The Big Bang Observer

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Gravitational Wave
Advanced Detector
Workshop

LIGO-G0900426

What BBO Is and Is Not

- Post-LISA space based GW detector
- No active BBO mission within NASA and/or ESA
- Currently no ongoing BBO research
- More of an idea than a project
- 2005 NASA collected a team to look at BBO technologies
  - Part time
  - Mostly LIGO and LISA scientists
- Designed to determine where NASA research efforts should be focussed
  - Which technologies are mature?
  - Which crucial technologies need support?
  - Where can LISA/LIGO solutions be used?
- No further work since 2005 (that we are aware of)
  - Some technology changes
  - Better understanding of some sources
  - Nothing happening in NASA

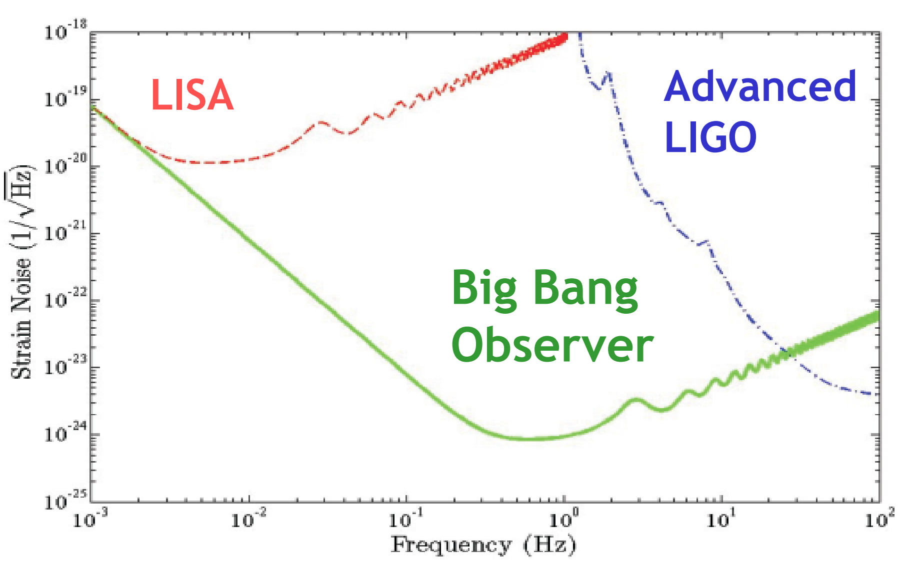
•Laser Interferometry for the Big Bang Observer. G. M. Harry, et al., *Classical and Quantum Gravity* 23 (2006) 4887.

Big Bang Observer Concept

Scientific Goals

- Detect gravitational wave relics from inflation ($\Omega_{gw}(f) < 10^{-17}$)
    - Prime scientific objective
    - LISA - too little sensitivity (?)
    - LIGO *et al* - too high frequency (?)
    - Low frequency has problems with foreground events (C. Miller talk)
    - Not compared to DECIGO
- Compact body inspirals
    - Triggers for ground based ifos
    - Detailed parameter measurement
- Burst localization
- Unexpected sources

(NASA OSS Vision Missions Program Proposal)



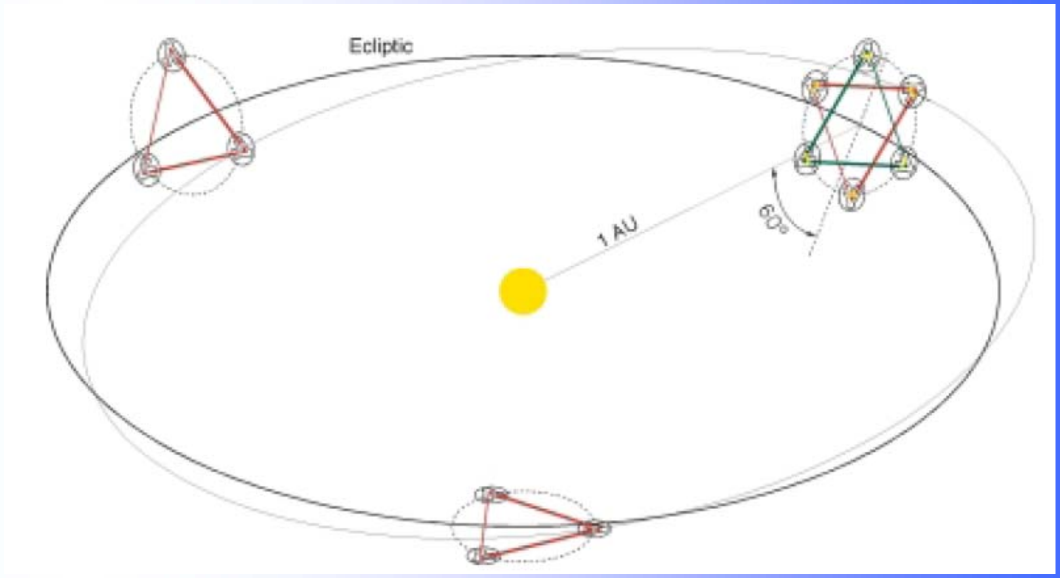
Mission Requirements

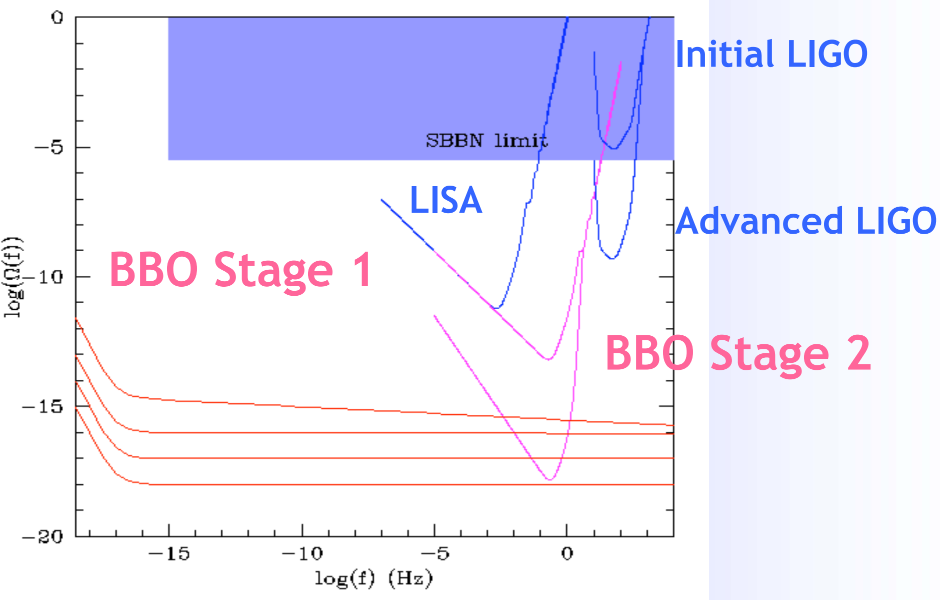
- Fill sensitivity gap between Advanced LIGO and LISA
    - 100 mHz - 10 Hz
- Must be space-based to get $f < 10$ Hz
- Shorter arms than LISA $f > 100$ mHz
    - Factor of 100
- Higher laser power for greater shot noise limited sensitivity
- Improved acceleration noise

BBO Stages

Stage One

- 3 spacecraft
- 5 X 10^7 m arm length
- Solar orbit at 1 AU
  - Constellation makes one rotation every year
- 10 kg drag-free masses
- Launch in 2025 (?)
- 5 year long mission

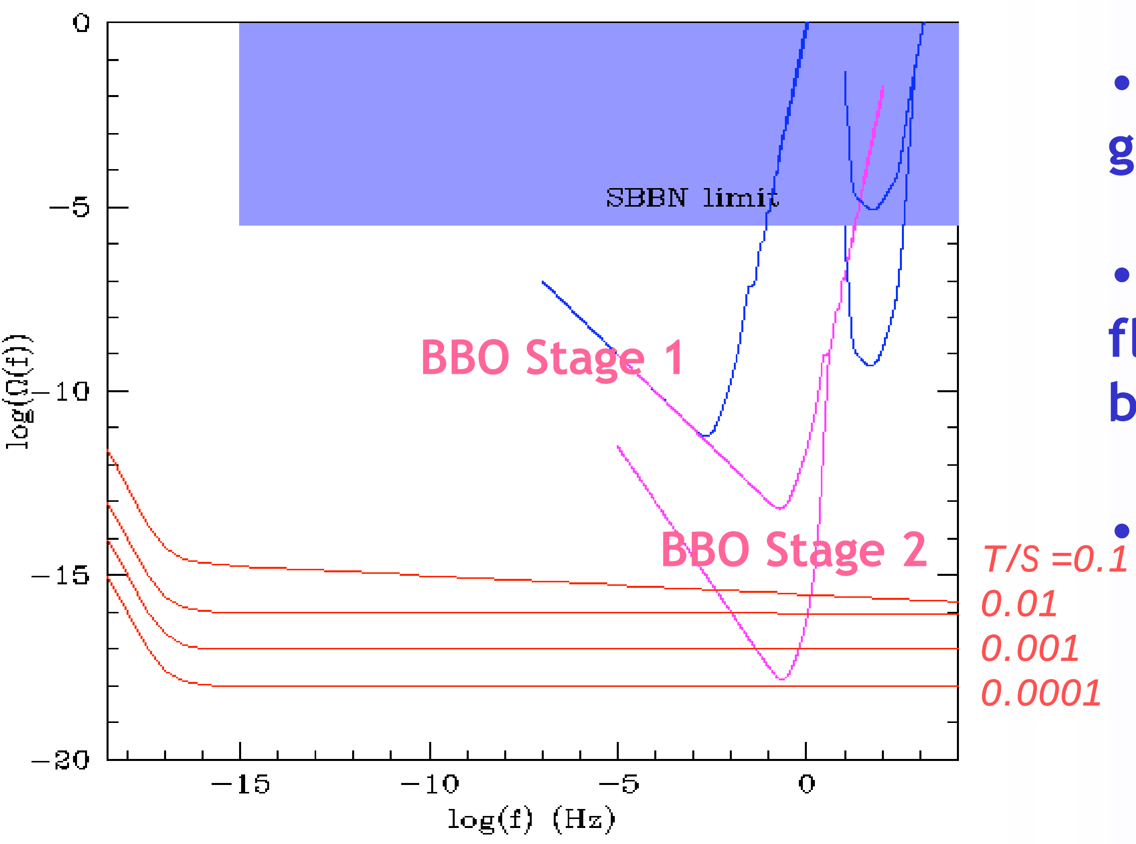




Stage Two

- 12 spacecraft
- 3 constellations
  - One with six spacecraft
  - Two with three spacecraft
- Solar plasma correction
  - Radio interferometer
- Technology informed by Stage One
- Launch in 2029 ???
- Mission length ???

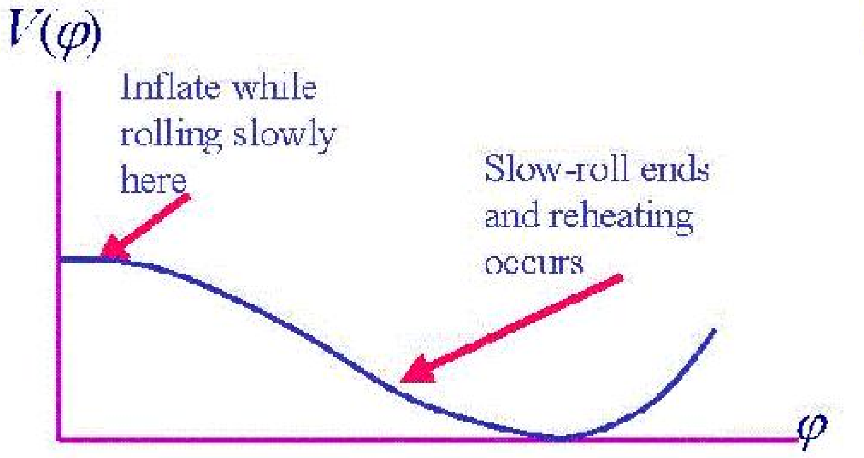
BBO Sources - Stochastic



- Alternate (non slow roll) inflation models can have different scales and spectras
    - Rising with f
    - Undetectably low Ω(f)

Detection of Inflation

- Measurement of stochastic gravitational wave spectrum
    - Parameter fitting
- Very low frequency (~ 10^{-17} Hz) by fluctuations in cosmic microwave background
    - Need a second, higher frequency
- Slow roll inflation
    - $\Omega(f) \sim 10^{-15} - 10^{-17}$
    - Decreasing with frequency
    - Well below AdvLIGO sensitivity



BBO Sources - Others

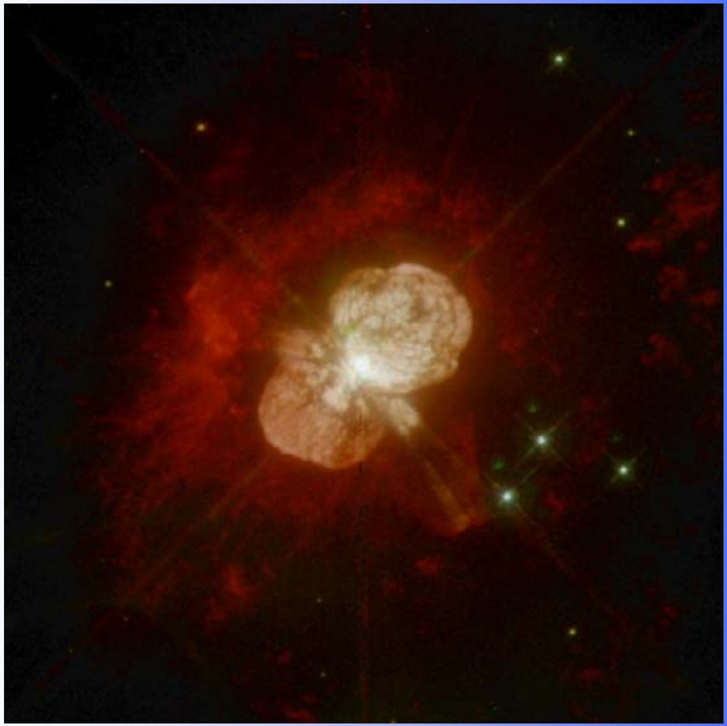
Compact Body Inspirals

- Last year of every NS/NS, NS/BH, and BH/BH (stellar mass BH) at z<8
  - Months of advanced notice for ground based ifos and γ ray bursts
  - All mergers of intermediate mass BH
- <1% distance accuracy

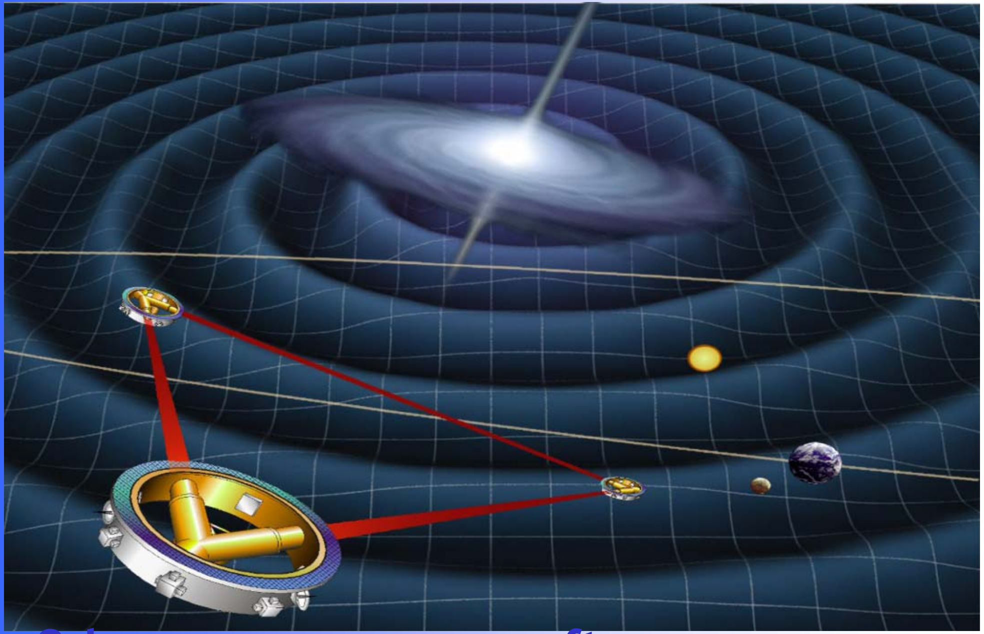
Inspirals	Position	NS/NS SNR	BH/BH SNR	Events/ year
Stage 1	~1 arcmin	20	100	$\sim 10^4$-10^5
Stage 2	~1 arcsec	60	300	$\sim 10^5$-10^6

Bursts

- Type 1a supernova
  - < 1 Mpc (Stage 1)
  - < 3 Mpc (Stage 2)
- Cosmic/superstrings over entire range of tensions $G\mu/c^2 > 10^{-14}$

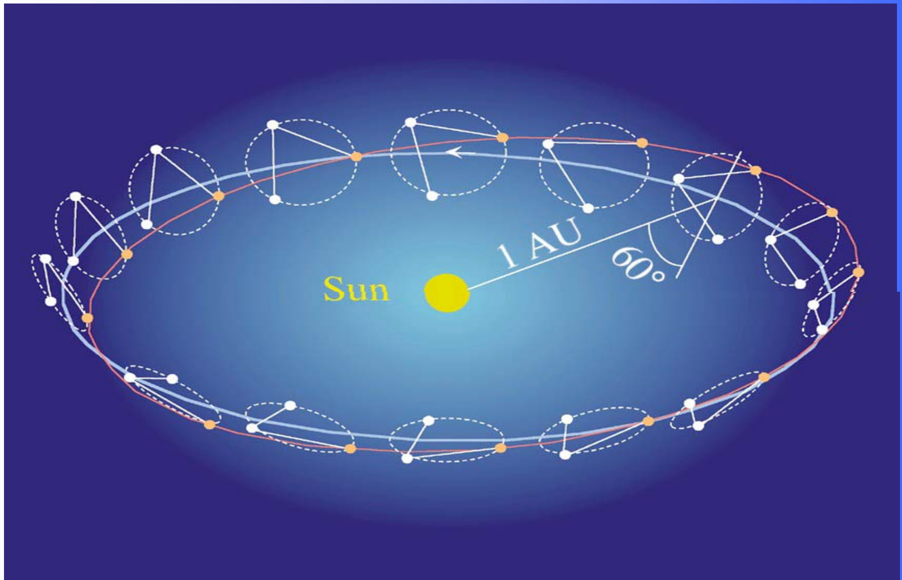


BBO Hardware Overview

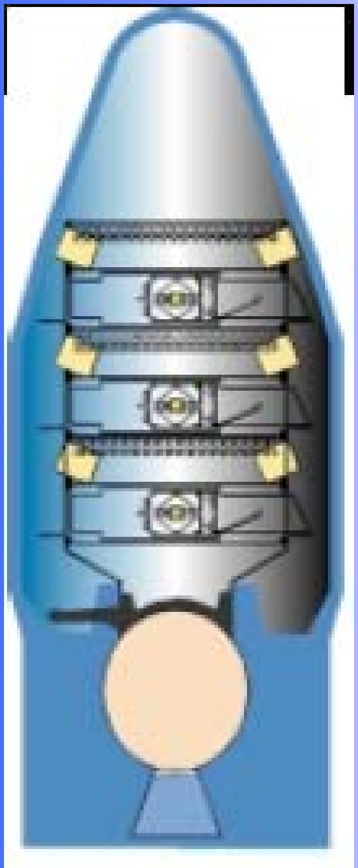


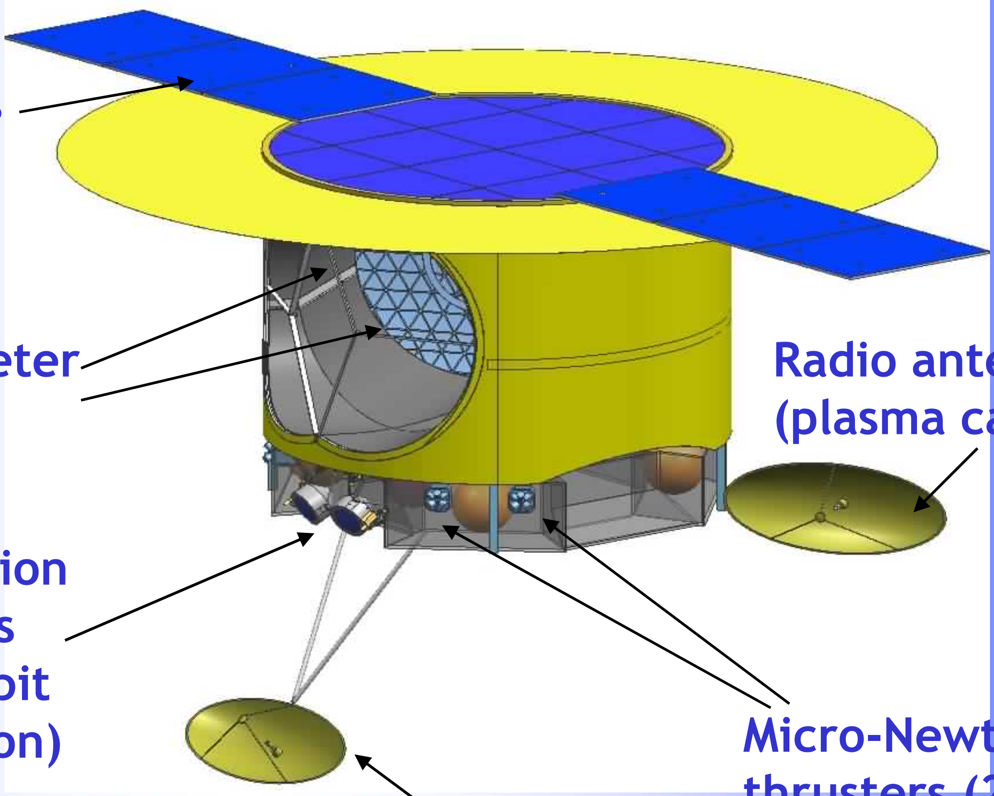
- 10 kg hex masses
  - 10 cm on a side
- About 6 kW of power
  - ~ ½ for lasers
- 21 m^2 solar panels
  - 0.28 efficiency
- 21 m^2 array of thrusters
  - 24 μN of total thrust

- 2 lasers per spacecraft
- Each laser 300 W at 355 nm
  - Frequency tripled Nd:YAG
- 2 X 2.5 m collecting mirrors
- Arm lengths controlled on dark fringe
  - More like LIGO than LISA
  - Reduce power on photodiode
  - Suggestion to use LISA scheme for better calibration



Spacecraft





Solar panels (deployed)

2.5 m diameter telescopes

Xenon ion engines (for orbit insertion)

Radio antenna (plasma calibration)

Micro-Newton thrusters (2 of 6)

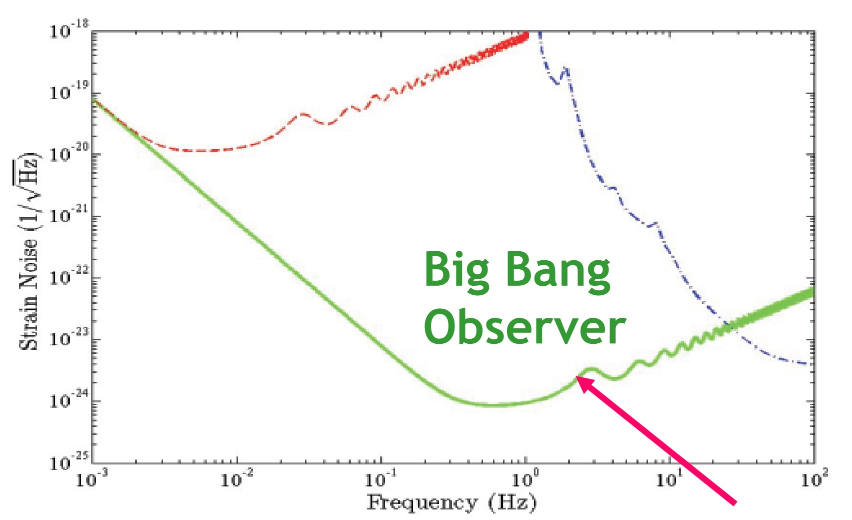
Radio antenna (to Earth)

2.5 m diameter telescopes so will fit in single 5 m launch vehicle

Laser Shot Noise

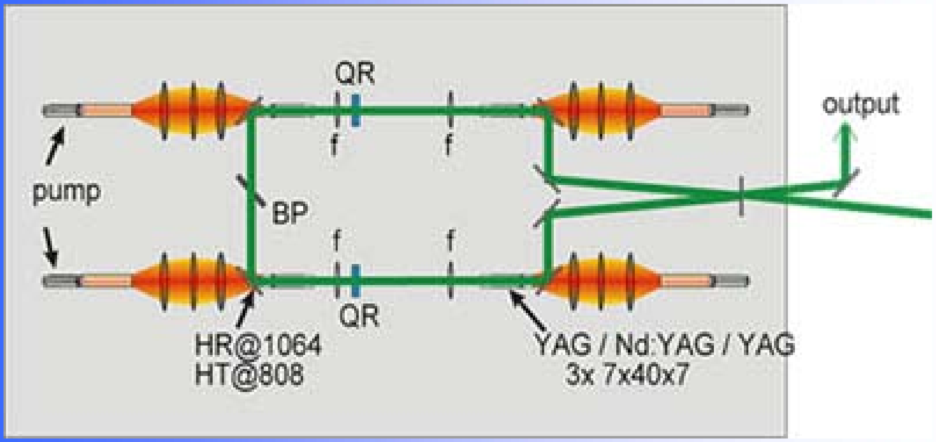
$$S_x(f) = h\,c\,\lambda^3 L^2 / (2\,\pi^2\,\eta\,P\,D^4)$$

h, c, π - Planck's constant, speed of light, pi
λ - laser wavelength
L - arm length
η - photodiode quantum efficiency
P - laser power
D - mirror diameter (collection ability)



Shot Noise Limited

Need low wavelength, high efficiency, high power, and large mirrors

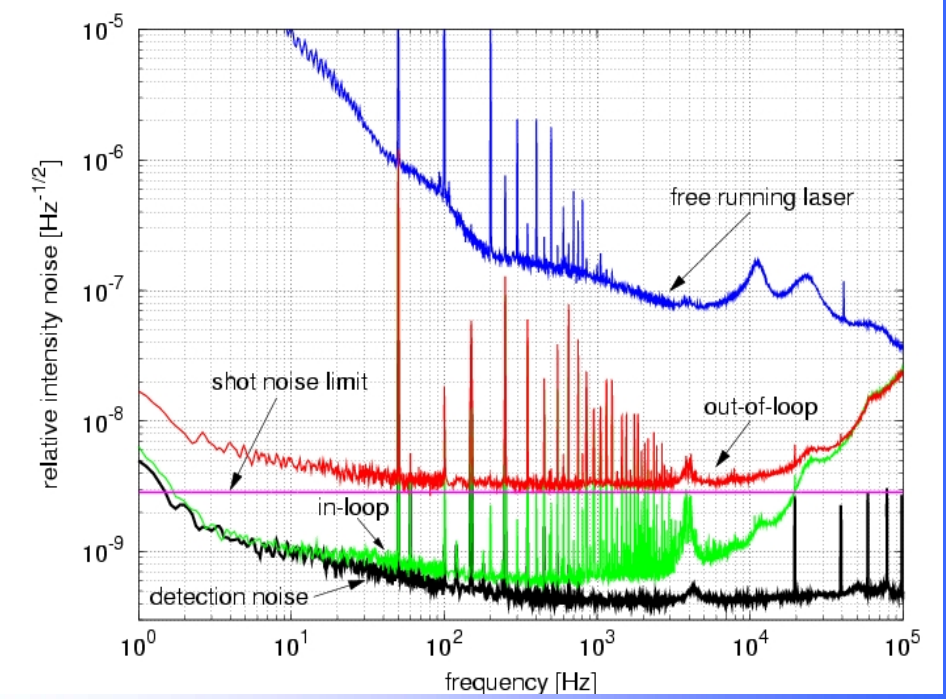


Advanced LIGO Nd:YAG Injection Locked End Pumped Rod Laser

- Largest mirrors that fit in launch vehicle
  - 2 X 2.5 m, all 3 fit in Delta IV
- Only things to improve are λ, η, and P
- Nd:YAG laser at 1064 nm
  - Frequency and intensity stabilization well understood
  - Frequency tripling practical limit
  - 300 W seems achievable
    - 200 W for Advanced LIGO
    - Must be space qualified

BBO Laser Noise Requirements

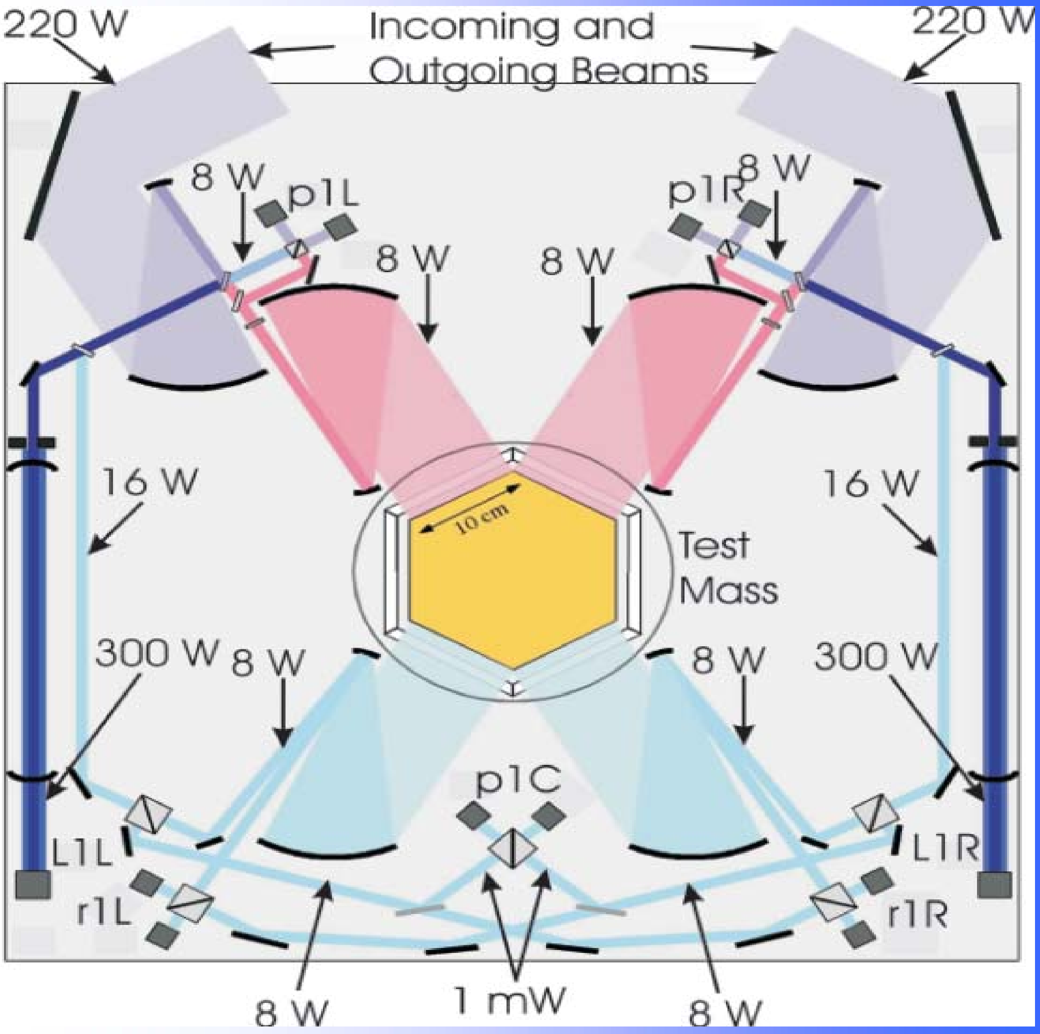
- Relative Intensity Noise (RIN)
  - 10^{-8}/√Hz at 100 mHz
  - Set by AC radiation pressure
  - 10^{-6}/√Hz at 100 mHz shown in LIGO laser
- Frequency noise set by arm length imbalance
  - ΔL = 1 m by using radio link
  - $\delta f / f = 10^{-3}$ Hz/√Hz
- Active frequency stabilization to Fabry-Perot cavity
  - 0.3 Hz/√Hz (thermal noise)
  - Further reduction stabilizing to arm
    - Proposed for LISA



Advanced LIGO Laser Relative Intensity Noise (RIN)

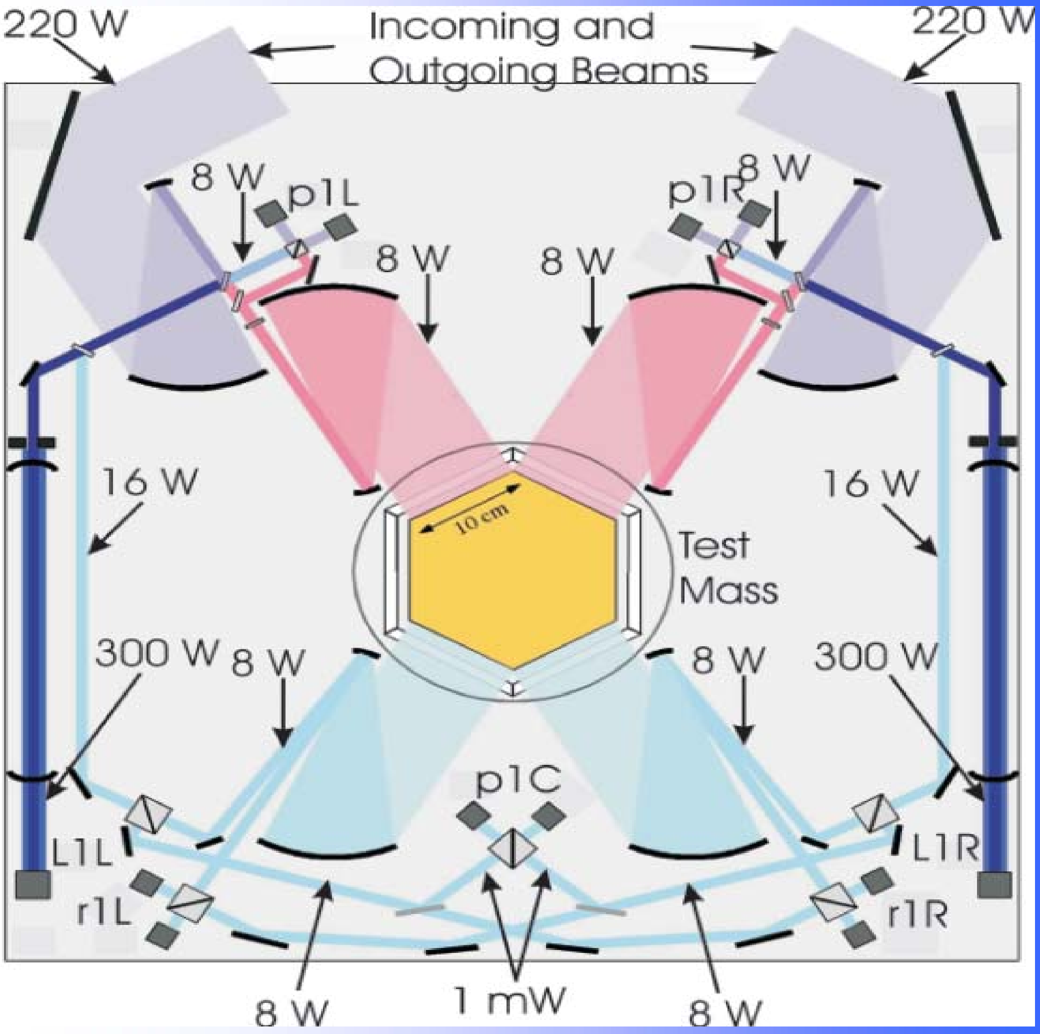
Optical Components - 1

- 2 lasers per spacecraft
  - 300 W output
  - Possibly delivered from other board
- Fabry-Perot cavity
  - Passive mode cleaner to stabilize beam direction and mode
  - Reference for frequency stabilization
  - Finesse of ~ 100, trade-off between shot noise and transmission
- 3 beams picked off
  - 16 W for sensing of local test mass
  - 8 W for interfering with incoming beam
  - 1 mW used to phase lock lasers
- Outgoing beam expanded to ~ 1 m
- Incoming beam reflected off of test mass before interference
  - Incoming beam Airy disk while local beam Gaussian
  - Contrast defect goal ~ 10^{-4}



Optical Components - 2

- 16 W local sensing beam
  - Controls linear DOF of spacecraft
  - Quad photodiodes allow for angular DOF control
  - Balances DC radiation pressure from incoming beam
  - AC pressure causes acceleration noise
- RF modulation used for locking
  - Separate frequency for each laser of order ~ 10 MHz
  - 2 possibilities to apply sidebands
  - Before FP cavity – cavity must pass RF control signal
  - After FP cavity – EOM must handle full 300 W of power
- Photodiode requirements
  - High power handling (~2 mW)
  - High quantum efficiency (~ 0.6)
  - Low capacitance for RF modulation
  - Quad elements for angular control



Thermal Noise and Materials Issues

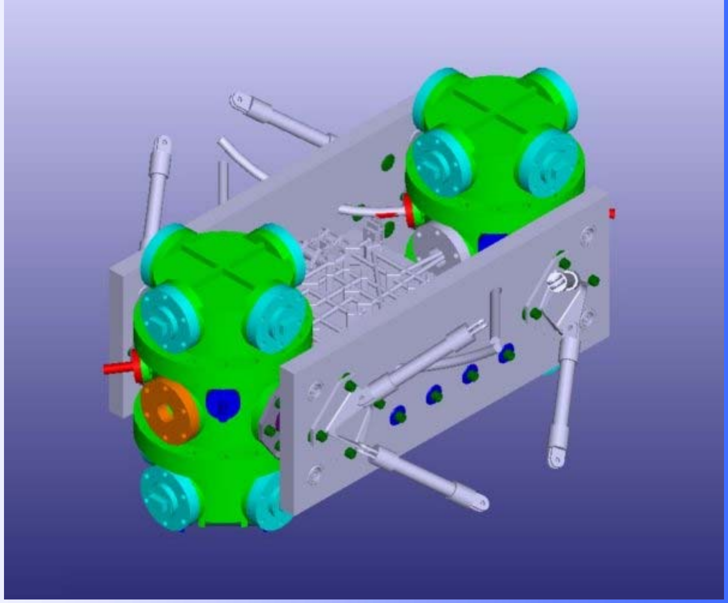
- Brownian motion of mirrors important
  - Limits frequency stabilization
  - Contributes to measurement noise
- Need to use low mechanical loss coatings
  - Fluctuation-Dissipation Theorem
  - Mechanical loss causes Brownian motion
- Most metals have high mechanical loss
  - Gold/Platinum used by LISA
- Coating thermal noise also problem for LIGO
  - Low mechanical loss dielectric coatings under development
  - Magnetic properties unknown
- Test mass material also important
  - 10 kg
  - Low mechanical loss
  - Low magnetic susceptibility
  - Control of charge build up

LISA Test Mass

LIGO Coated Optic

Required Technologies

- Laser
  - Power 300 W
  - Frequency tripled Nd:YAG
  - RIN < 10^{-8} /√Hz at 100 mHz (LIGO)
  - Frequency noise < 10^{-3} Hz/√Hz (LISA)
- High power optical components
  - EOM that takes 300 W
  - Photodiodes
    - High quantum efficiency at 355 nm
    - 2 mW with low capacitance (LIGO)
- Materials
  - Low thermal noise coatings (LIGO)
  - Low magnetic susceptibility test mass
- Techniques
  - Frequency stabilization to long arm (LISA)
  - Low acceleration noise actuators (LISA)
  - All hardware space qualified (LISA)



LISA Pathfinder

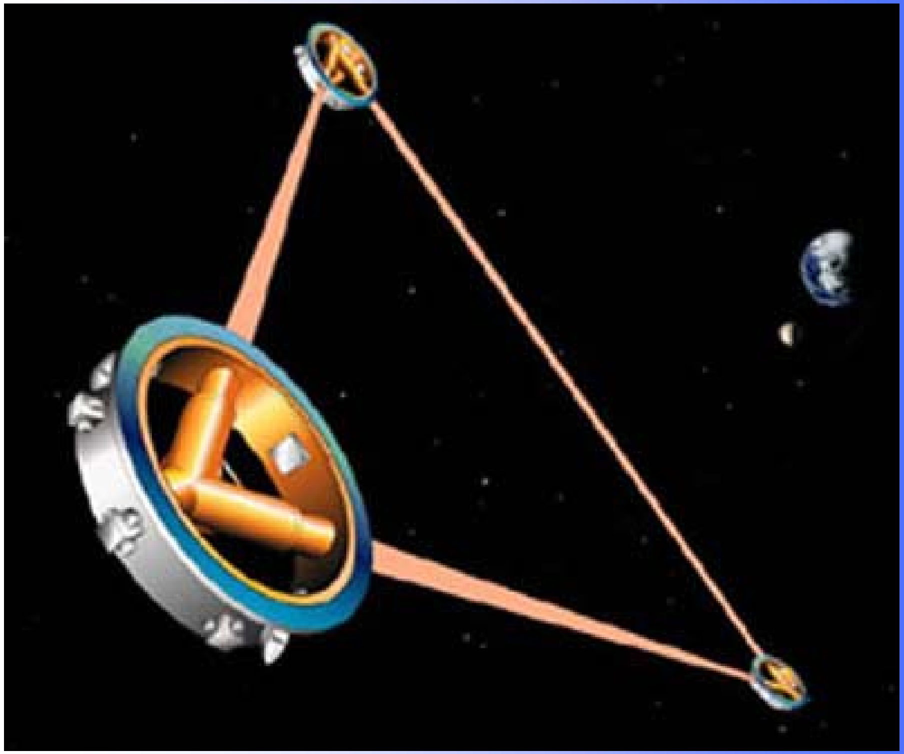
LIGO Commissioning

Conclusions

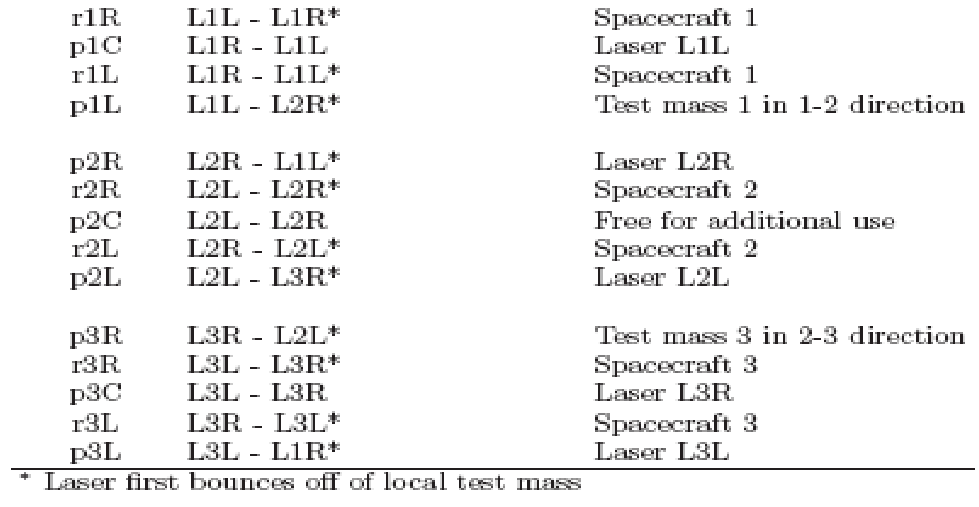
- Big Bang Observer will fill an important future roll
    - Search for stochastic background from inflation
    - Fill in frequency gap
- Plan developing for overall mission
- Suggestion for how to do BBO interferometry
- Many technologies must be developed
- High power, low wavelength laser is crucial
    - $P = 300$ W
    - $\lambda = 355$ nm
    - Very low intensity and frequency noise
- Photodiodes, EOMs, improved materials, etc. also important
- Have until 2025 or later to develop these
    - Very challenging, need to start soon

Outline

- Big Bang Observer Overview and Status
- Sources for BBO
- BBO Laser
  - Shot Noise
  - Other Noise Requirements
- BBO Optical Components
- BBO Control Scheme
- Materials Issues
  - Coating Thermal Noise
- Technology Research Needs
- Conclusion



Control Scheme



Photodiode	Interfering Lasers	Recipient of feedback
p1R	L1R - L3L*	Laser L1R
r1R	L1L - L1R*	Spacecraft 1
p1C	L1R - L1L	Laser L1L
r1L	L1R - L1L*	Spacecraft 1
p1L	L1L - L2R*	Test mass 1 in 1-2 direction
p2R	L2R - L1L*	Laser L2R
r2R	L2L - L2R*	Spacecraft 2
p2C	L2L - L2R	Free for additional use
r2L	L2R - L2L*	Spacecraft 2
p2L	L2L - L3R*	Laser L2L
p3R	L3R - L2L*	Test mass 3 in 2-3 direction
r3R	L3L - L3R*	Spacecraft 3
p3C	L3L - L3R	Laser L3R
r3L	L3R - L3L*	Spacecraft 3
p3L	L3L - L1R*	Laser L3L

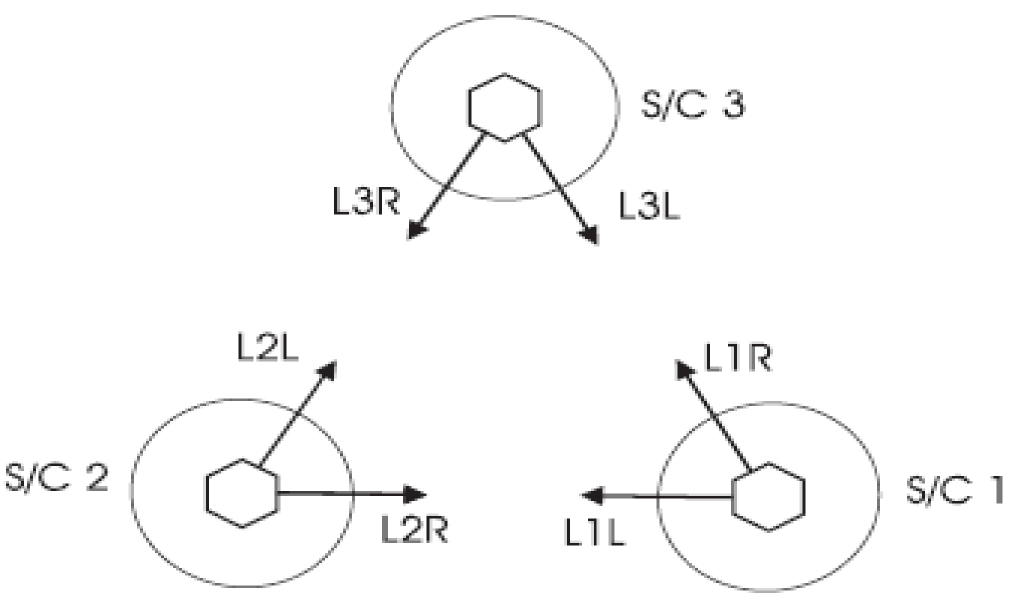
* Laser first bounces off of local test mass

Frequency Control

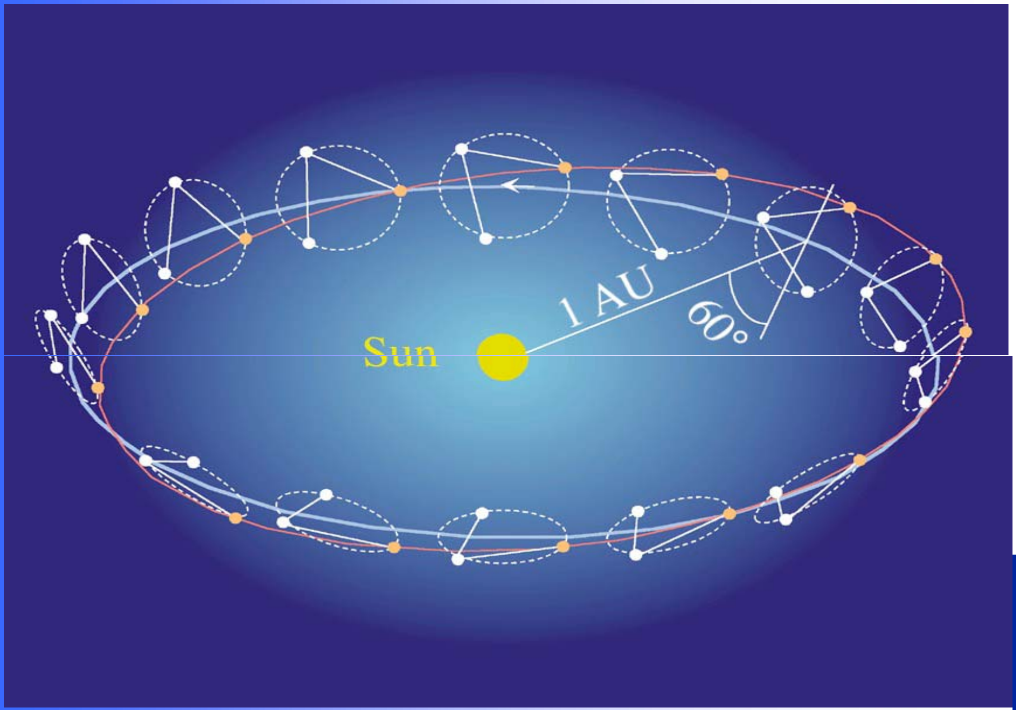
- Arm between S/C 1 and 3 used as stable frequency reference
  - Laser 1R locked to this reference
- Laser 1L locked to laser 1R
- Laser 2R locked to laser 1L
- Laser 3L locked to laser 1R

Position Control of Test Masses

- Test mass 1 controlled in direction 1-2
- Test mass 2 uncontrolled
  - Could be actuated on in direction 1-3 to get additional signal
- Test mass 3 controlled in direction 2-3

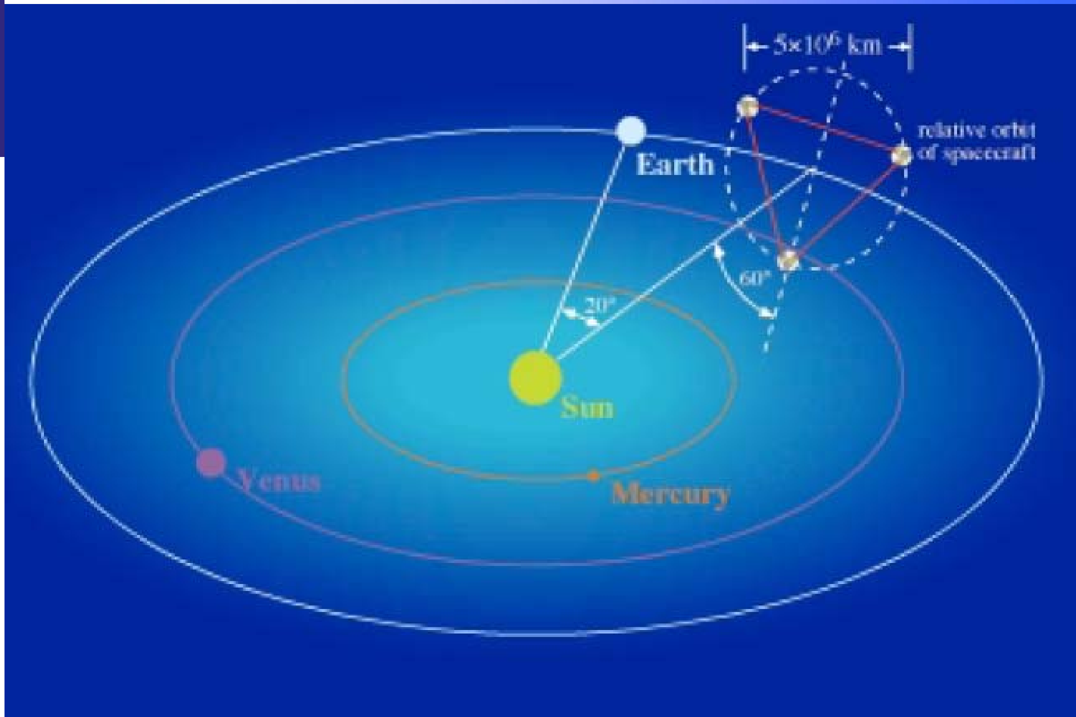


Orbits



- Test masses held in drag free spacecraft
- Each spacecraft in solar orbit at 1 AU from sun
- Individual orbits preserve triangle configuration
- Constellation rolls around center one time each orbit

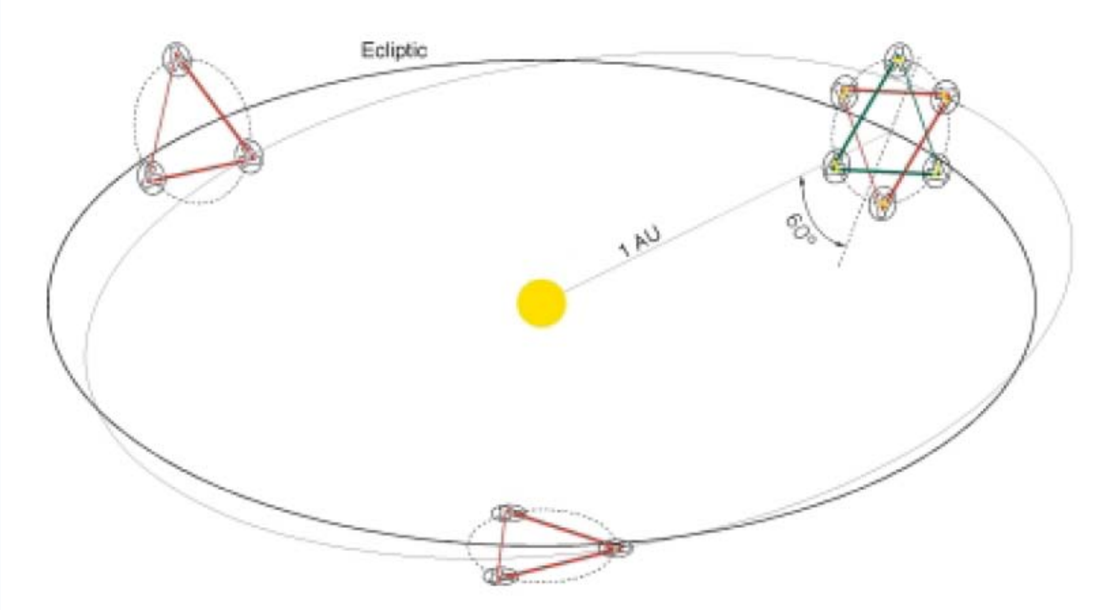
- Stage 1 constellation follows 20° behind Earth
- Stage 3 constellations separated by 120°
- Plane of triangle tilted 60° out of ecliptic

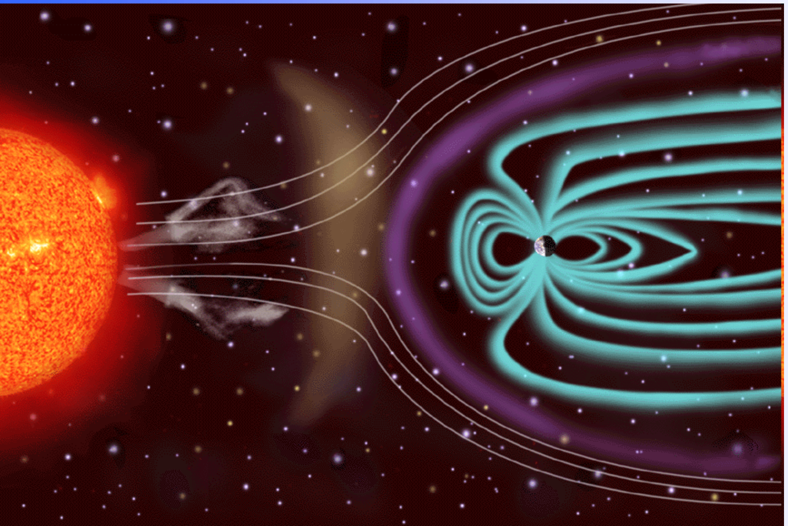


Stage 2 Improvements

- Four constellations
  - Two colocated
  - 12 spacecraft
  - ~ 1 AU of separation

    < 1 arcsecond positioning of burst sources
- Possible technology improvements
  - Higher laser power
  - Higher laser frequency
- Possible change in arm length
  - Will depend on Stage 1 results

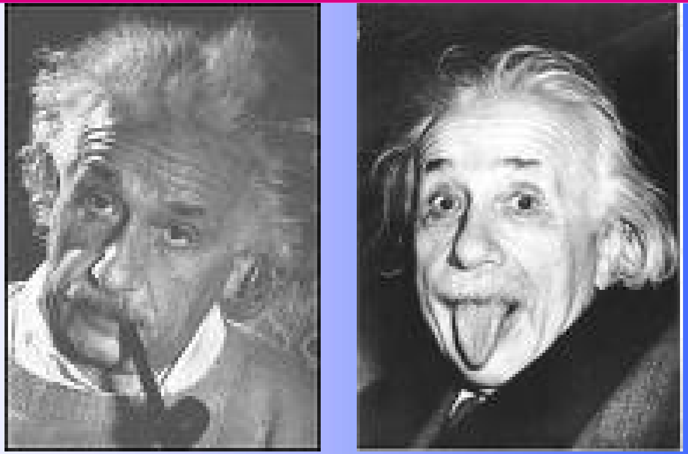




Correlated Noise

- Colocated constellations allow correlated search
- Must remove correlated noises
  - Refractive index fluctuations in solar wind plasma: Remove with added radio interferometer
  - Charging of proof mass from solar wind
  - Time varying B field gradients from solar wind
  - Thermal and radiation pressure fluctuations from solar radiation

BBO Status



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  - Which technologies are mature?
  - Which technologies are advancing?
  - Which crucial technologies need support?
  - Where can LISA solutions be used?
- Beyond Einstein Program (including LISA) being reviewed by NASA
  - Changing priorities away from basic science
  - Manned trip to Mars is expensive

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