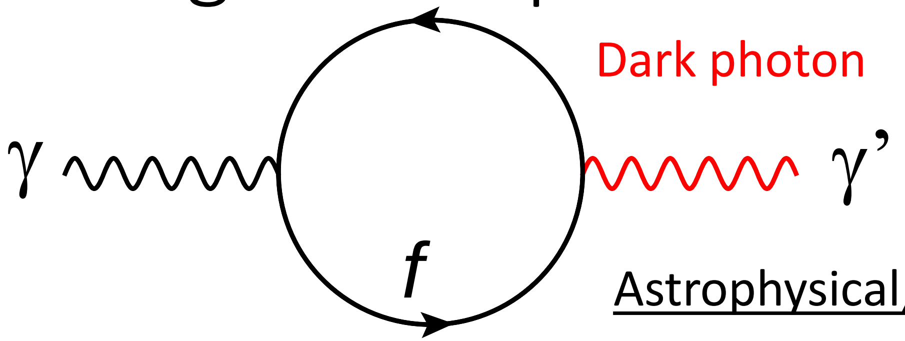
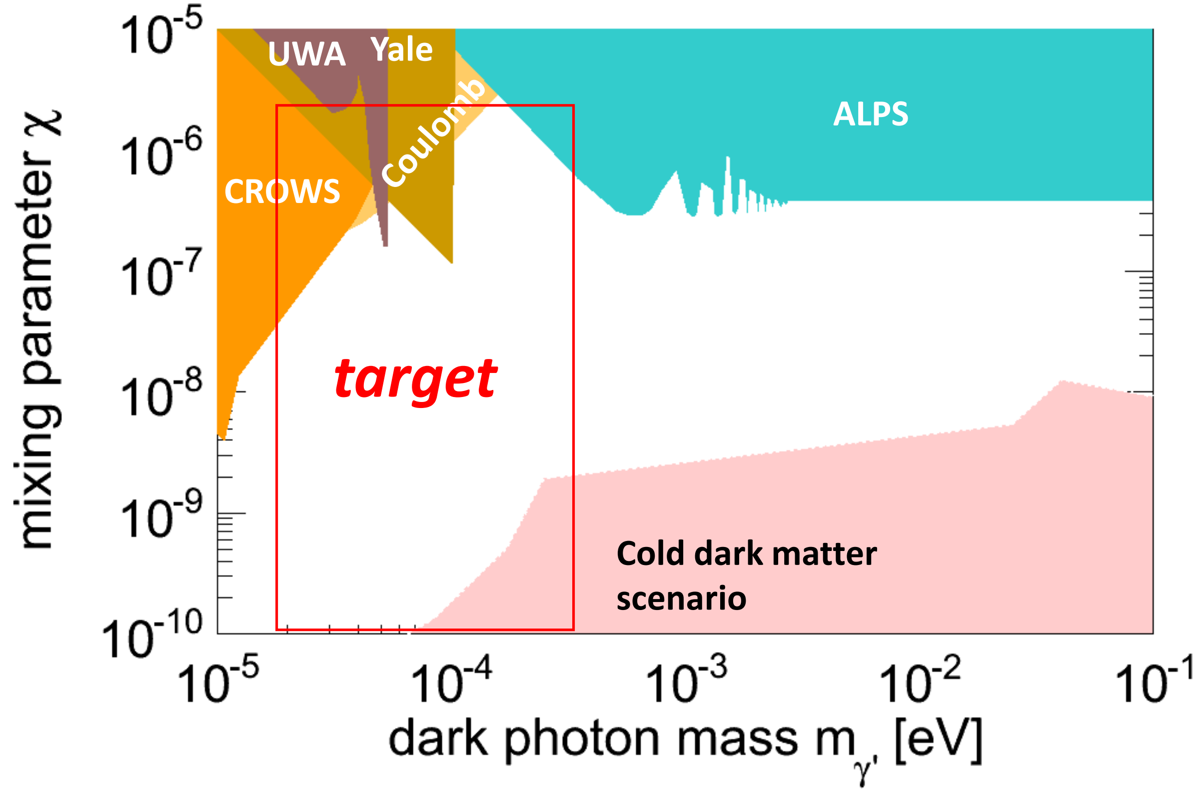
New dark photon search with millimeter waves above 20 GHz

A. Miyazaki (Uppsala University and CERN)

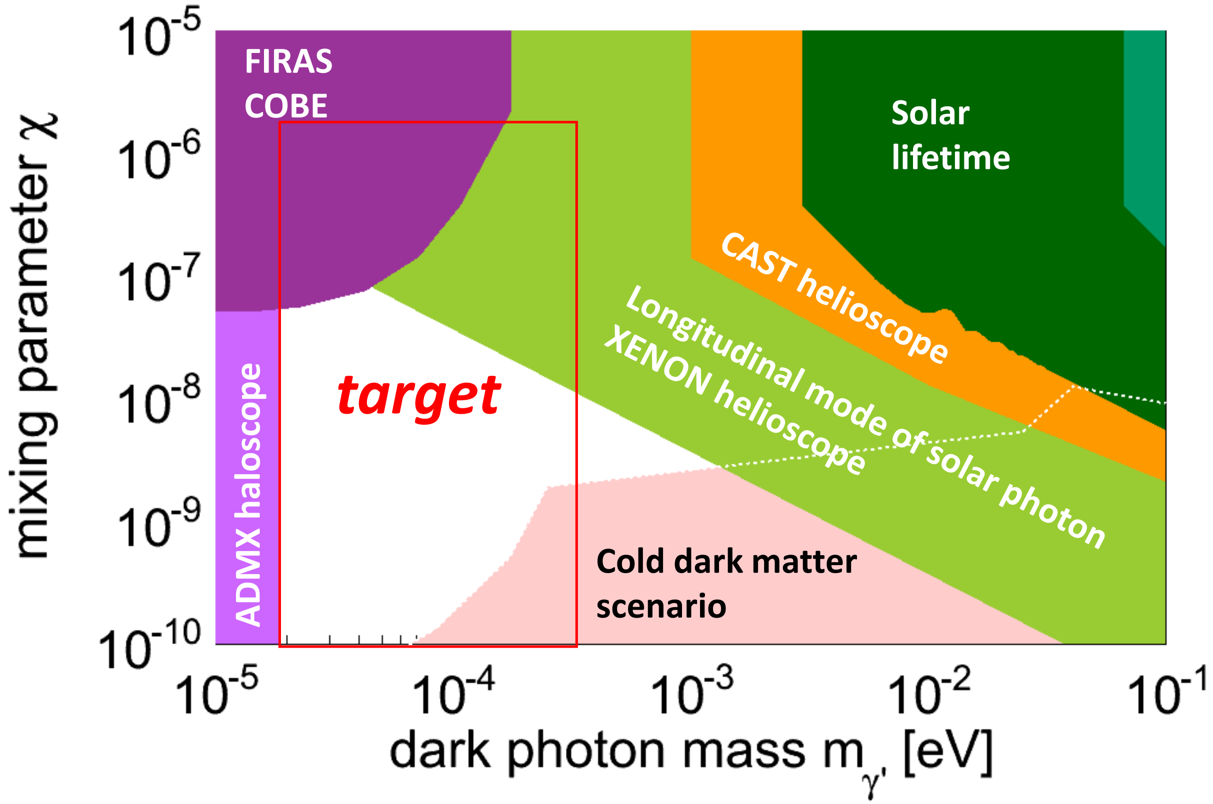
Open window in the light dark photon search (Kinetic mixing)



Purely laboratory constraints

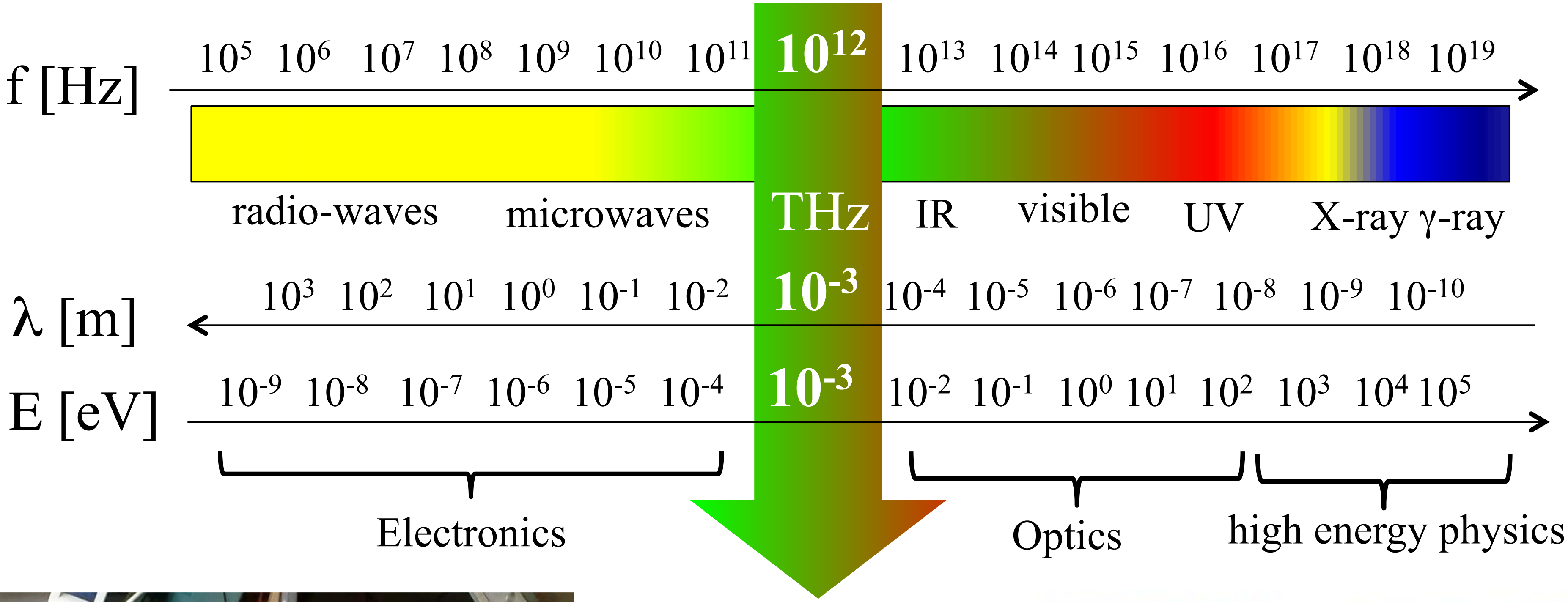


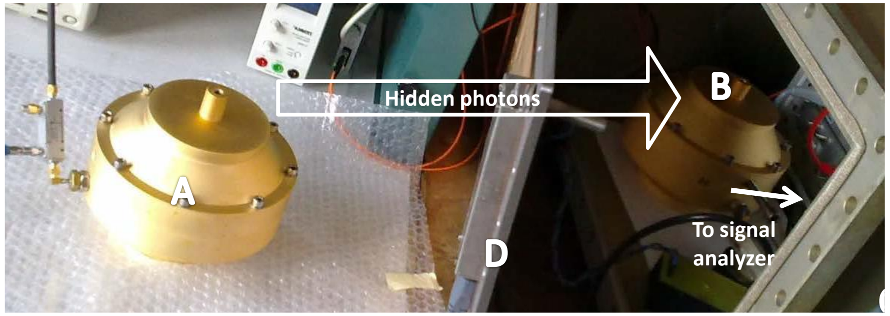
Astrophysical, haloscope, and helioscope



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

Previous Light-shining through a wall experiments and THz gap





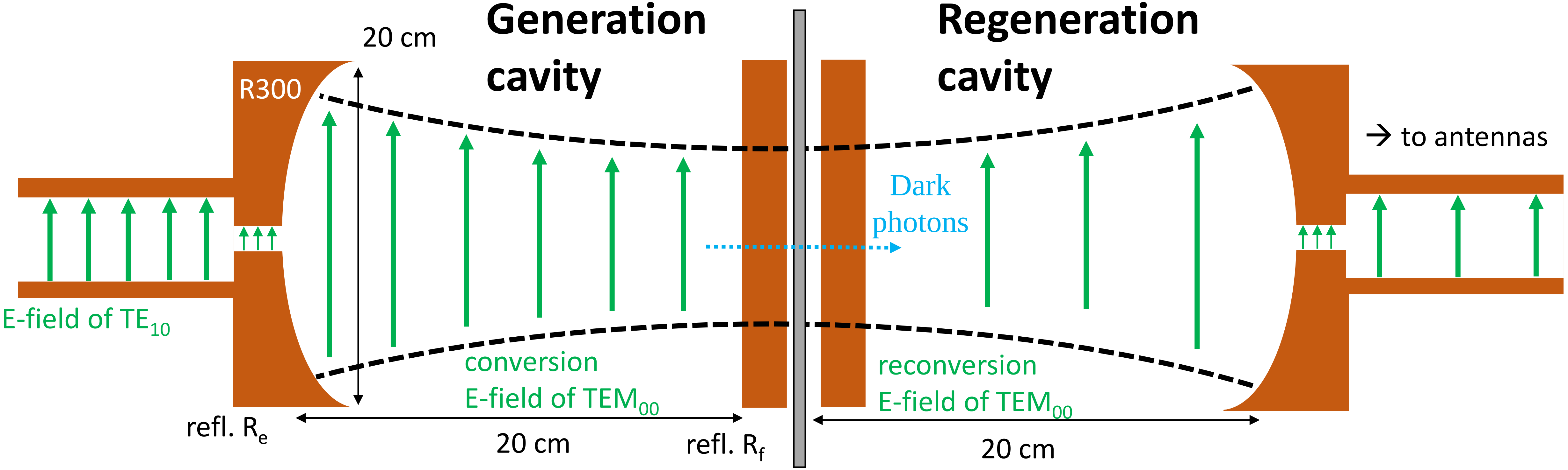
3 GHz: M Betz, F. Caspers, Gaior, M. Thumm, and S. W. Rieger PRD 88 075014 (2013)

New LSW in this frequency

On-resonance cavity approach by P.L. Slocum et al. NIMA 770 76 (2015)

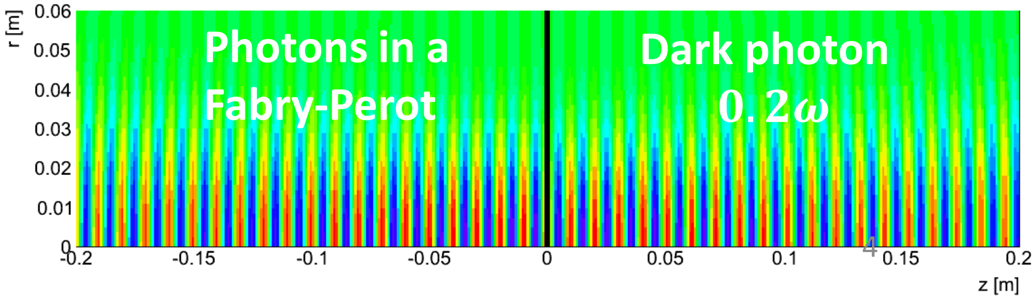
Laser: ALPS collaboration PLB 689 149 2010
X-ray: T. Inada, et al., PLB, 722, 301-304 (2013)

Fabry-Perot resonator for $m_{\gamma'}$<30 GHz



- Finesse $\mathcal{F} = 2\pi/(1 - R_e R_f) = 3300$
- Loaded Q $Q_L = \mathcal{F} \times L/\lambda = 6.6 \times 10^4$
- Band-width of the cavities: $BW = f/Q_L = 0.45$ MHz
- Spatial resonance width: $\delta L = \lambda/2\mathcal{F} = 1.5$ μm
- Resonator build-up factor $\beta = \mathcal{F}/\pi \sim$ **1000**
- Coupling between two resonators is to be evaluated

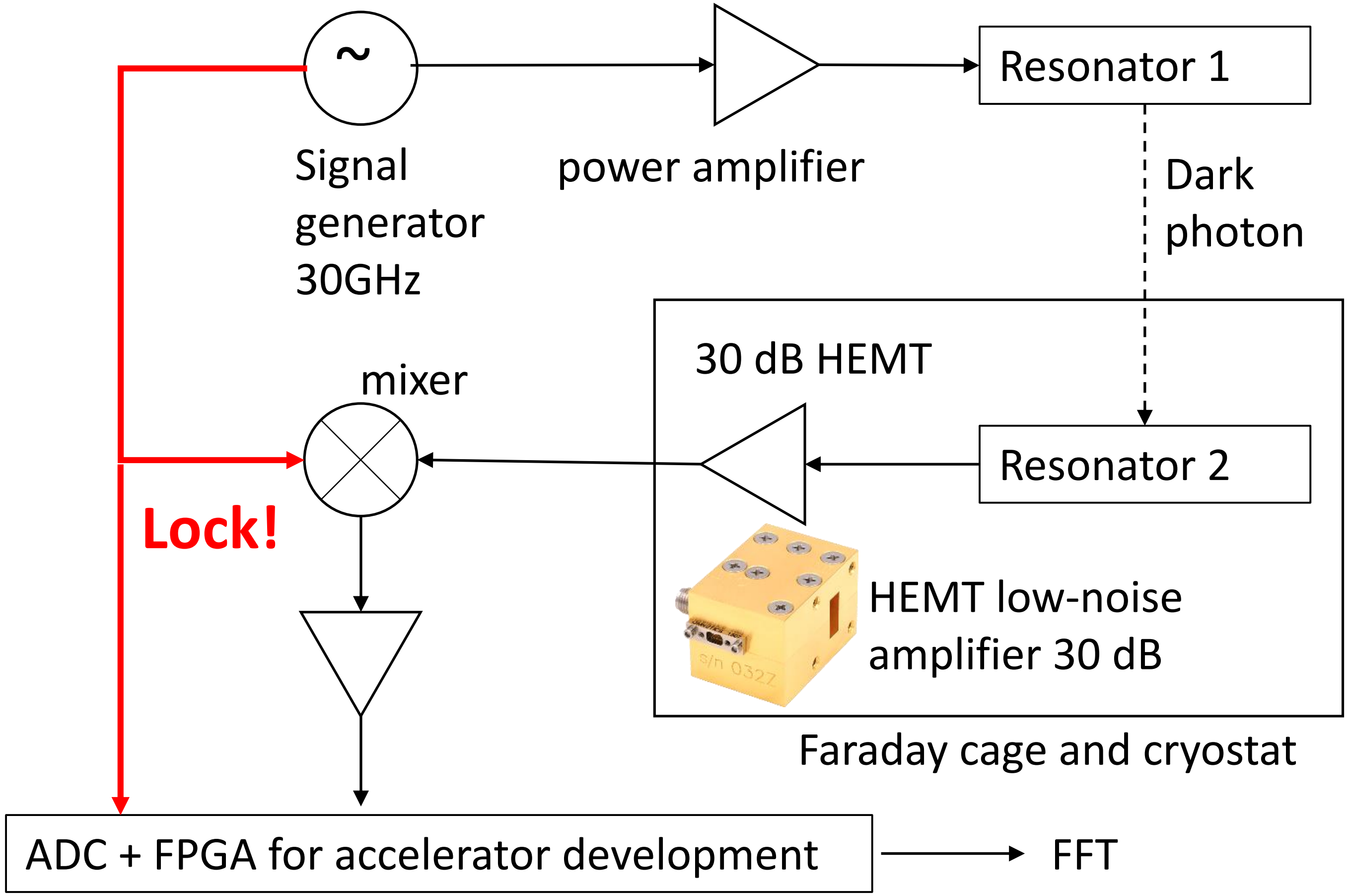
$$B(t, \boldsymbol{r}) = \chi m_{\gamma'}^2 \int_{V'} \frac{\exp(\mathrm{i}k_{\gamma'}|\boldsymbol{r} - \boldsymbol{r}'|)}{4\pi|\mathbf{r} - \mathbf{r}'|} \exp(-i\omega t)\, a(\boldsymbol{r}')dV'$$

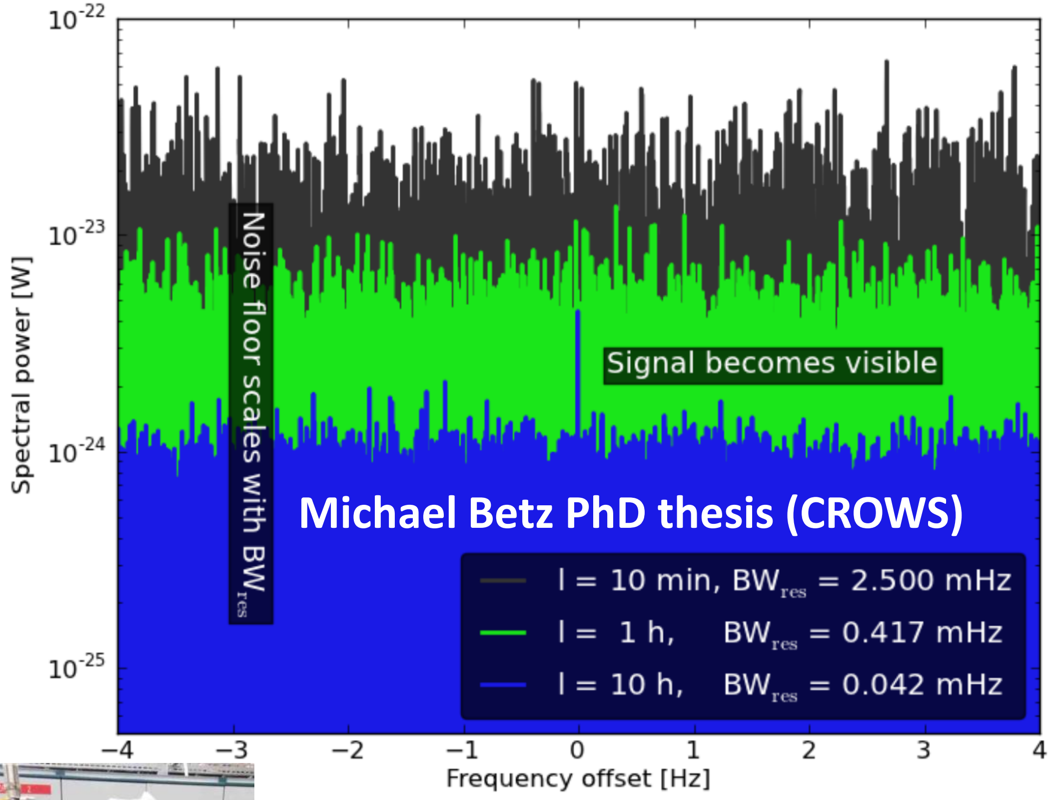


Synchronize the generator and the detector

SG up to 67GHz

Commercial solid-state amplifier 20W



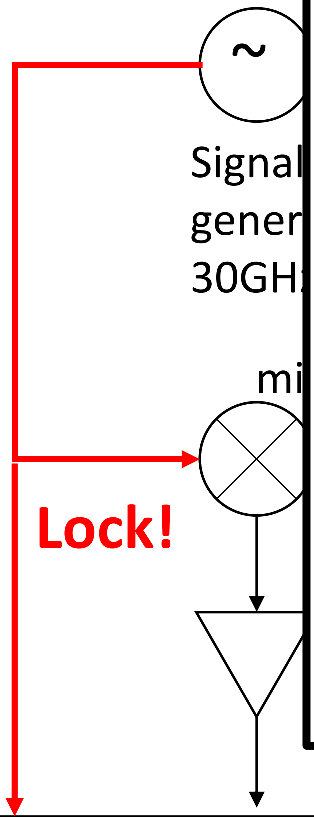


- Noise level of better than 10^{-22} W
- Proven to be feasible in case of 3 GHz
- Commercial amplifier 20W
- Number of input photons

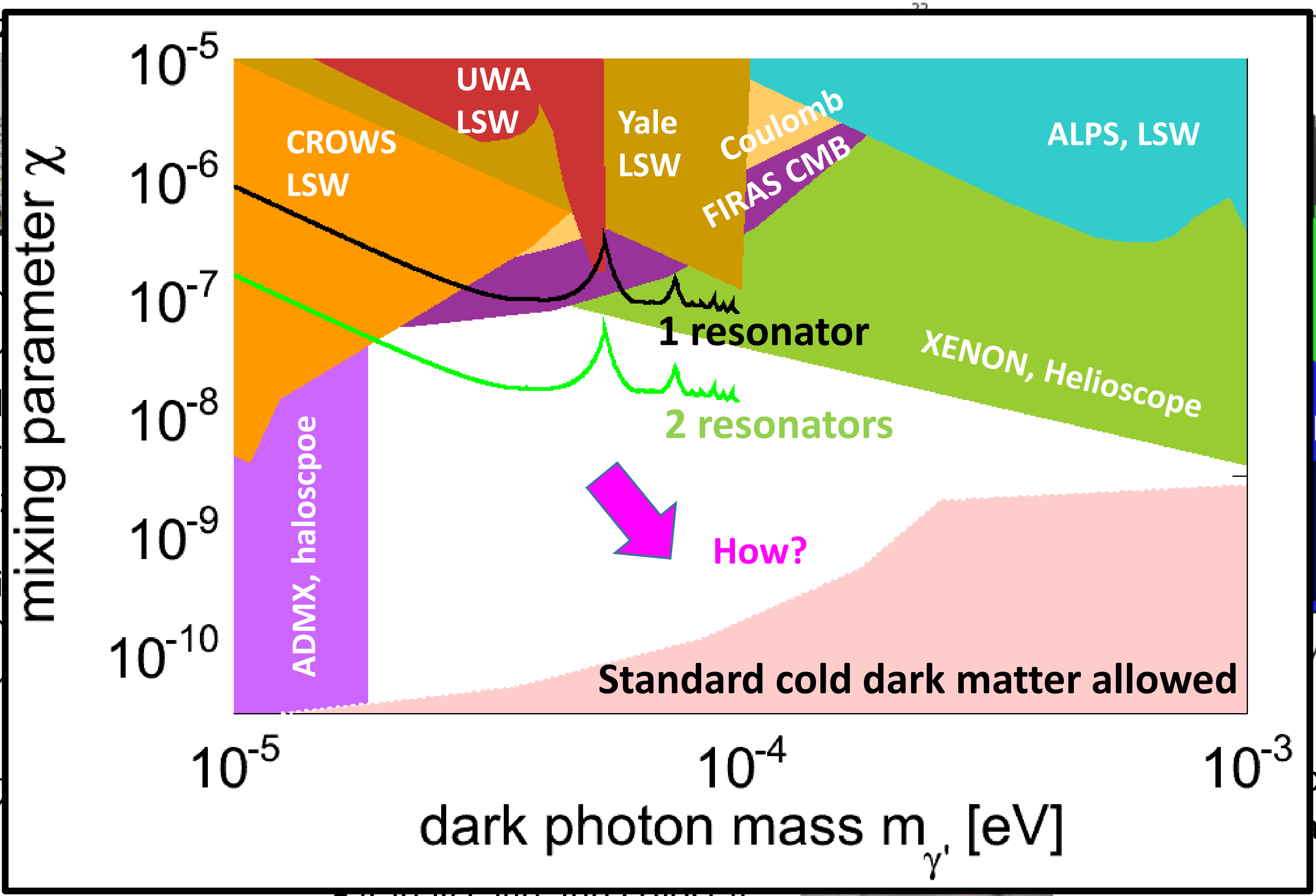
$$P/h\nu \sim 10^{24}\ \mathrm{s}^{-1}$$

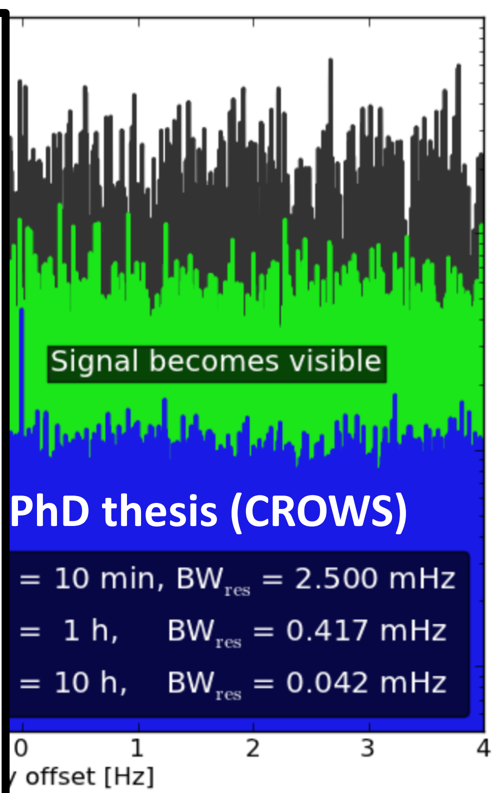
Synchronize the generator and the detector

SG up to 67GHz



ADC + FPGA for accelerator development → FFT





Faraday cage and cryostat

of better than 10^{-22} W

be feasible in case of 3 GHz

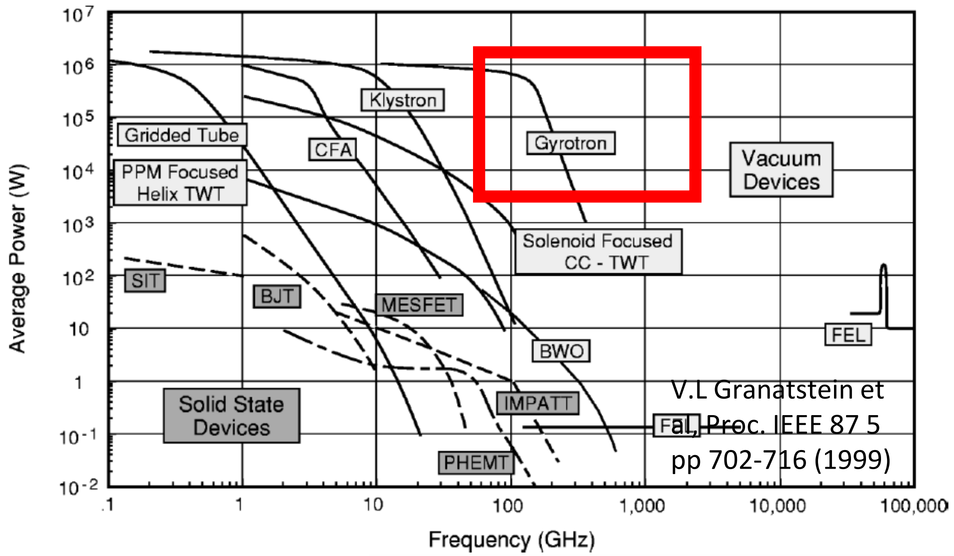
al amplifier 20W

input photons

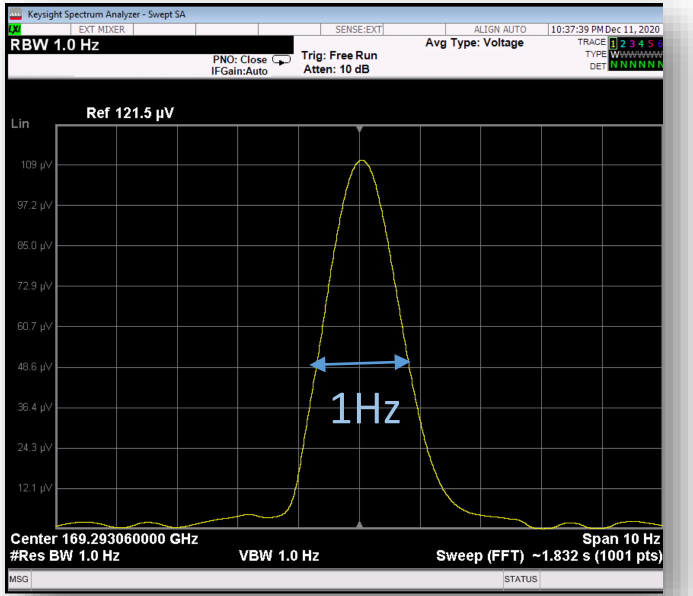
$P/h\nu \sim 10^{24}\ s^{-1}$

Future of millimeter-wave dark photon search

Super-stable high-power gyrotron by PLL

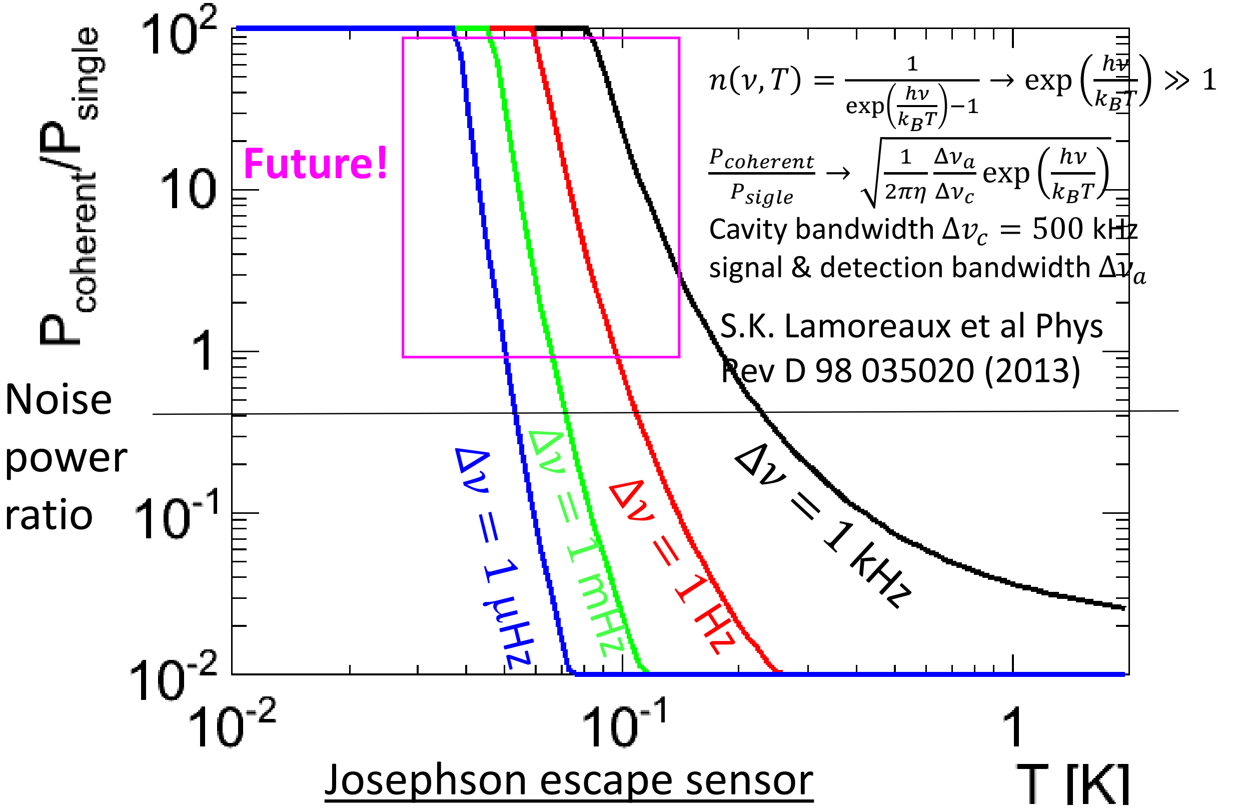


>20kW
<1Hz is just achieved

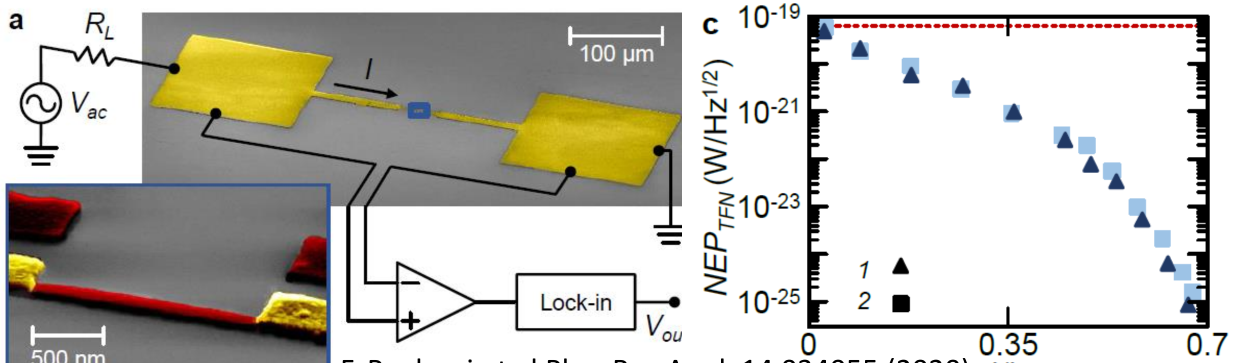


Tsvetkov A.I. et al "Progress in the development of ultra-stable gyrotrons for spectroscopy and plasma applications"
The national Workshop on Far-Infrared Technologies (IW-FIRT 2021), March 8-9, 2021

Superconducting quantum sensor (**STAX**)



Josephson escape sensor



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

Physics reach

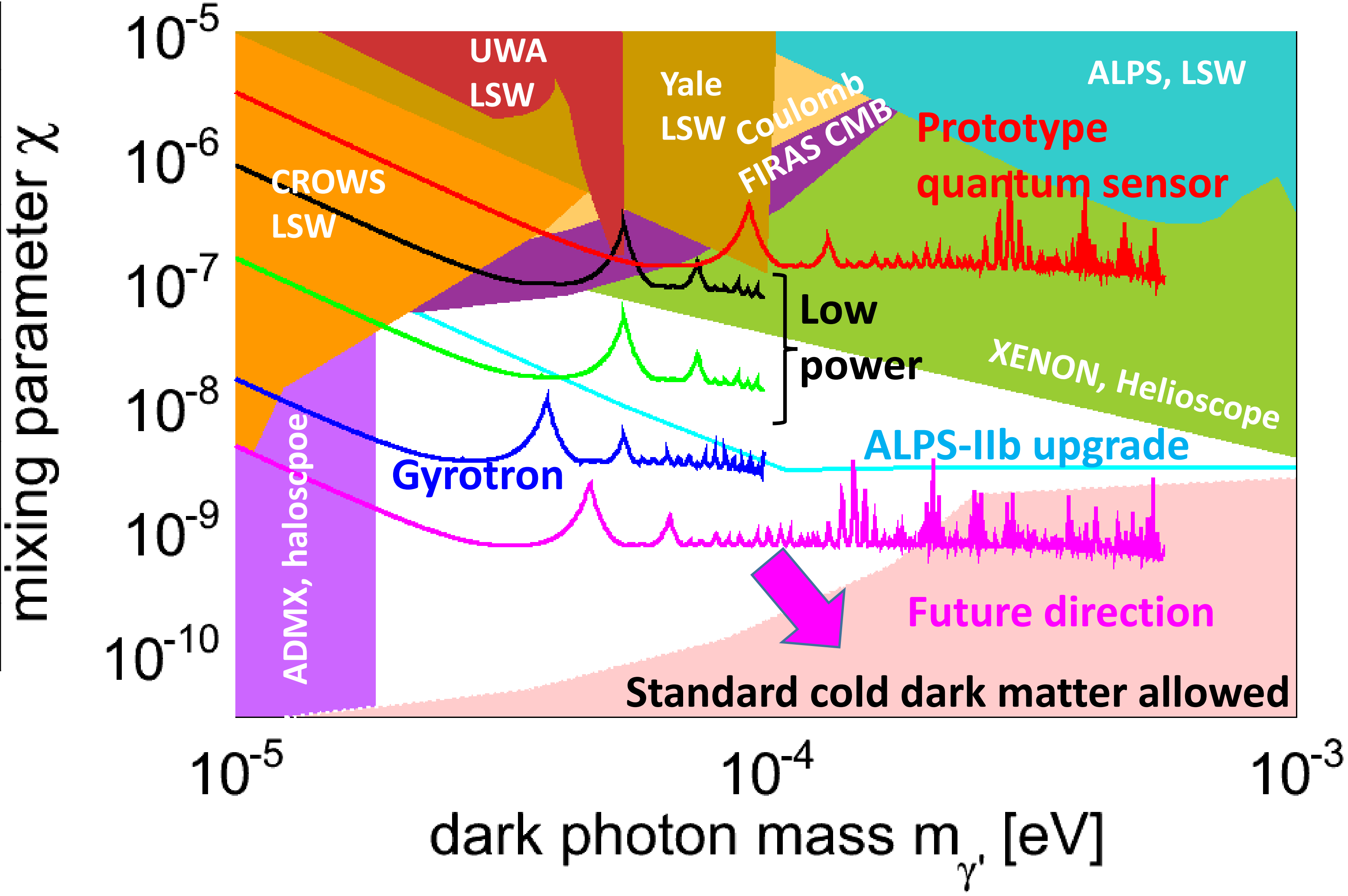
$$\chi \sim \left(\frac{2P_{NEP}}{P_{in}\beta_1\beta_2\eta(m_{\gamma'})\sqrt{t_{op}}} \right)^{\frac{1}{4}}$$

Coherent detection

$P_{NEP} = k_B T_{sys}\sqrt{\Delta\nu}$

Noise $T_{sys} = 10$ K/Hz

Experiment	1-a	1-b	2	3	4
f [GHz]	28	28	28	170	170
P_{in} [W]	20	20	2e4	1e6	2e4
β_1	1000	1000	1000	1	1000
β_2	1	1000	1000	1	1000
Efficiency $\eta(m_{\gamma'})$	0.1	0.1	0.1	0.1	0.1
$\Delta\nu$ [Hz]	1e-2	1e-2	10	1e6	1e6
P_{NEP} [W/Hz$^{1/2}$]	1e-23	1e-23	1e-22	1e-20	1e-25
t_{op}	100 s	100 s	1 day	30 min	1 day



One challenge is noise handling

→ Experience from CROWS

Conclusion

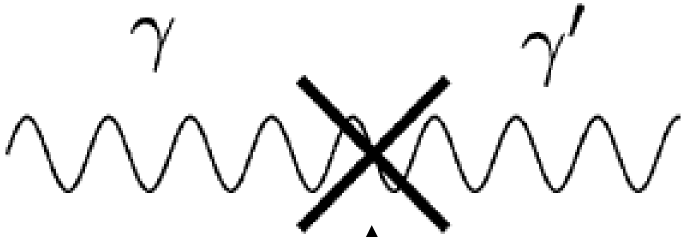
- Light-Shining-Through-a-Wall experiments with 30 GHz may be able to address a niche in the previous and future constraints of dark photon search
  - Resonator development
  - Narrow-band coherent detection
- New technology may open a new opportunity in WISPs search
  - Super-stable high-power microwave generator
  - Hypersensitive superconducting quantum sensor

- Acknowledgment (fruitful discussions during Covid-19 pandemic)
  - CERN (CROWS): Fritz Caspers, Michael Betz
  - Yale University: Penny Slocum
  - INFN and NEST Pisa: Paolo Spagolo, Francesco Giazotto, Federico Paolucci, Andrea Tartari, Gianluca Lamanna
  - KIT: John Jelonnek, Manfred Thumm, Gerd Gantenbein, Stefan Illy
  - Uppsala University: Dragos Dancila, Tor Lofnes
  - The University of Tokyo: Shoji Asai, Toshio Namba, Toshiaki Inada
  - Simons Array: Shunsuke Adachi

backup

Kinetic mixing between photon and dark photon

Ordinary photon Dark photon



Vector potential $\boldsymbol{A}$

Vector potential $\boldsymbol{B}$
Mass $m_{\gamma'}$

Very small 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

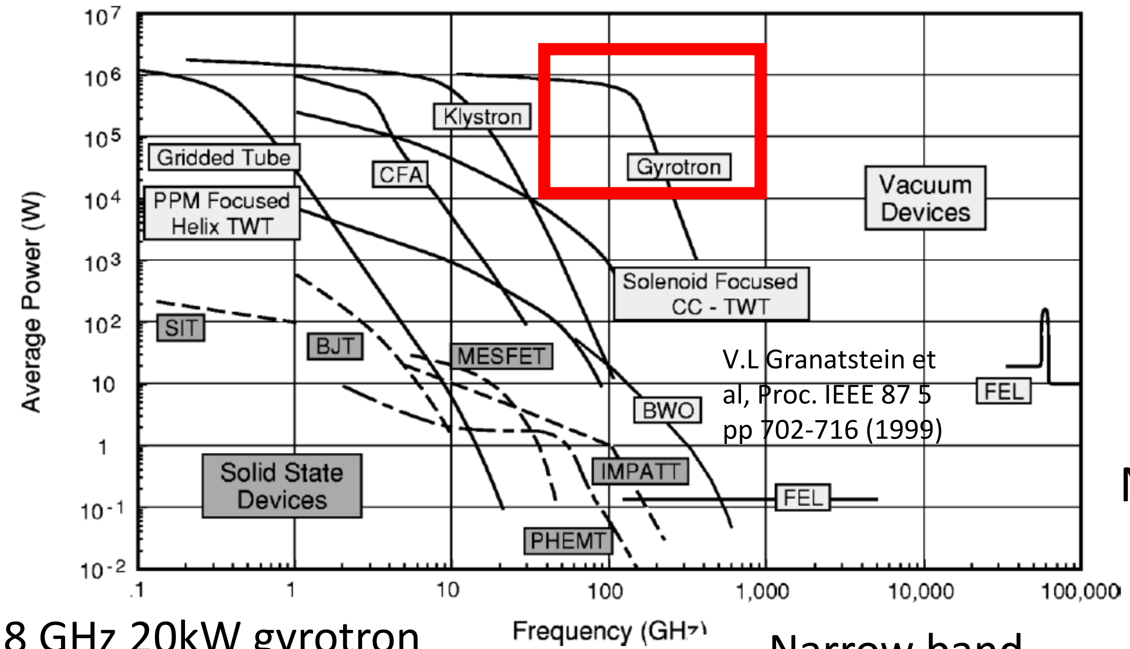
$$\left(\frac{\partial^2}{\partial t^2} - \nabla^2 + \chi^2 m_{\gamma'}^2\right)\boldsymbol{A} = \chi m_{\gamma'}^2 \boldsymbol{B}$$

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 light dark photon

More photons: gyrotron at Karlsruhe



V.L Granatstein et al, Proc. IEEE 87 5 pp 702-716 (1999)

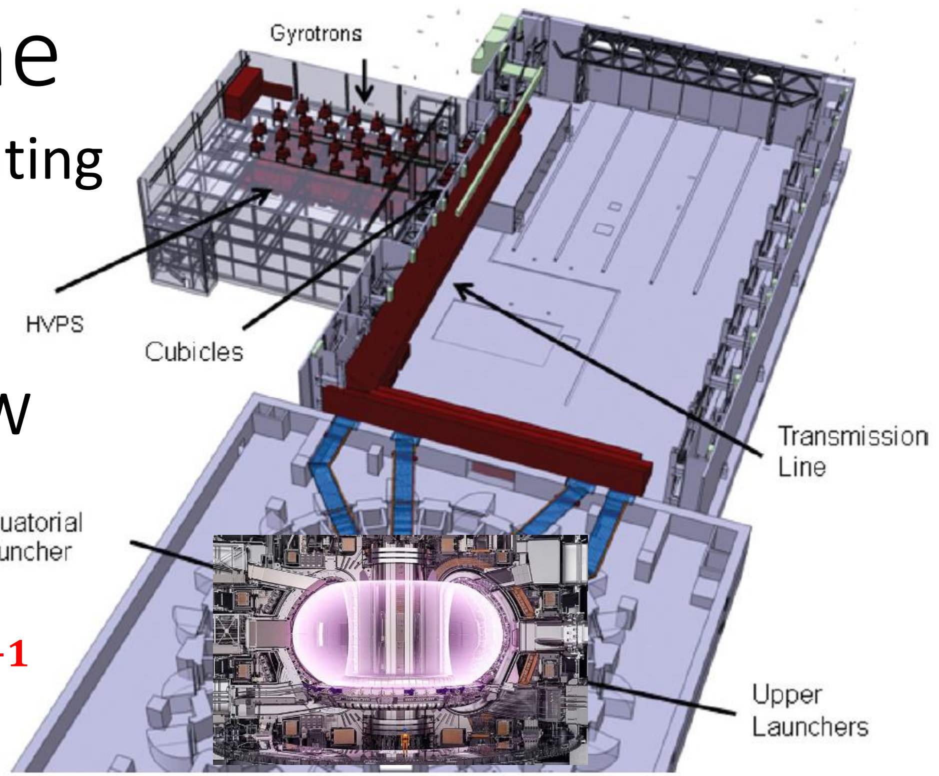
ITER plasma heating

M. Henderson, et al., Phys. Plasmas 22 021808 (2015)

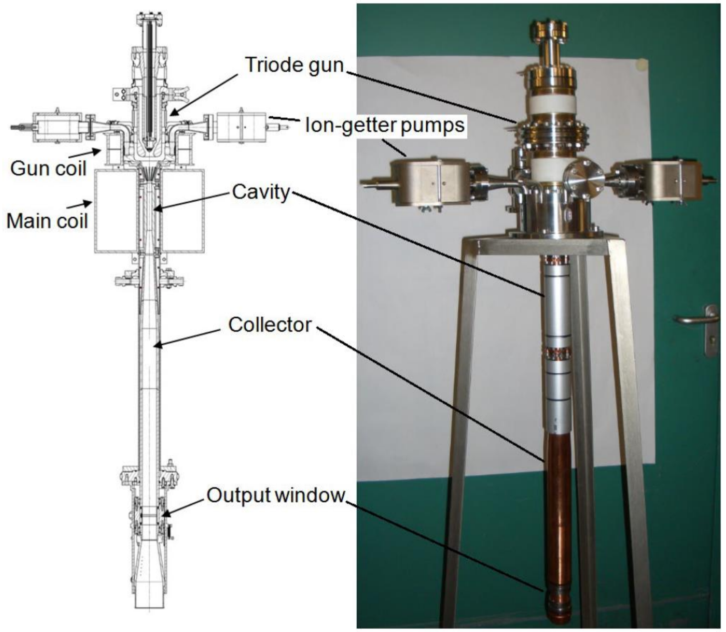
170 GHz 1MW

Number of photons

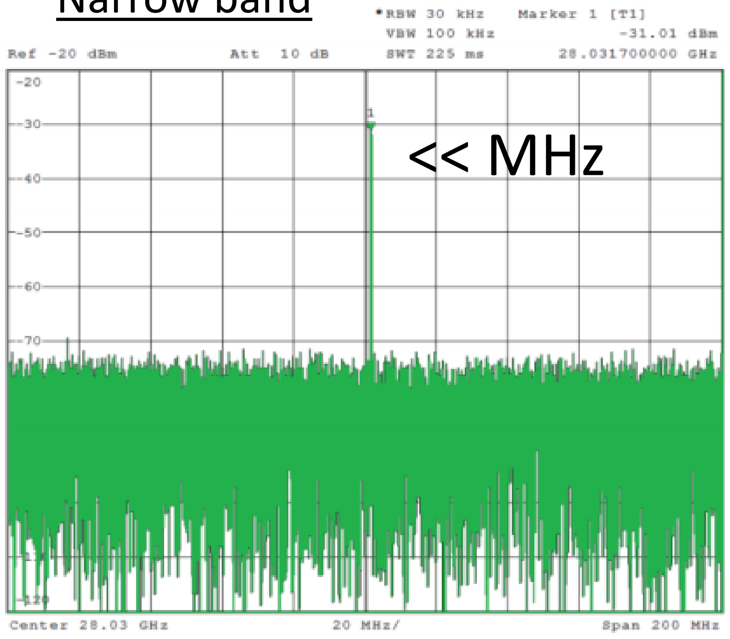
$$P/h\nu > 10^{27}\ s^{-1}$$



28 GHz 20kW gyrotron

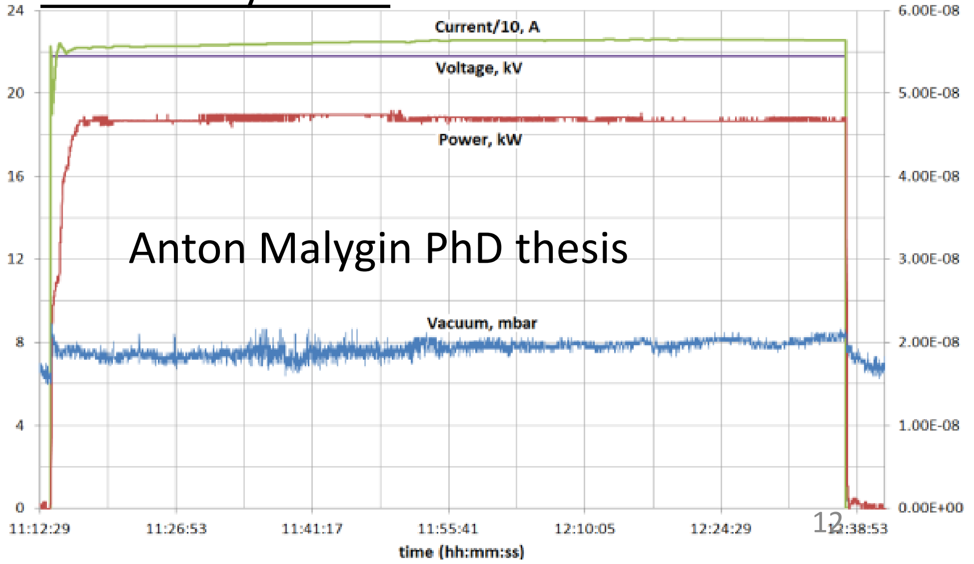


Narrow band



<< MHz

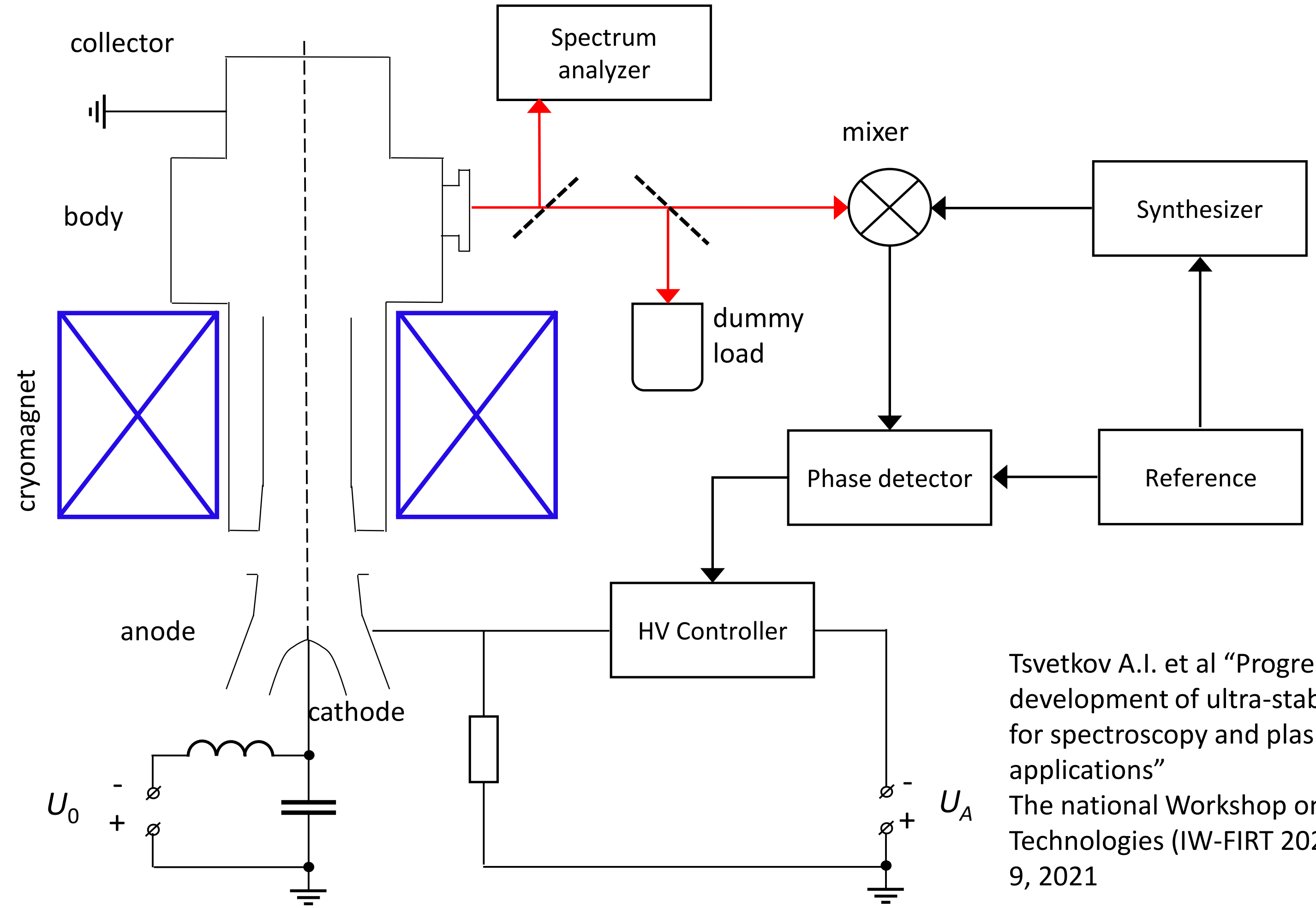
Intrinsically stable



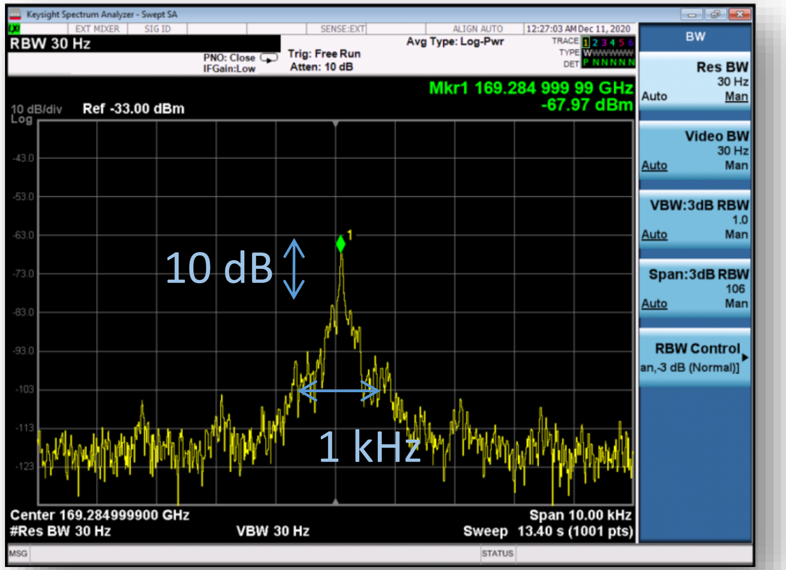
Anton Malygin PhD thesis

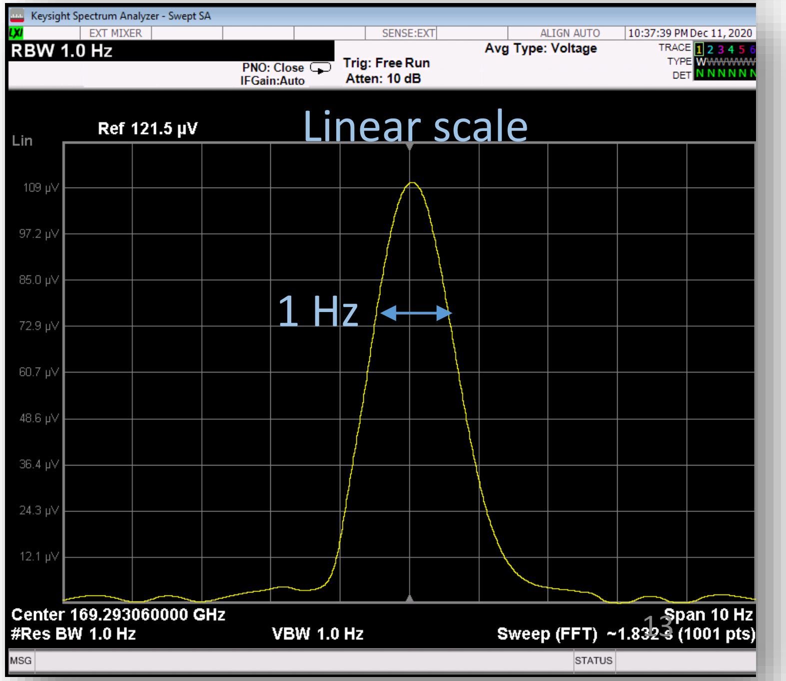
Super narrow-band gyrotron by Phase lock loop

- In March 2021, a Russian group reported Hz-level absolute bandwidth with 170 kHz 25 kW gyrotron



Tsvetkov A.I. et al "Progress in the development of ultra-stable gyrotrons for spectroscopy and plasma applications"
The national Workshop on Far-Infrared Technologies (IW-FIRT 2021), March 8-9, 2021





Promising and interesting classical microwave engineering

Is coherent detection useful forever?

No! Standard quantum limit

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

Coherent detection relies on phase information

Classical waves ~ coherent state

$$\lim_{\alpha\to\infty} e^{-|\alpha|^2/2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |\, n\rangle$$

Uncertainty principle

$$\Delta n \Delta\phi > 1$$

Smaller mean photon number α → phase error $1/\sqrt{\alpha}$

From zero point energy at 30 GHz

$$P_{SQL} = \boldsymbol{h\nu} \sim 2\times10^{-23}\ \mathrm{W/Hz}$$

Minimum possible power handled by coherent system

Direct photon counting

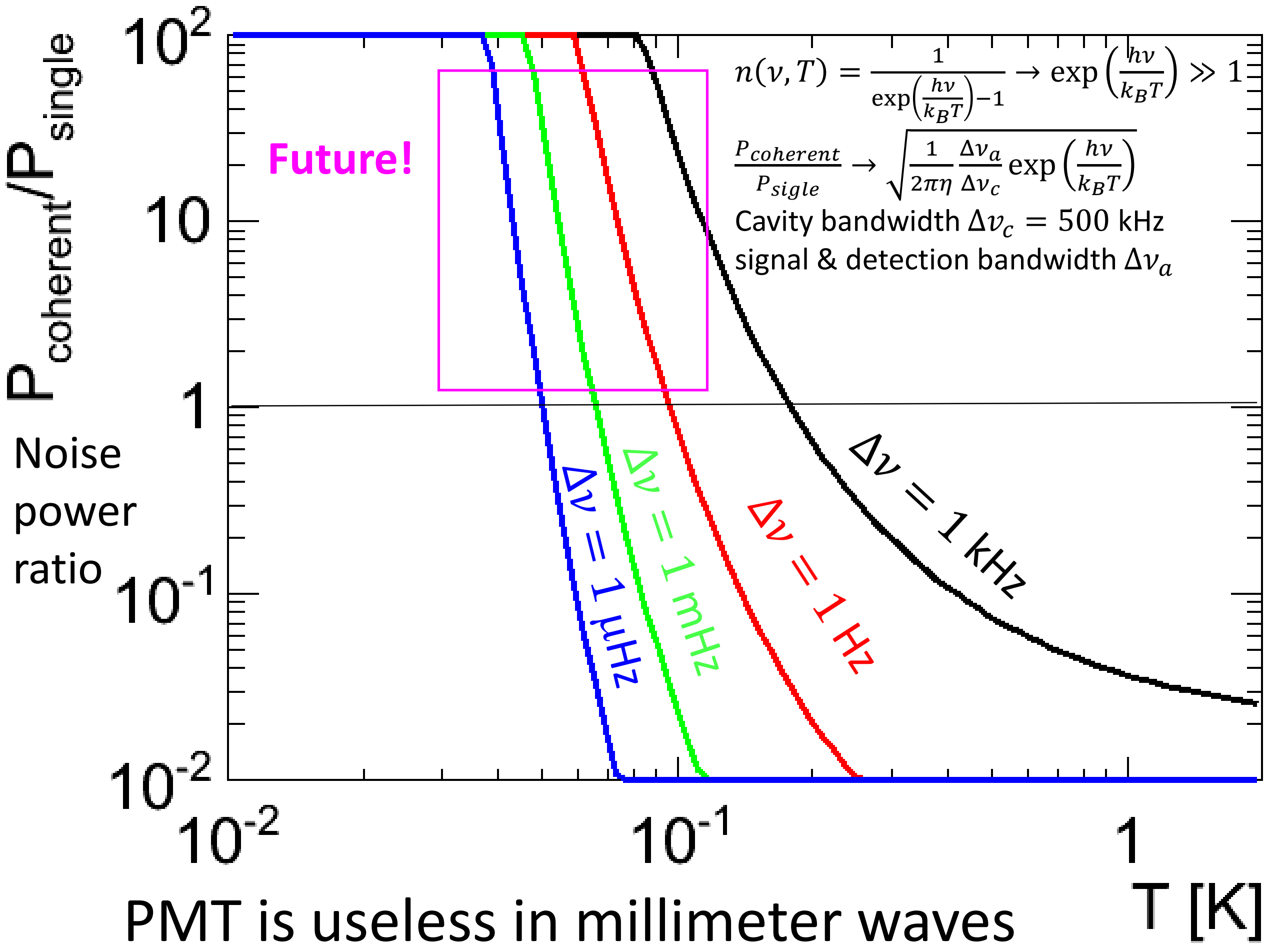
Poissonian error $\sqrt{\alpha}$

$$P_{single} = \frac{h\nu\sqrt{\alpha}}{t_{op}}$$

Background: **thermal photons from black body radiation**

→ Cooling down!

Single photon counting can defeat the quantum-limited detection at low temperature of any bandwidth

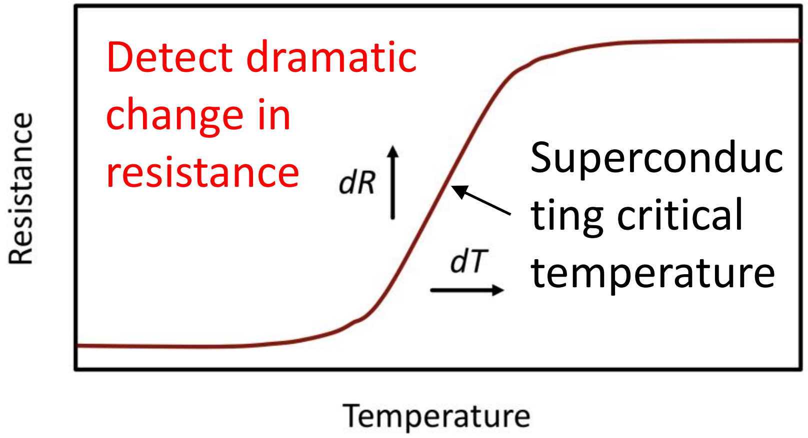


PMT is useless in millimeter waves

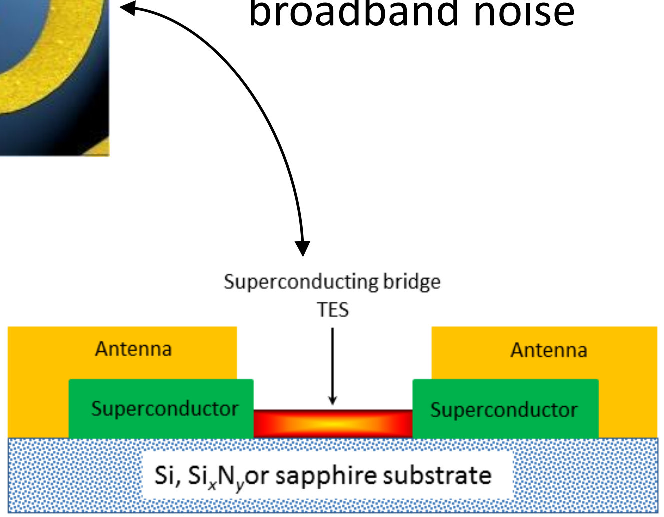
→ superconducting sensor

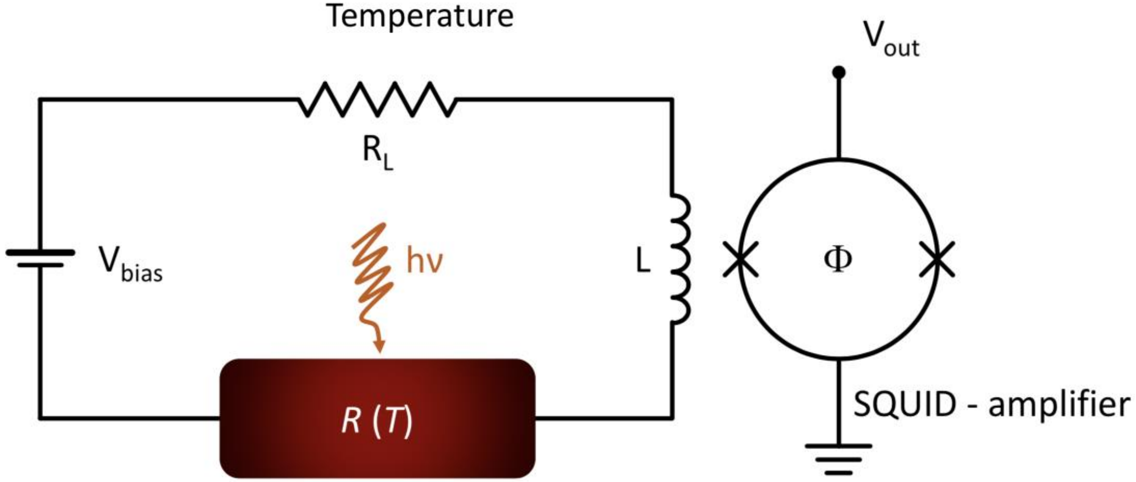
Transition Edge Sensor (TES) at NEST & INFN Pisa

TES operated in a dilution refrigerator (20-100 mK) in Pisa



antenna structure to reduce broadband noise





Established technology in astroparticle physics

D. H. Andrews, et al, Review of Scientific Instruments 13, 281 (1942)

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

Conventional TES can reach 10^{-17} W/Hz$^{1/2}$ with promising improvement to reach 10^{-20} W/Hz$^{1/2}$ and could even reach 10^{-25} W/Hz$^{1/2}$ (Josephson escape sensor)