Update on FUNK (work *in progress*)

Finding U(1)'s of a Novel Kind at Karlsruhe Institute of Technology:
Kai Daumiller, Ralph Engel, Dominik Haunss, Herman-Josef Mathes,
Markus Roth, Ralph Ulrich, Christoph Schäfer, Darko Veberic

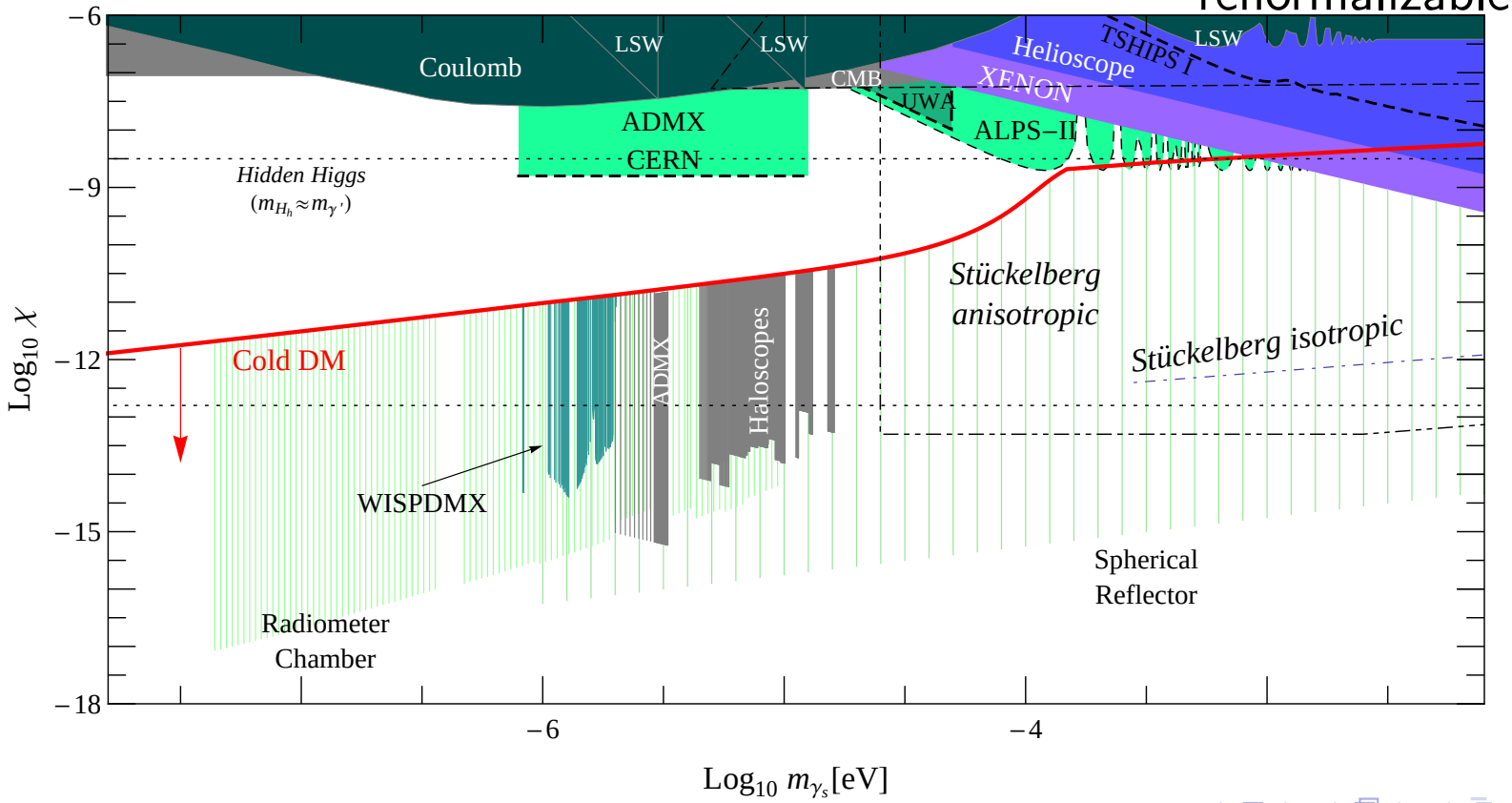
with outside support from I. Irastorza, J. Redondo (Zaragoza), J. Jaeckel (Heidelberg), D. Horns (Hamburg), A. Lindner,
M. Kowalski, A. Lobanov, A. Ringwald (DESY), Babette Döbrich (CERN) +...

PATRAS 2015 at Zaragoza

ultra-light Hidden Photons (HPs) as cold Dark Matter

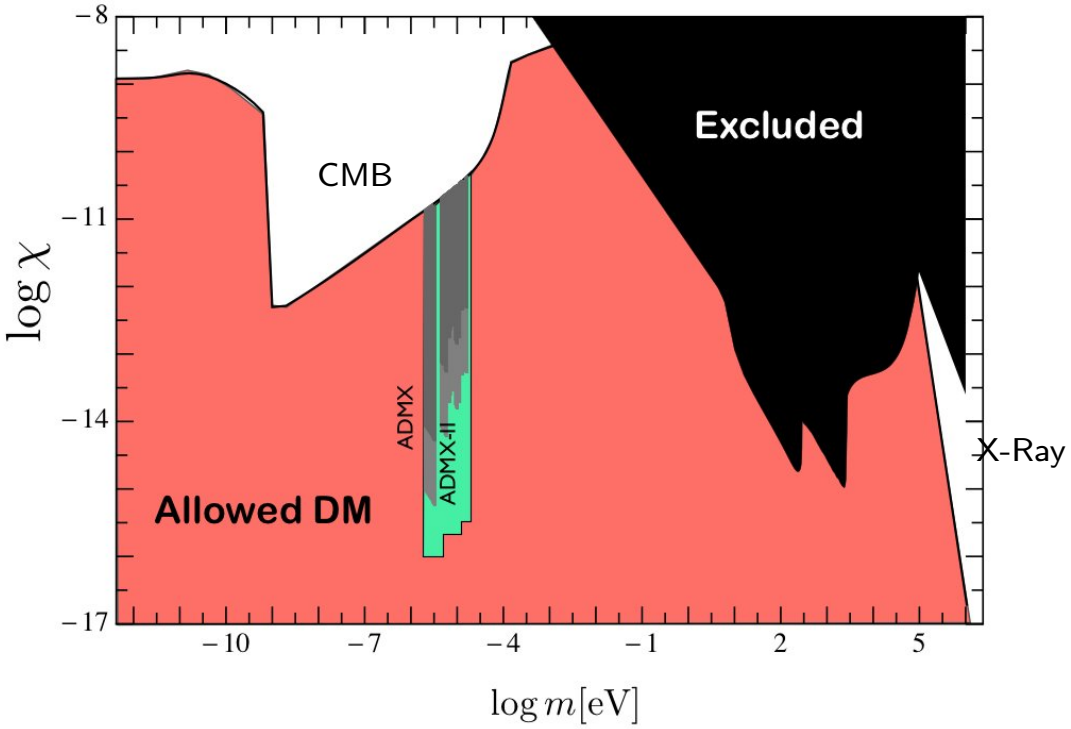
[figure below from 1410.6302]

- Hidden Photons
  - $\mathcal{L} \sim \chi F_{\mu\nu} X^{\mu\nu} + \frac{m^2}{2} X_\mu X^\mu$
  - e.g. with Stückelberg mass term, very simple renormalizable SM extension



ultra-light Hidden Photons (HPs) as cold Dark Matter

[figure below from 1311.5341]



- Hidden Photons
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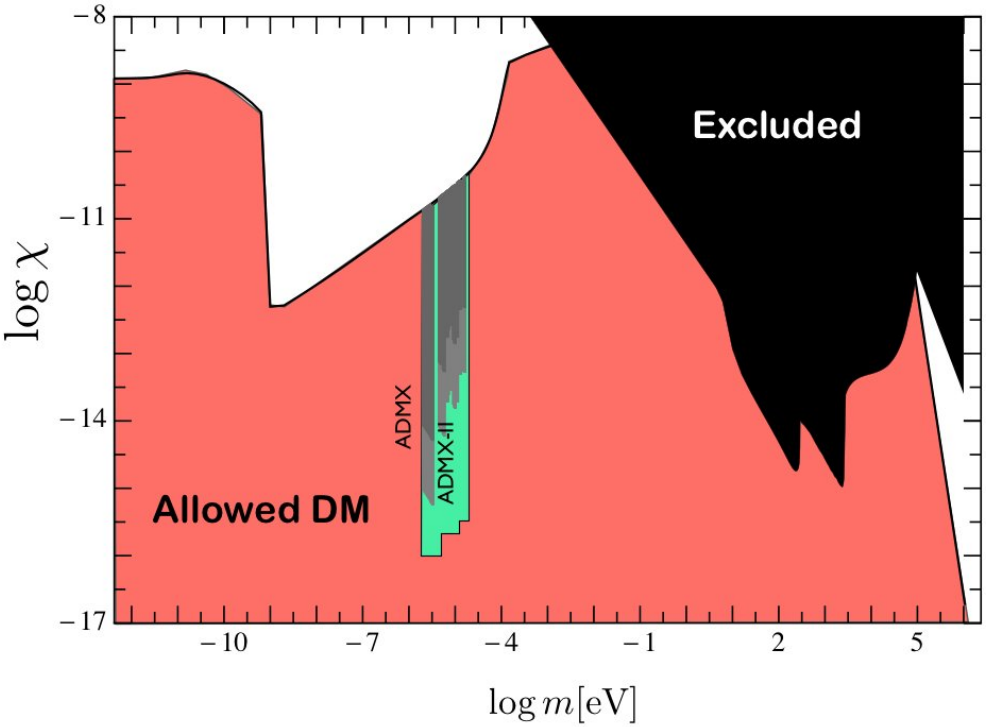
- Hidden Photon cDM
  - cold Dark Matter:[Nelson/Scholtz Phys.Rev. D84 (2011) 103501], [Arias et. al, JCAP 1206 (2012) 013]$\longrightarrow$ (misalignment), [Graham et al, 1504.02102] $\longrightarrow$ (inflationary fluctuations)
  - (see talk by Surjeet Rajendran for DM)
  - (see talk by ADMX/ADMX-HF)

Dark Matter Dish antenna concept review Horns et al. JCAP 1304 (2013) 016

- HP wide mass range suggests also non-resonant search



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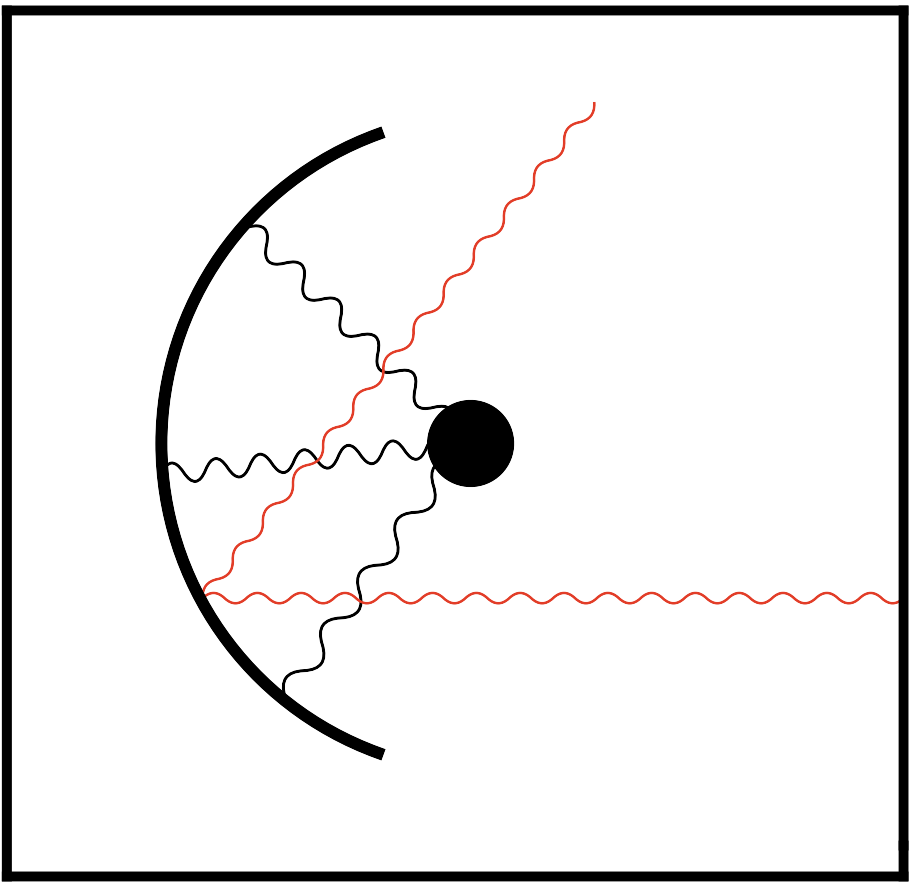
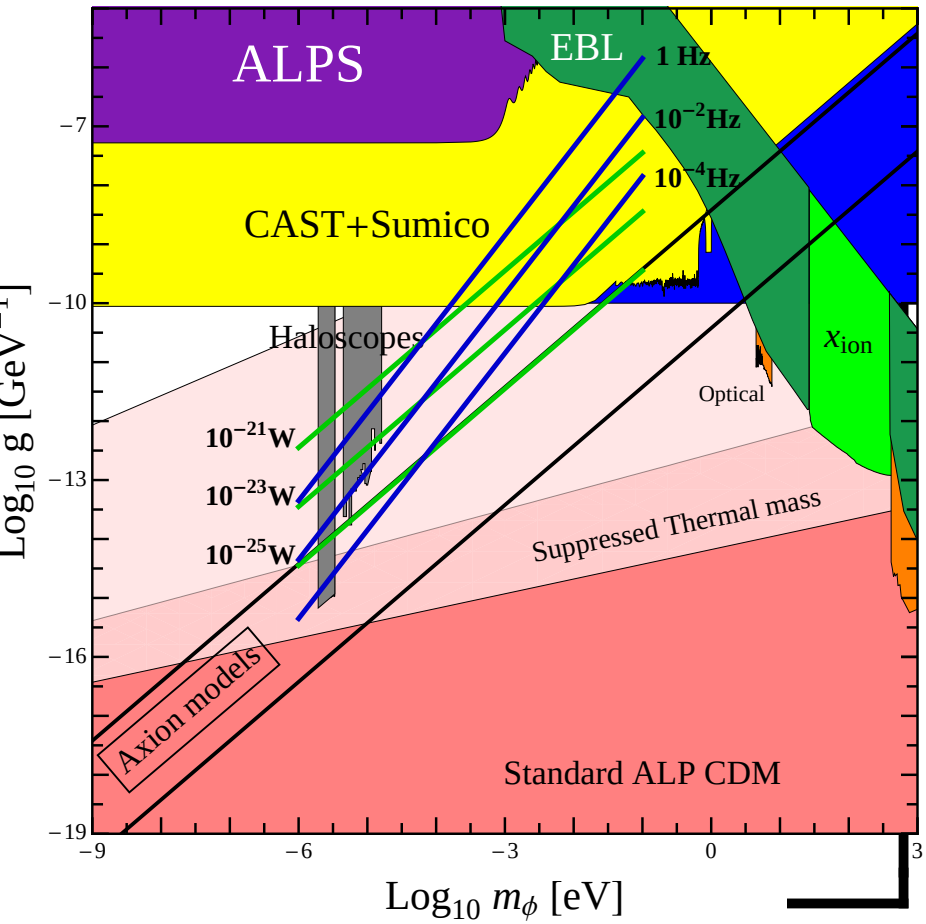


- HP wide mass range suggests also non-resonant search
- HP-photon mixing implies a 'DM solution' ($\vec{p} \simeq 0$) with a tiny electric field component
- HP DM can effectively move conductor electrons $\rightarrow$ radiation, $m_{\mathrm{HP}} \sim 1/\lambda$
- background-supressed at dish/mirror $\rightarrow$ collect light at center of LARGE reflecting sphere

See results by Suzuki on Thursday

Dark Matter Dish antenna concept review Horns et al. JCAP 1304 (2013) 016

For 1m^2 at 5T



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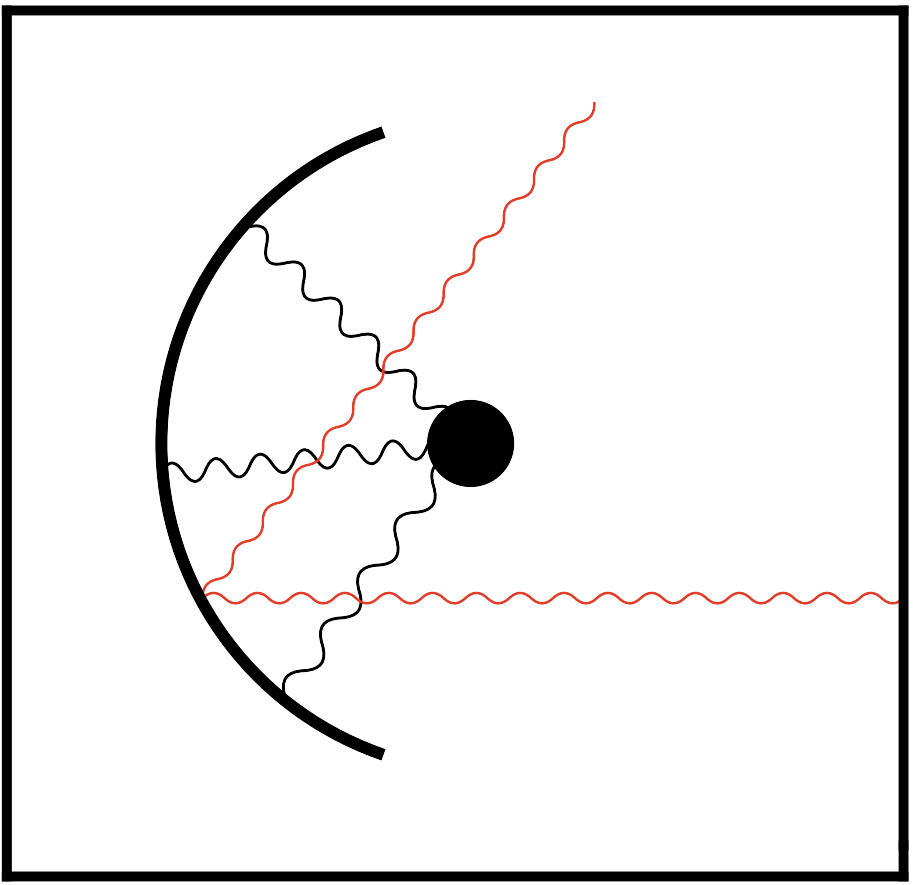
- background-supressed at dish/mirror $\rightarrow$ collect light at center of LARGE reflecting sphere
- ALPs/axions need *strong* $\vec{B}$ $\|$ surface, unlikely with what follows, remember: $\mathcal{L}_{\rm Ax} \sim g\phi\vec{B}\vec{E}$

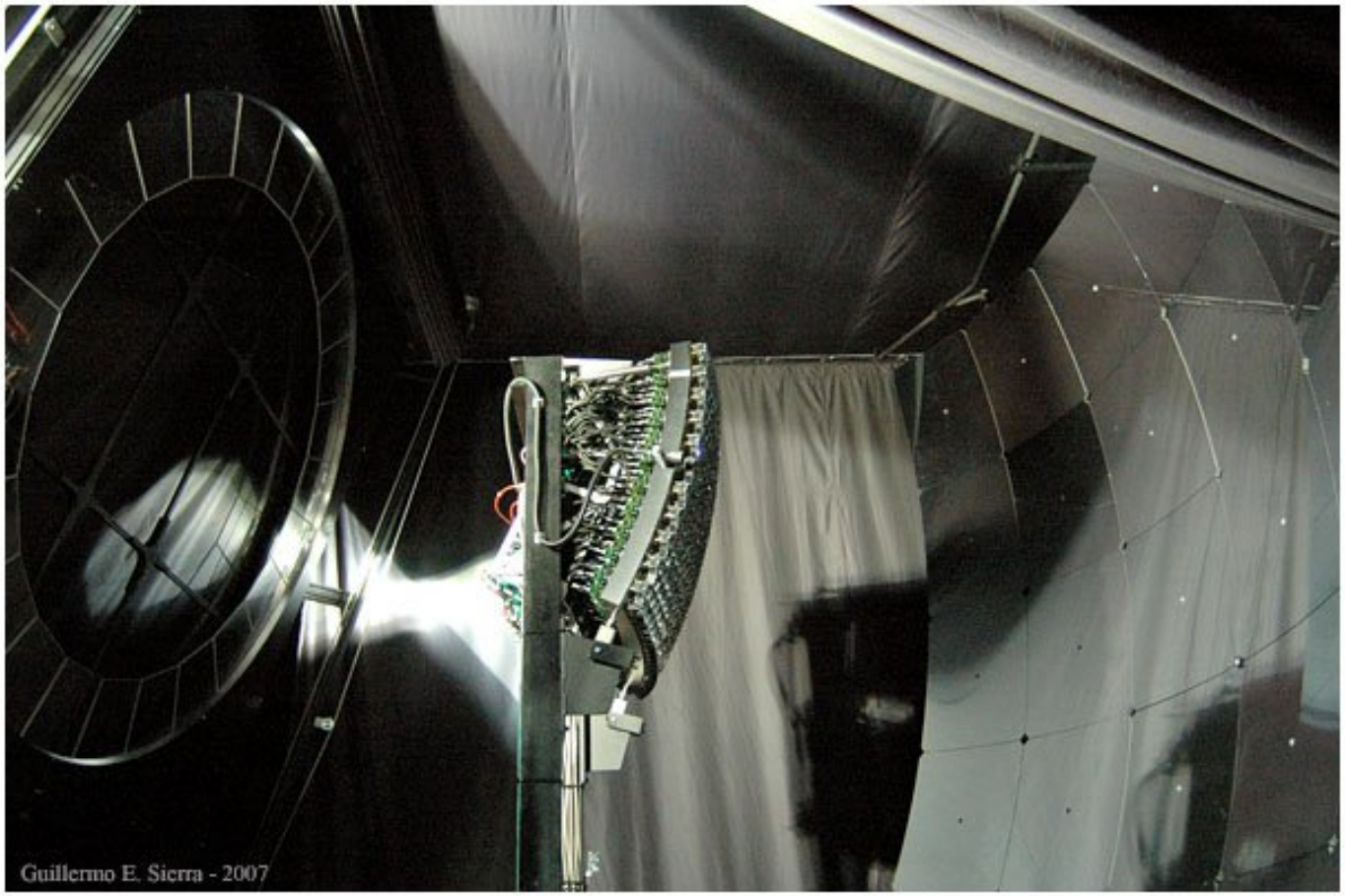
Dark Matter Dish antenna concept review Horns et al. JCAP 1304 (2013) 016

Artist's view of the setup:



Dark Matter Dish antenna concept review Horns et al. JCAP 1304 (2013) 016

particle physicist's "view of the setup":



HAP works. (thanks!) $\rightarrow$ M.Kowalski (ν, DESY) $\rightarrow$ R. Engel (KIT, Auger)

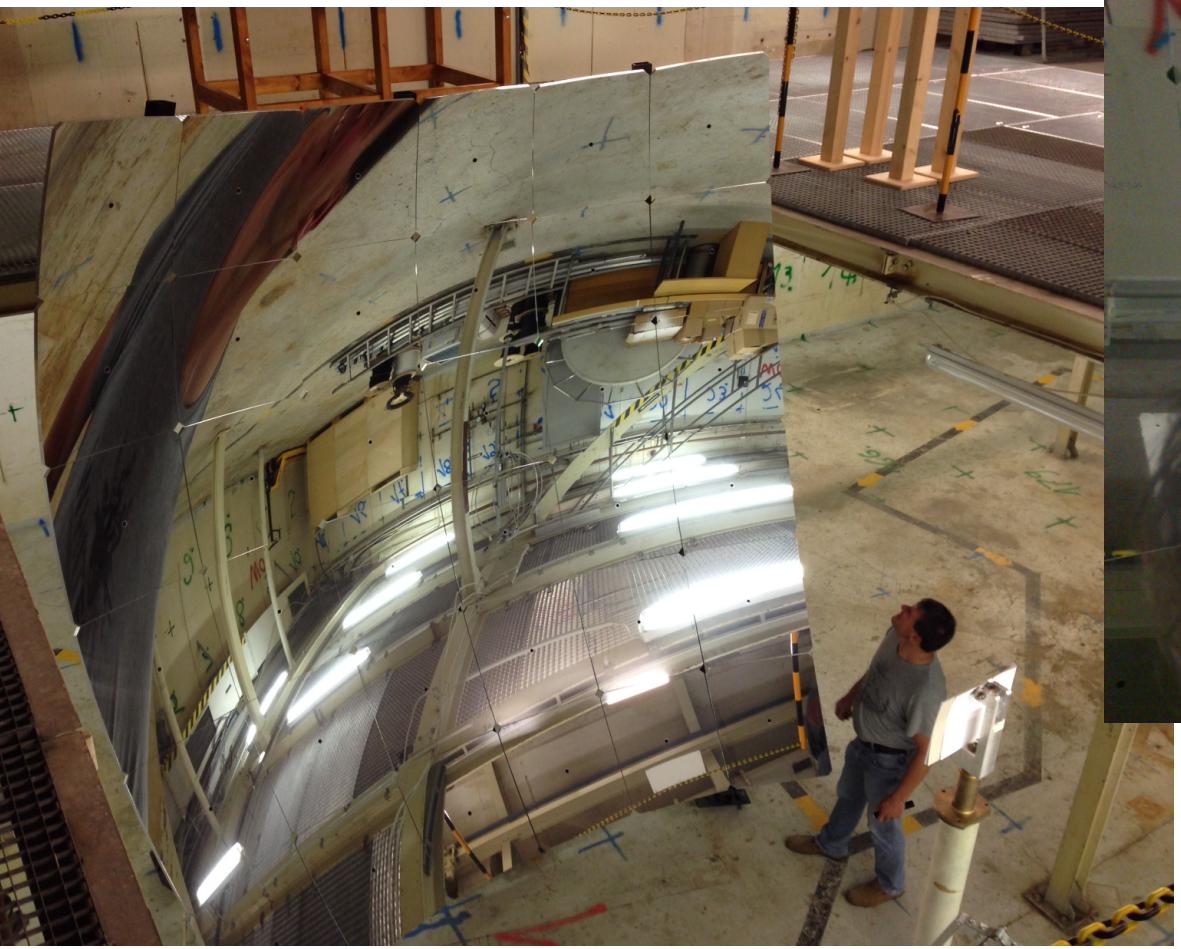
Mirror setup and adjustment at KIT, fall/winter 2014

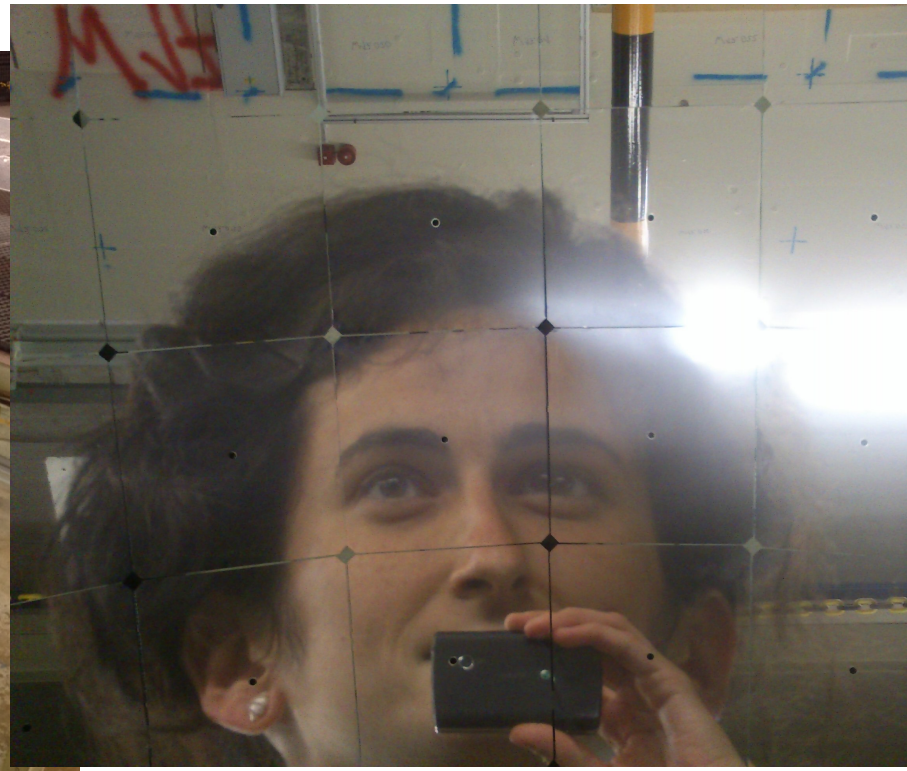
Last PATRAS: Skeleton, test Pierre Auger mirror of 13 m^2 at KIT, ROC=3.4m

Mirror setup and adjustment at KIT, fall/winter 2014

Set up in a former van-de-Graaff hall

$\rightarrow$ thick walls, electromagnetically quiet (qualitatively)

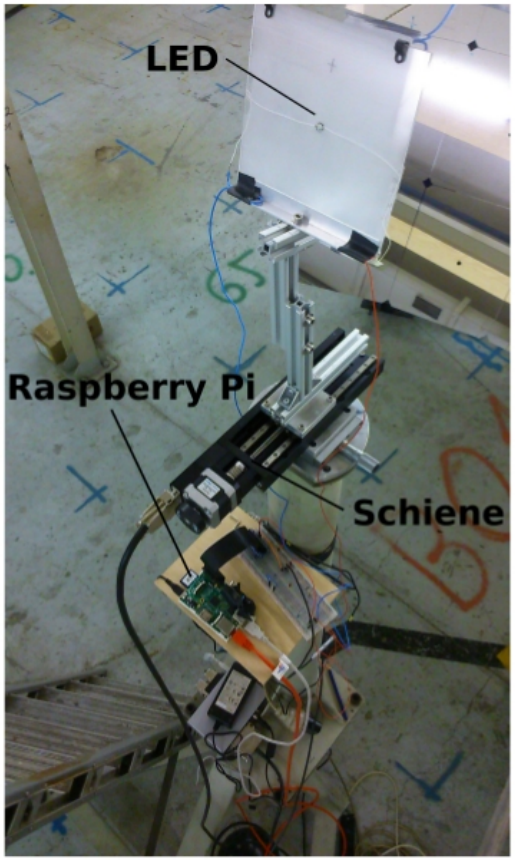


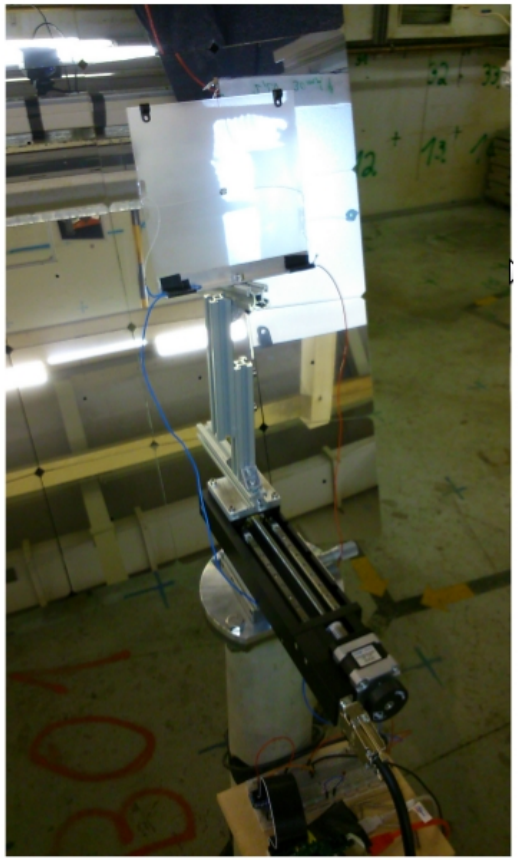


individual elements 65cm

Mirror setup and adjustment at KIT, fall/winter 2014

Comissioning: Radius point search





Moveable milk glas with LED

Mirror setup and adjustment at KIT, fall/winter 2014

curvature not perfect (non-rectangular images) &

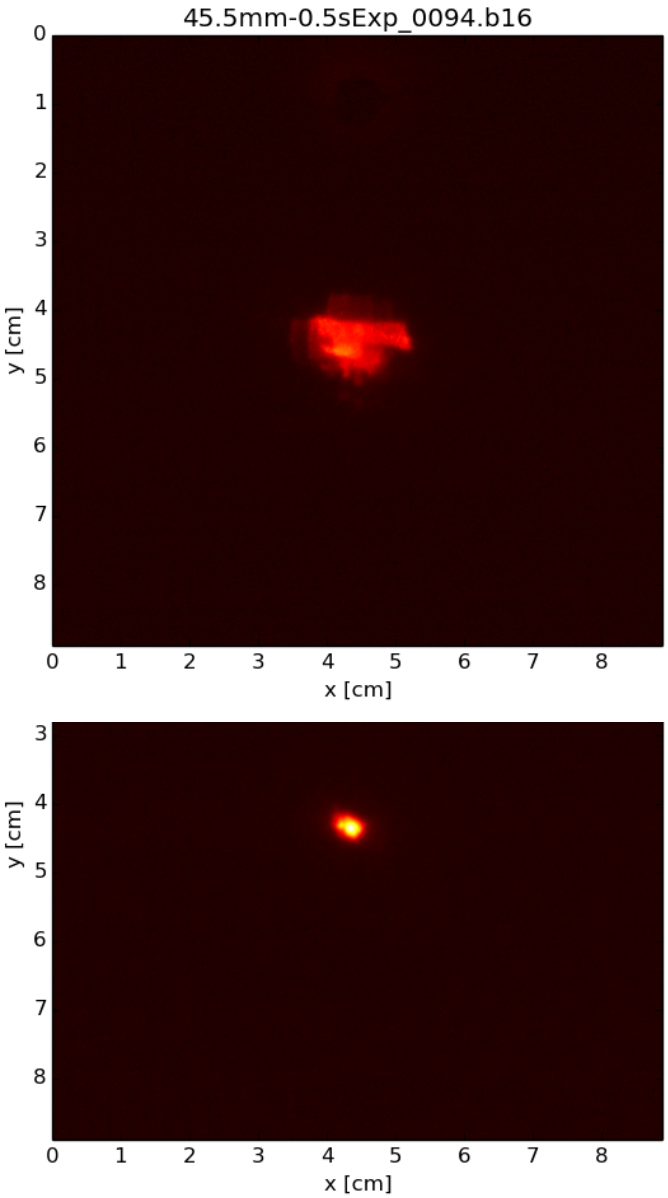
ROC of the individual elements $\pm$ 3 cm

Go piece by piece!

Mirror setup and adjustment at KIT, fall/winter 2014

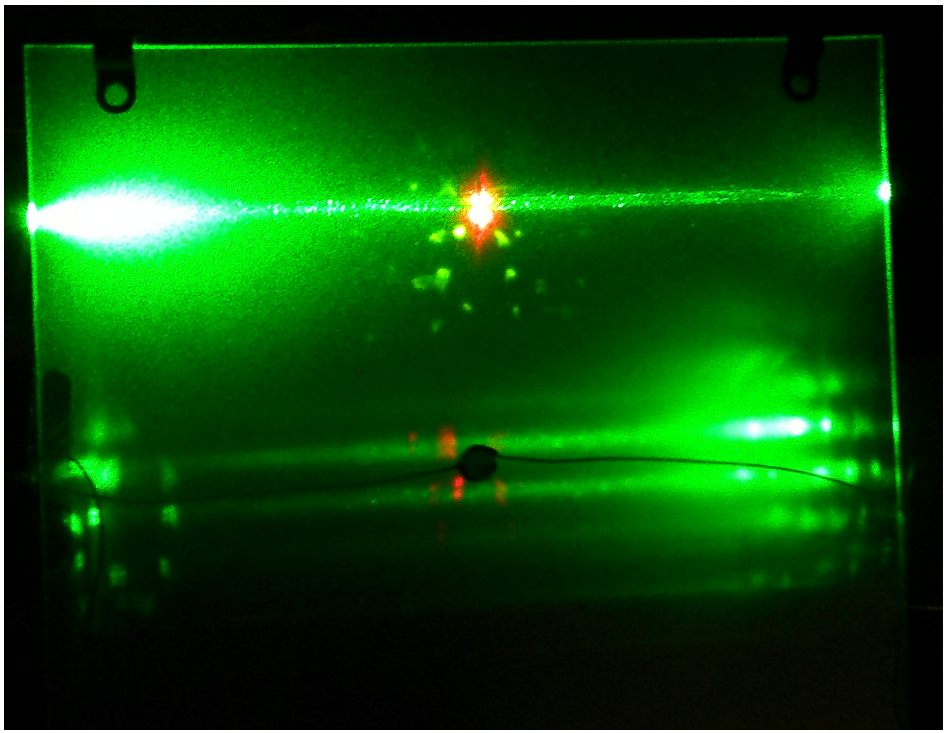
adjustable with 1mm ‘precision’

Mirror setup and adjustment at KIT, fall/winter 2014



spotradius from 7.5mm to 2.5 mm!

mark it $\rightarrow$ ready for measurement



(movie)

intermezzo: 2.5 mm not so bad! $\rightarrow$ slides by Klages ;-)

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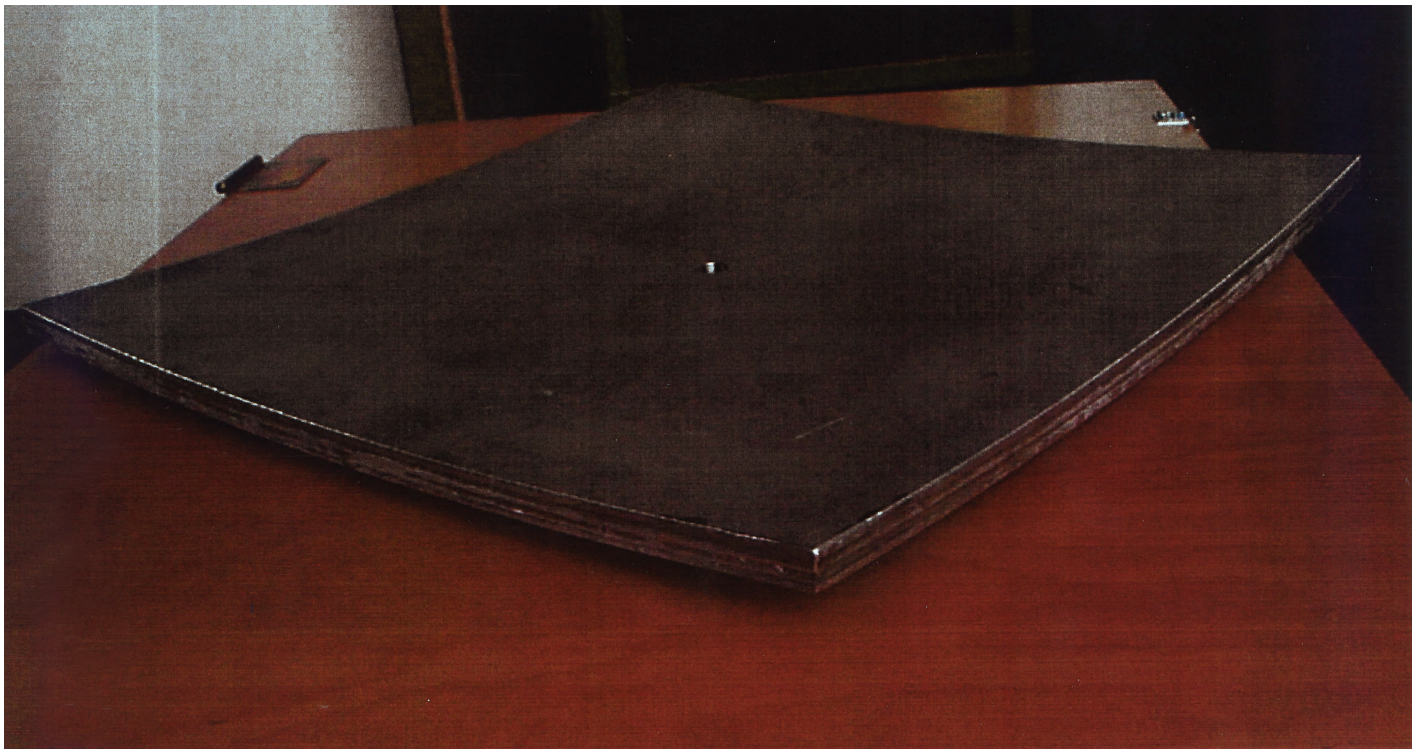

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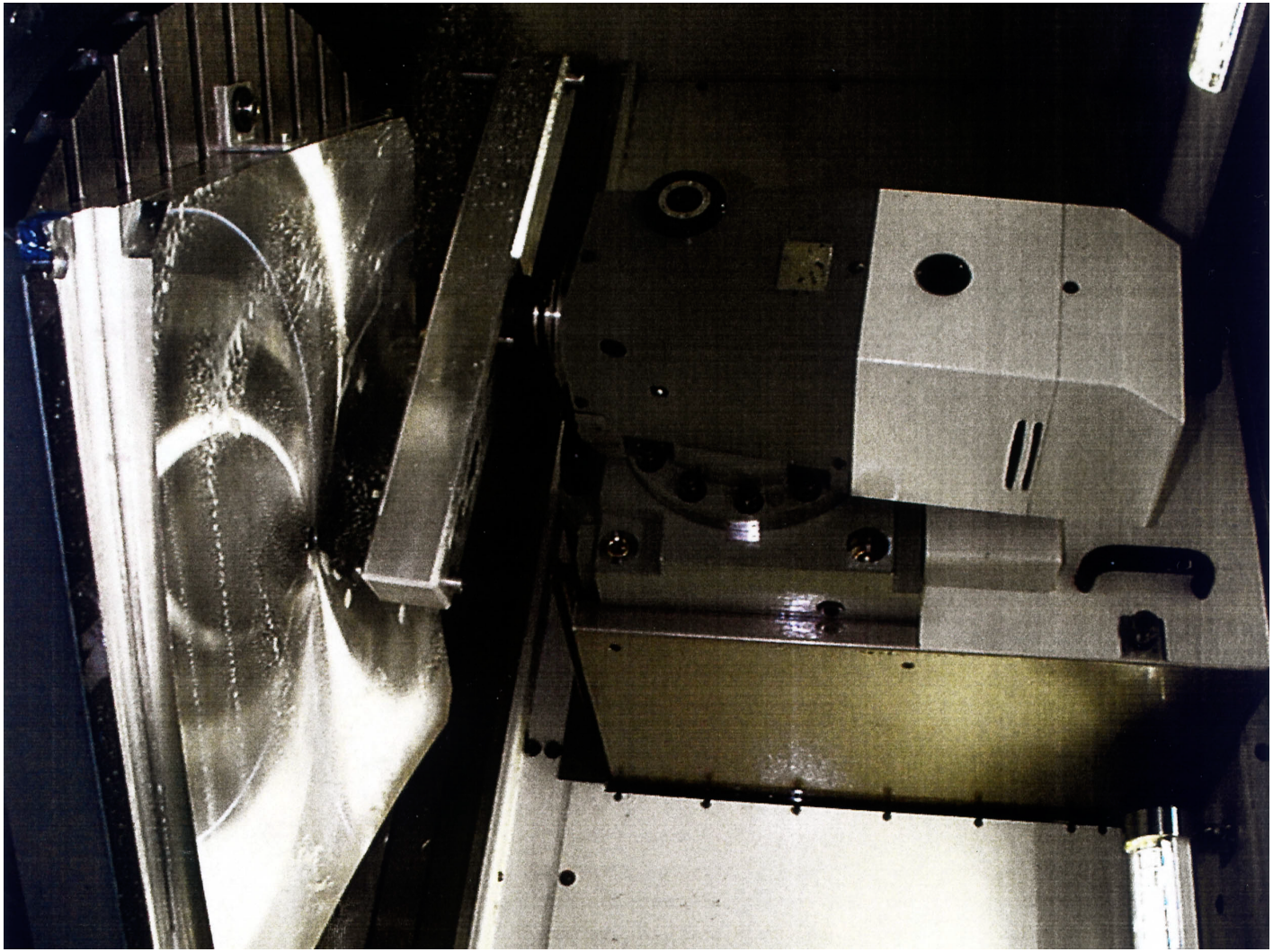

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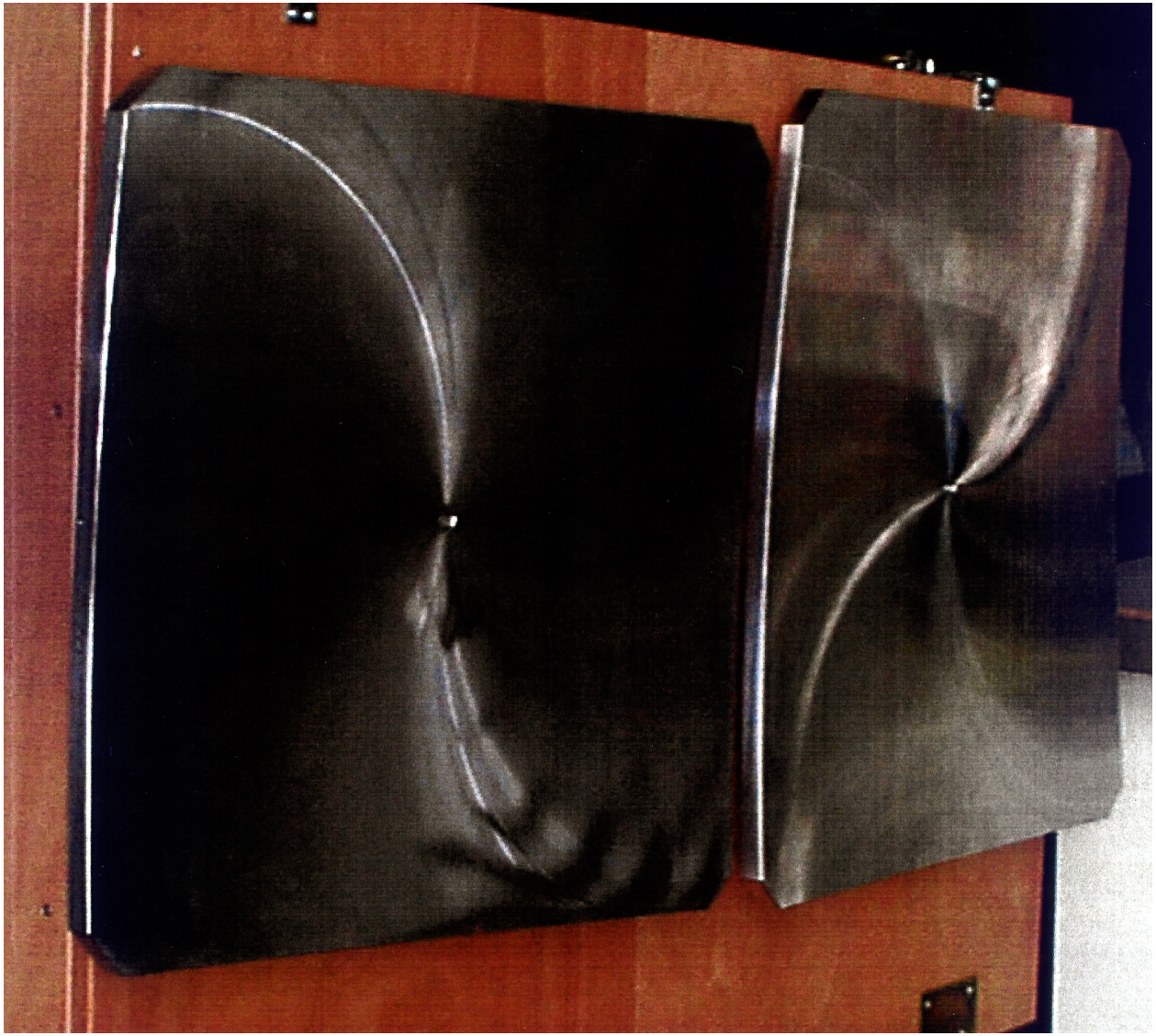

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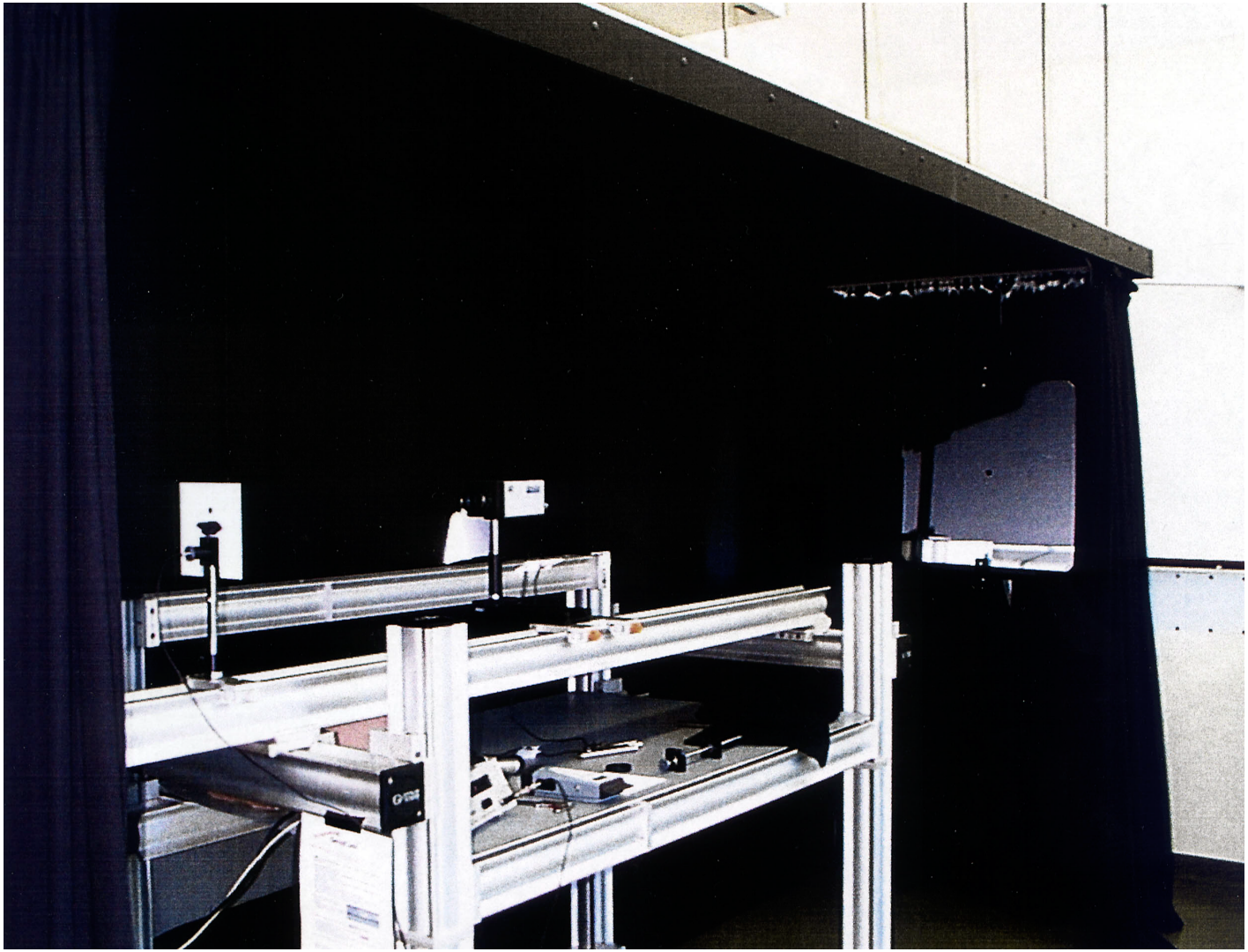

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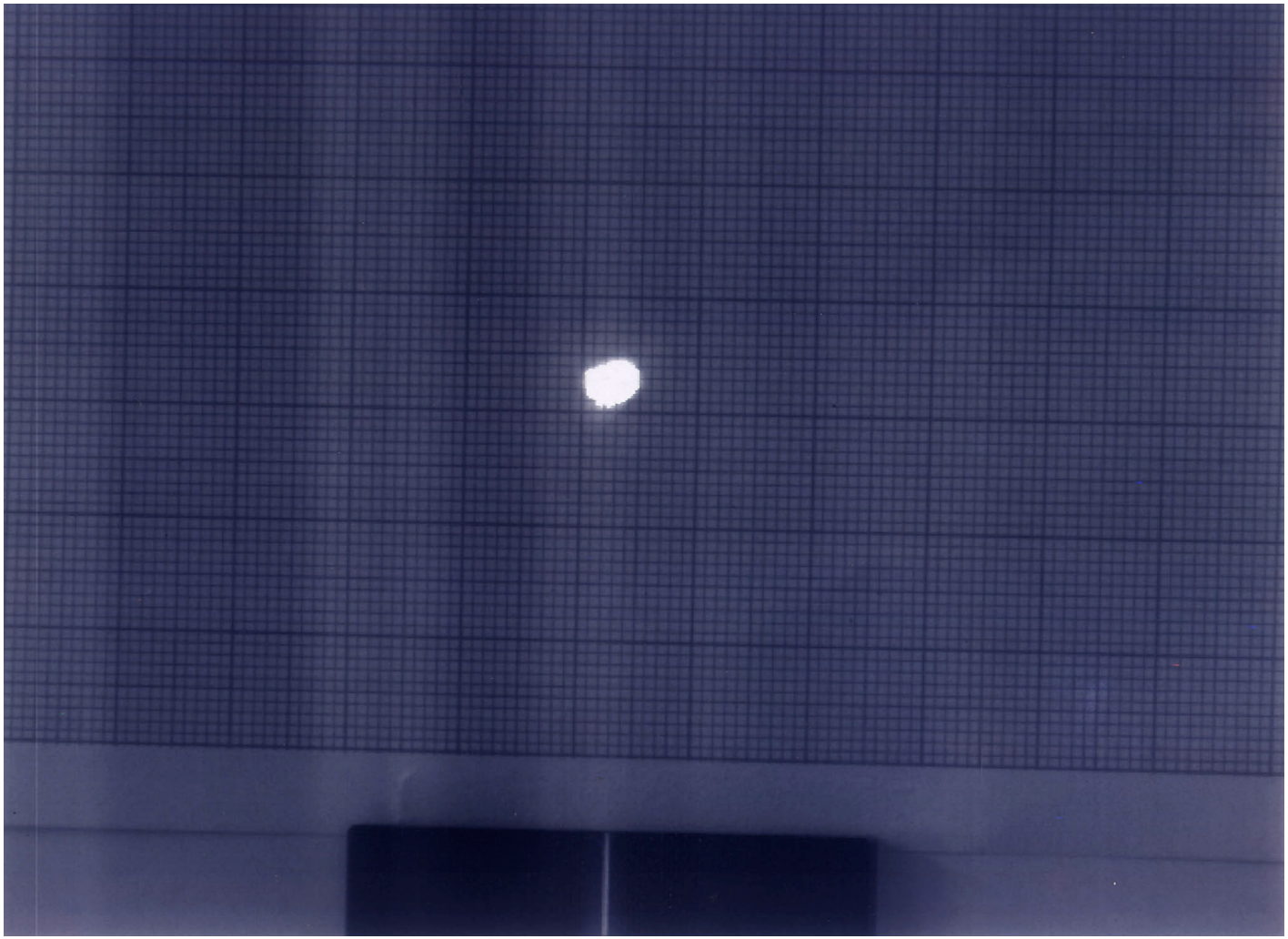
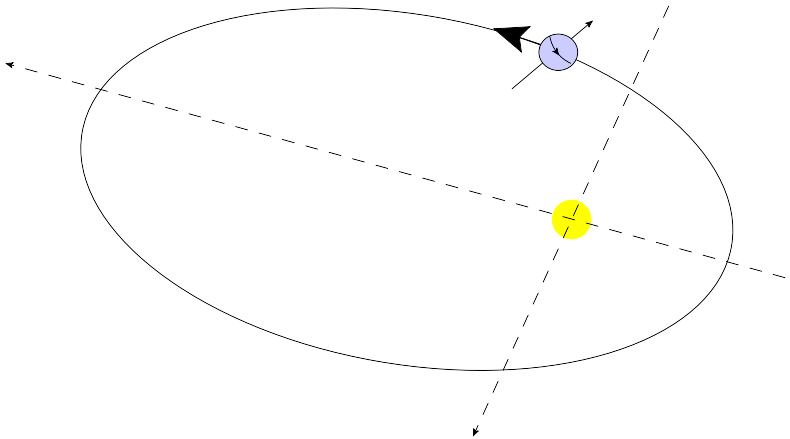
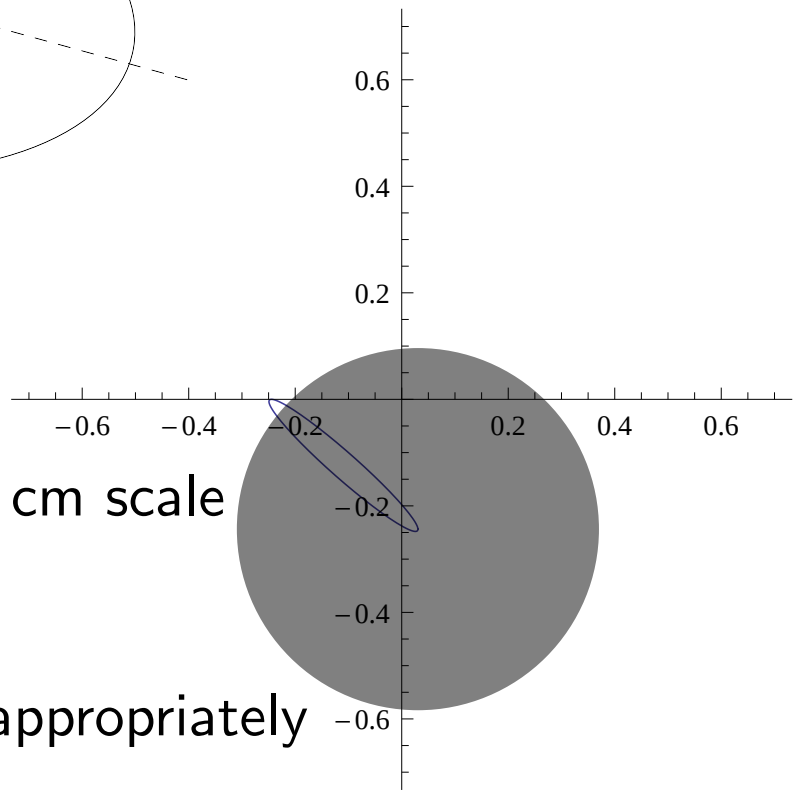


Spot dim. for $\lambda \ll$ dish scale general: Jae/Red, JCAP 1311 (2013) 016

DM @ 60° to ecliptic ↘





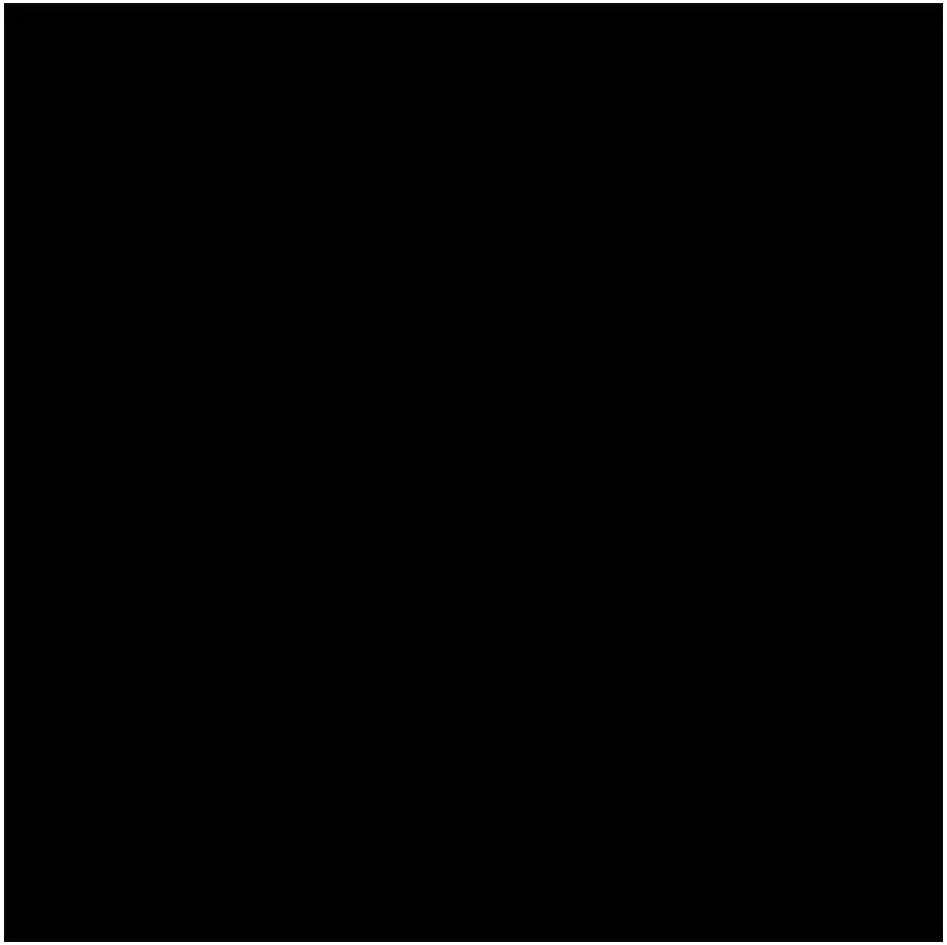
cm scale

example R=3.4m

choose detector size appropriately

- spot-radius-**broadening** DM velocity distribution $\Delta d \sim 1\mathrm{mm}(\frac{R}{\mathrm{m}})$ (if $\Delta v \sim 10^{-3}$) +**movement** (in DM frame)
- point spread ∼ mm and daily mod ∼ mm, yearly mod negligible. dependent on exact orientation

Measurements January-March 2015 (+write up last week!)



- Picture of FUNK run

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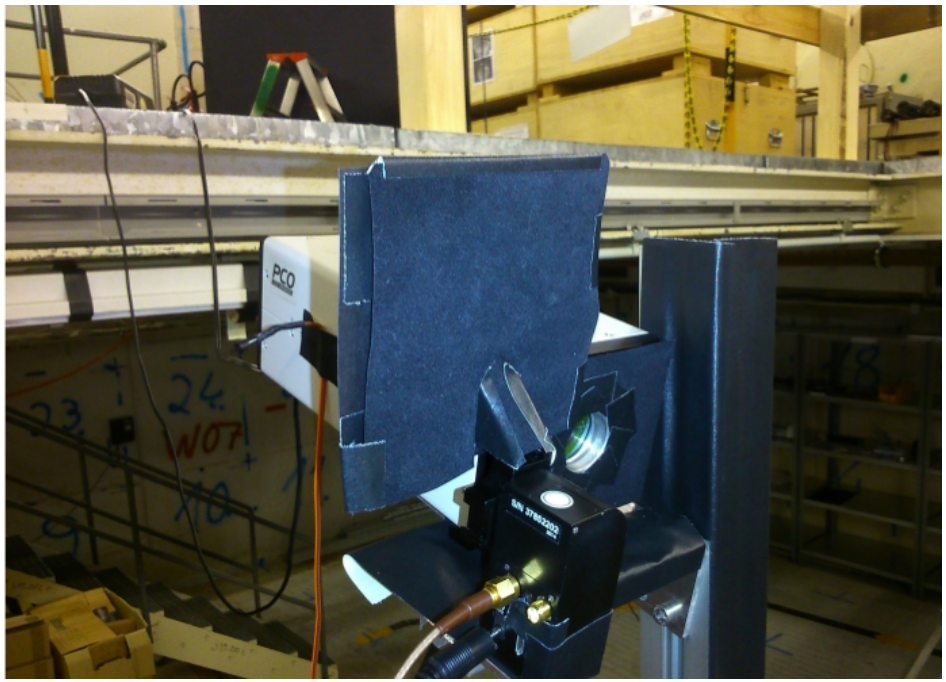

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- first step: SENSICAM CCD, understand background & temperature dep.

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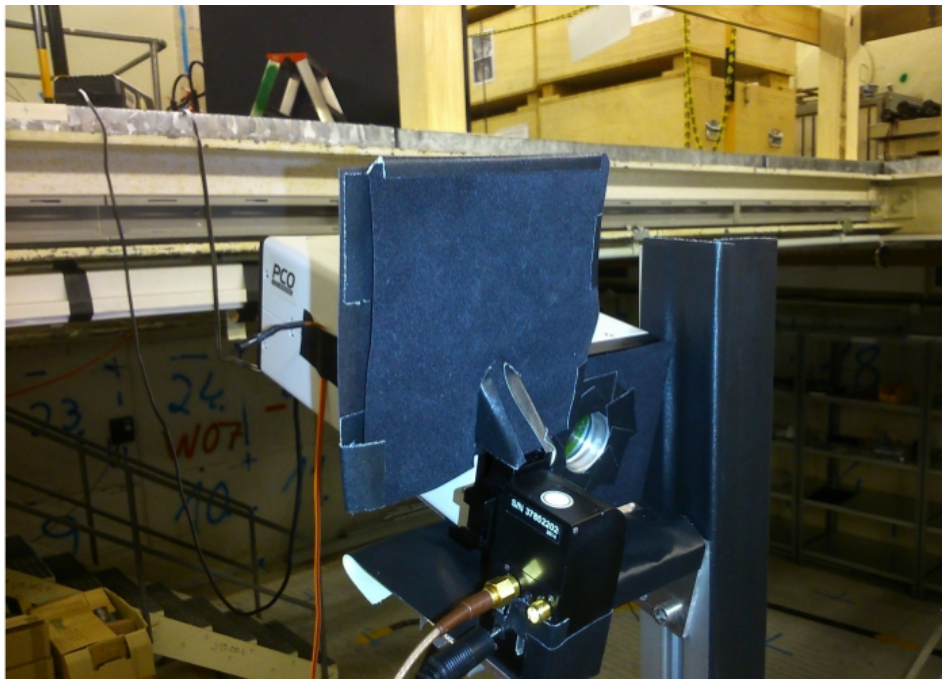

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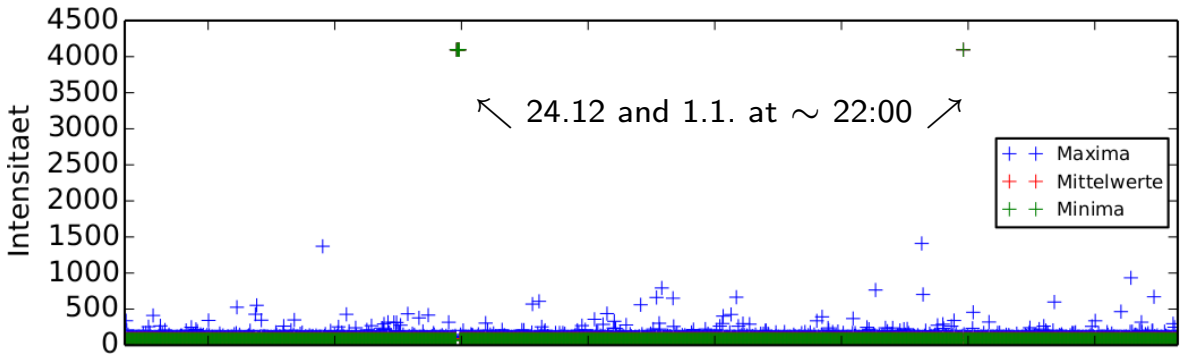

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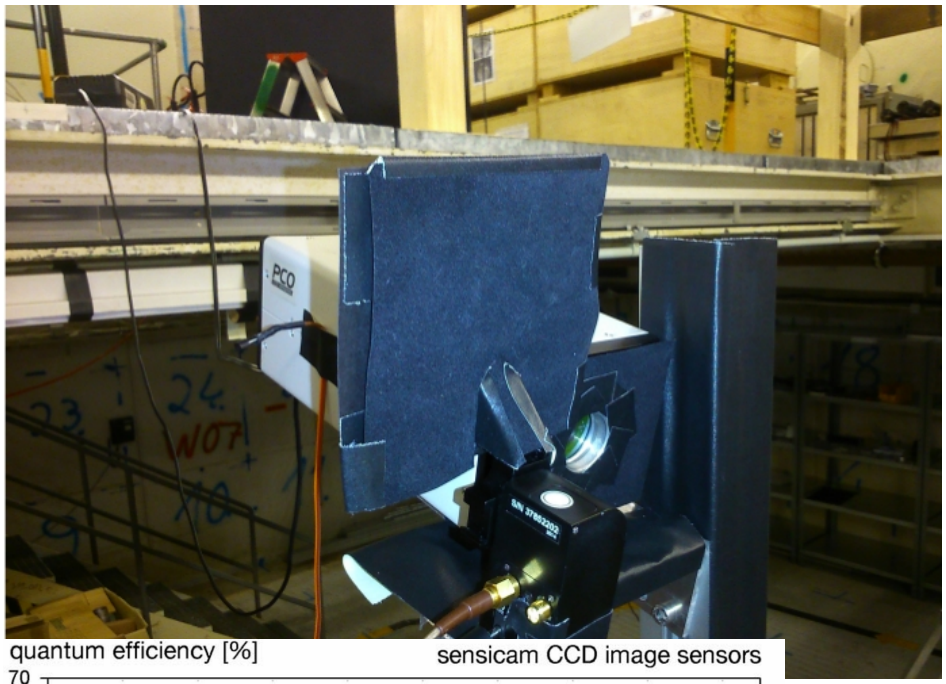
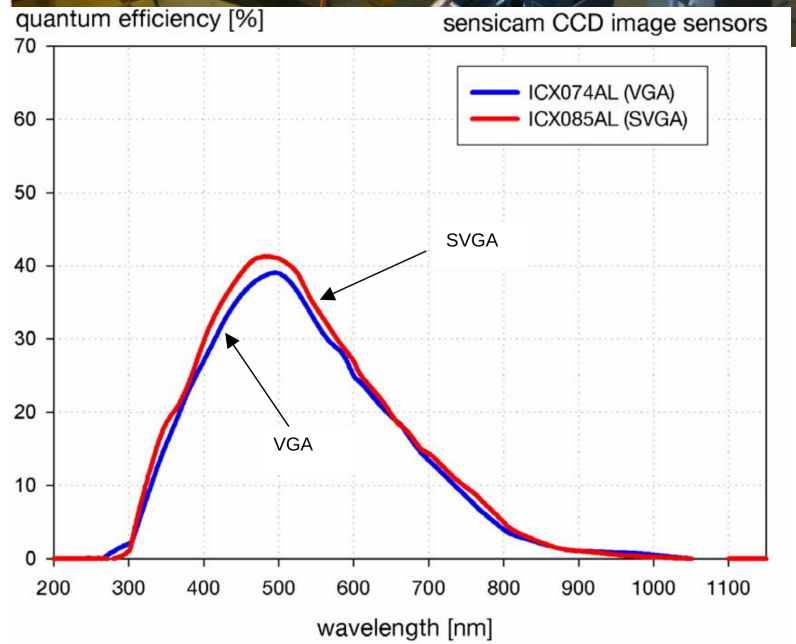
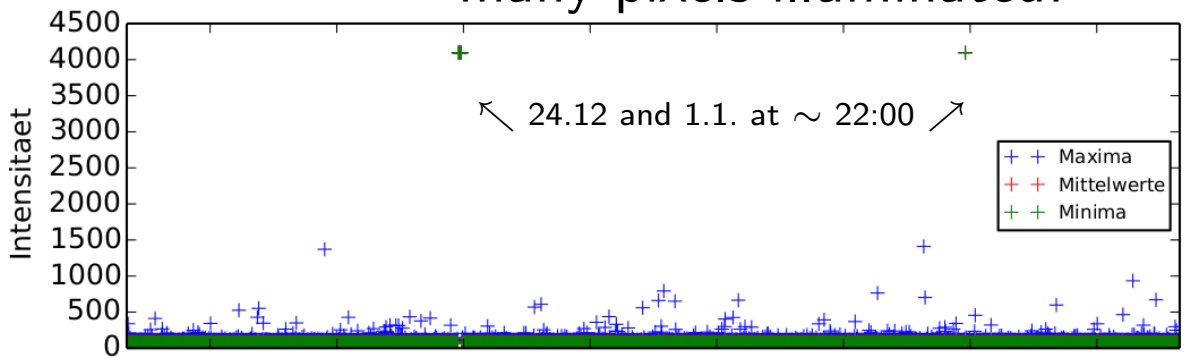




- Picture of FUNK run
- first step: SENSICAM CCD, understand background & temperature dep.
- e.g. test of nightly emergency lighting tests
- SENSICAM CCD rather noisy 0.1 e^-/px/s + 13 e^- readout $\rightarrow$ if signal, many pixels illuminated!

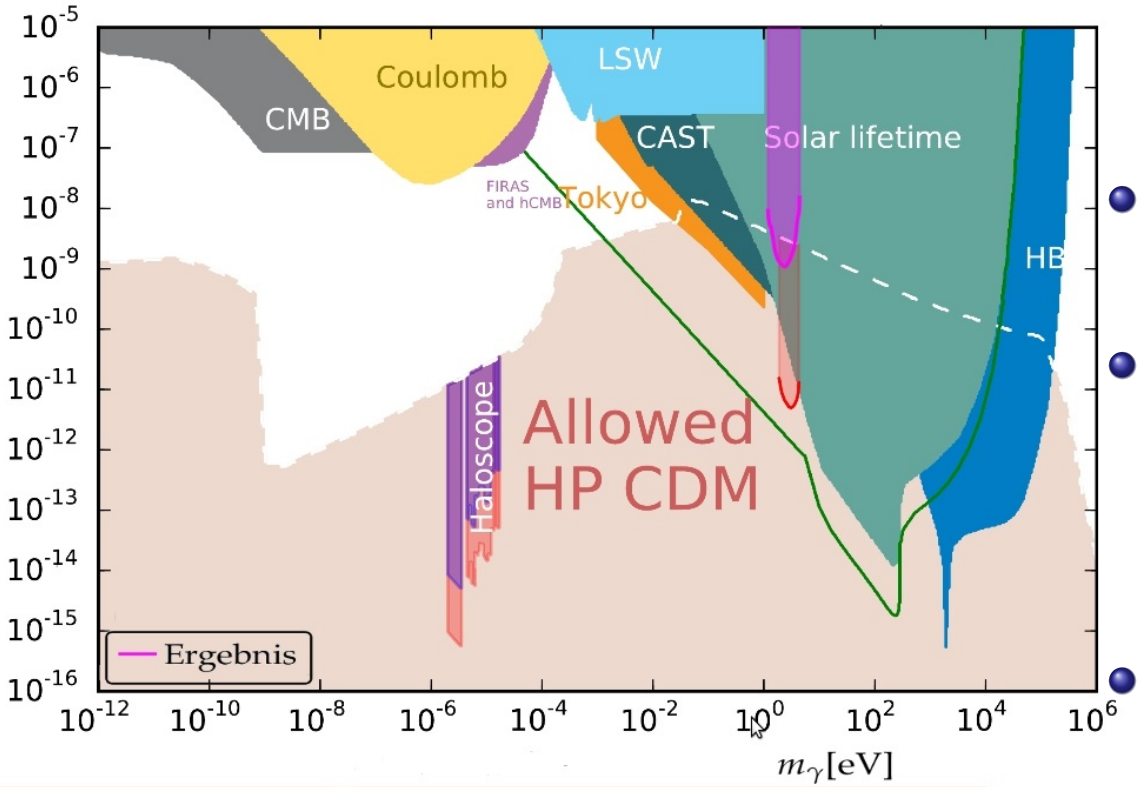


Measurements January-March 2015 (+write up last week!)

Plot & Red: Tokio 1504.00118

Drawn in Pink: FUNK CCD

Green line: Vinyoles 1501.01639



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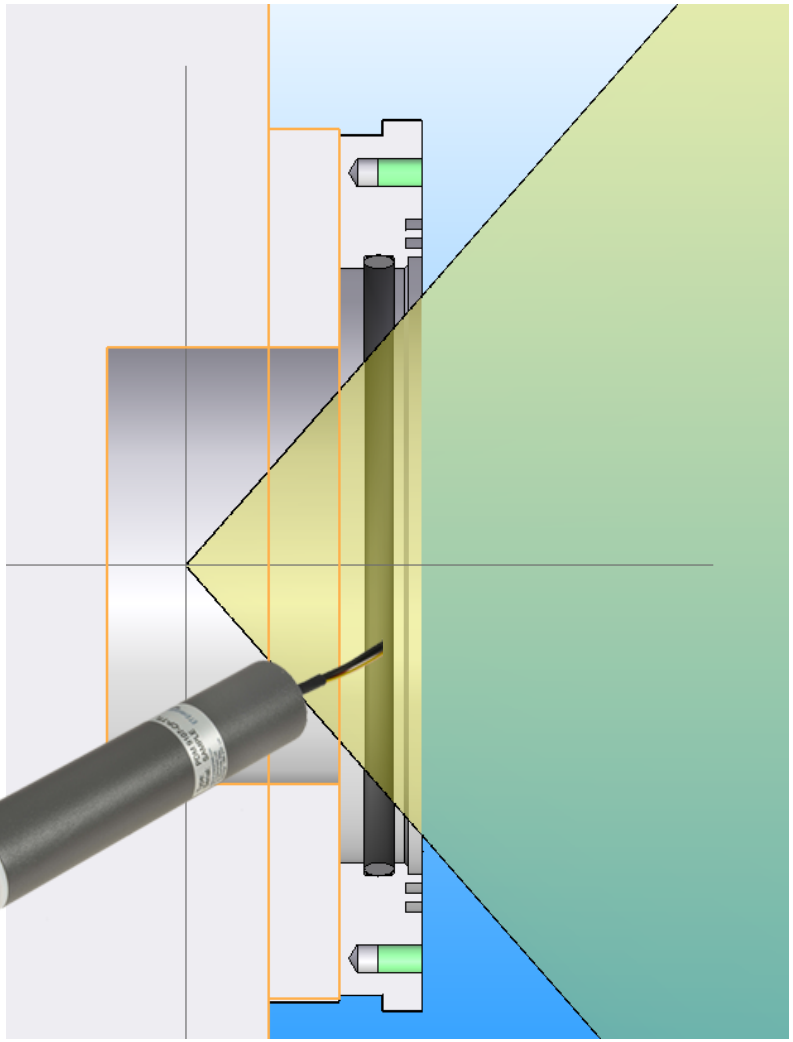
- e.g. test of nightly emergency lighting tests
- SENSICAM CCD rather noisy 0.1 e^-/px/s + 13 e^- readout $\rightarrow$ if signal, many pixels illuminated!
- first results in the Bsc thesis of Chr. Schäfer at KIT: $\chi \sim 2 \times 10^{-9}$ at masses $m_{\text{cent}} \sim 2.4$ eV

Next steps & on the longer run

Thanks to H.Krüger for shutter

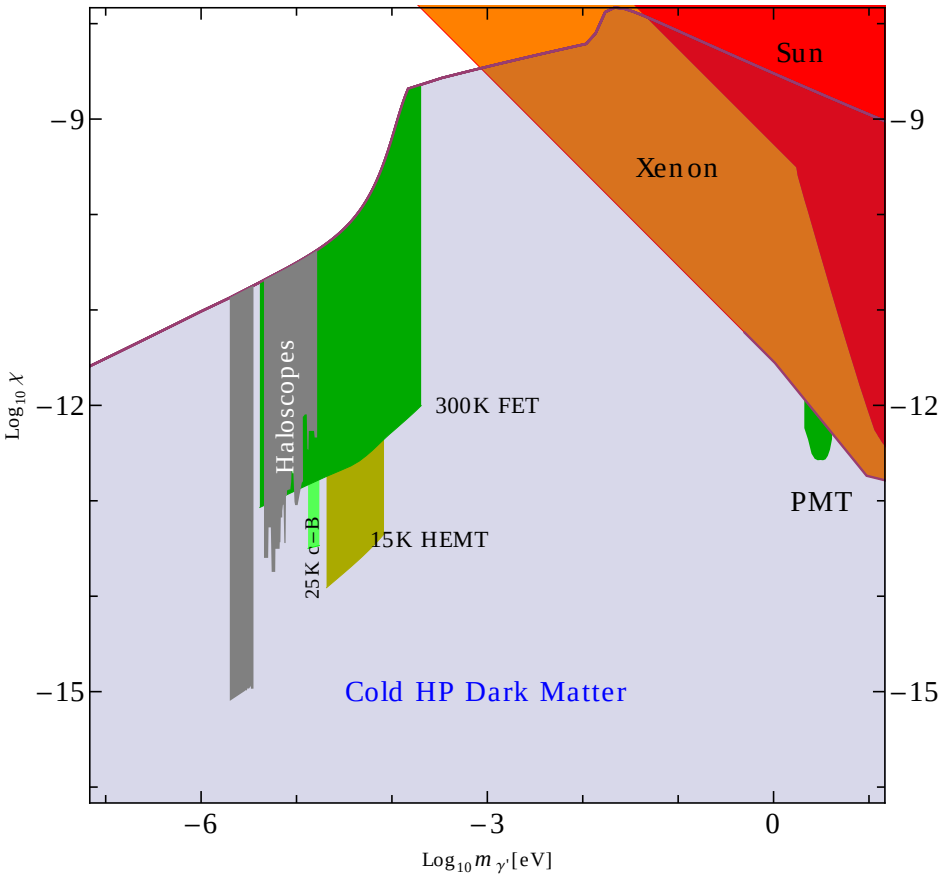


- new bachelor student
- cooled 'Enterprise' PMT 9107 with $\sim 1 - 3$Hz Dark noise [? PhD Lozza] delivered at 25mm active diameter
- detector is being characterized, shutter tested...

Next steps & on the longer run

From last Patras proceedings...

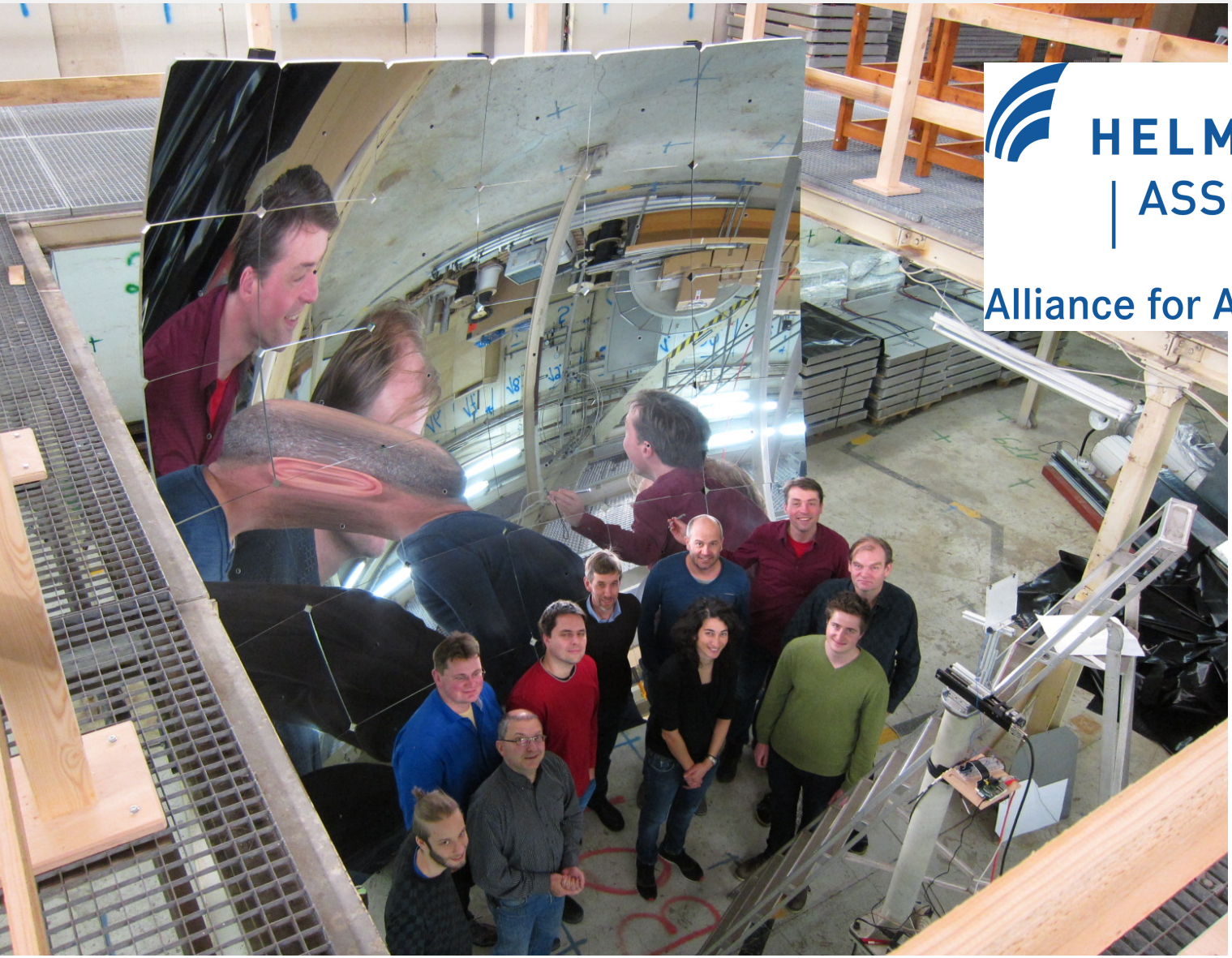
[1410.0200]



get the optical done first!

- new bachelor student
- cooled 'Enterprise' PMT 9107 with $\sim 1-3$Hz Dark noise [? PhD Lozza] delivered at 25mm active diameter
- detector is being characterized, shutter tested...
- new HP DM parameter space around 2-4 eV in couple hours measurement
- after that: check background & reflectivity at lower frequencies (MHz, THz?)

Thank you... and thanks to all my colleagues!



HELMHOLTZ ASSOCIATION

Alliance for Astroparticle Physics

Thanks to HAP for the PMT $!

CCD vs PMT?

- benchmark 1.2 $\chi \times 10^{-12}$ 1/m[eV]
- ideally, for same measurement time, CCD only 1 order of magnitude worse in χ, since $n \sim 10^5$ pixel with 0.1 Hz and $\chi \sim n^{1/4}/t^{1/4}+$ Readout noise
- in plot: PMT 4 orders of magnitude over CCD
- CCD limit from 1000s measurement, with PMT 90h $\rightarrow$ factor 320 in time (1 oom in χ), so only CCD should be only 2-3 oom worse in the plot than PMT estimate
- CCD intensity quite temperature dependent, discard measurements & shutter bad, what is true background?
- but backgrounds much worse than expected (still much too much light) $\rightarrow$ curtain around mirror? point away for background measurements?

sensitivity estimate cf JCAP 1304 (2013) 016

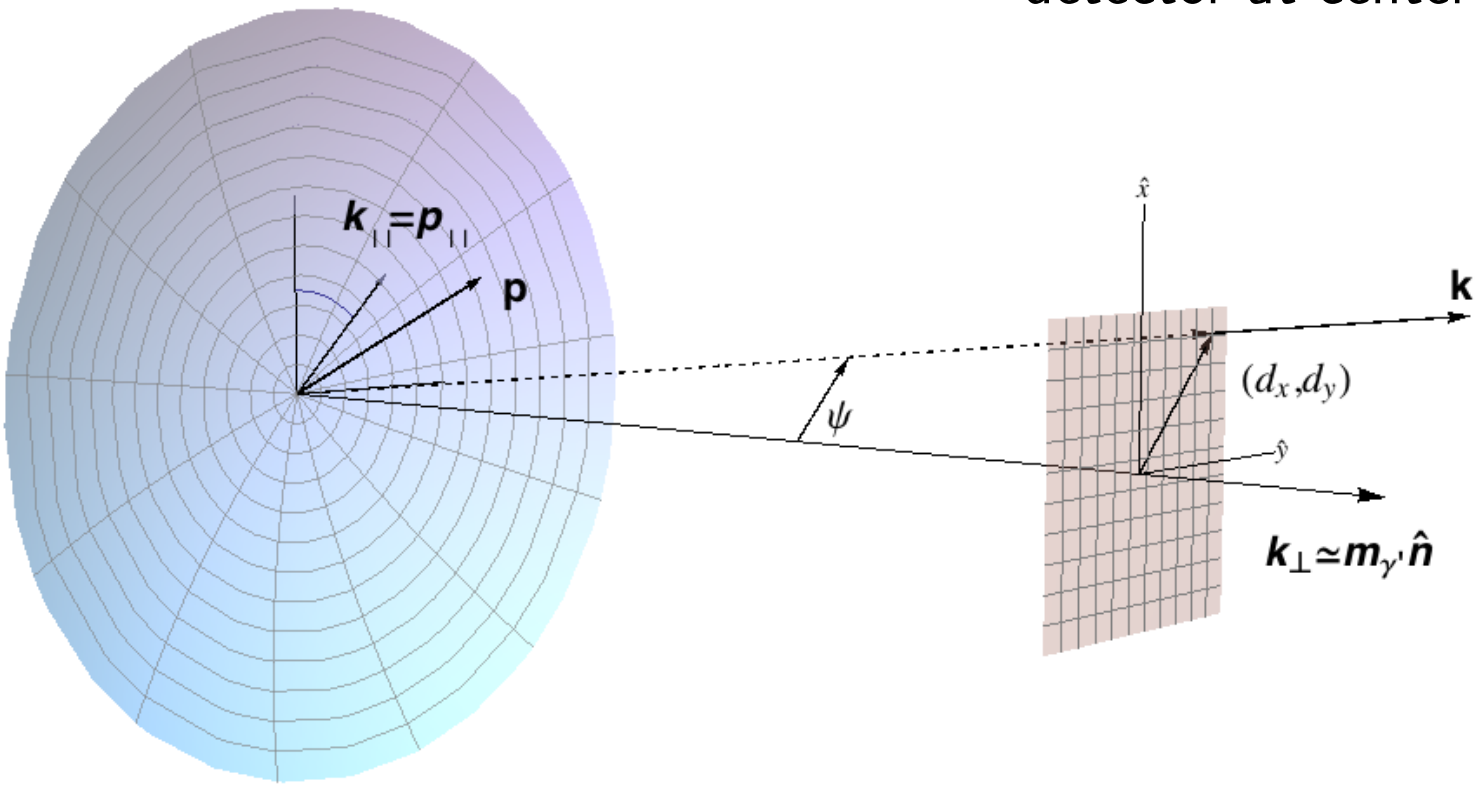
- Power at R due to HPs for a dish size of $A = 12.96\mathrm{m}^2$ and $\rho_{\mathrm{CDM}} = 0.3\mathrm{GeV}/\mathrm{cm}^3 \rightarrow P \simeq \chi^2 \rho_{\mathrm{CDM}} A \approx \chi^2\ (1.87 \times 10^5\ \mathrm{Watt})$
- signal rate in Hertz $s \equiv \frac{P}{\omega} \sim \chi^2\ 9.4 \times 10^{20} \frac{\lambda}{[\mathrm{nm}]} = \chi^2\ 1.2 \times 10^{24} \frac{[\mathrm{eV}]}{\mathrm{m}}$
- non-ideal detector, e.g. Quantum Efficiency: $s_{\mathrm{eff}} = s \times \mathrm{QE}$
- non-ideal mirror: almost negligible 1308.1103, Eqn. 2.20
- low noise n detector
- $\mathrm{SNR} \sim \frac{1}{2} \frac{s}{n} \sqrt{nt}$, can estimate how low we can go in χ as fct of time
- intrinsic background + cherenkov in PMT window

Auger mirror detail J. Abraham *et al.*, Nucl. Instrum. Meth. A **620**, 227 (2010)

- 20 mm thick aluminium, diamond-milled to $R = 3.4$m
- reflective surface was created by gluing a 2 mm sheet of AlMgSiO5 alloy, UV-optimized senis (200-400)nm
- 2mm thickness should mean that the light in the visible does not see what's below the surface
- imperfections (roughness) below 10nm
- Finally, a 90 nm thick aluminum-oxide layer was applied to the surface by chemical anodization to provide additional protection.

Directionality math general: Jae/Red, JCAP 1311 (2013) 016

- with energy conservation $\vec{k} = \sqrt{m^2 + |\vec{p}_\perp|^2}\,\vec{n} + \vec{p}_\parallel \Rightarrow$ $|\vec{p}| \ll m$ angular off-set $\psi \simeq |\vec{p}_\parallel|/m \Rightarrow d_i \simeq \frac{p_i}{m} R$, detector at center R



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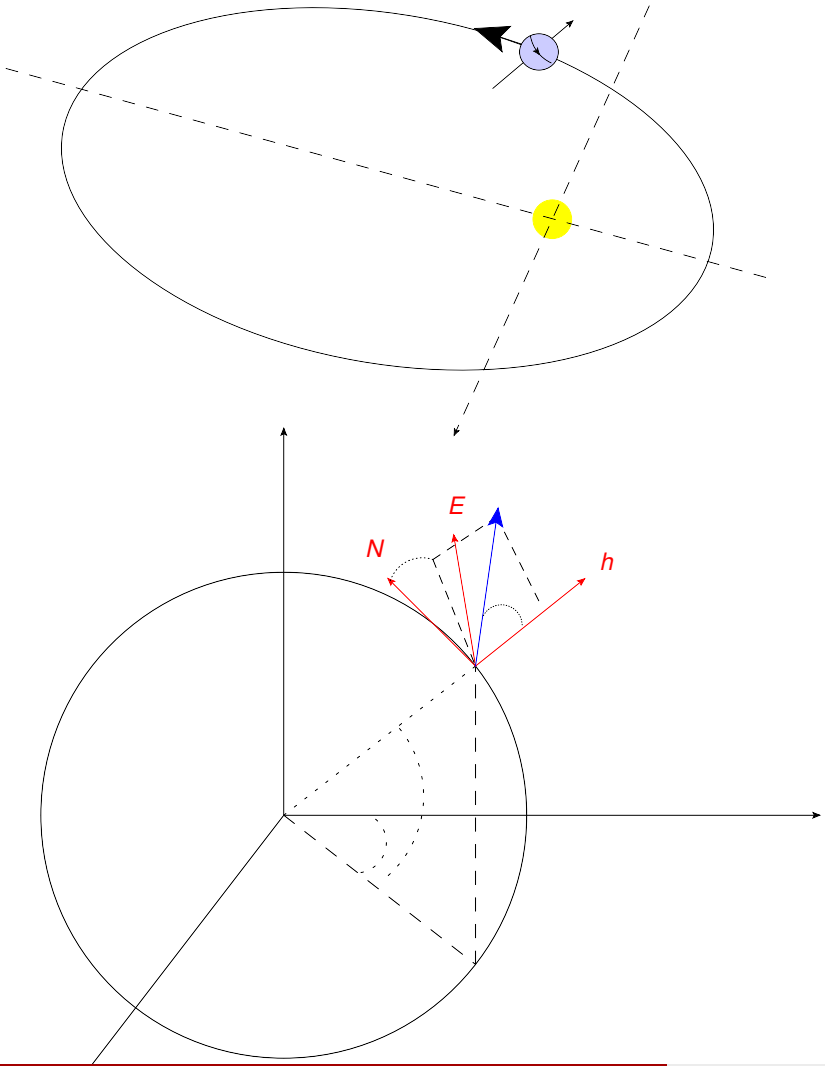
DM @ 60° to ecliptic ↘



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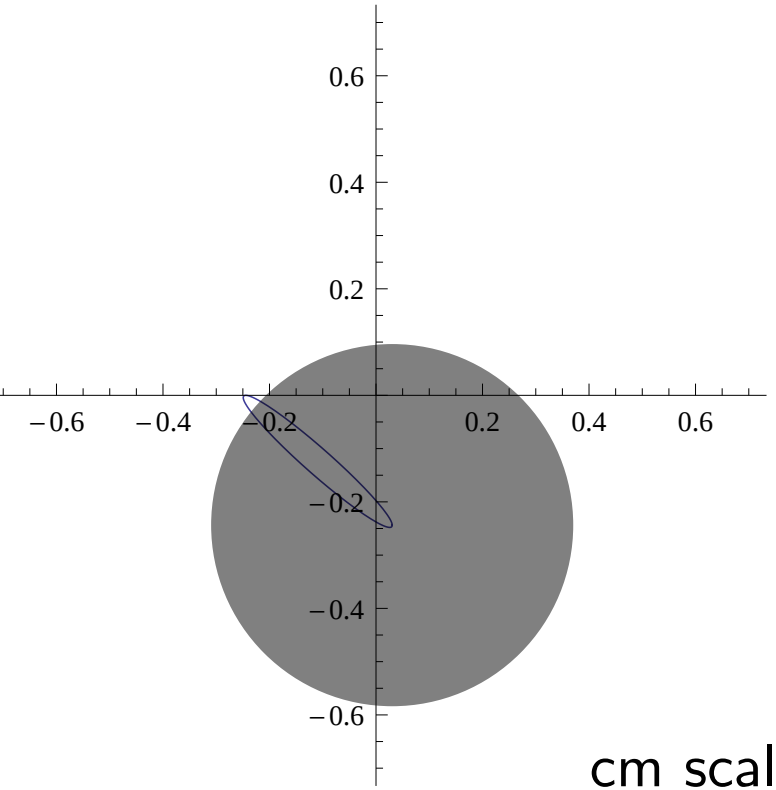

cm scale

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