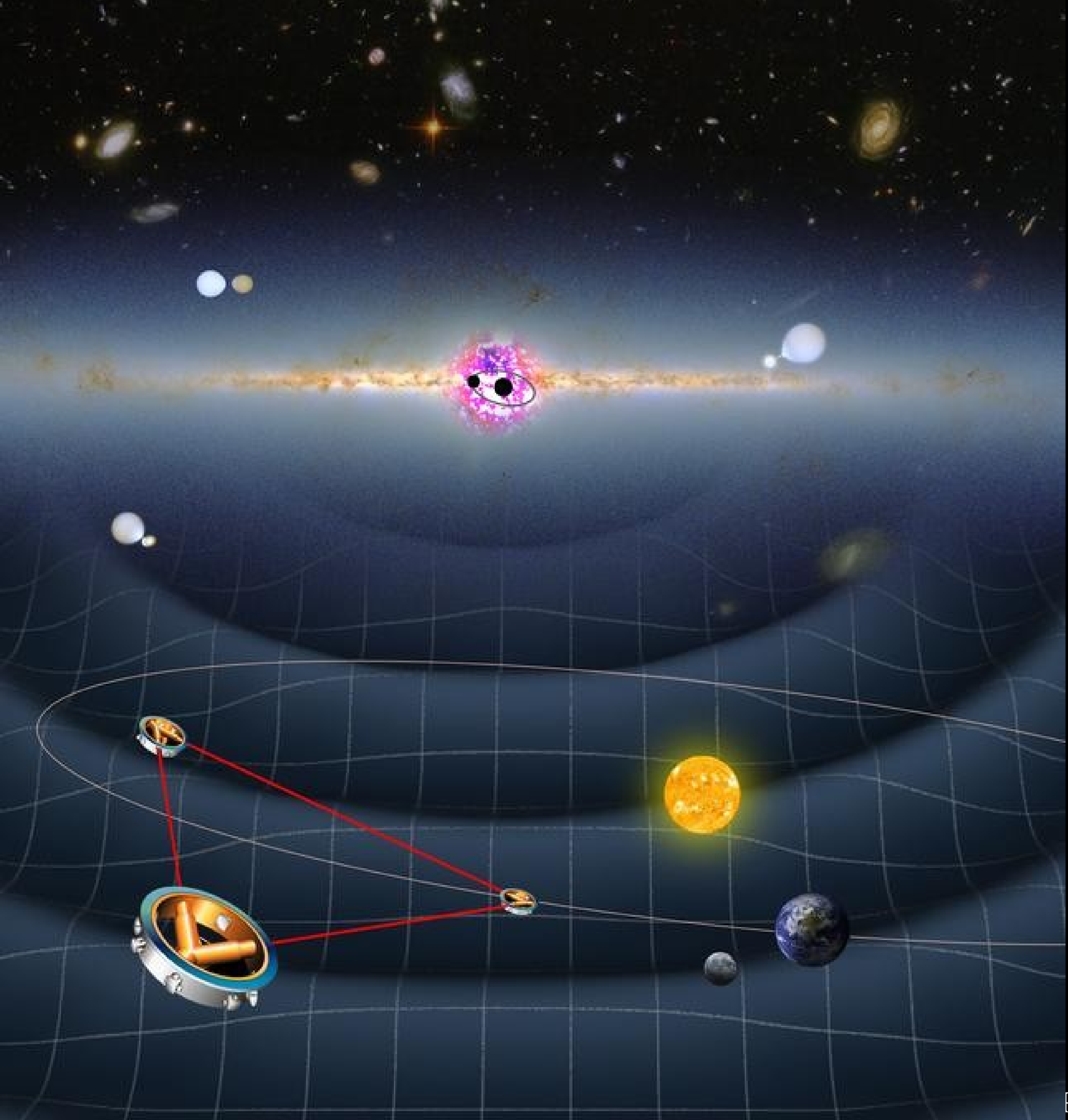
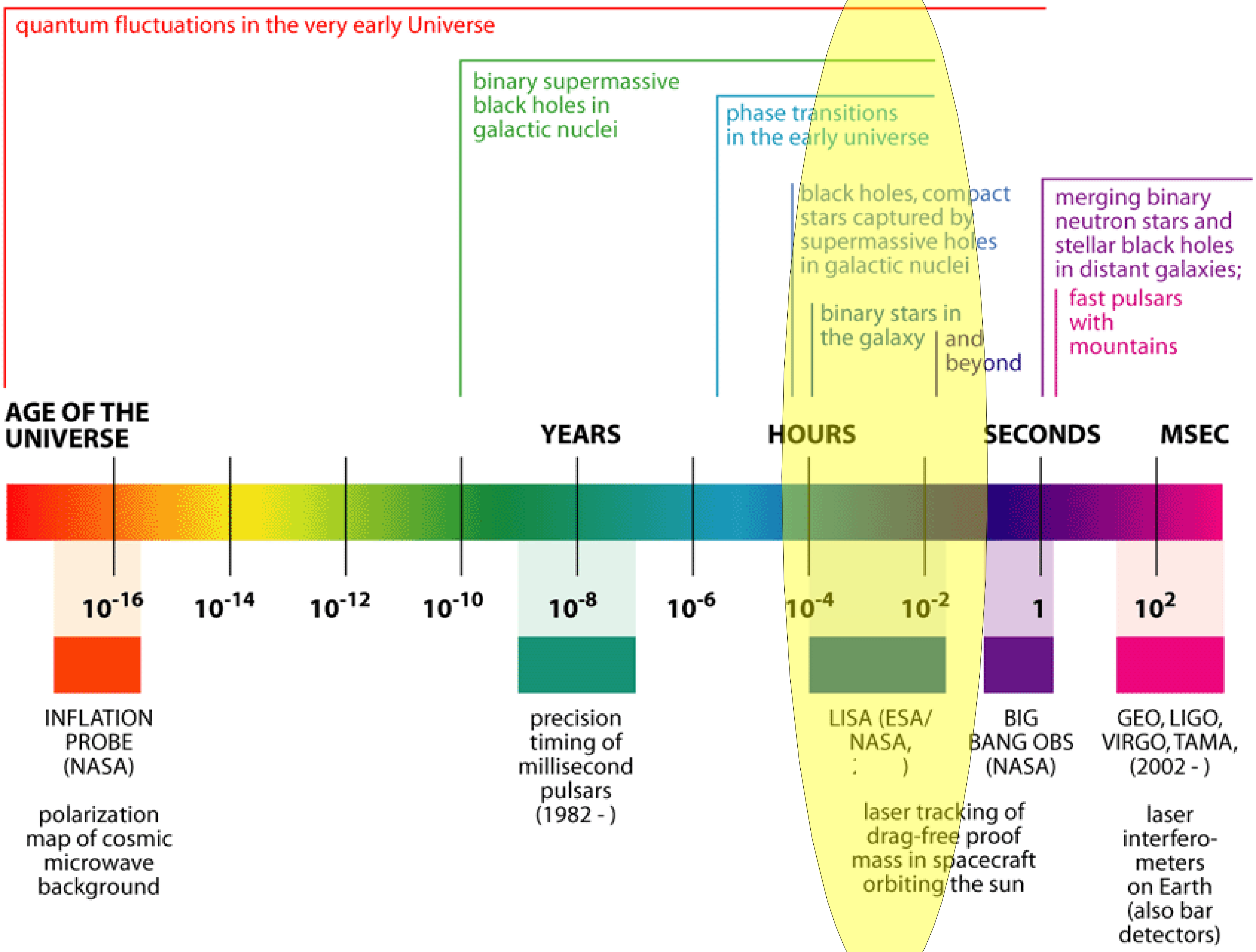


How LISA works: for radio astronomers

Sterl Phinney
Caltech

THE GRAVITATIONAL WAVE SPECTRUM



SOURCES

quantum fluctuations in the very early Universe

binary supermassive black holes in galactic nuclei

phase transitions in the early universe

black holes, compact stars captured by supermassive holes in galactic nuclei

binary stars in the galaxy and beyond

merging binary neutron stars and stellar black holes in distant galaxies;

fast pulsars with mountains

Wave Period

AGE OF THE UNIVERSE | **YEARS** | **HOURS** | **SECONDS** | **MSEC**

Frequency (Hz)

10^{-16} | 10^{-14} | 10^{-12} | 10^{-10} | 10^{-8} | 10^{-6} | 10^{-4} | 10^{-2} | 1 | 10^{2}

DETECTORS

INFLATION
PROBE
(NASA)

polarization
map of cosmic
microwave
background

precision
timing of
millisecond
pulsars
(1982 -)

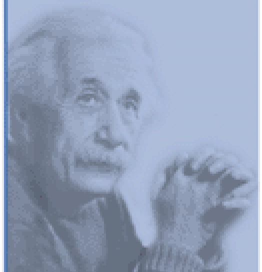
LISA (ESA/
NASA,
:   )

laser tracking of
drag-free proof
mass in spacecraft
orbiting the sun

BIG
BANG OBS
(NASA)

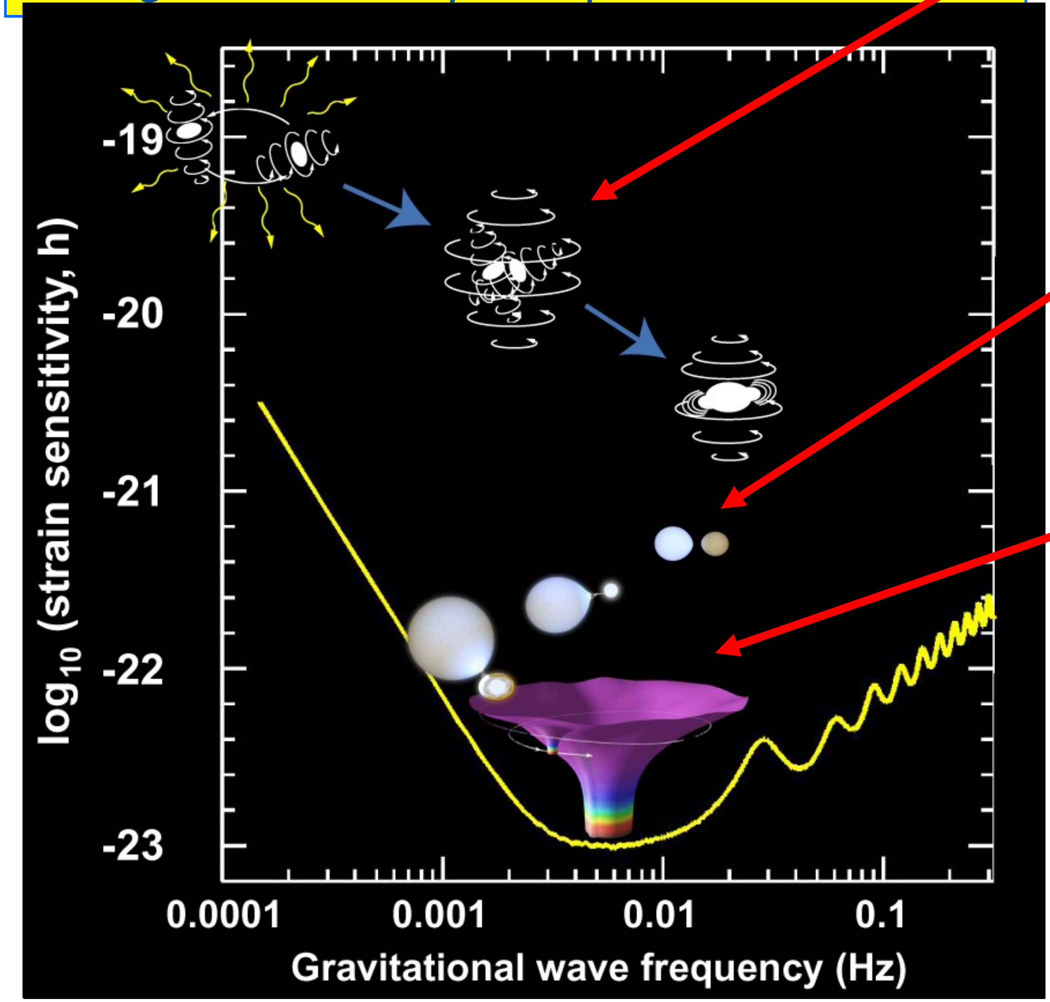
GEO, LIGO,
VIRGO, TAMA,
(2002 -)

laser
interfero-
meters
on Earth
(also bar
detectors)



What will this *h* sensitivity enable?

LISA will record a rich symphony of thousands of long-lived (>year) individually identifiable sources, plus backgrounds and perhaps bursts.



Massive Black Hole Binary (BHB) inspiral and merger
Sample: last 40 days of 10^6Msun at z=1, S/N=2500.

Ultra-compact Galactic binaries
Samples: 1kpc, S/N=6-210

Extreme Mass Ratio Inspiral (EMRI):
Samples: last 5 years of 1Msun into 10^6Msun, z=0.2, S/N=30

Cosmological backgrounds, superstring bursts?

Electromagnetic waves

Vector potential ***A***, scalar field ϕ

$$\boldsymbol{B}=\nabla\times\boldsymbol{A}$$

A depends on choice of gauge.

$$\boldsymbol{E}=-\nabla\phi\boxed{-\frac{1}{c}\frac{\partial\boldsymbol{A}}{\partial t}}$$

$$\boldsymbol{A}=\boldsymbol{A}_0\exp(i(\omega t-\boldsymbol{k}\cdot\boldsymbol{x}))$$

solves Maxwell equations in vacuum

$$\boldsymbol{S}=\frac{c}{4\pi}E^2=\boxed{\frac{1}{4\pi c}\omega^2 A^2}$$

flux of energy

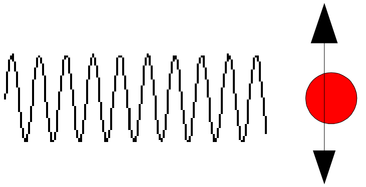
A transverse to ***k***. Two polarizations.

Detecting electromagnetic waves

$$m\ddot{\boldsymbol{x}} = q\boldsymbol{E} = -\frac{q}{c}\frac{\partial \boldsymbol{A}}{\partial t}$$

$$\rightarrow \quad \dot{\boldsymbol{x}} = -\frac{q}{mc}\boldsymbol{A}$$

$$\rightarrow \quad \boxed{q\dot{\boldsymbol{x}} = -\frac{q^2}{mc}\boldsymbol{A}}$$



$$\boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{A}}{\partial t}$$

charge q

mass m

current I (or voltage $V=IR$) in antenna measures $\boldsymbol{A}$

Power detection $\langle I^2R\rangle$ measures flux $\boldsymbol{S}$.

What Ron needs to remember

$$A \to h/2$$

vector potential

gravitational wave strain

For standard candles at distance *r*

$$A \propto \frac{1}{r}$$

$$h \propto \frac{1}{r}$$

For circular binary

$$\boxed{h \simeq \frac{GM_1/c^2}{r}\,\frac{G\,M_2/c^2}{a}}$$

proper-motion distance=$D_L/(1+z)$

semimajor axis of binary

Gravitational waves

Weak fields: expand metric as gravitational potential ϕ, wave tensor $\boldsymbol{h}$

$$\boldsymbol{g} = -\nabla\phi \boxed{-\frac{1}{c}\frac{\partial \boldsymbol{h}}{\partial t}}$$

$\boldsymbol{h}$ depends on choice of gauge.

$$\boldsymbol{h} = \boldsymbol{h}_0 \exp(i(\omega t - \boldsymbol{k}\cdot\boldsymbol{x}))$$

solves Einstein equations in vacuum

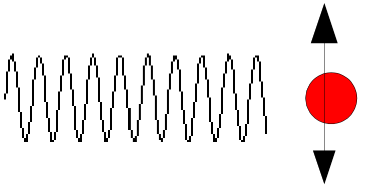
$$\boldsymbol{S} = \boxed{\frac{c^3}{G}\frac{1}{16\pi}\omega^2 h^2}$$

flux of energy

$\boldsymbol{h}$ transverse to $\boldsymbol{k}$. Two polarizations.

Detecting gravitational waves

$$\cancel{m}\,\ddot{\boldsymbol{x}} = \cancel{m}\,\boldsymbol{g} = -\frac{\cancel{m}}{c}\frac{\partial \boldsymbol{h}}{\partial t} - \cancel{m}\,\nabla\phi$$

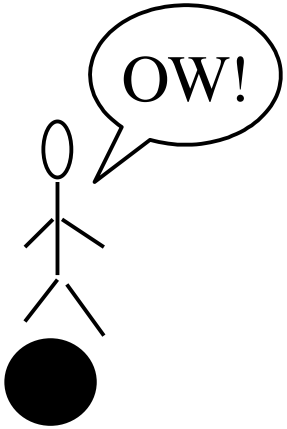


Equivalence principle: all freely falling bodies accelerated the same way. So impossible to detect ***h*** by measurement on single mass.

$$\boldsymbol{g} = -\frac{1}{c}\frac{\partial \boldsymbol{h}}{\partial t}$$

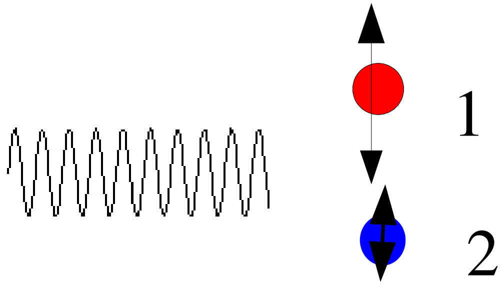
grav mass m
inertial mass m

But TIDES -gradients of ***g***- *are* physically measurable (Riemann curvature tensor).



Detecting gravitational waves

$$\ddot{\boldsymbol{x}}_1-\ddot{\boldsymbol{x}}_2=\boldsymbol{g}_1-\boldsymbol{g}_2=L\cdot\nabla\boldsymbol{g}=\overset{\text{wave tide}}{\boxed{-\frac{1}{c}L\cdot\frac{\partial\nabla\boldsymbol{h}}{\partial t}}}\overset{\text{static tide}}{-L\cdot\nabla\nabla\phi}$$



wave: $\boldsymbol{h}(z-ct)$, so $\nabla\boldsymbol{h}=-\frac{1}{c}\frac{\partial\boldsymbol{h}}{\partial t}$

NB assumes L << wavelength of grav wave

$$\ddot{\boldsymbol{x}}_1-\ddot{\boldsymbol{x}}_2=\boldsymbol{g}_1-\boldsymbol{g}_2=L\cdot\nabla\boldsymbol{g}=\boxed{L\cdot\frac{\partial^2\boldsymbol{h}}{\partial t^2}}-L\cdot\nabla\nabla\phi$$

$$\rightarrow\boldsymbol{x}_1-\boldsymbol{x}_2=\underset{\text{oscillates}}{\boxed{L\cdot\boldsymbol{h}}}+\underset{\text{smooth time variation -fit out}}{\boxed{L+\Delta v(0)t-L\cdot\nabla\nabla\phi(\frac{1}{2}t^2)}}$$

Summary of gravitational wave detection

More honestly:

$$\frac{d(x_1^i - x_2^i)}{dt^2} = -R_{itjt}(t, \boldsymbol{x})\, L^j = \boxed{\frac{1}{2}} \frac{d^2 h_{ij}^{TT}}{dt^2} L^j$$

Riemann curvature tensor

$$\rightarrow (x_1^i - x_2^i) = \boxed{\frac{1}{2}} h_{ij}^{TT} L^j \qquad + L + \Delta v(0)\, t + L^j \nabla_i \nabla_j \phi (t^2/2)$$

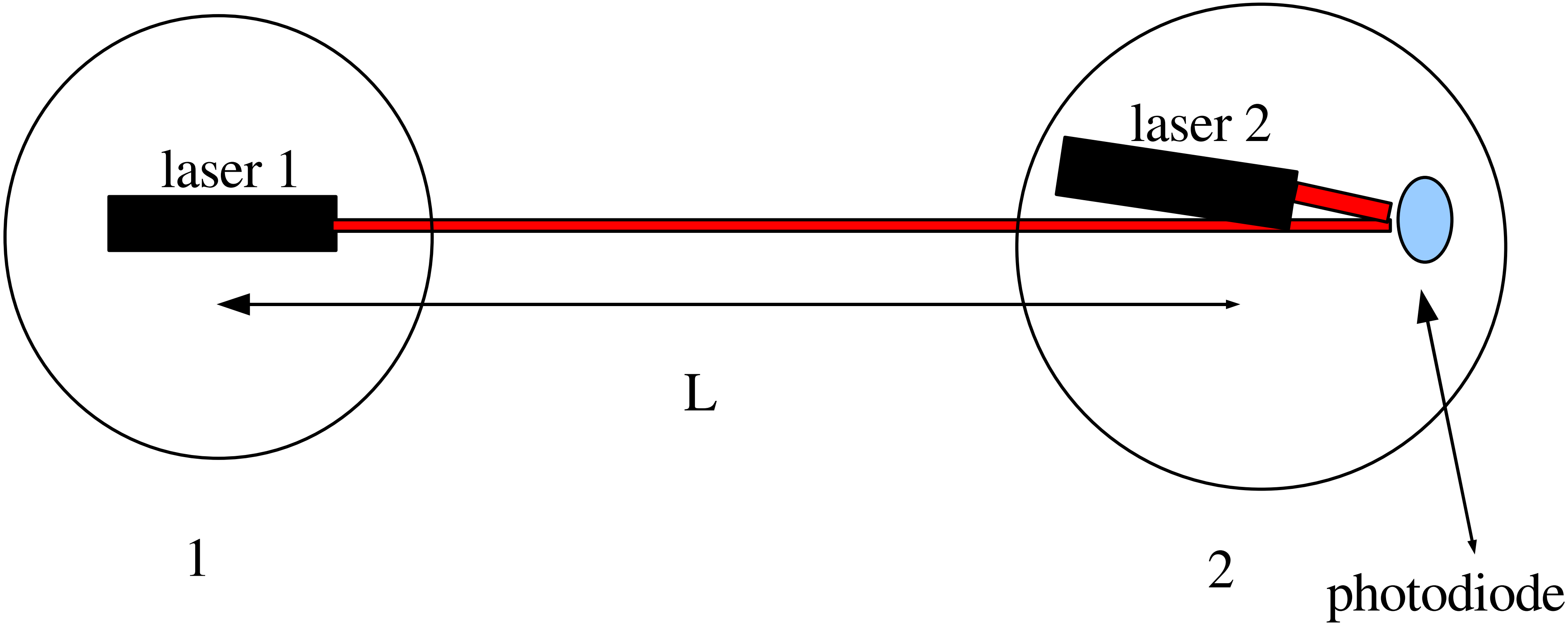
Measuring gravitational waves

$$\frac{d(x_1^i - x_2^i)}{dt^2} = \frac{1}{2}\frac{d^2 h_{ij}^{TT}}{dt^2} L^j + a_1(\mathit{nongrav}) - a_2(\mathit{nongrav})$$

Must measure
precisely
to detect since
h small.

must get rid of non-gravitational forces, so the masses really are freely falling.

Measuring distance changes with interferometry



Fringe rate = $[v(1)-v(2)]/\lambda$

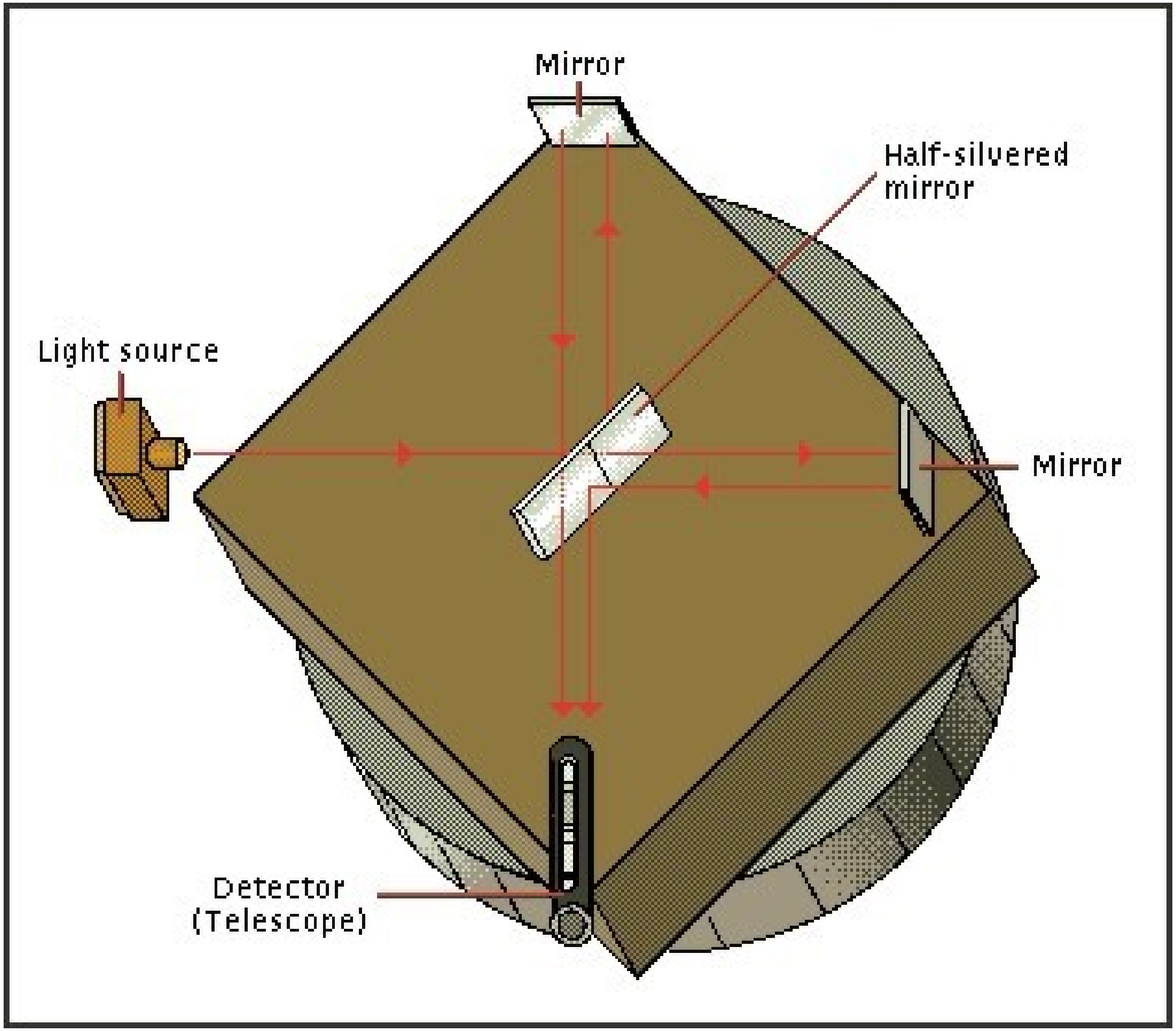
GW signal $d^2h/dt^2 = \lambda/L$ (rate of change of fringe rate)

Precision of fringe rate is indep of L -depends only on laser wavelength, power & integration time: $\delta\lambda = \lambda/\sqrt{N_{photons}}$

Everything else is details

- Large L=5,000,000km = 1/30 AU -makes h precise for fixed interferometer measurement!
- Lasers aren't perfect clocks -to eliminate frequency noise, need to compare measurements along two arms (Michelson: equal arms; LISA: unequal but known arms: shift signals to synthesise equal arms `Time Delay Interfeometry' or use one arm to lock lasers).
- Reflect laser light off `freely falling proof masses' (can be made to have less non-grav forces than whole spacecraft!)
- Take care to minimize all local forces on proof masses.

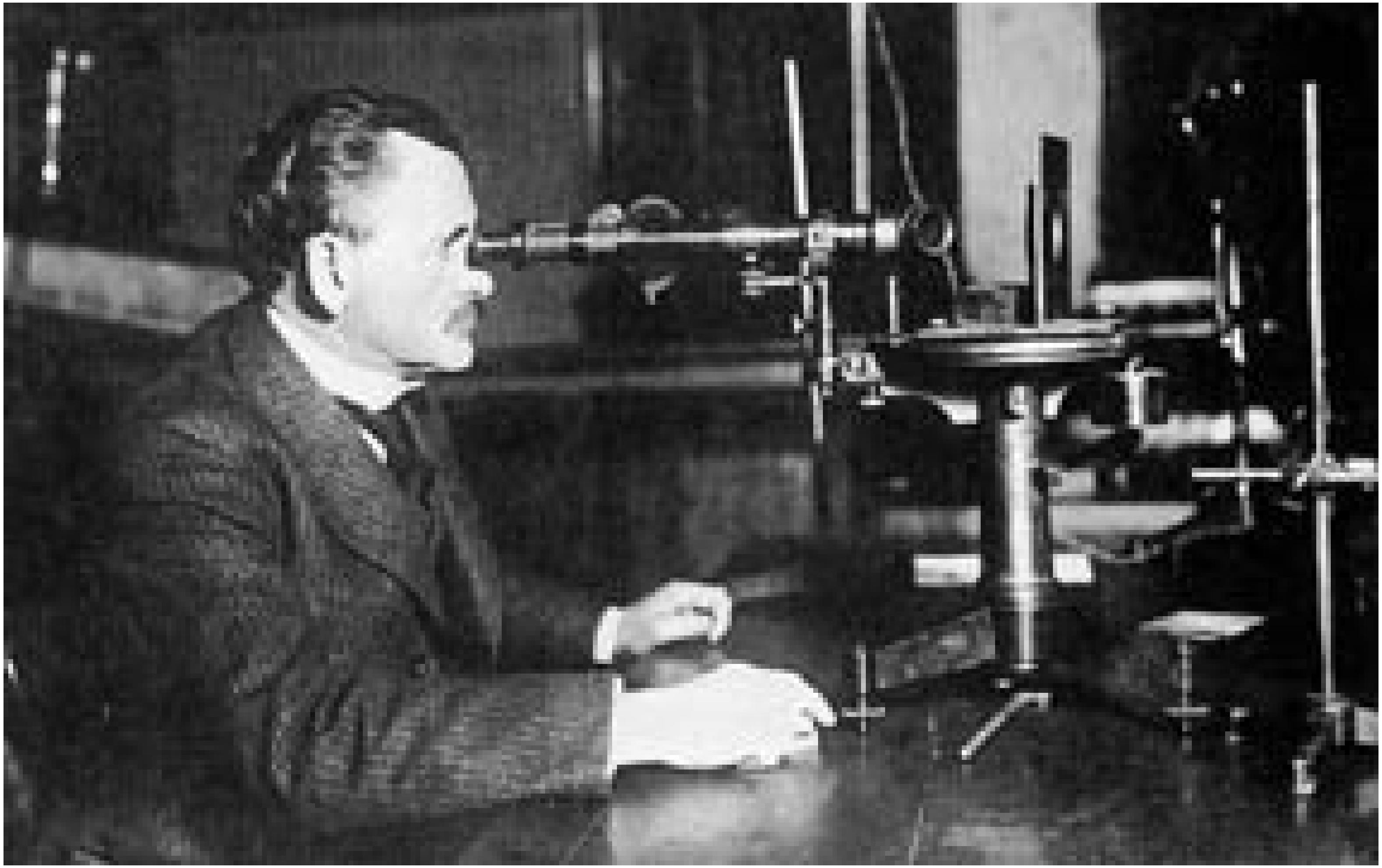
125 Years of Interferometry



- Michelson's 1st Interferometer 1881

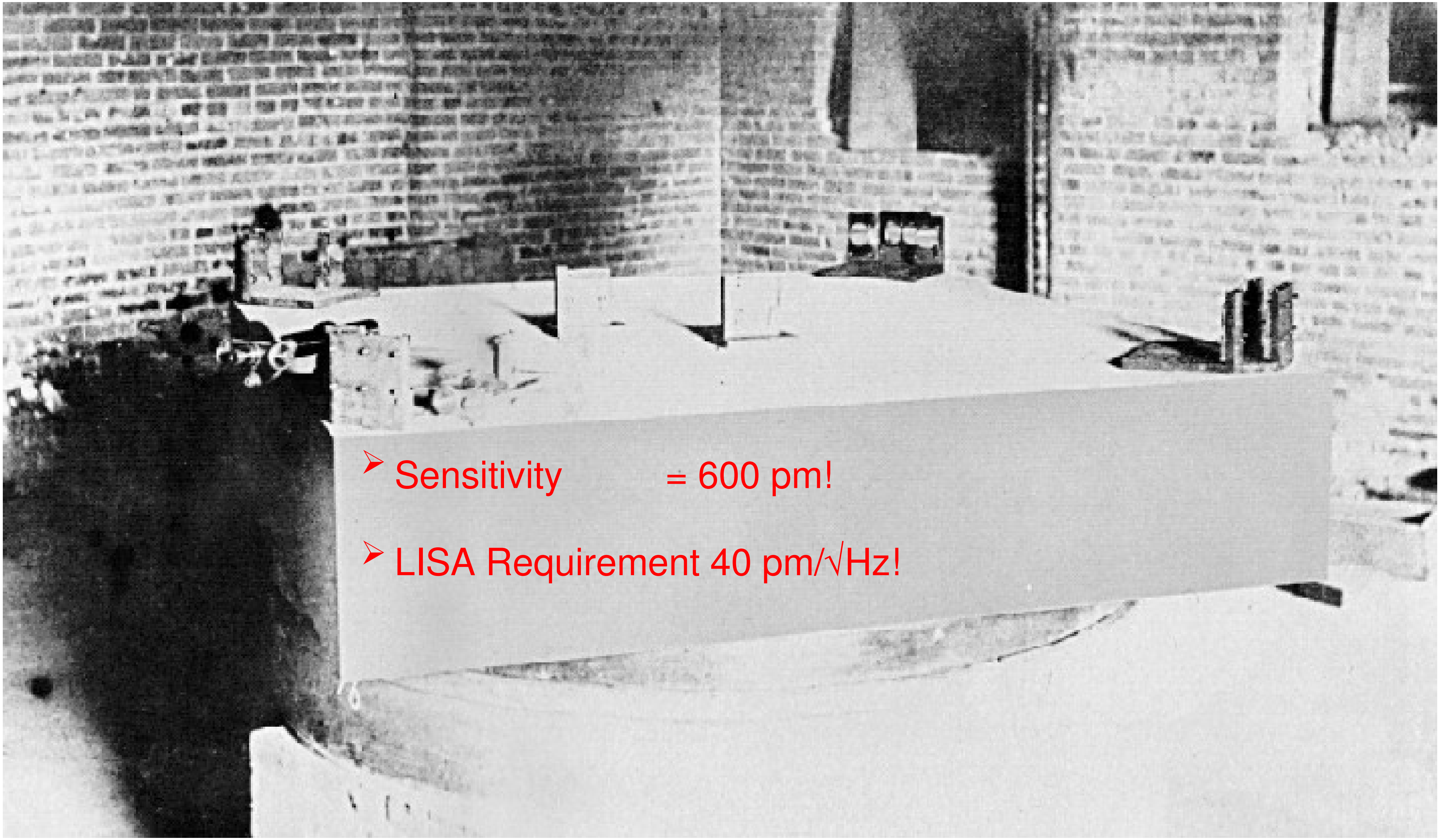
Michelson-Morley

- Albert Michelson reading Interference Fringes

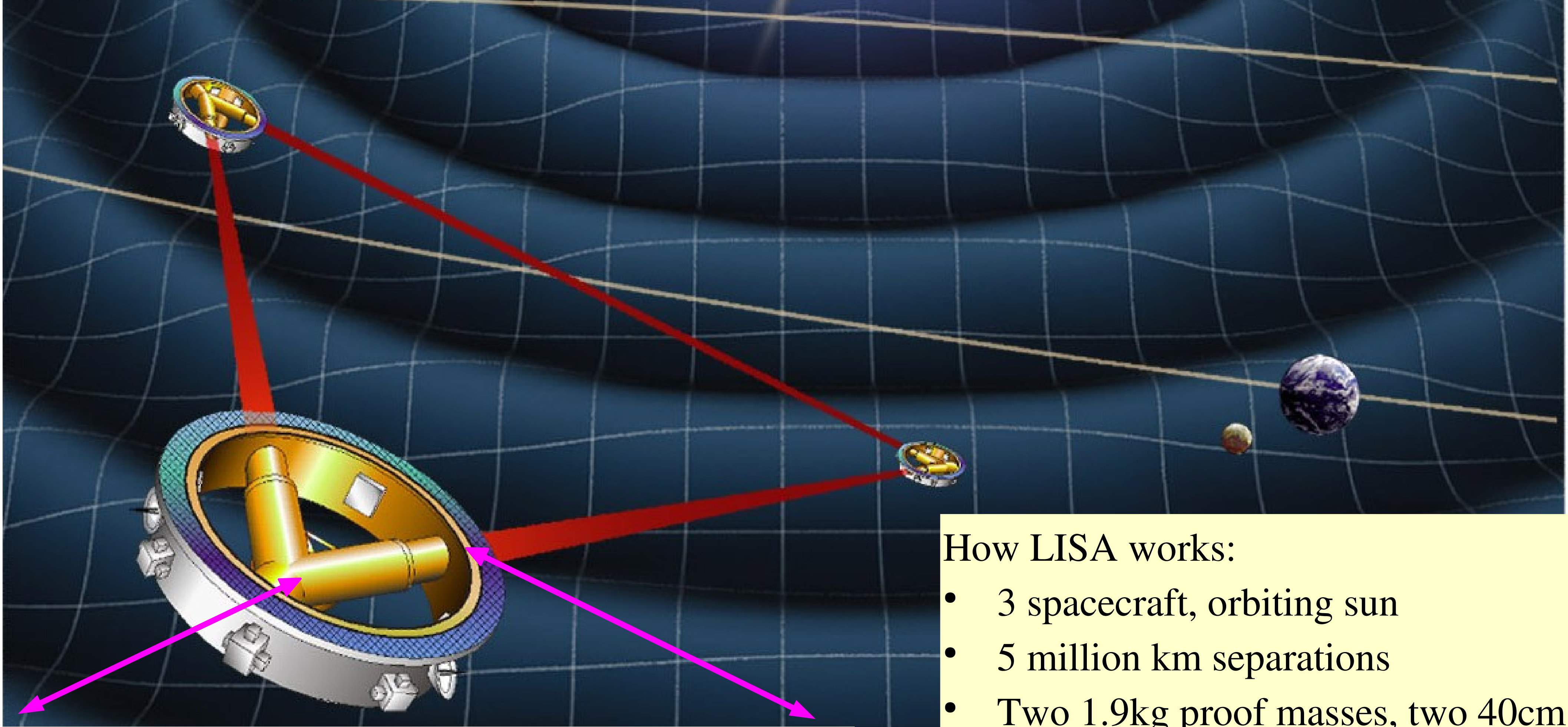


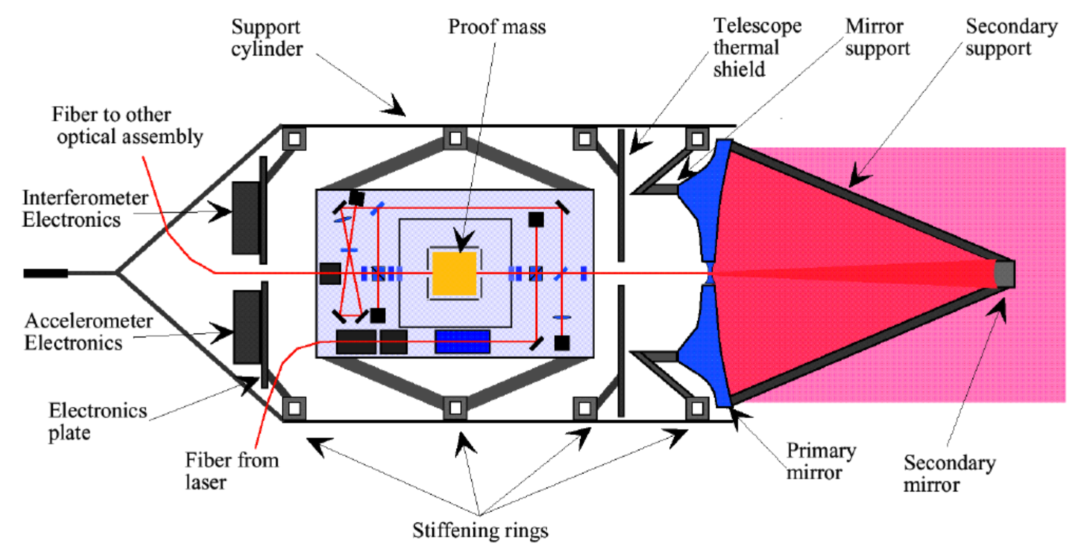
Michelson-Morley

Original apparatus used by Michelson and Morley, 1887



- Sensitivity = 600 pm!
- LISA Requirement 40 pm/√Hz!

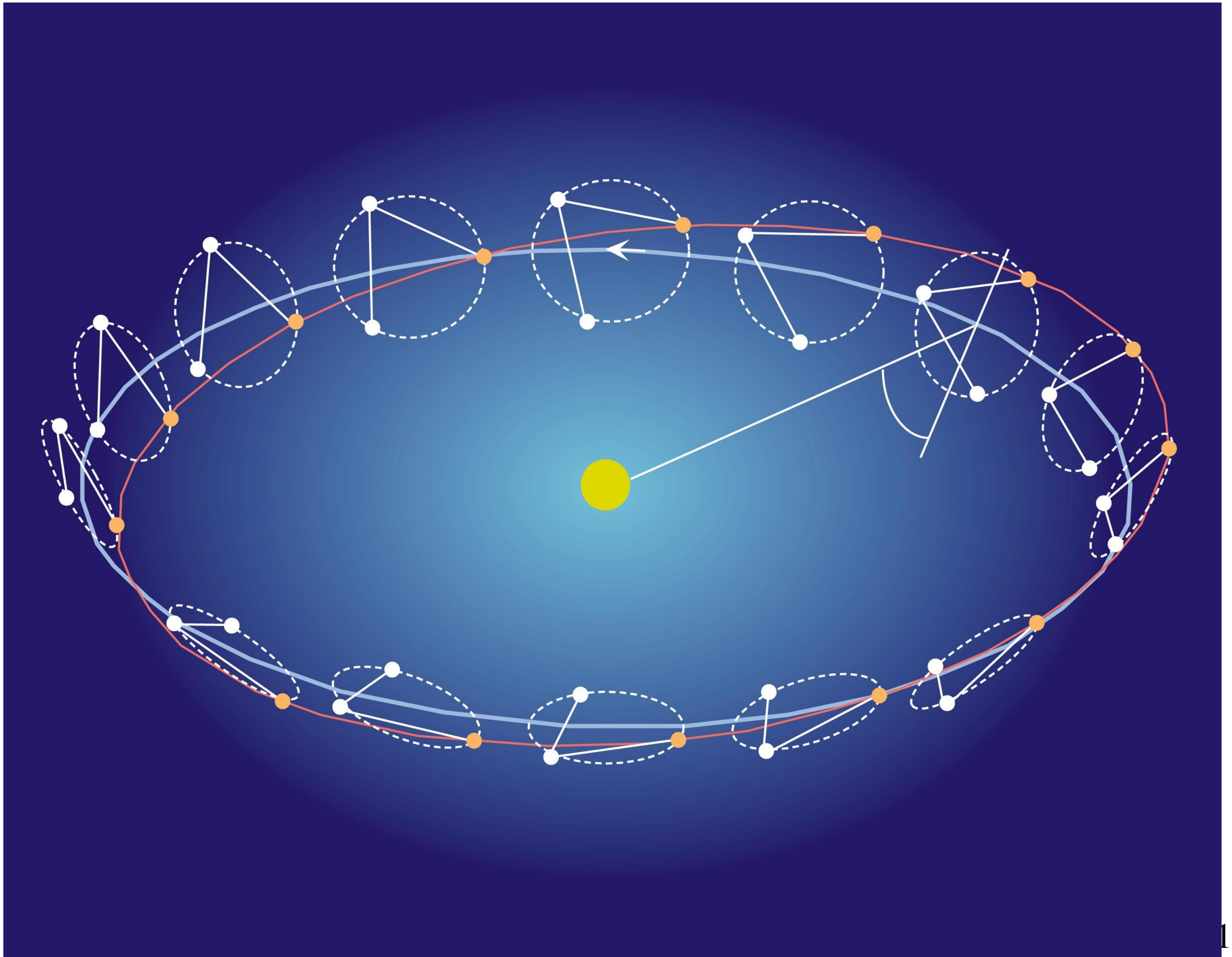




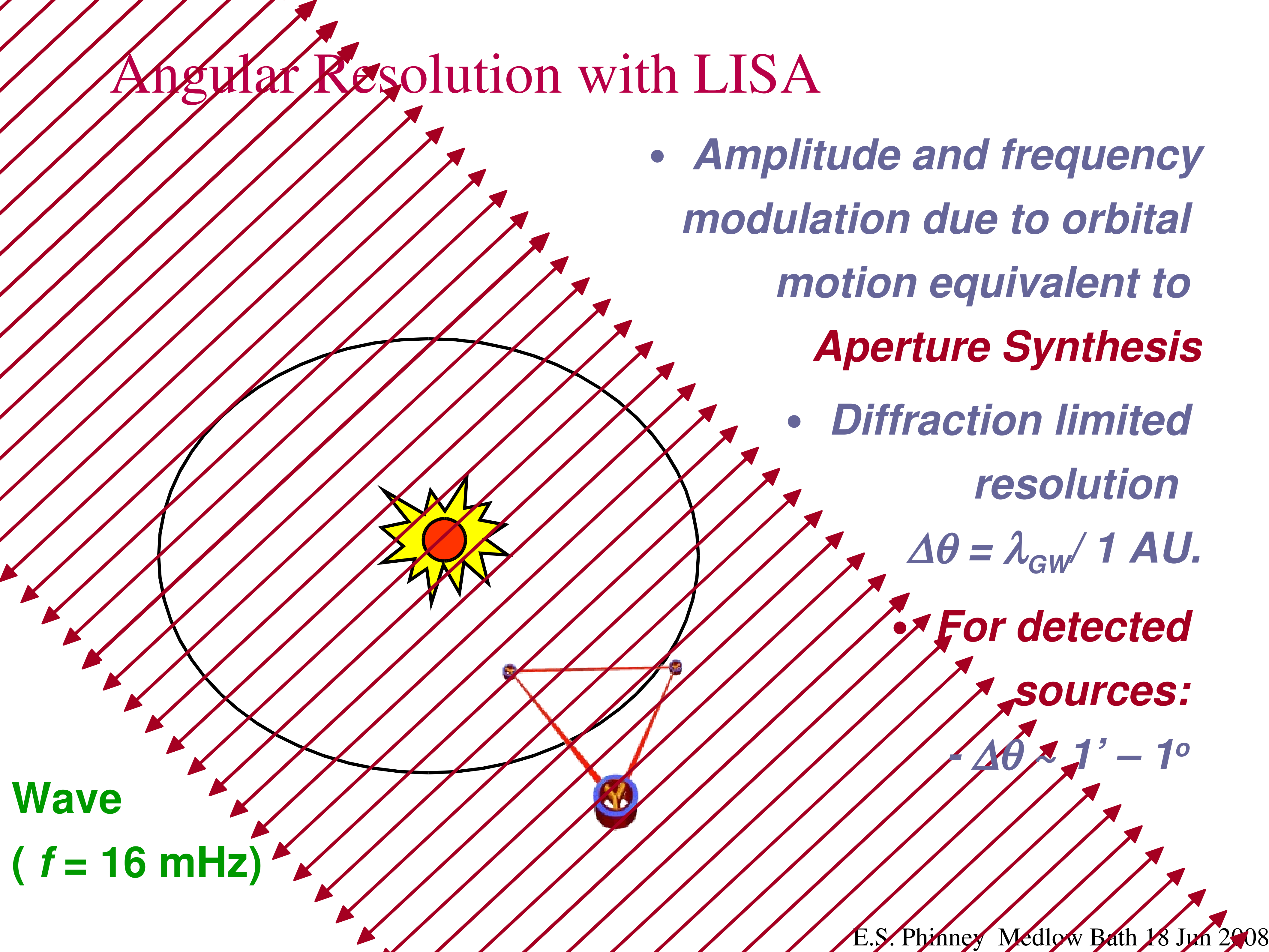
How LISA works:

- 3 spacecraft, orbiting sun
- 5 million km separations
- Two 1.9kg proof masses, two 40cm telescopes, and two phase-locked 1W lasers in each spacecraft.
- NO constellation control. Micronewton thrusters only to keep each s/c following its proof masses and all pointed at each other.
- 5 year mission (limited by component failure, not consumables)

Each LISA spacecraft on its own Keplerian orbit around Sun. NO stationkeeping or constellation flying. Epicyclic motion preserves equilateral triangle to O(e^2).



Angular Resolution with LISA



- *Amplitude and frequency modulation due to orbital motion equivalent to* ***Aperture Synthesis***
- *Diffraction limited resolution*

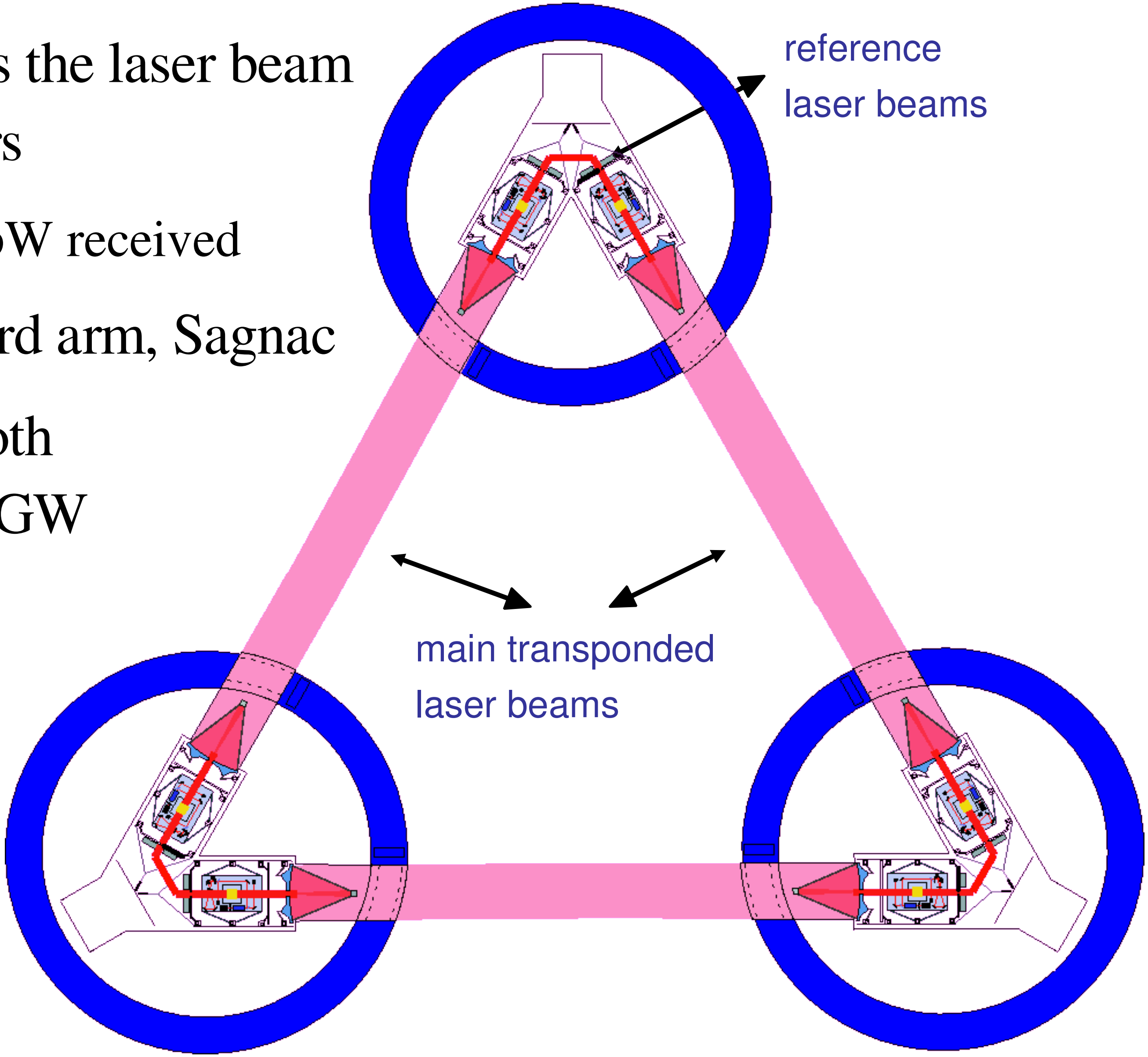
  $\Delta\theta = \lambda_{GW} / 1\ \mathrm{AU}.$
- ***For detected sources:***
  - $\Delta\theta \sim 1' - 1^{o}$

Wave

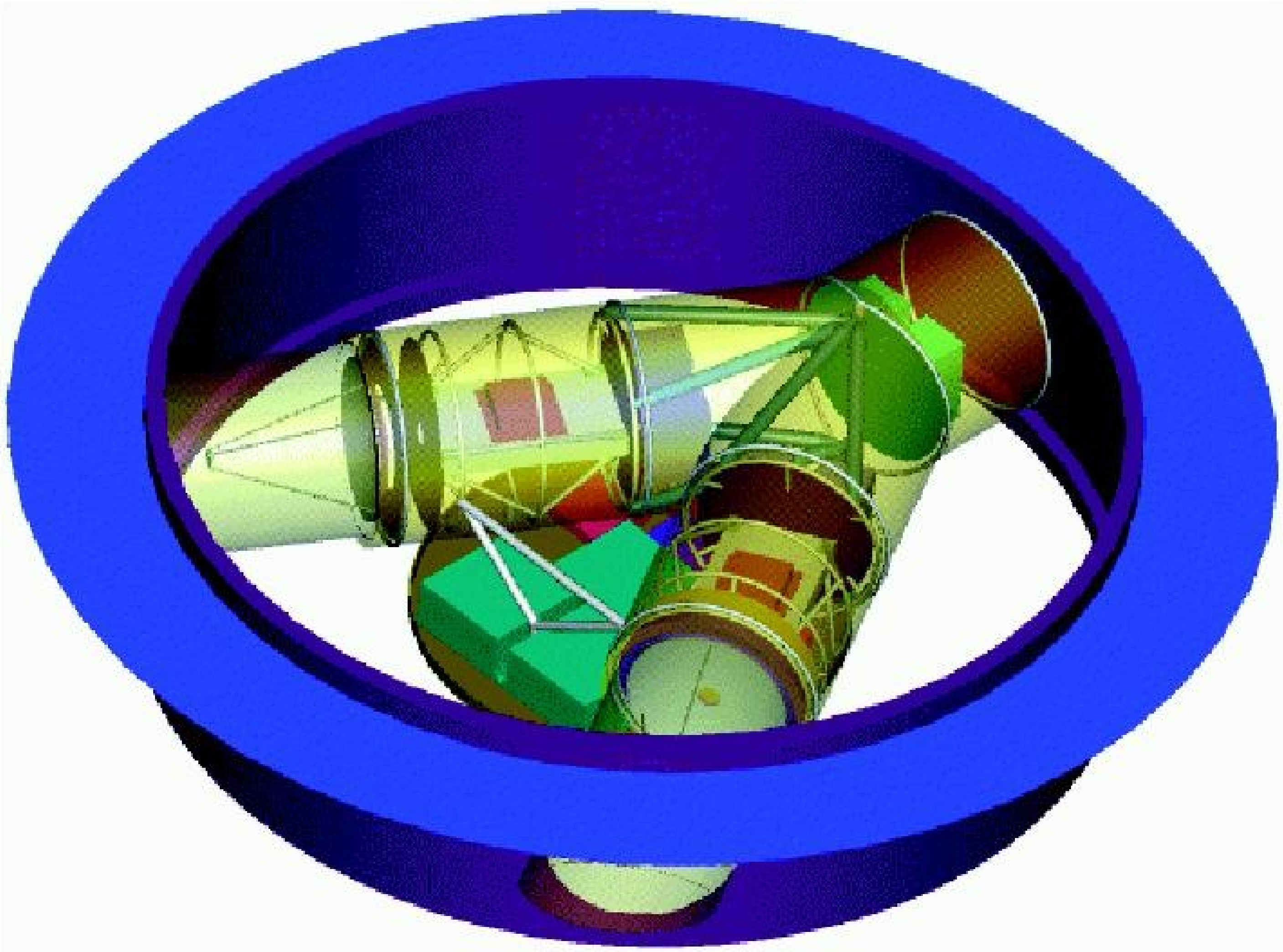
(*f* = 16 mHz)

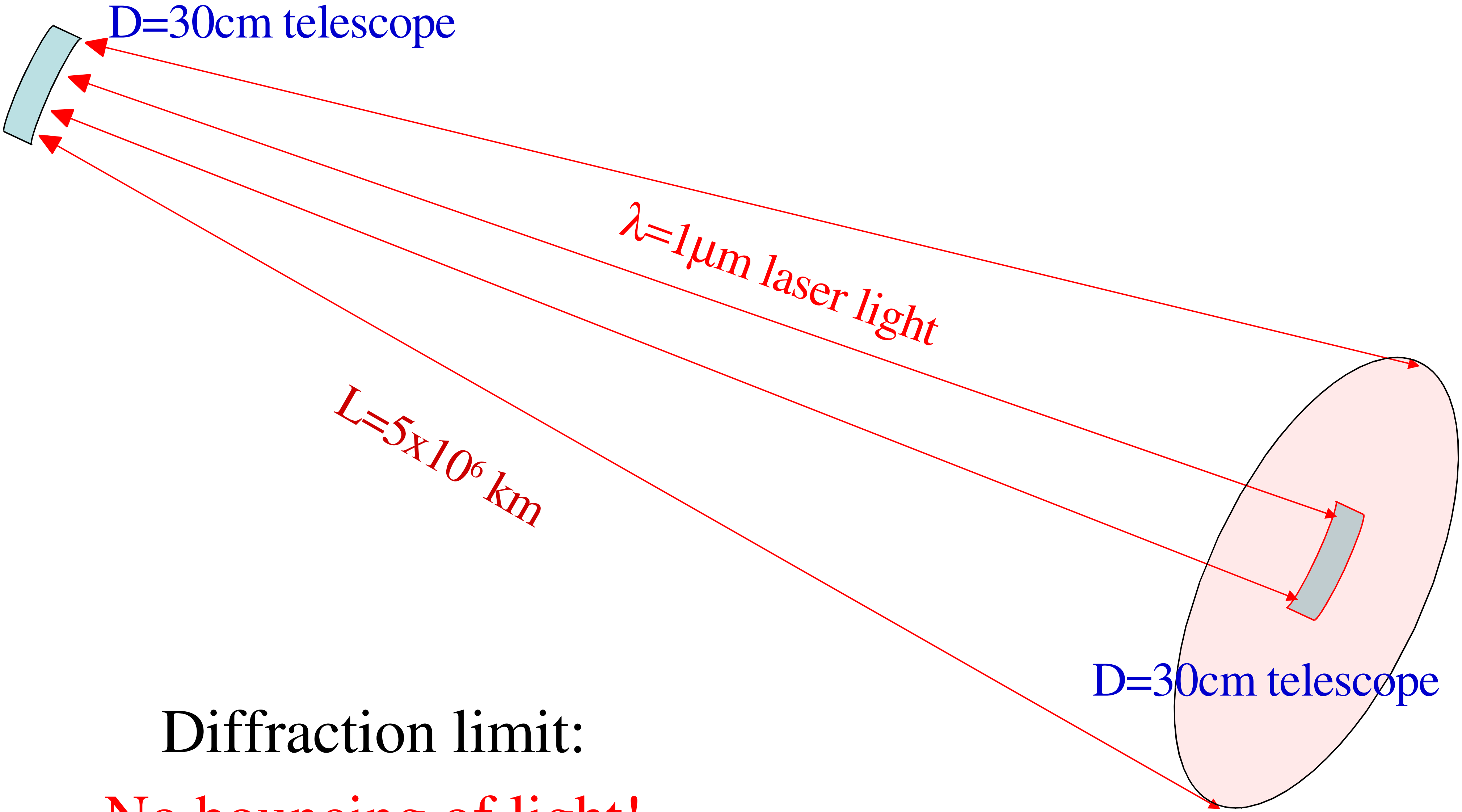
LISA layout

- Laser beams reflected off free-flying test masses
- Diffraction widens the laser beam to many kilometers
  - 0.7 W sent, 70 pW received
- Michelson with 3rd arm, Sagnac
- Can distinguish both polarizations of a GW



LISA spacecraft





Diffraction limit:

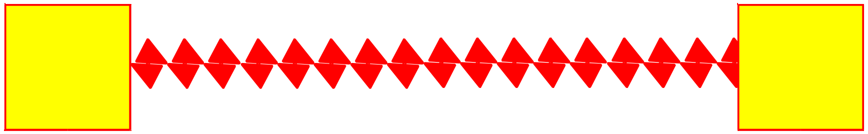
No bouncing of light!

Heterodyne received light against local laser.

$$\frac{\ }{D} L = 20\,km\ beam$$

Gravitational wave action

Gravitational waves change the distance between test masses at rest in free-falling frame.



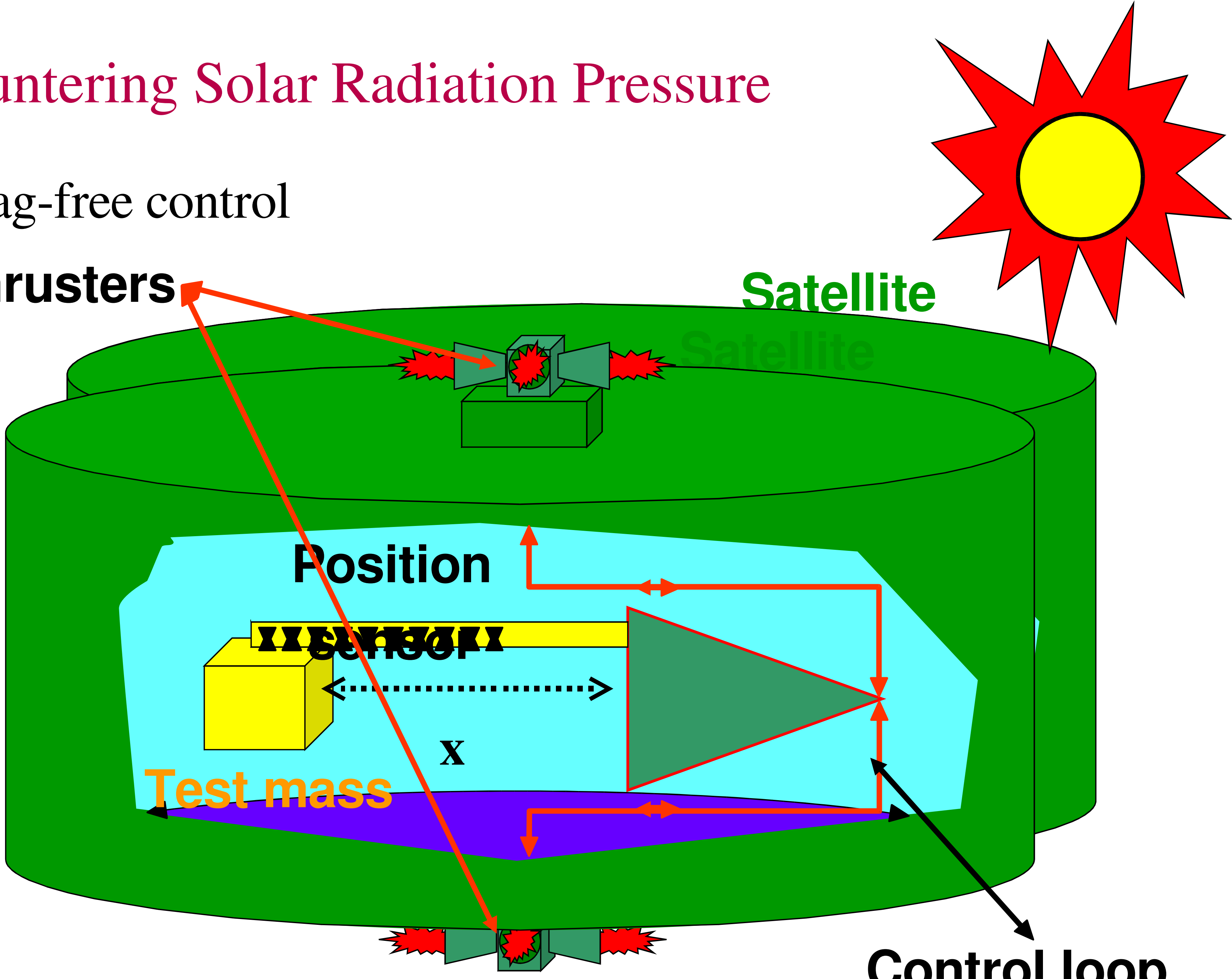
Spurious forces move masses as well

We need the perfect free fall!

⇒ Drag-free control

Countering Solar Radiation Pressure

Drag-free control



Thrusters

Satellite

Satellite

Position

sensor

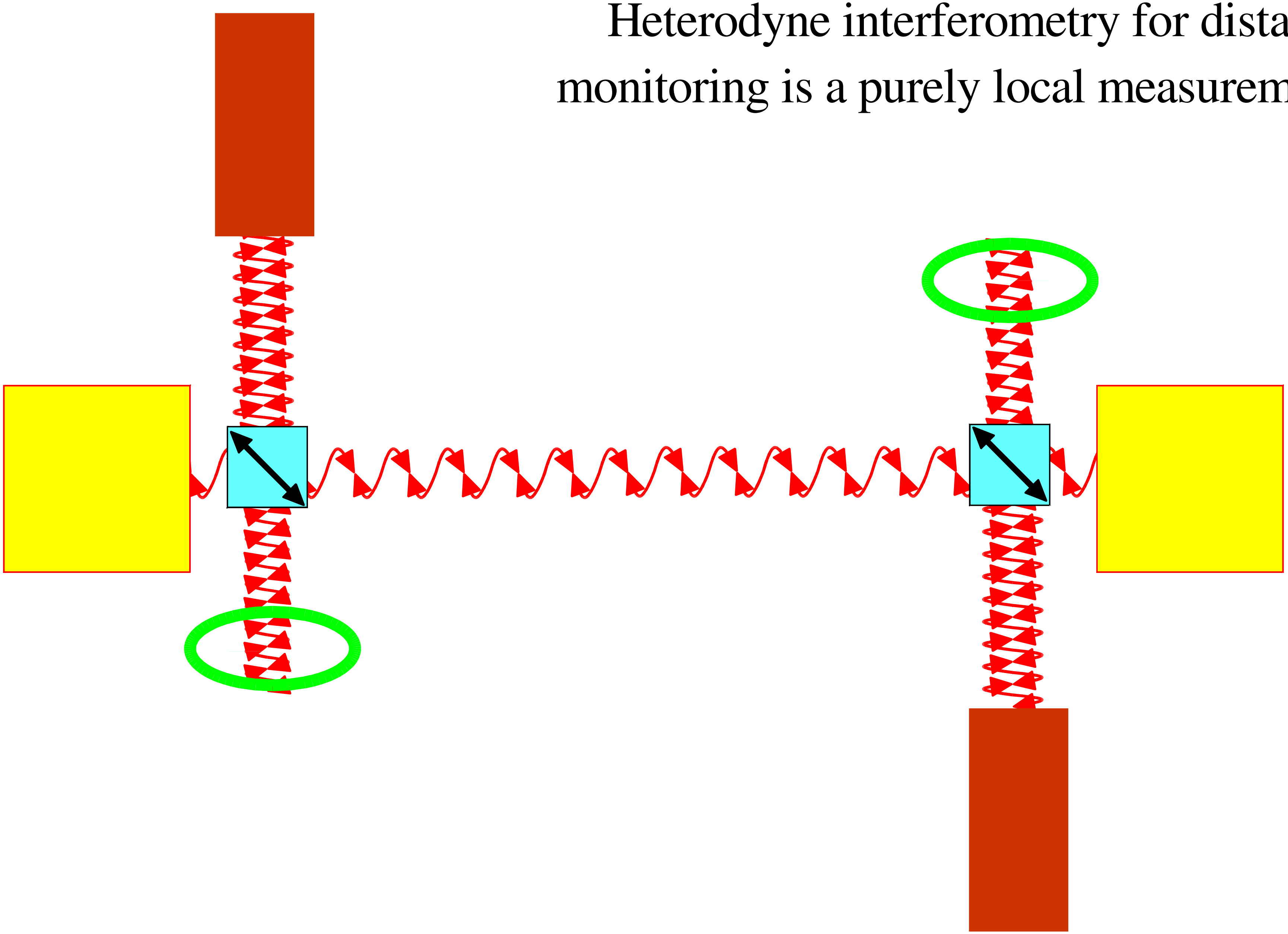
x

Test mass

Control loop

Heterodyne Interferometry

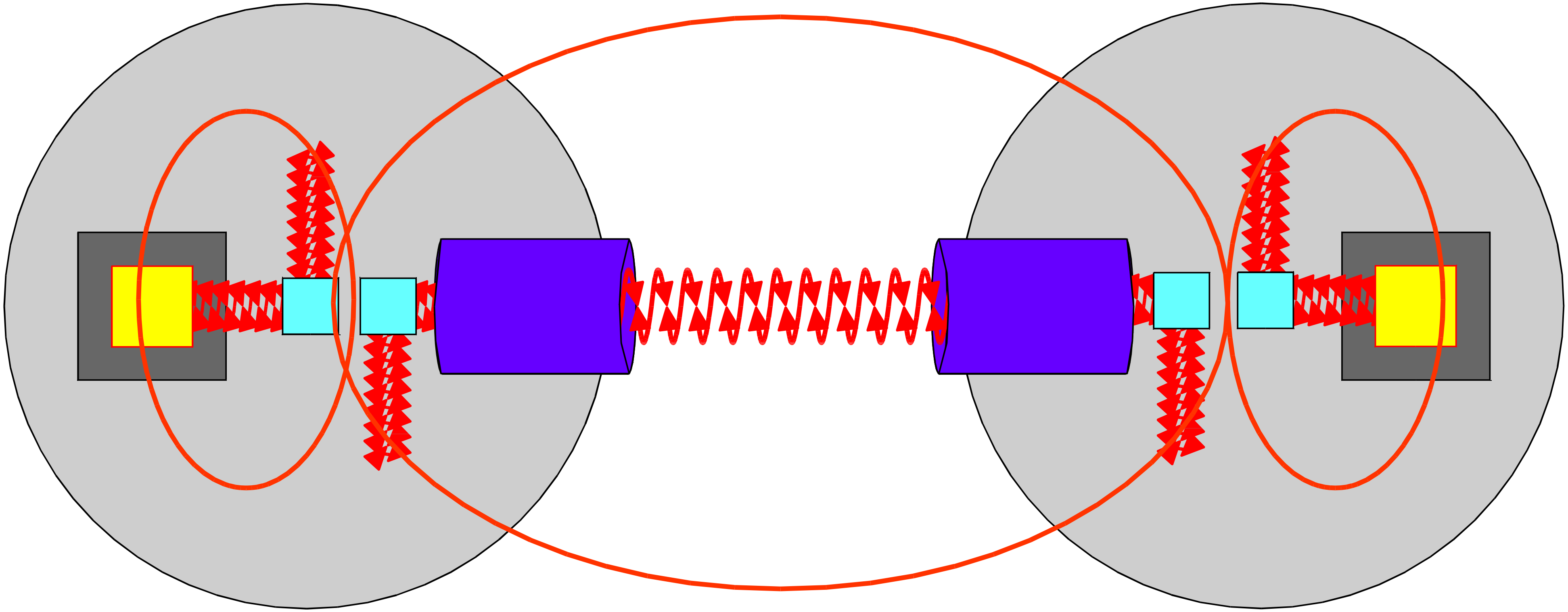
Heterodyne interferometry for distance monitoring is a purely local measurement!



Local measurements

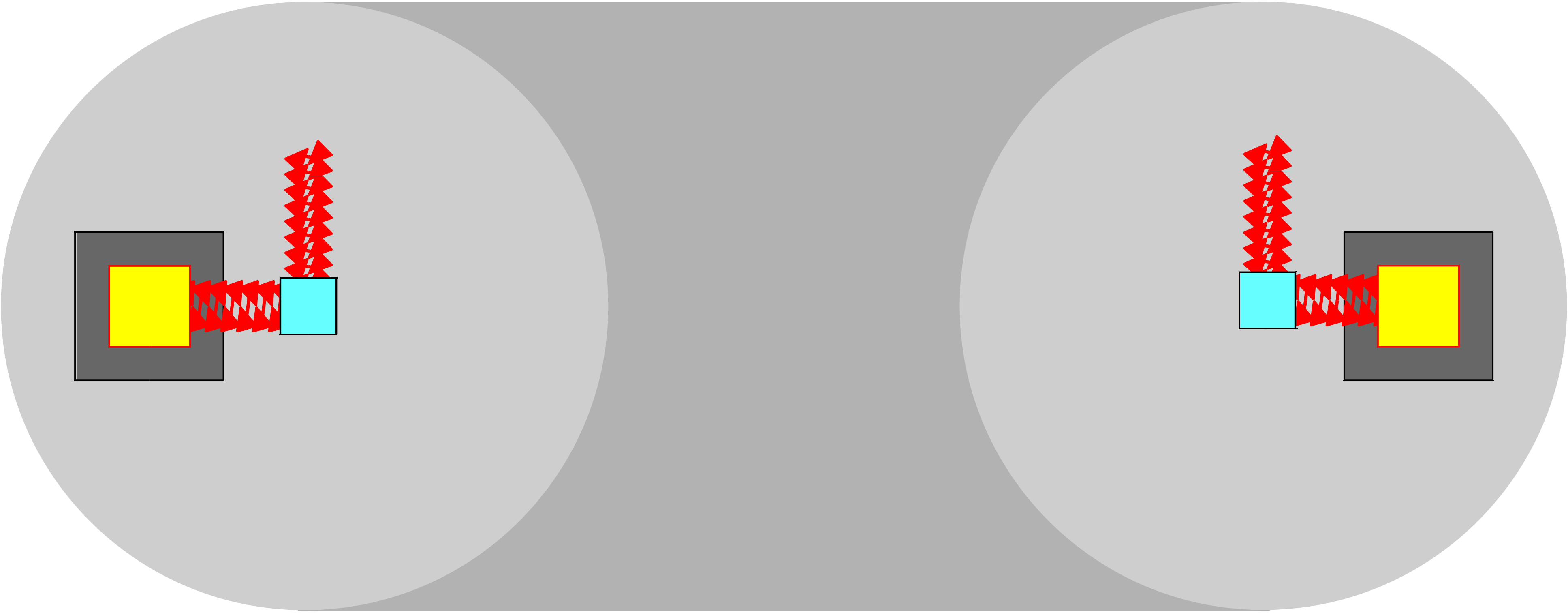
For convenience: Split measurement into 2 parts!

2. Spacecraft to test mass
3. Spacecraft to spacecraft



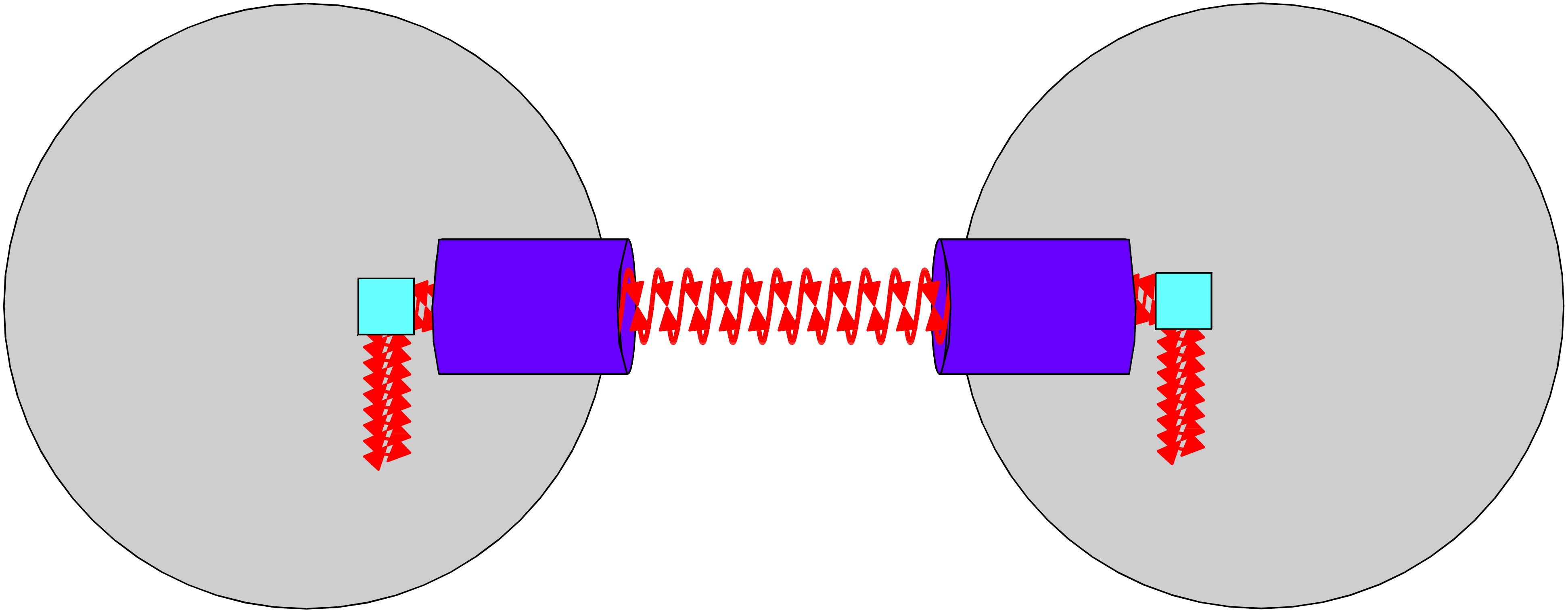
Measuring S/C to Test Mass

- Verification of measurement of SC to test mass on LISA Pathfinder
- Launch in 2009
- All subsystems beyond PDR!



Measuring S/C to S/C

- S/C-to-S/C Measurement: Laboratory testing!
- Heritage from LISA Pathfinder and ground based interferometers
- Verification by similarity and analysis!



Can we actually attain this *h* sensitivity?

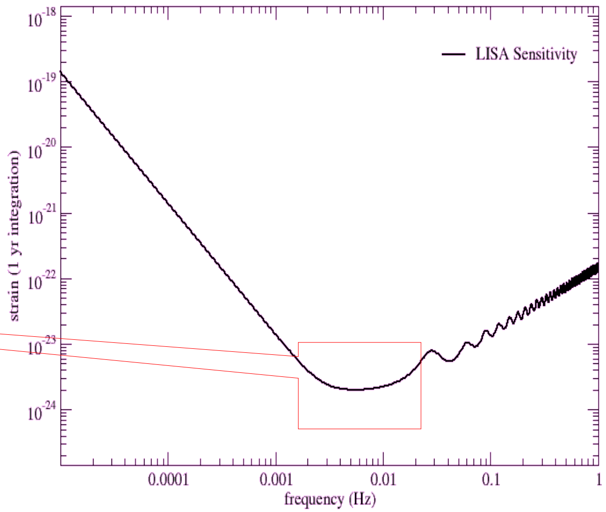
Yes!

Shot noise needs:

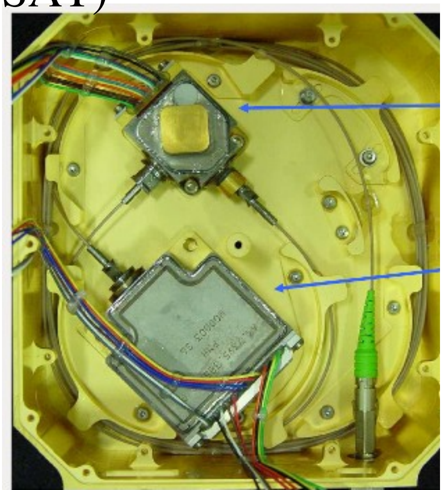
1W laser power

Frequency stabilization

10GHz Phase-meter measurement

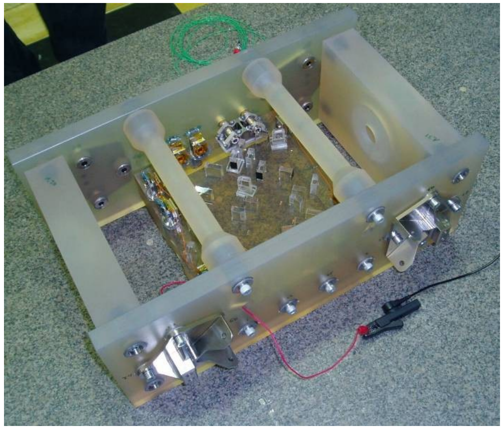


Space-qualified >1W laser two-stage oscillator-fiber amplifier master-slave (TESAT)

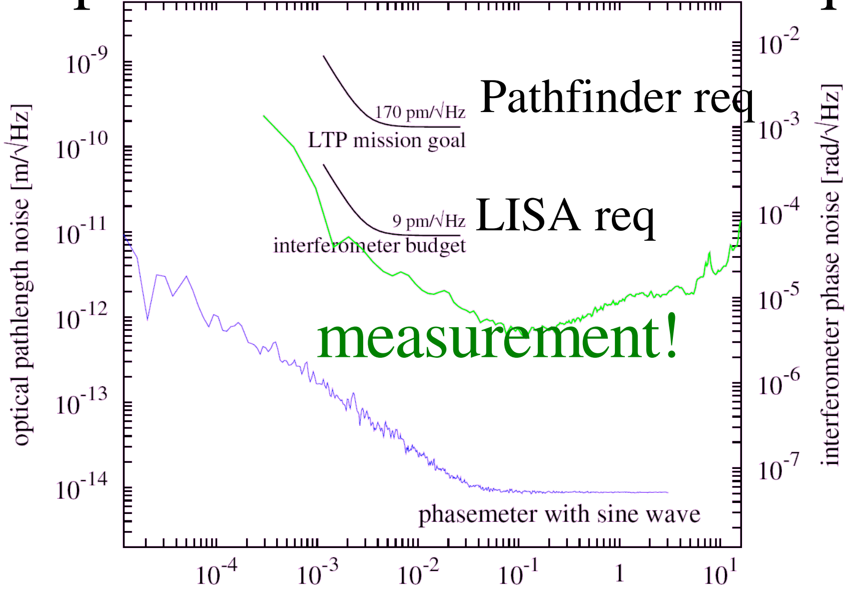


LTP optical bench.

Vibration, environment, performance qualified



phase meter measurements, optical bench exceed LISA reqs!

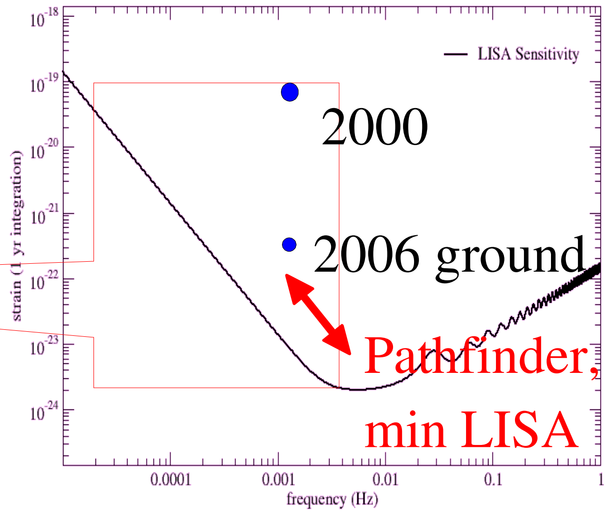


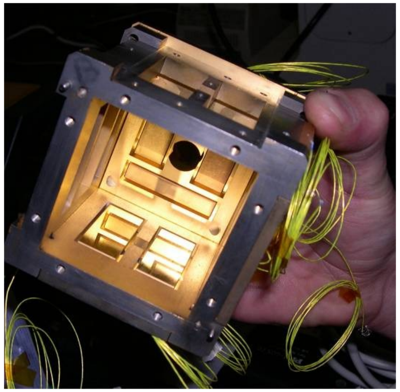
Can we actually attain this *h* sensitivity?

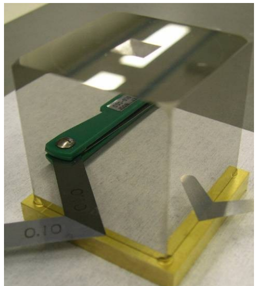
Yes!

Acceleration noise requirement on proof mass requires:

- Micronewton thrusters for s/c control
- low-noise Proof mass sensing
- low-noise servo control loop

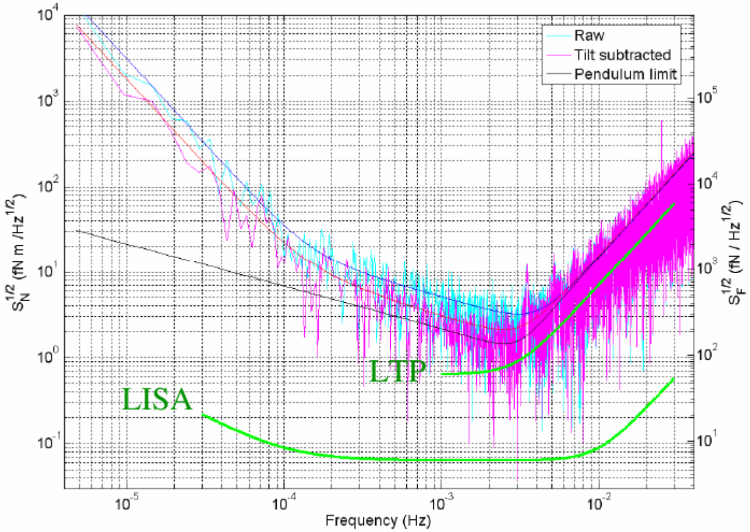






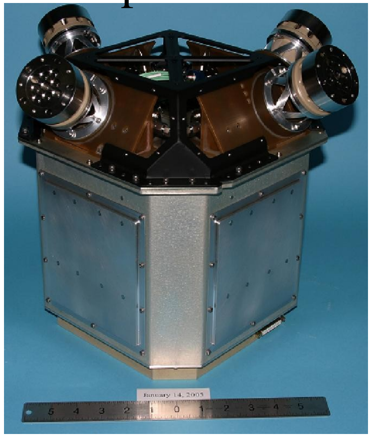
Torsion pendulum tests: limited by fiber and gravity gradient noise on earth. LISA Pathfinder will check noise 5x deeper (=LISA min mission; LISA goal 50 deeper at 1mHz.

Sensor force noise upper limits from torsion pendulum noise data



- Factor of 50 above LISA goal at 1 mHz
- Factor of 300 above LISA goal at 0.1 mHz

Busek colloid thrusters exceed LISA reqs on noise, linearity. LTP lifetime spec.



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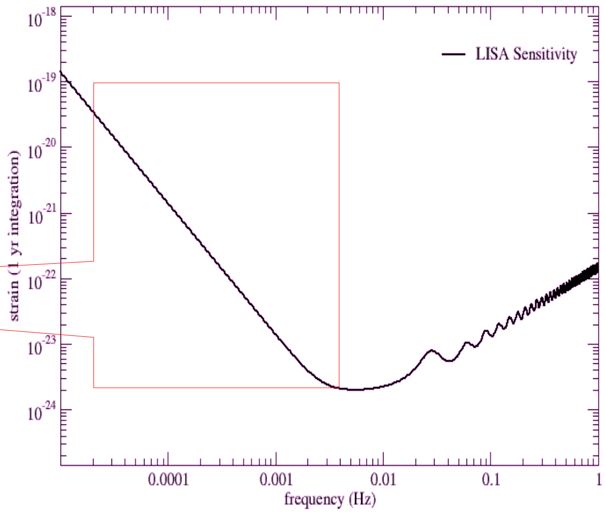
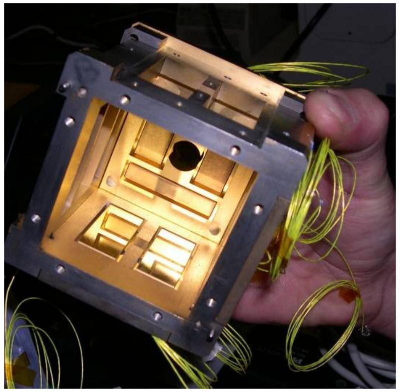
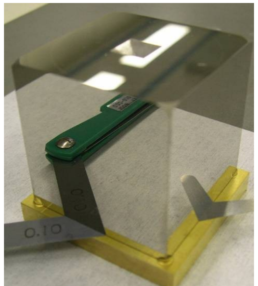
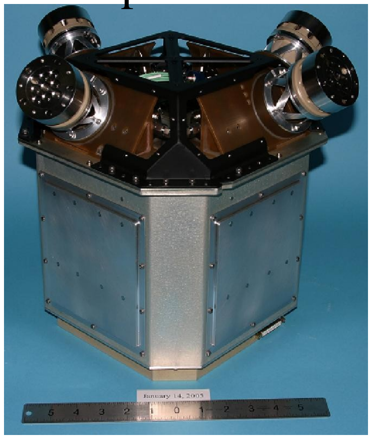






Torsion pendulum tests of proof mass sensing & control

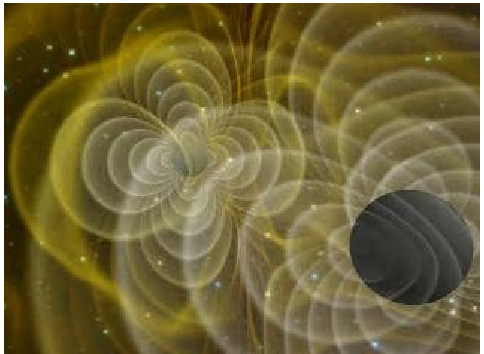
Busek colloid thrusters exceed LISA reqs on noise, linearity. LTP lifetime spec.

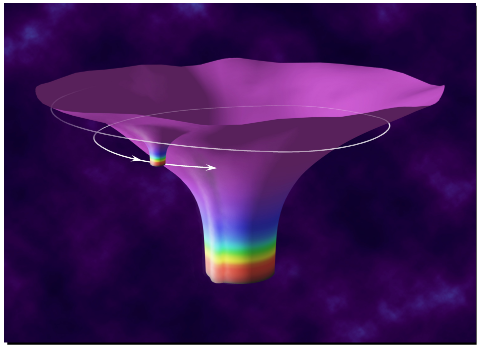


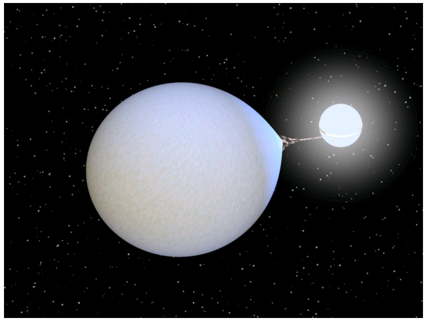
LISA Science Objectives and Sources

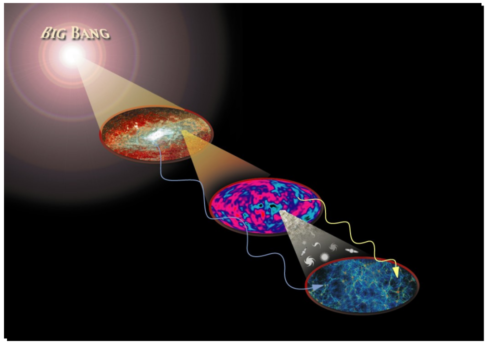
- Determine formation and growth of massive black holes in galaxy evolution z=0-30.
- Make *precision* tests of Einstein’s Theory of Relativity in weak, strong, dynamical gravity.
- Determine the population of ultra-compact binaries in the Galaxy.
- Search for electromagnetic counterparts: precision gastrophysics & cosmography.
- Probe the physics of the early universe, and the new frontier.

- Merging supermassive black holes
- Merging intermediate-mass/seed black holes
- Extreme mass ratio inspirals (EMRI = Gravitational captures)
- Galactic and verification binaries
- Cosmological backgrounds and bursts from TeV scale and strings
- The not predicted yet!









Mock LISA Data Challenges 1, 2

~40 scientists in ~ a dozen different collaborations have participated.

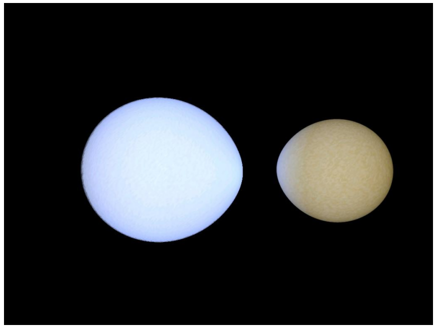
A large variety of methods were tried. Basically for all the challenges, at least one group was successful, though sometimes parameter estimates locked onto strong secondary maxima of the pdf.

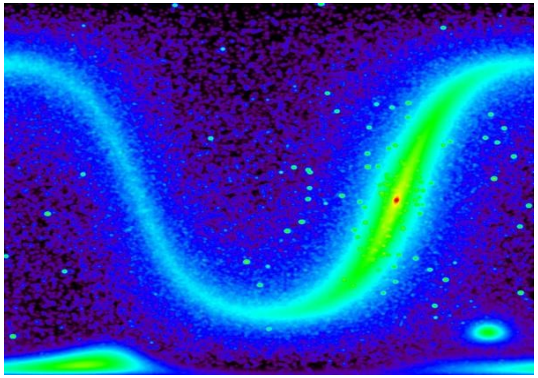
MLDCs have demonstrated we can handle

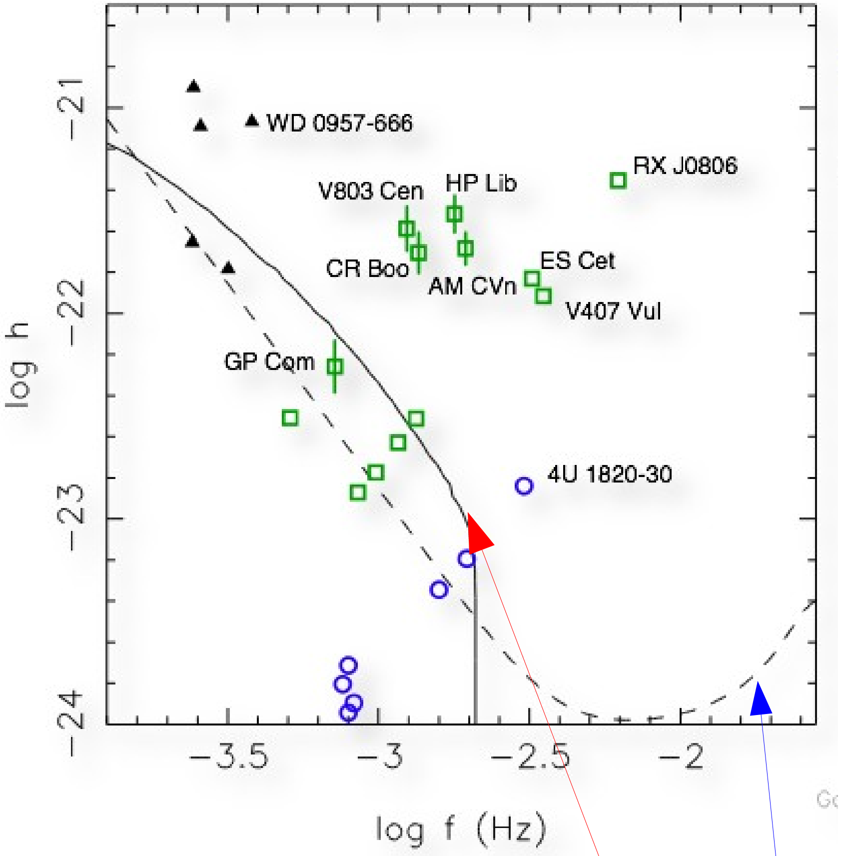
- Galaxy of WD binaries ✓
- SMBH inspirals (w/o spin) ✓
- EMRIs (for SNR > 80) ✓ –

Exploring a new Galaxy of compact binary stars

LISA will measure orbital motions and 3D positions throughout our Galaxy of binary stars at the extreme endpoints of their evolution





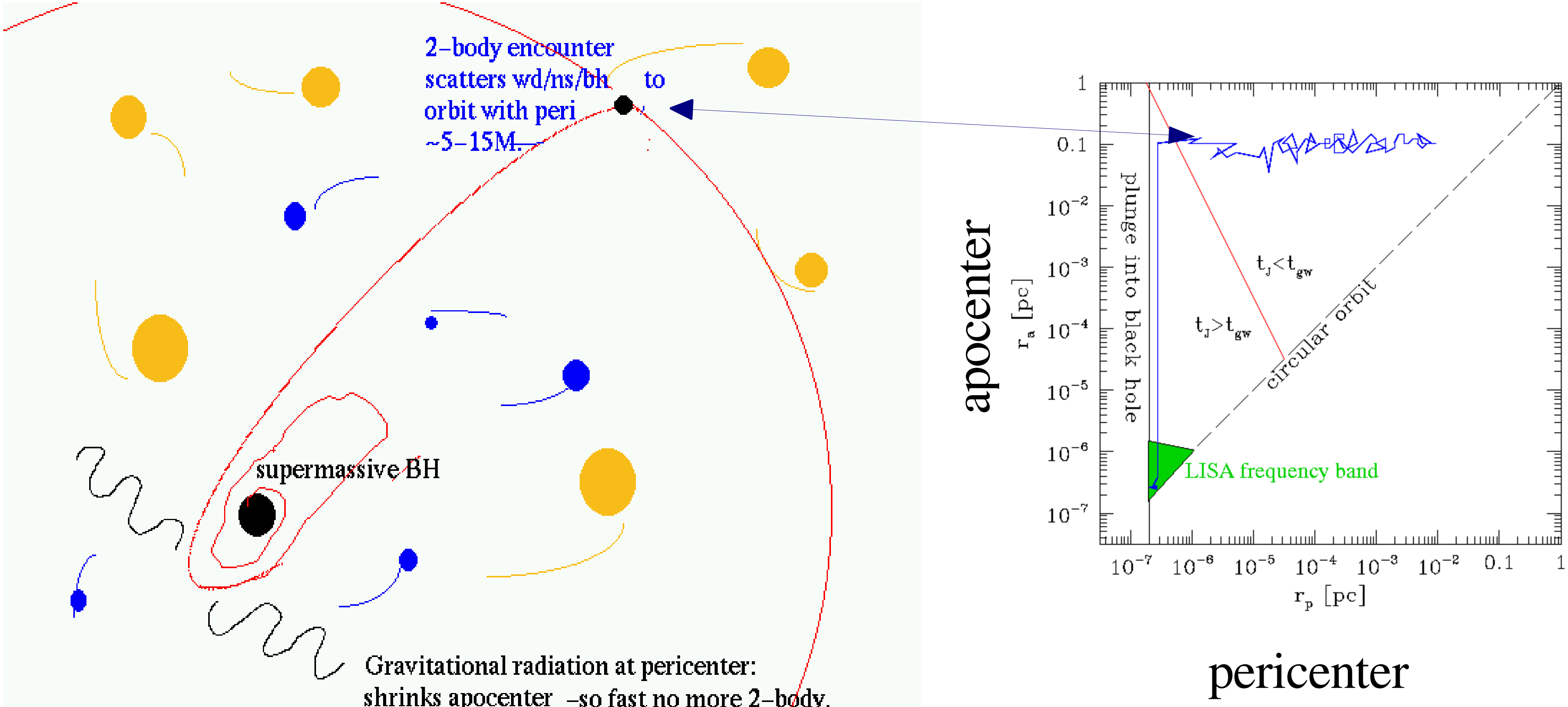


LISA sensitivity

unresolved background of white dwarfs

- ~10 known binaries are guaranteed "verification sources"
- ~10,000 more will be individually detected
- Extreme degenerate stars (mainly white dwarfs, some NS, BH)
- Precursors of Type Ia SNe, millisecond pulsars, exotic novae
- Undergoing strong tidal interactions and/or mass-transfer.

Extreme Mass Ratio Inspiral (EMRI)



2-body encounter scatters wd/ns/bh to orbit with peri ~5-15M.

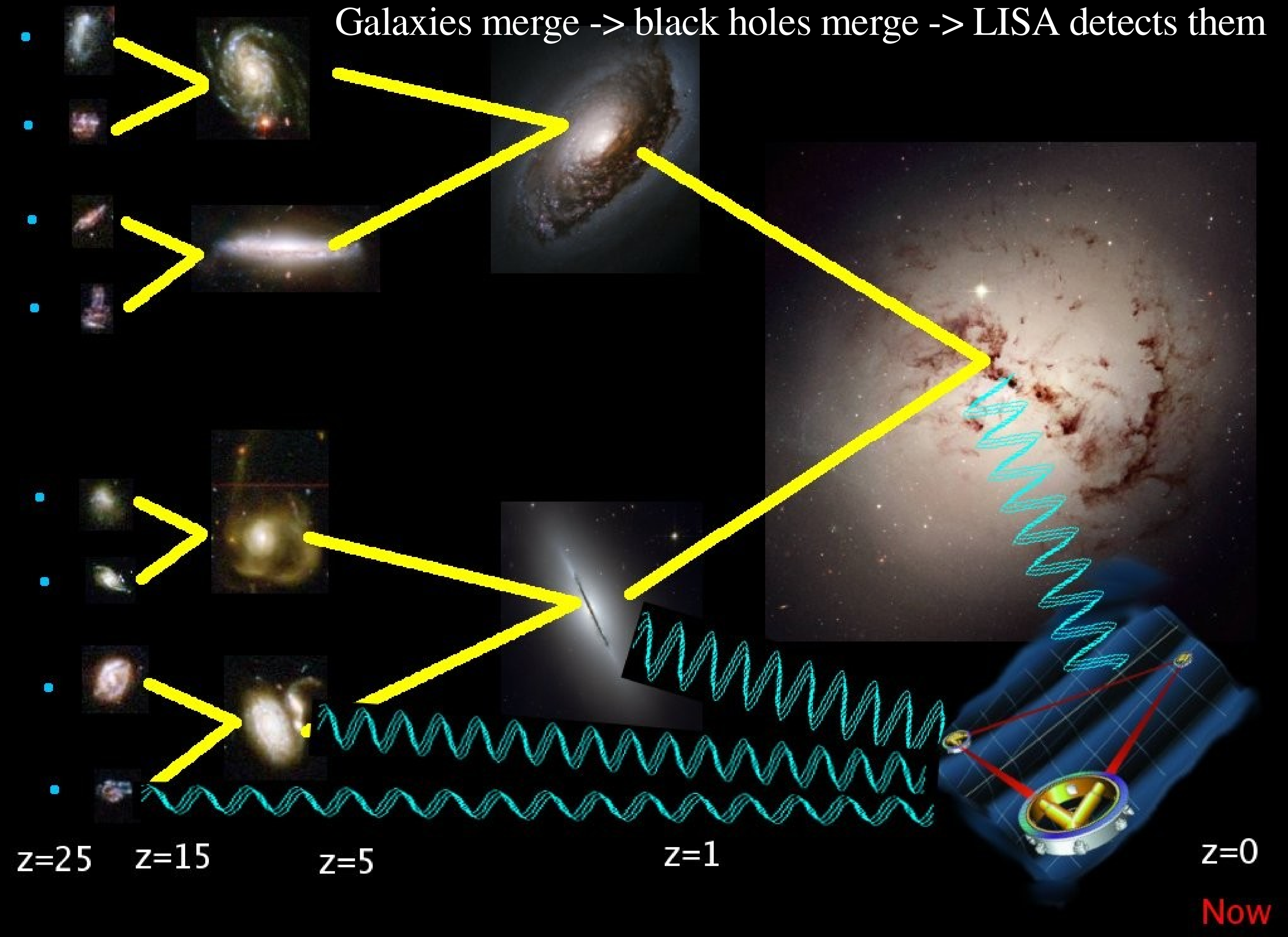
supermassive BH

Gravitational radiation at pericenter: shrinks apocenter –so fast no more 2-body.

EMRI capture loss cone defined by dln(a)/dt due to gravitational radiation < time to diffuse back out of loss cone.

Hils & Bender 1995, Sigurdsson & Rees 1997, Miralda-Escude & Gould 2000, Freitag 2001,2003, astro-ph/0703495

Galaxies merge -> black holes merge -> LISA detects them



LISA data: ~Gbytes.   All signal, little noise
Rich, multi-parameter, overlapping waveforms.
thousands to millions of cycles.
-high precision parameters
-data analysis not trivial! But proven tractable -
see MLDC

All phase
measurements
telemetered to
ground and archived.
All (3 independent)
TDI interferometer
signals synthesised
on earth.