IT'S A VIOLENT VHE SKY…

A transit IACT to survey half of the VHE γ-ray sky

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MACHETE: A transit IACT to survey half of the VHE γ-ray sky

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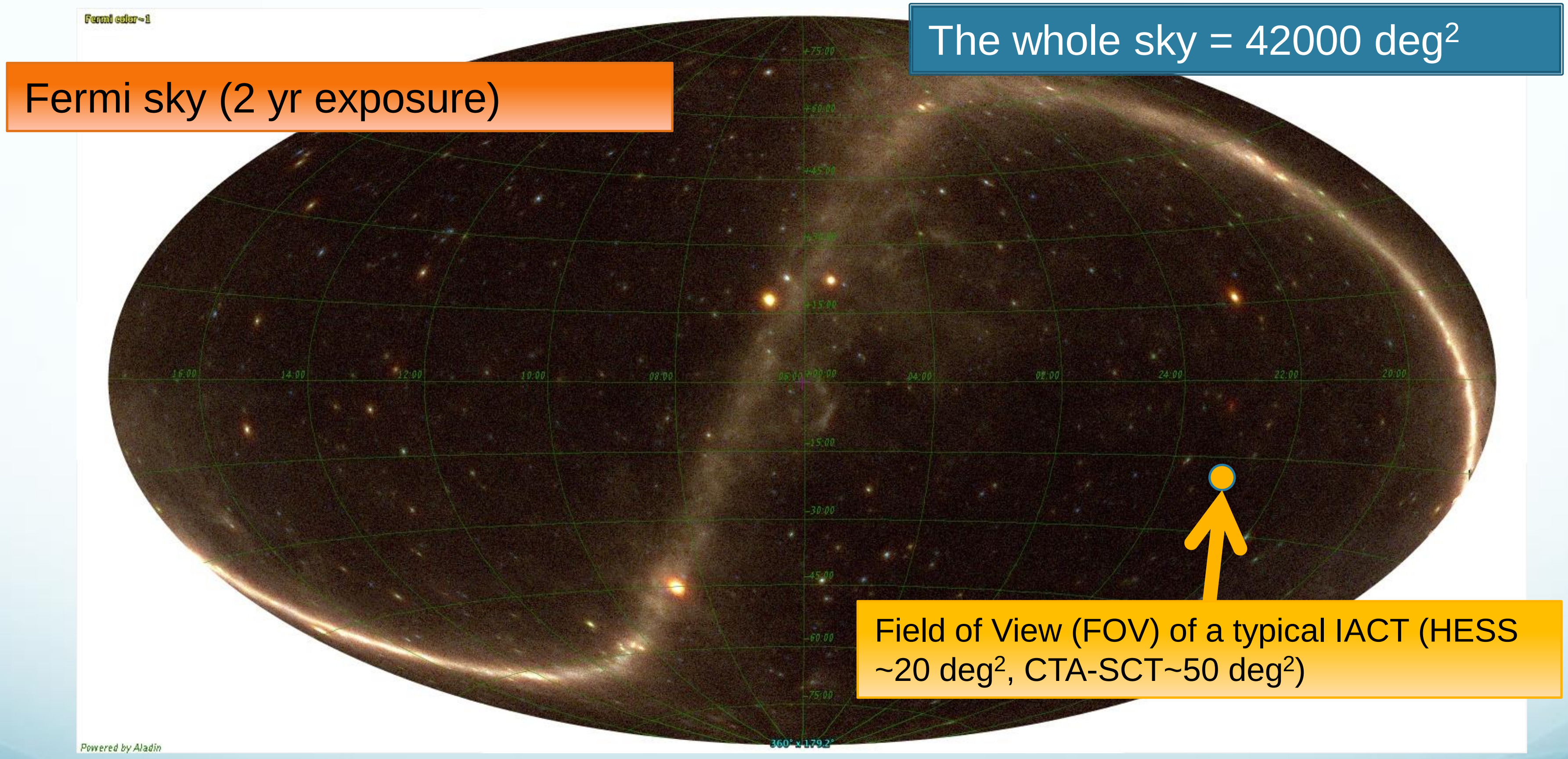
The Future of Research on Cosmic Gamma Rays
La Palma 2015

IACTs are pointing instruments

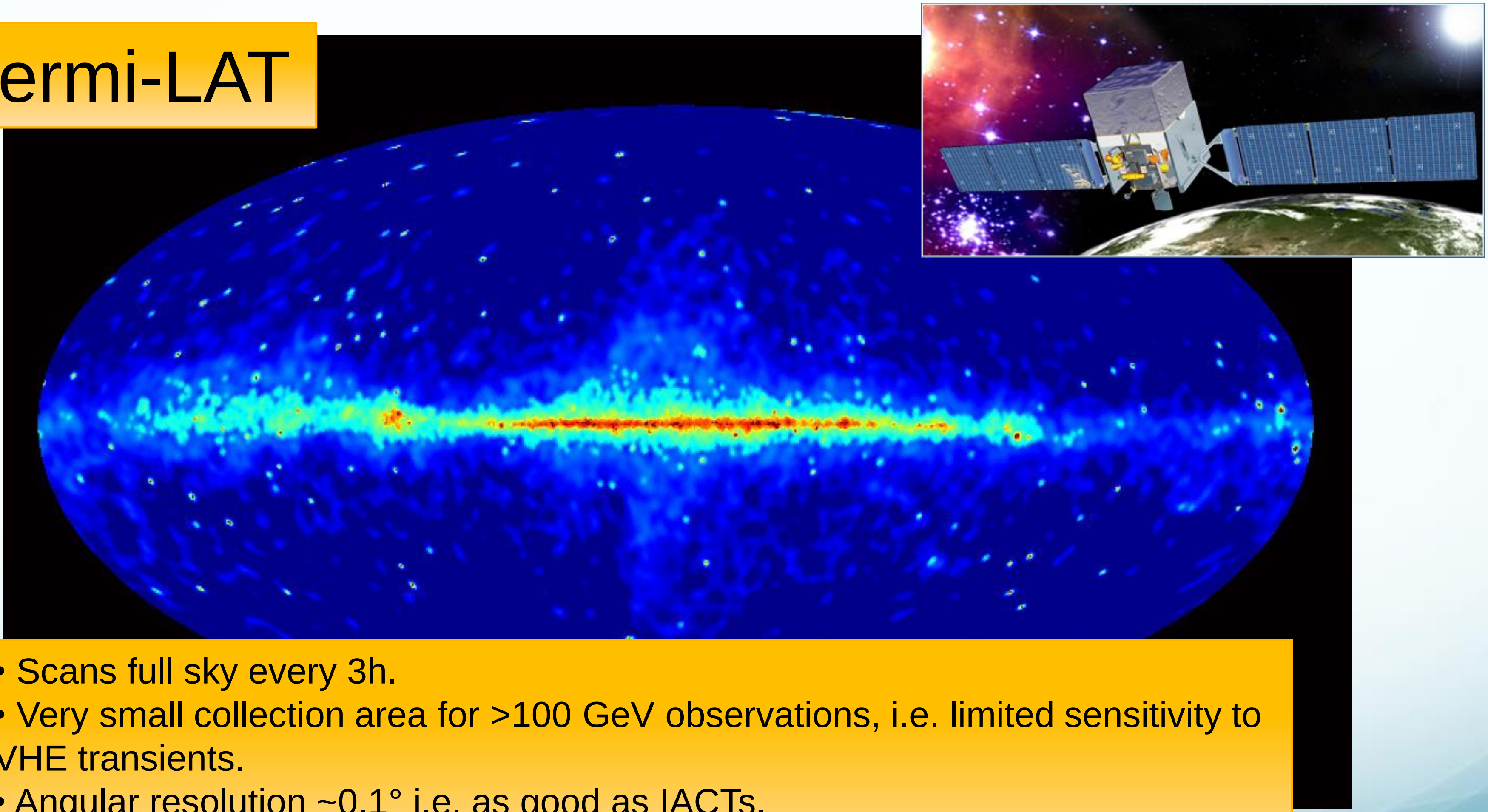


Surveys with IACTs

- Say we need 10h to achieve enough sensitivity. We would need 10000 hours to scan the whole sky: telescopes need ~10 years to collect them.
- It is achievable but there are many other ideas to exploit an IACT for 10 years.
- As a result only a survey of the galactic plane has been performed (HESS, about 1000 deg^2). Adding all pointing observations, we may have explored ~5% of the sky.
- What is in the other 95% of the sky? Active galaxies, off-plane galactic sources, dark matter clumps? Important to make a **Full sky survey in VHE**.
- What it's more, the VHE sky is changing all the time, so we would need to repeat the survey after a few years and we'd very much like to **monitor it every night**.

E_γ<100 GeV: space based surveys

Fermi-LAT



- Scans full sky every 3h.
- Very small collection area for >100 GeV observations, i.e. limited sensitivity to VHE transients.
- Angular resolution ~0.1° i.e. as good as IACTs.
- No obvious replacement for Fermi-LAT in the future (>2020?)

E_γ>1 TeV: surveys with non-IACTs

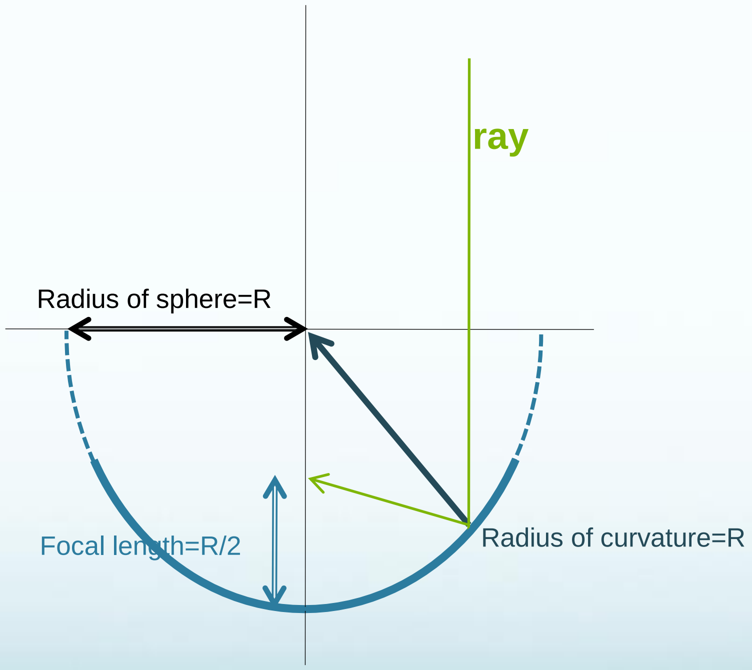
HAWC

Just started to take data

- ~10-15x more sensitive than Milagro.
- Angular resolution ~1°.
- Hadron rejection poorer than IACTs, i.e. worse sensitivity
- Energy range: >1 TeV.
- Larger: HiSCORE in Russia, LHASSO in China, under construction, but targeting higher energies

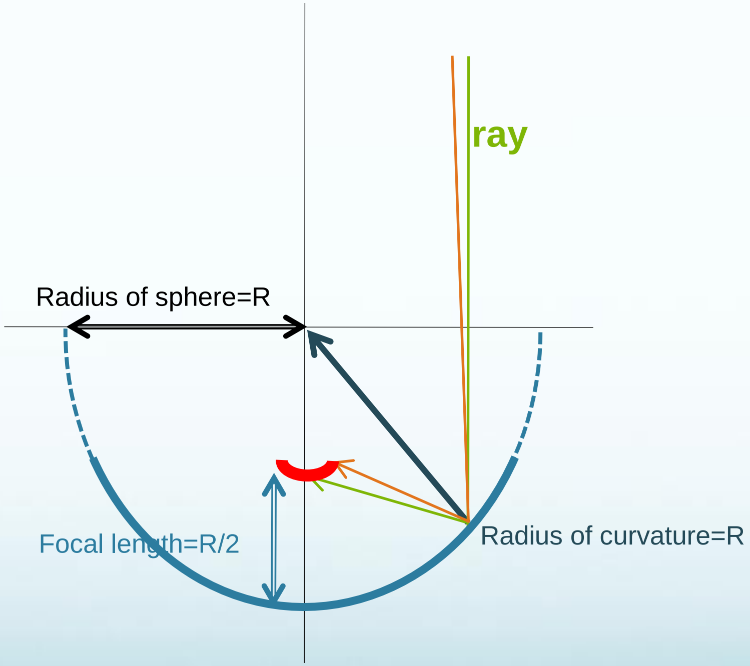
The archetypal wide FOV telescope: the Schmidt telescope

How to build a Schmidt:
STEP 1. Start with a **spherical mirror**. It has aberrations but only spherical aberrations.



The archetypal wide FOV telescope: the Schmidt telescope

STEP 2. Make the **focal plane spherical**, with center at center of mirror. All incident directions become equivalent.



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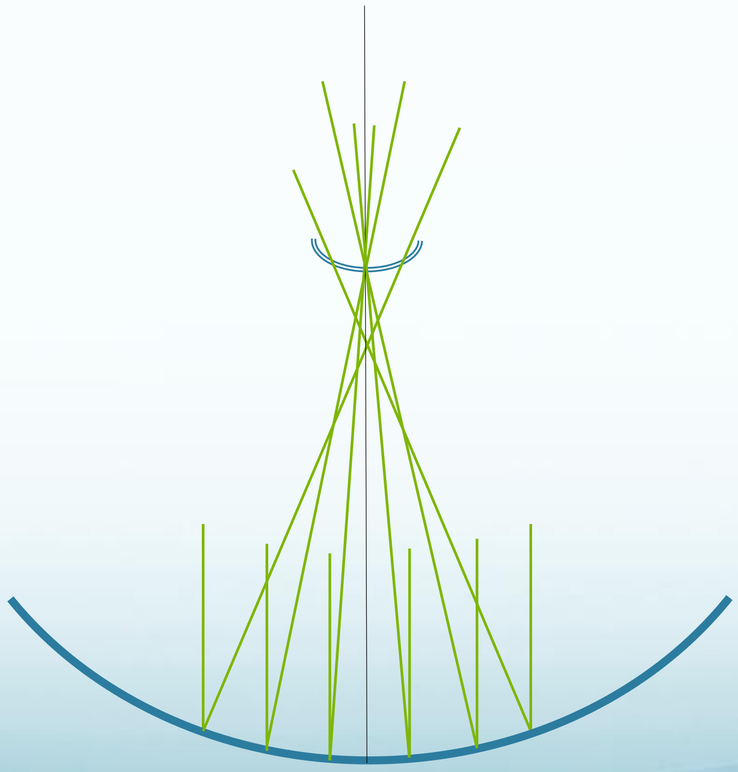
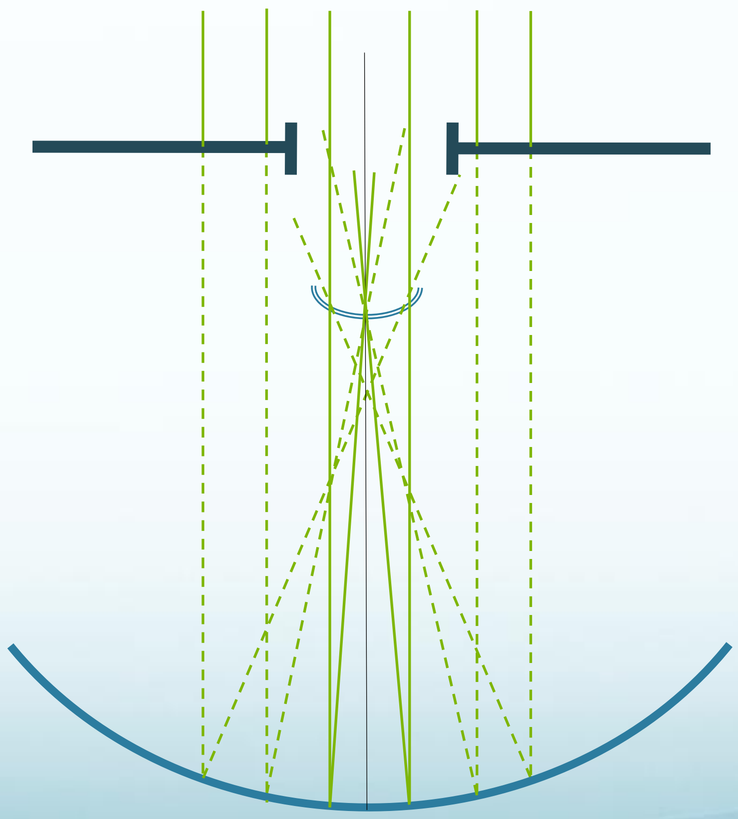
STEP 3. For a spherical mirror as rays hit further and further away from optical axis they get more a more defocused.



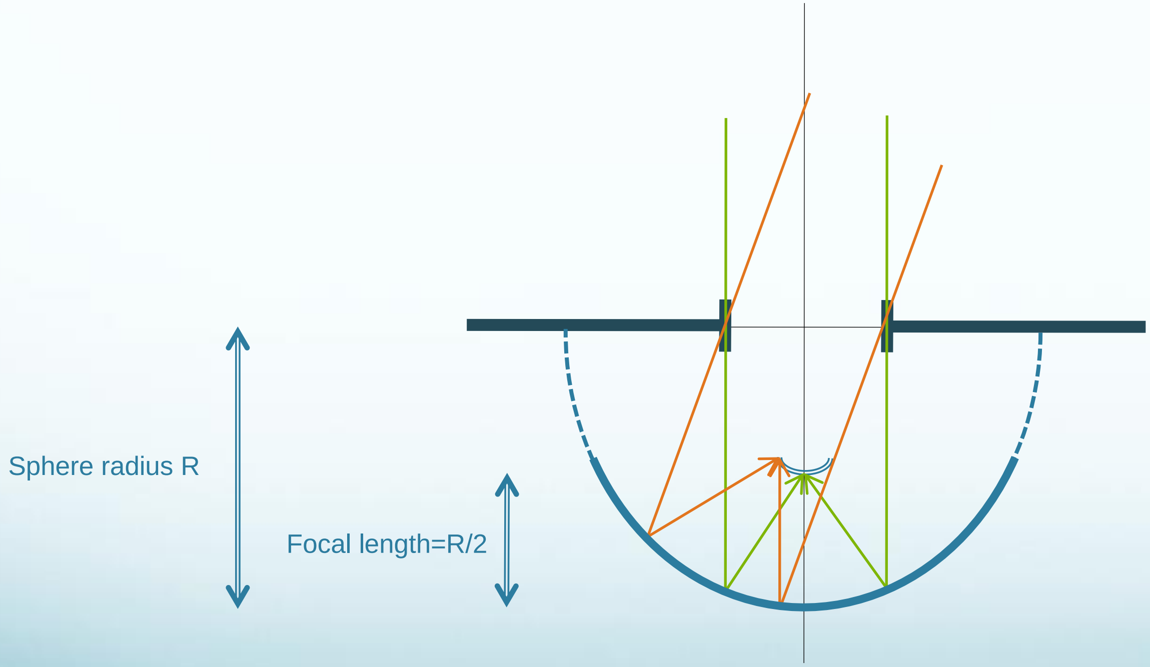
The archetypal wide FOV telescope: the Schmidt telescope

STEP 3. … adding a “stop” reduces the aberration.



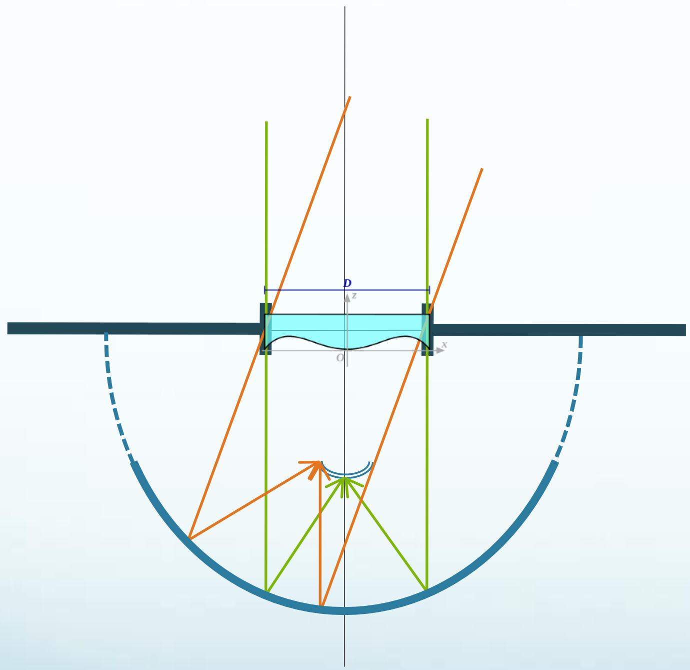
The archetypal wide FOV telescope: the Schmidt telescope

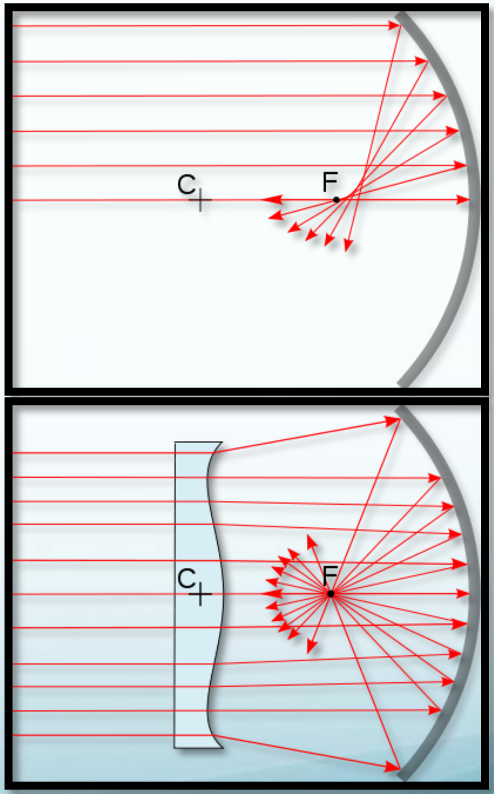
STEP 3. Considering all incident directions: where shall we place **the "stop"**?
At the mirror's center of curvature, so that all directions remain equivalent.



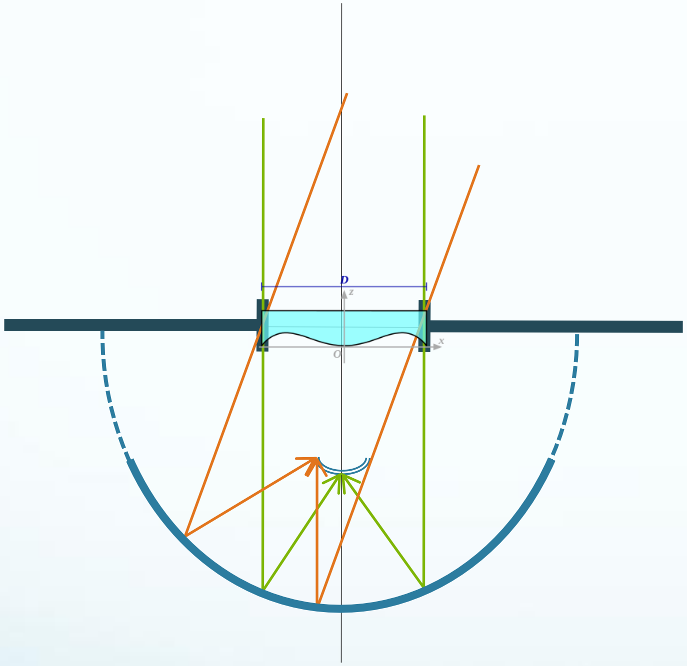
The archetypal wide FOV telescope: the Schmidt telescope

STEP 4. Add the Schmidt **corrector plate** at the stop. That eliminates spherical aberrations.





The archetypal wide FOV telescope: the Schmidt telescope



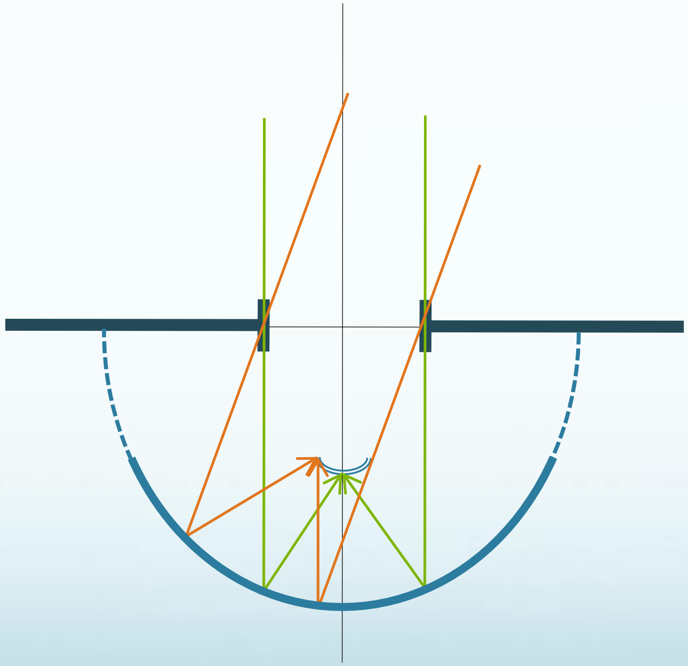
Well, let's build a "Schmidt IACT"!
This has been proposed: Mirzoyan & Andersen, ApP **31** (2009) 1,
with D=7m mirror, FOV ø=15°, **f/D=0.8**, PSF RMS=1 arcmin.

Unfortunately:

- It has chromatic aberration (lens!)
- For the corrector plate they propose a 7m ø PMMA Fresnel lense of 17mm max thickness: challenging and probably expensive.
- Bulky instrument: 3 large elements (mirror, camera and corrector plate).

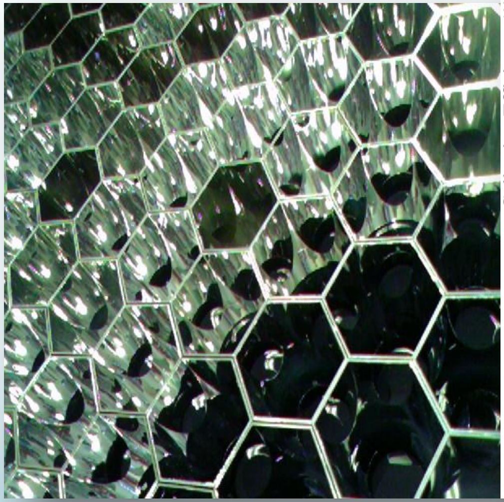
[redacted]

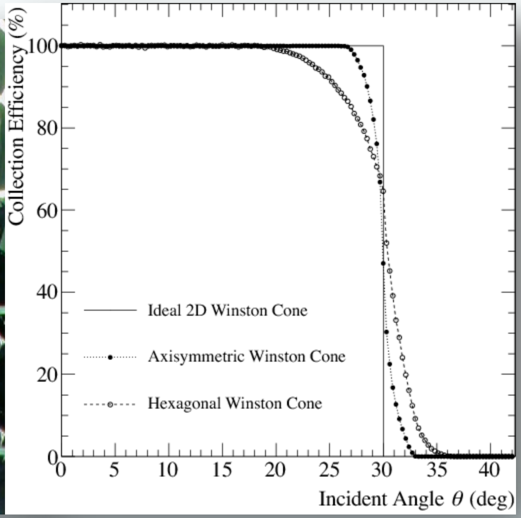
We live with the aberration: after all IACTs don't need excellent optics

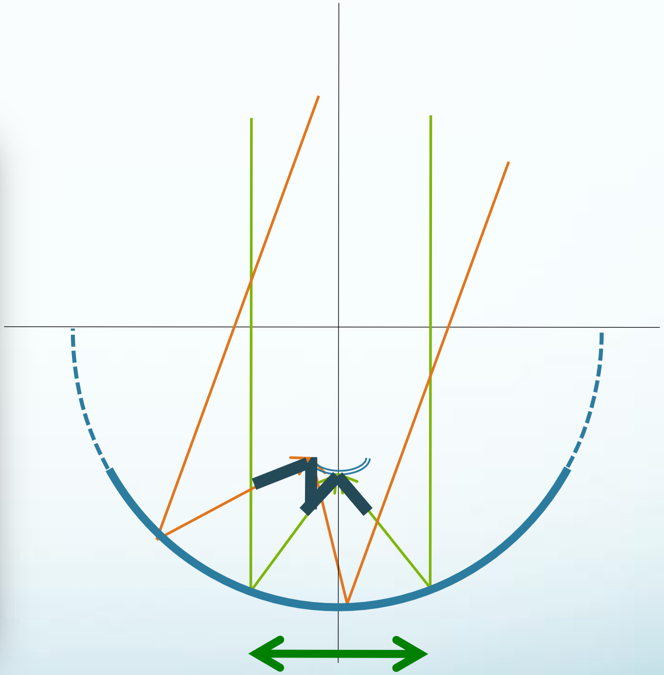


[redacted]

Implement it placing a “light concentrator” on each of the pixels



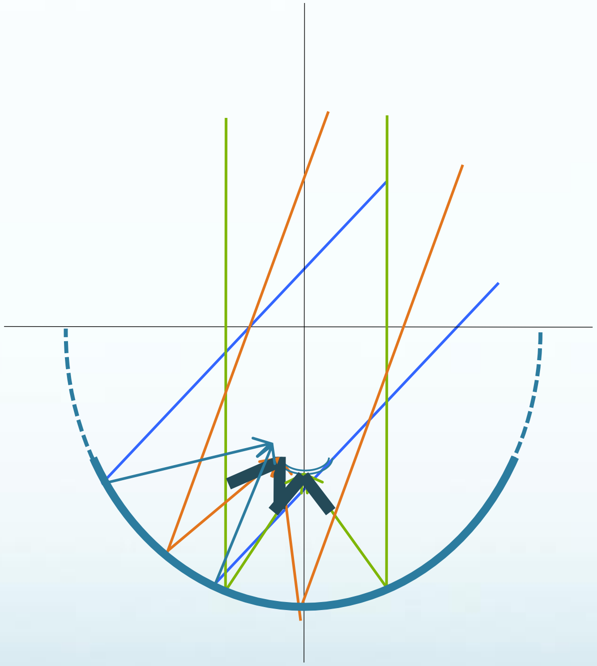




This effectively defines D

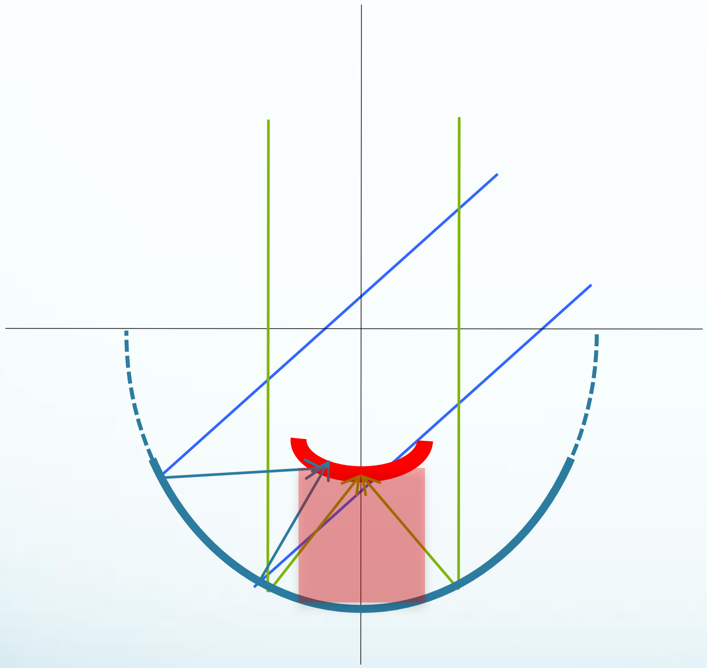
No limit to field of view!?!

Since there is no physical stop the aperture does not decrease as we go further and further off-axis. So we can go to any off-axis angle…!?



No, there's a limit

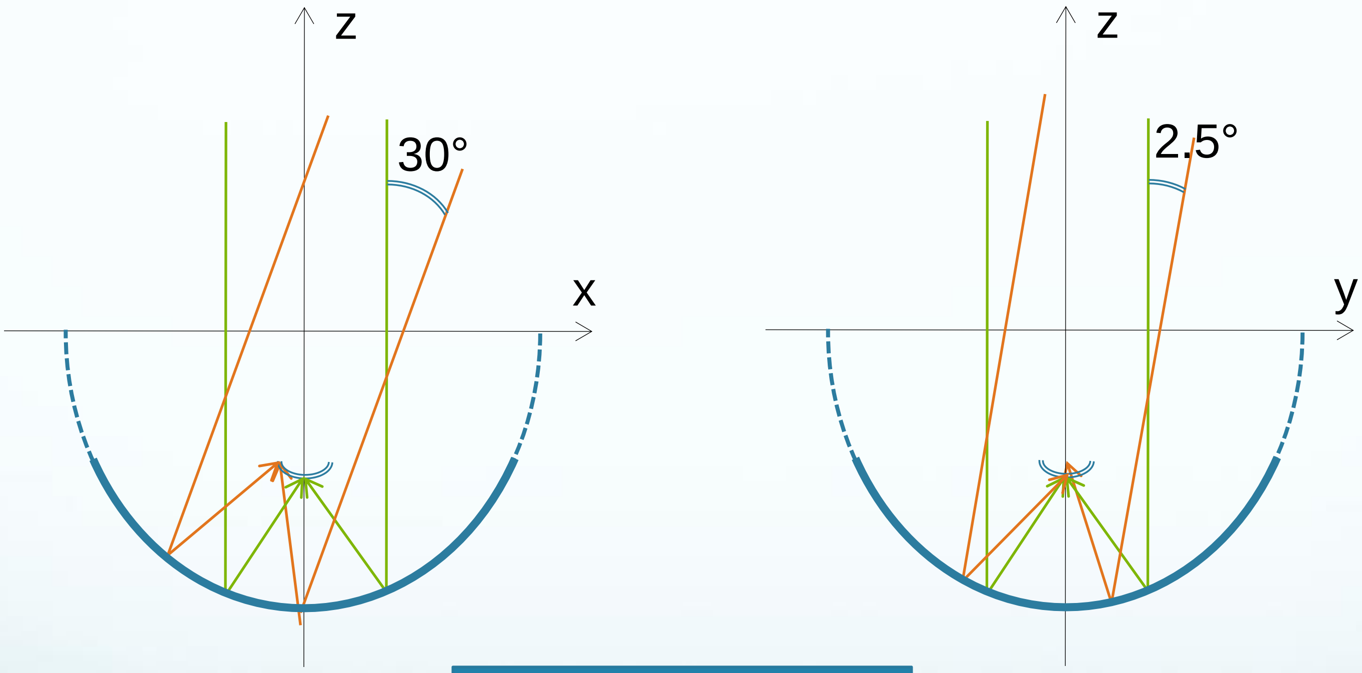
A limit is set by the **shadowing of the camera** on the mirror.



Here is an example: D=12 m, f=17 m (f/D=1.42), circular camera

FOV ø (°)	S_{cam} (m^2)	On-axis shadowing
5	1.77	1.6%
10	7.1	6.3%
15	16.0	14%
20	28.4	25%
25	44.4	40%

Solution: a non-circular camera



Shadowing ~ 15%

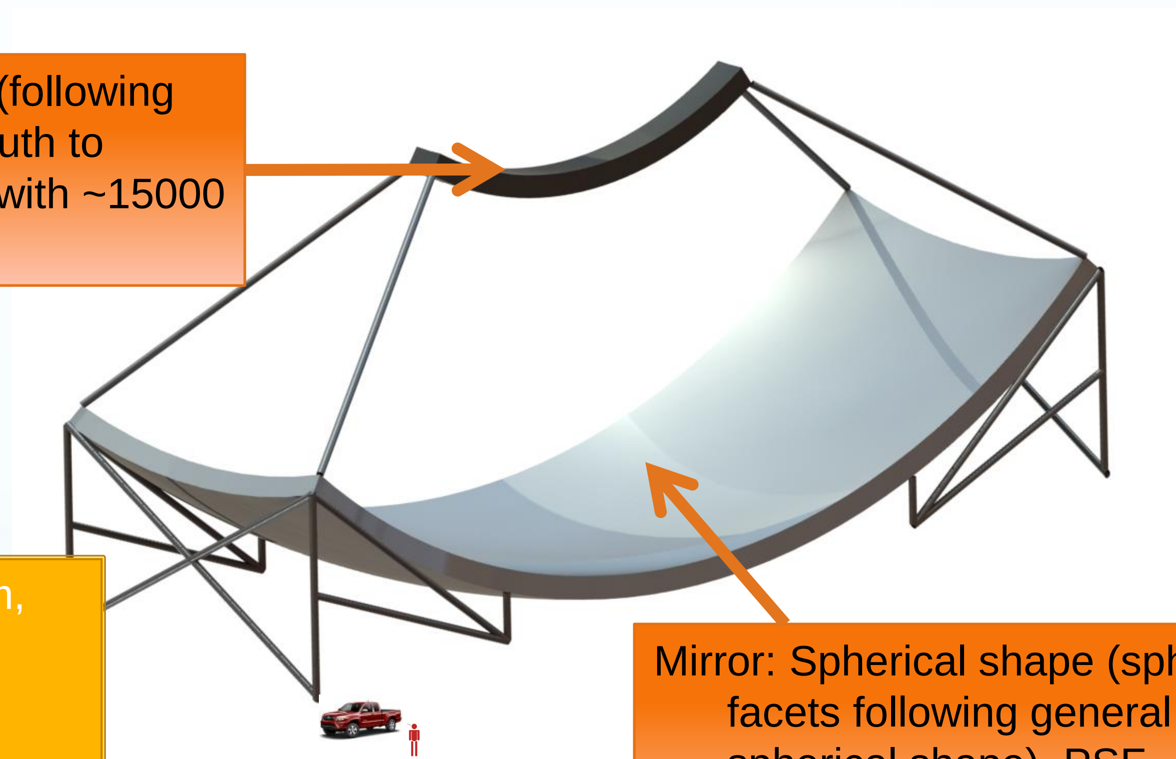
MACHETE= Meridian Atmospheric CHErenkov Telescope

Camera: rectangle of 60° (following the **meridian**, from south to north) x 5°. Equipped with ~15000 pixels.

Effective D=12m,

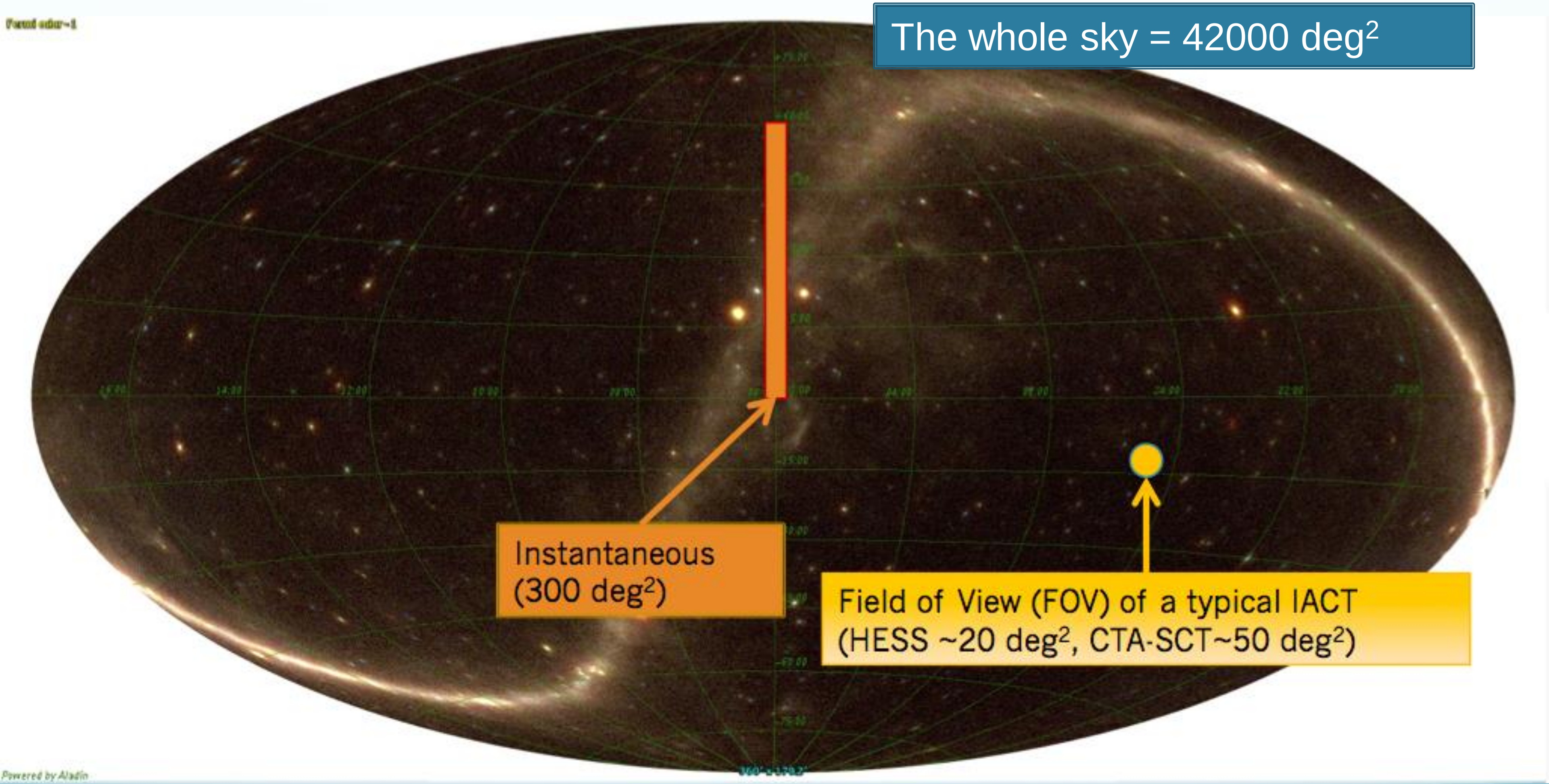
f=17m

(f/D=1.42)

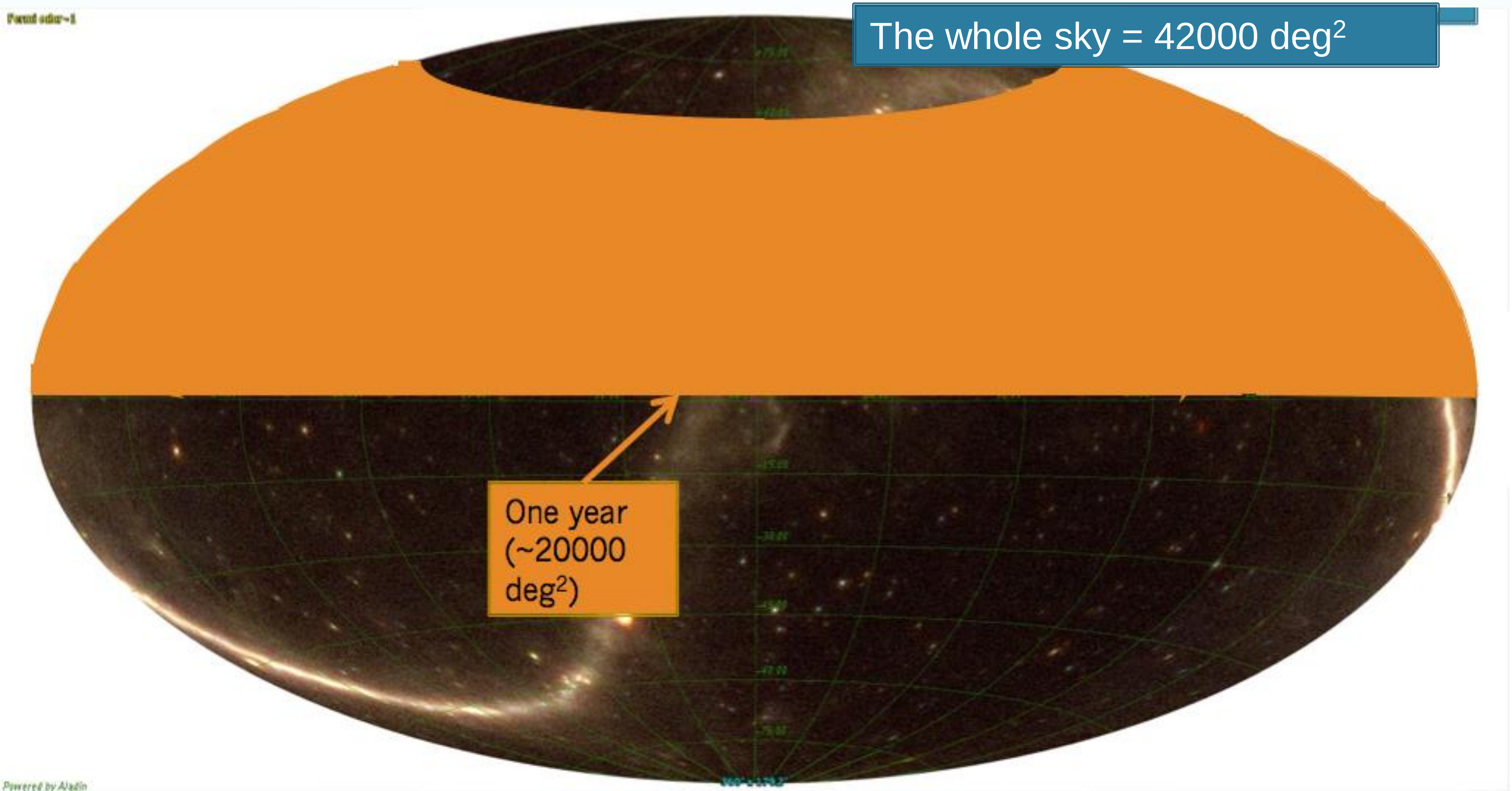


Mirror: Spherical shape (spherical facets following general spherical shape). PSF $r_{80\%}$=0.06°

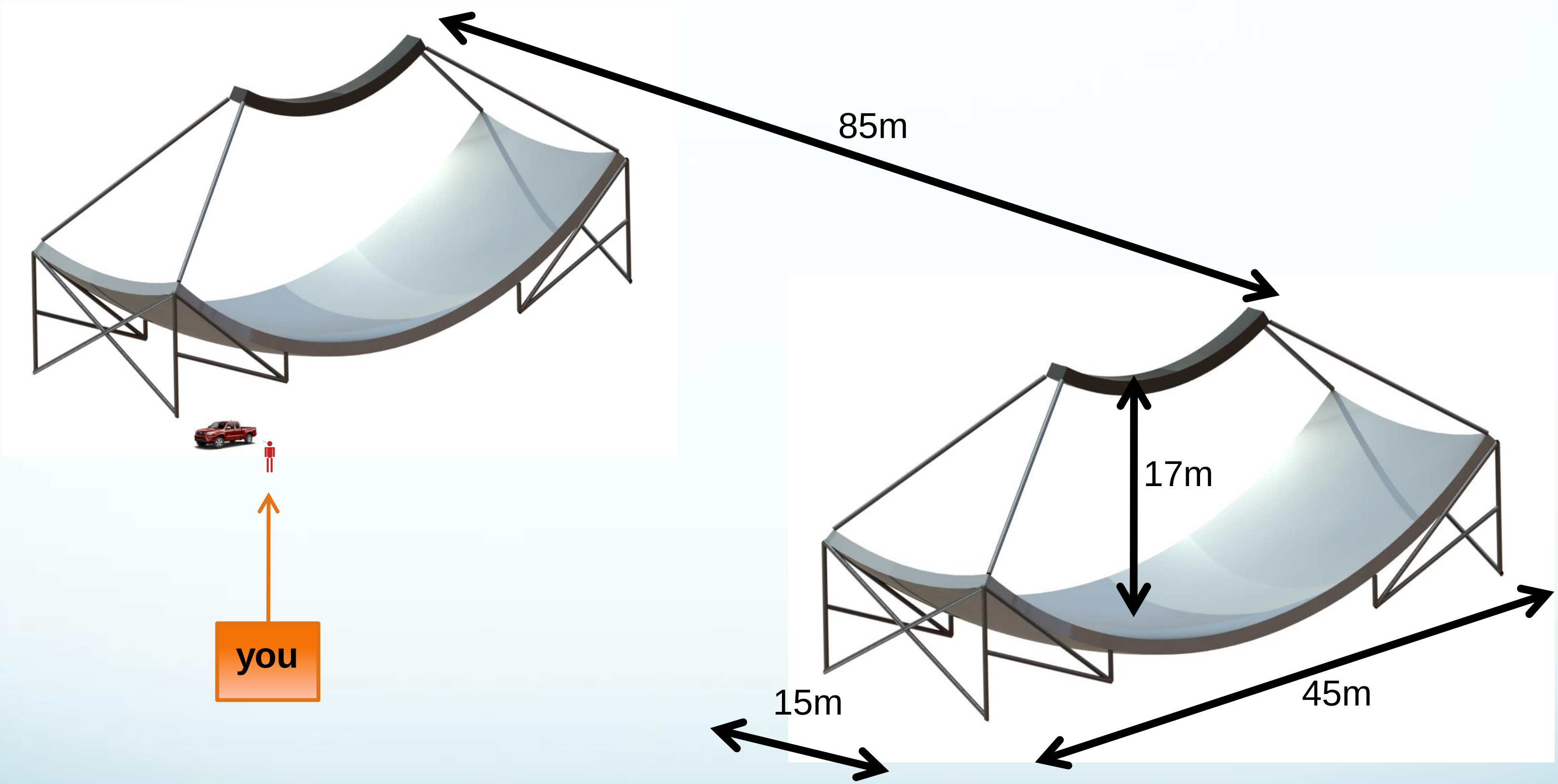
Field of view



Don't move the telescope! Move the sky!



MACHETE = stereo array

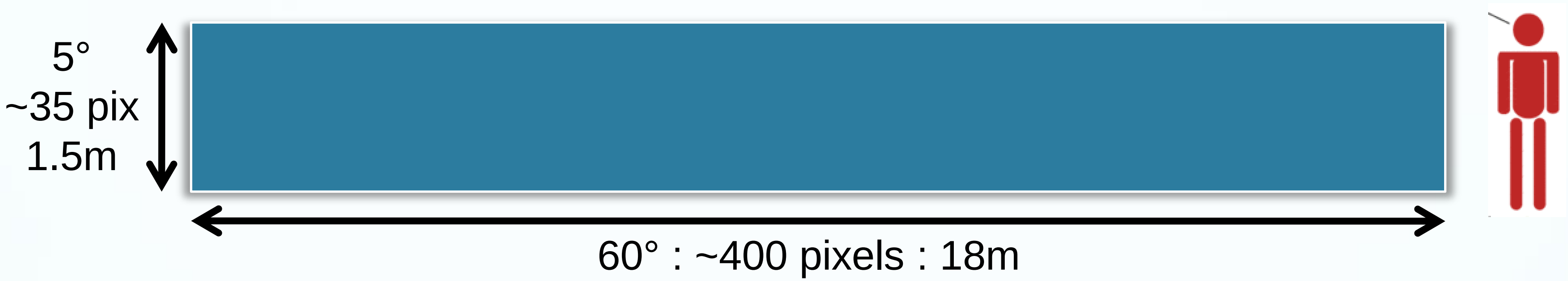


Optical parameters

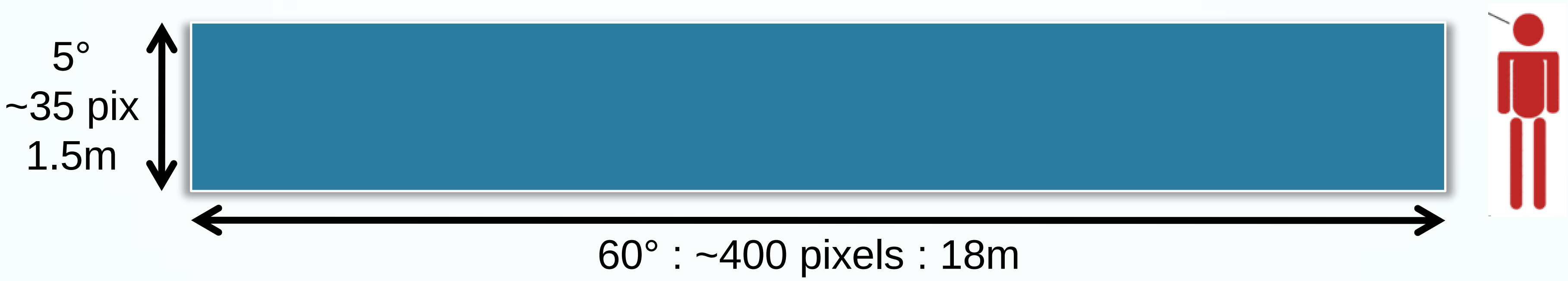
We've optimized some of these parameters using the ray-tracing program ZEMAX and used it to calculate the PSF (which btw is not gaussian)

	D=12m, f=17m, f/D=1.42
Plate scale	300 mm/deg
PSF $r_{80\%}$	0.06° for whole FOV (MAGIC: 0.07°on-axis —0.16° at 1.8° off-axis, MST: 0.02°on-axis —0.07° at 2.8° off-axis)
$Ø_{pix}$ >~ $2r_{80\%}$	0.16° = 48 mm
Total mirror surface	619 m^2
Mirror surface viewed by a pixel	113 m^2
Camera FOV	60° × 5° = 300 deg^2
Number pixels	~15 000
On-axis shadowing	16%
Δt_{max}	3 ns

Camera

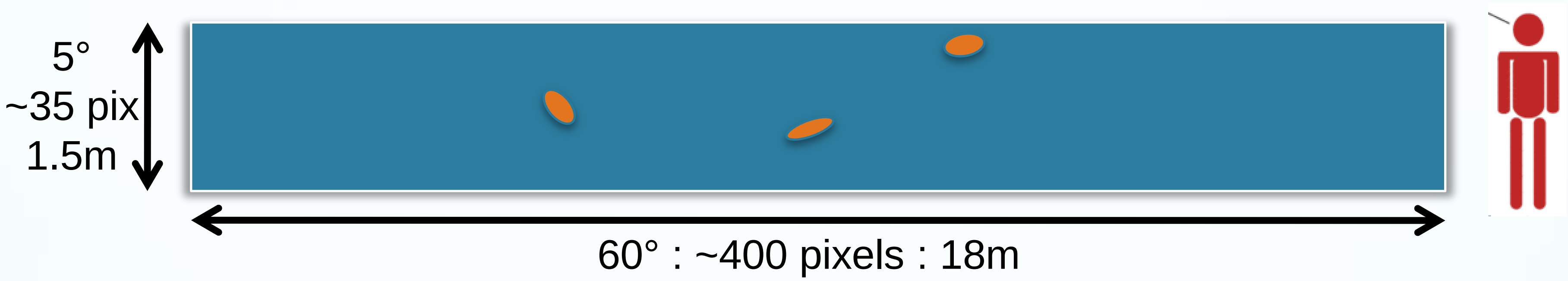


Photosensors



- We have not selected a specific photosensor.
- **PMTs** are standard in IACTs and reach QE>~40% these days, but they are expensive (~300 € / unit) and bulky.
- **Silicon PMs** (aka G-APDs) deliver even higher QE, would cost ~200 € for a MACHETE pixel (assuming 1 $/mm^2) and would allow smooth observations with strong Moon (important for such a telescope), but spectral response not optimal and unavailable for the necessary pixel size.

Readout



•Showers have a typical size ~<1°, so we only need to read out a small fraction of the camera (2°x2° = 256 pixels?).
•A fast local trigger identifies those channels and selects a Region of Interest (RoI). We only need to digitize/record the RoI.
•A possible solution (R. Paoletti, INFN Pisa): install cheap digitizers (TARGET5) in all pixels, break up camera in tiles, digitize tile if local trigger, keep only digitized information if stereo trigger.
•Challenge: 9 kHz proton stereo trigger rate (but each CTA-SCT has 11k pixels and is designed for 10 kHz trigger rate).

Monte Carlo simulation

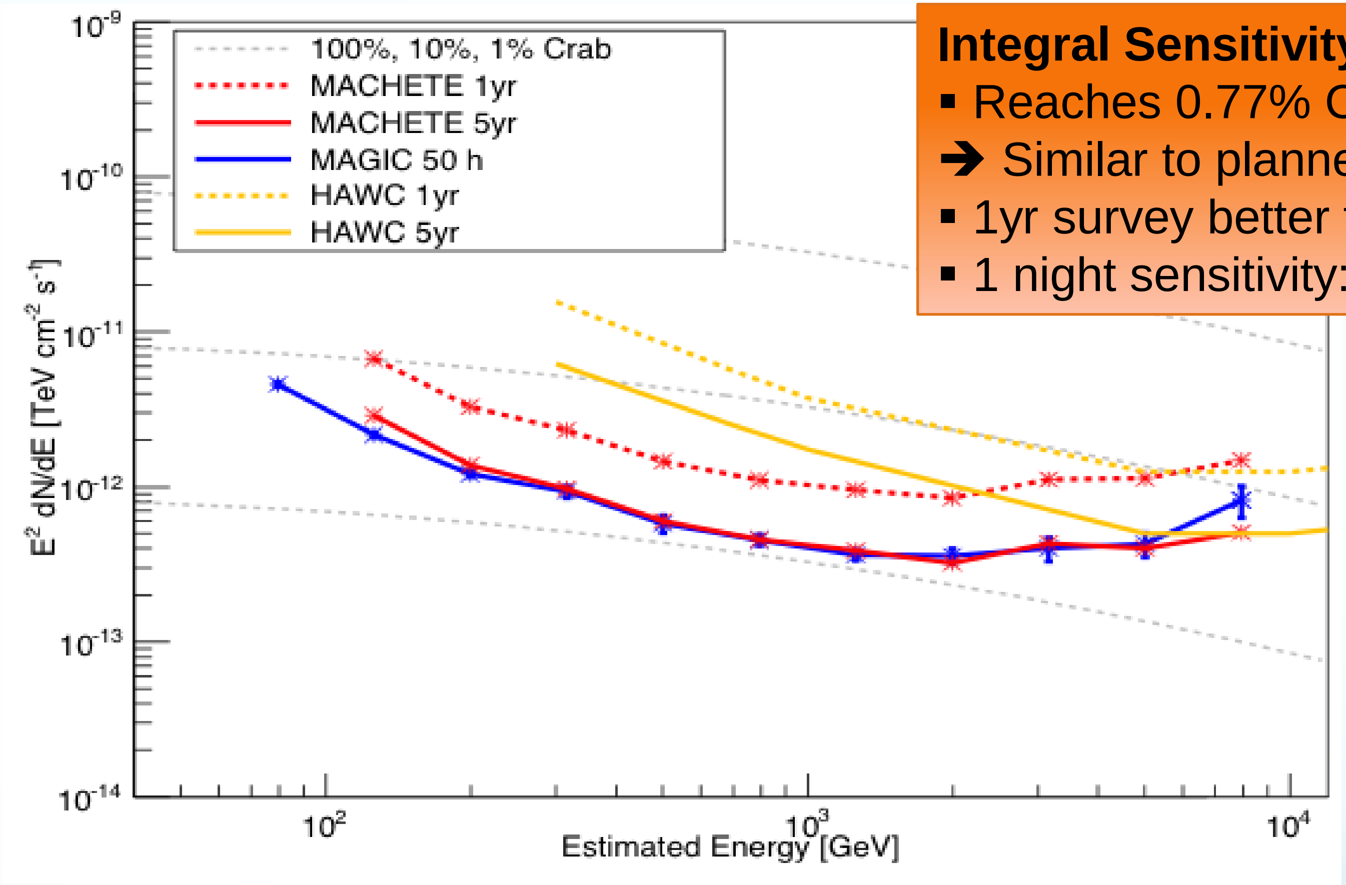
- We've made a full MC simulation of the instrument using the MAGIC MC and analysis software (thanks, MAGIC!!).
- We simulated a 4x4 deg^2 section of the camera and a section of the spherical mirror with estimated PSF ($r_{80\%}$=0.08°, considering facet misalignment).
- We assumed basically the same performance of MAGIC for all optical (PSF…) and electronic elements (noise, sampling…), except for PMT QE, which we increased by 50% (consistent with available PMTs).

Sky accessible by MACHETE

- Every object in ~half of the sky drifts through the camera of MACHETE along a year.
- In one year we integrate ~15 hours for each of these objects.
- Objects in ~¼ sky spend about 20 minutes every night in the FOV of the telescopes.

Performance

Astrop. Physics, in print, and arXiv:1507.02532



Integral Sensitivity:

- Reaches 0.77% C.U. after 5 year survey.

➔ Similar to planned CTA 1000h survey.

- 1yr survey better than HAWC 5yr survey.
- 1 night sensitivity: 12% CU.

Angular resolution: 0.1° and **spectral resolution**: 20-15% (standard IACT, much better than HAWC)

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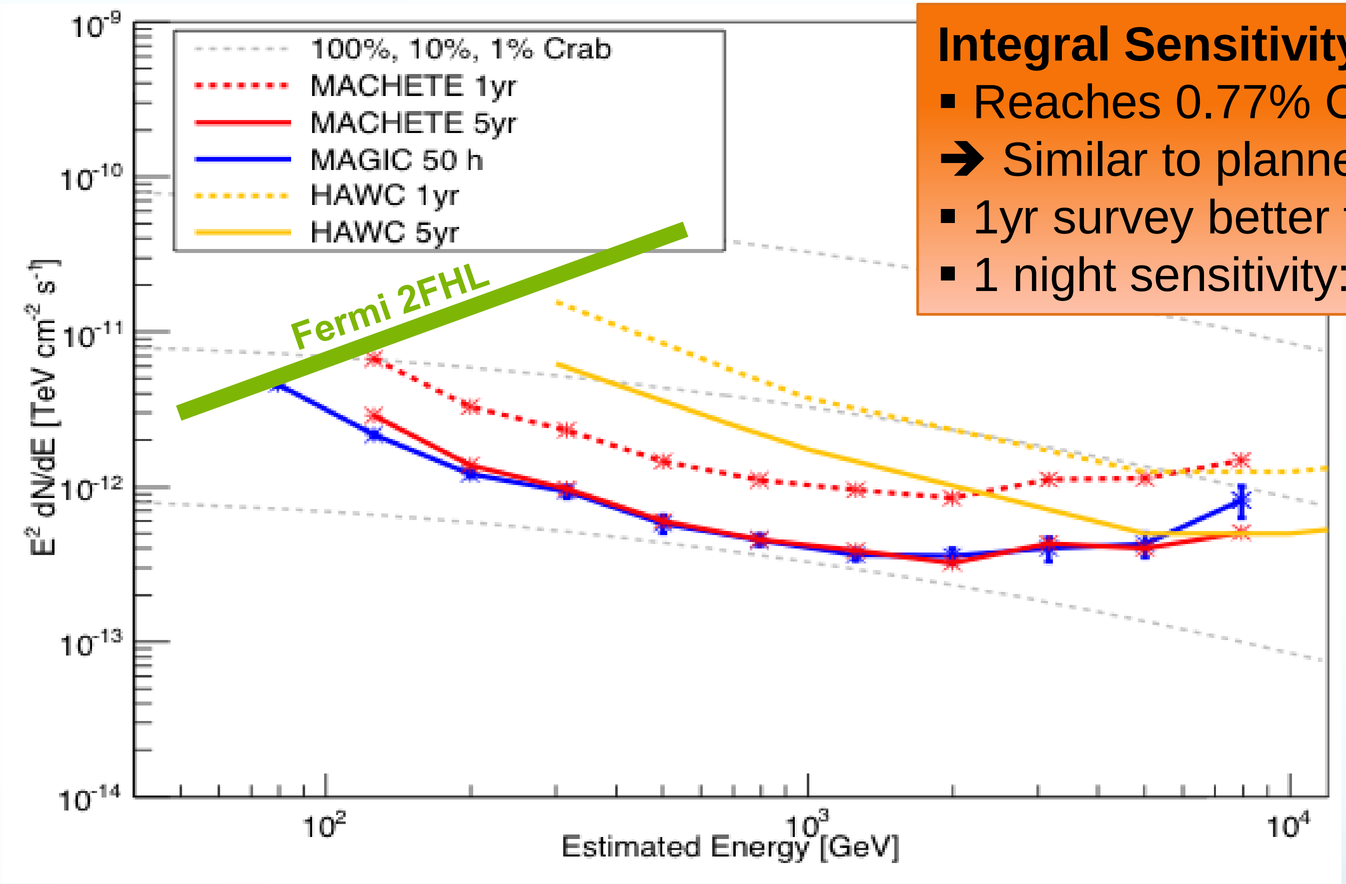

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Physics with MACHETE

- A survey of half of the sky:
  - New Active Galactic Nuclei (Fermi 2FHL: about 230 AGNs detected >50 GeV, most of them not detected by IACT yet).
  - New galactic sources, especially if built in the south.

… and the unknown:
  - "Dark sources" = sources emitting only in VHE.
    - Hadronic AGNs
    - Dark matter clumps?
  - New types of transients.
  - Valuable archive: would provide years-long data sample for phenomena discovered in the future (periodicities, transients)

- Monitor bright VHE sources:
  - Unbiased light curves of AGN and galactic sources.
  - Establish unknown duty cycles (e.g. IC-310).
  - Trigger CTA and other telescopes.

Cost: very rough estimate

- We can use standard IACTs like CTA MSTs to reach the same performance. Is MACHETE cheaper?
- Good:
  - No need for steering mechanics. Hardly any moving parts: reduction in construction cost and cheaper maintenance.
  - Mirrors or camera can be heavier: assuming 1k€/m^2 for mirrors (M. Mariotti, M. Doro, INFN Padova), it’s only 1.2 M€ for two telescopes.
- Bad:
  - 30000 pixels for two telescopes!
  - Number of pixels similar to CTA-SCT. Assuming similar readout, from SCT cost estimate we estimate 1.5 M€ for readout of two telescopes.
  - Significant cost of photosensors: 5.4 M€ for two telescopes assuming 1 \$/mm^2.
- All in all we estimate ~10 M€ capital cost for two telescopes.
- Compare to MSTs/SCTs: >3 times cheaper for same FOV.

Discussion/conclusions

- We have found a simple optical solution to build a very wide FOV IACT (300 deg^2 with PSF $r_{80\%}$=0.06° for D=12m and f/D=1.42).
- Implemented as 2 meridian telescopes, it reaches 0.77% CU integral sensitivity for ~half of the sky in 5 years and 12% CU in a night.
- Very rough cost estimate: 10 M€ for two telescopes.
- Main physics goals: discovery through survey (serendipity!), trigger of transient VHE sources.

Thanks!

Backup

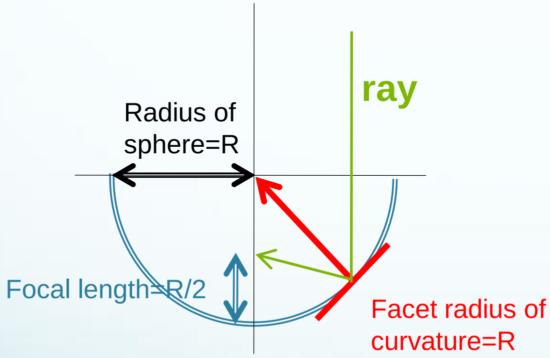
Can we make an IACT with a much wider FOV?

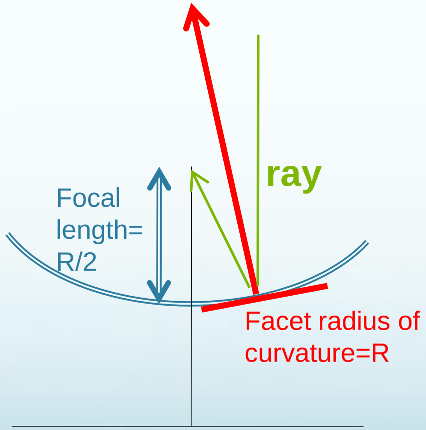
The most popular optics for IACTs are:

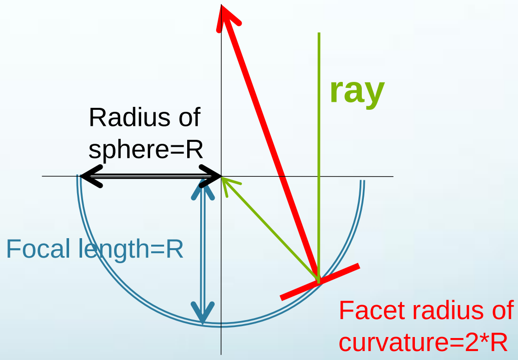
Spherical reflector shape, with spherical facets parallel to the sphere: Too strong spherical aberration

Parabolic reflector shape, with spherical facets parallel to the parabola: No spherical aberration, no aberration for small off-axis angle, but coma for large off-axis. Good timing.

Davies-Cotton, with spherical facets **not** parallel to the sphere, but pointing at 2*R: Moderate aberration at all off-axis angles. Worse timing.







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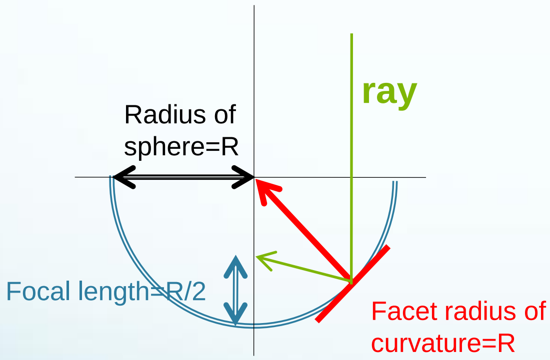

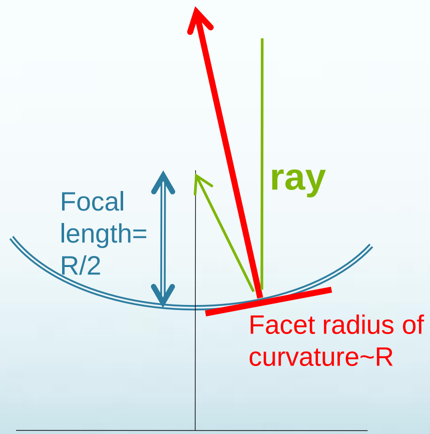

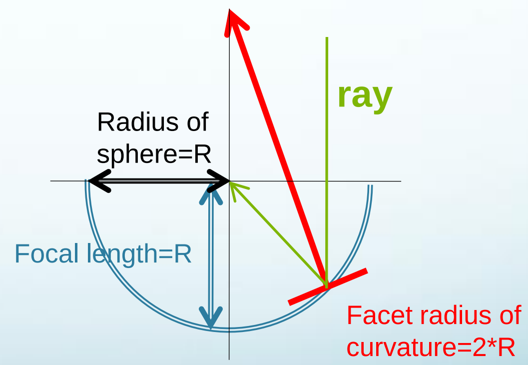

MAGIC, HESS-II, LST

VERITAS, HESS-I, MST

Can we make an IACT with a much wider FOV?

MST:

- Pretty large FOV ø=7°.
- Davis-Cotton mount with f=16 m, D=12 m (f/D=1.35).
- Pixel size=0.18°.
- PSF: r80%= 0.015° on-axis going up to 0.07° for off-axis=2.8°. Beyond that off-axis angle, PSF grows fast.

Detailed comparison to CTA

- MACHETE (stereo=2 telescopes): 10 M€ capital cost, 300 deg2.
- 1 MST: 2.2 M€ capital cost, 38 deg2 -> need to cover 8x larger FOV and stereo, so comparable cost is 35 M€
- 1 SCT: 2 M$ capital cost, 50 deg2 -> need to cover 6x larger FOV and stereo, so comparable cost is 32 M$