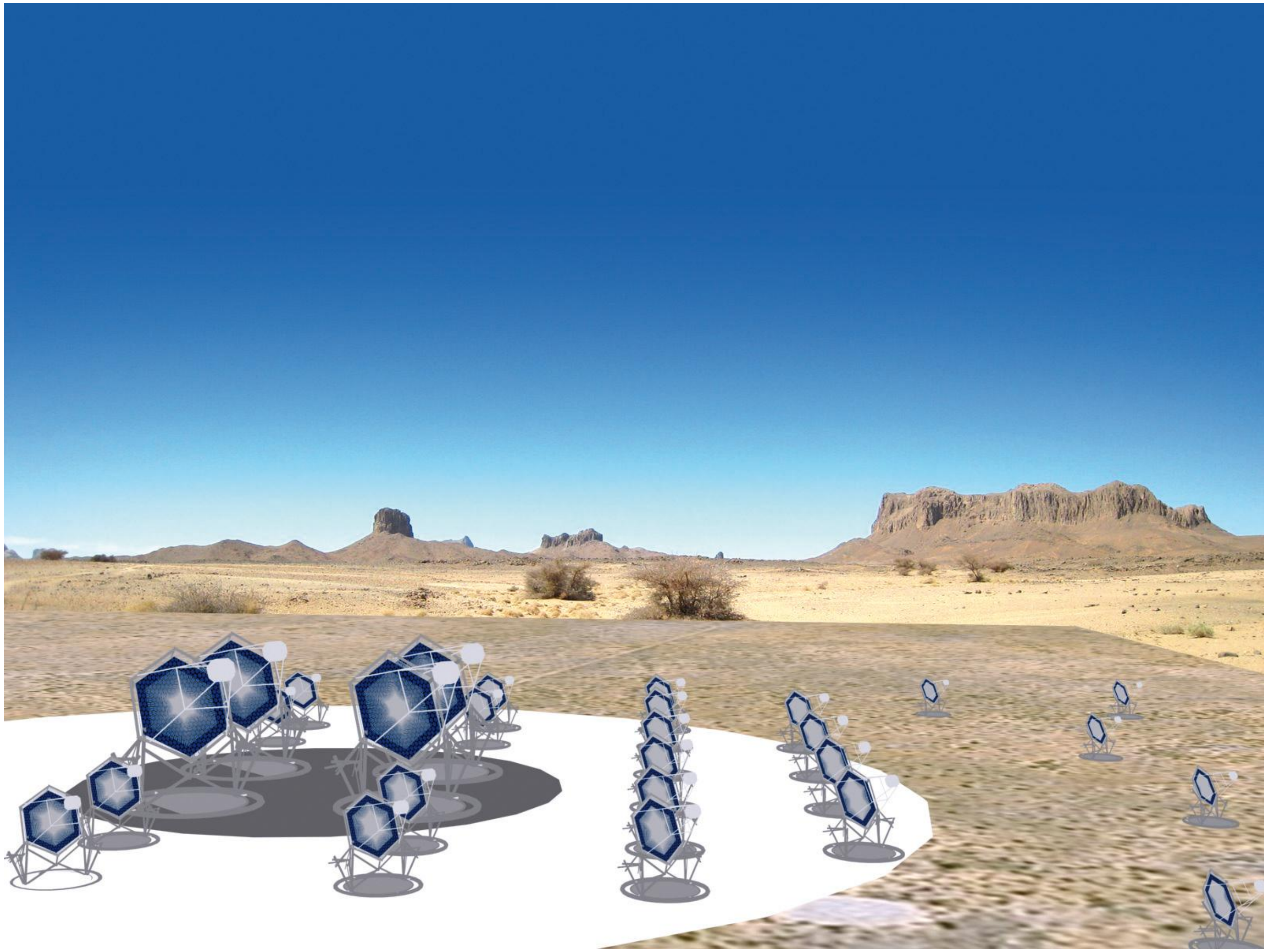
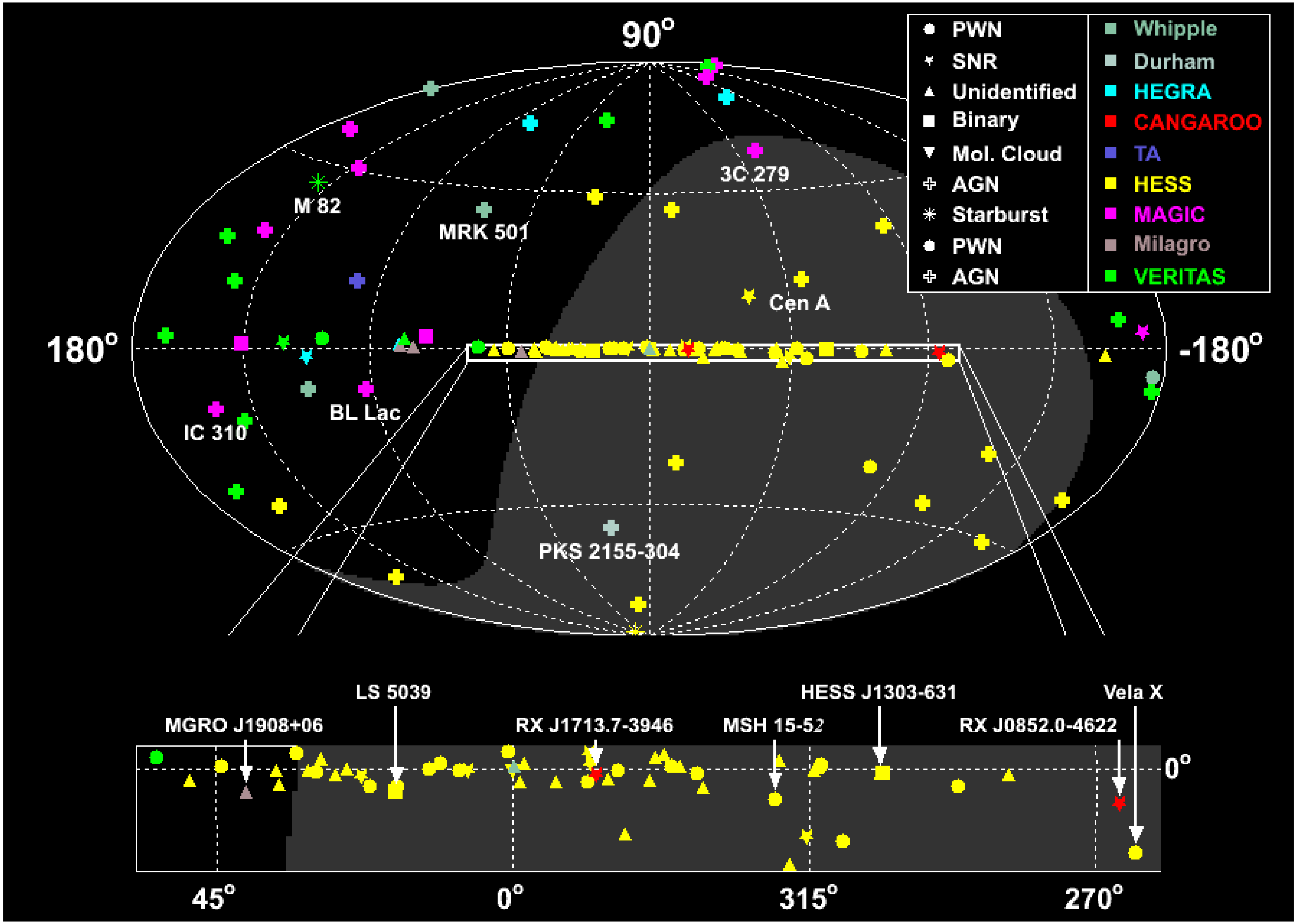
The Cherenkov Telescope Array Project

- CTA: motivation and performance goals
- Detecting atmospheric Cherenkov radiation
- Performance of imaging atmospheric Cherenkov telescope arrays
- The CTA concept
  - Large telescopes
  - Medium telescopes
  - Small telescopes
- Mirrors
- Sensors
- Summary



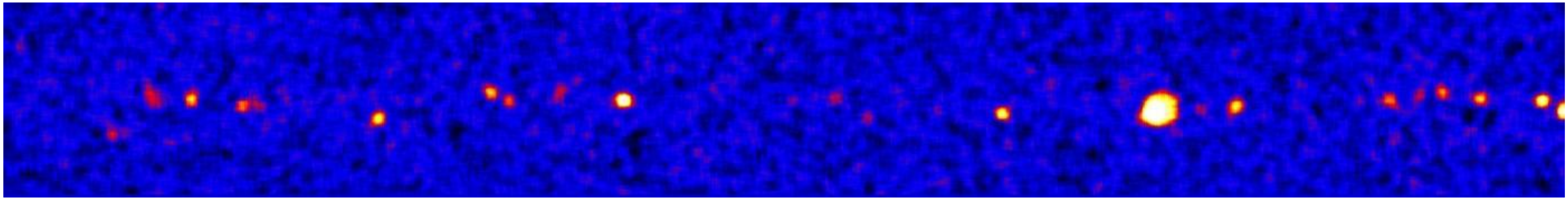
CTA performance goals

- July 2010.
- 113 TeV γ-ray sources.
    - 72 galactic.
    - 41 extra-galactic.
    - 109 found with IACTs.
- Progress requires improved sensitivity, better energy and angular resolution, larger area…

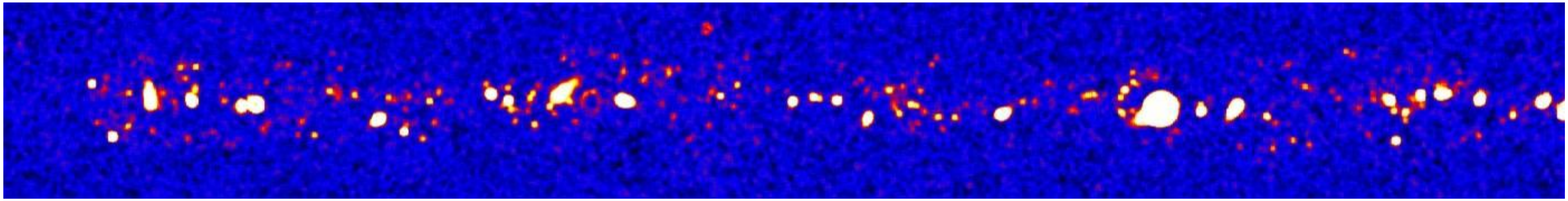


CTA performance goals

- Aim for factor of 10 improvement in sensitivity.
- Compare HESS ~ 500 hour image of section of galactic plane...



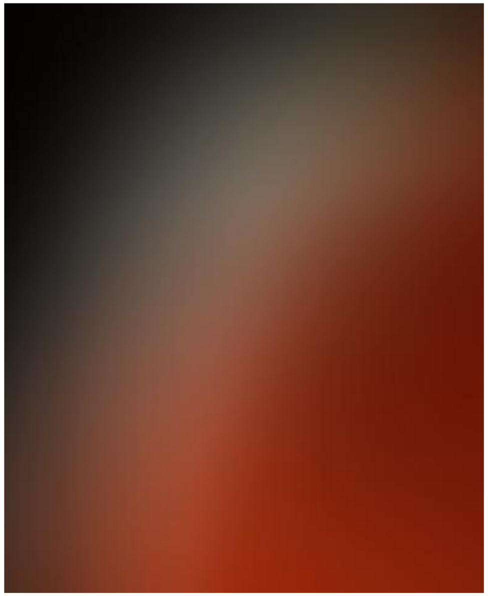
- ...with expectation with increased sensitivity, same exposure.



- Expect to observe around 1000 sources (galactic and extra-galactic).

CTA performance goals

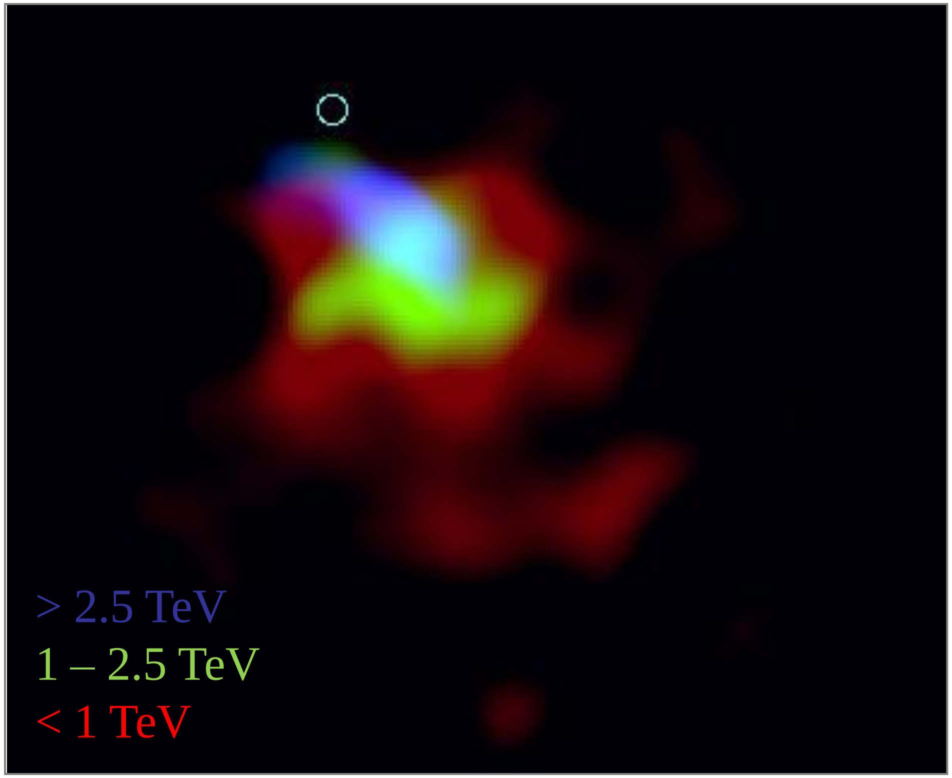
- Improve angular resolution by factor ~ 5.
- Substructure of SNR shock fronts can then be resolved:



Resolution 0.1°.

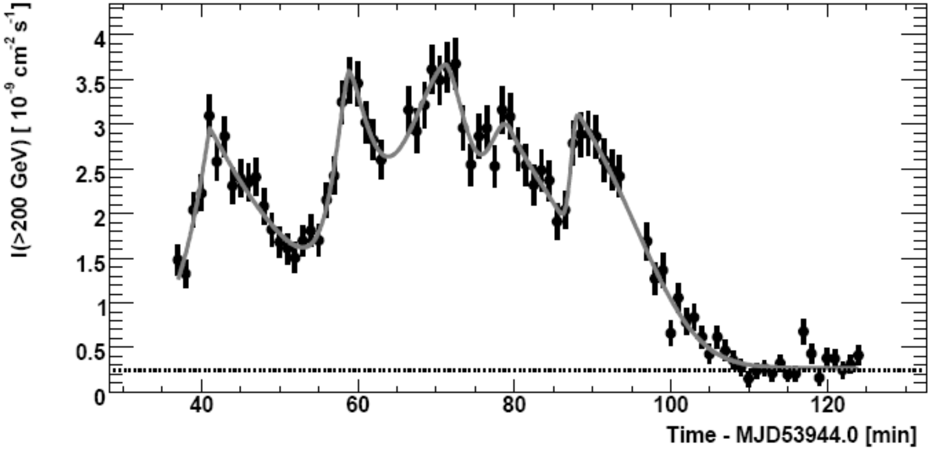
Resolution 0.02 °.

- Better understand energy dependent morphology of pulsar wind nebulae.
- HESS J 1825-137, PWN size decreases with energy:



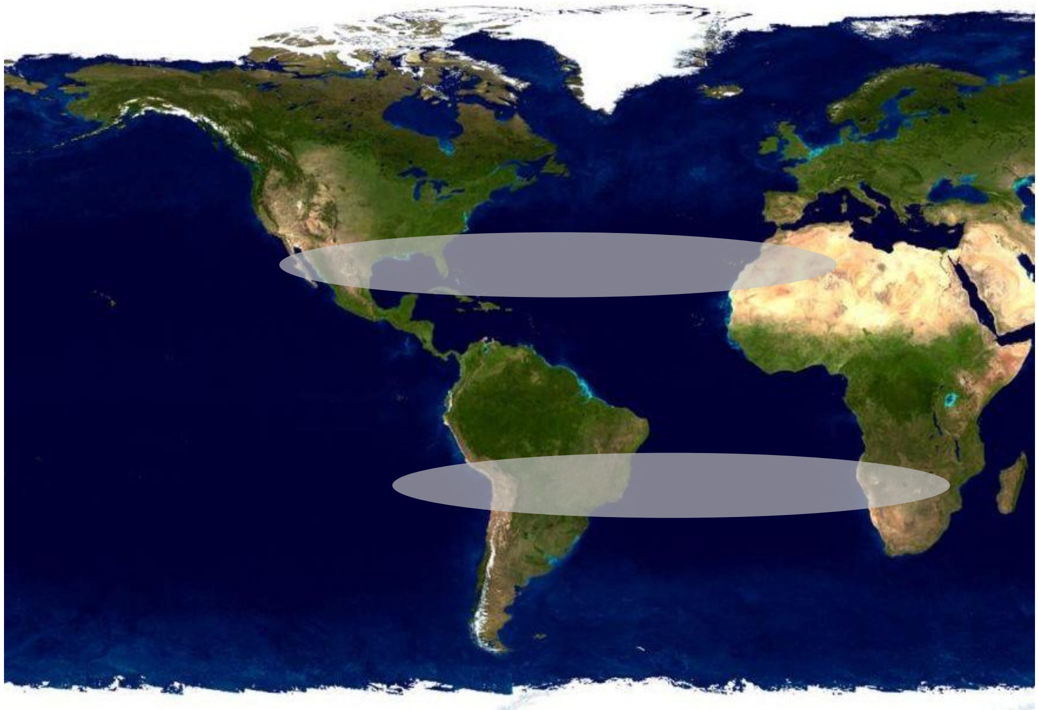
CTA performance goals

- Increased sensitivity allows mapping of activity on sub-minute timescales.
- E.g. blazar PKS 2155-304 (HESS):



- Study size of emission regions around AGNs, quantum gravity.

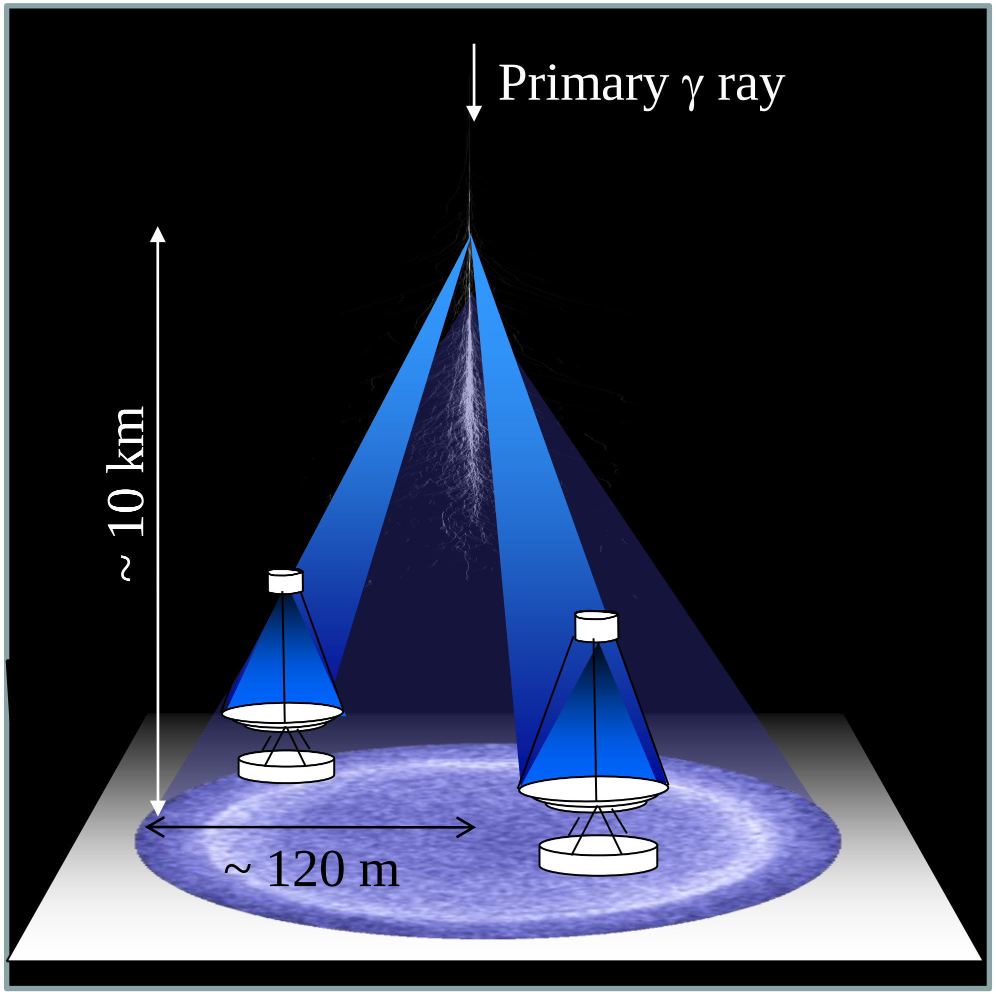
- GRB detection, fast slewing, large FoV needed.



- Southern array:
    - Galactic and extragalactic sources.
    - 10 GeV...100 TeV.
    - Angular resolution 0.02...0.2°.
- Northern array:
    - Mainly extragalactic sources.
    - 10 GeV...1 TeV.

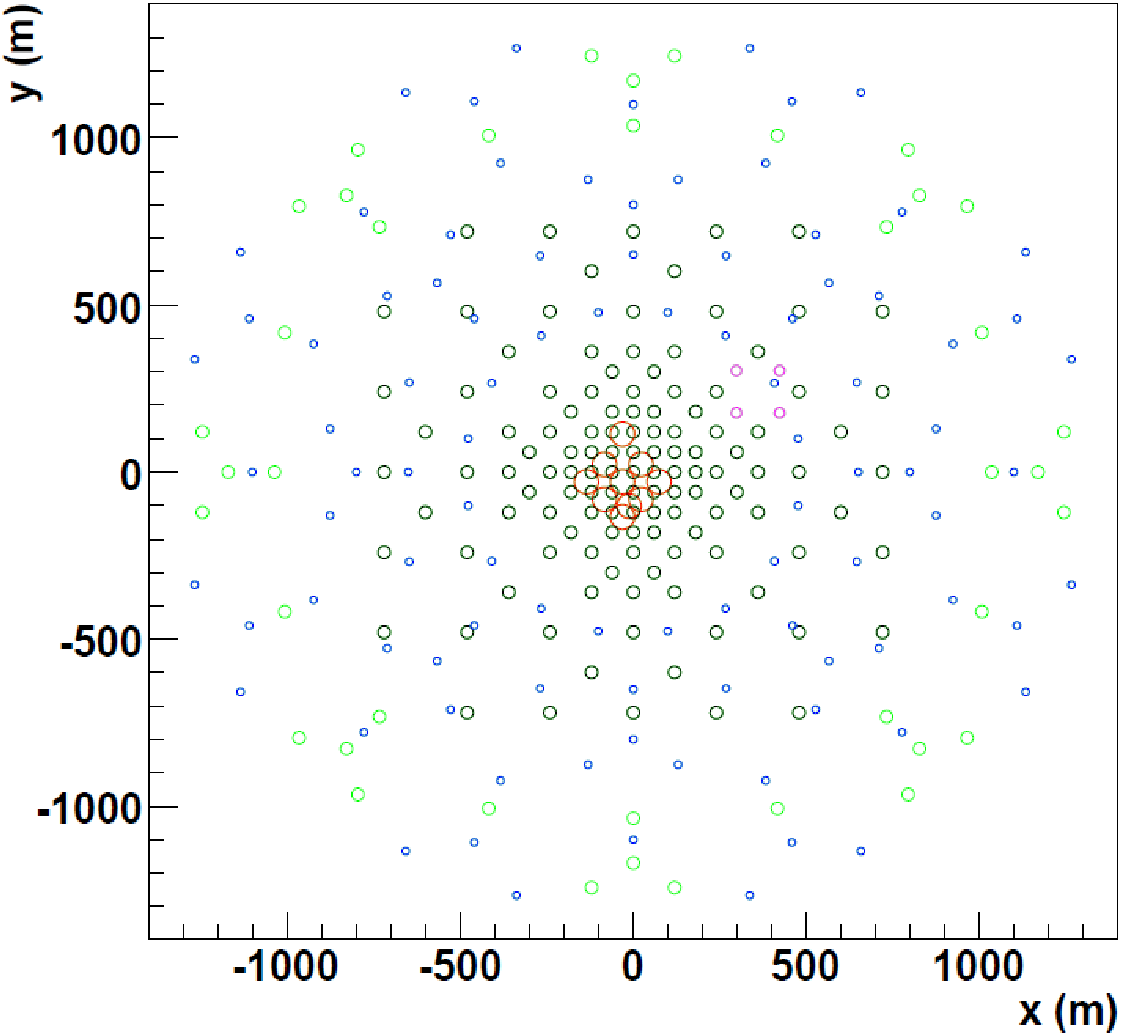
Detecting Cherenkov radiation from EM showers

- VHE γ causes shower in atmosphere with max. at height ~ 10 km.
- Cherenkov light from $e^{\pm}$, angle ~ 1°.
- Light pool on ground, radius ~ 120 m.
- Photomultiplier efficiency ~ 20%:
- $E_\gamma = 100$ GeV, ~ 1 p.e./m^2 in few ns.
- $E_\gamma = 10$ TeV, ~ 10^3 p.e./m^2 in ~ 100 ns.
- Limiting factors:
  - $E_\gamma < 100$ GeV, night sky background.
  - $E_\gamma = 0.1...5$ TeV, cosmic ray background (γ/h separation).
  - $E_\gamma > 5$ TeV, rate.
- Need array of different telescopes.



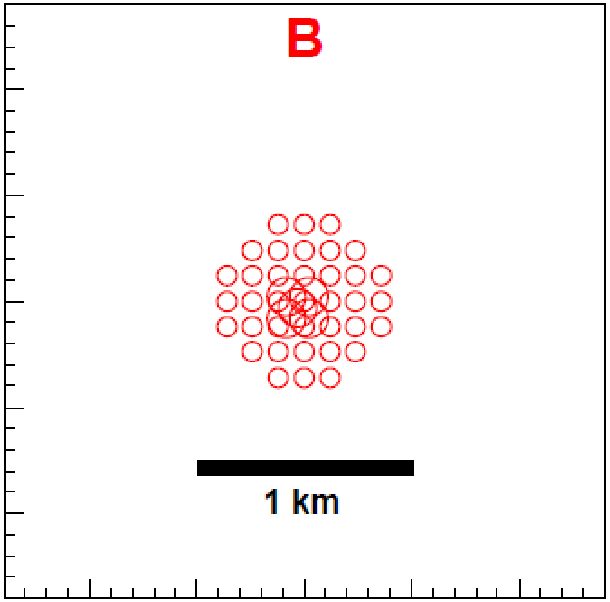
Performance of multi-telescope arrays

- Concentrate here on instrumentation for CTA southern site.
- Simulate large array with 275 telescopes of 5 different sizes.
- Select sub-sets of this array.
- Obey (approx.) constraint: construction cost ~ 80 M€.
- Study performance of these sub-arrays.

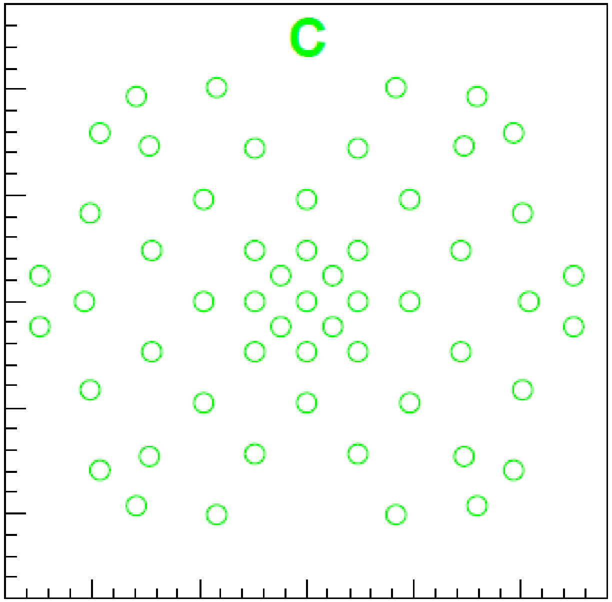


Performance of multi-telescope arrays

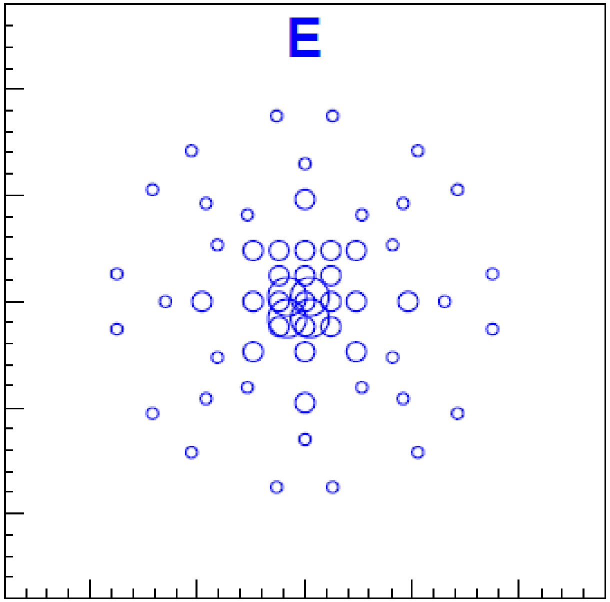
- Examples of sub-arrays:



- Dense array of 12 and 24 m telescopes.
- Good low E, but poor high E performance?



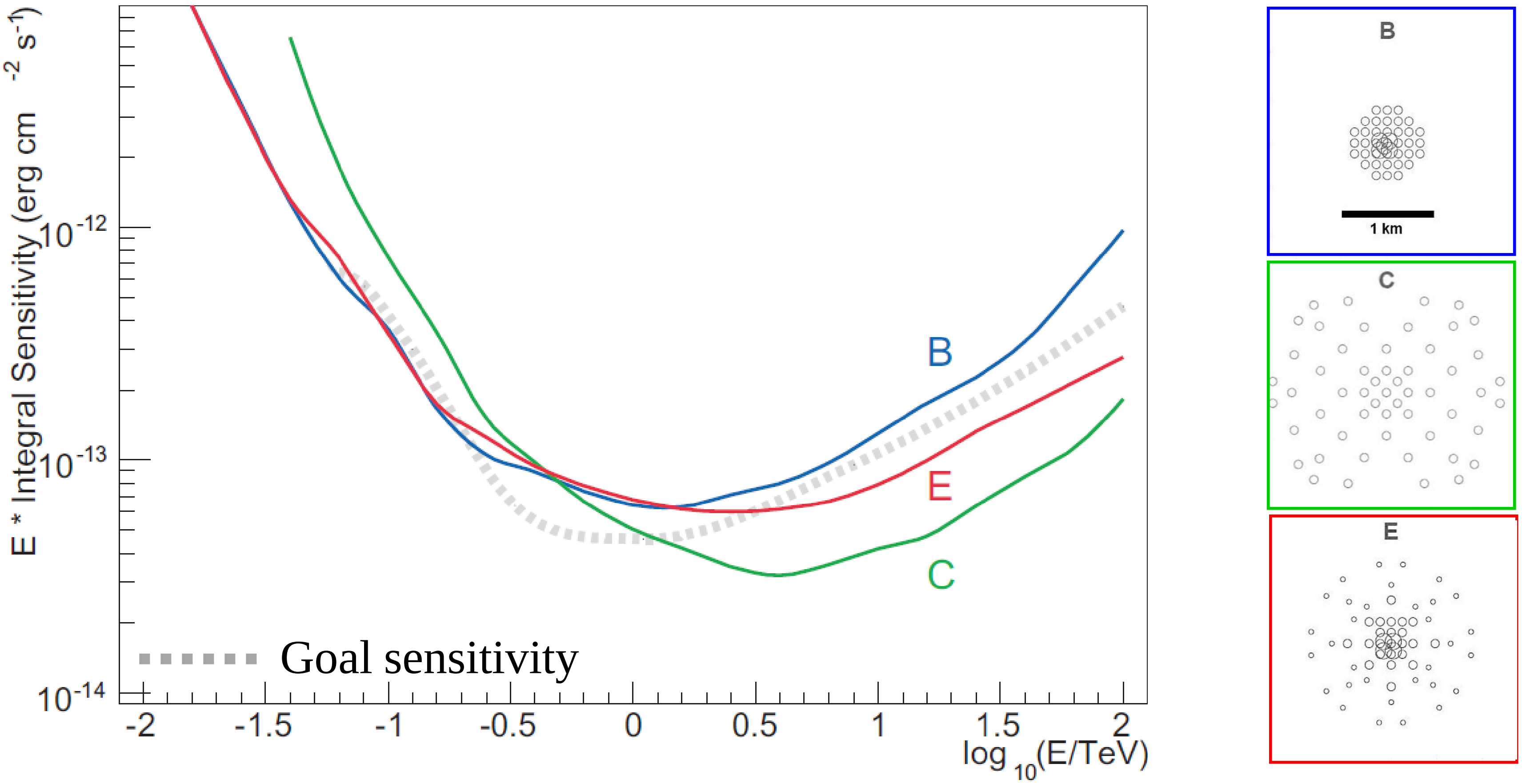
- Low density array of 12 m telescopes.
- Good high/medium E, but poor low E performance?



- Array of 7, 12 and 24 m telescopes.
- Provides sensitivity across complete energy range?

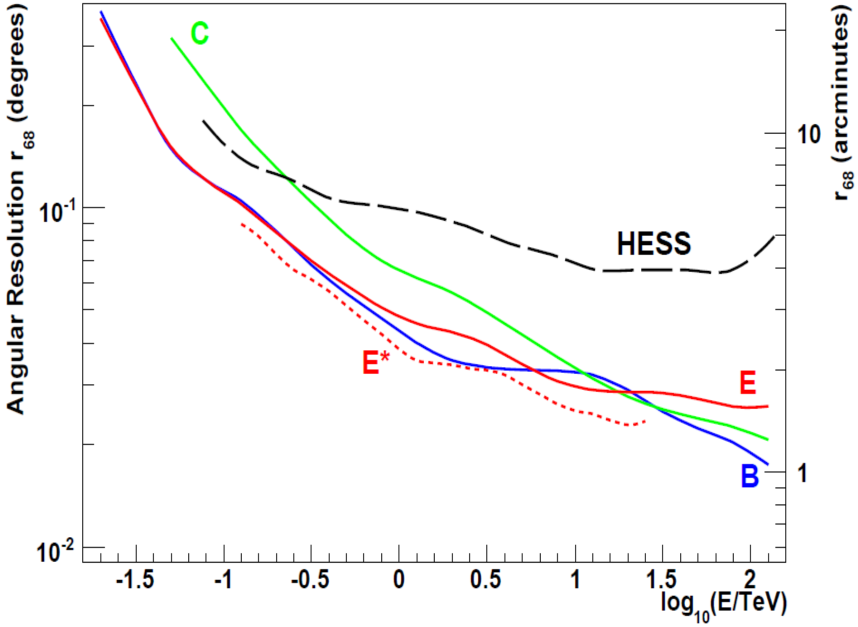
Performance of multi-telescope arrays

- Performance measure: integral sensitivity for point sources, 50 hour exposure.

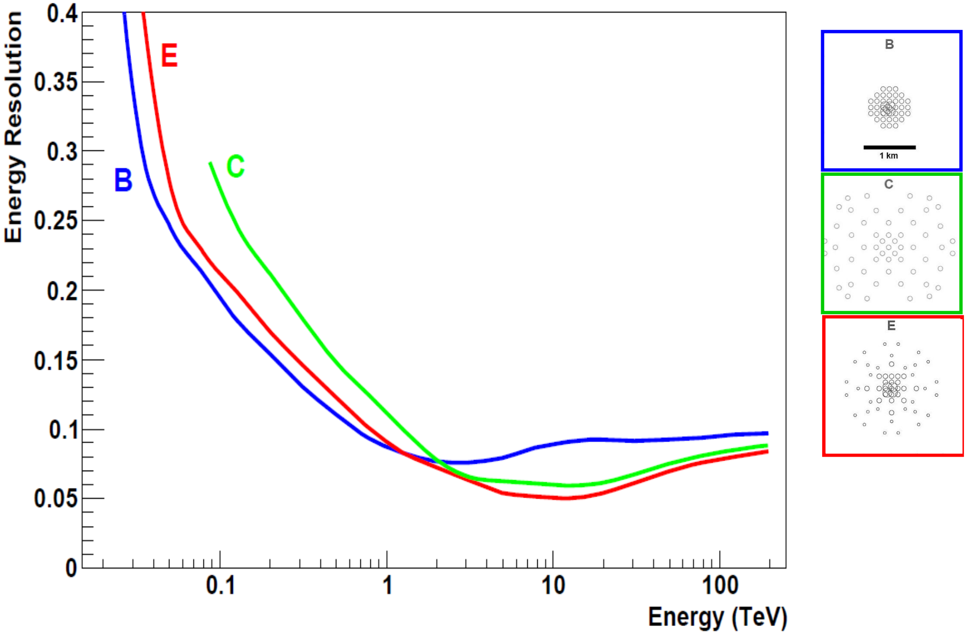


Performance of multi-telescope arrays

- Performance measure: angular res.



- Performance measure: energy res.



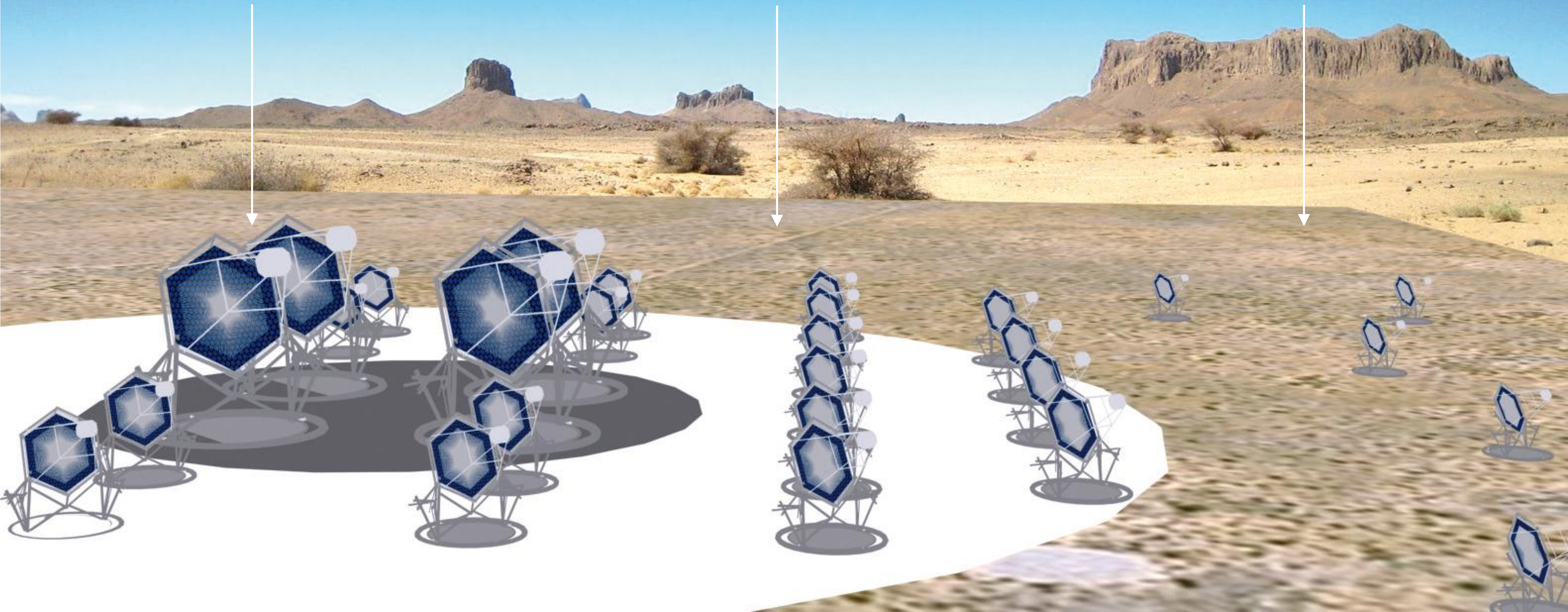
- 1...2 arcmin. resolution achieved for E > 1 TeV.
- Energy resolution 5...10% in TeV energy range.

The Cherenkov Telescope Array concept

Low energy
Few 24 m telescopes
4…5° FoV
2000…3000 pixels
~ 0.1°

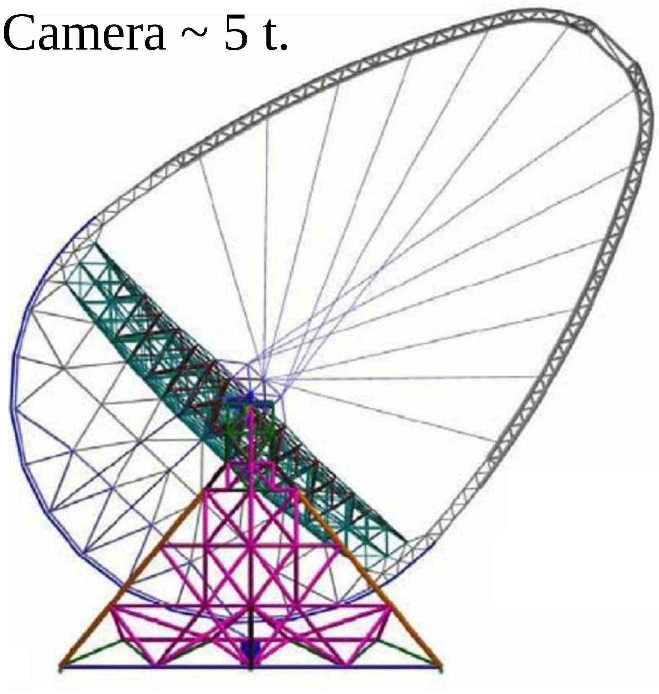
Medium energy
About twenty 12 m telescopes
6…8° FoV
~ 2000 pixels
~ 0.18°

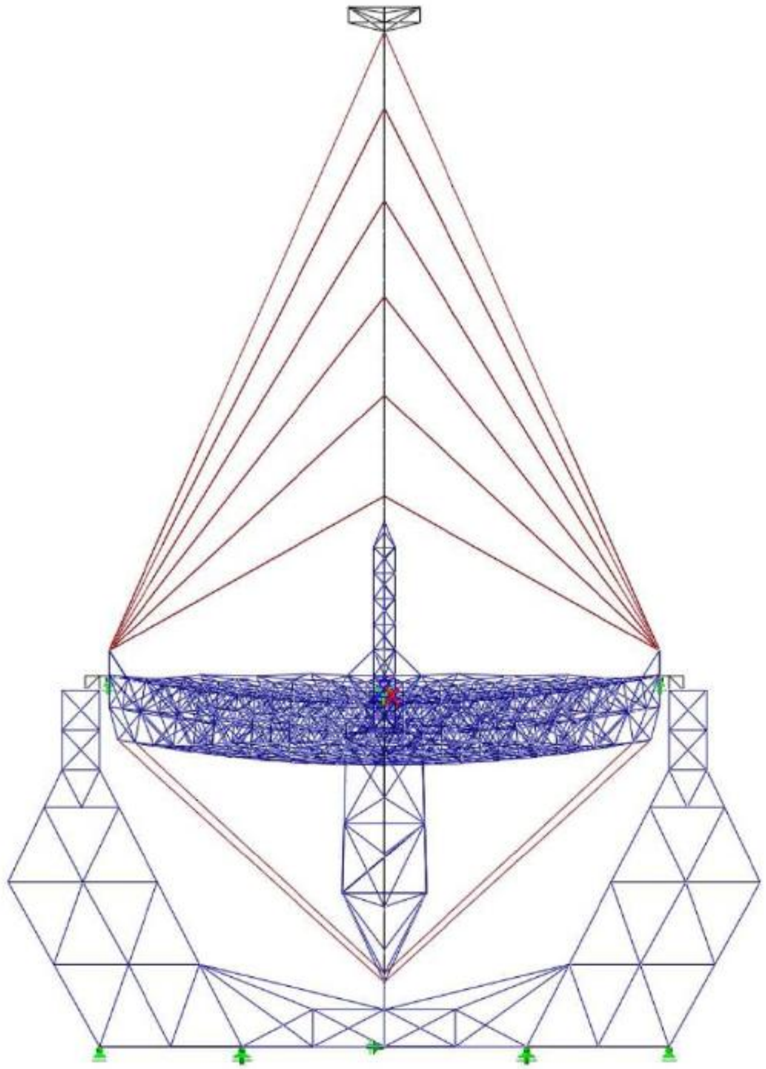
High energy
Fifty + 4…7 m telescopes
8…10° FoV
1000…2000 pixels
~ 0.2°…0.3°



Large size telescope design

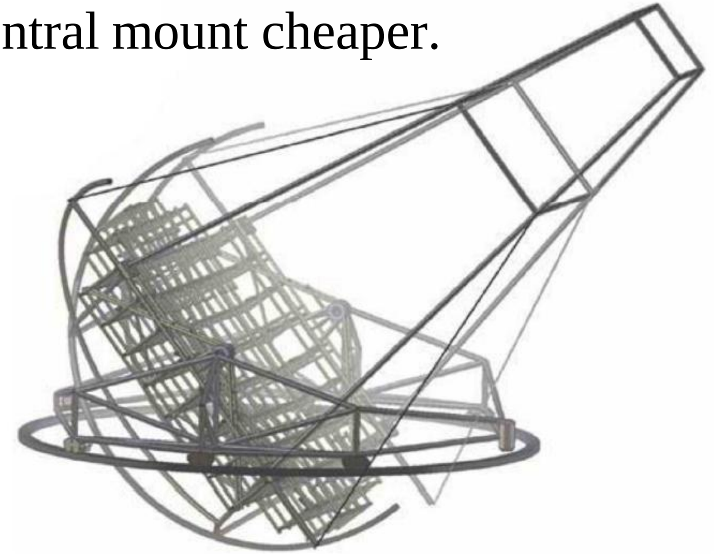
- Diameter 24 m.
- Focal length ~ 34 m.
- (Modified) Davies-Cotton optics.
- Support structure carbon fibre.
- Mount on rails.
- Camera ~ 5 t.

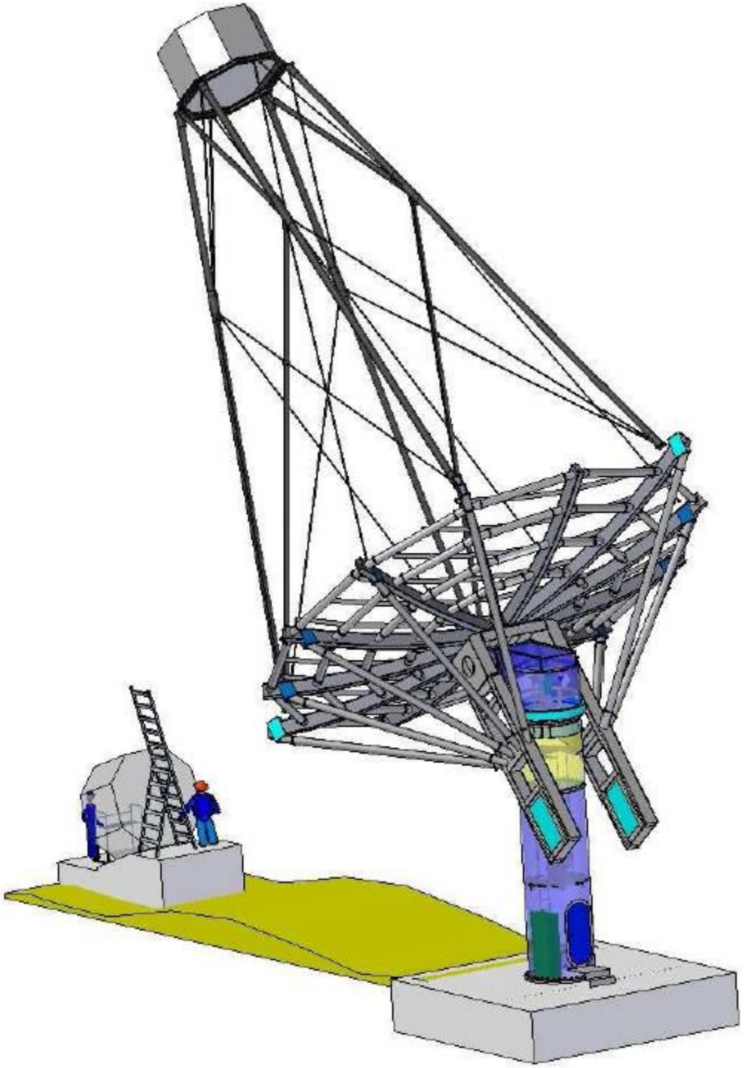




Medium size telescope design – take one

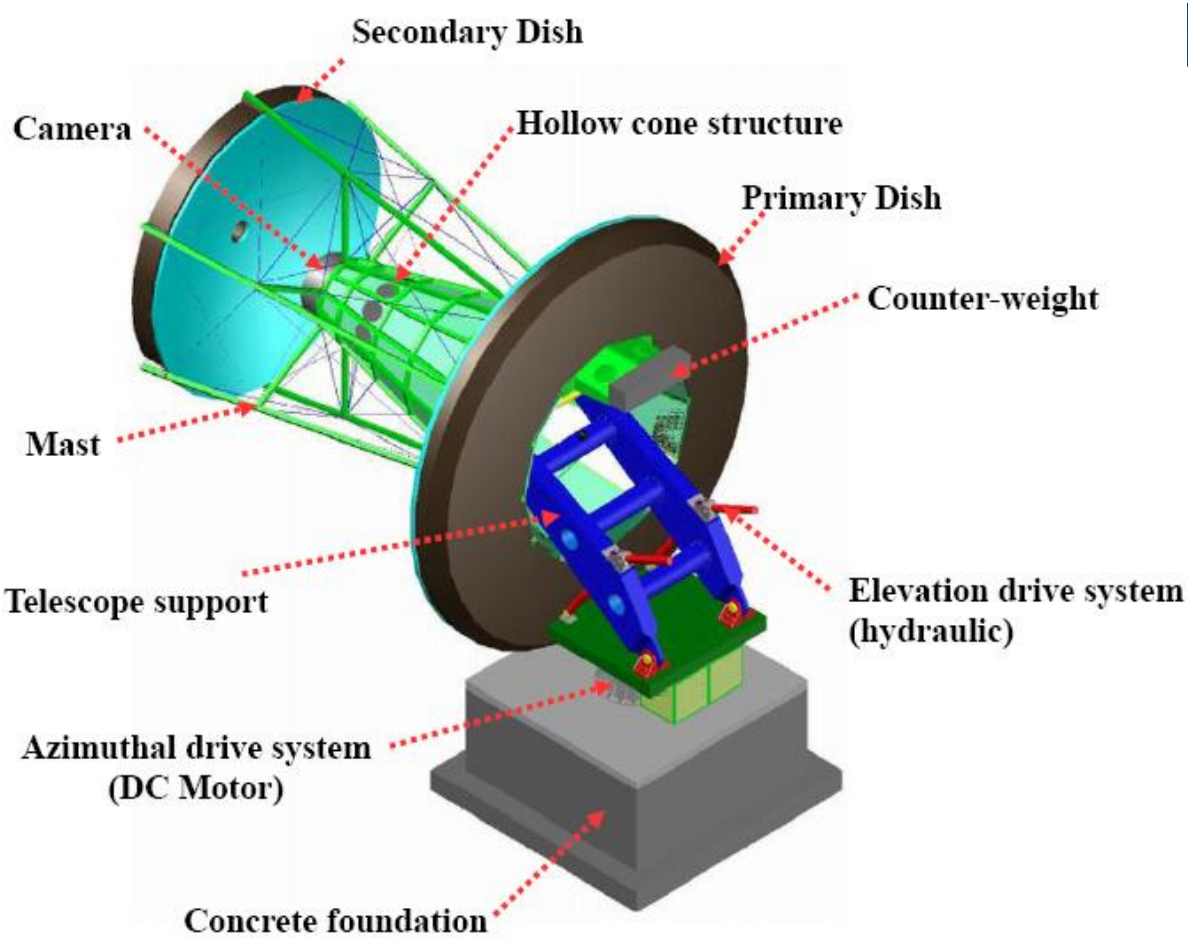
- Diameter ~ 12 m.
- Focal length ~ 17 m.
- (Modified) Davies-Cotton optics.
- Camera support carbon fibre, dish steel/aluminium.
- Camera ~ 2 t.
- Several alternative designs.
- Central mount cheaper.





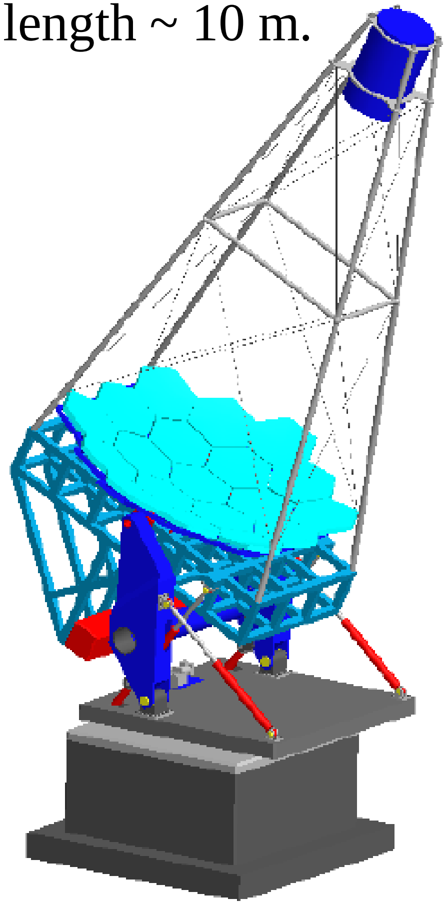
Medium size telescope design – take two

- Schwarzschild-Couder optics, better correction of aberrations at large field angles.
- Primary ~ 9.4 m, secondary ~ 6.6 m diameter.
- Effective focal length ~ 5 m.
- Allows use of small pixels, e.g. multi-anode photo-multipliers, silicon PMs.
- Proposed multi-pixel camera provides coverage to large field angles and 0.05...0.1° pixel angular resolution.
- Advantages in γ/h separation?

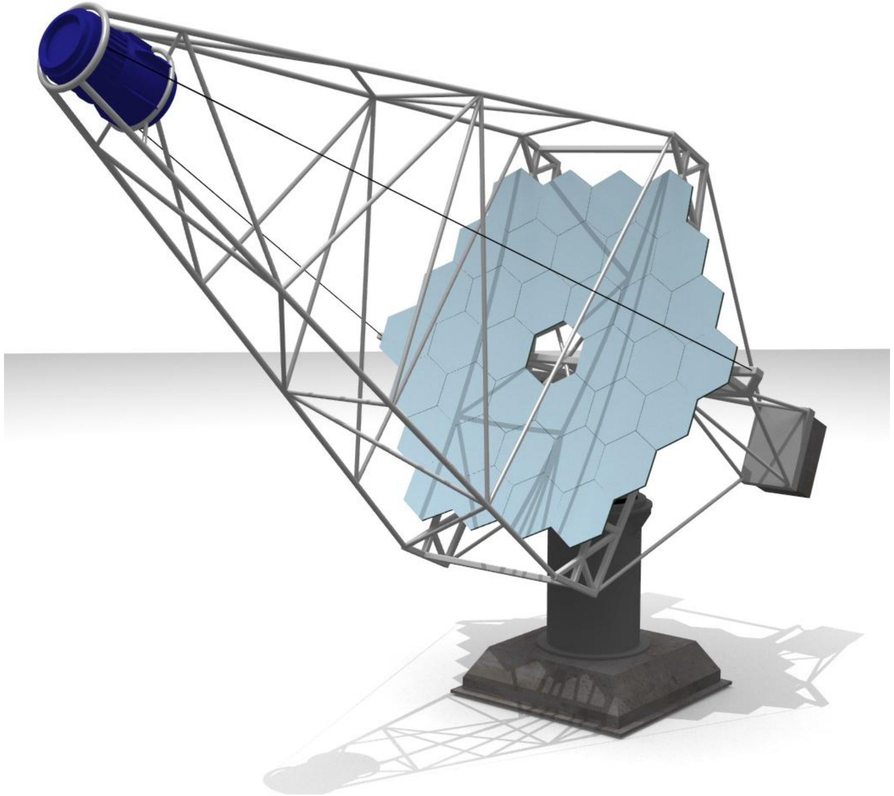


Small size telescope design – take one

- Davies-Cotton design.
- Diameter ~ 7 m.
- Focal length ~ 10 m.



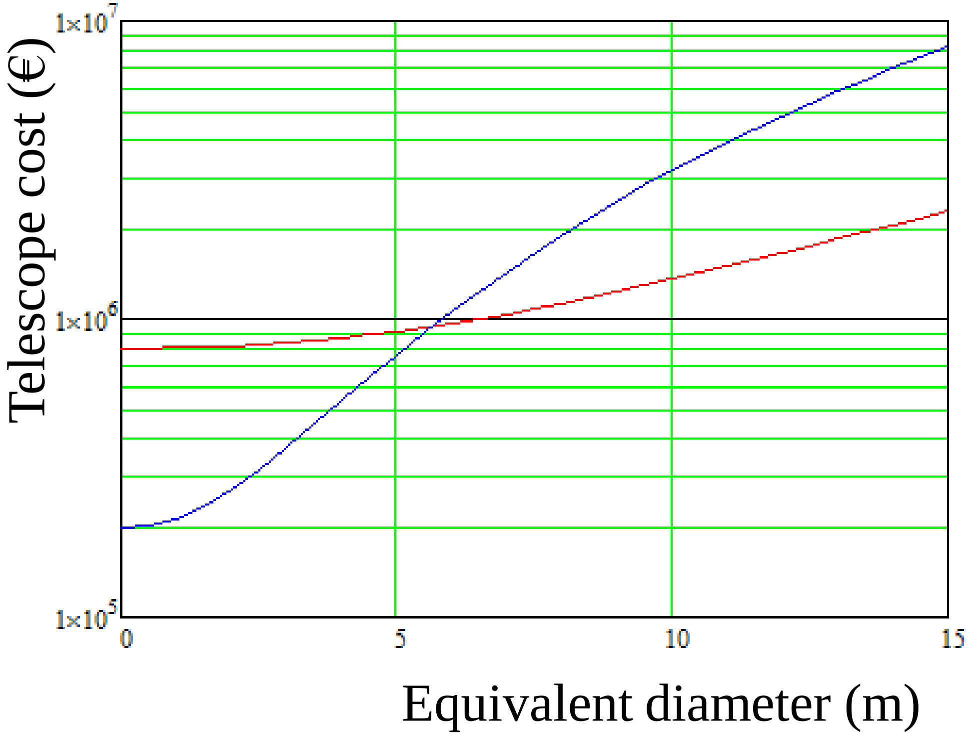
- Support structure steel.
- Camera ~ 2 t.
- Several designs – common feature camera cost dominates.



Small size telescope design – take two

- Investigate use of cheaper MAPM or SiPM based camera.
- Telescope then needs short focal length so ~ 6 × 6 mm^2 pixels match required angular resolution (~ 0.2°).
- Need reasonable area, hence “fast” focal ratio (f = F/D small).
- Require sophisticated optics to correct for aberrations – two mirrors.
- DC structure costs ~ 1.7 k€ × D[m]$^{2.7}$, assume DM cost 3 × DC.
- Mirrors/actuators for DC cost ~ 3 k€/m^2, for DM assume 3 × DC.
- Cameras have ~ 2000 pixels, DC costs ~ €400/pixel and DM ~ €100/pixel.

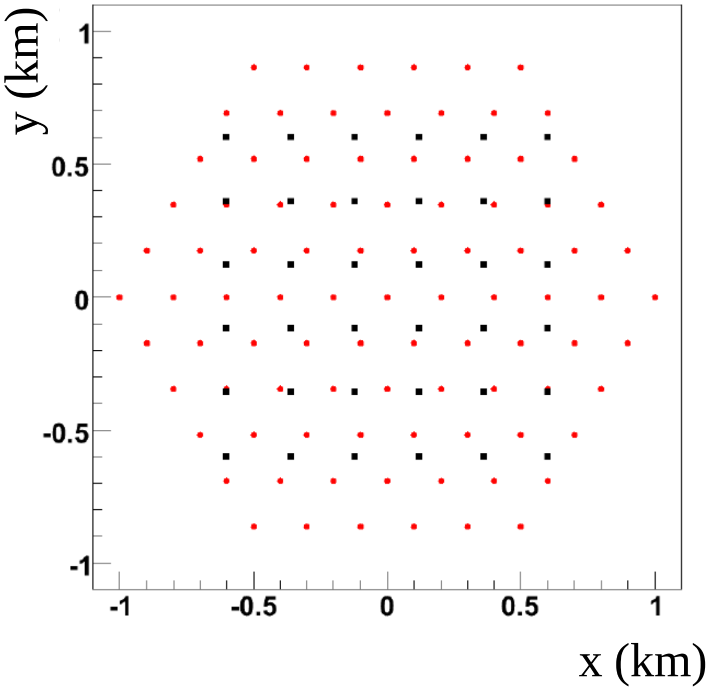
- Resulting costs:



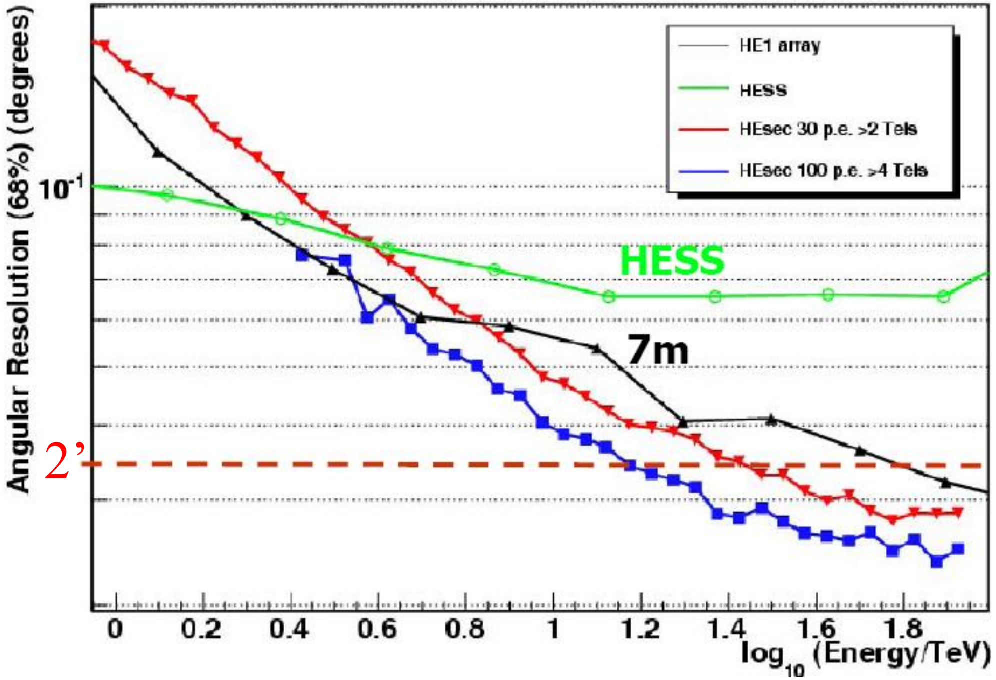
- For equivalent diameter (inc. effects of obscuration and reflection) below ~ 6 m, DM telescopes cheaper solution.

SST – dual mirror design

- Can dual mirror solution provide required performance in array?
- C.f. 7 m Davies-Cotton and 4 m dual mirror arrays, each €20M total cost.
- Cheaper dual mirror solution allows more telescopes (red dots)...



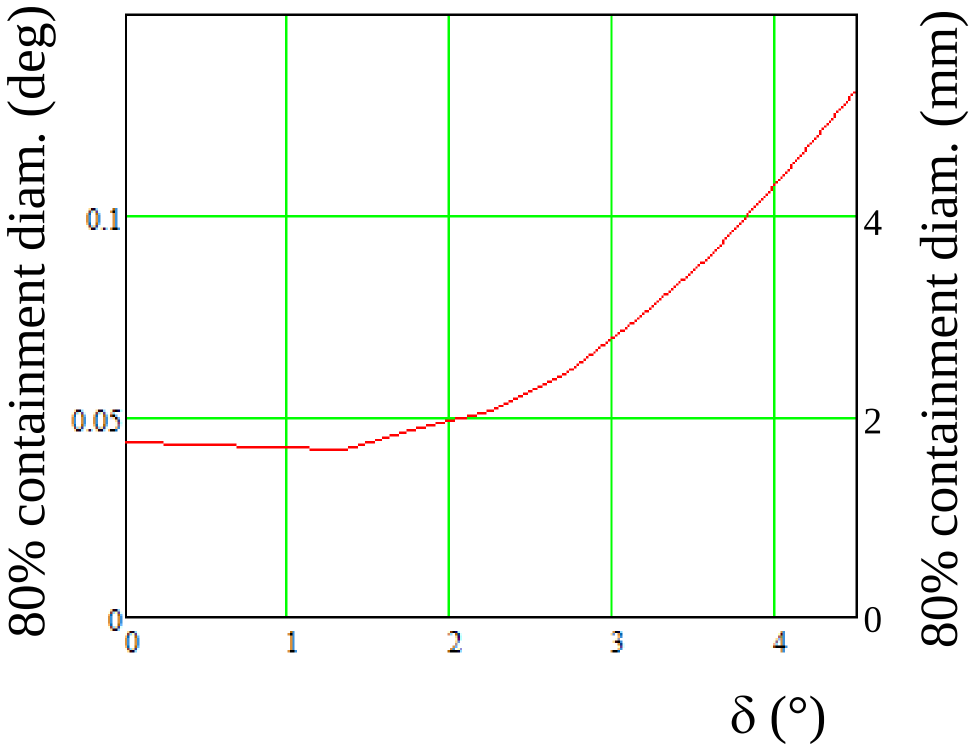
- ...which leads to increased multiplicity and higher angular resolution for dual mirror array:



- Physics benefits, e.g. in studies of morphology of SNRs.

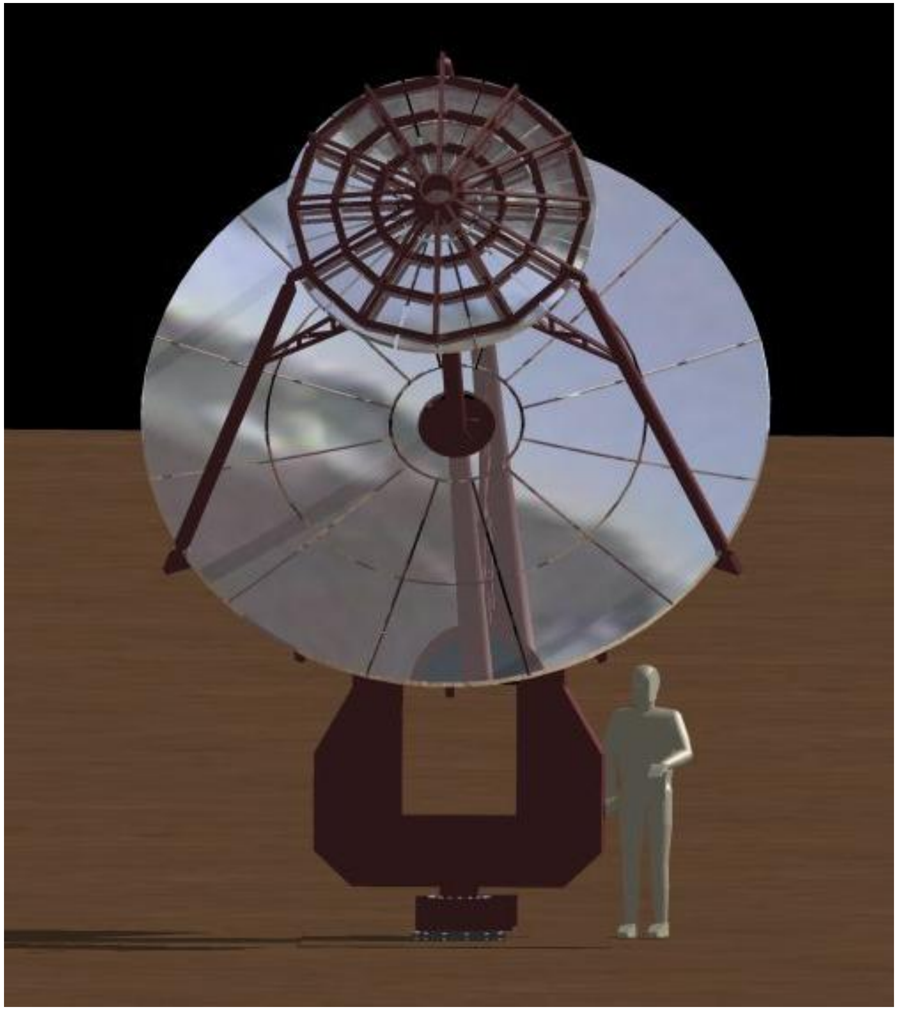
SST – dual mirror optics

- Can we build a dual mirror telescope which matches the required 0.2° angular resolution to pixel sizes of a few millimetres?
- Optics studies show can achieve PSFs of < 6 mm for field angles up to about $\delta = 4.5°$ with telescope parameters:
  - Focal length F = 2.283 m.
  - Primary diameter $D_p = 4$ m.
  - Secondary diameter $D_s = 2$ m.
  - Camera diameter $D_{cam} = 0.36$ m.
  - Dist. Prim. to Sec. 3.56 m.
  - Dist. Sec to Cam. 0.51 m.
  - Camera convex, $\rho_{cam} = 1$ m.
- PSFs

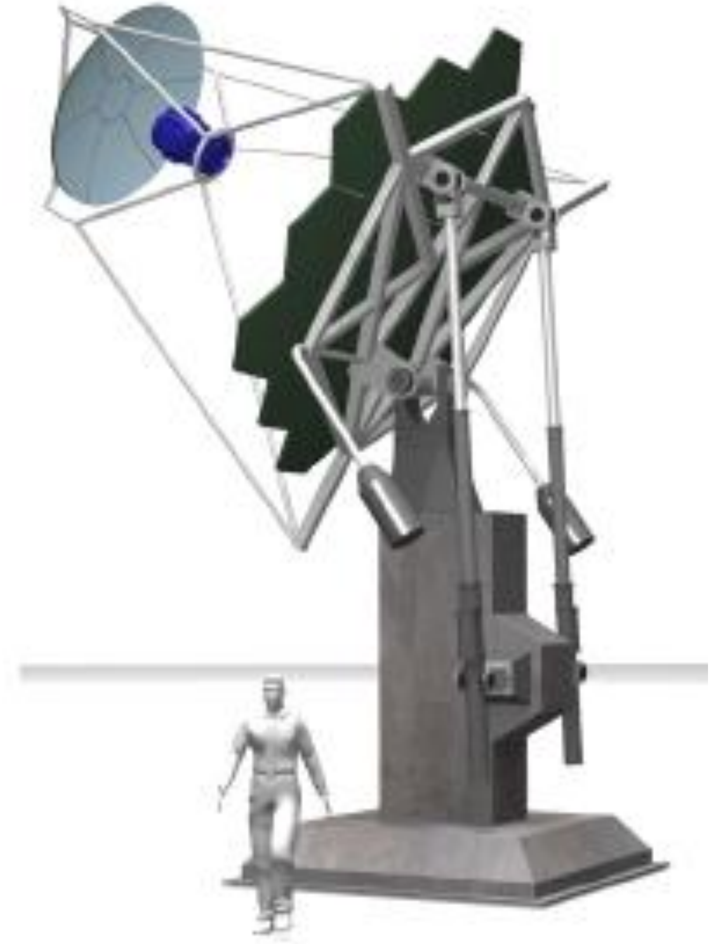


Dual Mirror SST structure

- Conventional design:

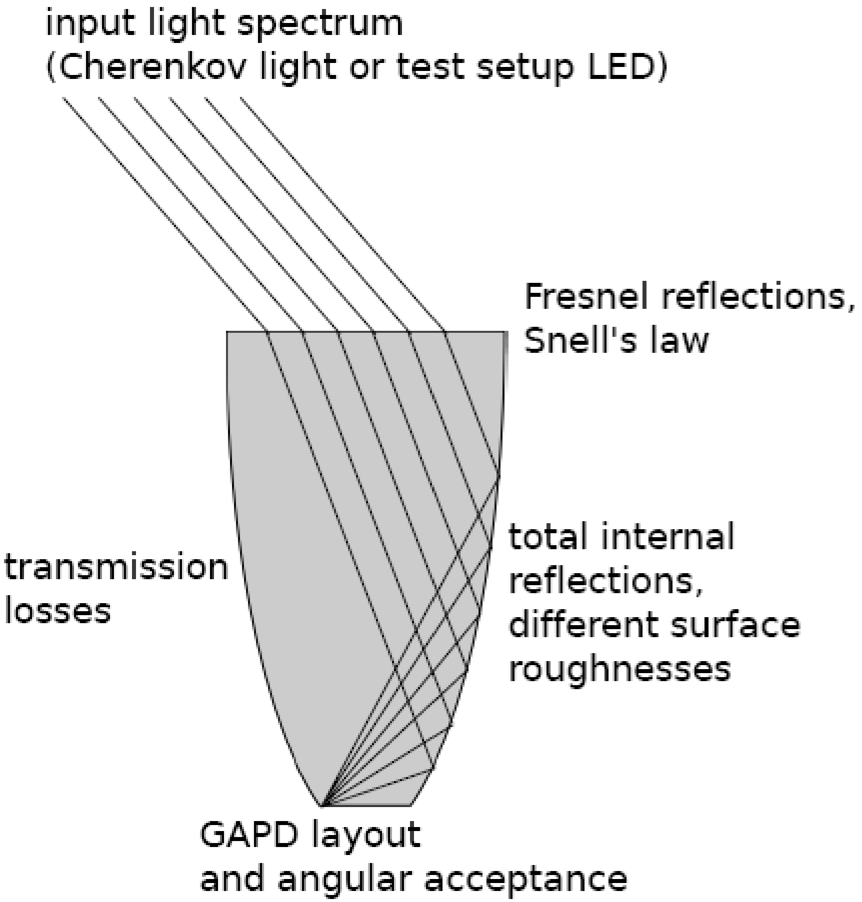


- “Cardan joint” design:



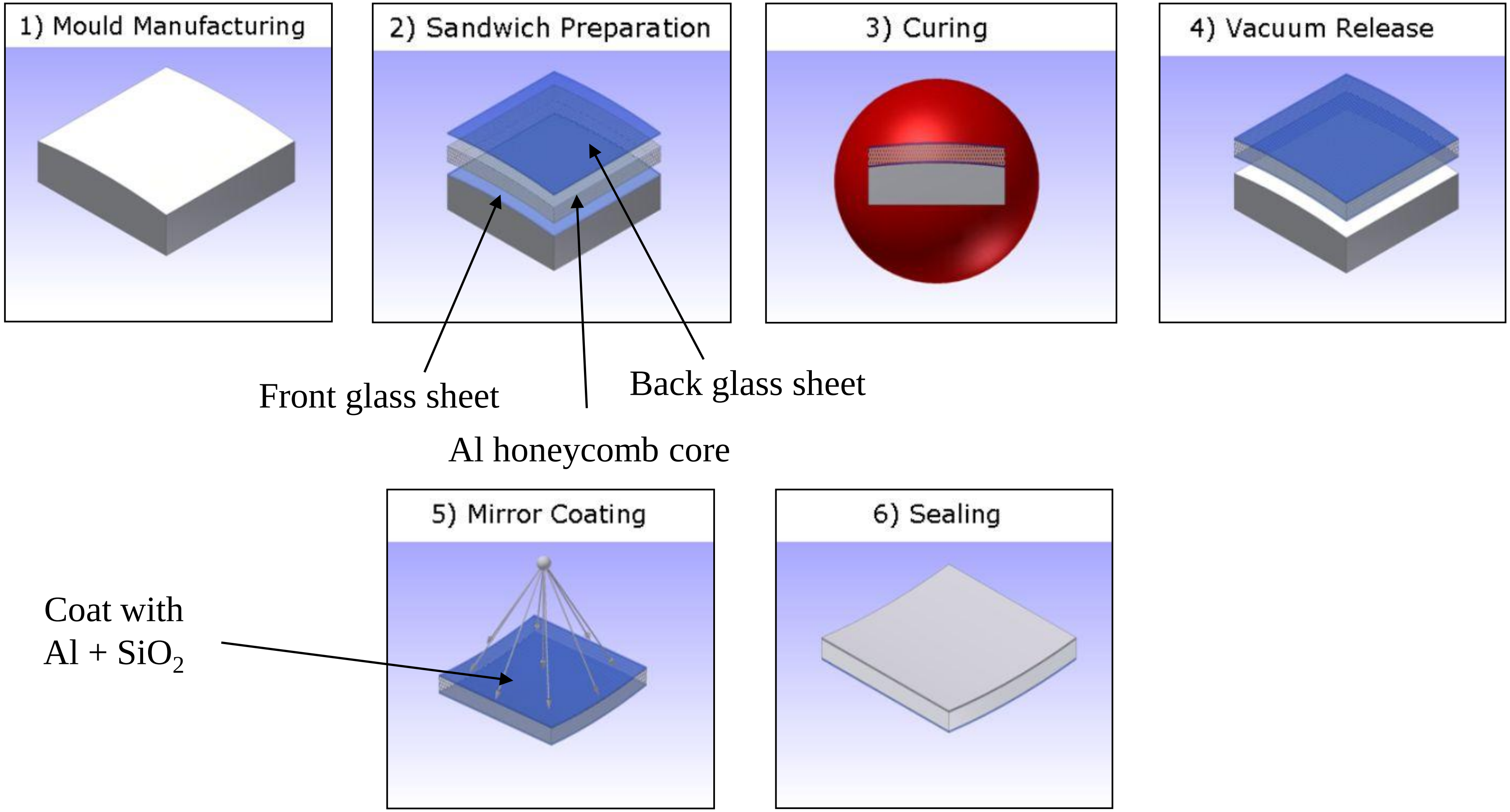
Davies Cotton with Winston Cones and SiPMs

- The project manager's nightmare – a good idea that comes along late in the day!
- Use SiPMs because they are efficient and cheaper than PMs.
- Attach to solid Winston Cones.
- Size, angular acceptance of SiPMs (approx. π!) and cone refractive index define relationship between "input" angular acceptance and dimensions of cones.
- With camera FoV, this determines parameters of matching Davies-Cotton telescope.
- E.g. if pixel size 5 × 5 mm^2 and 0.16°, mirror diameter ~ 3.5 m^2.



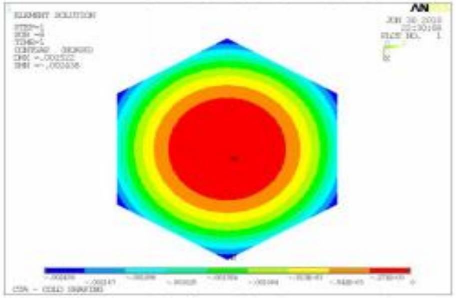
Mirrors

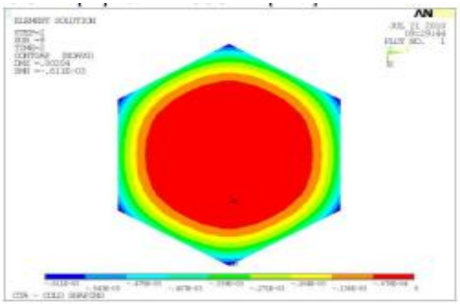
- Approach that will work for LST and MST is cold slumping:



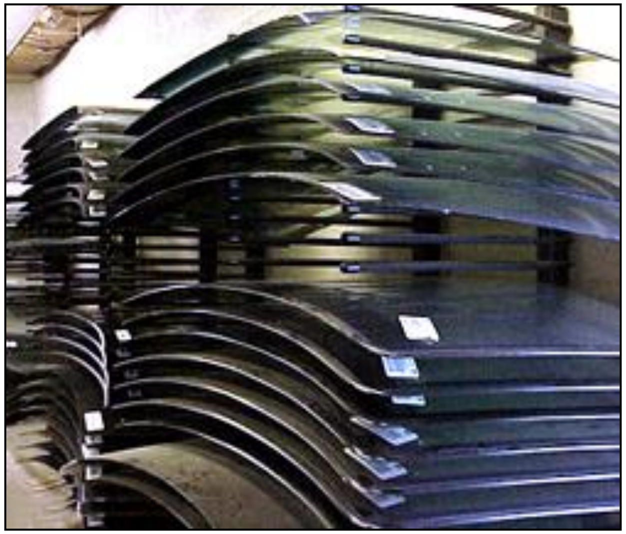
SST mirrors

- Cold slumping ~ possible for DC SST.


GAP due to panel self weight (no pressure)


GAP due to panel self weight + 0.08 kPa pressure

- Not for DM SST – stresses too high.
- Alternatives:
  - Electroforming.
  - Grinding/polishing.
  - Machining.
- None good for mass production!
- Mix of hot and cold slumping now under investigation.
- Hot slumping used e.g. in car industry.

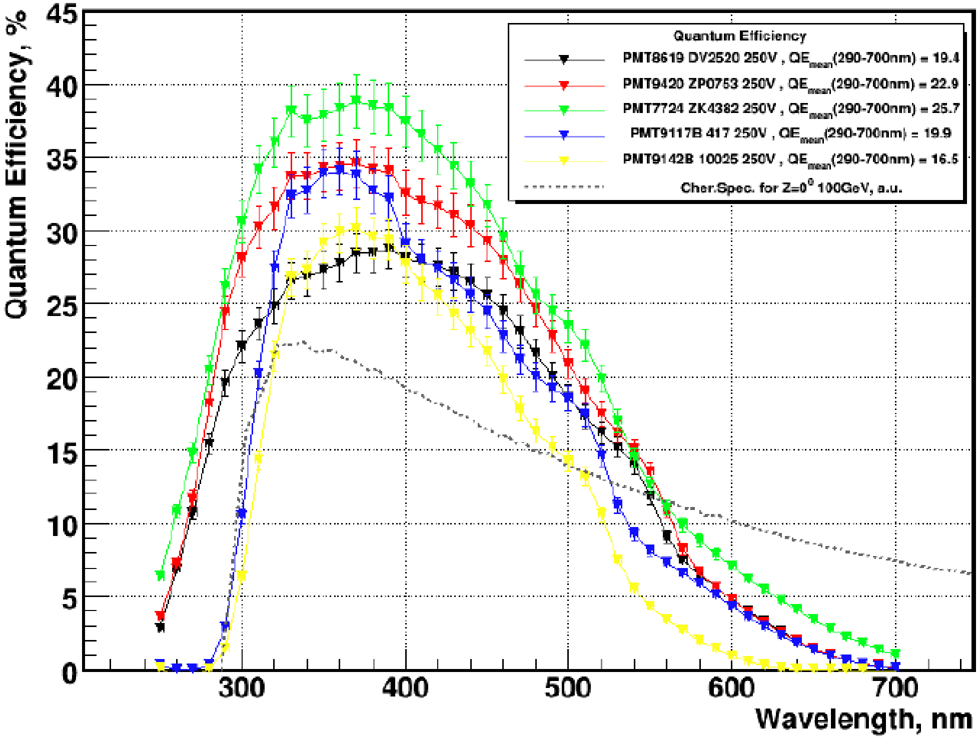


- Approximate costs:
  - Mould: 580 × 580 mm^2, ~ 5 m rad. of curvature, € 8500 (one-off!).
  - Glass/hot slumping: ~ € 300/piece.
  - Cold slumping: 2 k€/m^2.
- Tolerable cost increase over initial aggressive estimates.

Sensors – photomultipliers

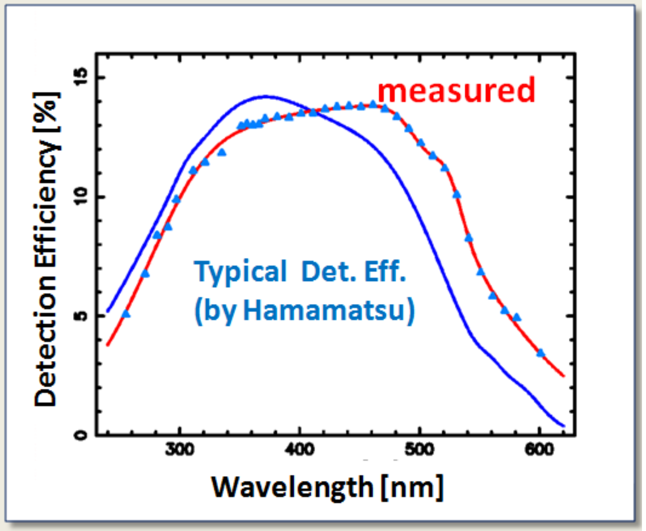
- Improvements in conventional photomultipliers will benefit CTA's "conventional" cameras.

- CTA programme with Hamamatsu, Electron Tubes and Photonis has resulted in significant improvements in after-pulsing and QE.

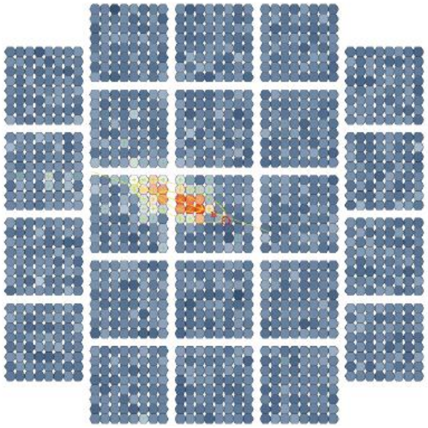


Sensors – MAPMs

- MAPMs have reasonable quantum efficiency:

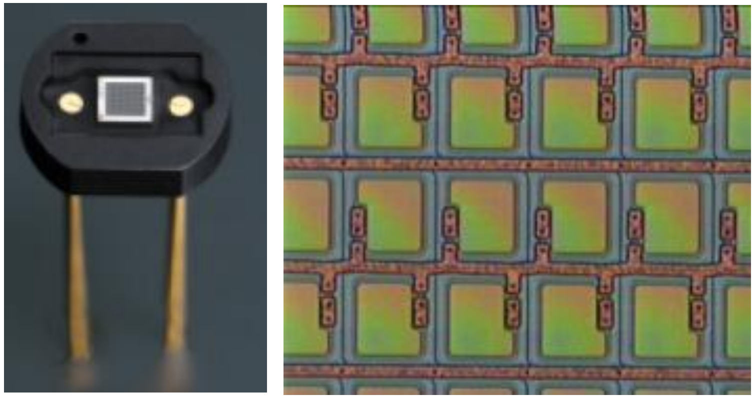


- Other good features:
  - High gain (10^6).
  - Very low after-pulsing and dark count rates, low cross-talk.
  - Easy relative and absolute calibration.
- Concerns for DM SST:
  - Response of MAPMs to large angle photons.
  - May need to reduce gain ($10^6 \rightarrow 10^5$) in high night sky background conditions.
- Further study needed, but no show-stoppers so far…

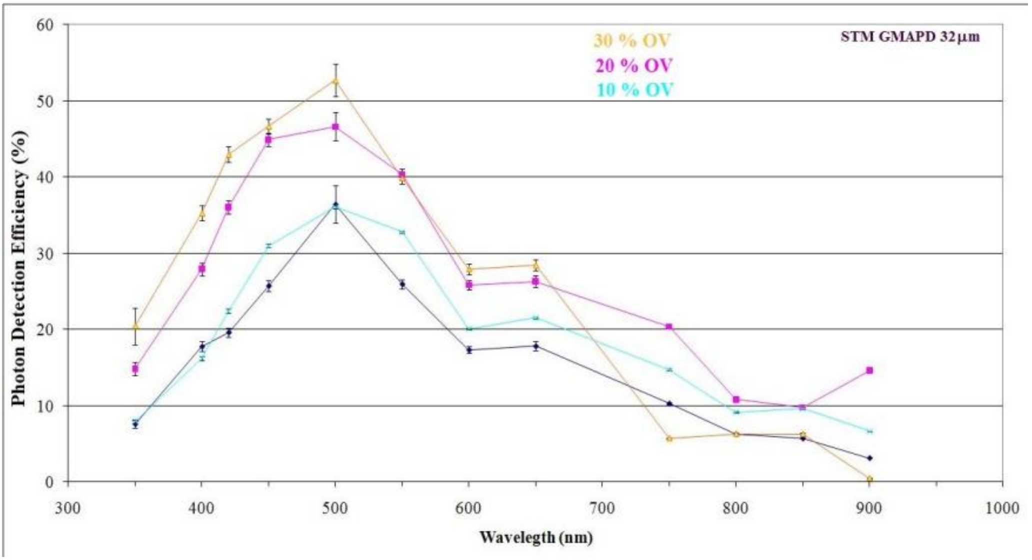


Sensors – Si PMs

- Silicon photomultipliers, reverse biased p-n junction.
- Photon liberates initial e-h pair.
- High bias voltage leads to “shower” of electrons and holes and significant current pulse.
- “Quench” by restricting bias voltage.
- Each pixel many cells:



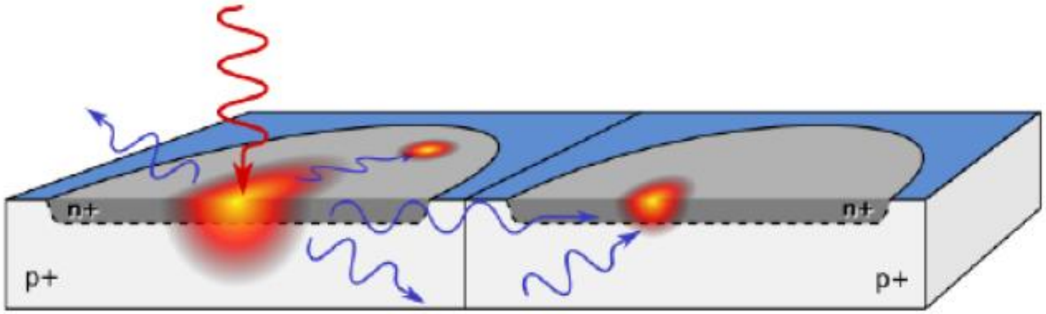
- Can have good QE...



- ...but need p-in-n to ensure photon induced showers close to Si surface for UV detection.
- Hamamatsu make “MPPC”, QE about 20% in Cherenkov wavelength range.

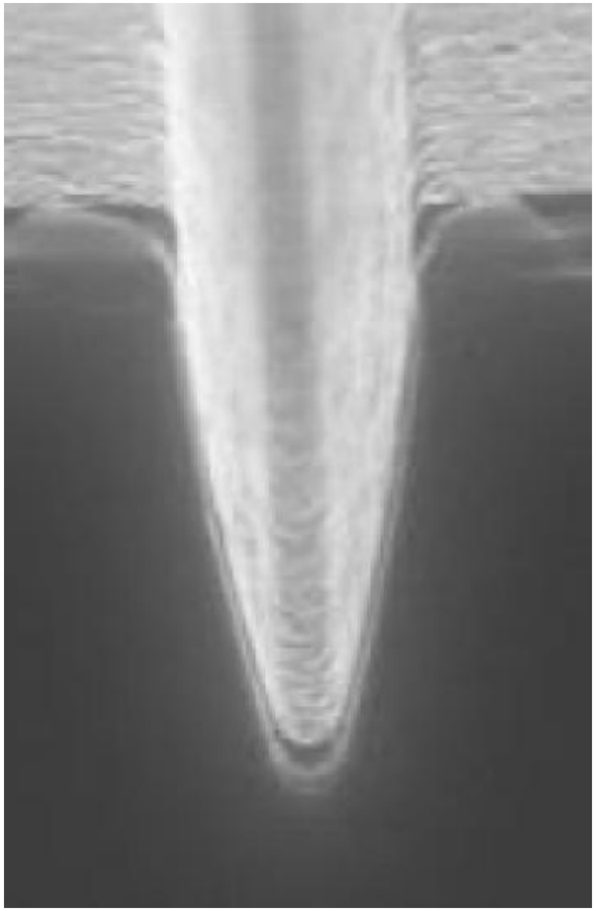
Sensors – Si PMs

- But there is a problem.
- Photons are generated in the showering process and these can trigger neighbouring cells in a pixel:



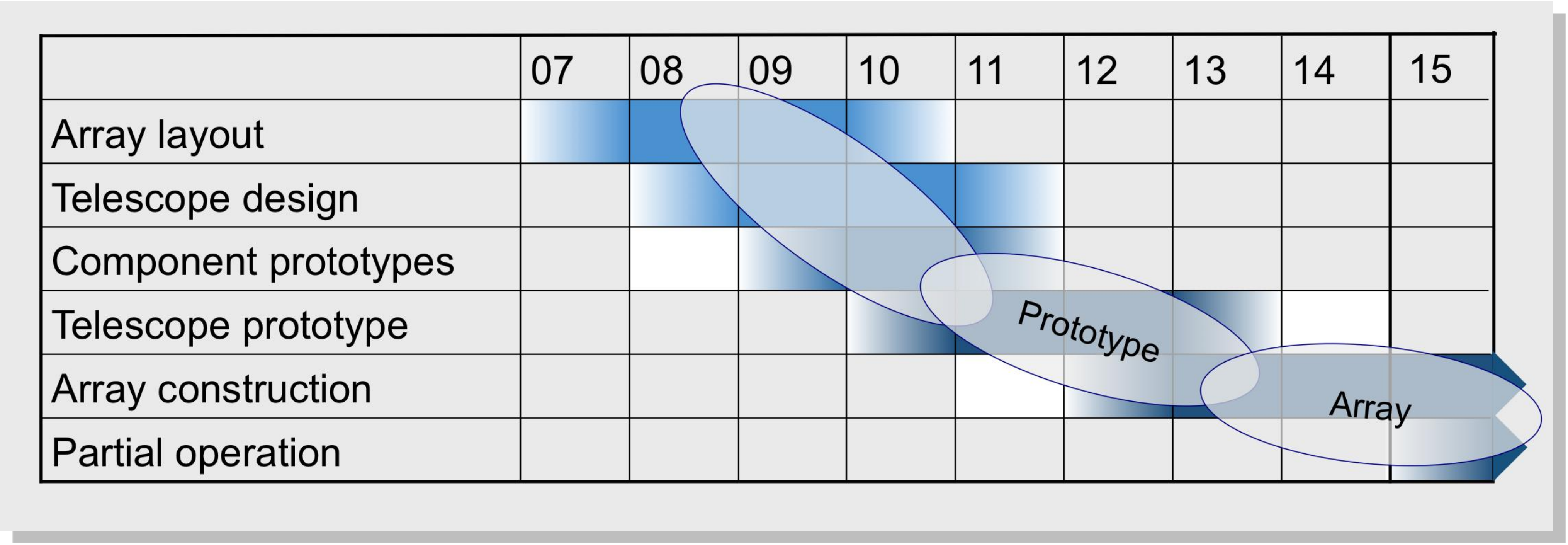
- Solution (e.g. ST Microelectronics) is optical trench between cells.
- Available, but so far only for n-in-p devices.
- Hope soon to have p-in-n SiPMs with optical trenches.

- Optical trench between cells of SiPM:



Summary

- Next steps in γ-ray astronomy/astrophysics require improved instruments – CTA.
- CTA could be built now, using existing technologies.
- But there are areas where good ideas could lead to better performance per €/$/£.
- Want to build CTA on a tight timescale...



	07	08	09	10	11	12	13	14	15
Array layout	▨	▨	▨	▨					
Telescope design		▨	▨	▨	▨				
Component prototypes			▨	▨	▨				
Telescope prototype				▨	▨	▨	▨		
Array construction						▨	▨	▨	▨
Partial operation									▨

Summary

- ...avoid both incompetence and L.W.F.s!