The Big Bang Observer: High Laser Power for Gravitational-wave Astrophysics

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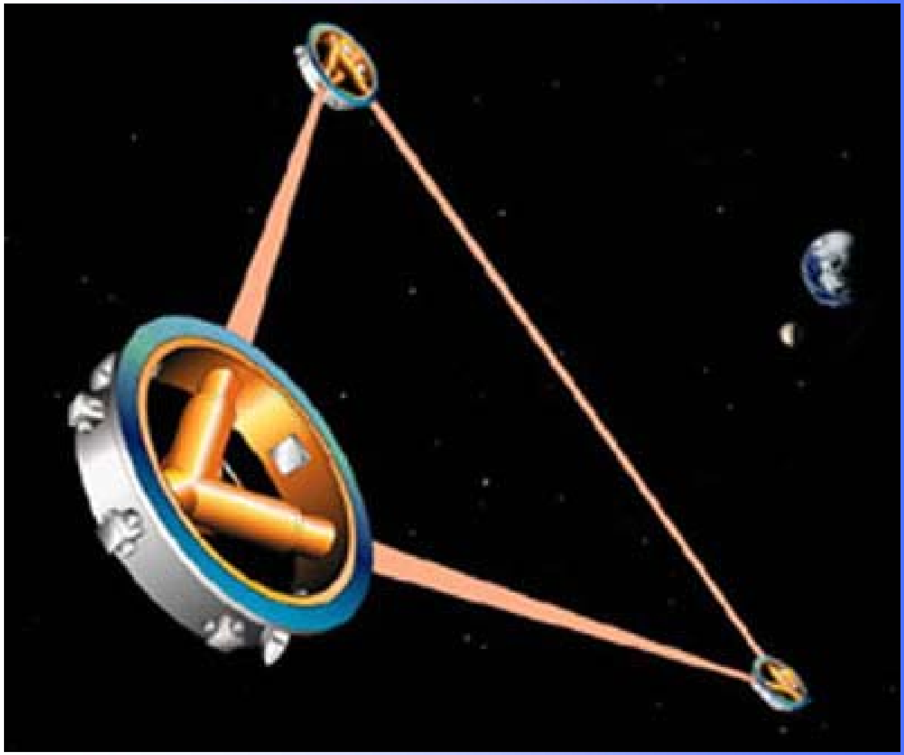
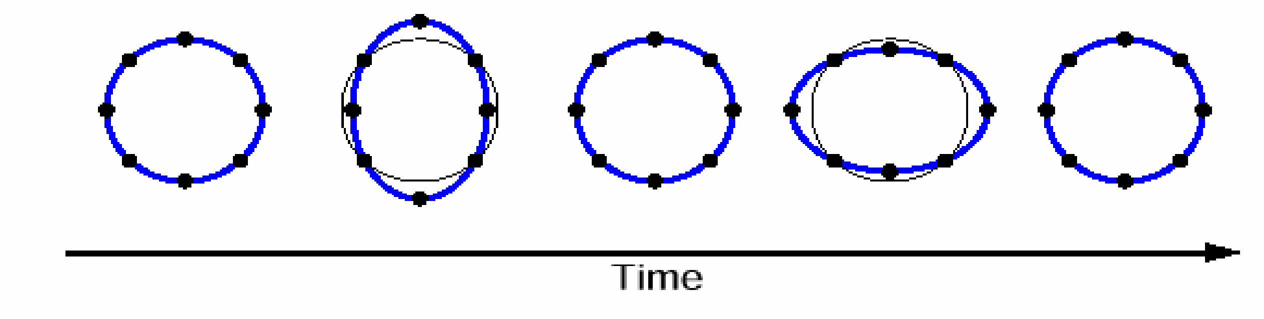
Outline

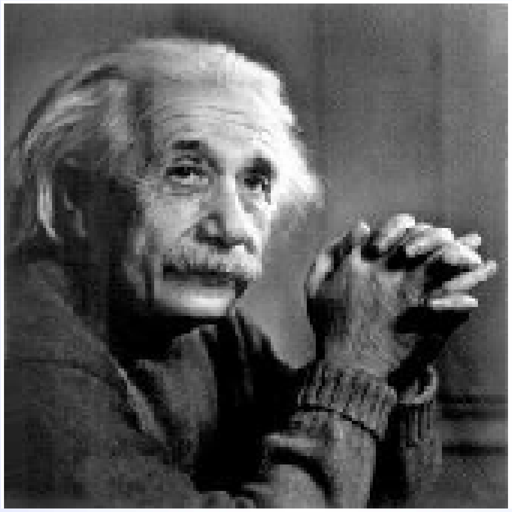
- Brief Introduction to Gravitational Waves
  - Astronomical Sources
- Detection of Gravitational Waves
  - Indirect
  - Direct - Earth based and Space based
- Big Bang Observer Overview and Status
- BBO Optical Components
- BBO Control Scheme
- BBO Laser
  - Shot Noise
  - Other Noise Requirements
- Materials Issues
  - Coating Thermal Noise
- Technology Research Needs
- Conclusion

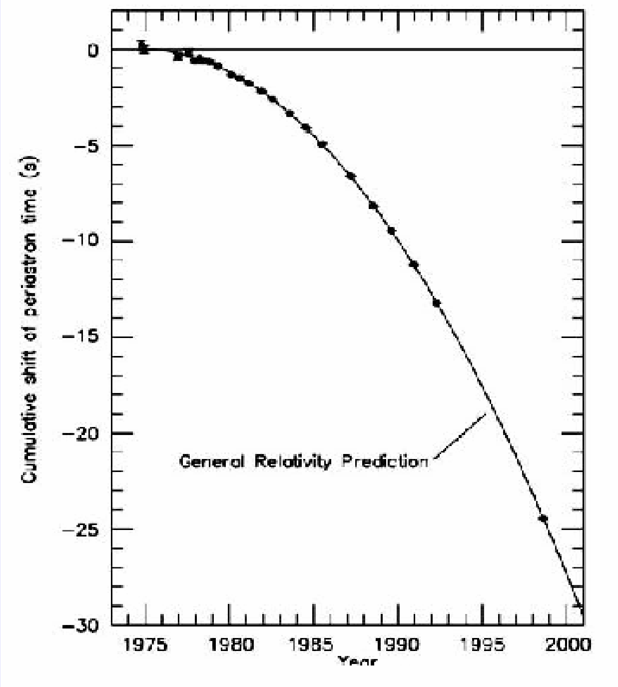


Gravitational Waves



- Predicted by Einstein’s General Theory of Relativity
- Analogous to electromagnetic waves
    - Quadrupolar source (graviton spin 2)
    - Newton’s *G* very small compared to Coulomb’s *k*
- Need large masses moving fast
    - Astronomical sources
    - Compact bodies
- Strain in space
    - $h = \Delta l / l = 10^{-21}$
    - Need long baseline
        - 10^{-18} m over 1 km
        - 10^{-14} m over 10^{4} km

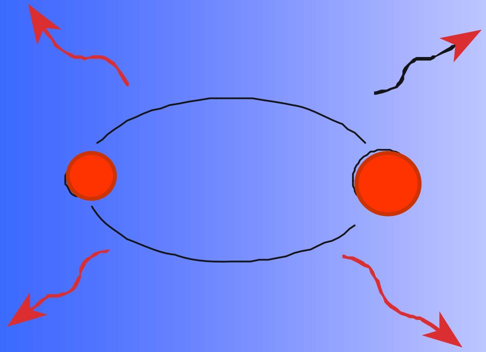




Hulse and Taylor

- Binary pair of pulsars
- Orbit is slowly decaying
- Data from 1975 - present
- Gravitational waves
    - Decay of orbit
    - Line is prediction, not fit
- Nobel prize 1993

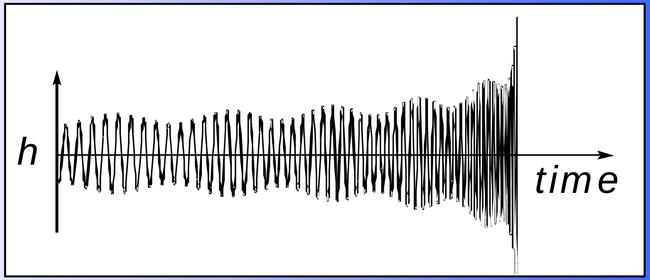
Astronomical Sources of Gravitational Waves



Inspiraling masses

Compact Body Inspirals

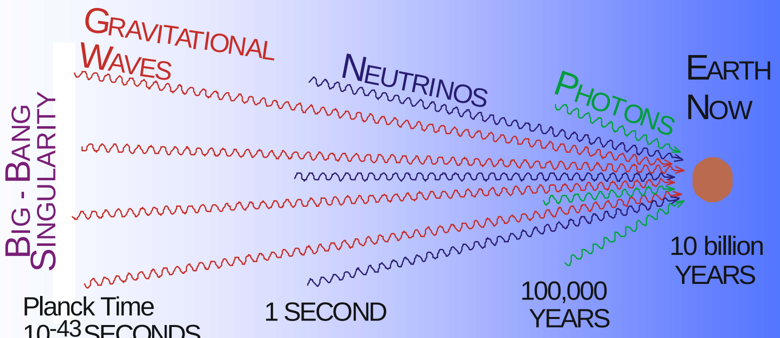
- Neutron Stars *f* < *500 Hz*
- Black Holes *f* < *300 Hz*
- White Dwarves *f* < *1 Hz*



Waveform from inspiral

Stochastic Background

- Incoherent sum of inspirals
- Background from the Big Bang
  - Probes further back than CMB
  - Signature of inflationary models



BIG - BANG SINGULARITY

GRAVITATIONAL WAVES

NEUTRINOS

PHOTONS

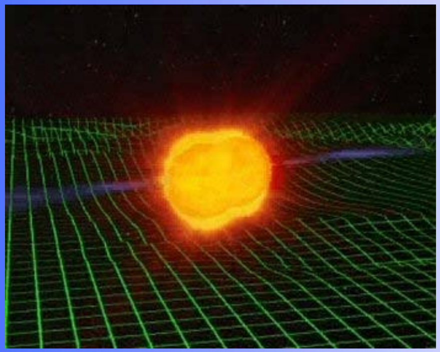
EARTH NOW

10 billion YEARS

100,000 YEARS

1 SECOND

Planck Time
10^{-43} SECONDS
Singularity
creates
Space & Time
of our universe



Asymmetric pulsar

Bursts and Continuous Wave

- Important at high frequencies
- Bursts from supernova
- CW from pulsars

Supernova 1987A

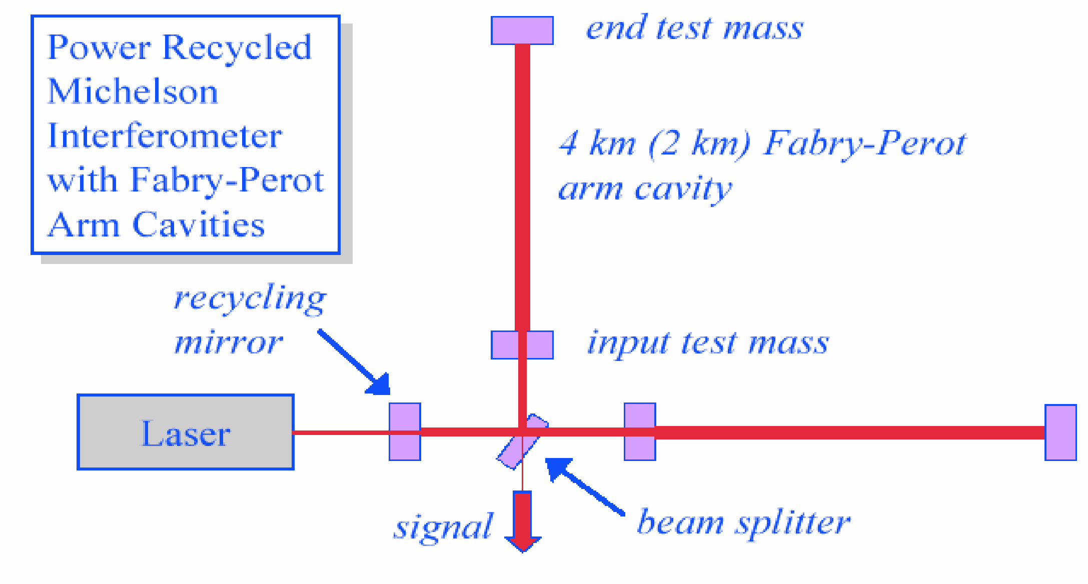
Earth-based Gravitational Wave Detectors

AURIGA Antenna

Resonant Mass (Bar) Detectors

- 1960's -1990's
- Low sensitivity
- Very high frequency (~ 1 kHz)
- Narrow bandwidth (~100 Hz)
- Cryogenic
- Obsolete now

LIGO Livingston Observatory



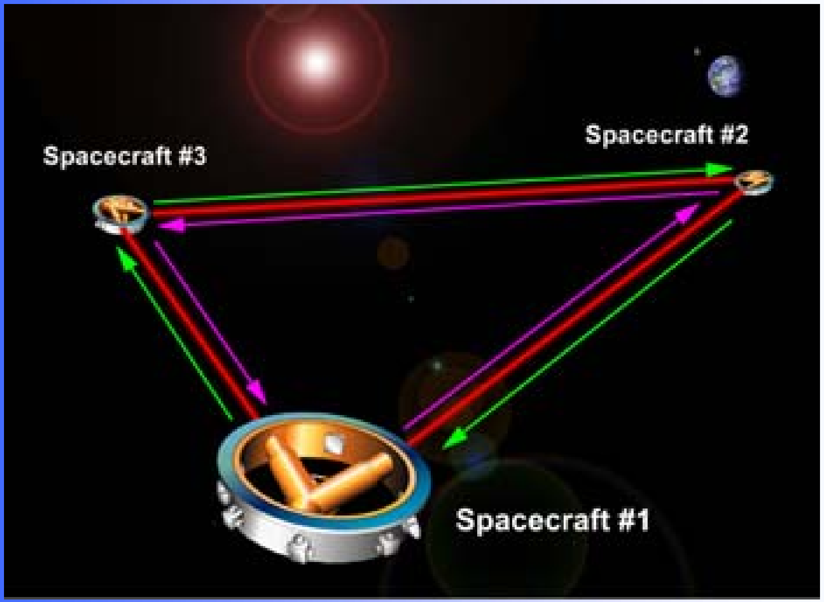
Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities

Interferometers

(LIGO, Virgo, GEO600, TAMA)

- 1980's – today
- 4 km long arms
- High sensitivity
- High frequency (~ 10 Hz - 3 kHz)
- Wide bandwidth
- Taking data now
- No detections, interesting upper limits

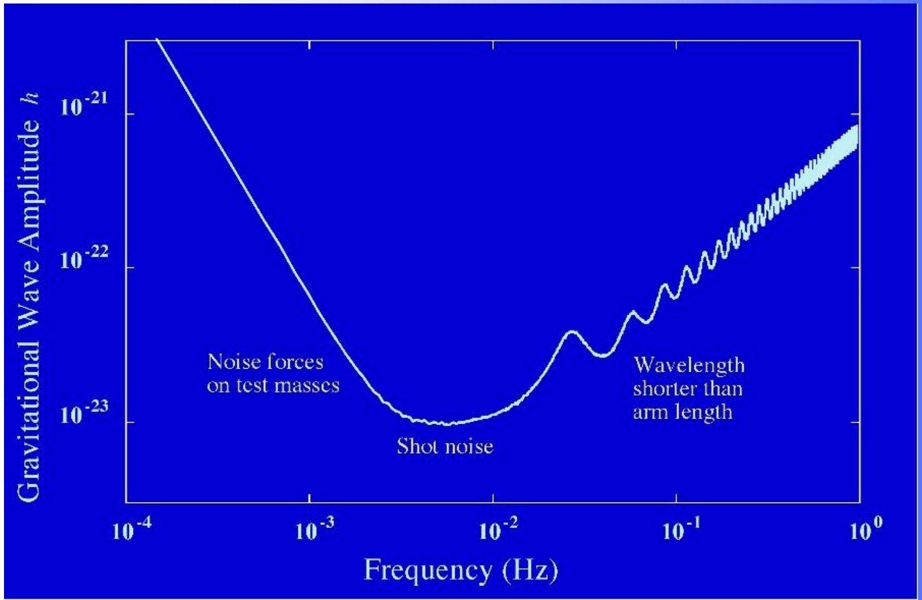
Space-based Gravitational Wave Detectors



Laser Interferometer Space-based Antenna (LISA)

- Being developed now
- Launch date ~ 2018
- 3 spacecraft
- 5 X 10^9 m long arms
- Low frequency (0.1 mHz – 1 Hz)
- Arms are not cavities, uses time delay interferometry

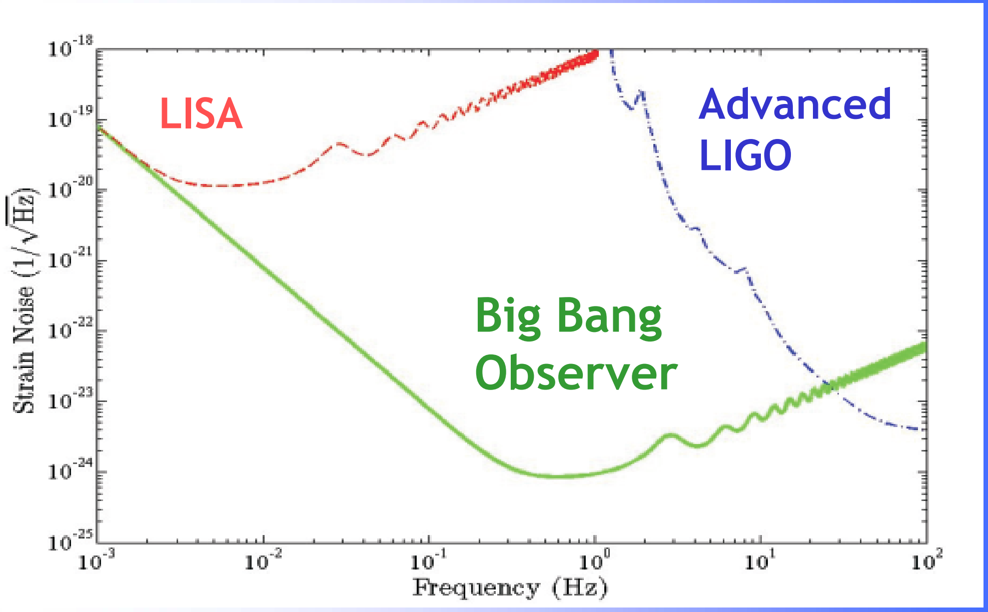
- Low frequency dominated by acceleration noise on test masses
- Middle range limited by shot noise
  - Need more laser power
- High frequency limited by arm length being longer than wavelength
  - Changes with arm length

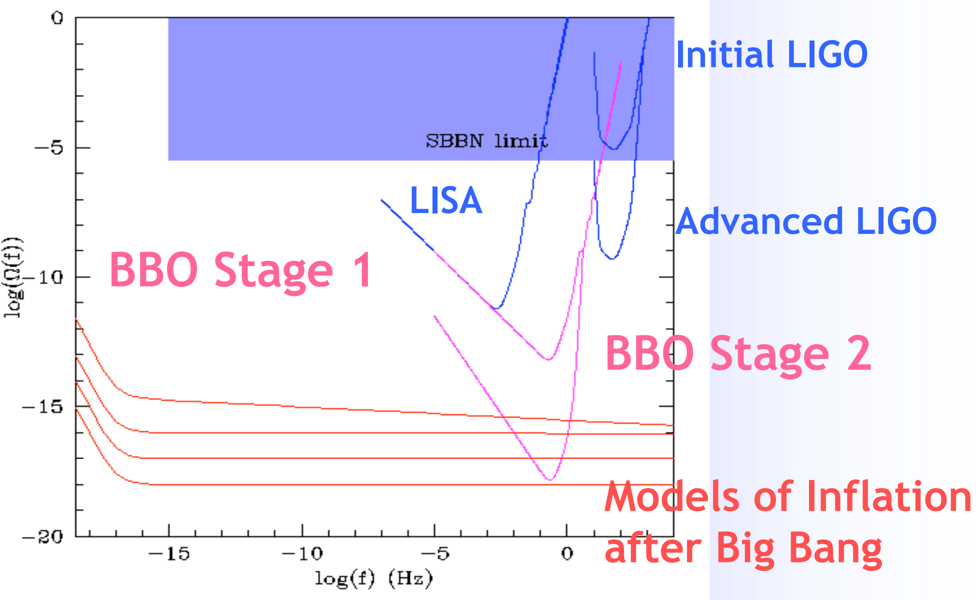


Big Bang Observer

Incomplete Detector Array

- Sensitivity gap between Advanced LIGO and LISA
  - 100 mHz - 10 Hz
- May not have sensitivity to detect background from Big Bang
  - LISA - too little sensitivity
  - LIGO - too high frequency

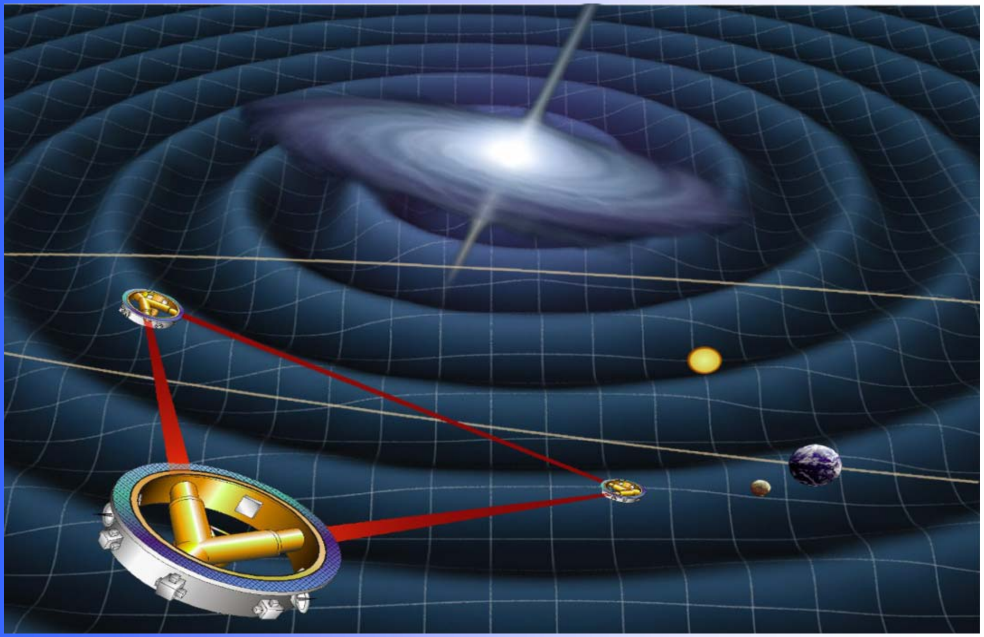




Need Big Bang Observer to fill in gaps

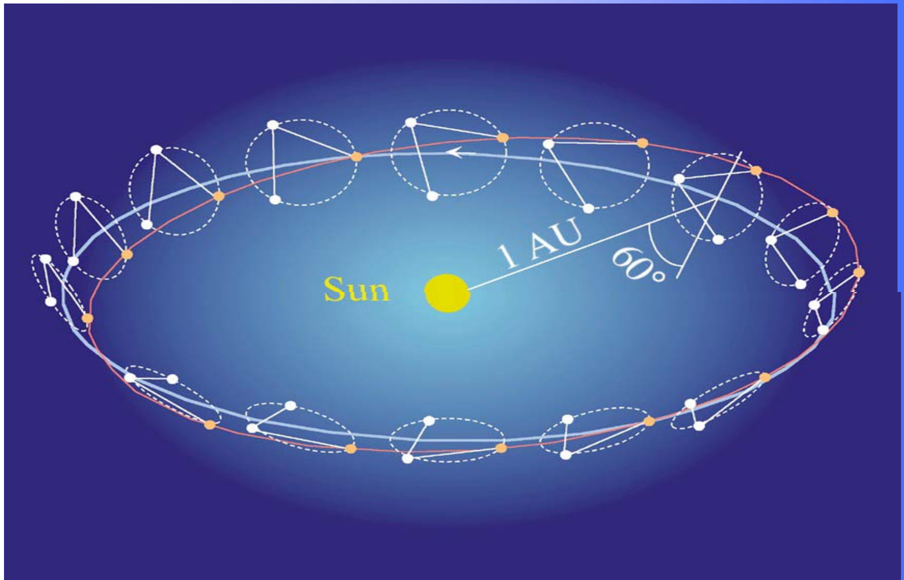
- Must be space-based to get *f < 10 Hz*
  - Seismic noise limiting on Earth
- Shorter arms than LISA *f > 100 mHz*
- Higher laser power for greater shot noise limited sensitivity
- Also improved acceleration noise

BBO Overview

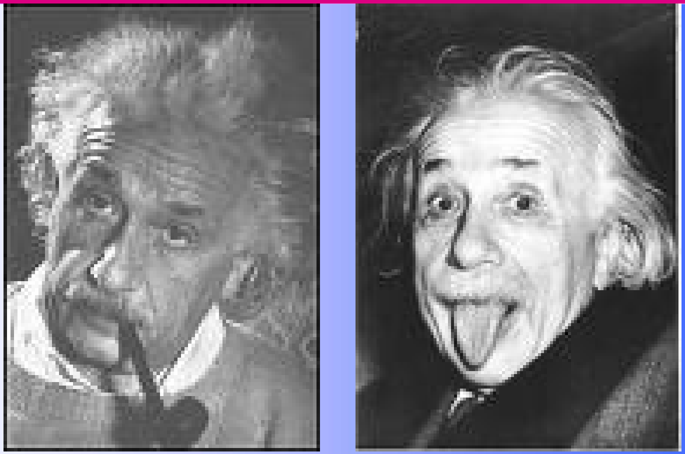


- 3 spacecraft
- 5 X 10^7 m arm length
- Solar orbit at 1 AU
  - Constellation makes one rotation every year
- 10 kg drag-free masses
- Launch in 2025 (?)
- Follow on missions possible
  - More spacecraft
  - More constellations
  - Higher power lasers

- 2 lasers per spacecraft
- Each laser 300 W at 355 nm
- Local laser interfered with laser from other spacecraft
- Arm lengths controlled to keep on dark fringe
  - More like LIGO than LISA
  - Reducing power handling requirements on photodiode



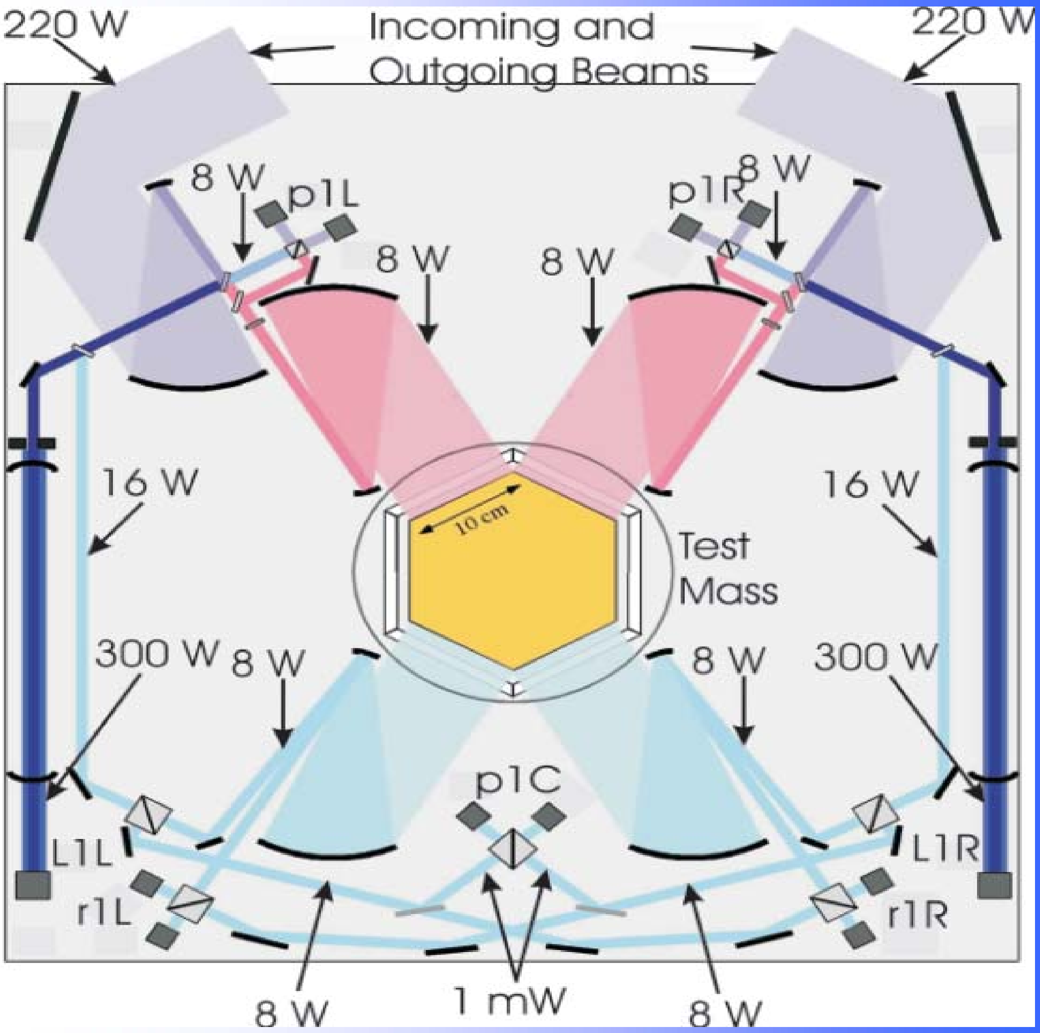
BBO Status



- No active BBO mission within NASA
- Currently no ongoing BBO research
- 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 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

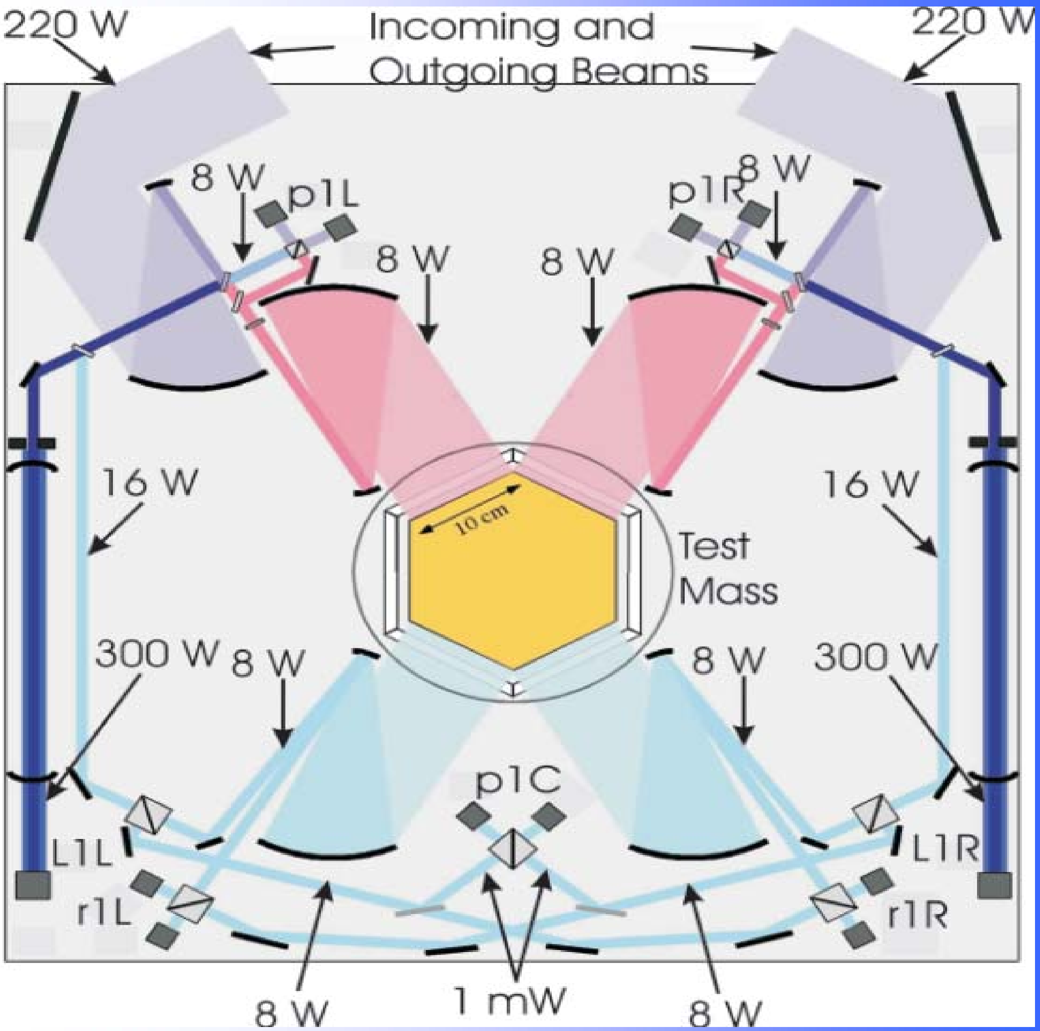
Optical Components - 1

- 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}

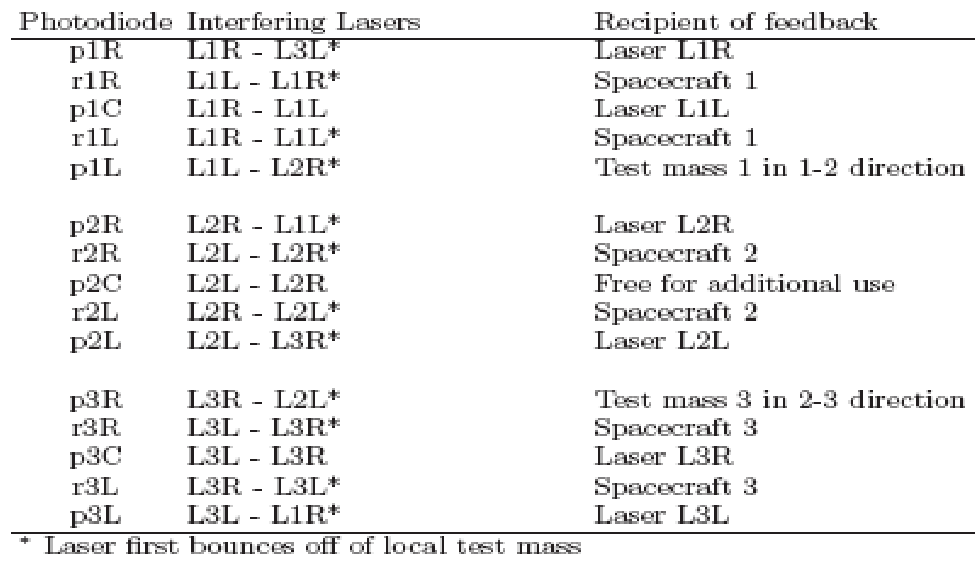


Optical Components - 2

- 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 needed 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



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

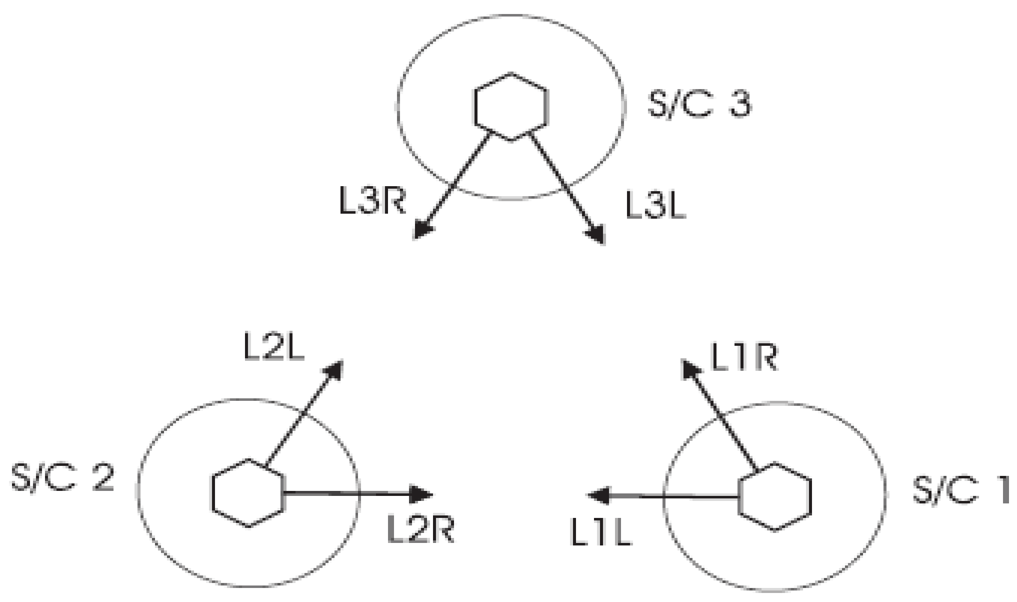
* Laser first bounces off of local test mass

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

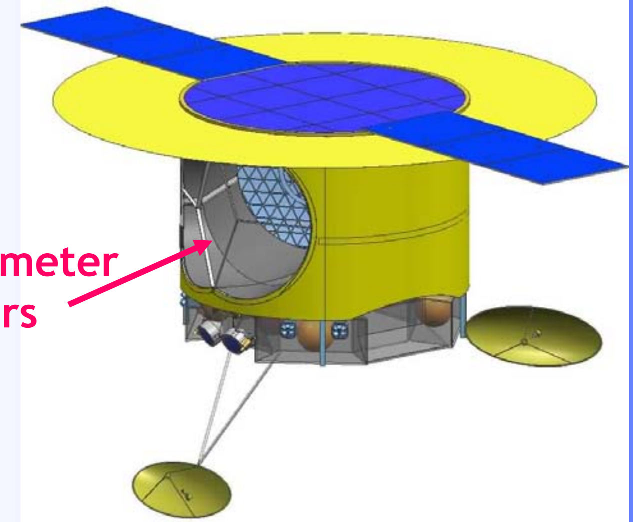


Laser Shot Noise

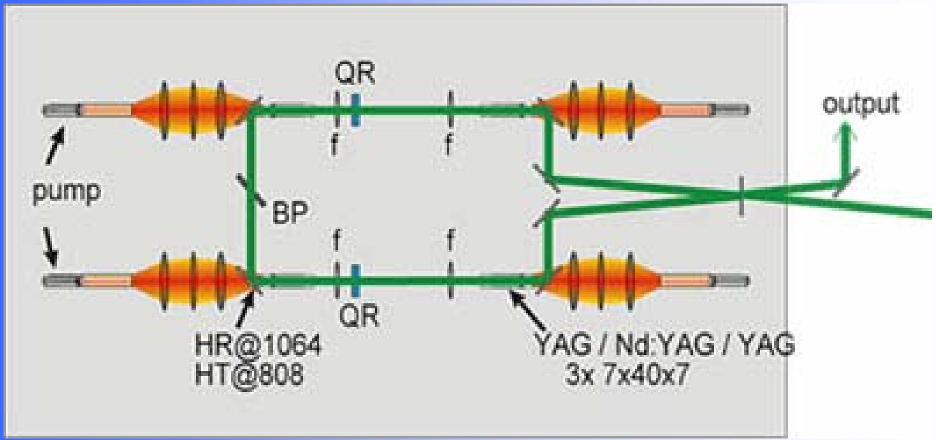
$$S_x(f) = h\, c\, \lambda^3 L^2 / (\, 2\, \pi^2\, \eta\, P\, D^4\,)$$

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)

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


2.5 m diameter mirrors

BBO Spacecraft

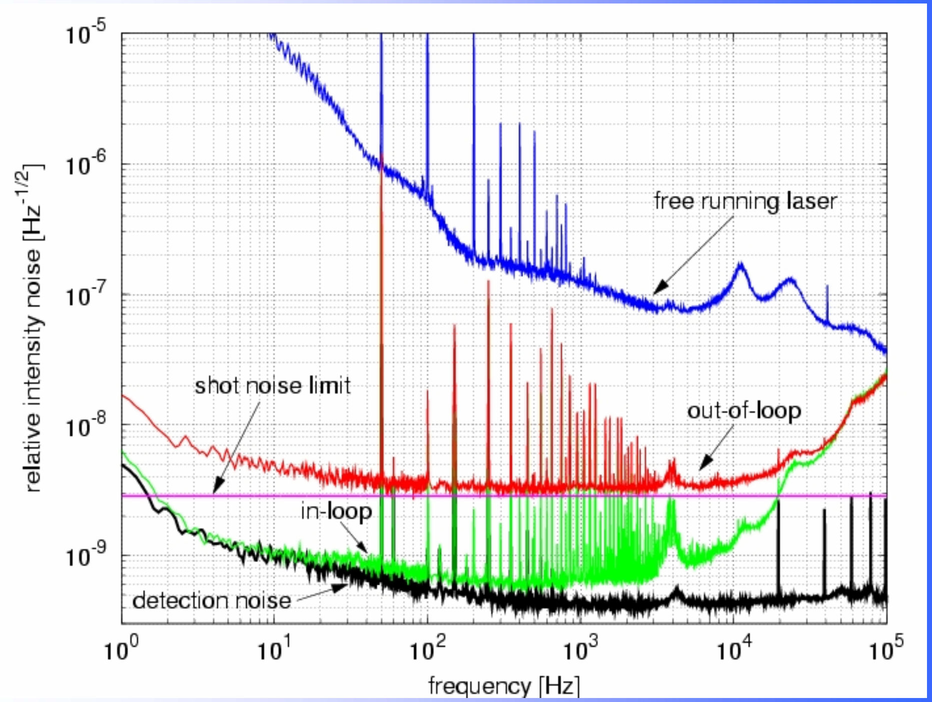


Advanced LIGO Nd:YAG Injection Locked End Pumped Rod Laser

- 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)
  - $10^{-8}/\sqrt{\text{Hz}}$ at 100 mHz
  - Set by AC radiation pressure
  - $10^{-6}/\sqrt{\text{Hz}}$ at 100 mHz shown by LIGO
  - If EOM before Fabry-Perot cavity, no reduction of RIN
- Frequency noise set by arm imbalance
  - ΔL = 1 m or better by using radio link
  - $\delta f / f = 10^{-3}$ Hz/$\sqrt{\text{Hz}}$
- Active frequency stabilization to the Fabry-Perot cavity
  - 0.3 Hz/$\sqrt{\text{Hz}}$ (limited by thermal noise)
  - Further reduction by stabilizing to arm
    - Proposed for LISA



Advanced LIGO Laser Relative Intensity Noise (RIN)

Thermal Noise and Materials Issues

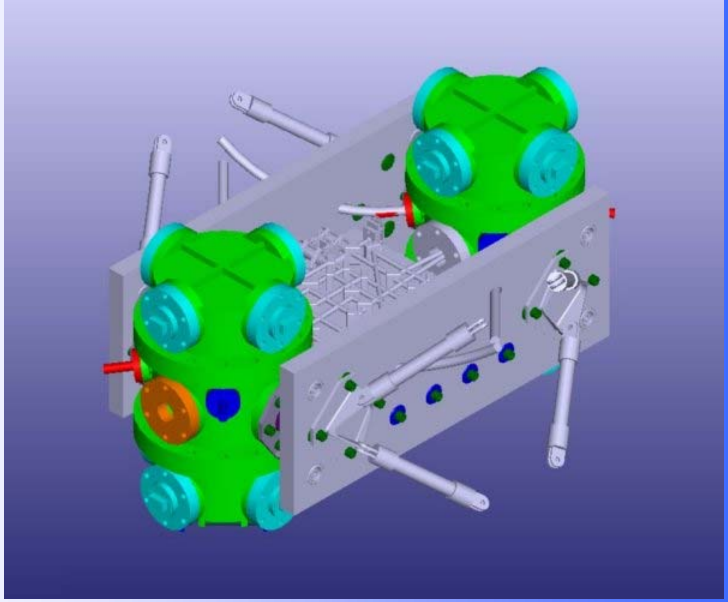
- Brownian motion of mirrors in cavity limits frequency stabilization
  - Mirror coatings crucial
- Need to use low mechanical loss coatings
  - Fluctuation-Dissipation Theorem
  - Mechanical loss causes Brownian motion
- Most metals have high mechanical loss
  - Gold/Platinum used by LISA
- Coating 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

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Conclusions

- Gravitational wave detection is a promising, emerging field
- Gravitational wave astronomy will open new window on universe
- Space based detectors are crucial to getting a full view of the gravitational wave sky
- Big Bang Observer will fill an important future roll
- Plan for how to do BBO interferometry
- Many technologies must be developed for successful BBO mission
- High power, low wavelength laser is crucial
  - P = 300 W
  - λ = 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