Université Paris Cité

Marcos Morote Balboa

An analysis of the Virgo arm cavities imperfections using Machine Learning

Let’s break the title down:

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1) Cavities imperfections

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1) Cavities imperfections
2) What is Machine Learning and why do we need it?

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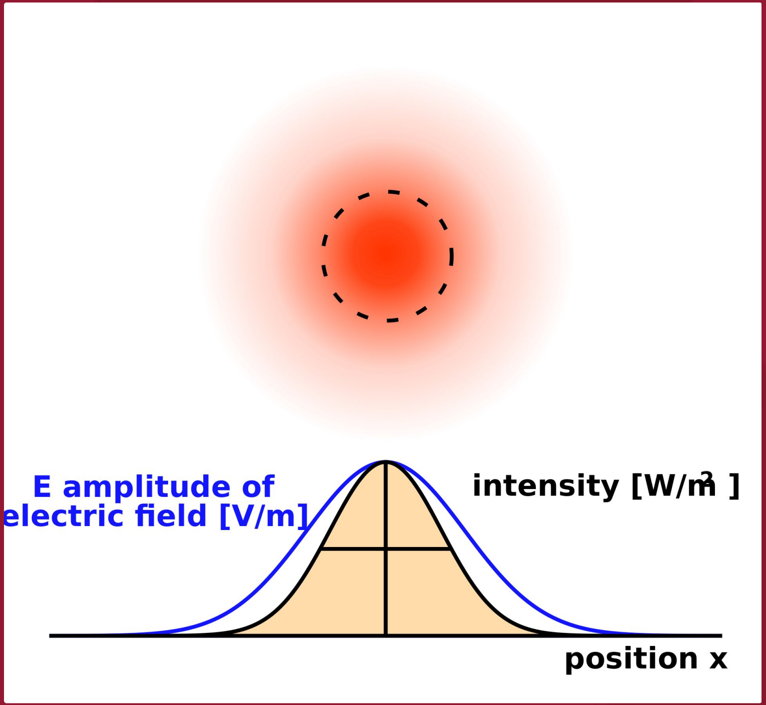
1) Cavities imperfections

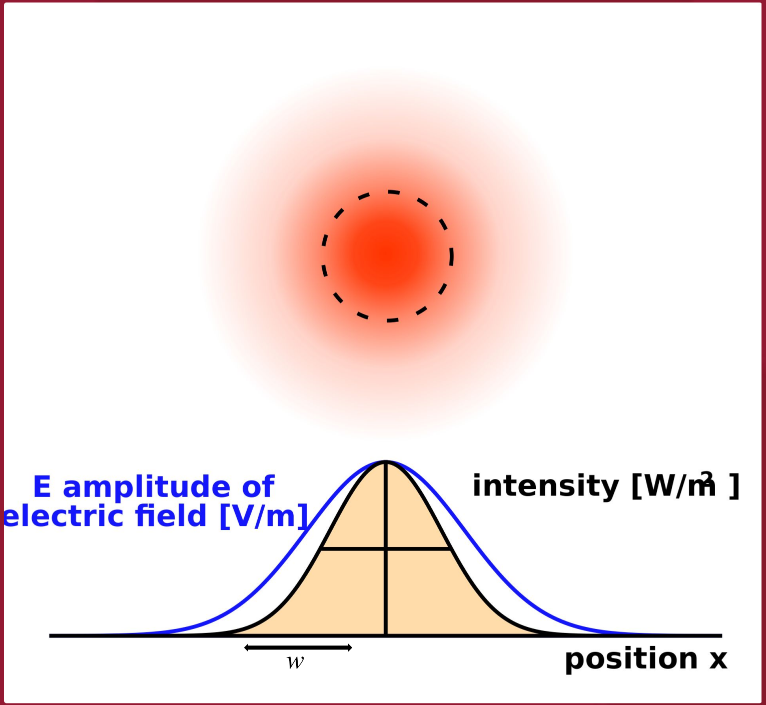
2) What is Machine Learning and why do we need it?

3) The analysis

1) Cavities imperfections: mismatching, misalignment and astigmatism

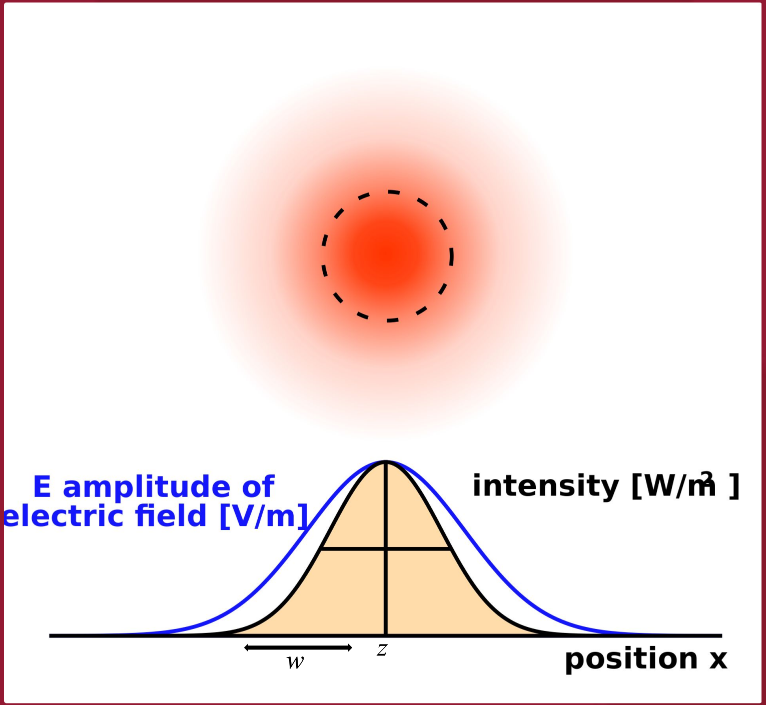


Gaussian beam



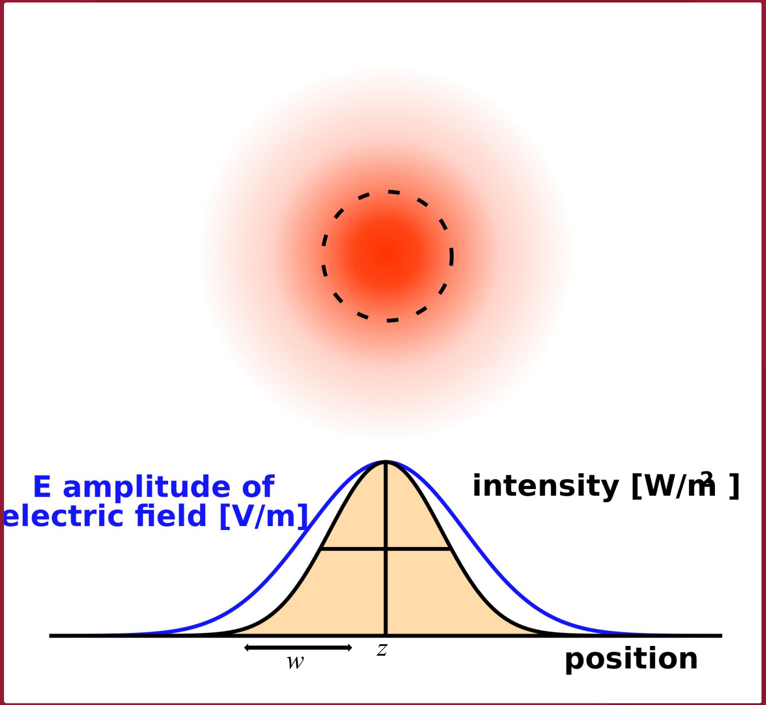
Gaussian beam

- Waist size w



Gaussian beam

- Waist size w
- Waist position z



Gaussian beam

- Waist size *w*

- Waist position *z*

⟶ The cavity has the same parameters (*target*)!

If the parameters match

If the parameters match $\longrightarrow$ the beam is *coupled* to the cavity

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If the parameters **don't** match

If the parameters match $\longrightarrow$ the beam is *coupled* to the cavity

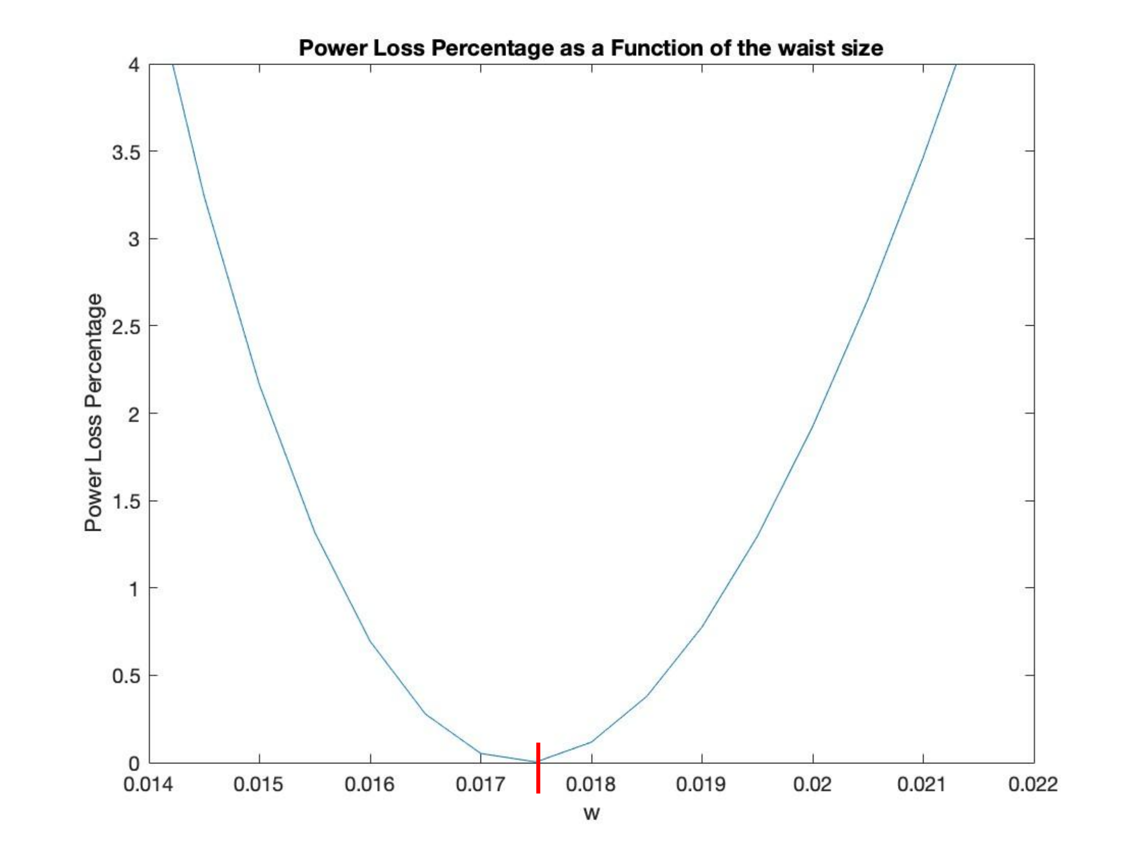
If the parameters **don't** match $\longrightarrow$ *mode mismatch*

If the parameters match $\longrightarrow$ the beam is *coupled* to the cavity

If the parameters **don't** match $\longrightarrow$ *mode mismatch*

$\longrightarrow$ power loss

Fabry-Perot mismatching and misalignment

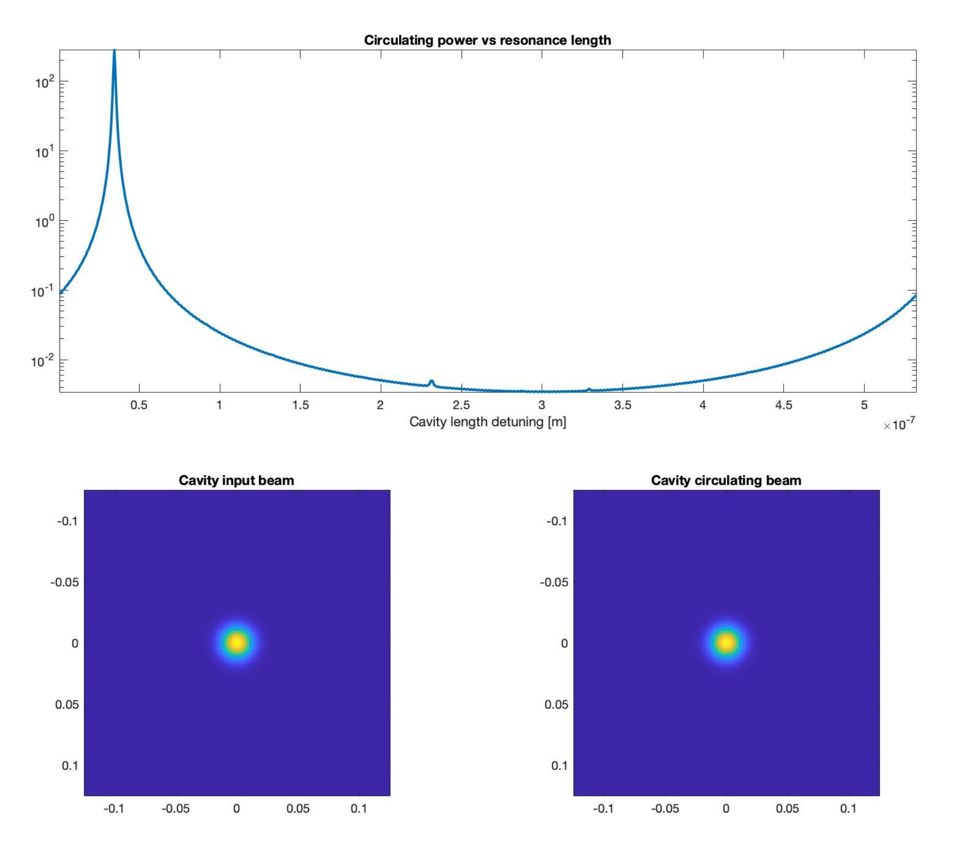


Target parameters

Target parameters

$\longrightarrow$ *Fundamental mode* of the cavity

Fabry-Perot mismatching and misalignment



Target parameters

$\longrightarrow$ *Fundamental mode* of the cavity

Different parameters

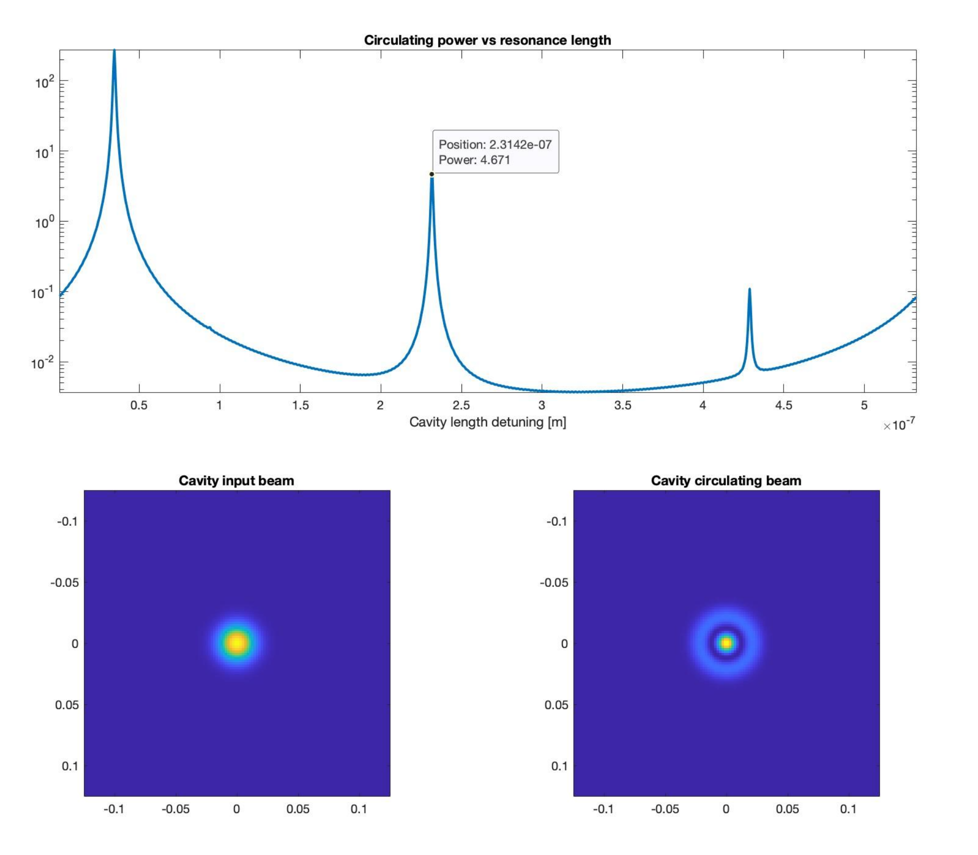
Target parameters

⟶ *Fundamental mode* of the cavity

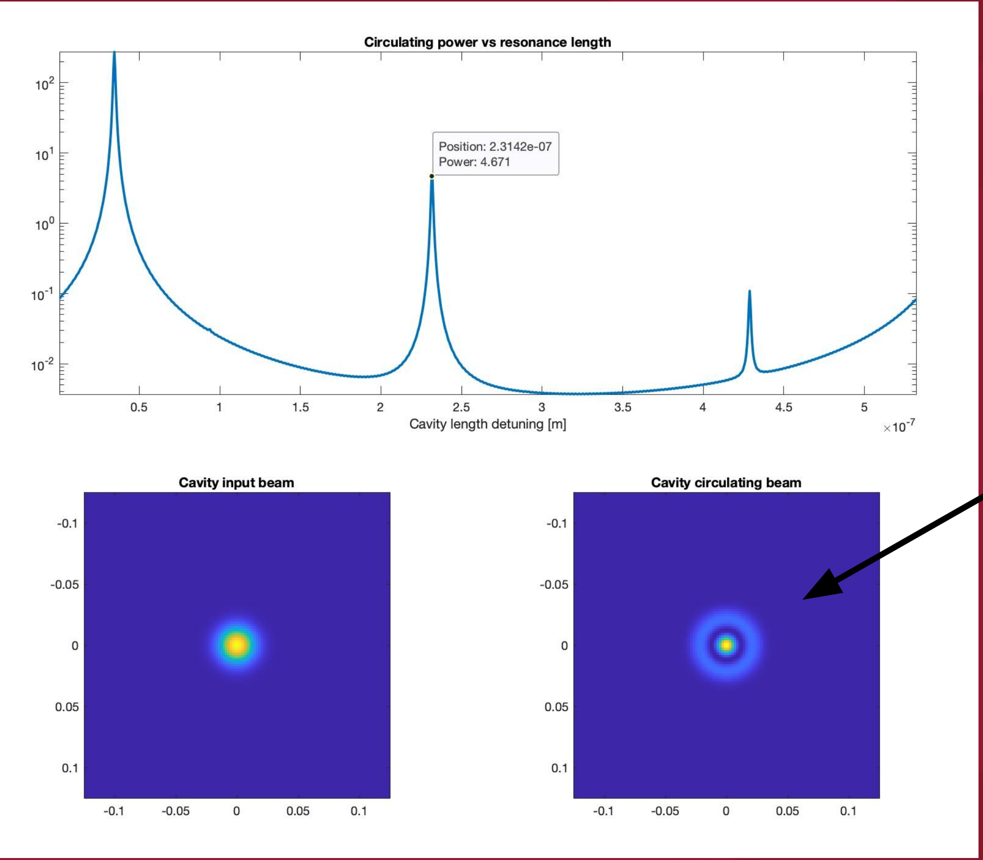
Different parameters

⟶ *High Order Modes* (HOM)

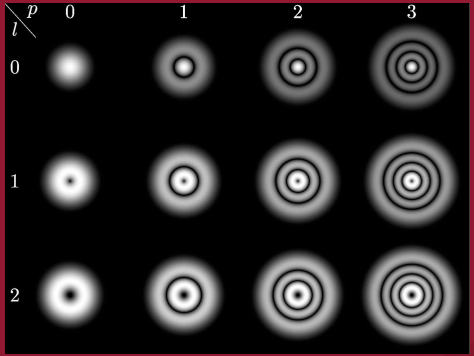
Fabry-Perot mismatching and misalignment



Fabry-Perot mismatching and misalignment



Laguerre-Gauss mode



<u>Misalignment</u>: input axis not aligned to cavity axis

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- Mirrors tilted in same direction

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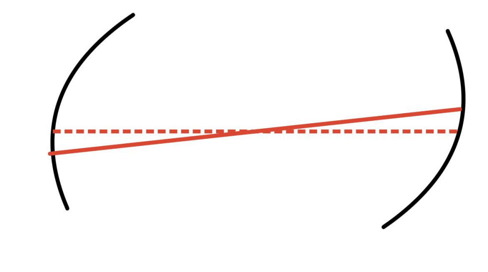
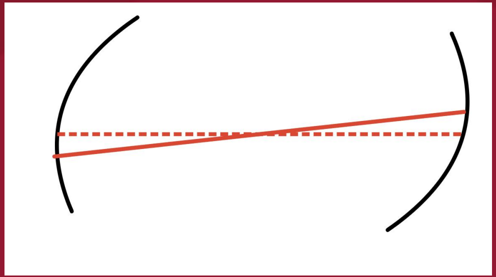
- Mirrors tilted in same direction ⟶ *tilt*



<u>Misalignment</u>: input axis not aligned to cavity axis

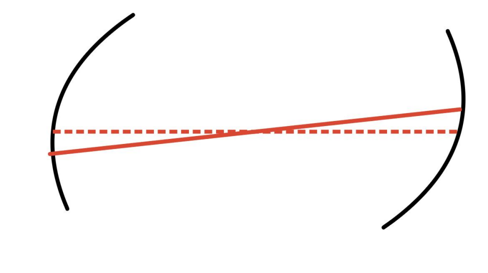
- Mirrors tilted in same direction ⟶ *tilt*



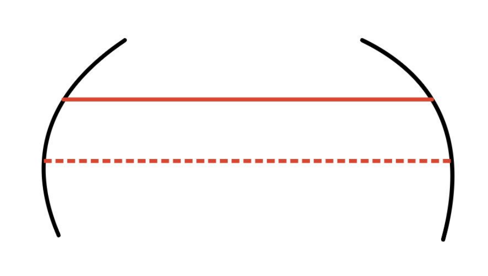
- Mirrors tilted in opposite direction

<u>Misalignment</u>: input axis not aligned to cavity axis

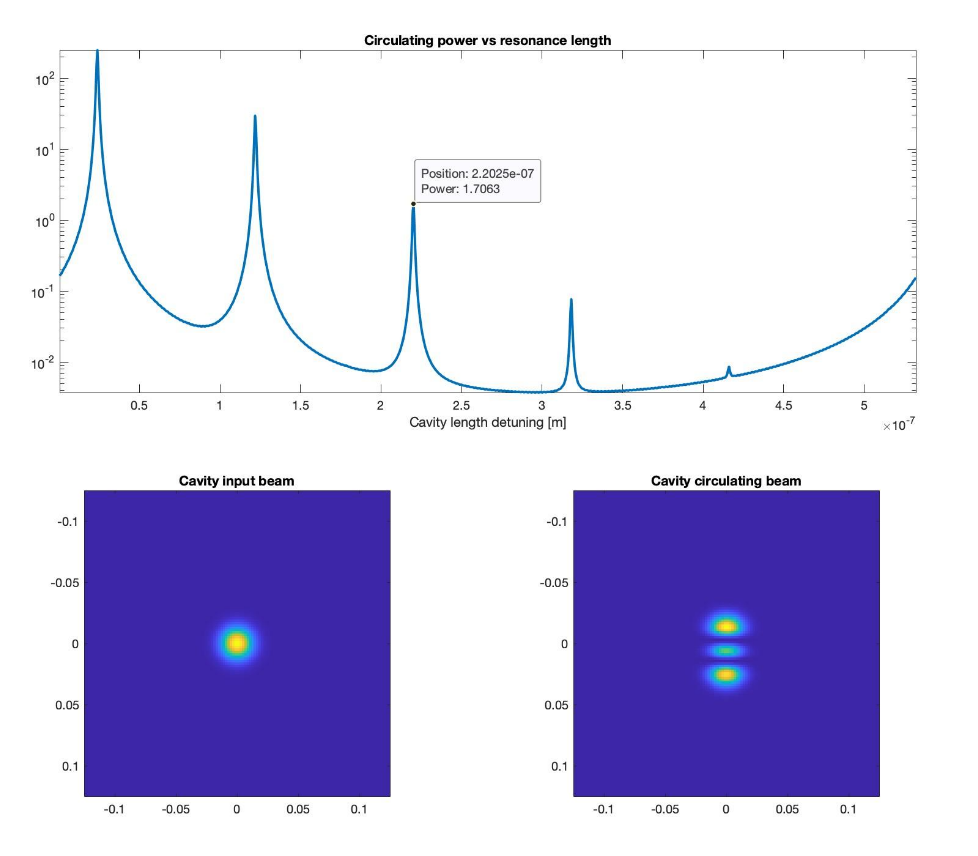
- Mirrors tilted in same direction ⟶ *tilt*



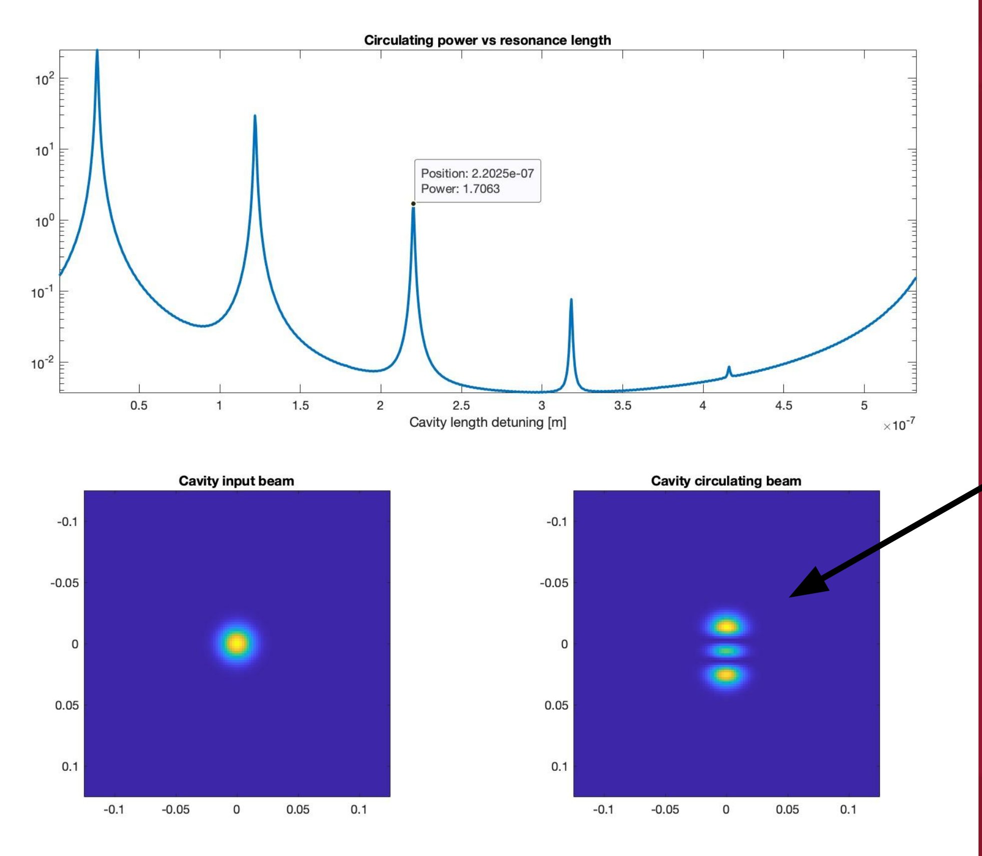
- Mirrors tilted in opposite direction ⟶ *shift*



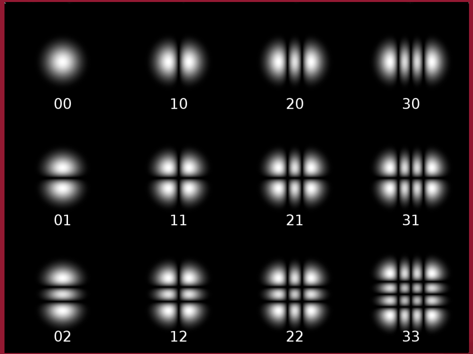
Fabry-Perot mismatching and misalignment



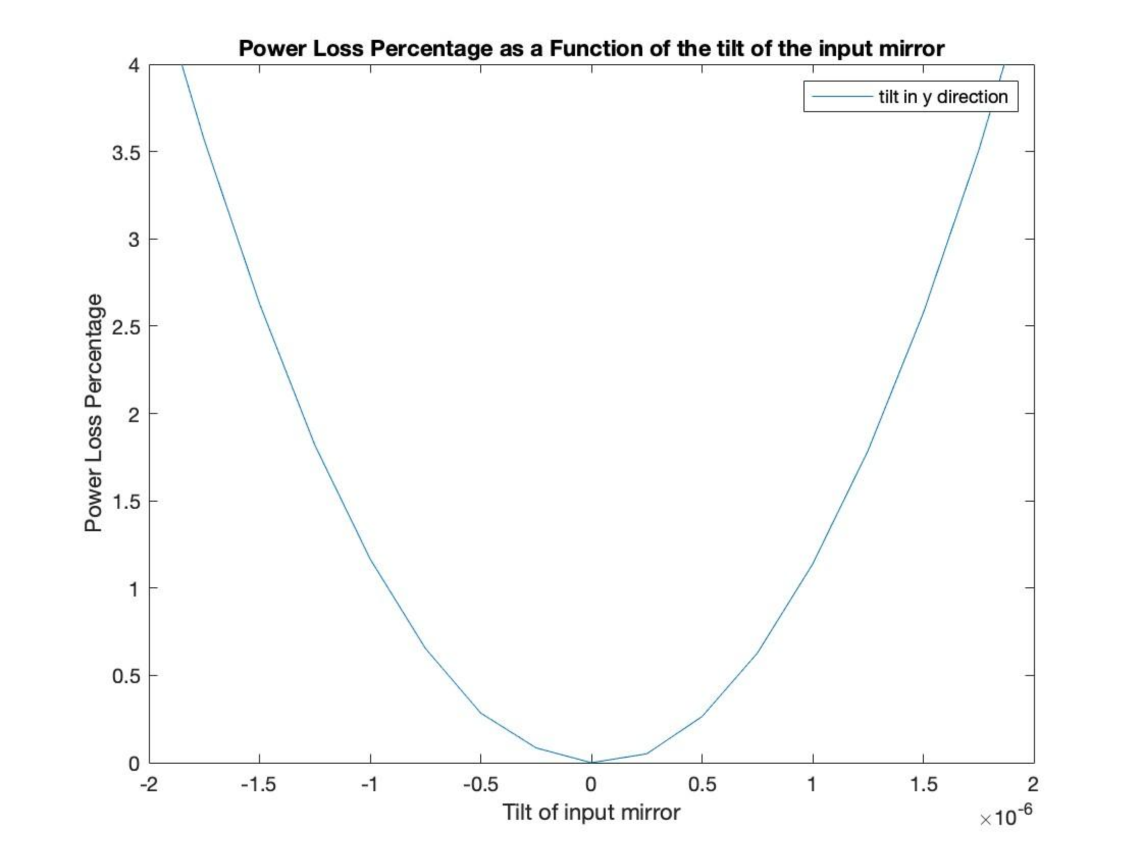
Fabry-Perot mismatching and misalignment



Hermite-Gauss mode



Fabry-Perot mismatching and misalignment



Astigmatism: asymmetric beam

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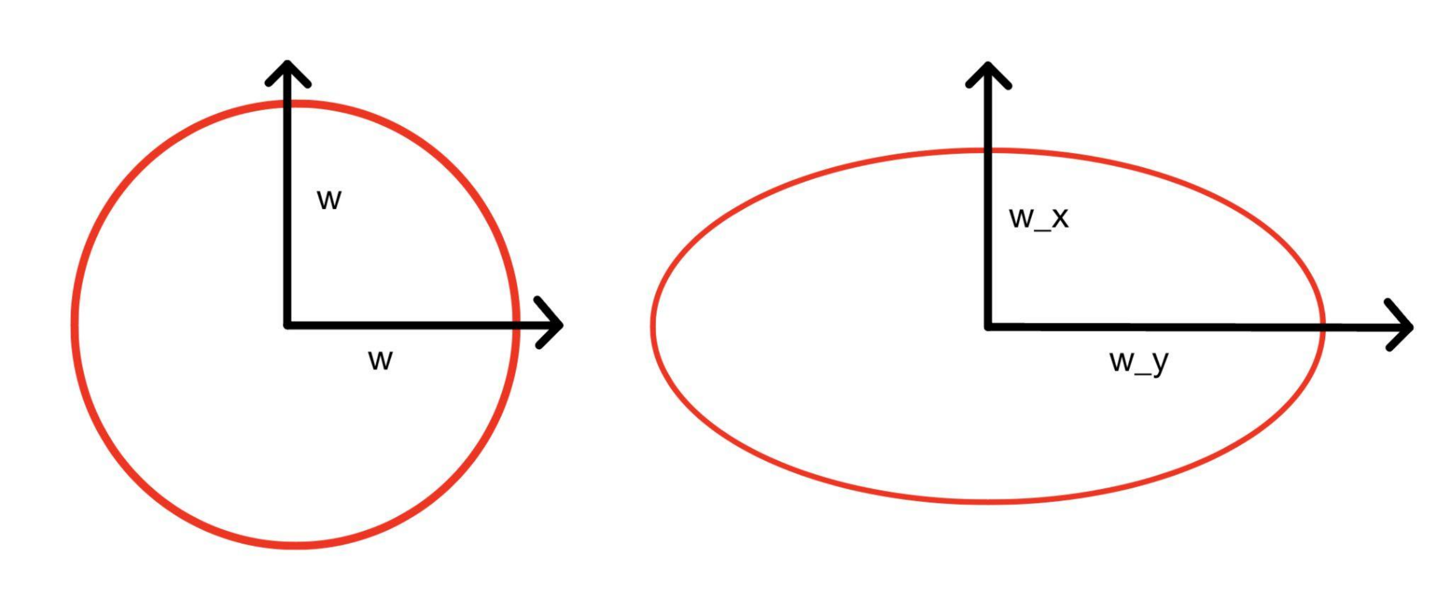
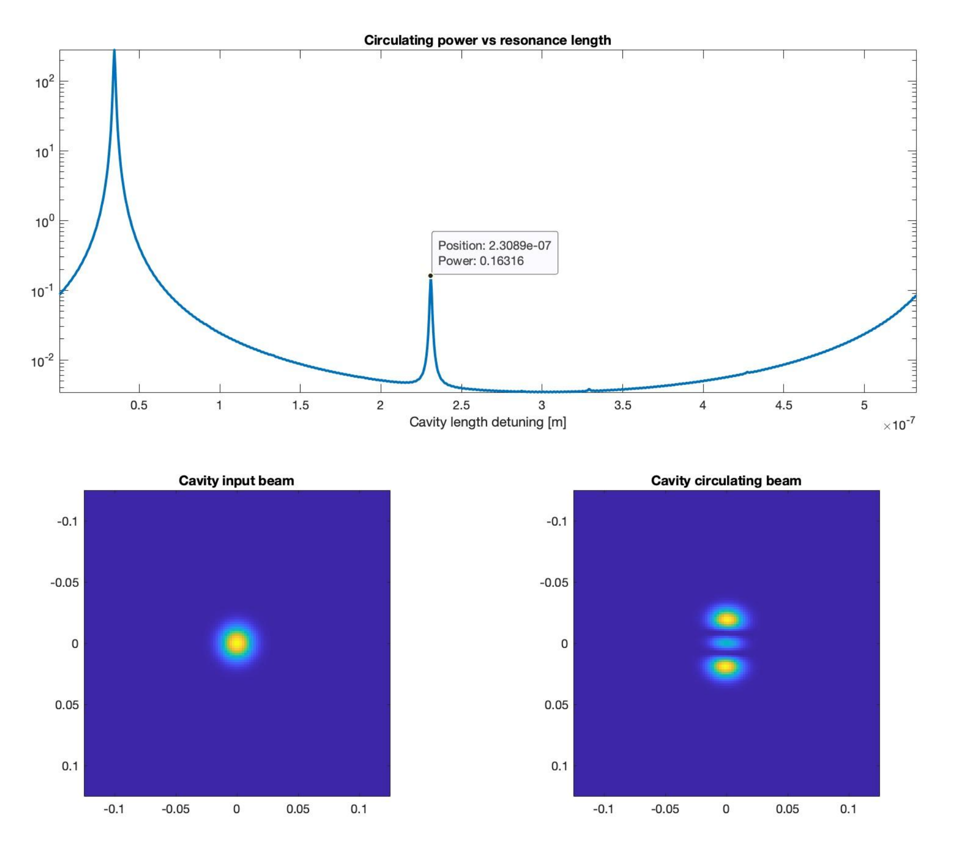
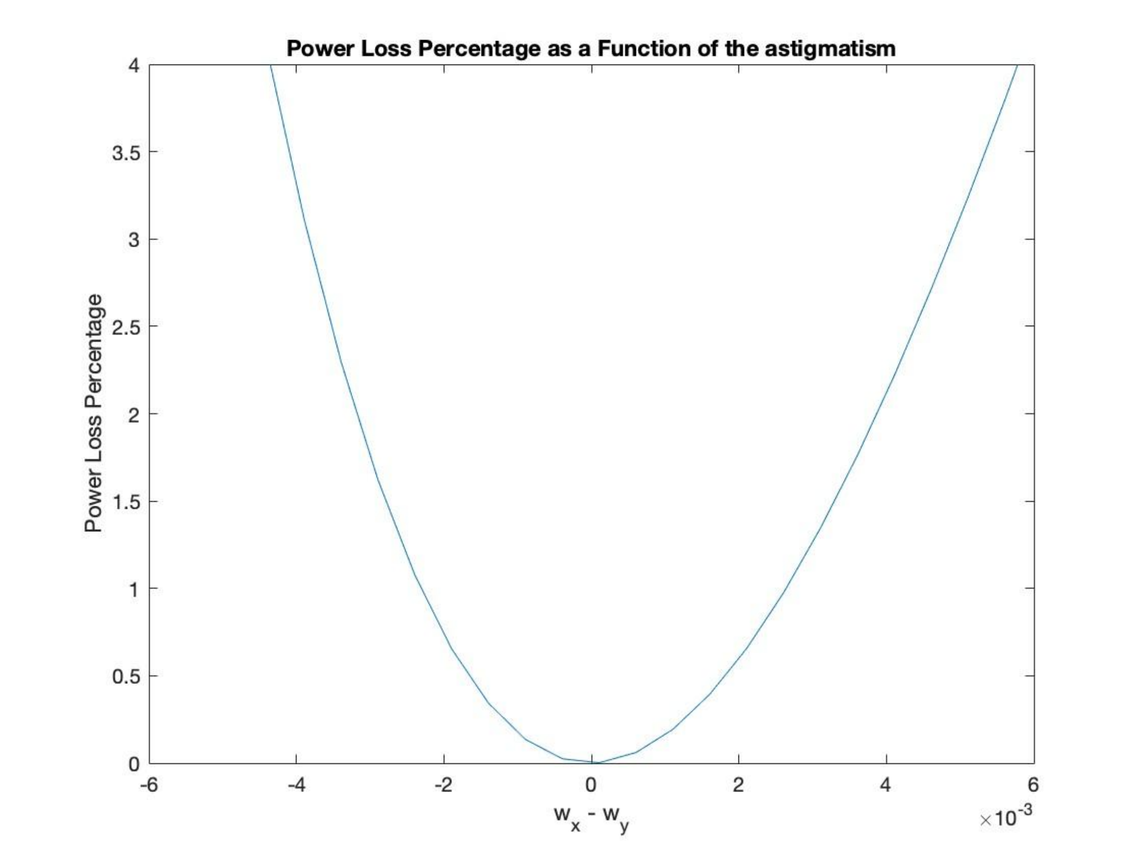


Fabry-Perot mismatching and misalignment



Fabry-Perot mismatching and misalignment



Power loss

Power loss

Different parameters

Power loss

Different parameters

Mode mismatch

Power loss

Different parameters

Mode mismatch

Laguerre-Gauss modes

Power loss

Different parameters

Tilt in the mirrors

Mode mismatch

Laguerre-Gauss modes

Power loss

Different parameters

Tilt in the mirrors

Mode mismatch

Misalignment

Laguerre-Gauss modes

Power loss

Different parameters

Tilt in the mirrors

Mode mismatch

Misalignment

Laguerre-Gauss modes

Hermite-Gauss modes

Fabry-Perot mismatching and misalignment

Power loss

Different parameters → Mode mismatch → Laguerre-Gauss modes

Tilt in the mirrors → Misalignment → Hermite-Gauss modes

Asymmetric beam

Fabry-Perot mismatching and misalignment

Power loss

Different parameters

Tilt in the mirrors

Asymmetric beam

Mode mismatch

Misalignment

Astigmatism

Laguerre-Gauss modes

Hermite-Gauss modes

Power loss

Different parameters

Mode mismatch

Laguerre-Gauss modes

Tilt in the mirrors

Misalignment

Hermite-Gauss modes

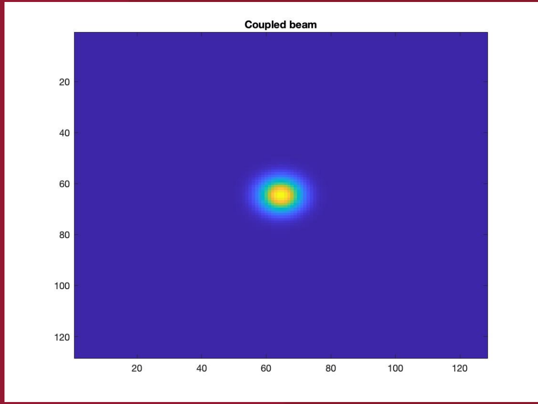
Asymmetric beam

Astigmatism

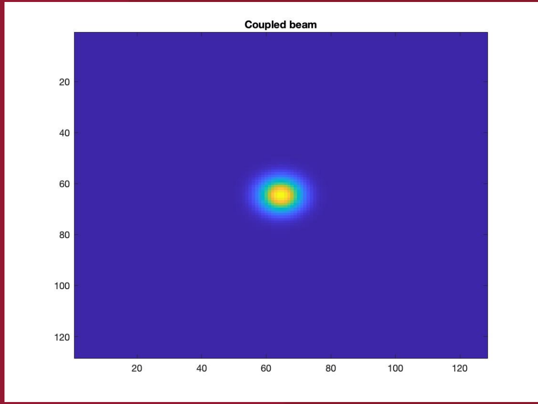
Combined modes

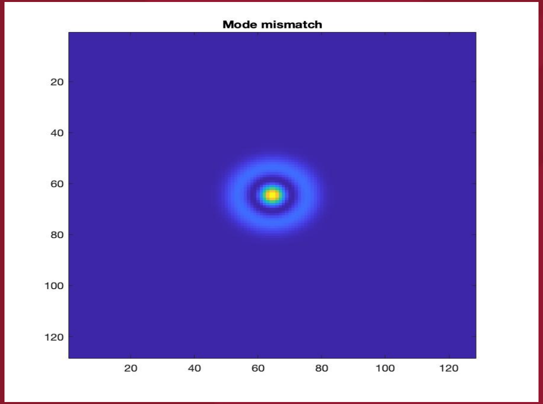
Fabry-Perot mismatching and misalignment

Fabry-Perot mismatching and misalignment

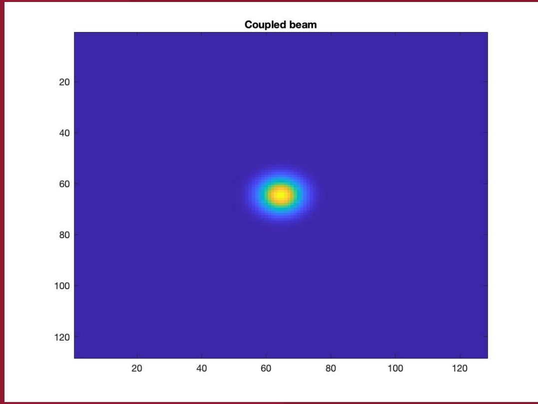


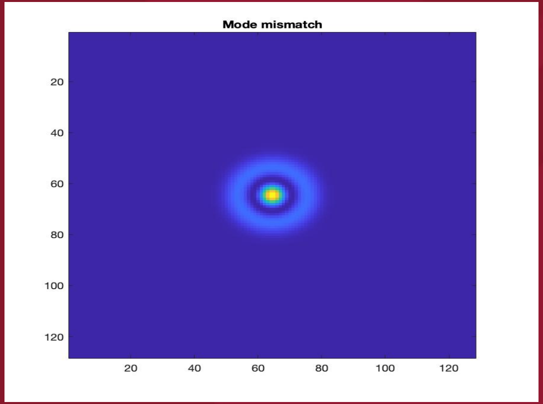
Fabry-Perot mismatching and misalignment

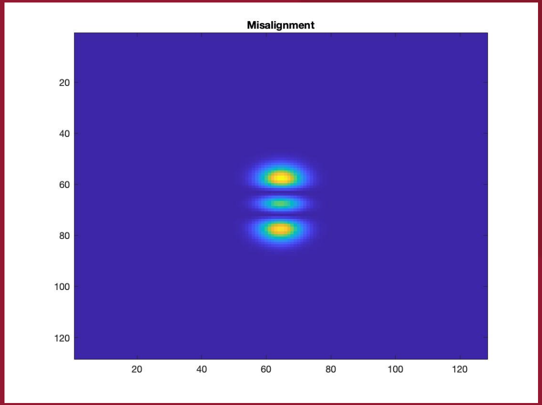




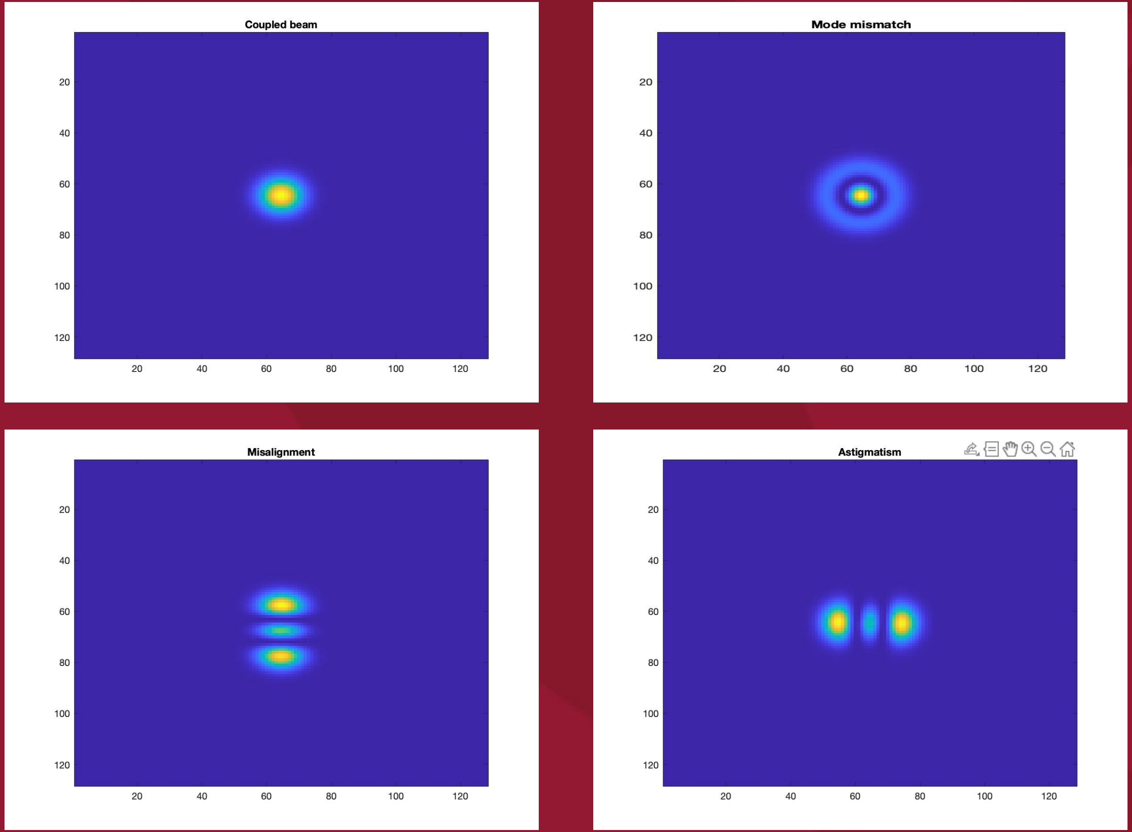
Fabry-Perot mismatching and misalignment



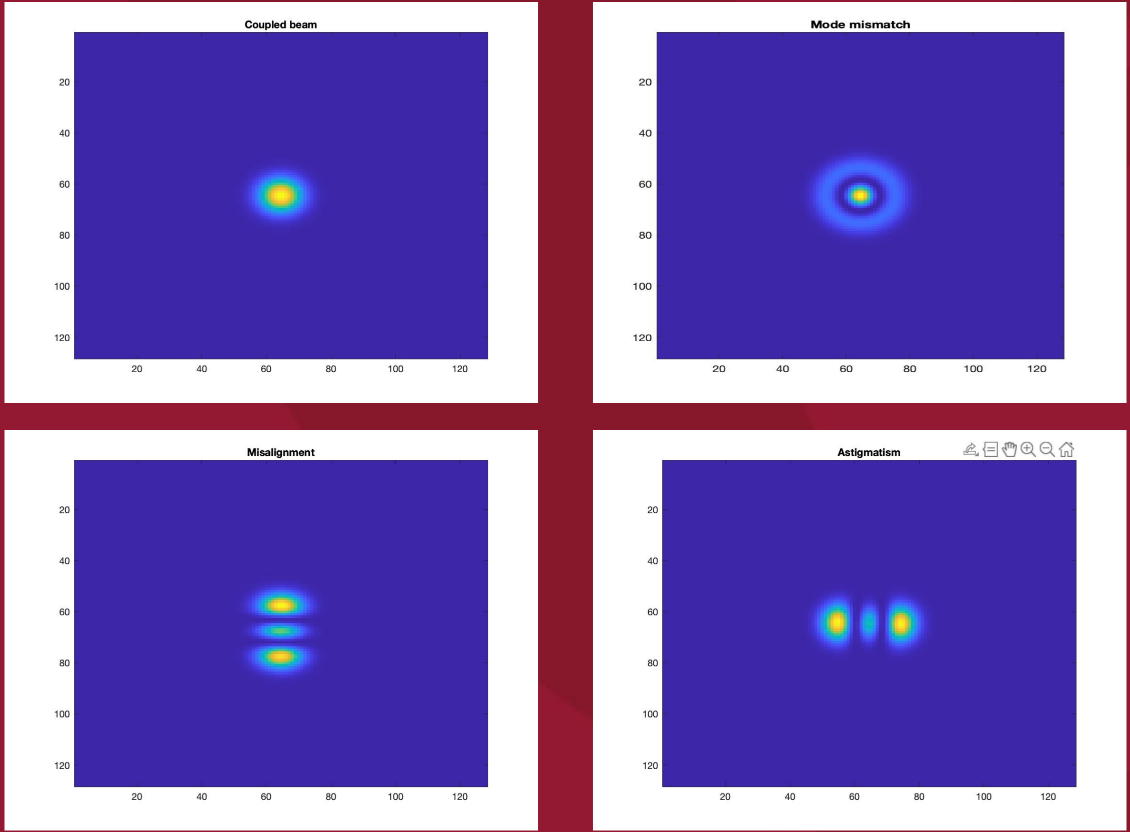




Fabry-Perot mismatching and misalignment

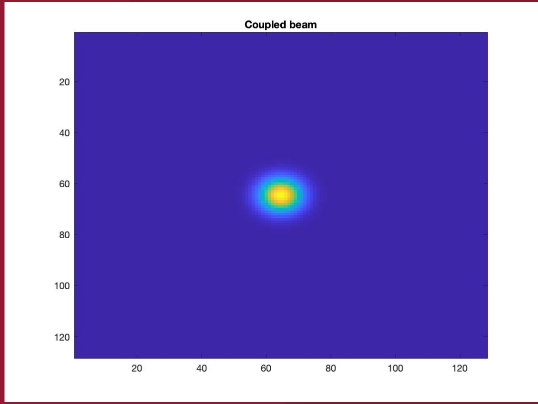


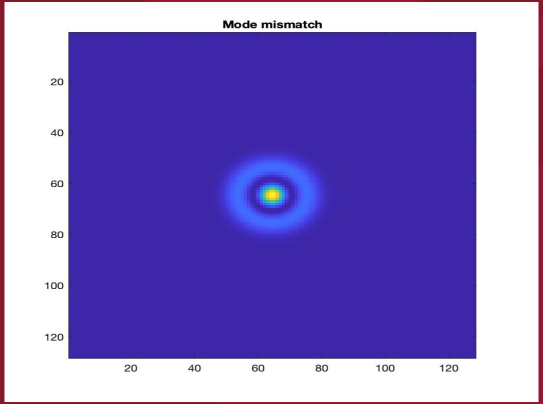
Fabry-Perot mismatching and misalignment

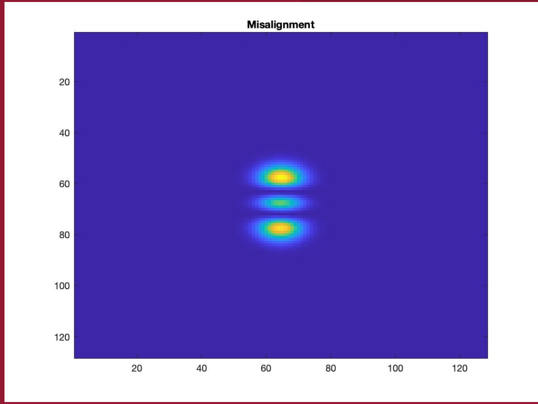


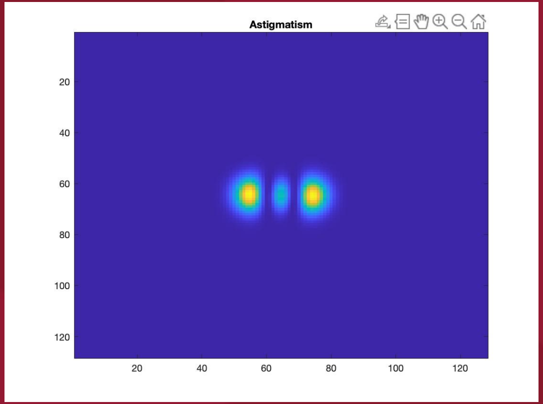
→ We can easily tell the difference, but not the exact contribution of each parameter

Fabry-Perot mismatching and misalignment









→ We can easily tell the difference, but not the exact contribution of each parameter

→ How then?

2) What is Machine Learning and why do we need it?

Machine learning (ML) is a field devoted to understanding and building methods that let machines "learn".

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Machine learning algorithms build a <u>model</u> based on sample data, known as training data, in order to make predictions or decisions without being explicitly programmed to do so.

- "Complex fit" (with too many parameters)

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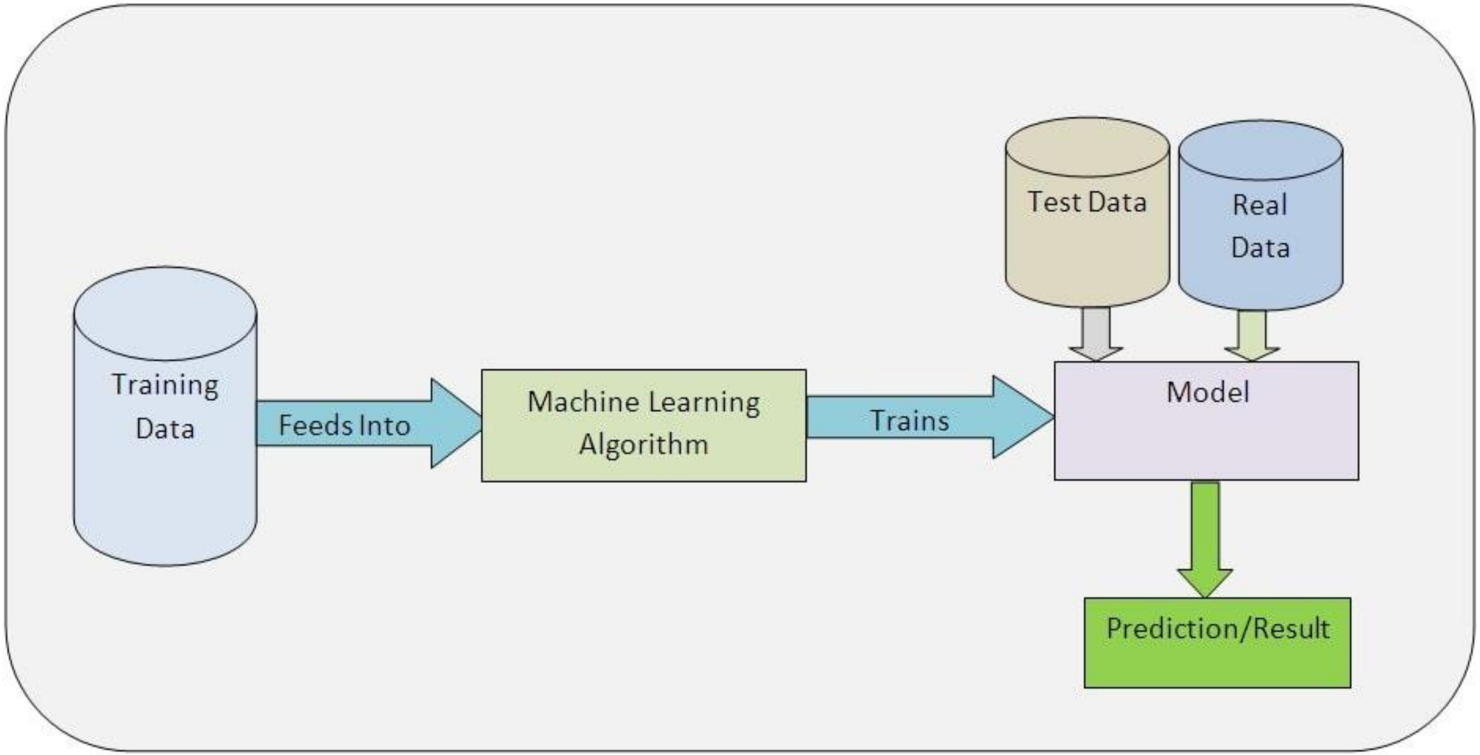
- Useful for evolving systems

- "Complex fit" (with too many parameters)

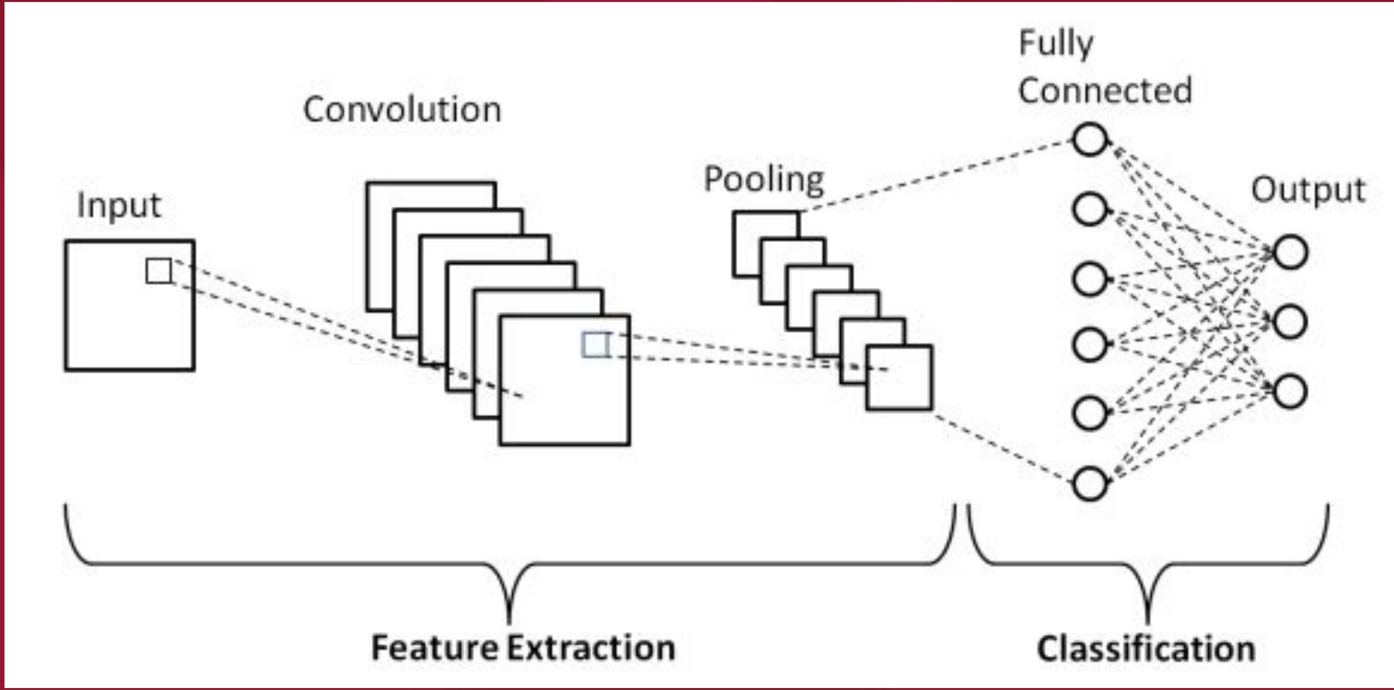
- Useful for evolving systems

- Can handle nonlinearity

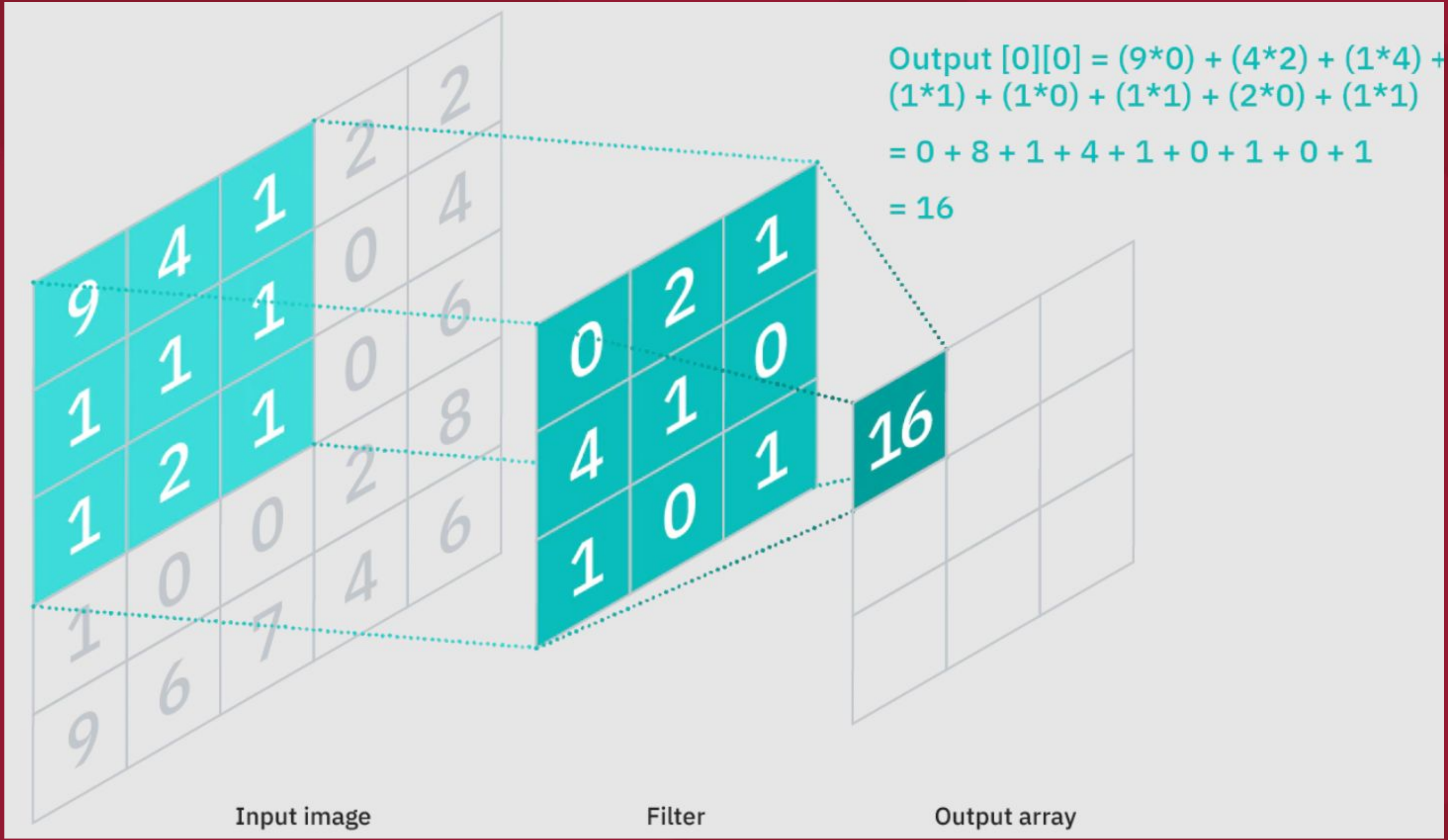
What is Machine Learning and why do we need it?



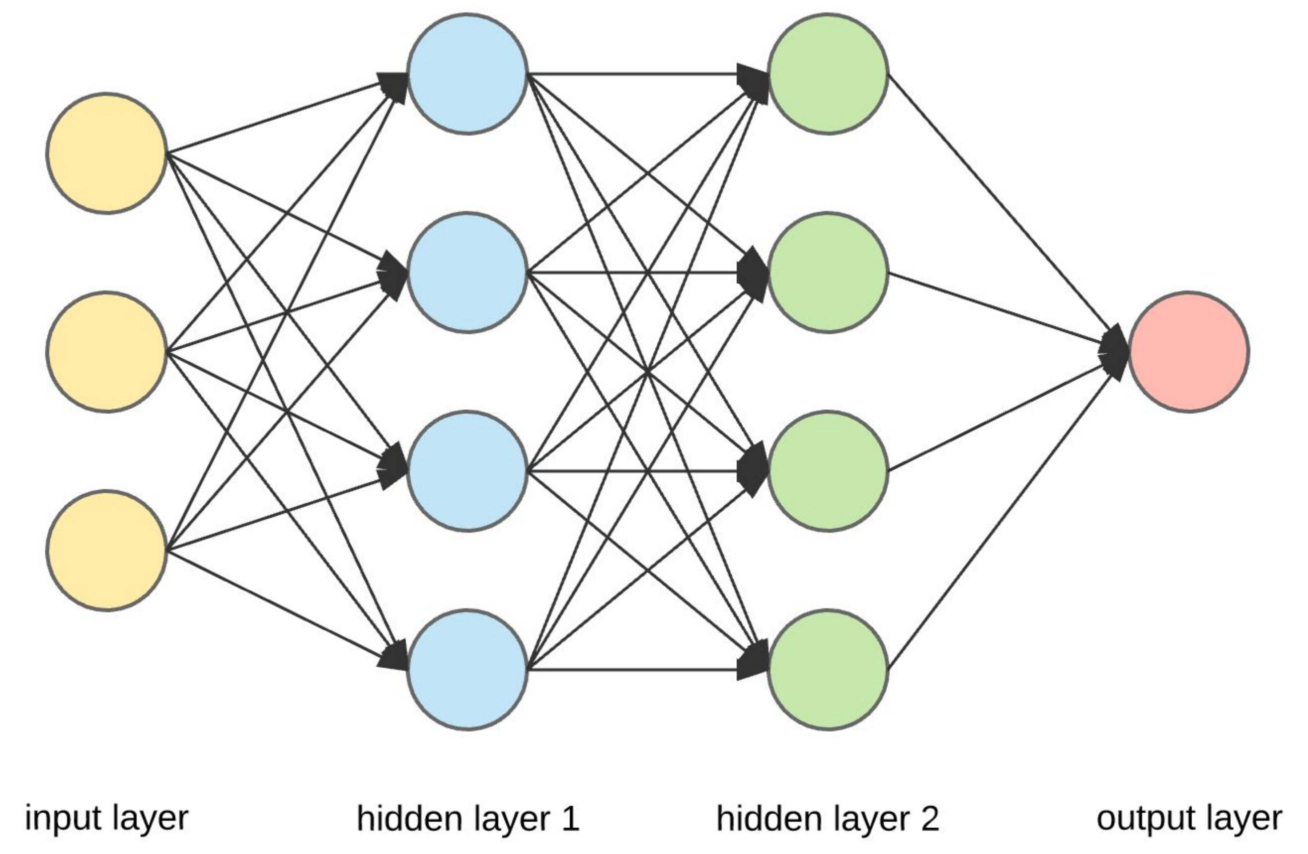
A Simple Machine Learning Pipeline Explanation


Convolution
Fully
Connected
Input
Pooling
Output
Feature Extraction
Classification

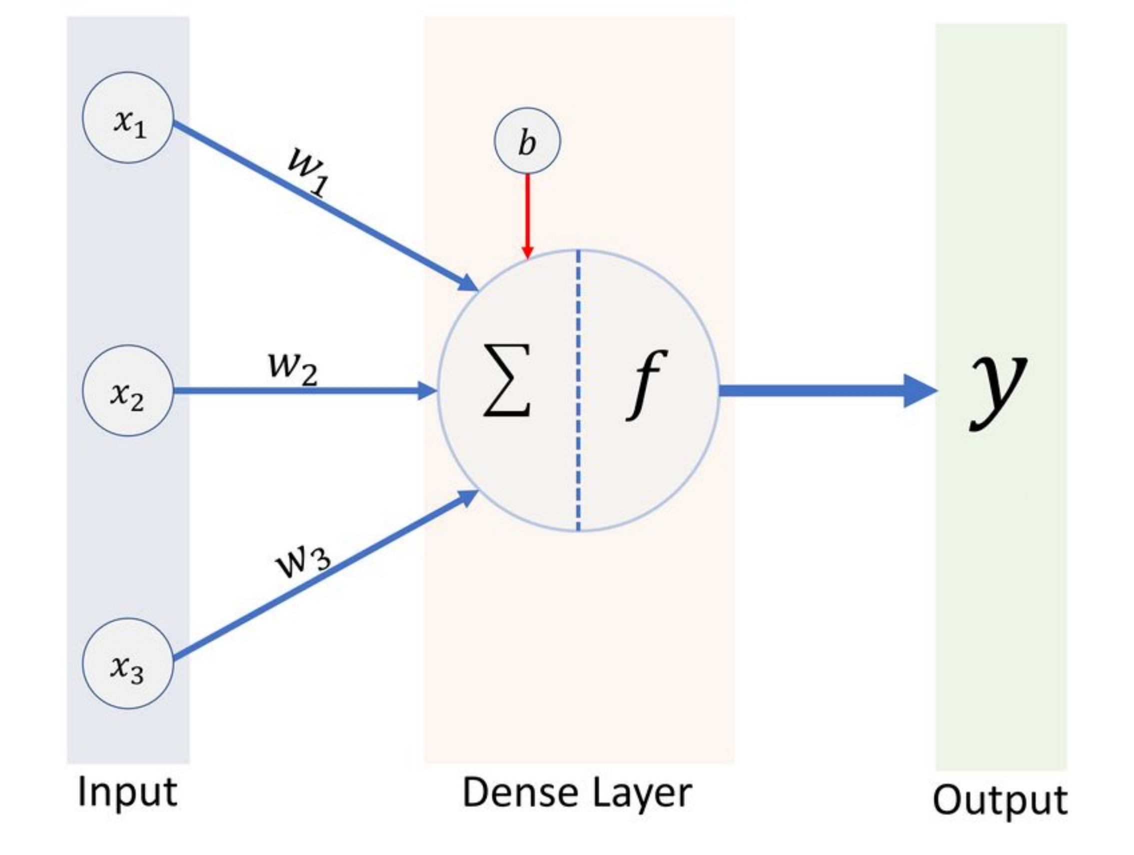
What is Machine Learning and why do we need it?



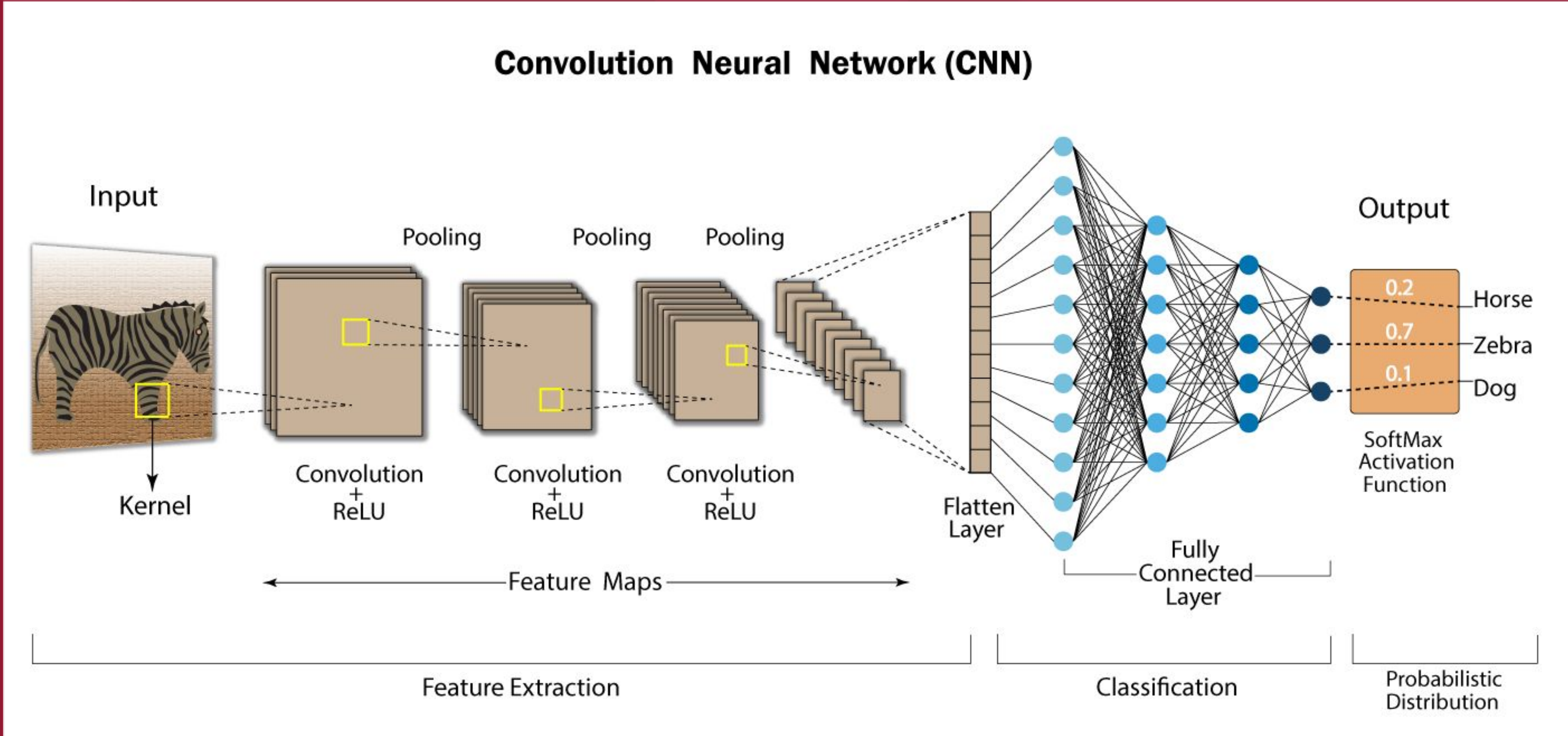
What is Machine Learning and why do we need it?



What is Machine Learning and why do we need it? 21



Weighted sum + activation function


Convolution Neural Network (CNN)
Input
Kernel
Pooling
Pooling
Pooling
Convolution + ReLU
Convolution + ReLU
Convolution + ReLU
Feature Maps
Flatten Layer
Fully Connected Layer
Output
0.2
0.7
0.1
Horse
Zebra
Dog
SoftMax Activation Function
Feature Extraction
Classification
Probabilistic Distribution

3) The analysis

- “Machine Learning for Quantum-Enhanced Gravitational-Wave Observatories” - Chris Whittle, Ge Yang, Matthew Evans, Lisa Barsotti (05/2023)

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- “Predicting the motion of a high-Q pendulum subject to seismic perturbations using machine learning” - Nicolas Heimann, Jan Petermann, Daniel Hartwig, Roman Schnabel, Ludwig Mathey

Input:

Input: Cavity scan

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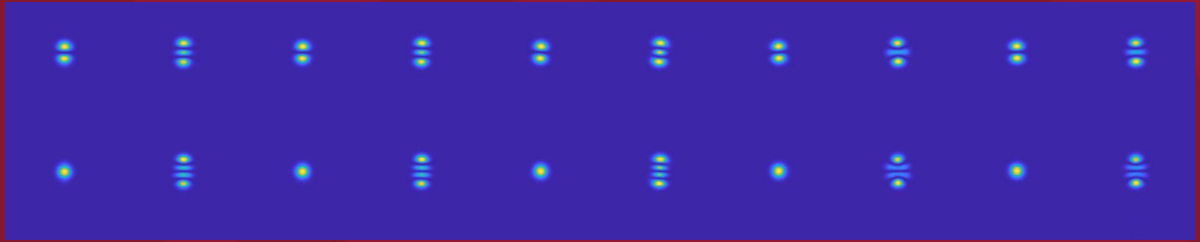

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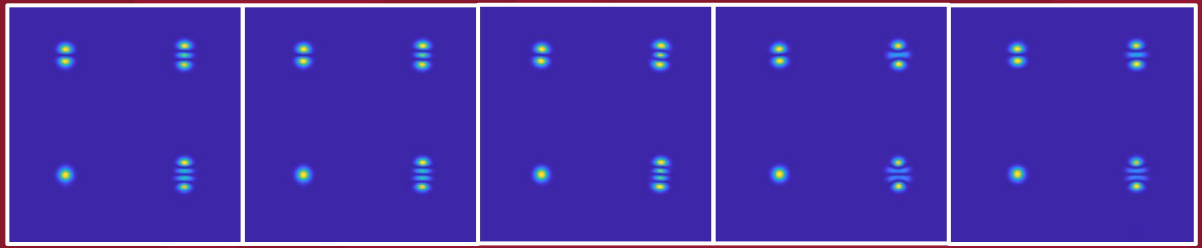
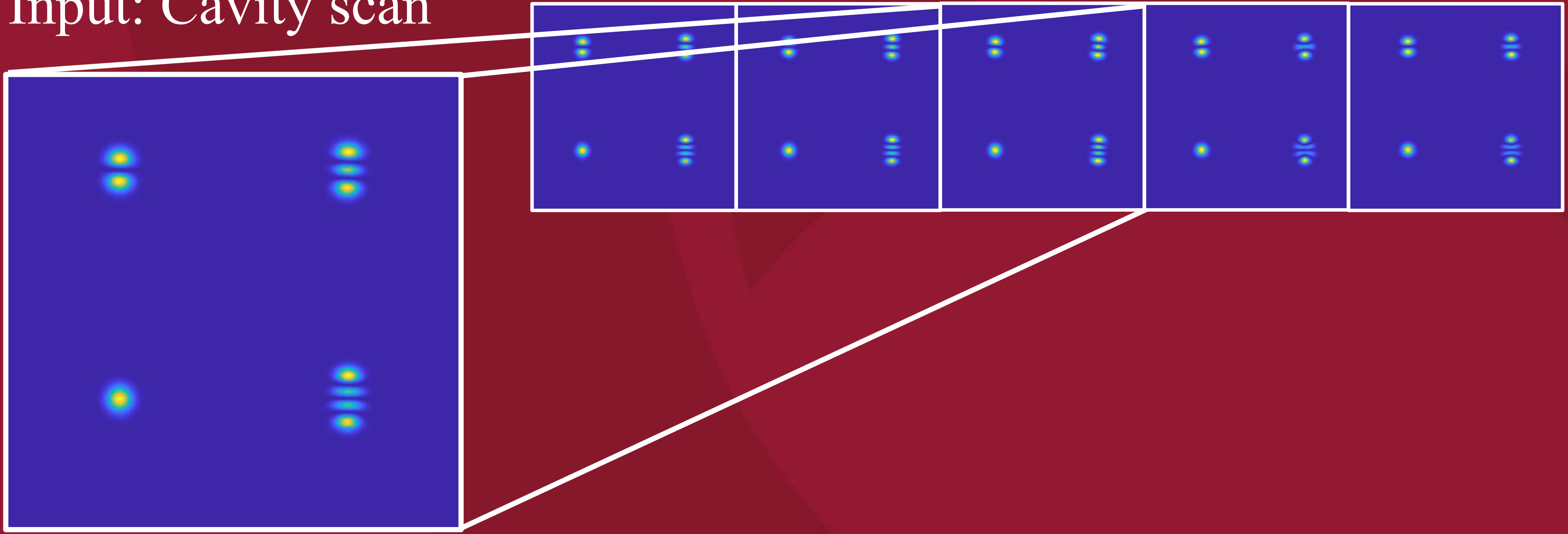


Input: Cavity scan



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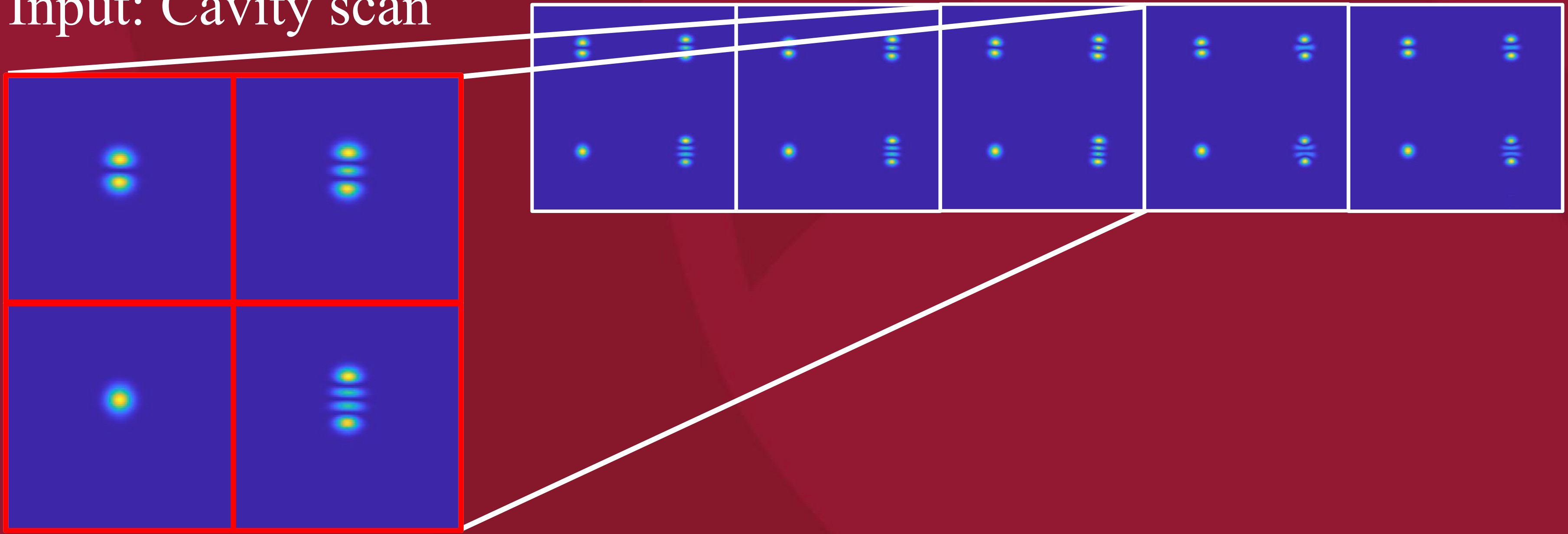
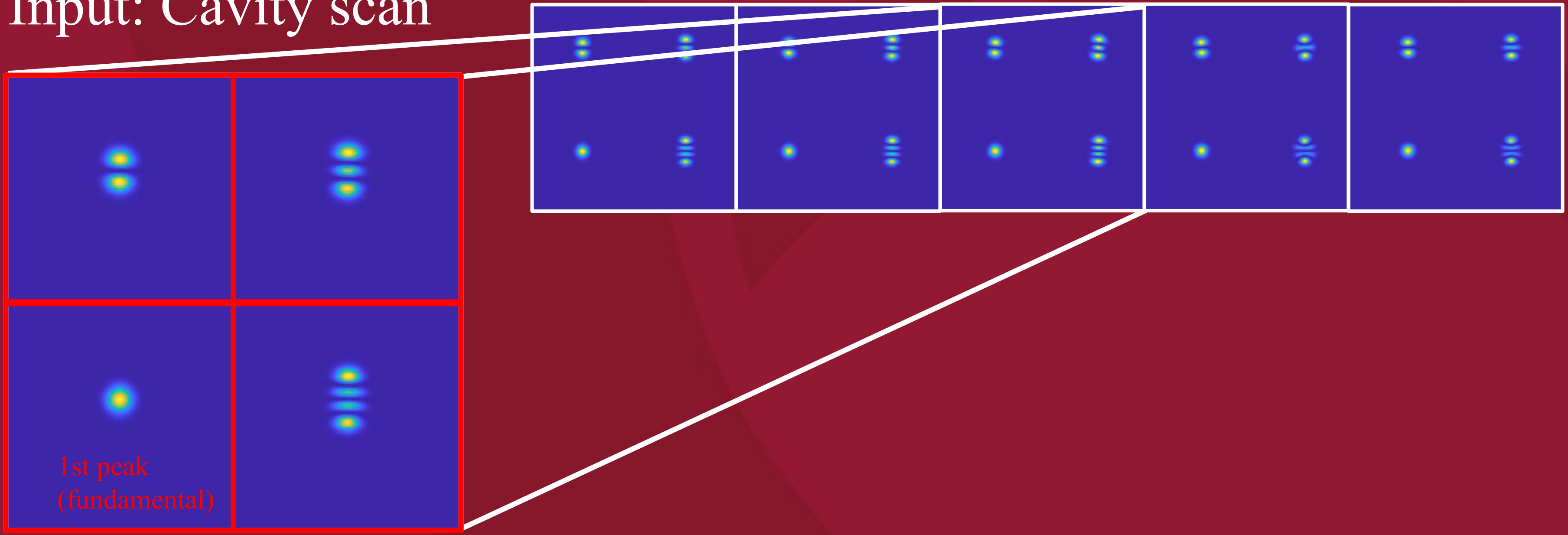


Input: Cavity scan



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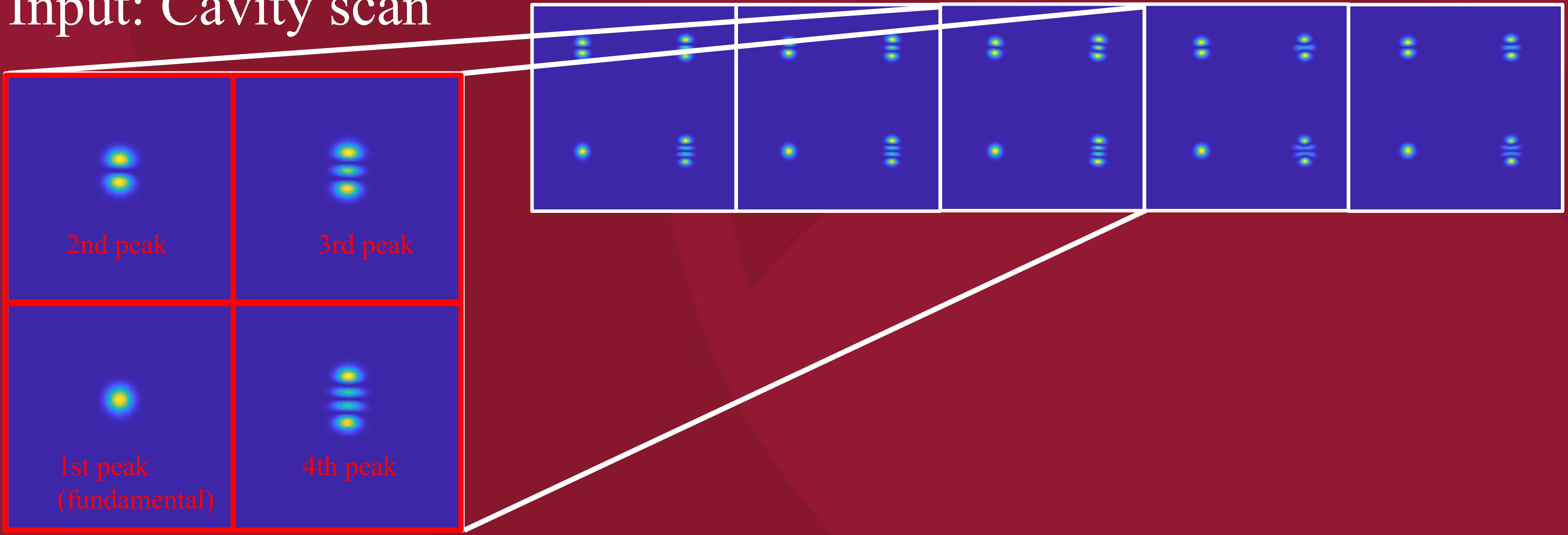

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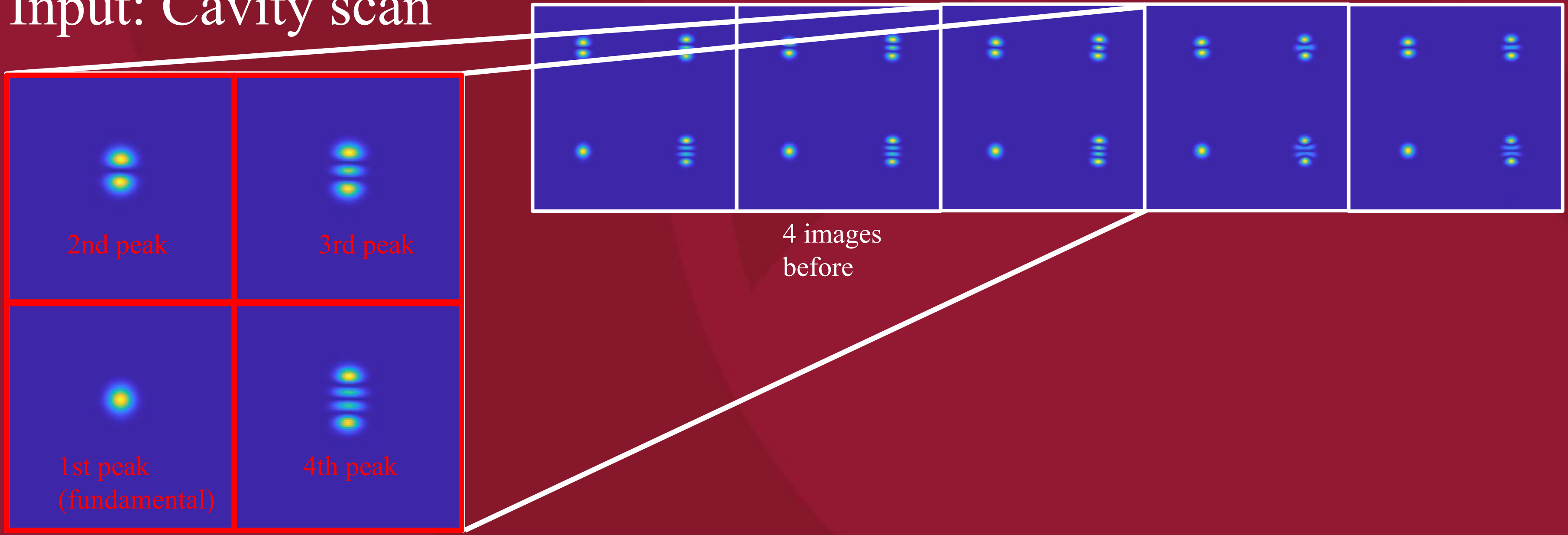

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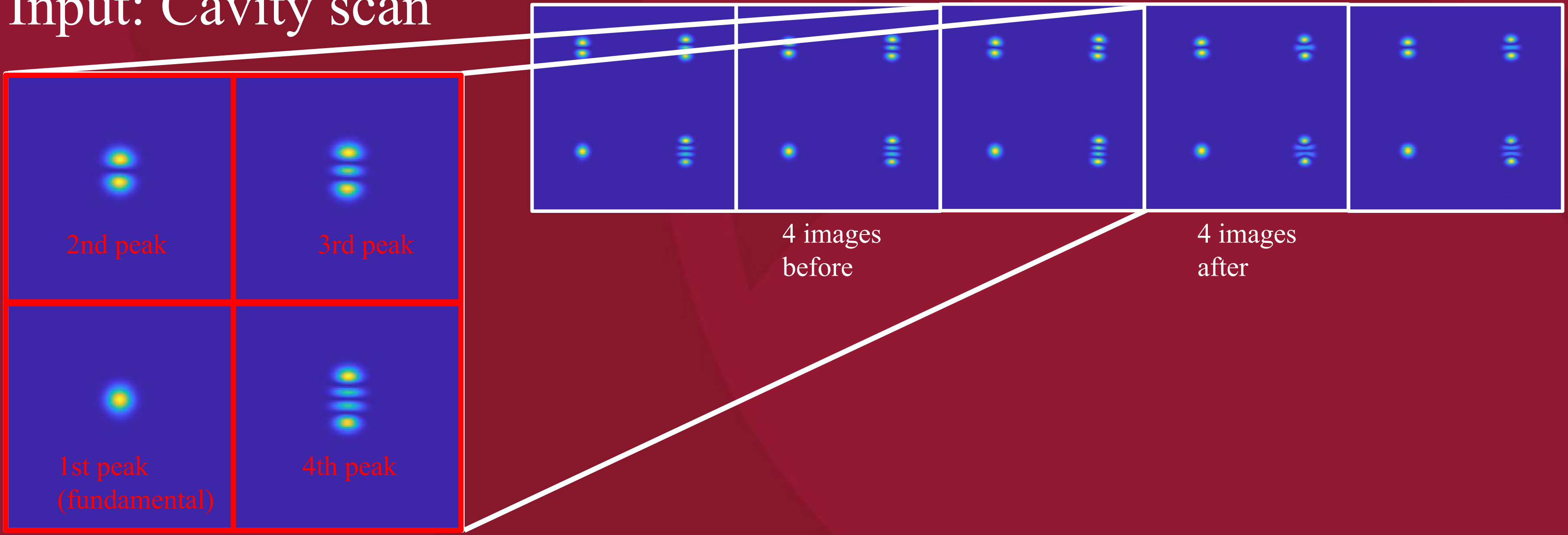

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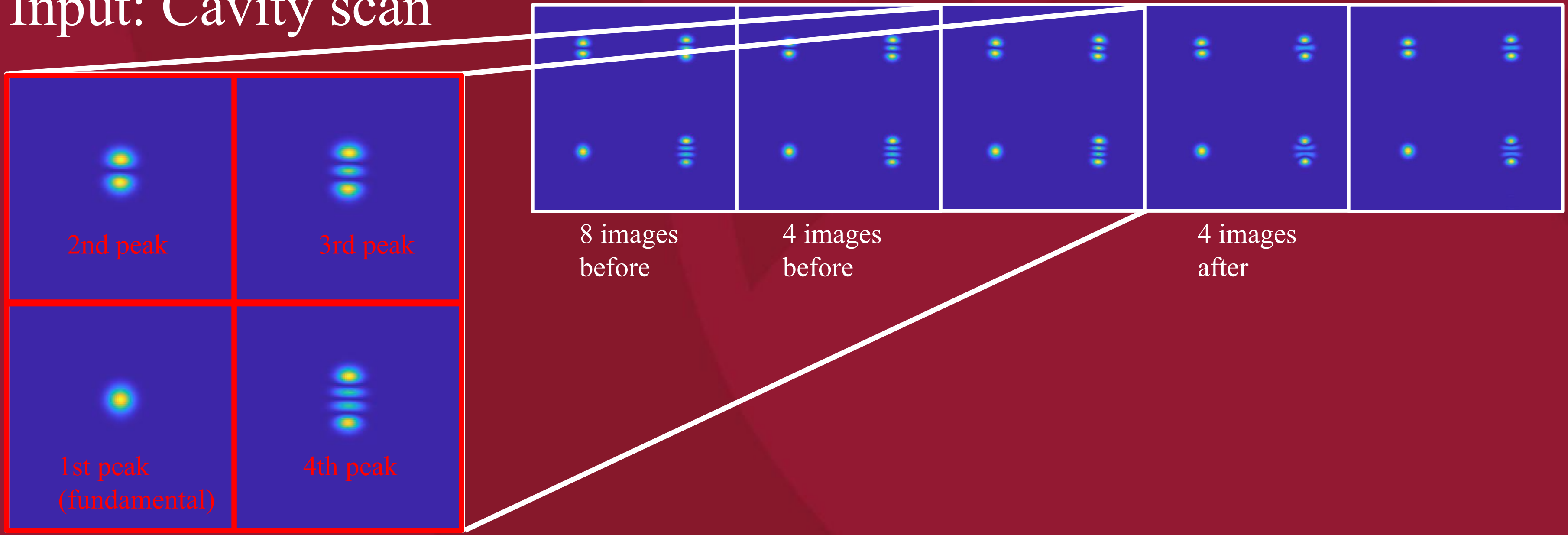
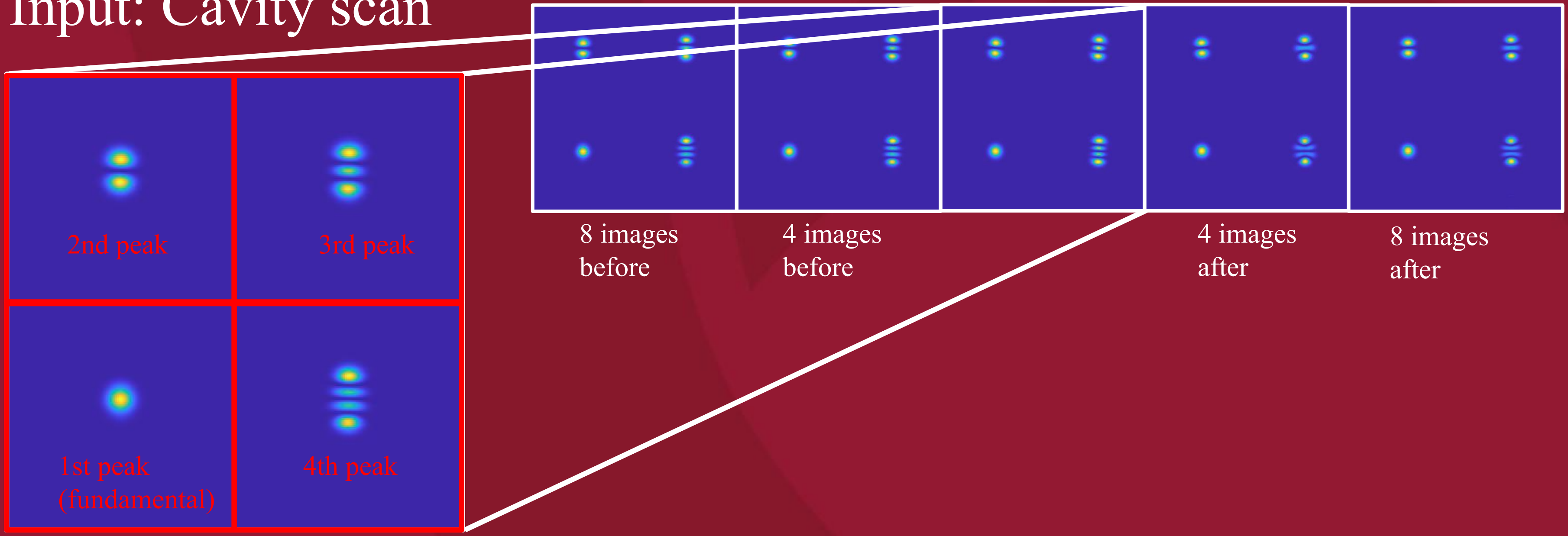
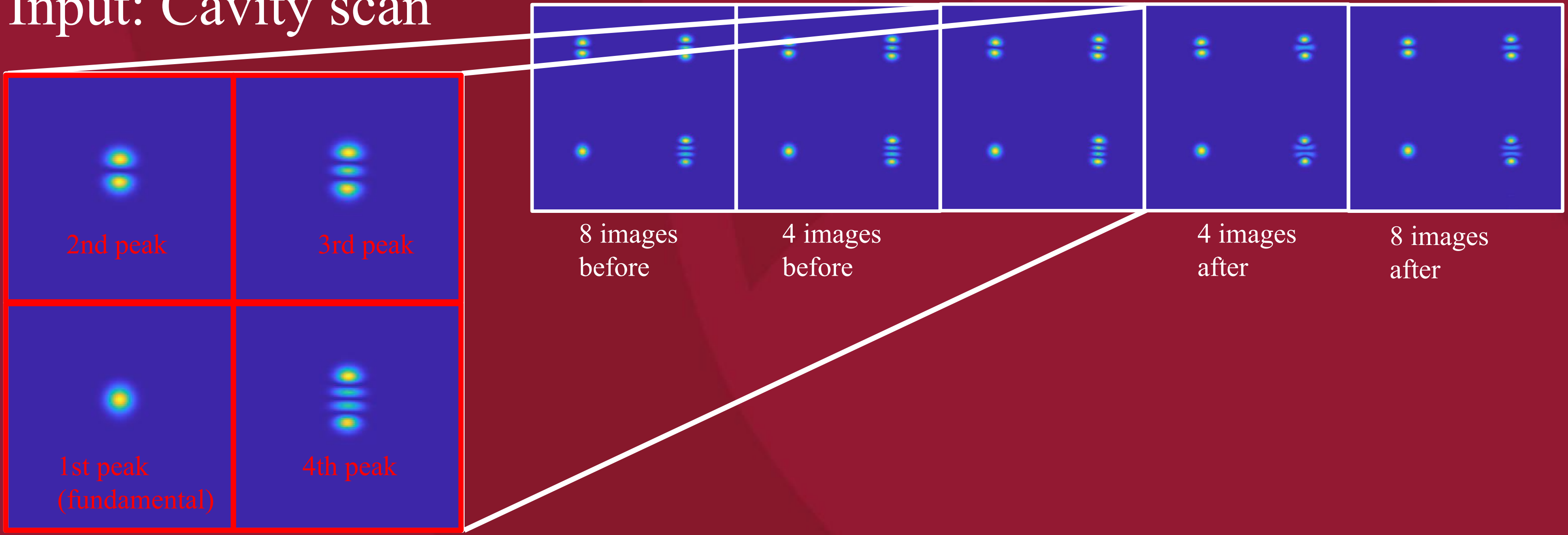


Input: Cavity scan

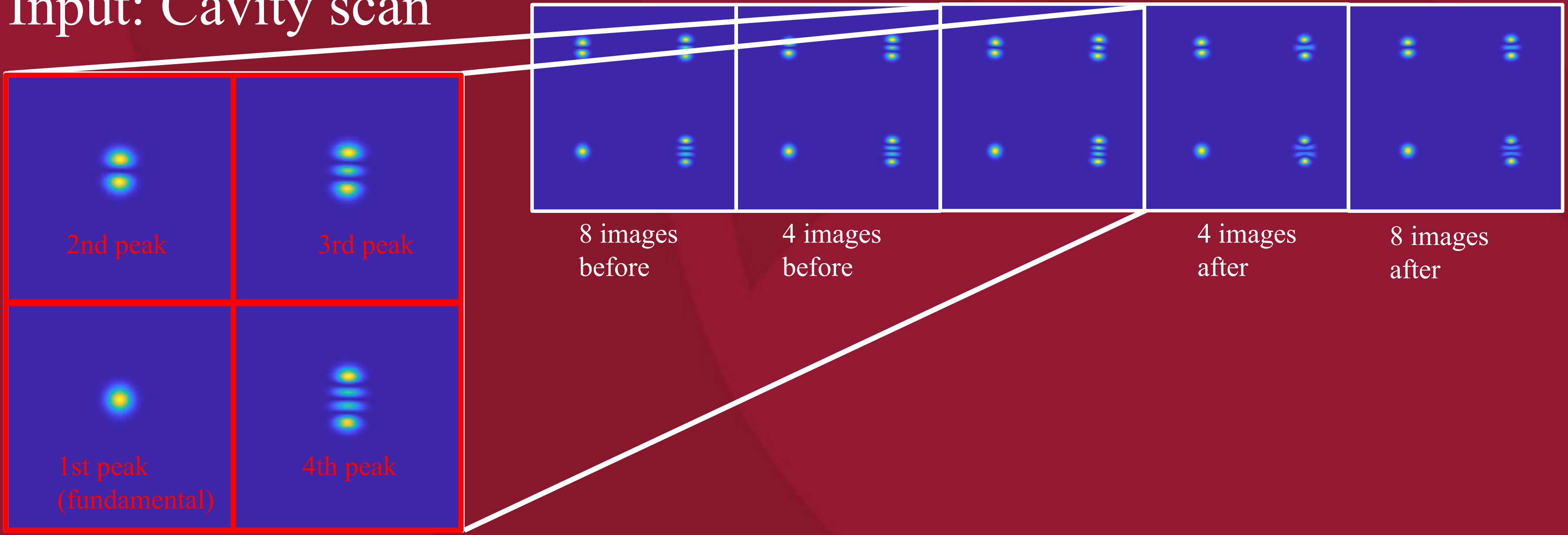


Input: Cavity scan



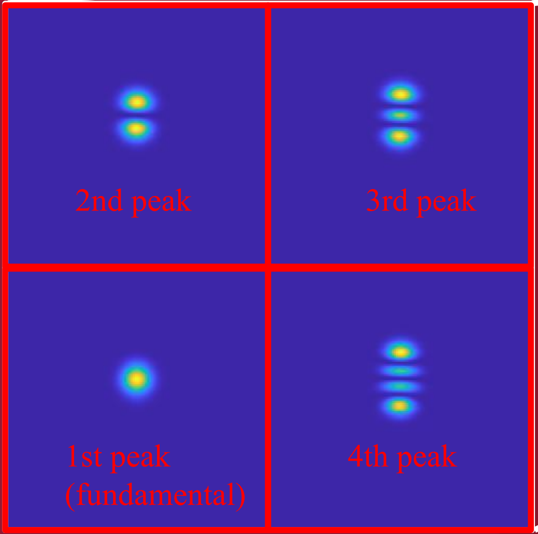
Output:

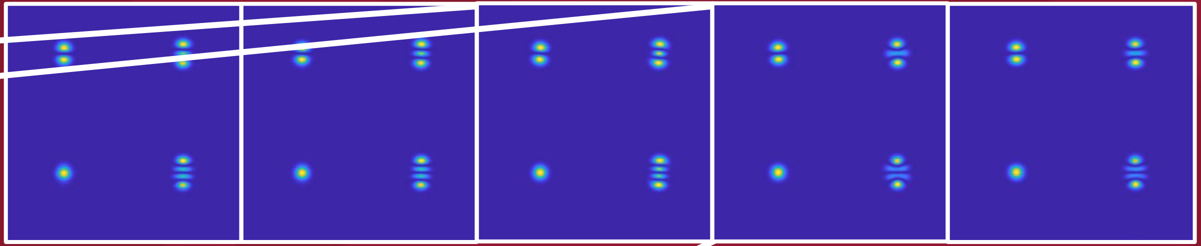
Input: Cavity scan



Output: 6 parameters

Input: Cavity scan





8 images before | 4 images before | 4 images after | 8 images after

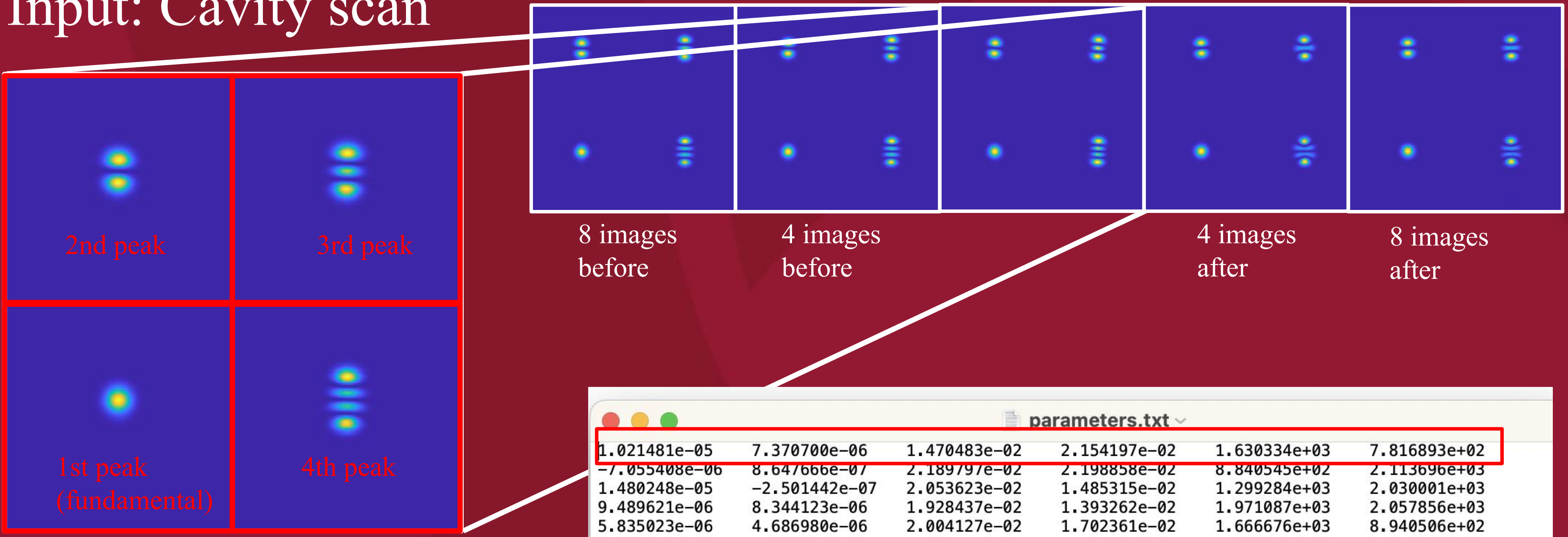
Output: 6 parameters

parameters.txt

1.021481e-05	7.370700e-06	1.470483e-02	2.154197e-02	1.630334e+03	7.816893e+02
-7.055408e-06	8.647666e-07	2.189797e-02	2.198858e-02	8.840545e+02	2.113696e+03
1.480248e-05	-2.501442e-07	2.053623e-02	1.485315e-02	1.299284e+03	2.030001e+03
9.489621e-06	8.344123e-06	1.928437e-02	1.393262e-02	1.971087e+03	2.057856e+03
5.835023e-06	4.686980e-06	2.004127e-02	1.702361e-02	1.666676e+03	8.940506e+02
6.714626e-06	-8.471469e-06	1.600343e-02	1.402331e-02	7.889807e+02	1.889214e+03
6.353345e-06	-3.300469e-06	2.183487e-02	1.392165e-02	1.325980e+03	1.215013e+03
8.629999e-06	5.366009e-06	1.522350e-02	1.786926e-02	1.336735e+03	1.618946e+03
6.821513e-06	4.631630e-06	1.599565e-02	1.951602e-02	1.666078e+03	8.809679e+02
-1.219244e-05	-1.470467e-08	2.191734e-02	1.657414e-02	1.556308e+03	9.743404e+02
8.171058e-06	-4.424416e-06	1.798709e-02	1.968400e-02	2.036754e+03	2.096454e+03
1.599171e-06	-6.535669e-06	1.489804e-02	1.585560e-02	1.957863e+03	1.020829e+03
1.020067e-05	-4.634147e-06	2.165335e-02	1.665736e-02	9.453327e+02	1.015949e+03
3.815951e-06	-4.692404e-07	1.665072e-02	2.082628e-02	1.556303e+03	1.471580e+03

The analysis

Input: Cavity scan

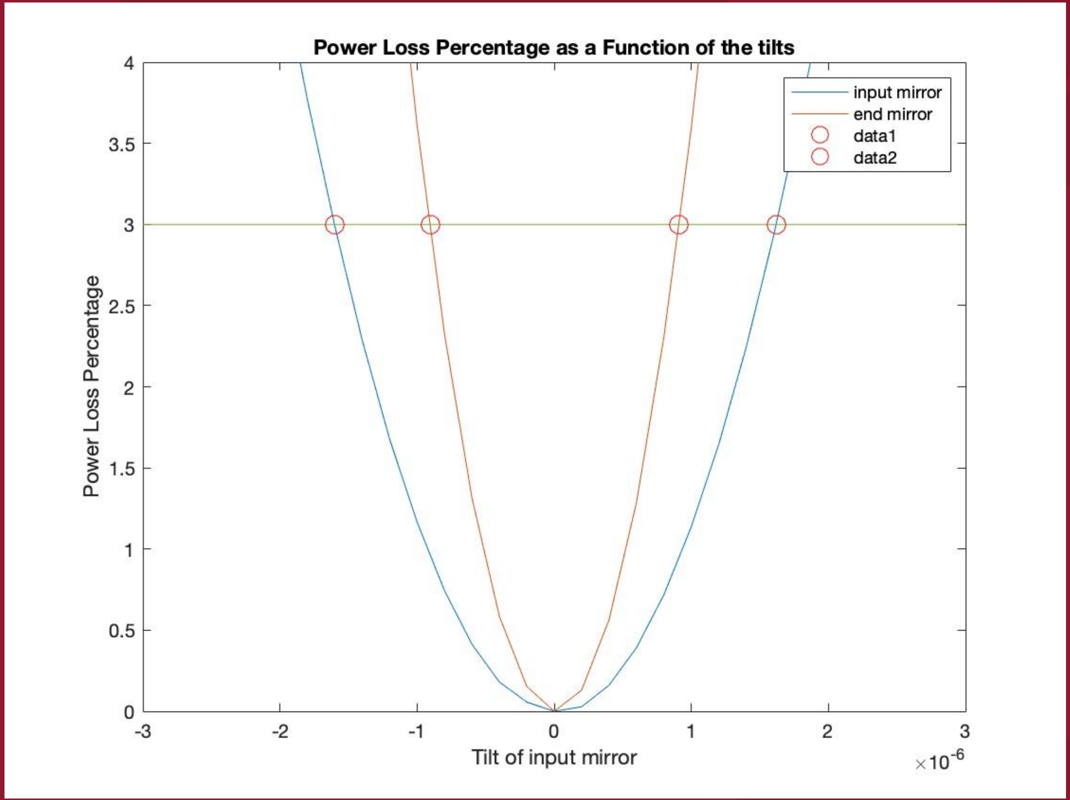


Output: 6 parameters

parameters.txt

1.021481e-05	7.370700e-06	1.470483e-02	2.154197e-02	1.630334e+03	7.816893e+02
-7.055408e-06	8.647666e-07	2.189797e-02	2.198858e-02	8.840545e+02	2.113696e+03
1.480248e-05	-2.501442e-07	2.053623e-02	1.485315e-02	1.299284e+03	2.030001e+03
9.489621e-06	8.344123e-06	1.928437e-02	1.393262e-02	1.971087e+03	2.057856e+03
5.835023e-06	4.686980e-06	2.004127e-02	1.702361e-02	1.666676e+03	8.940506e+02
6.714626e-06	-8.471469e-06	1.600343e-02	1.402331e-02	7.889807e+02	1.889214e+03
6.353345e-06	-3.300469e-06	2.183487e-02	1.392165e-02	1.325980e+03	1.215013e+03
8.629999e-06	5.366009e-06	1.522350e-02	1.786926e-02	1.336735e+03	1.618946e+03
6.821513e-06	4.631630e-06	1.599565e-02	1.951602e-02	1.666078e+03	8.809679e+02
-1.219244e-05	-1.470467e-08	2.191734e-02	1.657414e-02	1.556308e+03	9.743404e+02
8.171058e-06	-4.424416e-06	1.798709e-02	1.968400e-02	2.036754e+03	2.096454e+03
1.599171e-06	-6.535669e-06	1.489804e-02	1.585560e-02	1.957863e+03	1.020829e+03
1.020067e-05	-4.634147e-06	2.165335e-02	1.665736e-02	9.453327e+02	1.015949e+03
3.815951e-06	-4.692404e-07	1.665072e-02	2.082628e-02	1.556303e+03	1.471580e+03

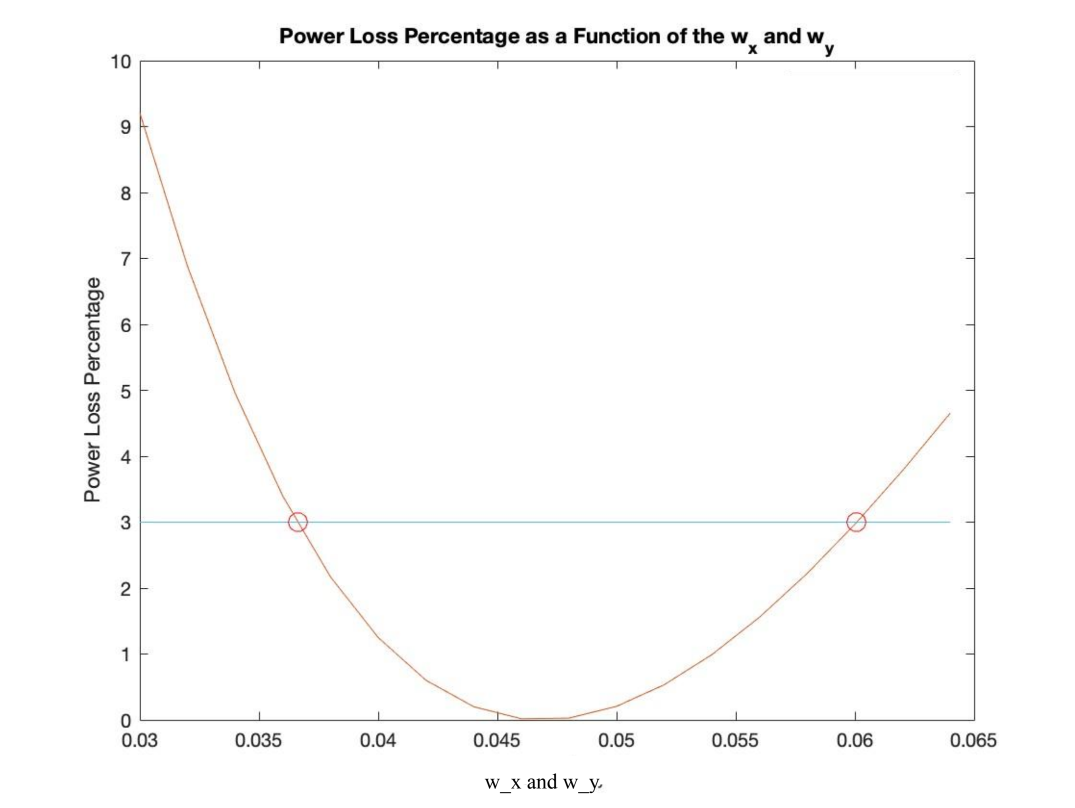
The analysis



Intersection points for input mirror:
(-1.6025e-06, 3)
(1.6182e-06, 3)

Intersection points for end mirror:
(-9.0485e-07, 3)
(9.0784e-07, 3)

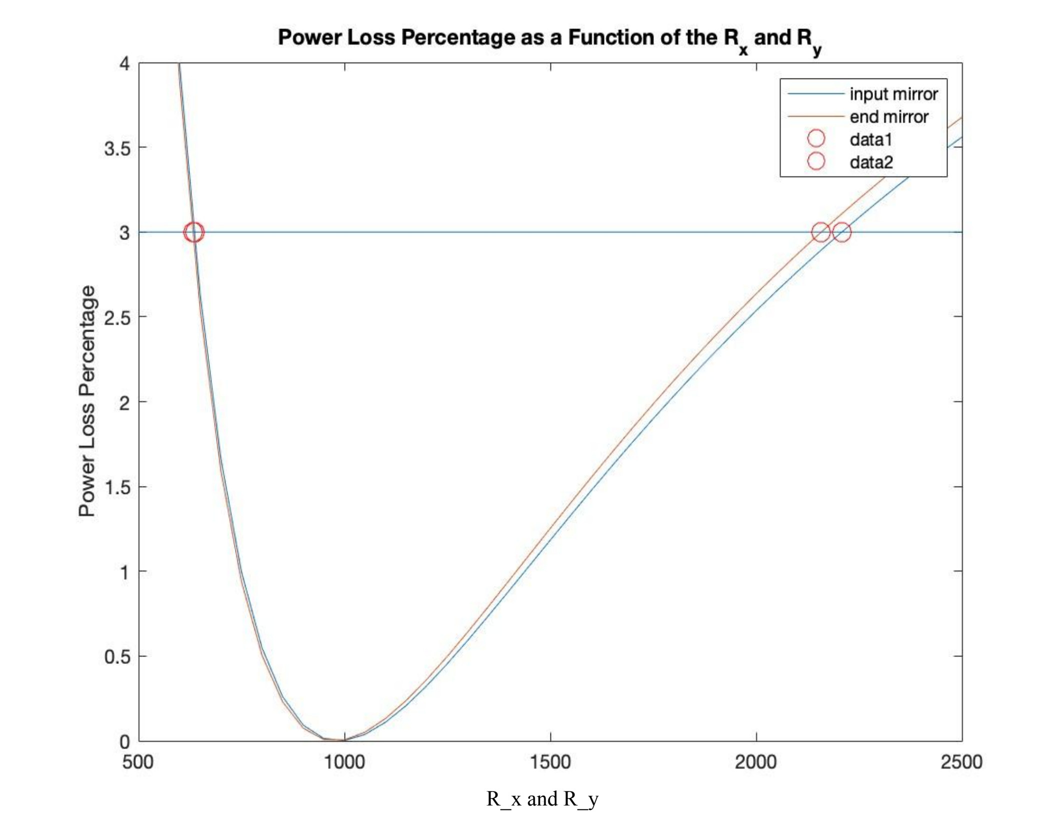
The analysis



Intersection points for w_x:
(0.036643, 3)
(0.060077, 3)

Intersection points for w_y:
(0.036643, 3)
(0.060077, 3)

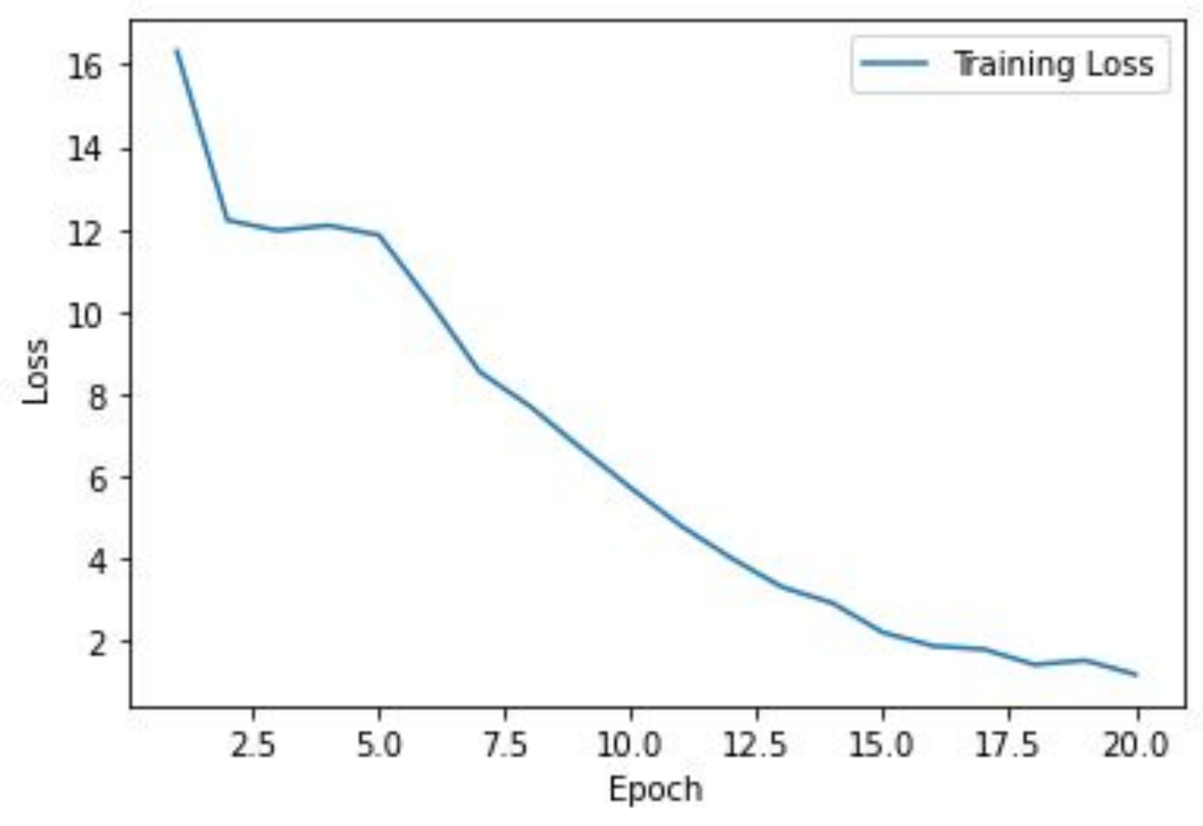
The analysis



Intersection points for R_x:
(636.2939, 3)
(2208.2487, 3)

Intersection points for R_y:
(632.8729, 3)
(2158.5623, 3)

The analysis



Next steps

Variable number of inputs
(number of peaks)

Variable number of inputs
(number of peaks)

Truncation

Variable number of inputs
(number of peaks)

Truncation

Loss of data

Variable number of inputs
(number of peaks)

Truncation

Padding

Loss of data

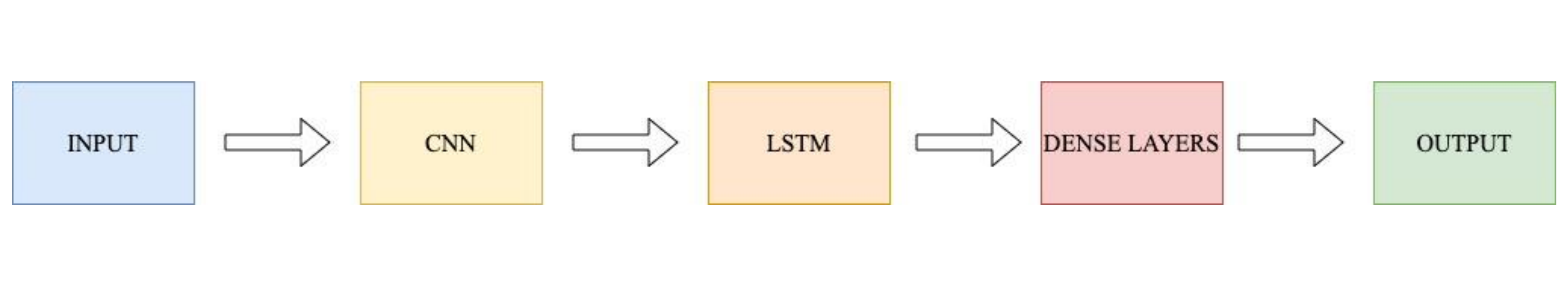
Variable number of inputs
(number of peaks)

Truncation → Loss of data

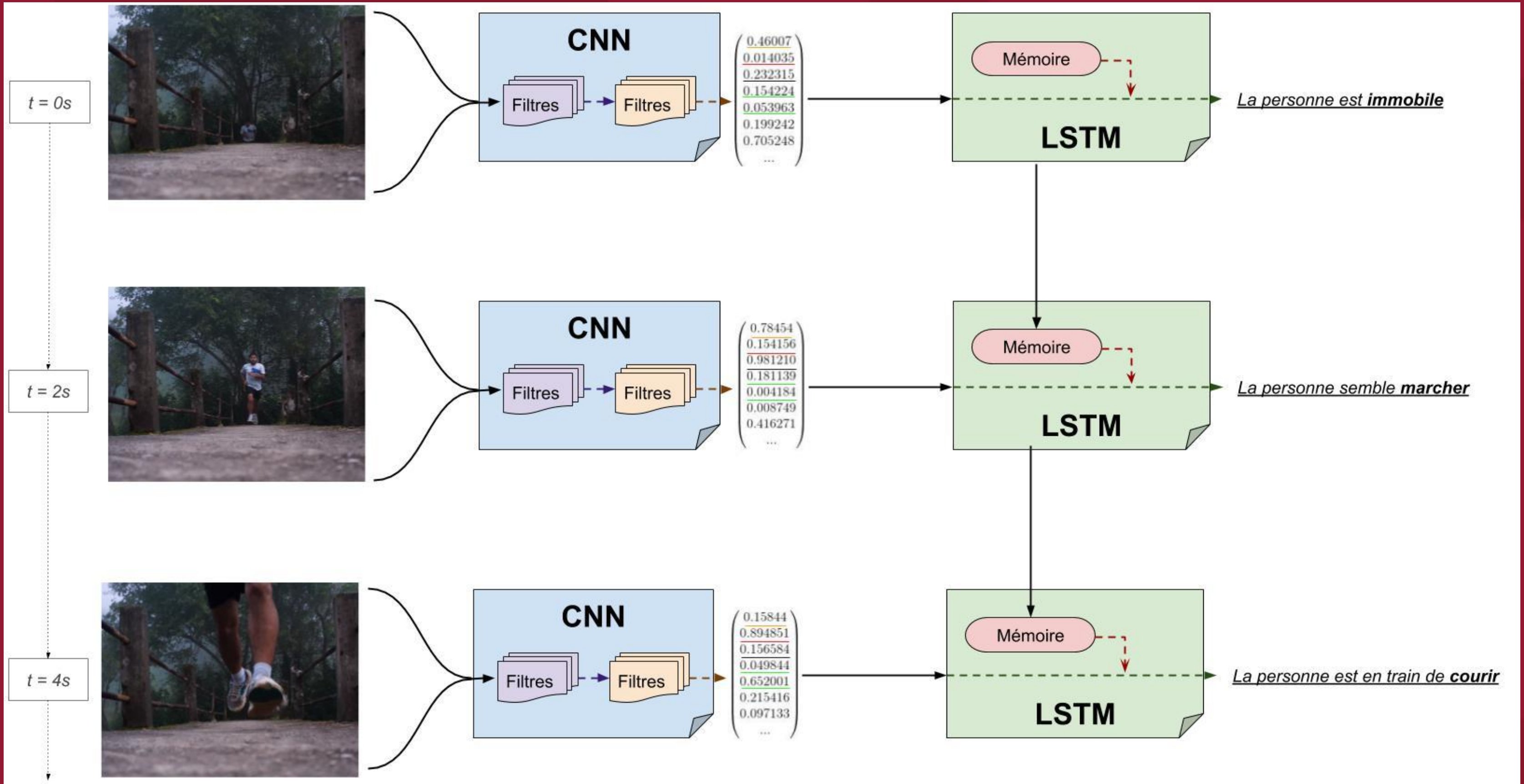
Padding → Extra worthless data

Long Short-Term Memory Convolutional Neural Network (LSTM CNN)

Long Short-Term Memory Convolutional Neural Network (LSTM CNN)



Next steps


t = 0s
CNN
Filtres
Filtres
0.46007
0.014035
0.232315
0.154224
0.053963
0.199242
0.705248
...
Mémoire
LSTM
La personne est immobile
t = 2s
CNN
Filtres
Filtres
0.78454
0.154156
0.981210
0.181139
0.004184
0.008749
0.416271
...
Mémoire
LSTM
La personne semble marcher
t = 4s
CNN
Filtres
Filtres
0.15844
0.894851
0.156584
0.049844
0.652001
0.215416
0.097133
...
Mémoire
LSTM
La personne est en train de courir

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Thank you for listening!