Albert Einstein Institute
Max Planck Institute for Gravitational Physics and
Leibniz Universität Hannover

lisa pathfinder

Coupling of relative intensity noise and path length noise to the length measurement in the optical metrology system of LISA Pathfinder

Andreas Wittchen
on behalf of the LPF Collaboration

LISA Symposium
Zürich, Switzerland
5. September 2016

LPF Interferometry

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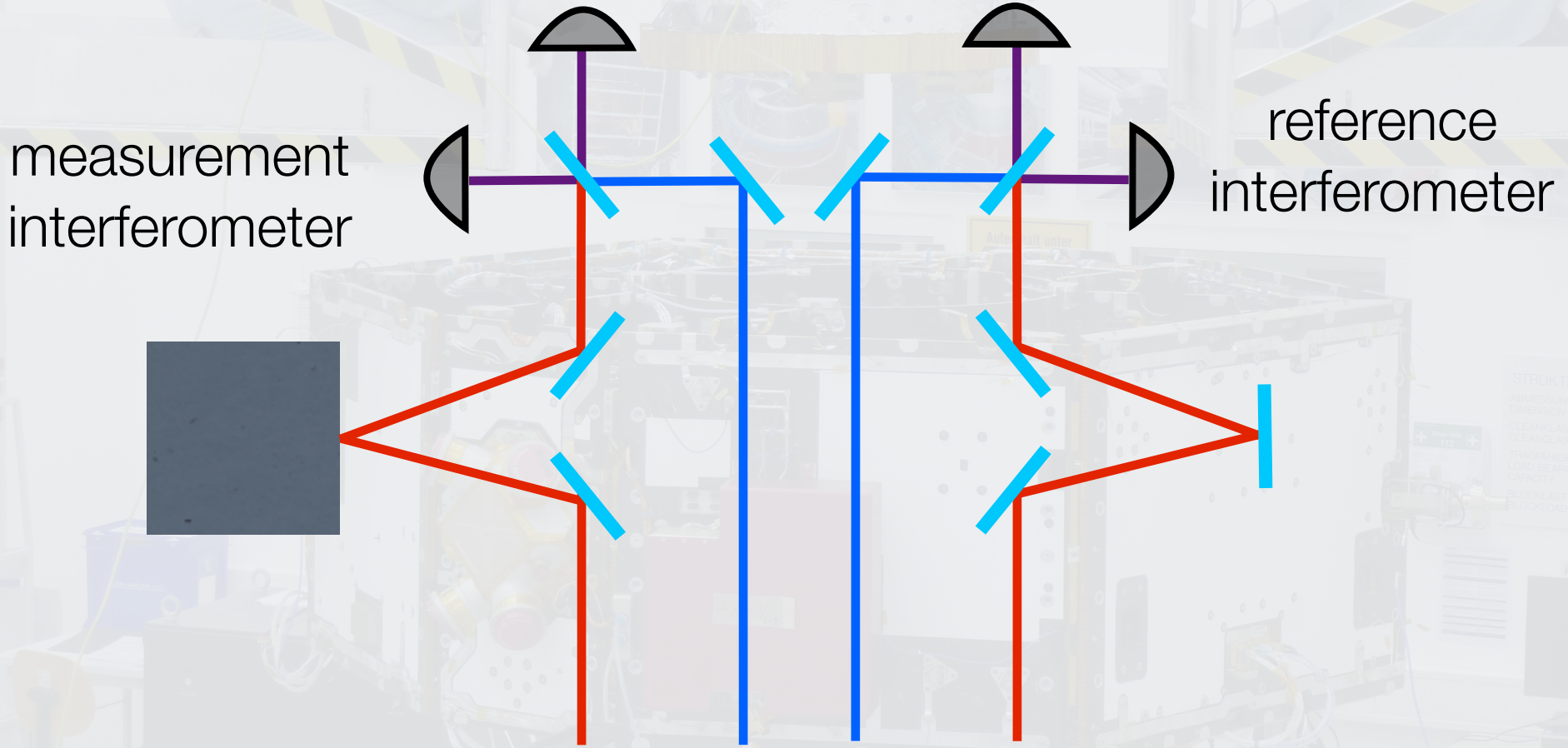

LPF Interferometry

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$$I_{photo} = P(t)\left(1 \pm c\cos(\omega_{het}\, t + \varphi)\right)$$

$$P(t) = P_0\left(1 + \hat{r}\cos(\omega_{RIN}\, t + \alpha)\right)$$

Relative Intensity Noise

LPF Interferometry

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$$I_{photo} = P_0 \left(1 + \hat{r} \cos(\omega_{RIN} t + \alpha)\right) \left(1 \pm c \cos(\omega_{het} t + \varphi)\right)$$

constant

regular beatnote

Noise freq.			

LPF Interferometry

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$$I_{photo} = P_0 \left(1 + \hat{r} \cos(\omega_{RIN} t + \alpha)\right) \left(1 \pm c \cos(\omega_{het} t + \varphi)\right)$$

ω_{RIN}

$\omega_{RIN} + \omega_{het}$

$\omega_{RIN} - \omega_{het}$

Noise freq.	ω_{RIN}	$\omega_{RIN} + \omega_{het}$	$\omega_{RIN} - \omega_{het}$

LPF Interferometry

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$$I_{photo} = P_0 \left(1 + \hat{r} \cos(\omega_{RIN} t + \alpha)\right) \left(1 \pm c \cos(\omega_{het} t + \varphi)\right)$$

ω_{RIN}

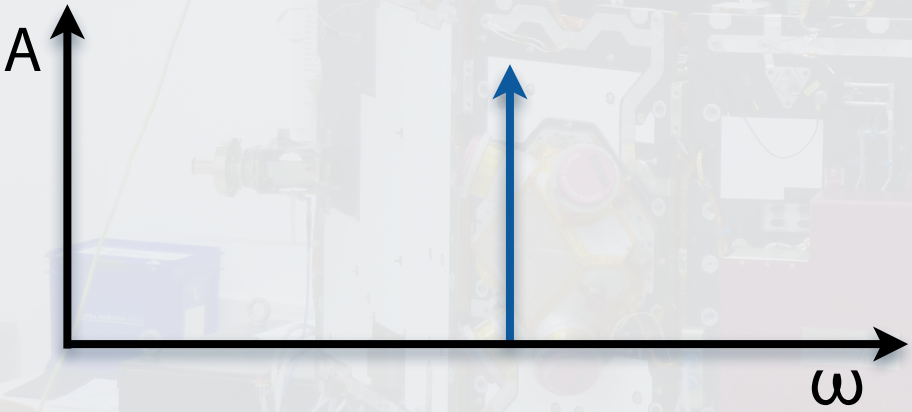
$\omega_{RIN} + \omega_{het}$

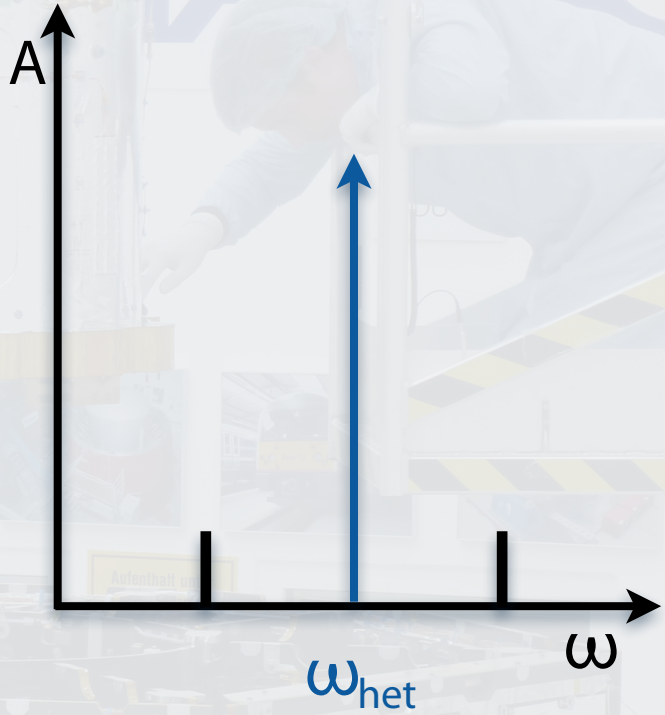
$\omega_{RIN} - \omega_{het}$

Noise freq.	ω_{RIN}	$\omega_{RIN} + \omega_{het}$	$\omega_{RIN} - \omega_{het}$
$\omega_{RIN} \approx 0$	DC	ω_{het}	ω_{het}
$\omega_{RIN} \approx \omega_{het}$	ω_{het}	$2\,\omega_{het}$	DC
$\omega_{RIN} \approx 2\omega_{het}$	$2\omega_{het}$	$3\,\omega_{het}$	ω_{het}

From light signal to phase signal

ω_{het}

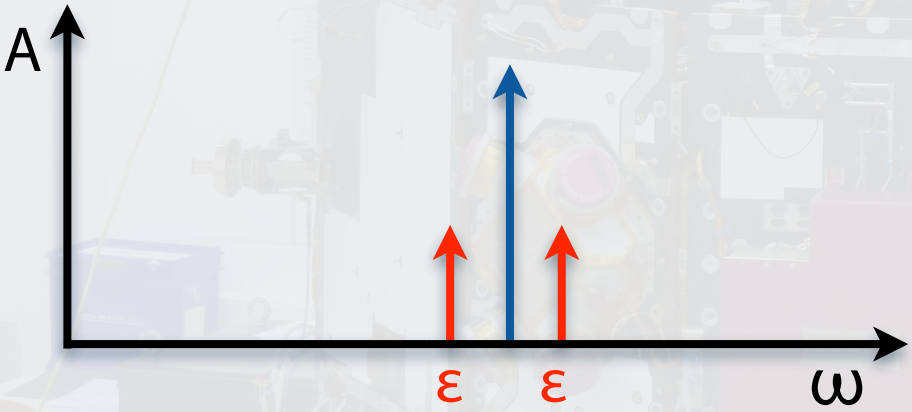


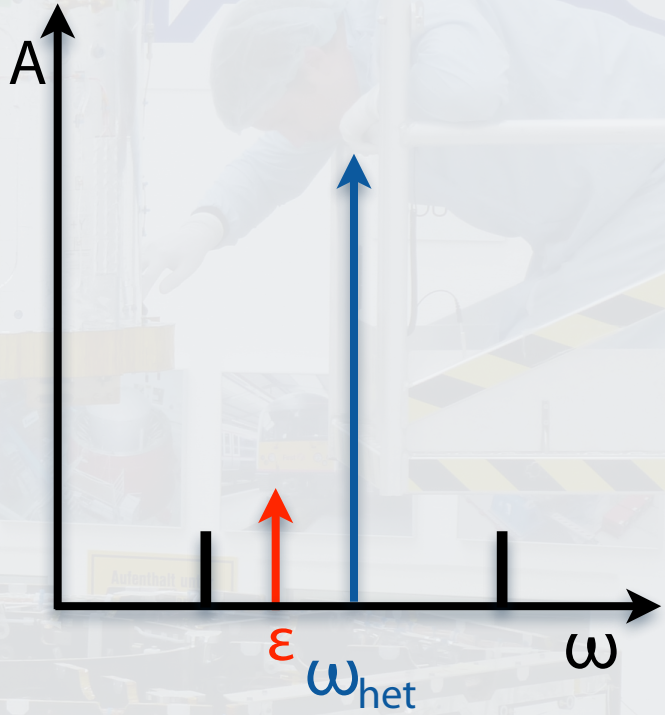


Noise freq.	ω_{RIN}	$\omega_{RIN} + \omega_{het}$	$\omega_{RIN} - \omega_{het}$
$\omega_{RIN} \approx 0$	DC	ω_{het}	ω_{het}
$\omega_{RIN} \approx \omega_{het}$	ω_{het}	$2\,\omega_{het}$	DC
$\omega_{RIN} \approx 2\,\omega_{het}$	$2\,\omega_{het}$	$3\,\omega_{het}$	ω_{het}

From light signal to phase signal

$\omega_{het} - \varepsilon$



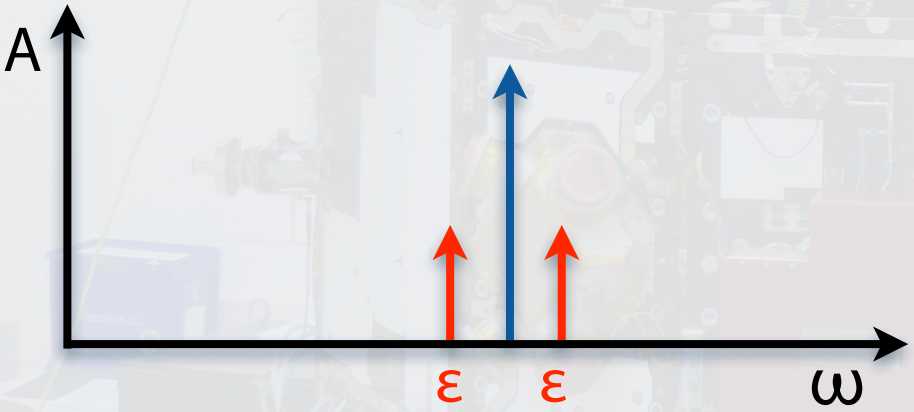


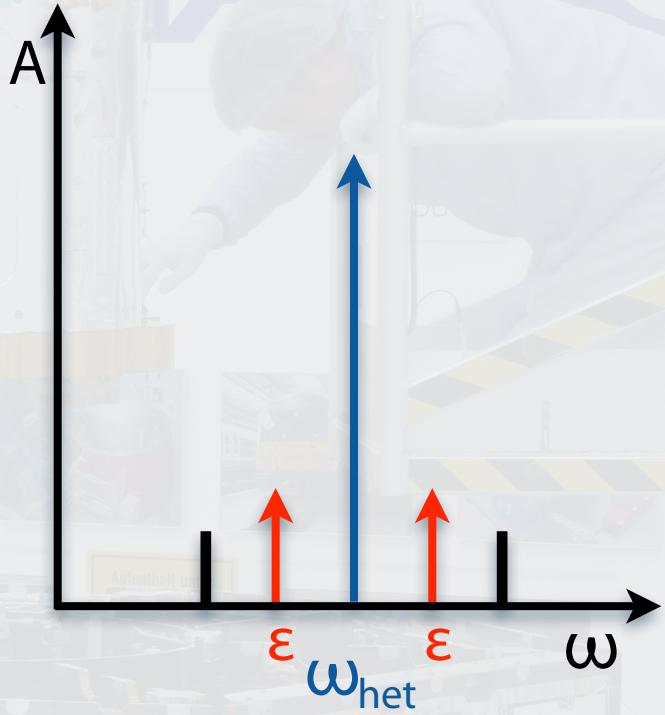
ω_{het}

Noise freq.	ω_{RIN}	$\omega_{RIN} + \omega_{het}$	$\omega_{RIN} - \omega_{het}$
$\omega_{RIN} \approx 0$	DC	ω_{het}	ω_{het}
$\omega_{RIN} \approx \omega_{het}$	ω_{het}	$2\,\omega_{het}$	DC
$\omega_{RIN} \approx 2\,\omega_{het}$	$2\,\omega_{het}$	$3\,\omega_{het}$	ω_{het}

From light signal to phase signal

$\omega_{het} + \varepsilon$

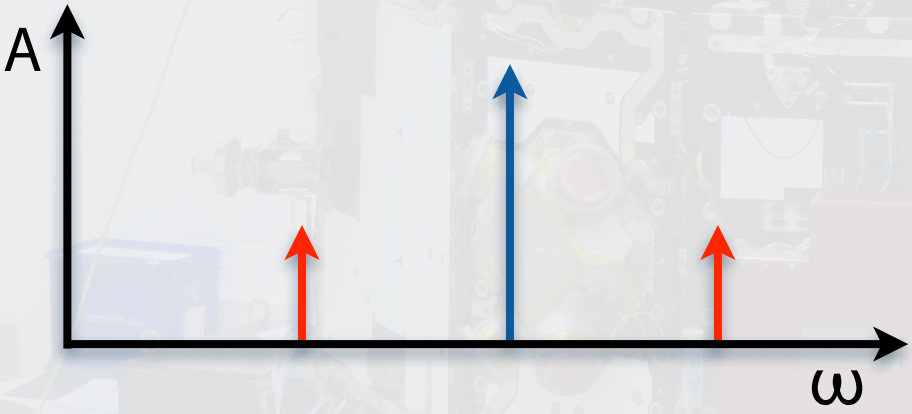


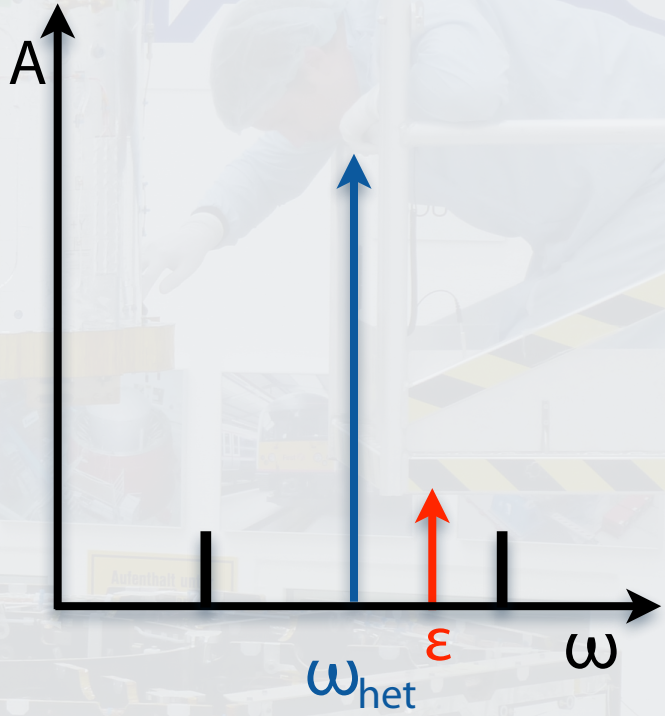


Noise freq.	ω_{RIN}	$\omega_{RIN} + \omega_{het}$	$\omega_{RIN} - \omega_{het}$
$\omega_{RIN} \approx 0$	DC	ω_{het}	ω_{het}
$\omega_{RIN} \approx \omega_{het}$	ω_{het}	$2\,\omega_{het}$	DC
$\omega_{RIN} \approx 2\,\omega_{het}$	$2\,\omega_{het}$	$3\,\omega_{het}$	ω_{het}

From light signal to phase signal

$\omega_{het}+\varepsilon$ $\omega_{het}+\varepsilon$



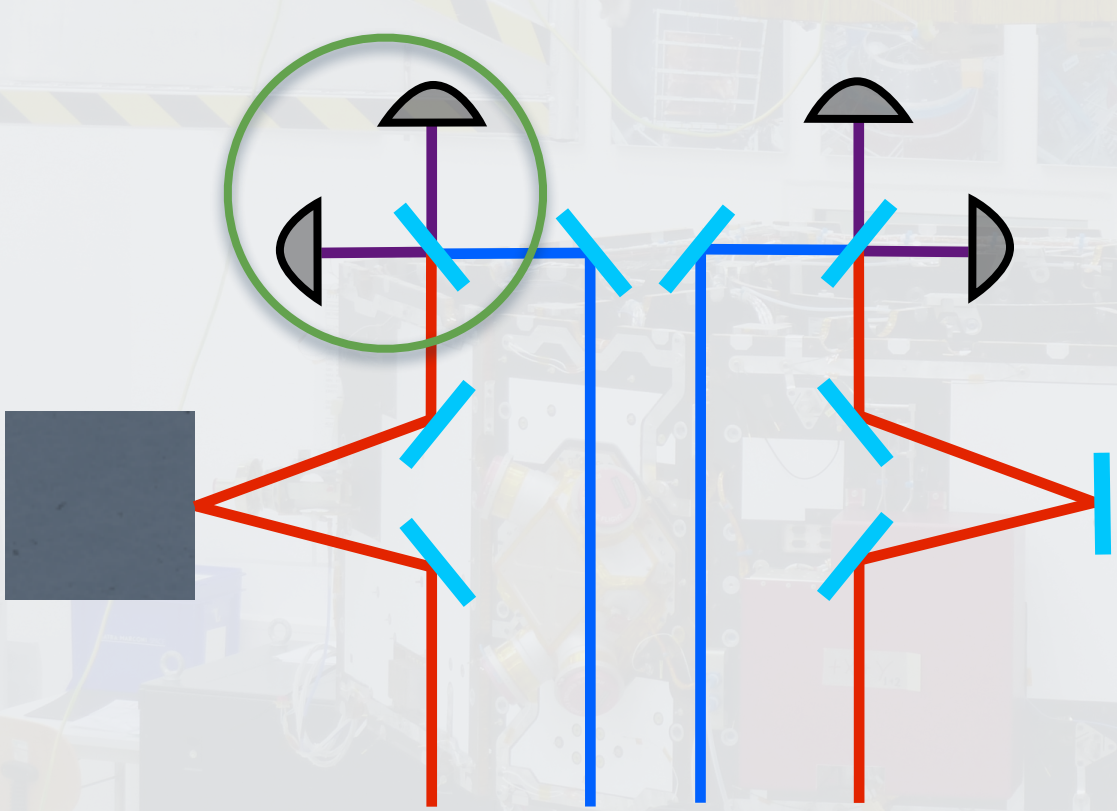


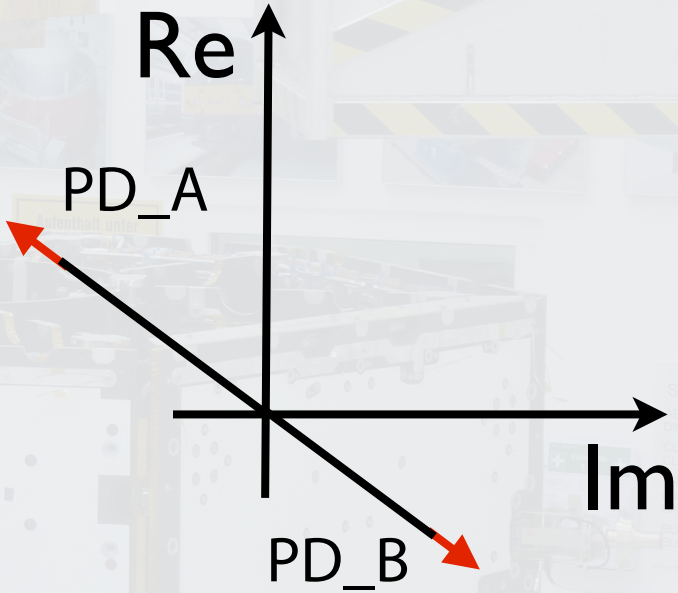
ω_{het}

Noise freq.	ω_{RIN}	$\omega_{RIN} + \omega_{het}$	$\omega_{RIN} - \omega_{het}$
$\omega_{RIN} \approx 0$	DC	~~ω_{het}~~	~~ω_{het}~~
$\omega_{RIN} \approx \omega_{het}$	ω_{het}	$2\,\omega_{het}$	DC
$\omega_{RIN} \approx 2\,\omega_{het}$	$2\,\omega_{het}$	$3\,\omega_{het}$	ω_{het}

LPF Interferometry

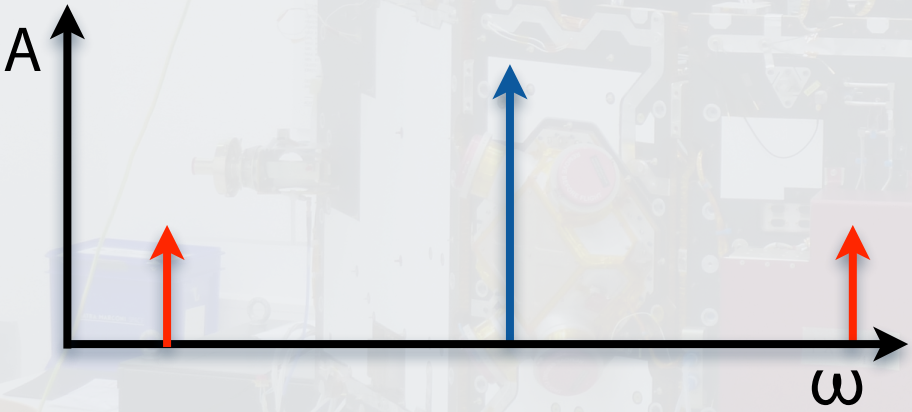
- Balanced detection
- suppresses some noise sources

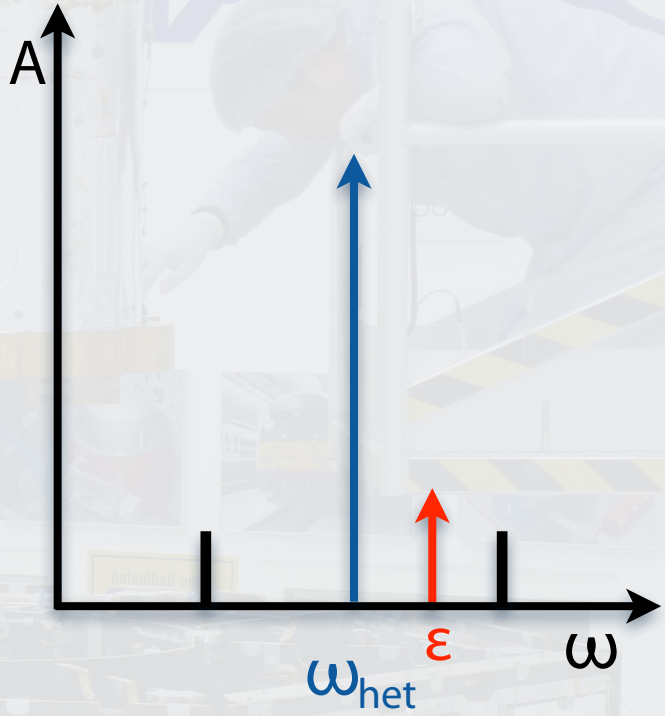




From light signal to phase signal

$\omega_{het} + \varepsilon$



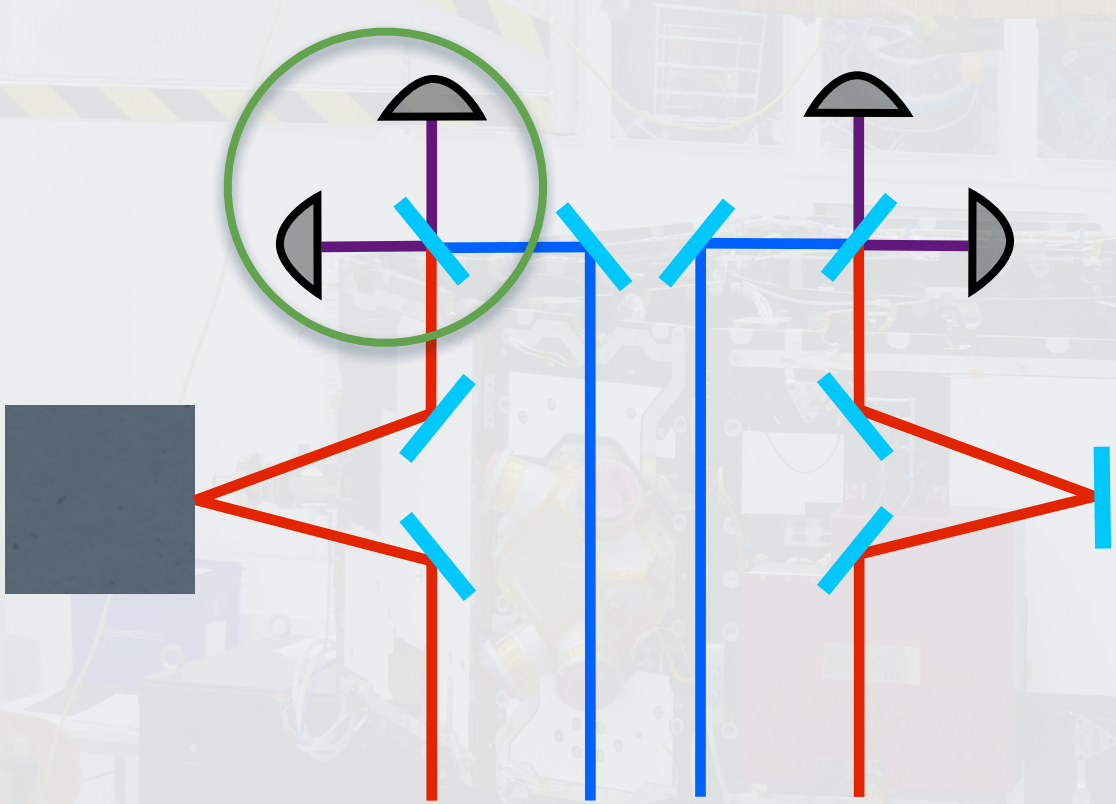


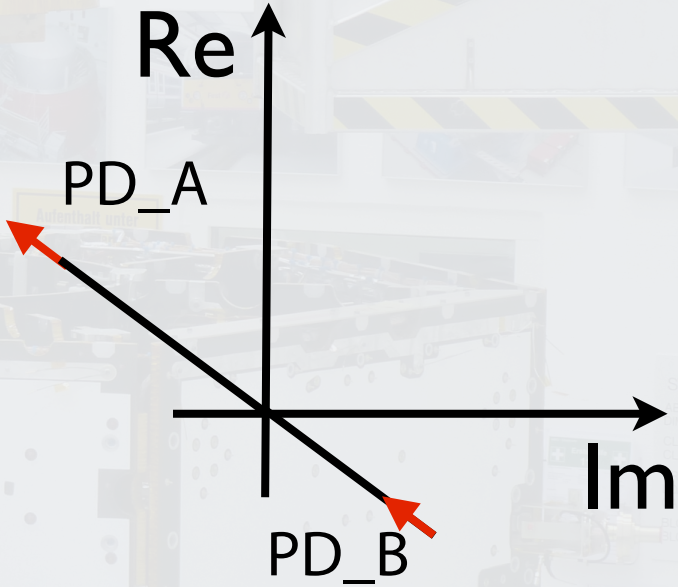
ω_{het}

Noise freq.	ω_{RIN}	$\omega_{RIN} + \omega_{het}$	$\omega_{RIN} - \omega_{het}$
$\omega_{RIN} \approx 0$	DC	~~ω_{het}~~	~~ω_{het}~~
$\omega_{RIN} \approx \omega_{het}$	~~ω_{het}~~	$2\,\omega_{het}$	DC
$\omega_{RIN} \approx 2\,\omega_{het}$	$2\,\omega_{het}$	$3\,\omega_{het}$	ω_{het}

LPF Interferometry

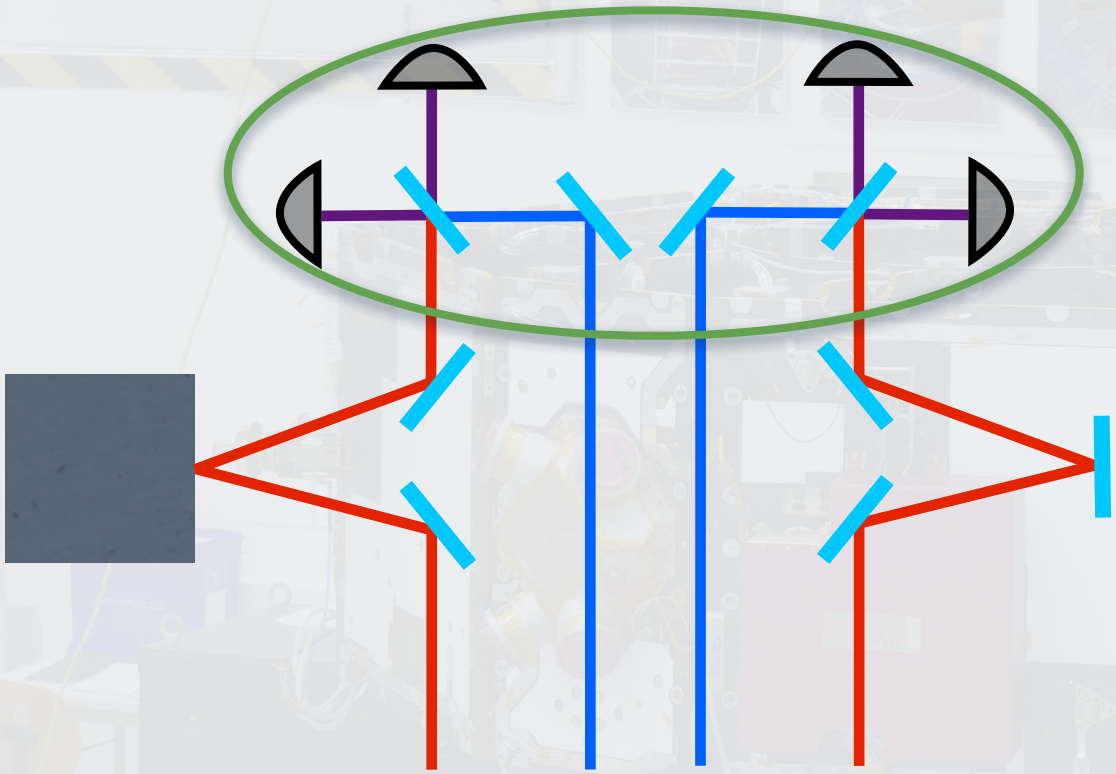
- Balanced detection
- does not suppress RIN at $2\omega_{het}$

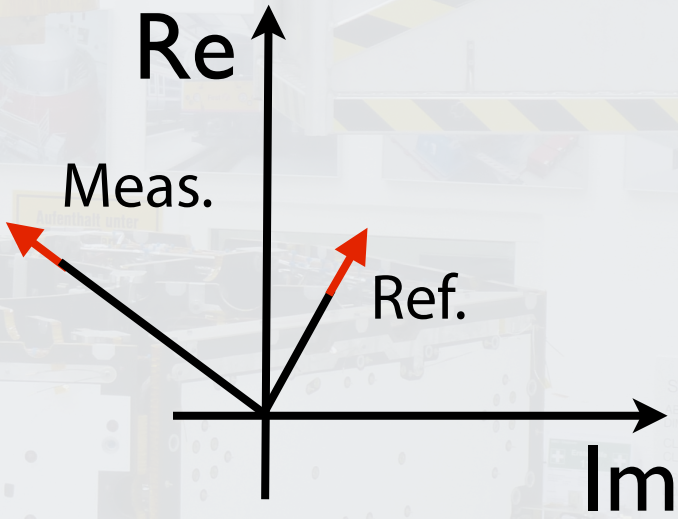




LPF Interferometry

- Remaining noise subtracted with reference Interferometer
- depends on phase difference





Subtraction overview

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Noise freq.	ω_{RIN}	$\omega_{RIN} + \omega_{het}$	$\omega_{RIN} - \omega_{het}$
$\omega_{RIN} \approx 0$	DC	~~ω_{het}~~	~~ω_{het}~~
$\omega_{RIN} \approx \omega_{het}$	~~ω_{het}~~	$2\,\omega_{het}$	DC
$\omega_{RIN} \approx 2\omega_{het}$	$2\omega_{het}$	$3\,\omega_{het}$	ω_{het}

Subtraction overview

lisa pathfinder

$$\psi^{(1)} = \sqrt{2}\sqrt{\left(\hat{r}^{(1)}\, 2 \sin\left(\frac{\varphi_M - \varphi_R}{2} \right) \cos\left(\varepsilon t - \frac{\varphi_M + \varphi_R}{2} \right) \right)^2}$$

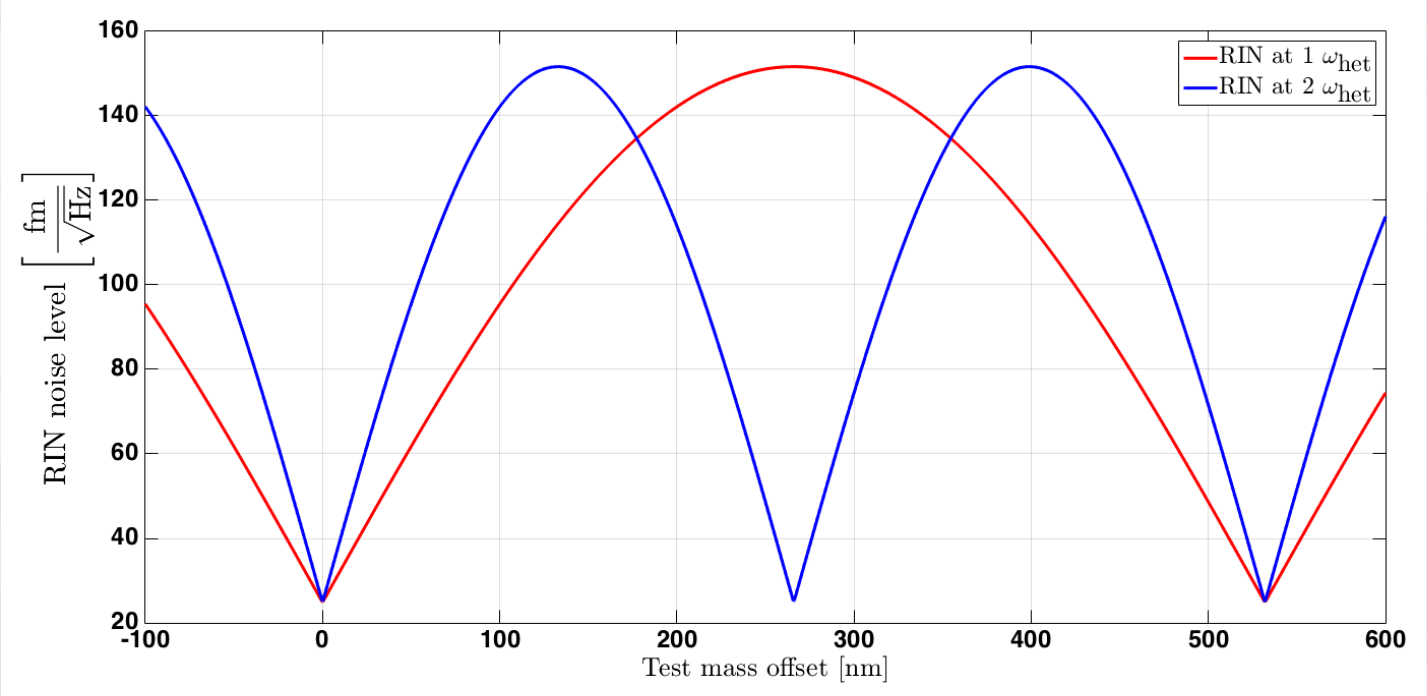
$$\psi^{(2)} = \sqrt{2}\sqrt{\left(\frac{1}{2} c\, \hat{r}^{(2)}\, 2 \sin\left(\varphi_M - \varphi_R \right) \cos\left(\varepsilon t - \varphi_M + \varphi_R \right) \right)^2}$$

Noise freq.	ω_{RIN}	$\omega_{RIN} + \omega_{het}$	$\omega_{RIN} - \omega_{het}$
$\omega_{RIN} \approx 0$	DC	~~ω_{het}~~	~~ω_{het}~~
$\omega_{RIN} \approx \omega_{het}$	~~ω_{het}~~	$2\,\omega_{het}$	DC
$\omega_{RIN} \approx 2\omega_{het}$	$2\omega_{het}$	$3\,\omega_{het}$	ω_{het}

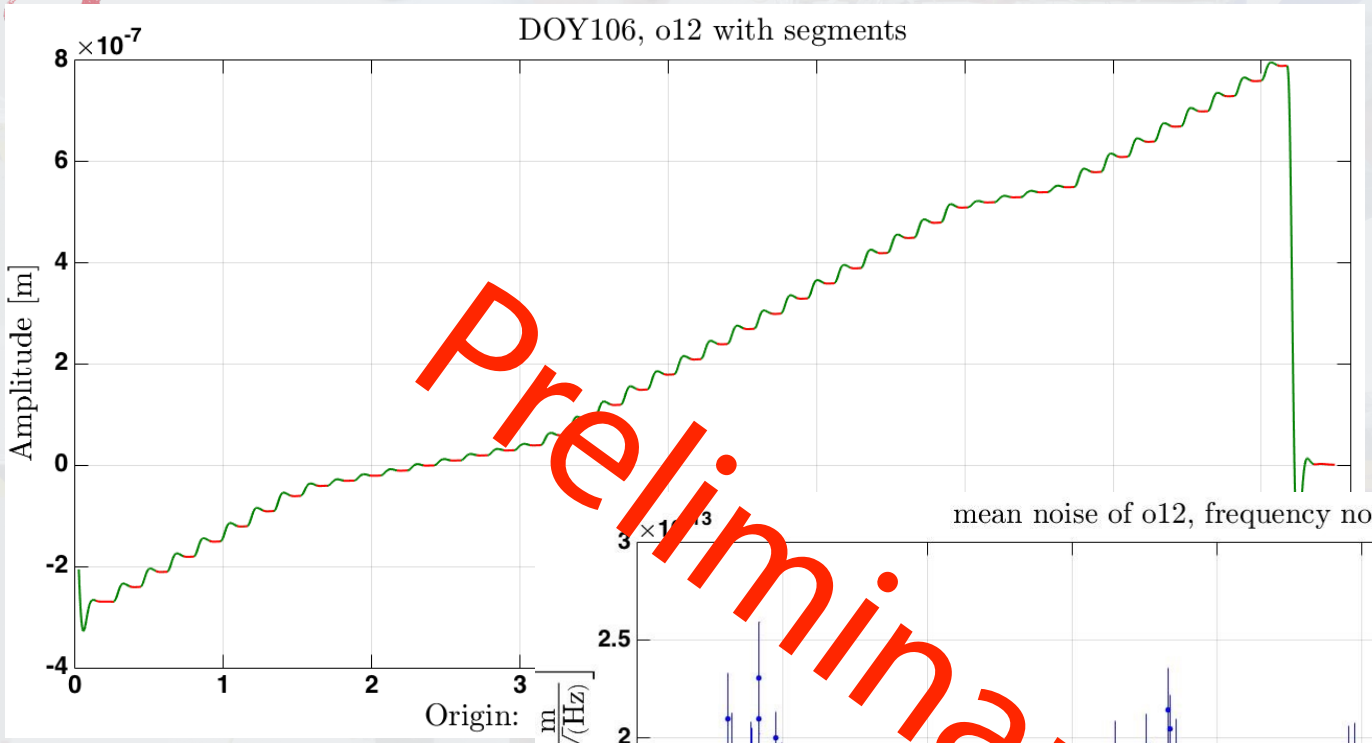
Subtraction overview

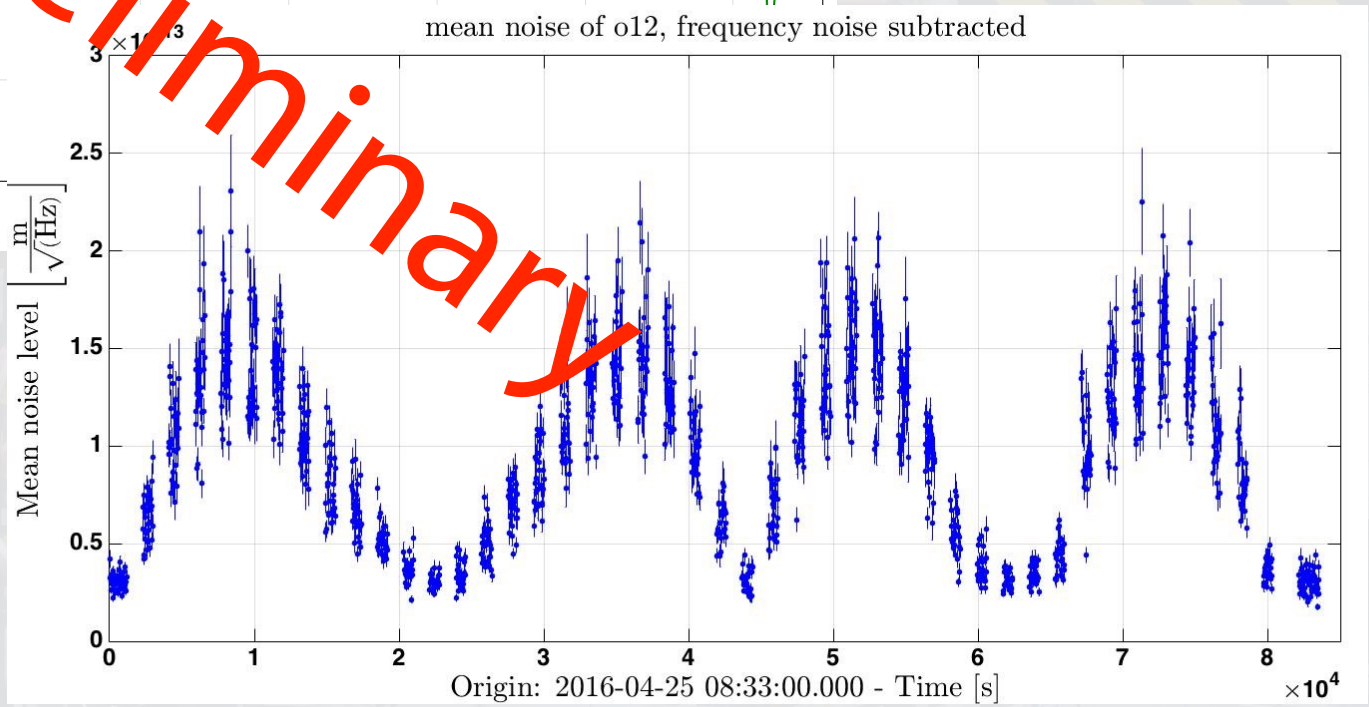
$$\psi^{(1)} = \sqrt{2}\sqrt{\left(\hat{r}^{(1)}\, 2 \sin\left(\frac{\varphi_M - \varphi_R}{2} \right) \cos\left(\varepsilon t - \frac{\varphi_M + \varphi_R}{2} \right) \right)^2}$$

$$\psi^{(2)} = \sqrt{2}\sqrt{\left(\frac{1}{2} c\, \hat{r}^{(2)}\, 2 \sin\left(\varphi_M - \varphi_R \right) \cos\left(\varepsilon t - \varphi_M + \varphi_R \right) \right)^2}$$



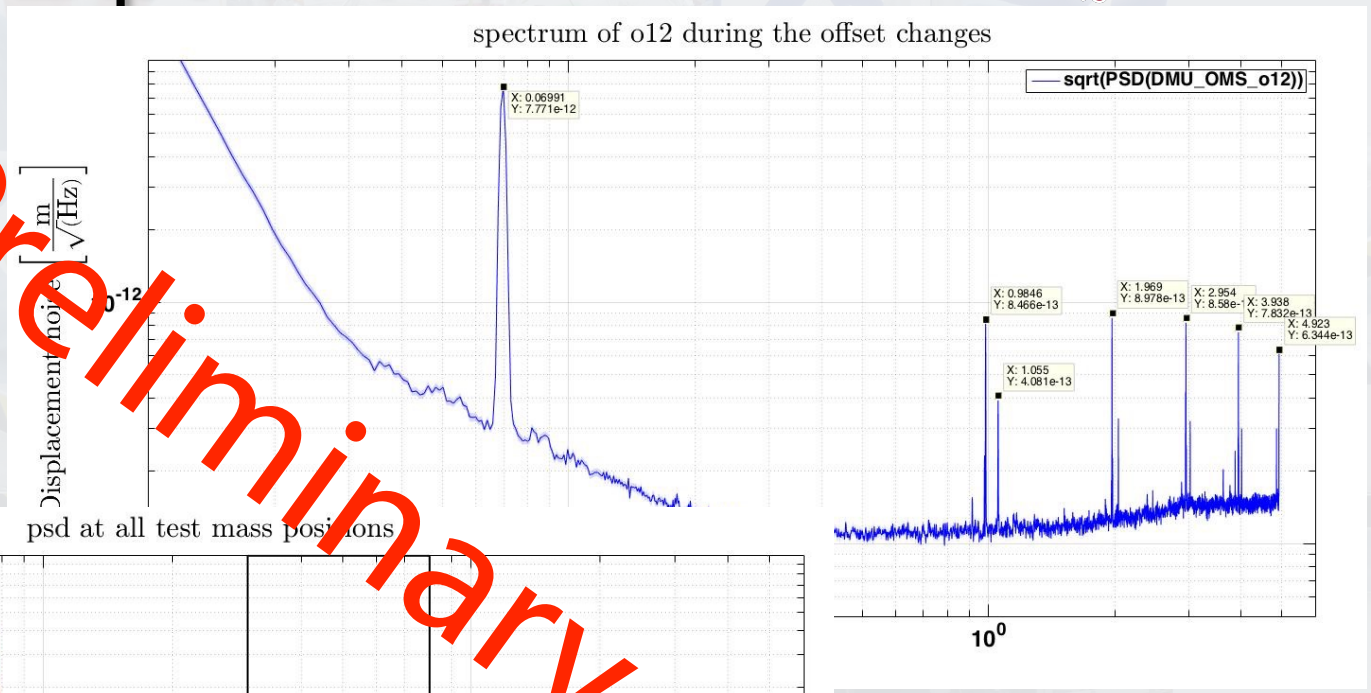
In-flight Experiment

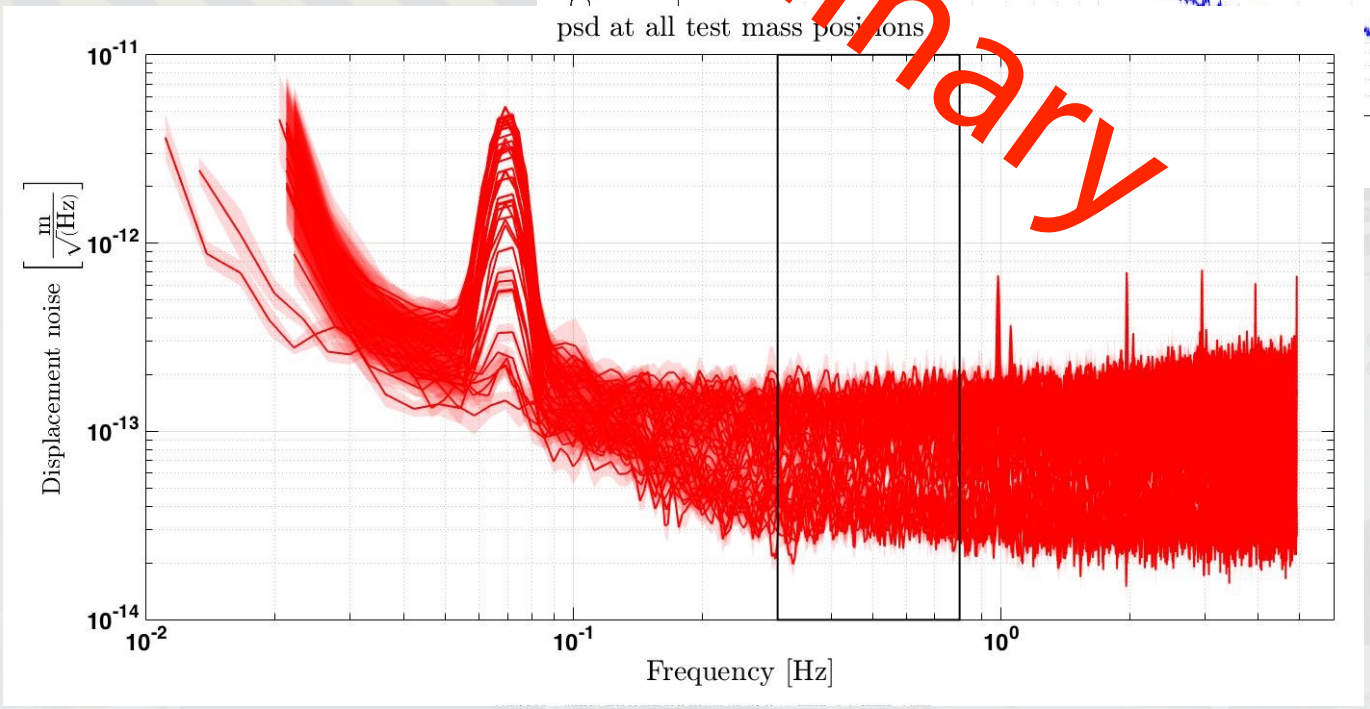




Preliminary

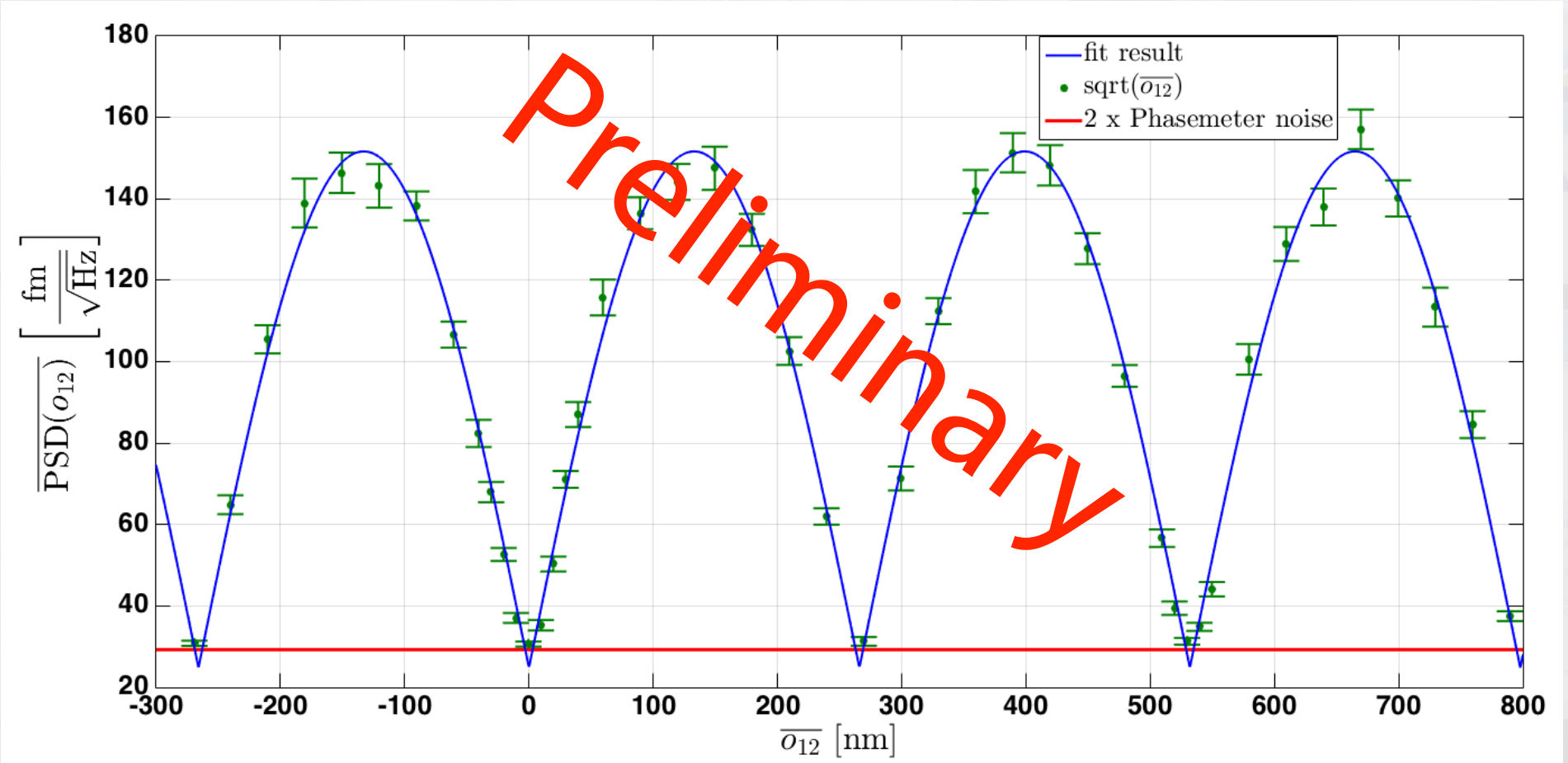
In-flight Experiment





Preliminary

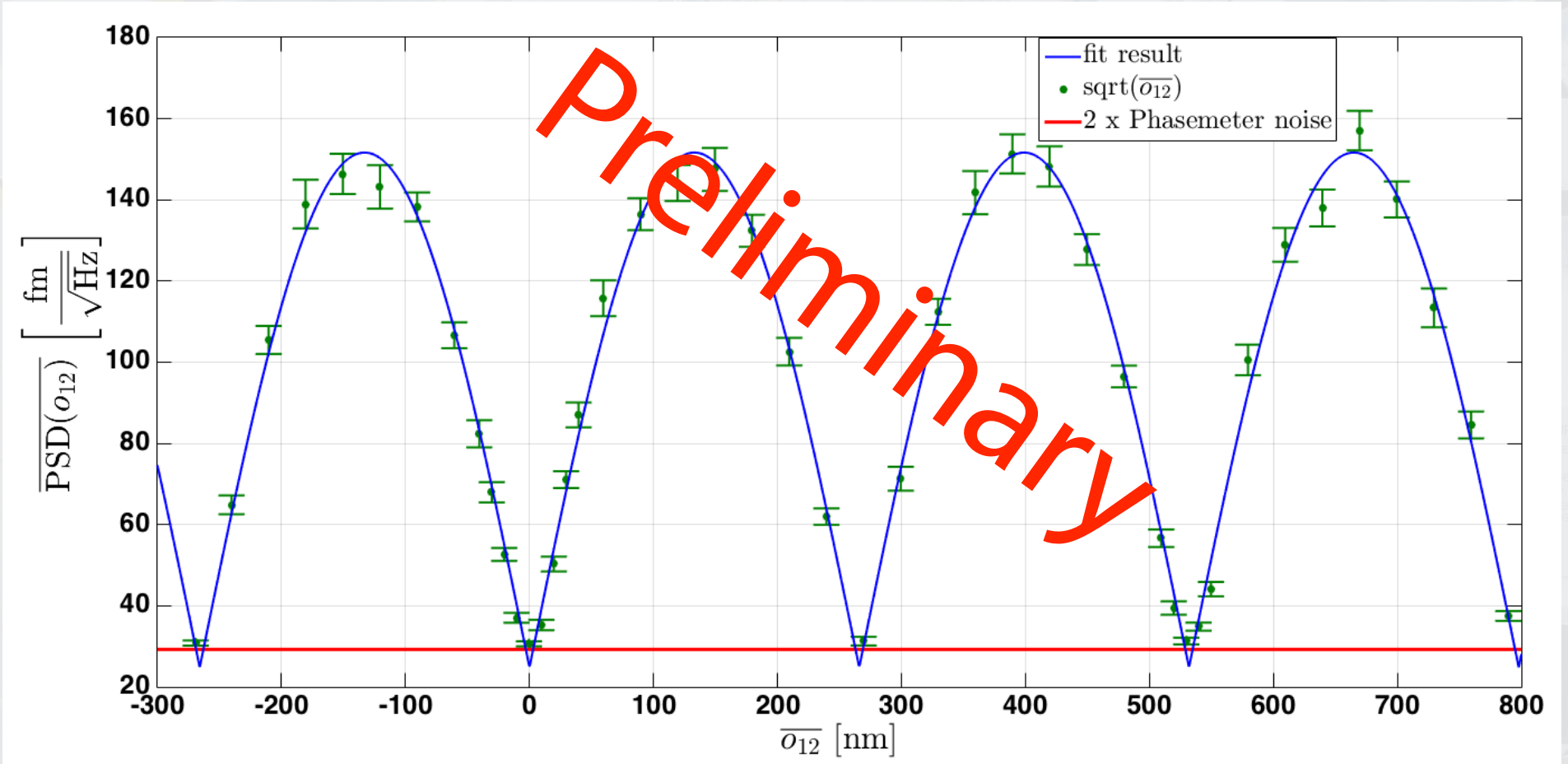
In-flight Experiment



In-flight Experiment

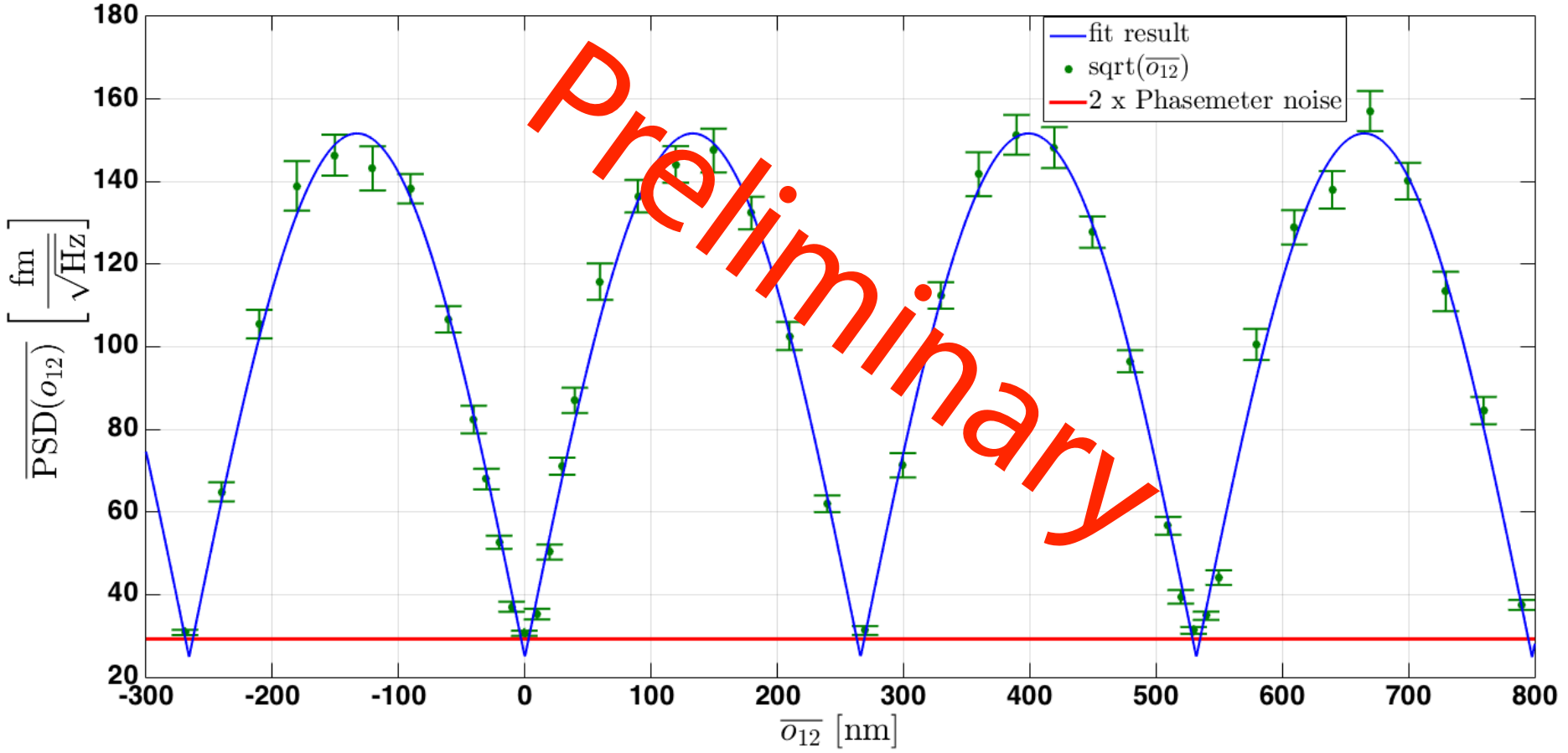
```
RIN2f = 'sqrt( (  A2f.*sin(4*pi*1/w*(samples))  ).^2 ) ';
noise_floor = 'noise_floor';

fit_function = [RIN2f '+' noise_floor];
```

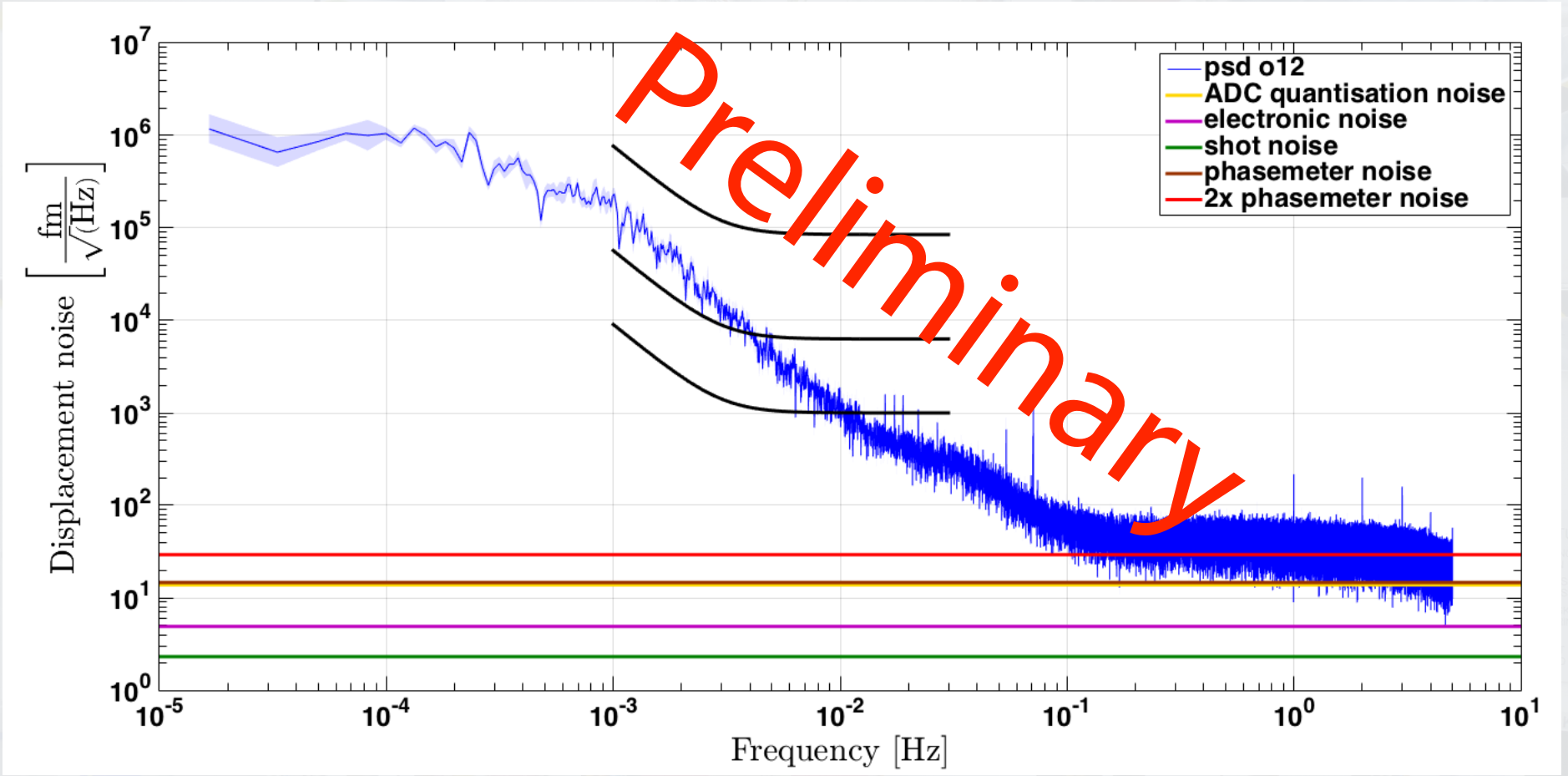


In-flight Experiment

	fminsearch(chi2)	fminsearch(chi2) (error)	Units
A2f	126.82	6.649	[fm Hz^(-1/2)]
w	1063.9	5.485	[nm]
noise_floor	24.834	4.264	[fm Hz^(-1/2)]



Noise floor


Preliminary
psd o12
ADC quantisation noise
electronic noise
shot noise
phasemeter noise
2x phasemeter noise
Displacement noise [fm/√(Hz)]
Frequency [Hz]
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
10^1

Conclusion

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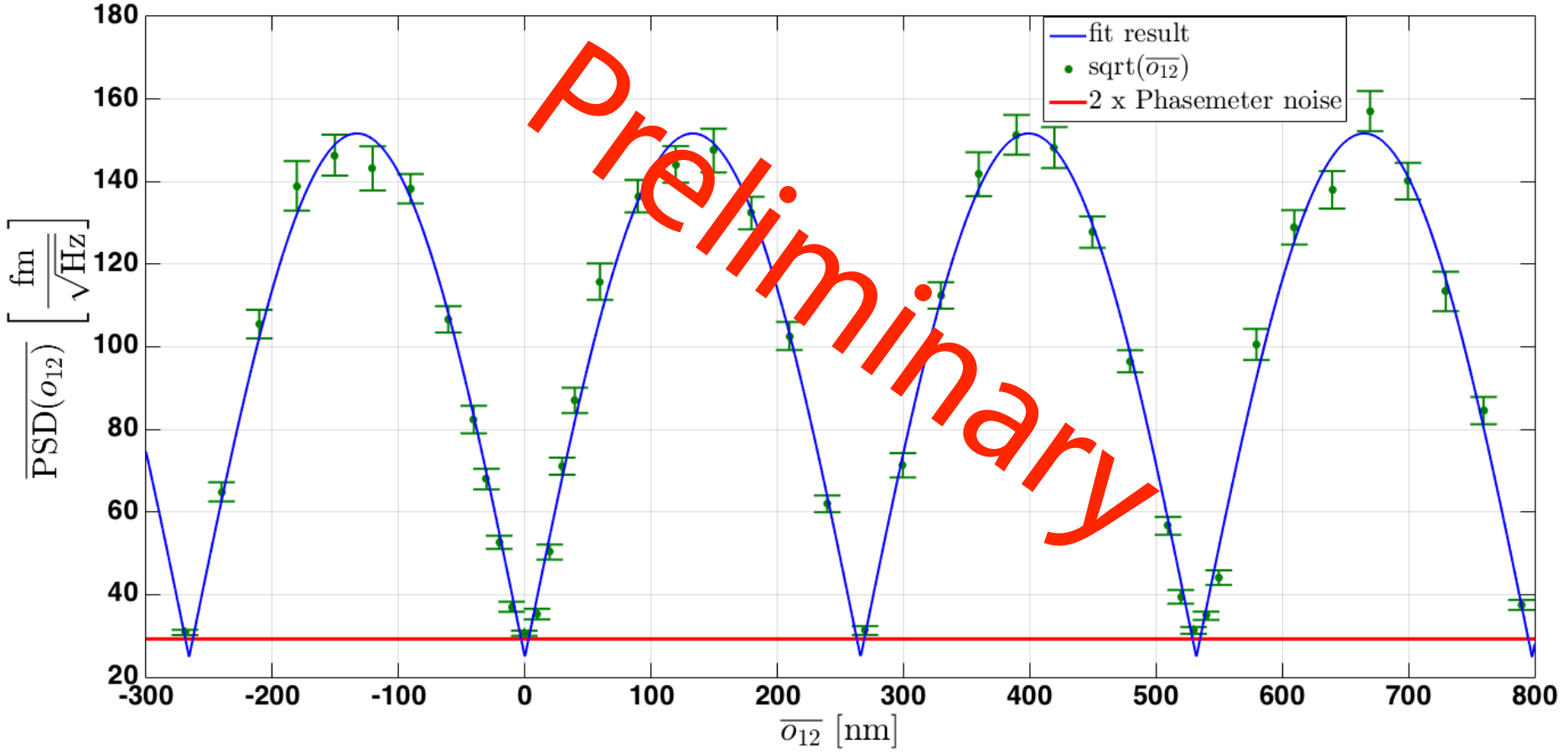
RIN matters

balanced detection and test mass position are important



Thanks!

```
p = [...
    LPFParam('A2f', 130, 'fm Hz^(-1/2)', 'The Amplitude of RIN at 2kHz'),...
    LPFParam('w', 1064, 'nm', 'The wavelength'),...
    LPFParam('noise_floor', 1, 'fm Hz^(-1/2)', 'The noise floor, this is the minimum noise
    ];

p = p.toPest;
p.setName('p');

% changed 2pi to 4pi
% RIN1f = 'sqrt((A1f.*sin(4*pi*0.5*1/w*(samples))).^2)';
RIN2f = 'sqrt( (  A2f.*sin(4*pi*1/w*(samples))  ).^2 ) ';
noise_floor = 'noise_floor';

fit_function = [RIN2f '+' noise_floor];
mdl = mfh(plist(...
                'name',             'temp',...
                'built-in',         'custom',...
                'numeric',          true,...
                'params',           p,...
                'func',             fit_function,...
                'constants',        {'stupid', 'data','samples'},...
                'constant objects', {o12, dataset, xValues}));
```

Amplitude noise - 2009

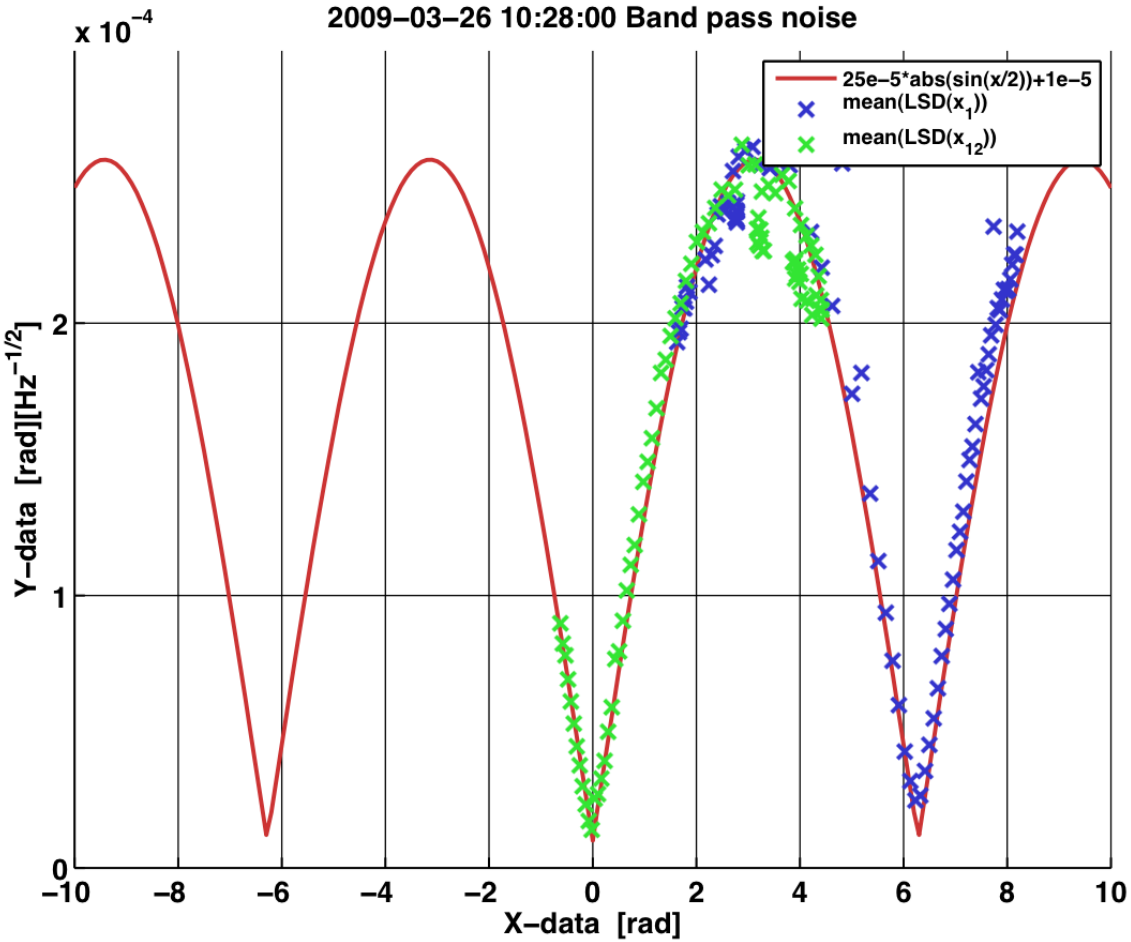


Figure 3: Average phase noise with respect to the DC value of the phase, when band passed amplitude noise is injected via de AOM drivers.