Title: Cosmology with 300,000 Standard Sirens

Date: Jun 16, 2010 02:00 PM

URL: http://pirsa.org/10060006

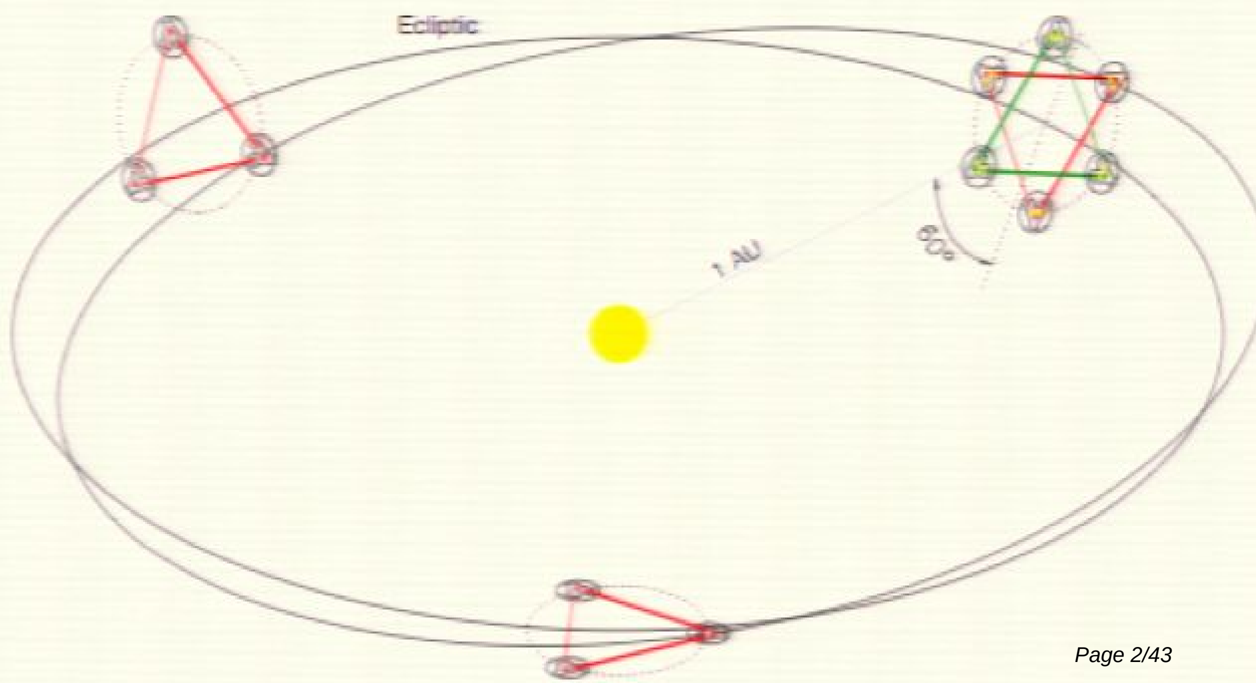
Abstract: I will describe recent work by Cutler&Holz and Hirata, Holz, & Cutler showing that a highly sensitive, deci-Hz gravitational-wave mission like BBO or Decigo could measure cosmological parameters, such as the Hubble constant H_0 and the dark energy parameters w_0 and w_a, far more accurately than other proposed dark-energy missions. The basic point is that BBO’s angular resolution is so good that it will provide us with hundreds of thousands of “standard sirens.” These standard sirens are inspiraling neutron star and black hole binaries, with gravitationally-determined distances and optically determinable redshifts. I explain why a BBO-like mission would also be a powerful weak lensing mission, and I briefly describe some further astrophysics that would flow from such a mission.

Cosmology with 300,000 standard sirens

C.Cutler & D.Holz, PRD 80, 104009 (2009)

Big Bang Observer (BBO) and DECIGO:

4 very sensitive mini-LISAs



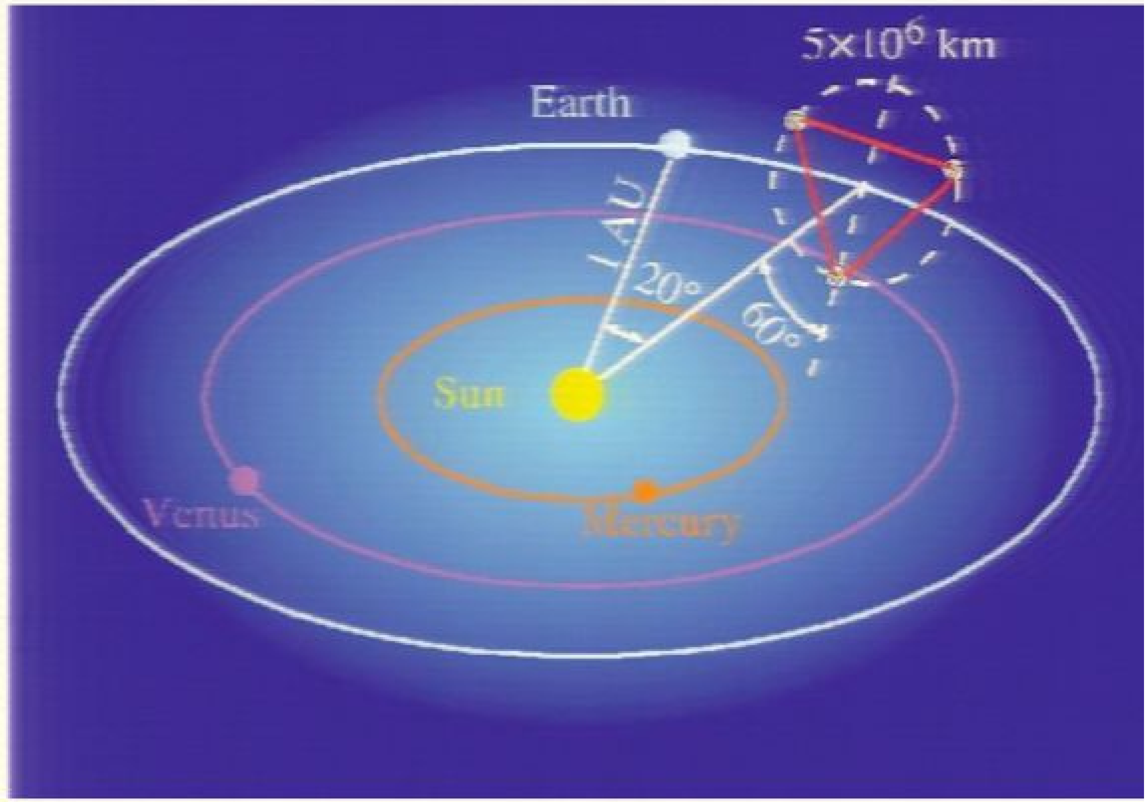
Outline

- Background: LISA, standard sirens, BBO
- Ultra-high-precision cosmology from BBO
- BBO as a weak lensing mission
- Recent work on lensing issues
- Caveats
- Future work

Overview of LISA

LISA:

- is a joint ESA/NASA mission
- is 3 drag-free satellites, separated by 5×10^6 km, and trailing the Earth by 20 deg
- will detect GWs in $10^{-5} - 10^{-1} Hz$ band; main sources are:



✓ Compact binaries in Milky Way, especially WD-WD binaries

✓ Mergers of $\sim 10^6 M_{sun}$ black holes in galactic nuclei at z > 1

✓ Inspirals of compact stars (BHs, NSs, WDs) into massive BHs

? Bursts from cusps on cosmic (super-)strings

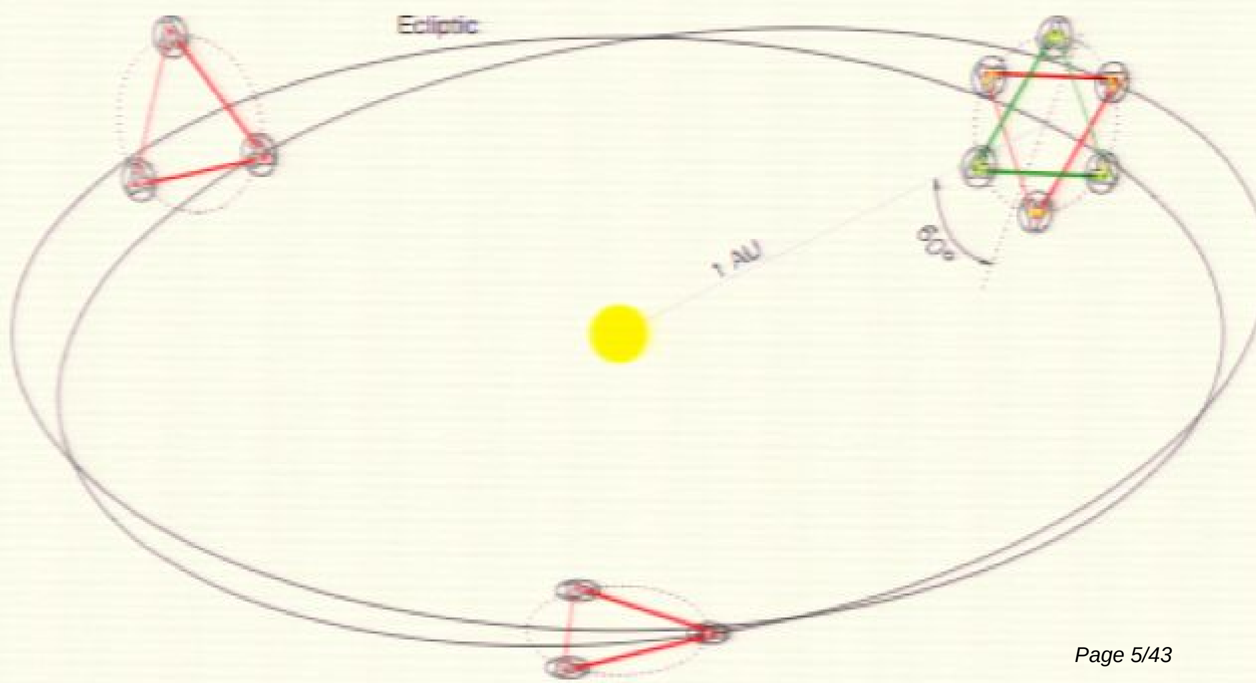
? Stochastic GWs generated by electro-weak phase transition

Big Bang Observer

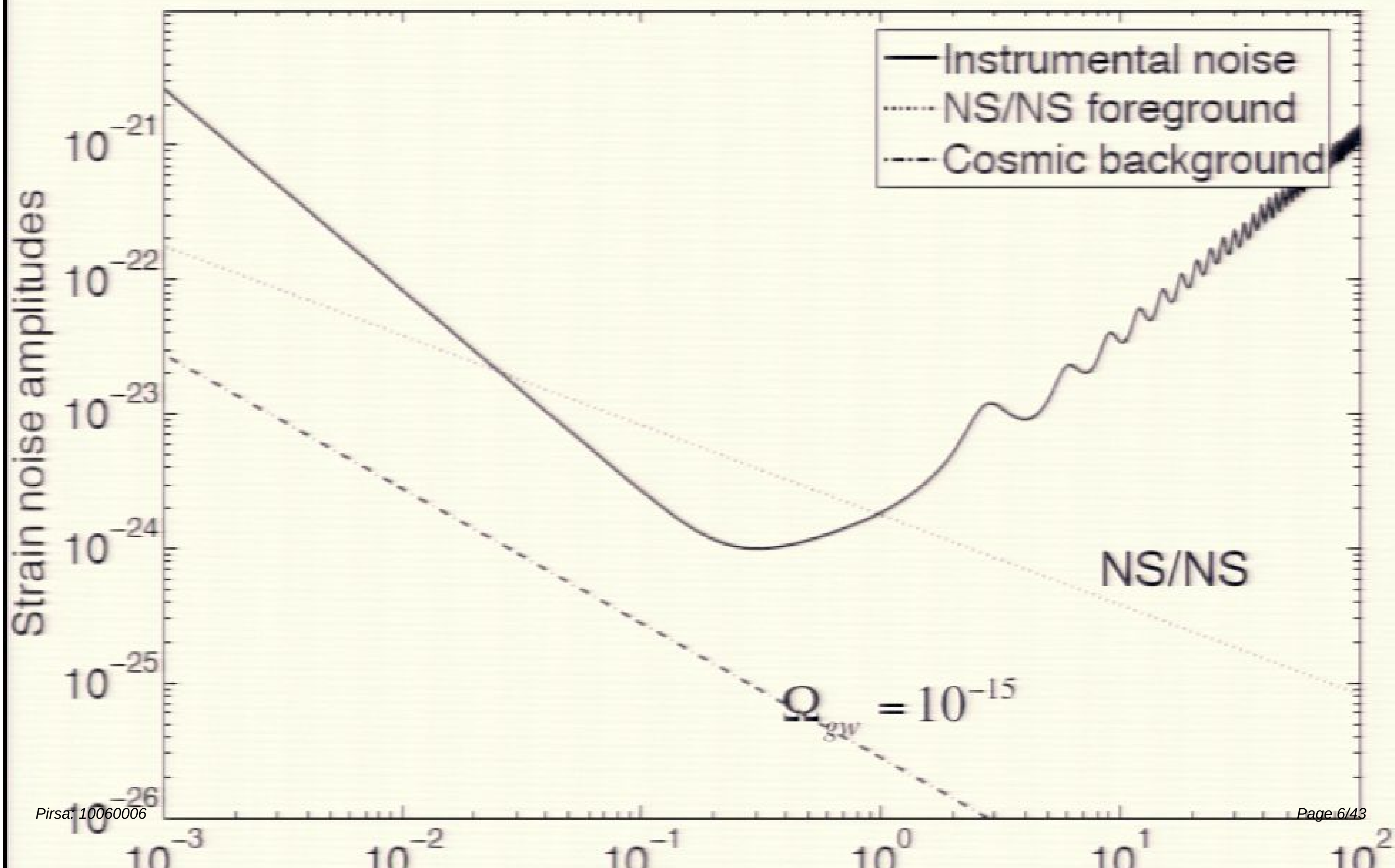
Designed to detect stochastic GWs from inflation, down to $\Omega_{gw} \sim 10^{-17}$

Big Bang Observer (BBO) and DECIGO:

4 very sensitive mini-LISAs



BBO Noise Curve



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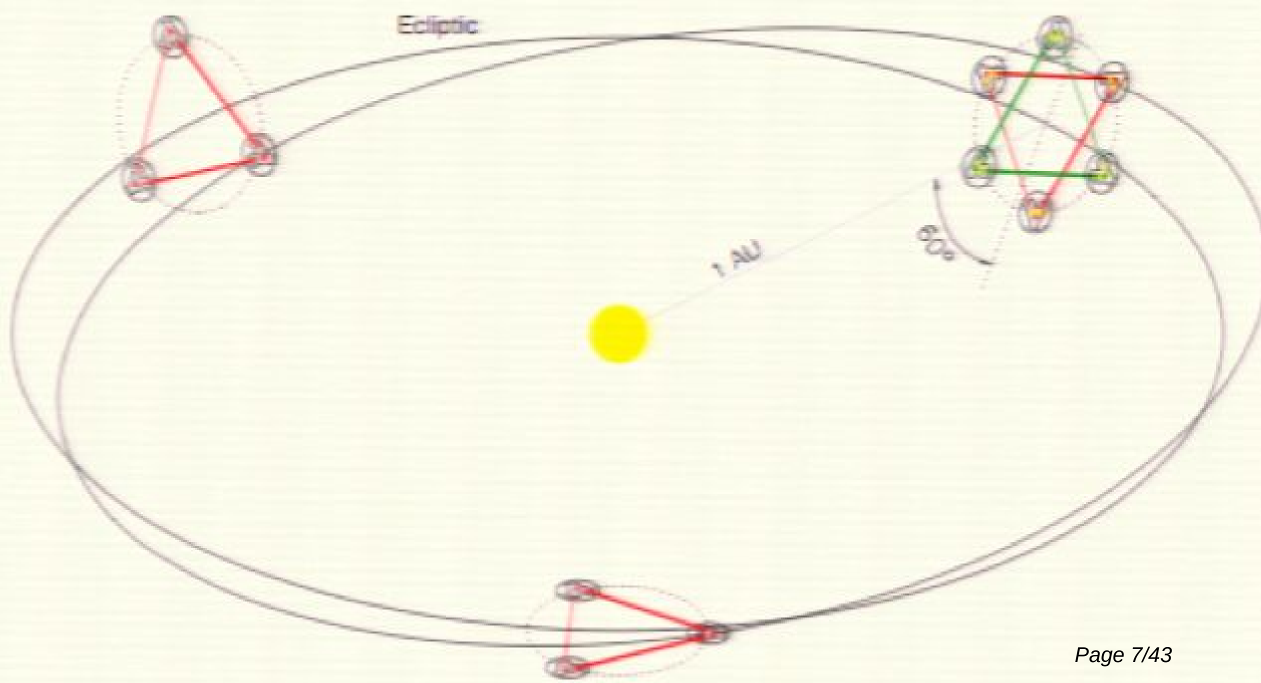

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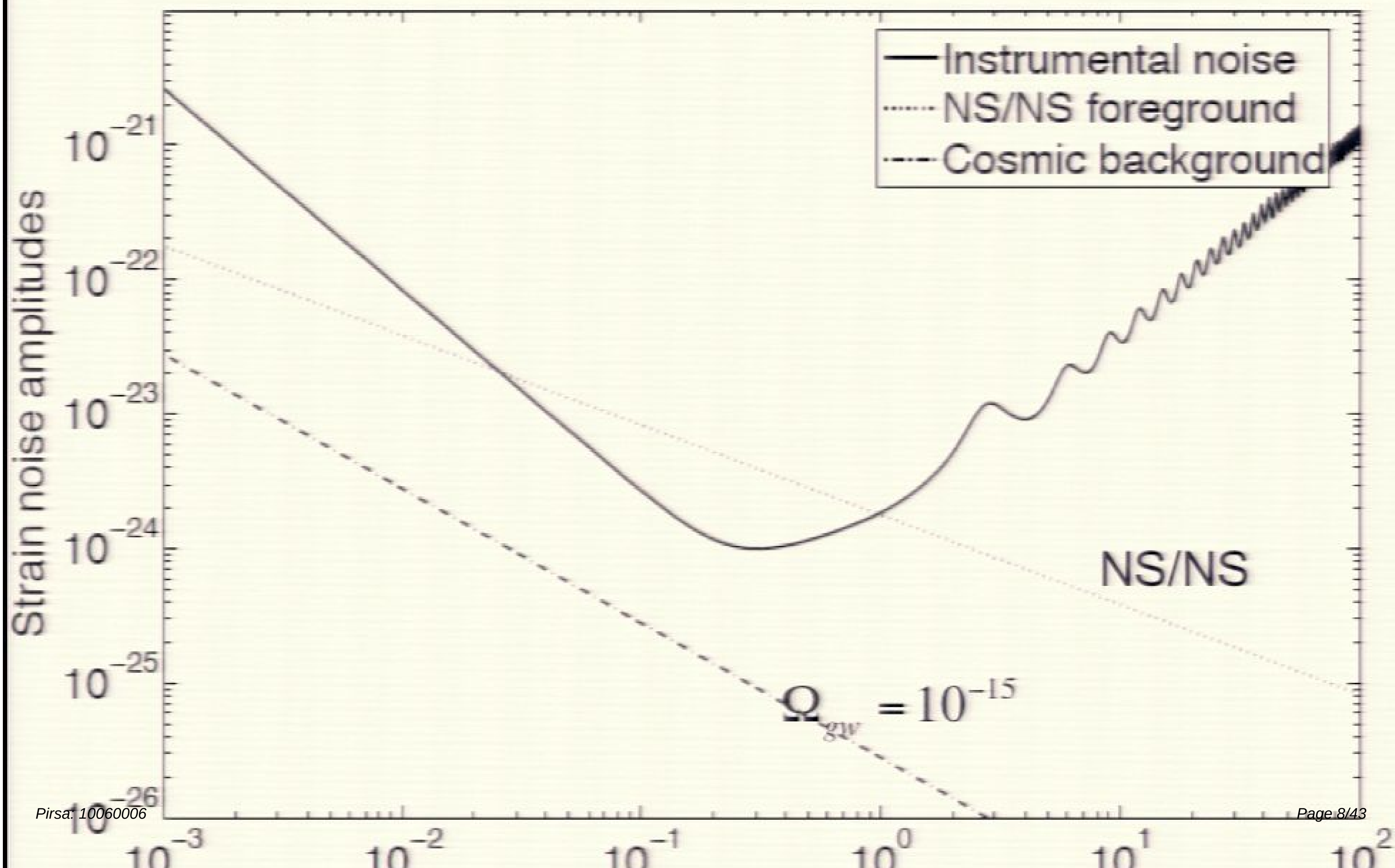


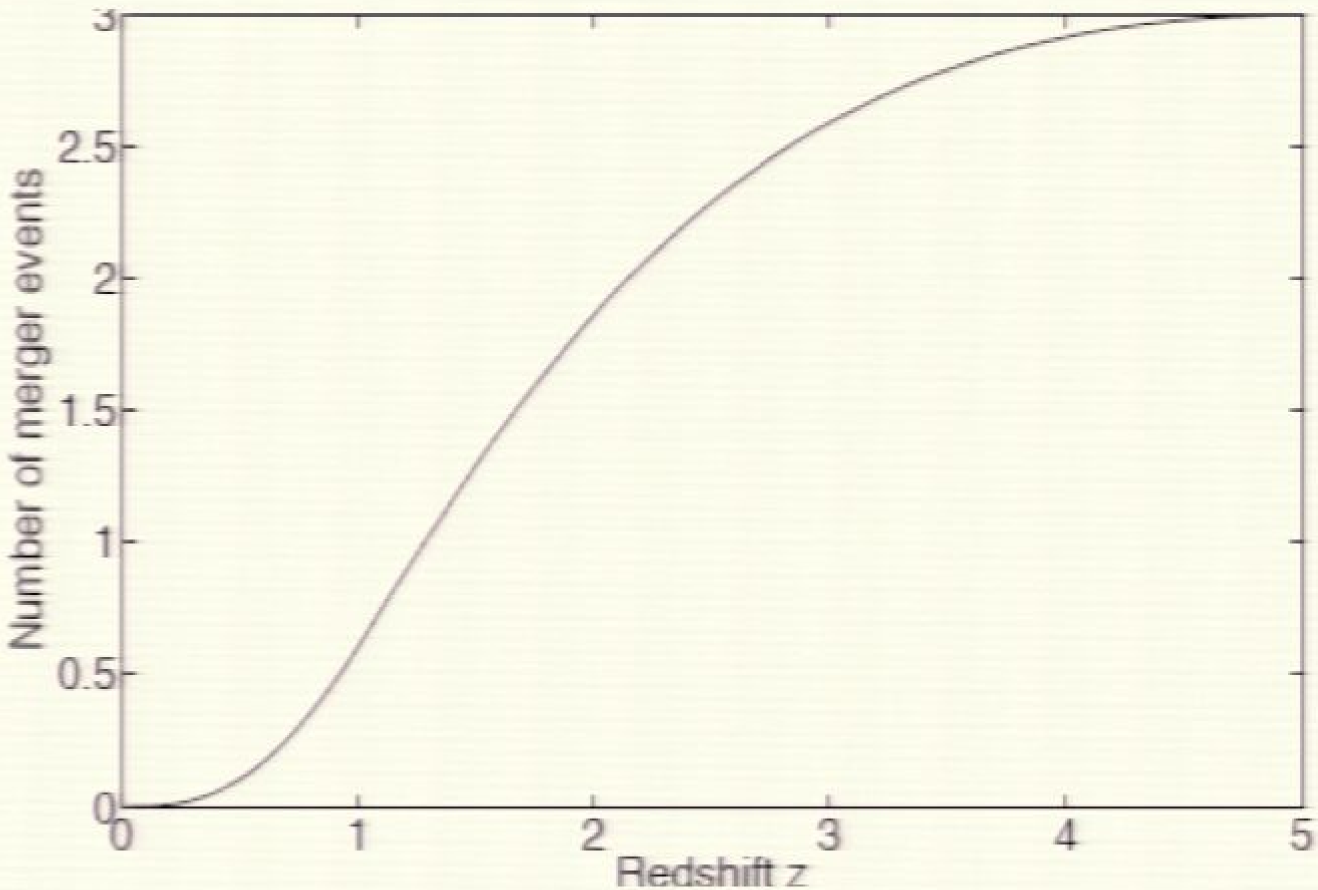
Nominal BBO parameters (used in paper)

	Symbol	Value
Laser power	P	300 W
Mirror diameter	D	3.5 m
Optical efficiency	ϵ	0.3
Arm length	L	$5 \cdot 10^7$ m
Wavelength of laser light	λ	$0.5\,\mu$m
Acceleration noise	$\sqrt{S_{\rm acc}}$	$3 \cdot 10^{-17}\ {\rm m}/({\rm s}^2\sqrt{\rm Hz})$

TABLE I: BBO parameters.

Laser power = 300 x LISA, mirror D ~ 10 x LISA,
arm length = 0.01 x LISA, $S_{acc}^{1/2}$ = 0.01 x LISA

$$\Delta N_{\rm m} = 3.0 \cdot 10^5 \left(\frac{\Delta\tau_0}{3\,{\rm yr}}\right)\left(\frac{\dot{n}_0}{10^{-7}\,{\rm Mpc}^{-3}{\rm yr}^{-1}}\right)$$



The total number of NS-NS mergers closer than redshift z,

for a 3-yr observation w/ $\dot{n}_0 = 10^{-7}{\rm Mpc}^{-3}{\rm yr}^{-1}$

Merger timescale

$$t(f) = 4.64 \times 10^5\,\mathrm{s} \left(\frac{\mathcal{M}(1+z)}{1.22 M_\odot} \right)^{-5/3} \left(\frac{f}{1\mathrm{Hz}} \right)^{-8/3}$$

$\Rightarrow$

For two $1.4 M_\odot$ NSs, $f \approx 0.205\,\mathrm{Hz}$, $0.136\,\mathrm{Hz}$, and $0.112\,\mathrm{Hz}$ at one year, three years, and five years before merger, respectively.

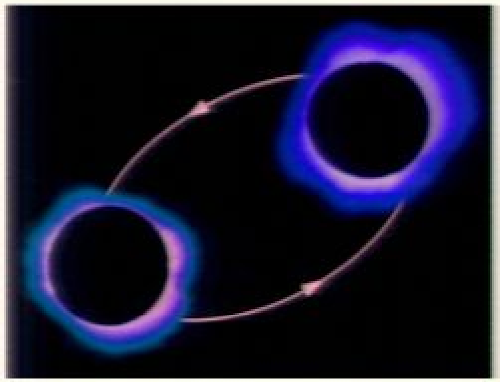
Can all the NS-NS binaries be detected and subtracted out to sufficient precision?

- Cutler&Harms(2006) considered a simple algorithm: detect and subtract out the brightest sources, which reduces the foreground. Then detect and subtract out the next-brightest sources, further reducing foreground.

- C&H showed by a analytic calculation that you can iterate like this all the way out to z = 5.

However this particular scheme would fail if BBO's sensitivity were a factor ~ 2– 4 worse than its current target sensitivity.

Binaries as standard GW sirens

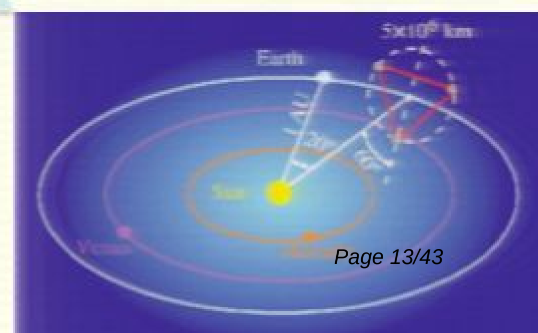


(using quadrupole approximation for simplicity)

$$I^{ij} = \sum_A M_A r_A^i r_A^j$$

D

$$h_{ij} = \frac{1}{D} P_{TT} \frac{d^2}{dt^2} I_{ij}(t - D)$$



$$h(t) \sim D^{-1} \mu\, r^2 \Omega^2 \sim D^{-1} \frac{M_1 M_2}{M^{1/3}} f^{2/3}$$ x F(angles)

$$\frac{df}{dt} = \frac{96}{5} \pi^{8/3} \frac{M_1 M_2}{M^{1/3}} f^{11/3}$$ + higher order terms

In cosmological context, what GWs really measure are:

- Luminosity distance: D_L
- Redshifted masses: $M_1(1+z)\,,M_2(1+z)$

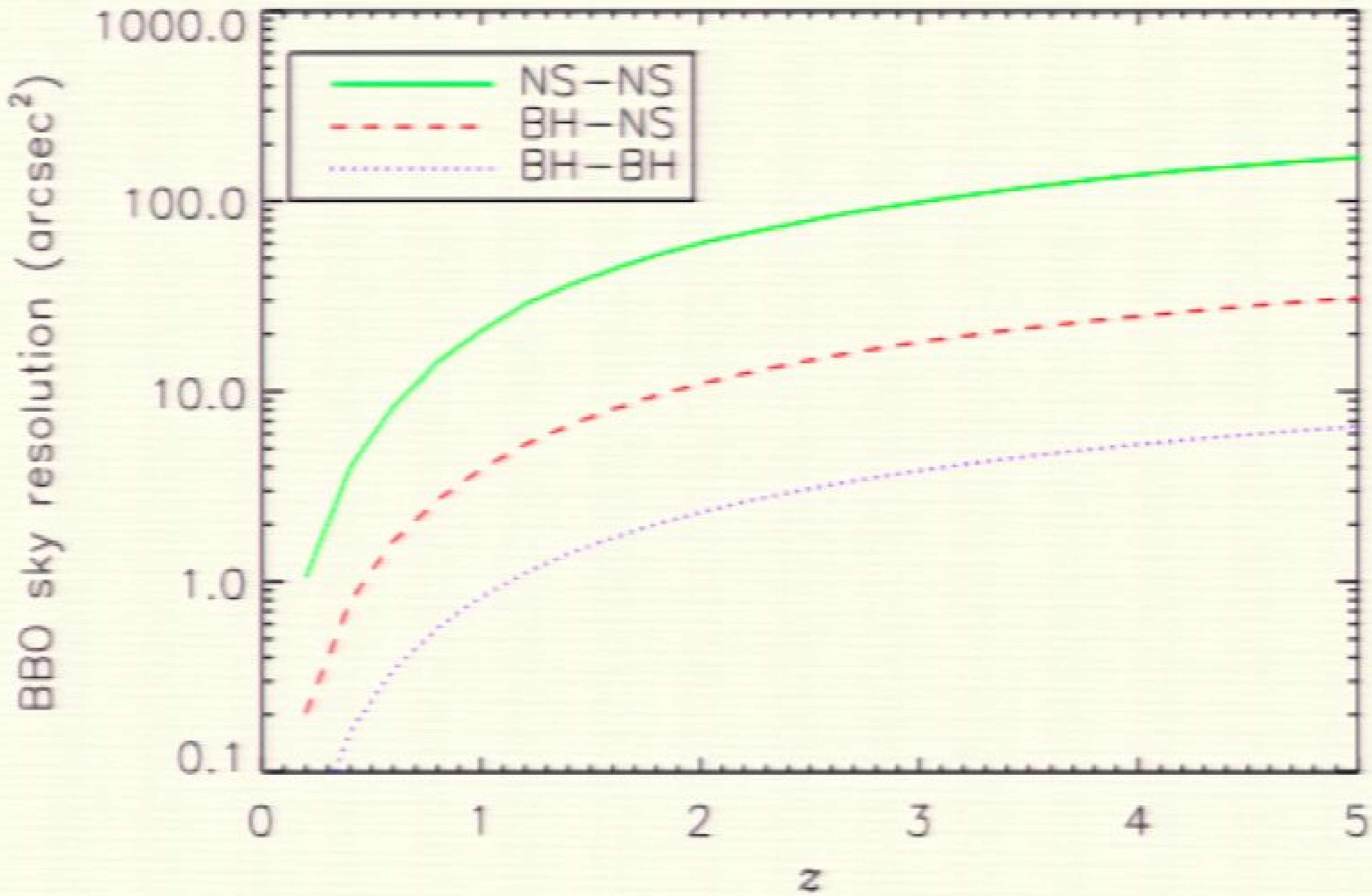
Inspiraling Binaries as GW "Standard Sirens"

- Schutz(1986) pointed out that cosmological distances in are hard to obtain in optical astronomy, getting D_L from a merging binary is straightforward in GW astronomy. IF can also obtain redshift z, then get a point on the $D_L(z)$ relation, which is the fundamental goal of physical cosmology.

- Holz&Hughes(2005) considered in detail what LISA could learn from a handful of "gold-plated" binaries– GW sources for which one could also obtain the redshift. Showed that weak lensing was a major limitation to using them in practice. Without WL, a handful could determine H_0 to ~1%.

BBO's angular resolution

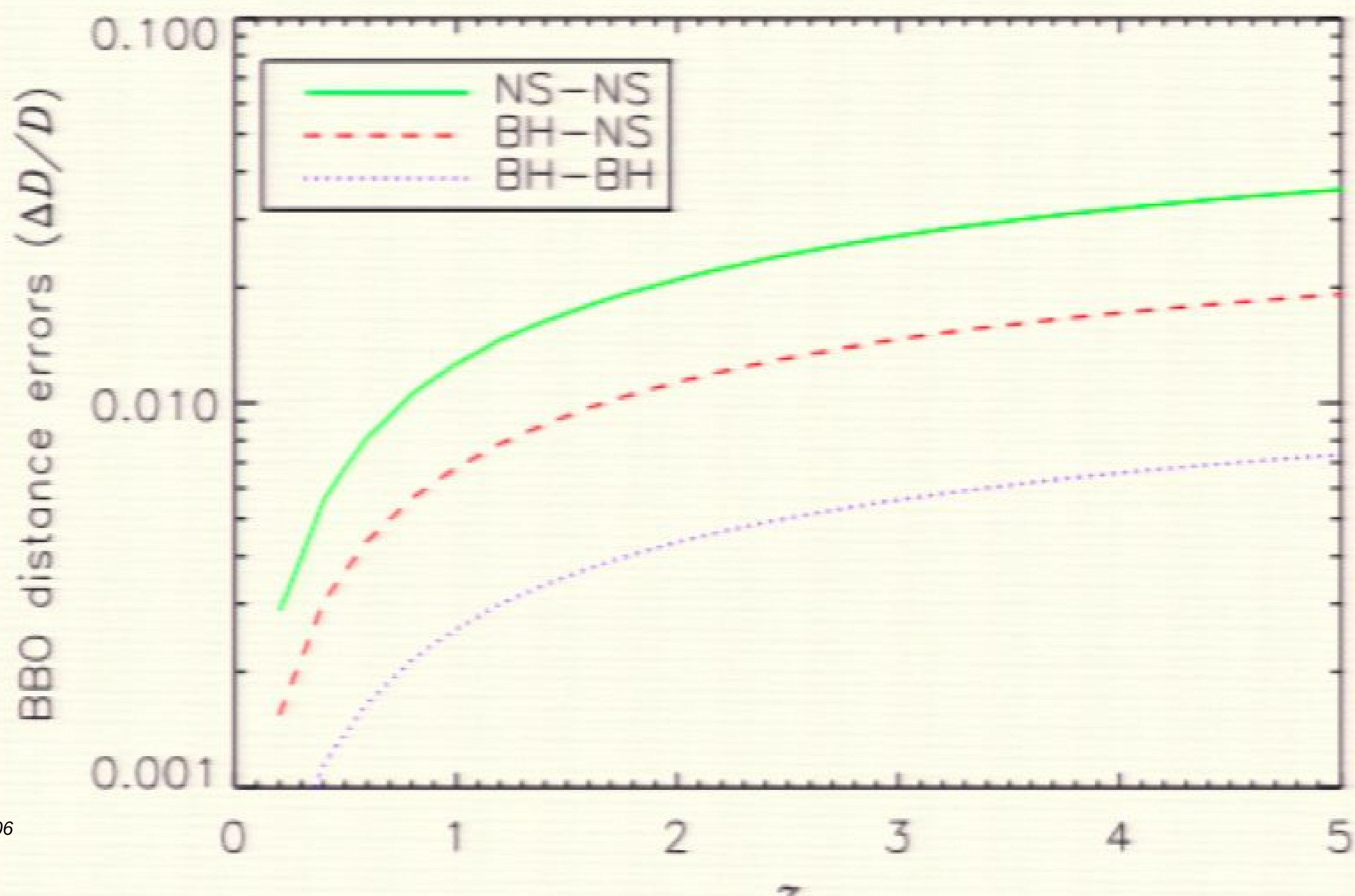
$$\Delta\theta \sim [(500s)(2\pi \times 0.3\,Hz)\,SNR]^{-1} \sim 1\,arc\sec$$



--consistent with earlier results by Cornish&Crowder(2005)

BBO's distance error (from noise)

$$\Delta D / D \sim 1/SNR \sim 0.01$$



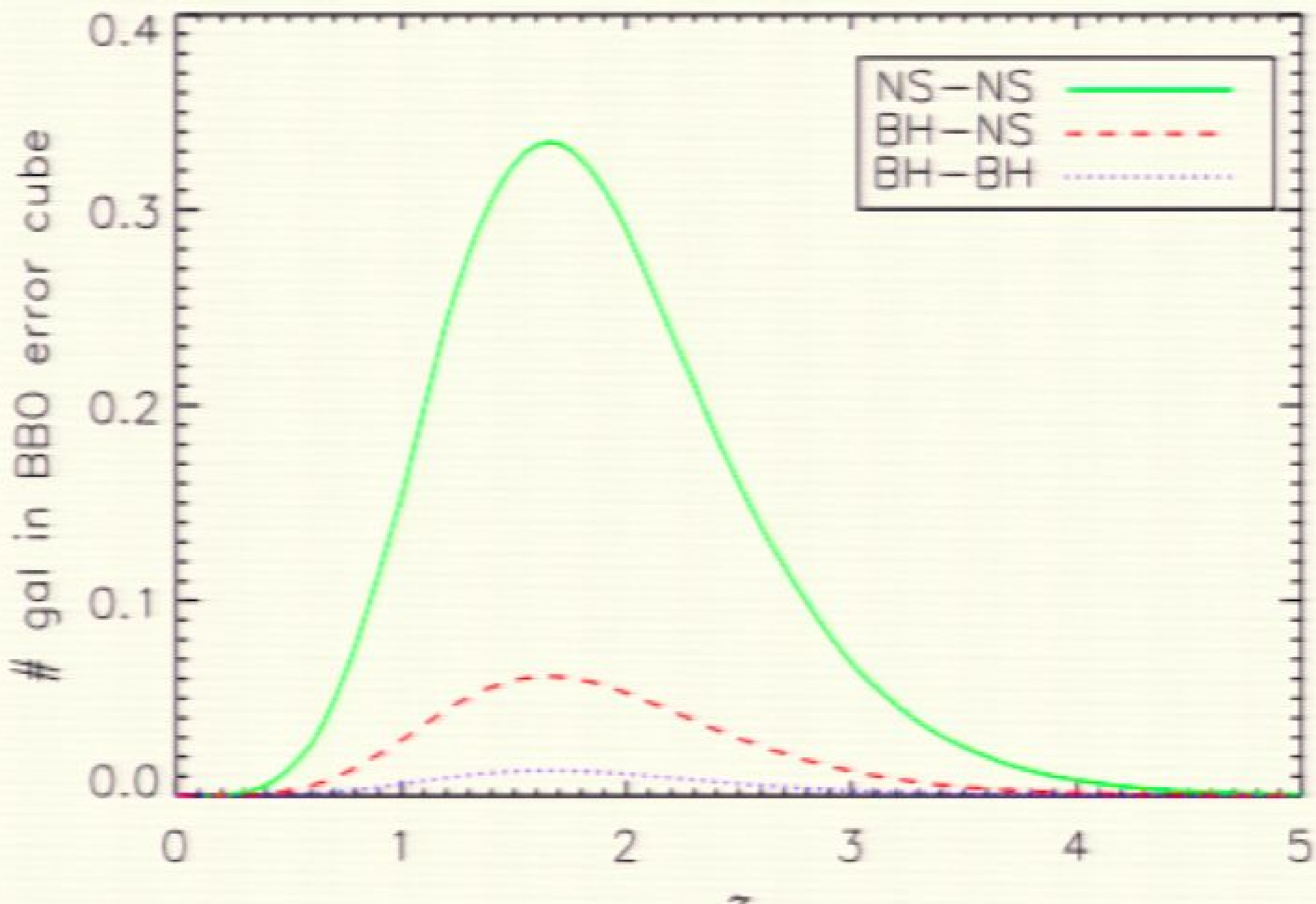
Actually, BBO's distance error is dominated by Weak Lensing

$$\frac{\Delta_{WL} D}{D} = 0.044\, z$$

Holz&Linder (2005)

Number of Galaxies in Error Cylinder

Hubble Ultra Deep Field: $dN/d\Omega = 1{,}000 / arc\,\min^2$



Cosmological Parameter Extraction

What goes in: Assume have measured 250,000 NS-NS binaries out to z=3, with perfectly determined redshifts, z. Fit for 5 parameters:

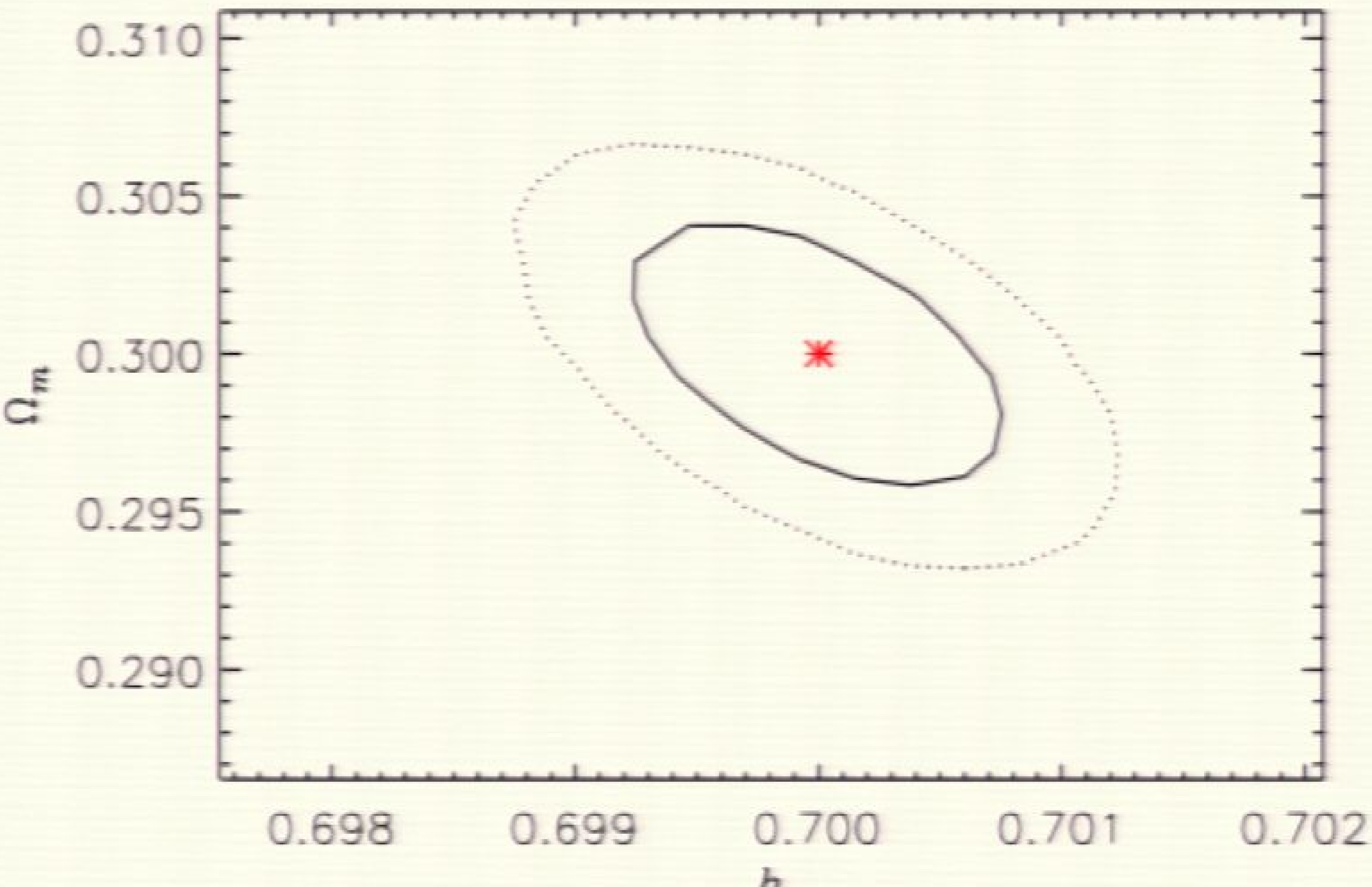
$$H_0\,,\ \Omega_m,\ \Omega_X,\ w_0, w_a$$

where

$$w(z) \equiv p/\rho \quad \&$$

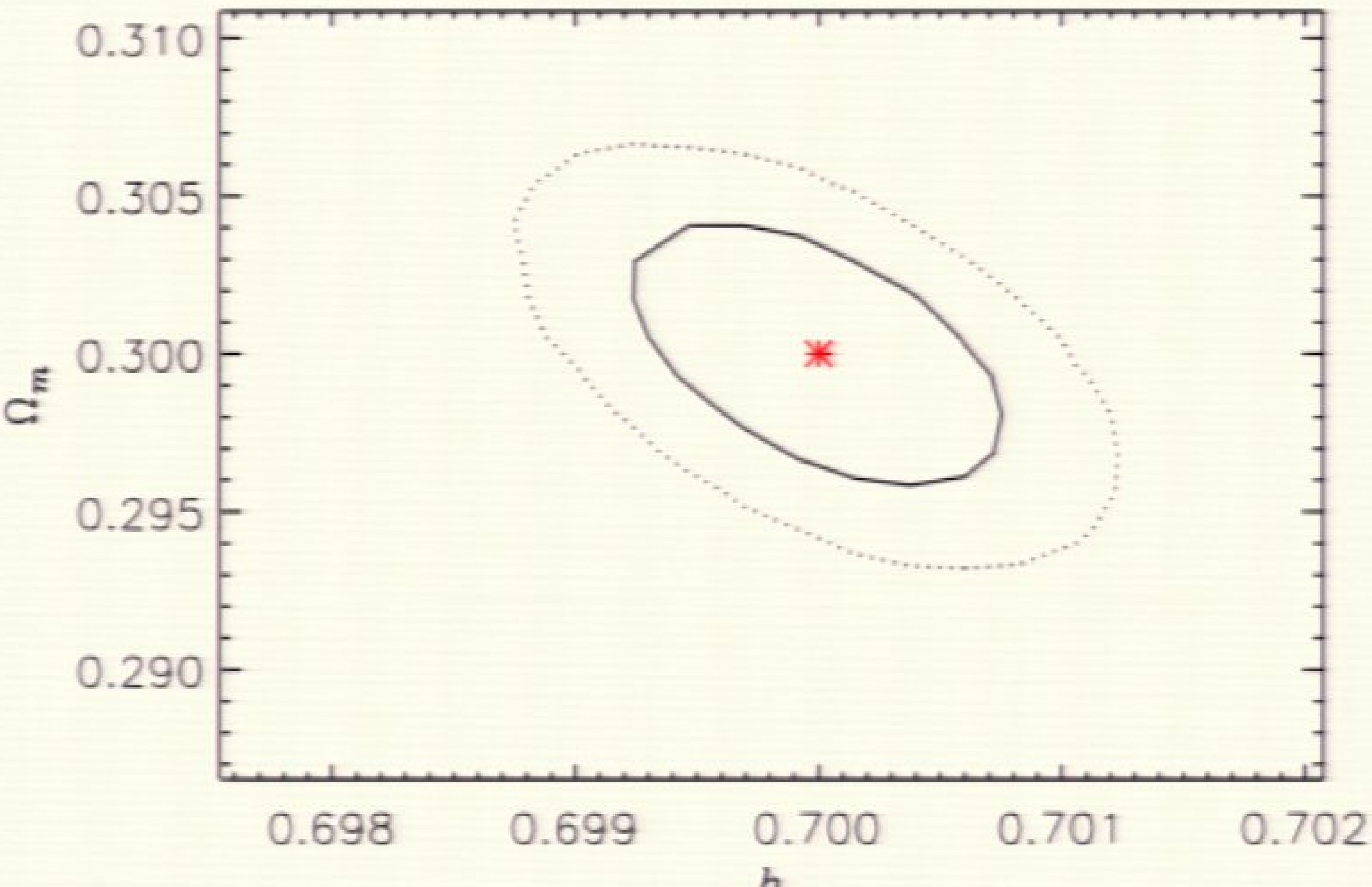
Following standard convention, also assume forecasted Planck prior: constrains $\Omega_m h^2$ to ~1%, plus a constraint on D of Hubble scale at decoupling

2.5e5 NSs up to z=3 $\Rightarrow H_0$ to 0.1%



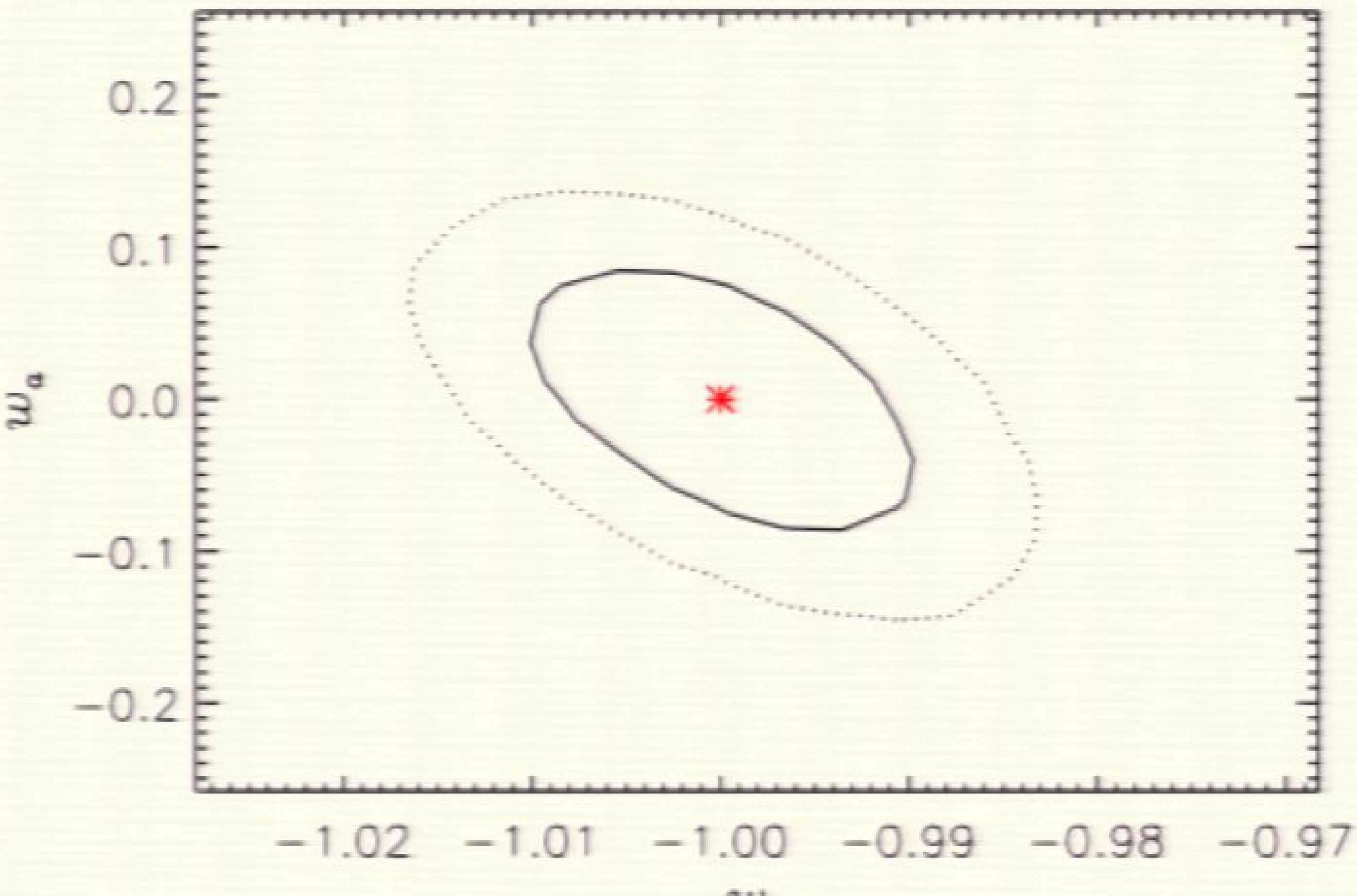
2.5e5 NSs up to z=3 $\Rightarrow H_0$ to 0.1%

For $\Lambda CDM \Rightarrow H_0$ to 0.025%



2.5e5 NSs up to z=3 $\Rightarrow w_0$ to ~0.007

$\Rightarrow w_a$ to ~0.05



Caveat re Calibration

LISA calibration expected to be accurate to $\sim 10^{-6}$.

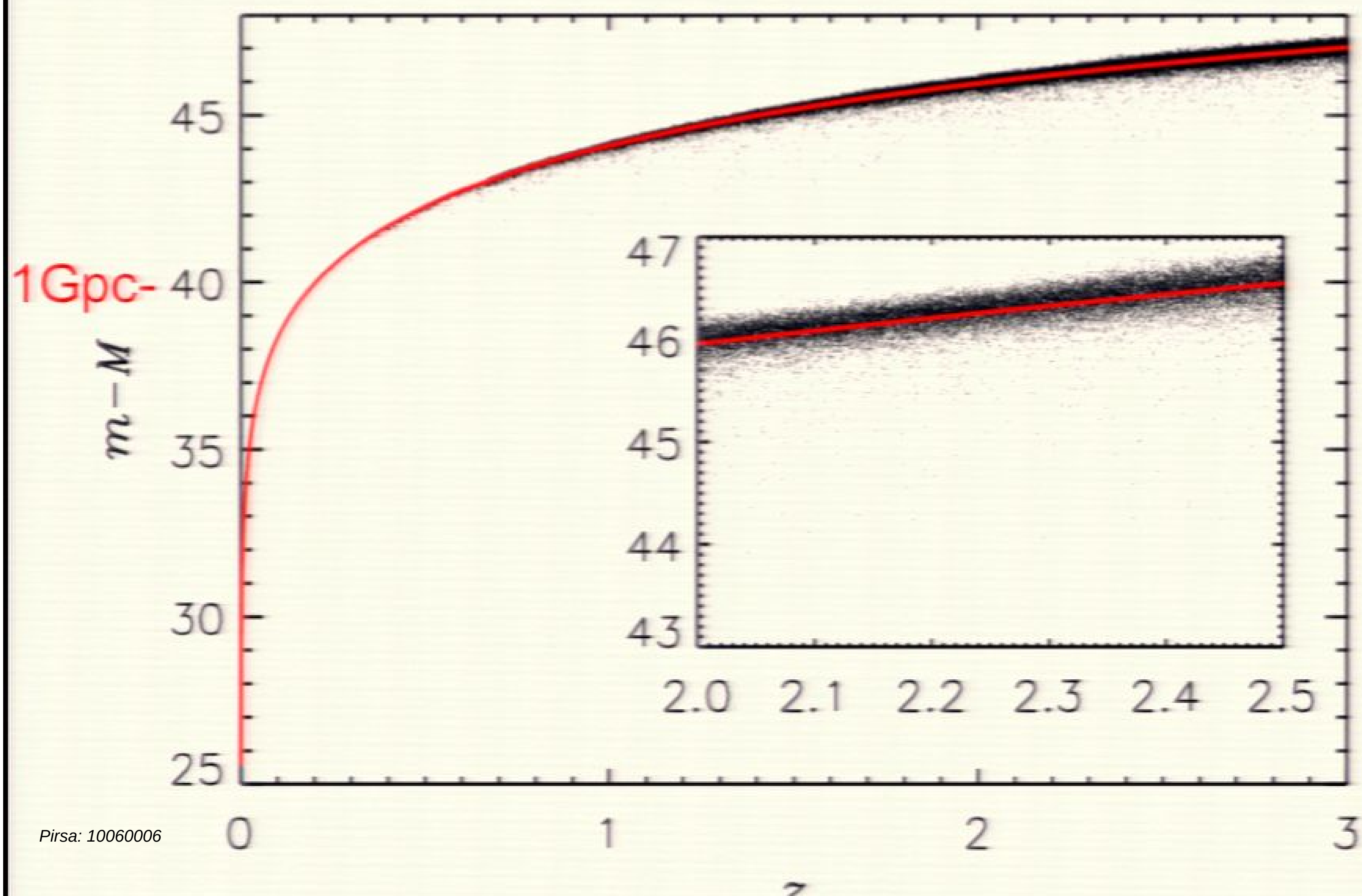
BBO interferometry in BBO Mission Concept Study (Phinney et al., 2003) is very "LISA-like": no applied forces along sensitive direction.

Harry et al.(2006) realized that the 2003 design would greatly oversaturate today's photodiodes; they proposed a more "LIGO-like" design, with forces on the test masses to keep photodiode operating near a dark fringe. But this spoils calibration accuracy unless the force is measured very accurately.

We have spoken with several instrumentalists, and are optimistic that this is a solvable problem; e.g.,

1) Widen beam onto array of ~1000 photodiodes
2) Use interferometry to measure applied force

BBO as a Weak Lensing mission



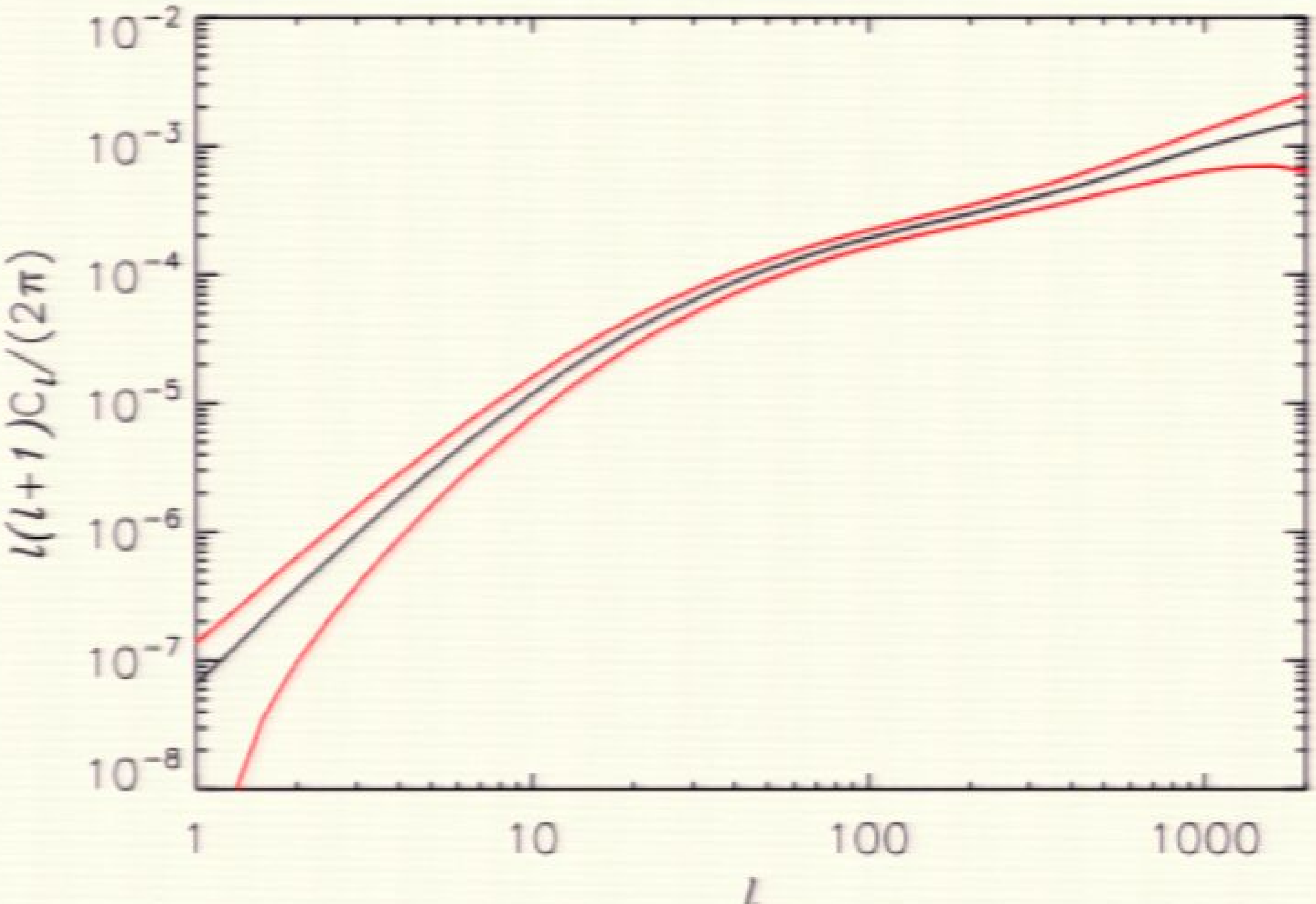
BBO/Decigo as WL mission

$$\rho^2 = \sum_i \left(\mu_i / \Delta\mu_i \right)^2 \sim 10^7$$

Comparable to most ambitious/optimistic other WL experiments, such as JDEM or LSST, which measure WL shear thru correlations in galaxy shape distortions.

We estimate that BH-BH binaries likely contribute about as much to ρ^2 as NS-NS binaries. Though we assume the BH-BH merger rate is ~1/20 the NS-NS rate, each $\left(\mu_i / \Delta\mu_i \right)^2$ is ~25 times larger.

BBO's measurement of lensing convergence power spectrum



BBO/Decigo as WL mission

The above calculations are just our “first-cut” analysis of BBO as weak lensing mission. In follow-up work we plan to

•Calculate how well these WL measurements can constrain cosmological models.

•Consider the synergies from combining GW magnification measurements with optical shear measurements.

Other Astrophysics from BBO/Decigo (1)

1. Early Warning System for ALL short/hard gamma-ray bursts (assuming they are due to mergers)

❖ BBO will predict time and location of ALL NS-NS and BH-NS mergers, months in advance. Because of beaming, probably only a small fraction, will lead to observable gamma-ray bursts.

❖ We will learn which kinds of mergers (components, masses, orientations) lead to observable bursts, and which do not. In particular, BBO will tell us binary's orientation, so we can study beaming.

❖ Can still look for afterglows, even when there are no

Recent work: more careful analysis of WL error.

$$\frac{\Delta_{WL} D}{D} = 0.044\, z$$ for single source

Cutler&Holz(2009) estimated that for N sources at same z:

$$\frac{\Delta_{WL} D}{D} = (0.044\, z) / N^{1/2}$$ for N sources

That's correct if you take an average, but because the distribution of magnifications is quite skew, the average is not the best estimator. The maximum likelihood estimator gives:

$$\frac{\Delta_{WL} D}{D} \approx (0.030\, z) / N^{1/2}$$ for N>4 sources

see Hirata,Holz&Cutler(2010); Shang&Haiman(2010)

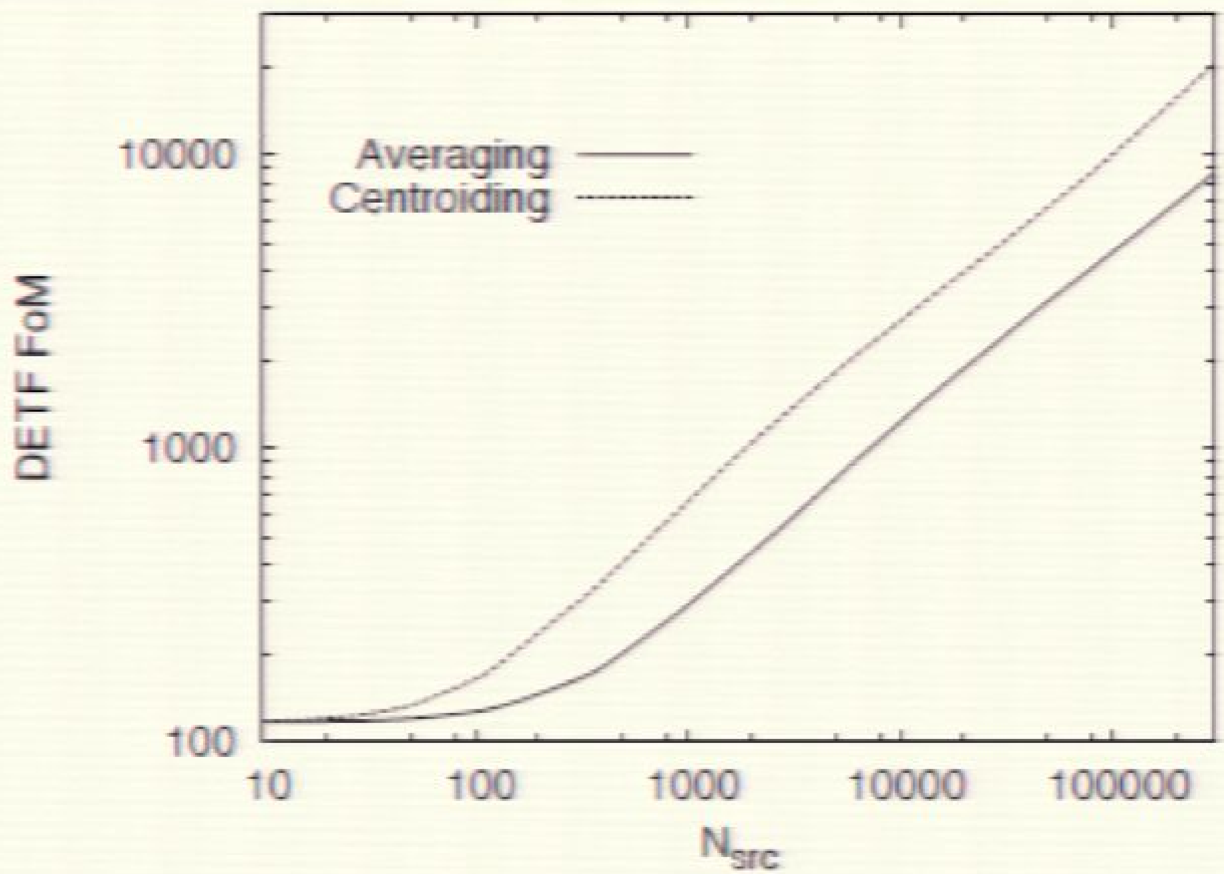


FIG. 5: The DETF FoM as a function of the number of gravitational wave sources N_{src} used. We also include both the *Planck* mission and next-generation ground-based dark energy projects (Stage III). The highest N_{src} value plotted corresponds to $N_{src} = 3 \times 10^5$, the rough number expected for BBO.

Caveat re a Selection Effect

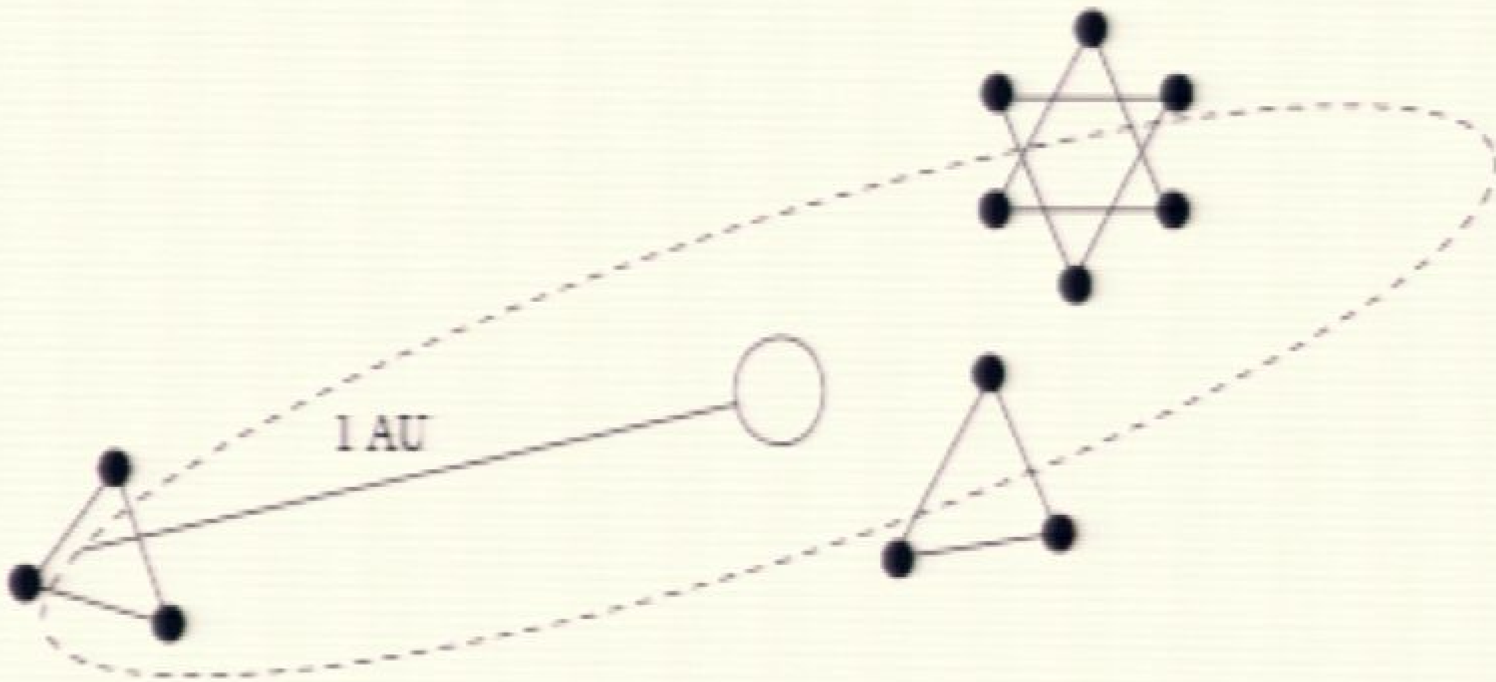
Hirata pointed out: the probability of correctly identifying the host galaxy has a small but non-negligible dependence on its magnification: higher μ means higher SNR, so a smaller error box and a brighter galaxy. If not accounted for, would lead to systematic bias in $D_L(z)$.

Possible ways of "correcting" for this effect:

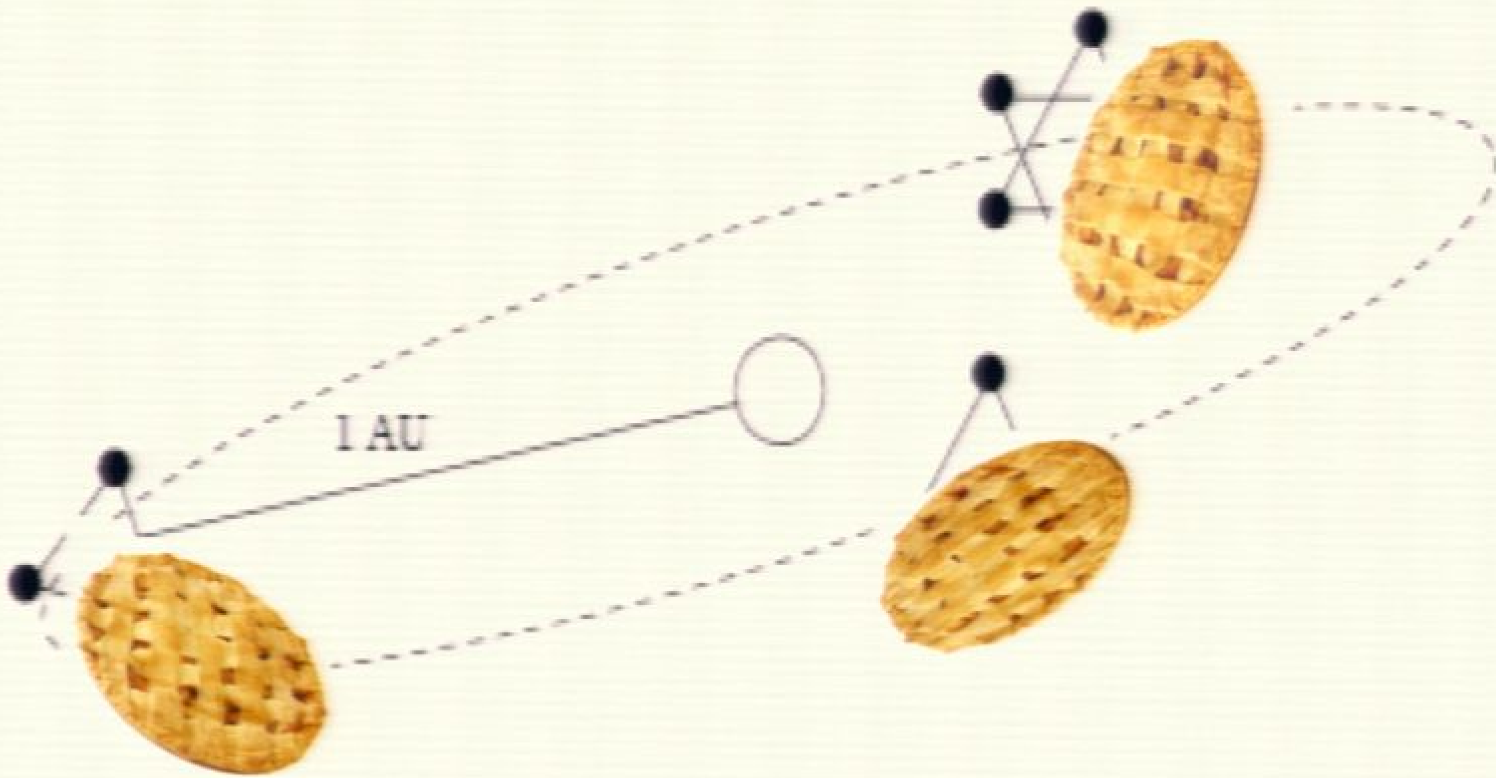
1) Use the gamma-ray burst sources to calibrate it out. I.e., using those same ~1000 galaxies to create a new synthetic data set giving the "calibration" binaries random orientations and coalescence times. Analyze the data 2 different ways: with and without the benefit of the exact sky location. The difference is an estimate of the systematic bias.

2) Include this effect in a proper Bayesian analysis. Would need to include more parameters, especially a parametrized model of the NS-NS merger rate as a function of z, galaxy type, etc.

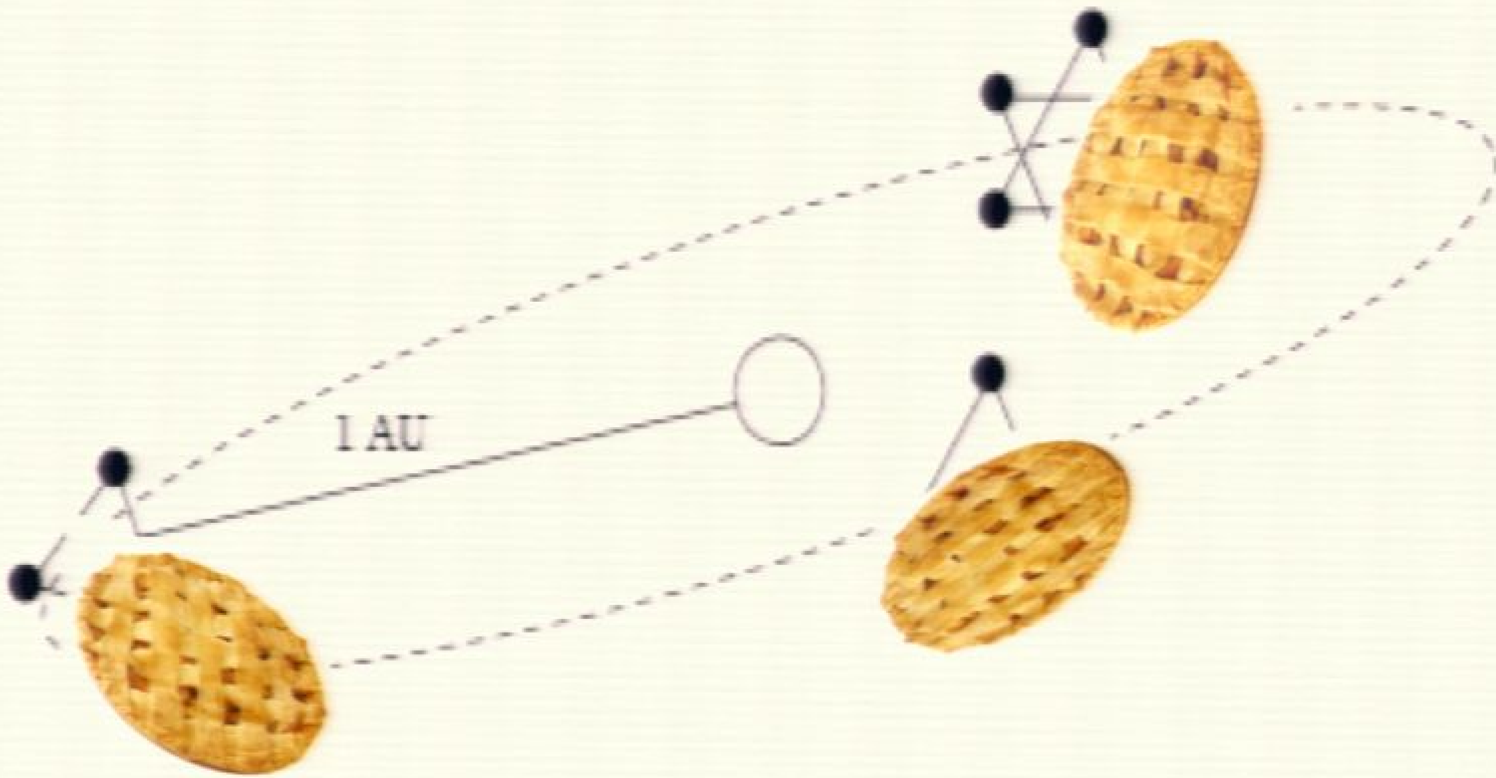
BBO:



BBO:

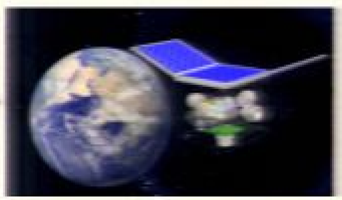
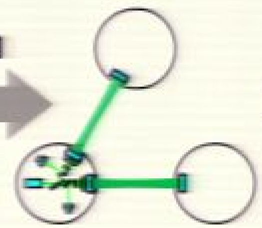
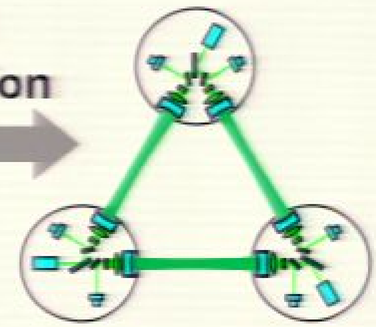


BBO: Pie in the Sky?



Decigo Roadmap

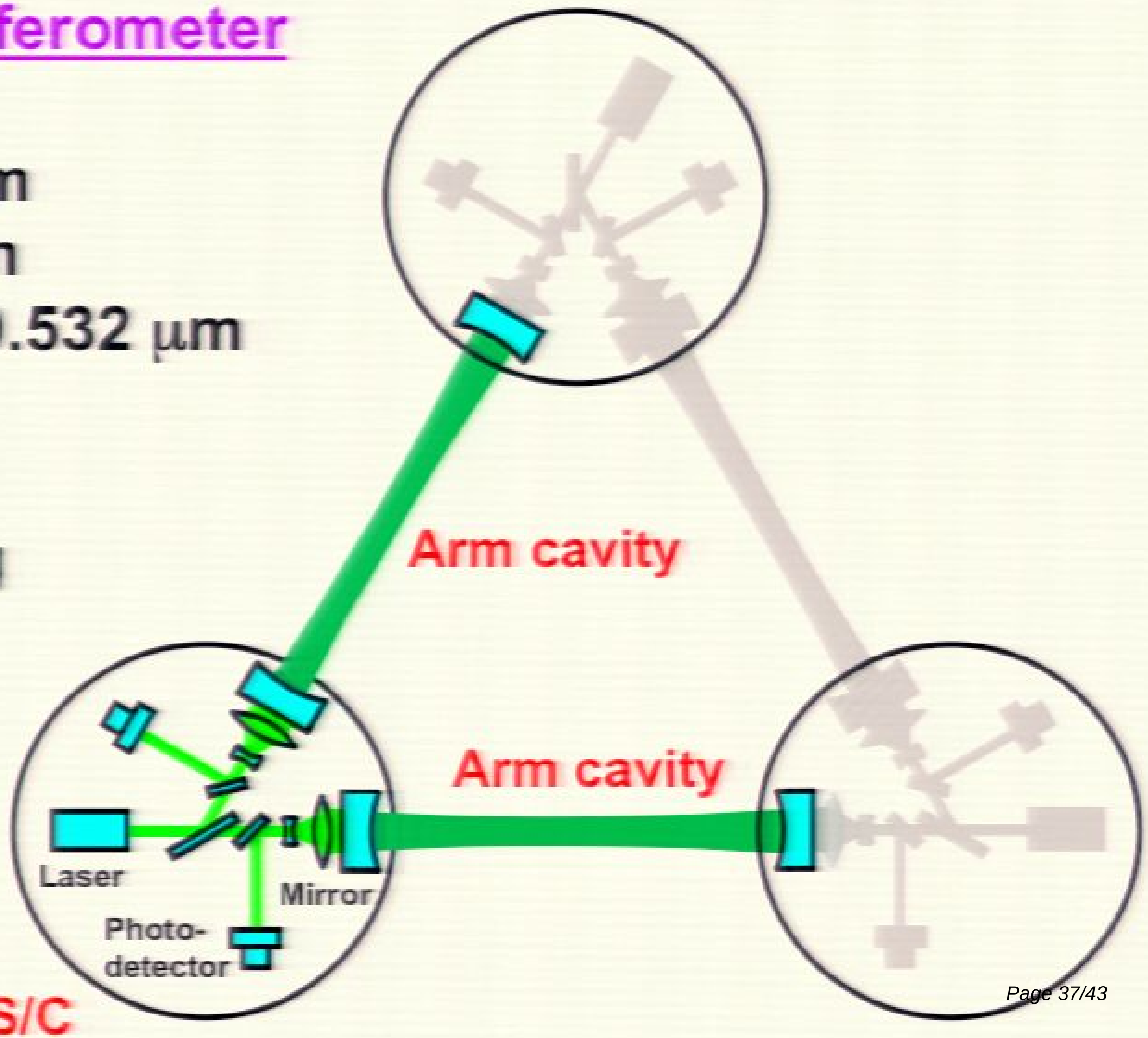
	2007	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26

Mission	R&D Fabrication →  DECIGO Pathfinder (DPF)	R&D Fabrication →  Pre-DECIGO	R&D Fabrication →  DECIGO
Objectives	Test of key technologies Observation run of GW	Detection of GW w/ minimum spec. Test FP cavity between S/C	Full GW astronomy
Scope	1 S/C 1 arm	3 S/C 1 interferometer	3 S/C, 3 interferometer 3 or 4 units

Decigo: Pre-conceptual design

Differential FP interferometer

Arm length: 1000 km
Mirror diameter: 1 m
Laser wavelength : 0.532 μm
Finesse: 10
Laser power: 10 W
Mirror mass: 100 kg
S/C: drag free
3 interferometers



Many see BBO as unrealistic, in my lifetime

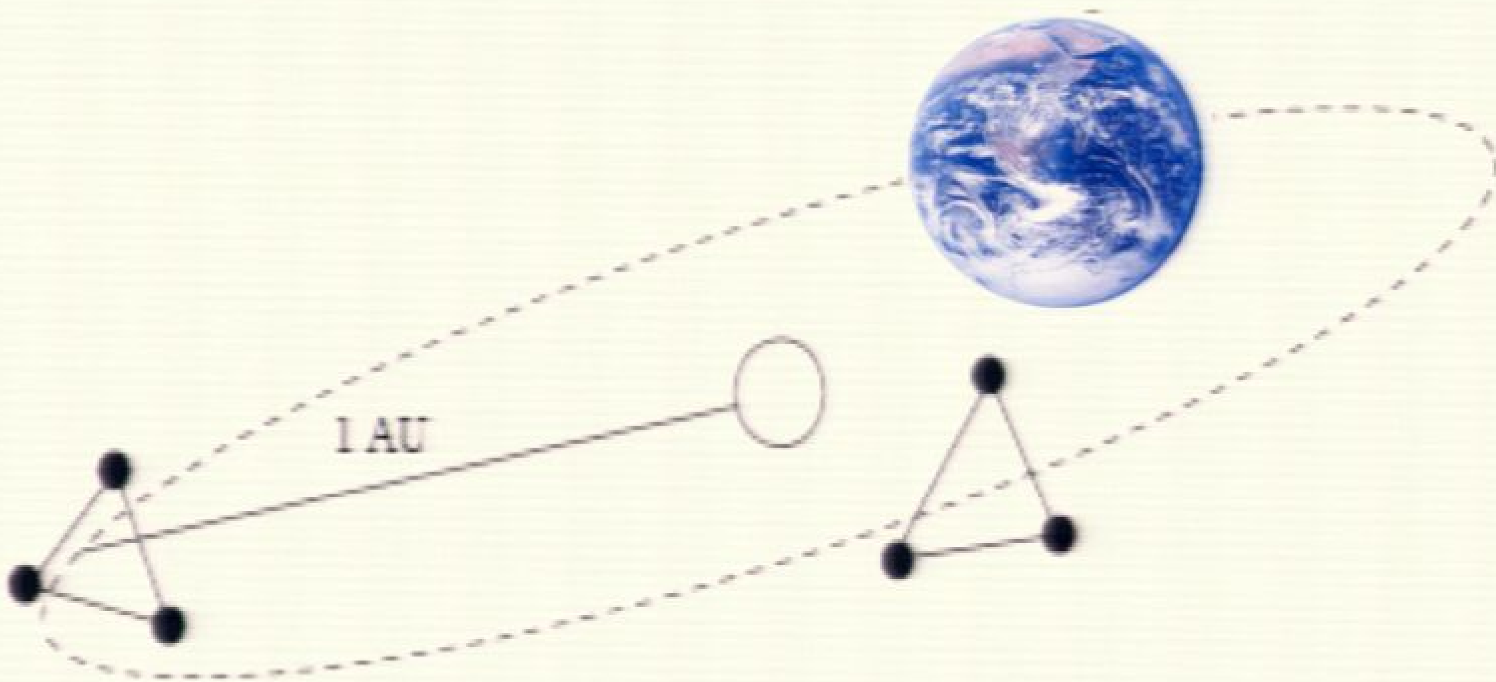
However if one re-defines the goal of the mission, from searching for stochastic GWs from inflation, to doing ultra-high-precision cosmology, then

all the mission parameters are up for grabs again.

Work in progress:

Calculate the science yield of cheaper versions of BBO.

6-satellite BBO +EinsteinTelescope:



How much can BBO sensitivity be descoped, and still do high precision cosmology?

Summary:

If we can build a deci-Hz space-based GW mission approaching the target sensitivities of BBO or Decigo, and with excellent calibration accuracy (at $\sim 10^{-4}$ level), then

inspiraling Compact Binaries will be a Cosmology Goldmine

Offer cosmological measurements, with far better accuracy than with any other proposed methods, and potentially far better systematics (modulo those 2 caveats).

Plus: great WL mission, gamma-ray burst monitor, high-z IMBHs, strong lensing, …..

Other Astrophysics from BBO/Decigo (2)

2. Detect mergers of Intermediate Mass BHs to z>20

M_1	1e2	3e2	3e2	1e3	1e3	1e3
M_2	1e2	1e2	3e2	1e2	3e2	1e3
med SNR	1.4e3	1.9e3	2.7e3	1.6e3	2.2e3	2.2e3

TABLE II: Median matched-filtering SNRs for inspiralling intermediate-mass black hole binaries (IMBHs) at redshift $z = 20$. The masses are the locally measured ones (i.e., *not* redshifted masses), given in units of $M_\odot$.

Estimated rate ~30/yr, with ~20/yr at z > 10, based on merger-tree simulations by Volonteri, assuming MBHs do grow from stellar BH remnants. (By comparison, for same model, Einstein Telescope would detect ~2/yr, almost all at z<8.)

Decigo Roadmap

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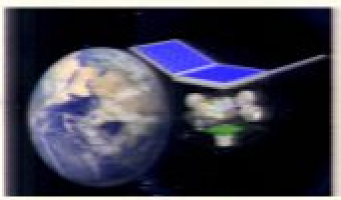
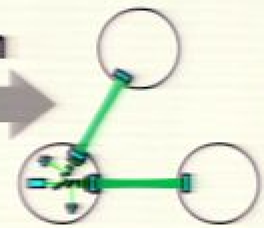
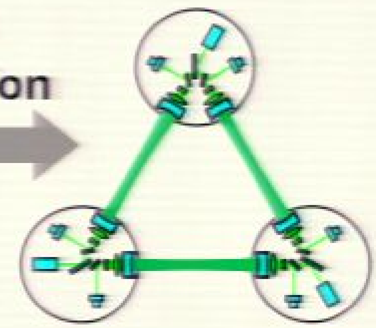
Mission	R&D Fabrication →  DECIGO Pathfinder (DPF)	R&D Fabrication →  Pre-DECIGO	R&D Fabrication →  DECIGO
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