UPPSALA UNIVERSITET

Milli-eV axion and dark photon experiments with millimeter-wave resonators

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Supported by international excellence fellowship program 2021 in KIT

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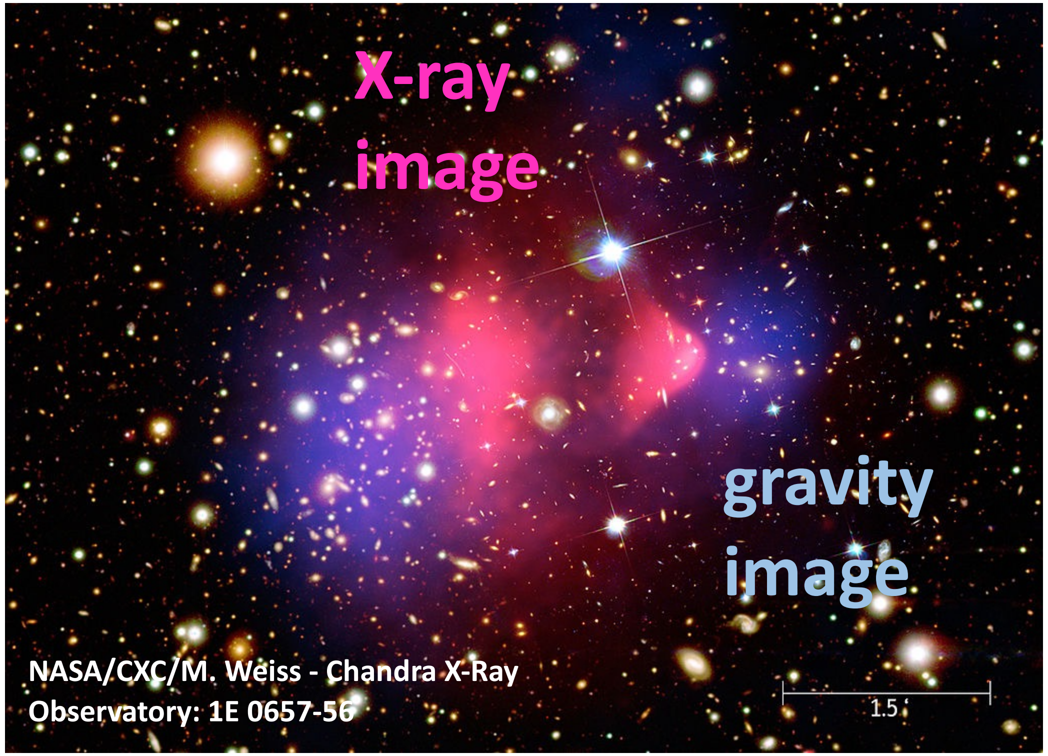
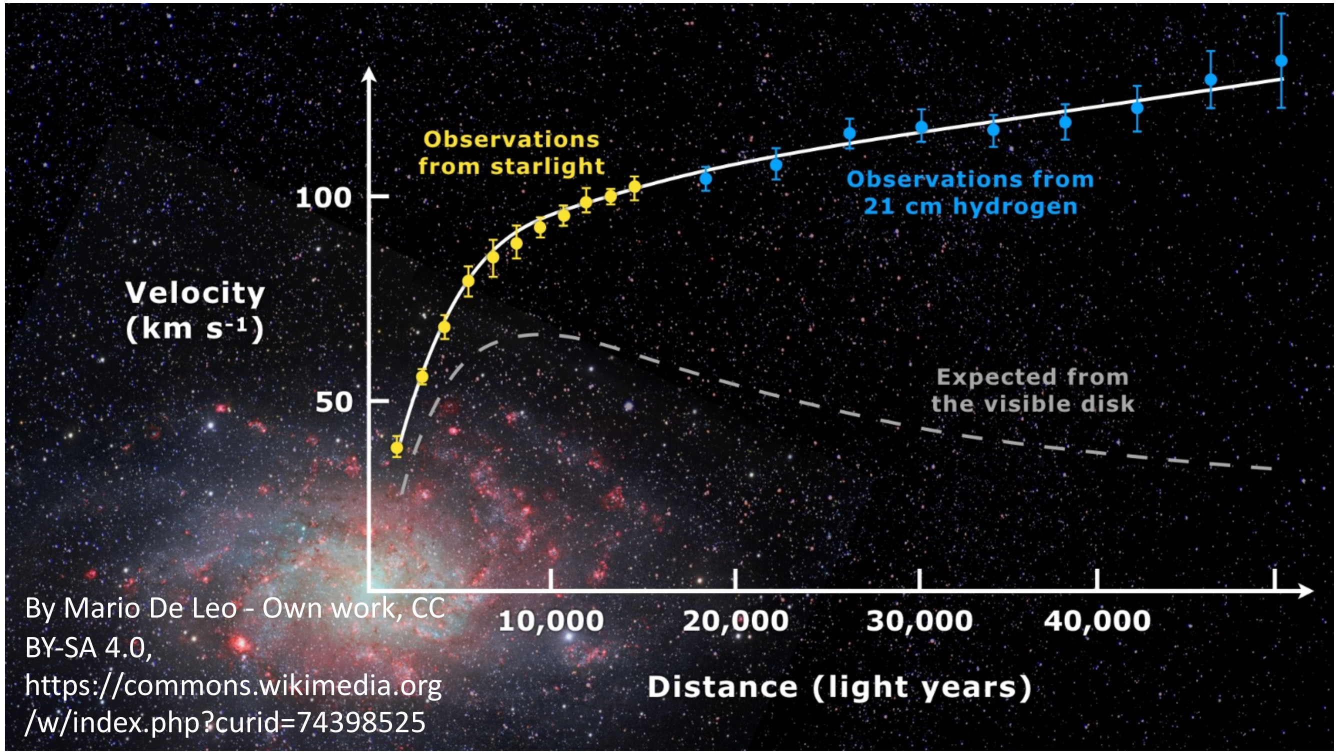
Outline

- Introduction: dark matter and dark photons
  - Why millimeter waves are motivated?
- Two typical methods
  - Direct detection: plasma haloscope
  - Light-Shining-Through-a-Wall
- Single photon detection vs wave detection
  - Phase lock: benefit of wave detection scheme
  - Ultimate limit of wave detection → photon counting
- Expected exclusion limit
- Toward axion search
- Conclusion

Clear need for new physics: e.g. Dark Matter (DM)





~~Neutrino~~?

~~Dark astrophysical objects~~?

~~Modified gravity~~? van Dokkum, *et al. Nature* **555,** 629–632 (2018)

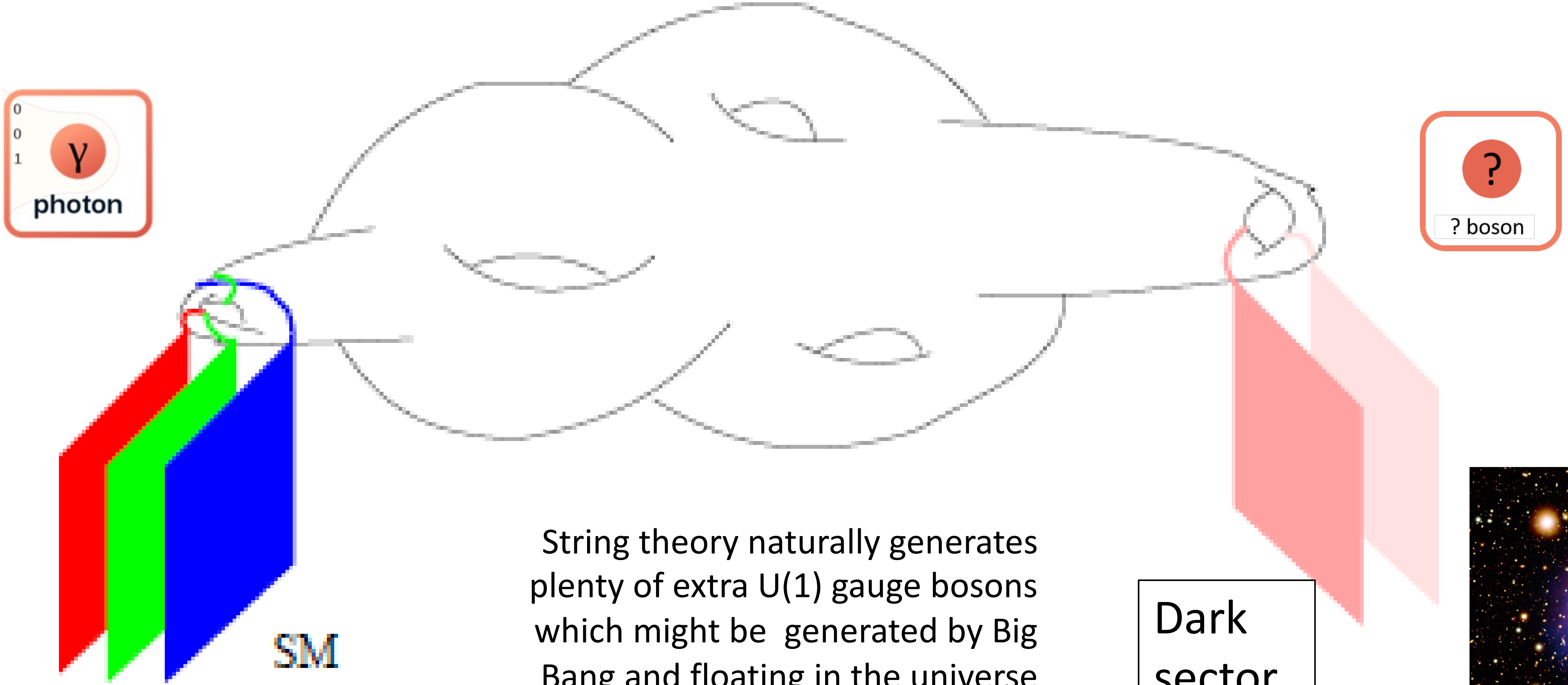
Primordial black holes? arXiv:2208.13178

Hypothetical new particles beyond the Standard Model?

- Something heavy (WIMP)
- Something light (WISP)

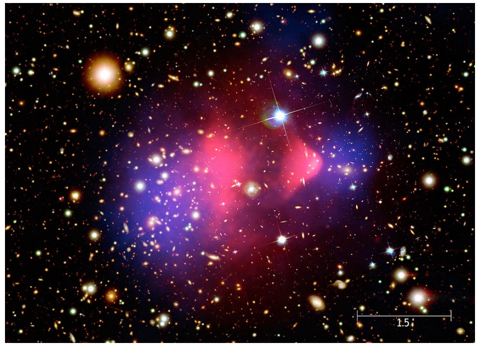
Massive extra U(1) gauge bosons

Lust, 0707.2305



String theory naturally generates plenty of extra U(1) gauge bosons which might be generated by Big Bang and floating in the universe

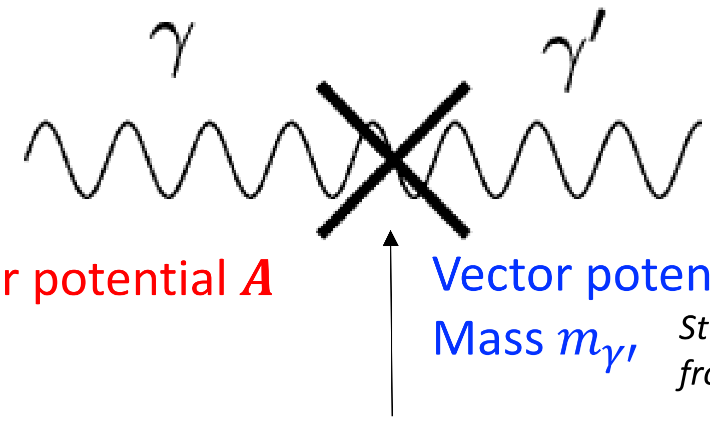
Dark sector



We consider massive dark photon which weakly interact with SM particles

Dark photon enters the Maxwell equation

Ordinary photon   Dark photon



Vector potential $\boldsymbol{A}$

Vector potential $\boldsymbol{B}$

Mass $m_{\gamma'}$ *Stückelberg or from Higgs*

Very small kinetic coupling constant $\chi < 10^{-5}$

J. Jaeckel and A. Ringwald PLB 659 509 (2008)

Maxwell equation in vacuum

$$\left(\frac{\partial^2}{\partial t^2} - \nabla^2\right)\boldsymbol{A} = 0$$

→ Modified by the dark photon

$$\left(\frac{\partial^2}{\partial t^2} - \nabla^2 + \chi^2 m_{\gamma'}^2\right)\boldsymbol{A} = \chi m_{\gamma'}^2 \boldsymbol{B}$$

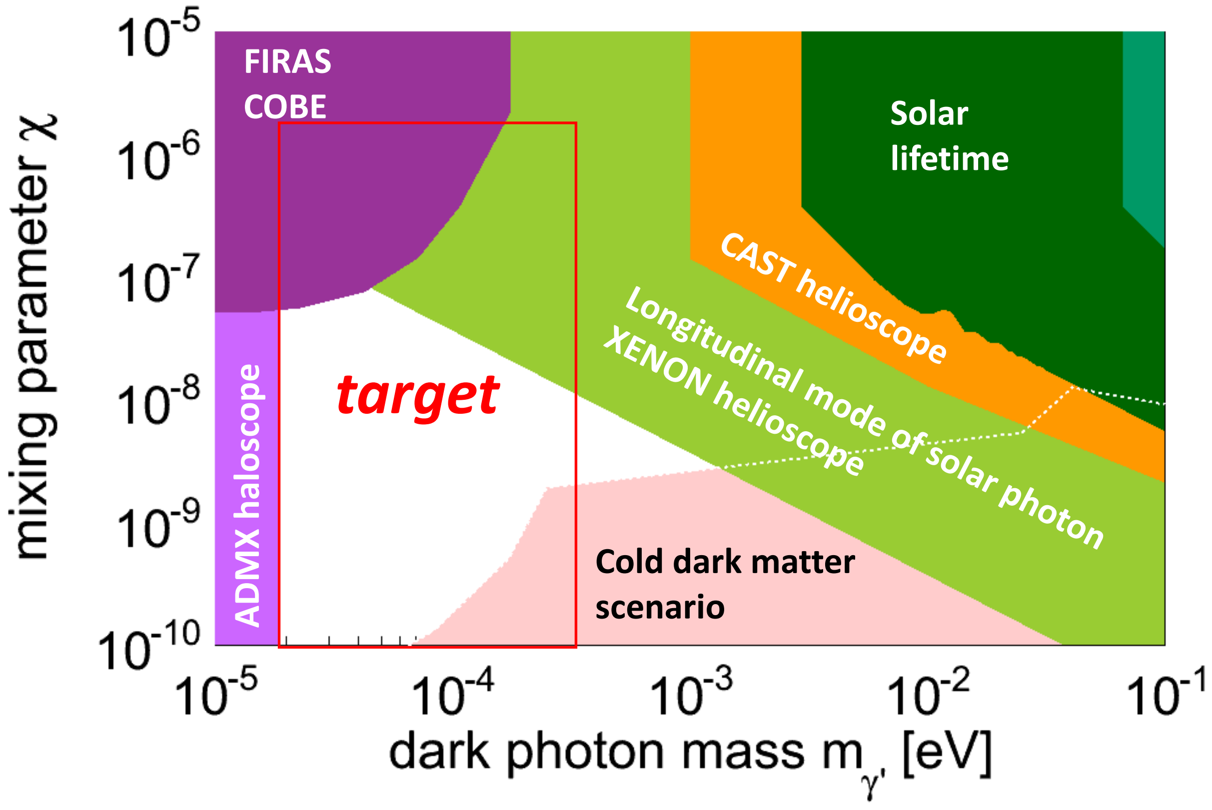
In parallel, another equation for the dark photon

$$\left(\frac{\partial^2}{\partial t^2} - \nabla^2 + m_{\gamma'}^2\right)\boldsymbol{B} = \chi m_{\gamma'}^2 \boldsymbol{A}$$

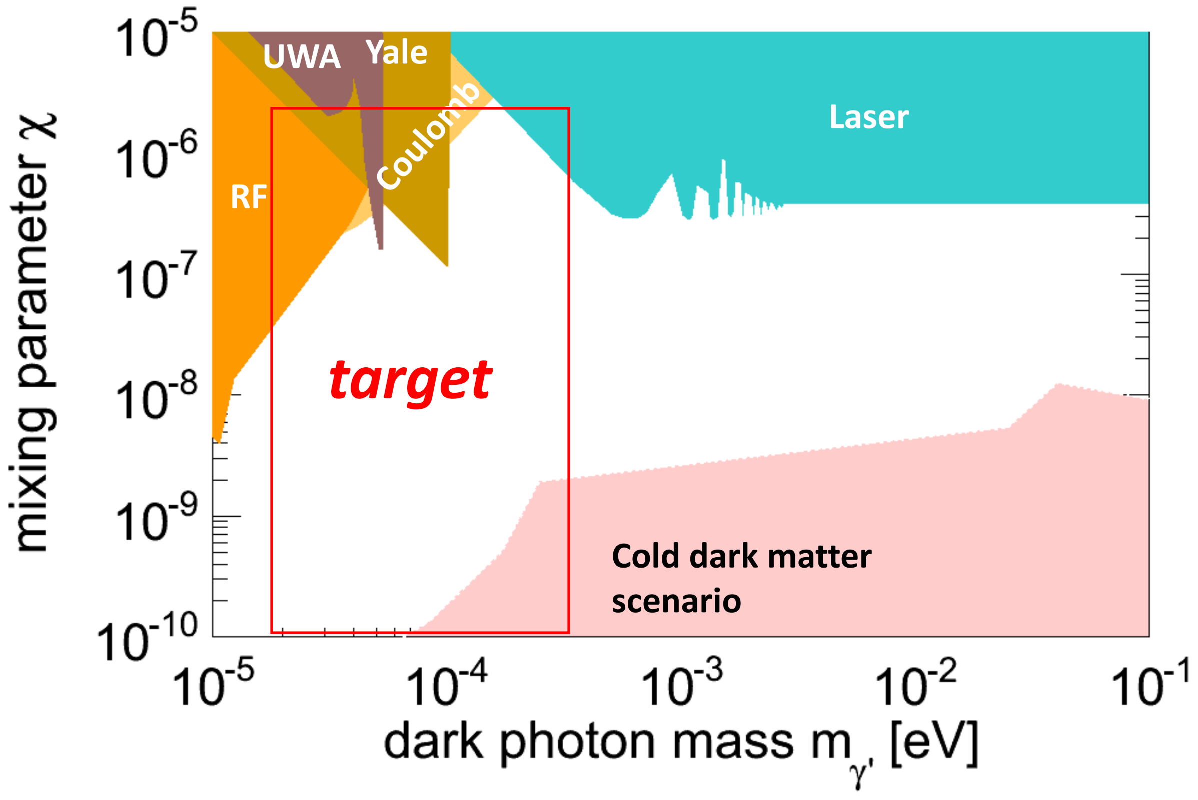
→ Photon is a tool to investigate dark photon

Open window in dark photon search

Astrophysical, haloscope, and helioscope



Purely laboratory constraints

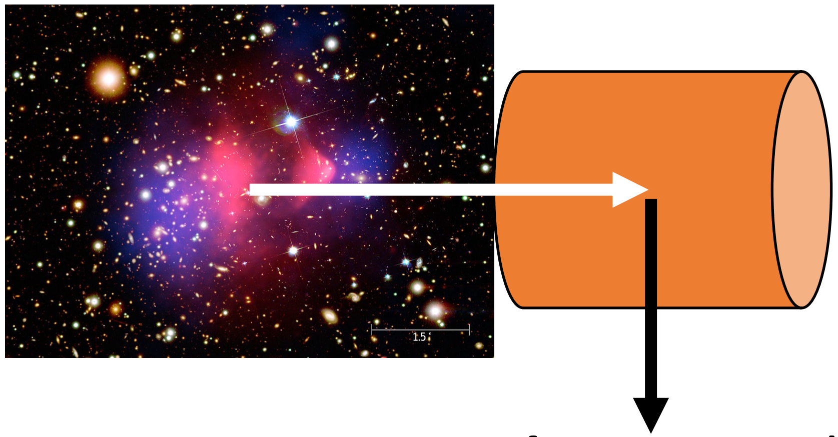


The mass range between 10^{-5} and 10^{-4} eV is wide open

→ Corresponding to 20-100GHz photons

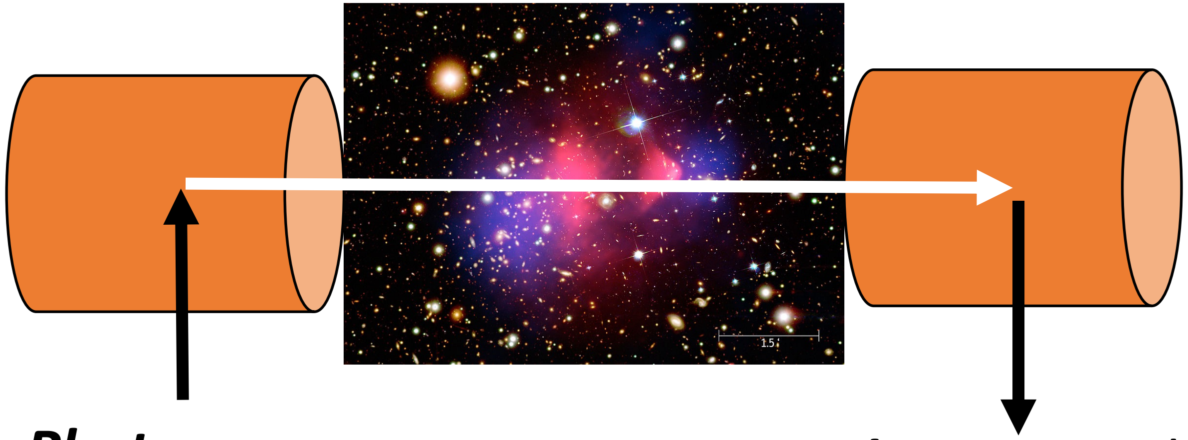
Principle of dark photon (/ axions) search via photons

Dark matter halo search



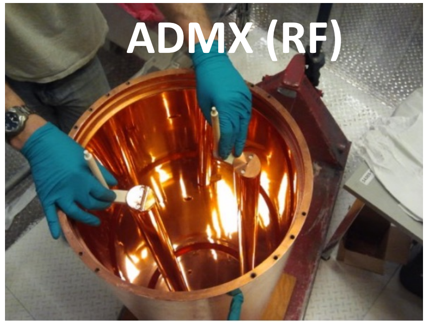
Photon signal

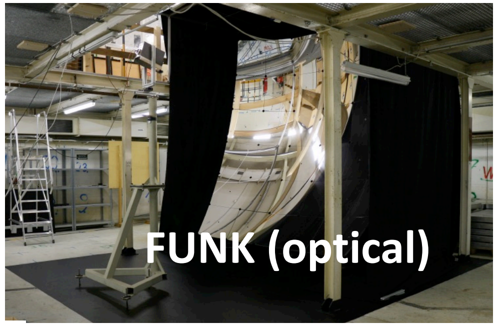
Laboratory-based search (LSW-type)

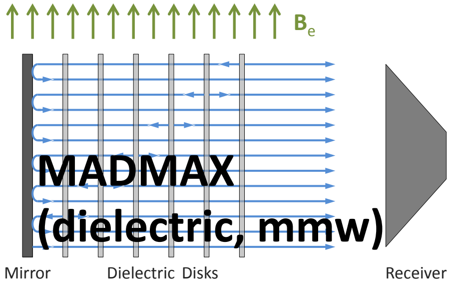


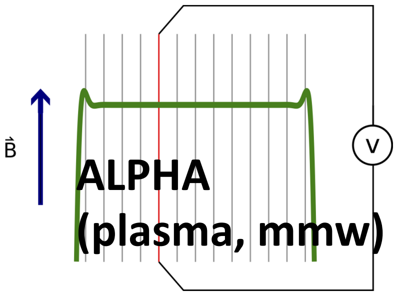
Photon pump

Photon signal

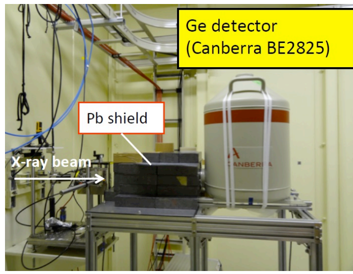


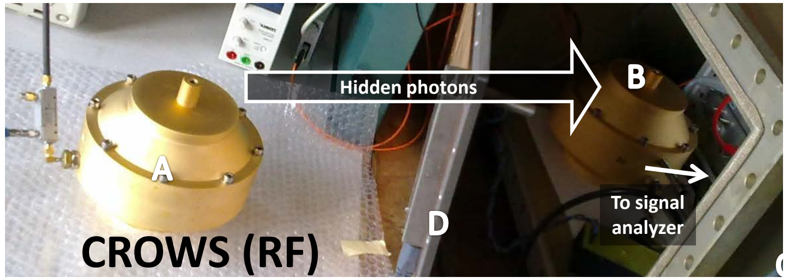


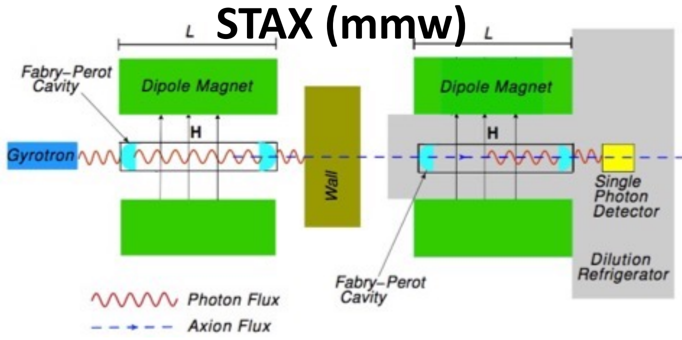




Spring-8 (X-ray)

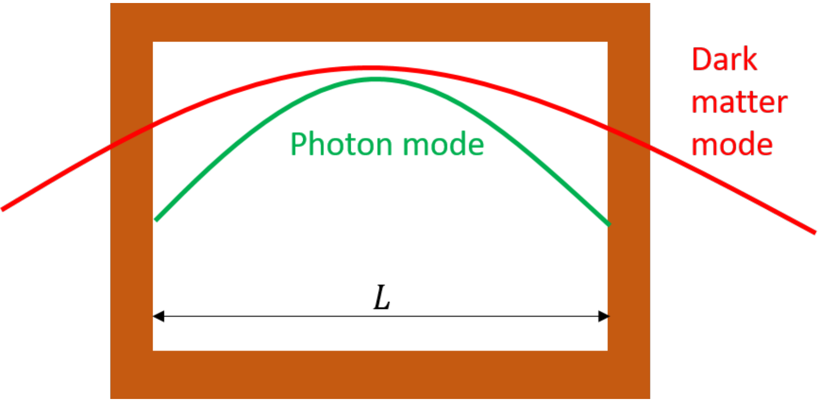






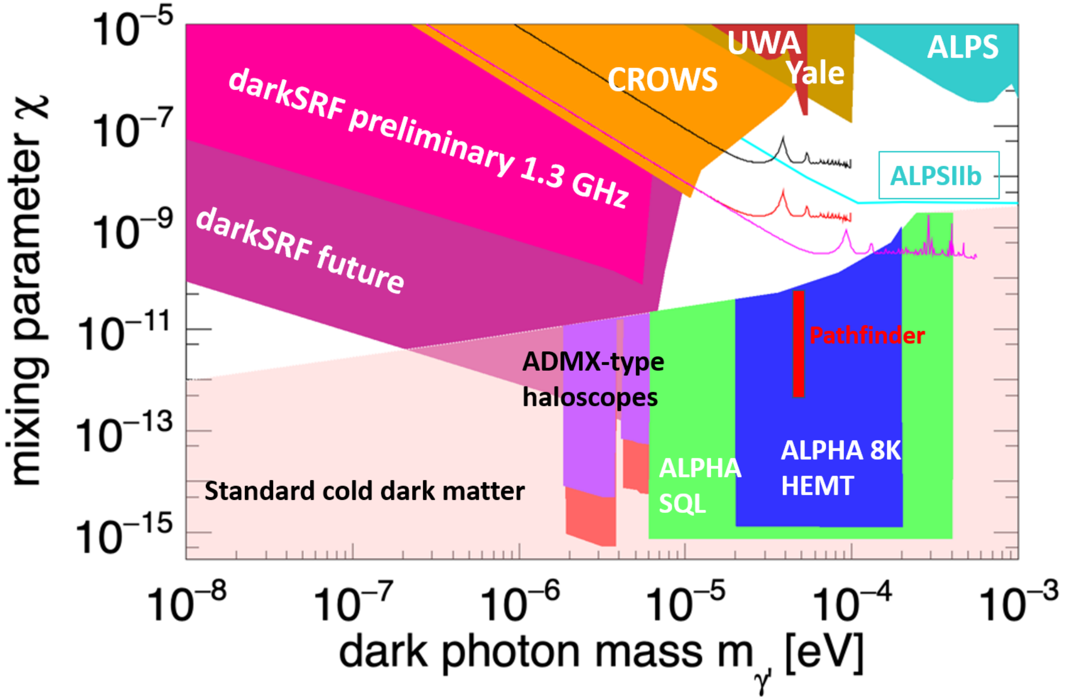
Ex) Plasma halocsope ALPHA

Signal: $\propto VQ$ but an RF cavity becomes $V \sim f^{-3}$



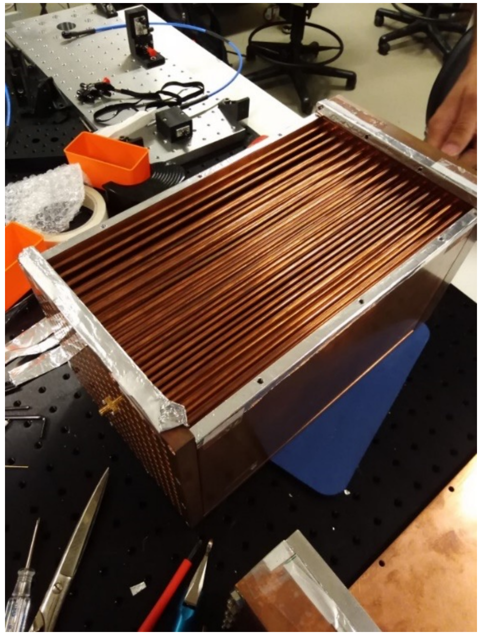
The signal is lost by higher frequency

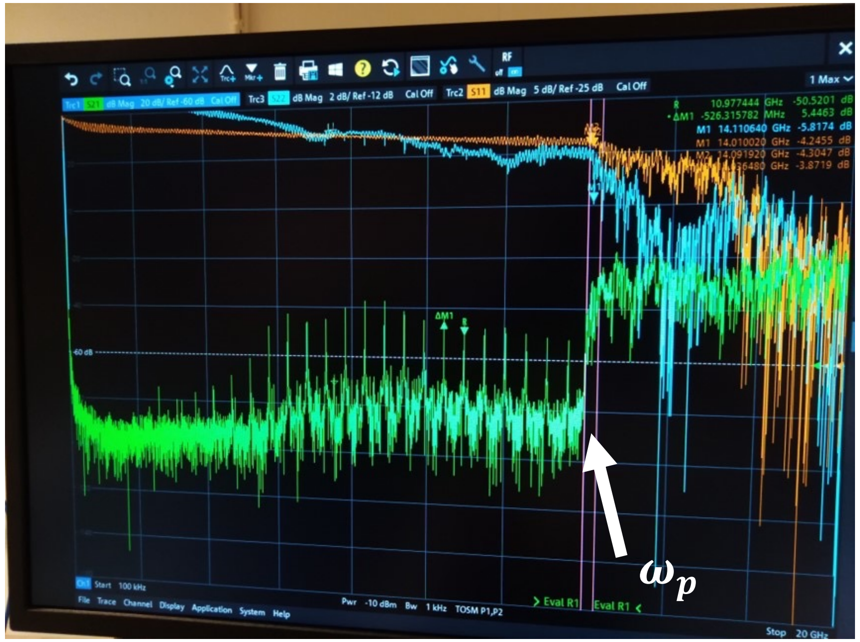
→ Wire metamaterial to couple plasmon to dark photons



Phys. Rev. D 102, 043003 (2020)

ALPHA collaboration

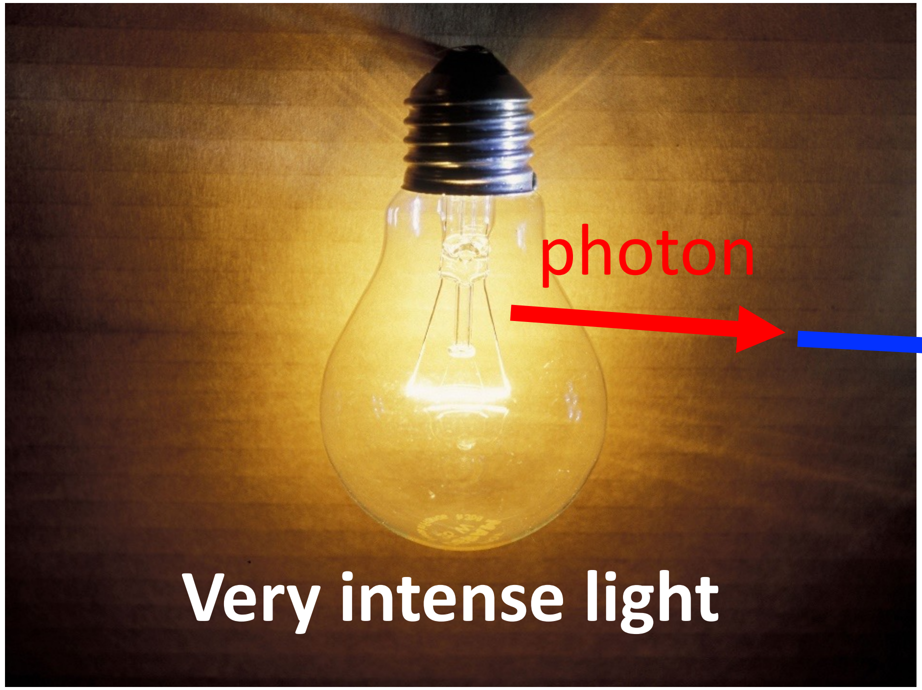




$$P_{\mathrm{out}} = 1.1 \times 10^{-22}\ \mathrm{W} \left(\frac{\kappa}{0.5}\right) \left(\frac{\mathcal{G}}{1}\right) \left(\frac{\chi}{10^{-15}}\right)^2 \left(\frac{Q}{100}\right) \times \left(\frac{V_d}{0.8\ \mathrm{m}^3}\right) \left(\frac{\nu}{10\ \mathrm{GHz}}\right) \left(\frac{\rho}{0.45\ \mathrm{GeV/cm}^3}\right).$$

The signal explicitly depends on dark matter density around us

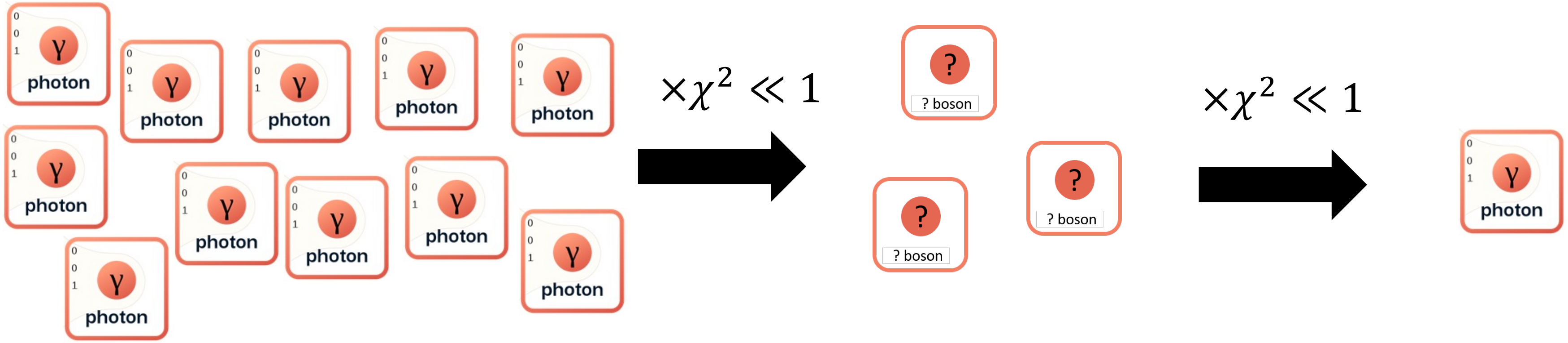
To be free from astrophysical uncertainty in ρ



https://www.independent.co.uk/news/science/old-fashioned-light-bulbs-could-be-set-comeback-after-light-recycling-breakthrough-a6806446.html

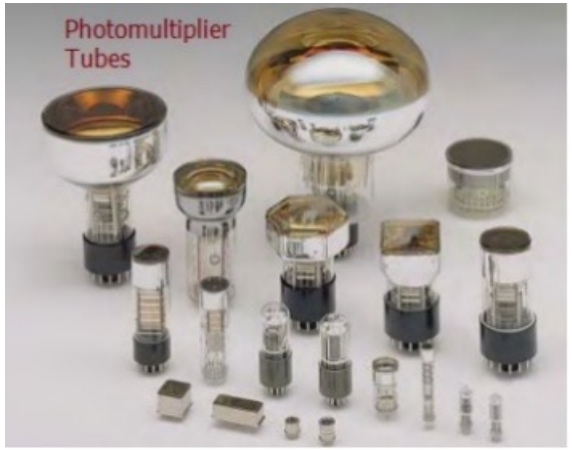
Dark photon

https://tomroyreleased.files.wordpress.com/2016/12/wp-1481922375633.jpeg

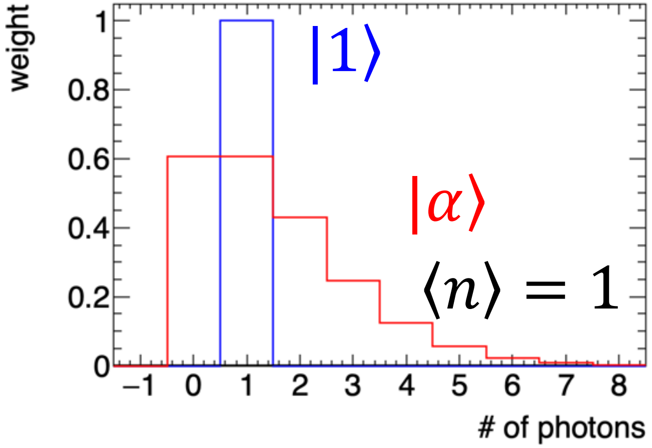


Naively, single photon detection seems required

Photon counting vs coherent wave detection



$$\Delta N \Delta \phi > \hbar$$

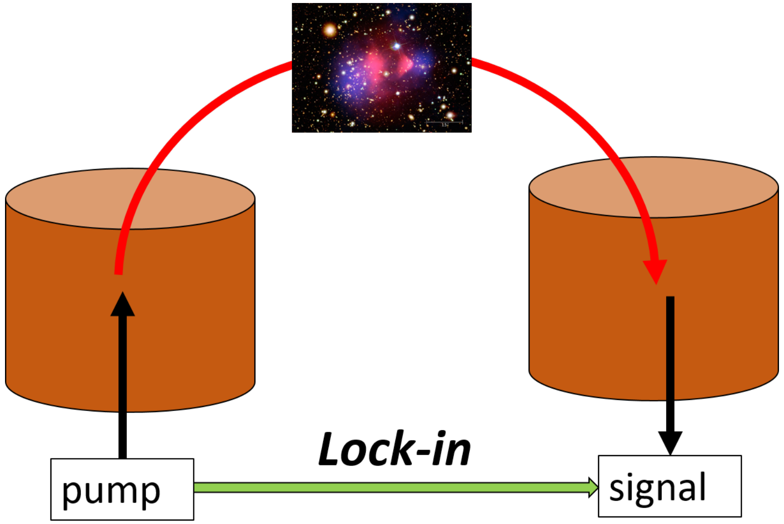


<u>LSW: coherent state (semi-classical)</u>

$$\hat{E}^{+}|\alpha\rangle = i\sqrt{\frac{\hbar\omega}{2\epsilon_0 V}}\,\hat{a}|\alpha\rangle = \boxed{i\alpha\sqrt{\frac{\hbar\omega}{2\epsilon_0 V}}}\,|\alpha\rangle$$

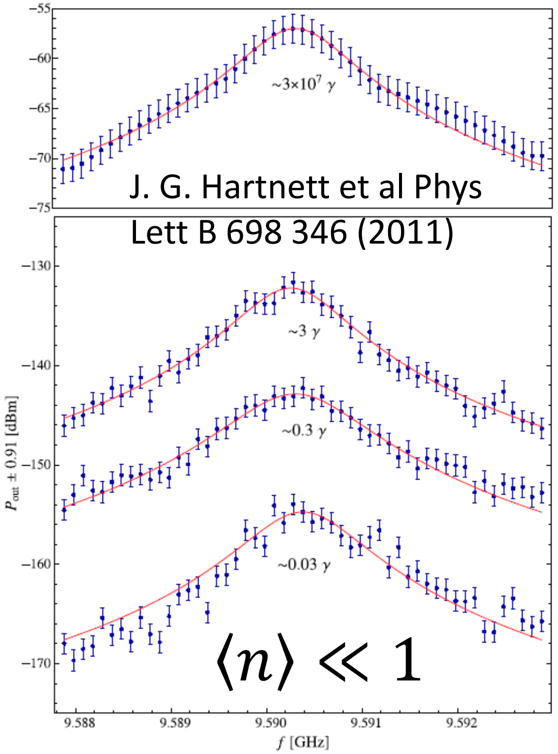
E^{+}

$$\langle\alpha|\hat{E}(\boldsymbol{r},t)|\alpha\rangle = E^{+}e^{-i(\omega t-\boldsymbol{k}\cdot\boldsymbol{r})} + E^{-}e^{i(\omega t-\boldsymbol{k}\cdot\boldsymbol{r})}$$



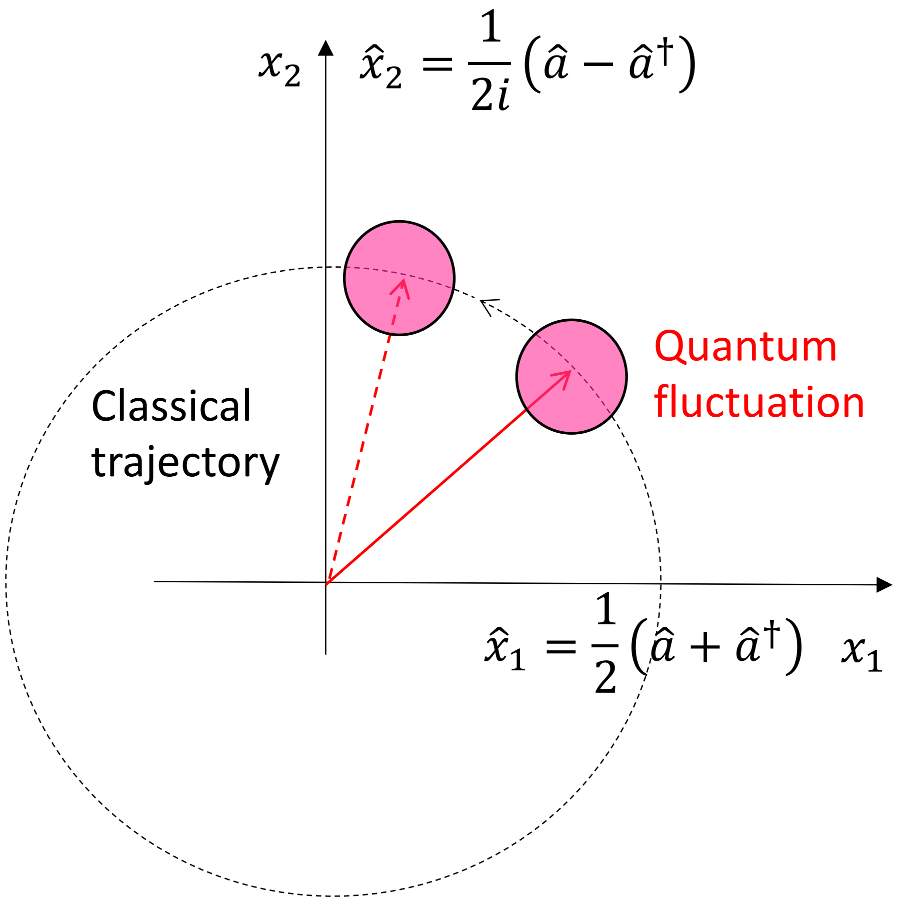
The photon counting loses the phase information

→ The wave detection surpasses if coherency is ensured over long period

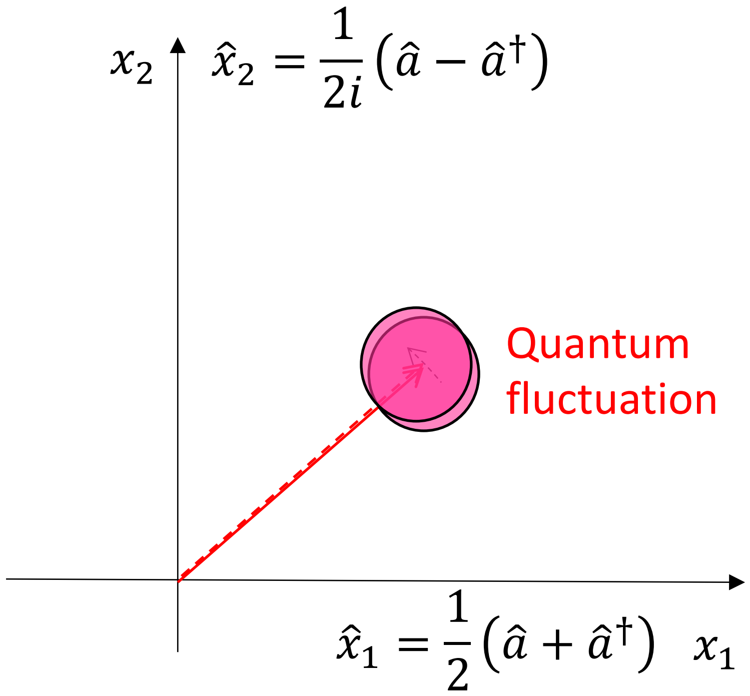


Intuitive image of phase locking

The phase rotates within the bandwidth



Relative phases are locked-in



- Classical drift (decoherence) is suppressed
- The signal to noise ratio is **linearly** enhanced by integral over the relative coherence time
- The precision of the locking must be checked

The implementation is RF/MW/mmw is feasible with modern devices (5G)

FFT (>>1s) → dramatic filtering of **white noise**

Noise power in given detection bandwidth

$$P_N = k_B T_S \frac{\sqrt{BW}}{\sqrt{t}}$$

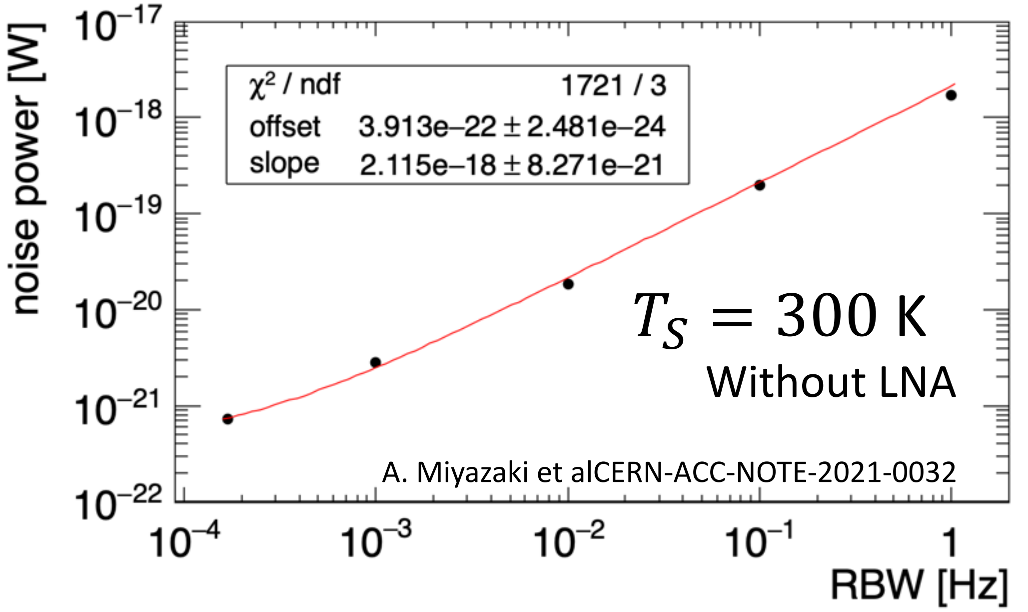
With noise temperature T_s and integration time of FFT

$$t = BW^{-1}$$

30 GHz single photon per second

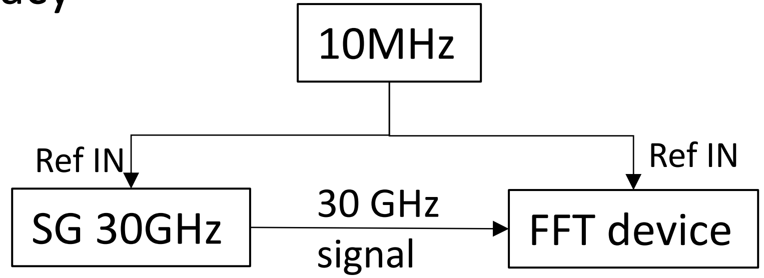
$$h\nu/s \sim 2\times10^{-23}\ \mathrm{W}$$

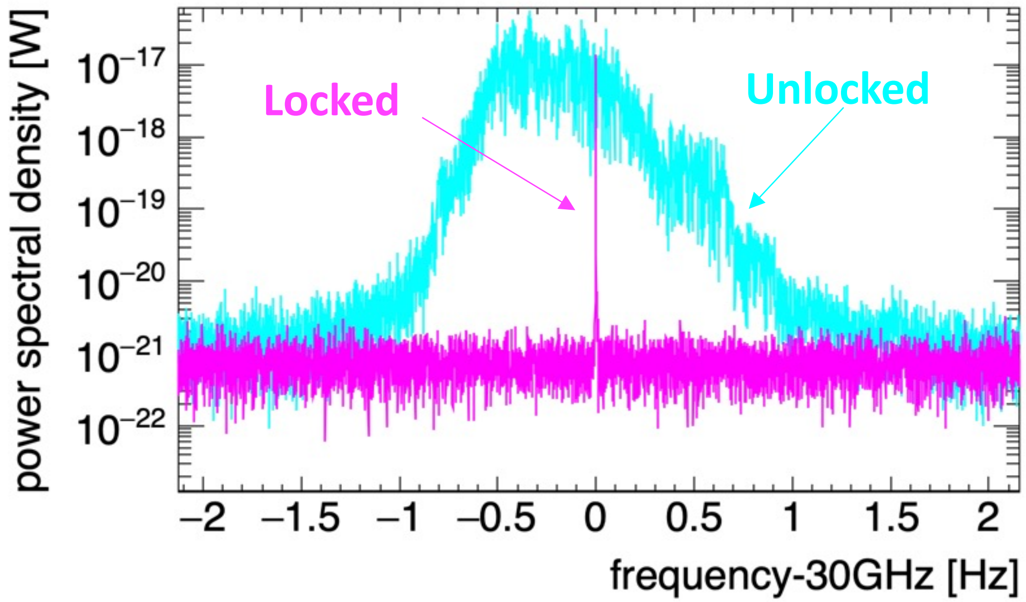
→ Thermal photons (white noise) can be dramatically suppressed by FFT without cooling



The ***signal*** is demonstrated to be narrow-band within the BW

Phase-locking of photon generator and emitter enables this relative accuracy

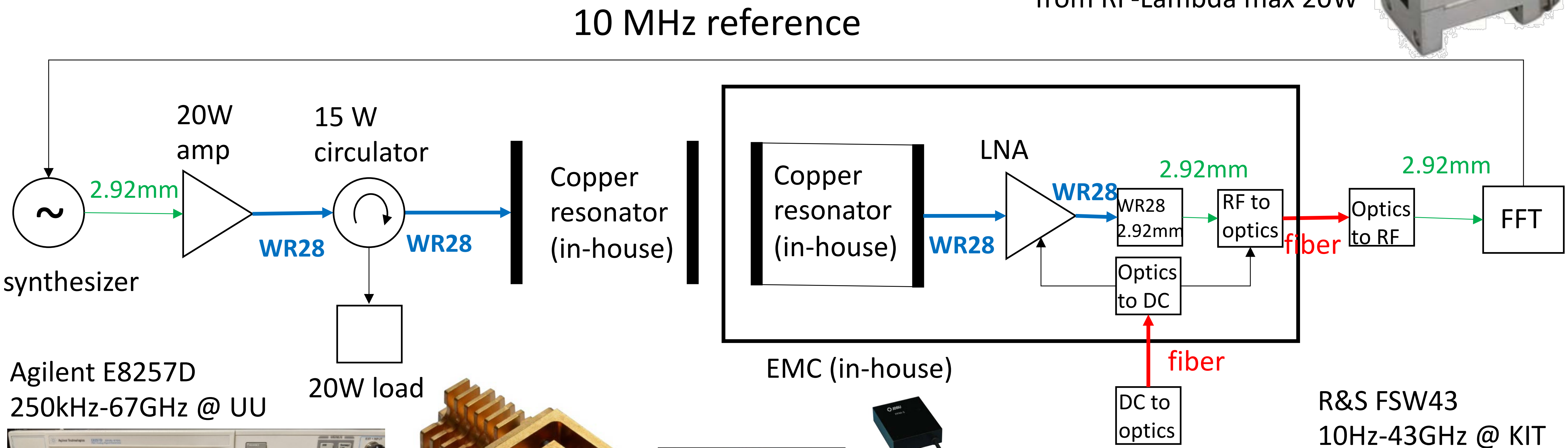




Coherence time $t_{coherence} = BW^{-1}$ > 1 hour was achieved!

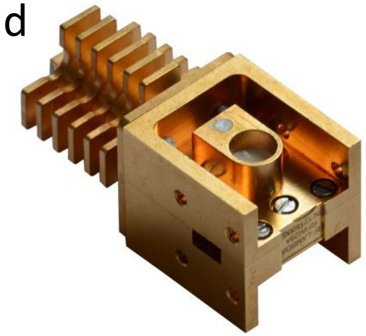
Lower power prototype schematic

WR28 to coaxial adaptor
RFWA28E0F
from RF-Lambda max 20W



Agilent E8257D
250kHz-67GHz @ UU

ERZ-HPA-
3000-3100-46
From ERZIA



RFWI28A27G32G
from RF-Lambda

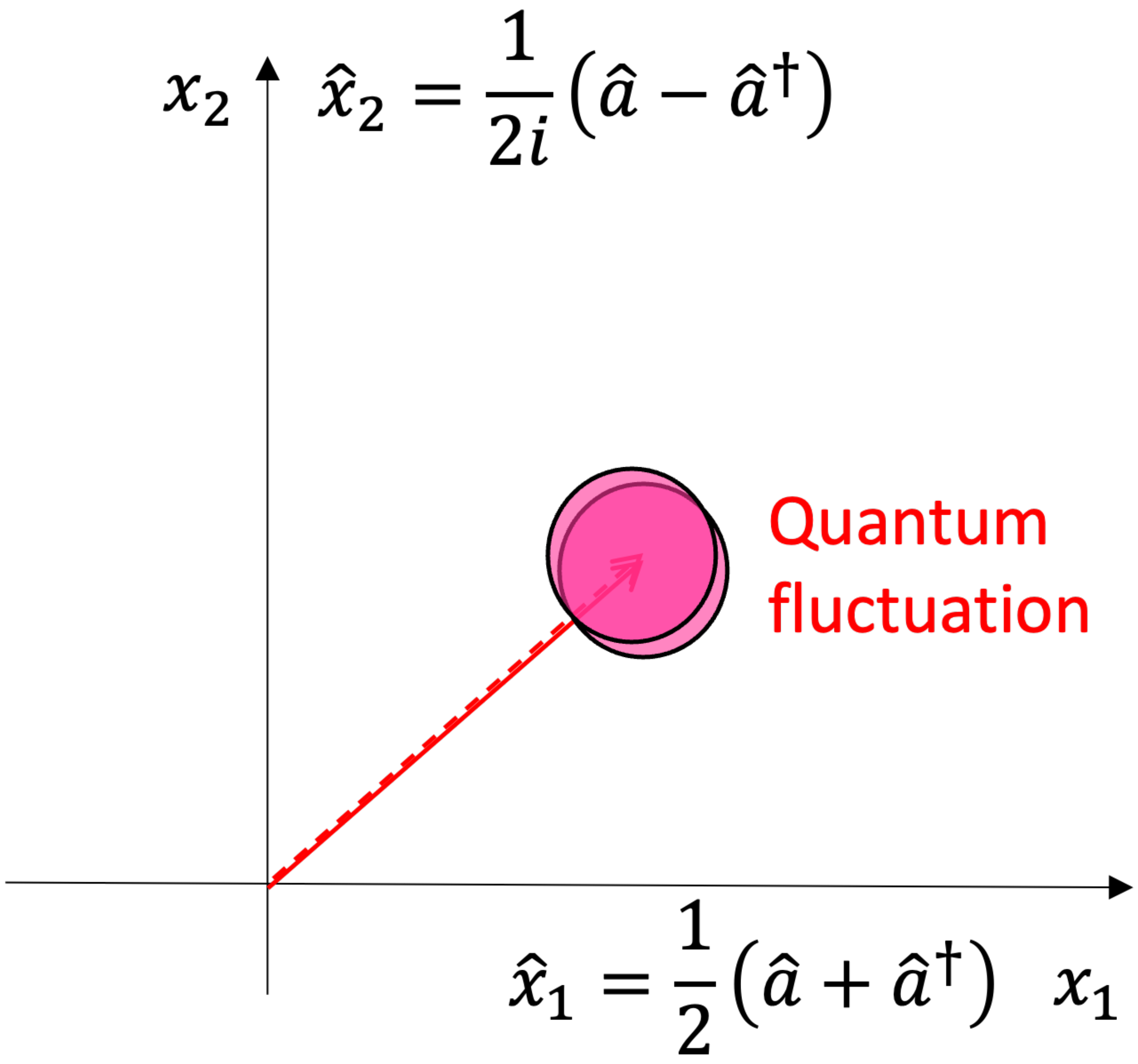
LNF-LNR23_42WB
From Low noise factory

PPM-5 DC
5VDC 1W
From JDSU

RFoF-30GHz-Q2-Mini
gain 10dB, noise figure 17dB

R&S FSW43
10Hz-43GHz @ KIT

Standard quantum limit



$$k_B T_S > h\nu$$

Cooling down does not help

Single photon sensors surpass coherent method of any $\Delta\nu$ at cold

Ratio of noise power

$$\frac{P_l}{P_{sp}} = \frac{1}{\sqrt{2\pi\eta}}\left(\sqrt{\bar{n}} + \frac{1}{\sqrt{\bar{n}}}\right)\sqrt{\frac{Q_c}{Q_a}}$$

$\nu = 30$ GHz

$\Delta\nu_c = 500$ kHz

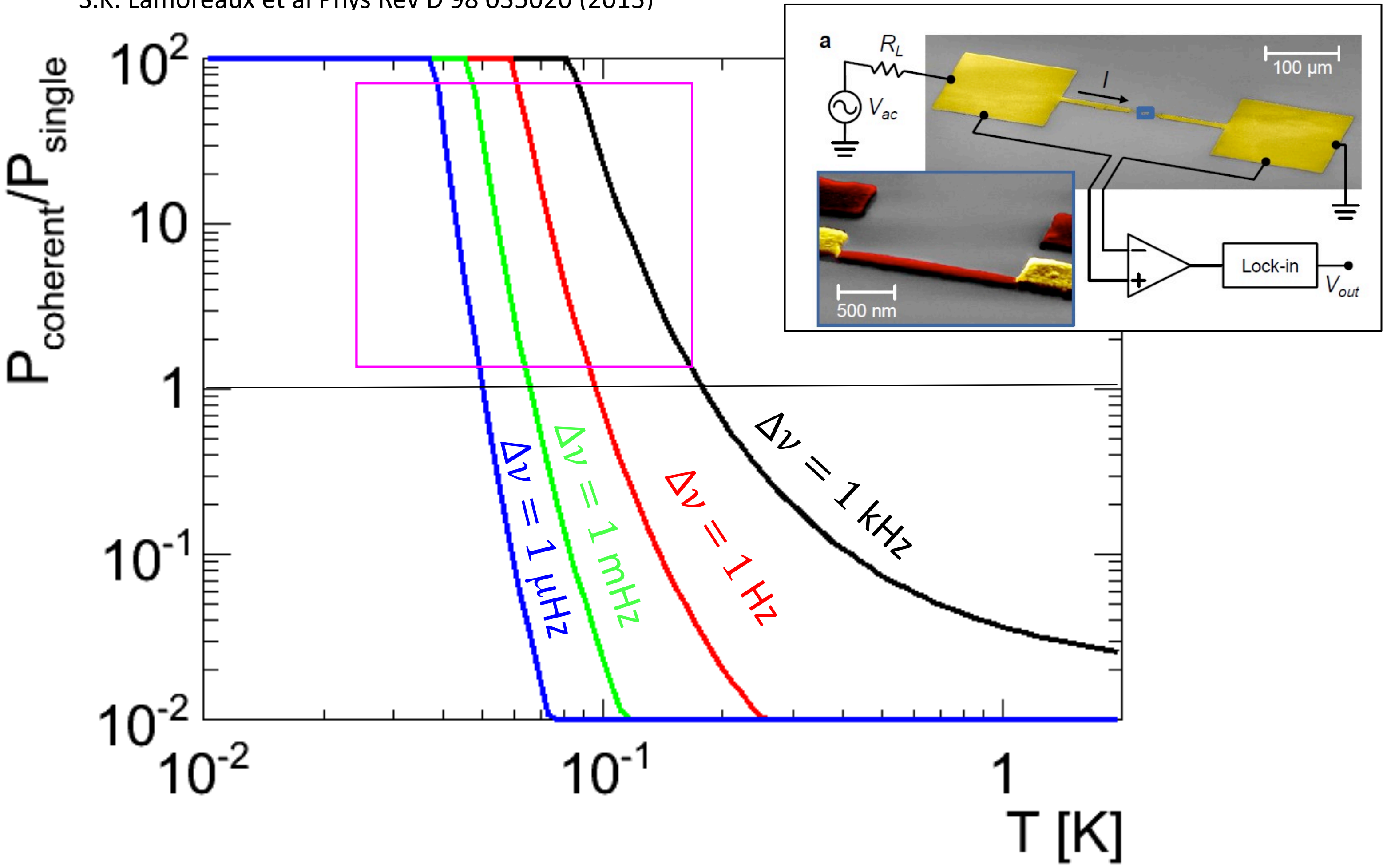
$$\bar{n} = \frac{1}{e^{h\nu/k_B T} - 1}$$

Q_c: cavity quality factor

Q_a: signal quality factor

F. Paolucci et al Phys Rev Appl. 14 034055 (2020)

S.K. Lamoreaux et al Phys Rev D 98 035020 (2013)

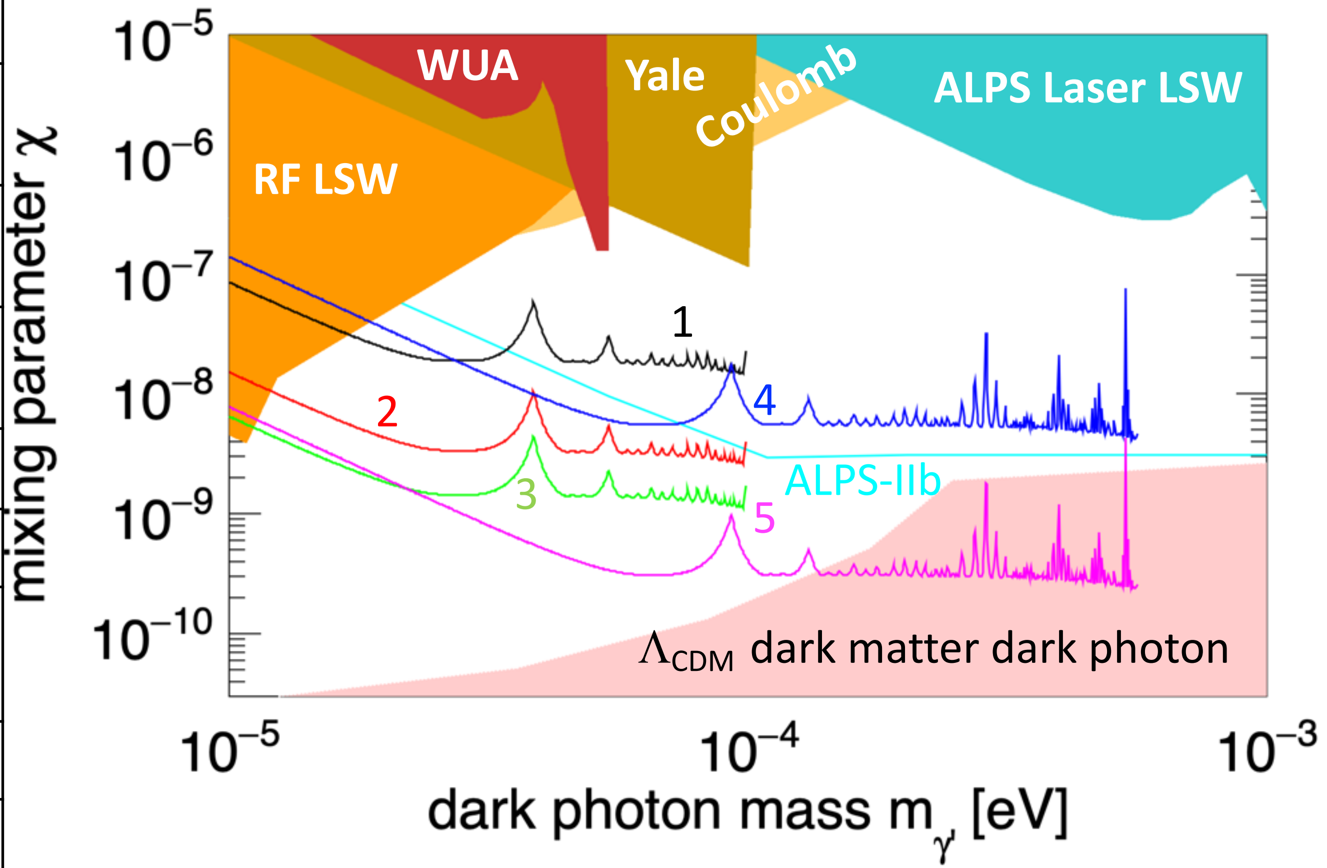


Superconducting single photon sensors may be a solution in the future

→ Launch 1st physics run with coherent method and continue on developing photon sensors

Outlook: dark photon search with mmw

	1	2	3	4	5
Frequency [GHz]	30	30	30	170	170
Power source P_{in} [W]	20	20e3	20e3	1e6	1e6
Generation cavity build-up β_1	1000	1000	1000	1	1000
Regeneration cavity build-up β_2	1000	1000	1000	1000	1000
Efficiency $\eta(m_{\gamma'})$	0.1	0.1	0.1	0.1	0.1
Temperature	300K	300K	10K	4K	20mK
sensor	LNA	LNA	LNA	SIS-LNA	Single photon
BW [Hz]	3e-4	3e-4	3e-4	6e-3	-
t_{OP}	1h	1h	1h	3min	3min



The results will be complementary to the ALPS-IIb (IR 100m-100m resonators)

The coherent detection scheme is a good starting point

Dark photon is *not* the goal → axion search with millimeter waves

QCD axion: to solve the strong CP problem

$$L_{QCD} = -\frac{1}{4} G^{a}_{\mu\nu} G^{\mu\nu a} + \frac{g_s^2}{32\pi^2} \boldsymbol{\theta} G^{a}_{\mu\nu} \tilde{G}^{\mu\nu a}$$

Neutron EDM

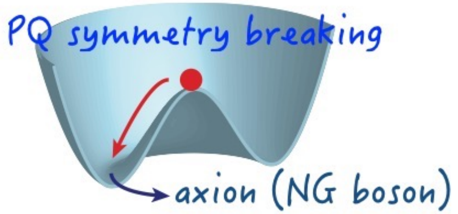
Theory: $d_n \sim 4.5\times10^{-15} \boldsymbol{\theta}$ ecm

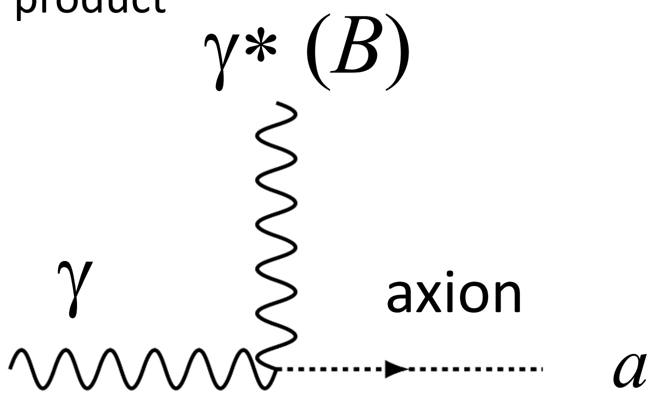
Experiment: $|d_n| < 2.9\times10^{-29}$ ecm

→ $|\theta| < 0.7\times10^{-11} \ll 1$: **naturalness problem**!

Global chiral U(1)→ NG boson as a by product

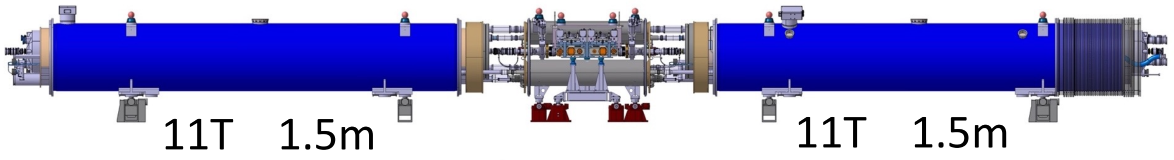
$$\frac{g_s^2}{32\pi^2}\left(\theta + \frac{\boldsymbol{a}}{\boldsymbol{F_a}}\right) G^{a}_{\mu\nu} \tilde{G}^{\mu\nu a}$$

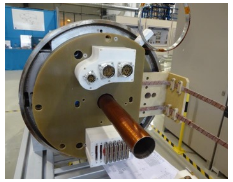


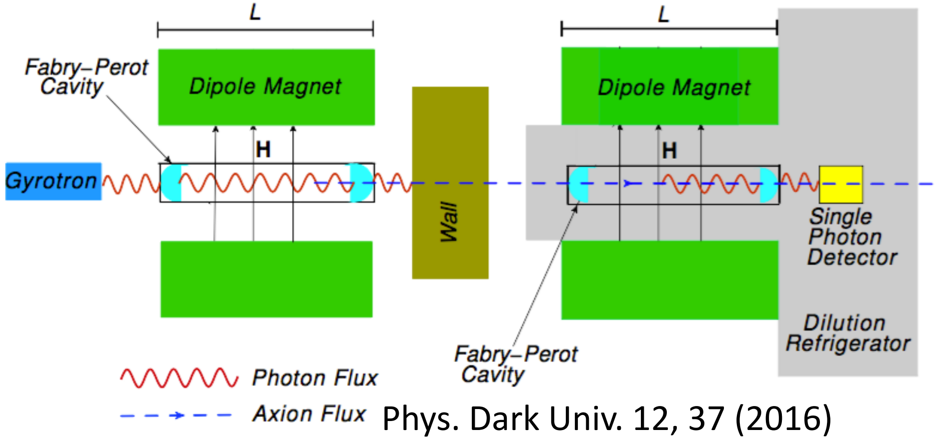


The millimeter wave technology for dark photon search can also be used for axion search

STAX@INFN: Nb_3Sn dipole for HL-LHC

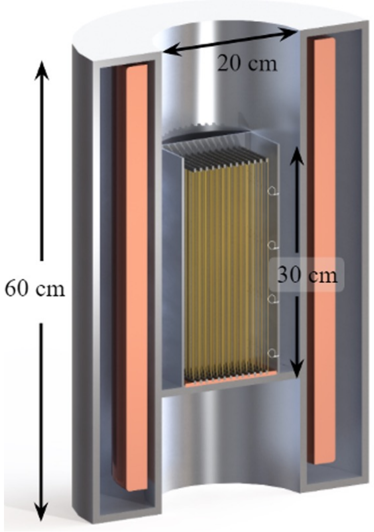


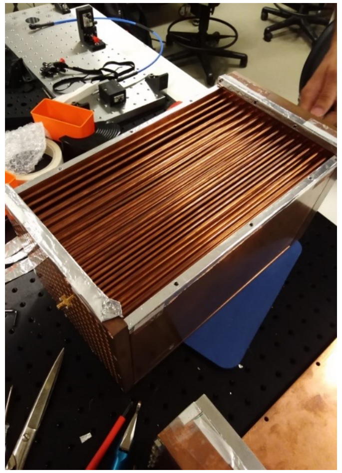


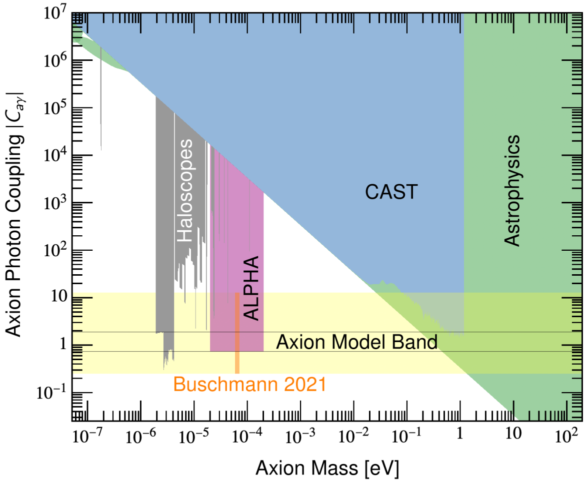


Phys. Dark Univ. 12, 37 (2016)

ALPHA@Stockholm (dark matter axion)







Phys. Rev. Lett. 123 (2019) 141802

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- F. Giazotto, F. Paolucci, P. Spagnolo (INFN & NEST Pisa)

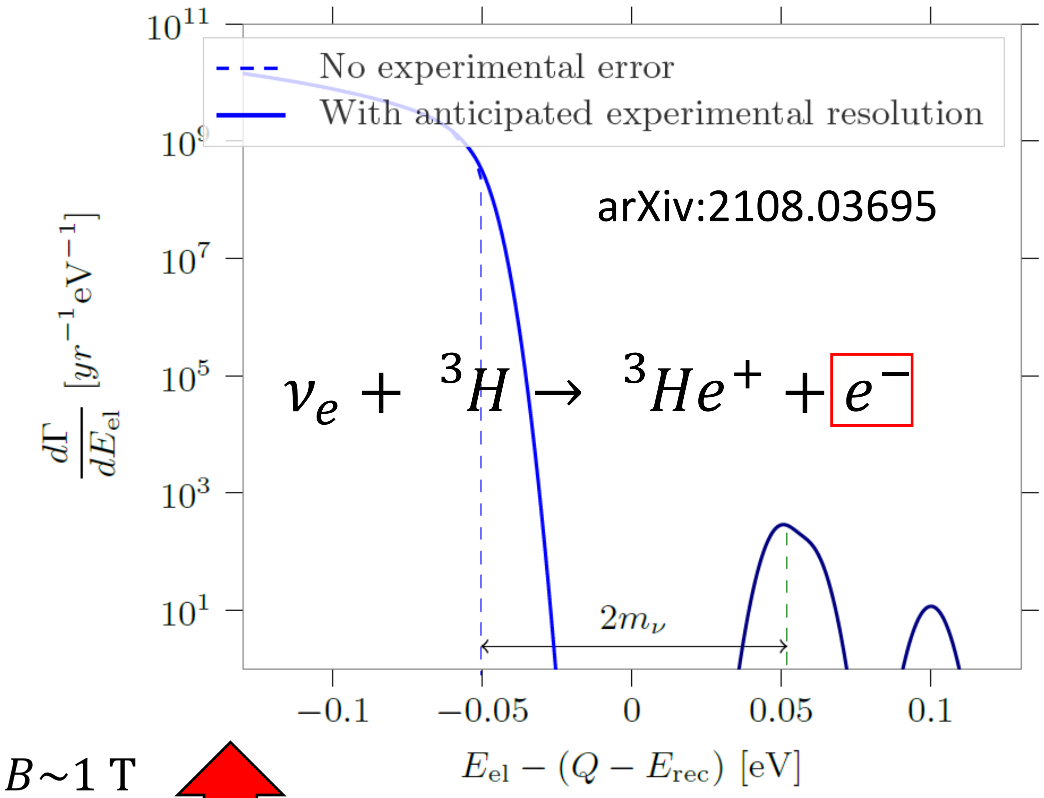
- This study is supported by international excellence fellowship program 2021 in KIT

Conclusions

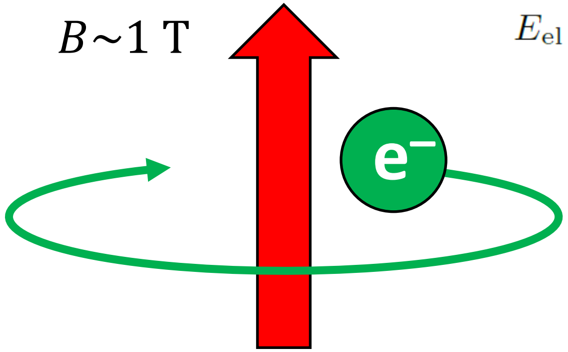
- Dark matter may be explained by dark photons
  - Milli-eV is least constrained and may be addressed with millimeter waves
- Two typical methods
  - Direct detection: plasma haloscope
  - Light-Shining-Through-a-Wall
- Single photon detection vs wave detection
  - Phase lock & coherency: benefit of wave detection scheme
  - Ultimate limit of coherent wave detection → photon counting
- Expected exclusion limits are complementary to other experiments
- Dark photon experiment + magnet = axion search

MMW might be a gold mine

Capturing relic neutrino

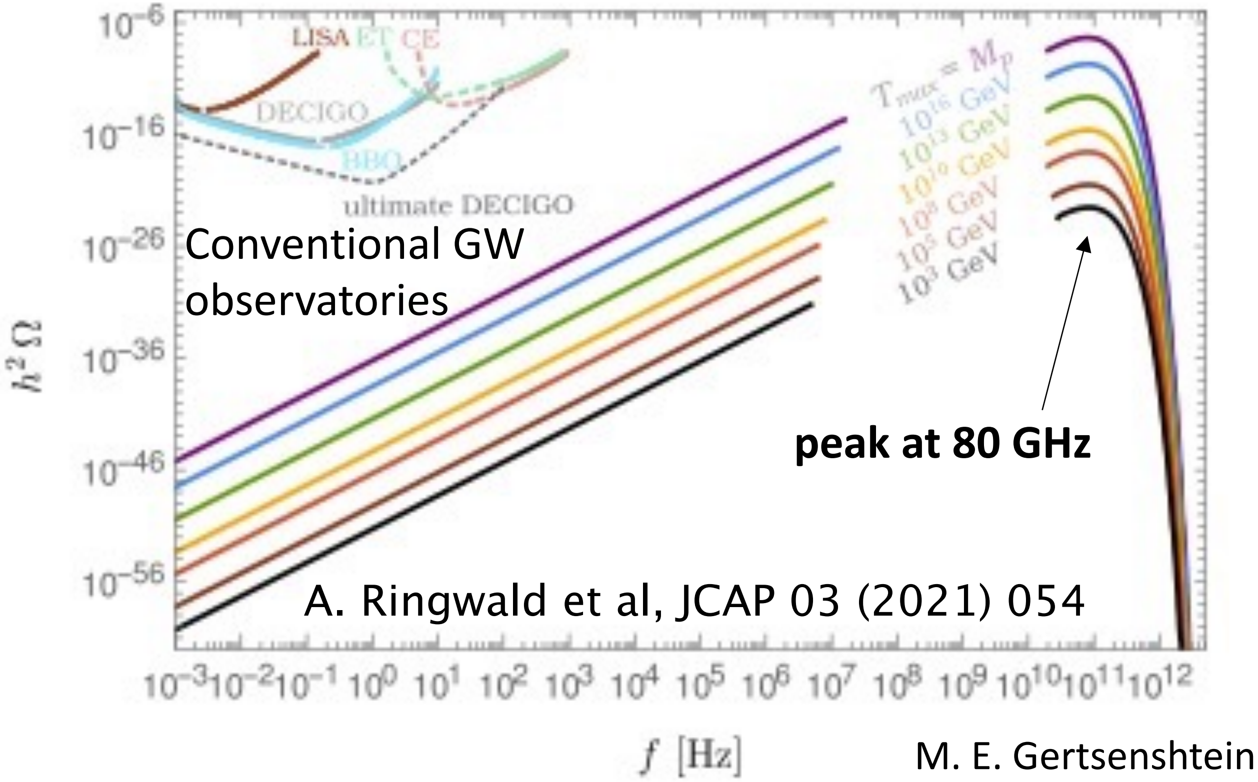


$B\sim 1$ T



$$f = \frac{eB}{2\pi\gamma m_e} \sim 27\ \text{GHz}$$

Capturing relic GW



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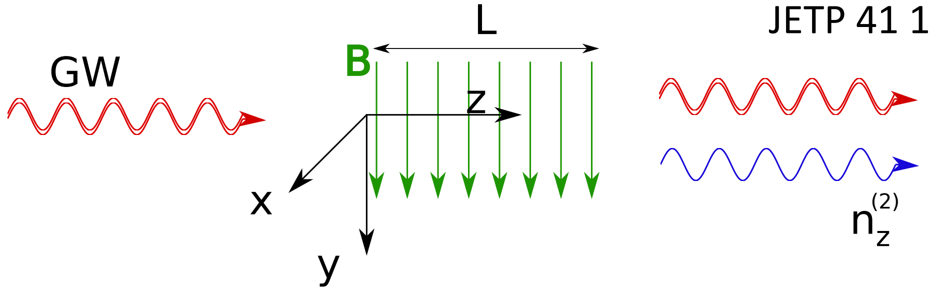


background

FFT (>>1s) → dramatic filtering of **white noise**

Noise power in given detection bandwidth

$$P_N = k_B T_S \frac{\sqrt{BW}}{\sqrt{t}}$$

With noise temperature T_s and integration time of FFT

$$t = BW^{-1}$$

30 GHz single photon per second

$$h\nu/s \sim 2\times10^{-23}\ \mathrm{W}$$

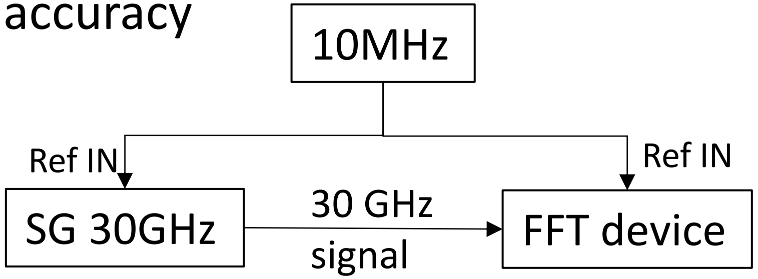
→ Thermal photons (white noise) can be dramatically suppressed by FFT without cooling

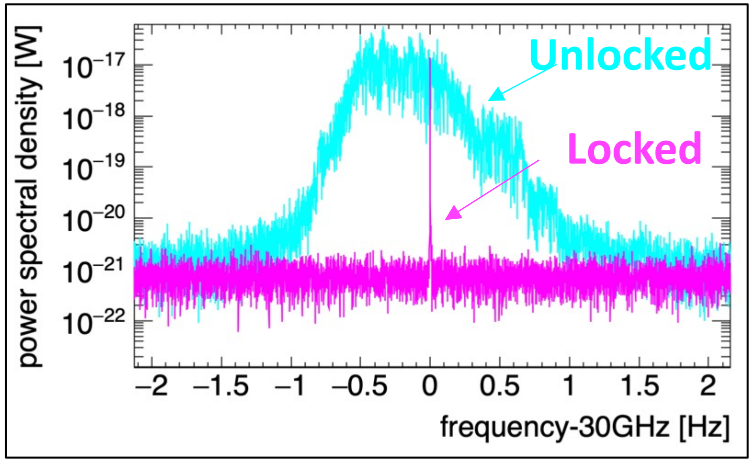
$$T_S = 300\ \mathrm{K}$$

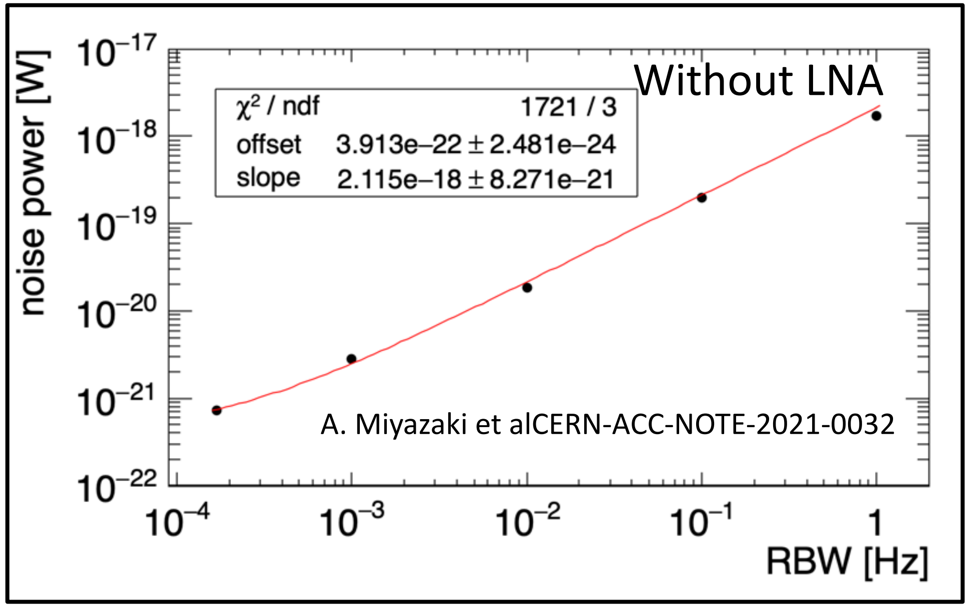
t	BW	P_N	#photon/s
100 ms	10 Hz	4.2e–20 W	2100
1 s	1 Hz	4.1e–21 W	200
10 s	100mHz	4.1e–22 W	21
5 min	3 mHz	1.4e–23 W	0.7
1 hour	278 μHz	1.1e–24 W	0.06
1 day	12μHz	4.8e–26 W	0.002

The ***signal*** is demonstrated to be narrow-band within the BW

Phase-locking of photon generator and emitter enables this relative accuracy







Coherence time $t_{coherence} = BW^{-1}$ > 1 hour was achieved!

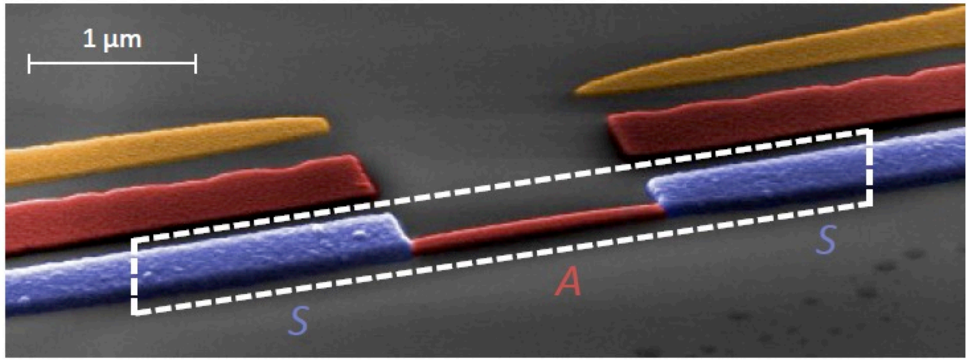
Superconducting photon sensors in NEST Pisa are promising

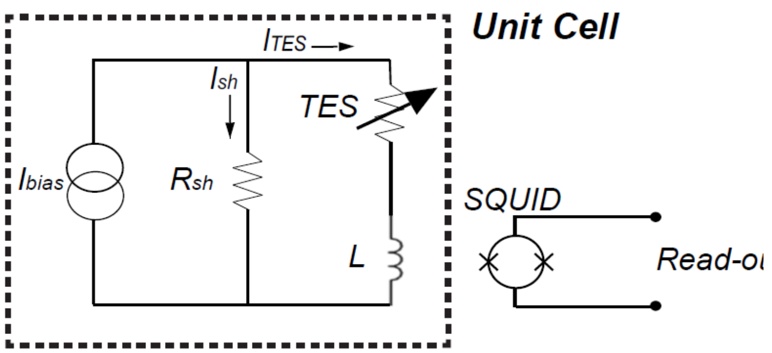
Nano-Transition Edge Sensor (TES)

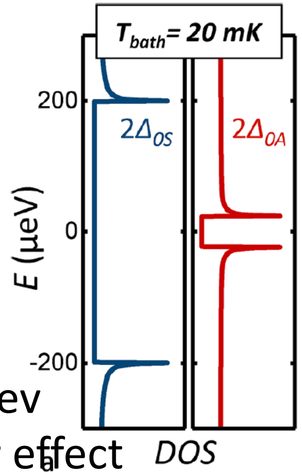
Tiny volume & Andreev mirror effect at the border

→ Reactive to small heat dissipation

→ Extremely high sensitivity **10^{-20} WHz$^{-1/2}$**





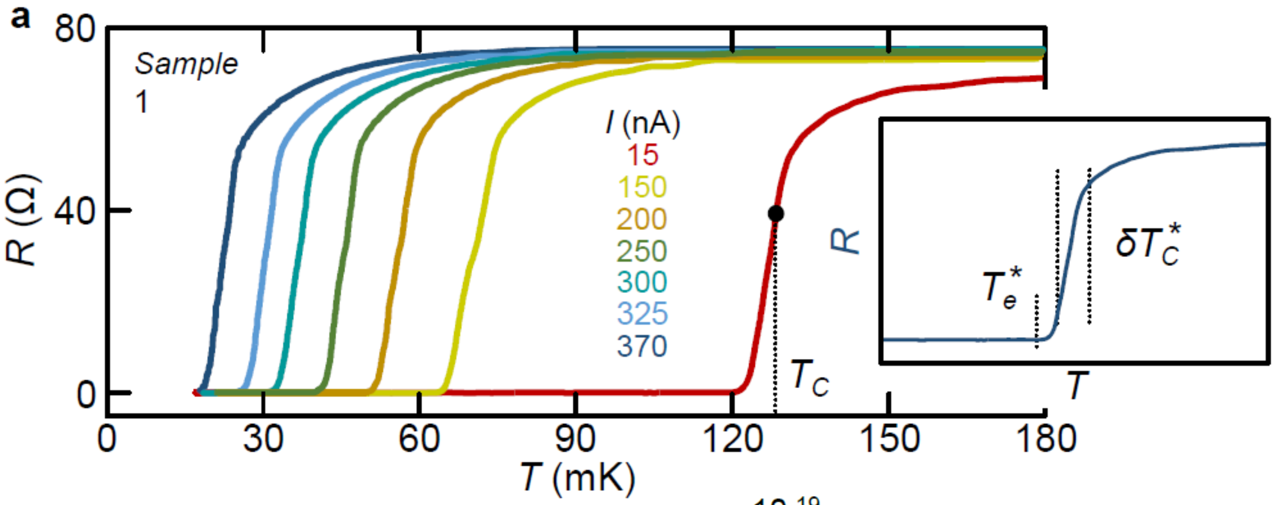


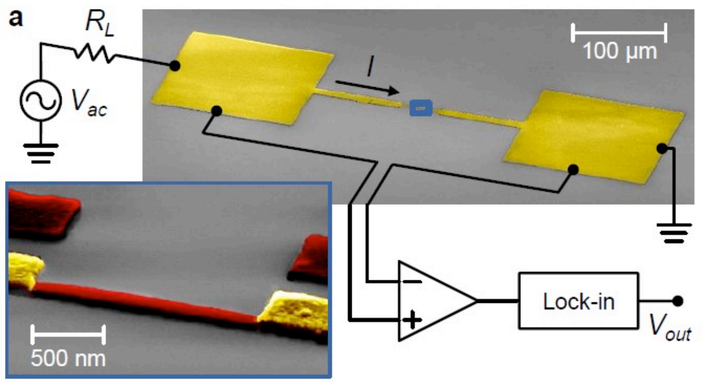
Andreev mirror effect

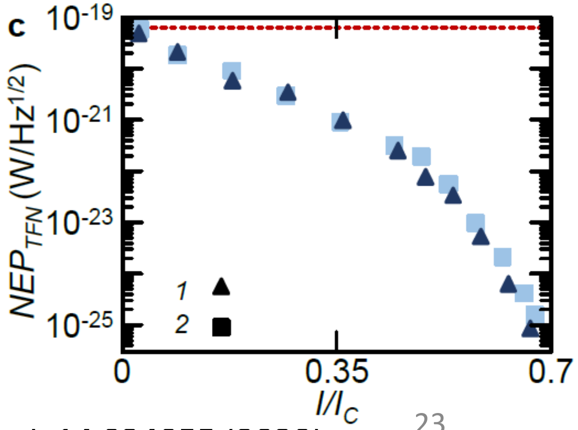
F. Paolucci et al Journal of Applied Physics 128, 194502 (2020)

Josephson Escape Sensor (JES)

- Absorption of a photon by "phase particle" in JJ under current
- Tunable sensitivity *in-situ* by bias current
- → expected **10^{-25} WHz$^{-1/2}$** with similar infrastructure as TES







F. Paolucci et al Phys Rev Appl. 14 034055 (2020)