Experimental estimates of the photon background in a potential light-by-light scattering study

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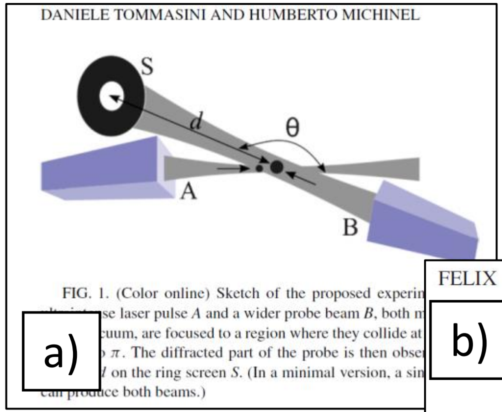
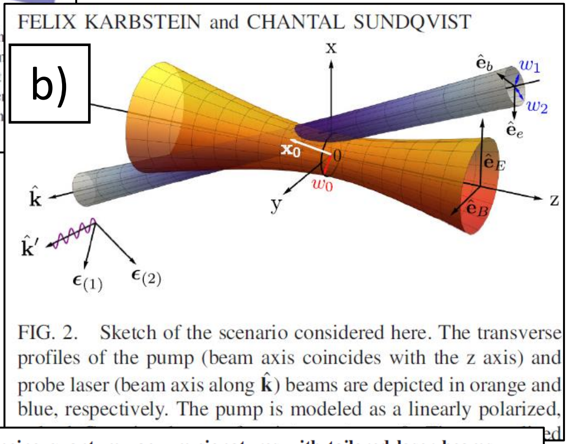
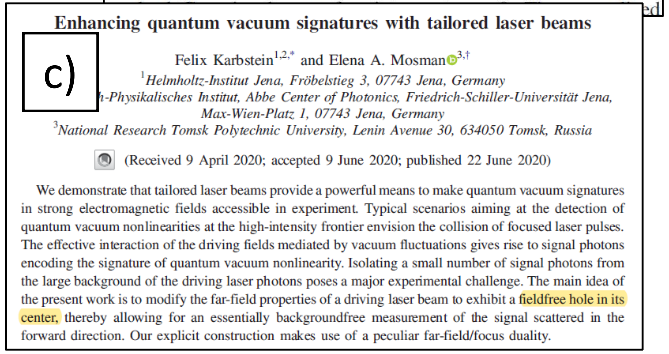
http://quantumvacuum.org/

Motivation

- all-optical photon-photon scattering: 2 pulse, 3 pulse schemes proposed for
- 2 pulse has drawbacks, but experimentally easiest
  - Dominant signal at driver frequency and direction
  - Solutions (*w/o claim of completeness*):
    - Different sized foci → larger scattering angles
    - Impact parameter $\neq 0$ → scattering away from driving beams
    - Hole in beam center → suppress driver background
  - → worthwhile to investigate concrete detection setup
- This study: single beam only!



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Enhancing quantum vacuum signatures with tailored laser beams

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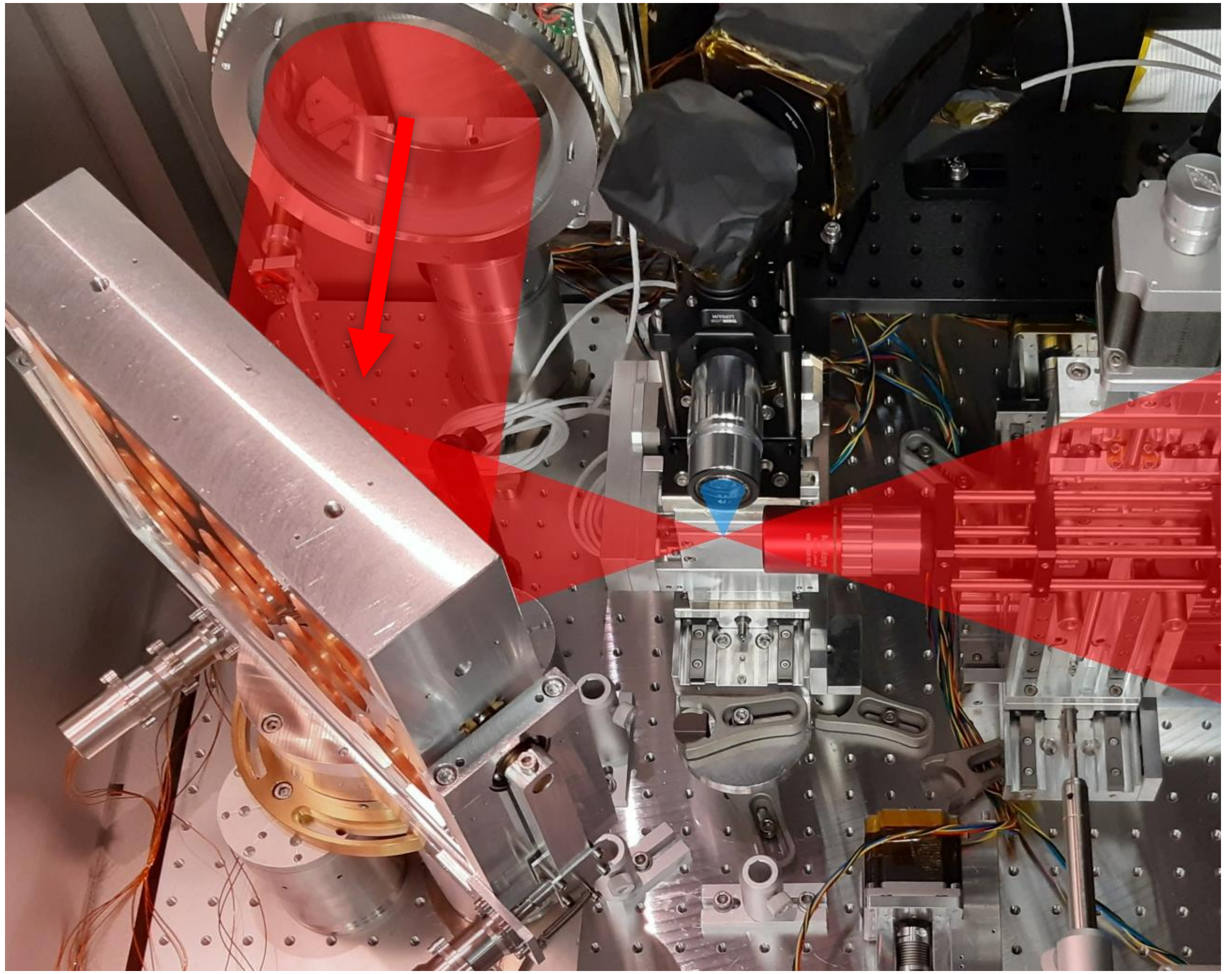
We demonstrate that tailored laser beams provide a powerful means to make quantum vacuum signatures in strong electromagnetic fields accessible in experiment. Typical scenarios aiming at the detection of quantum vacuum nonlinearities at the high-intensity frontier envision the collision of focused laser pulses. The effective interaction of the driving fields mediated by vacuum fluctuations gives rise to signal photons encoding the signature of quantum vacuum nonlinearity. Isolating a small number of signal photons from the large background of the driving laser photons poses a major experimental challenge. The main idea of the present work is to modify the far-field properties of a driving laser beam to exhibit a fieldfree hole in its center, thereby allowing for an essentially backgroundfree measurement of the signal scattered in the forward direction. Our explicit construction makes use of a peculiar far-field/focus duality.

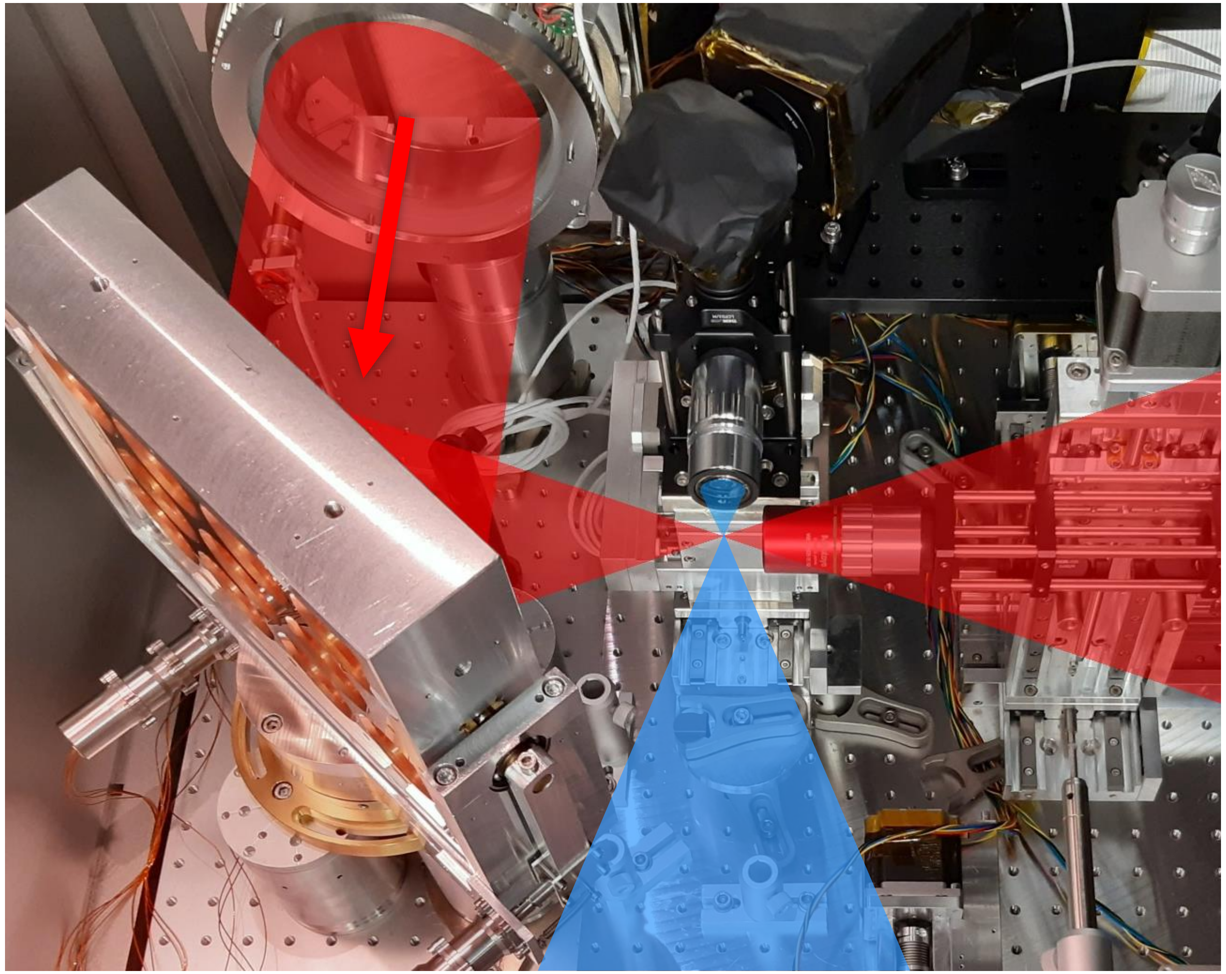
a) D. Tommasini and H. Michinel, *Phys. Rev. A*, vol. 82, no. 1, p. 011803, Jul. 2010, doi: 10.1103/PhysRevA.82.011803.
b) F. Karbstein and C. Sundqvist, *Physical Review D*, vol. 94, no. 1, Jul. 2016, doi: 10.1103/PhysRevD.94.013004.
c) F. Karbstein and E. A. Mosman, *Phys. Rev. D*, vol. 101, no. 11, p. 113002, Jun. 2020, doi: 10.1103/PhysRevD.101.113002.

Setup

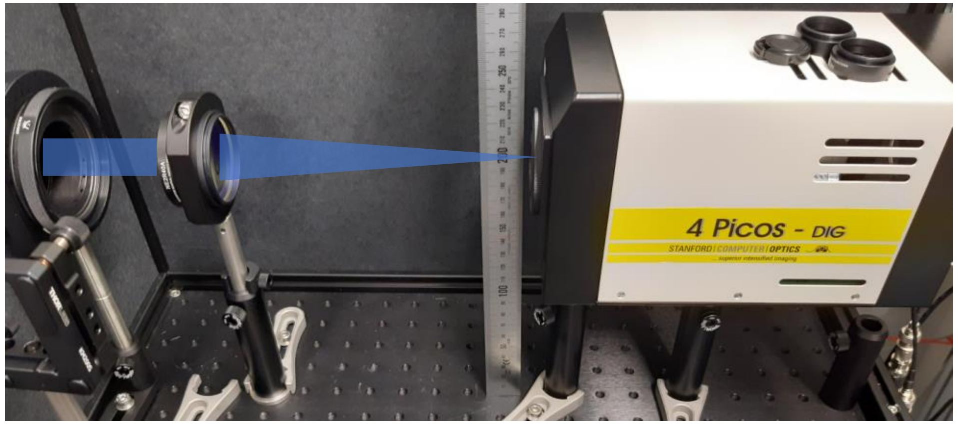


- JETI-200 laser, Jena
- Single laser beam
- 24fs, 175mJ in focus (~5TW)
- f/1.5 focusing
  - off-axis parabola, OAP
  - Measured $d_{FWHM} \approx 2.2\mu m$
  - I_peak ~ 5e19 W/cm²
- Polarization H or V

Setup

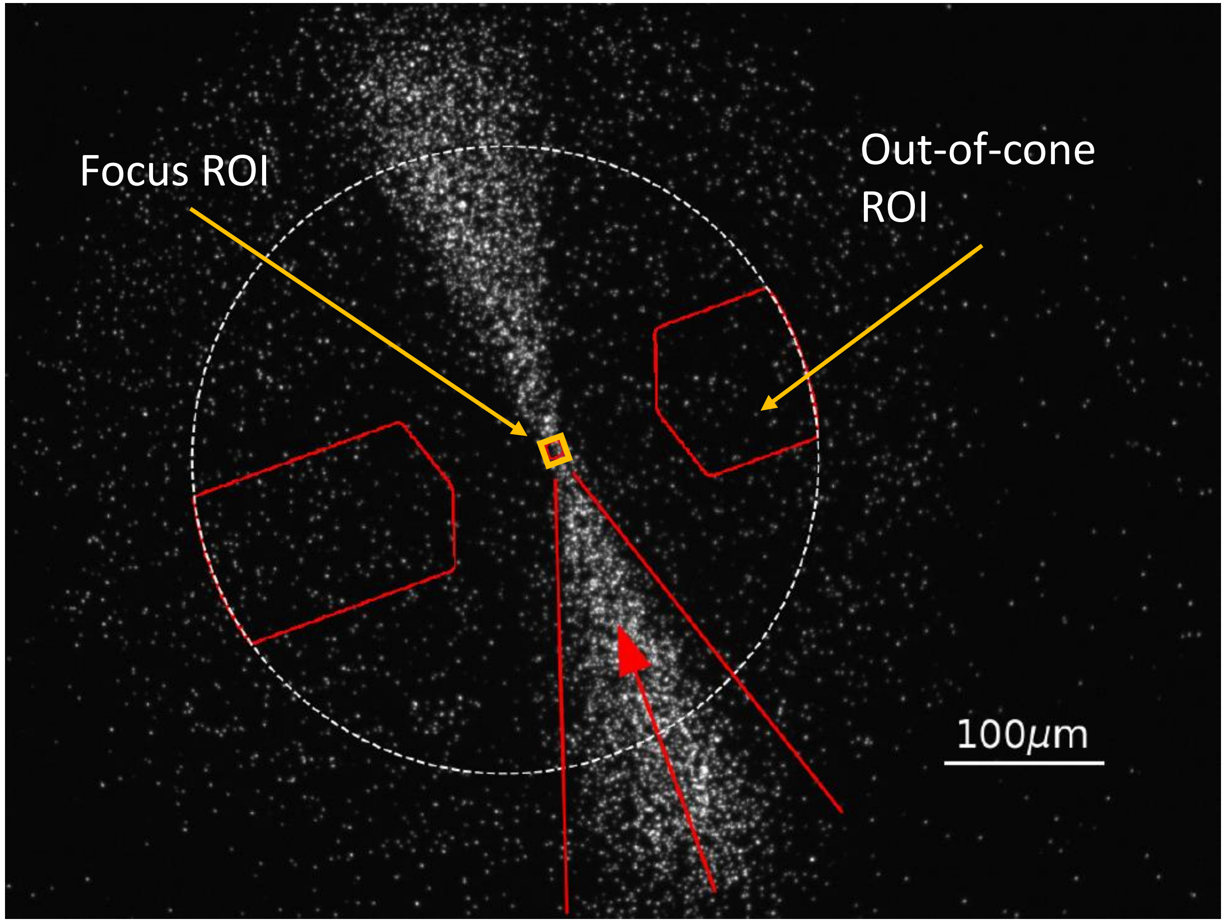


- Focus oberserved from 90° angle
- Large collection angle objective
- In air: 4Picos camera
  - Single photon sensitive
  - Time gated (1ns in this study)



- light tight imaging path
- viewing cone free of scatterers

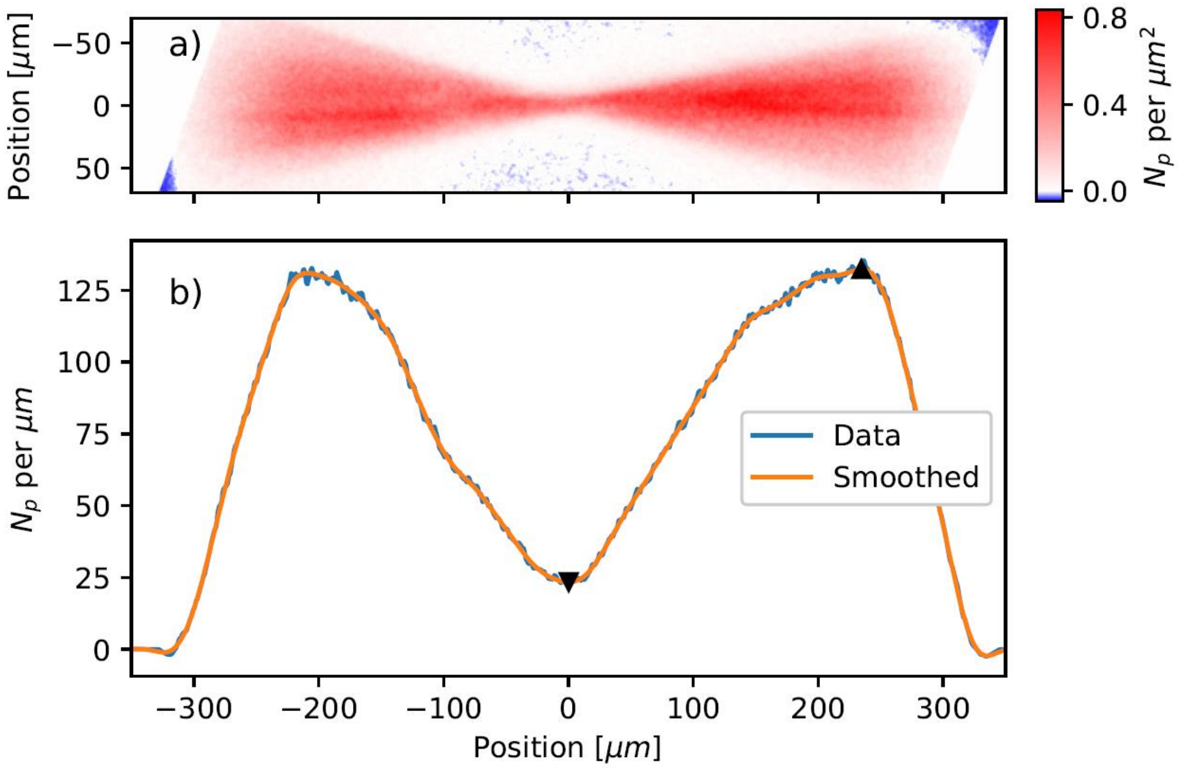
Typical image on gated single photon camera



175mJ, V polarization, p=5e-4mbar, image angle due to setup

- Laser cone seen as „bow tie“ (p-dependent)
- Homogeneous static background (p-independent)
- Analysis in 2 Regions of Interest (ROI)
  - Focus ROI 10x10um²
  - Out-of-cone background ROI
  - Limited by vignetting (dashed)
- Calibrated estimated photon number N_p (incl. optics losses)

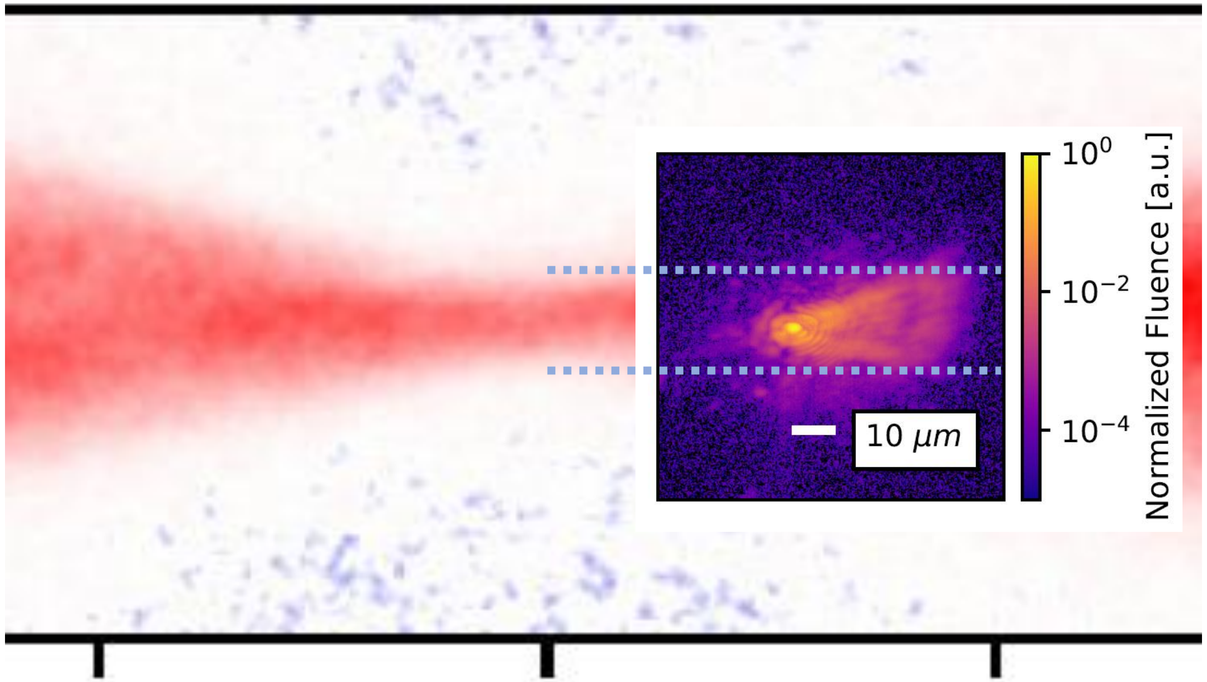
Accumulated image lineout



175mJ, V polarization, p=5e-4mbar, 242 shots accumulated

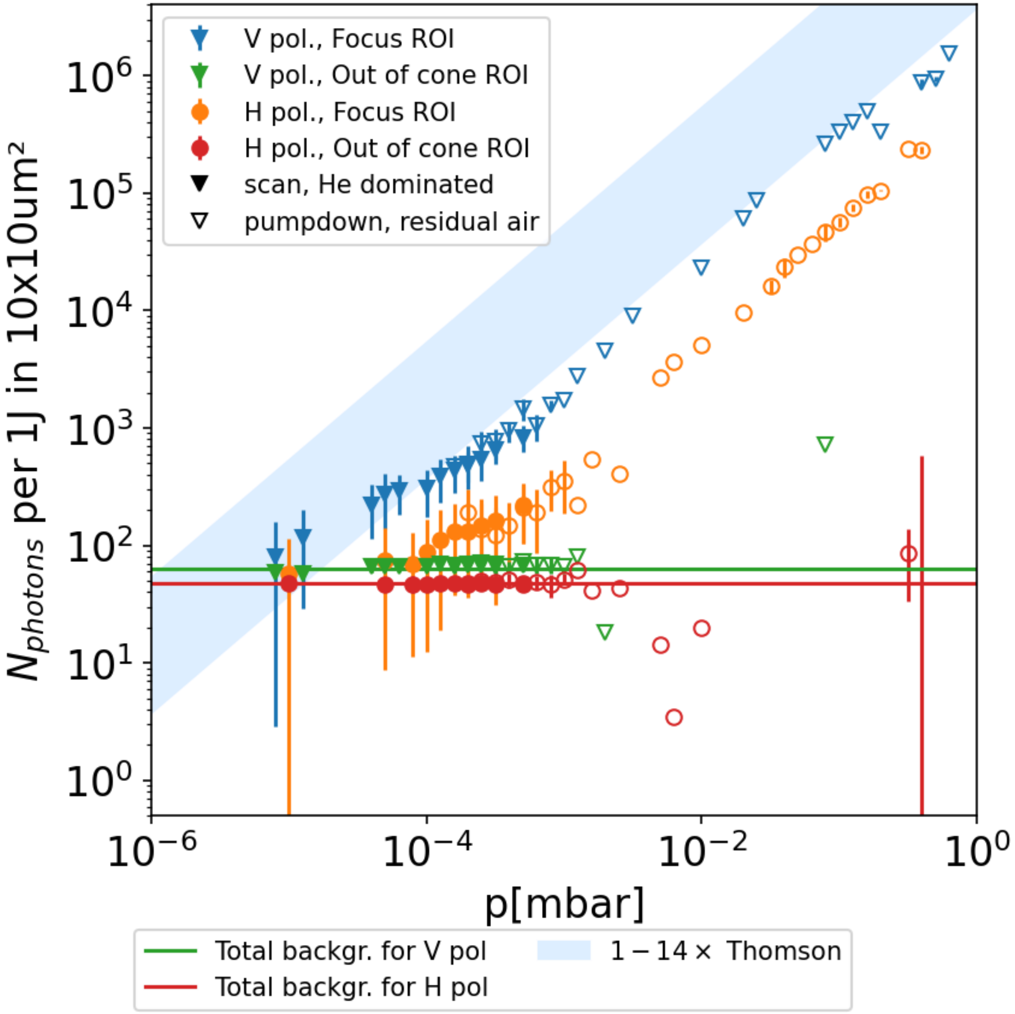
- If linear scattering + constant scatterer density: focus brightest
- **Instead**:
- 4-10x reduced integrated brightness
- → ponderomotive electron cavitation due to high peak intensity

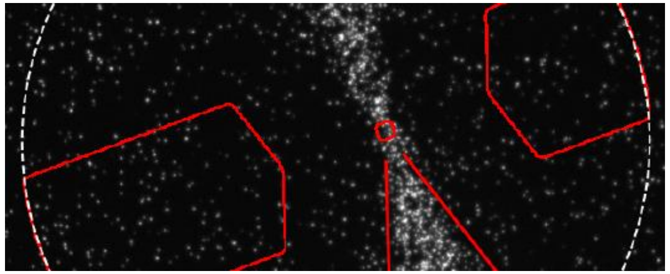
Accumulated image lineout



- Ponderomotive electron cavitation due to high peak intensity
- expected completely empty on axis, rest of light from outer regions, pedestal
- → reducible and suppressible for future experiments

Pressure dependence

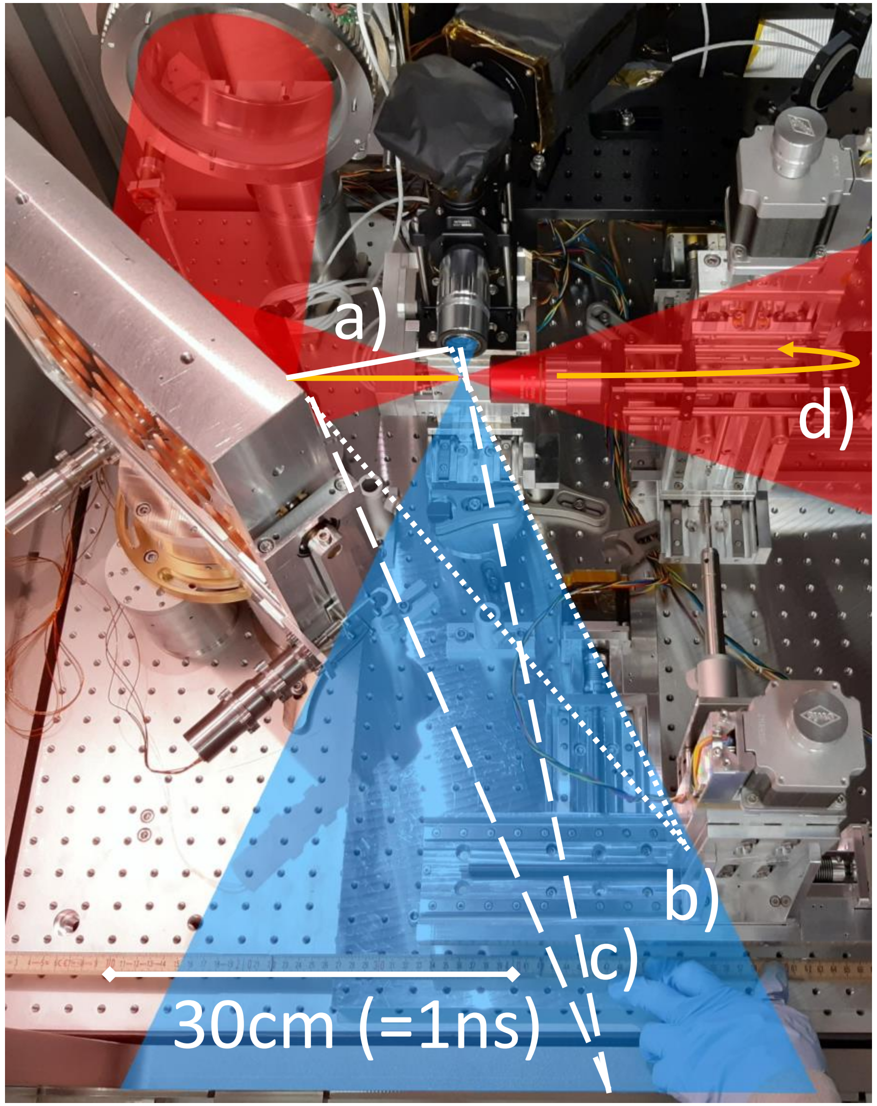




- Only inside ROI
- per 10x10um²
- per 1J pulse energy

- pressure-dependent – only in focus ROI
  - Compare to Thomson scattering (1-14 free electrons)
  - V polarization: reduced by factor 4-10
  - H polarization: reduced 8x over V (dipole characteristic)
- p-independent – both ROIs
  - dominates $< 10^{-4} mbar$
  - Mean = $63\ J^{-1}$ for V polarization
  - Mean = $47\ J^{-1}$ for H polarization
- → static scattering dominant in relevant pressure region

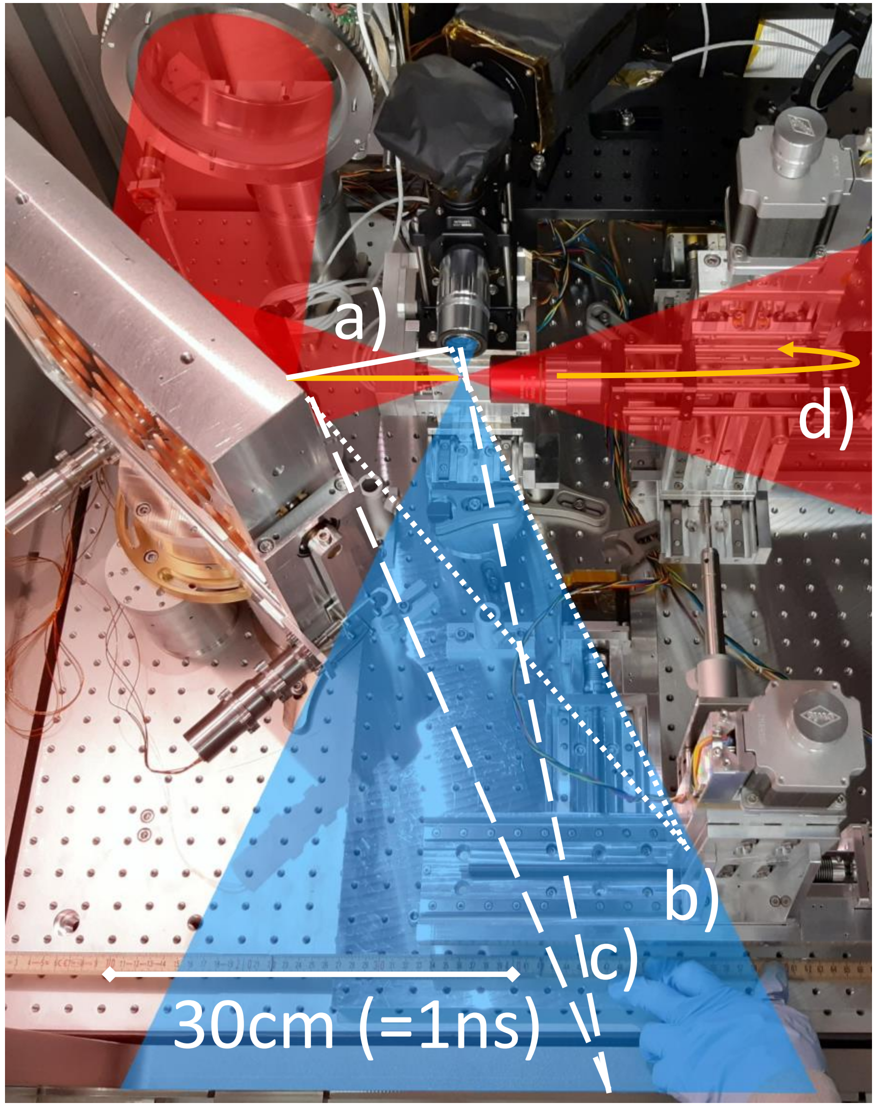
Potential sources of background

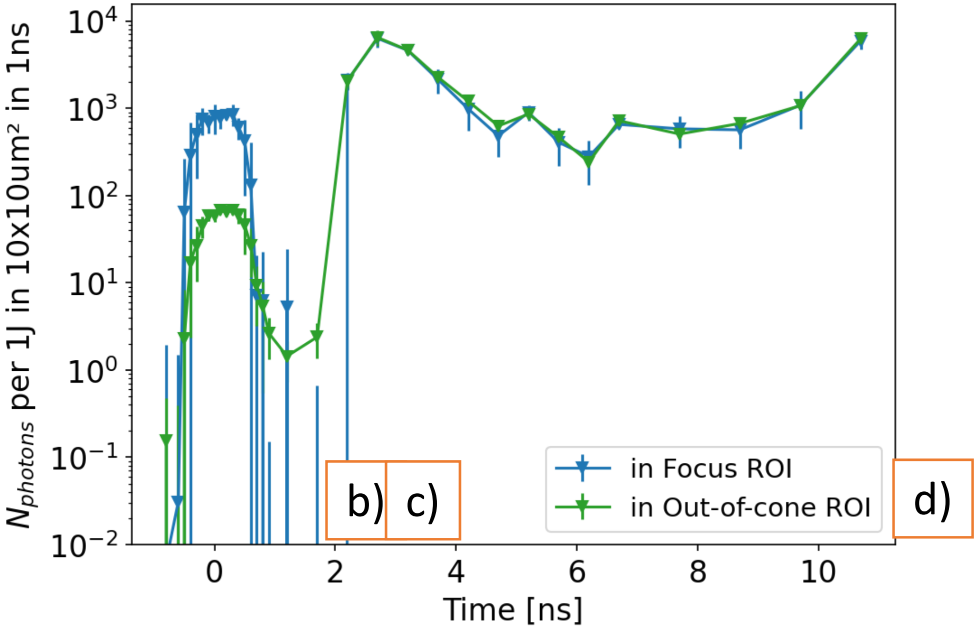


- 99%: inside expected cone (red)
- ~1%: scattered off OAP

- Laser path (orange)
- a) $\Delta t \approx 0ns$
- b) $\Delta t \approx 2.7ns$
- c) $\Delta t > 3ns$
- d) $\Delta t > 11ns$
- → need to consider light
  - at $t = 0$ and
  - at $t = -2.7ns$ to $-11ns$

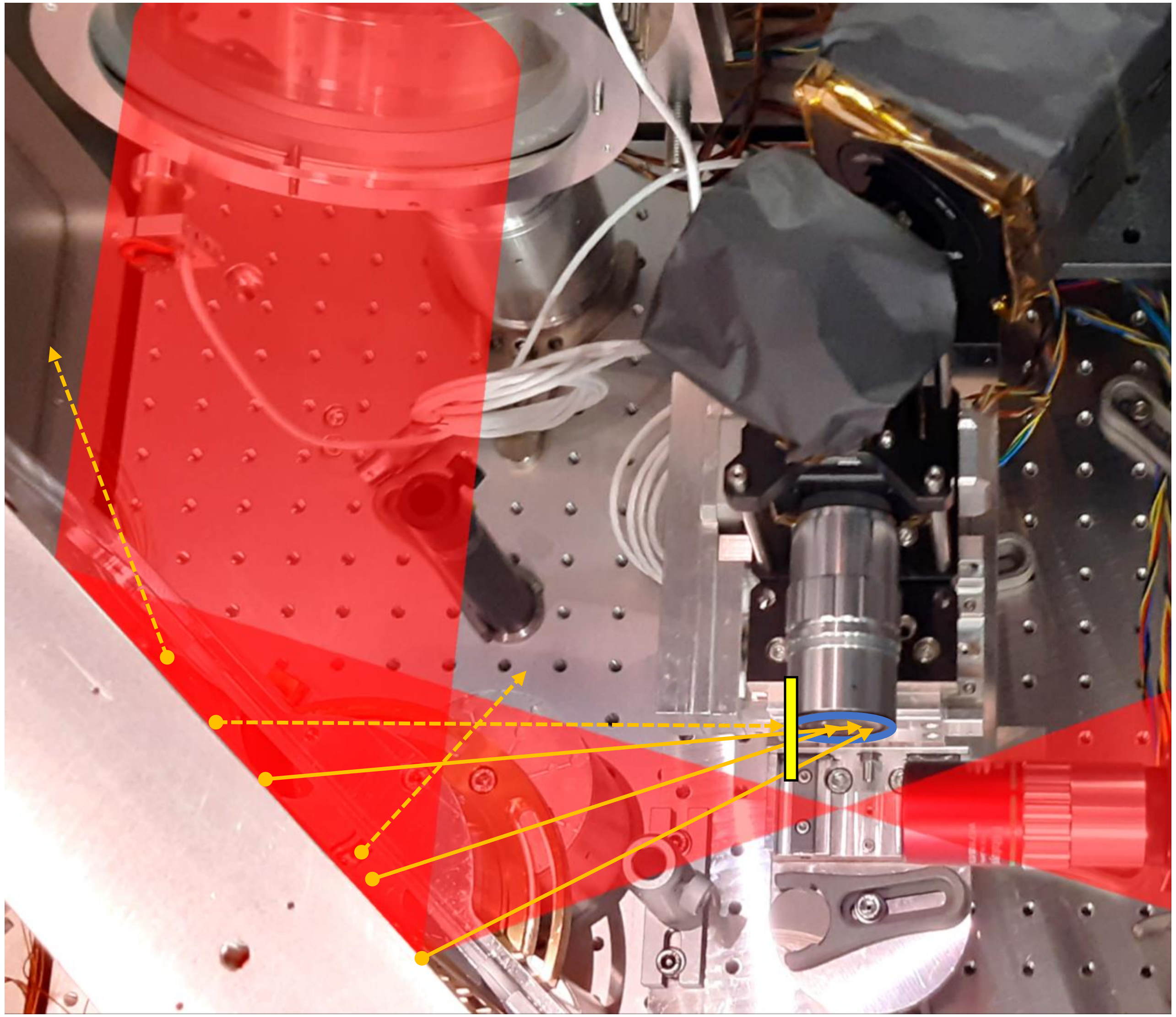
Potential sources of background



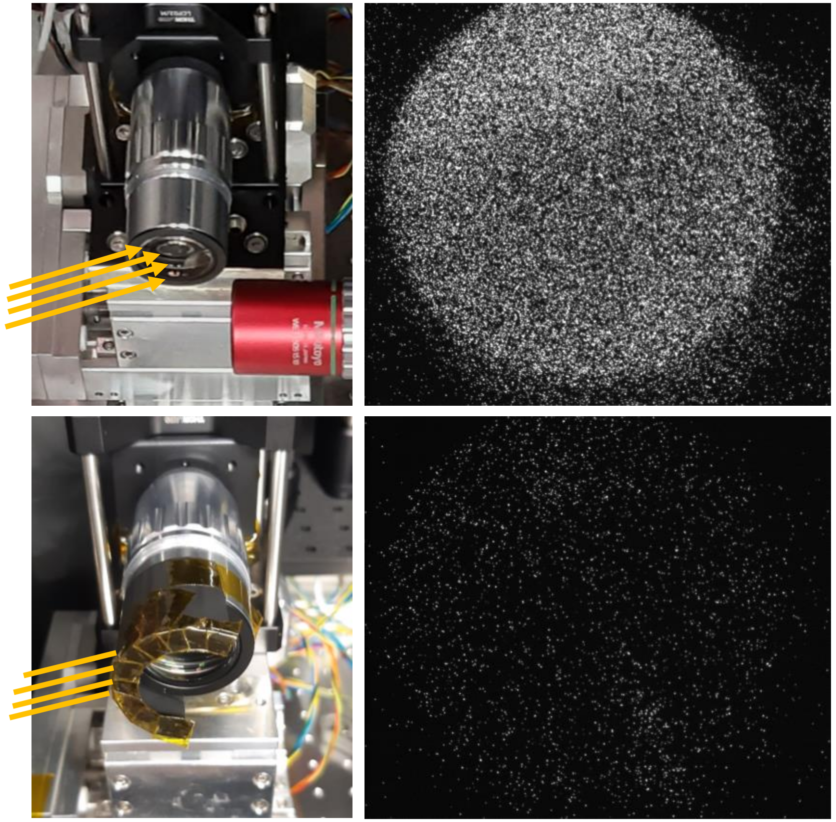


- Paths b) c) d): match
- Temporal effects:
  - Prepulses and amplified spontaneous emission (ASE) → contribute $< 1\ J^{-1}$
  - camera gating suppression → $5\ J^{-1}$
- → path a) must contribute 40-60 photons per 1J

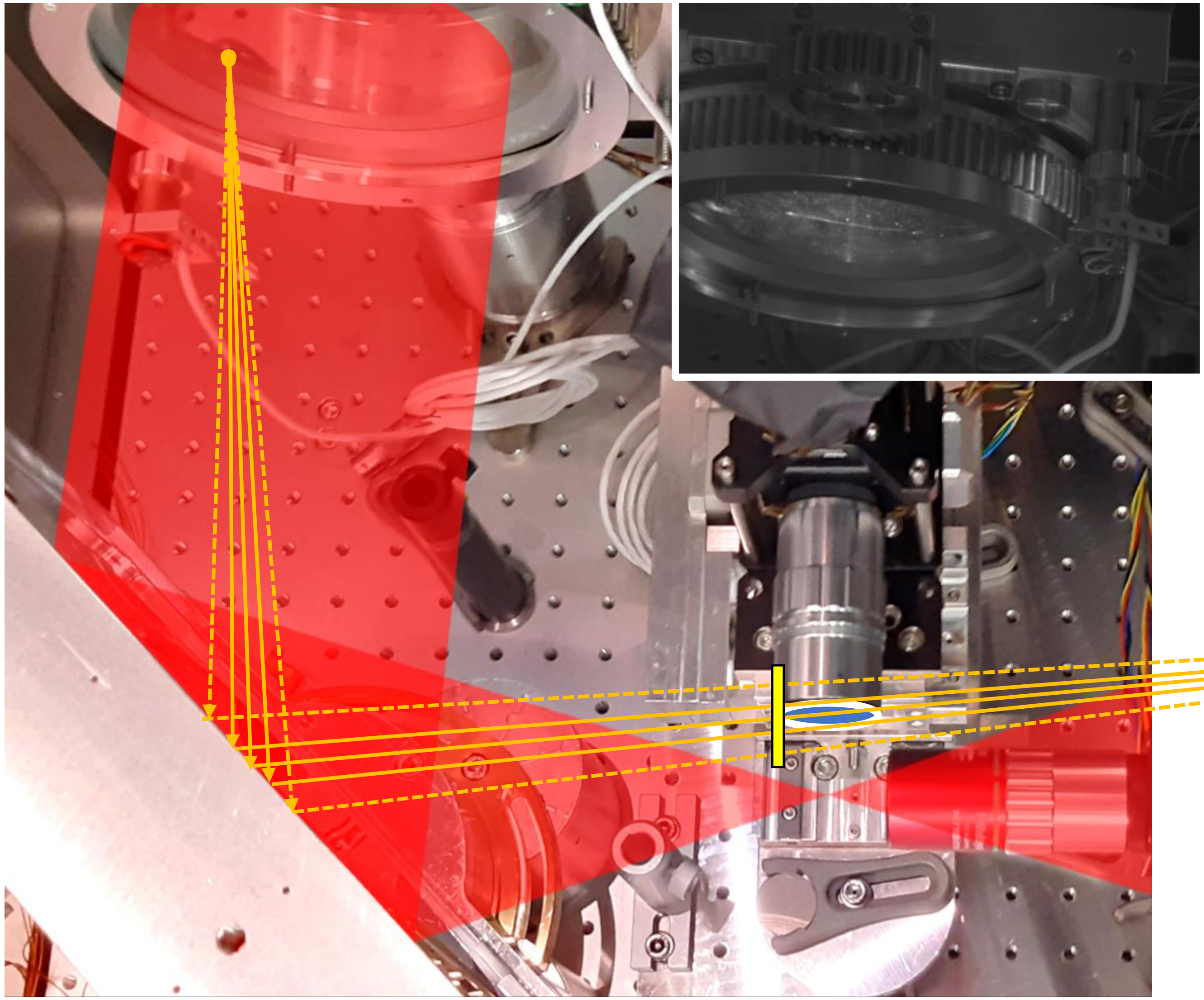
Potential sources of background: direct scattered light



- Scattered off OAP + upstream optics
- Without light shielding baffle:



Potential sources of background: direct scattered light



- Real image behind OAP

$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f}$$

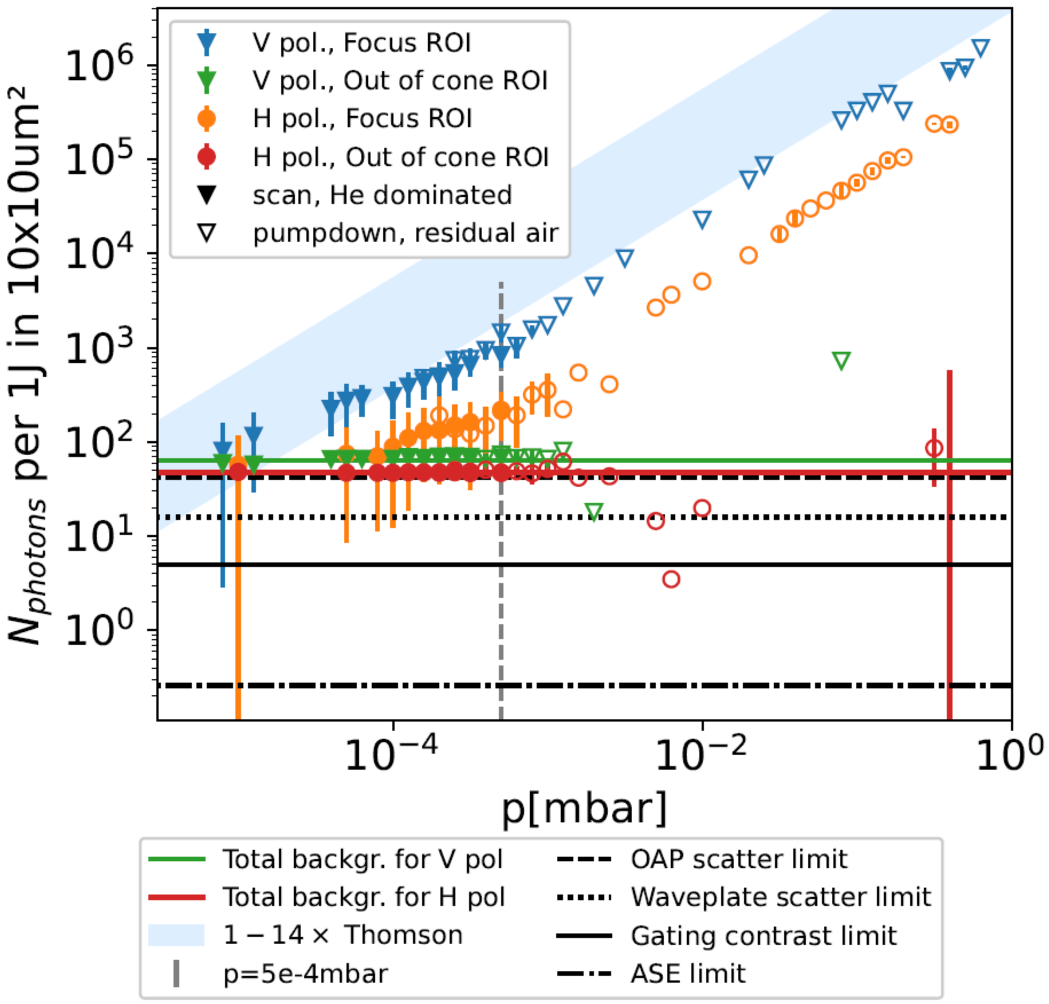
- Construct rays → will intersect objective aperture

- Both effects should be 0 with baffle

All background contributions

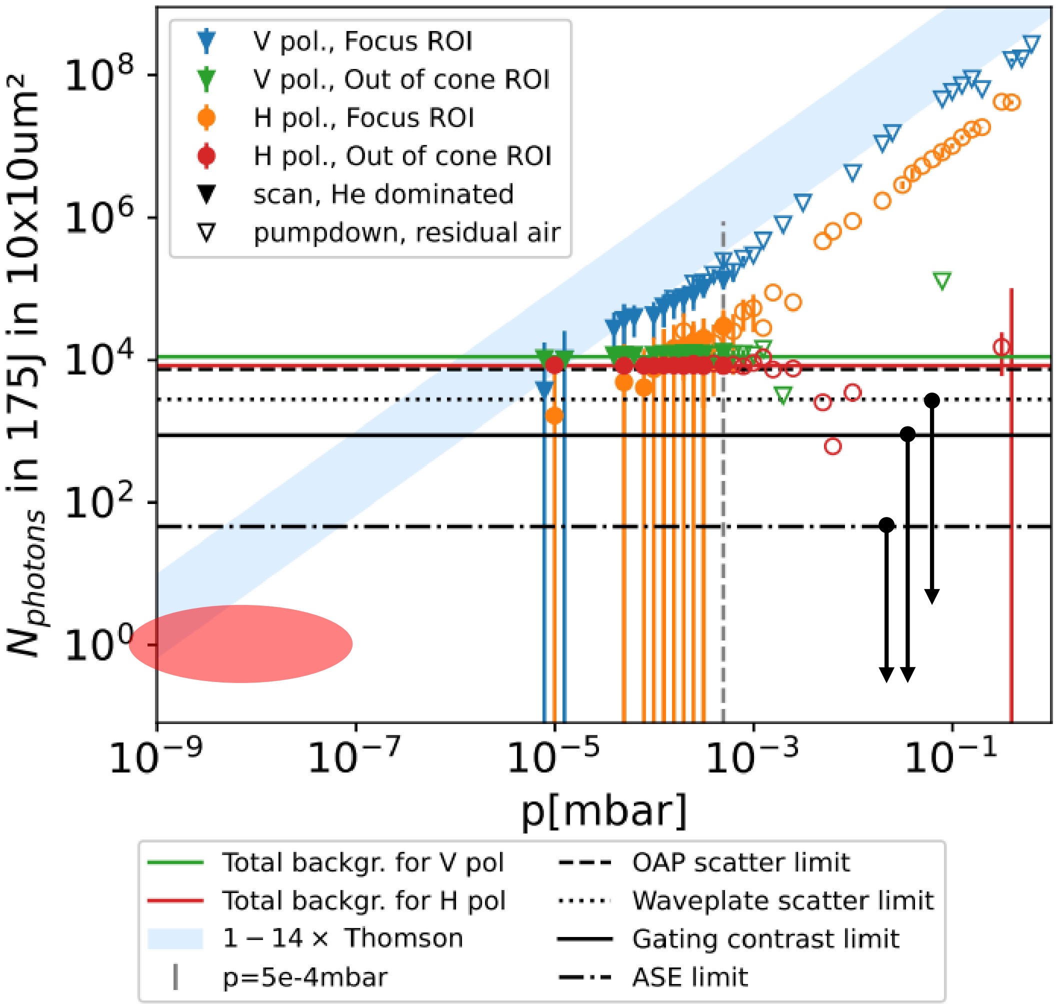
- Split total background number into contributions determined:

Contribution	H polarization	V polarization
Prepulses/ASE	0.3	0.3
Gating limit	5	5
Waveplate	-	16
OAP	42	42
Total	**47**	**63**



Towards multi-beam Petawatt experiments

- Scale from 175mJ to 175J
- Determine level for O(1) photon
- Residual gas scattering
  - $p \approx 10^{-9} mbar$ required assuming simple Thomson scattering
  - $p \approx 10^{-7}$ to $10^{-8} mbar$ sufficient with ponderomotive cavitation
- Temporal effects
  - Suppressible with shorter gating time
- Static scattering
  - Upstream optics: move further upstream
  - OAP: still $O(10^4)$ photons



- Word of caution
  - Future experiments likely not at 90°
  - → Scattering off optics (and rest gas) may be harder to suppress

Conclusion

- Experimental setup to measure background for future PW-compatible photon-photon-scattering setup
- Single photon detection of background from
  - Residual gas
  - scattering off mechanical components
- Scaling to PW level
  - Rest gas scattering and prepulses/ASE suppressible in future
  - Reduction of static scattering to be determined (light shielding, optical gating)
  - Especially when not observing at 90° but closer to laser axis

- *Paper submitted in NJP*
- *Funded by the Deutsche Forschungsgemeinschaft (DFG) under Grant No. 416702141; Research Unit FOR2783/1*
- *http://quantumvacuum.org/*