

# Characterisation of LTP

M Hewitson for the LTP Team



UNIVERSITÀ DEGLI STUDI  
DI TRENTO

# Outline



- Physics of LTP
- Data Analysis Tools
- Experiment Master Plan
- Mock Data Challenges

# Mission Goals



- Technology demonstration for LISA
- Characterisation of the instrument subsystems
- Noise reduction and noise budget

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- Characterisation of the instrument subsystems
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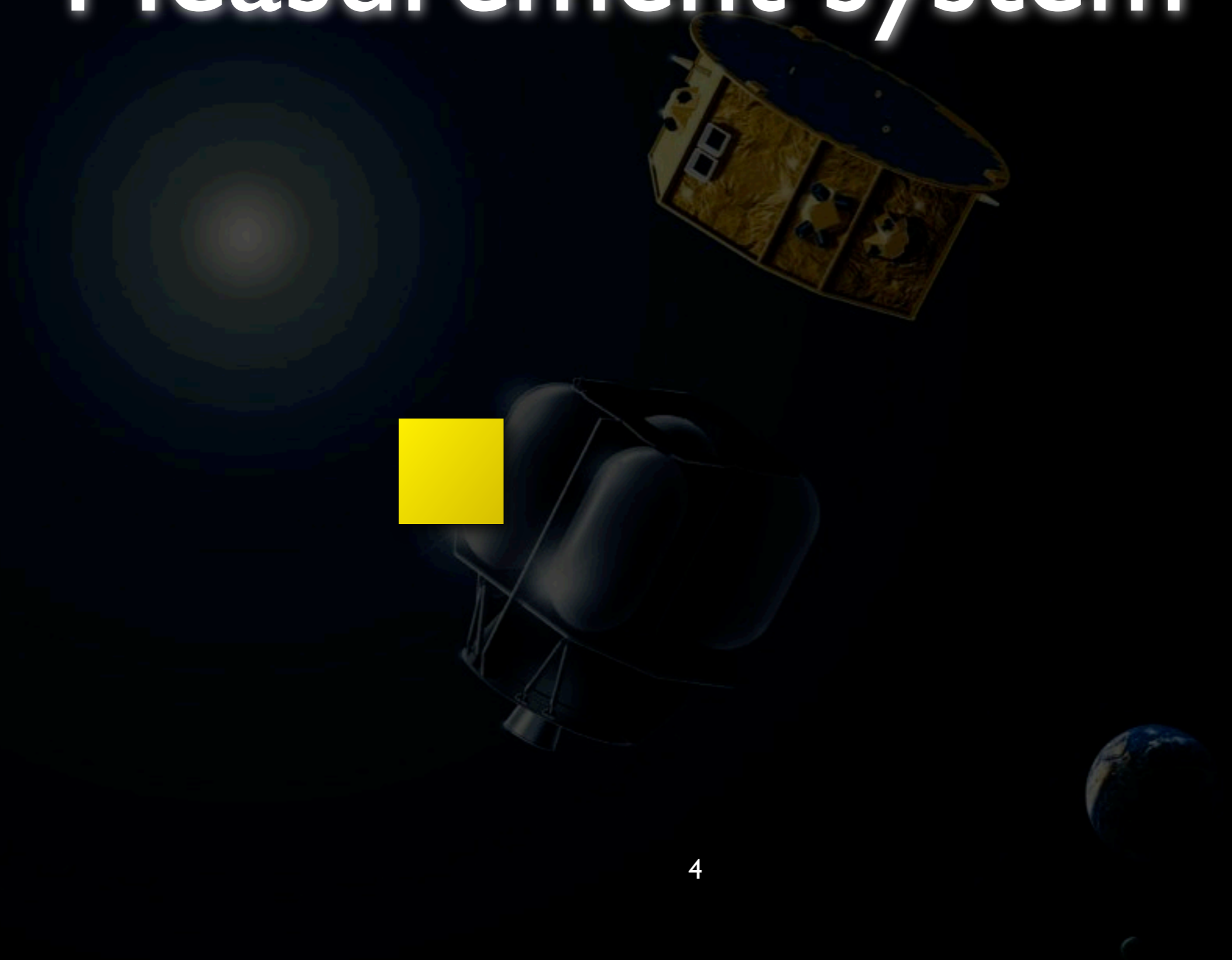
Free-falling test-mass at the level of about

$$3 \times 10^{-14} \text{ m s}^{-2} / \sqrt{\text{Hz}} @ 1 \text{ mHz}$$

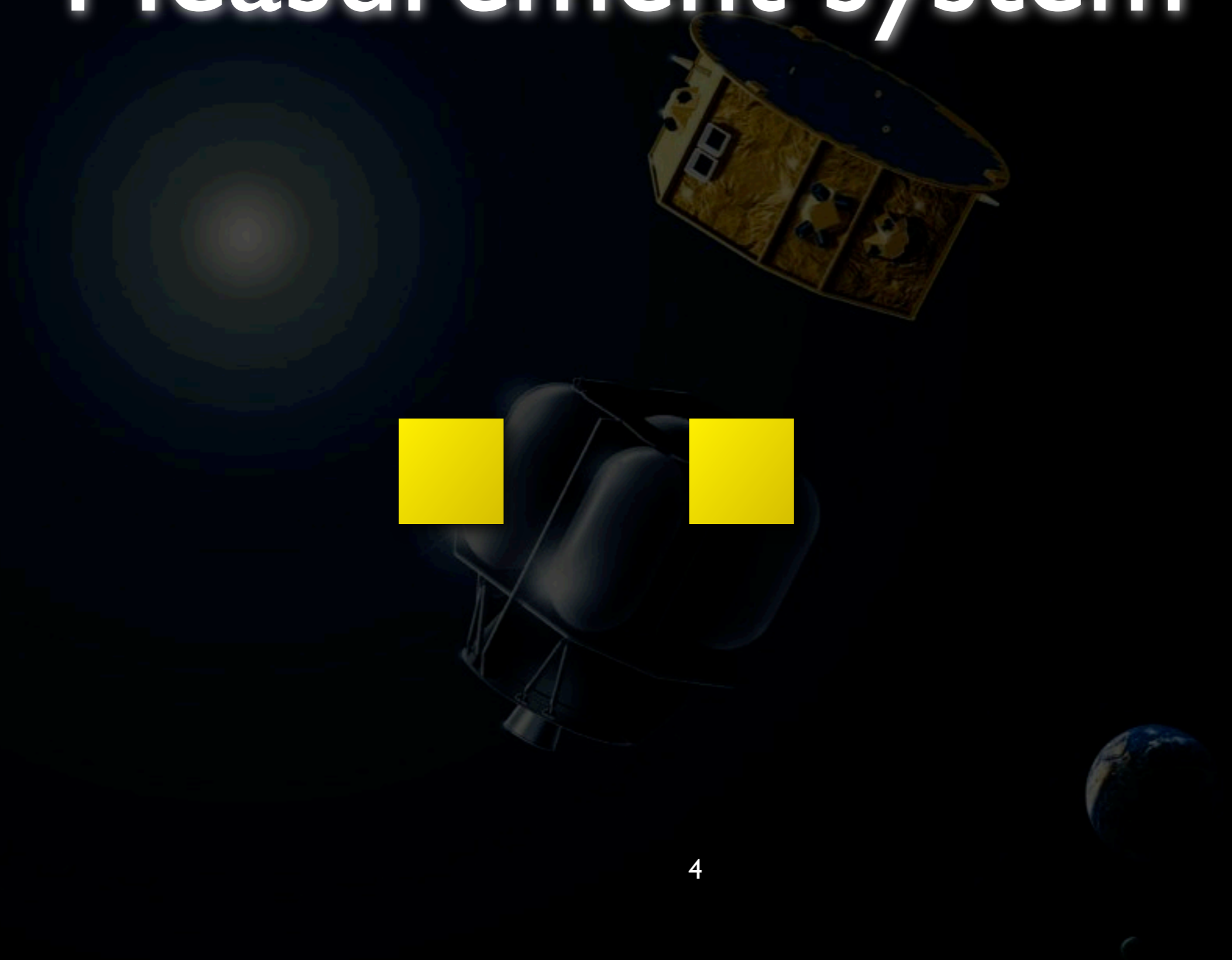
# Measurement system



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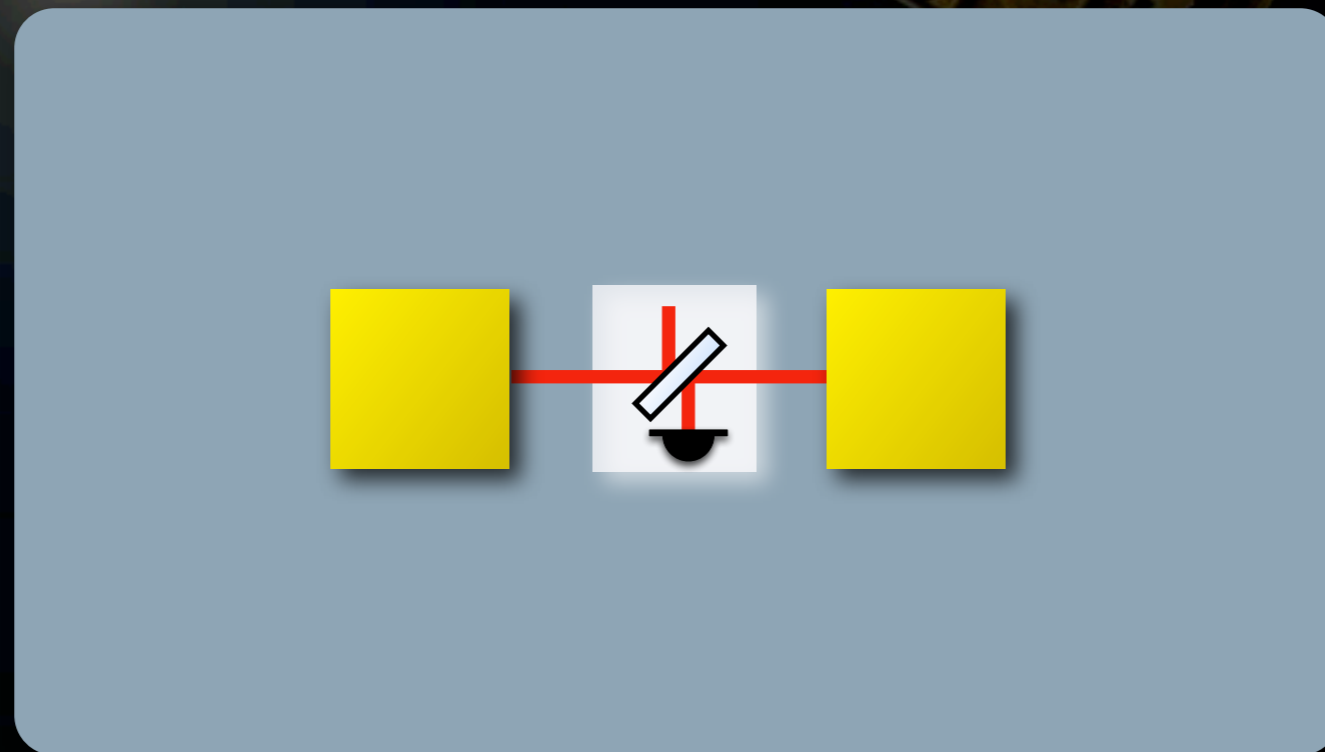


# Measurement system

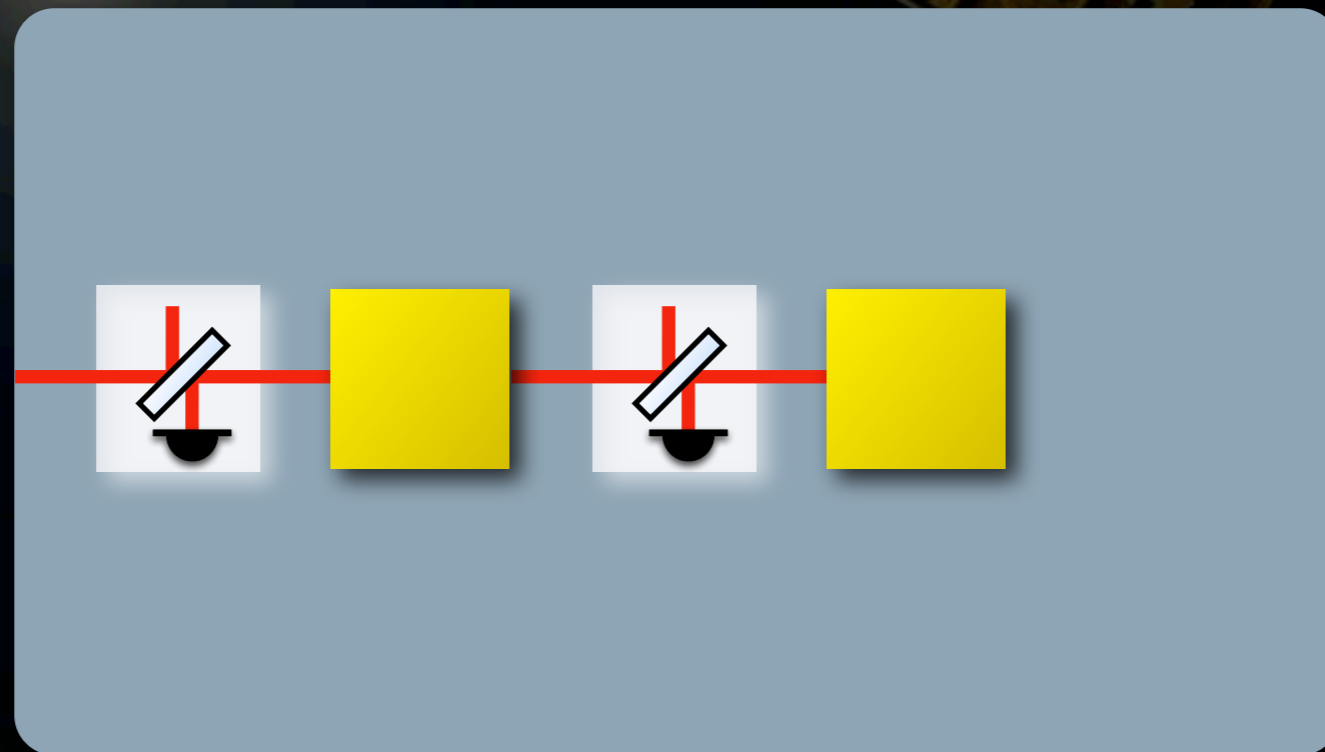




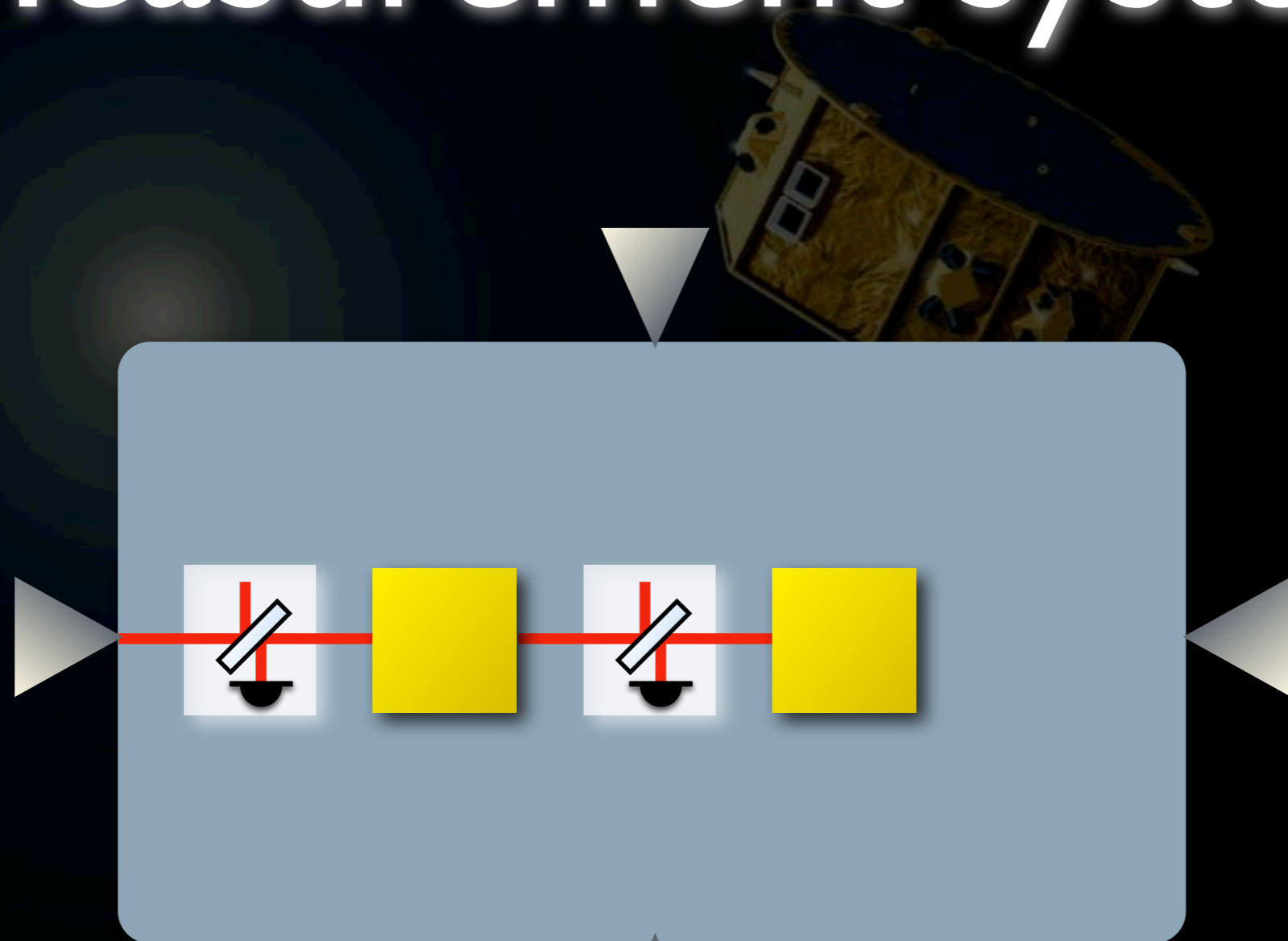
# Measurement system



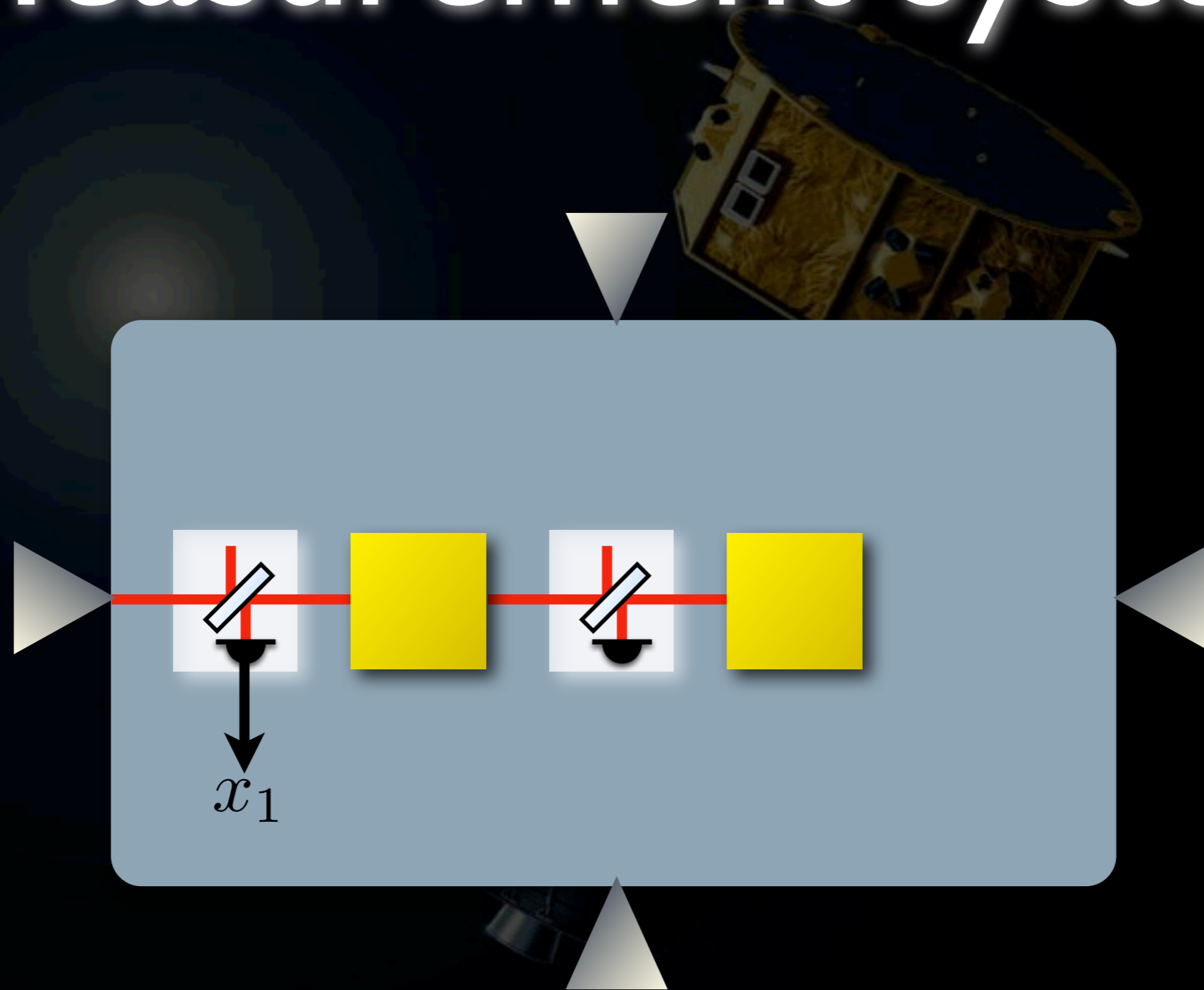
# Measurement system



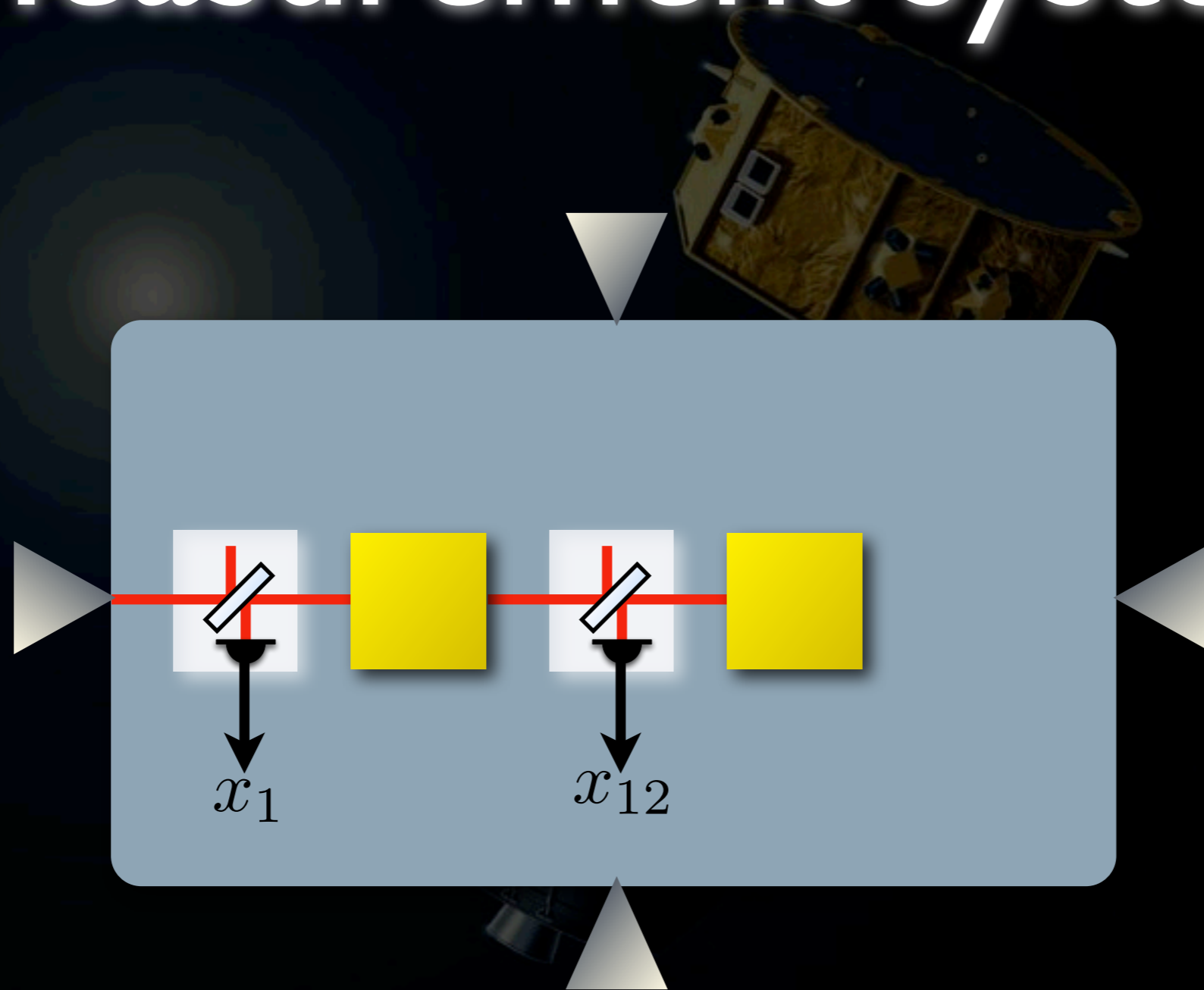
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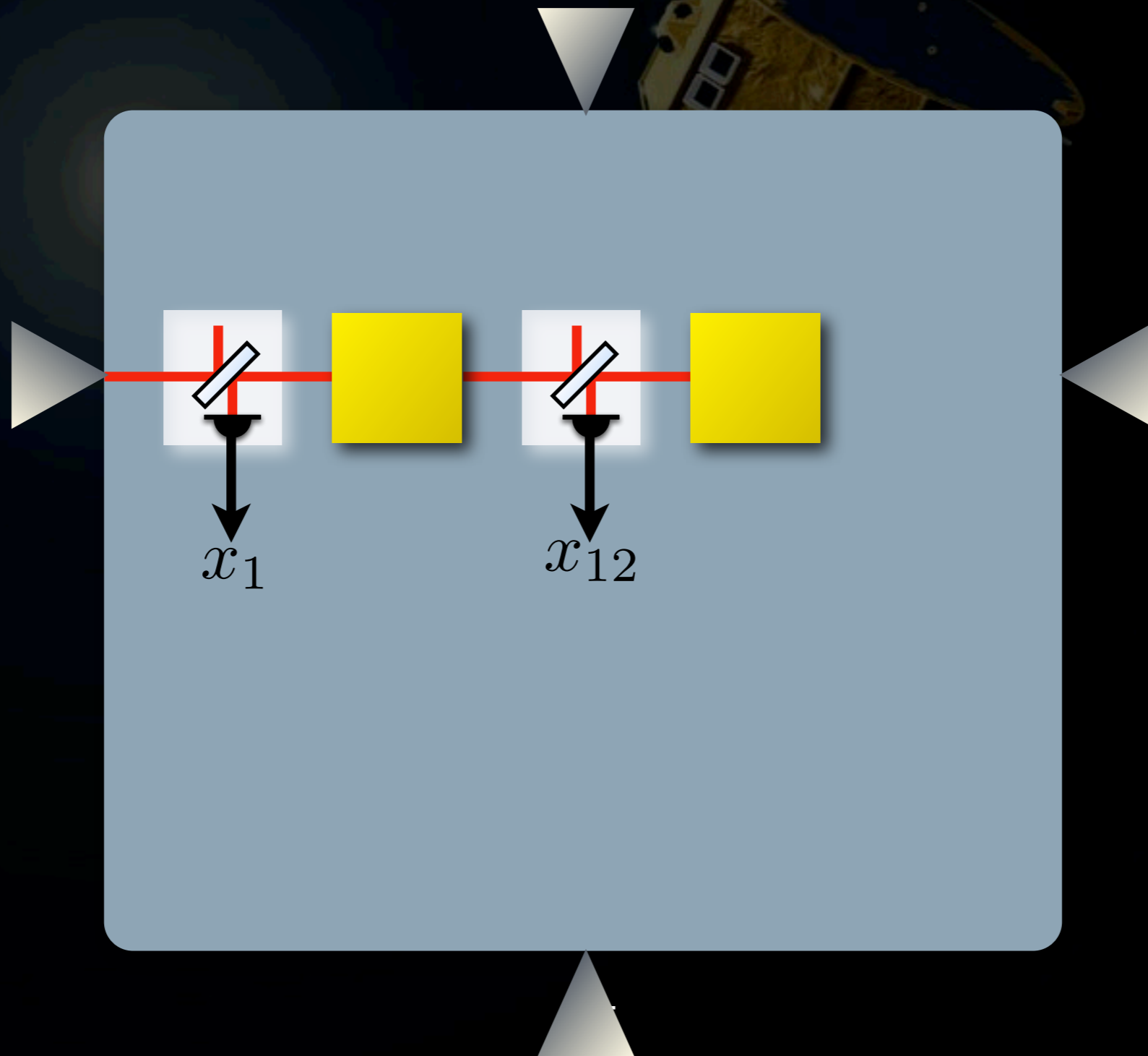
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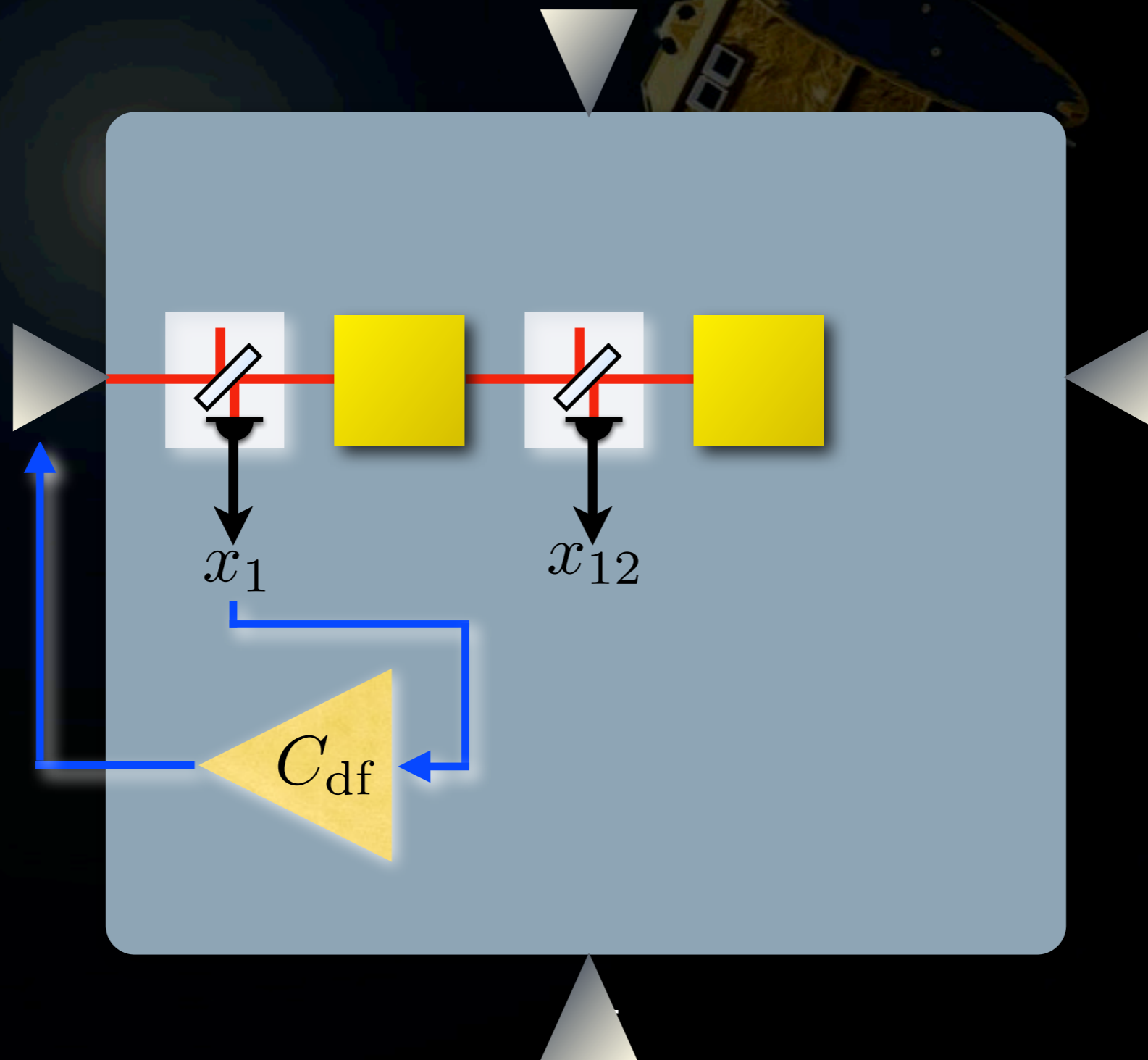
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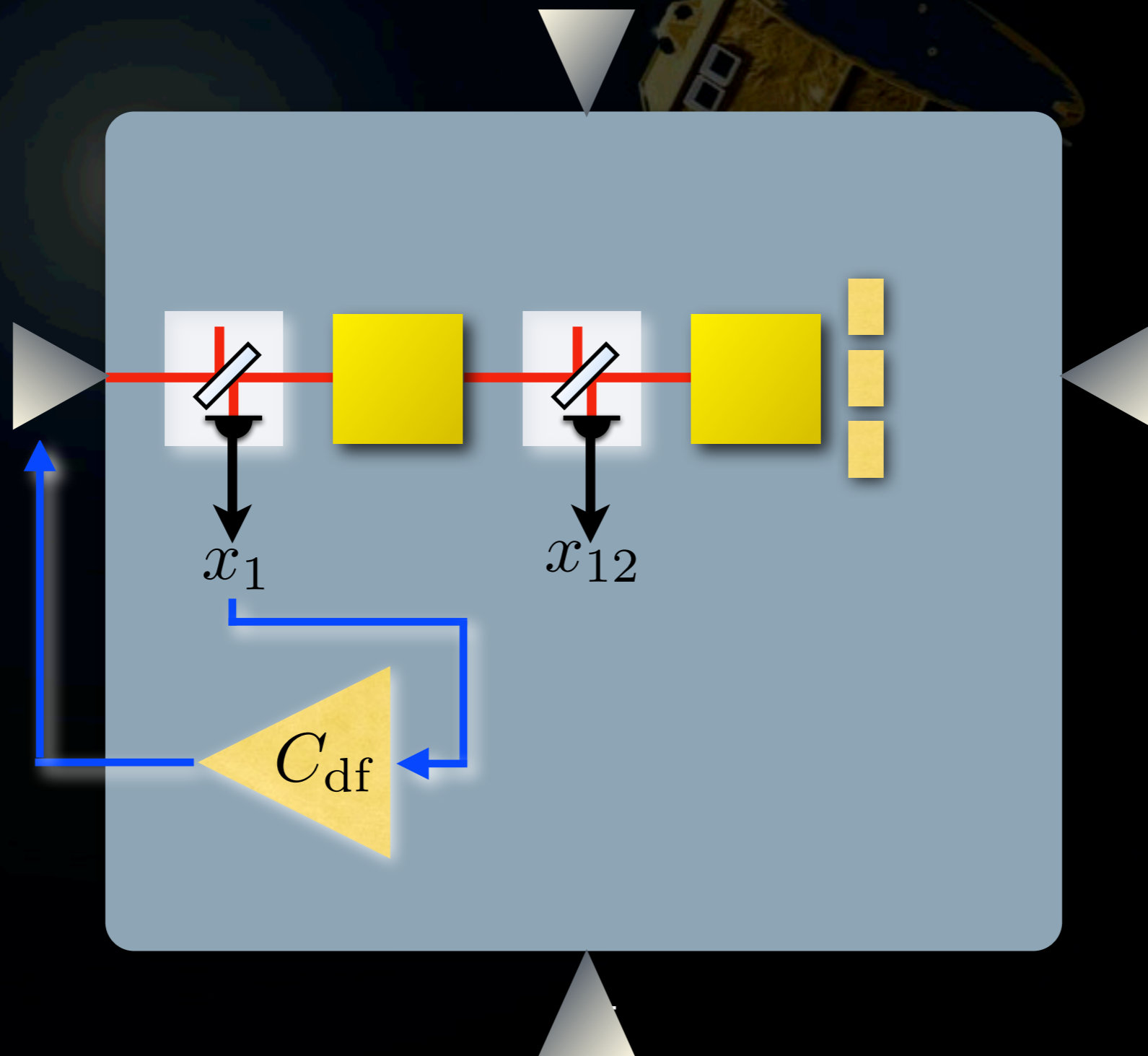
# X-axis control



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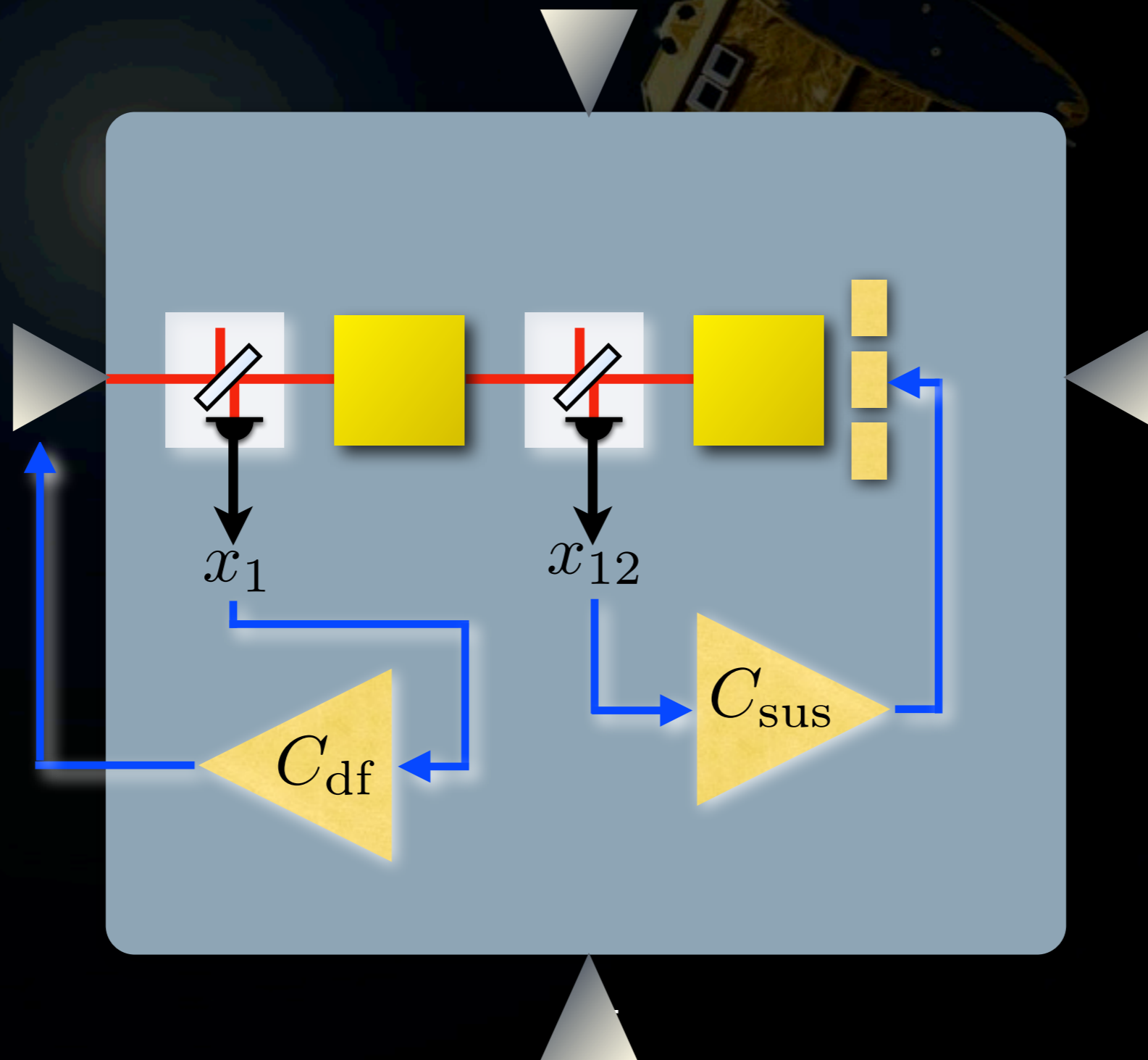


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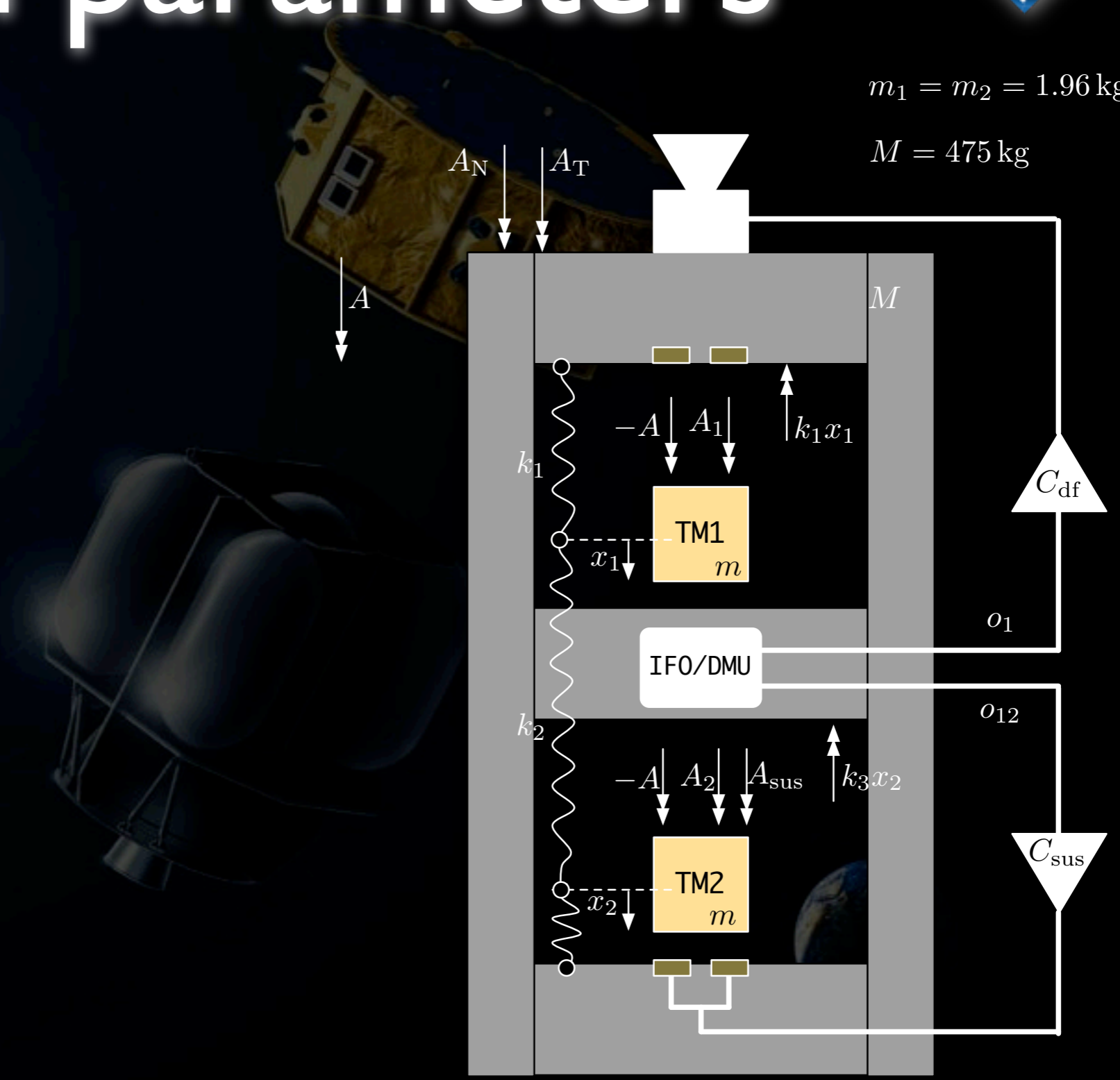


# Main parameters



$$m_1 = m_2 = 1.96 \text{ kg}$$

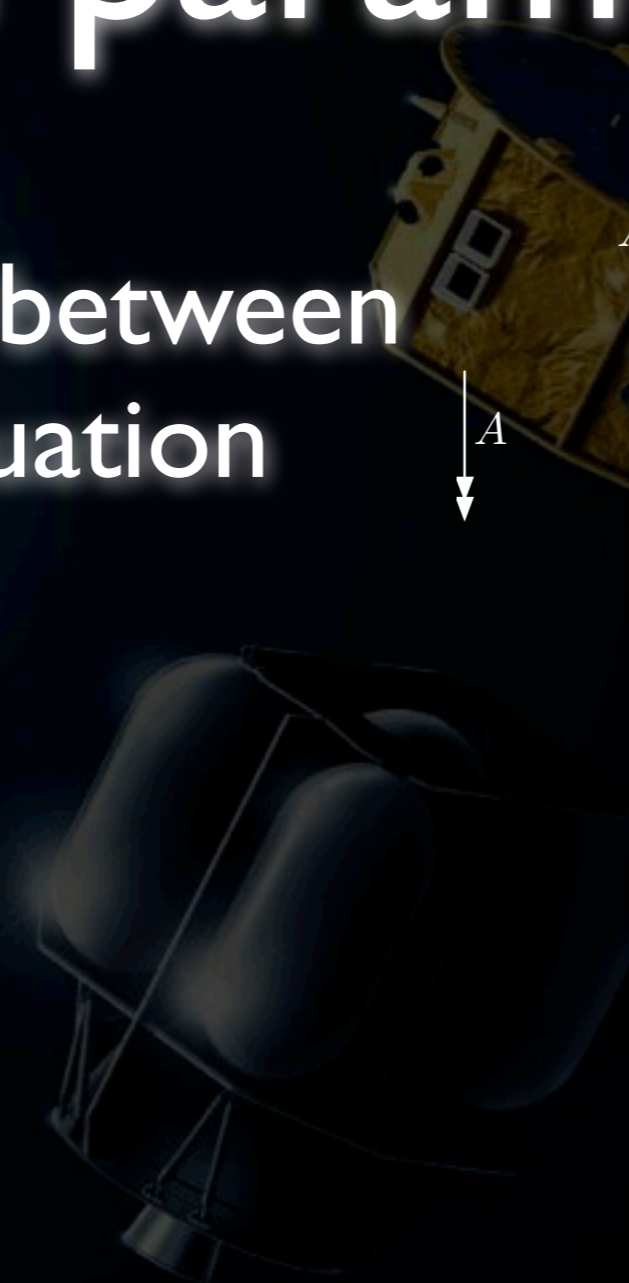
$$M = 475 \text{ kg}$$



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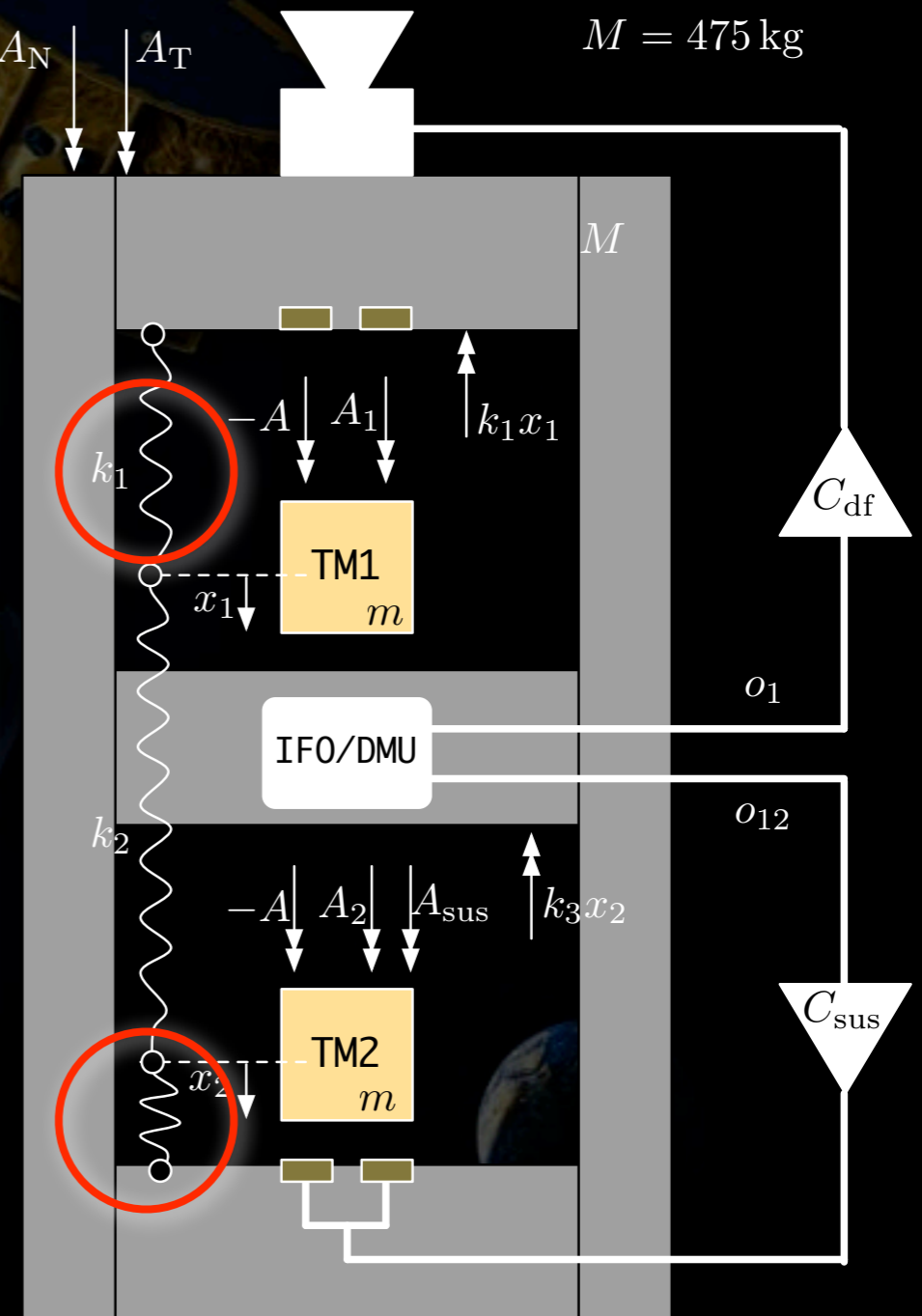


- Spring couplings between SC and TMs (actuation stiffness)



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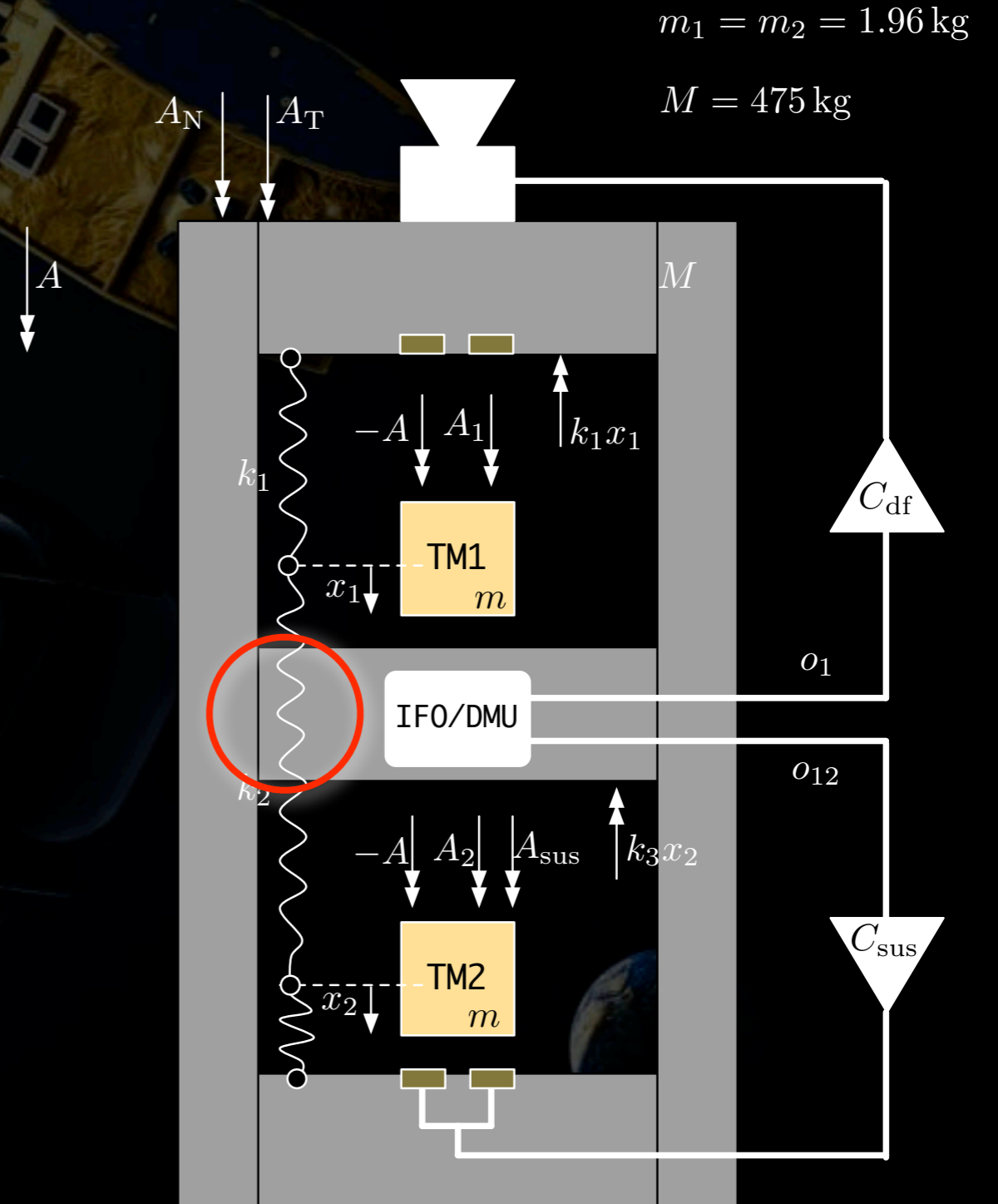
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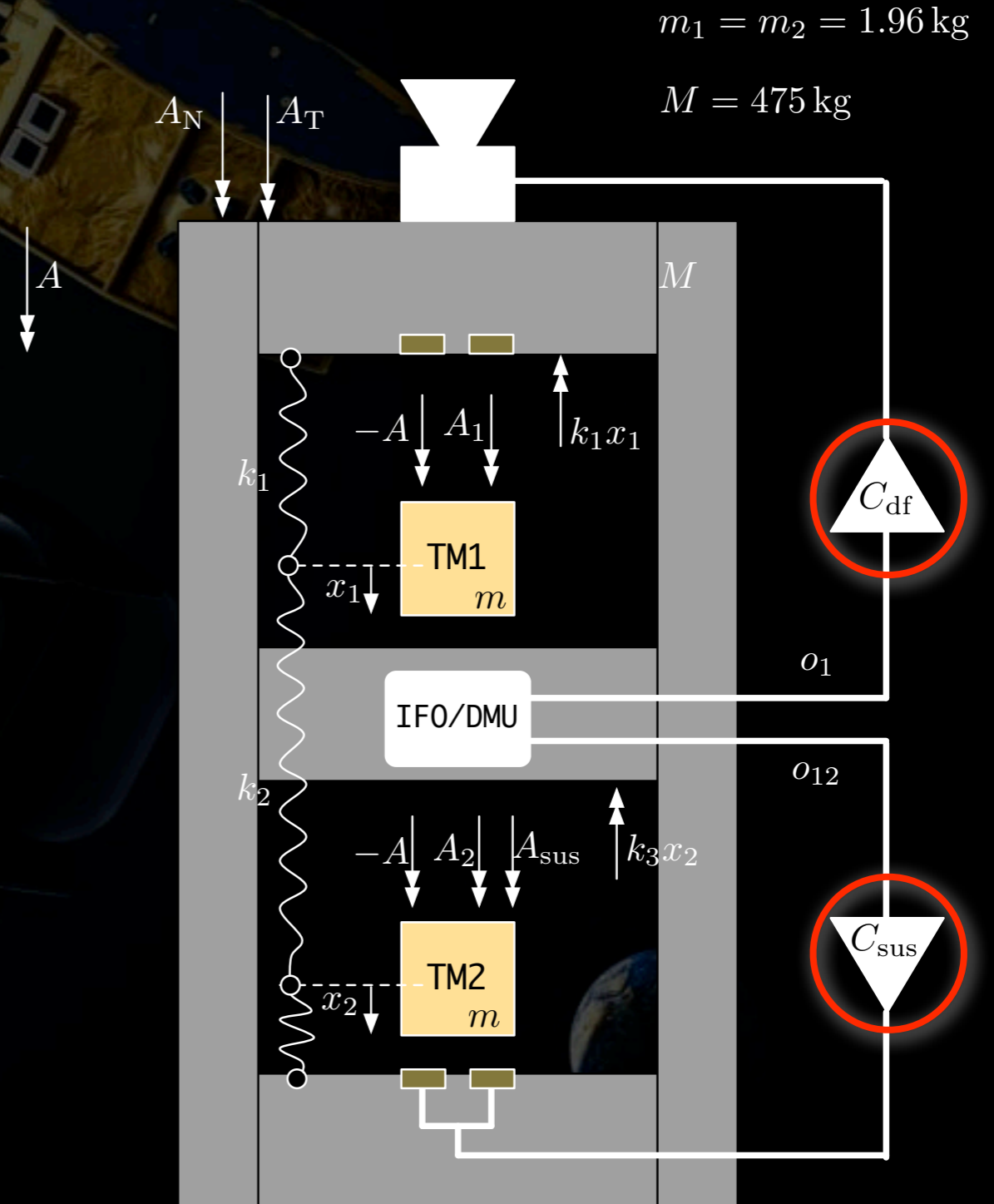
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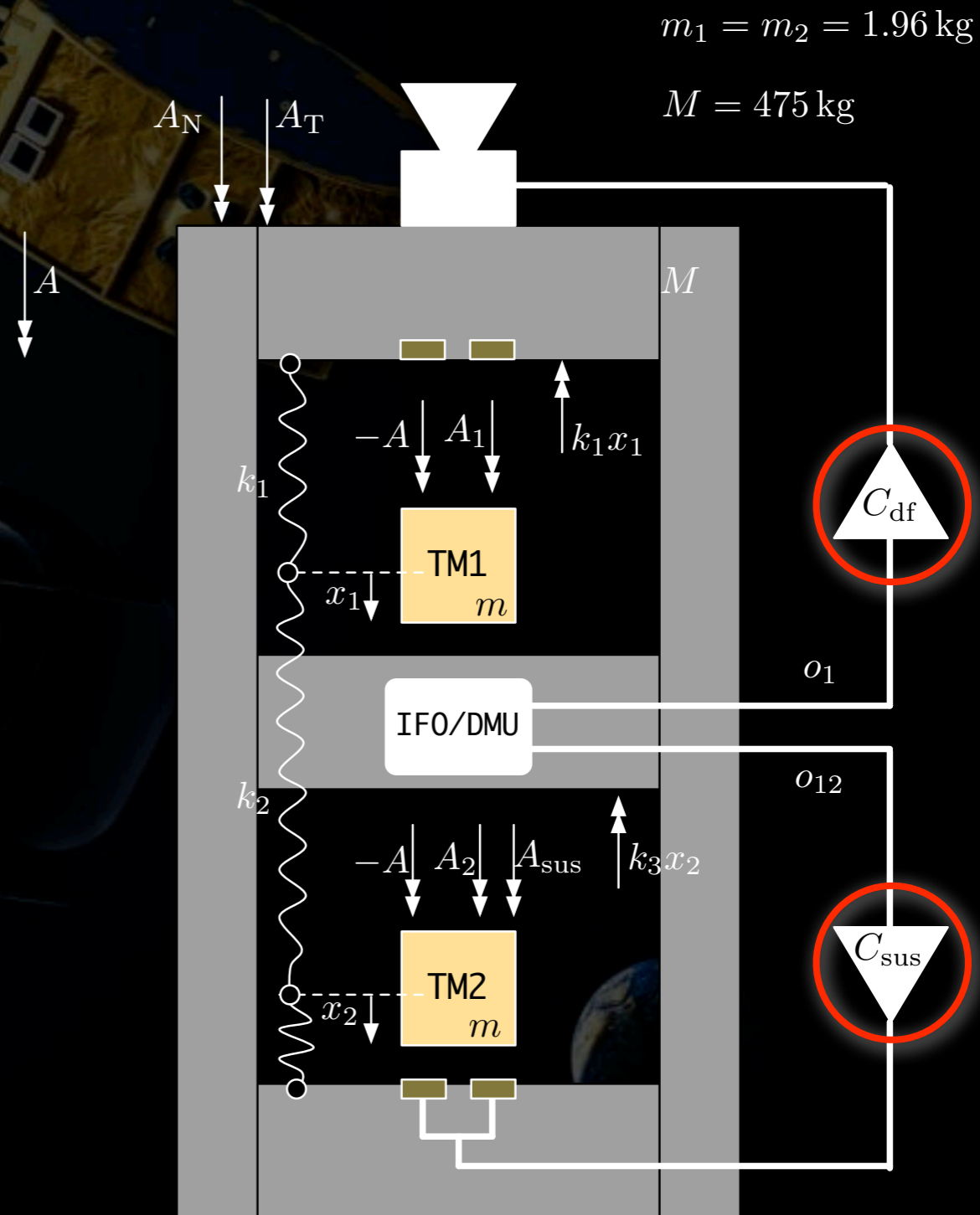
- Spring couplings between SC and TMs (actuation stiffness)
- Spring coupling between TMs (gravitational attraction)
- Loop gains (actuation calibrations, etc)



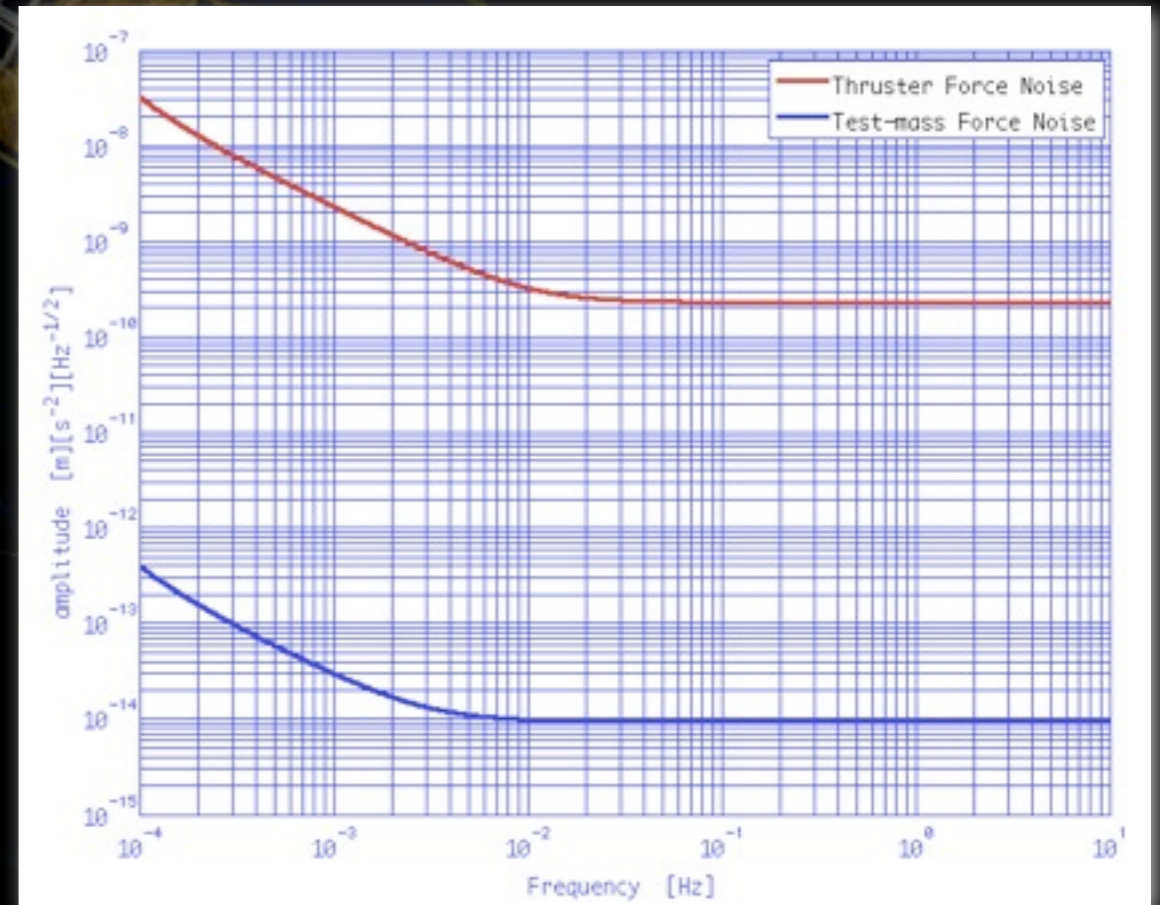
# Main parameters



- Spring couplings between SC and TMs (actuation stiffness)
- Spring coupling between TMs (gravitational attraction)
- Loop gains (actuation calibrations, etc)
- Cross-couplings (various)



# Main noise sources



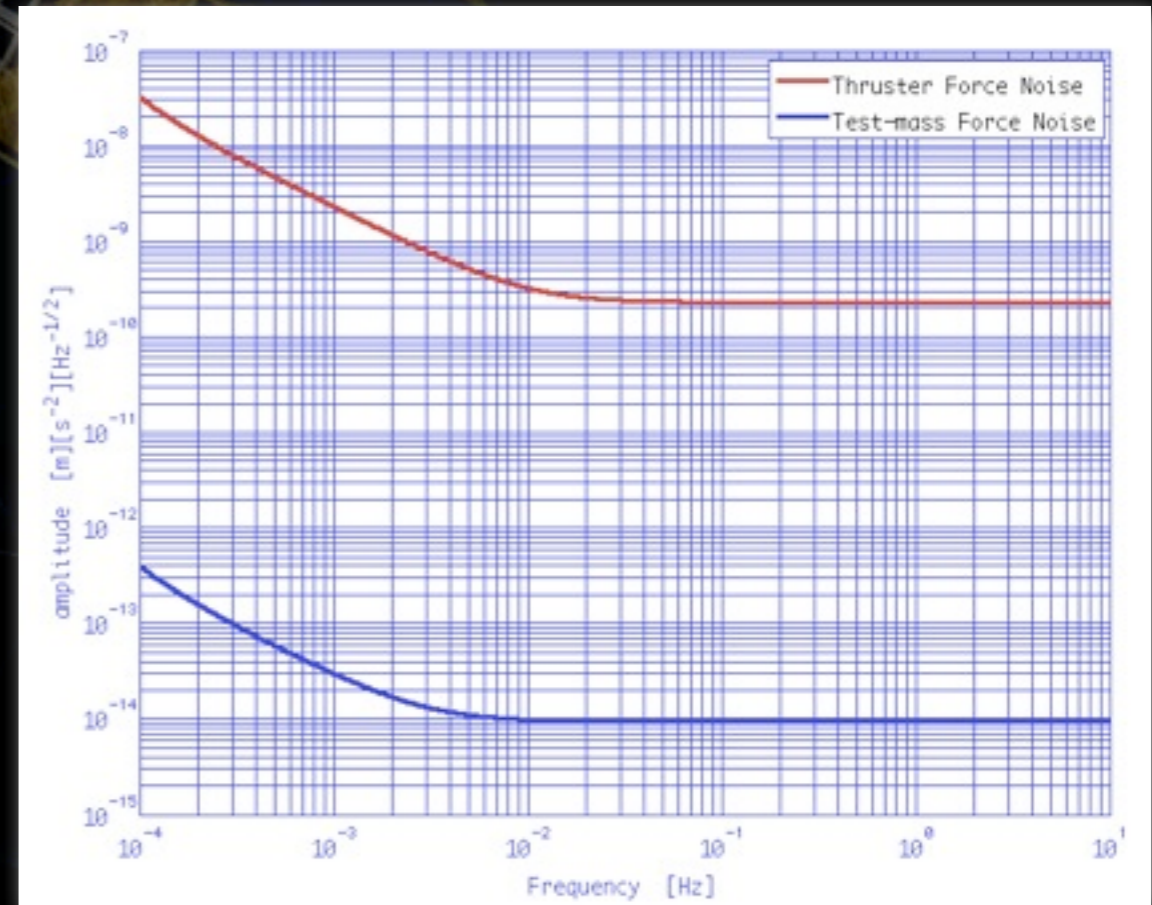
# Main noise sources



## Thruster force noise

Force noise of the thrusters couples directly to the TM-SC measurement.

Also couples to TM-TM measurement via differences in the stiffness of each TM to SC.





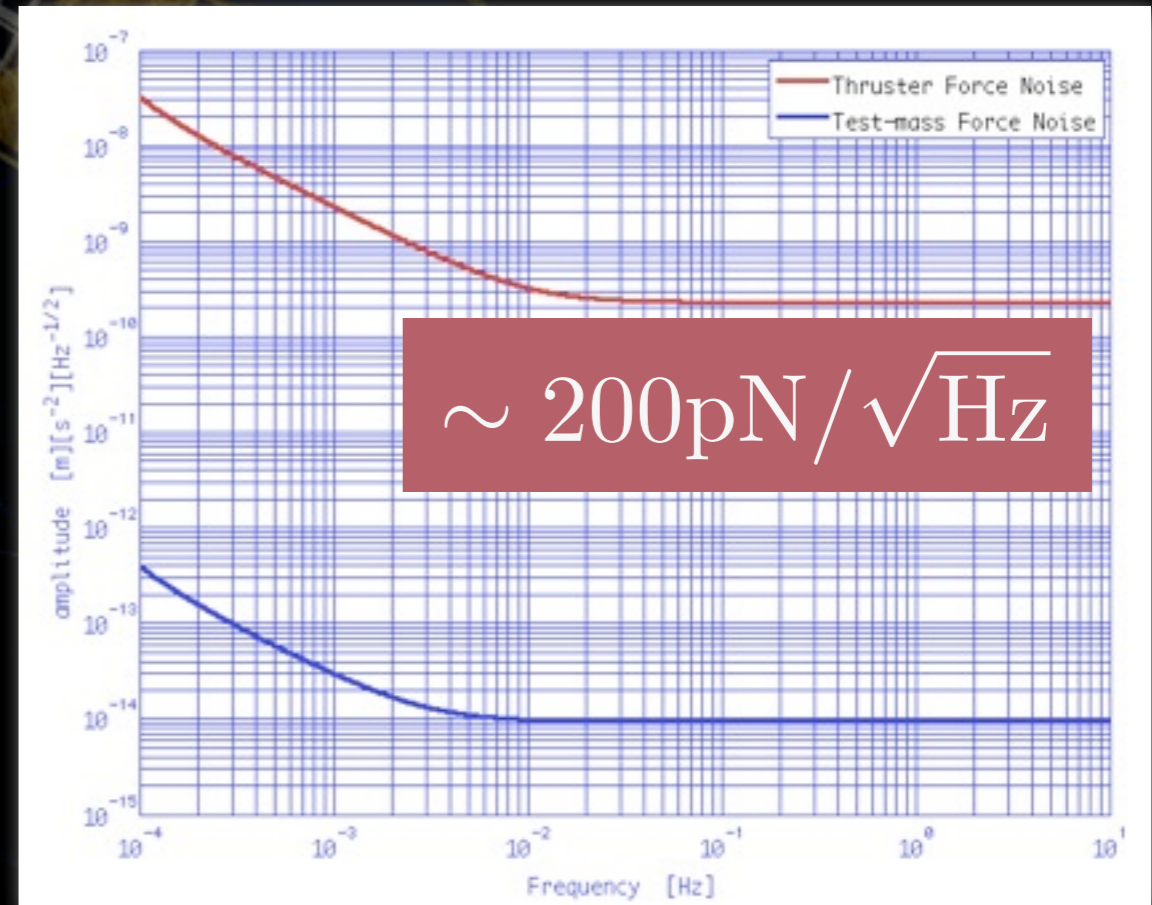
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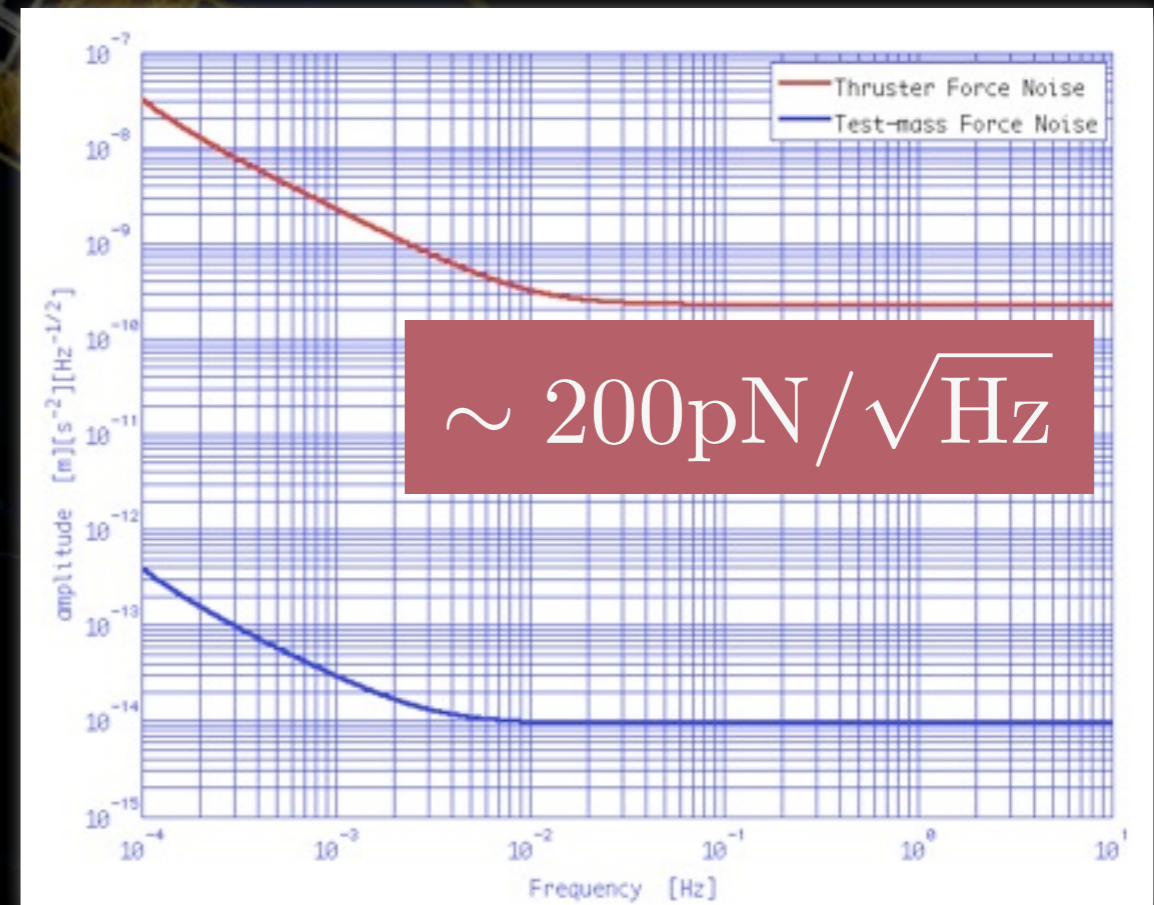
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## Residual force noise on TMs

Environment forces acting on test-masses: radiometer, actuation, thermal, charging, magnetic, etc

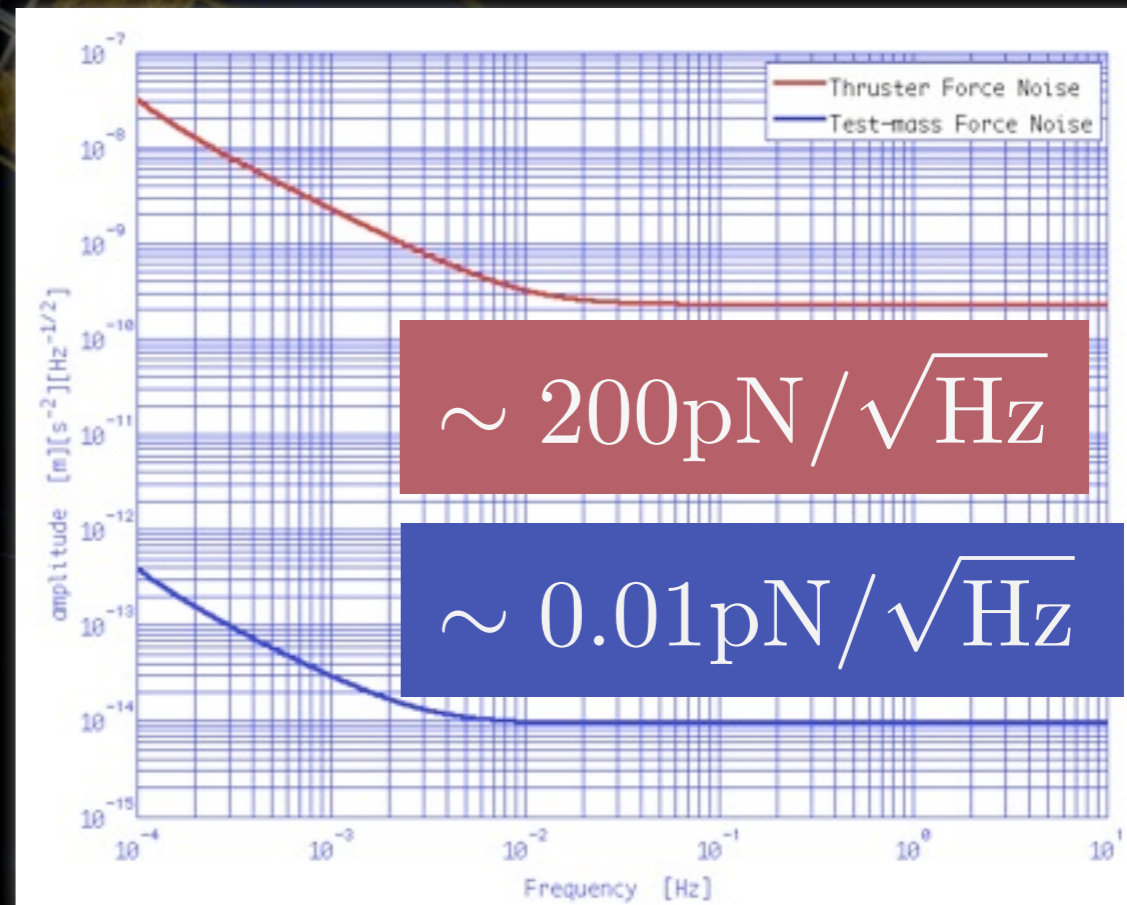
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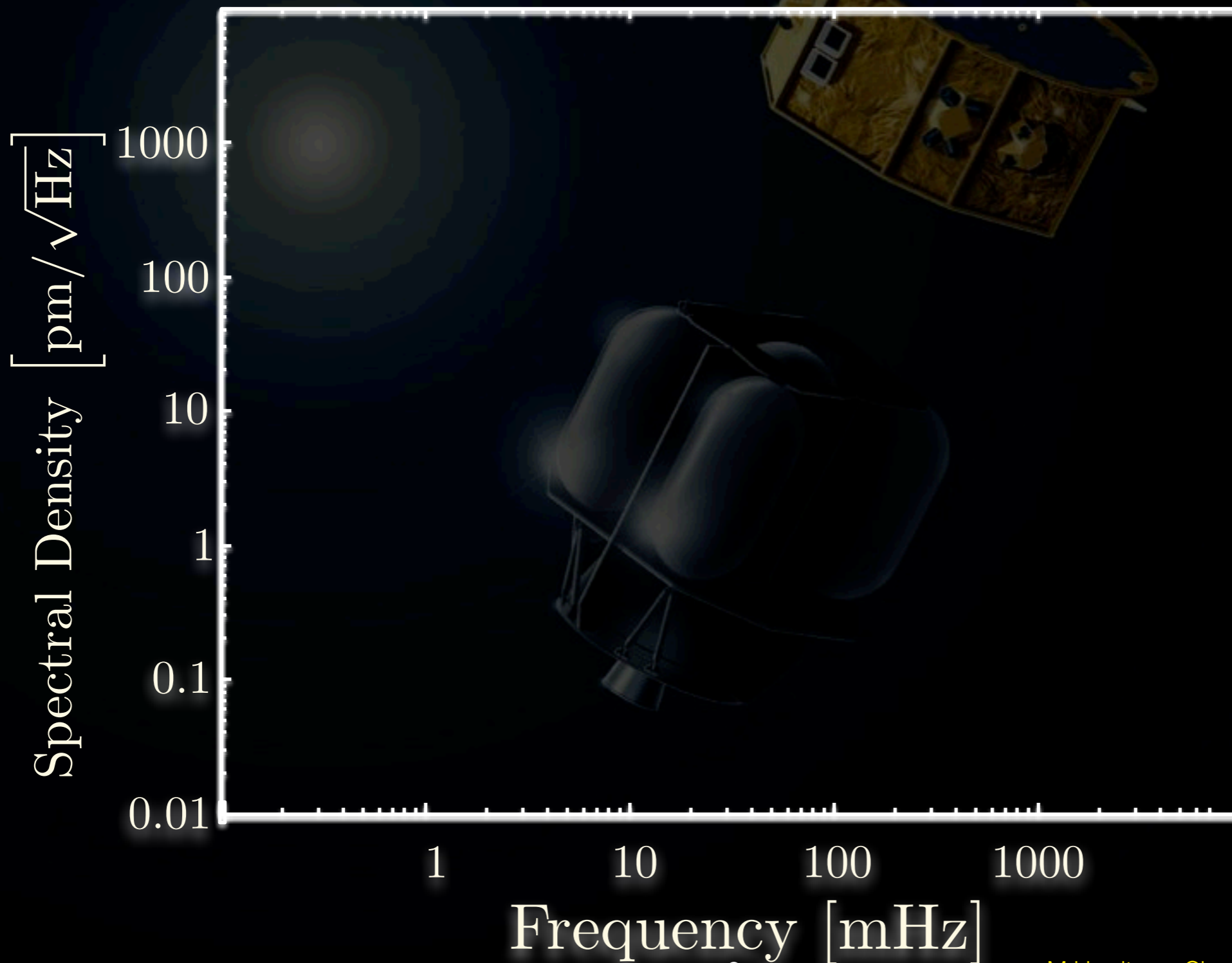
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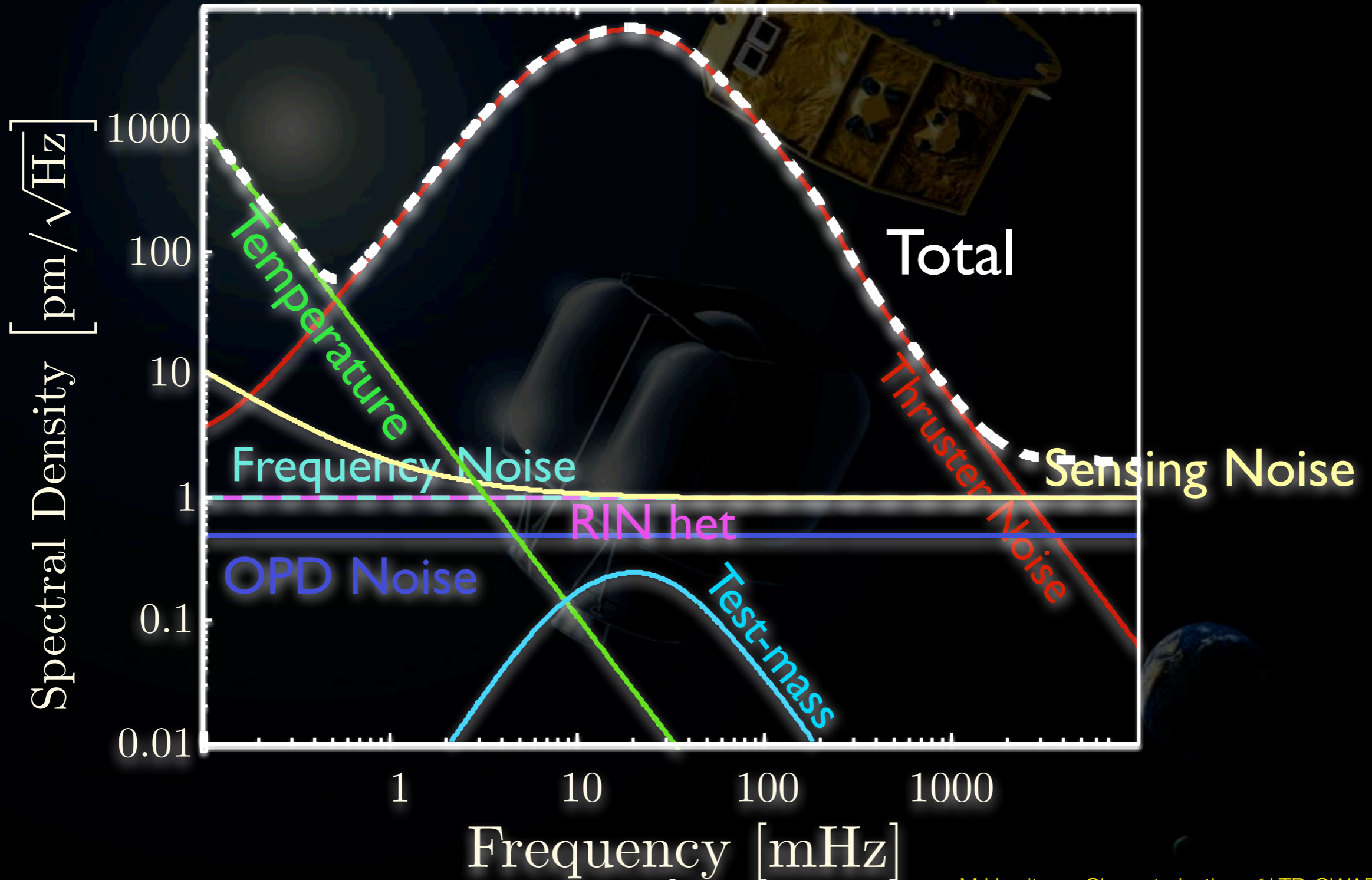
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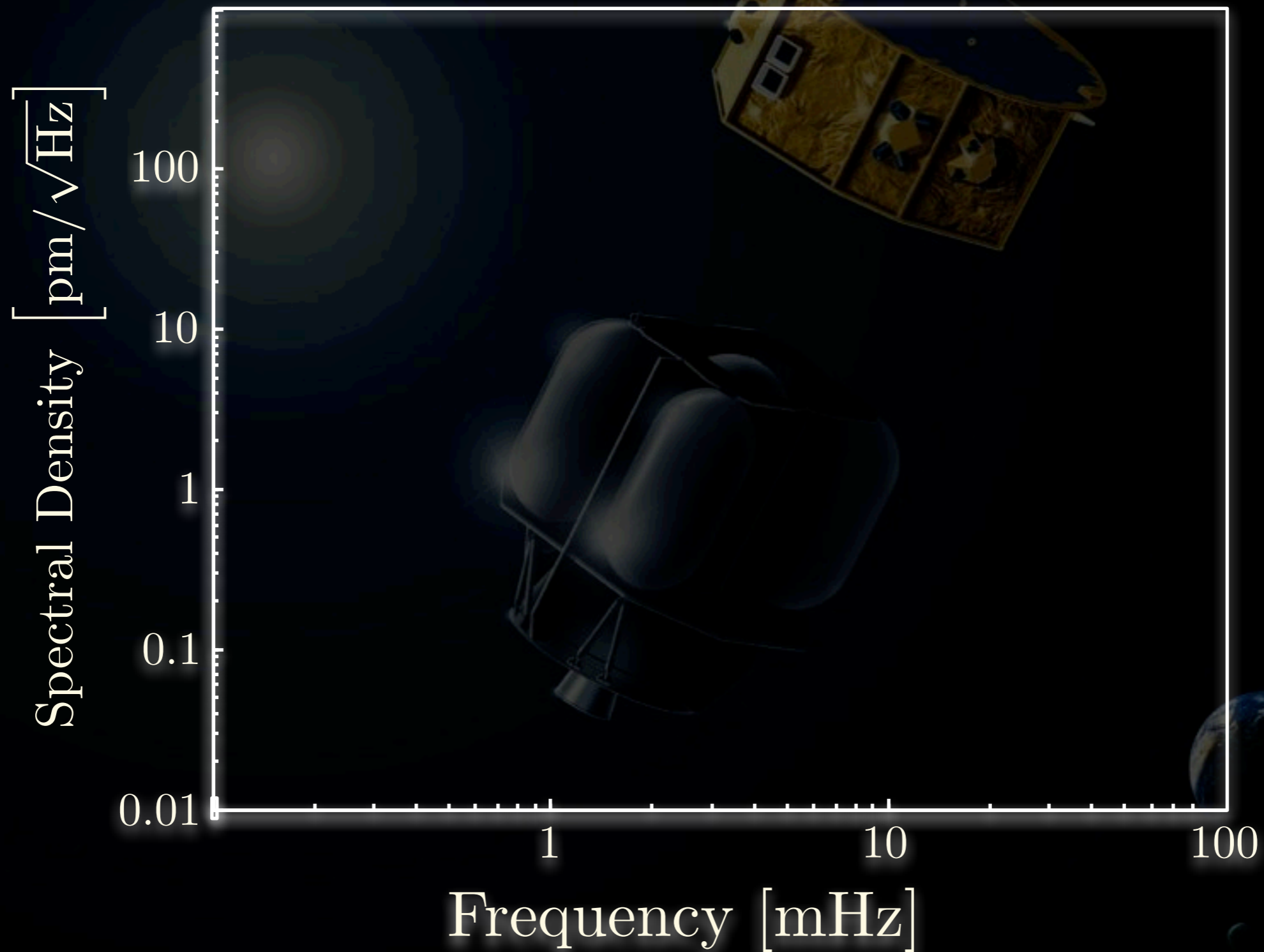
# Noise budget - XI



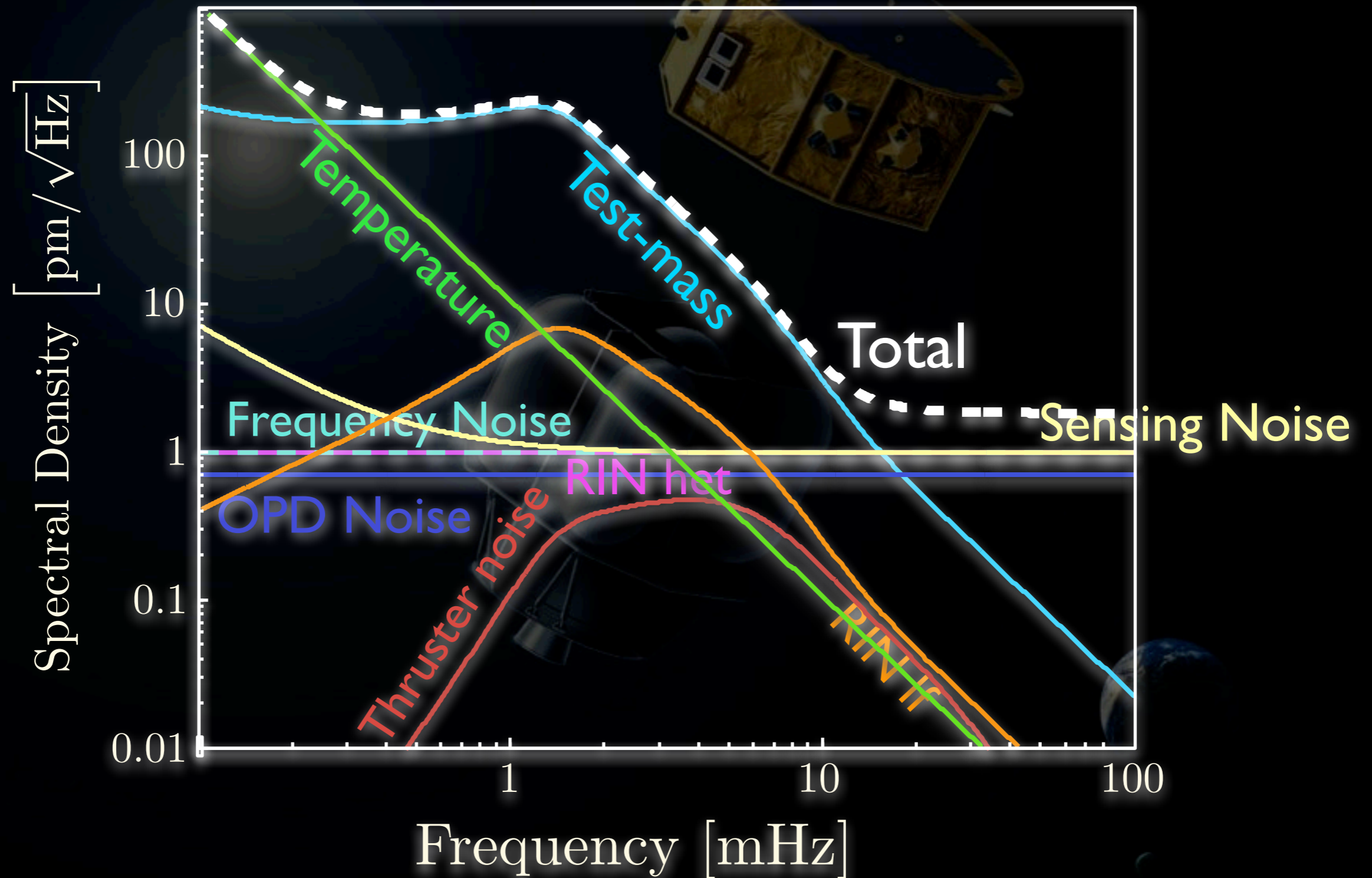
# Noise budget - XI



# Noise Budget - X12



# Noise Budget - X12



# Experiment Master Plan

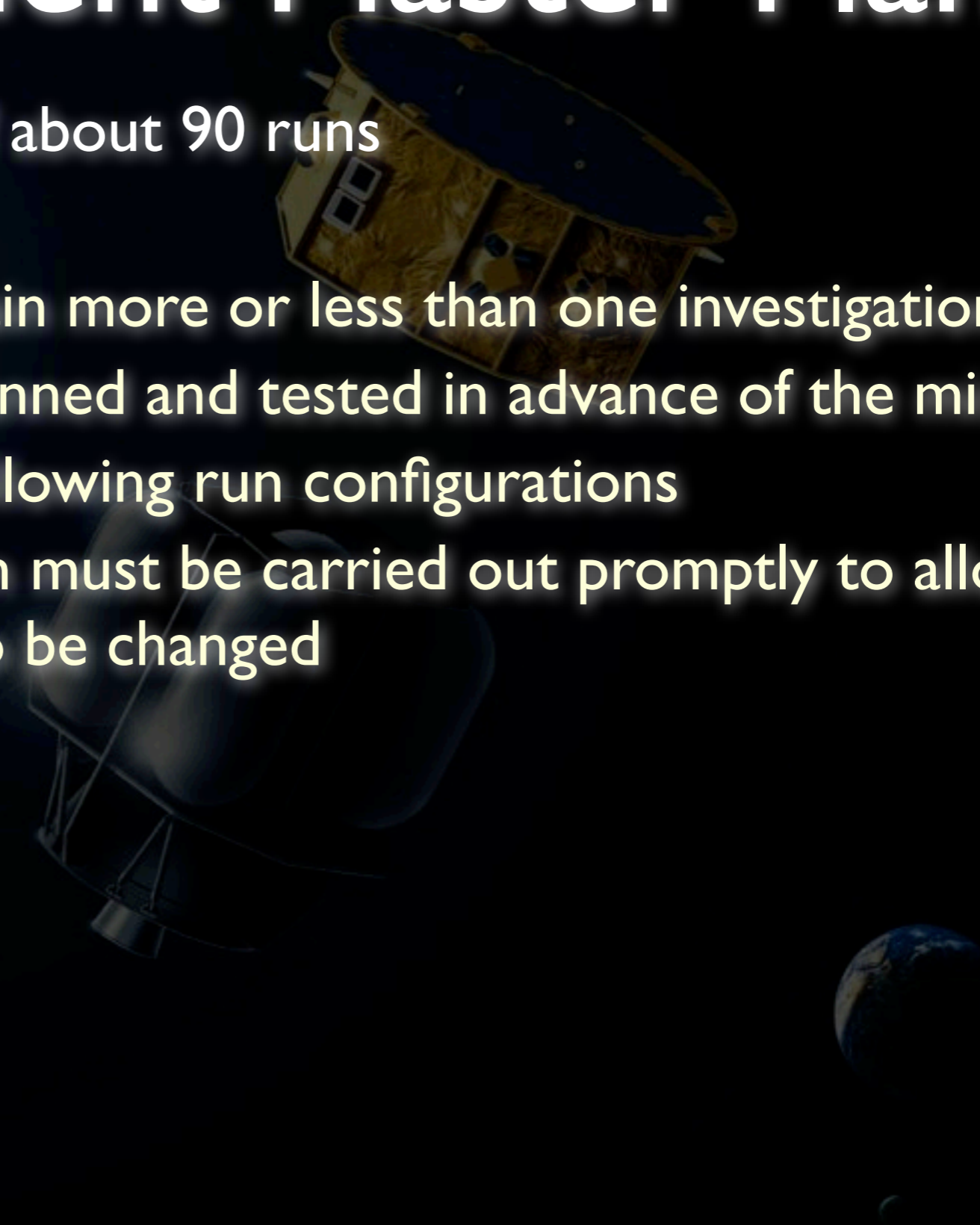




# Experiment Master Plan



- Mission will consist of about 90 runs
  - Each run lasts 24H
  - Each run may contain more or less than one investigation
  - Each run will be planned and tested in advance of the mission
  - A run may affect following run configurations
  - Analysis of each run must be carried out promptly to allow the mission time-line to be changed



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  - A run may affect following run configurations
  - Analysis of each run must be carried out promptly to allow the mission time-line to be changed
- Designing a run involves
  - defining the experiment and goals
  - defining the state of instrument
  - design the analysis
  - calculate the expected result/sensitivity
  - perform simulations / MDCs

# Data Analysis - Requirements



- Analysis is typical of commissioning and characterisation of ground-based detectors (except with limited/no access to the instrument)
- Multiple scientists to analyse data concurrently
  - centralised data access
- Analysis results need to have a long life to carry forward to LISA
  - an analysis result should contain a full processing history
- Mission will generate a large number of 'results'
  - searching for these with meta-data must be possible
- Graphical User Interface
  - avoid the need for 'programming' experts during the mission

# Introducing LTPDA

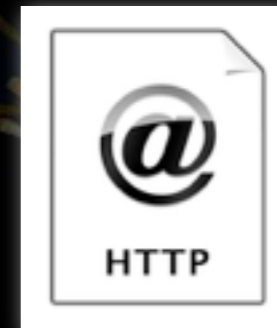
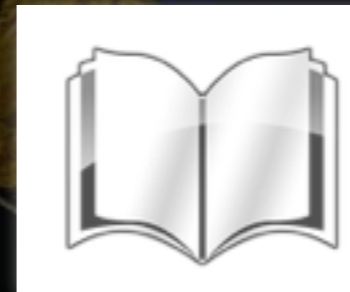
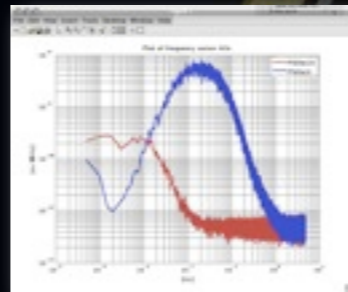


- Object-oriented data analysis toolbox for MATLAB
- Concept of 'Analysis Objects' which track their processing history
- Toolbox contains a large number of 'standard' signal processing algorithms which all work on AOs
- LTPDA Repository for storing AOs
- Client/server system allows access to AOs in repository directly from within MATLAB
- Graphical programming via drag-n-drop pipeline construction

# Analysis Objects



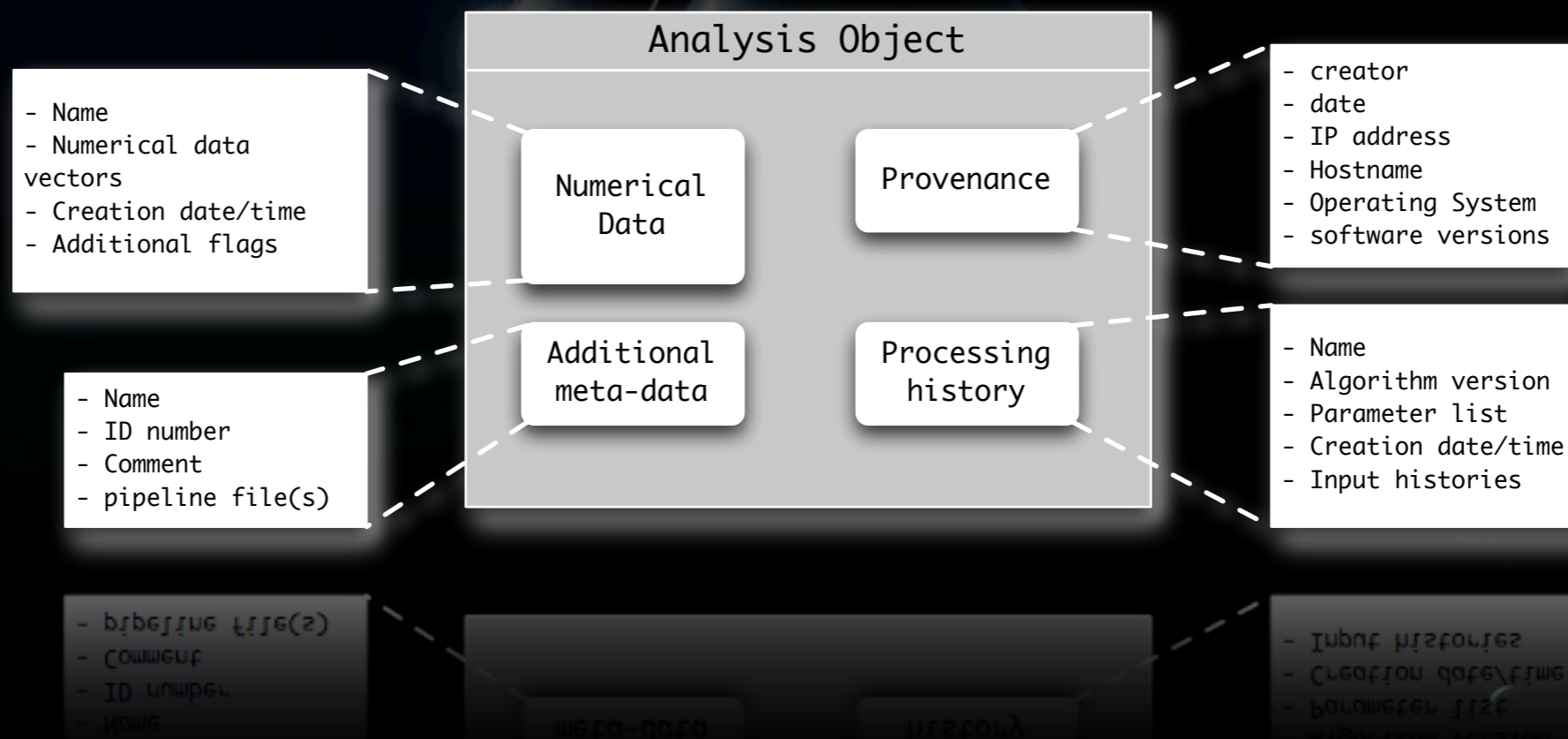
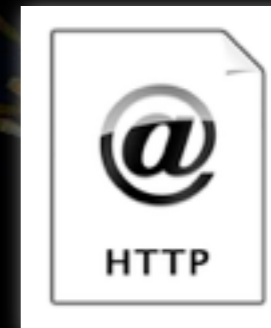
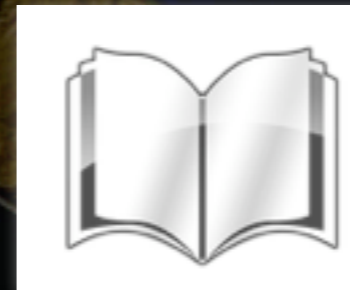
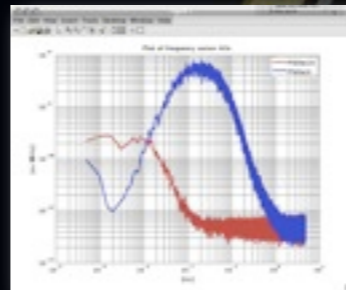
- Not results:



# Analysis Objects



- Not results:

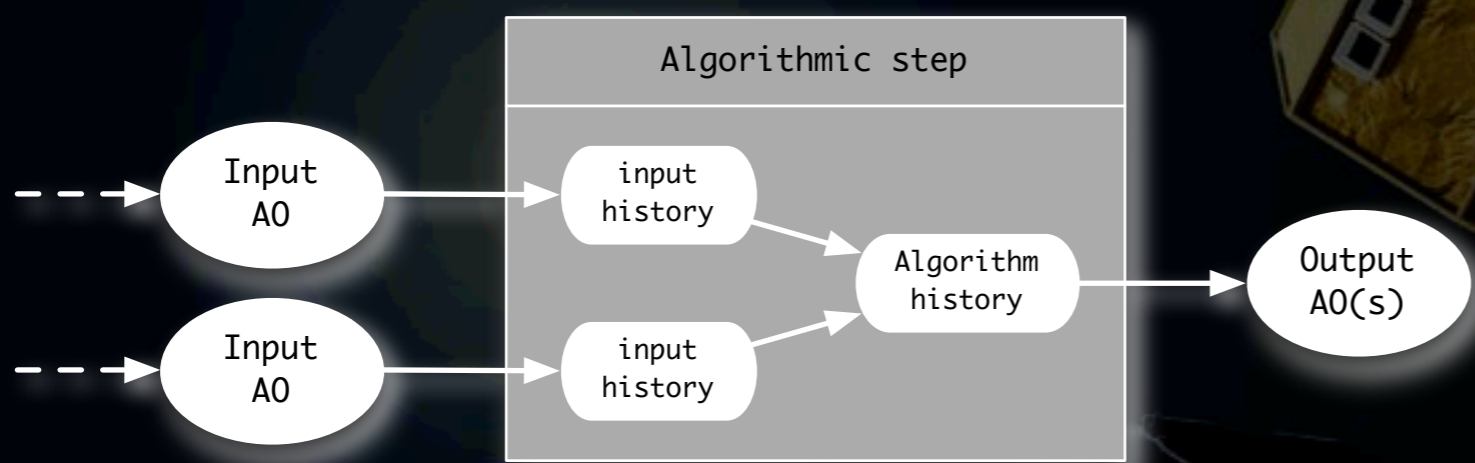


# Tracking history





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# Tracking history



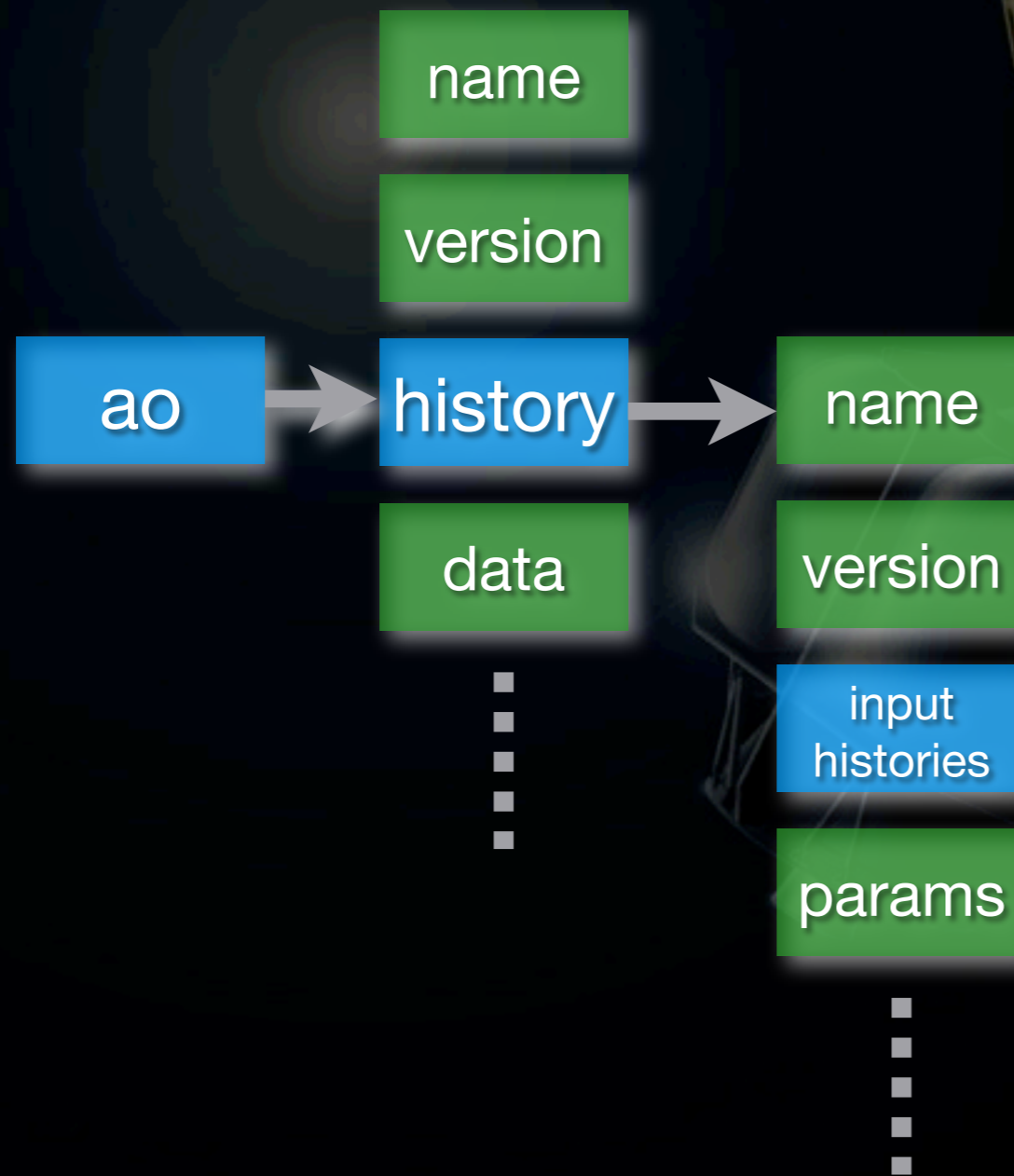
ao



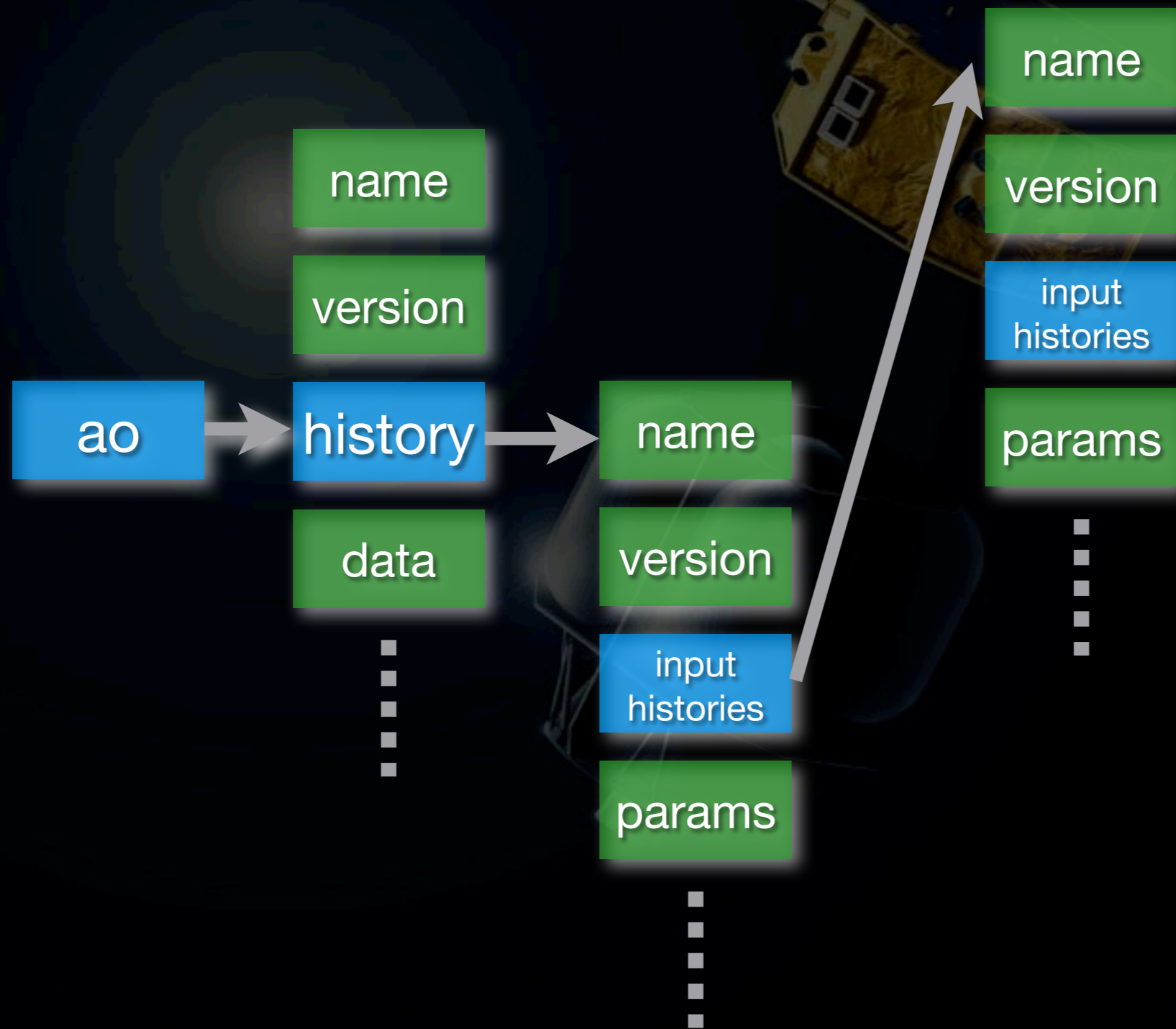
# Tracking history



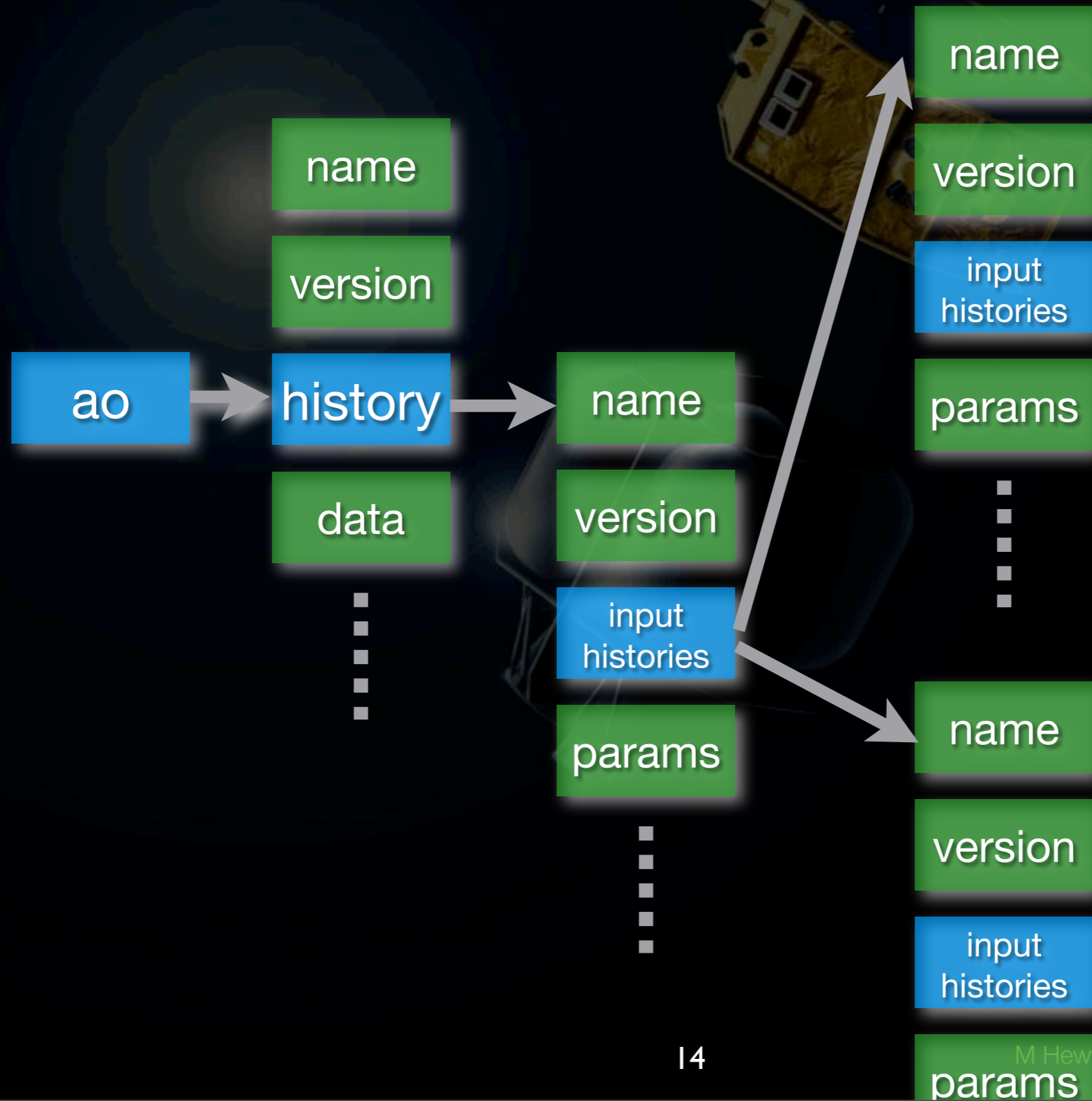
# Tracking history



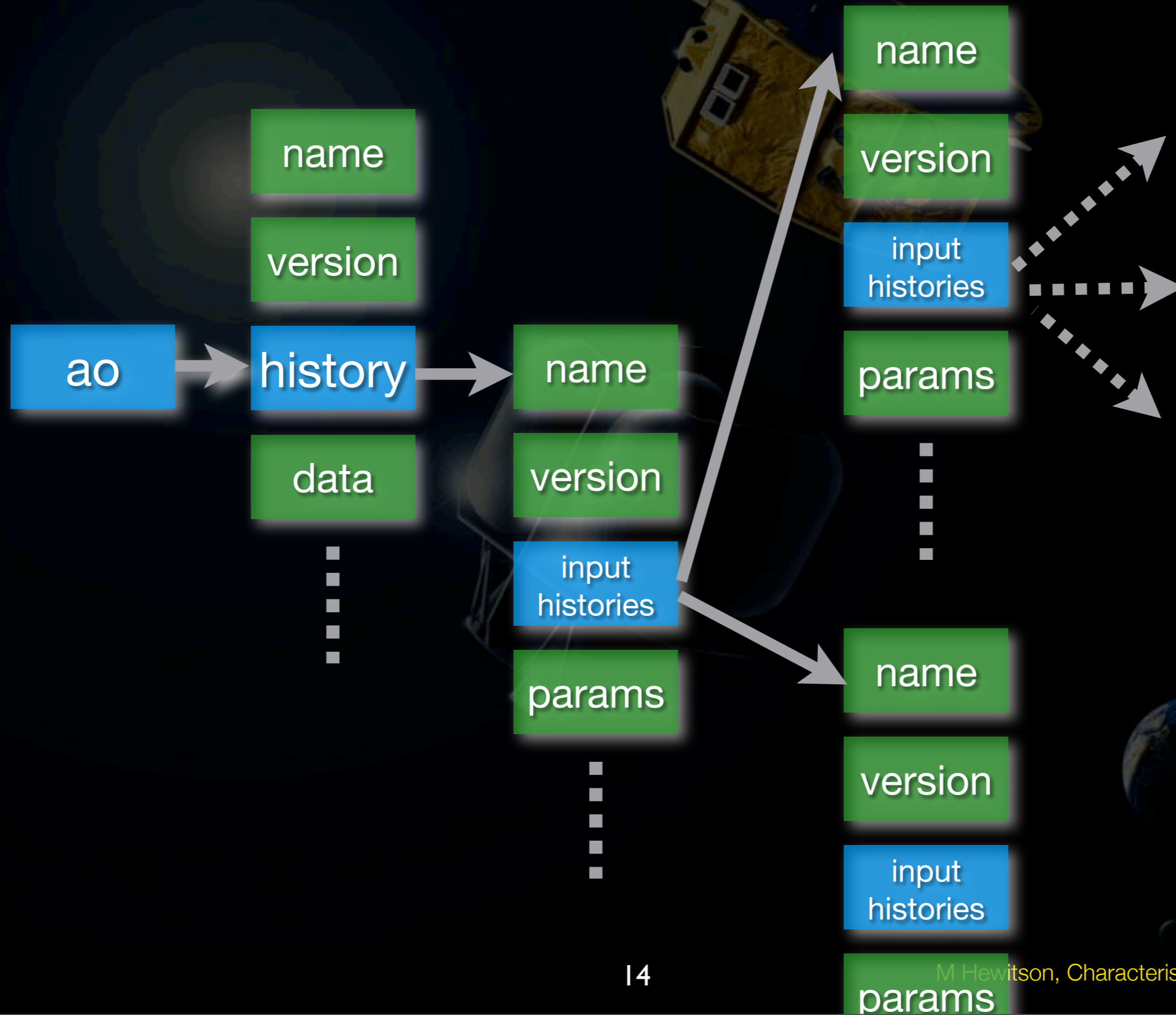
# Tracking history



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# Tracking history



# Reliving history

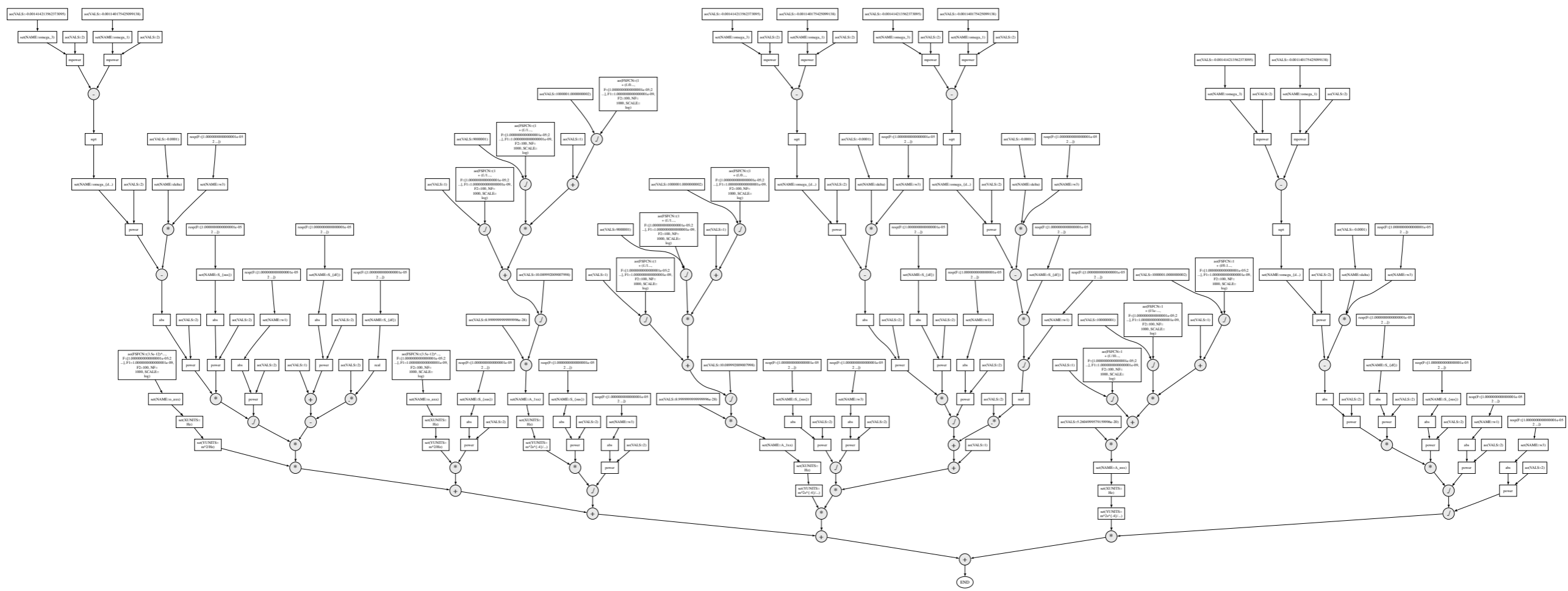


- rebuild objects
- produce block-diagrams from objects
- produce scripts from objects
- view history tree

# Reliving history



- rebuild objects
- produce block-diagrams from objects





# Classes of objects



... and more

# Classes of objects



## AO

*Objects containing different data series: time-series, frequency-series, x-y data, etc*

abs	gapfilling	acos
angle	rebuild	report
resample	asin	rms
heterodyne	sDomainFit	ifft
interp	iplot	corr
lincom	cpsd	curvefit
spectrogram	detrend	downsample
filter	whiten1D	polyfit
zDomainFit	zeropad	psd

## ssm

*Objects describing state-space systems*

## ltpdamodel

*Objects which describe parametric models, eg,  $y=ax+b$*

## pzmodel

*Objects describing a pole/zero system*

## miir/mfir

*Objects describing an IIR/FIR filters*

... and more

# Graphical Design



- Use a drag-n-drop based pipeline construction method
- Pipeline just executes underlying LTPDA functions

# Graphical Design



mdc2\_whiten\_fit.lwb\*

File Edit View Format Pipeline Tools Window Help

Pipelines Library

- Whiten Data / save o1 filters
- Whiten Data / save o12 filters
- Whiten Data
- Measure Transfer Functions Ex
- Measure Transfer Functions Ex
- Measure Transfer Functions Ex
- Fit Gsus / White Filt Resp
- Fit Gsus
- Check TFs
- Test AO Models
- Fit Gdf / White Filt Resp
- Fit Gdf
- Fit for delta / White Filt Resp
- Fit for delta

Fit for delta

created by: hewitson  
created on: 2009-02-21 19:31:50  
modified on: 2009-05-07 16:29:10

Analysis of experiment 2 to get a fit for the value of the IFO cross-coupling.

Property Value

Name	fit gain
Keep Result	true
Modifier	false

Current Parameters

Key	Value
FUNCTION	PORT_2
NO FIT	false
P0	1e-4
LB	-1
UB	1
OPTSET	
FITUNCERTAINTY	true
FITFUNCRETURN	abs
ADDP	[PORT_1, PORT_3, P...

Set

Verboisity OFF

x: 0222 y: 0156

# Graphical Design



mdc2\_whiten\_fit.lwb\*

File Edit View Format Pipeline Tools Window Help

Property Value  
Name fit gain  
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Fit for delta

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Analysis of experiment 2 to get a fit for the value of the IFO cross-coupling.

White Filt Resp

select freqs\_1

take abs\_1

curvefit

fit gain

evaluateModel

save

New Block\_2

select freqs

take abs

model=A...

ao

l1o12w\_m

ao

Gdf

ao

Gsus

New Block

iplot

New Block\_1

current Parameters

Key	Value
FUNCTION	PORT_2
NO FIT	false
P0	1e-4
LB	-1
UB	1
OPTSET	
FITUNCERTAINTY	true
FITFUNCRETURN	abs
ADDP	{PORT_1, PORT_3, P...

Set

Verbosity OFF

x: 0222 y: 0156

Parameter Panel

# Graphical Design



The screenshot shows a graphical design environment with a central workspace containing a circuit diagram. The diagram includes blocks for data processing (find, abs, select freqs, take abs), a 'White Filt Resp' block, a 'curvefit' block with a 'fit gain' parameter, and an 'evaluateModel' block. The interface also features a menu bar, a toolbar, and a left-hand panel with various tool options.

**Properties Panel (blue border):**

Property	Value
Name	fit gain
Keep Result	true
Modifier	false

**Parameter Panel (orange border):**

Key	Value
FUNCTION	PORT_2
NO FIT	false
P0	1e-4
LB	-1
UB	1
OPTSET	
FITUNCERTAINTY	true
FITFUNCRETURN	abs
ADDP	{PORT_1, PORT_3, P...

# Graphical Design



The screenshot shows a graphical design software interface. On the left is a terminal window with the following text:

```
hist: ltpda_uoh
filename:
filename:
-----
executing: [New_Docu
running miir/miir
executing: New_Docu
--- miir/1 -----
      b: [1 -0.88163
histin: 0
version: $Id: miir.n
ntaps: 2
fs: 1000
infile:
      a: [0.94080929
histout: 0
iunits:  [1x1 uni
ounits:  [1x1 uni
hist: miir.hist
cription:
      name: New Block_1
-----
executing: [New_Docu
running ao/filter
      filtering with IIR
executing: [New_Docu
running ao/tfe
running ao/len
running ao/len
running ao/len
      using default Nff
      reset window to E
      using recommende
      computing tfe(a1 ->
running ao/ao
      constructing from c
running ao/ao
```

The main window, titled "test\_ao\_interp.lwb\*", contains a "New Document 1" window. The document contains the following text:

```
created by: newitson
created on: 2009-01-31 16:12:45
modified on: 2009-05-07 16:50:49

A test model for the transfer function estimator, tfe.
```

The diagram shows a signal flow from two input blocks, "ao" and "miir", through a "filter" block, then to a "tfe" block, and finally to an "iplot" block. The "ao" and "miir" blocks are green, while the "filter", "tfe", and "iplot" blocks are blue. Red lines represent the signal paths. The "filter" block is labeled "New Bloc...", the "tfe" block is labeled "New Block", and the "iplot" block is labeled "New Bloc...".

At the bottom of the interface, there is a "Verbosity" dropdown menu set to "OFF" and a set of navigation buttons (rewind, play, stop, etc.).

# Get it now!

A screenshot of a web browser window showing the LTPDA website. The browser's address bar displays "http://www.lisa.aei-hannover.de/ltpda/". The website content includes a header "LTPDA" with the subtitle "a MATLAB toolbox for accountable and reproducible data analysis". Below this is a paragraph describing the toolbox's object-oriented approach. A list of features is provided, including pre-processing of time-series data, spectral analysis, digital filtering, and model construction. A sidebar on the right contains navigation buttons for "home", "Installation", "System requirements", "Downloads", "File repository", "Release Schedule", "User manual", "Training Sessions", and "Documents". At the bottom of the page, there is a code snippet and a graphical design interface. The code snippet shows MATLAB commands for creating objects, adding them, setting names, and plotting. The graphical interface shows a flowchart with boxes for "find", "abs", and "save" connected by arrows, and another diagram showing a pipeline from "ao(VALS=[1:2:4:5:6:7:8:9:10])" and "ao(VALS=2)" through a "plus(empty-plb)" block to a "setName(NAME='const')" block, ending at "END".

```
a = ao(1:10);  
b = ao(2);  
  
% Add them together  
c = a+b;  
  
% Set the name  
c.setName('const')  
  
% Plot the result  
c.iplot
```

```
graph TD  
    A["ao(VALS=[1:2:4:5:6:7:8:9:10])"] --> B["plus(empty-plb)"]  
    C["ao(VALS=2)"] --> B  
    B --> D["setName(NAME='const')"]  
    D --> E((END))
```

<http://www.lisa.aei-hannover.de/ltpda/>



# Mock Data Challenges



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- We use mock data challenges (MDCs) to
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  - test/exercise the analysis tools
  - train scientists

# How they work



1 Define MDC model(s), assumptions, etc



# How they work

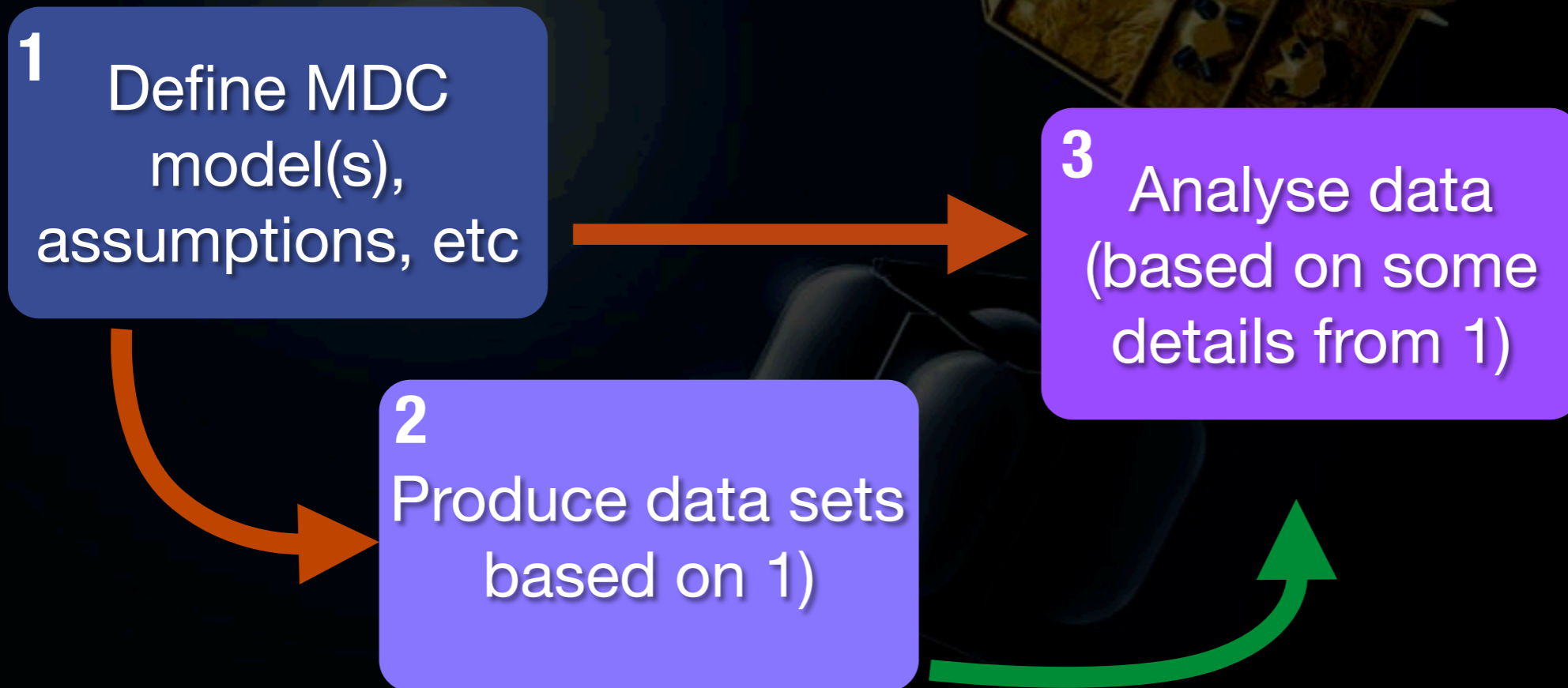


**1** Define MDC model(s), assumptions, etc

**2** Produce data sets based on 1)

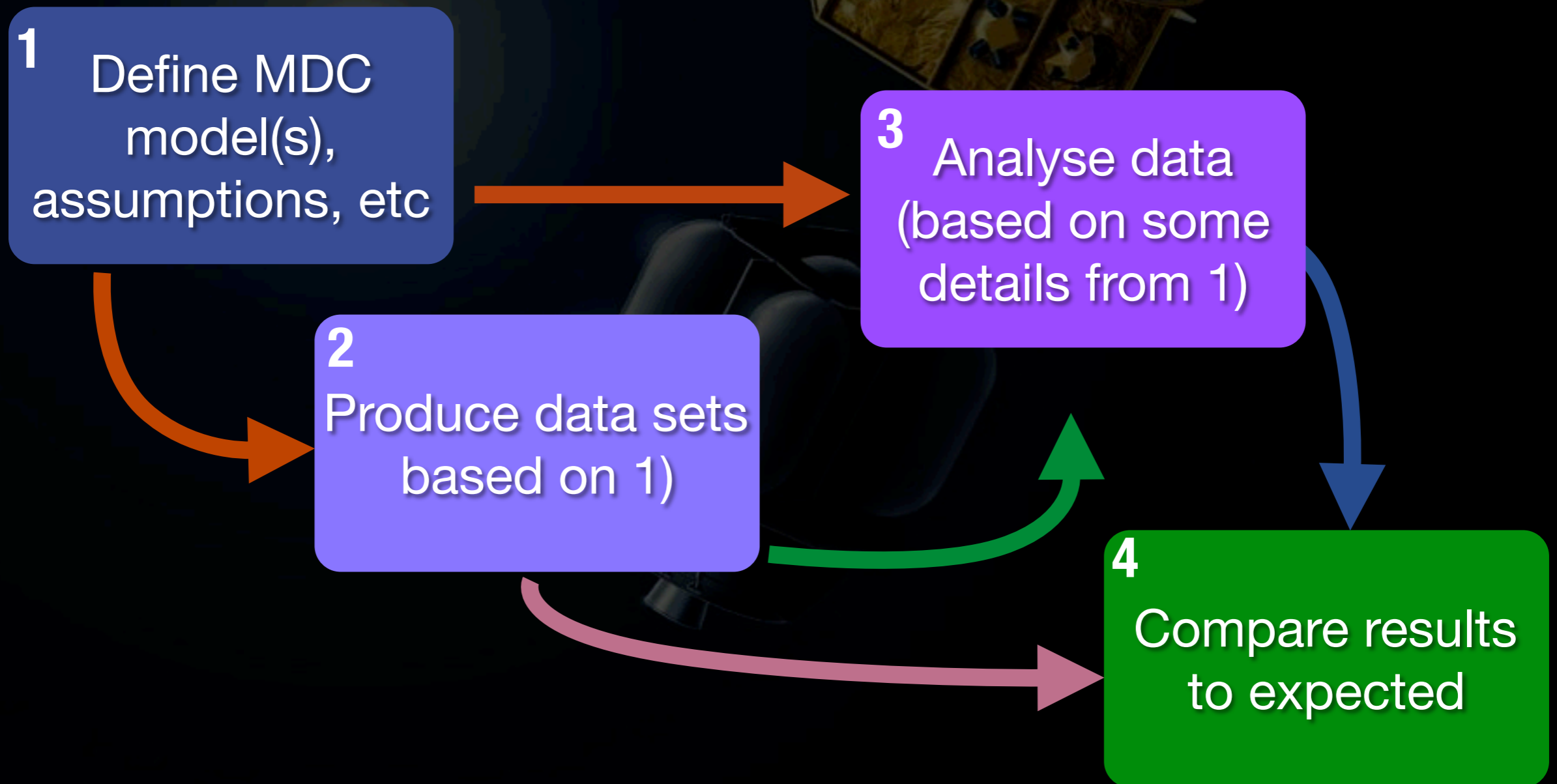


# How they work

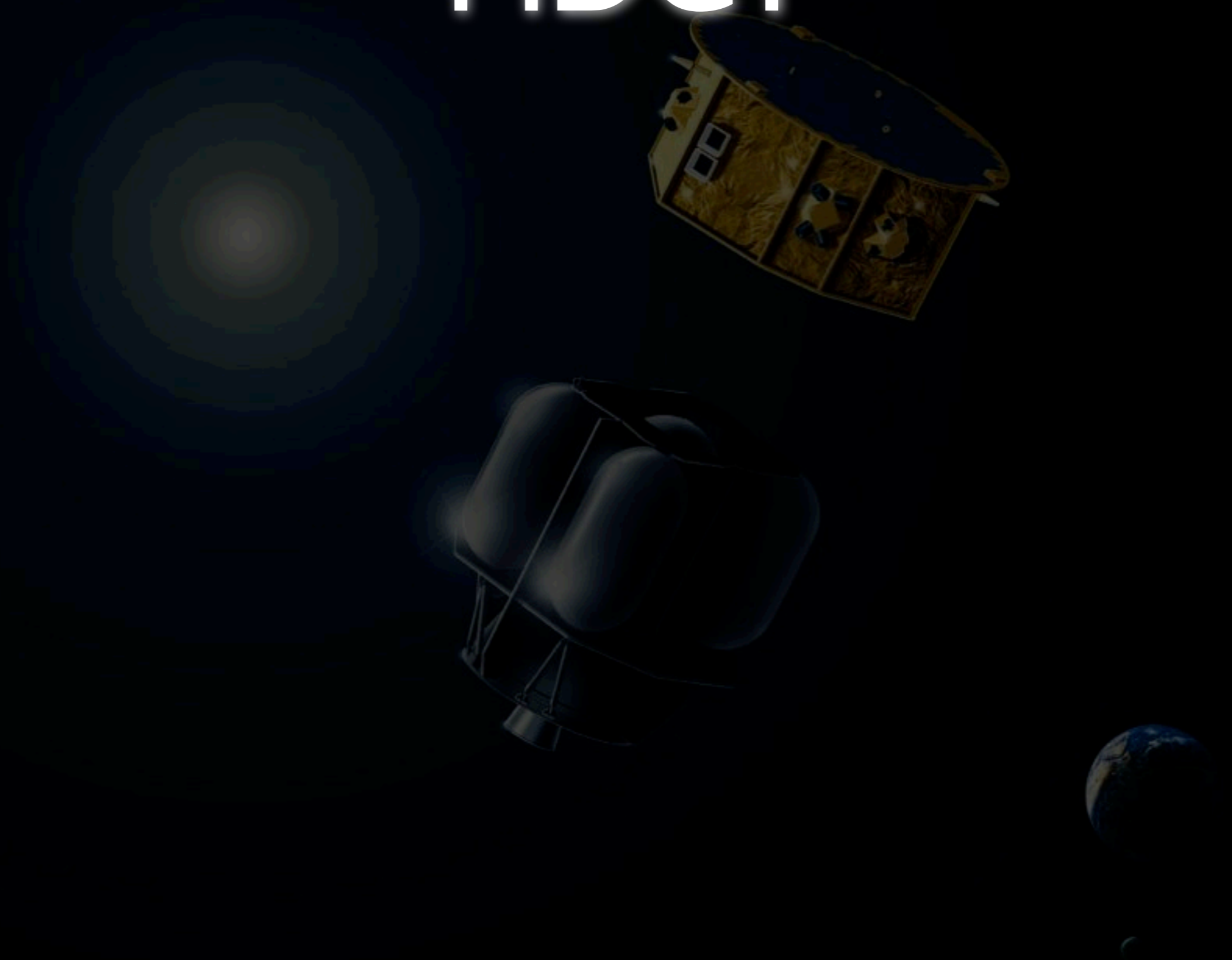




# How they work



# MDCI



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- Simple model of LTP (x-axis dynamics)



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- Simple model of LTP (x-axis dynamics)
- Data generation
  - Model is based on 5 parameters of the system
    - stiffness of two test-masses, gains of two control servos, cross-coupling in IFO from XI to XI2
  - Generate two IFO output time-series

# MDCI



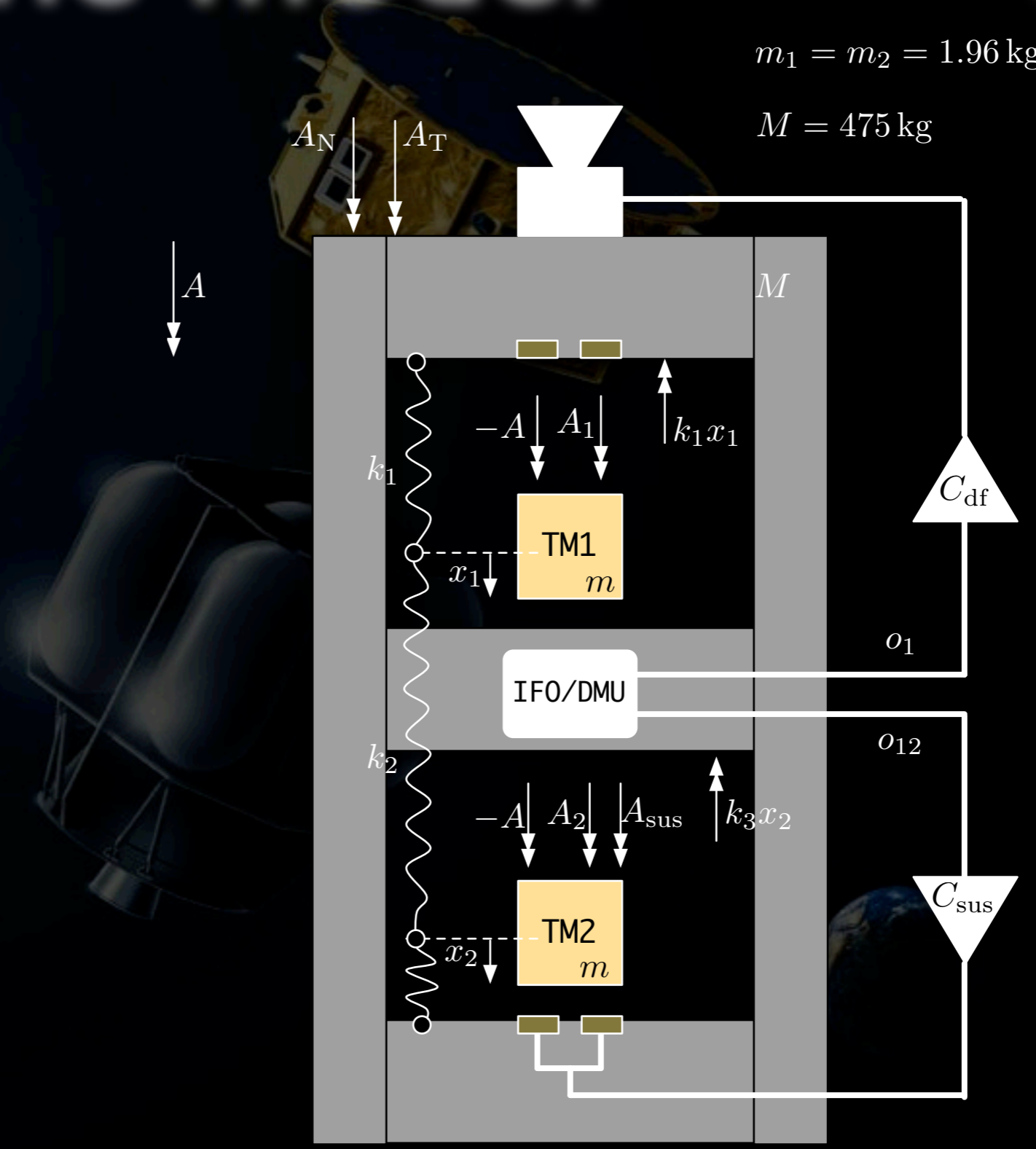
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- Data generation
  - Model is based on 5 parameters of the system
    - stiffness of two test-masses, gains of two control servos, cross-coupling in IFO from XI to XI2
  - Generate two IFO output time-series
- Data analysis
  - convert the two IFO outputs to out-of-loop acceleration
    - convert each to in-loop acceleration
    - account for control forces

# The model



$$m_1 = m_2 = 1.96 \text{ kg}$$

$$M = 475 \text{ kg}$$



# The model

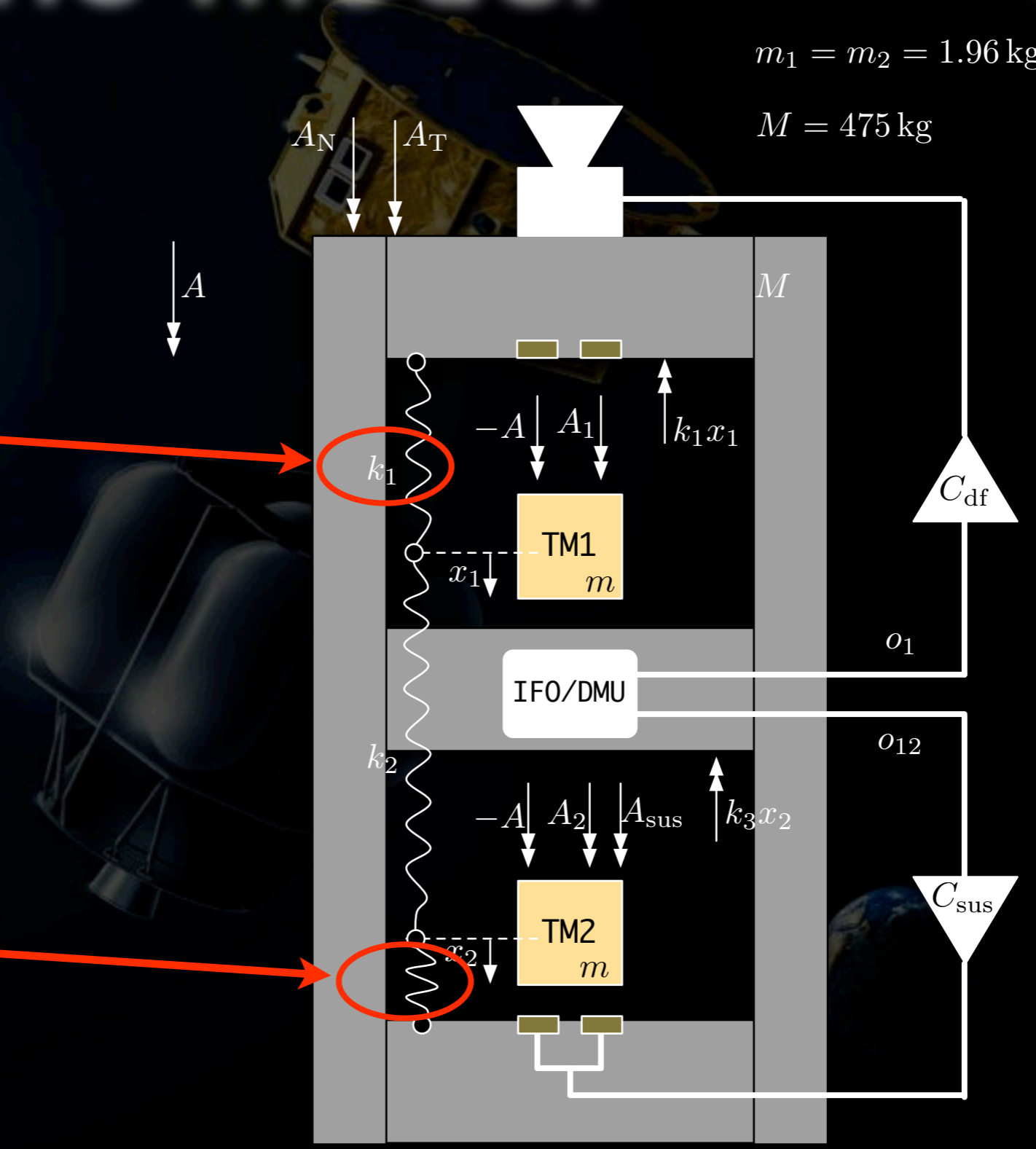


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TM1  
Stiffness

TM2  
Stiffness

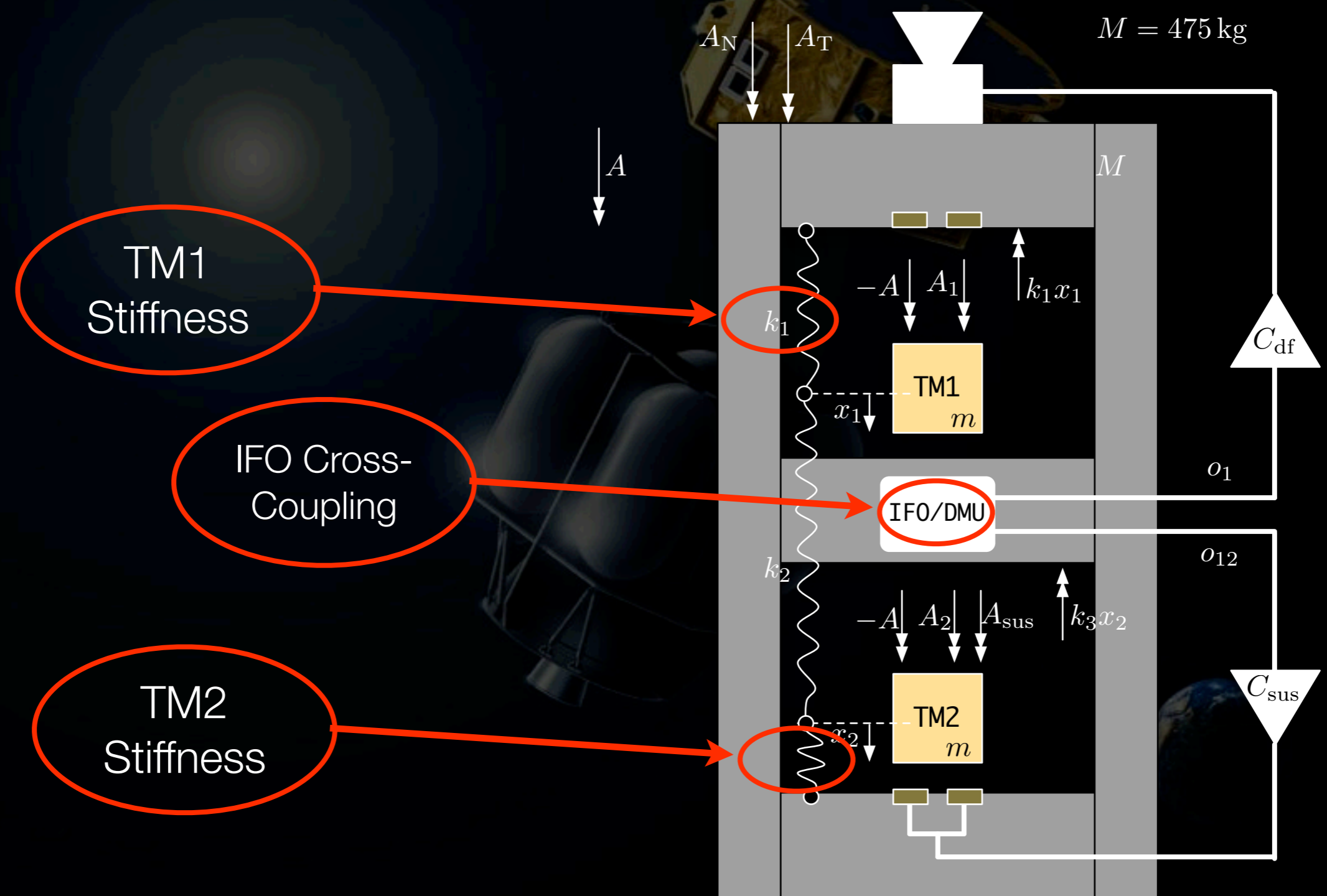


# The model



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TM1  
Stiffness

IFO Cross-  
Coupling

TM2  
Stiffness

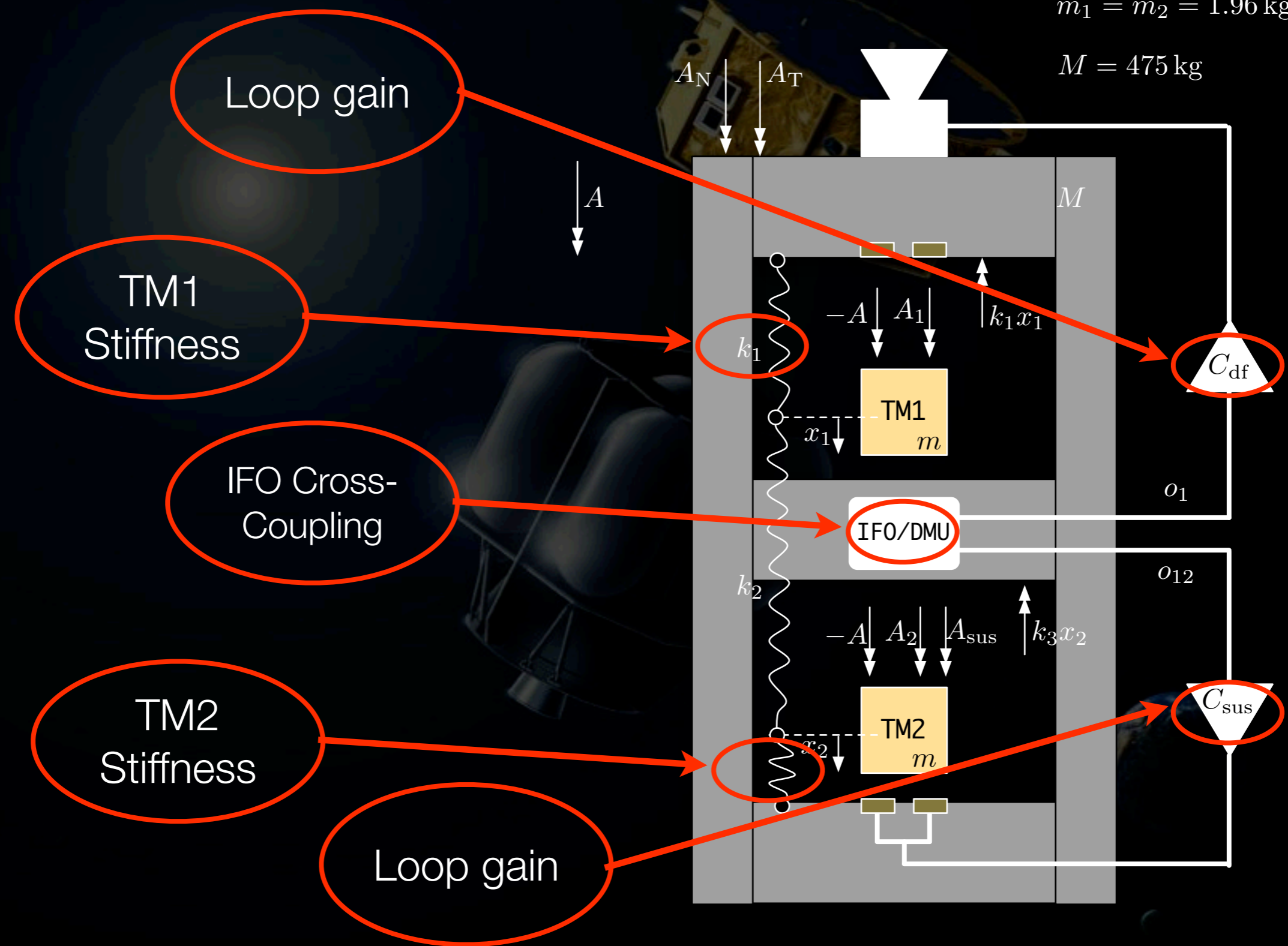


# The model



$m_1 = m_2 = 1.96 \text{ kg}$

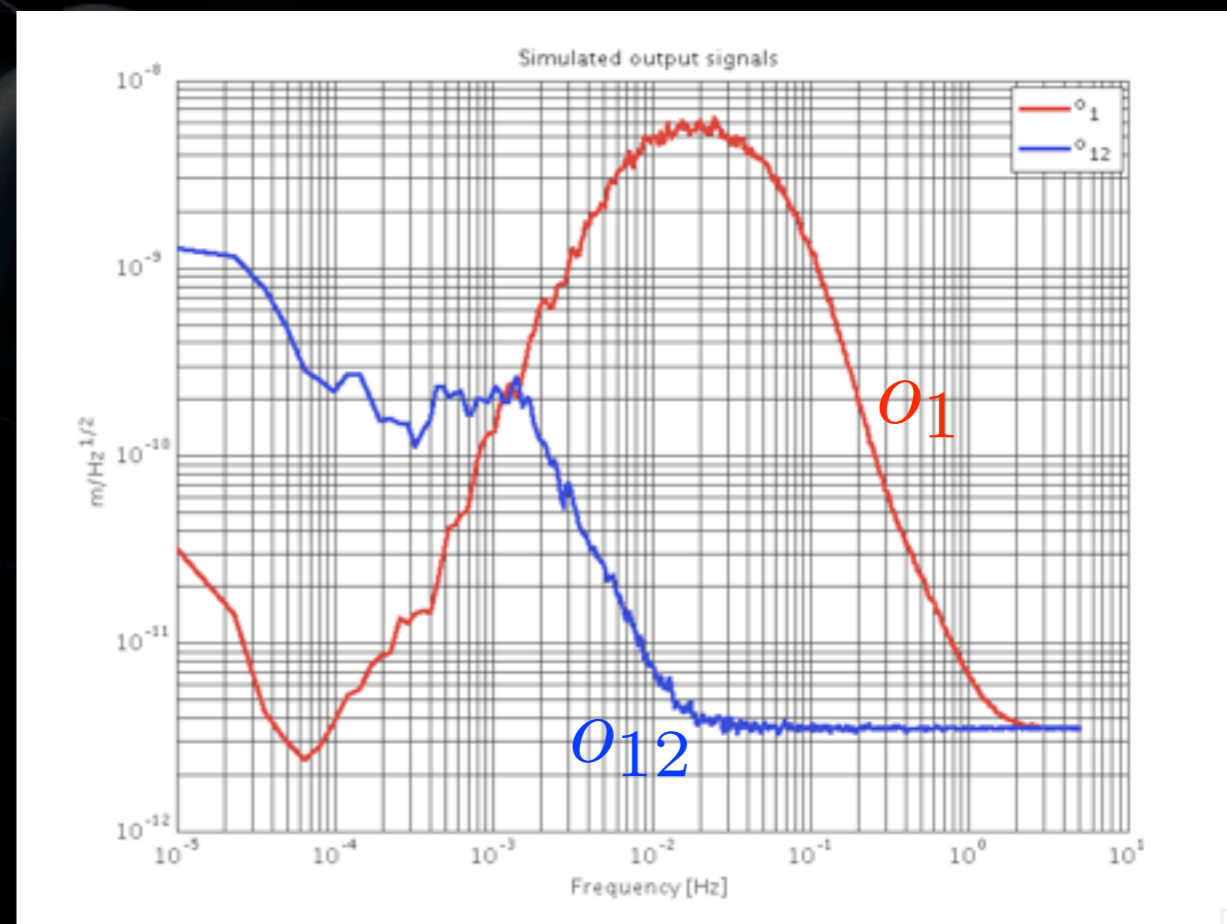
$M = 475 \text{ kg}$



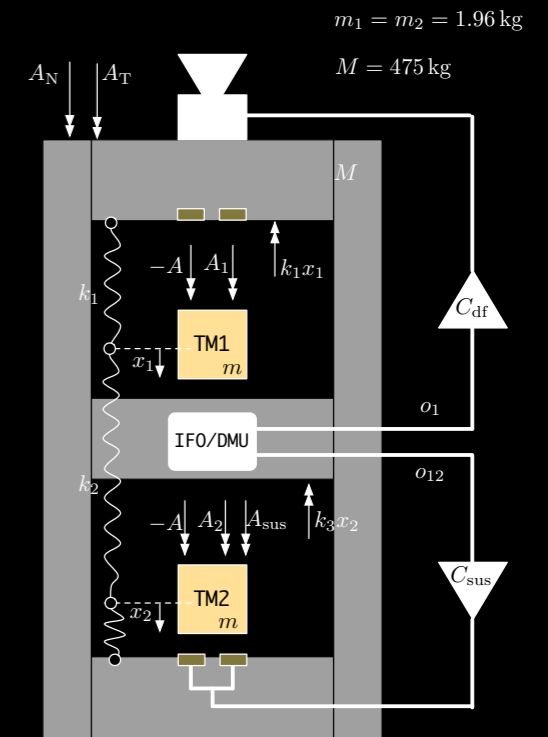
# Data generation



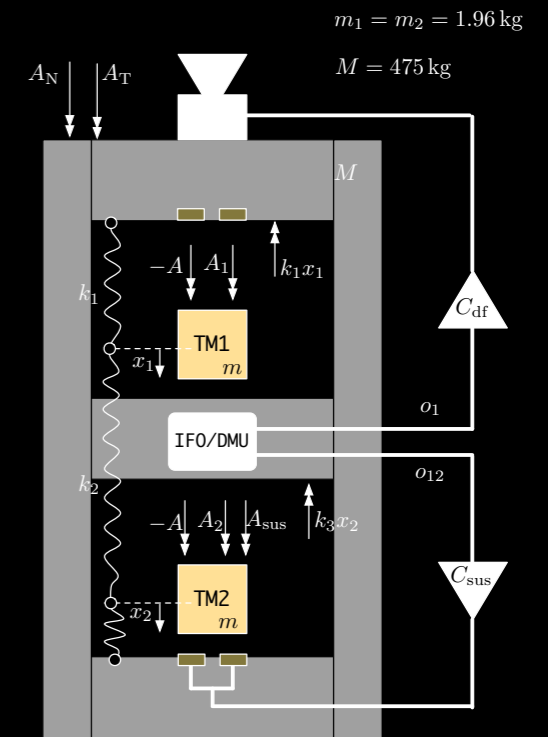
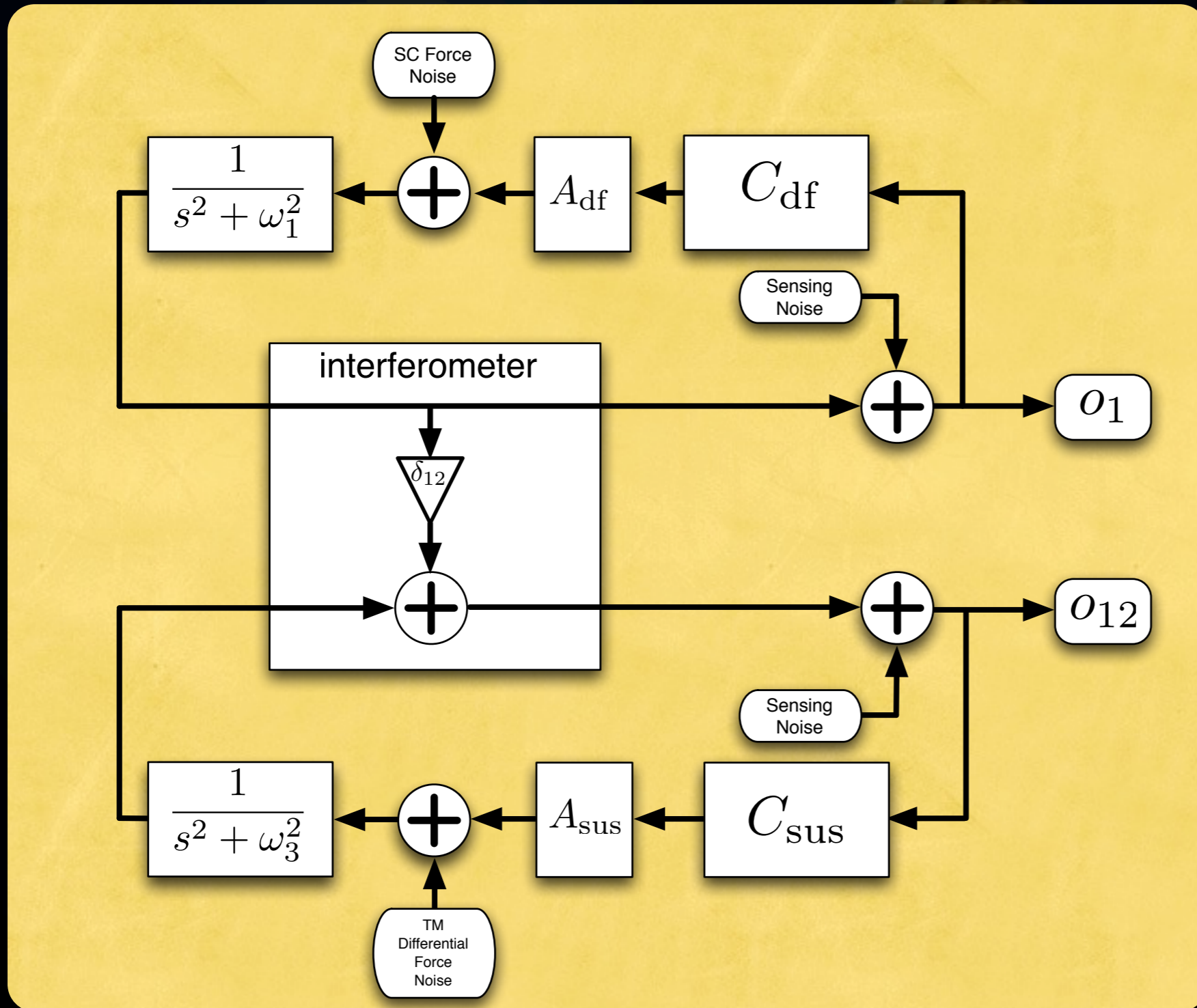
- Frequency-domain analytical model of transfer functions
- Fit sets of digital filters to the transfer functions
- Filter white-noise time-series to produce simulated IFO outputs



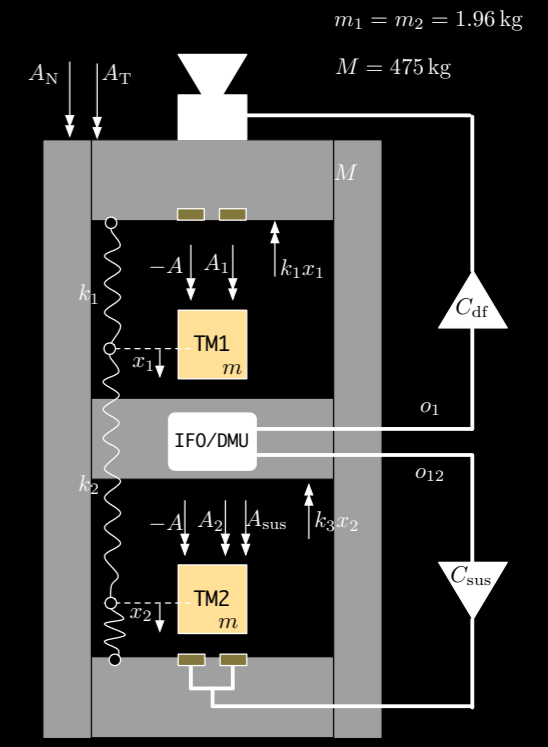
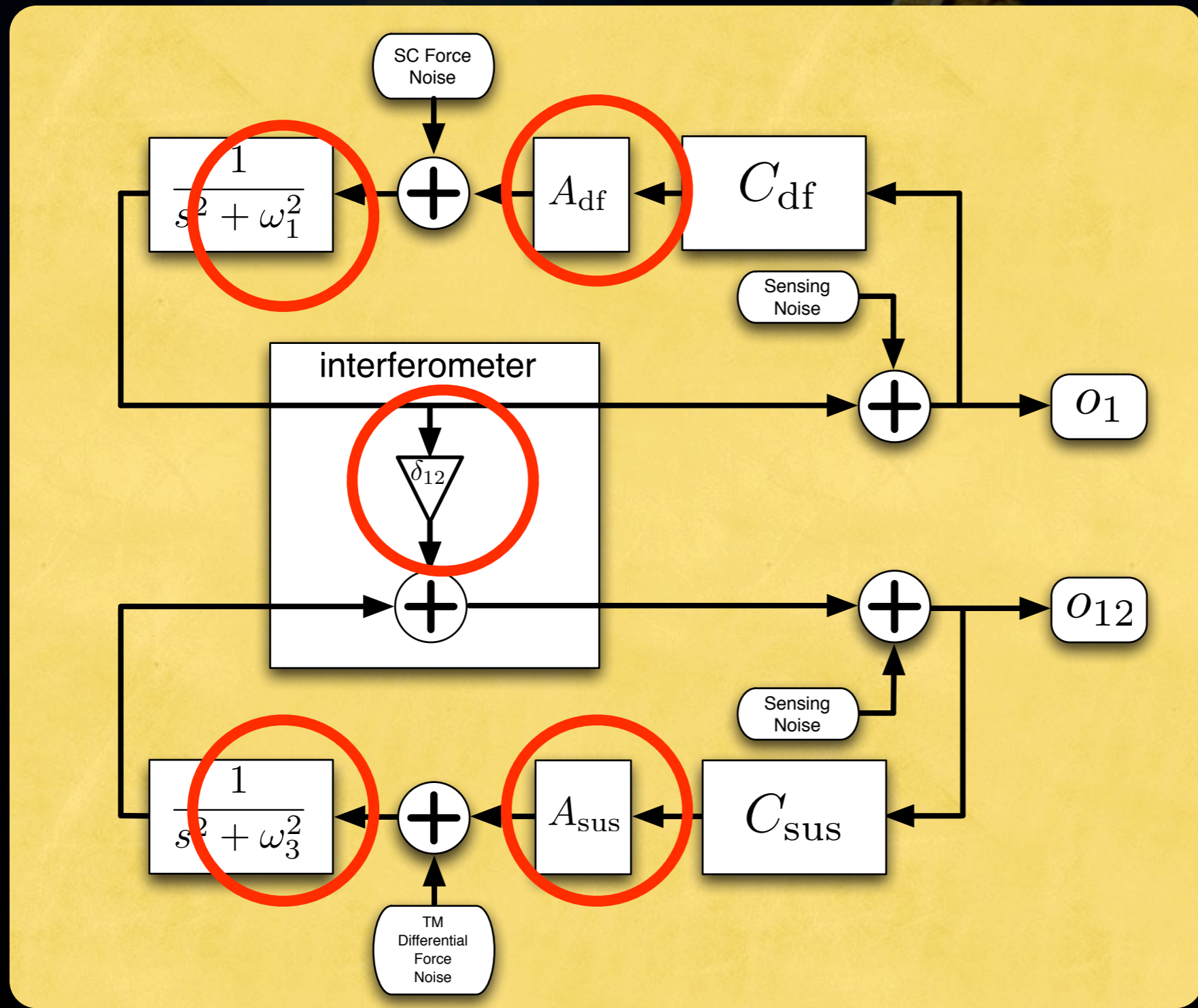
# Control loops



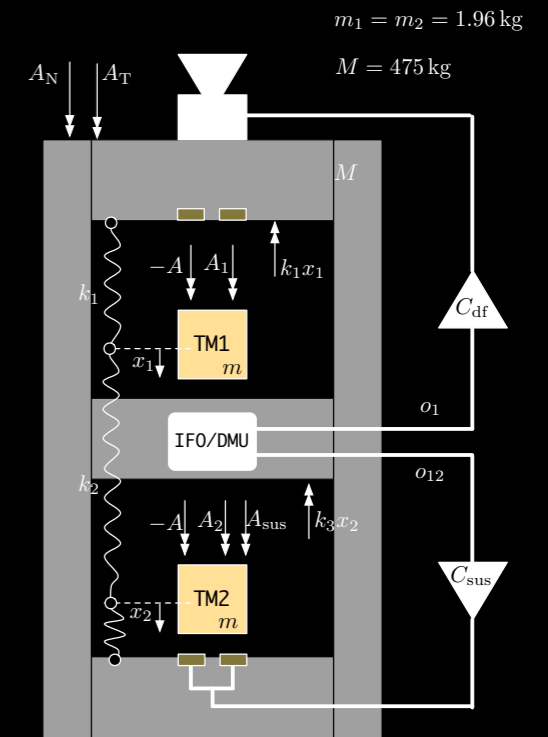
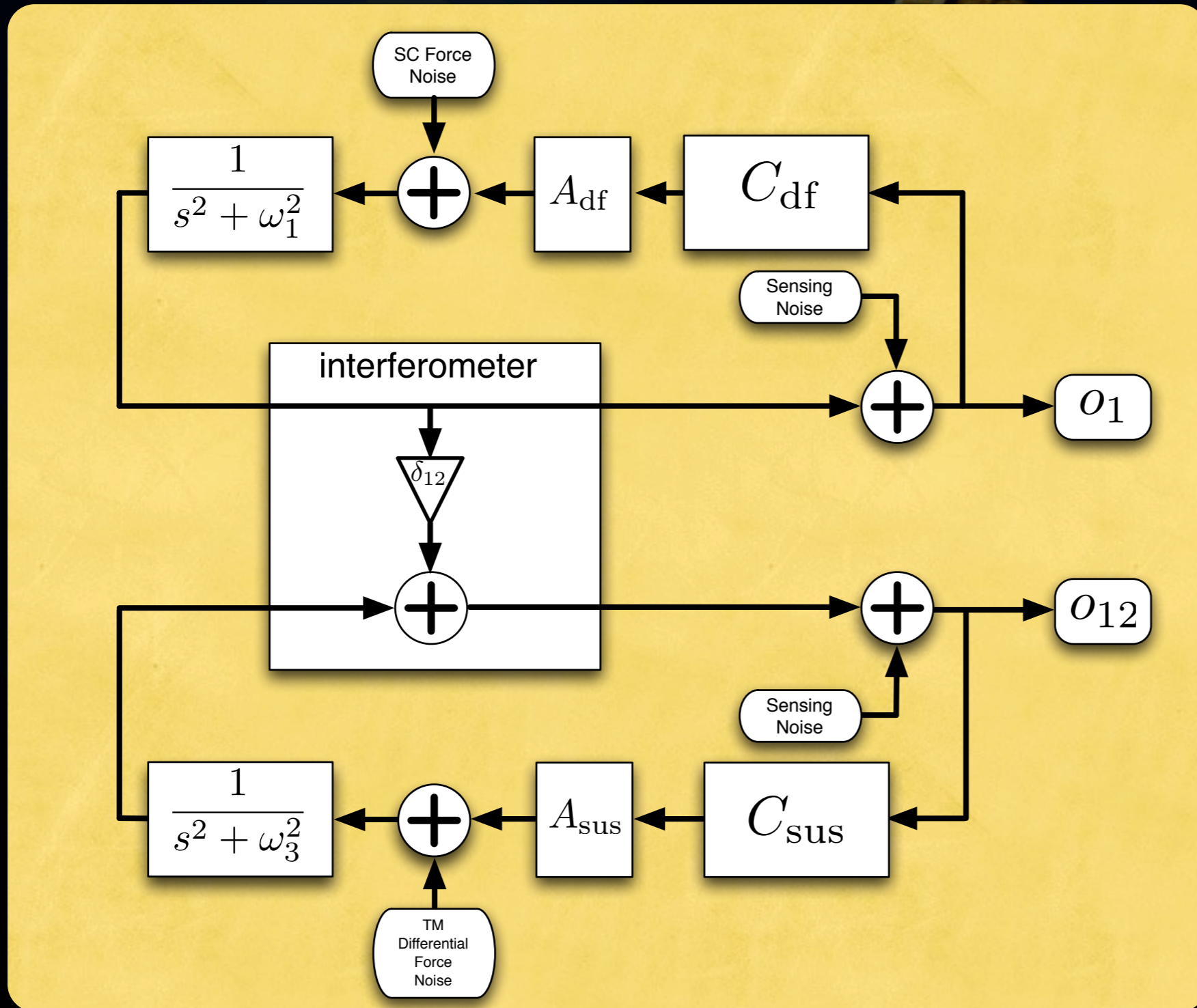
# Control loops



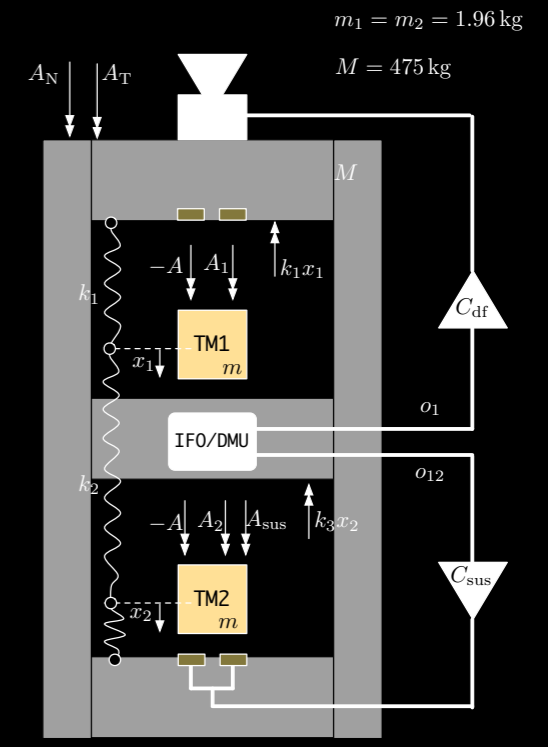
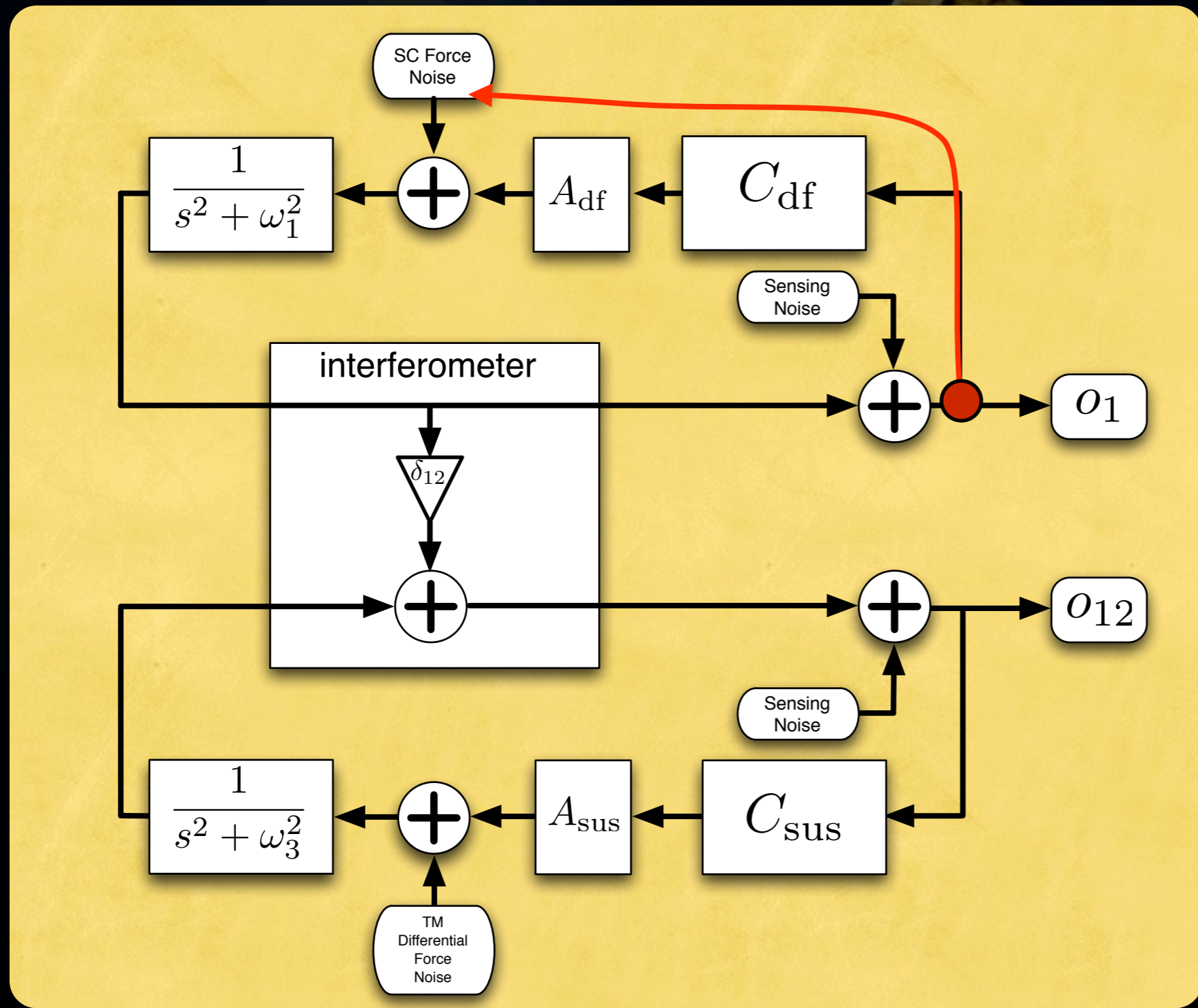
# Control loops



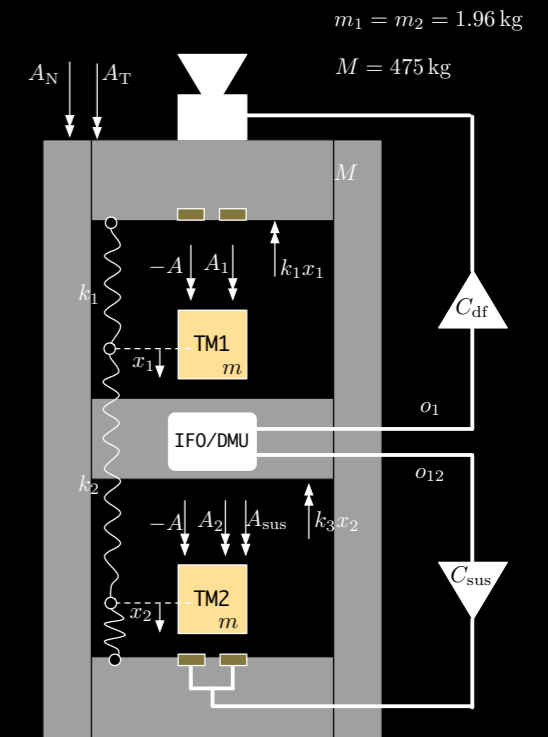
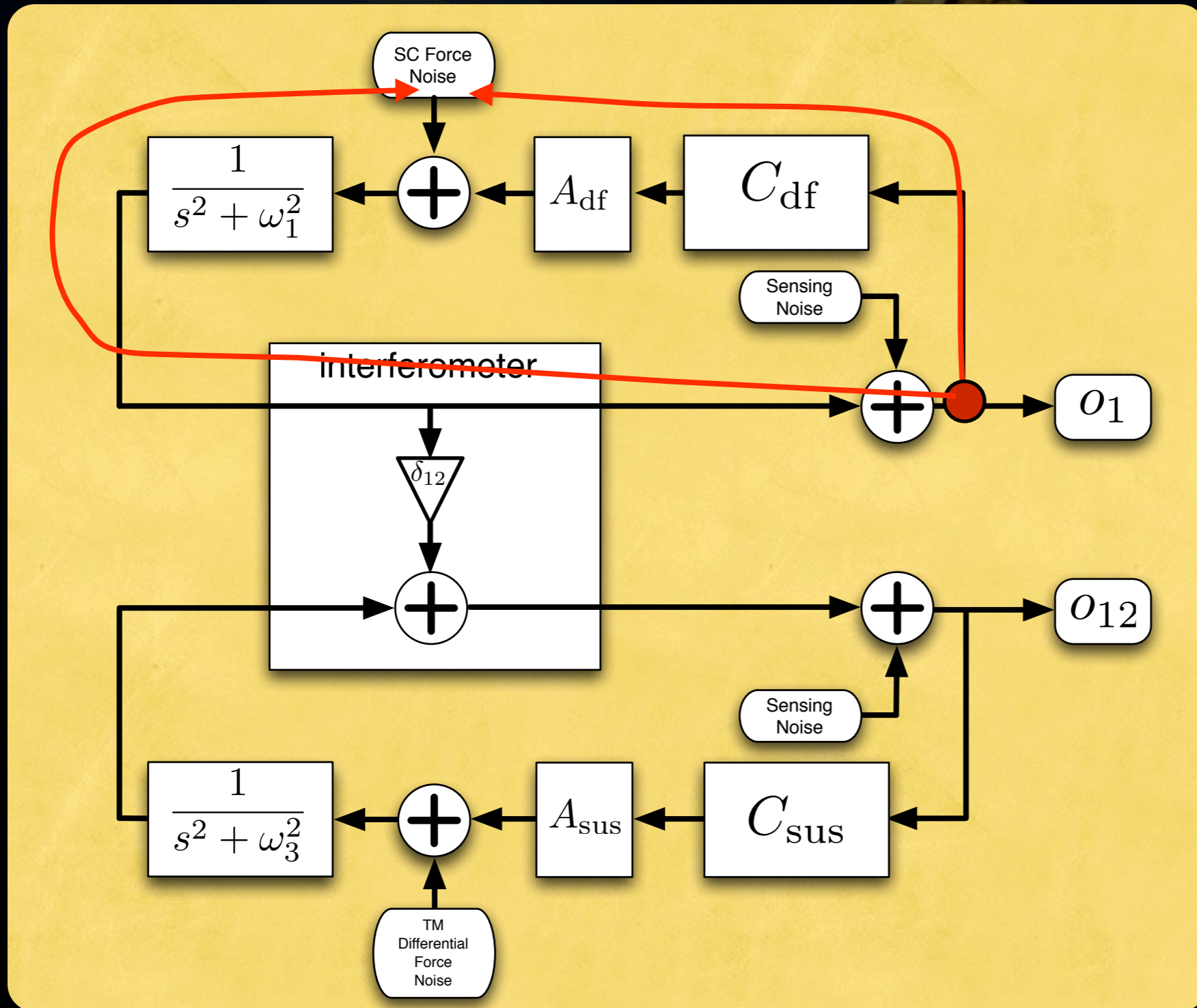
# Control loops



# Control loops

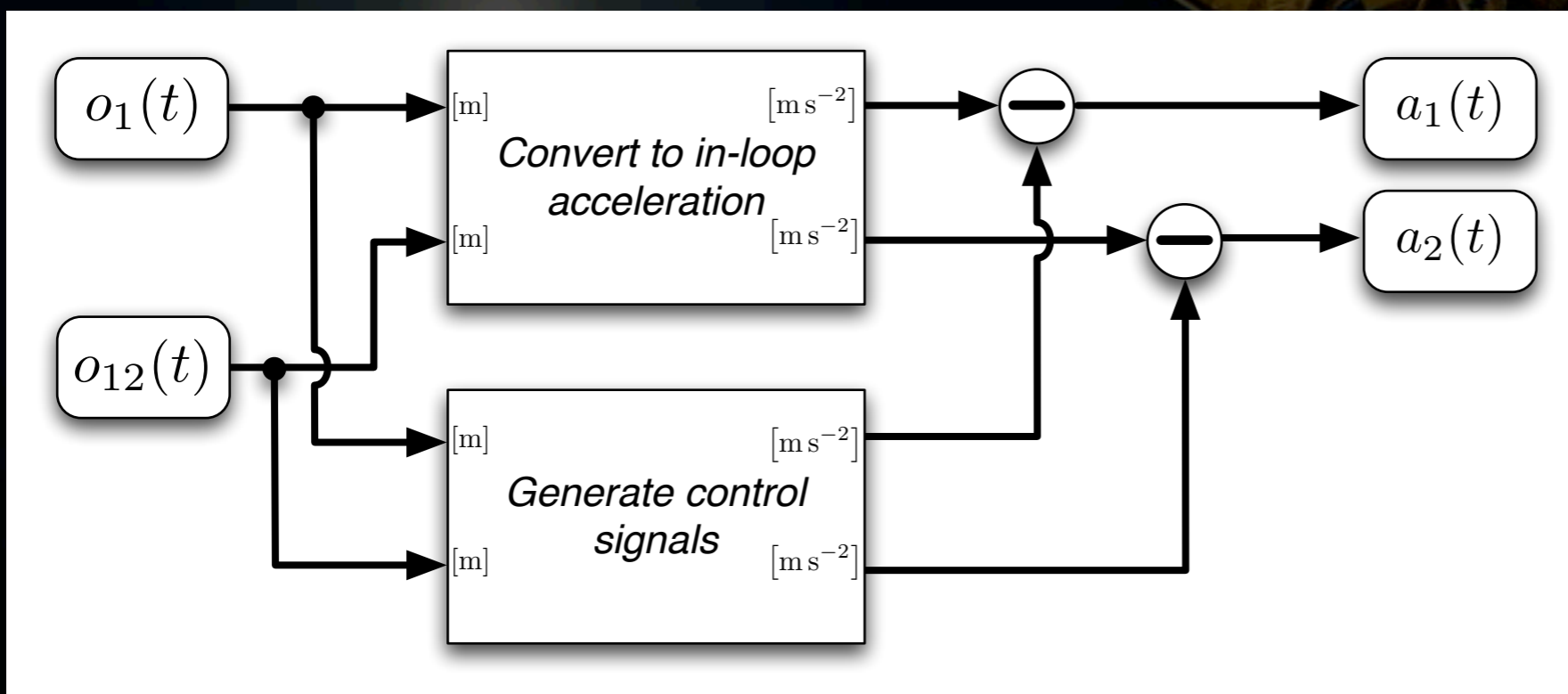


# Control loops





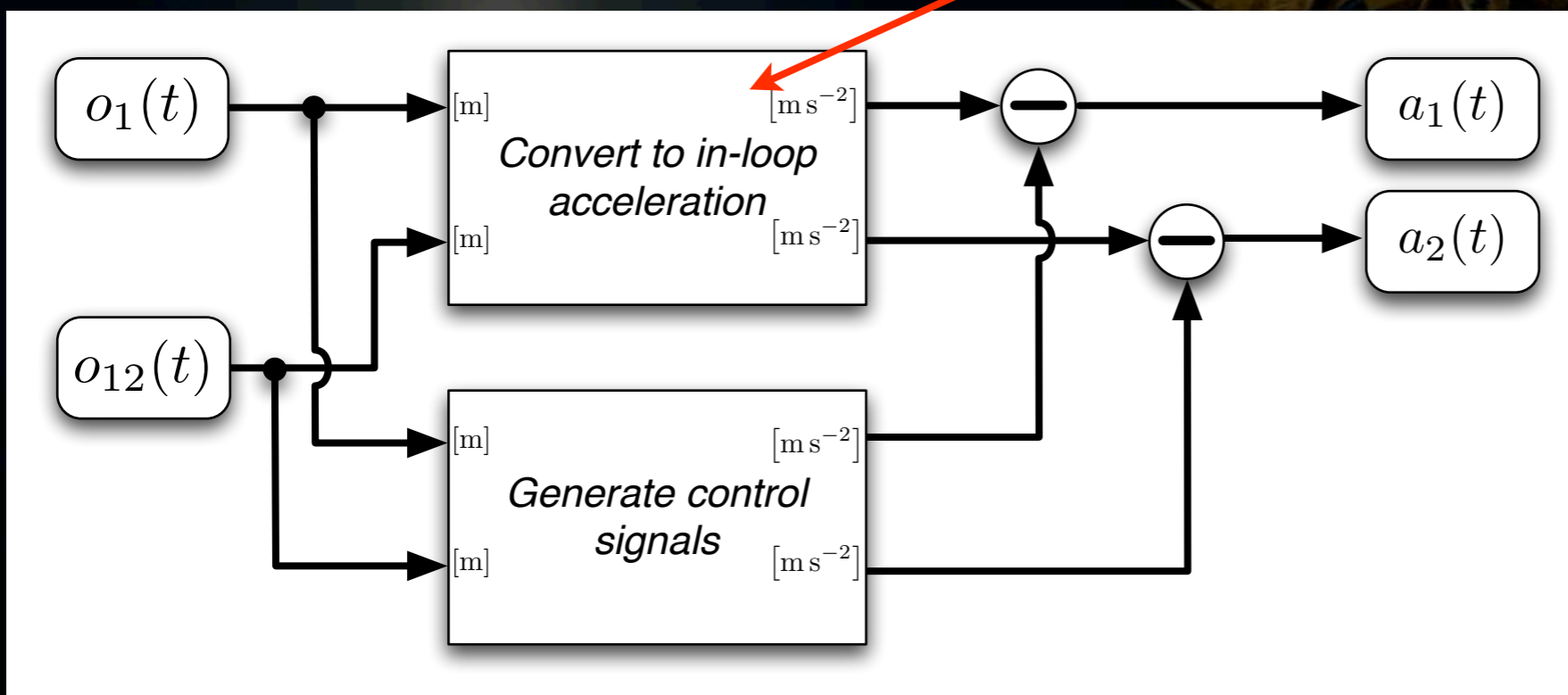
# Calibration procedure



# Calibration procedure



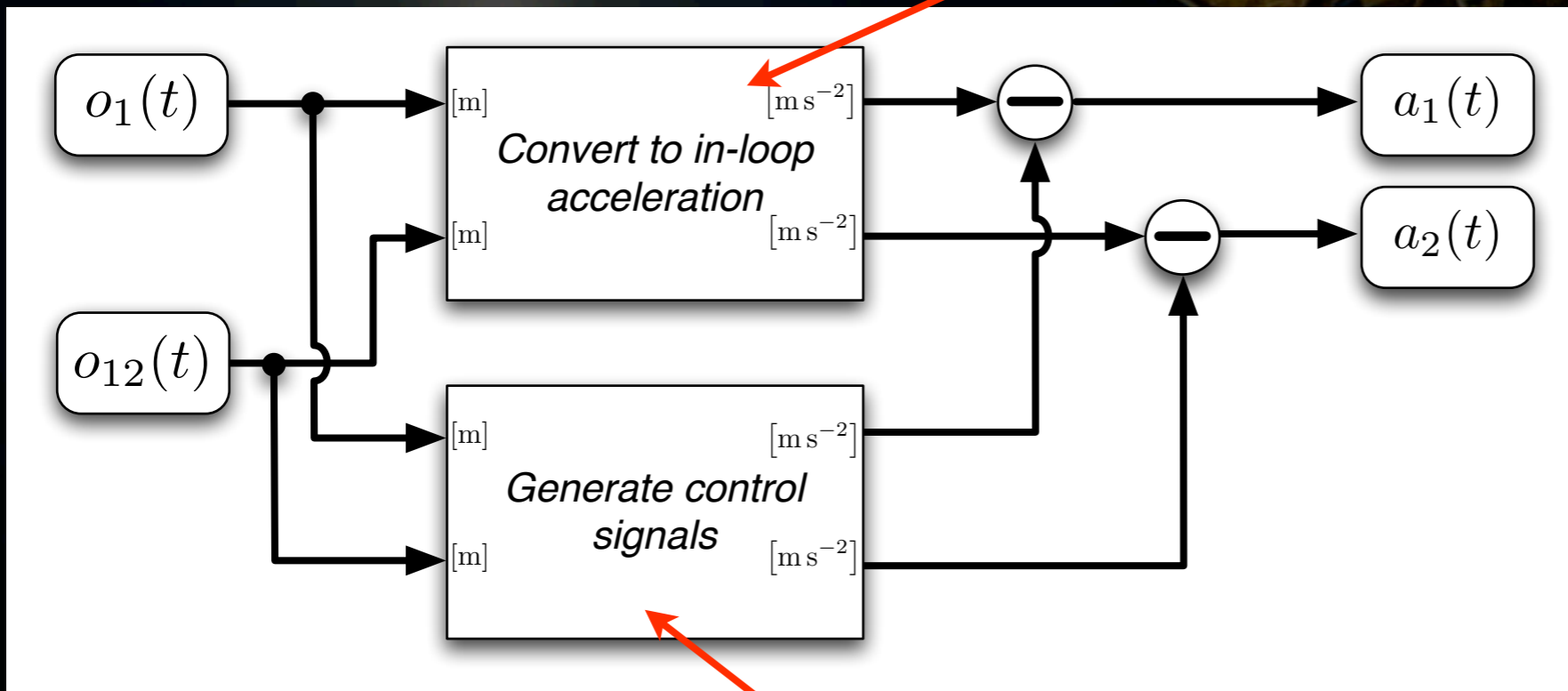
Double differentiation



# Calibration procedure



Double differentiation

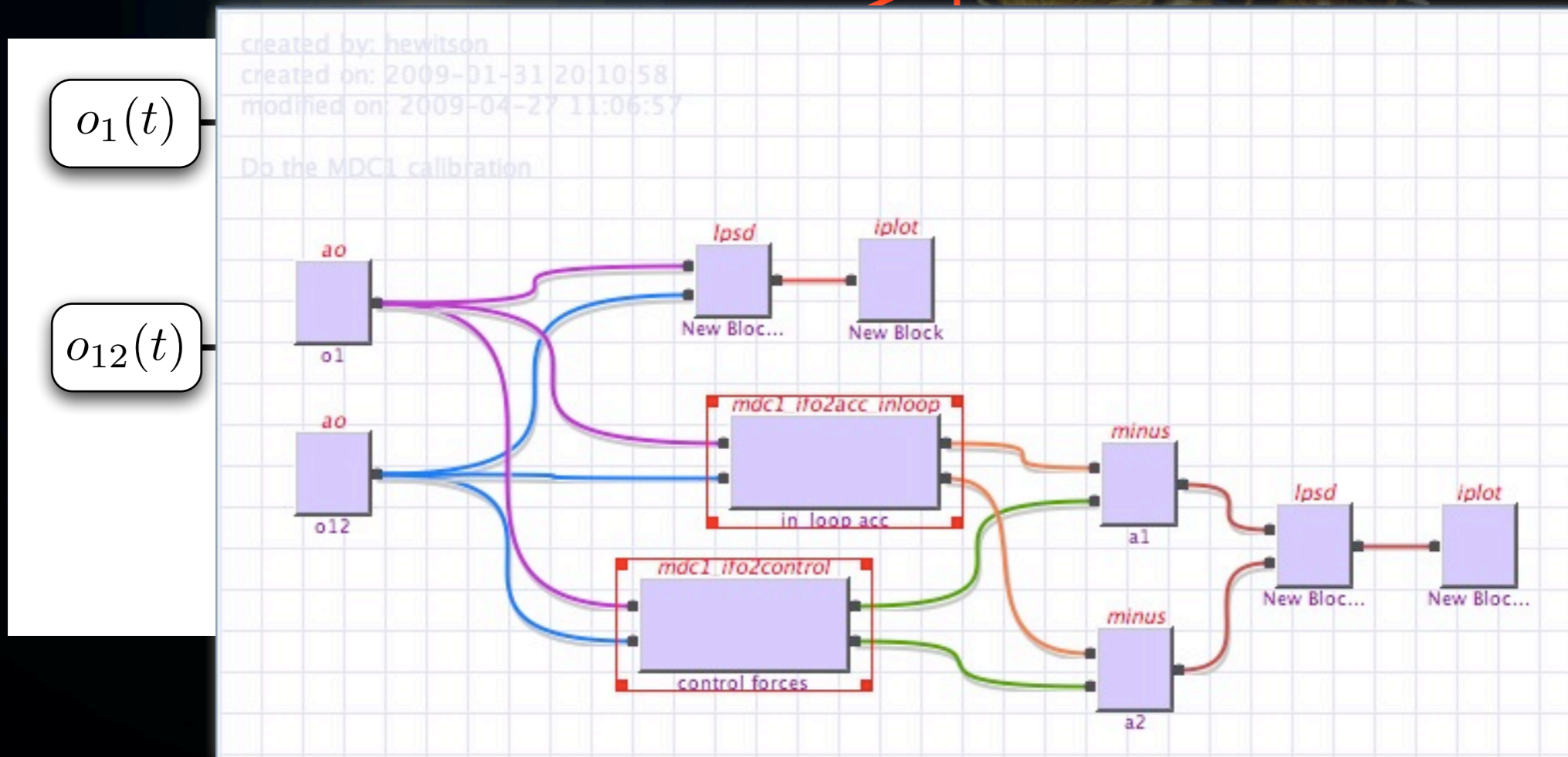


Filter with controller transfer functions

# Calibration procedure

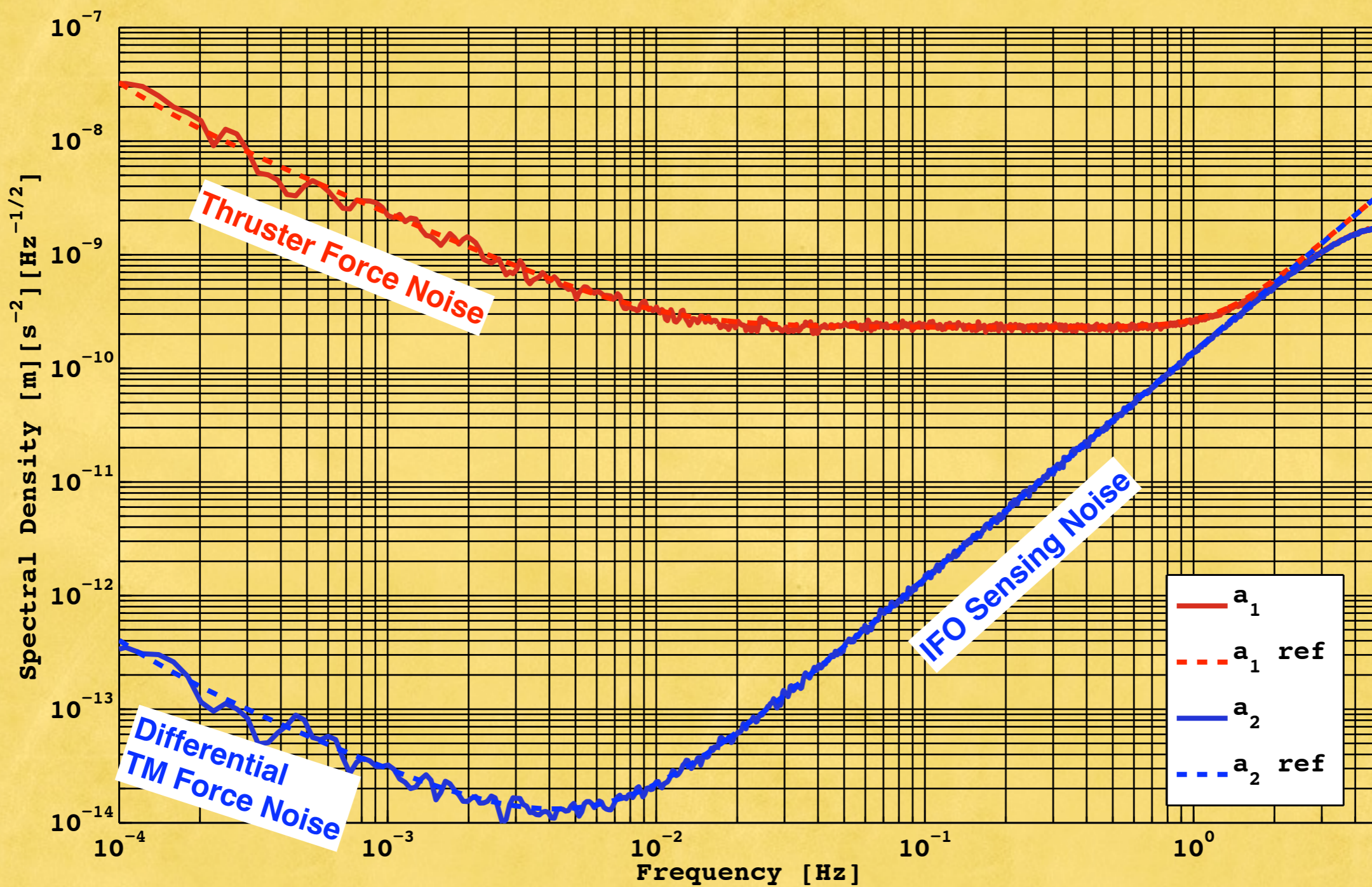


Double differentiation

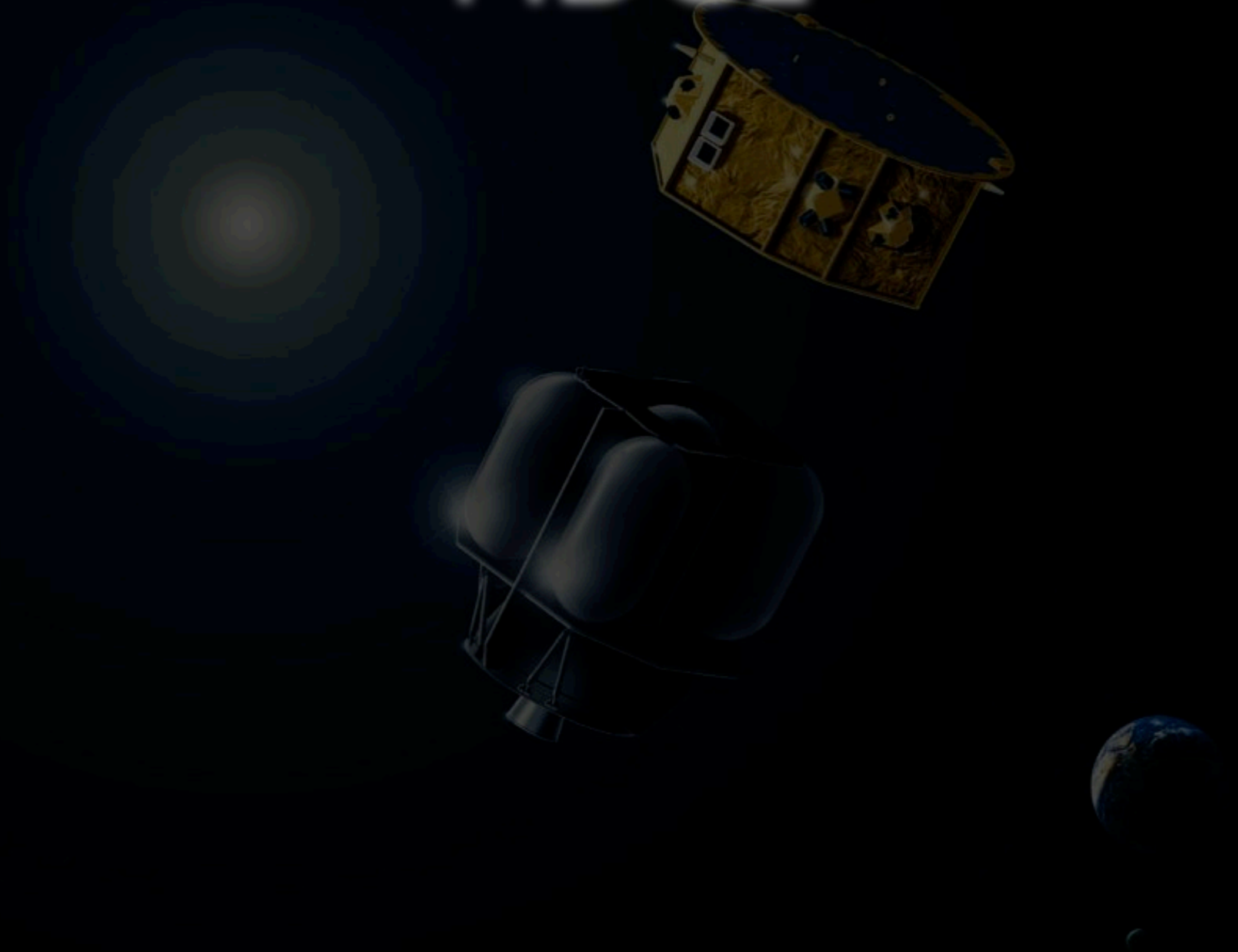


transfer functions

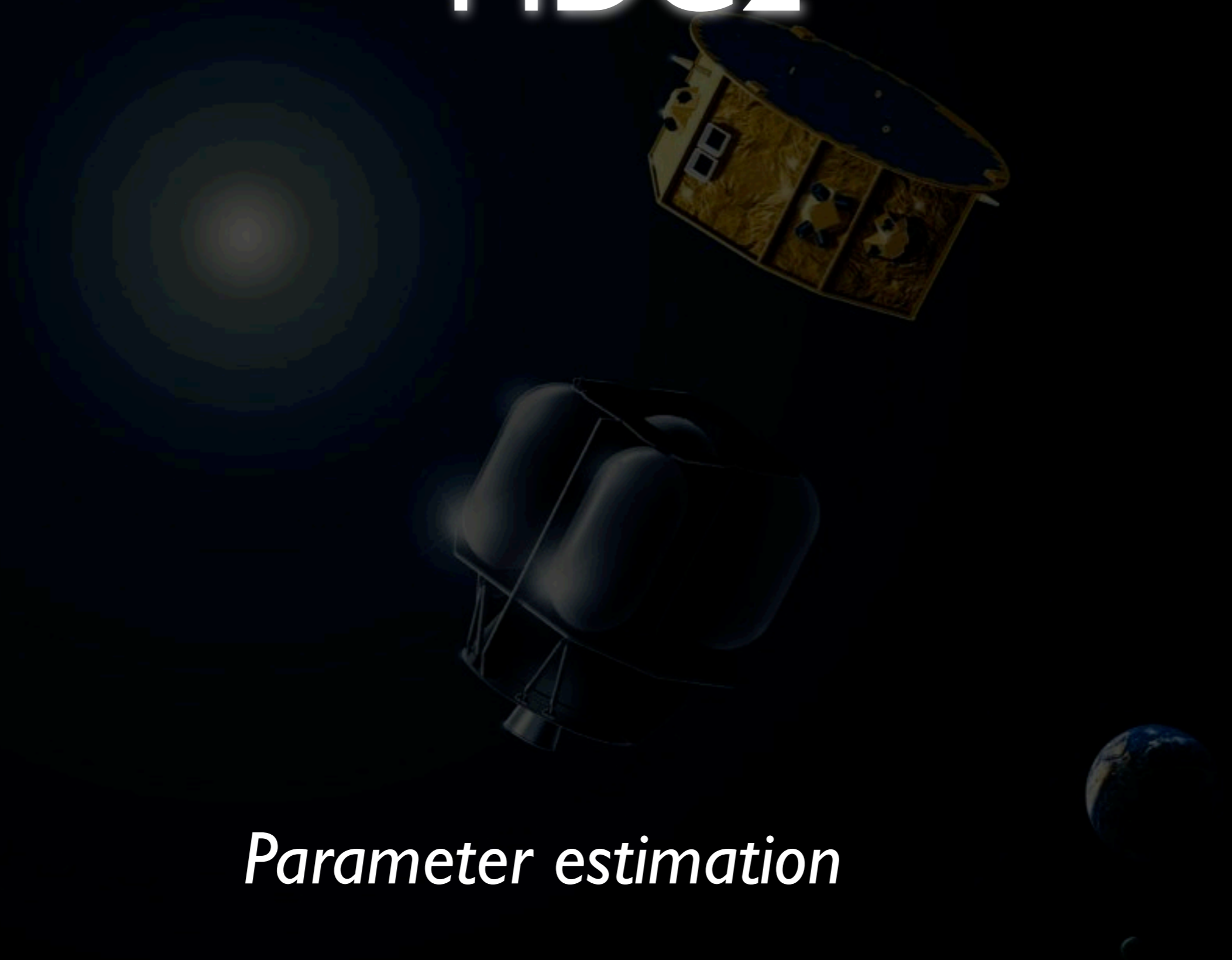
# Results



# MDC2



# MDC2



## *Parameter estimation*

# MDC2



- Model same as MDC1

*Parameter estimation*



# MDC2



- Model same as MDC1
- Analysis team does not know exact parameter values for the model

*Parameter estimation*

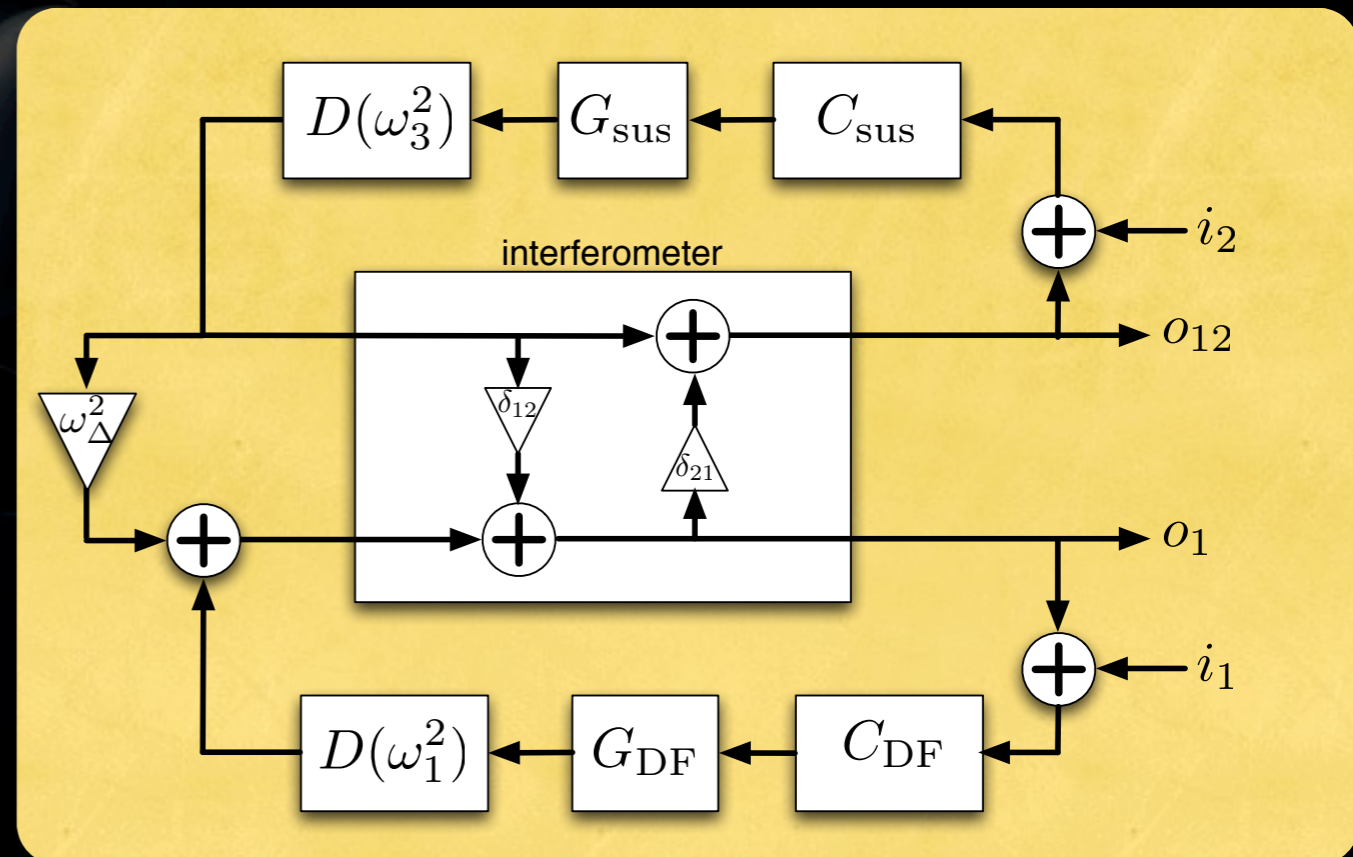
# MDC2



- Model same as MDC1
- Analysis team does not know exact parameter values for the model
- Instead, they must be determined from a series of experiments where the system is excited

*Parameter estimation*

# The experiments

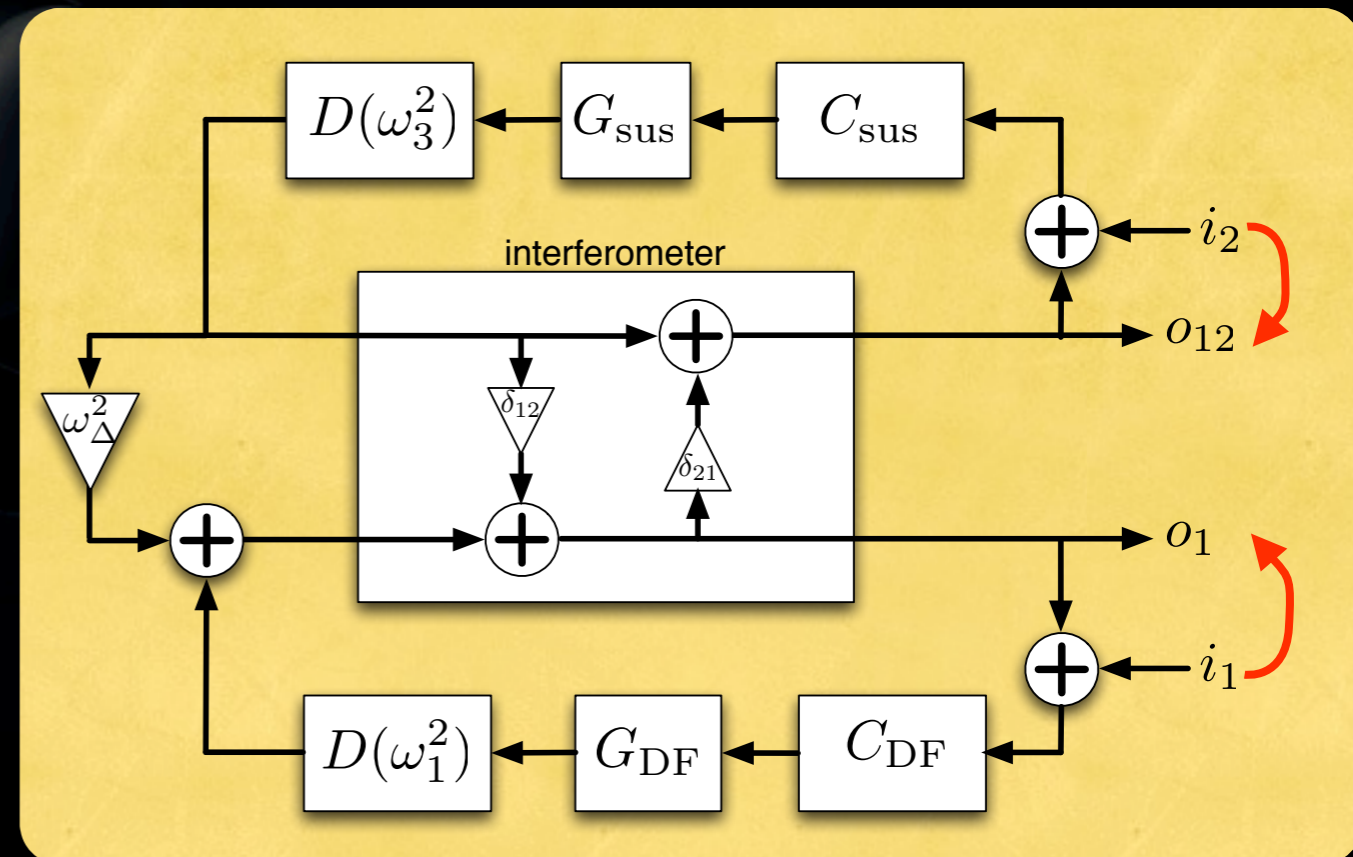




- Experiment I
  - inject signals into both control loops and measure at the outputs
    - $i_1 \rightarrow o_1$  and  $i_2 \rightarrow o_2$ 
      - $G_{df}$ ,  $G_{sus}$  (stiffnesses?)



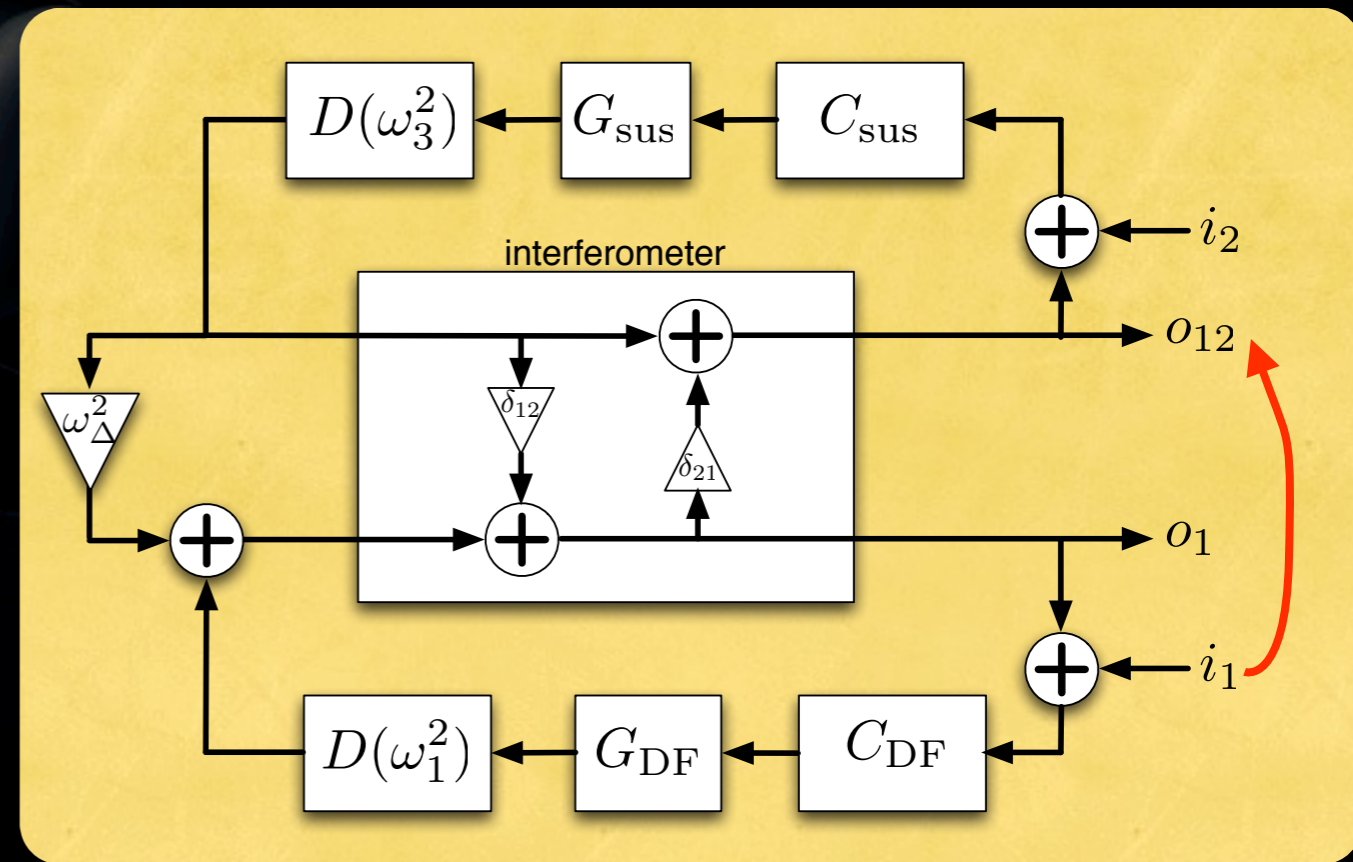
# The experiments





- Experiment 1
  - inject signals into both control loops and measure at the outputs
    - $i_1 \rightarrow o_1$  and  $i_2 \rightarrow o_2$ 
      - $G_{df}, G_{sus}$  (stiffnesses?)
- Experiment 2
  - Match stiffness of two TMs
  - Inject in drag-free loop, measure in X12 loop
    - $i_1 \rightarrow o_2$ 
      - IFO cross-coupling

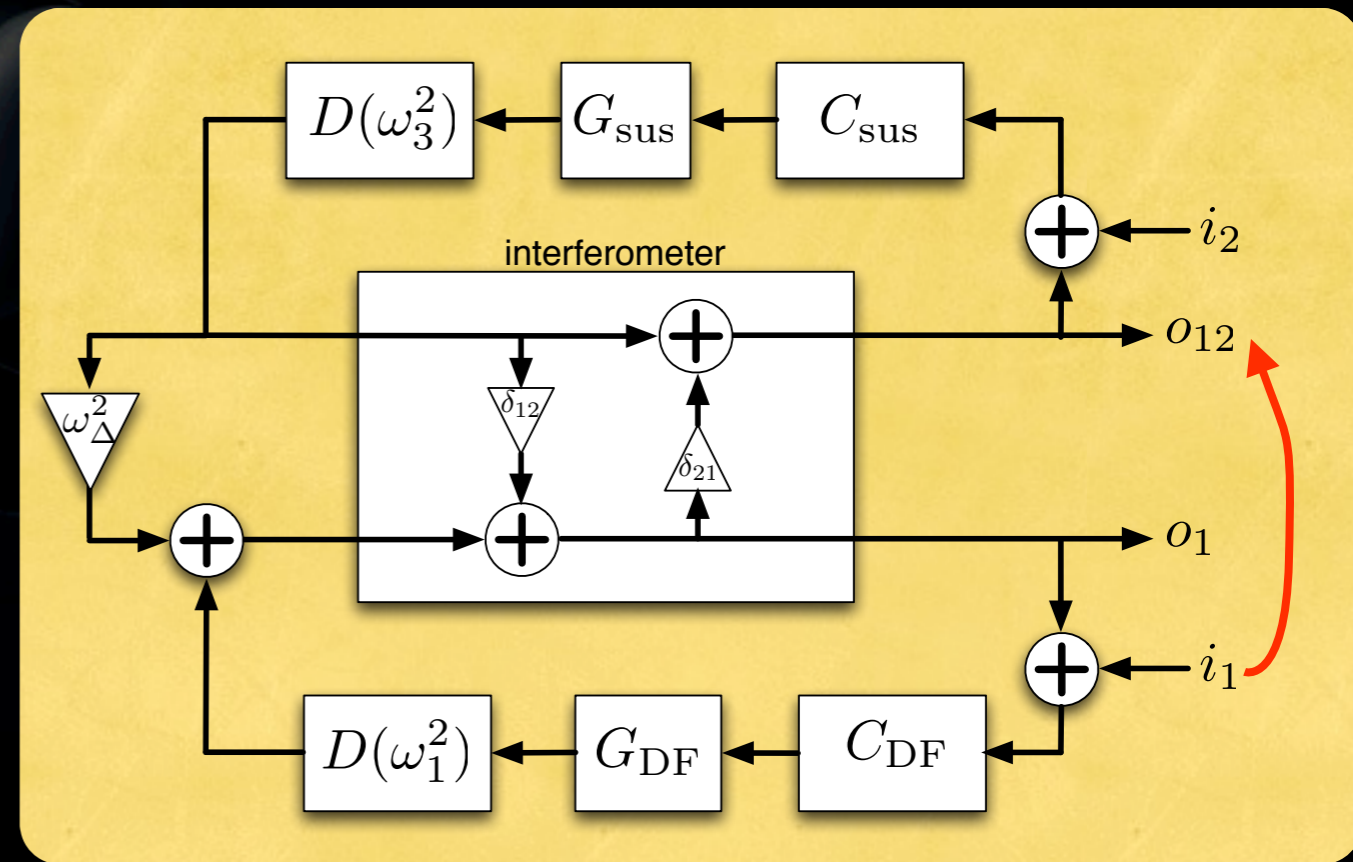
# The experiments





- Experiment 1
  - inject signals into both control loops and measure at the outputs
    - $i1 \rightarrow o1$  and  $i2 \rightarrow o12$ 
      - $G_{df}, G_{sus}$  (stiffnesses?)
- Experiment 2
  - Match stiffness of two TMs
  - Inject in drag-free loop, measure in X12 loop
    - $i1 \rightarrow o12$ 
      - IFO cross-coupling
- Experiment 3
  - Un-matched stiffness
  - Same injection
    - $i1 \rightarrow o12$ 
      - difference of stiffness

# The experiments



# Experiment 3



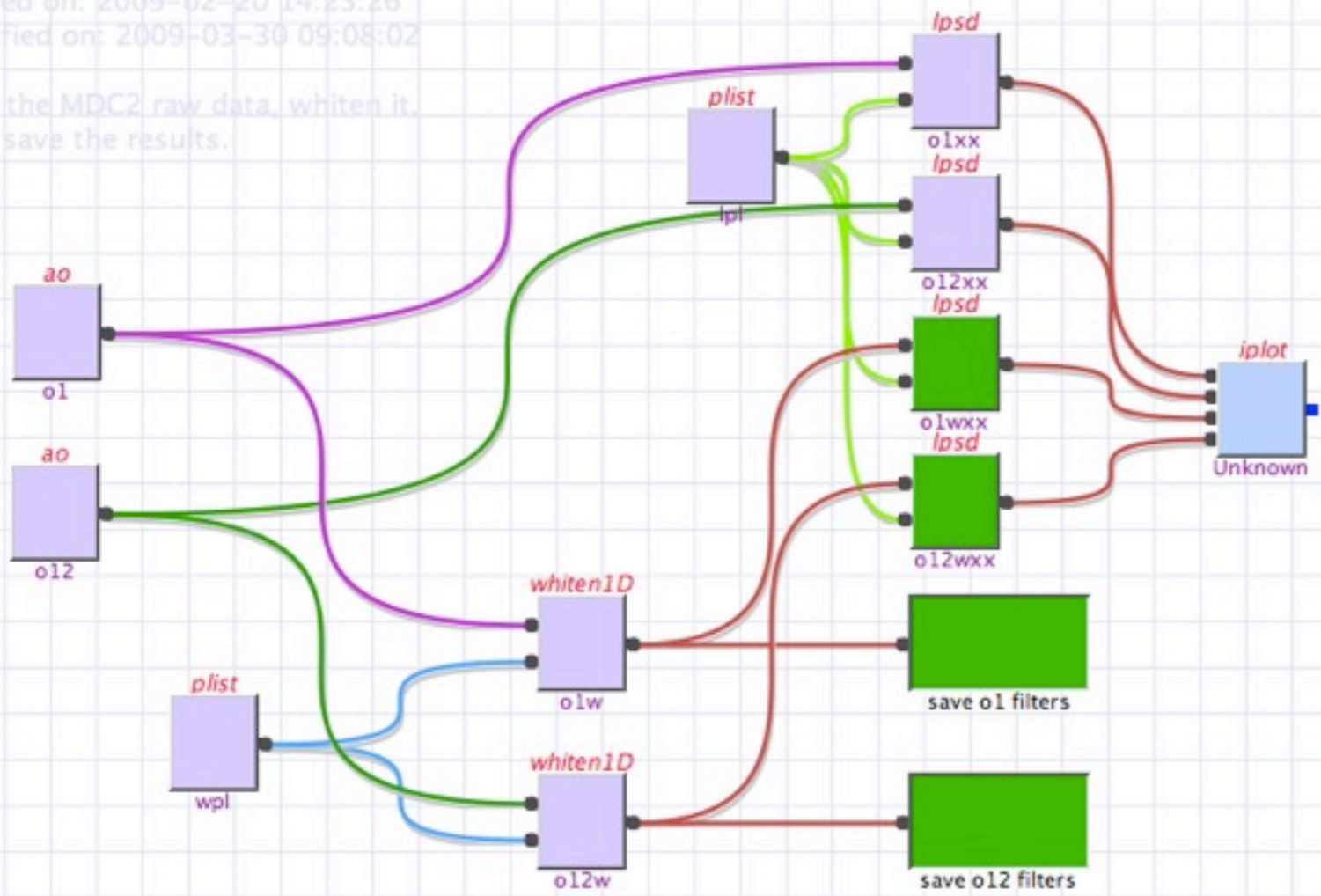
- Whitening data
- Measuring Transfer function
- Building the model to fit
- Fitting the model to the data
- Calibrate to acceleration

# Whiten data



created by: hewitson  
created on: 2009-02-20 14:23:26  
modified on: 2009-03-30 09:08:02

Load the MDC2 raw data, whiten it,  
then save the results.



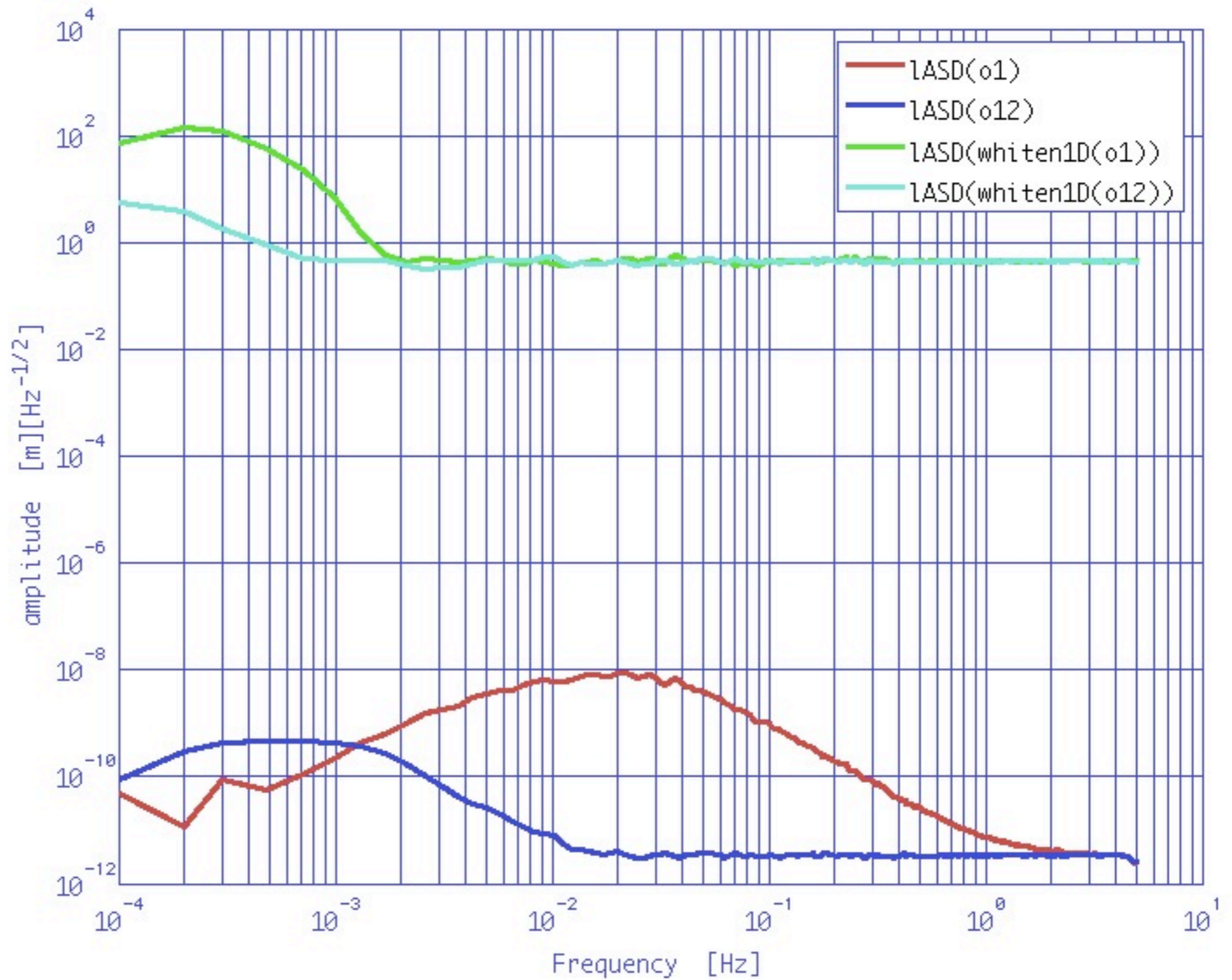
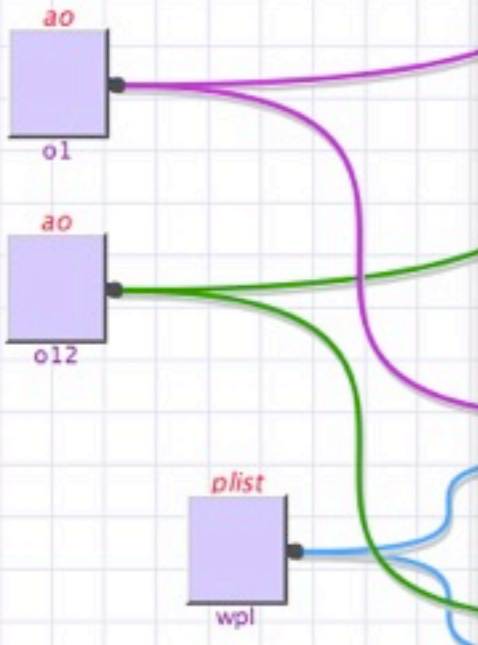


# Whiten data



created by: hewitson  
created on: 2009-02-20 14:23:26  
modified on: 2009-03-30 09:08:02

Load the MDC2 raw data, whiten it,  
then save the results.

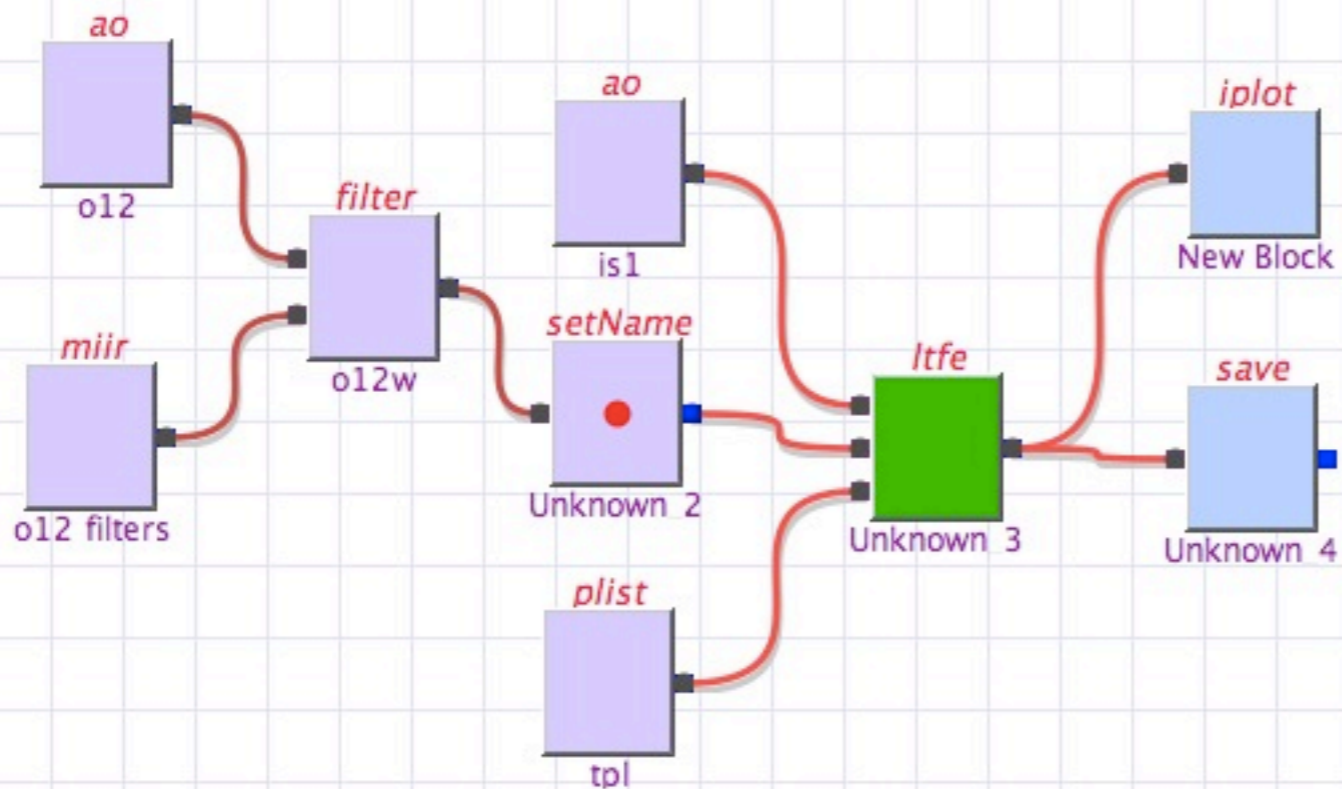


# Measure TF



created by: hewitson  
created on: 2009-02-20 14:23:26  
modified on: 2009-03-30 09:40:34

Measure the transfer function from channel X1 input to channel X12 output. This is experiment 3 of MDC2.

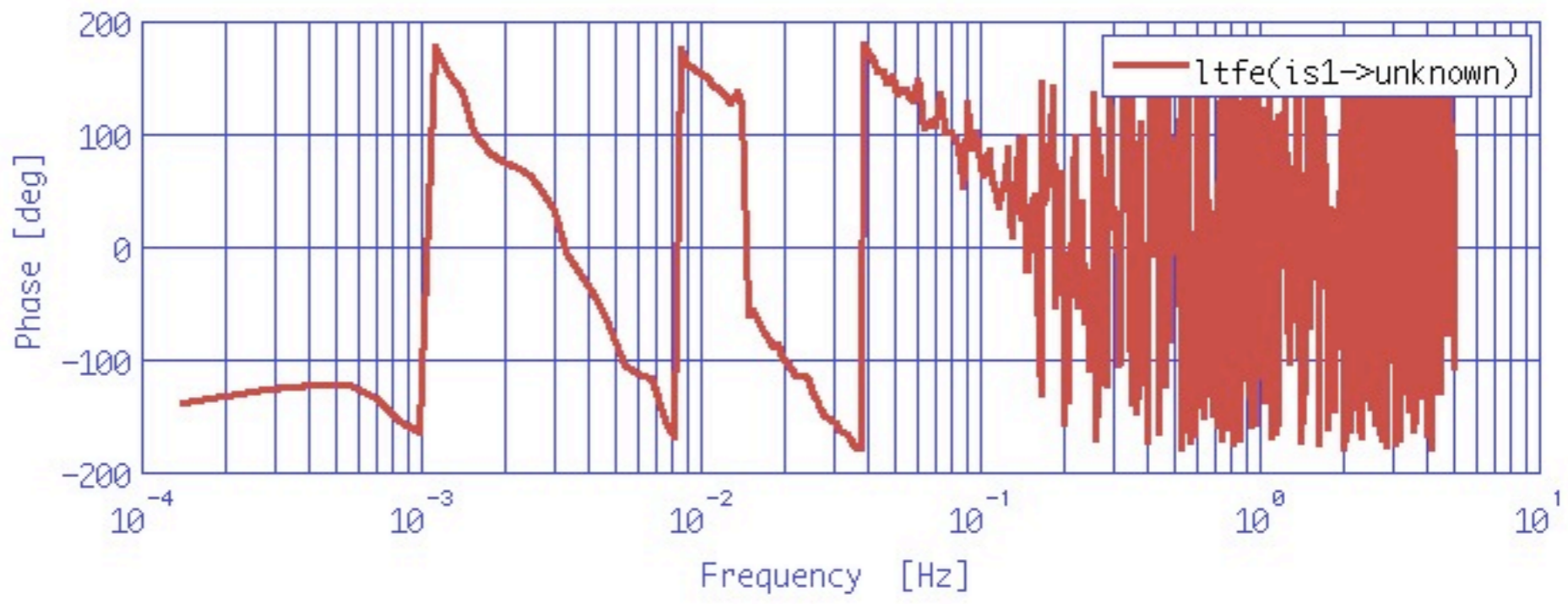
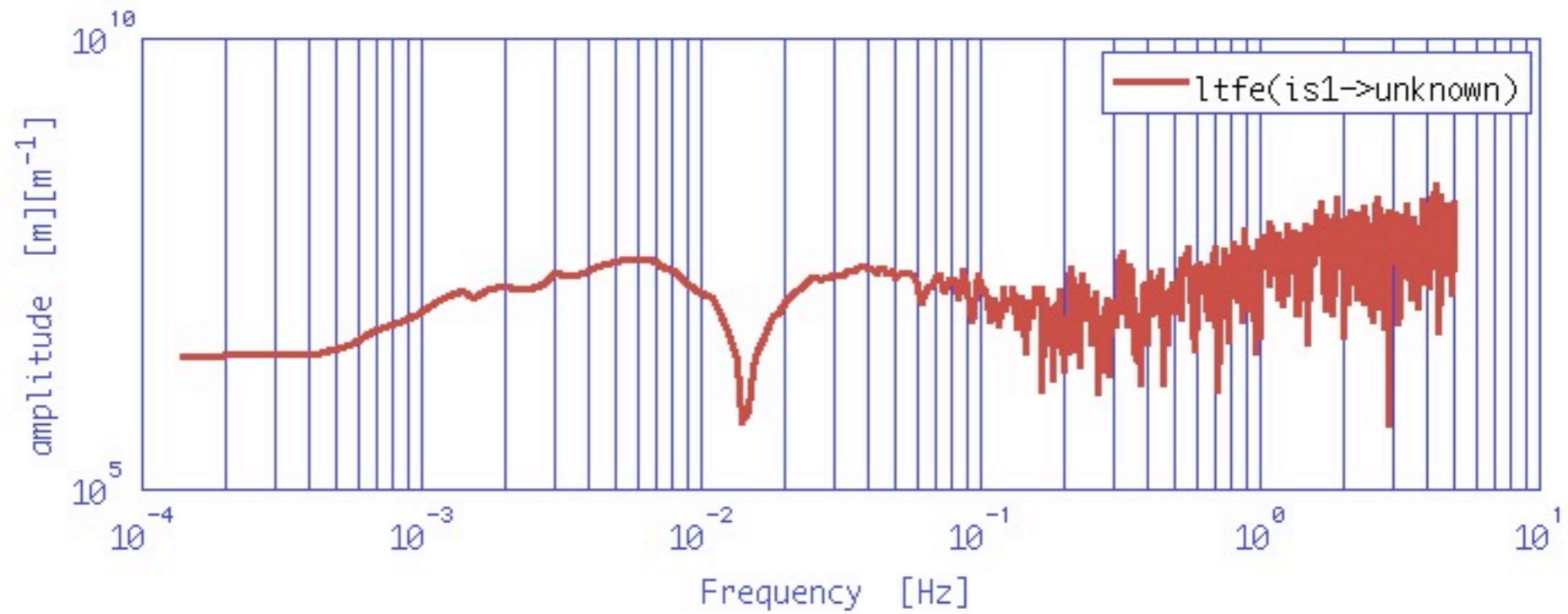


# Measure TF



created by: hewitson  
created on: 2009-02-20 1  
modified on: 2009-03-30

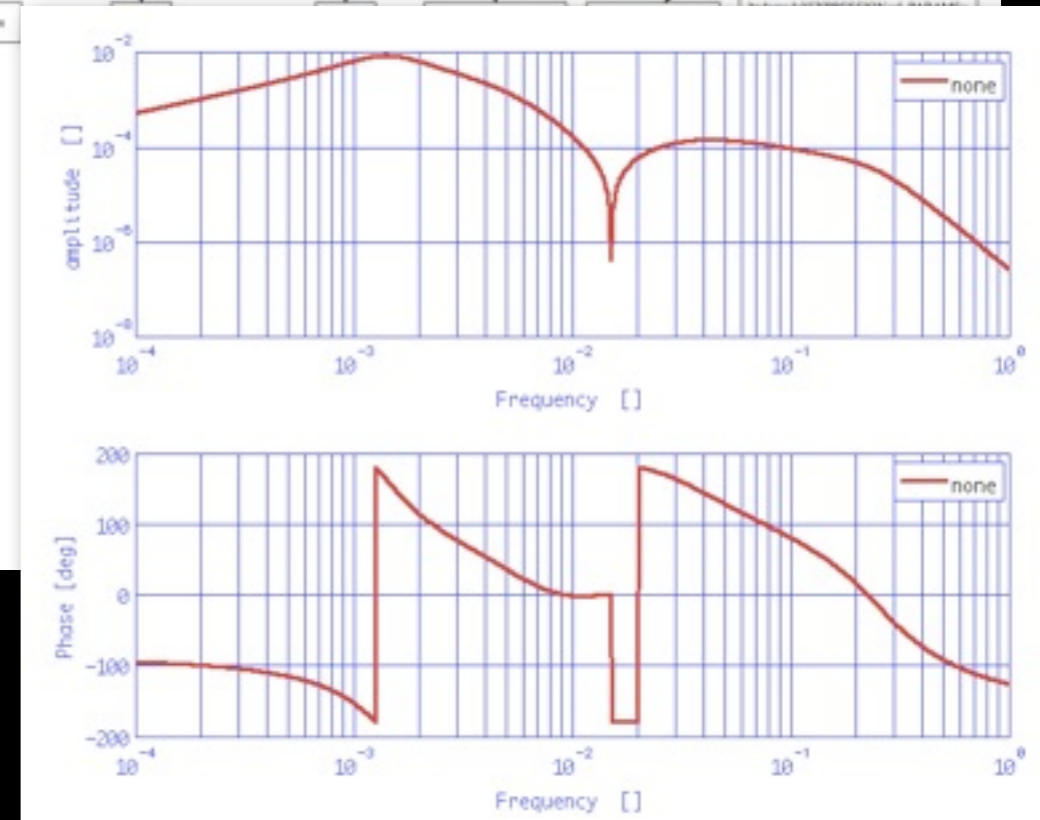
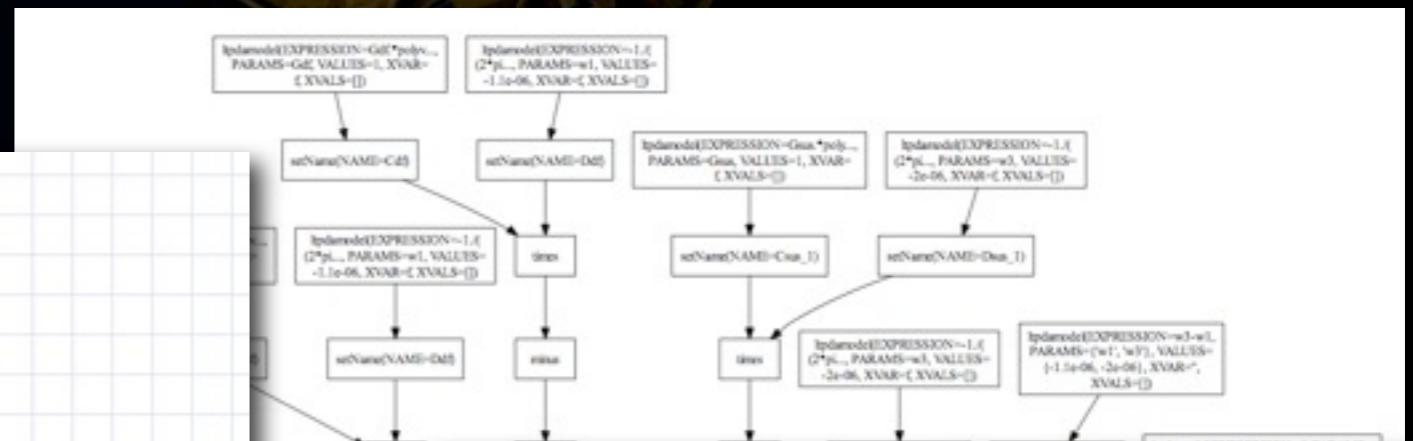
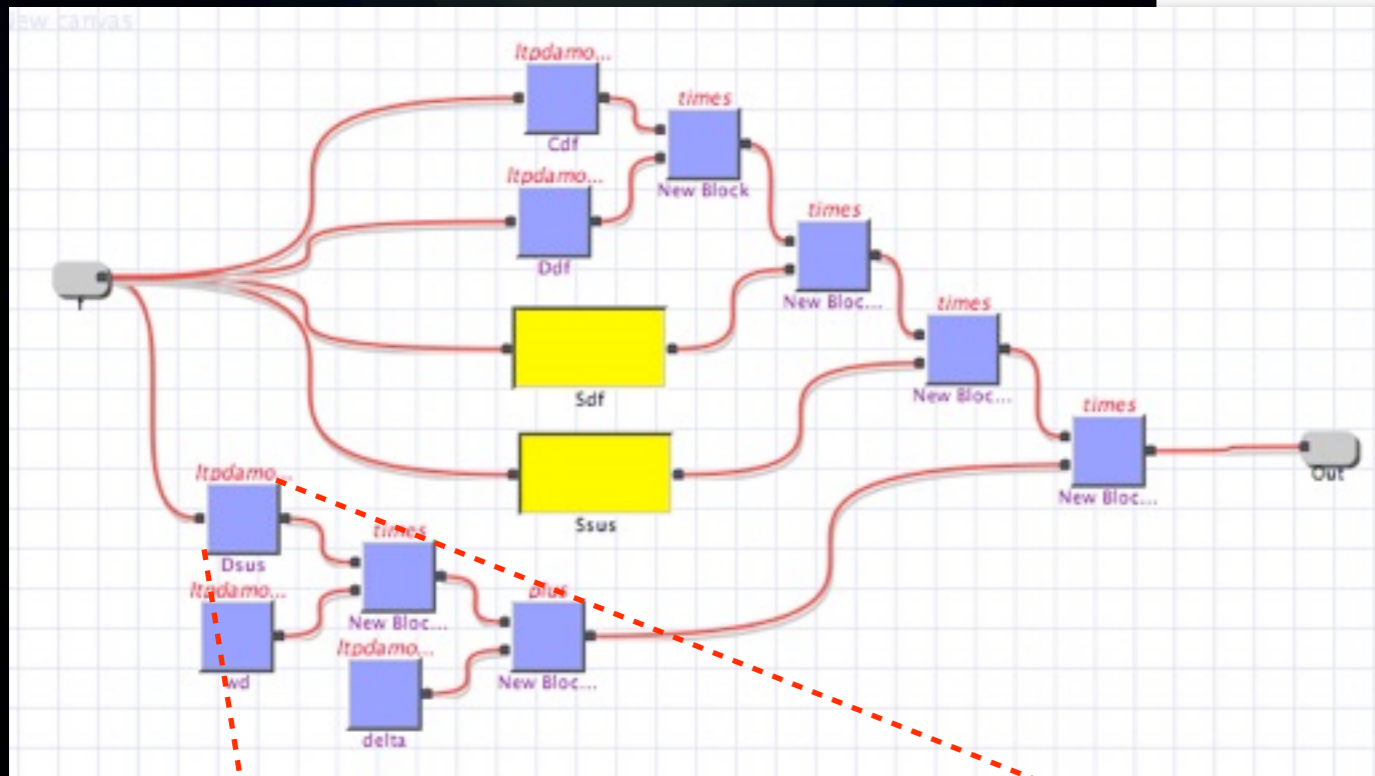
Measure the transfer func  
channel X1 input to chann  
output. This is experimen



# Build the model



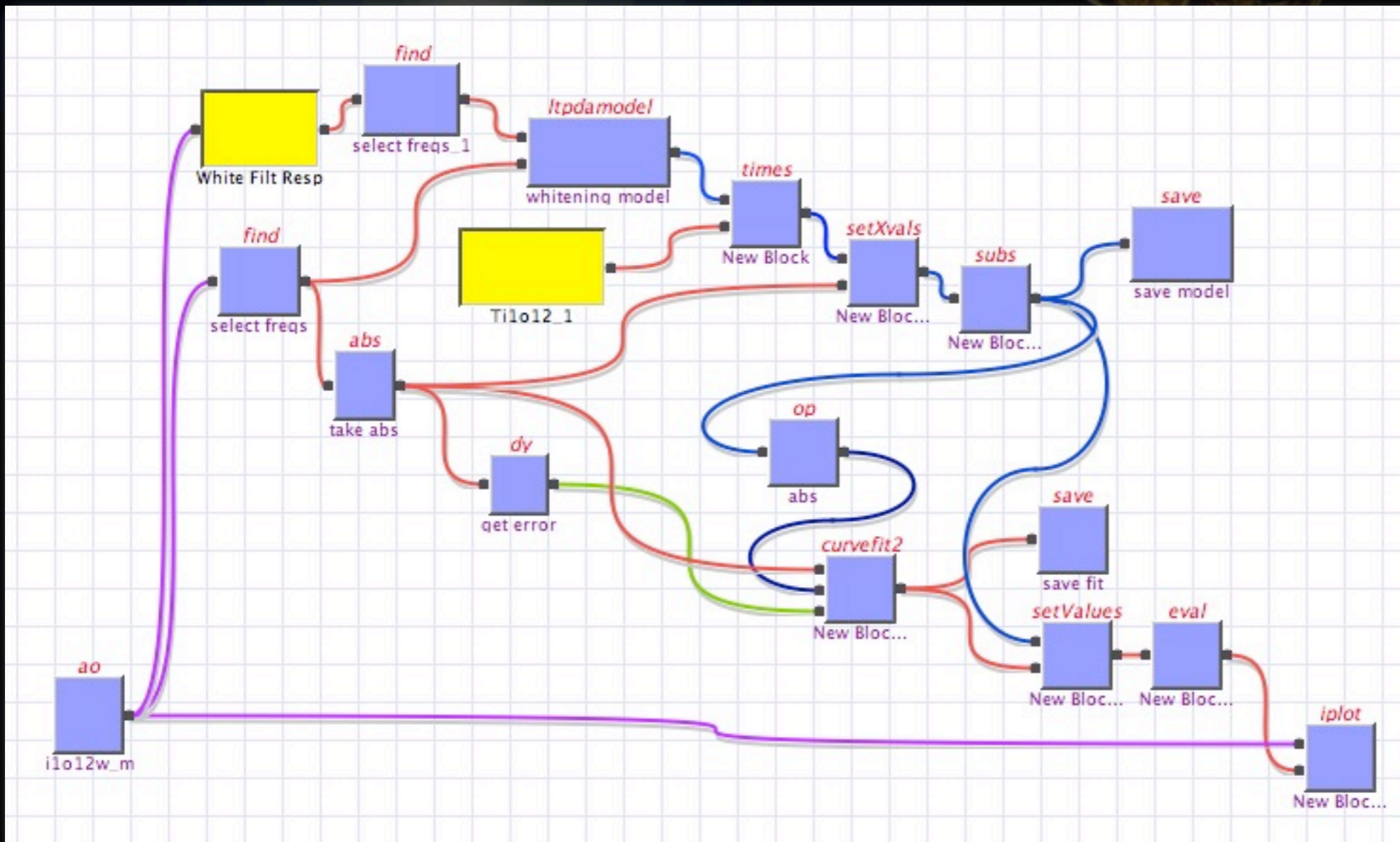
- Model is built with various `ltpdamodel` objects



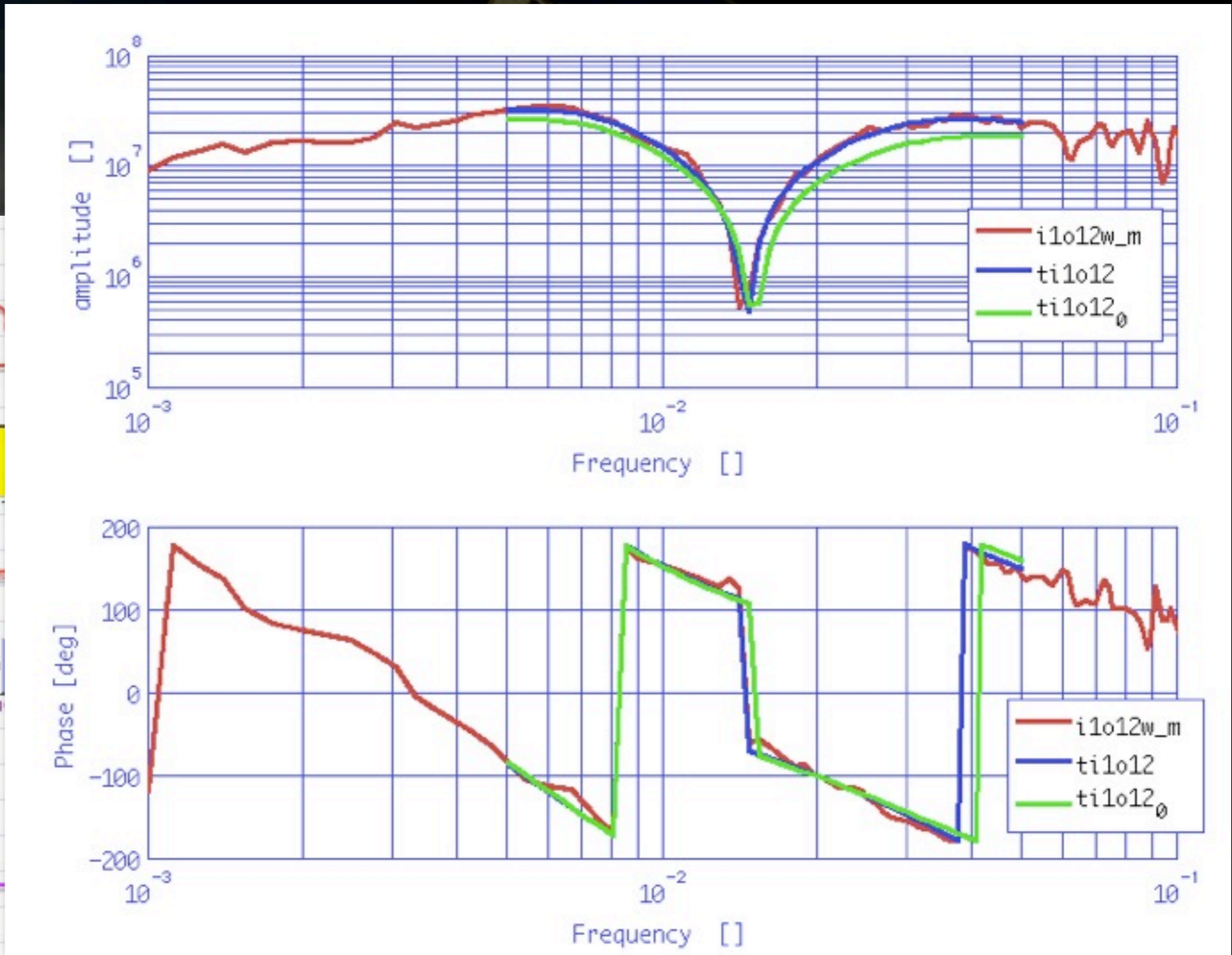
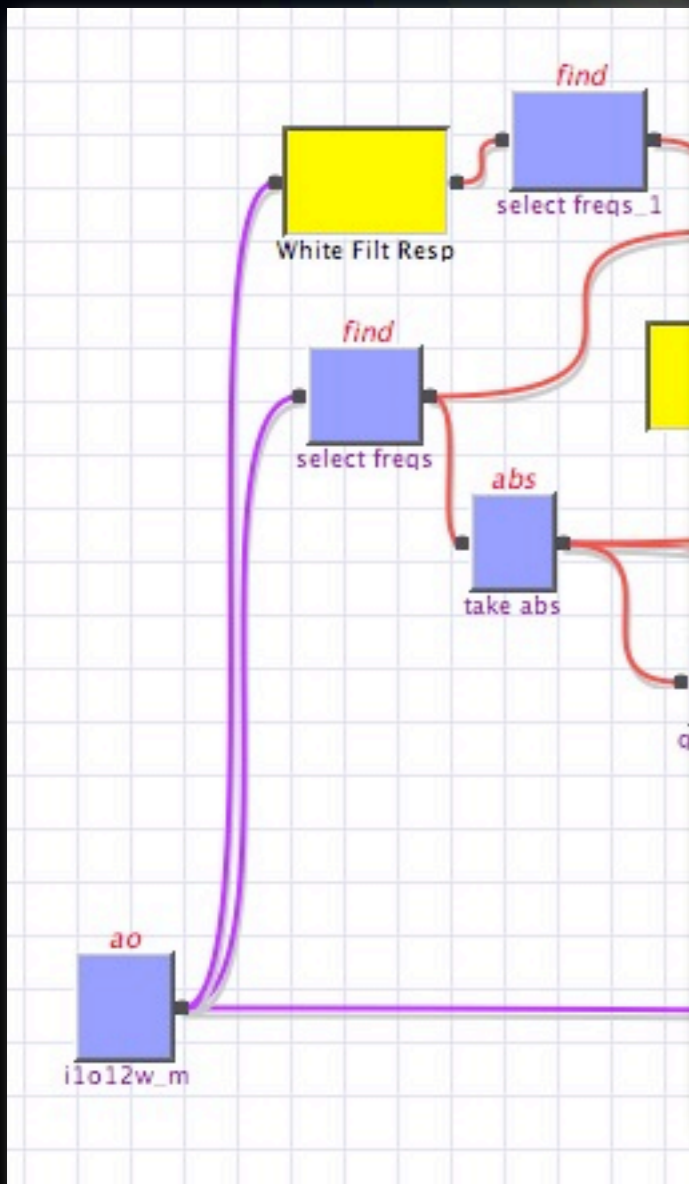
```

---- ltpdamodel 1 ----
name: Dsus
expr: -1./((2*pi*1i*f).^2 + w1)
params: {'w1'}
values: {-1.1e-06}
xvar: f
xvals: [0.0001 0.000100926219098705 ...]
-----
    
```

# Fit model to data



# Fit model to data



# Calibration to acceleration

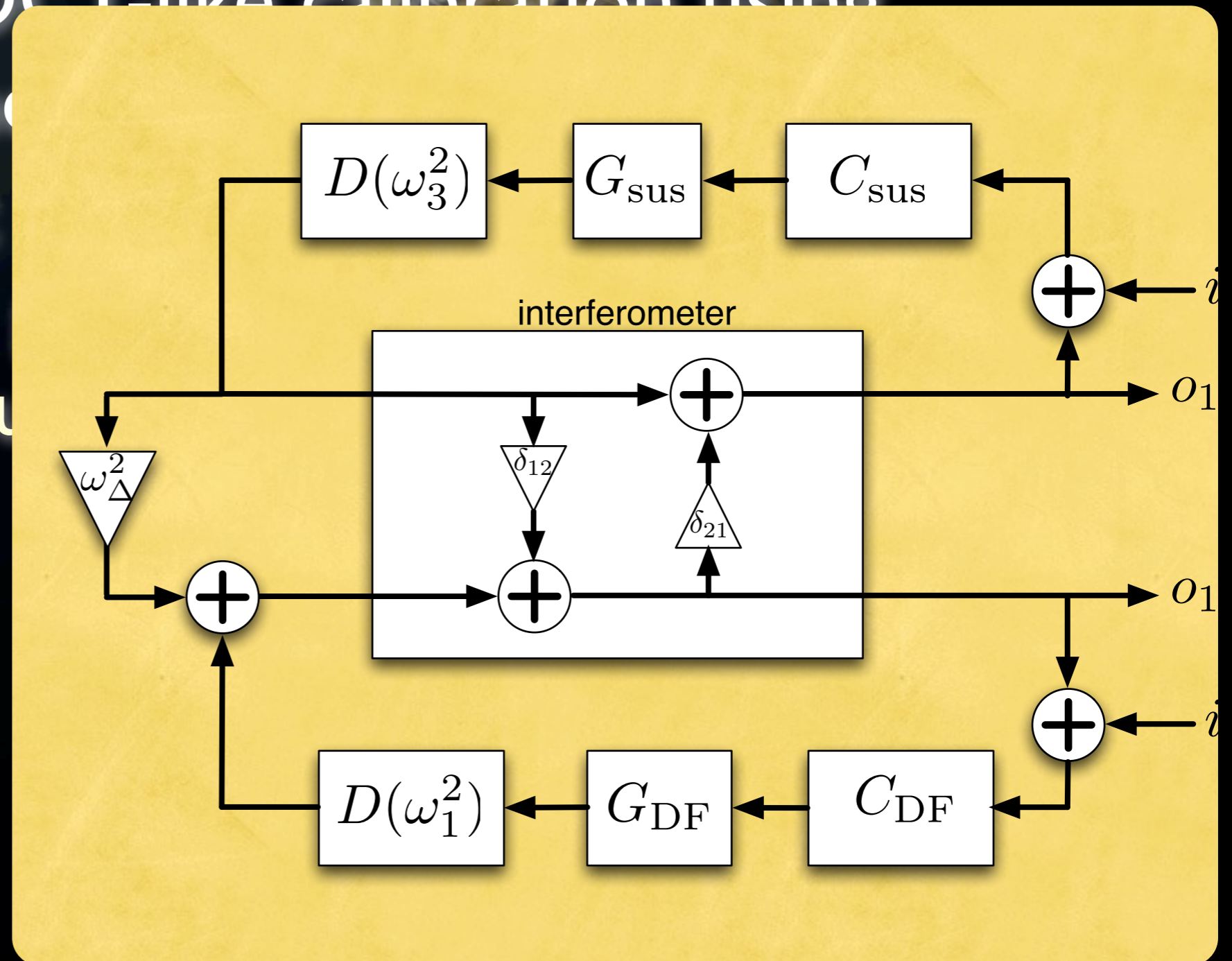


- Perform MDCI-like calibration using the experiment 3 data
- for perfect parameter estimation and calibration process the injected signals should subtract!

# Calibration to acceleration



- Perform MDCI-like calibration using the experimental signals
- for perfect calibration signals should be

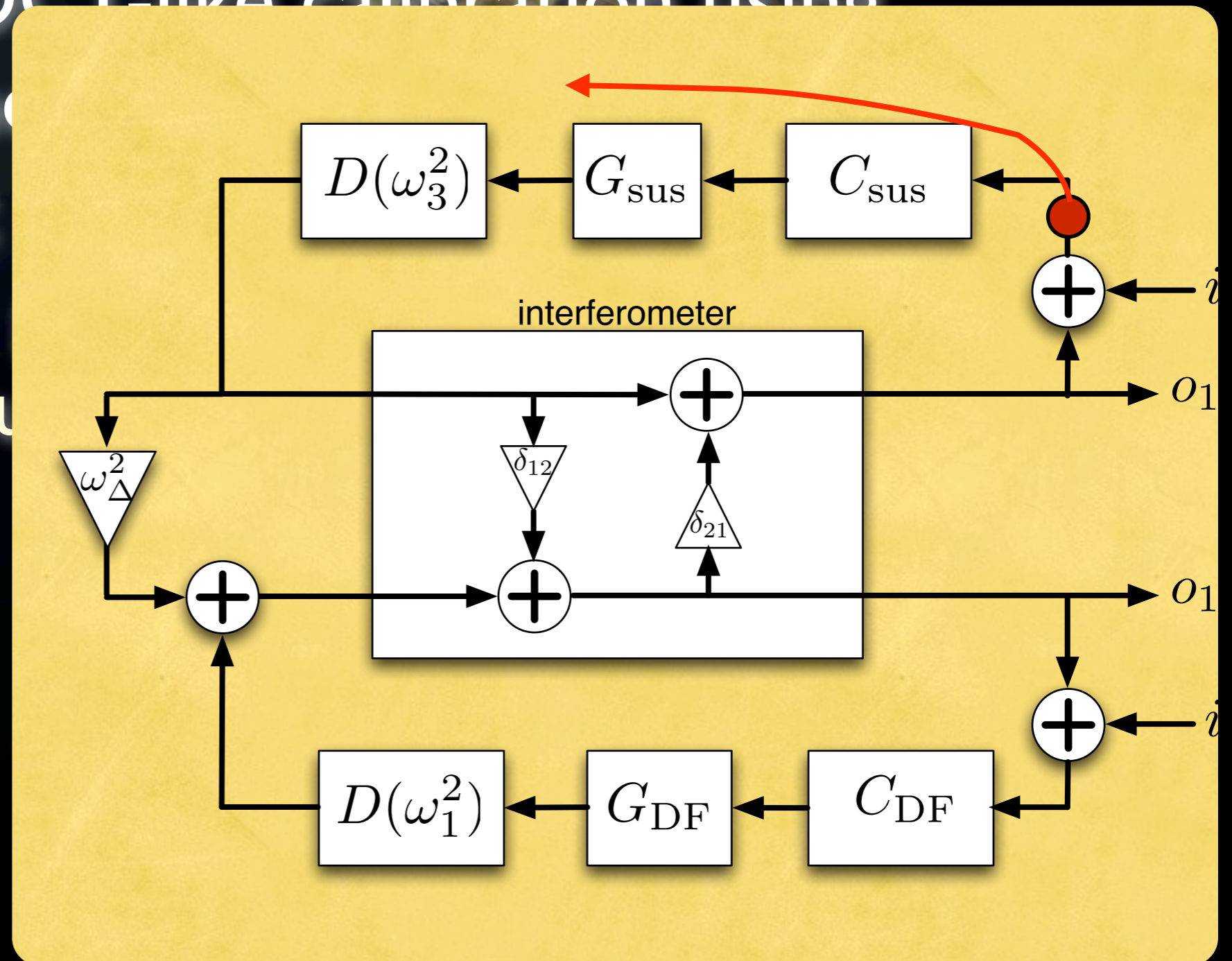




# Calibration to acceleration



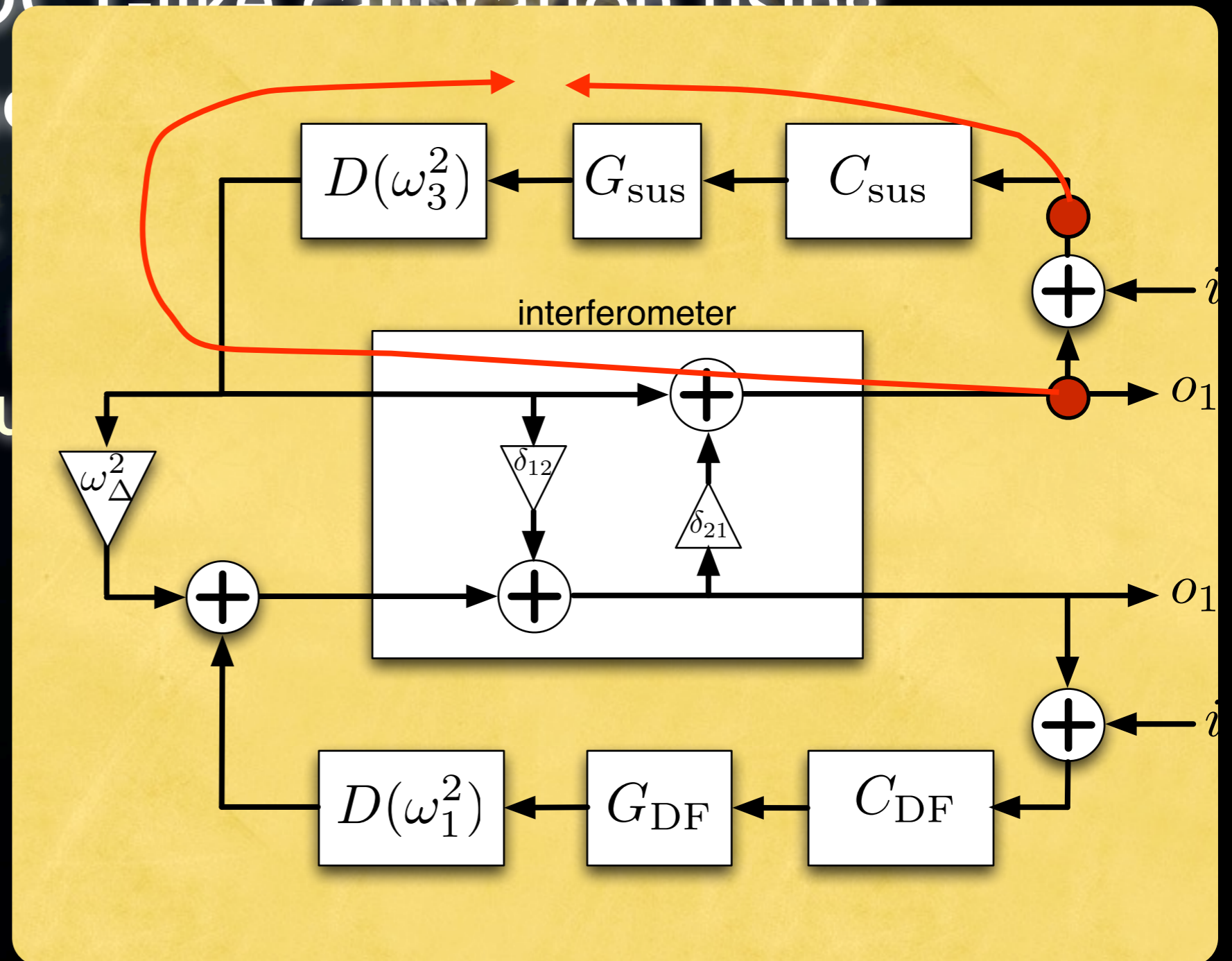
- Perform MDCI-like calibration using the experimental signals
- for perfect calibration signals should



# Calibration to acceleration



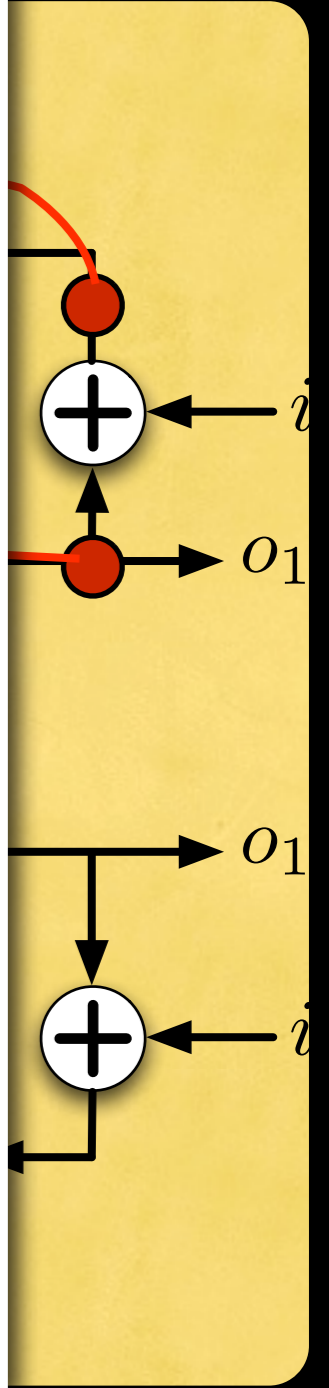
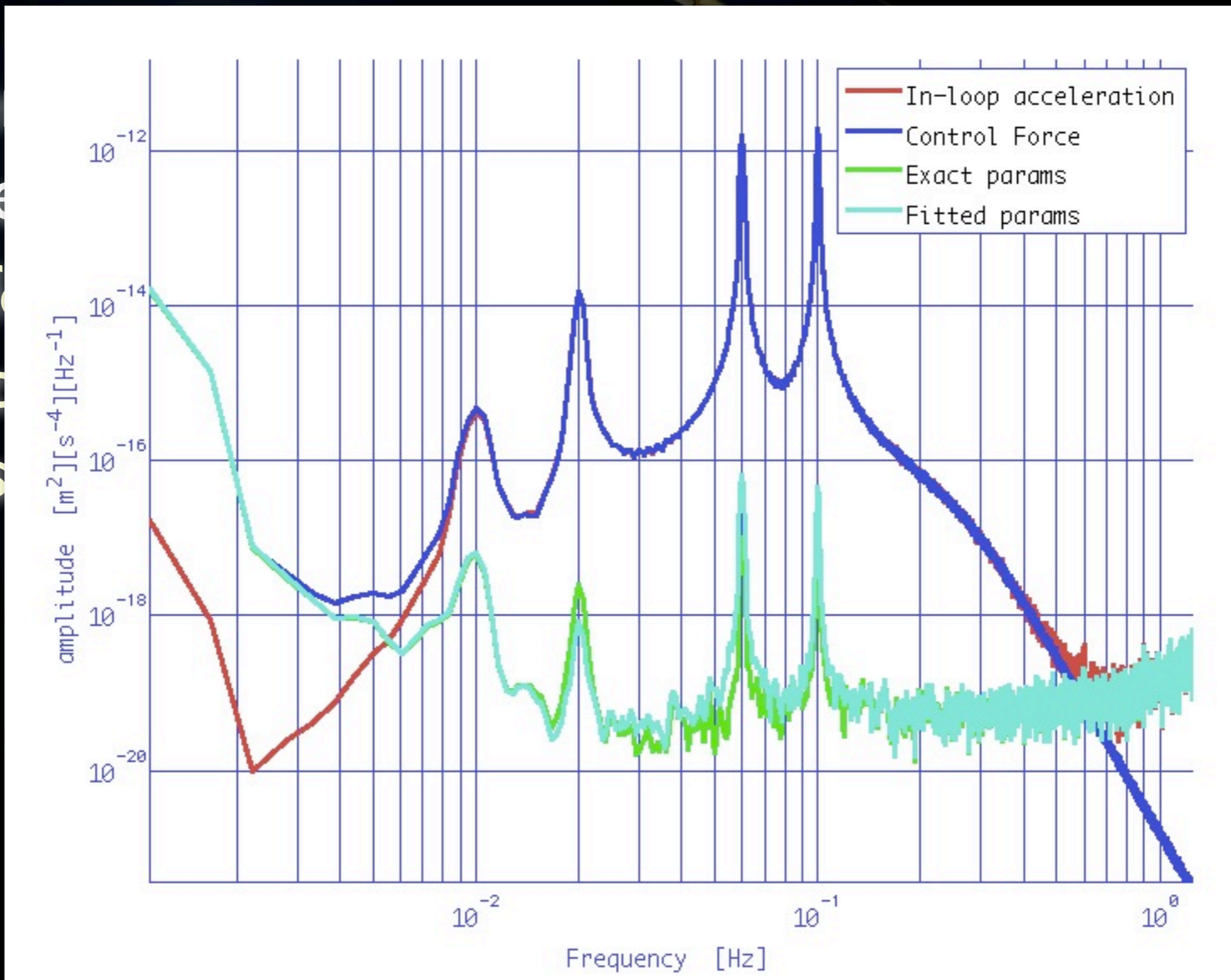
- Perform MDCI-like calibration using the experimental signals
- for perfect calibration signals should be



# Calibration to acceleration



- Performance
- the
- for
- C
- S

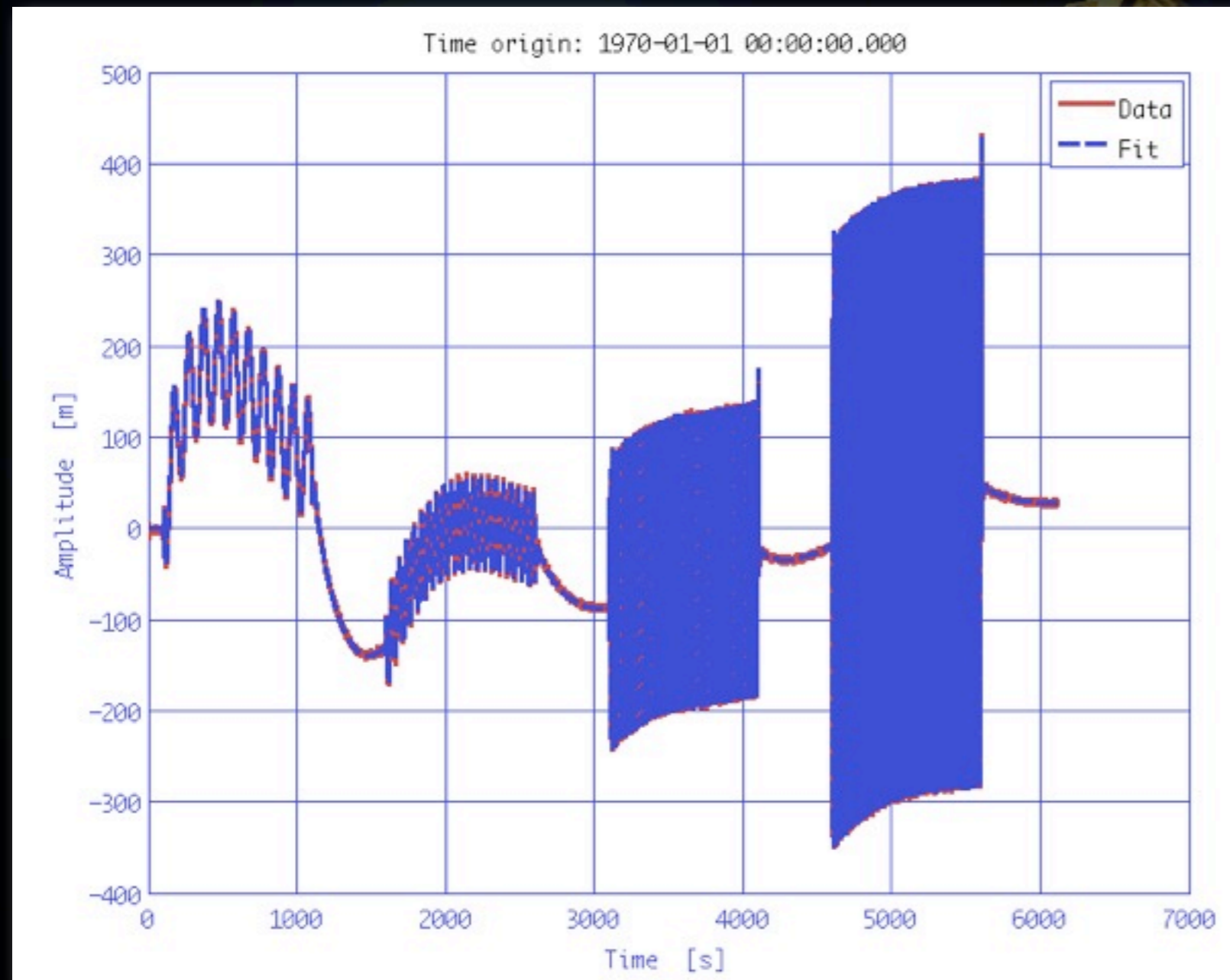


# Time-domain fitting



- Try to generate template signals in time-domain and fit these to the measured data
- use `Ltpdamodel` objects with FFT filtering technique

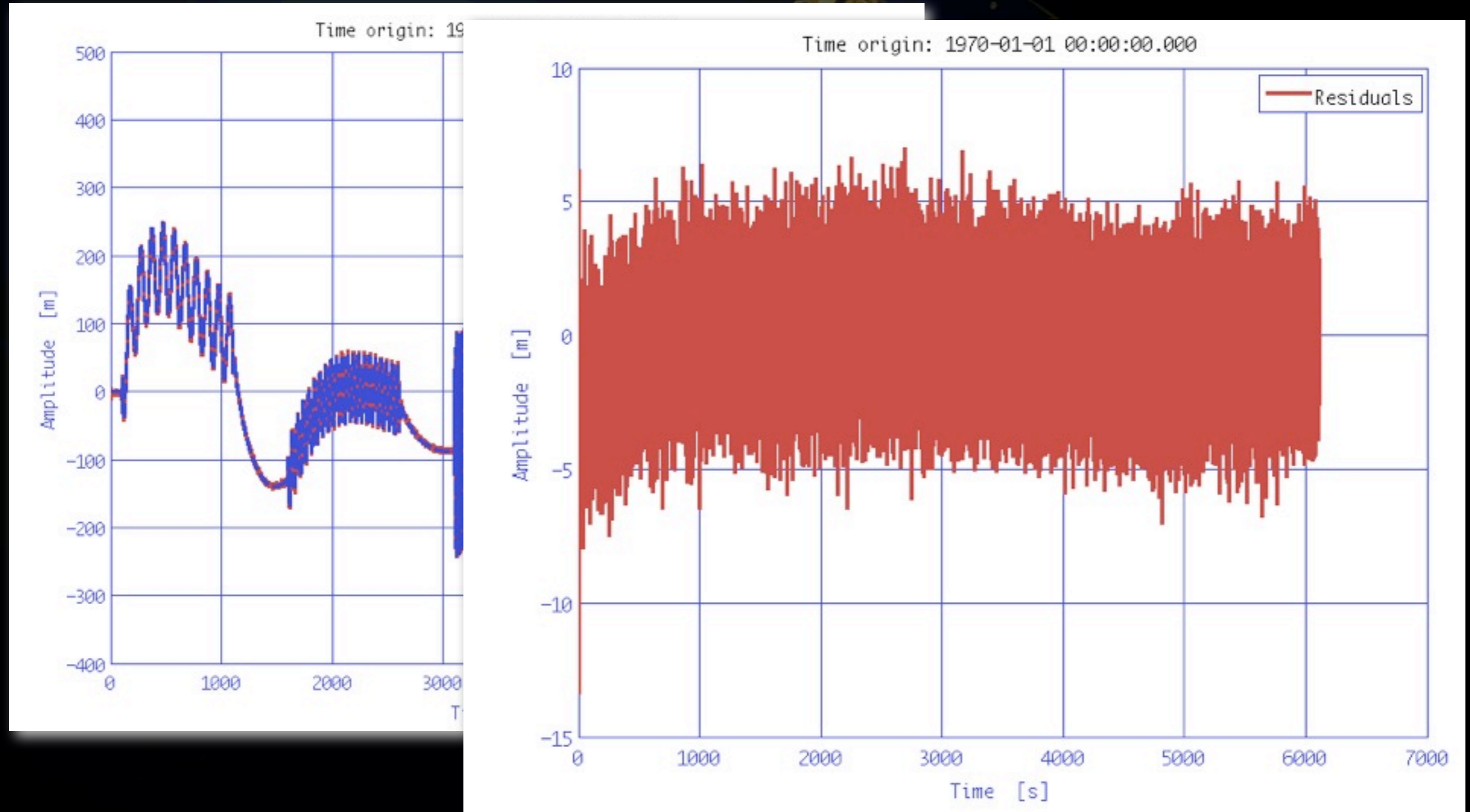
# Time-domain fitting



te signals in  
se to the

s with FFT

# Time-domain fitting



# Monte Carlo Analyses

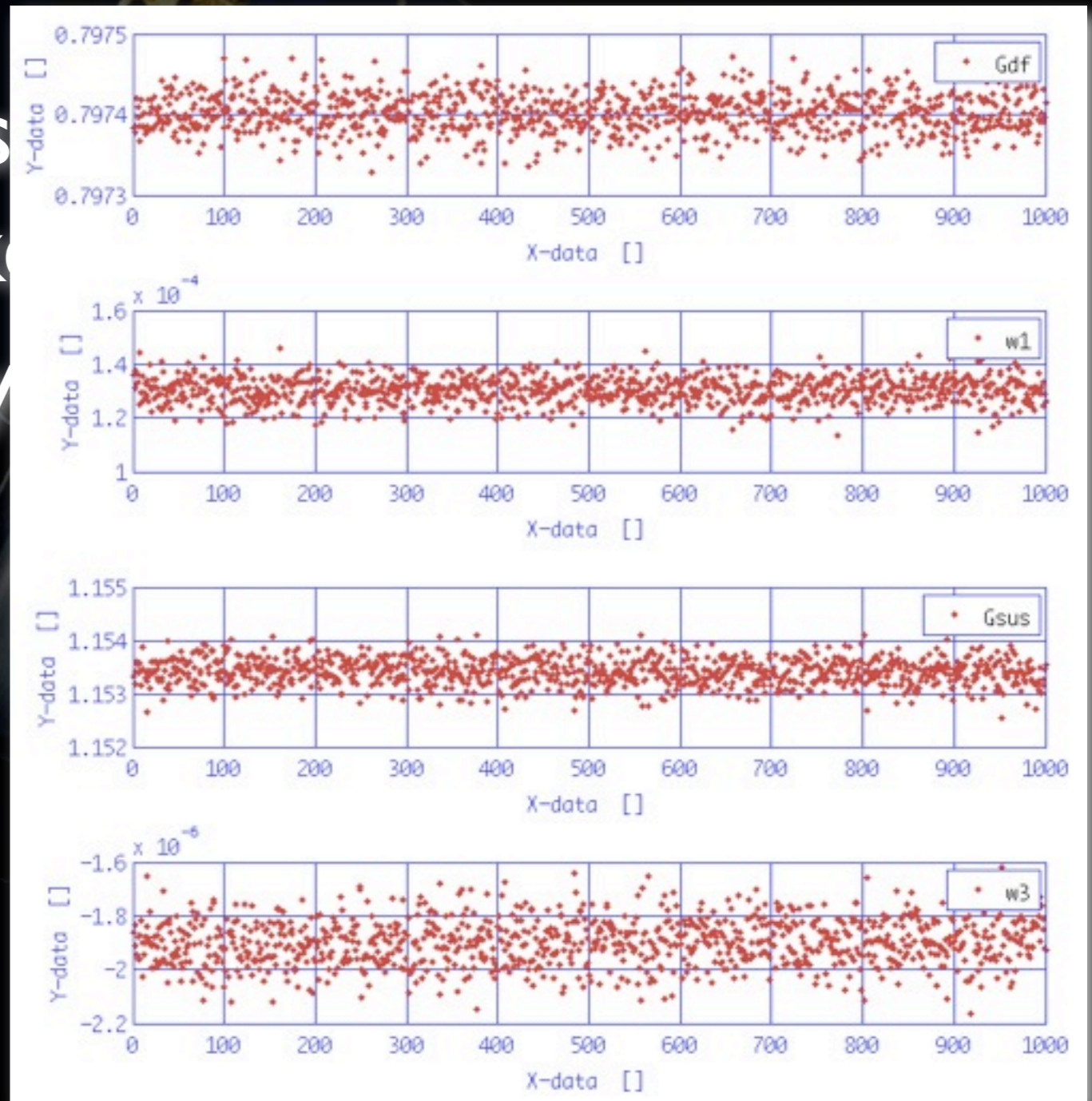


- Do our error estimates on the parameters make sense?
- Are there any systematic errors?

# Monte Carlo Analyses



- Do our error estimates for parameters make sense?
- Are there any systematic errors?

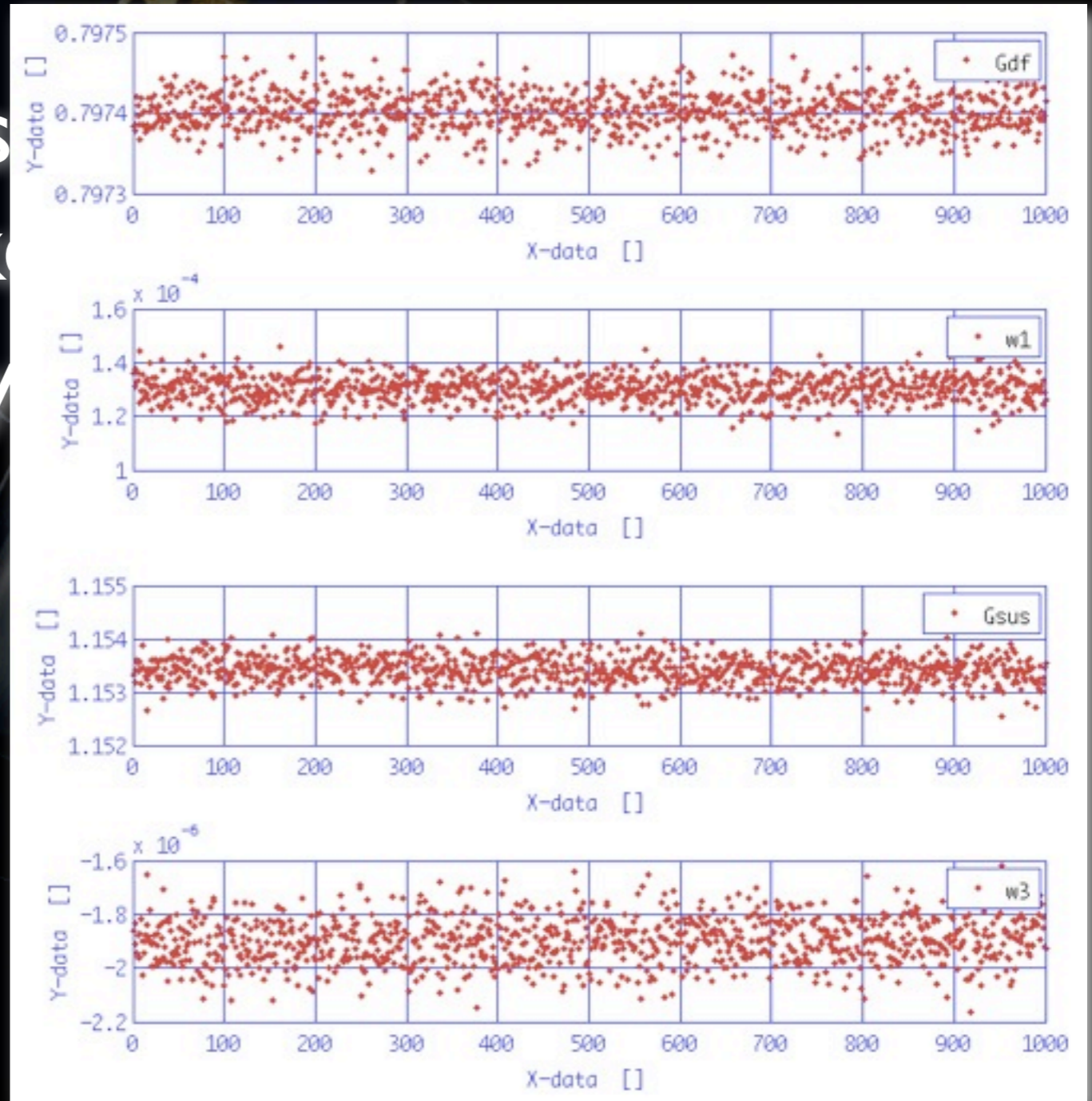
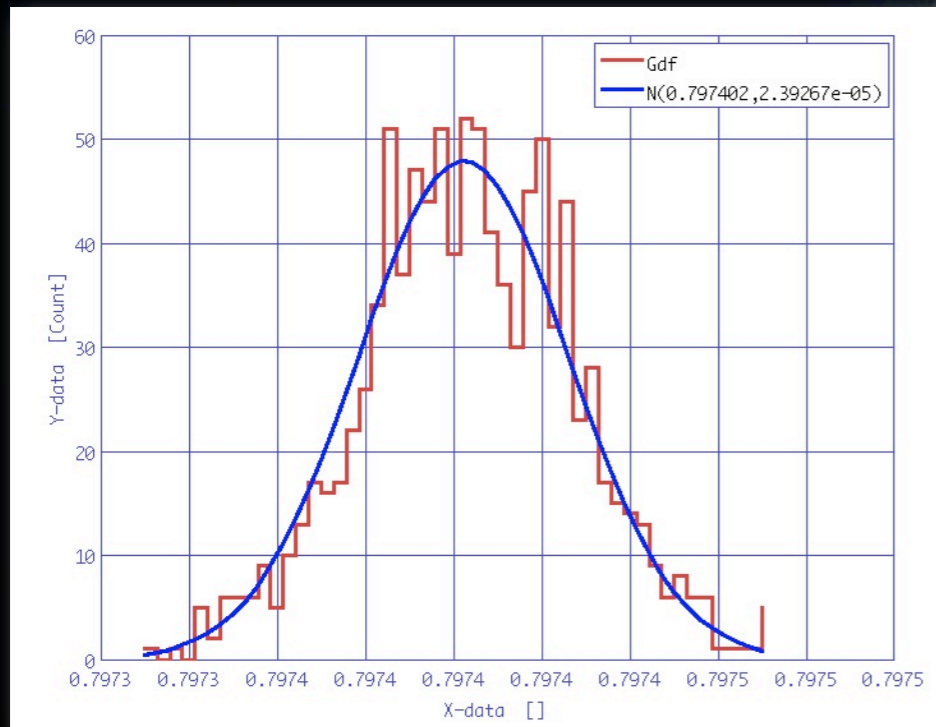




# Monte Carlo Analyses



- Do our error estimates for parameters make sense?
- Are there any systematic errors?



# Future MDCs



- MDC3
  - aim to demonstrate the proposed system-identification runs for x-axis dynamics
- Further MDCs
  - demonstrate other planned experiments
  - working through technical notes of the EMP