# Superconducting On-chip Fourier Transform Spectrometer

Ritoban Basu Thakur (NASA-JPL & Caltech)

Chicago, 2023

# Introduction

Fourier Transform Spectrometer (FTS), i.e.,
interferometers have a storied heritage in physics:

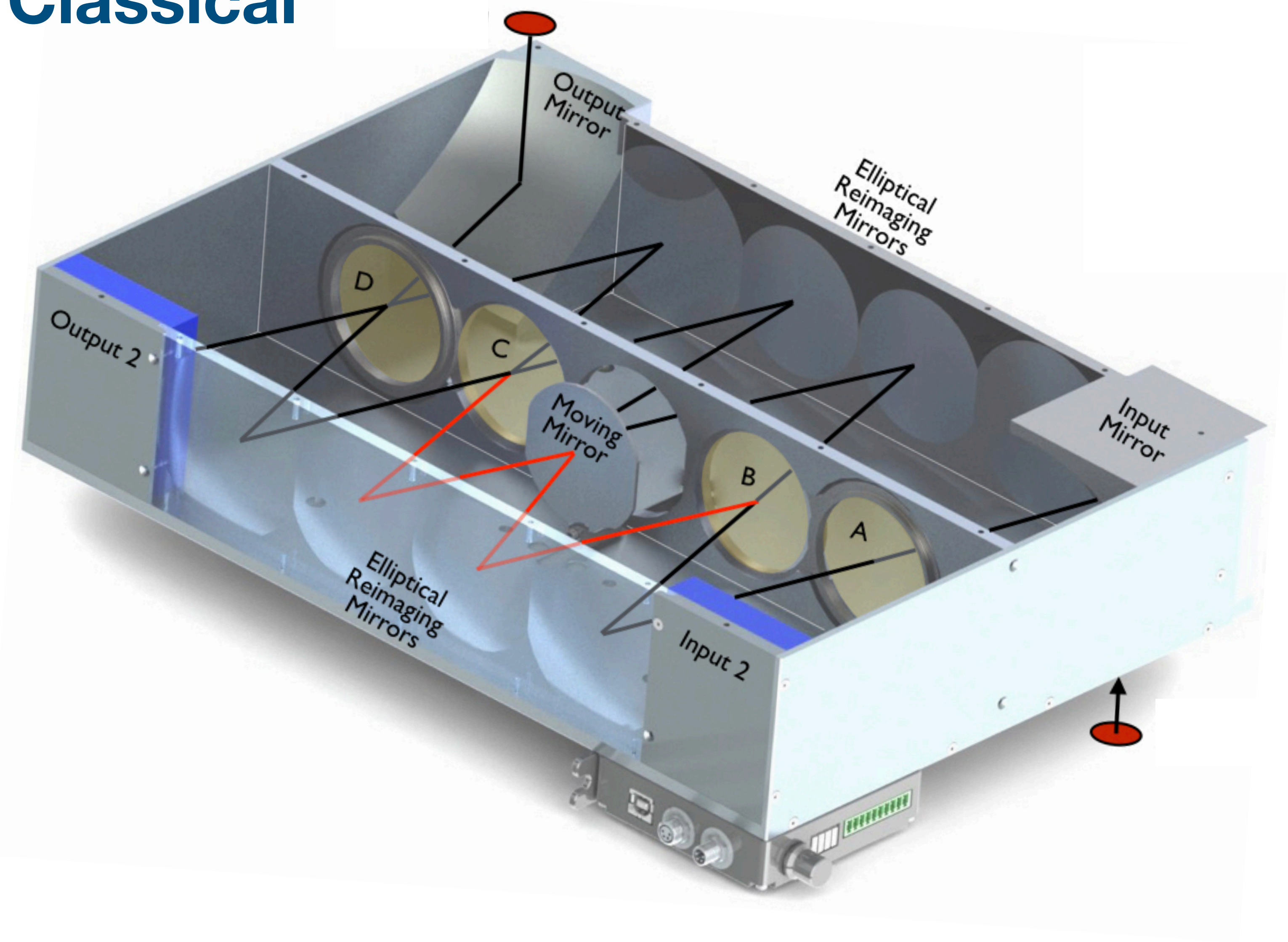
**Michelson-Morley** -> Disproves aether

**COBE / FIRAS** -> Measures CMB color spectrum

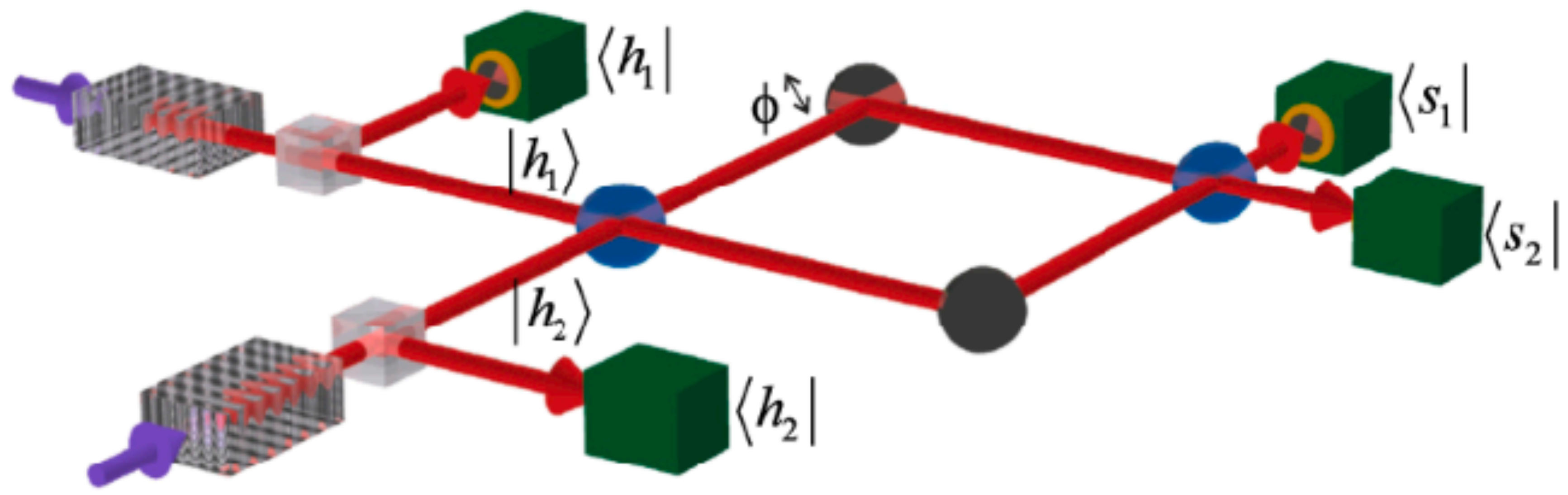
**LIGO** -> Measures gravitational waves

**Quantum Optics** -> 2022 Nobel for Aspect and colleagues testing photon interference and entanglement

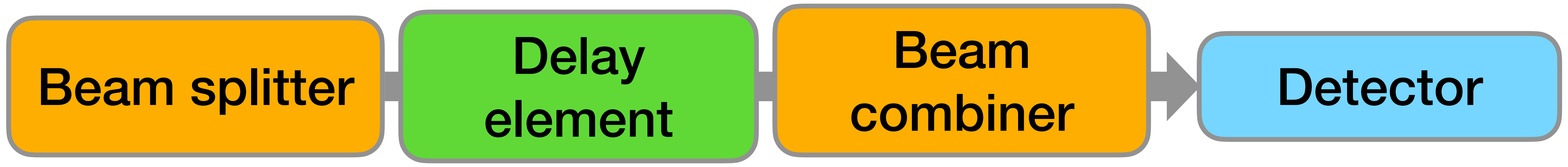
**Classical**



**Quantum**



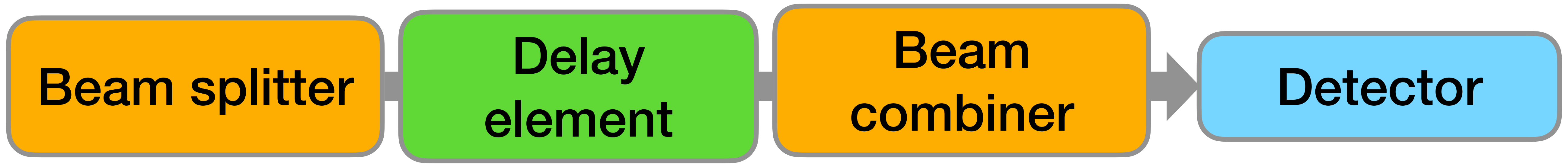
**FTS: wide scientific applications with only,**



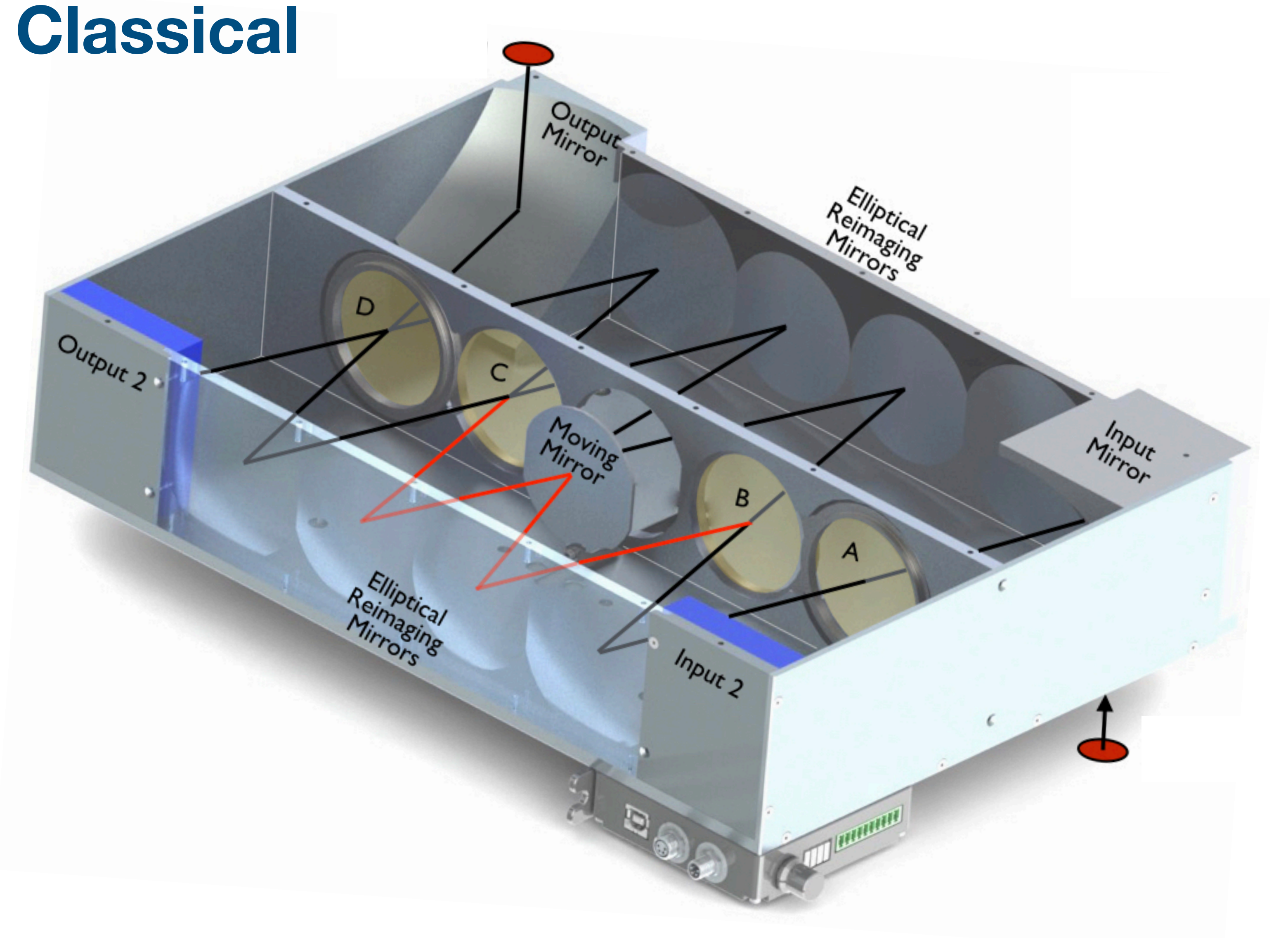
Beam splitter → Delay element → Beam combiner → Detector

# Introduction

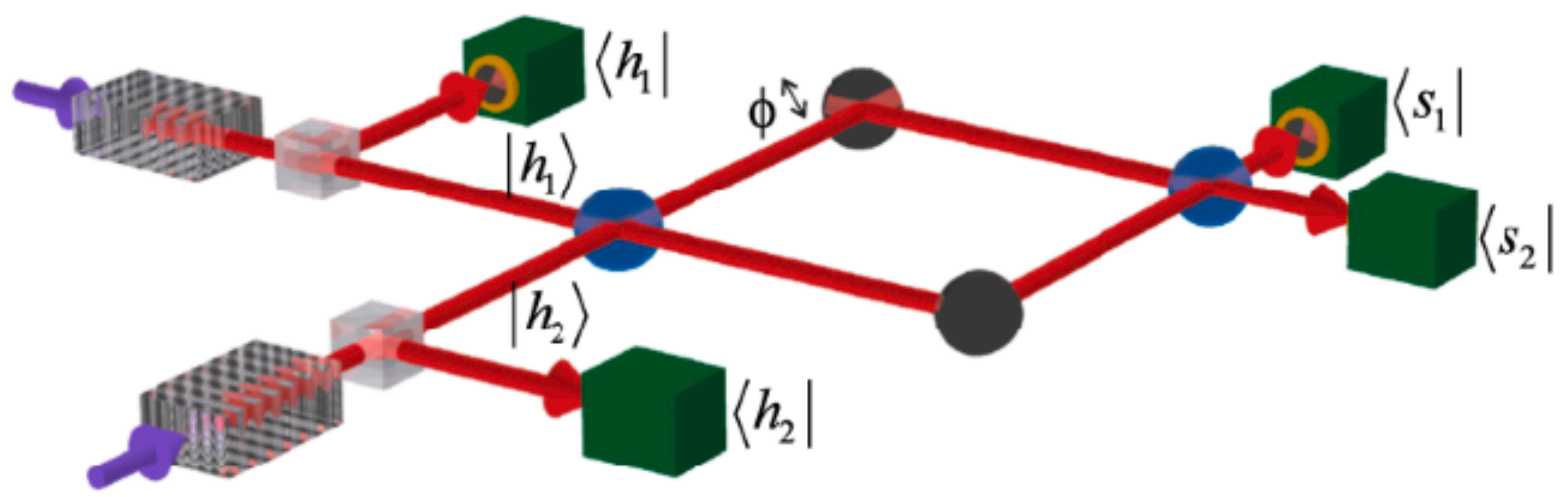
OSA Applied optics Vol. 58, Issue 23 Pan, Liu, **RBT** , Meyer et al
OSA Applied optics Vol. 59, Issue 25 Liu, Pan, **RBT** , Meyer et al
NPJ Quantum Inf 6, 89 (2020).


Beam splitter
Delay element
Beam combiner
Detector

**Classical**



**Quantum**

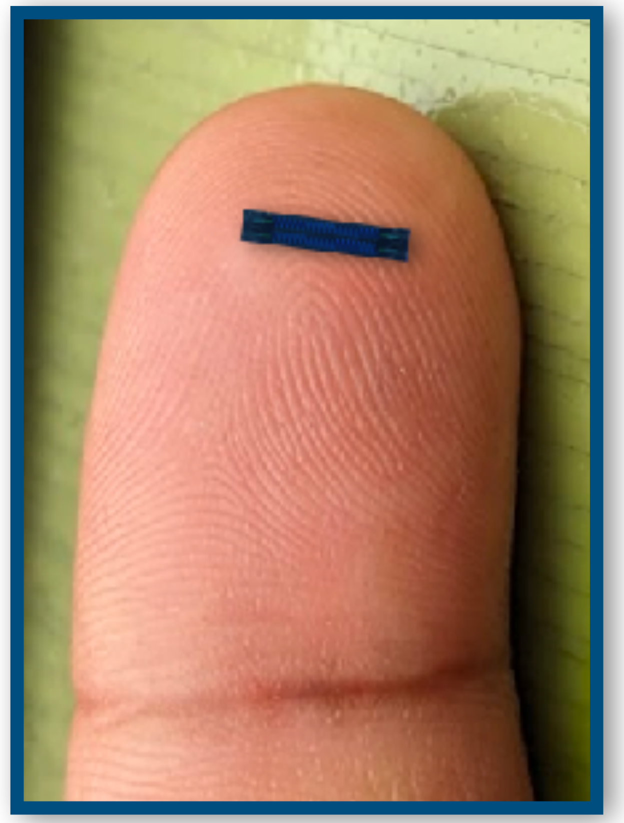


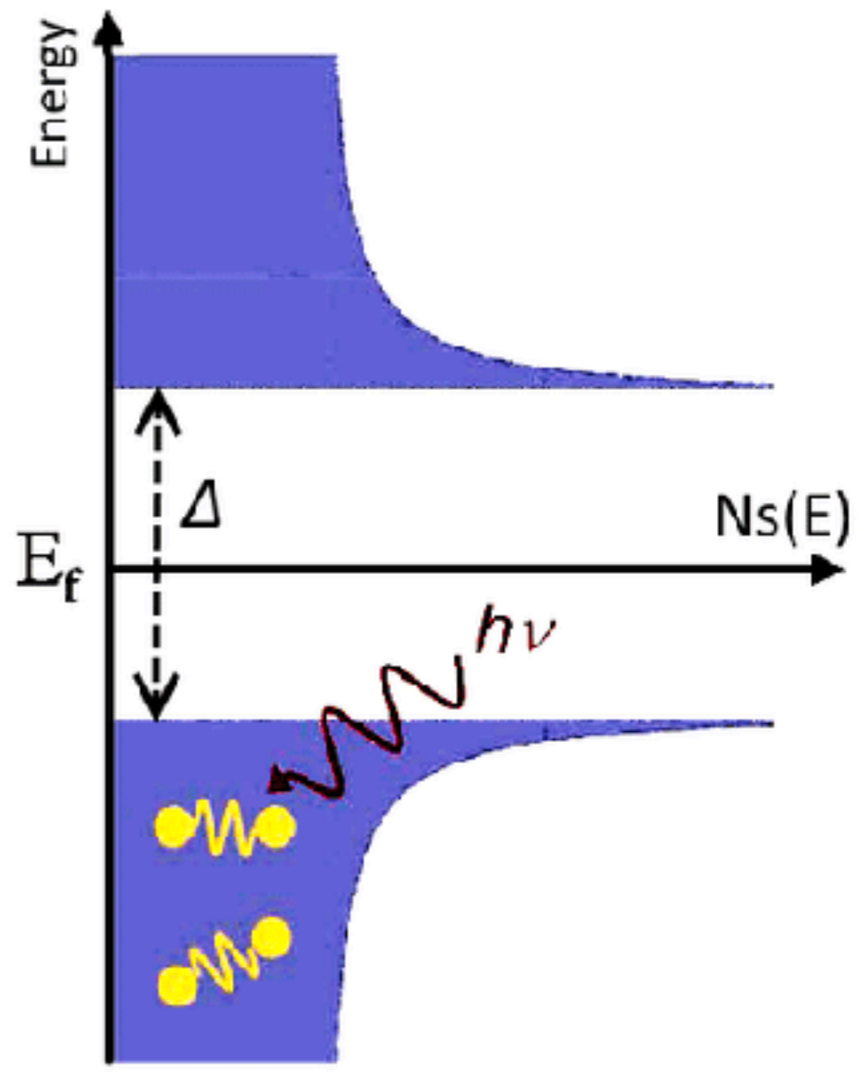
At long-wavelengths optical elements are large…
Challenges with integration, alignment, loading, systematics and scalability issues

Long ☞ $\nu$ ~GHz - THz / $\lambda$ ~10 cm - 0.1 mm

## Superconducting & quantum techniques help

Maintain key FTS advantages (broad-band, tunable resolution)
… whilst making it lossless, planar, ultra-compact, electronic, & integrable with different antennas + detectors.





**FTS: wide scientific applications with only,**

Beam splitter → Delay element → Beam combiner → Detector

?

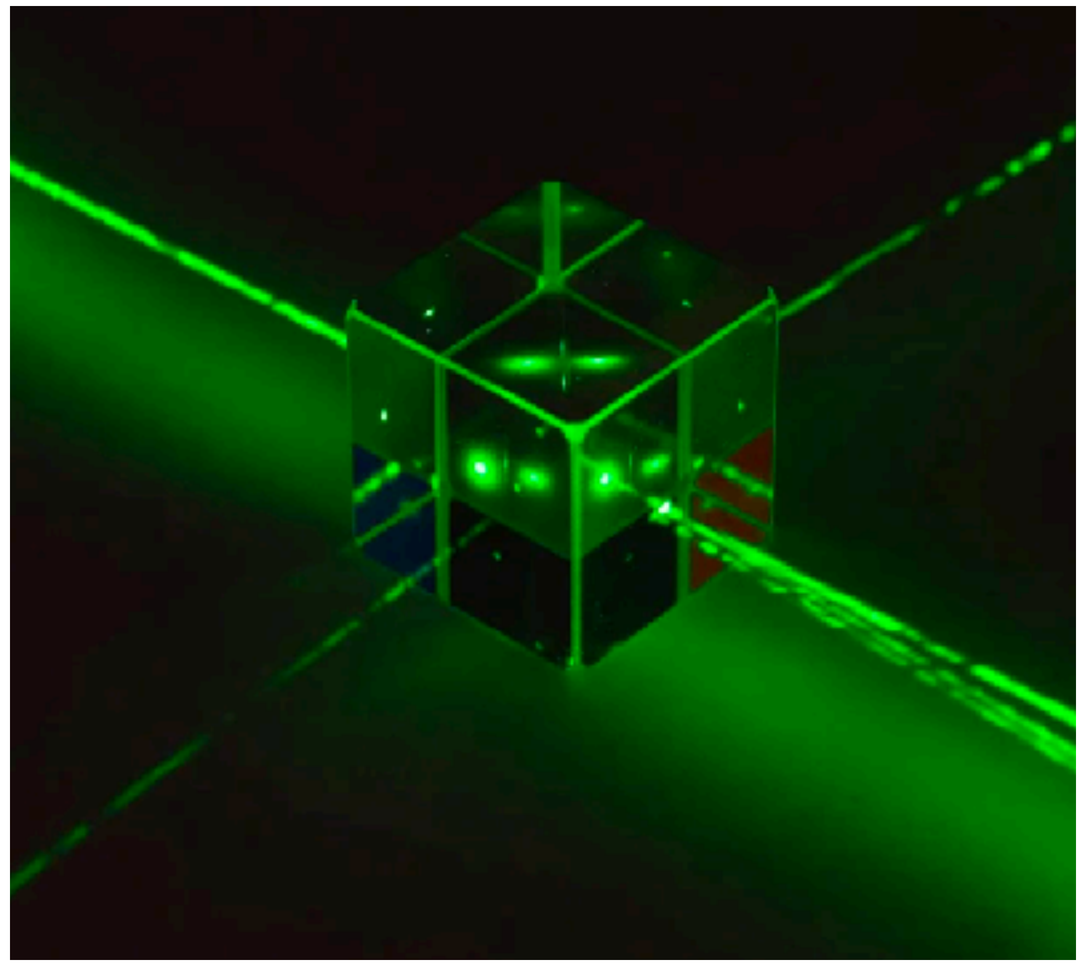
?

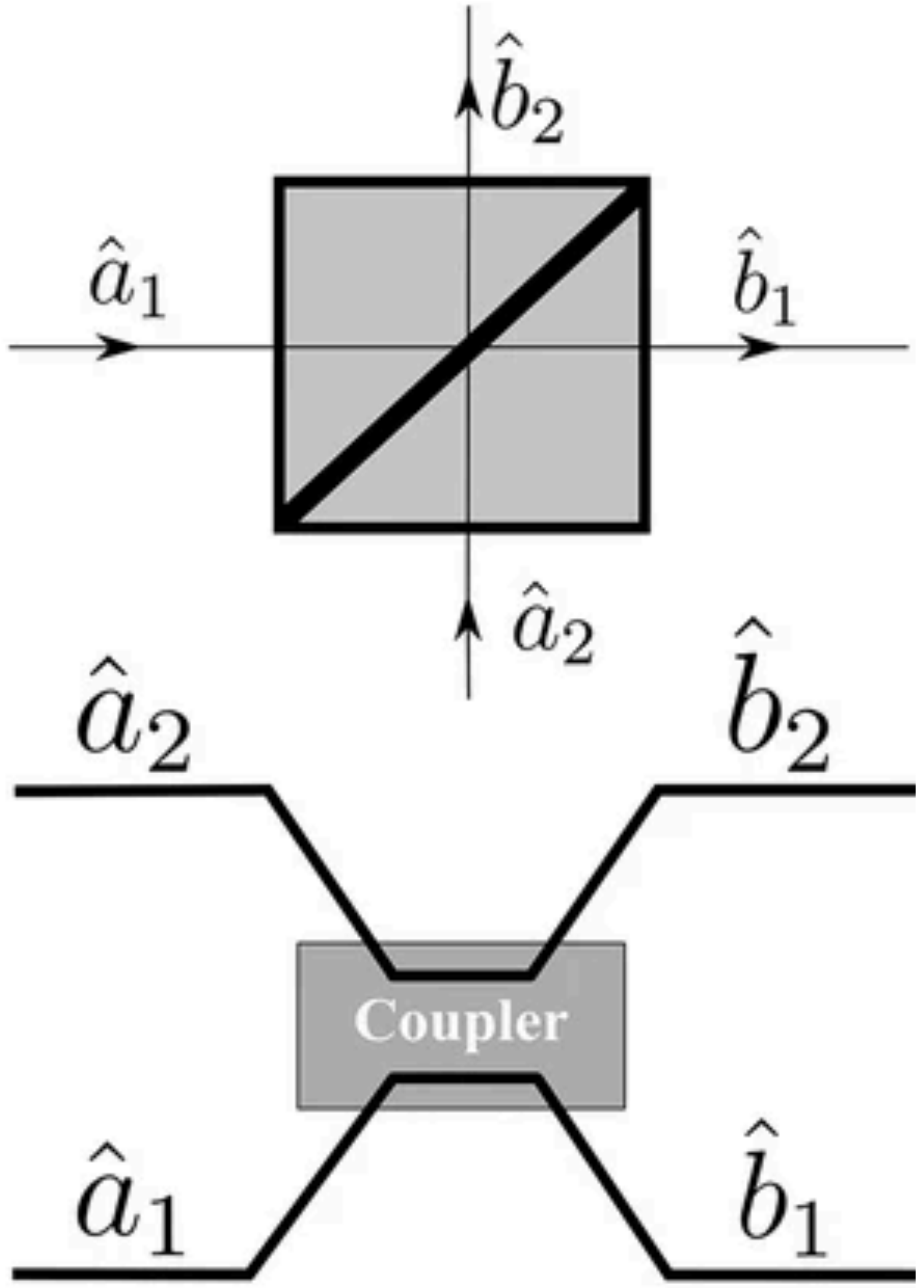
?

✓

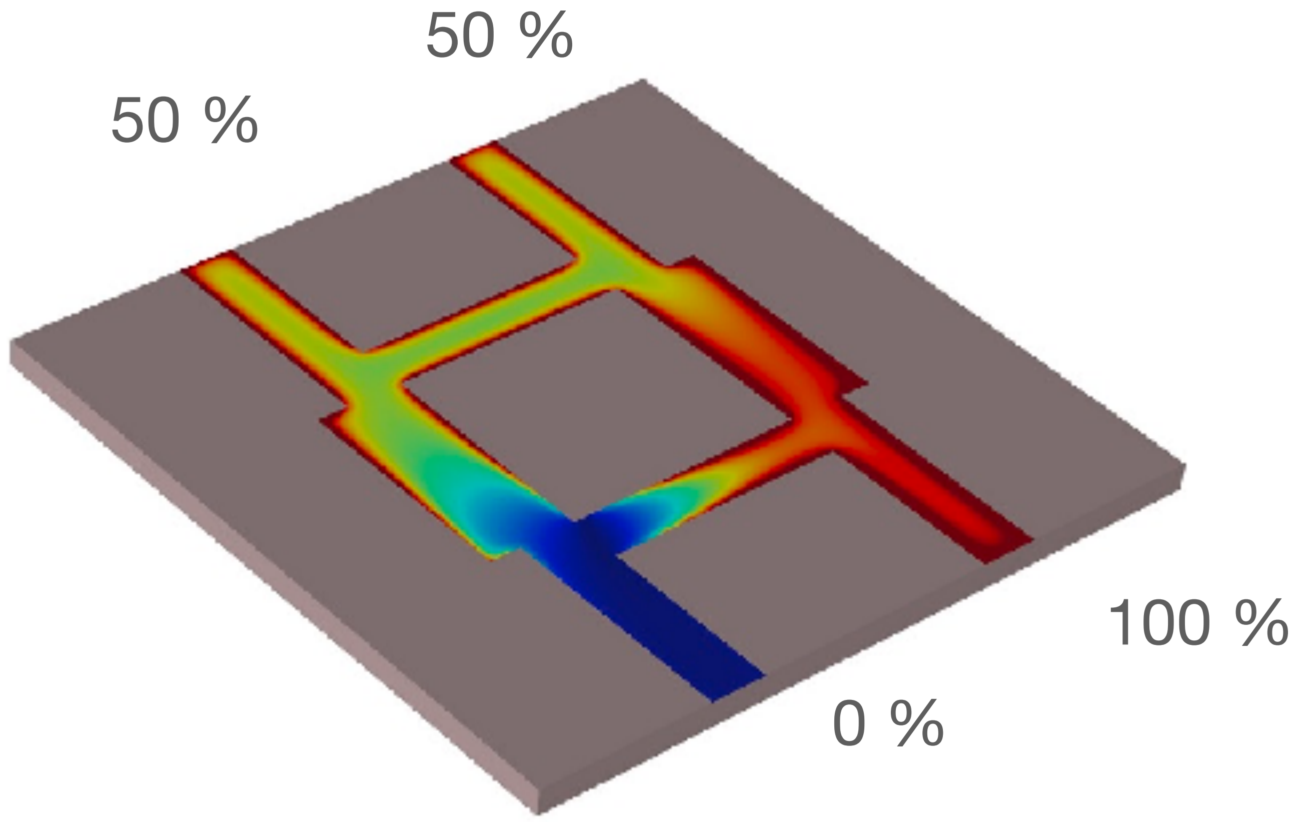
MKID
QUBIT
QCD
Bolos
....

# Beam splitter / combiner





Hybrids or branch-line couplers are commonly used in microwave engineering as beam splitters / combiners



E-field in a single-cell splitter / combiner

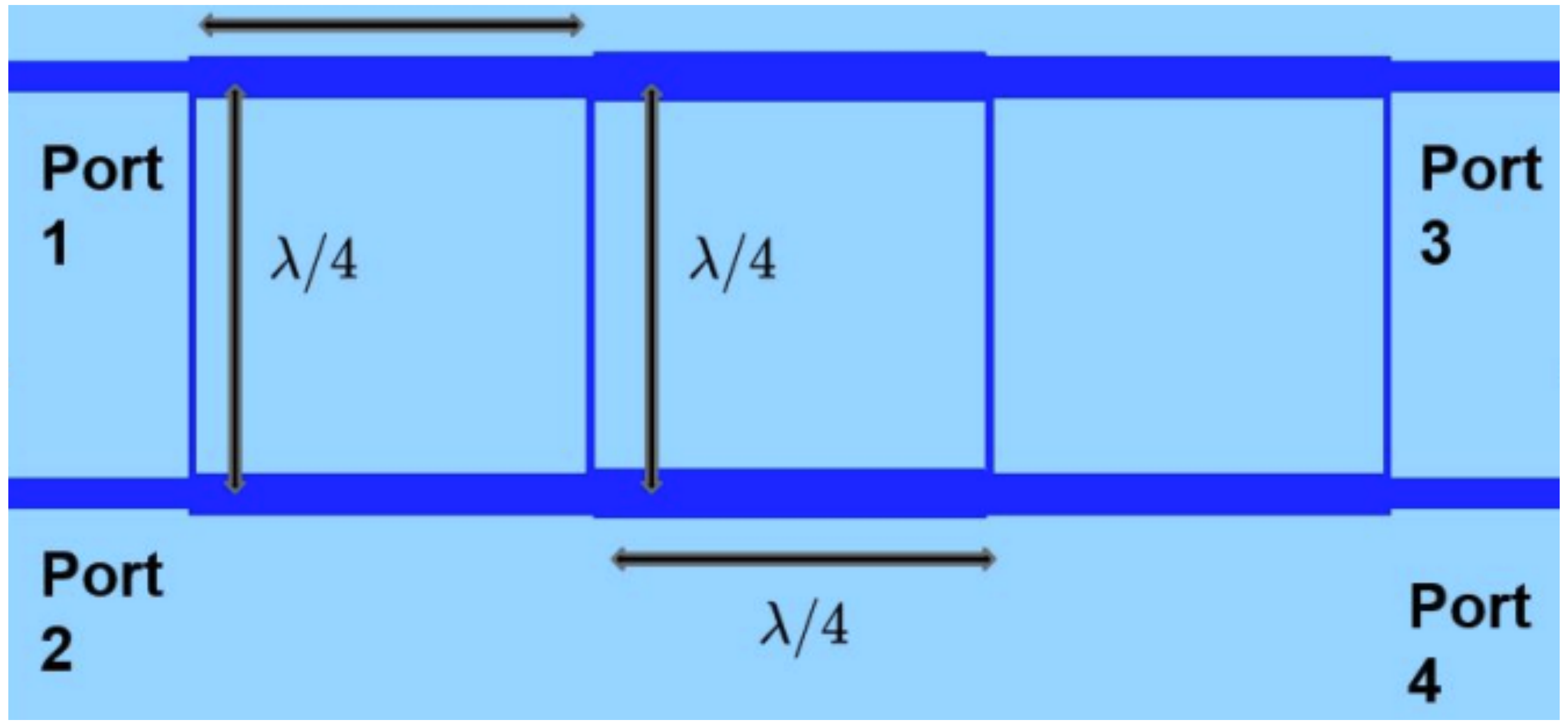
Theory of a frequency-dependent beam splitter in the form of coupled waveguides
Dmitry N. Makarov Scientific Reports volume 11, Article number: 5014 (2021)

Pozar, David M. Microwave Engineering. Hoboken, NJ :Wiley, 2012.

# Beam splitter / combiner

$$|1\rangle$$

$$|2\rangle$$



$$|1\rangle + e^{i\pi/2}|2\rangle$$

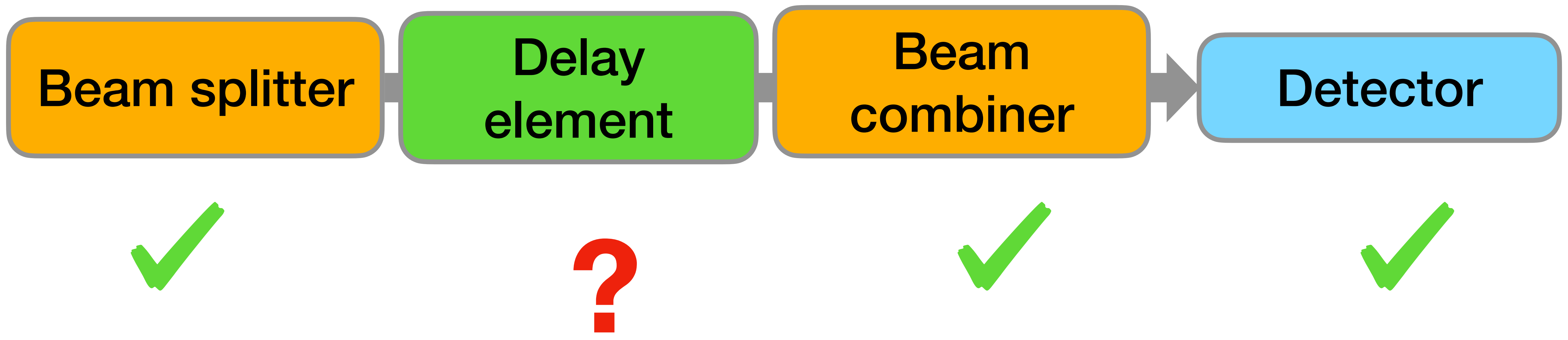
$$|1\rangle - e^{i\pi/2}|2\rangle$$

Photon states / E-field combined (or split) with constant phase and *without loss*

Easy to make 90° or 180° hybrid couplers for 4 port or 3 port applications

We choose the number of cells to increase bandwidth

## FTS: wide scientific applications with only,

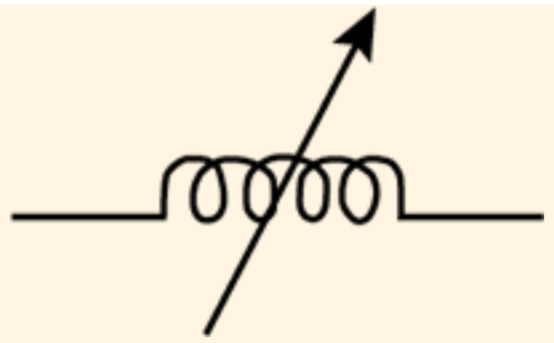

Beam splitter → Delay element → Beam combiner → Detector

✓ ? ✓ ✓

# Non linear Kinetic Inductance

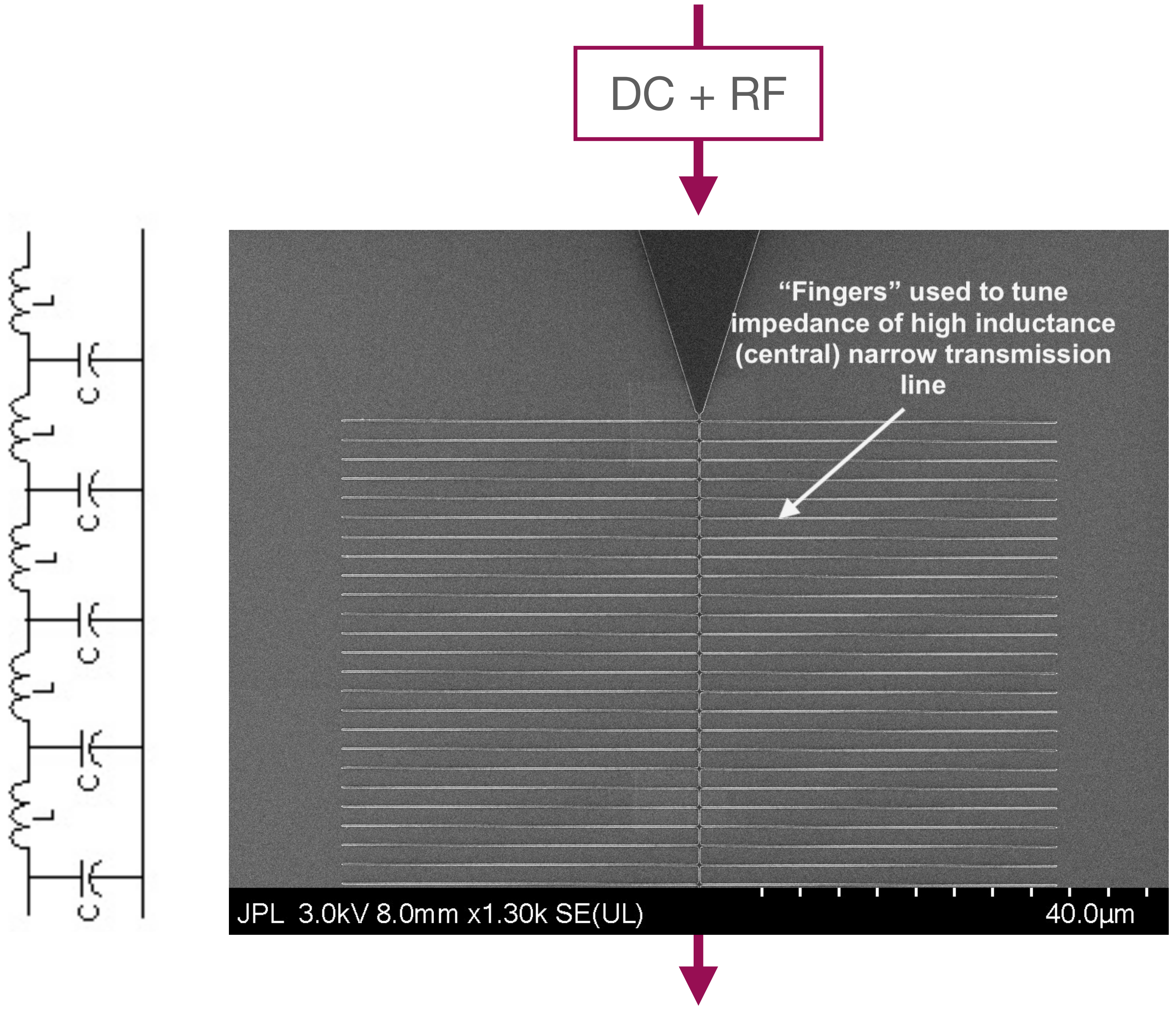
Inertia of Cooper-pairs leads to **kinetic inductance**, or lag w.r.t oscillating EM fields…
depends **nonlinearly** on current in thin-film superconductors like NbTiN, MgB2

$$\mathcal{L}(I) = \mathcal{L}_0 \left(1 + \left(\frac{I}{I_*}\right)^2 \dots\right) =$$



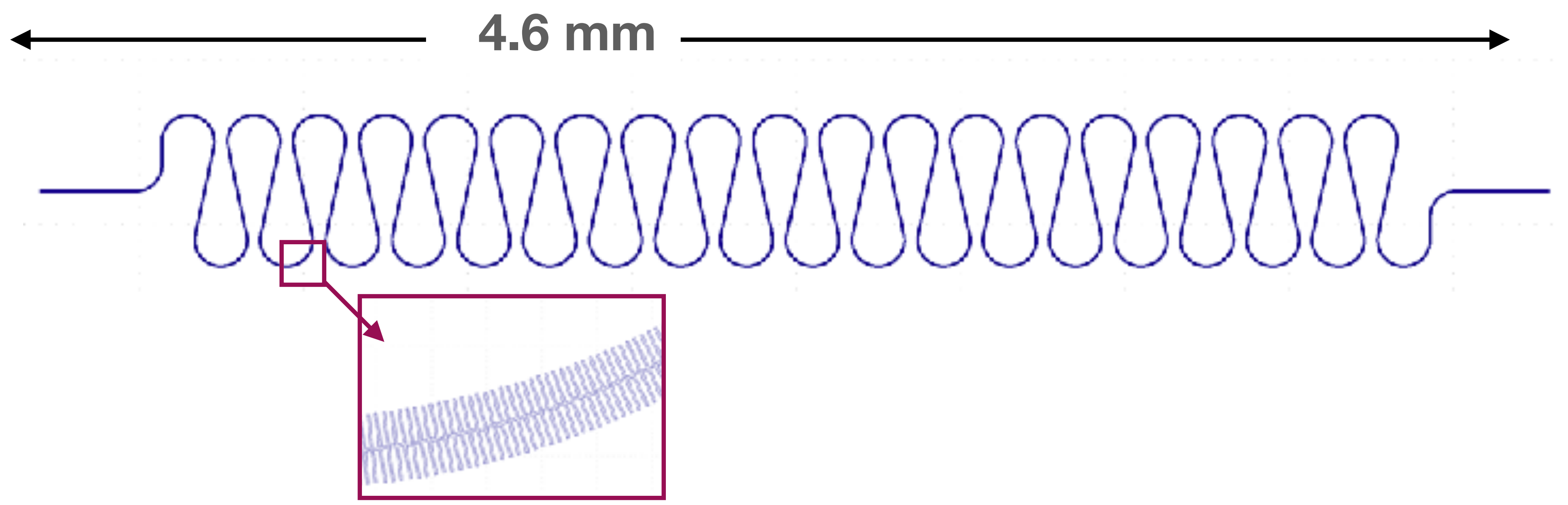
A transmission line = ladder of inductors and capacitors, i.e., “waveguides” in GHz-THz

Ours are 30nm thin, 250nm wide NbTiN lines with capacitative fingers for impedance matching

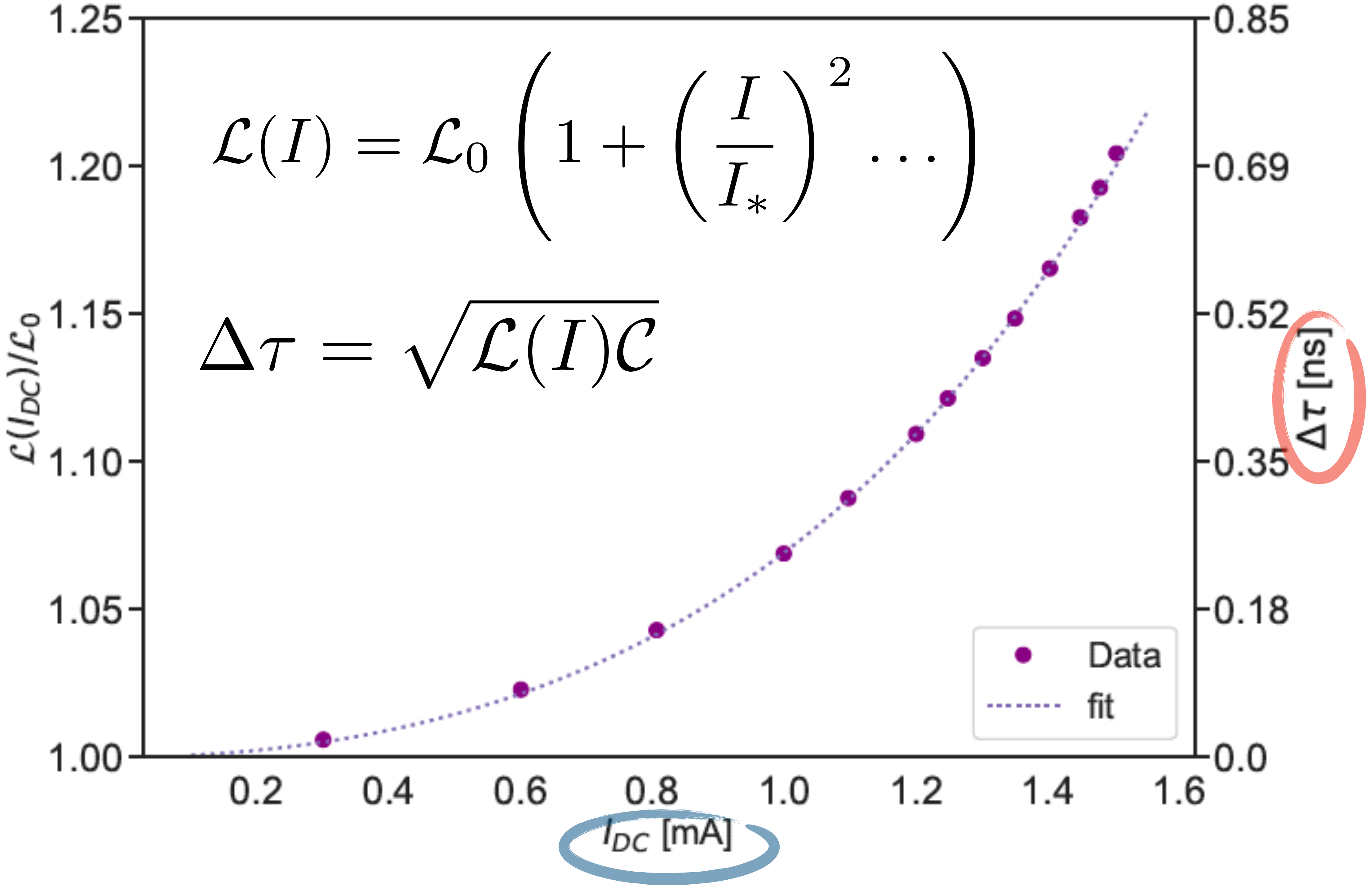


DC bias and measure the inductance and delay $\Delta\tau = \sqrt{\mathcal{L}(I)\mathcal{C}}$ with a commensurate RF signal

# Delay engineering



NbTiN line


$$\mathcal{L}(I) = \mathcal{L}_0 \left(1 + \left(\frac{I}{I_*}\right)^2 \dots\right)$$

$$\Delta\tau = \sqrt{\mathcal{L}(I)\mathcal{C}}$$

**Delay via nonlinear kinetic inductance**

DC bias *increases inductance, reduces phase-velocity & adds delay* in transmission line. Delay measured at 25-40 GHz, with a 21 mm total / 4.6 mm wrapped line.

We achieve electronically tunable delay and also very low phase velocities in these transmission lines

- **Phase velocity ~0.1%c**
- **~10% modulation**

1000x smaller than free-space optics

Delay with DC, **no moving mirrors and optics**

S. Shu, N. Klimovich, B. H. Eom, A. D. Beyer, **RBT**, H. G. Leduc, and P. K. Day Phys. Rev. Research **3**, 023184 arxiv.org:2305.15190

**FTS: wide scientific applications with only,**

Beam splitter → Delay element → Beam combiner → Detector

✓ ✓ ✓ ✓

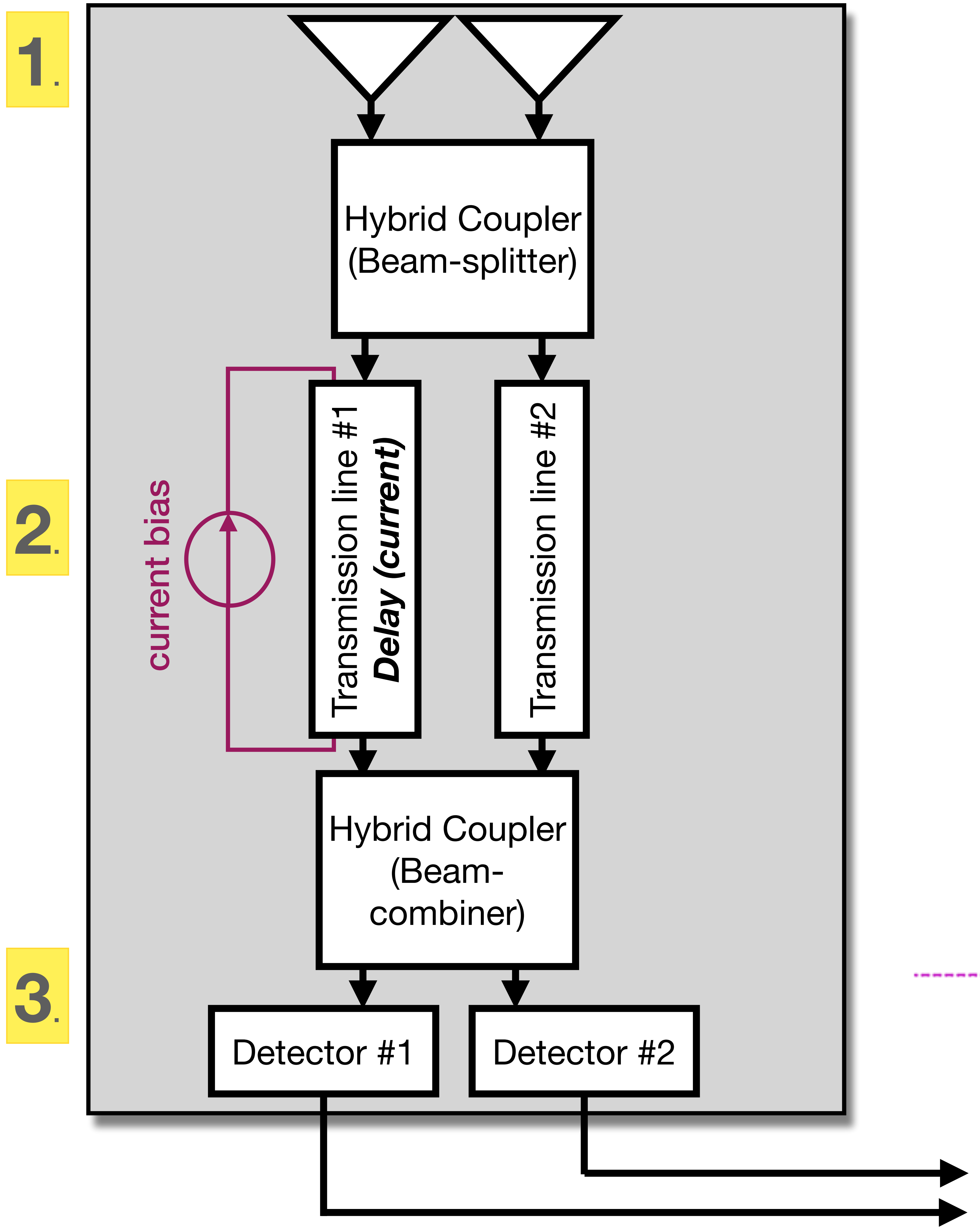
# Now we can build a Superconducting On-Chip FTS (SOFTS) !

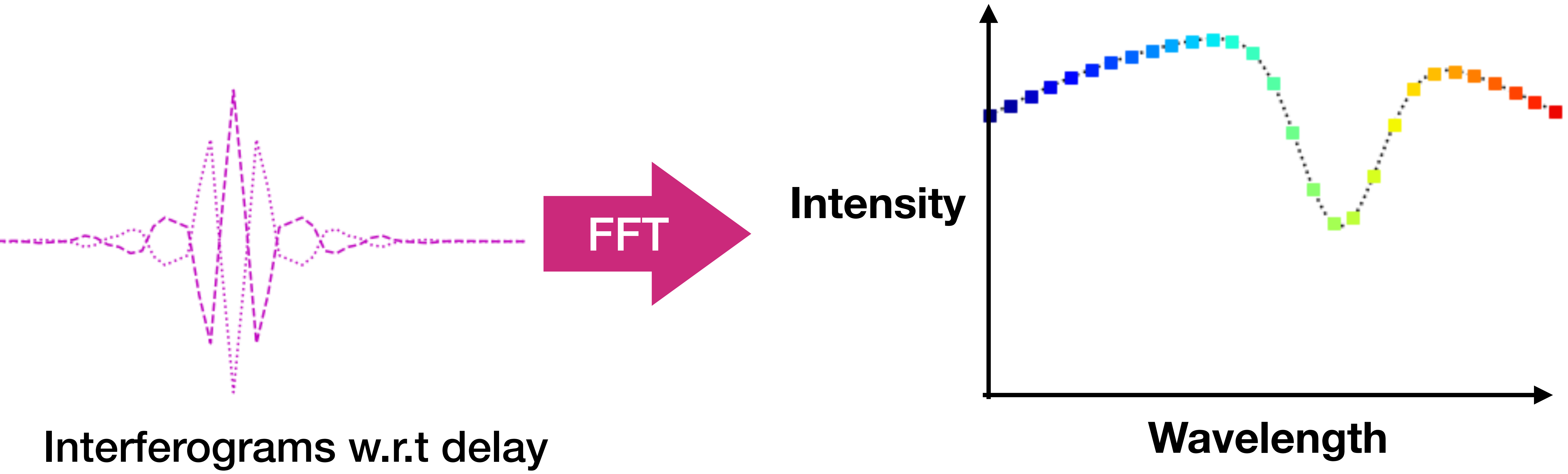
# SOFTS

## Superconducting On-chip Fourier Transform Spectrometer (**SOFTS**) as Mach-Zehnder interferometer

1. Input + reference (or 2$^{nd}$ input) split in two
2. DC bias transmission lines to introduce delay
3. Signals combined into interferograms

**Fourier transform to get spectra**





Interferograms w.r.t delay

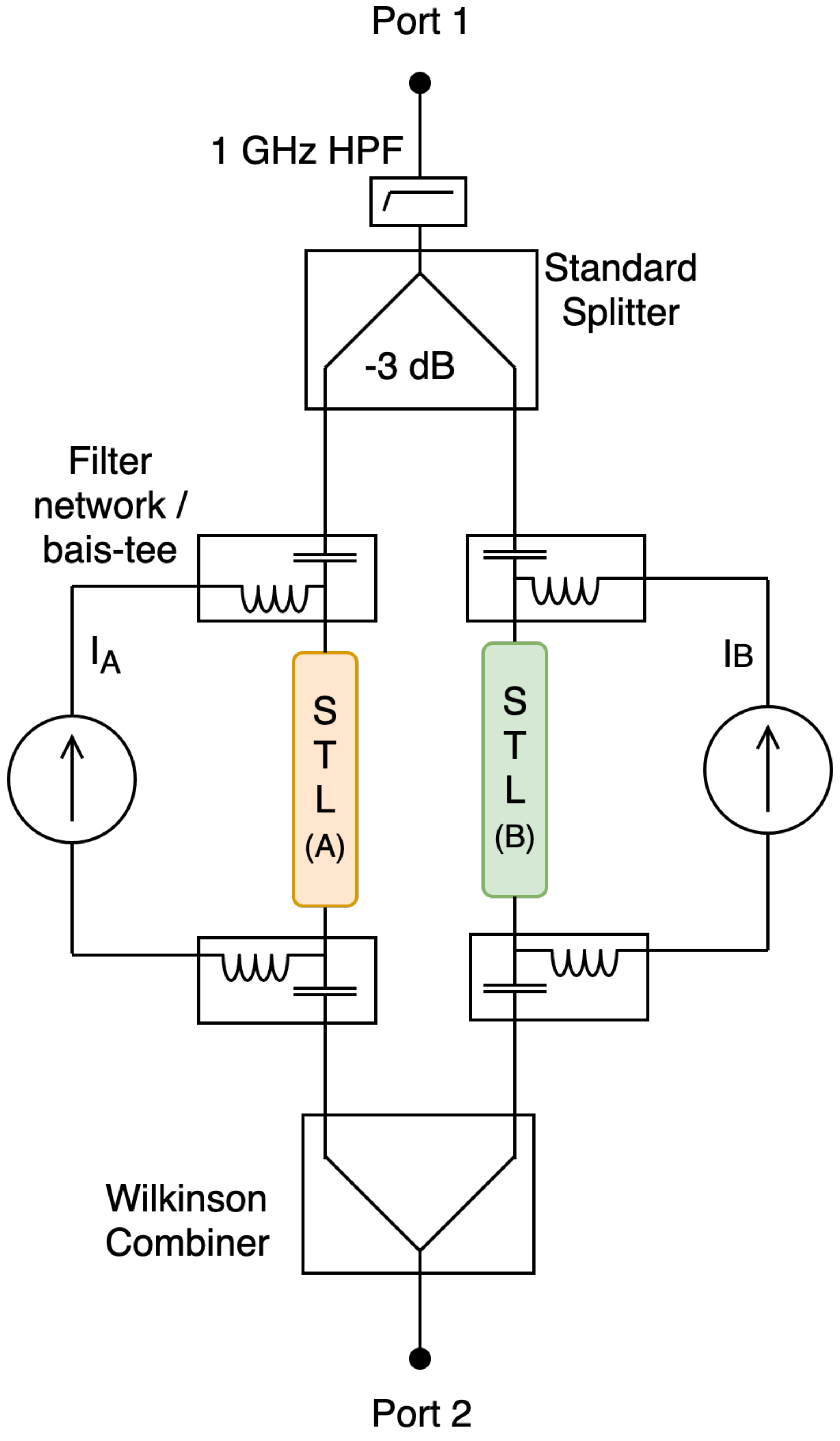
# Prototype SOFTS

$$P_{FTS} \sim P(\nu)(1 \pm \cos(2\pi\nu\Delta\tau))$$

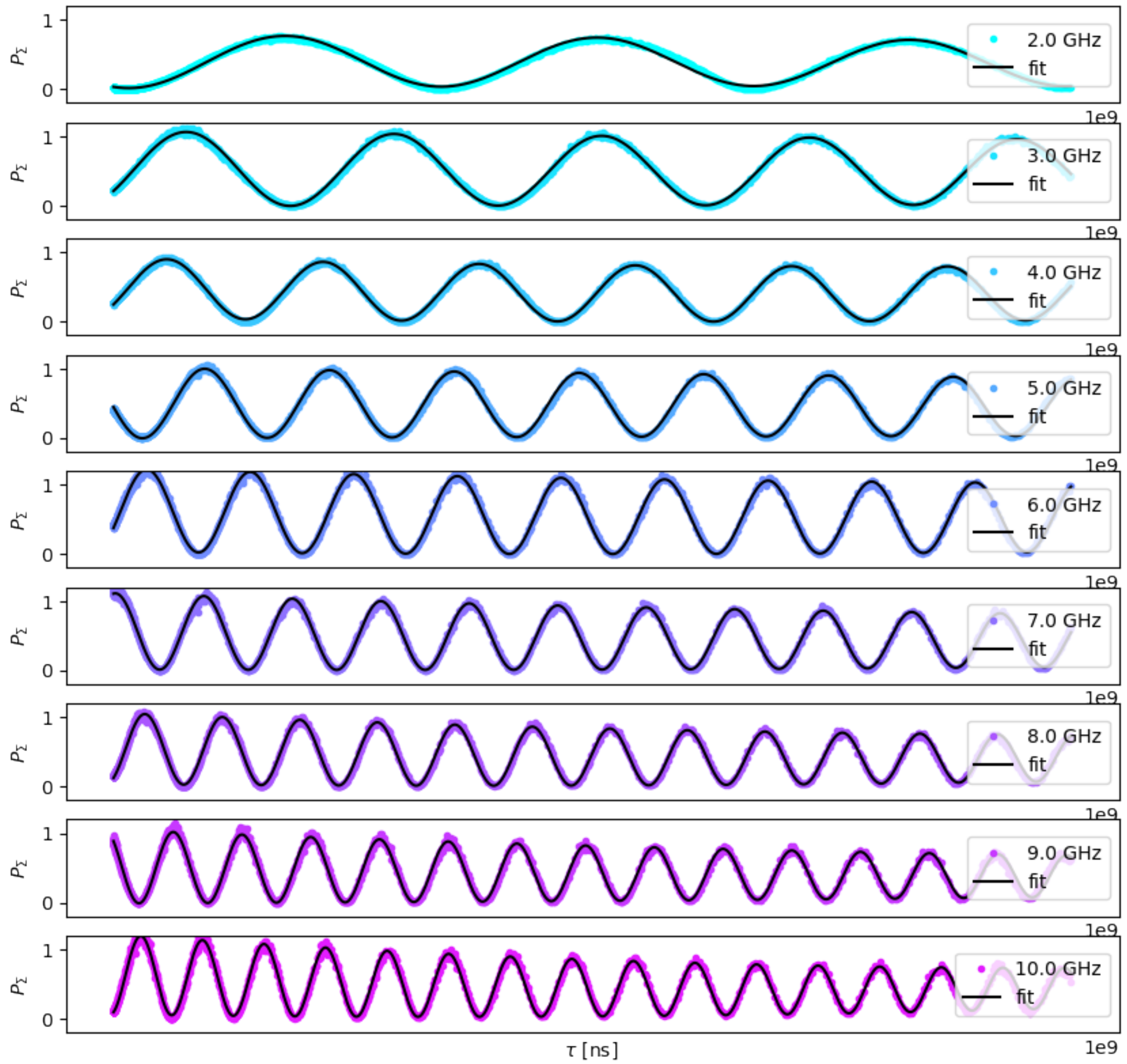
Crux of FTS operation

$$\Delta\tau = \sqrt{\mathcal{L}(I)\mathcal{C}}$$

Delay via current bias



**Basu Thakur, R.**, Klimovich, N., Day, P.K. *et al.* Superconducting On-chip Fourier Transform Spectrometer. *J Low Temp Phys* **200,** 342–352



**Laboratory measurements of interferograms with single color input.**
Current converted to delay using measured phase

***δν*** = 670 MHz achieved

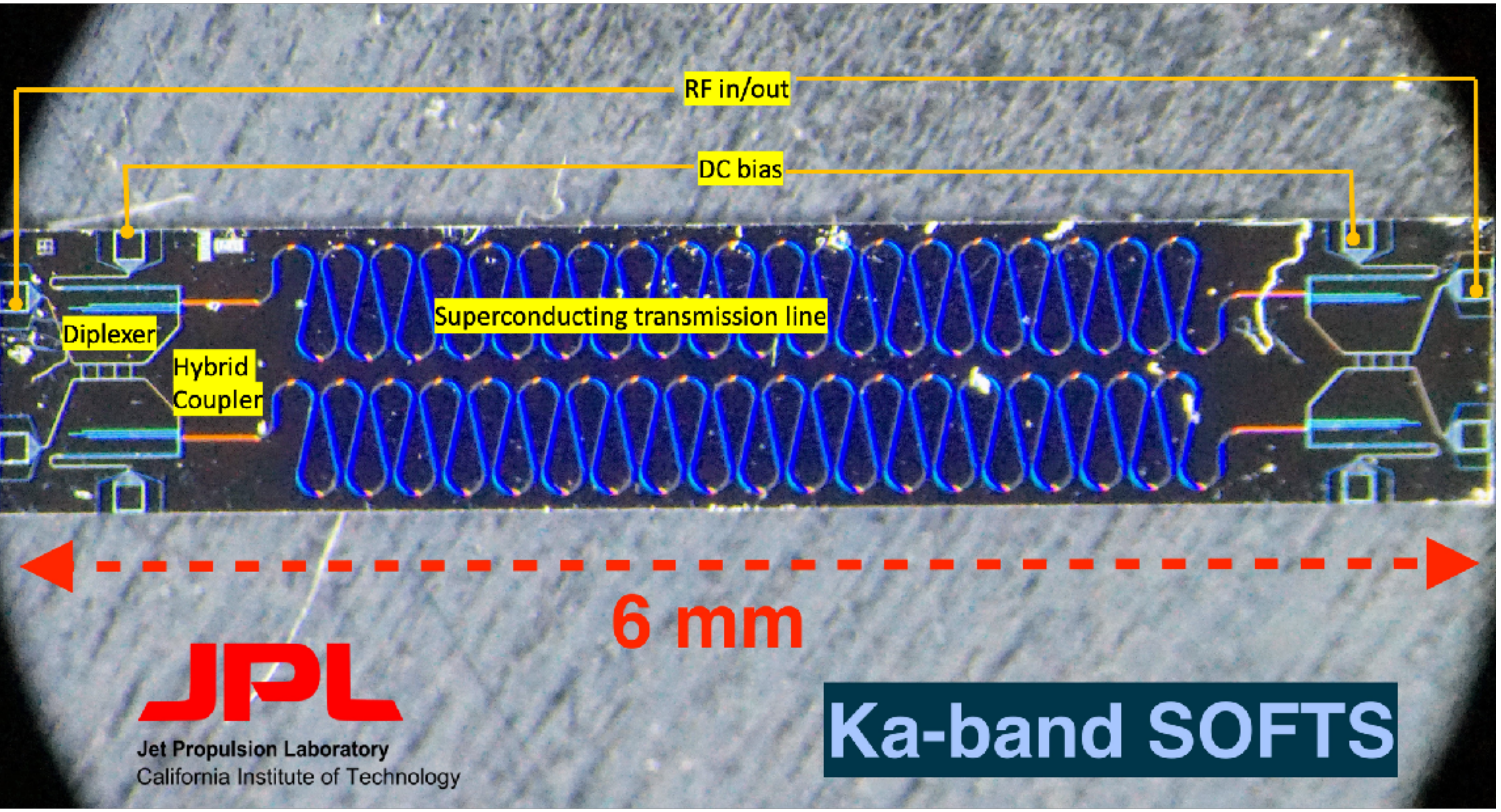
Prototype device 2.5 cm

Optical FTS equivalent would be > meter-scale

No moving parts, scan rate can be ~kHz

Measurements completely modeled with S-parameters

# Current SOFTS



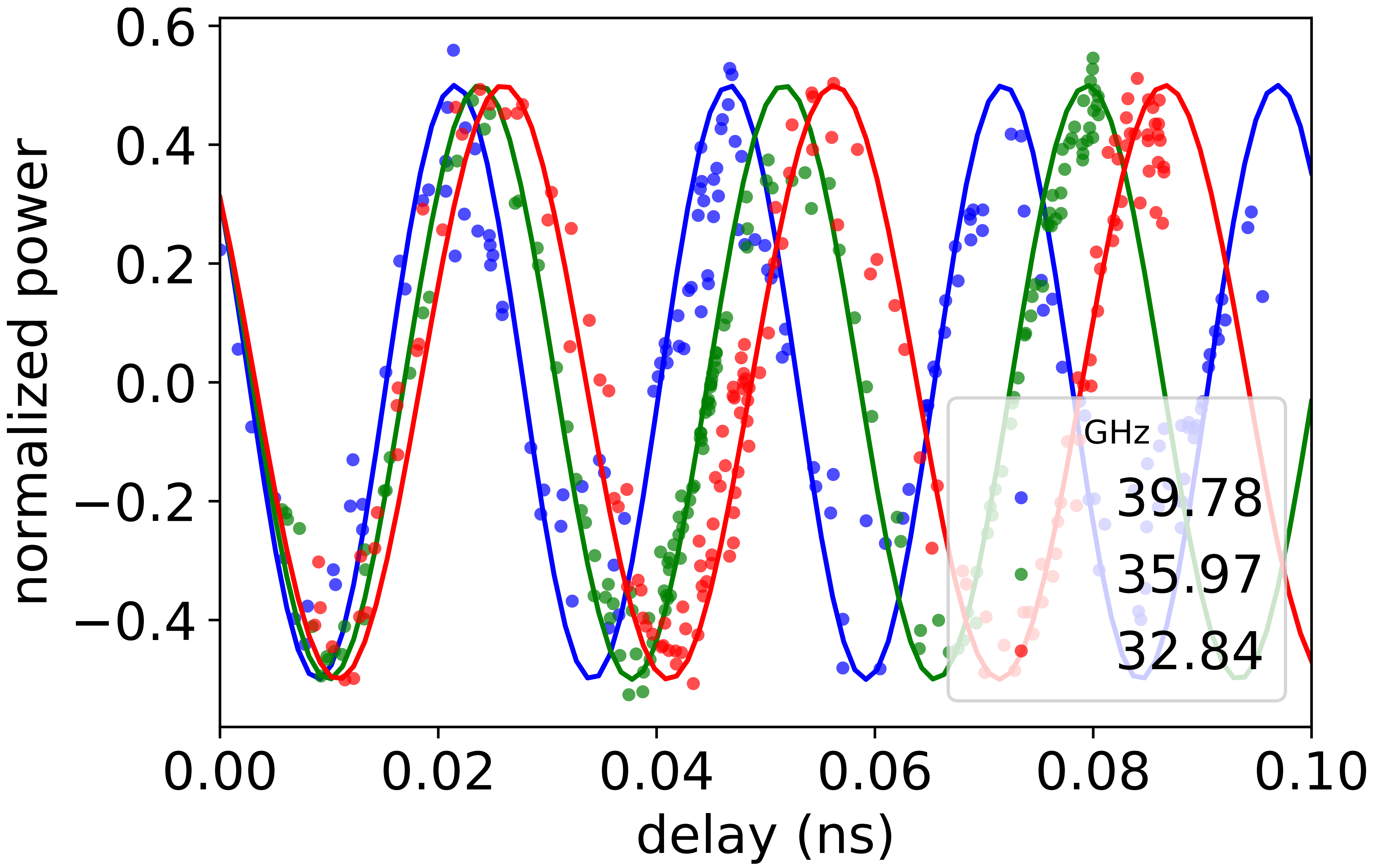
**RBT** *et al.* Development of Superconducting On-chip Fourier Transform Spectrometers. *J Low Temp Phys* (2022)

Low-frequency (25-40 GHz) cm-wave SOFTS above

Higher-frequency SOFTS being developed at JPL & ASU
Sub-mm reach: NbTiN (< 1 THz), MgB2 (< 2 THz)

**Preliminary measurements**

$$P_{FTS} \sim P(\nu)(1 \pm \cos(2\pi\nu\Delta\tau))$$



Expected cosine modulations seen! Single tone reconstruction indicates formal FTS capabilities.

At ~30 GHz it’s so small … at ~THz SOFTS will enable revolutionary focal plane arrays.

# SOFTS

Target is
R ~ $10^3$ at 100 GHz
R ~ $10^4$ at THz

| **Properties** | Possible | Done | Under dev | Future |
|---|---|---|---|---|
| $\nu$ Min-Max (**GHz**) | 0 - $2\times10^3$ | 0-40 | 200-700 | $\geq 10^3$ |
| $\delta\nu$ Resolution (**GHz**) | $10^{-2}$ | 0.67 | 0.1 | < 0.1 |
| Bandwidth ratio = $\nu_{Max} / \nu_{Min}$ | ~4 | >1.5 | ~2 | ~3 |
| scan-speed (**kHz**) | ~$10^3$ | ~1 | ~$10^2$ | ~$10^2$ |

Tc driven: NbTiN stops at ~1 THz, MgB2 ~2 THz

Line-length and material driven: can go to ~10s of cm and increase magnitude of delay. Loss measurements need to be done to verify operations near THz

Demo'd ~1.5 GHz with 5mm, can easily get 0.2 GHz with longer lines and higher inductance

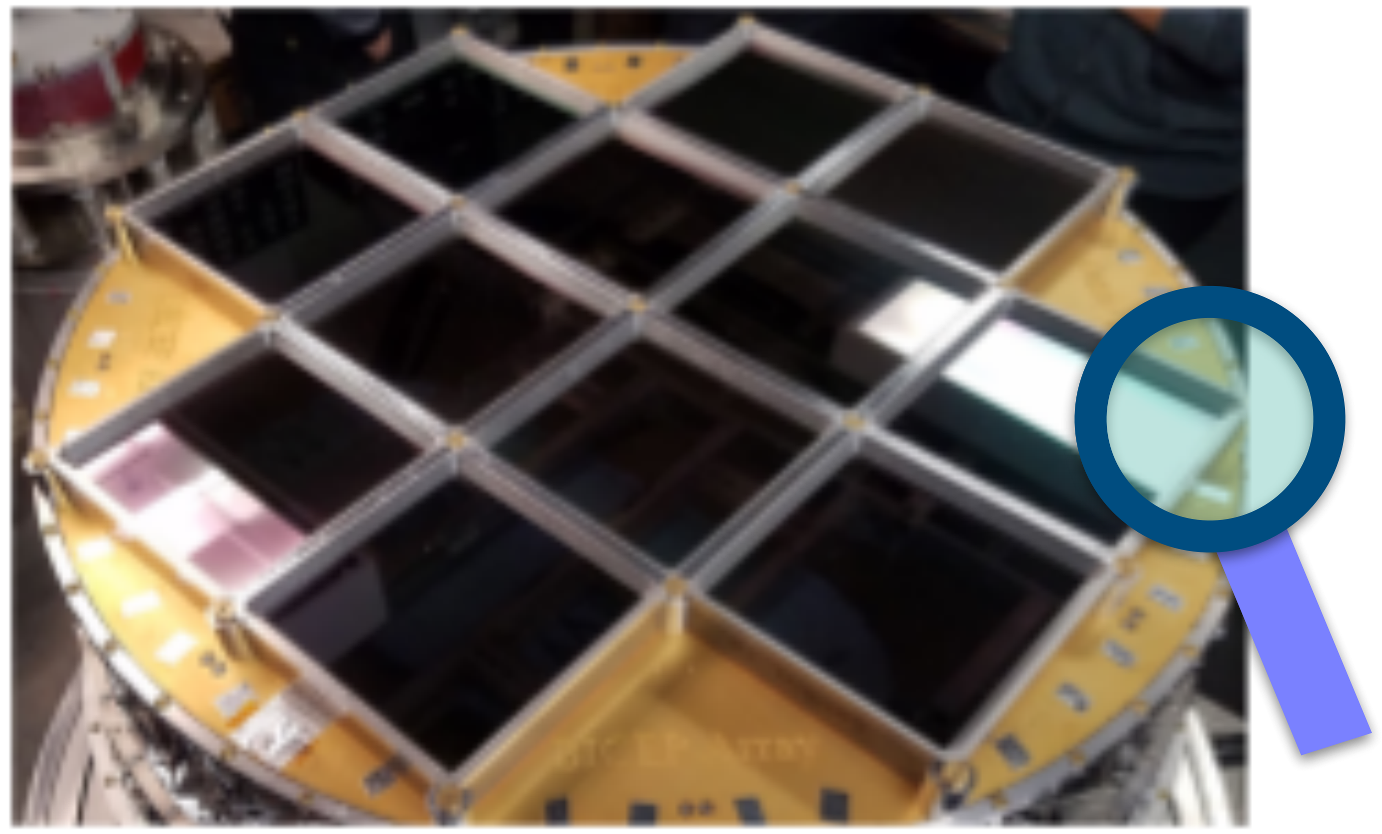
Overall efficiency drops (atmospheric photons etc.) at high BWRs, ~2 is optimal in most cases

Will be limited by detector time-constant

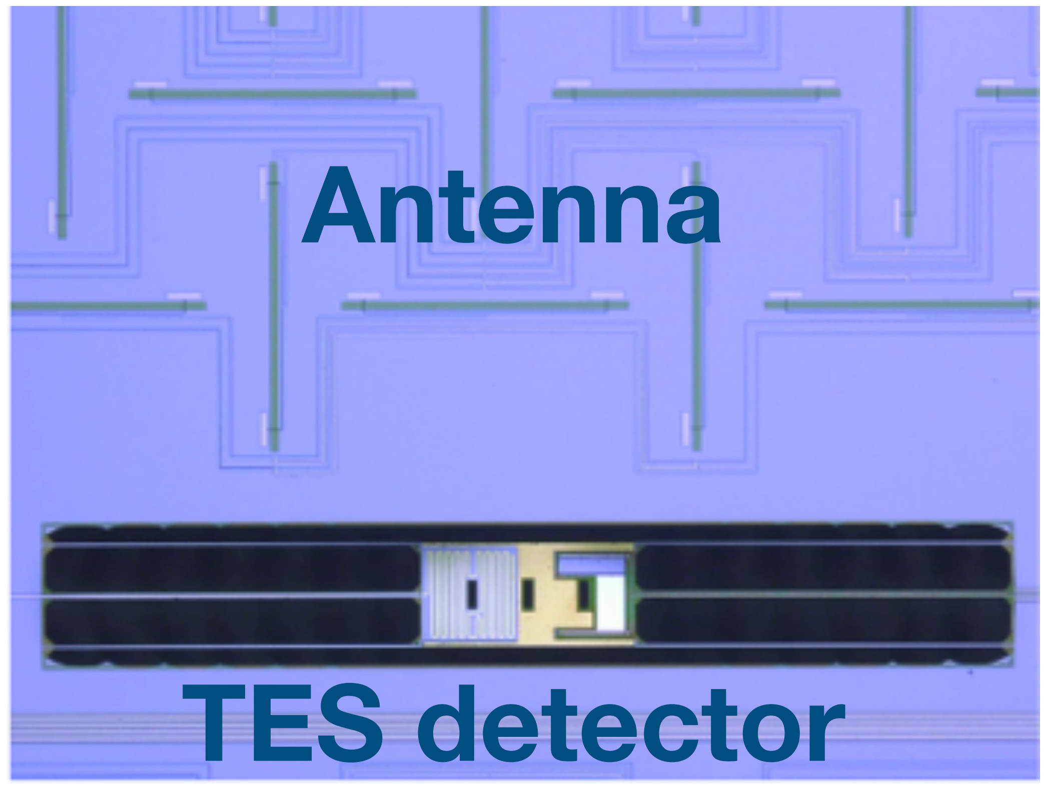
# Astrophotonics

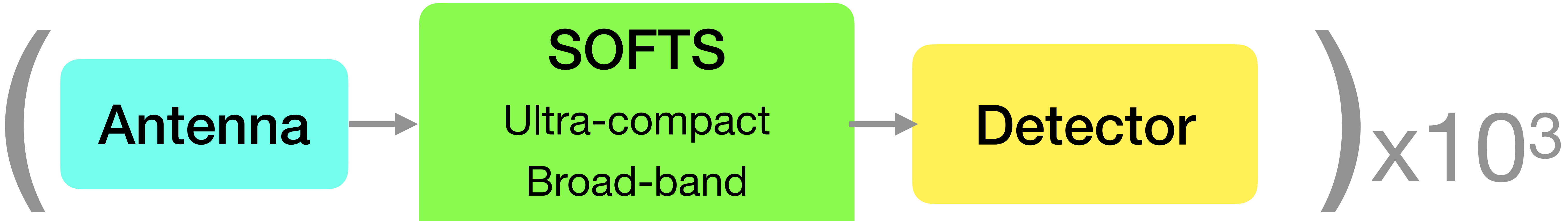
Imagers use thousands of superconducting antenna coupled detectors to map the sky

O(10) tiles on focal plane, BICEP

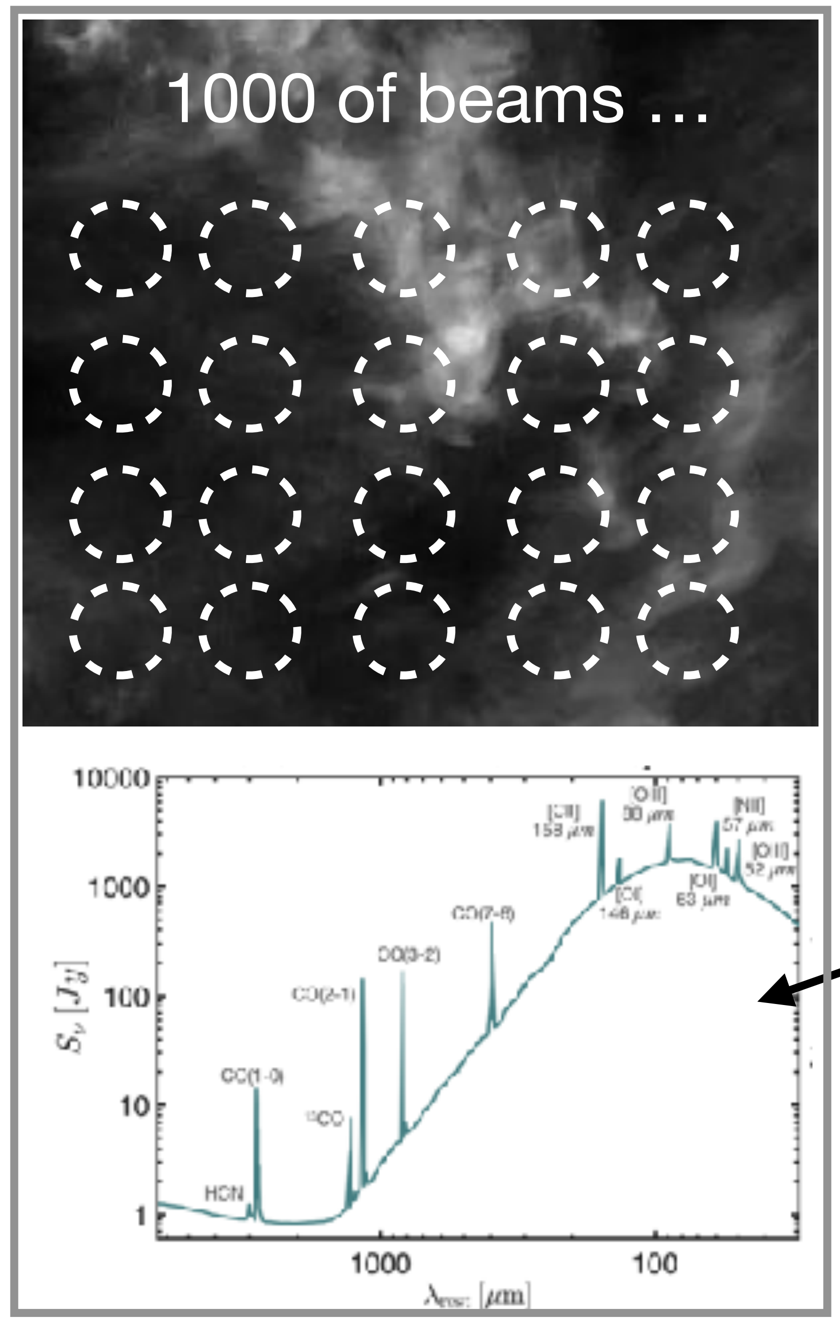


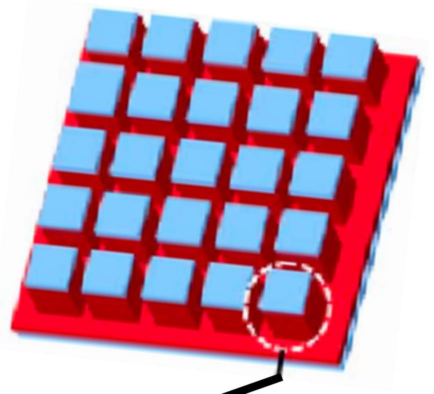
O(100) detectors per tile





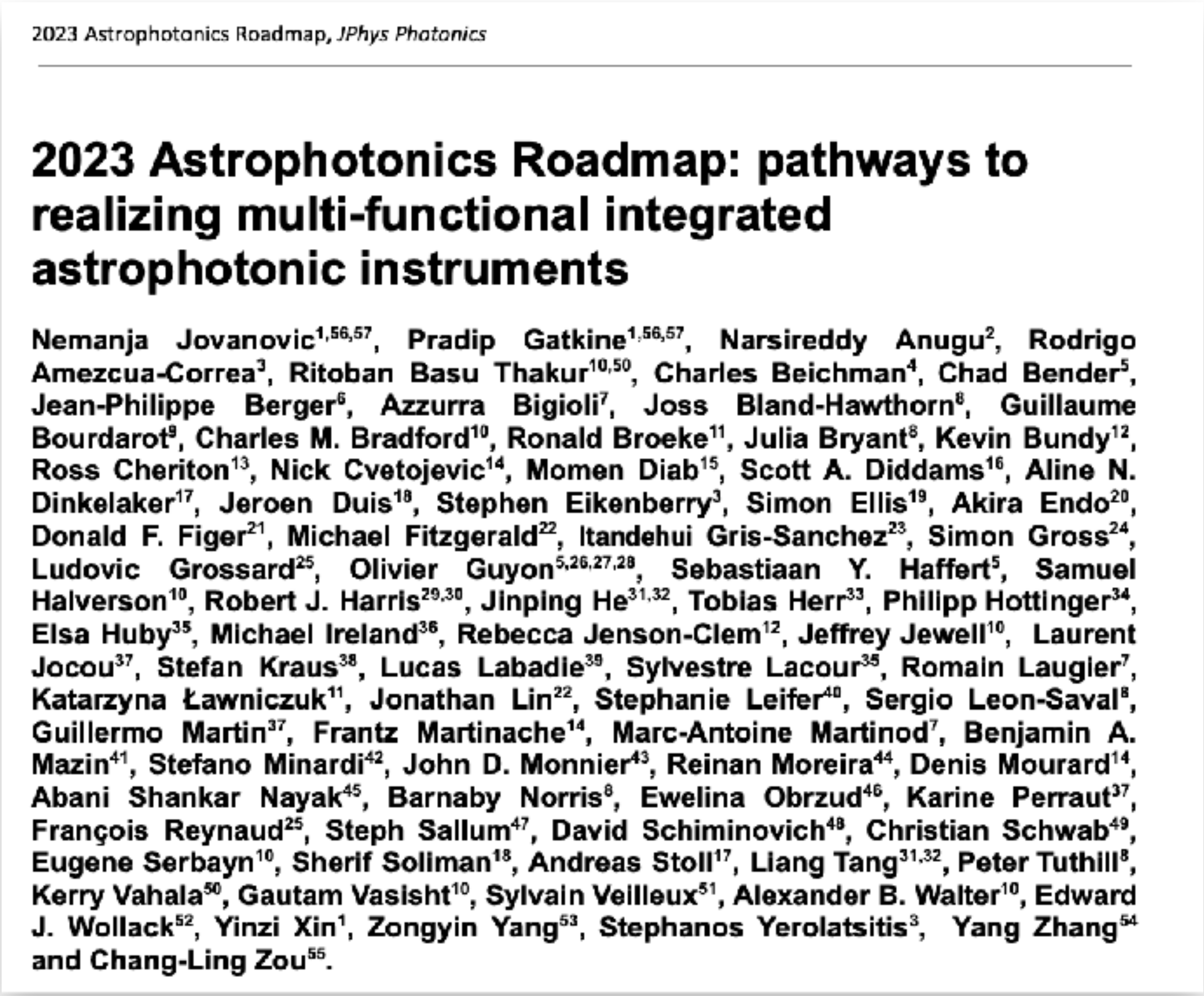
( **Antenna** → **SOFTS**
Ultra-compact
Broad-band
Decent resolution → **Detector** )x10$^3$





Each spaxel obtains spectrum per imaging beam

We can drop-in SOFTS to add spectroscopy to each imaging / spatial pixel — build **spaxels**



2023 Astrophotonics Roadmap, *JPhys Photonics*

## 2023 Astrophotonics Roadmap: pathways to realizing multi-functional integrated astrophotonic instruments

Nemanja Jovanovic[1,56,57], Pradip Gatkine[1,56,57], Narsireddy Anugu[2], Rodrigo Amezcua-Correa[3], Ritoban Basu Thakur[10,50], Charles Beichman[4], Chad Bender[5], Jean-Philippe Berger[6], Azzurra Bigioli[7], Joss Bland-Hawthorn[8], Guillaume Bourdarot[9], Charles M. Bradford[10], Ronald Broeke[11], Julia Bryant[8], Kevin Bundy[12], Ross Cheriton[13], Nick Cvetojevic[14], Momen Diab[15], Scott A. Diddams[16], Aline N. Dinkelaker[17], Jeroen Duis[18], Stephen Eikenberry[3], Simon Ellis[19], Akira Endo[20], Donald F. Figer[21], Michael Fitzgerald[22], Itandehui Gris-Sanchez[23], Simon Gross[24], Ludovic Grossard[25], Olivier Guyon[5,26,27,28], Sebastiaan Y. Haffert[5], Samuel Halverson[10], Robert J. Harris[29,30], Jinping He[31,32], Tobias Herr[33], Philipp Hottinger[34], Elsa Huby[35], Michael Ireland[36], Rebecca Jenson-Clem[12], Jeffrey Jewell[10], Laurent Jocou[37], Stefan Kraus[38], Lucas Labadie[39], Sylvestre Lacour[35], Romain Laugier[7], Katarzyna Ławniczuk[11], Jonathan Lin[22], Stephanie Leifer[40], Sergio Leon-Saval[8], Guillermo Martin[37], Frantz Martinache[14], Marc-Antoine Martinod[7], Benjamin A. Mazin[41], Stefano Minardi[42], John D. Monnier[43], Reinan Moreira[44], Denis Mourard[14], Abani Shankar Nayak[45], Barnaby Norris[8], Ewelina Obrzud[46], Karine Perraut[37], François Reynaud[25], Steph Sallum[47], David Schiminovich[48], Christian Schwab[49], Eugene Serbayn[10], Sherif Soliman[18], Andreas Stoll[17], Liang Tang[31,32], Peter Tuthill[8], Kerry Vahala[50], Gautam Vasisht[10], Sylvain Veilleux[51], Alexander B. Walter[10], Edward J. Wollack[52], Yinzi Xin[1], Zongyin Yang[53], Stephanos Yerolatsitis[3], Yang Zhang[54] and Chang-Ling Zou[55].

# Single photon input

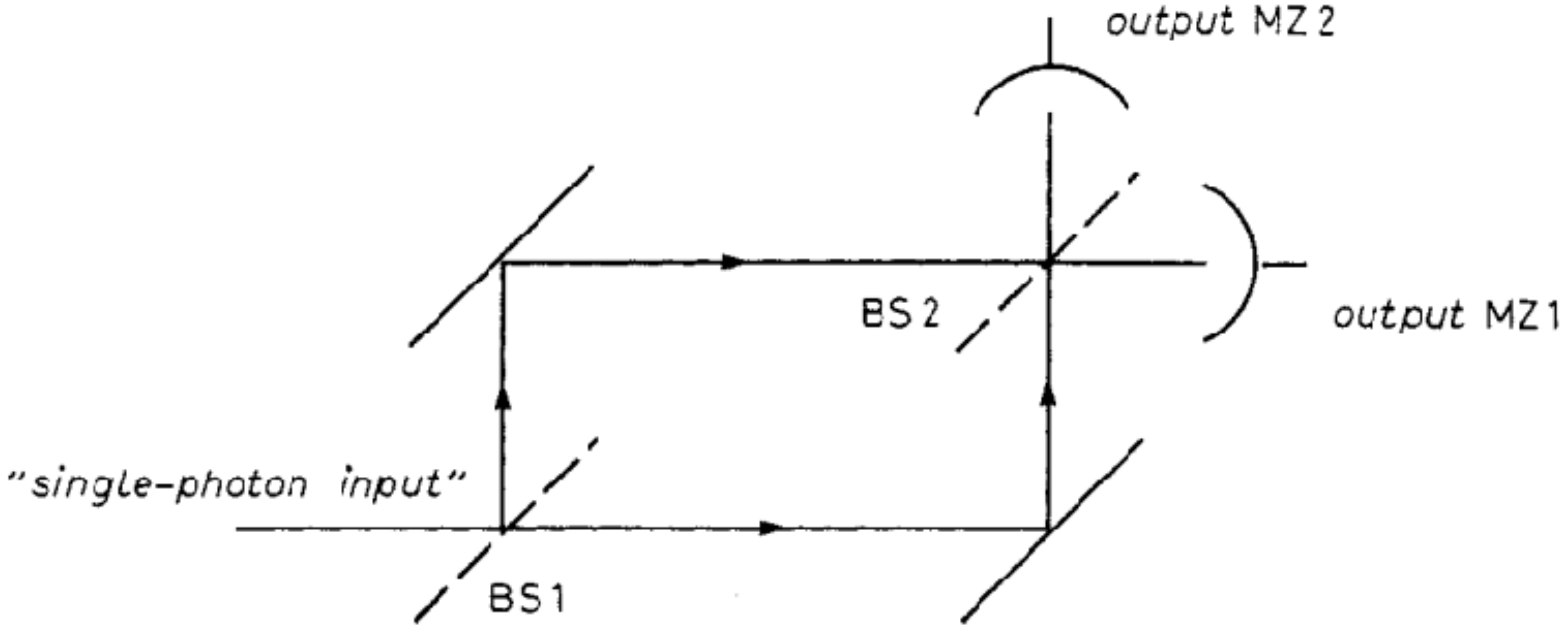
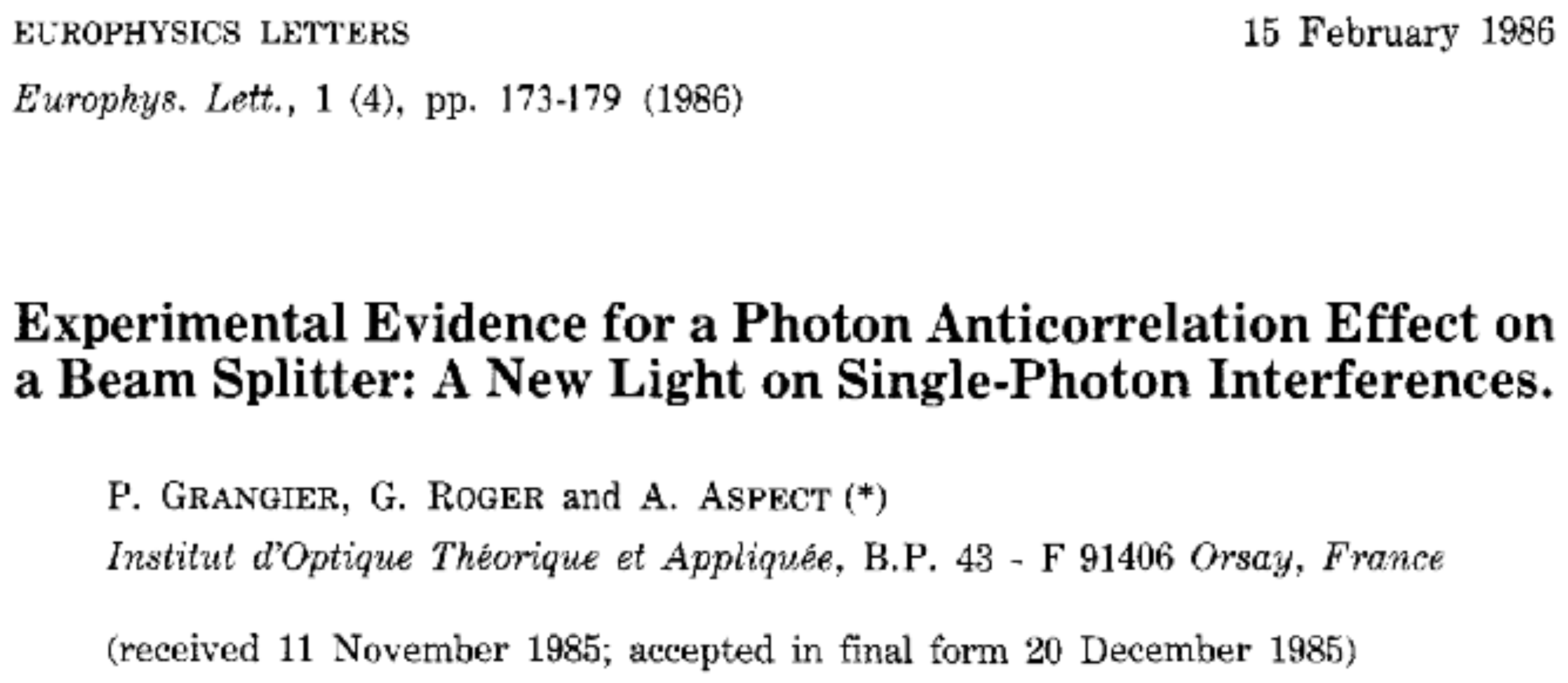


Fig. 3. – Mach-Zehnder interferometer. The detection probabilities in outputs MZ1 and MZ2 are oppositely modulated as a function of the path difference between the arms of the interferometer.



EUROPHYSICS LETTERS 15 February 1986

*Europhys. Lett.*, 1 (4), pp. 173-179 (1986)

**Experimental Evidence for a Photon Anticorrelation Effect on a Beam Splitter: A New Light on Single-Photon Interferences.**

P. GRANGIER, G. ROGER and A. ASPECT (*)

*Institut d'Optique Théorique et Appliquée*, B.P. 43 - F 91406 *Orsay, France*

(received 11 November 1985; accepted in final form 20 December 1985)

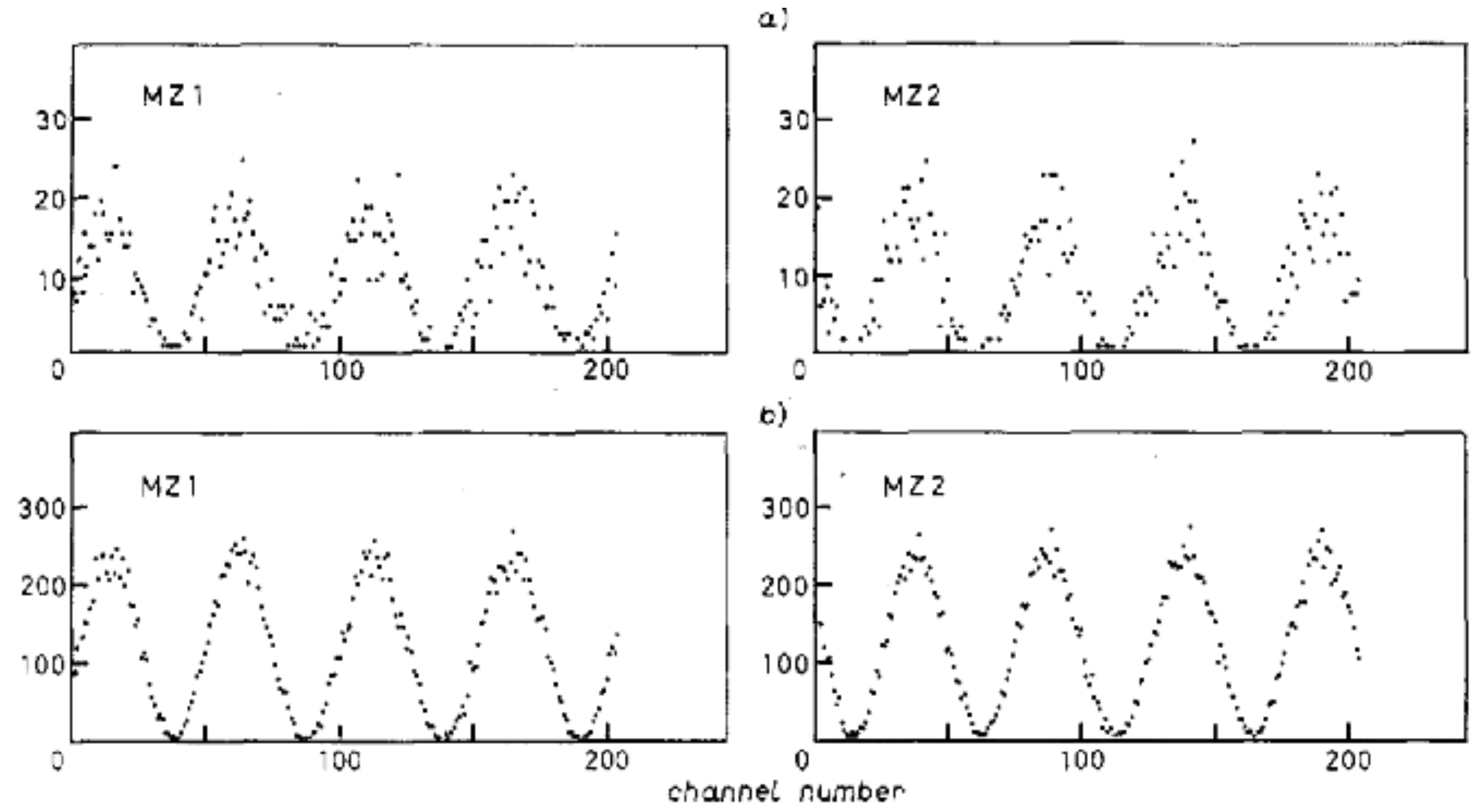


Fig. 4. – Number of counts in outputs MZ1 and MZ2 as a function of the path difference $\delta$ (one channel corresponds to a $\lambda/50$ variation of $\delta$). $a$) 1 s counting time per channel $b$) 15 s counting time per channel (compilation of 15 elementary sweeps (like ($a$)). This experiment corresponds to an anticorrelation parameter $\alpha = 0.18$.

SOFTS operating

- in a cryogenic environment (like QUALIPHIDE, with negligible loading)
- with single photon detectors (e.g. QCDs)

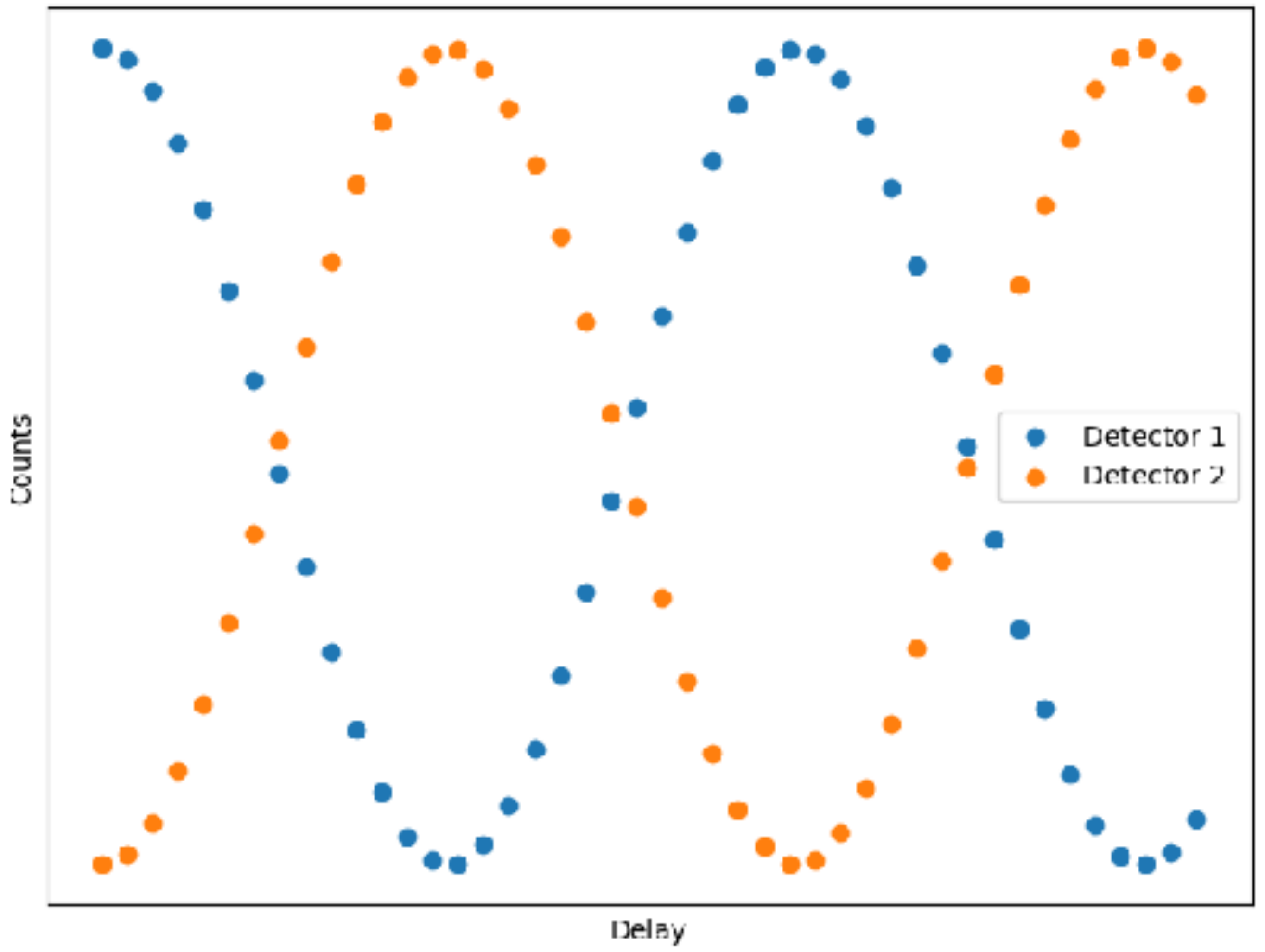
Can be a highly sensitive spectrum analyzer (not SQL limited)

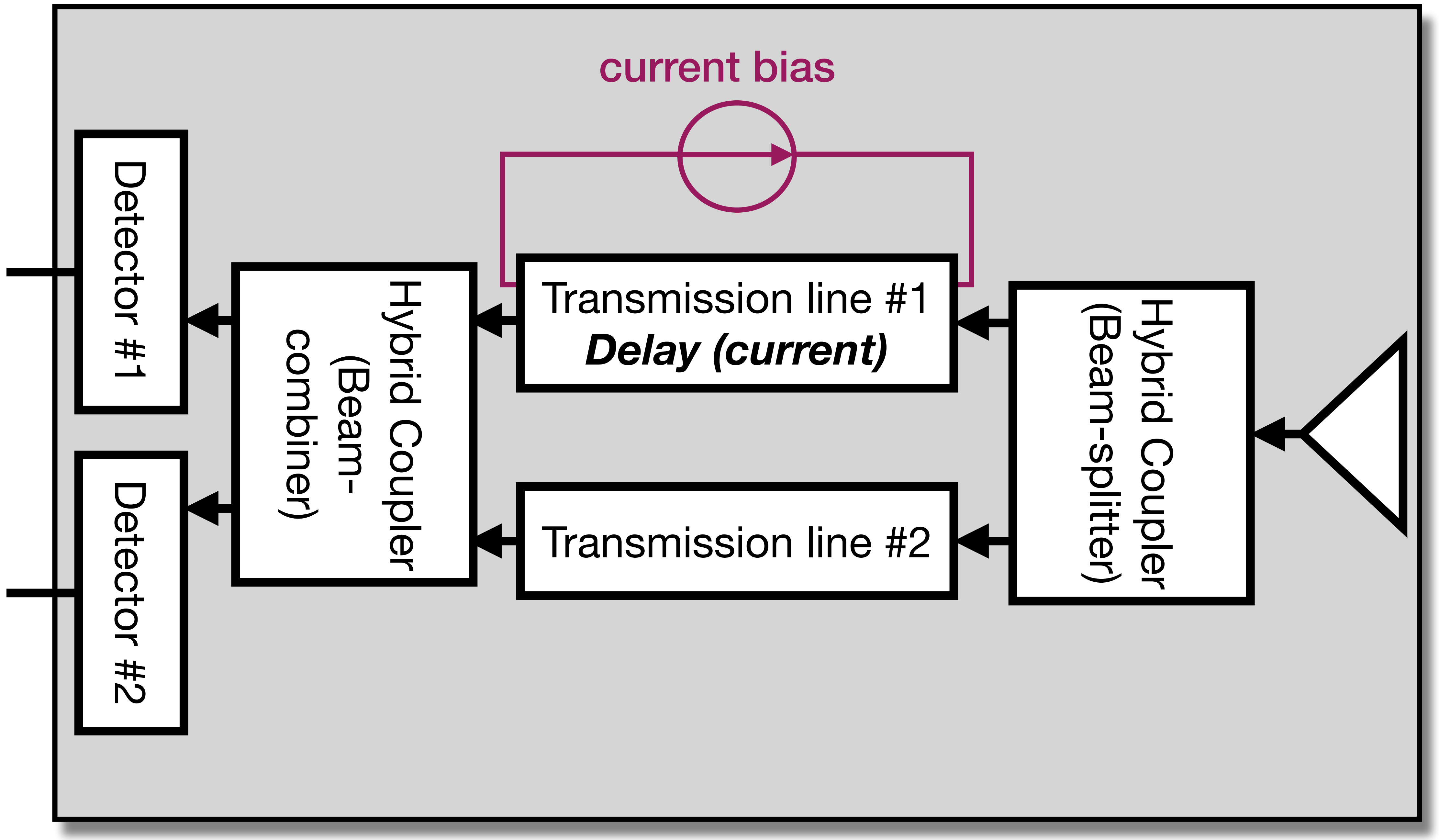
# Hidden Photon search

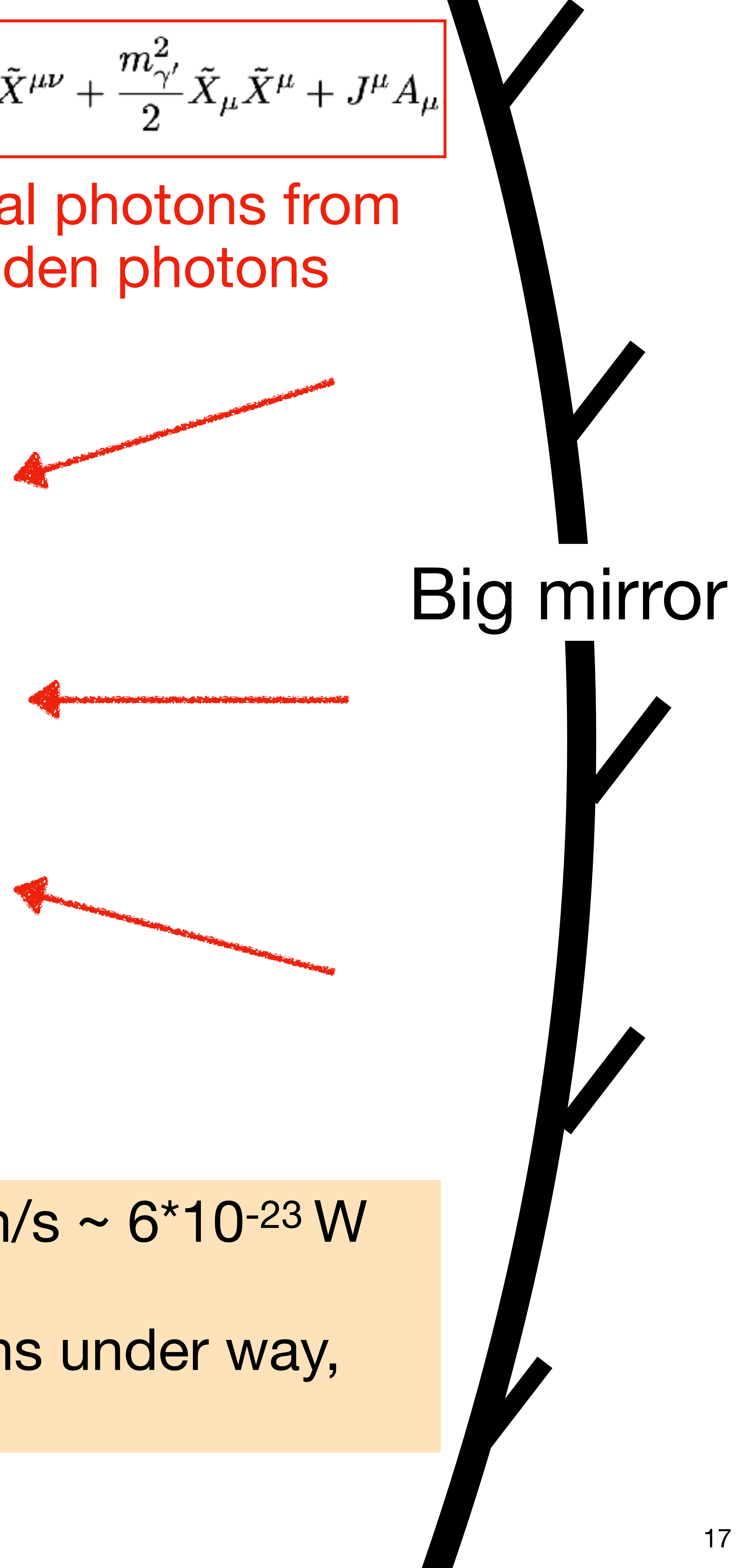
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} - \frac{\chi}{2}F_{\mu\nu}\tilde{X}^{\mu\nu} + \frac{m^2_{\gamma'}}{2}\tilde{X}_{\mu}\tilde{X}^{\mu} + J^{\mu}A_{\mu}$$

Real photons from hidden photons

**Sketch of SOFTS with BREAD-like setup**







SOFTS will work in a broad-band

If the whole system is sub-kelvin, then at 0.1-1 THz we expect no real backgrounds… likely limited by dark count of detectors

One 100-GHz photon/s ~ 6*10$^{-23}$ W

Sensitivity calculations under way, estimate $\chi$ ~10$^{-13}$

# Conclusions

SOFTS is an ultracompact, broadband, electronic, on-chip interferometer / FTS

Our goal is to build kilospaxel spectro-imagers for cosmology and astrophysics.

Other applications in quantum optics, **dark matter searches** etc. being explored.

*Looking for new members as JPL Postdoc or Caltech PhD student*

*Please reach out with suggestions / questions / for collaborations. Thanks!*

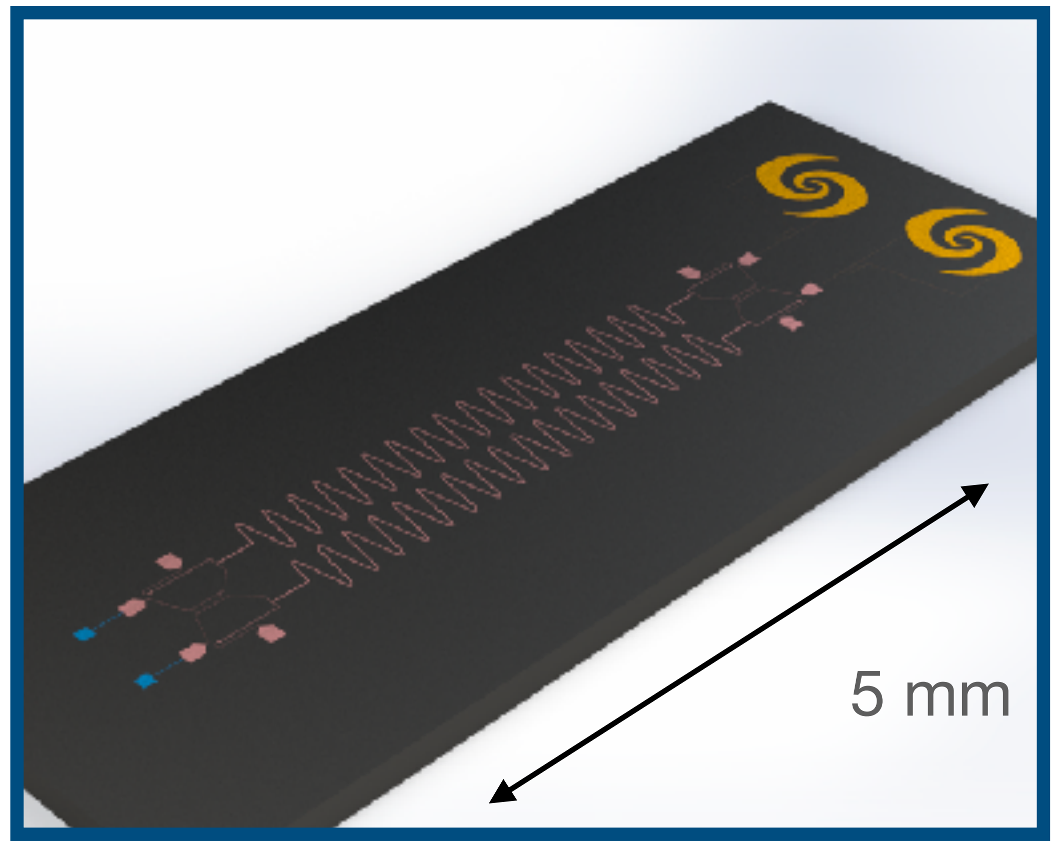
ritoban@caltech.edu

**R. Basu Thakur,** D. Cunanne, P. K. Day , J. Sayers, S. Shu, E. Rapaport, A. Steiger, F. Faramarzi, T.-C. Chang, O. Dore, P. Goldsmith

P. Mauskopf, C. Bell, J. Greenfield

N. Klimovich

P. Barry

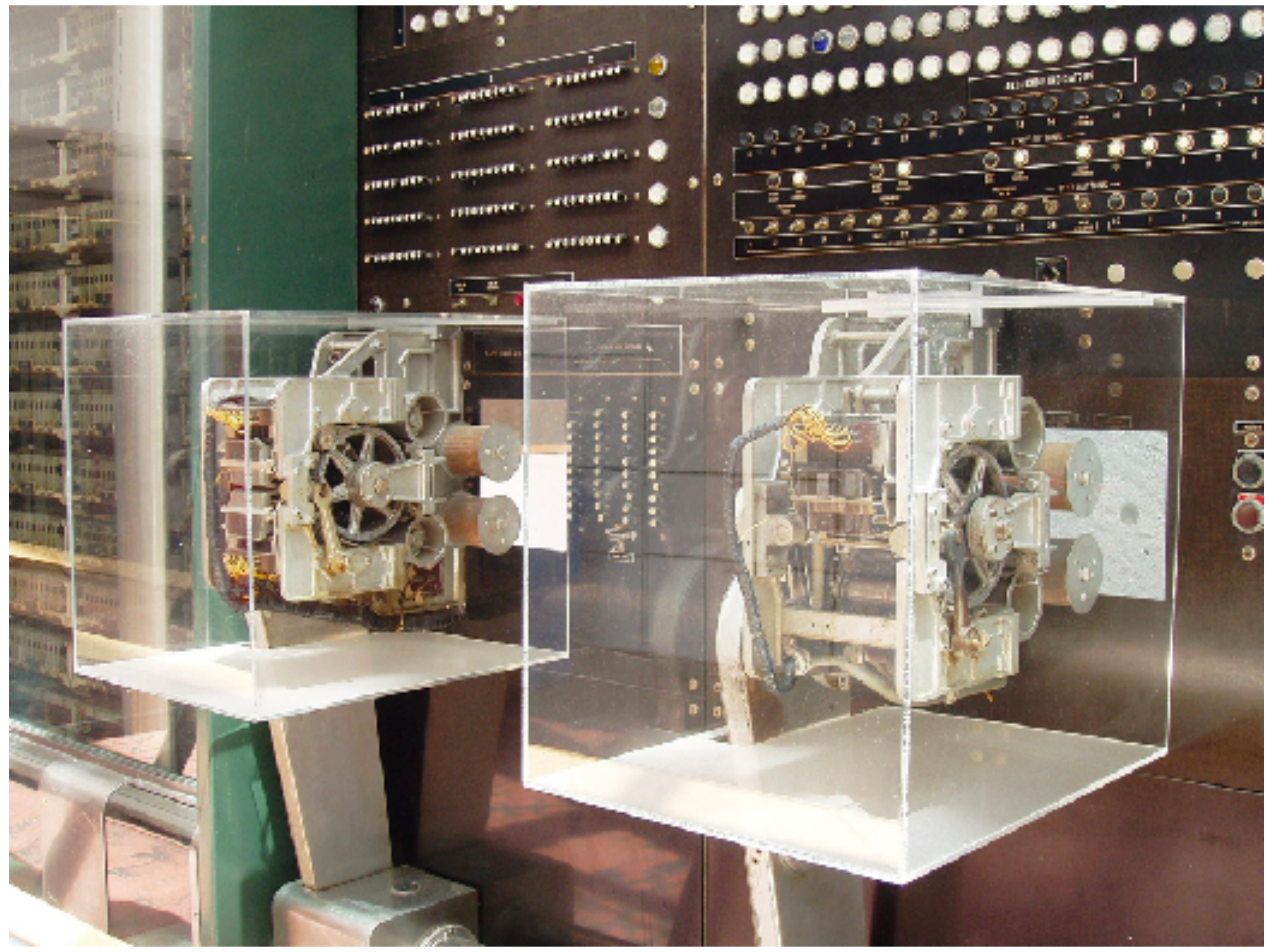


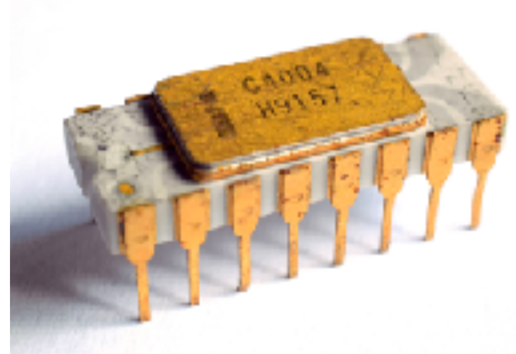
# Astrophotonics

Opto mechanical sub-mm wave FTS and a human for scale
355 × 260 × 64 mms

SOFTS and (the same) human's finger scale
6 x 1 mms

Harvard Mark 1 computer (late 1940's)





Intel 4004 (early 1970's)

Electronics revolution was enabled by miniaturized semiconductors

Photonics with superconductors …
revolution in quantum & astrophotonics