BIRKELAND CENTRE
FOR SPACE SCIENCE

Modeling and *constraining* a **gamma-ray glow observed at 20 km altitude** during the FEGS/ALOFT campaign

David Sarria(1), Nikolai Ostgaard(1), Hugh J Christian(2), J Eric Grove(3), Mason Quick(4), Samer Al-Nussirat(2), Eric Wulf(3), Georgi Genov(1), Kjetil Ullaland(1), Pavlo Kochkin(1), Martino Marisaldi(1), Nikolai Lehtinen(1), Andrey Mezentsev(1), Shiming Yang(1) and Richard Blakeslee (2)

(1) University of Bergen, Birkeland Centre for Space Science, Physics and Technology, Bergen, Norway
(2) University of Alabama, Huntsville, Alabama, US
(3) U.S. Naval Research Laboratory, Washington DC, US
(4) Marshall Space Flight Center, Huntsville, Alabama, US

Contact: *david.sarria@uib.no*

December 12th, 2018
AGU Fall Meeting, Washington, D.C.
AE31A-01

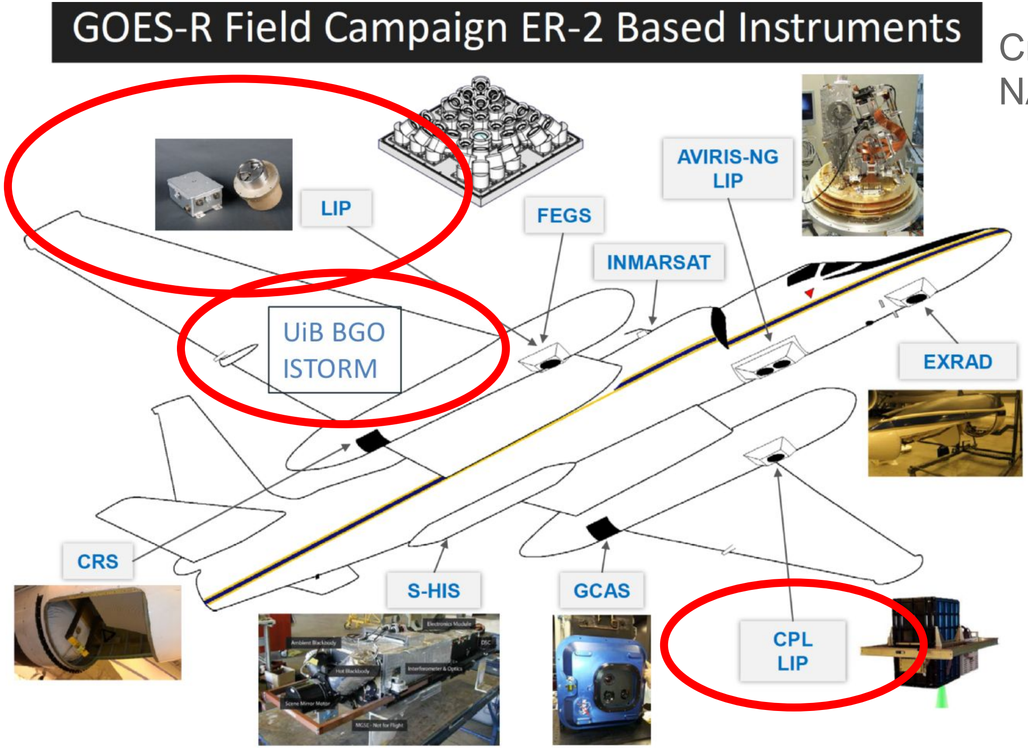
UNIVERSITAS BERGENSIS
UNIS
The University Centre in Svalbard
NTNU
Det skapende universitet

The ALOFT campaign

BIRKELAND CENTRE FOR SPACE SCIENCE

- spring 2017: part of the "GOES-R Validation Flight Campaign"
- 16 flights, total of about 70 flight hours ...
- ... of these, **45 hours over thunderstorm regions.**
- **cruise altitude ≈ 20 km**
- **observed a few Gamma-Ray glows** (but no Terrestrial Gamma-ray Flashes :( )

The FEGS/ALOFT campaign

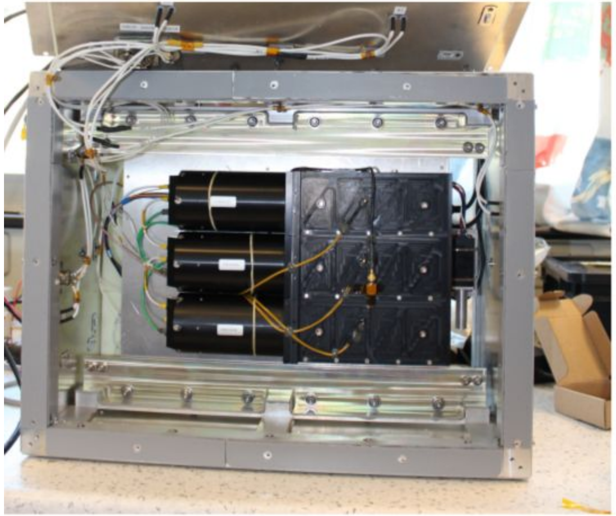


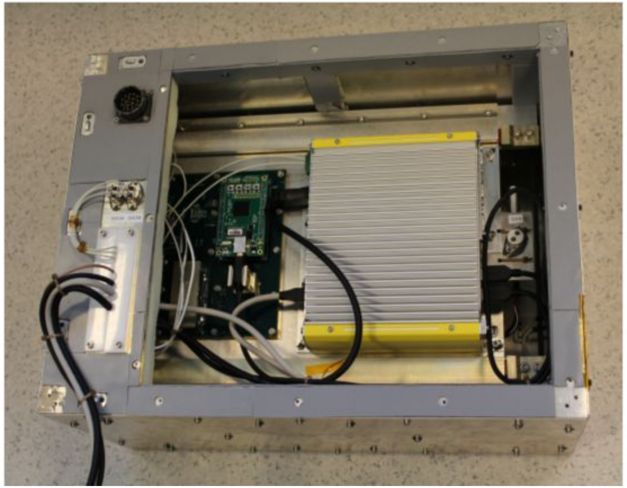
Credits: M. Quick
NASA MSFC

+ ground based networks : COLMA, WWLLN, NLDN

UiB BGO instrument

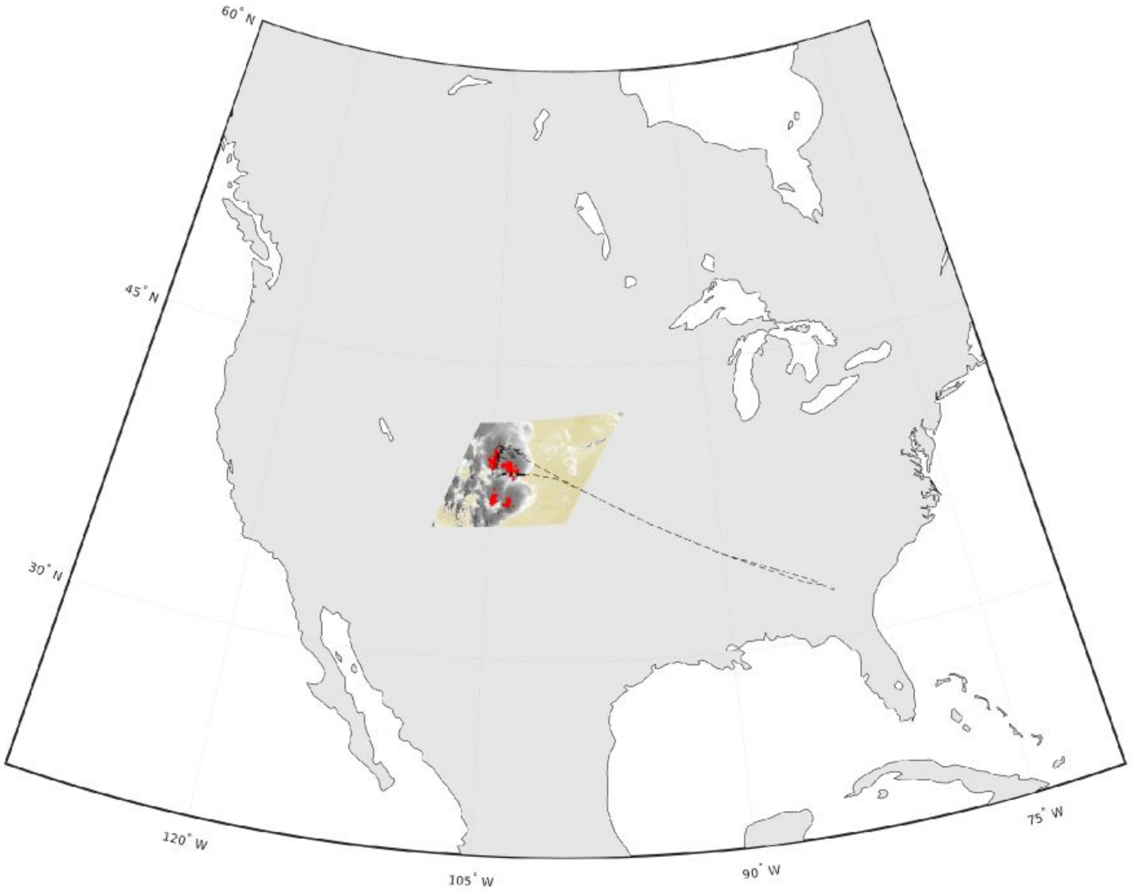
- 3 BGO detectors (15 x 3.2 x 5 cm^3 each), spare from ASIM
- 300 keV to ~40 MeV, ~ 15% resolution @ 511 keV
- 27 ns time resolution
- Continuous high resolution data acquisition
- GPS for absolute time reference





Credits: G. Genov, UiB

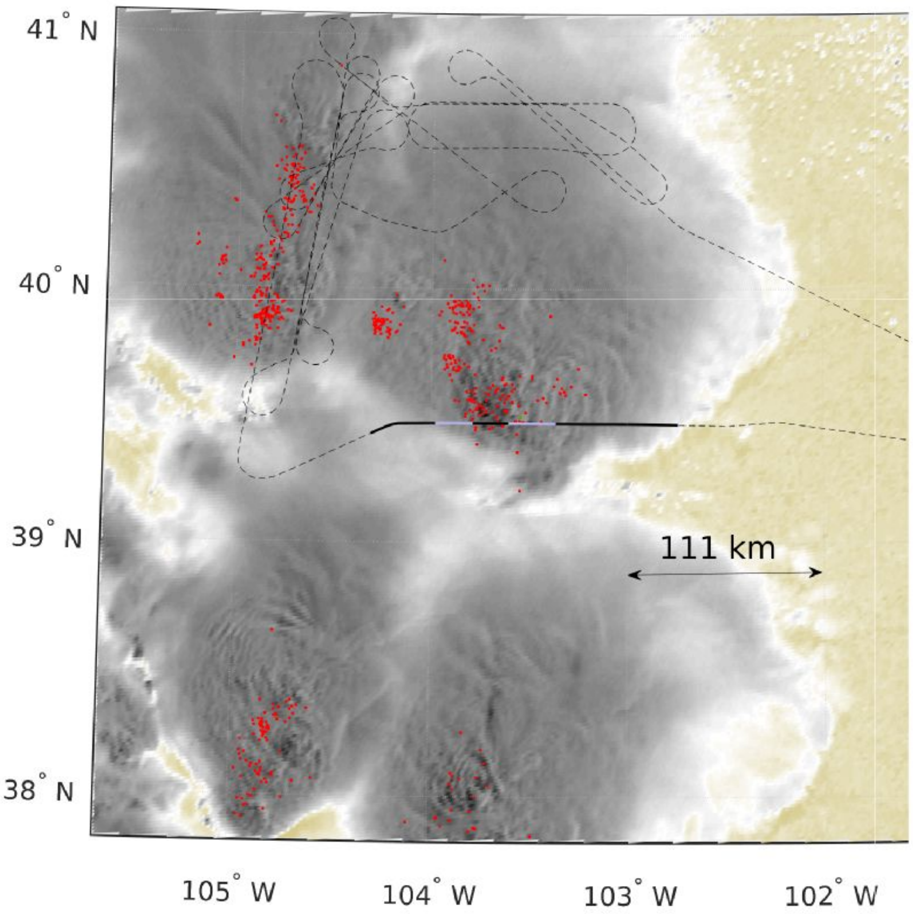
Gamma-Ray Glow Observation



Gamma-Ray Glow Observation

BIRKELAND CENTRE FOR SPACE SCIENCE

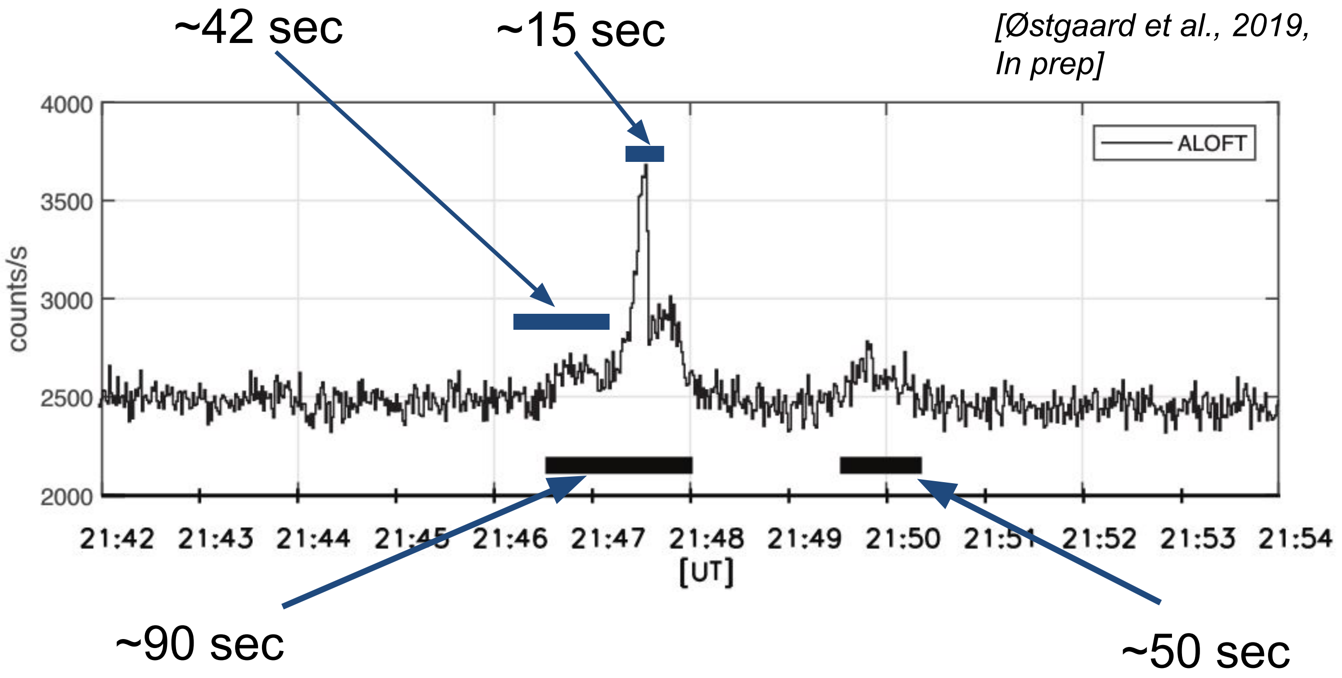
[Østgaard et al., 2019, In prep]



Gamma-Ray Glow Observation: *lightcurve*

BIRKELAND CENTRE FOR SPACE SCIENCE

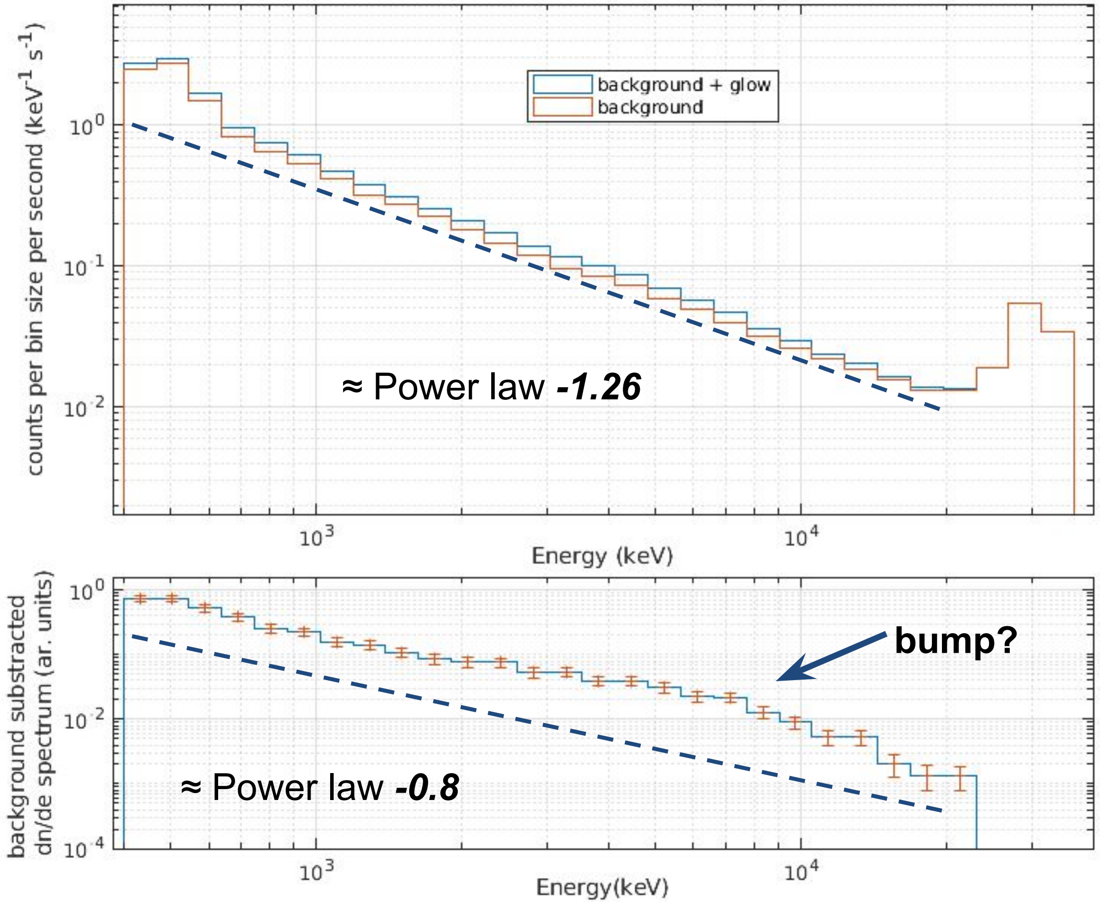
[Østgaard et al., 2019, In prep]



- Background level: ~2500 counts/second
- Glow is between **~10% to ~45%** above background

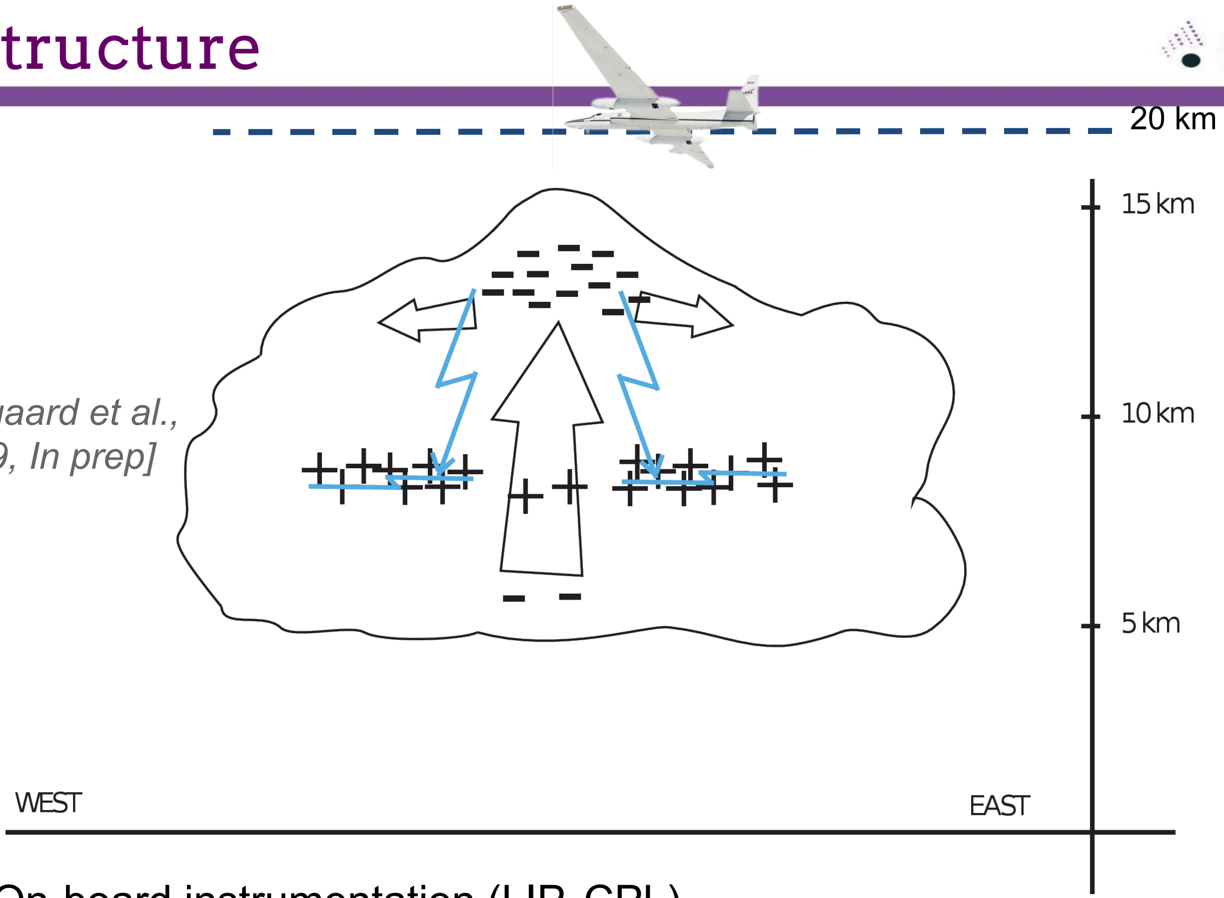
Gamma-Ray Glow Observation: *spectrum*

BIRKELAND CENTRE FOR SPACE SCIENCE



[Østgaard et al., 2019, In prep]

Charge structure



[Østgaard et al., 2019, In prep]

- On-board instrumentation (LIP, CPL)
- + Ground based networks (COLMA, NLDN, WWLLN)

→ **Inverted charge structure**

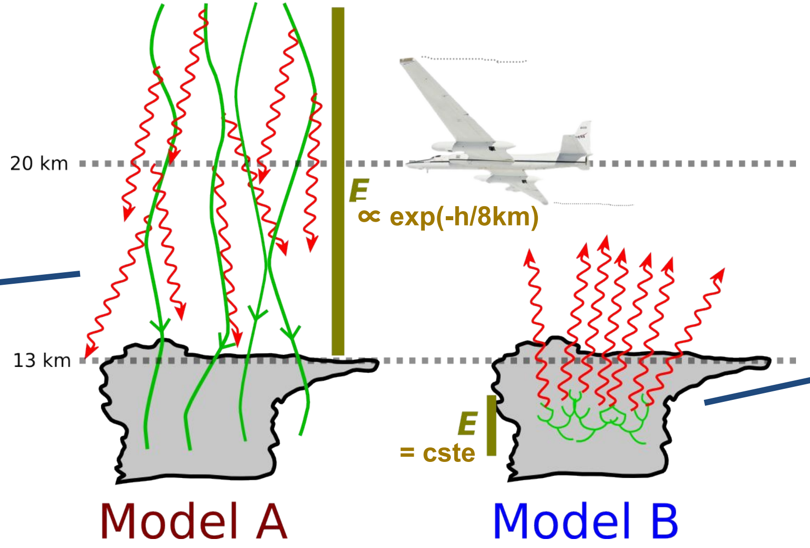
How is the glow produced?

Proposed Models

- **Two** tested **hypothesis** for the **glow production mechanism**:
  - Both consider **cosmic ray** secondaries (mostly e-) as **seed particles**
  - **A** (Above) :
    - E-field **above** the thundercloud *exponentially decaying with altitude*
    - E-field **smaller** than the *RREA* threshold
  - **B** (Below) :
    - E-field **inside** the thundercloud, *constant*
    - E-field **larger** than the *RREA** threshold

*(*RREA = Relativistic Runaway Electron Avalanche)*

requires electron number increase >~ 2

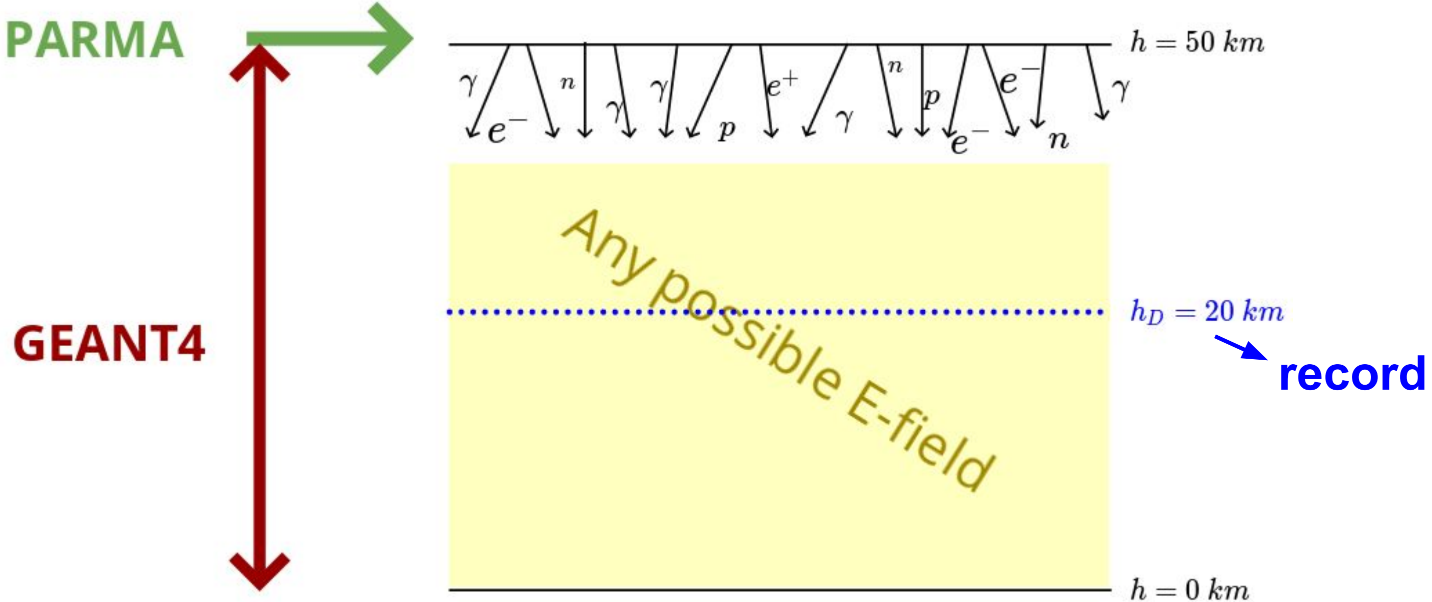


requires electron multiplication factors >~ 1000

- **Can model A and/or model B reproduce the measurements ?**
  - **What magnitude of E-fields are required?**
- **Is it compatible with the E-fields measurements / charge structure?**

Modeling strategy (1/2)

- We use: **PARMA** *[Sato et al., 2008]* and **GEANT4** [Agostinelli et al., 2003]
  - **PARMA is used to generate cosmic ray (secondary) particles at 50 km altitude**
    - photons (γ), electrons(e^-), positrons(e^+), neutrons(n), protons(p)
  - **GEANT4** takes over **below 50 km altitude**, it can handle any possible **Electric field**



RK: advices on setting up Geant4 for this context *[Sarria et al., 2018]*

Modeling strategy (2/2)

Forward modeling

Run a given simulation set-up (A or B, with a given parameter set)

+ background simulation (no E-field)

↓

Record photons (20 km altitude)

↓

Apply response matrix

↙ ↘

Calculate flux increase compared to background

(should be 10 % to 45 %)

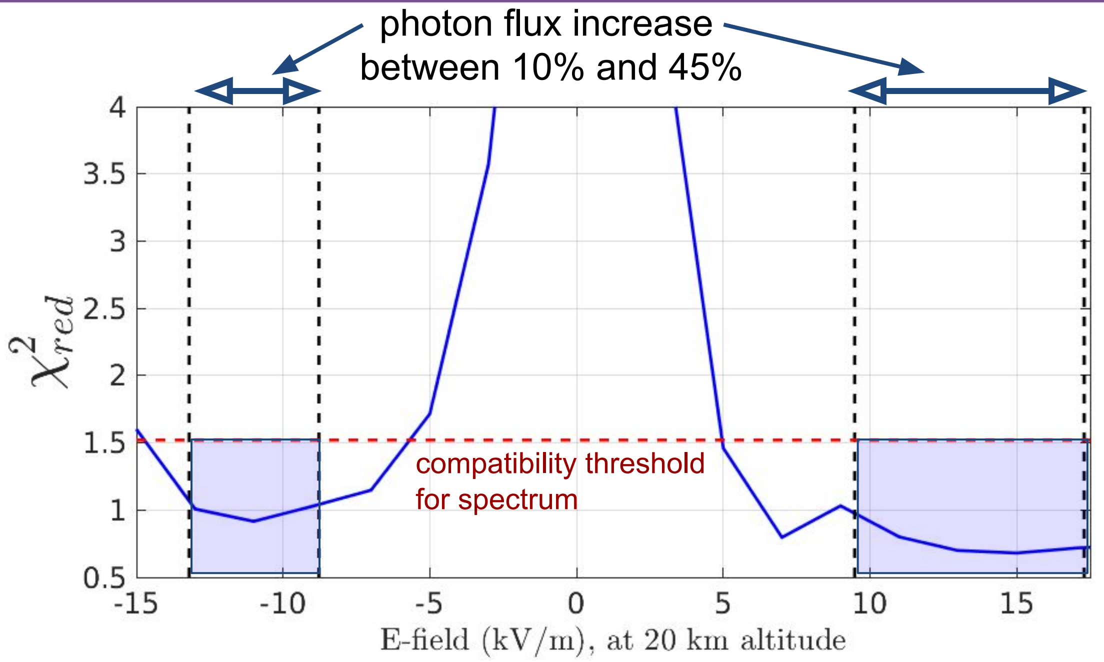
Calculate **X^2** of ***simulated*** **energy spectra** with ***measured***

↘ ↙

Compatible ?

Model A Results

[Østgaard et al., 2019, In prep]



Compatible model A simulations require, at 20 km altitude :

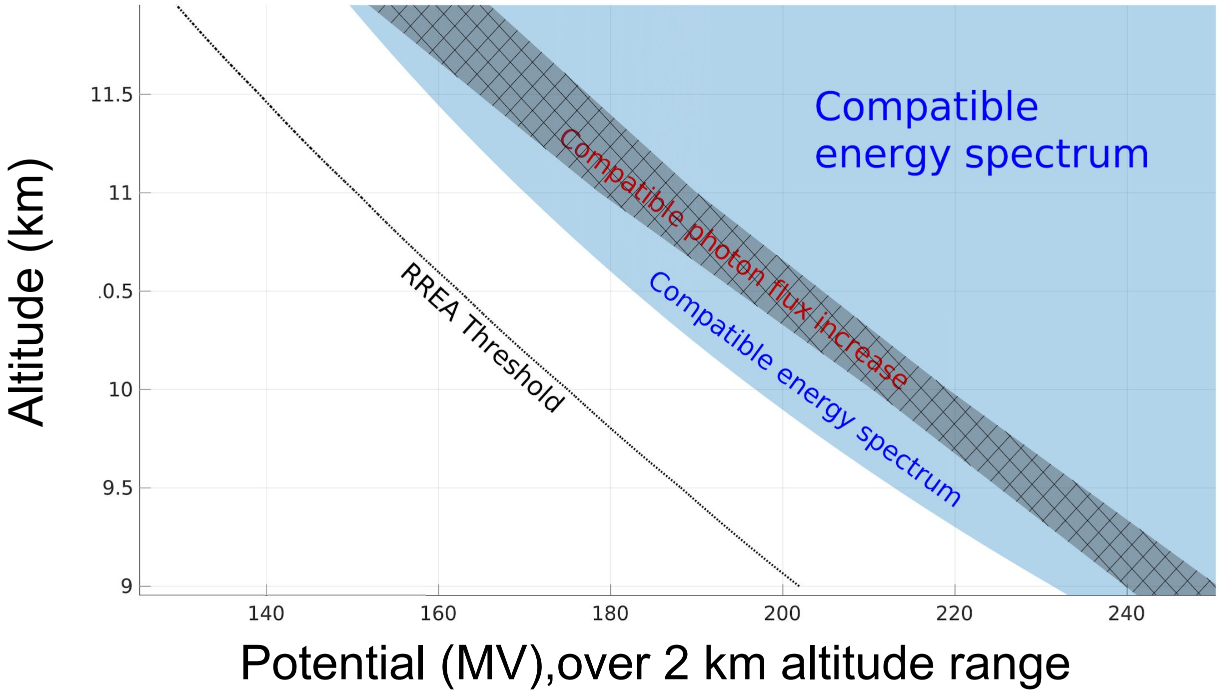
- **-9** kV/m **> E-field > -13** kV/m
- **9.5** kV/m **< E-field < 17** kV/m

But:

Real (measured) **electric fields** (LIP instrument on aircraft) **show values ~10 times lower**

Model B results

- **Probing the Altitude / Potential parameter space**



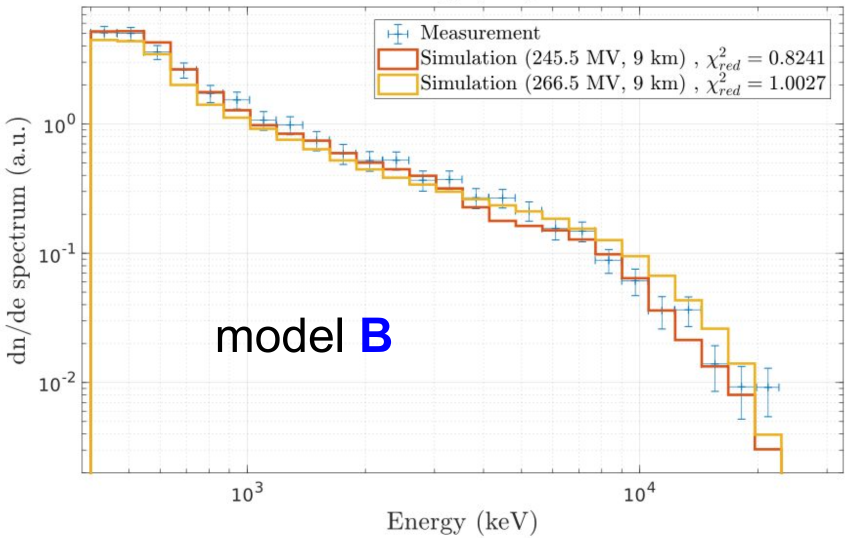
[Østgaard et al., 2019, In prep]

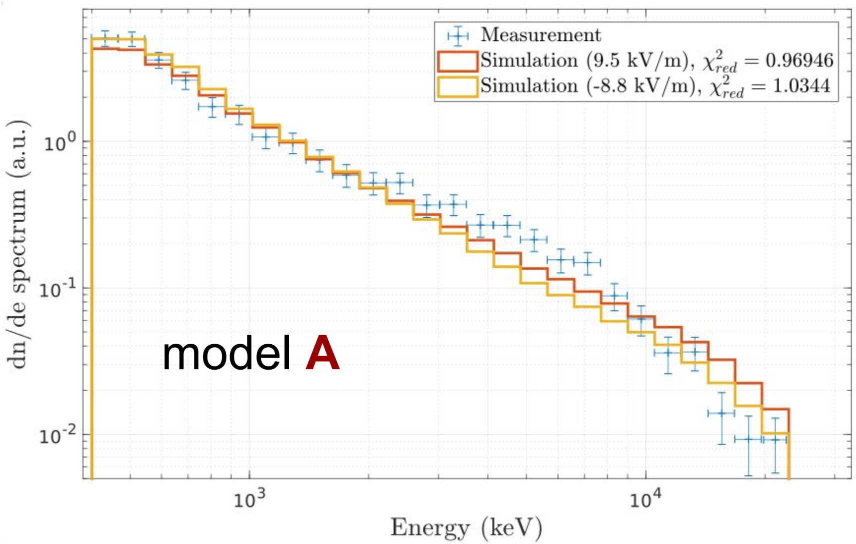
- For any altitude, required electric fields are about **1.2 times the RREA threshold**
- Only **positive potentials can give compatible spectrum fits** (huge 511 keV for negative)
  - ***But*** the **inverted charge structure implies negative potentials**

Model B and A spectra

BIRKELAND CENTRE FOR SPACE SCIENCE

[Østgaard et al., 2019, In prep]





Conclusions / discussion

BIRKELAND CENTRE FOR SPACE SCIENCE

- a Gamma-Ray Glow was observed by the FEGS / ALOFT campaign (May 2017)
  - aircraft was flying at **20 km altitude** over thunderstorm
  - X/gamma ray increase of **10% to 45% above background**
  - **thundercloud likely presents an inverted charge structure**
- we **investigated two possible production mechanisms** that may explain it :
  - The Above model :
    - An electric field with field strength
      - below the RREA threshold
      - starting from the cloud top (13 km), decaying with altitude
  - The Below model :
    - RREA process inside the cloud (9-12 km)
- **both models** can give**:**
  - **compatible spectra**
  - **compatible particle increase**
- but **both require E-fields inconsistent with** at least **one observation**:
  - Above model : **measured E-field at 20 km altitude 10 times too low**
  - Below model : **- incompatible with inverted charge structure**,
    - long lasting glow with large potential (>160 MV)
    lots of lightning, but no TGF observed *[Smith et al., 2018]*

BIRKELAND CENTRE FOR SPACE SCIENCE

Thank you for your attention

References:

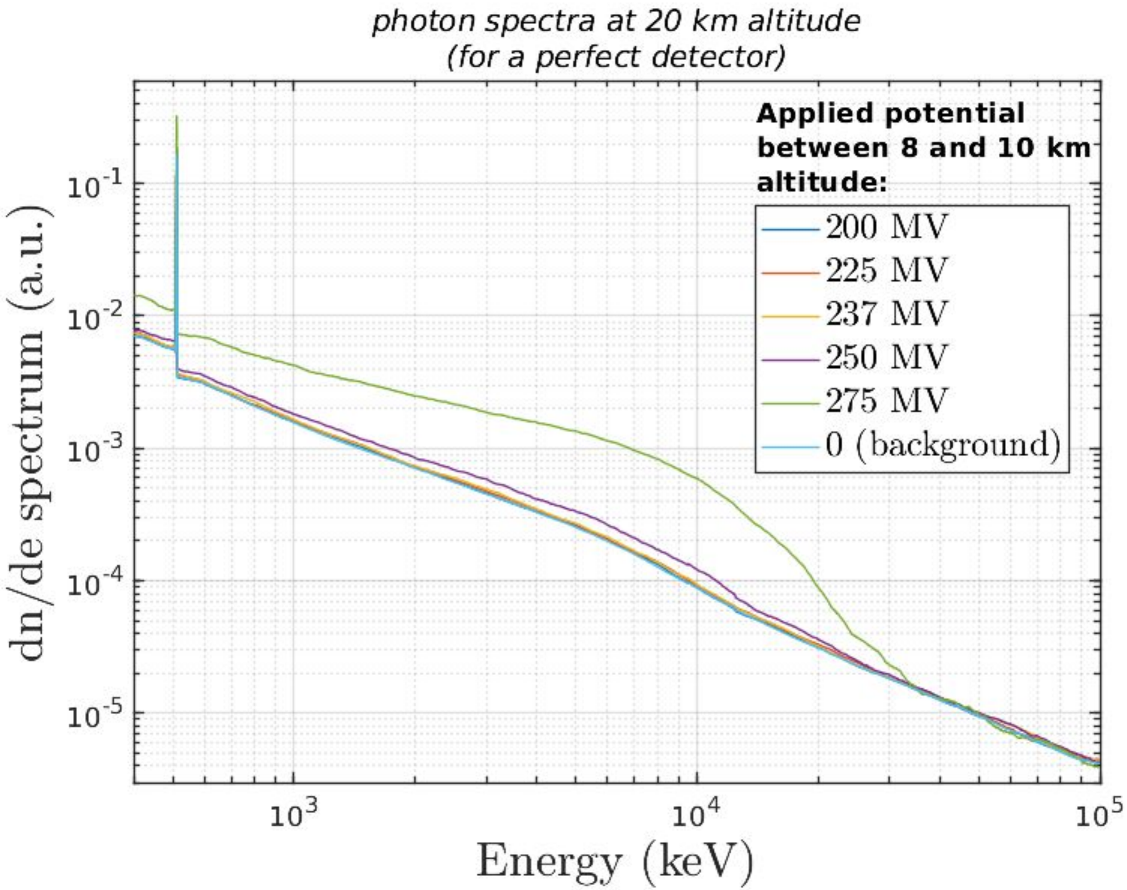
- *N. Østgaard et al.*, ***in preparation***
  Gamma-ray glow observations at 20 km altitude,
  To be submitted to Journal of Geophysical Research, Atmospheres
- *Sato, T., H. Yasuda et al.* (2008),
  Development of PARMA: PHITS-based Analytical Radiation Model in the Atmosphere,
  Radiation Research, 170, 754 244–259, doi:10.1667/RR1094.1.
- *Agostinelli, S., J. Allison, et al.* (2003),
  GEANT4 - a simulation toolkit,
  Nuclear Instruments and Methods in Physics Research A, 506, 250–303,
- *Sarria D. et al* (2018)
  Evaluation of Monte Carlo tools for high energy atmospheric physics II : relativistic runaway electron avalanches
  Geoscientific Model Development
- *Smith D. M. et al.* (2018)
  Characterizing upward lightning with and without a terrestrial gamma-ray flash
  Journal of Geophysical Research, Atmospheres

The ALOFT campaign

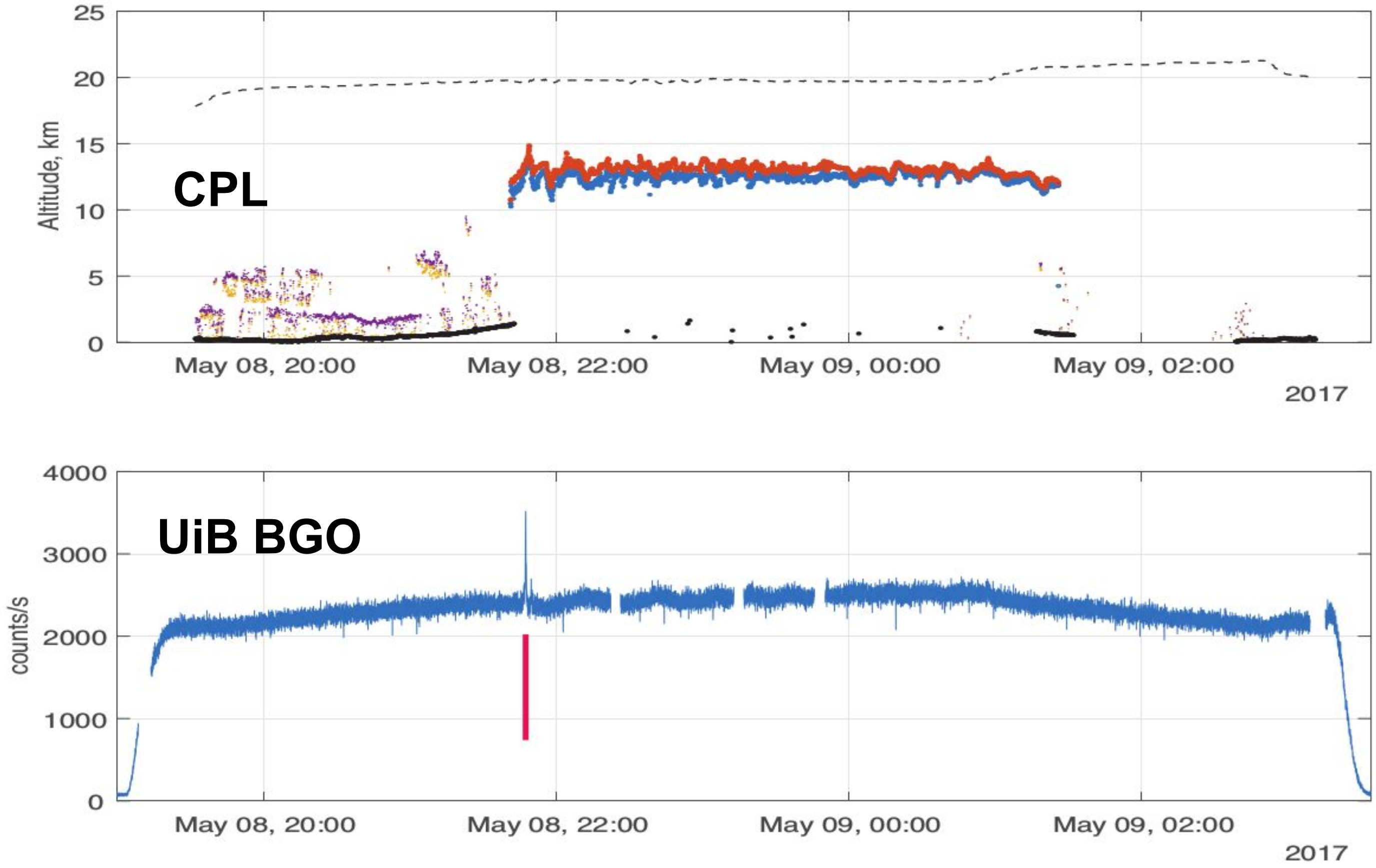
BIRKELAND CENTRE FOR SPACE SCIENCE

- In this presentation:
  - Focus on the **May 8th** **Gamma-ray Glow(s)**
  - Charge structure of the cloud system
  - Possible mechanisms that can produce the gamma-ray glows
    - Monte-Carlo modeling, comparison with data

Model B results

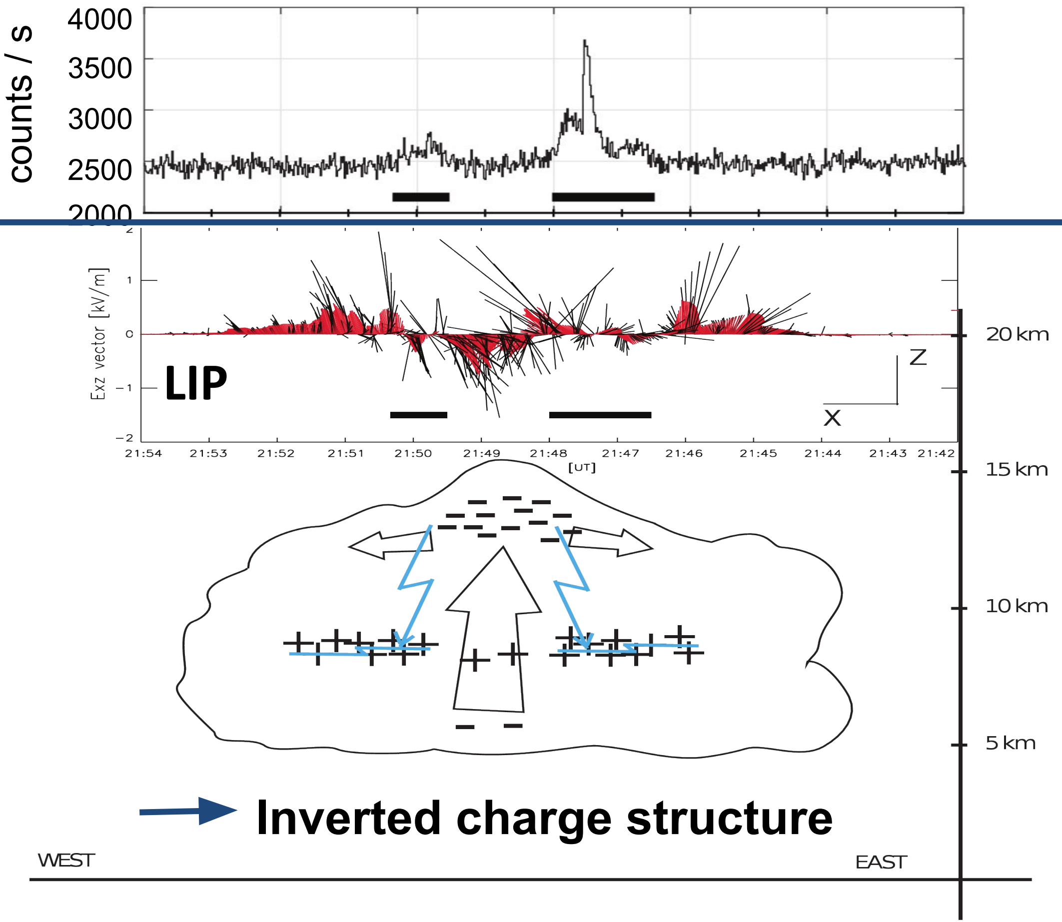


Gamma-Ray Glow Observation



Charge structure

[Østgaard et al., 2019, In prep]

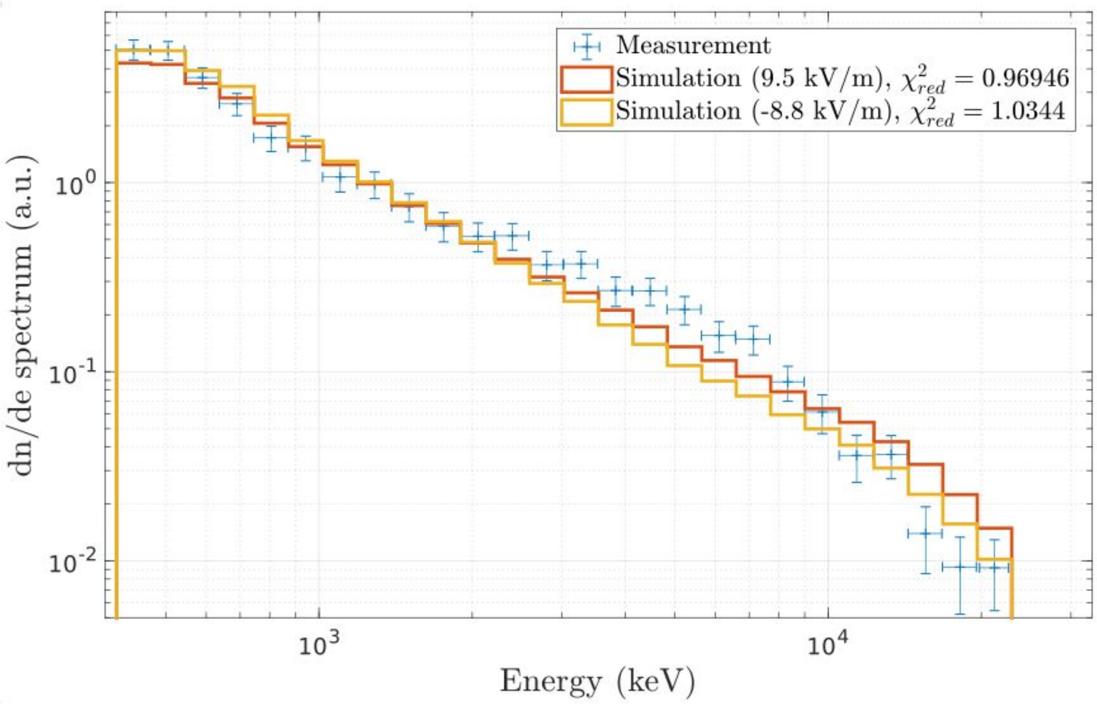


Inverted charge structure

Model A Results: energy spectra

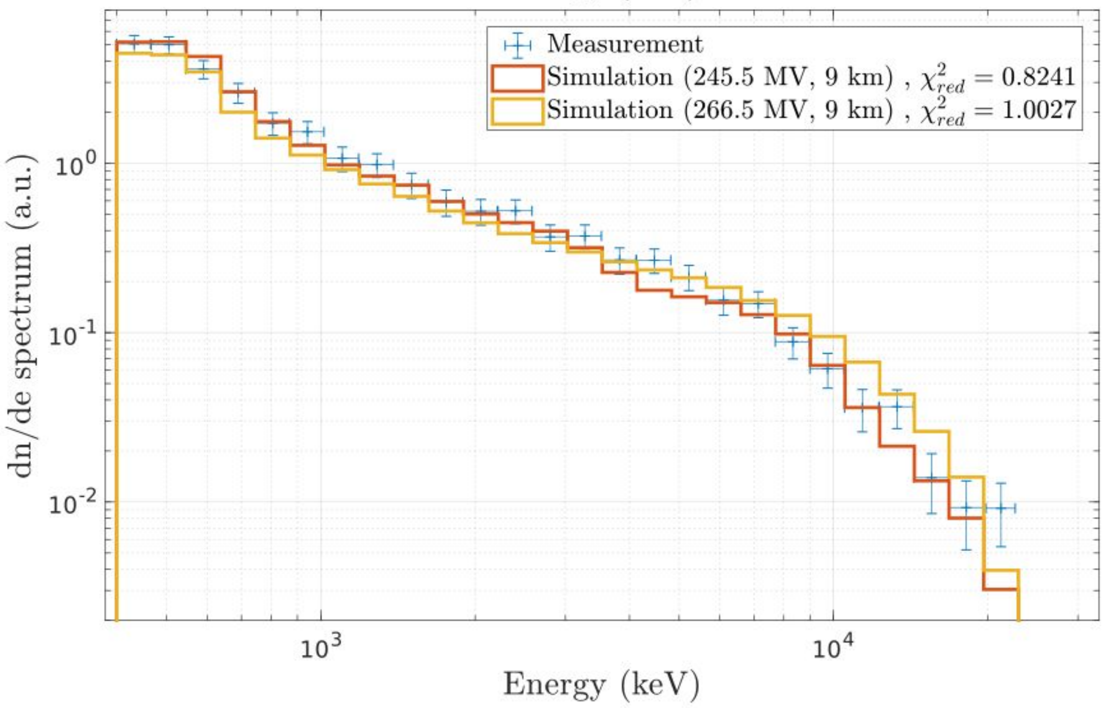
BIRKELAND CENTRE FOR SPACE SCIENCE

[Østgaard et al, 2019, In prep]



Model B results

[Østgaard et al, 2019, In prep]



Model A (Above) description

BIRKELAND CENTRE FOR SPACE SCIENCE

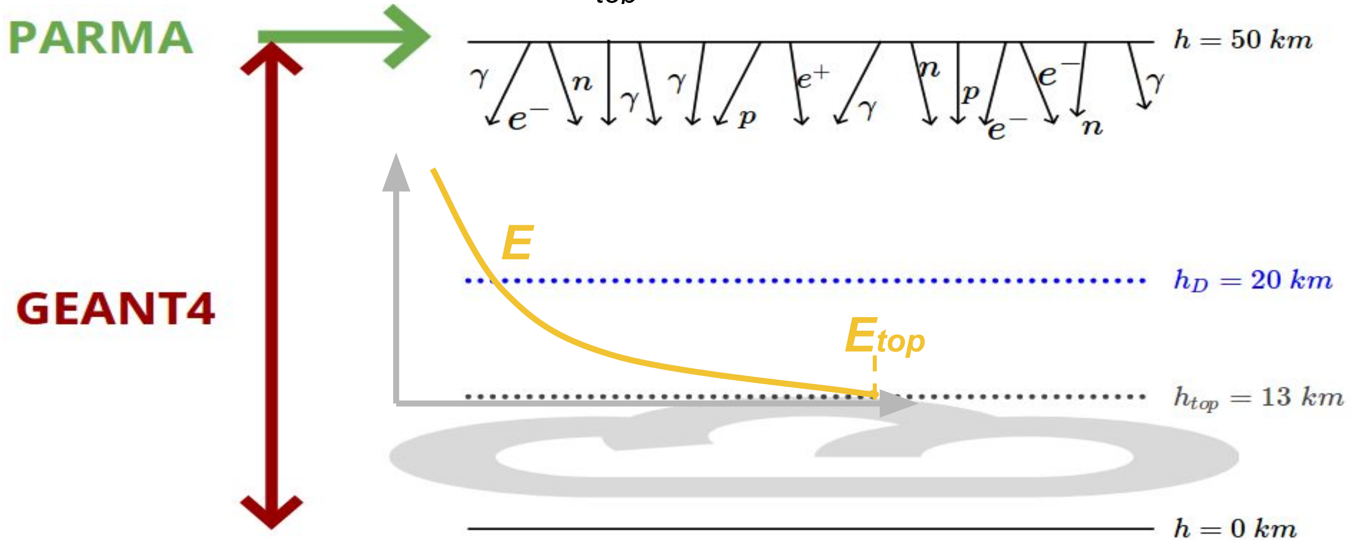
Electric field starts from the top of the clouds and decays exponentially with altitude

$$E(h) = E_{top} \exp\left(\frac{-(h - h_{top})}{H}\right)$$

H~8 km

One free parameter :

- **E-field at the at the cloud top**: E_{top} (implies a given E-field at 20 km altitude)

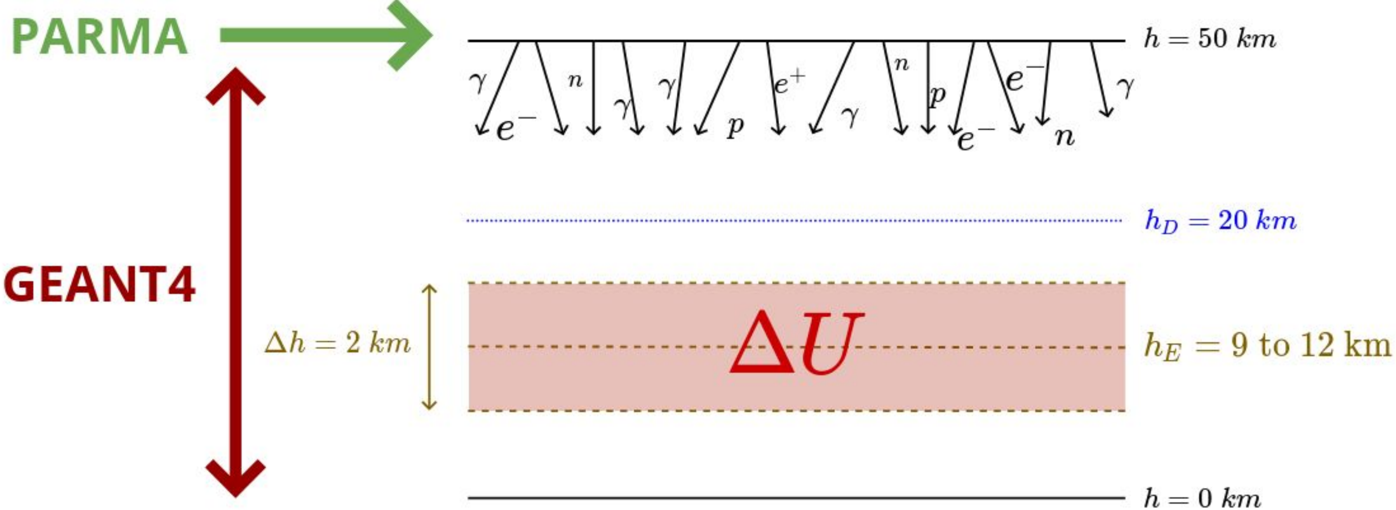


Model B description

E-field is applied over a region of 2 km height within the cloud.

Two free parameters :

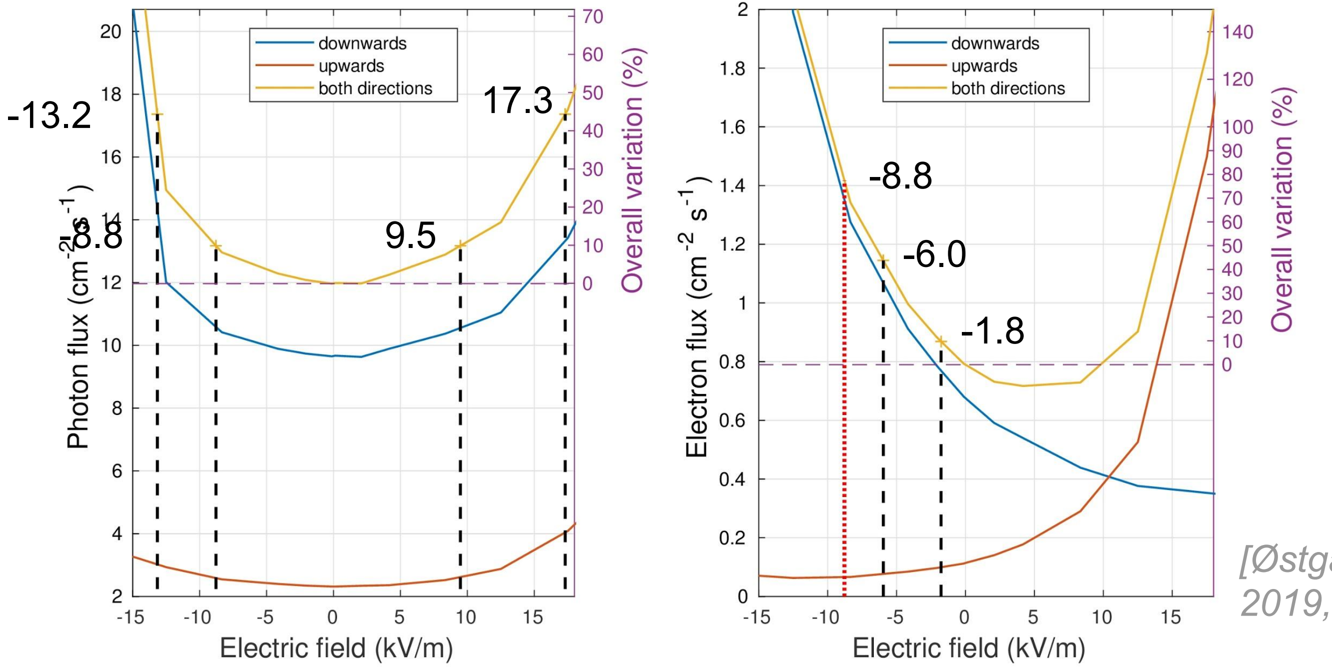
- altitude of the center of the E-field: h_E *(9 to 12 km)*
- applied potential ΔU *(0 to 250 MV)*



Model A Results: particles' flux variation

BIRKELAND CENTRE FOR SPACE SCIENCE

Records at 20 km altitude



[Østgaard et al, 2019, In prep]

Important:

- Background flux is ~ 90 % photons
- 10 % photon flux increase <-> 80 % electron increase

→ **each extra electron produces ~ 2.5 extra bremsstrahlung photons**

Discussion

BIRKELAND CENTRE FOR SPACE SCIENCE

Both **models A and B** can **give**
- **compatible spectrum fit**
- **compatible particle increase**

Both have problems :
- **Above** model :
  - **measured E-field at 20 km altitude is 10 times lower than required**.
- **Below** model :
  - requires **cloud charge structure inconsistent with measurements**
  - requires **E-field > 1.2 times RREA threshold maintained for more than two minutes**
    - How can a large potential be maintained for so long ?
    - A lot of **lightning at the same time of the glow**:
      - why is it not discharging the field below RREA ?
      - why is there no TGF produced ?
        - See Smith et al., 2018 "Characterizing upward lightning with and without a terrestrial gamma-ray flash"