Revisiting photon detection scheme for dark photon / axions search with millimeter waves

A. Miyazaki

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Outlook

- Introduction: axions and dark photons
- Photon detection and wave detection
- Dark matter axion search
- Light-Shining-Through-a-wall
- Potential of photon detection
- Conclusion

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Axion: pseudo-Nambu Goldston boson of broken global U(1)

QCD contains a term which violates CP

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

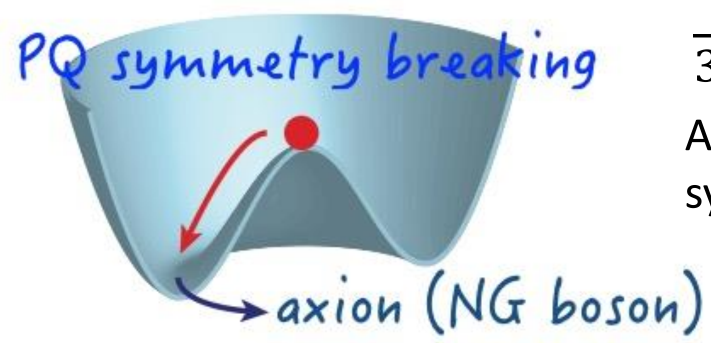
However, neutron EDM shows

- Theory: $d_n \sim 4.5 \times 10^{-15} \boldsymbol{\theta}$ ecm
- Experiment: $|d_n| < 2.9 \times 10^{-29}$ ecm

→ $|\theta| < 0.7 \times 10^{-11} \ll 1$: **naturalness problem**

(No anthropic solution)

Global U(1)→ NG boson as a by product

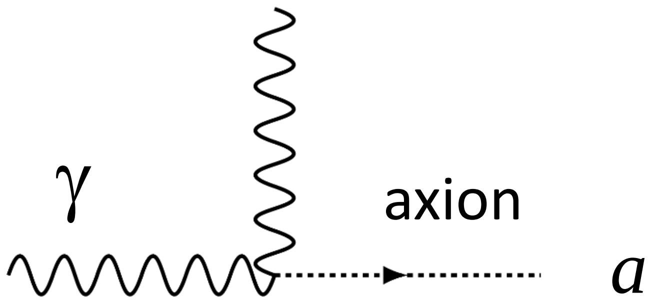


$$\frac{g_s^2}{32\pi^2}\left(\theta + \frac{\boldsymbol{a}}{\boldsymbol{F_a}}\right) G^a_{\mu\nu} \tilde{G}^{\mu\nu a}$$

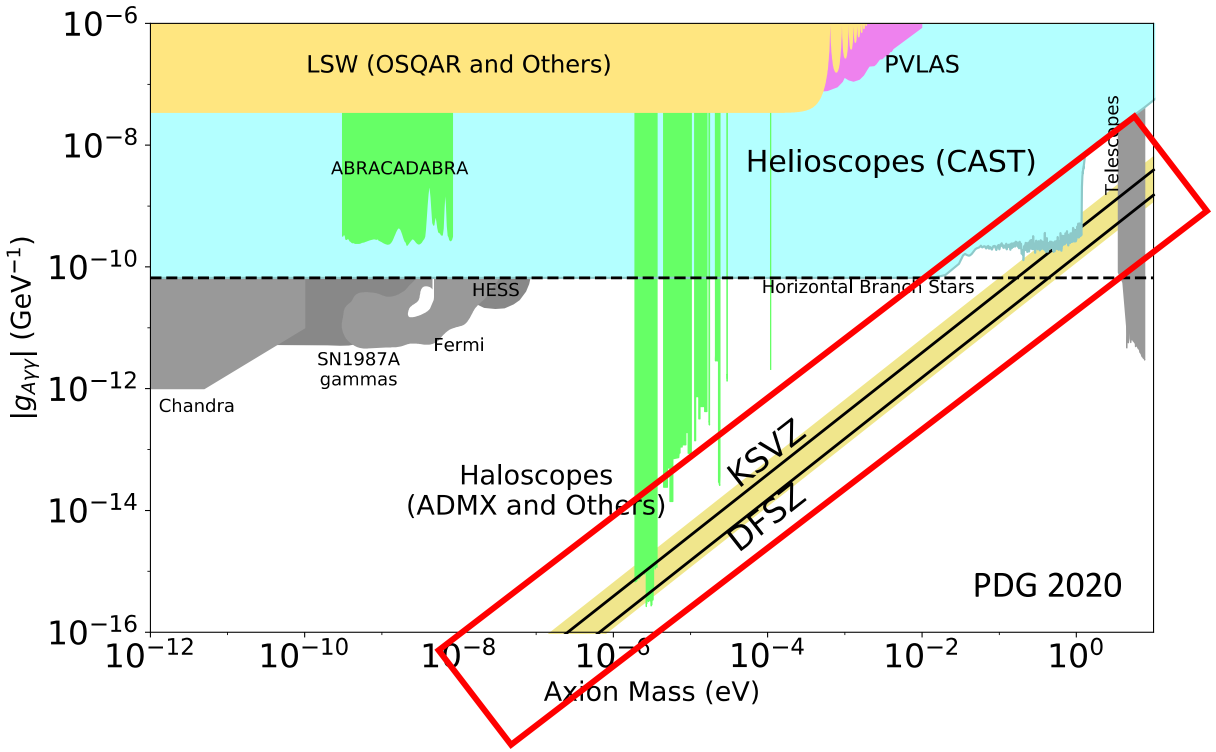
Axion coupling, mass, and symmetry breaking scale

$$\boxed{g_{a\gamma\gamma} \propto m_a \propto \frac{1}{\Lambda}}$$

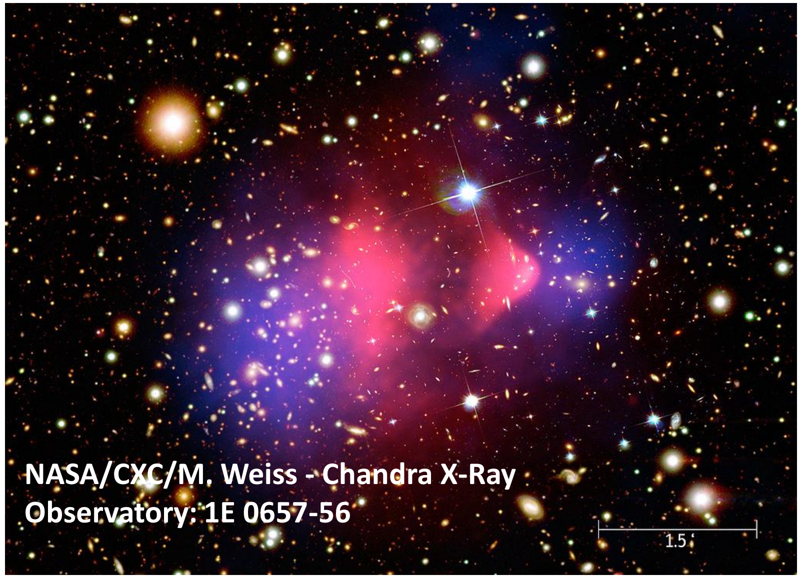
Primakoff effect: axion to photon coupling



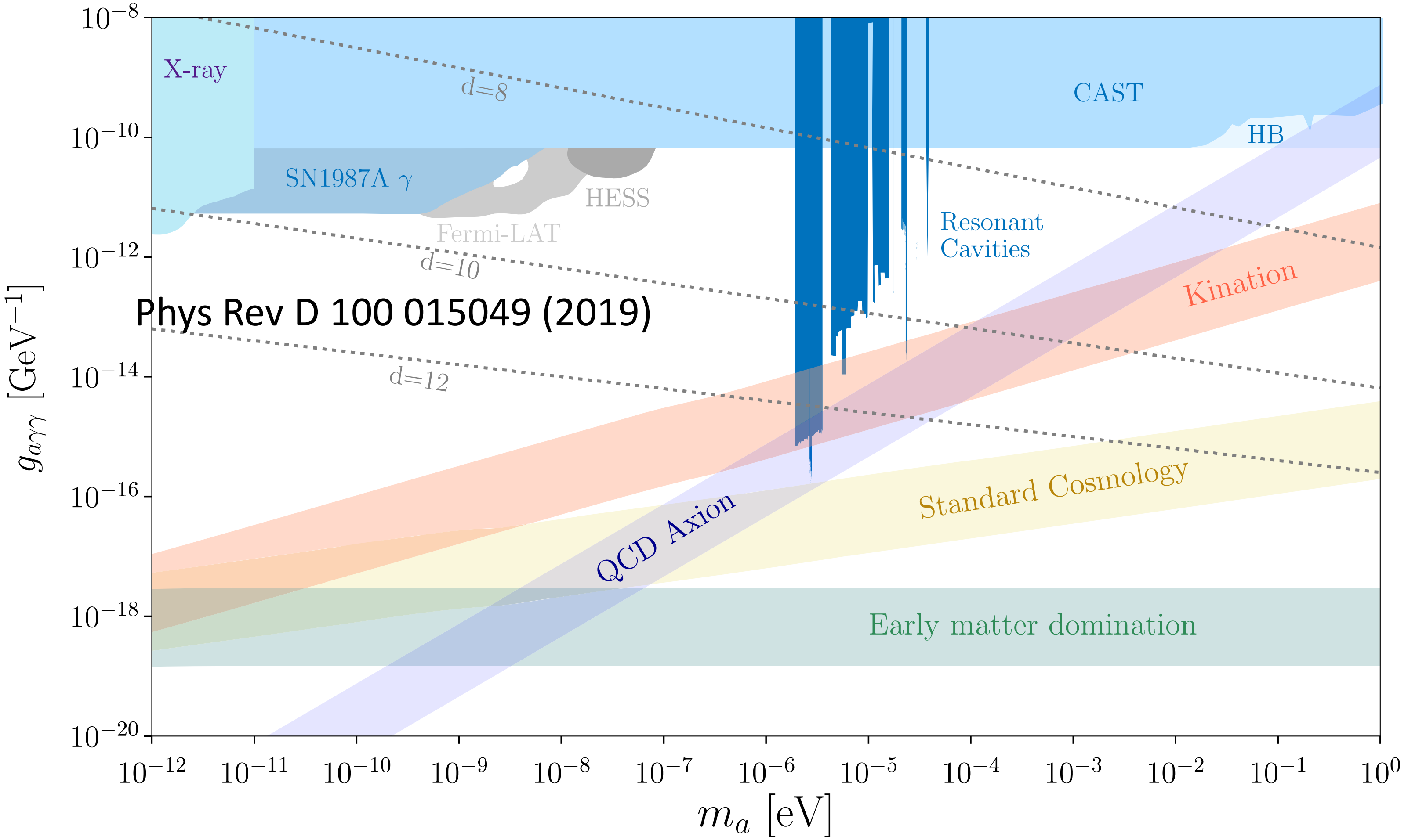
Photon and magnets are two key technology



Dark matter axion(s)



- Axion can be a cold dark matter by cooling via some mechanisms (eg. Misalignment mechanism)
- Several cosmological scenarios are considered

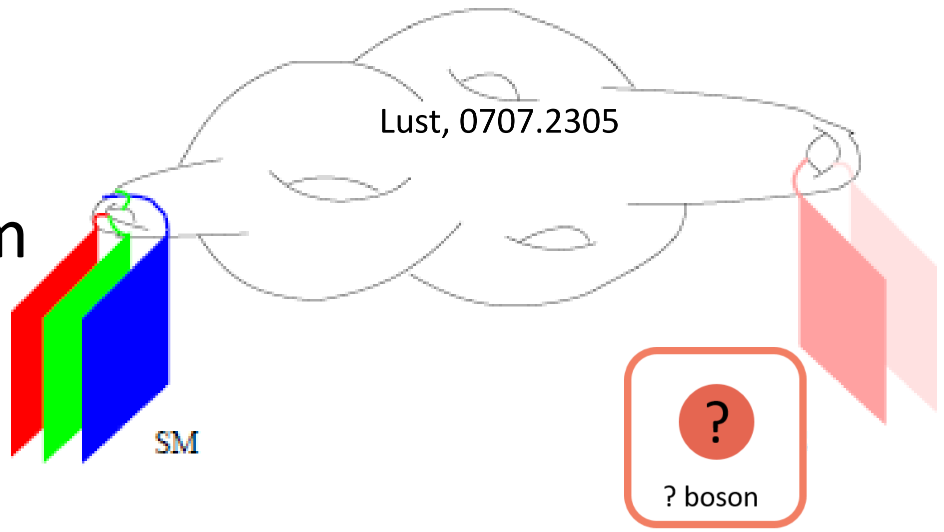


Phys Rev D 100 015049 (2019)

Post-inflationary scenario is recently a trend in Europe (MADMAX, ALPHA, …) and this indicates meV axions corresponding to **20-100 GHz microwave photons → Millimeter waves**

axion“s” → Axion-Like-Particles (ALPs)

String thery also naturally predicts NB bosons,
not necessarily a solution of strong QCD problem



4 different categories

	Dark matter	Non dark matter
QCD axion	**ADMX**,…	LSW, CAST,…
ALPs	ADMX,…	**LSW**, CAST,…

QCD axion can be more general if SUSY is introduced but here we do not consider this

Today, we focus on the technical difference between **ADMX** and **LSW**

Dark photons: extra U(1) gauge bosons

Classic example: Grand Unified theories

$$SU(5) \rightarrow \boxed{SU(3)_C \times \boxed{SU(2)_L \times U(1)_Y}}$$

QCD

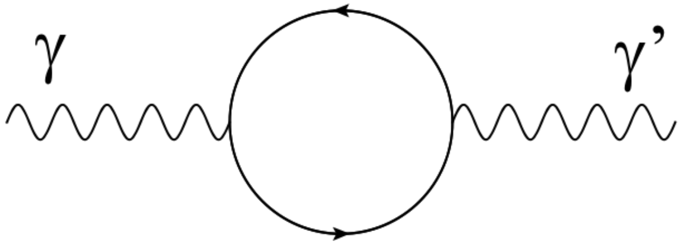
Electroweak theory

SM

$$SO(10) \rightarrow SU(5) \times U(1)$$

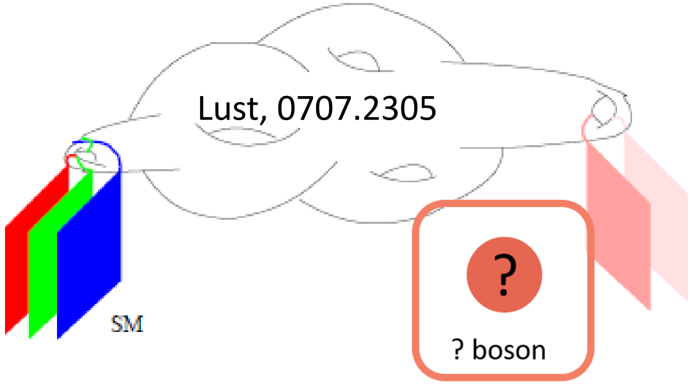
$$E_6 \rightarrow SO(10) \times U(1)$$

Kinetic mixing to a photon



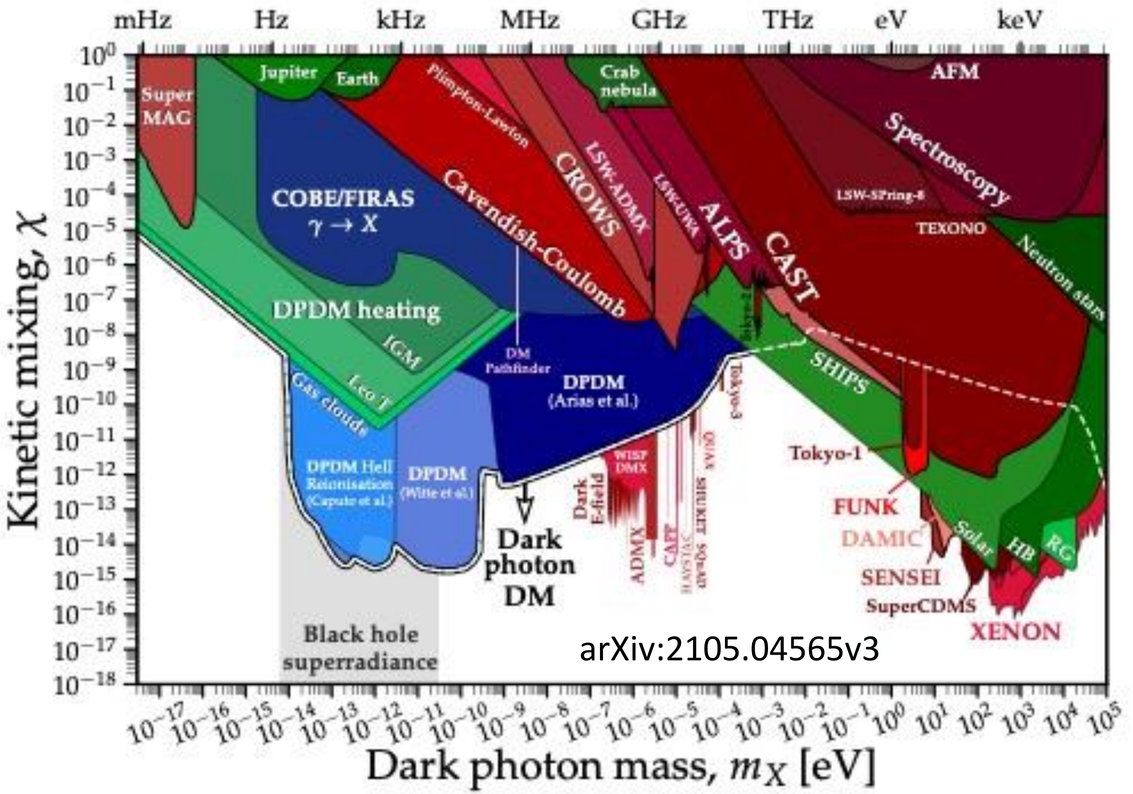
Dark photon search can be considered as a proof-of-concept before axion search without magnets

String theory naturally generates extra U(1)



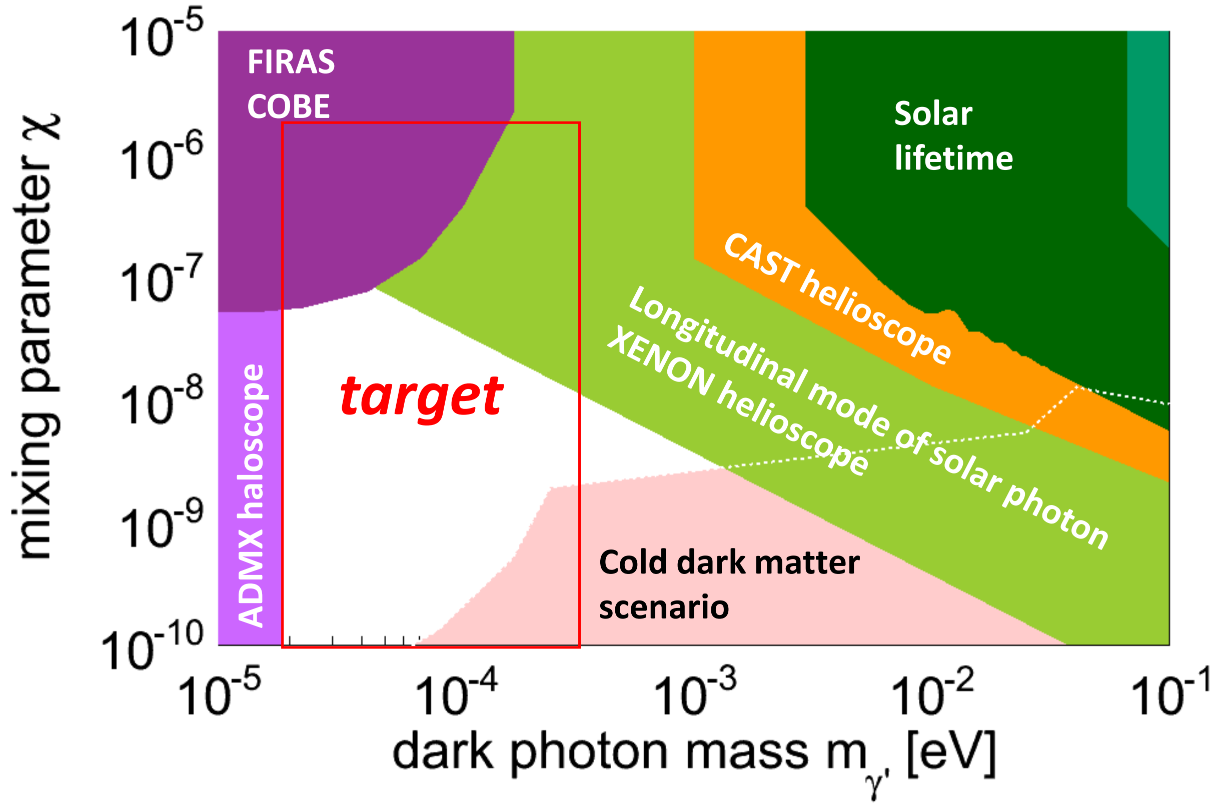
Origin of mass

- Dark Higgs
- Stückelberg
- (massless DP)

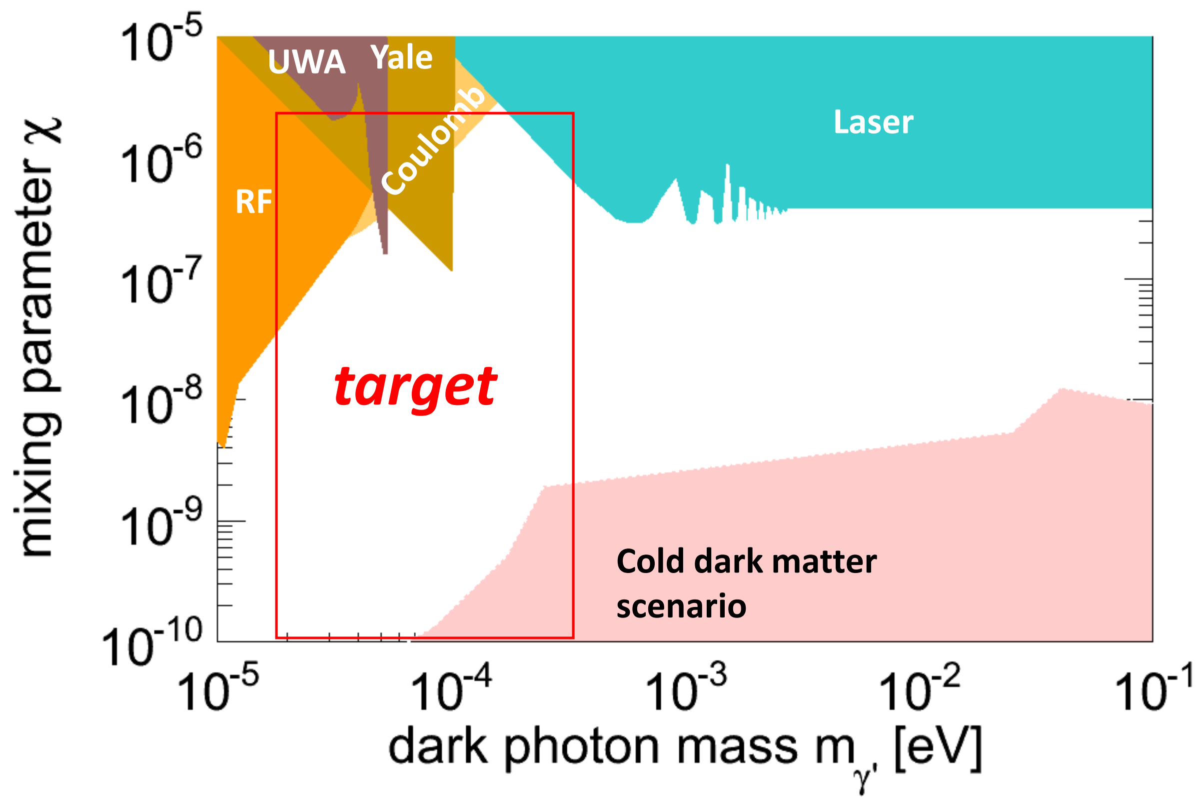


20-100 GHz is an open window in dark photon search

Astrophysical, haloscope, and helioscope



Purely laboratory constraints

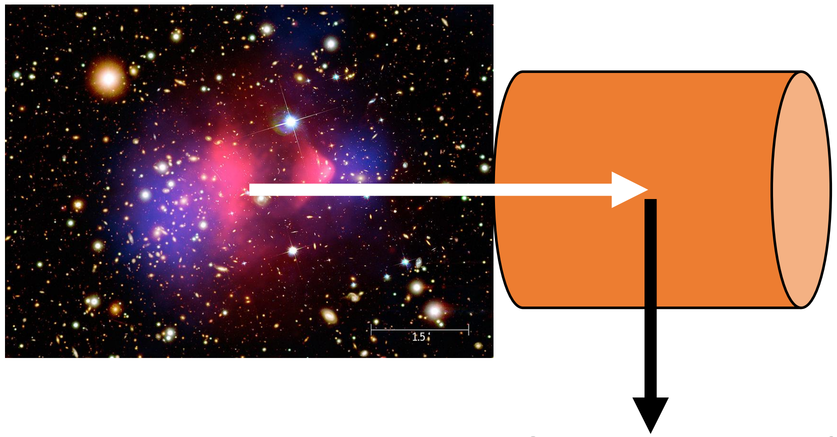


The mass range between 10^{-5} and 10^{-4} eV is wide open

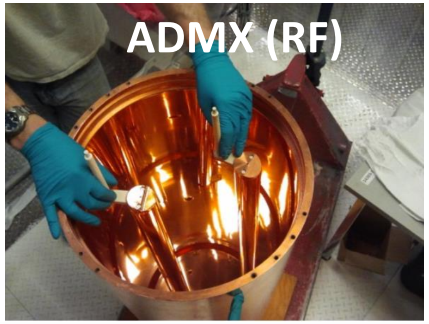
→ Corresponding to 20-100 GHz photons

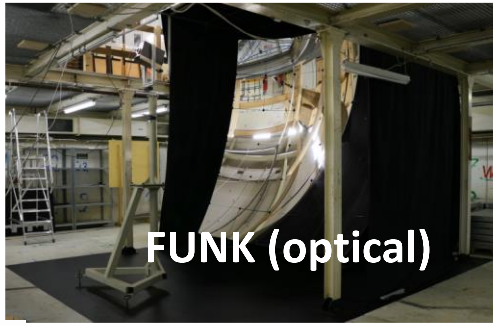
Principle of dark photon / axions search via photons

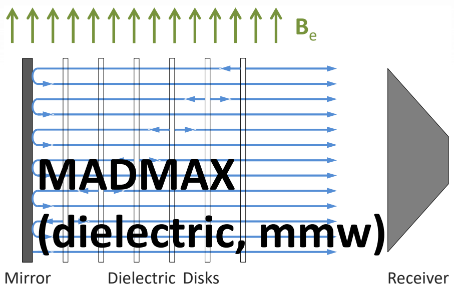
Dark matter search

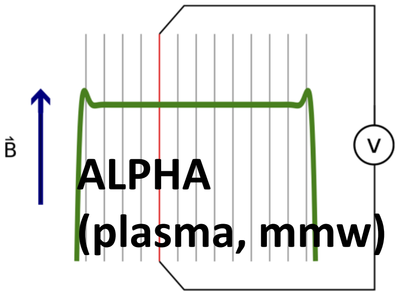


Photon signal

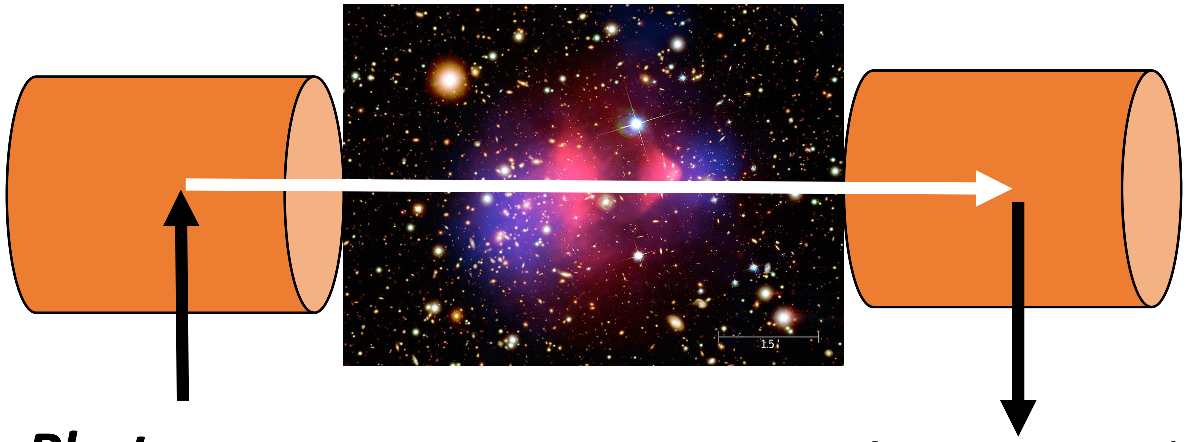








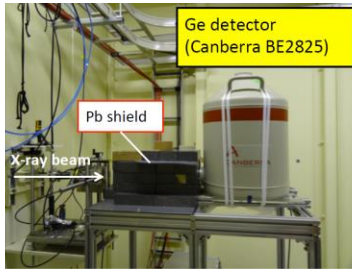
Laboratory-based search (LSW-type)

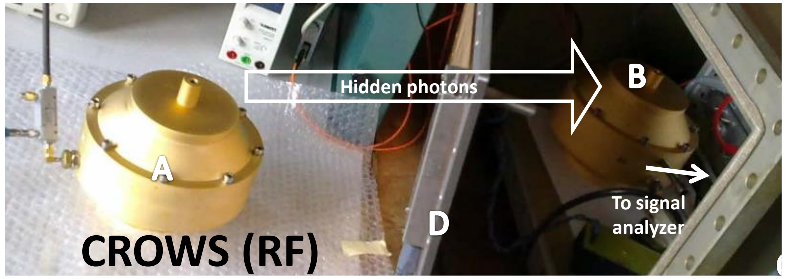


Photon pump

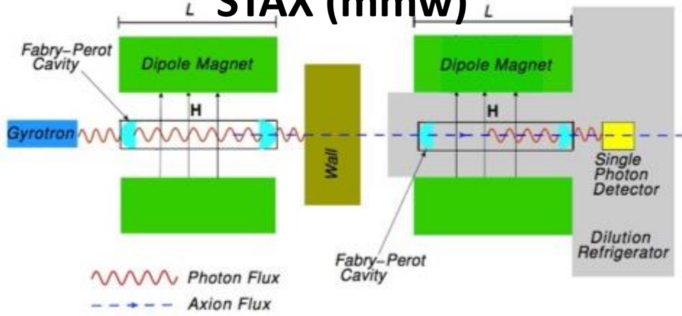
Photon signal

Spring-8 (X-ray)



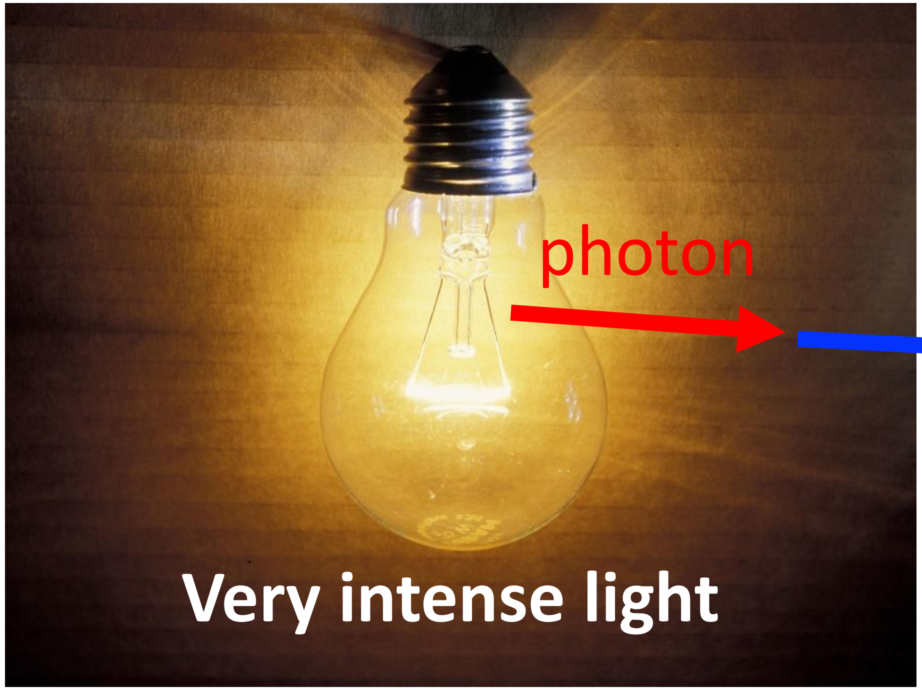


STAX (mmw)



Laboratory-based search: main idea

We look at an opaque wall



Dark photon

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

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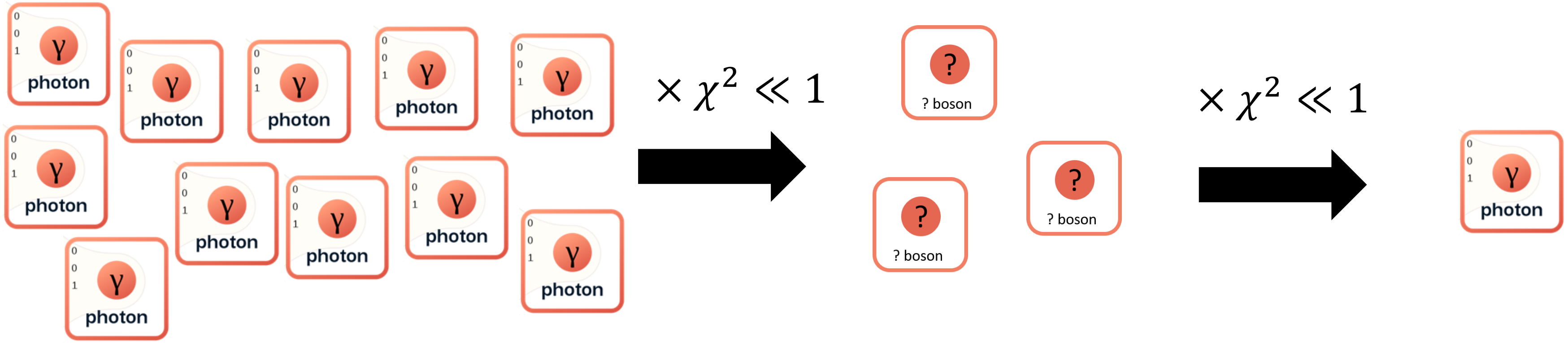

Single photon detection!?

Technological keys

1. Photon generation
2. Photon resonator
3. Photon detection
4. Magnetic field (for axions)

What is a photon?

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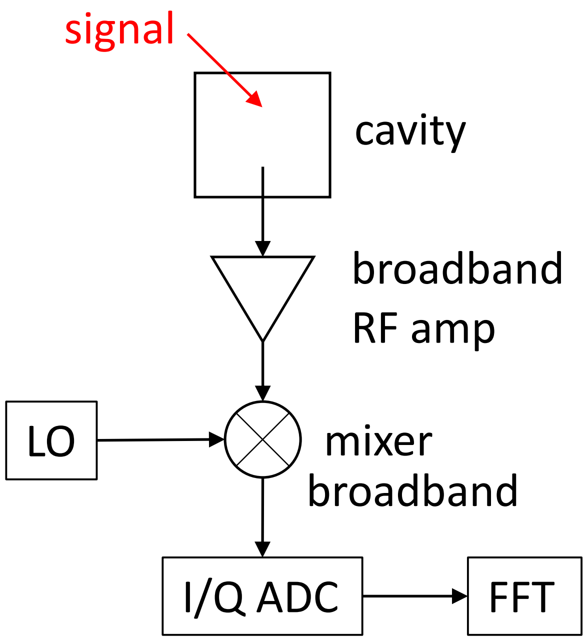
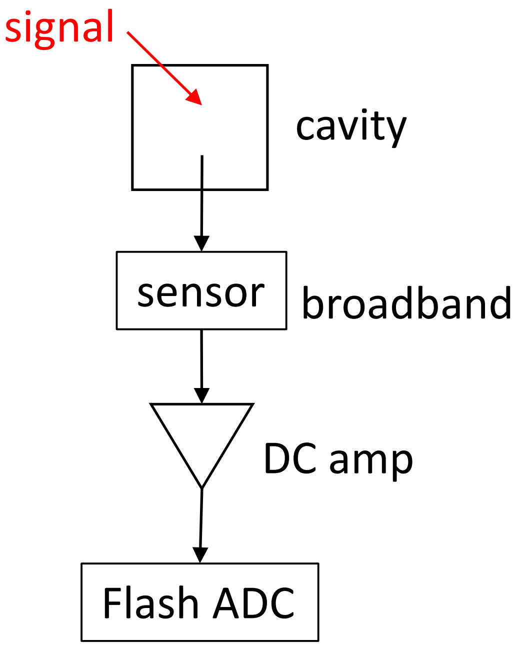
Wave detection vs photon detection

Coherent wave detection



$$S/N = \frac{P_{sig}}{k_B T}\sqrt{\frac{t}{\Delta\nu}}$$

Incoherent photon detection



$$S/N = \frac{P_{sig}}{k_B T}\sqrt{\frac{t}{\Delta\nu}}$$

What is a “photon” of given frequency ω?

Classical electromagnetic wave

$$\begin{cases} \nabla \cdot E = 0 \\ \nabla \cdot B = 0 \\ \nabla \times E = -\dfrac{\partial B}{\partial t} \\ \nabla \times B = \dfrac{1}{c^2}\dfrac{\partial E}{\partial t} \end{cases} \rightarrow \left(\frac{\partial^2}{\partial t^2} - \nabla^2\right) E = 0$$

$$E = E^+ e^{-i(\omega t - \boldsymbol{k}\cdot\boldsymbol{r})} + E^- e^{i(\omega t - \boldsymbol{k}\cdot\boldsymbol{r})}$$

→ “Quantization”

$$\hat{E}^+ = i\sqrt{\frac{\hbar\omega}{2\epsilon_0 V}}\,\hat{a} \qquad \hat{E}^- = \left(\hat{E}^+\right)^\dagger$$

“electric field operator is proportional to the annihilation operator”

Quantized electromagnetic field

$$\begin{cases} \hat{H} = \left(\hat{n} + \dfrac{1}{2}\right)\hbar\omega = \left(\hat{a}^\dagger\hat{a} + \dfrac{1}{2}\right)\hbar\omega \\ \hat{E}(\boldsymbol{r},t) = i\sqrt{\dfrac{\hbar\omega}{2\epsilon_0 V}}\left[\hat{a}e^{-i(\omega t - \boldsymbol{k}\cdot\boldsymbol{r})} - \hat{a}^\dagger e^{i(\omega t - \boldsymbol{k}\cdot\boldsymbol{r})}\right] \end{cases}$$

$$\left[\hat{a}, \hat{a}^\dagger\right] = 1; \qquad [\hat{a}, \hat{a}] = \left[\hat{a}^\dagger, \hat{a}^\dagger\right] = 0$$

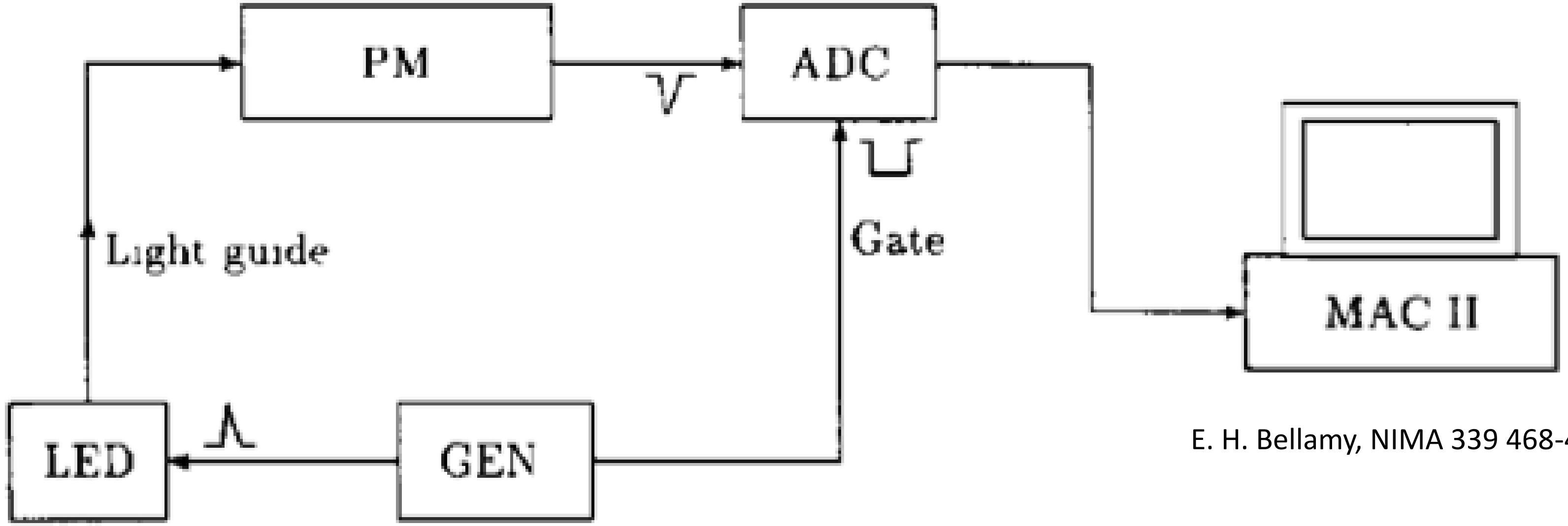
$$\hat{a}|n\rangle = \sqrt{n}|n-1\rangle$$

$$\hat{a}^\dagger|n\rangle = \sqrt{n+1}|n+1\rangle$$

A single photon state

$$|1\rangle = \hat{a}^\dagger|0\rangle$$

Particle physics primer: single photon counting



E. H. Bellamy, NIMA 339 468-476 (1994)

Quantum state of photons: $|\phi\rangle$

Measurement: projection onto $|n\rangle$

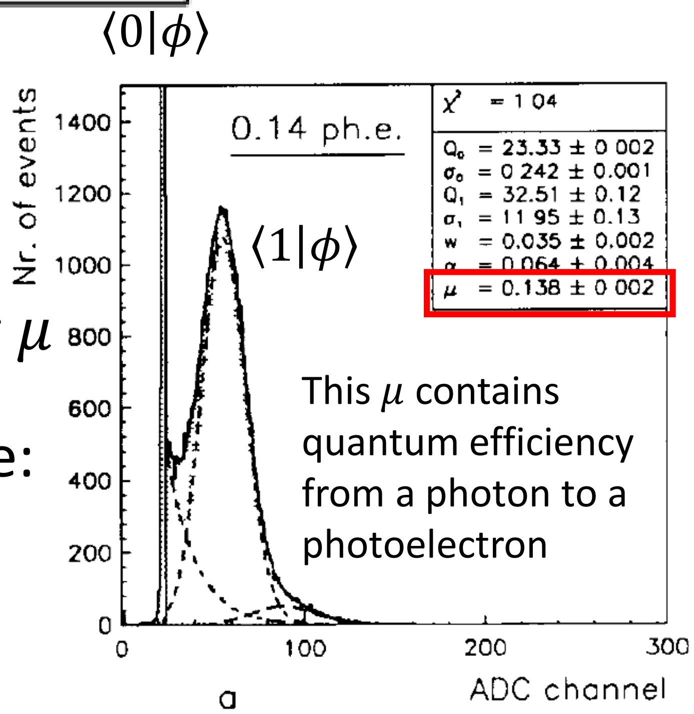
$\rightarrow P(n;\mu) = |\langle n|\phi\rangle|^2$

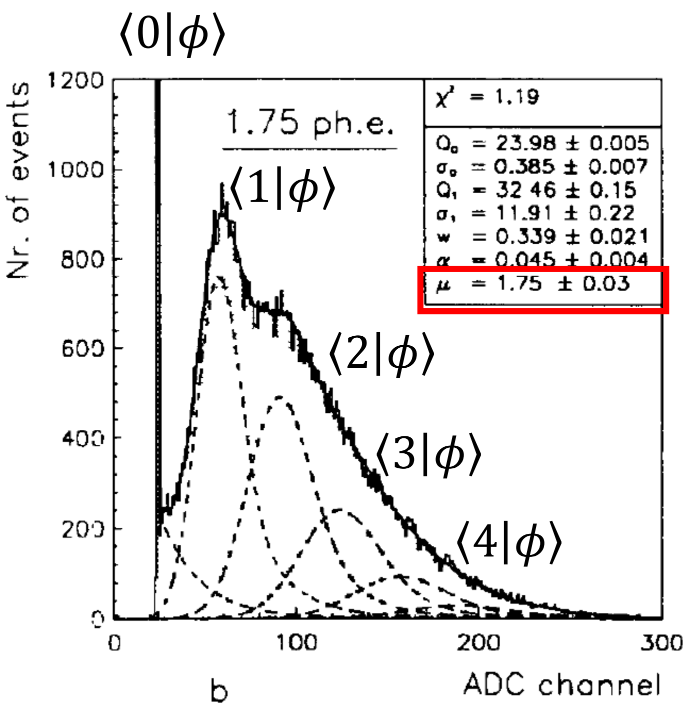
Poisson distribution of with mean photon # μ

The data is convoluted with PMT's response:

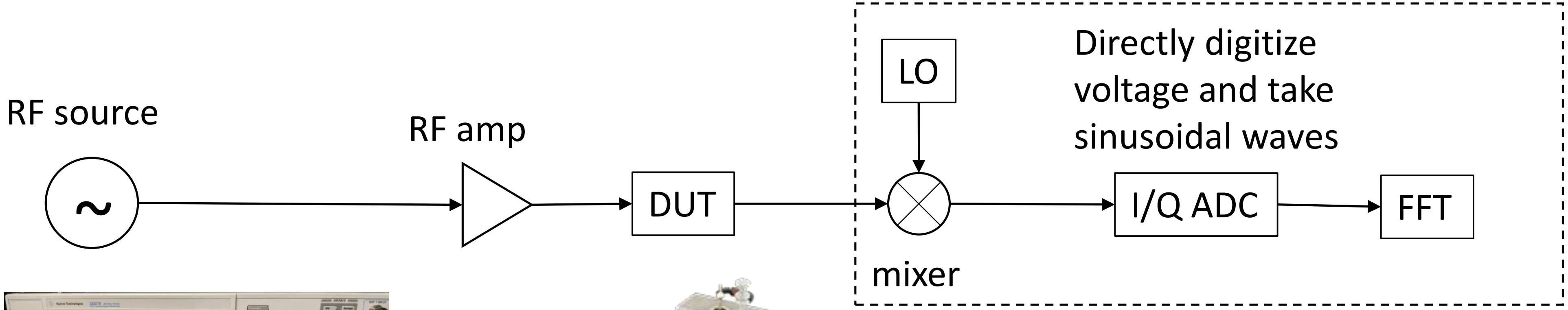
$$S_{\text{ideal}}(x) = P(n;\mu) \otimes G_n(x)$$

$$= \sum_{n=0}^{\infty} \frac{\mu^n e^{-\mu}}{n!} \frac{1}{\sigma_1\sqrt{2\pi n}} \exp\left(-\frac{(x-nQ_1)^2}{2n\sigma_1^2}\right)$$





Microwave engineering primer: coherent wave detection



Spectrum analyzer

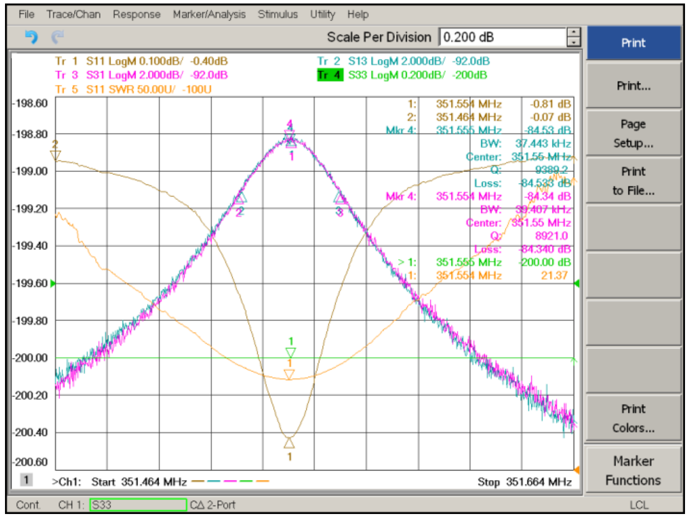
Quantum state of photons: $|\phi\rangle$

Measurement: expectation value of $\hat{E}(\boldsymbol{r}, t)$

$\rightarrow \langle\phi|\hat{E}(\boldsymbol{r}, t)|\phi\rangle$

Under coupled cavity reflection

Cavity resonance



Paradox: electric field of a single photon state

$$\langle 1|\hat{E}(\boldsymbol{r},t)|1\rangle = \langle 0|\hat{a}\hat{E}(\boldsymbol{r},t)\hat{a}^\dagger|0\rangle = i\sqrt{\frac{\hbar\omega}{2\epsilon_0 V}}\langle 0|\hat{a}\left(\hat{a}e^{-i(\omega t-\boldsymbol{k}\cdot\boldsymbol{r})} - \hat{a}^\dagger e^{i(\omega t-\boldsymbol{k}\cdot\boldsymbol{r})}\right)\hat{a}^\dagger|0\rangle$$

$$\propto \langle 0|\hat{a}\hat{a}\hat{a}^\dagger|0\rangle e^{-i(\omega t-\boldsymbol{k}\cdot\boldsymbol{r})} - \langle 0|\hat{a}\hat{a}^\dagger\hat{a}^\dagger|0\rangle e^{i(\omega t-\boldsymbol{k}\cdot\boldsymbol{r})}$$

$$= \langle 0|\hat{a}(1-\hat{a}^\dagger\hat{a})\,|0\rangle e^{-i(\omega t-\boldsymbol{k}\cdot\boldsymbol{r})} - \langle 0|(1-\hat{a}^\dagger\hat{a})\hat{a}^\dagger|0\rangle e^{i(\omega t-\boldsymbol{k}\cdot\boldsymbol{r})}$$

$$= 0 - \langle 0|\left[\hat{a}^\dagger - \hat{a}^\dagger(1-\hat{a}^\dagger\hat{a})\right]|0\rangle e^{i(\omega t-\boldsymbol{k}\cdot\boldsymbol{r})} = 0$$

→ “Uncertainty relation” between number of photons and phase

$$\Delta\phi\Delta n > 0$$

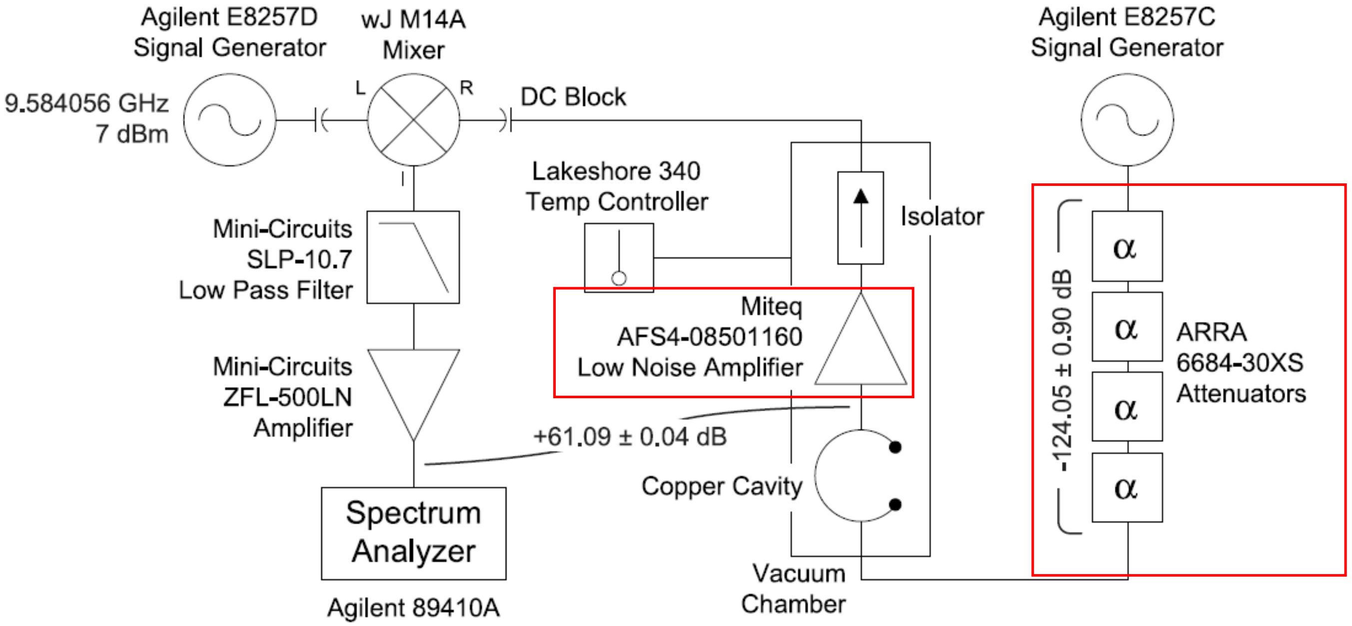
Single photon state has a single photon by definition so $\Delta n = 0$

→ Phase information is totally lost

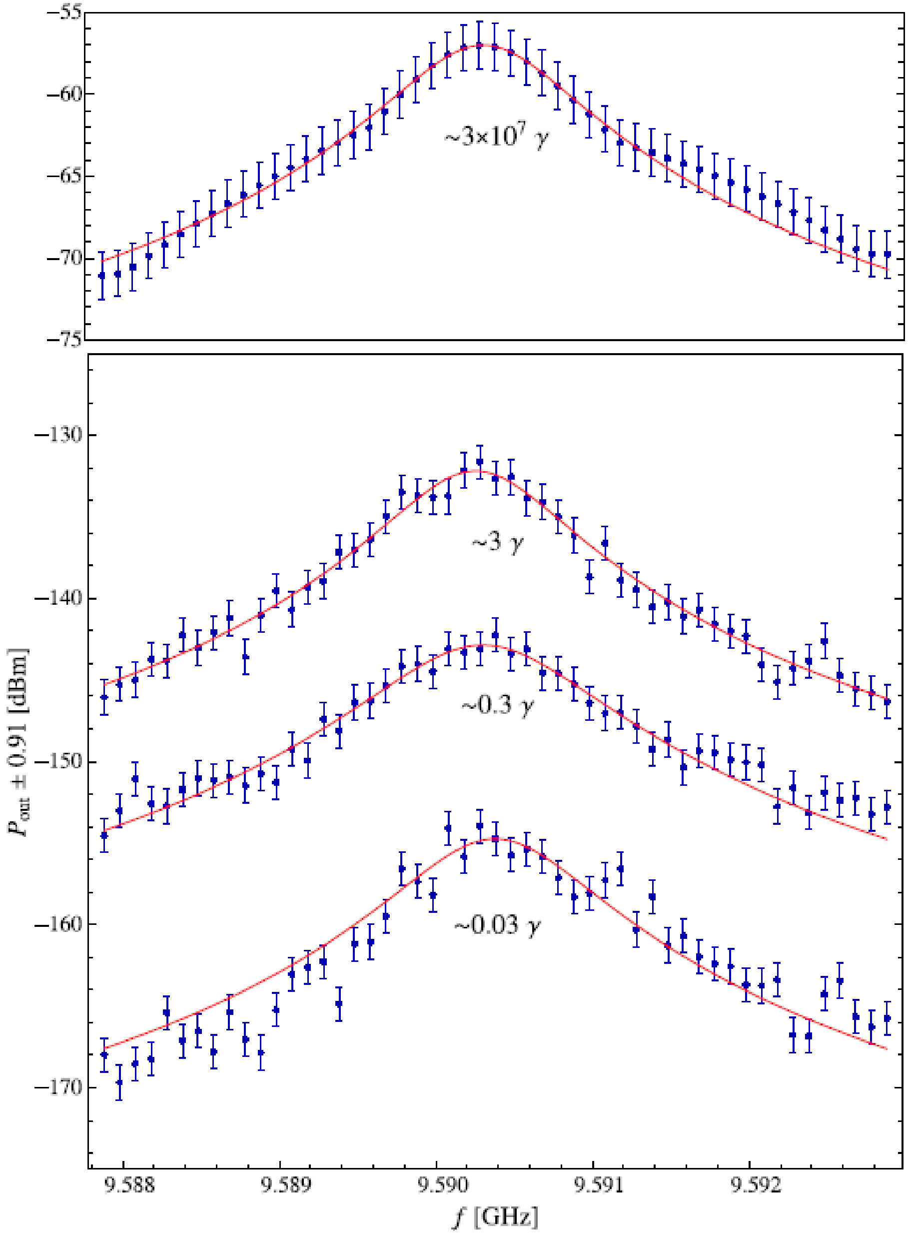
But energy is non-zero $\langle 1|\hat{E}^2(\boldsymbol{r},t)|1\rangle \neq 0$

An RF cavity can be resonated with “<<1 photons”

J. G. Hartnett et al Phys Lett B 698 346 (2011)

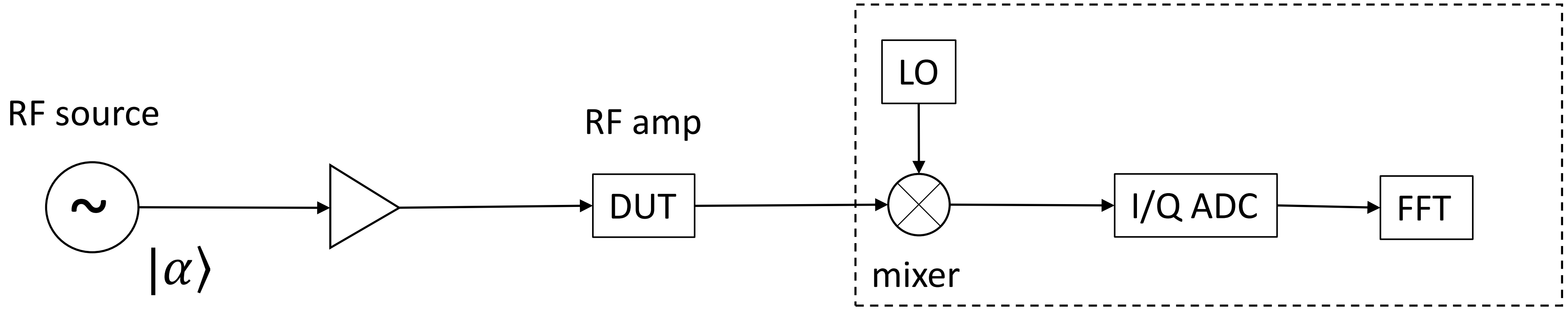


$P_{\rm in}$ [dBm]	$\#\gamma$ in cavity	Q_L
-55	$\sim 3 \times 10^7$	8800
-125	~ 3	8900
-135	~ 0.3	7100
-145	~ 0.03	8200



What does “<<1 photons” rigorously mean?

Quantum coherent state = quasi-classical theory



The wave detection measures the expectation value of electric field (voltage)

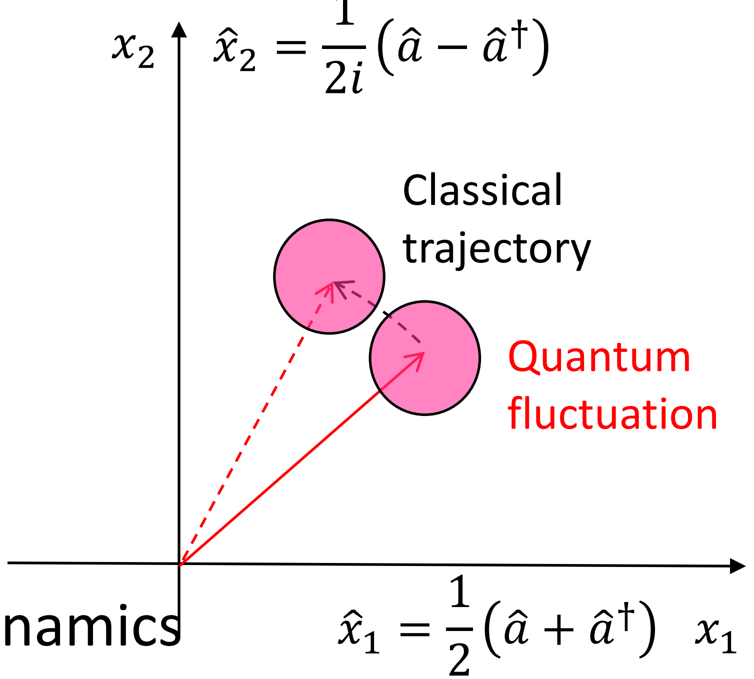
An engengstate of annihilation operator with a complex engenvalue

$\hat{a}|\alpha\rangle = \alpha|\alpha\rangle$: Coherent state is a typical model of laser, maser, and signal generator

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

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 expectation value of the electric field is the classical electrodynamics

Single photon counting of a coherent state

Expansion by number states

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

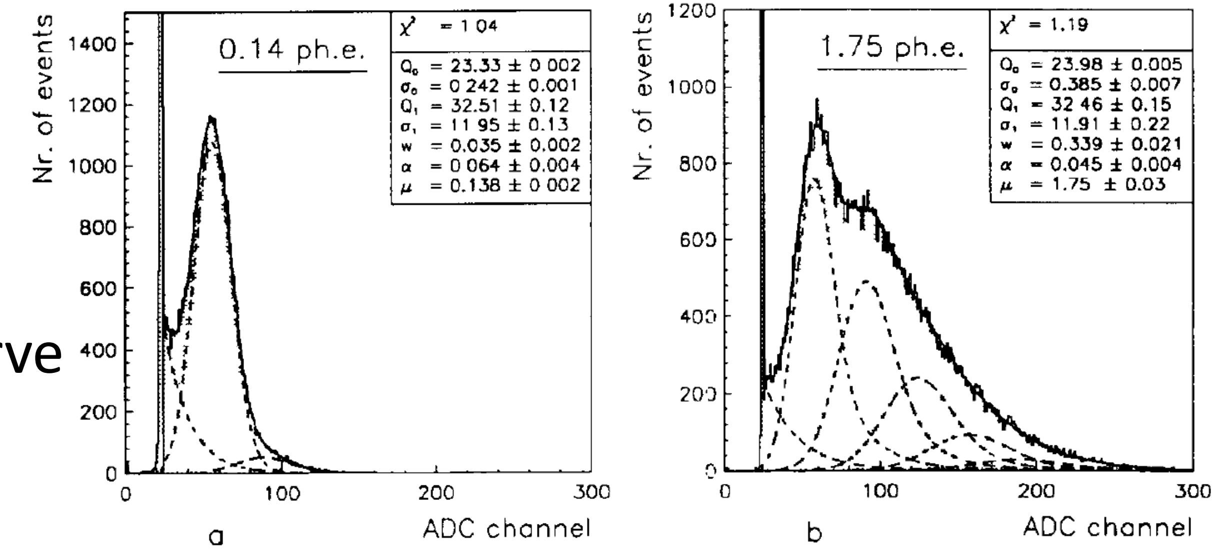
Projection measurement

$$P(n) = |\langle n|\alpha\rangle|^2 = \left| e^{-|\alpha|^2/2} \sum_{m=0}^{\infty} \frac{\alpha^m}{\sqrt{m!}} \langle n|m\rangle \right|^2 = \left| e^{-|\alpha|^2/2} \frac{\alpha^n}{\sqrt{n!}} \right|^2 = \frac{(|\alpha|^2)^n}{n!} e^{-|\alpha|^2}$$

Poisson distribution is reproduced by $|\alpha|^2 = \mu$

$$P(n;\mu) = \frac{\mu^n}{n!} e^{-\mu}$$

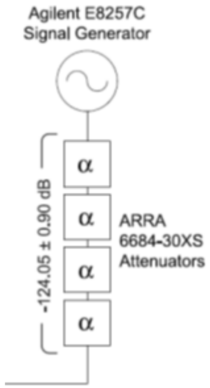
If single photon counting is feasible, we will observe Poisson distribution with a very small μ in axion experiment but wave detection is still an option



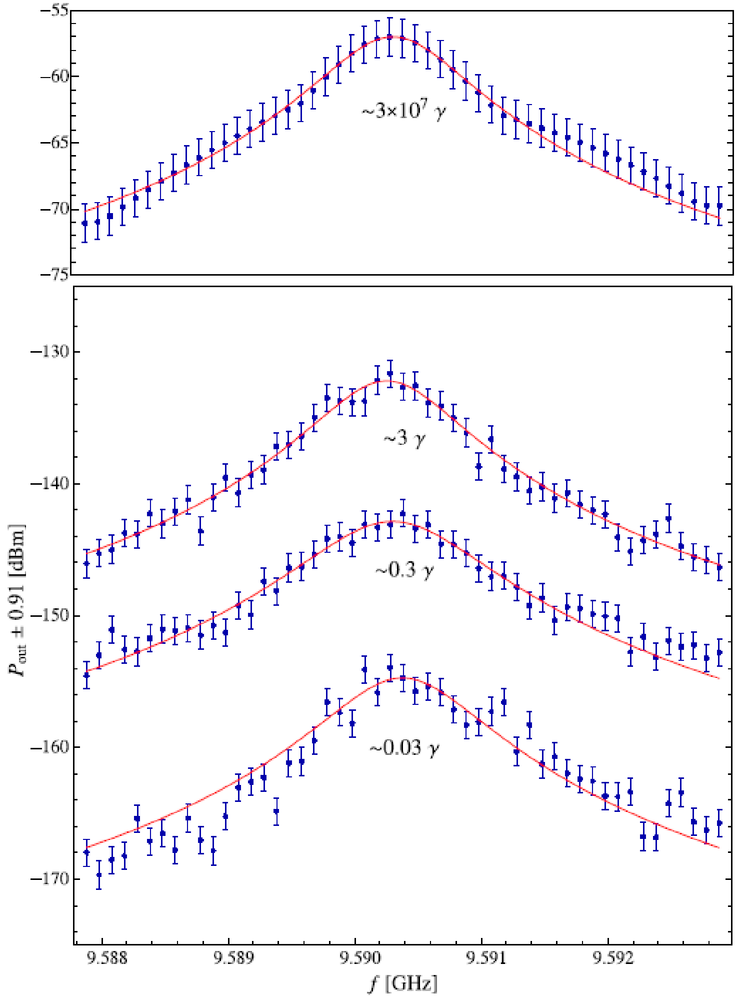
Single photon state ≠ attenuated coherent state

Minimum power
$-140\ \mathrm{dBm} = 10^{-17}\ \mathrm{W}$

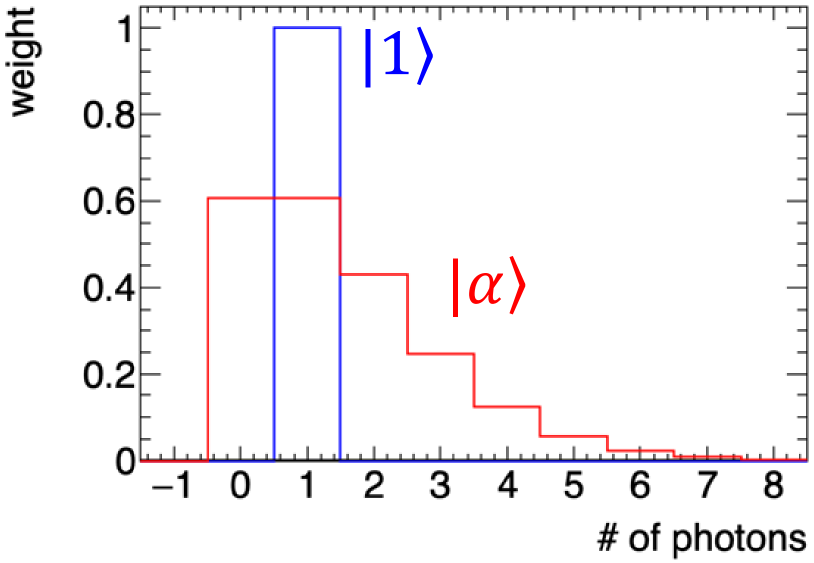
Power
$-30\ \mathrm{dBm} = 1/1000$



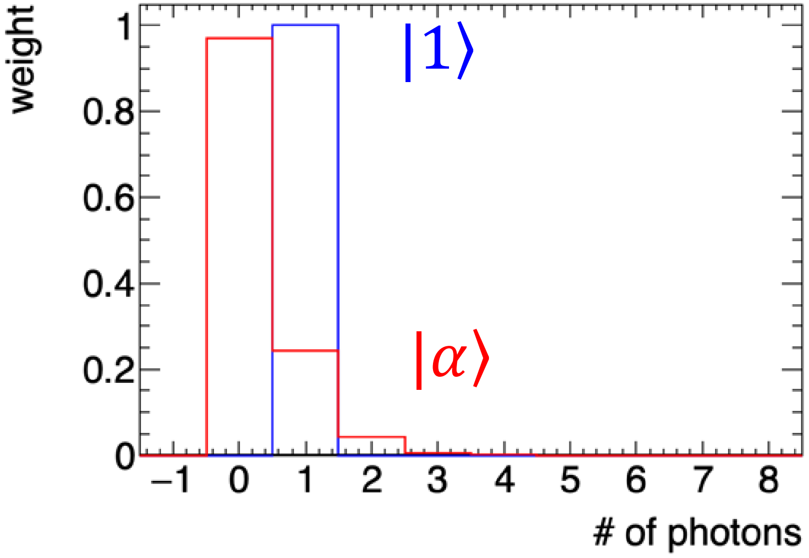
Series attenuation
→ Single photon
energy of 30 GHz
$h\nu = 2 \times 10^{-23}$ J
Per 1 s: -200 dBm



$\mu = |\alpha|^2 = 1$ mean # of photons

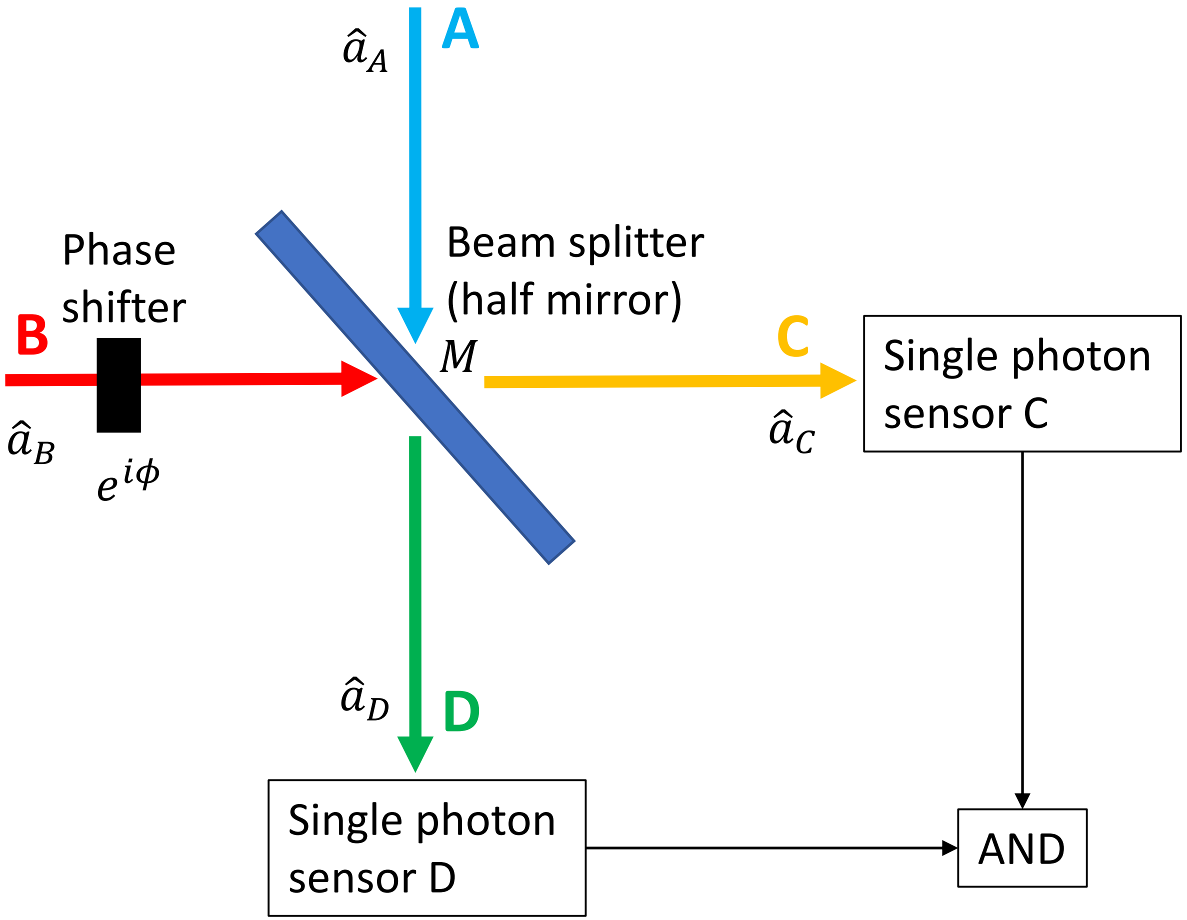


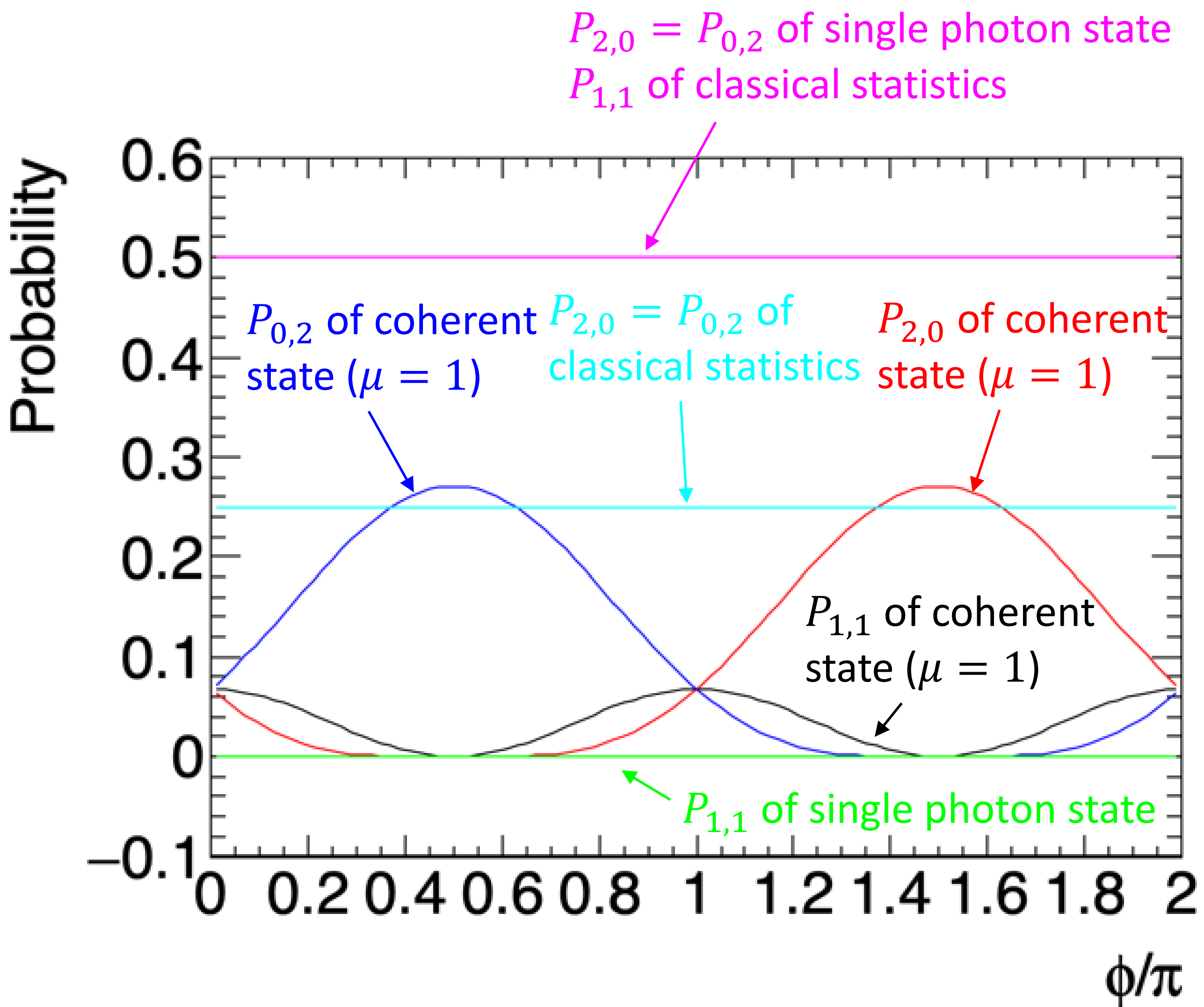
$\mu = |\alpha|^2 = 0.5$



Attenuated coherent signal shows completely different statistics from the single photon state

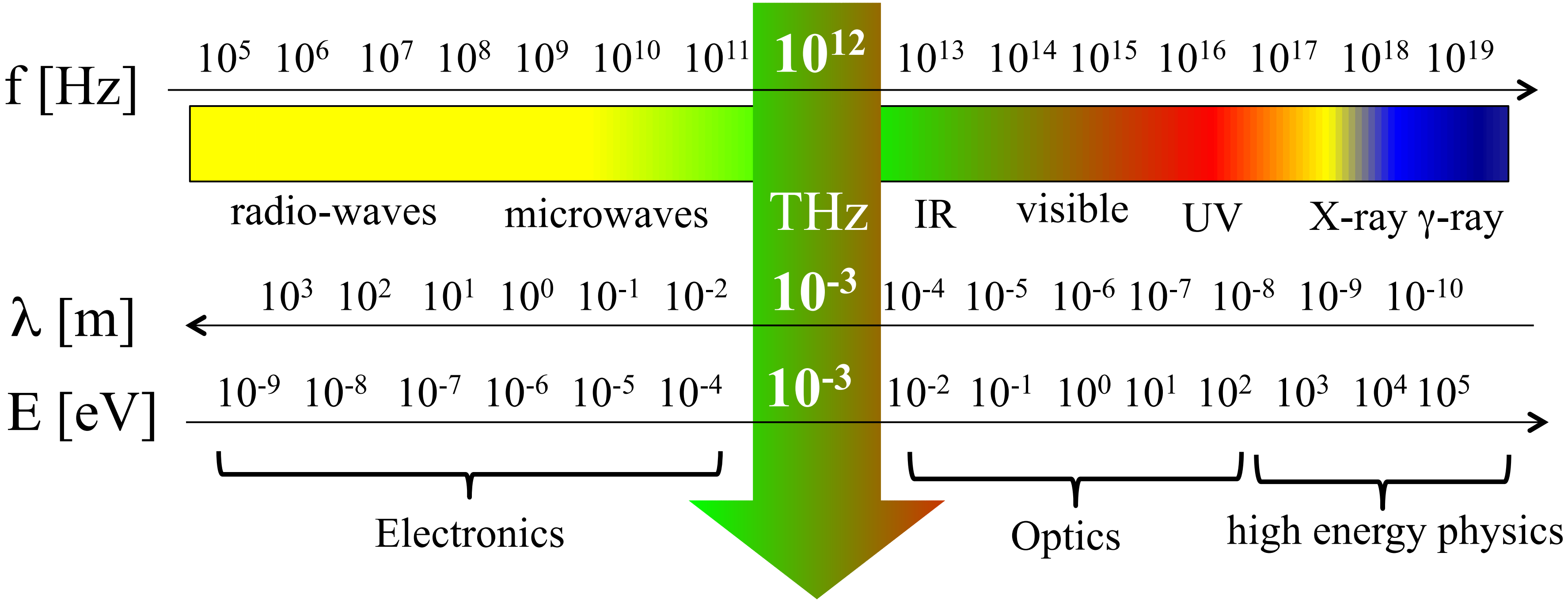
Cf. well-known example in quantum optics





- A single photon state $|1\rangle$ and a coherent state $\lim_{|\alpha|^2 \to 1} |\alpha\rangle$ can be distinguished by the inference pattern
- Both have a completely different inference pattern from incoherent classical statistics

Coherent detectors vs photon sensors



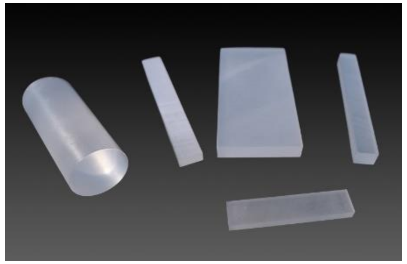
Coherent wave detection




In competition

Depends on the expected signal and background level

Incoherent photon detection


Pros and cons

Coherent detectors

- Phase information is kept
  - Via down conversion and direct sampling of sinusoidal voltage
- Standard quantum limit
  - Amplifiers is subject to a fundamental noise due to zero-point oscillation $h\nu$ [W/Hz]
- Narrow-band detection
  - Digital filter can distinguish narrow-band signal and broad-band noise background
- Difficult in higher frequency
  - RF, microwaves, millimeter waves are straightforward
  - Optical heterodyne is still possible
  - X-ray and γ-rays are true challenge
- Cooling is not necessary in the beginning

Photon sensors

- Phase information is lost
  - $\Delta\phi\Delta n = 0$
- No fundamental limit
  - Zero-point oscillation causes the shot noise but particle counting is still feasible
- Broad-band detection
  - We need to cool-down the system to address signal below black body radiation
- Difficult in lower frequency
  - X-ray, γ-rays and optical photons are straightforward
  - IR is possible with TES
  - Microwaves are (beyond) state-of-the-art
- Cooling is critical for low frequency applications

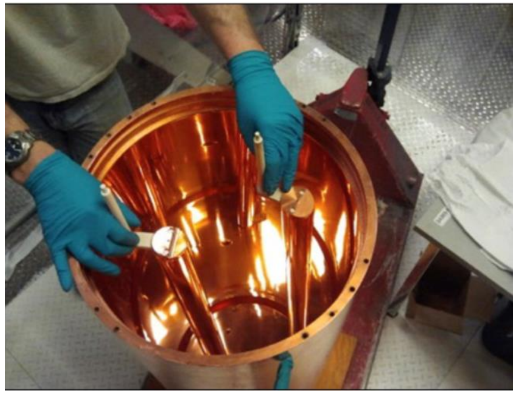
Outlook

- Introduction: axions and dark photons
- Photon detection and wave detection
- Dark matter axion search
- Light-Shining-Through-a-wall
- Potential of photon detection
- Conclusion

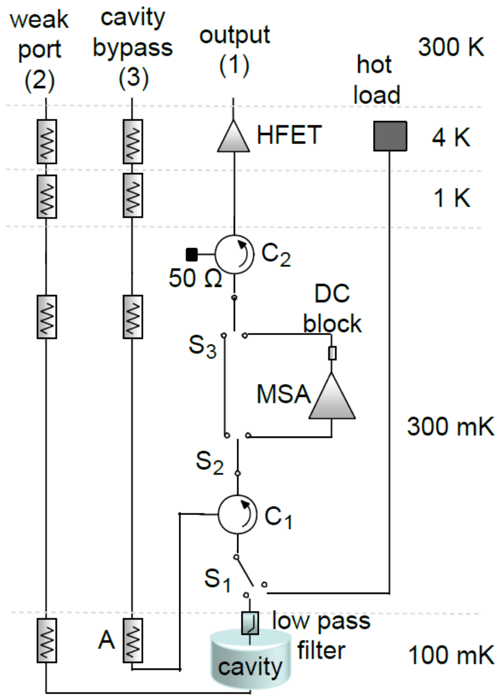
Dark matter axion search

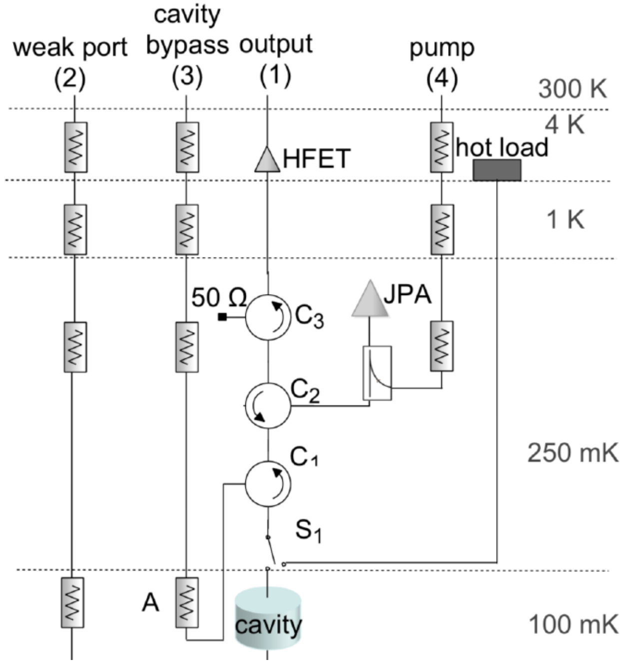
Review of Scientific Instruments **92**, 124502 (2021)

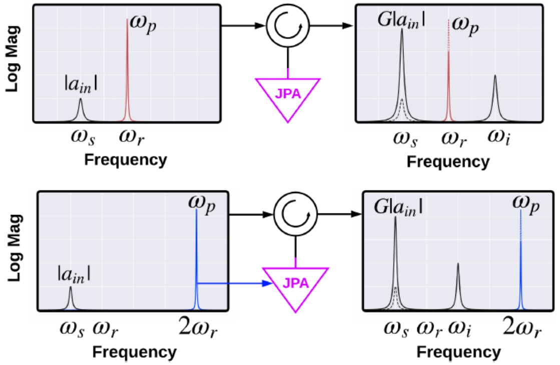
ADMX cavity



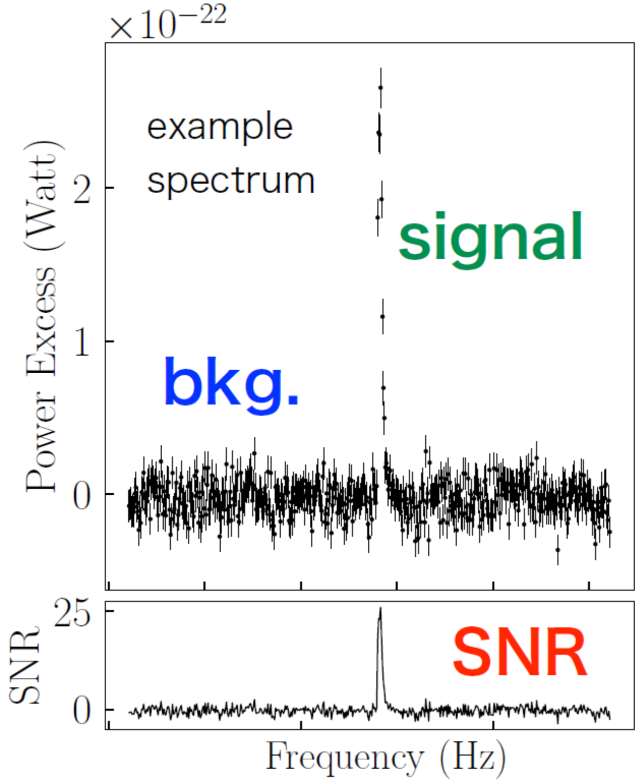
$f = 580 - 890$ MHz
$Q = (4-8) \times 10^4$ MHz

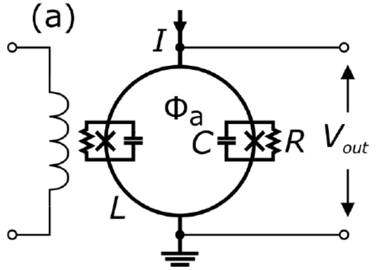


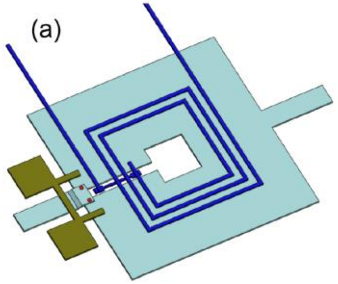




$$S/N = \frac{P_{a\to\gamma}}{k_B T_{sys}}\sqrt{\frac{t}{\Delta\nu}}$$







T. Nitta, Patras2021

They reached the standard quantum limit $k_B T_{sys} = h\nu$
$\rightarrow T_{sys} = 0.05$ K for 1 GHz

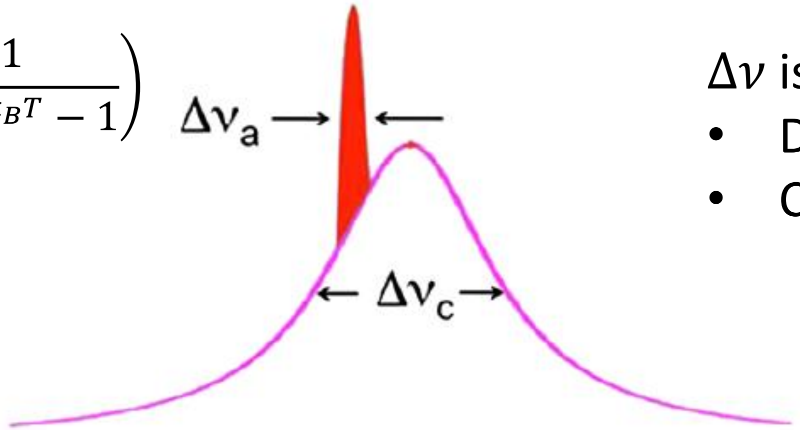
Toward single photon detection

S. K. Lamoreaux et al PRD 88 035020 (2013)

S/N of the coherent detection is limited by the standard quantum limit

$$P_l = h\nu(\bar{n}+1)\sqrt{\frac{\Delta\nu}{t}} \qquad \left(\bar{n} = \frac{1}{e^{h\nu/k_B T}-1}\right)$$

$$S/_N = \frac{P_{a\to\gamma}}{k_B T_{sys}}\sqrt{\frac{t}{\Delta\nu}} \sim \frac{P_{a\to\gamma}}{h\nu(\bar{n}+1)}\sqrt{\frac{t}{\boxed{\Delta\nu}}}$$



$\Delta\nu$ is limited by either

- DM axion's velocity spread $Q_a \sim 10^6$
- Cavity Q
  - Normal conducting $Q_c \sim 10^{4-5}$
  - Superconducting $Q_c \sim 10^{5-7}$

S/N of the photon sensor is given by Poisson statistics

$$P_{sp} = \frac{h\nu\delta N}{t} = \frac{h\nu}{t}\sqrt{\eta\bar{n}\nu_c t}$$

$$S/_N = \frac{P_{a\to\gamma}}{h\nu}\sqrt{\frac{t}{\eta\bar{n}\Delta\nu_c}}$$

<u>Ratio of noise power</u>

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

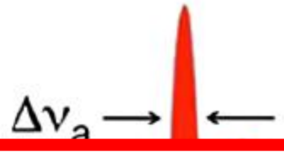
Since Q_a is fixed by the dark matter halo, the single photon sensor can have lower noise power for lower temperature (blackbody radiation $\bar{n} \to 0$), higher frequency and higher Q_c

Toward single photon detection

S. K. Lamoreaux et al PRD 88 035020 (2013)

S/N of the coherent detection is limited by the standard quantum limit

$$P_l = h\nu(\bar{n}+1)\sqrt{\frac{\Delta\nu}{t}} \qquad \left(\bar{n} = \frac{1}{e^{h\nu/k_BT}-1}\right)$$



$\Delta\nu$ is limited by either

- DM axion's velocity spread $Q_a \sim 10^6$

Example:

If dark current rates are negligible, the single photon detectors become better than the coherent detection with 100 mK, $Q_a/Q_c = 20$, and 10 GHz

→ Development of single photon sensors is motivated for DM axion search

$$S/N = \frac{P_{a\to\gamma}}{h\nu}\sqrt{\frac{t}{\eta\bar{n}\Delta\nu_c}}$$

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

Since Q_a is fixed by the dark matter halo, the single photon sensor can have lower noise power for lower temperature (blackbody radiation $\bar{n} \to 0$), higher frequency and higher Q_c

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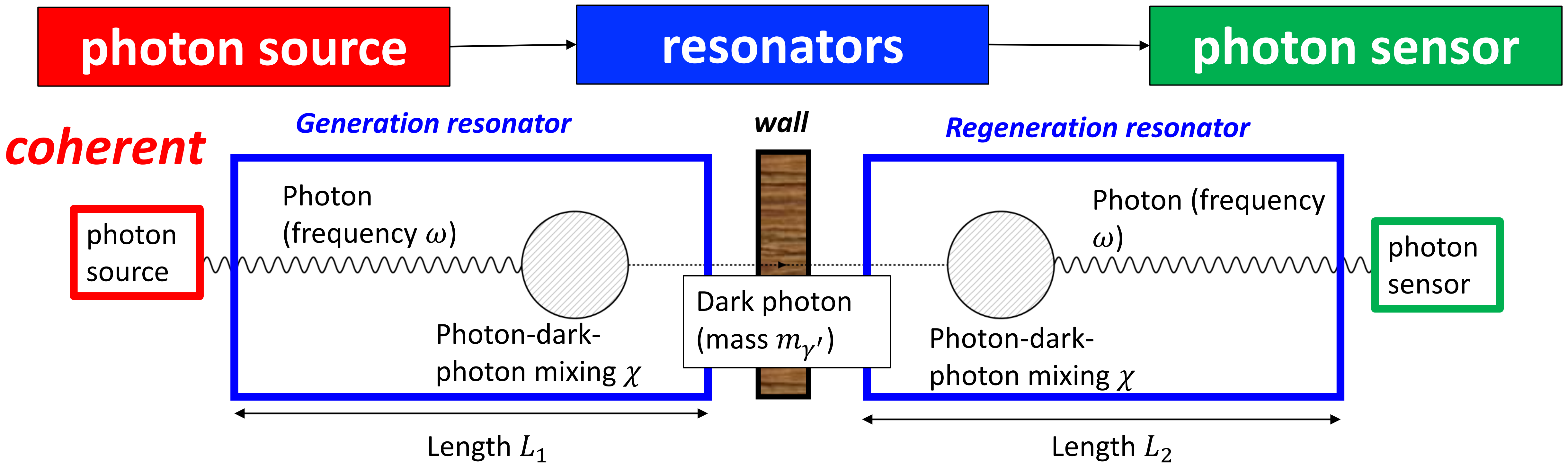
Conceptual setup for the dark photon search



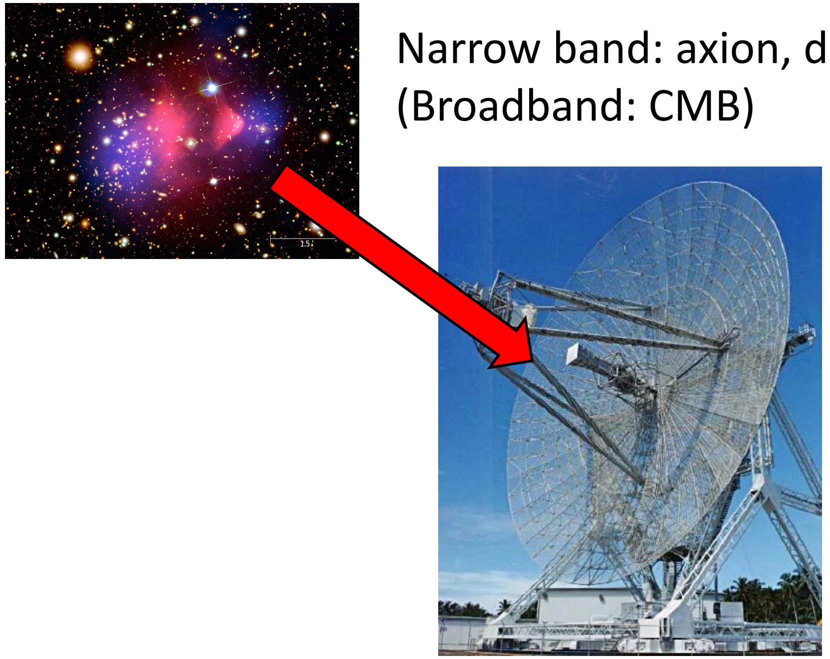
The probability of one photon penetrating the wall via dark photon mixing is

$$p_{\gamma\to\gamma'\to\gamma} = p_{\gamma\to\gamma'}(L_1)p_{\gamma'\to\gamma}(L_2) = \left(\frac{\omega + \sqrt{\omega^2 - m_{\gamma'}^2}}{\sqrt{\omega^2 - m_{\gamma'}^2}}\right)^4 \chi^4 \sin^2\left[\frac{L_1}{2}\left(\omega - \sqrt{\omega^2 - m_{\gamma'}^2}\right)\right] \sin^2\left[\frac{L_2}{2}\left(\omega - \sqrt{\omega^2 - m_{\gamma'}^2}\right)\right]$$

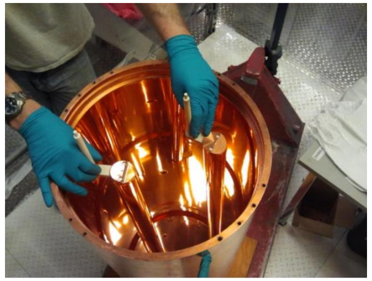
Major difference from DM: $\Delta\nu_a$ is under control

Dark matter: Passive radar

Narrow band: axion, dark photons
(Broadband: CMB)



ADMX is this type

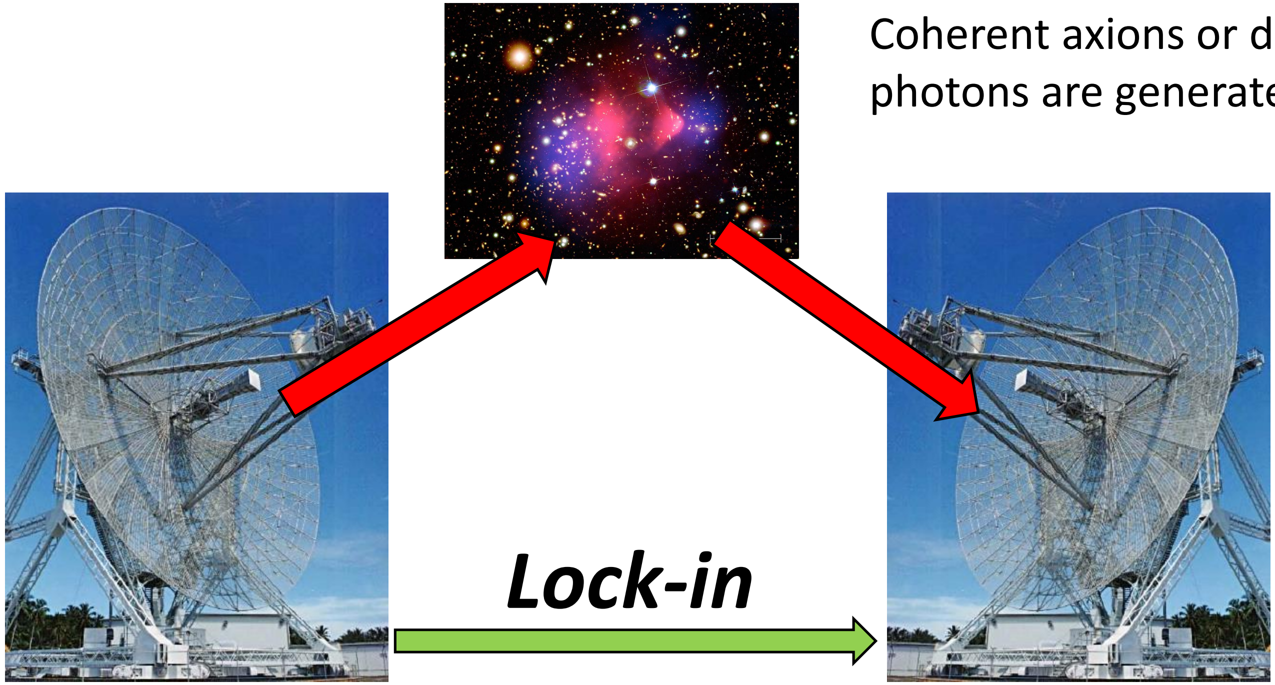


$$S/N = \frac{P_{sig}}{k_B T}\sqrt{\frac{\Delta t}{\Delta\nu_a}}$$

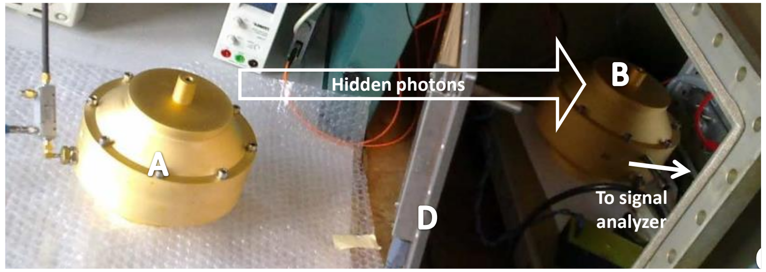
Single photon counting can be better above 10 GHz

LSW: Active radar

Coherent axions or dark photons are generated



LSW can be this type if we can lock-in the signal

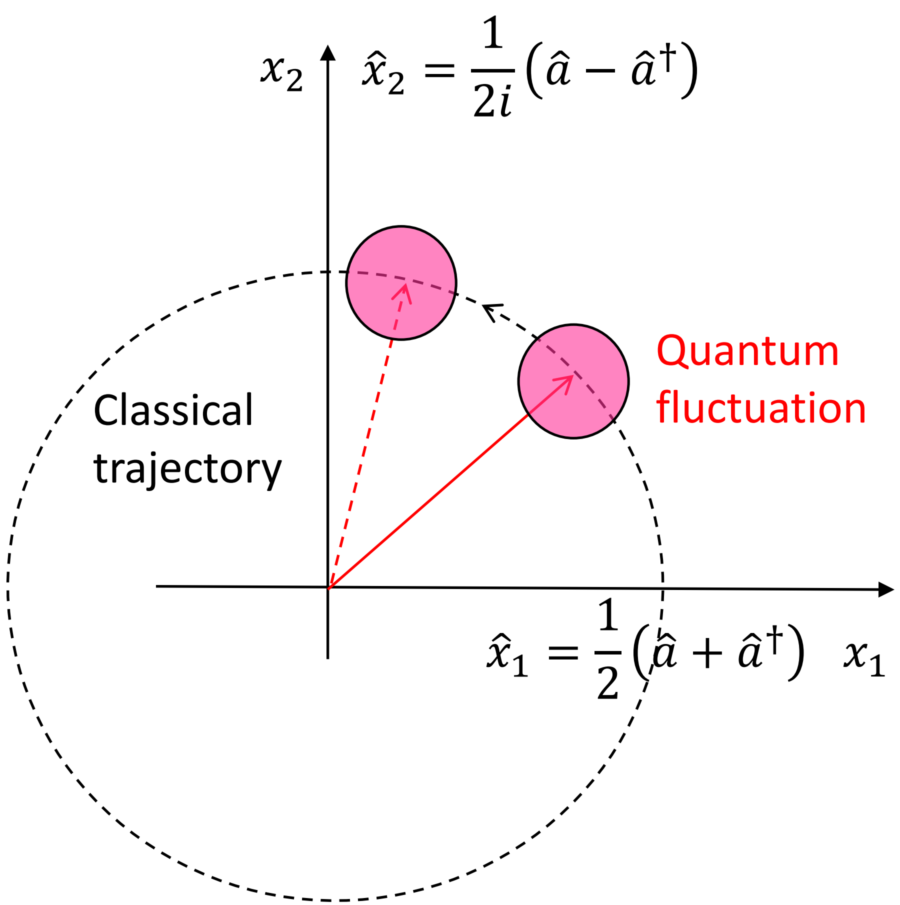


$$S/N = \frac{P_{sig}}{k_B T}\sqrt{\frac{\Delta t}{\Delta\nu_r}} = \frac{P_{sig}}{k_B T}\Delta t$$

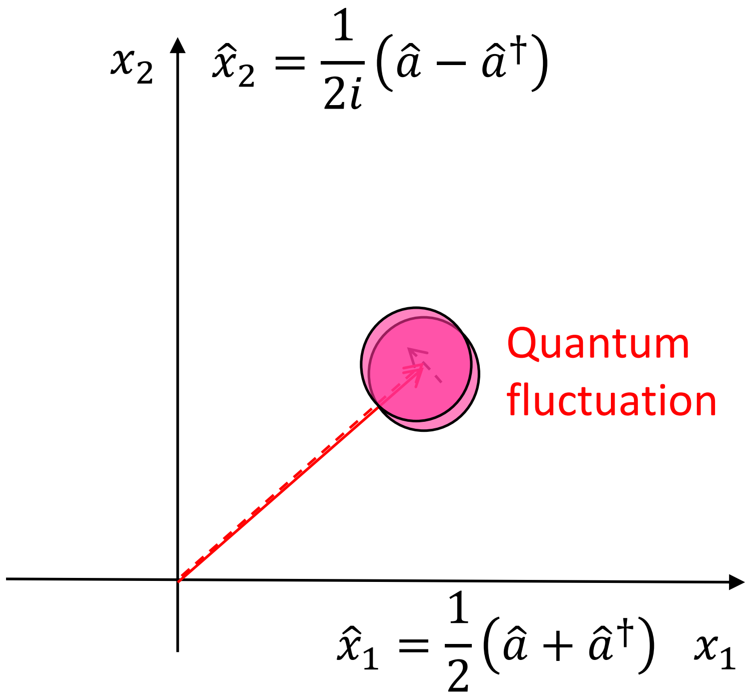
The sensitivity can be increased over the coherence time

Intuitive image of phase locking

The phase rotates within the bandwidth



Relative phases are locked-in

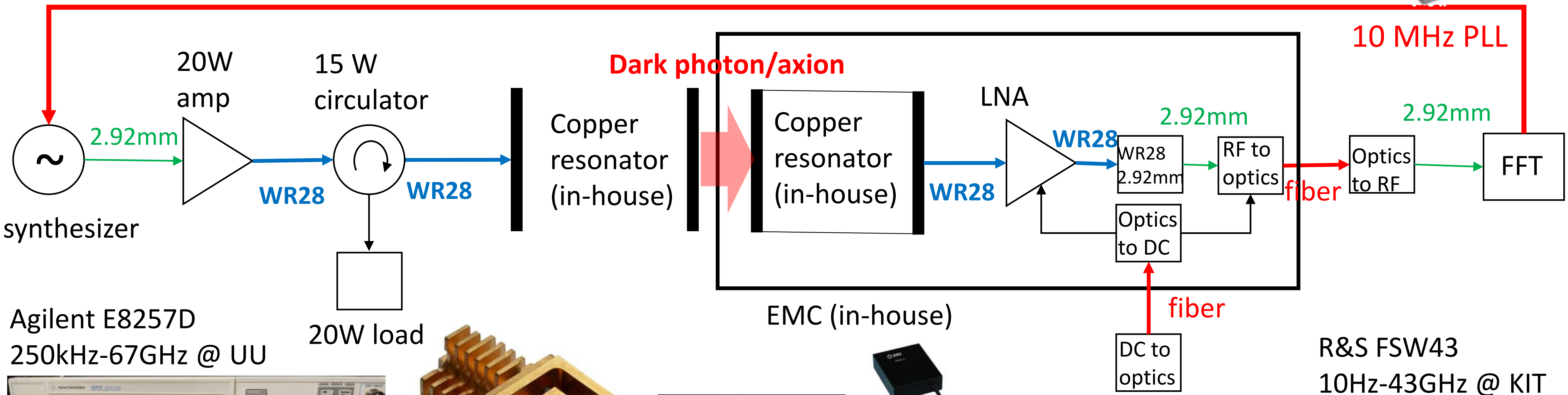


- Classical drift (decoherence) is suppressed
- The signal is linearly enhanced by integral over the relative coherence time
- The precision of the locking must be checked

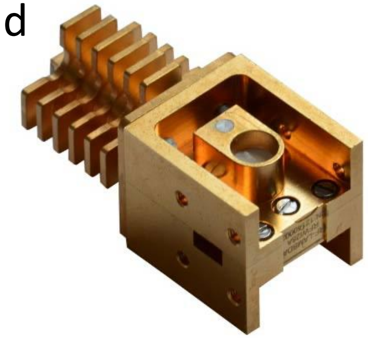
The implementation is RF/MW/mmw is very simple

PoP of coherent detection for studying dark photons with low power

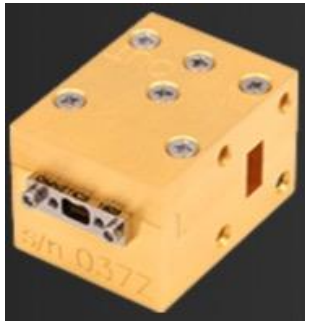
WR28 to coaxial adaptor
RFWA28E0F
from RF-Lambda max 20W



Agilent E8257D
250kHz-67GHz @ UU



RFWI28A27G32G
from RF-Lambda



LNF-LNR23_42WB
From Low noise factory

PPM-5 DC
5VDC 1W
From JDSU

ERZ-HPA-
3000-3100-46
From ERZIA

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

R&S FSW43
10Hz-43GHz @ KIT

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

$$h\nu/s \sim 2 \times 10^{-23}\ \mathrm{W}$$

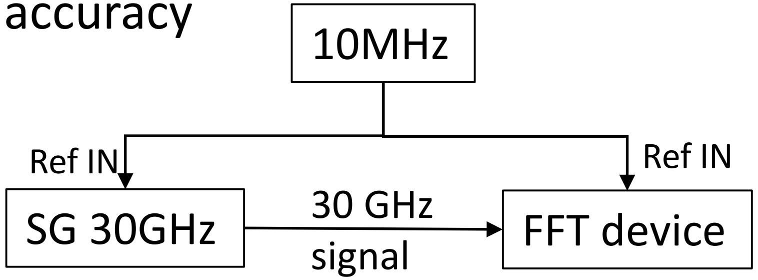
→ Thermal photons (white noise) can be dramatically suppressed by FFT without cooling

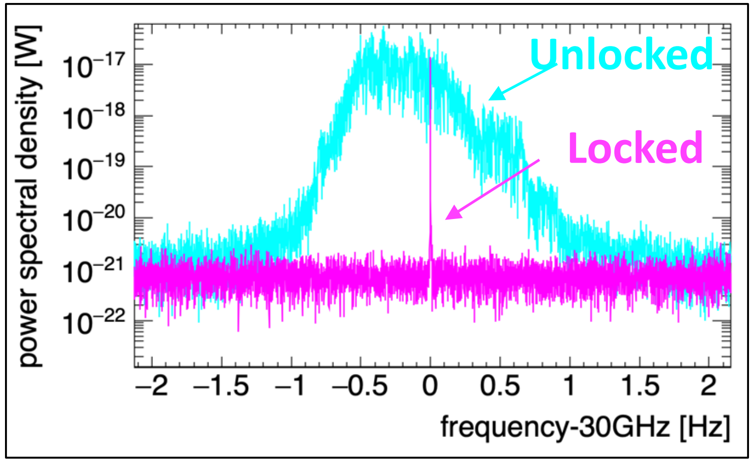
$T_S = 300$ K

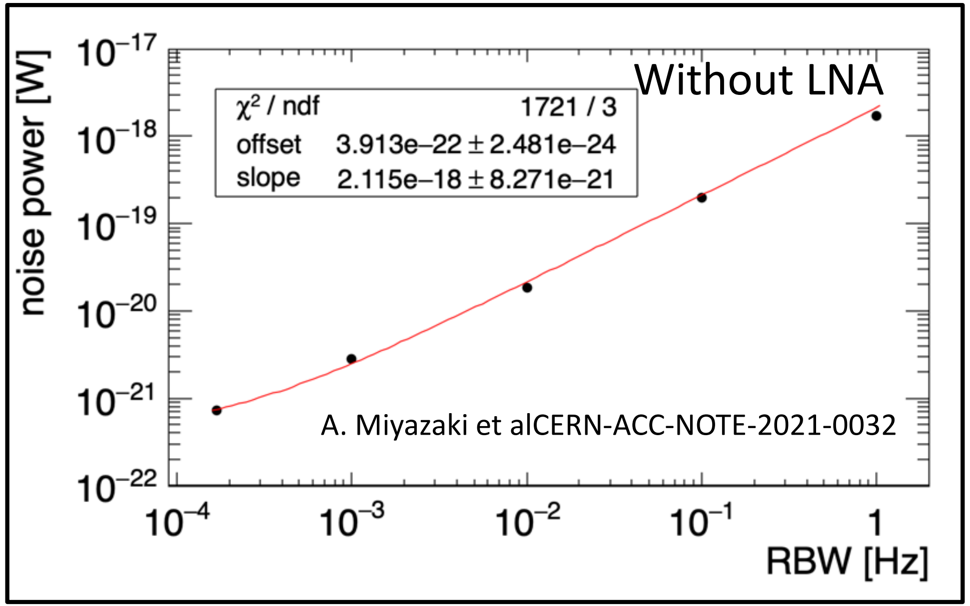
t	BW	P_N	#photon/s
100 ms	10 Hz	4.2e–20 W	2100
1 s	1 Hz	4.1e–21 W	200
10 s	100mHz	4.1e–22 W	21
5 min	3 mHz	1.4e–23 W	0.7
1 hour	278 μHz	1.1e–24 W	0.06
1 day	12μHz	4.8e–26 W	0.002

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!

Limitation of coherency

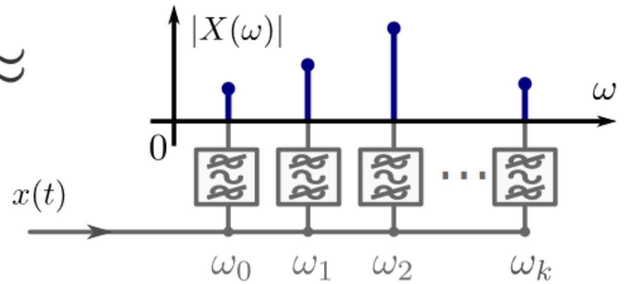
- Decoherence by phase noise of amplifiers and mixers
  - Marginal because of "relative" phase locking between signal generator, detector, and local oscillators
  - The "absolute" phase stability is only a few Hz over hours
  - Ultimate "relative" phase stability is unknown (mHz? uHz? nHz?)
- Fundamental decoherence due to the axions/dark photons
  - The unknown finite mass causes unknown time of flight and leads to decoherence but is still very small if $\omega > m$
- Systematic caused by the digital circuit and self-locking
  - The S/N was preliminary evaluated with the digital circuit (FPGA + software)
  - Digital down-conversion and filtering cause systematic uncertainty which would reduce the true S/N
  - A critical evaluation of the digital circuit and/or implementation of analog circuit may be required

Digital circuit may distort the true S/N and therefore the exclusion limit→

Fourier transformation:

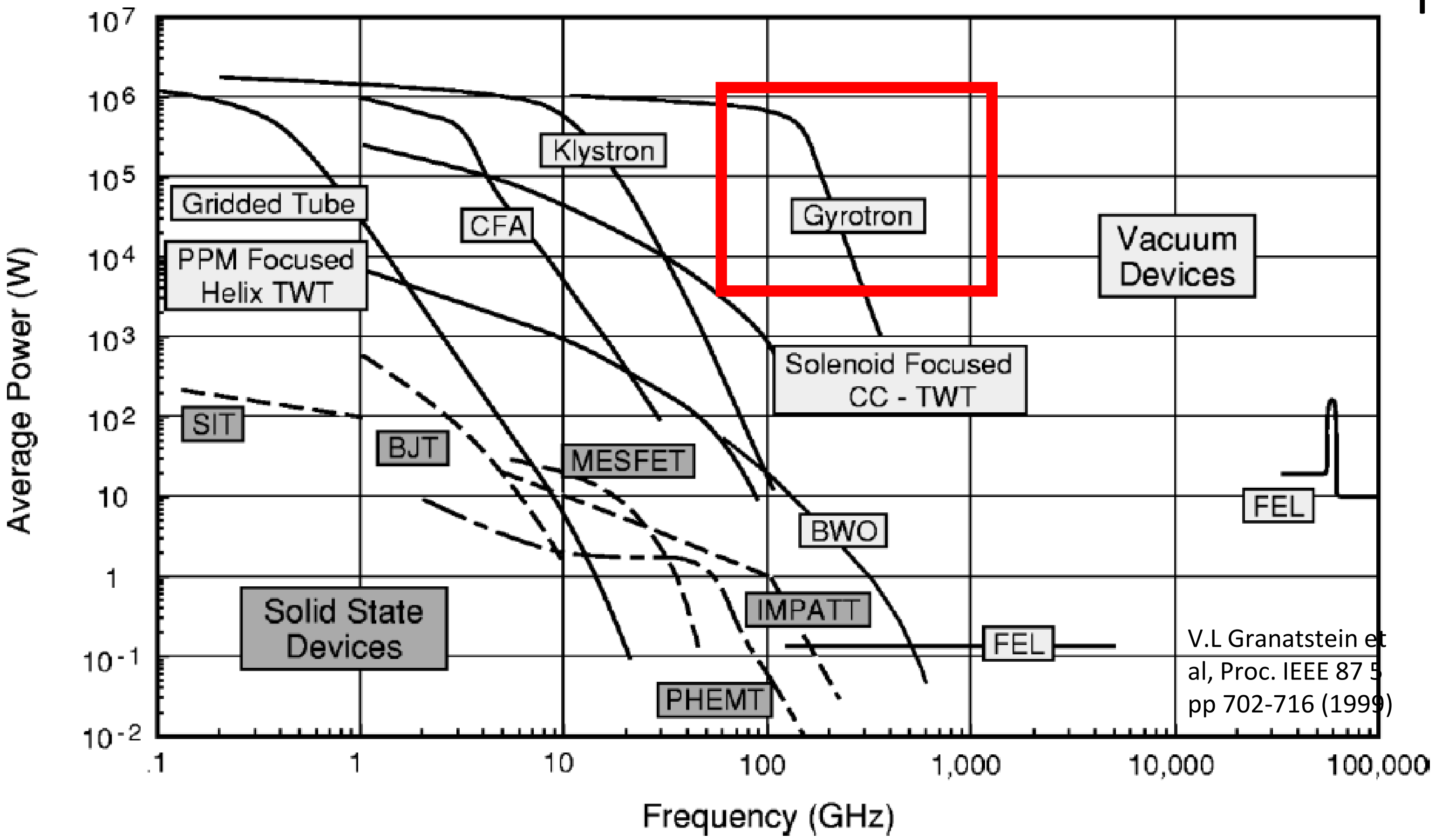
$$X(\omega_k) = \int_{t=0}^{l} x(t) \cdot e^{-j\omega t} dt \approx$$

Array of bandpass filters



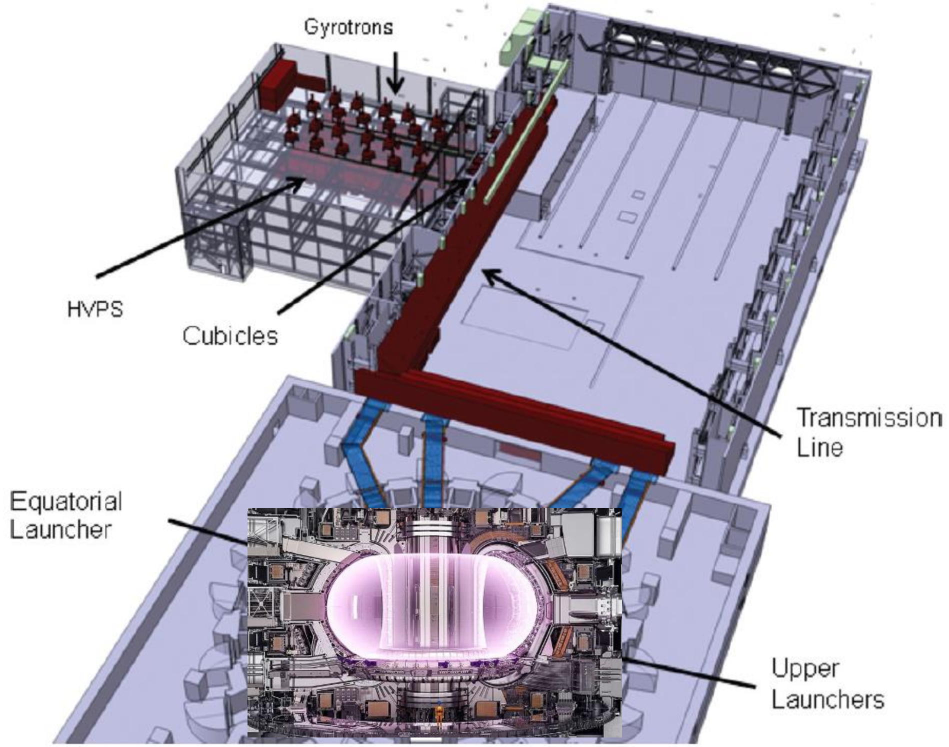
M. Betz PhD thesis

High power coherent source is available



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

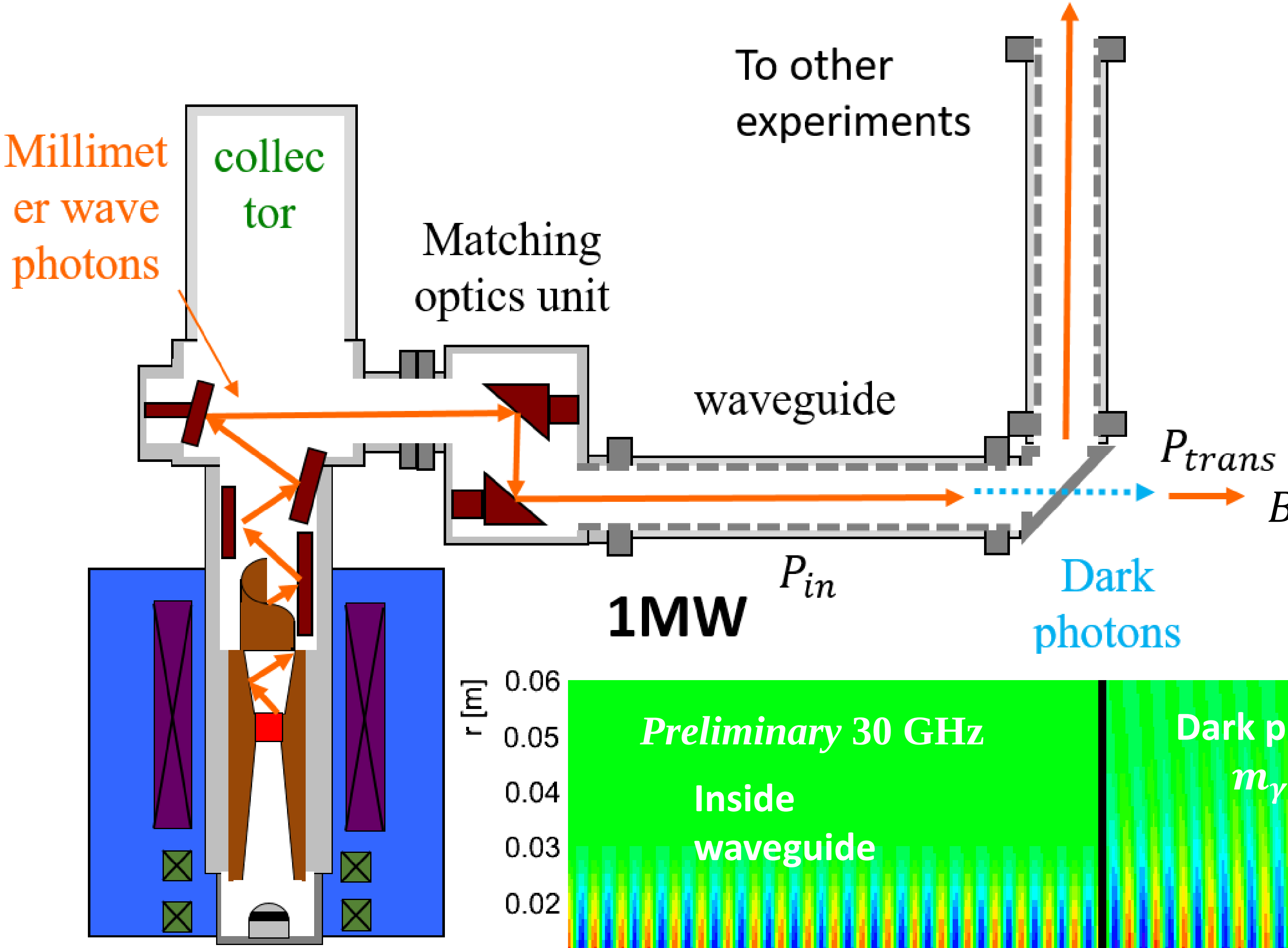
ITER plasma heating



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

- Gyrotrons are a unique microwave source in millimeter-wave range
- Coherent (<MHz), high-power (>>kW), high frequency (>30GHz), CW

Gyrotron as a dark photon generator



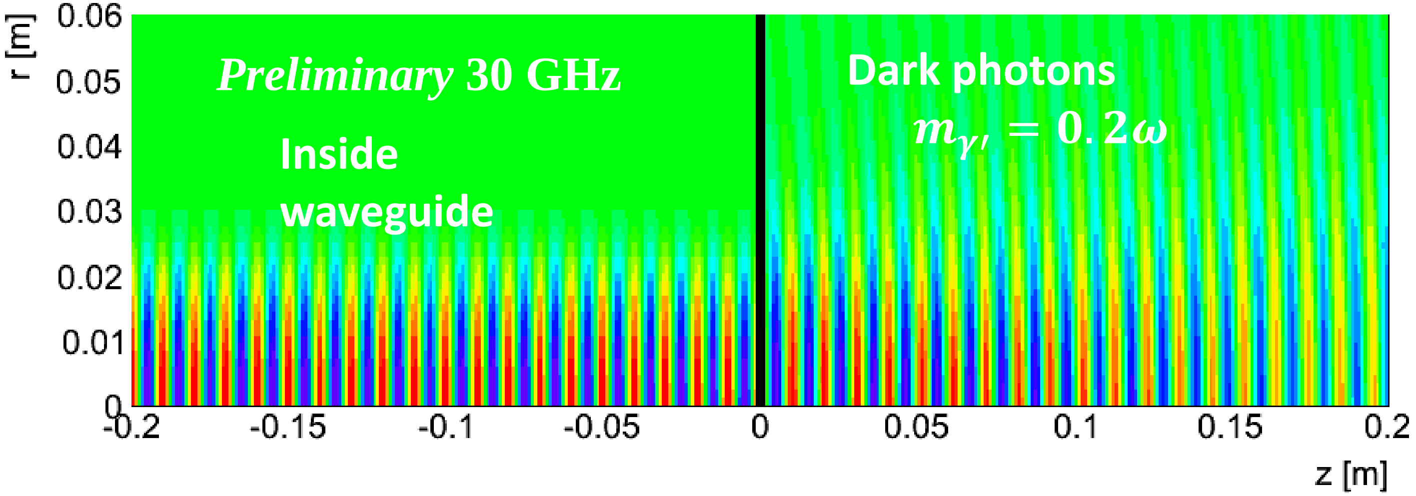
Number of photons in 170 GHz 1MW

$$P/_{h\nu} \sim 10^{27}\ \mathrm{s}^{-1}$$

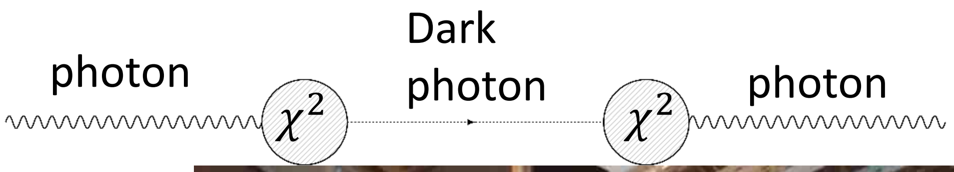
$$\left(\frac{\partial^2}{\partial t^2} - \nabla^2 + m_{\gamma'}^2\right)\boldsymbol{B} = \chi m_{\gamma'}^2 \boldsymbol{A}$$

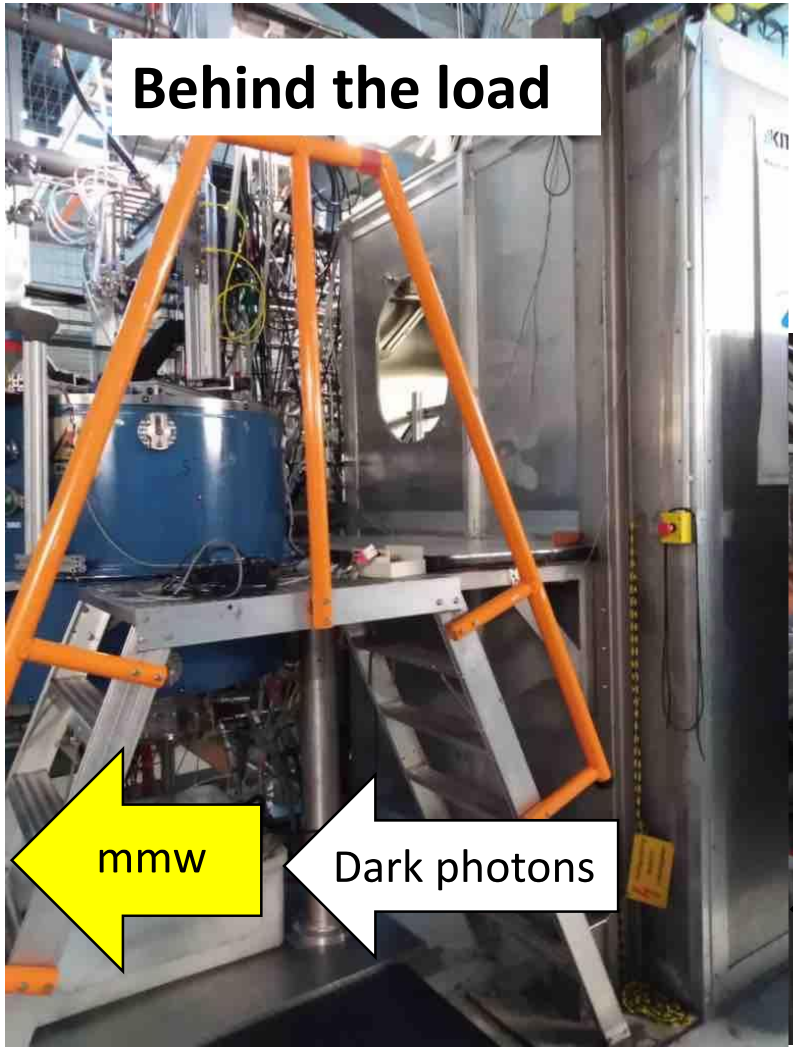
$$B(r,t) = \chi m_{\gamma'}^2 \int_{V'} \frac{\exp(ik'|\boldsymbol{r}' - \boldsymbol{r}|)}{4\pi|\boldsymbol{r}' - \boldsymbol{r}|} A(r',t) d\boldsymbol{r}'$$

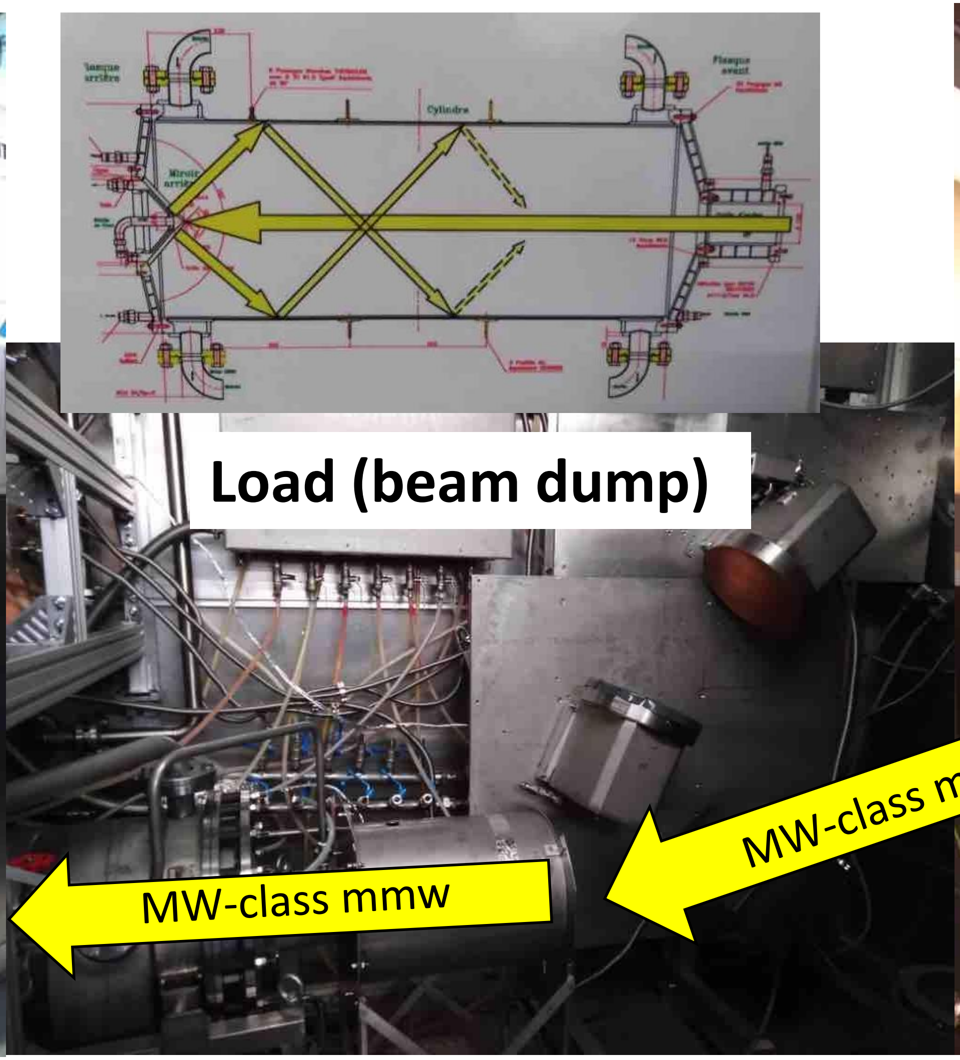
$$k' = \sqrt{\omega^2 - m_{\gamma'}^2}$$



Naïve consideration @ KIT





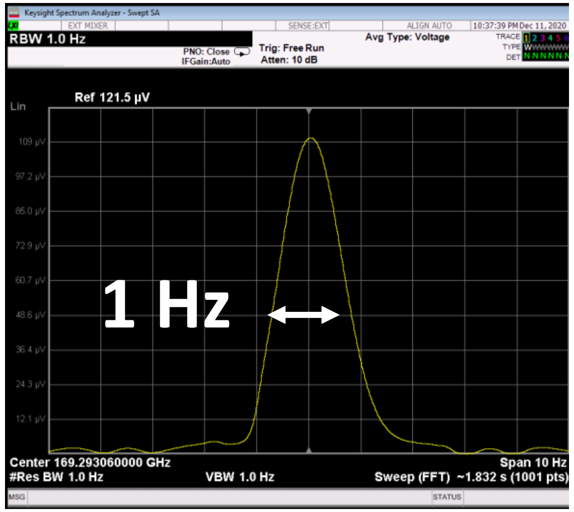


If $\chi = 10^{-7}$, 1 MW gyrotron generates

$$P_{trans} \sim P_{in} p_{\gamma \to \gamma'} p_{\gamma' \to \gamma} = P_{\mathrm{in}} \chi^4 = 1\mathrm{MW} \times 10^{-7 \times 4}$$
$$= 10^{-22}\ \mathrm{W} < \mathbf{4.1 \times 10^{-21}}\ (300\mathrm{K\ blackbody\ radiation})$$

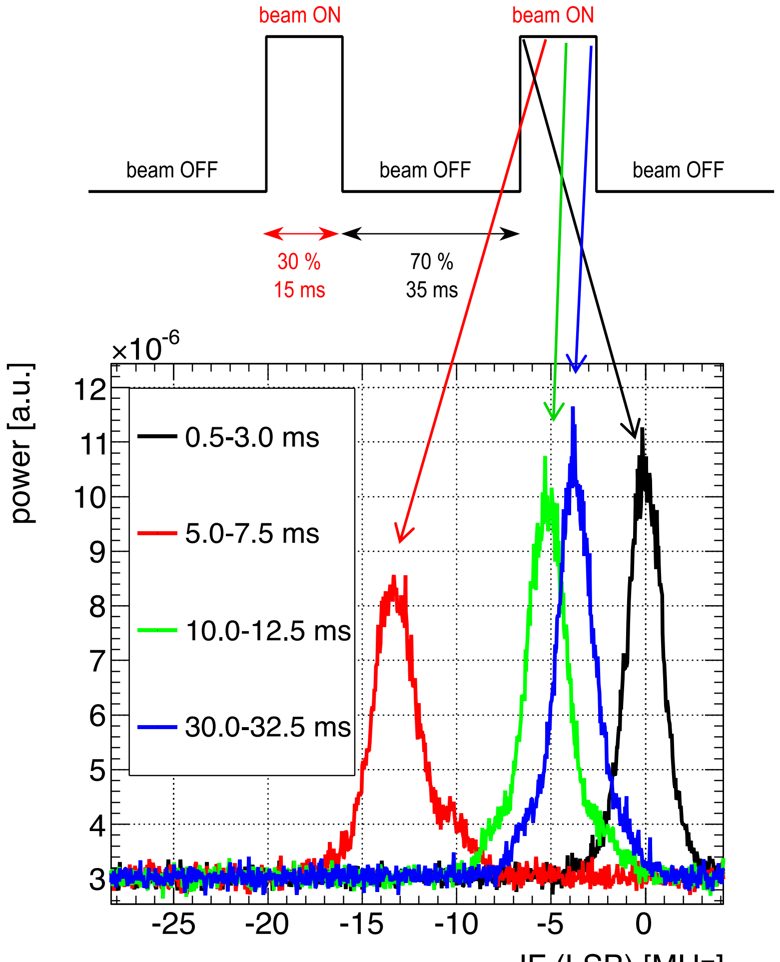
How about the coherency?

Recent breakthrough: *super narrow-band gyrotron*



free running gyrotron (2014)

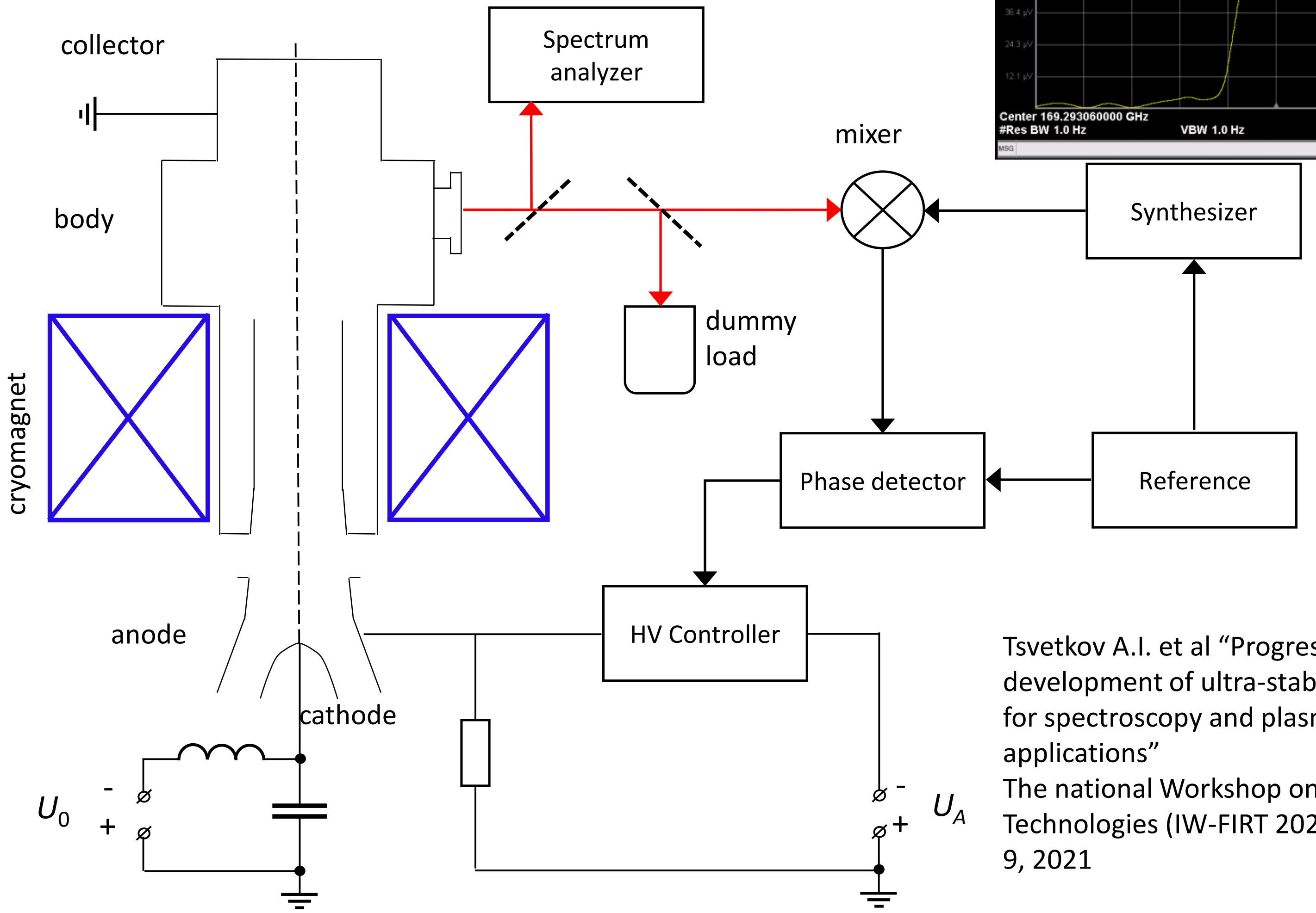
- Line-width **2MHz**
- frequency drift **20MHz**



A. Miyazaki, Springer thesis, 2015

Phase locked gyrotron (2021)

- **Absolute BW** of **1Hz**
- KIT is developing a similar system



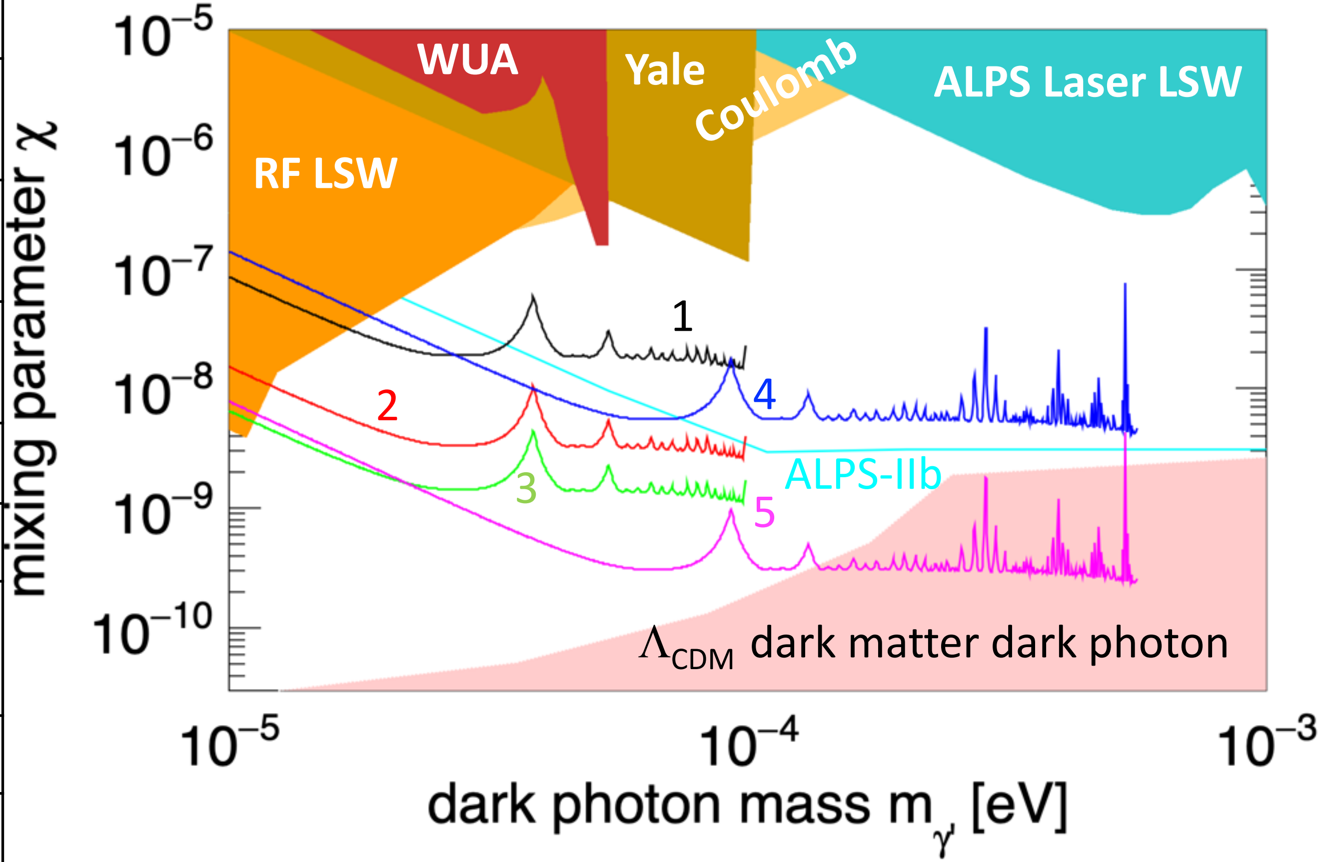
Tsvetkov A.I. et al "Progress in the development of ultra-stable gyrotrons for spectroscopy and plasma applications"
The national Workshop on Far-Infrared Technologies (IW-FIRT 2021), March 8-9, 2021

Very encouraging for mmw science (and accelerators)

40

Some scenarios of 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

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

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

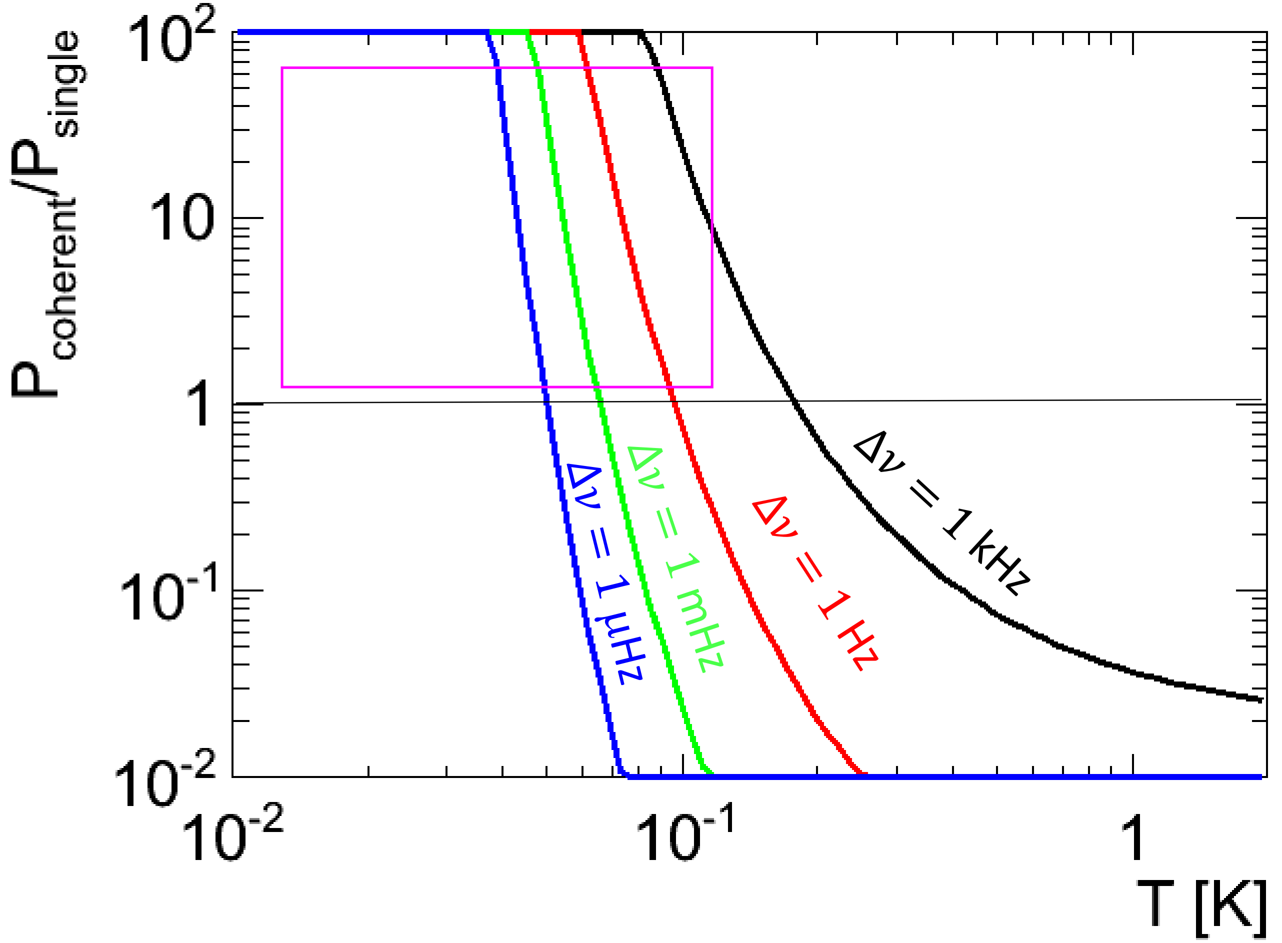
<u>Ratio of noise power</u>

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

$\nu = 30$ GHz

$\Delta\nu_c = 500$ kHz

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



Superconducting single photon sensors may be a solution in the future

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

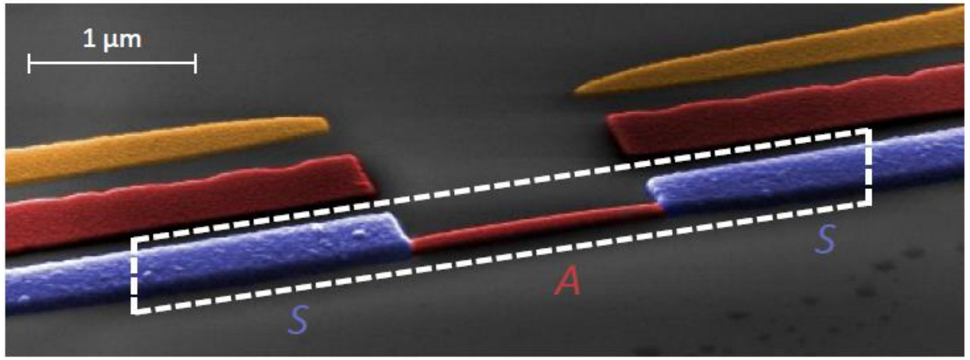
Superconducting photon sensors in Pisa are promising

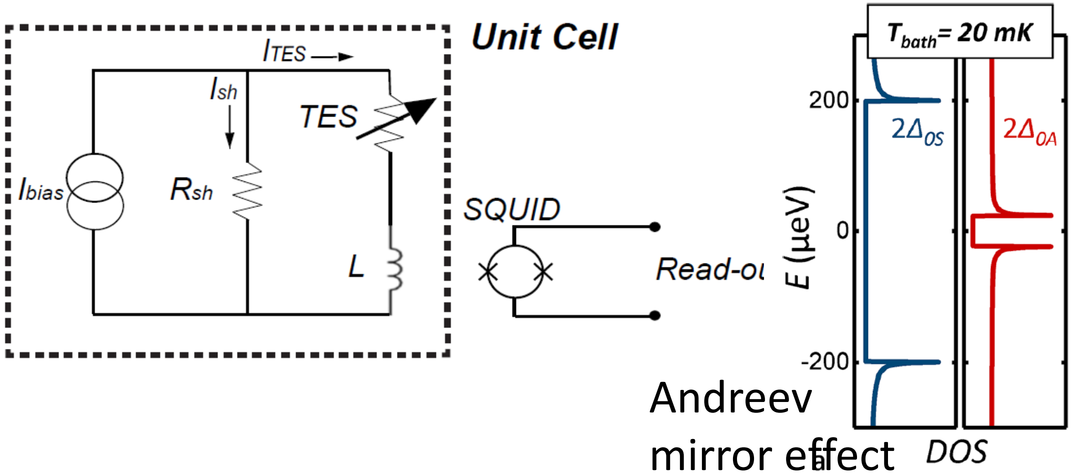
Nano-Transition Edge Sensor (TES)

Tiny volume & Andreev mirror effect at the border

→ Reactive to small heat dissipation

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



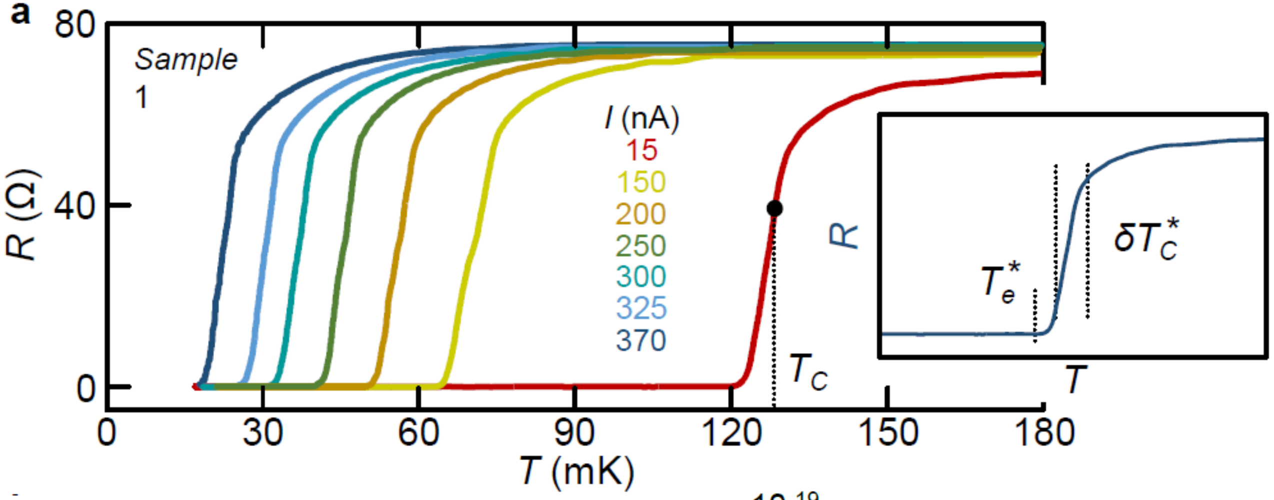


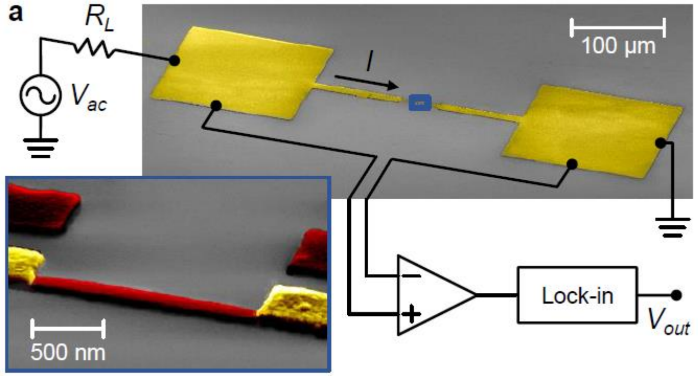
Andreev mirror effect

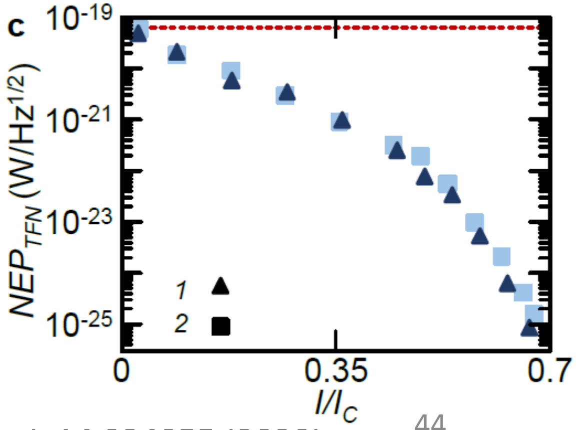
F. Paolucci et al Journal of Applied Physics 128, 194502 (2020)

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)

Further application: relic neutrino?

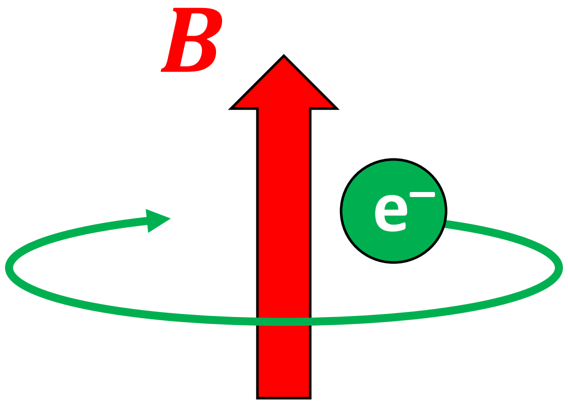
Cosmic neutrino background can be captured by tritium

$$\nu_e + {}^3H \rightarrow {}^3He^+ + \boxed{e^-}$$

With a background of β-decay process (KATRIN)

$$^3H \rightarrow {}^3He^+ + \boxed{e^-} + \bar{\nu}(e)$$

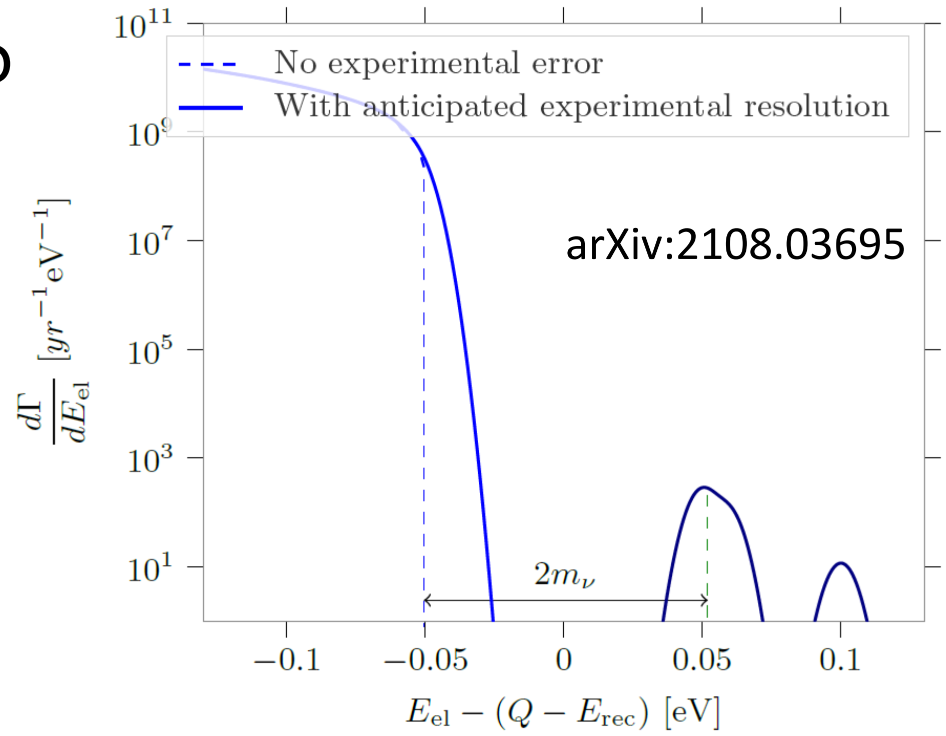
How to separate the signal from the background?

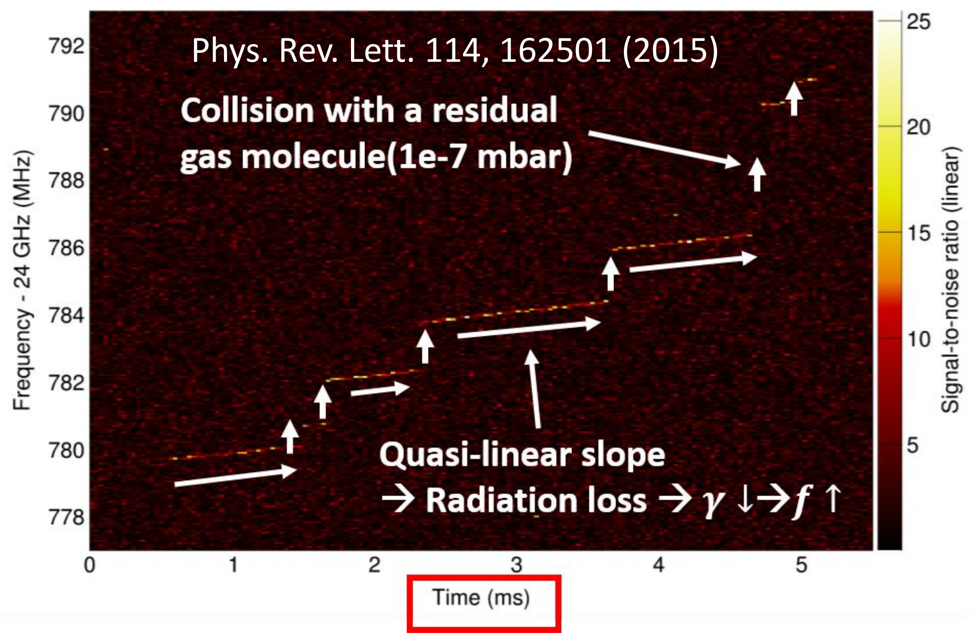


$$K \sim 18\ \text{keV} \ \rightarrow \gamma = \frac{m_e + K}{m_e} \sim 1.035$$

$$B \sim 1\ \text{T}$$

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

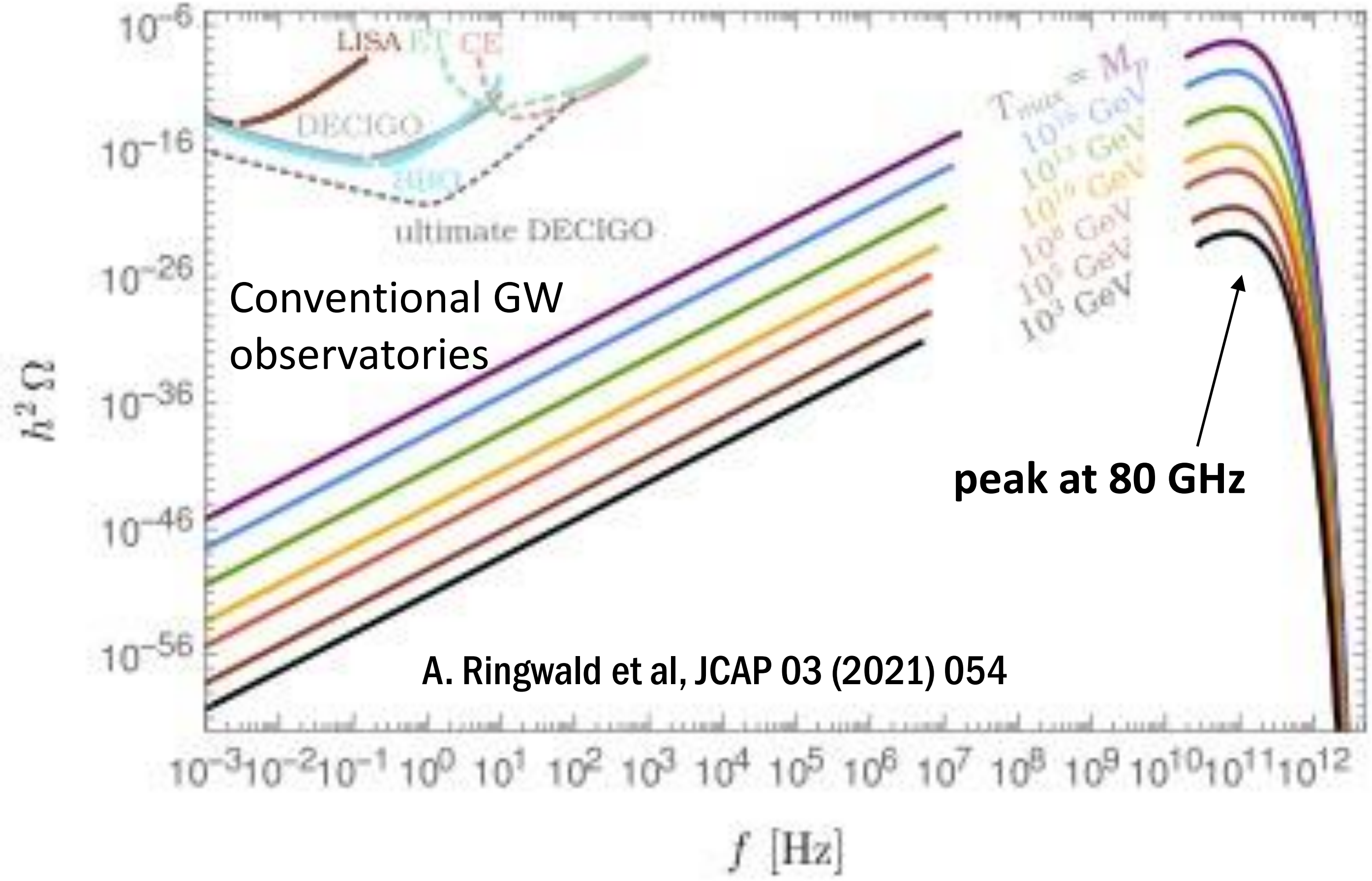




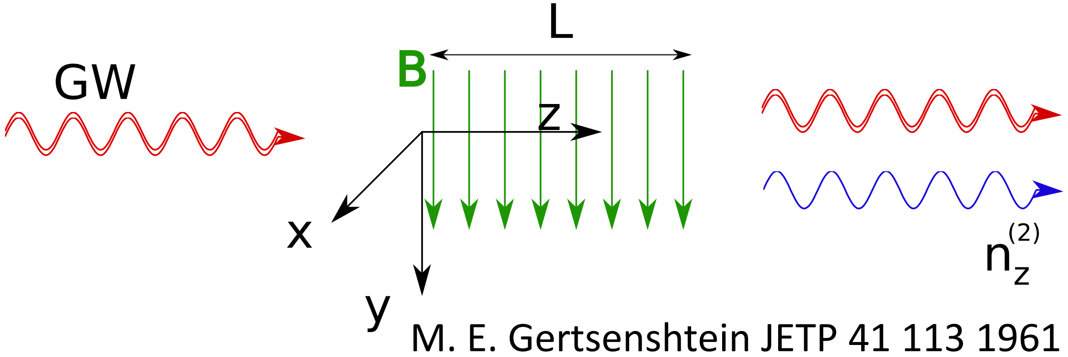
Coherent detection was already achieved to observe the background
→ Opportunities of single photon sensors?

Even further: Gravitational wave?

<u>Relic gravitational wave radiation from the Big Bang</u>



GW couples to photons of the same frequency under static magnetic field



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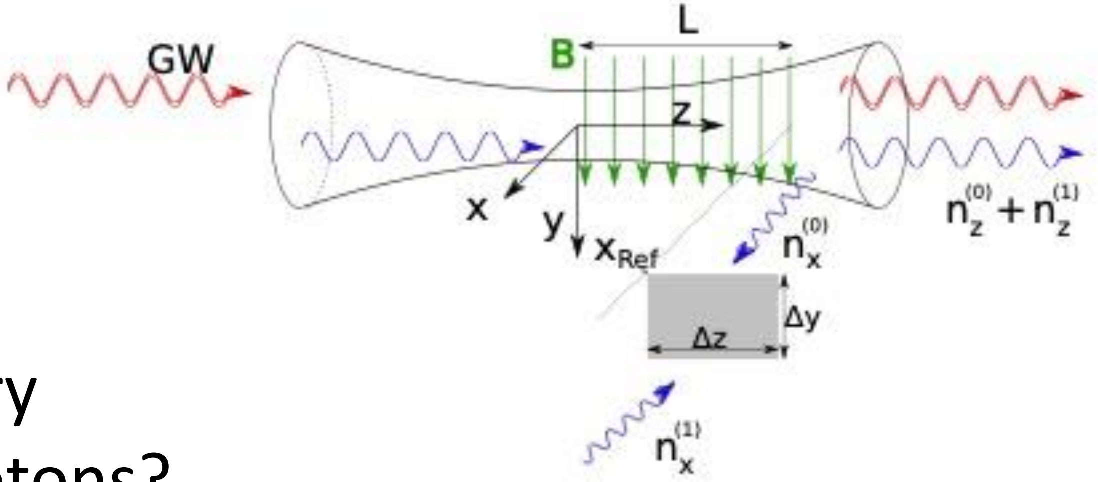
High-power 80GHz gaussian beam may enhance the signal level



- Wide-band tunability is probably necessary
- How to separate the pump and probe photons?

Outlook

- Introduction: axions and dark photons
- Photon detection and wave detection
- Dark matter axion search
- Light-Shining-Through-a-wall
- Potential of photon detection
- Conclusion

Conclusion

- Axions and dark photons are motivated both in particle physics and in cosmology as dark matter candidates
- Experimental searches of these particles are linked to photon science
- Electromagnetic wave detection and photon detection are in competition
- The wave detection scheme can benefit from the phase information
- The dark matter axion search is approaching to the standard quantum limit of the coherent detection scheme
- The very sensitive coherent detection is still appealing in LSW via the Lock-in amplifier method
- The coherent LSW around 30 GHz for dark photons is a good starting point
- Single photon detection is extremely important in the future for relatively incoherent phenomena