NIRFE,
the Near InfraRed Fluorescence Eye:
A new way to detect UHECR ?

E. Conti - INFN Padova

INFN
Istituto Nazionale
di Fisica Nucleare

Outline

- Motivation: NIR vs. UV
- NIR fluorescence main features
  - spectrum
  - light yield
- On the NIR light sensors
- The night sky noise
- The test prototype
  - goal
  - possible setup
- Present situation and future in Italy

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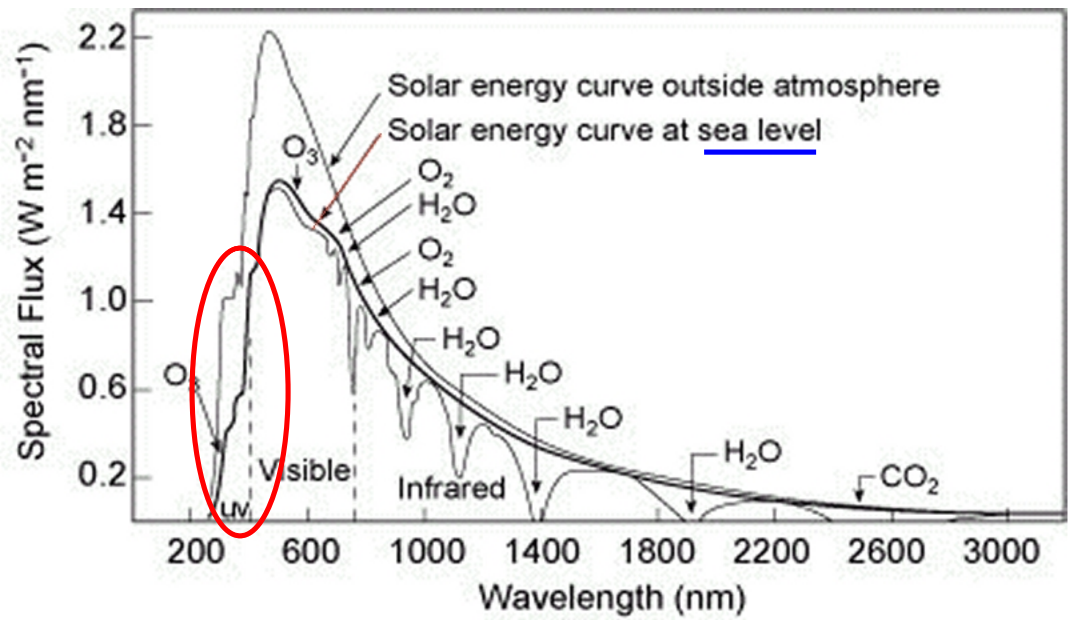
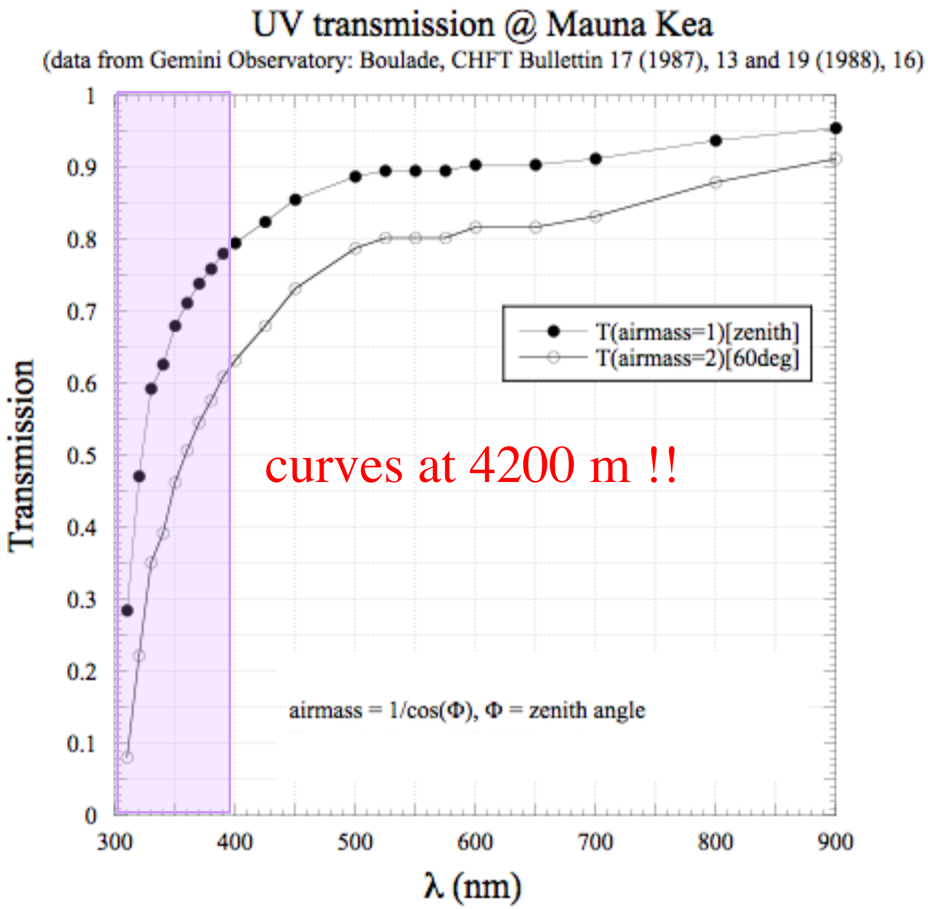
UV transmission in the atmosphere

UV fluorescence (300-400 nm) is an efficient way to detect UHECRs but suffers from the problem of air transmission:

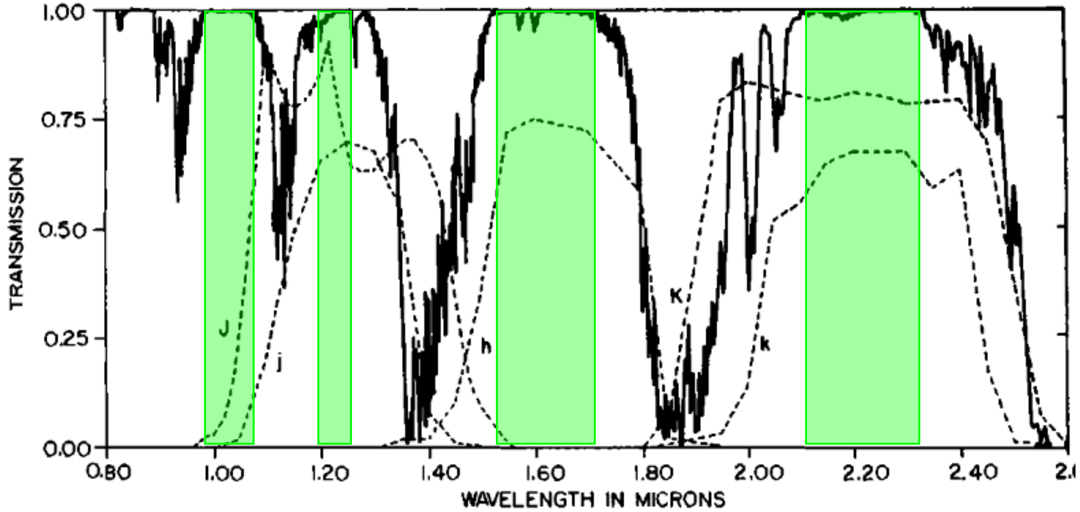
- ➔ O_3 absorption
- ➔ Rayleigh scattering ($1/\lambda^4$)
- ➔ Mie scattering





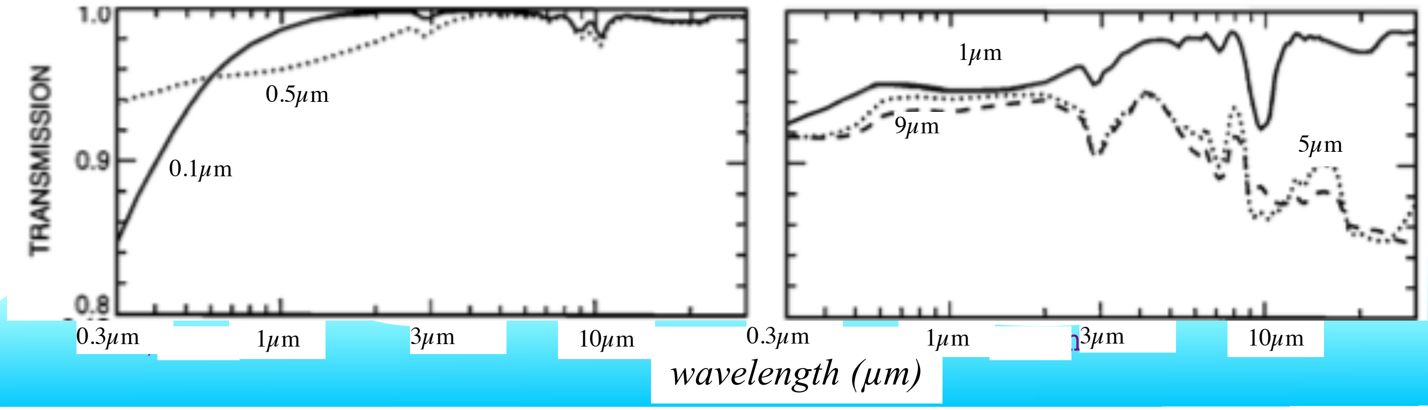
NIR transmission in the atmosphere

- In the NIR, absorption is due to H_2O. There are windows with very high transmission, where absorption is negligible.



Transmission from 0.80 to 2.60 μm above Kitt Peak in summertime [from Manduca and Bell (1979)]

- Rayleigh scattering is negligible ($1/\lambda^4$ dependence)
- Mie scattering depends on dust size, in general is lower than UV.



[Tegen & Lacis, J. Geophys. Res. (1996)]

Goal: increase the event rate

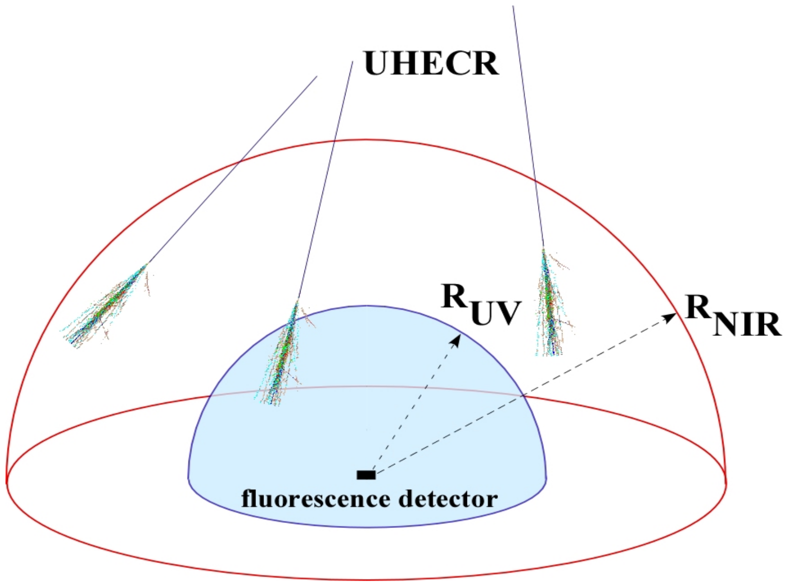
- Introducing an extinction length $\Lambda(\lambda)$

$$I(x) = I(0)\, exp(-x/\Lambda)$$

the absorption of the air reflects into a short Λ. For UV, $\Lambda \sim 10$ km.

- This has implications on the observable event rate, which goes approximately as Λ^2 .

Maximum useful range $R \propto \Lambda$



- The ultimate goal of the NIR fluorescence is to increase <u>a lot</u> the observable event rate.

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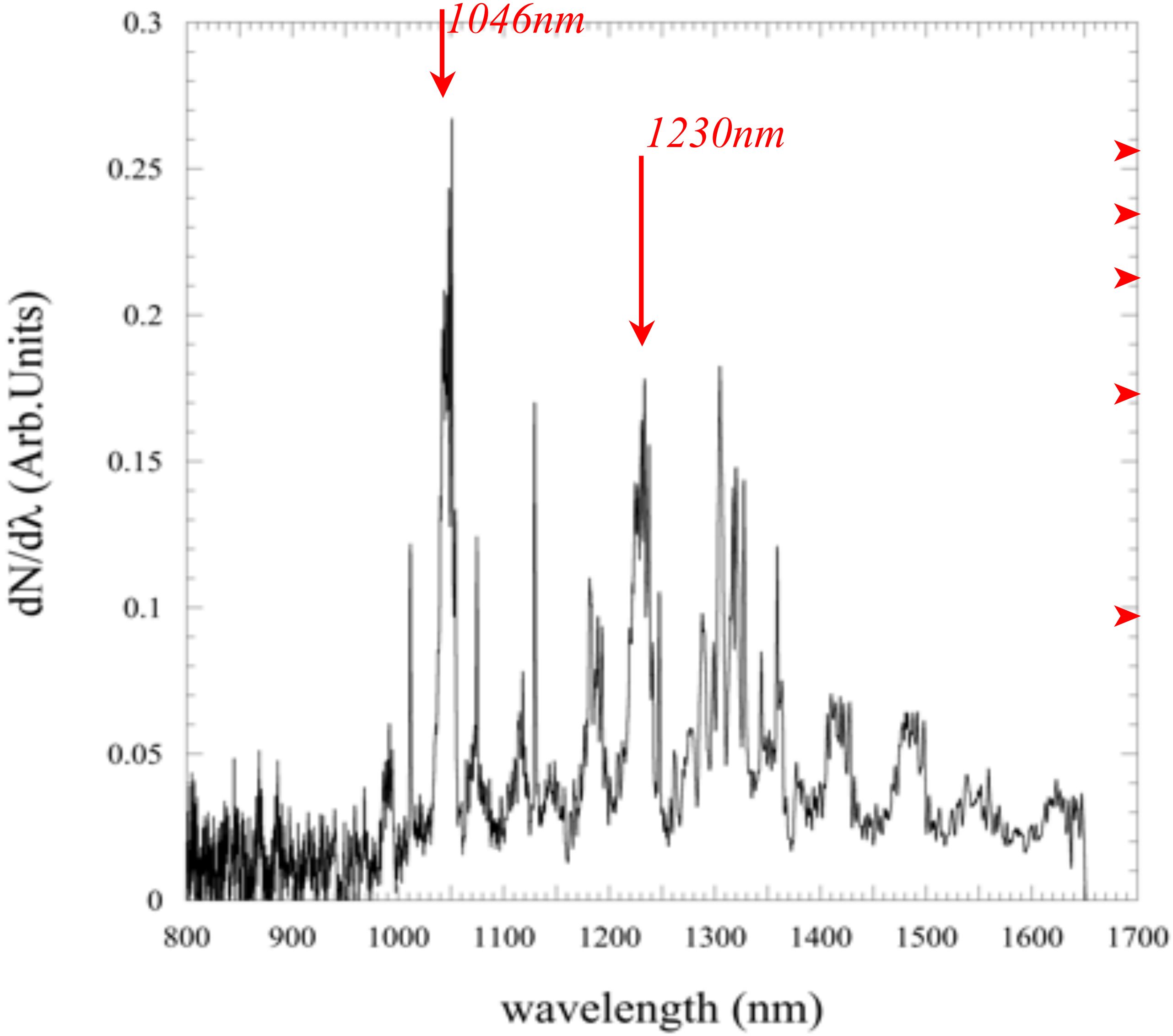
for details see:

E.Conti, G.Sartori, G.Viola
*"*Measurement of the near-infrared fluorescence of the air for the detection of ultra-high-energy cosmic rays*"*
Astrop. Phys. 34 (2011), 333-339

Dry air NIR spectrum



- NIR detector: InGaAs (0.8-1.7µm)
- Dry Air = *80%* N_2 + *20%* O_2
- At room temperature and atmospheric pressure
- Spectrum is not simply the weighted sum of the single gas spectra, because of molecular/atomic interactions.
- **Main structures at 1046 nm and 1230 nm**

NIR light yield

- NIR Light Yield Y_{NIR} [0.8-1.7μm] is obtained by comparing the NIR light signal with the UV light signal, whose light yield Y_{UV} is known:

$$\boxed{\frac{Y_{IR}}{Y_{UV}} = 0.21 \pm 0.03}$$

- Since $Y_{UV} = 19.88 \pm 0.51 ph/MeV$ (average of the literature data), then

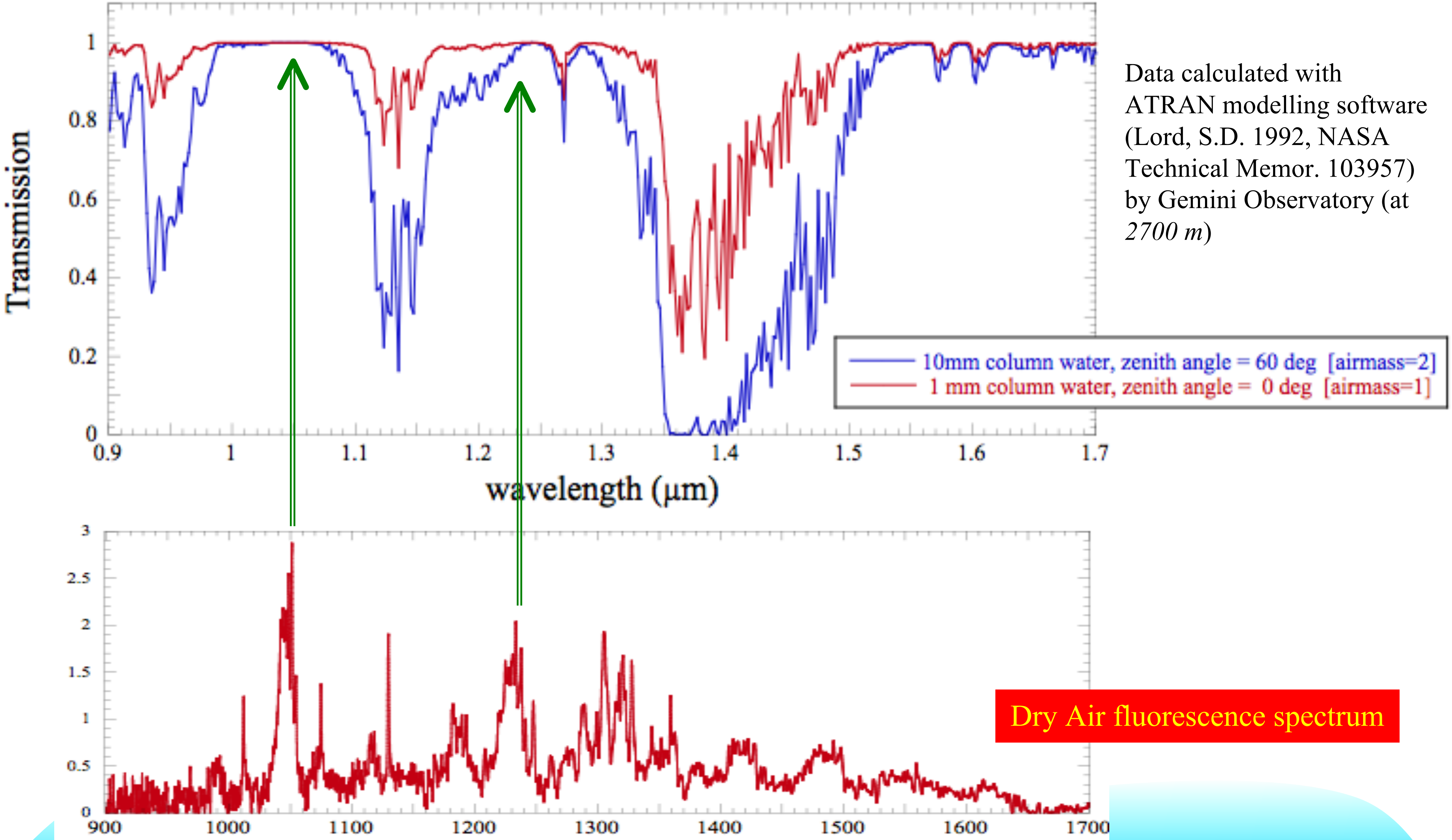
$$\mathbf{Y_{IR} = 4.17 \pm 0.53}\ \boldsymbol{photons/MeV}$$

- If we limit the spectrum at *1.1μm* (Si bandwidth), then the light yield is

$$\mathbf{Y_{IR}\ (\lambda \leq 1.1\mu m) = 1.4}\ \boldsymbol{photons/MeV}$$

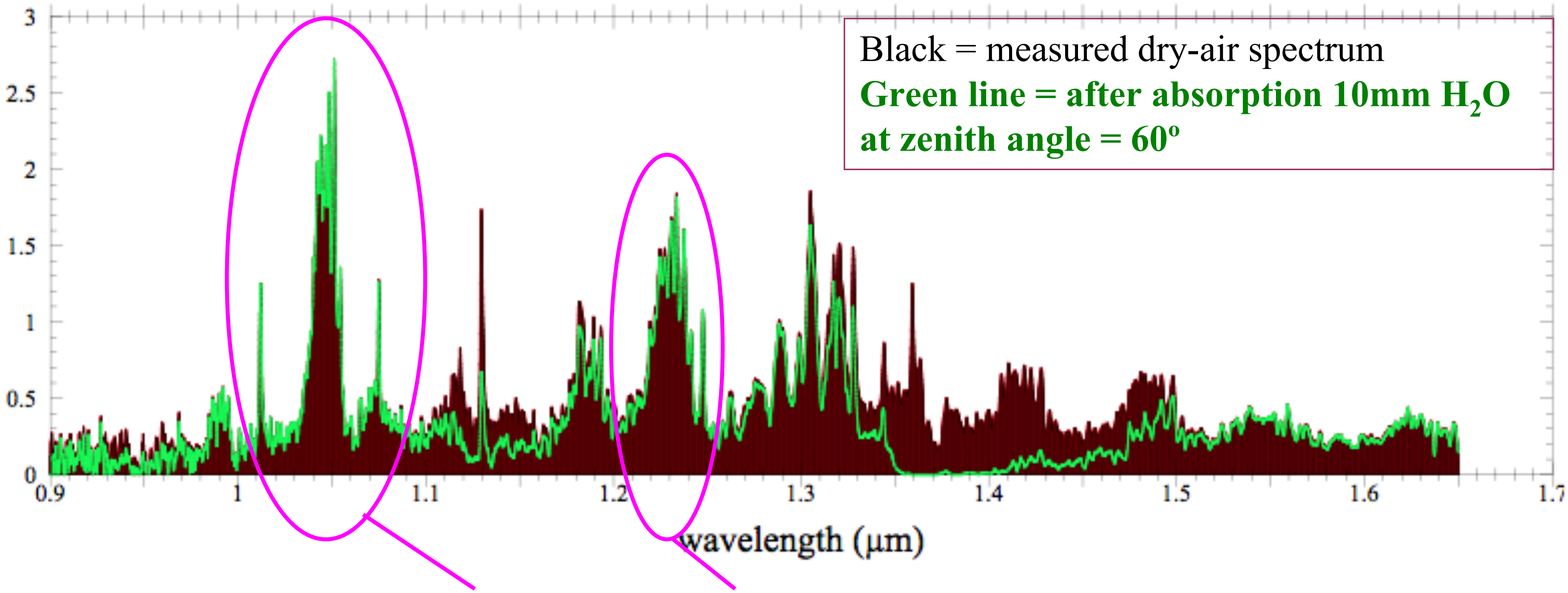
- We have also measured Y_{IR} also at low pressure (i.e., high altitude), obtaining a trend similar to that of the UV fluorescence.

Atmosphere transmission



Data calculated with ATRAN modelling software (Lord, S.D. 1992, NASA Technical Memor. 103957) by Gemini Observatory (at *2700 m*)

Spectrum after absorption



- The two bands at *1045 nm* and *1230 nm* are completely transmitted. Air is perfectly transparent almost independently from water content !!
- The extinction length $\Lambda(\lambda)$ is very, very long !

  $\Longrightarrow$ the limit on the detection of a UHECR is NOT given by the atmosphere transmission.

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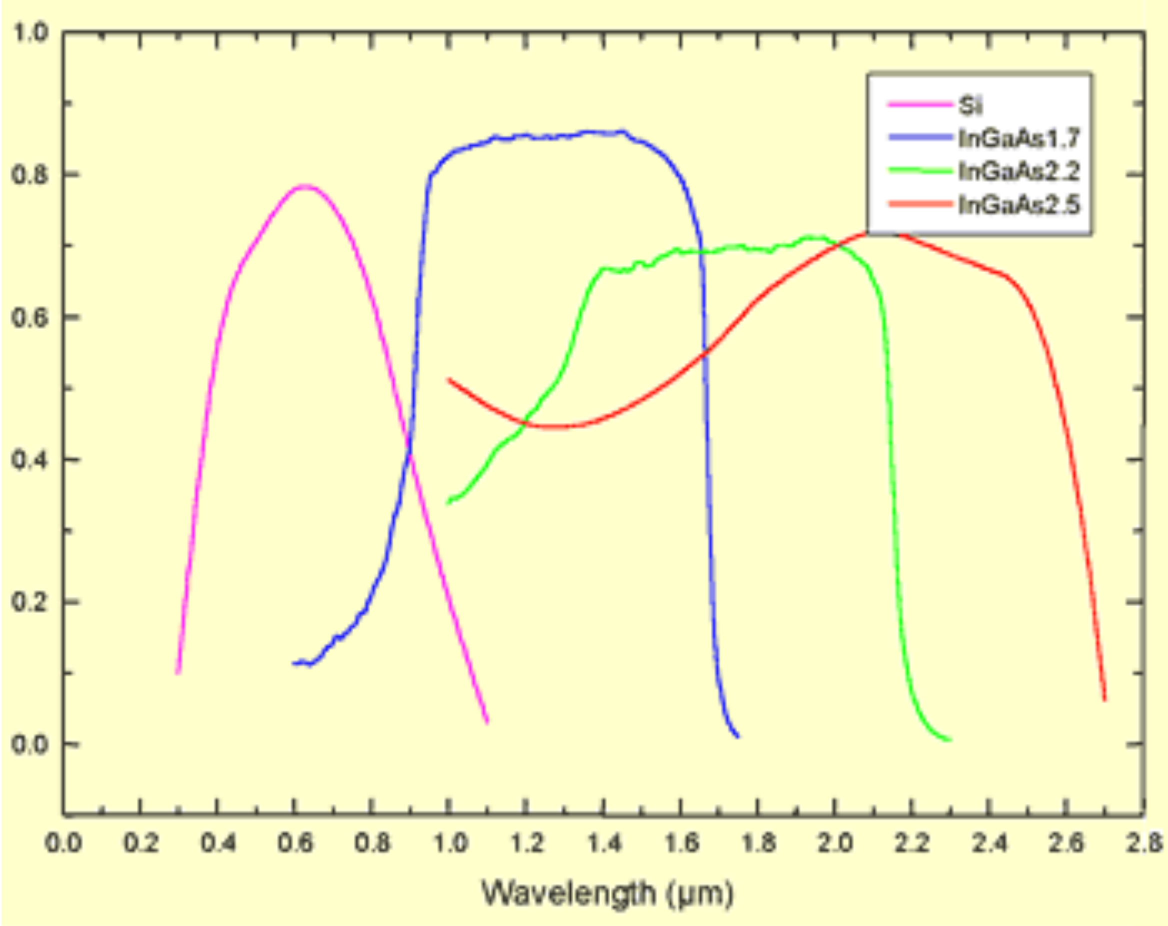
Detectors in the range 0.8÷2 μm [1]

- The sensor with the highest QE (>80%) is the **InGaAs**, semiconductor, which can extend down to 2.6 μm. But:
  - ★ small area (< 1 cm^2);
  - ★ no multiplication;

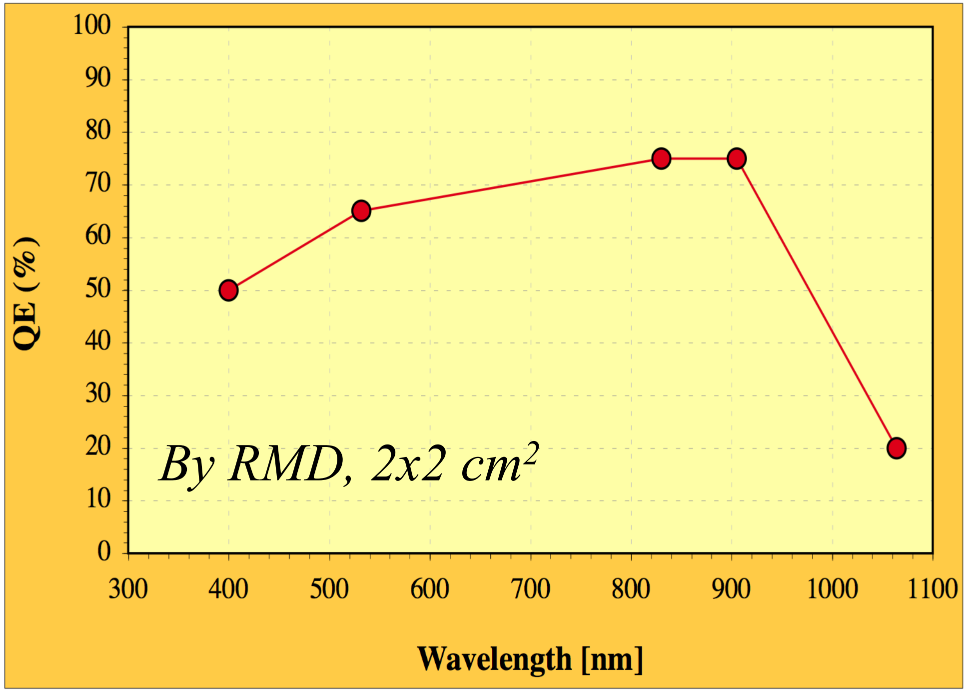


- **Avalanche InGaAs** exists, Gain ~ 10^2, but diameter $\leq 200\mu m$

Detectors in the range 0.8÷2 μm [2]

- **Photomultiplier**: Hamamatsu produces PMTs with QE ~ 1% 1÷1.6 μm.
  Gain ~ 10^4-10^6, but very small sensitive area and need LN_2. Very expensive.
- **Silicon devices.** Si extends to 1.1μm because of the 1.1eV bandgap. After it becomes transparent.
  Si APD, gain ~10^3-10^5, area ≥ 1 cm². Decent QE @ 1000-1100 nm.

QE ≈ 30% @ 1040nm



Si APD

- The detection of NIR light is TODAY a weak point. No NIR device is comparable with a UV PMT w.r.t. area, gain, noise.
- To us, the only viable solution today seems to be the Si APD.
  This means to restrict the detection of the NIR fluorescence at *1.1 μm*, and use only 30% of the NIR light yield.
- The Si APD, when **cooled down at 77K**, can detect 16 electrons with a decent signal-to-noise ratio [NIM A 508 (2003), 388, for an 13x13 mm^2 APD by RMD]. It can also detect the single photoelectron [NIM A504 (2003), 58, for a Hamamatsu APD].
- Si APD price is about 700-1000 $\$/cm^2$. To contain the cost, we must think of a small size detector.

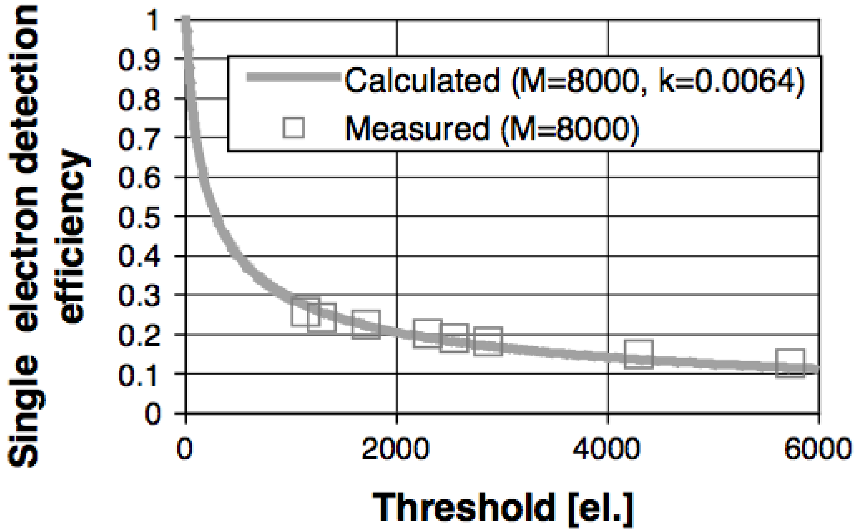


Fig. 7. Photoelectron detection efficiency, measured with S8148 APD and calculated for $M = 8000$ and $k = 0.0064$.

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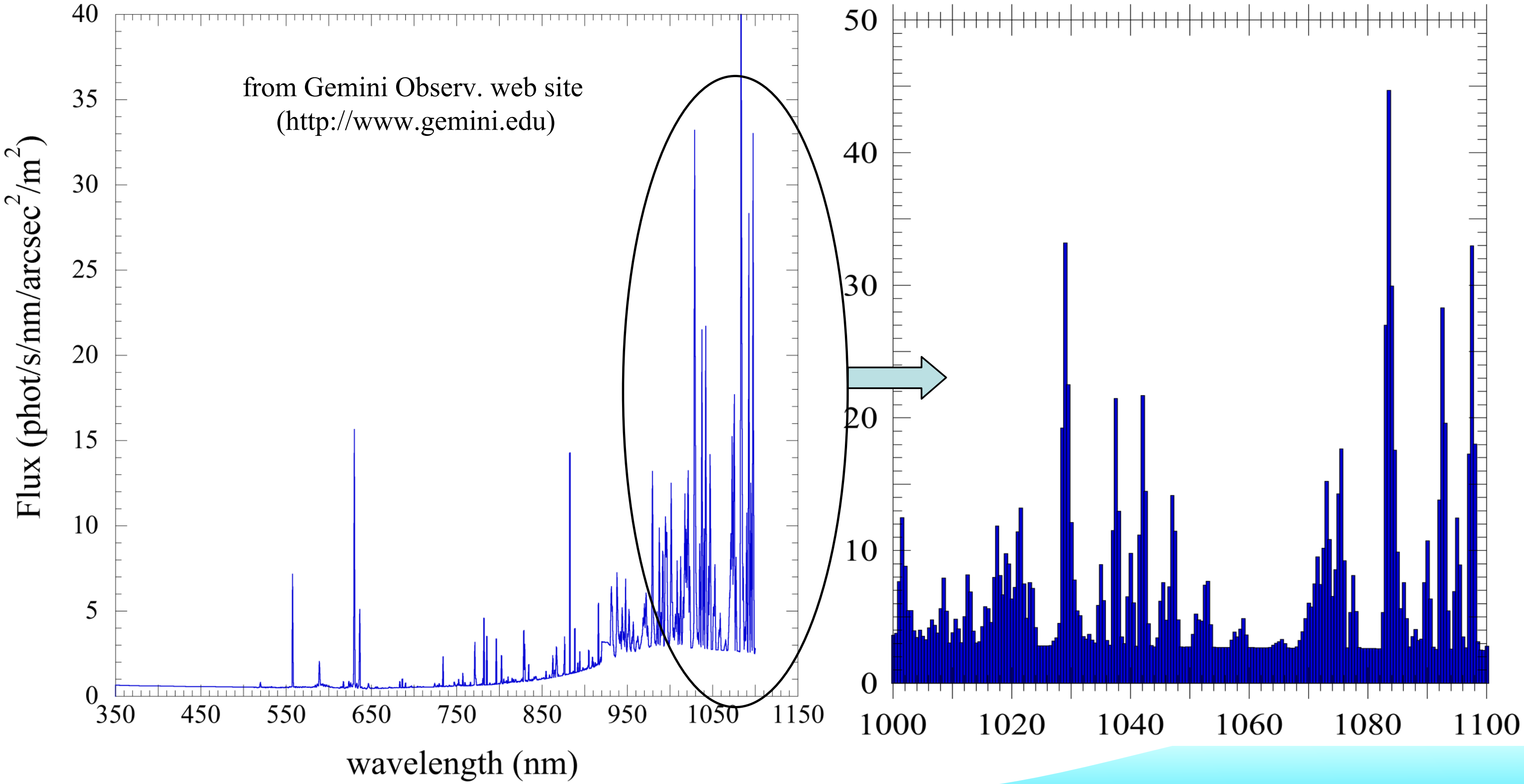
Night sky noise in the NIR [1]

- In the NIR, below 2 μm the night sky brightness is dominated by the OH airglow emission.
  Above 2 μm, it is dominated by the thermal emission (black body).



Night sky noise in the NIR [2]

- NIR: sky brightness $B_{NIR} \sim 7$ ph/s ·arcsec^{-2} ·m^{-2} ·nm^{-1} *@ 1045 nm*

  about the same *@ 1230 nm*
- UV : $B_{UV} \sim 0.6$ ph/s ·arcsec^{-2} ·m^{-2} ·nm^{-1} ,

  ==> i.e., about a *factor 10 lower* than NIR
- What matters is the fluctuation of the background $\propto \sqrt{B_{NIR}}$
- Consider the ratio R between the signal-to-noise ratio (S/N) in the NIR and the UV:

$$R = \frac{(S/N)_{NIR}}{(S/N)_{UV}}$$

- At parity of geometrical conditions:

$$R = \frac{Y_{NIR} \cdot T_{NIR} \big/ \sqrt{B_{NIR}}}{Y_{UV} \cdot T_{UV} \big/ \sqrt{B_{UV}}} = \left(\frac{Y_{NIR}}{Y_{UV}}\right) \cdot \sqrt{\frac{B_{UV}}{B_{NIR}}} \cdot \exp\left(\frac{D}{\Lambda_{UV}}\right)$$

where $T_{NIR} = 1$ and $T_{UV} = \exp(-D/\Lambda_{UV})$

Night sky noise in the NIR [3]

- The numbers:

$$\sqrt{\frac{B_{UV}}{B_{NIR}}} = 3 \qquad \left(\frac{Y_{NIR}}{Y_{UV}}\right) = \frac{1.4}{19.9} = 0.07 \qquad \Lambda_{UV} \approx 18km$$

give:

R = 1/18 @ D = Λ_{UV} = 18 km

R = 1/3 @ D = 50 km

R = 1 @ D = 70 km

- Also regarding S/N, the NIR fluorescence is more difficult. Competitive only at large distance (D ≥ 70 km)
- In AUGER, S/N ~ 10 (depending of course on E and D of UHECR). For NIR fluorescence, we must live with S/N ~ 1 or increase the energy threshold.
- **The night sky noise is a delicate point which must be studied more deeply**. Measurements in the site are required.

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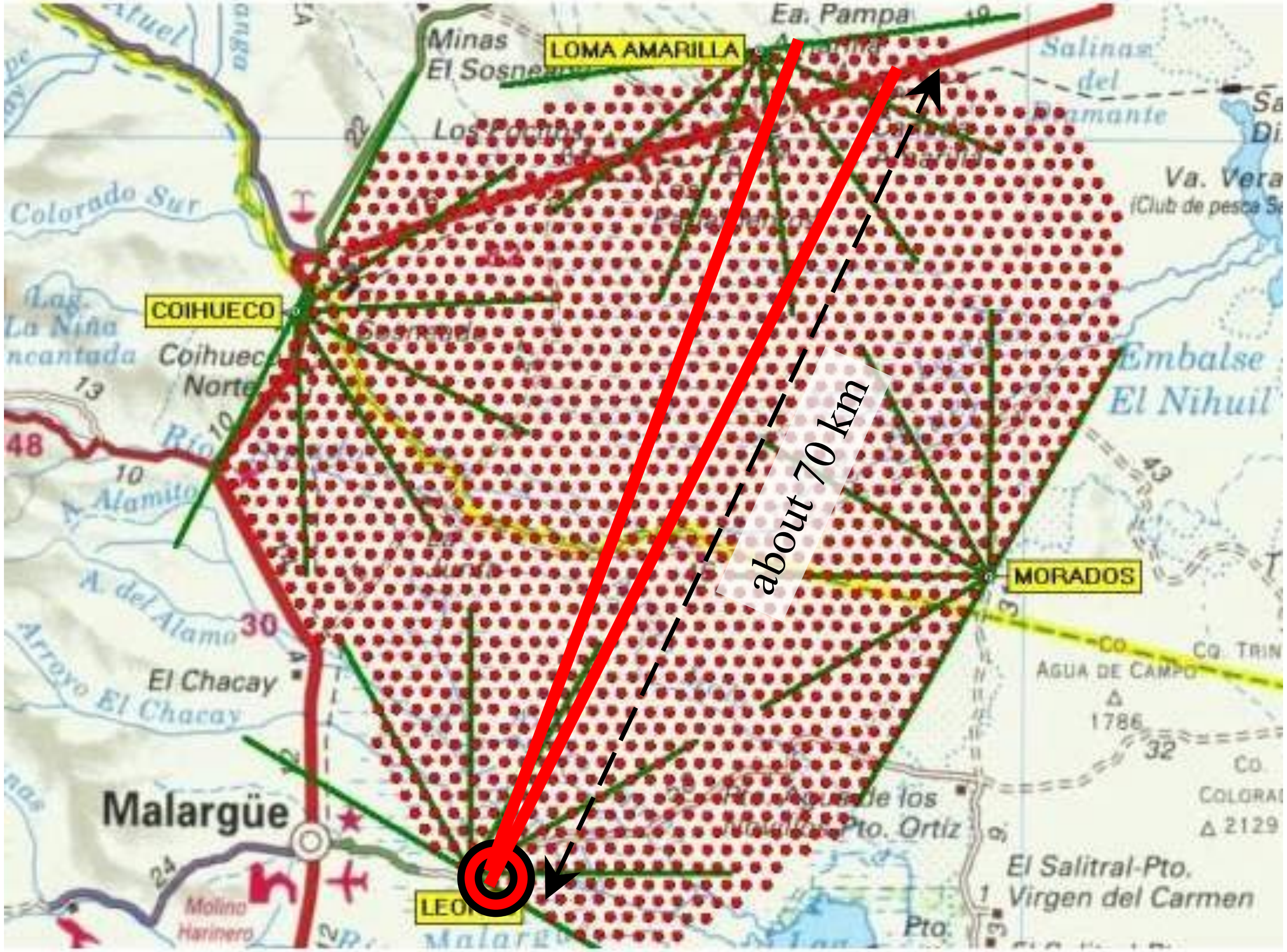
Test prototype: goal

- We want to show that the NIR fluorescence technique works, even for events at very long distance.
- The final goal is to demonstrate that we can detect EAS at distance> 30 km, which is more or less the actual limit for the AUGER FD.
- To accomplish this, we don't need an apparatus with excellent optical quality. We don't need either to measure the light profile of the shower.
- We need only to detect the presence of the shower.
- Therefore, we think that a "small" dimension prototype is adequate, and we need the comparison with a calibrated and well-known detector (AUGER).
- To contain costs, if possible reuse old mirrors/optics.

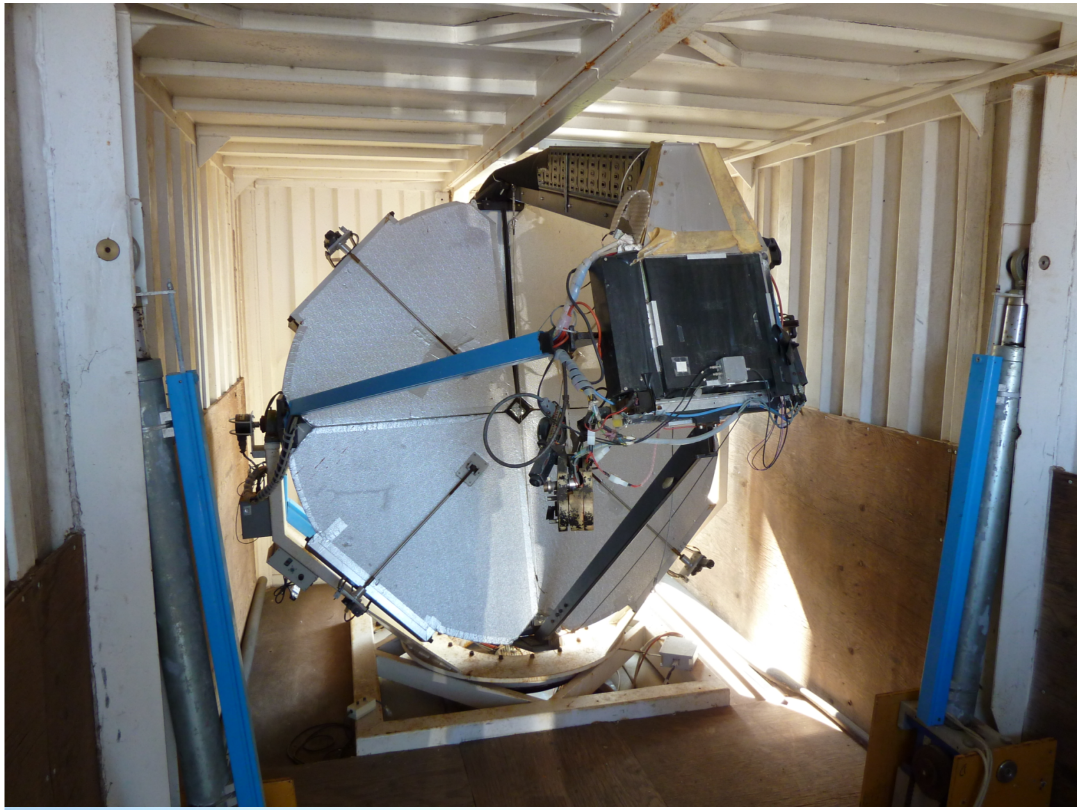
Just for example



TEST PROTOTYPE

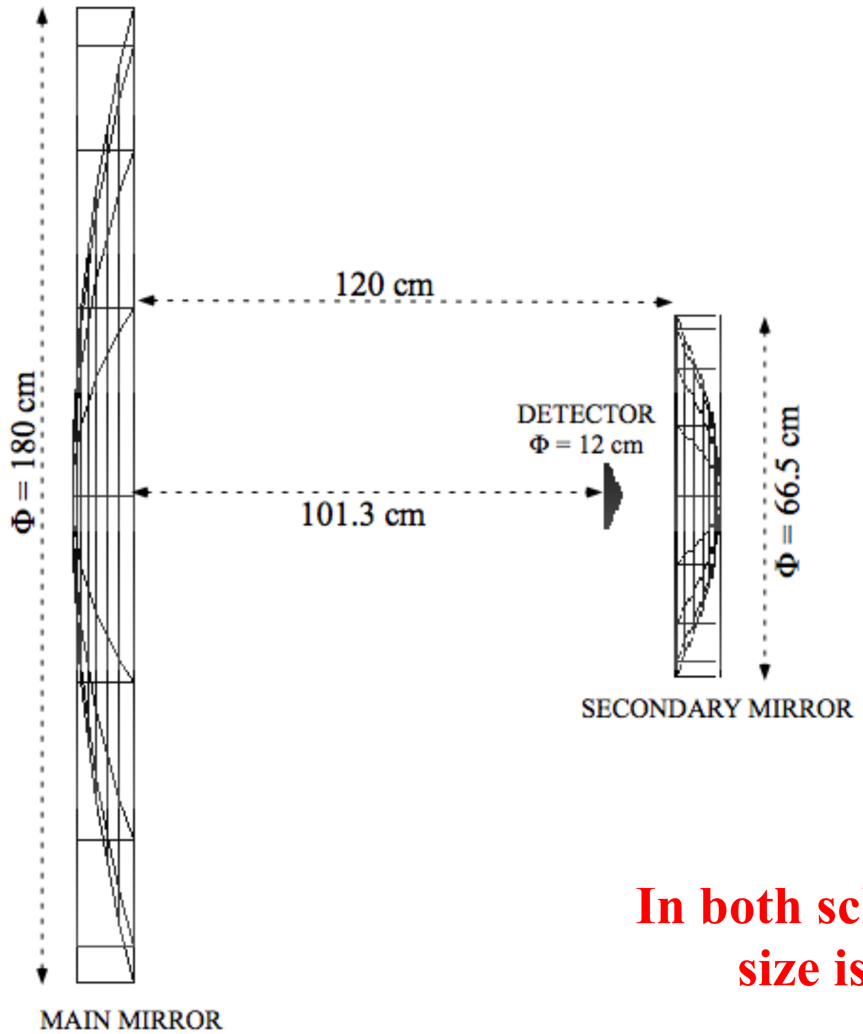
Detection scheme

- Simple scheme:
  - main parabolic mirror or composite-mirror;
  - secondary mirror, to increase the angular acceptance of the system (i.e., to lower the focal length);
  - (small, i.e. not too much expensive) detector on the focus
- We have 3 parabolic mirrors, from the old experiment CLUE, with diameter 180 cm and focus 180 cm:
  - area = 2.5 m^2;
  - F/# = 1
  - need to be re-aluminized
- Two possible configurations:
  - single main parabolic mirror + secondary;
  - main mirror composed by 3 parabolic mirror in a clover configuration + secondary.
- In both cases, the Field Of View [FOV] is small, order of 10°, so we cannot see the whole development of the EAS and measure its total energy.
  We can only detect the presence of the shower.



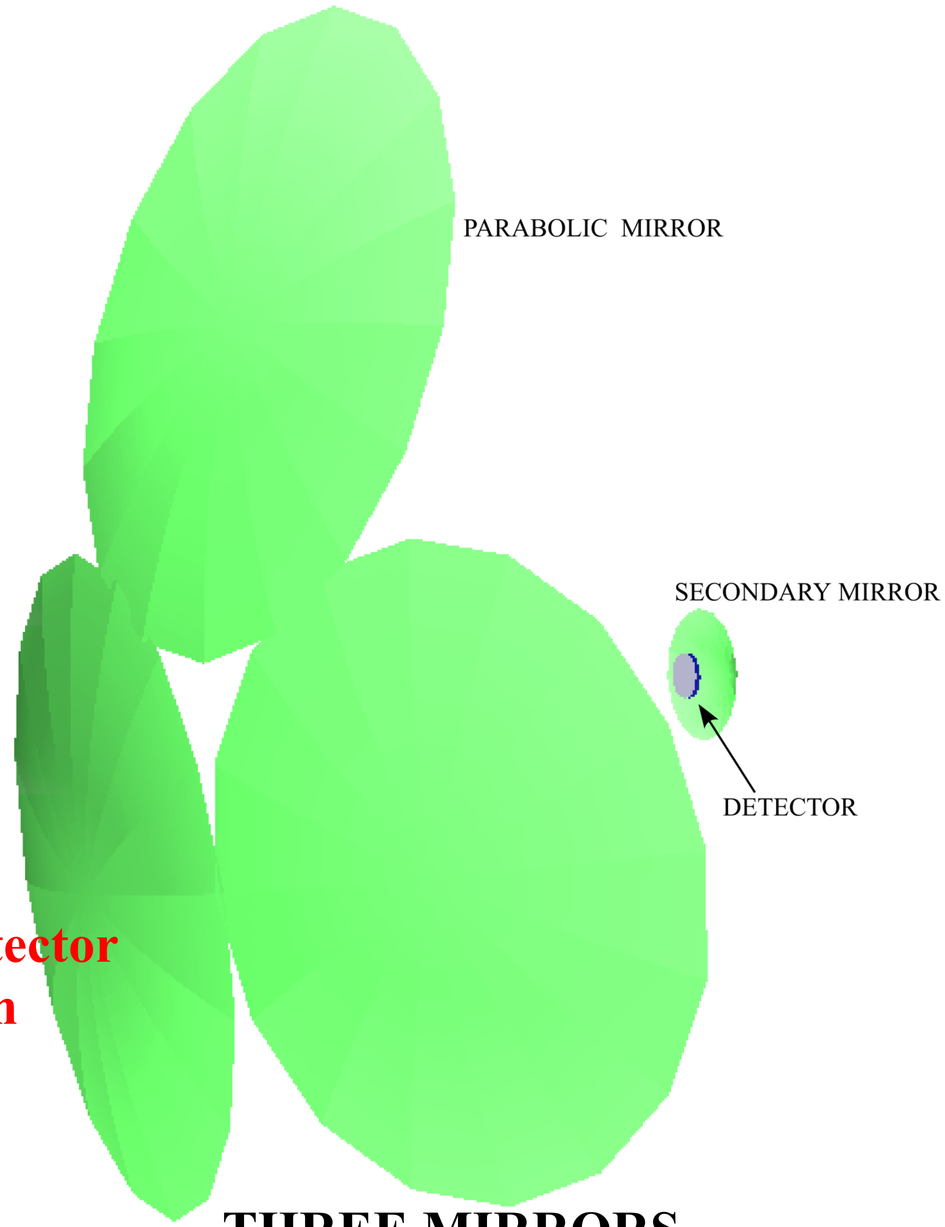

Φ = 1.8 m

Possible optical schemes



SINGLE MIRROR

In both schemes, detector size is $\Phi = 12$ cm



THREE MIRRORS

Putting some numbers [1]

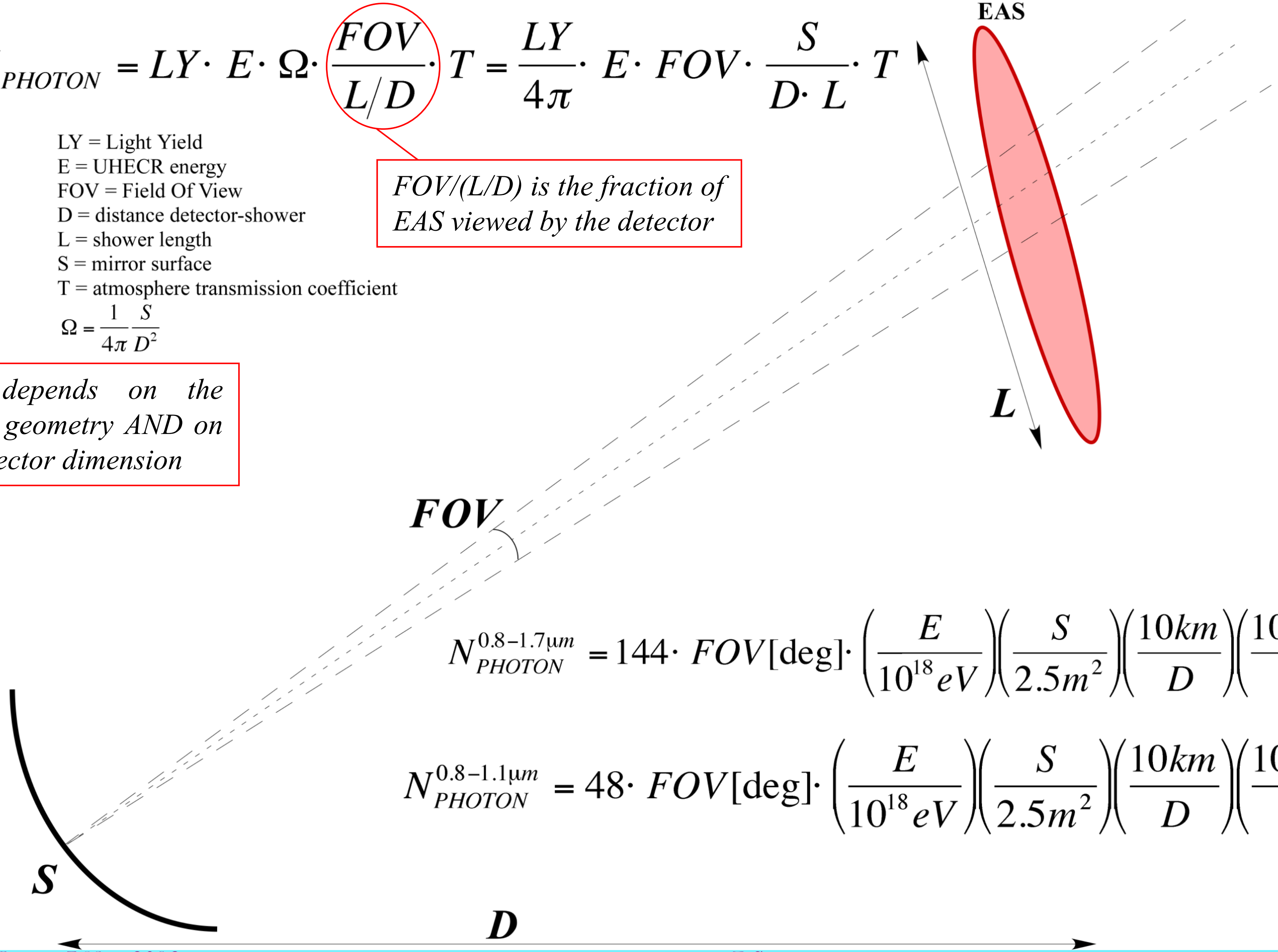
$$N_{PHOTON} = LY \cdot E \cdot \Omega \cdot \frac{FOV}{L/D} \cdot T = \frac{LY}{4\pi} \cdot E \cdot FOV \cdot \frac{S}{D \cdot L} \cdot T$$

LY = Light Yield
E = UHECR energy
FOV = Field Of View
D = distance detector-shower
L = shower length
S = mirror surface
T = atmosphere transmission coefficient

$$\Omega = \frac{1}{4\pi}\frac{S}{D^2}$$

FOV/(L/D) is the fraction of EAS viewed by the detector

FOV depends on the mirror geometry AND on the detector dimension



$$N_{PHOTON}^{0.8-1.7\mu m} = 144 \cdot FOV[\mathrm{deg}] \cdot \left(\frac{E}{10^{18}eV}\right)\left(\frac{S}{2.5m^2}\right)\left(\frac{10km}{D}\right)\left(\frac{10km}{L}\right) \cdot T$$

$$N_{PHOTON}^{0.8-1.1\mu m} = 48 \cdot FOV[\mathrm{deg}] \cdot \left(\frac{E}{10^{18}eV}\right)\left(\frac{S}{2.5m^2}\right)\left(\frac{10km}{D}\right)\left(\frac{10km}{L}\right) \cdot T$$

Putting some numbers [2]

Energy = $1 \cdot 10^{18}$ eV, D = 10 km, T = 1, Si APD

A) 1 mirror, S = 2.5 m^2;

- FOV = 10° with detector diameter = 12 cm (simulation with Zemax):

$$\mathbf{N_{PH,TOT} = 480}$$

- This is the total number arriving on the detector, which is composed by many devices, say, *1x1 cm^2*. Then the signal must be divided for the nr. of illuminated APDs, say 12 (the whole diameter). The number of photon on each APD is then

$$\mathbf{N_{PH,sigleAPD} \approx 40}$$

which seems to be a decent number.

B) 3 mirrors, S = 7.5m^2;

- FOV = 6° with the same detector, we gain about a factor of 2:

$$\mathbf{N_{PH,singleAPD} \approx 70}$$

Putting some numbers [3]

- Those numbers at 10 km distance. At 70 km, the EAS energy must be increased by a factor of 7 to have the same signal.
- We can/must put in coincidence the various APDs to reduce the noise.
- However, even at 70 km, an EAS of $\mathbf{5 \cdot 10^{18}\ eV}$ seems detectable, which is about the same threshold of the AUGER FD.

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Situazione attuale

- Il Gr.V dell' INFN ha approvato la sigla NIRFE per 3 anni, e finanziato, per il momento, il primo anno
- La collaborazione e' attualmente composta da INFN+Univ. Padova e Lecce
- Il progetto si sviluppa temporalmente in 3 punti:
  1) 2012. Definizione del progetto finale: ottica [specchi primari e secondari], sensori NIR ..., fino ad arrivare ad un "technical proposal"
  2) 2013. Realizzazione del telescopio e dei sensori NIR. Montaggio e test preliminary in Italia
  3) 2014. Trasporto e montaggio dell'apparato a Malargue. Inizio della presa dati
- Chiaramente i punti 2) e 3) richiedono fondi che il Gr. V non puo' dare => bisogna passare in Gr. II => la collaborazione deve essere ampliata. Anche per il punto 1) siamo ora sottodimensionati.

- Sottolineo che si tratta del primo step di un R&D probabimente lungo
- Ora c'è da dimostrare sul campo che la tecnica ha senso e funziona, con un setup il piú possibile economico.
- Poi, eventualmente, c'è da fare R&D sui sensori, per estendere la banda si osservazione del NIR oltre *1.1μm* e recuperare parte del light yield e migliorare il S/N.

Letter of Intent a AUGER

- Come sicuramente sapete, a fine 2012 e' stata sottoposta al Collaboration Board di AUGER una LoI nella quae si chiede essenzialmente di ospitare l'apparato di test e un minimo supporto per le infrastrutture.
- In Feb 2012, ottenuta una positiva risposta dallo spokeman:

  [...] "The proposal is considered very interesting, and the Pierre Auger Collaboration welcomes you to work with us in pursuing the IR fluorescence detection. As a first step, we highly encourage you to build and test a prototype instrument before installing it in Malargue." [...]

Spokesperson:
Prof. Dr. Karl-Heinz Kampert
University Wuppertal (Germany)
Tel: +49 202 439 2856 (Secr: -2640)
Fax: +49 202 439 2662
email: kampert@uni-wuppertal.de

PIERRE AUGER OBSERVATORY

26.02.2012

Near-Infrared fluorescence technique to detect Ultra High Energy Cosmic Rays

Dear Prof. Enrico Conti,

Thank you very much for submitting a letter of intent to the Pierre Auger Collaboration aimed at verifying the feasibility to detect Ultra High Energy Cosmic Rays by Near-Infrared Fluorescence Technique (NIRFE) at the Malargüe site. Please apologize for the long delay in answering to you.

The Pierre Auger Collaboration Board has discussed your proposal and charged an ad-hoc committee to review the science and technique. The committee has reported to the Technical Board of the Pierre Auger Collaboration and a summary of the report is probably provided to you by Prof. Sergio Petrera.

The proposal is considered very interesting, and the Pierre Auger Collaboration welcomes you to work with us in pursuing the IR fluorescence detection. As a first step, we highly encourage you to build and test a prototype instrument before installing it in Malargüe. Considering our experience we recommend the detector to be tested outdoors, pointed at the sky, to confirm that the background photon flux is not overwhelming. In addition, the same detector should be demonstrated to be sensitive to the small flux of IR photons that are expected from an air shower. These tests can be done without help from an air shower detector.

More information about technical details, required personnel for minimal maintenance, power consumption, etc., should be clarified after testing the prototype and reported to us. Particularly, we would like to see results of the measurement of night sky in IR by this instrument.

In the meantime, the collaboration will investigate suitable locations at the observatory.

Grazie della vostra attenzione