# Introduction to Air Shower Observation using Microwave Radiation

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***Acknowledgments:*** *Radomir Smida, Felix Werner,*
*and colleagues from the Auger and KASCADE-Grande collaborations*

Karlsruhe Institute of Technology

# Motivation

PHYSICAL REVIEW D **78,** 032007 (2008)

## Observations of microwave continuum emission from air shower plasmas

P. W. Gorham,[1] N. G. Lehtinen,[1,*] G. S. Varner,[1] J. J. Beatty,[2] A. Connolly,[3] P. Chen,[4] M. E. Conde,[5] W. Gai,[5] C. Hast,[4] C. L. Hebert,[1,+] C. Miki,[1] R. Konecny,[5] J. Kowalski,[1] J. Ng,[4] J. G. Power,[5] K. Reil,[4] L. Ruckman,[1] D. Saltzberg,[3] B. T. Stokes,[1,‡] and D. Walz[4]

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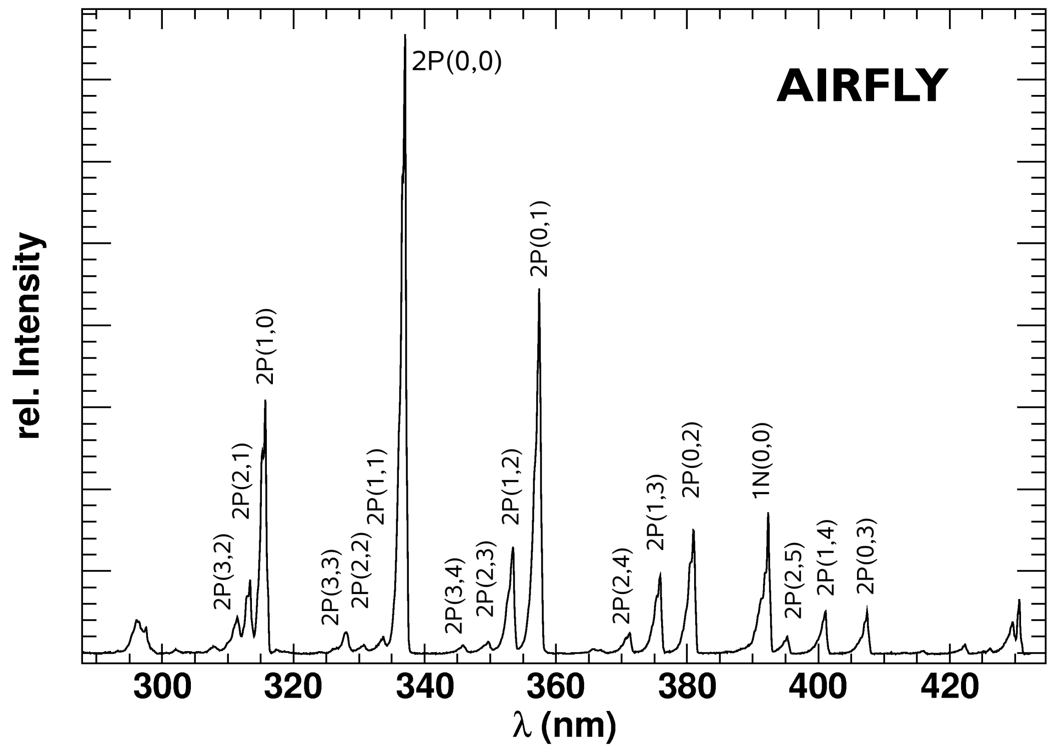
We investigate a possible new technique for microwave detection of cosmic-ray extensive air showers which relies on detection of expected continuum radiation in the microwave range, caused by free-electron collisions with neutrals in the tenuous plasma left after the passage of the shower. We performed an initial experiment at the Argonne Wakefield Accelerator laboratory in 2003 and measured broadband microwave emission from air ionized via high-energy electrons and photons. A follow-up experiment at the Stanford Linear Accelerator Center in the summer of 2004 confirmed the major features of the previous Argonne Wakefield Accelerator observations with better precision. Prompted by these results we built a prototype detector using satellite television technology and have made measurements suggestive of the detection of cosmic-ray extensive air showers. The method, if confirmed by experiments now in progress, could provide a high-duty cycle complement to current nitrogen fluorescence observations.

# Re-cap: shower detection using fluorescence light



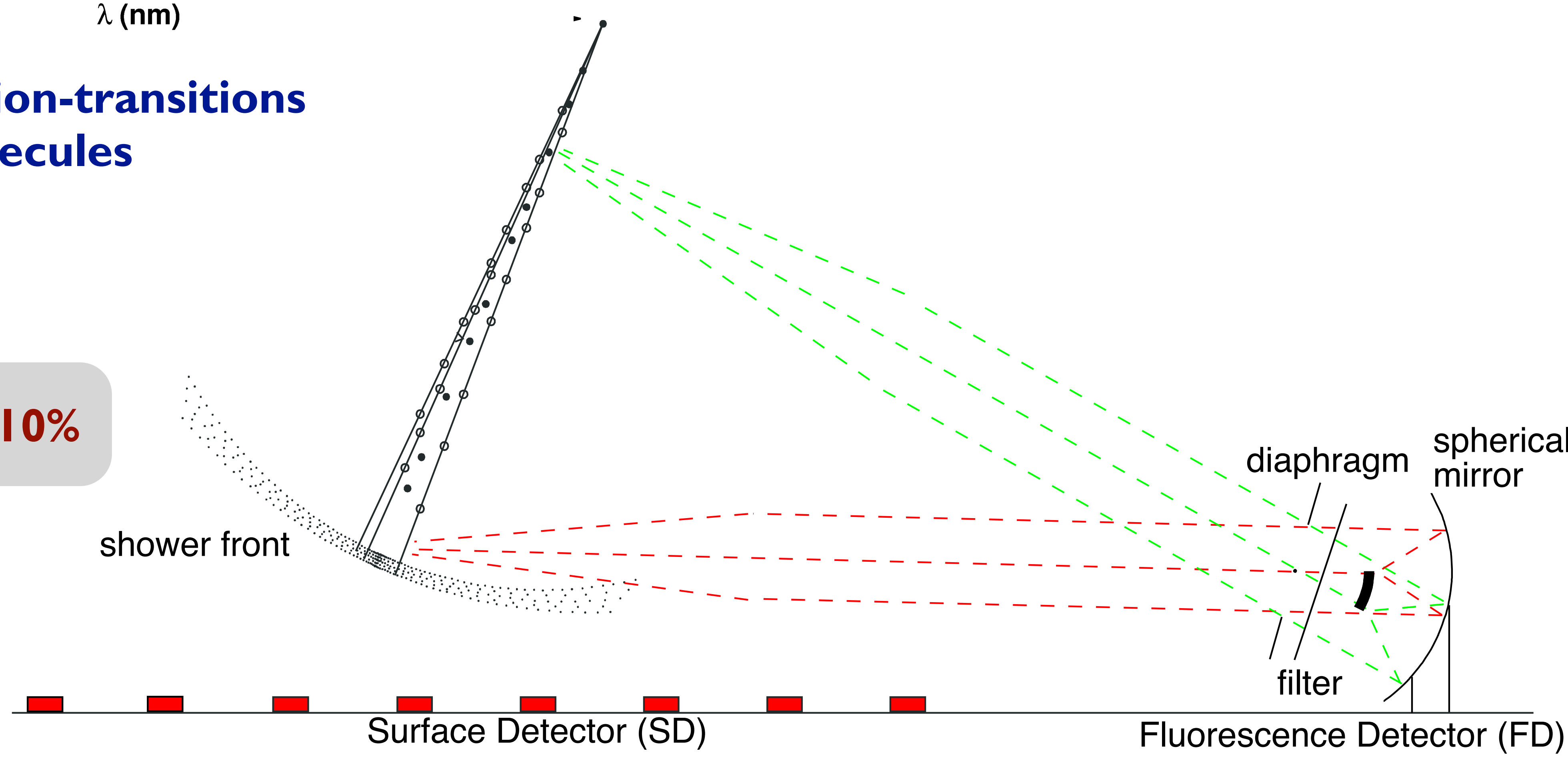

Fluorescence: molecular excitation of $N_2$, isotropic photon emission in UV ($E_\gamma \sim 3.7$ eV)

About 20 fluorescence photons emitted per MeV deposited ionization energy:

- $10^{-4}$ of deposited energy radiated off
- other radiation channels, possibly including microwave production?

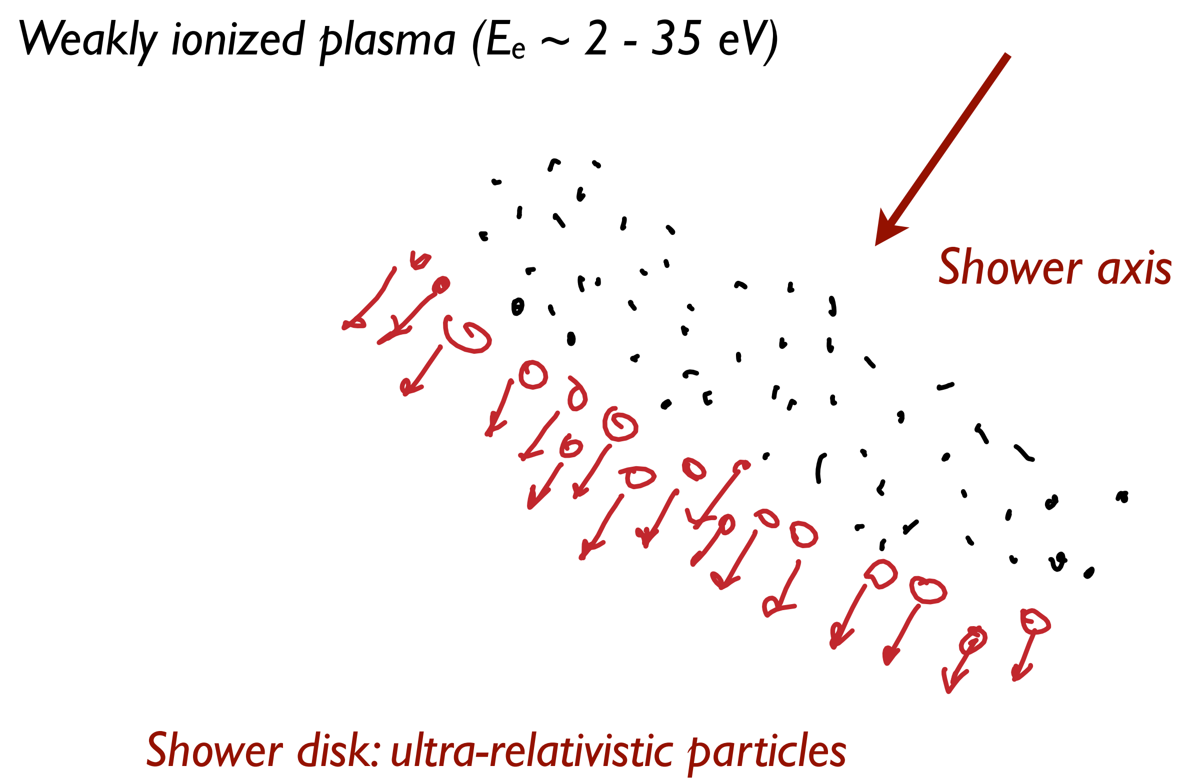
**Vibration/rotation-transitions of nitrogen molecules**

**Duty cycle ~10%**



# Radiation induced by extensive air showers

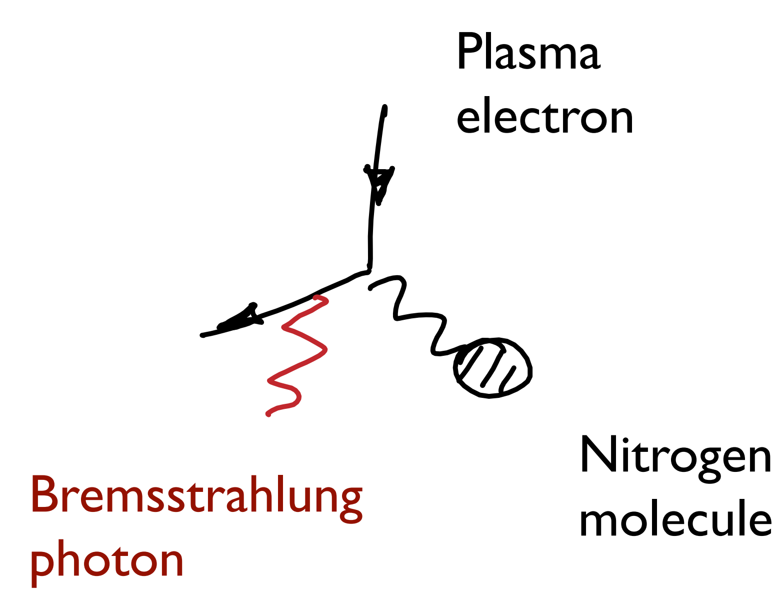
Passage of high-energy particles of shower disk through air produces ionized air




**① Excited/ionized nitrogen molecules:**
fluorescence radiation in UV and IR ranges

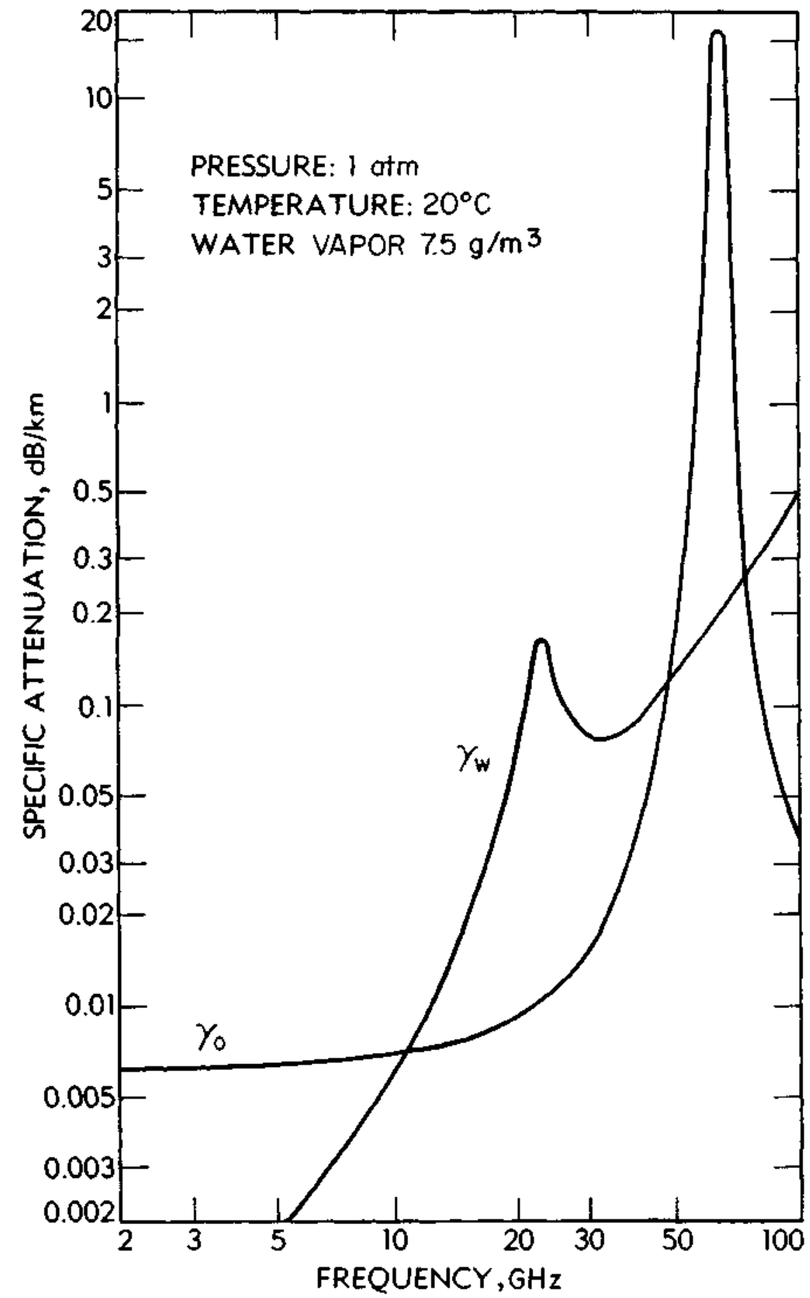
**③ Low-energy electrons (E ~10 eV):**
molecular bremsstrahlung in GHz range

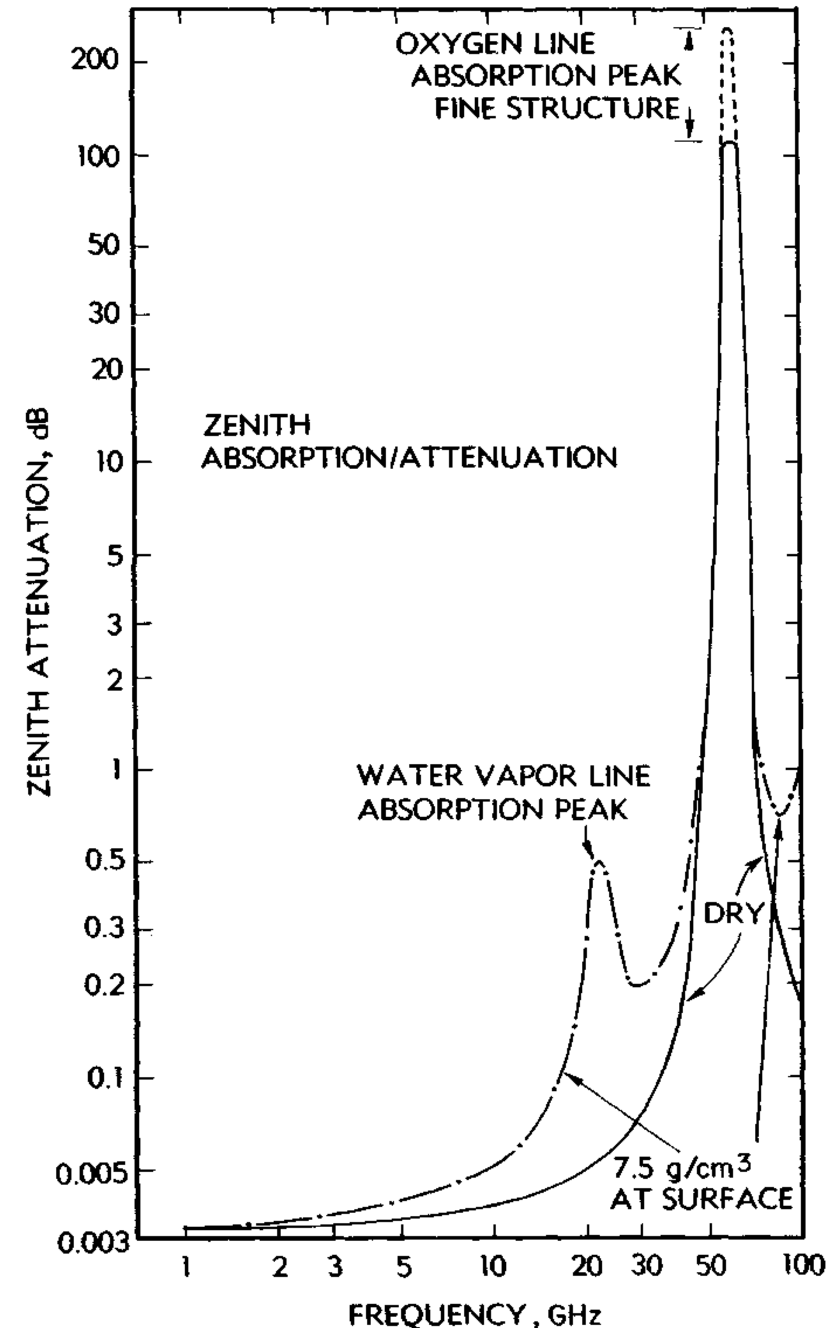
**② High-energy particles (E > 80 MeV):**
Geo-synchrotron & charge-excess radiation in MHz range



# Microwave attenuation in the atmosphere

Significant absorption only by oxygen and water vapor



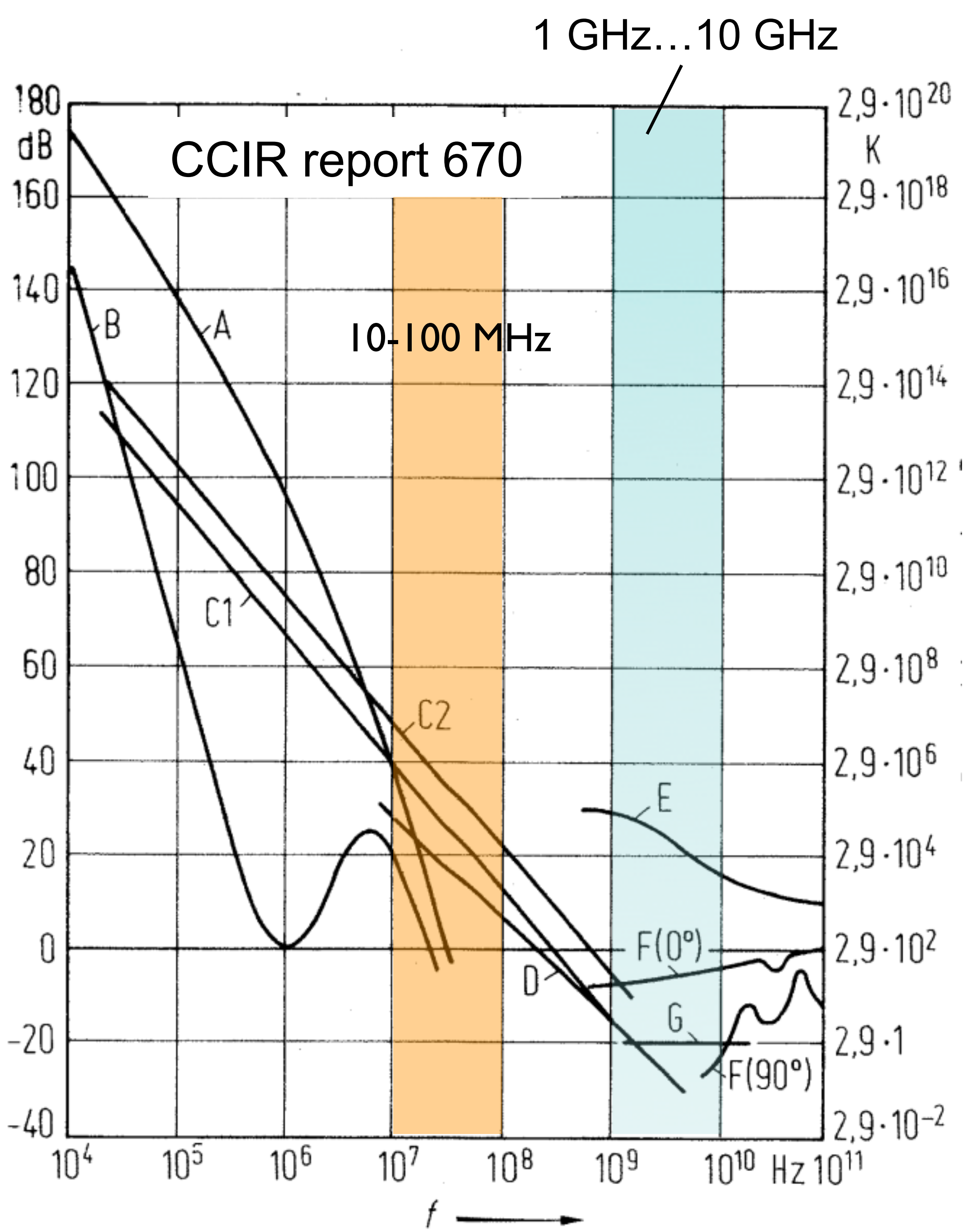




**Absorption in atmosphere very small (negligible)**

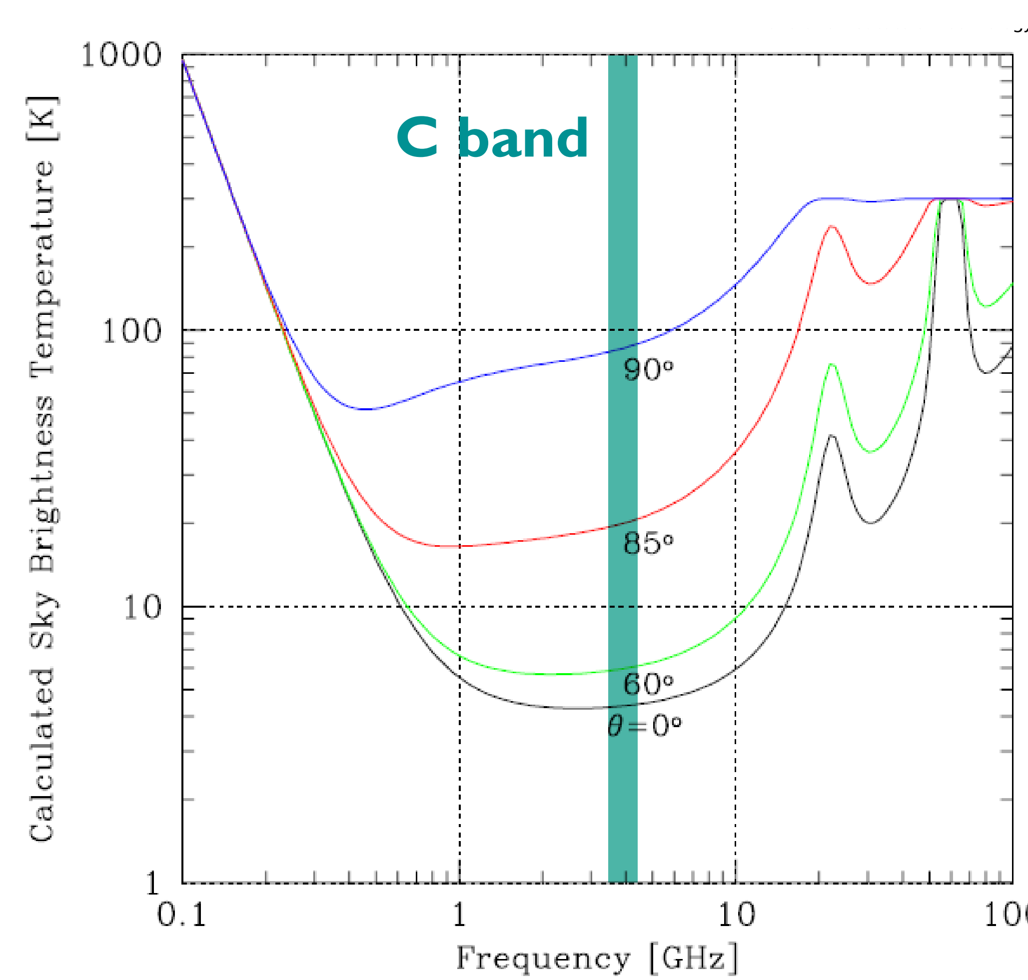
Example: absorption over distance of 20 km at sea level

- *Microwaves (4 GHz) reduction by 3%, little sensitivity to clouds*
- *UV light (350 nm) reduction by 80%, further attenuation by Mie scattering*

# Expected background signal




| | | |
|---|---|---|
| A | atmospheric (max) | million…billion K |
| B | atmospheric (min) | million…billion K |
| C1 | man made (rural) | several 10 000 K |
| C2 | man made (city) | several 100 000 K |
| D | galactic | 1000…30 000 K |
| **E** | **sun (0.5° beamwidth)** | **≈ 5000 K** |
| **F(0°)** | **horizontal line-of-sight** | **200…300 K** |
| **F(90°)** | **zenith line-of-sight** | **few K (< 10 GHz)** |
| **G** | **big bang** | **2.7 K** |




## Commercial satellite bands

***C: 3.4 - 4.2 GHz***
***Ku: 10.7 - 11.7, 11.7 - 12.75 GHz***

# Commercially available equipment

**Parabolic reflectors with off-axis or center-axis focus points**

**Low-noise blocks (LNBs) as fast receivers**

**Digitization of signal envelope** ***(log. power detector ZX47-60+)***


**LNB (C band)**

Signal 3.4 - 4.2 GHz →

**Mixer** → **Amplifier** (55 - 70 dB)

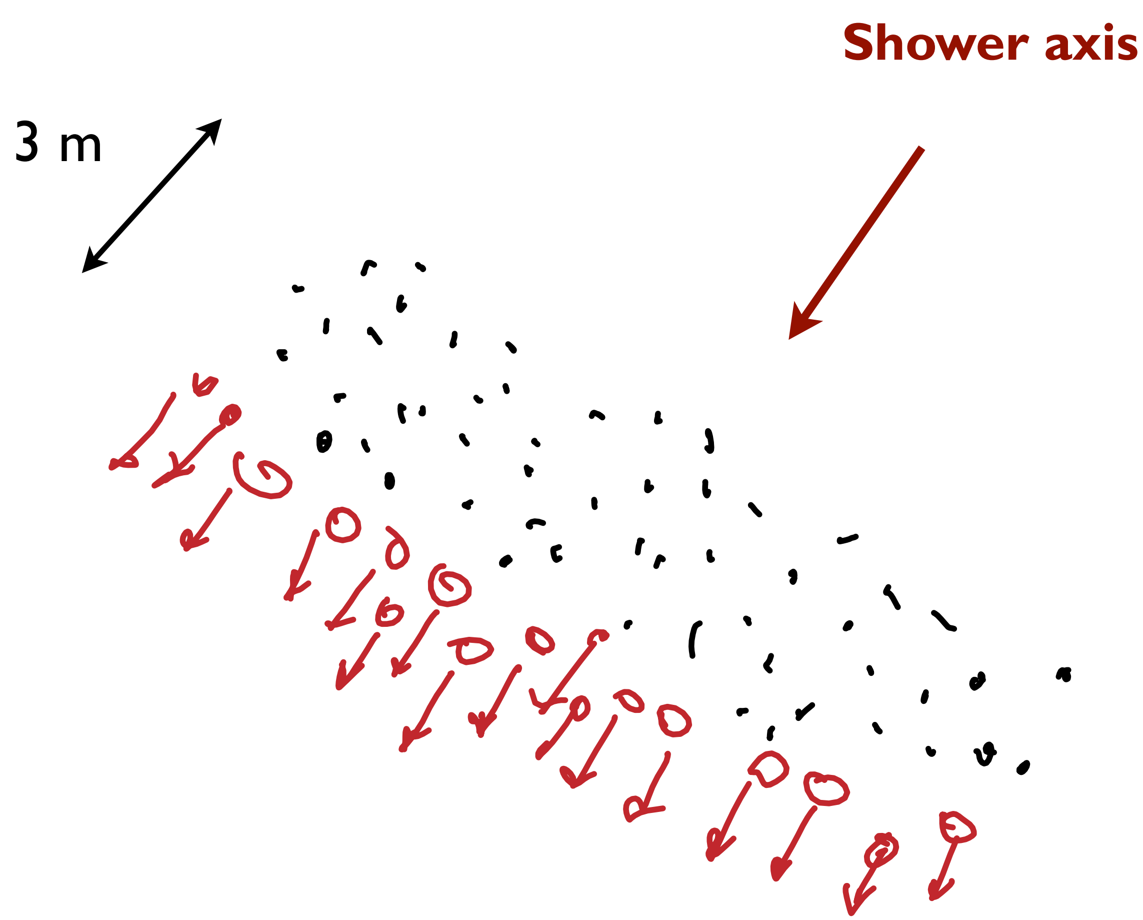
↑ Reference frequency 5.15 GHz ± 100 kHz

→ Down-converted signal 950 - 1750 MHz

***$T_{rise}$ ~ 5ns***

***Ratings: $T_{sys}$ = 13 - 20 K***

# Production of plasma region by shower particles




**Plasma:**

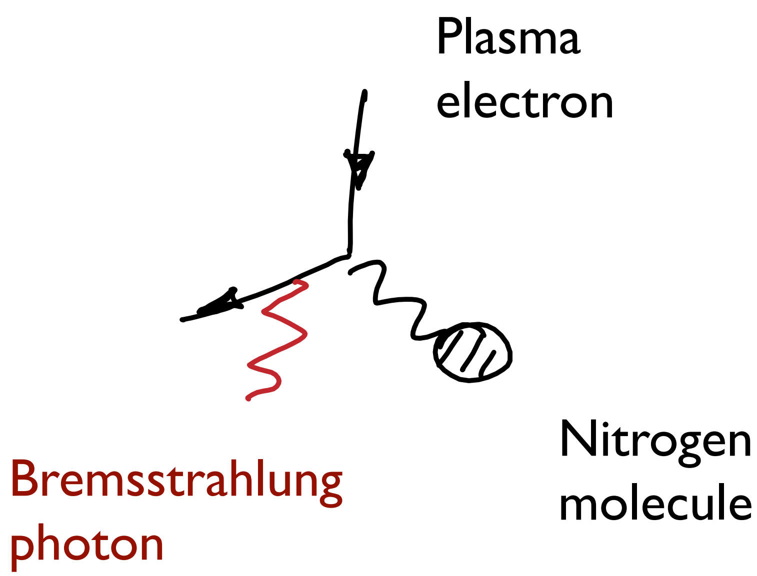
- Electrons from ionization ($E_e$ ~ 2 - 35 eV)
- Plasma stationary (no bulk motion)
- Velocity distribution almost isotropic
- 30,000 ion pairs per MeV deposited energy

**Shower disc:** ultra-relativistic particles

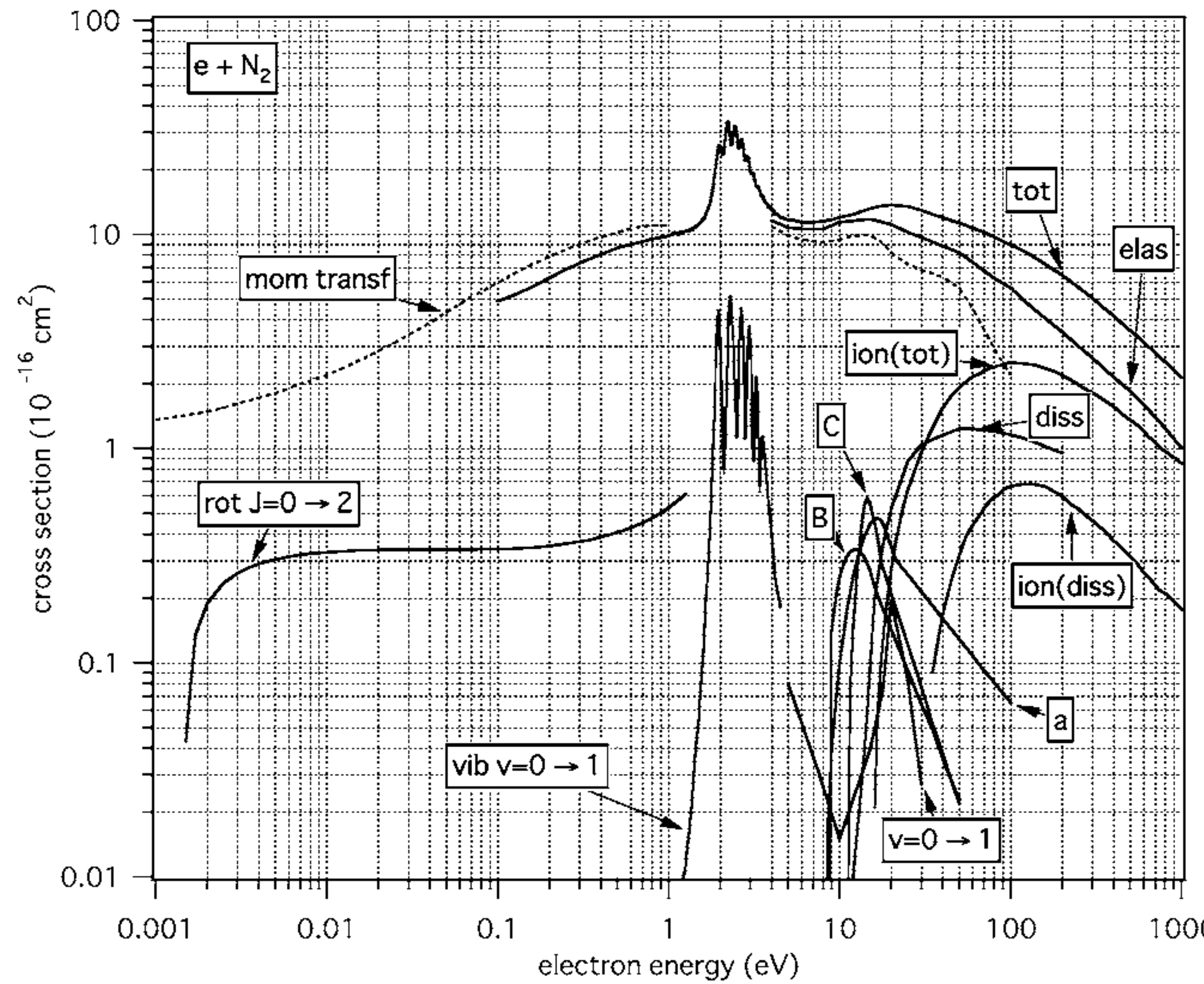
**Competing processes:**

- Thermalization due mainly to collisions with neutral atoms ~ 10 ns (sea level)
- Attachment of electrons to atoms by three-body processes involving oxygen ions
- Expected lifetime of plasma ~10 ns

# Process of molecular bremsstrahlung




*Itakawa, J. Phys. Chem. Ref. Data 35 (2006) 31*




## Radiated energy per collision

$$W_\omega = \frac{e^2}{6\pi\varepsilon_0 c}\left|\int_{-\infty}^{+\infty}\dot{\vec{v}}(t)e^{i\omega t}\mathrm{d}t\right|^2$$

$$\approx \frac{e^2}{6\pi\varepsilon_0 c}|\Delta\vec{v}|^2 \approx \frac{e^2}{3\pi\varepsilon_0 c}|\vec{v}|^2(1-\cos\theta)$$

*(Bekefi, Radiation processes in plasmas, 1966)*

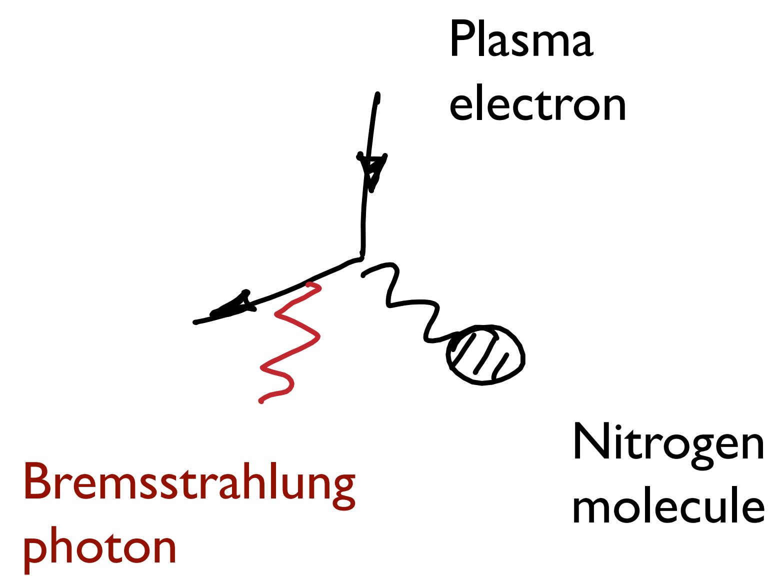
$$\omega\cdot\Delta t \ll 1$$

**Flat frequency dependence with range of approximation**

# Molecular bremsstrahlung (i)

Theory developed only for thermal plasmas (probably not reached in air showers)

Radio emission in free-free and free-bound transitions expected




**Following Gorham et al. Phys. Rev. D78 (2008)**

**Emissivity (free-free transitions):**

$$\eta_\omega(\mathrm{u}) = \frac{e^2}{16\pi^3\varepsilon_0 c^3}\mathrm{u}^2\nu_{\mathrm{en}}(\mathrm{u})\zeta(\nu_{\mathrm{en}},\,\omega).$$

Electron velocity

Collision frequency

**Plasma suppression factor (dispersion):**

$$\zeta(\nu_{\mathrm{en}},\,\omega) = \frac{1}{1+(\nu_{en}(\mathrm{u})/\omega)^2}.$$

Electrons of 2 eV in air at 5 km altitude: $\nu_{\mathrm{en}} \approx 3\,\mathrm{THz}$ $\zeta(\nu_{\mathrm{en}},\omega) \sim 5\times 10^{-5}$

# Molecular bremsstrahlung (ii)

**Thermal (Maxwellian) electron distribution**

$$f(\mathrm{u}) = \left(\frac{m_e}{2\pi k T_e}\right)^{3/2} \exp\left(\frac{-m_e \mathrm{u}^2}{2kT_e}\right)$$

**Emission coefficient**

$$j_\omega = \int_0^\infty \eta_\omega(\mathrm{u}) f(\mathrm{u}) \mathrm{u}^2 d\mathrm{u},$$

**Absorption coefficient**

$$\alpha_\omega = -\frac{4\pi}{3c}\frac{\omega_p^2}{\omega^2}\int_0^\infty \nu_{\mathrm{en}}(\mathrm{u})\zeta(\nu,\omega)\frac{\partial f(\mathrm{u})}{\partial \mathrm{u}}\mathrm{u}^3 d\mathrm{u},$$

Plasma frequency $\omega_p^2 = \dfrac{e^2 n_e}{m_e \varepsilon_0}$

**Emission intensity per unit radian frequency**

$$I_\omega = \int_0^s \frac{1}{n^2}\frac{j_\omega(s)}{\alpha_\omega(s)}\, e^{-\alpha_\omega(s)\cdot s}\, ds$$

units:
$\mathrm{W/m^2\ (rad/s)^{-1}\ sr^{-1}}$

# Coherence effects in molecular bremsstrahlung

**Air shower:** electrons not in thermal distribution, energy inversion possible

$$\frac{\partial f(u)}{\partial u} > 0$$

stimulated emission expected: coherent emission (isotropy?)

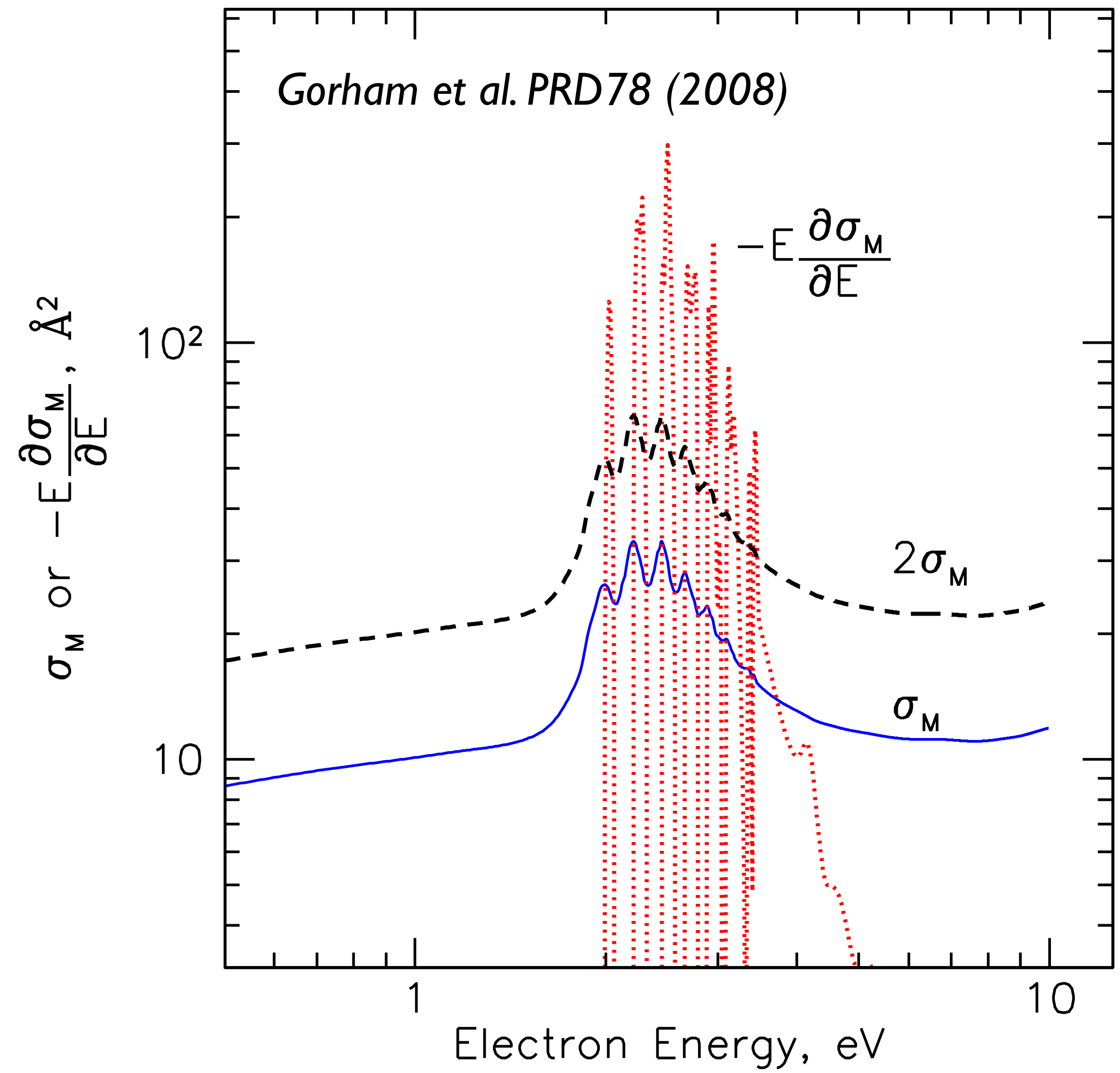
Necessary (but not sufficient) conditions:

electron velocity parallel to emitted radiation

$$-E\frac{\partial \sigma_M}{\partial E} > \sigma_M$$

electron velocity perpendicular to emitted radiation

$$-E\frac{\partial \sigma_M}{\partial E} > 2\sigma_M$$




**Coherence length limited by Debye length**

$$\lambda_D = \sqrt{\varepsilon_0 k_B T/(e^2 n_e)} \sim 1-2\,\mathrm{cm}$$

*(for shower of $10^{18}$ eV)*

# Signal scaling and coherence effects

Radiated power per unit area (far-field approximation): $P/A = |\vec{E}|^2/Z_0$

$$\vec{E} = \sum_{j=1}^{N_e} \vec{\varepsilon}(u) \exp(-i\vec{k} \cdot \vec{x}_j + \varphi_j)$$

**Full coherence ~ $(N_e)^2$**

$$\vec{E} = \sum_{j=1}^{N_e} \vec{\varepsilon}(u) = N_e \vec{\varepsilon}(u)$$

**No coherence ~ $N_e$**

$$|\vec{E}|^2 = N_e |\vec{\varepsilon}(u)|^2$$

**Partial coherence**

$$\vec{E}_{\mu_e} = \sum_{j=1}^{\mu_e} \vec{\varepsilon}(u) = \mu_e \vec{\varepsilon}(u)$$

$$|\vec{E}|^2 = M|\vec{E}_{\mu_e}|^2 = M\mu_e^2|\vec{\varepsilon}|^2$$

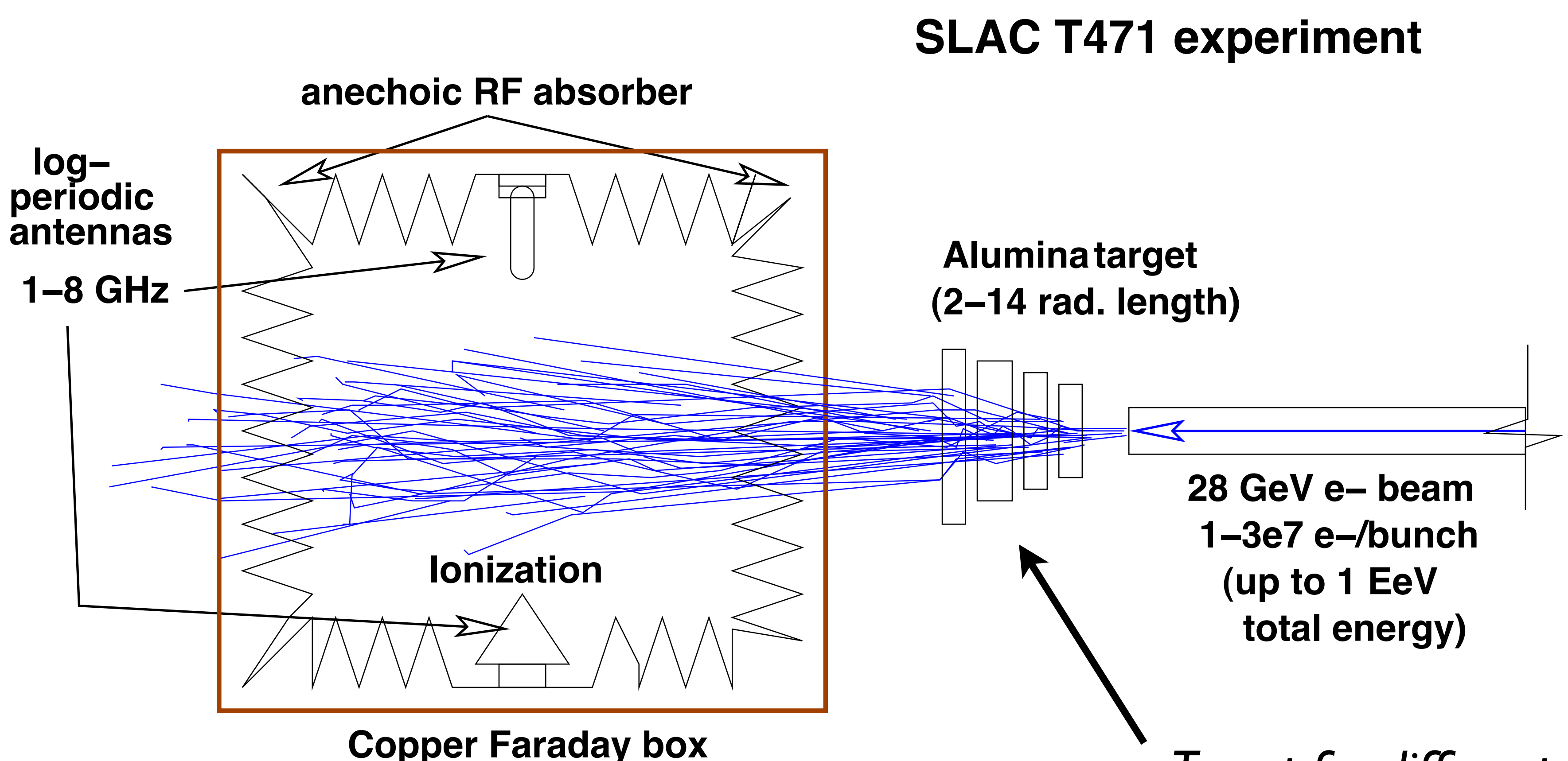
$$N_e = M\mu_e$$

number of clusters

number of electrons in cluster

Quadratic scaling for both full and partial coherence

# Initial beam measurements by Gorham et al.

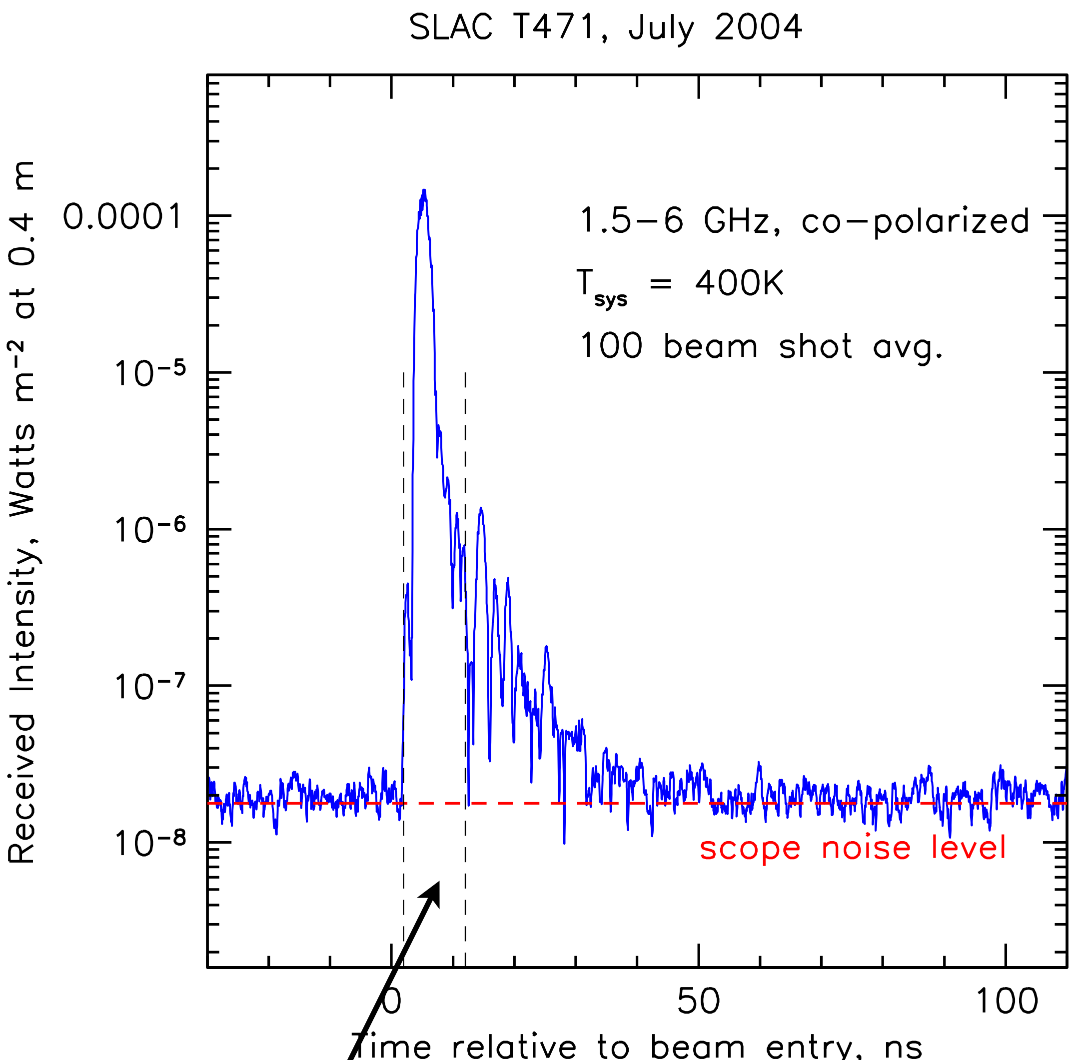



Equivalent shower energy 3.36 $10^{17}$ eV

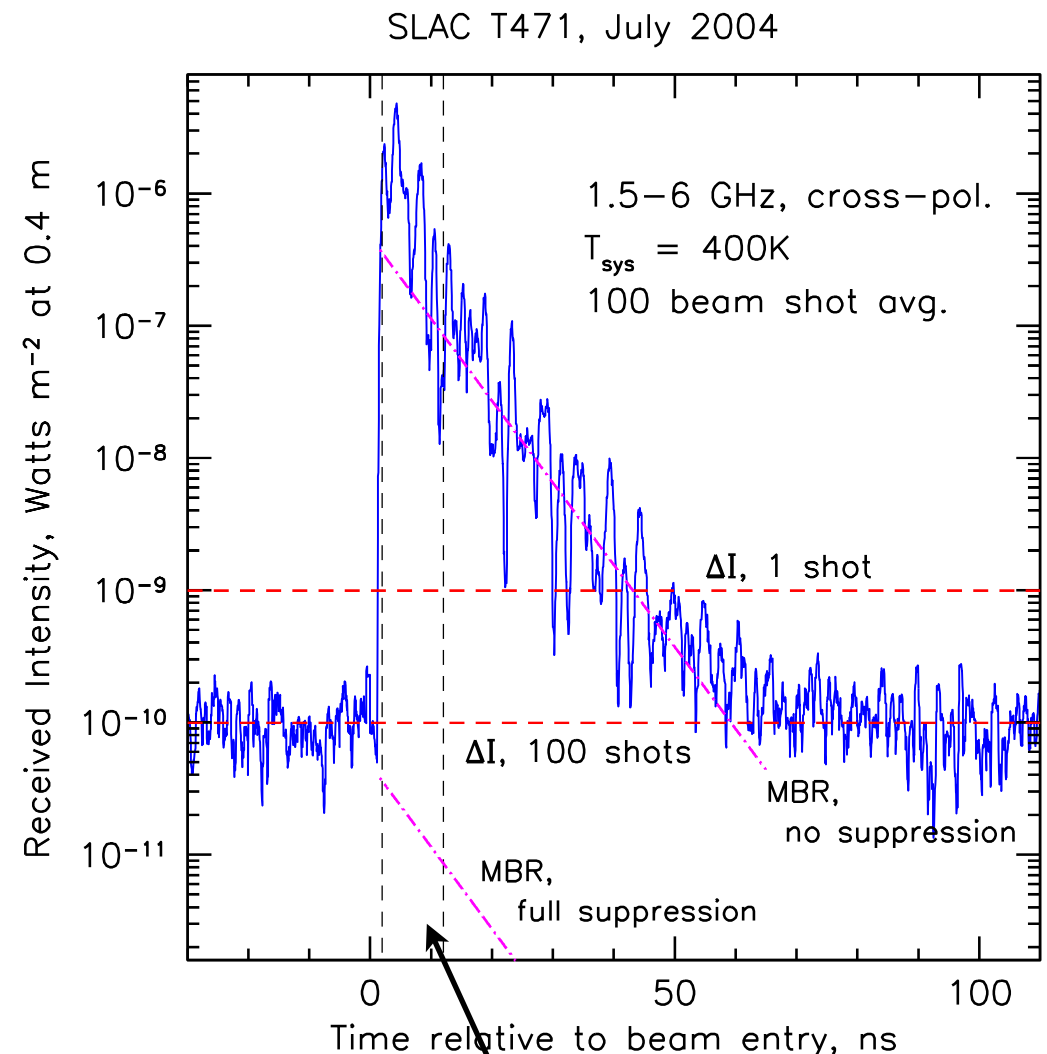
*Target for different shower ages*

*Measurements at Argonne (12 MeV) and SLAC (28.5 GeV)*

# Results of beam measurements (i)




Transition radiation



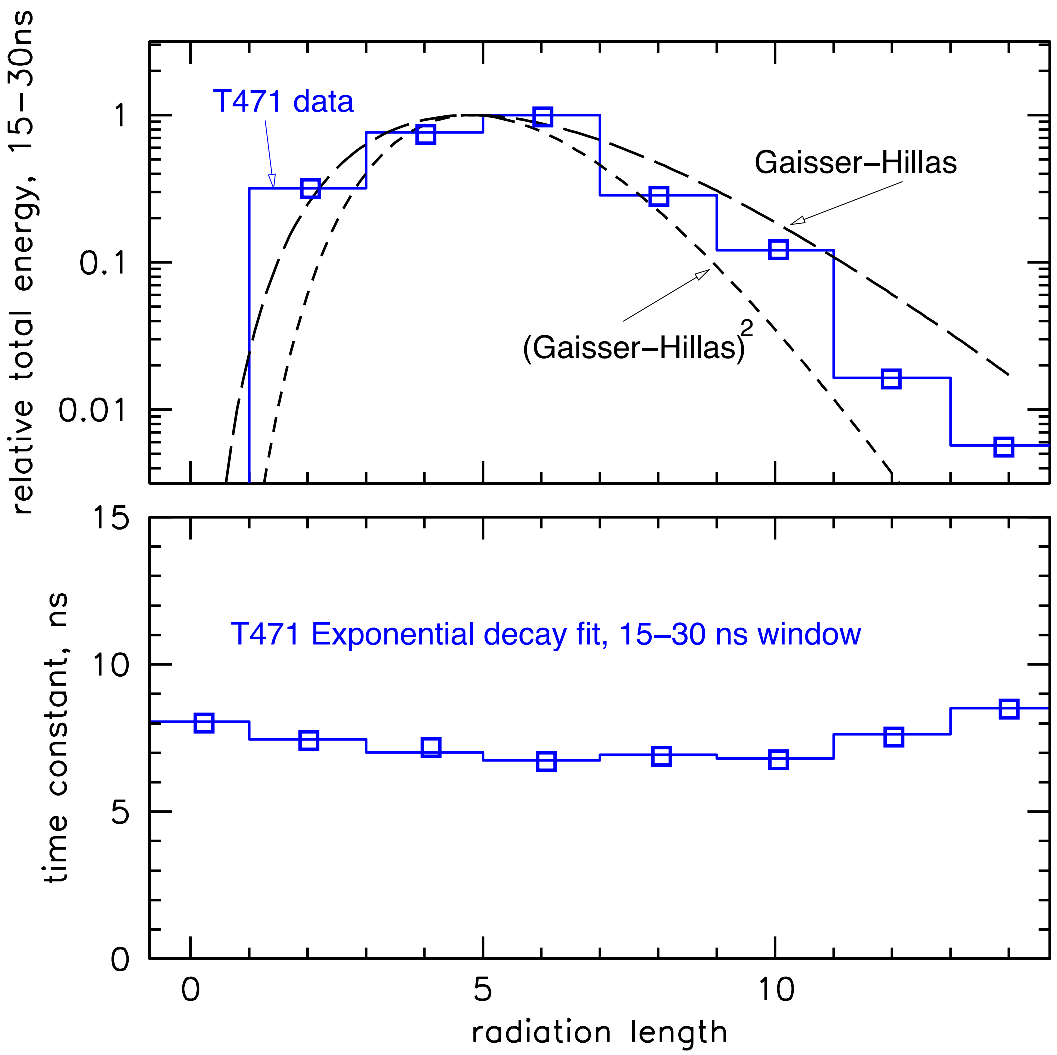

prob. leakage due to limited polarization separation (-20dB)

Clear signal from plasma decay with ~7ns lifetime seen

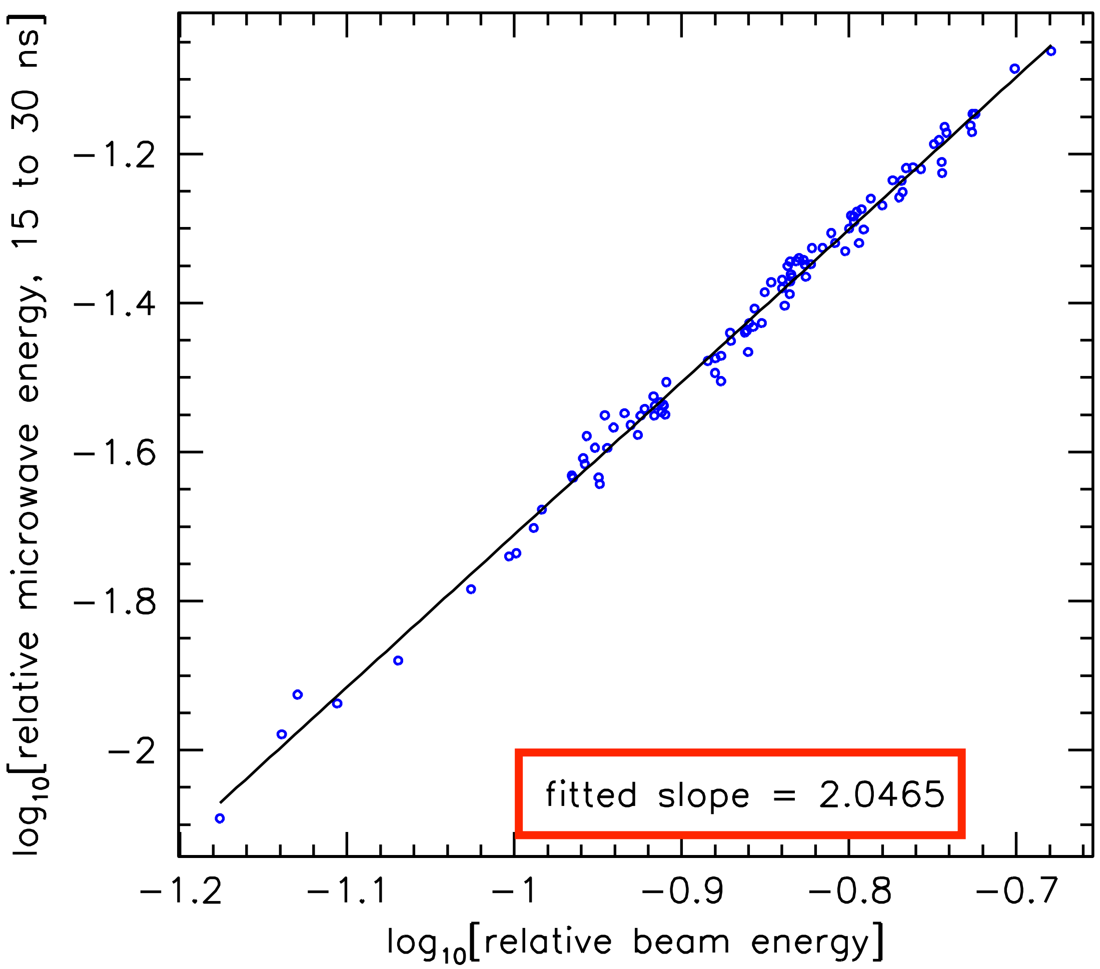
*(Chamber crossing time ~ 3ns)*

# Results from beam measurements (ii)

**Signal scaling with shower depth**



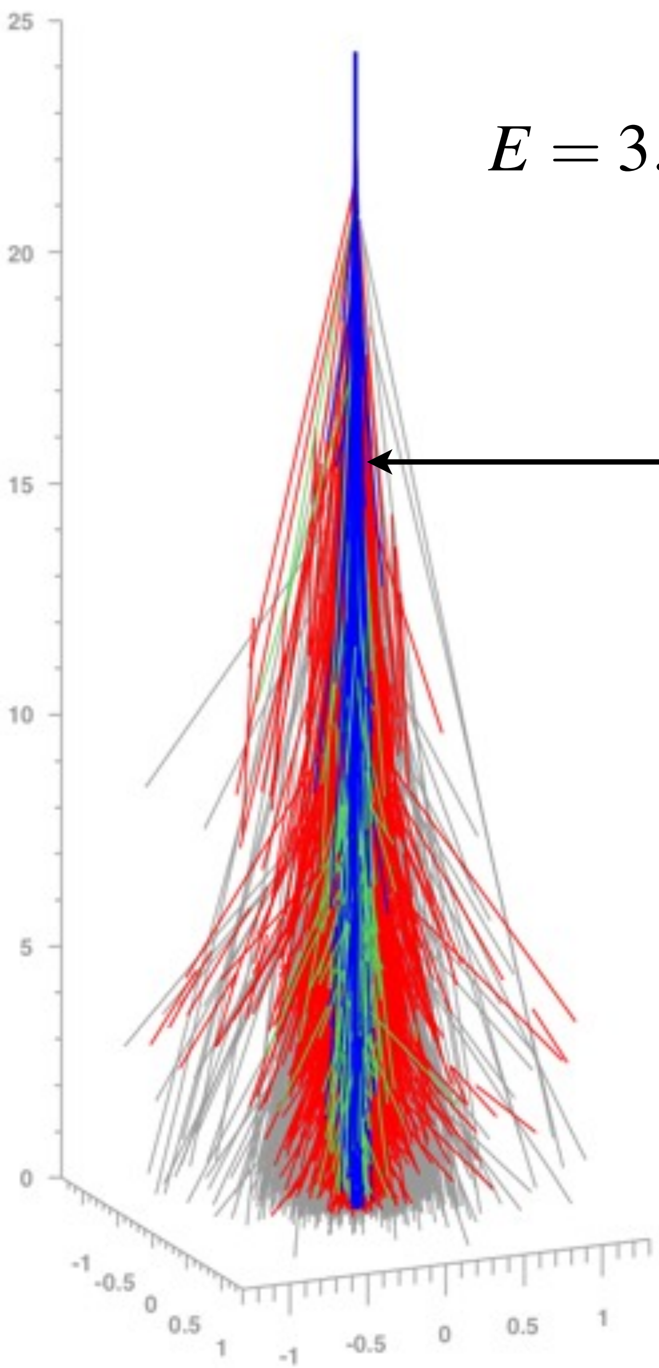

**Signal scaling with shower energy**




- Lifetime data consistent with plasma as main source of radiation
- Scaling indicates partial coherence of radiation

# Estimated reference flux for air shower

*Gorham et al. Phys. Rev. D78 (2008) 032007*




$$E = 3.36 \times 10^{17}\,\mathrm{eV}$$

$$I_{\mathrm{ref}} = 2.77 \times 10^{-24}\ \mathrm{W\,m^{-2}\,Hz^{-1}}$$

*Observation at 10 km distance*

**Microwave yield in terms of energy deposit**

$$Y_{\mathrm{MW}}(\nu) = \frac{1}{E_{\mathrm{dep}}} \frac{\mathrm{d}E_{\mathrm{MW}}}{\mathrm{d}\nu}$$
$$= (1.17 \pm 0.21) \times 10^{-18}\,\mathrm{Hz}^{-1}$$

$$Y_{\mathrm{MW}} = (283.5 \pm 50.7)\ \mathrm{ph/MeV}$$

(consistency, re-scaling with density?)

# AMBER (Air-shower Microwave Bremsstrahlung Experimental Radiometer)

*Initial measurements taken at Univ. of Hawaii*

- 2.4 m offset parabolic antenna
  (2.4° beamwidth FWHM)
- Optical axis 30° in elevation
- Camera of 16 feedhorns (28 channels)
  - 4 C & Ku band feeds, dual polarization
  - 12 C band feeds
  - Calibration with liquid nitrogen
- 100 MHz digitizer, 5 sec ring buffer

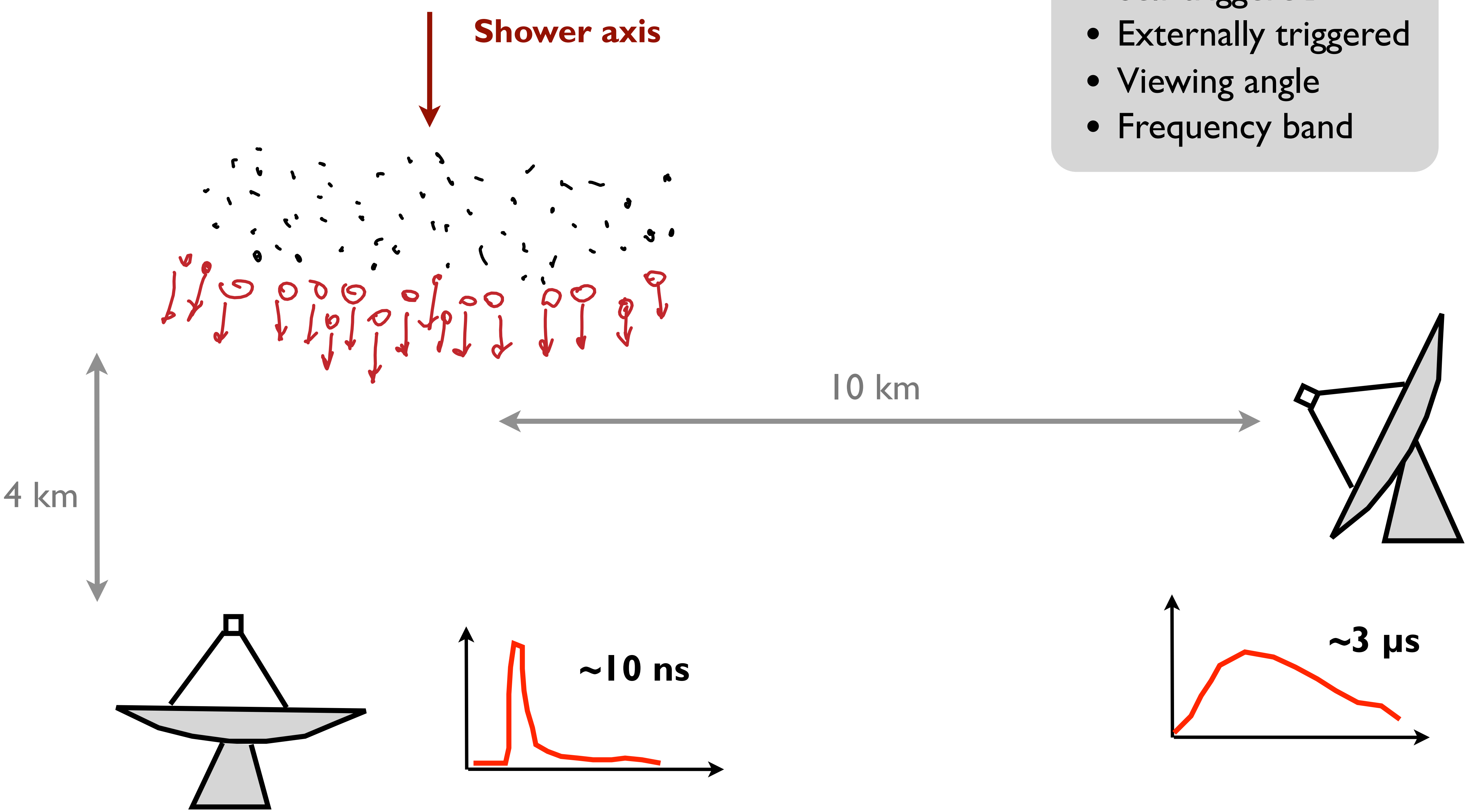
More down-doing shower candidates than upward ones, results inconclusive

***C band: 3.4 - 4.2 GHz***
***Ku band: 10.7 - 11.7, 11.7 - 12.75 GHz***

*(Gorham et al. Phys. Rev. D78 (2008) 032007)*

# Explorative follow-up experiments

- Self-triggered
- Externally triggered
- Viewing angle
- Frequency band



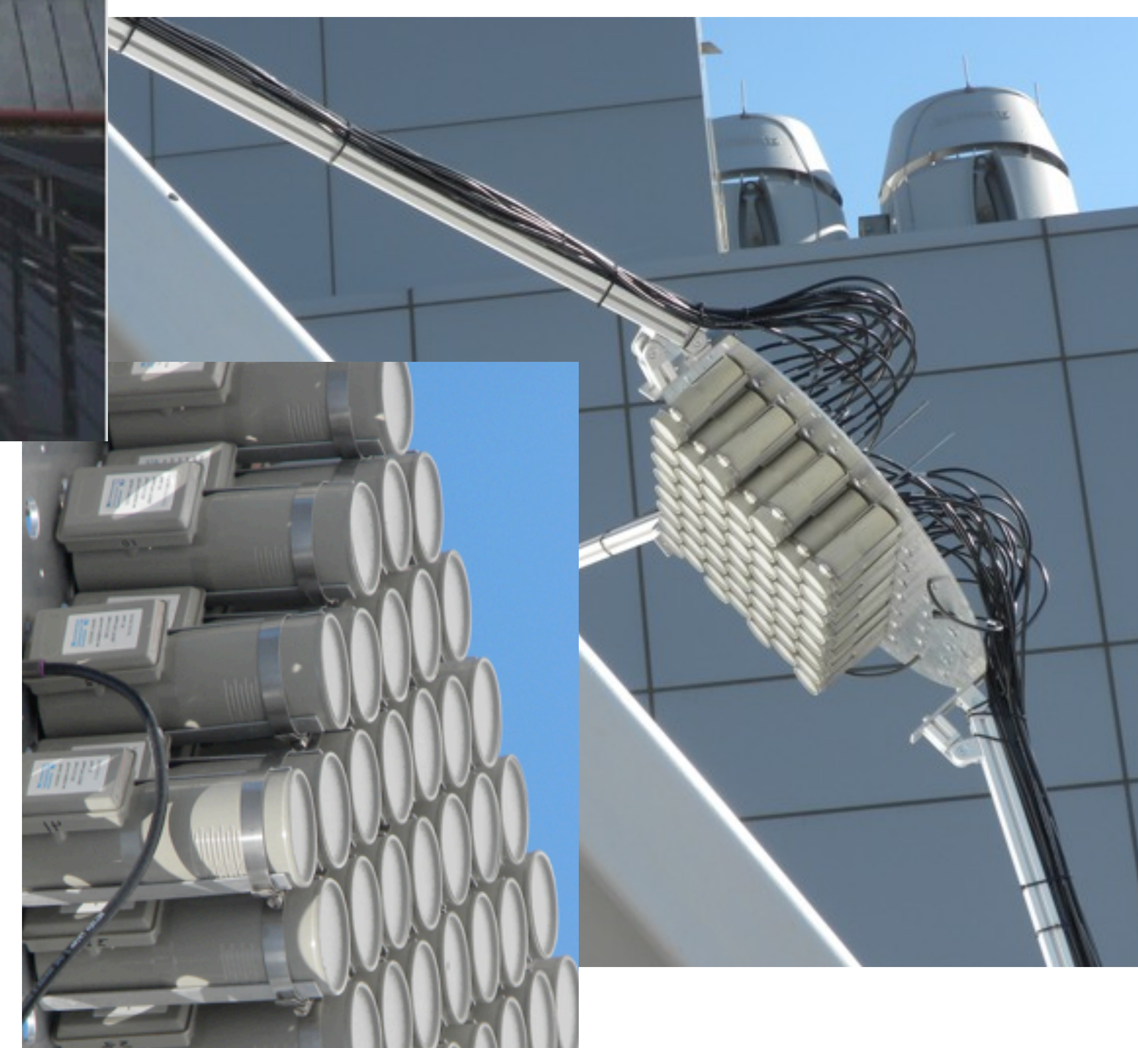

- Signal time-compressed, large peak power
- No change in frequency

- Signal similar to fluorescence pluse
- Shower profile directly measured

# MIDAS (MIcrowave Detection of Air Showers)

- Roof-top Univ. of Chicago
- 4.5 m center-focus parabolic antenna (1.3x1.3° per pixel, 20°x10° in total)
- Astronomical mount
- Camera of 53 feedhorns C band feeds
- 20 MHz digitizer, shower trigger

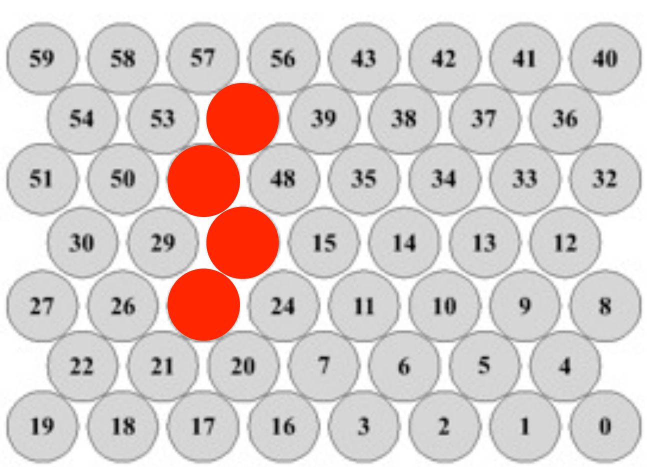
*(Alvarez-muniz et al., arXiv:1205.5785)*



## Stand-alone trigger

**FLT:** threshold (100 Hz)

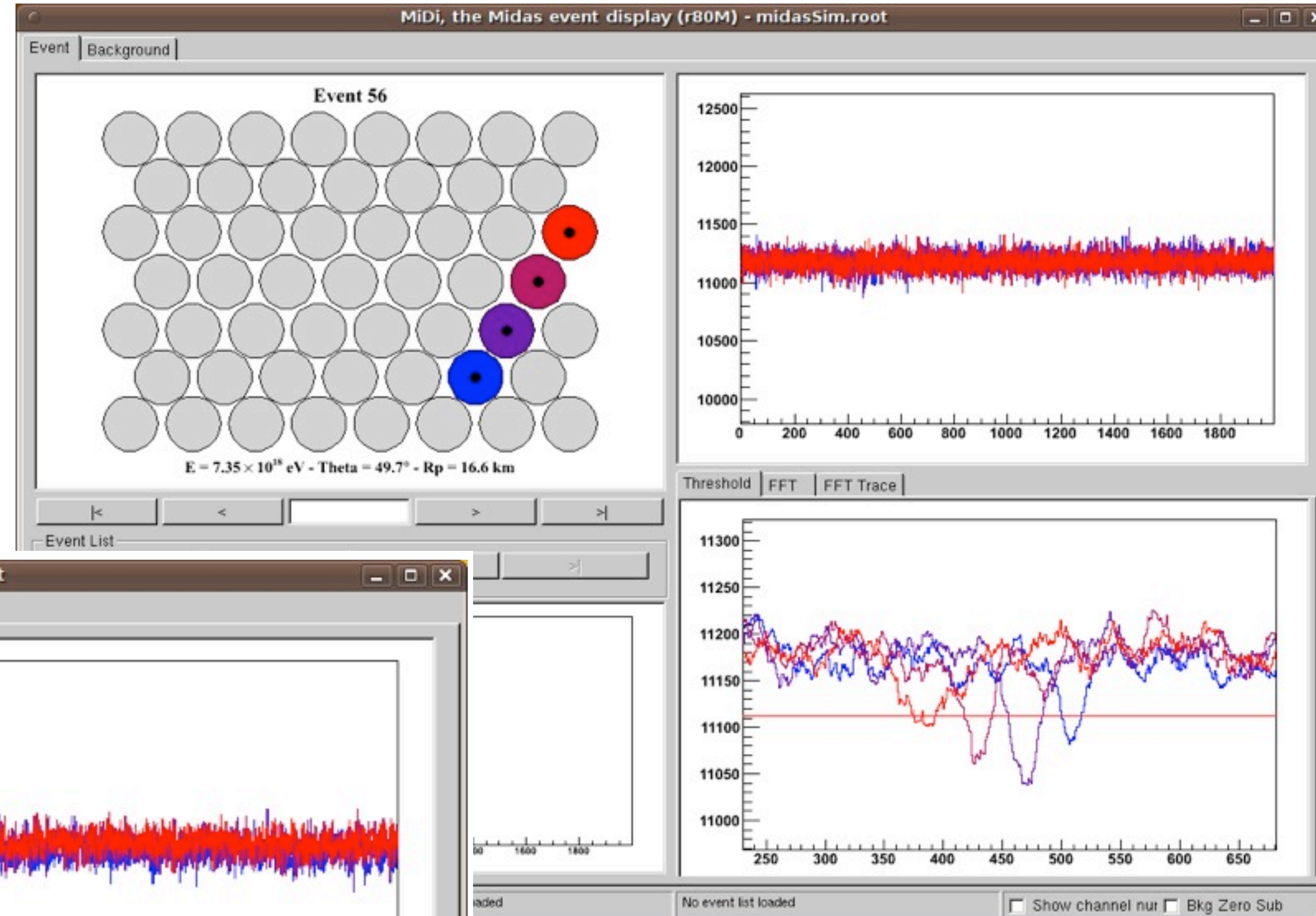
**SLT:** 4 FLTs in row in 20μs (0.2 Hz noise rate)

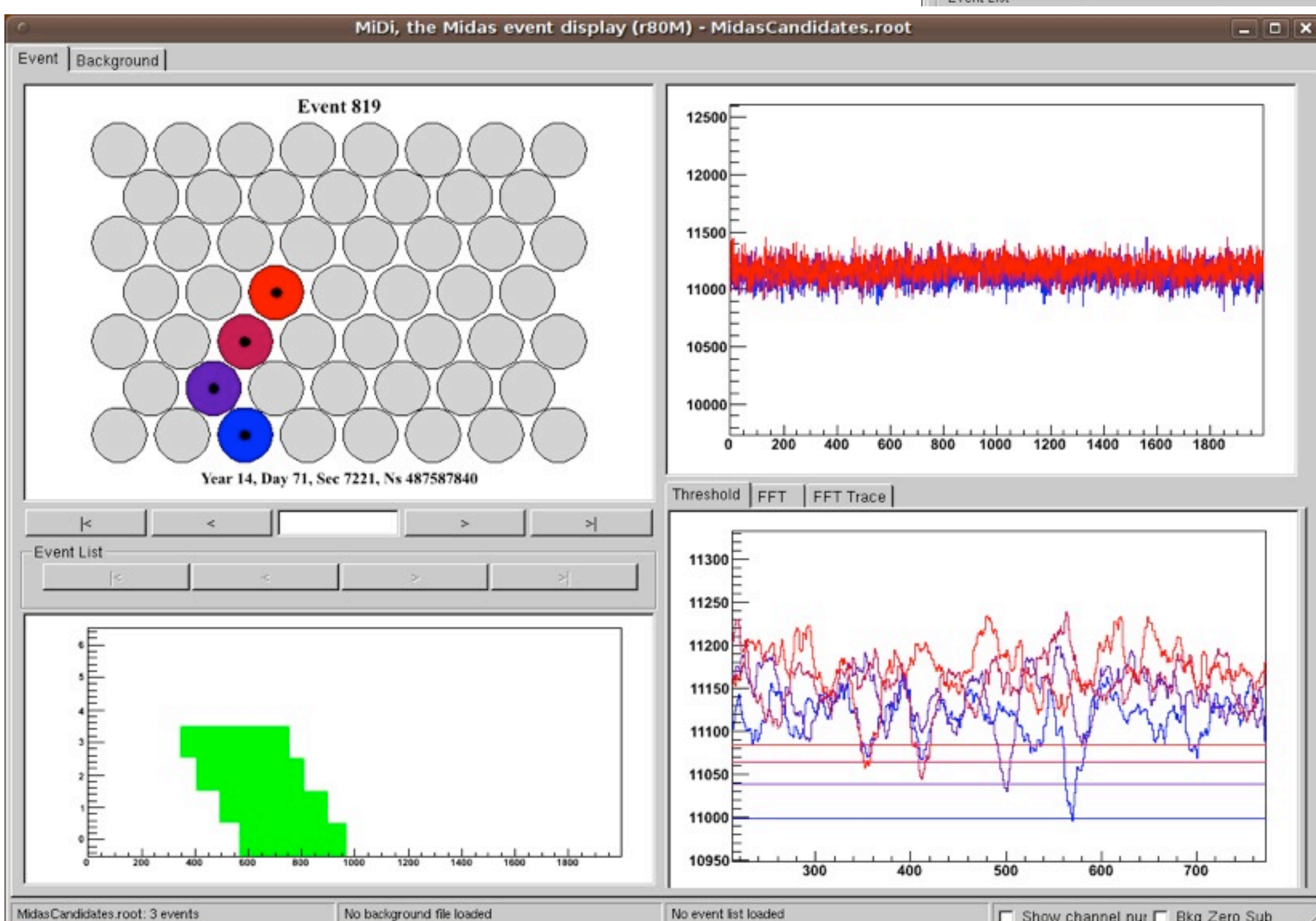


# MIDAS event simulation and event candidates

Operation in Chicago: 6 months

**Event candidate**
(down-going candidates more frequent)




**Simulated event**

E = 7 x $10^{18}$ eV
Rp = 16.6 km
$\theta$ = 50°

MIDAS: to be installed in Auger Observatory soon

# AMBER with external trigger in Auger Observatory

*(Auger Collab. arXiv:1107.4807)*

**Expected event triggers from Auger array**

~ 3 events per month (quad. scaling)

$E_{min}$ ~ 1.6 x $10^{18}$ eV (quad. scaling)

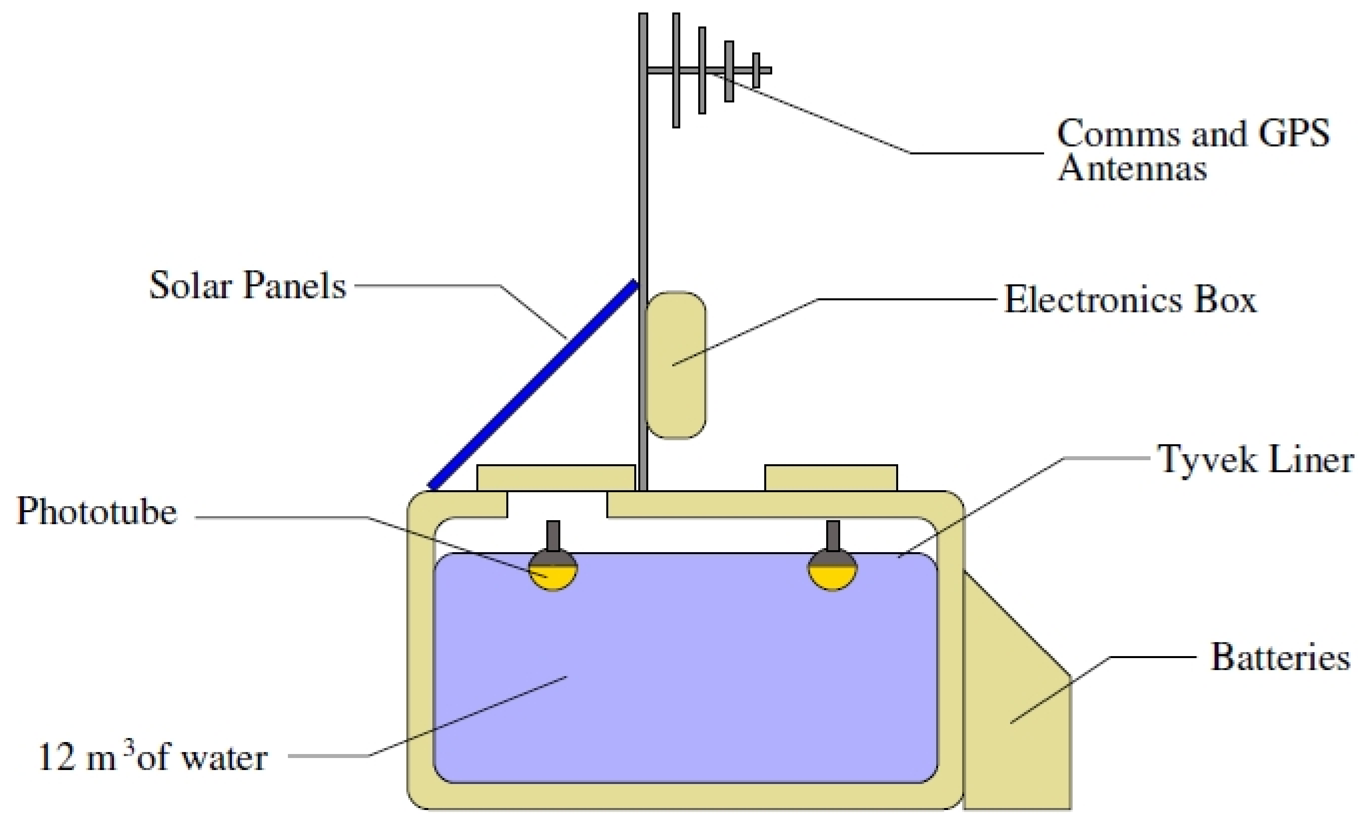
~ 8 x $10^{18}$ eV (lin. scaling)

**Installed in Auger array since April 2011**

- 2.4 m offset parabolic antenna (2.4° beamwidth)
- Optical axis 30° in elevation
- Camera of 16 feedhorns
- Calibration with liquid nitrogen
- 100 MHz digitizer, 5 sec ring buffer

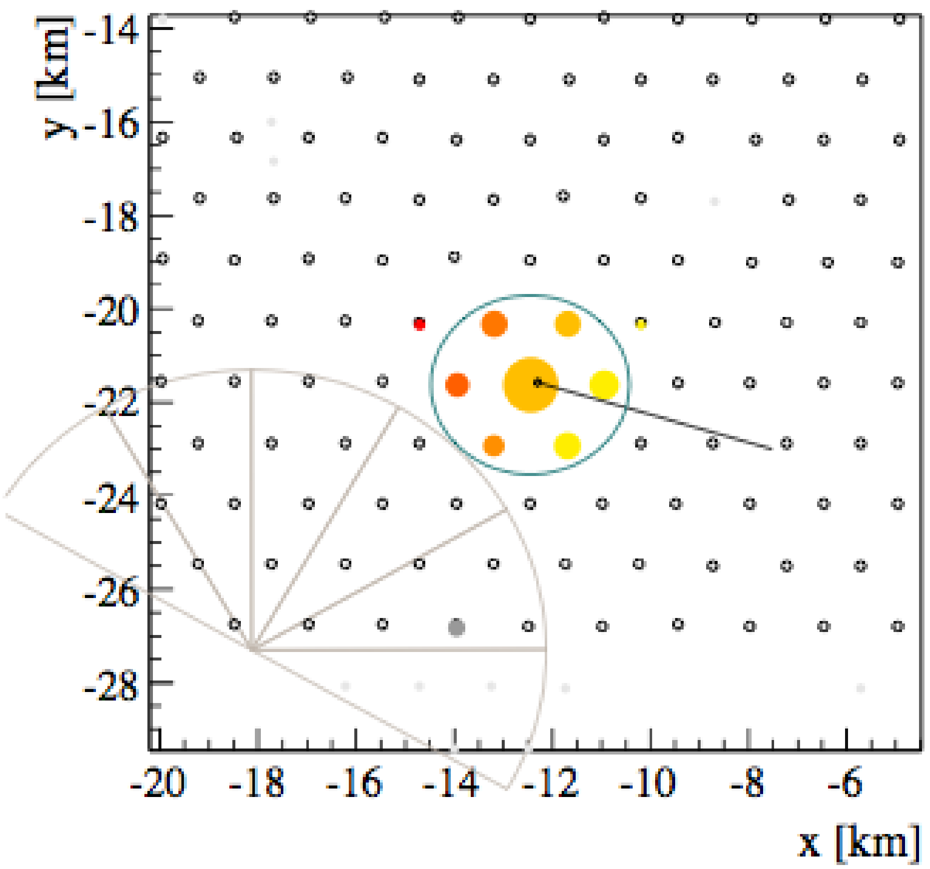
# EASIER (Extensive Air Shower Identification using Electron Radiometer)

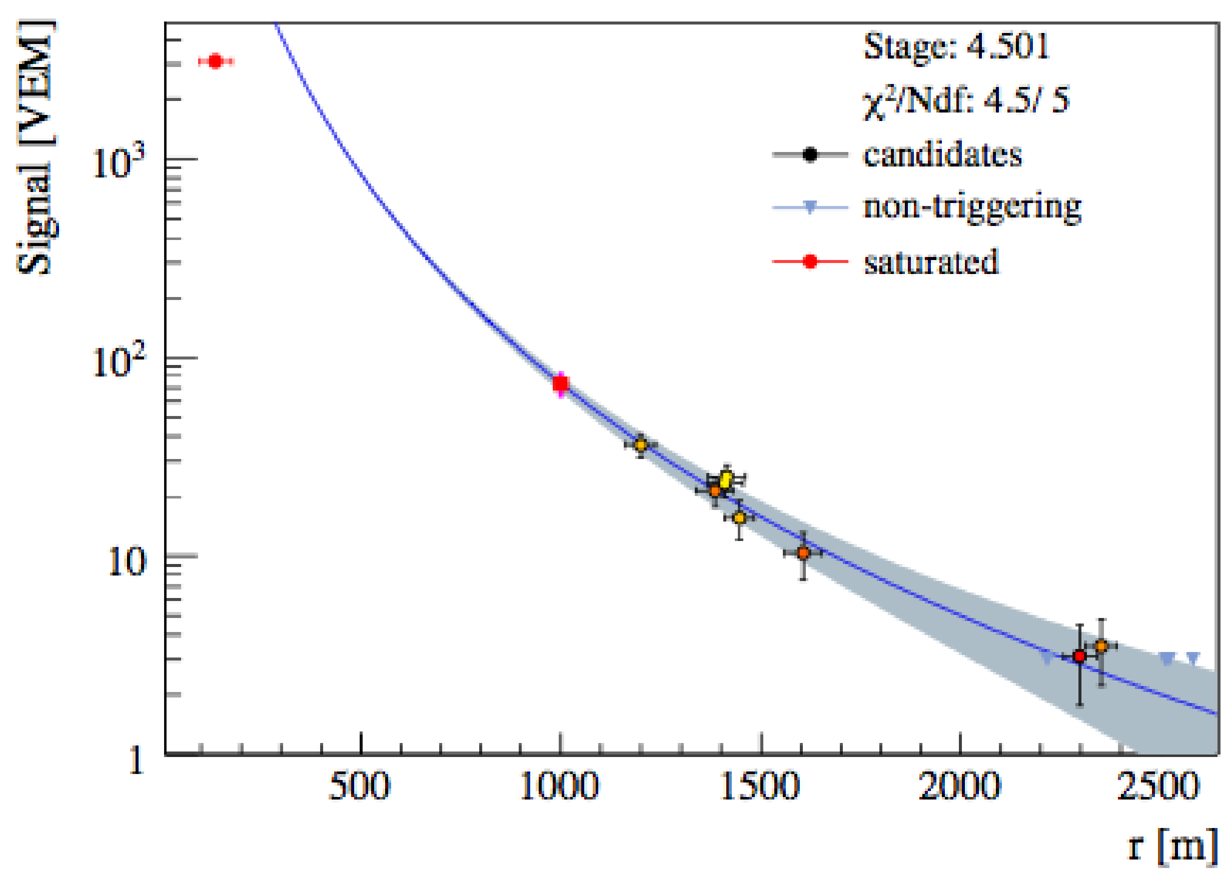
- Upward-facing feedhorn/LNBs
- Opening angle ~120° and low $T_{sys}$
- Trigger from local surface detector station
- Digitization as low-gain signal of Auger DAQ (25ns)




Prototype hexagon (7 stations, 1500 m baseline) running in Auger array since April 2011
61 stations since April 2012, Data analysis in progress,

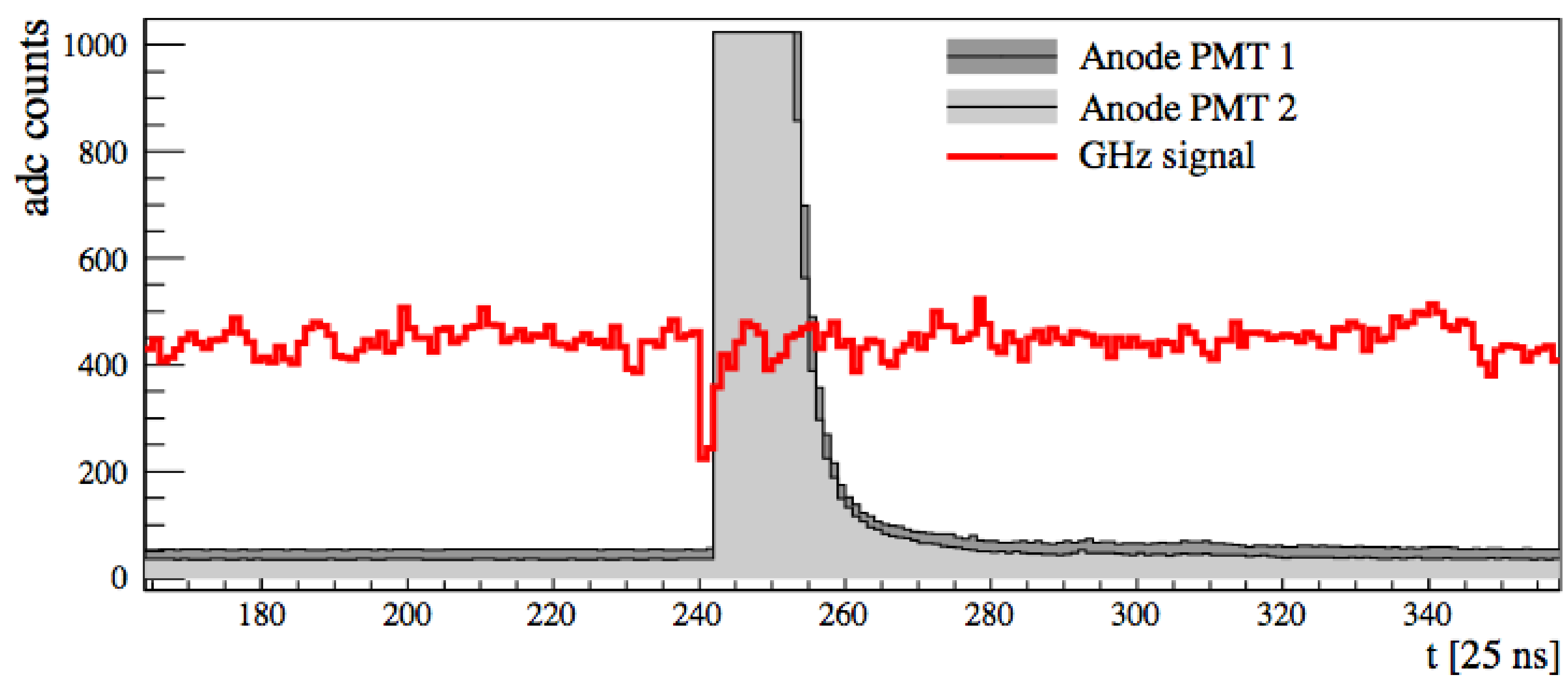
# EASIER GHz event candidate




**Shower reconstruction**

$E \approx 1.4\ 10^{19}$ eV
$\theta \approx 30°$
$R_{core} \sim 140$ m



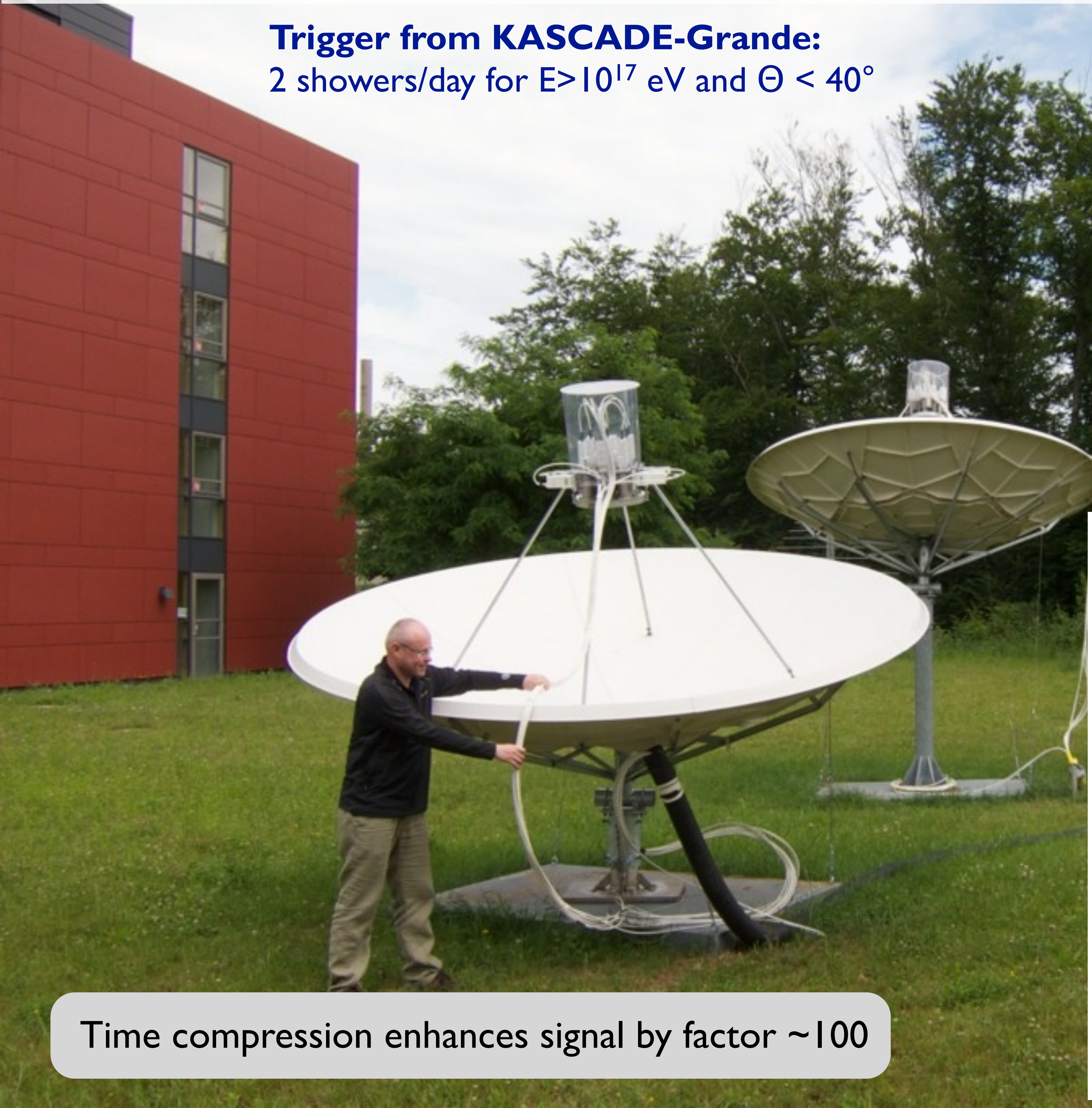

First evidence of GHz radiation from an air shower

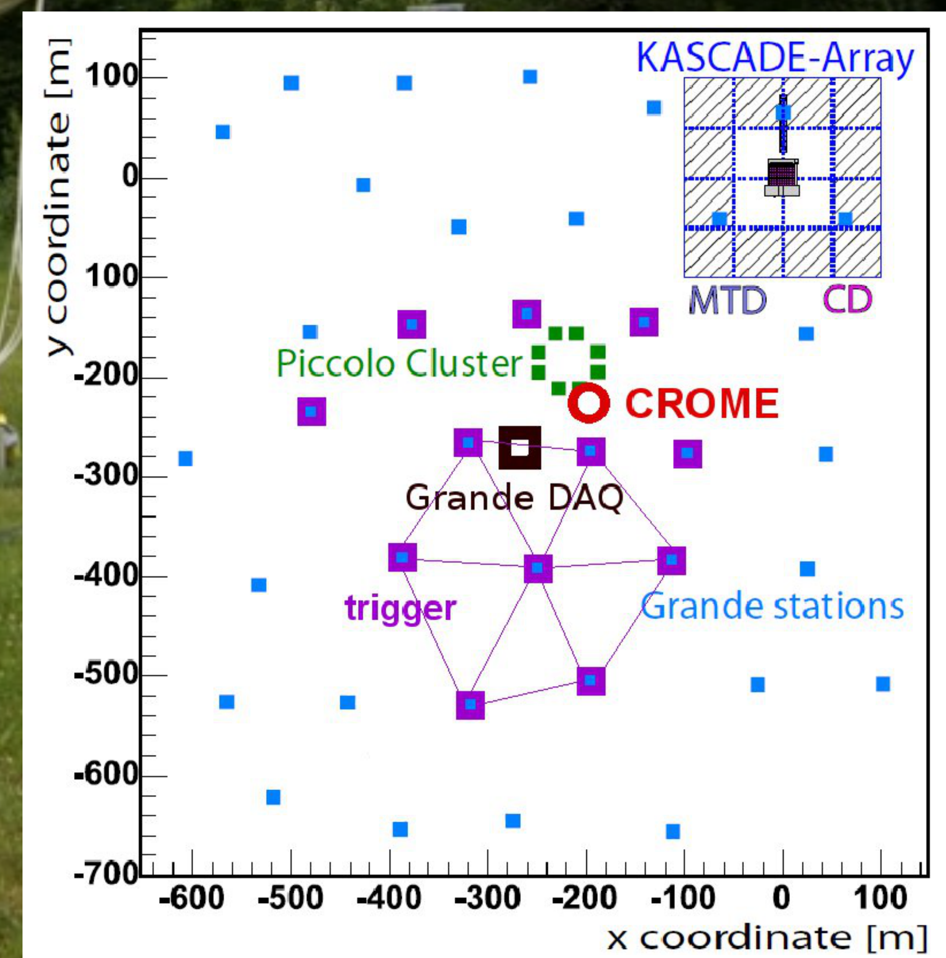
*(Facal San Luis, Auger Collab., UHECR 2012)*

# CROME (Cosmic Ray Observation by Microwave Emission)

**Trigger from KASCADE-Grande:**
2 showers/day for E>$10^{17}$ eV and $\Theta < 40°$

- Karlsruhe (KIT)
- Three 3.40 m reflectors, 3x3 cameras, C band, FoV 1.6° at 3 dB per pixel, digitization 350 MHz, bandwidth (0.8 ns sampling)
- 1.2-1.8 GHz antenna (2.3m)



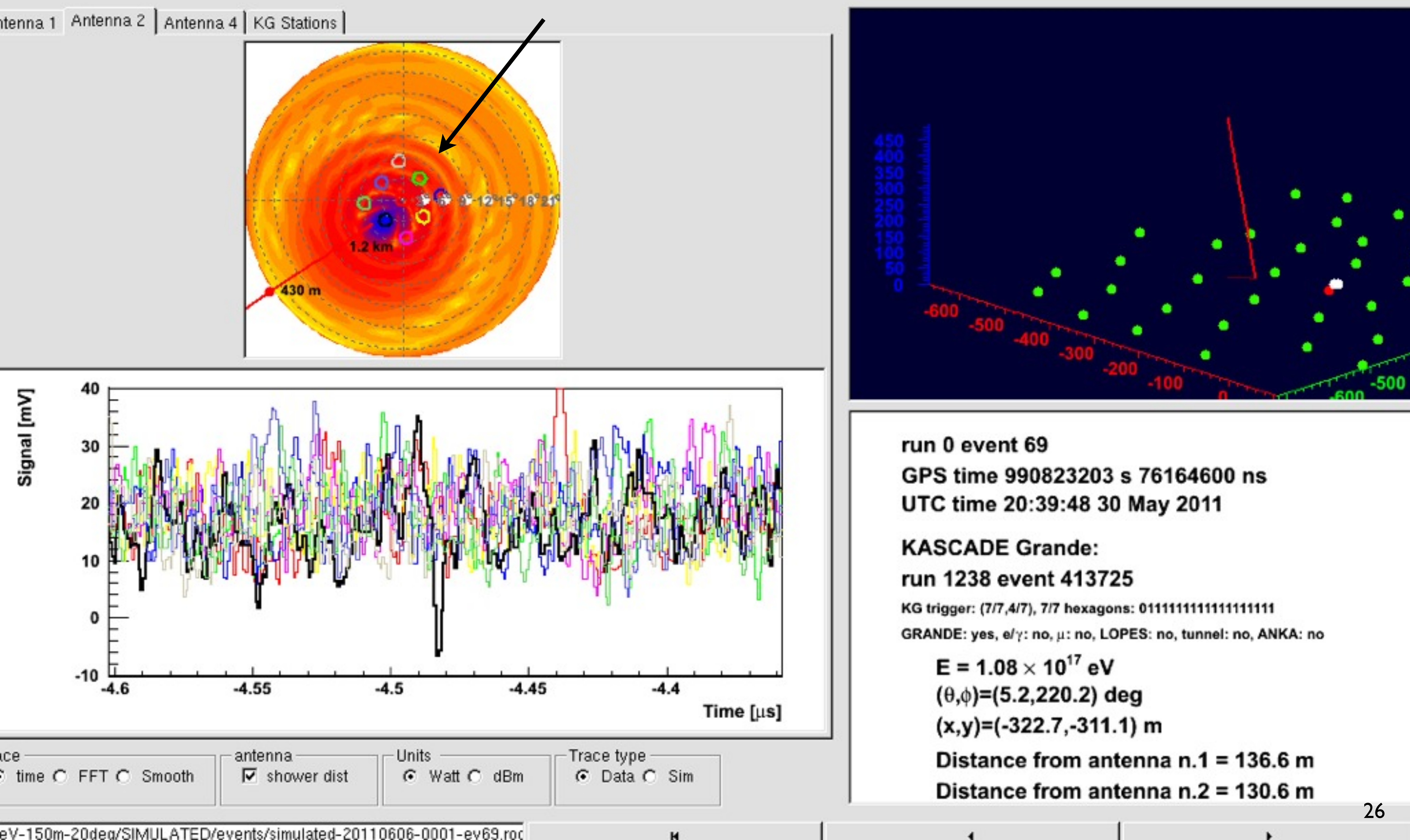



Time compression enhances signal by factor ~100

# CROME GHz event candidate

*(Smida et al., UHECR 2012)*

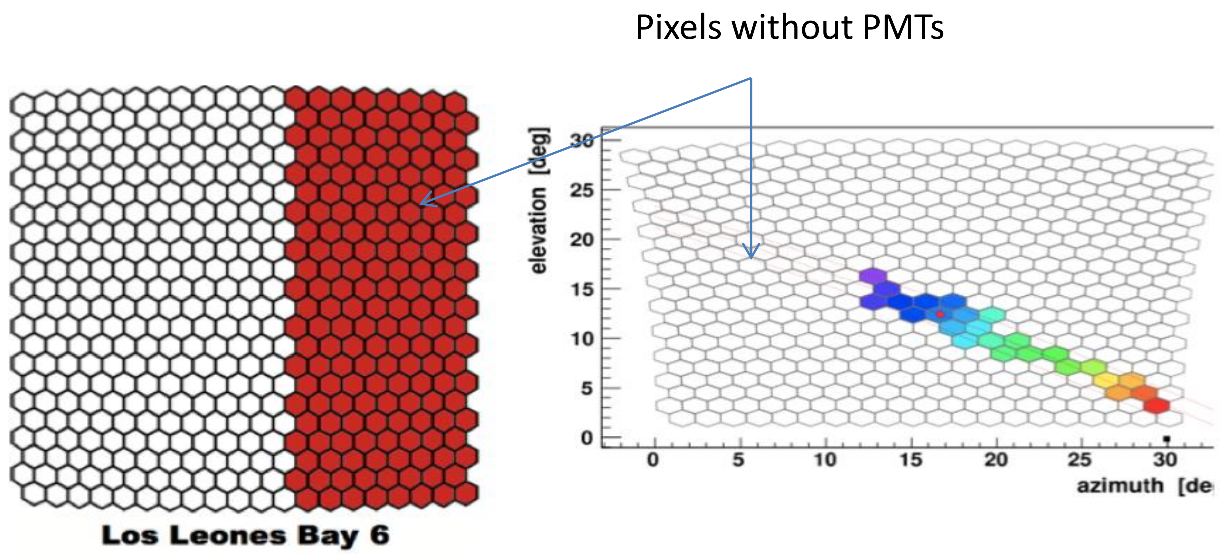
**Color displays sensitivity pattern of selected receiver**

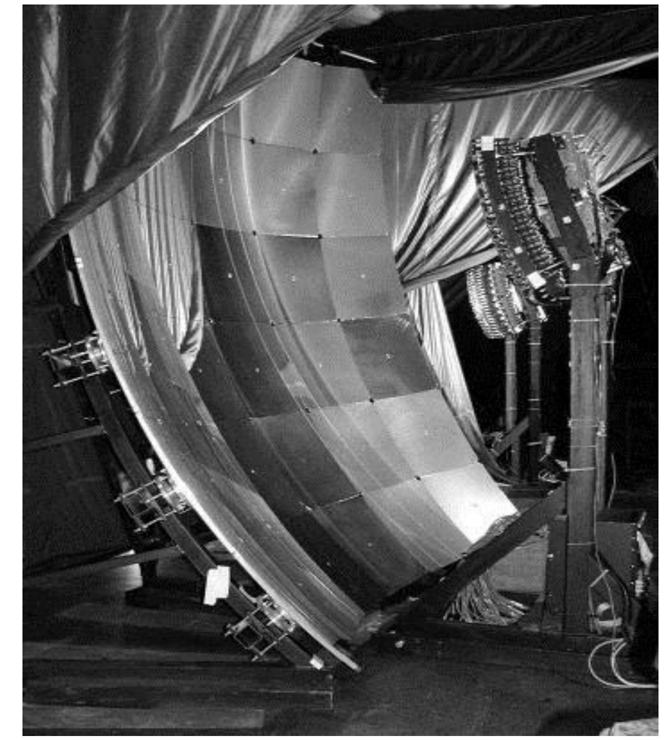


# Other air shower installations

**FDWave at Auger:**

refurbish partially unused fluorescence telescope with Ku band receivers



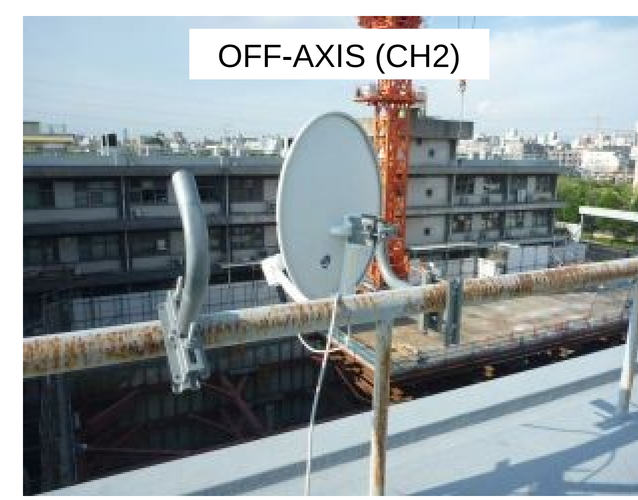



**Konan Univ., Kobe:**

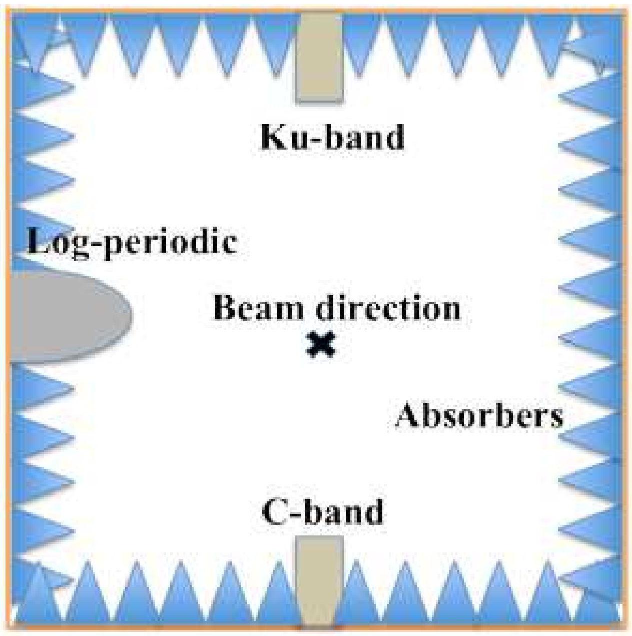
12 K band antennas (1.2 m)

**Osaka Univ.:**

two K band antennas (45 cm)

# MAYBE (Microwave Air Yield Beam Experiment)

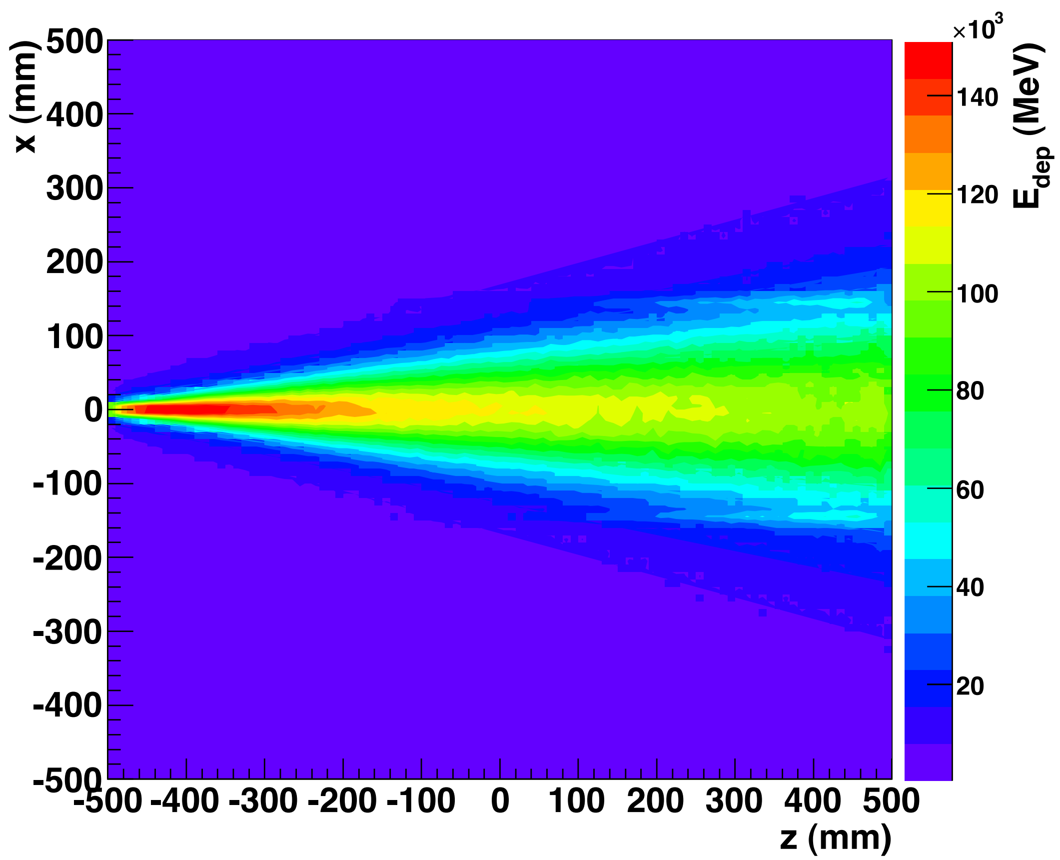


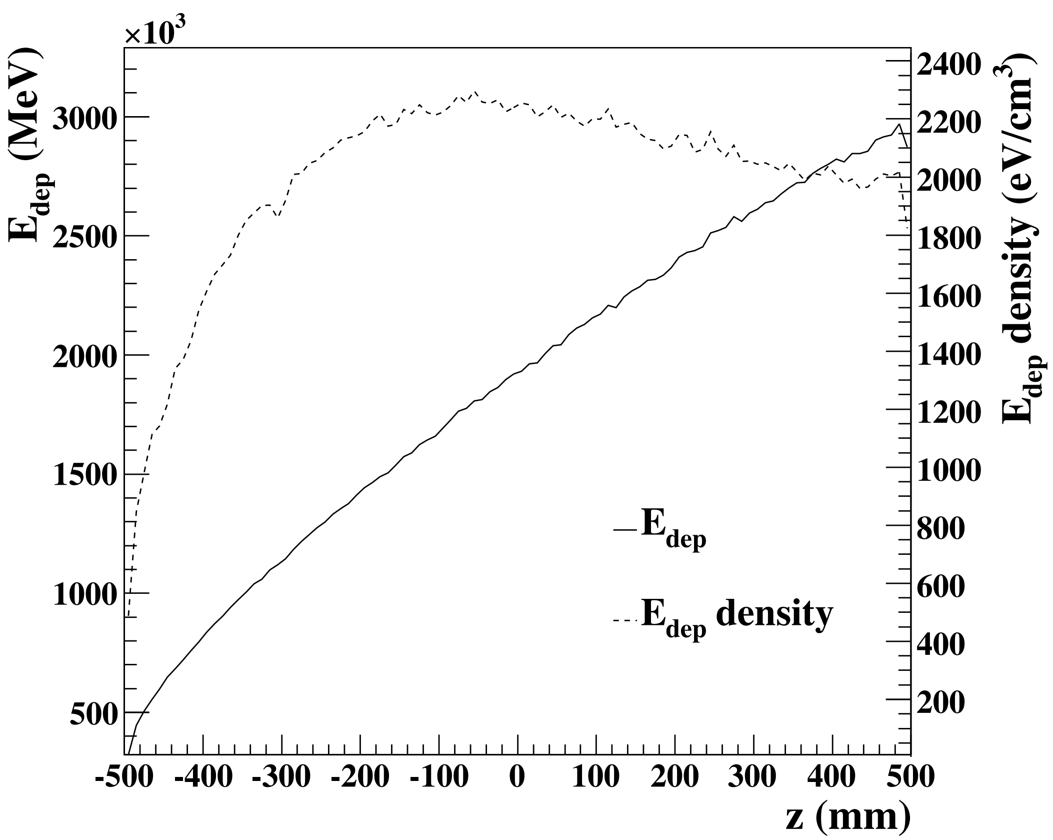

- Anechoic chamber of Gorham et al.
- Electron beam of 3 MeV (Argonne accelerator)
- Energy below Cherenkov threshold
- Equivalent shower energy $10^{18}$ - $10^{19}$ eV
- Measurement in several bands

  broad band 0.7 - 2.4 GHz

  C band (3.4 - 42. GHz)

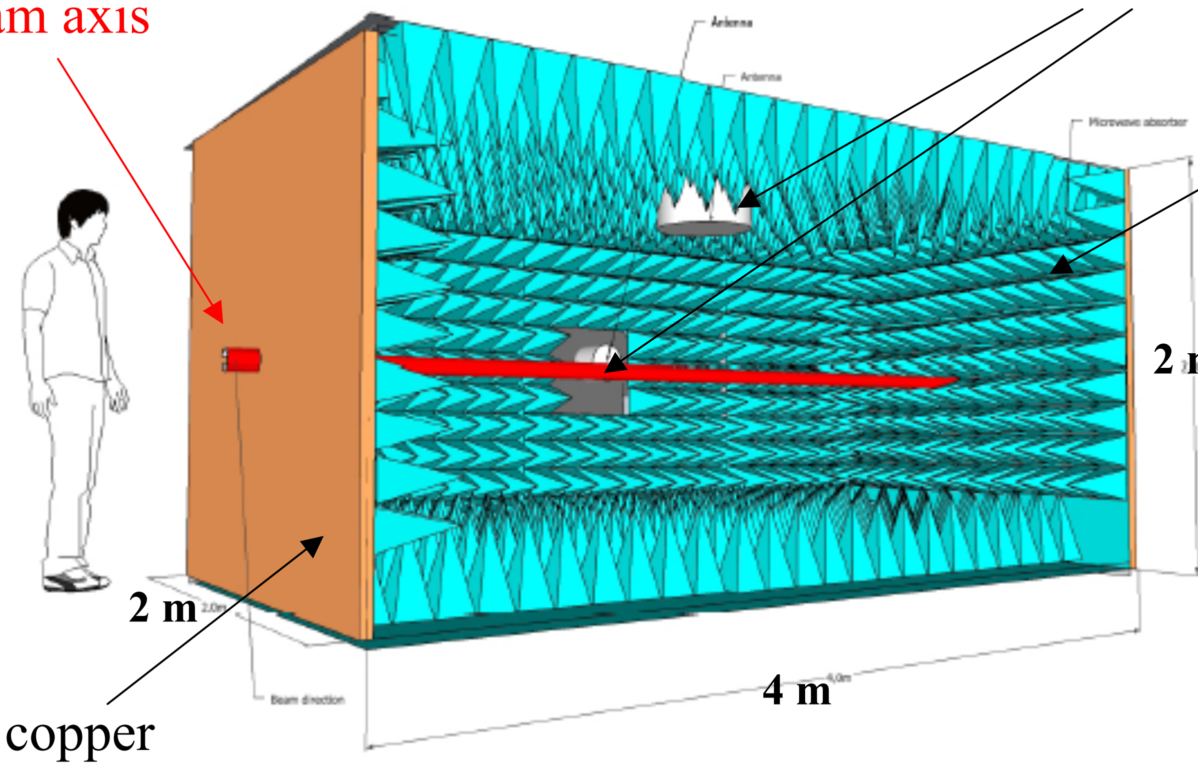
  Ku band (12.2 - 12.7 GHz)

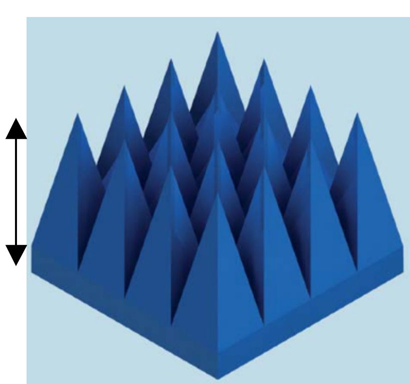


# AMY (Air Microwave Yield)

Beam experiment at Frascati accelerator, data taken Nov 2011, May 2012



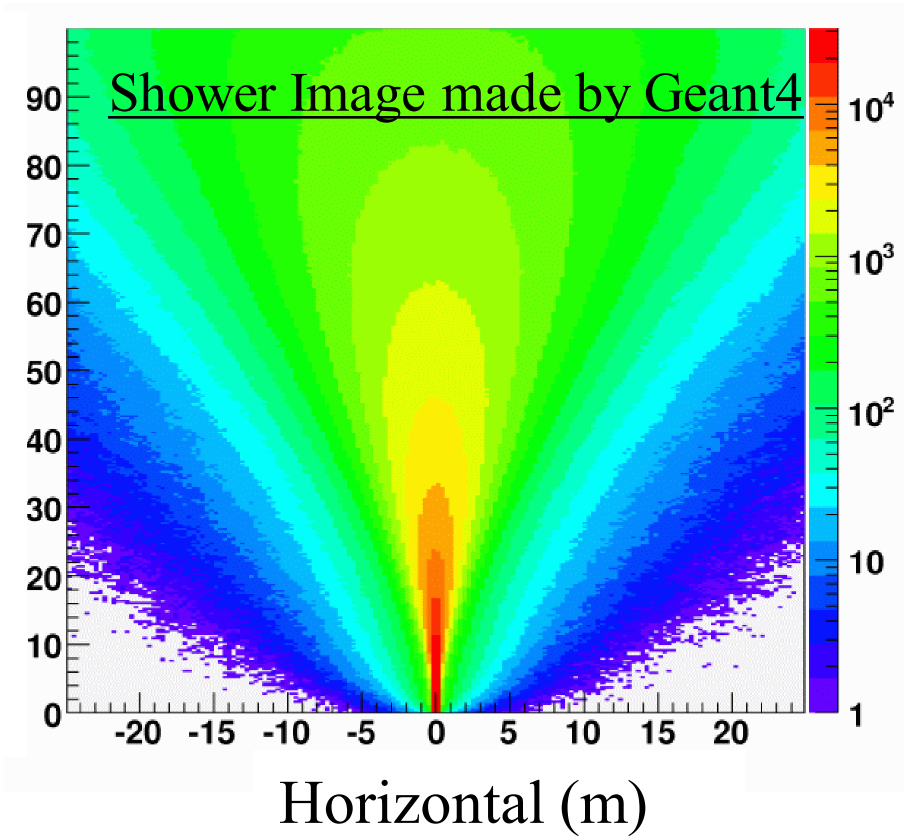



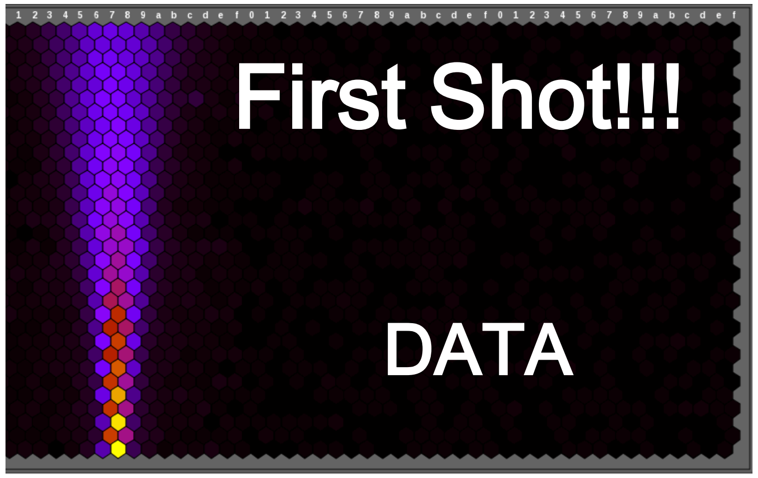

## Beam properties

| | |
|---|---|
| Energy range | 25-750 MeV |
| Max. repetion rate | 50 Hz |
| Pulse duration | 1 - 10 ns |
| Particles/bunch | Up to $10^{10}$ |

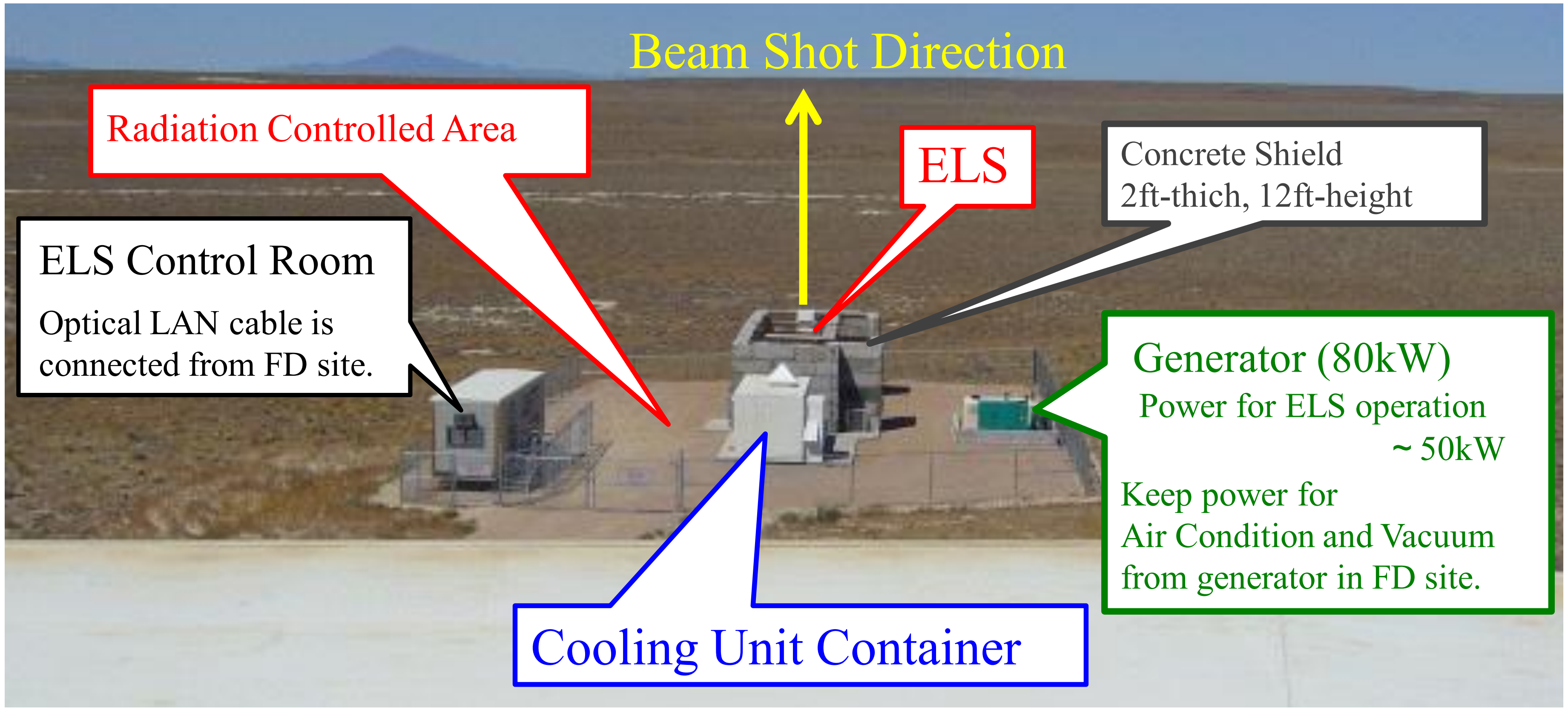
Equivalent shower energy ~ 7 $10^{18}$ eV

# Direct measurement at ELS (Electron Light Source)



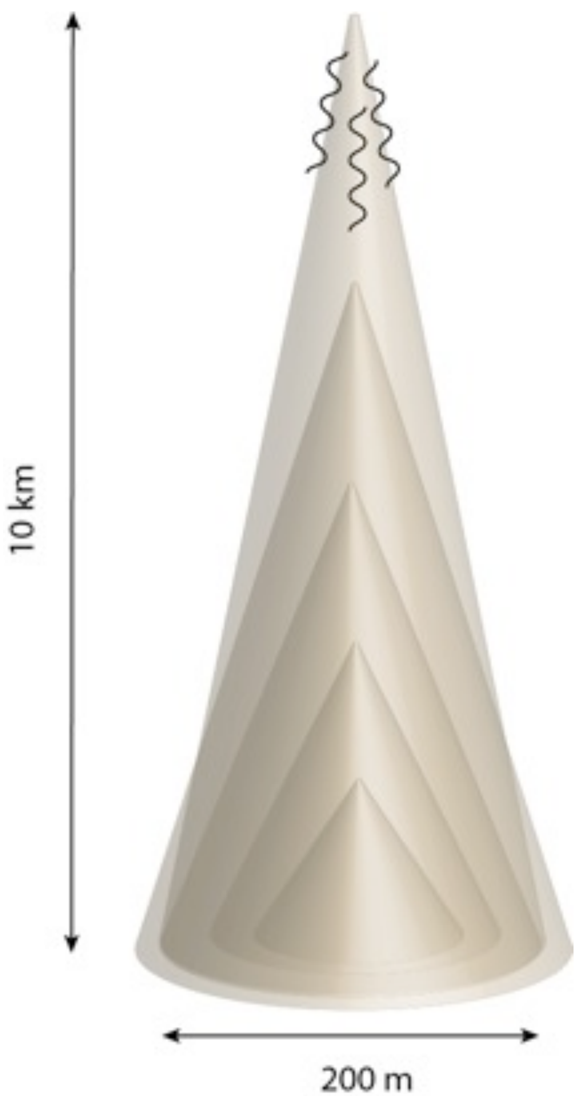

- Electron LINAC, beam in air
- $E_{beam}$ = 40 MeV, $10^9$ electrons
- Equivalent energy 6 x $10^{16}$ eV
- Setup still under development
- First data taken March 2011, next campaign fall 2012



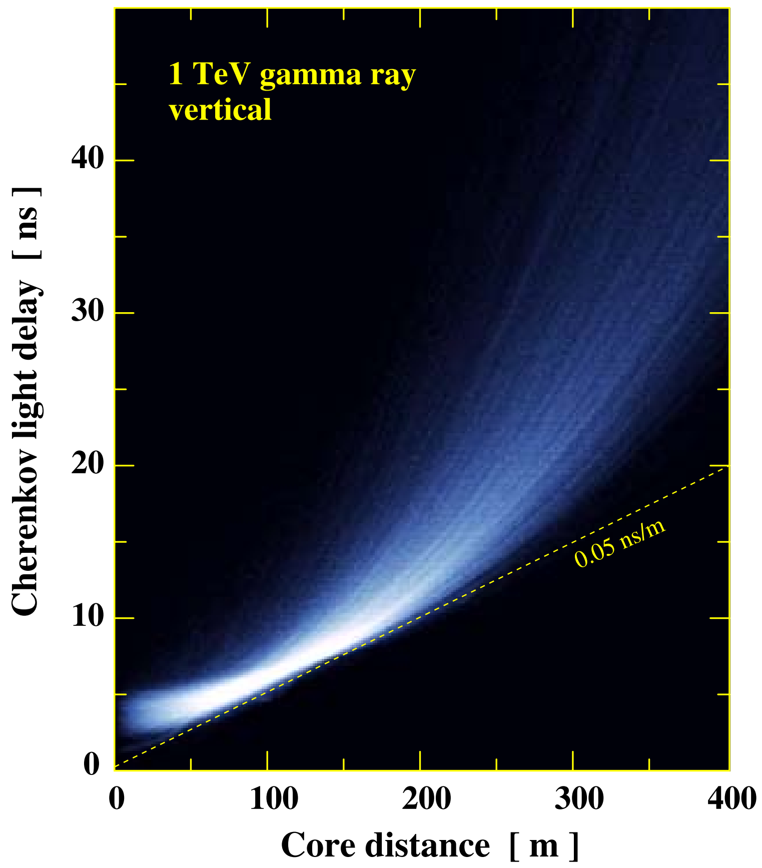

Radiation background due to high-power clystron (2.85 GHz, 20 MW peak power)

*(see poster by Blümer et al.)*

# Incoherent Cherenkov radiation ?

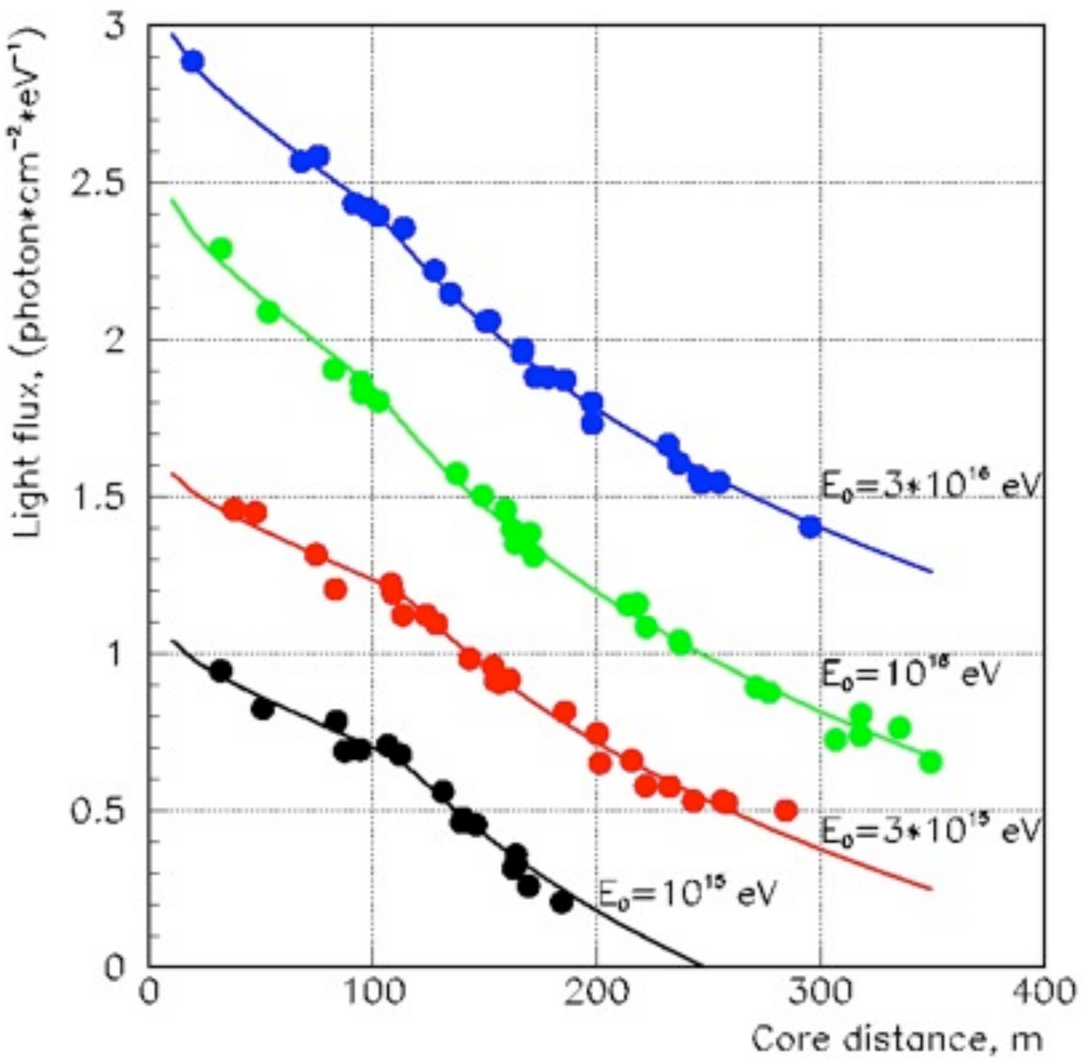



Interplay of refractive index and geometry



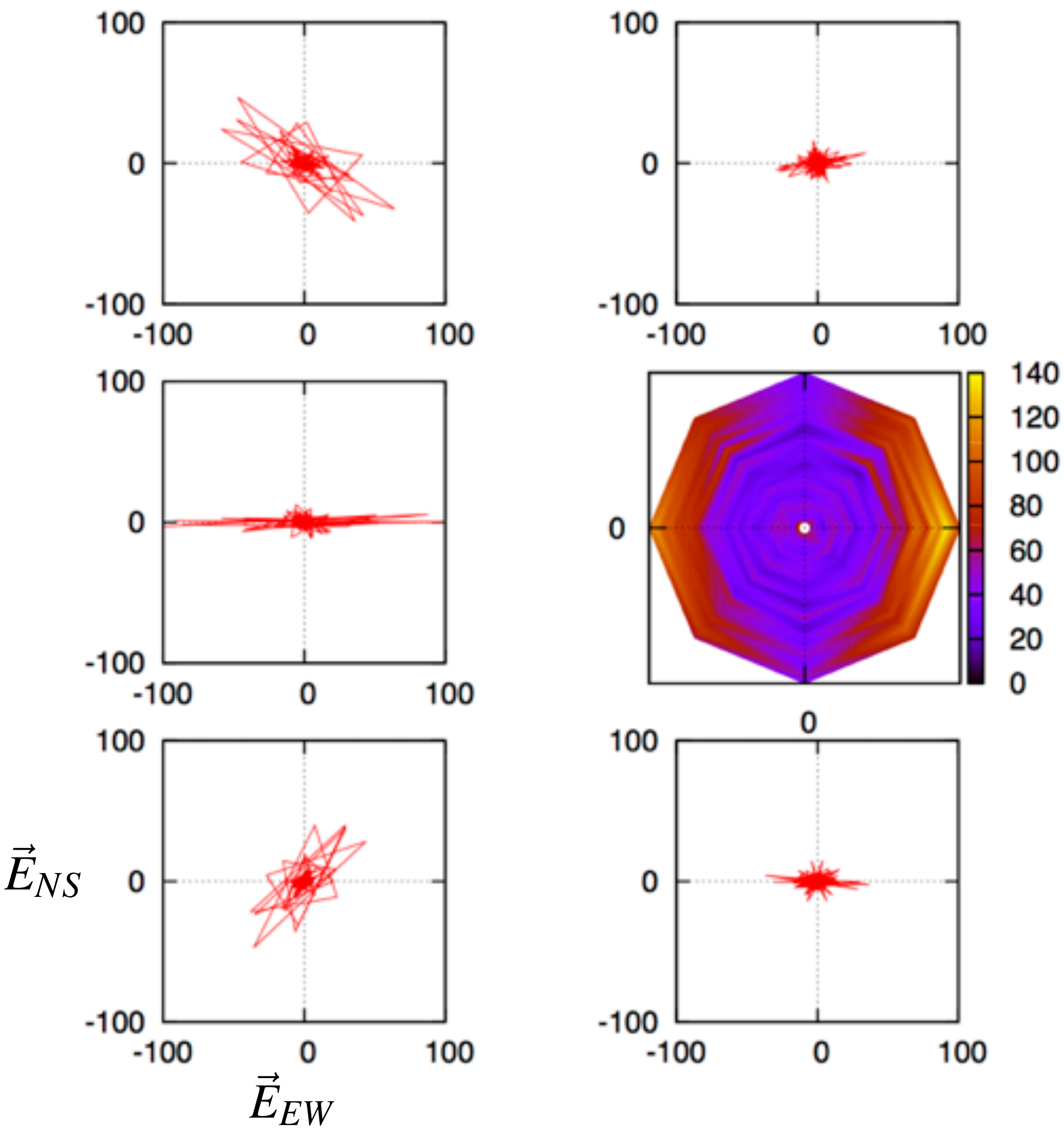

Very short (~10 ns), incoherent pules expected, unpolarized, linear energy scaling

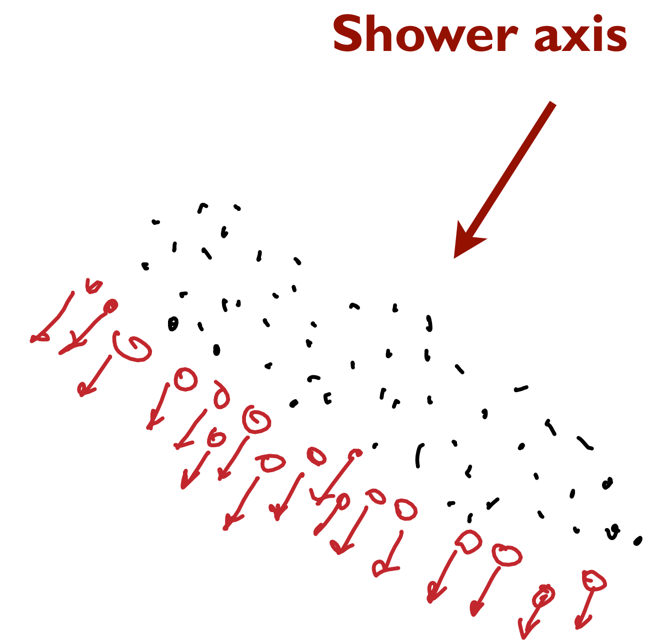
Data from TUNKA experiment




Low energy: filled Cherenkov ring
High energy: falling lateral distribution

# Coherent radiation from shower disk ?



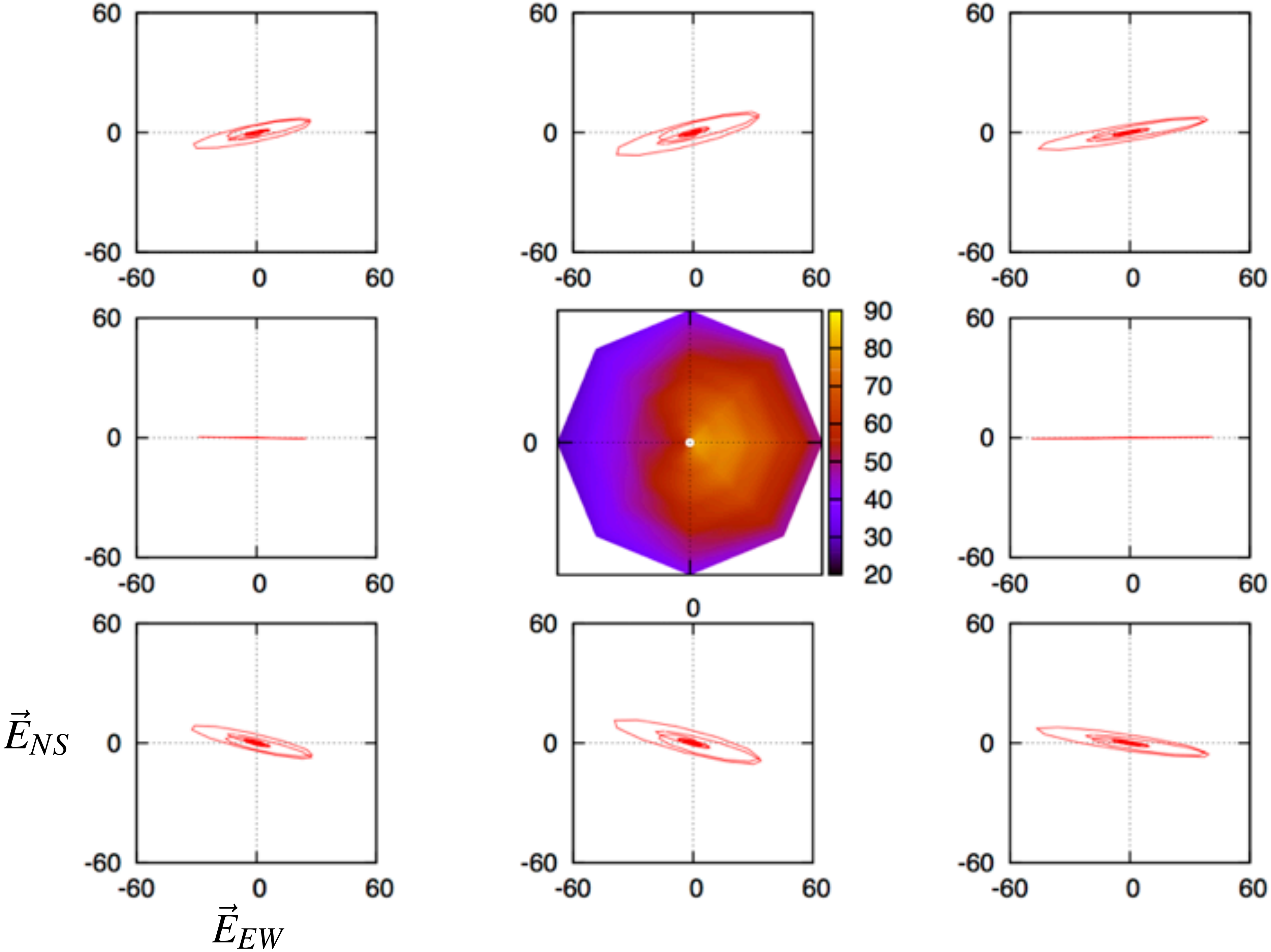

Frequency range 3.4 - 4.2 GHz

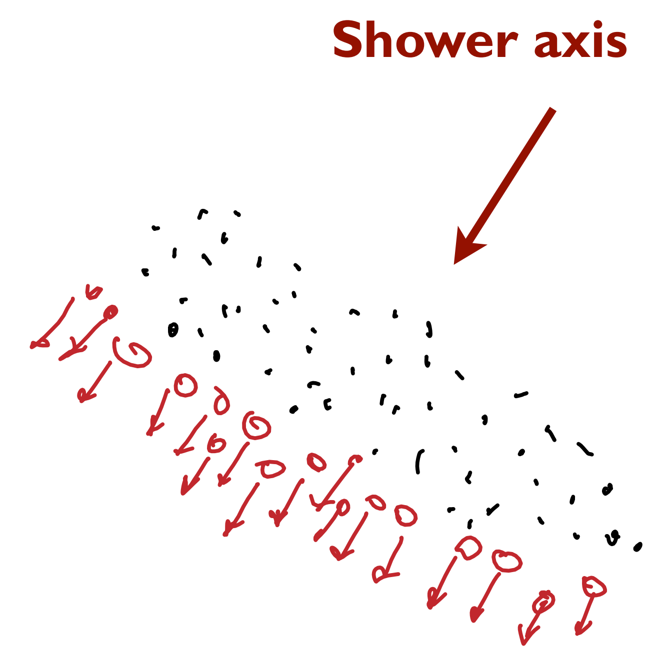
**Radiation of particles in shower disk**

- Incomplete Cherenkov ring at ground
- Characteristic polarization pattern
- Coherent radiation, i.e. quadratic energy scaling

*(Huege et al., CoREAS, vertical Fe shower)*

# Comparison: predictions for MHz range




Frequency range 30 - 80 MHz

**Radiation of particles in shower disk**

- Cherenkov ring at ground
- Characteristic polarization pattern
- Coherent radiation, i.e. quadratic energy scaling

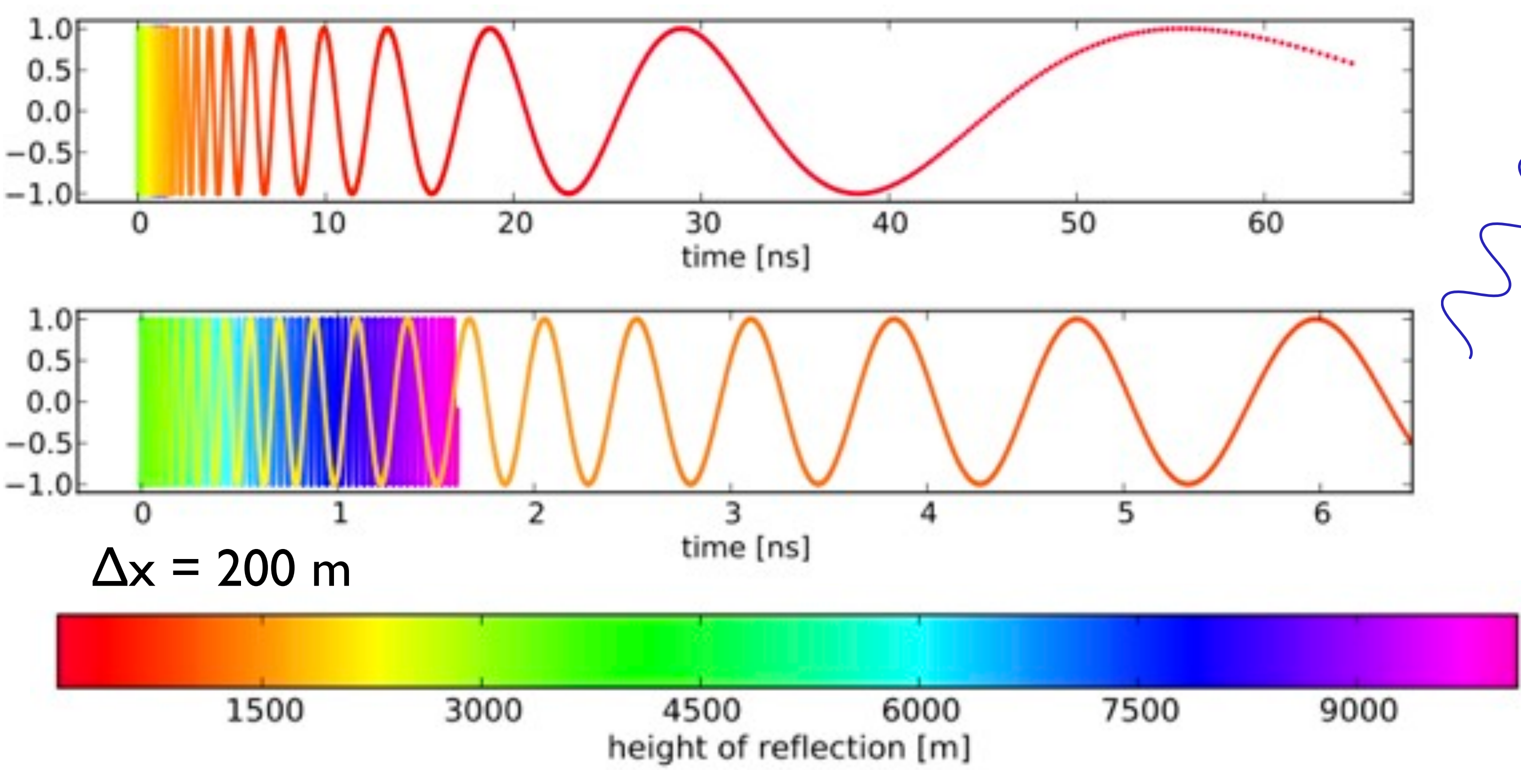
*(Huege et al., CoREAS, vertical Fe shower)*

# RADAR signal of air shower plasma ?

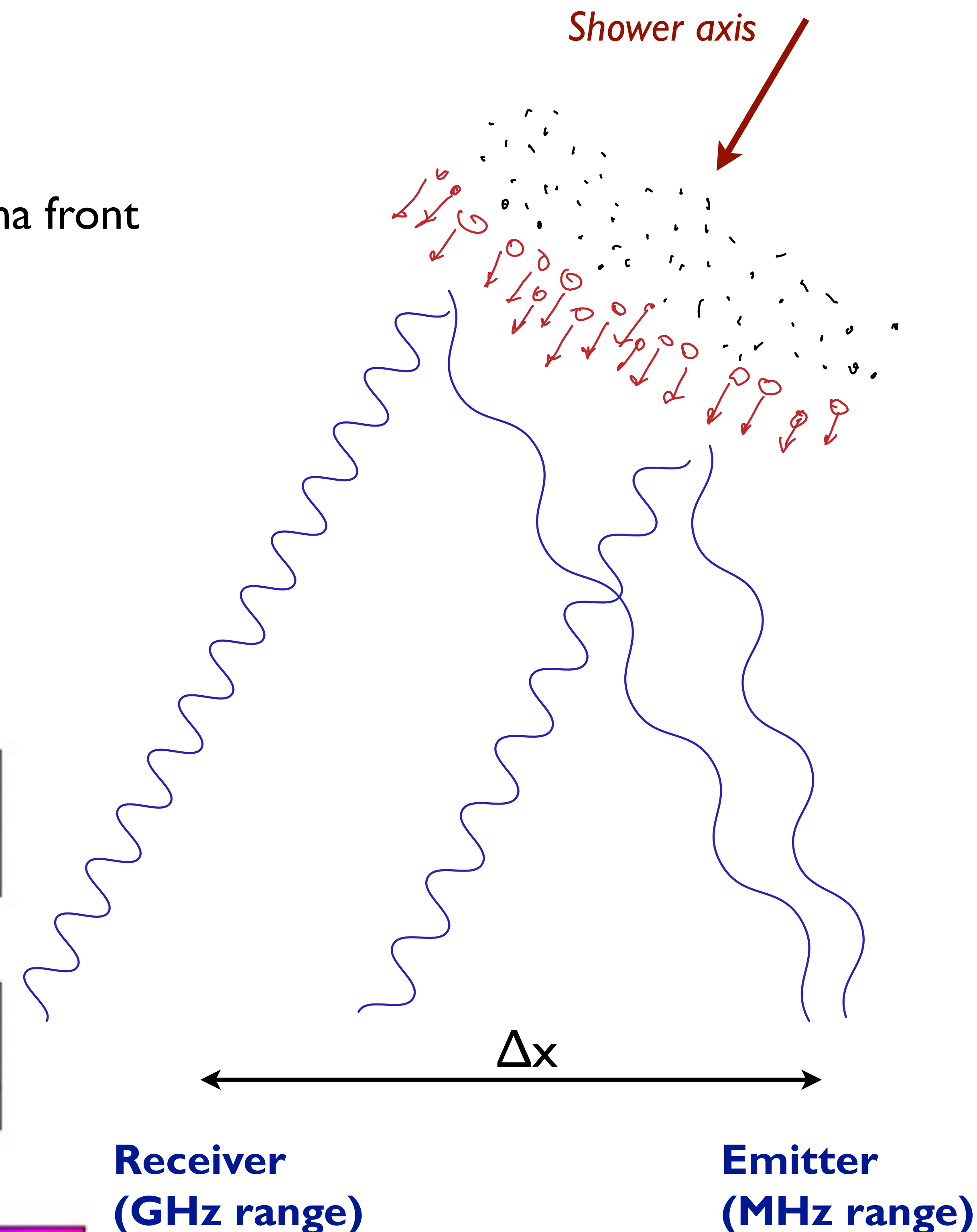
**Reflection off shower plasma**

- Frequency upshift due to relativistic motion of plasma front (not plasma itself)
- Receiver has to be at small angle to shower
- Most configurations without frequency upshift
- No reliable theoretical calculations

**Calulated signal for 30° shower**




*(Baur et al., 2011)*




Cherenkov ring expected

# Conclusions and outlook

- Microwave radiation promising new channel of shower observation

- Strong signal and coherence effects found in early beam experiments, interpreted as **molecular bremsstrahlung**

- Complementary air shower detectors to search for signal

  *AMBER (externally triggered, observation from side)*
  *MIDAS (self-trigger, observation from side)*
  *CROME (externally triggered, narrow beam, Cherenkov cone)*
  *EASIER (externally triggered, wide beam)*

- New generation of beam test experiments

  *MAYBE (E = 3 MeV, near field, first data indicate linear scaling)*
  *AMY (E = 750 MeV, large Faraday chamber)*
  *ELS (E = 40 MeV, realistic air shower)*

- Other sources of GHz radiation from showers

  *Geo-synchrotron and charge excess radiation near Cherenkov cone*
  *Radar reflection off shower disc with frequency upshift*