lambda=h/(mv)$ could be small, de Broglie $k=mv/\hbar$ could be high, but it is δk that matters
- How do atom mirrors transfer momentum?



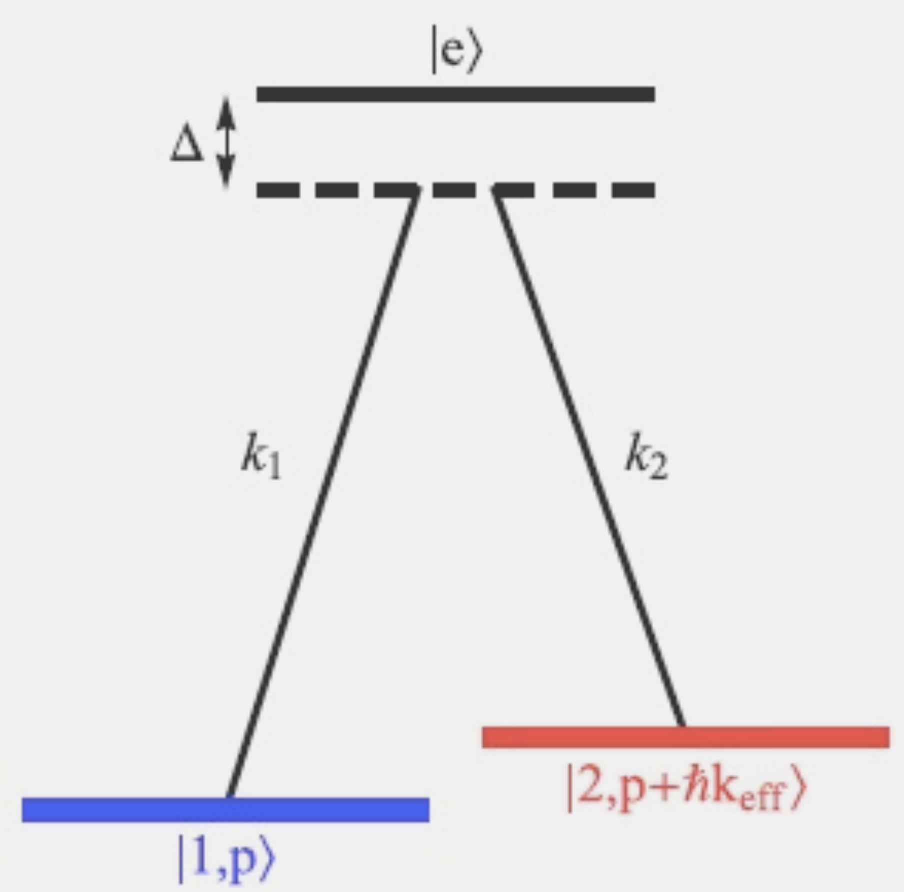
$$\Phi = (\mathbf{k}_2 - \mathbf{k}_1) \cdot \mathbf{x}$$

How does an atom mirror work?

- Atoms are deflected by photons, for example Stimulated Raman Transition

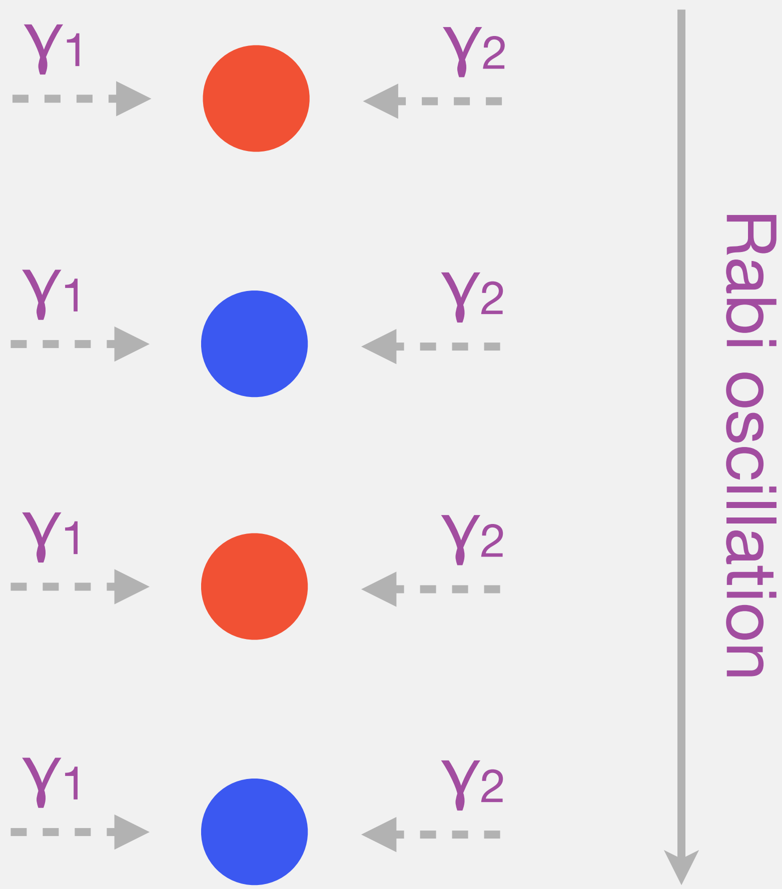


In reality, excited state has negligible occupation number

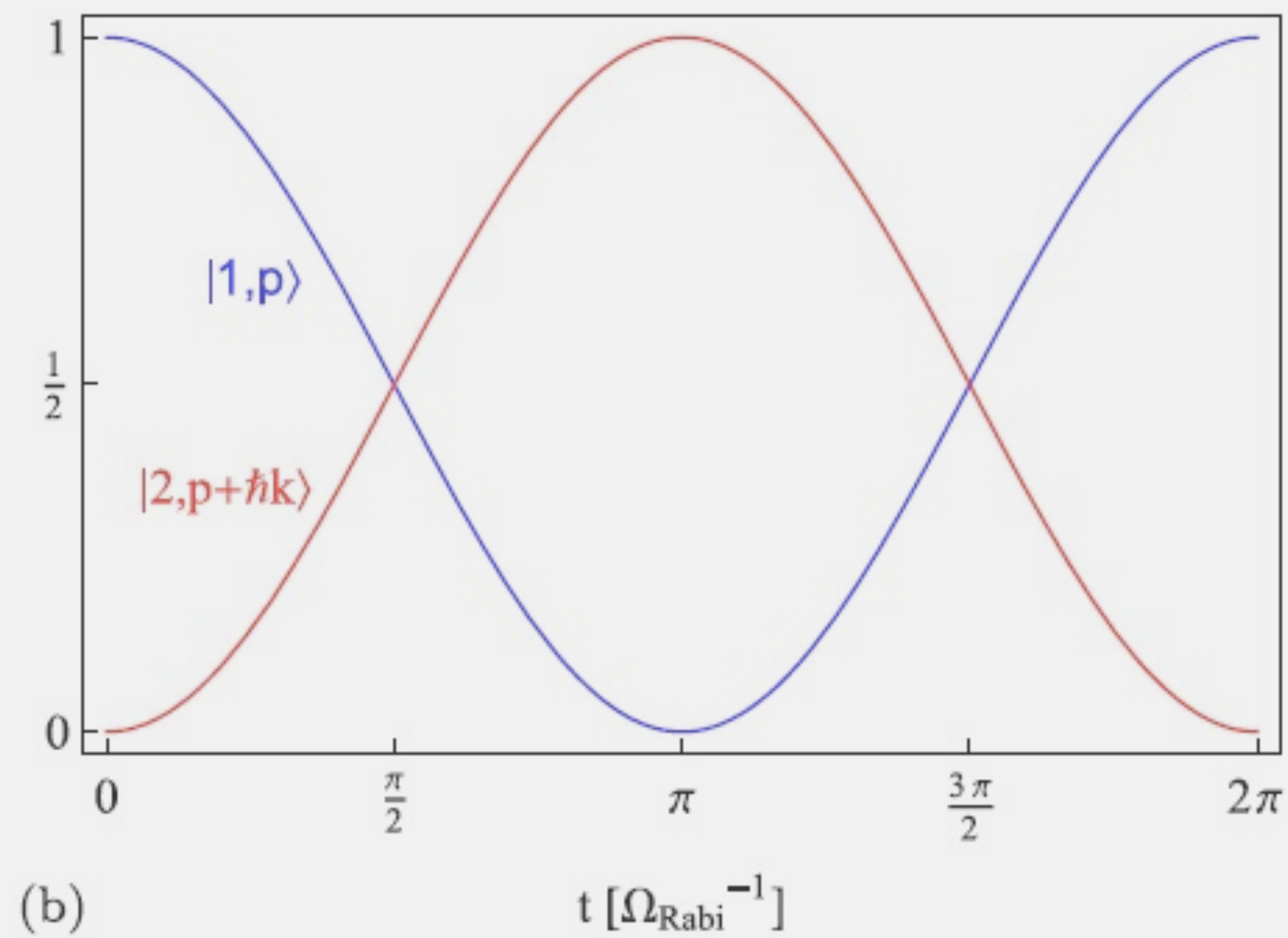


Stimulated Raman Transition
Picture from Dimopoulos et al.

Mirror vs Beamsplitter: Phase of Rabi Oscillation



continuous pumping
with two opposite beams:
atom sloshes between
state 1 and state 2



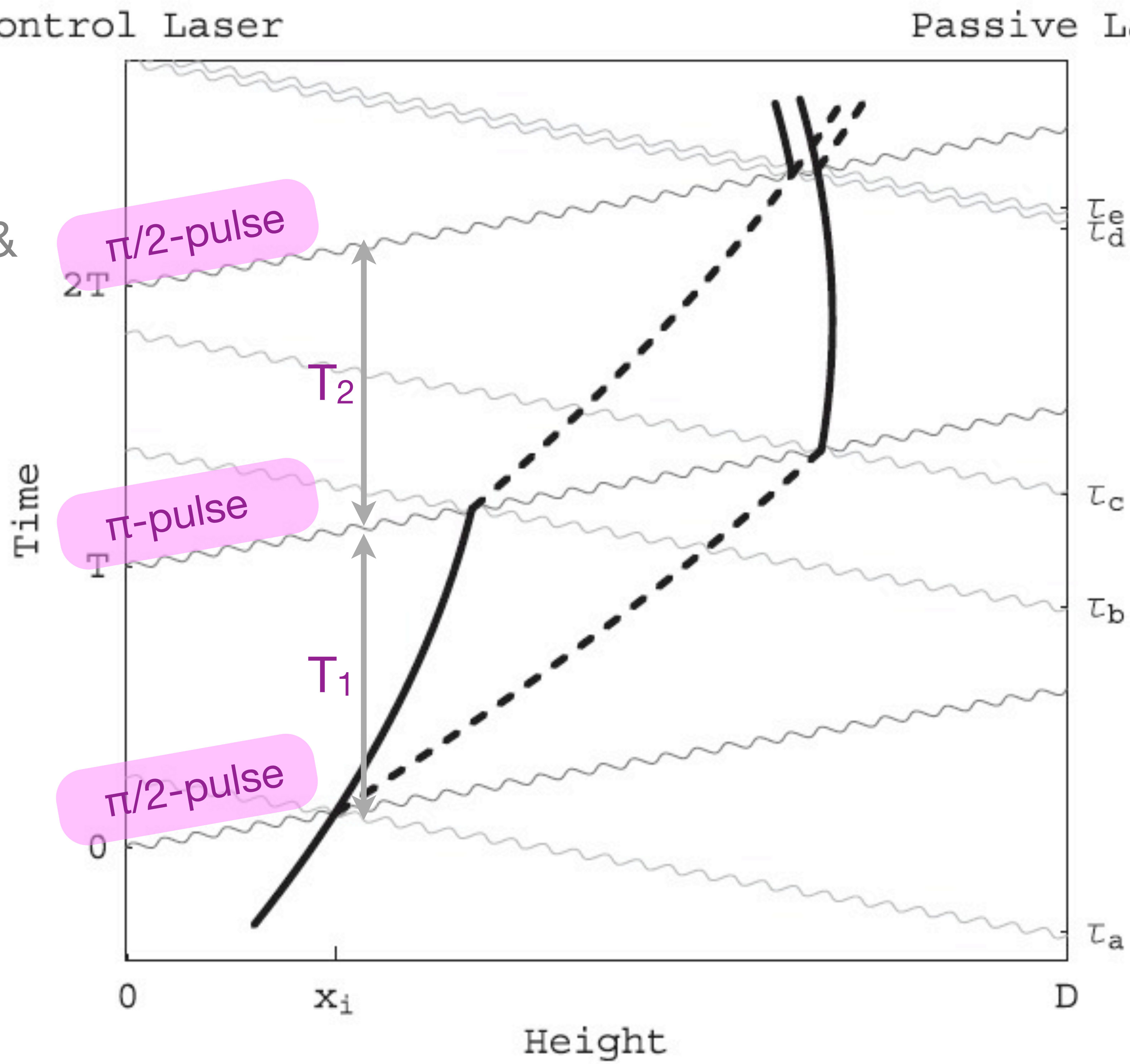
Rabi Oscillation
Picture from Dimopoulos et al.

- Depending on phase of the Rabi oscillation, one can make a mirror (π-pulse) or beamsplitter (π/2-pulse)

An Atom Interferometer

supplies γ_1
pulsed to
create mirrors &
beamsplitters

supplies γ_2
always on



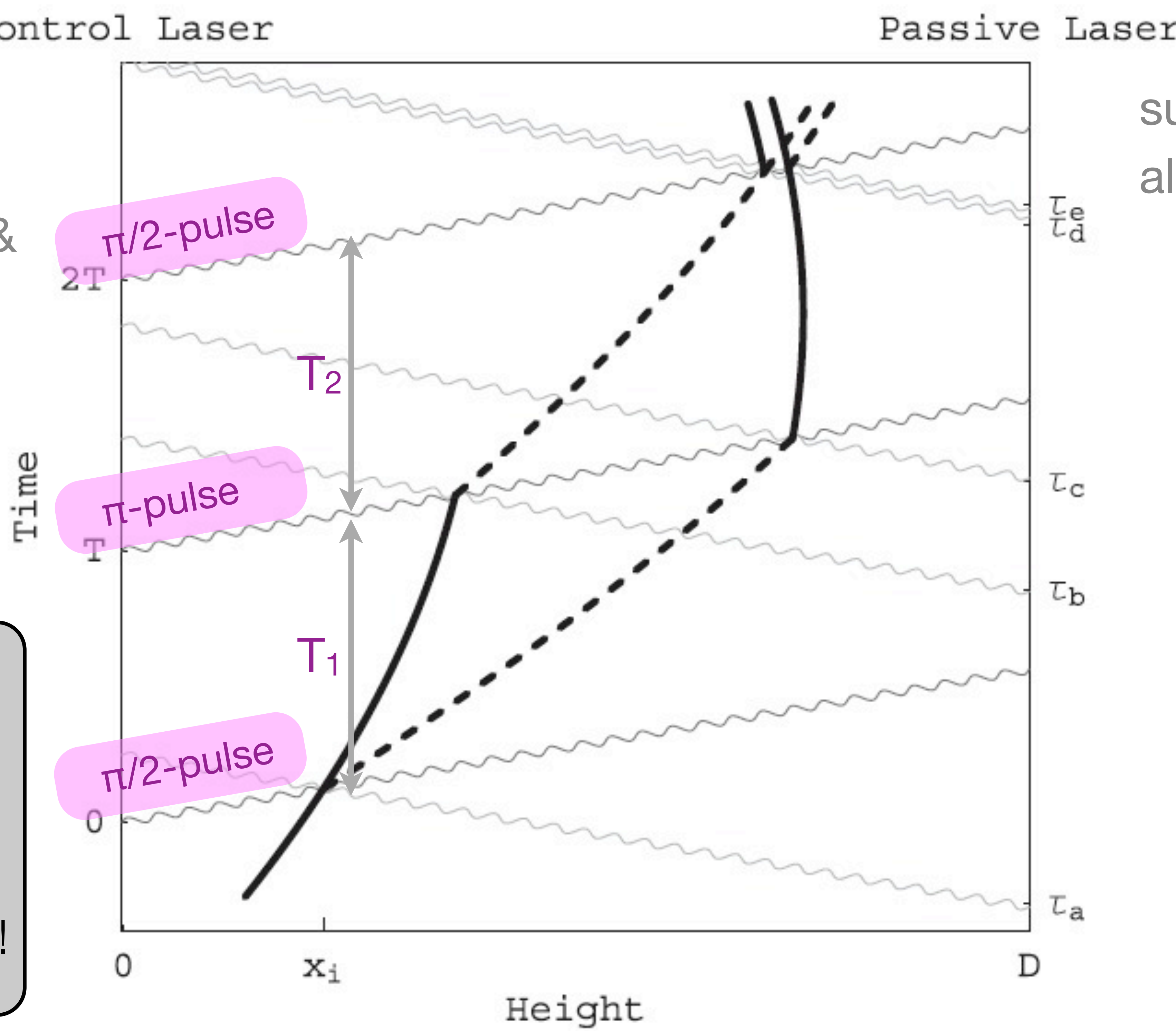
Space-time diagram of a "linear" atom interferometer

Picture from Dimopoulos et al.

An Atom Interferometer

supplies γ_1
pulsed to create mirrors & beamsplitters

supplies γ_2
always on



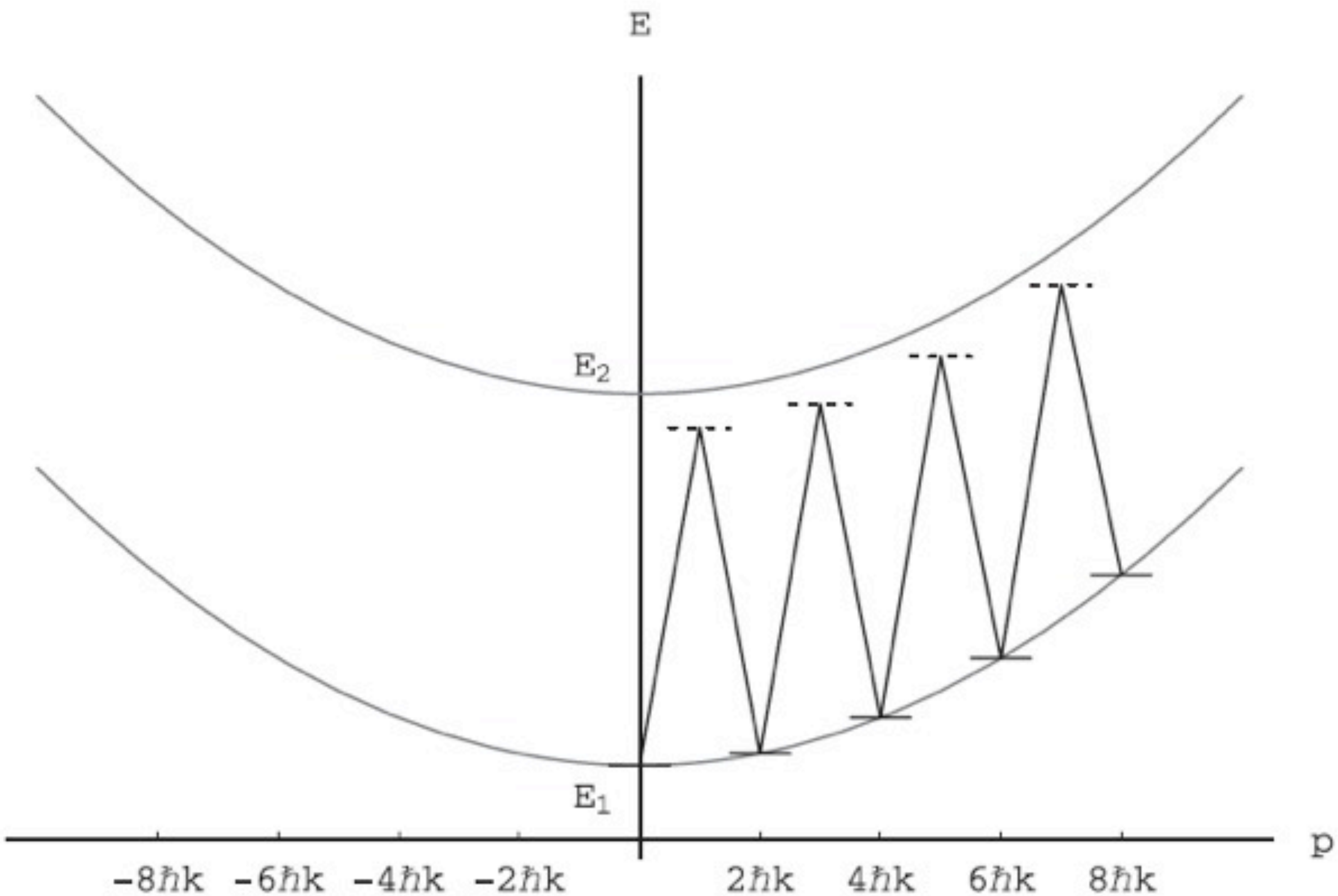
But δk is only $2k_\gamma$, and there won't be any improvement in length resolution!

Space-time diagram of a "linear" atom interferometer

Picture from Dimopoulos et al.

Large Momentum Transfer & Atom Squeezing

- It is possible to transfer more momenta, if the transition is Bragg, not Raman



Picture from Dimopoulos et al.

Pulses can be iterated to give *N* times the momentum

N ~ 100 - 1000 might be realizable

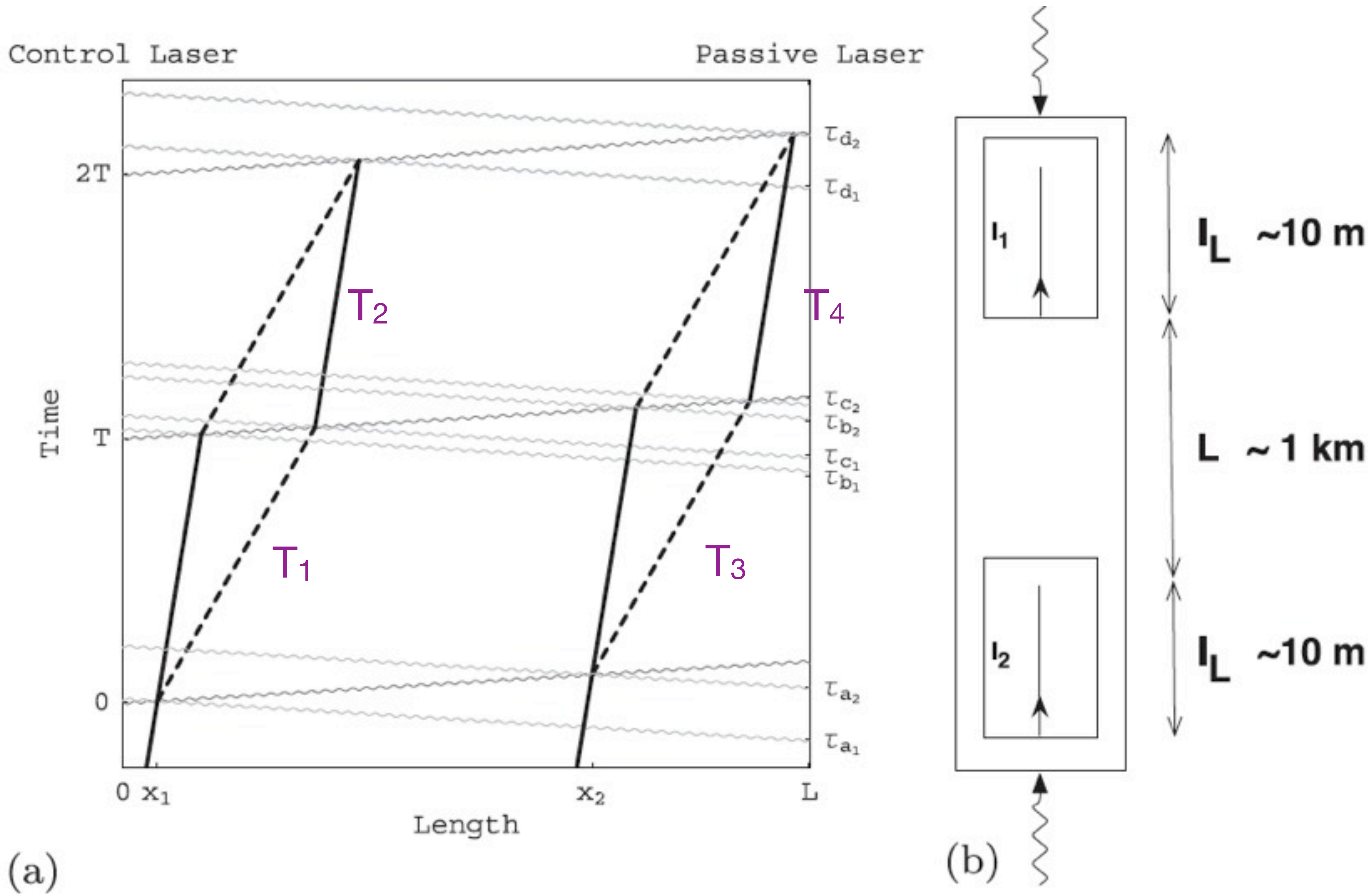
- Roughly equivalent to the use of a cavity with Finesse equal to *N*, which is not very high.

Why are we still interested in Atom Interferometry?

- Atoms might be usable as test masses for low-frequency detectors
  - they do not need to be suspended
  - they do not couple to vibration during flight

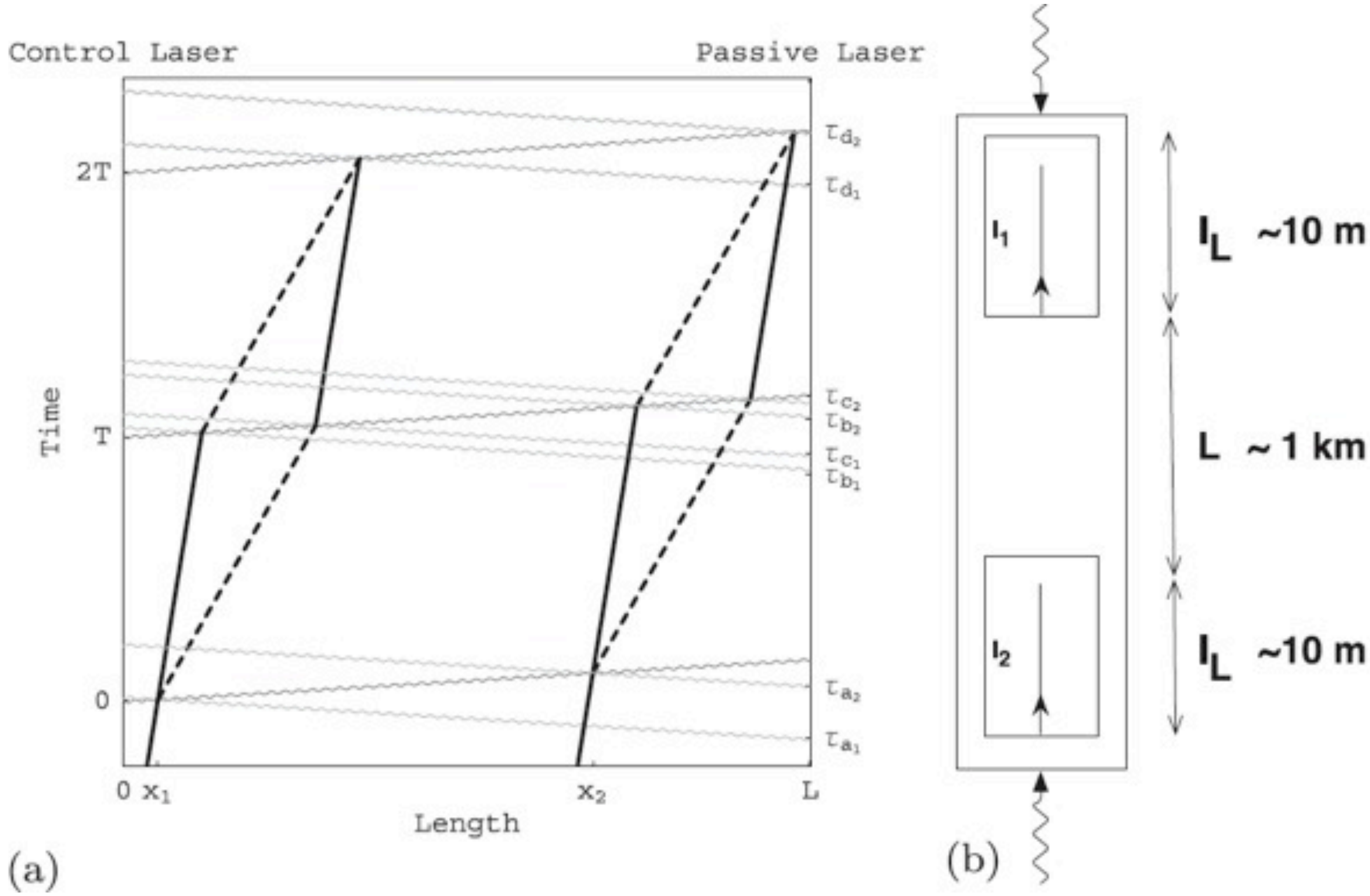
- Recent proposal
  - S. Dimopoulos, P.W. Graham, J.M. Hogan, M.A. Kasevich and S. Rajendran, Phys. Rev. D **78**, 122002, (2008).
  - Two versions: terrestrial & space-based

Dimopoulos et al.'s Detector



- Two co-linear atom interferometers sharing the same control and passive light
- Measures delays of laser pulses due to gravitational wave: $(T_4 - T_3) - (T_2 - T_1)$

Ground-based version



l_L~10 m because atoms drop during the 2T interrogation time

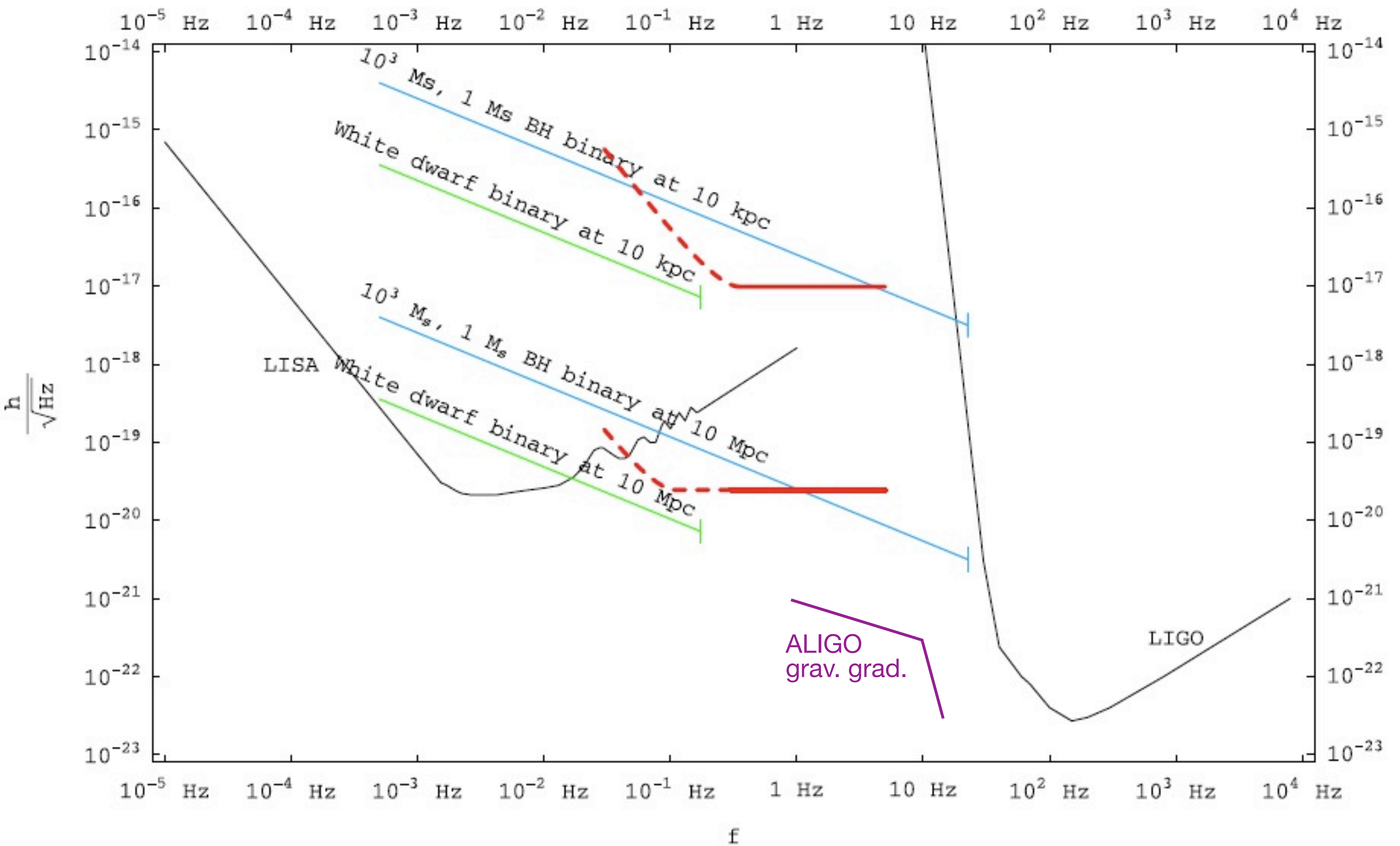
Advanced version L = 4 km

vacuum 10^{-10} Torr, average collision time 200s

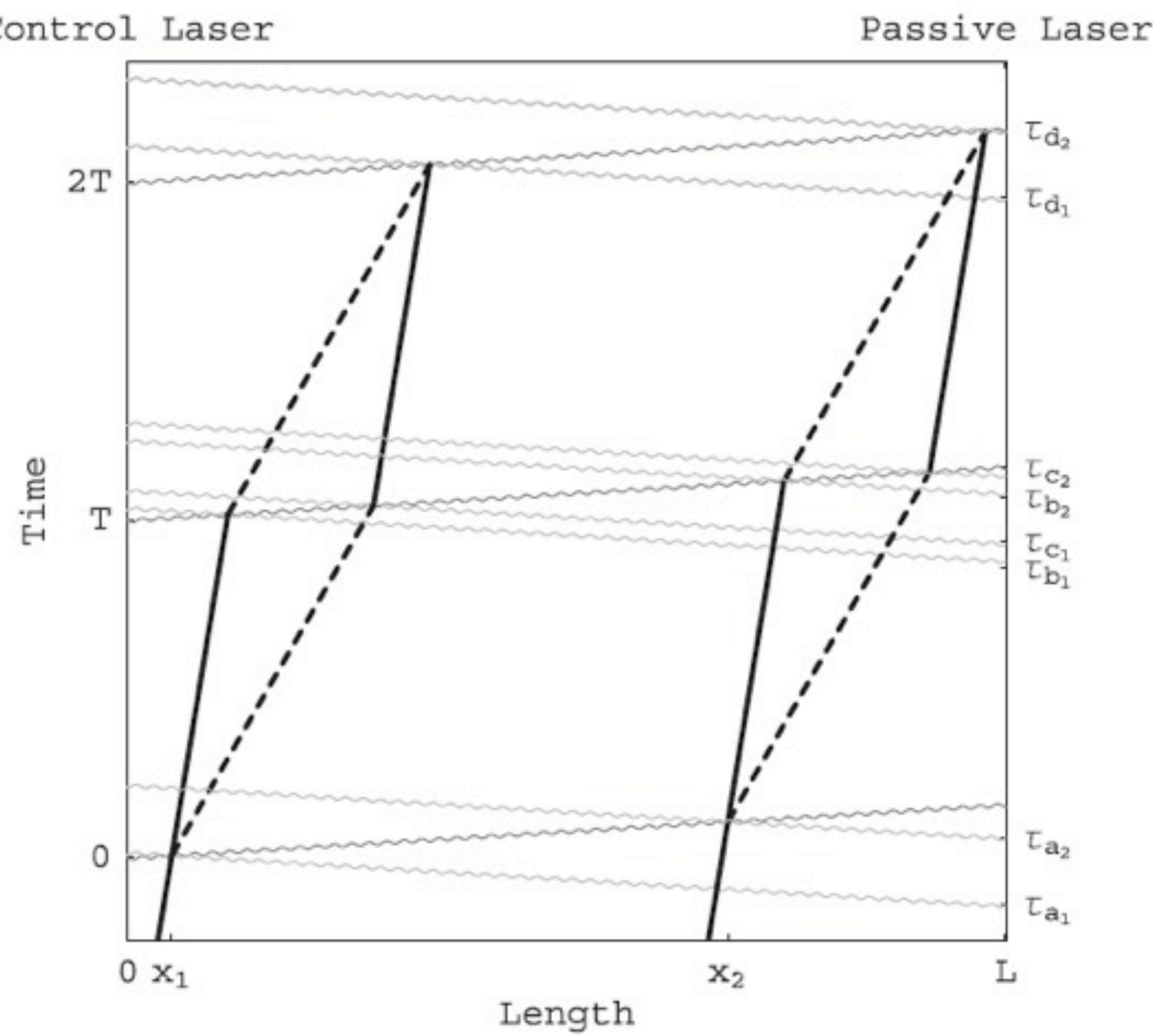
1 W laser waist size 10 cm

- T ~ 1 s, k_{eff} ~ 1.6×10^9 (with N~1000), n ~ 10^8, 5 clouds simultaneously, h~10^{-17}/rtHz at 1 Hz (advanced version is 10x better)

Sensitivity of Ground-Based Version

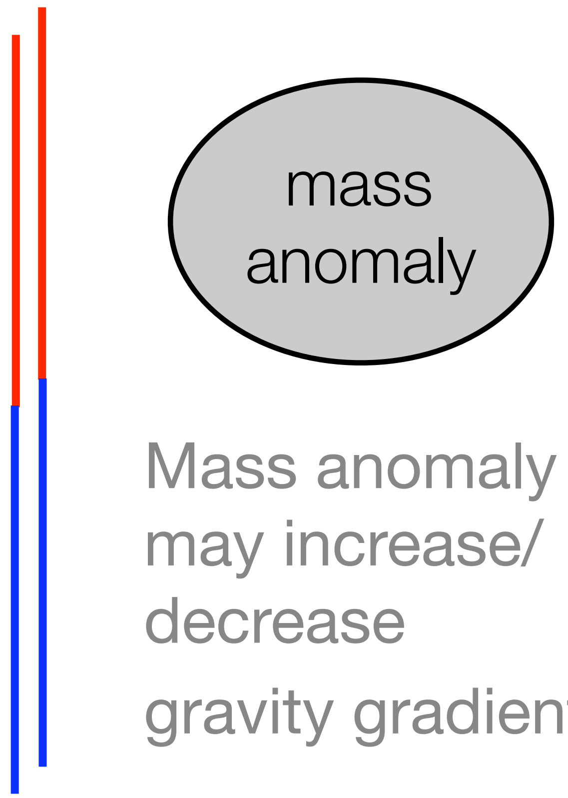


Noises: vibration & laser phase noise



- Phase noise in control pulse unimportant (except for quantum part which seems small anyway)
- Vibration & Phase noise: phase noise of passive laser are subtracted between times of L/c (short). Requires $\delta x \sim 10^{-15}$m (for 4 km version) or 10^{-14}m (for 1 km version)

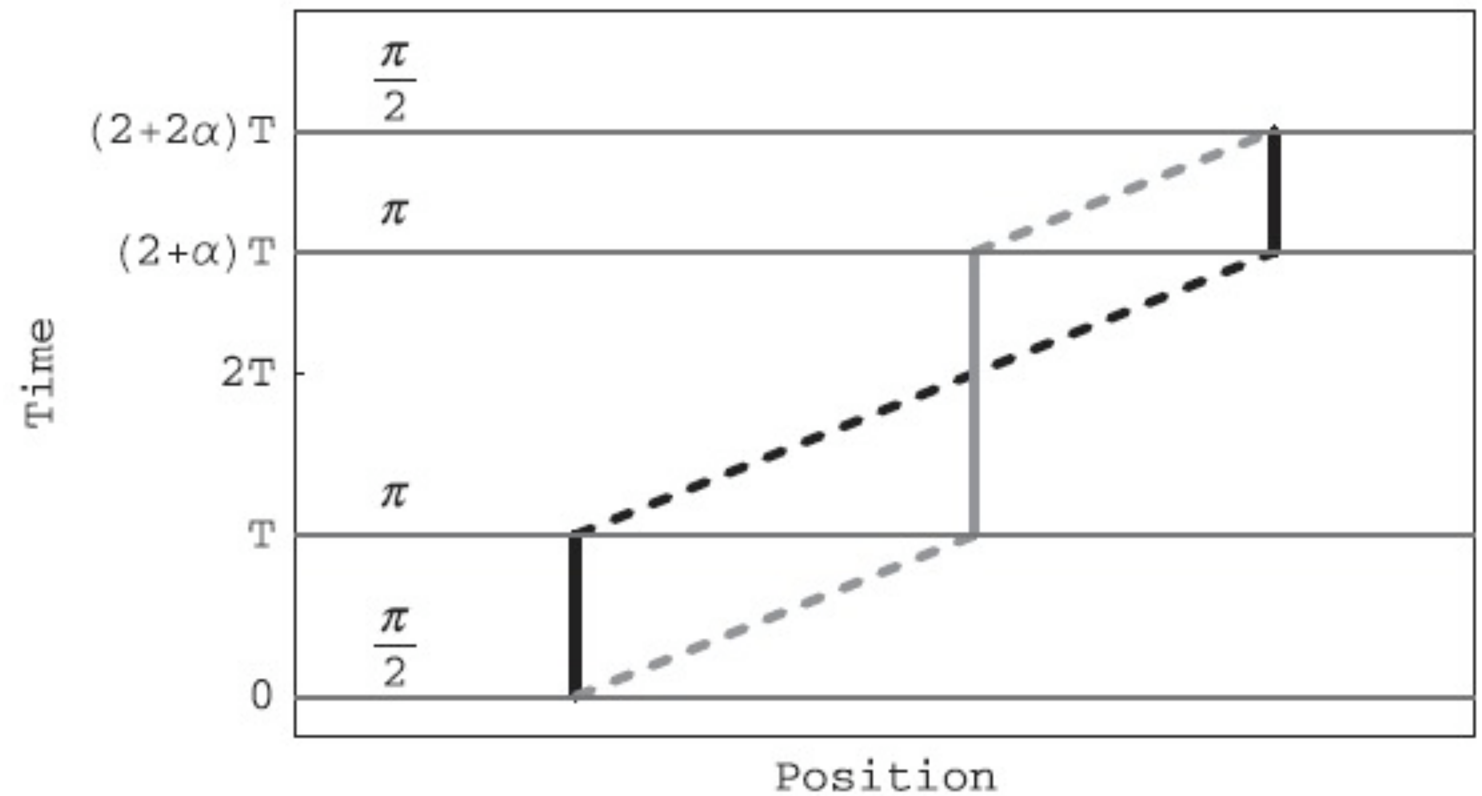
Noises: Gravity Gradient



Mass anomaly may increase/ decrease

gravity gradient

Different paths sense different **g**



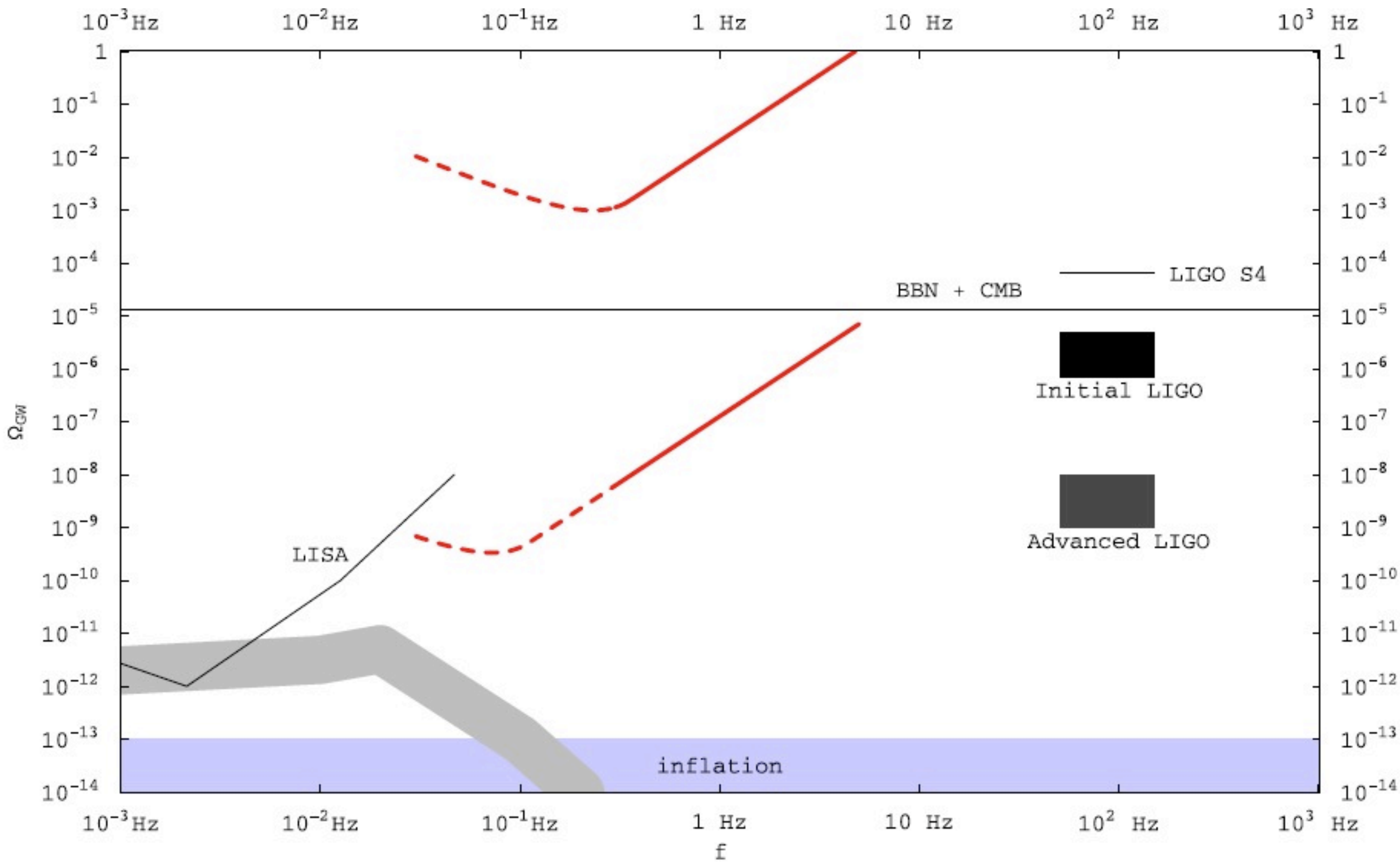
Double loop configuration, cancels g gradient

- Gravity Gradient: mostly due to gradient of g --- fluctuations in atoms' path cause difference in g. This sets requirement on the path of atoms, and therefore on the atom trap.
- Tricks can be used to avoid measuring them
  - Add compensation mass
  - Using fancy pulses
- Temporal fluctuations in gravity gradient seems unimportant.

Rotation

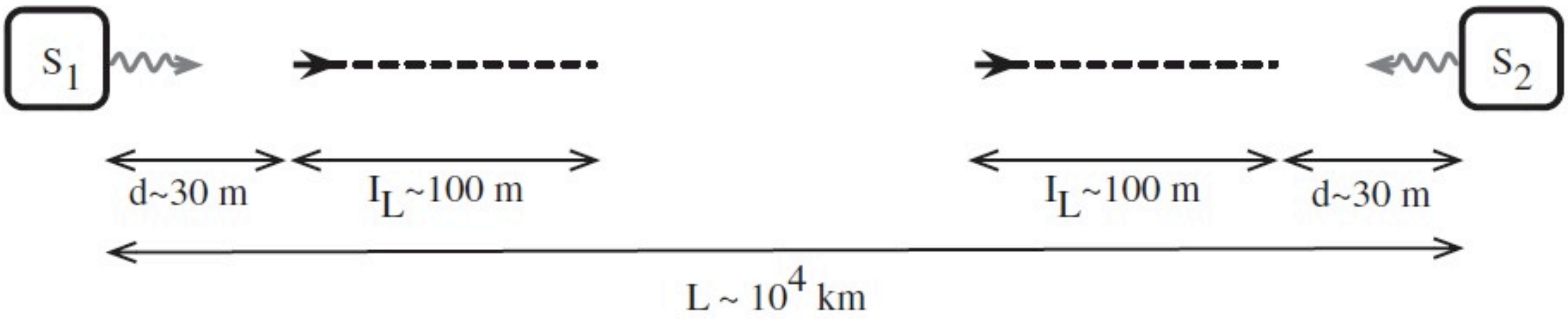
- Coriolis force cause acceleration larger than GW $\delta a=2\omega_e\delta v$ with $\delta v\sim10^{-8}$m/s
  - Can be cancelled if laser axis is not rotating together with earth. Requires accuracy of $\delta\omega<10^{-9}$(rad/s/rtHz)$\times$(1 km/L)$^{1/2}$
- Laser jittering will cause the atoms to sense different **g**, and this requires laser beam to have $\delta\omega<10^{-9}$(rad/s/rtHz) (for 1 km version)

Sensitivity to Stochastic Background



Ground-based versions

Space-Based Version



T ~ 100s, aiming at waves below 0.01 Hz

d ~30 m to minimize gravity gradient caused by spacecraft

l_L ~100 m is the maximum that spacecraft can provide bias B field. For T ~ 100s, this limits k_{eff} to ~10^9. [$v = \hbar k/m$]

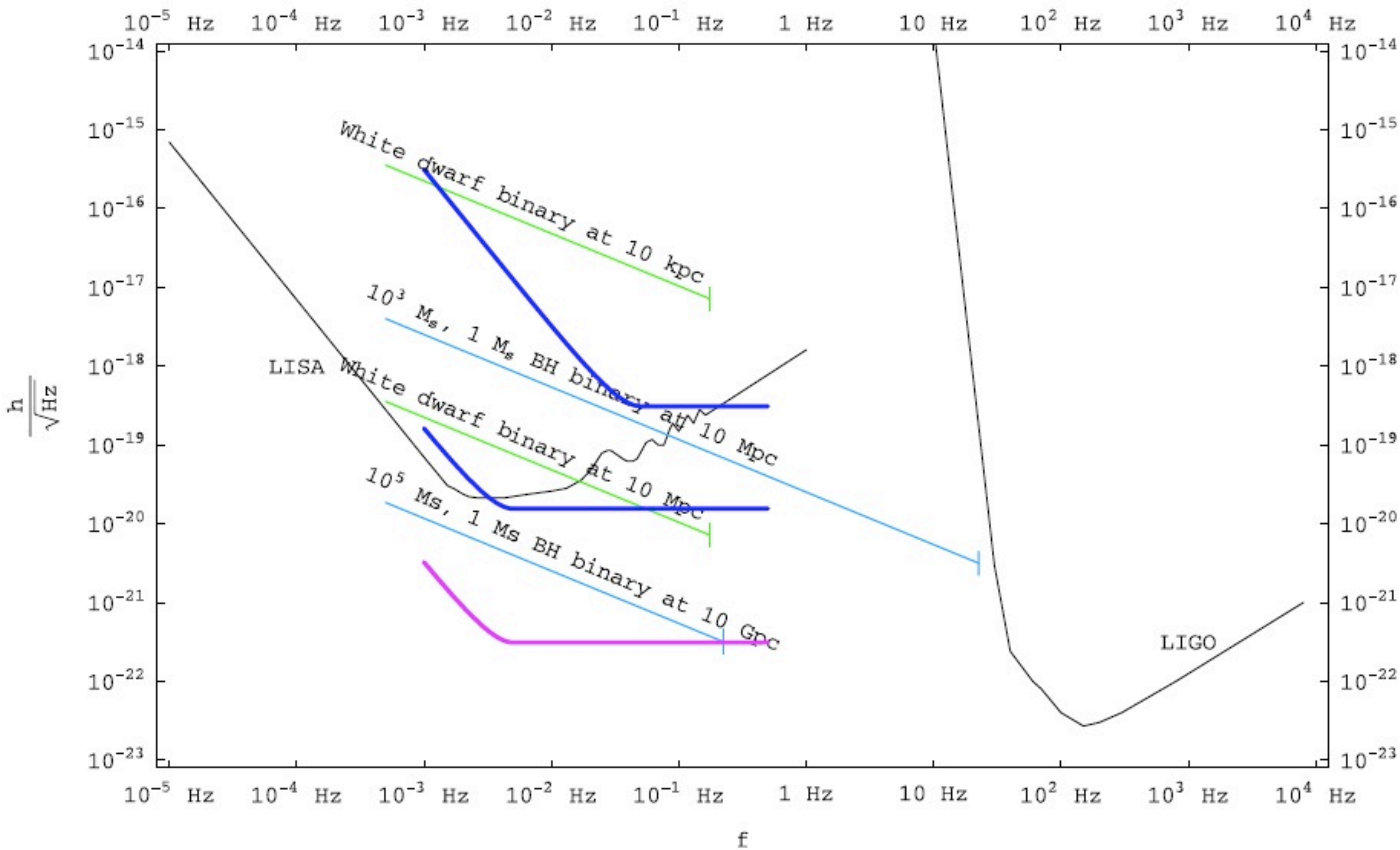
For 10^3 km version, Laser 1 W waistsize 0.5m

Must be shielded from sunlight, otherwise will only work when it's behind the earth, when photon-atom scattering timescale is longer than T

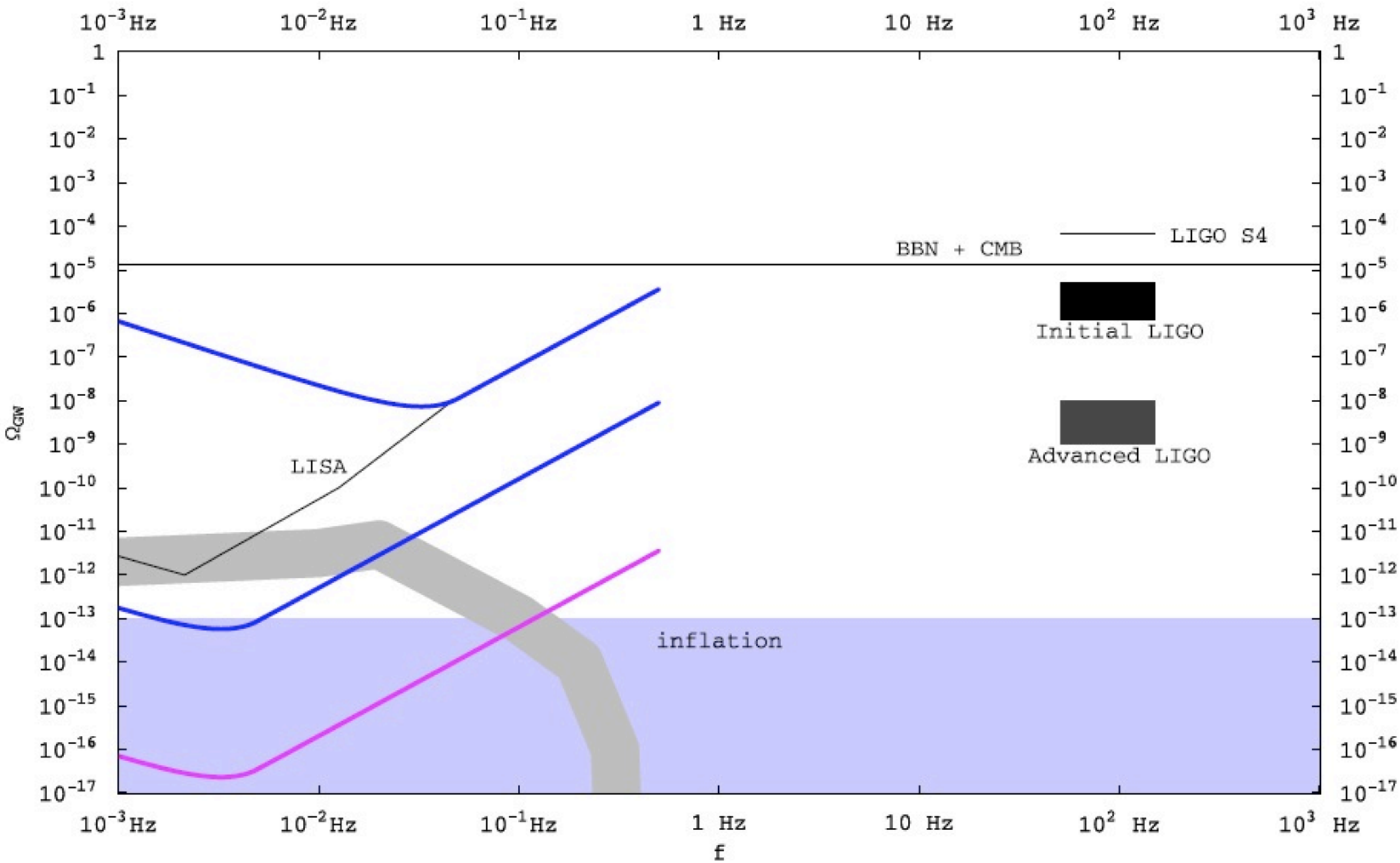
Effect from solar wind considered unimportant

Interplanetary magnetic field can be dealt with

Sensitivity of Space-Based Detector



Sensitivity to Stochastic Background



Space Versions

Comparison with LISA requirements

TABLE II. A comparison between specifications for a three-satellite AGIS configuration that could potentially allow comparable sensitivity to LISA, and the LISA requirements. There are many caveats and details that cannot be captured in a table and are discussed in Secs. V B and V C and in the LISA papers (see e.g. [42,47]).

Attribute	AGIS	LISA
Baseline	10^3 km	5×10^6 km
Satellite control (at $\sim 10^{-2}$ Hz)	$10^4 \frac{\text{nm}}{\sqrt{\text{Hz}}}$	$1 \frac{\text{nm}}{\sqrt{\text{Hz}}}$
Laser frequency control (at $\sim 10^{-2}$ Hz)	$10^4 \frac{\text{Hz}}{\sqrt{\text{Hz}}}$	$1 \frac{\text{Hz}}{\sqrt{\text{Hz}}}$
Rotational control (at $\sim 10^{-2}$ Hz)	$10^{-2} \frac{\text{nrad}}{\sqrt{\text{Hz}}}$	$1 \frac{\text{nrad}}{\sqrt{\text{Hz}}}$
Electromagnetic forces	Atoms neutral, EM forces naturally small, predictable response to measured EM field	Cosmic ray charging of proof mass
Collisions with background gas	Delete atoms, not a noise source	Cause acceleration noise

	Photon shot noise does not seem to have been taken into account	Limited by photon shot noise

Discussions?