The Big Bang Observer (BBO)

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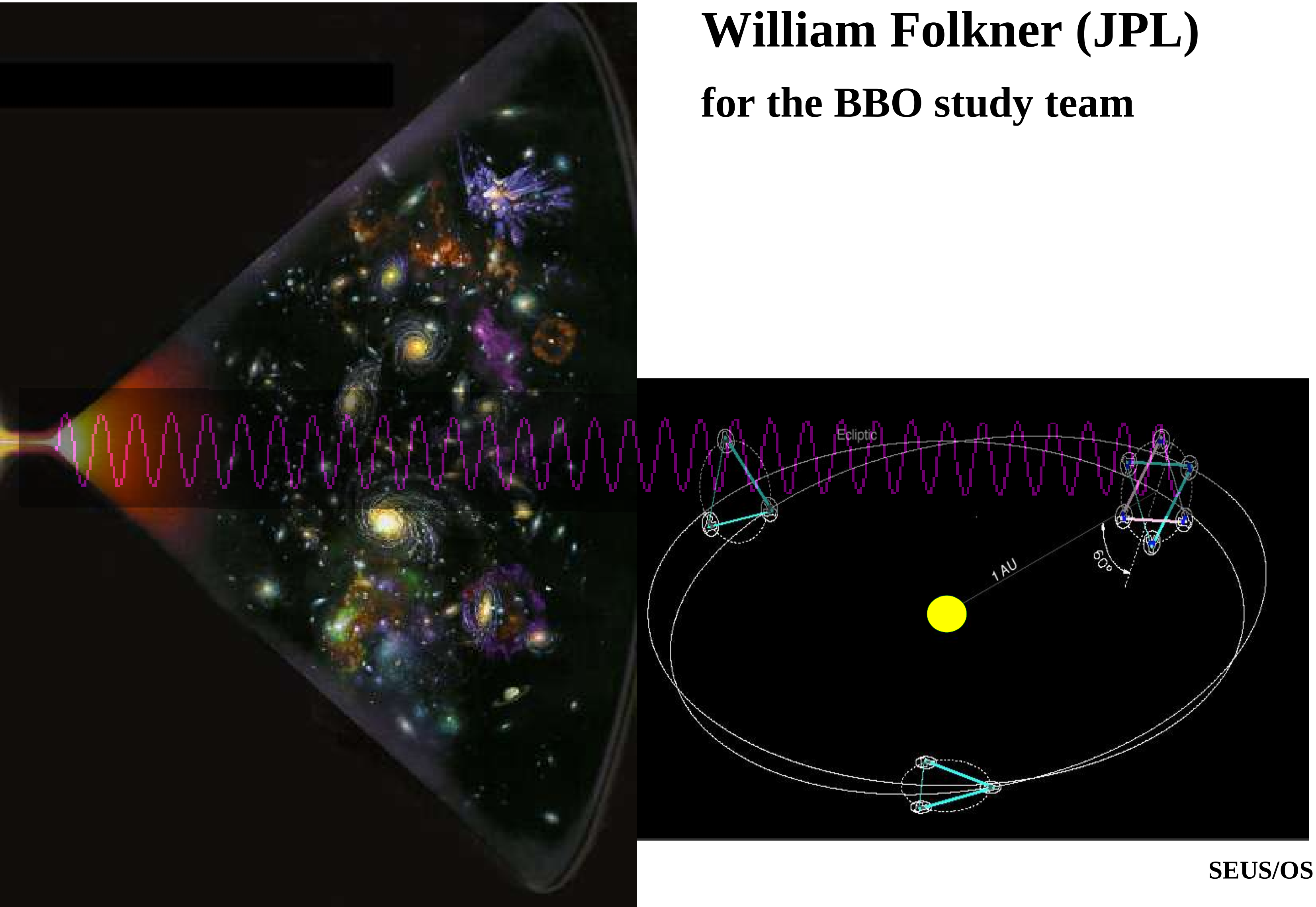
for the BBO study team



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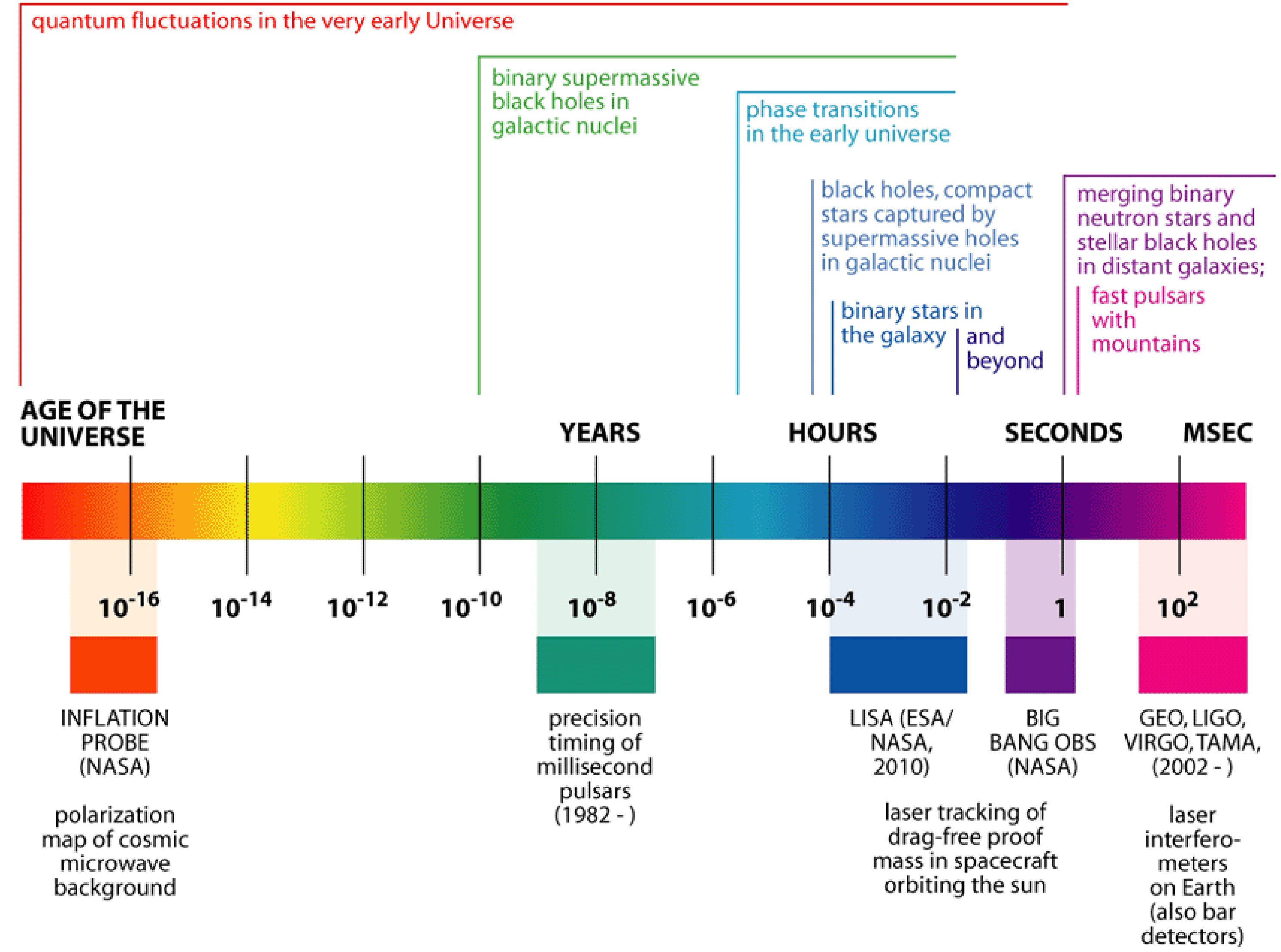
THE GRAVITATIONAL WAVE SPECTRUM



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 -)

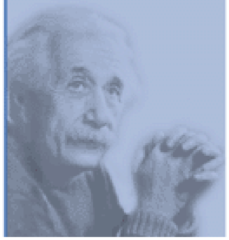
LISA (ESA/ NASA, 2010)

BIG BANG OBS (NASA)

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

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

laser interfero-meters on Earth (also bar detectors)

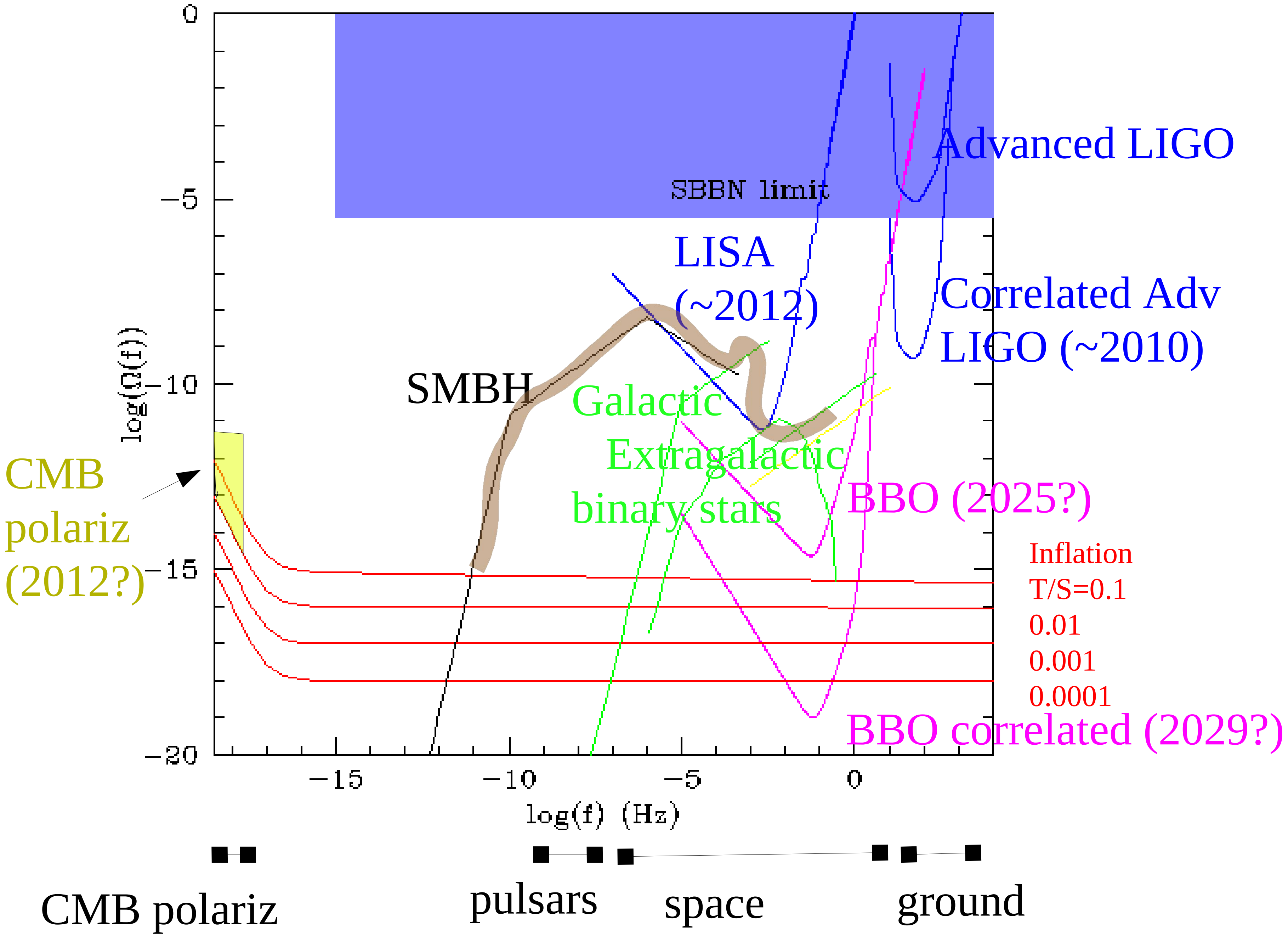


Design Goal: Big Bang Observer

- **Direct detection of gravitational waves due to quantum fluctuations in the pre-inflation universe, to $\Omega_{gw}(f) < 10^{-17}$.**

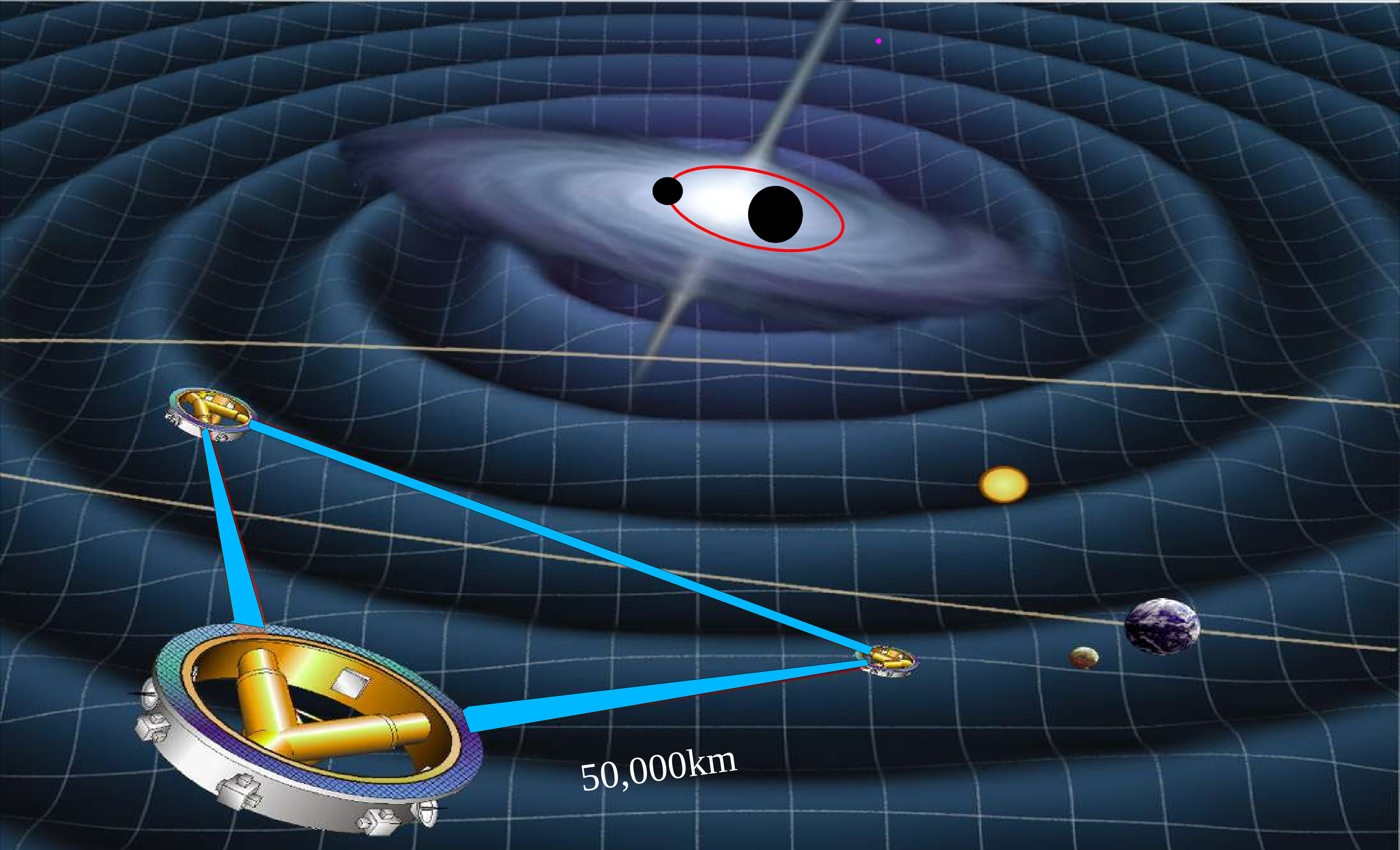
Consequences:

- $f \sim 0.5$Hz to avoid astrophysical foregrounds.
- Must correlate collocated pair of interferometers to reach desired Ω_{gw}
- Must measure and subtract astrophysical foreground sources from correlation.
- To do this, must get subarcsecond positions of short-lived sources.
- Requires multiple interferometers separated by ~1AU.


0
−5
−10
−15
−20
log(Ω(f))
−15
−10
−5
0
log(f) (Hz)
SBBN limit
Advanced LIGO
LISA
(~2012)
Correlated Adv
LIGO (~2010)
SMBH
Galactic
Extragalactic
binary stars
BBO (2025?)
Inflation
T/S=0.1
0.01
0.001
0.0001
BBO correlated (2029?)
CMB
polariz
(2012?)
CMB polariz
pulsars
space
ground

Instrument parameters: BBO vs LISA

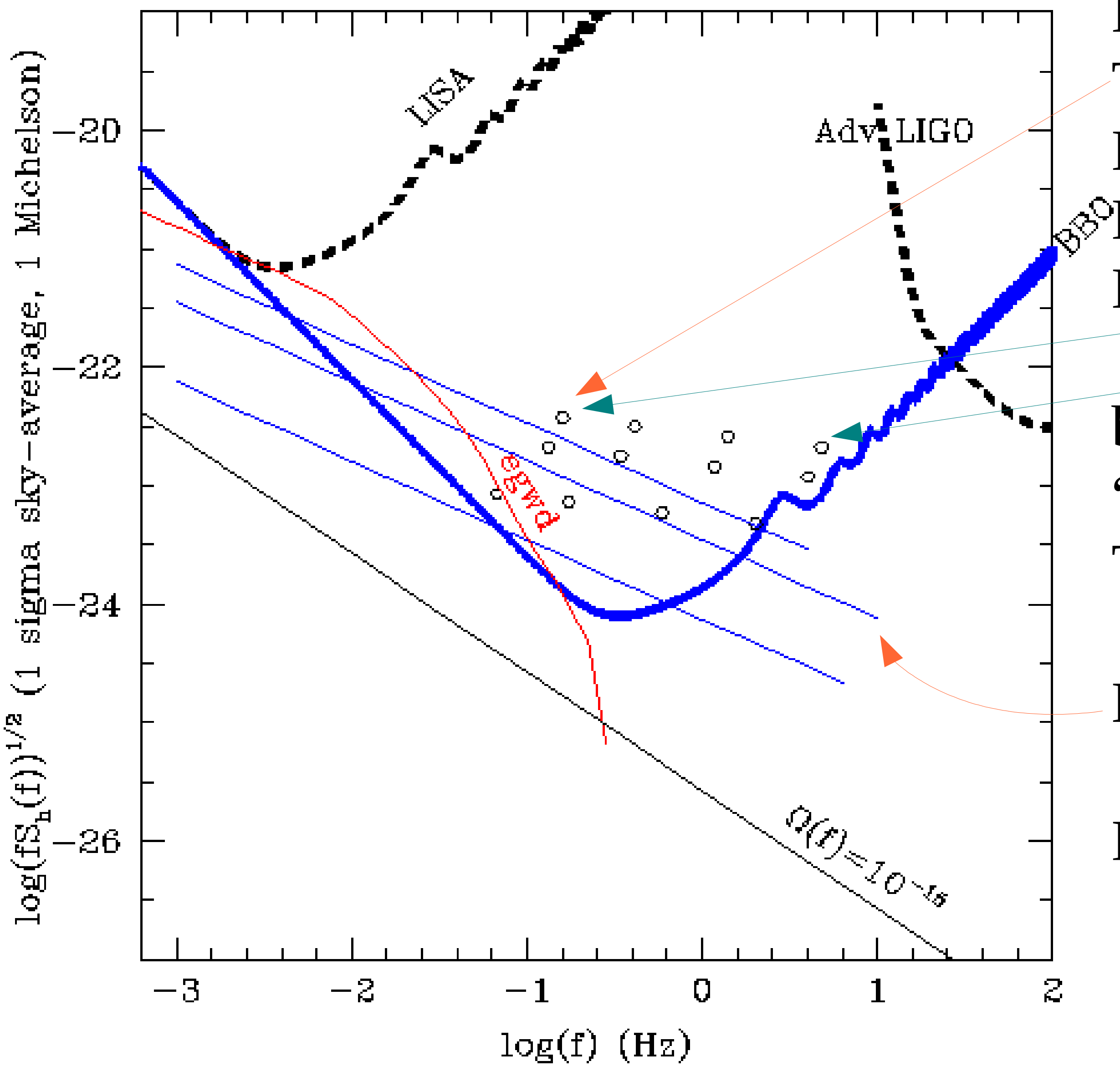
	BBO	LISA
Arm length L (km)	5×10^4	5×10^6
Laser Power L (W)	300	1
Laser λ (nm)	355	1065
Mirror diam D (m)	2.5	0.3
Accel. noise (m $s^{-2}Hz^{-1/2}$)	3×10^{-17} at 0.1 Hz	3×10^{-15} at 1mHz
Proof Mass M (kg)	~ 100	1.6
Interferometer op	dark fringe	fringe counting
Proof mass accel	3×10^{-10}m s^{-2}	0
$c/(2\pi L)$ (Hz)	1	0.01
Position shot noise (m $Hz^{-1/2}$)	1.5×10^{-17}	1.1×10^{-11}
Pointing stability req	10^{-12}rad $Hz^{-1/2}$	10^{-8}rad $Hz^{-1/2}$



BBO Stage 1: 3 Spacecraft, no solar plasma correction.

Goal: determine nature and number of sources in 0.1-1Hz

Design optimal arm length for Stage 2 correlated pair.



NS-NS mergers
Top circles: z=0.5
Middle: z=1
Bottom: z=5
L-R: 1y, 1 mo, 1d, 1hr

blue lines:
“backgrounds”
Top: high BH-BH
50,000/y <z=1
Middle: high NS-NS
200,000/y <z=1
Bottom: low NS-NS
8000/y <z=1

1yr bits in “background” at 0.1Hz~3x10^6 >(# sources x bits/source)

Resolvable into sources above ~0.1Hz!

BBO Stage 1: Sources

1)Last year of every merging NS-NS, NS-BH, BH-BH of stellar mass at $z<8$. ~1 arcmin positions. Months advance notice for gamma-ray bursts, LIGO.

2)<1% Precision luminosity distances to (1): ~10^4-10^5 sources

3)Measure dz/dt in galactic sources from stretching of chirp, gives H(z). Dark energy probe.

4)Detect acceleration in globular cluster sources: can distinguish them from the galactic ones.

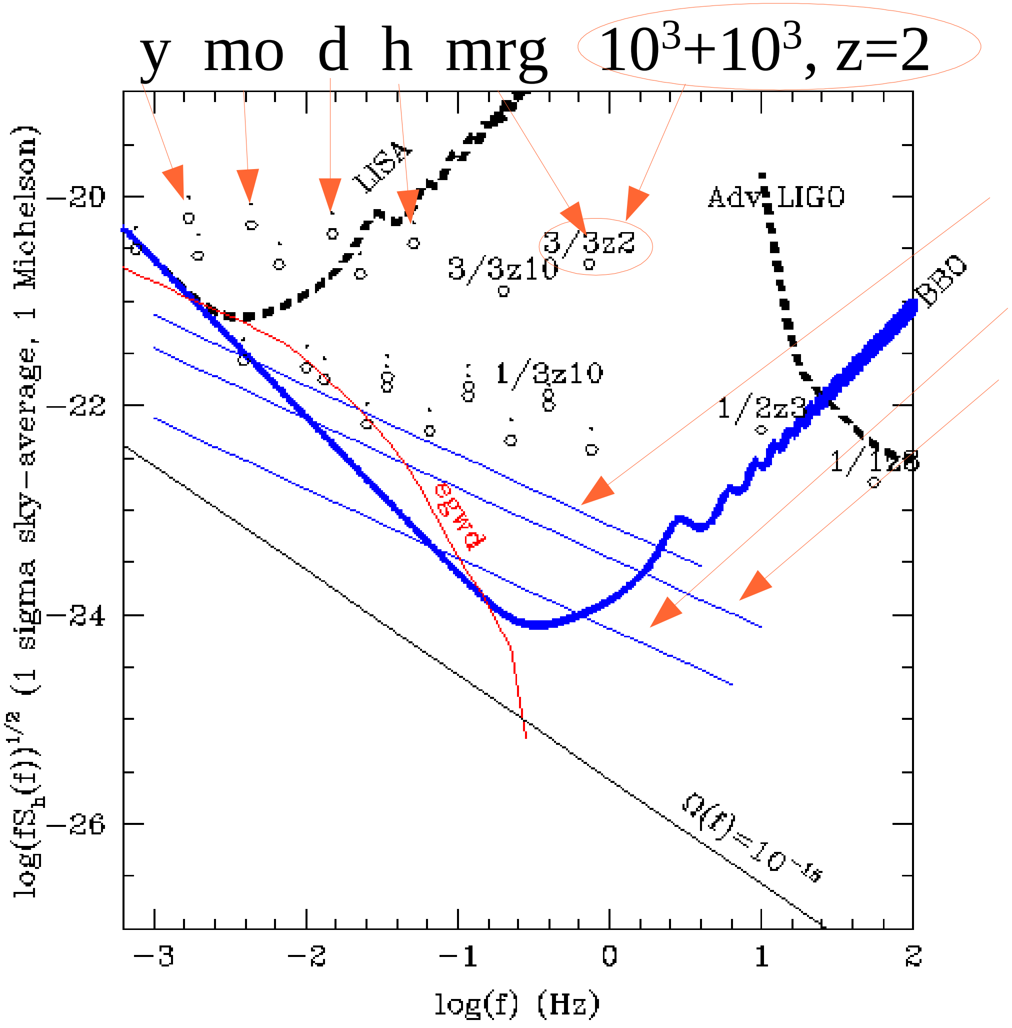
5)All mergers of intermediate mass BH at any z.

6)Type Ia supernova (rapidly rotating WD explosion) at D<1Mpc (1/25 yrs).

7)1Hz pulsars with nonaxisymmetric internal $B>3\times10^{14}$G, r<1kpc.

8) Cosmic/Superstrings over entire allowed range $G\mu/c^2>10^{-14}$

Stellar and Intermediate Mass BH mergers



- Advanced LIGO local event rates will predict for BBO:

Adv LIGO 10$M_\odot$ BH 50,000/y

Adv LIGO NS-NS 60/y

Adv LIGO NS-NS 4000/y

- Need BBO to study evolution at z>1. Get 500x more events/y (NS-NS), 1-10x more/y (BH)
- BBO stage 1: measure rates and redshift evolution; determines optimal arm length/design for BBO stage 2
- BBO stage 2 will give <1arcsec positions.

Gravitational waves from Cosmic Strings

from some GUT theories and some* superstrings

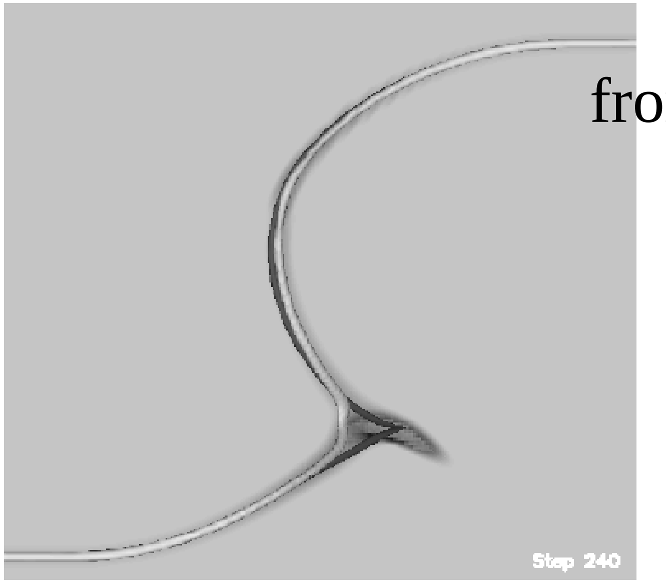
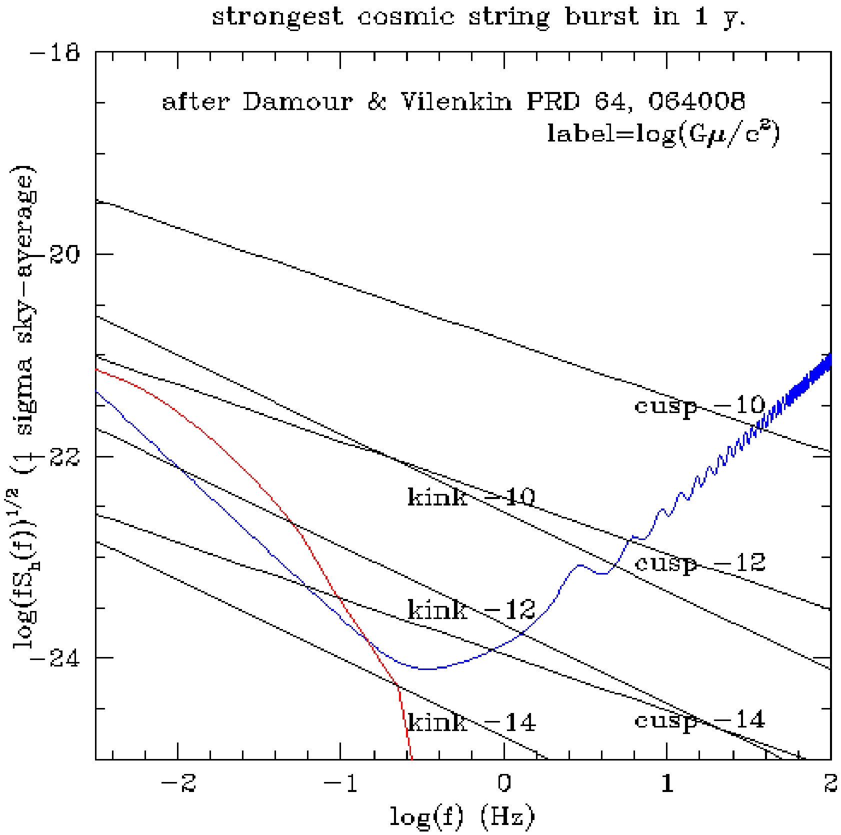


FIG. 7. String evolution at the cusp for $L \approx 17$. The core of the string in the field theory simulation is shown light, and the Nambu-Goto prediction dark. The "fog" shows areas of high energy density. The string core has collapsed away from the point of the cusp, leaving the energy behind in radiation.



Olum & Blanco-Pillado Phys.Rev. D60 (1999) 023503

*See Polchinski, hep-th/0312067, hep-th/0405229: characteristic of braneworlds with warp. In models w/ brane inflation that reproduce CMB, $10^{-12}<G\mu/c^2<10^{-6}$

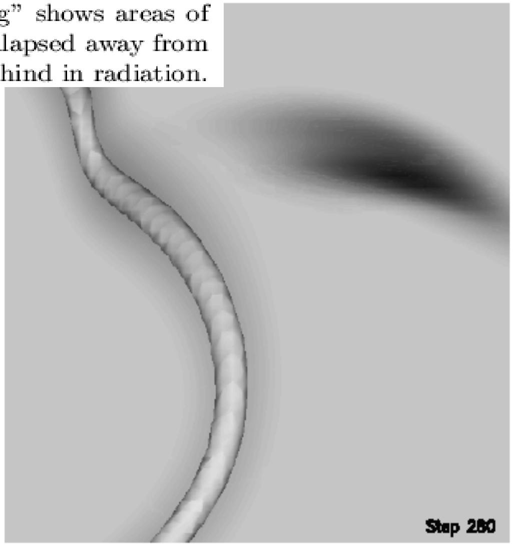


FIG. 9. Close-up view of the core of the string and the radiation after the cusp evaporation. The cloud of radiated energy travels in an expanding shell.

BBO will constrain cosmic string cusps/kink radiation: to $G\mu/c^2<10^{-14}$

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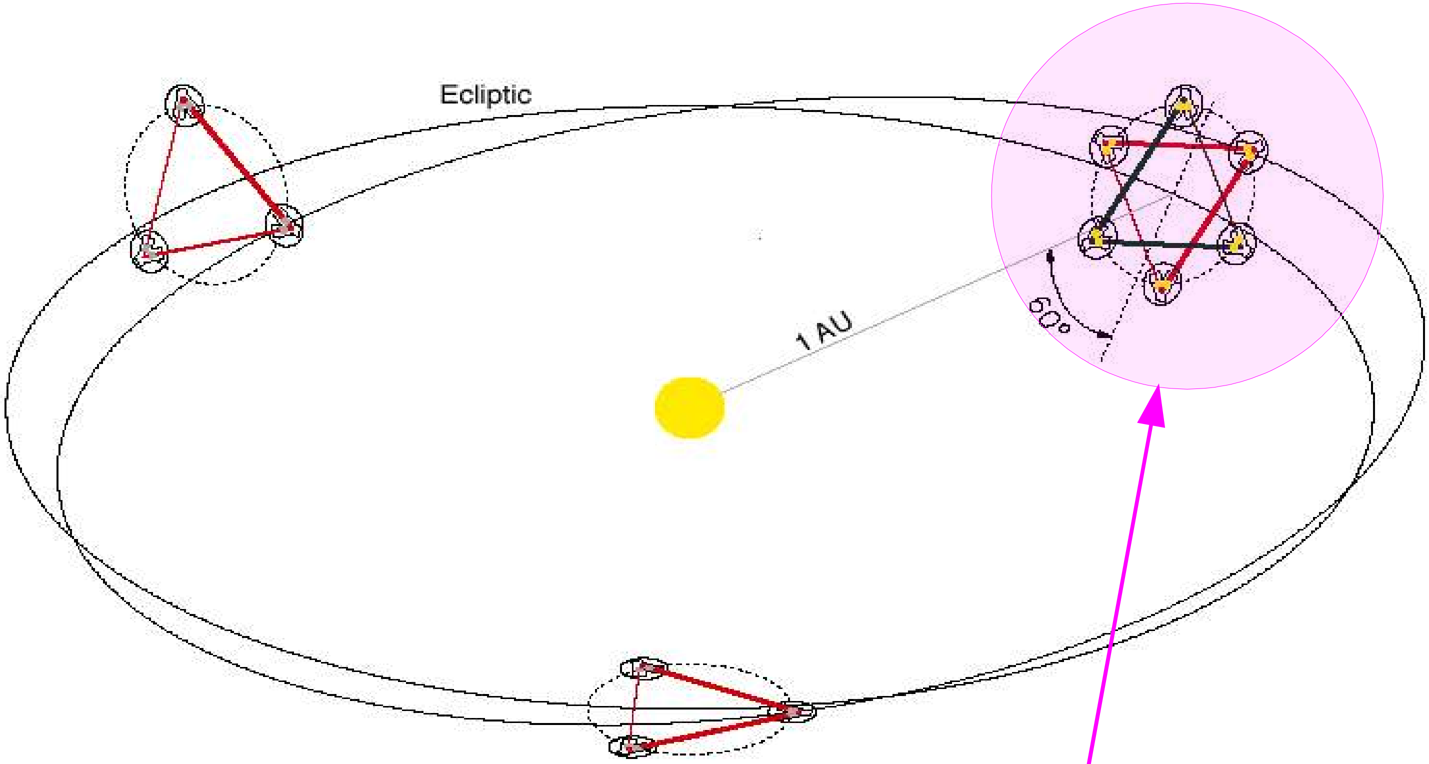
BBO stage 2: orbit



- **Overlapping pair for correlation to seek isotropic inflation background**

Two independent interferometers 1,2 separated by $1/(2\pi)$ gravitational wavelengths. If aligned, are sensitive to same sources & polarization. Then gravitational wave signals $s_1(t)$ and $s_2(t)$ are correlated, $s_1(t) \simeq s_2(t)$. In single interferometer, signal is undetectable if much less than measurement noise $\langle s_i^2 \rangle \ll \langle n_i^2 \rangle$. But if all sources of measurement noise $n_1(t)$ and $n_2(t)$ are uncorrelated,

$$\int_0^T (s_1 + n_1)(s_2 + n_2)\, dt \simeq \langle s_1^2 \rangle T$$

while the standard deviation of the noise contribution to the integral at frequency f is $\sim (\langle n_1^2 n_2^2 \rangle f T)^{1/2}$.

So in long integration, can detect signal with

$$\frac{s^2}{n^2} > \frac{1}{(fT)^{1/2}}$$

So the sensitivity to $\Omega_{gw} \propto s^2$ scales as $(fT)^{-1/2}$.

More precisely

$$SNR^2 = \frac{81H_0^4}{800\pi^4} T \int_0^\infty \frac{|\gamma(f)|^2 \Omega_{gw}^2(f)}{f^6 S_{n1}(f) S_{n2}(f)}\, df$$

where $\gamma(f)$ (~ 1 for $f < f_* = c/(2L\pi) = 1\text{Hz}$, ~ 0 for $f > f_*$; for detailed form see Cornish & Larson 2001, Class Quant Grav 18, 3473) is the overlap-reduction function for a pair of equilateral-triangle interferometers in star-of-David configuration.

For two correlated BBO, this gives

$$\Omega_{gw} = 1.1 \times 10^{-17} T_{yr}^{-1/2} (\text{SNR})$$

with most of the contribution coming from 0.1-0.5 Hz.

Correlated noise?

- Correlation only works if the noises in the 2 interferometers are uncorrelated.
- refractive index fluctuations in turbulent solar wind plasma appear as correlated optical-path variations, and are > correlated sensitivity. Remove by adding radio interferometry to measure plasma.
- Appears feasible to mitigate other sources of correlated noise:
  - Correlated charging of proof mass due to solar wind's modulation of cosmic ray flux.
  - Magnetic remnance in proof mass due to correlated time-varying magnetic field gradients in solar wind.
  - Thermal and solar radiation pressure fluctuations (can isolate through spacecraft)

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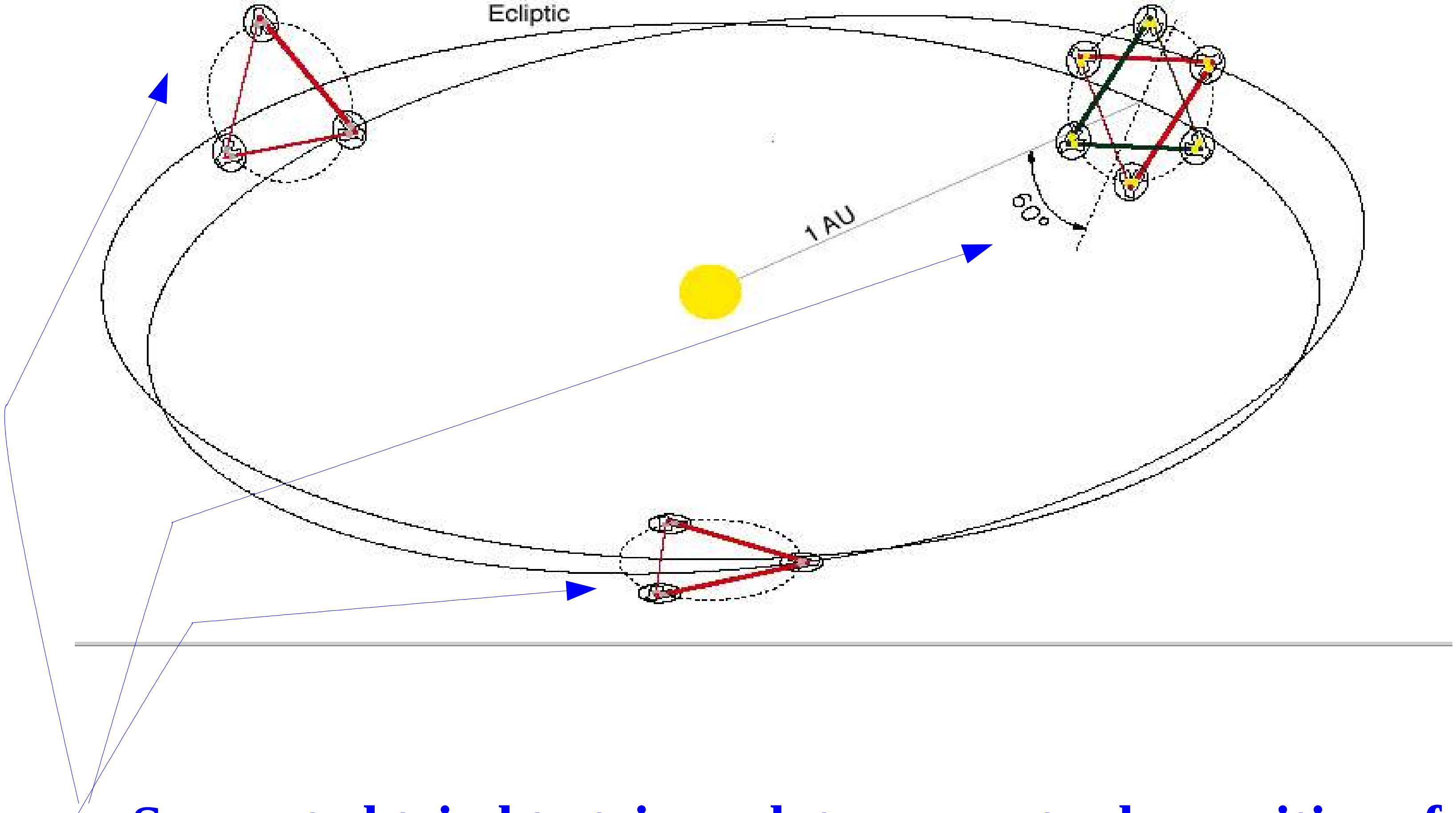
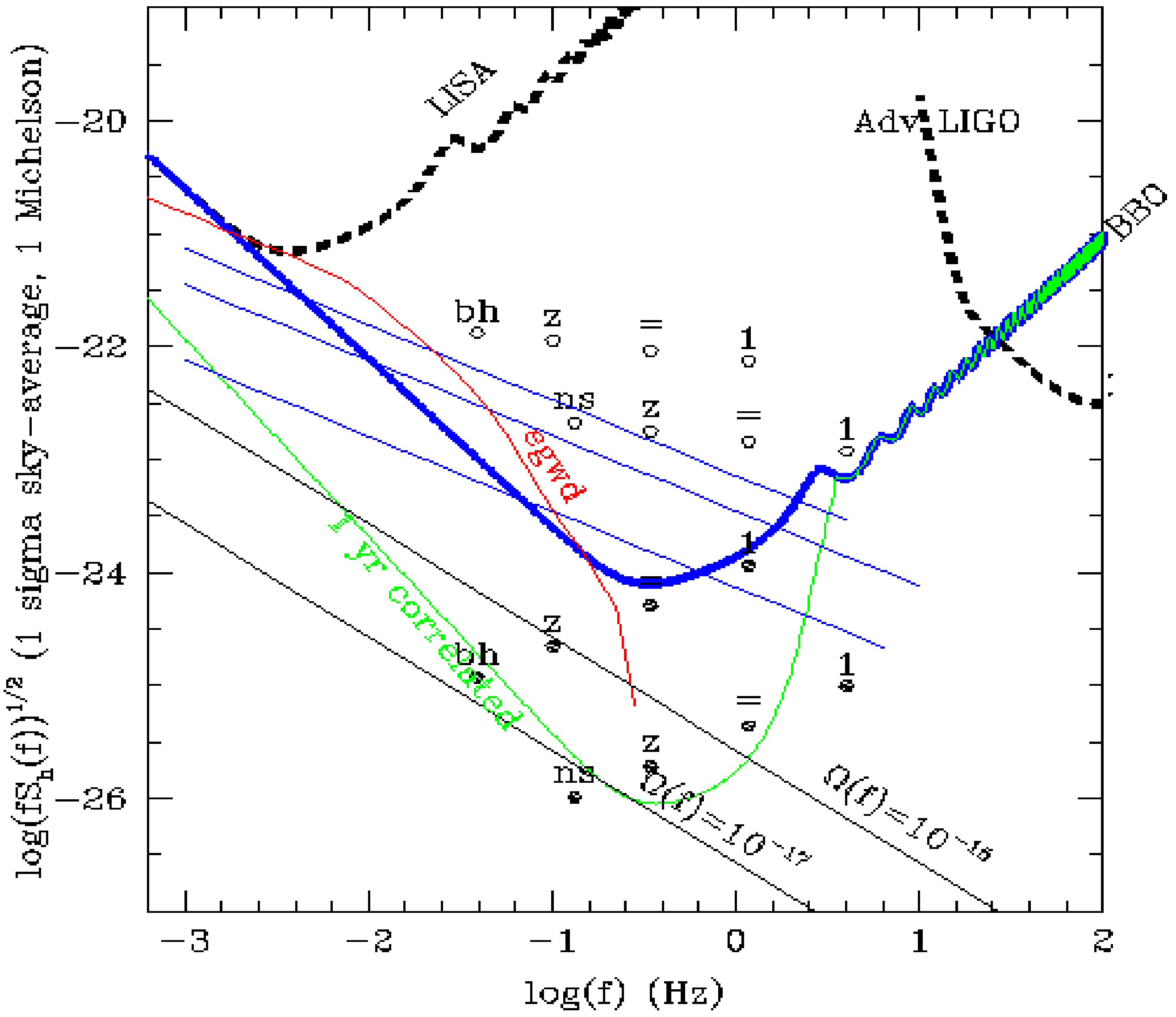


- Separated triad to triangulate accurate sky positions for short-lived sources. All Stage 1 sources now get <1 arcsec positions.

NASA vision BBO burst sensitivity curve
Can remove foreground sources to reach correlated sensitivty



Upper blue:
Background from
BH merger rate

Middle blue:
Background
From High NSNS
Merger rate

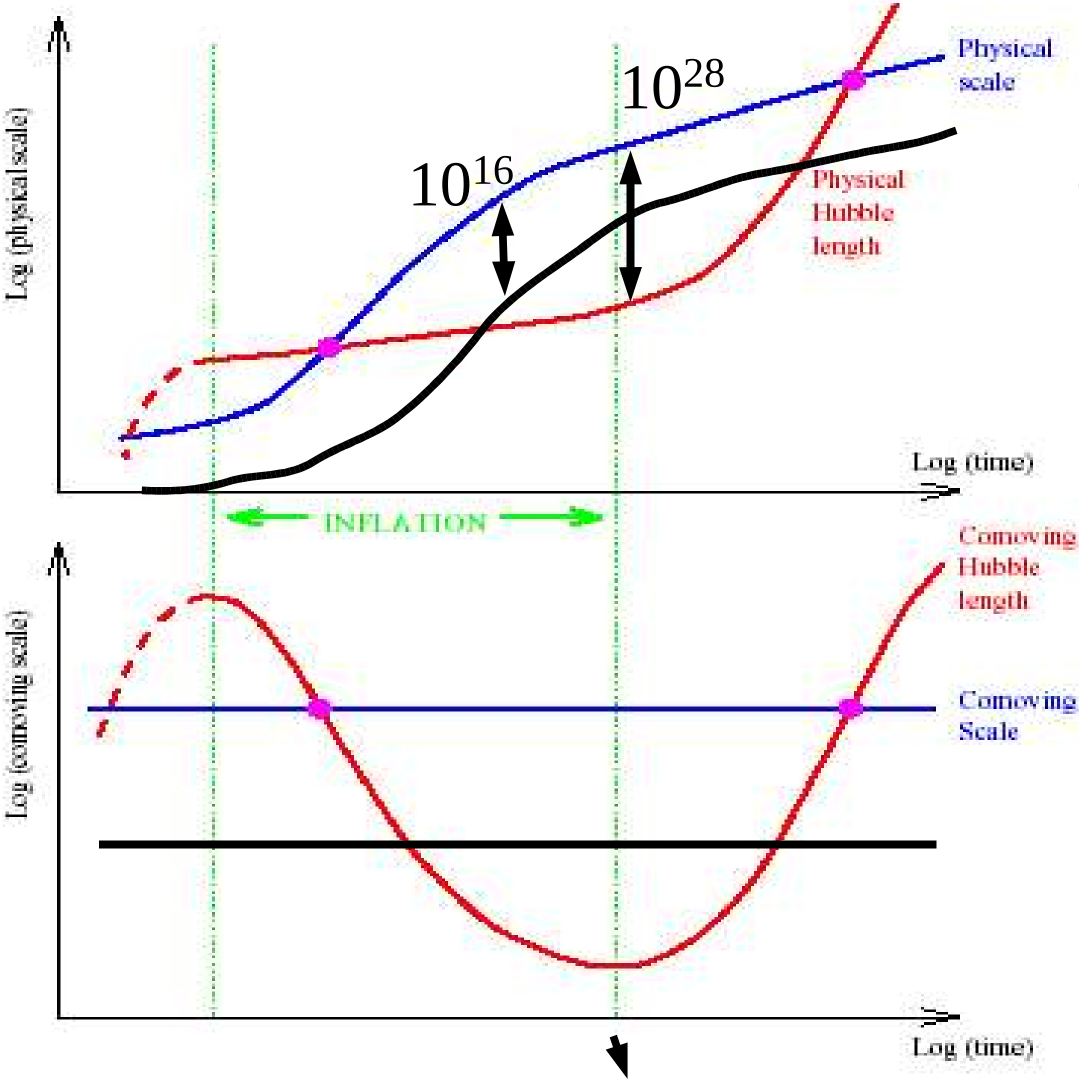
Lower blue:
Background from
Standard NSNS
Merger rate.

Open circles:
Coherent SNR

Closed:
Instantaneous SNR
(t~1/f).

Astrophysics with Stage 2 BBO

- subarcsecond positions of burst sources (e.g. cosmic strings, type Ia and type II supernovae...): electromagnetic followup.
- subarcsecond positions of all merging NS, BH, IMBH:
  - are they in star formation regions?
  - in clusters, halos, galactic nuclei? (IMBH made by PopIII, or merging in dense star clusters [cf Miller, Rasio, Morris, Portegies-Zwart...])
  - neutron star recoil, gravitational wave recoil?



(CMB)

(BBO)

(CMB)

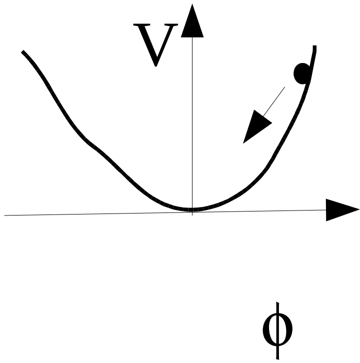
(BBO)

$10^{-38}\mathrm{s}\ (10^{16}\mathrm{GeV}/V_{\mathrm{inf}}^{\ 1/4})^2$

Universe today $\sim 2ct \sim 10^{28}$cm across.

At $t \sim 10^{-37}$s ($kT \sim 10^{16}$GeV), today's universe was $\sim$ 10cm across. Yet horizon size was $2ct \sim 10^{-26}$cm. Causality, monopole problem.

Inflation: false vacuum



$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\rho_V = \text{const}$$

So $a \propto \exp(\sqrt{G\rho_V}\, t)$.

Need to expand 10^{-26}cm to at least 10cm, i.e. factor greater than $10^{27} = e^{62}$.

Single scalar field slow roll inflation:

$$H^2 = \frac{8\pi}{3m_{pl}^2}[V(\phi) + \dot{\phi}^2/2]$$

$$\ddot{\phi} + 3H\dot{\phi} = -V'(\phi)$$

Number of e-foldings

$$N = ln(a_f/a_i) = \int_{t_i}^{t_e} H\,\frac{dt}{d\phi} d\phi = \frac{8\pi}{m_{pl}^2}\int_{\phi_e}^{\phi_i} \frac{V}{V'}\,d\phi$$

Variance of density fluctuations S and grav waves T in CMB quadrupole

$$S \sim \frac{1}{m_{pl}^6} \frac{V^3}{(V')^2} \tag{1}$$

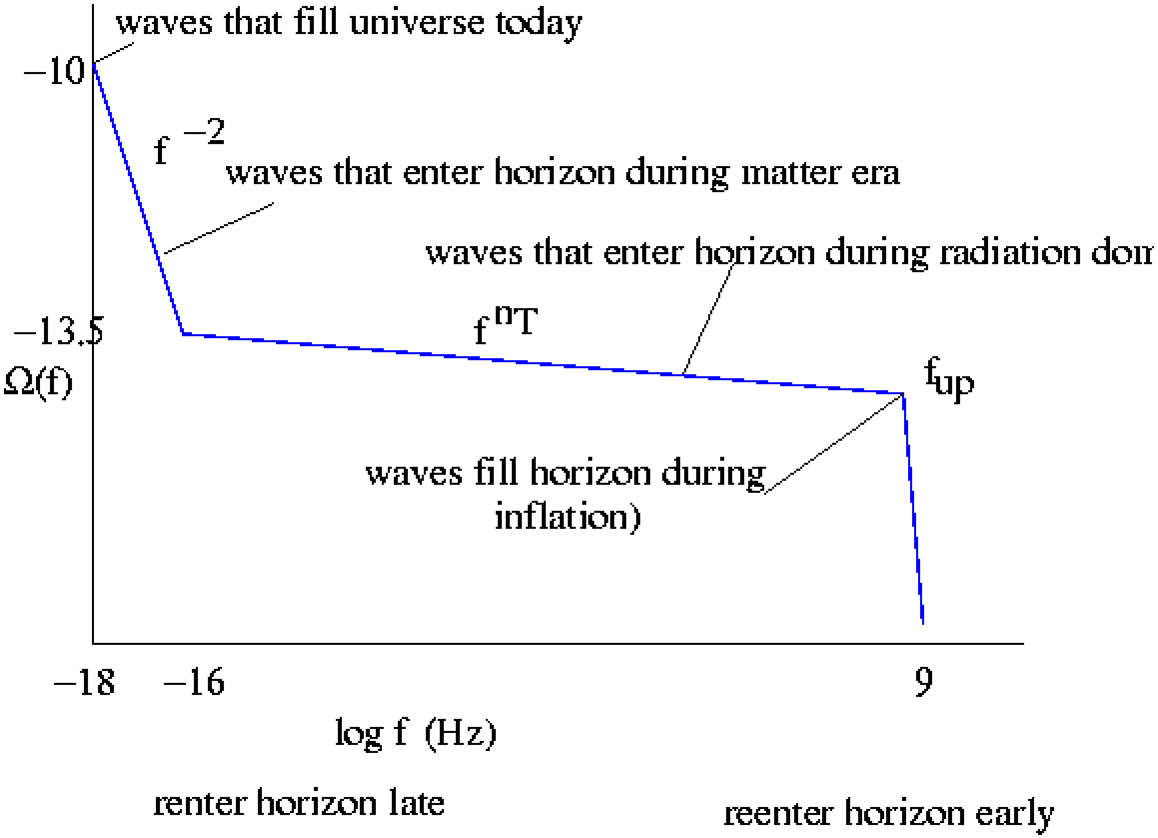
$$T \sim V/M_p^4 \propto \Omega_{gw}(f) \tag{2}$$

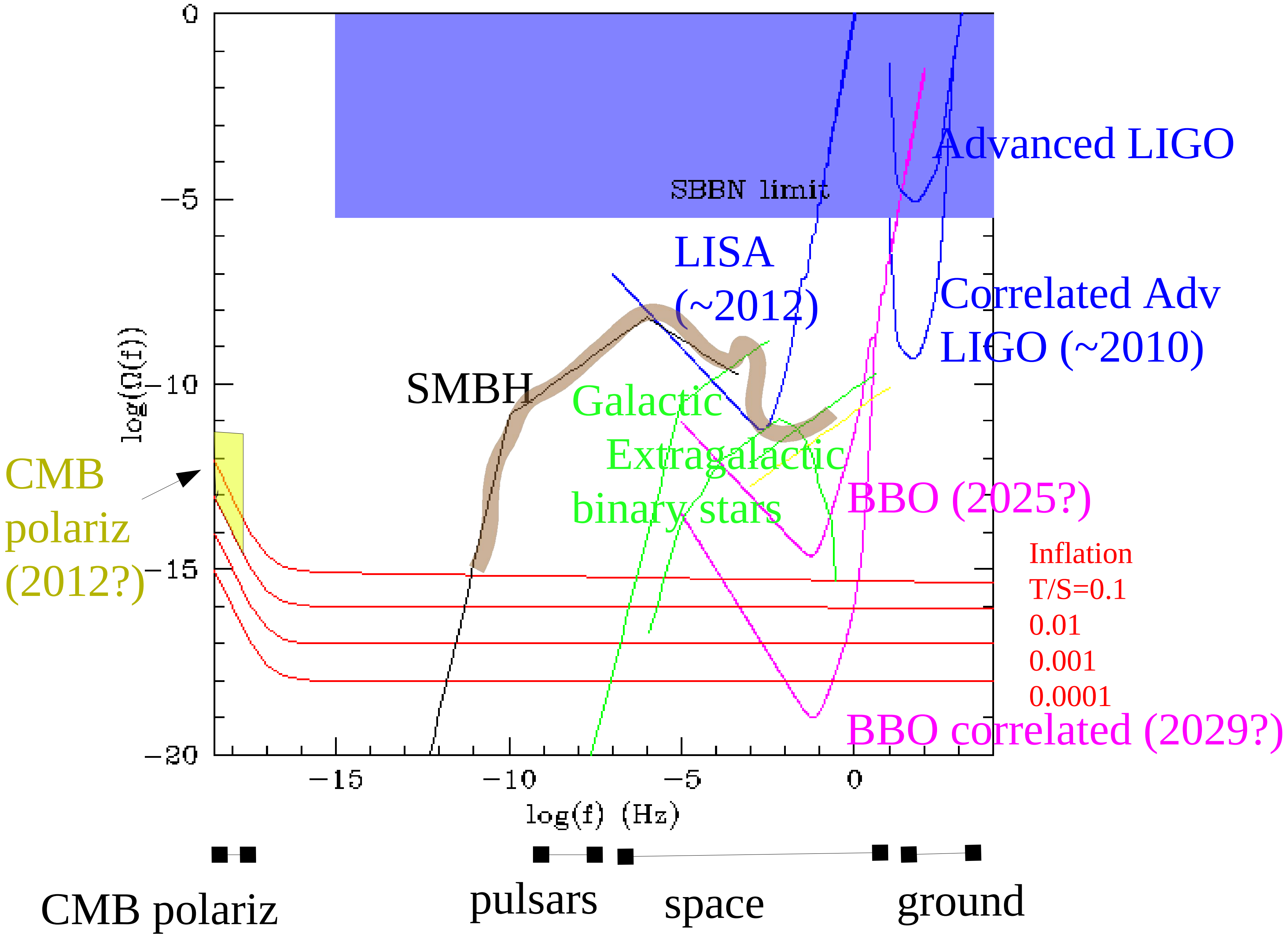
Consistency condition: same roll down V that determines S also sets difference in T as function of gravitational wavelength (horizon size when leaves horizon):

$$d\ln\Omega_{gw}/d\ln k = -\frac{1}{8}\frac{T}{S} \ll 1$$

With Ω_{gw} (CMB B-mode), Ω_{gw} (1Hz), CMB scalar, Can do consistency check of single-scalar slow-roll inflation.

Alternative inflation models (hybrid, natural, braneworlds, etc), can have quite different relations (including blue spectra, undetectably low Ω_{gw}, etc).


waves that fill universe today
−10
f^{-2}
waves that enter horizon during matter era
waves that enter horizon during radiation dom
−13.5
$\Omega(f)$
f^{n_T}
f_{up}
waves fill horizon during inflation)
−18
−16
9
log f (Hz)
renter horizon late
reenter horizon early


0
−5
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log(Ω(f))
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0
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SBBN limit
Advanced LIGO
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T/S=0.1
0.01
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pulsars
space
ground

BBO: the Big Bang Observer

NASA-funded vision mission (launch ~2025?) under study.

- Stage 1: 3 spacecraft. Stage 2: 12 spacecraft in 3 groups (3,3,2x3). Correlate outputs of 2x3.
- $5\text{x}10^4$ km =b arms (1/100 LISA)
- 2x300W lasers/sc, $0.35\mu\text{m}=\lambda$ (freq tripled (70%) diode pumped NdYAG or fiber laser (30%): 2.8kWe power, 2.3kWth dissipated.
  - plus microwave or 1μm lasers to correct for phase fluctuations due to solar wind plasma.
- 2.5m =d mirrors (~ HST). Fresnel $N=(d/2)^2/(b\lambda)=0.09$
- 0.01 LISA acceleration noise (scaled as white from 0.001Hz to 0.1Hz) at 0.1-3 Hz. `Easy'?
- Distant spacecraft receives 18W, requires large proof mass to avoid heating.
- Probably stationkeep to dark fringe rather than free flying like LISA. Proof mass acceleration to keep on fringe $\sim 3\text{x}10^{-10}$ m $\text{s}^{-2.}$ (apply out of band, like LIGO!)

Mission Characteristics

- **Each spacecraft payload contains;**
  - **One test mass (hexagonal cross-section)**
    - **Optical position readout and forcing for drag-free control**
  - **Two telescopes 2.5 m diameter**
  - **Two lasers (wavelength 355 nm, power ~ 300W)**
  - **Two radio antennas for plasma calibration**
    - **Measure apparent change in range between spacecraft**
    - **2.5 m diameter, 200 W RF power (each frequency)**
  - **Micro-propulsion system**
    - **Counter force of sunlight on spacecraft**

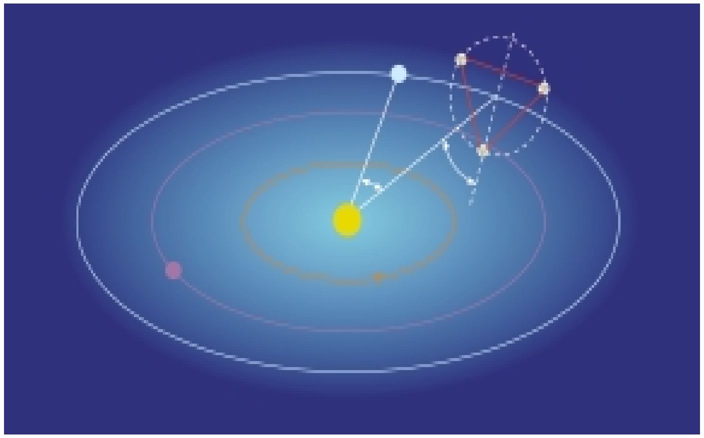
Shot Noise Limit

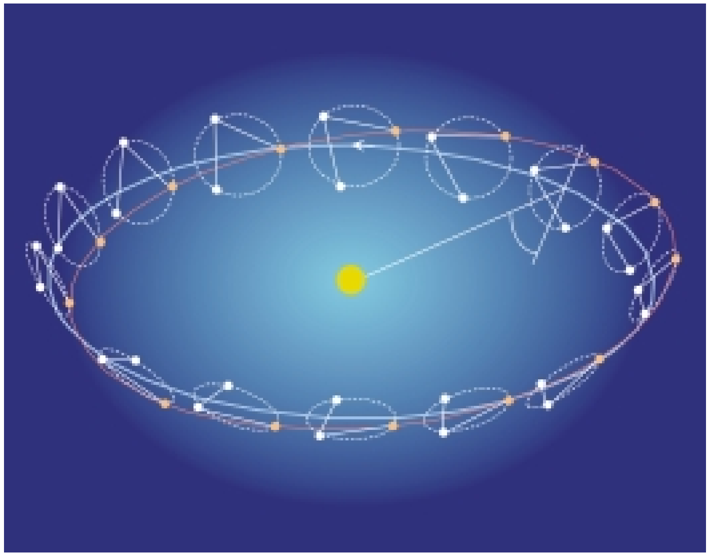
$$\sqrt{S_x} \approx 1.5 \times 10^{-17} \left(\frac{\lambda}{355 nm} \right)^{3/2} \left(\frac{0.4 \times 300 W}{\varepsilon P_L} \right)^{1/2} \left(\frac{L}{5 \times 10^7 m} \right) \left(\frac{2.5 m}{D} \right)^2 m / \sqrt{Hz}$$

- **Mirror diameter chosen to fit two within 5 m fairing**
- **Wavelength for Nd:YAG laser with frequency tripling**
- **Efficiency of 0.4 compatible with UV photodiodes**
  - **Assuming operation on dark fringe**
  - **May require development of beam splitters and modulators**
- **300 W of laser power based on lab demonstrations at 1064 nm**
  - **Frequency tripling to that power level represents extrapolation**

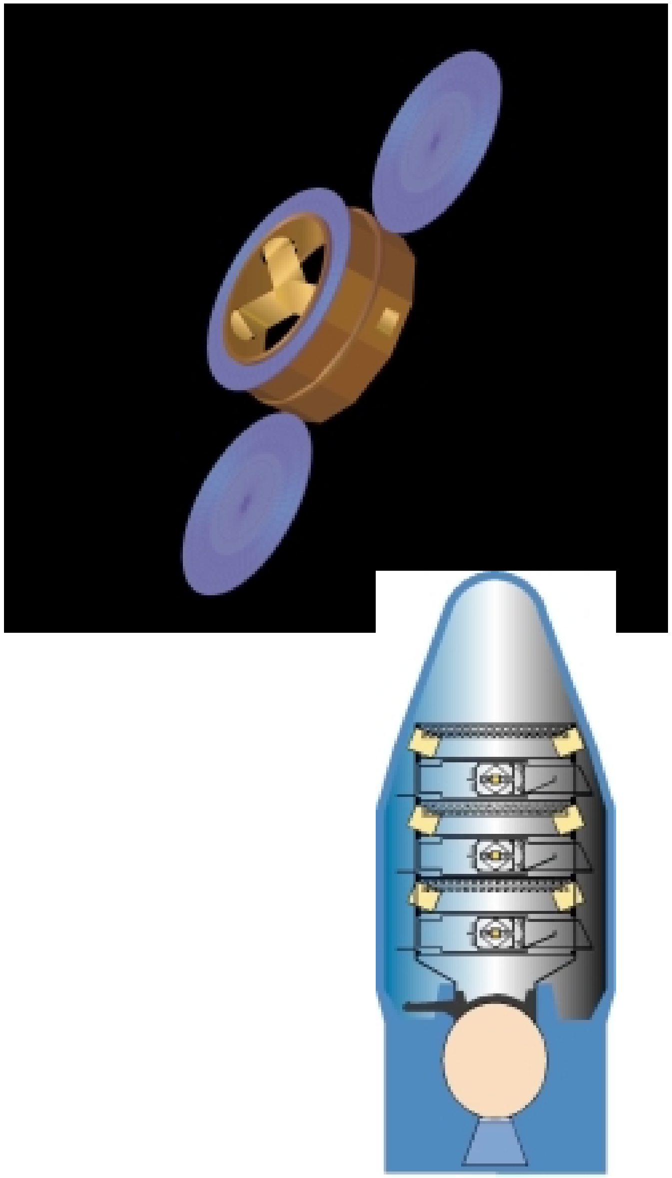
Orbit Considerations

- Orbits are chosen so that individual elliptical orbits about sun form a triangle with nearly constant lengths
- Test mass orbits are controlled (at low frequencies) to force equality of arms lengths
  - Interferometer kept on dark fringe
  - Single test mass with 60 degree facets
  - Pointing change smaller than beamwidth
- Control acceleration small
  - Due to shorter arm lengths
  - <1 nm/s^2 required
    - which is allowed uncertainty for LPF
    - Need to investigate for BBO



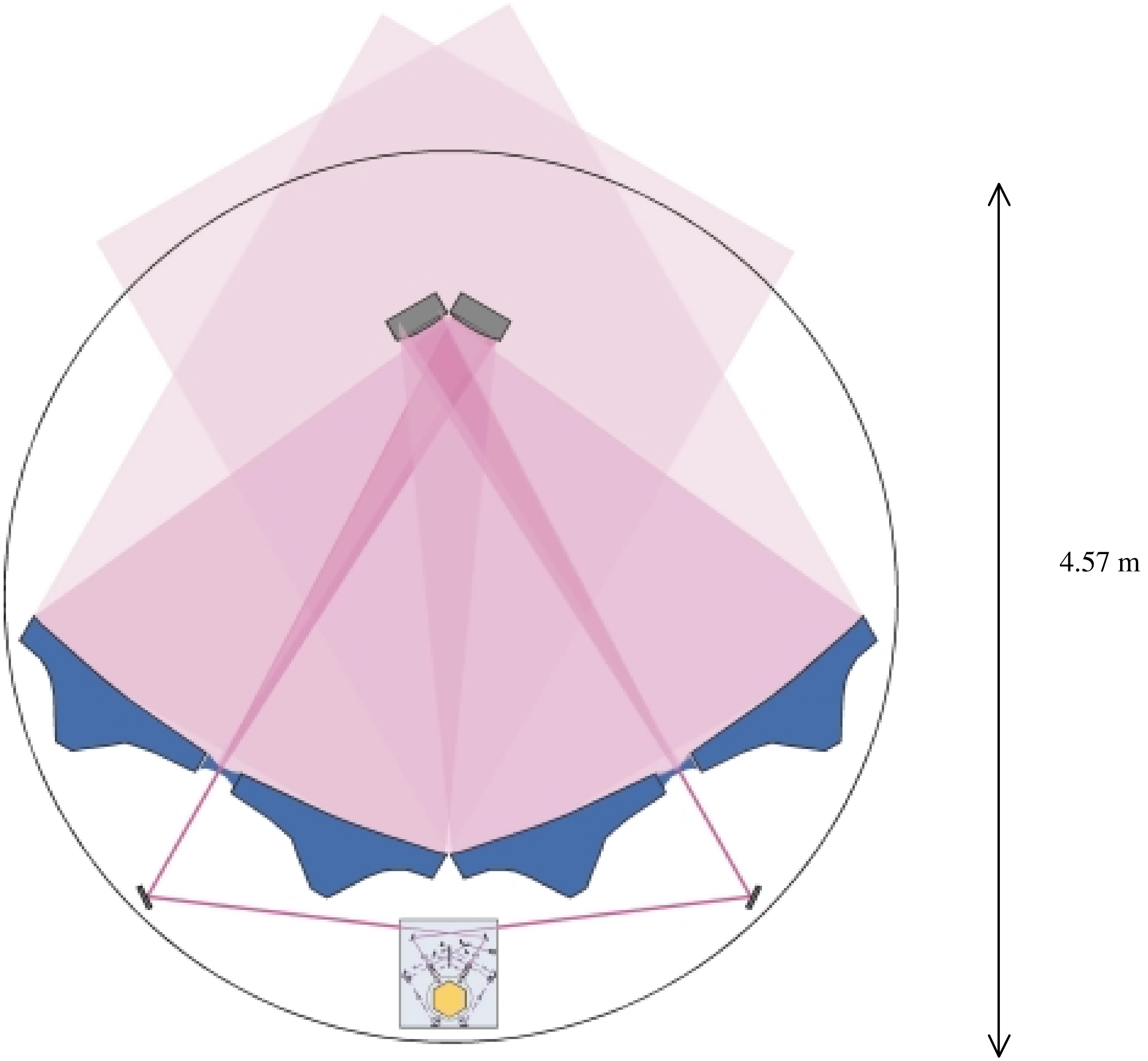


Possible Spacecraft Configuration

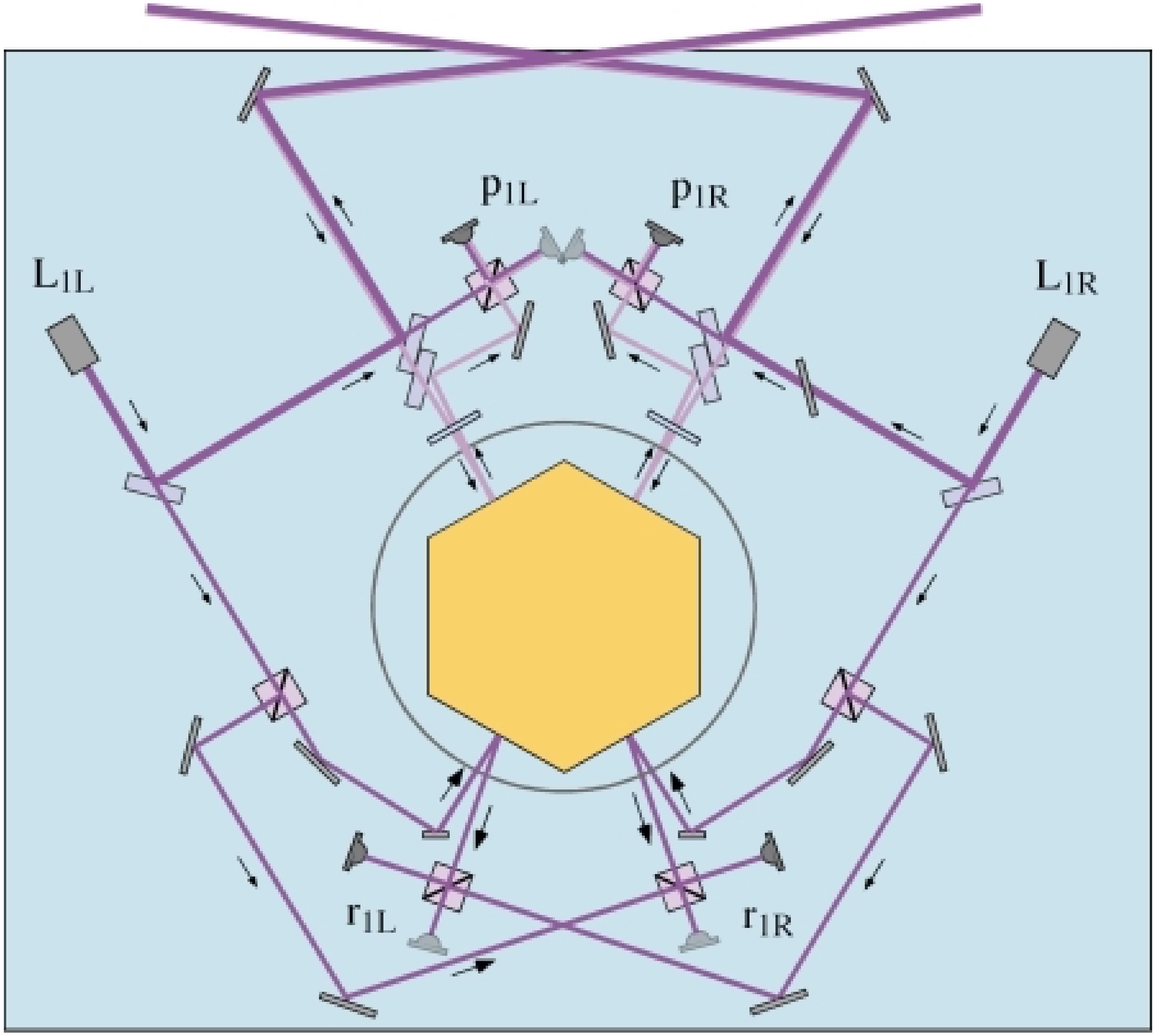


- Configuration may be similar to LISA
  - Desirable to launch three spacecraft in single 5 m fairing (4.57 m diameter)
- Two telescopes in cylindrical section
    - 2.5 m, f/1.4
- Radio calibration system and spacecraft support equipment in second cylindrical section
  - 2.5 m antenna for s/c-s/c ranging
- Deployed solar arrays
  - Power for laser
  - Xe ion engine for orbit insertion
    - Cooling system may be challenge

Telescope Configuration



Optical Bench/Test Mass



Interferometer Signals

- 4 primary signals from interferometer
  - One used to lock lasers together
  - One used to control position of test mass
    - In direction bisecting directions to other two spacecraft
  - One used to control position of spacecraft
    - In direction bisecting directions to other two spacecraft
  - One used to lock laser
    - To arm length (Master)
    - To laser from Master (Slaves)
- All kept on dark fringe
- Transverse positions signals not shown;
  - Interferometer pointing signals
  - Auxiliary test mass readout interfereomters

Radio Link Budget

	A	B	C	D
1	**Transmitter Parameters**			
2		RF Power, dBm	53.01	
3		*(Watts)*		200.00
4		Transmit Circuit Loss, dB	0.00	
5		Antenna Circuit Loss, dB	0.00	
6		Antenna Gain, dBi	43.77	
7		*Antenna diameter, m*		2.50
8		*Wavelength, cm*		3.60
9		*Efficiency*		0.50
10		Pointing Error, dB	0.00	
11	**Path Parameters:**			
12		Space Loss, dB	-204.84	
13		*Range, km*		50000.00
14	**Receiver Parameters:**			
15		Polarization Loss, dB	0.00	
16		Antenna Gain, dBi	43.77	
17		*Antenna diameter, m*		2.50
18		*Efficiency*		0.50
19		Noise Spectral Dens, dBm/Hz	-173.83	
20		*System Temp, K*		300.00
21	**Power Summary:**			
22		Received Power, dBm	-64.30	
23		Received Pt/N0, dB-Hz	109.53	
24		SNRV(1-sec)	423835.40	
25		Range noise, m/sqrt(Hz)	8.49E-08	
26		Range noise @ UV, m/sqrt(Hz)	8.21E-18	

Power Budget

effective laser power (W)	120	each arm
optical efficiency	0.4	
laser power (W)	600	for both arms
tripling efficiency	0.7	
pump efficiency	0.3	
laser electrical power (W)	2857	
x-radio system power (W)	400	50% efficiency
ku-radio power (W)	600	33% efficiency
electronics power (W)	200	
micro-prop power (W)	100	
spacecraft power (W)	1000	
Total	5879	
Margin	2000	
array power (W)	7,879	26%
solar panel efficiency	0.28	
array area needed (m^2)	21	

Micro Propulsion System

array area (m^2)	21
force on spacecraft (uN)	142
drive thrusters (uN)	200
counter thrust (uN)	40
total thrust (uN)	241
Total w redundancy (6/4)(uN)	361
specific impulse (s)	500
mission duration (years)	5
propellant mass (kg)	12
propellant tank mass (kg)	2
thruster mass/cluster (kg)	15
#clusters	6
Thruster mass total (kg)	90
Total prop mass (kg)	104

Next Steps

- **Develop acceleration noise budget**
  - **For hexagonal test mass**
- **Complete optical train notional design**
  - **Define modulation scheme**
  - **Include test mass sensing in transverse degrees of freedom**
  - **Identify requirements for optical elements**
- **Finish preparations for Team -X exercise**
  - **Complete instrument mass budget**
    - **Will be dominated by structure for telescopes**
  - **Define telemetry requirements**
  - **Study cooling concept**
    - **Radiation from ‘bottom’ appears feasible**