Roadmap to free space optics for bridging the digital divide

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School of Electrical and Information Engineering

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OPTICAL COMMUNICATION LABORATORY
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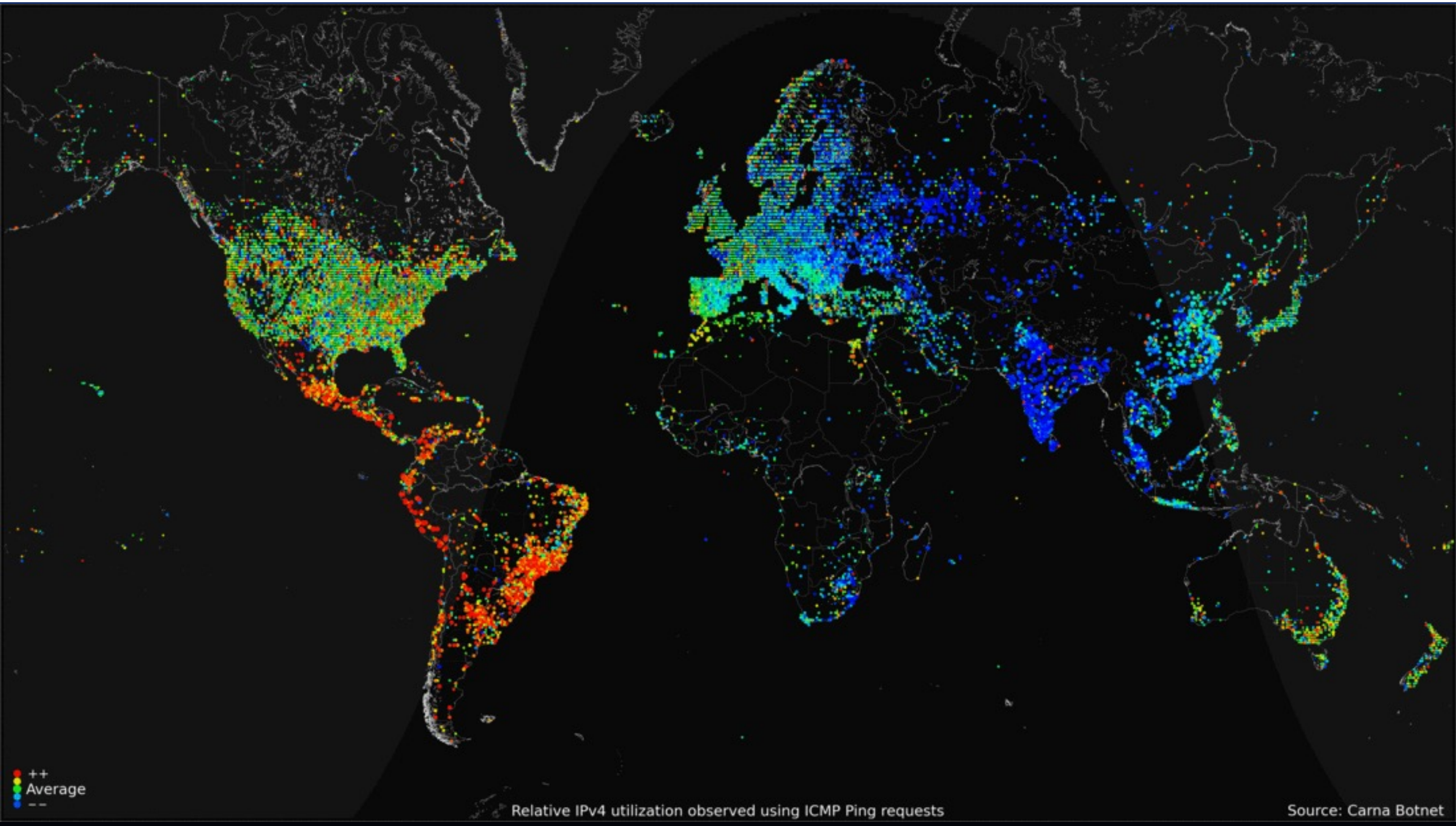
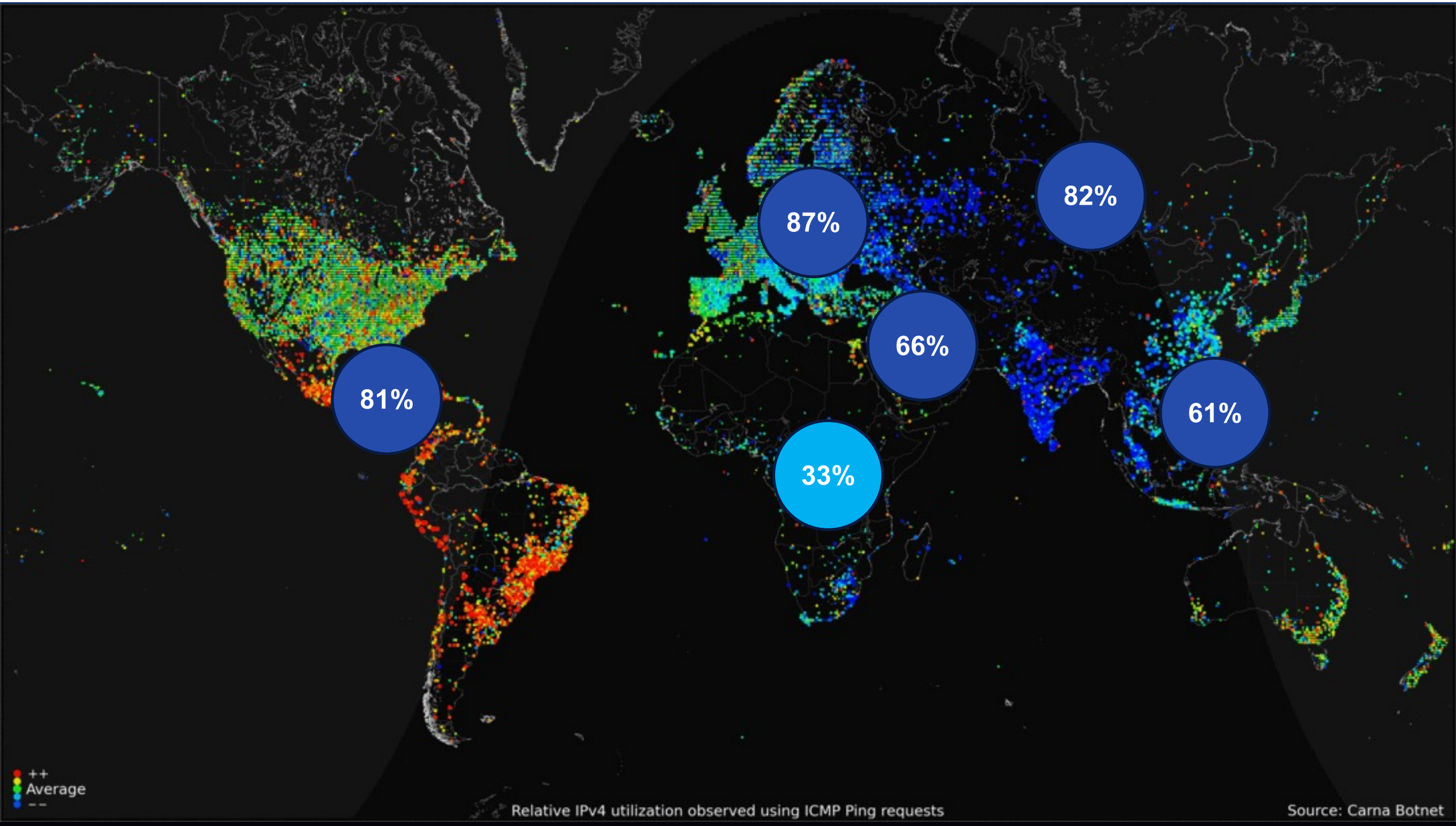
This was the internet in 2012…



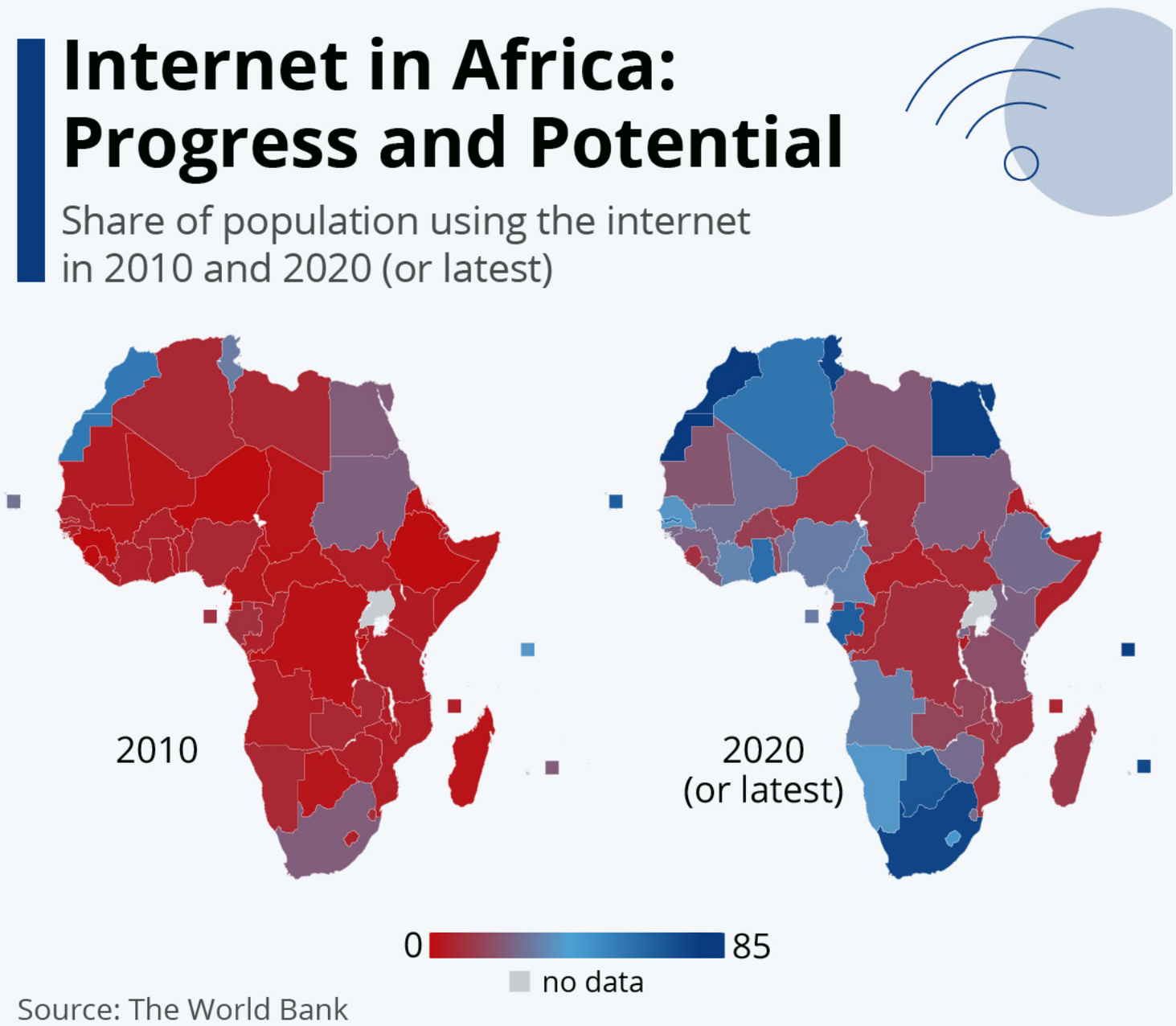
How many people are using the internet now?

As a percentage of population… (Statista, 2021)



One billion African people don't use the Internet

This is the digital divide…

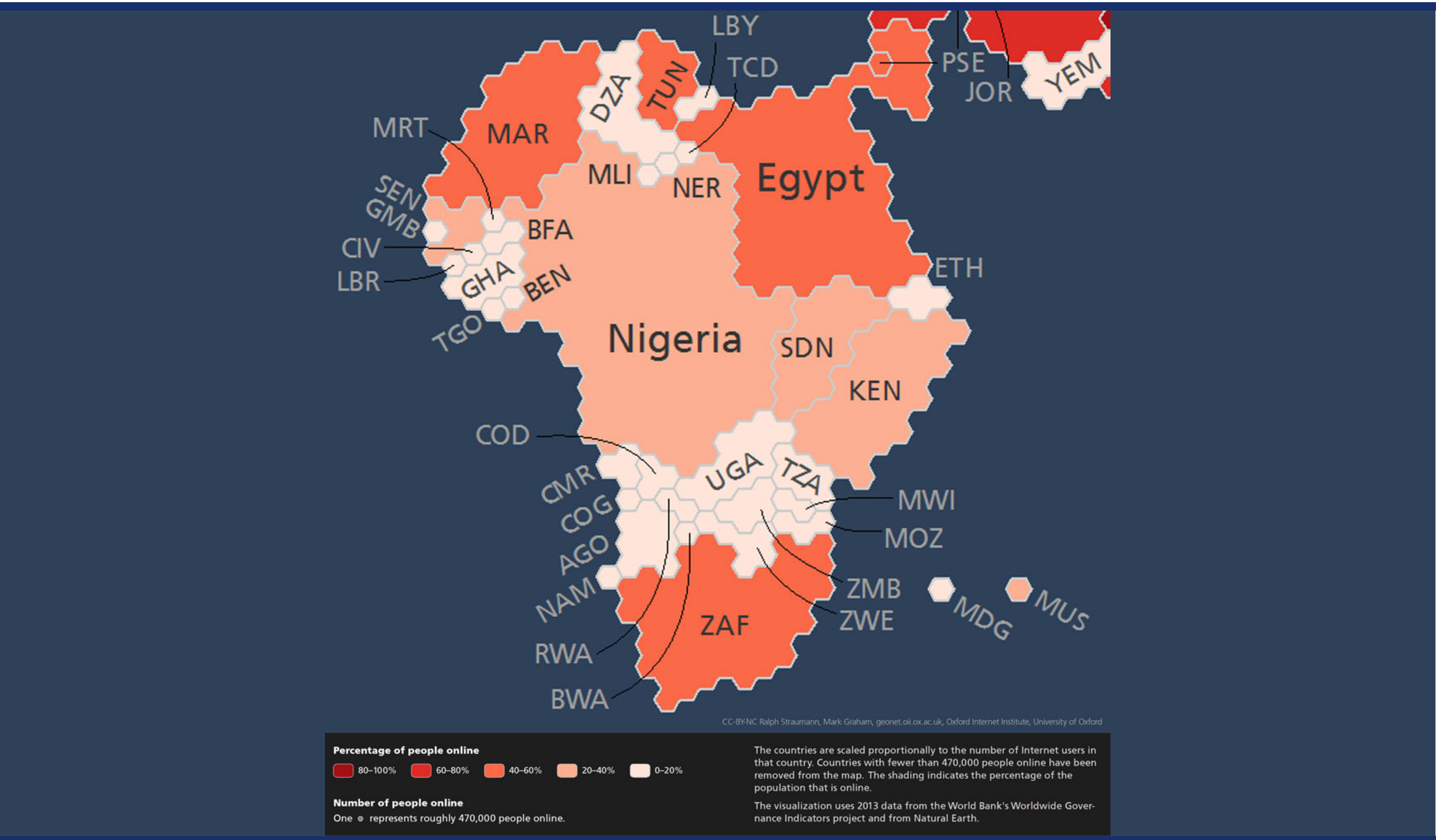


1.5 billion people (18% Earth)

45 people / km^2

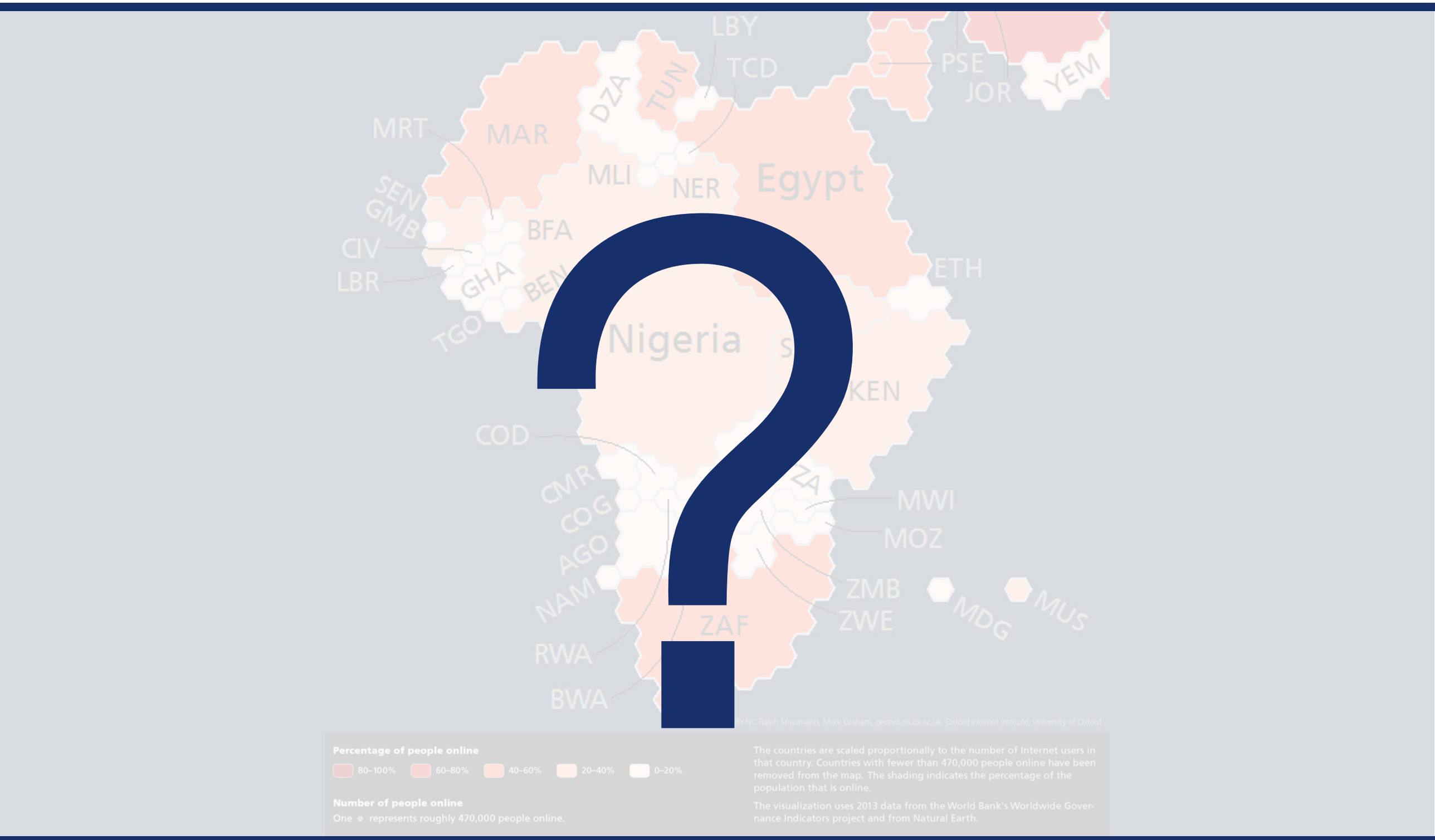
Certain countries are “well” connected

The area represents absolute number, with colour the proportion Internet users



Why is this?

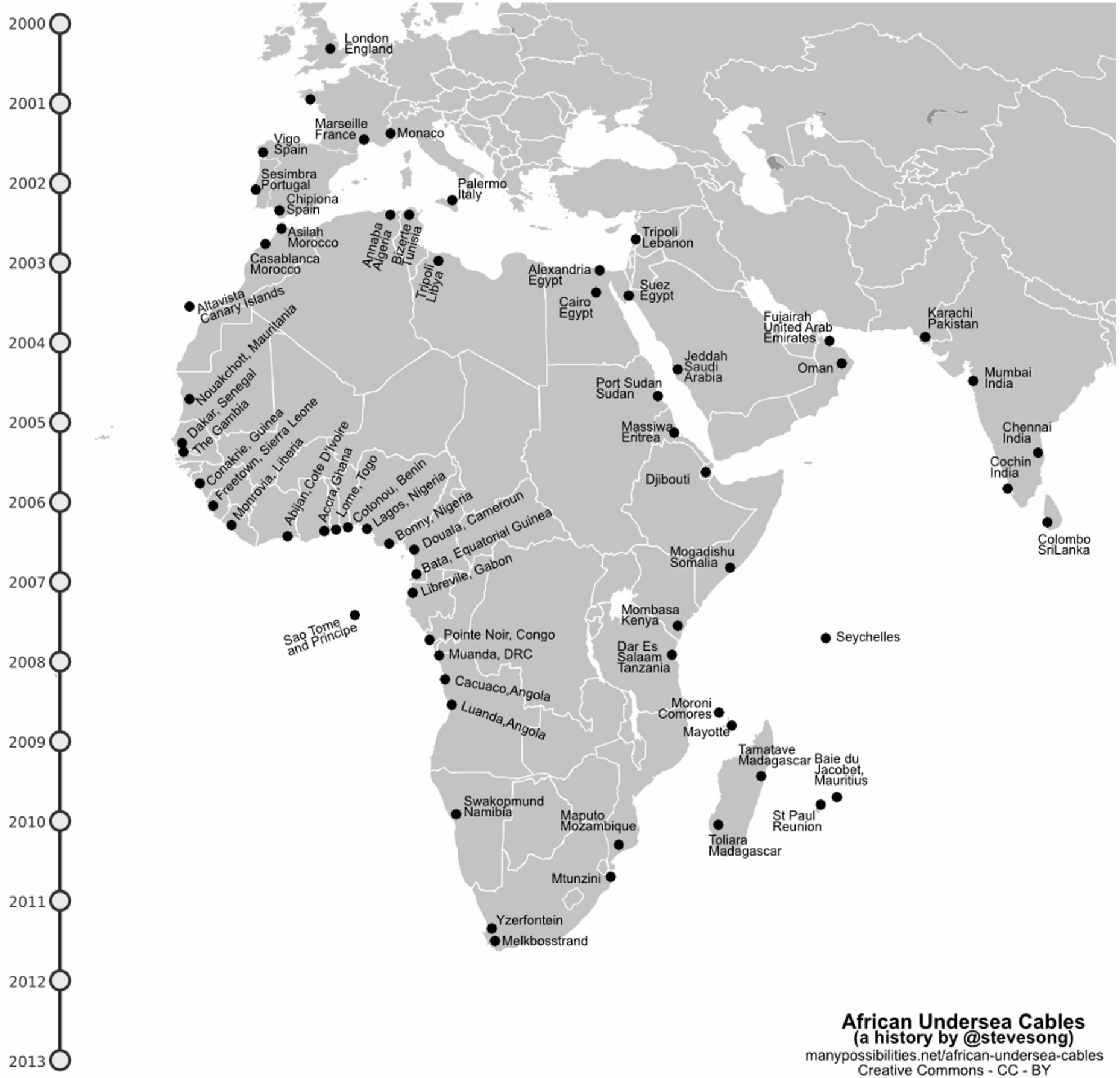
And what are the possible solutions?



340 Gb/s

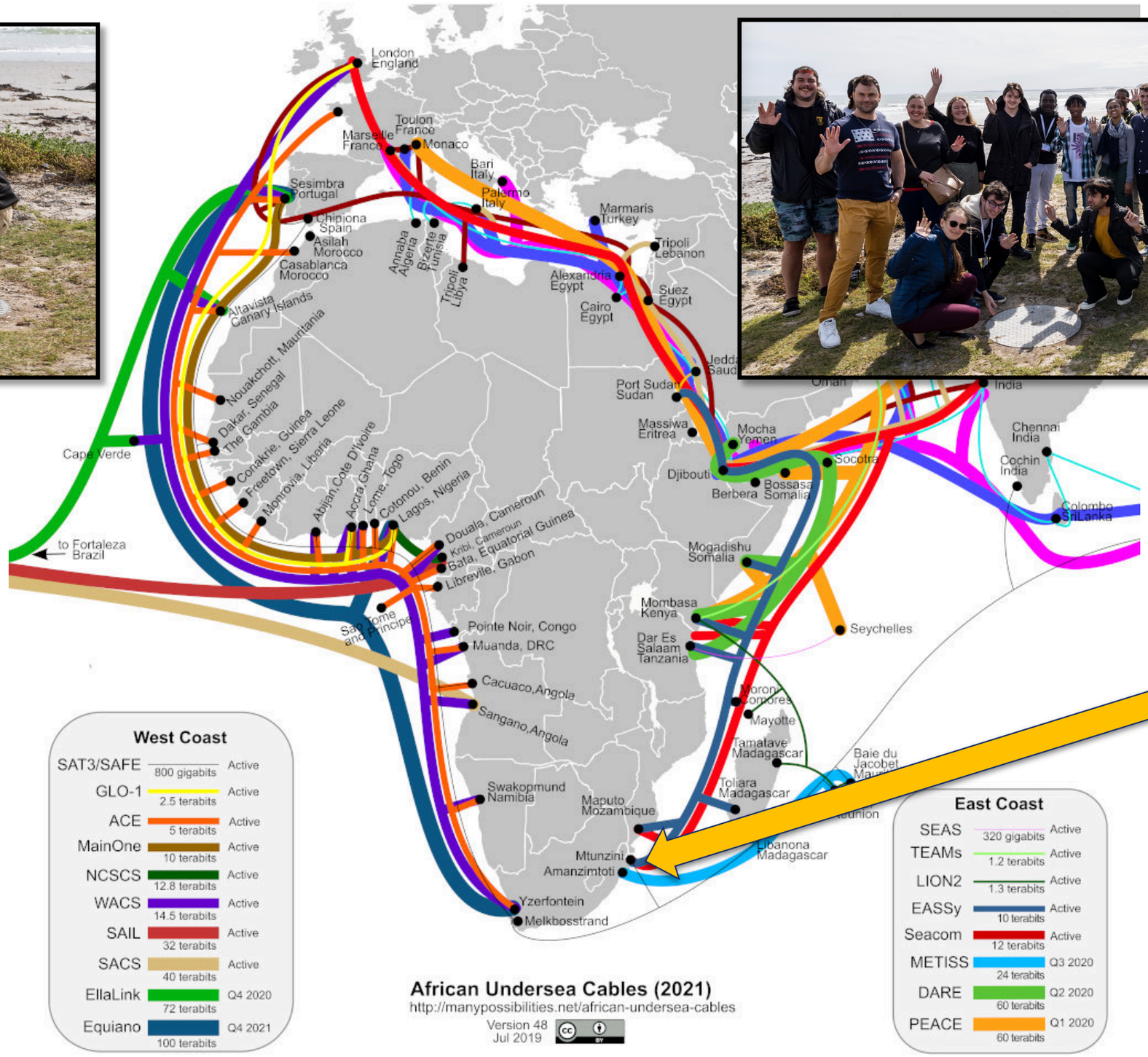
12 Tb/s

14.5 Tb/s



Subsea fibre connectivity seems good?

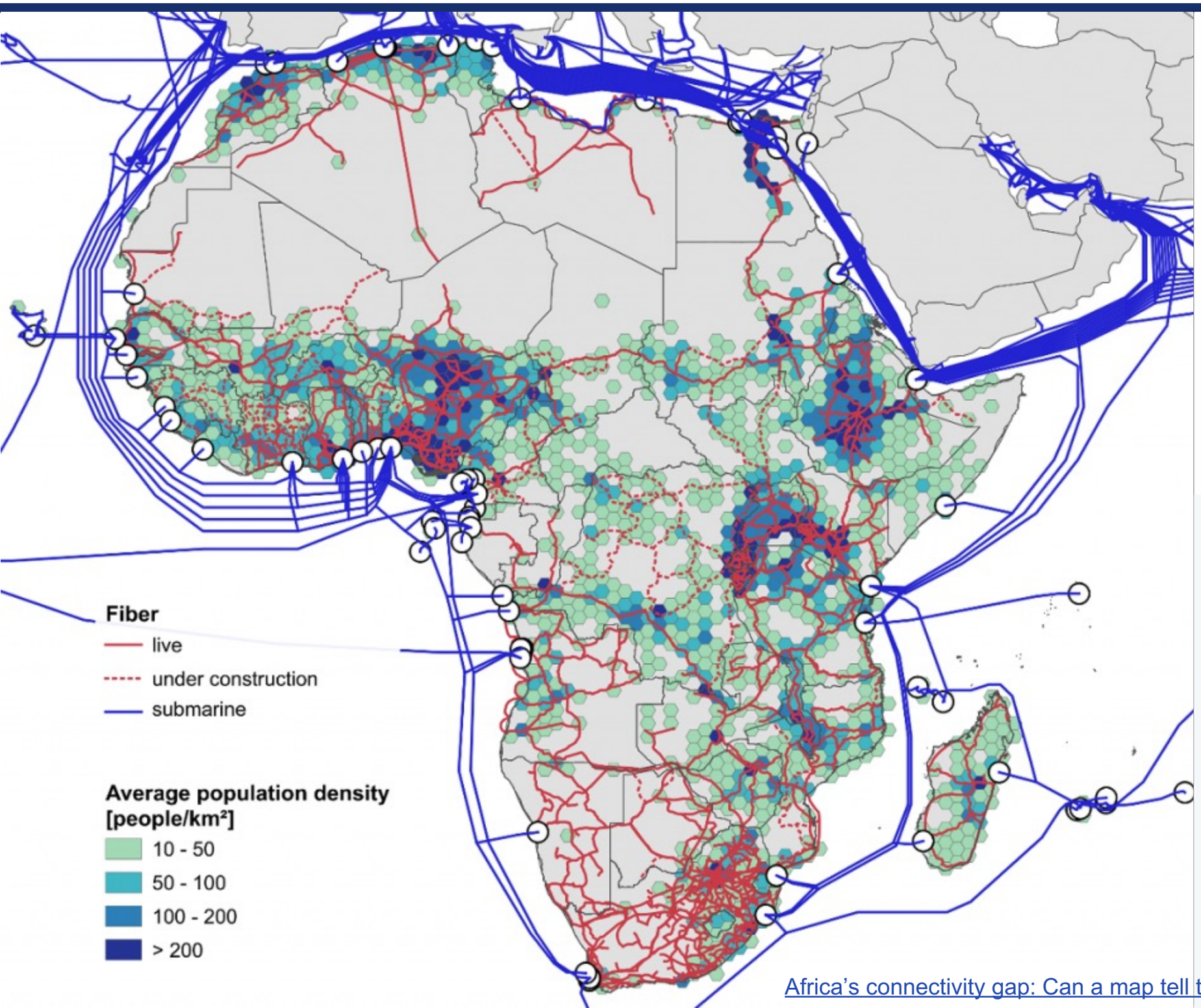
Adding it up, South Africa has at least 50 Tbps total capacity.

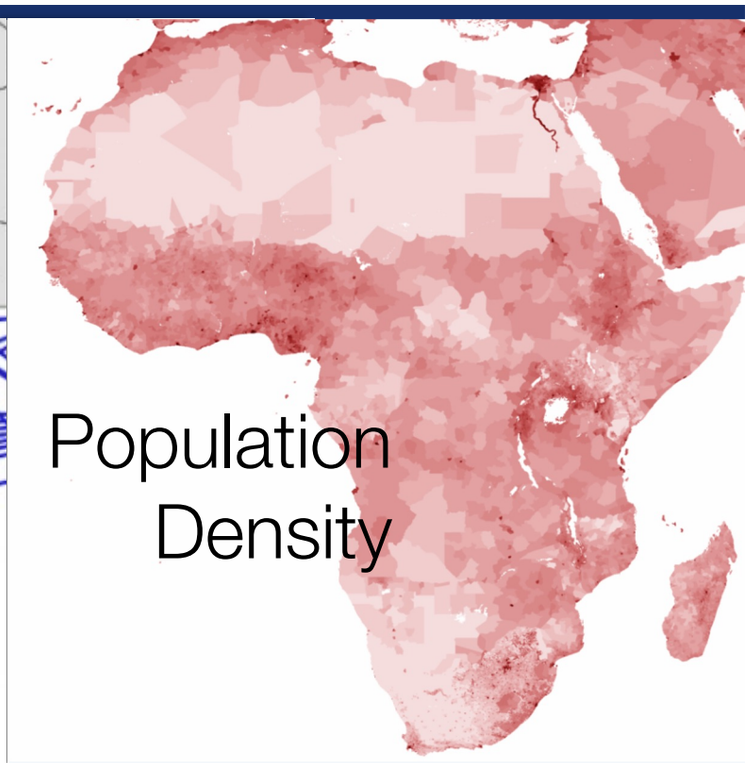


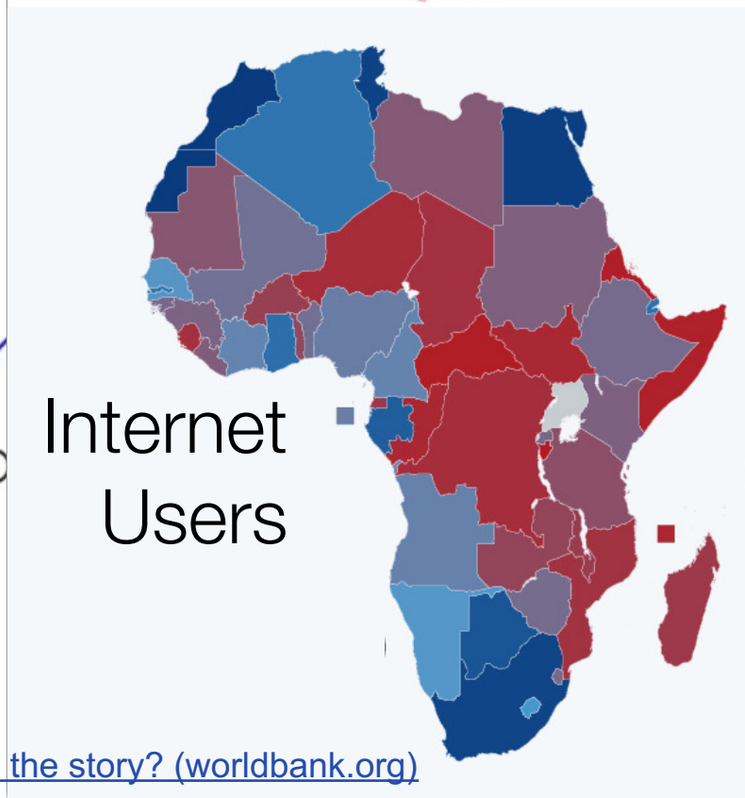
~50 Tb/s
(+144Tb/s
for Equiano!)

The real issue is terrestrial connectivity

There's a mismatch between where people live, and where there's fibre.

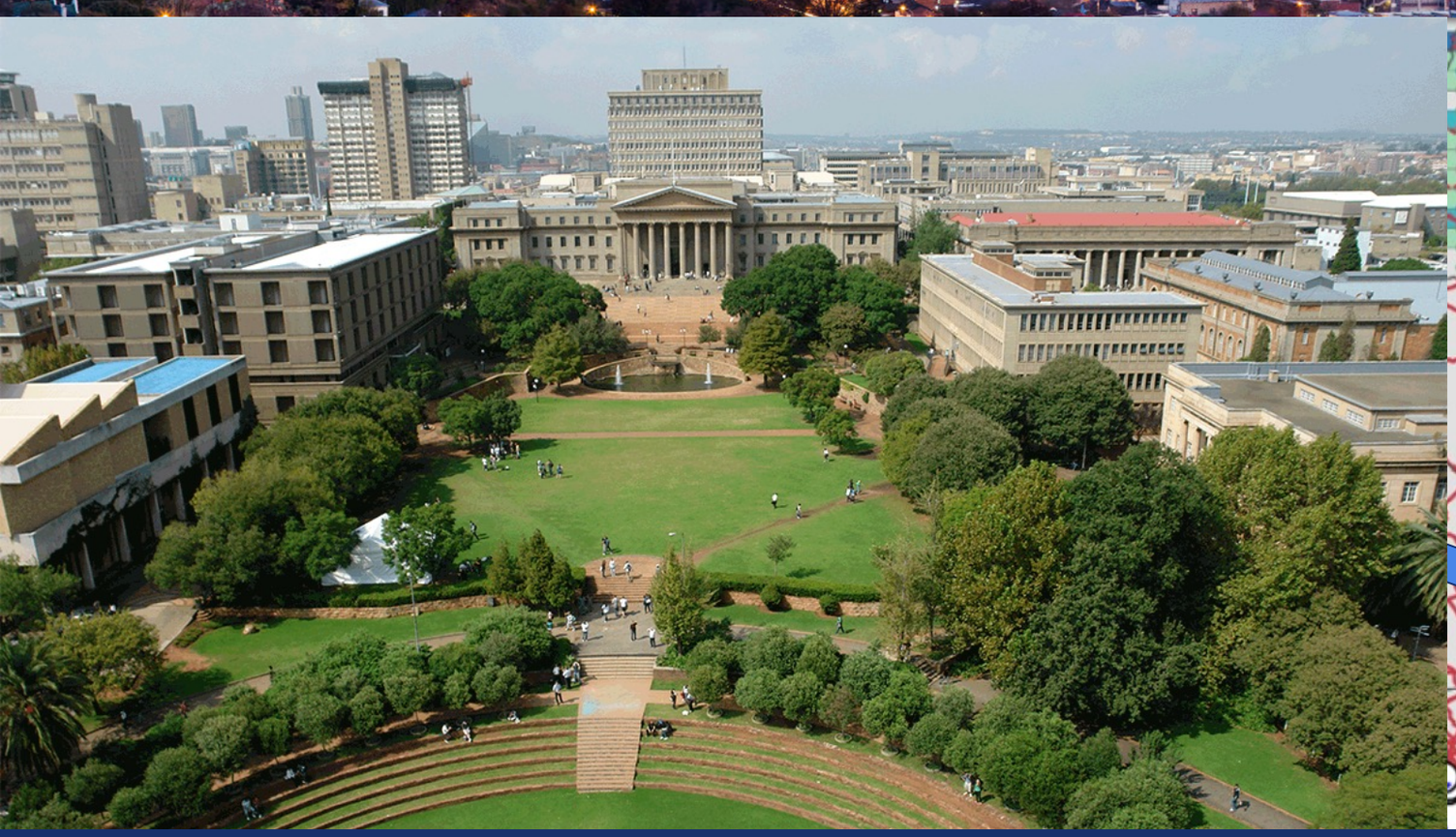


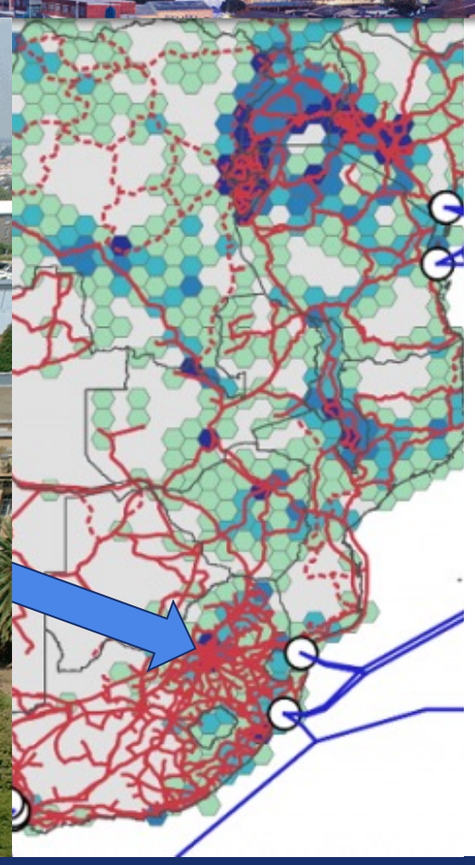




Africa's connectivity gap: Can a map tell the story? (worldbank.org)

In Johannesburg, connectivity isn’t really an issue anymore.





101 years old
1.1k **academics**
40k students
(14k **postgrads**)

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JOHANNESBURG

Cities like Johannesburg are the exception

Many people live in rural villages with poor internet connectivity.

Much of Africa is “wild”

This means long distances between human settlements.

Meanwhile in Johannesburg…

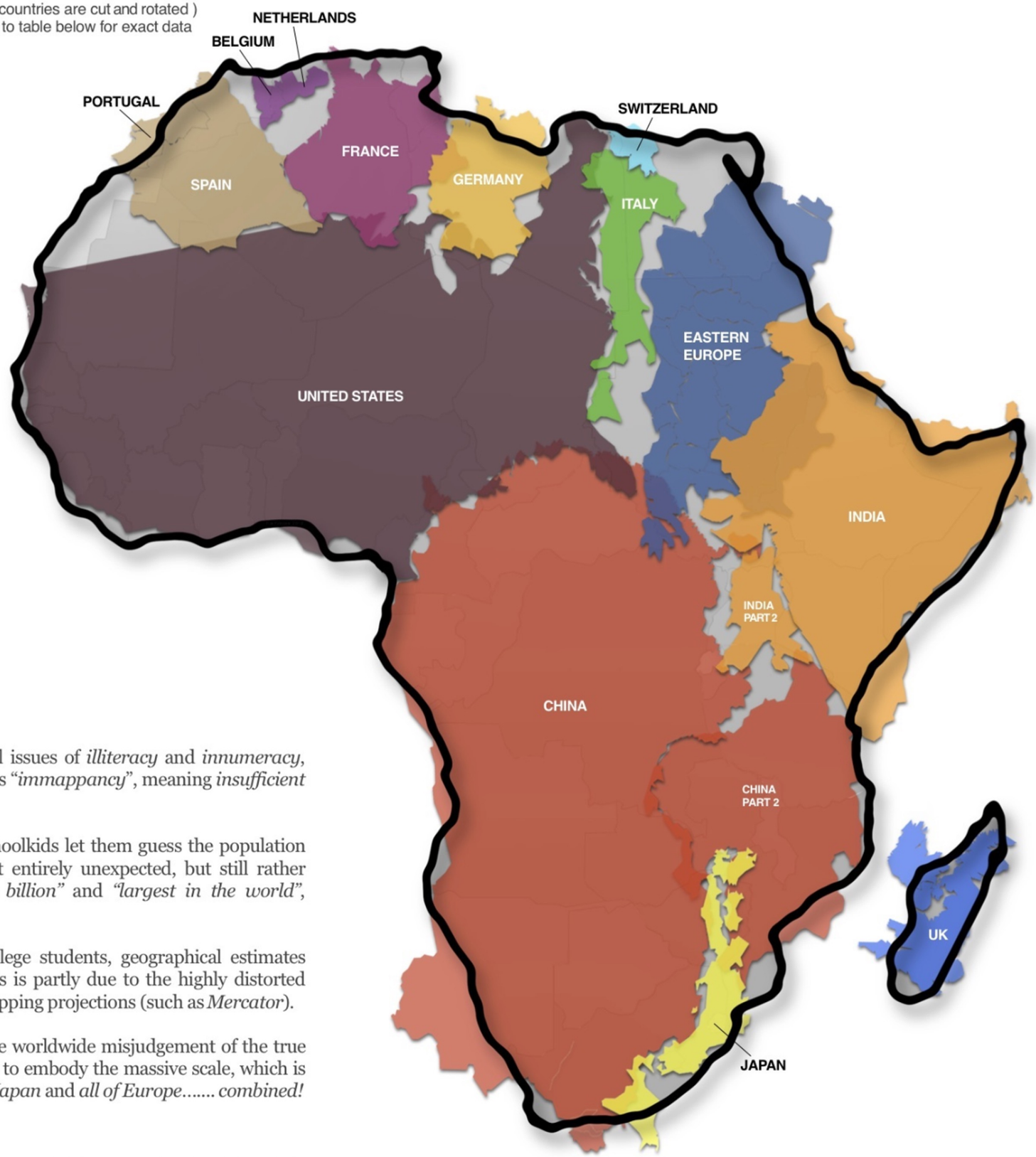
Lions don’t usually roam the streets. Unless it’s for a TV advert.

The **True Size** of **Africa**

A small contribution in the fight against rampant *Immappancy*, by **Kai Krause**

Graphic layout for visualization only (some countries are cut and rotated)
But the conclusions are very accurate: refer to table below for exact data

COUNTRY	AREA x 1000 km²
China	9.597
USA	9.629
India	3.287
Mexico	1.964
Peru	1.285
France	633
Spain	506
Papua New Guinea	462
Sweden	441
Japan	378
Germany	357
Norway	324
Italy	301
New Zealand	270
United Kingdom	243
Nepal	147
Bangladesh	144
Greece	132
TOTAL	**30.102**
AFRICA	**30.221**



In addition to the well known social issues of *illiteracy* and *innumeracy*, there also should be such a concept as "*immappancy*", meaning *insufficient geographical knowledge*.

A survey with random American schoolkids let them guess the population and land area of their country. Not entirely unexpected, but still rather unsettling, the majority chose *"1-2 billion"* and *"largest in the world"*, respectively.

Even with Asian and European college students, geographical estimates were often off by factors of *2-3*. This is partly due to the highly distorted nature of the predominantly used mapping projections (such as *Mercator*).

A particularly extreme example is the worldwide misjudgement of the true size of *Africa*. This single image tries to embody the massive scale, which is larger than the *USA*, *China*, *India*, *Japan* and *all of Europe..... combined!*

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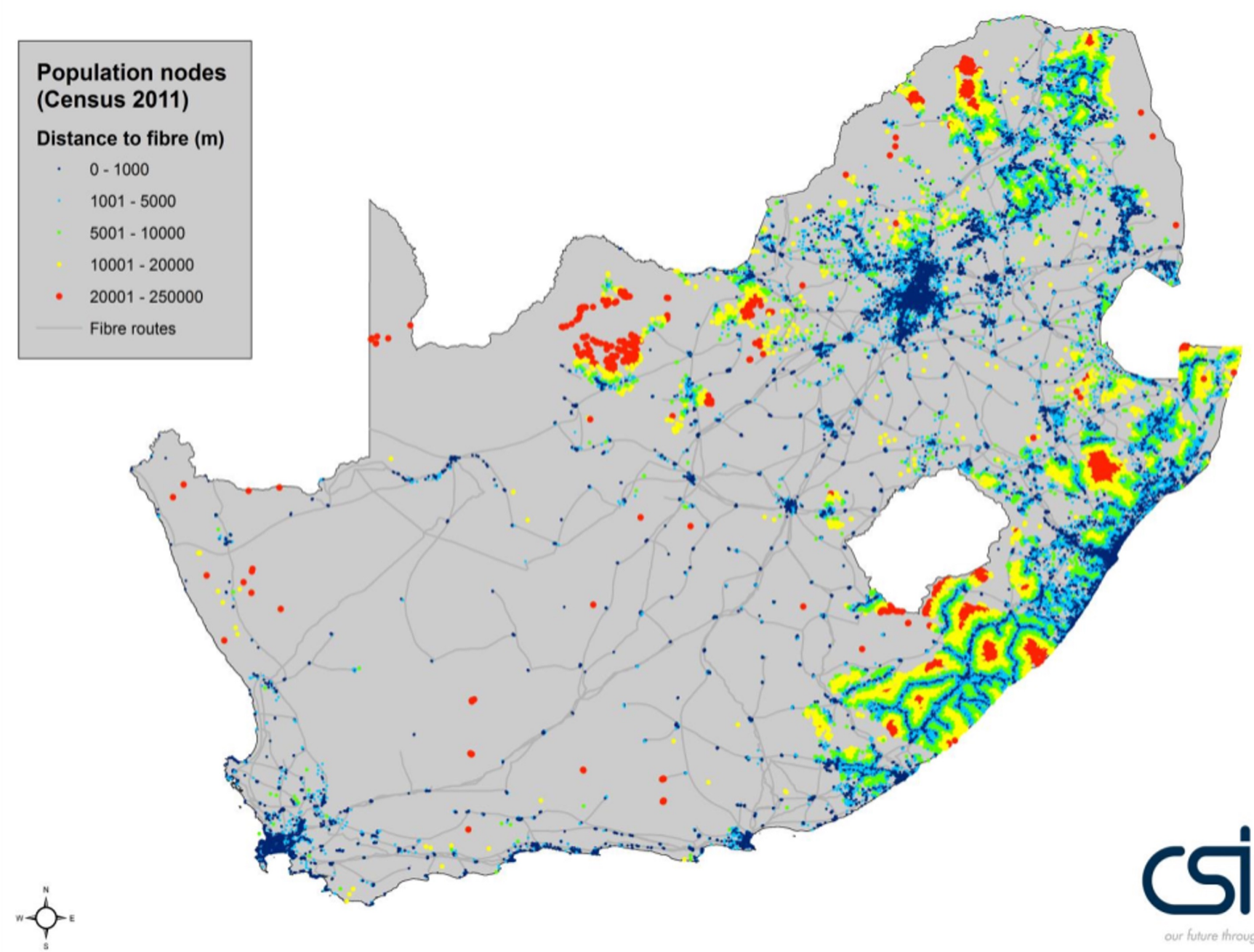
Top 100 Countries

Area in square kilometers, Percentage of World Total
Sources: Britannica, Wikipedia, Almanac 2010

		AREA km²	%
1	Russia	17.098.242	11,50
2	Canada	9.984.670	6,70
3	China	9.596.961	6,40
4	United States	9.629.091	6,40
5	Brazil	8.514.877	5,70
6	Australia	7.692.024	5,20
7	India	3.287.263	2,30
8	Argentina	2.780.400	2,00
9	Kazakhstan	2.724.900	1,80
10	Sudan	2.505.813	1,70
11	Algeria	2.381.741	1,60
12	Congo	2.344.858	1,60
13	Greenland	2.166.086	1,50
14	Saudi Arabia	2.149.690	1,40
15	Mexico	1.964.375	1,30
16	Indonesia	1.860.360	1,30
17	Libya	1.759.540	1,20
18	Iran	1.628.750	1,10
19	Mongolia	1.564.100	1,10
20	Peru	1.285.216	0,86
21	Chad	1.284.000	0,86
22	Niger	1.267.000	0,85
23	Angola	1.246.700	0,85
24	Mali	1.240.192	0,83
25	South Africa	1.221.037	0,82
26	Colombia	1.141.748	0,76
27	Ethiopia	1.104.300	0,74
28	Bolivia	1.098.581	0,74
29	Mauritania	1.025.520	0,69
30	Egypt	1.002.000	0,67
31	Tanzania	945.087	0,63
32	Nigeria	923.768	0,62
33	Venezuela	912.050	0,61
34	Namibia	824.116	0,55
35	Mozambique	801.590	0,54
36	Pakistan	796.095	0,53
37	Turkey	783.562	0,53
38	Chile	756.102	0,51
39	Zambia	752.612	0,51
40	Myanmar	676.578	0,45
41	Afghanistan	652.090	0,44
42	Somalia	637.657	0,43
43	France	632.834	0,43
44	C. African Rep	622.984	0,42
45	Ukraine	603.500	0,41
46	Madagascar	587.041	0,39
47	Botswana	582.000	0,39
48	Kenya	580.367	0,39
49	Yemen	527.968	0,35
50	Thailand	513.120	0,34
51	Spain	505.992	0,34
52	Turkmenistan	488.100	0,33
53	Cameroon	475.442	0,32
54	Papua New Guinea	462.840	0,31
55	Uzbekistan	447.400	0,30
56	Morocco	446.550	0,30
57	Sweden	441.370	0,30
58	Iraq	438.317	0,29
59	Paraguay	406.752	0,27
60	Zimbabwe	390.757	0,26
61	Japan	377.930	0,25
62	Germany	357.114	0,24
63	Rep o.t. Congo	342.000	0,23
64	Finland	338.419	0,23
65	Vietnam	331.212	0,22
66	Malaysia	330.803	0,22
67	Norway	323.802	0,22
68	Côte d'Ivoire	322.463	0,22
69	Poland	312.685	0,21
70	Oman	309.500	0,21
71	Italy	301.336	0,20
72	Philippines	300.000	0,20
73	Burkina Faso	274.222	0,18
74	New Zealand	270.467	0,18
75	Gabon	267.668	0,18
76	Western Sahara	266.000	0,18
77	Ecuador	256.369	0,20
78	Guinea	245.857	0,17
79	United Kingdom	242.900	0,16
80	Uganda	241.038	0,16
81	Ghana	238.539	0,16
82	Romania	238.391	0,16
83	Laos	236.800	0,16
84	Guyana	214.969	0,14
85	Belarus	207.600	0,14
86	Kyrgyzstan	199.951	0,13
87	Senegal	196.722	0,13
88	Syria	185.180	0,12
89	Cambodia	181.035	0,12
90	Uruguay	176.215	0,12
91	Suriname	163.820	0,11
92	Tunisia	163.610	0,11
93	Nepal	147.181	0,10
94	Bangladesh	143.998	0,10
95	Tajikistan	143.100	0,10
96	Greece	131.957	0,09
97	Nicaragua	130.373	0,09
98	North Korea	120.538	0,08
99	Malawi	118.484	0,08
100	Eritrea	117.600	0,08
	TOP 100 TOTAL	132.632.524	89,34

How about South Africa?

We have a predominantly “last few miles” challenge: 89% of us live within 5 km of fibre.



Distance to fibre:

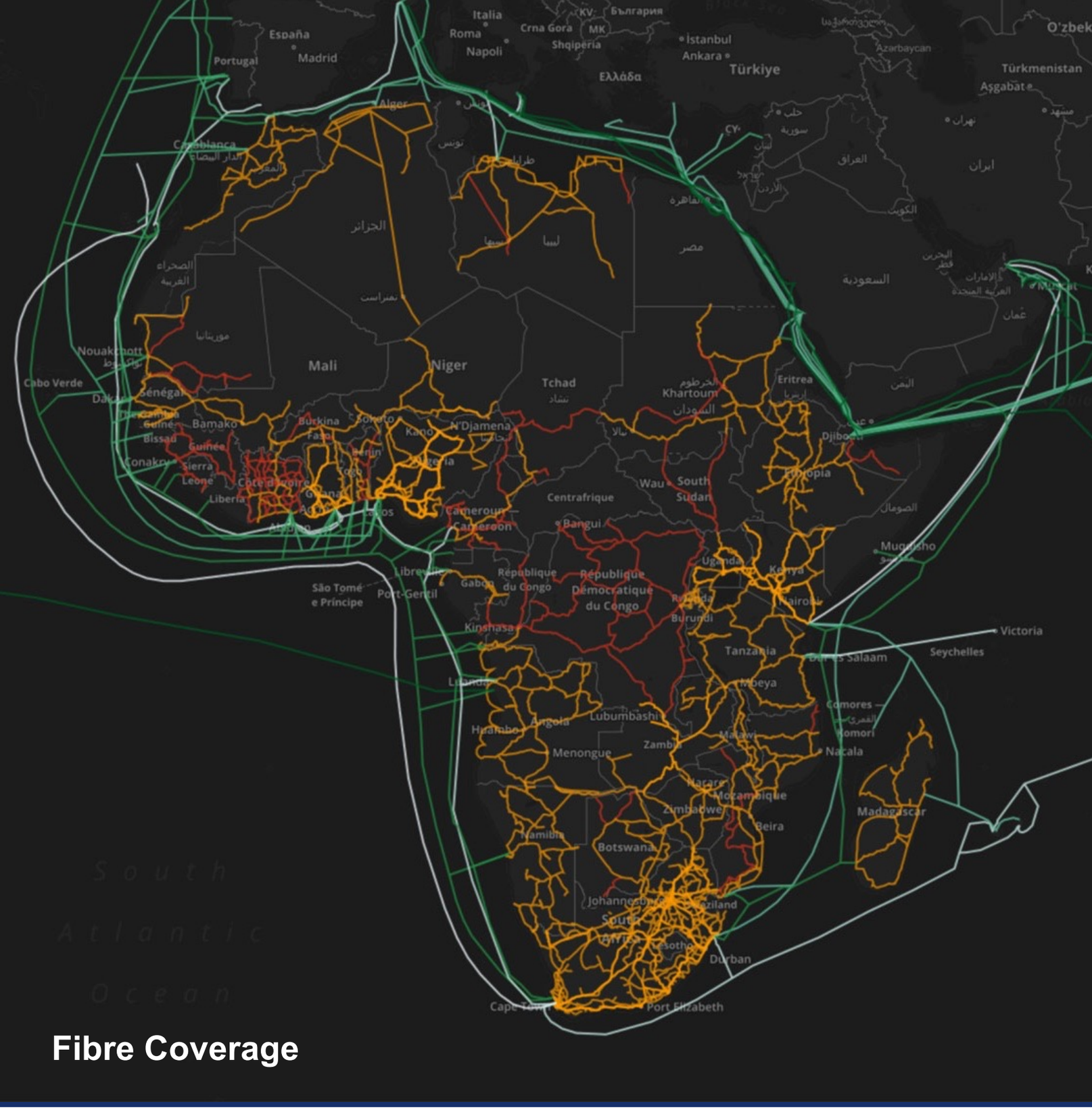
< 1 km: 67%
< 5 km: 89%
< 10 km: 95%
< 20 km: 99%

Thanks: Kobus Roux, CSIR

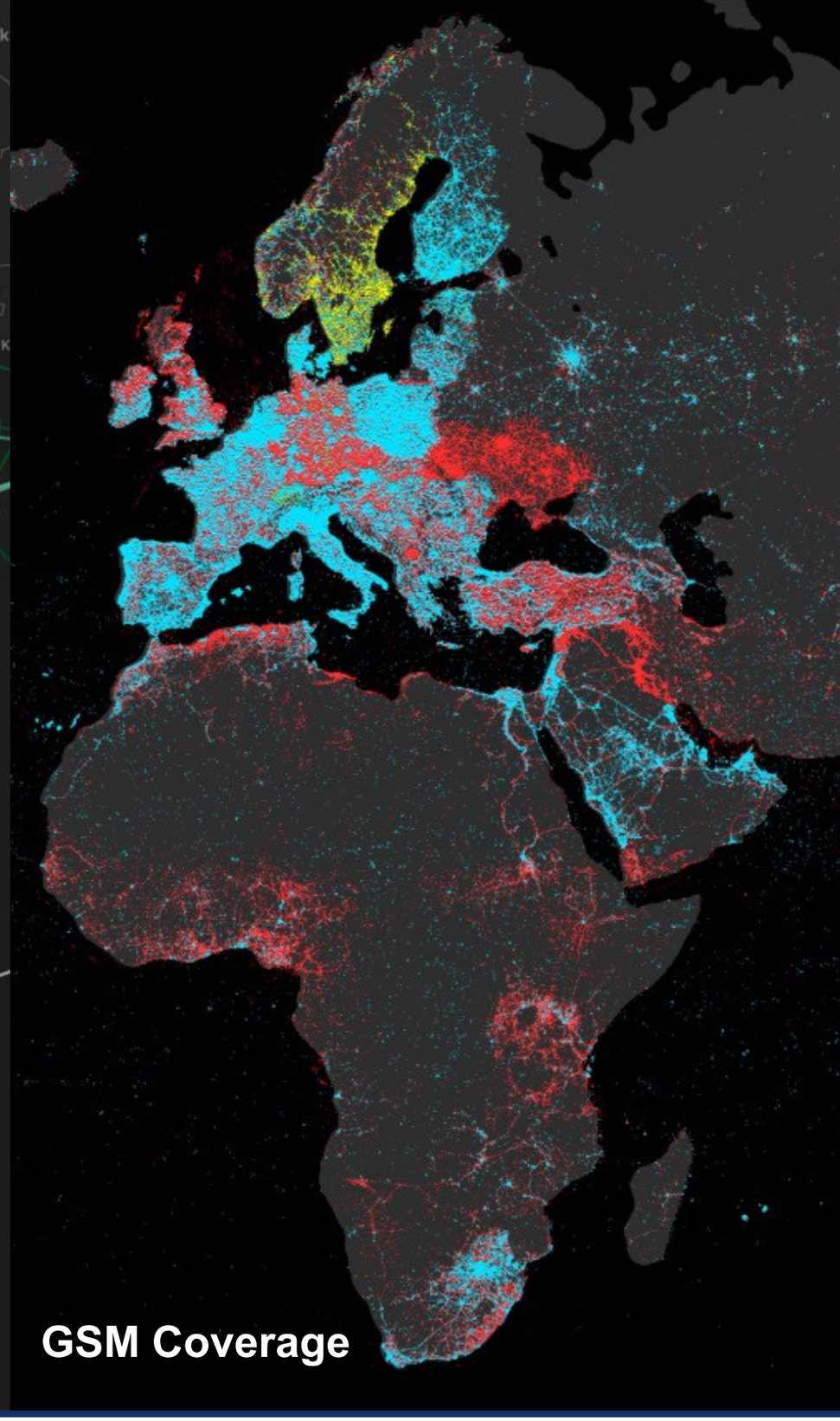
Aren’t mobile technologies sufficient?

Unfortunately, there’s a catch…

	2016	2017	2018	2021
2G Coverage	99.9%	99.9%	99.9%	99.9%
3G Coverage	99%	99.3%	99.5%	99.9%
LTE/4G Coverage	75%	76.7%	85.7%	97.7%
5G Coverage				7.5%
Smartphone Penetration	43.5%	74.2%	60%	
Gender Disparity				0.76



Fibre Coverage



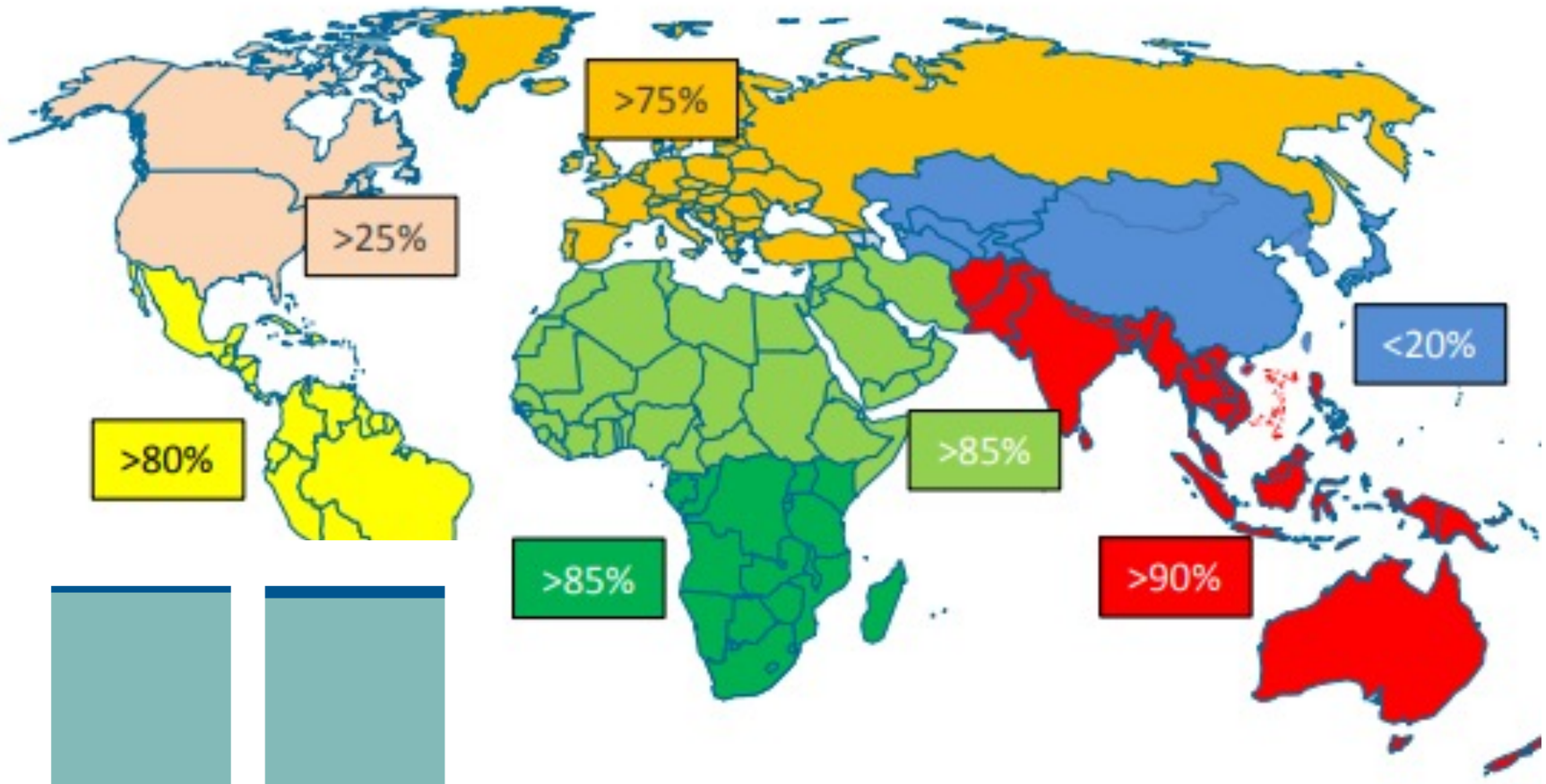
GSM Coverage

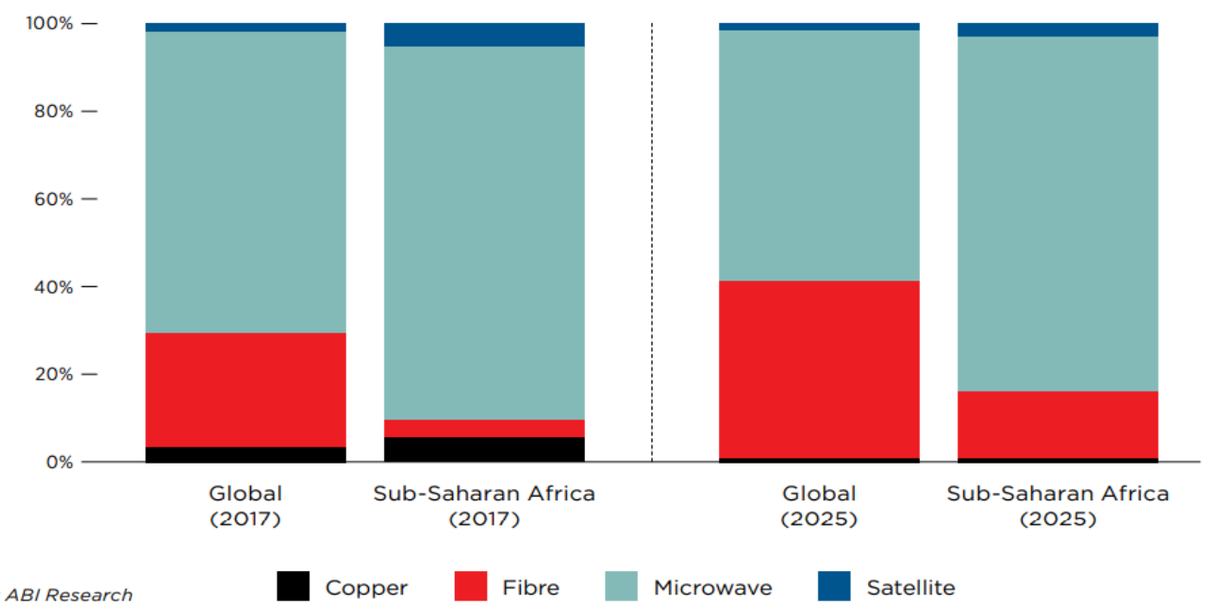
Just because your phone says 4G…

It doesn't mean it's fast or reliable…

Radio is ubiquitous in mobile networks

There are **four million wireless links** for mobile backhaul worldwide, mostly in the developing world.





Source: ABI Research

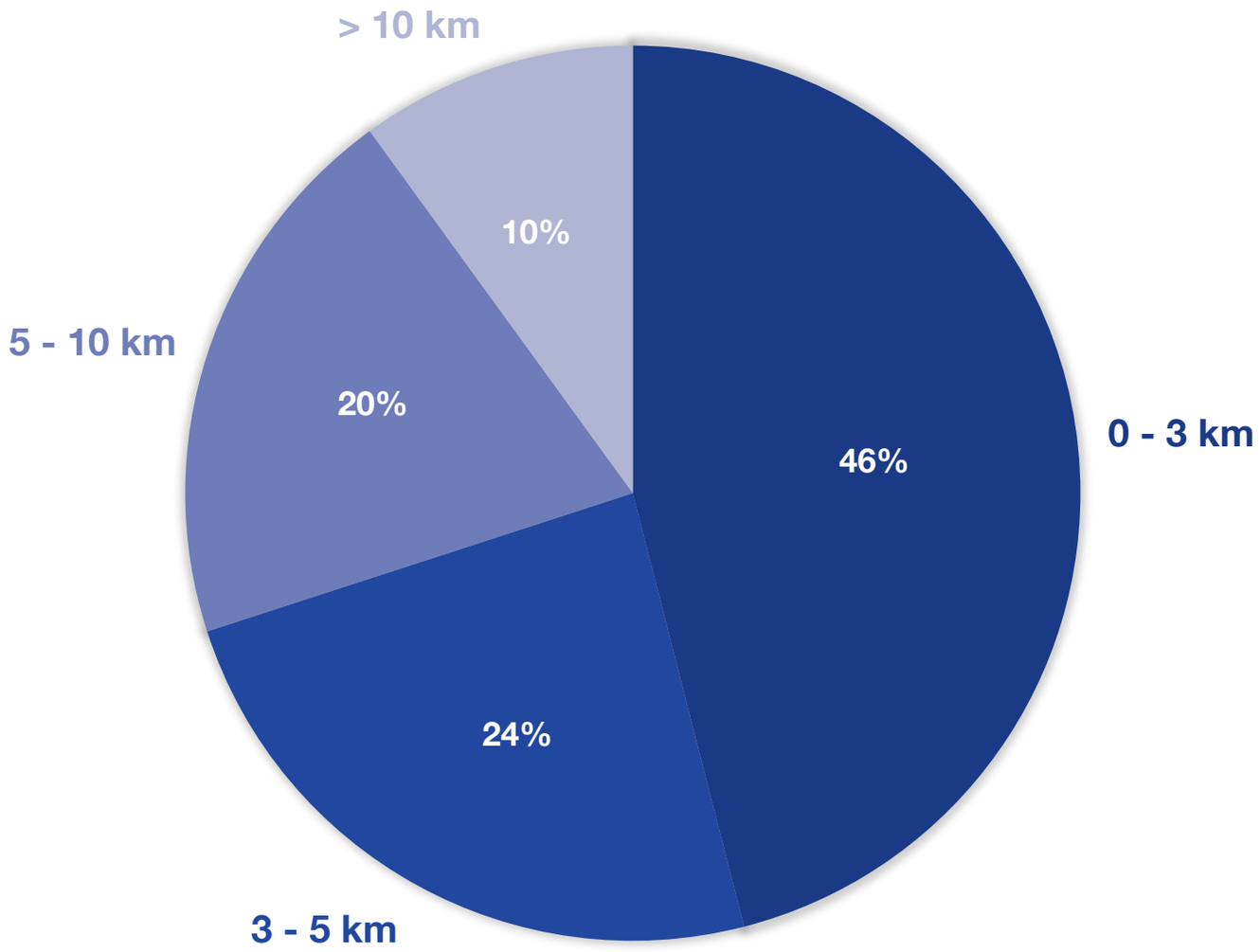
Sources

"Evolution of fixed services for wireless backhaul of IMT 2020 / 5G", ITU-R Workshop, Geneva, 2019

"Closing the coverage gap", GSMA, 2019

Most wireless links are less than 5 km long

With most being up to 3 km.

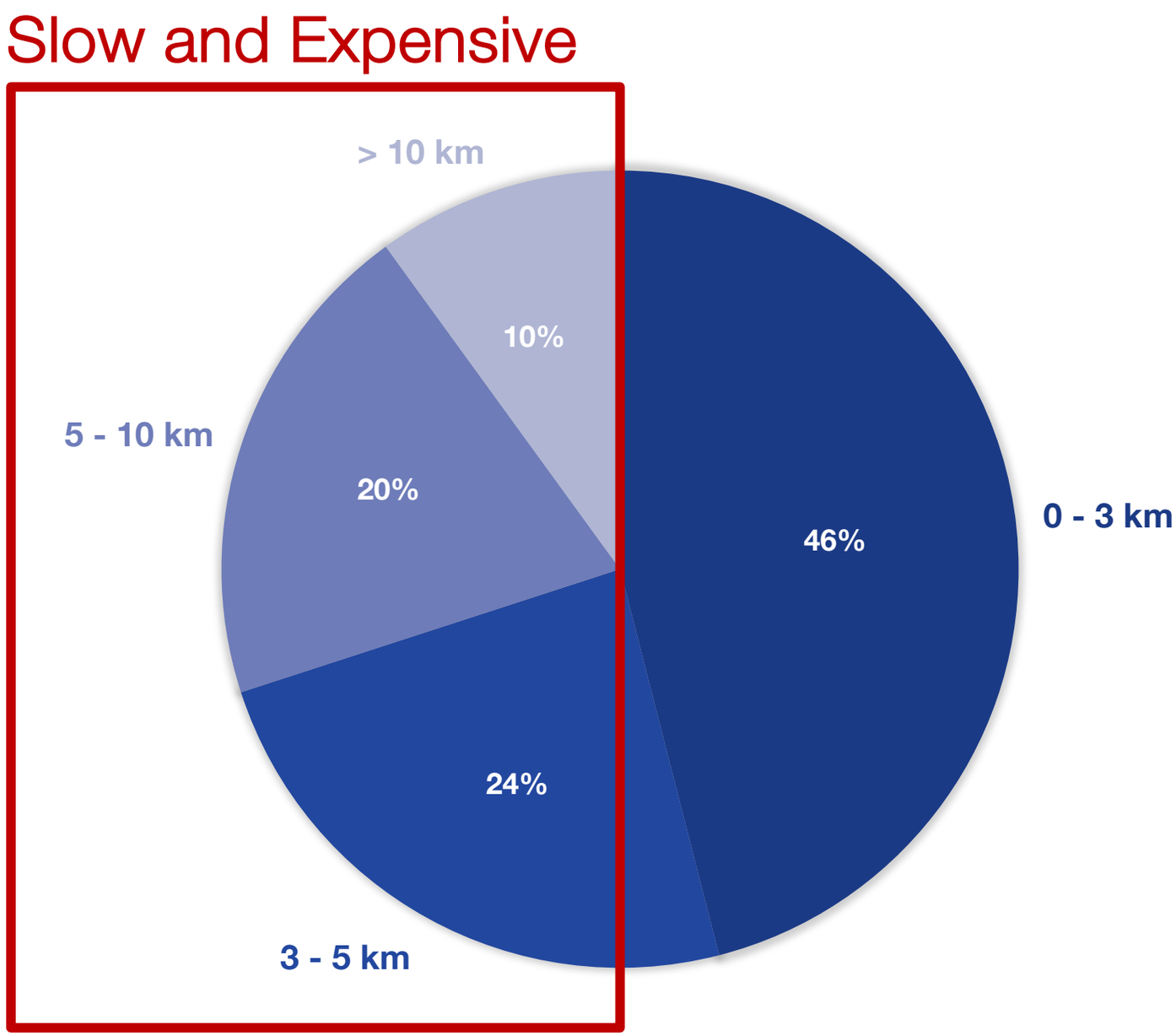


Source

"Evolution of fixed services for wireless backhaul of IMT 2020 / 5G", ITU-R Workshop, Geneva, 2019

Unfortunately, radio isn't very fast over about 3 km

There are also **high annual license fees** for microwave links (non-ISM).



Source

"Evolution of fixed services for wireless backhaul of IMT 2020 / 5G", ITU-R Workshop, Geneva, 2019

Zooming back into the big city (Johannesburg)…

The “peri-urban” digital divide is also a real challenge.

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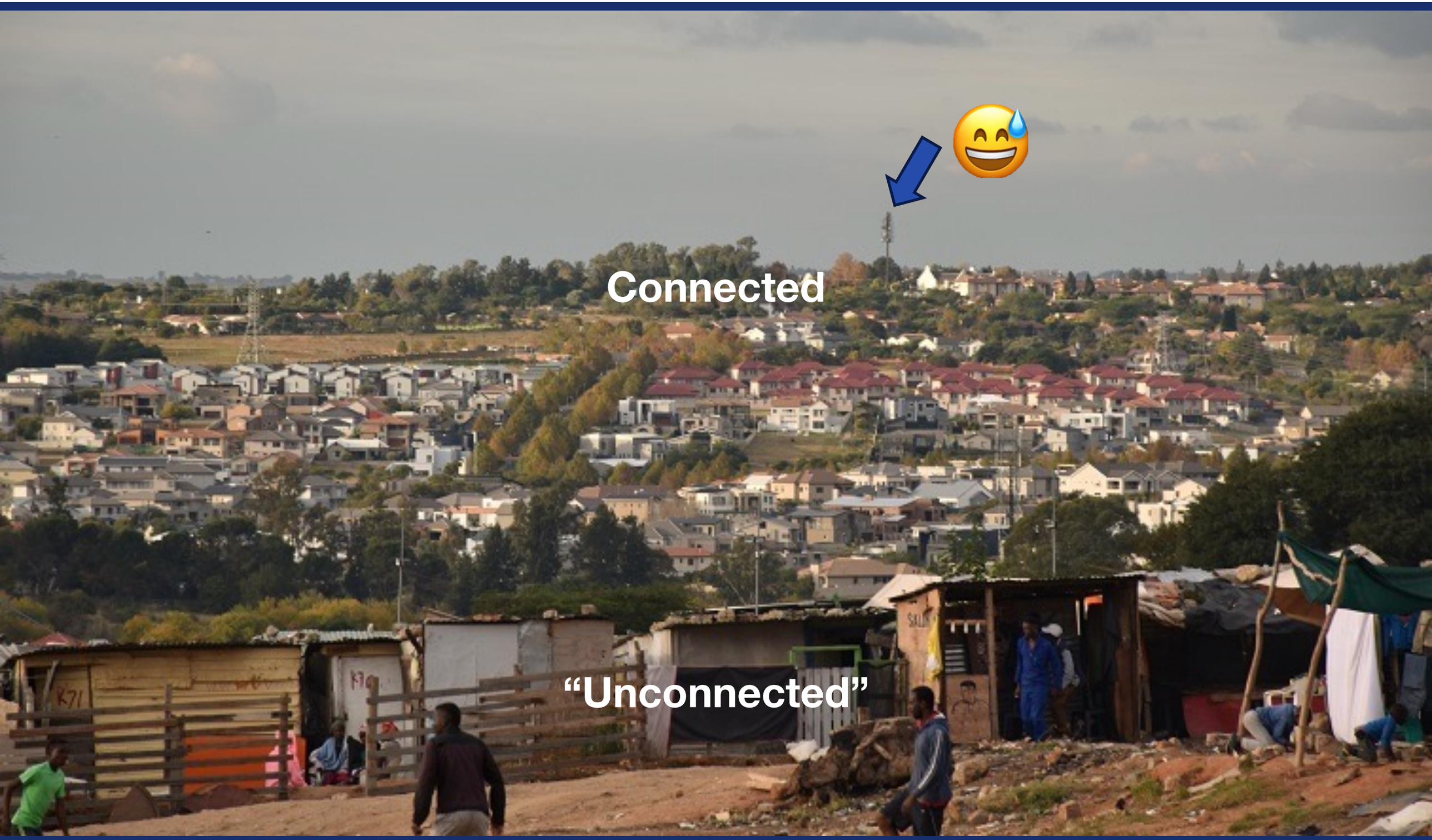
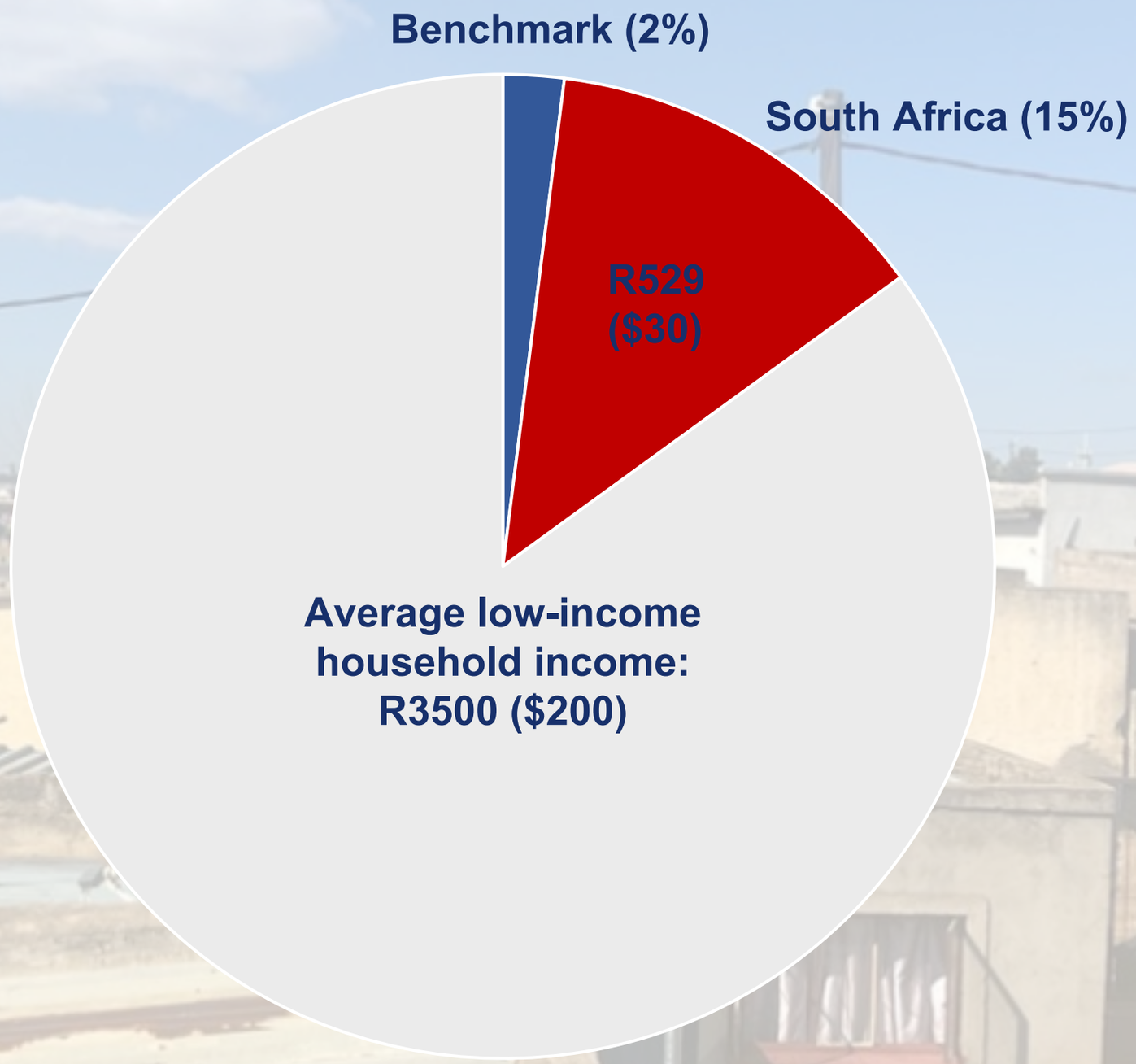
The “peri-urban” digital divide is also a real challenge.



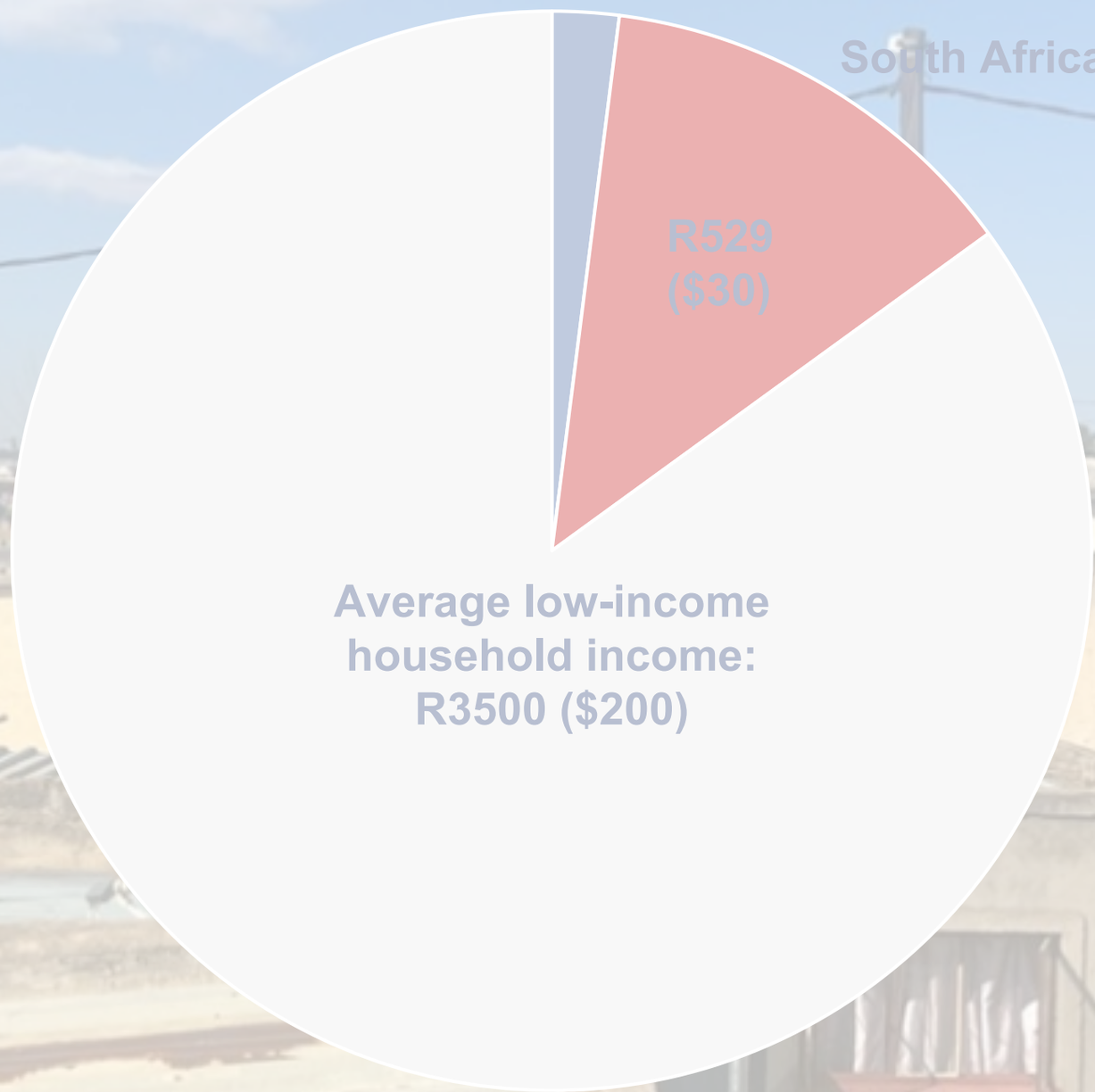
When internet's available, can people actually afford it?

In South Africa, a 15 GB bundle costs R529pm… uncapped is a little more.



Do people have smart phones? 60% of South African's do!

Roughly half of those who don't **either can't afford it**, and half **don't know how to use it**, or make the most out of it.



Why no smart phone in 2020?

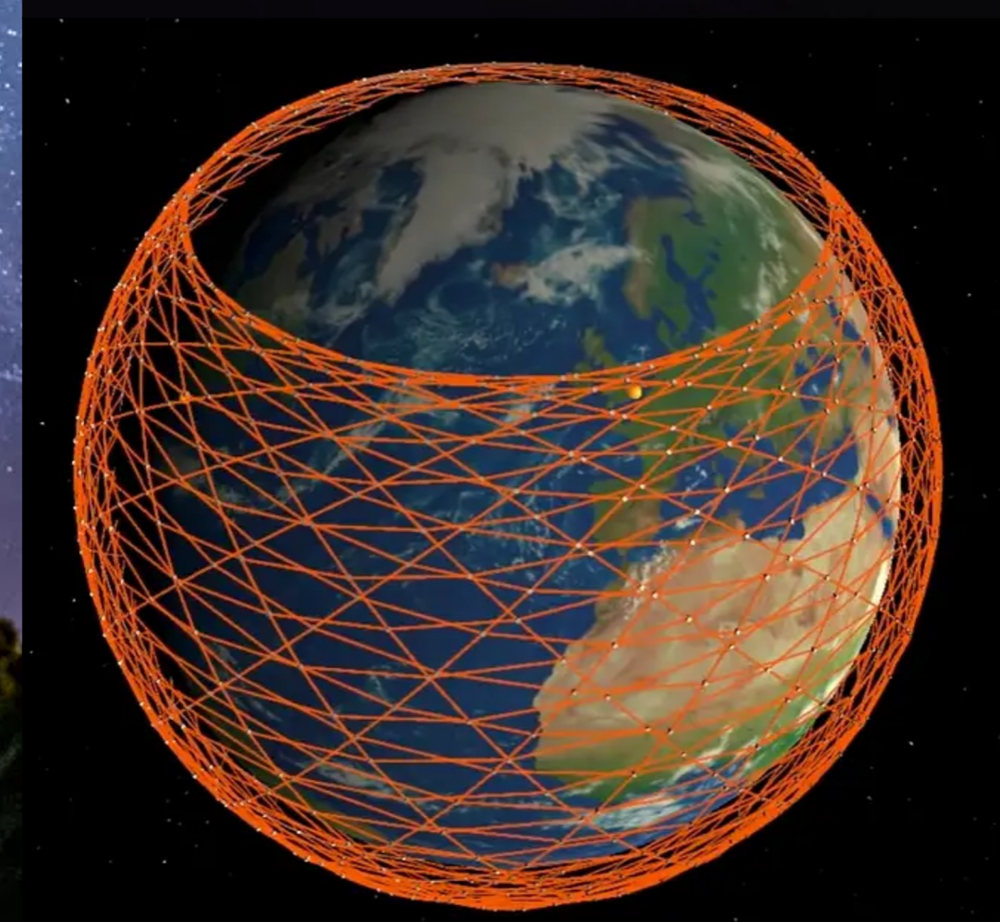
40% **too expensive ($30)**

30% **"no necessity"**

15% **"too complicated"**

Satellite internet might be an option, one day…

Starlink provides >50 Mbps for about $100 per month. That's 25x more than the benchmark!

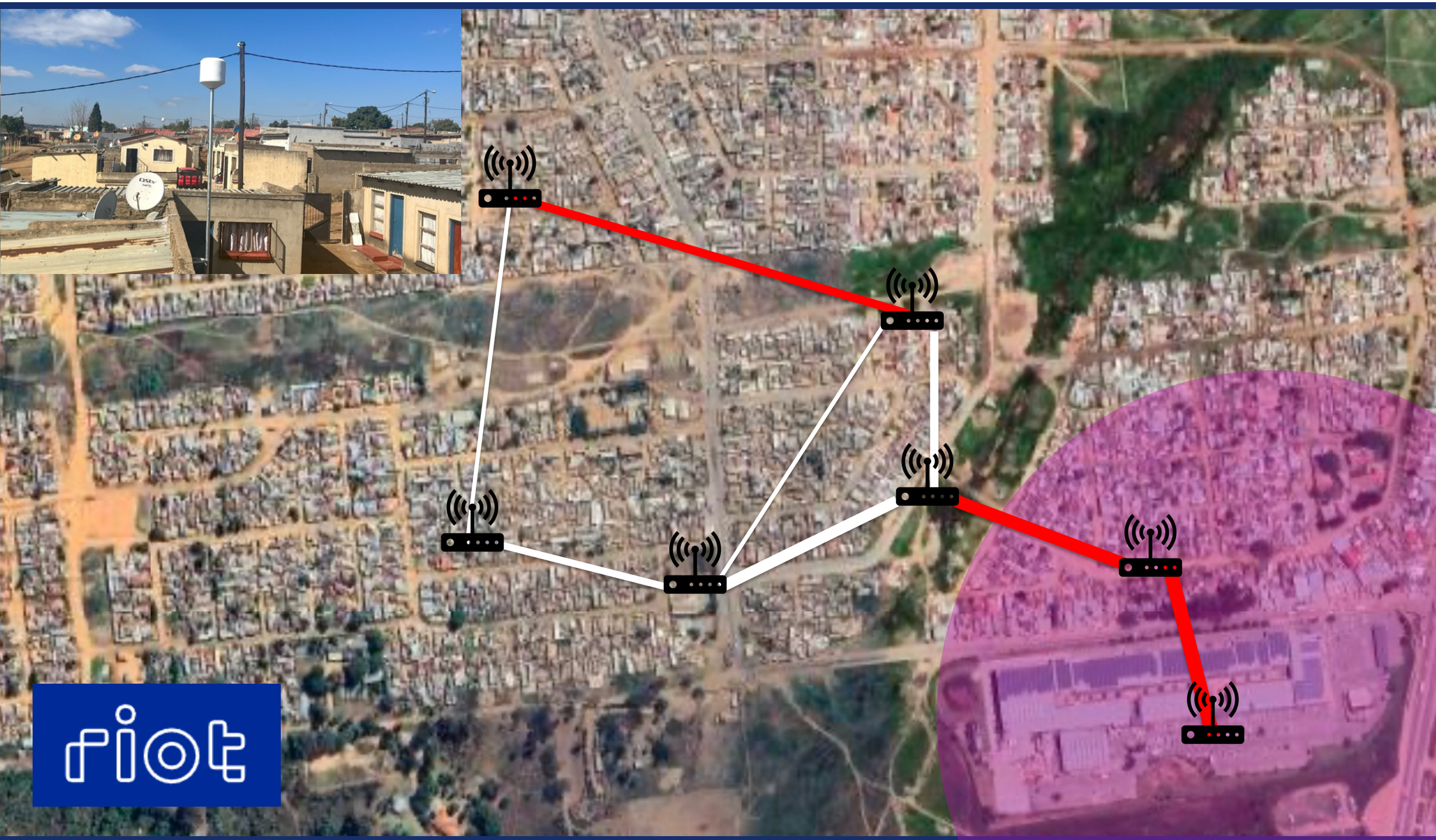


The best solution I know of…

“Community” WiFi mesh networks allow resource sharing (lower cost to the end-user), making “decent” internet affordable.

What about these links?

WiFi is **congested** and **slow over distance**, but are they **ways to improve** the situation?



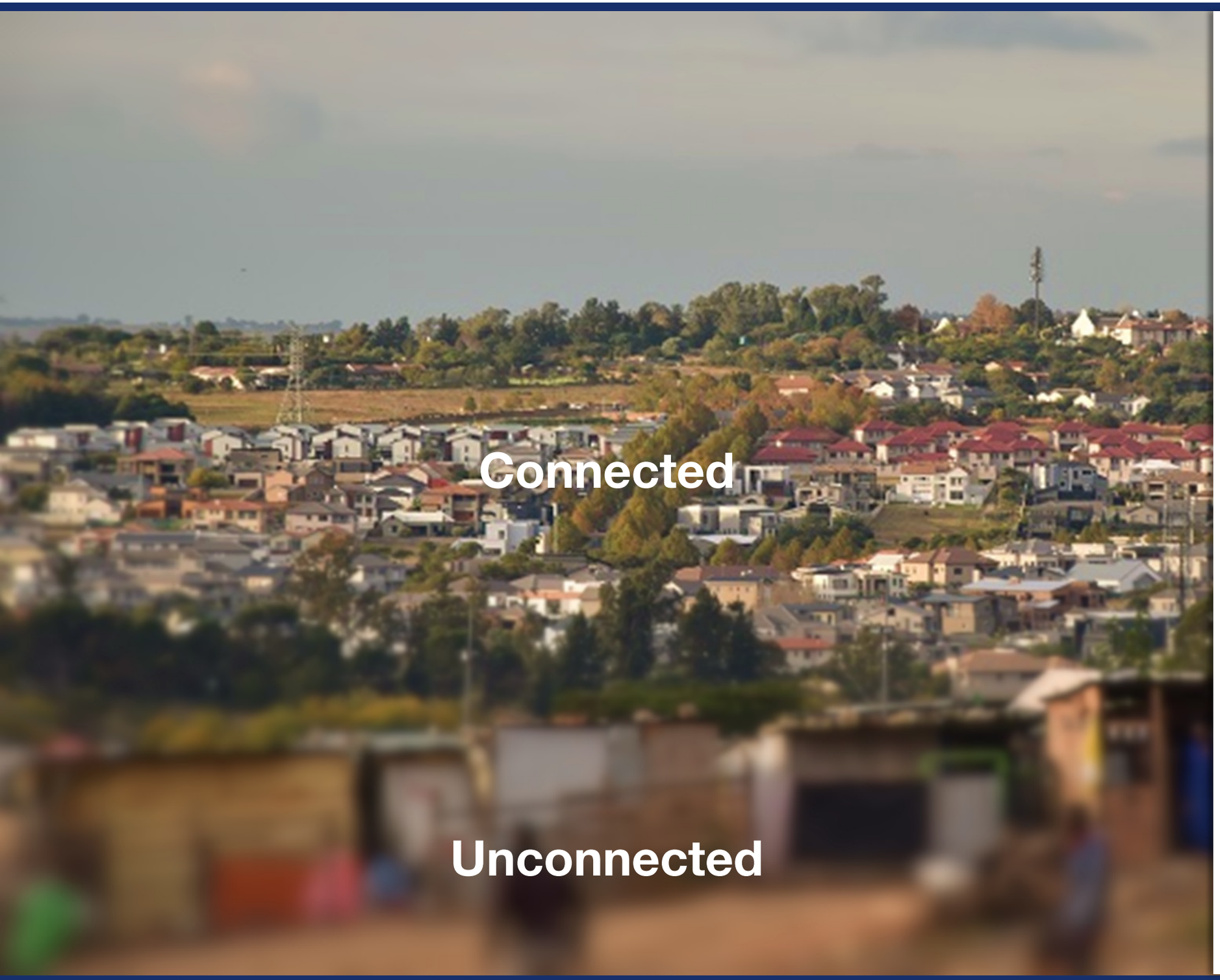
High speed | Long range | Cost effective

Wireless (or free-space) Optical Communications

Free-space optical communications are **faster than radio** and **cheaper than fibre**.

Beaming spare internet across the digital divide

Short range links may allow us to provide internet to schools and community centers in informal settlements – fed by existing FTTH from “across the valley”. **“Fibre”, before the fibre?**



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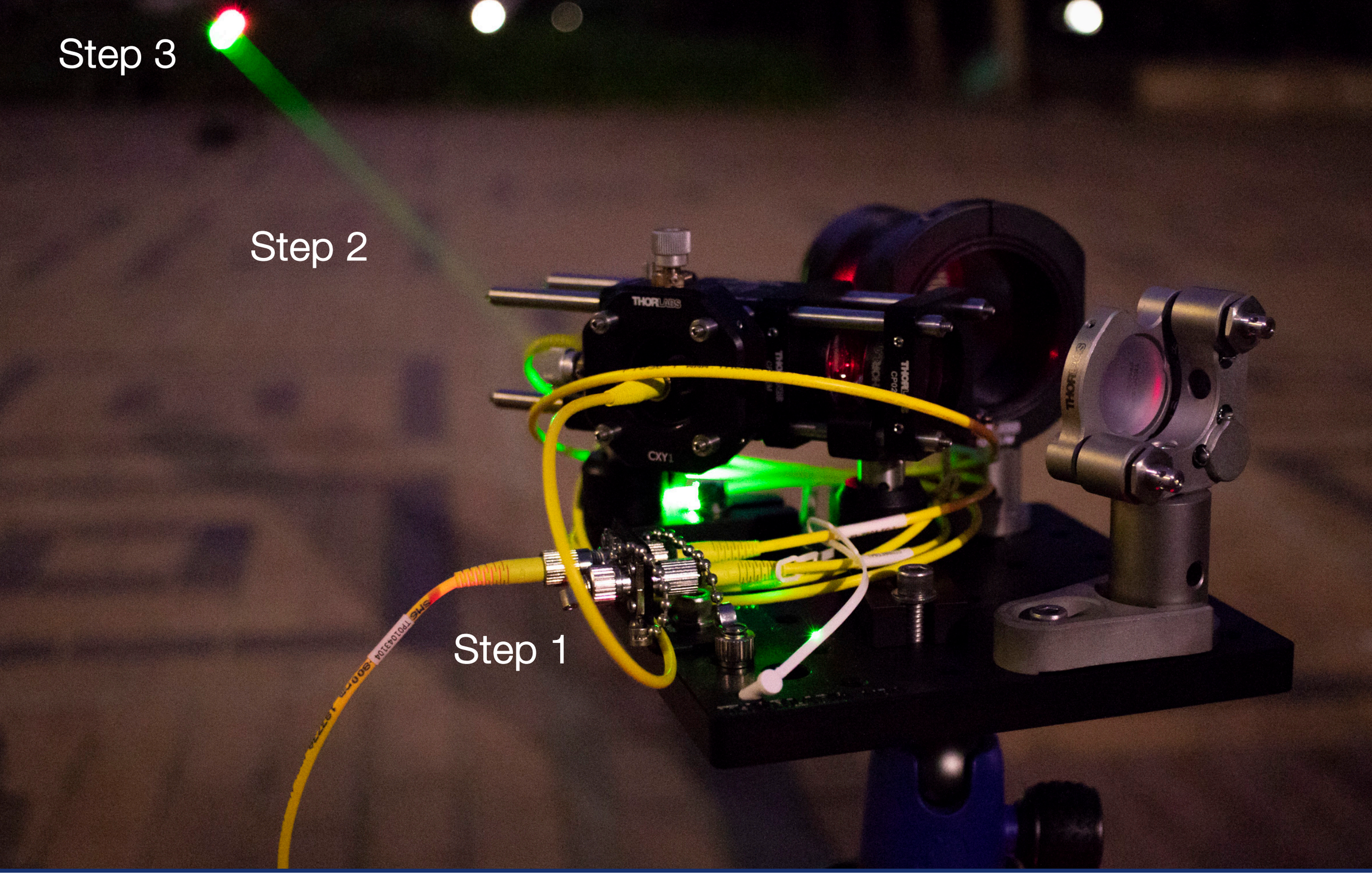
Royal Academy of Engineering



How does “fibre without the fibre” work?

1. Cut the fibre. **2.** Shine the light through the air. **3.** Get the light back into the fibre on the other side!

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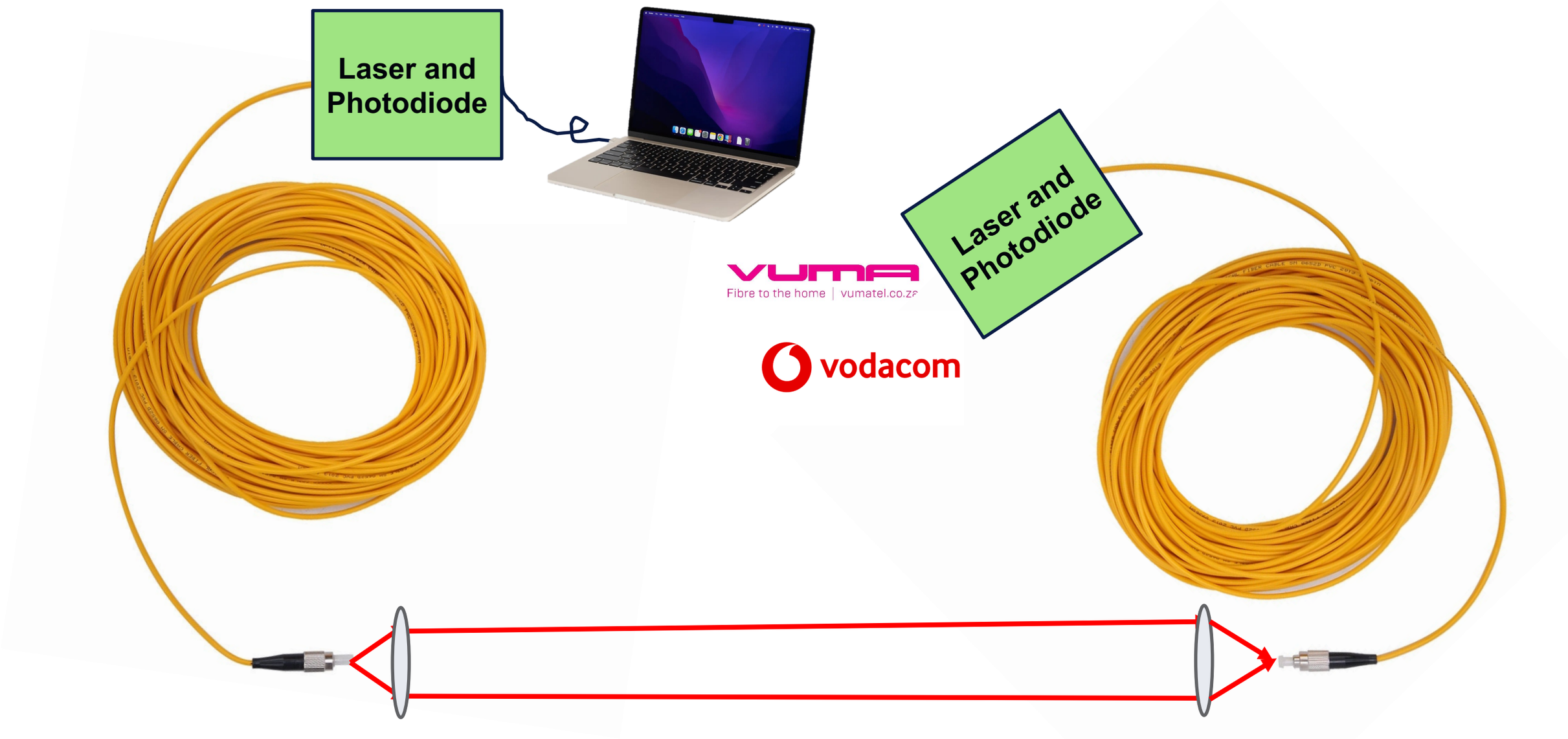
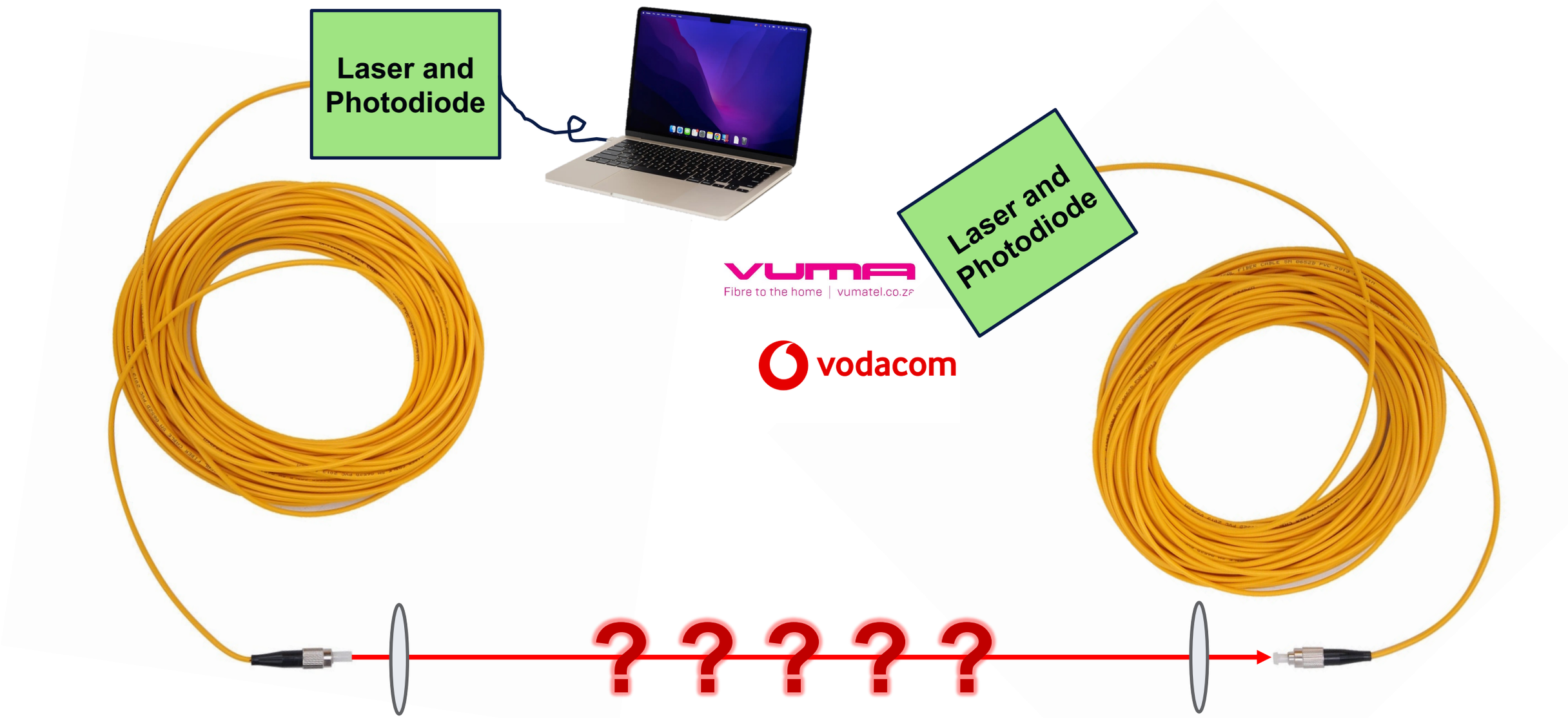
Let’s get technical!

Free-space optical communications is simple.



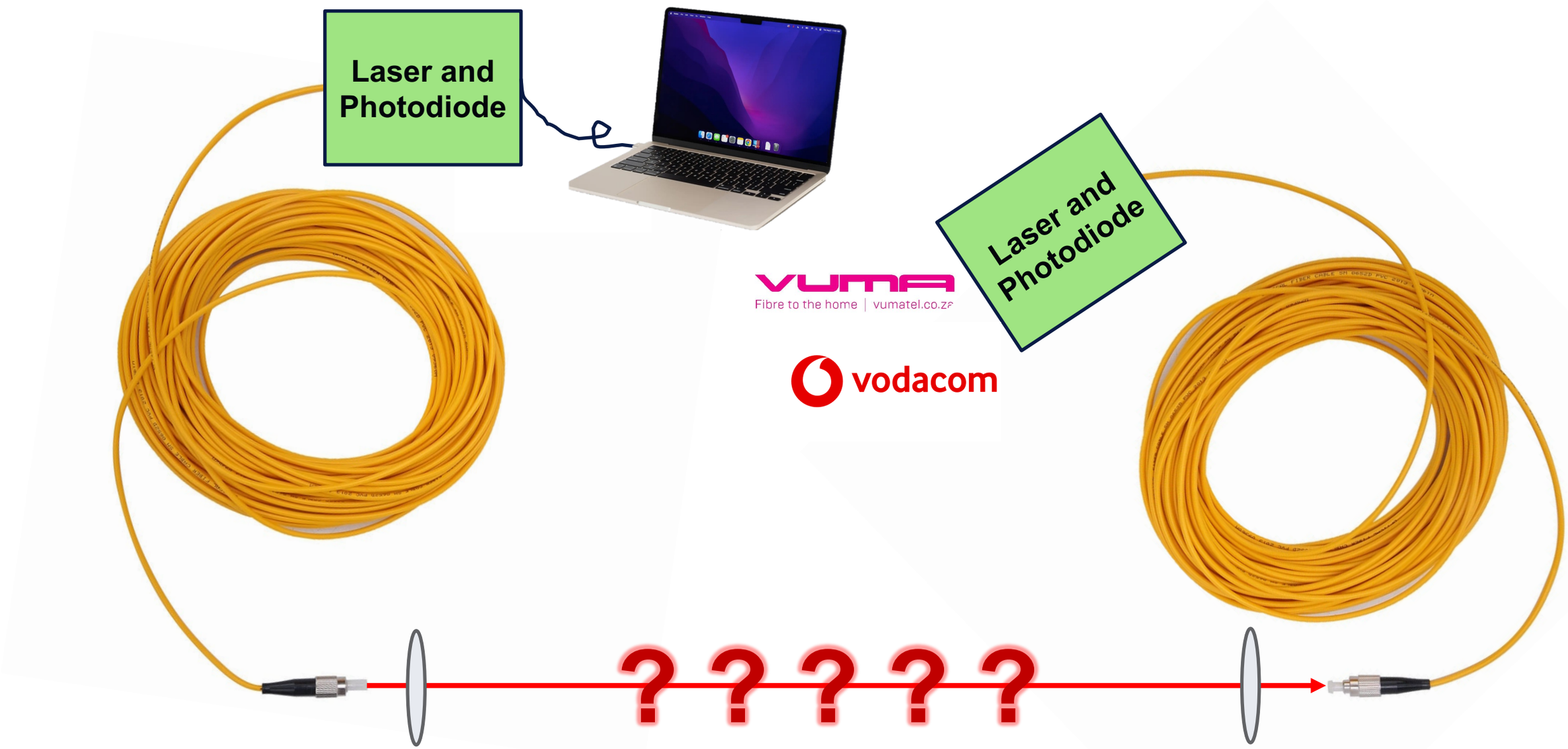
Let’s get technical!

Free-space optical communications is simple **(in principle).**



Attenuation is the obvious channel impairment

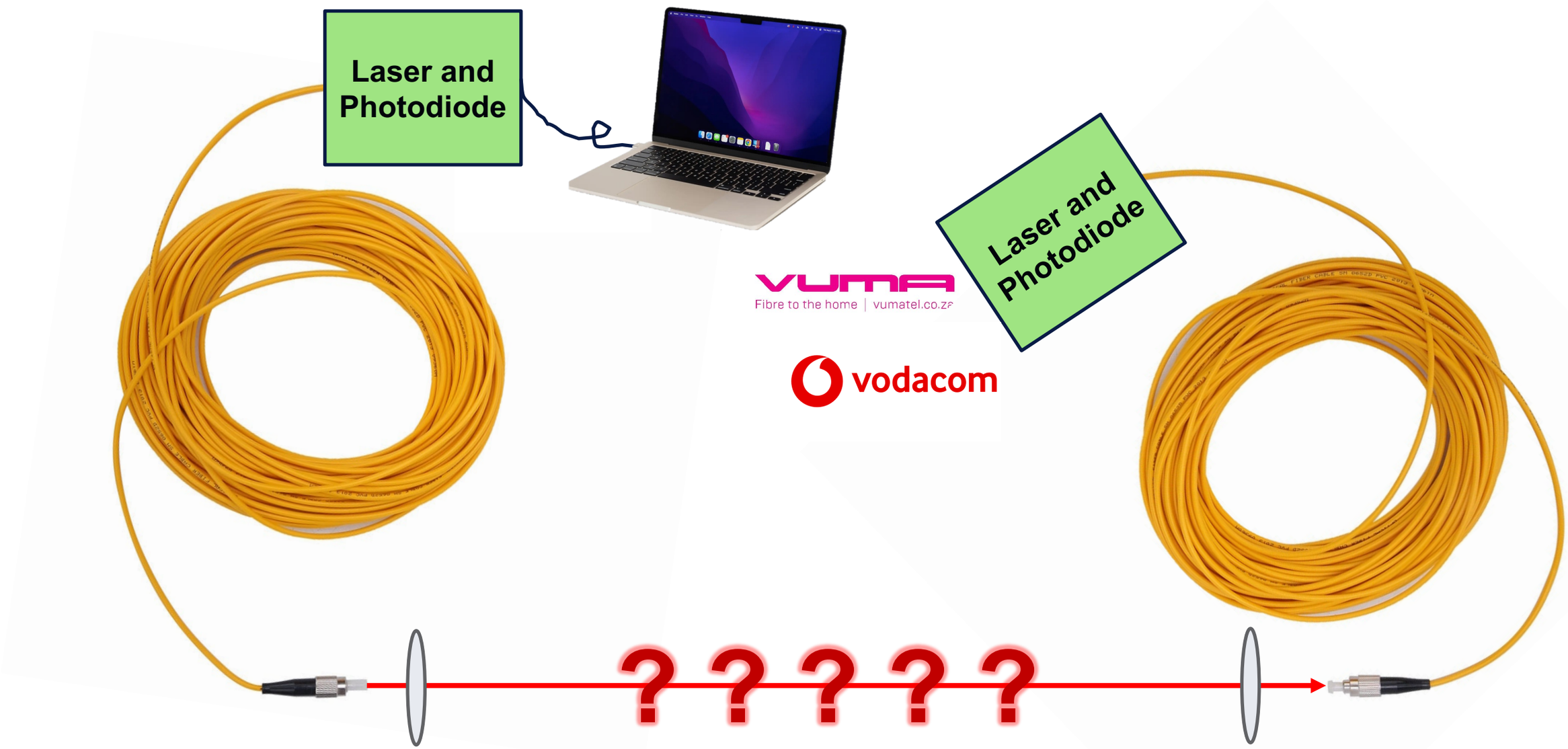
It can be engineered away with higher power transmitters, larger apertures, choice of wavelength, etc.



Attenuation (absorption, scattering, divergence)

Pointing error is a little more challenging

A simple solution is a larger beam at the receiver (attenuation issues again…), or an active system.

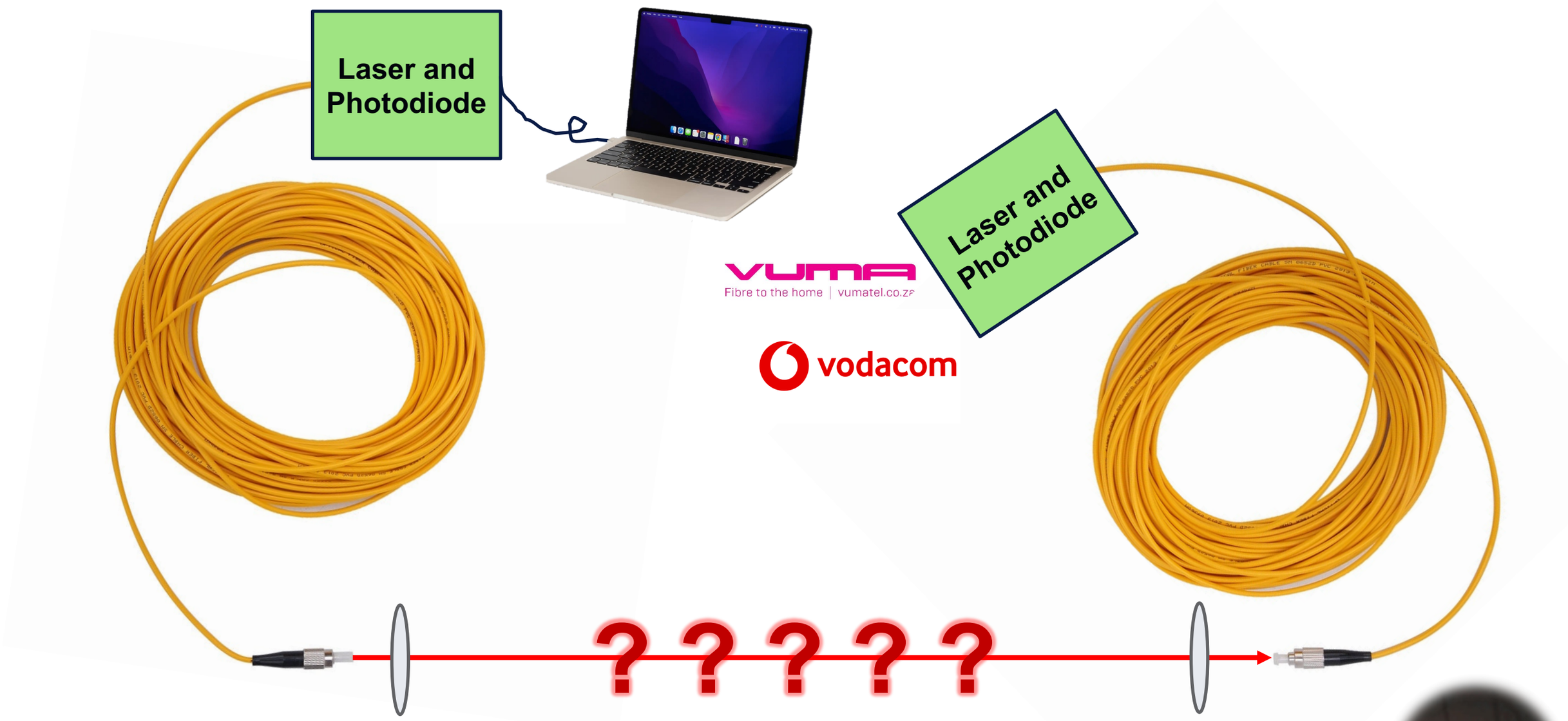


Attenuation (absorption, scattering, divergence)

Pointing Error (building sway, vibrations, etc.)

Atmospheric turbulence is a major issue for longer range

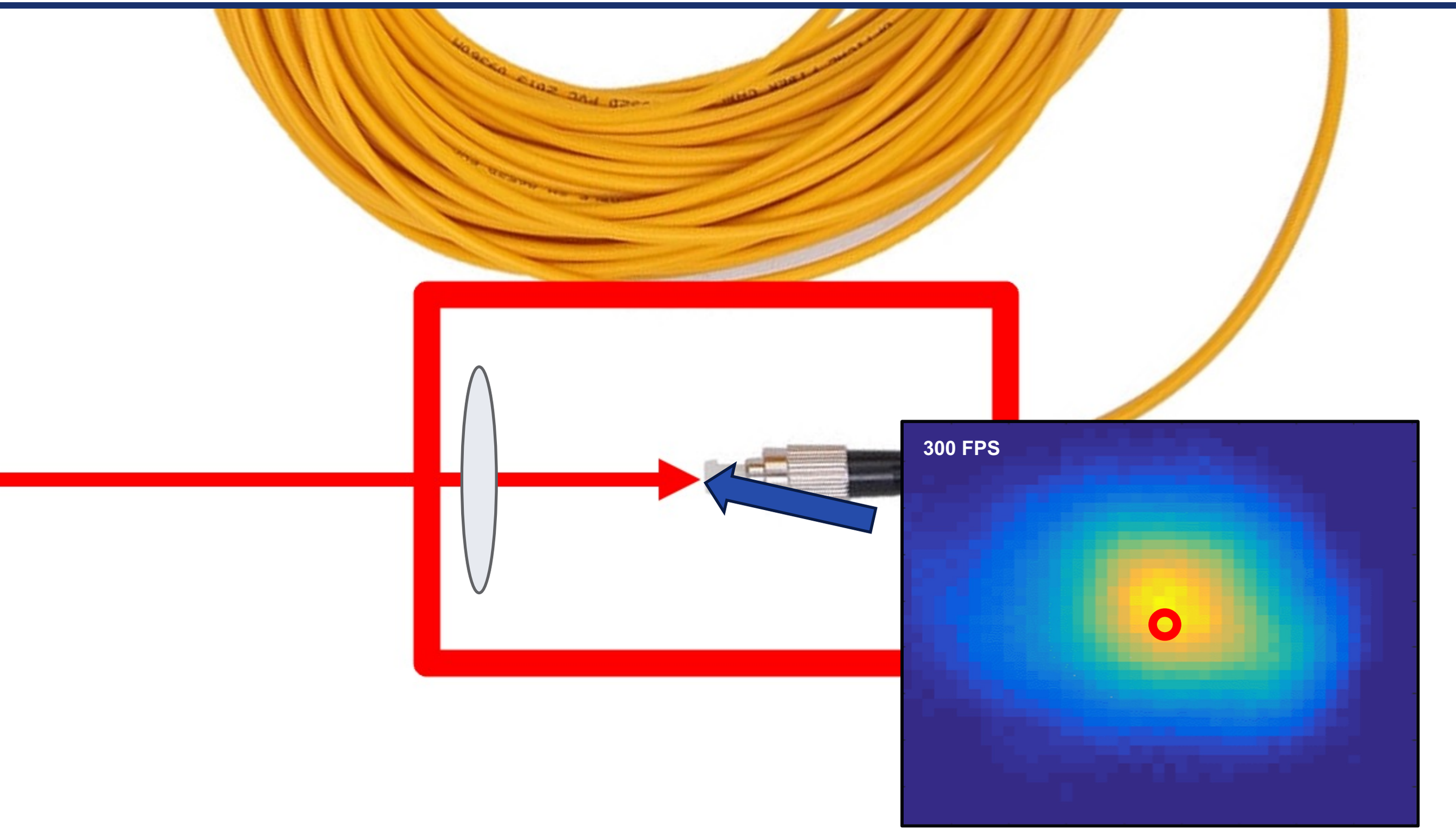
It cases **extra divergence** (power issues), **scintillation** (fading) and **beam wander** (deep fades).



Attenuation (absorption, scattering, divergence)
Pointing Error (building sway, vibrations, etc.)
Atmospheric Turbulence

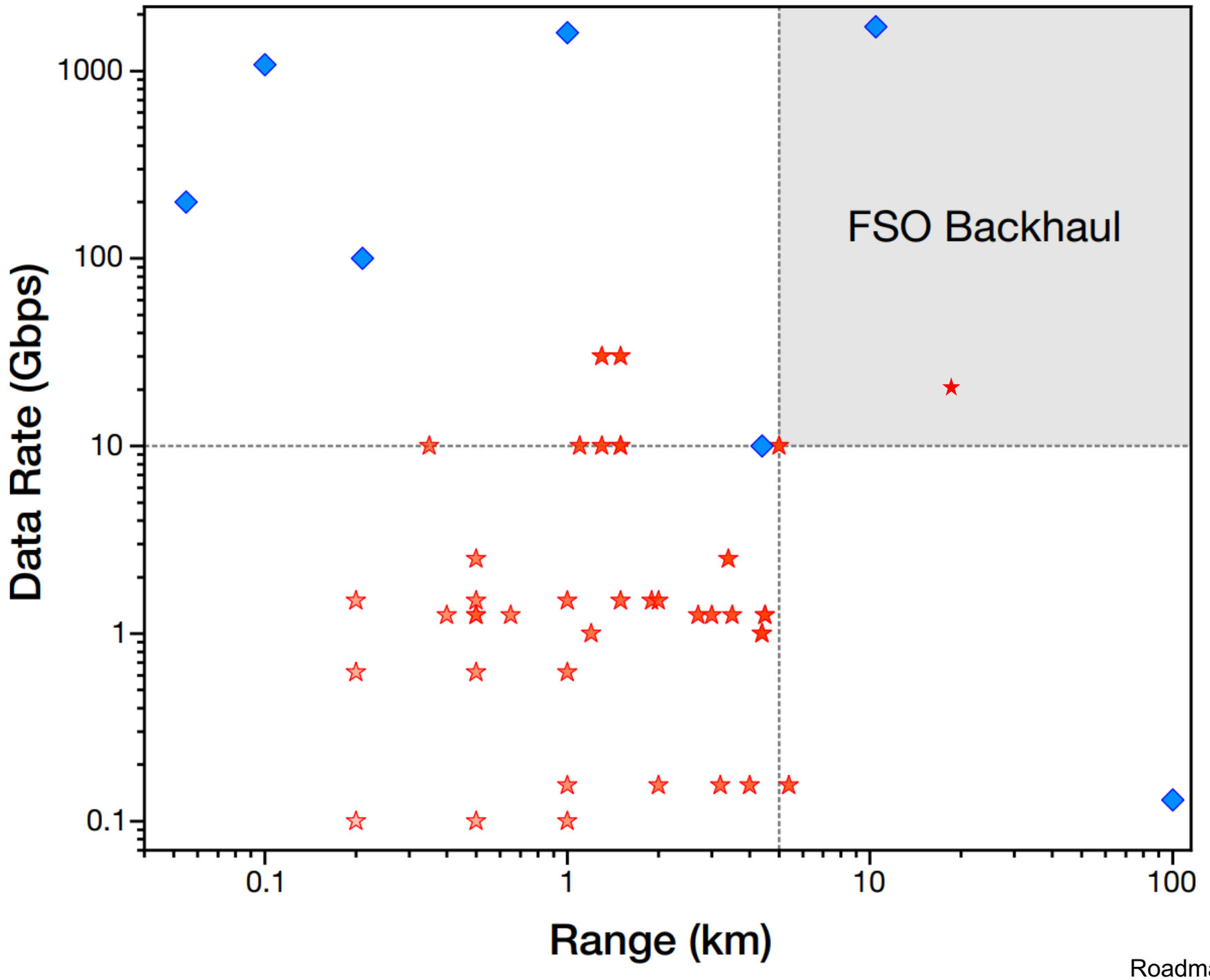
The real world isn’t a stable place!

In many ways, unfortunately…



Commercial FSO systems exist

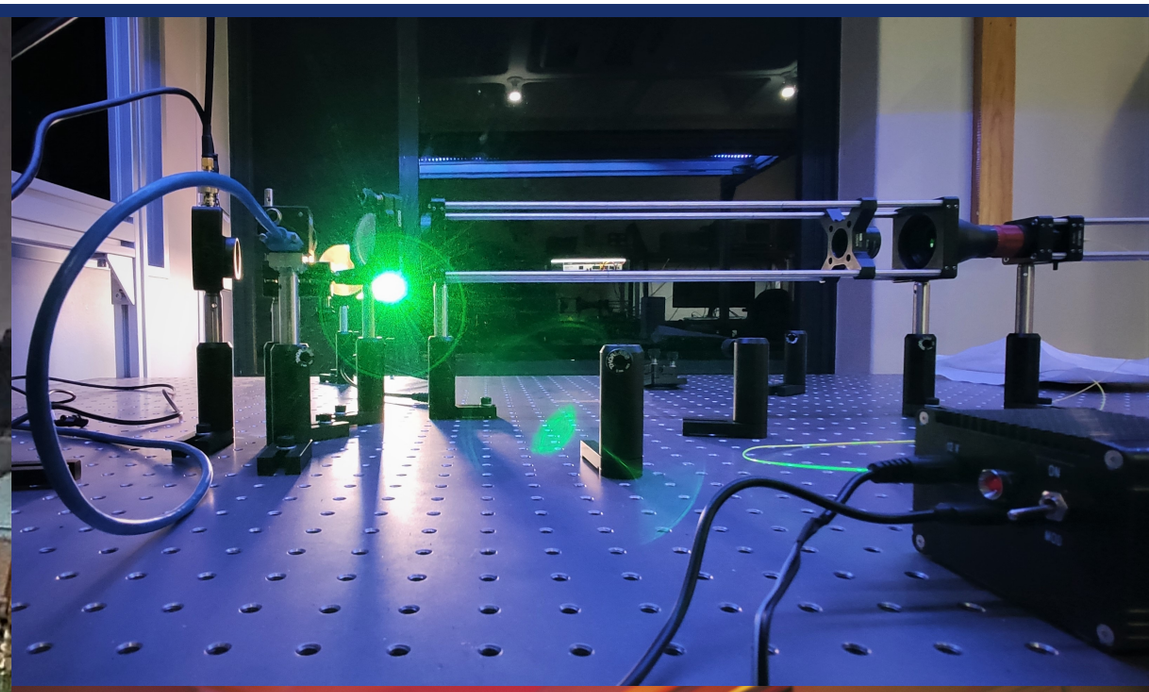
1-10 Gbps up to 5 km are relatively common, but it's a niche product and usually expensive.

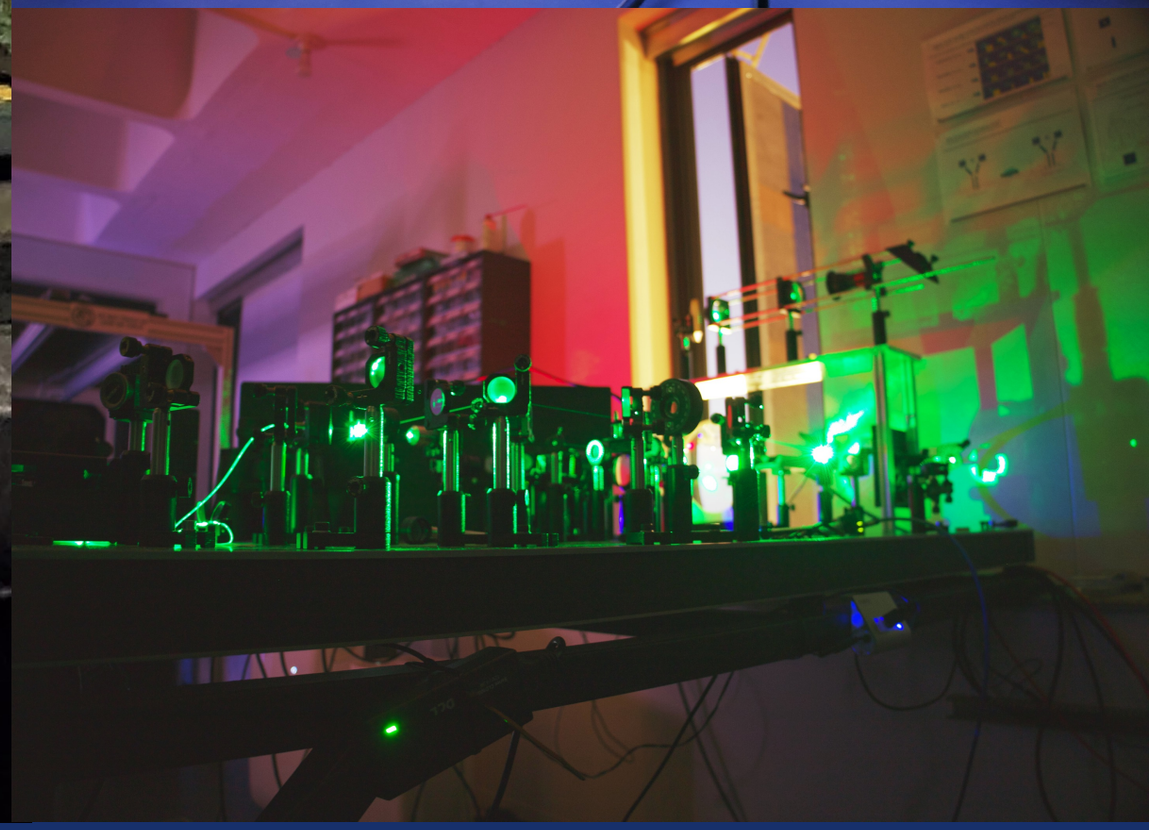


Roadmap to free-space optics | 10.1364/JOSAB.399168

The Wits OC Lab

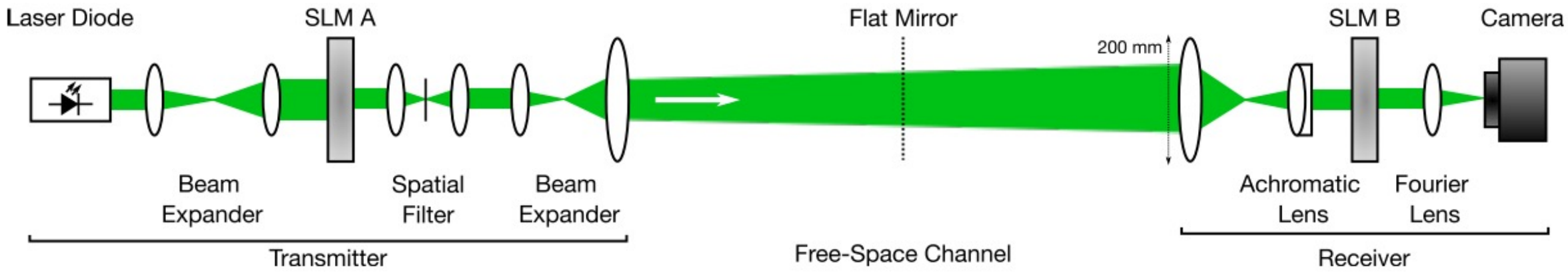
Our location allows us to do various wireless optical experiments and structured light research.

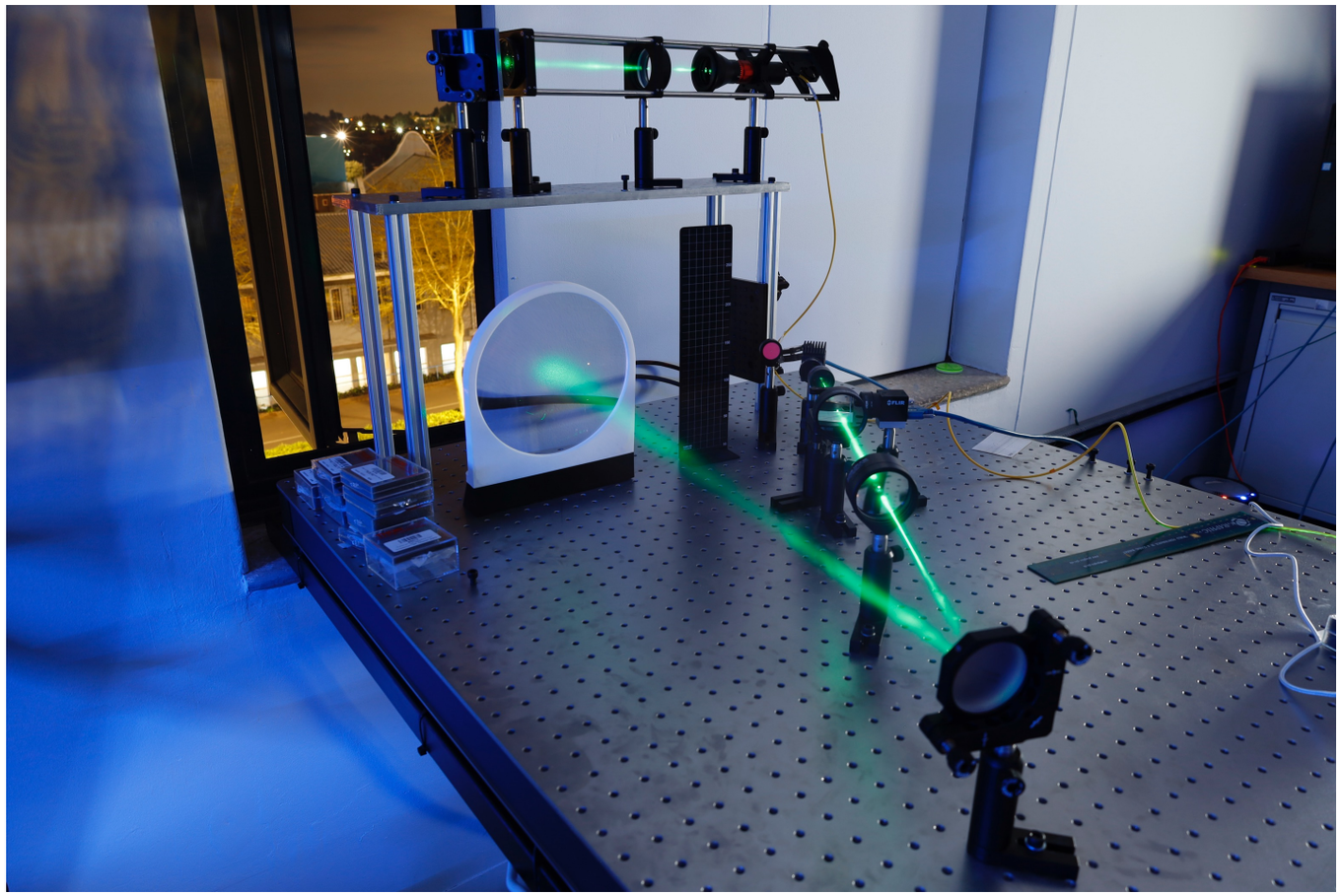




The OC Lab FSO Link

It took a few iterations to get this perfect! We have a reliable 270 m FSO link which supports $M^2 < 8$.

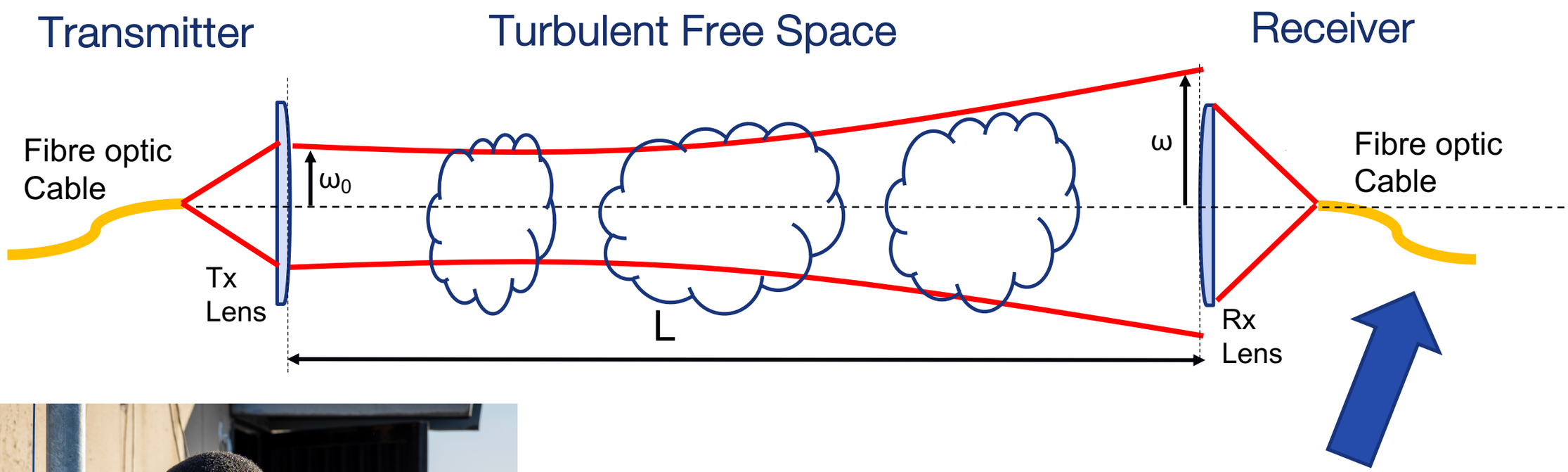


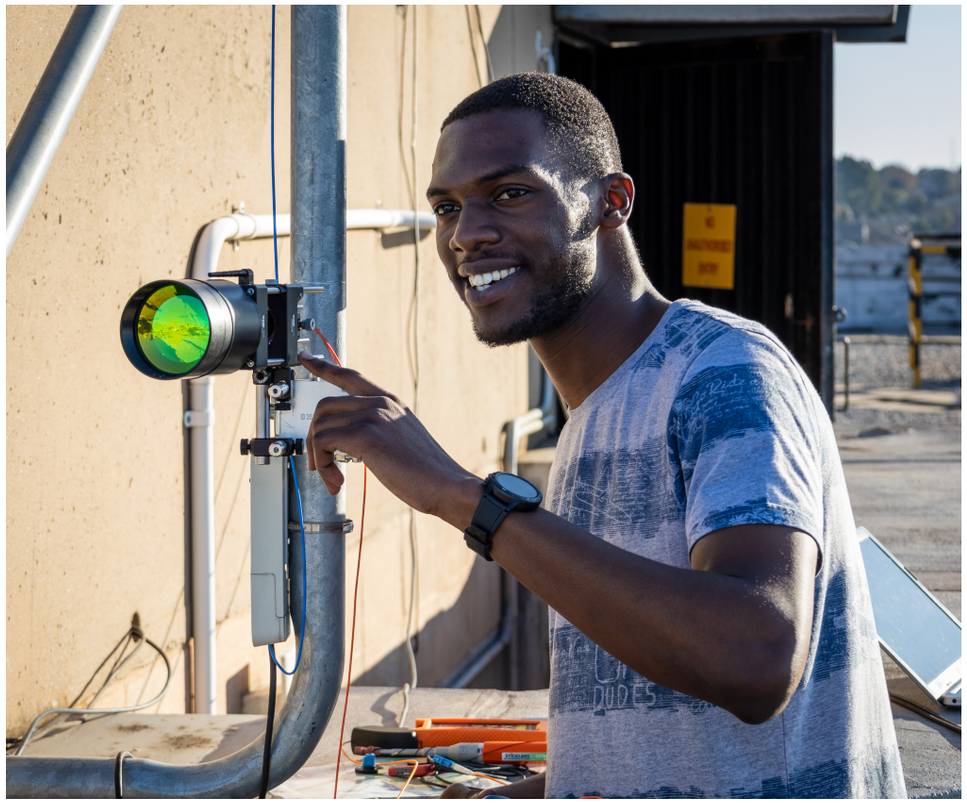


DOI: 10.1117/12.2626881

Affordable FSO Communication with Fibre Components

We are investigating which fibre we should use in a bi-directional system.

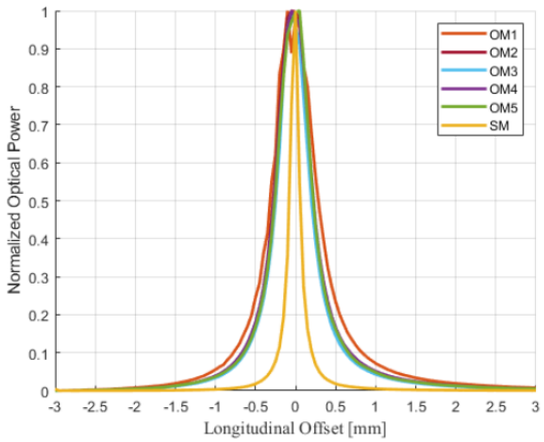




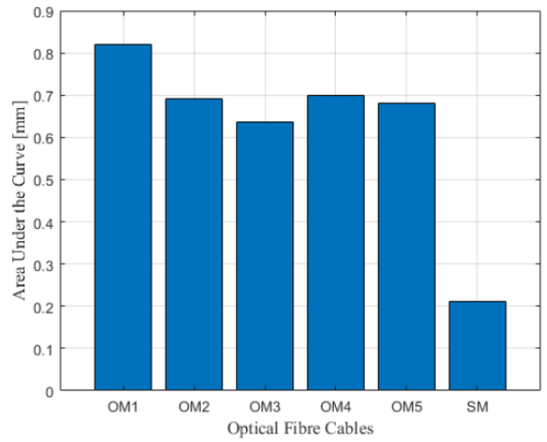
The fibre is the problem… maybe there's an optimal type?

We tested all the standard telecom fibres…

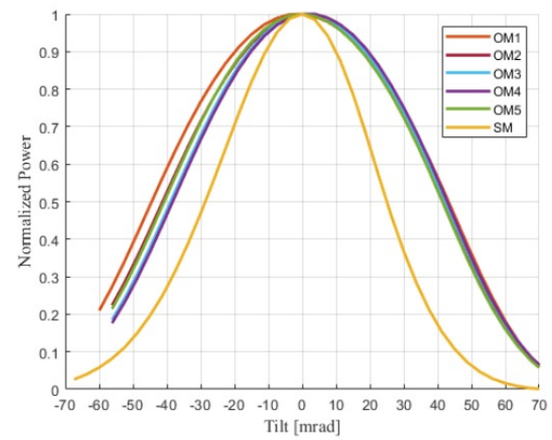
Over 400 m and they seemed to perform differently (in terms of BER). What makes them different?



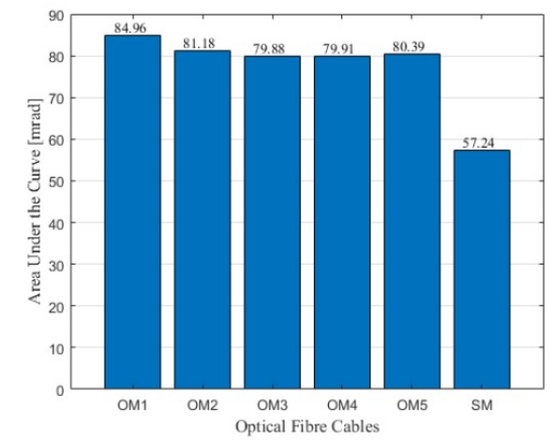
(a) Effect of Longitudinal Misalignment



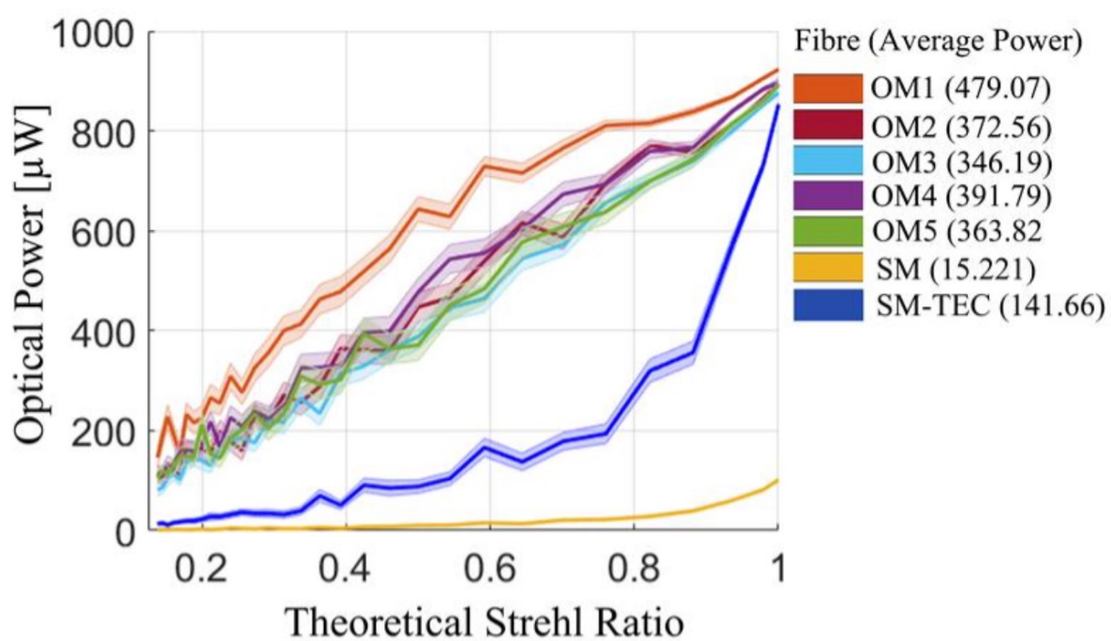
(b) Curve Area Analysis



(a) Effect of Angular Misalignment

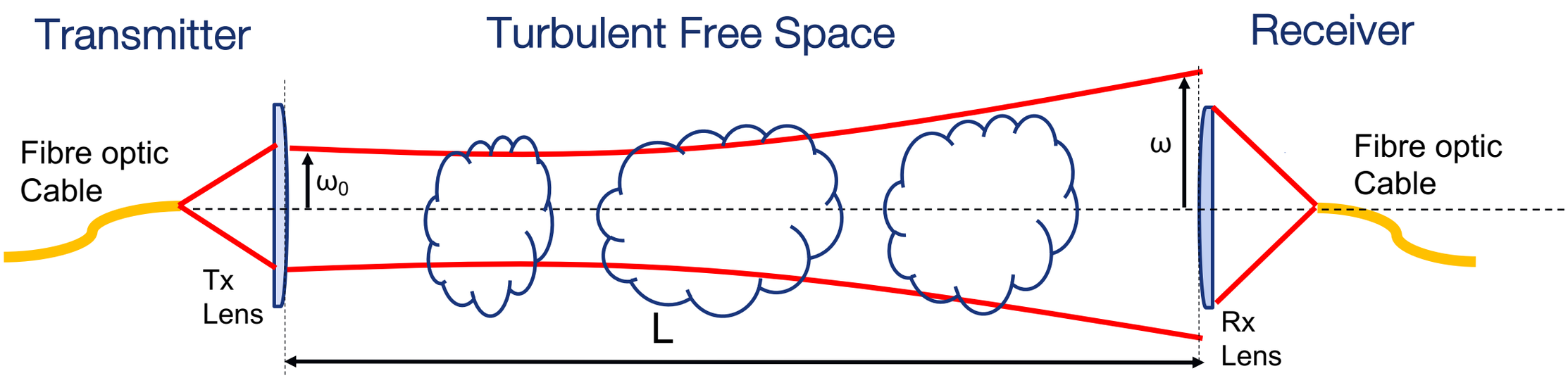


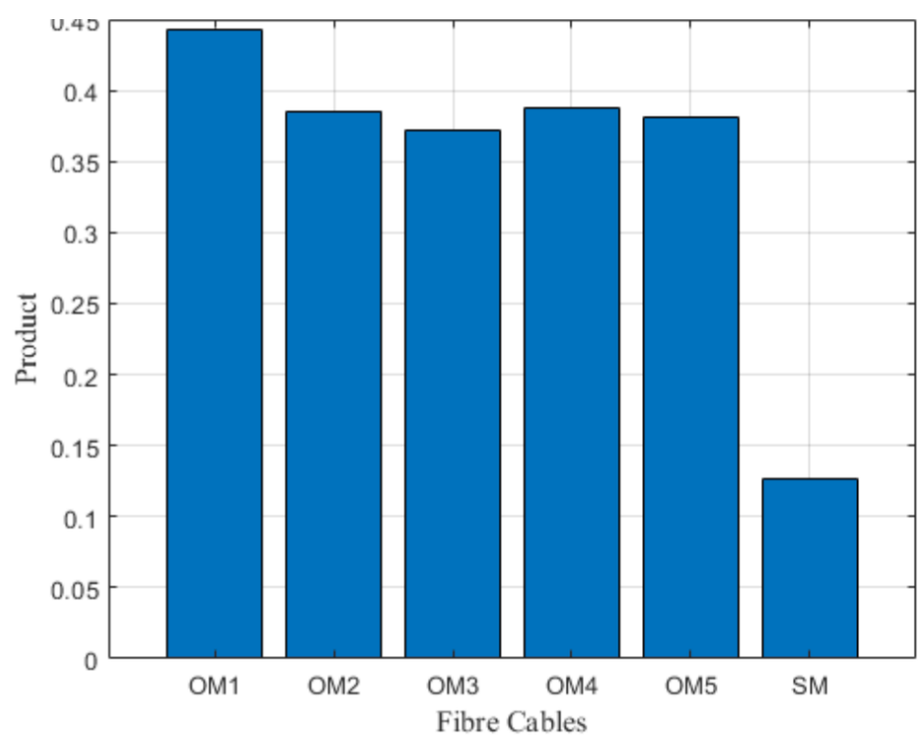
(b) Curve Area Analysis



Since it's bi-directional…

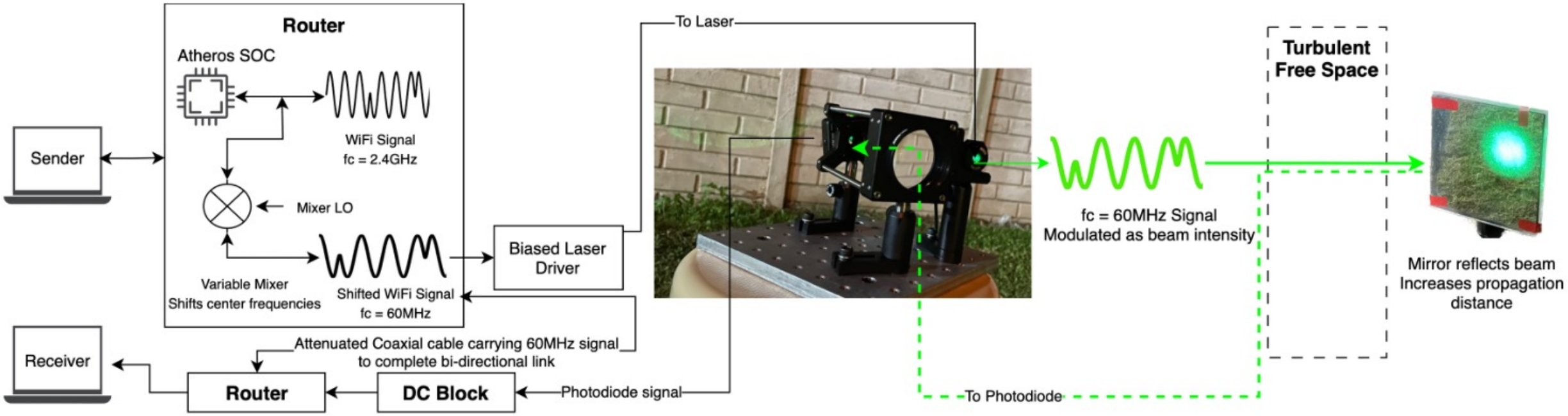
We need a good receiver *and* transmitter.

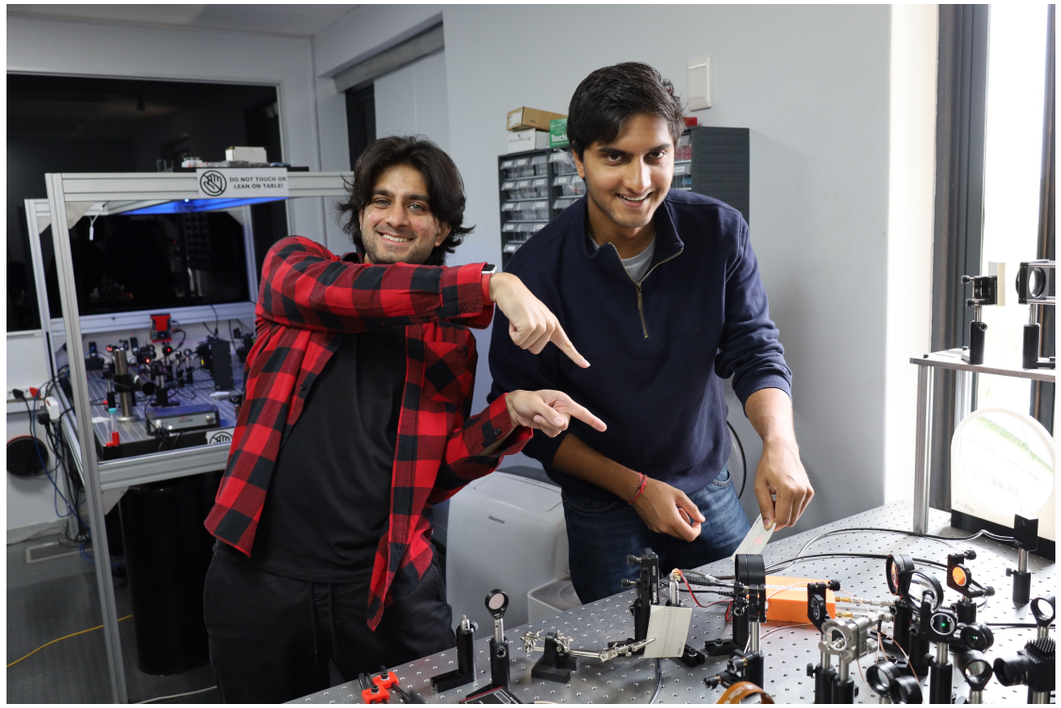


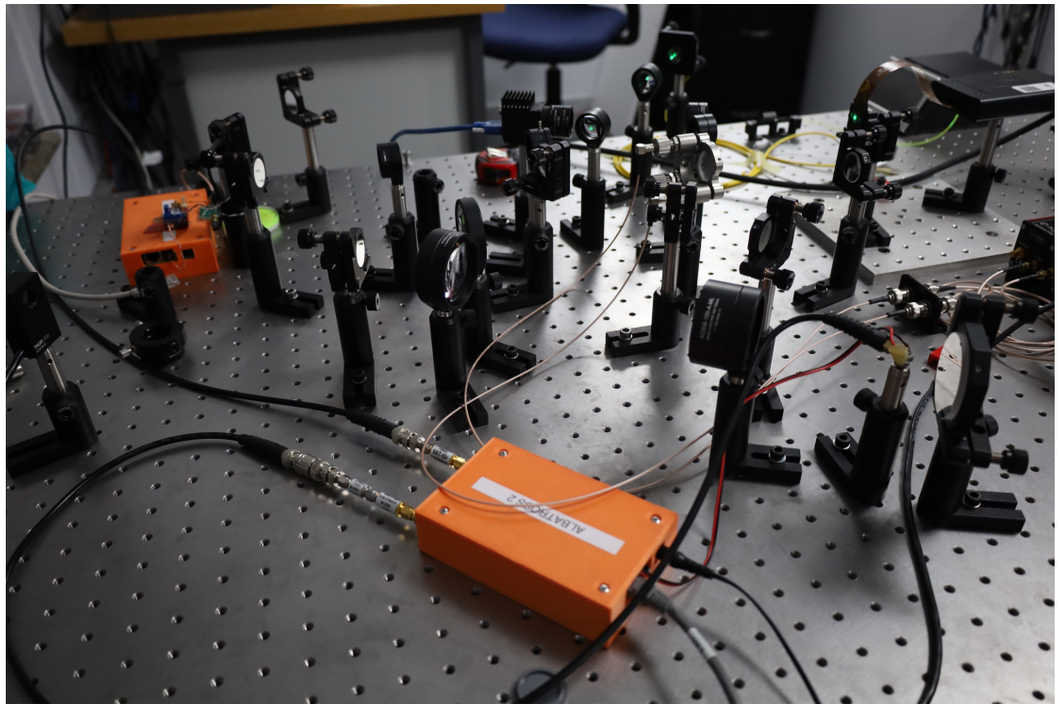


Affordable FSO Communication 2.0: WiFoO

The second avenue is “low carrier frequency” **WiFi over Optical** – and it works quite well so far!

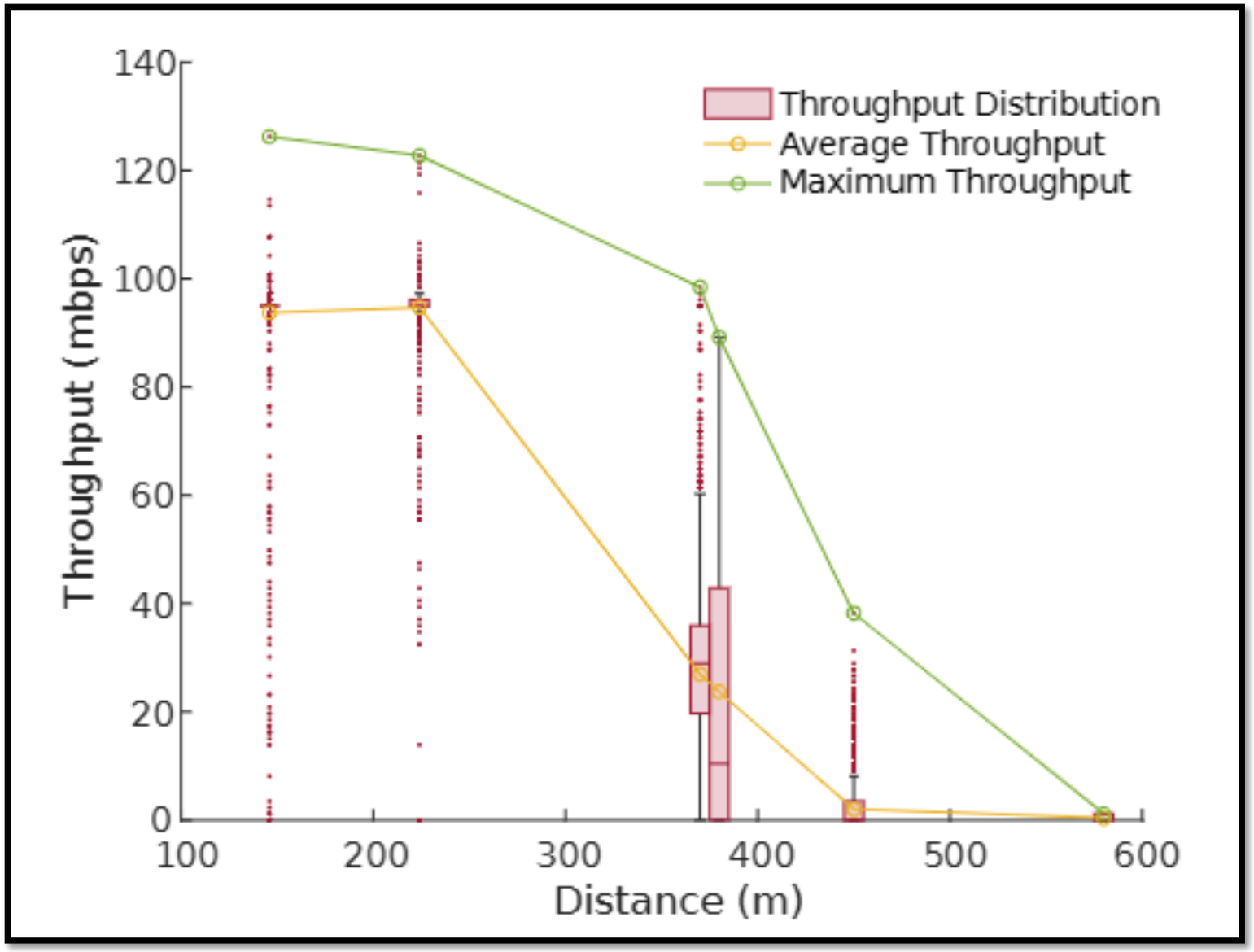


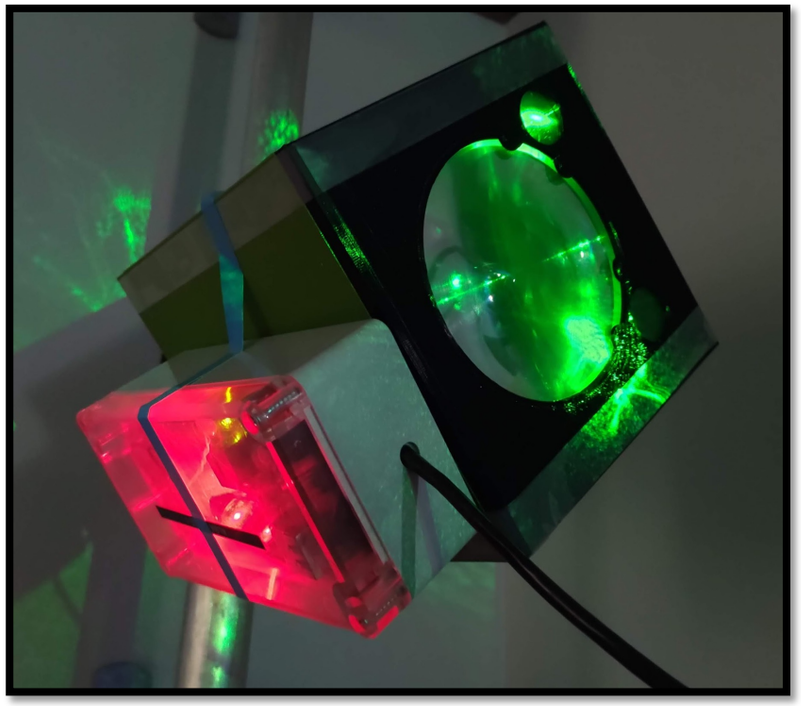


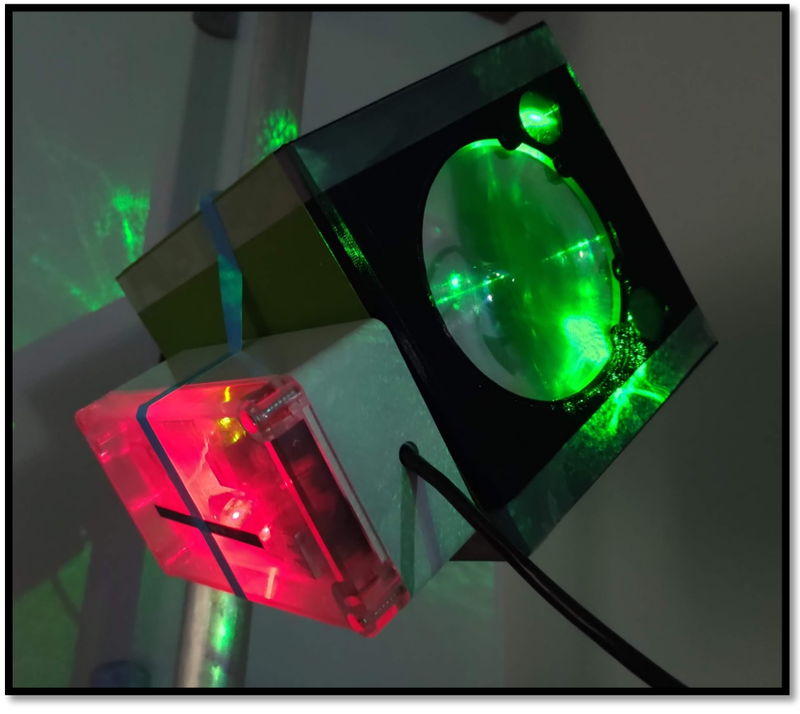


Affordable FSO Communication 2.0: WiFoO

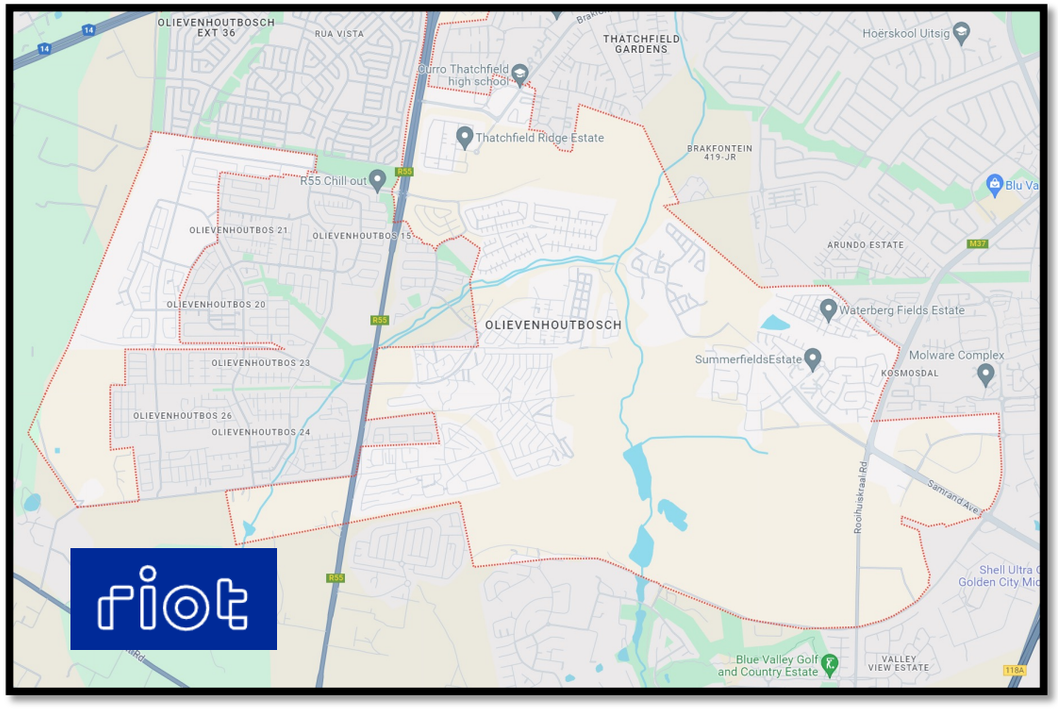
A very rudimentary prototype worked reliably up to a few hundred meters.







TRL 7 Prototype

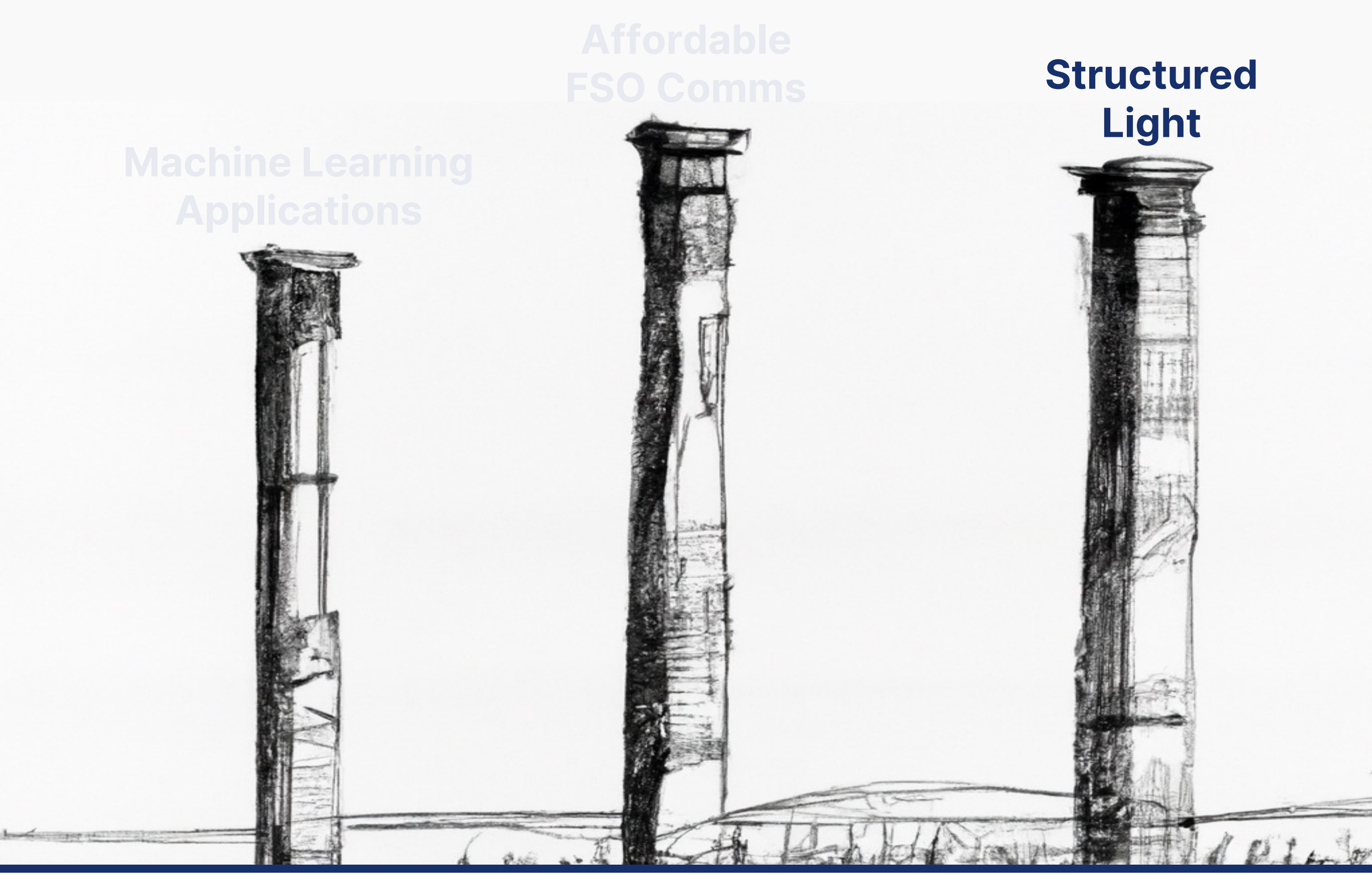


Deploy to fix bottlenecks

Investigate usage trends

What's next at my lab in terms of low cost FSO?

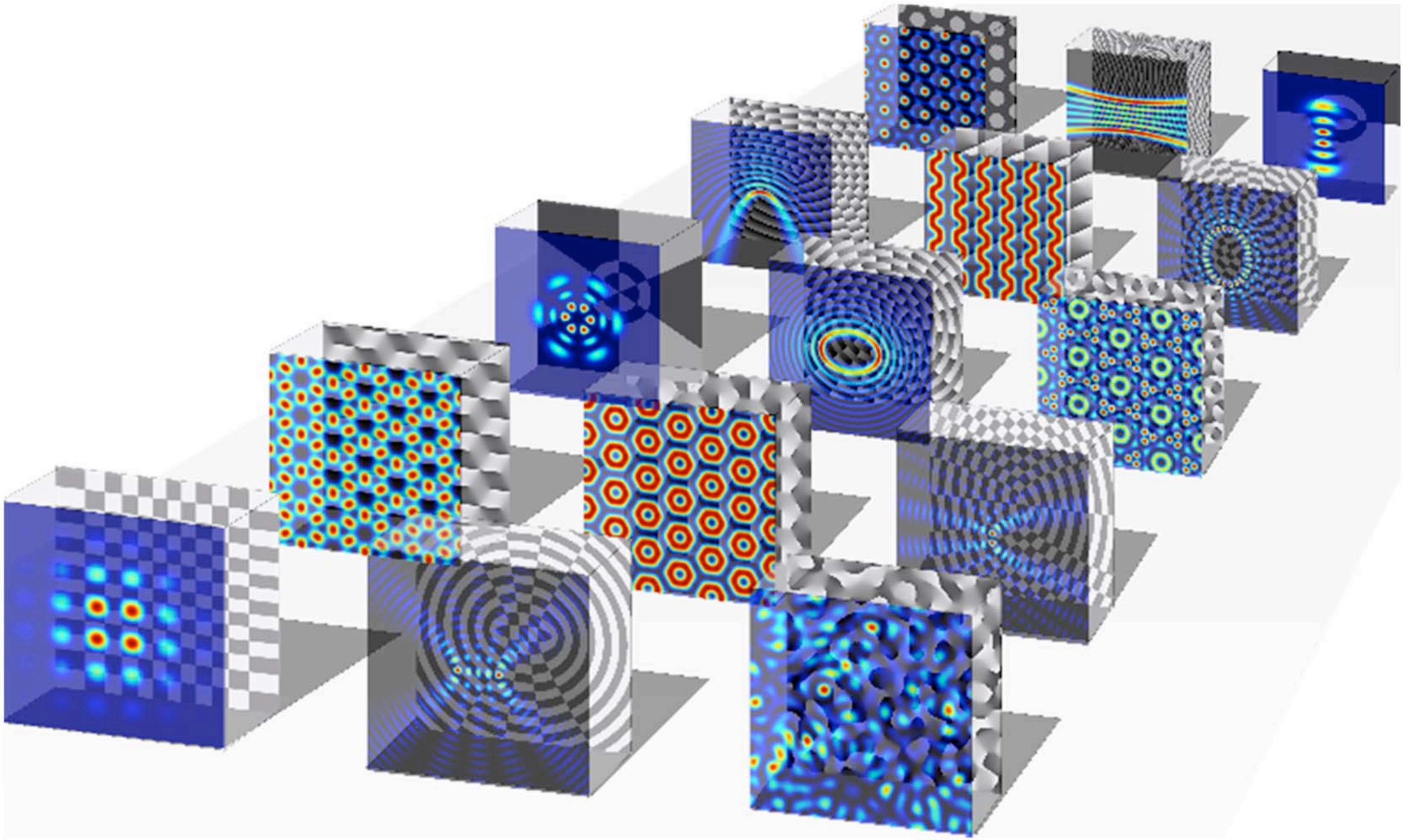
This is the plan for 2024…



Why? **What** is it? **How** are we doing it? **Next** steps…

Structured Light

Loosely defined as beams with intentionally shaped spatial intensity, phase and polarization.
We typically do this shaping in the lab using digital holograms.



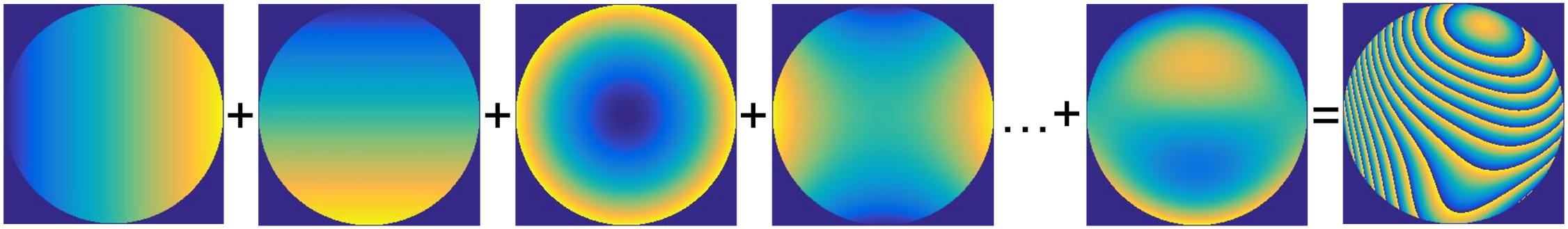
Understanding Turbulence

We can decompose Kolmogorov turbulence into component aberrations in the Zernike basis.

$$I_{nm} = \frac{0.15337(-1)^{n-m}(n+1)\Gamma(14/3)\Gamma(n-5/6)}{\Gamma(17/6)^2\Gamma(n+23/6)}$$

$$\sigma_{nm}^2 = I_{nm}\left(D/r_0\right)^{5/3}$$

0.45 σ_1 0.45 σ_2 0.02 σ_3 0.02 σ_4 0.006 σ_6



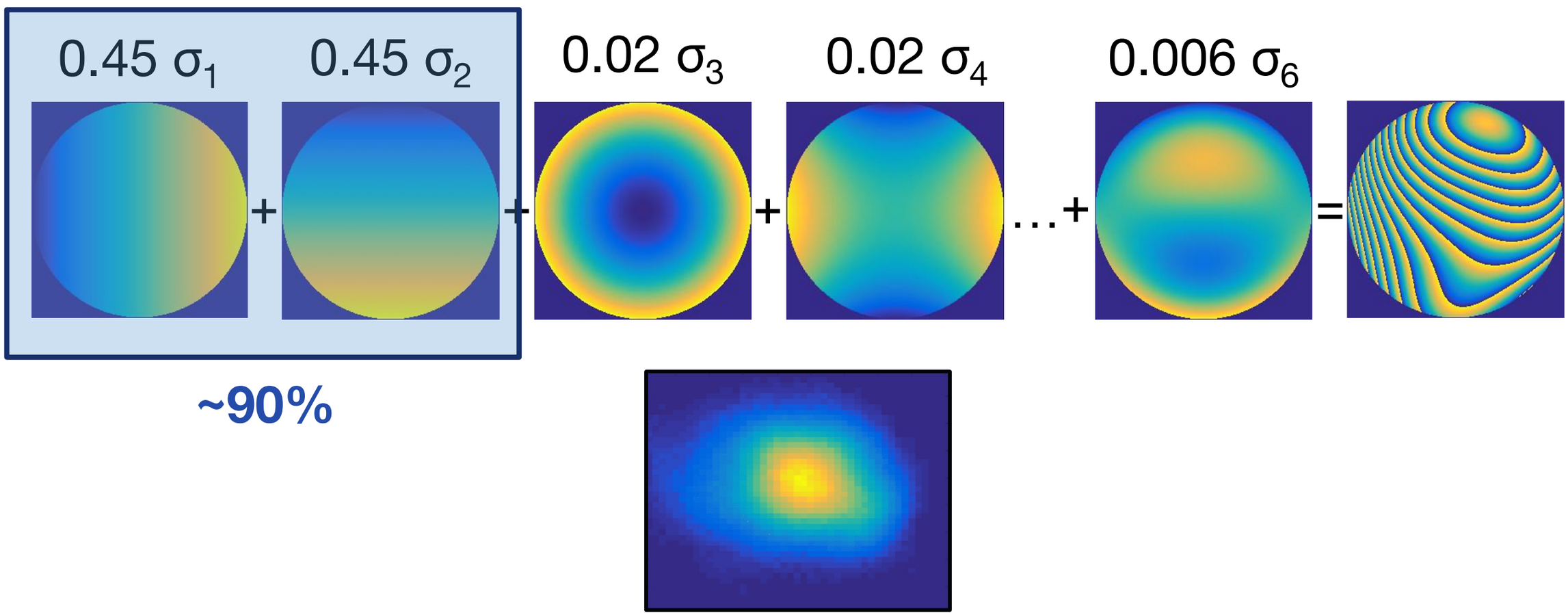
R. J. Noll, *"Zernike polynomials and atmospheric turbulence."* **Journal of the Optical Society of America**, 66(3), 207 (1976)

Turbulence is mostly tip and tilt

About 90% is tip and tilt, which results in “misalignment”. Can we use this to our advantage?

$$I_{nm} = \frac{0.15337(-1)^{n-m}(n+1)\Gamma(14/3)\Gamma(n-5/6)}{\Gamma(17/6)^2\Gamma(n+23/6)}$$

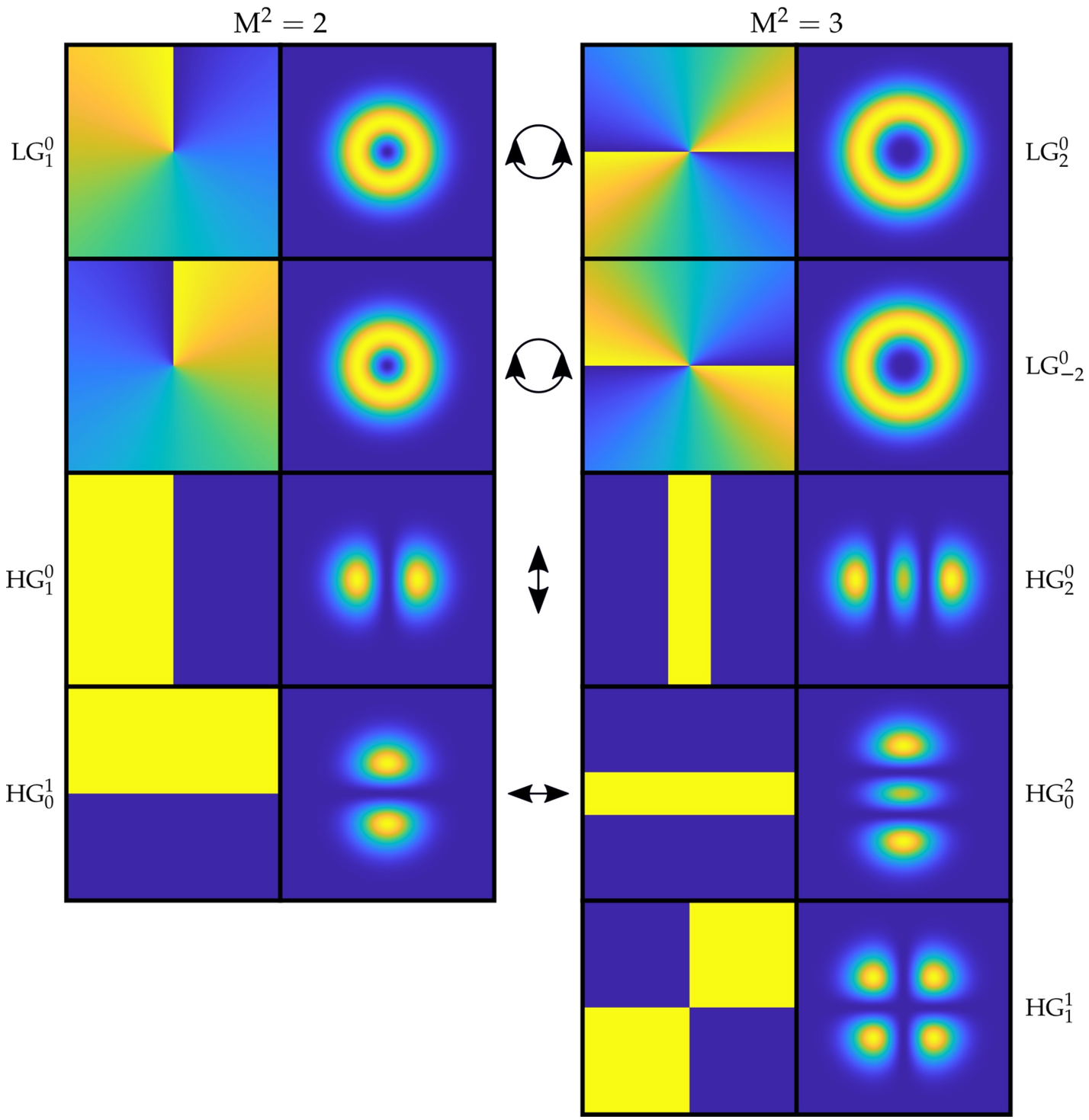
$$\sigma_{nm}^2 = I_{nm}\left(D/r_0\right)^{5/3}$$



R. J. Noll, *“Zernike polynomials and atmospheric turbulence.”* **Journal of the Optical Society of America**, 66(3), 207 (1976)

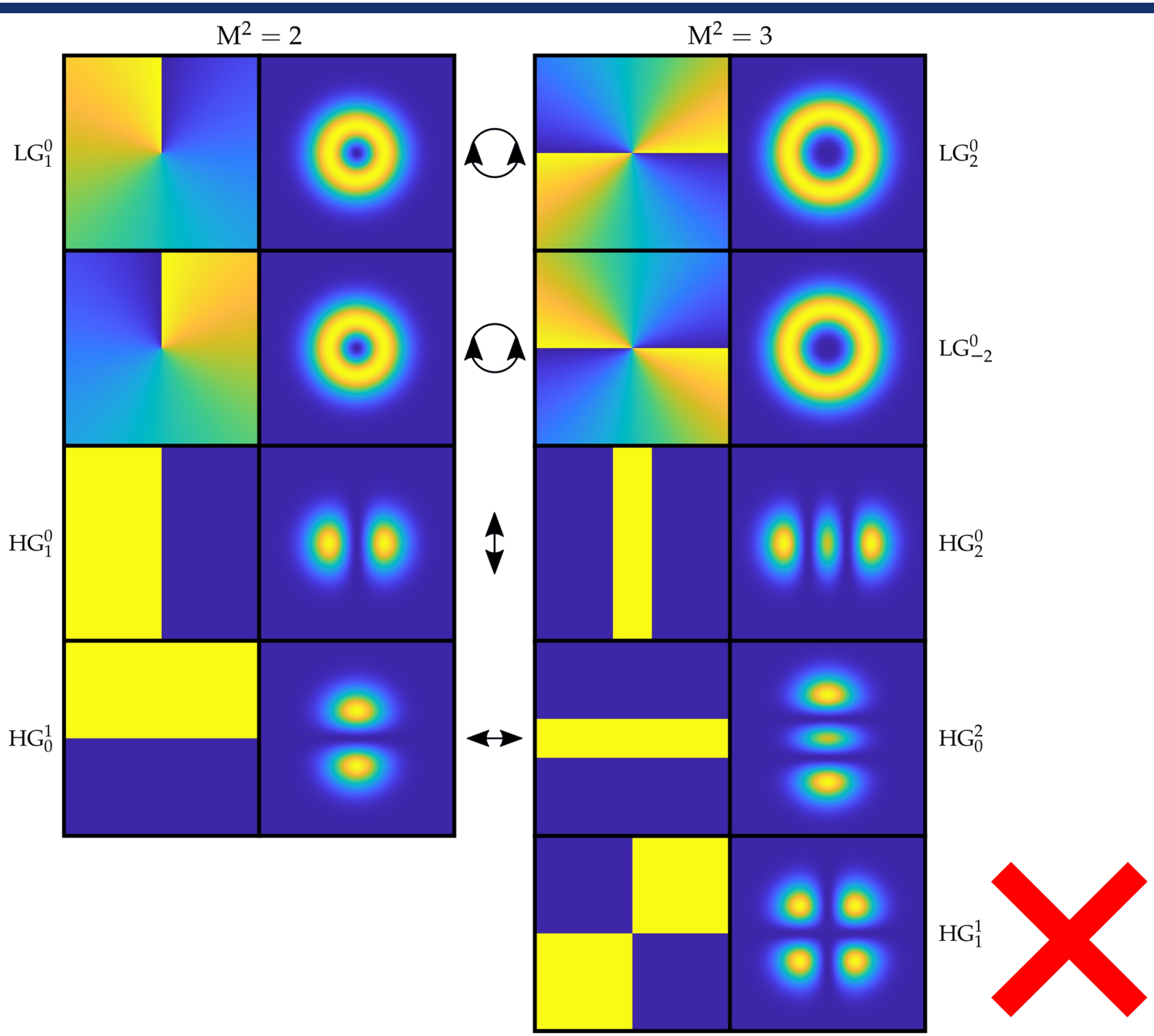
Aberrations affect modes differently

Is there a “better” basis to use for FSO communication?



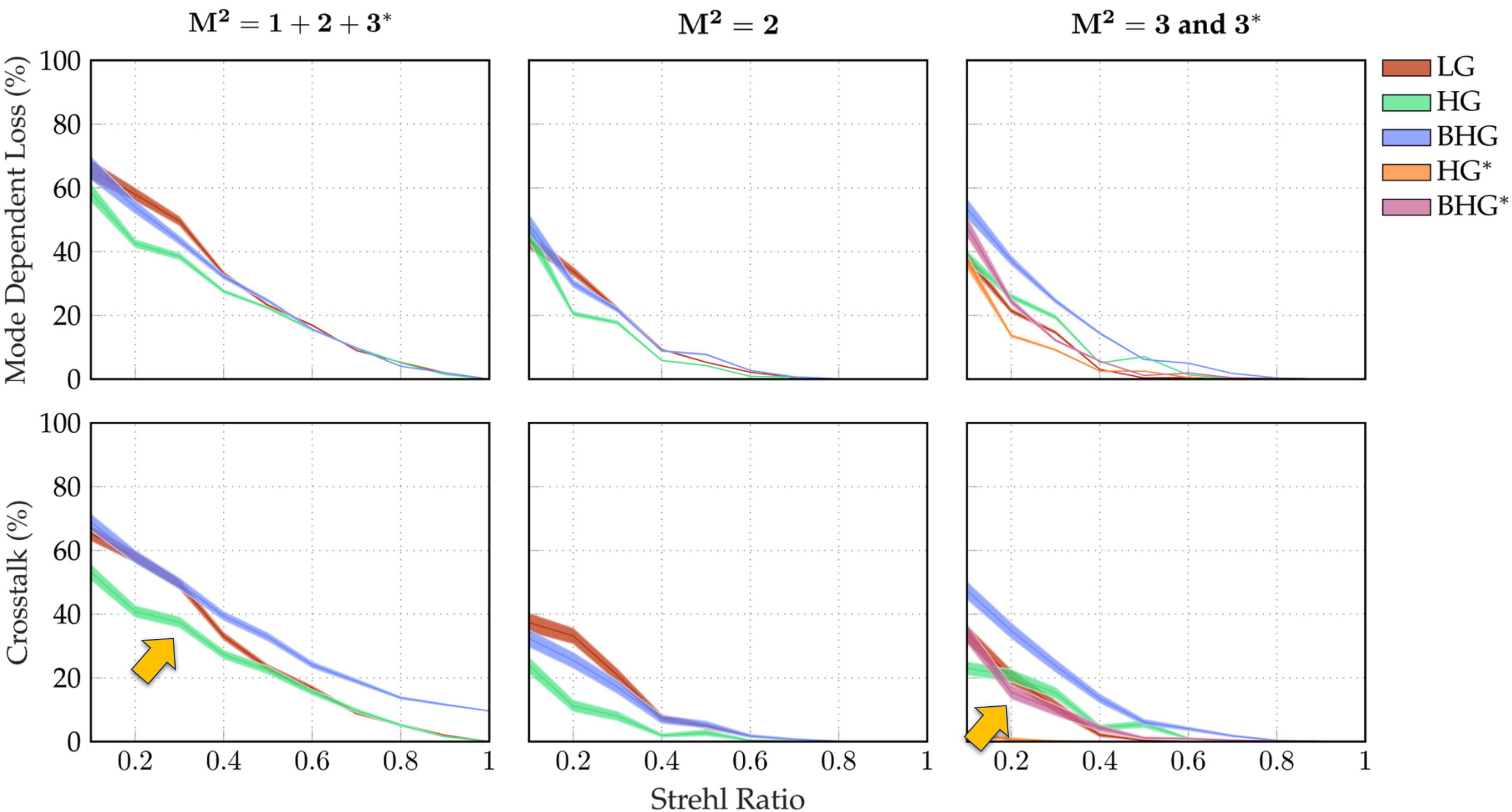
HG modes are resilient to tip and tilt

But not all of them. So how well do these modes work in turbulence?



HG is significantly better than LG modes in turbulence

But not if we include the “symmetrical” mode, according to our hypothesis.



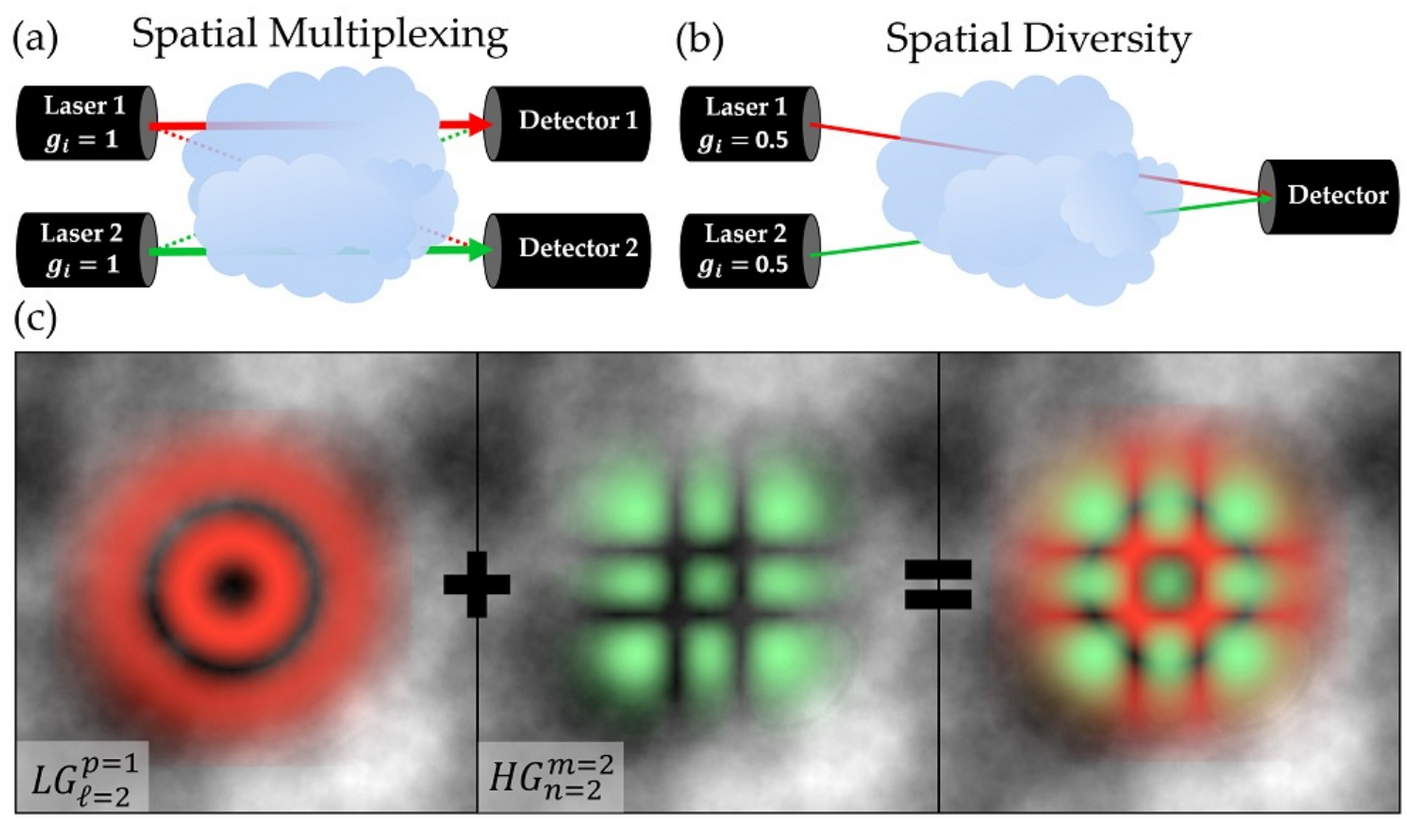
Cox, M. A. et al. *“The Resilience of Hermite- and Laguerre-Gaussian Modes in Turbulence”* **Journal of Lightwave Technology**, (2019)

What about “Modal Diversity”?

If each mode is independent in turbulence (hypothesis) then the probability of error will be reduced.

If the modes are independent in turbulence:

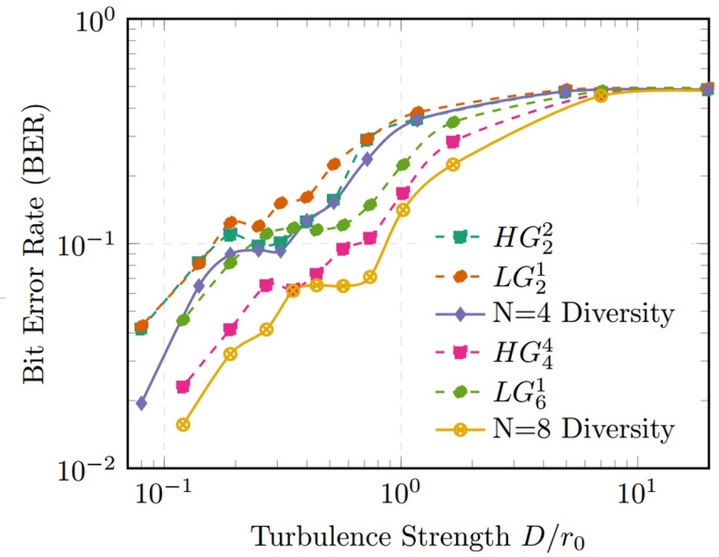
$$P(A \text{ and } B) = P(A)P(B)$$

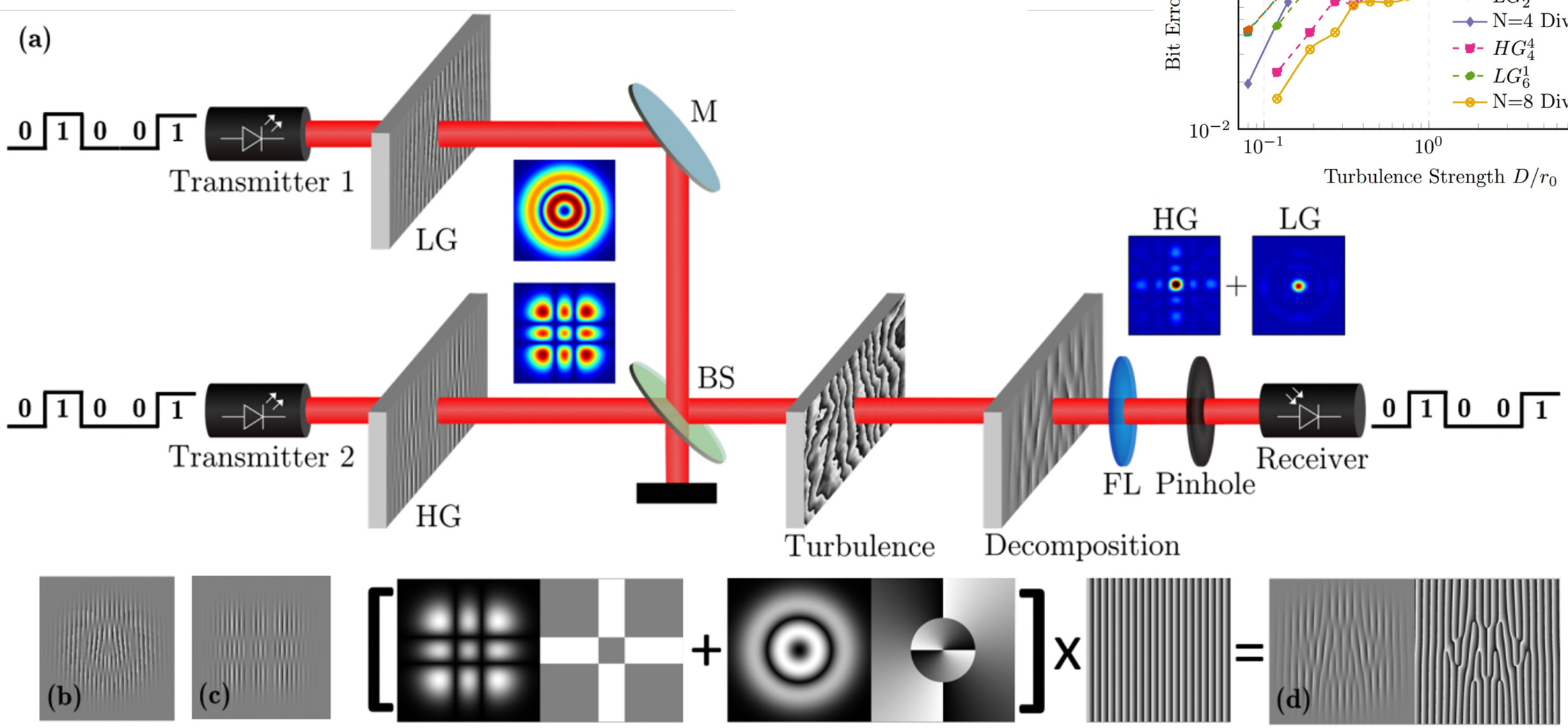


M. A. Cox *et al.*, *Modal Diversity for Robust Free-Space Optical Communications*, Physical Review Applied, (2018)

What about “Modal Diversity”?

It turns out that modal diversity provides some “gain”!

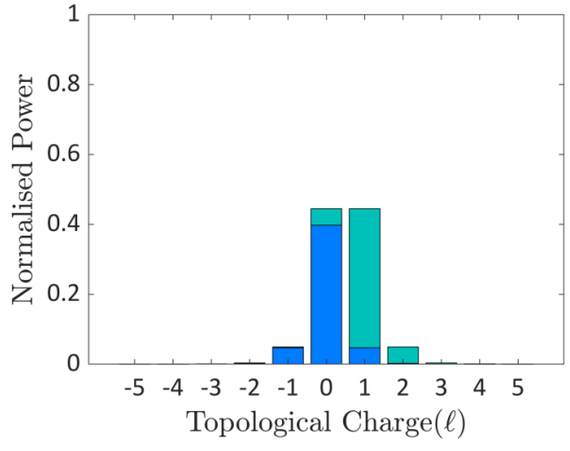


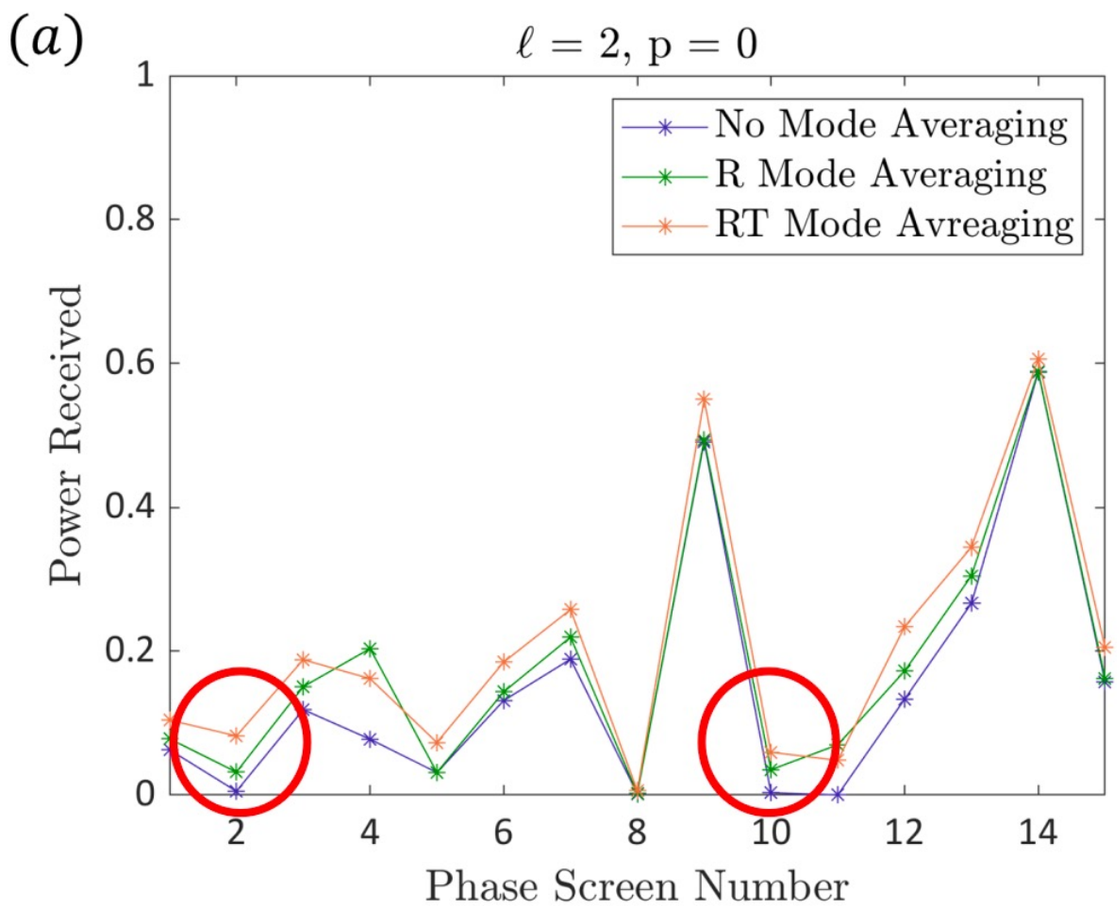


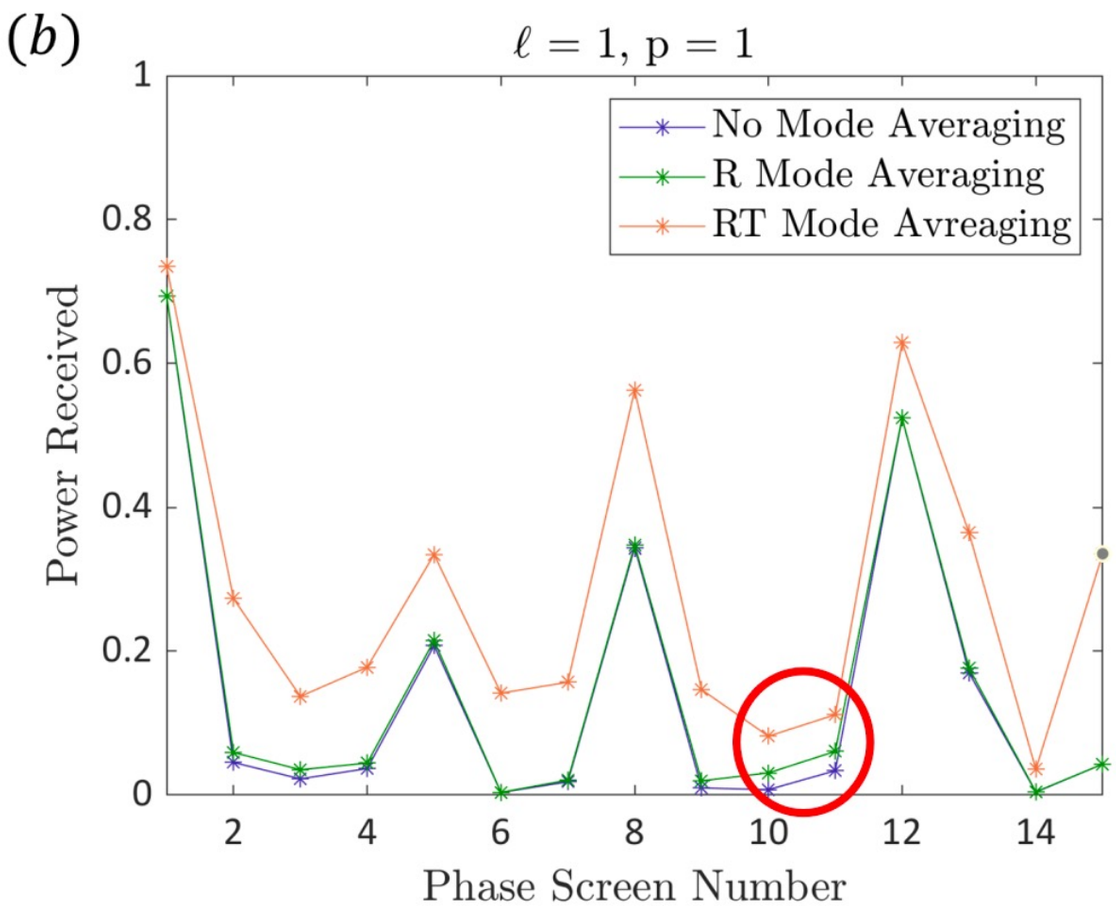
M. A. Cox *et al.*, *Modal Diversity for Robust Free-Space Optical Communications*, Physical Review Applied, (2018)

Mode averaging is similar…

Using the right mode combinations, we can prevent deep fades!



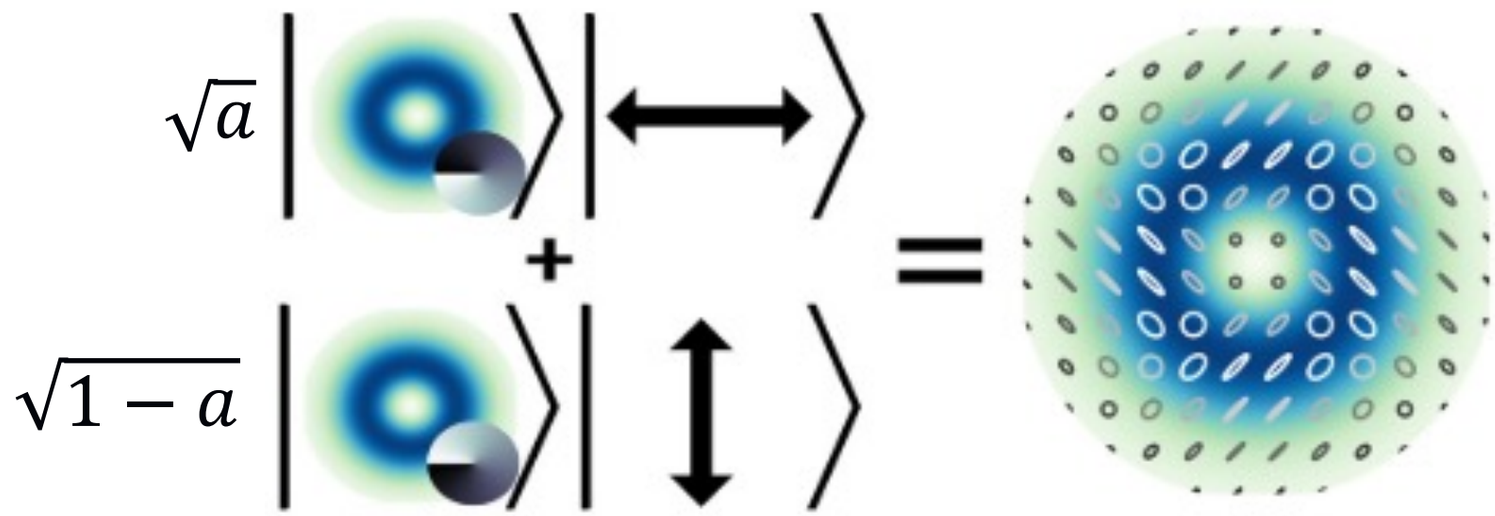




Structured Light: **Vector Modes**

We can also structure the polarization of a beam. Vector Vortex Modes are OAM modes with a vectorial polarization.

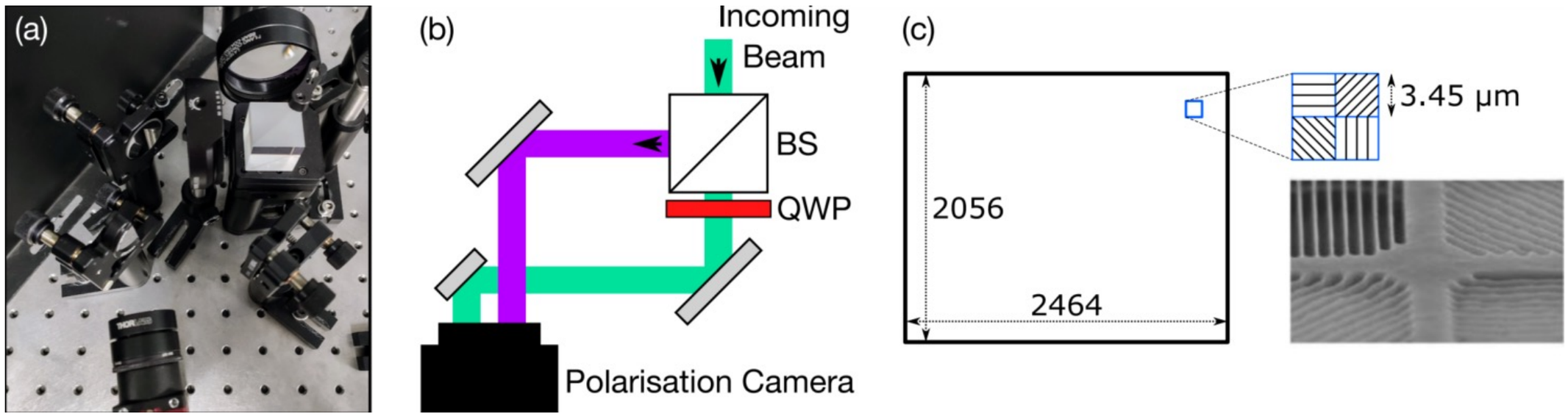
$$|\psi\rangle = \sqrt{a}|\pm\ell\rangle|R\rangle \pm \sqrt{1-a}|\mp\ell\rangle|L\rangle$$

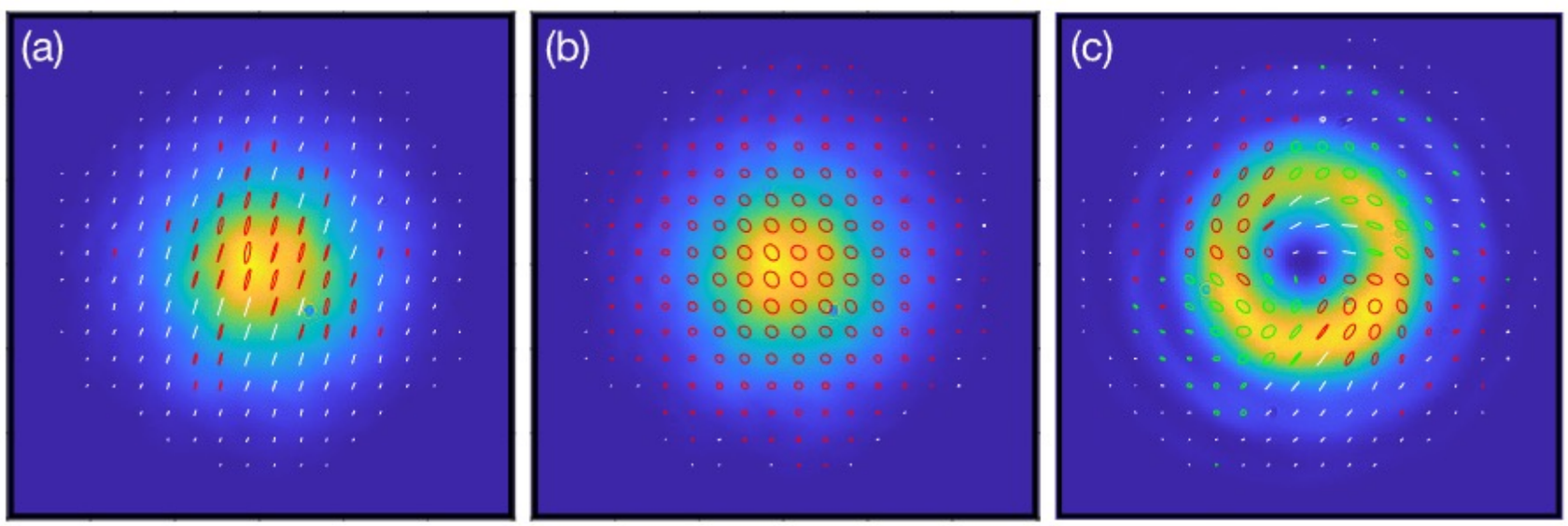


$$C = 2|\sqrt{a(1-a)}|$$

Measuring Vector Modes Easily: The Stokes Camera

We recently published a paper on how to build one…





7828 Vol. 62, No. 29 / 10 October 2023 / Applied Optics Engineering and Laboratory Note

applied optics

Real-time Stokes polarimetry using a polarization camera

Mitchell A. Cox[1,*] and Carmelo Rosales-Guzmán[2]

https://doi.org/10.1364/AO.504249

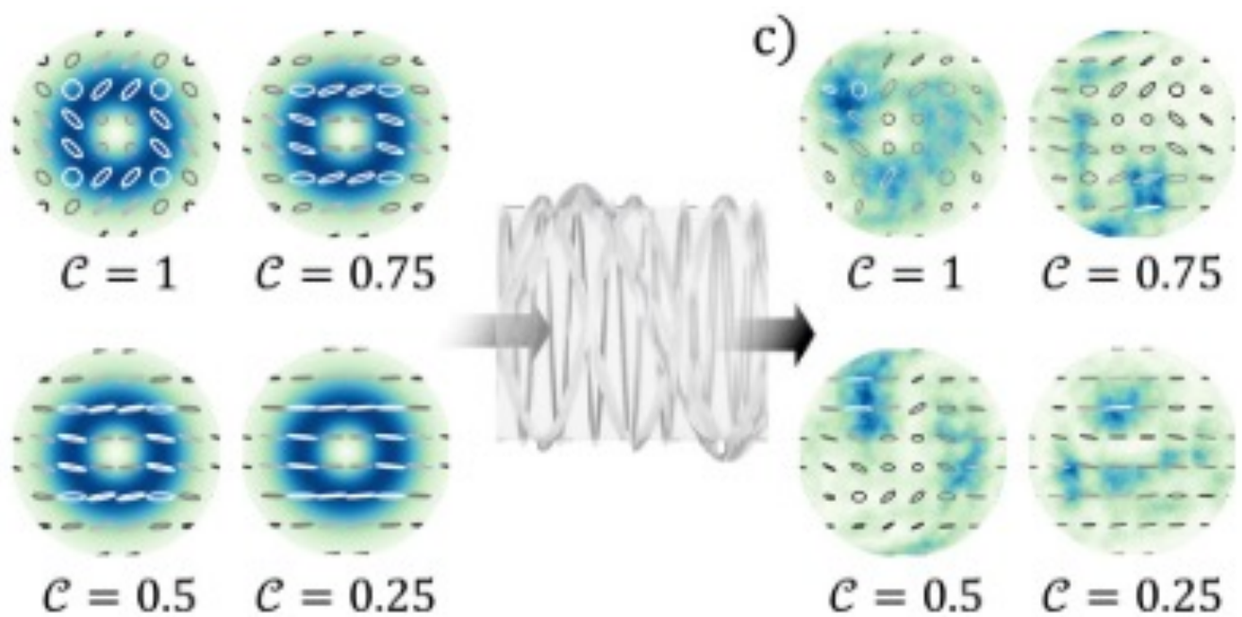
Vector modes in atmospheric turbulence

It turns out that the concurrence is preserved, and easy to generate and detect…

$$|\psi\rangle = \sqrt{a}|\pm\ell\rangle|R\rangle \pm \sqrt{1-a}|\mp\ell\rangle|L\rangle$$

$$C = 2|\sqrt{a(1-a)}|$$

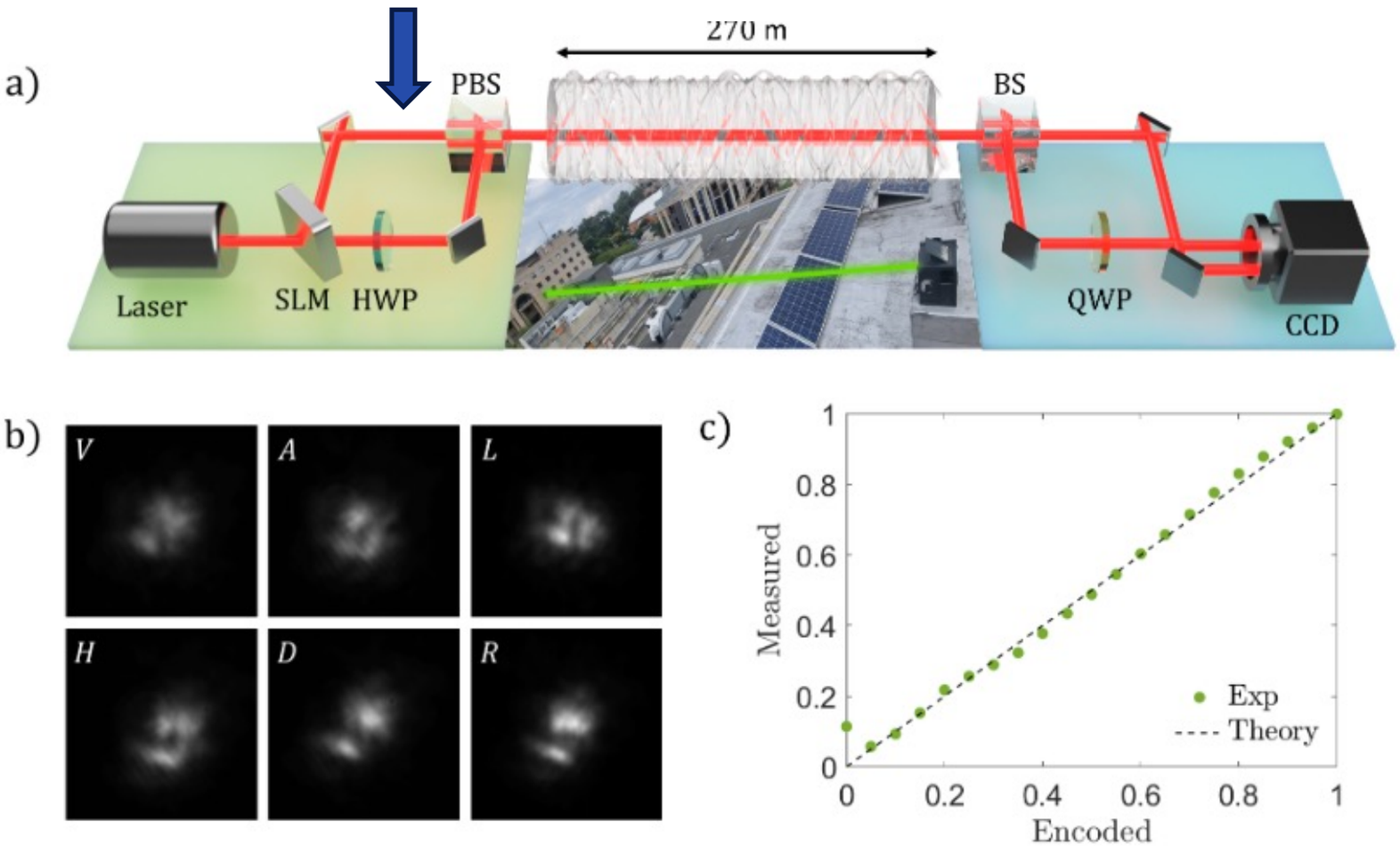
Transmit

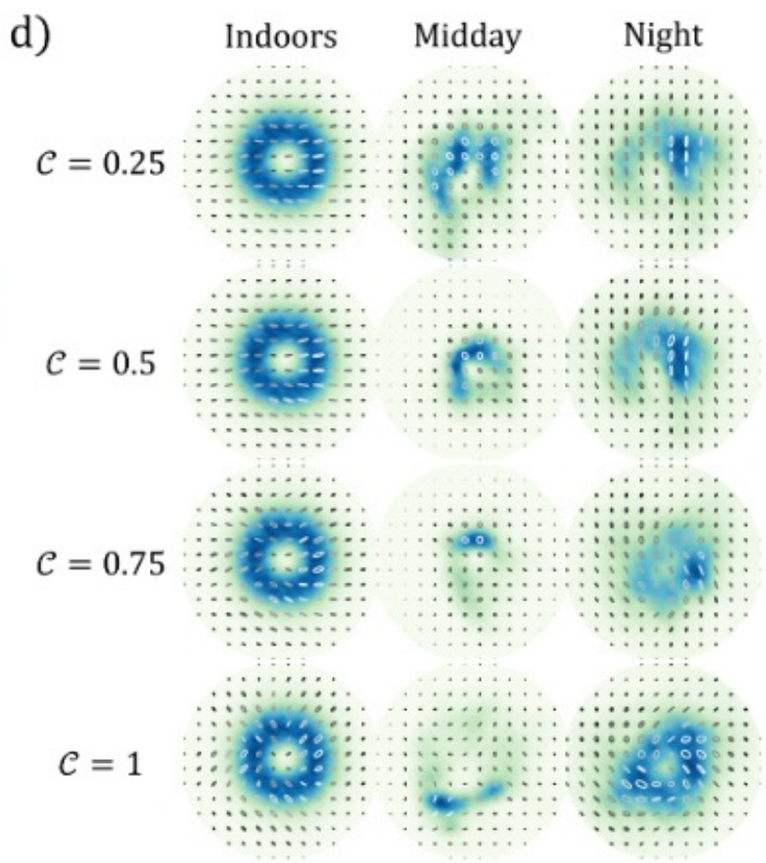


Receive

The future: robust propagation in turbulence?

Using “concurrence”, we have multi-level modulation robust to turbulence aberrations.





Applied Physics Letters ARTICLE pubs.aip.org/aip/apl

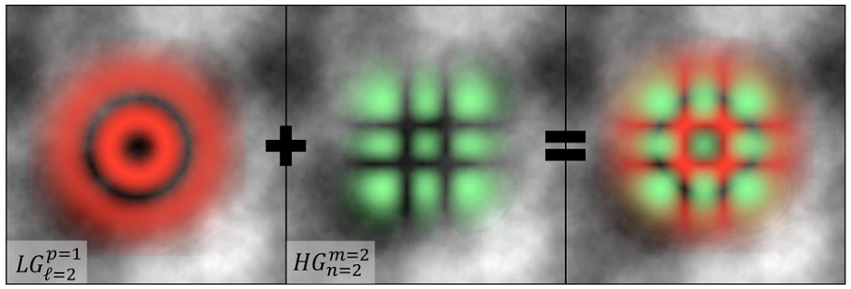
The invariance and distortion of vectorial light across a real-world free space link

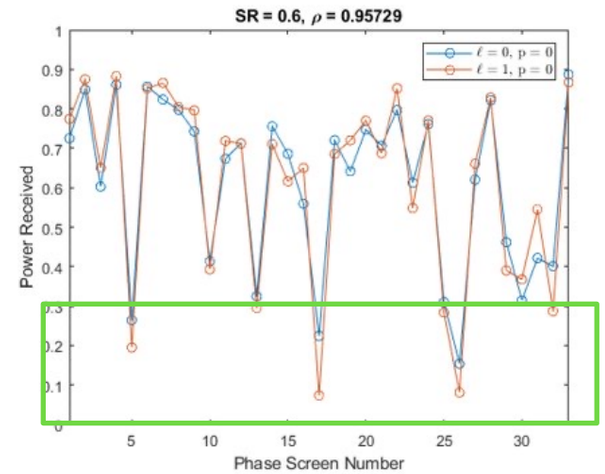
Cite as: Appl. Phys. Lett. **123**, 021103 (2023); doi: 10.1063/5.0152065
Submitted: 27 March 2023 · Accepted: 20 June 2023 ·
Published Online: 10 July 2023

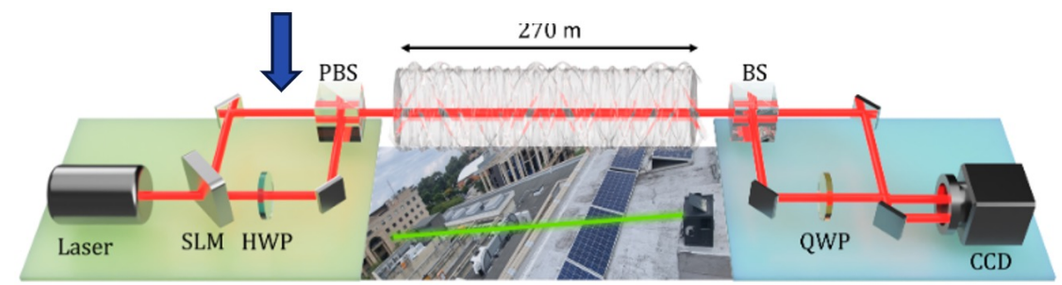
Cade Peters,[1] Mitchell Cox,[2] Alice Drozdov,[2] and Andrew Forbes[1,a)]

https://doi.org/10.1063/5.0152065

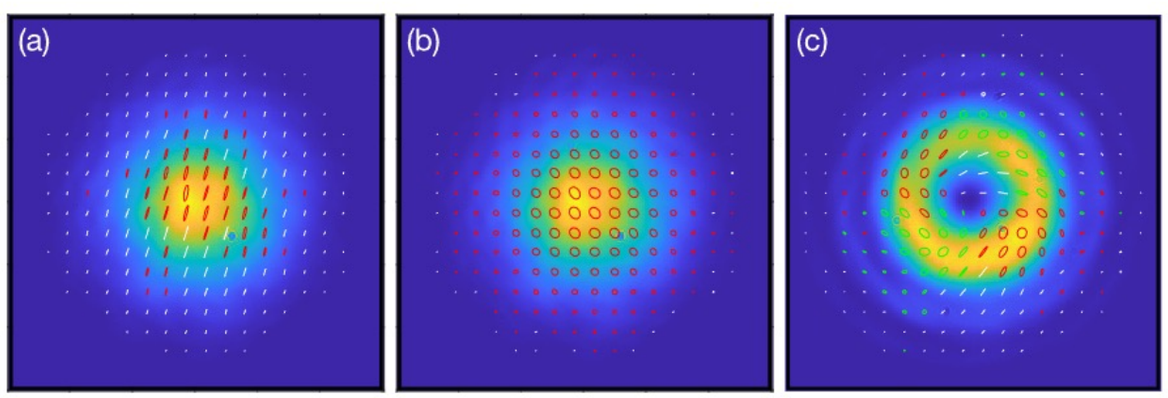
Modal Diversity and Mode Averaging for longer range or reliability

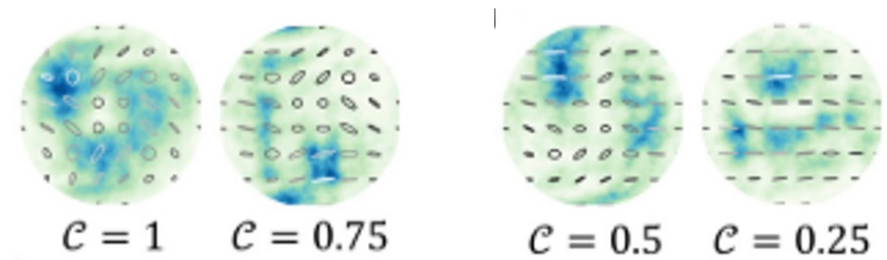






Instrumentation: The Stokes Camera





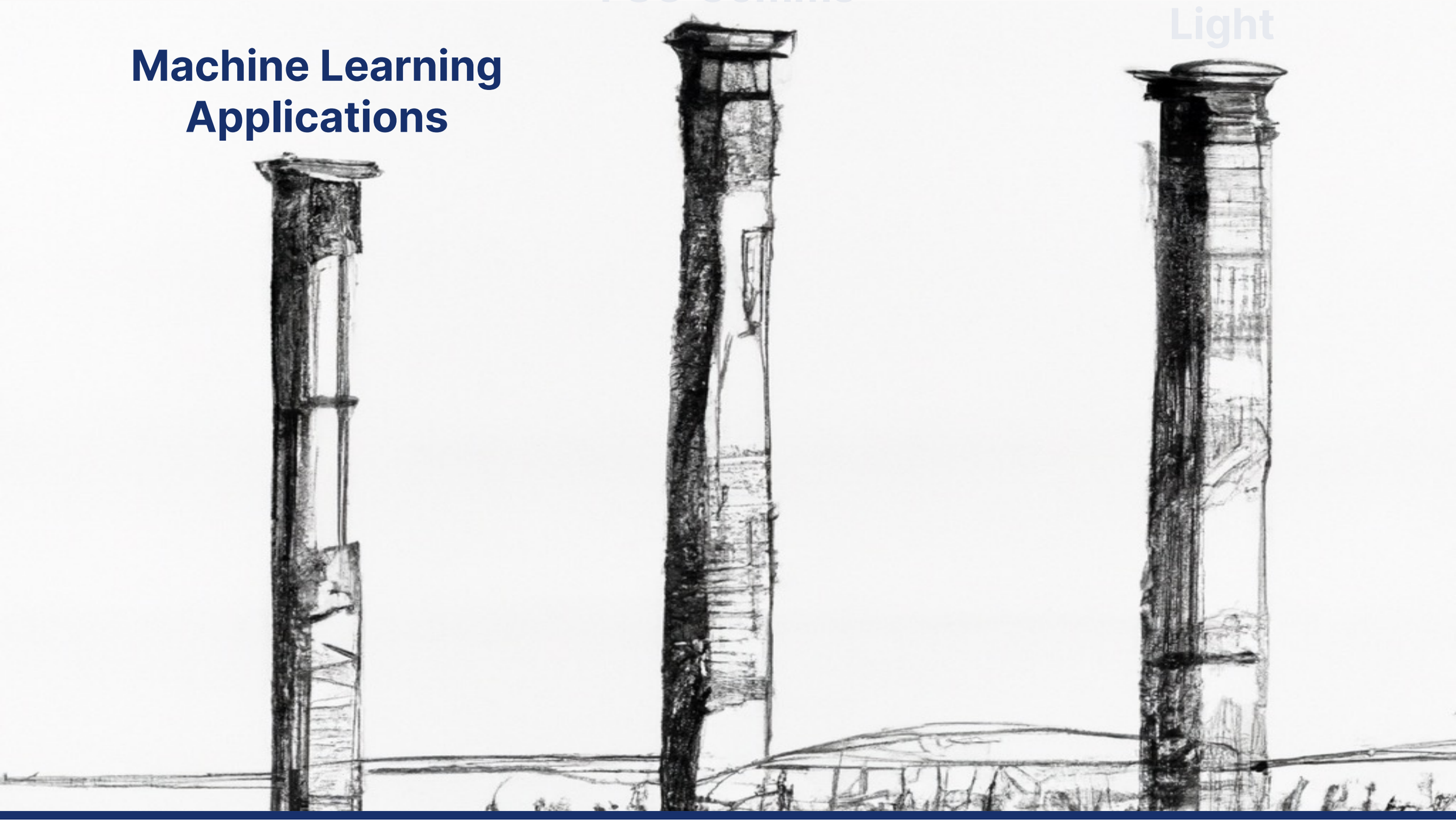
Scintillation immune modulation format?

Long Range FSO with Structured Light Summary

Affordable FSO Comms

Structured Light

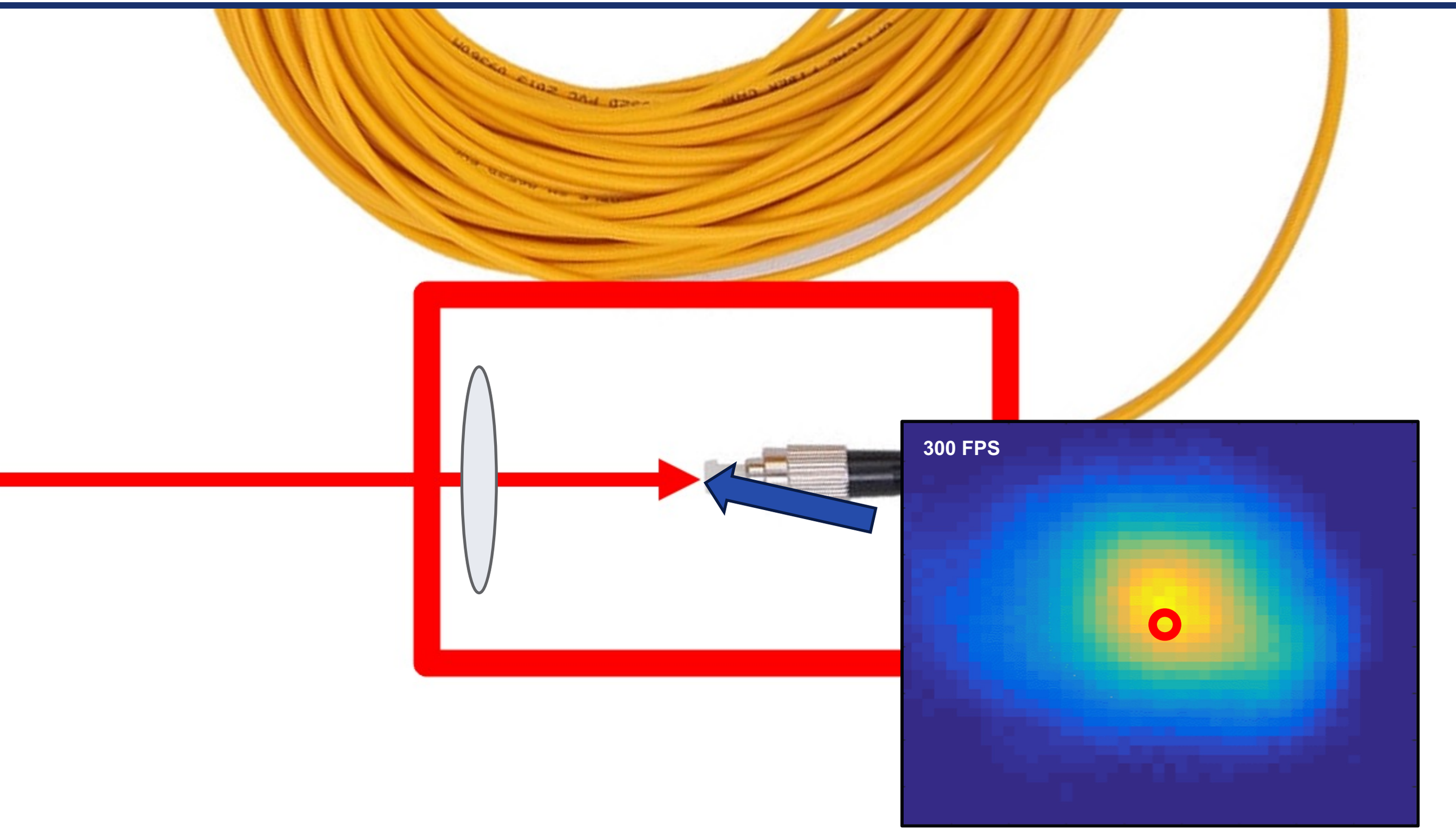
Machine Learning Applications



Why? **What** is it? **How** are we doing it? **Next** steps…

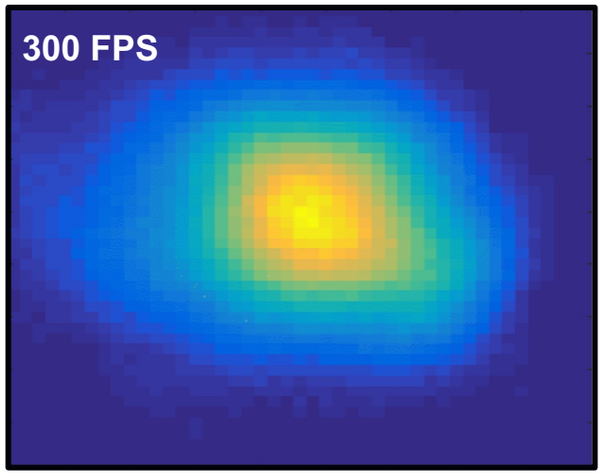
Taking a step back to turbulence-induced “wobble”…

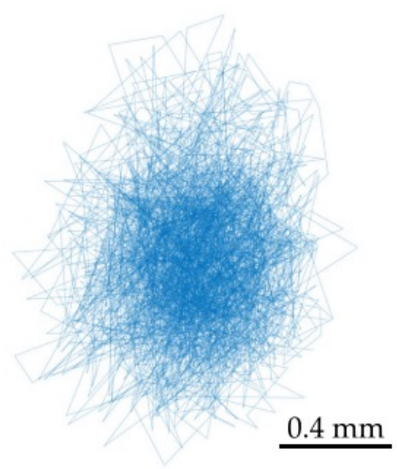
Is there a way to predict it?

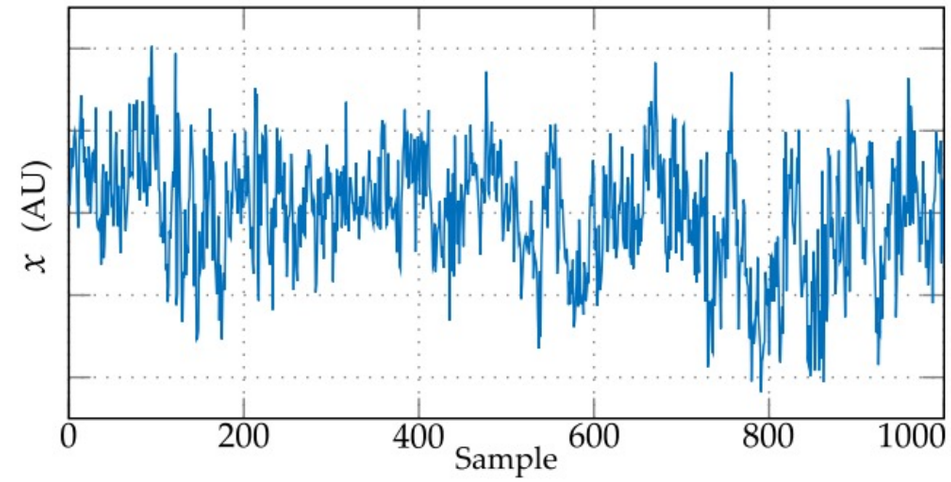


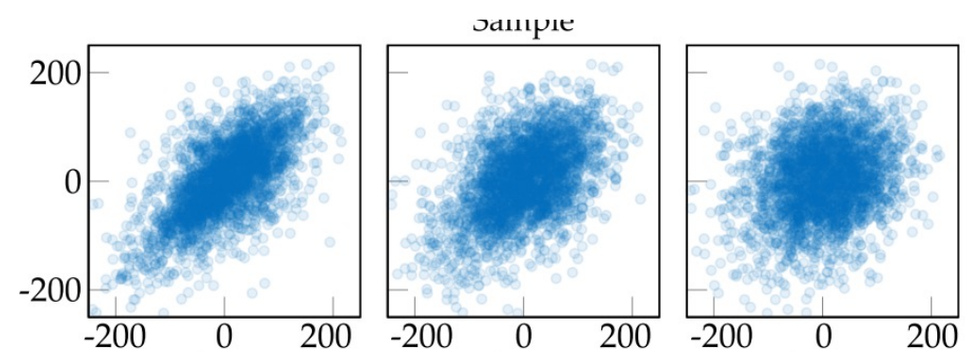
Centroid positions over time are correlated

(this assumes adequate sampling)







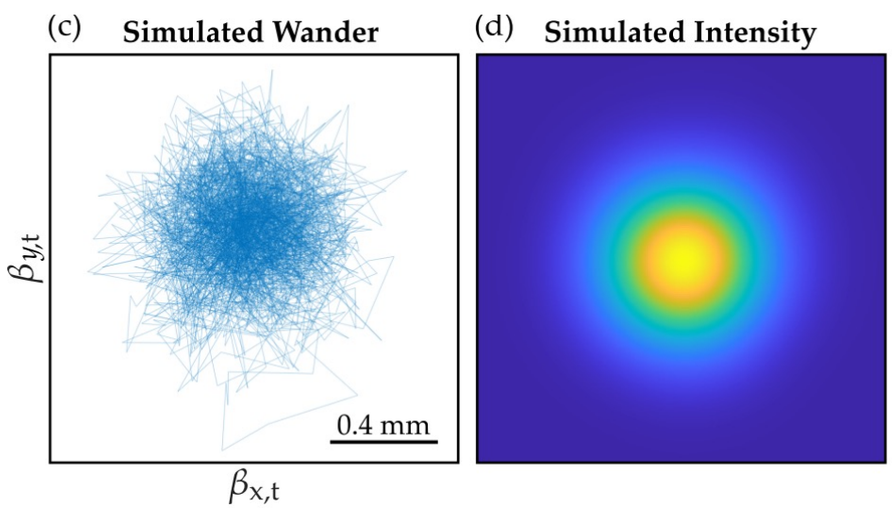


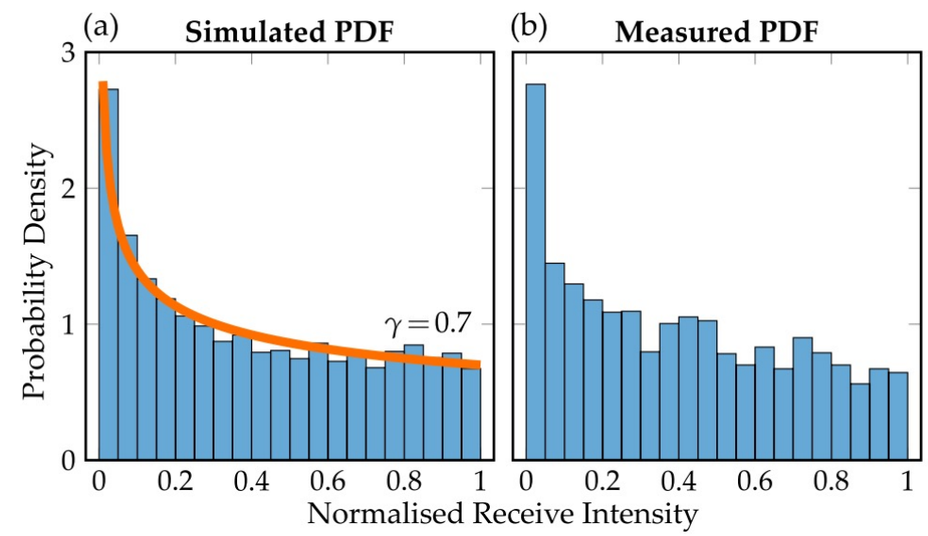
Structured Light in Turbulence. *IEEE Journal of Selected Topics in Quantum Electronics*, doi.org/10.1109/JSTQE.2020.3023790

We can model the beam wander very accurately

Using an auto-regressive moving average time series.

$$x_t = y_t = c + \sum_{i=1}^{p} M_i x_{t-i} + \sum_{j=1}^{q} N_j \epsilon_{t-j} + \epsilon_t$$



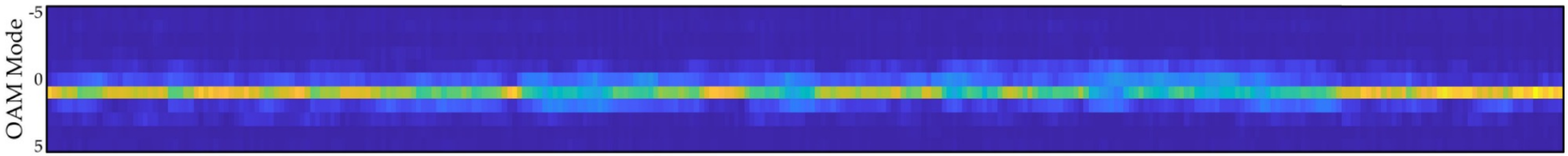


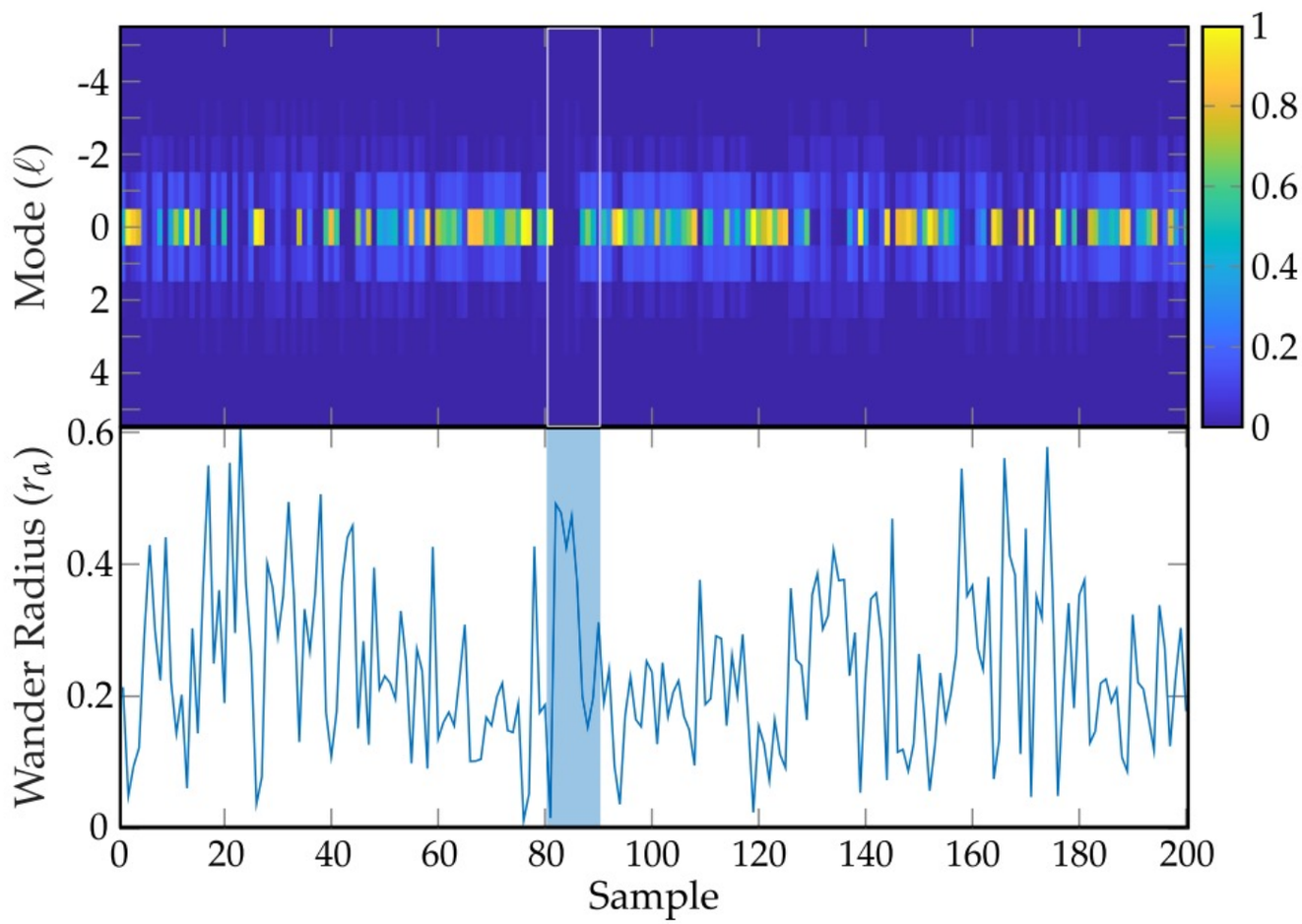
Structured Light in Turbulence, *IEEE Journal of Selected Topics in Quantum Electronics*, doi.org/10.1109/JSTQE.2020.3023790

We can map beam wander to OAM crosstalk

This means we can “predict” crosstalk, and then use OAM channels strategically?

Tilt and displacement causes OAM crosstalk, so we have a dynamic model now:

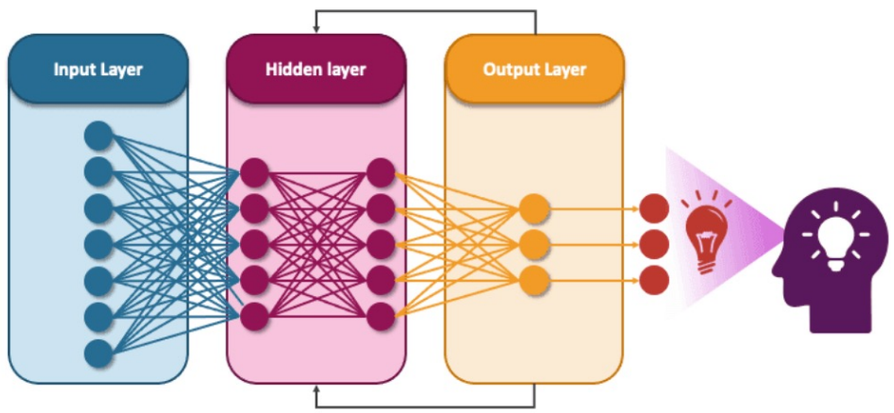


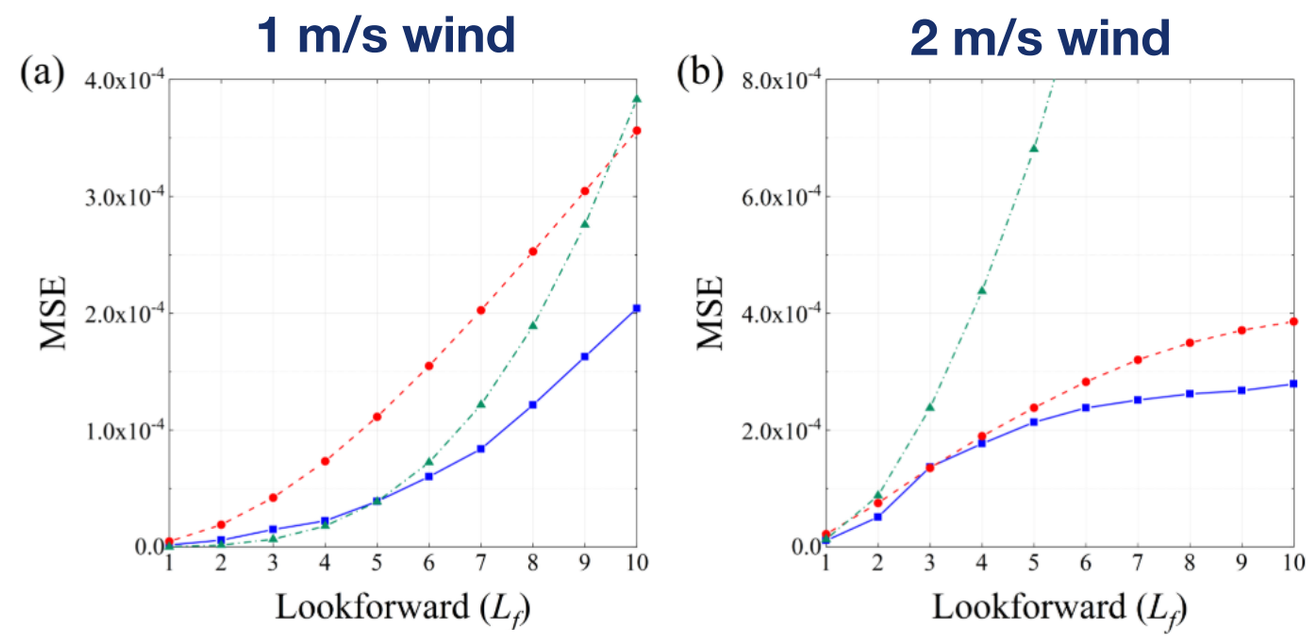


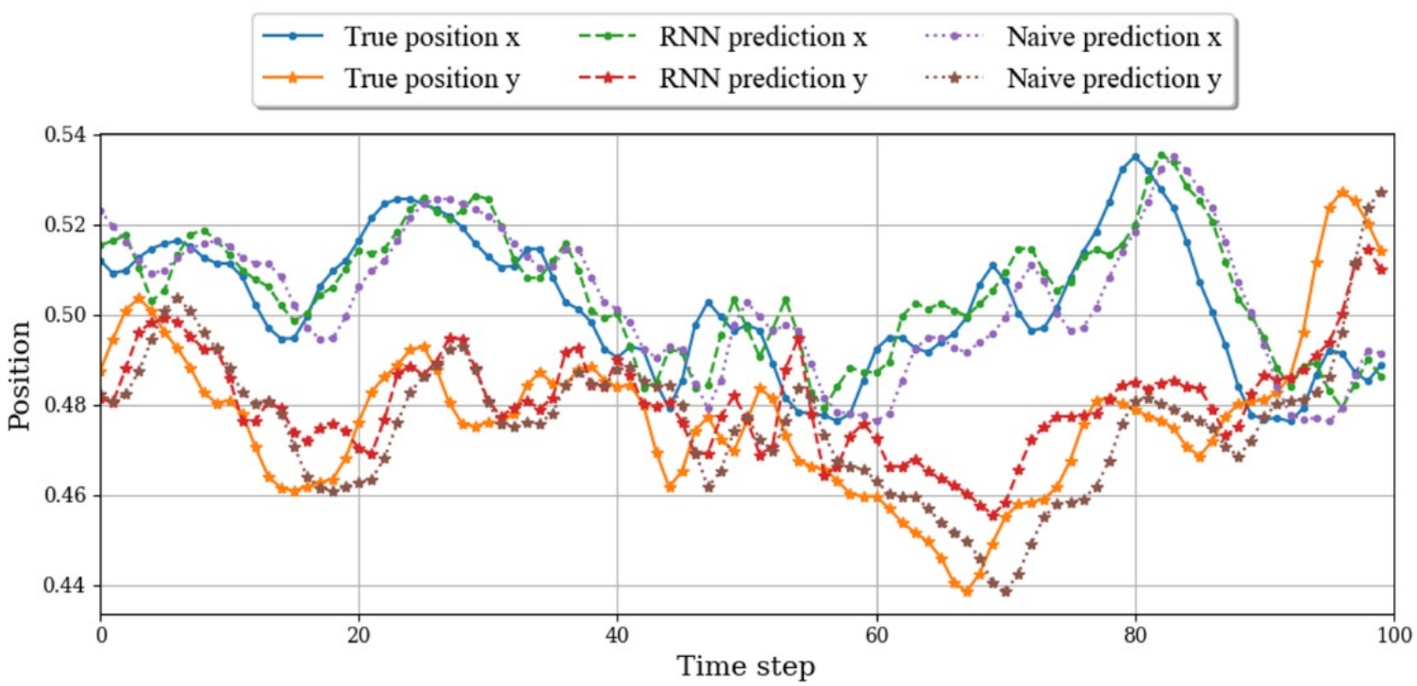
Structured Light in Turbulence, *IEEE Journal of Selected Topics in Quantum Electronics*, doi.org/10.1109/JSTQE.2020.3023790

We repeated this using a recurrent neural network

And stronger turbulence with varying wind conditions. Predictive power is quite good!







Beam wander prediction with recurrent neural networks, *Optics Express*, doi.org/10.1364/oe.496690

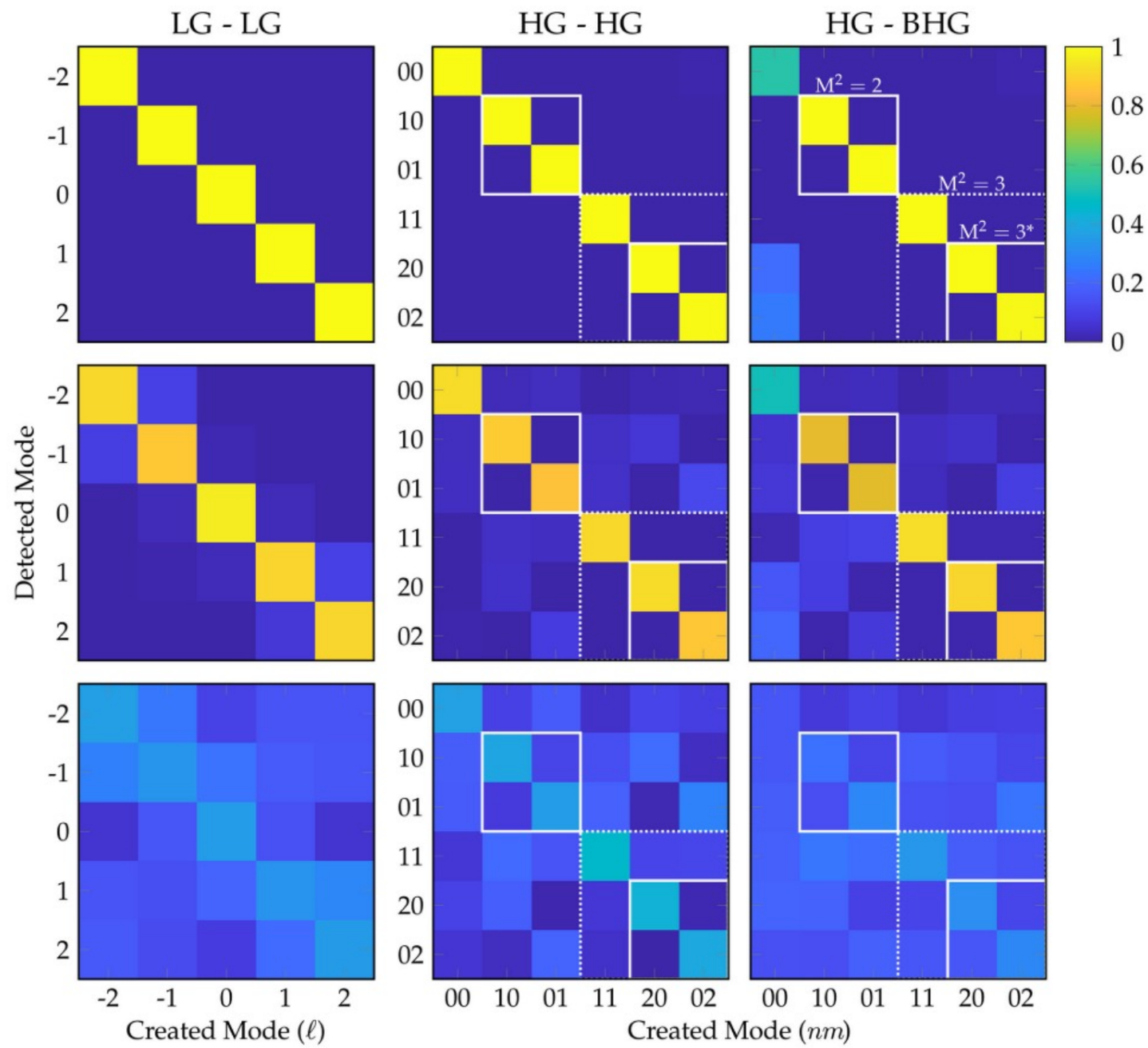
Crosstalk is a challenge that need to be understood…

Structured light in turbulence is (very) tough to model analytically.

No Turbulence

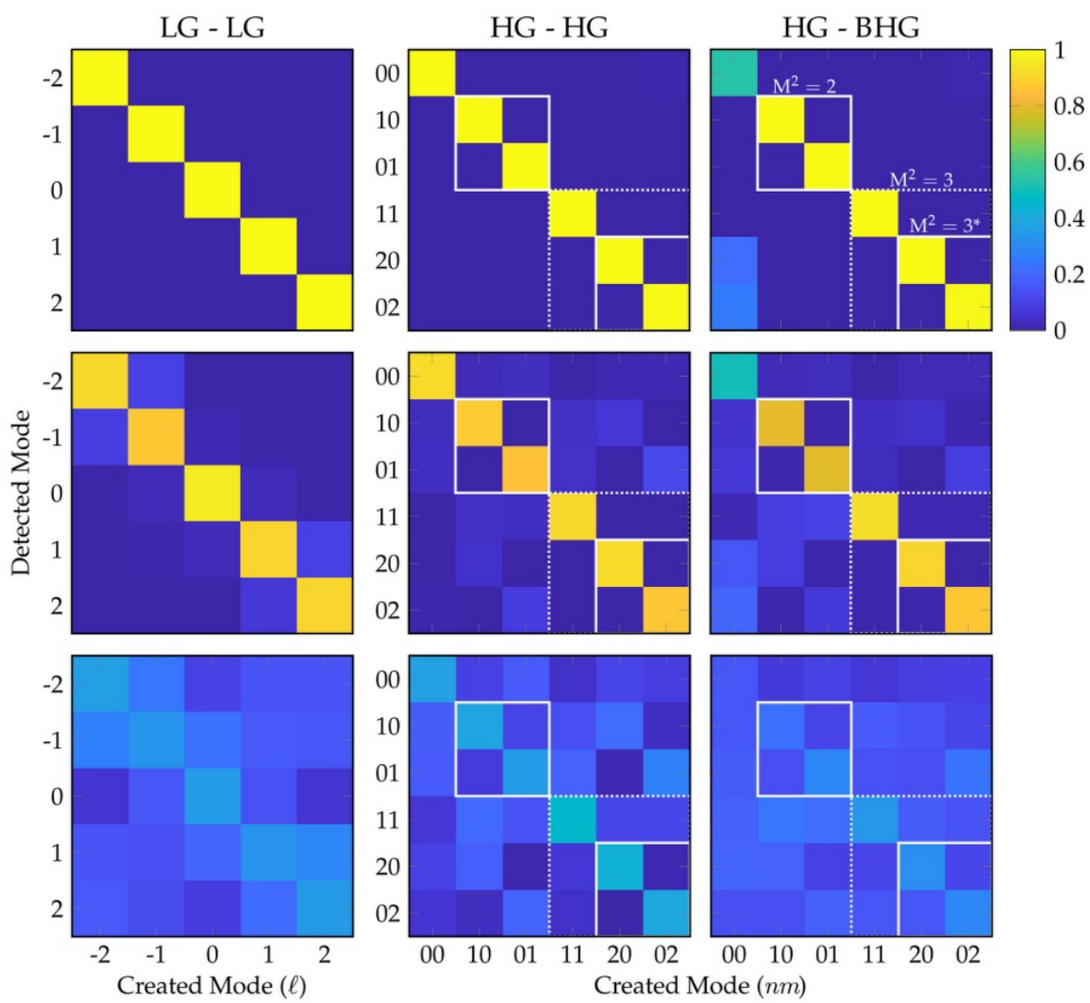
Weak Turbulence

Stronger Turbulence



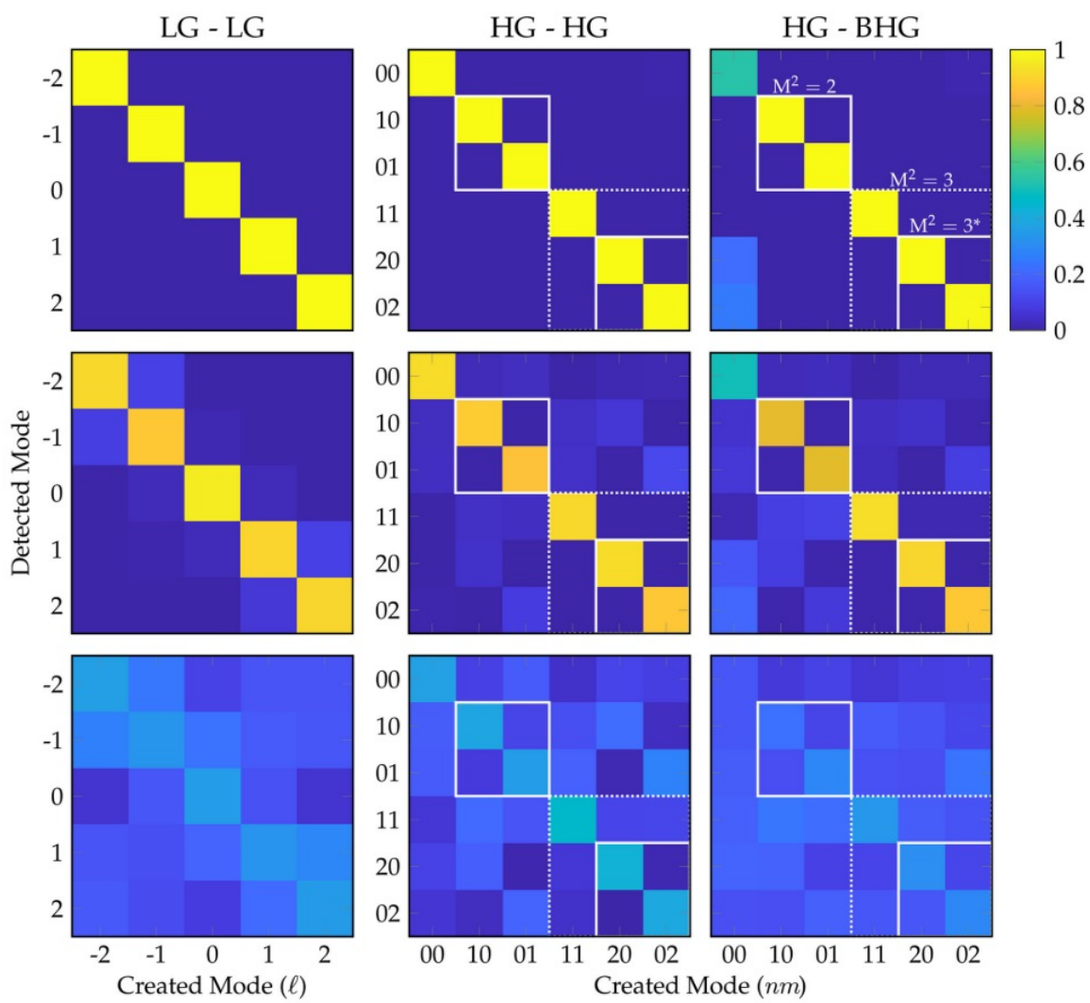
The Resilience of Hermite– and Laguerre–Gaussian Modes in Turbulence, *J. Light. Technol.*, 10.1109/JLT.2019.2905630.

How is this plot and this “AI Art” similar?



How is this plot and this “AI Art” similar?

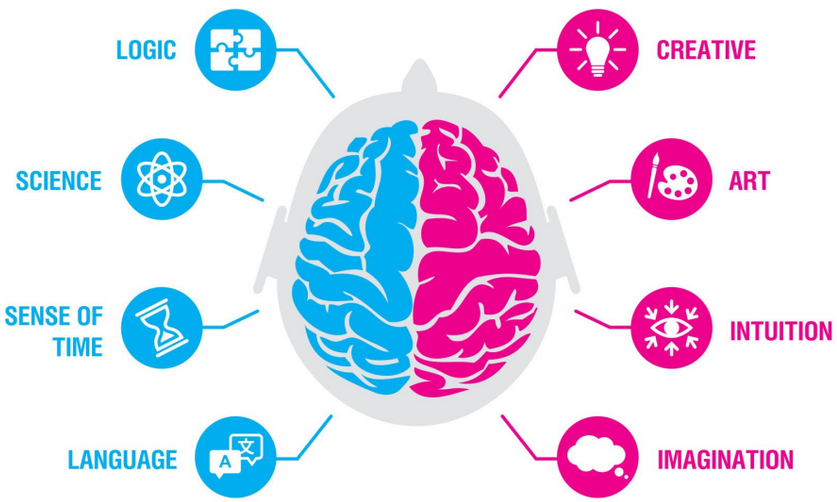
Both are just **probability distributions**… Can we model the statistics of crosstalk with ML?

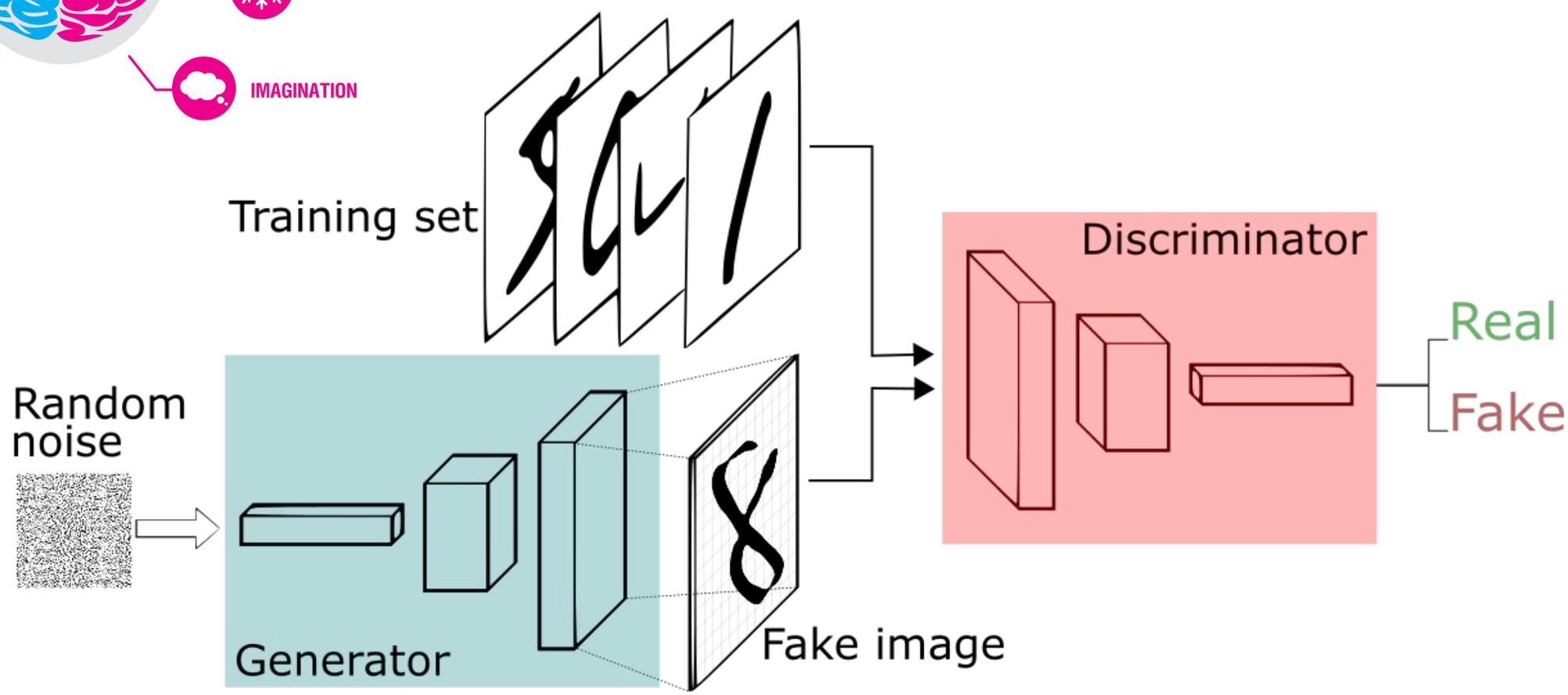


Efficient channel modeling of structured light in turbulence using generative adversarial networks, *Optics Express*, 10.1364/OE.448899

Generative Adversarial Networks

They seem to work like our brains do…





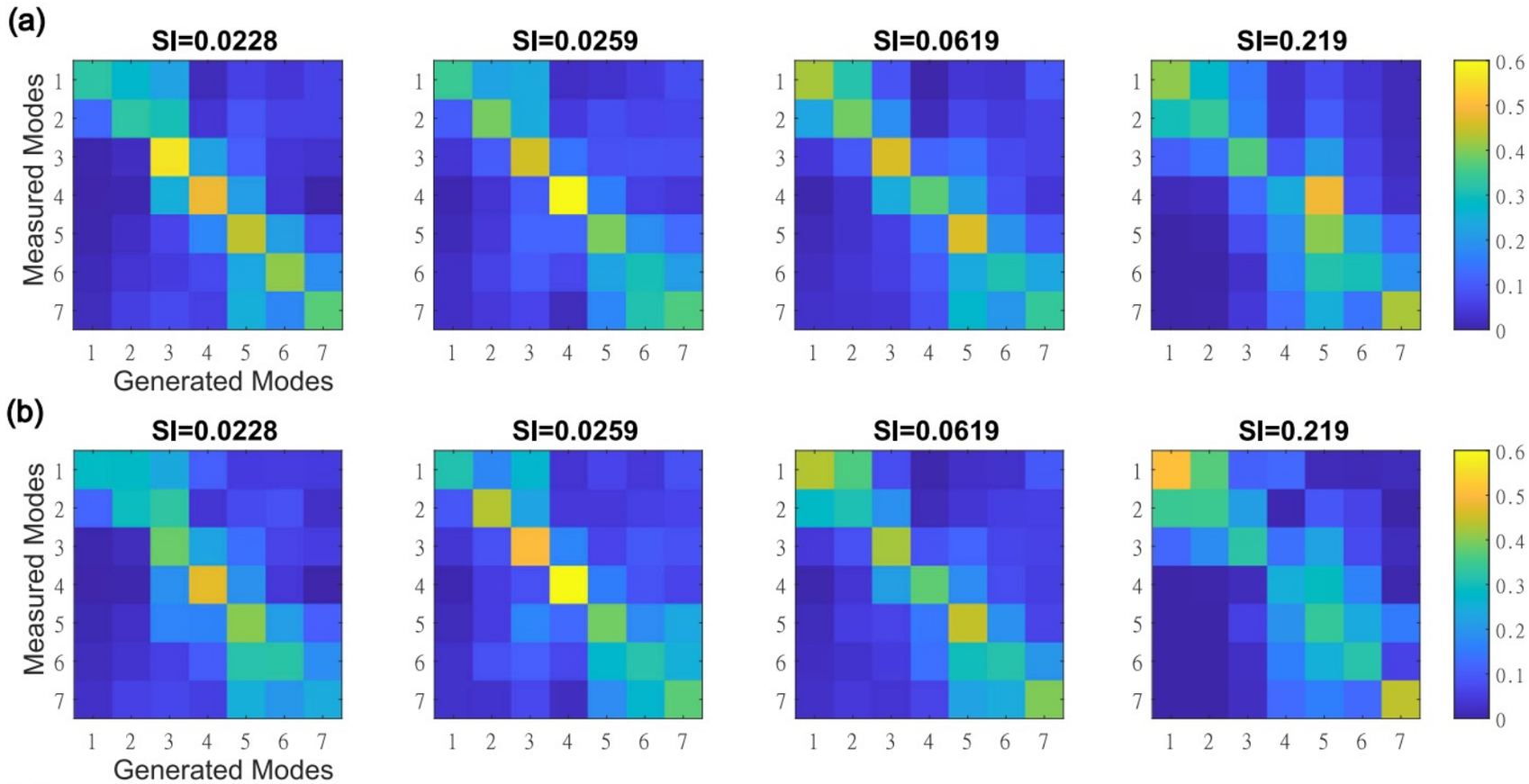
Efficient channel modeling of structured light in turbulence using generative adversarial networks, *Optics Express*, 10.1364/OE.448899

We trained our GAN to generate samples of LG and HG crosstalk

On average (~1000 samples), what we generate matches the experimental measurements.

Experimental Average

GAN Average



Efficient channel modeling of structured light in turbulence using generative adversarial networks, *Optics Express*, 10.1364/OE.448899

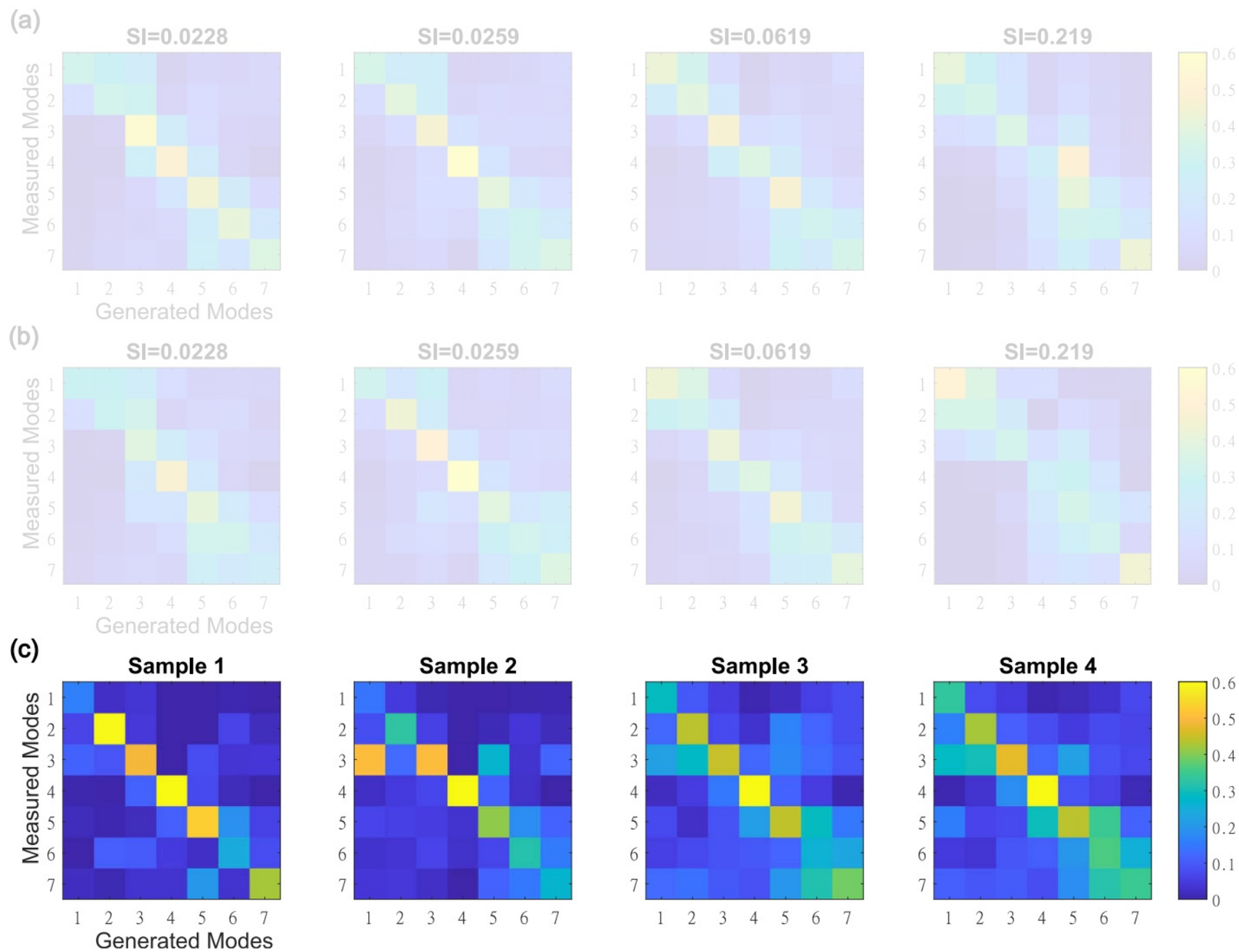
The model is also accurate sample by sample

Analytical methods rely on long term averages or probability distributions, and it takes a while for some clever mathematicians to produce this theory (if ever).

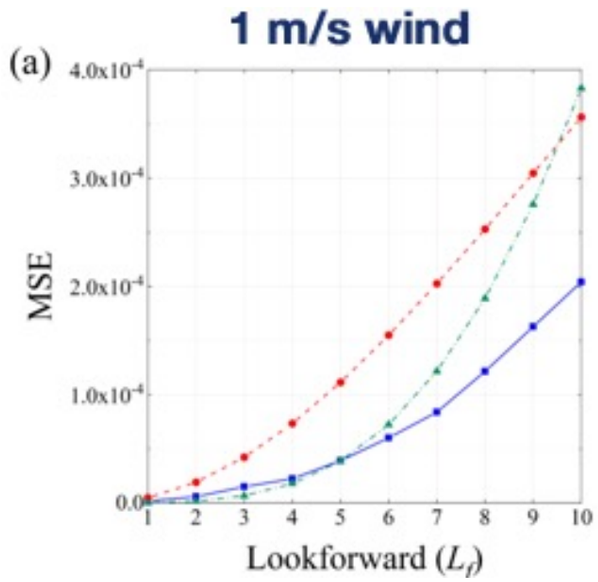
Experimental Average

GAN Average

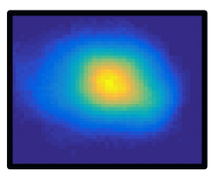
GAN Samples



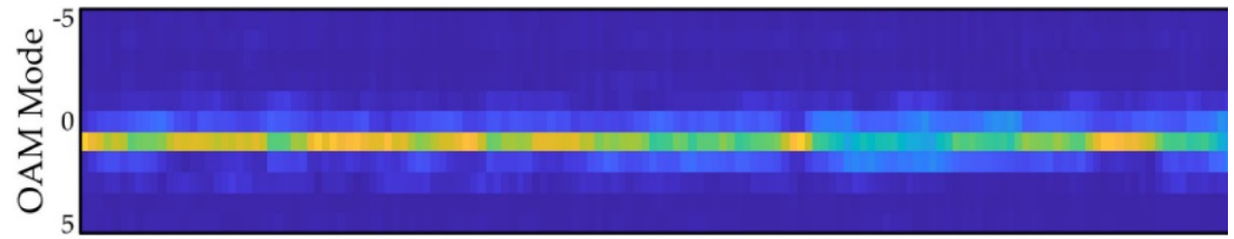
Efficient channel modeling of structured light in turbulence using generative adversarial networks, *Optics Express*, 10.1364/OE.448899



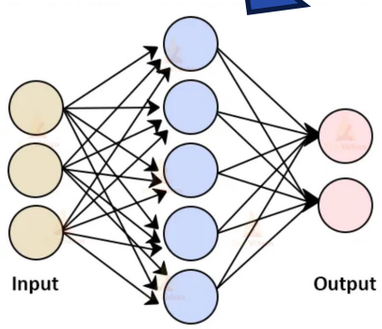
Modelling the dynamics of beam wander



Mapping this to the dynamics of OAM crosstalk



Analytically this is tough, so we are modelling this with ML too. (WIP)



"Arbitrary" Mode Crosstalk Simulation

Modelling and Machine Learning Summary

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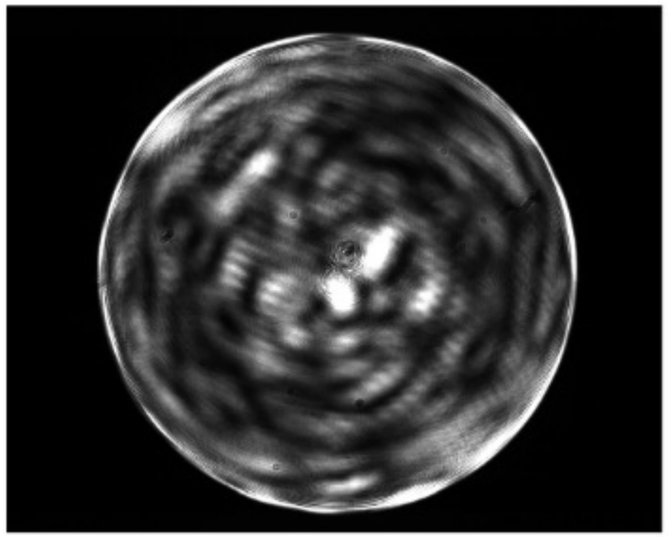
Modelling the dynamics of beam wander

Mapping this to the dynamics of OAM crosstalk

Analytically this is tough, so we are modelling this with ML too. (WIP)



Optical Neural Networks?

"Arbitrary" Mode Crosstalk Simulation

Modelling and Machine Learning Summary

Thank you!

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OPTICAL COMMUNICATION LABORATORY
WITS UNIVERSITY