The Near-Infrared Fluorescence of the Air for the Detection of UHECRs

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Outline

- Motivations
- Our Near-Infrared (NIR) experimental measurements:
  - Spectra of N_2, O_2, dry air
  - Light yield of dry air
- Briefly, on the detection of NIR light
- Application of NIR fluorescence to detection of UHECRs:
  pros and cons

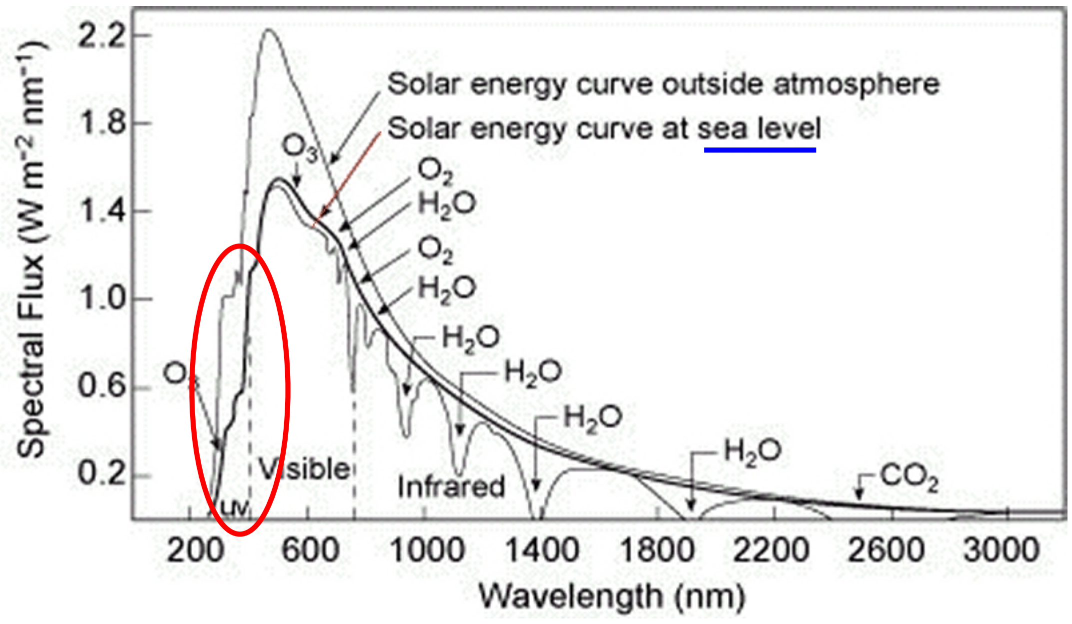
Motivations

Air transmission: NIR vs. UV

UV transmission in atmosphere

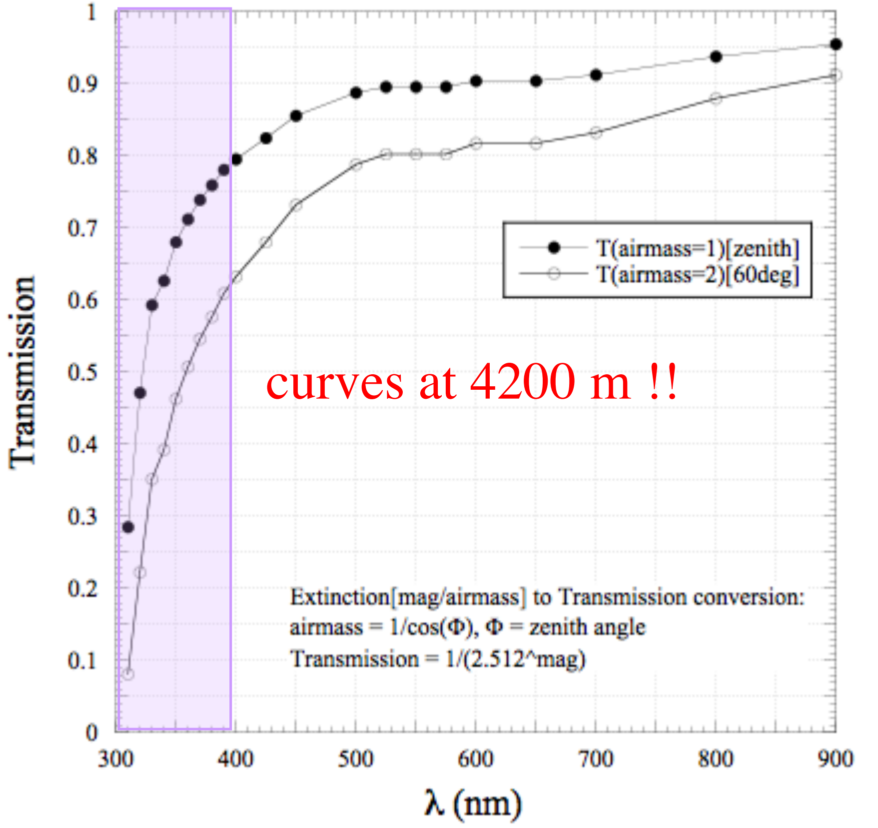
UV fluorescence (300-400 nm) is an efficient way to detect UHECRs but suffers from the problem of air transmission:

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



UV transmission @ Mauna Kea

(data from Gemini Observatory: Boulade, CHFT Bullettin 17 (1987), 13 and 19 (1988), 16)

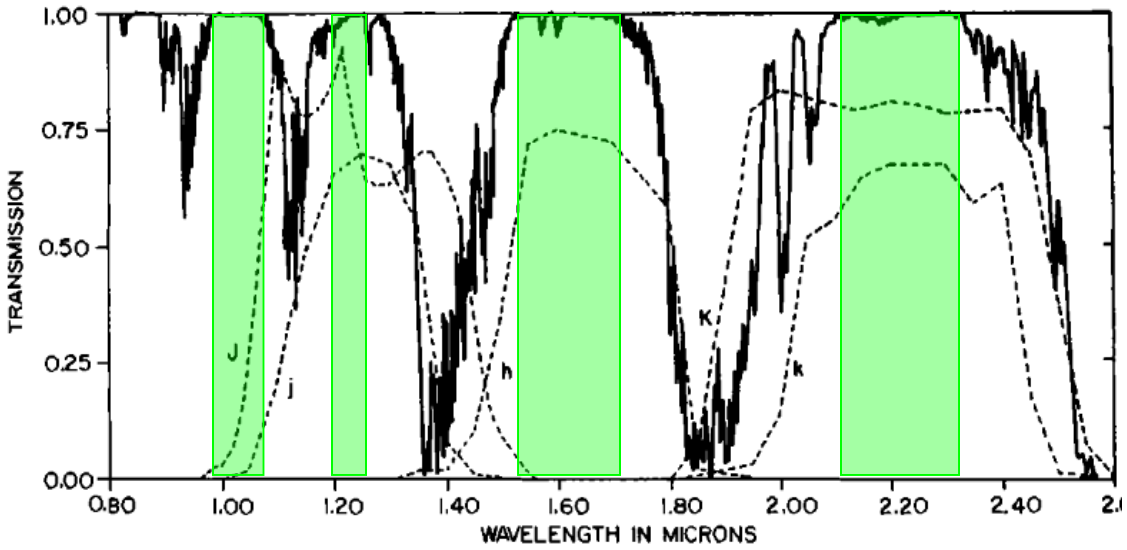


curves at 4200 m !!

Extinction[mag/airmass] to Transmission conversion:
airmass = 1/cos(Φ), Φ = zenith angle
Transmission = 1/(2.512^mag)

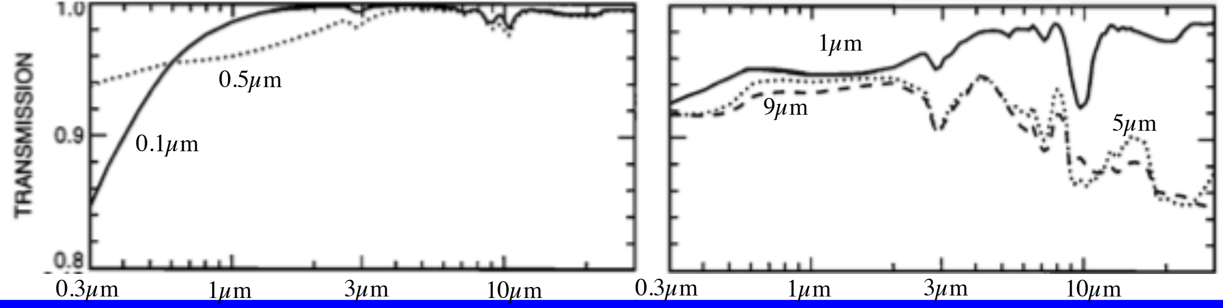
NIR transmission

- 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.
- Mie scattering depends on dust size, in general is lower than UV.



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

Ultimate goal: increase event rate

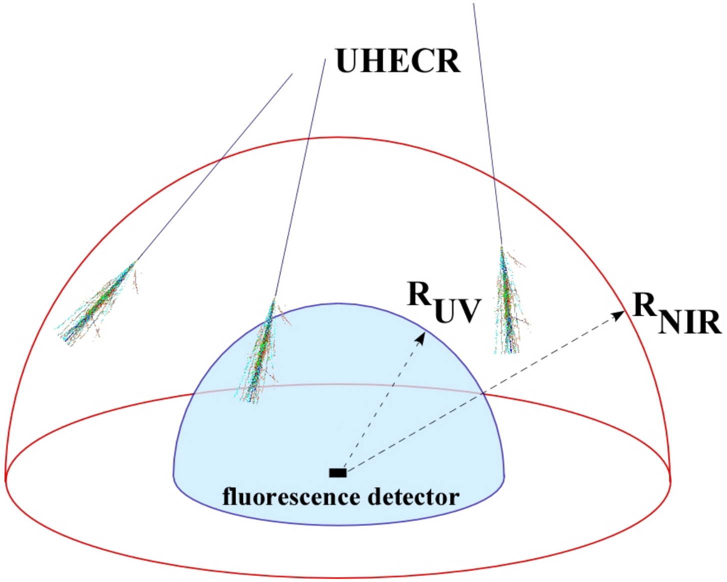
- Introducing an extinction length $\Lambda(\lambda)$

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

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 $R \propto \Lambda$

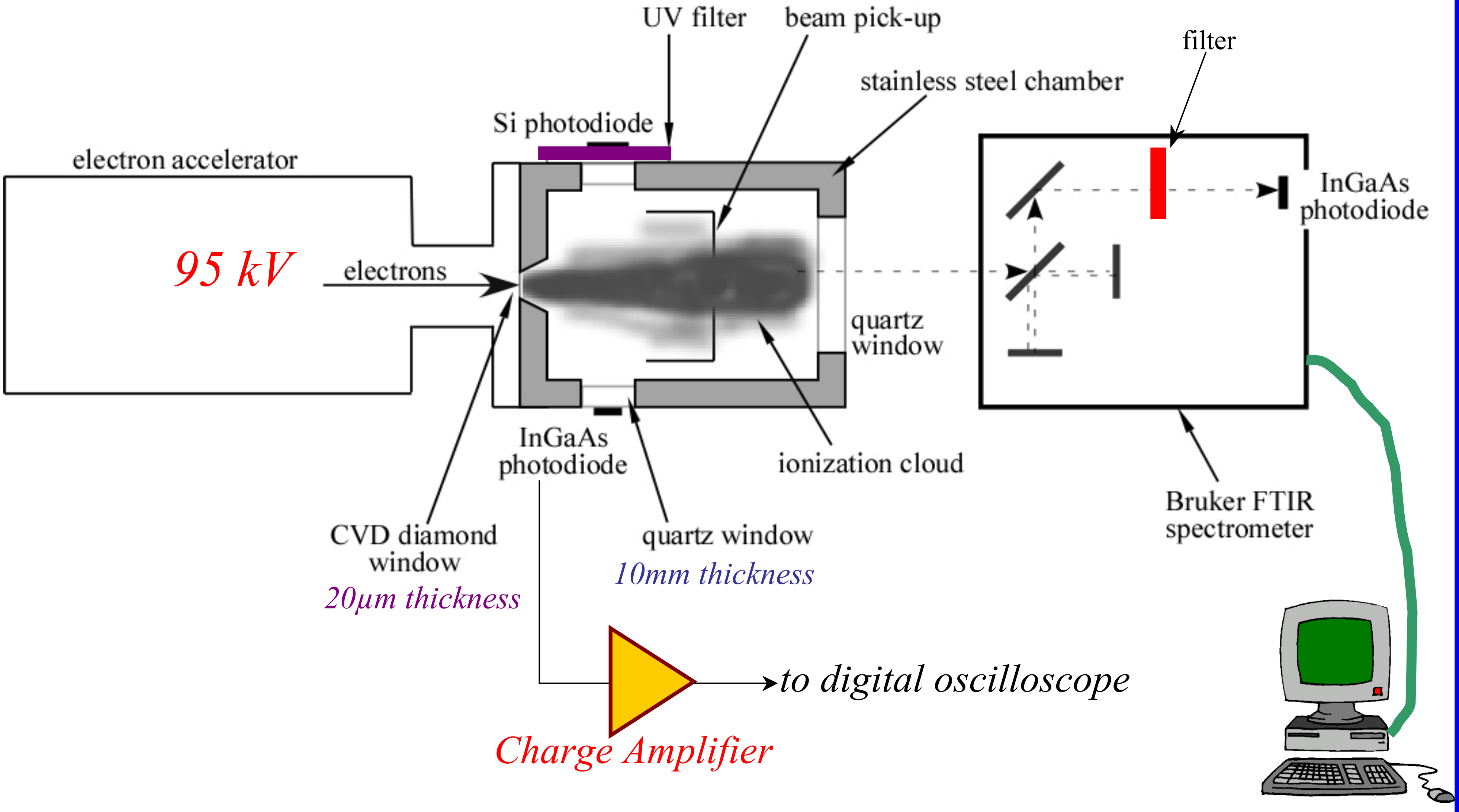


- The ultimate goal of the NIR fluorescence is to increase a lot the observable event rate.

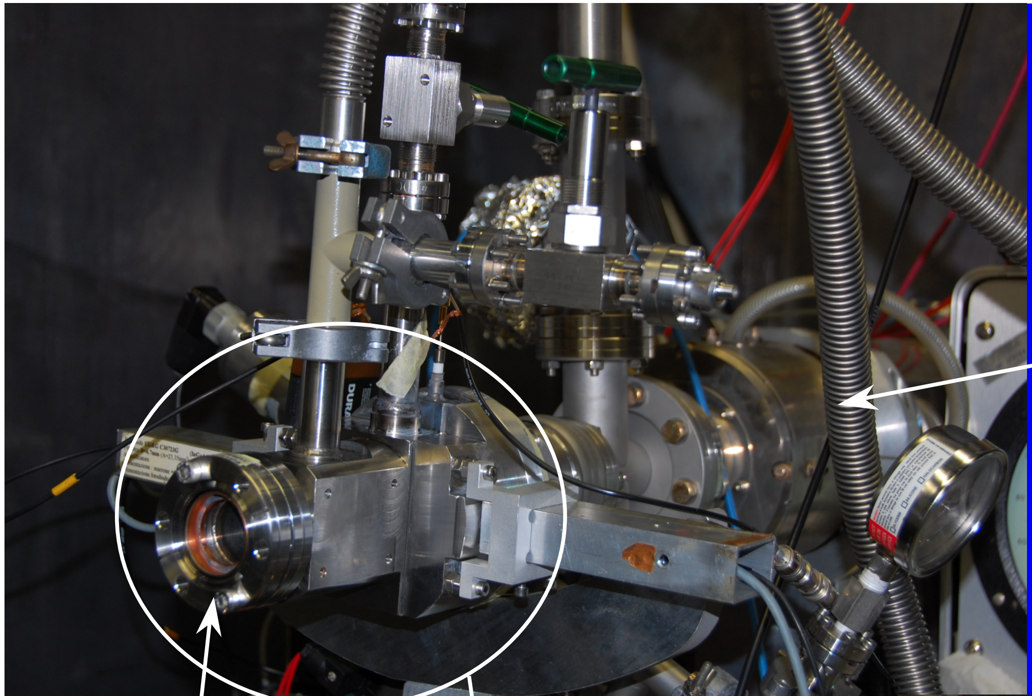
Experimental measurements

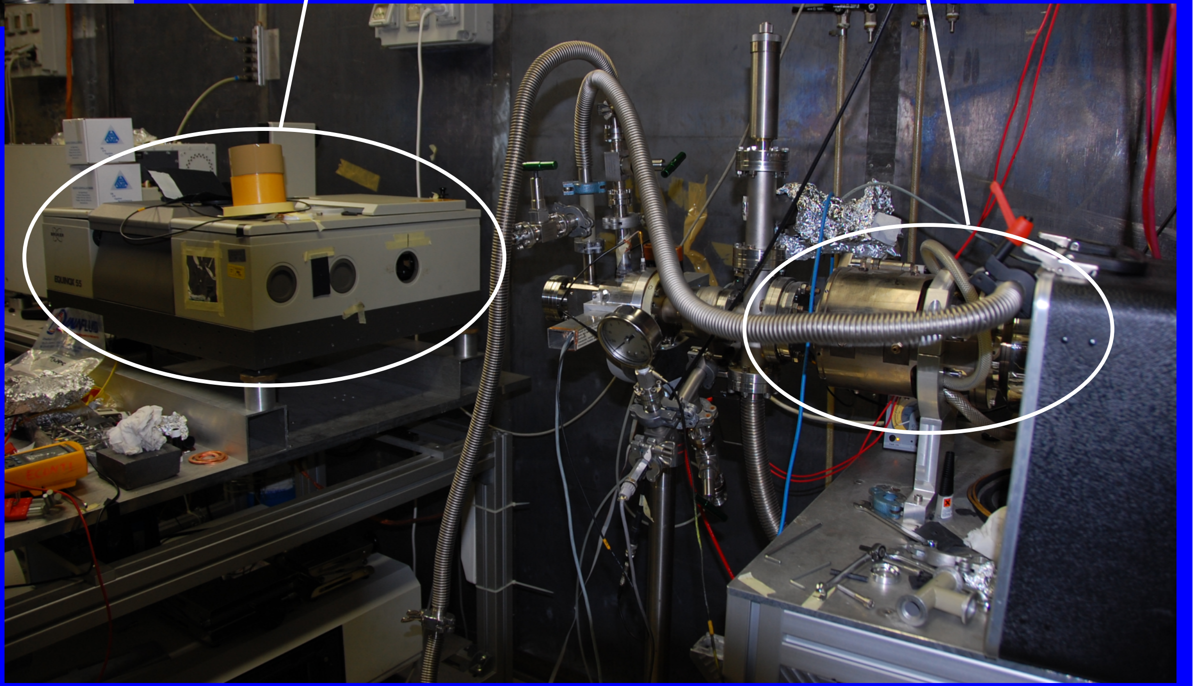
see the paper:
E.Conti, G.Sartori, G.Viola
“Measurement of the near-infrared fluorescence of the air for the detection of ultra-high-energy cosmic rays”
accepted for publication in Astrop. Phys.,
available on arxiv at http://arxiv.org/abs/1008.0329

Experimental setup



software OPUS 5.5





electron accelerator

Bruker FTIR spectrometer

gas chamber

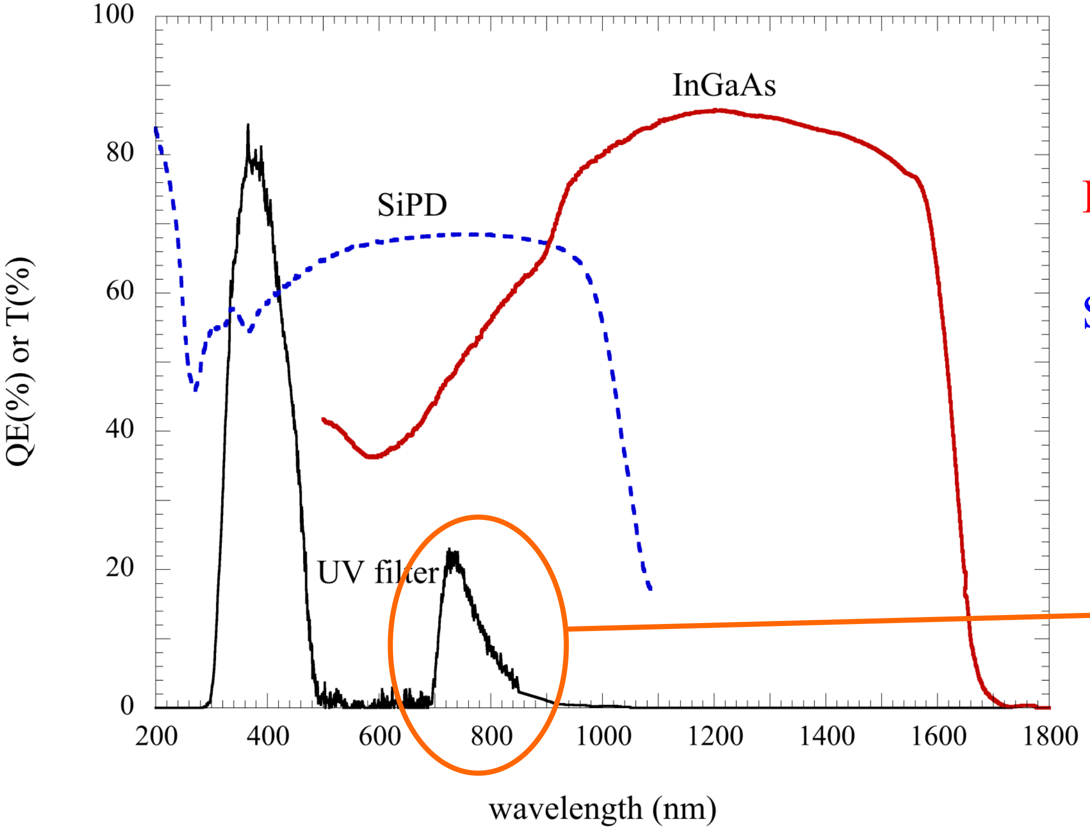
exit quartz window

Experimental details

- Electrons are accelerated at *95 keV* by an electron gun, operating in pulse mode (*300 μs* duration, *50 Hz* repetition rate).
- Electrons cross a *20μm* thick CVD diamond window and enter the gas chamber (volume *300* cm^3).
- NIR light is detected by InGaAs photodiodes.
- UV light is detected by a Si photodiode which has a UV filter in front.
- **Light yield** is obtained by comparing the NIR signal with the known UV signal.
- **Spectra** recorded using a Fourier Transform Infrared (FTIR) Spectrometer.
  It has a He-Ne laser (*632nm*) to measure/control moving mirror.
  Longpass filter (cutoff *780 nm*) to cut laser light which reaches the PD.
- Useful spectrum range: *800 - 1650 nm*.
- Gas at room temperature and atmospheric pressure from certified bottles, purity *5-10 ppm*.
  Flux = *0.2 l/min* .
- Beam pick-up, readout by charge preamplifier, for beam monitoring and normalization.

Photodetectors

- InGaAs photodiode (for NIR) by Judson, $\Phi = 5\ mm$, cooled by built-in Peltier at $-40\ ^{o}C$.
- Si photodiode (for UV) by Hamamatsu, $10x10\ mm^2$.
- Each PD is readout by a charge preamplifier.
- The Si and InGaAs placed on the chamber look **exactly** at the same gas region, few cm^3.



InGaAs QE above 80% from *1.1* to *1.5 μm*

Si QE ≈ 55% from *300* to *400 nm*

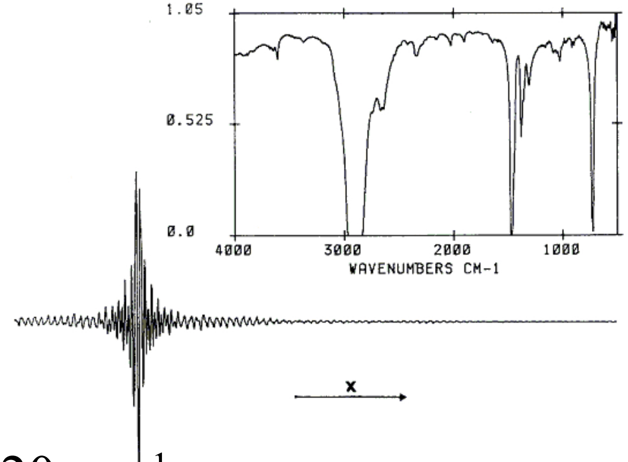
In this region, the UV light output is negligible

Fourier Transform Spectrometer

- The FTIR spectrometer is a two-arm Michelson interferometer with a moving mirror. You measure the interference between the two light beams as a function of the position *x* of the moving mirror. This figure is called *interferogram*.
- The Fourier transform of the interferogram gives the spectrum as a function of the *wavenumber* $k = 1/\lambda$.

  Then

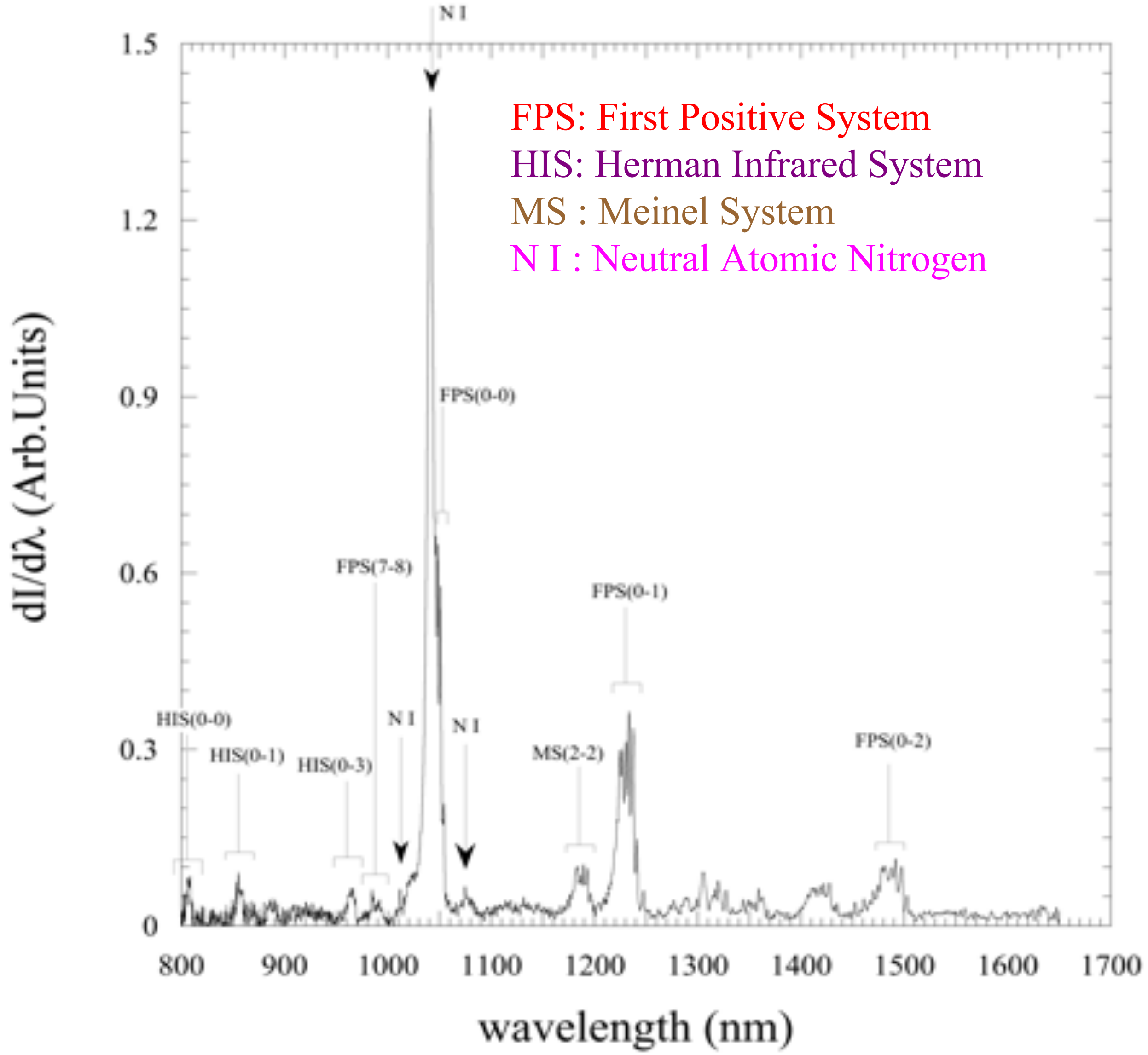
$$\frac{dI}{d\lambda} = \frac{dI}{dk}\frac{dk}{d\lambda} = \frac{1}{\lambda^2}\frac{dI}{dk}$$



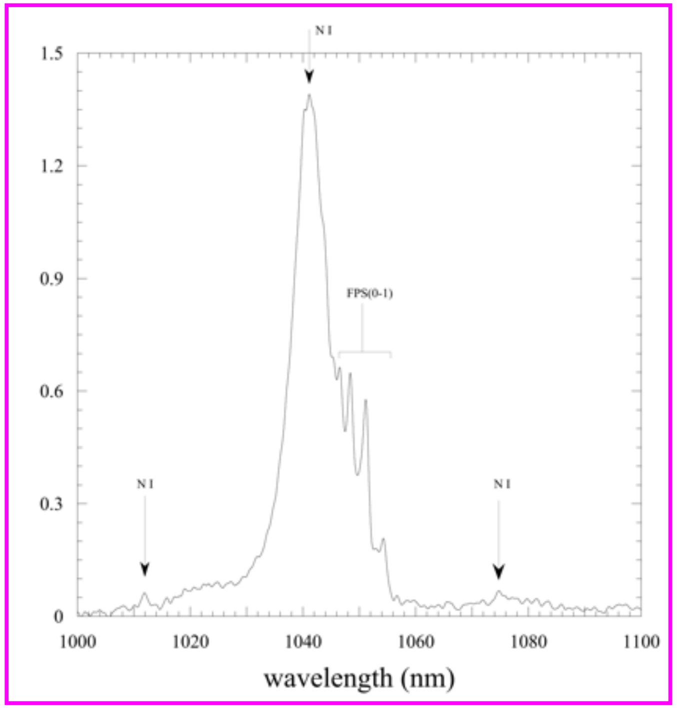
- Spectrometer resolution δk on k is set between 5 and 20 cm^{-1}.
- Note that the resolution $\delta\lambda$ on λ is not constant: $\delta\lambda = \lambda^2\, \delta k$.
- $\delta k = 5\ cm^{-1}$ corresponds to $\delta\lambda = 0.5\ nm$ @ $\lambda = 1 \mu m$.

  However, final resolution is worse because of the low spatial coherence of the light source and of interferogram-to-spectrum conversion.
- To reduce fluctuations, final spectra are the average of many different spectra.

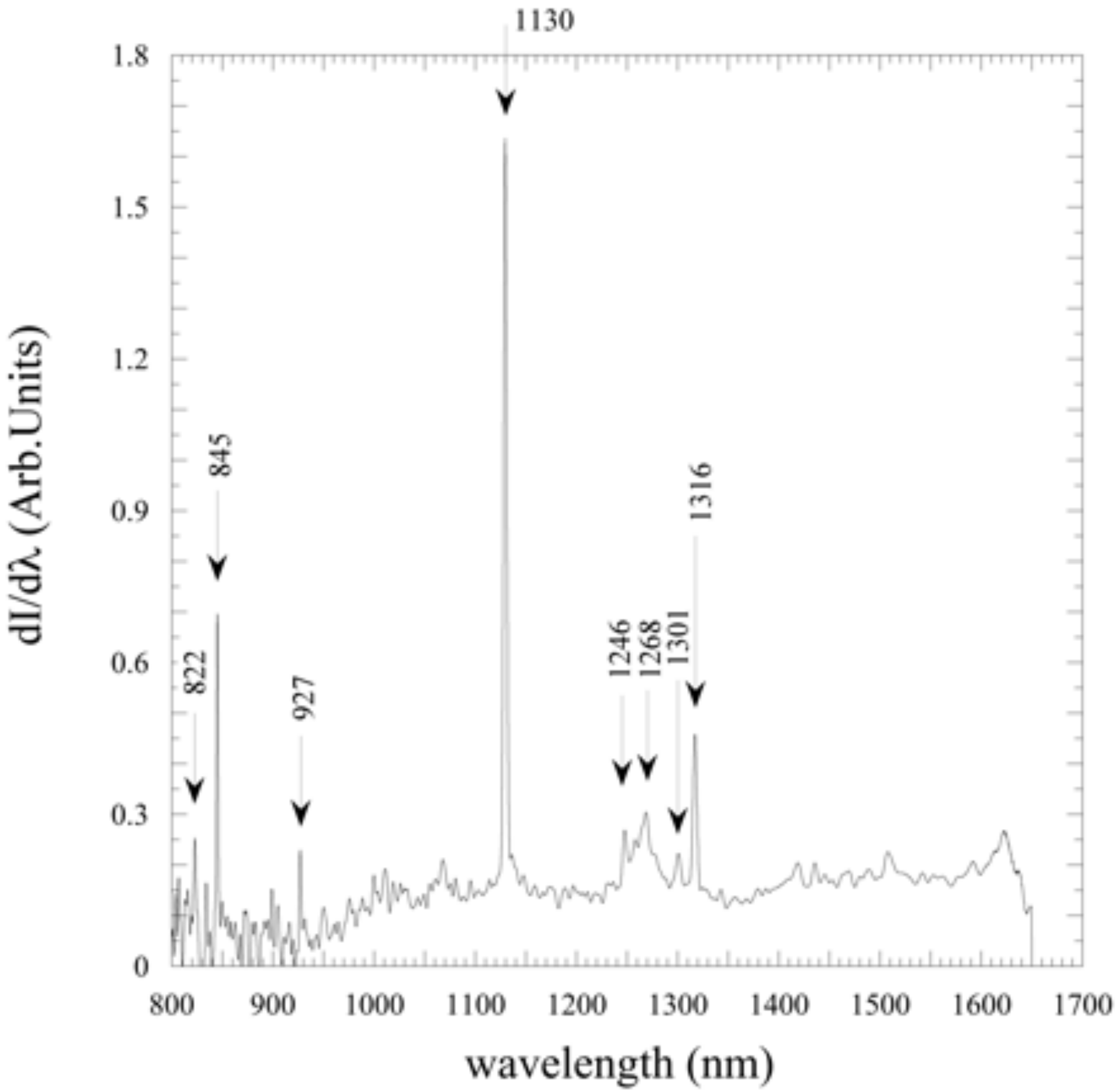
Results: N_2 spectrum



- Dominated by the band at *1040-1050 nm*: unresolved atomic lines N I + FPS (0-0)
- Second more intense band is at *1230 nm*: FPS (0-1)

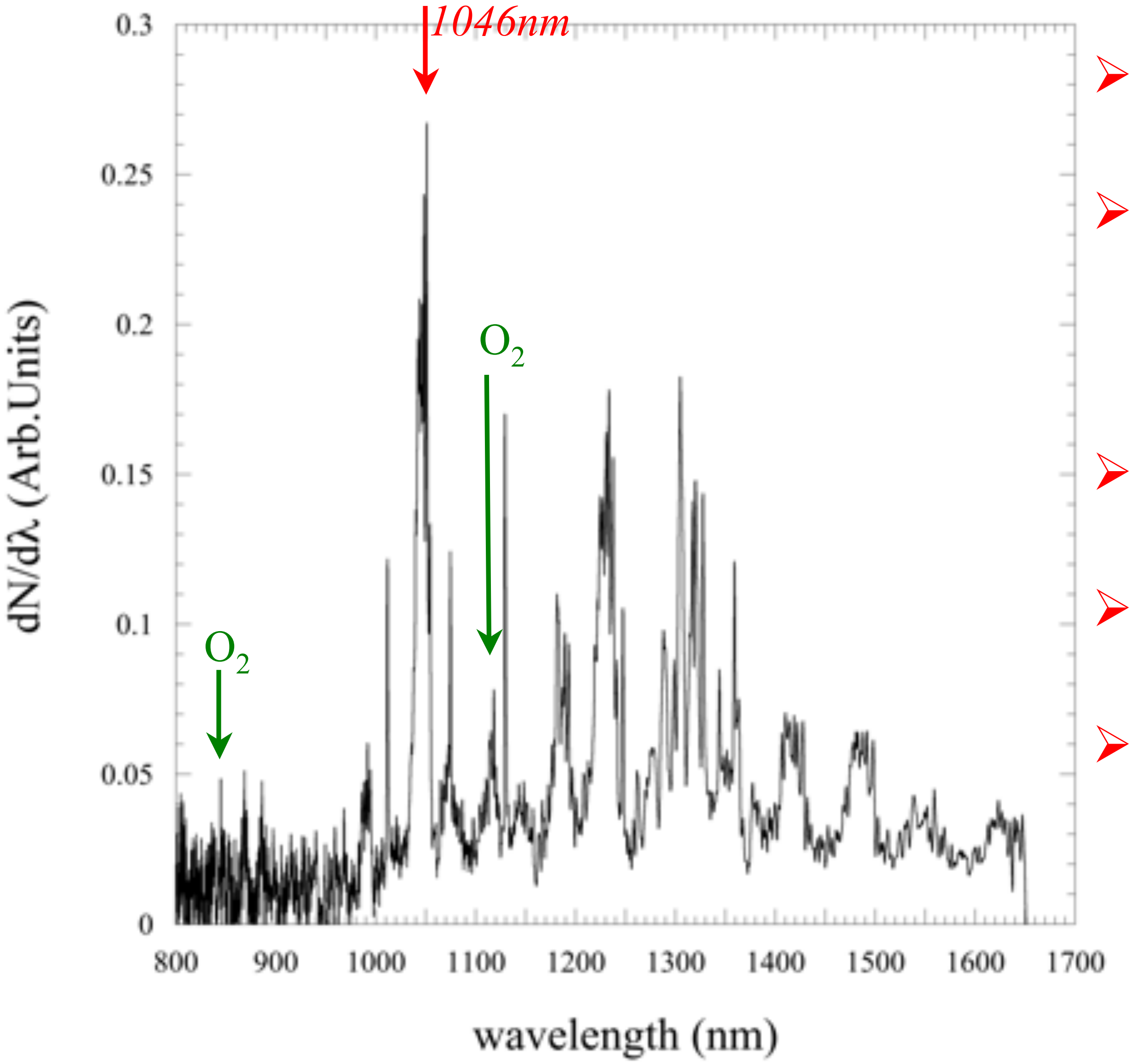


Results: O_2 spectrum



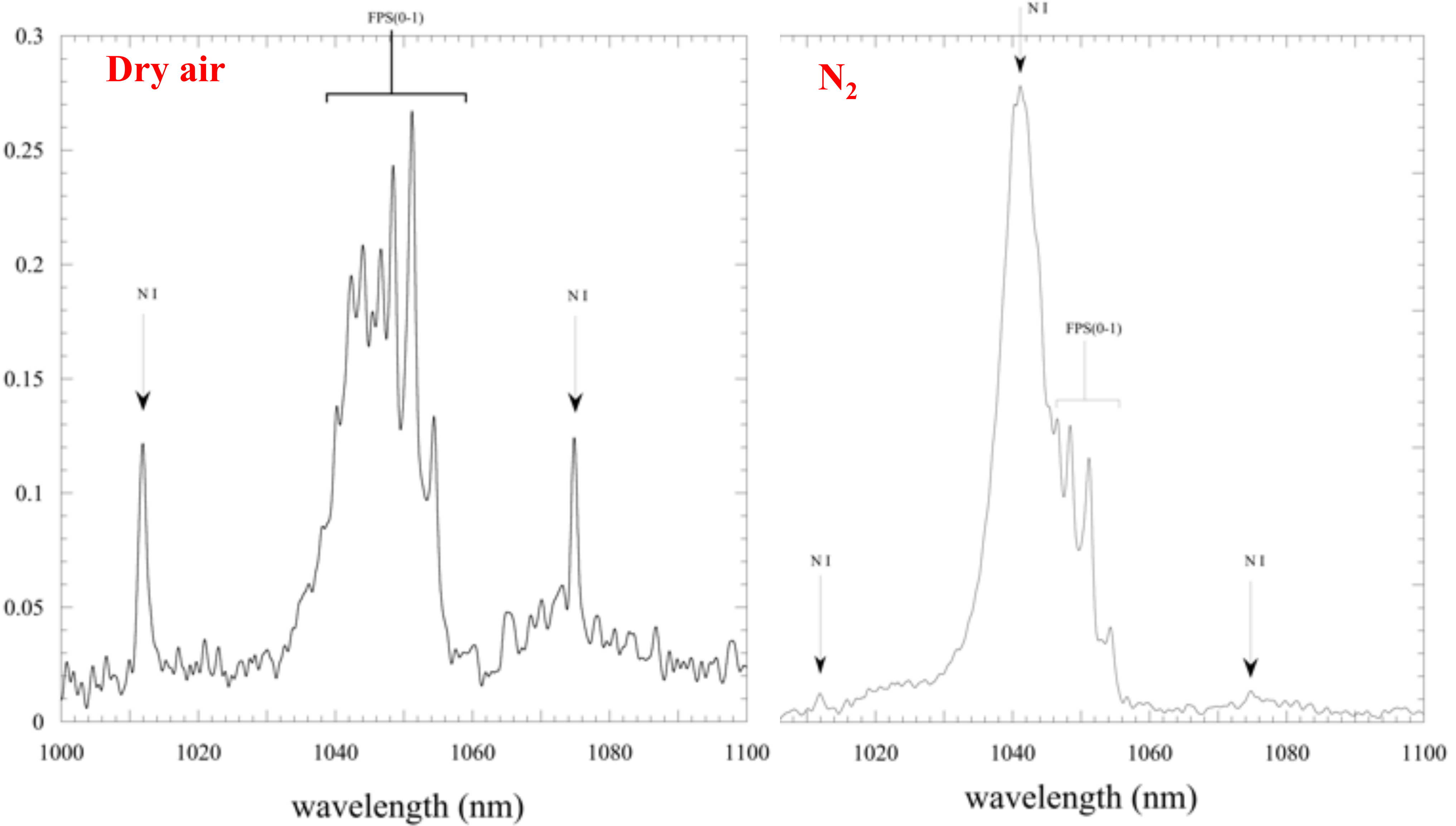
- ★ Oxygen has a low light yield because transitions from most of the excited states to ground state are strongly forbidden.
- ★ Only 1 molecular transition @ *1268 nm*, the well-known $^1\Delta_g \rightarrow {}^3\Sigma_g$
- ★ Other lines are from O I and O II.

Results: Dry Air spectrum



- **Dry Air = *80%* N$_2$ + *20%* O$_2$**
- Spectrum is not simply the weighted sum of the single gas spectra, because of molecular/atomic interactions.
- Main structure at *1046 nm* (vs. *1040 nm* N$_2$).
- N I atomic lines more intense than pure N$_2$.
- Weak O$_2$ lines @ *845 nm* and *1130 nm*.

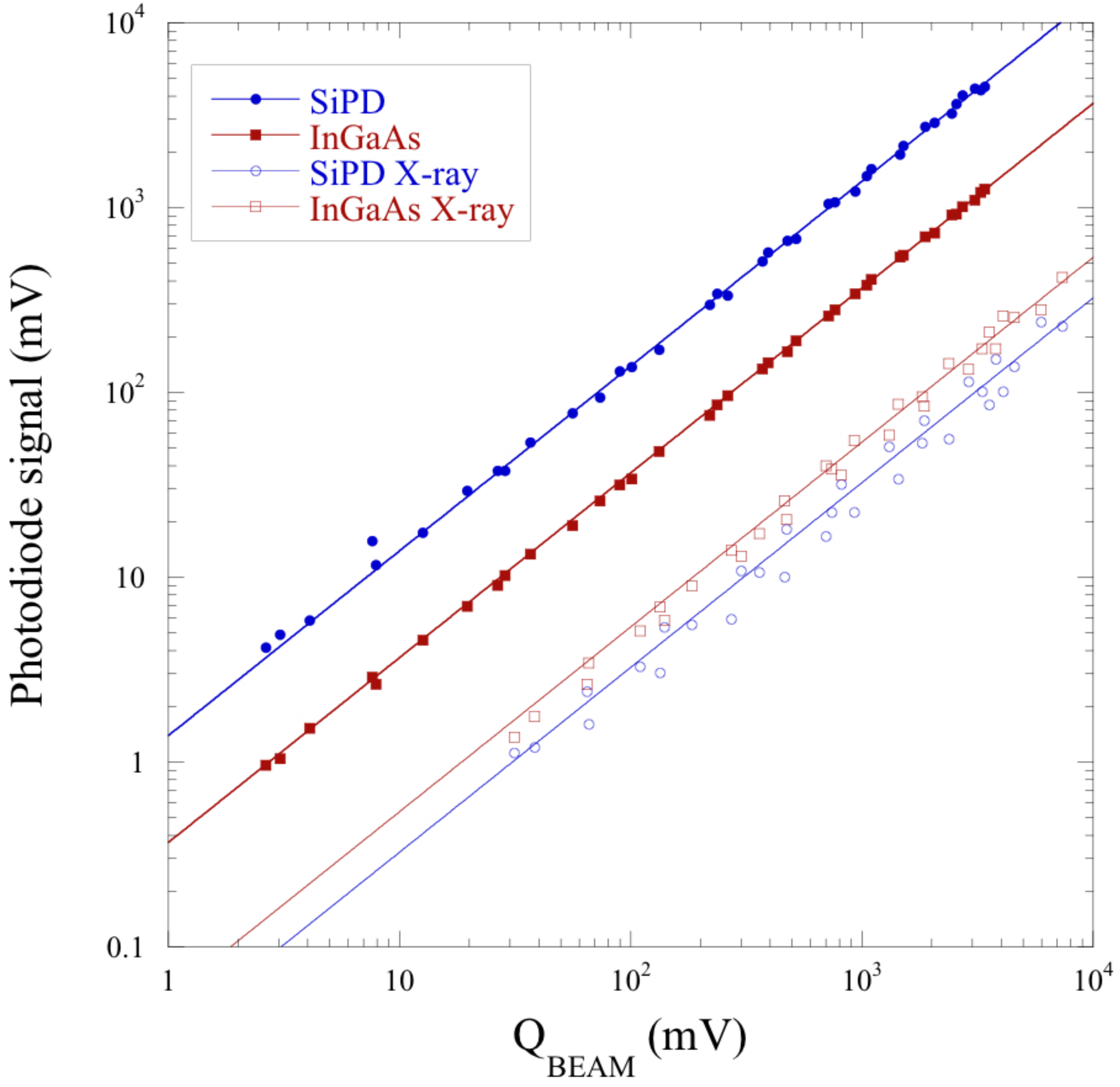
Dry Air Vs. N_2 spectrum



Light yield measurement

- The **NIR light yield Y_{IR}** is obtained by comparing the NIR signal of the InGaAs PD V_{IR} with the UV signal of the Si PD, V_{UV}, and knowing the **UV yield Y_{UV}** (from literature data).
- The strong assumption is that the two PDs are looking at the same amount of energy. In this way you don't have to know the energy. This is true by construction, since the detectors view the same region of gas.
  It is verified experimentally exchanging the position of the PDs and verifying that the signals do not change.
- X-Ray background must be measured and subtracted.
  A black paper foil is placed in front of the PDs to screen them from the light, but not from the X-rays. Then we measure the signals.
- V_{UV} and V_{IR} measured as a function of the beam intensity, measured by the charge collected on the pick-up, Q_{BEAM}, to verify whether saturation or non-linear effects, due to the high ionization density, are present.

Experimental data



- Each point is the average of hundred signals, performed by the digital oscilloscope.
- Data are fitted with the function $y = \alpha \cdot x$
- V_{IR} and V_{UV} are proportional to Q_{BEAM} over 3 orders of magnitude ==> there are not non-linear or saturation effects.
- The X-ray contribution to the total signal is :

  2% for SiPD

  17% for InGaAs

Data analysis

➔ $$V_{IR,UV} = A_{IR,UV} \cdot \mathrm{Q}_{\mathrm{BEAM}} + B_{IR,UV} \cdot \mathrm{Q}_{\mathrm{BEAM}}$$

where:

- → $B_{IR,UV}$ are constants and are related to the X-ray background;
- → $A_{UV} = \mathrm{C} \cdot \mathrm{Y}_{\mathrm{UV}} \cdot \Omega_{\mathrm{UV}} \cdot \mathrm{G}_{\mathrm{Si}} \cdot <\varepsilon_{\mathrm{UV}}>$
- → $A_{IR} = \mathrm{C} \cdot \mathrm{Y}_{\mathrm{IR}} \cdot \Omega_{\mathrm{IR}} \cdot \mathrm{G}_{\mathrm{InGaAs}} \cdot <\varepsilon_{\mathrm{IR}}>$

C = constant, Ω = PD solid angle, G = charge preamplifier gain, <ε> = average quantum efficiency ε(λ) (with filter transmission curve T(λ) when present) weighted by the fluorescence spectrum S(λ) :

$$<\varepsilon> = \frac{\int \varepsilon(\lambda) \cdot T(\lambda) \cdot S(\lambda) d\lambda}{\int S(\lambda) d\lambda}$$

➔ Therefore $$Y_{IR} = Y_{UV} \cdot \frac{A_{IR}}{A_{UV}} \cdot \frac{\Omega_{UV}}{\Omega_{IR}} \cdot \frac{G_{SiPD}}{G_{InGaAs}} \cdot \frac{<\varepsilon_{UV}>}{<\varepsilon_{IR}>}$$

Results

- With our numbers $\Omega_{UV}/\Omega_{IR} = 4.19 \pm 0.15$ $G_{SiPD}/G_{InGaAs} = 0.500 \pm 0.006$

  $< \varepsilon_{UV} >= 0.35$ $< \varepsilon_{IR} >= 0.80$

  $A_{IR}/A_{UV} = 4.19 \pm 0.15$

  we obtain

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

- For the absolute light yield we need Y_{UV}. We take the (weighted) average of all measurements so far in the range *300-400 nm*, obtaining

$$Y_{UV} = 19.88 \pm 0.51 \; ph/MeV$$

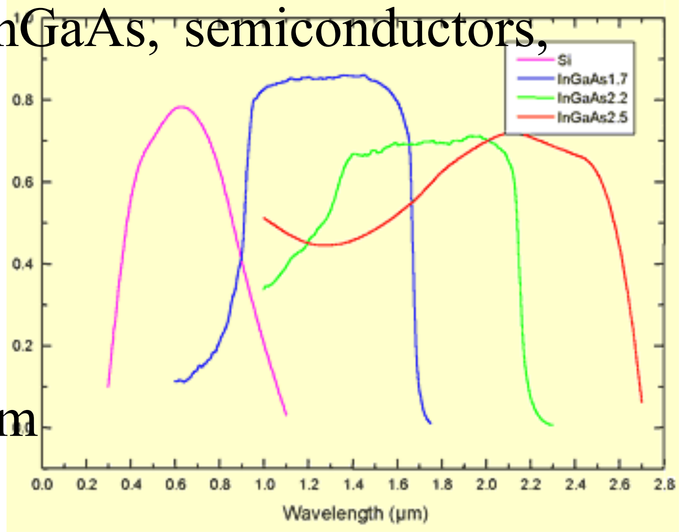
  Therefore

$$\boxed{Y_{IR} = 4.17 \pm 0.53 \; ph/MeV}$$

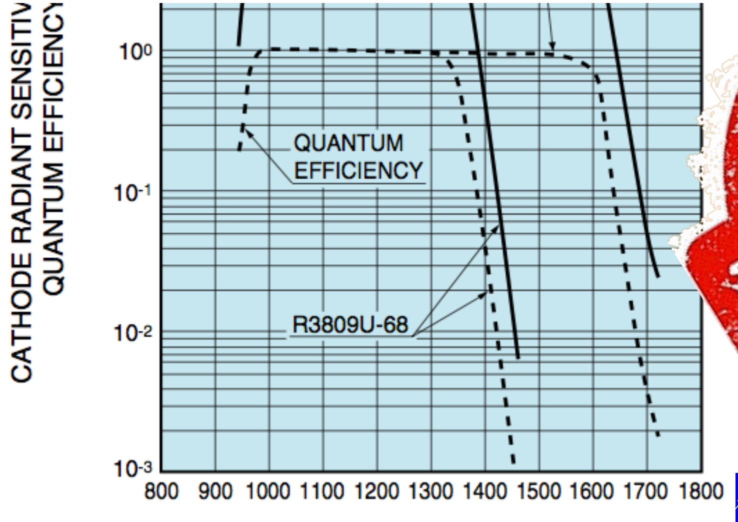
On the detection of NIR radiation

Range 0.8 - 2 μm

- The detectors with the highest QE (>80%) are the InGaAs, semiconductors, which can extend down to 2.6 μm. But:
  - small area (< 1 cm^2);
  - no multiplication;
  - need low noise electronics.
- Avalanche InGaAs exist, Gain ~ 10^2, diameter ≤ 200μm



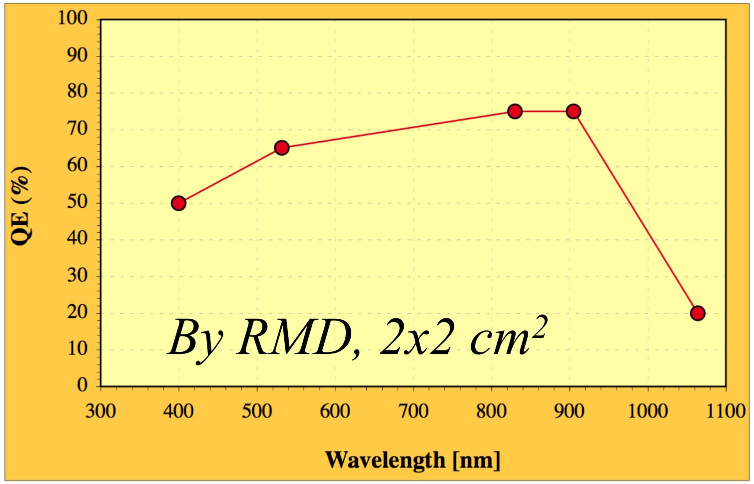
- Photomultiplier: Hamamatsu produce PMTs with QE ~ 1% till 1.6 μm. Gain ~ 10^4-10^6, but small sensitive area and need LN_2.



REJECTED

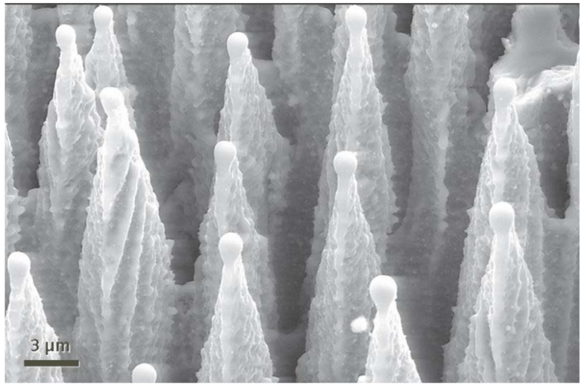
Silicon

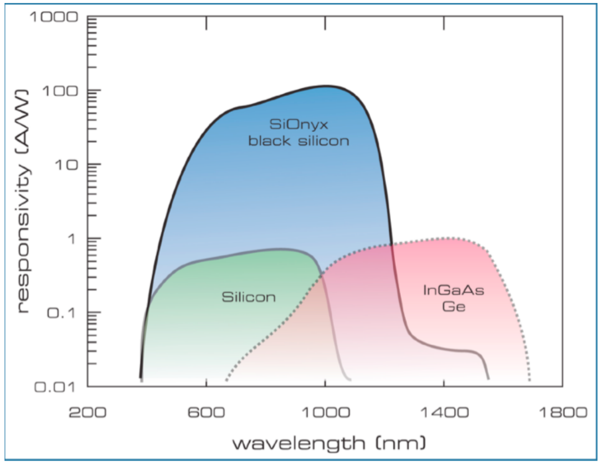
- Si extends to 1.1µm because of the 1.1eV bandgap. After it becomes transparent. Si APD, gain ~10^3, area ≥ 1 cm^2. Decent QE @ 1000-1100 nm.



QE ≈ 30% @ 1040nm

- R&D in progress with different techniques to extend QE and/or increase QE @ 1.1µm (for example, "Black silicon" by SiOnyx)



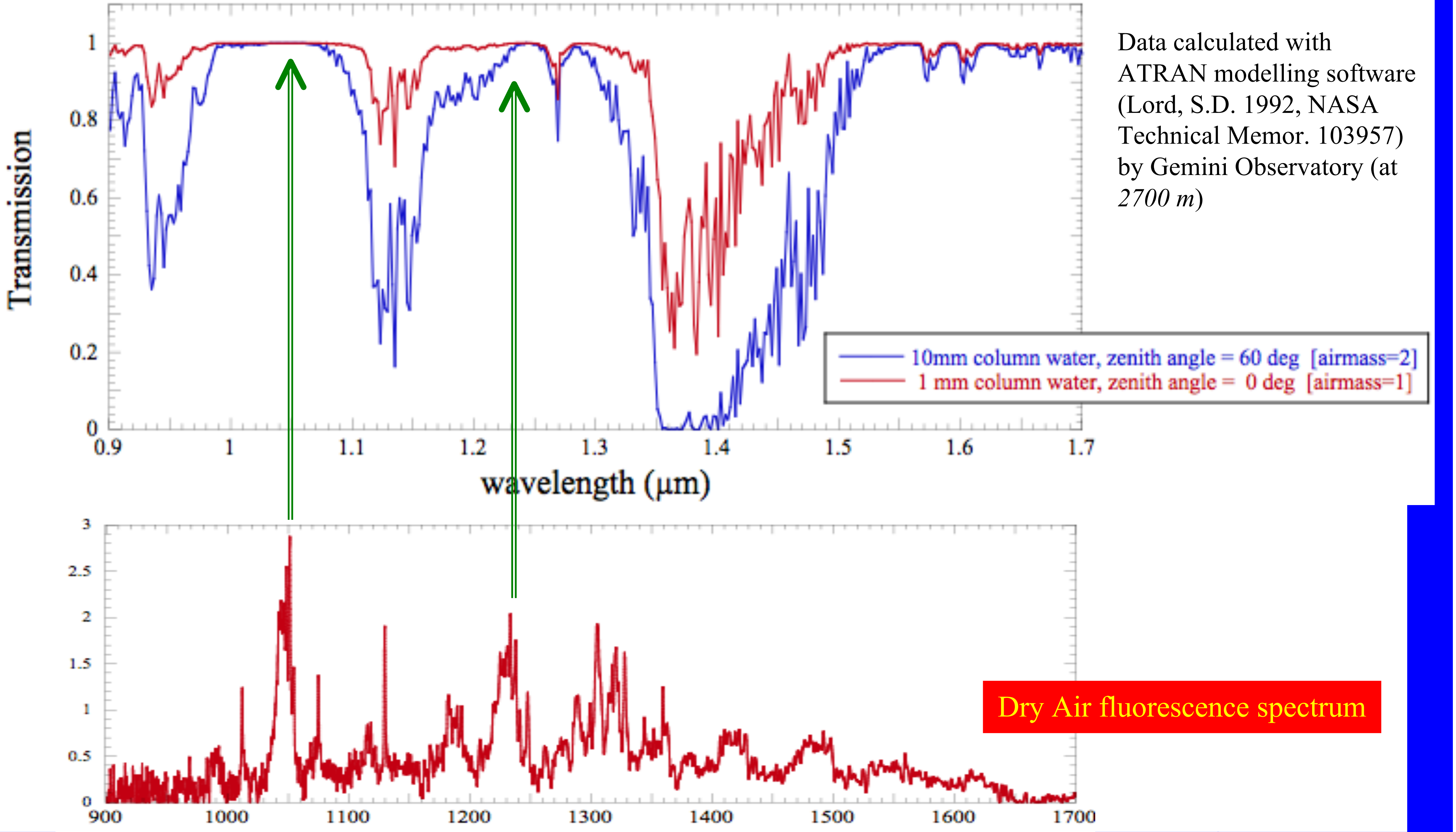


summarizing …

- 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.
- TODAY, the only viable solution is the Si APD.
  This means to restrict the detection of the NIR fluorescence at $1.1\ \mu m$.
- Light yield for $\lambda \leq 1.1\ \mu m$ is 30% of the total.
- However, technological research is advancing and make us optimistic that in a near future we can use better devices.
- This is a technological limit. Don’t concentrate (only) to it.

Let’s see what are the intrinsic limits and problems of this novel approach.

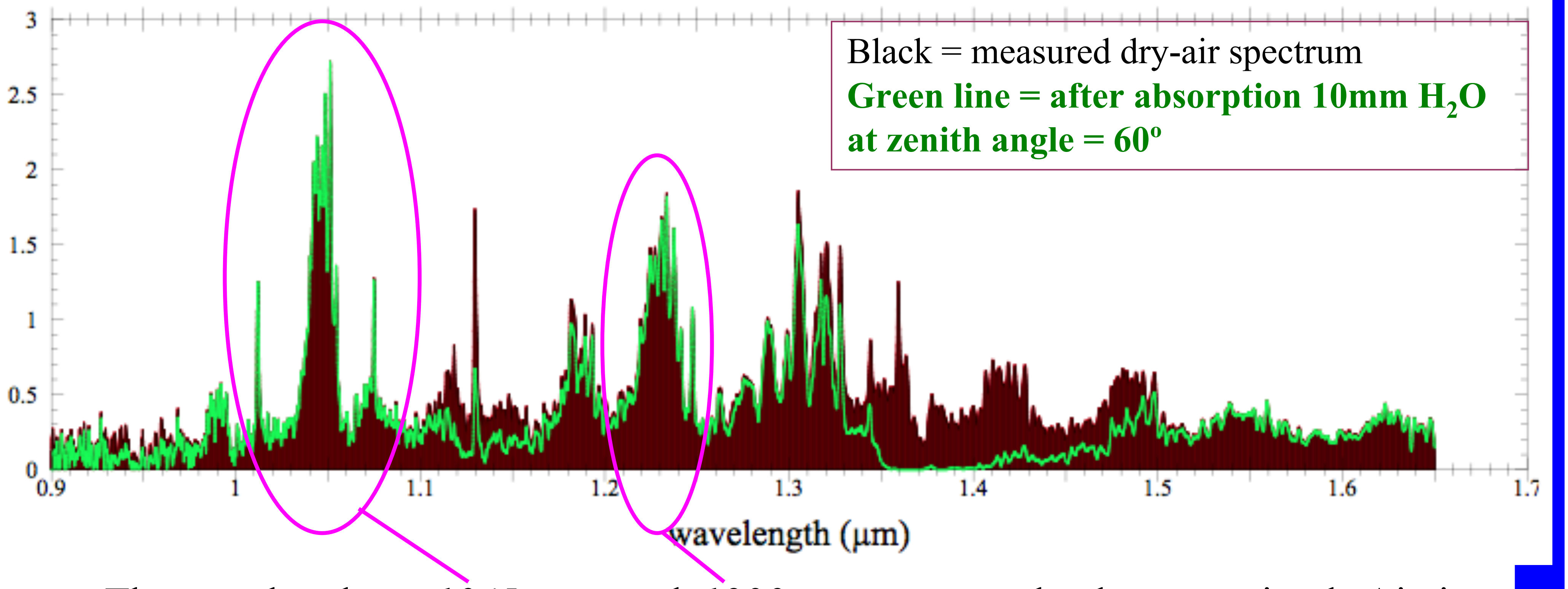
Atmosphere transmission



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

Dry Air fluorescence spectrum

Spectrum after absorption



Black = measured dry-air spectrum

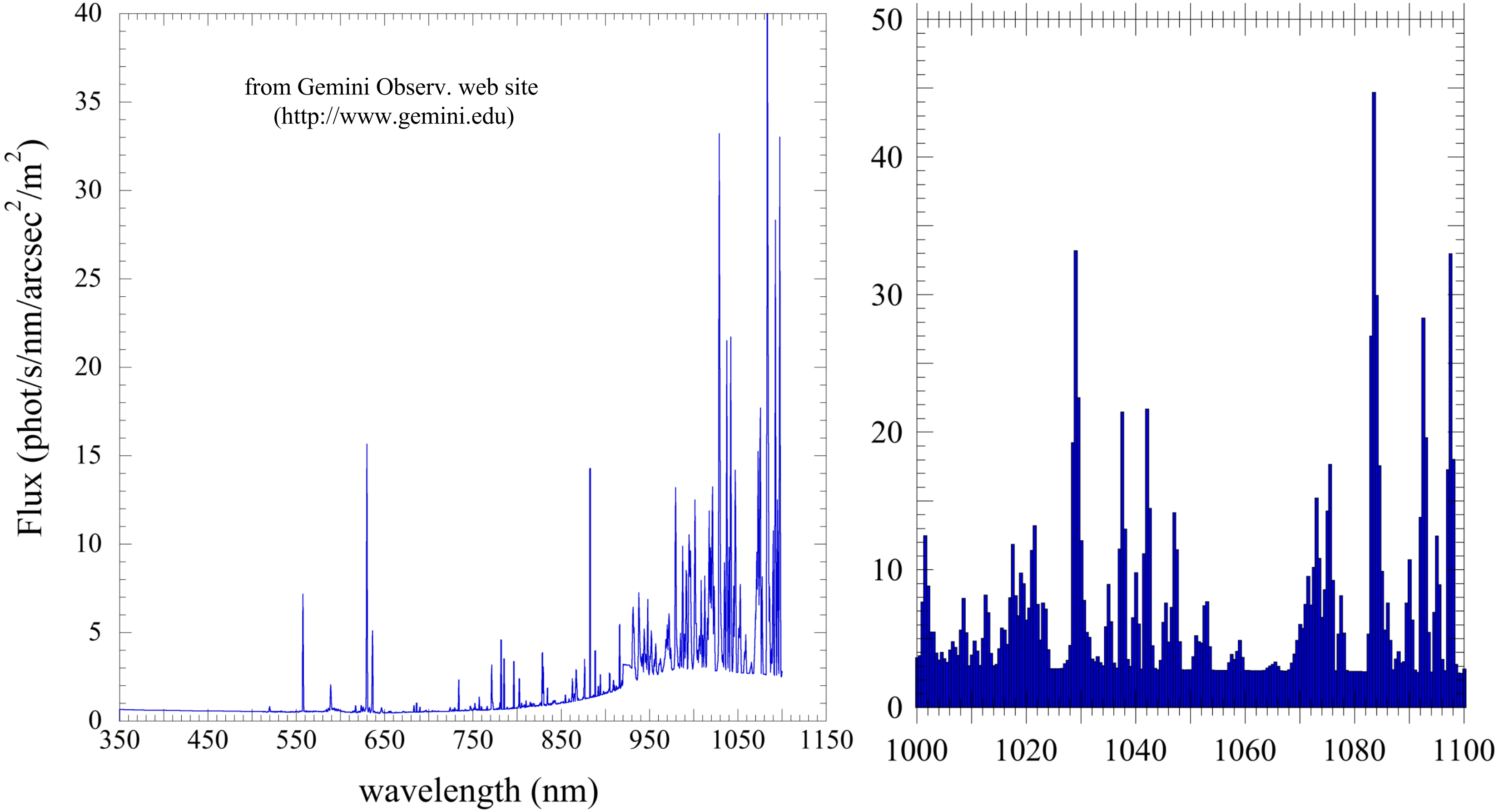
Green line = after absorption 10mm H_2O at zenith angle = 60º

- 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 !
  ==> the limit on the detection of a UHECR is NOT given by the atmosphere transmission.

The night sky brightness

NIR sky brightness

- 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).



NIR vs. UV sky noise

- 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

- The Signal-to-Noise ratio S/N is $\dfrac{S}{N} = \dfrac{N_{ph}^{signal}}{\sqrt{N_{ph}^{noise}}}$
- The ratio of the S/N NIR/UV is

$$\frac{\left(S/N\right)_{NIR}}{\left(S/N\right)_{UV}} = \frac{N_{NIR}^{signal}}{N_{UV}^{signal}}\sqrt{\frac{B_{UV}}{B_{NIR}}} = \frac{Y_{NIR}}{T_{UV}\cdot Y_{UV}}\sqrt{\frac{B_{UV}}{B_{NIR}}} \approx 1\cdot\sqrt{1/10} \approx 1/3$$

what you lose in light yield you gain in atmosph. transmission

coincidence method

- The Si PD detects only the first band at *1045 nm*, then it is transparent.
- After it, it is possible to place another detector, for example an InGaAs PD, with detects the second band at *1230 nm*.
- The coincidence of the two signals reduces the random noise and establishes that the event is good.
  You gain in reducing the noise paying in terms of energy threshold.

- A similar device already exists, the so-called *two-color detector,* for flame or thermal radiation measurement (for example, Hamamatsu K3413-09).

Conclusions

Conclusions

- We have measured for the first time the Near Infrared fluorescence of the air in the range *800-1700 nm*.
- The air fluorescence spectrum is characterized by several bands and lines.
  The most interesting for the detection of UHECRs is the band @ *1045 nm* (detectable with Si devices) and the band at *1230 nm*.
- The NIR fluorescence light yield is about 1/5 of the UV yield.
  Limiting the detection band at *1100 nm* (Si QE limit), the yield decrease to about 1/15 of the UV yield.
- The water absorption of the NIR radiation is very small at those wavelength ==> very long light extinction length ==> event rate not depends on atmosphere transparency
- Drawbacks:
  - *technological*: devices for NIR detection not comparable to UV PMT.
  - *intrinsic :* (slighly) lower Signal-to-Noise ratio.
- Nevertheless, the reward in case of success is exciting, to increase the UHECR observation rate by several order of magnitude ! We think that such a goal justify us to pursue this possibility.