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Lightning Detection and Meteorological Applications from Ground and Space

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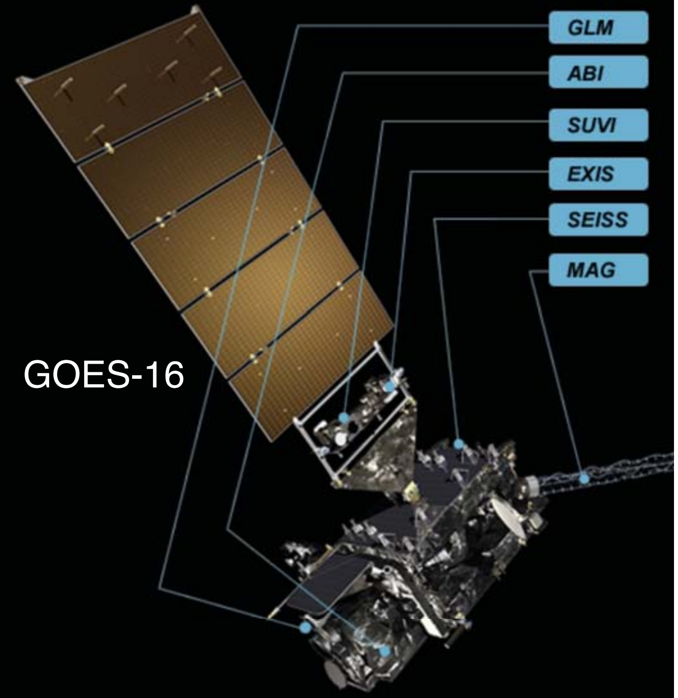
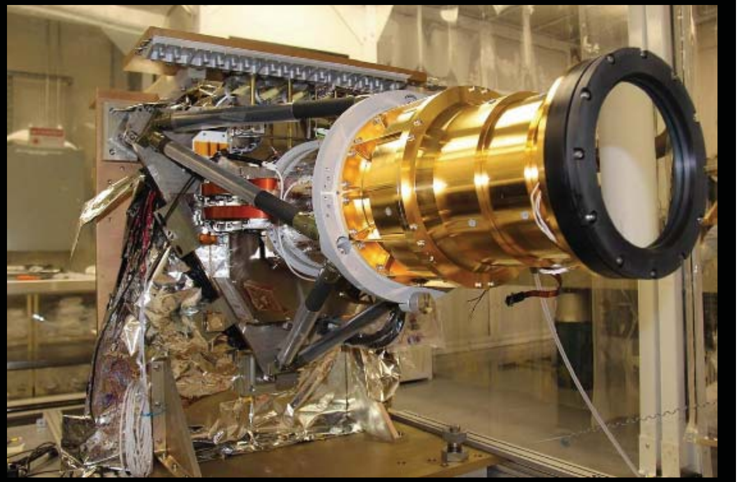
Acknowledgments: Scott Rudlosky, Kristin Calhoun, Chad Gravelle, Joe Zajic, Clem Tillier, Samantha Edgington, Matt Brothers, Ted Mansell, Vicente Salinas, Chris Schultz

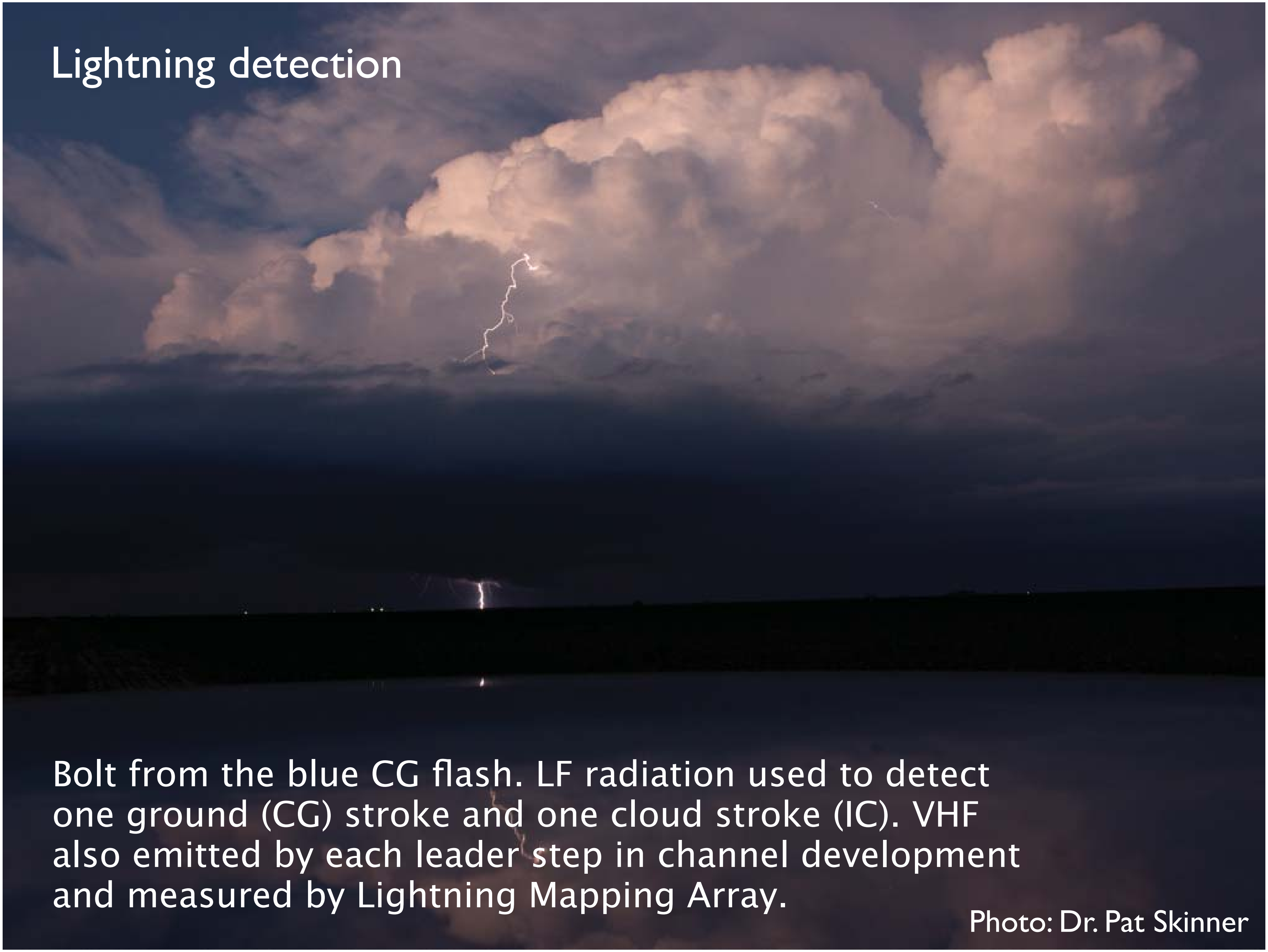


Geostationary Lightning Mapper

Source: goes-r.gov



This work supported by NSF-1352144 and NASA/NOAA through the GOES-R GLM Validation program


Lightning detection
Bolt from the blue CG flash. LF radiation used to detect one ground (CG) stroke and one cloud stroke (IC). VHF also emitted by each leader step in channel development and measured by Lightning Mapping Array.
Photo: Dr. Pat Skinner

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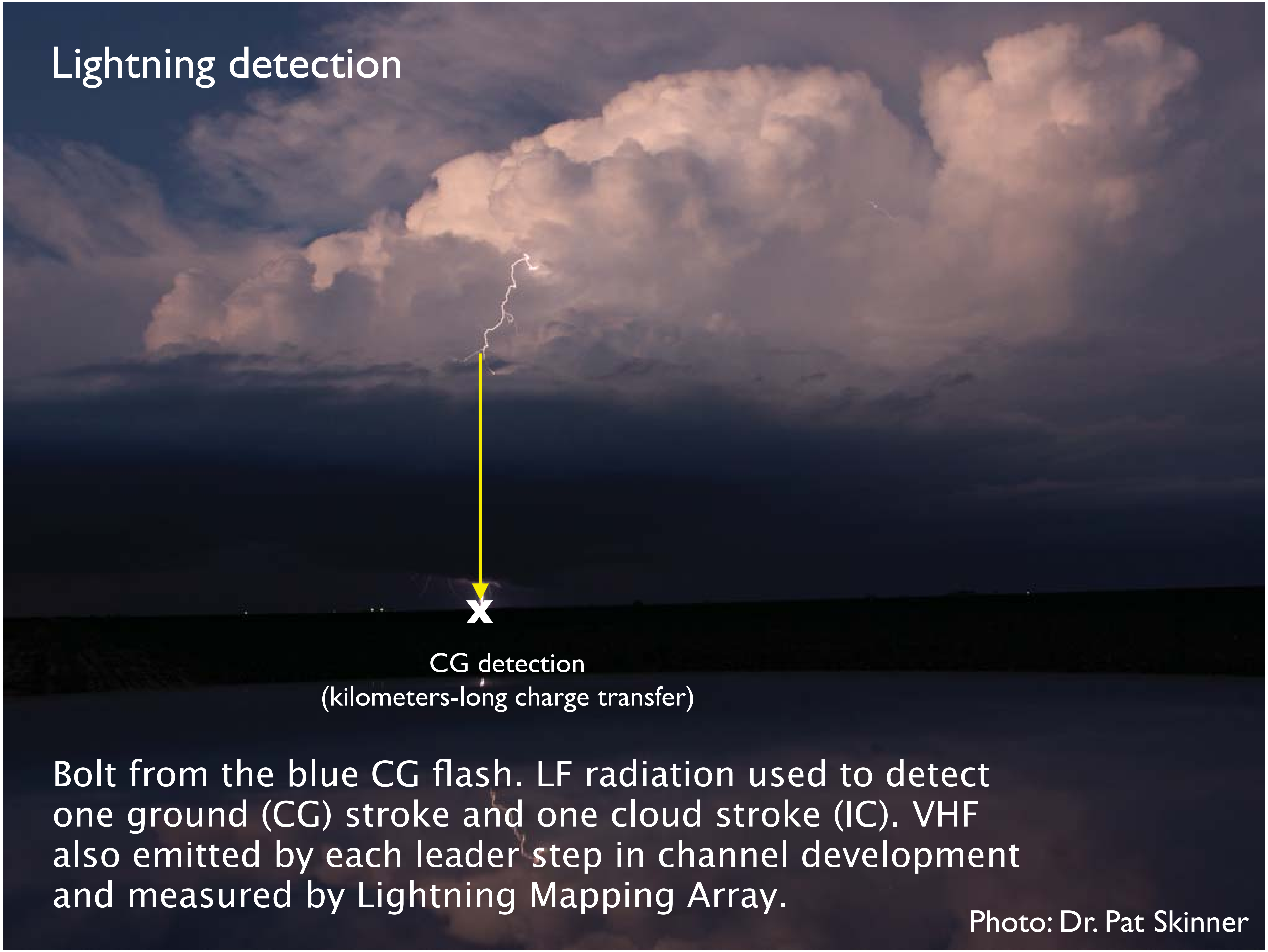

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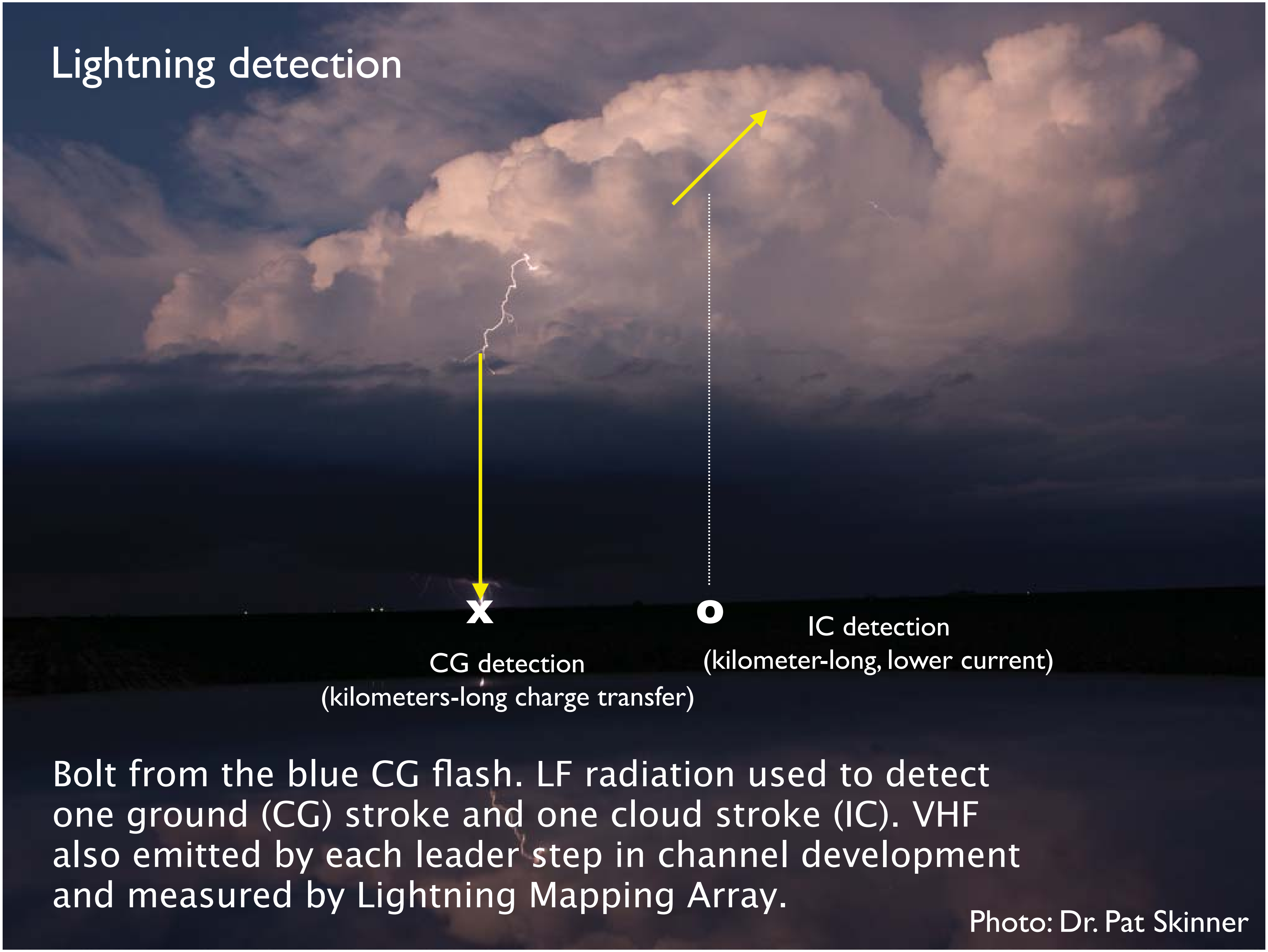

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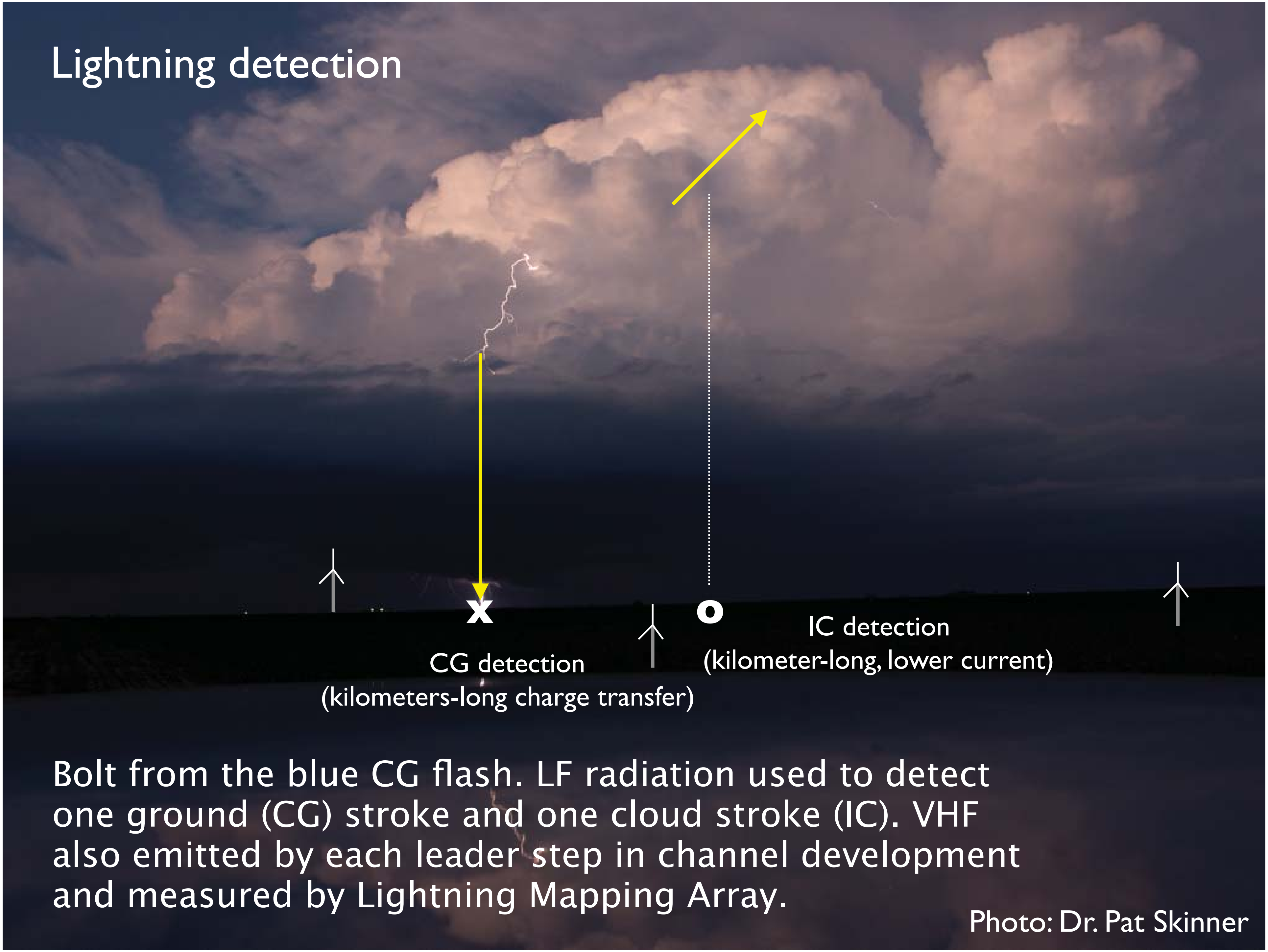
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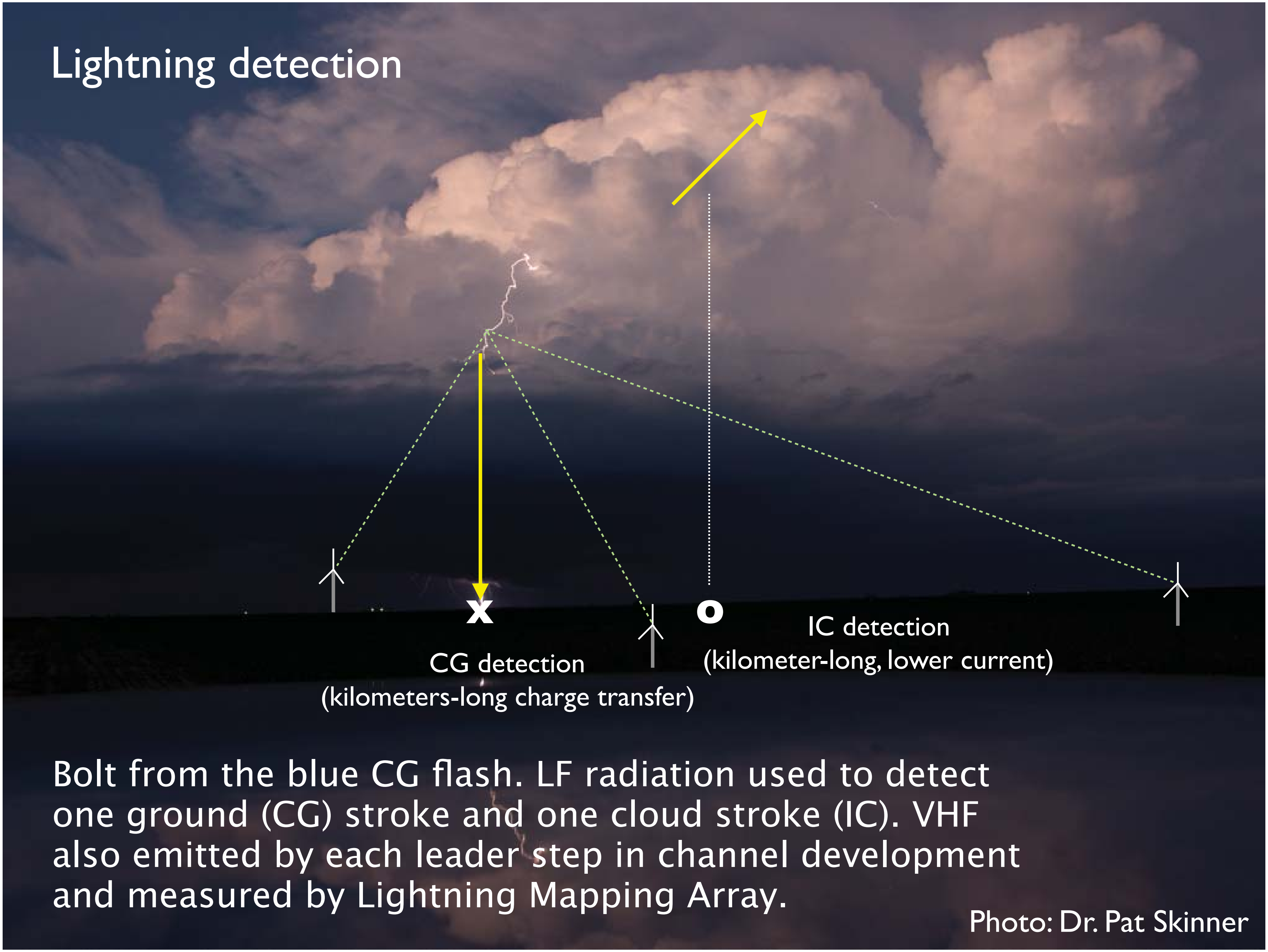
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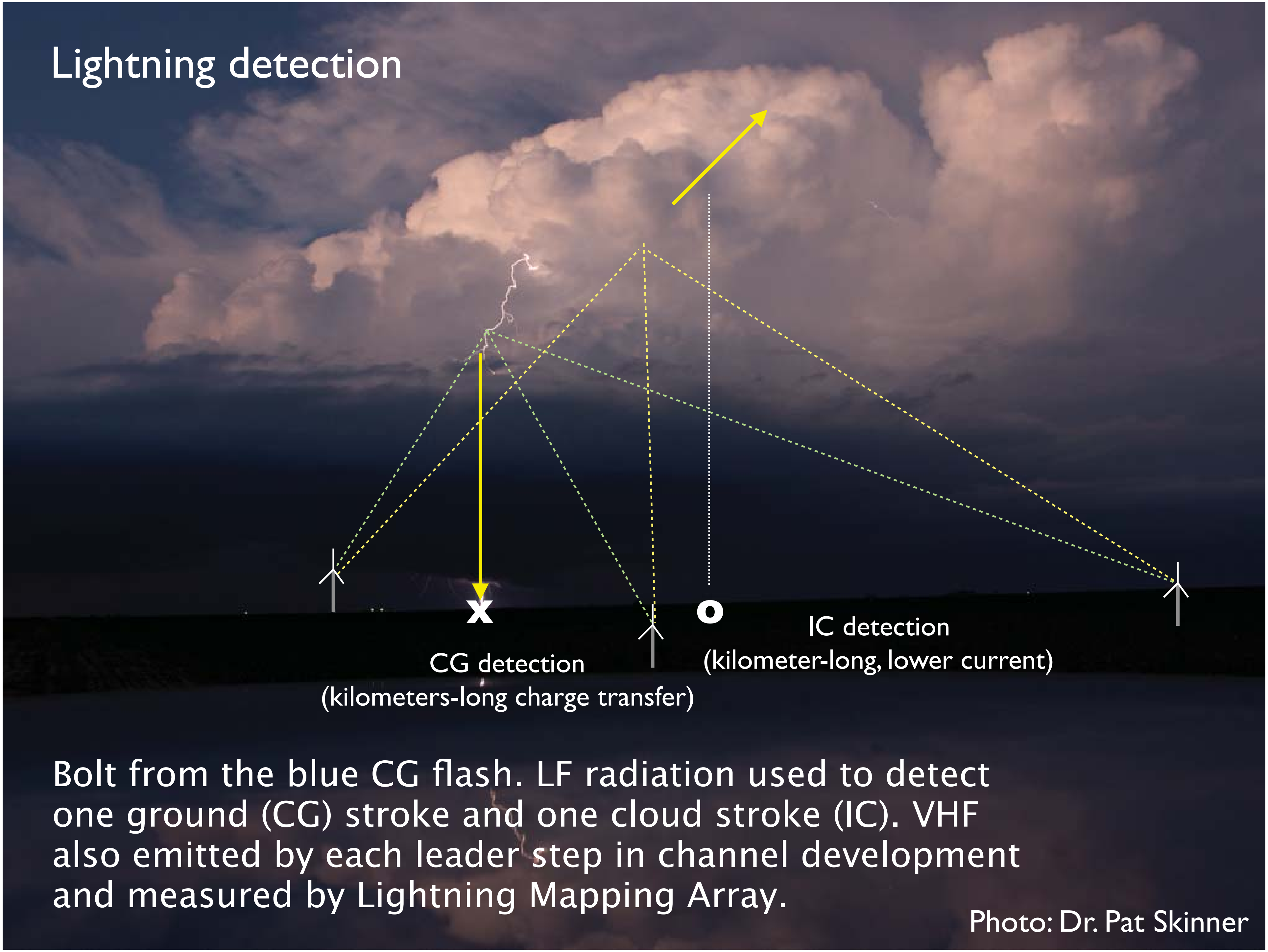

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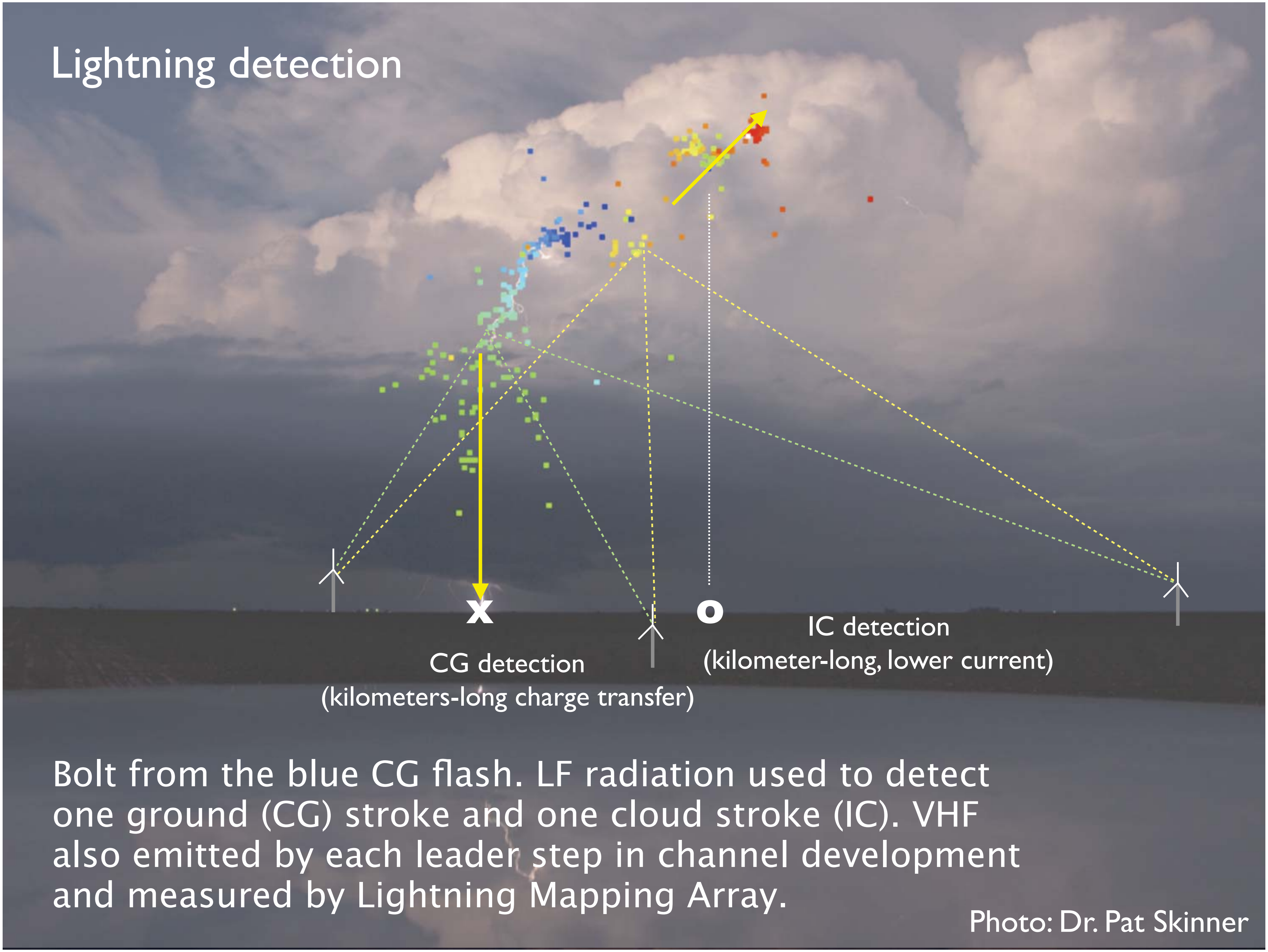
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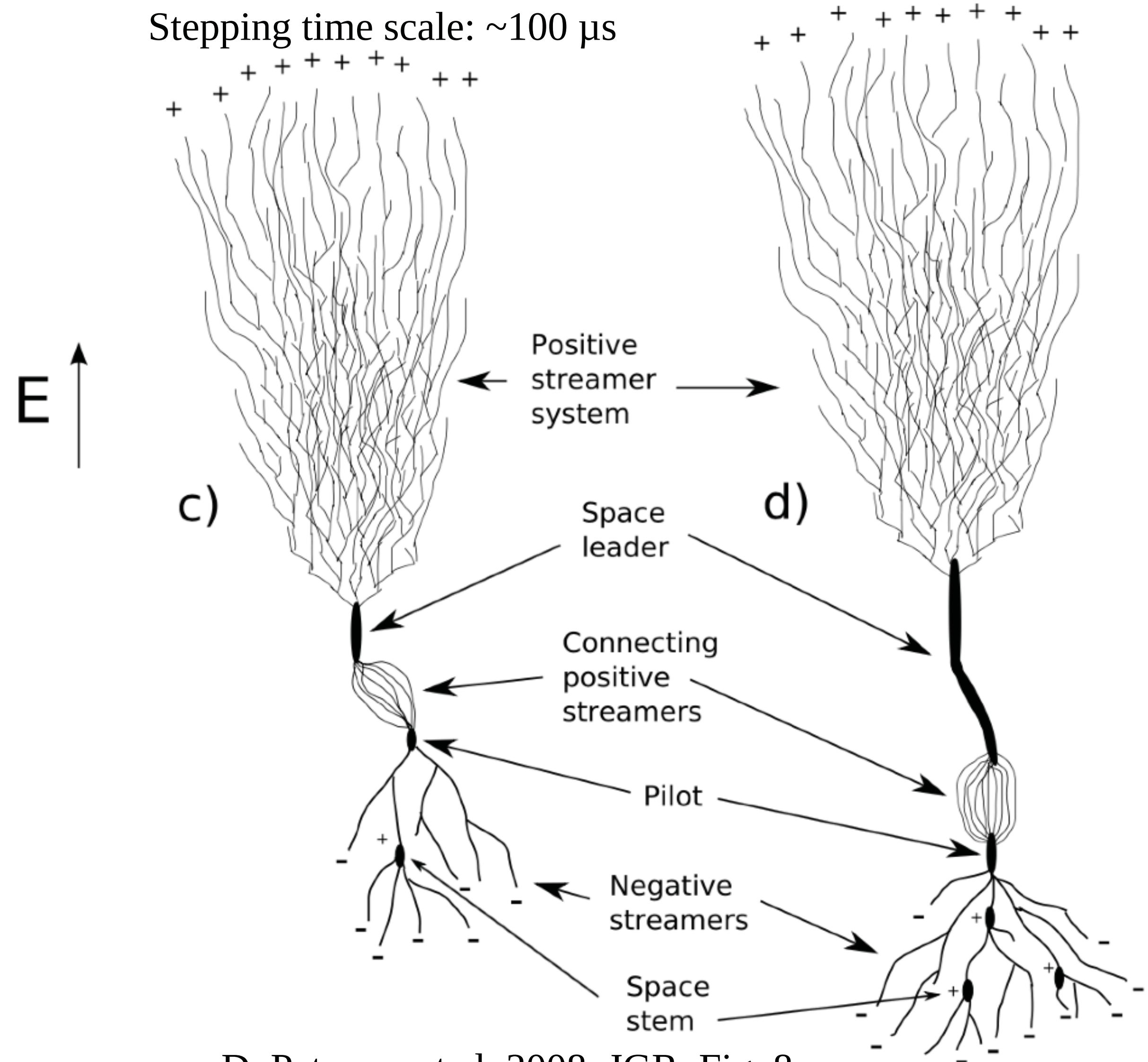
Leader stepping in a baby lightning flash

- The LMA, at VHF (~60 MHz), detects the development of the stepped leader (10-100 m) – thick black lines in the figure to the right.
- After the leader channel network is established, larger, brighter current flows (“strokes”) take place along those channels over O(1) km distances. GLM detects these processes.
- Breakdown is bidirectional, beginning in large E and proceeding into potential extrema formed by charges of opposite polarity

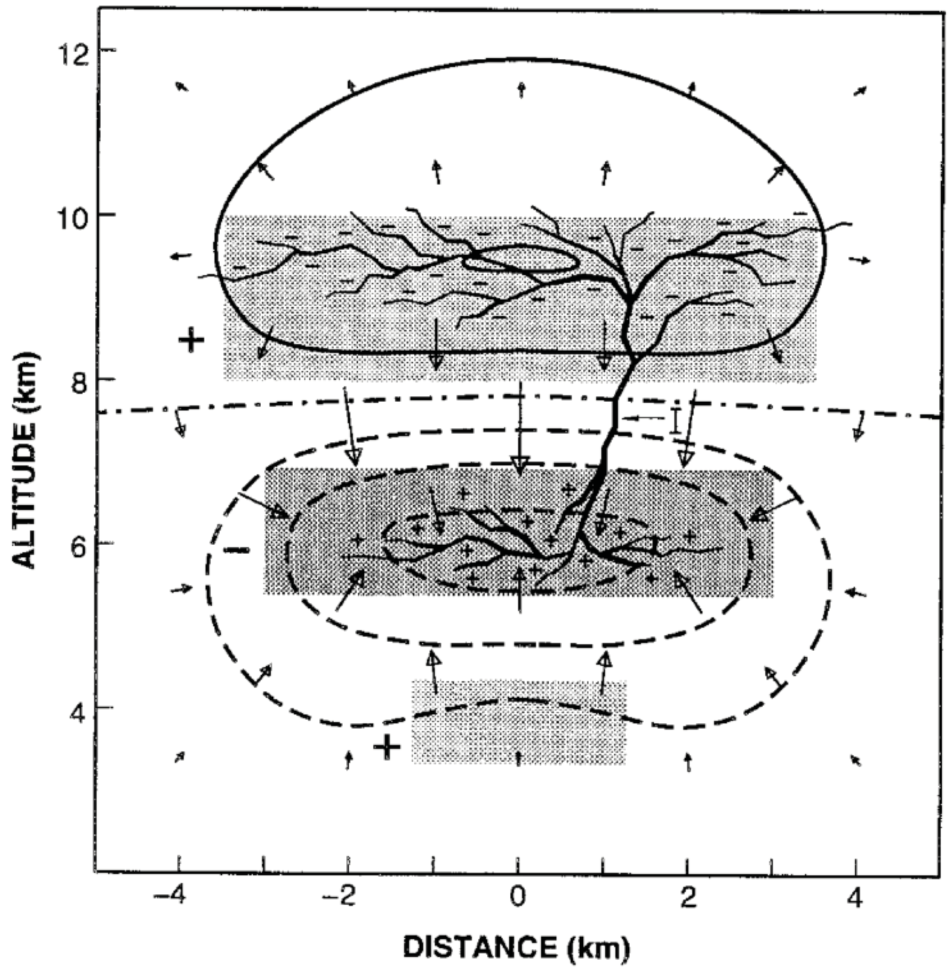
Stepping time scale: ~100 μs



D. Petersen et al. 2008, JGR, Fig. 8

How is charge organized in storms?

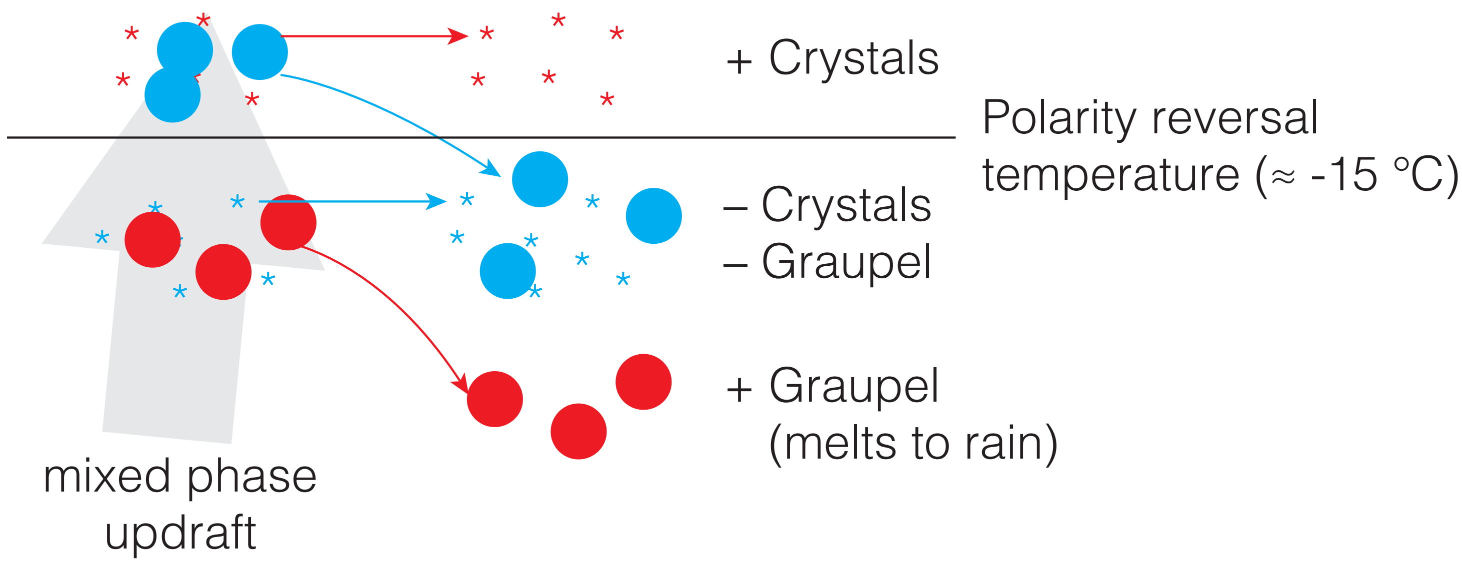
- The figure to the right depicts a mature lightning leader network along which large currents can travel.
- Most atmospheric electricity literature uses a sedimentation-dominated paradigm for organization of net charge: horizontally extensive layers.
- Charge is carried on hydrometeors.
- Organization of precipitation should correspond to the net charge structures and should be reflected in the flashing patterns.



MacGorman et al. (2001, JGR) Fig. 5

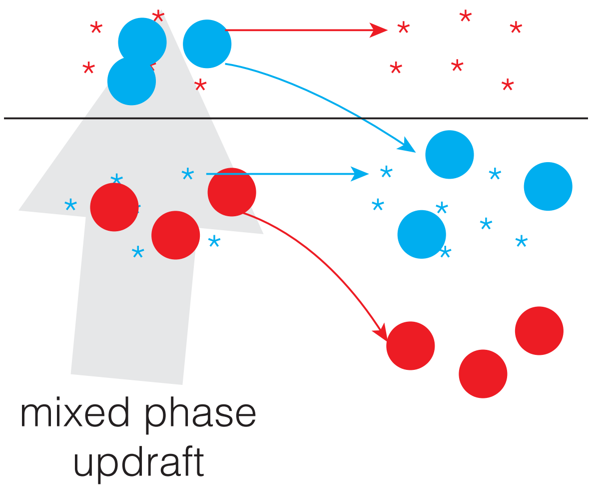
Contours of potential, E vectors, shaded charge regions

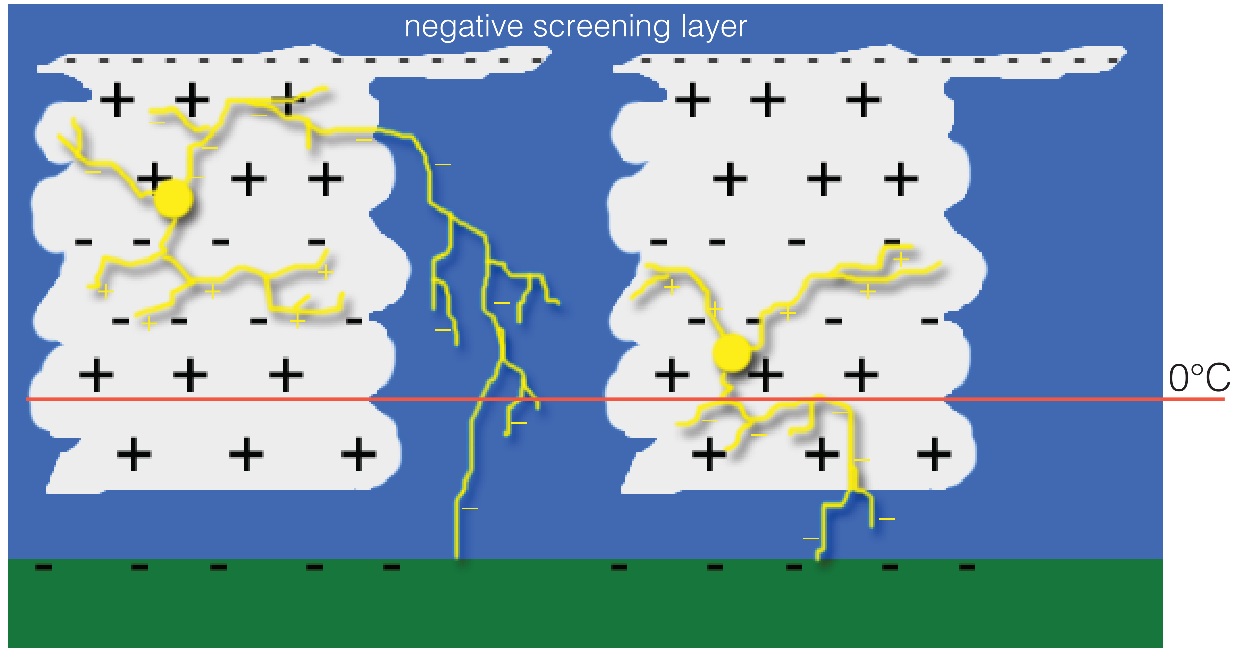
Electrification Basics
From microphysical charging to regions of net charge



Thunderstorm primary electrification takes place by ice-ice collisions in the presence of supercooled liquid water, followed by sedimentation of graupel. It is non-inductive, operating independently of the background electric field.

LIGHTNING'S RESPONSE TO STORM NET CHARGE STRUCTURE





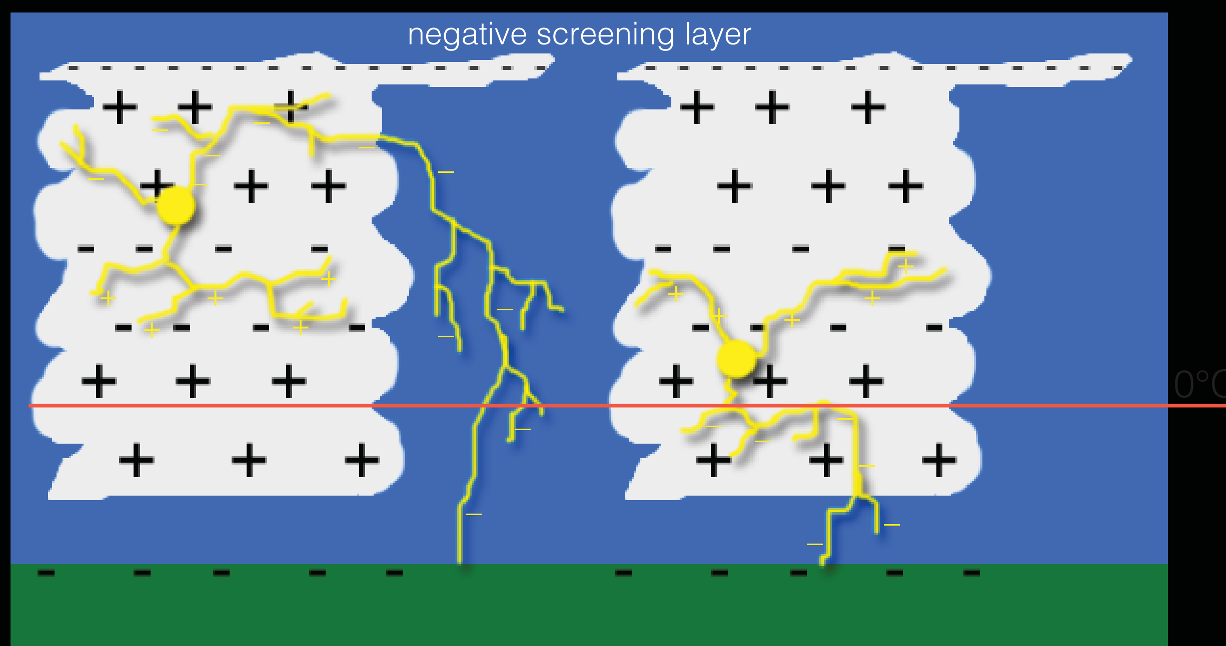
+ cloud flash (+IC) or
bolt-from-blue –CG

–IC or –CG

- Lightning can be produced between any pair of net charge regions
- Includes both cloud (IC) flashes and Ground (CG) flashes. Polarity of the flash is, by convention, the sign of charge which is lowered.
- 5:1 ratio of cloud to ground flash activity

Net charge structures reflect storm structure

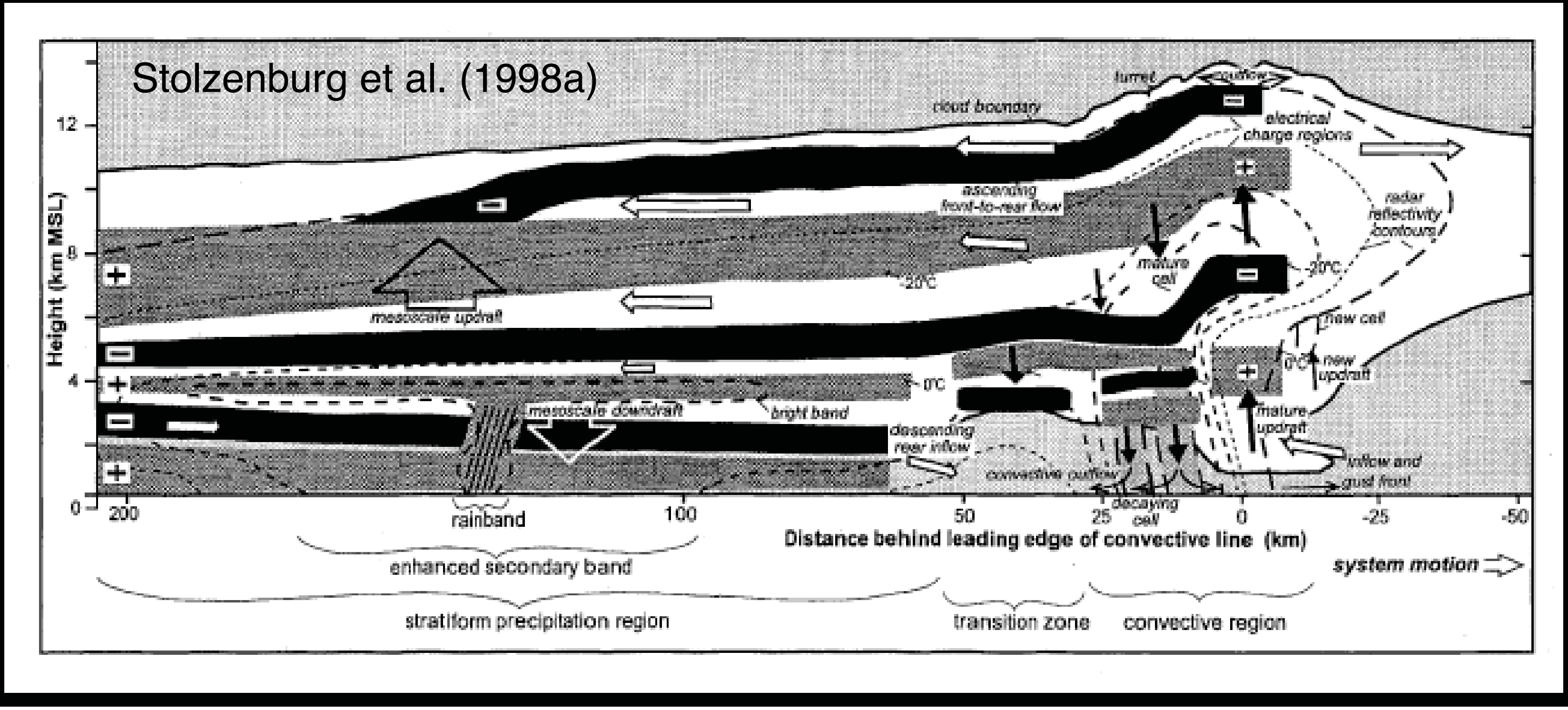
Multicellular storms: 1D (up / down)



Net charge structures reflect storm structure

Multicellular storms: 1D (up / down)

Squall line / MCSs: 2D (up / down, front / rear)

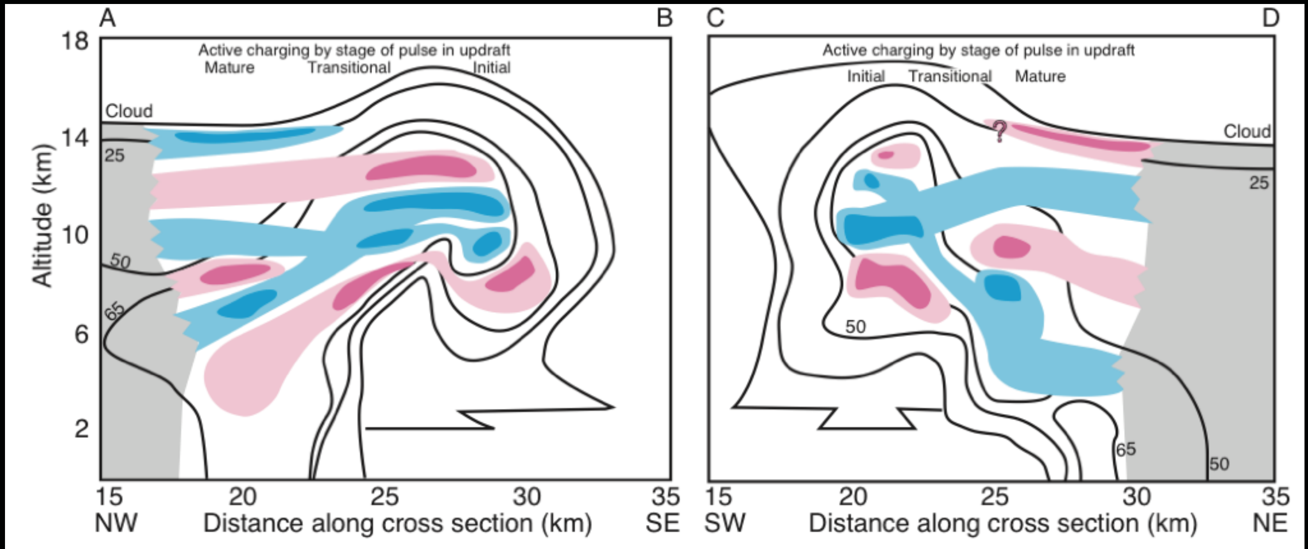


Net charge structures reflect storm structure

Multicellular storms: 1D (up / down)

Squall line / MCSs: 2D (up / down, front / rear)

Supercell: 3D (up/down, left/right, front/rear)

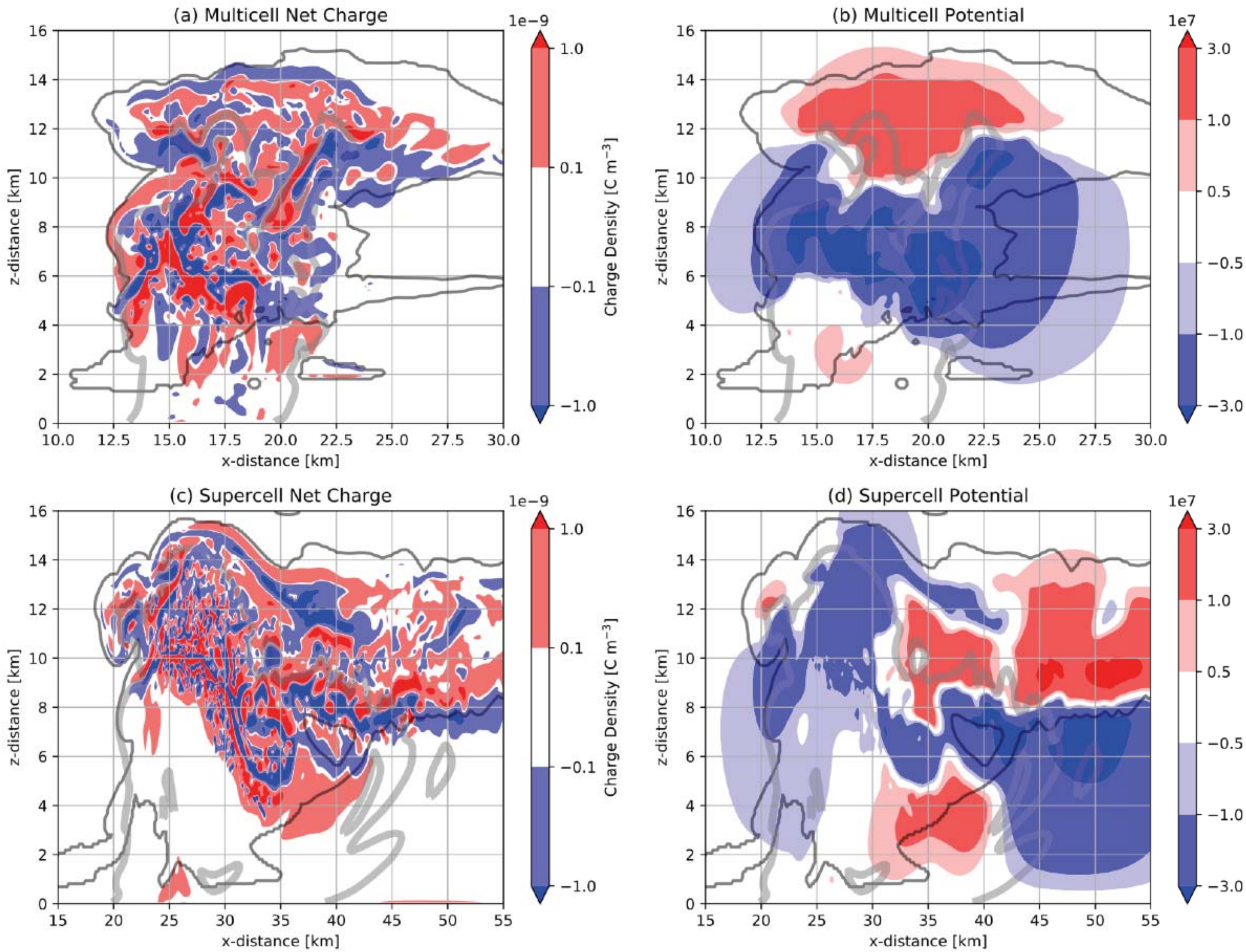


Bruning et al. (2010)

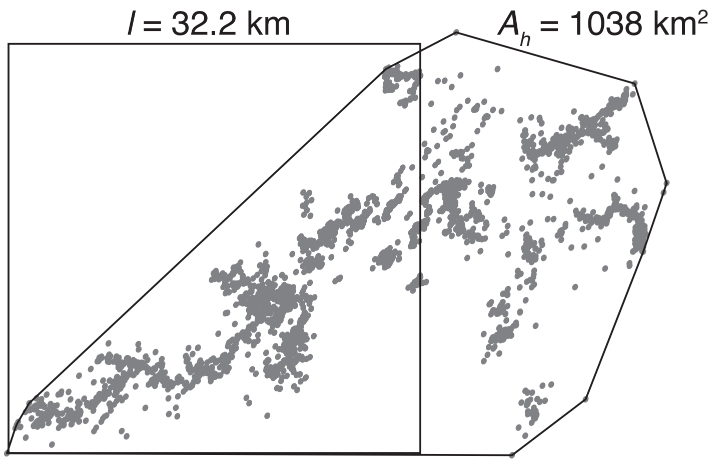
Spatial heterogeneity in charge is tied to the large-eddy turbulence in updrafts (Brothers/Bruning/Mansell 2018, JAS, in review)

Simulation with N-COMMAS (Mansell et al. 2010), 125 m grid spacing

Turbulent flow in updraft complicates charge regions, but potential remains simpler, as expected from electrostatic laws (Bruning and MacGorman 2013, JAS)



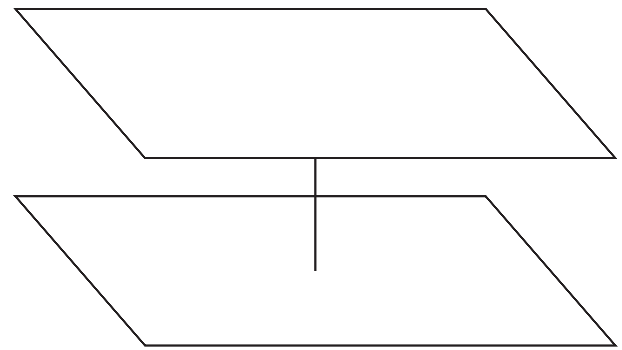
FLASH ENERGY IS RELATED TO FLASH SIZE



$$l = \sqrt{A_h}$$

Capacitor energy model for one flash

$$E(l) = \frac{\rho^2 l^2 d^3}{2\epsilon_0} = Kl^2$$



More complex charge regions reduce the size of lightning discharges between the charge regions.

For each flash, define a flash area

- Convex hull of the VHF sources in plan projection

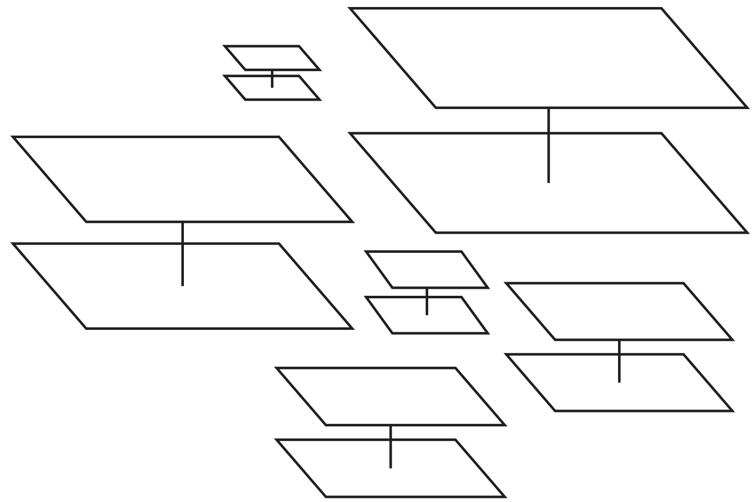
Flash area is proportional to energy in a capacitor-like discharge

- Hold charge density and plate spacing constant to simplify
- Sum to get total energy for an ensemble of flashes

MOMENTS OF THE FLASH SIZE DISTRIBUTION

Total energy
for an ensemble of
flashes

$$E_T = \frac{\rho^2 d^3}{2\epsilon_0} N_T \left(\mu^2 + \sigma^2\right)$$



For an ensemble of flashes, the moments of the flash size distribution can be calculated (Bruning and Thomas 2015, JGR), and the 0th-2nd moments uniquely determine total flash energy for the ensemble.

- Count
- Average width
- Variance of width

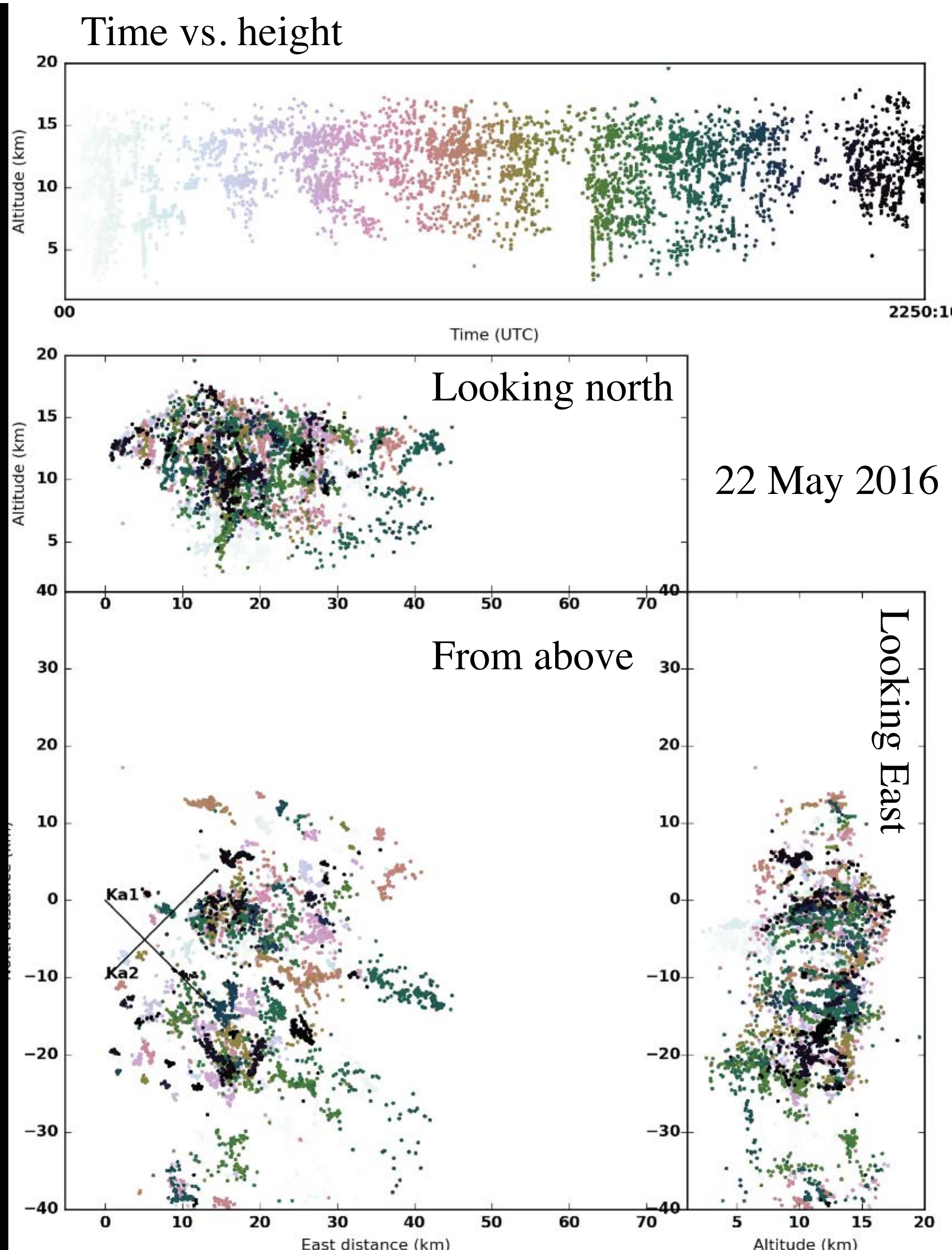
There is a great diversity in observed lightning flash sizes, and flash activity fills the entire cloud volume

Plot shows
ten seconds of data

Movie is one minute of lightning activity from a supercell in West Texas

3x real-time

Color is time
Dark: recent
Light: oldest



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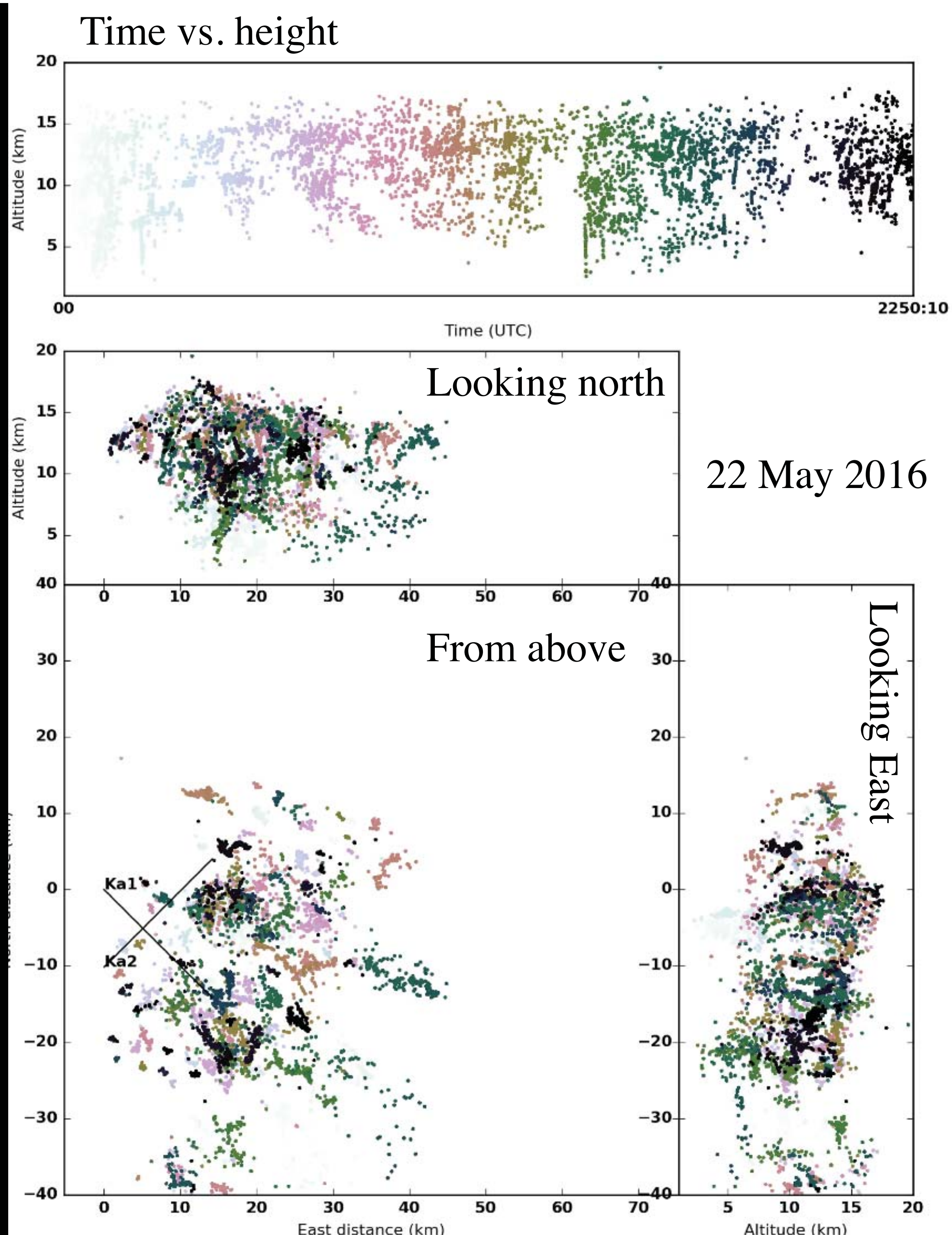
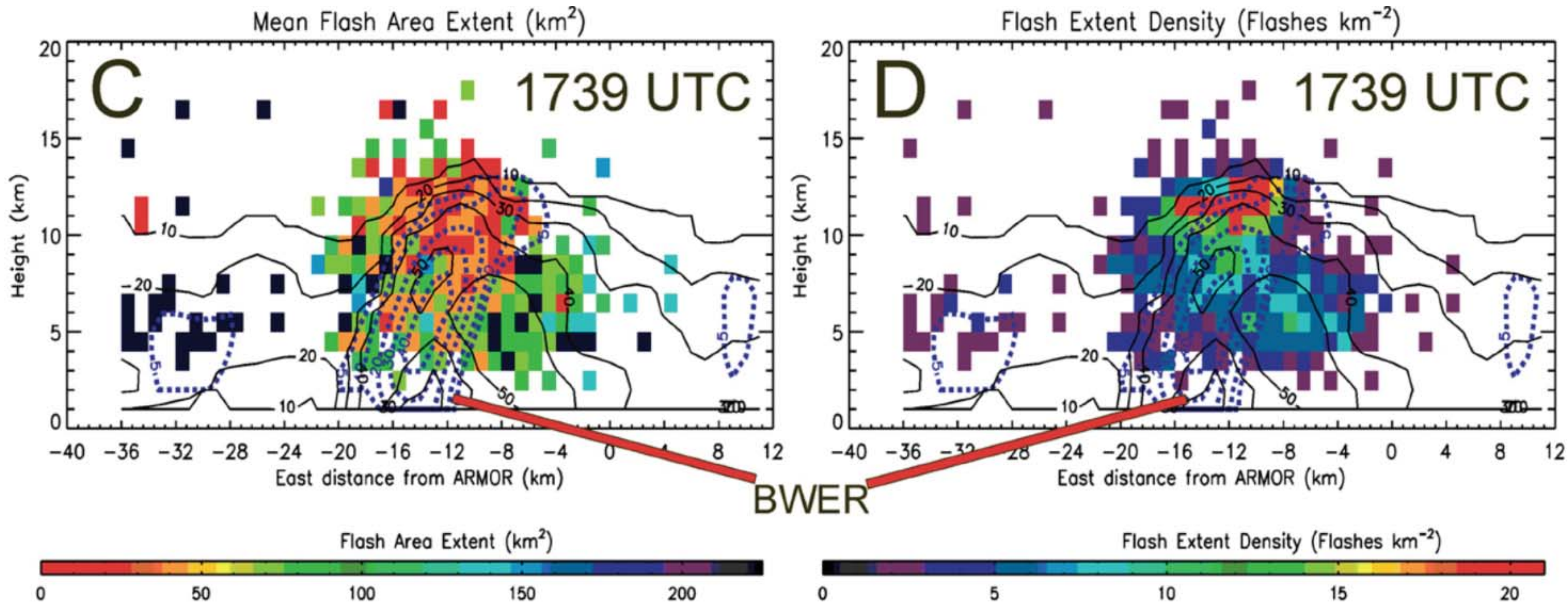


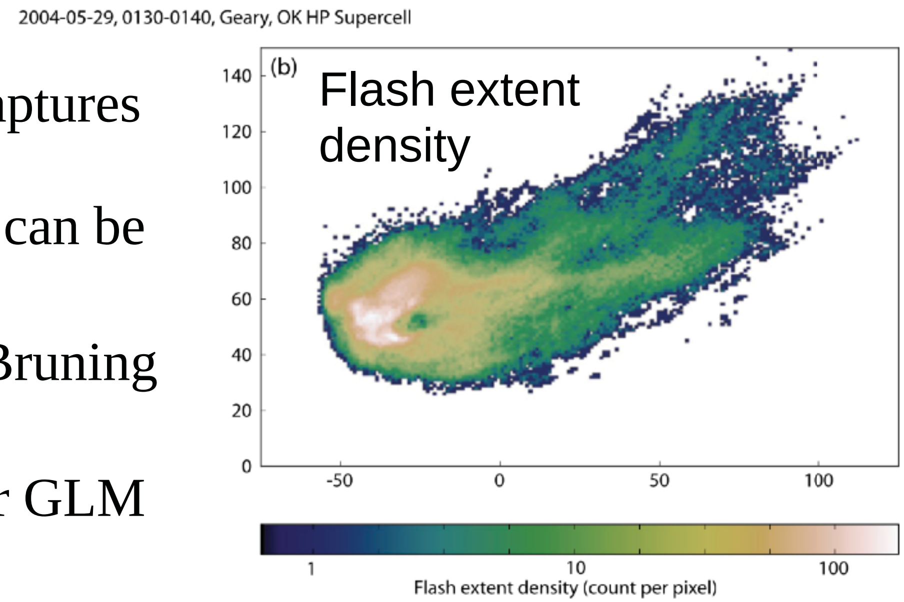
LIGHTNING JUMPS, FLASH SIZE, AND THE MIXED PHASE UPDRAFT

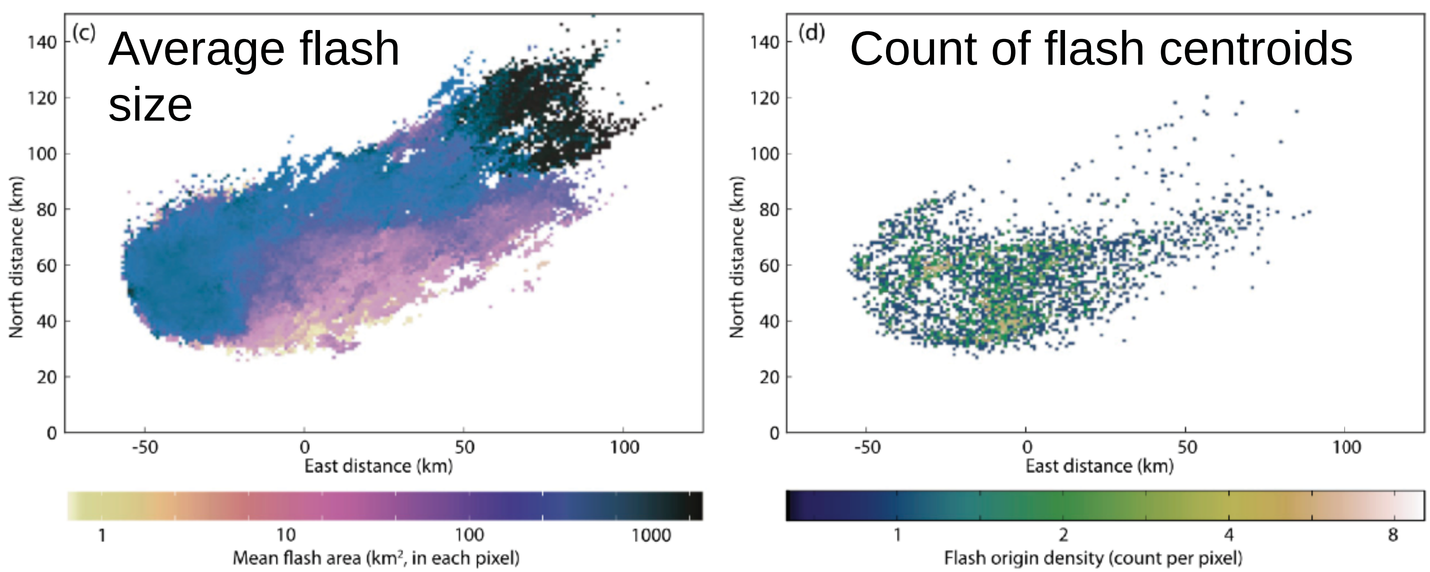


- Schultz et al. (2015, WAF) showed that lightning jumps (a sudden increase in flash rate) correspond to a decrease in flash size.
- Prior lightning jump studies showed skill in predicting severe weather occurrence
- A sudden increase in flash rate and a decrease in flash size is an excellent signal of a significant invigoration of the mixed-phase updraft

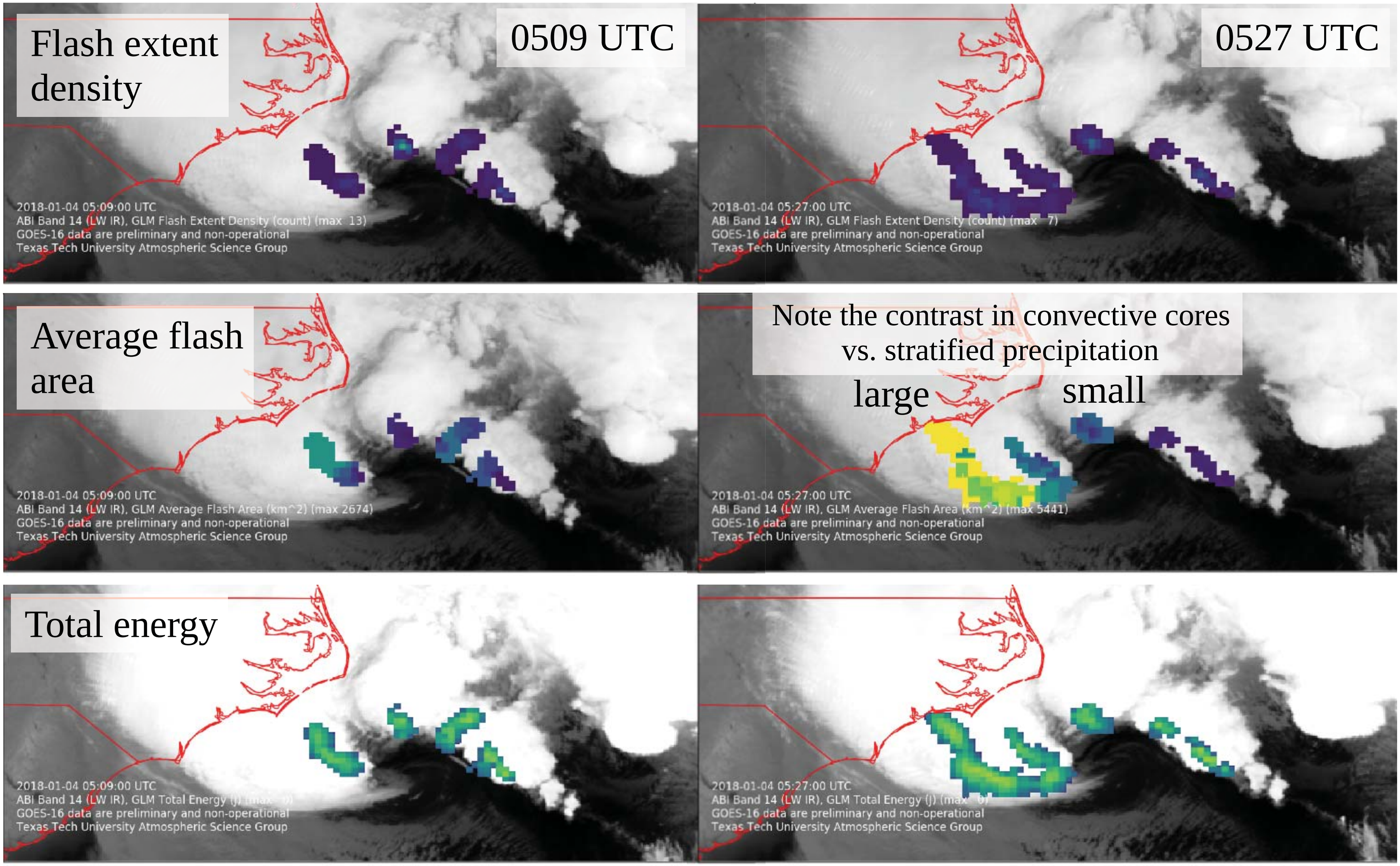
VISUALIZATION OF FLASH ENSEMBLE BEHAVIOR

- We can design lightning imagery that captures the flash size, flash rate, and energy information, and loops of such imagery can be used to assess trends.
- 10 min of LMA data from a supercell (Bruning and MacGorman 2013, JAS)
- Similar products have been designed for GLM

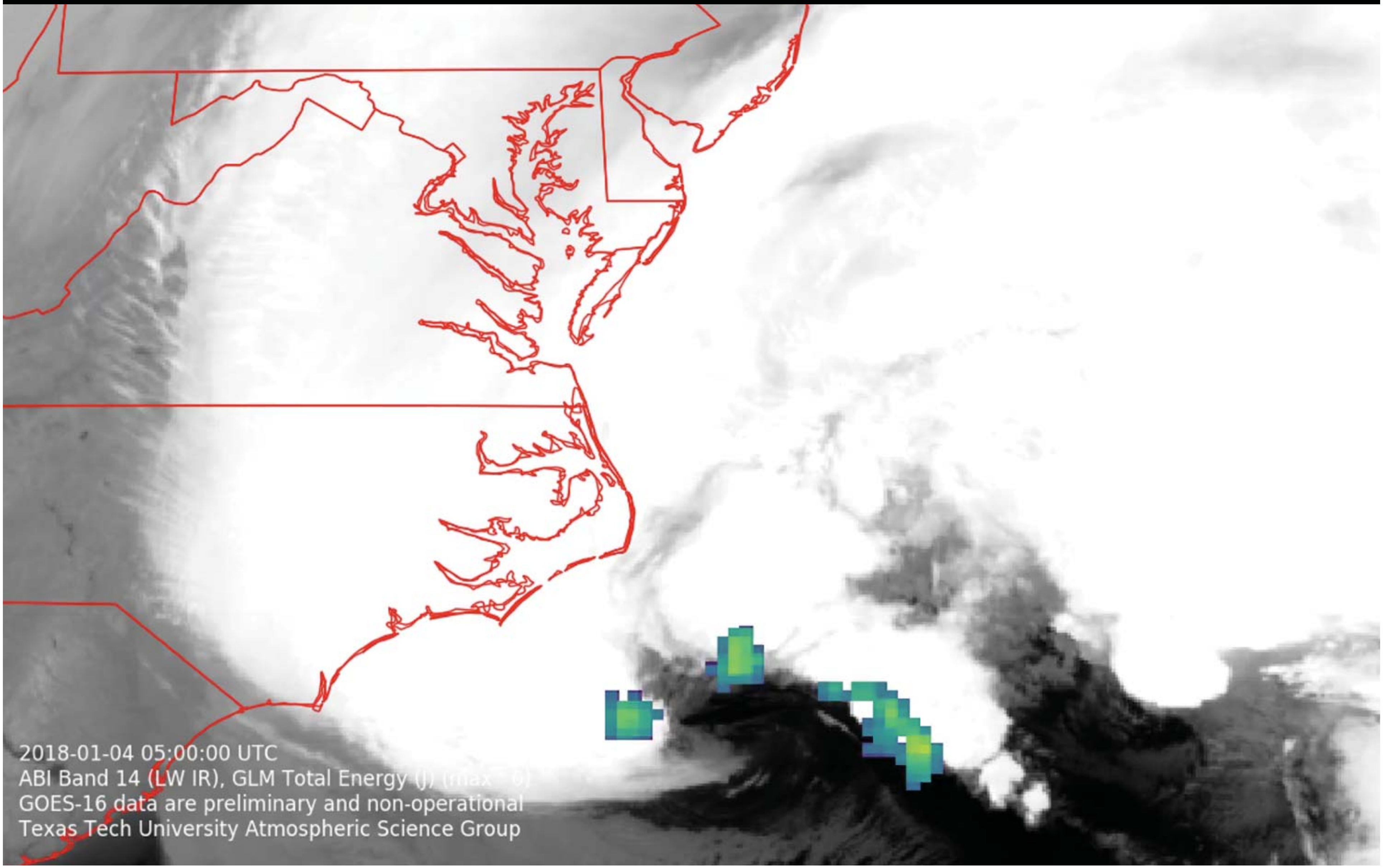




GLM imagery (4 January 2018, Nor'easter)
Makes full use of GLM flash/group/event data



TOTAL OPTICAL ENERGY



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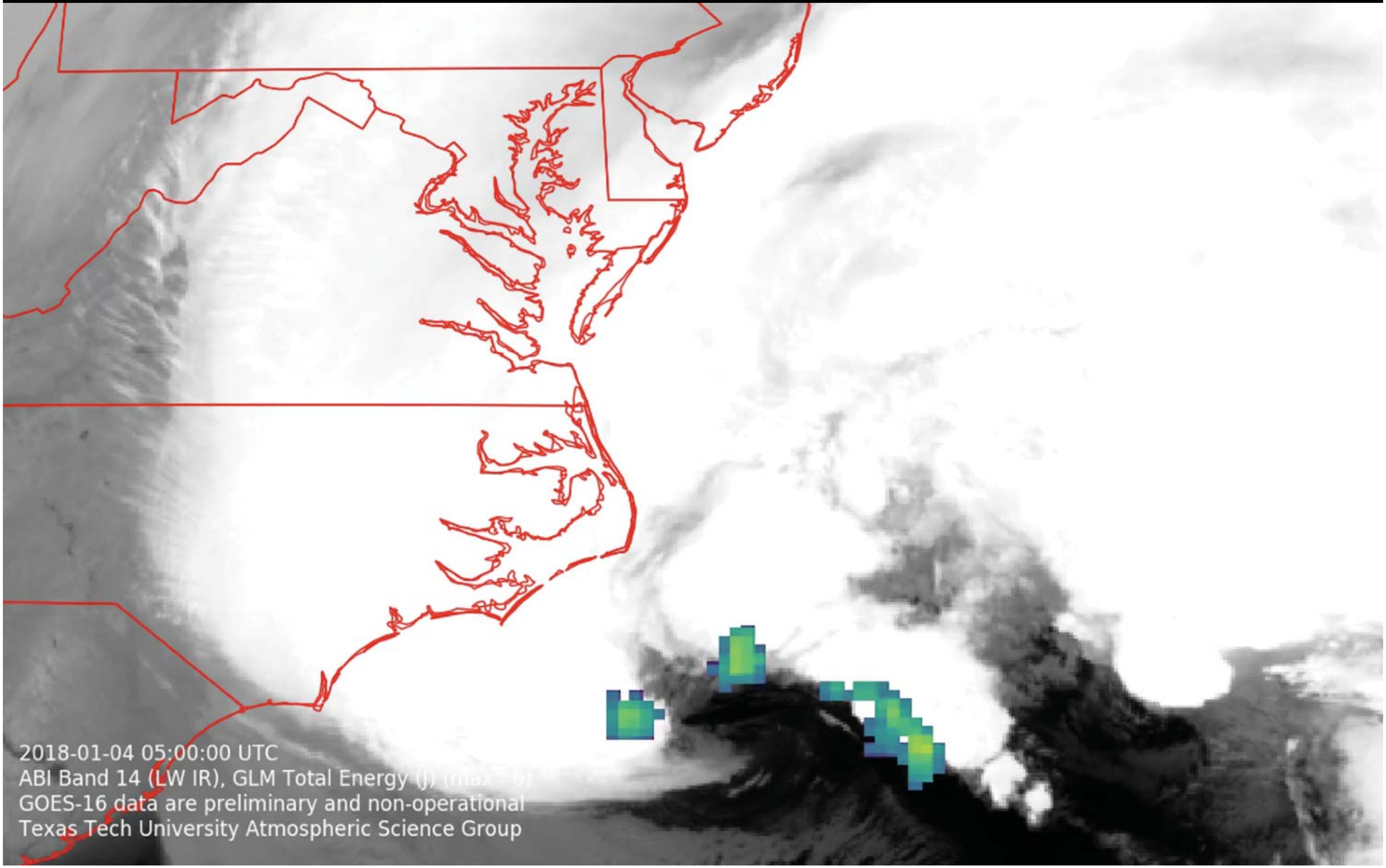
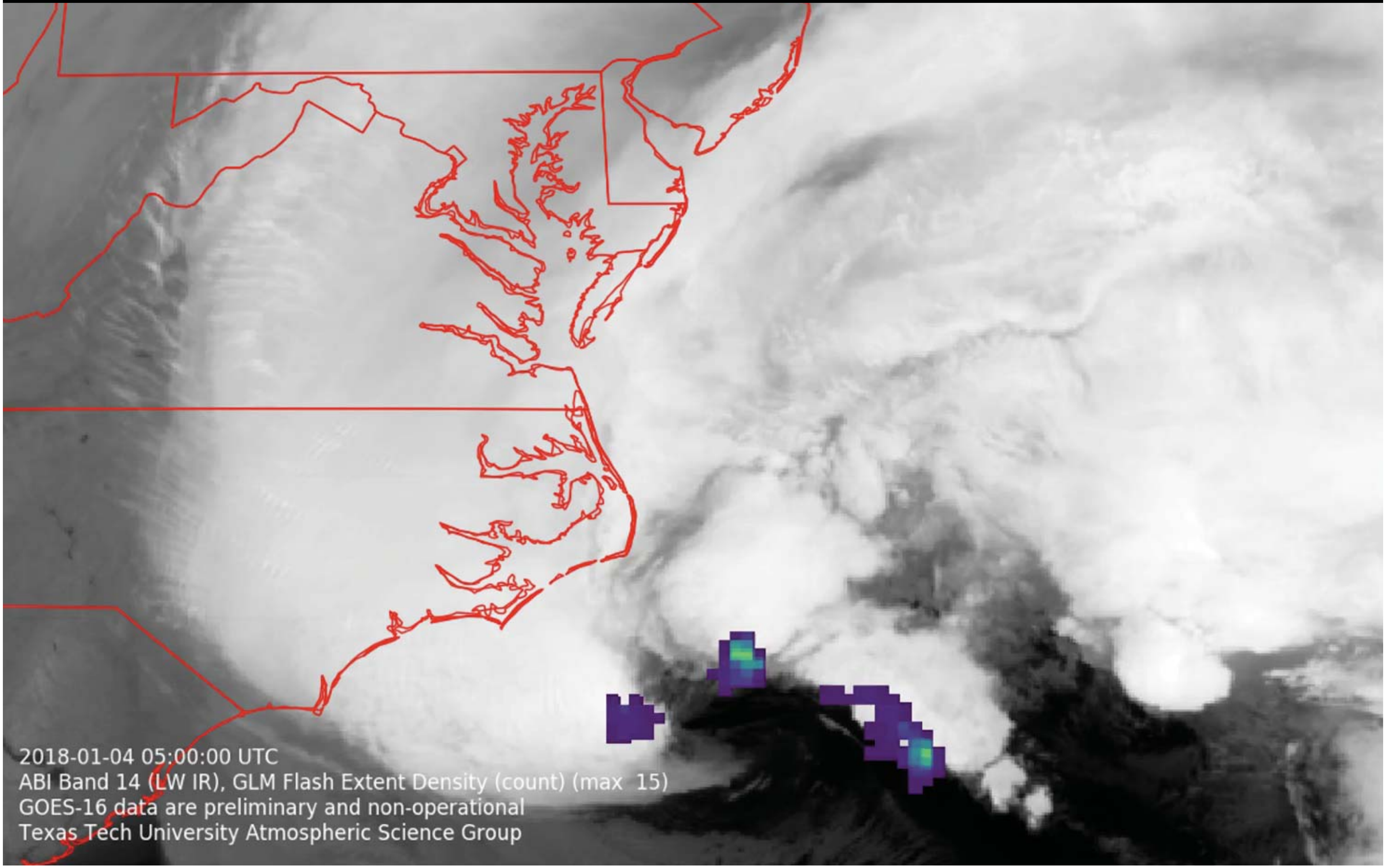


Flash extent density



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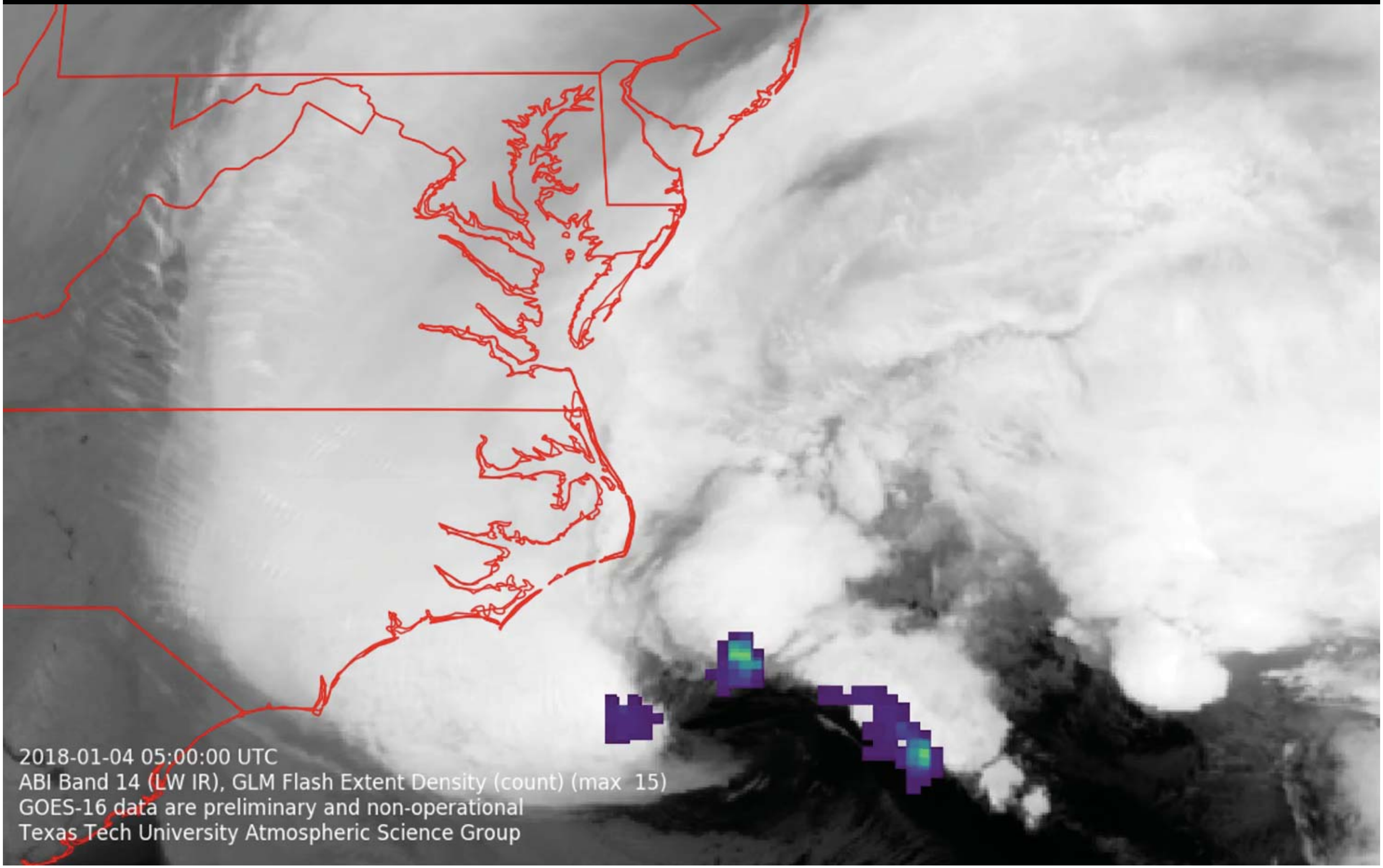
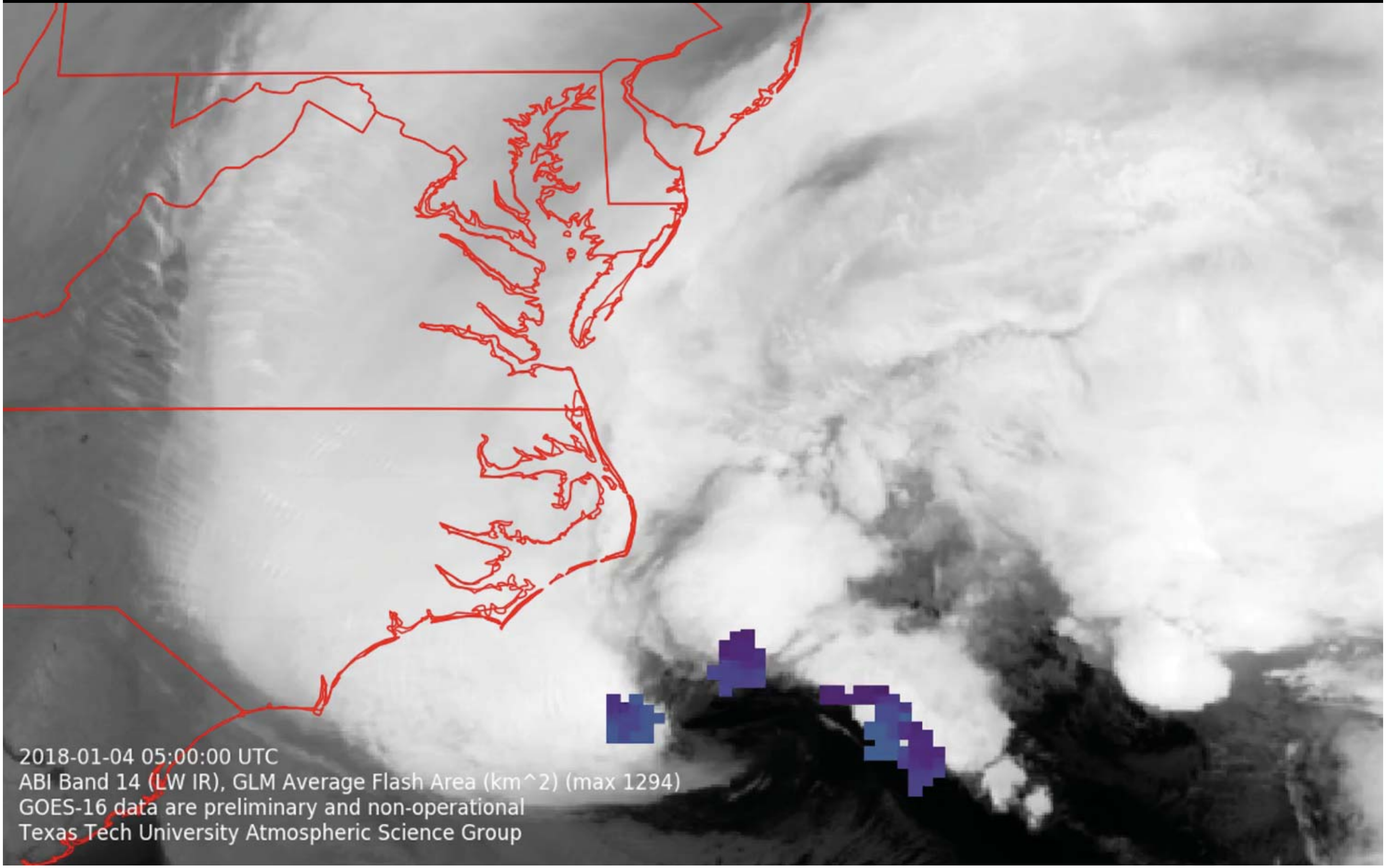


AVERAGE FLASH AREA



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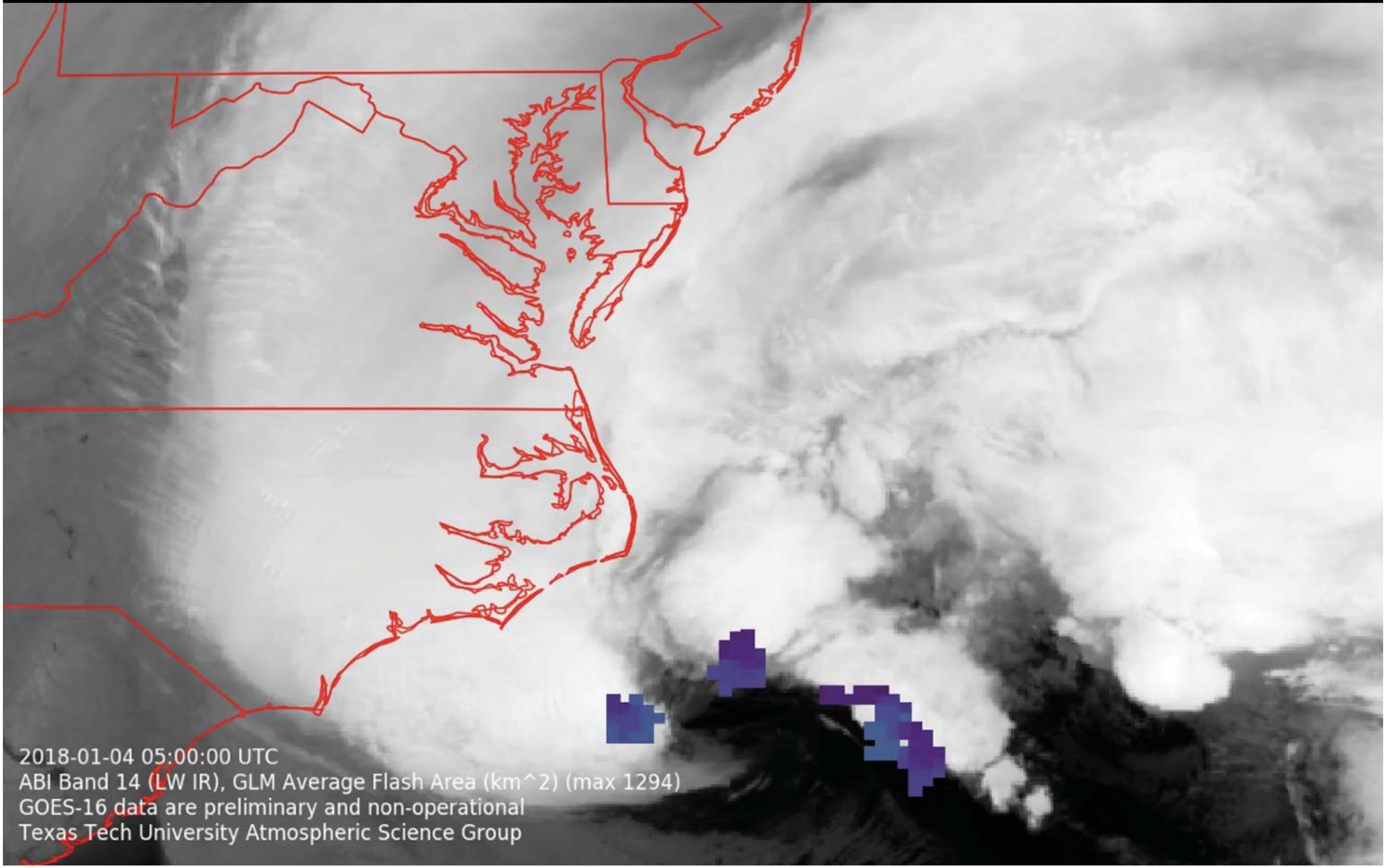


Flash size and optical energy: transfer function remains a mystery

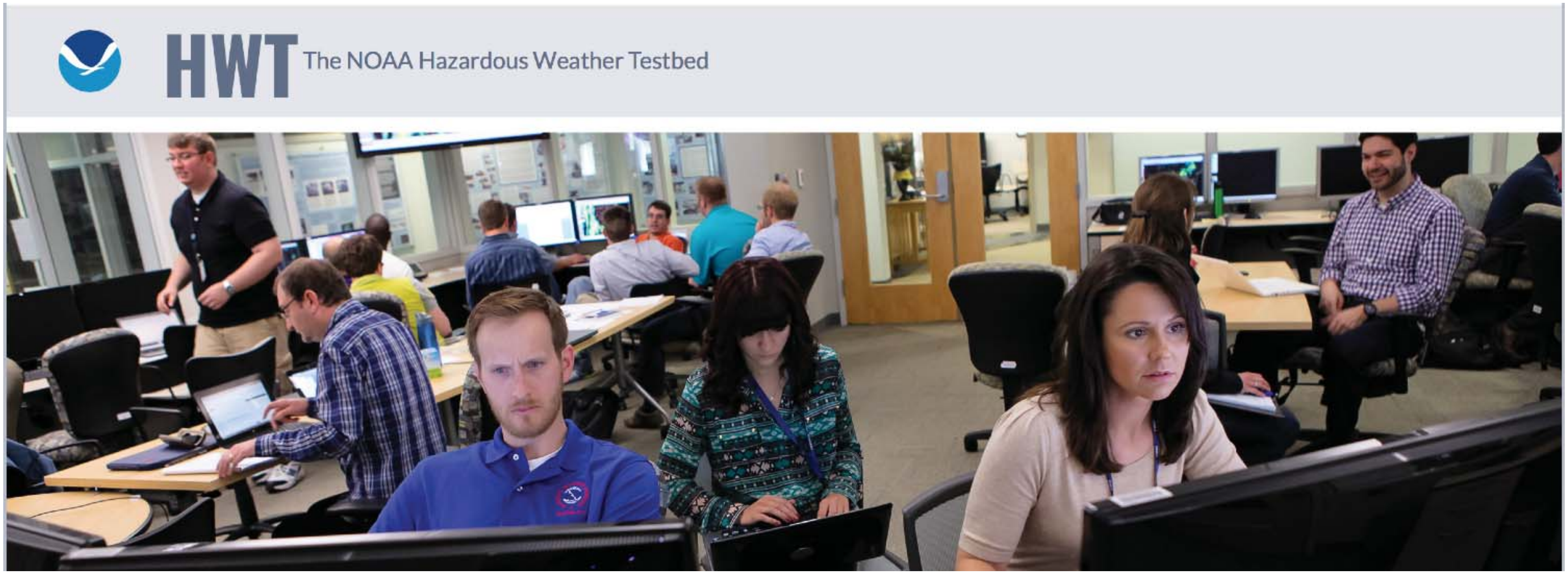
- Can we use flash size from LMA data to predict how much light GLM will see?
- Surprisingly, flash area and total radiant energy from GLM and/or LIS are uncorrelated (Bitzer, Zhang, and Cummins, 2017 AGU Fall Meeting; earlier study by Bateman during proxy data development)
- Possible reasons:
    - *Scattering of light by clouds (optical depth + flash altitude) affects the flash size and energy measurements*
    - *The energy that is emitted as light is some variable, and highly nonlinear, fraction of the electrostatic energy modeled by flash size.*

The road to GLM imagery

- GLM imagery not part of L2 baseline. Developed in a sprint over last 6 months, building on lessons learned in GOES-R Proving Ground and Testbed activities.
- Combined effort by NOAA (NESDIS, OAR, NWS), universities (TTU, OU, UMD), NASA SPoRT, and Lockheed Martin. Organized by S. Rudlosky.
- Deploy TTU research prototype (Bruning) in NWS ISatSS
- Rapid development of training material by subject matter experts (Rudlosky, Stano, Calhoun, others).
- Evaluation with forecasters in NWS Operations Proving Ground
  - *Preliminarly tests with forecast offices beginning May 2018, focused on flash extent density and ensuring timeliness and stability*
  - *Additional tests throughout summer, aiming at operationalized products in fall 2018*
- NSSL Hazardous Weather Testbed Experimental Warning Program
  - *Evaluation of additional products, colormaps, and methods for use in warning operations alongside existing (ABI, radar, etc.) datasets*

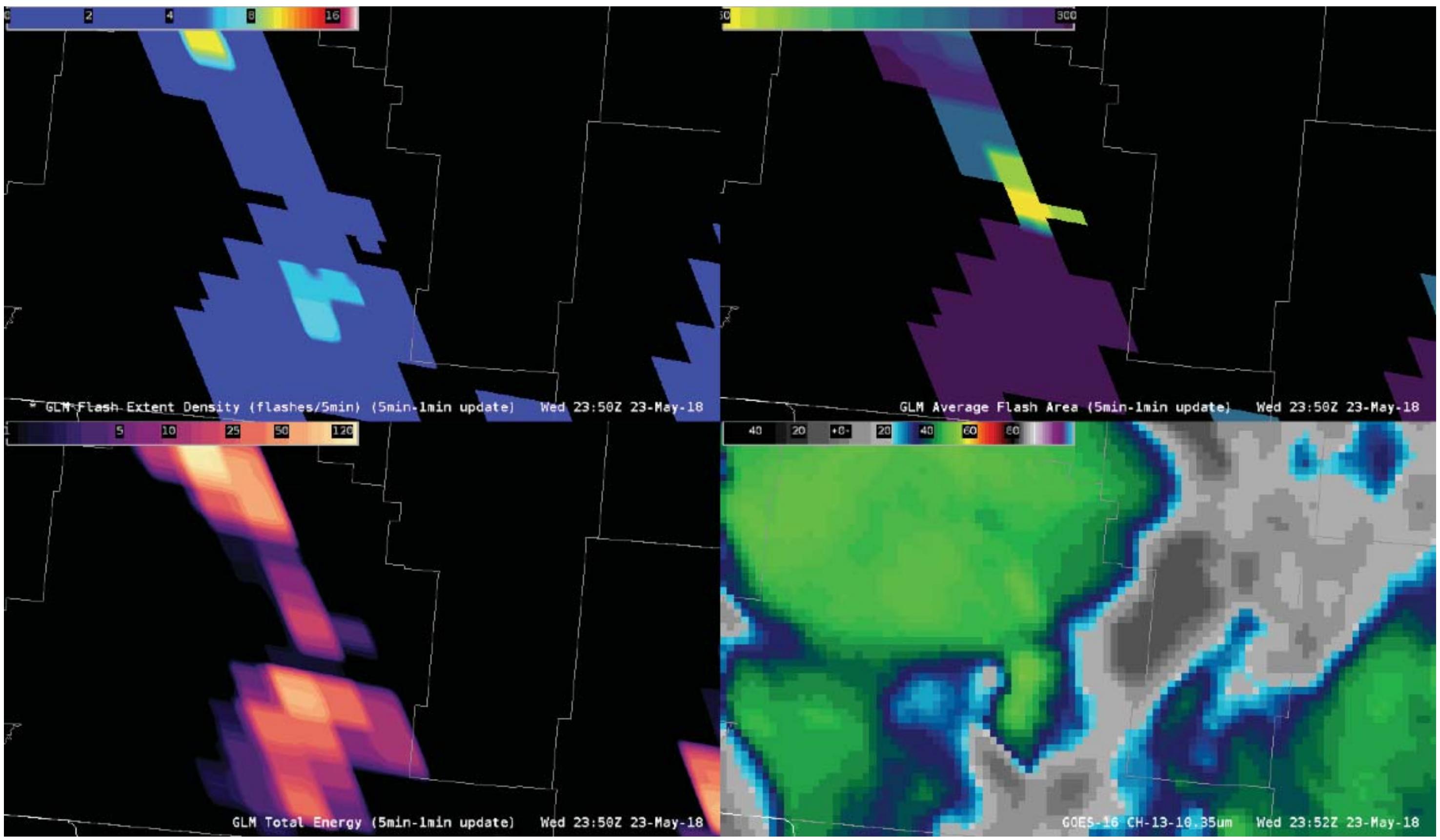
Hazardous weather testbed (NSSL/OU) evaluation of GLM products

- Simulated operational environment allows for experimentation with new product types without disrupting ordinary operations. 2018 GOES-R evaluation (4 weeks) led by Kristin Calhoun (https://hwt.nssl.noaa.gov/ewp/)
- Resulted in addition of average flash area and total energy to OPG preliminarily tests - greater utility when looking at multiple fields with complimentary signals.



GLM example from forecaster blog
Many more examples: http://goesrhwt.blogspot.com

- “[00:30 UTC] Storms continue to maintain (if not increase) their strength as their pivot north and northeast through the Billings [Montana] CWA. Of particular interest is the rapid increase in GLM flash extent density collocated with smaller average flash area and high total energy with a quickly-developing and strengthening updraft.”



GLM EXAMPLE FROM FORECASTER BLOG
MANY MORE EXAMPLES: HTTP://GOESRHWT.BLOGSPOT.COM

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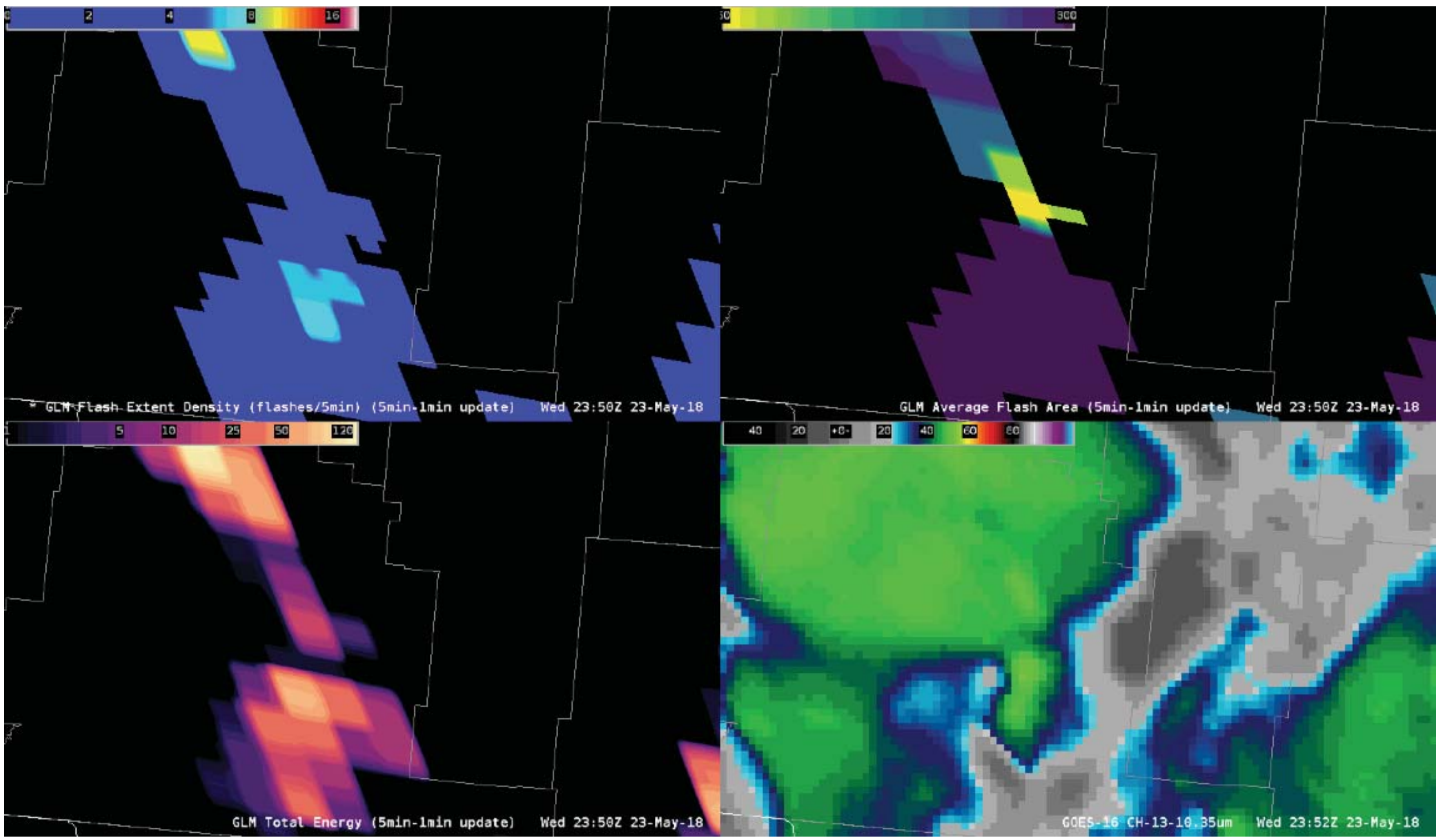
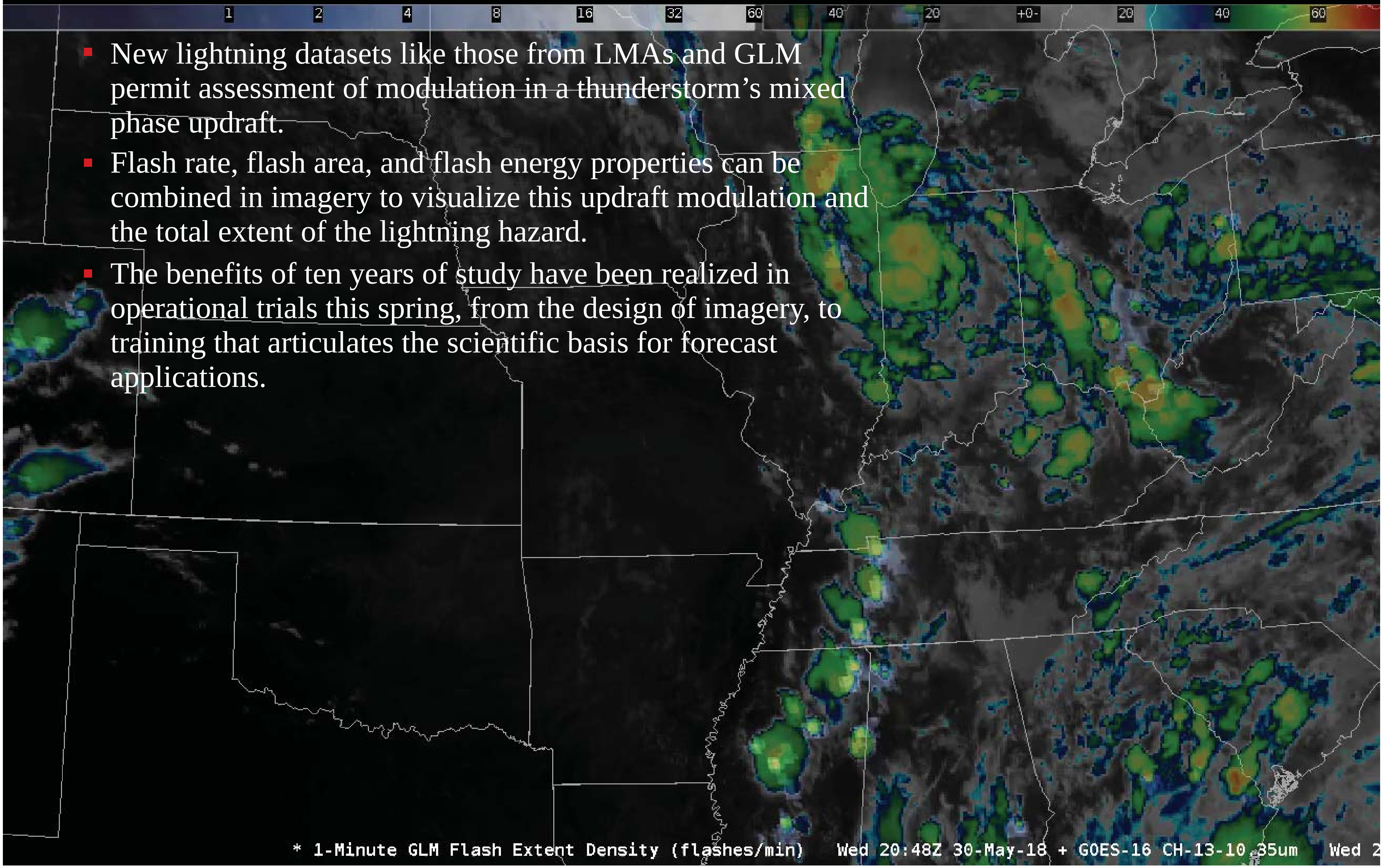


SUMMARY

(Loop courtesy
Scott Rudlosky/
NESDIS/UMD)

- New lightning datasets like those from LMAs and GLM permit assessment of modulation in a thunderstorm's mixed phase updraft.
- Flash rate, flash area, and flash energy properties can be combined in imagery to visualize this updraft modulation and the total extent of the lightning hazard.
- The benefits of ten years of study have been realized in operational trials this spring, from the design of imagery, to training that articulates the scientific basis for forecast applications.



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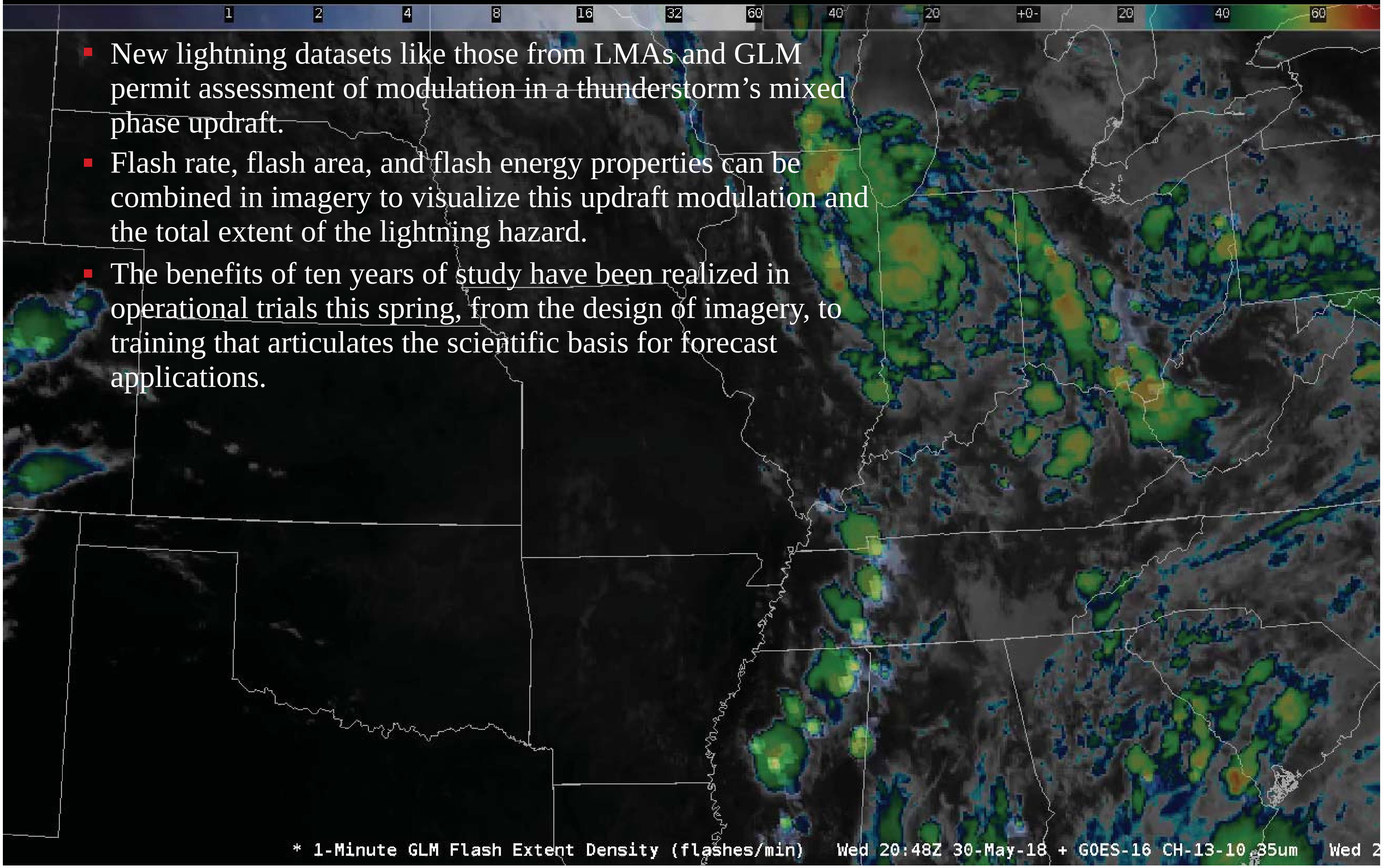


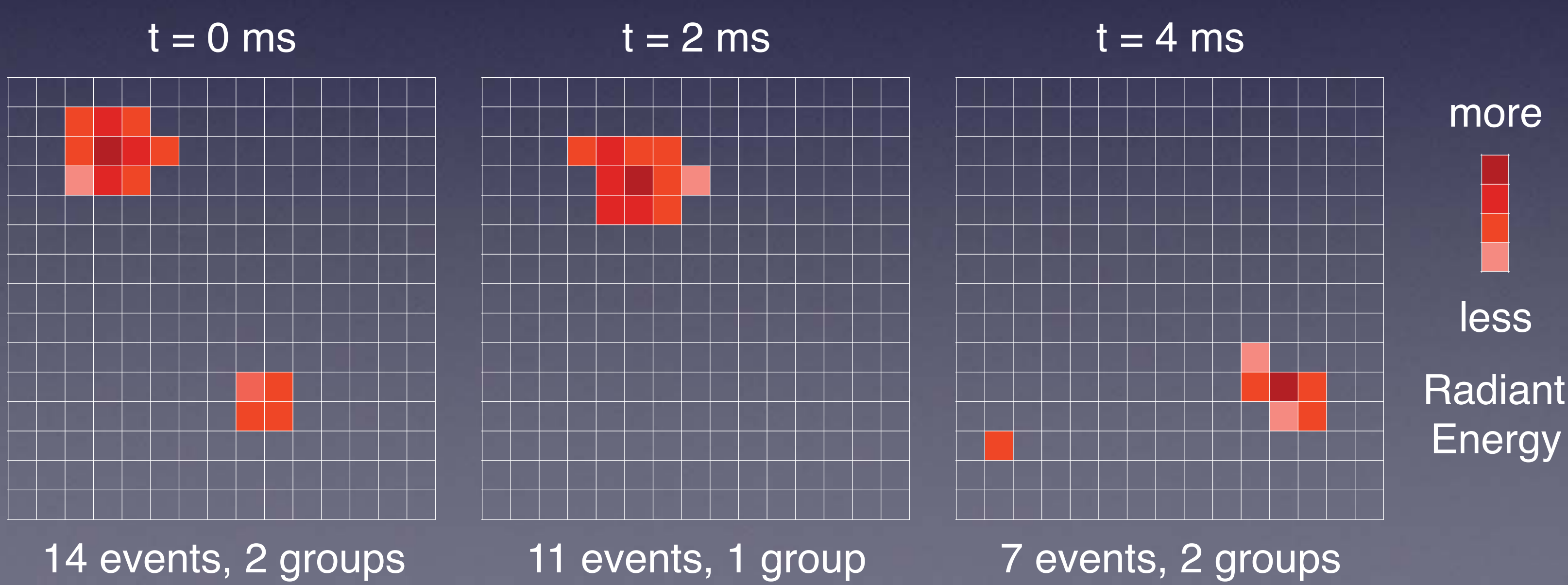
[redacted]

Space-based lightning sensing:
optical pulses from lightning at 500 fps

Data are hierarchically clustered, time-tagged, and geolocated detections

- **Events**: triggered pixels above background threshold
- **Groups**: adjacent pixels in a single frame – ‘strokes’
- **Flashes**: collection of groups close in space/time — all strokes along connected channels

3 total flashes



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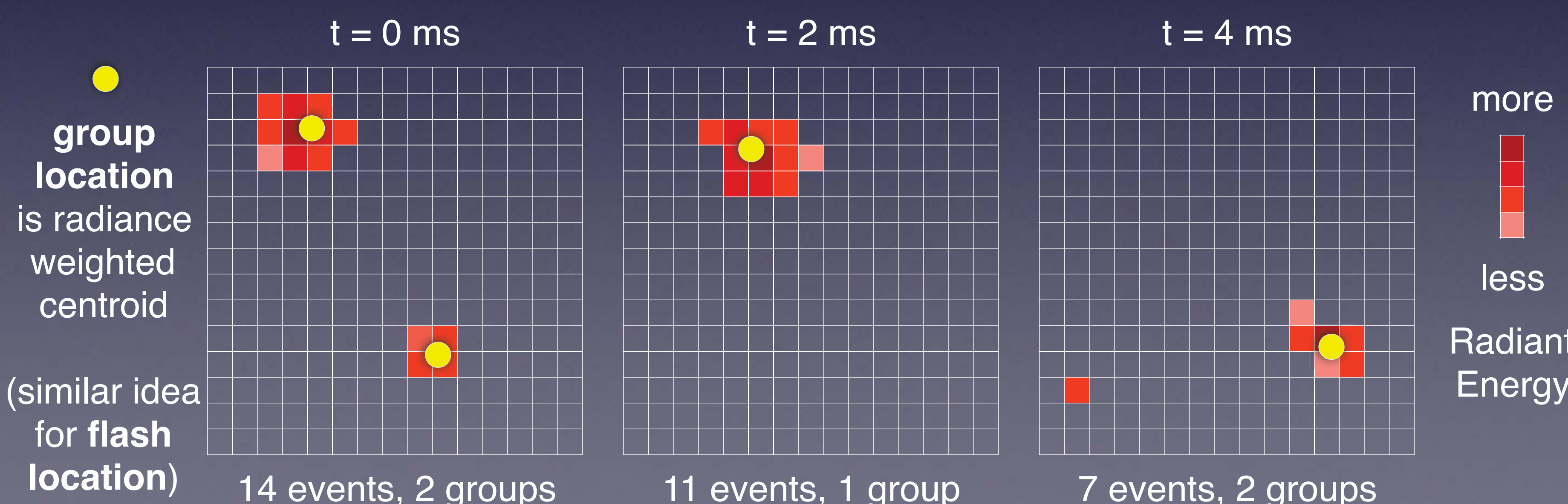

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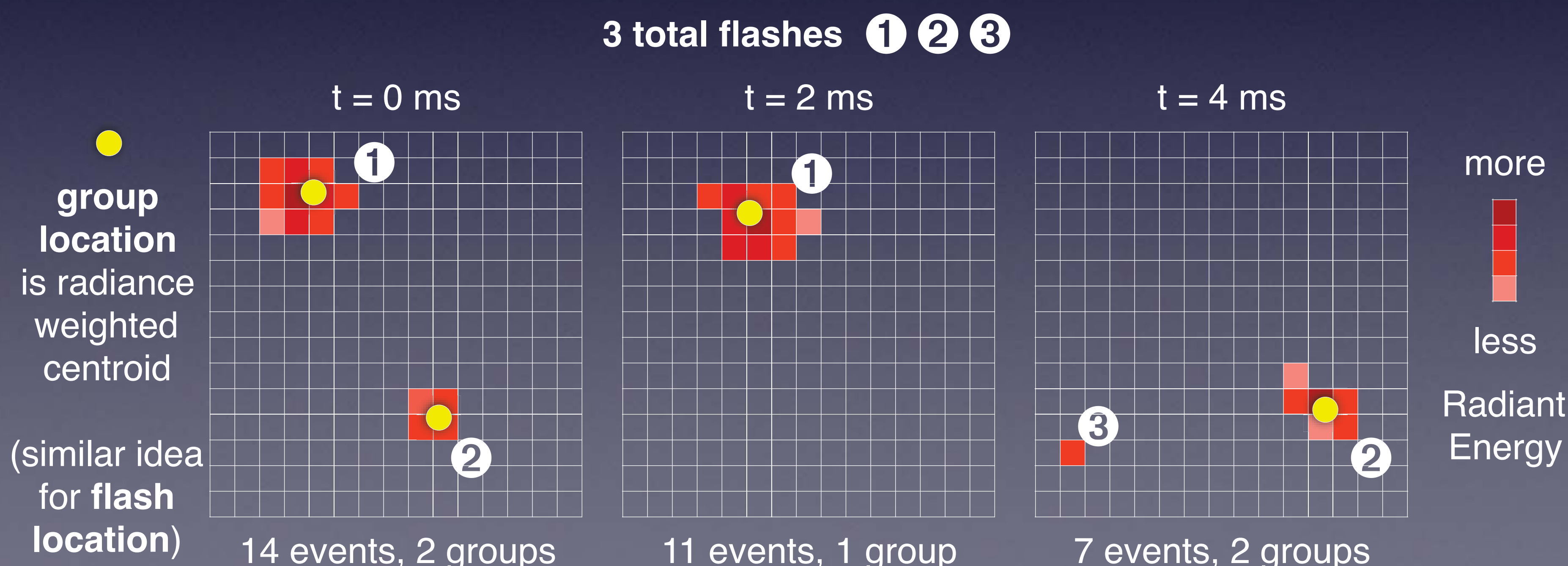

VALIDATION OF SIMPLE ENERGY MODEL

- Bruning and MacGorman (2013, JAS) proposed a simple area-dependent, capacitor-discharge model of flash energy model.
- Salinas et al. (2018, JGR, submitted) refined and validated this model using the Brothers et al. simulations
- After scaling by 20%, the simple model reproduced quite well the time series of total flash energy from the full solver in N-COMMAS
- The variability in flash size is a key component in understanding the per-flash (electrostatic) energy, and its trend with time