Stochastic Gravitational-Wave Searches with Ground-Based Detectors

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Outline

I Techniques for Detecting a Stochastic Background

- Cross-Correlation Statistic
- Optimal Filter
- Overlap Reduction Function

II Ground-Based Stochastic Background Searches

- Past (Existing Upper Limits)
- Present (Work in Progress)
- Future (Prospects for Detector Combinations)

Cartoon courtesy of E. Coccia, NAUTILUS Group (Rome)

Stochastic Background

Backgrounds in 10–1000 Hz frequency band likely extragalactic in origin, thus isotropic, unpolarized, gaussian, & stationary.

Describe i.t.o. GW contribution to $\Omega = \frac{\rho}{\rho_{\text{crit}}}$:

$$\Omega_{\text{GW}}(f) = \frac{1}{\rho_{\text{crit}}} \frac{d\rho_{\text{GW}}}{d \ln f} = \frac{f}{\rho_{\text{crit}}} \frac{d\rho_{\text{GW}}}{df}$$

Note $\rho_{\text{crit}} \propto H_0^2$, so $h_{100}^2 \Omega_{\text{GW}}(f)$ is independent of

$$h_{100} = \frac{H_0}{100\,\text{km/s/Mpc}}$$

How to Tell Stochastic Signal from Random Noise

- Need correlations among detectors
  - Detector 1: $h_1 = s_1 + n_1$, Detector 2: $h_2 = s_2 + n_2$
- Assume noise uncorrelated with signal & between detectors
- Cross-correlation:

$$\langle h_1 h_2 \rangle \;=\; \langle n_1 n_2 \rangle + \langle n_1 s_2 \rangle + \langle s_1 n_2 \rangle + \langle s_1 s_2 \rangle$$

  only surviving term is from stochastic GW signal

Sensitivity to Stochastic GW Backgrounds

- Optimally filtered CC statistic

$$Y = \int df\, \tilde{h}_1^*(f)\, \tilde{Q}(f)\, \tilde{h}_2(f)$$

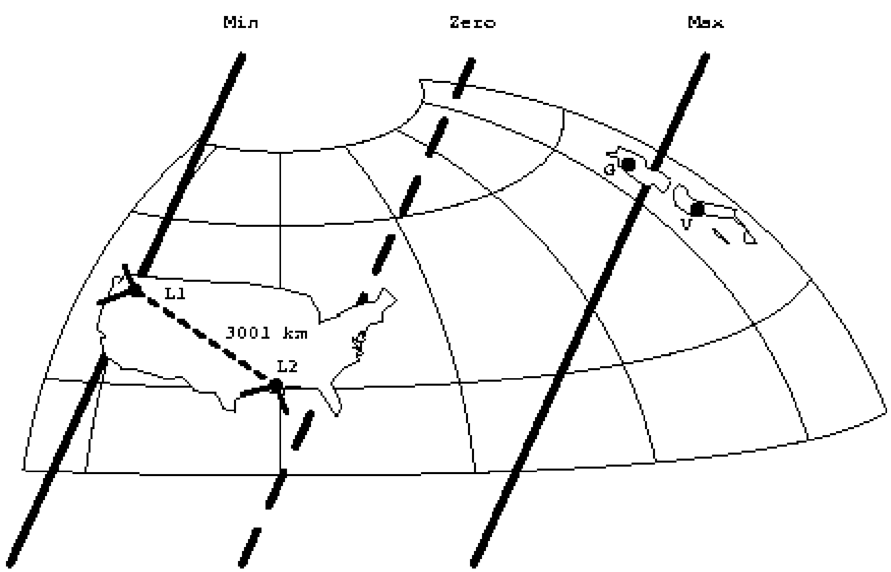
- Optimal filter $\tilde{Q}(f) \propto \frac{f^{-3}\Omega_{GW}(f)\gamma_{12}(f)}{P_1(f)P_2(f)}$
  (Initial analyses assume $\Omega_{GW}(f)$ constant across band)
- Optimally filtered cross-correlation method sensitive to

$$\Omega_{GW} \propto \left(T \int \frac{df}{f^6} \frac{\gamma_{12}^2(f)}{P_1(f)P_2(f)} \right)^{-1/2}$$

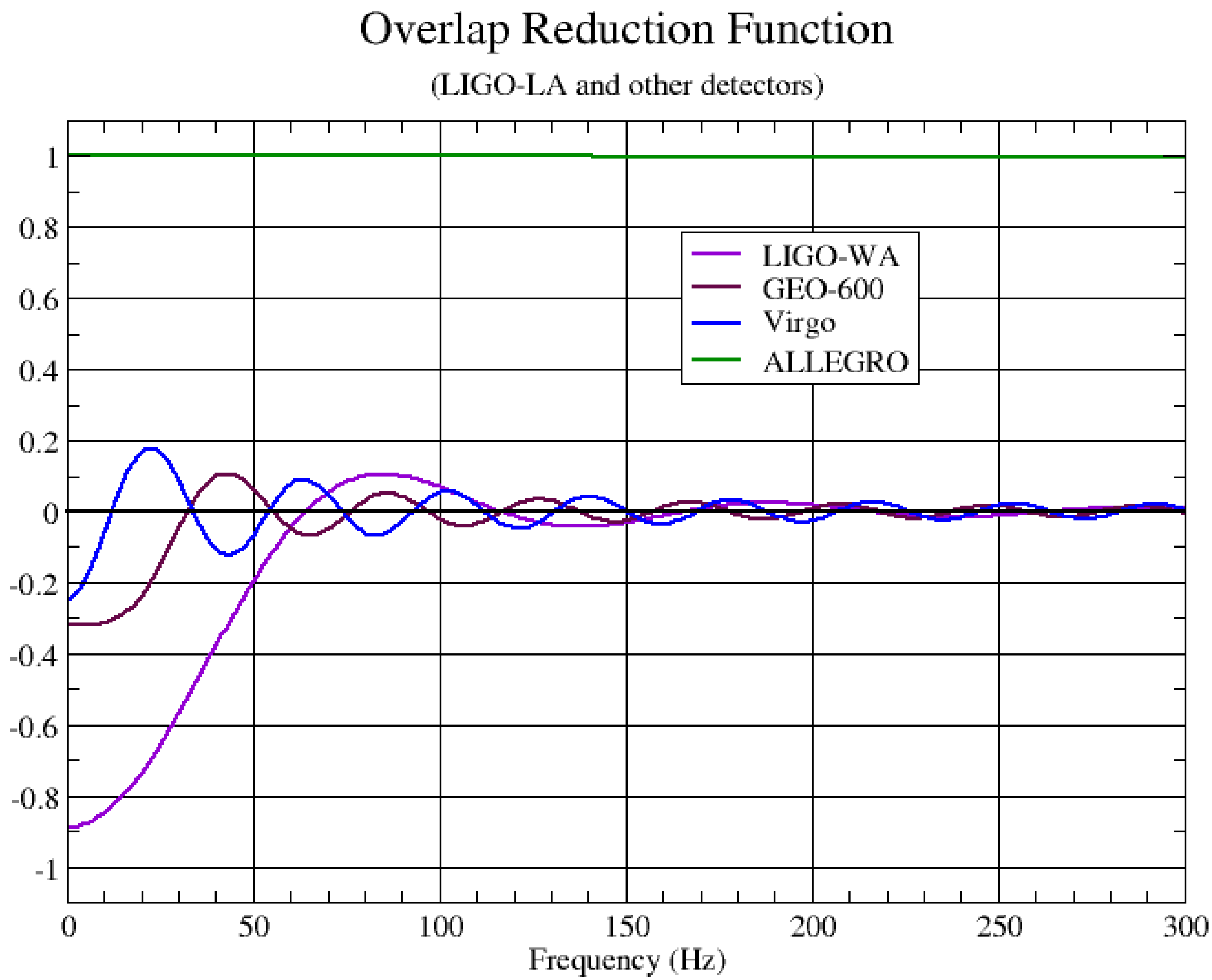
- Significant contributions when
  - detector noise power spectra $P_1(f)$, $P_2(f)$ small
  - overlap reduction function $\gamma_{12}(f)$ (geom correction) near ± 1

Overlap Reduction Function

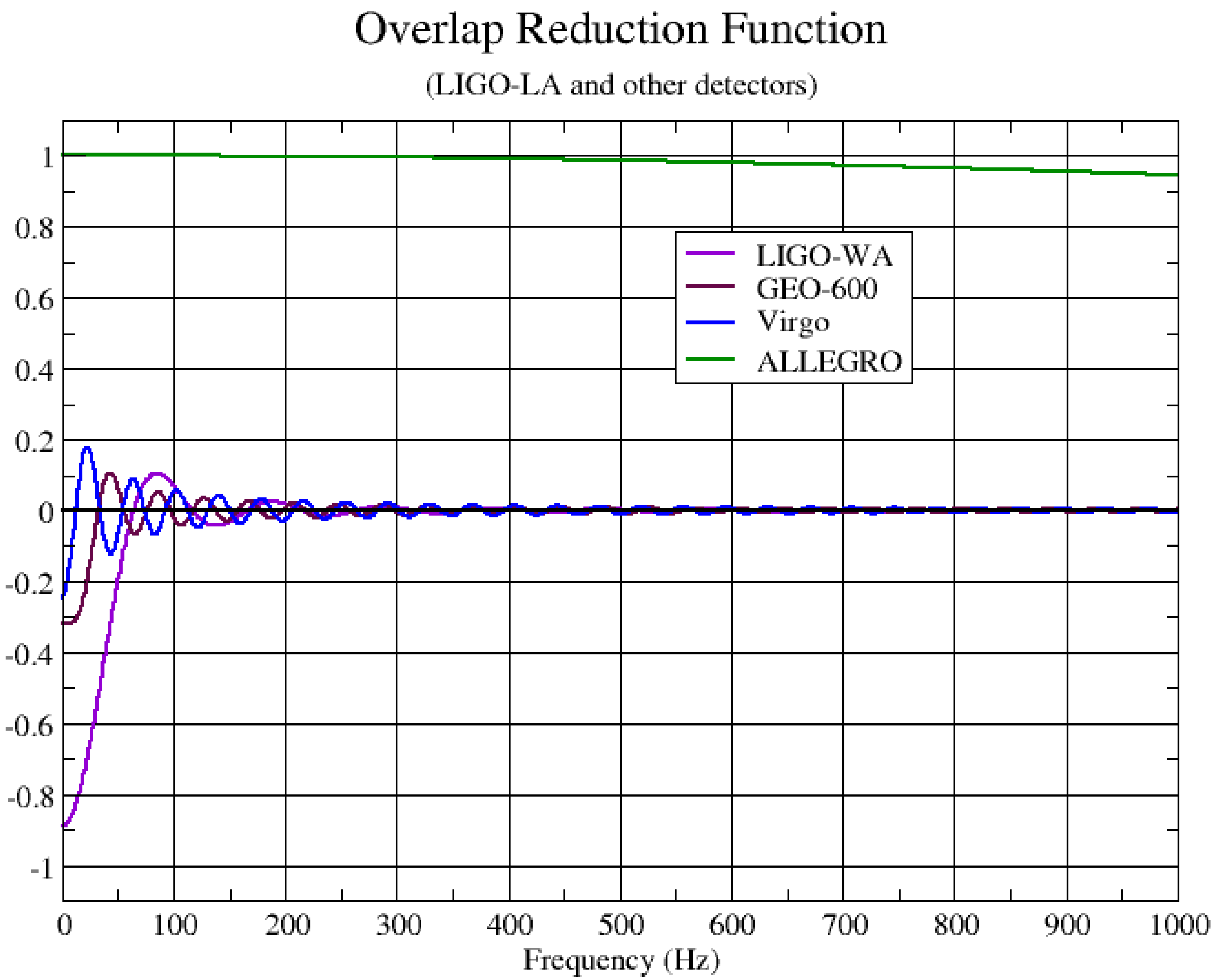
Depends on alignment of detectors (polarization sensitivity)
Frequency dependence from cancellations when $\lambda \lesssim$ distance
$\longrightarrow$ Widely separated detectors less sensitive at high frequencies

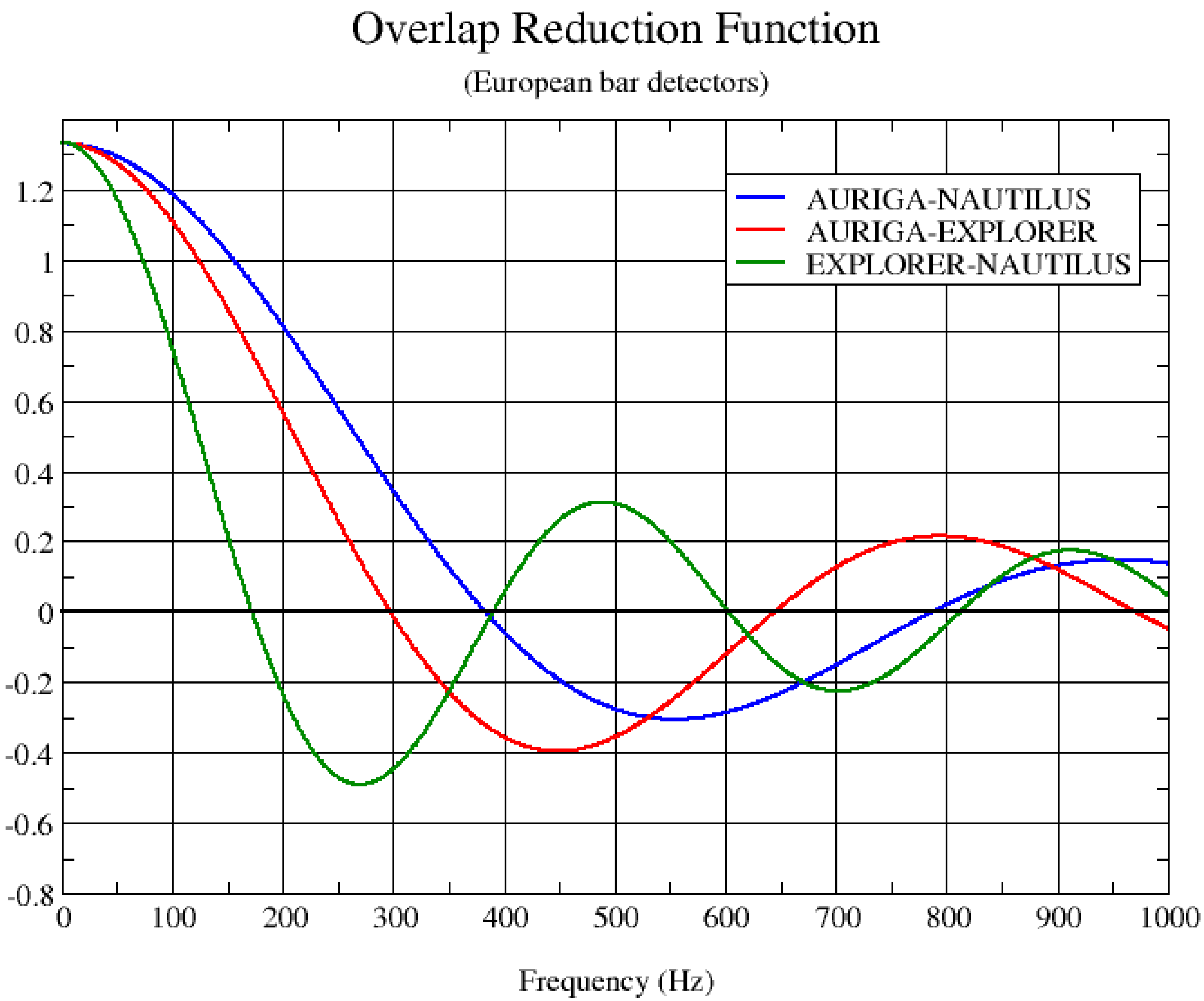


(figure from Allen & Romano PRD, gr-qc/9710117)



Overlap Reduction Function
(LIGO-LA and other detectors)
LIGO-WA
GEO-600
Virgo
ALLEGRO
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
50
100
150
200
250
300
Frequency (Hz)


Overlap Reduction Function
(LIGO-LA and other detectors)
LIGO-WA
GEO-600
Virgo
ALLEGRO
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)


Overlap Reduction Function
(European bar detectors)
AURIGA-NAUTILUS
AURIGA-EXPLORER
EXPLORER-NAUTILUS
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)

Previous Results

- Current best upper limit: correlation between EXPLORER & NAUTILUS bars (Astone et al, 1999): $h_100^2\Omega_{\rm GW}(907\,{\rm Hz}) \le 60$
- Correlation between Garching & Glasgow prototype IFOs (Compton et al, 1994): $h_100^2\Omega_{\rm GW}(f) \lesssim 3 \times 10^5$
- Correlation between 70 hrs of LIGO Hanford & Livingston engineering (E7) data (Tech Doc LIGO-T020115-00-Z): $h_100^2\Omega_{\rm GW}(f) \lesssim 8 \times 10^4$

Present Research: LIGO/LIGO

- 3 IFOs: LLO 4 km (L1), LHO 4 km (H1), LHO 2 km (H2)
- H1-H2 correlations have $\gamma = 1$, but likely correlated noise
- H1-L1 & H2-L1 correlations: LHO & LLO 3000 km apart; LHO/LLO Overlap Reduction Function kills correlations above ~300Hz; most information from 50–250Hz
- LIGO Science Data (S1 Run):
  - 50–100 hr of coïncident data from all three LIGO IFOs
  - Results to be presented next week at Amaldi
  - Sensitivity will improve with S2 & beyond

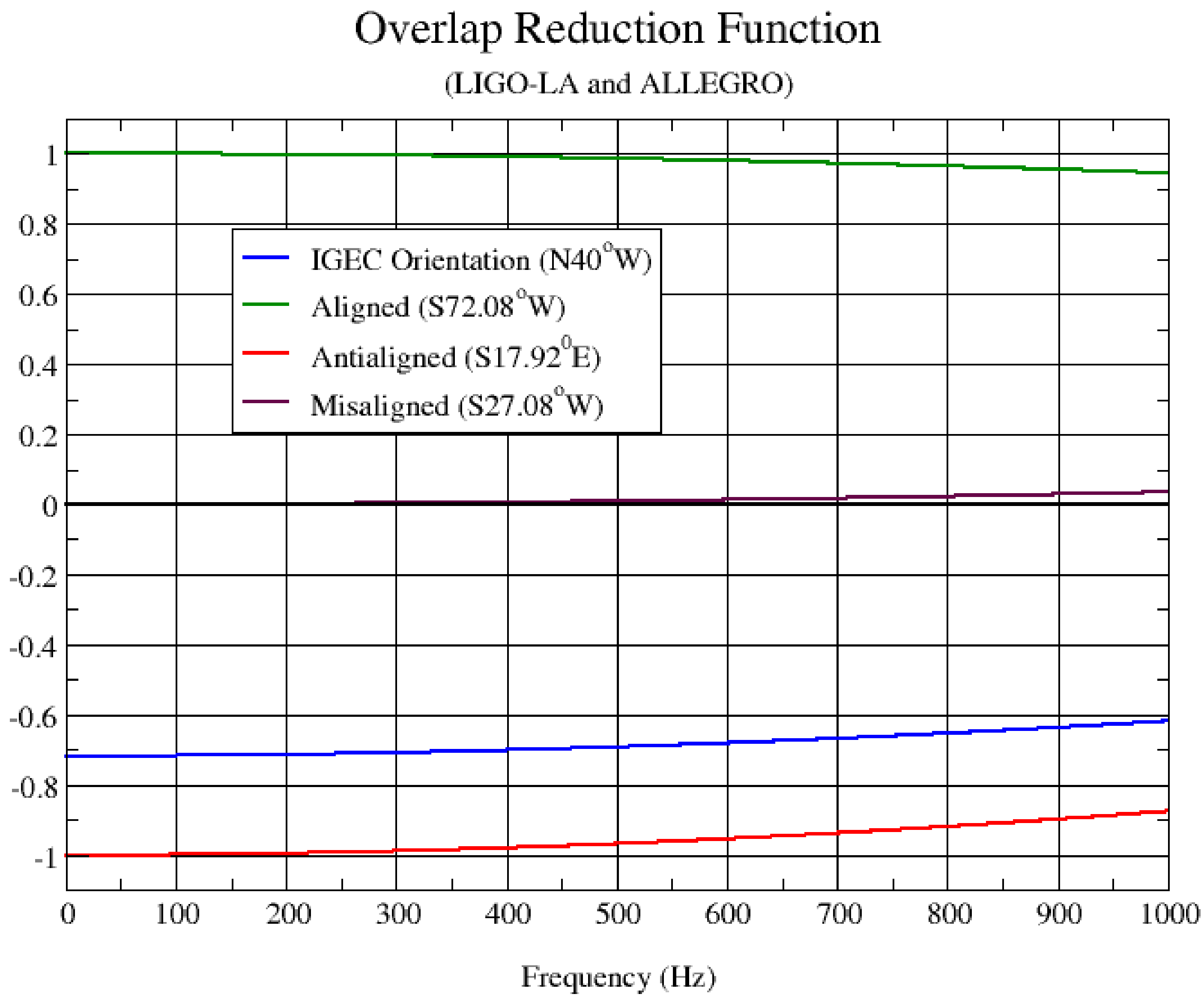
Ongoing Research: LLO/ALLEGRO

- Only $\sim$40 km apart $\rightarrow$ γ(900 Hz) $\approx$ 95% for best alignment

- Sensitive in different freq band from LLO/LHO pair

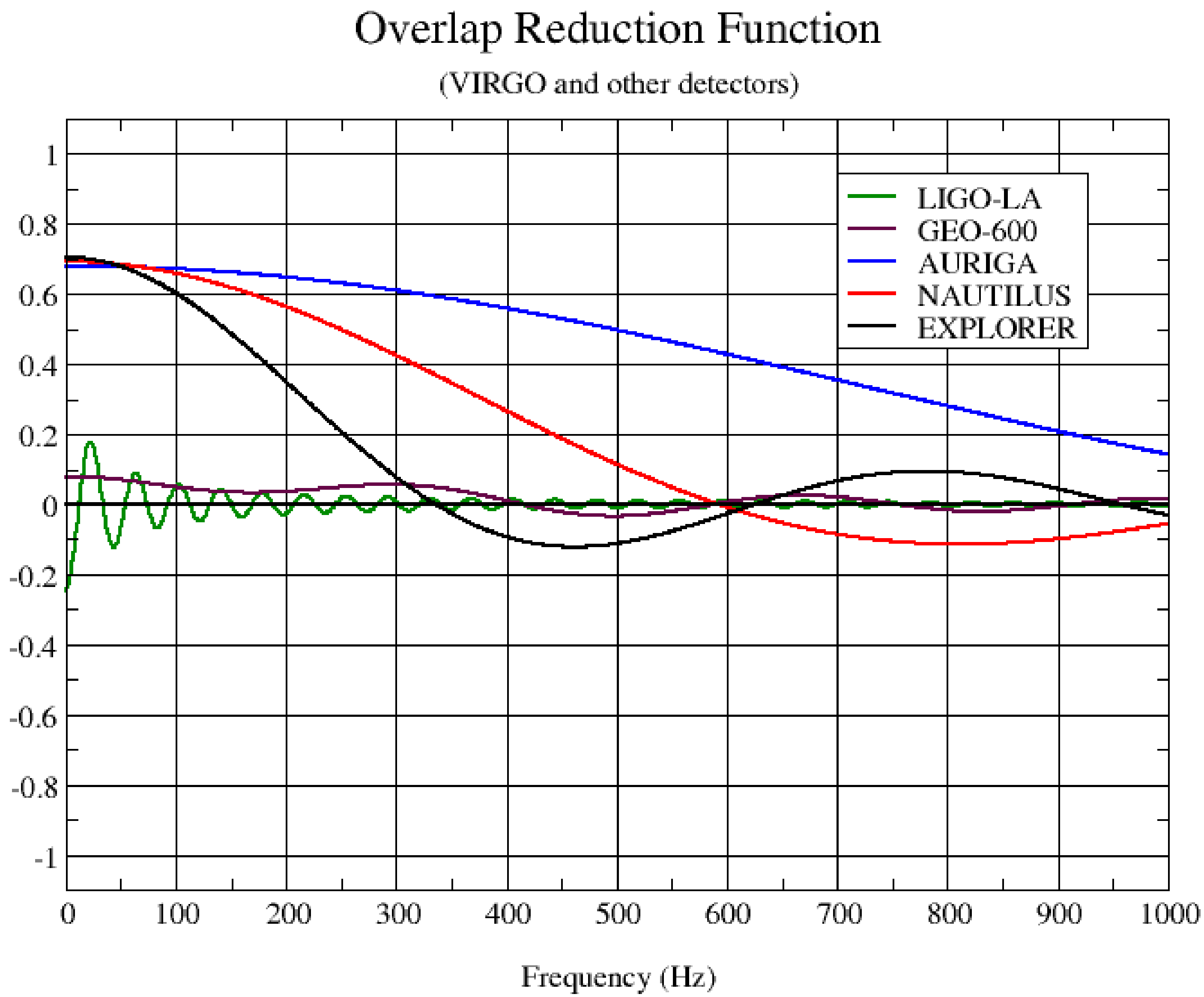
- New experimental technique: rotate ALLEGRO to callibrate cross-correlated noise (Finn & Lazzarini gr-qc/0104040)
  - Aligned & Anti-aligned orientations have opposite GW sign $\longrightarrow$ can "cancel" out CC noise by subtracting results
  - Null orientation has no expected GW signal $\longrightarrow$ "off-source" measurement of CC noise

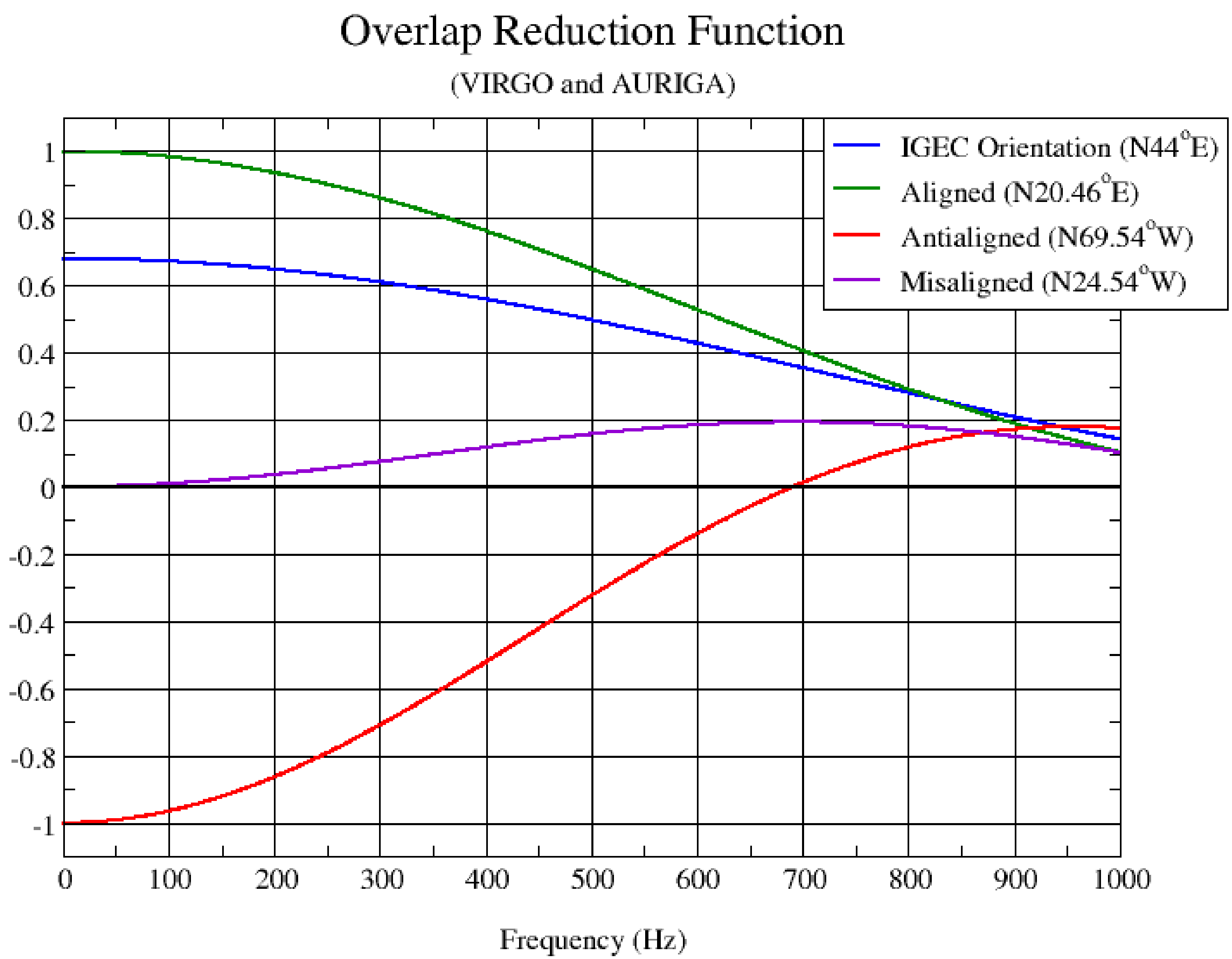
- Some data from E7 & S2; primary analysis planned for S3


Overlap Reduction Function
(LIGO-LA and ALLEGRO)
IGEC Orientation (N40°W)
Aligned (S72.08°W)
Antialigned (S17.92°E)
Misaligned (S27.08°W)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)

Future Prospects: Searches Involving VIRGO

- LIGO & TAMA far away
- GEO-600 interferometer close, but almost 45° off $\longrightarrow$ different polarization.
- Some potential for correlations with bars (but note bar resonance near onset of high-frequency cancellations)


Overlap Reduction Function
(VIRGO and other detectors)
LIGO-LA
GEO-600
AURIGA
NAUTILUS
EXPLORER
Frequency (Hz)



Overlap Reduction Function
(VIRGO and AURIGA)
IGEC Orientation (N44°E)
Aligned (N20.46°E)
Antialigned (N69.54°W)
Misaligned (N24.54°W)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)

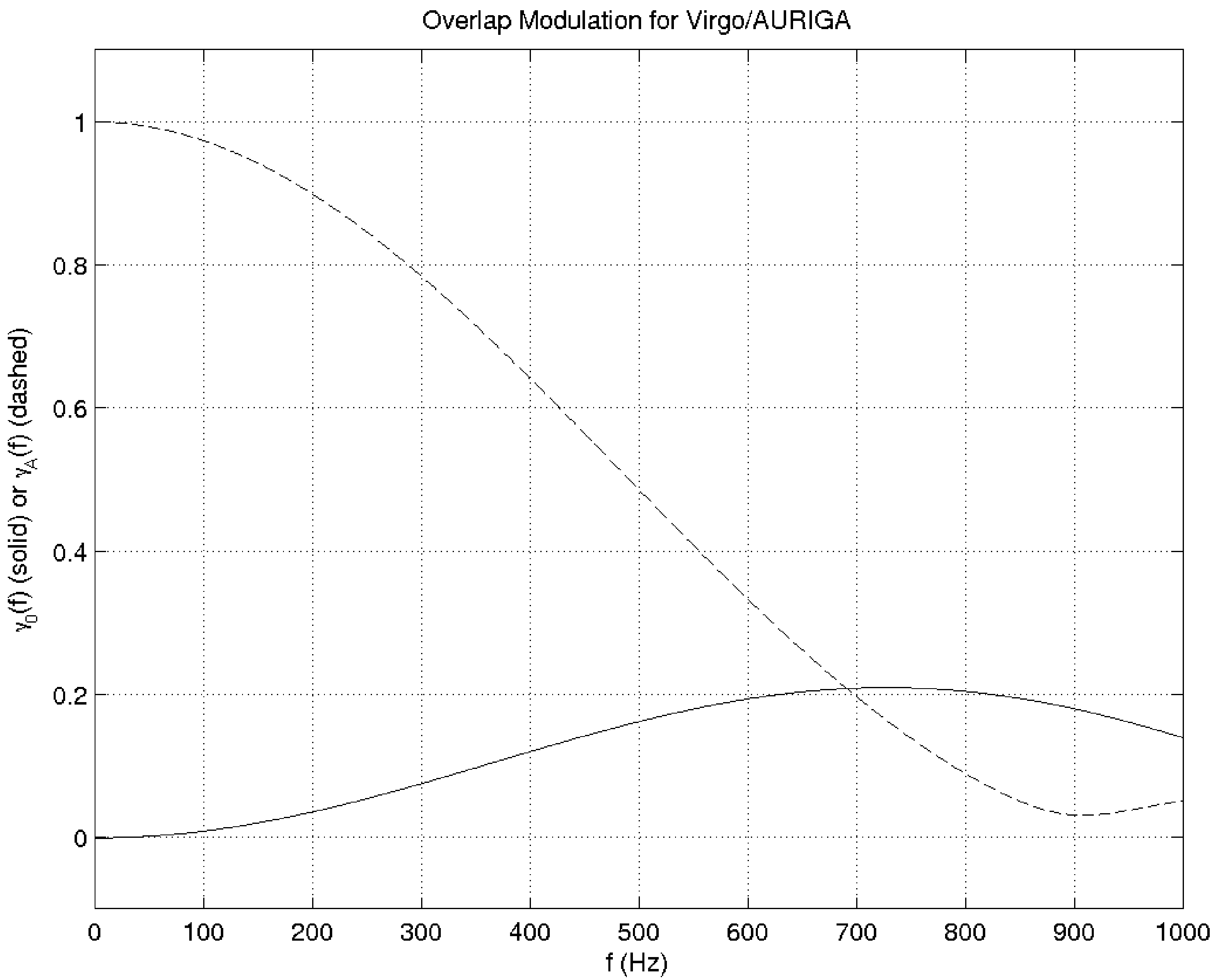
VIRGO-AURIGA Correlations

- $15\% \le \gamma(900\,\mathrm{Hz}) \le 20\%$ for *all* orientations

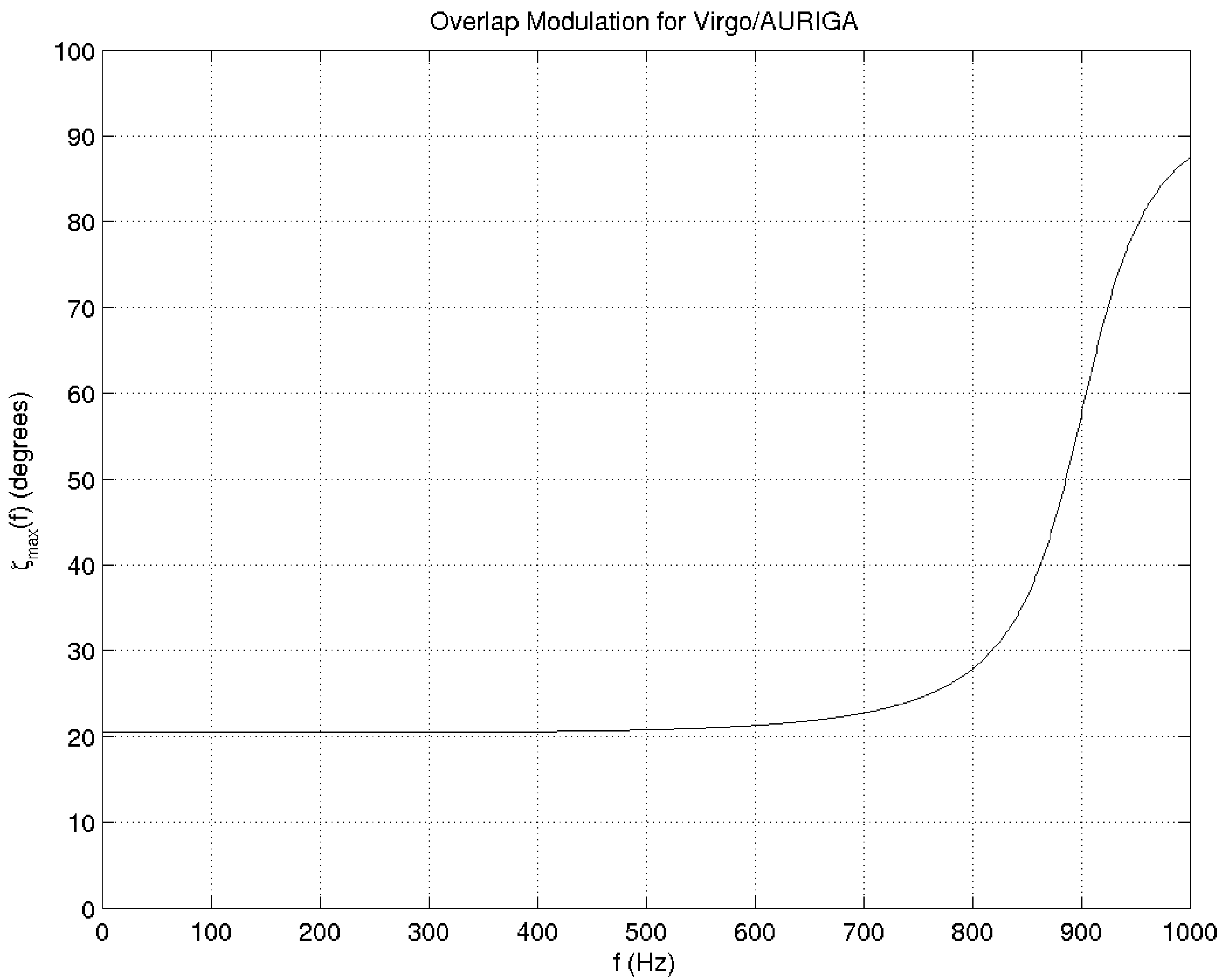
- Reasonable for correlations, but not much modulation (in particular, no null alignment)

- In general, for azimuth ζ

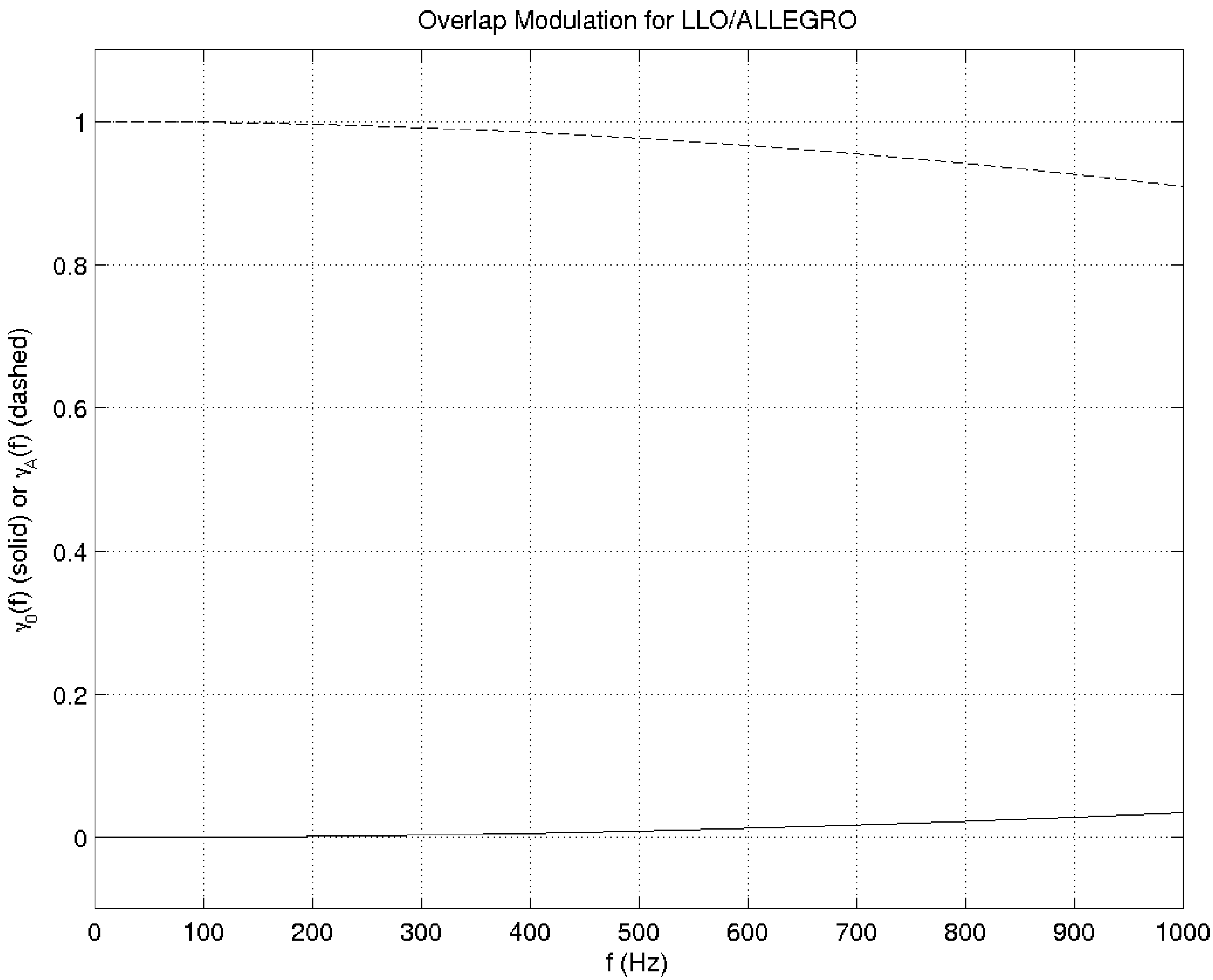
$$\gamma(f) = \gamma_0(f) + \gamma_A(f) \cos 2(\zeta - \zeta_{\mathrm{max}}(f))$$

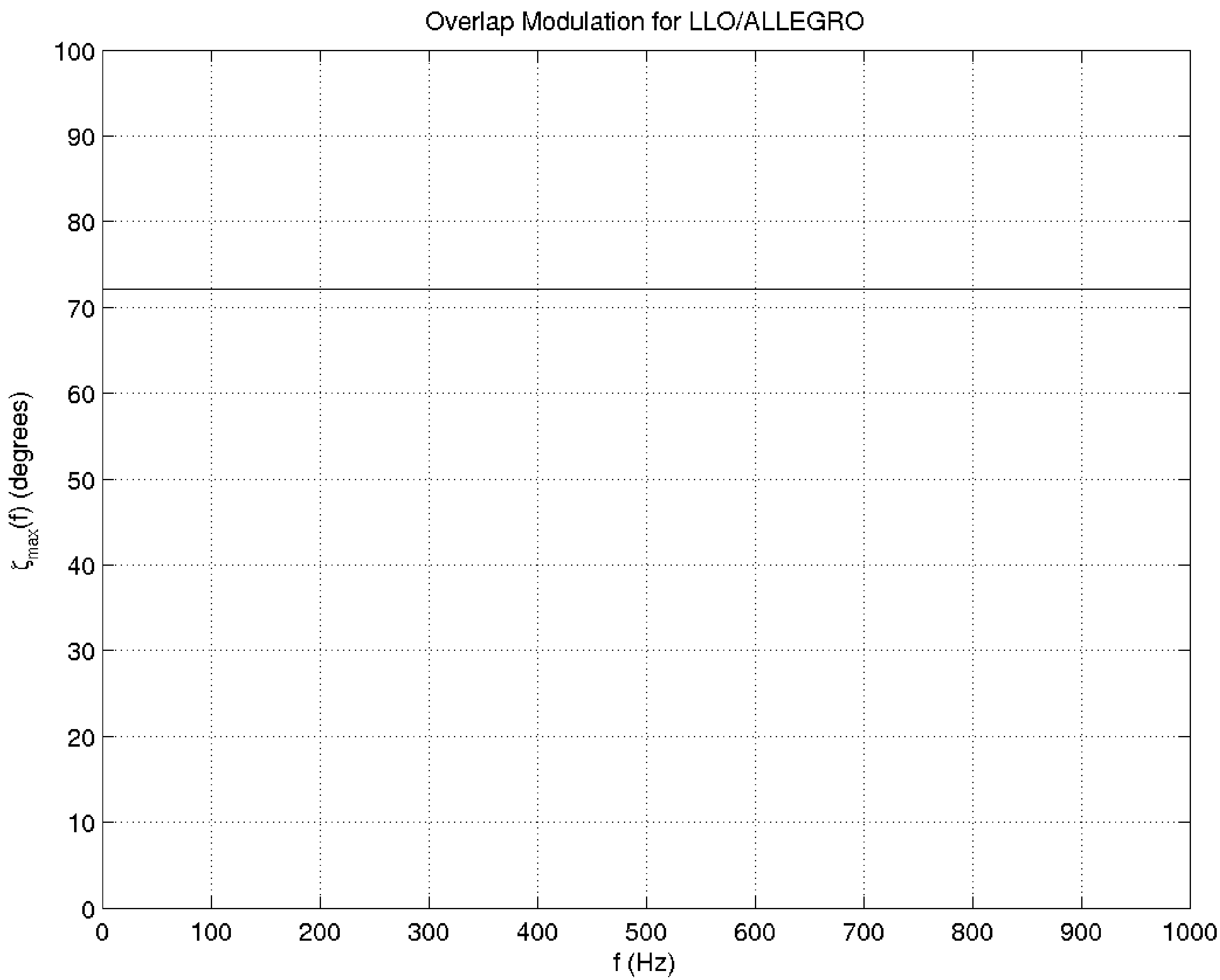


Overlap Modulation for Virgo/AURIGA
$\gamma_0(f)$ (solid) or $\gamma_A(f)$ (dashed)
f (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
0.2
0.4
0.6
0.8
1



Overlap Modulation for Virgo/AURIGA
ζmax(f) (degrees)
f (Hz)
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
700
800
900
1000


Overlap Modulation for LLO/ALLEGRO
$\gamma_0(f)$ (solid) or $\gamma_A(f)$ (dashed)
f (Hz)
0
0.2
0.4
0.6
0.8
1
0
100
200
300
400
500
600
700
800
900
1000



Overlap Modulation for LLO/ALLEGRO
100
90
80
70
60
50
40
30
20
10
0
$\zeta_{max}(f)$ (degrees)
0
100
200
300
400
500
600
700
800
900
1000
f (Hz)

Summary

- Stochastic BG search technique
  - optimally filtered cross-correlation statistic
  - geometry enters thru overlap reduction function

- Individual experiments
  - Previous upper limits: bars, prototype IFOs, eng data
  - First LIGO science results next week at Amaldi
  - LLO/ALLEGRO allows for GW signal modulation by rotating bar
  - VIRGO/AURIGA reasonably efficient, but little modulation

References

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10. LSC Stochastic UL Page: `http://www.phys.utb.edu/stochastic/`
11. LIGO Algorithm Library: `http://www.lsc-group.phys.uwm.edu/lal/`