Search for dark photons as candidates for Dark Matter with FUNK

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Hidden photons as Dark Matter particles (i)

Hidden photon

kinetic mixing, coupling

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

mass term

U(1) is simplest extension of SM, predicted by many theories

WISPy cold dark matter

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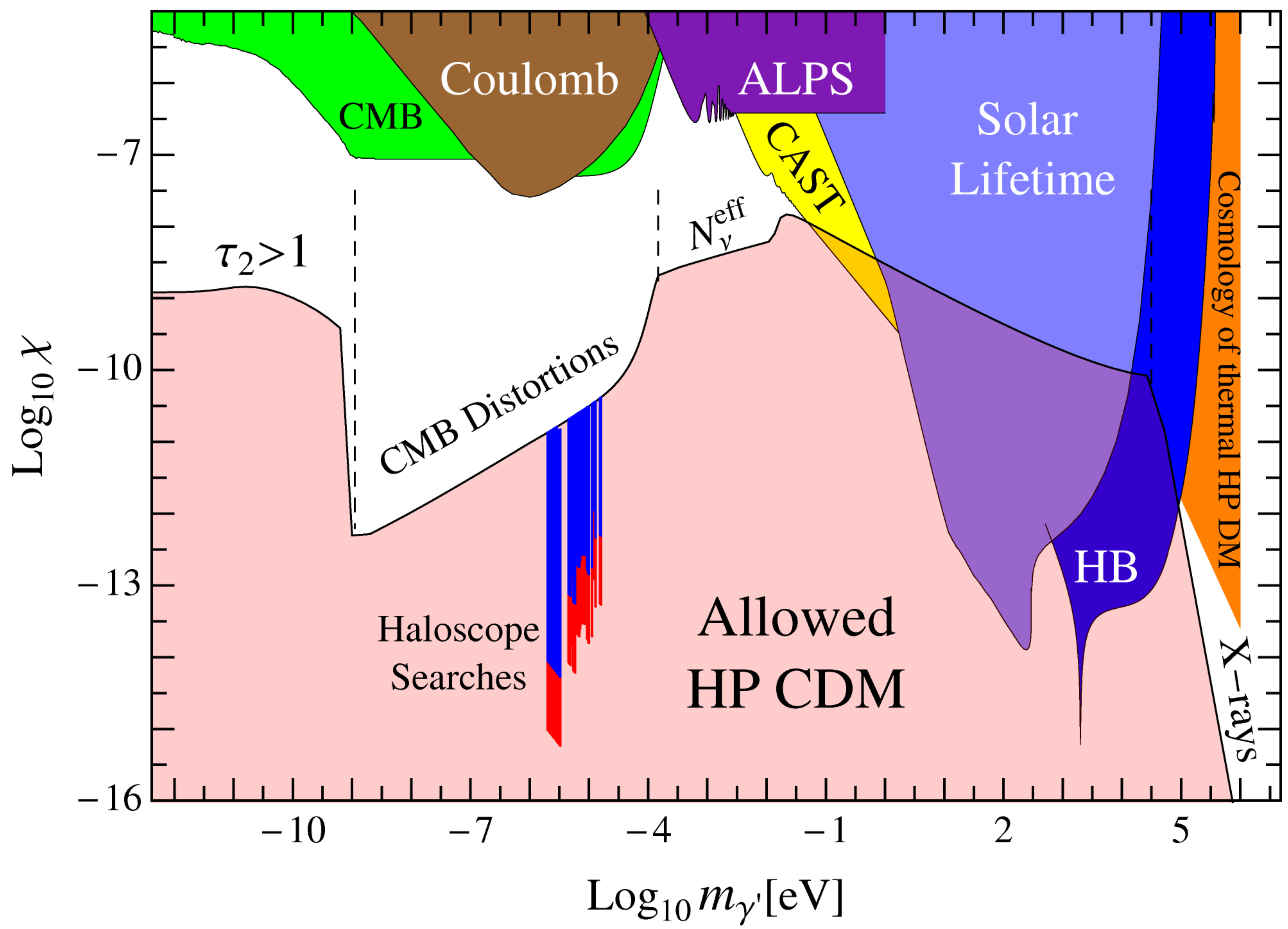
Dark Matter: *non-thermal production, formation of a condensate*

$$\rho_{\rm CDM} = \frac{m_{\gamma'}^2}{2}|\mathbf{X}|^2$$



Hidden photons as Dark Matter particles (ii)

Spatially constant oscillating field

$$\left.\begin{pmatrix} \mathbf{A} \\ \mathbf{X} \end{pmatrix}\right|_{\rm DM} = \mathbf{X}_{\rm DM} \begin{pmatrix} -\chi \\ 1 \end{pmatrix} \exp(-i\omega t)$$

Constraint on energy density

$$\frac{m_{\gamma'}^2}{2} \langle |\mathbf{X}_{\rm DM}|^2 \rangle = \rho_{\rm CDM,halo} \sim \frac{0.3\,{\rm GeV}}{{\rm cm}^3}$$

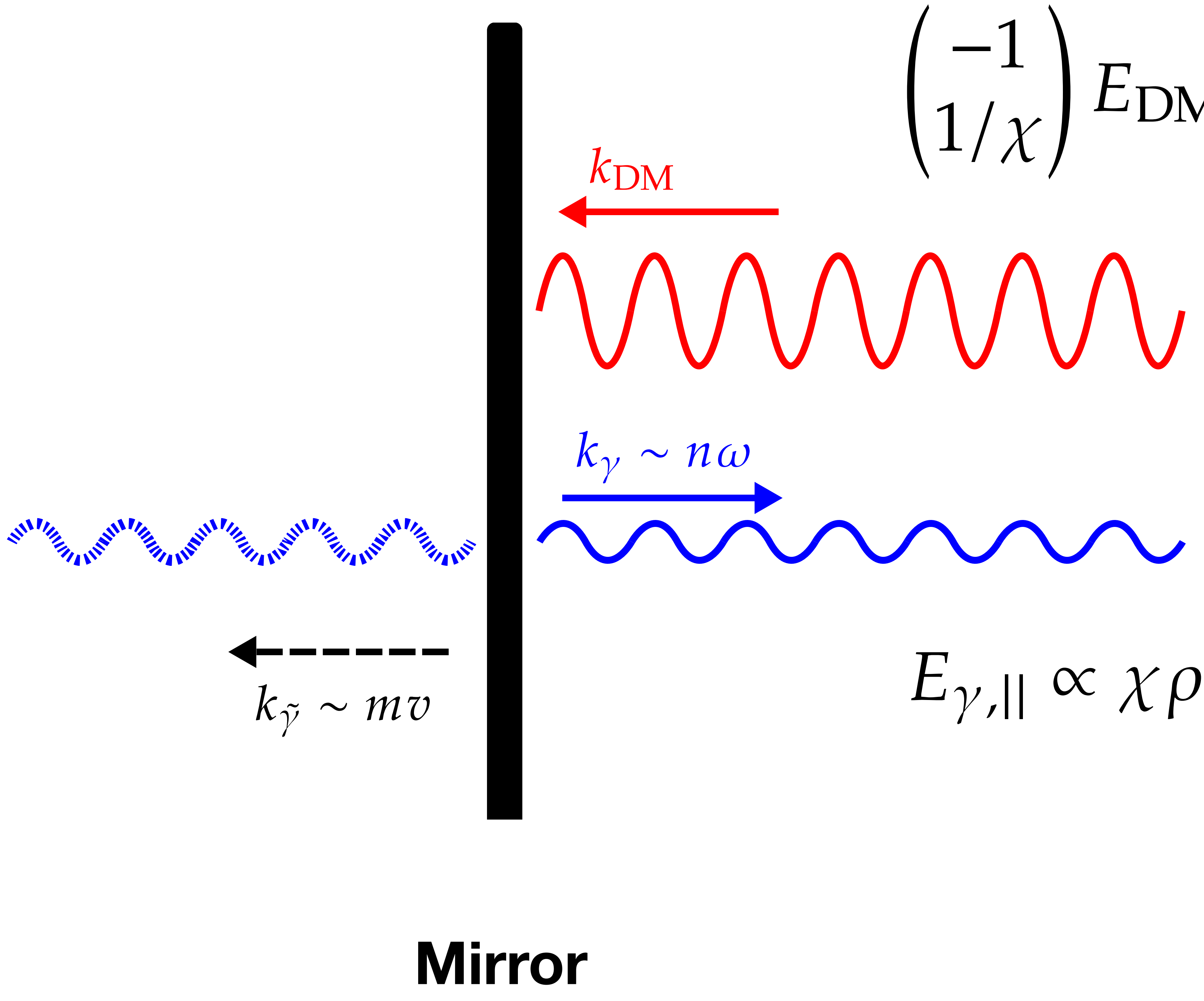
Relevant frequencies

$$f = \frac{m_{\gamma'}}{2\pi} = 0.24\ {\rm GHz}\ \left(\frac{m_{\gamma'}}{\mu{\rm eV}}\right)$$

Maxwellian-like transition at a dielectric interface

$\begin{pmatrix} -1 \\ 1/\chi \end{pmatrix} E_{\rm DM}$ oscillating at $240\,{\rm THz}\,(m/{\rm eV})$

with $\sqrt{\langle |E_{\rm DM}|^2 \rangle} \sim 10^{-9}\,{\rm V/m}$



$E_{\gamma,||} \propto \chi \rho_{\rm CDM}^{1/2} \sqrt{(1+R)/2}$

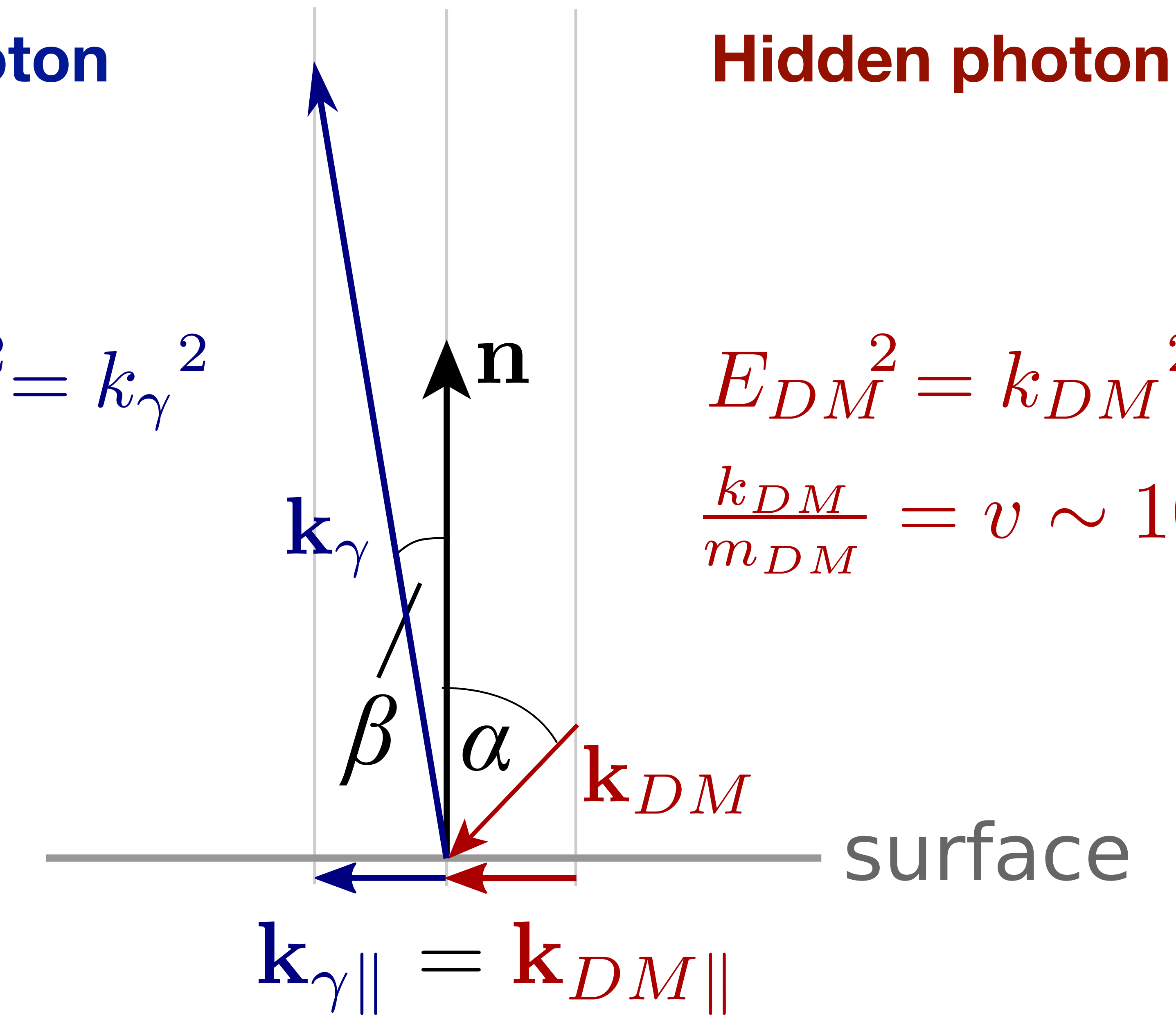
mirror reflectivity

Detection principle using spherical mirror

Transition conditions at metallic mirror: production of photons

Photon

$E_\gamma{}^2 = k_\gamma{}^2$



Hidden photon

$E_{DM}{}^2 = k_{DM}{}^2 + m_{DM}{}^2$

$\frac{k_{DM}}{m_{DM}} = v \sim 10^{-3}$

(Knirck & Jaeckel, PATRAS 2016)

- *Signal in radius point*
- *Daily / seasonal shift by ~ few mm*

$$\sin\beta = v\,\sin\alpha \approx 10^{-3}$$

$$P_{\text{center}} \approx \chi^2\,\rho_{\text{CDM}}\,A_{\text{mirror}}$$

Searching for WISPy cold dark matter with a dish antenna

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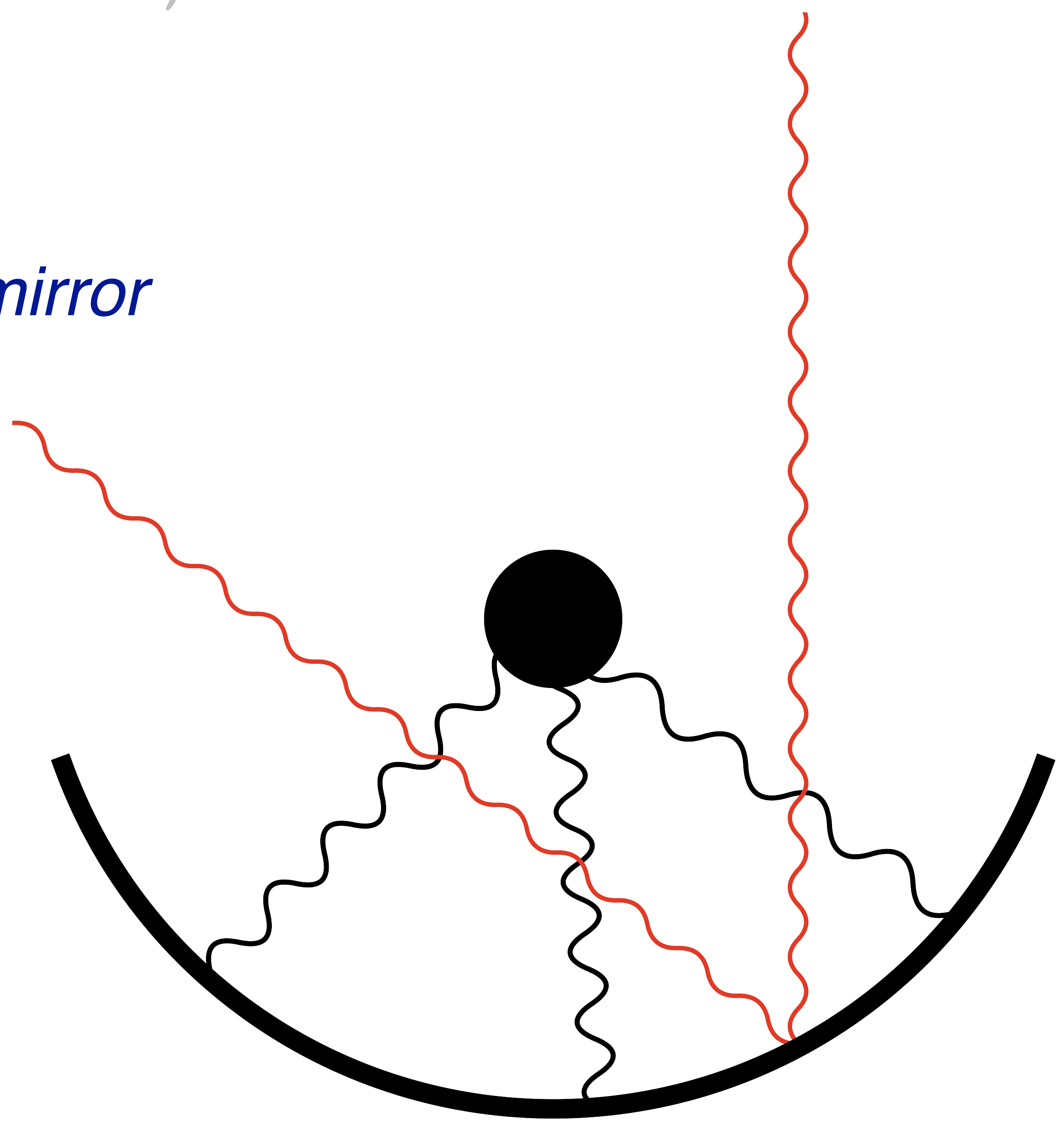
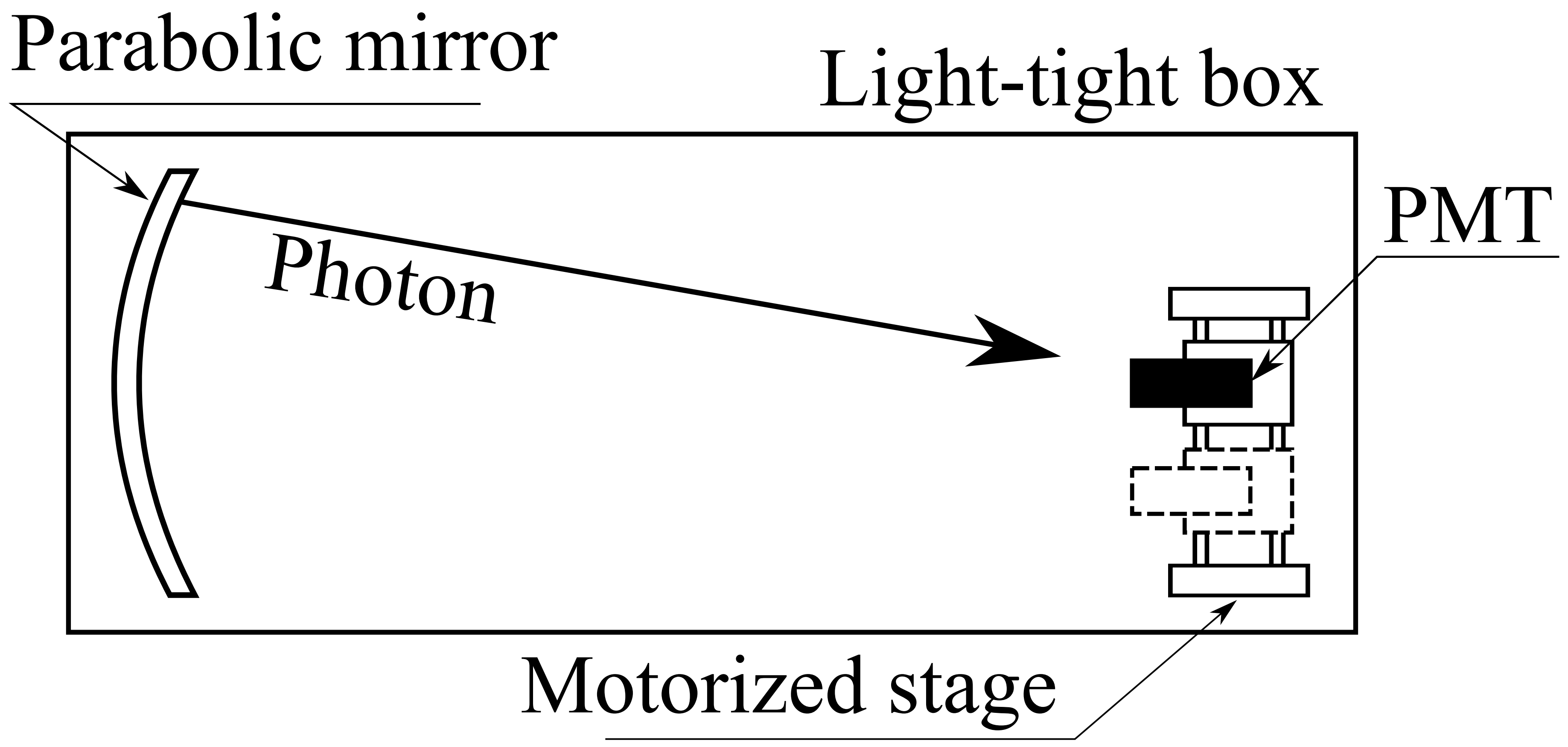
Setup with spherical mirror



First measurement of this type: Tokyo group



$$m_\gamma = 3.1 \pm 1.2\,\mathrm{eV}$$

Experimental search for hidden photon CDM in the eV mass range with a dish antenna

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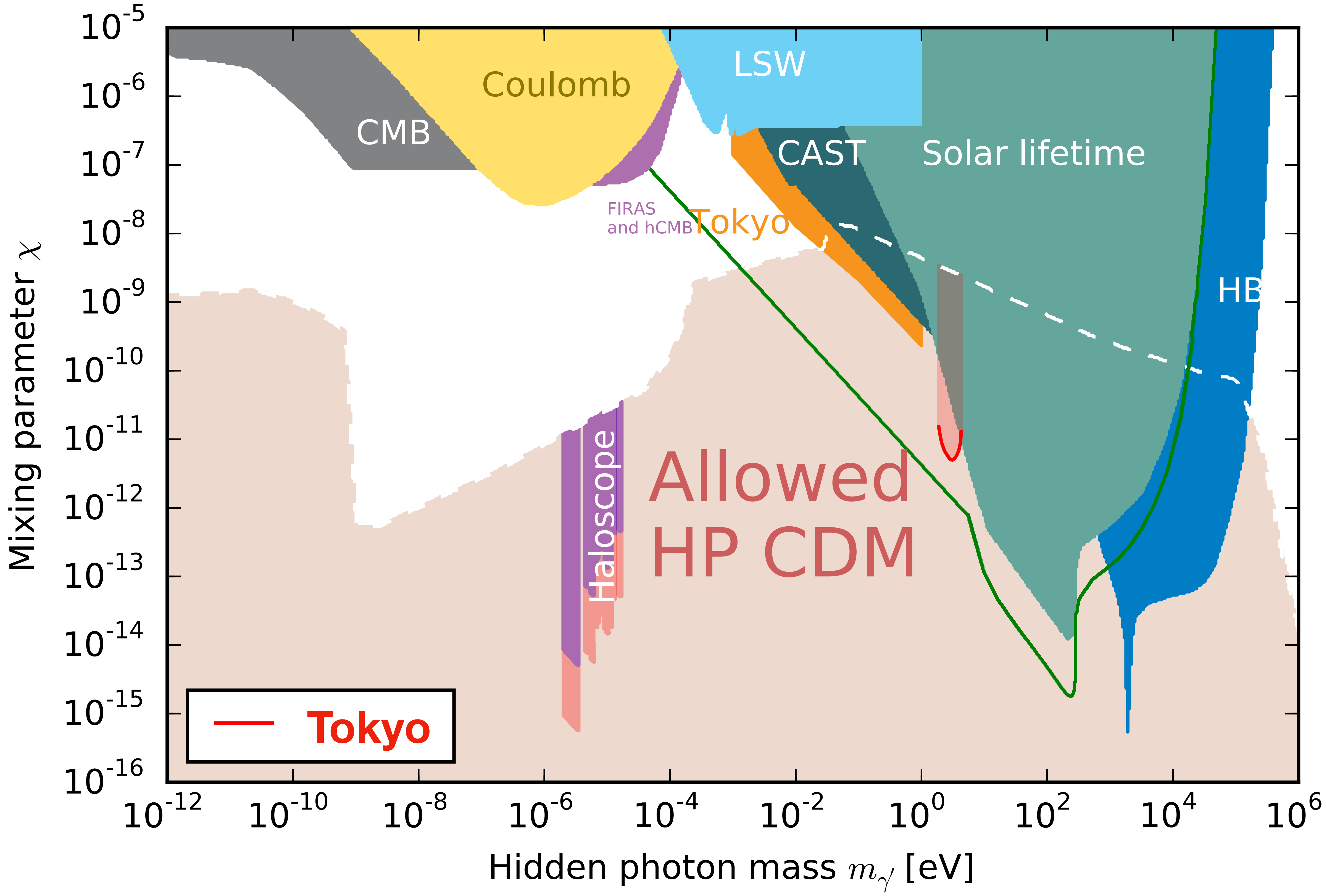
J. Suzuki,[a] T. Horie,[a] Y. Inoue[b] and M. Minowa[a,c]

Comparison of signal of low-noise PMT in radius point and outside (motorized stage)

Dark box of 1 x 1 x 3 m³
Mirror of d = 0.5 m (A = 0.196 m²)
Data taking ~ 1 month

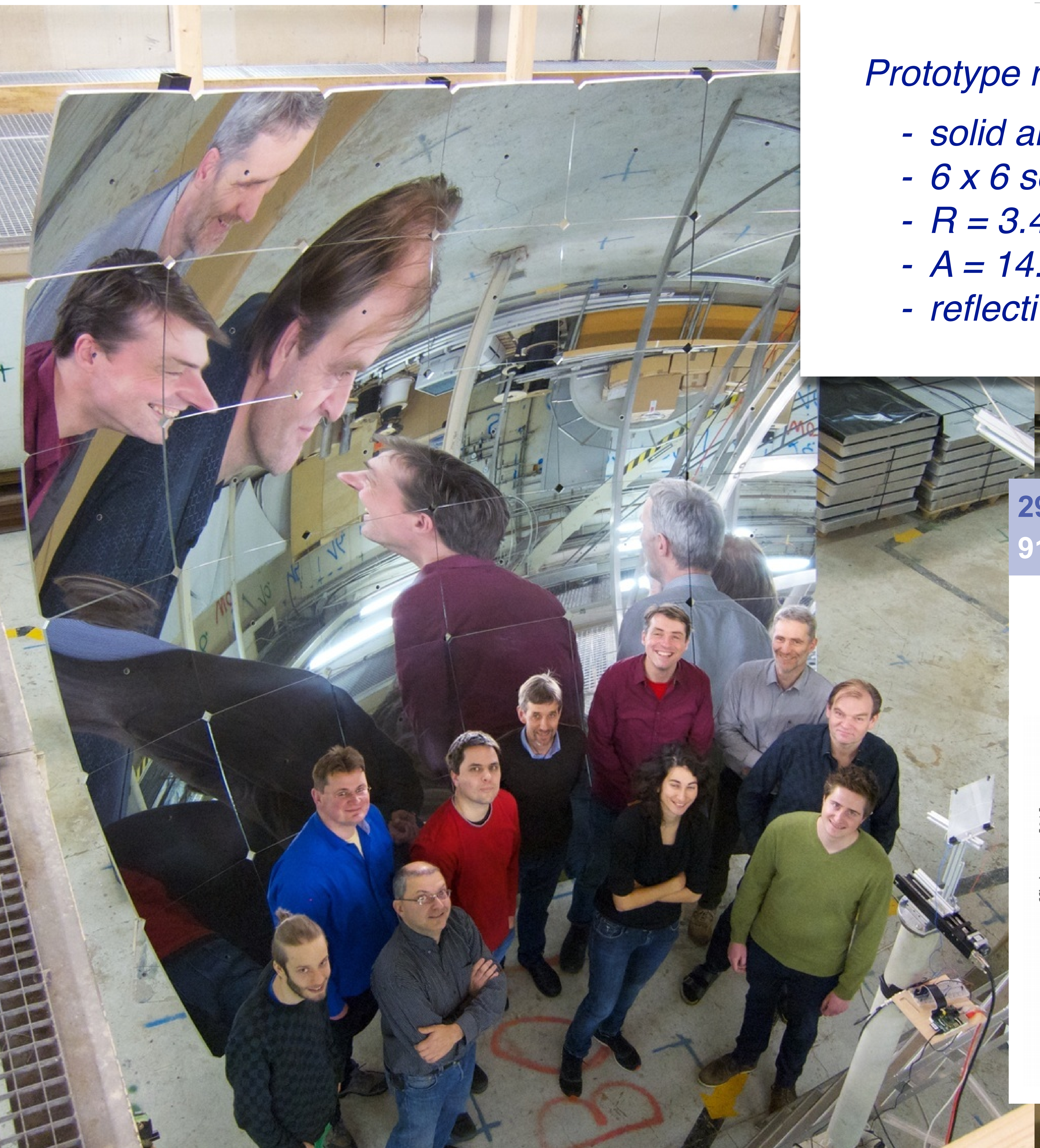
Photon rate In - Out (at 4.5 Hz rate):

$$N = (-1.9 \pm 3.8(\mathrm{stat.}) \pm 0.5(\mathrm{sys.})) \times 10^{-3}\,\mathrm{Hz}$$



Much larger mirror – Auger fluorescence telescopes

FUNK – Finding U(1)s of a Novel Kind

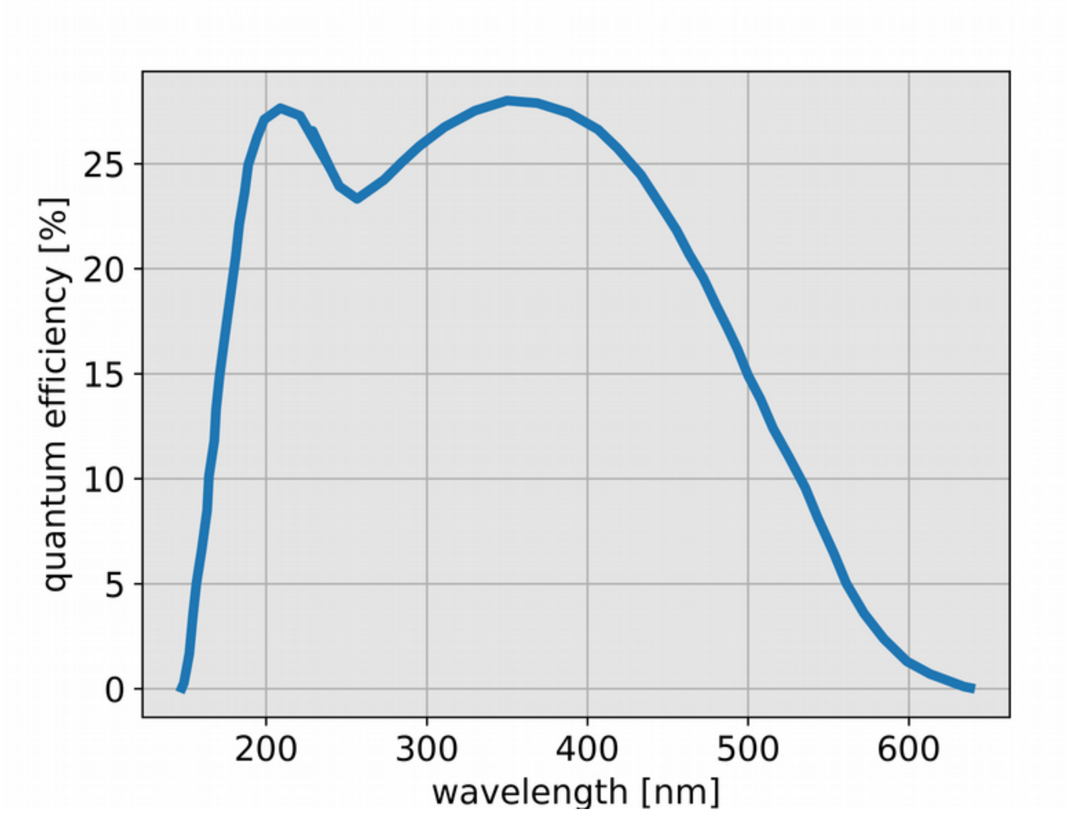


Prototype mirror (Auger Observatory)

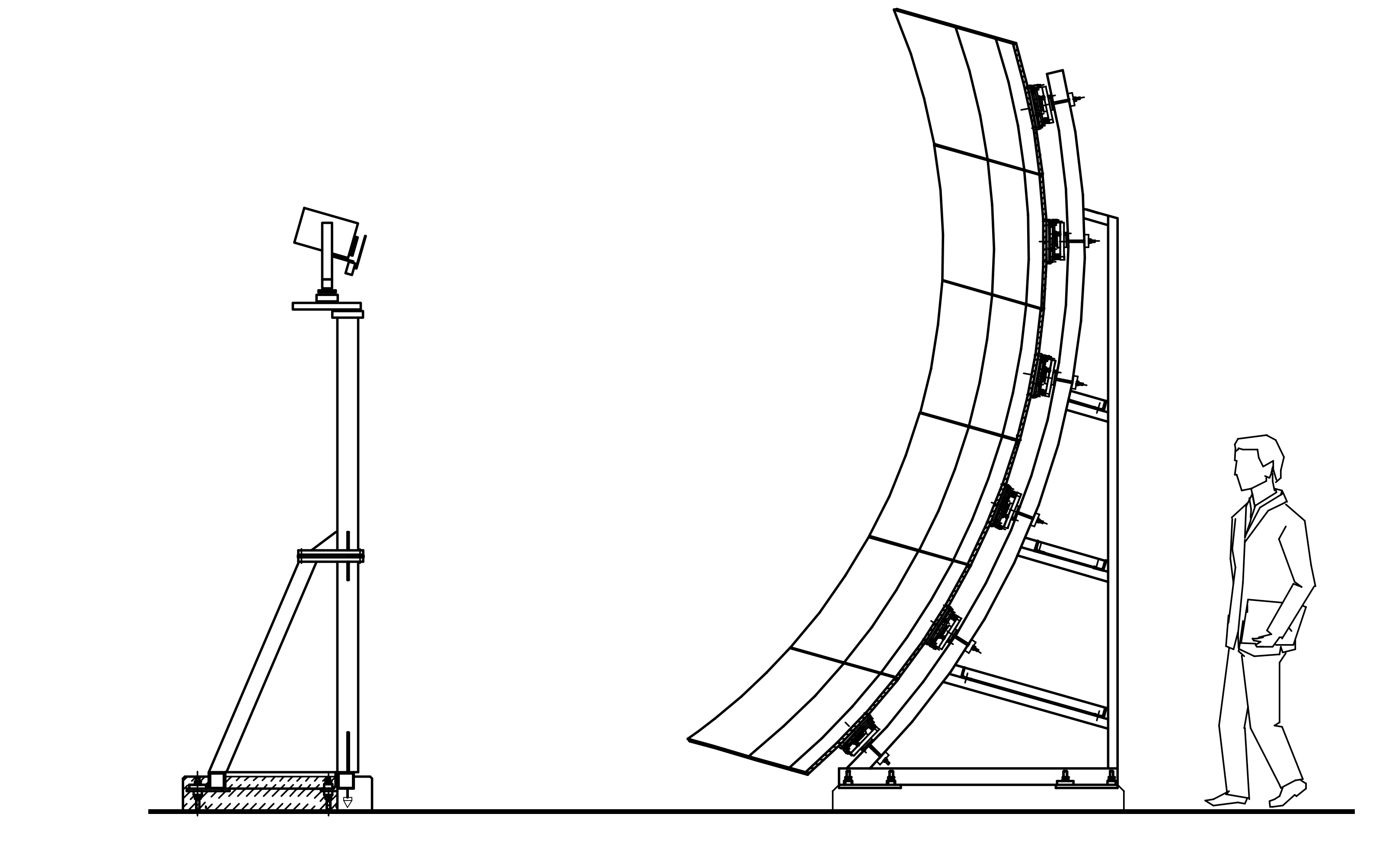
- *solid aluminum mirror*
- *6 x 6 segments*
- *R = 3.4 m*
- *A = 14.56 m²*
- *reflectivity ~ 0.8*

29 mm (1.13") photomultiplier
9107B series data sheet

ET Enterprises electron tubes

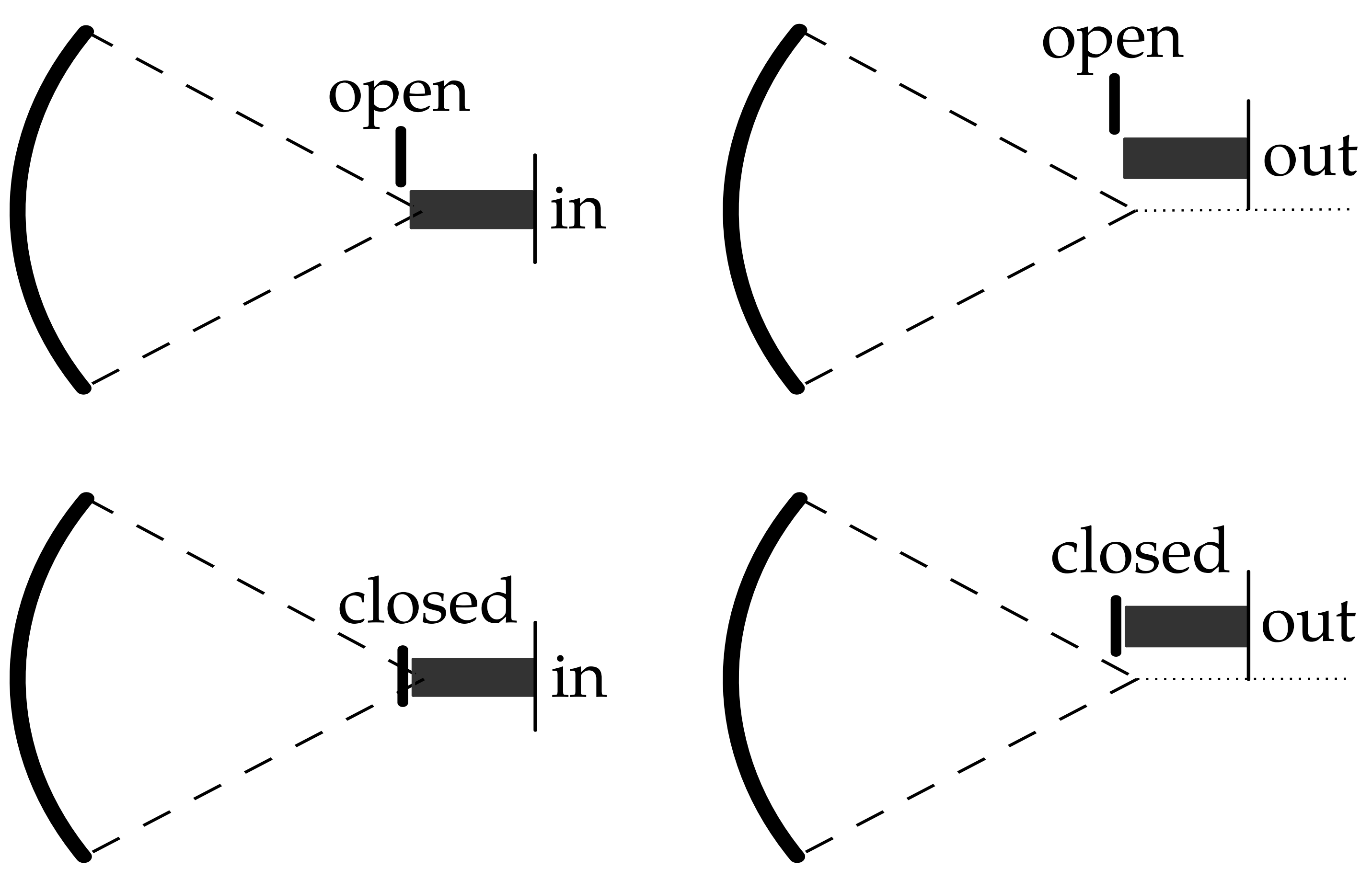


Motorized stage and shutter

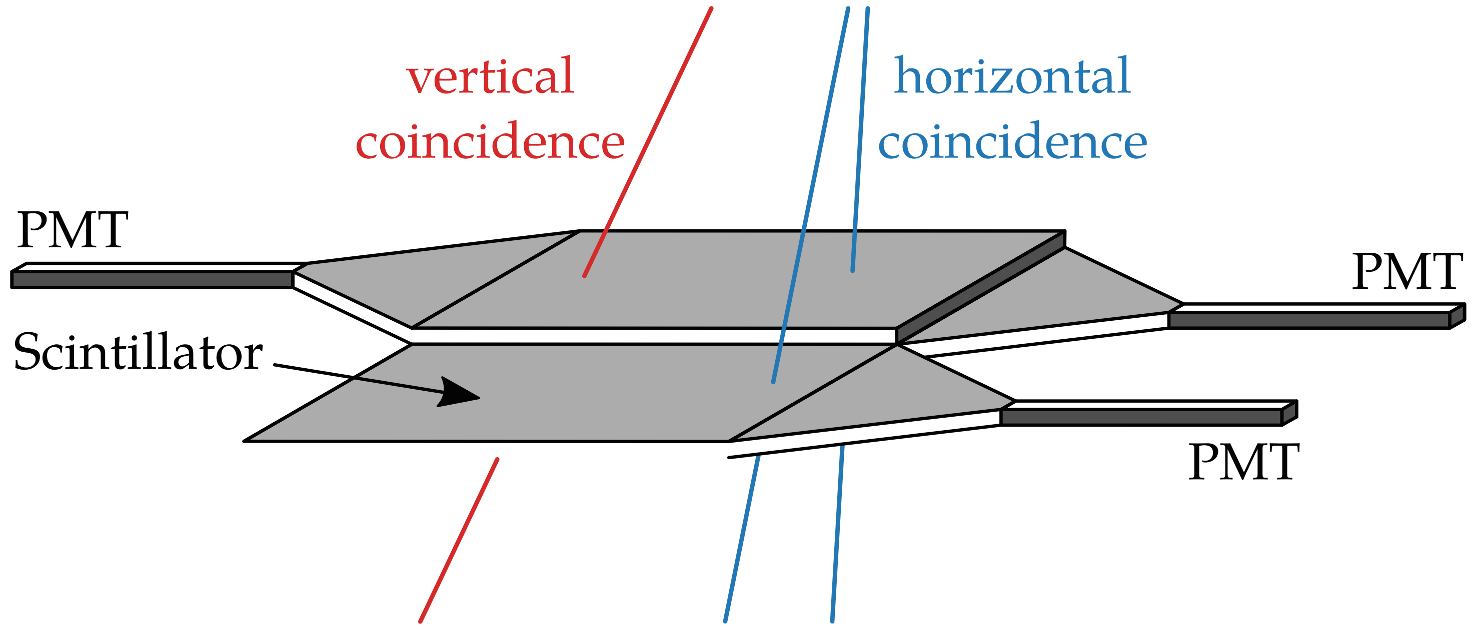


Data taken with FUNK

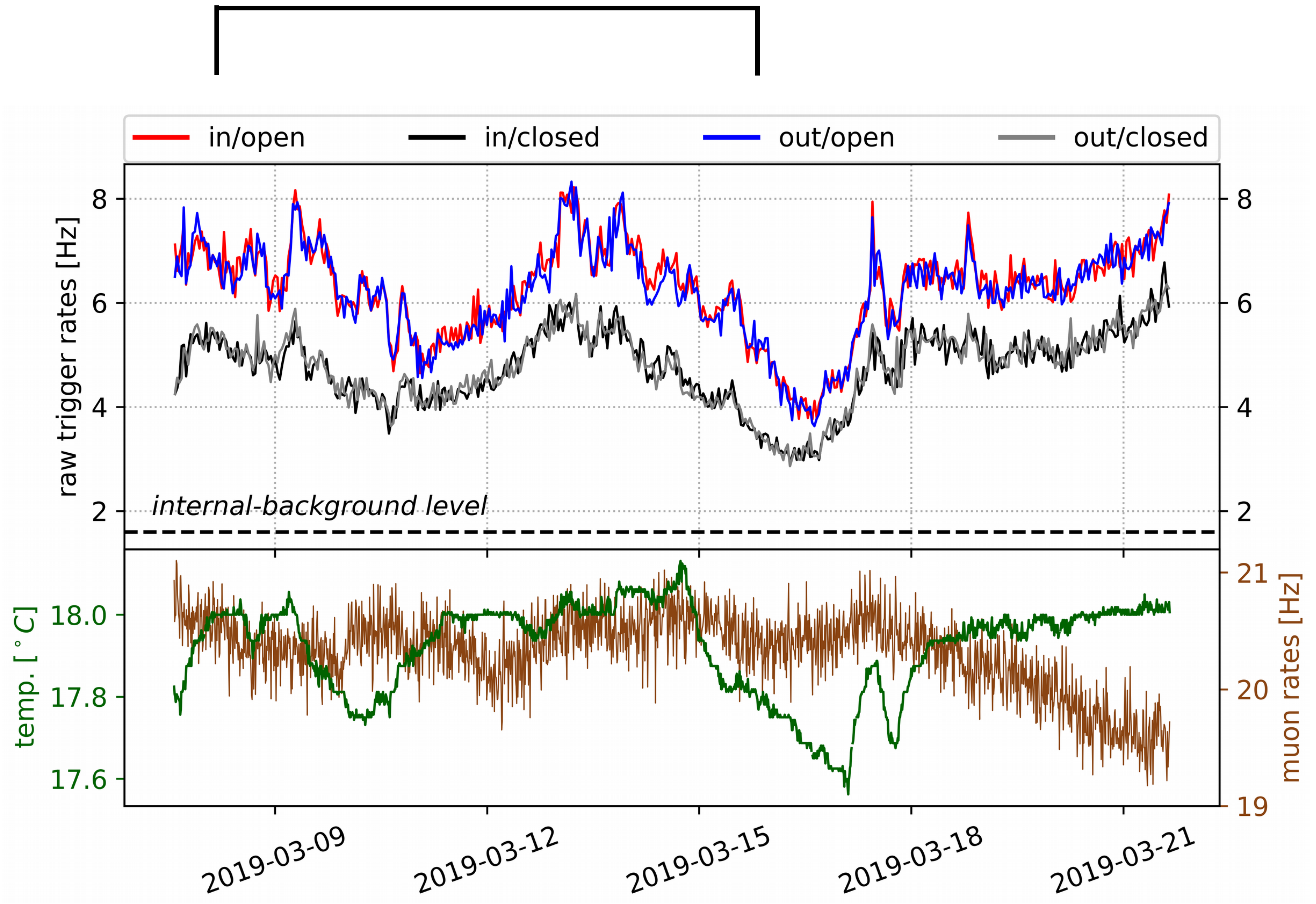
Four channels of data taking (60 sec. each)



Scintillators for muon background

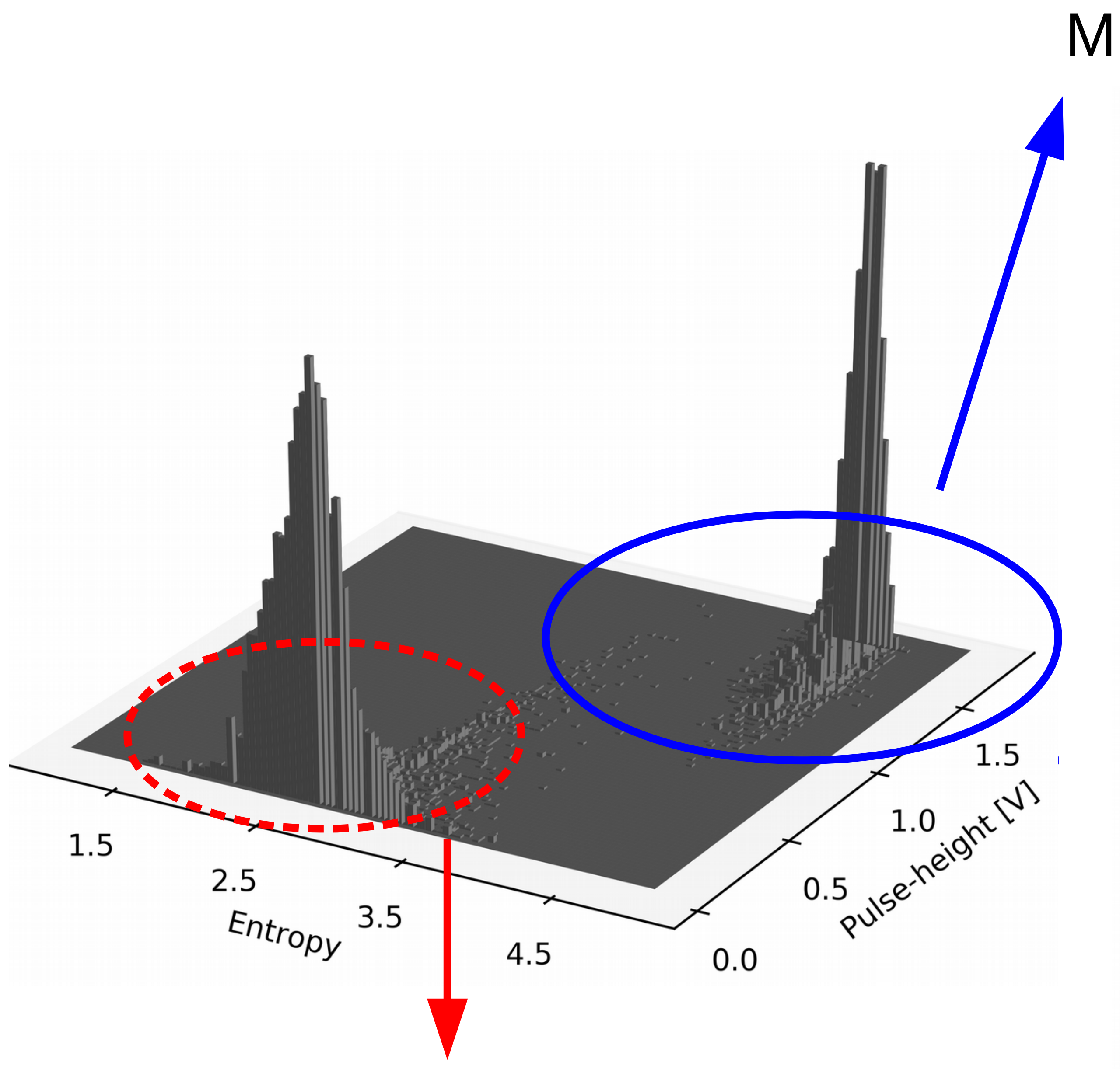


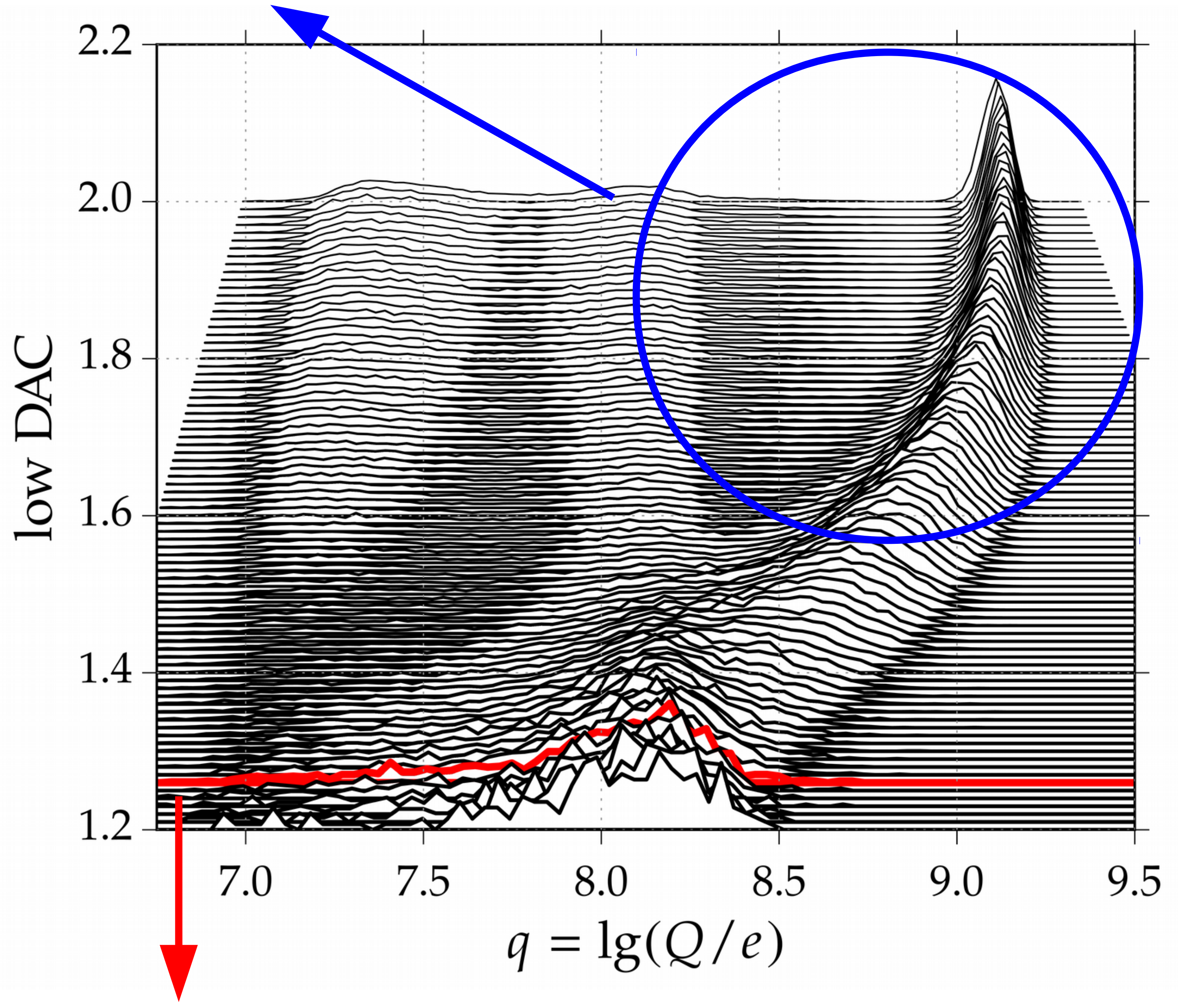
Signal: difference of these channels



Data analysis – selection of single photon pulses

Run with LED flasher

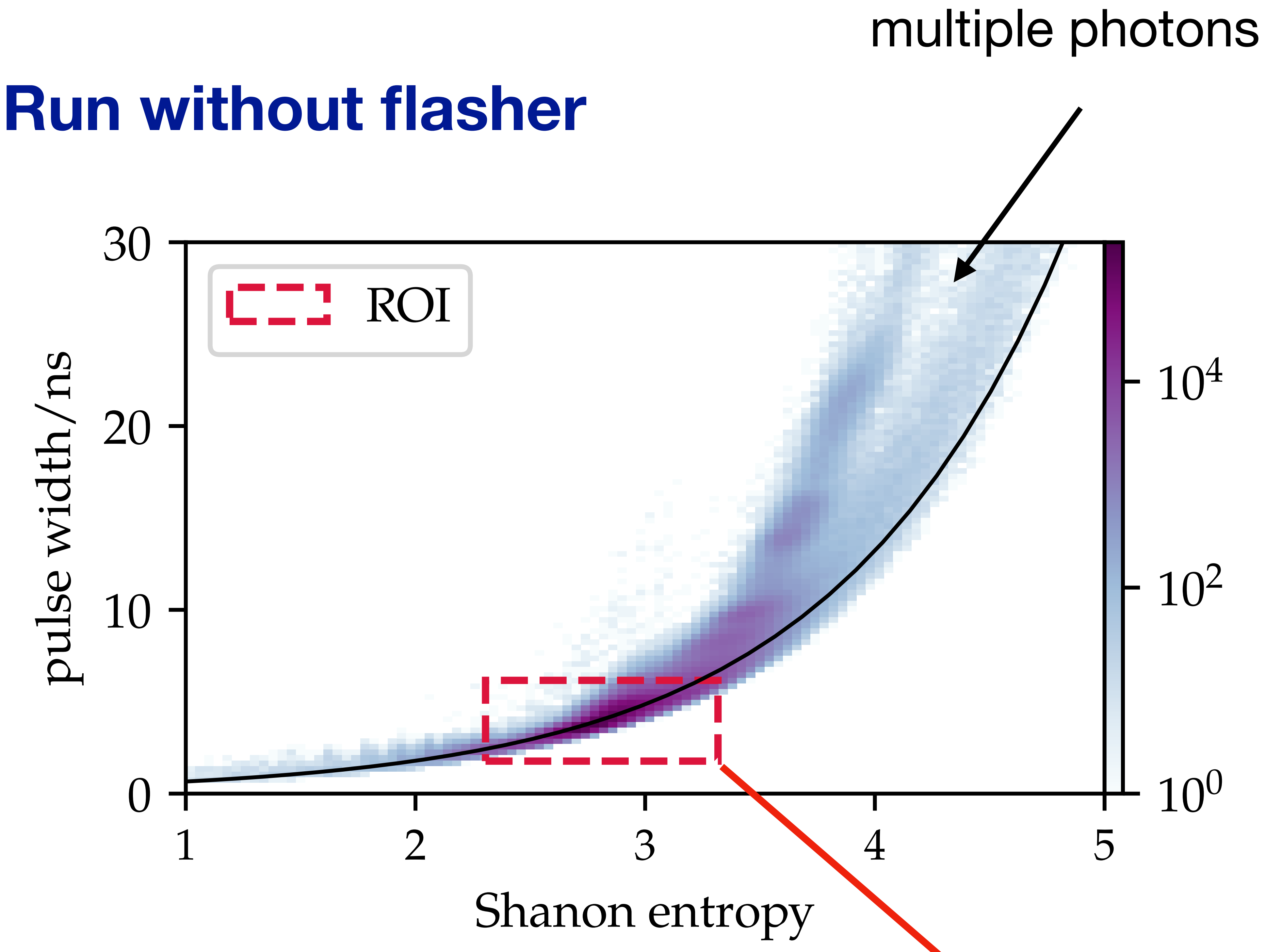


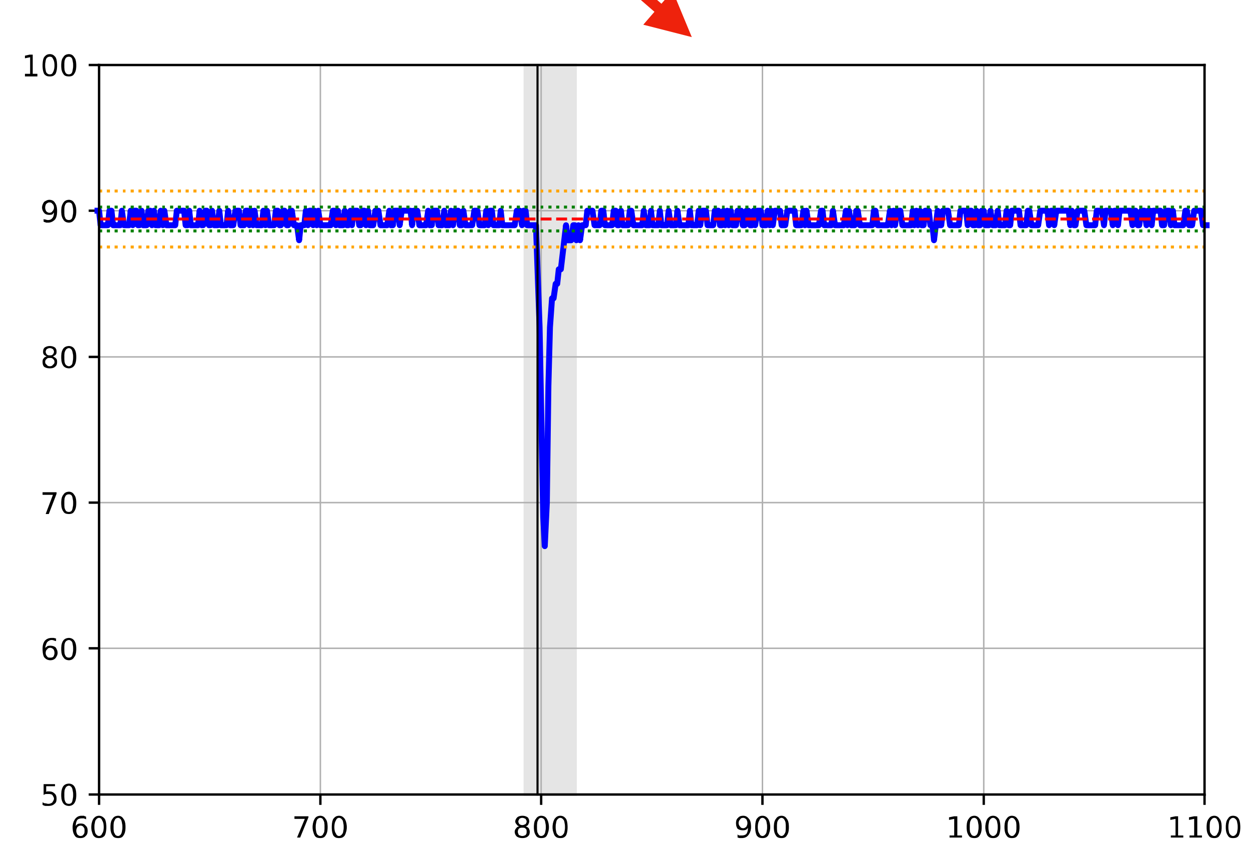


Optimal settings for SPE calibration

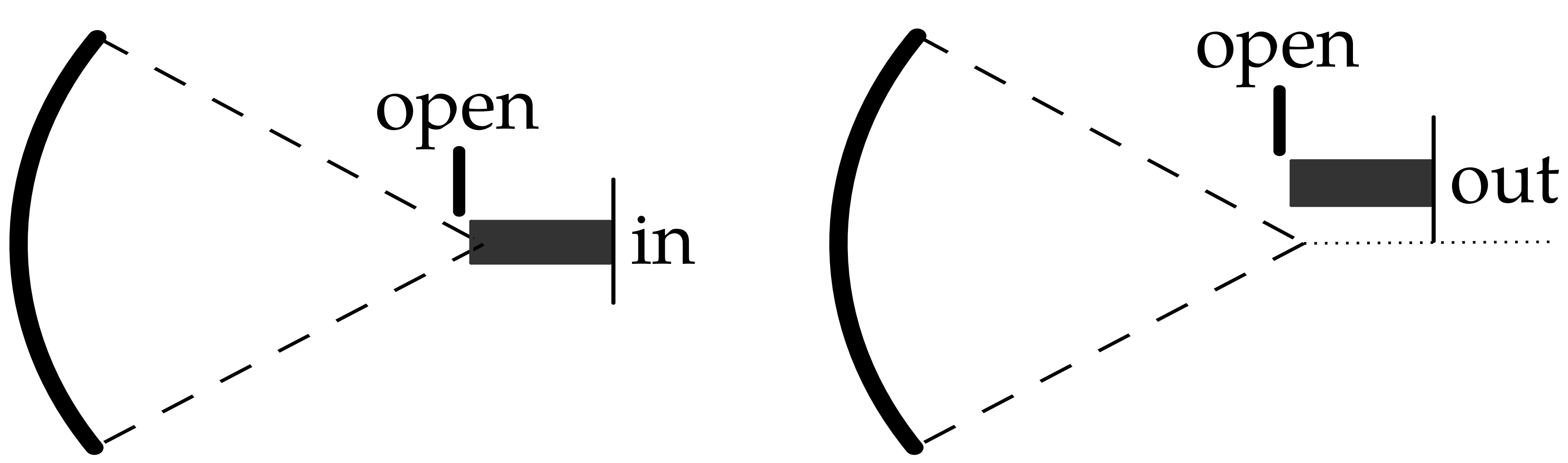
- PMT sees SPE for ~ 20% of the time
- Capture single pulse per trace ~ 95% of the time
- Photon arrival time ~ 290 ns

Run without flasher



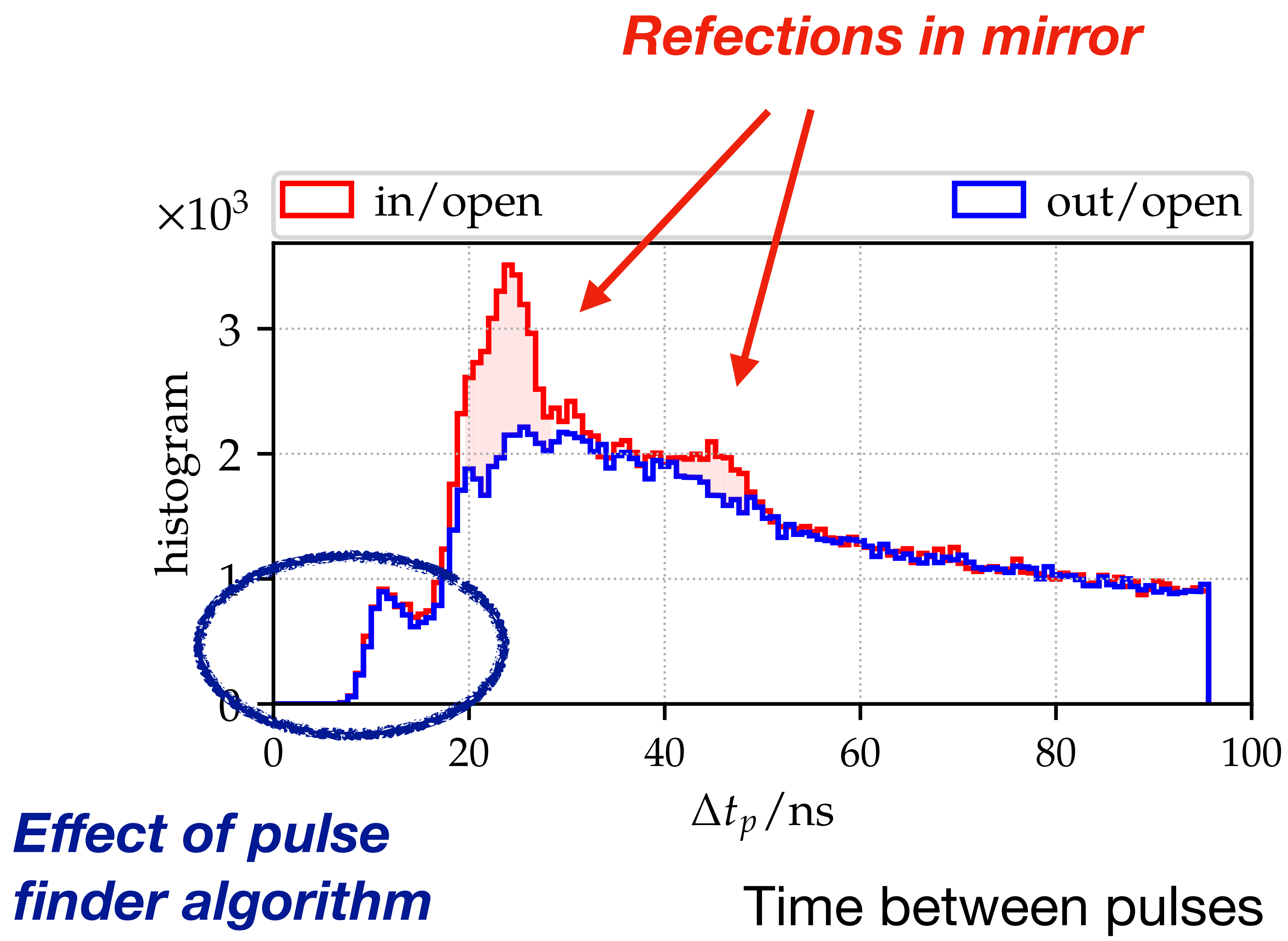


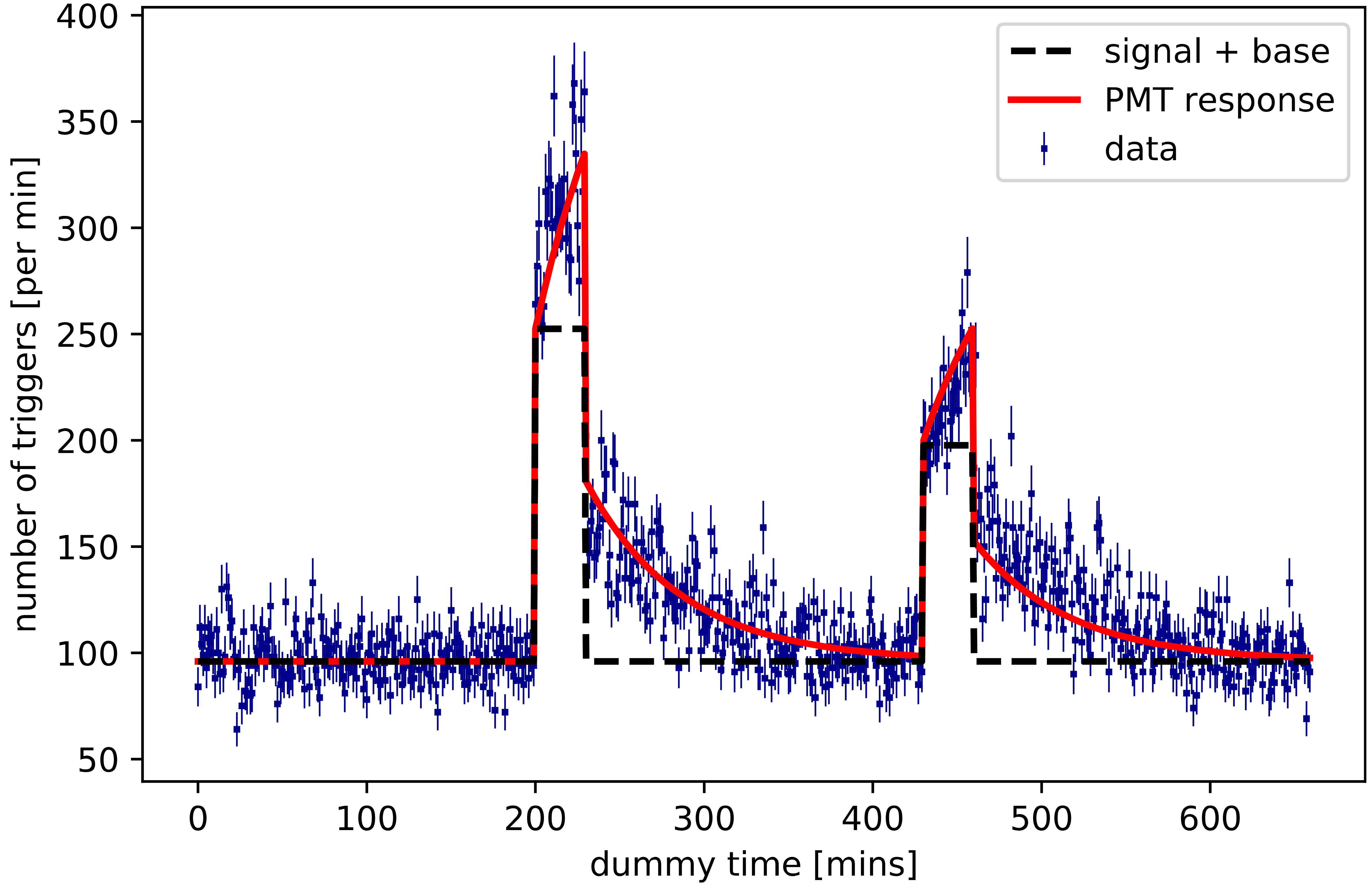
Data analysis – reflections and PMT memory effect



$$R(t) = S(t) + \alpha \int_{-\infty}^{t} S(t') \exp\left(-\frac{t-t'}{\tau}\right) \mathrm{d}t'$$

instantaneous signal *historical response*





Data analysis – results

$$\chi = 4.1\times10^{-12}\left(\frac{\phi_{\rm det}/q_{\rm eff}}{\rm Hz}\,\frac{m_{\tilde\gamma}}{\rm eV}\right)^{1/2}\left(\frac{\eta A_{\rm mirror}}{\rm m^2}\right)^{-1/2}\left(\frac{\langle\cos^2\theta\rangle}{2/3}\right)^{-1/2}\left(\frac{\rho_{\rm CDM}}{0.3\,{\rm GeV/cm^3}}\right)^{-1/2}$$

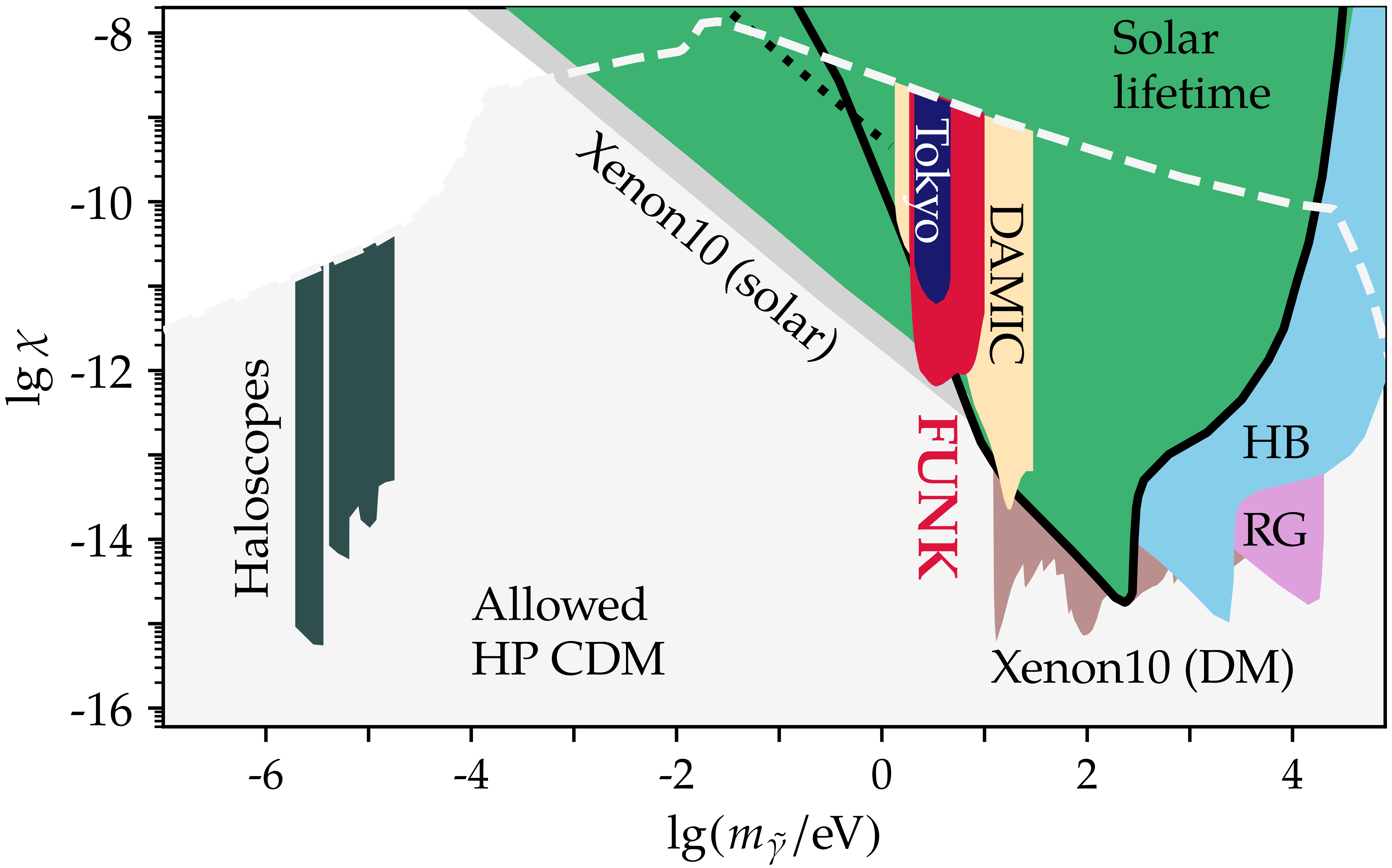
$$(r_{\rm in/open} - r_{\rm out/open})/{\rm Hz} = -0.0161 \pm 0.0119$$

$$(r_{\rm in/closed} - r_{\rm out/closed})/{\rm Hz} = -0.0278 \pm 0.0112$$

$$\rho_{\rm CDM} = 0.3\,{\rm GeV/cm^3}$$

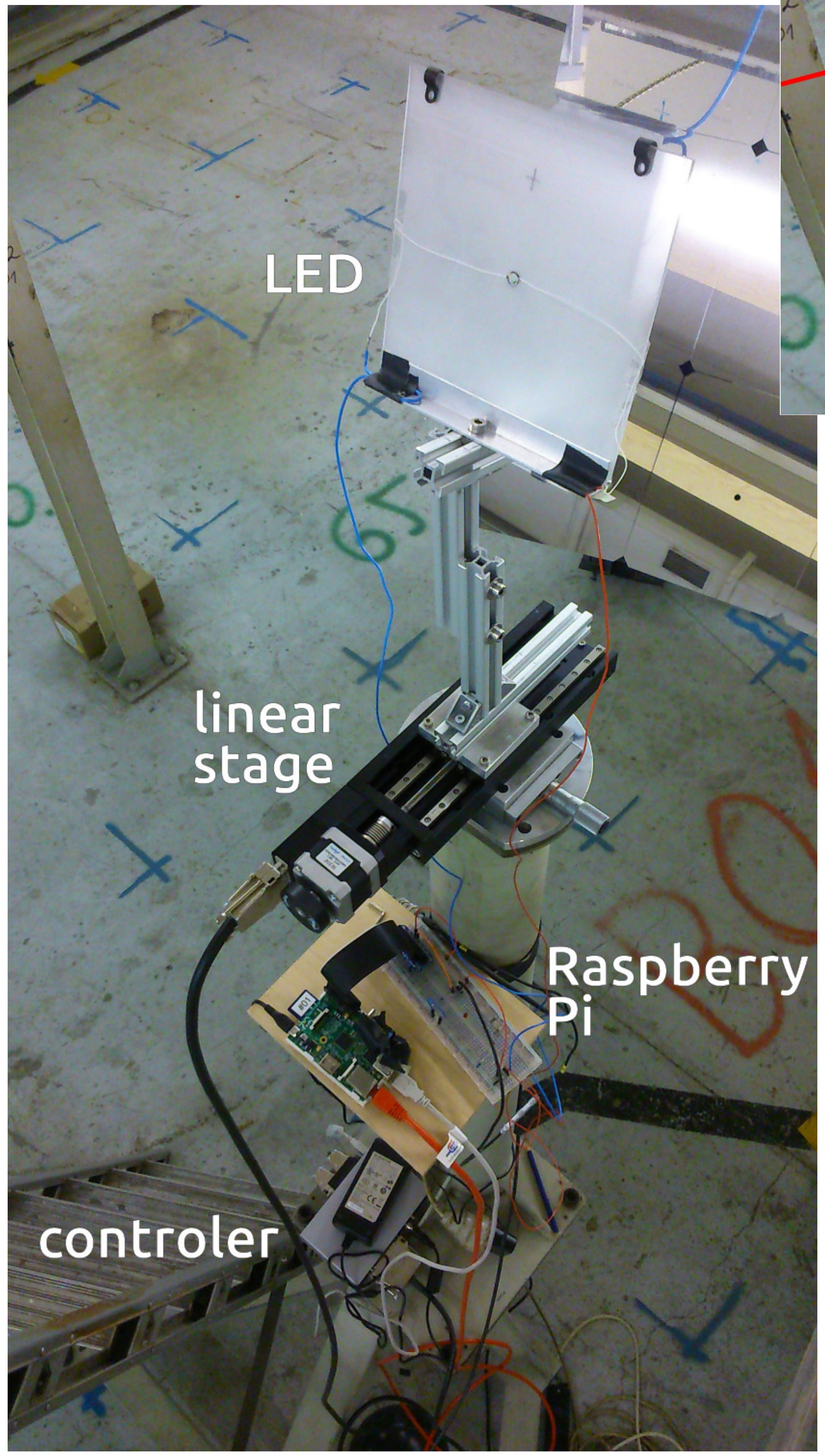
$$\chi \lesssim 6.87\times10^{-13} \text{ at } 95\% \text{ CL}$$

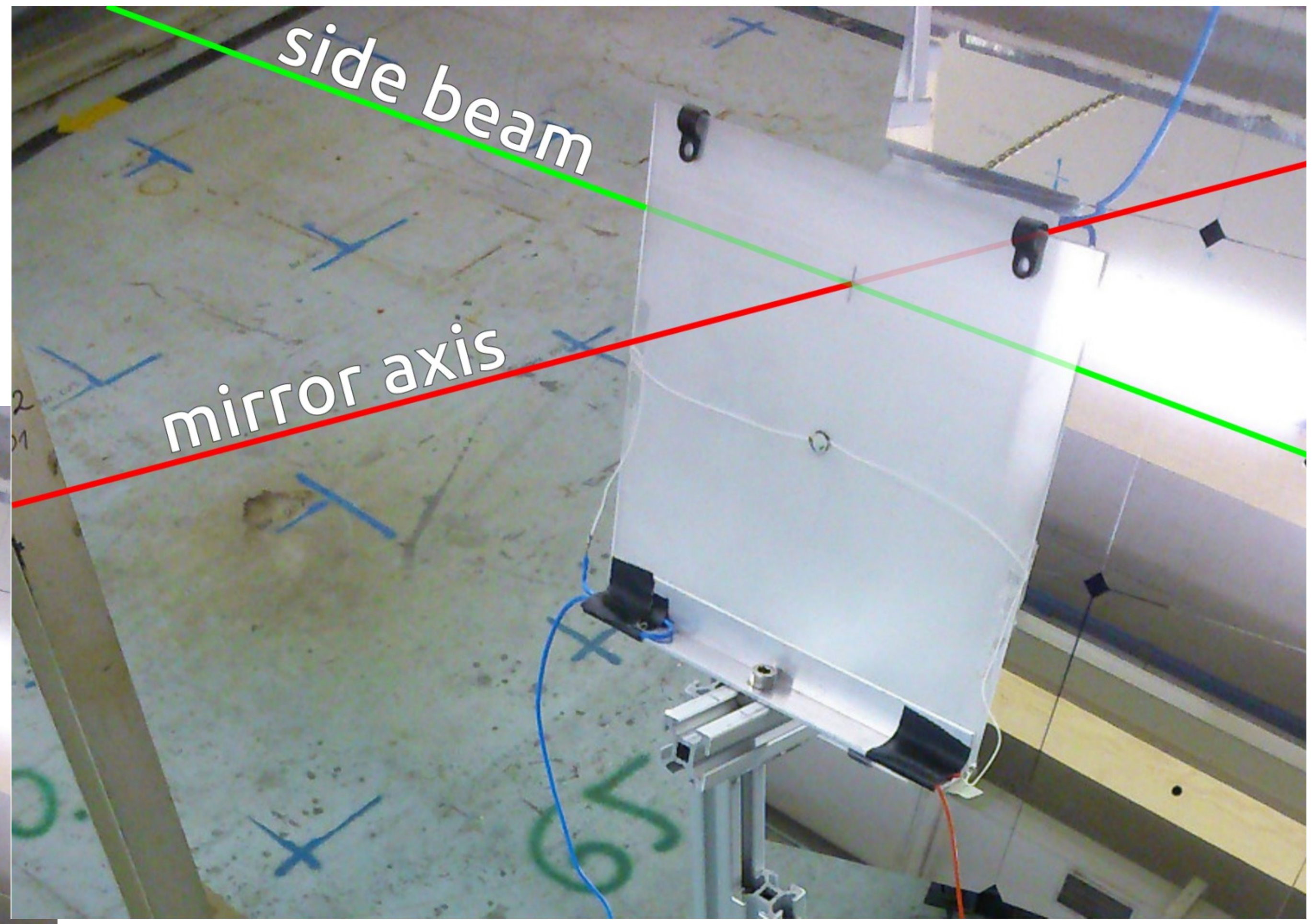
$$1.94 \leqslant m_{\tilde\gamma}/{\rm eV} \leqslant 8.40$$



Backup slides

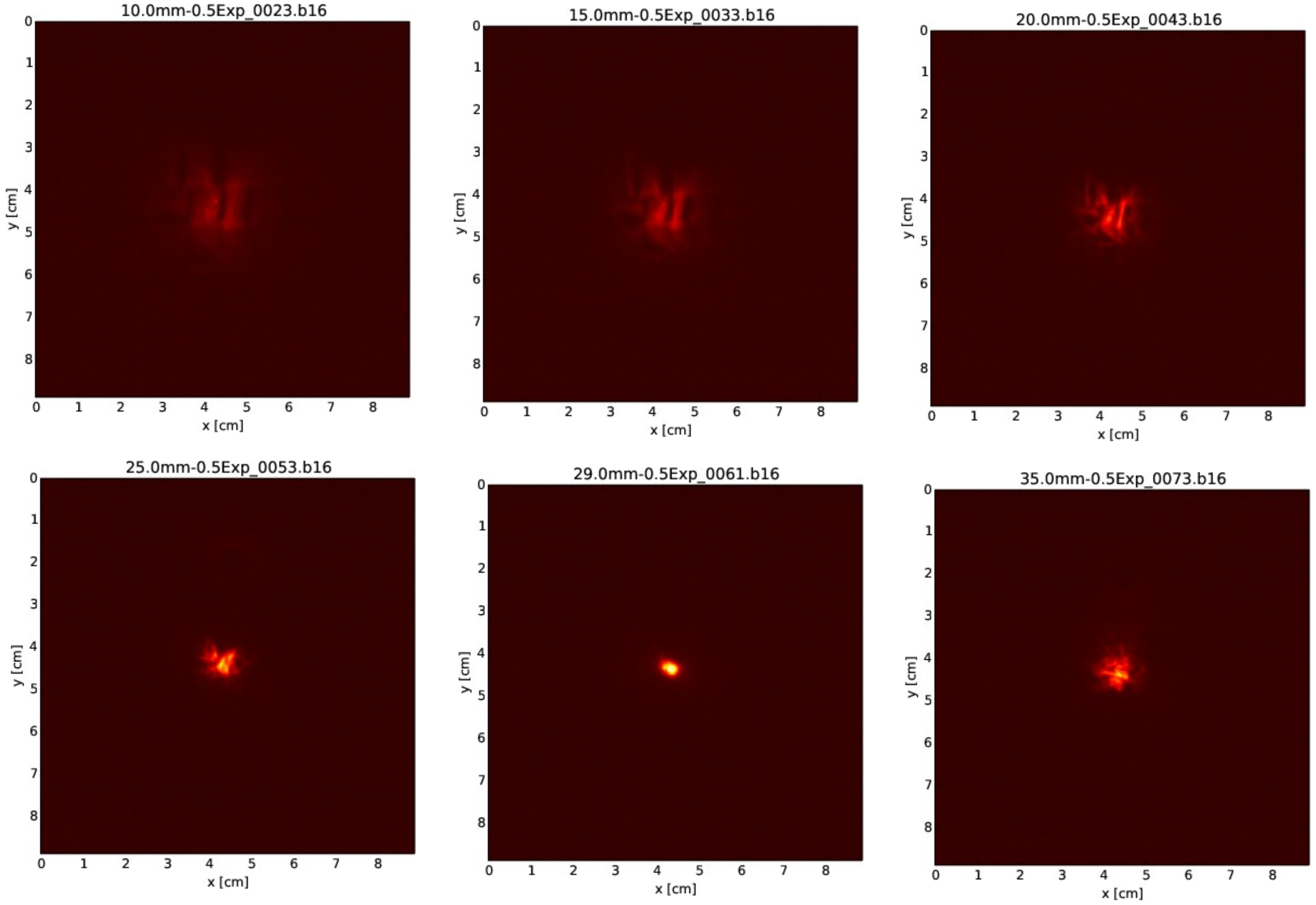
Alignment of mirror segments – point spread function

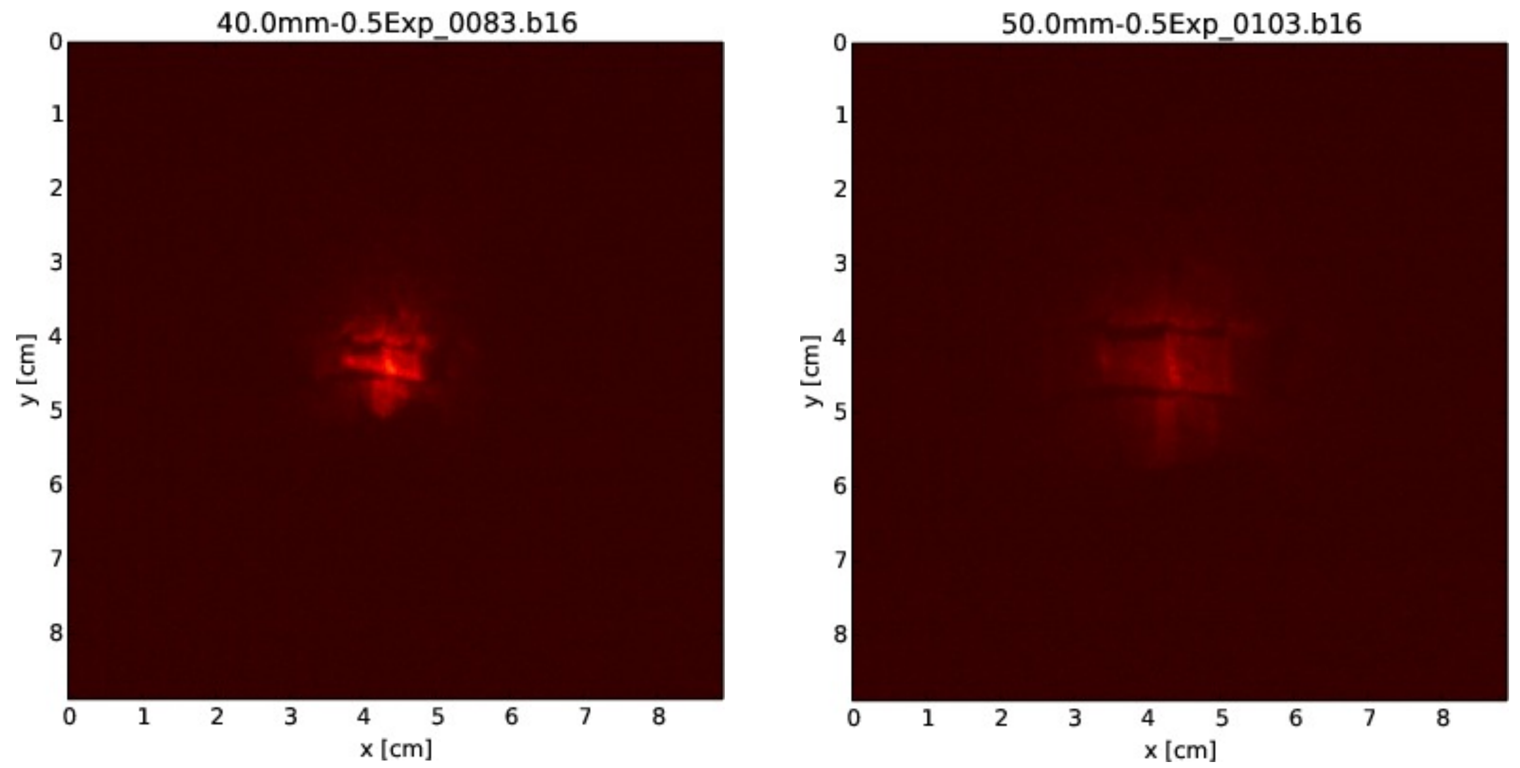




LED mounted next to radius point

Optimum radius point marked by two laser beams





Spot size 2 mm after alignment

Radius point marked by lasers