Flavour and
Dark matter
Workshop

Search for hidden-photon dark matter with FUNK
Status and perspectives

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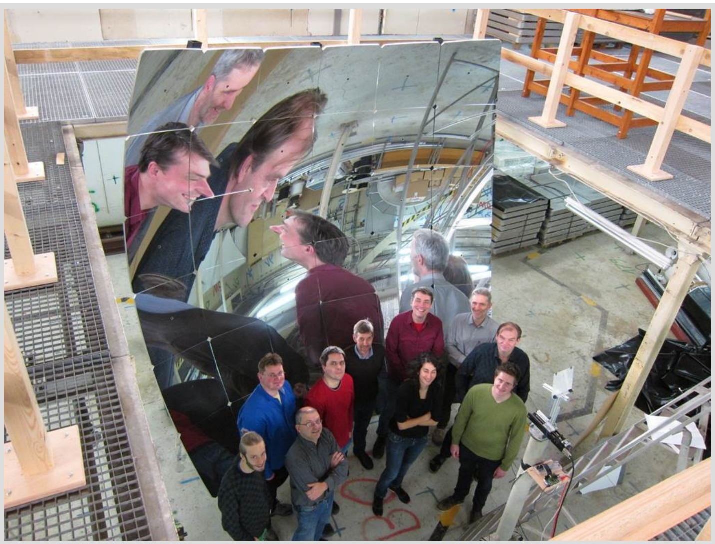
September 25th, 2018

INSTITUTE FOR NUCLEAR PHYSICS (IKP)



Hidden-photons (HP) in a nutshell

- A hidden, light U(1) in addition to the SM

$$-\mathcal{L}_{\text{eff}} \supset \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{m^2}{2} X_\mu X^\mu + \frac{\chi}{2} F_{\mu\nu} X^{\mu\nu}$$

- Modified Maxwell equations in vacuum

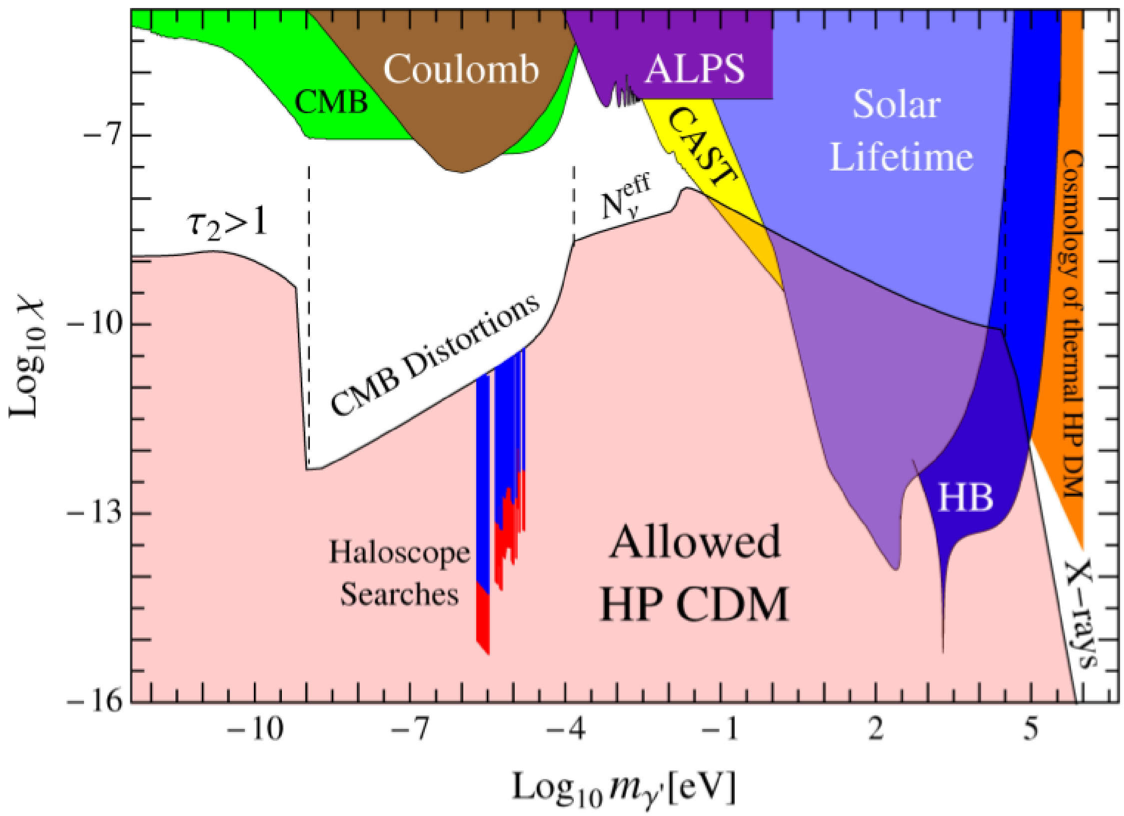
$$\nabla \cdot \mathbf{E} = \rho + \chi m^2 X^0 + \mathcal{O}(\chi^2)$$
$$\nabla \cdot \hat{\mathbf{E}} = -m^2 X^0 - \chi\rho + \mathcal{O}(\chi^2)$$

- Field solution in free-space

$$\begin{pmatrix} \mathbf{E} \\ \hat{\mathbf{E}} \end{pmatrix} = \mathbf{E}_m \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{i(\omega t - \mathbf{k}\cdot\mathbf{x})} + \hat{\mathbf{E}}_m \begin{pmatrix} -\chi \\ 1 \end{pmatrix} e^{i(\omega t - \mathbf{p}\cdot\mathbf{x})}$$

oscillating at $\nu \sim 240\,\mathrm{THz}\left(\frac{m}{\mathrm{eV}}\right)$

HP as cold dark matter



P. Arias et al., JCAP 06 (2012) 013 [arXiv:1201.5902]

Energy density $\rho_{\rm HP} = \frac{\langle|\mathbf{E}_{\rm DM}|^2\rangle}{2\chi^2} \equiv \rho_{\rm CDM} \sim 0.3\,\mathrm{GeV/cm^3}$

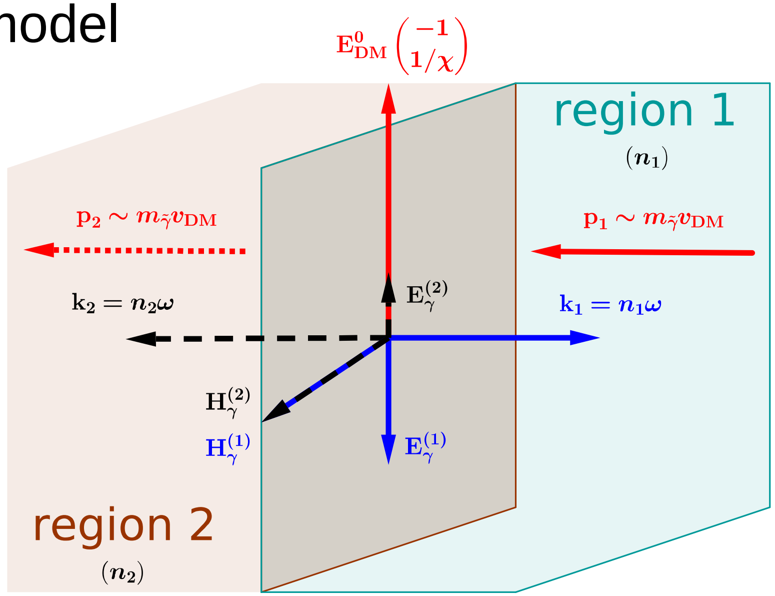
Visible DM field $\sqrt{\langle|\mathbf{E}_{\rm DM}|^2\rangle} \equiv \chi\sqrt{\langle|\hat{\mathbf{E}}_m|^2\rangle} \sim 10^{-9}\,\frac{\rm V}{\rm m}\left(\frac{\chi}{10^{-12}}\right)\left(\frac{\rho_{\rm CDM}}{0.3\,\mathrm{GeV/cm^3}}\right)$

- Field solution in matter

$$\begin{pmatrix}\mathbf{E}\\ \hat{\mathbf{E}}\end{pmatrix} = \mathbf{E}_\gamma \begin{pmatrix}1\\ \chi_{\text{eff}}-\chi\end{pmatrix} e^{i(\omega t-\mathbf{k}\cdot\mathbf{x})} + \mathbf{E}_{\text{DM}} \begin{pmatrix}-1\\ 1/\chi_{\text{eff}}\end{pmatrix} e^{i(mt-\mathbf{p}\cdot\mathbf{x})}$$

$$\chi_{\text{eff}} = \chi\frac{m^2}{m^2+(n^2-1)\omega^2}$$

- Toy model



- ➔ Continuity of the parallel components
- ➔ Outgoing ordinary electric field

$$E^{(1)}_{\gamma,||} = \frac{\chi_1-\chi_2}{\chi_1}\frac{n_2}{n_1+n_2}E^0_{\text{DM},||}$$

HP propagating across two different media

- Emission of an oscillating ($\omega \approx m$) ordinary electric field at the interface

$$E^{(1)}_{\gamma,||} = \frac{\chi_1 - \chi_2}{\chi_1} \frac{n_2}{n_1 + n_2} E^{0}_{\mathrm{DM},||}$$

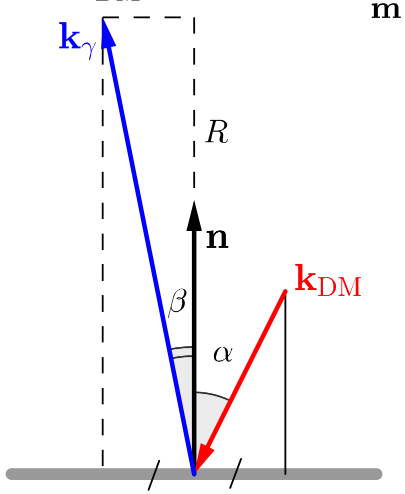
$\propto \chi \sqrt{\rho_{\mathrm{CDM}}}$ (in average)

$\frac{1}{n_1^2} - \frac{1}{n_2^2} \implies$ ***want a good reflector***

- Directionality

$$\delta x \approx v_{\mathrm{DM}} R \sin\alpha \sim \mathrm{mm}\, \frac{R}{\mathrm{m}}$$

$\implies$ ***signal is focused***



- In Power

$$\overline{\mathcal{P}} \sim 10^{-19}\,\mathrm{W} \left(\frac{\chi}{10^{-12}}\right)^2 \left(\frac{\mathcal{A}_{\mathrm{eff}}}{1\,\mathrm{m}^2}\right) \xi_{\mathrm{CDM}}$$

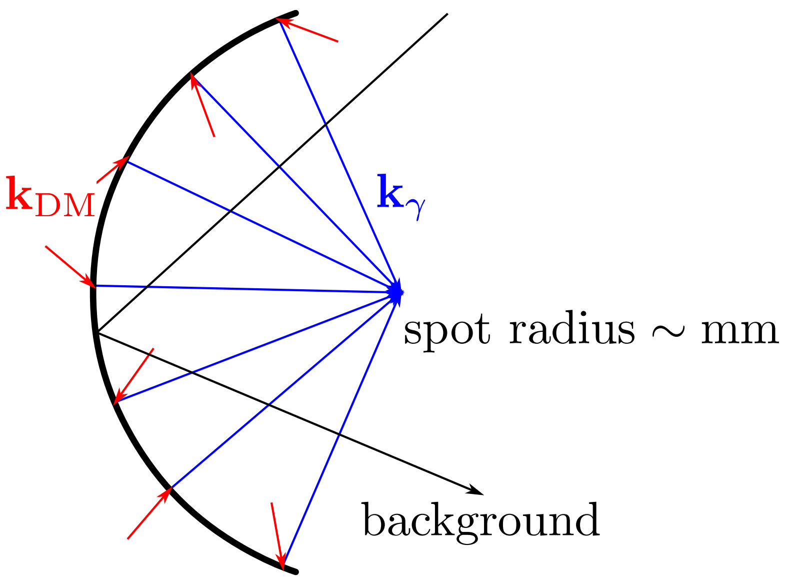
want a large area *(and need to be able to neglect diffraction)*

The idea: A dish antenna

D. Horns et al., JCAP 1304, 016 (2013) [arXiv:1212.2970]

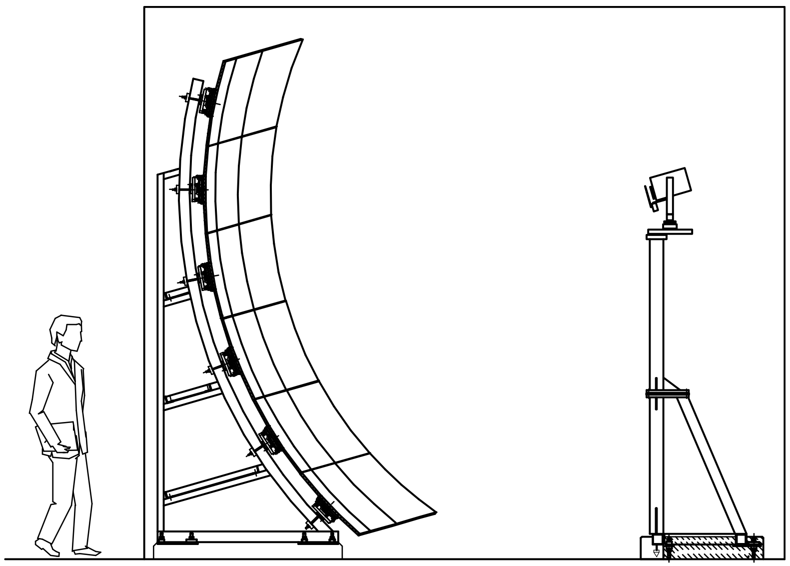
Karlsruhe Institute of Technology

Geometrical amplification



C. Schäfer, Bachelor thesis

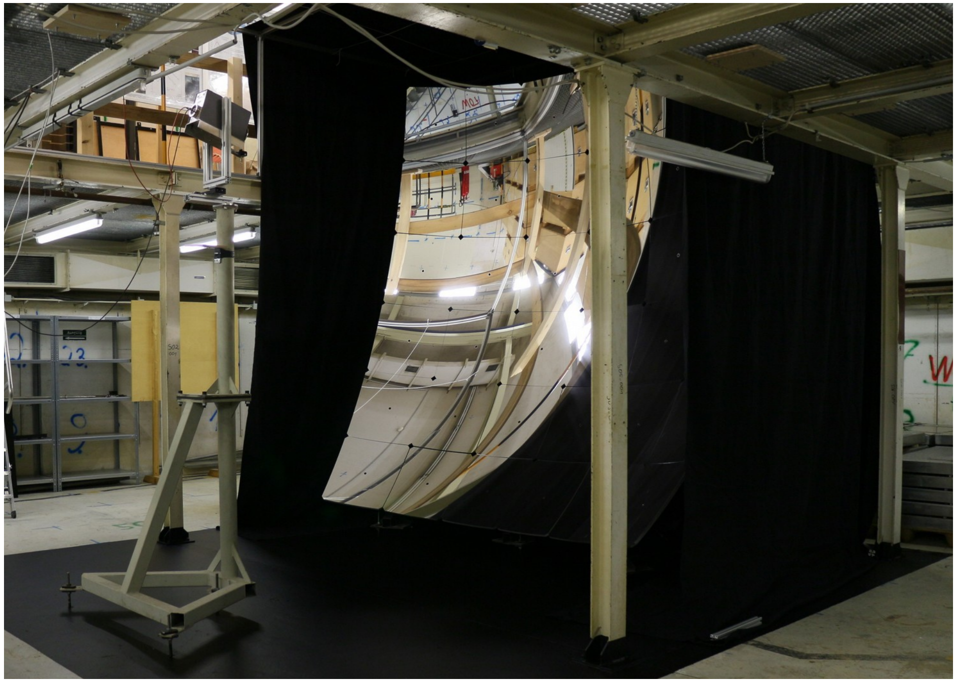
Design

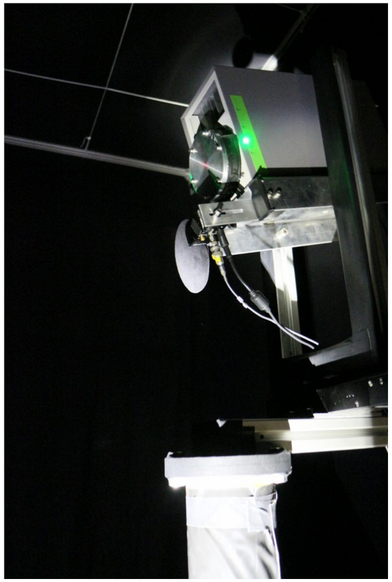


Prototype mirror of Auger Fluorescence telescope

- 6x6 aluminum mirror matrix
- Total area $\sim 15\,\mathrm{m}^2$
- Radius $\sim 3.4\,\mathrm{m}$
- Reflectivity $\in (0.7, 0.8)$
- PSF spot radius $\sim 2\,\mathrm{mm}$

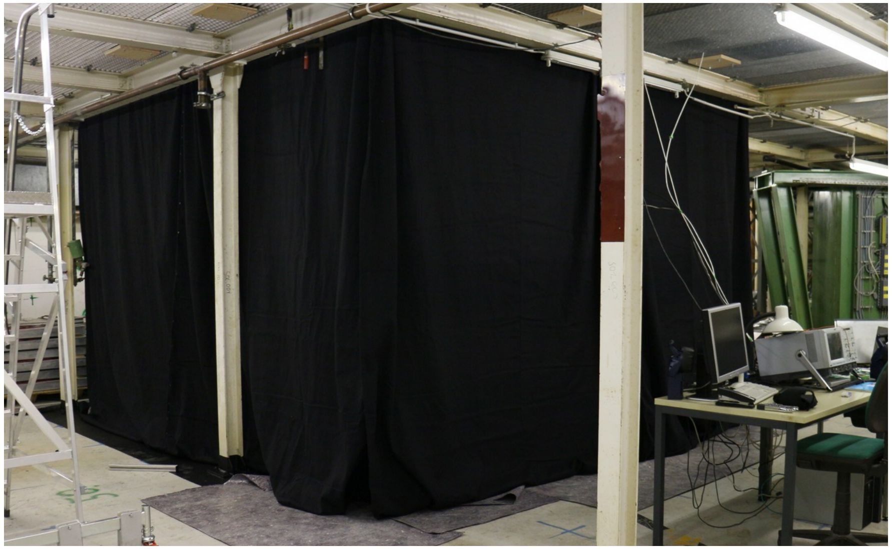
FUNK: Finding U(1)s of Novel Kind





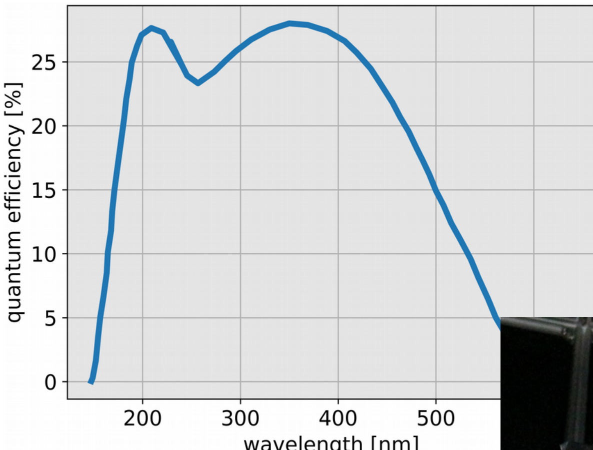
Sensor:
- Test phase: CCD camera
- Current phase: low noise PMT (covering far-UV to visible)

Location: IKP B425, KIT Campus Nord
- Windowless experimental hall with $\sim 2\,\mathrm{m}$ thick walls
- Floor painted black
- Additional black curtain + polyethylene foil around the setup

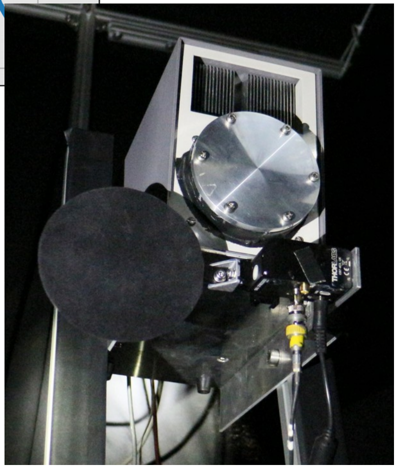


Search in the optical range

Sensor



- Model 9107QB (low noise)
- Spectral coverage (160, 630) nm
- Active diameter 25 mm



Data acquisition

- Model PS 6000 series
- ADC resolution 8 bits
- Sampling period 0.8 ns

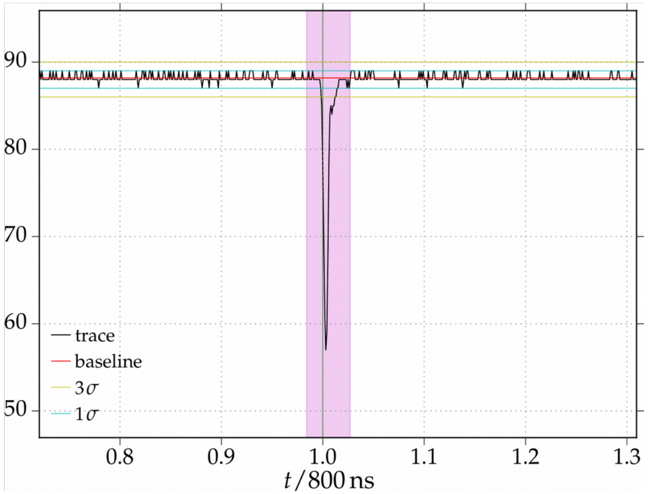
Computer

Save:

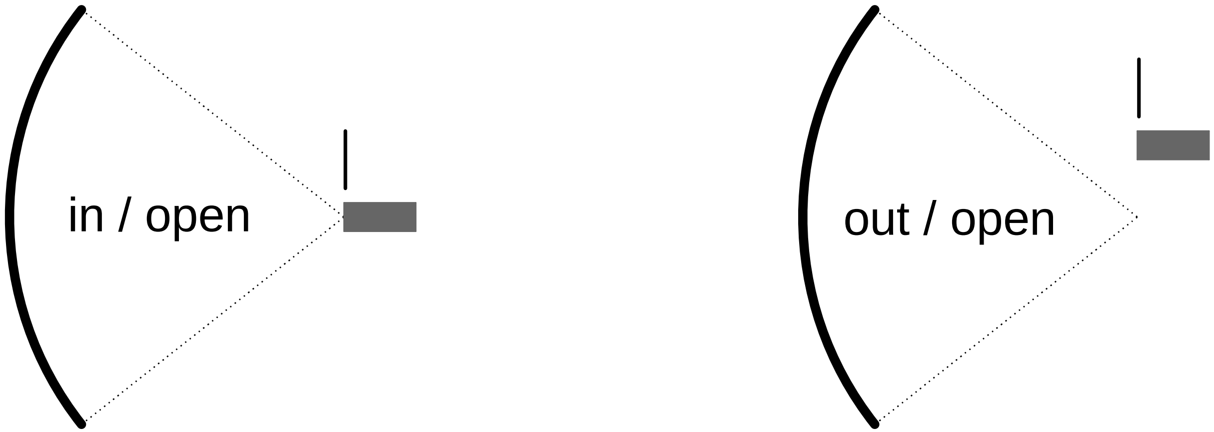
- Trace of 1600 ns (1000 bins before and after trigger)
- Environmental data (T, p)
- Configurations

In parallel:

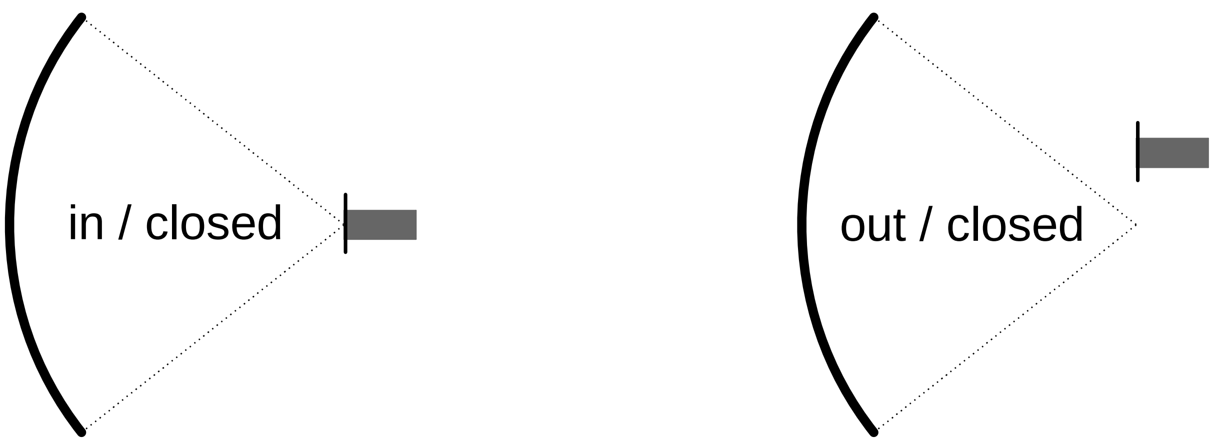
- Muon monitoring



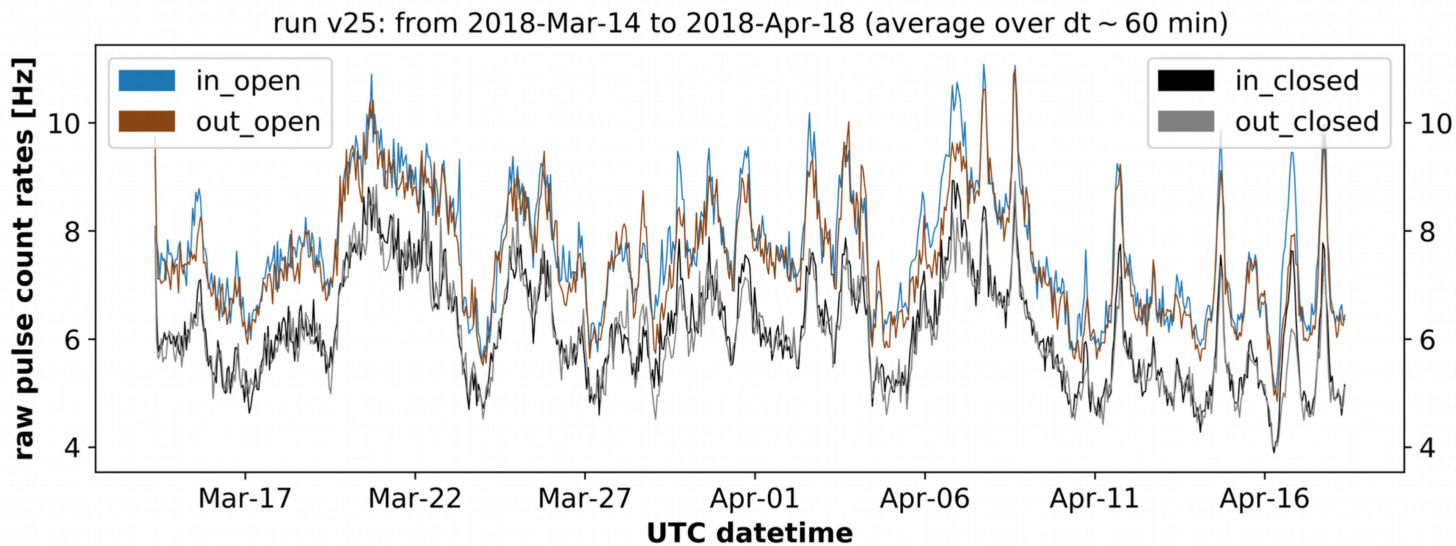
Measurement scheme

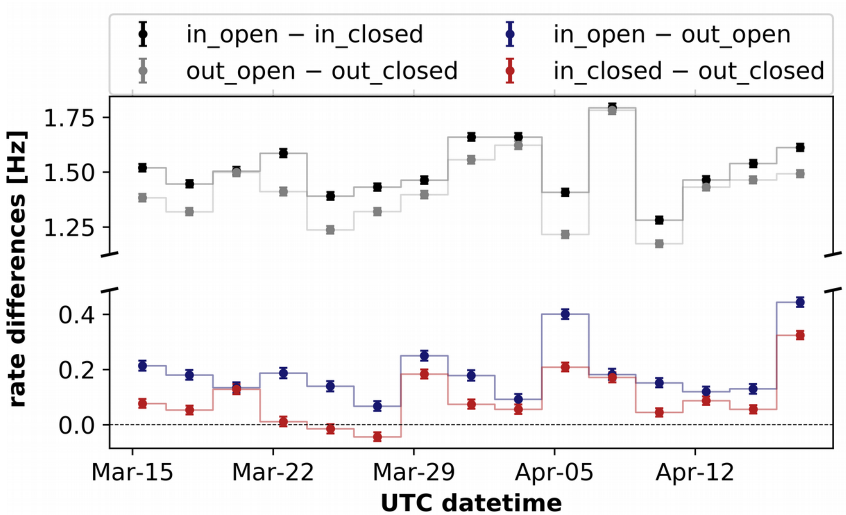


60 sec at each configuration (~4.4 min per cycle)



FUNK run (raw data)





$$\left[\frac{\text{in open} - \text{in closed}}{\text{in closed}}\right] \sim 24.6\,\% \qquad \left[\frac{\text{out open} - \text{out closed}}{\text{out closed}}\right] \sim 23.4\,\%$$

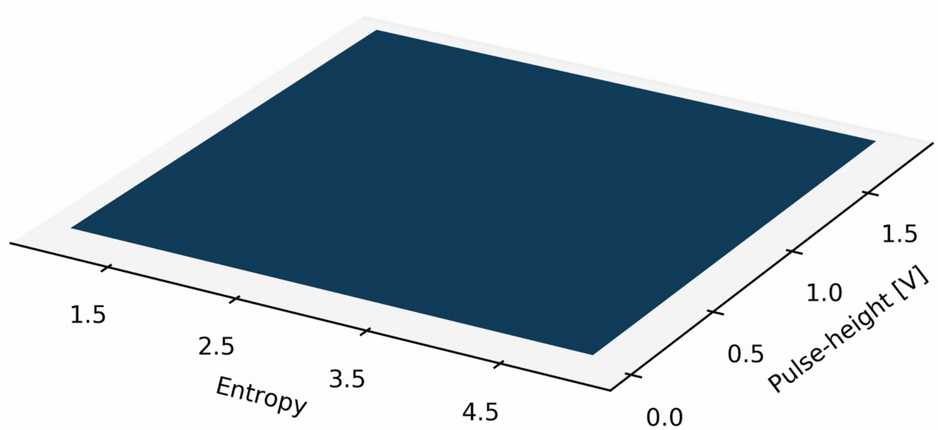
$$\left[\frac{\text{in open} - \text{out open}}{\text{in open}}\right] \sim 2.5\,\% \qquad \left[\frac{\text{in closed} - \text{out closed}}{\text{out closed}}\right] \sim 1.5\,\%$$

The differences ***in / out*** for the two statuses ***open / closed*** are compatible.

Flasher run

- Measure SPE response:

  Fire a faint led (blue) → external trigger → capture trace of 1600 ns



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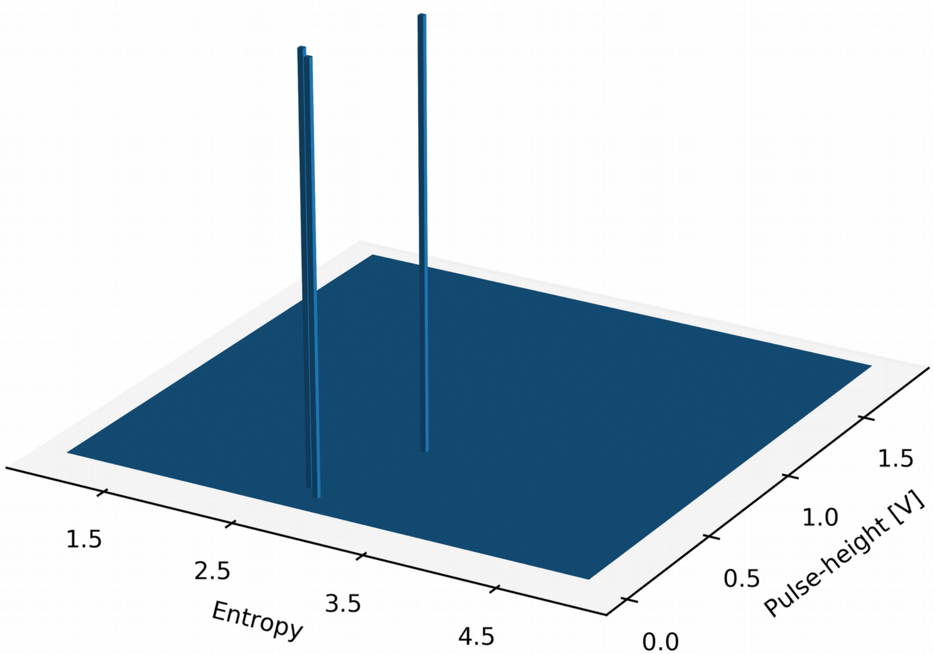

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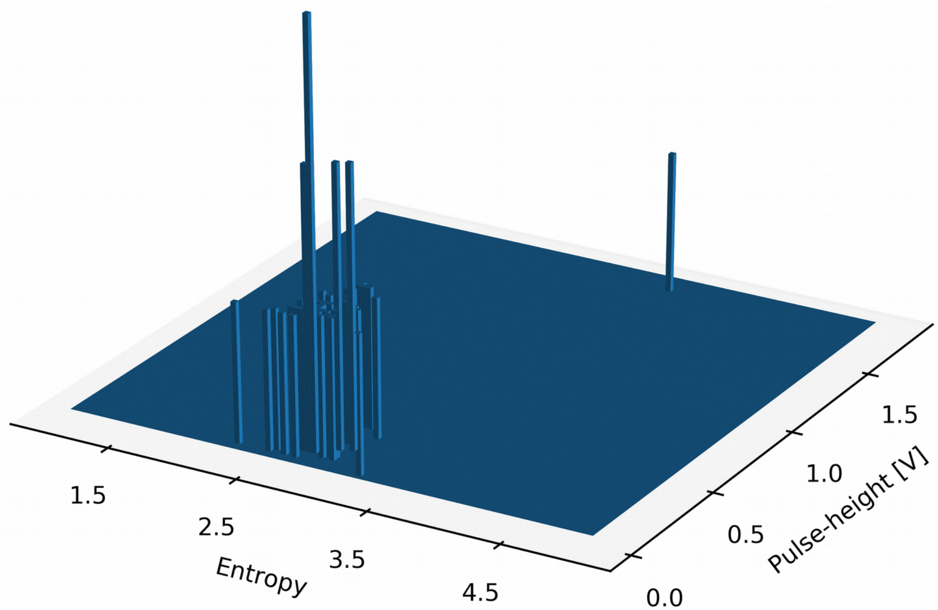

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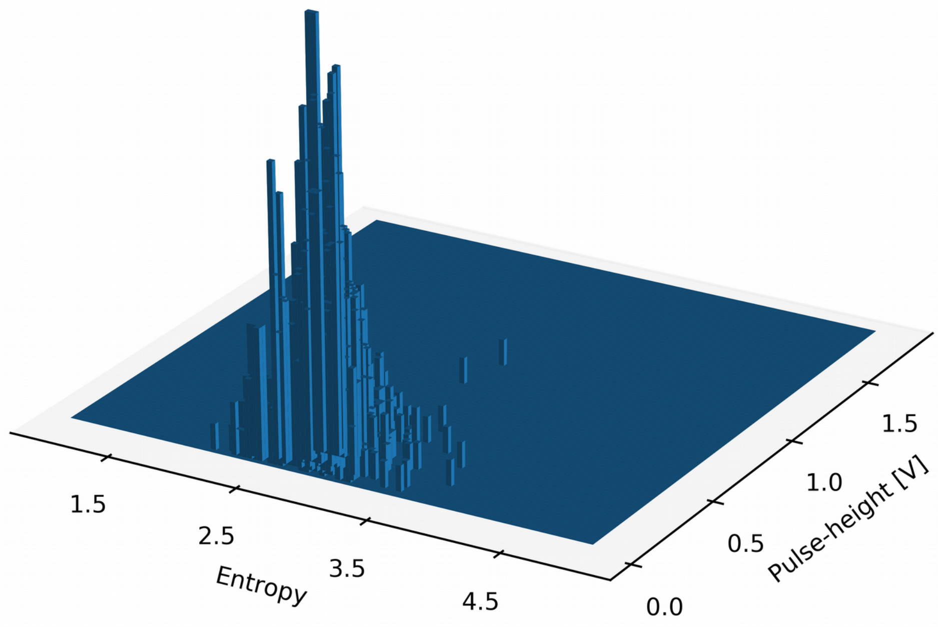

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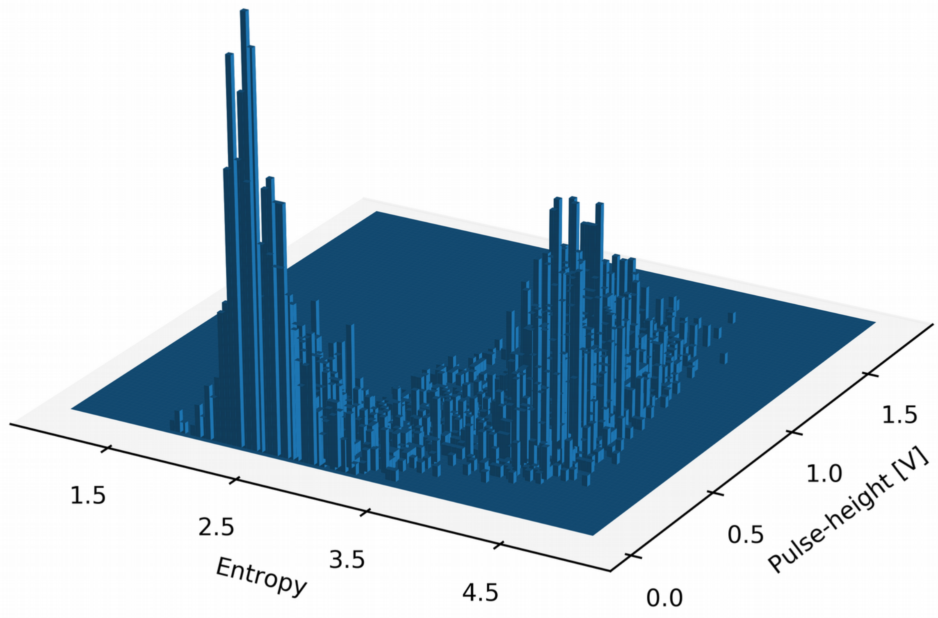
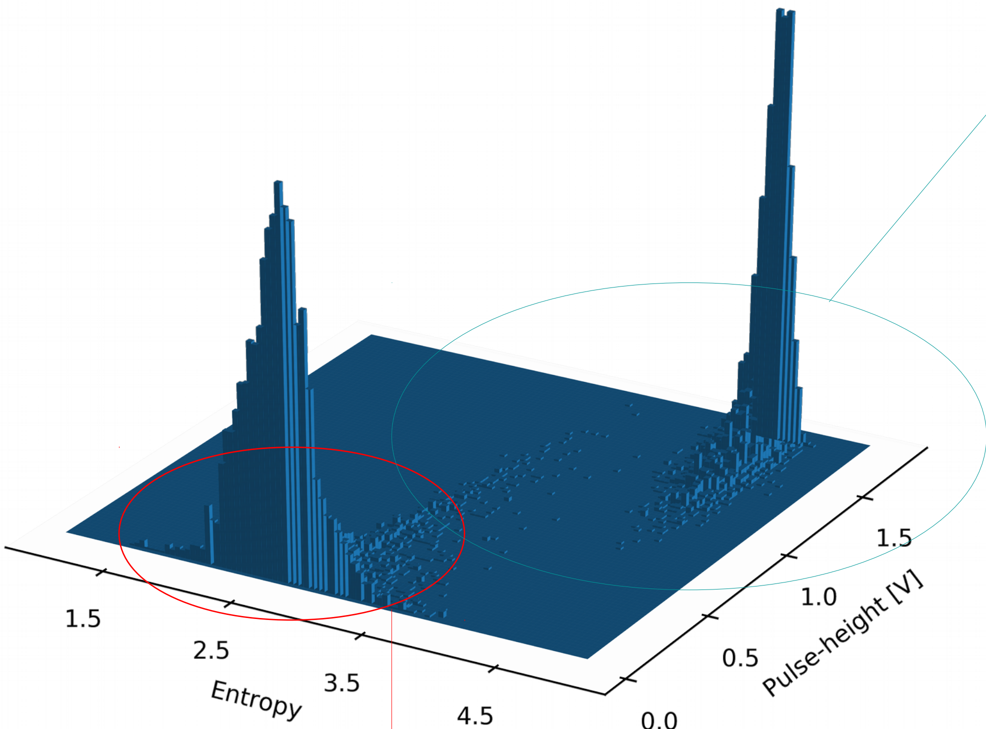
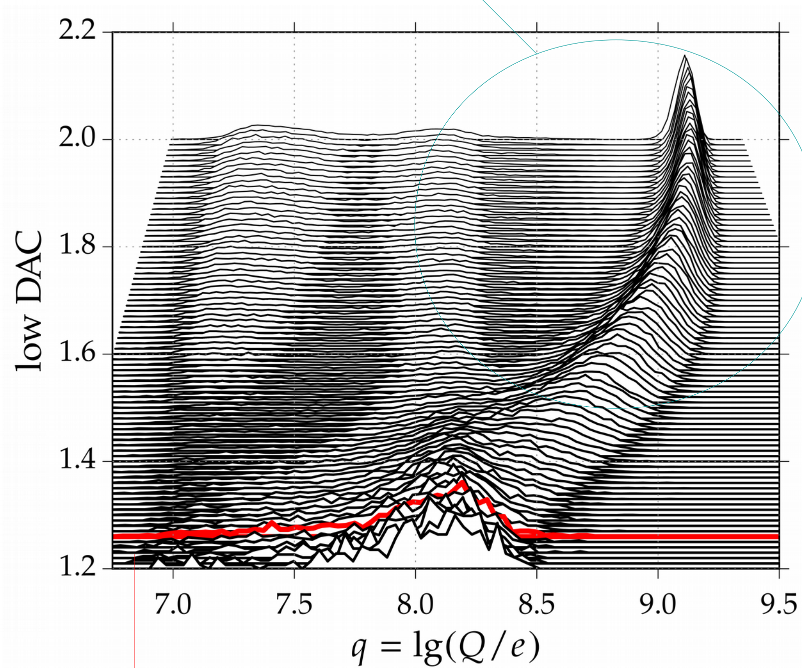


Flasher run





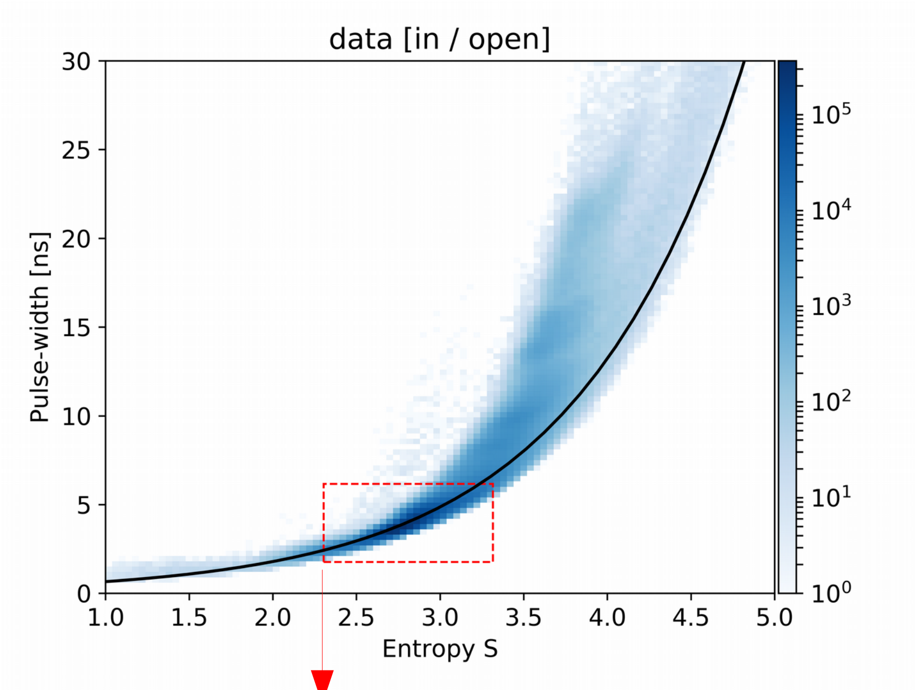
multiple hits

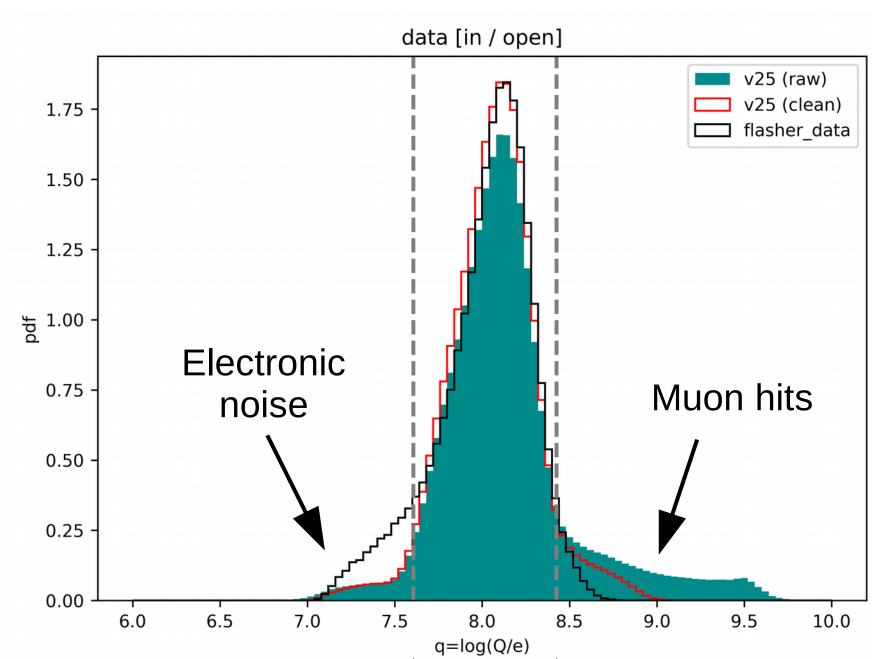
SPE events

Optimal setting for the spe calibration

- PMT sees SPE ~ 20% of the time
- Capture single pulse per trace ~ 95 % of the time
- Photon arrival time ~ 290 ns

FUNK data





1.5σ around the PMT gain for SPE

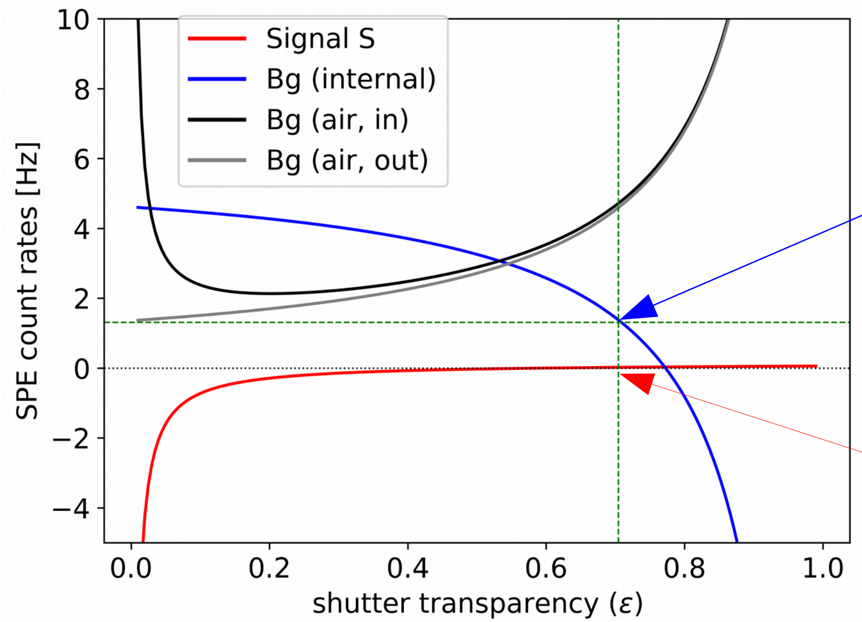
Region of interest

- selection on the pulse-entropy, -width, and -rise-time
- contains ~ 90 % of triggers

FUNK status (preliminary)

- Possible signal extracted by modeling the four measurement configurations

$$\Phi_{\text{in/open}} = S + B_{\text{int}} + B_{\text{air/in}}$$
$$\Phi_{\text{in/closed}} = B_{\text{int}} + \epsilon B_{\text{air/in}}$$
$$\Phi_{\text{out/open}} = B_{\text{int}} + B_{\text{air/out}}$$
$$\Phi_{\text{out/closed}} = B_{\text{int}} + \epsilon B_{\text{air/out}}$$

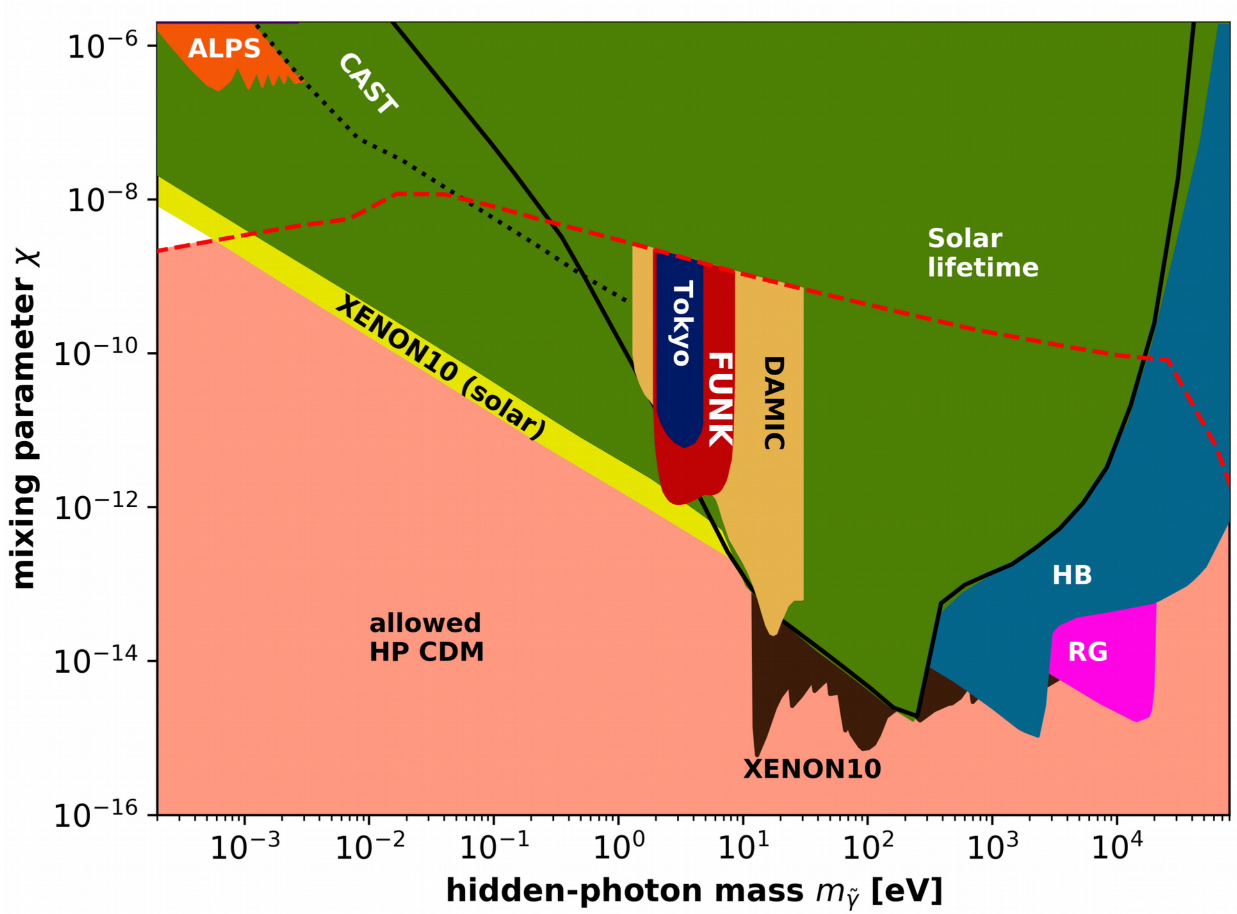


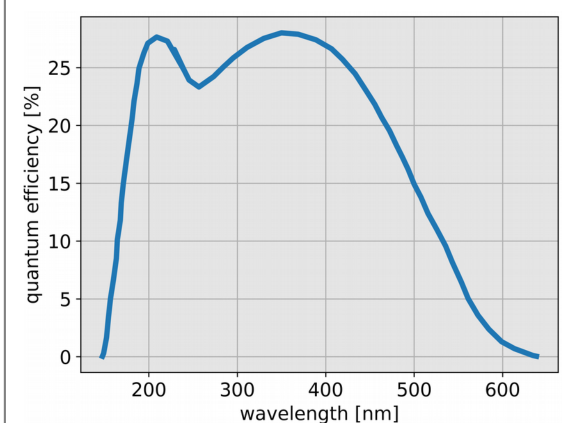
level of the internal background

$$S = (0.0231 \pm 0.0260)\text{Hz}$$

FUNK status (preliminary)

$$\chi = 4.1 \times 10^{-12} \left(\frac{\Phi_{\gamma,\mathrm{det}}}{\mathrm{Hz}} \frac{m}{\mathrm{eV}} \right)^{\frac{1}{2}} \left(\frac{1}{\eta(m)} \right)^{\frac{1}{2}} \left(\frac{1\,\mathrm{m}^2}{\mathcal{A}_{\mathrm{eff}}} \right)^{\frac{1}{2}} \left(\frac{0.3\,\mathrm{GeV/cm}^3}{\rho_{\mathrm{CDM}}} \right)^{\frac{1}{2}} \left(\frac{2/3}{\langle \cos^2 \alpha \rangle} \right)^{\frac{1}{2}}$$



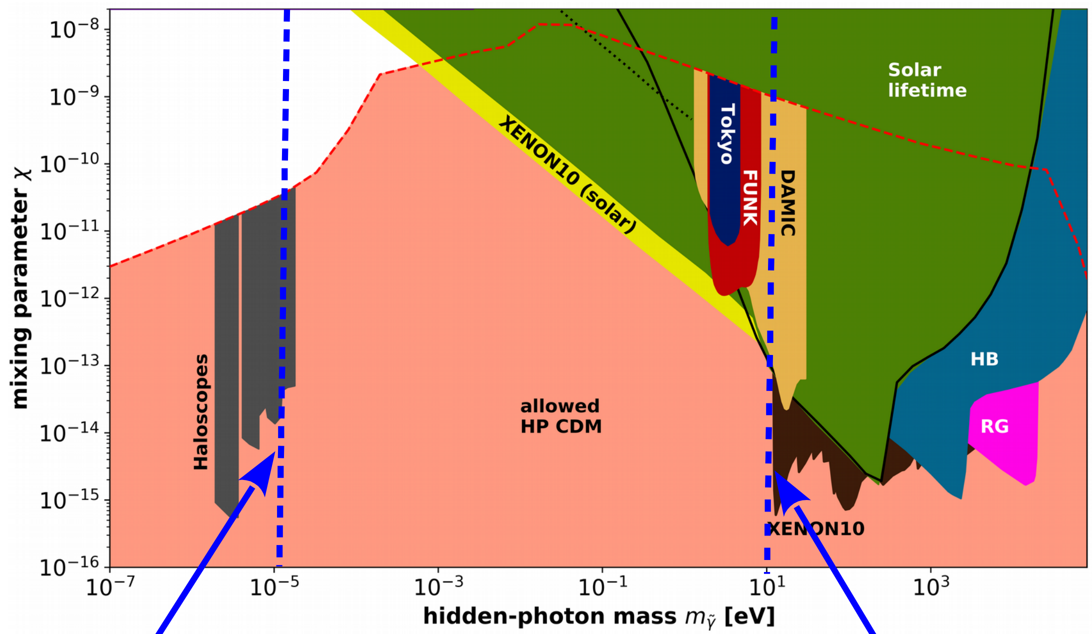


$$1.9 \lesssim m/\mathrm{eV} \lesssim 7.8$$

$$\chi < 1.12 \times 10^{-12}$$
at $99.7\,\%$CL

So what else… FUNK++

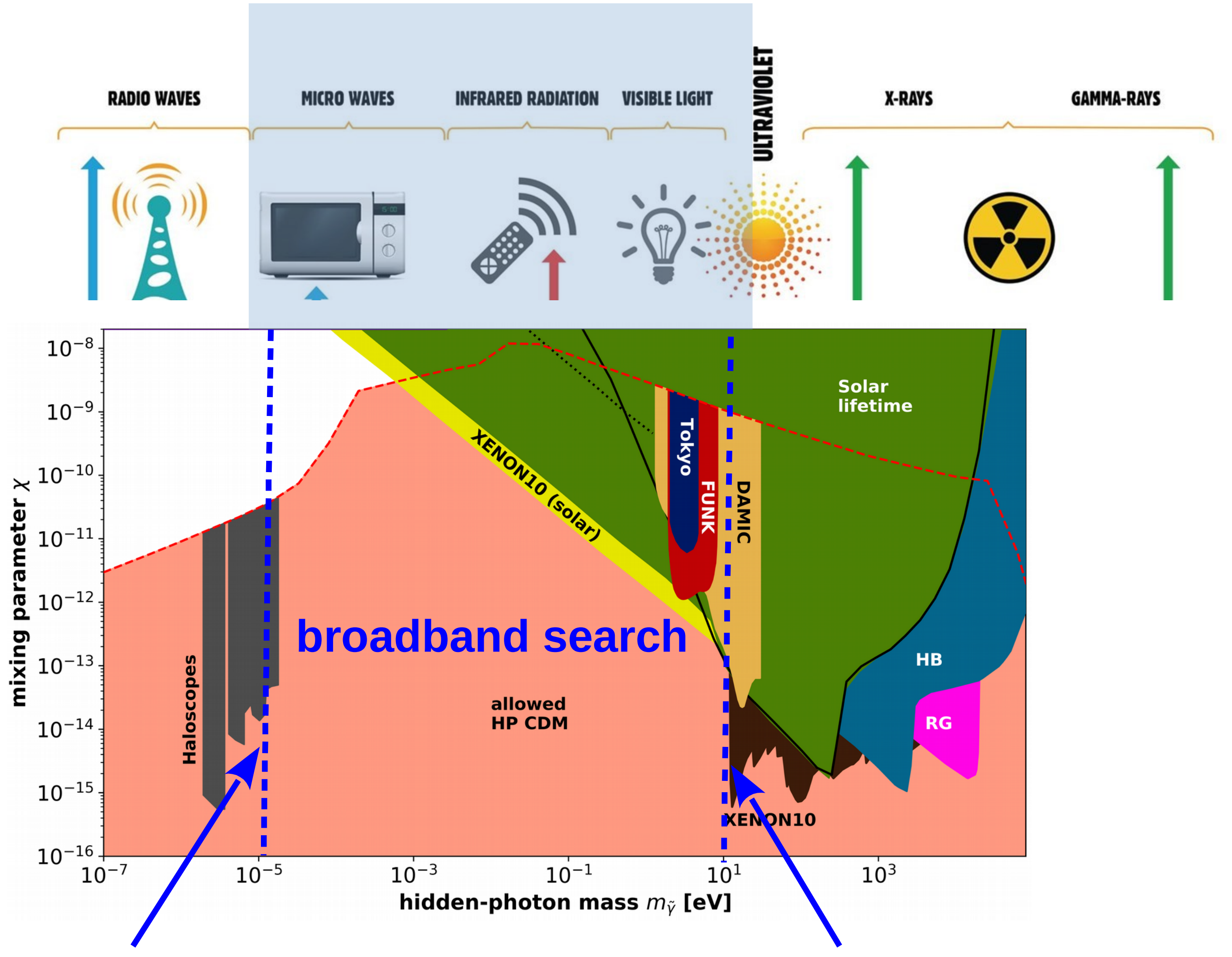
- Recall $\frac{\chi}{10^{-12}} \sim \left(\frac{\overline{\mathcal{P}}}{10^{-19}\,\mathrm{W}} \frac{1\,\mathrm{m}^2}{\mathcal{A}_{\mathrm{eff}}} \right)^{1/2}$
- Expect a narrow peak $\Delta\nu_{\mathrm{FWHM}} \sim 280\,\mathrm{kHz} \left(\frac{m}{\mathrm{meV}} \right)$



Diffraction-limited in the radio

Poor reflection in the UV

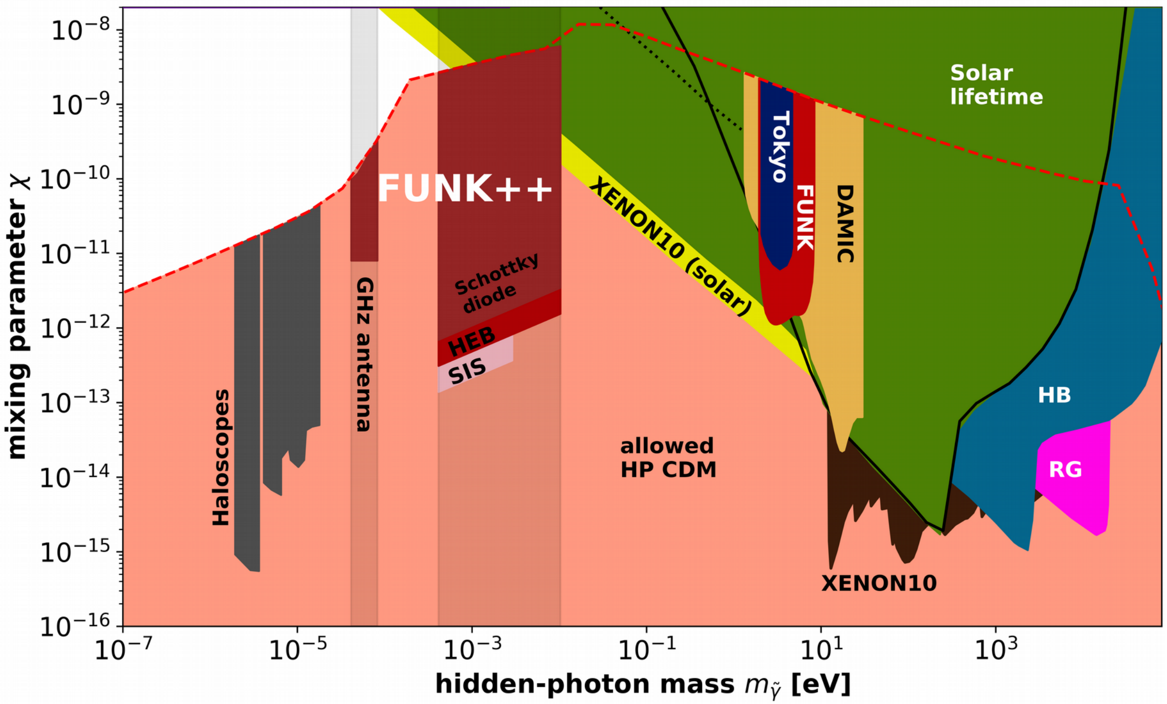
So what else… FUNK++



Diffraction-limited in the radio

Poor reflection in the UV

Receiver-driven sensitivity



GHz (commercial) antenna

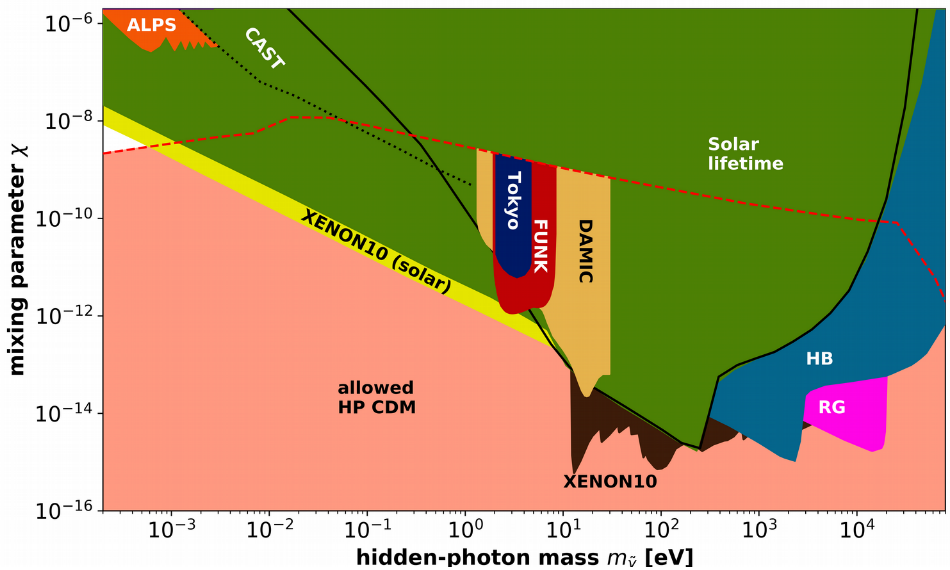
- Coverage $(10-20)\,\mathrm{GHz}$
- Broad scan
- $T_{\mathrm{rec}} = 300\,\mathrm{K},\ \Delta t = 30\,\mathrm{h}$

THz receiver

- Different front-end mixers
- Coverage $(0.1-2.5)\,\mathrm{THz}$
- Bandwidth $\Delta\nu = 90\,\mathrm{KHz/ch}$
- $T_{\mathrm{rec}} \propto h\nu/k_B,\ \Delta t = 3\,\mathrm{h}$

Summary

- HP are viable CDM candidate
  - Hidden $\chi \lesssim 10^{-8}$
  - Slim $m \lesssim 10^{6}\,\mathrm{MeV}$
- DM field $\begin{pmatrix}\mathbf{A}\\ \mathbf{X}\end{pmatrix}_{\mathrm{DM}} = \begin{pmatrix}\text{tiny} \propto \chi \\ \text{mostly hidden}\end{pmatrix}$
  - Dish antenna technique
  - Resonant cavity, Helioscope ...



- The FUNK experiment motivates the search of WISPy DM
  - Broadband search / High sensitivity
  - Cover a huge region of the HP parameter space with the same setup

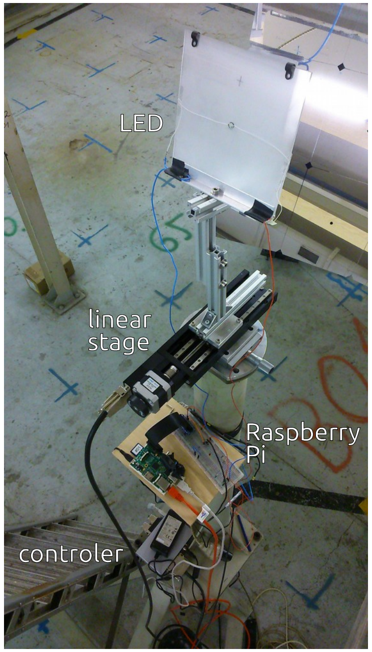
$$\text{few GHz} \lesssim m \lesssim \text{few PHz}$$

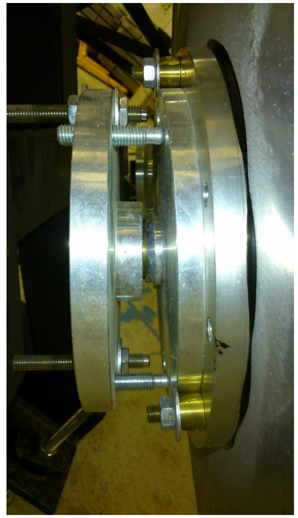
  - Could also obtain information on the DM velocity distribution

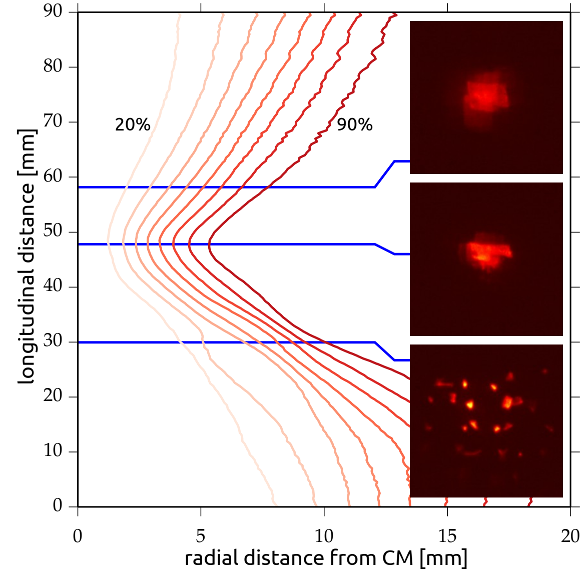
THANK YOU FOR YOUR ATTENTION

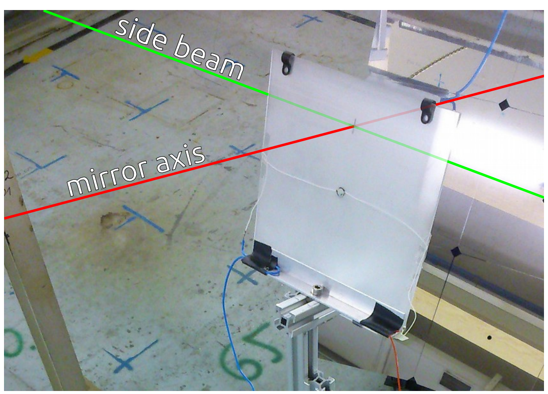
BACK-UP

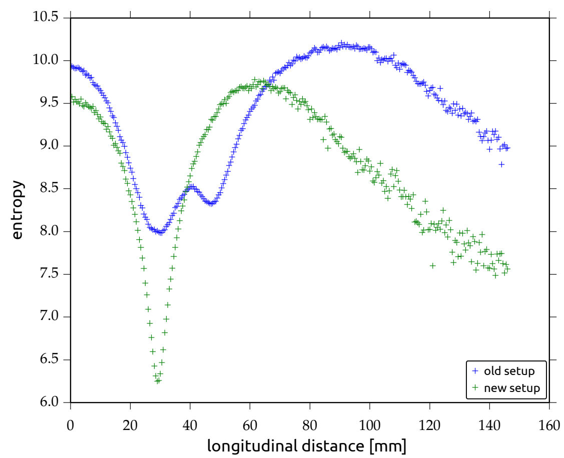
Alignment of the mirror segments

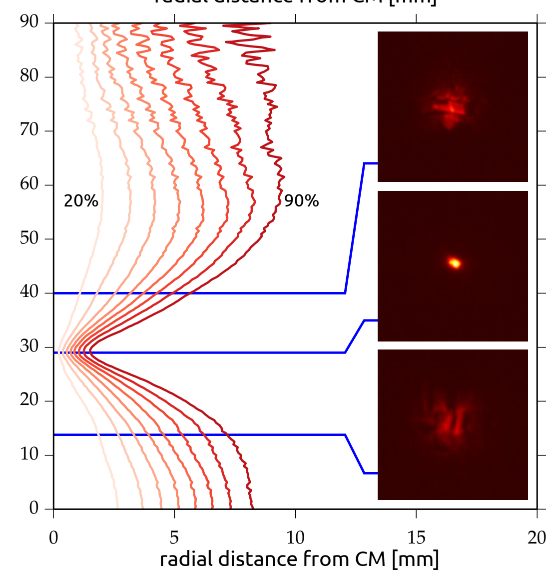












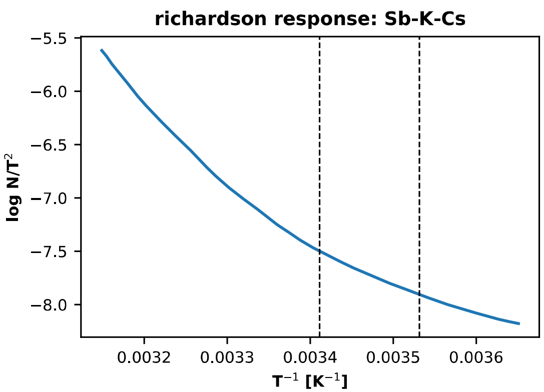
FUNK runs

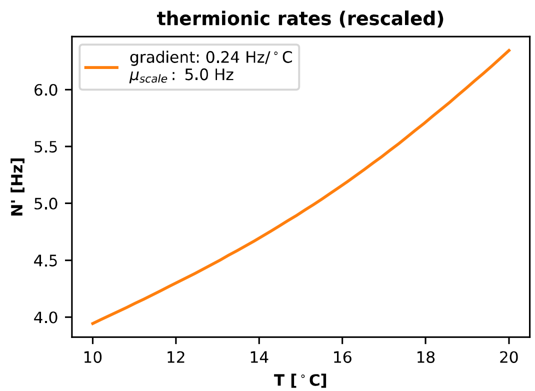
funk runs
in_open
out_open
in_closed
out_closed
pmt count rates [Hz]
v23
v24
v25
T1
T2
p
temperatures [°C]
pressures [hPa]
T200m
vert. coinc.
muon rates [Hz]
Feb-08
Feb-15
Feb-22
Mar-01
Mar-08
Mar-15
Mar-22
Mar-29
Apr-05
Apr-12
Apr-19
UTC time

Bg1: Thermal background

- Thermionic emission from the PMT photocathode (and dynodes)

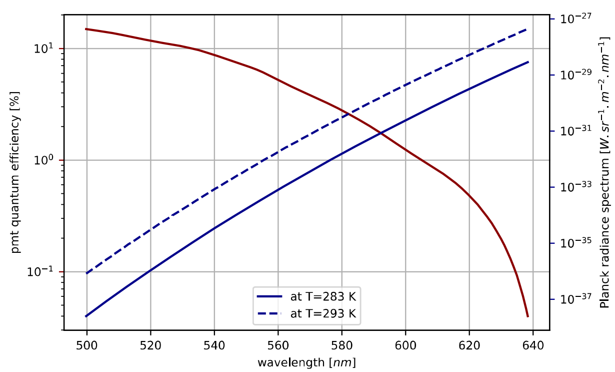
$$N = AT^2 \exp\left(-\phi_E/kT\right)$$





$$\frac{\sigma_{N'}}{\mu_{N'}} = 0.048\left(\frac{\sigma_T}{\mathrm{deg}}\right) \lesssim 1\,\%$$

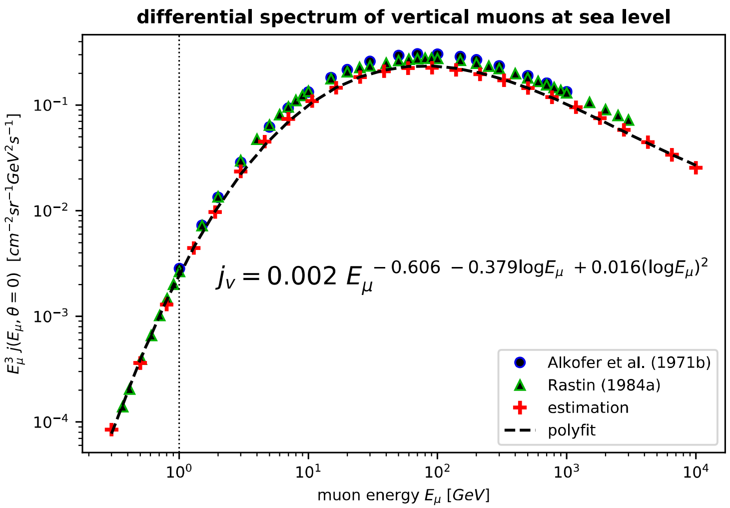
- Thermal emission from the surrounding

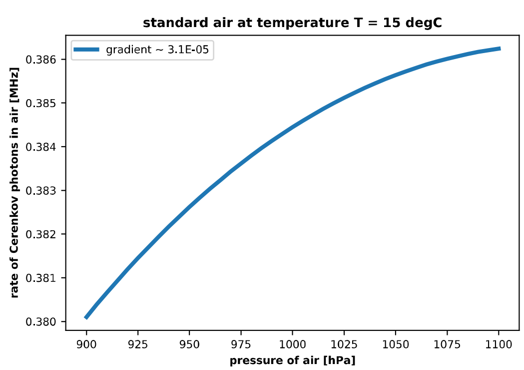


$$\Phi_\gamma = \frac{A\Omega}{\overline{E}_\gamma}\int_{\Delta\lambda} d\lambda\;\epsilon(\lambda)\mathrm{Planck}(\lambda) \sim 2.4\times10^{-7}\,\mathrm{Hz}\quad(\mathrm{at}\ 20\,\mathrm{deg})$$

Bg2: Cherenkov photons from muons

- Muon direct hits → handled in event selection
- Photons in air





$$\frac{dE_\mu}{ds} \approx 2\,\mathrm{MeV}/(\mathrm{g}/\mathrm{cm}^2)$$

$$\Longrightarrow E_\mu \gtrsim 1\,\mathrm{GeV} \text{ for } 2\,\mathrm{m} \text{ of concrete}$$

$$\Phi_\mu \sim 1.4\,\mathrm{KHz} \text{ (entering the enclosing area)}$$

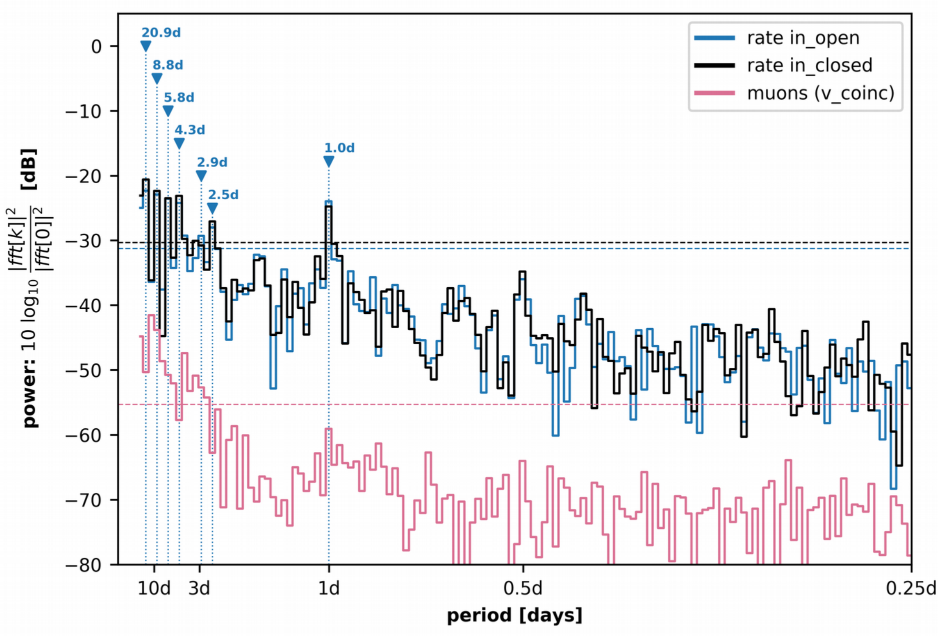
$$\Phi_{\mathrm{ch}.\gamma} \sim 90\,\mathrm{photons}/\mathrm{m}/\mathrm{muon} \sim 3000\,\mathrm{Hz}/\mathrm{m}^3$$

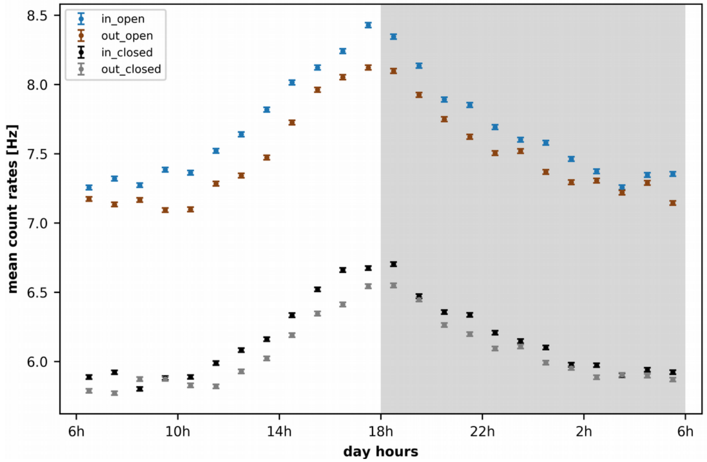
$$\text{for } \lambda \in (150, 640)\,\mathrm{nm}$$

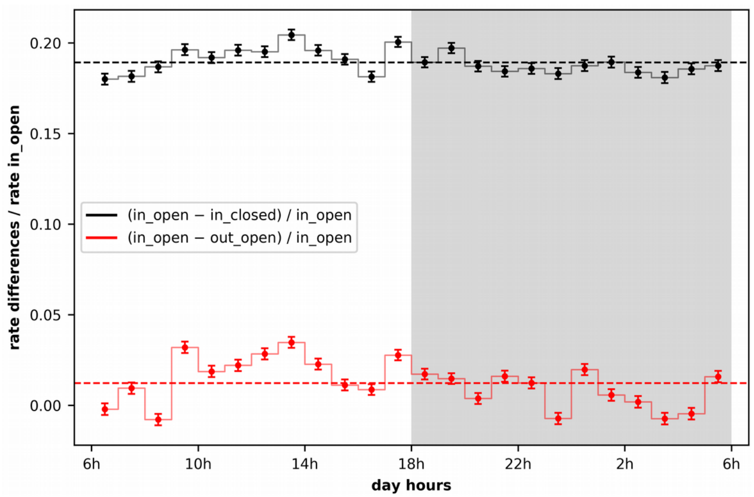
$$\frac{\sigma_{\mathrm{ch}.\gamma}}{\overline{\Phi}_{\mathrm{ch}.\gamma}} = \frac{\sigma_\mu}{\overline{\Phi}_\mu} \lesssim 3\,\%$$

$$\delta \sim 0.03\,\mathrm{mHz}/\mathrm{hPa}$$

(Apparent) daily modulation







THz detection technique

- About a single photon $\nu = 1\,\mathrm{THz} \rightsquigarrow E \sim 600\,\mathrm{fW/GHz} \rightsquigarrow T \sim 48\,\mathrm{K}$
- Power radiometer

$$\sigma_{\overline{T}_{\mathrm{in}}} = \frac{k_{\mathrm{rec}} T_{\mathrm{sys}}}{\sqrt{\tau \Delta\nu}} \Longrightarrow \mathrm{SNR} = \frac{T_{\mathrm{sig}}}{\sigma_{\overline{T}_{\mathrm{in}}}} \propto \sqrt{\Delta t \Delta \nu}$$

$$T_{\mathrm{sys}} = T_a + T_{\mathrm{rec}} = T_a + l_1 T_1 + \frac{l_2 T_2}{G_1} + \frac{l_3 T_3}{G_1 G_2} + \cdots$$

- Heterodyne detection