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# Stochastic Gravitational Wave Background from Non-Tensorial Polarizations

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# Overview

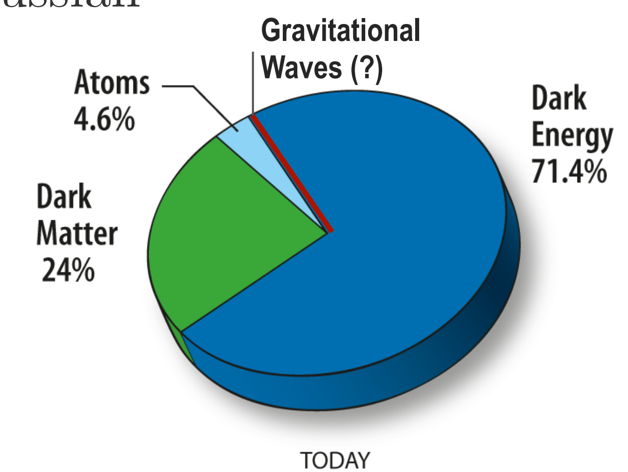
- The Stochastic Background
- Gravitational Wave Polarizations
- Project Description and Motivation
- Cross-Correlated Analysis
- Simulations
- O1 Result
- Conclusion and Outlook

# The Stochastic Background

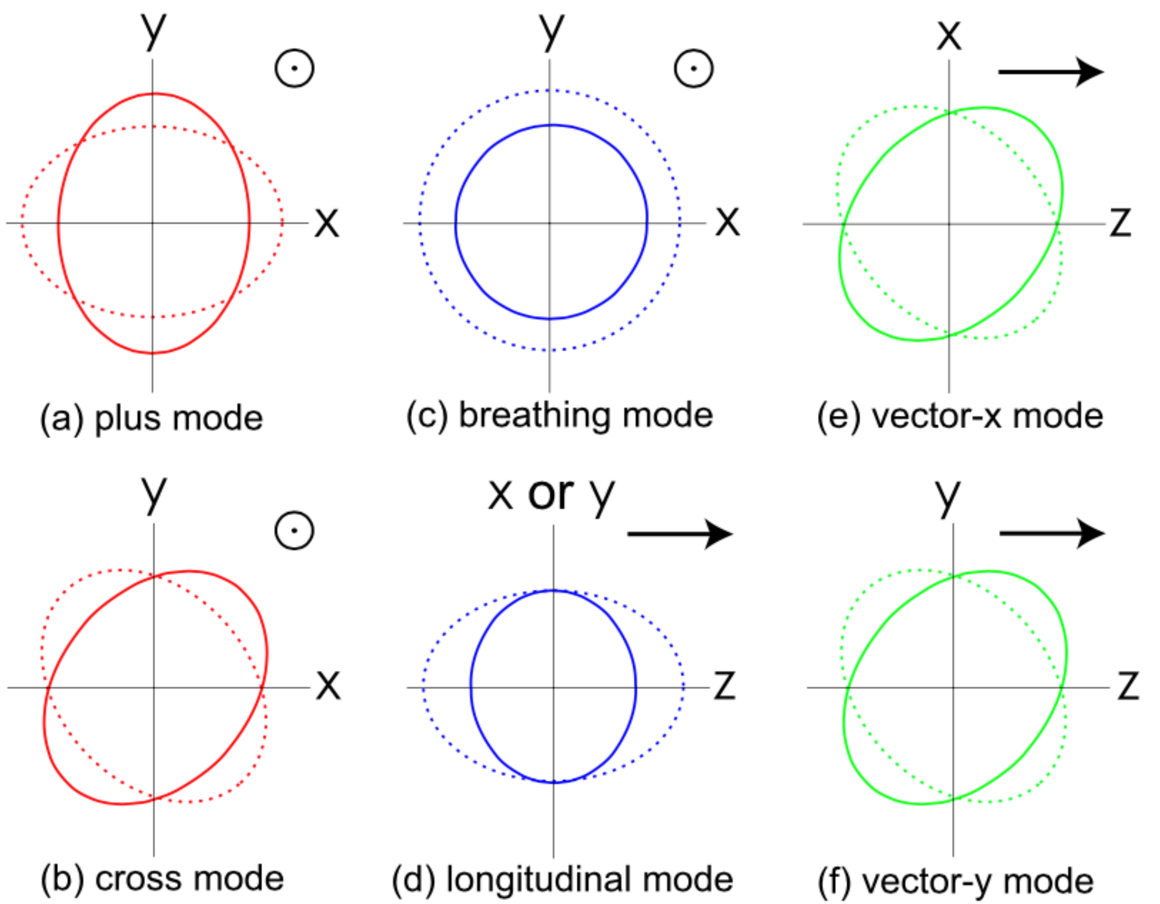
- A random gravitational wave signal produced by many overlapping, individually indistinguishable sources
  - Astrophysical
  - Cosmological
- Isotropic, unpolarized, stationary, and Gaussian

$$\Omega_{\rm gw}(f) = \frac{1}{\rho_{\rm critical}} \frac{d\rho_{\rm gw}}{d \ln f}$$

$$\Omega_{\rm gw} = \Omega_\alpha (f/f_0)^\alpha$$



# Gravitational Wave Polarizations




A. Nishizawa et al. Phys. Rev. D 79, 082002 (2009).

- Extra polarizations due to extra degrees of freedom associated with scalar fields or massive gravity
- Stochastic search can provide information about gravitation in the early universe and about sources which are too rare for individual detections.

# Project Description

- Modify the stochastic search pipeline to allow for searches for vector and scalar polarizations
- Run the search over O1 data [redacted]
- Use a Bayesian approach to model selection and component separation [redacted]

# Cross Correlated Analysis - GR

$$\tilde{s}(f) = \tilde{h}(f) + \tilde{n}(f)$$

- Correlate the strain signal from two detectors sufficiently far apart to minimize common noise sources

$$Y \propto \langle \tilde{s}_I^*(f)\tilde{s}_J(f)\rangle$$

$$\sigma^2 \propto \frac{P_I(f)P_J(f)}{\gamma_{IJ}^2(f)}$$

$$\langle Y \rangle = \Omega_{gw}$$

$$\mathrm{SNR} = \frac{\langle Y \rangle}{\sigma}$$

# Cross Correlated Analysis – Non GR

$$\tilde{s}(f) = \tilde{h}(f) + \tilde{n}(f)$$

- Correlate the strain signal from two detectors sufficiently far apart to minimize common noise sources

$$Y \propto \langle \tilde{s}_I^*(f)\tilde{s}_J(f)\rangle \qquad \sigma^2 \propto P_I(f)P_J(f)$$

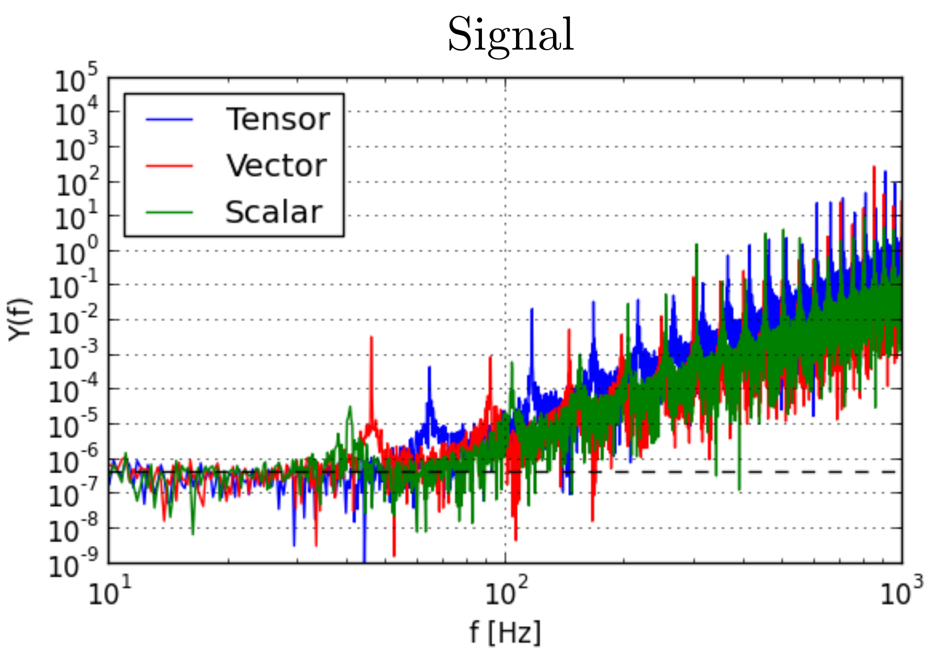
$$\langle Y \rangle = \sum_A \gamma_A \Omega_A \qquad \mathrm{SNR}^2 = \frac{\left[\frac{Y\gamma_M\Omega_M}{\sigma^2}\right]^2}{\frac{[\gamma_M\Omega_M]^2}{\sigma^2}}$$

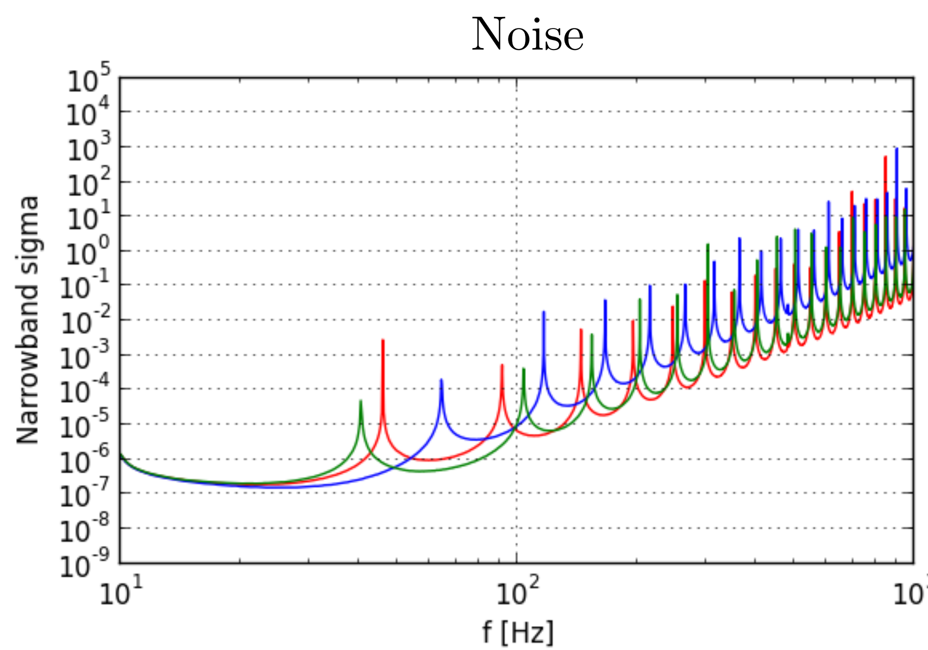
# Simulations

- Flat signal ($\alpha = 0$) with amplitude $\Omega_{gw} = 2 \times 10^{-7}$

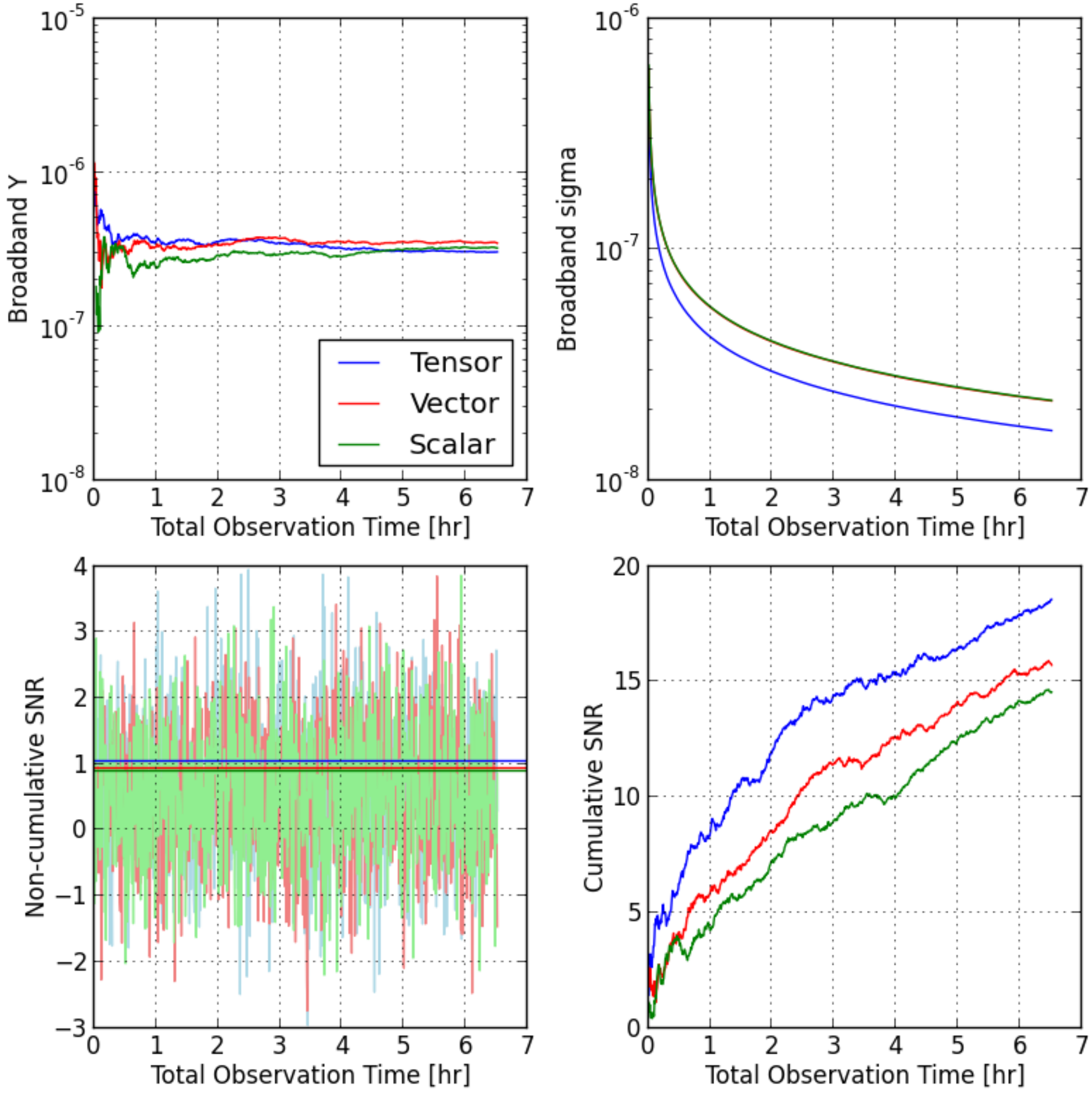
| | Recover Tensor | Recover Vector | Recover Scalar |
|---|---|---|---|
| Inject Tensor | 18.56<br>18.90 | 15.72<br>16.76 | 14.55<br>14.00 |
| Inject Vector | 12.88<br>12.58 | 12.89<br>14.19 | 12.10<br>13.73 |
| Inject Scalar | 10.70<br>10.30 | 13.53<br>13.45 | 14.84<br>13.91 |

# Injecting a Tensor Signal

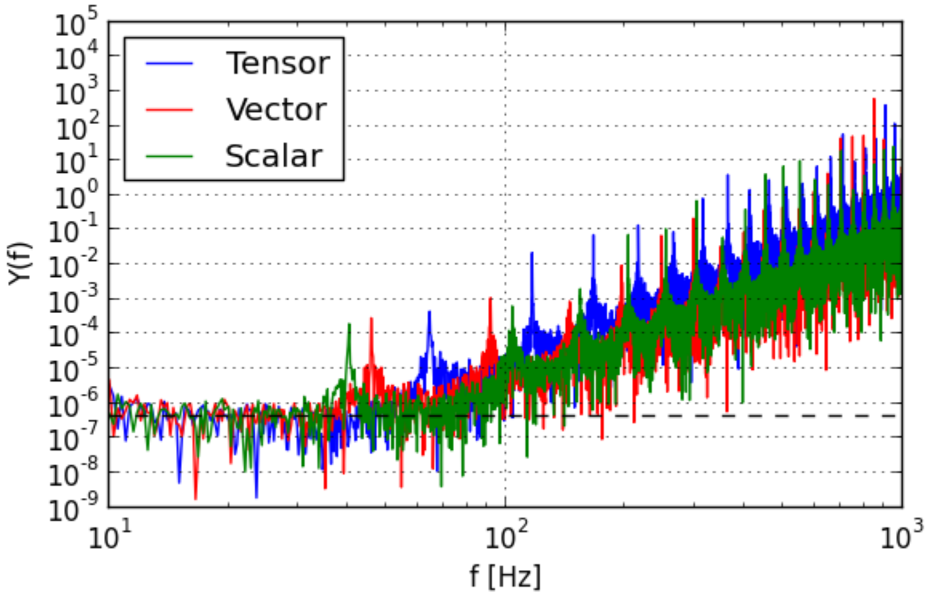


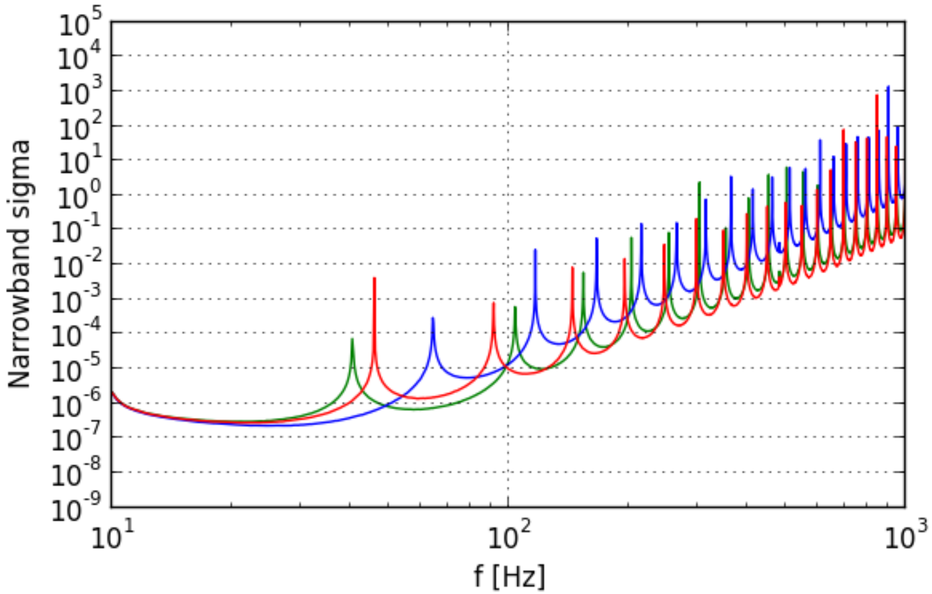



# Injecting a Tensor Signal

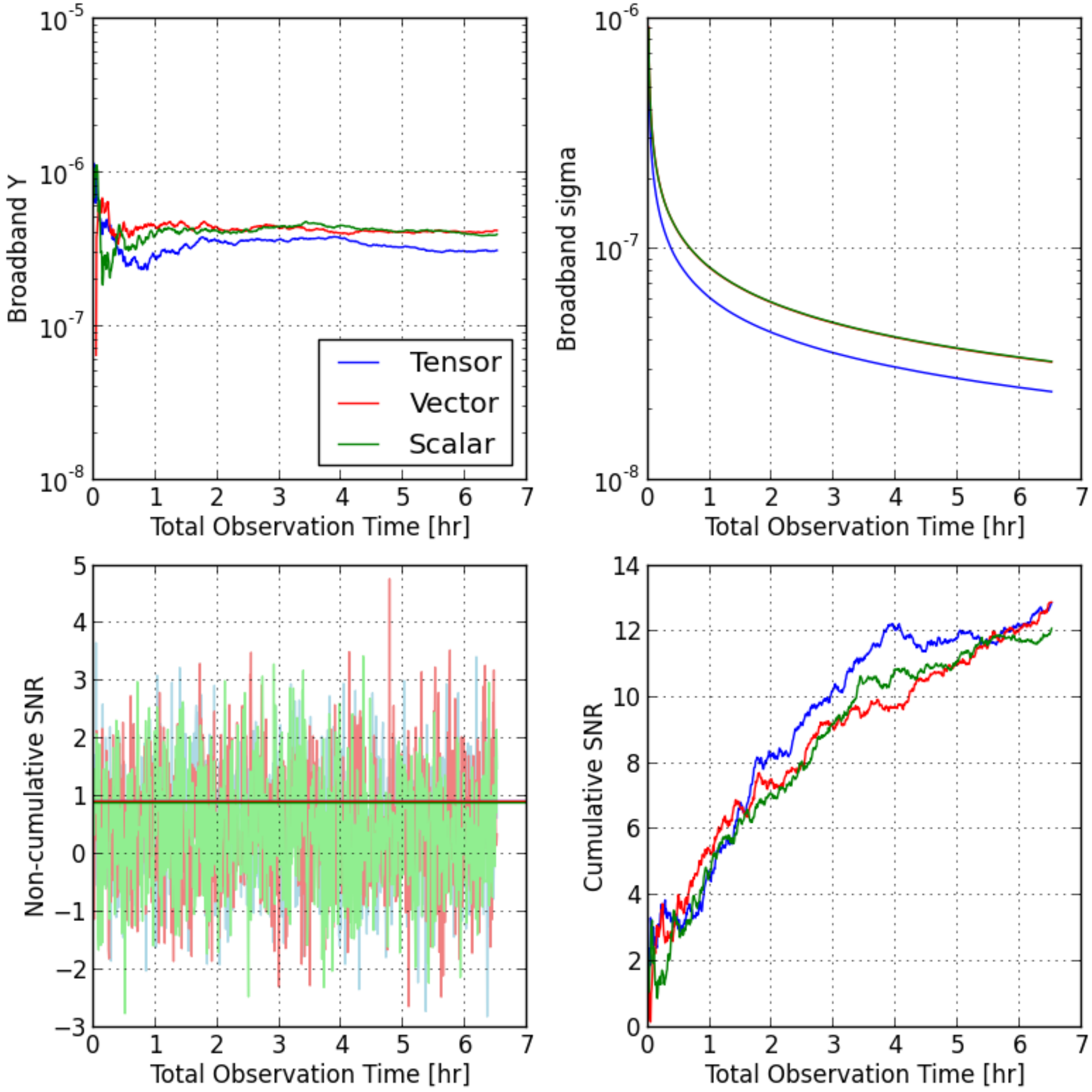


# Injecting a Vector Signal

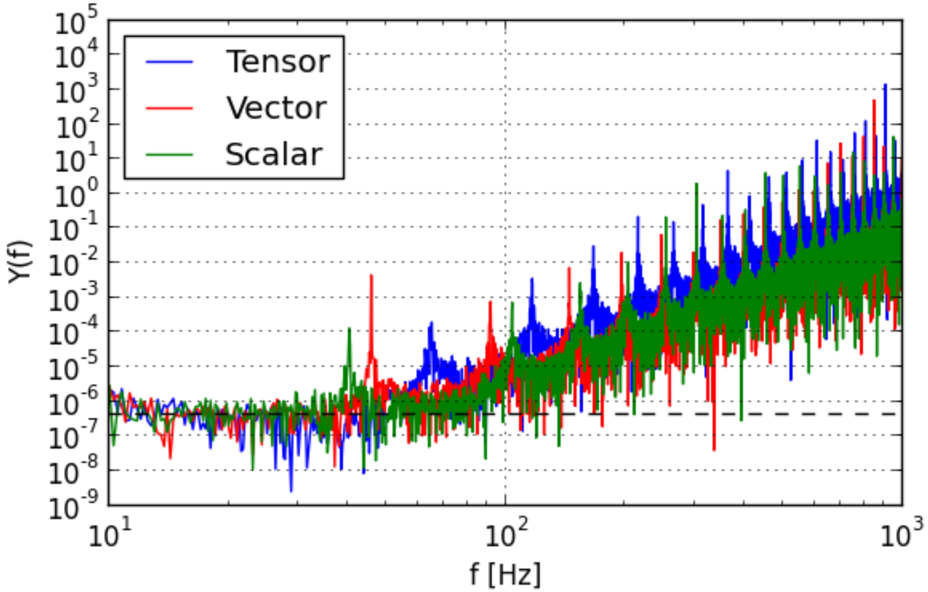


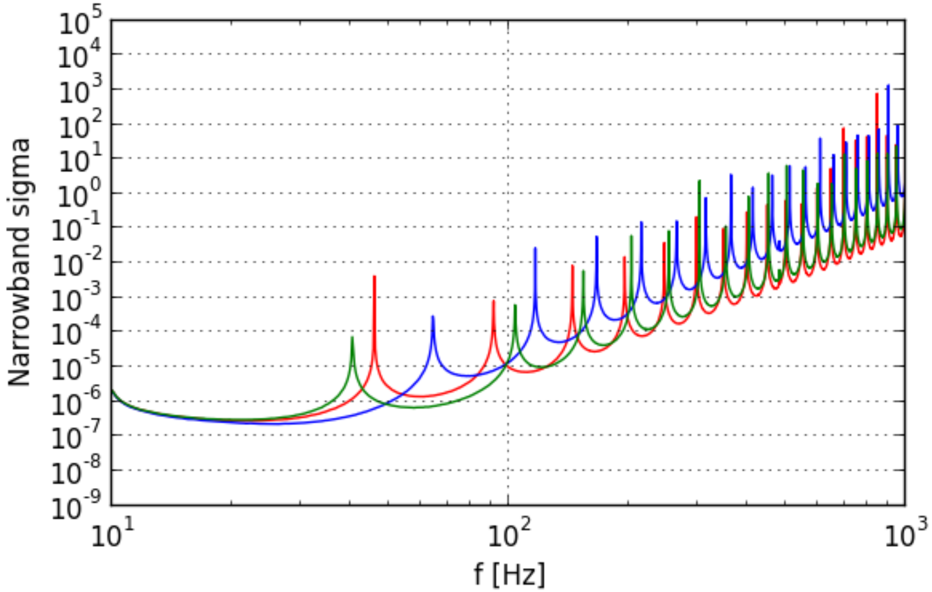



# Injecting a Vector Signal

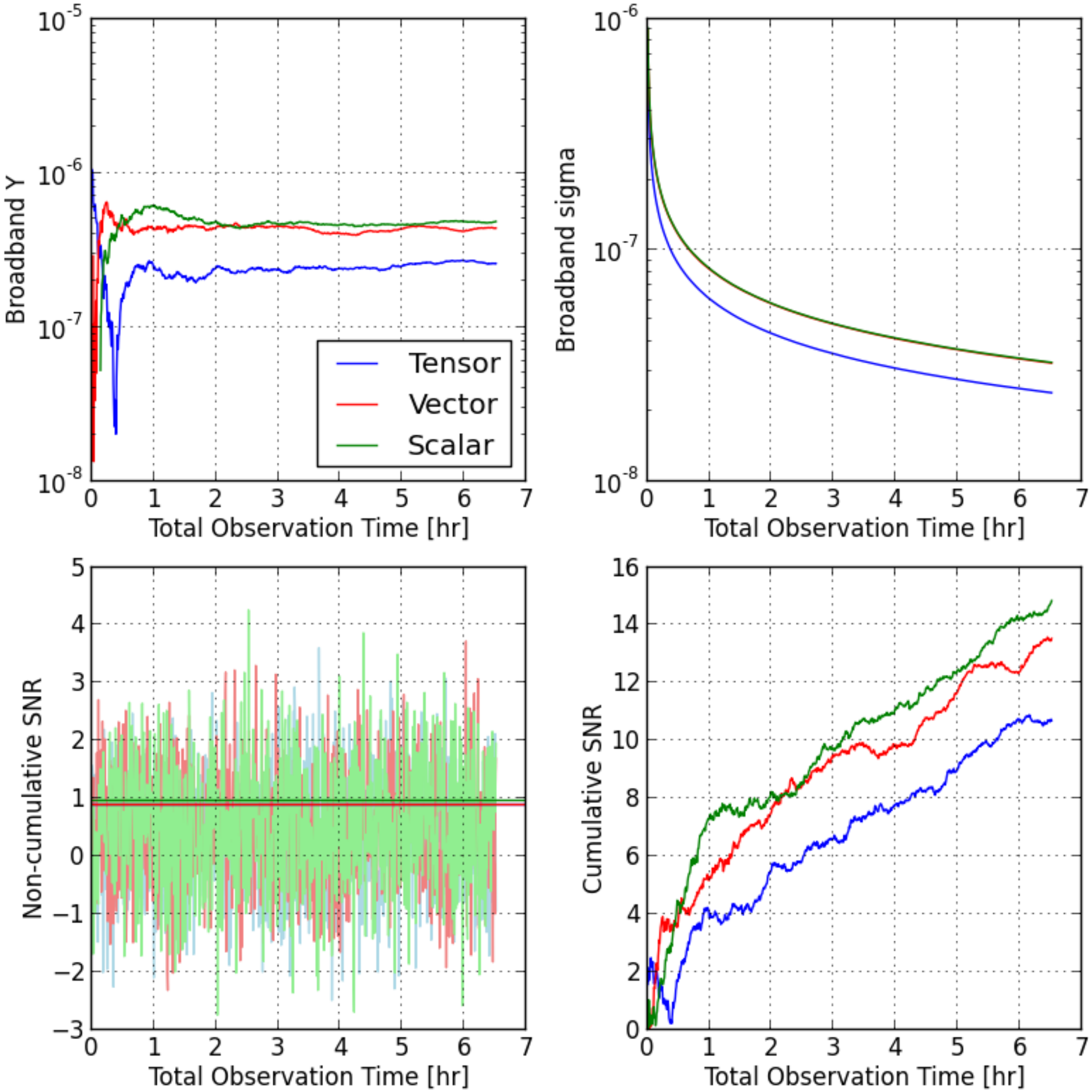


# Injecting a Scalar Signal

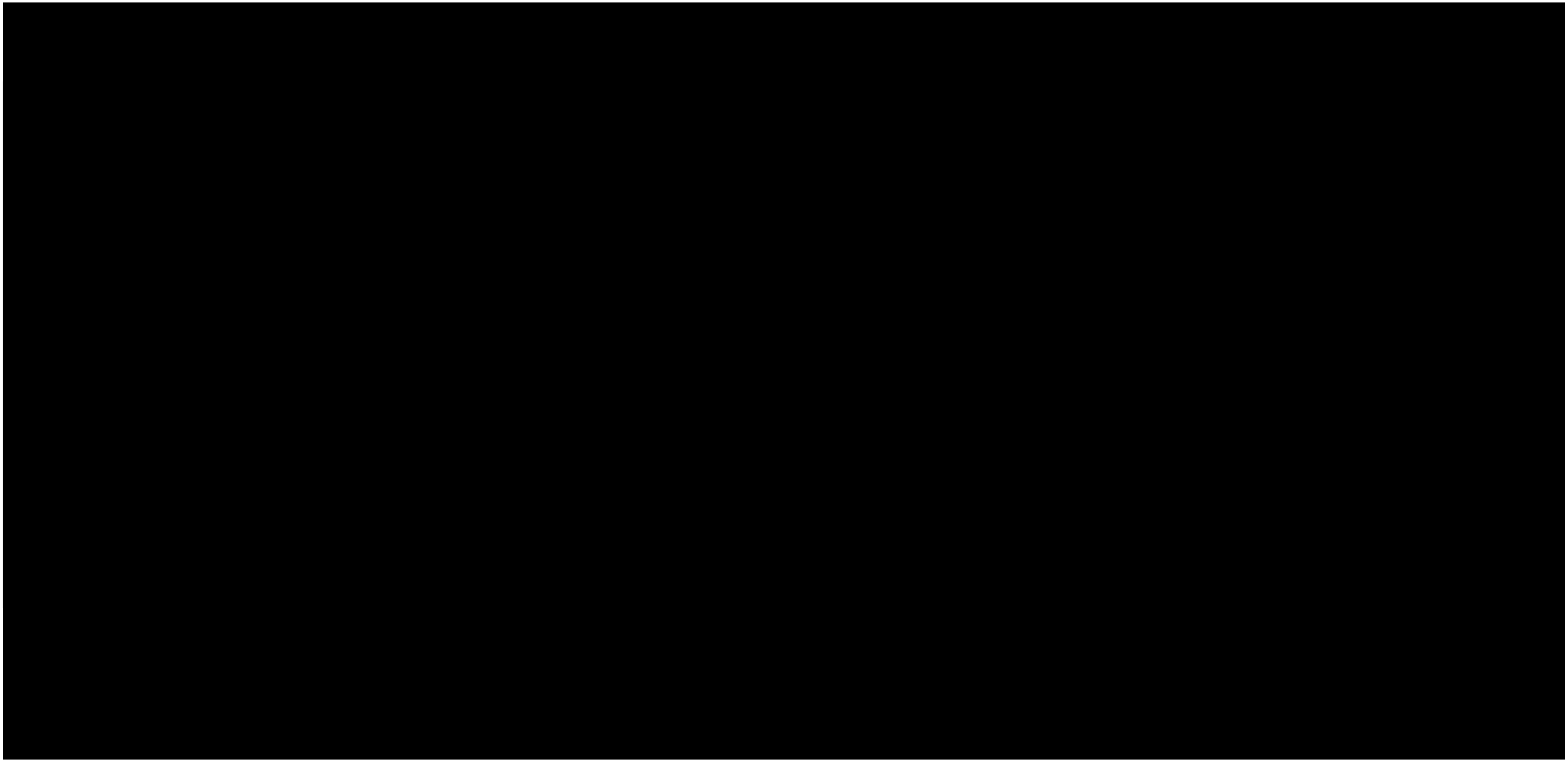


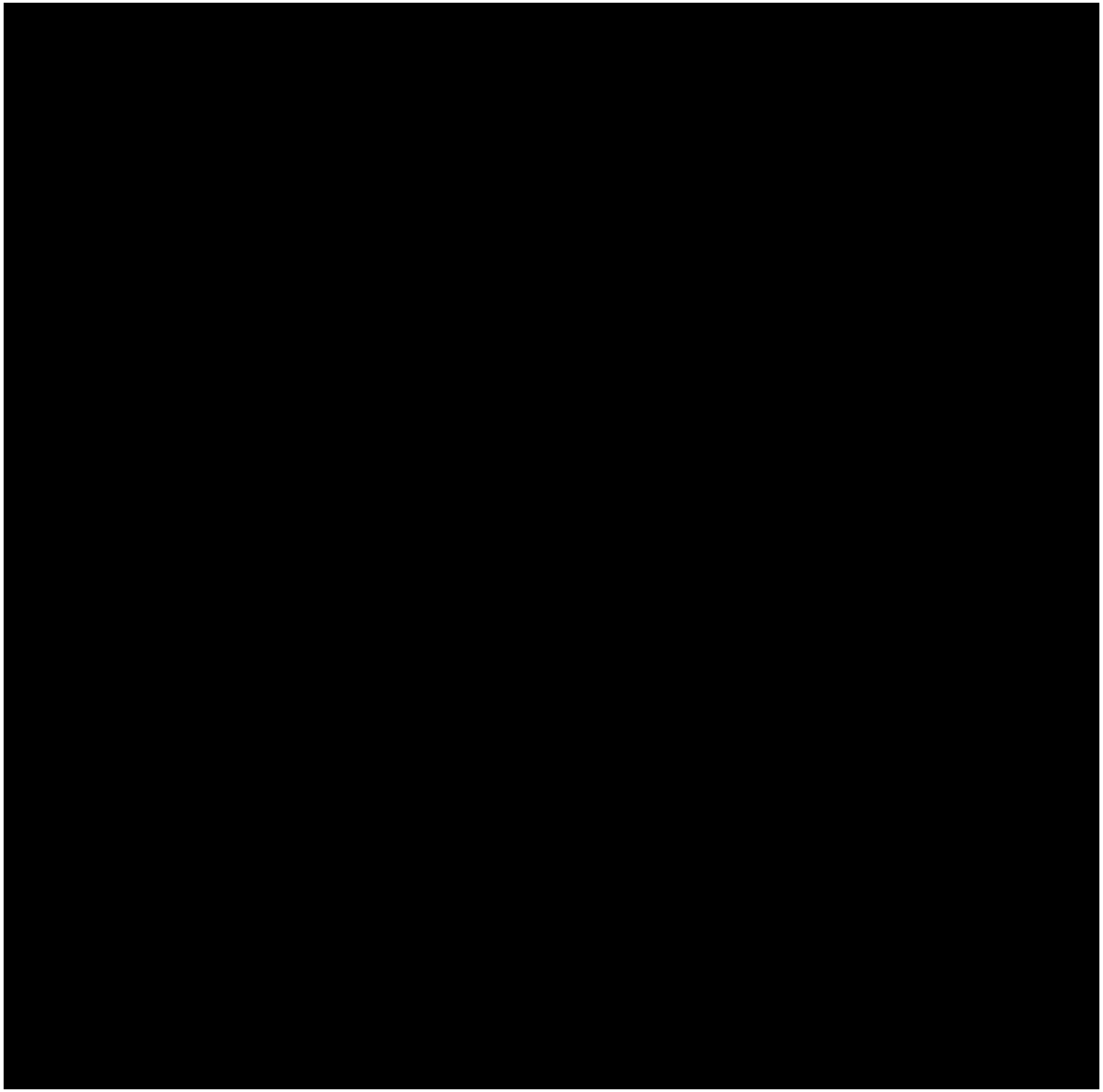
# Injecting a Scalar Signal



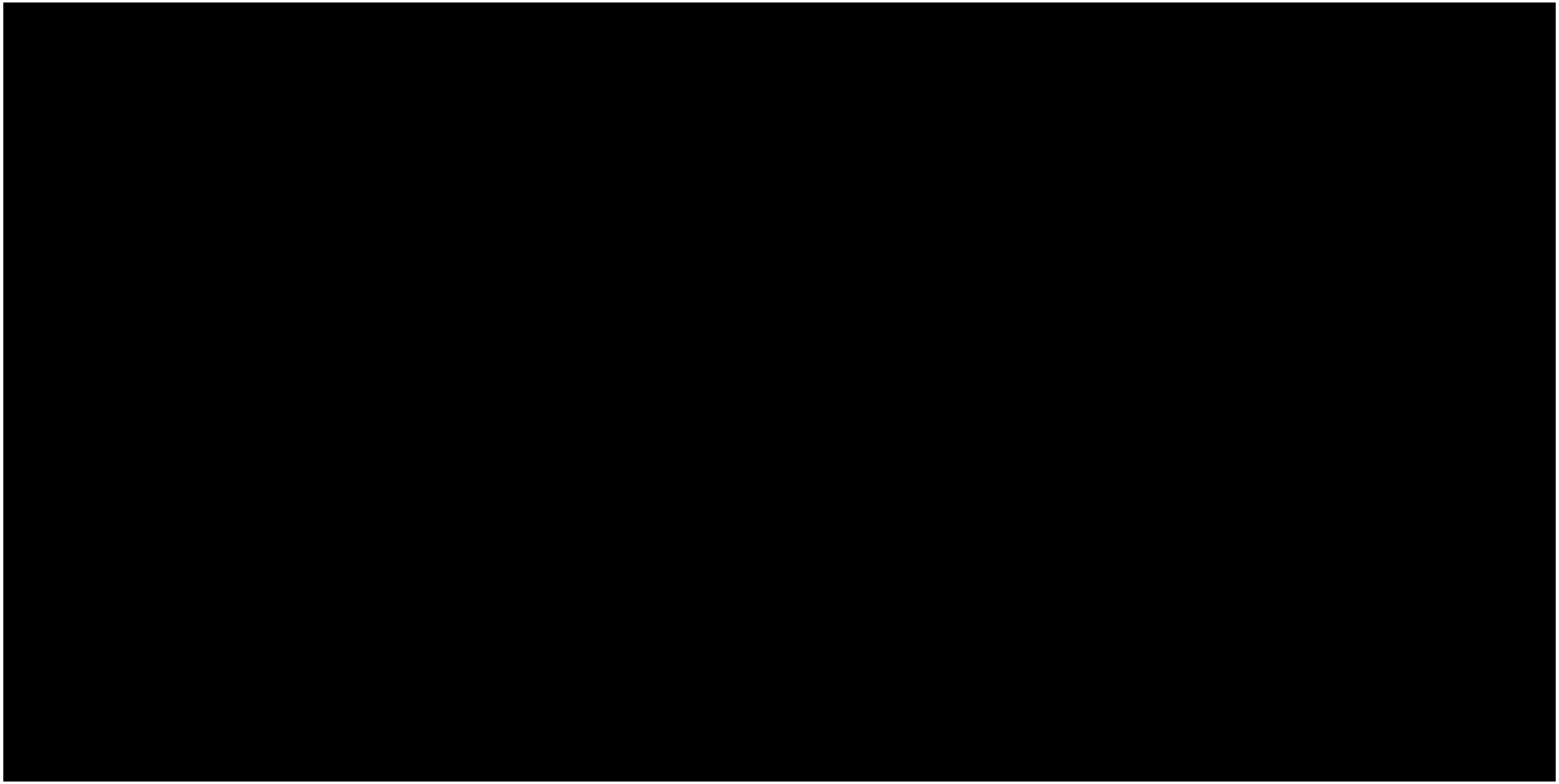
# O1 Vector Result



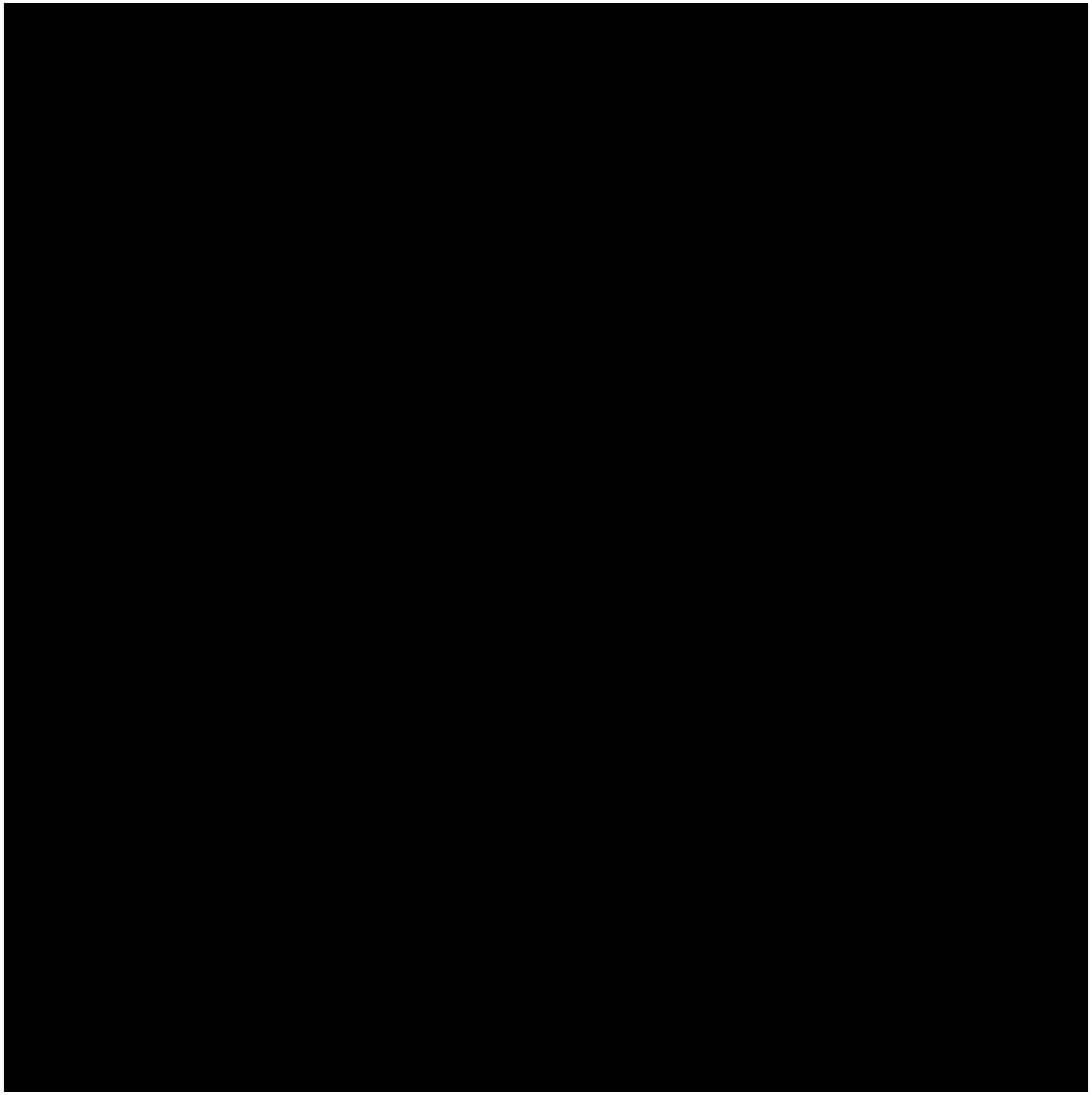
# O1 Vector Result



# O1 Scalar Result



# O1 Scalar Result



# Conclusion and Outlook

- [redacted]
- [redacted]
- [redacted]
- Long term goal: Prepare a component separation scheme for a three detector system to be implemented when Virgo comes live.

# Acknowledgements


- Thank you to Alan, the LIGO stochastic group, and my mentor Tom for the patience, guidance, and support.
- Thank you to the NSF and the CIT LIGO Lab for sponsoring and organizing this project.

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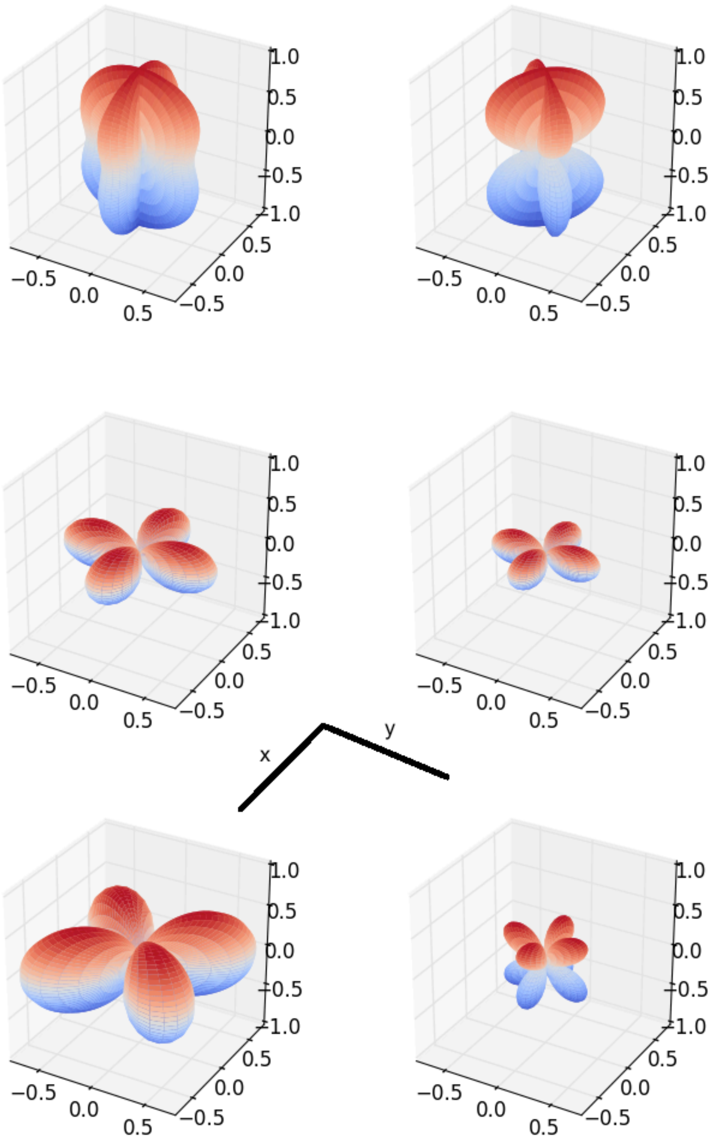
- [14] Correspondence with Tom Callister.
- [15] Correspondence with Joe Romano.

# Backup Slides

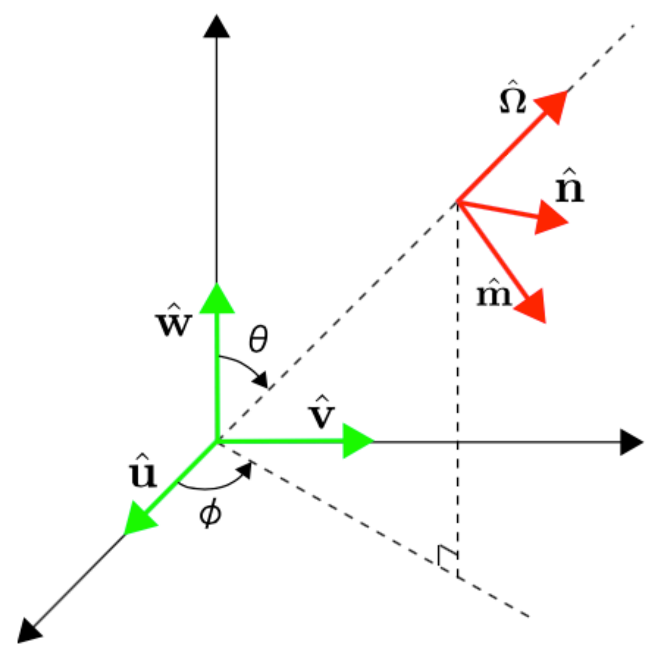
# Single Detector Response






$$F_A(\hat{\mathbf{\Omega}}) = \mathbf{D} : \tilde{\mathbf{e}}_A(\hat{\mathbf{\Omega}})$$

$$\mathbf{D} = \frac{1}{2}(\hat{\mathbf{u}} \otimes \hat{\mathbf{u}} - \hat{\mathbf{v}} \otimes \hat{\mathbf{v}})$$



# Overlap Reduction Functions

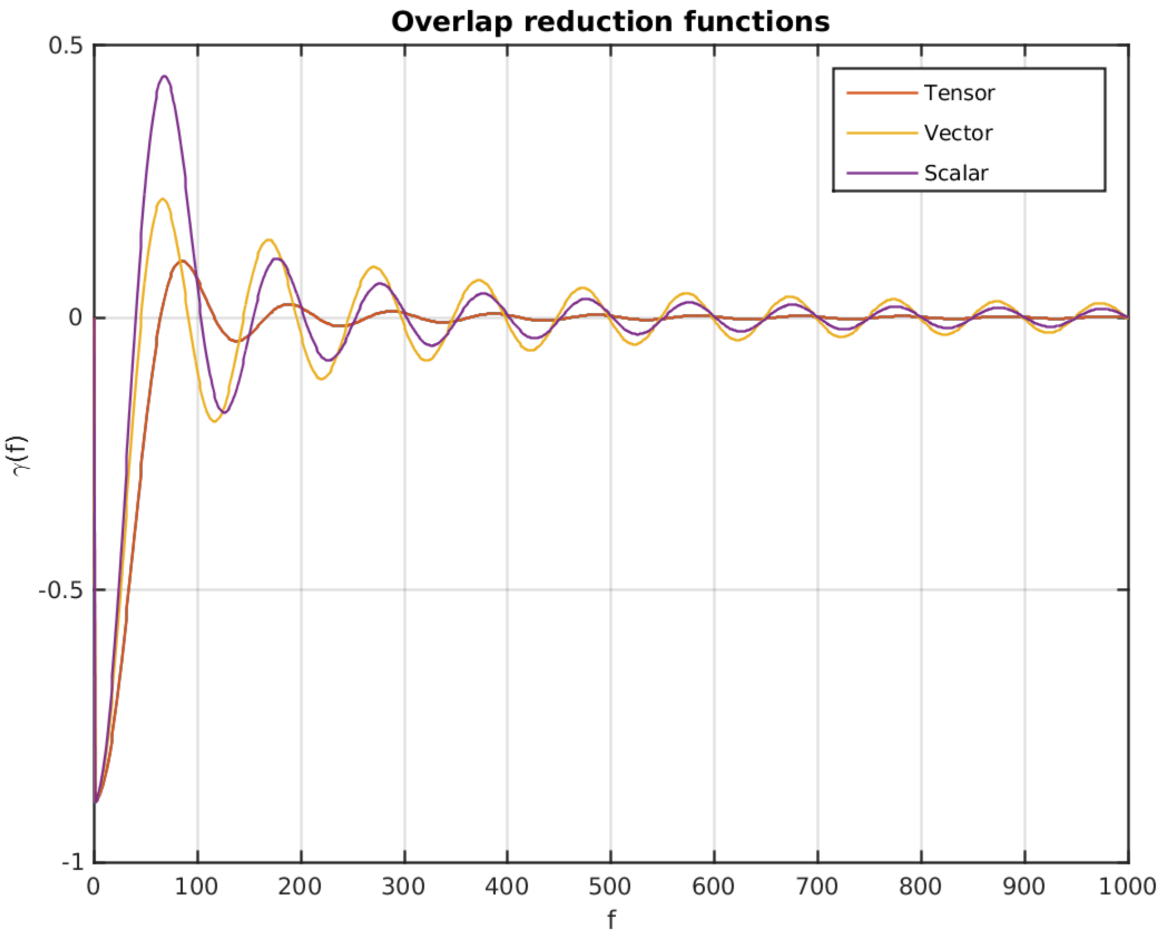
$$\gamma^T_{IJ} = \frac{5}{8\pi} \int_{S^2} e^{2\pi i f \hat{\mathbf{\Omega}} \cdot \Delta \vec{X}/c} (F_I^+ F_J^+ + F_I^\times F_J^\times) d\Omega$$

$$\gamma^V_{IJ} = \frac{5}{8\pi} \int_{S^2} e^{2\pi i f \hat{\mathbf{\Omega}} \cdot \Delta \vec{X}/c} (F_I^x F_J^x + F_I^y F_J^y) d\Omega$$

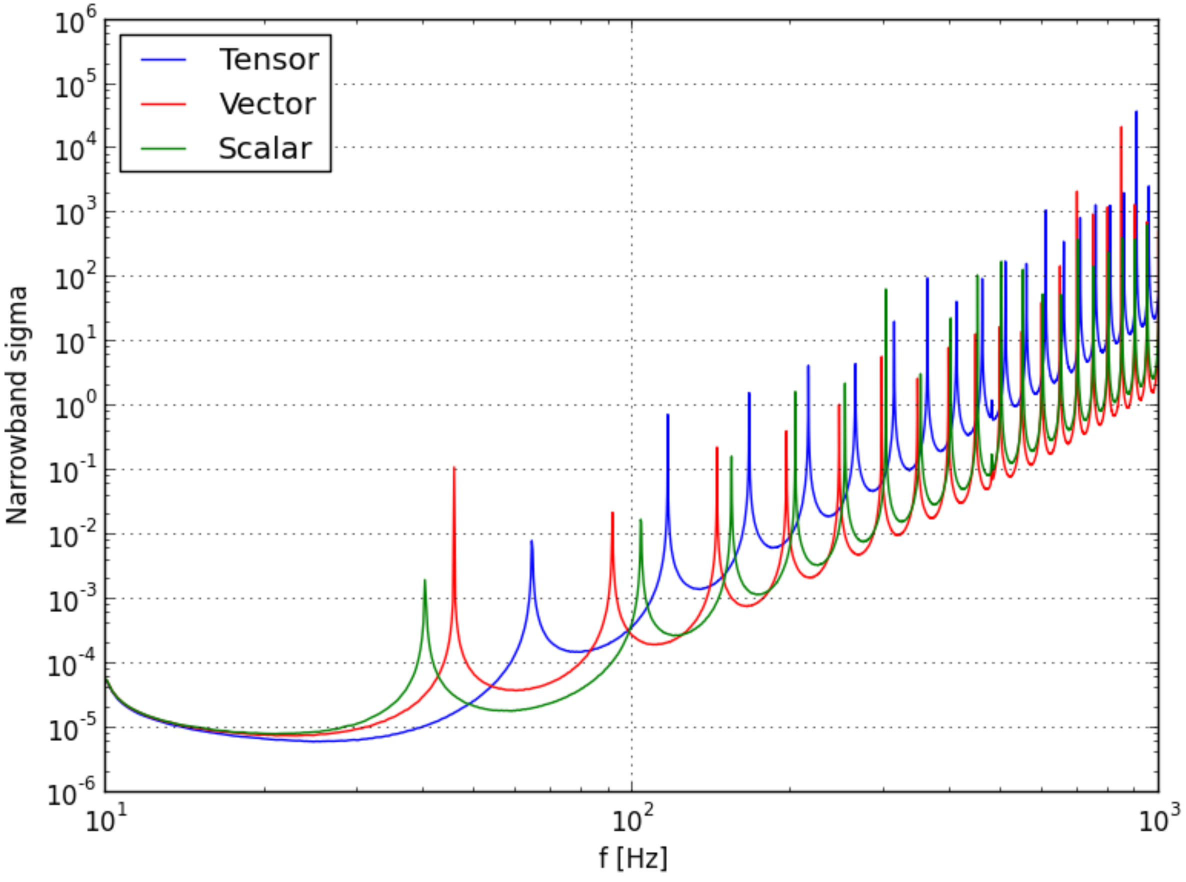
$$\gamma^S_{IJ} = \frac{5}{4\pi} \int_{S^2} e^{2\pi i f \hat{\mathbf{\Omega}} \cdot \Delta \vec{X}/c} (F_I^l F_J^l + F_I^b F_J^b) d\Omega$$

- Normalized to 1 for coincident and coaligned detectors
- Separation and lack of perfect arm alignment reduces sensitivity in cross-correlated analysis

# Overlap Reduction Functions



# Simulated Gaussian Noise



# Broadband Estimators

$$Y_i = \frac{\sum_f Y(f)\sigma^{-2}(f)}{\sum_f \sigma^{-2}(f)}$$

$$\sigma_i^{-2} = \sum_f \sigma^{-2}(f)$$

$$Y_C = \frac{\sum_i Y_i \sigma_i^{-2}}{\sum_i \sigma_i^{-2}}$$

$$\sigma_C^{-2} = \sum_i \sigma_i^{-2}$$

# Signal to Noise Ratio

- Optimal Filter found by maximizing the SNR

$$\mu \equiv \langle Y \rangle = \frac{3H_0^2}{10\pi^2} T \sum \frac{\gamma(f)\Omega_{gw}(f)\tilde{Q}(f)}{f^3} df,$$

$$\sigma^2 = \frac{T}{2} \sum \tilde{Q}^2(f) P_1(f) P_2(f) df$$

$$\tilde{Q}(f) = K \frac{\gamma(f)\Omega_{gw}(|f|)}{|f|^3 P_I(|f|) P_J(|f|)}$$

$$\mathrm{SNR}^2 = \frac{\mu^2}{\sigma^2} = \frac{\left[\frac{3H_0^2}{10\pi^2} T \sum \frac{\gamma(f)\Omega_{gw}(f)\tilde{Q}(f)}{f^3} df\right]^2}{\frac{T}{2} \sum \tilde{Q}^2(f) P_1(f) P_2(f) df}$$

# Signal to Noise Ratio

- Redefine the filter such that $\mu = \gamma_A \Omega_A$

$$\tilde{Q}(f) = \left(\frac{3H_0^2}{10\pi^2}\right) \frac{2}{f^3 P_1(f) P_2(f)}$$

$$\mathrm{SNR}^2 = \left(\frac{3H_0^2}{10\pi^2}\right)^2 2T \frac{\left[\sum \frac{\gamma(f)\Omega_{gw}(f)\gamma_M(f)\Omega_M(f)}{f^6 P_1(f) P_2(f)} df\right]^2}{\sum \frac{(\gamma_M(f)\Omega_M(f))^2}{f^6 P_1(f) P_2(f) df}}$$

# Component Separation

$$p(Y|\mathcal{A}) \propto \exp\Big[-\frac{1}{2}(Y - M\mathcal{A})^{\mathrm{T}}\mathcal{N}^{-1}(Y - M\mathcal{A})\Big]$$

$$M = \begin{bmatrix} \gamma^T(f_1)\left(\frac{f_1}{f_0}\right)^\alpha & \gamma^V(f_1)\left(\frac{f_1}{f_0}\right)^\alpha & \gamma^S(f_1)\left(\frac{f_1}{f_0}\right)^\alpha \\ \gamma^T(f_2)\left(\frac{f_2}{f_0}\right)^\alpha & \gamma^V(f_2)\left(\frac{f_2}{f_0}\right)^\alpha & \gamma^S(f_2)\left(\frac{f_2}{f_0}\right)^\alpha \\ \vdots & \vdots & \vdots \\ \gamma^T(f_N)\left(\frac{f_N}{f_0}\right)^\alpha & \gamma^V(f_N)\left(\frac{f_N}{f_0}\right)^\alpha & \gamma^S(f_N)\left(\frac{f_N}{f_0}\right)^\alpha \end{bmatrix} \quad \mathcal{A} = \begin{bmatrix} \Omega^T \\ \Omega^V \\ \Omega^S \end{bmatrix}$$

$$\mathcal{A} = F^{-1}X, \quad F \equiv M^T\mathcal{N}^{-1}M, \quad X \equiv M^T\mathcal{N}^{-1}Y$$