CSI - 1st year

PCal Calibration of Virgo

&

Earth’s rotation impact on ET

Mathieu SCHOOR
Damir BUSKULIC
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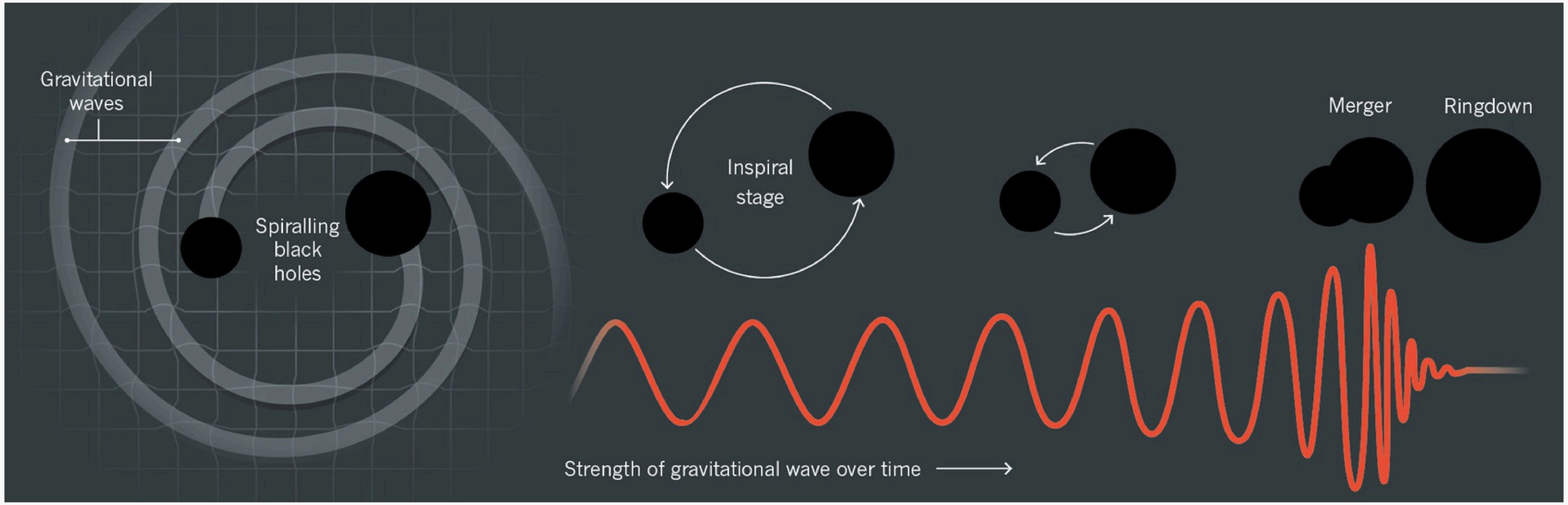
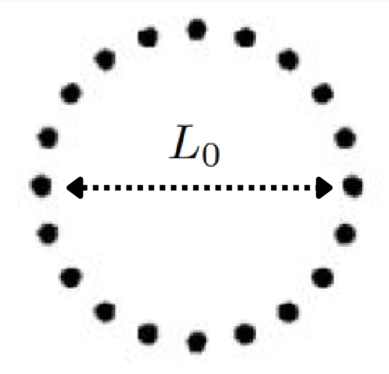
- *Introduction*
- *Virgo calibration (Loïc)*
- *Earth's rotation impact on ET (Damir)*
- *Conclusion - Miscellaneous*

Introduction

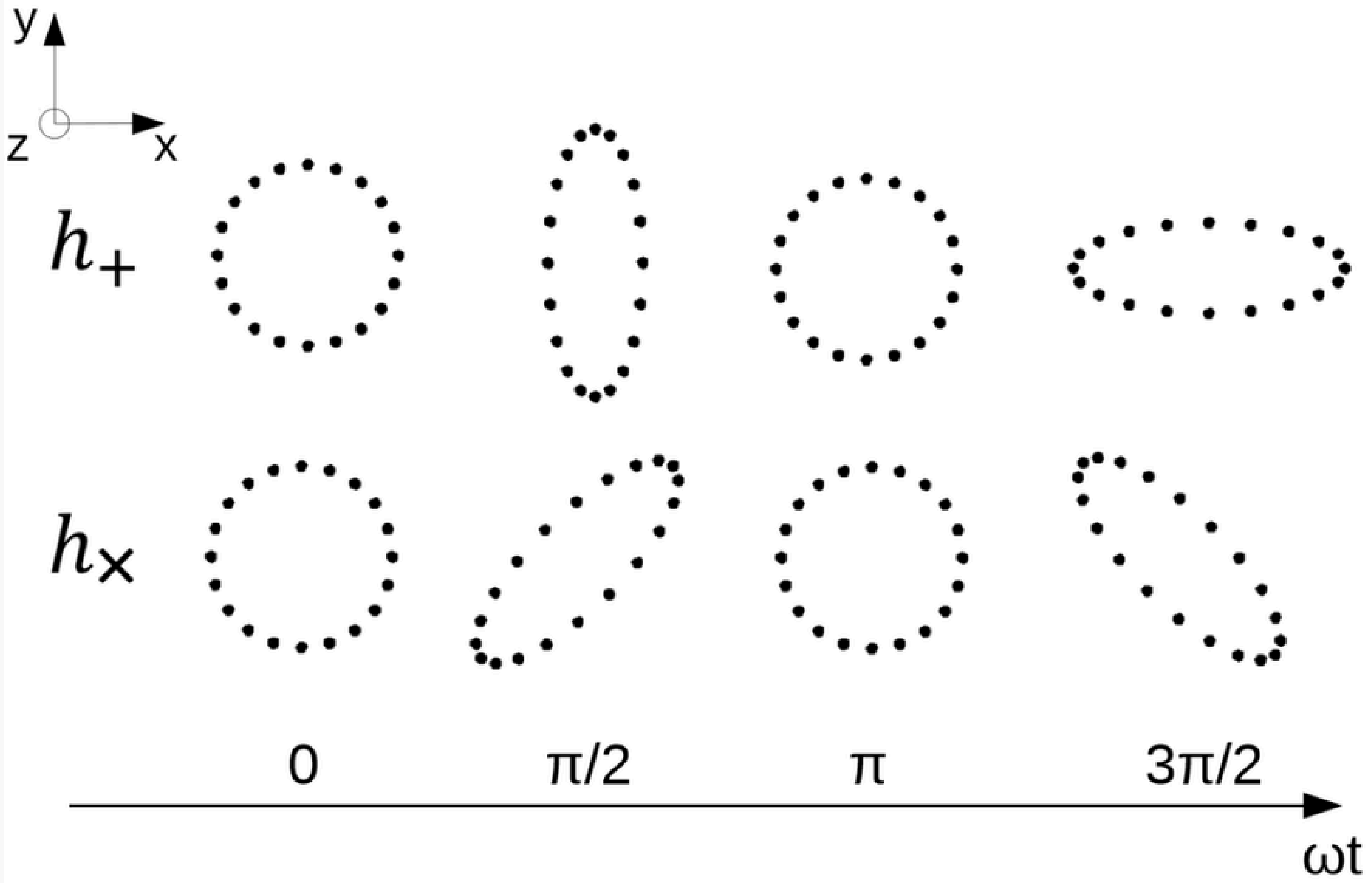


Test masses

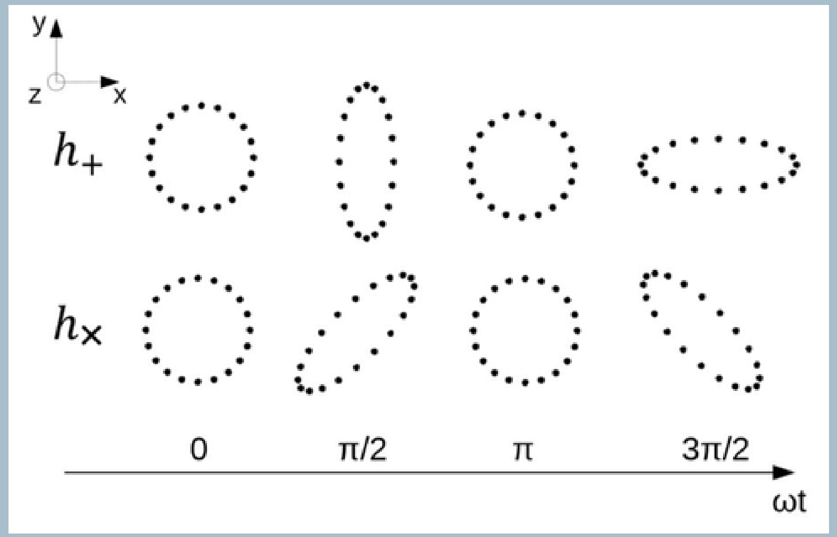


Elongation

$$\Delta L = L_0 \frac{h}{2}$$



(Reminders)



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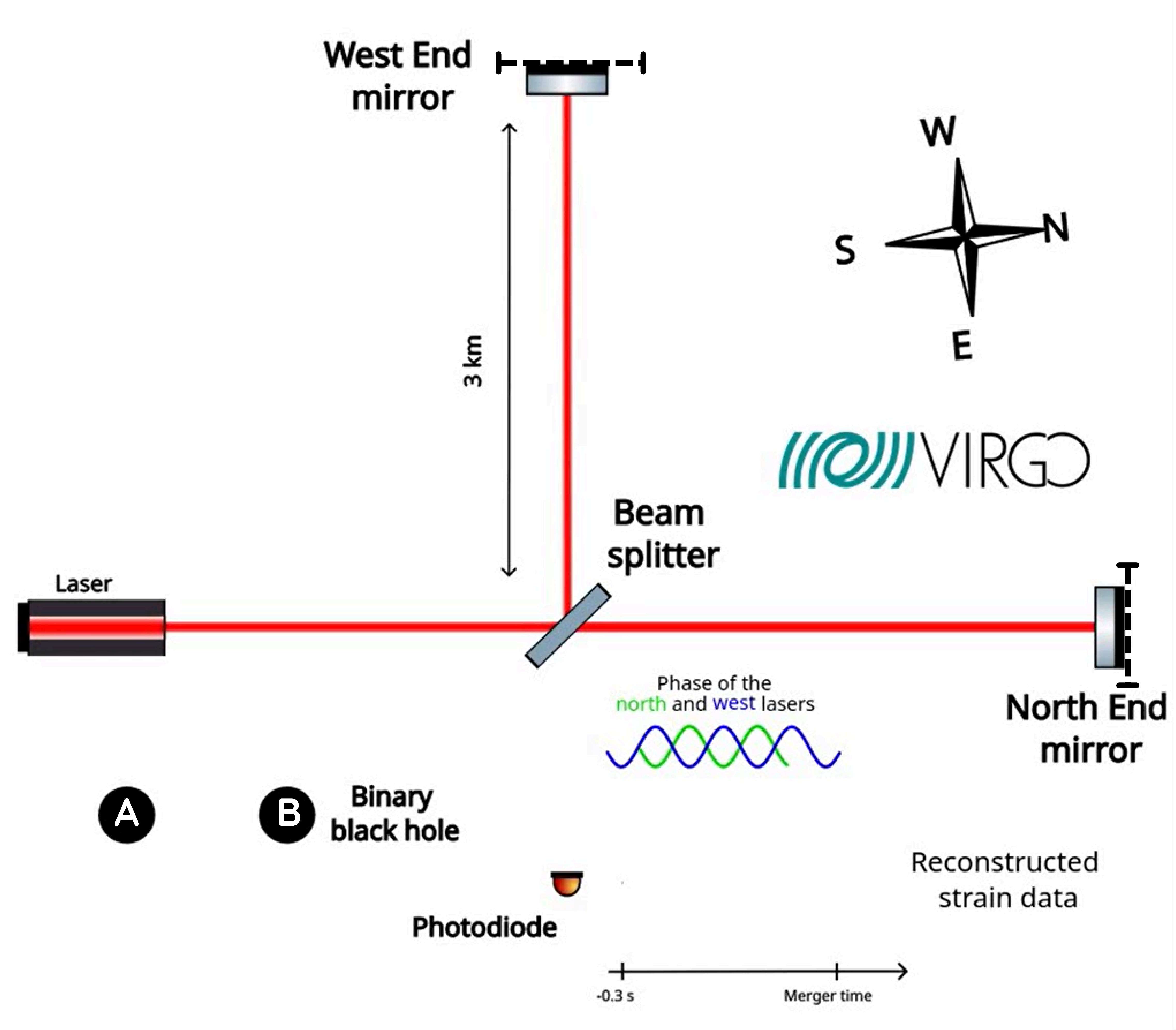

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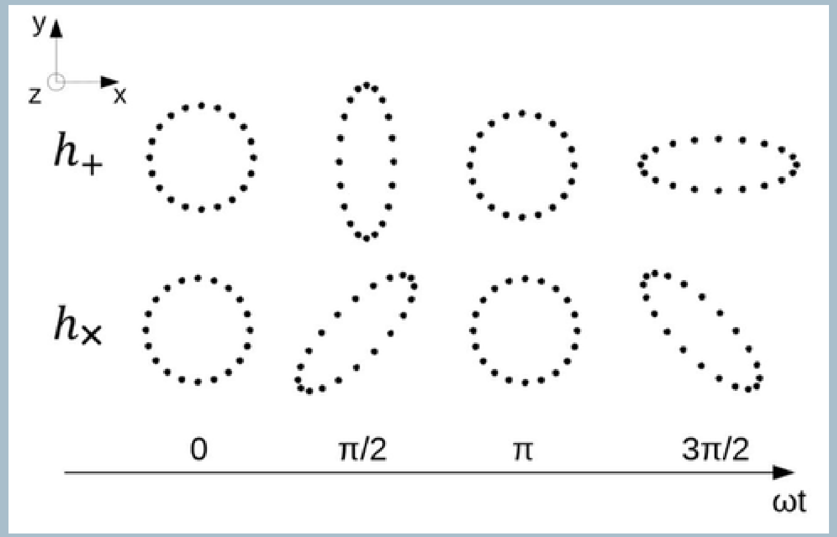

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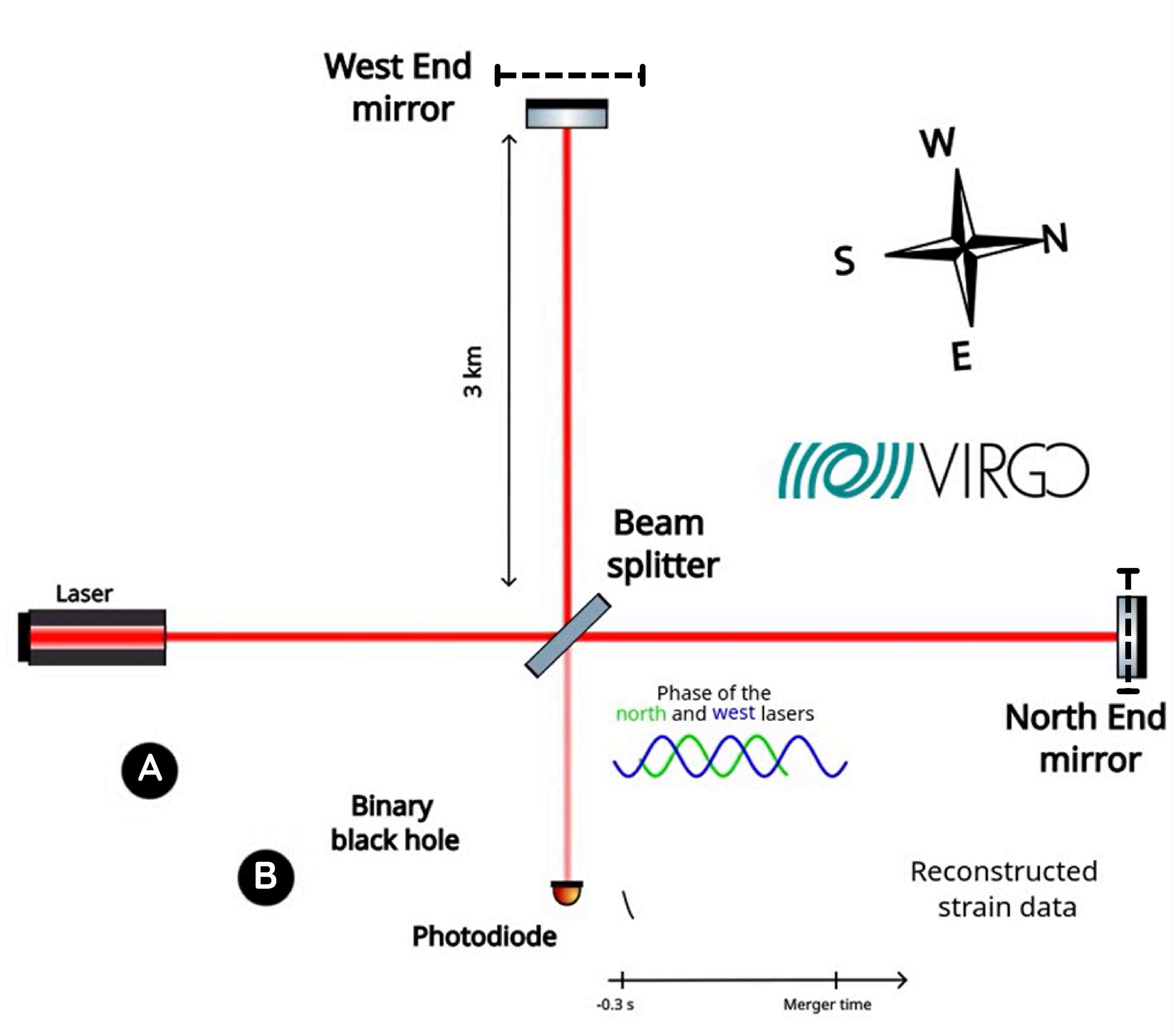
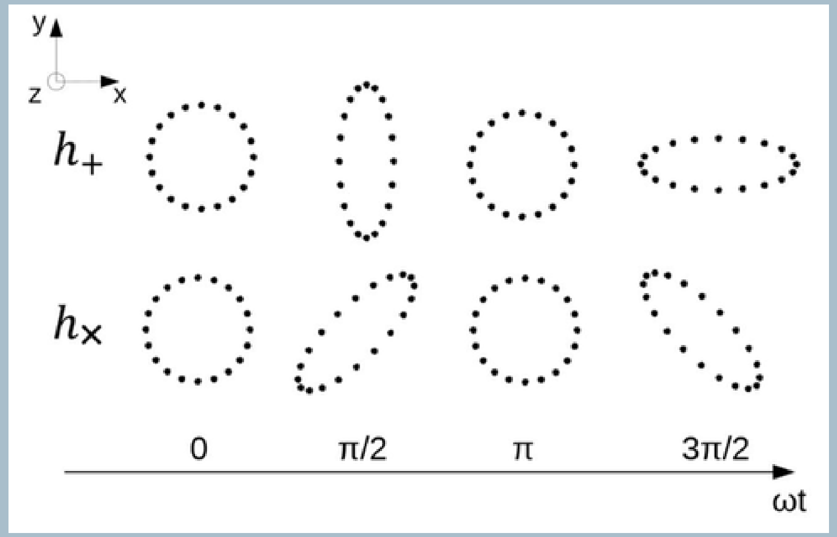
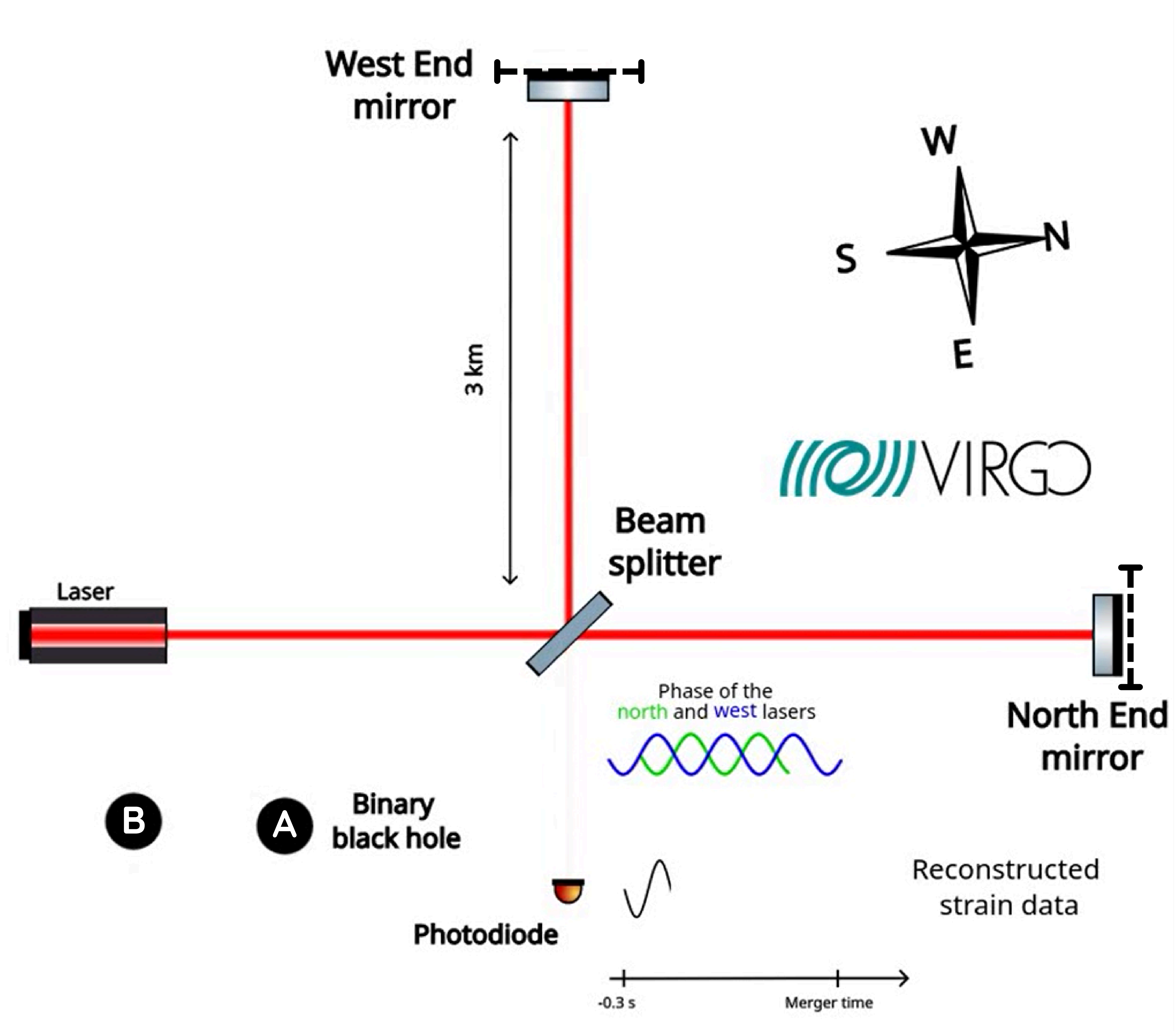


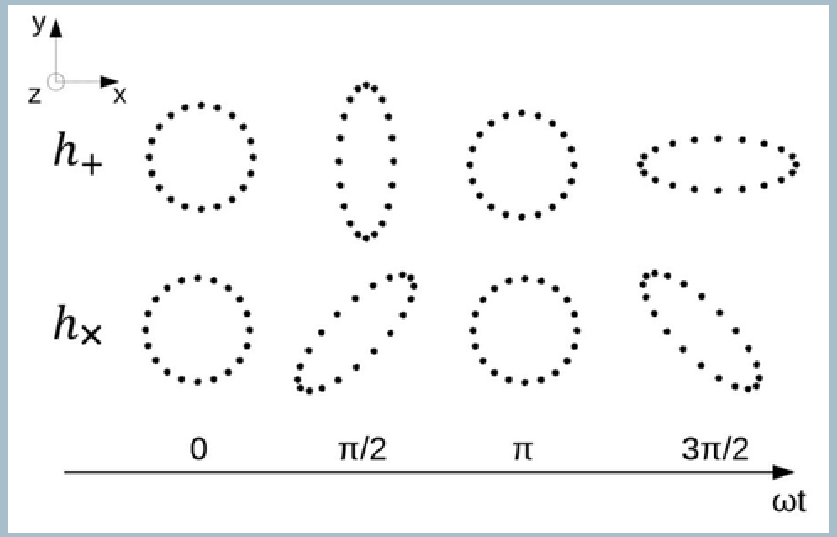
(Rappels)



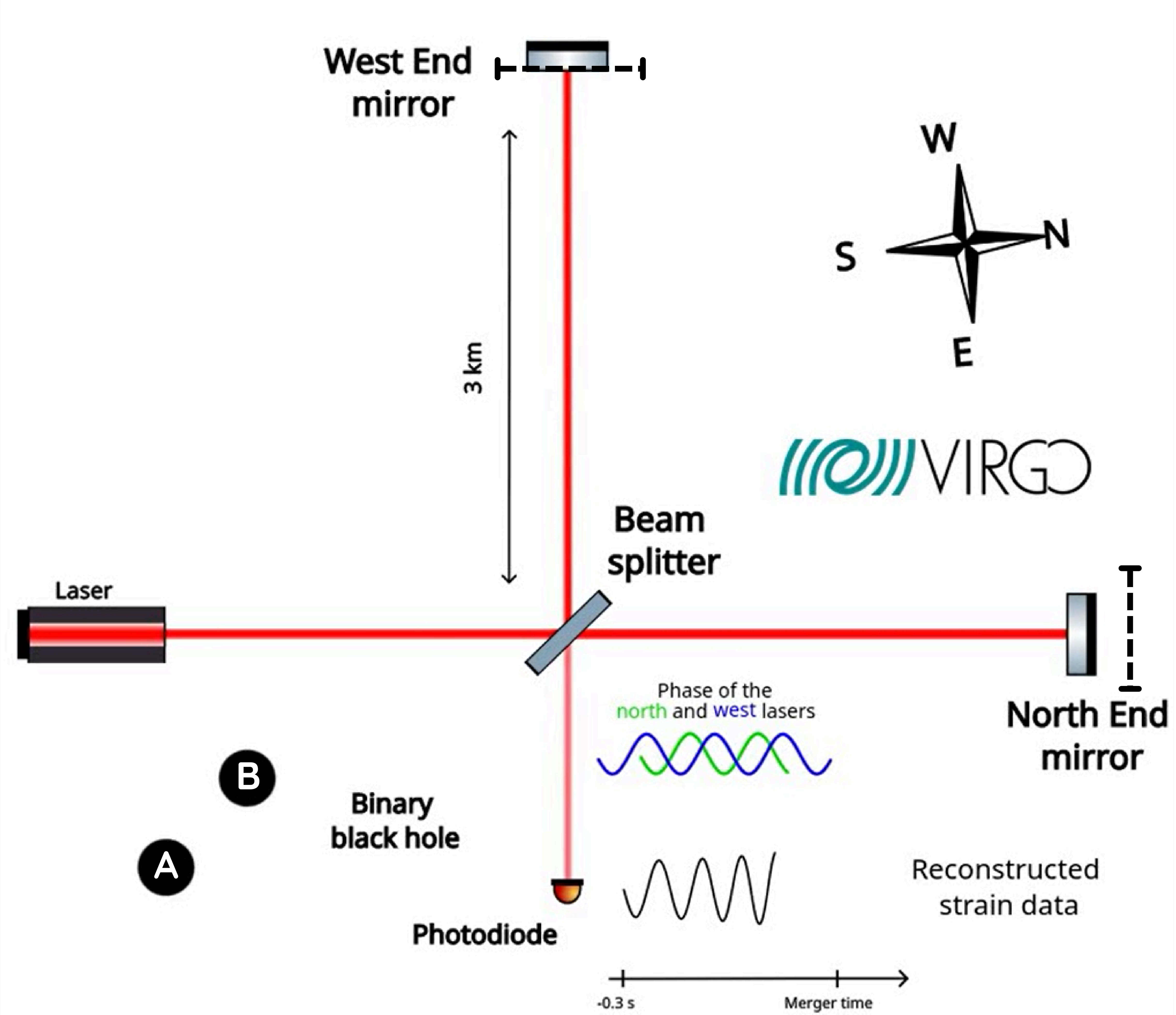
$$\Delta L = L_0 \frac{h}{2}$$



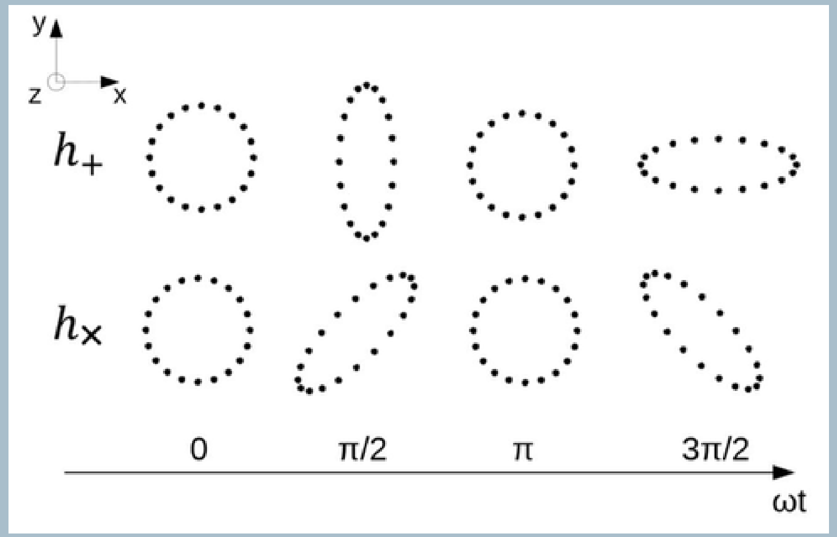
(Reminders)



$$\Delta L = L_0 \frac{h}{2}$$



(Reminders)



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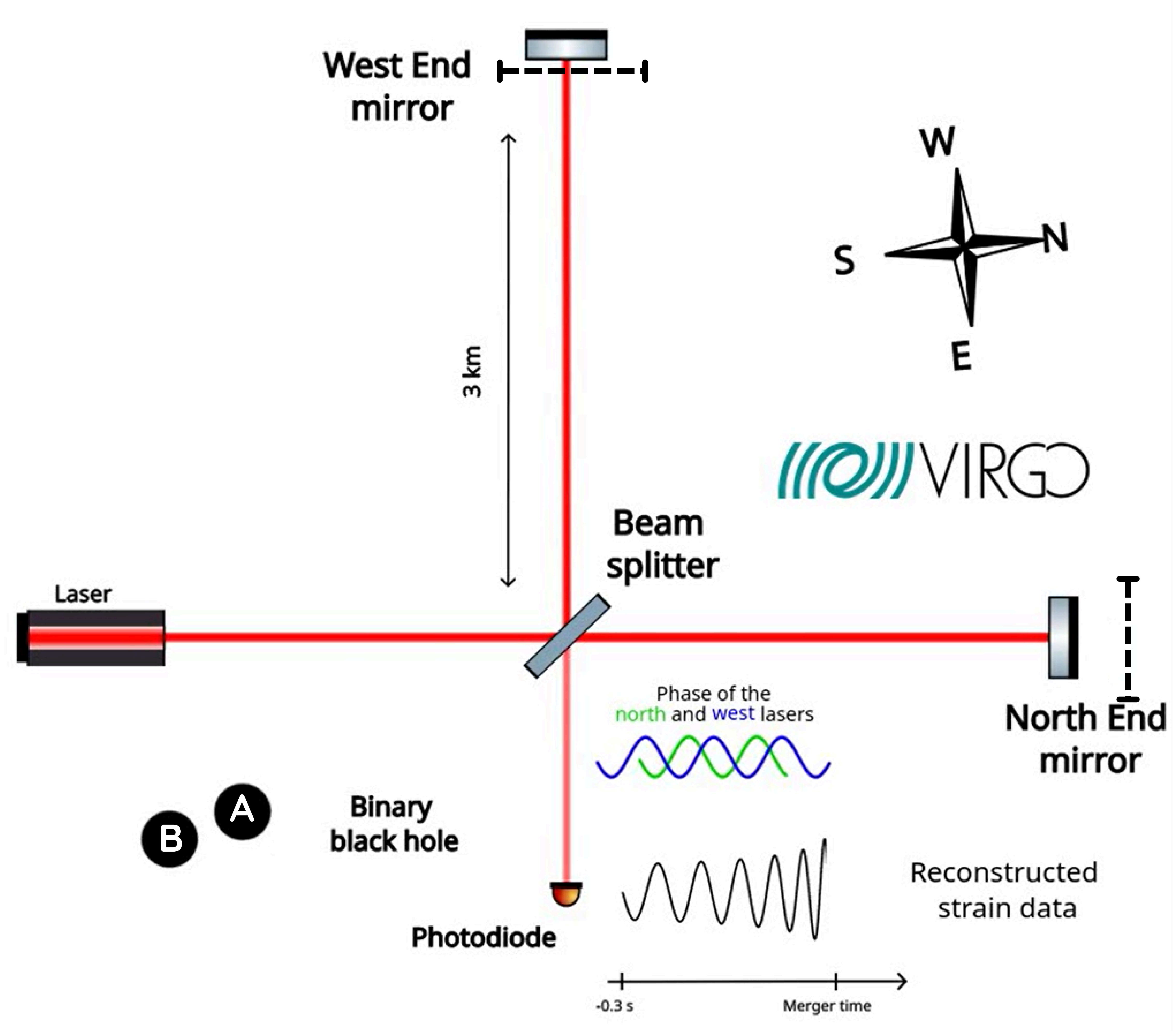

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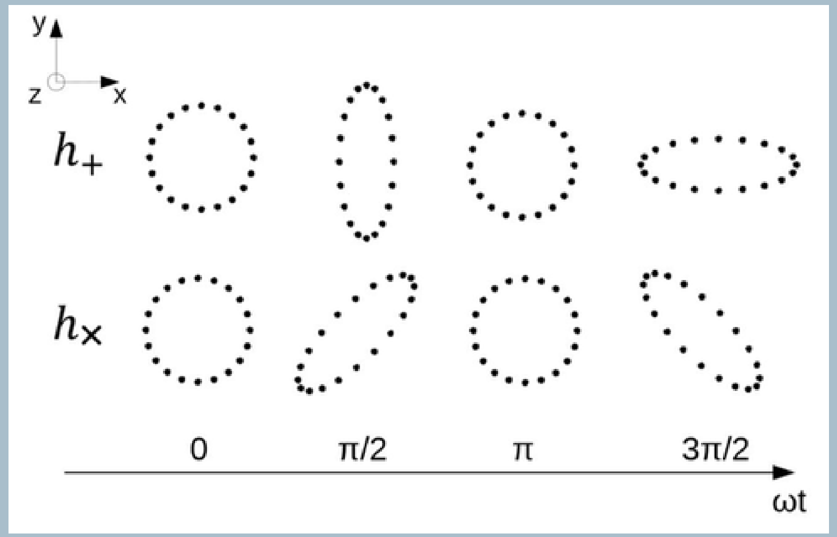

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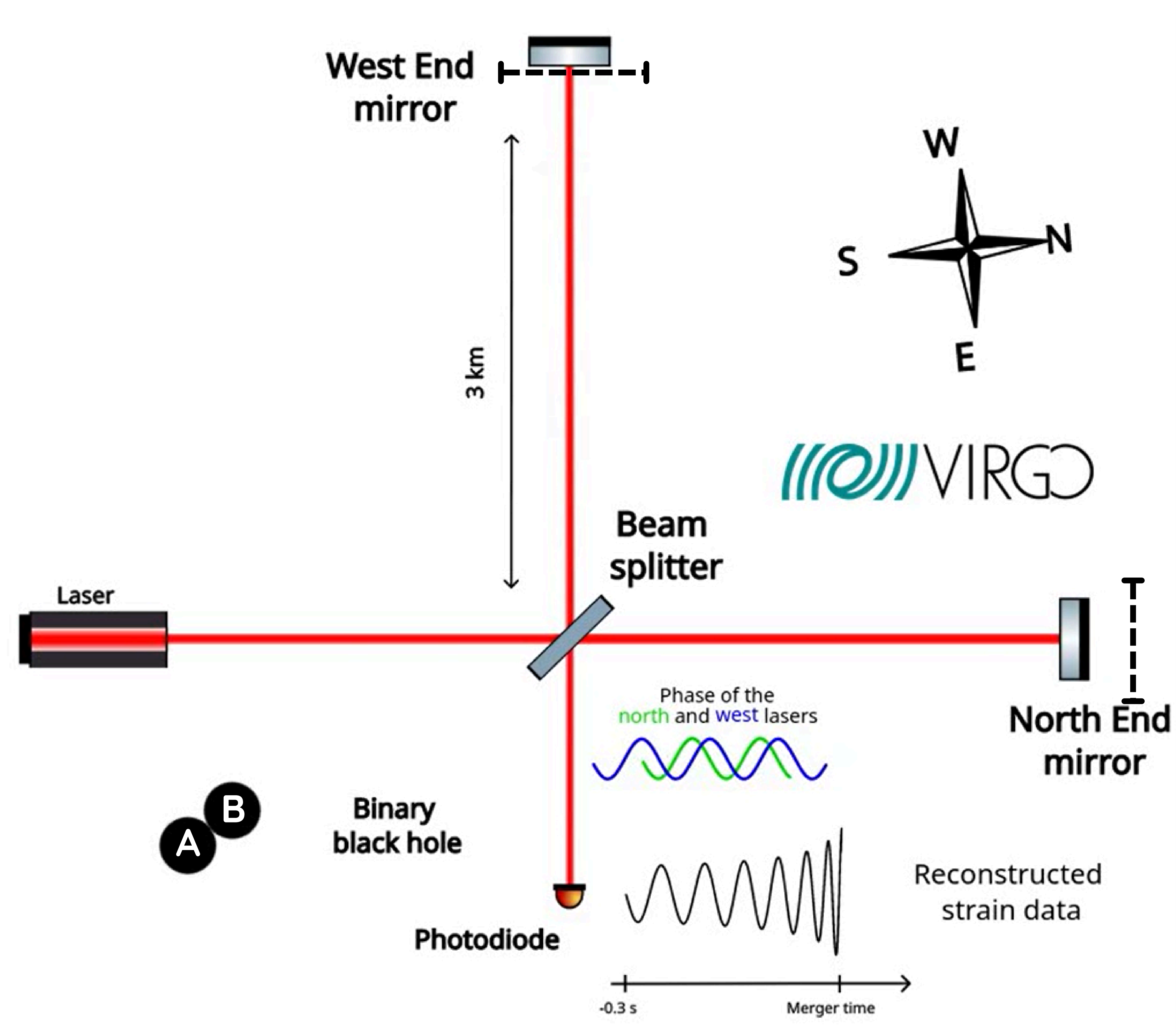
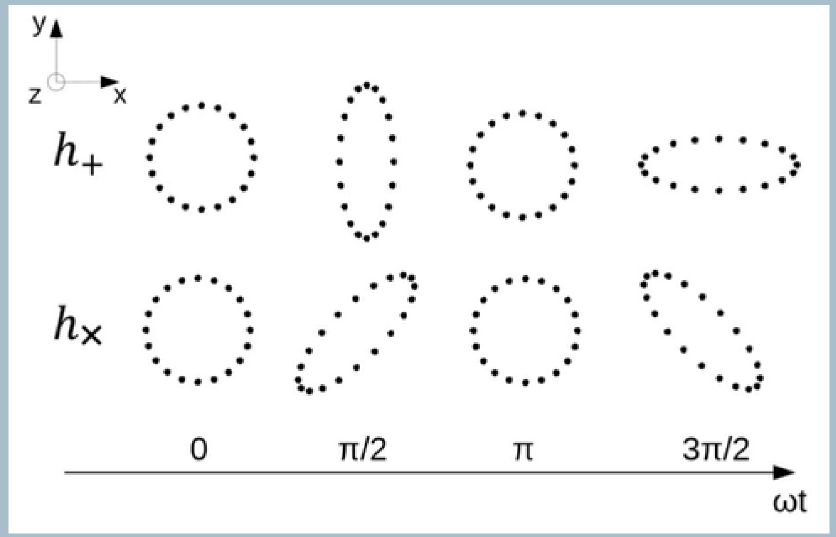


(Reminders)



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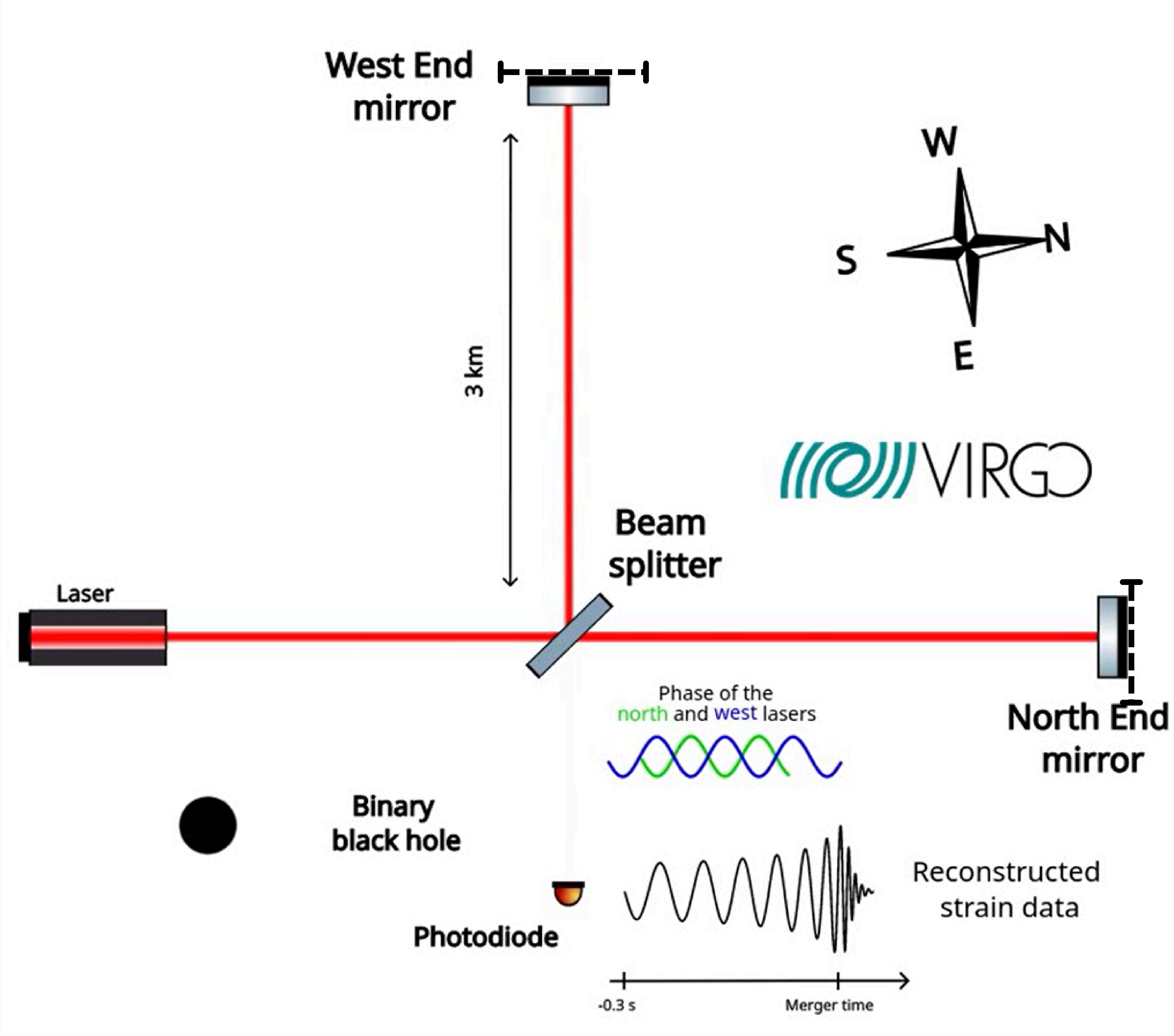
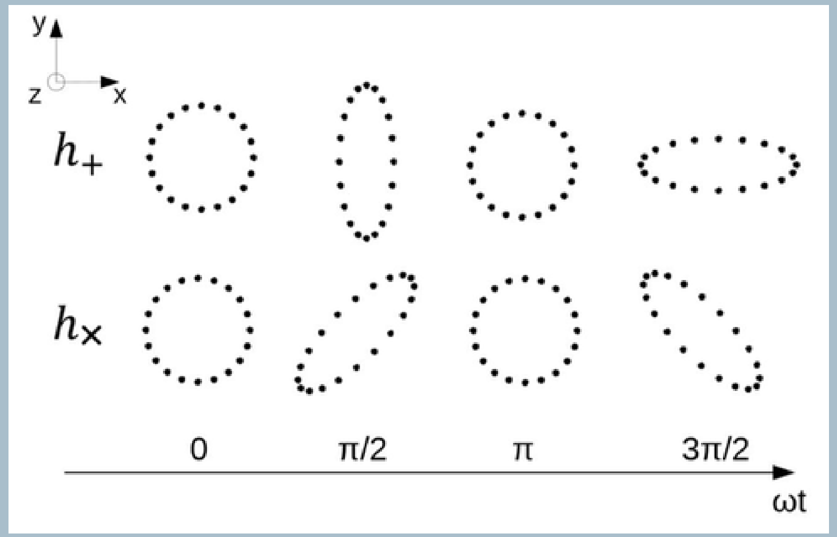


(Reminders)



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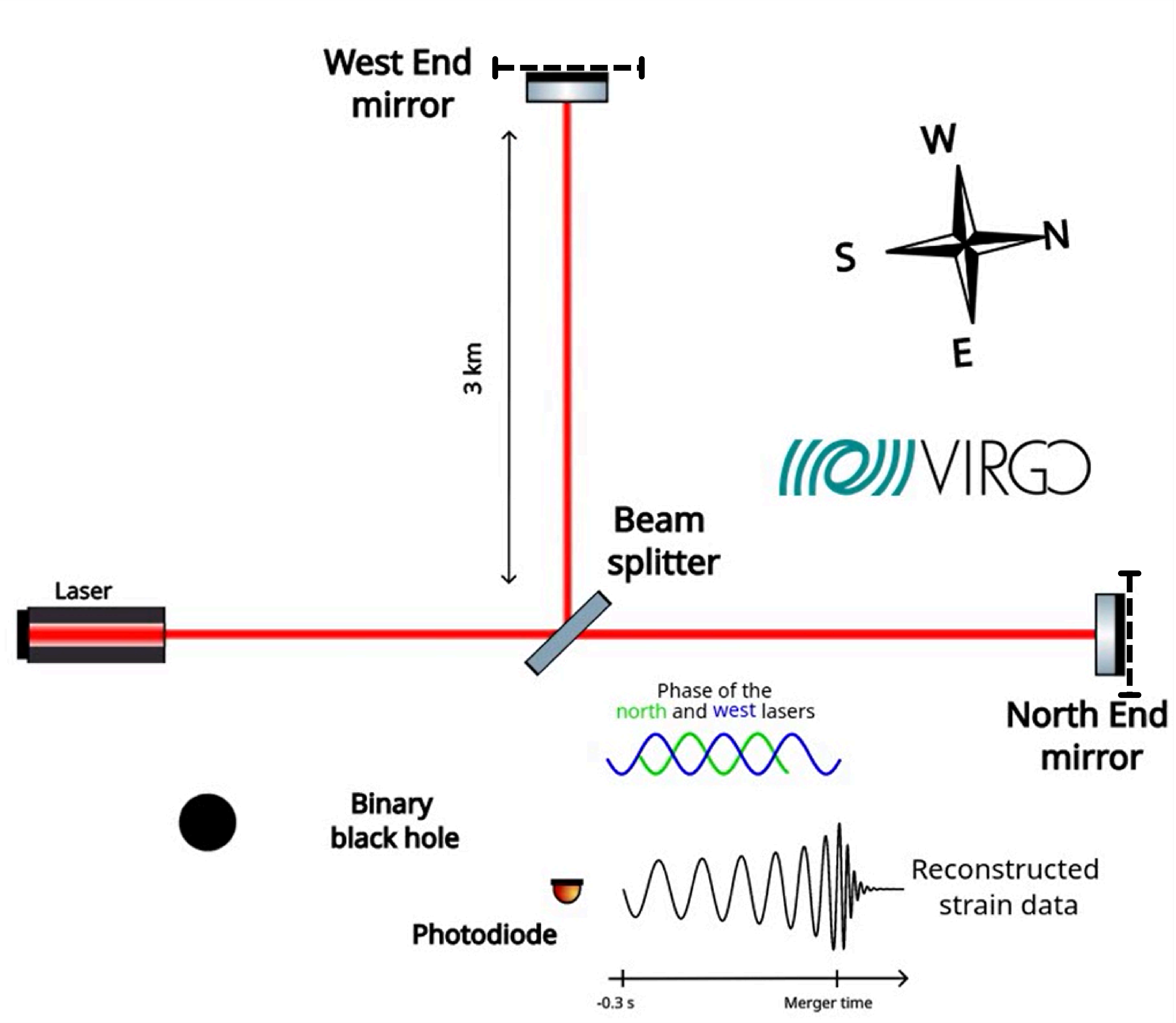
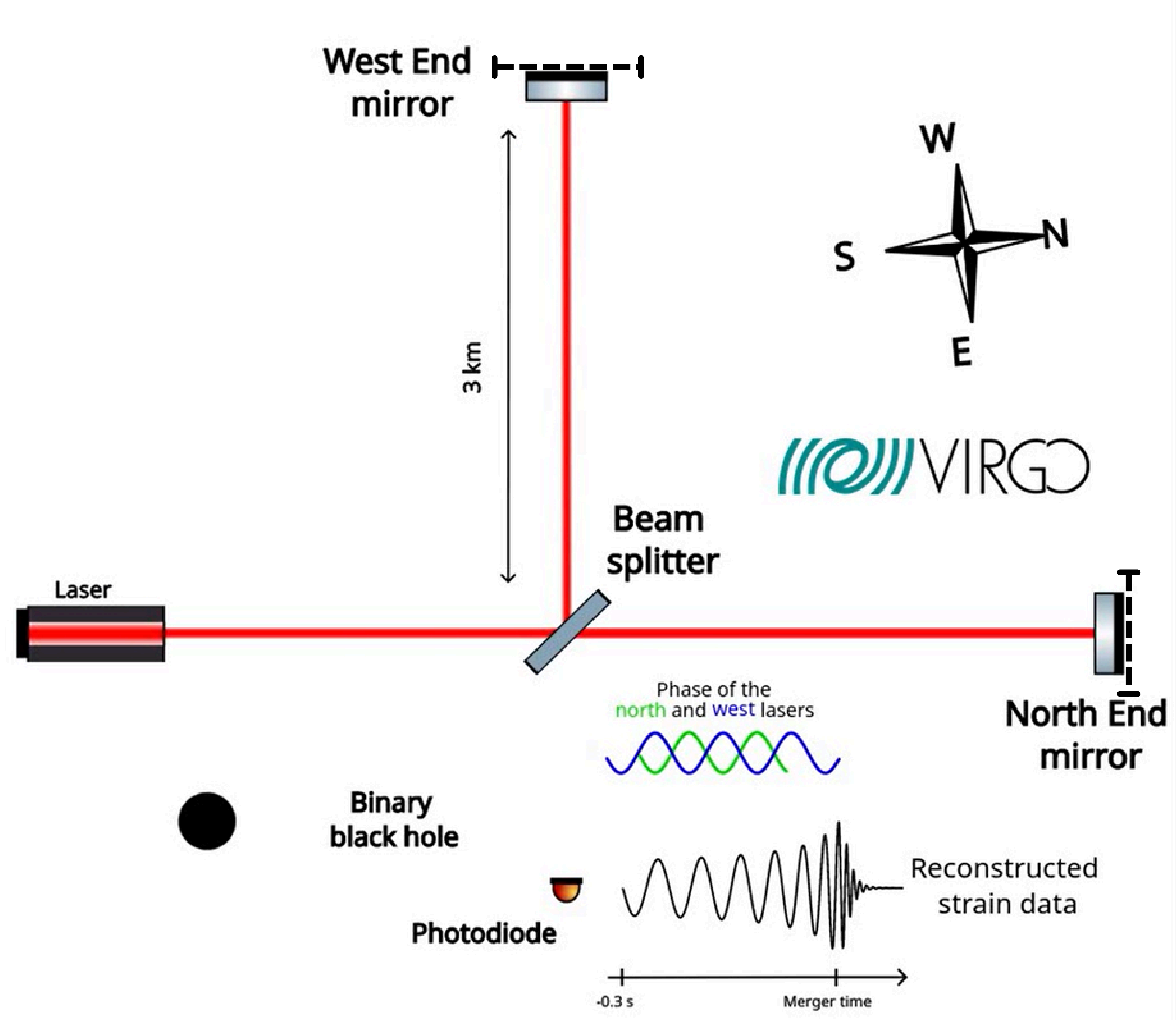
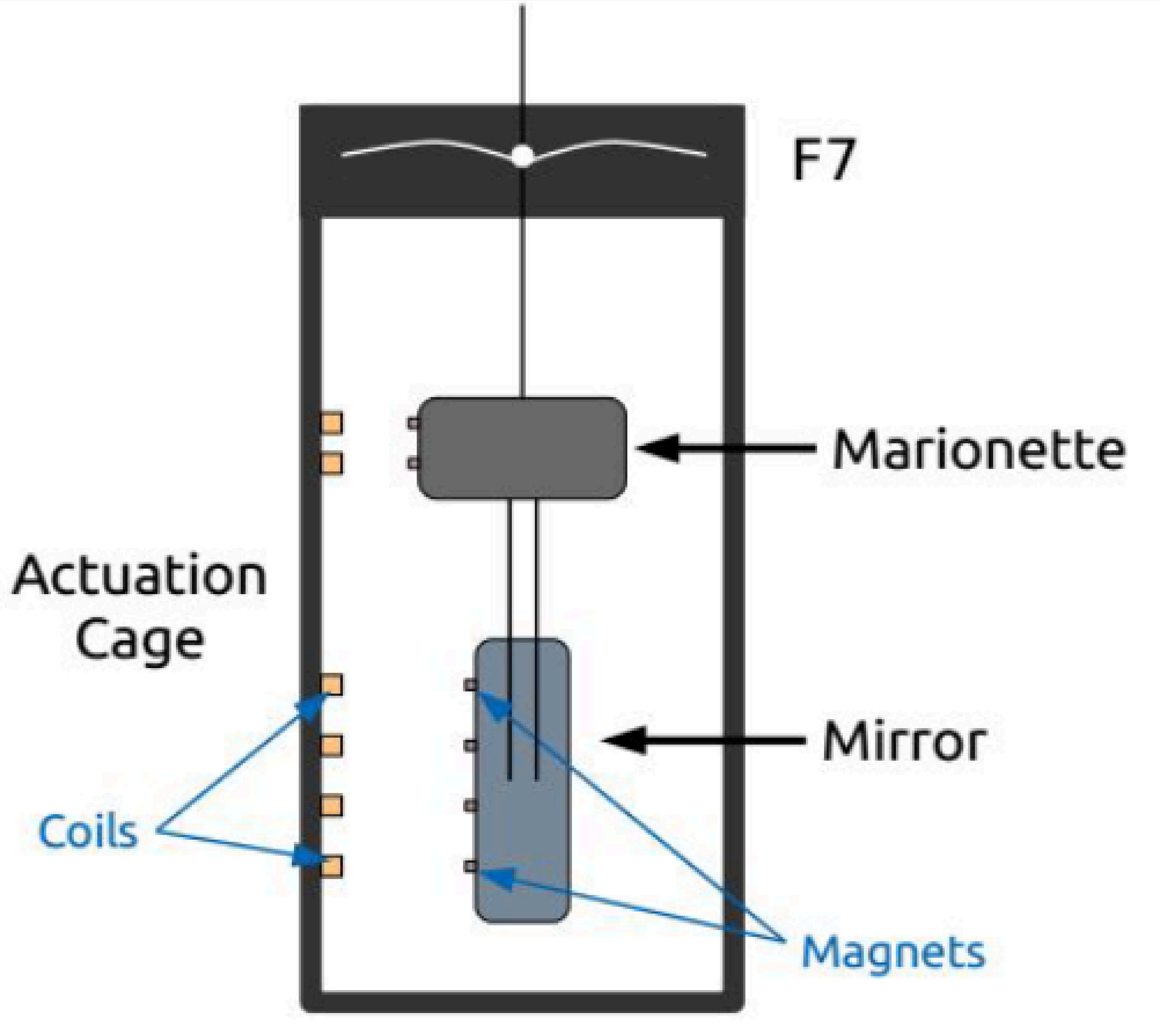
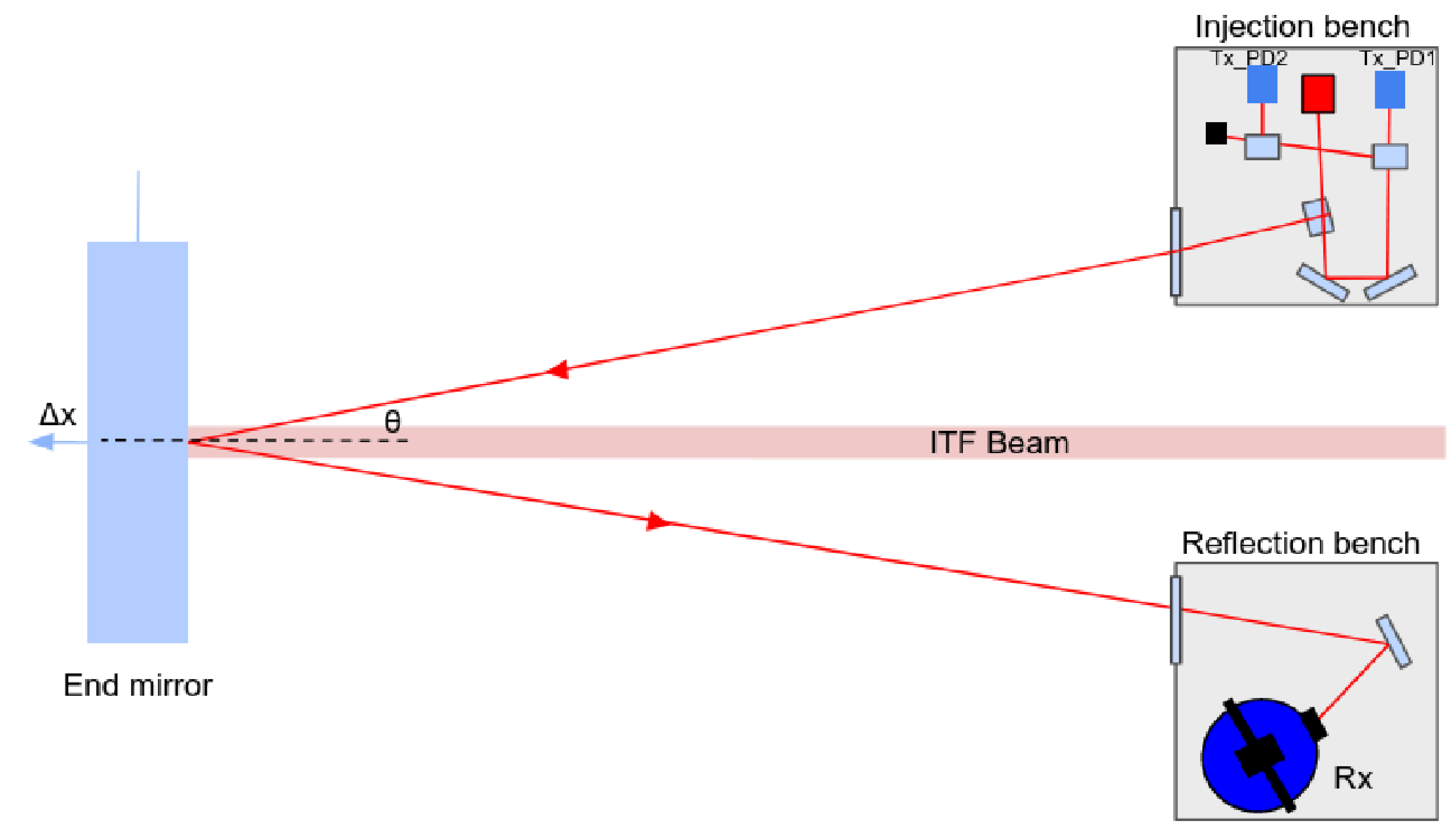


PCal calibration of Virgo

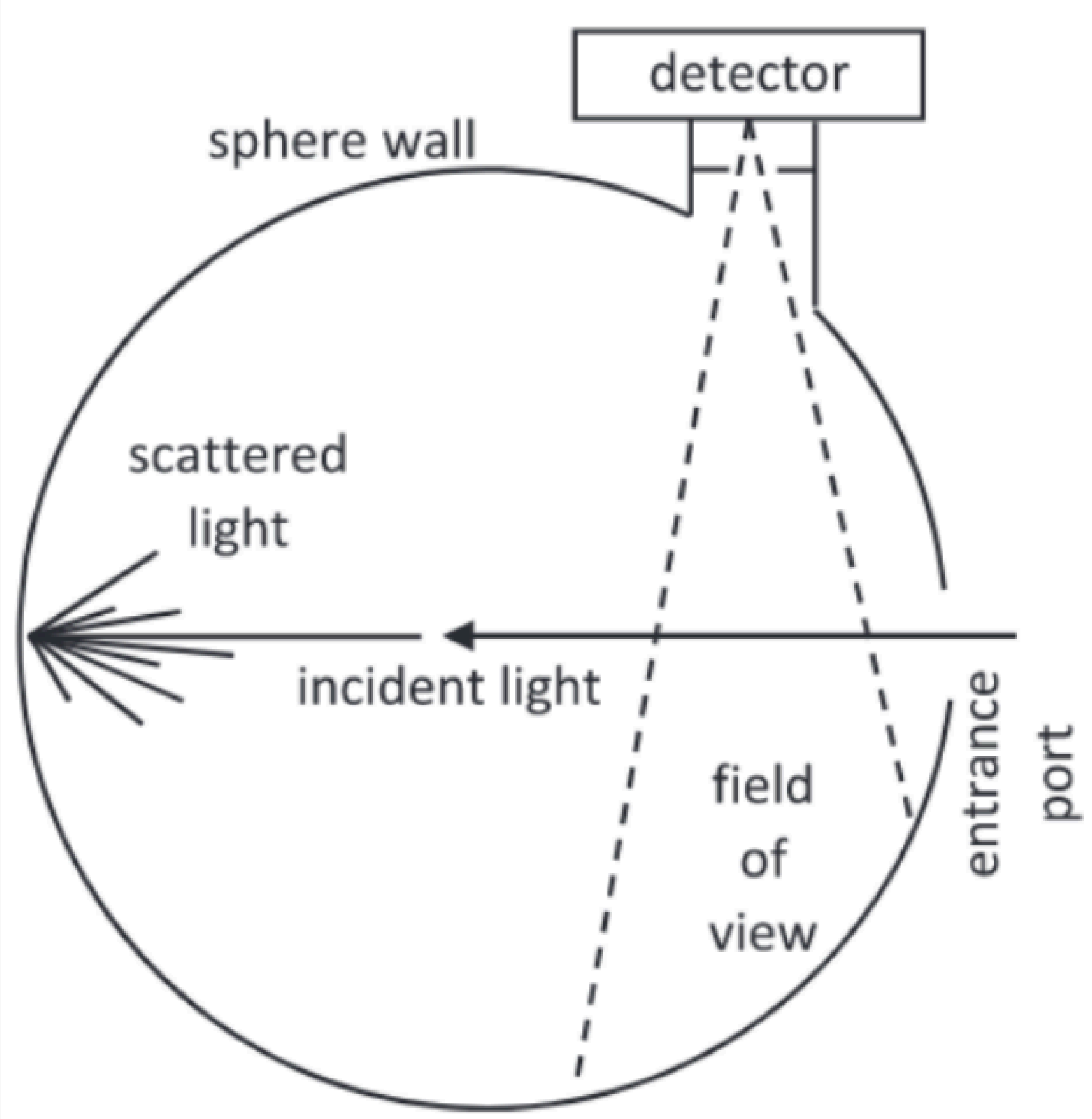




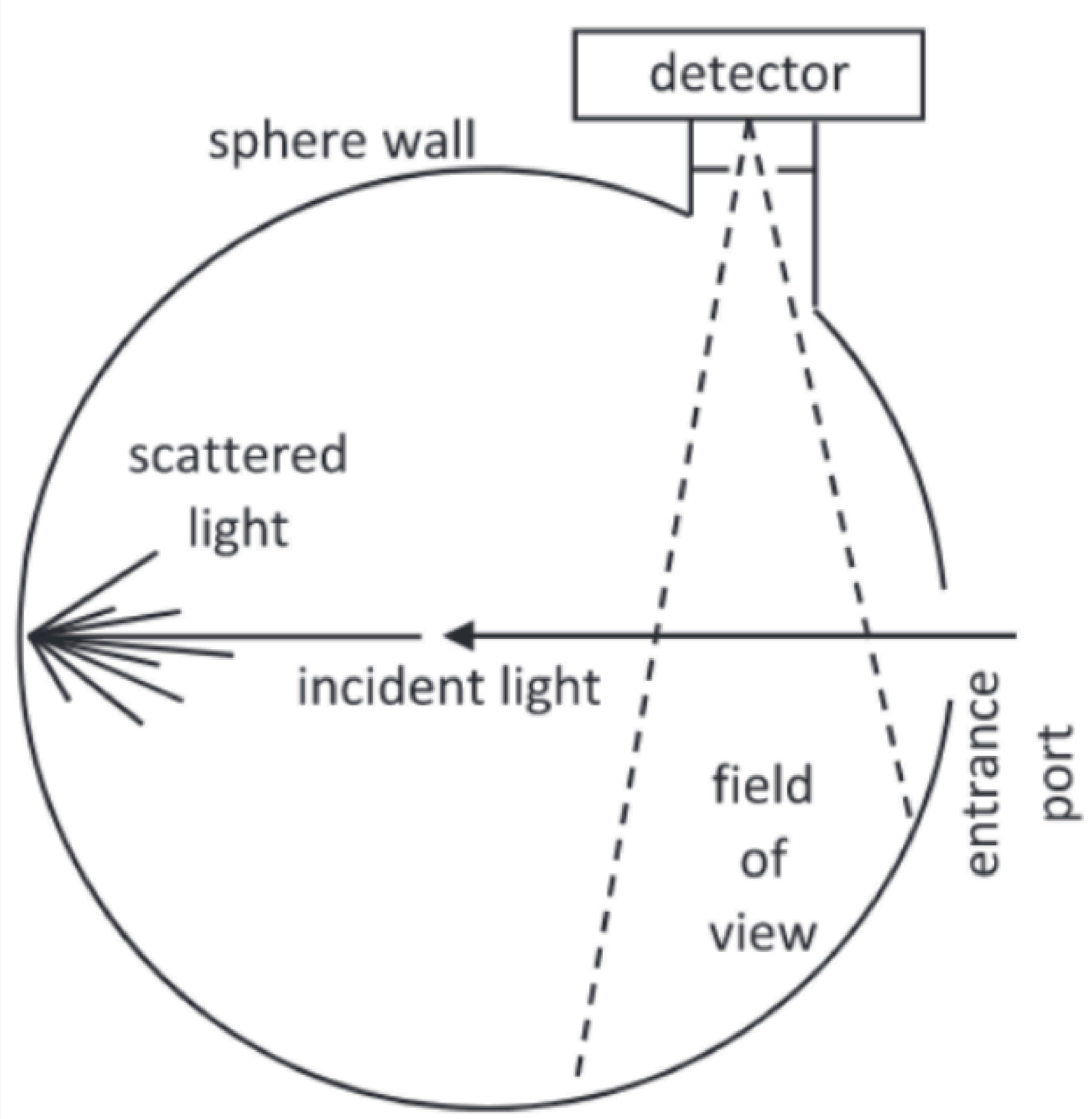
SOURCE - PhD thesis D. Estevez



$$\Delta x_{pend}(f) = -\frac{1}{M} \cdot \frac{2\cos(\theta)}{c} \cdot \frac{\Delta P_{ref}(f)}{(2\pi f)^2}$$



$$V_{output} = \rho.P$$

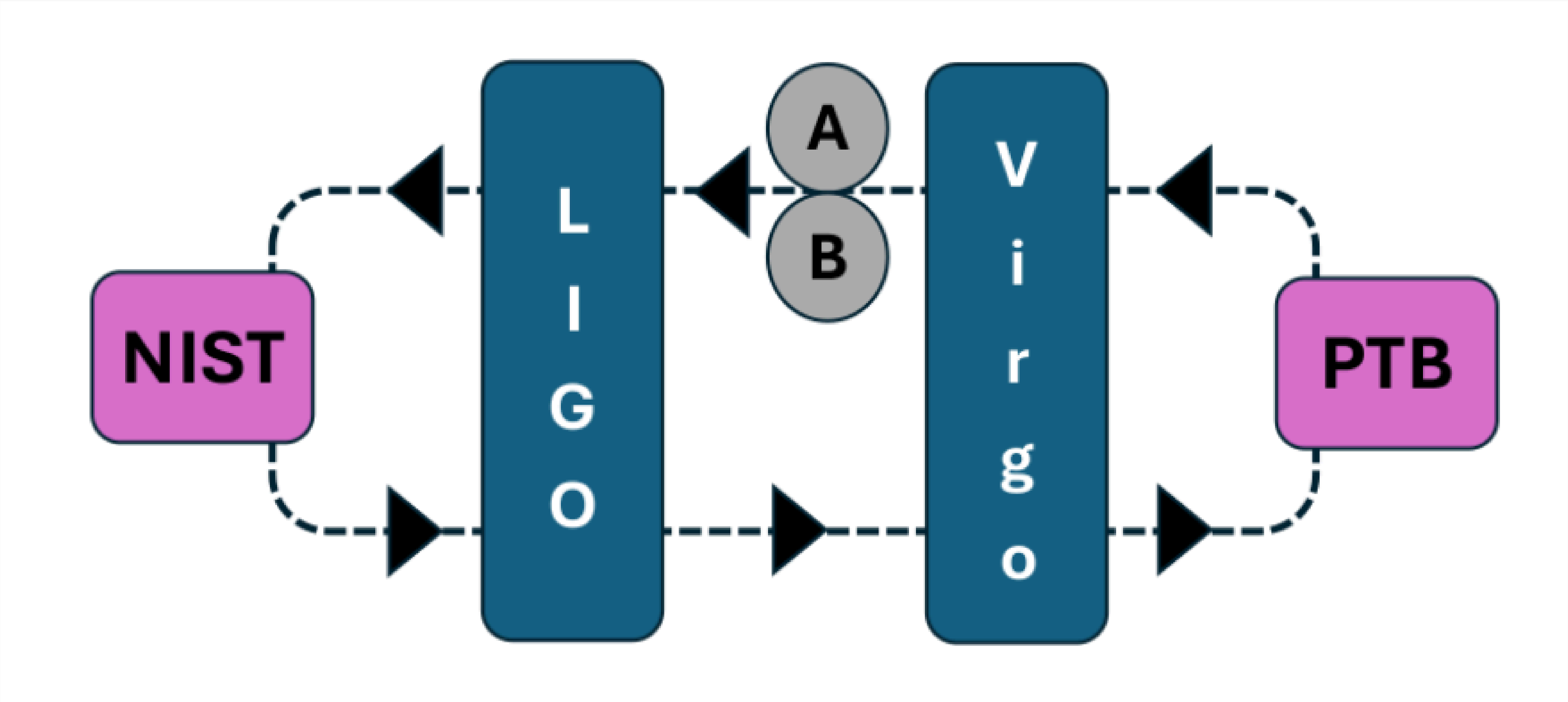


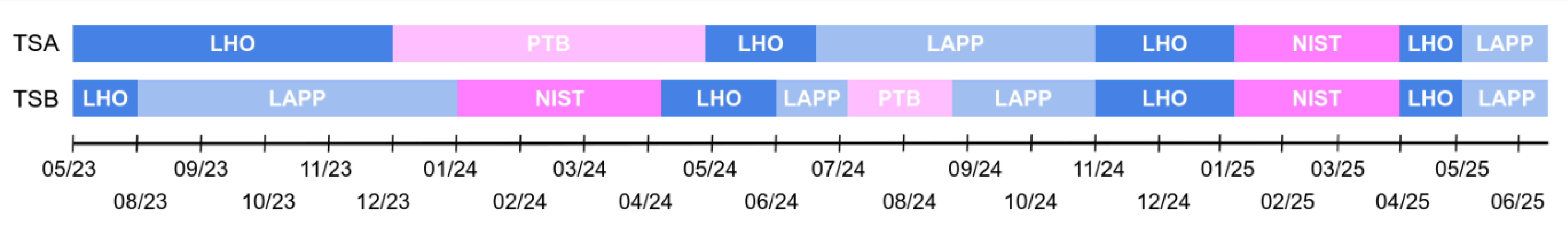
$$V_{output} = \rho . P$$

Responsivity

Source	**Relative uncertainty [%]**
Rx responsivity	0.22
Deformation model	0.38
Incident angle, $\cos(\theta)$	0.16
ETM mass, M	0.05
ETM rotation	0.09
Optical efficiency	0.10
Total	**0.49**

Intercalibration


NIST
LIGO
A
B
Virgo
PTB


TSA
LHO
PTB
LHO
LAPP
LHO
NIST
LHO
LAPP
TSB
LHO
LAPP
NIST
LHO
LAPP
PTB
LAPP
LHO
NIST
LHO
LAPP
05/23
08/23
09/23
10/23
11/23
12/23
01/24
02/24
03/24
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05/24
06/24
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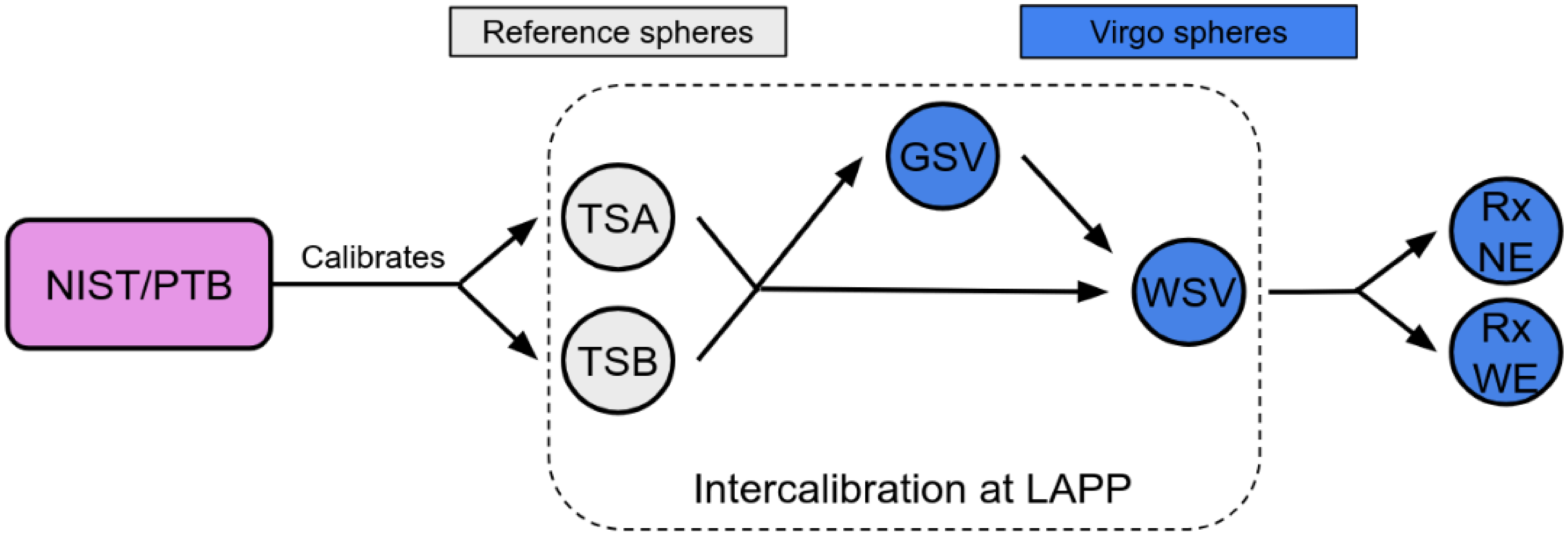
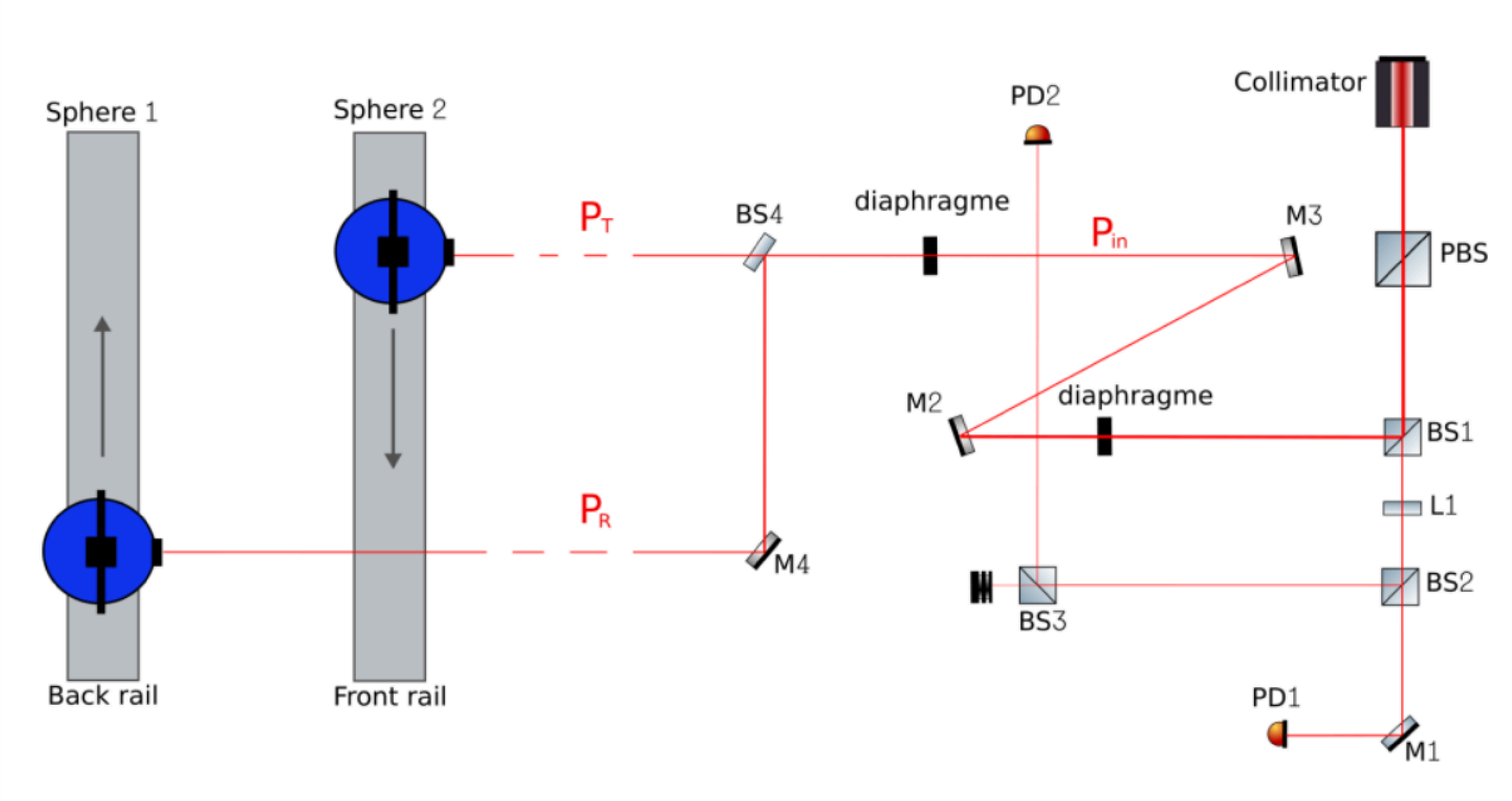
06/25



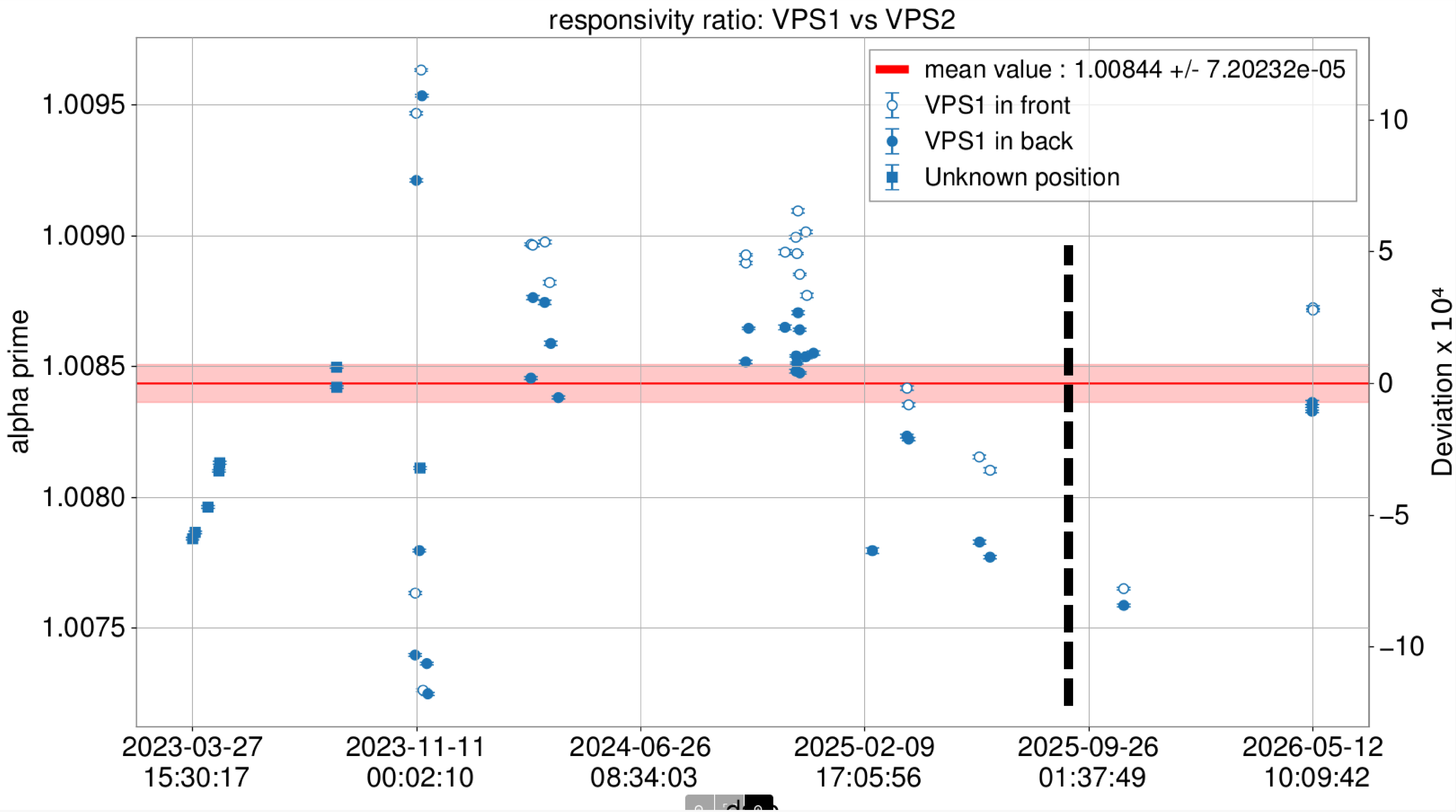
Reference spheres
Virgo spheres
NIST/PTB
Calibrates
TSA
TSB
GSV
WSV
Rx NE
Rx WE
Intercalibration at LAPP

Intercalibration setup



$$\alpha = \sqrt{\frac{V_{raw}(T.P_{in})}{V_{ref}(T.P_{in})}\frac{V_{raw}(R.P_{in})}{V_{ref}(R.P_{in})}}$$

WSV / GSV ratio monitoring



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ETM mass, M	0.05
ETM rotation	0.09
Optical efficiency	0.10
Total	**0.49**

Source	Relative uncertainty [%]
WSV responsivity	0.11
Rx calibration	0.19
Total	**0.22**

Linearity measurements of integrating spheres

Intercalibration

Done P_laser = 0.3W

Calibration transfer from WSV to Rx (on site)

Done P_laser = 1.3W

Source	Relative uncertainty [%]
Rx responsivity	0.22
Deformation model	0.38
Incident angle, $\cos(\theta)$	0.16
ETM mass, M	0.05
ETM rotation	0.09
Optical efficiency	0.10
Total	**0.49**

Source	Relative uncertainty [%]
WSV responsivity	0.11
Rx calibration	0.19
Total	**0.22**

$$V_{sphere}(\phi_1 + \phi_2) = V_{sphere}(\phi_1) + V_{sphere}(\phi_2)$$

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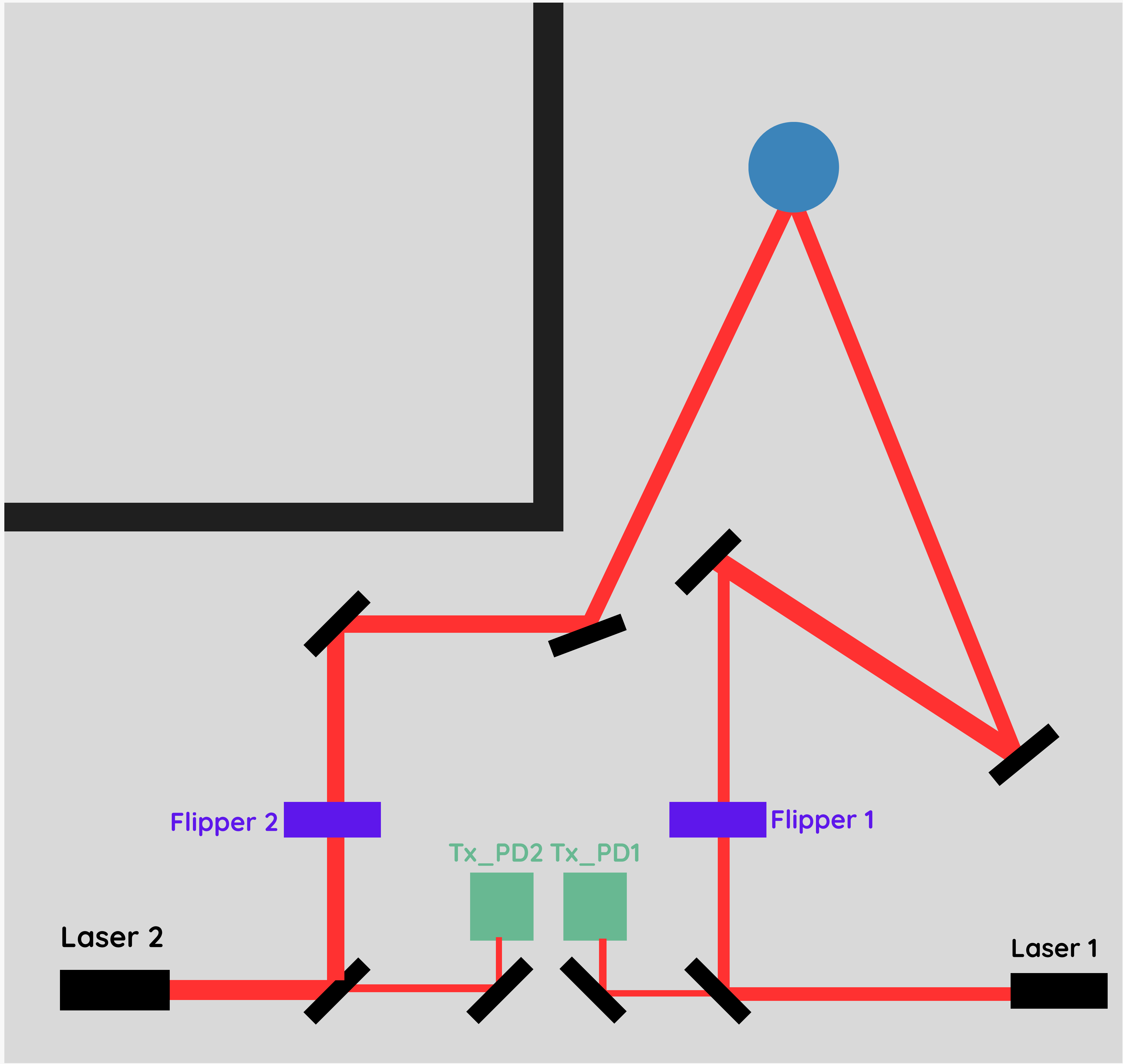
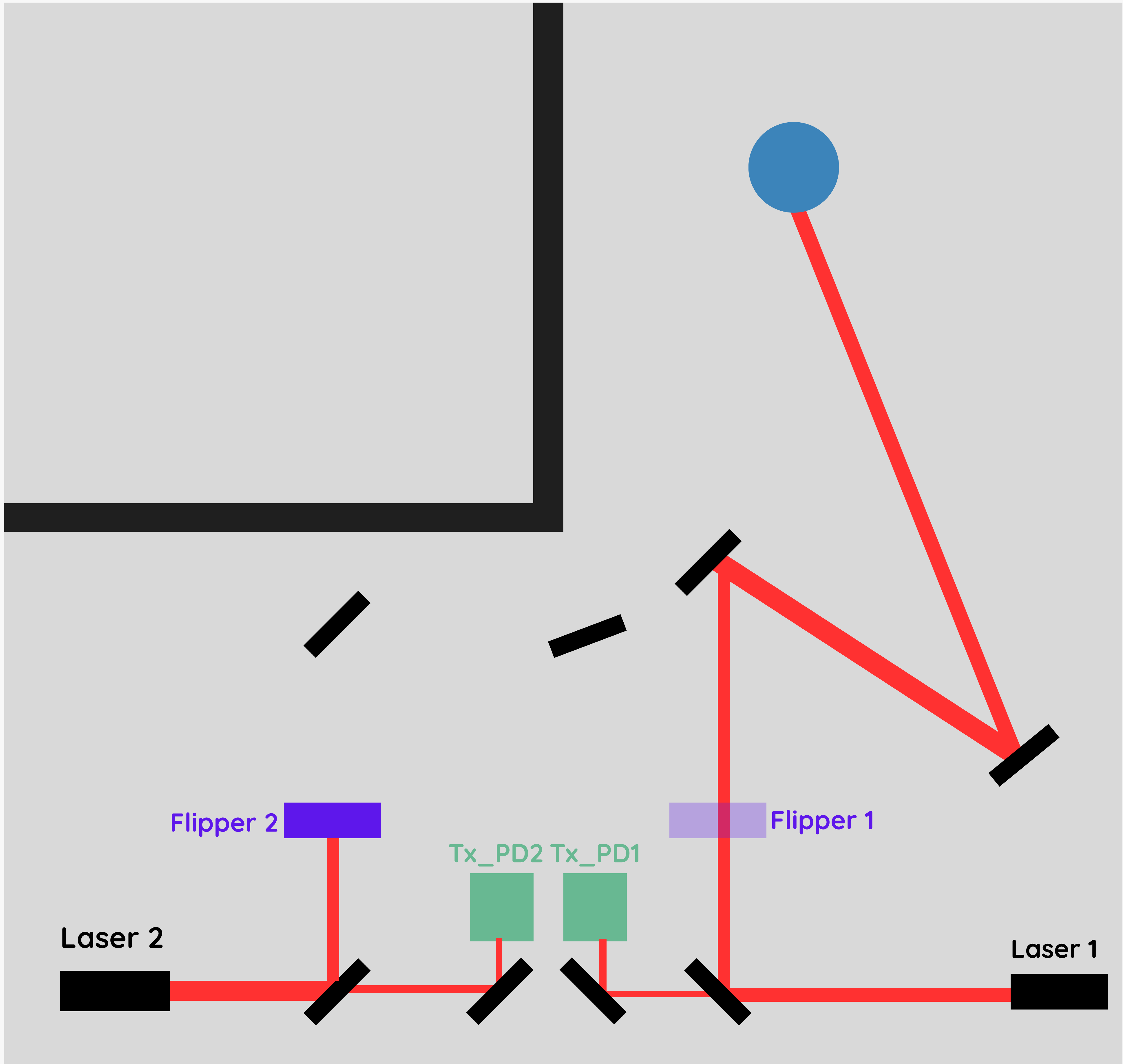
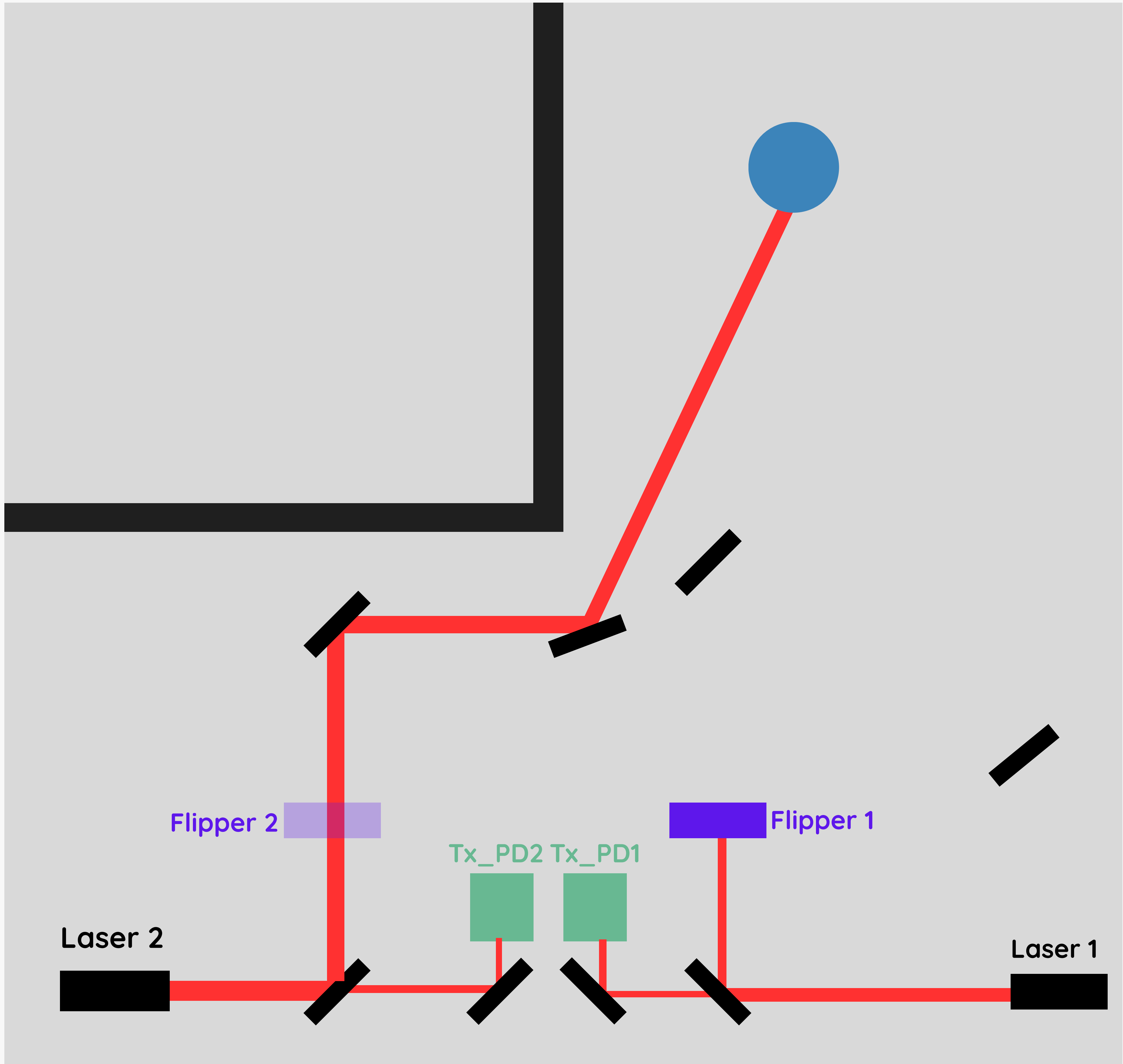


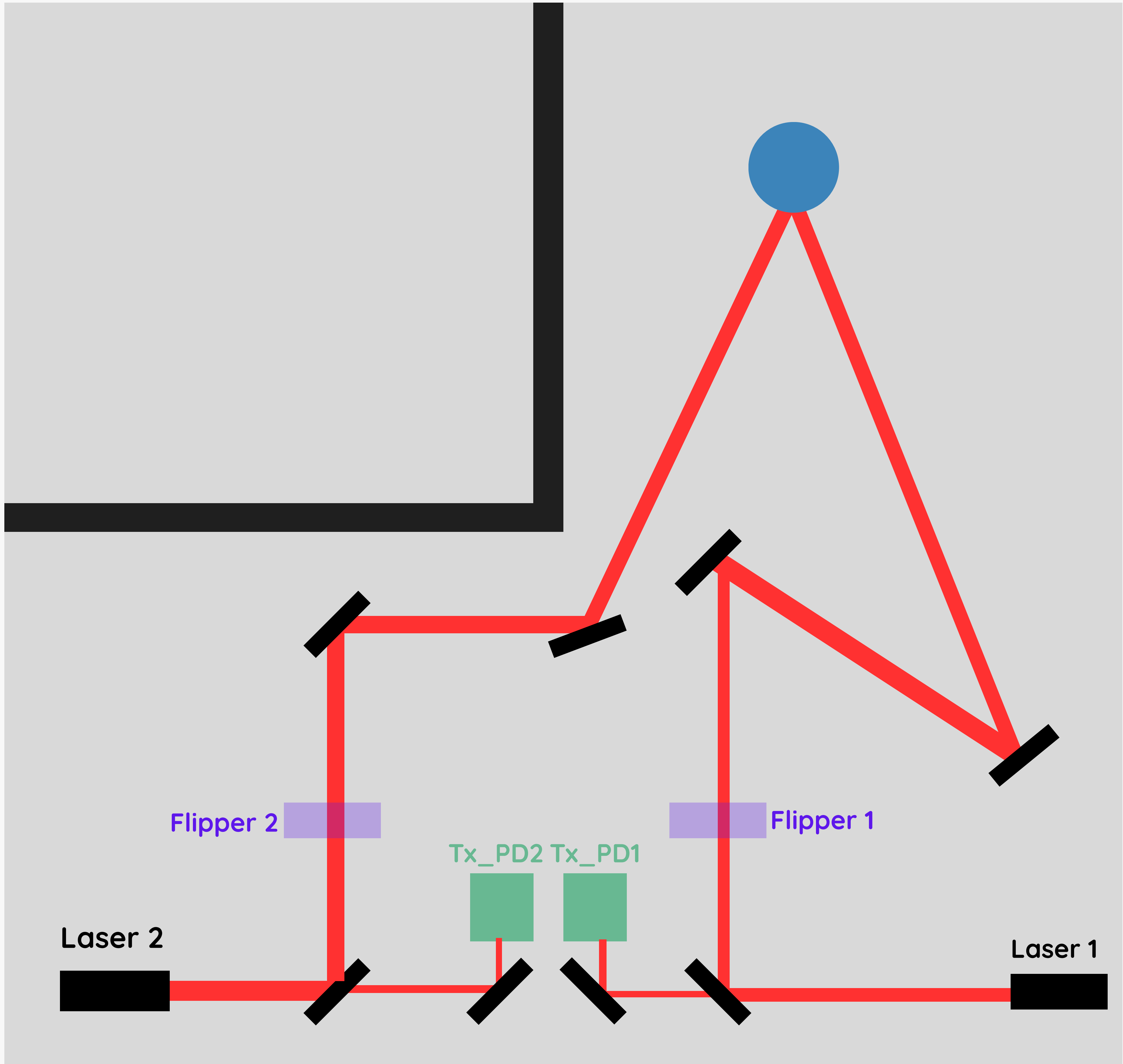
$$V_{sphere}(\phi_1 + \phi_2) = V_{sphere}(\phi_1) + V_{sphere}(\phi_2)$$

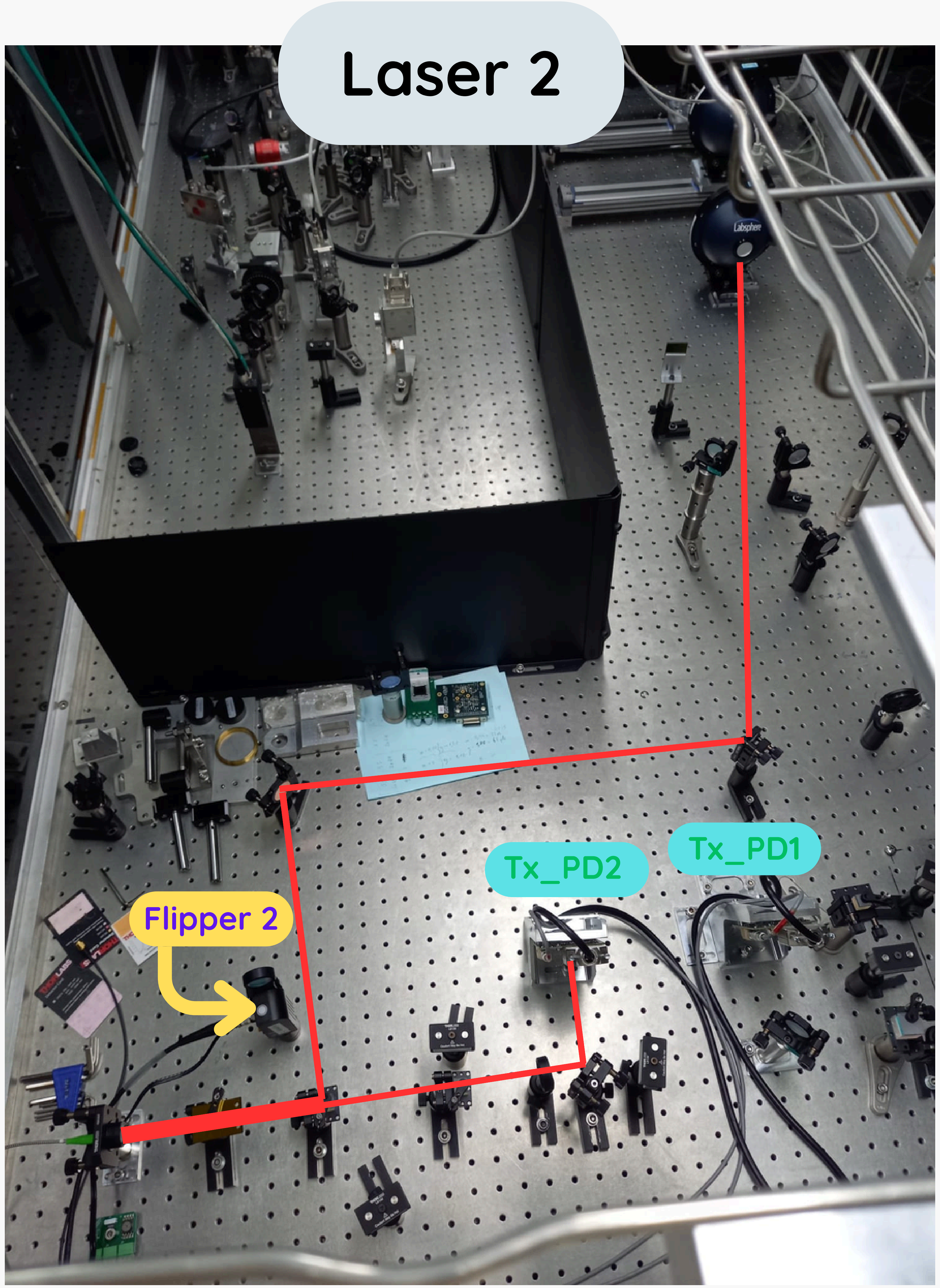


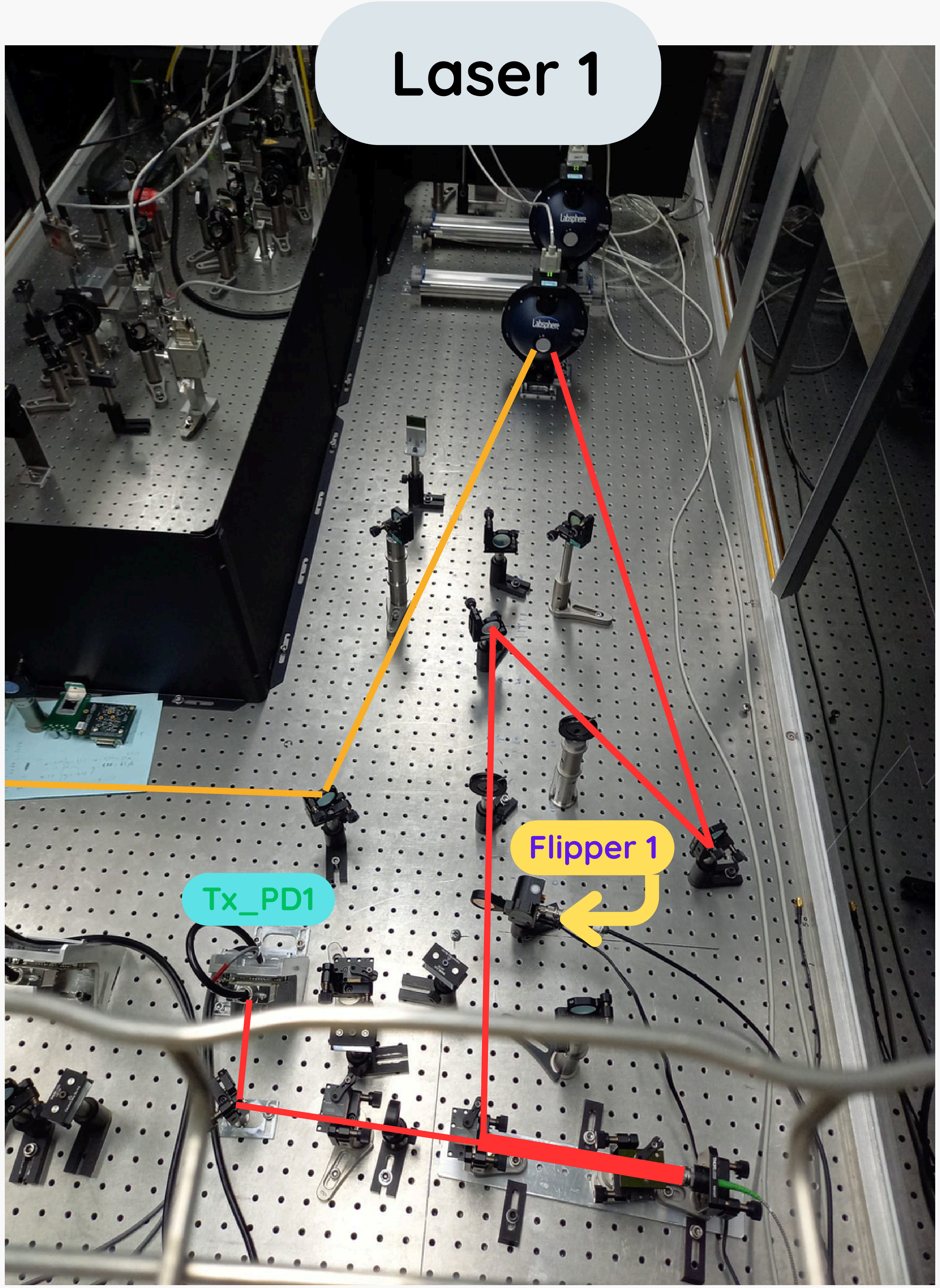
$$V_{sphere}(\phi_1 + \phi_2) = V_{sphere}(\phi_1) + V_{sphere}(\phi_2)$$



$$V_{sphere}(\phi_1 + \phi_2) = V_{sphere}(\phi_1) + V_{sphere}(\phi_2)$$




Laser 2
Tx_PD2
Tx_PD1
Flipper 2


Laser 1
Flipper 1
Tx_PD1

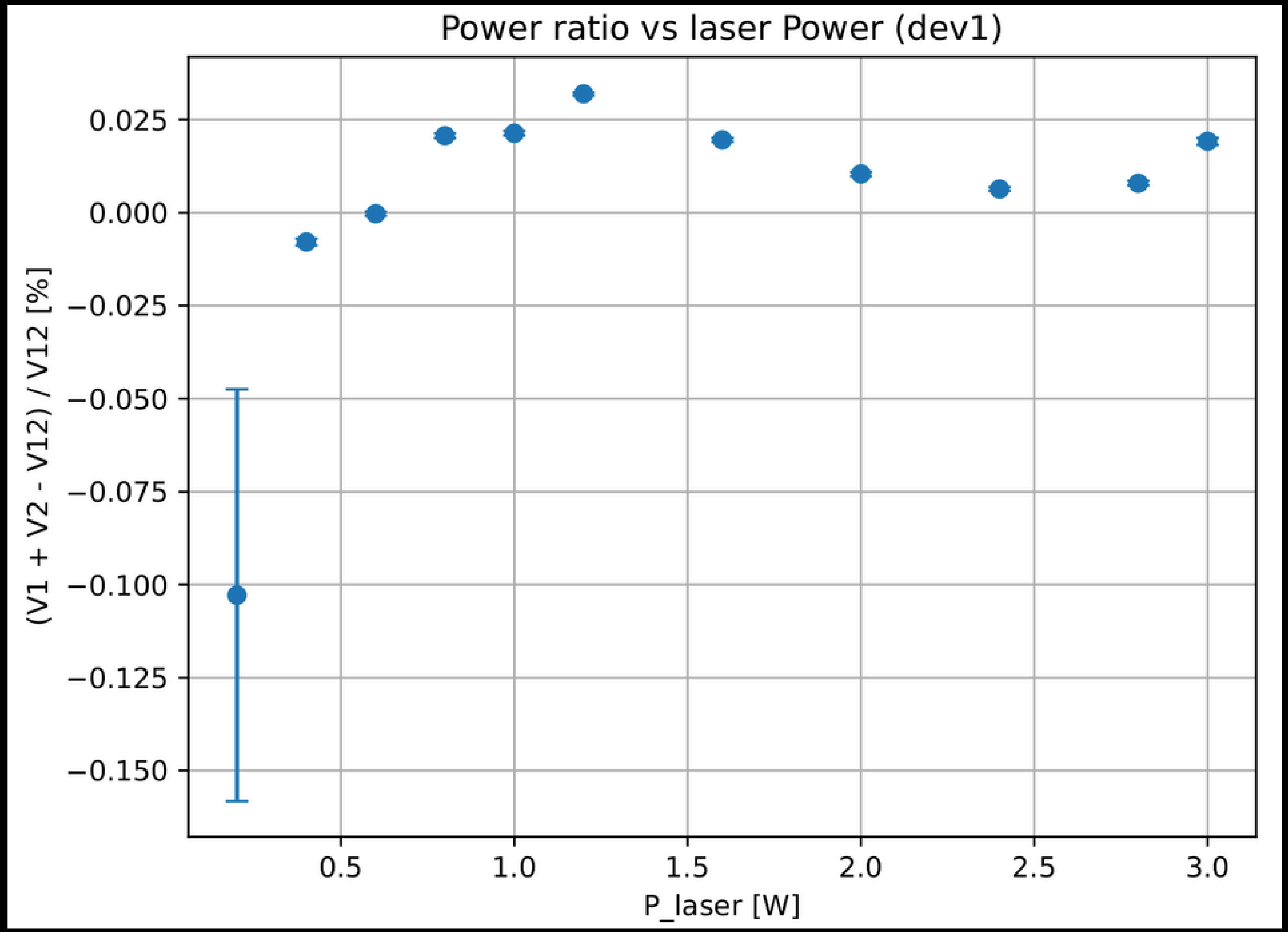
$$\frac{[V(\phi_1)+V(\phi_2)]-V(\phi_1+\phi_2)}{V(\phi_1+\phi_2)}$$

Correction

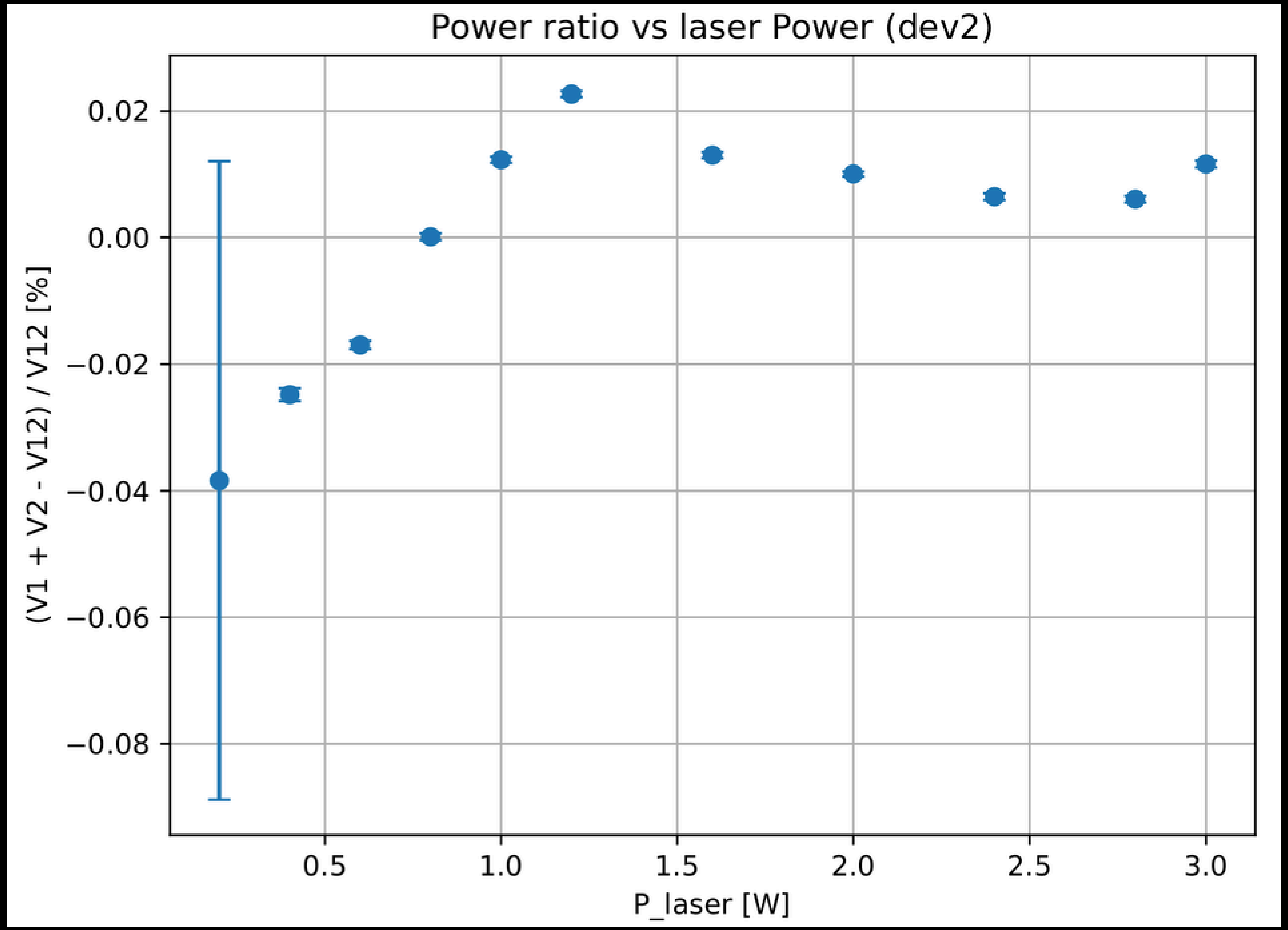
Tension offset + Temperature

WSV

GSV



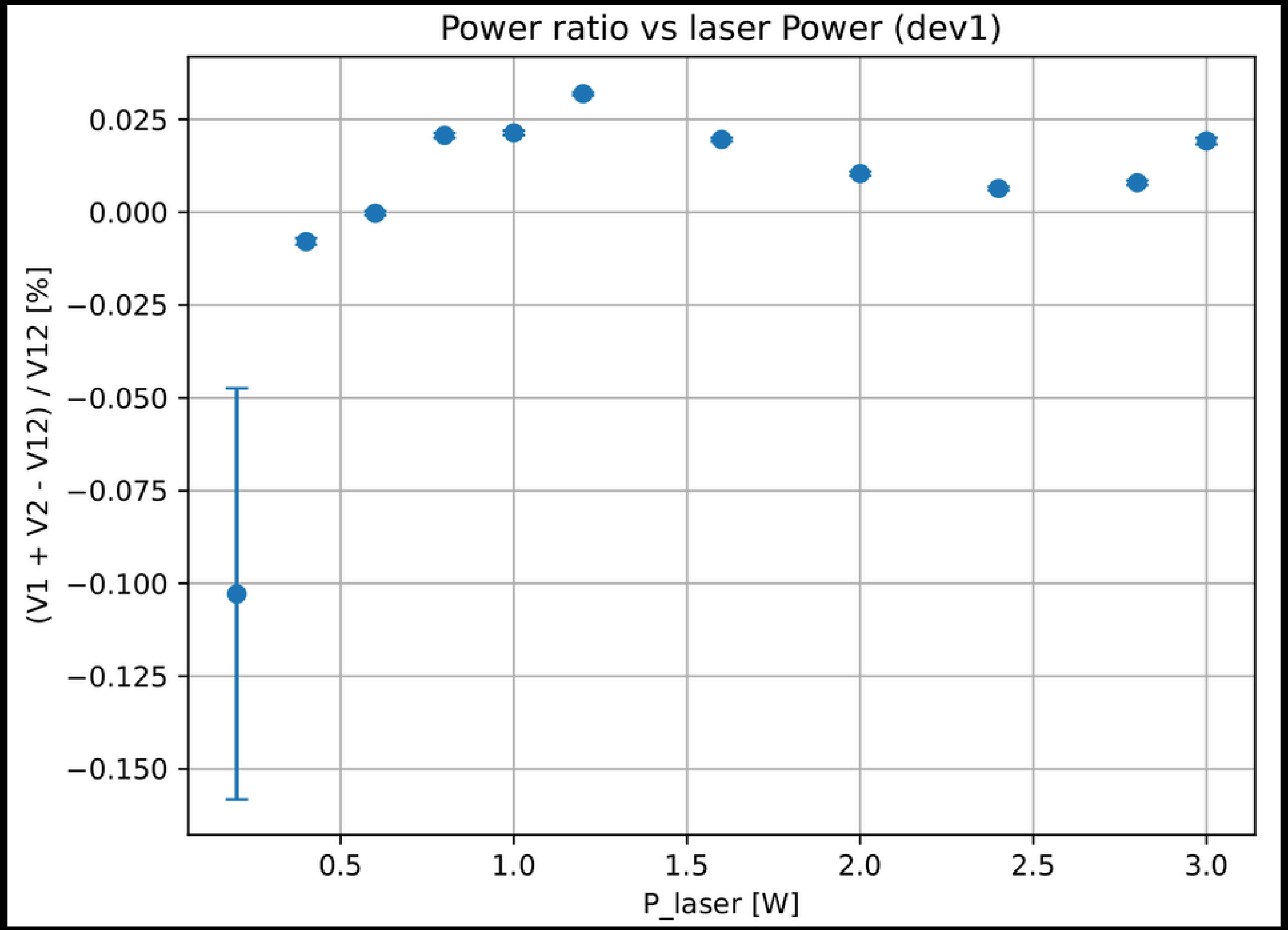
Power (L1 + L2) [W]



Power (L1 + L2) [W]

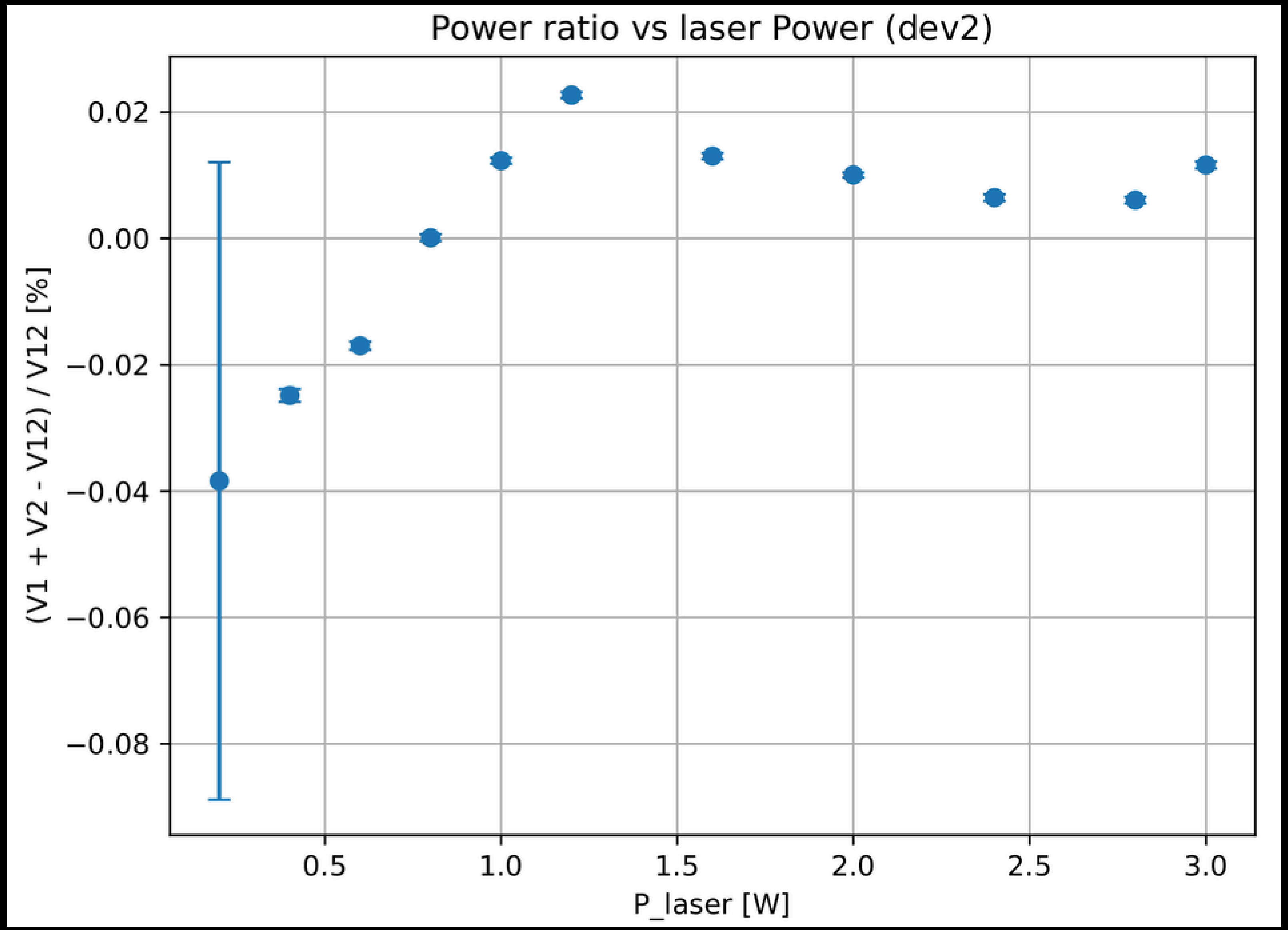
Spheres are linear at <0.1%

WSV



Power (L1 + L2) [W]

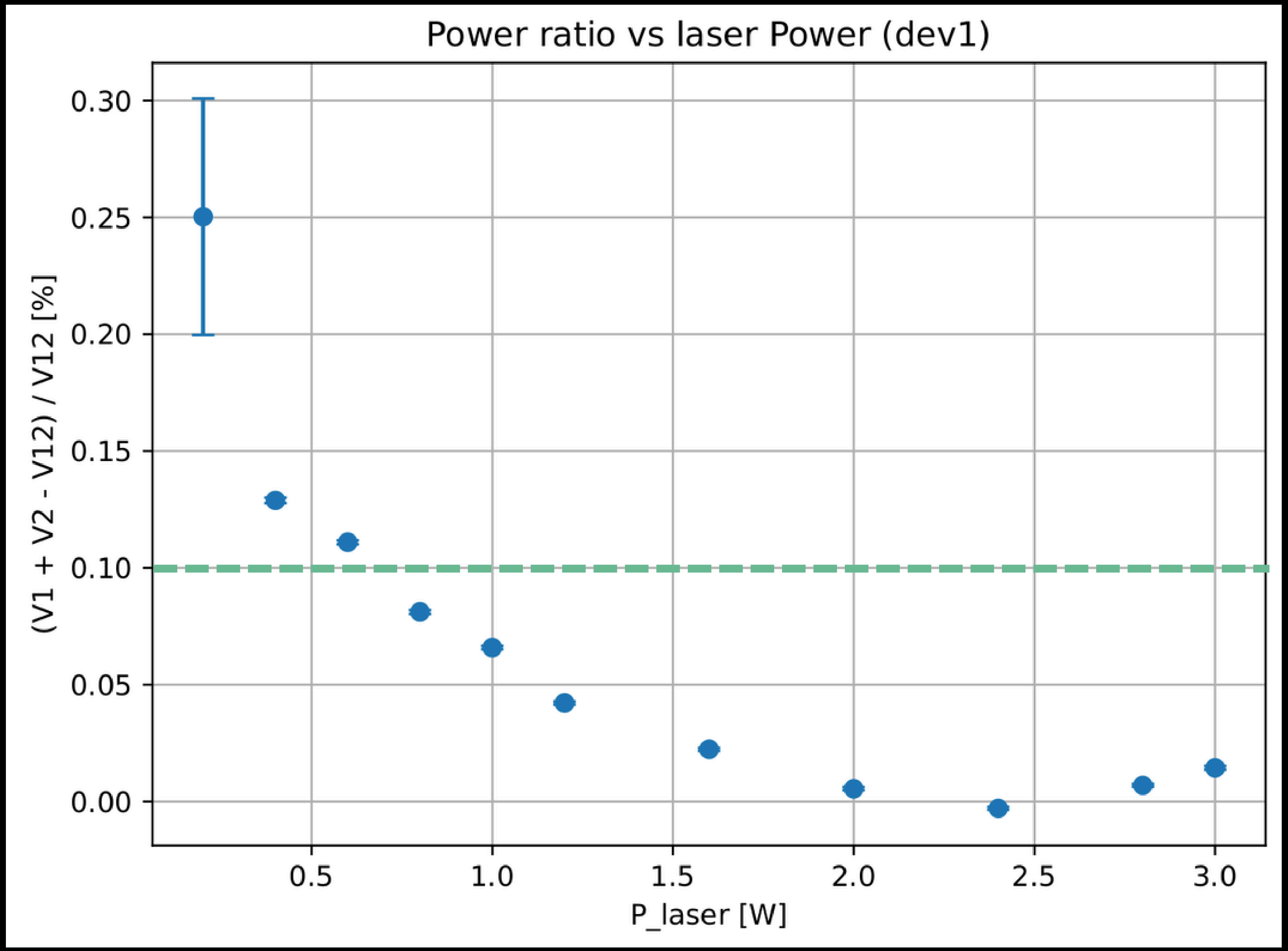
GSV



Power (L1 + L2) [W]

RxNE not linear below 0.1% everywhere

RxNE



Power (L1 + L2) [W]

NE bench mirror characterization

Source	Relative uncertainty [%]
Rx responsivity	0.22
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Incident angle, $\cos(\theta)$	0.16
ETM mass, M	0.05
ETM rotation	0.09
Optical efficiency	0.10
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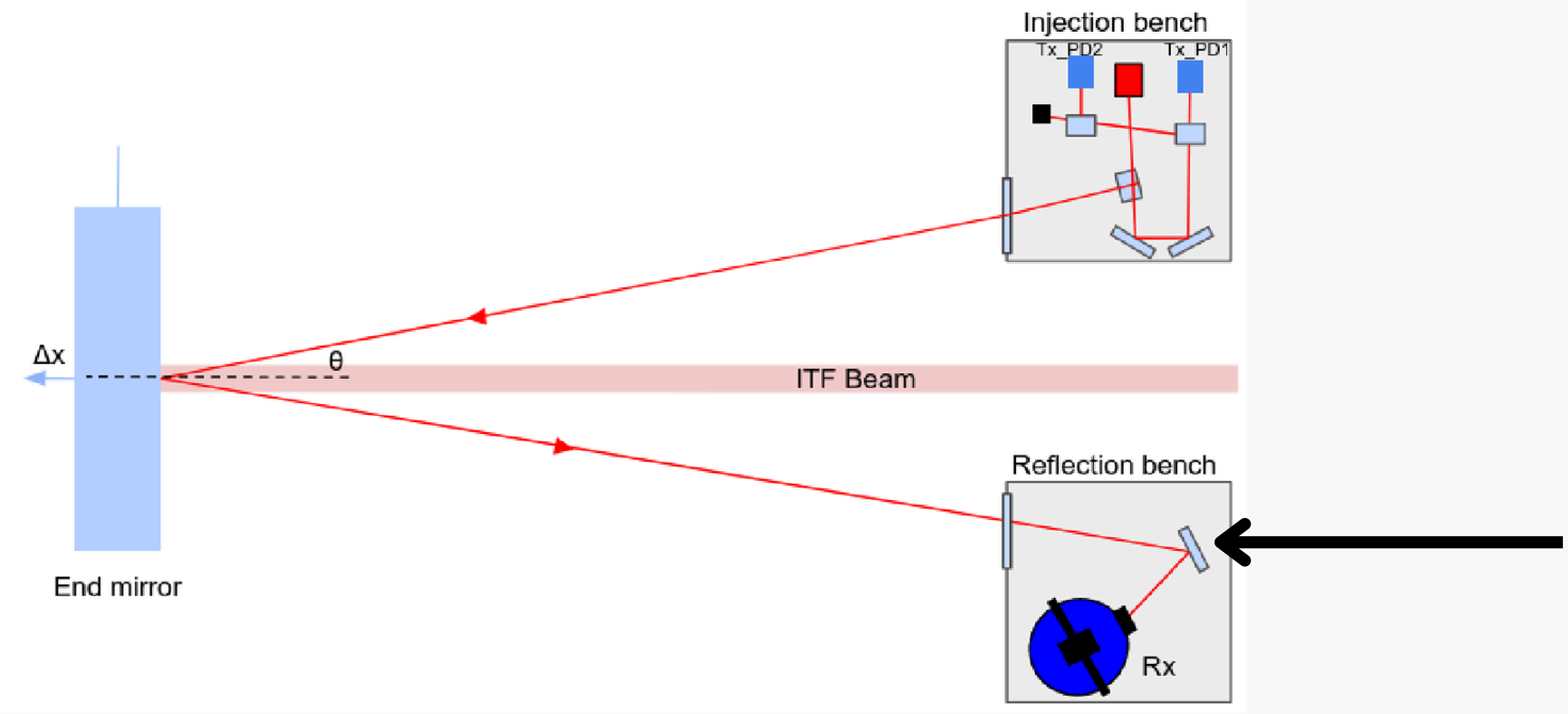
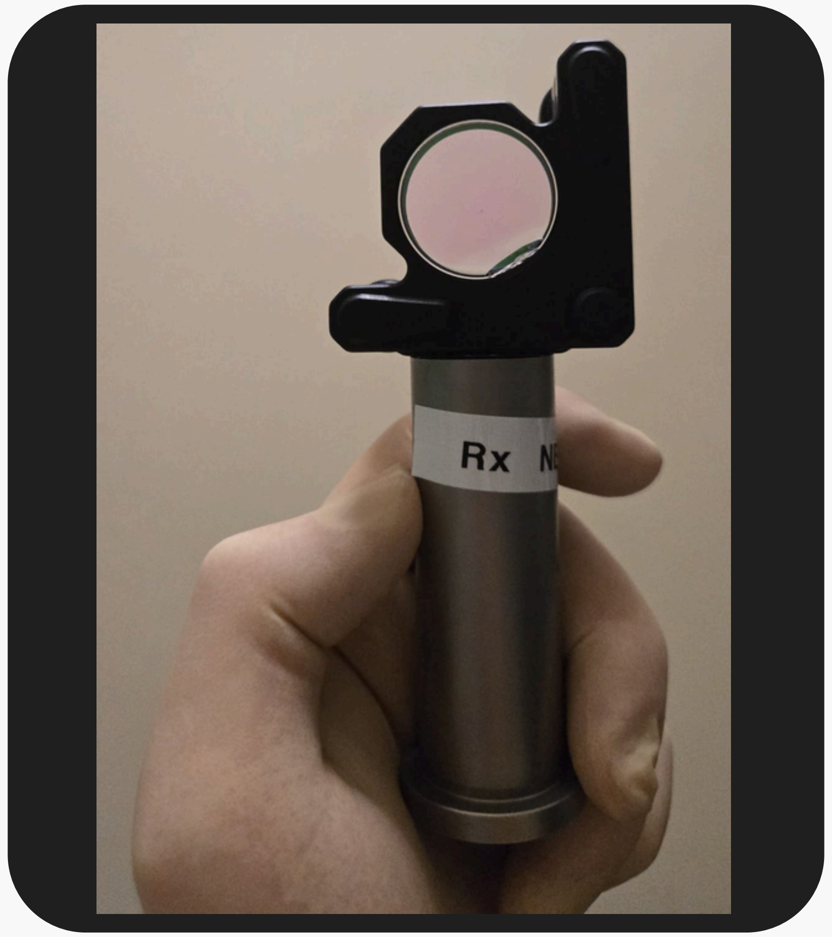
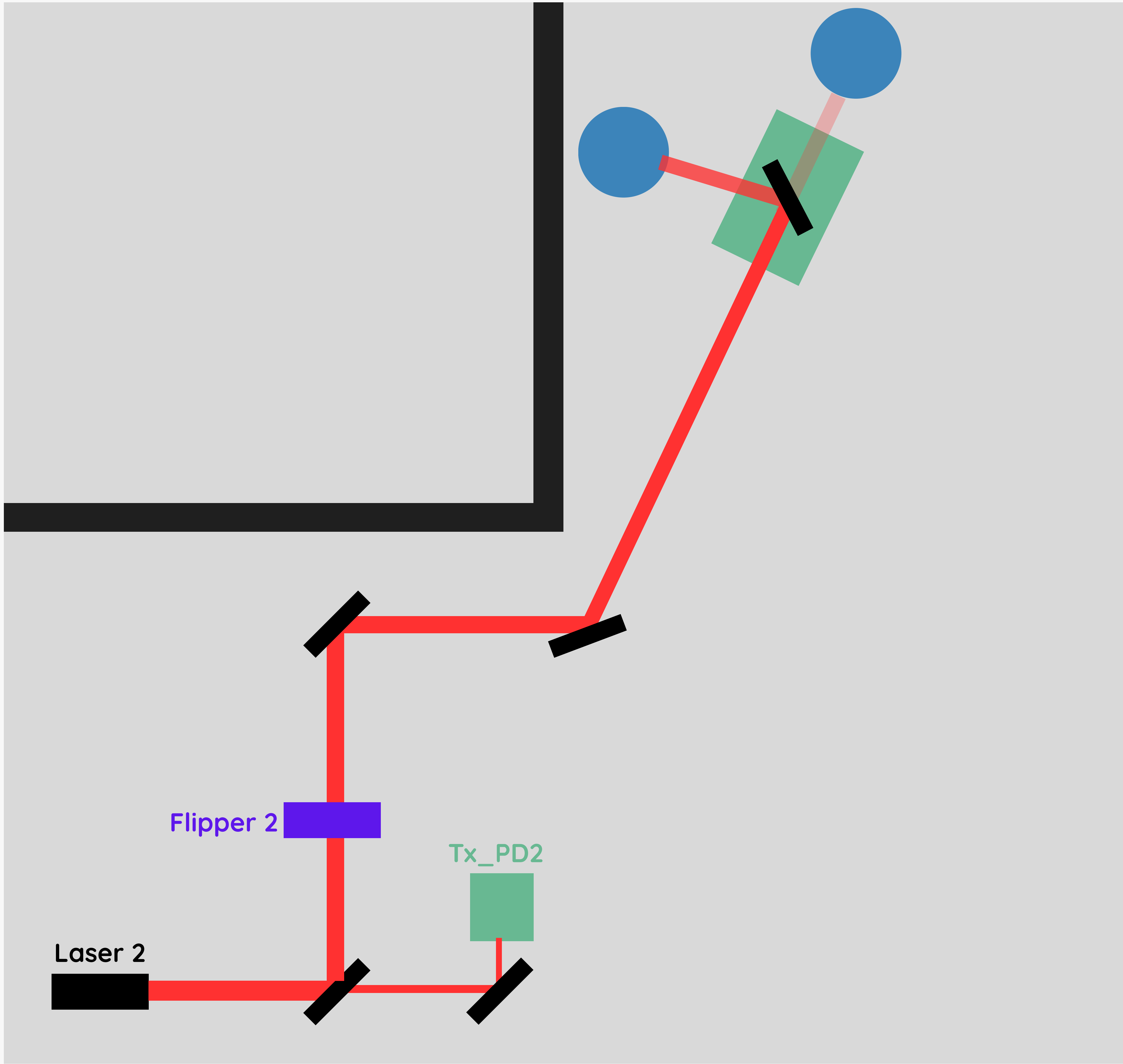

Injection bench
Tx_PD2
Tx_PD1
Δx
θ
ITF Beam
End mirror
Reflection bench
Rx


Rx


Flipper 2
Tx_PD2
Laser 2

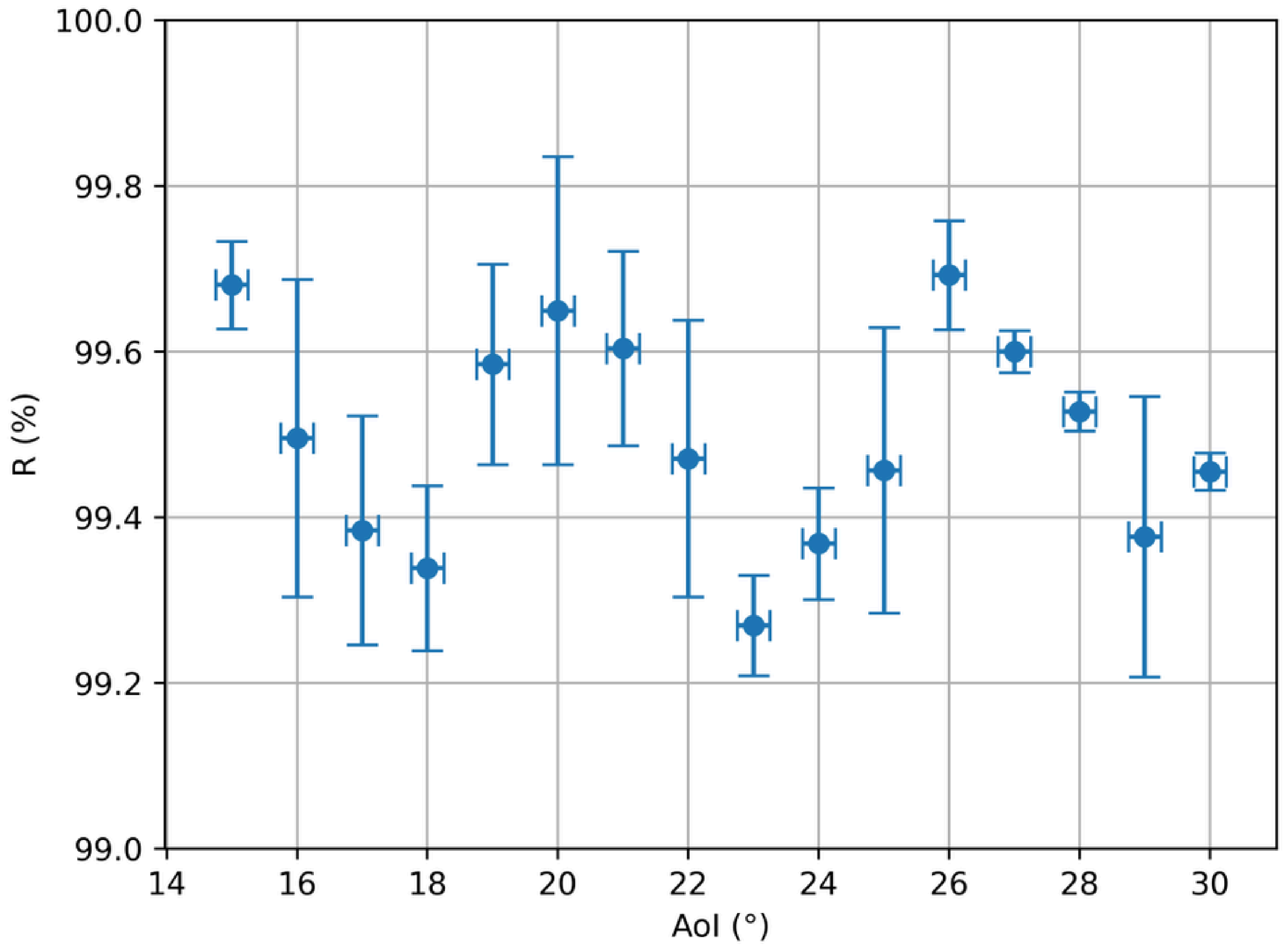


Figure 3: R as a function of AoI.

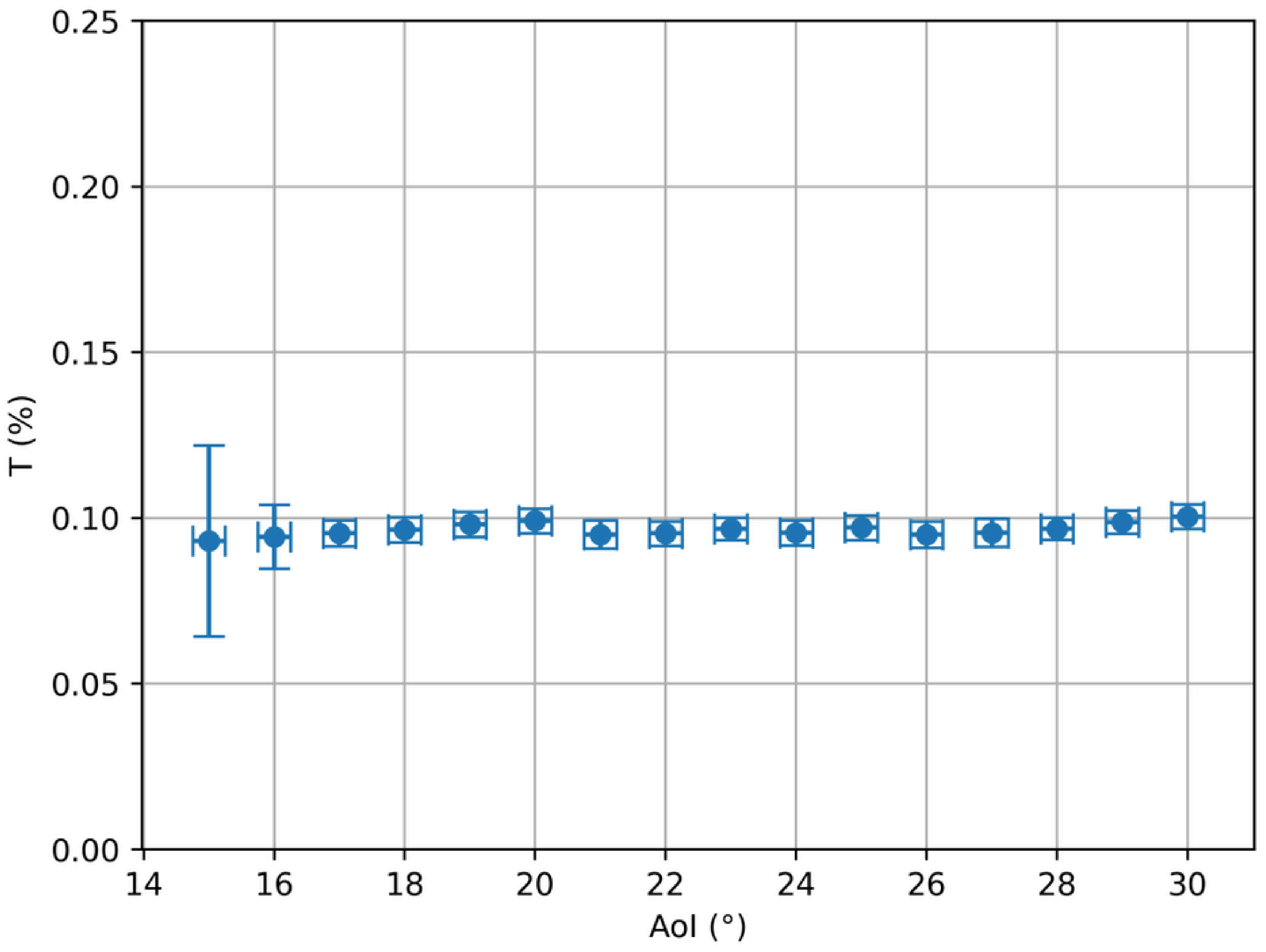
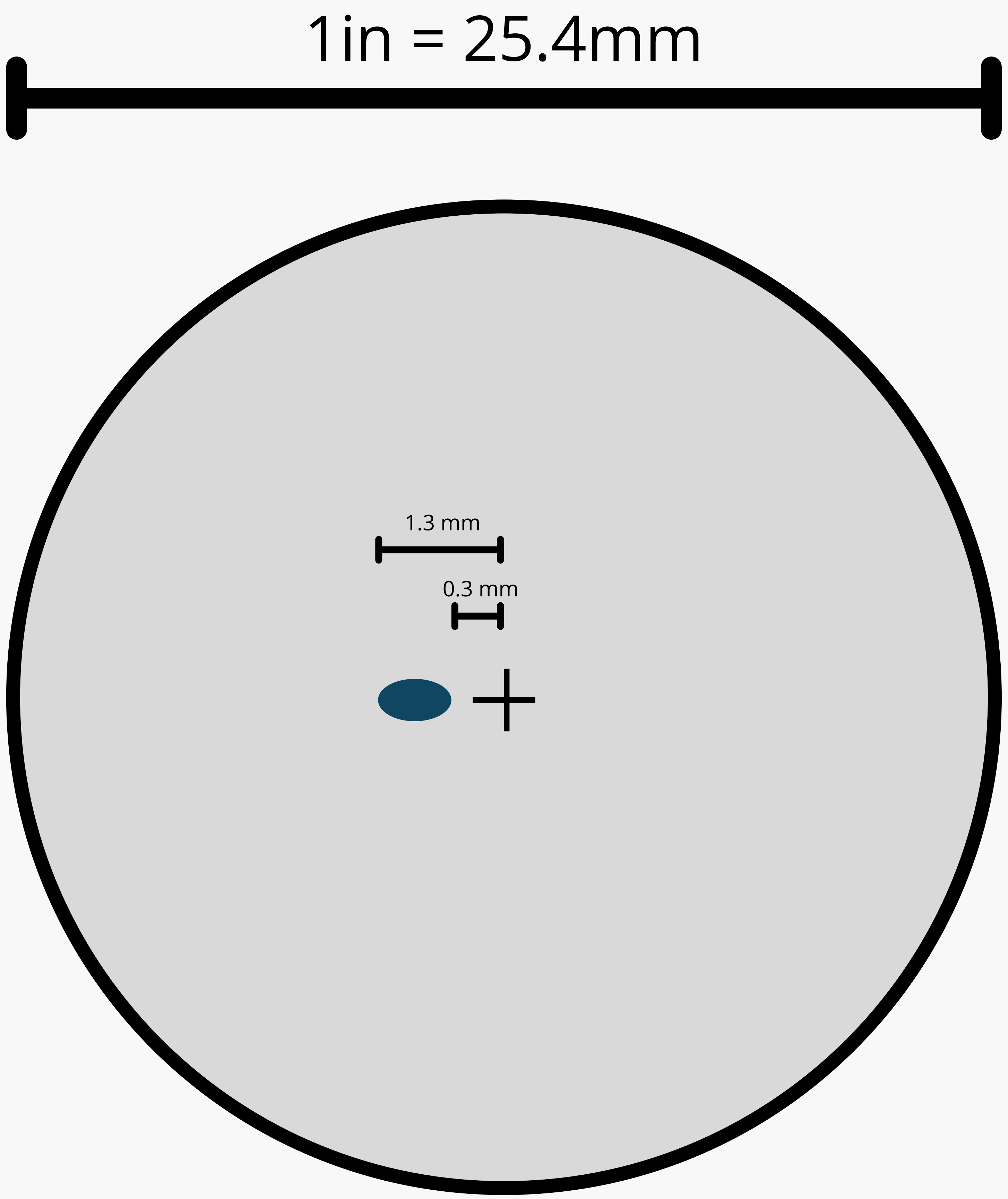
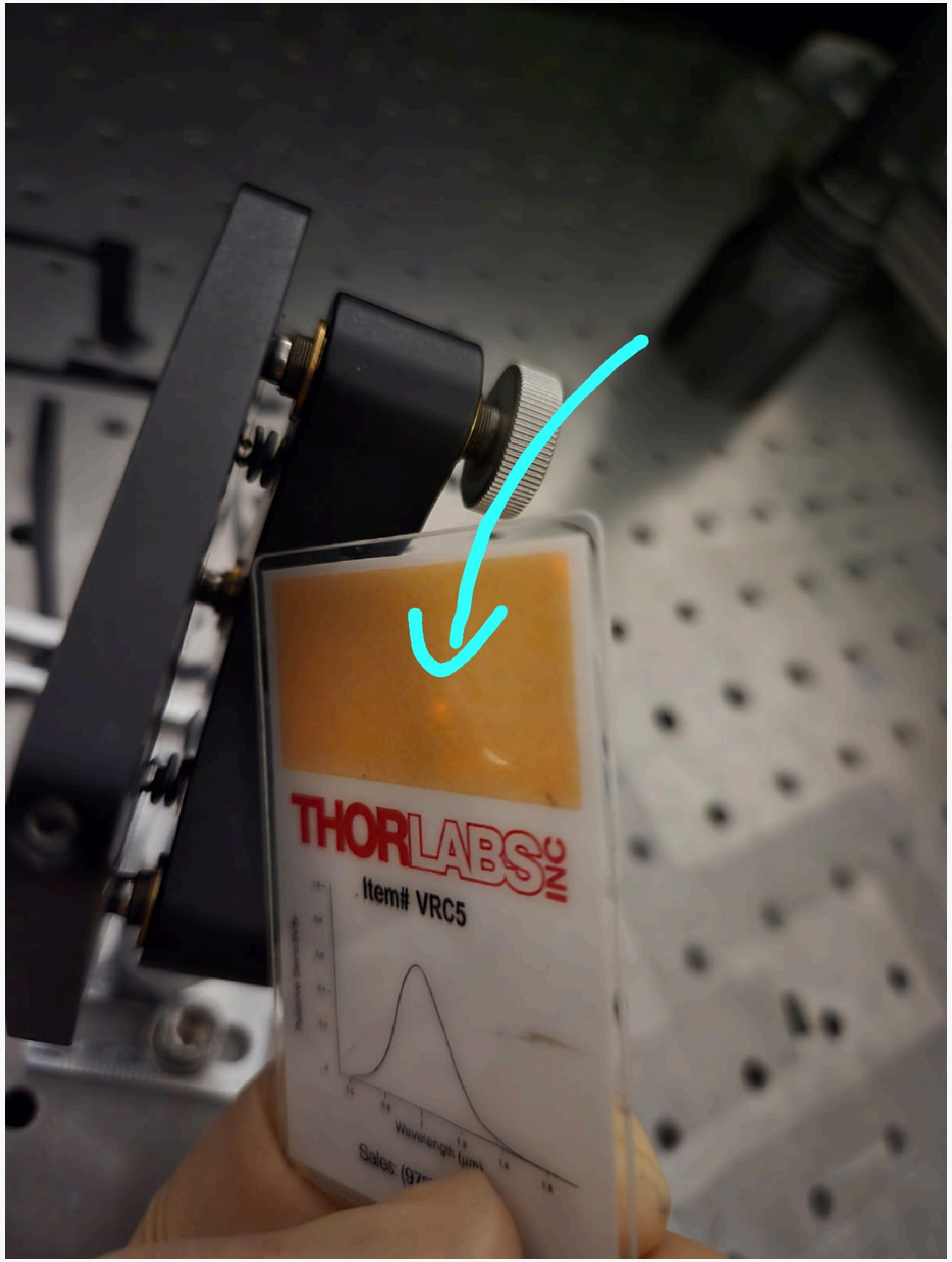
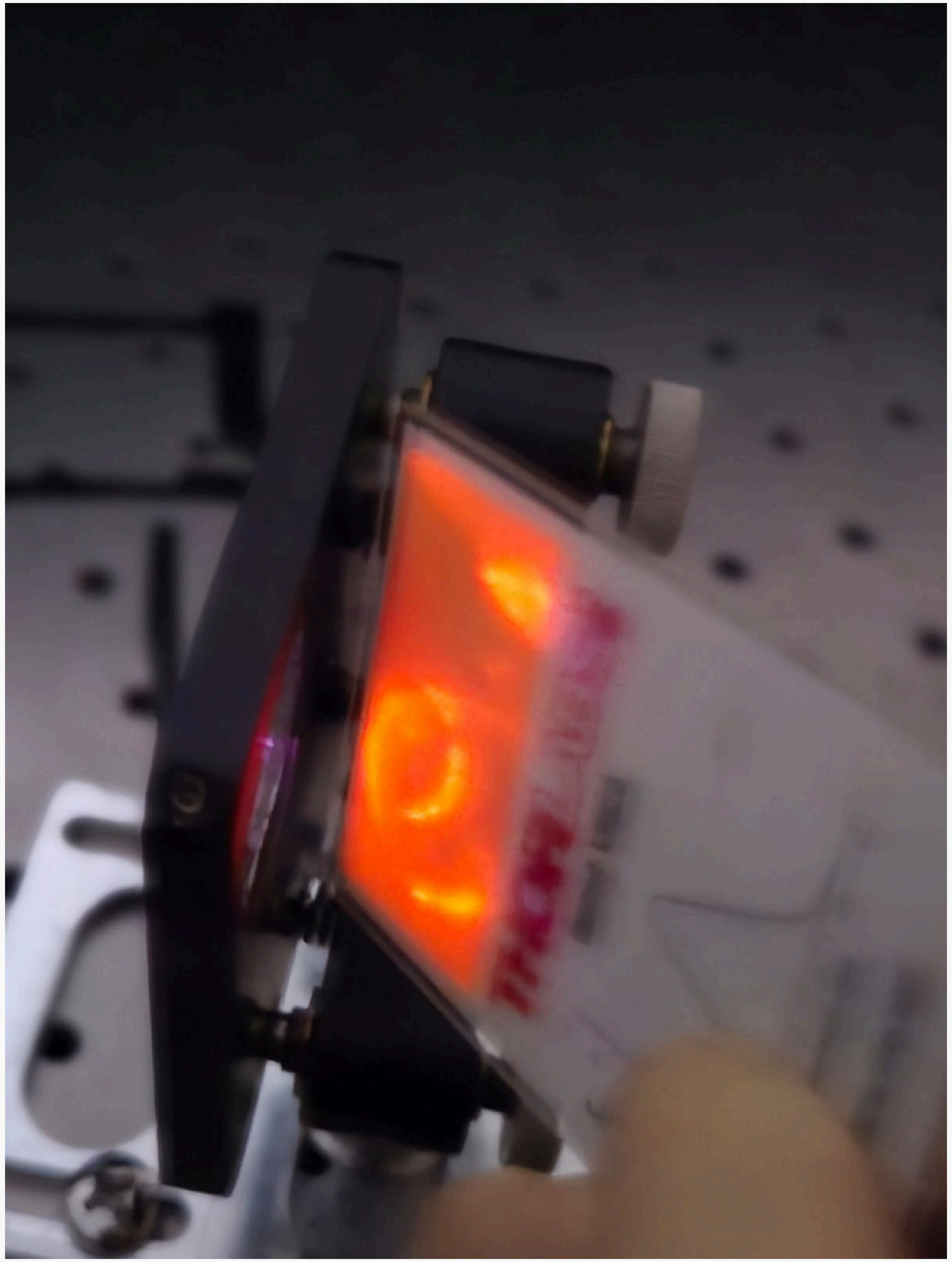


Figure 4: T as a function of AoI.

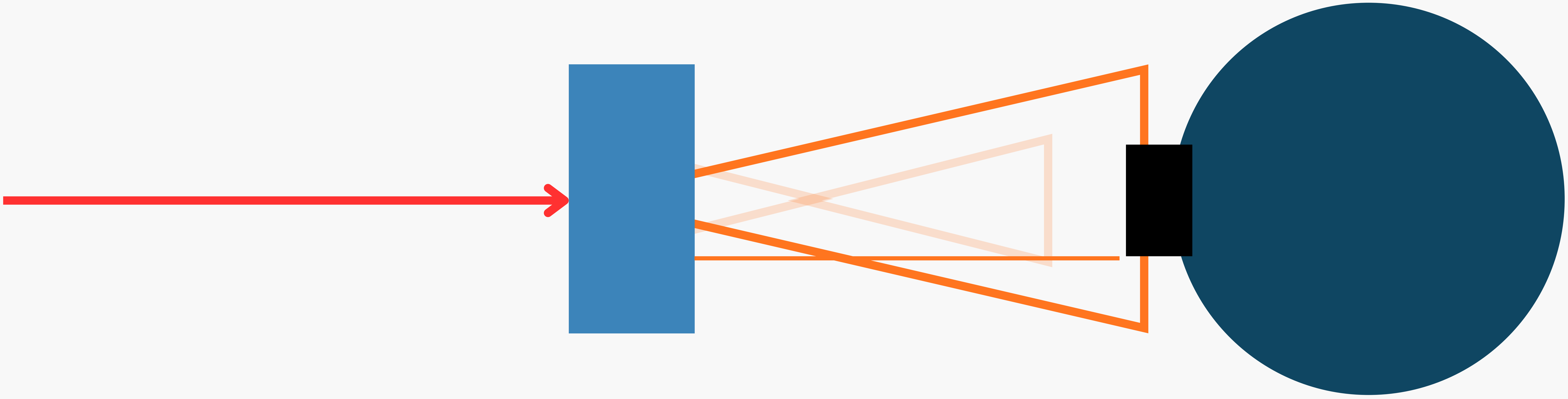


Defect ~1mm on the left from the center


THORLABS INC
Item# VRC5

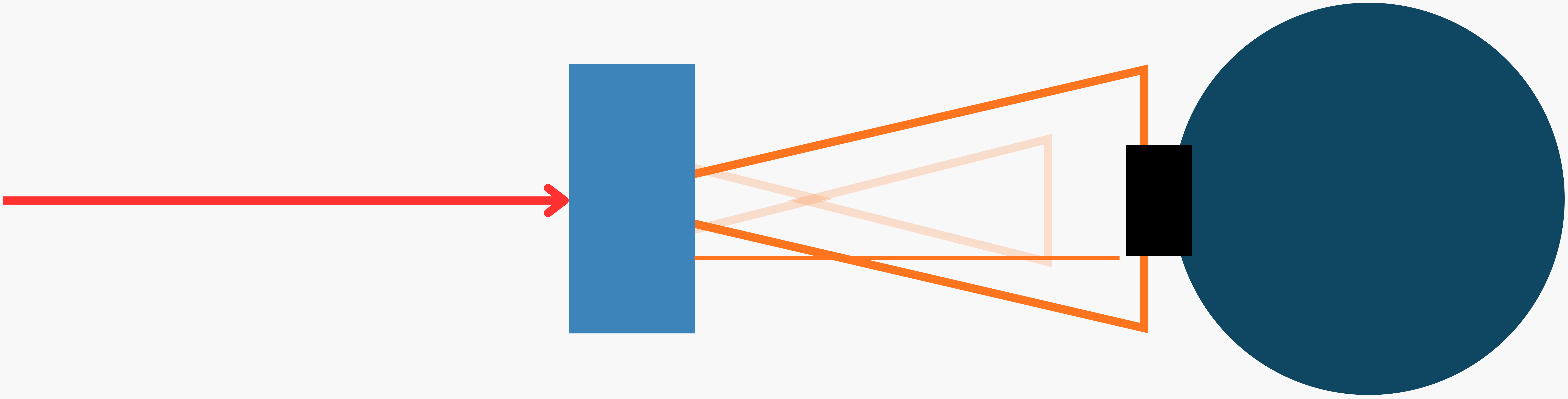



THORLABS



Mirrors to be changed

:(



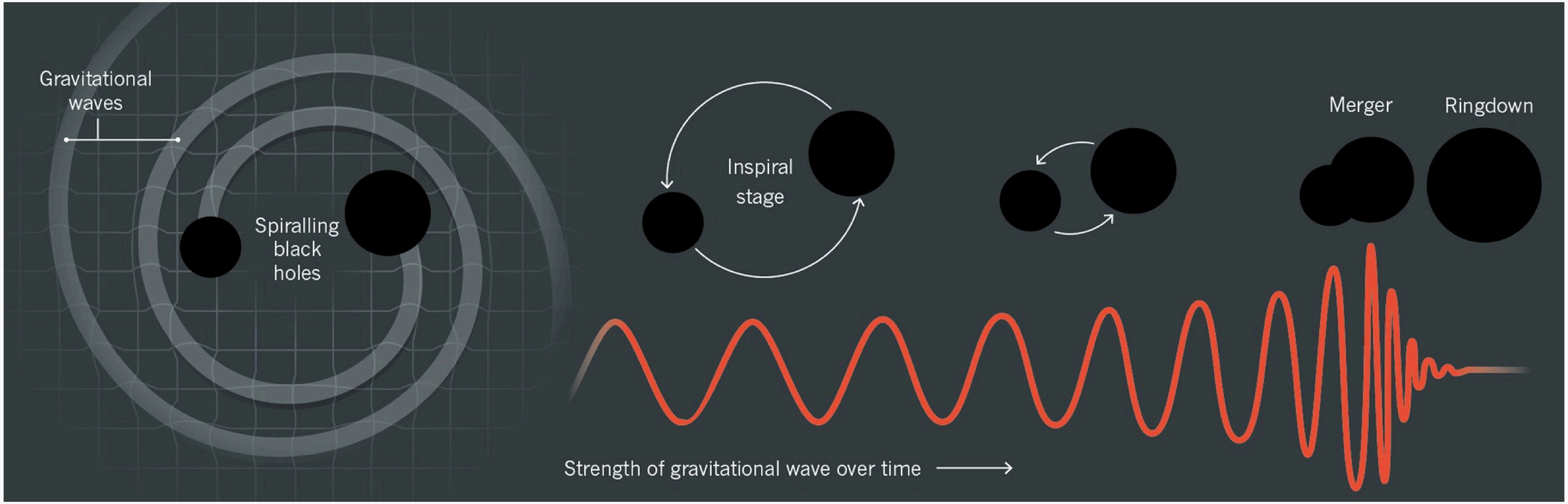
Conclusion

Intercalibration is going on well

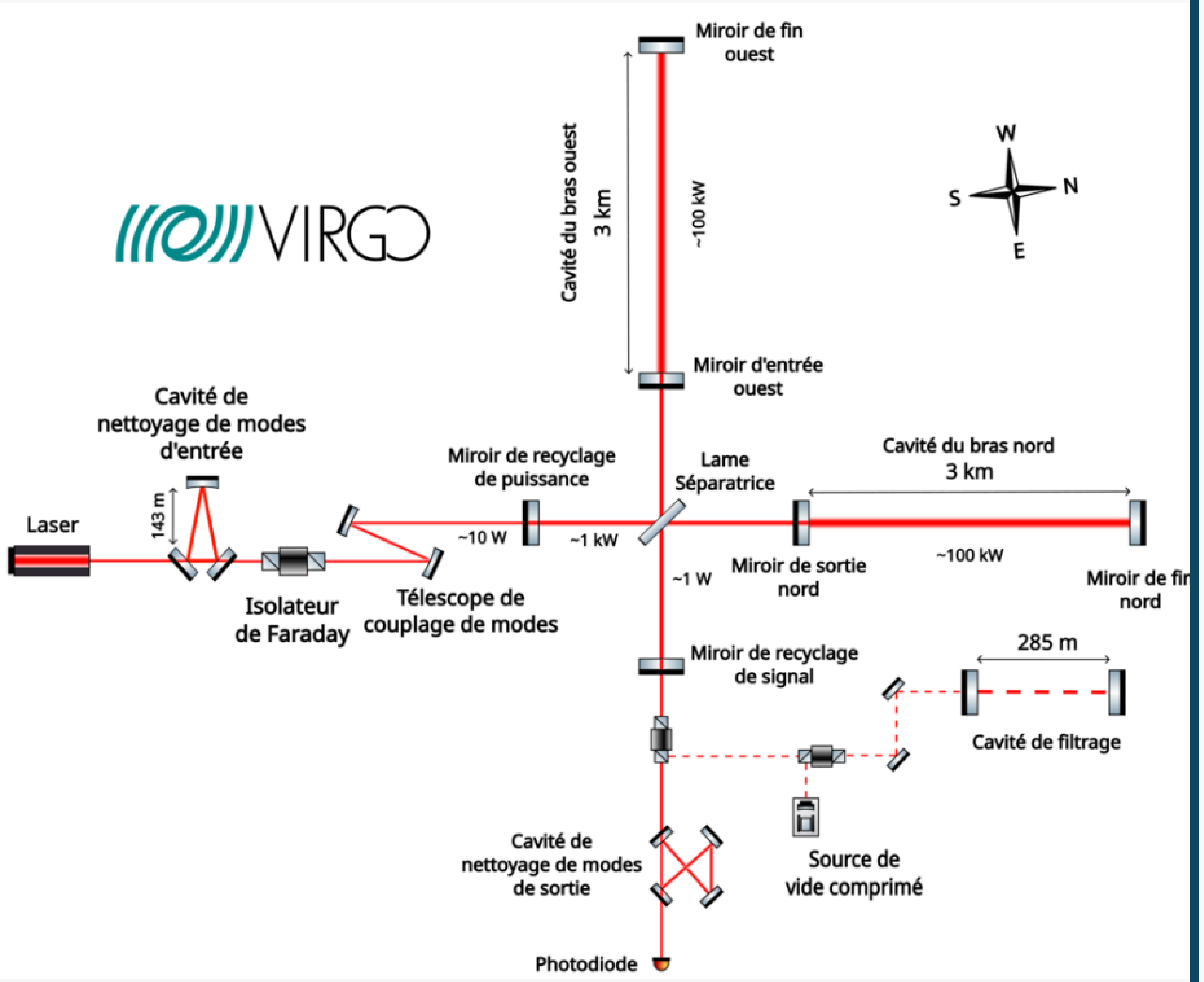
Integrating spheres are linear below 0.1% (except for RxNE)

PCal mirrors have to be changed

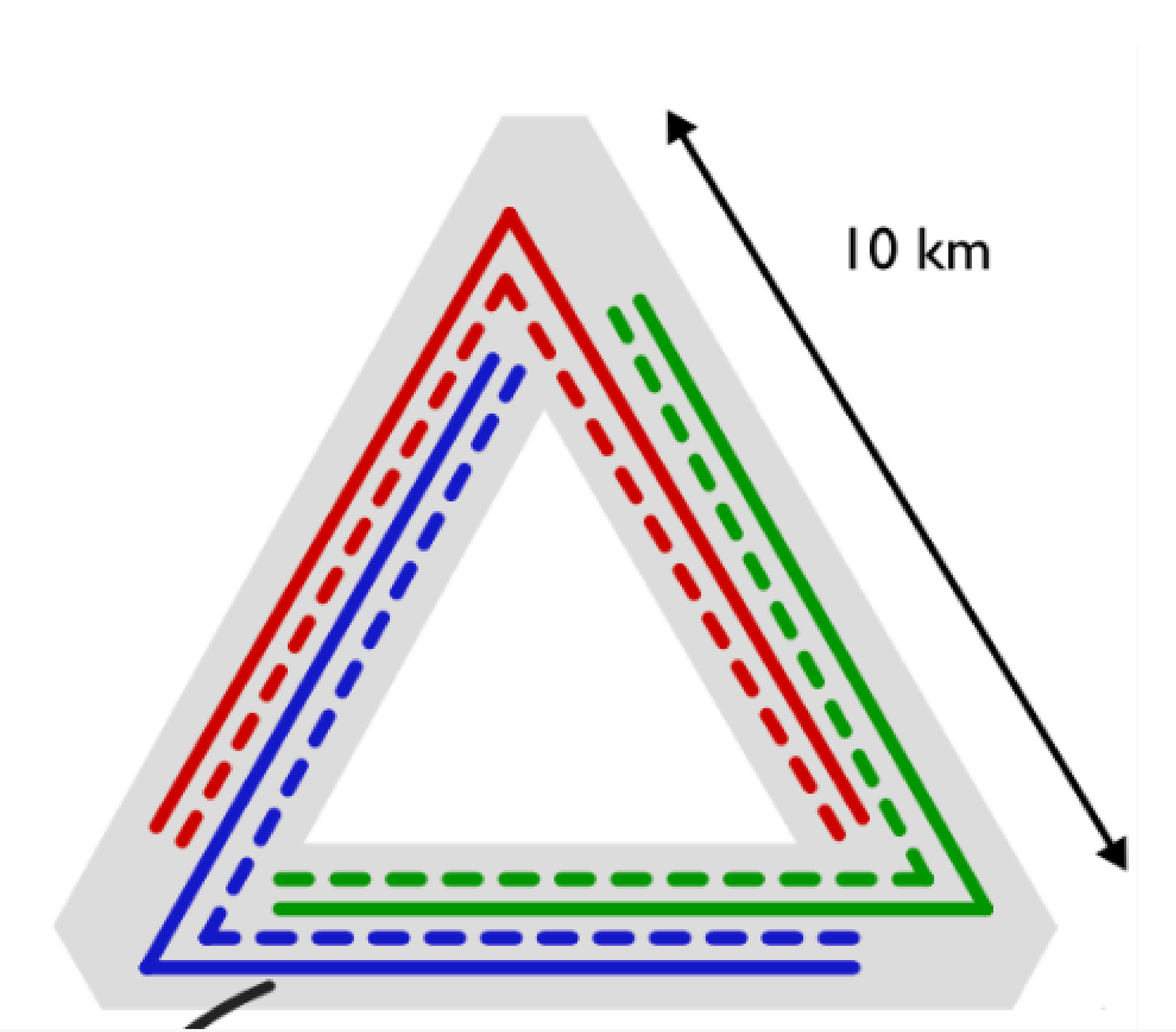
Earth's rotation impact on ET


Gravitational waves
Spiralling black holes
Inspiral stage
Merger
Ringdown
Strength of gravitational wave over time

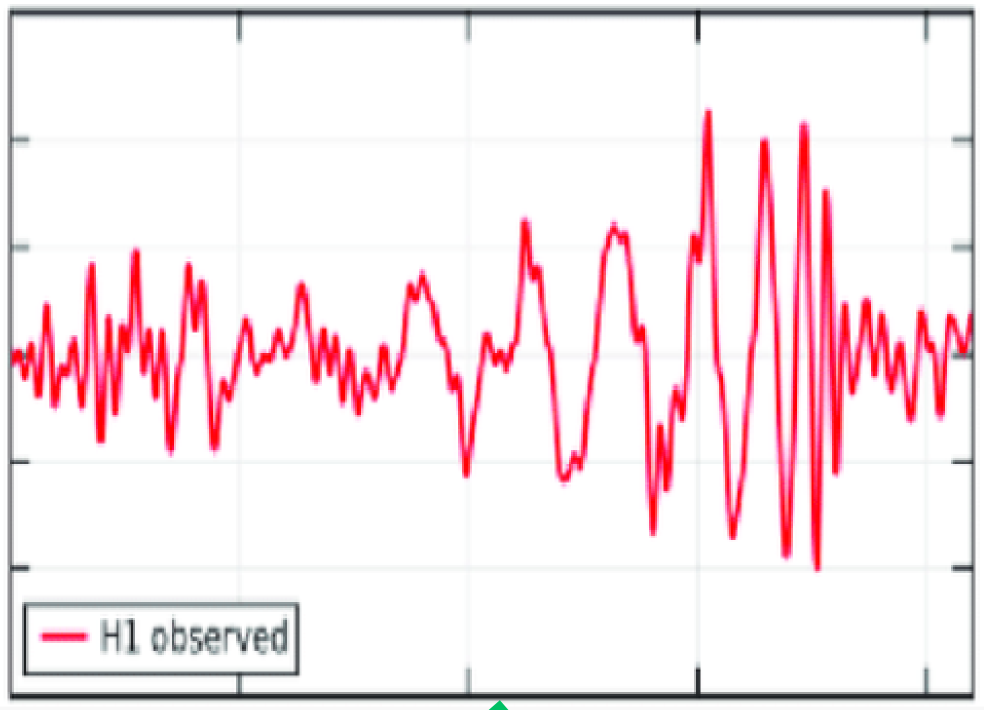
Virgo



Einstein Telescope



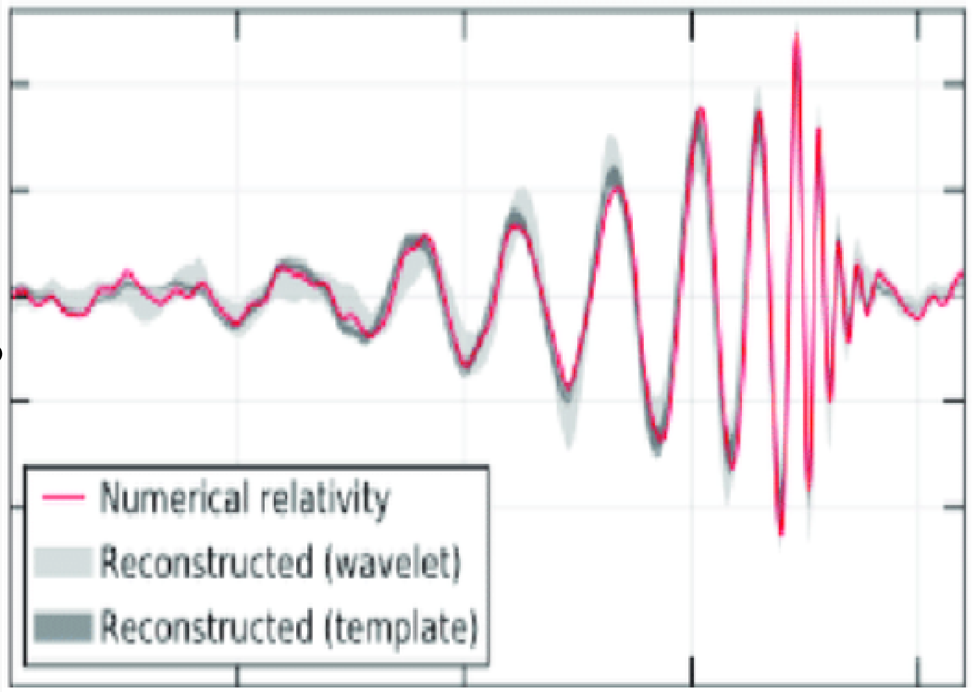
Signal reception



Analysis

Template bank
(simulated GW, known parameters)

Data output



Matching with templates → SNR

$$\mathcal{M}(s,T) = \max_{\Delta t, \Delta\phi} \frac{< s, T >}{||s||.||T||}$$

$$\rho = \frac{|(h|T)|}{\sqrt{(T|T)}}.$$

Template Q(t) with highest SNR kept

$$h(t) = h_+(t) F_+(\theta, \phi, \psi) + h_\times F_\times(\theta, \phi, \psi)$$

ET-Xylophone

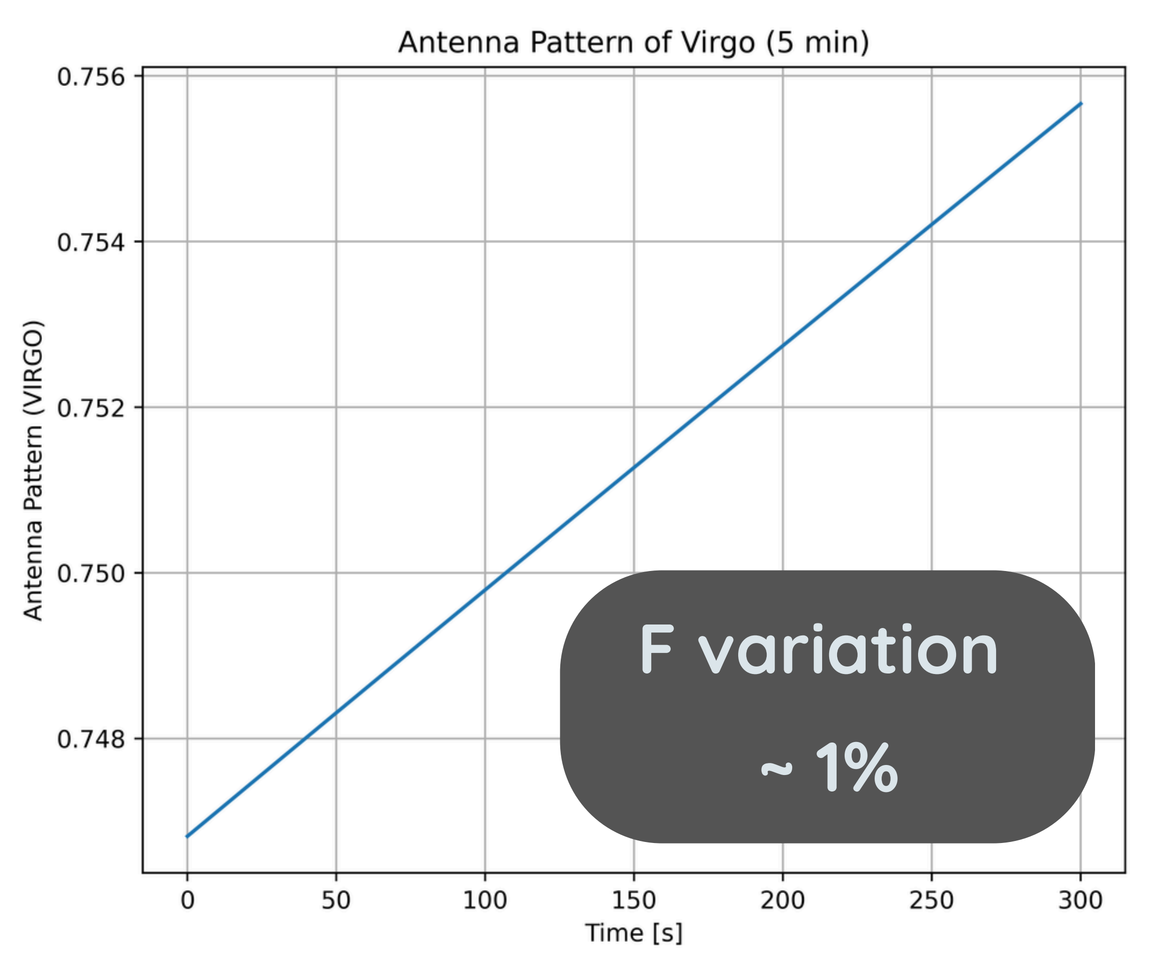
Signal duration

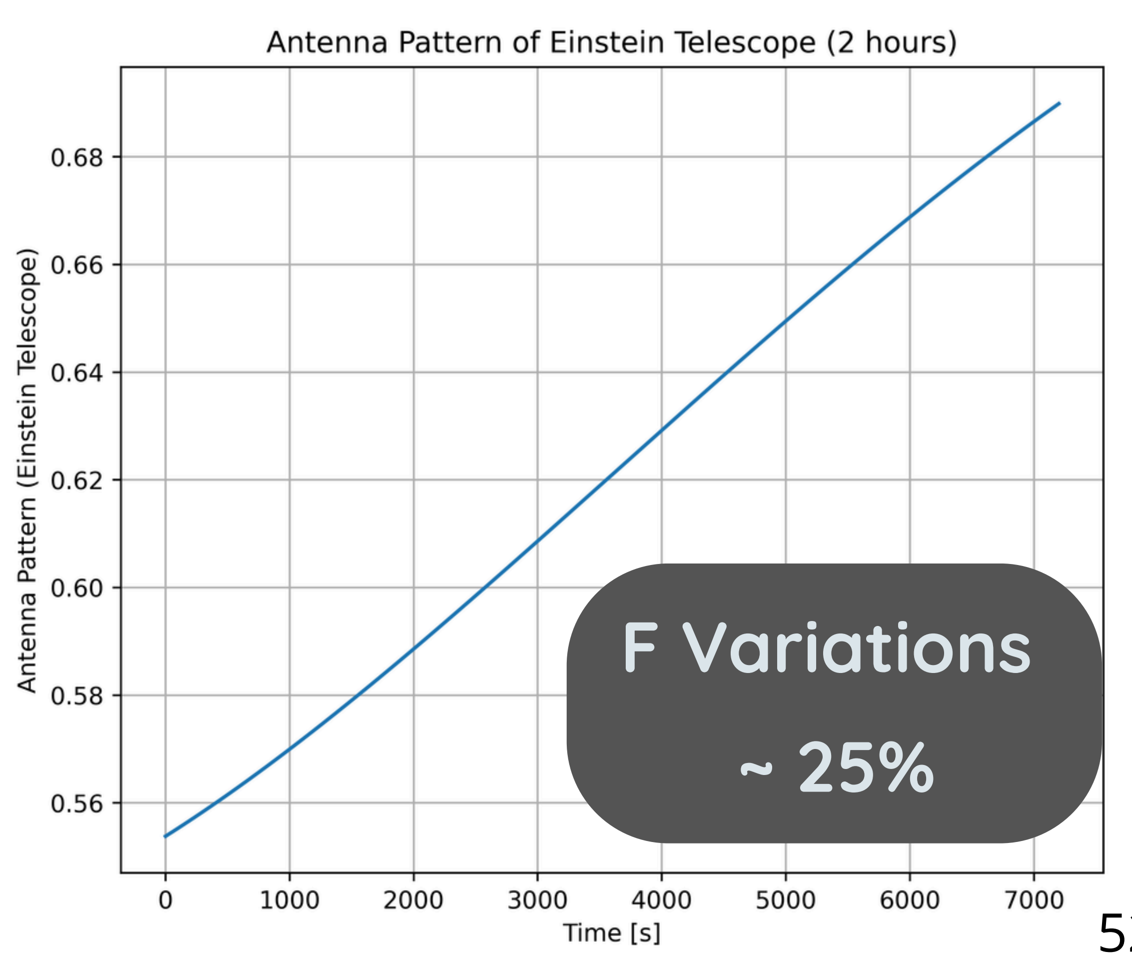
- Virgo : ~5 min
- ET : ~1-2h

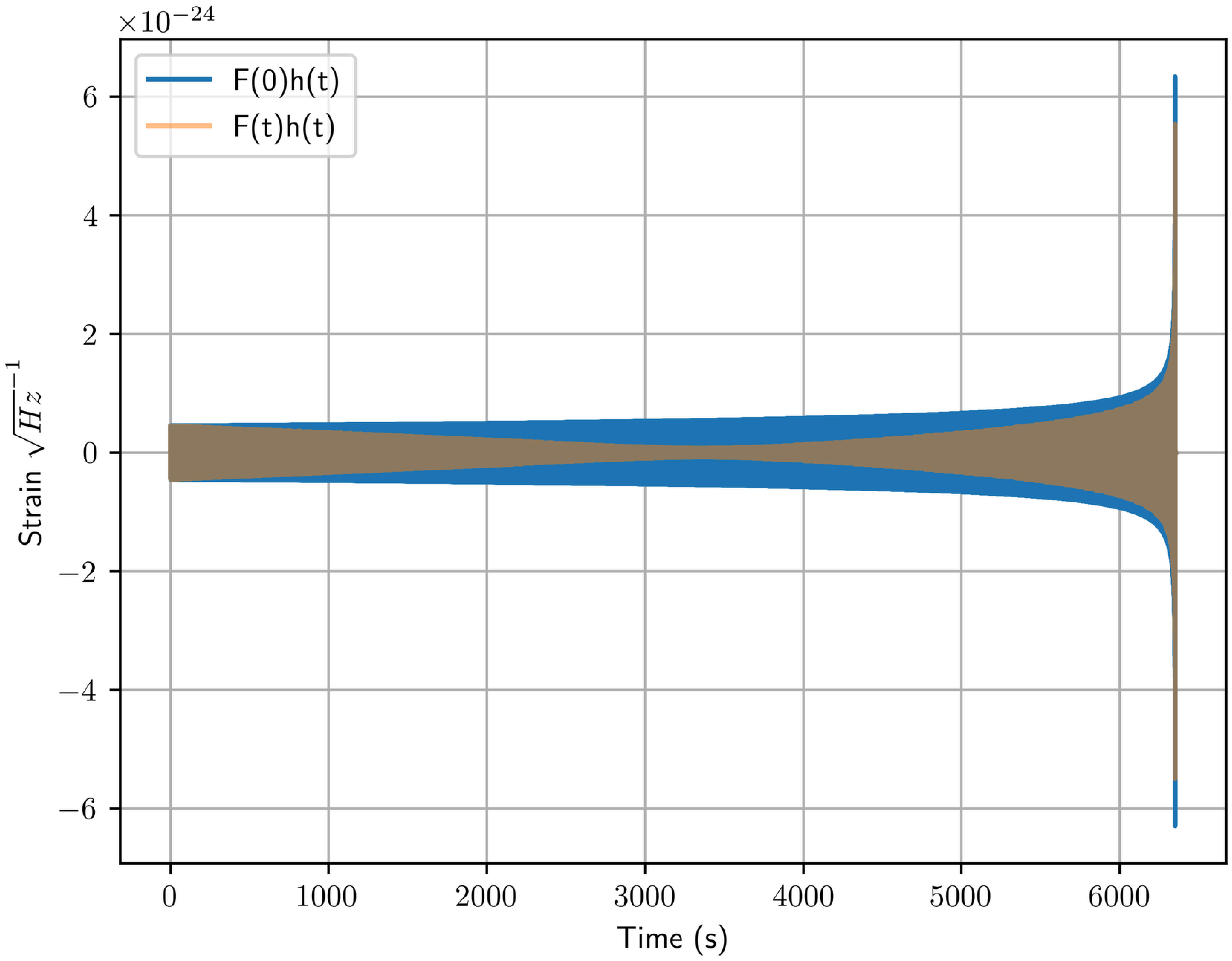
Random example

RA = 3.45 [rad]

DEC = -0.408 [rad]







$\times 10^{-24}$
F(0)h(t)
F(t)h(t)
Strain $\sqrt{Hz}^{-1}$
6
4
2
0
−2
−4
−6
0
1000
2000
3000
4000
5000
6000
Time (s)

Incoming signal
(Naturally modulated by F(t))

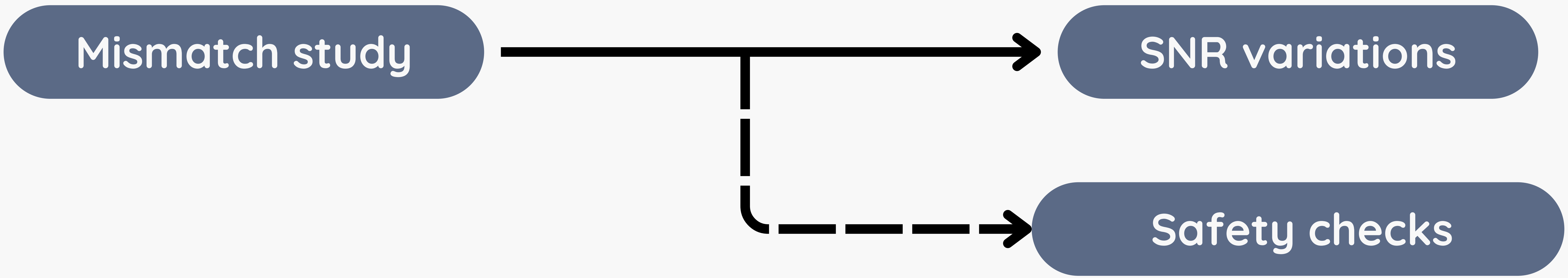
Optimal template
=
Time-modulated template
F(t)h(t)
(Complexifies the bank)

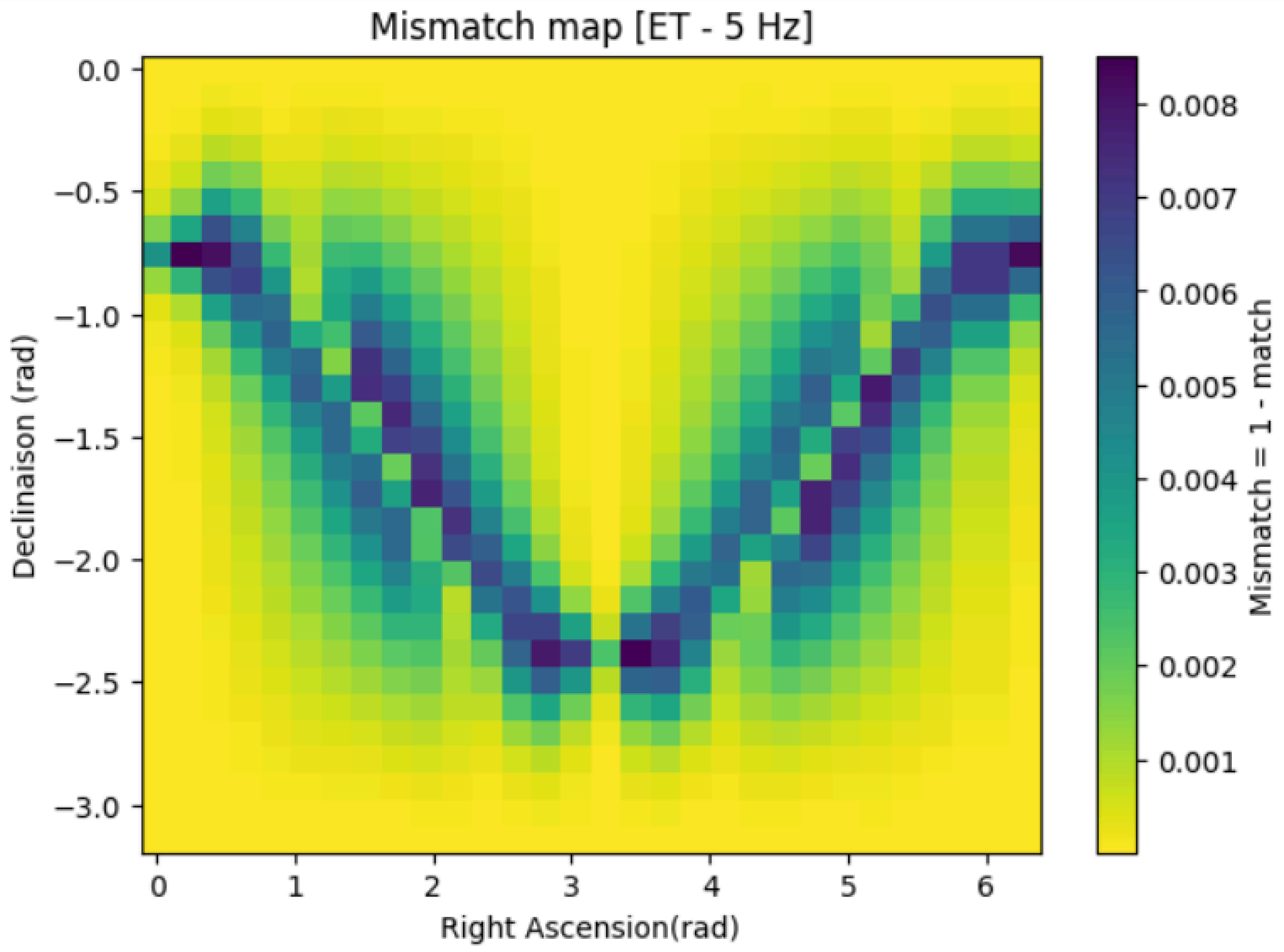
Simple template
=
Non time-modulated template
F(0)h(t)
(Virgo-like)

Which one do we choose ?

How much Match and SNR do we loose if E.R. neglected ?

$$\frac{\Delta\rho}{\rho} := \frac{\rho_{mod} - \rho_{const}}{\rho_{mod}} \approx 1 - \mathcal{M}[F(t)h(t), F(0)h(t)]$$





Max ~ 0.8%

Earth rotation can be neglected here

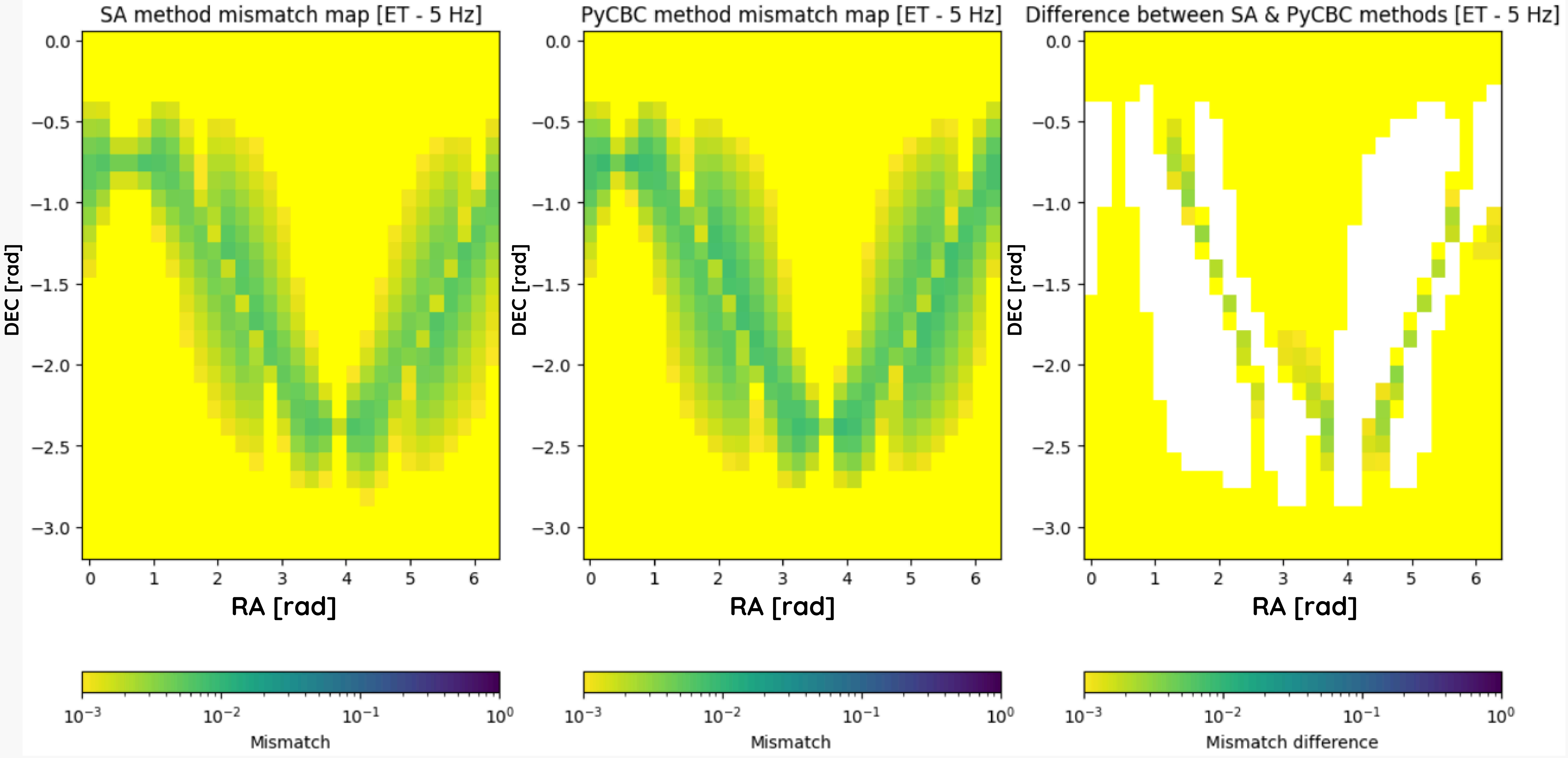
Slow computation

ET Xylo, f_{low} = 5 Hz, ι = 0°, Ψ = 0°, M_{Chirp} = 1.2$M_{\odot}$

SA method (Max = 0.006)

PyCBC (Max = 0.008)

Differences



Global study of the mismatch Monte-Carlo simulation

Sky position

$$\alpha, \cos(\delta) \sim \mathcal{U}[0, 2\pi], \mathcal{U}[0, 1]$$

Polarisation

$$\Psi \sim \mathcal{U}[0, 2\pi]$$

Inclination

$$\cos(\iota) \sim \mathcal{U}[0, 1]$$

Individual masses

$$M_i \sim \mathcal{N}(1.35,\ 0.1)$$

Low frequency cutoff

$$f_{low} = 5\, Hz$$

Coalescence time

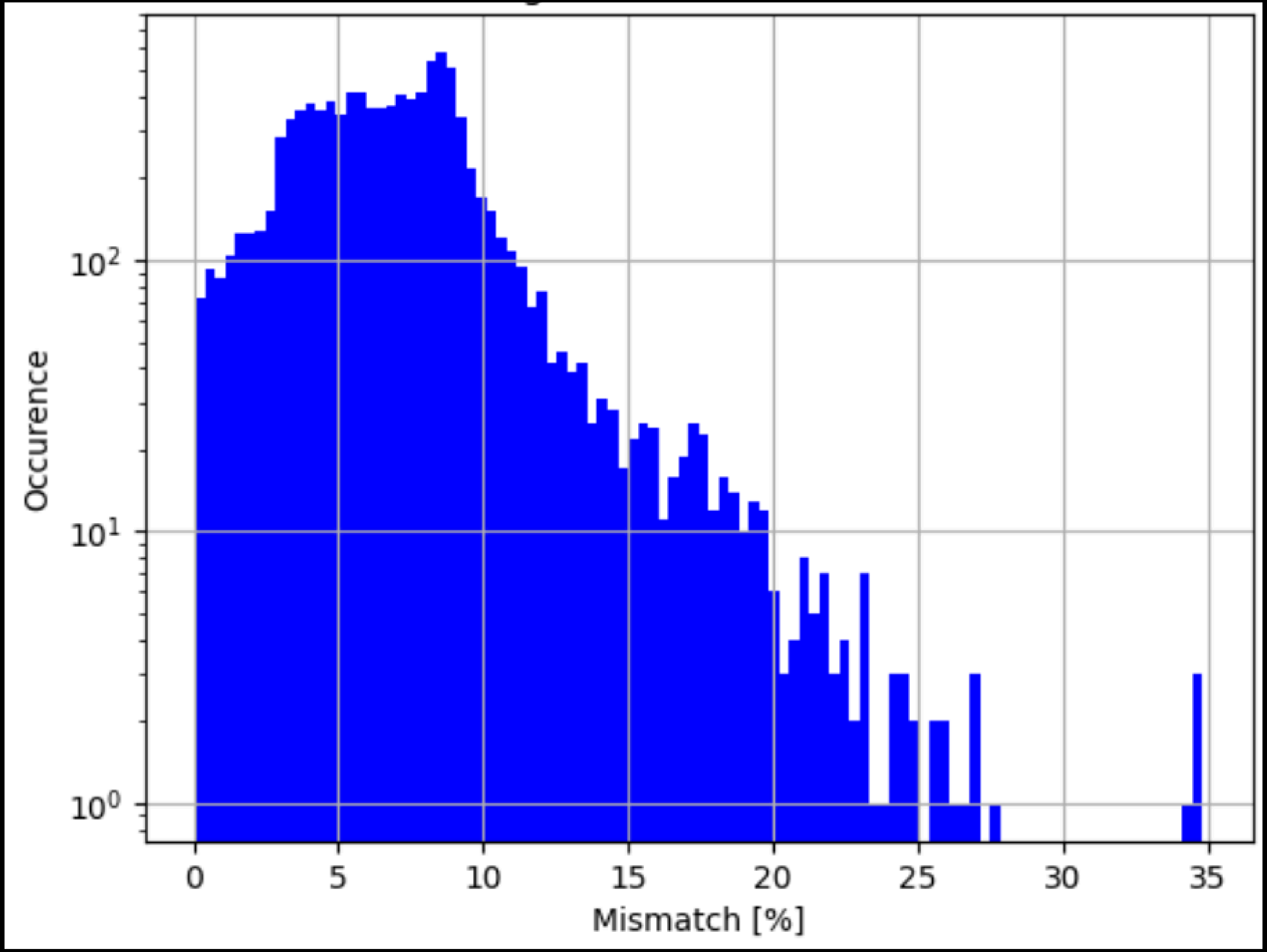
$$t_c \sim \mathcal{U}[0, 86400]$$

Redshift

$$p(z) \propto \frac{dV_c}{dz}\mathcal{R}(z)$$

Tidal and spin neglected

Mismatch histogram



(10.000 sources)

Up to 40% Mismatch

~13% of sources have Mismatch > 10%

~70% of sources have Mismatch > 5%

~90% of sources have Mismatch > 3%

Global study of the SNR

We necessarily loose SNR

$$\rho_{const} \leq ||h|| = \rho_{opt,mod}$$

Let's do a Monte-Carlo !

Sky position

$$\alpha, \cos(\delta) \sim \mathcal{U}[0, 2\pi], \mathcal{U}[0, 1]$$

Polarisation

$$\Psi \sim \mathcal{U}[0, 2\pi]$$

Inclination

$$\cos(\iota) \sim \mathcal{U}[0, 1]$$

Individual masses

$$M_i \sim \mathcal{N}(1.35,\ 0.1)$$

Low frequency cutoff

$$f_{low} = 5\, Hz$$

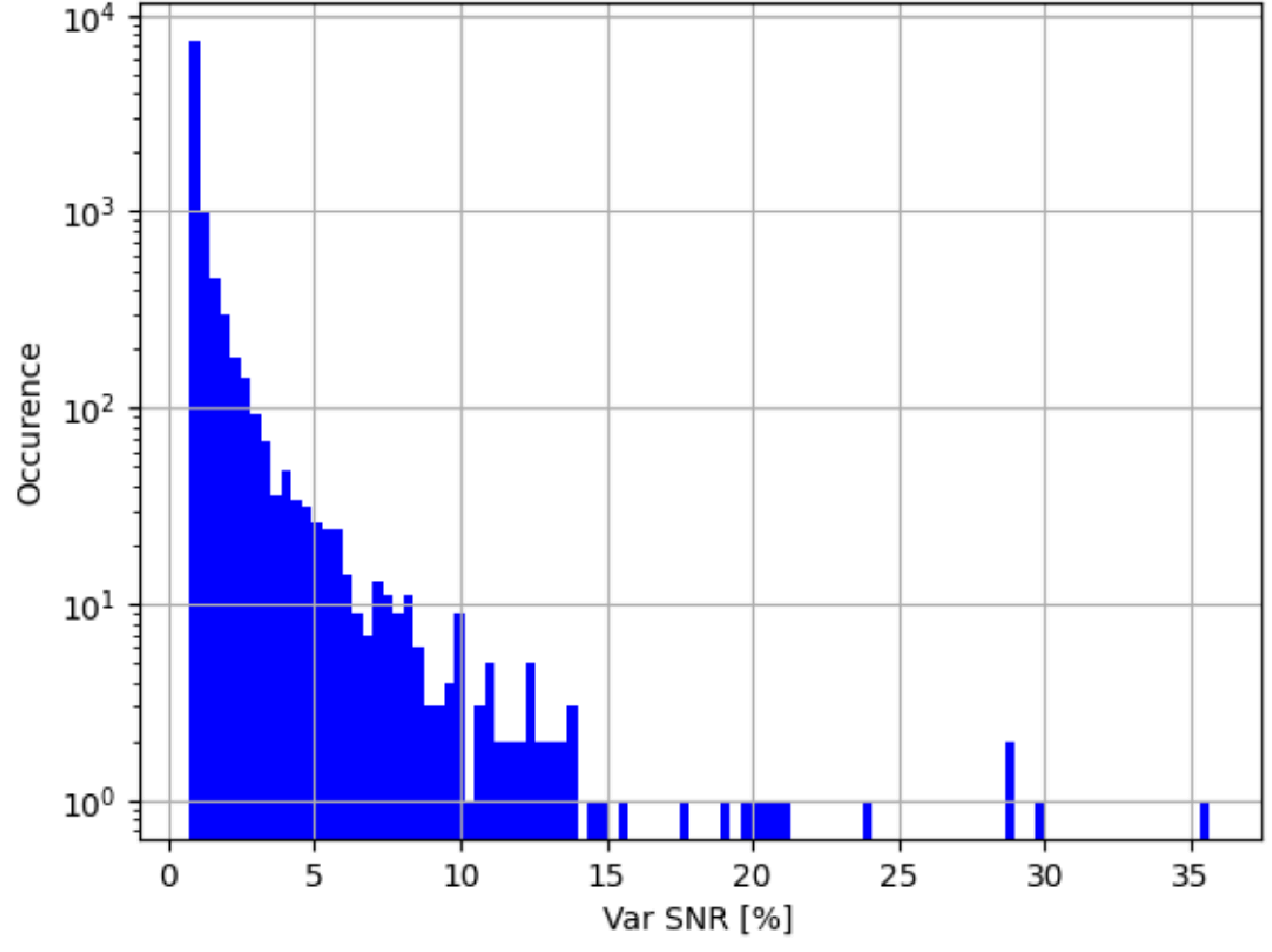
Coalescence time

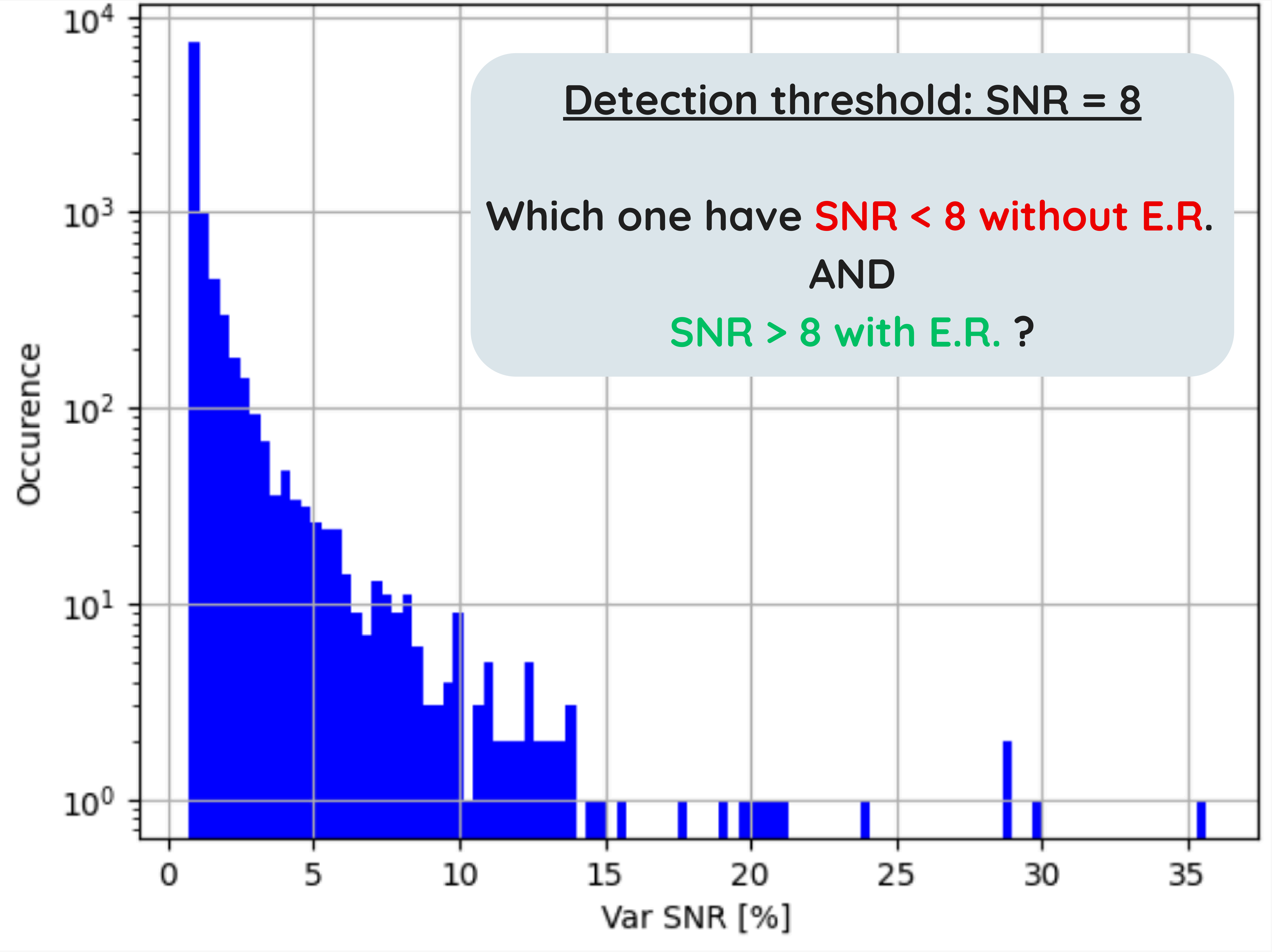
$$t_c \sim \mathcal{U}[0, 86400]$$

Redshift

$$p(z) \propto \frac{dV_c}{dz} \mathcal{R}(z)$$

Tidal and spin neglected


Occurence
Var SNR [%]
10^4
10^3
10^2
10^1
10^0
0
5
10
15
20
25
30
35



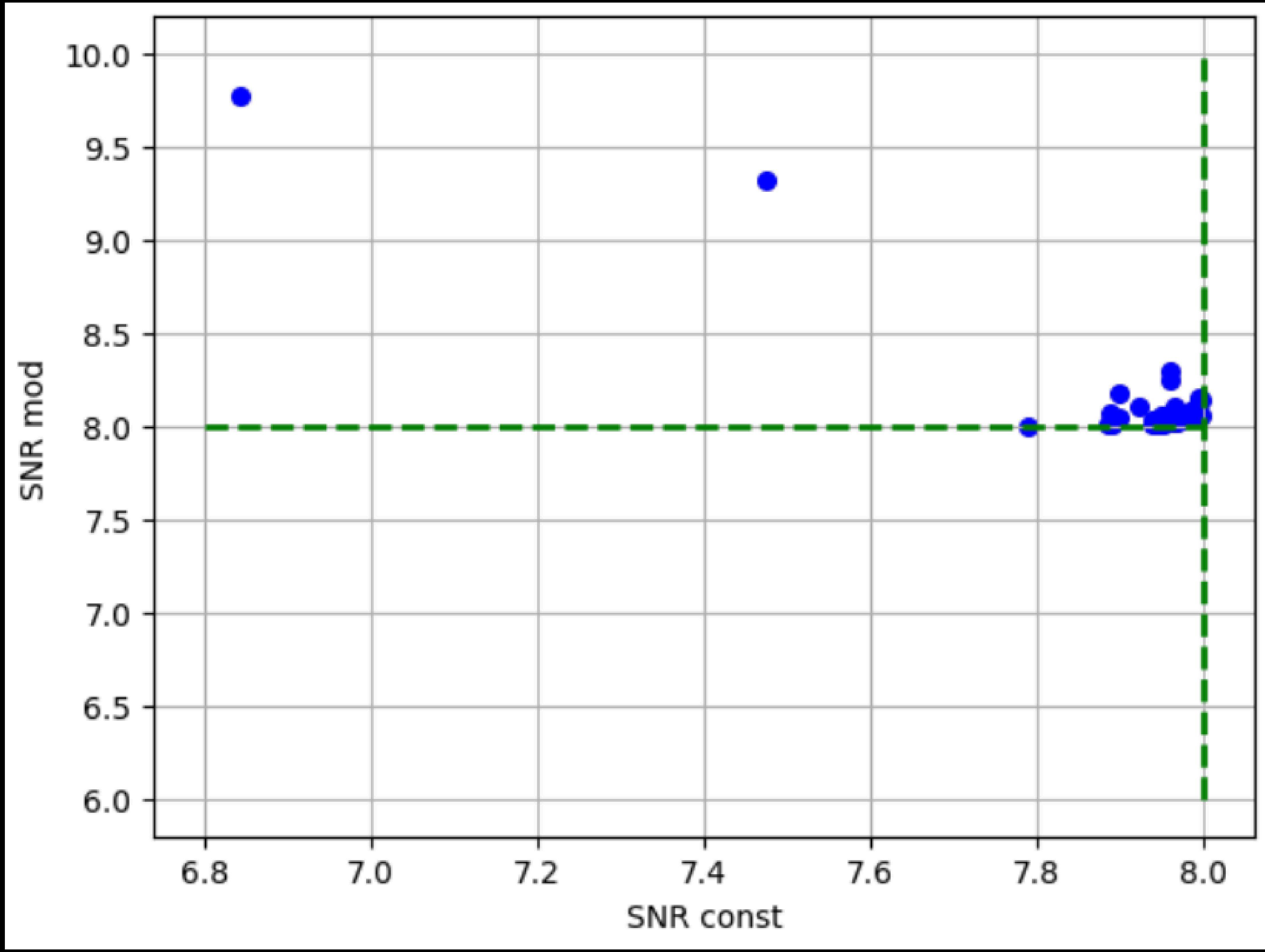
Detection threshold: SNR = 8

Which one have SNR < 8 without E.R.

AND

SNR > 8 with E.R. ?

Recovered SNR stay around SNR = 8



Statistics !

About ~ 0.6% de ALL sources detected at 5 Hz

~ 25% of ALL sources can be retrieved if starting at 2 Hz

Conclusion

MC simulations show that
Mismatch can be severely affected

Earth rotation induced SNR variations can be neglected for f_{low} > 5Hz

Taking E.R. into account would complexify the Match Filtering process for <1% of sources

Conclusion - Miscellaneous

Virgo

- Intercalibration still going on without problems
- Integrating spheres are linear at <0.1%
- M3 mirror has a defect leading to a loss of <1% of R

ET

Earth's rotation not that easily negligeable
(at 5Hz, ~10% of sources could be missed because of high mismatch)

Scientific contributions

ET internal note
about Earth rotation

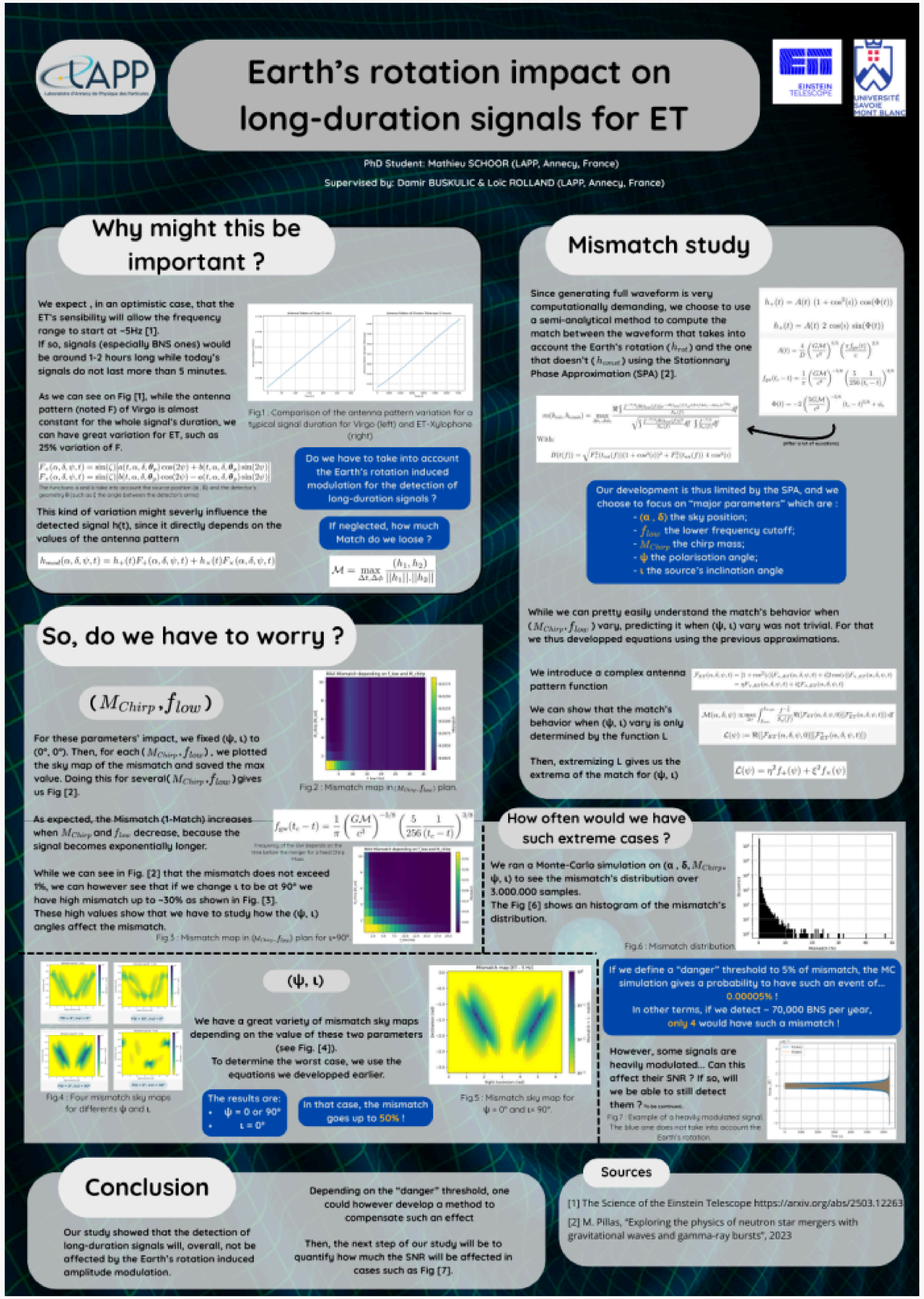
Virgo technical notes x2
(linearity + M3)

Calibration mission at Virgo
(December)

PCal article
co-author

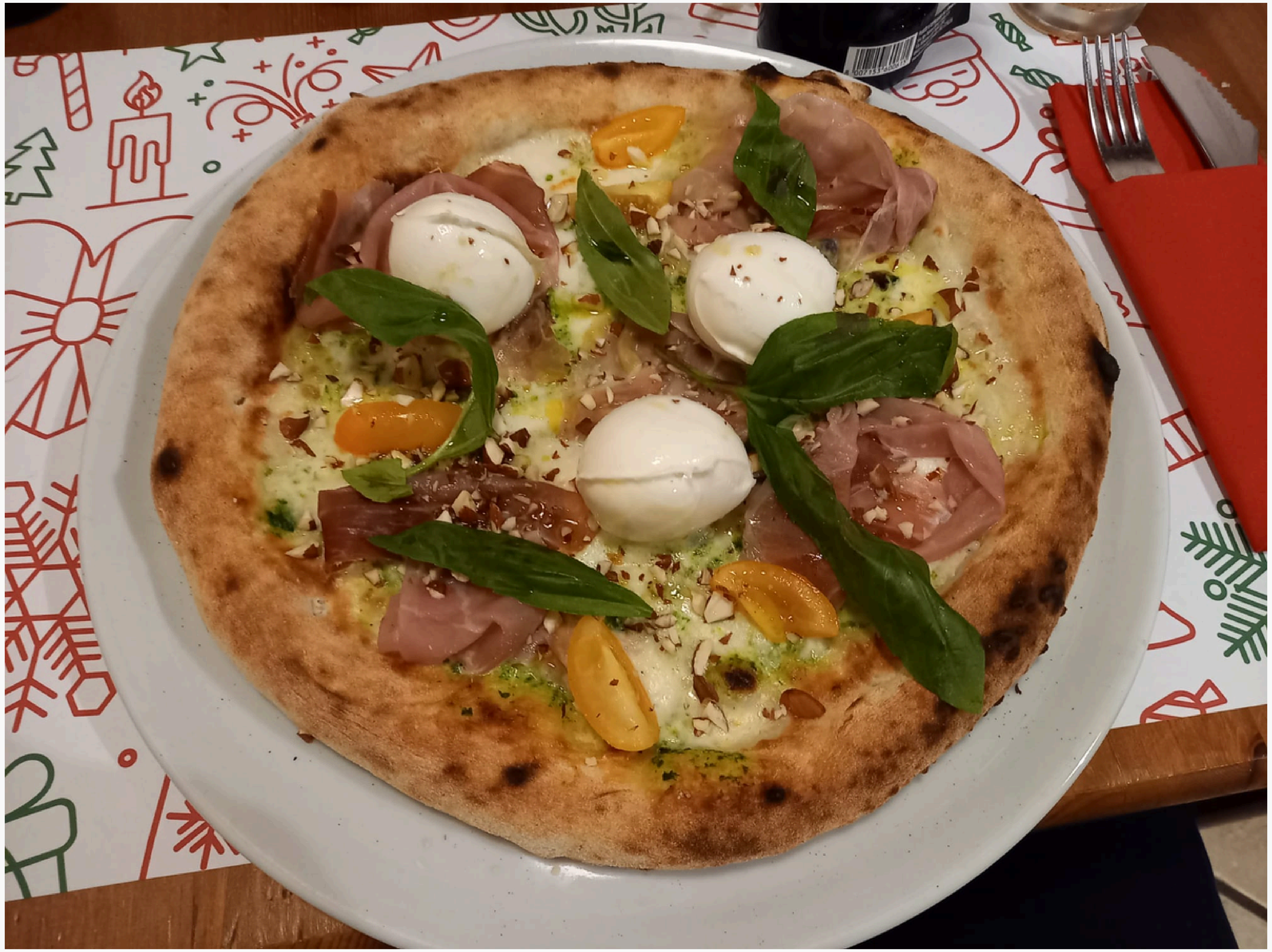
ET France talk
(Paris, April)

Poster at Workshop ET
(Rome, February)



Earth's rotation impact on long-duration signals for ET
PhD Student: Mathieu SCHOOR (LAPP, Annecy, France)
Supervised by: Damir BUSKULIC & Loïc ROLLAND (LAPP, Annecy, France)
Why might this be important ?
We expect , in an optimistic case, that the ET's sensibility will allow the frequency range to start at ~5Hz [1].
If so, signals (especially BNS ones) would be around 1-2 hours long while today's signals do not last more than 5 minutes.
As we can see on Fig [1], while the antenna pattern (noted F) of Virgo is almost constant for the whole signal's duration, we can have great variation for ET, such as 25% variation of F.
Fig1 : Comparison of the antenna pattern variation for a typical signal duration for Virgo (left) and ET-Xylophone (right)
This kind of variation might severly influence the detected signal h(t), since it directly depends on the values of the antenna pattern
Do we have to take into account the Earth's rotation induced modulation for the detection of long-duration signals ?
If neglected, how much Match do we loose ?
Mismatch study
Since generating full waveform is very computationally demanding, we choose to use a semi-analytical method to compute the match between the waveform that takes into account the Earth's rotation (h_{rot}) and the one that doesn't (h_{const}) using the Stationnary Phase Approximation (SPA) [2].
Our development is thus limited by the SPA, and we choose to focus on "major parameters" which are :
- (α , δ) the sky position;
- f_{low} the lower frequency cutoff;
- M_{Chirp} the chirp mass;
- ψ the polarisation angle;
- ι the source's inclination angle
While we can pretty easily understand the match's behavior when (M_{Chirp}, f_{low}) vary, predicting it when (ψ, ι) vary was not trivial. For that we thus developped equations using the previous approximations.
We introduce a complex antenna pattern function
We can show that the match's behavior when (ψ, ι) vary is only determined by the function L
Then, extremizing L gives us the extrema of the match for (ψ, ι)
So, do we have to worry ?
(M_{Chirp}, f_{low})
For these parameters' impact, we fixed (ψ, ι) to (0°, 0°). Then, for each (M_{Chirp}, f_{low}), we plotted the sky map of the mismatch and saved the max value. Doing this for several(M_{Chirp}, f_{low}) gives us Fig [2].
Fig.2 : Mismatch map in (M_{Chirp}, f_{low}) plan.
As expected, the Mismatch (1-Match) increases when M_{Chirp} and f_{low} decrease, because the signal becomes exponentially longer.
While we can see in Fig. [2] that the mismatch does not exceed 1%, we can however see that if we change ι to be at 90° we have high mismatch up to ~30% as shown in Fig. [3].
These high values show that we have to study how the (ψ, ι) angles affect the mismatch.
Fig 3 : Mismatch map in (M_{Chirp}, f_{low}) plan for ι=90°.
(ψ, ι)
We have a great variety of mismatch sky maps depending on the value of these two parameters (see Fig. [4]).
To determine the worst case, we use the equations we developped earlier.
Fig4 : Four mismatch sky maps for differents ψ and ι.
The results are: ψ = 0 or 90° ι = 0°
In that case, the mismatch goes up to 50% !
Fig.5 : Mismatch sky map for ψ = 0° and ι= 90°.
How often would we have such extreme cases ?
We ran a Monte-Carlo simulation on (α , δ, M_{Chirp}, ψ, ι) to see the mismatch's distribution over 3.000.000 samples.
The Fig [6] shows an histogram of the mismatch's distribution.
Fig.6 : Mismatch distribution.
If we define a "danger" threshold to 5% of mismatch, the MC simulation gives a probability to have such an event of... 0.00005% !
In other terms, if we detect ~ 70,000 BNS per year, only 4 would have such a mismatch !
However, some signals are heavily modulated... Can this affect their SNR ? If so, will we be able to still detect them ?
Fig 7 : Example of a heavily modulated signal. The blue one does not take into account the Earth's rotation.
Conclusion
Our study showed that the detection of long-duration signals will, overall, not be affected by the Earth's rotation induced amplitude modulation.
Depending on the "danger" threshold, one could however develop a method to compensate such an effect
Then, the next step of our study will be to quantify how much the SNR will be affected in cases such as Fig [7].
Sources
[1] The Science of the Einstein Telescope https://arxiv.org/abs/2503.12263
[2] M. Pillas, "Exploring the physics of neutron star mergers with gravitational waves and gamma-ray bursts", 2023


YOU SHALL
NOT PASS!



Contributions scientifiques

Calibration meetings

Electronics meeting

Optics meetings

MBTA meetings (Virgo)

Div10 ET meetings (data analysis)

Next works

Study of MBTA for ET-like signals

Speed up the h(t) reconstruction algorithm

????

Virgo calibration for autumn observation run

Divers

48h of teaching
(Optics, Math, EM)

~40h ED formation:

- 15h Scientific journalism
- 15h Research ethics
- 4h VSS

Pint of Science

ILE Project
Fête de la Science
End of the year Party organisation
Lab visits x7 (secondary school, high school, students, public)

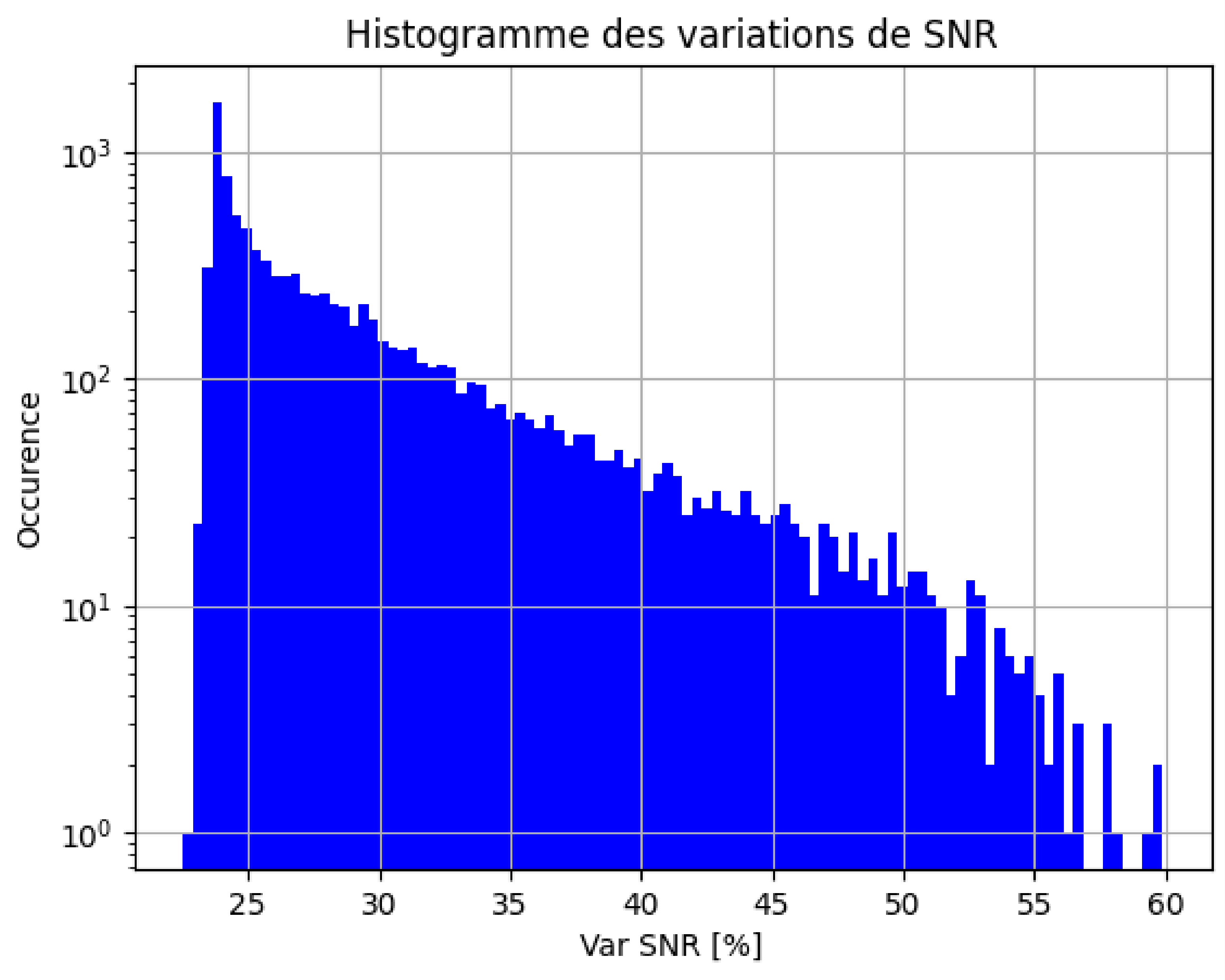
Thank you !

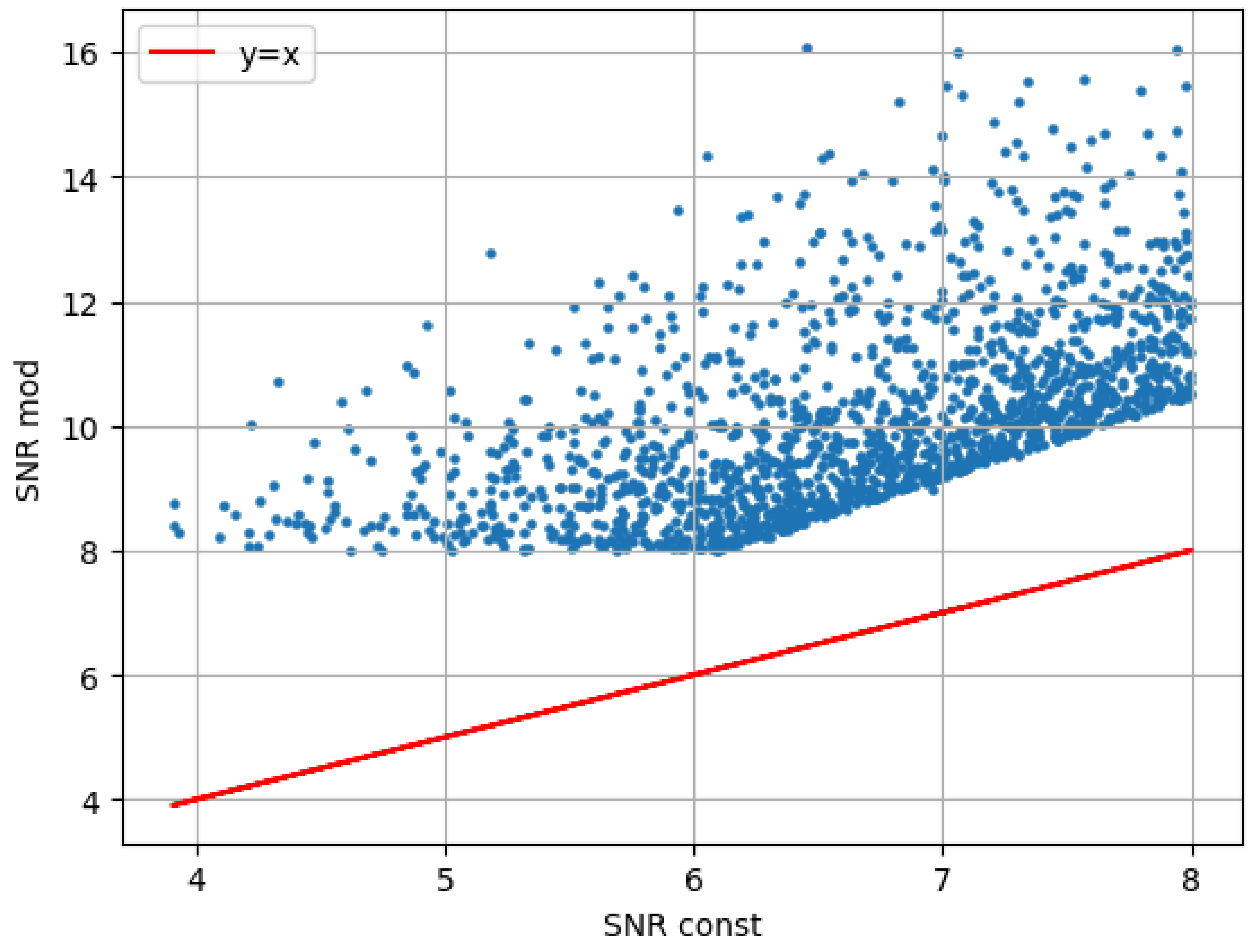
Backup

$$\mathcal{M}(\alpha,\delta,\psi) \propto \sqrt{A+\mathcal{B}\sin(4\psi+\Phi_1)+\mathcal{C}\sin(8\psi+\Phi_2)} + \sqrt{A-\mathcal{B}\sin(4\psi+\Phi_1)+\mathcal{C}\sin(8\psi+\Phi_2)}$$
$$= f_+(\psi) + f_\times(\psi)$$

$$\mathcal{L}(\psi) = \eta^2 f_+(\psi) + \xi^2 f_\times(\psi)$$

$$F_{+,ET}(\alpha,\delta,\psi,t) = \sqrt{\sum_{i=1}^{n} F_{+,i}^2(\alpha,\delta,\psi,t)}$$
$$F_{\times,ET}(\alpha,\delta,\psi,t) = \sqrt{\sum_{i=1}^{n} F_{\times,i}^2(\alpha,\delta,\psi,t)}$$





~ 25% de TOUTES les sources
peuvent être récupérées

Match Filtering Output (complexe)

$$\rho_{const} = \frac{< h, T >}{||T||}$$

Cauchy-Schwarz

$$| < h, T > | \leq ||h||.||T||$$

On perd nécessairement du SNR

$$\rho_{const} \leq ||h|| = \rho_{opt,mod}$$

Faisons une Monte-Carlo !

Pour chaque point (RA, DEC) dans le ciel

Génération de h(t) (+ et x)

Calcul de F(t) et F(0) (+ et x)

Calcul de F(t)h(t) et F(0)h(t)

Calcul du Mismatch entre F(t)h(t) et F(0)h(t)

Codé en Python (PyCBC)

$$\mathcal{M}(s,T) = \max_{\Delta t, \Delta\phi} \frac{< s, T >}{||s||.||T||}$$

Cas simple
(2h)

M1 = M2 = 1.4 $M_{\odot}$

f_low = 5 Hz

WF model:
IMRPhenomD

Distance = 100 Mpc

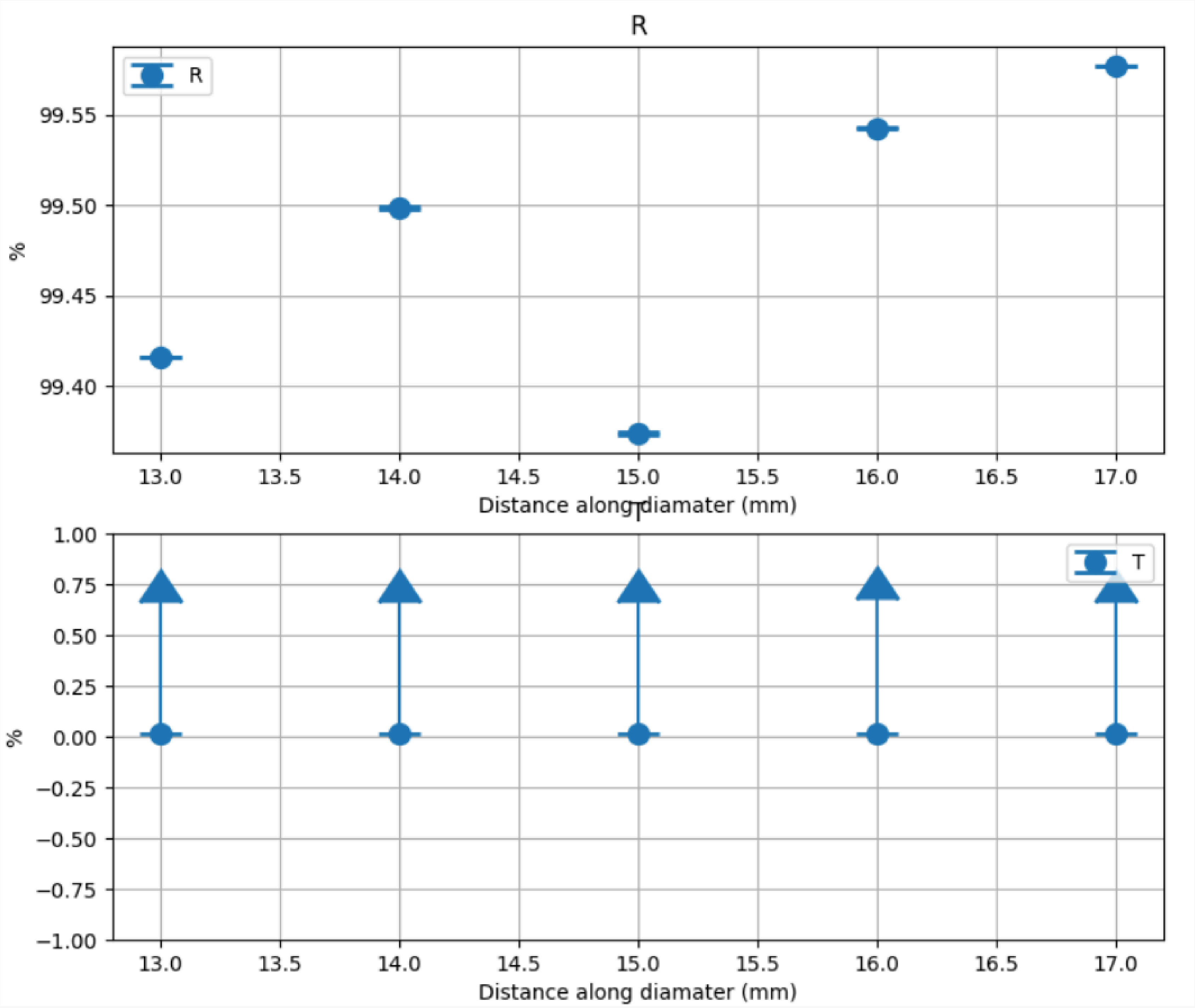
Pas de spin

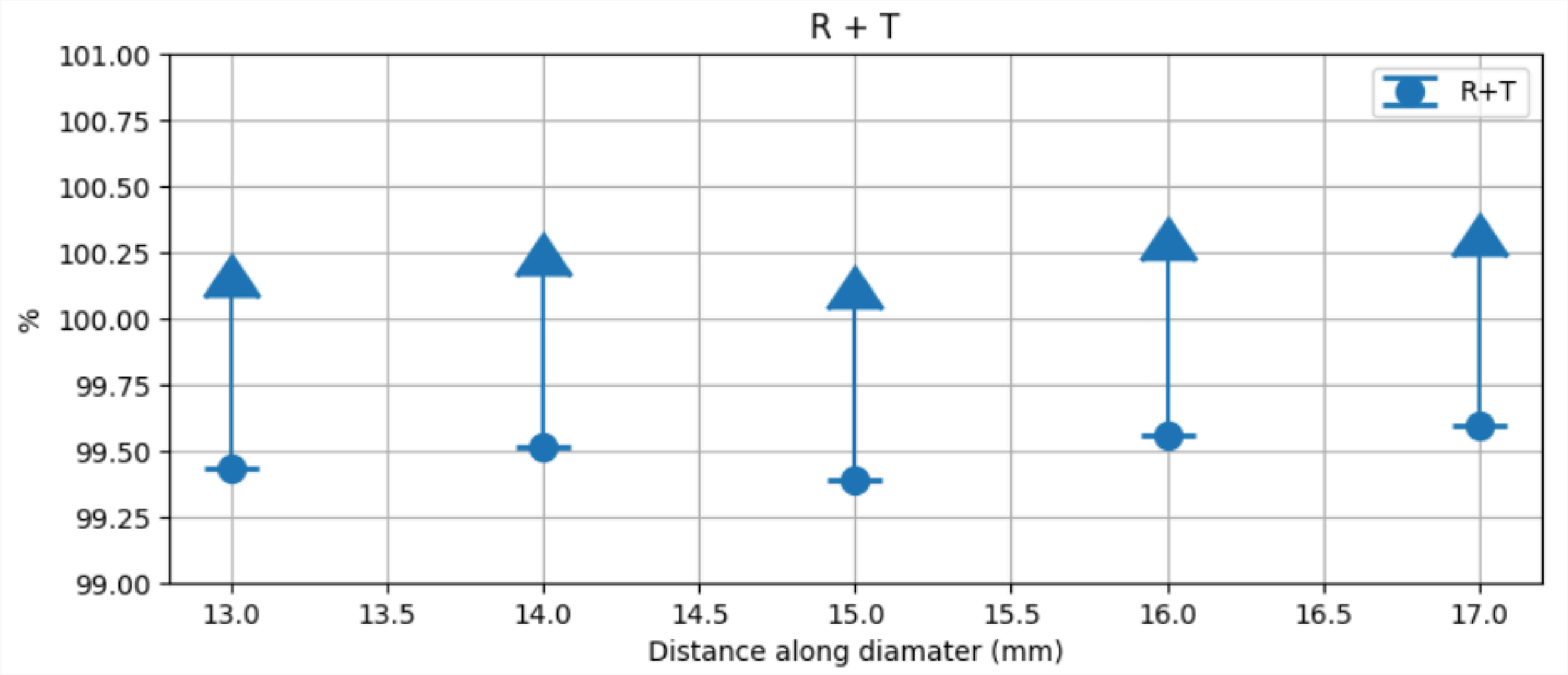
Inclinaison = 0°

PSI = 0 *

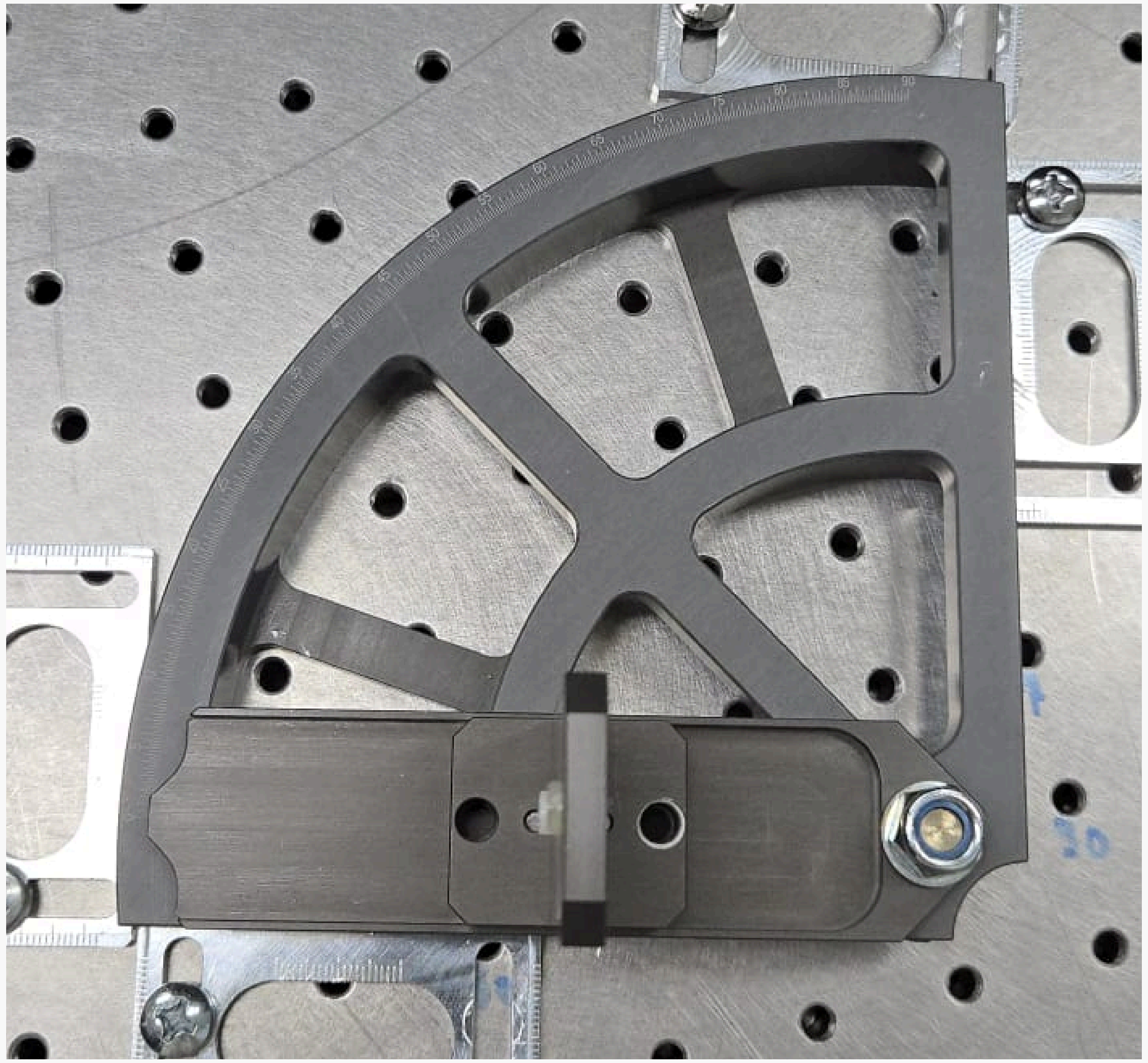
*Contribution égale de F+ et Fx
dans le Match

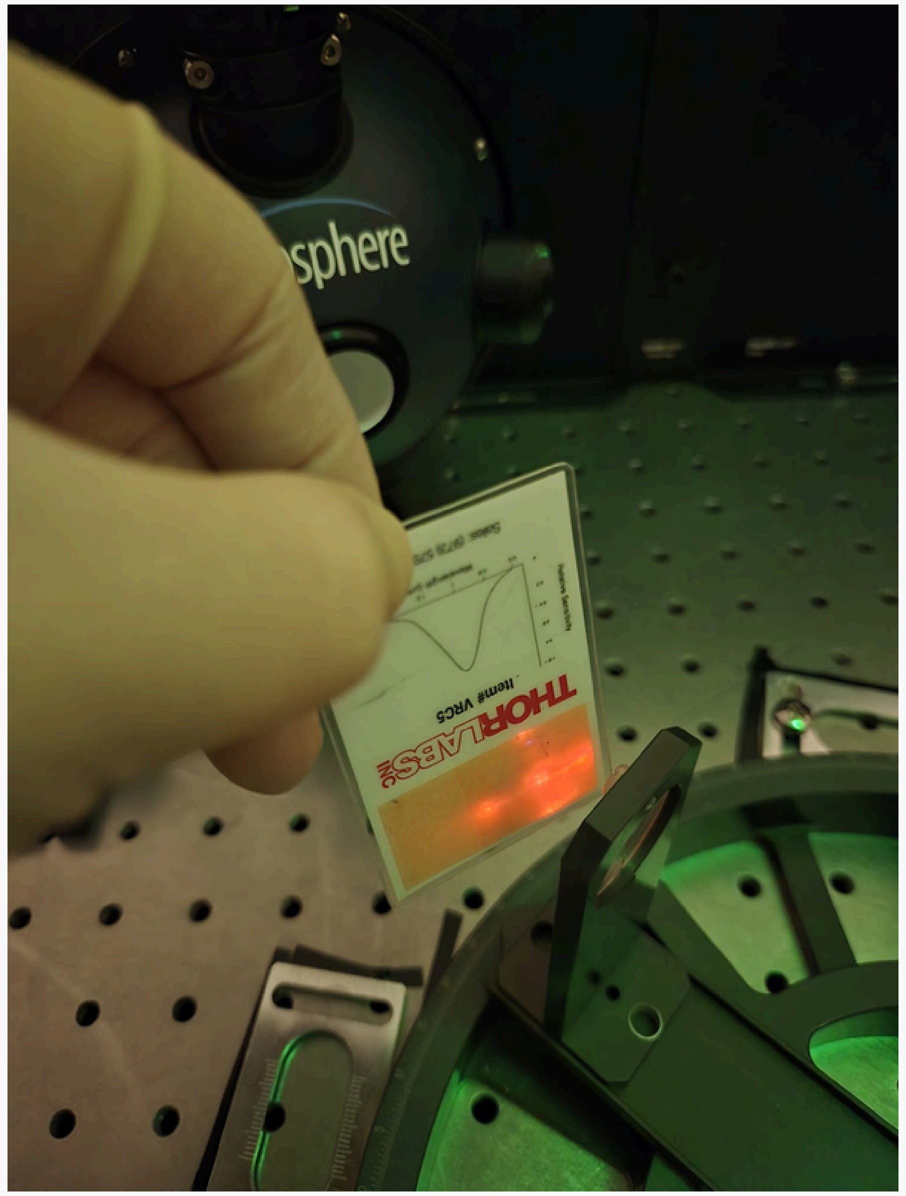
Sphère T voit ~25% de la lumière transmise





Supposant que la sphère voit ~25% de la lumière transmise




THORLABS

Mesures

Measures jusqu'à 3W dans la sphere (1.5W chacun)

Mettre les lasers à 1.5W:

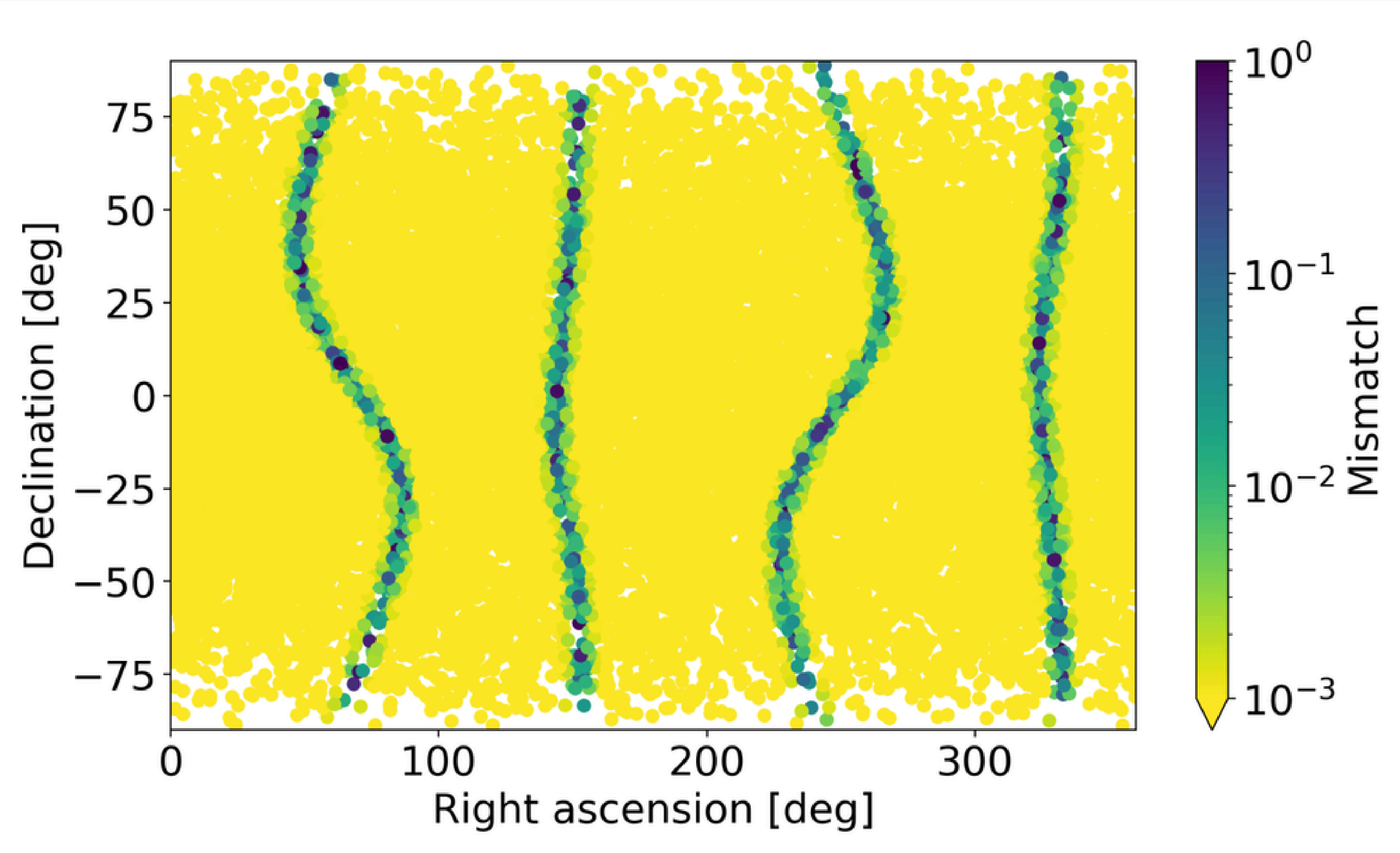
- Seulement laser 1
- Seulement laser 2
- Deux faisceaux

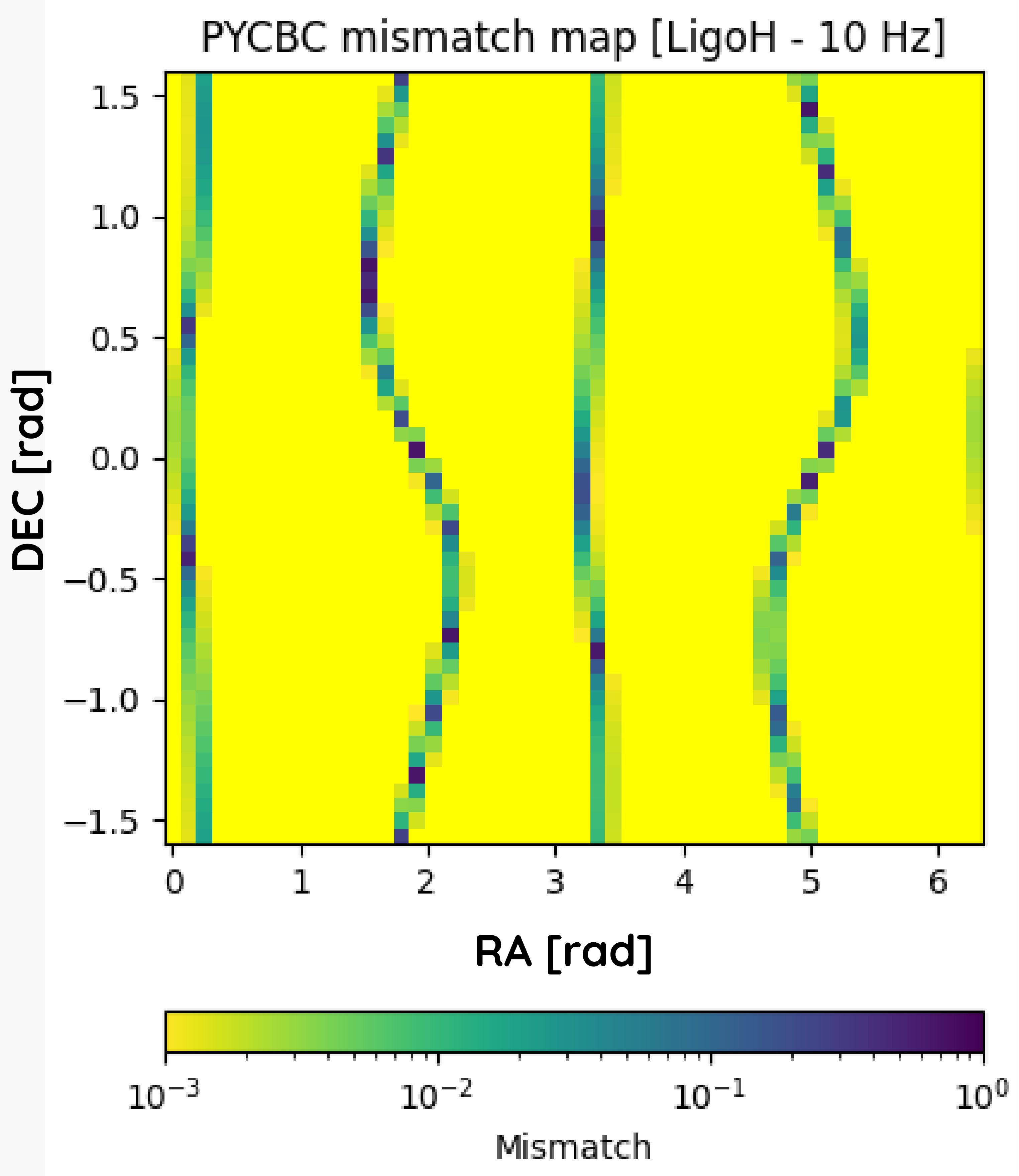
Recommencer en descendant la puissance à 0W

Recommencer en montant à 1.5W

Faire plusieurs cycles
(mise en lumière d'éventuels effets tels la mémoire optique, paramètres variant avec le temps, etc...)

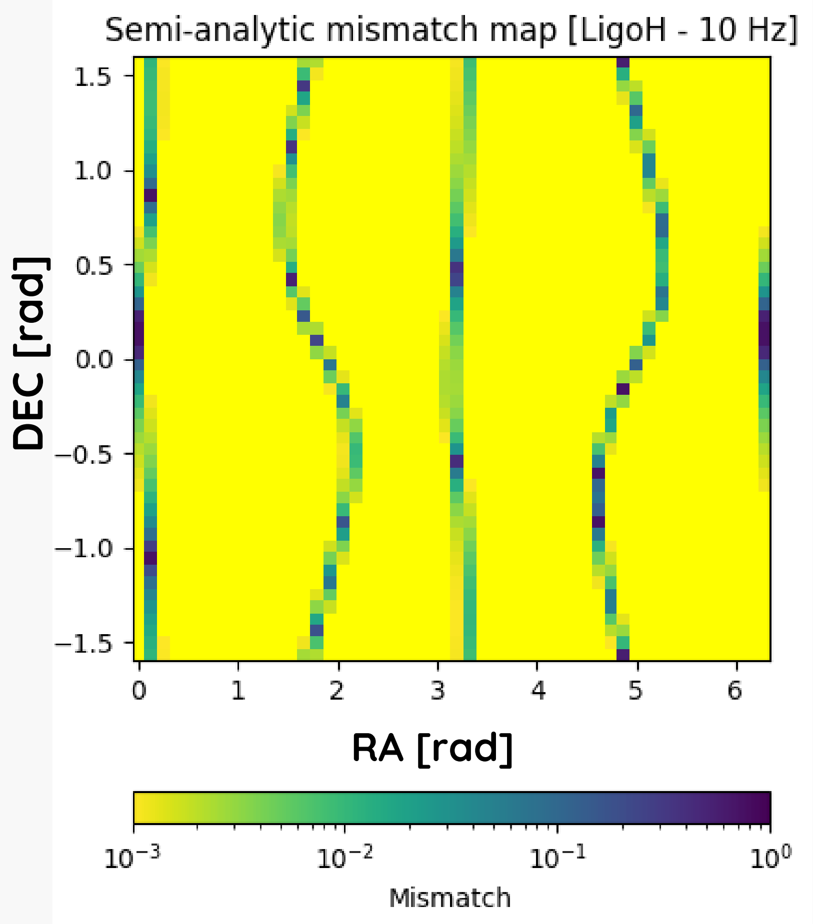
Comparison avec ma méthode

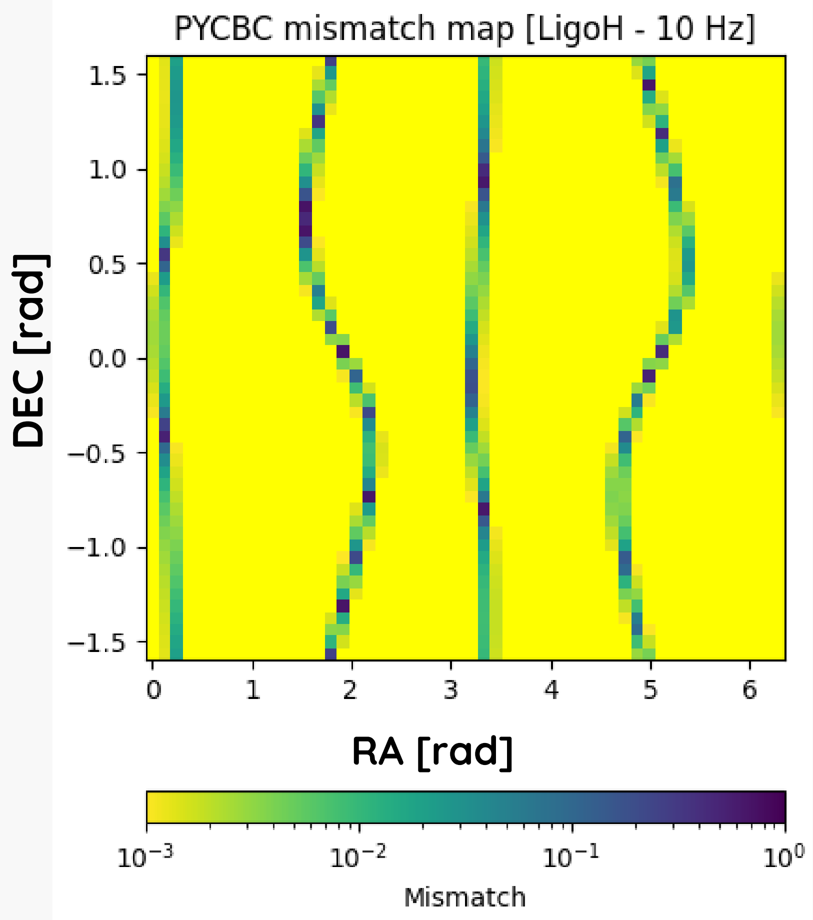




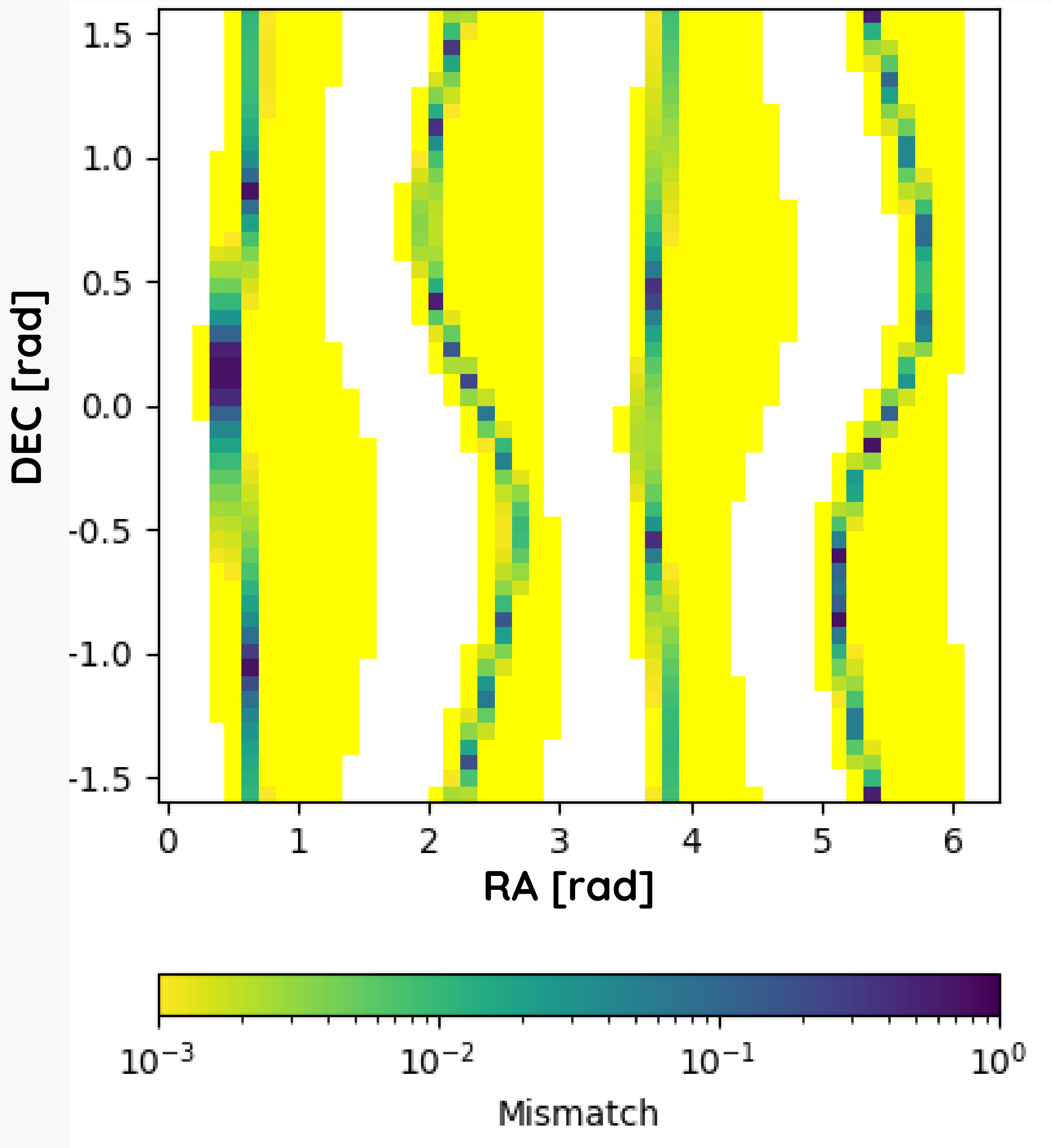
LigoH, f_low = 10 Hz, inclination = 90°
M_chirp = 1.2 M_sol

Différence entre méthodes SA et PyCBC

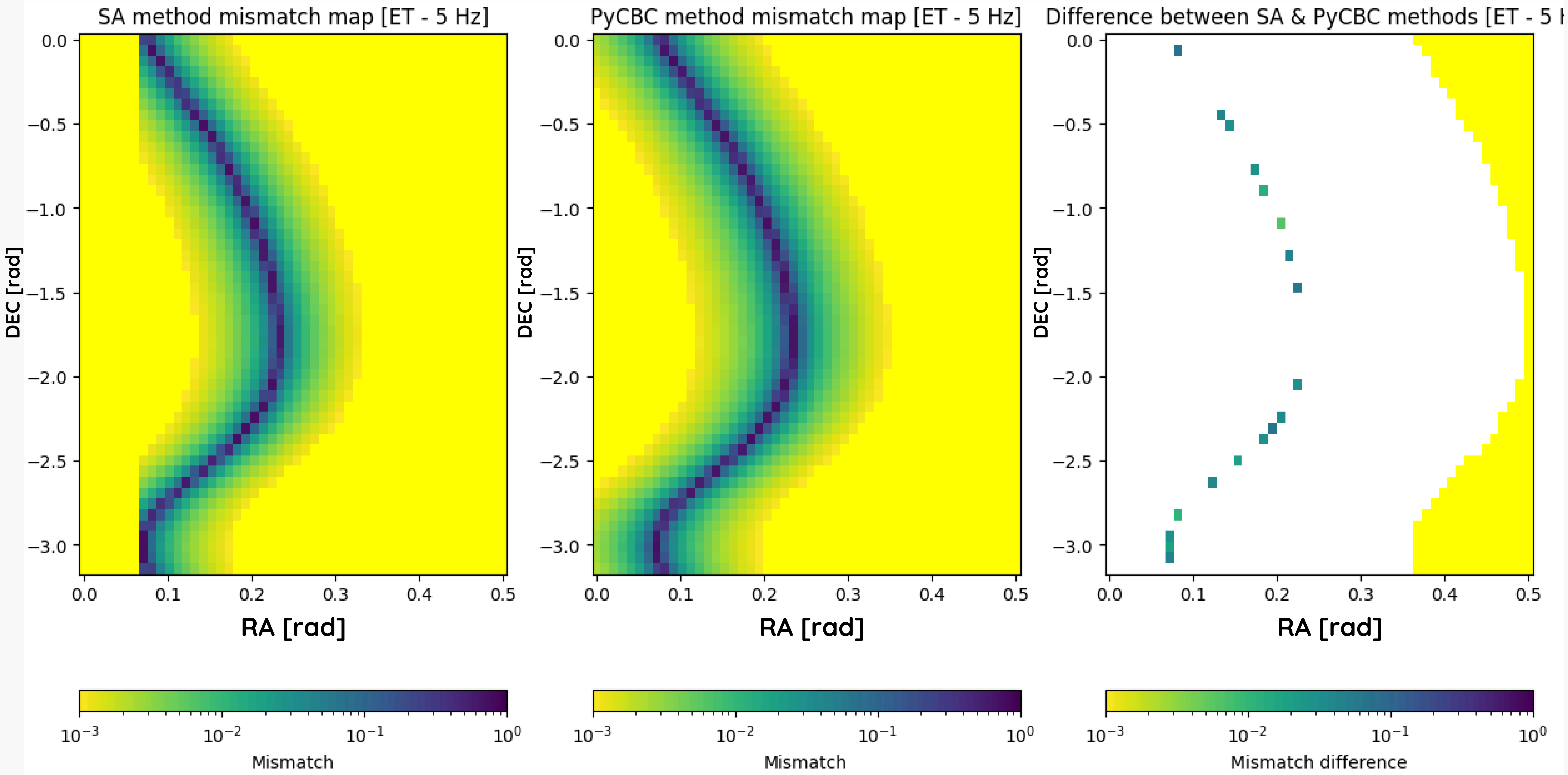




SA - PyCBC



Causées par faible résolution de la carte



Zoomer retire les divergences

Simulation de la même physique

Match Filtering Output (complex)

$$z(t_s) = 4 \int_0^{\infty} \mathrm{d}f \, \frac{\tilde{h}_{\mathrm{data}}(f)\tilde{h}^*_{\mathrm{template}}(f, t_s = 0, \phi_0 = 0)}{S_n(f)} \, e^{2\pi i f t_s}$$

SNR optimal

$$\rho^2_{\mathrm{opt}} = 4 \int_0^{\infty} \mathrm{d}f \, \frac{|\tilde{h}(f)|^2}{S_n(f)}$$

SNR (Time Serie)

$$\rho(t_s) = \frac{|z(t_s)|}{\rho_{\mathrm{opt}}}$$

(Template's optimal SNR)

SNR (Time Serie)

$$\rho(t_s) = \frac{|z(t_s)|}{\rho_{opt}}$$

(Template's optimal SNR) → ρ_{opt}

SNR

$$\rho = \max_{t_s} \rho(t_s)$$

SNR Total pour ET

$$\mathrm{SNR}^2_{tot} = \rho_1^2 + \rho_2^2 + \rho_3^2$$

ρ_{const}

$$\rho[F(t)h(t), F(0)h(t)]$$

ρ_{mod}

$$\rho[F(t)h(t), F(t)h(t)] = \rho_{opt}[F(t)h(t)]$$

Développement d'une formule SA pour calculer le match dans cette situation

$$h_+(t) = A(t)\ (1 + \cos^2(\imath))\ \cos(\Phi(t))$$

$$h_\times(t) = A(t)\ 2\ \cos(\imath)\ \sin(\Phi(t))$$

$$A(t) = \frac{4}{D}\left(\frac{G\mathcal{M}}{c^2}\right)^{5/3}\left(\frac{\pi f_{\mathrm{gw}}(t)}{c}\right)^{2/3}$$

$$f_{\mathrm{gw}}(t_c - t) = \frac{1}{\pi}\left(\frac{G\mathcal{M}}{c^3}\right)^{-5/8}\left(\frac{5}{256}\frac{1}{(t_c - t)}\right)^{3/8}$$

$$\Phi(t) = -2\left(\frac{5G\mathcal{M}}{c^3}\right)^{-5/8}(t_c - t)^{5/8} + \phi_c$$

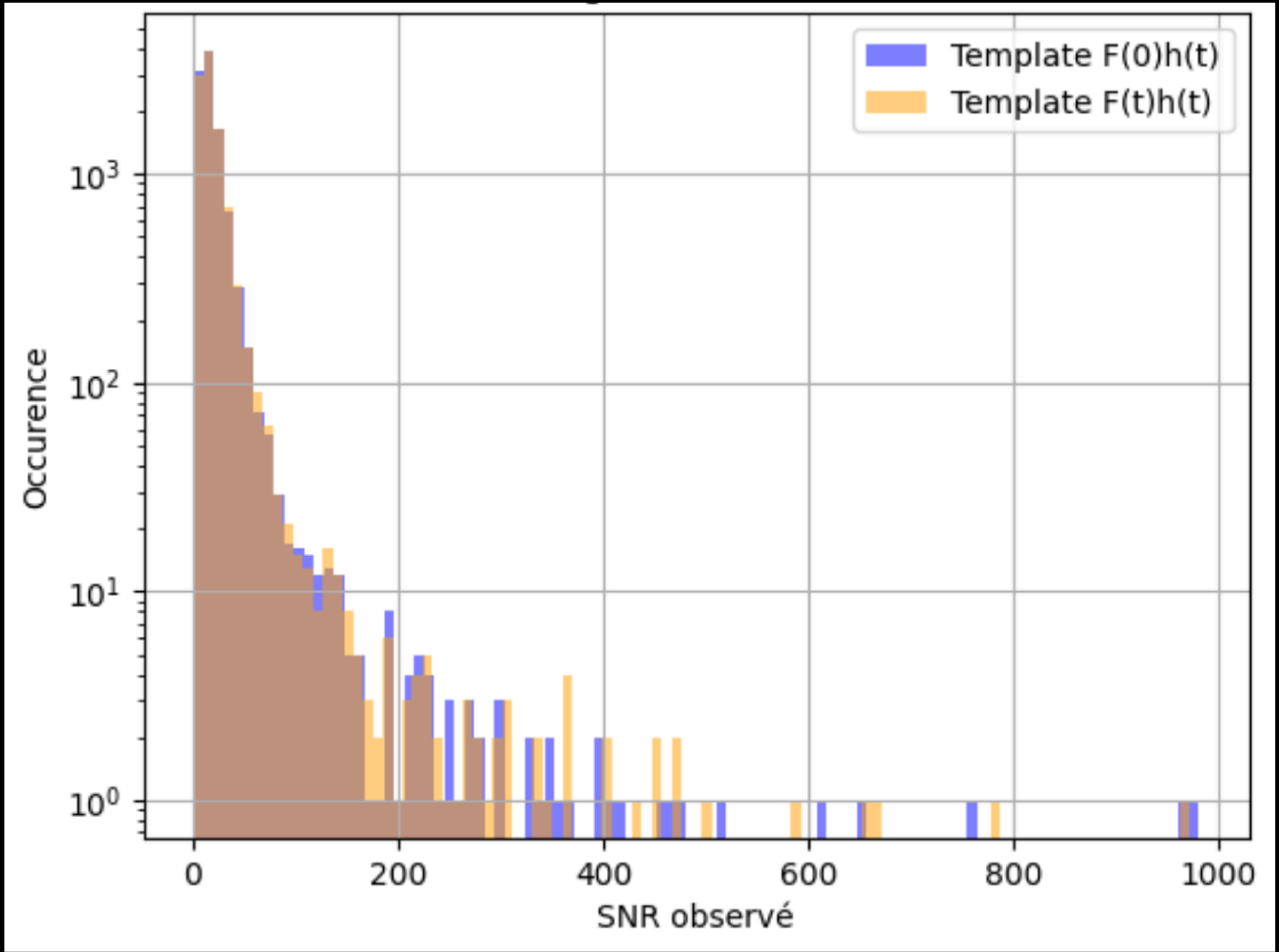
$$m(h_{\rm rot}, h_{\rm const}) = \max_{\Delta t_c, \Delta\phi_c} \frac{\Re \int \frac{f^{-7/3}|B(t_{\rm rot}(f))|e^{-i\theta(t_{\rm rot}(f))}e^{i(2\pi f \Delta t_c - \Delta\phi_c)}e^{i\phi_0}}{S_n(f)} df}{\sqrt{\int \frac{f^{-7/3}|B(t_{\rm rot}(f))|^2}{S_n(f)} df \ \int \frac{f^{-7/3}}{S_n(f)} df}}$$

With:

$$B(t(f)) = \sqrt{F_+^2(t_{\rm rot}(f))(1+\cos^2(\imath))^2 + F_\times^2(t_{\rm rot}(f))\ 4\ \cos^2(\imath)}$$

$$\theta(t(f)) = \arctan\left(\frac{-F_\times(t_{\rm rot}(f))\ 2\ \cos(\imath)}{F_+(t_{\rm rot}(f))(1+\cos^2(\imath))}\right)$$

SNR histogram



(10.000 sources)

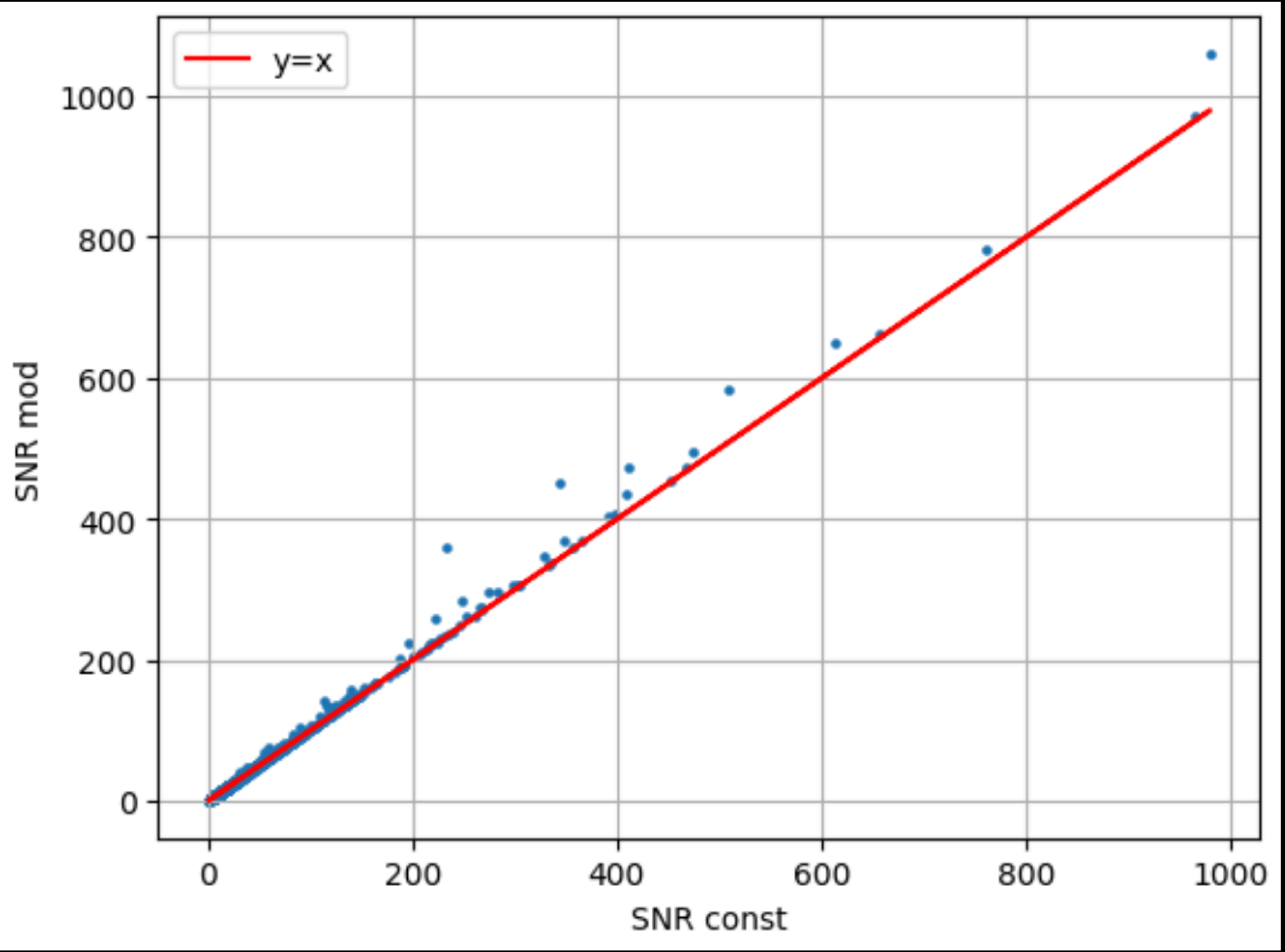
SNR entre 0 and 1000

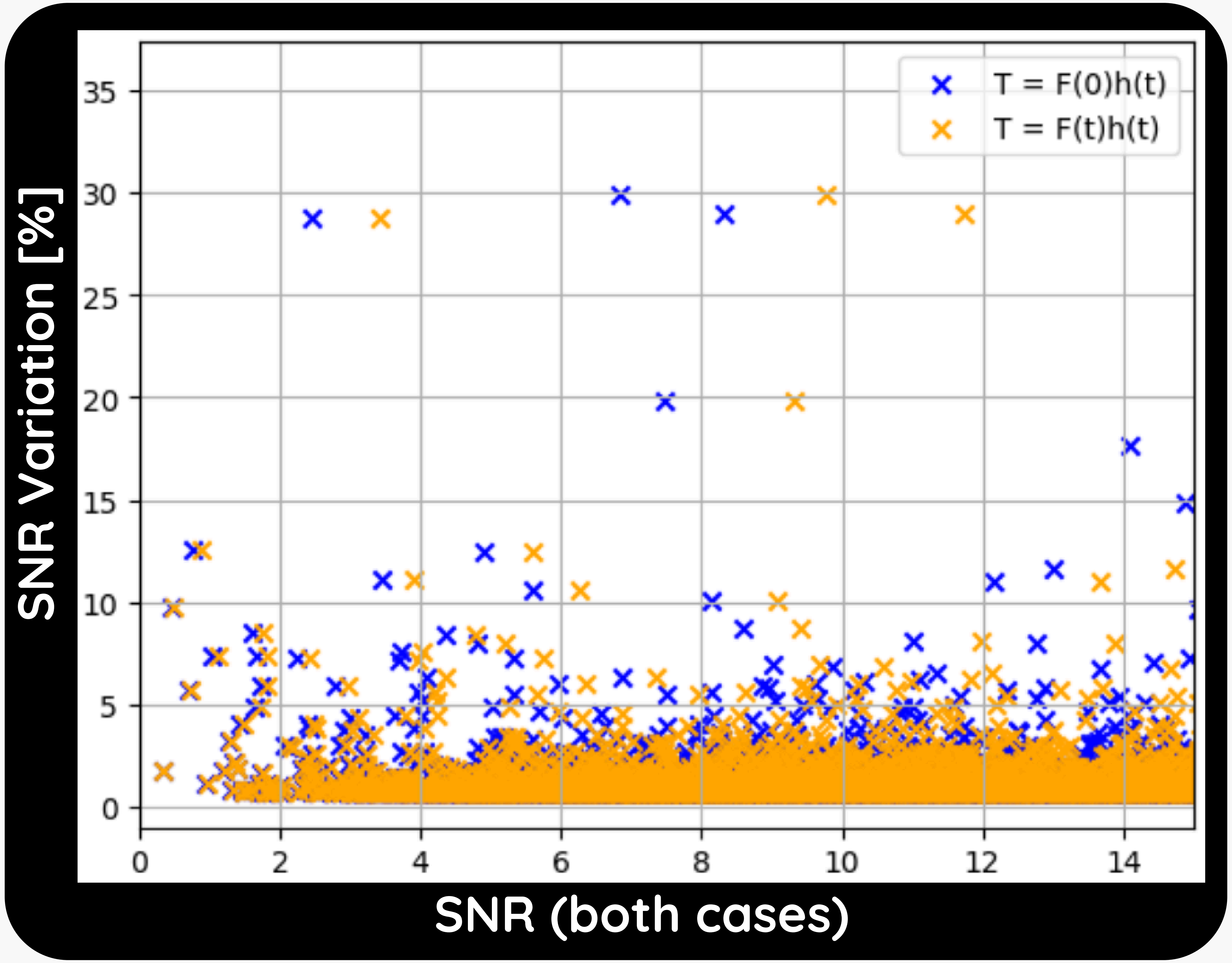
SNR moyen ~24

~75% des sources ont
8 < SNR < 55

Plus optimiste que le MDC

ρ_{const} vs ρ_{mod}





(10.000 sources
9.200 detected)

45 sources with

SNR_const < 8 BUT SNR_mod > 8

$$\frac{\rho_{mod} - \rho_{const}}{\rho_{mod}} = 1 - \frac{\rho_{const}}{\rho_{mod}}$$

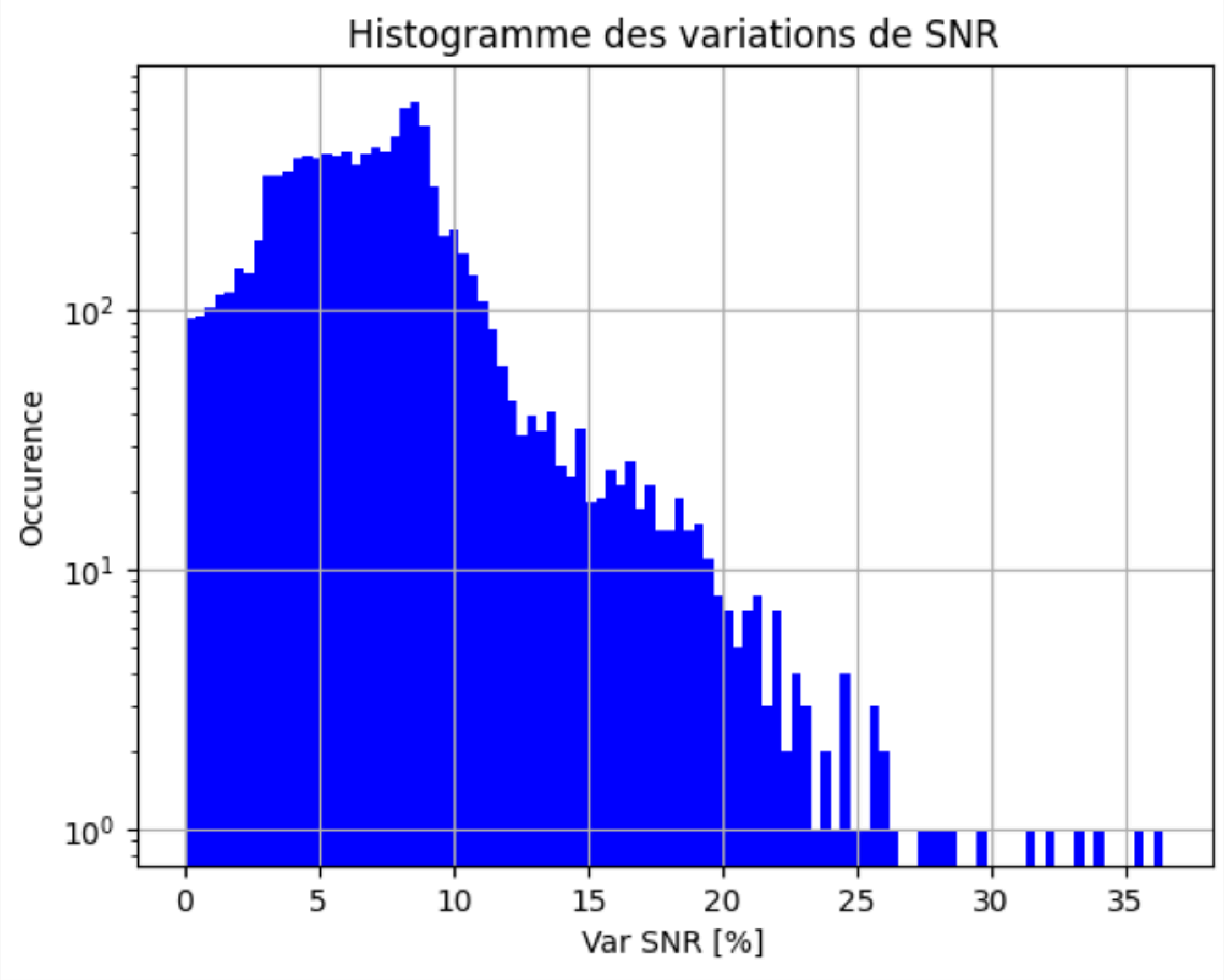
$$\frac{\rho_{mod} - \rho_{const}}{\rho_{mod}} = 1 - \frac{\rho_{const}}{||s||}$$

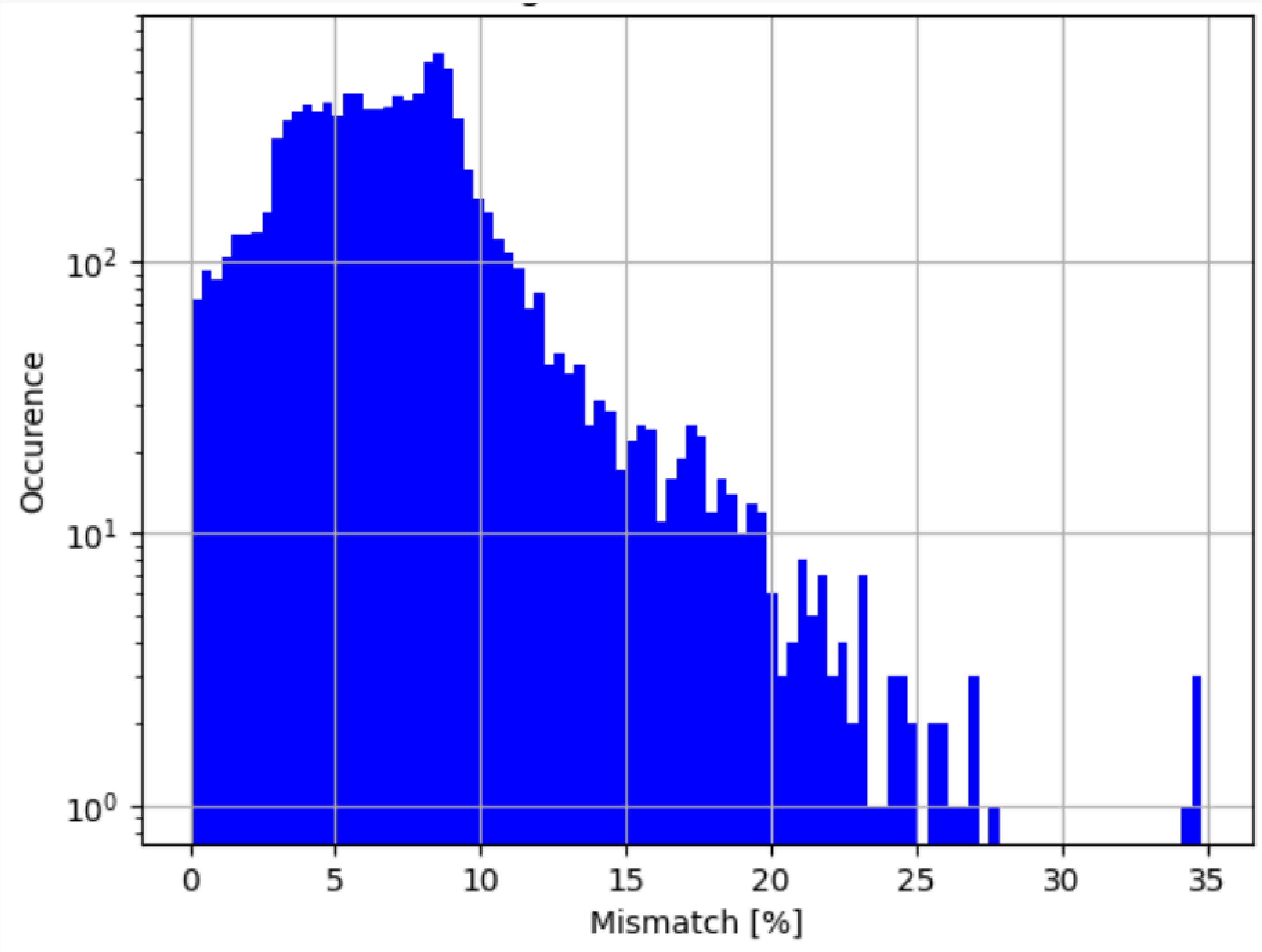
$$\mathcal{M}(s,T) = \max_{\Delta t, \Delta\phi} \frac{< s, T >}{||s||.||T||}$$

$$\mathcal{M}(s,T) \approx \frac{< s, T >}{||s||.||T||}$$

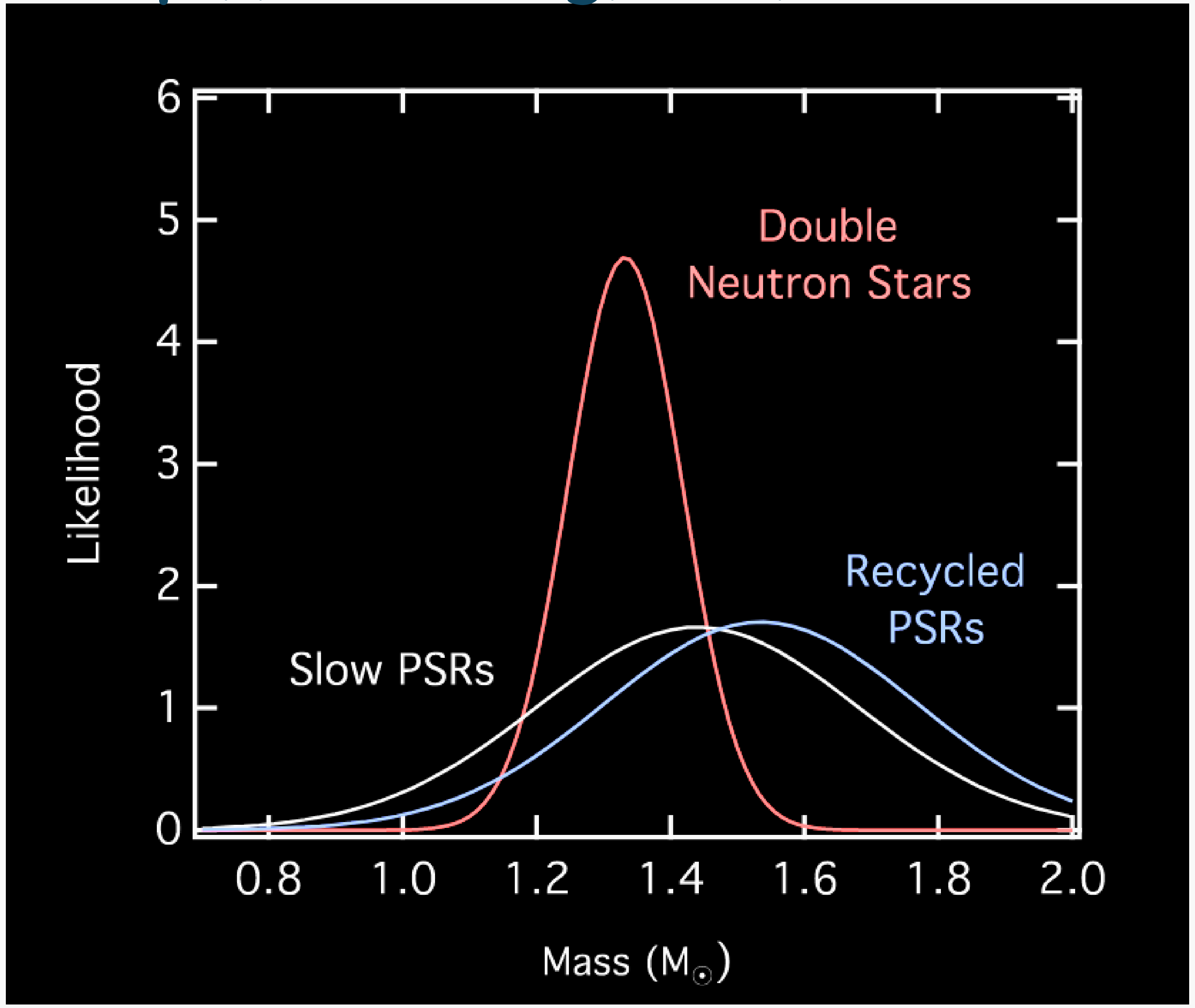
$$\mathcal{M}(s,T) \approx \frac{\rho_{const}}{||s||}$$

$$\rho_{const} = \frac{< h, T >}{||T||}$$


Histogramme des variations de SNR
Occurence
Var SNR [%]


Occurence
Mismatch [%]

http://arxiv.org/abs/1603.02698



http://arxiv.org/abs/1403.0007

$$\psi(z) = 0.015 \frac{(1+z)^{2.7}}{1 + [(1+z)/2.9]^{5.6}} \mathrm{M}_\odot \,\mathrm{year}^{-1}\, \mathrm{Mpc}^{-3}.$$

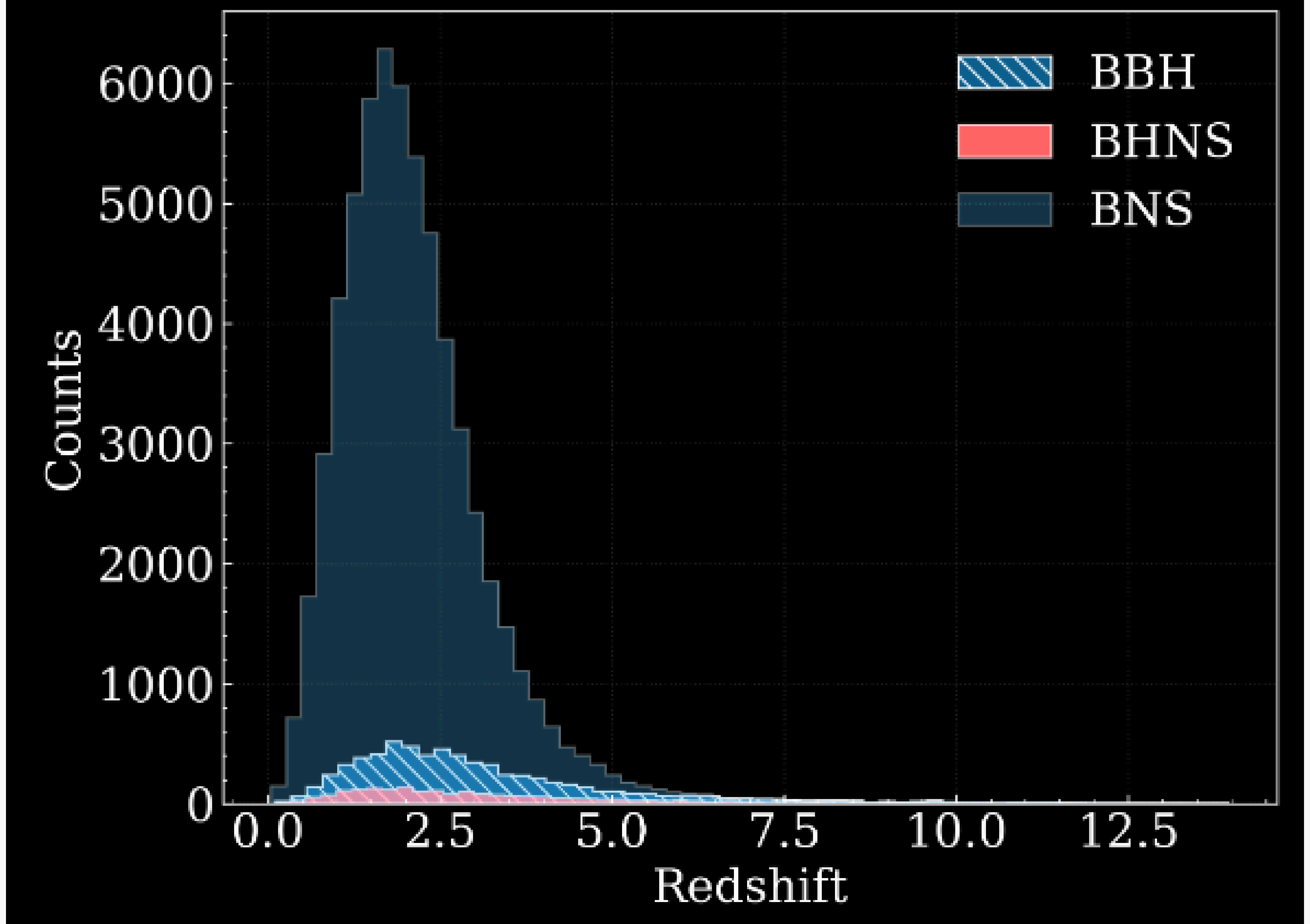


FIG. 10. Histogram of redshifts for the sources in our dataset. BNSs are shown in blue, BHNSs in green, and BBHs in red.

- 61031 BNSs: 19% have SNR > 8, 7% have SNR > 12.

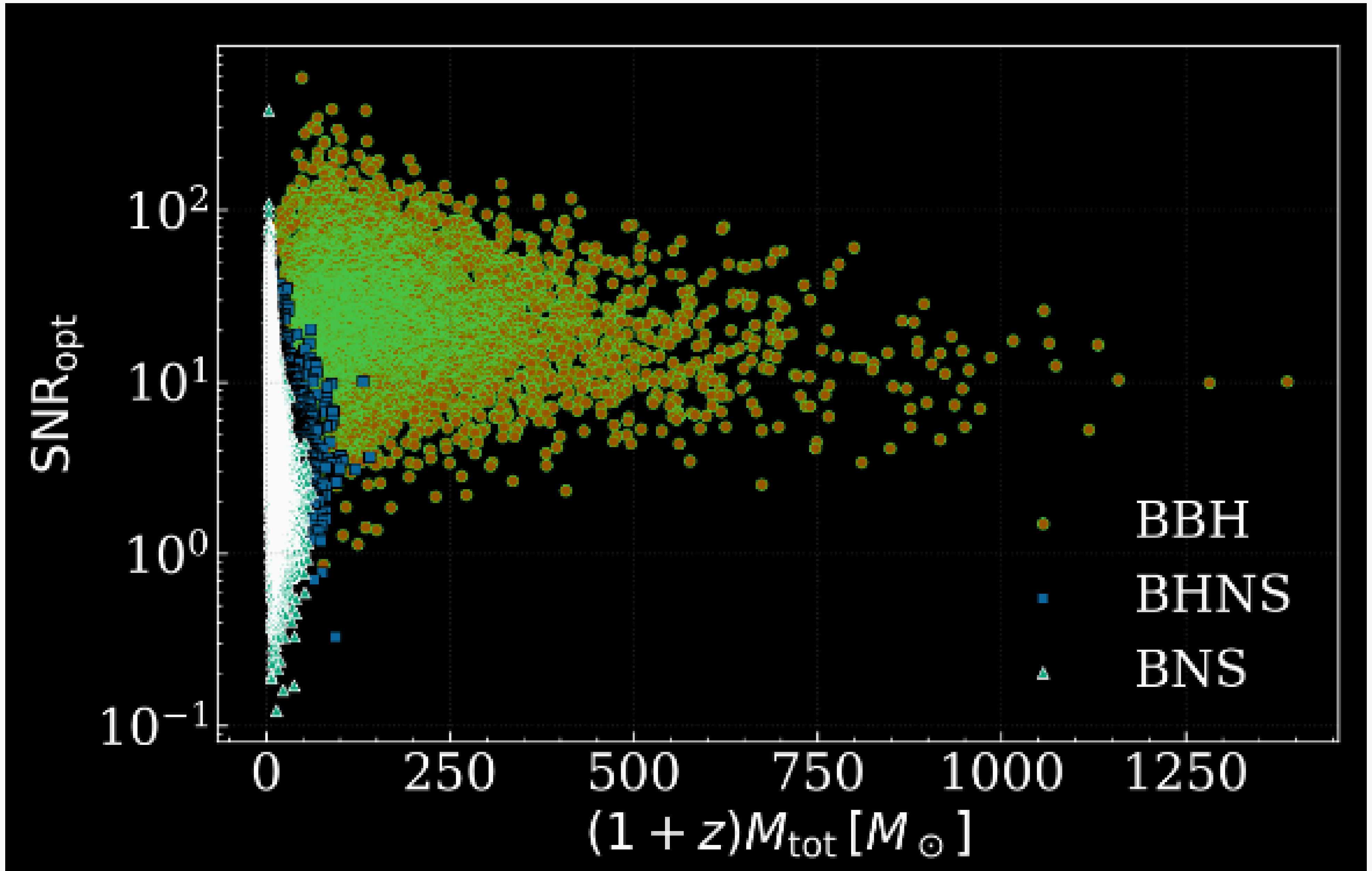
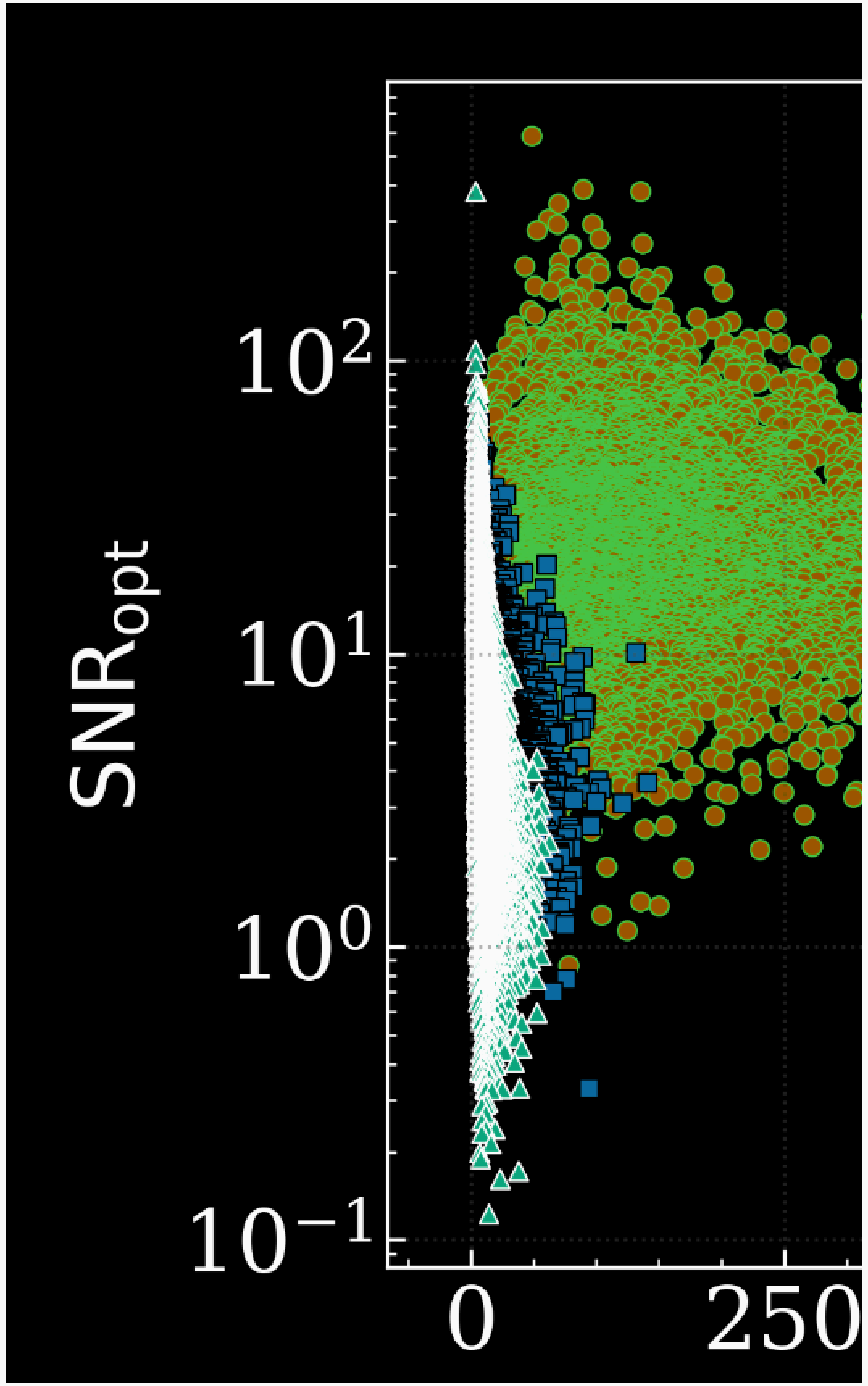
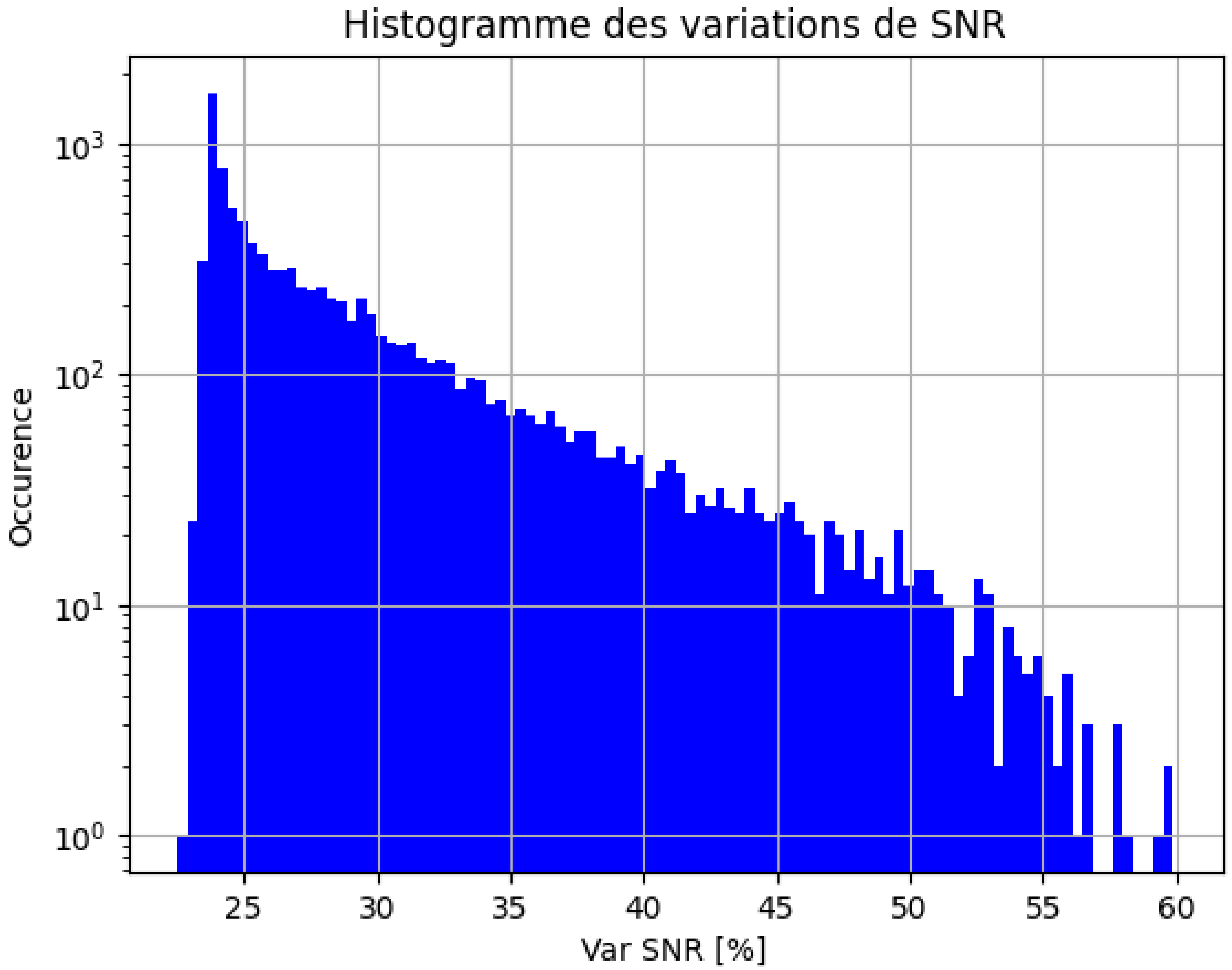
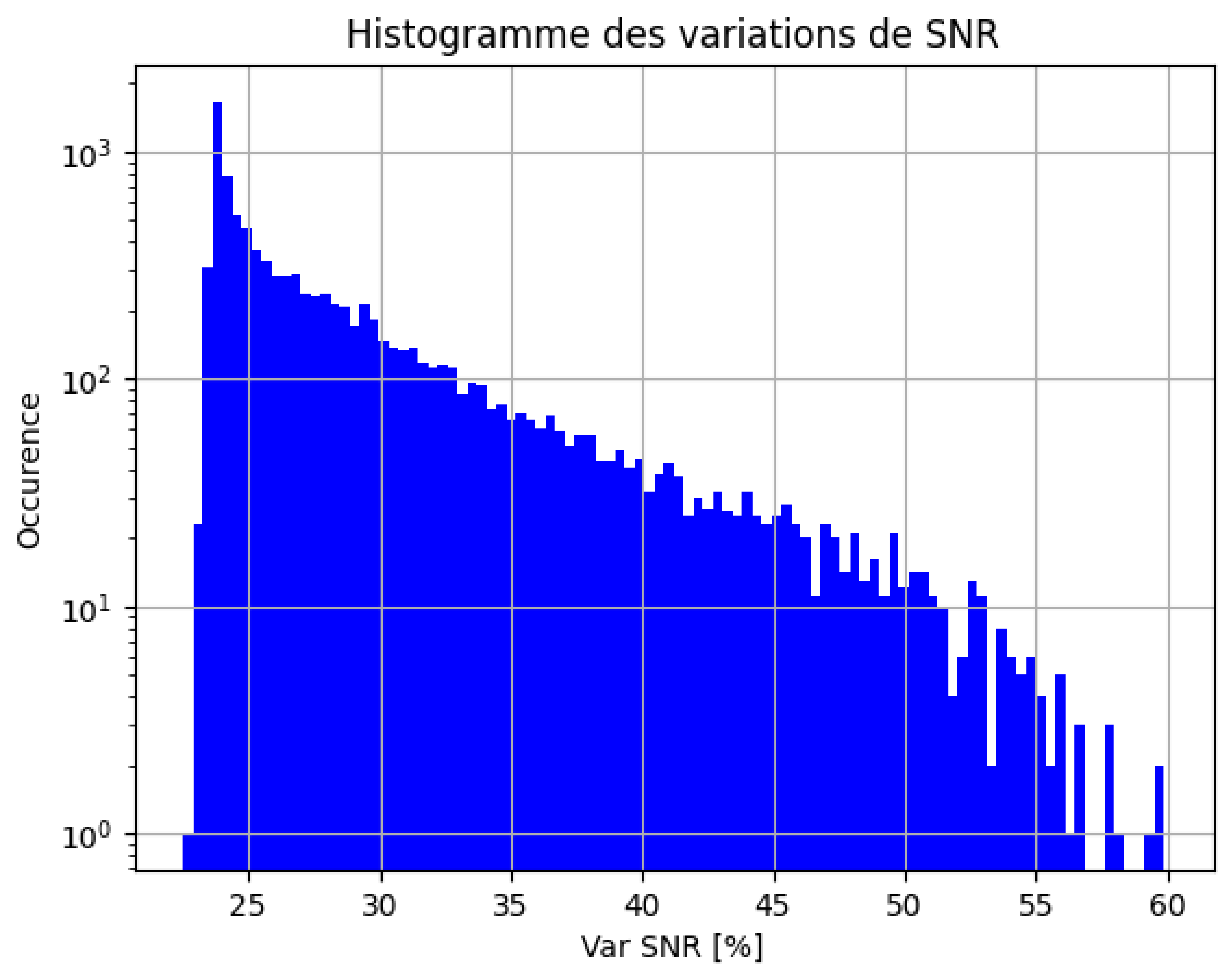


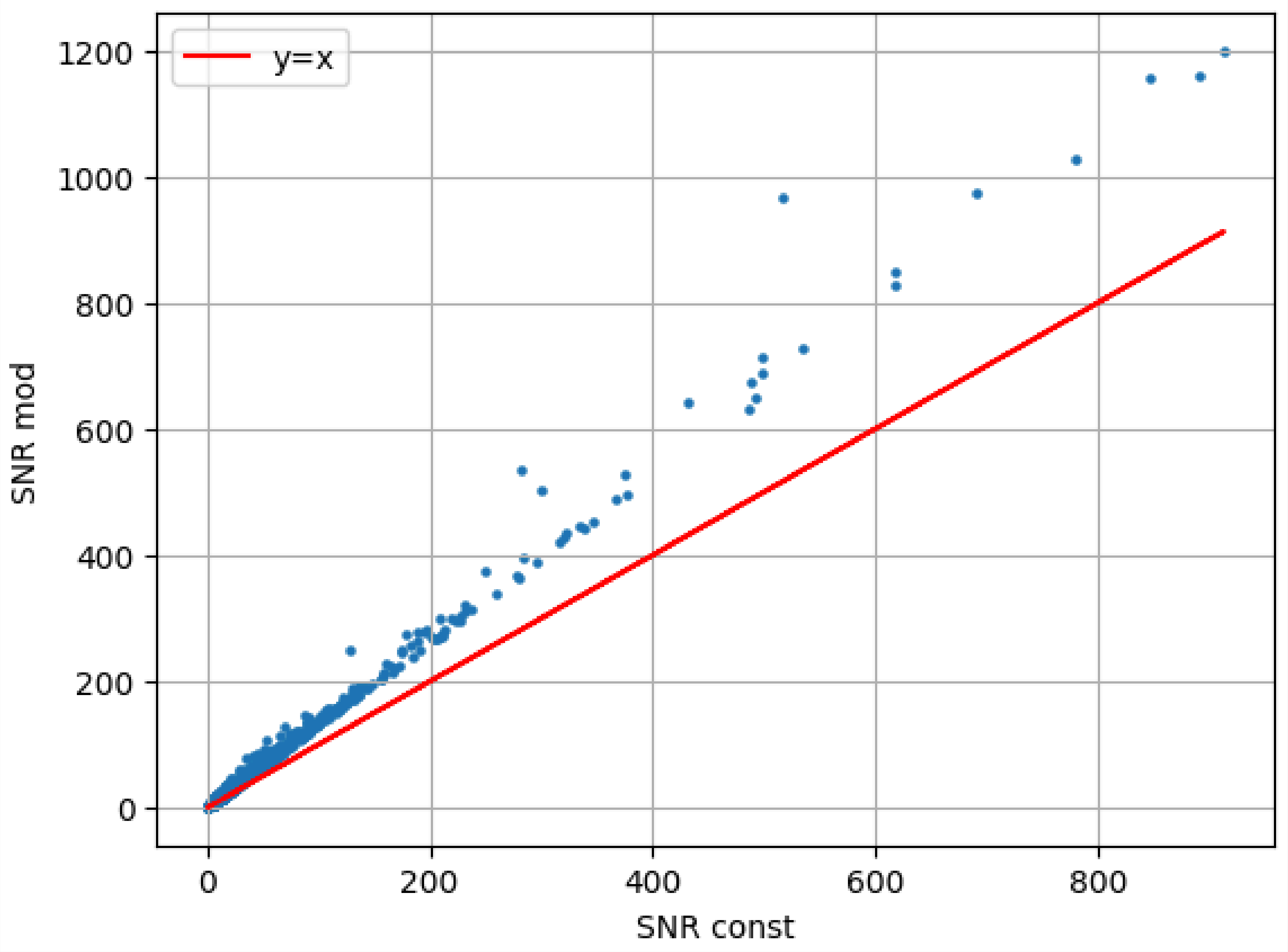
FIG. 13. Optimal signal-to-noise ratio (ρ_{opt}) as a function of the observed total mass $M_{z,tot}$.

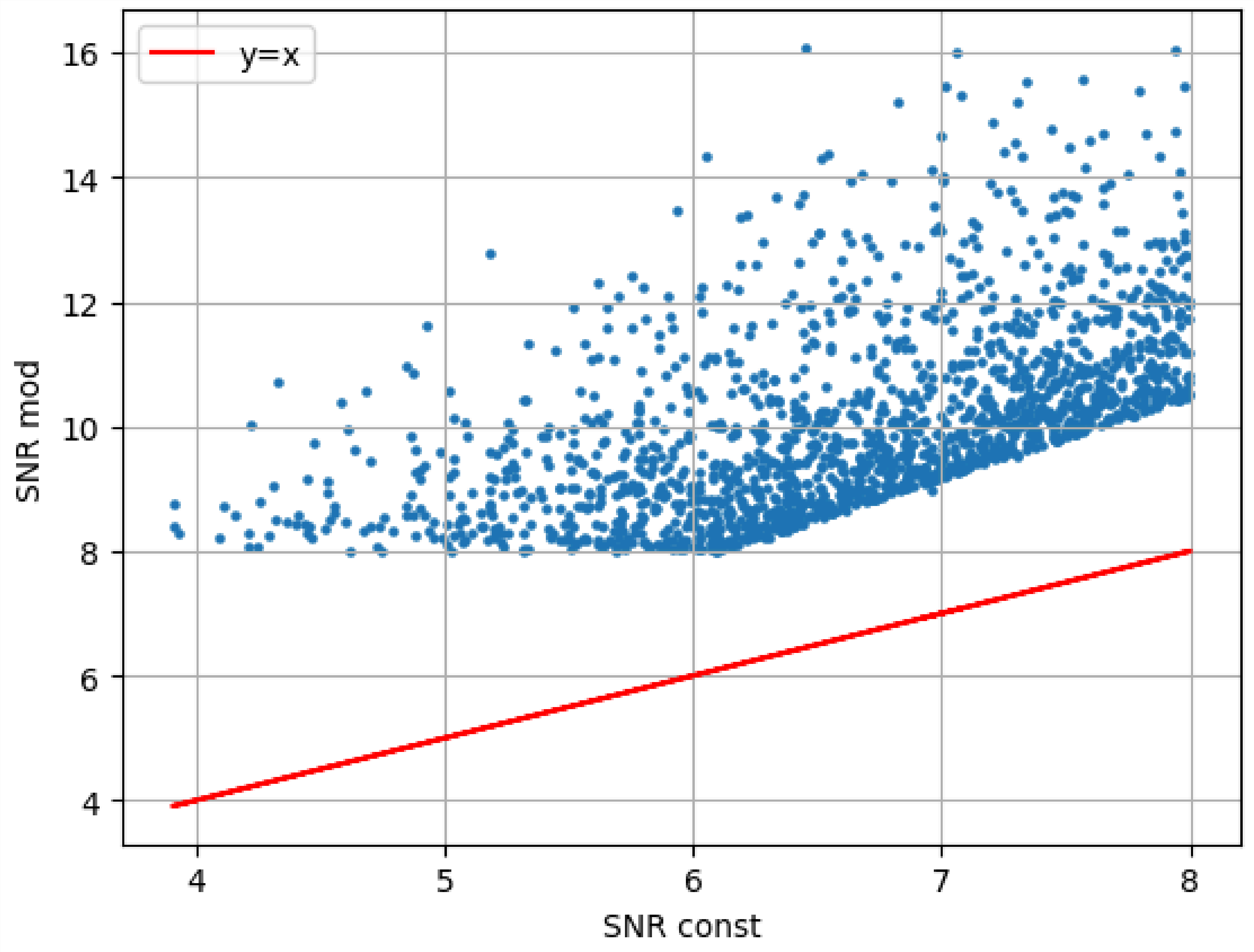




Histogramme des variations de SNR
Occurence
10^3
10^2
10^1
10^0
25
30
35
40
45
50
55
60
Var SNR [%]

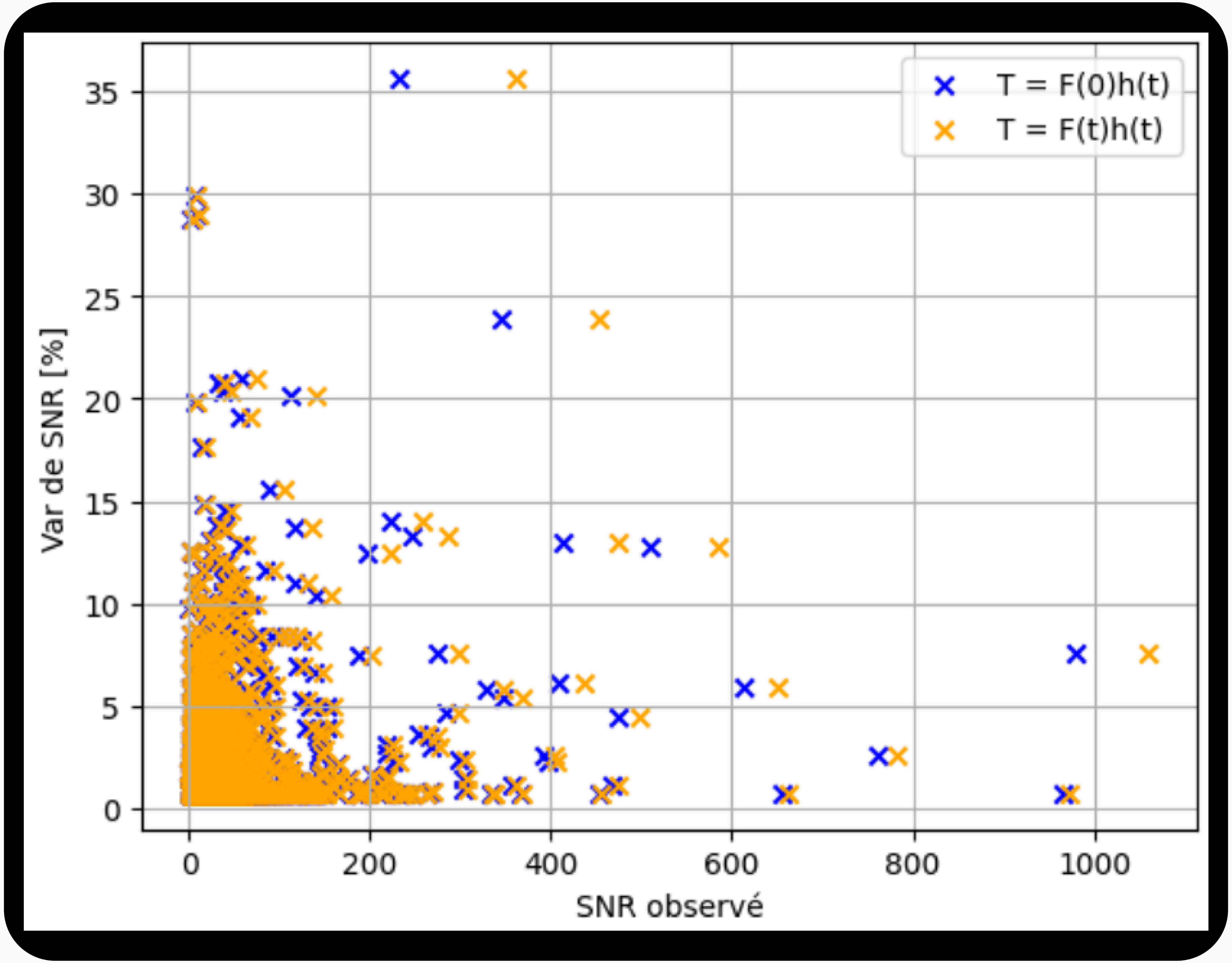

Histogramme des variations de SNR
Occurence
Var SNR [%]

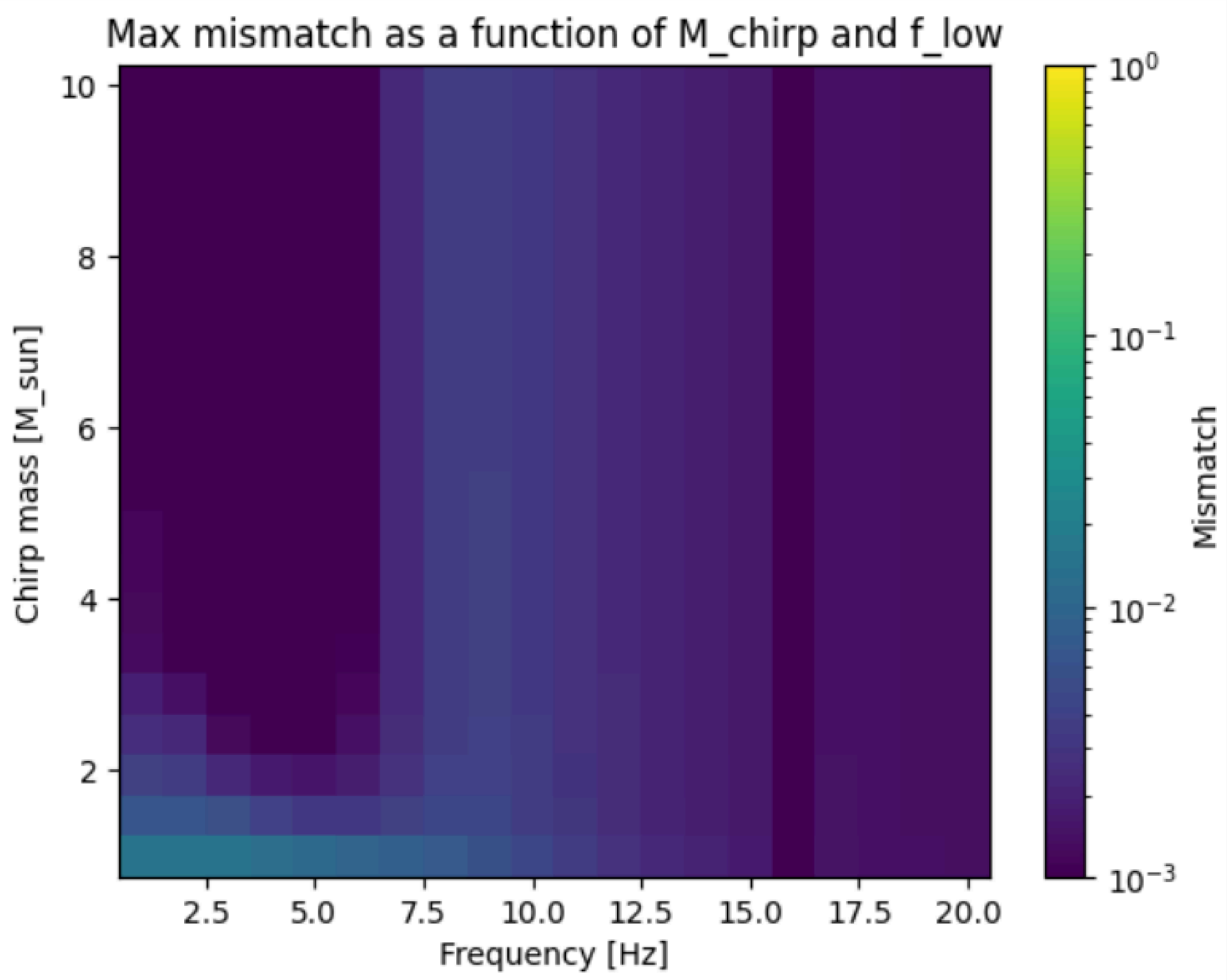

y=x
SNR mod
SNR const

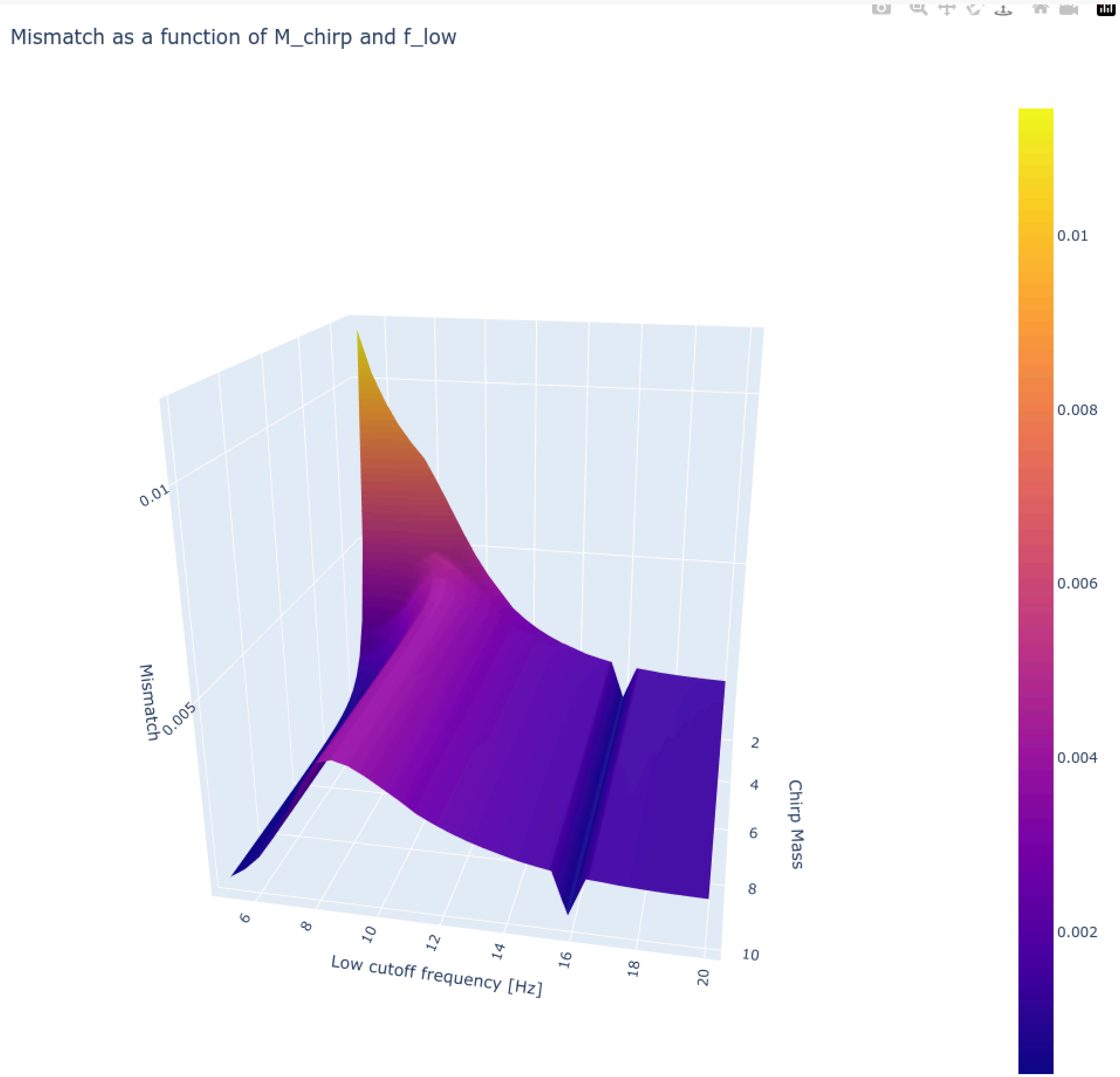


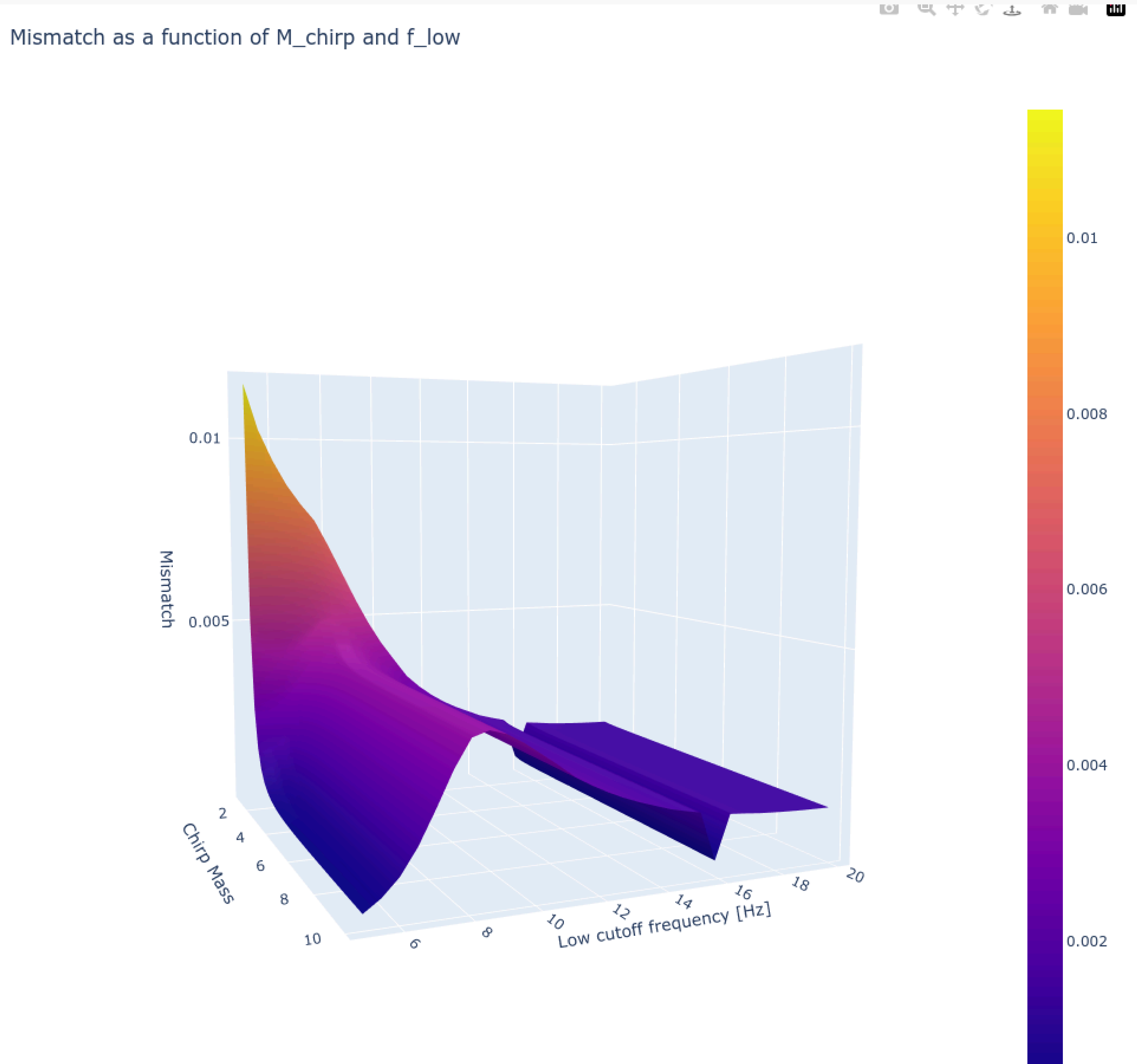
If f_{low} = 2Hz

~ 25% of ALL detected sources can be retrieved

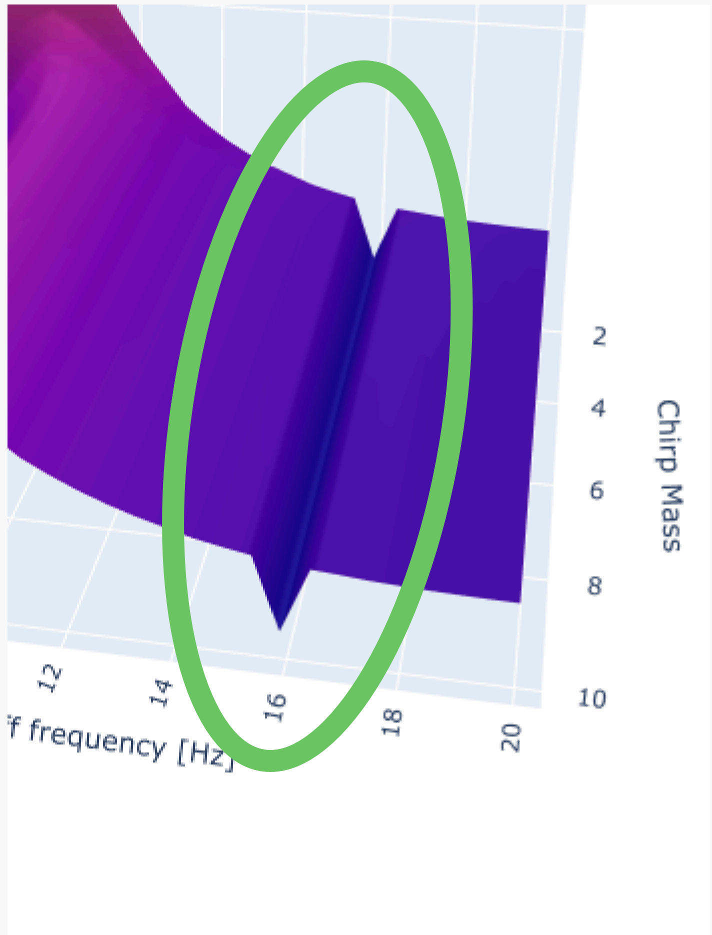

T = F(0)h(t)
T = F(t)h(t)
35
30
25
20
15
10
5
0
Var de SNR [%]
0
200
400
600
800
1000
SNR observé


Max mismatch as a function of M_chirp and f_low
Chirp mass [M_sun]
10
8
6
4
2
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
Frequency [Hz]
Mismatch
10^0
10^{-1}
10^{-2}
10^{-3}


Mismatch as a function of M_chirp and f_low
0.01
0.005
Mismatch
6
8
10
12
14
16
18
20
Low cutoff frequency [Hz]
2
4
6
8
10
Chirp Mass
0.01
0.008
0.006
0.004
0.002

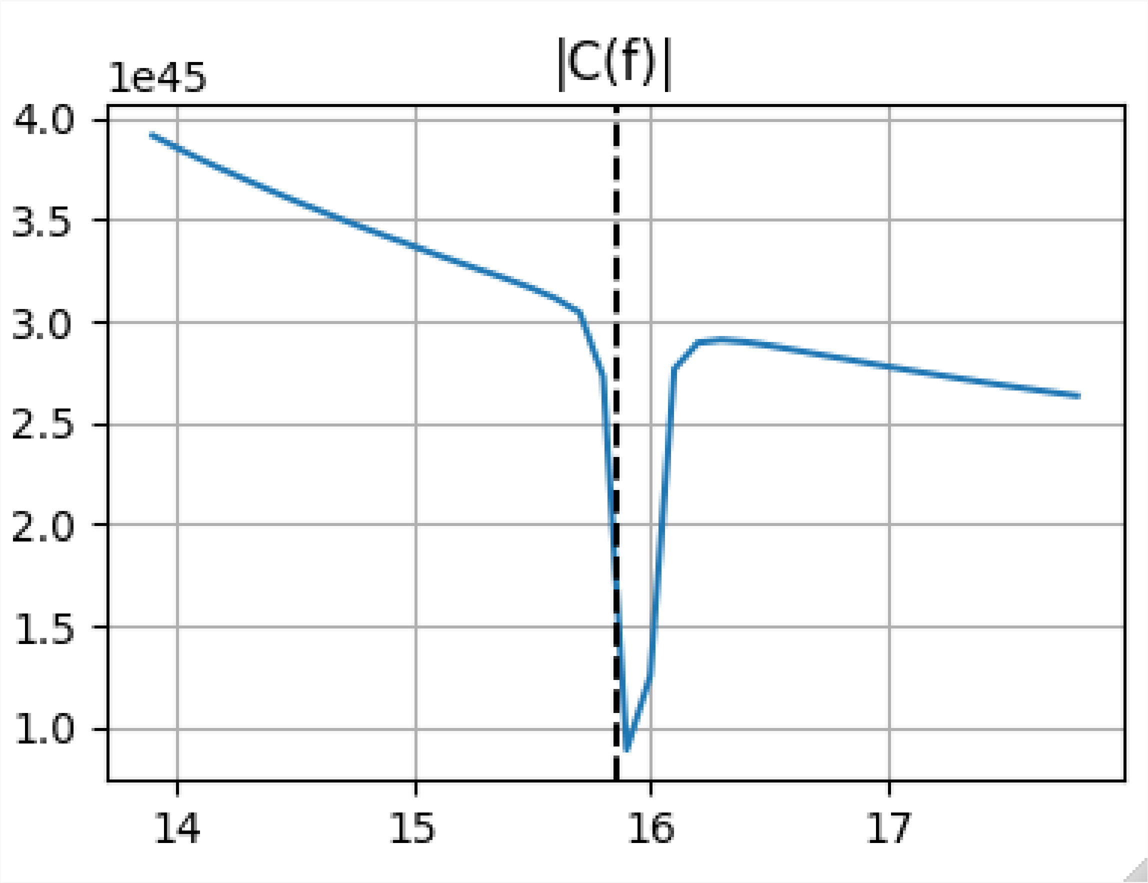

Mismatch as a function of M_chirp and f_low
0.01
0.005
Mismatch
2
4
6
8
10
Chirp Mass
6
8
10
12
14
16
18
20
Low cutoff frequency [Hz]
0.01
0.008
0.006
0.004
0.002

Caused by the PSD

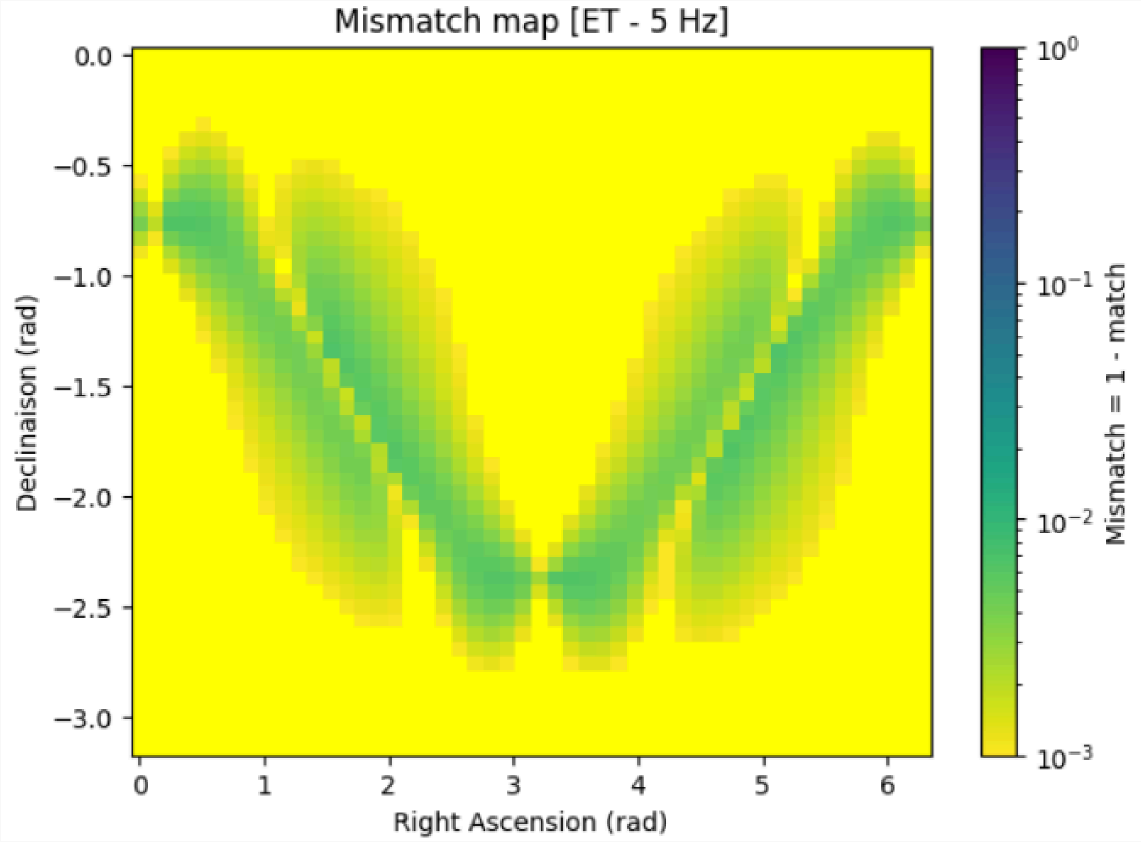


$$m(h_{\mathrm{rot}}, h_{\mathrm{const}}) = \max_{\Delta t_c, \Delta\phi_c} \frac{\Re \int \frac{f^{-7/3}|B(t_{\mathrm{rot}}(f))|e^{-i\theta(t_{\mathrm{rot}}(f))}e^{i(2\pi f \Delta t_c - \Delta\phi_c)}e^{i\phi_0}}{S_n(f)} df}{\sqrt{\int \frac{f^{-7/3}|B(t_{\mathrm{rot}}(f))|^2}{S_n(f)} df \int \frac{f^{-7/3}}{S_n(f)} df}}$$

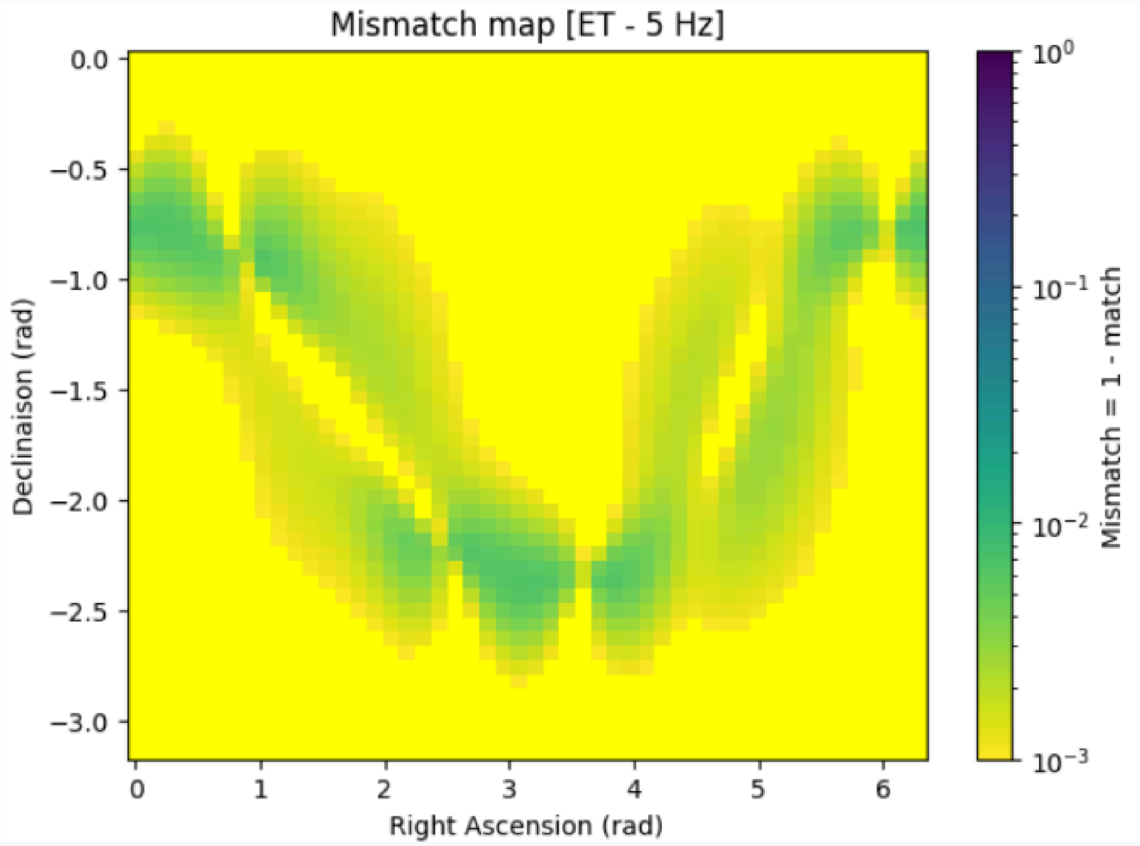
Modulus of numerator's integrand



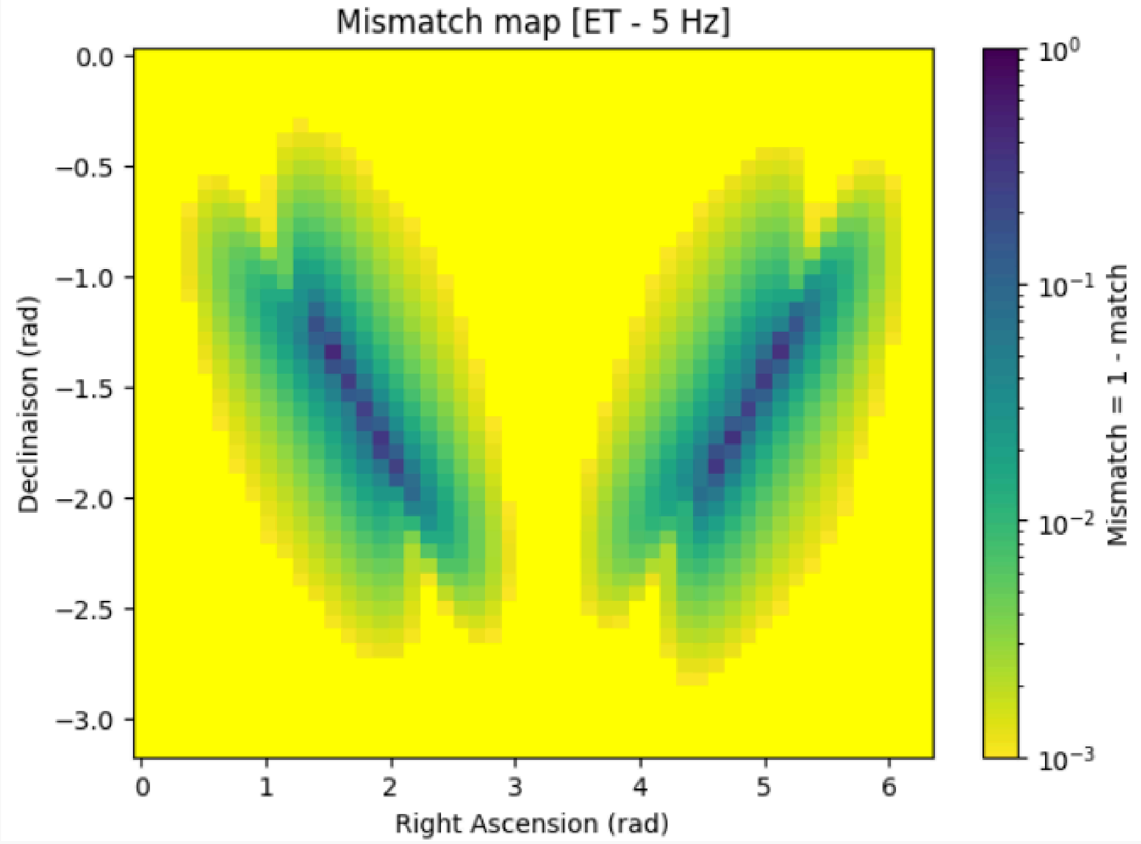
Physical interpretation yet to be given (if not an error)



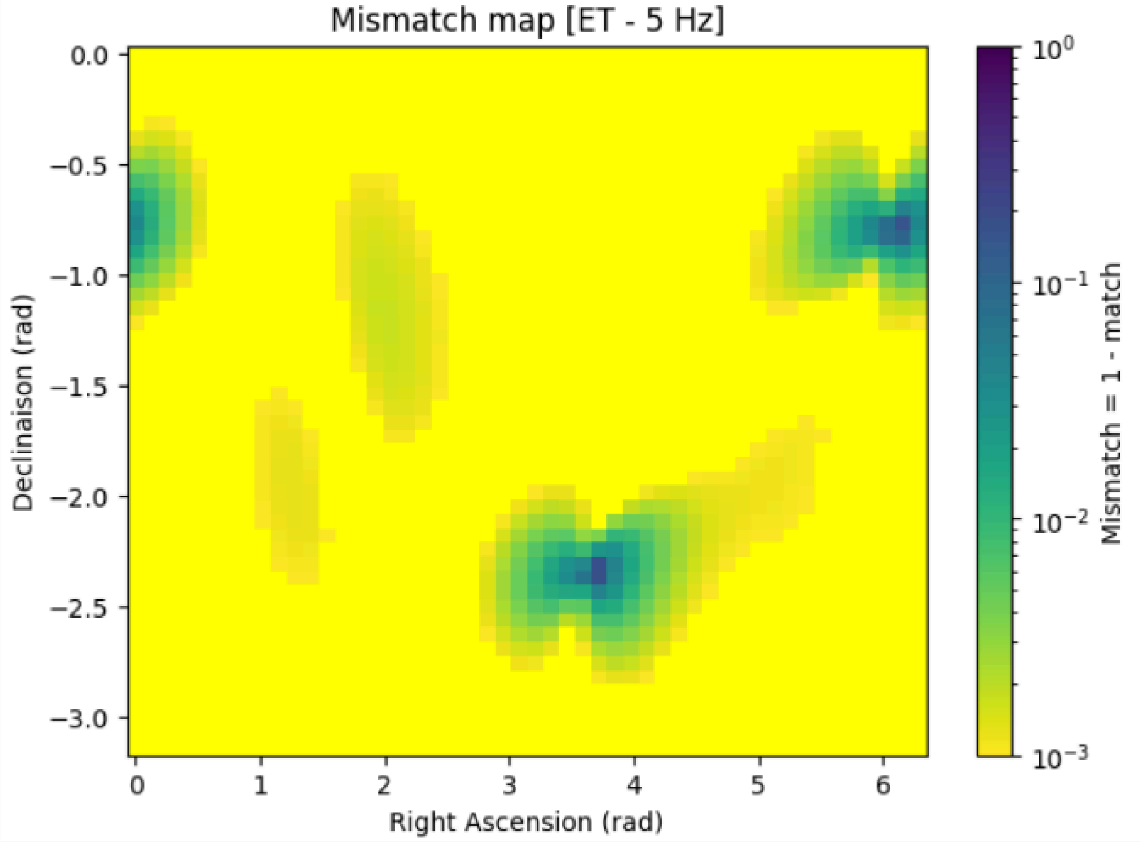
PSI = 0°, incl = 0°



PSI = 30°, incl = 0°



PSI = 0°, incl = 90°



PSI = 30°, incl = 90°

Development of equations using Marion's formalism

$$\mathcal{F}(\alpha, \delta, \psi, t) = F_+(\alpha, \delta, \psi, t) + iF_\times(\alpha, \delta, \psi, t)$$

$$\begin{cases} h_{mod}(\alpha, \delta, \psi, t) = f^{-\frac{7}{6}}(t)(F_+(\alpha, \delta, \psi, t) + iF_\times(\alpha, \delta, \psi, t)) = f^{-\frac{7}{6}}\mathcal{F}(\alpha, \delta, \psi, t) \\ h_{const}(\alpha, \delta, \psi) = f^{-\frac{7}{6}}(t)(F_+(\alpha, \delta, \psi, 0) + iF_\times(\alpha, \delta, \psi, 0) = f^{-\frac{7}{6}}\mathcal{F}(\alpha, \delta, \psi, 0) \end{cases}$$

For 3 detectors (ET-Xylophone)
&
inclination = 0°

$$\mathcal{M}(\alpha,\delta,\psi) \propto \max_{\Delta\tau} \int_{f_{low}}^{f_{high}} \frac{f^{-\frac{7}{6}}}{S_n(f)} \Re([\mathcal{F}_{ET}(\alpha,\delta,\psi,0)][\mathcal{F}^*_{ET}(\alpha,\delta,\psi,t)])\, df$$

$$\mathcal{L}(\psi) := \Re([\mathcal{F}_{ET}(\alpha,\delta,\psi,0)][\mathcal{F}^*_{ET}(\alpha,\delta,\psi,t)])$$

$$\begin{aligned}\mathcal{L}(\psi) &= \sqrt{A+\mathcal{B}\sin(4\psi+\Phi_1)+\mathcal{C}\sin(8\psi+\Phi_2)} + \sqrt{A-\mathcal{B}\sin(4\psi+\Phi_1)+\mathcal{C}\sin(8\psi+\Phi_2)} \\ &= f_+(\psi)+f_\times(\psi)\end{aligned}$$

Match has a non-trivial polarisation angle depedency

For 3 detectors (ET-Xylophone)
&
any inclination angle (iota)

$$\mathcal{F}_{ET}(\alpha,\delta,\psi,t) = [1+\cos^2(\iota)]F_{+,ET}(\alpha,\delta,\psi,t) + i[2\cos(\iota)]F_{\times,ET}(\alpha,\delta,\psi,t)$$
$$= \eta F_{+,ET}(\alpha,\delta,\psi,t) + i\xi F_{\times,ET}(\alpha,\delta,\psi,t)$$

$$\mathcal{L}(\psi) = \eta^2 f_+(\psi) + \xi^2 f_\times(\psi)$$

Match has a non-trivial
polarisation angle depedency

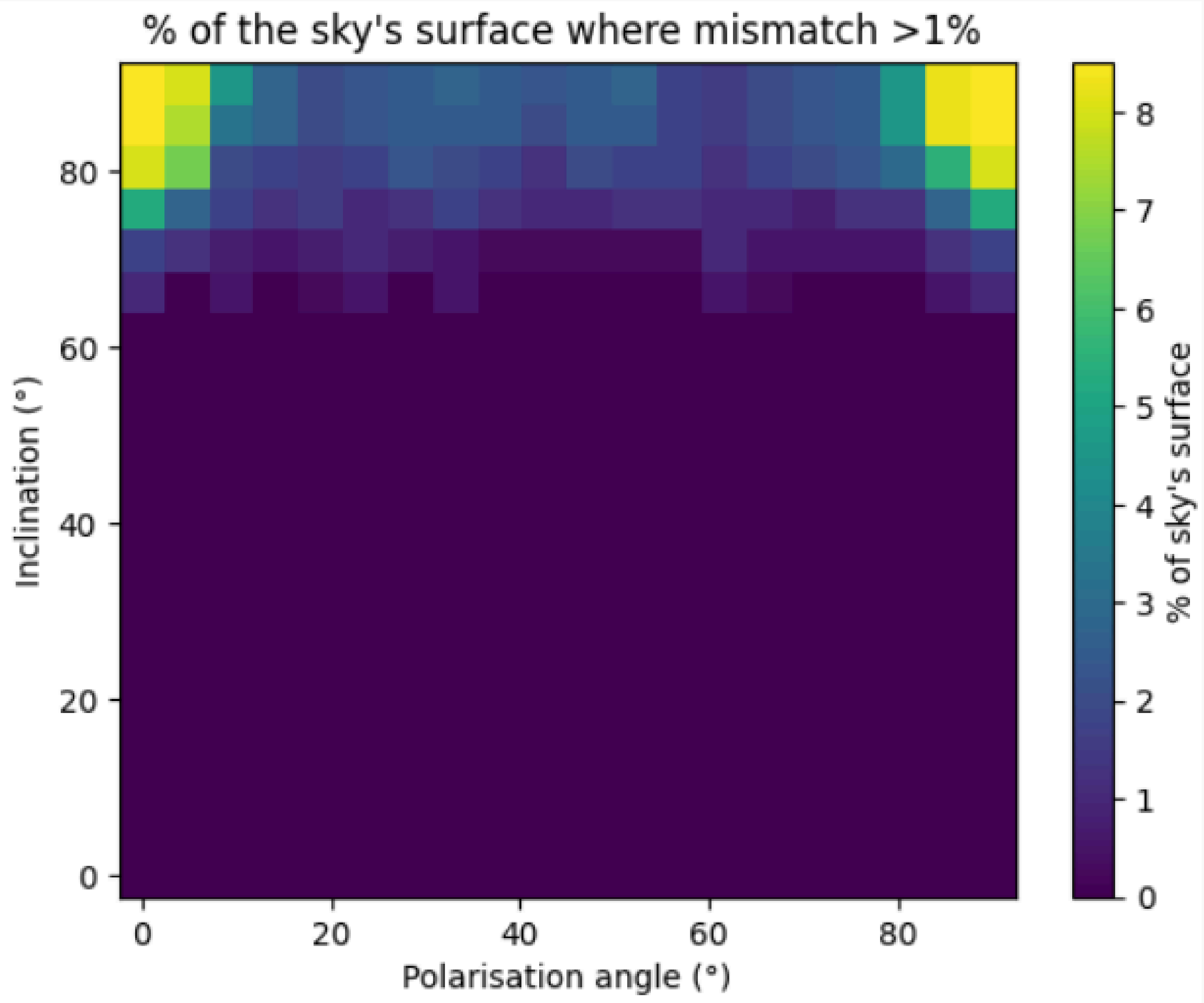
Studying the L function gives us the “geometric” behavior of the match

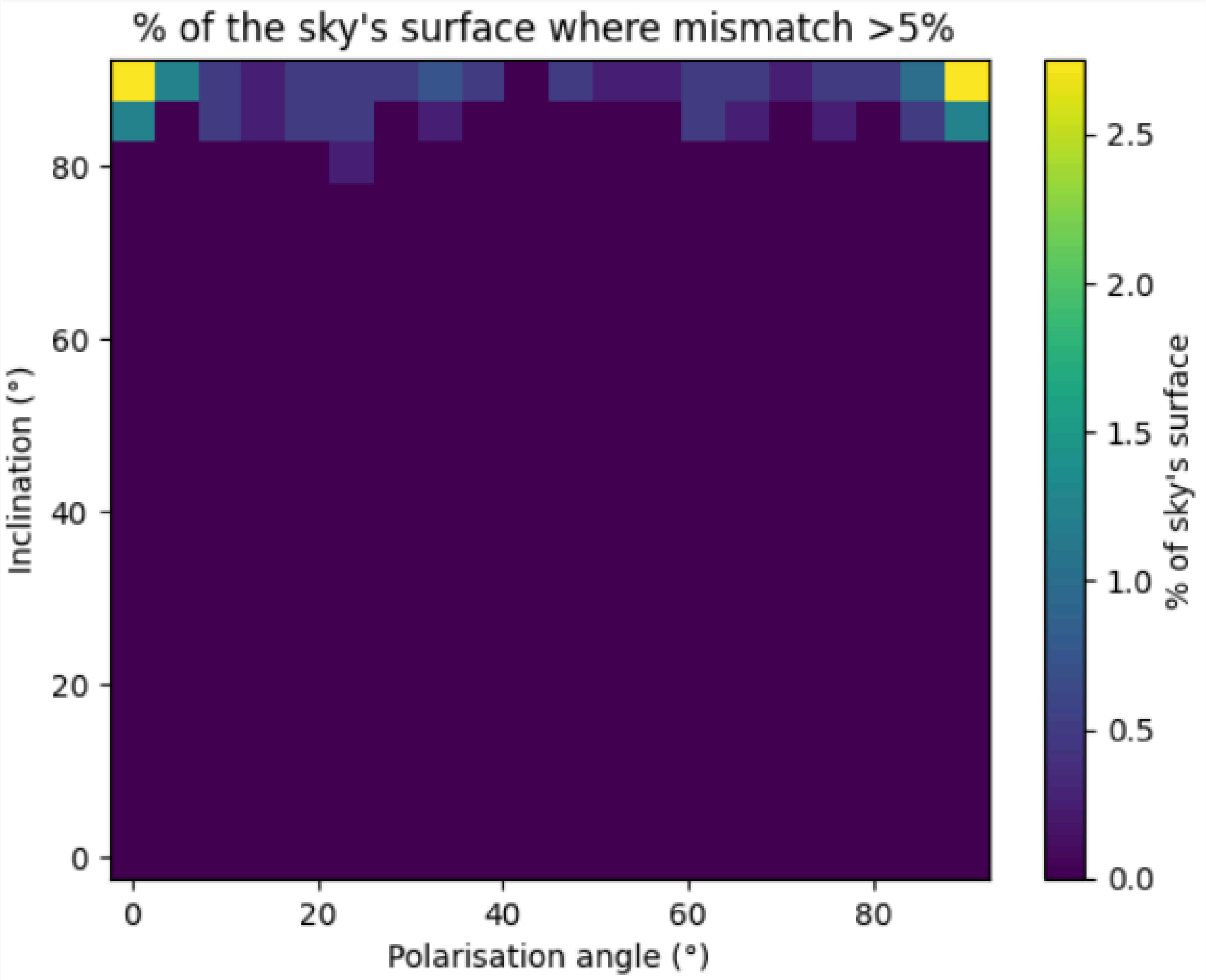
$$\mathcal{L}(\psi) = \eta^2 f_+(\psi) + \xi^2 f_\times(\psi)$$

Extendable to any network of L-shaped detectors

$$F_{+,\text{net}}(\alpha, \delta, \psi, t) = \sqrt{\sum_{i=1}^{n} F_{+,i}^2(\alpha, \delta, \psi, t)}$$
$$F_{\times,\text{net}}(\alpha, \delta, \psi, t) = \sqrt{\sum_{i=1}^{n} F_{\times,i}^2(\alpha, \delta, \psi, t)}$$

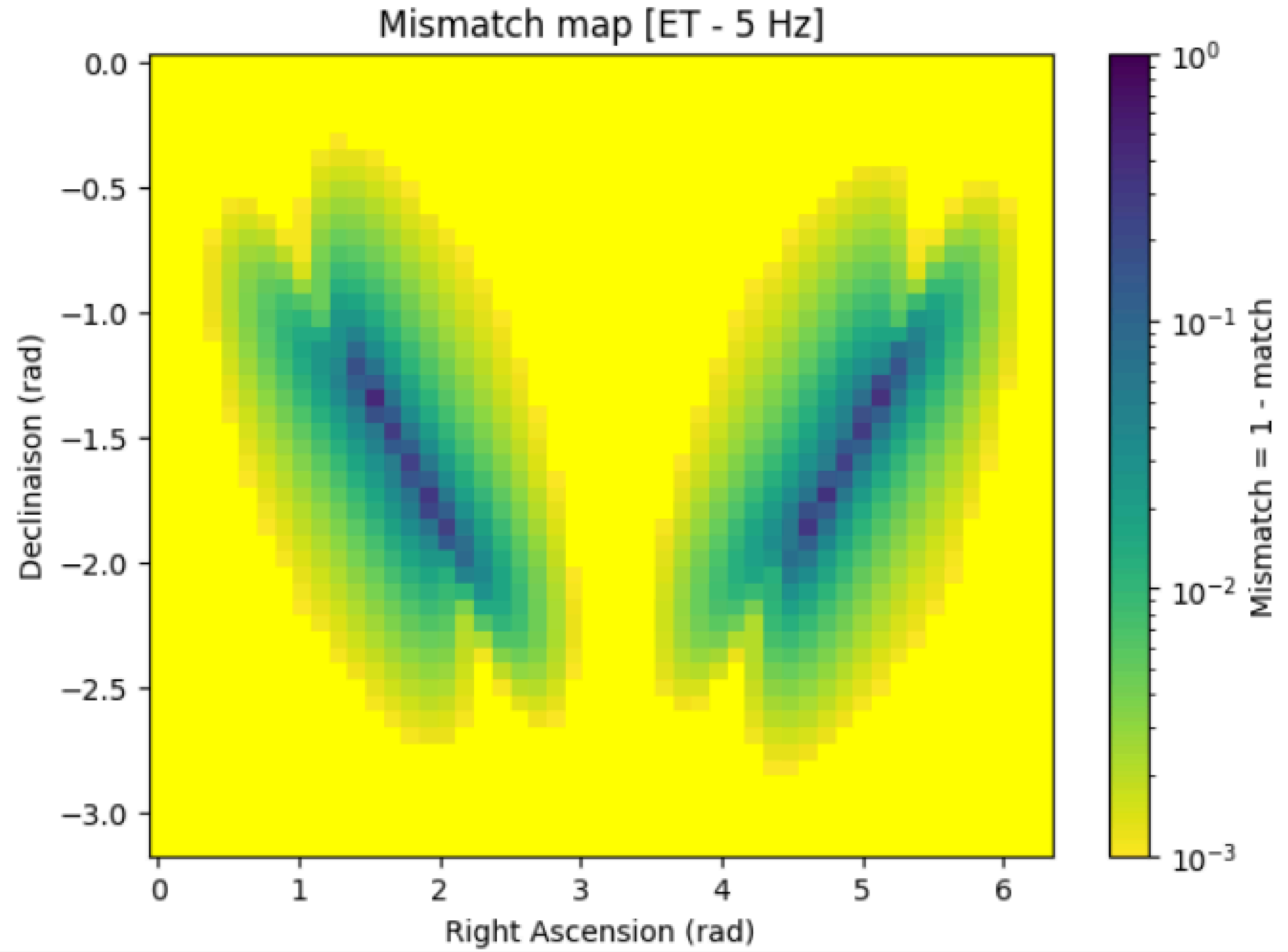
Areas where mismatch >1% and 5%





Confirmed !

Inclination = 90°, PSI = 90°



Max mismatch ~ 50%