Optical Configurations

From optical elements to detector design

Lecture 2

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STGWD 2026 — PhD International School on Technologies in Gravitational Waves Detection

Erice (TP), Italy - May 2026

Lecture 1

- Gaussian beam (essential tools)
- Michelson interferometer
- Fabry-Perot cavities
- Power Recycling
- Signal Recycling
- Toward real detectors

Lecture 2

How do we combine these elements into a real large scale detector layout?

ET Optical layout design

The design problem

What are we trying to design?

Design knobs

- Arm cavity length
- Beam size
- Mirror curvature
- Circulating power
- Cavity bandwidth
- Recycling cavities
- Response shaping

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→

A third-generation gravitational wave detector

- Better sensitivity
- Broader frequency coverage
- Higher duty cycle
- Compatibility with real infrastructures

Sensitivity is not a number
Frequency bands

A gravitational-wave detector must cover a broad band

Low frequency
→ seismic, Newtonian noise, suspension thermal noise, radiation pressure

Mid frequency
→ coating thermal noise, quantum noise

High frequency
→ shot noise

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Frequency bands

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One interferometer cannot be optimal at all frequencies

High power helps high frequency
but increases radiation pressure and thermal load

Large beams reduce coating thermal noise
but require large mirrors and stable cavities

Long arms “improve” the strain sensitivity
but make optical cavity design harder

The Xylophone idea

Different interferometers optimized for different frequency bands

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Low-frequency interferometer

Goal:
Low-frequency sensitivity

Choices:
→ cryogenic optics
→ lower circulating power
→ low-frequency optimized suspensions/control

High-frequency interferometer

Goal:
High-frequency sensitivity

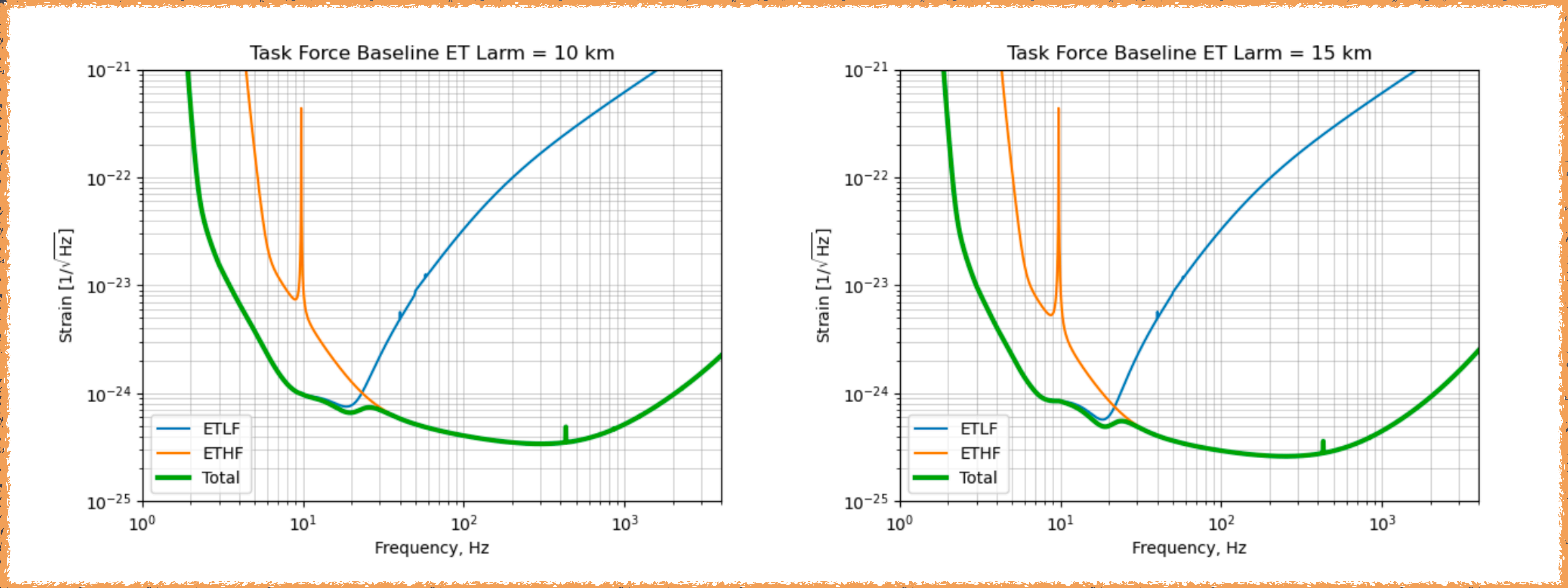
Choices:
→ room temperature optics
→ higher circulating power
→ high-frequency optimized optical response

Xylophone idea is a sensitivity strategy, not a specific design shape

Different instruments, different frequency bands, same observatory.

The Xylophone idea

Different interferometers optimized for different frequency bands



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Optical layout design

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From optical layout to construction

Definitions

Optical Layout

Arm & recycling cavity geometry

+ laser injection + detection + squeezing

+ auxiliary benches

+ adjustments for clashes/physical constraints

Managed by Interferometer division with contributions from the Optics division in close interaction with ETO

Detector Layout

+ Vacuum envelope

+ Suspension tower design

+ scaffolding, clean rooms, working space, safety ...

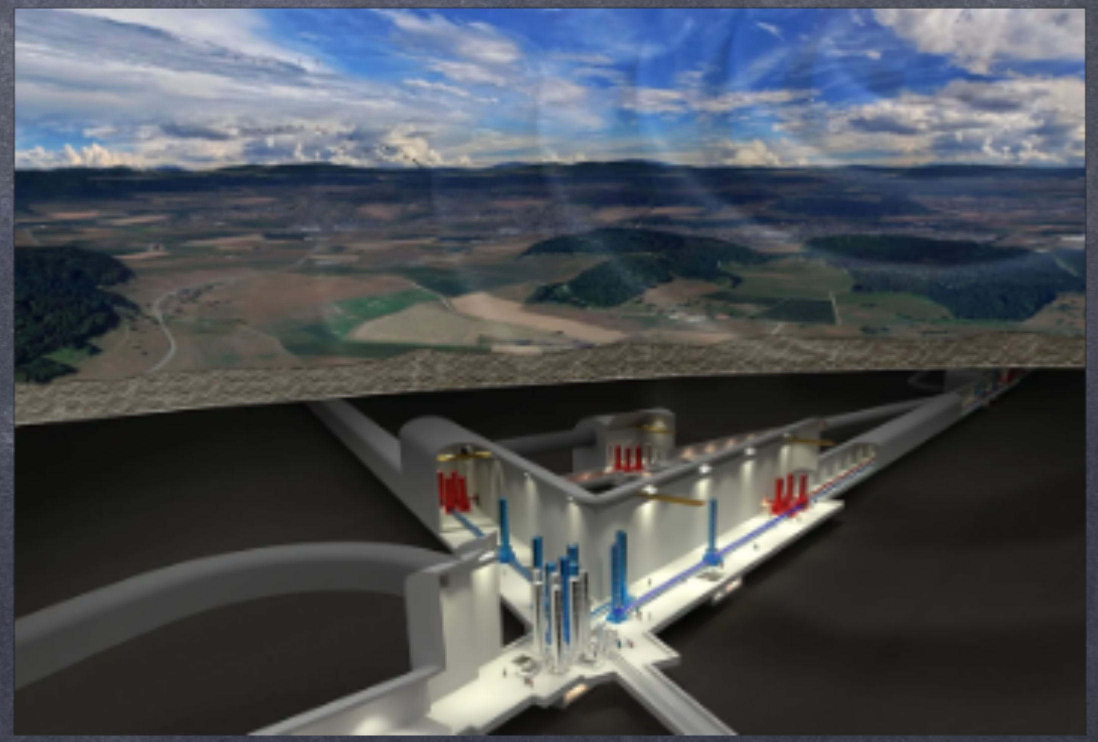
Coordinated by ETO with the Suspensions, Active noise mitigation, and Vacuum and Cryogenics divisions in close interaction with IFO/Optics

Infrastructure Layout(s)

+ Tunnels / caverns / shafts

+ Cooling & ventilation

+ Logistic, + pipes, electrical distribution + buildings, access, ...



Optical Layout Baseline
Basics

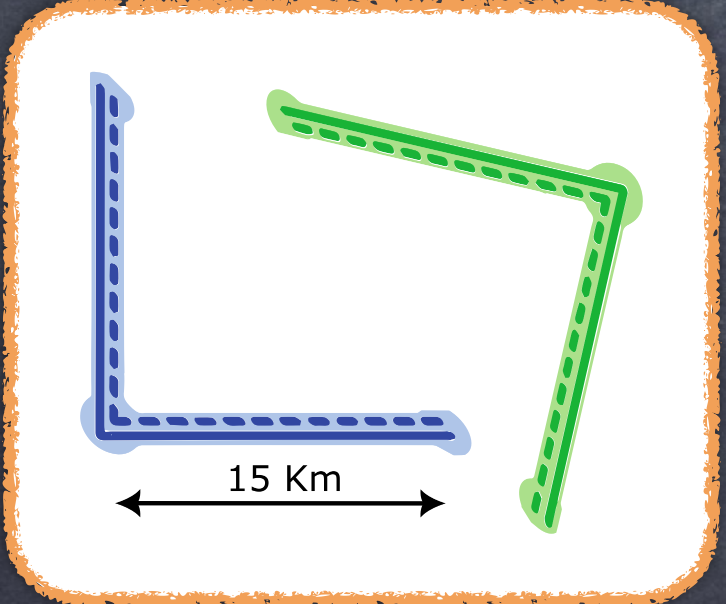
Xylophone concept: LF & HF
Basic Assumptions

- Minimise the number of optics as far as reasonably possible (optical losses, controls, noise)
- HF is more tolerant to suspension/ controls noises
  - Simplified suspension
  - Less strict number of optics
  - HF plane can sit above LF plane
- Each interferometer sits in a 2D plane

Optical Layout Baseline
Basics

Requirement we start with:

- Overall geometry: **L-shape,** ~**15km** arm length
- Just **2** arm cavities per 'side': one **LF** + one **HF**



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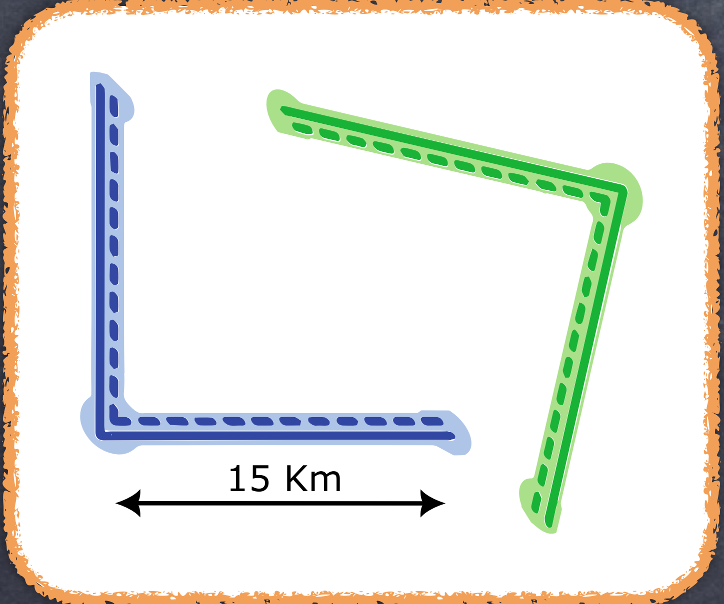

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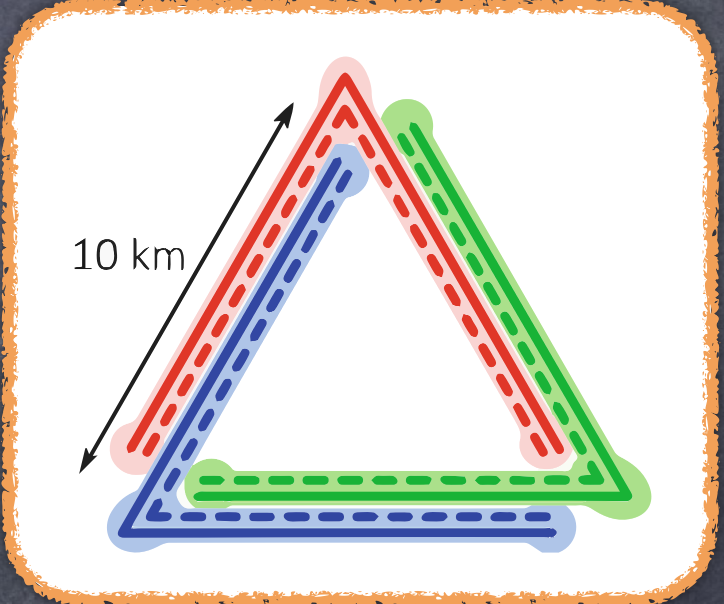
Requirement we start with:

- Overall geometry: **Triangle -shape, ~10km** arm length
- **4** arm cavities per 'side': two **LF** + two **HF** of the detector



Optical Layout Baseline
Process

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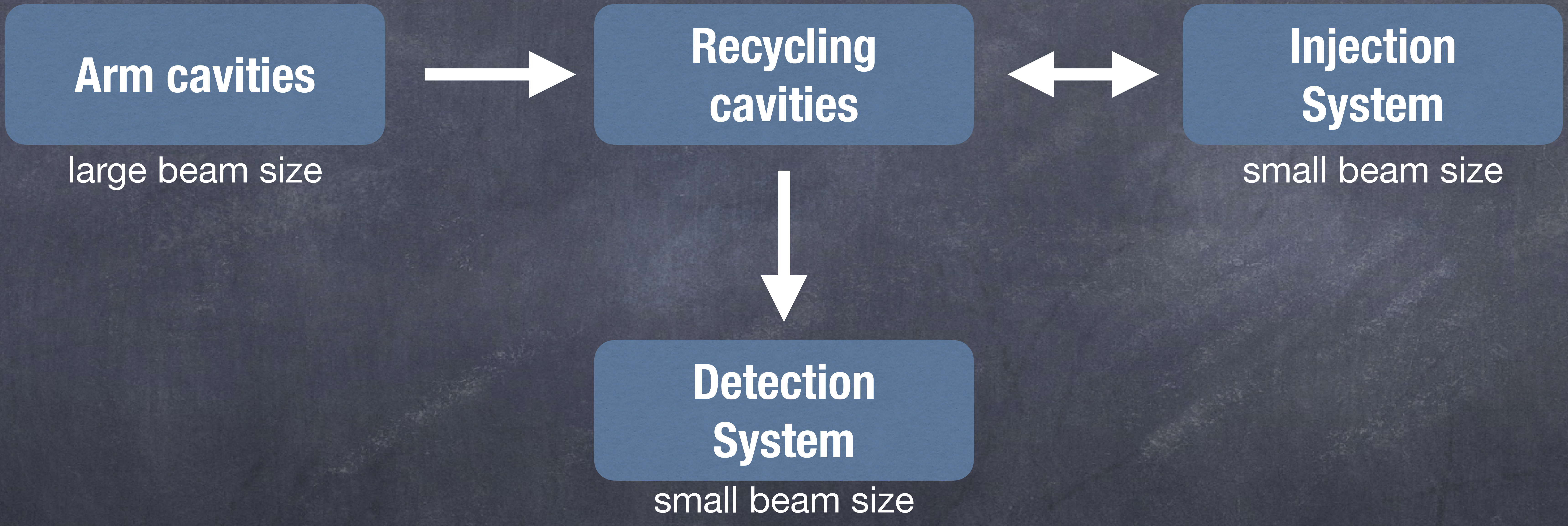


Arm cavities design

Arm cavities
The starting point

LF:

- λ = 1550 nm
- 211 kg silicon test masses
  - 45cm diameter (projected)
- low power + cryogenics

HF:

- λ = 1064 nm
- 200 kg fused silica test masses
  - more freedom in diameter
- High power

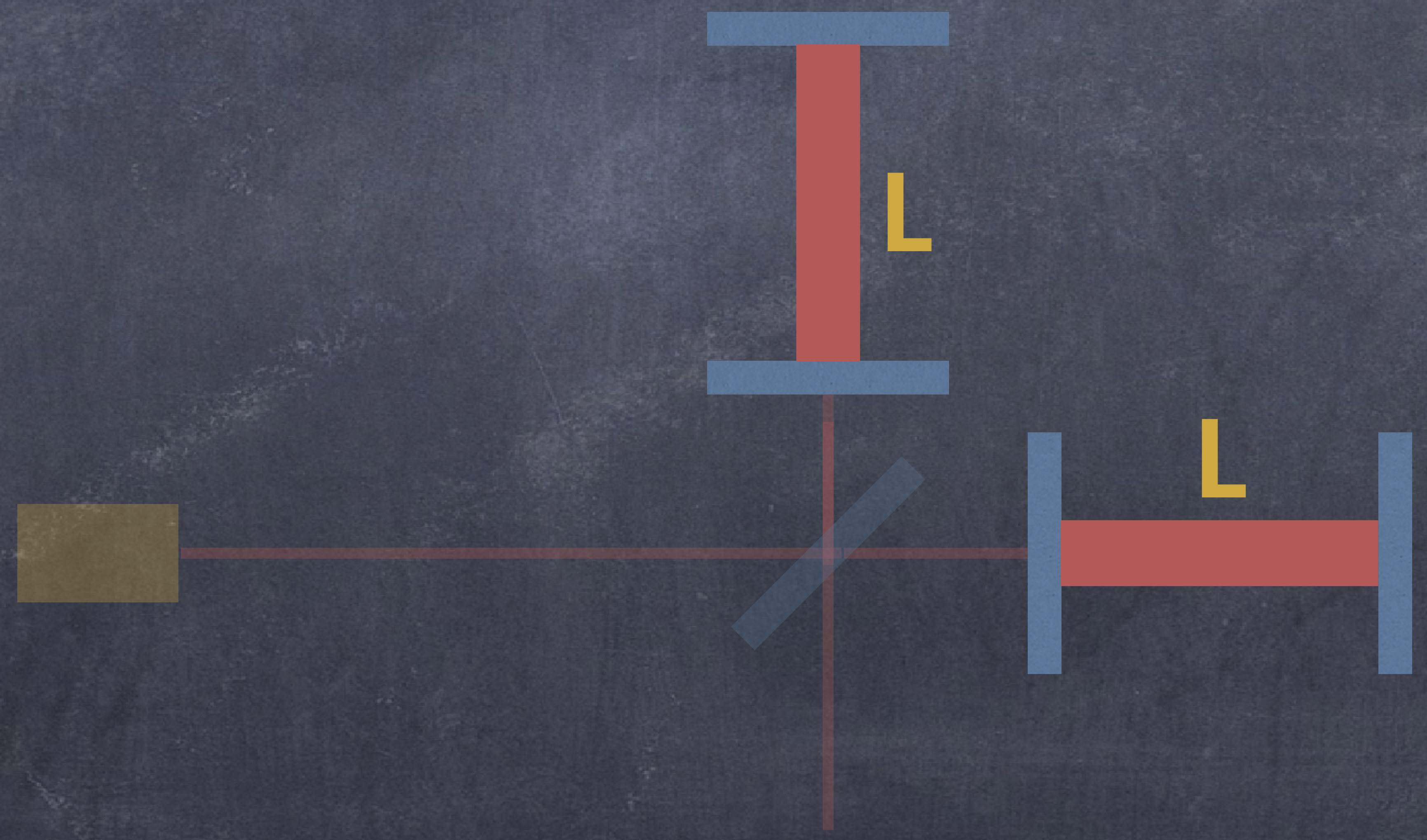
- Fixed cavity length (~10km or ~15km)
- Thermal noise reduction —-> beam size vs geometrical stability

Arm cavities
The starting point

Thermal Noise reduction

↓

Large beam size on Test Masses (TM)



Arm cavities
The starting point

Thermal Noise reduction

↓

Large beam size on Test Masses (TM)

ET-HF ←

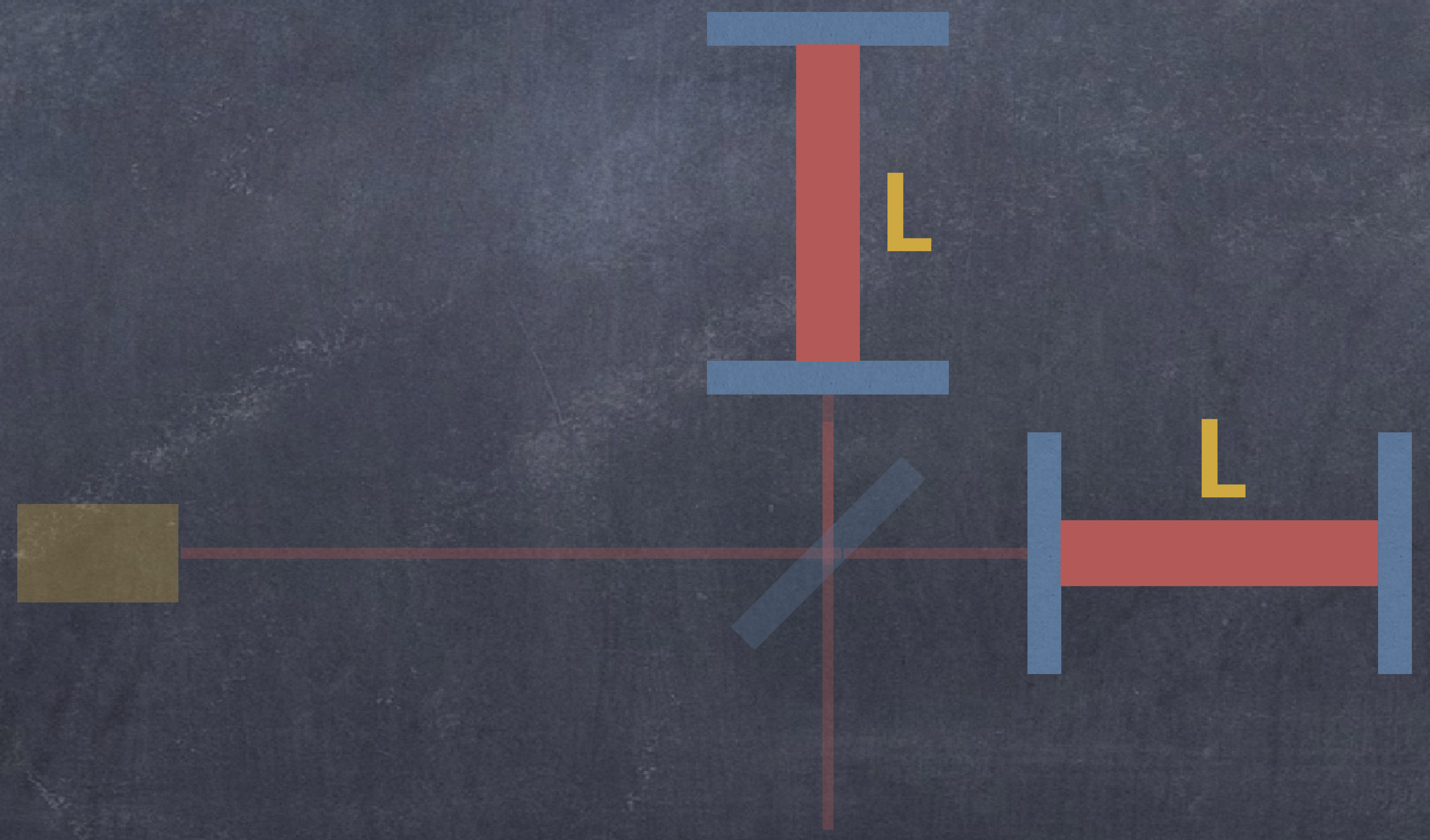
Choose g-factor for fixed L

↓

Beam size

↓

Mirror size



Arm cavities
The starting point

Thermal Noise reduction

↓

Large beam size on Test Masses (TM)

ET-HF ←

Choose g-factor for fixed L

↓

Beam size

↓

Mirror size

ET-LF →

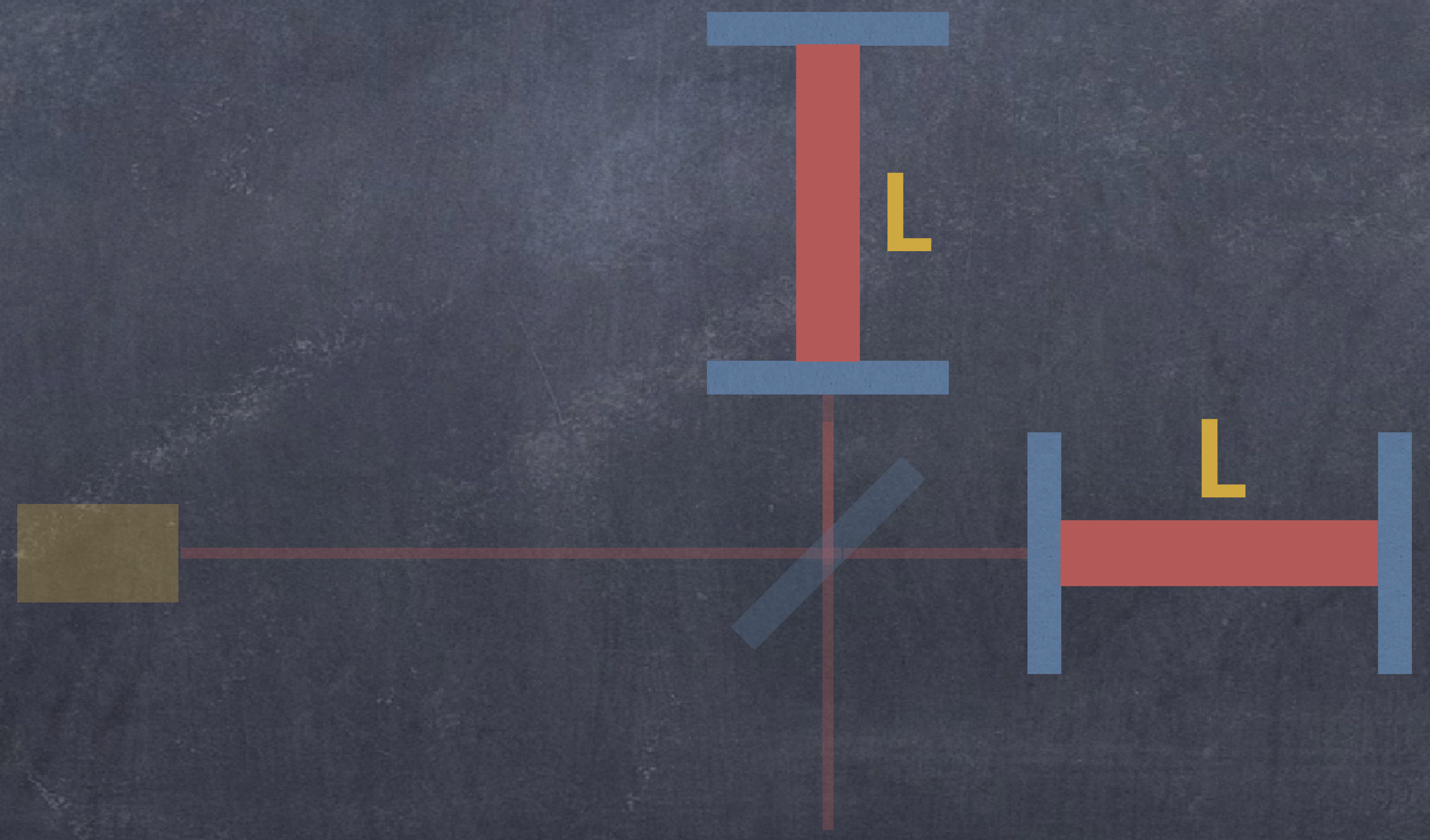
Substrate requirement

↓

Mirror size

↓

Beam size and g- factor

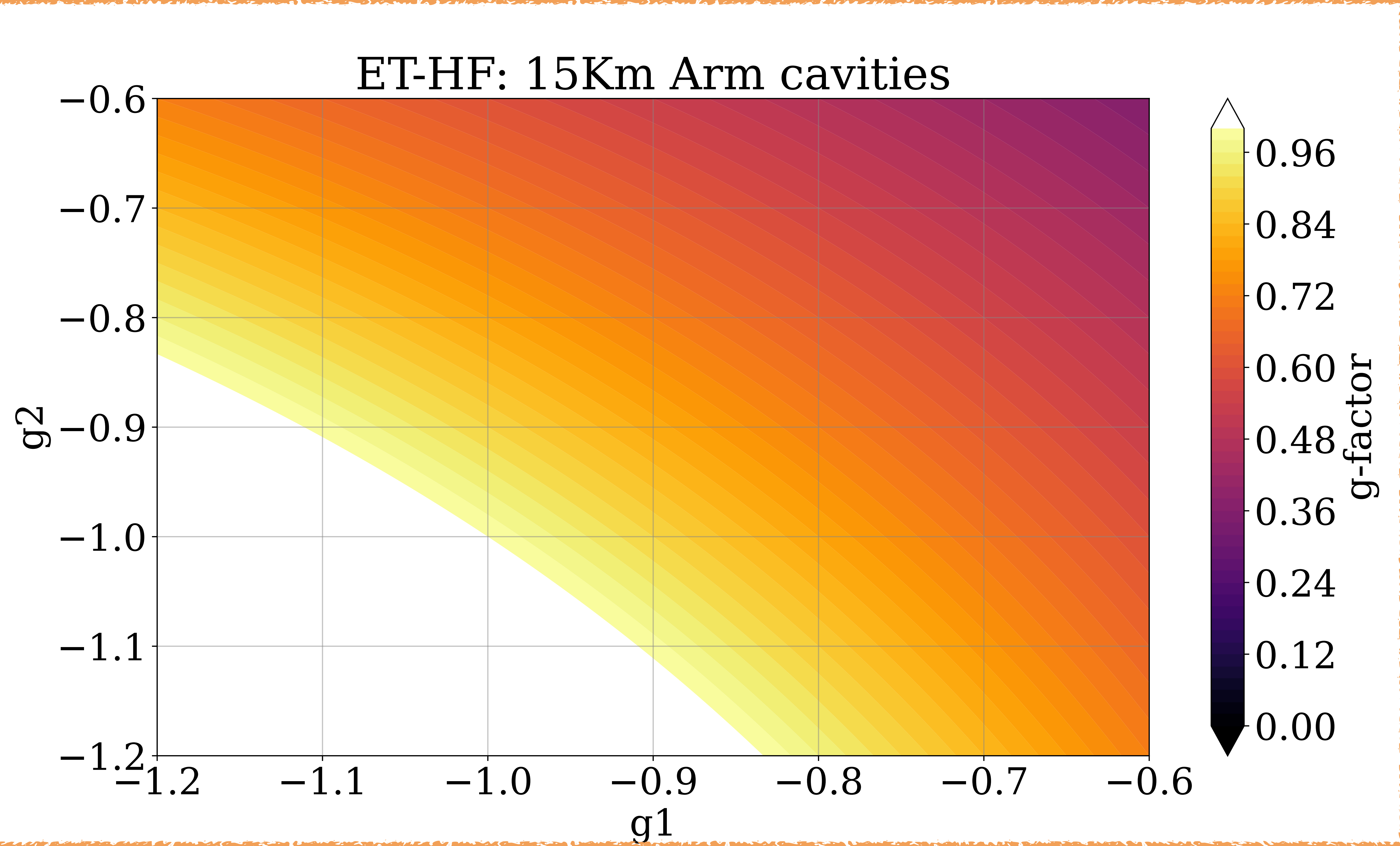


Arm cavities
Design: stability vs beam size

Thermal noise requirement:

Beam size >= 12 cm

Pay attention



Stability condition

$0 < g = g1\,g2 < 1$

with gi = 1- L/Rci

Remember

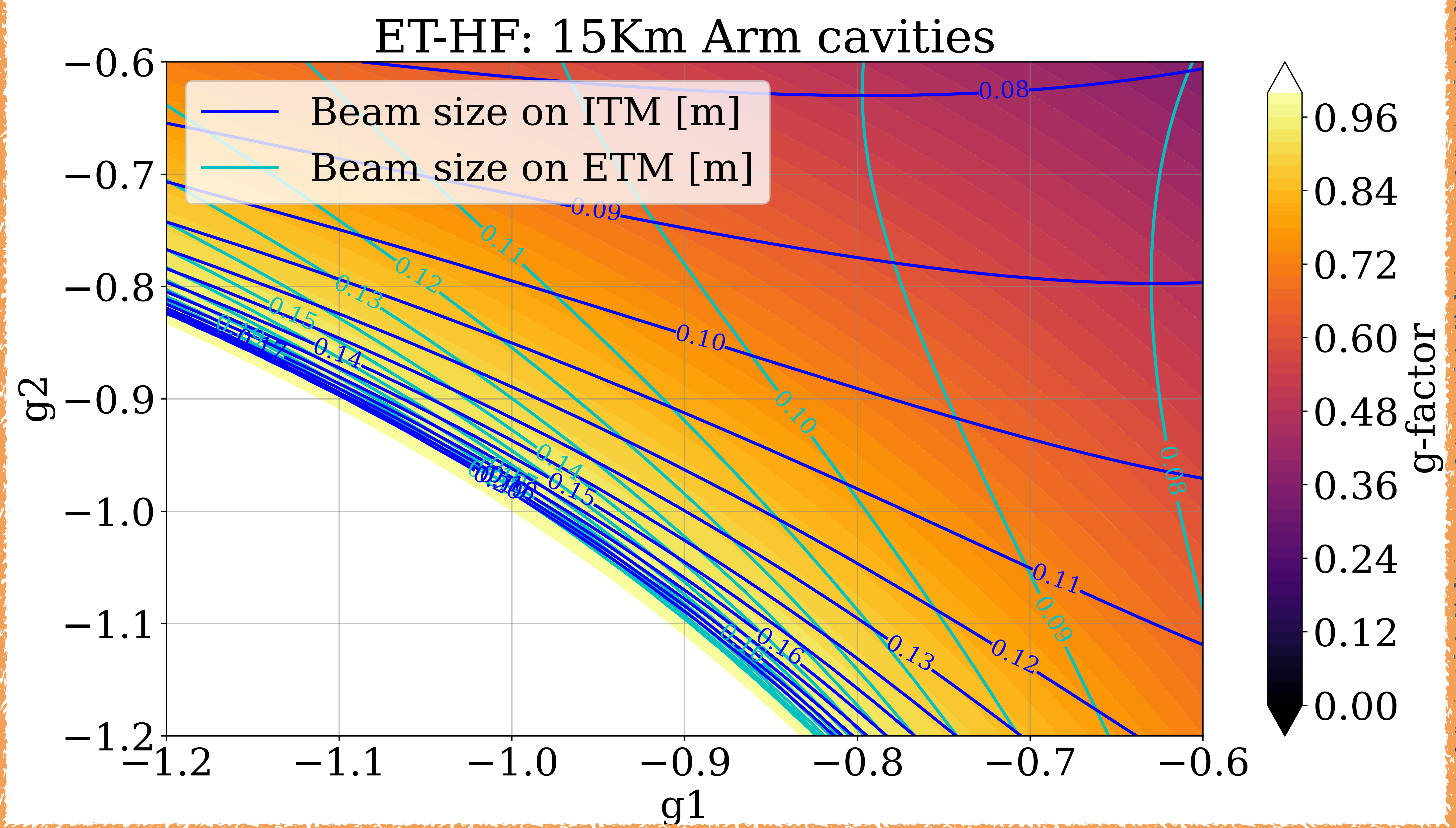
Arm cavities

Design: stability vs beam size

Thermal noise requirement:

Beam size >= 12 cm

Pay attention



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Design: stability vs beam size

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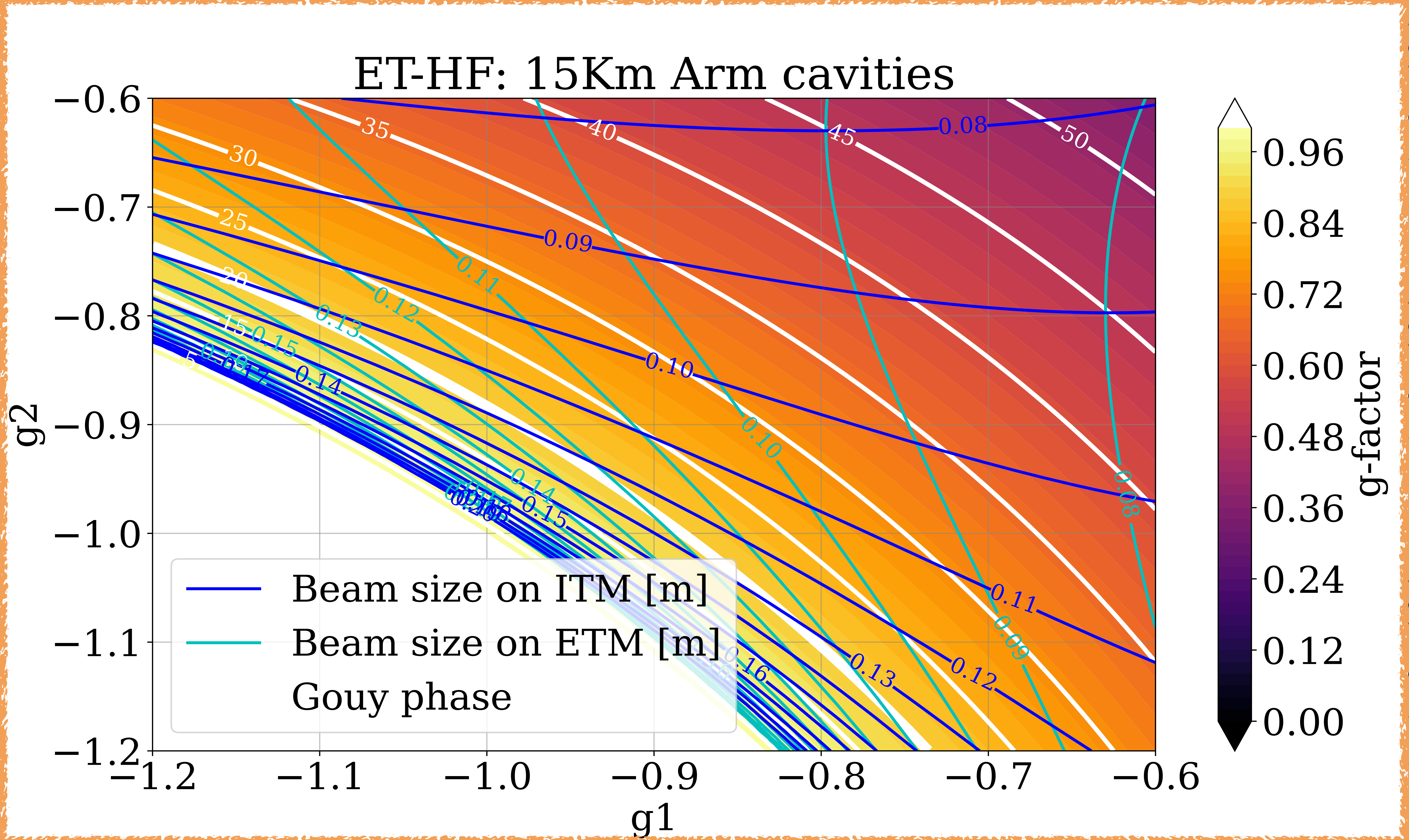
Beam size >= 12 cm

Stability

Gouy phase ~ 20 deg

Pay attention



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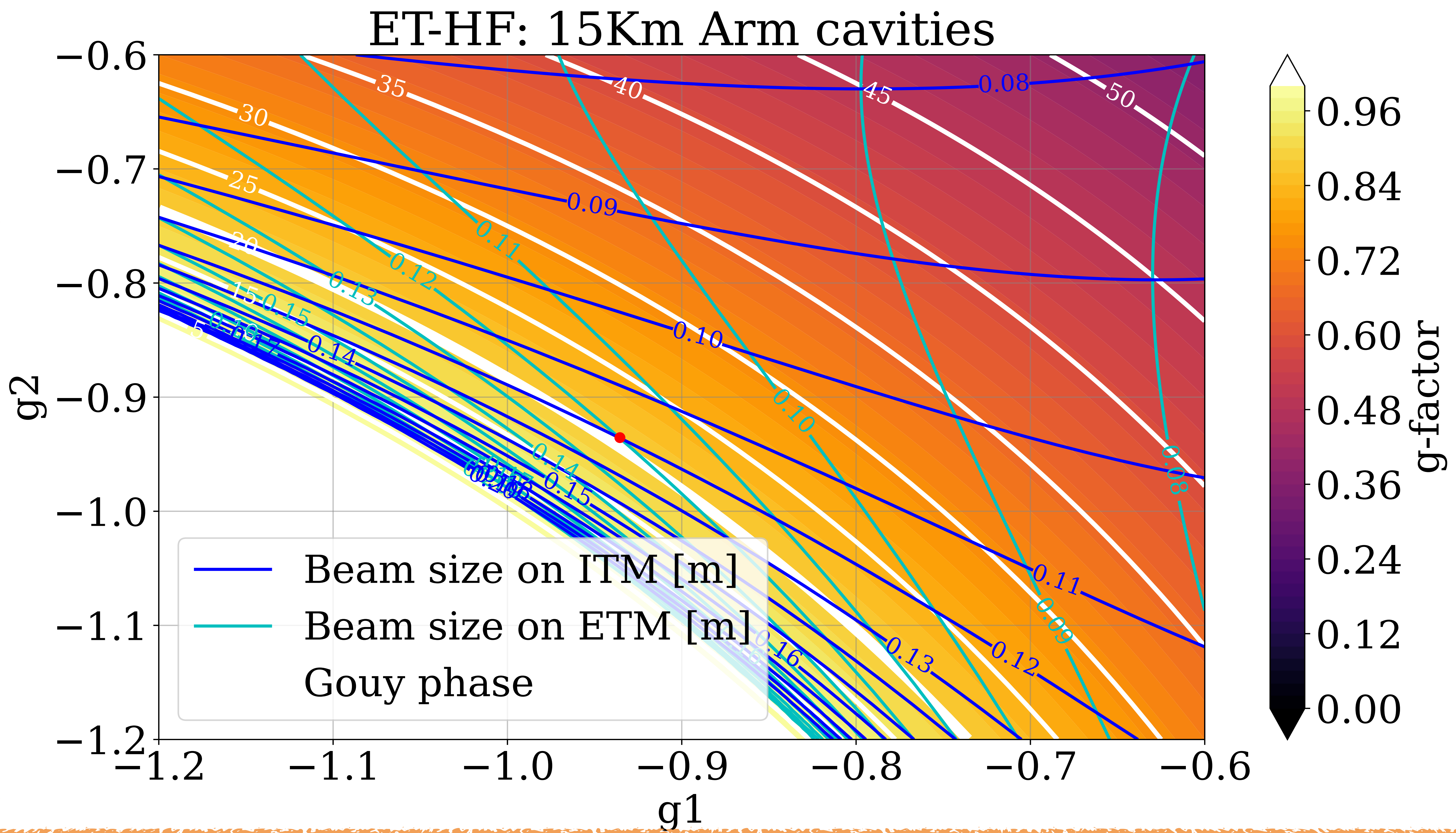


Chosen point: g = 0.88, w1 = w2 = 12cm,

Gouy phase ~ 20 deg

Stability condition

0 < g = g1 g2 < 1

with gi = 1- L/Rci

Remember

Arm cavities
Design: stability vs beam size

Thermal noise requirement:

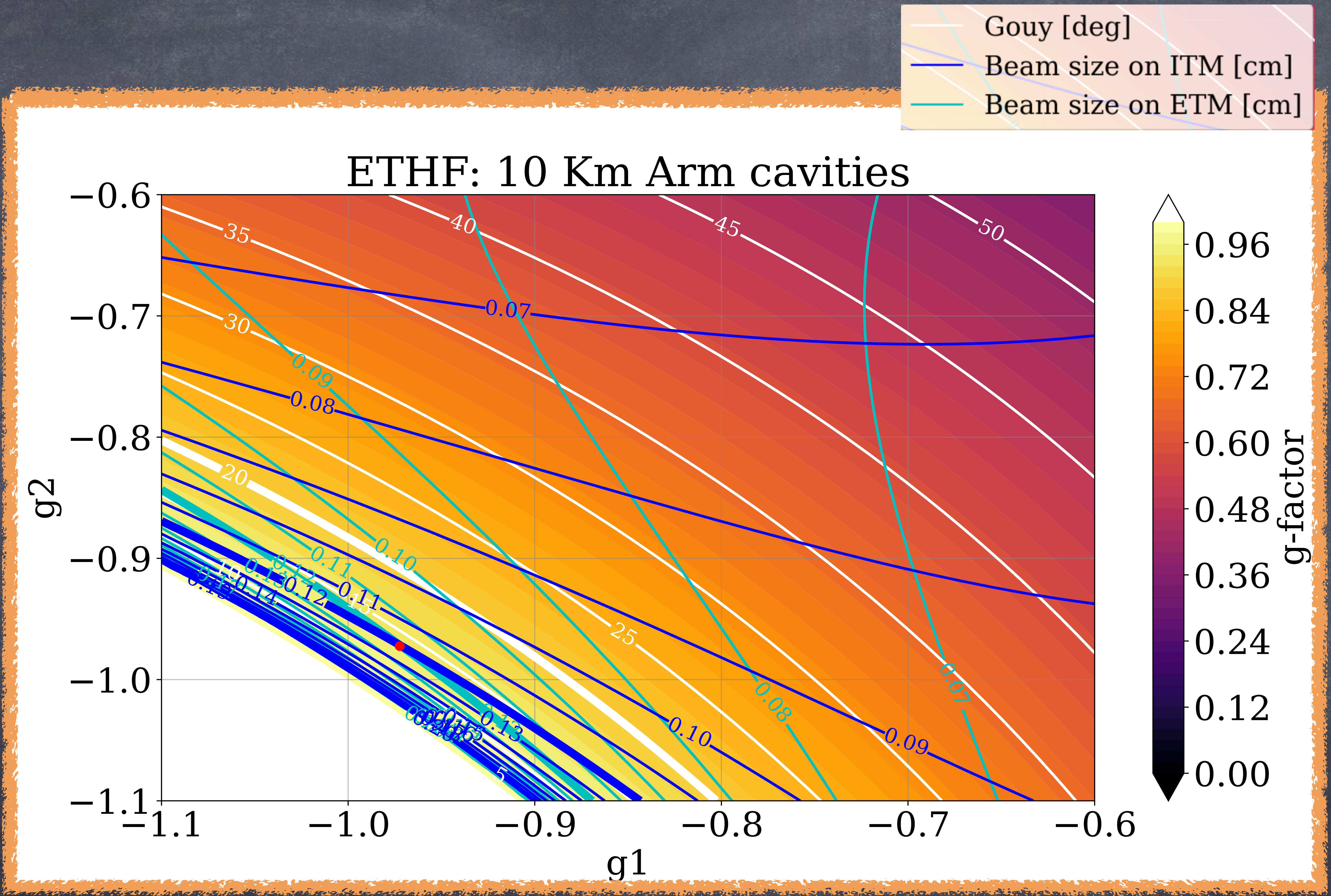
Beam size >= 12 cm

Stability

~~Gouy phase ~ 20 deg~~

↑

Pay attention



Stability condition

$0 < g = g1\,g2 < 1$

with gi = 1- L/Rci

↑

Remember

Chosen point: g = 0.95, w1 = w2 = 12cm,

Gouy phase ~ 13.5 deg

Arm cavities
Design: stability vs beam size

Thermal noise requirement:

Beam size not too small

Manufacturing:

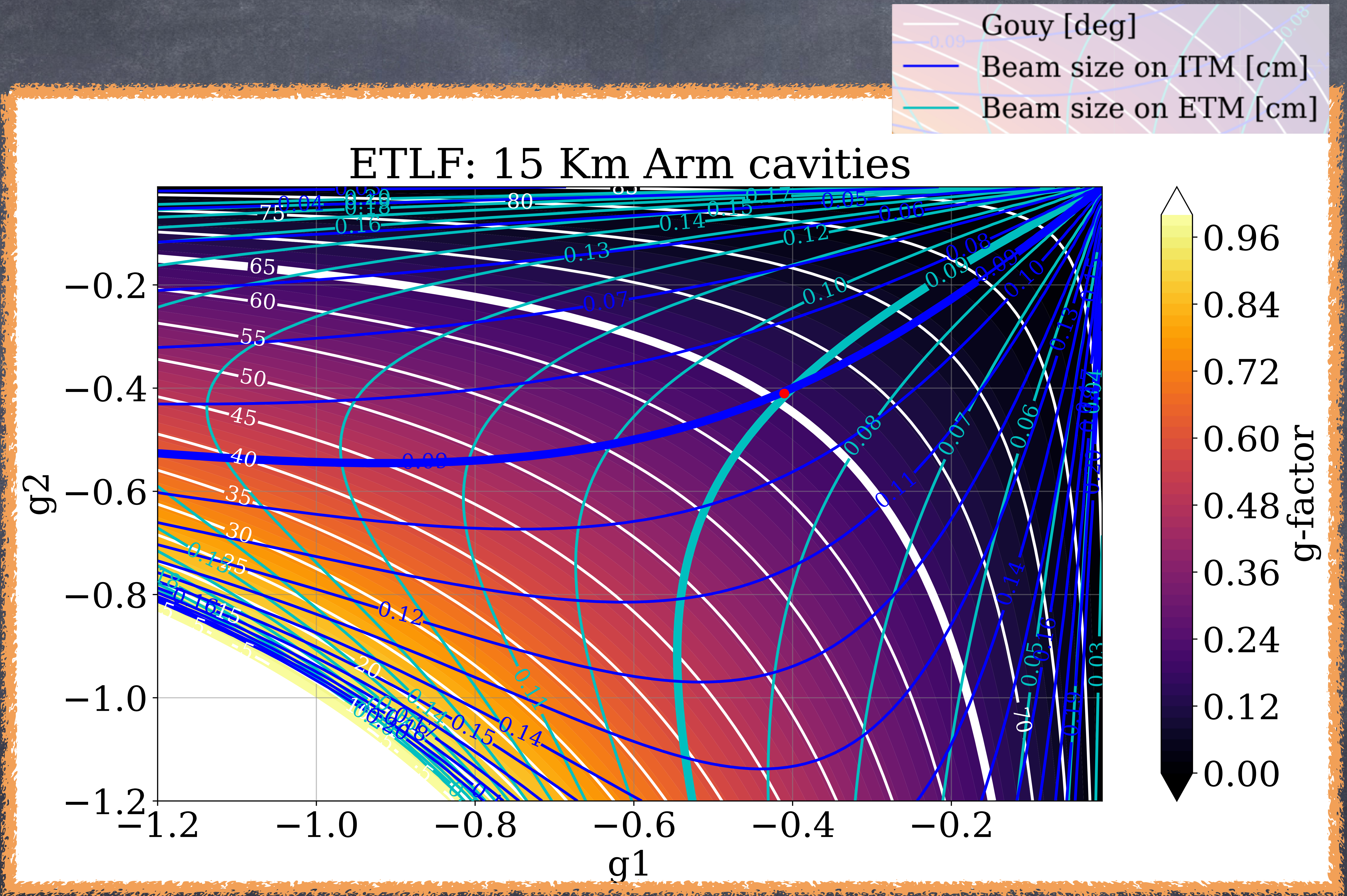
Beam size not too big

Stability

Gouy phase > 20 deg,

but not too big

Pay attention



Stability condition

0 < g = g1 g2 < 1

with gi = 1- L/Rci

Remember

Chosen point: g = 0.17, w1 = w2 = 9cm,

Gouy phase ~ 65 deg

Beam size not too big: Manufacturing problems

Arm cavities
Results

2L:

IFO	λ	Length	Mirror ⌀	RoC	w_0	z_0	w	g-factor	Gouy phase
ET-HF	1064 nm	15000 m	62 cm	7750 m	2.15 cm	7500 m	12 cm	0.88	$\sim 20.7°$
ET-LF	1550 nm	15070 m	45 cm	10670 m	4.90 cm	7535 m	9 cm	0.17	$\sim 65.8°$

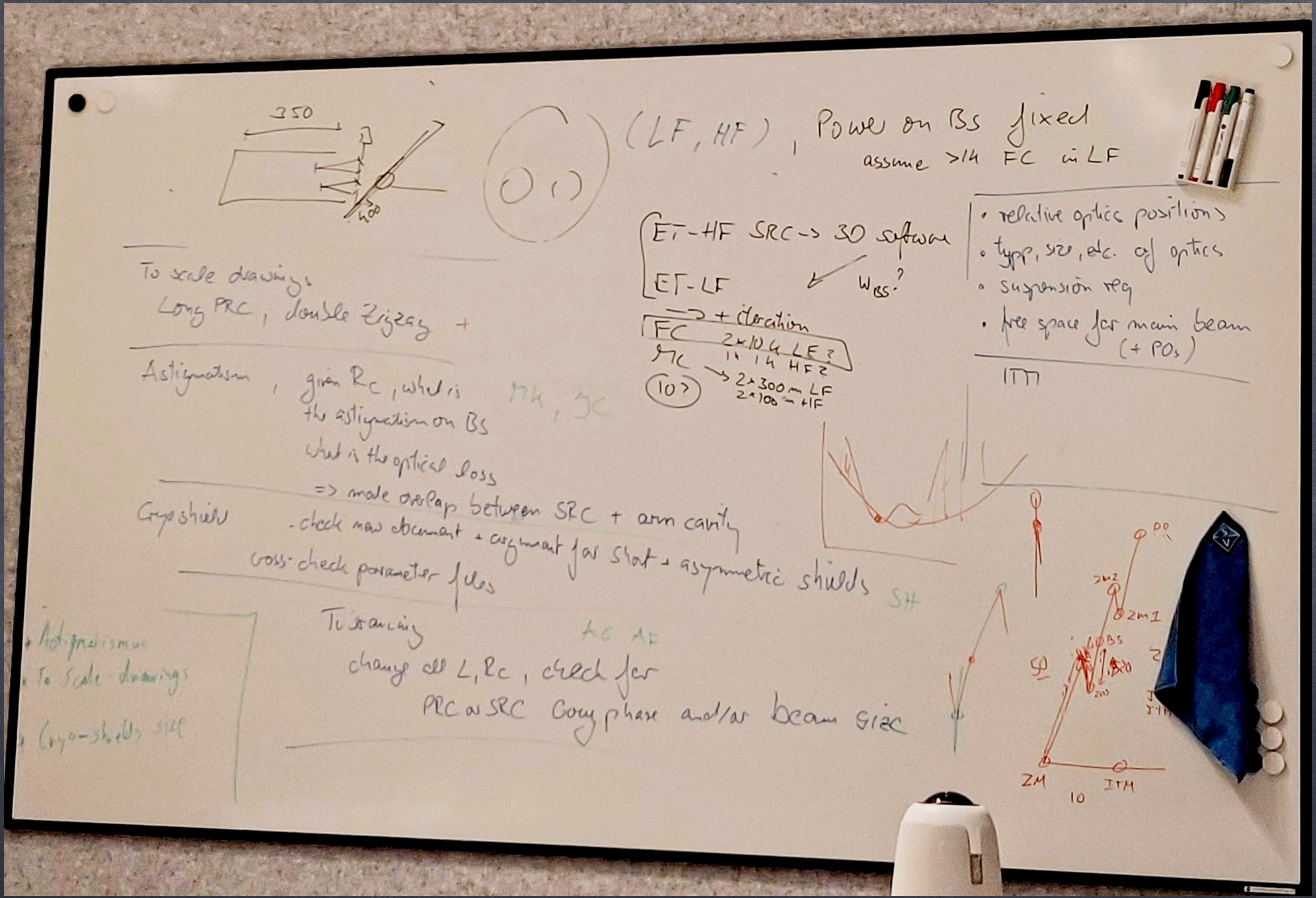
(Δ:)

IFO	λ	Length	Mirror ⌀	RoC	w_0	z_0	w	g-factor	Gouy phase
ET-HF	1064 nm	10000 m	62 cm	5070 m	1.42 cm	5000 m	12 cm	0.95	$\sim 13.5°$
ET-LF	1550 nm	10070 m	45 cm	5580 m	2.86 cm	5035 m	9 cm	0.65	$\sim 45.4°$

Recycling cavities design

Recycling cavity design

Starting from a white board



Recycling cavity design

Larger beam size on cavity mirrors: Consequences

Thermal Noise reduction

↓

Large beam size on Test Masses (TM)

↓

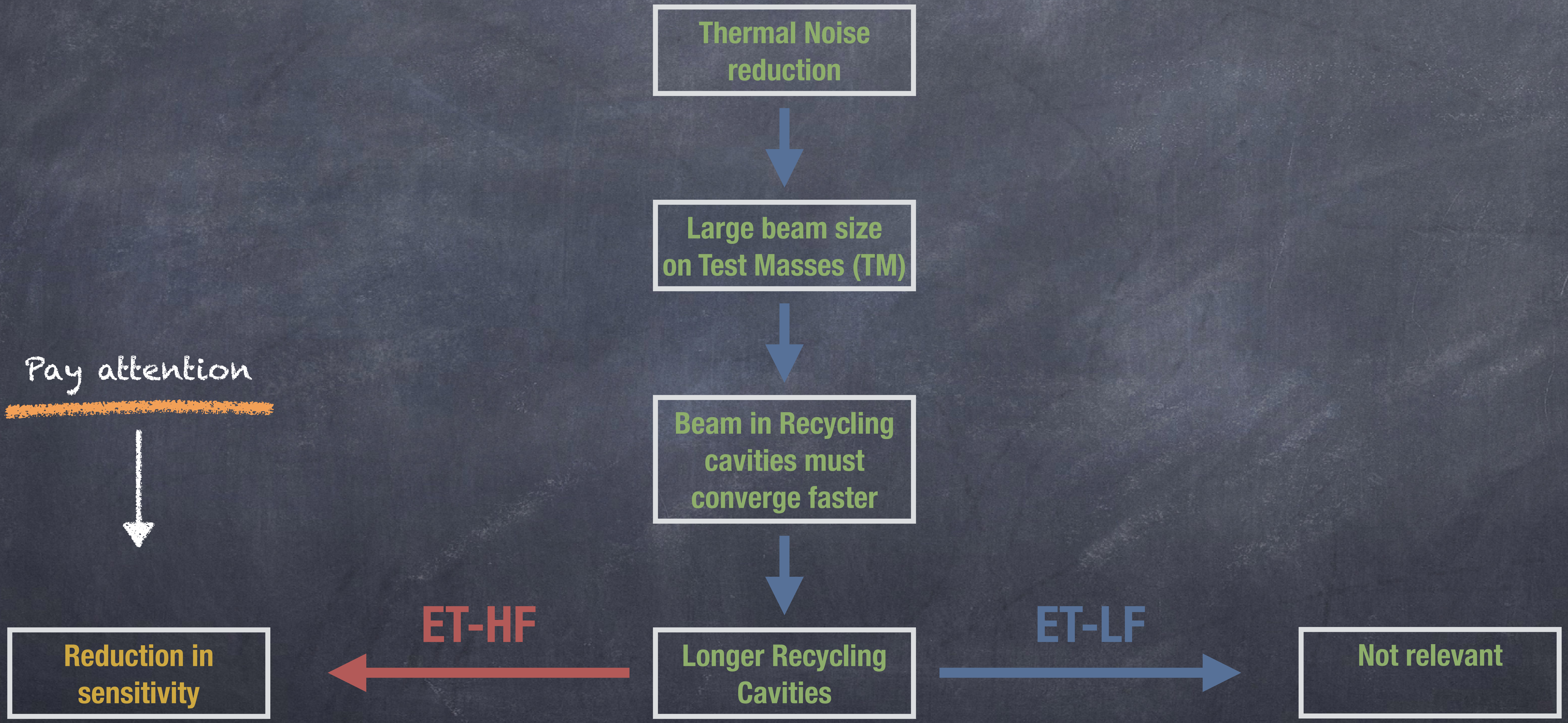
Beam in Recycling cavities must converge faster

↓

Longer Recycling Cavities

Recycling cavity design

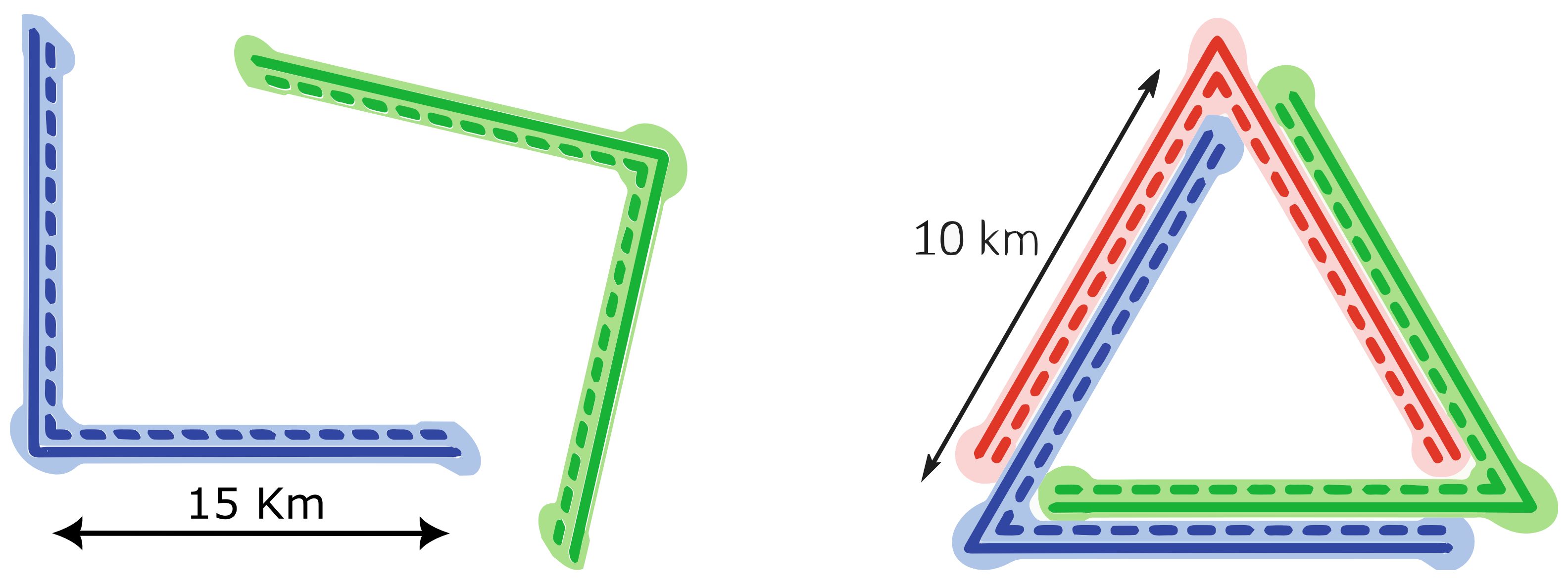
Larger beam size on cavity mirrors: Consequences



Recycling cavity design
First constraints

General requirements for the recycling cavities (same for SRC and PRC):

- Reduce the beam size from the arm cavities
- Stable cavities with Gouy phase ~ 20°
- Collimated beam at beamsplitter
- Minimize astigmatism and number of optics



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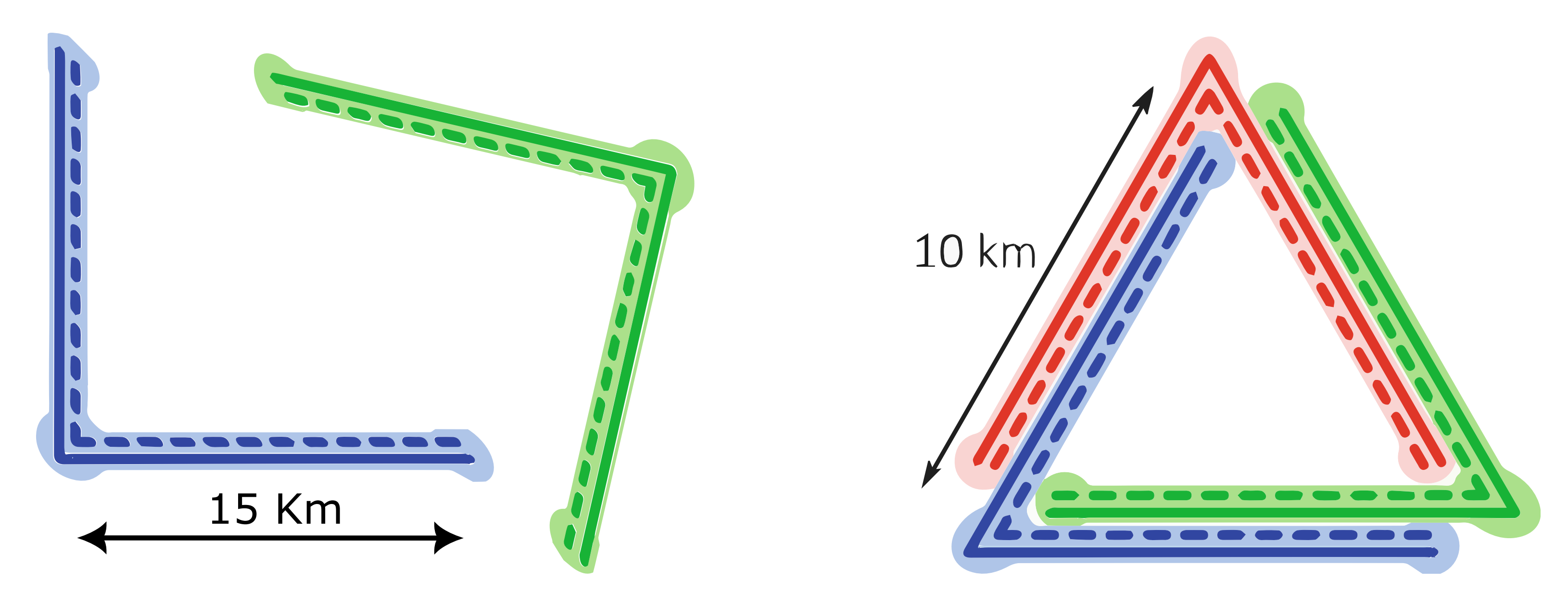

LF

- Low power + cryogenics = no thermal effects
    - Can have small beam sizes
- No length constraint for the recycling cavities

Recycling cavity design
First constraints

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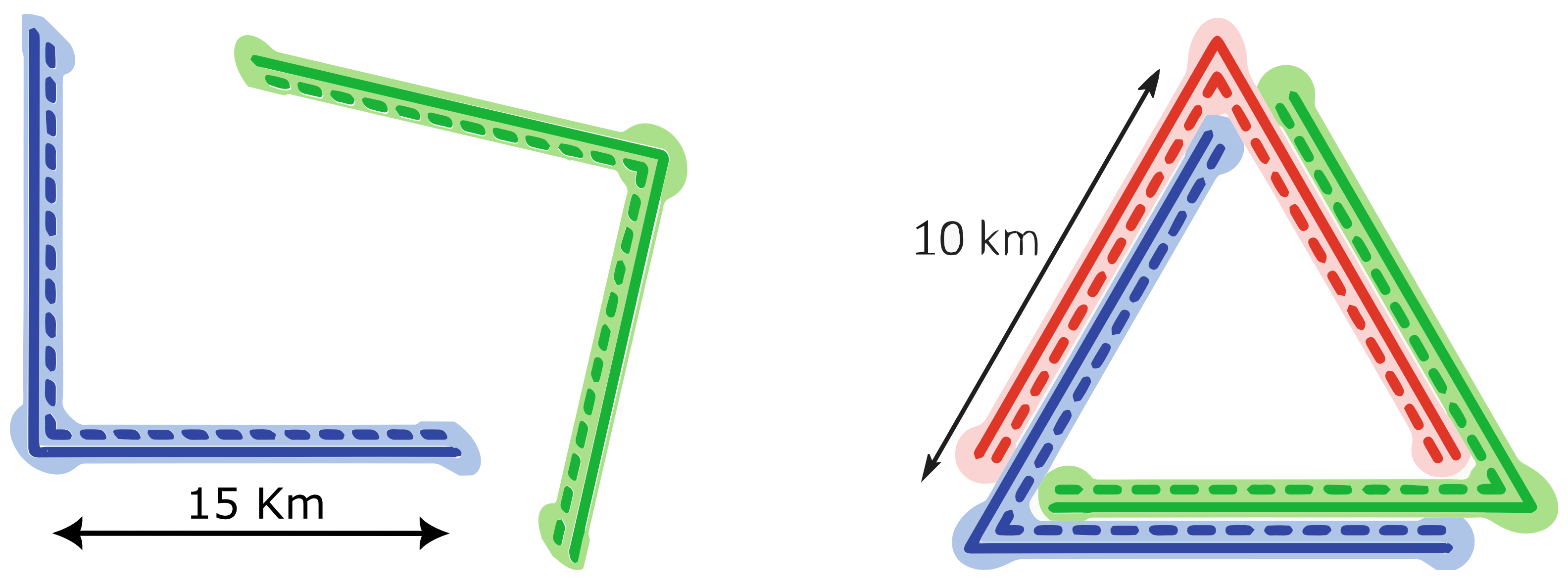


LF

- Low power + cryogenics = no thermal effects
  - Can have small beam sizes
- No length constraint for the recycling cavities

HF

- We can tolerate (some) more optics for HF
  - Can have small beam sizes
- No length constraint for PRC
- Strong length constraint for SEC
- Significant thermal deformation
  - We cannot tolerate small spot sizes in the PRC
- Additional requirements for the path to the BS
- Beam radius > 26 mm at the BS (thermal effects)
- Size on PRM > 10mm

Recycling cavity design

First constraints

	Power/Signal Recycling Mirror		Input Test Mass
	PR/SR	BS	ITM
Beam size	> 10 mm	30-50 mm	120 mm

Get the right Gouy phase

Get the beam size reduction

- Typical difficulty: Increasing the stability will decrease the beam size

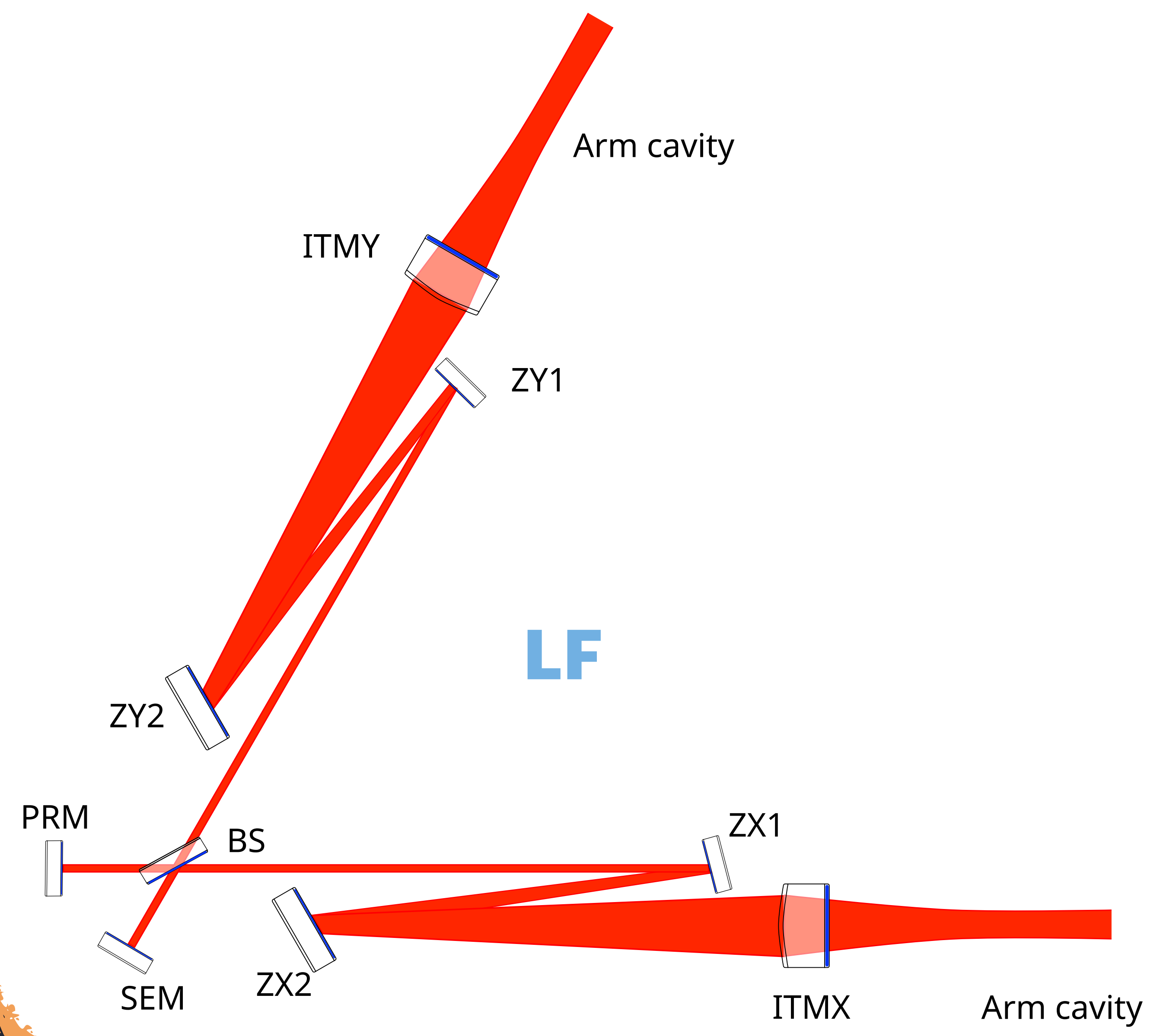
Recycling cavity design
Practical constraints

- **HF restricted by LF ITM cryoshields**
  - Test masses cannot be arbitrarily close together
  - Prefer solutions with HF ITM further from the corner than LF ITM

- **Cavern sizes and separations limit our options**
  - Single caverns cannot be arbitrarily large
  - Separation between caverns should be > ~40m for stability (driven by cavern height)

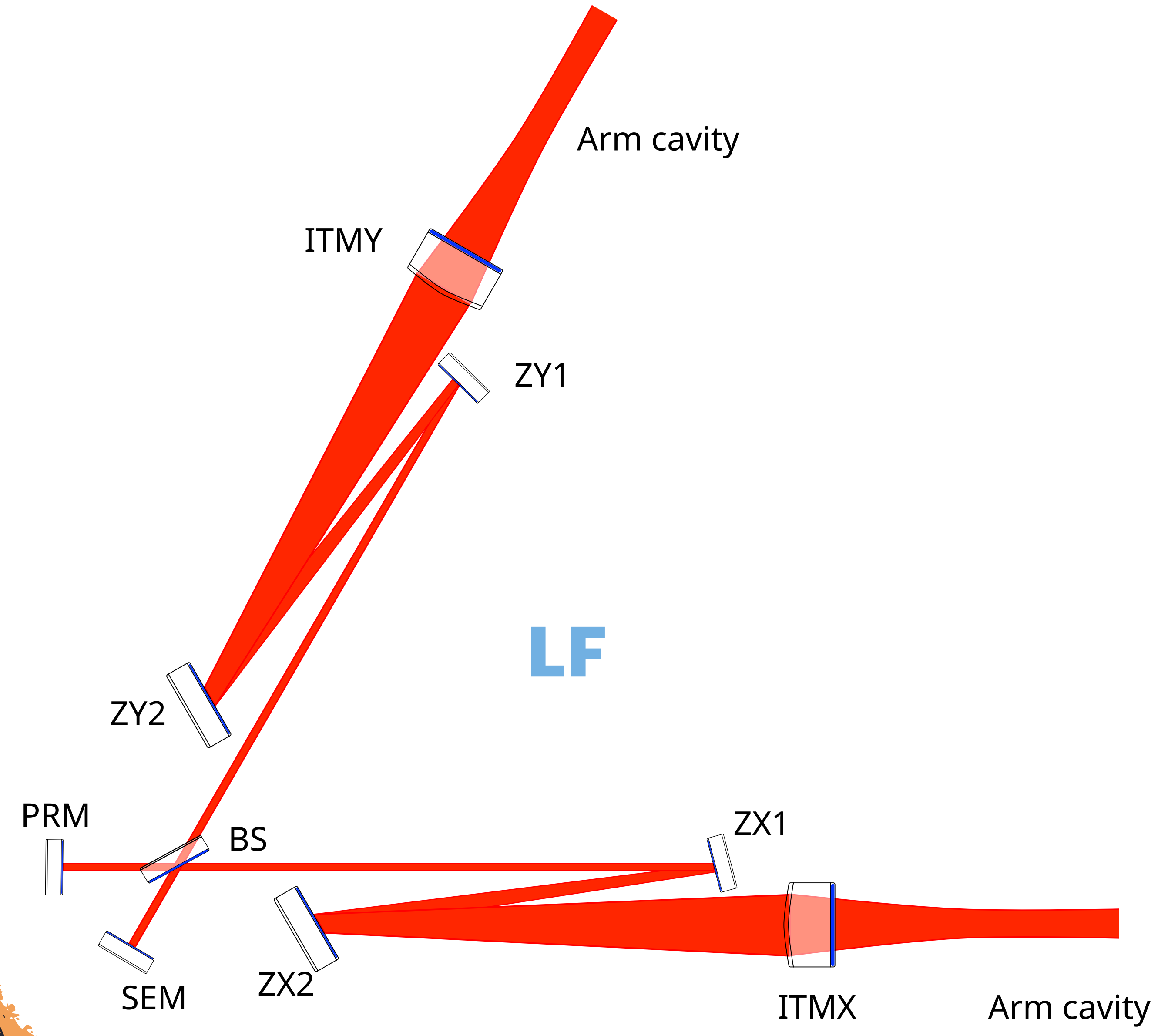
Recycling cavity design
Telescopes for LF

Triangle

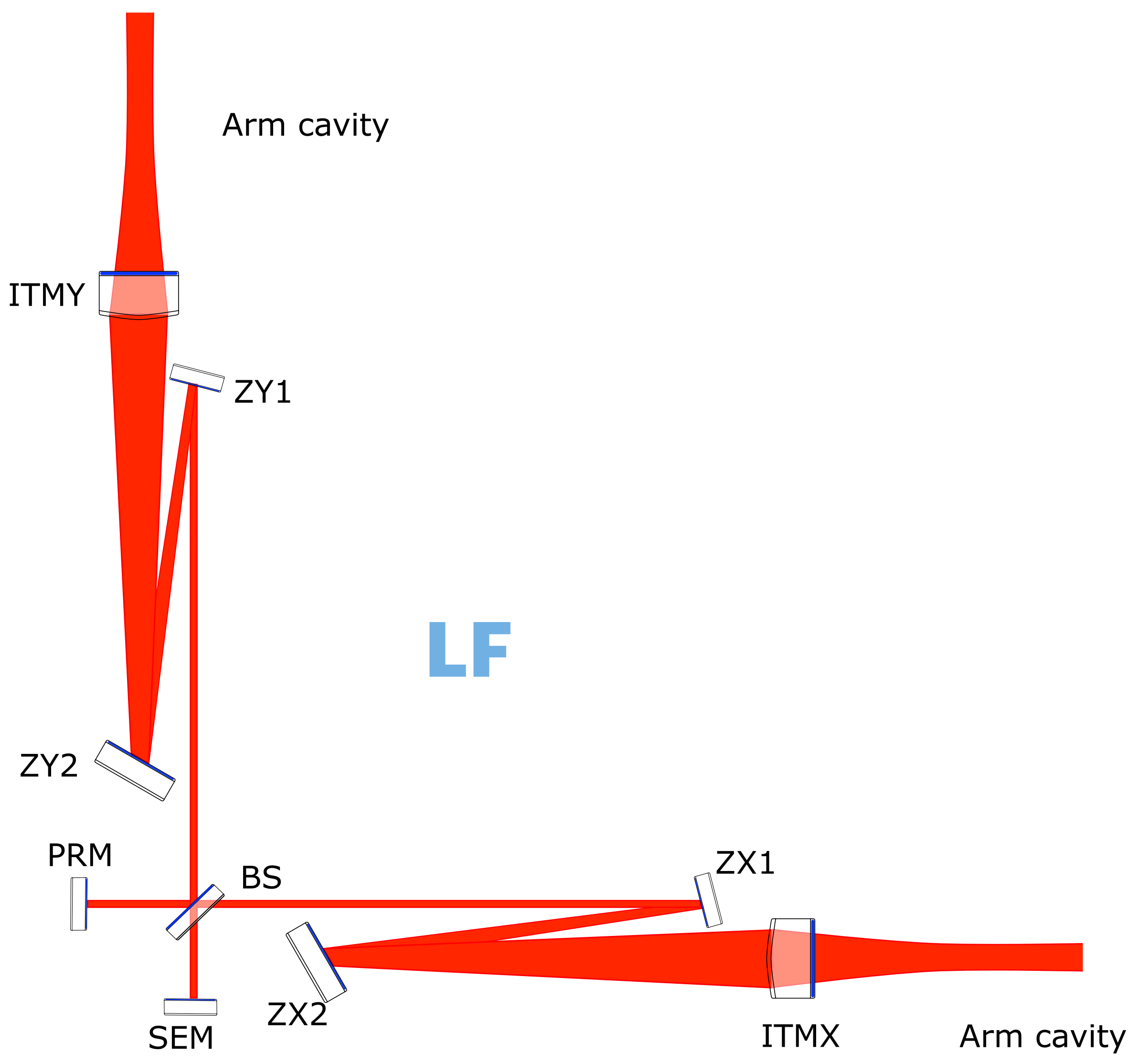


Recycling cavity design
Telescopes for LF

Triangle



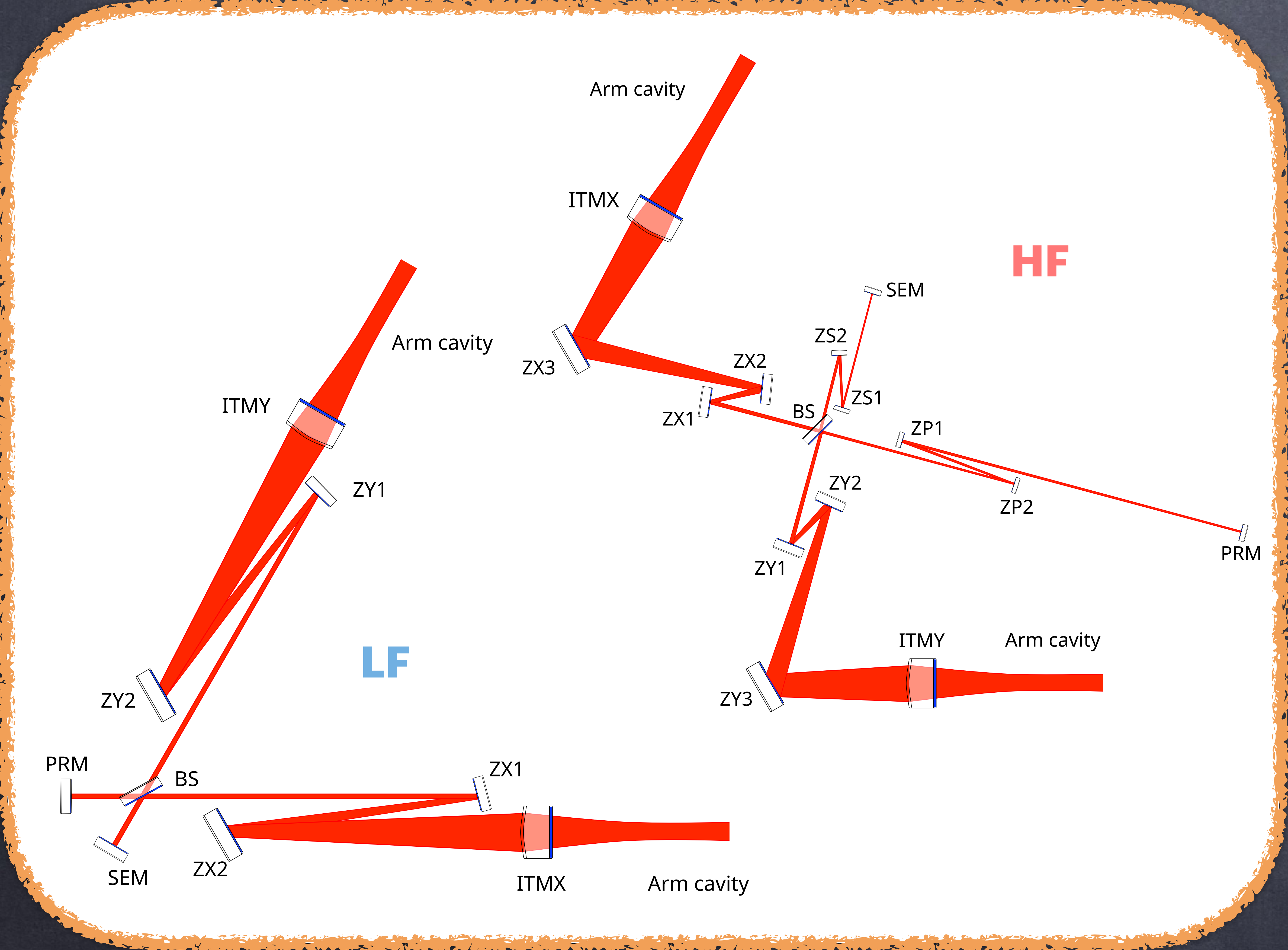
2L



Recycling cavity design

Telescopes for HF

Triangle



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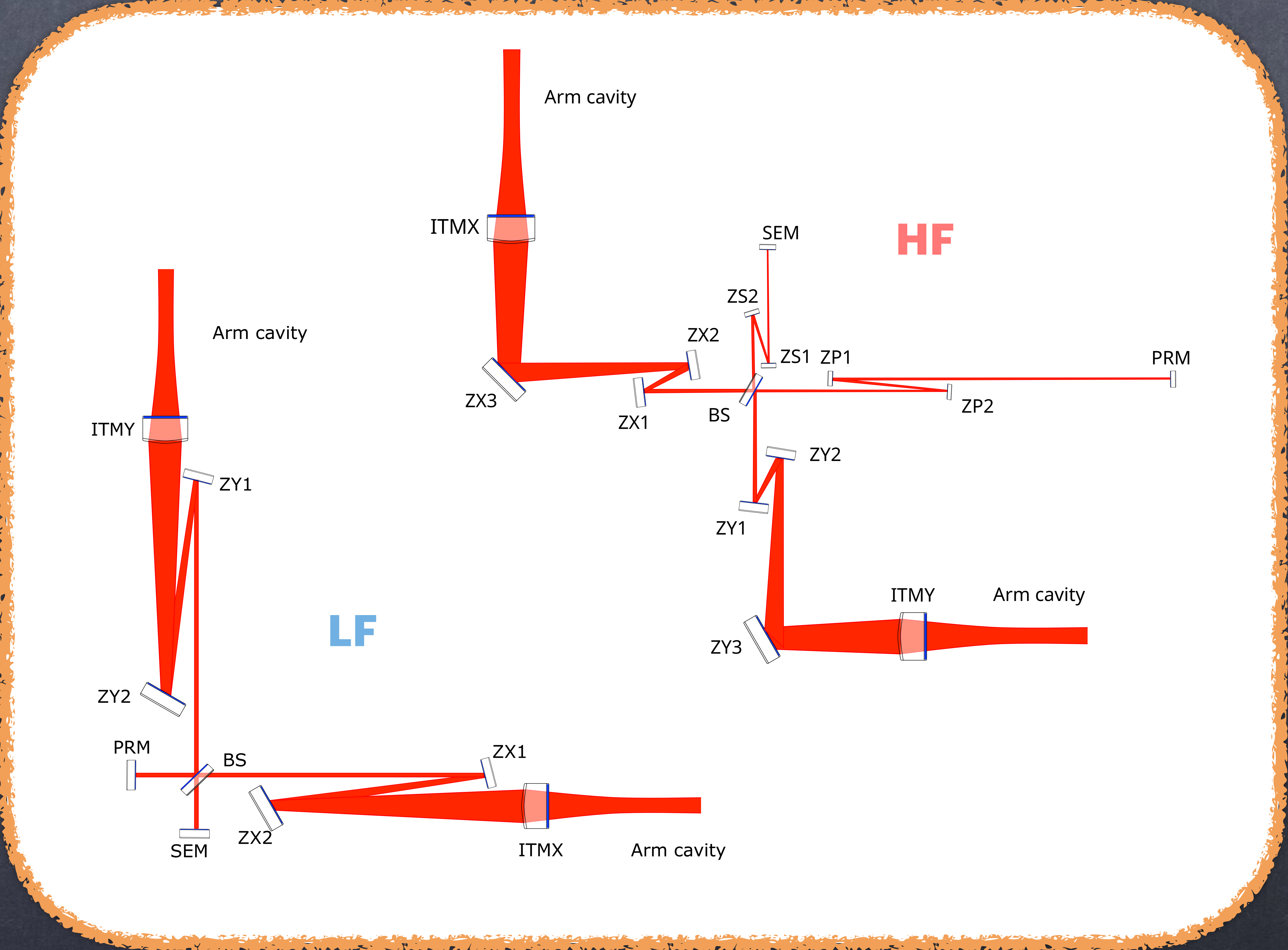
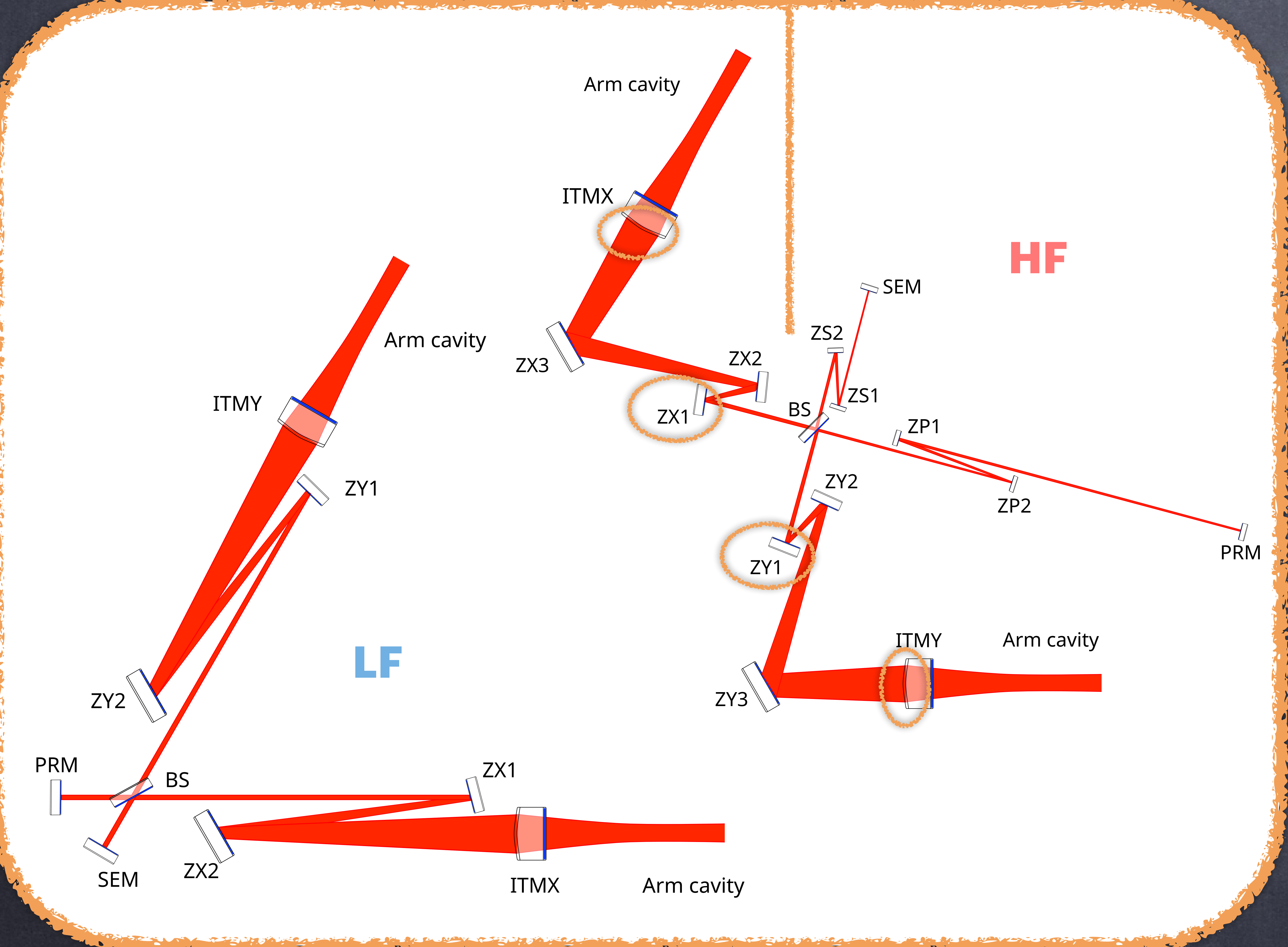


Recycling cavity design
Telescopes for HF

- Beam collimation on beam splitter (BS)
- Beam size on BS

Triangle



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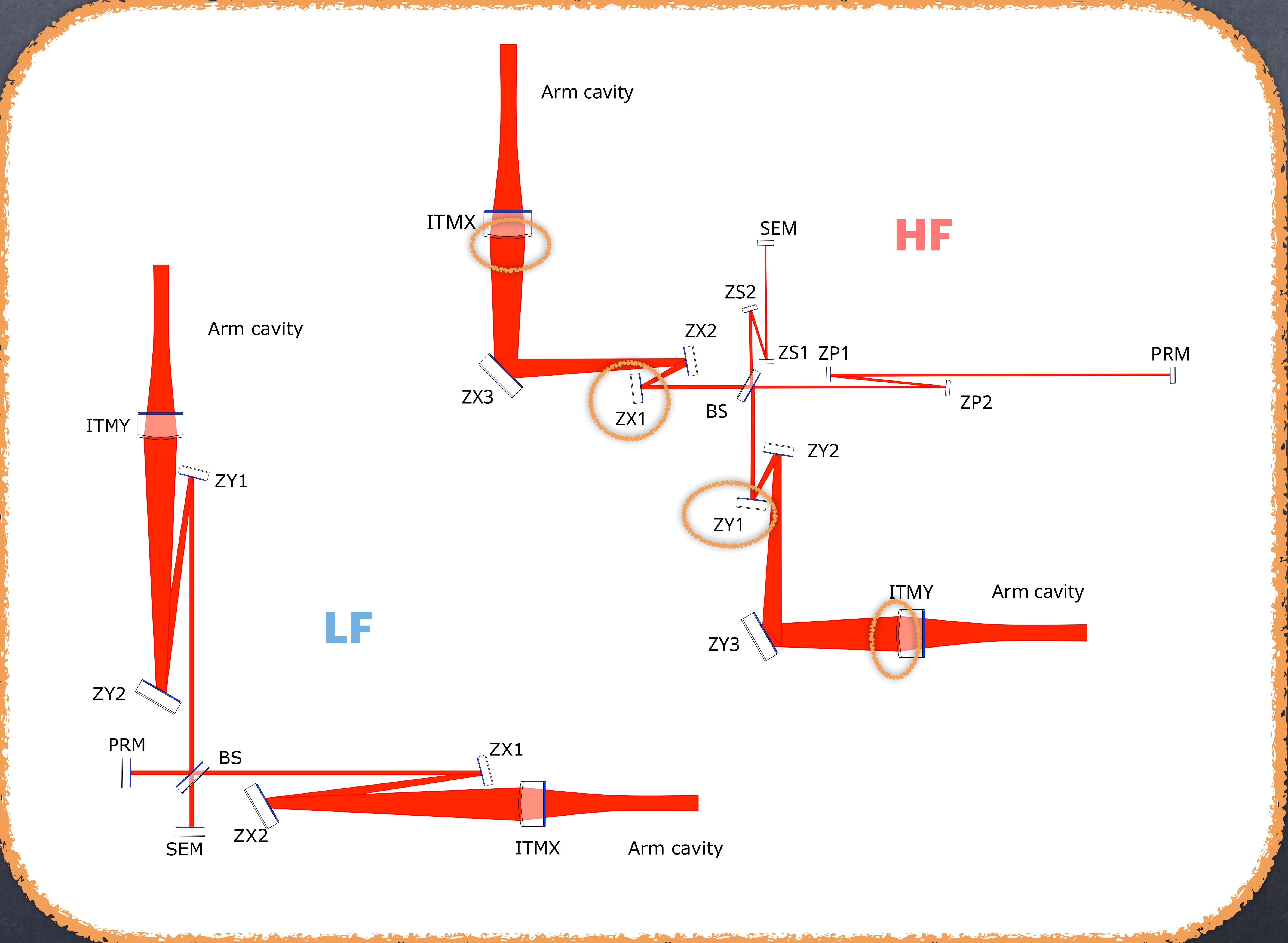

Recycling cavity design
Telescopes for HF

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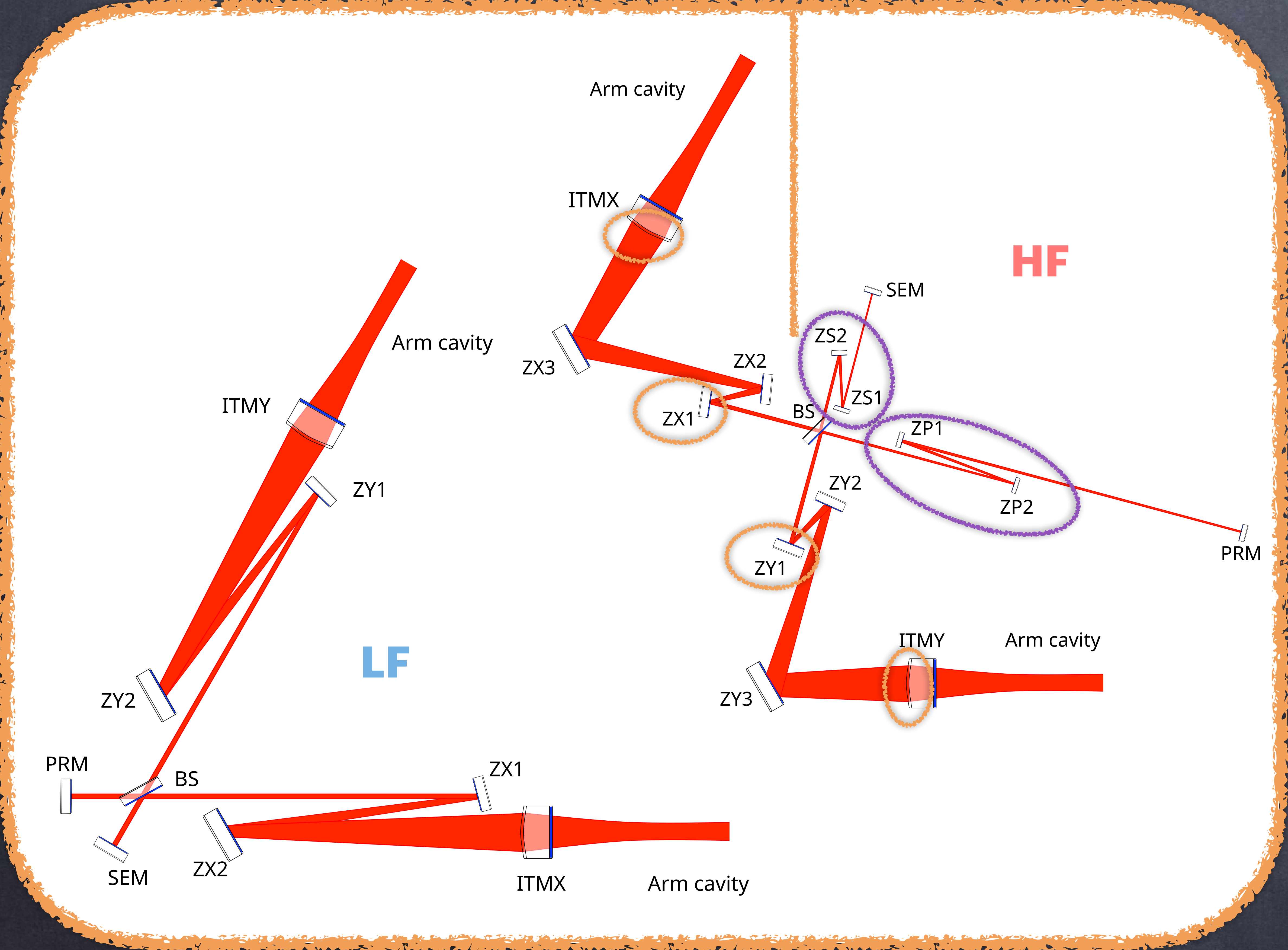
- Beam collimation on beam splitter (BS)
- Beam size on BS

- Stability
- Beam size on PRM/SEM (or SRM)

Triangle



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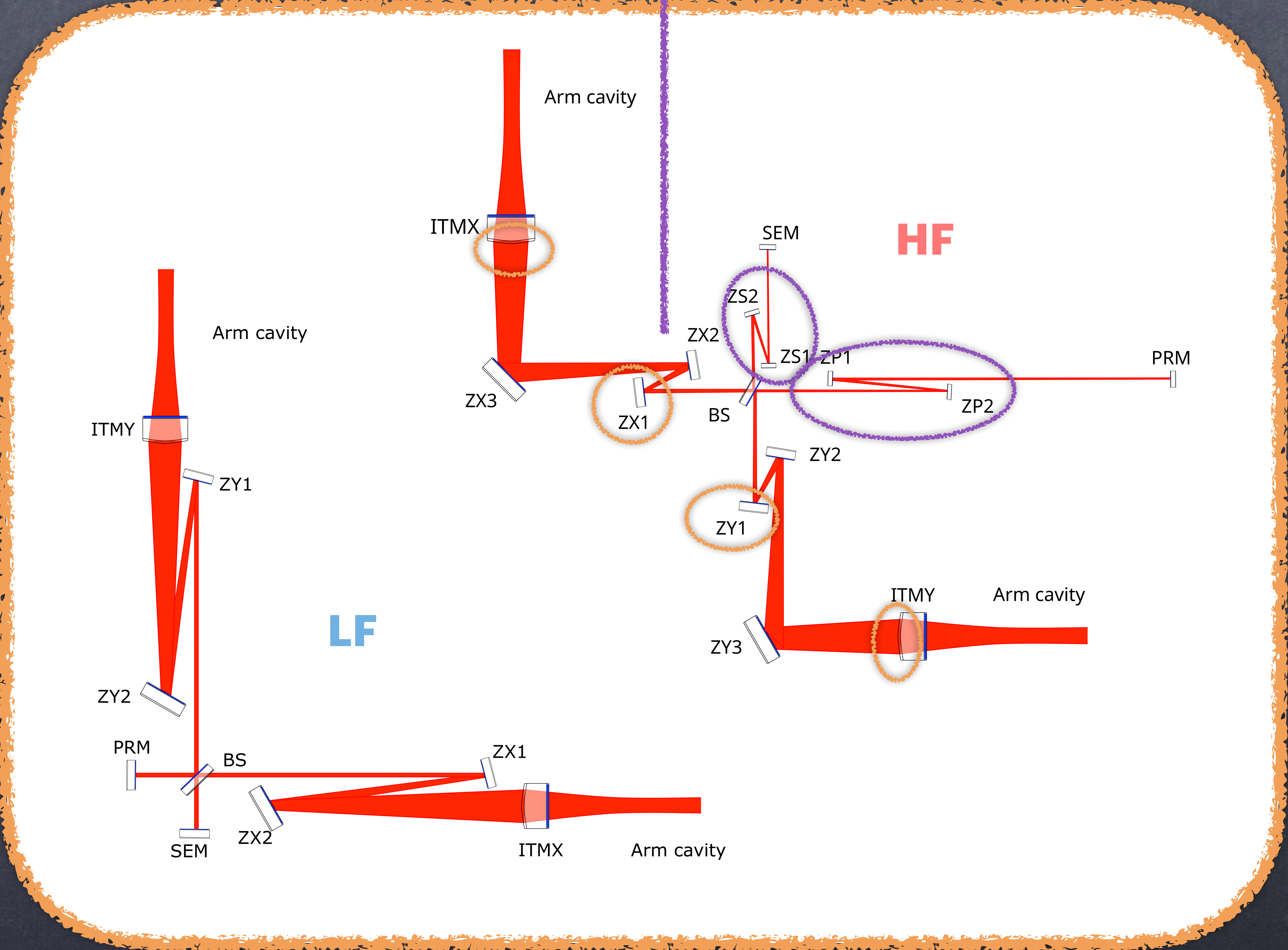
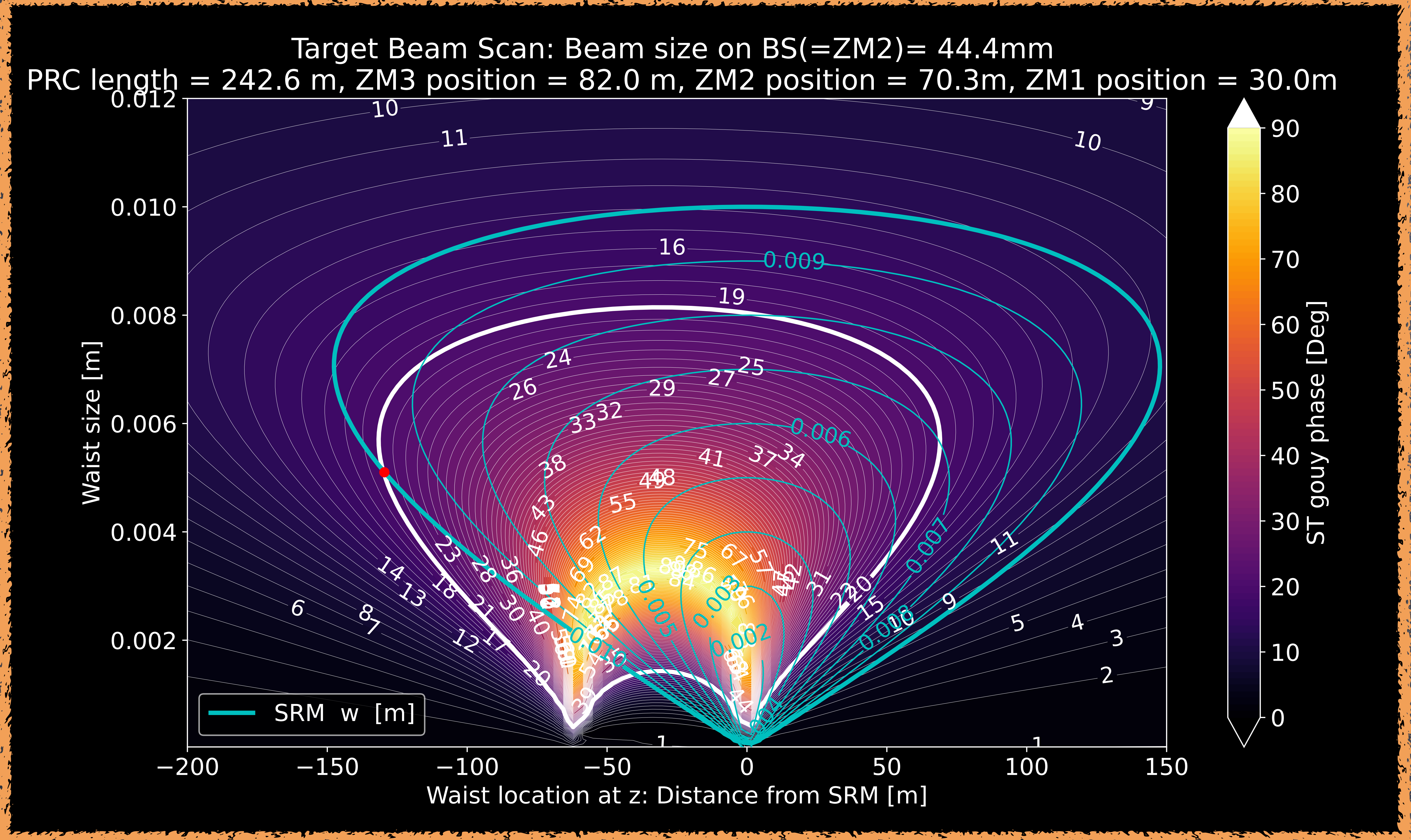
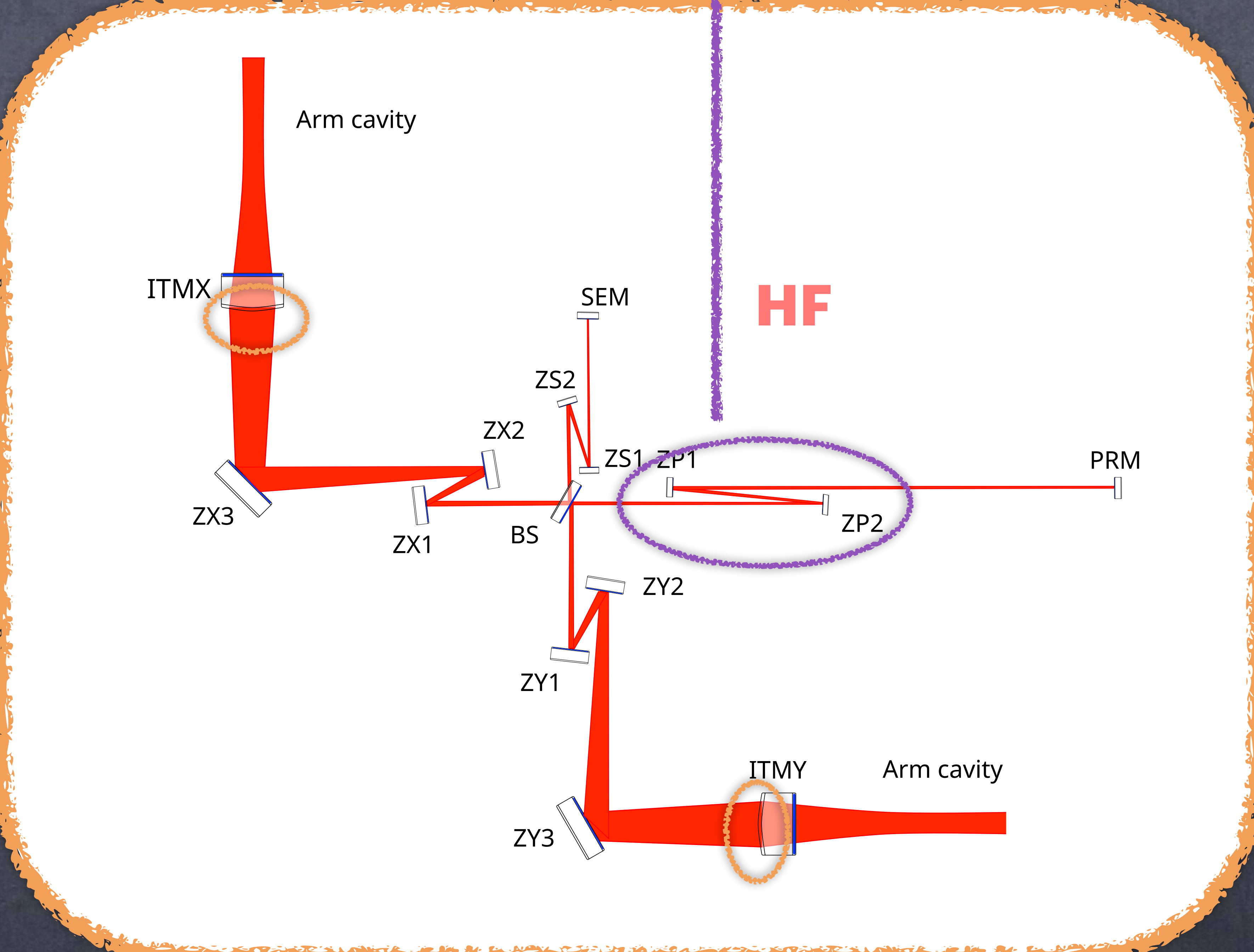


Recycling cavity design
Telescopes for HF-PRC

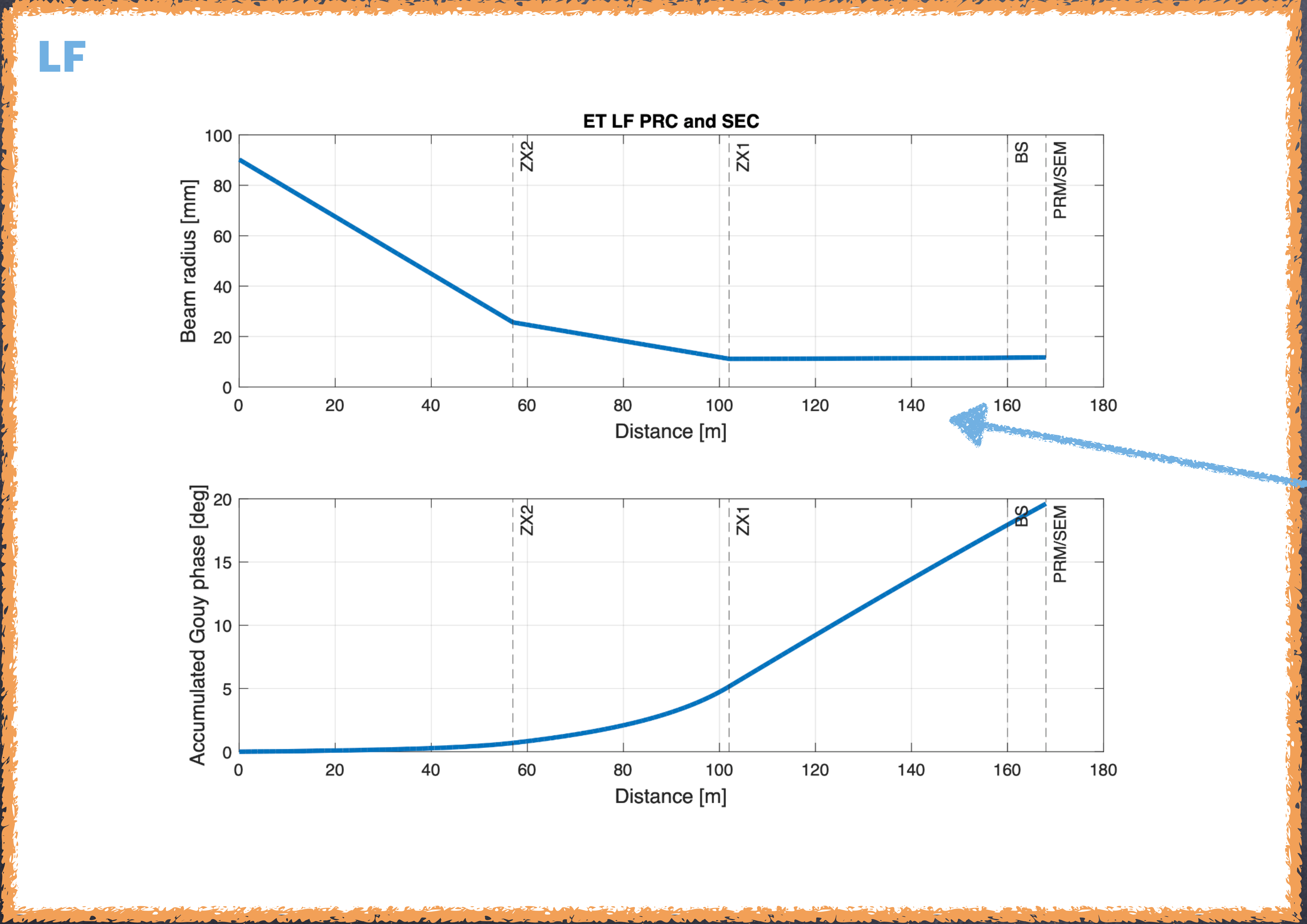
2L



PRC telescope



Recycling cavity design
2L: LF Beam evolution



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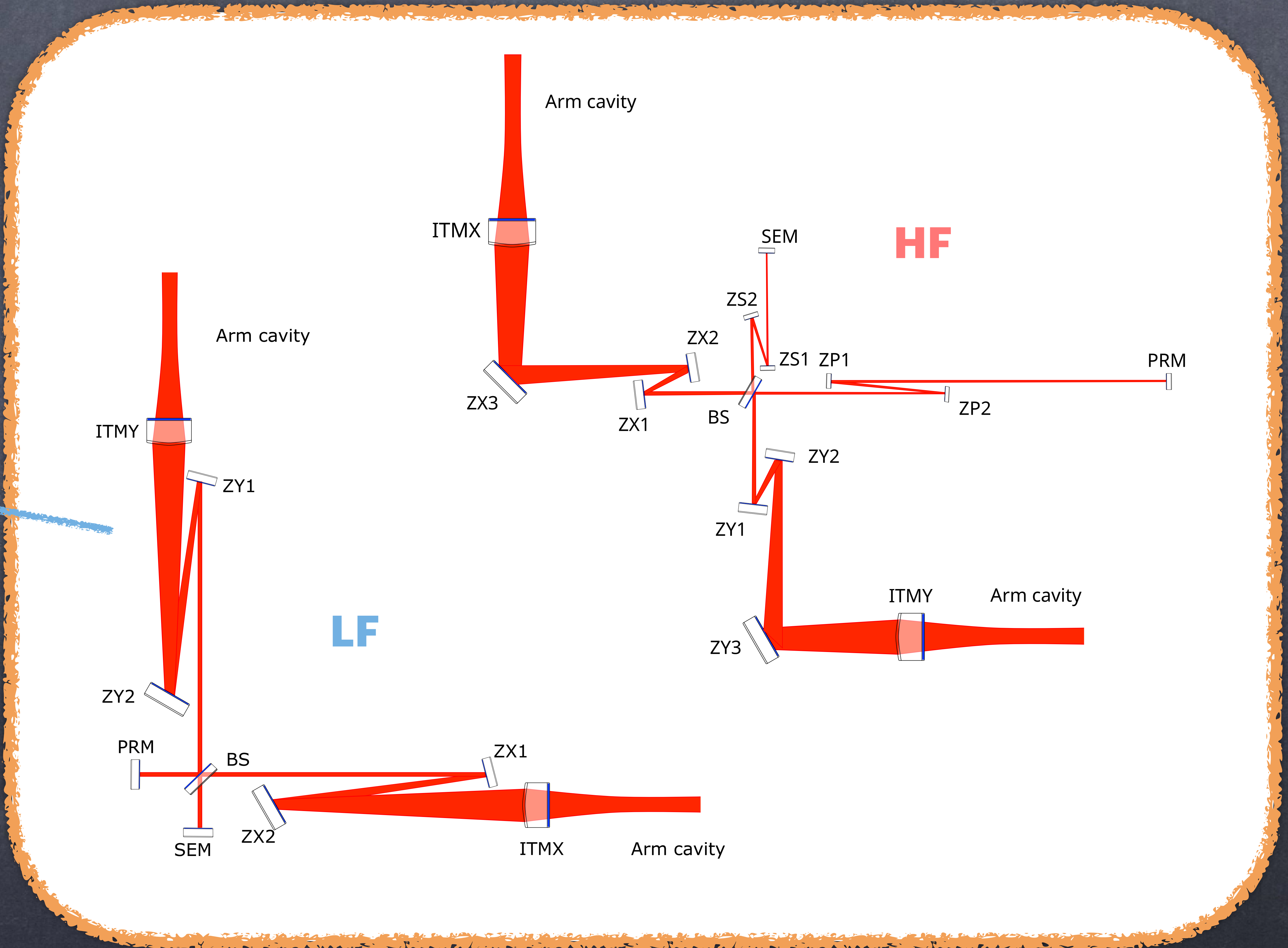
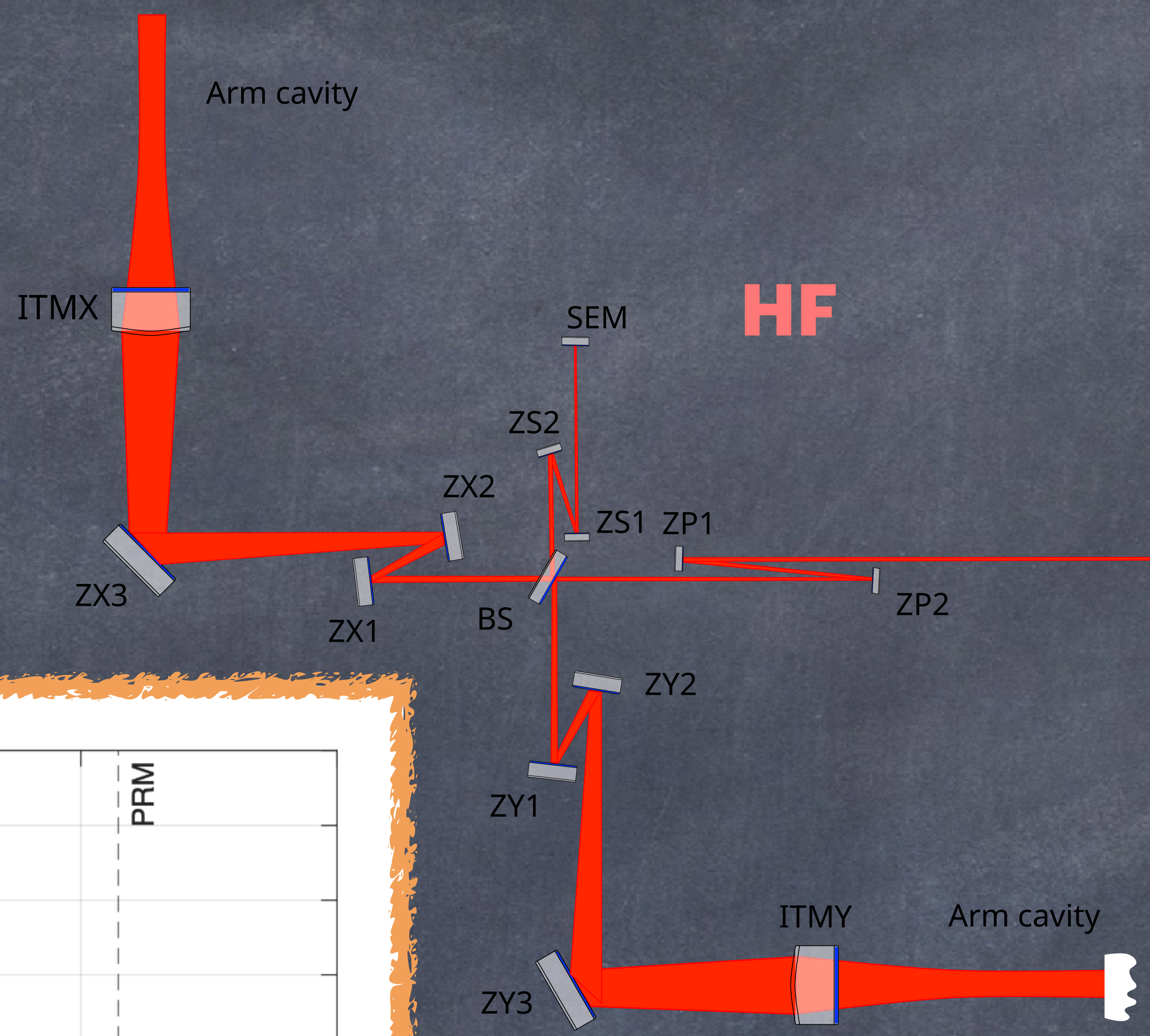
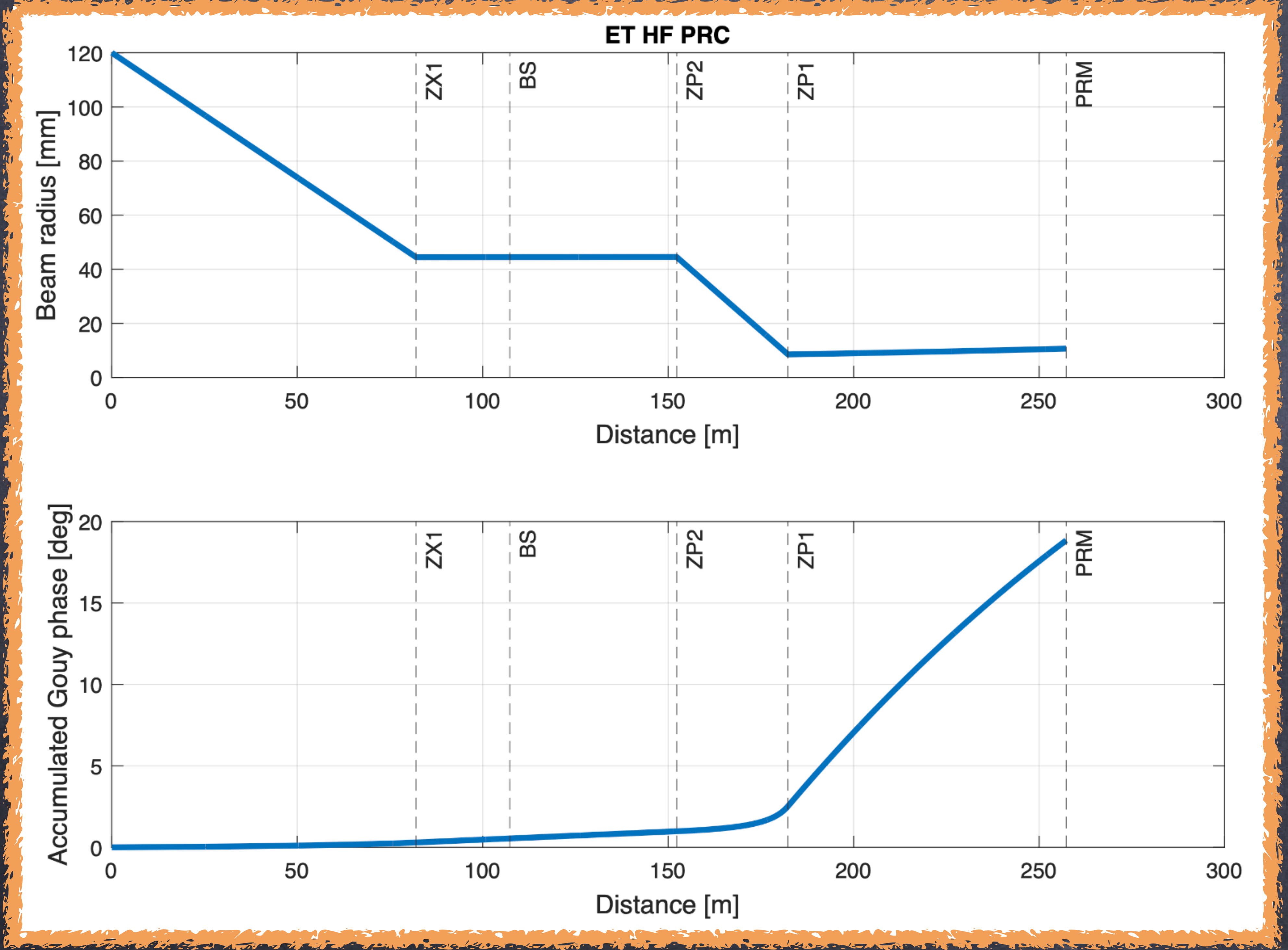
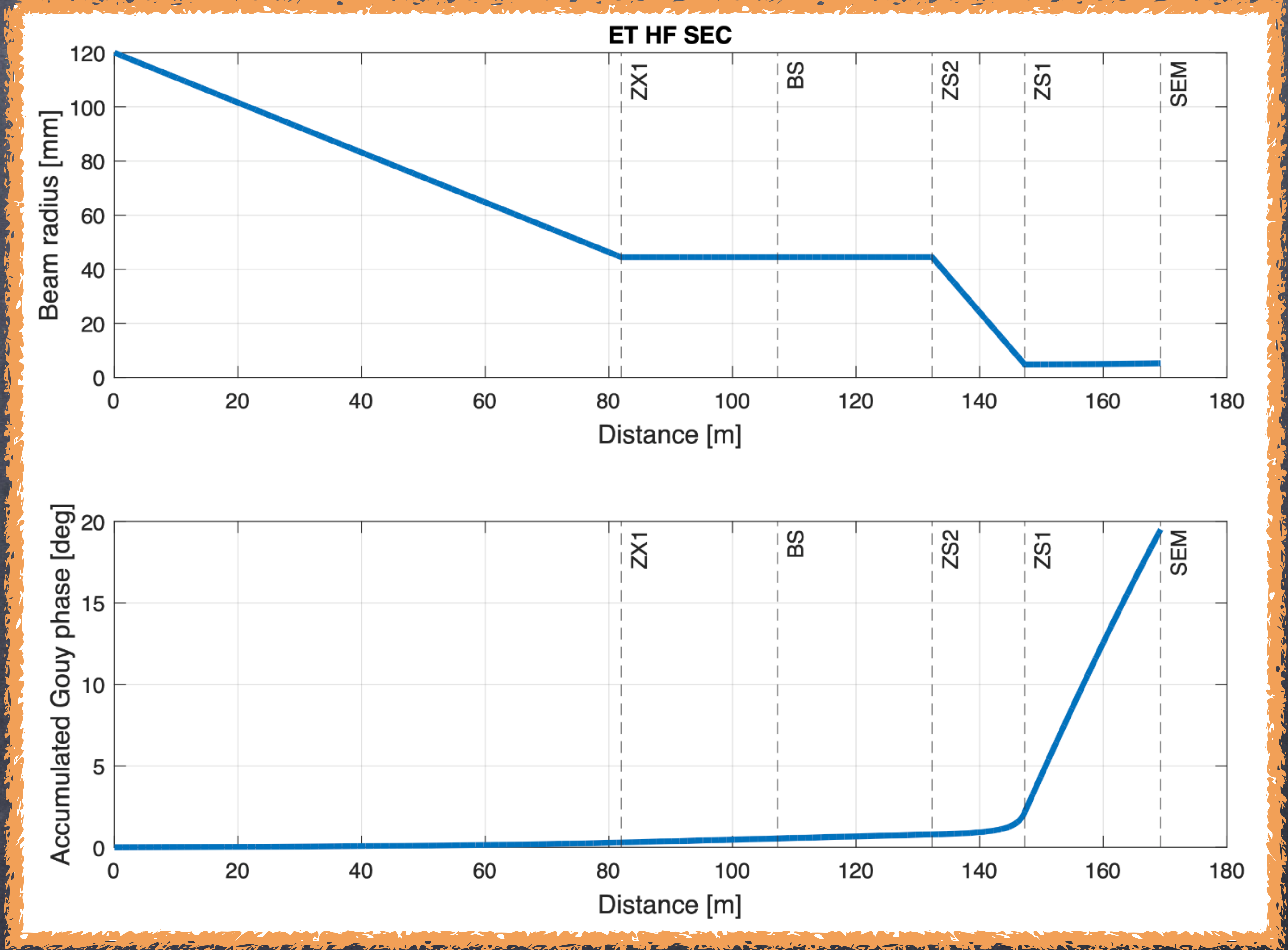


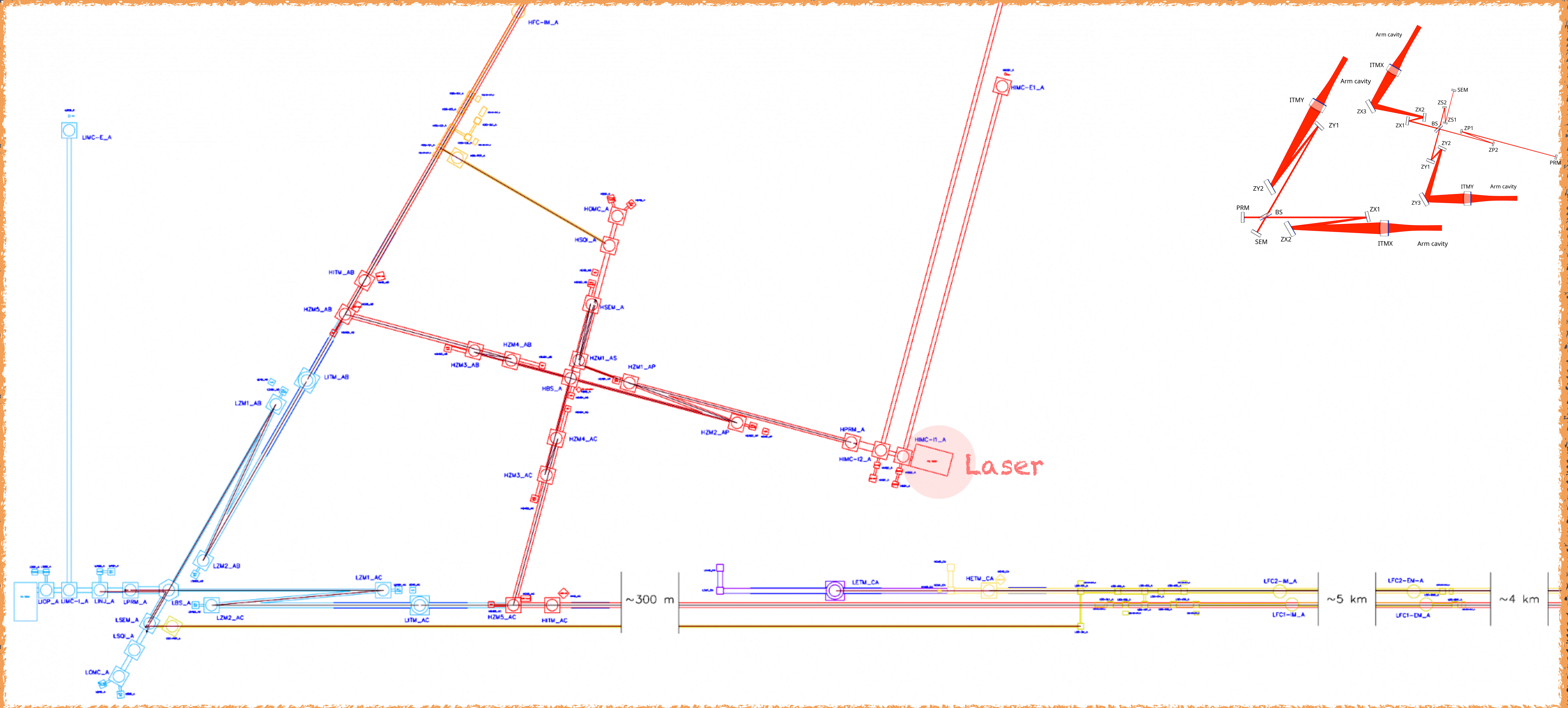
Recycling cavity design
2L: HF Beam evolution



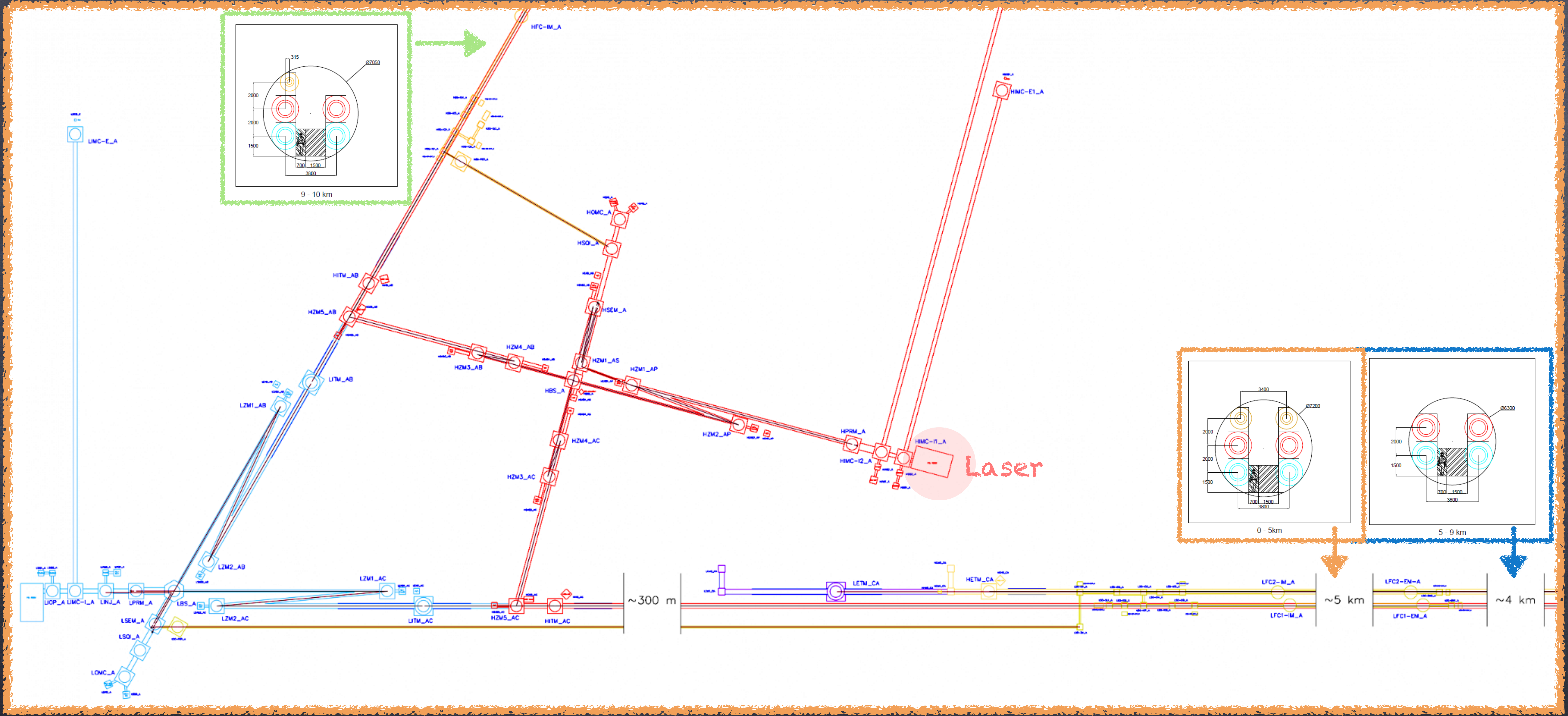




Toward detector layout
Triangle

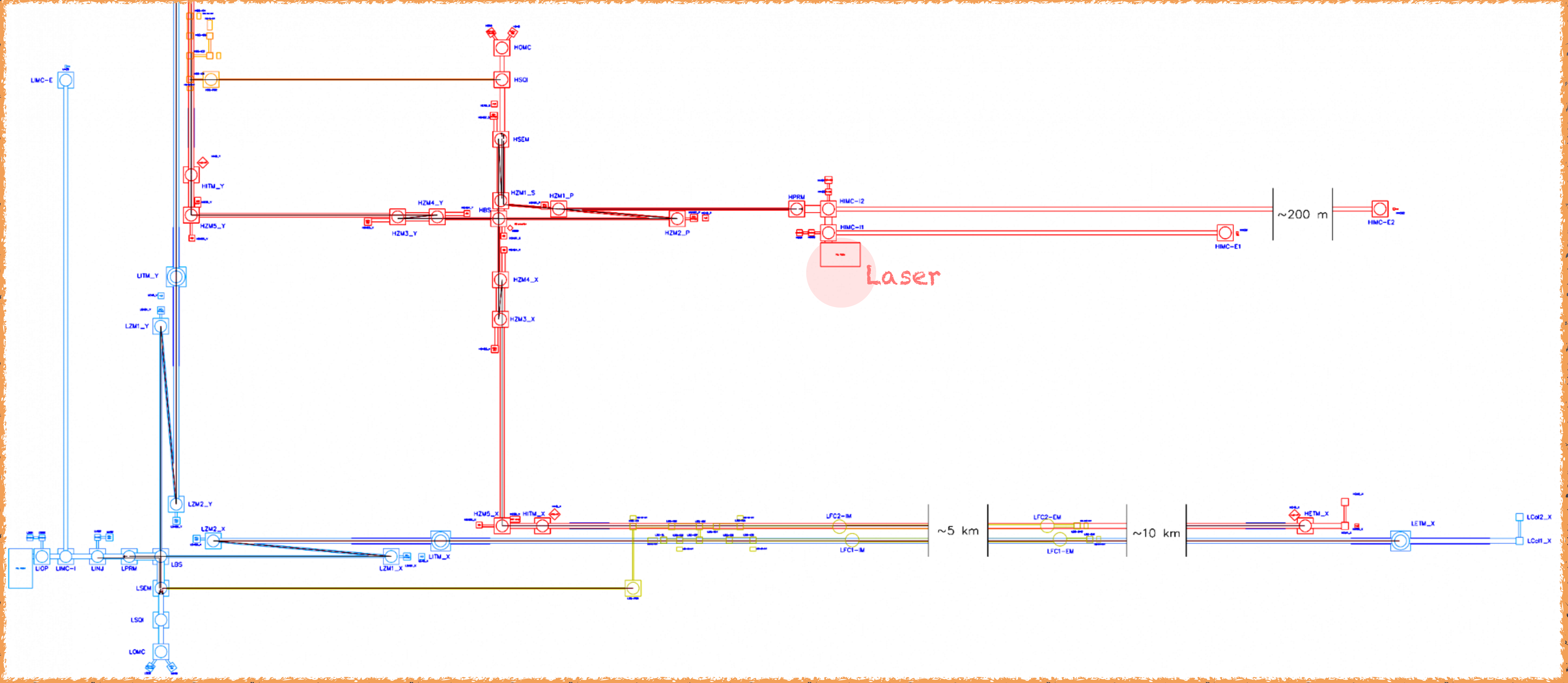


Toward detector layout
Triangle



Toward detector layout

2L



Toward detector layout

2L

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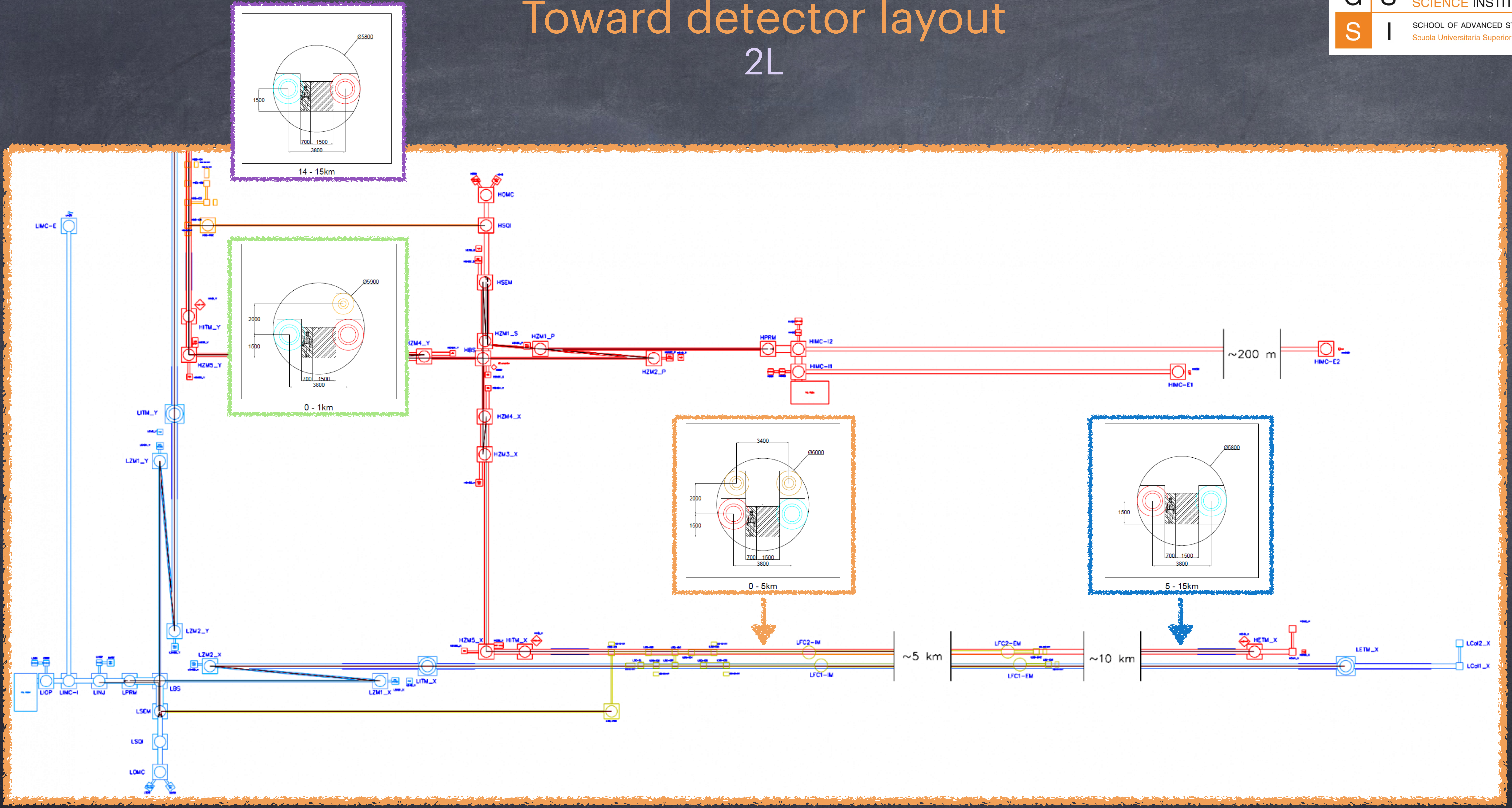
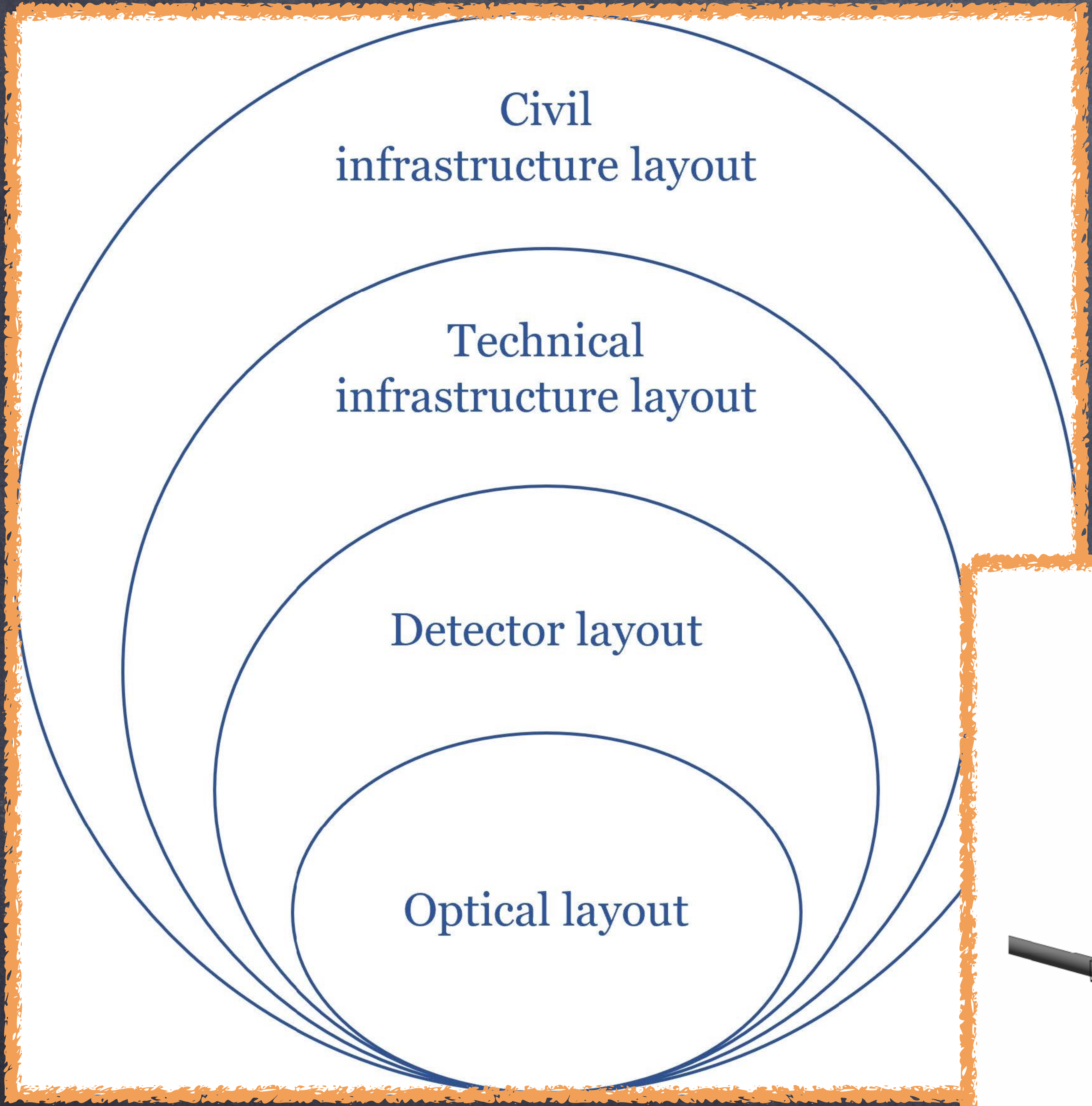
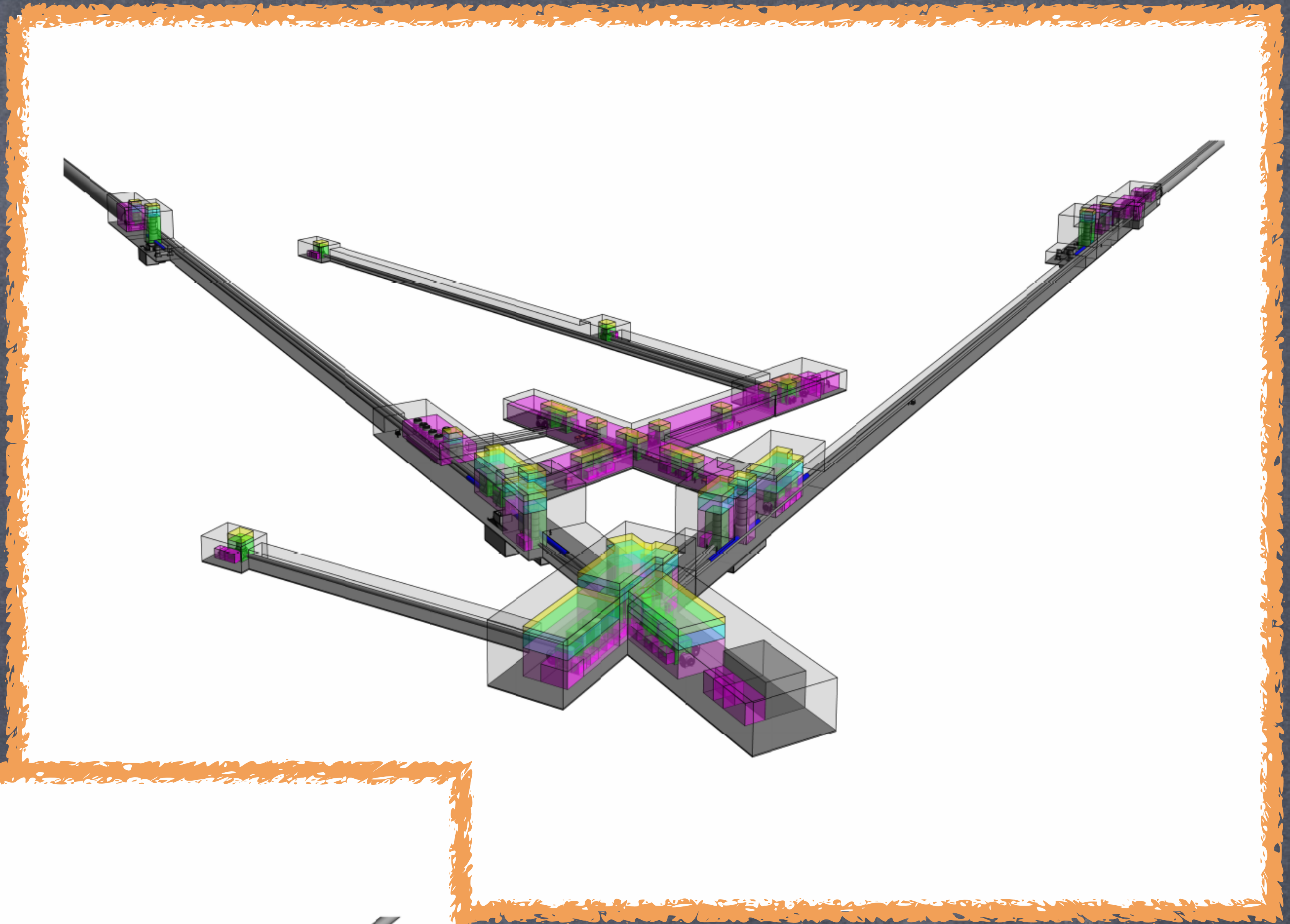
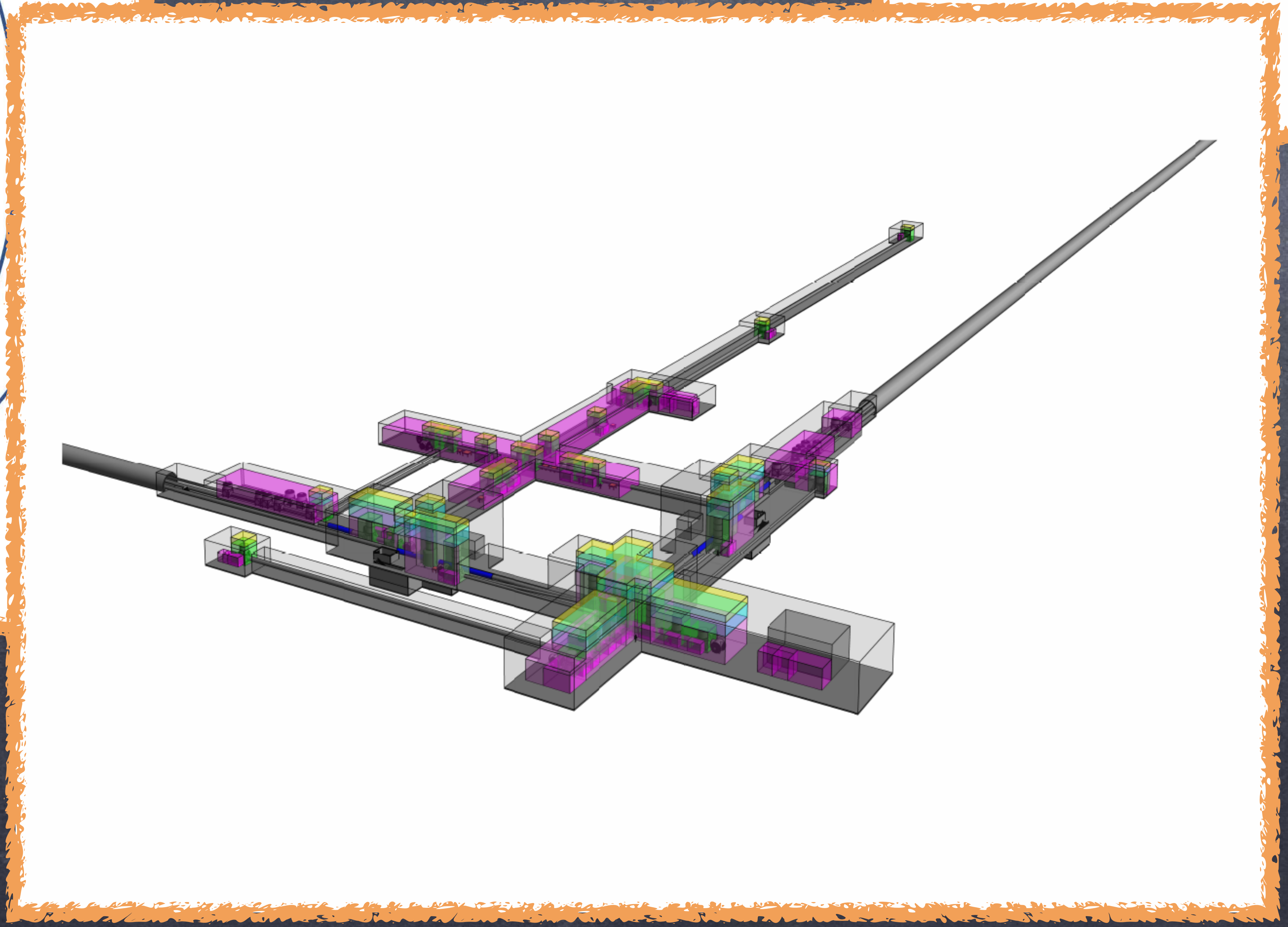


Toward detector layout
Definitions again







The team

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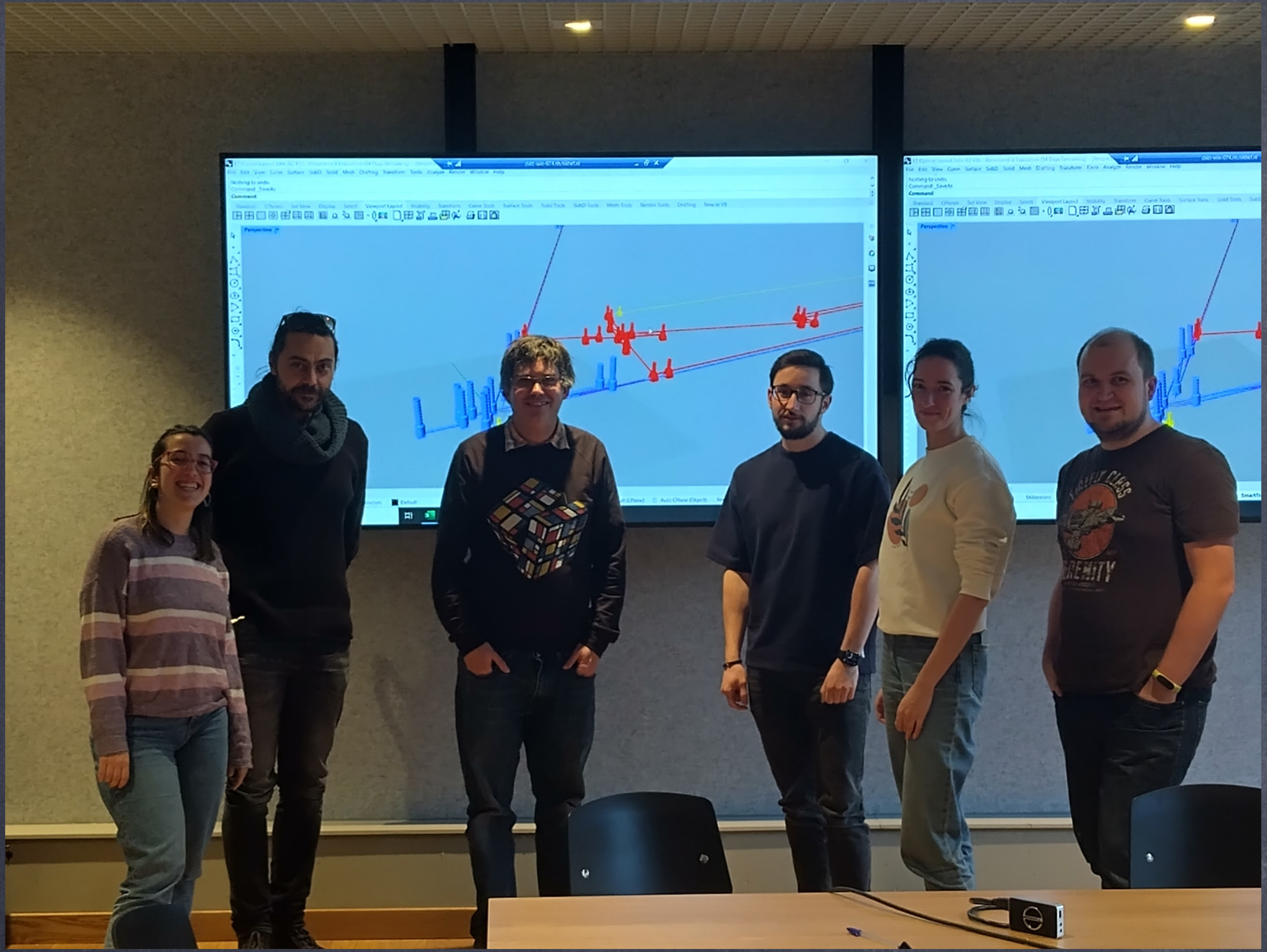

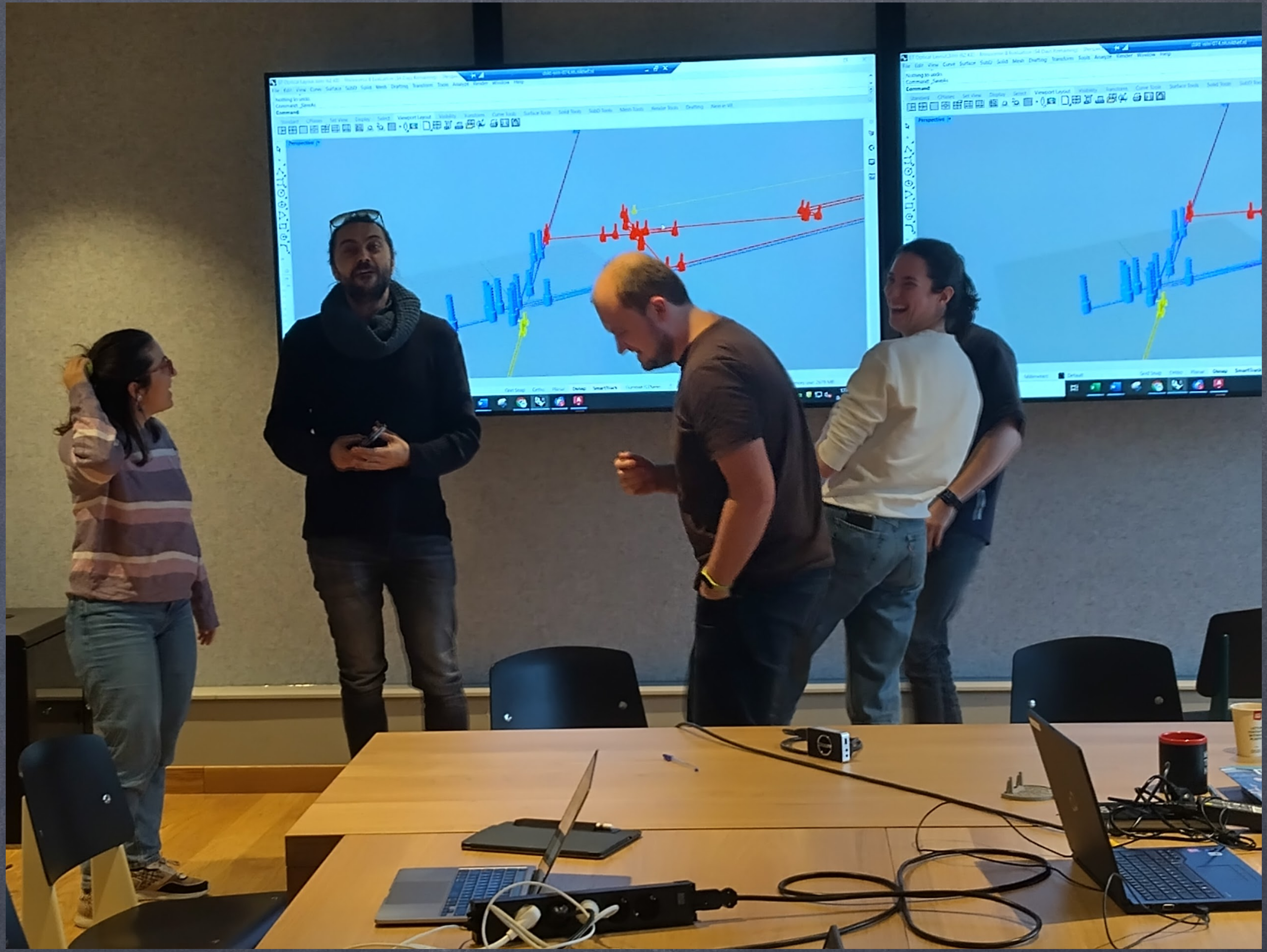

Key Messages

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- **ET is not only a geometry**
  → triangle and 2L are different layout concepts
- **The xylophone concept is a sensitivity strategy**
  → LF and HF interferometers are optimized for different frequency bands
- **Arm cavities set the starting point of the optical design**
  → length, beam size, mirror curvature and stability are coupled
- **Central/recycling cavities are shaped by competing optical constraints**
  → beam-size reduction, Gouy phase, collimation, losses, astigmatism, thermal effects, etc.
- **The optical layout is constrained by detector and infrastructure requirements**
  → cryostats, cavern sizes, cavern separations, vacuum envelope, suspensions, access, etc.
- **The final detector layout emerges from an iterative process**
  → optical designers and infrastructure/civil engineers must converge together

The final layout is the result of an iterative negotiation between optical performance and infrastructure feasibility.

Further reading

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- P. R. Saulson, Fundamentals of Interferometric Gravitational Wave Detectors, World Scientific, 1994 / 2017
- A. Freise and K. A. Strain, “Interferometer techniques for gravitational-wave detection”, Living Reviews in Relativity 13, 1 (2010); updated version, Living Reviews in Relativity 19, 1 (2016)
- B. J. Meers, “Recycling in laser-interferometric gravitational-wave detectors”, Physical Review D 38, 2317–2326 (1988)
- J. Mizuno, Comparison of optical configurations for laser-interferometric gravitational-wave detectors, PhD thesis, Universität Hannover / Max-Planck-Institut für Quantenoptik, 1995
- S. Hild et al., “Demonstration and comparison of tuned and detuned signal recycling in a large-scale gravitational wave detector”, Classical and Quantum Gravity 24, 1513–1523 (2007)
- Finesse 3 documentation and examples.

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Next lectures

14. Stray light
Dr Livia Conti (INFN)
25/05/2026, 11:05
Optics & interferometry

15. Thermal compensation
Ilaria Nardecchia
25/05/2026, 14:30
Interferometer test mas...

16. Noise control in a space-based observatory
Lorenzo Sala
25/05/2026, 16:35
Noise control

17. Squeezing
Fiodor Sorrentino
26/05/2026, 09:00
Optics & interferometry

18. Stray light
Dr Livia Conti (INFN)
26/05/2026, 11:05
Optics & interferometry

13. Laser Technologies
Marco Galimberti
26/05/2026, 14:30
Optics & interferometry

20. Data Analysis for space-based detectors
Riccardo Buscicchio
26/05/2026, 16:35
Data Analysis

23. Environmental noise and impact on the detector
Rosario De Rosa
27/05/2026, 09:00
Noise control

22. Elements of cryogenics in GW detectors
Ettore Majorana
27/05/2026, 11:05
Interferometer test mas...

...THANK YOU