Hunting Chameleons with the CAST Experiment at CERN

Justin Baier on behalf of the CAST collaboration

15th Patras Workshop on Axions, WIMPs and WISPs

3rd – 7th June 2019

University of Freiburg

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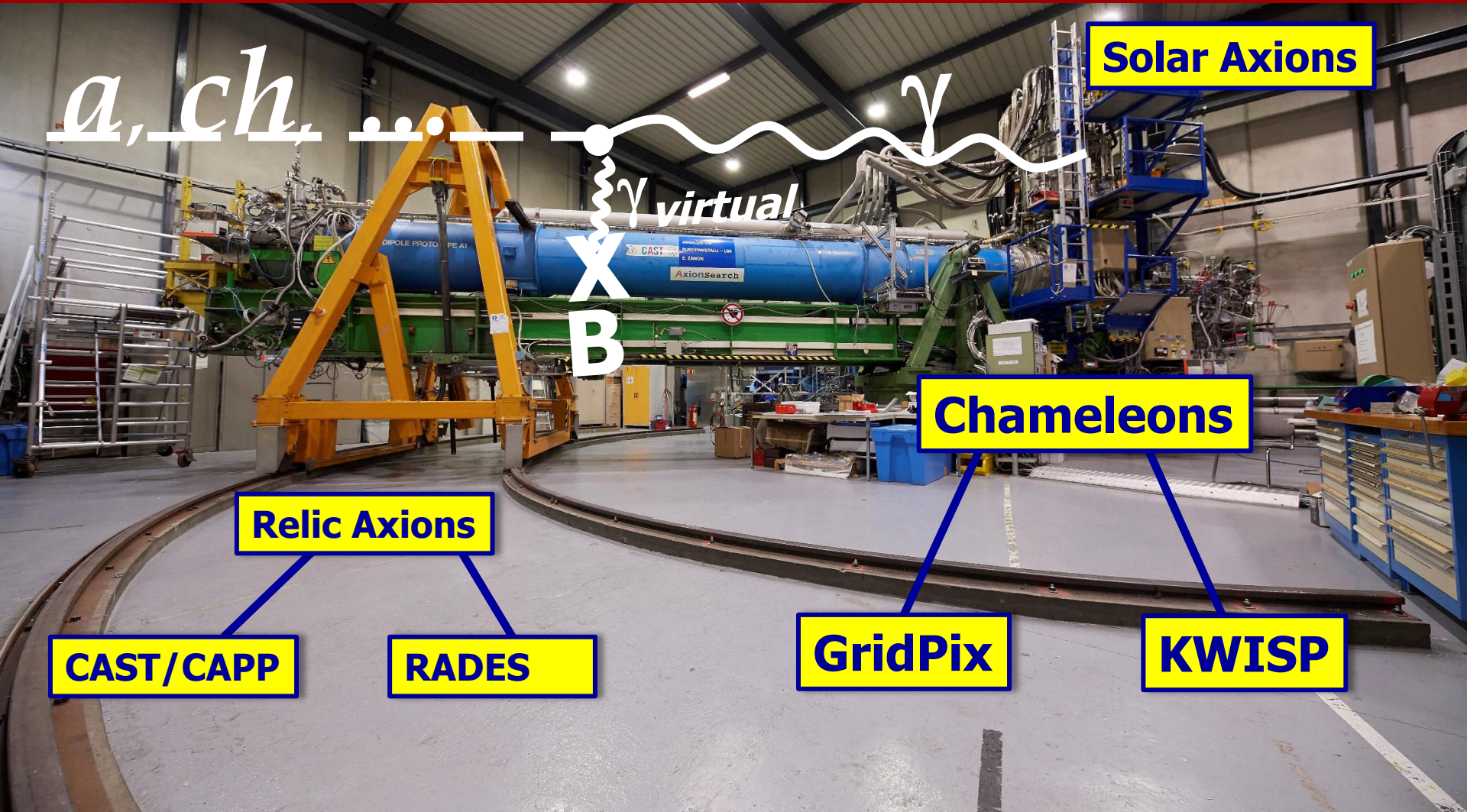
CAST EXPERIMENT

The CAST Physics Programme



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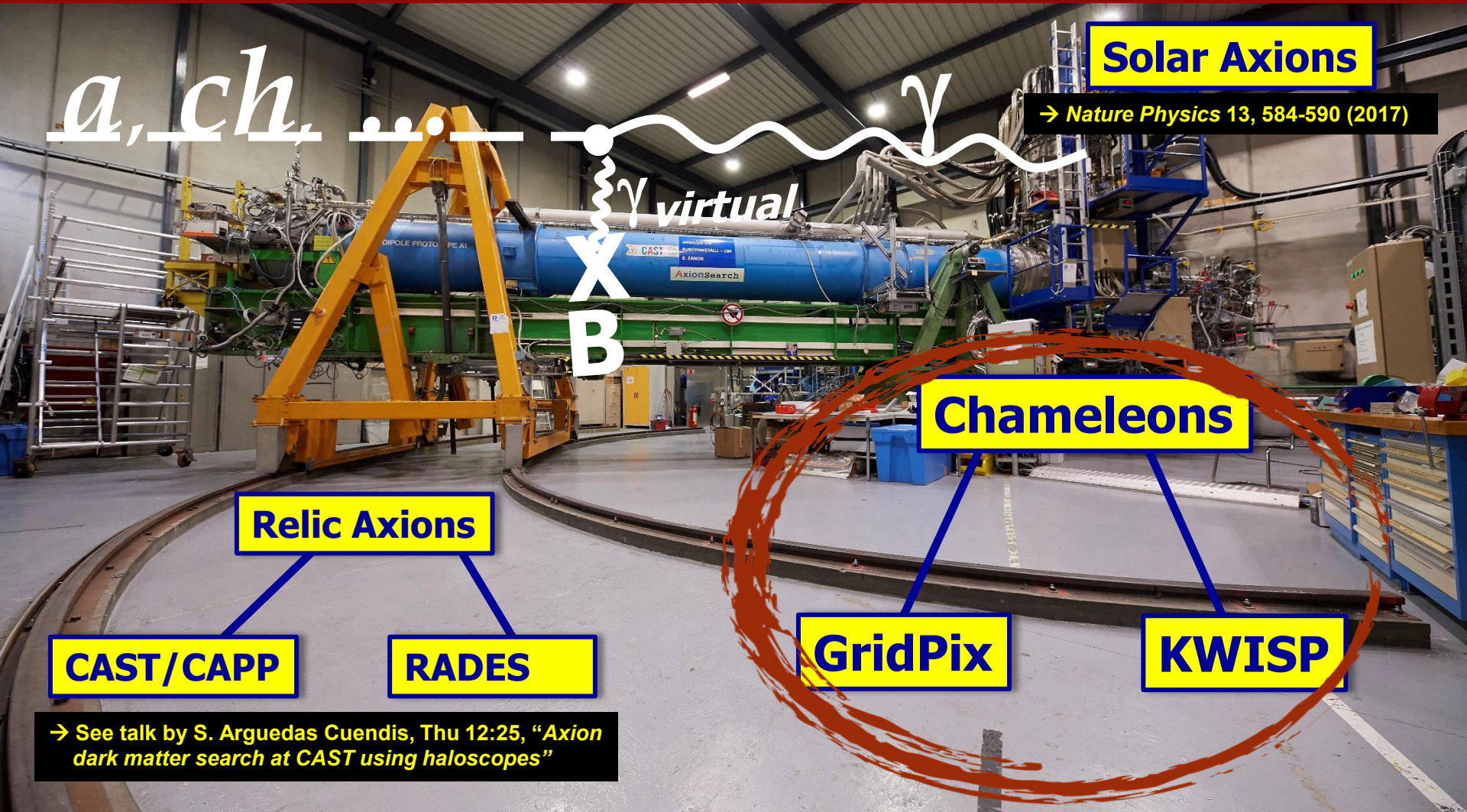

Chameleon Primer

- proposed 2003 as possible **dark energy candidate** (Phys. Rev. D 69, 044026)
- scalar field with effective potential dependent on ambient matter / EM field

$$V_{eff}(\phi) = \frac{\Lambda^{4+n}}{\phi^n} + e^{\frac{\beta_m}{M_{Pl}}\phi}\rho_m$$

Coupling to matter

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Coupling to matter

Coupling to photons

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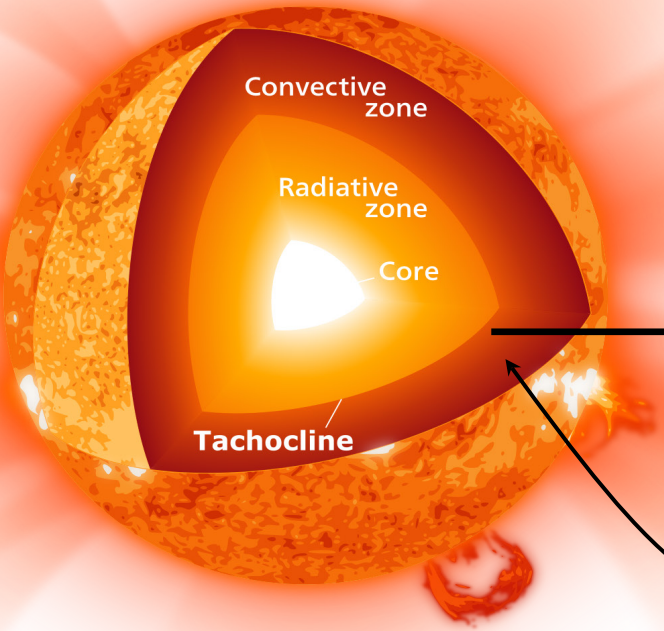
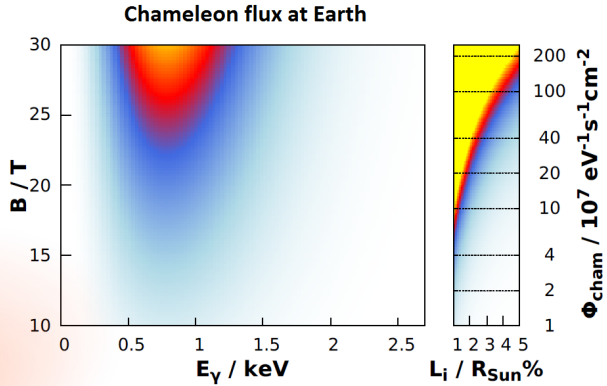
Coupling to photons

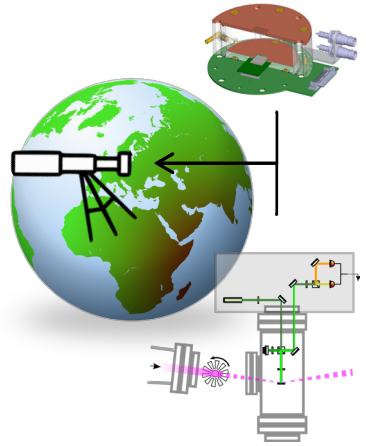
- photon ⟷ chameleon conversion inside strong magnetic fields
- Detection via Primakoff effect (GridPix)

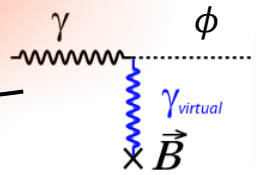
Solar Chameleons





Chameleons leaving the Sun reach the Earth unhindered.

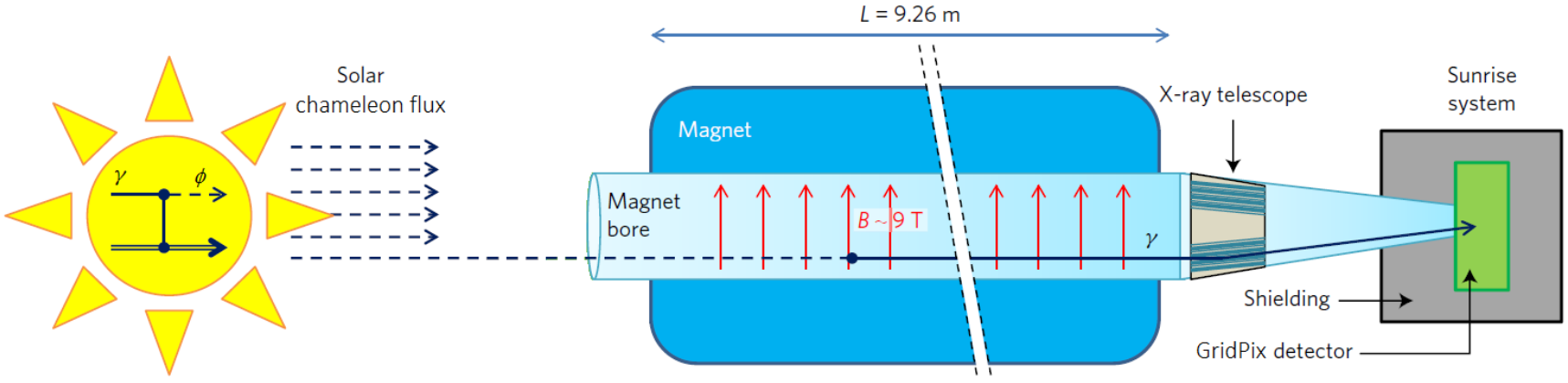




Chameleon production via Primakoff effect in the tachocline region.

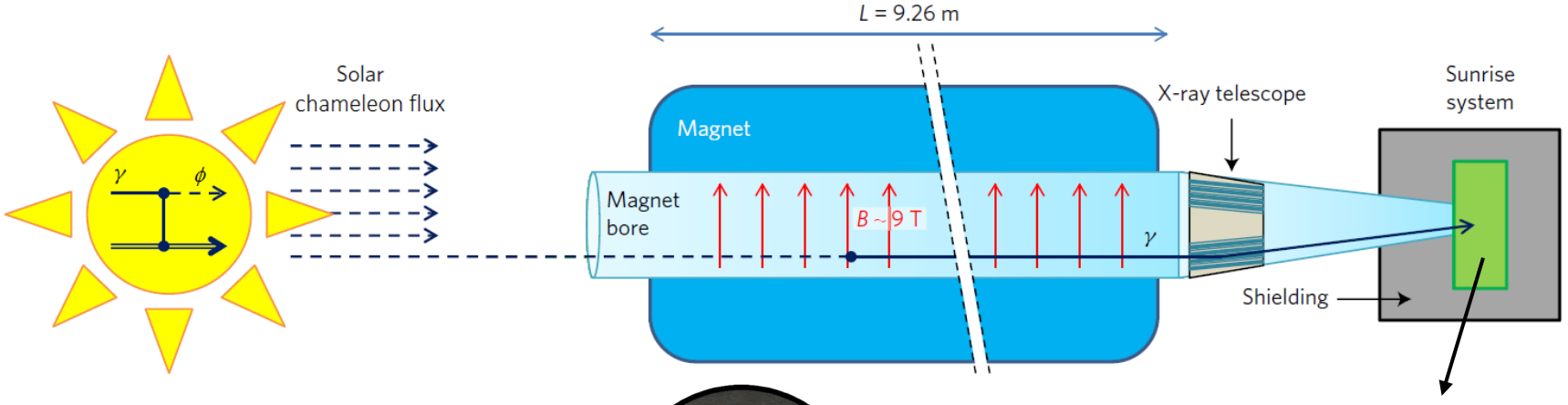
Search via Chameleon-Photon Coupling

Detection Principle

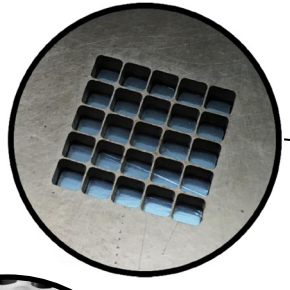


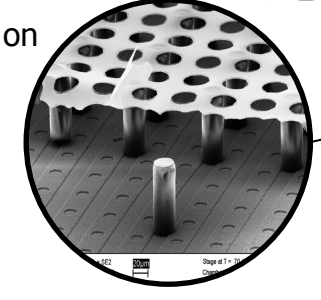
- chameleon to photon conversion inside magnet bore by inverse Primakoff effect
- conversion probability: $p_{\phi\to\gamma}(L) \propto \beta_\gamma^2 B^2 L^2$
- photon detection via GridPix detector

GridPix Detector



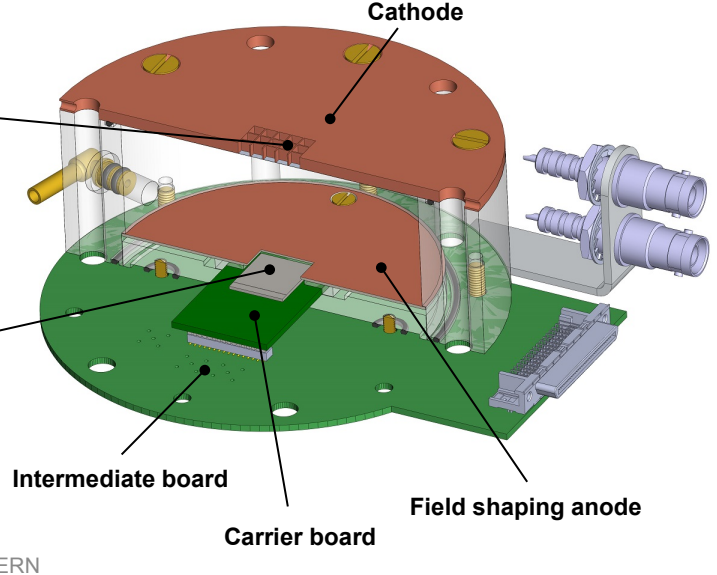
X-ray window
(2 µm aluminized Mylar on strongback)



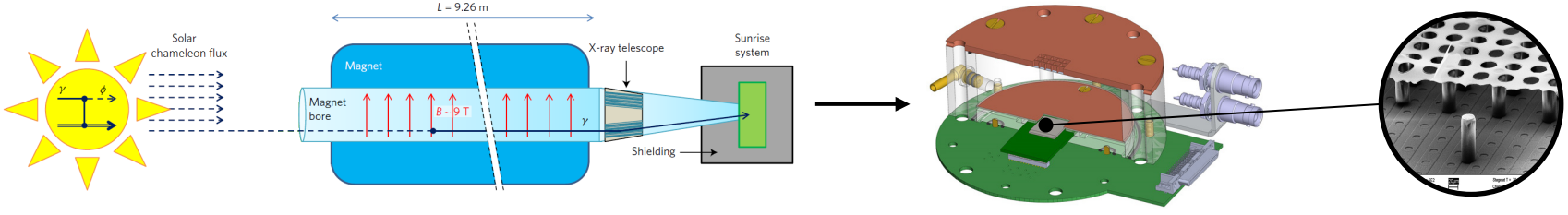


GridPix - Integrated MicroMegas on top of Timepix ASIC:

- 256 x 256 pixels
- 55 x 55 µm² pitch

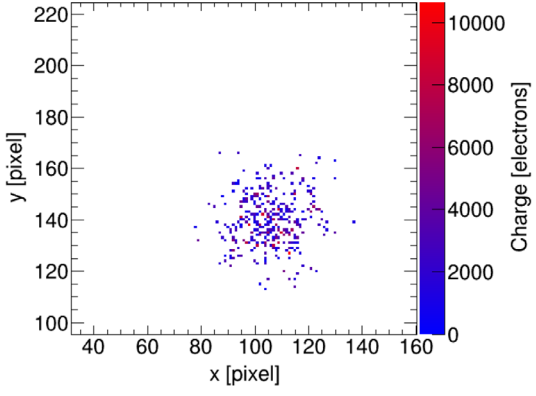


GridPix Detector

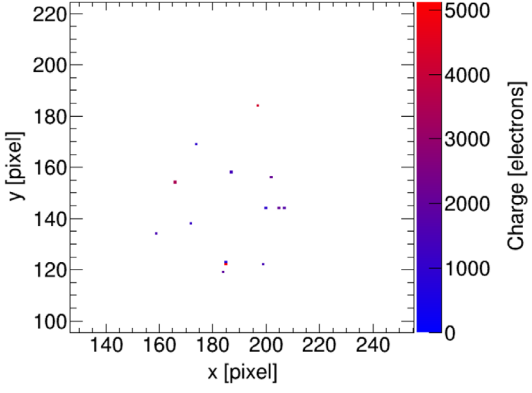


Typical events as seen by GridPix:

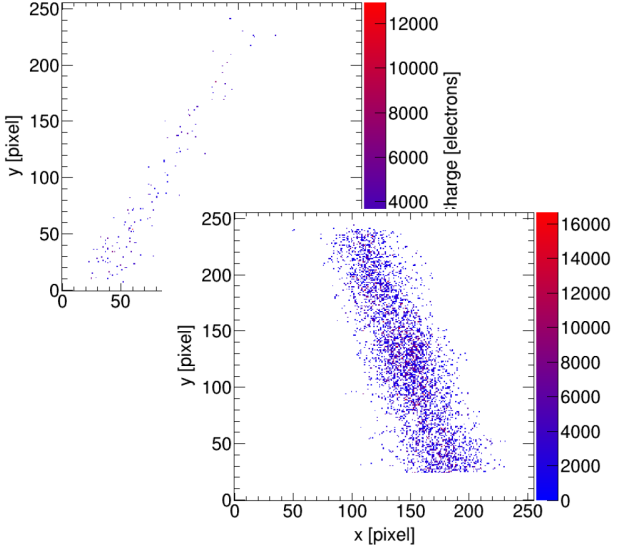
X-ray event (5.9 keV)



X-ray event (277 eV)

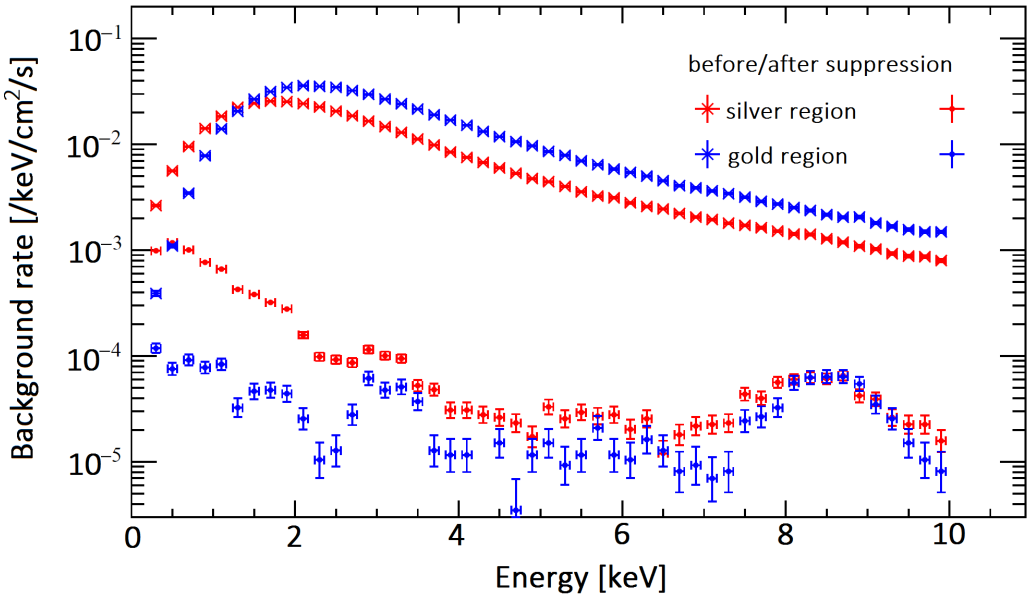


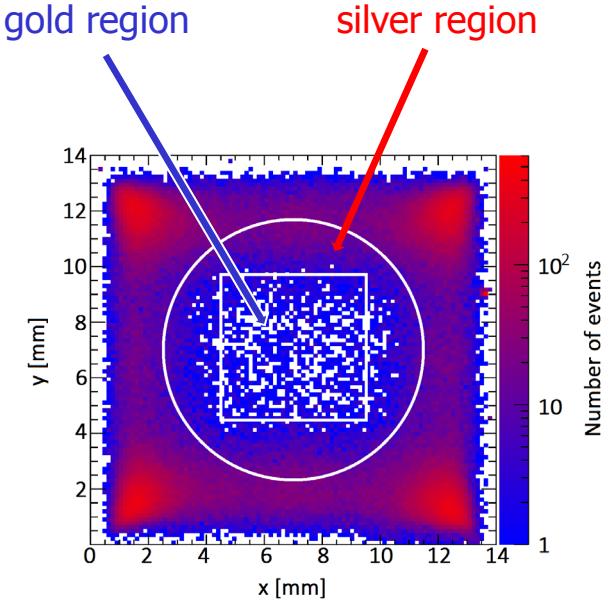
Non-X-ray events (e.g. cosmic or α)



Background Rate

- background suppression by likelihood method derived from eventshape variables and calibration data
  → background rate < 10^{-4}/keV/cm^2/s
- chip divided into two relevant areas for data analysis





Expected Signal

Solar chameleon spectrum

Conversion probability

Geometry of CAST magnet

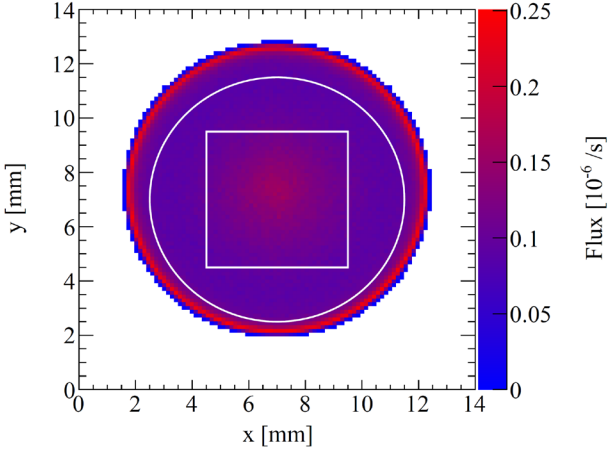
XRT imaging

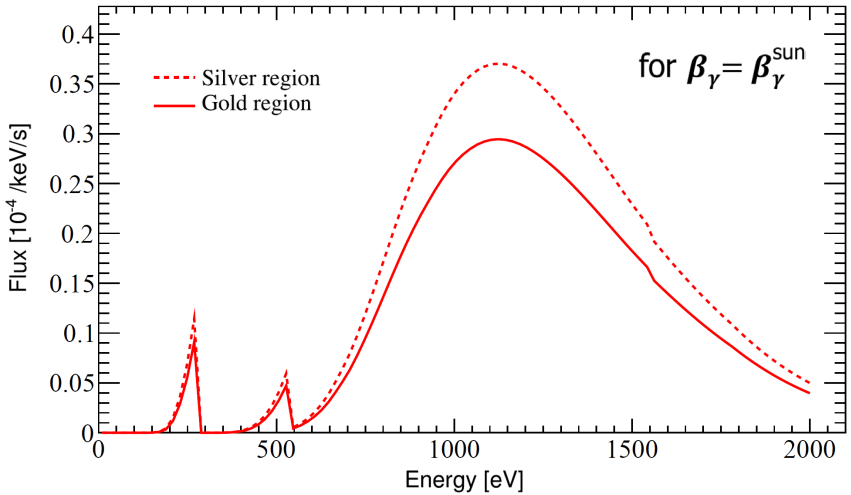
Detection efficiency

(X-ray window transmission &

absorption in detector volume)

Software efficiency (80%)

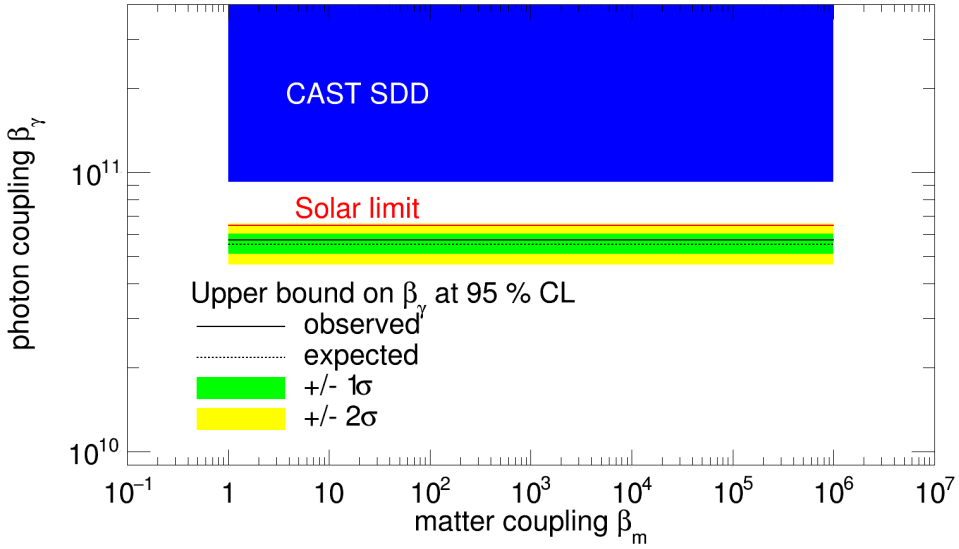




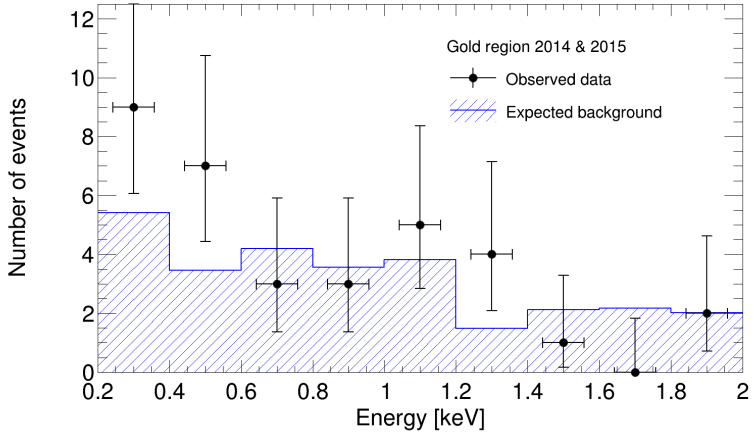
Data Taking Campaign 2014/15

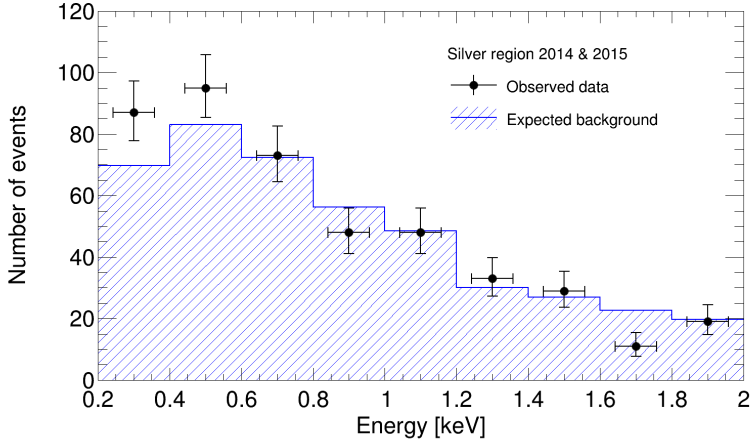
- statistics: 254 h solar tracking, 4785 h background
- daily calibration with ^{55}Fe source
- no significant excess over expected background

→ $\beta_\gamma \lesssim 5.7 \times 10^{10}$ for $1 < \beta_m < 10^6$

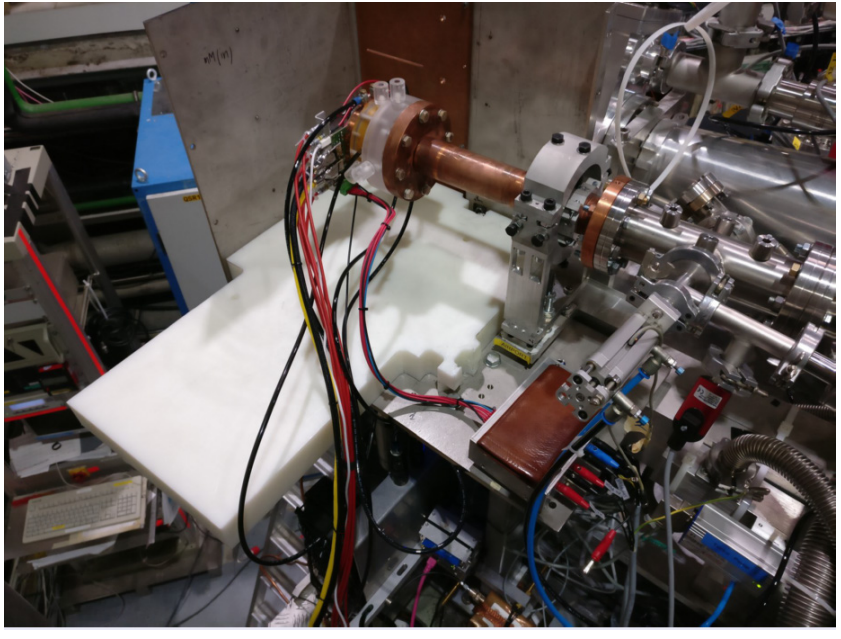


V. Anastassopoulos *et al* JCAP01(2019)032





Outlook Data Taking Campaign 2017/18



Implementation of new features!

For more information check out the poster of Tobias Schiffer tomorrow!

Data taking statistics:

- 106,5 h solar tracking
- 2288 h background
- 105 h calibration with ^{55}Fe source

Analysis ongoing!

Search via Chameleon-Matter Coupling

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Coupling to matter

Coupling to photons

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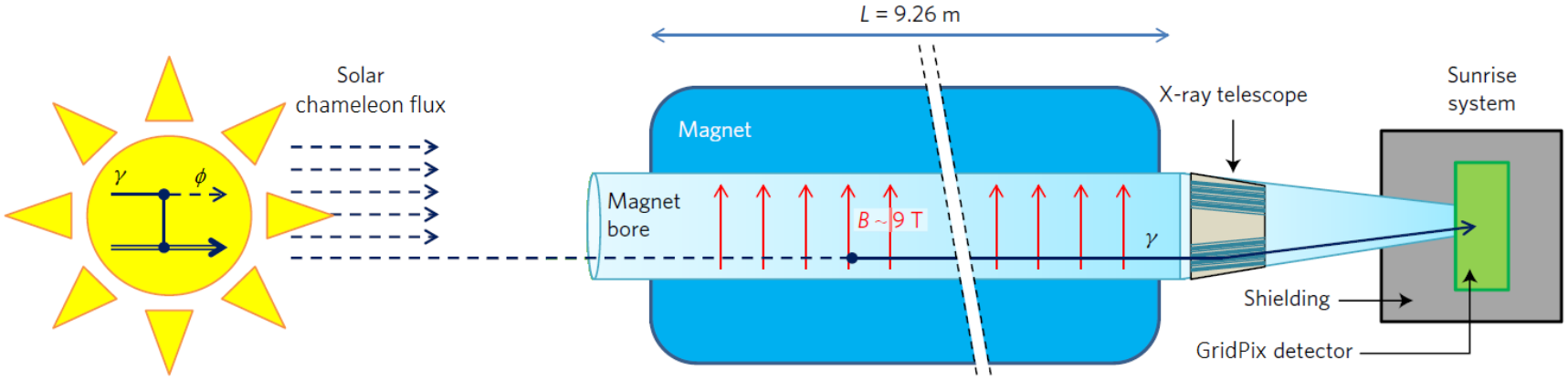
Coupling to matter

- effective chameleon mass m_{eff} in material of density ρ_m → screening mechanism
- if at boundaries $E_\phi < m_{\text{eff}}$ → reflection

Detection Principle



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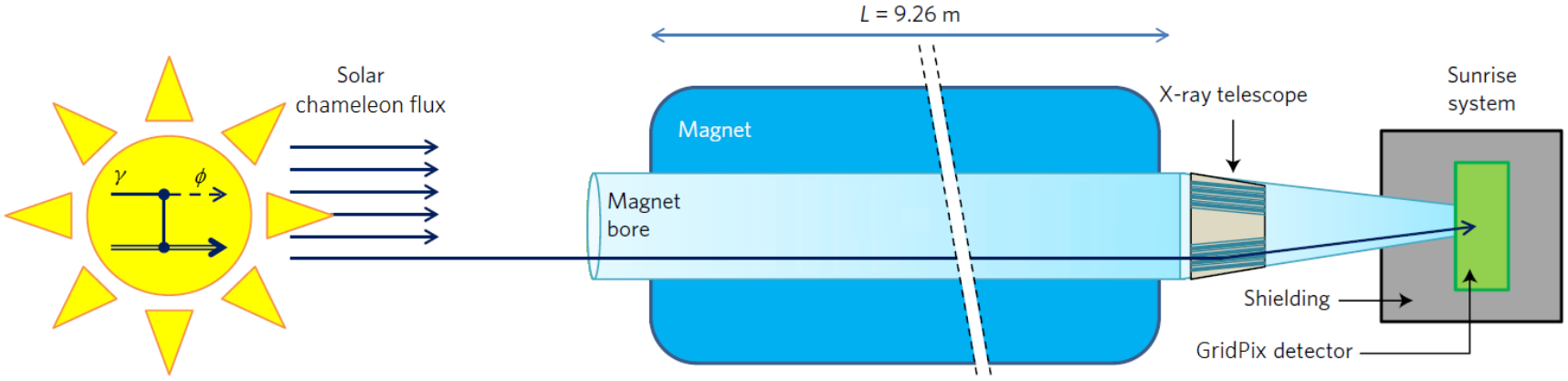

- chameleons pass through magnet bore and focused onto detector by X-ray telescope
- magnetic field of no interest, only sun tracking and XRT important

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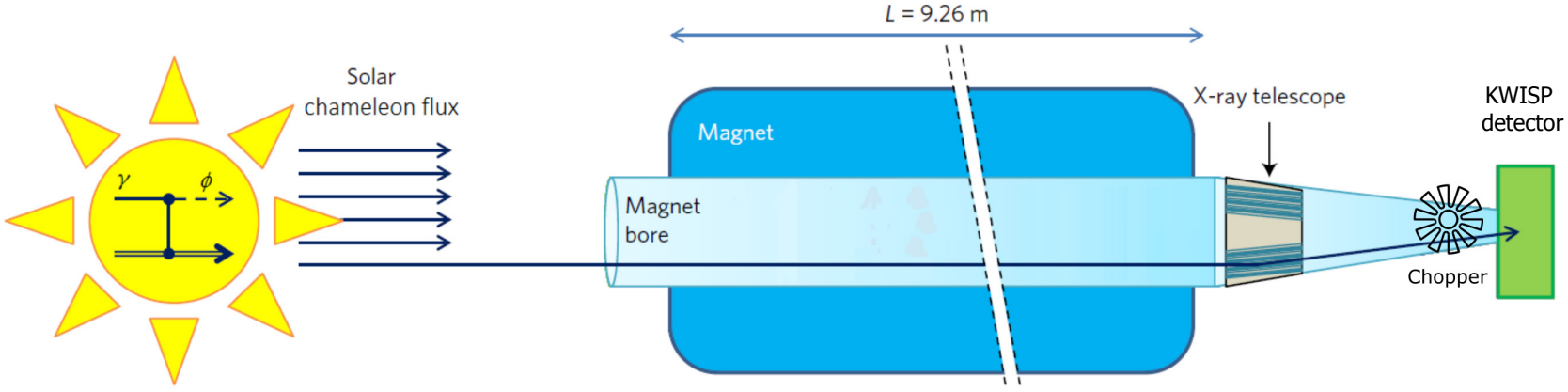
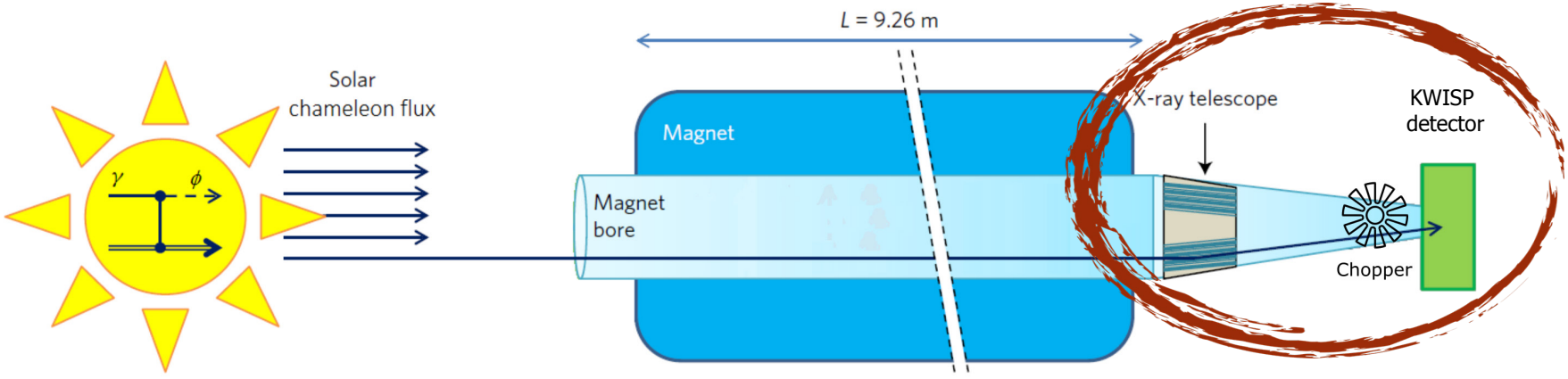


- chameleons pass through magnet bore and focused onto detector by X-ray telescope
- magnetic field of no interest, only sun tracking and XRT important
- chameleon detection via mechano-optical KWISP detector

Detection Principle



- chameleons pass through magnet bore and focused onto detector by X-ray telescope
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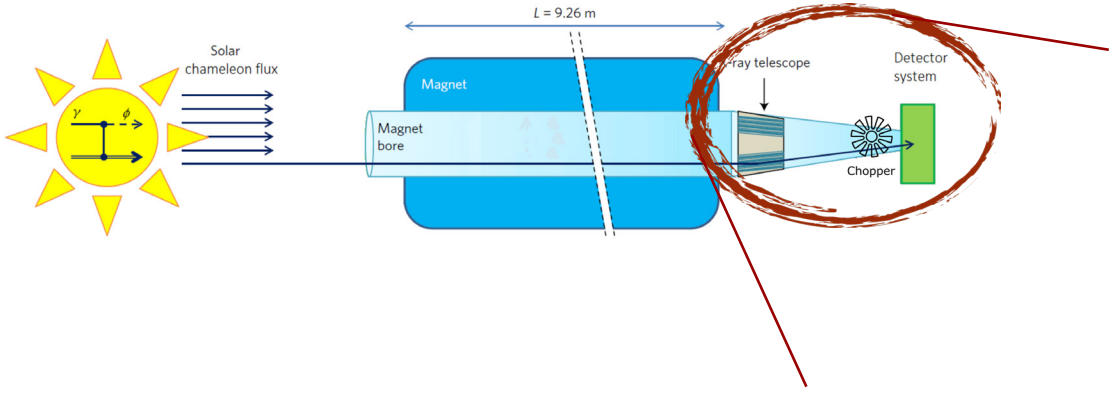
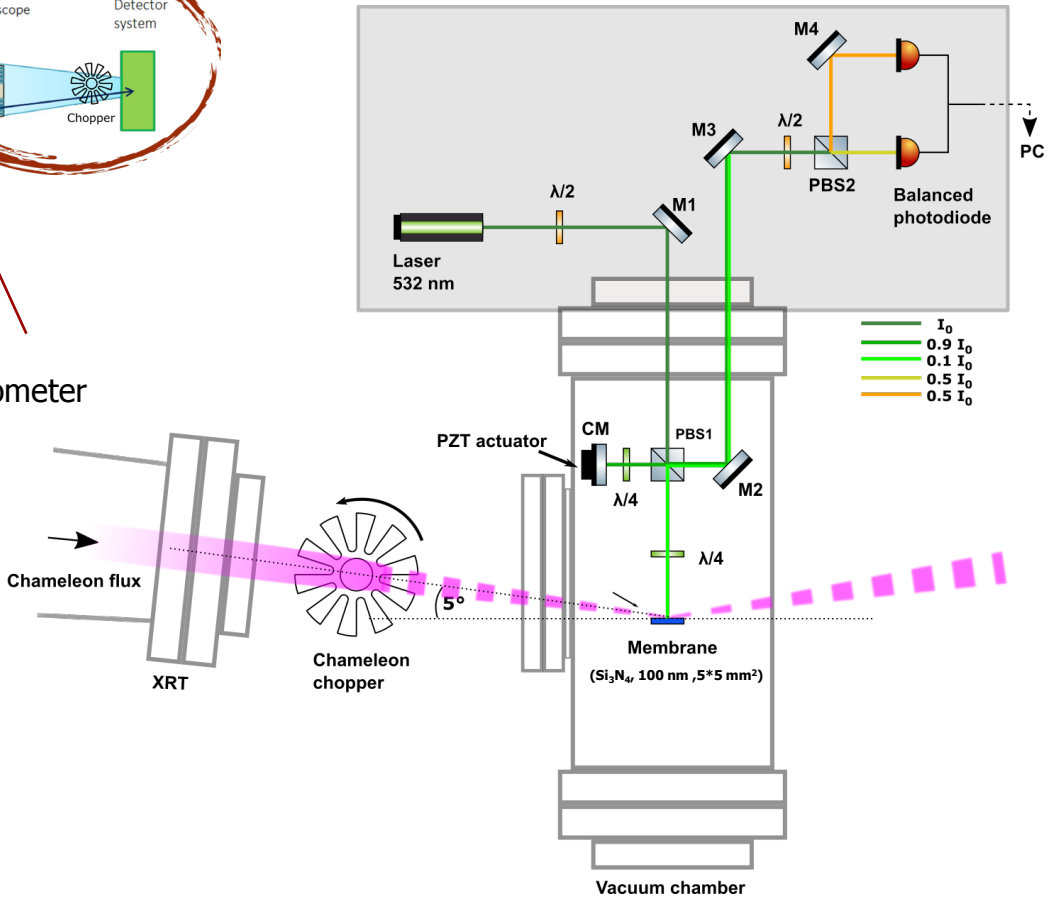
- chameleon detection via KWISP detector

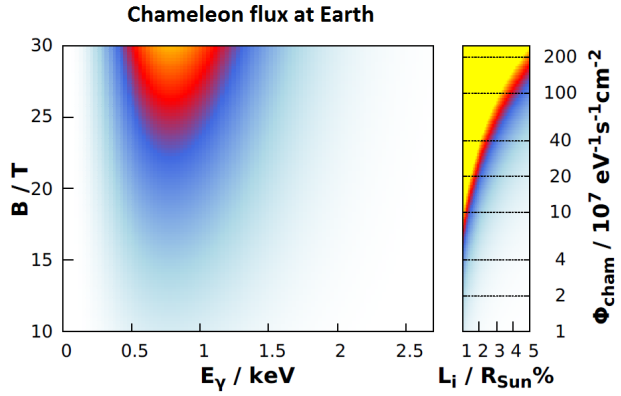
Michelson Interferometer Setup



- thin membrane acting as mirror of Michelson interferometer
- if $E_\phi < \frac{m_{eff}}{sin\ \alpha}$ → reflection → membrane displacement
  → change in intensity of fringes
- homodyne readout
- chameleon flux modulation via chopper
- expected signal → at chopper frequency!
  → only during sun tracking!



Expected Force on Membrane



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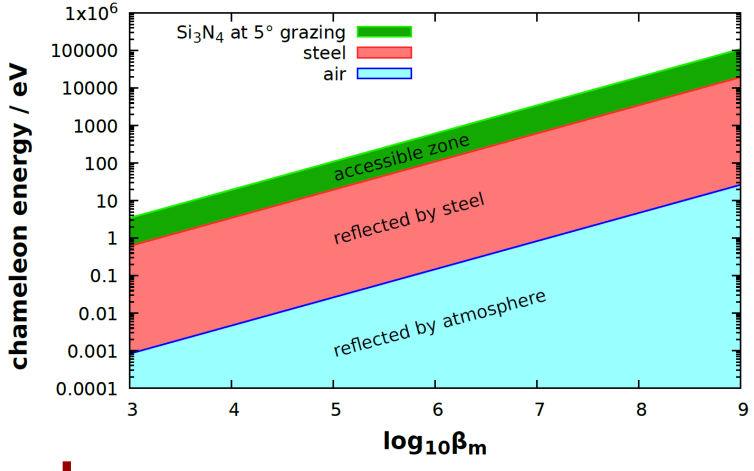
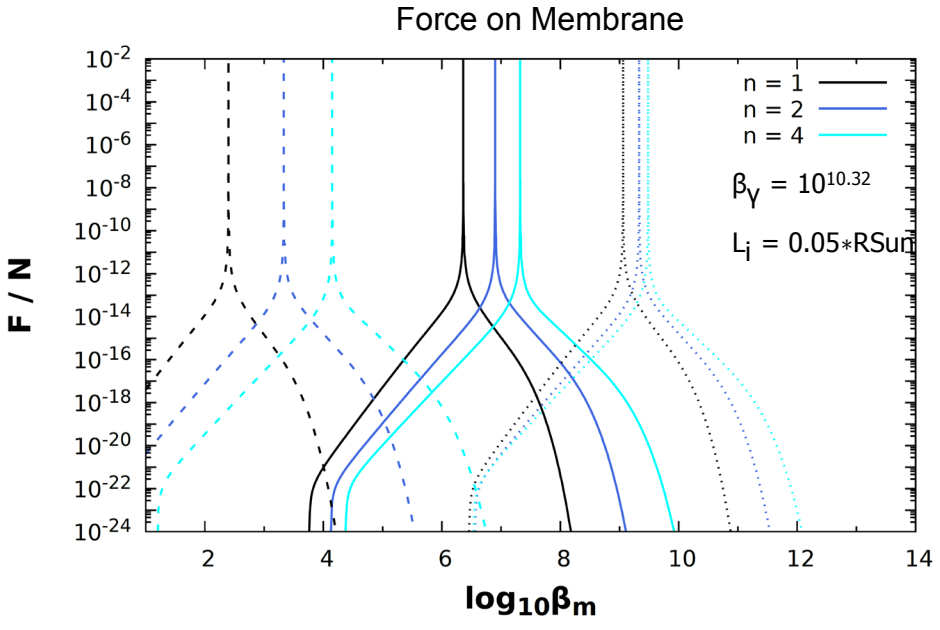




solid → $\Lambda = 2.4*10^{-3}$eV

dashed → $\Lambda = 1*10^{-5}$eV

dotted → Λ = 0.1 eV

+ distance Sun-Earth, chopper efficiency, magnet bore diameter

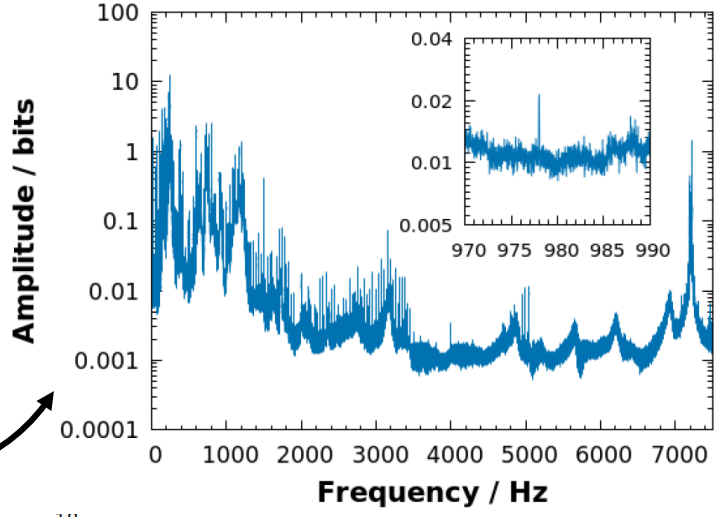
Data Taking Campaign 2017

- background and sensitivity studies in the lab

  → displacement sensitivity: $1 \times 10^{-15} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$
  (at high frequencies)

- data collected during 10 solar tracking runs

Averaged FFT spectrum of a single tracking

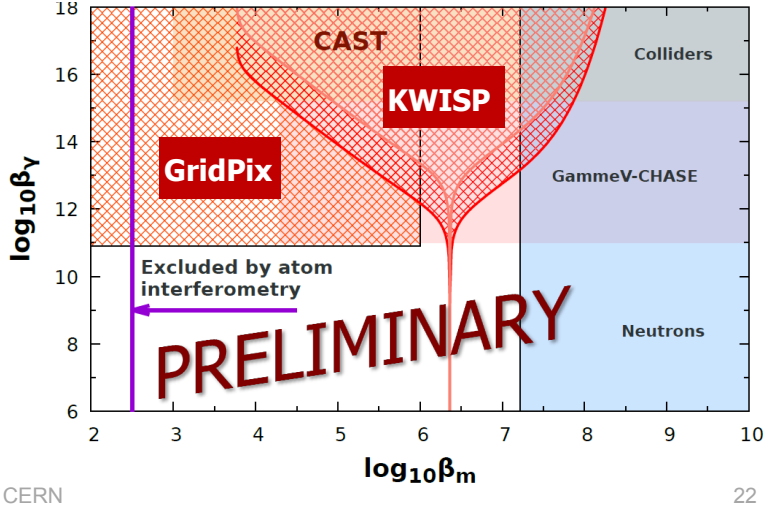


- no signal at set chopper frequency (984 Hz)

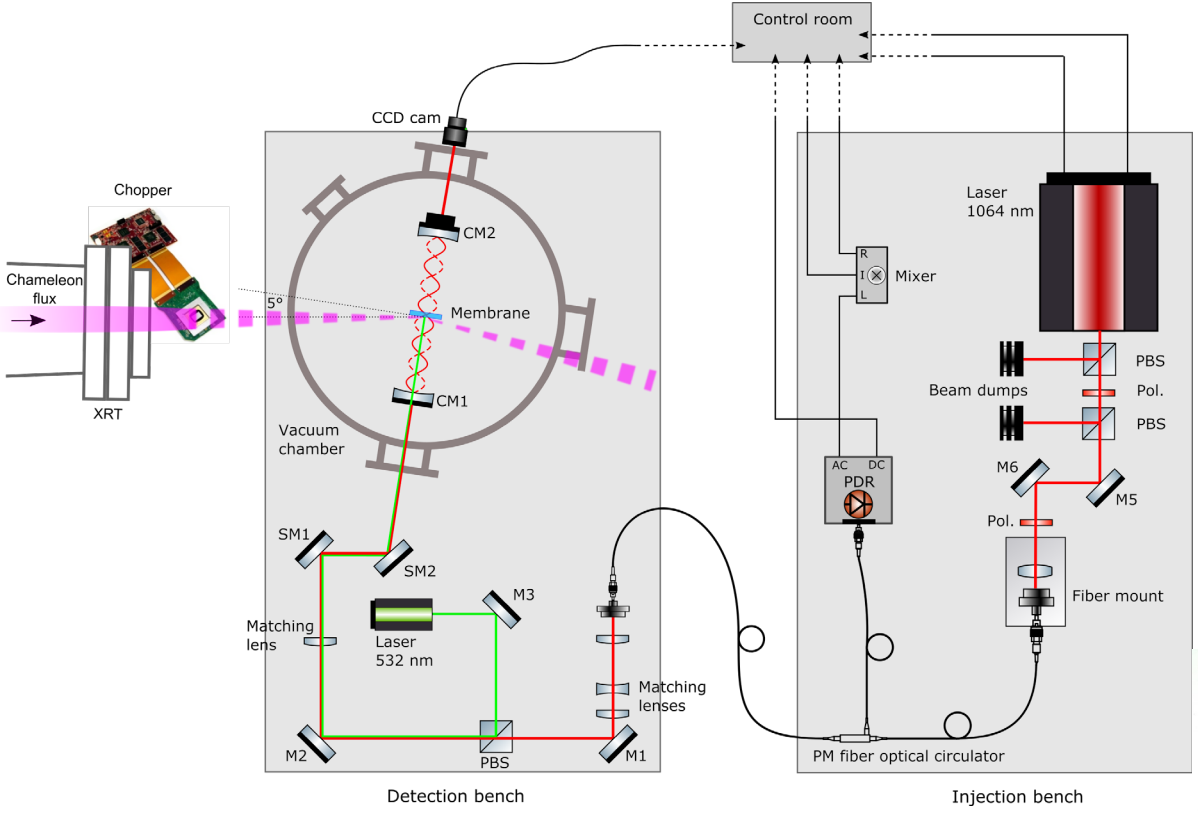
  → minimum detectable force on membrane:

  80 pN at 95% C.L.

Publication in the next days!

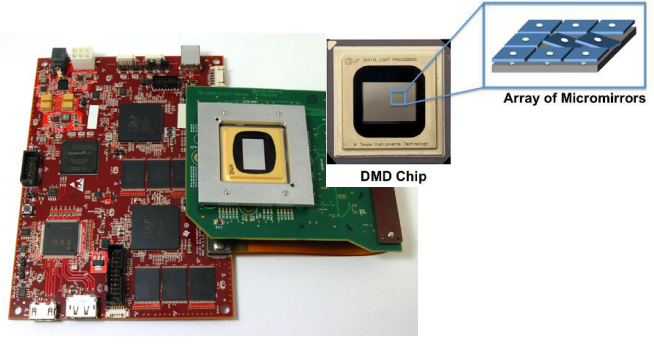


Upgrade 2018 – Fabry-Pérot Interferometer



Features:

- Fabry–Pérot interferometer
- IR laser (Coherent Mephisto 500mW)
- fiber optic circulator
- injection and detection bench
- chopper: DLP® LightCrafter™ 9000
  - aluminum micromirrors
  - ±12° tilt angle
  - max. freq. for binary pattern: (9467±1) Hz



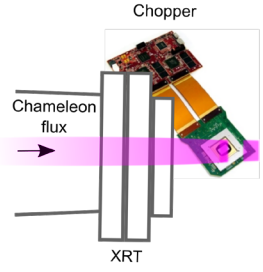
- 14 solar tracking runs
- analysis ongoing

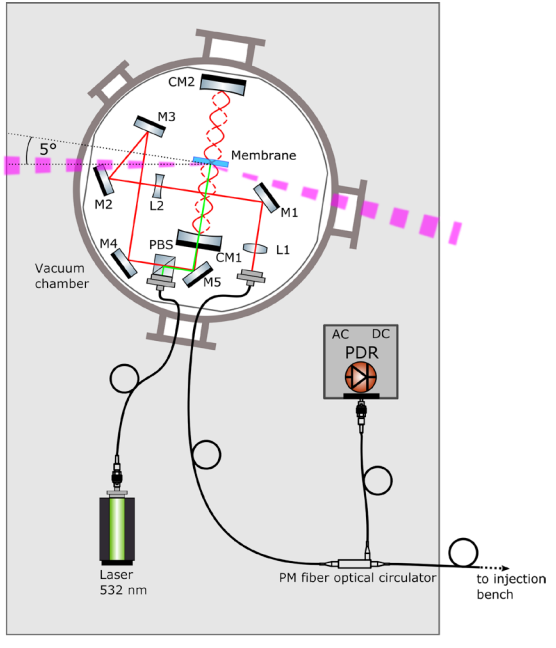
Outlook

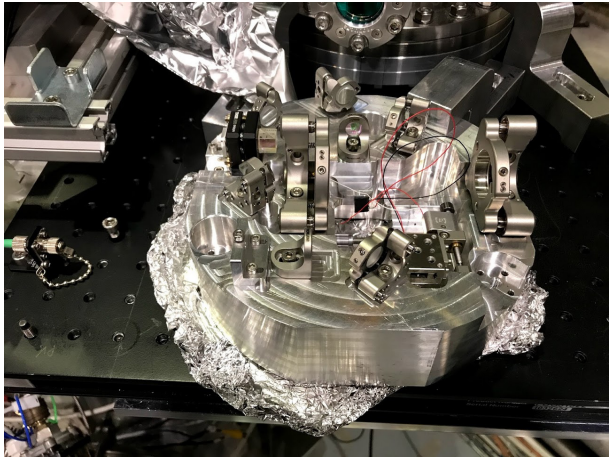
- additional fiber optics
  (mode cleaning)
- improved mechanic/acoustic isolation
  (reduce background noise)
- homodyne detection
  (insensitive to frequency fluctuations of laser)
- coated membrane
  (change resonance frequency, gain from membrane Q-factor)

⋮

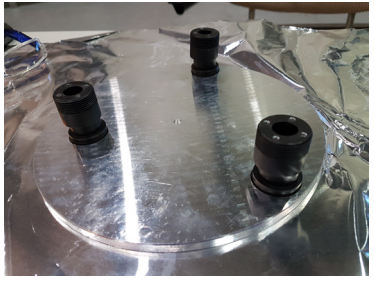
- membrane cooling
  (reduce thermal noise, gain factor >100)







Detection bench



Summary

- CAST searches for solar chameleons following two complementary approaches

- GridPix aims for the detection of X-rays originating from the chameleon-photon conversion inside the CAST magnet
  - data taking 2014/15: no signal above background

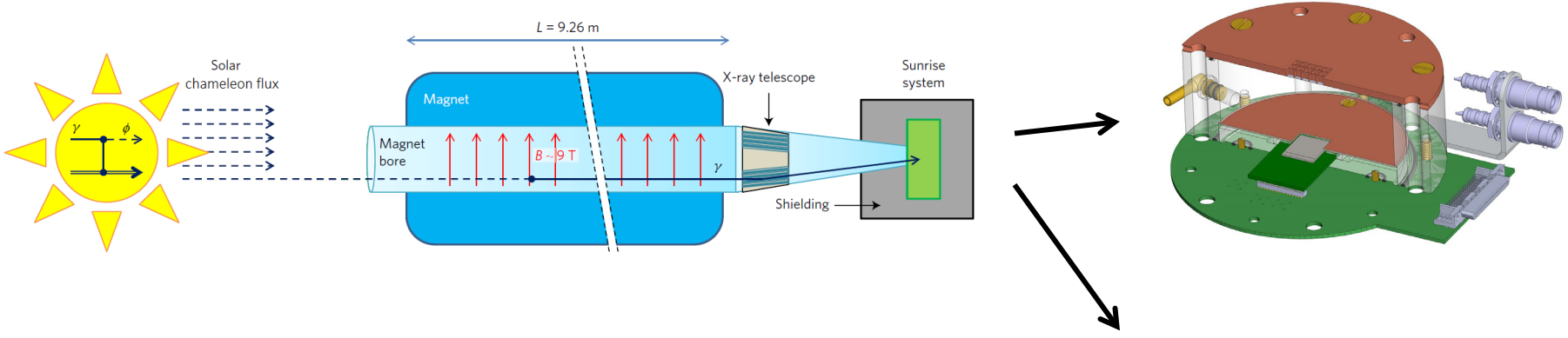
$$\text{for } \; 1 < \beta_{\mathrm{m}} < 10^{6} \;\; \rightarrow \;\; \beta_{\gamma} \lesssim 5.7 \times 10^{10}$$

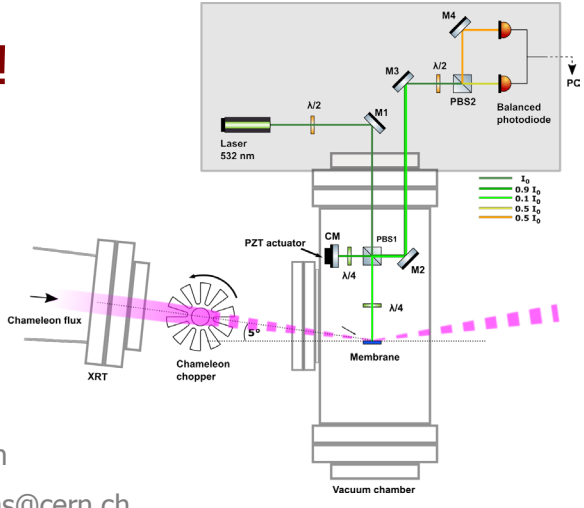
  - data taking 2017/18: analysis ongoing

- KWISP looks for tiny displacements of a thin membrane caused by the reflection of chameleons
  - data taking 2017: no signal above background, upper force limit of 80 pN

$$\rightarrow \beta_{\gamma} \leq 10^{11} \quad (\text{for a certain } \beta_{\mathrm{m}})$$

  - data taking 2018: analysis ongoing





Stay tuned for more news from GridPix and KWISP!

Also check out the axion search performed by CAST!

Contact: Justin Baier - justin.sillvan.baier@cern.ch

CAST Spokesperson: Konstantin Zioutas - Konstantin.Zioutas@cern.ch

Website: cast.web.cern.ch

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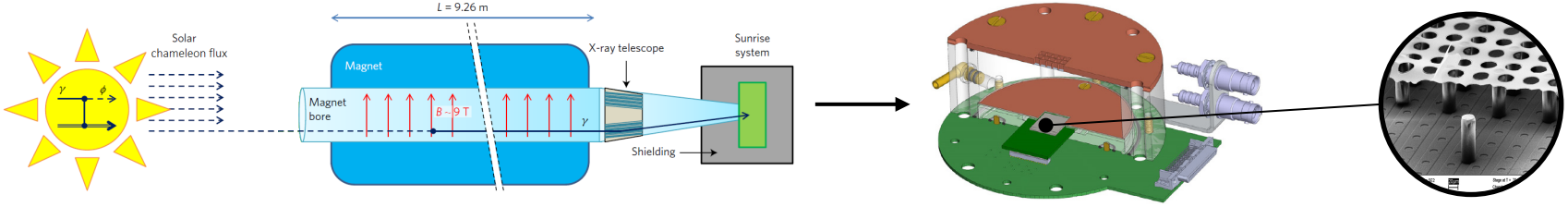
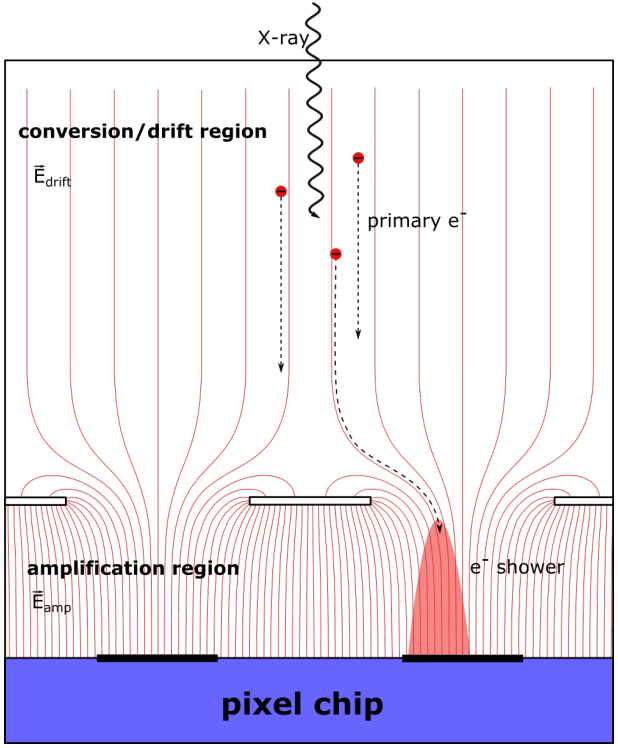
CAST EXPERIMENT

Backup

Detection Principle





- γ enters detector volume through X-ray window in the cathode
- gas atoms get ionized (Ar/iC_4H_{10} - 97.2/2.3 @ 1050 mbar) → primary e^-
- e^- drift towards amplification region and create e^- shower

  (E_{drift}=0.5 $\frac{kV}{cm}$, L_{drift}=3 cm, E_{amp}=50 $\frac{kV}{cm}$, gas gain G≈2500)
- e^- shower of single primary e^- collected on single pixel

First Chameleon Search at CAST with a SDD

- Silicon Drift Detector (SDD) built from commercially available components
- Data taking end of 2013, obtained limit:

$\beta_\gamma \leq 9.3 \times 10^{10}$ at 95% C.L. (Physics Letters B 749 (2015) 172–180)

(above upper limit given by solar luminosity constraints)