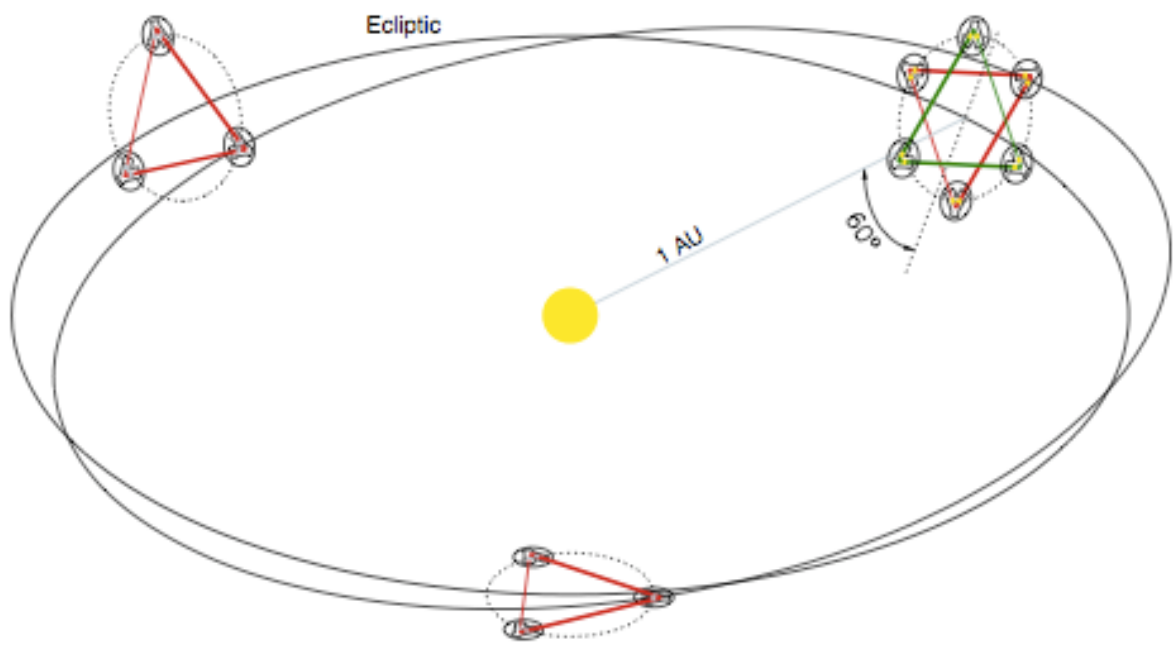
Cosmology with 300,000 standard sirens

C.Cutler[1] & D.Holz[2], arXiv:0906.3752

Big Bang Observer (BBO) and DECIGO:

4 very sensitive mini-LISAs



1.JPL and Caltech 2. LANL

Inspiraling Binaries as GW "Standard Sirens"

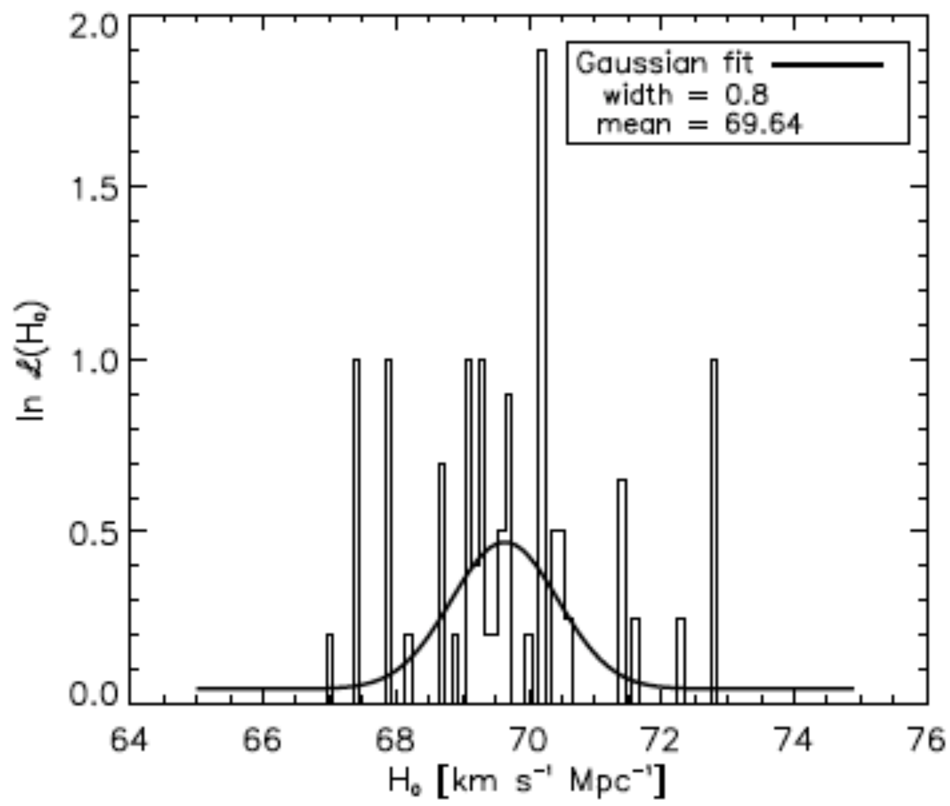
- Schutz(1986) pointed out that cosmological distances in are hard to obtain in optical astronomy, getting D_L from a merging binary is straightforward in GW astronomy. IF can also obtain redshift z, then get a point on the $D_L(z)$ relation, which is the fundamental goal of physical cosmology.

- Holz&Hughes(2005) called binaries for which one can also obtain a redshift "gold-plated" binaries. Showed that weak lensing was a major limitation to using them in practice. (Without WL, a handful could determine H_0 to ~1%.)

- Sathyaprakash, Schutz, & Van den Broeck(2009) showed that with 1,000 short/hard gamma-ray bursts from NS-NS mergers, and assuming H_0 is also known accurately from EM data, Einstein Telescope could measure $(\Omega_\Lambda, \Omega_m, w)$ to (4%, 18%, 18%). (Worse than current constraints, but with independent method.)

GW "Standard Sirens", cont'd

• Macleod&Hogan(2008) pointed out that even if a unique galaxy identification is not possible, for a large number of events one can still take advantage of the clustering of galaxies to constrain cosmology:



They estimate that with 20 EMRI events at z < 0.5, one could measure H_0 to 1%.

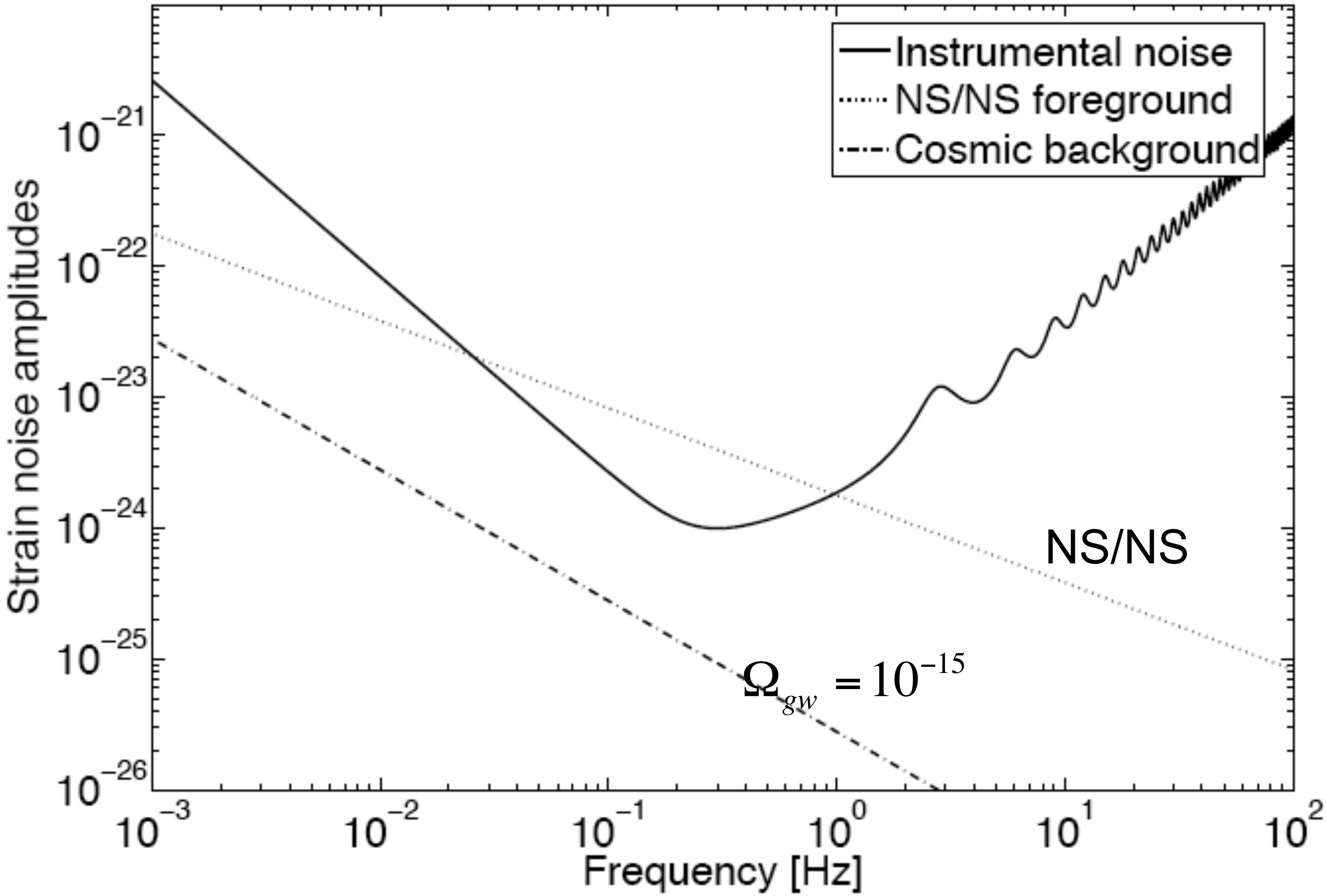
Nominal BBO parameters (used in paper)

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

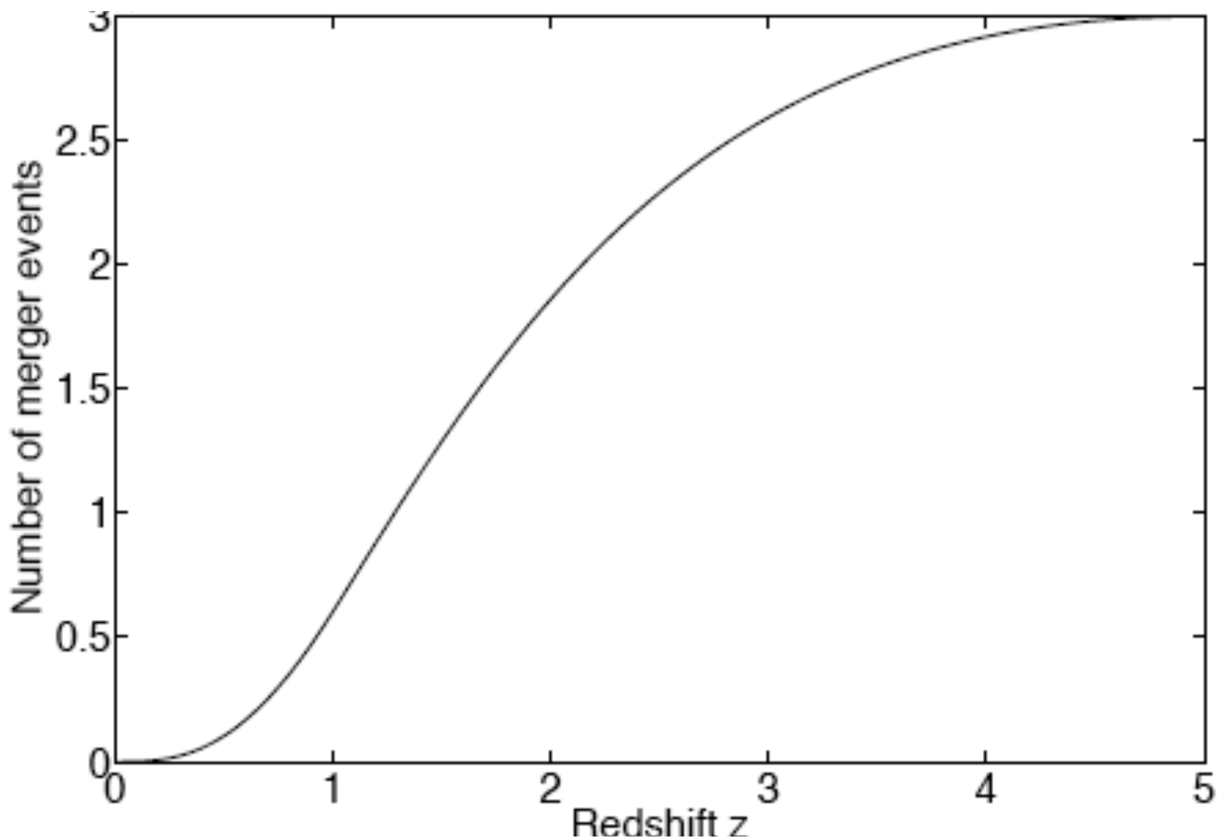
TABLE I: BBO parameters.

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

BBO Noise Curve



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



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

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

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.

Merger timescale

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

$\Longrightarrow$

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.

BBO's parameter estimation accuracy: the standard recipe

Use Fisher matrix formalism:

(1) BBO effectively produces 8 time series $s_\alpha(t), \quad \alpha = 1,..,8$

(2) Neglect spin precession effects, but include effects of spin on waveform phase. Then waveform depends on 10 parameters $\lambda^\mu, \quad \mu = 1,...,10$

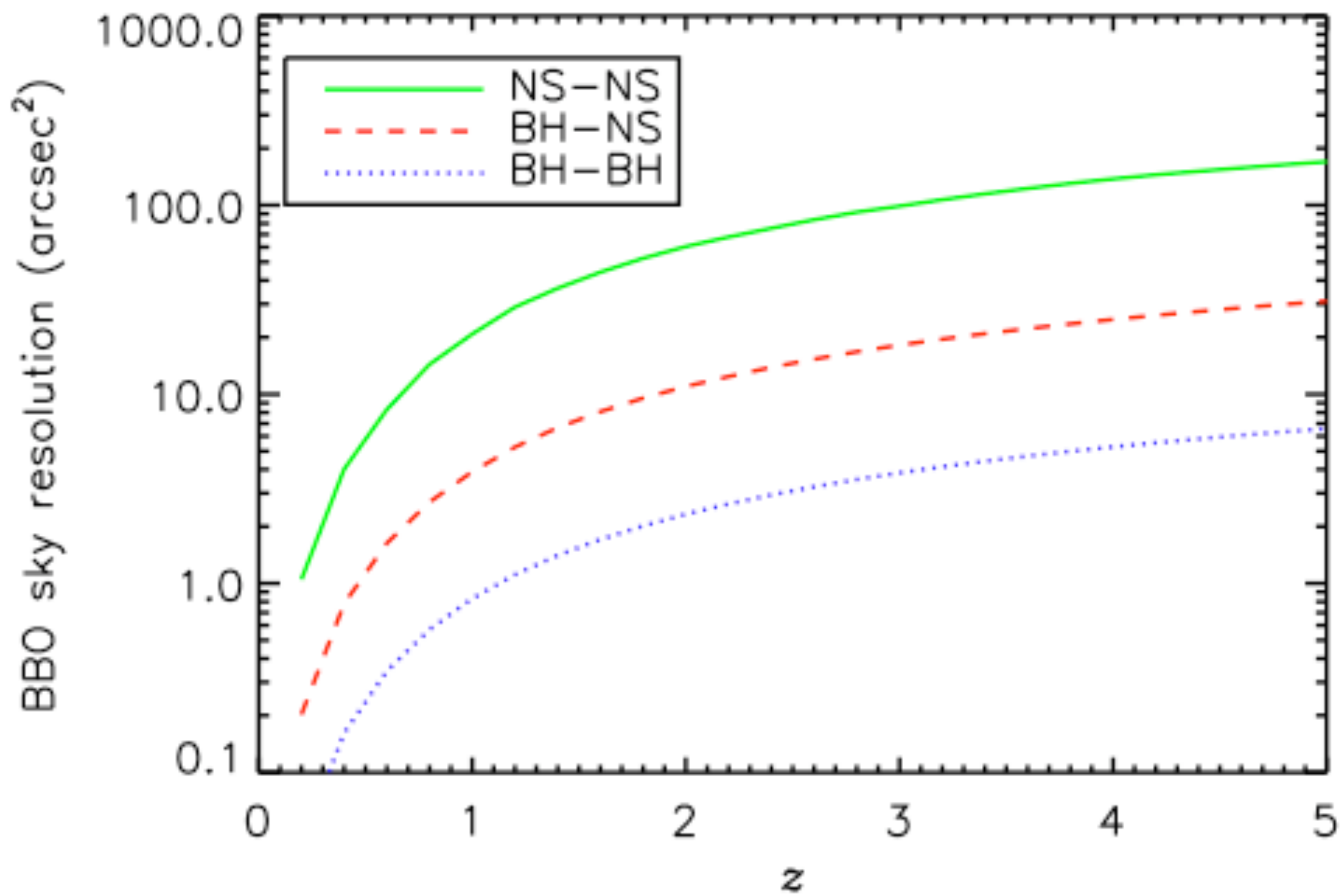
(3) Calculate Fisher matrix: $\Gamma_{\mu\nu} \equiv \left\langle \frac{\partial \mathbf{h}}{\partial \lambda^\mu} \,\middle|\, \frac{\partial \mathbf{h}}{\partial \lambda^\nu} \right\rangle$ where

$$\langle \mathbf{g} \,|\, \mathbf{k} \rangle = 2 \sum_{\alpha=1}^{8} \int_{-\infty}^{\infty} \mathrm{d}f \, \frac{(3/20)\tilde{g}_\alpha^*(f)\tilde{k}_\alpha(f)}{S_\mathrm{h}(f)} .$$

(4) Then $\overline{\Delta\lambda^\mu \Delta\lambda^\nu} = (\Gamma^{-1})^{\mu\nu}\left(1 + \mathcal{O}(\mathrm{SNR})^{-1}\right)$

BBO's angular resolution

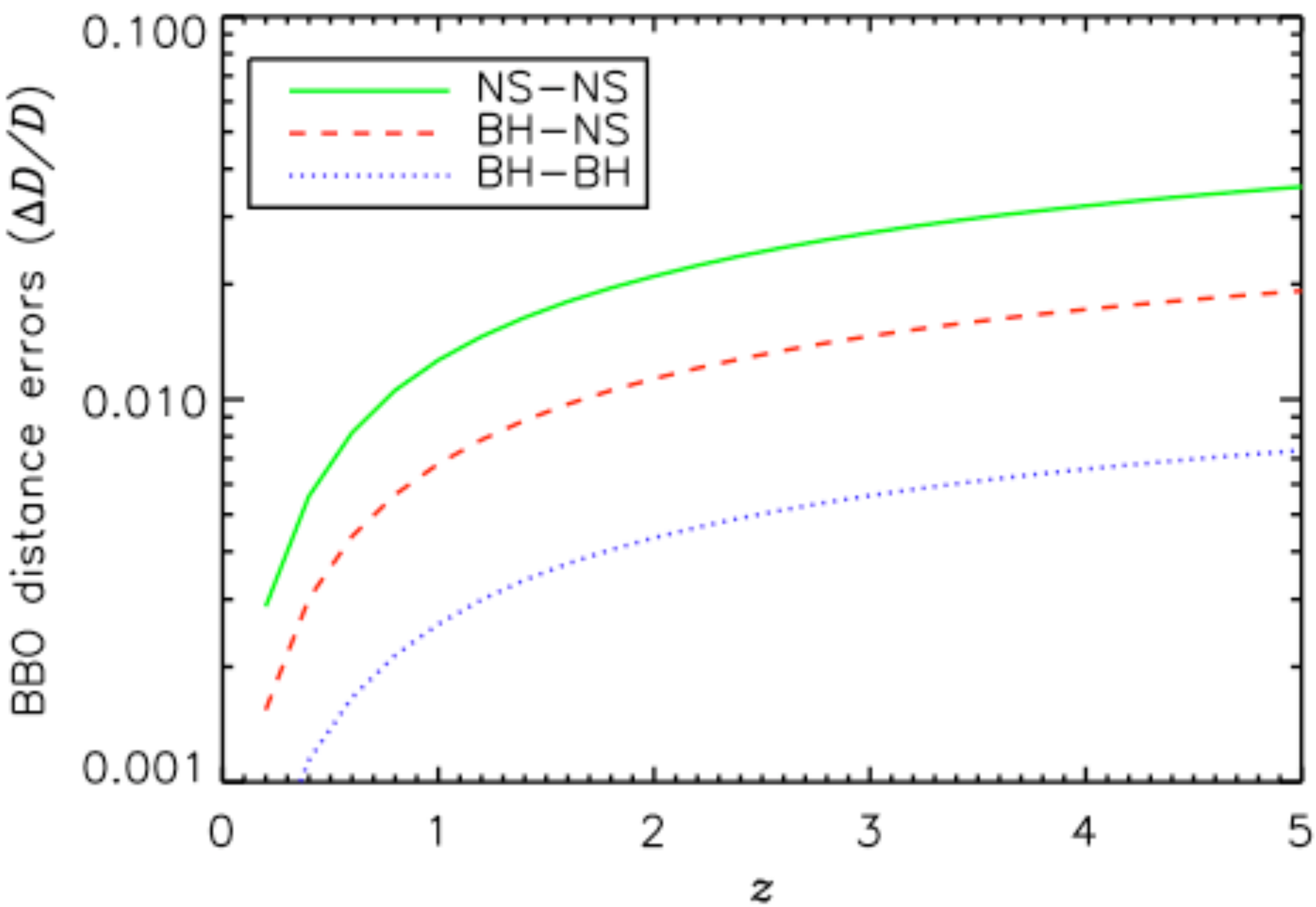
$$\Delta\theta \sim (500s)(2\pi \times 0.3\,Hz)/SNR \;\sim 1\,arc\sec$$



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

BBO's distance error (from noise)

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



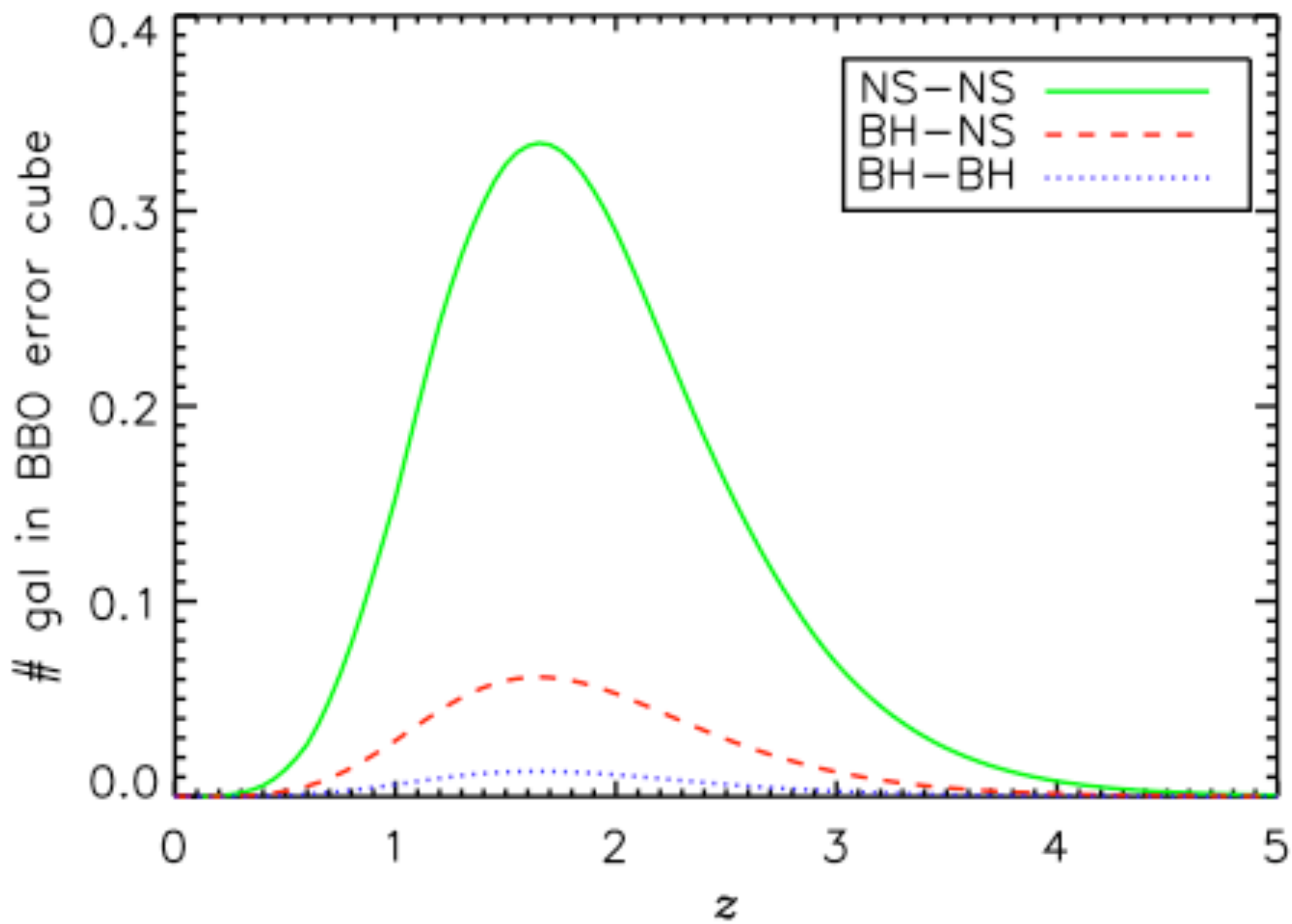
Actually, BBO's distance error is dominated by Weak Lensing

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

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:

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

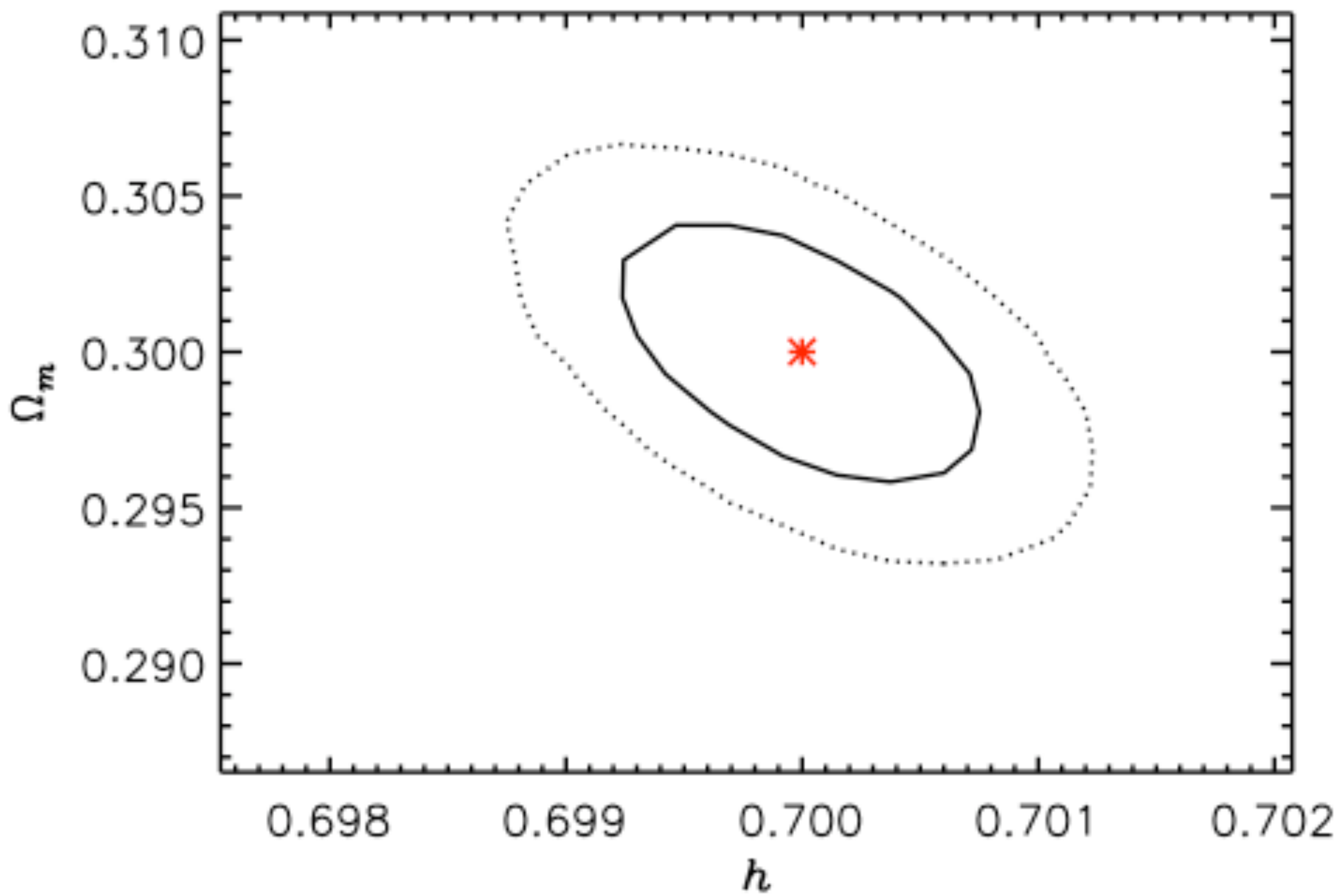
where

$$w(z) \equiv p/\rho \quad \& \quad w(z) = w_0 + w_a \frac{z}{(1+z)}$$

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

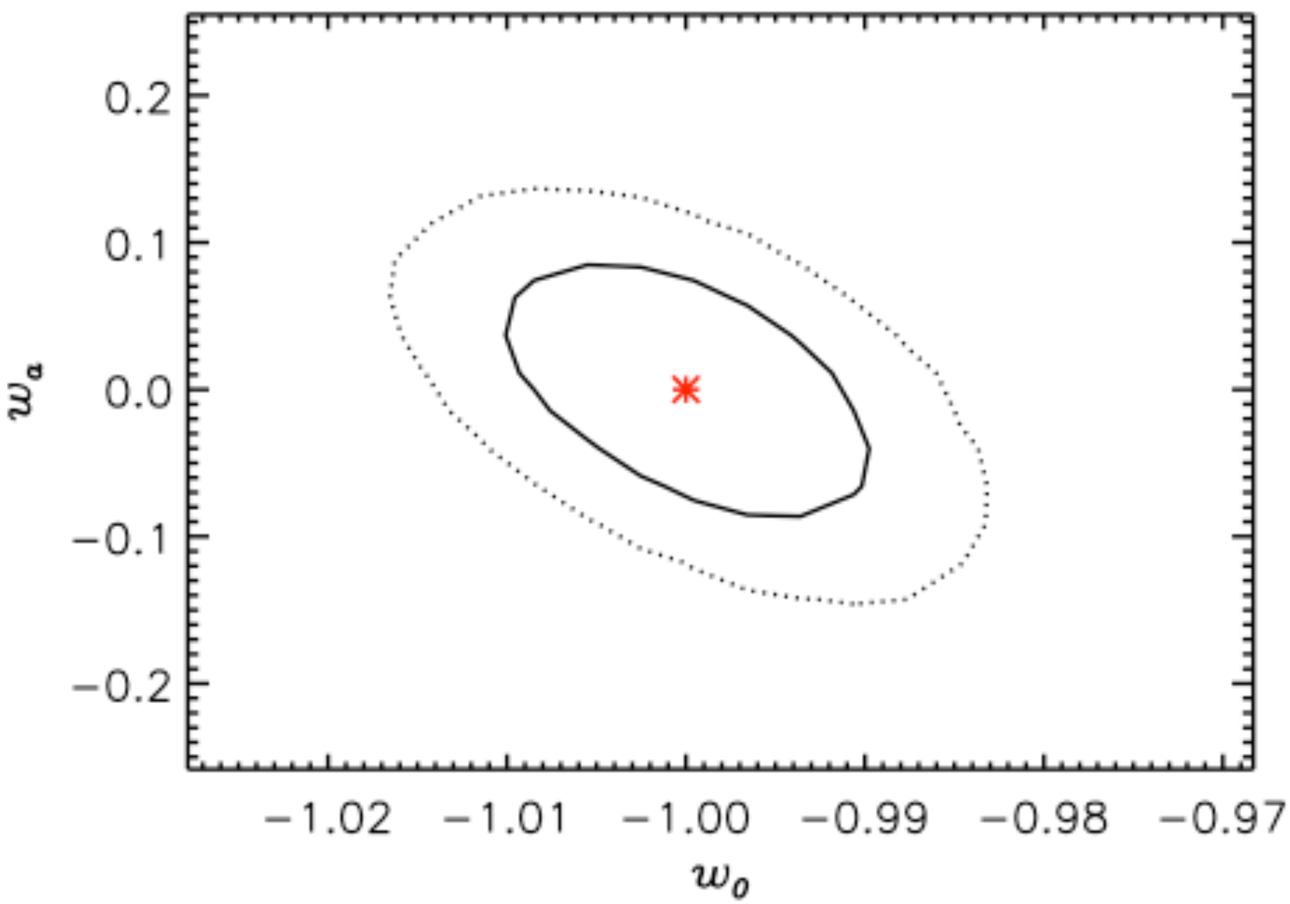
2.5e5 NSs up to z=3 $\Rightarrow H_0$ to 0.1%

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

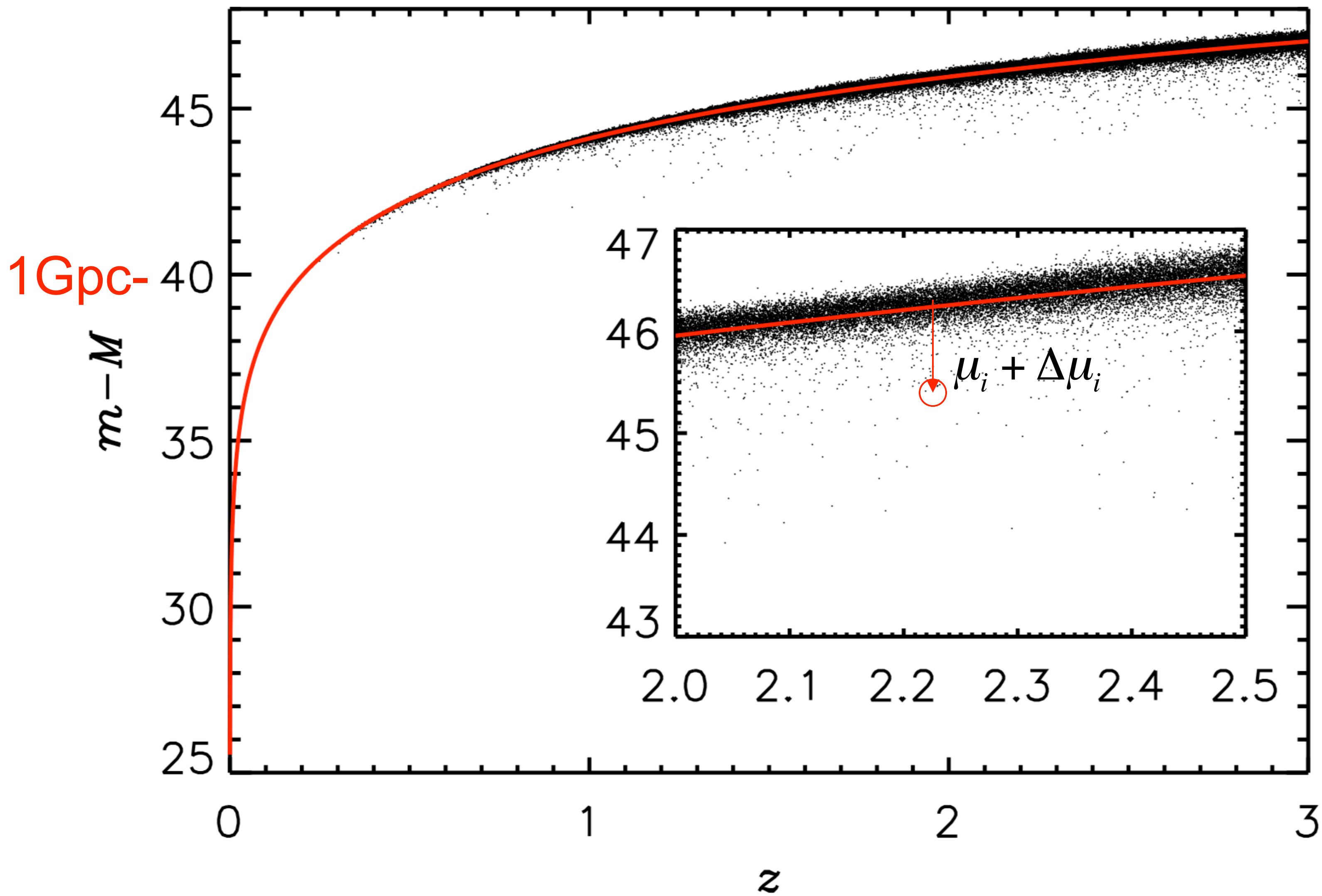


2.5e5 NSs up to z=3 $\Rightarrow w_0$ to ~0.01

$\Rightarrow w_a$ to ~0.1



BBO as a Weak Lensing mission



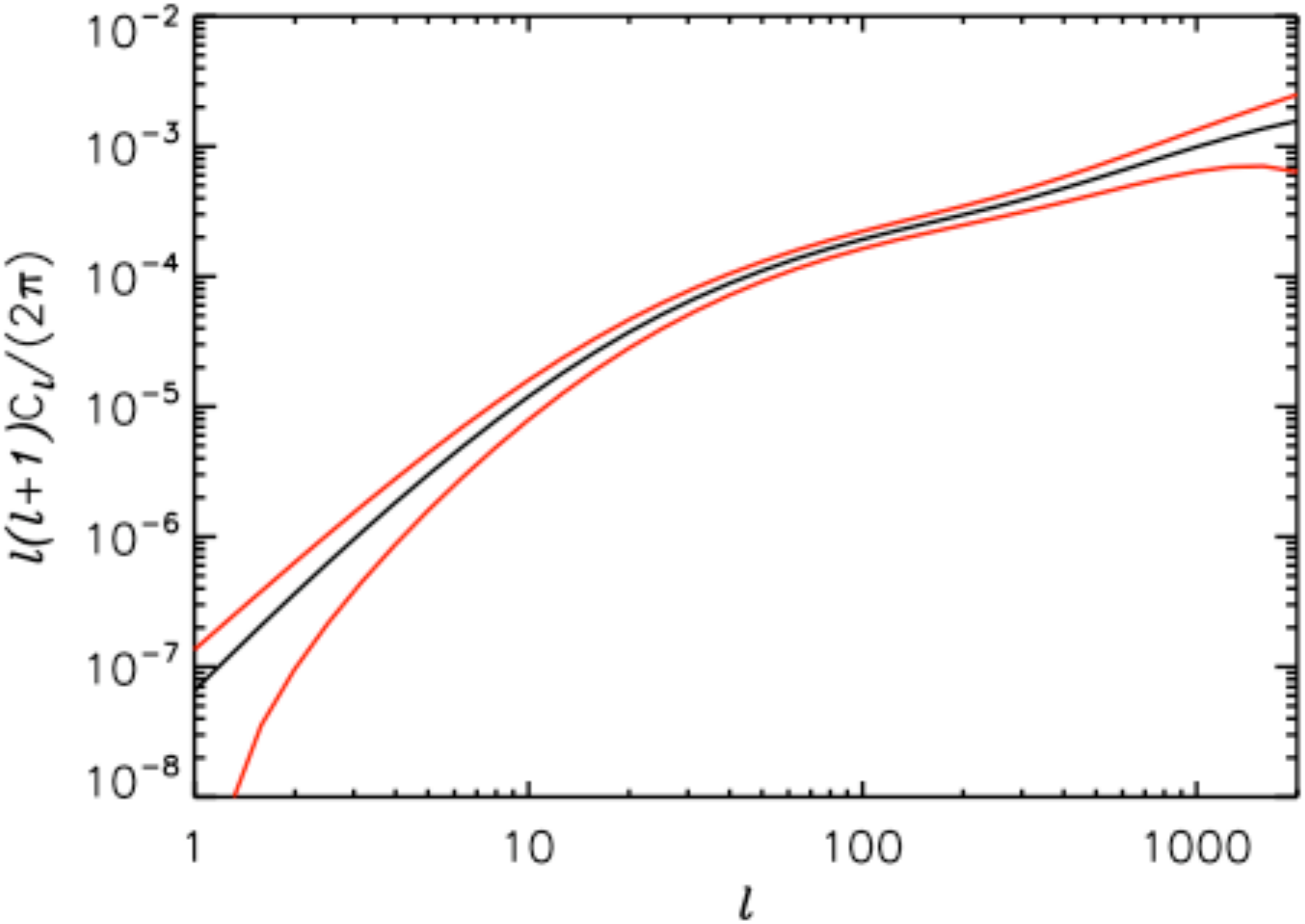
BBO/Decigo as WL mission

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

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 will

- Calculate how well these WL measurements can constrain cosmological models. Include the information not contained in the $\delta\rho$ power spectrum, but available in the 3-pt function.

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

Optical Follow-ups

Recall that BBO gives D_L and a small error box on sky. Optical astronomers must still provide 300,000 redshifts. Is this realistic?

• By the time BBO flies, the LSST could have determined photometric redshifts (accurate to 2-3%) for a large fraction of galaxies over 1/3 of the sky.

•There are several proposed wide-field spectroscopic surveys. E.g., BigBOSS would meaure ~5 million spectroscopic redshifts per year (~4,000 at a time) for galaxies in the range $0.2 < z < 3.5$, over an area of 14,000 sq. degrees.

(WFMOS instrument on Subaru telescope would have been Comparable to BigBoss, but their funding was just cut.)

Other Astrophysics from BBO/Decigo (1)

1. 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.

Other Astrophysics from BBO/Decigo (2)

2. 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 observed gamma rays.

Other Astrophysics from BBO/Decigo (3)

3. Strong Lensing of merging binaries

❖ ~1/1000 of quasars are “multipy-imaged”, so we would expect BBO to observer hundreds of “mulitply-imaged” binaries.

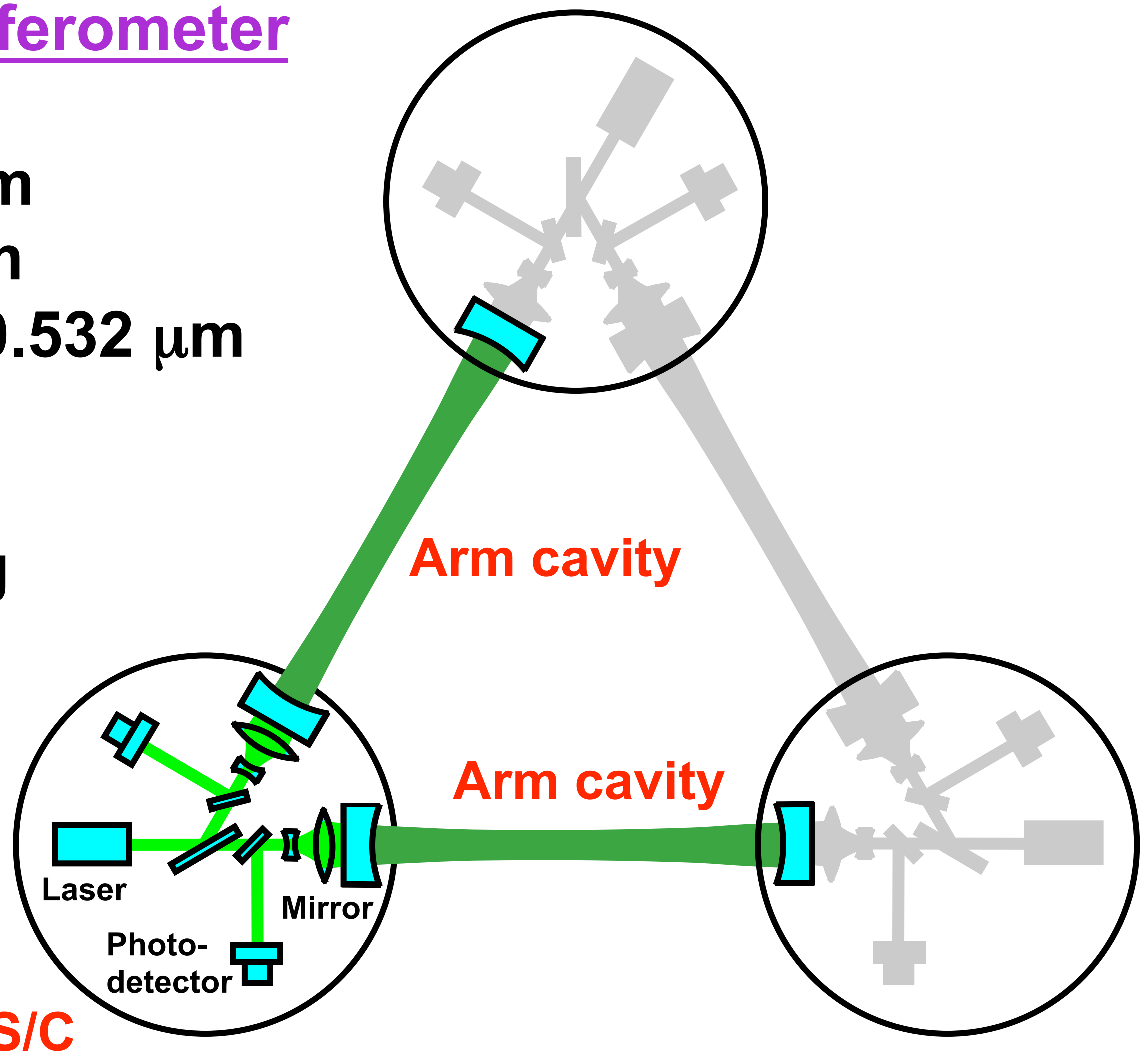
❖Time-delays will be of order a year, and measured to <0.1 sec. Give independent estimates of H_0 .

❖Time delays and amplifications probe the structure of the lensing galaxies/clusters.

Decigo: Pre-conceptual design

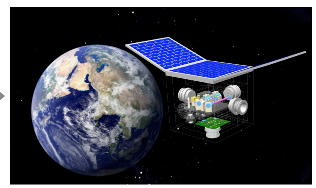
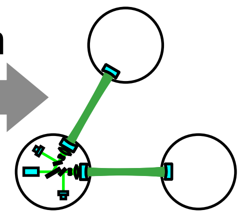
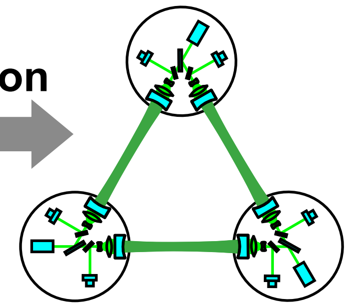
Differential FP interferometer

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



from Kawamura

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					

from Kawamura

Caveat re Calibration

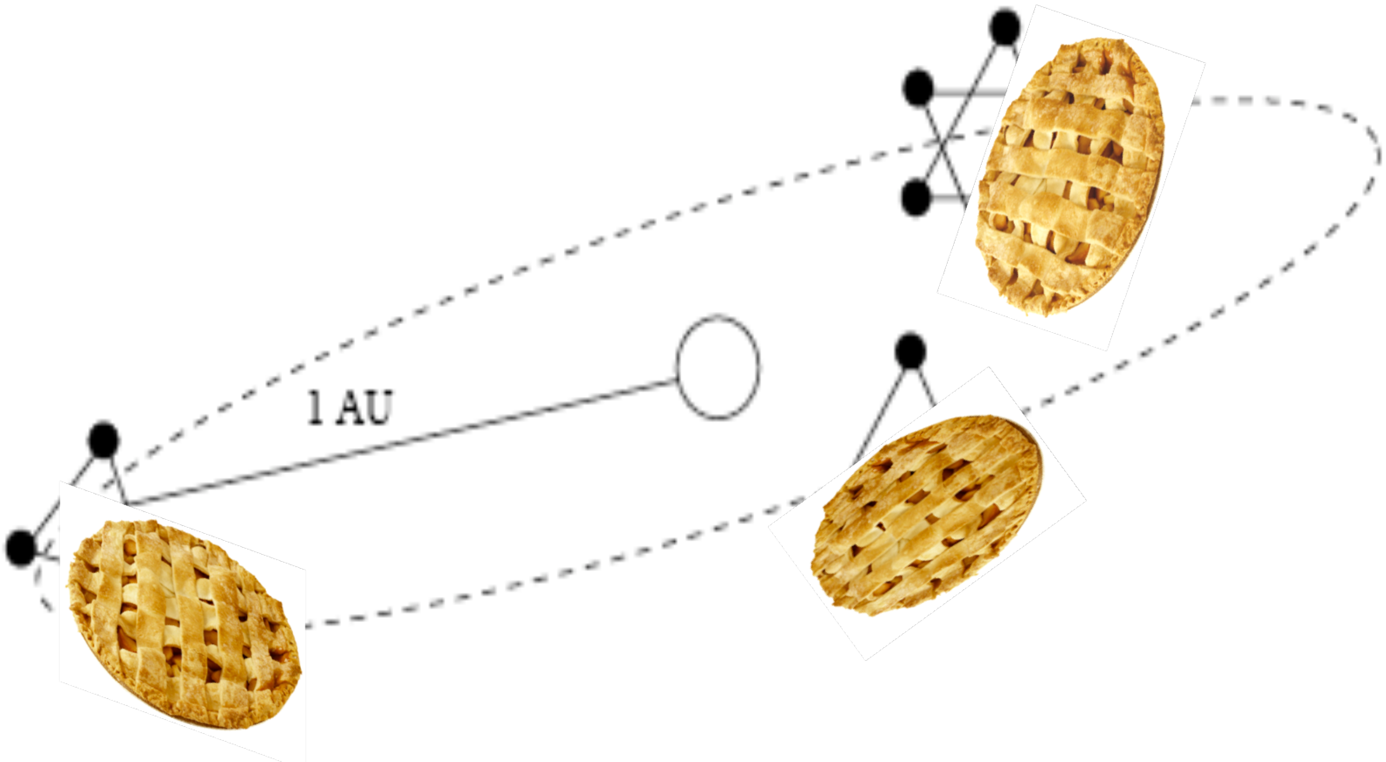
BBO interferometry in BBO Mission Concept Study (Phinney et al., 2003) is very "LISA-like": no applied forces along sensitive direction.

Later it was realized that this design would greatly oversaturate current UV photodiodes. Harry et al.(2006) proposed a more "LIGO-like" design,with forces on the test mass to keep photodiode operating near dark fringe. But this spoils calibration accuracy unless the force is measured very accurately. DECIGO is in same situation.

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: Pie in the Sky?

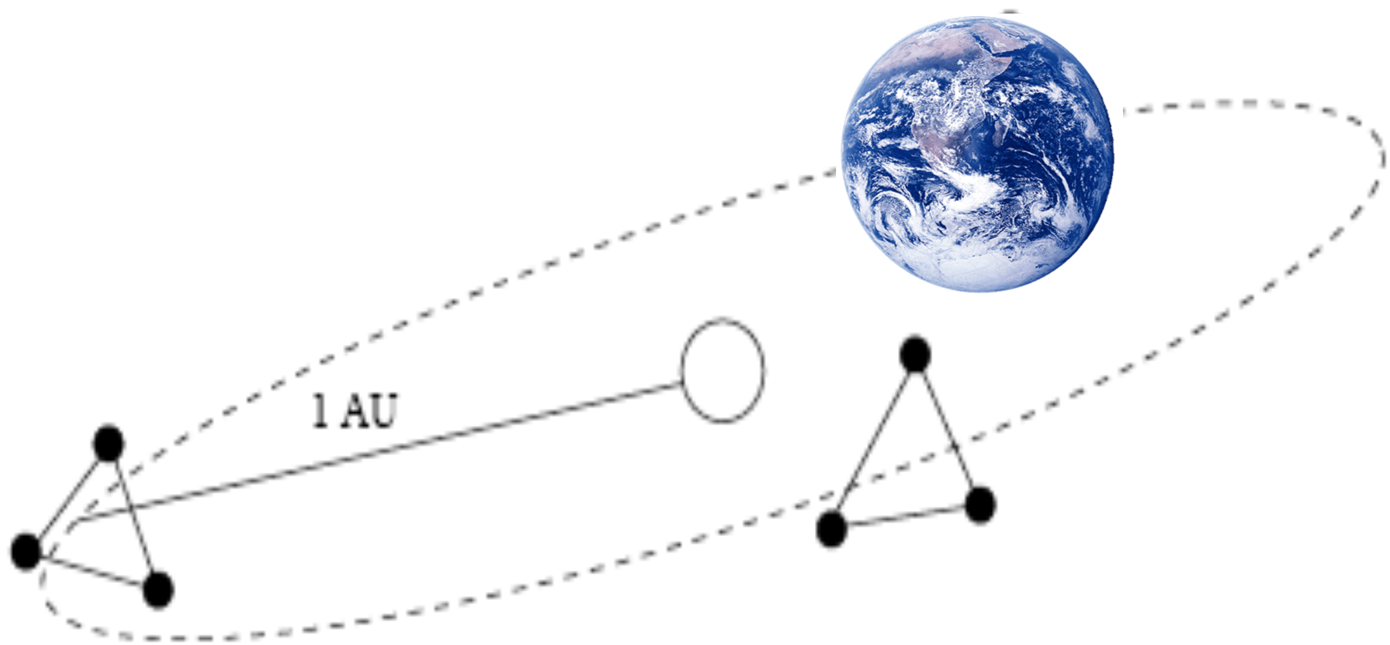


Many see BBO as unrealistic, in our lifetime timescale of our remaining lifetime) Fortunately in its current version it is probably overqualified for doing high-precision cosmology. For this, don’t need to detect EVERY NS-NS binary: a good fraction out to z~2 would probably do. Once you redefine the goal, all the mission parameters are up for grabs again.

Next step in this project:

Calculate the science yield of de-scoped versions of BBO.

6-satellite BBO +ET:



How much can mini-LISA sensitivity be descoped, and still do high precision cosmology?

Example of possible plan:

Step 1. One mini-LISA +ET

Step 2. Two mini-LISAs + ET: high – precision cosmology

Step 3. Full BBO: Inflationary GW background.

Conclusion:

If we can build a deci-Hz space-based GW mission approaching the target sensitivities of BBO or Decigo, then

inspiraling Compact Binaries will be a Cosmology Goldmine

Offer virtually systematics-free cosmological measurements, with far better accuracy than with any other proposed methods.

These missions should be designed to have calibration accuracy at $\sim 10^{-4}$ level.