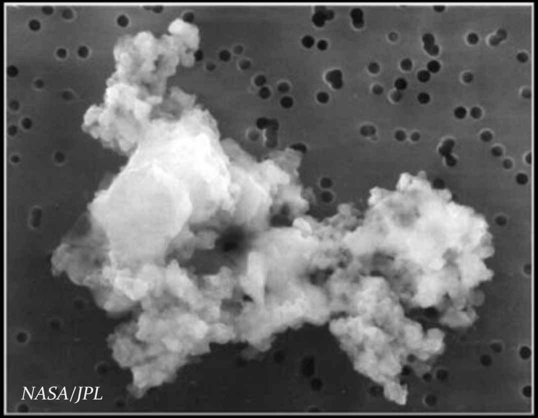
FIREBALL NETWORKS AND THE HUNT FOR METEORITES

Bill Cooke and Danielle Moser
NASA Meteoroid Environment Office
256 544-9136

Email: william.j.cooke@nasa.gov

Terminology


NASA/JPL


NASA/JPL


UWO

Meteoroids

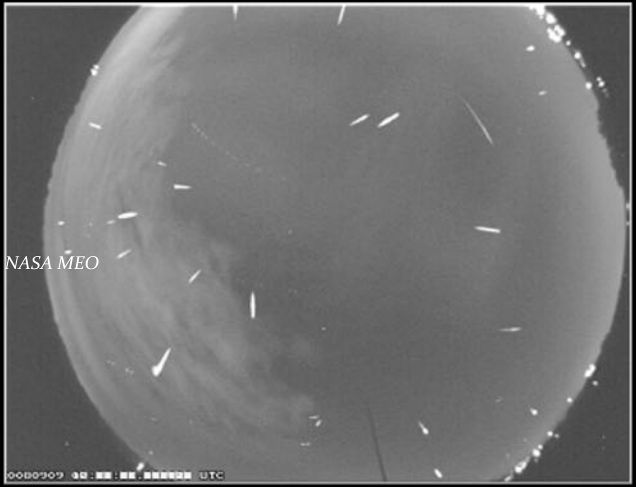
- Chunks of rock and ice out in space
- ~The size of a boulder or smaller
- Smaller than an asteroid

Meteors

- Streaks of light that you see as a meteoroid ablates, or burning up, in the Earth's atmosphere
- 'Shooting star' or 'falling star'

Meteorites

- What is left of the meteoroid if it survives the trip through the atmosphere and hits the Earth.
- Made of silicate minerals and/or iron-nickel.



Fireballs or Bolides

- Bright meteors.
- Peak magnitude brighter than Venus, $m_{app} = -4$.

Superbolides

- VERY bright meteors.
- Peak magnitude brighter than the full Moon, $m_{app} = -17$.
- Show up in space-based detectors, infra-sound, seismic, etc.
- Sources of major meteorite falls.

In the beginning…

There were visual observers (and still are)

Data limited to radiants and rough estimates of speed and brightness

Can get very cold during winter nights

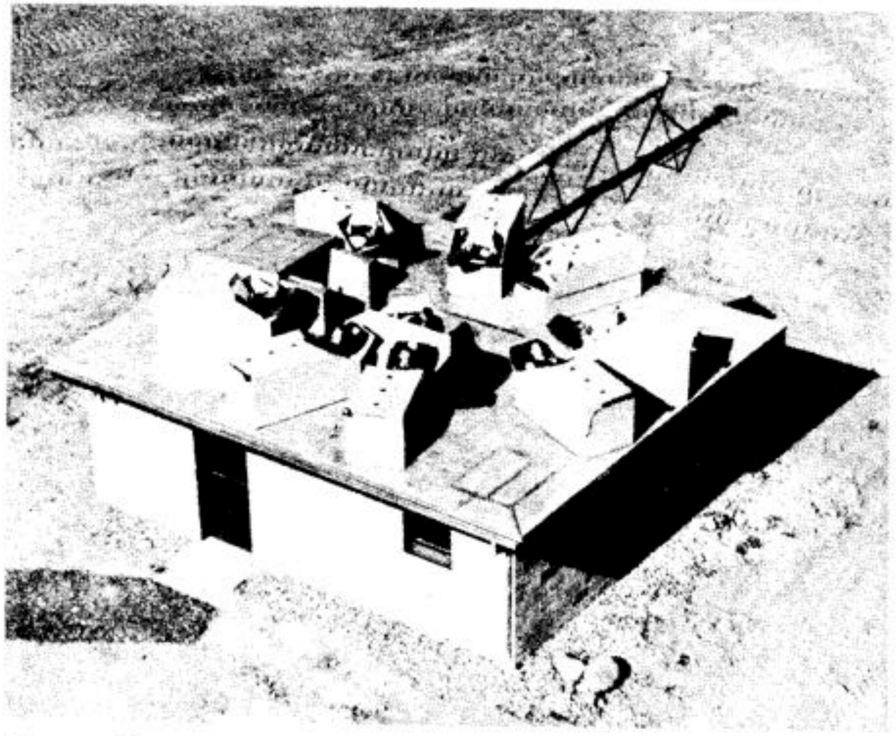


FIG. 3-3. Modern visual meteor observing at Springhill Meteor Observatory near Ottawa. Warm air is supplied to the individual compartments.

Photographic observations

Wide field

Meteorite Observation and Recording Program (MORP)

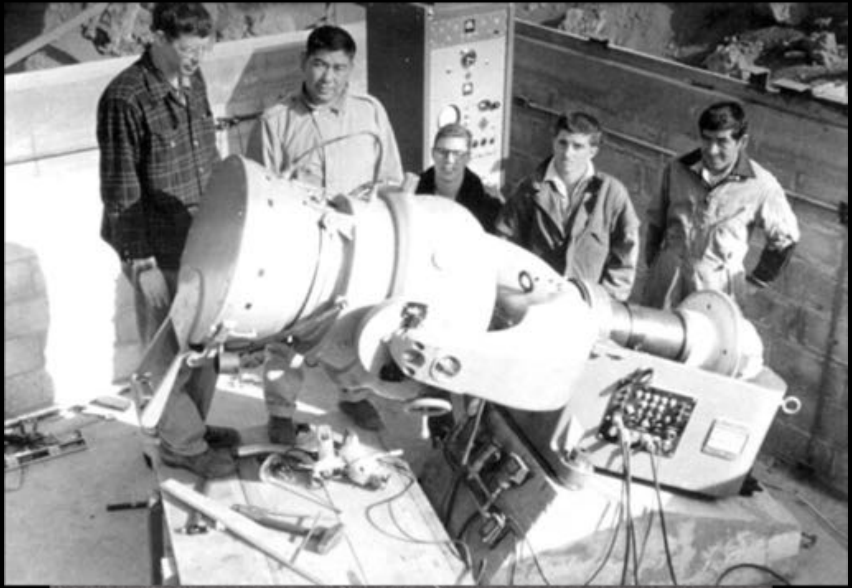
All sky

Modra Observatory

- All sky systems are nice because only 1 needed per station

Super Schmidt Cameras

- First employed in the 1940’s
- Detected bright meteors (magnitudes > +3)
- Large FOV
- Multiple stations and use of rotating shutter enabled location, speed, and orbit determinations



Super Schmidt camera (Haleakala, HI)

- The advent of fast, wide field photographic systems led to the creation of the first meteor networks
- European Fireball Network began in early 1950’s in Germany and Czechoslovakia (Only one still operating)
- The Prairie Network began in 1964 in the U.S. Funding was terminated in 1975 (1 fall)
- MORP began in Canada in 1968. Its 12 stations used Super-Komura cameras. Funding discontinued in 1985 (1 fall)

Advantages of photographic systems

- Large dynamic range
  - Good photometry
- High resolution
- Precise astrometry
- Can be automated to some degree

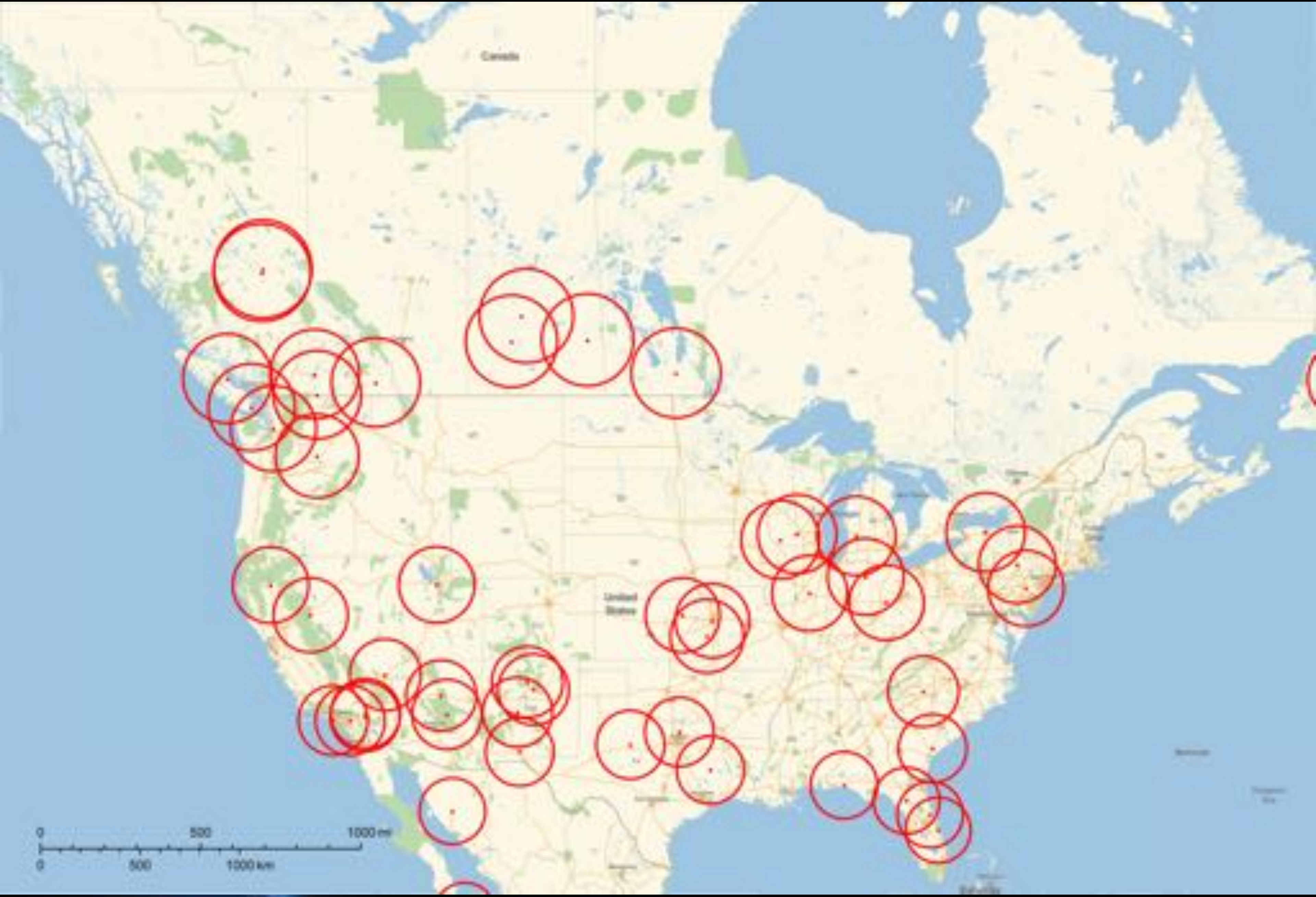
Czech system

Video observations

- Largely pioneered by Clifton and Naumann in the 1960's at MSFC (Meteor Physics Branch)
- Advantages:
  - 100x better sensitivity over Super Schmidt cameras
  - 30 fps rate gives better temporal resolution than rotating shutter
  - Unrivaled temporal accuracy thru GPS time stamps
- Disadvantages:
  - Limited resolution compared to photographic
  - Limited dynamic range (most systems are 8 bit)

Current Fireball Networks

Name	System Type	Start Year	Reference
European Network	Photographic/video	1951?	Oberst et al. (1998)
Japan Fireball Network	Video	1977	Shiba et al. (1998)
Sky Sentinel (formerly Sandia)	Video	1997	
Spanish Meteor Network	Video	1997	Trigo-Rodriguez et al. (2008)
Colorado Fireball Network	Video	2001	Sullivan and Klebe (2004)
Southern Ontario Meteor Network	Video	2004	Weryk et al. (2008)
Desert Fireball Network	DSLR	2004	Spurny and Borovicka (2006)
Polish Fireball Network	Video	2004	Olech et al. (2006)
NASA Fireball Network	Video	2008	Cooke and Moser (2011)
FRIPON	Video	2013	Colas et al. (2014)


Canada
United States
0
500
1000 mi
0
500
1000 km

The Sandia Sentinel Systems

- Sentinel I (1998) - “look down” system with hardware meteor detection. 6 second buffer, parallel connection to computer (Moooo)
- Sentinel II (2004) - conventional all sky with hardware detection. USB connection to computer
- Sentinel III (2007) - all sky system with software detection

Figure 1. The All-Sky Camera installed on the roof of The King's University College Observatory (approximately 20 kilometres east of Edmonton)


Map
Satellite
NORTHERN TERRITORY
Townsville
Mackay
Coral Sea
QUEENSLAND
Alice Springs
Australia
WESTERN AUSTRALIA
Geraldton
Brisbane
Toowoomba
Gold Coast
SOUTH AUSTRALIA
Perth
Mandurah
Bunbury
NEW SOUTH WALES
Newcastle
Sydney
Adelaide
Canberra

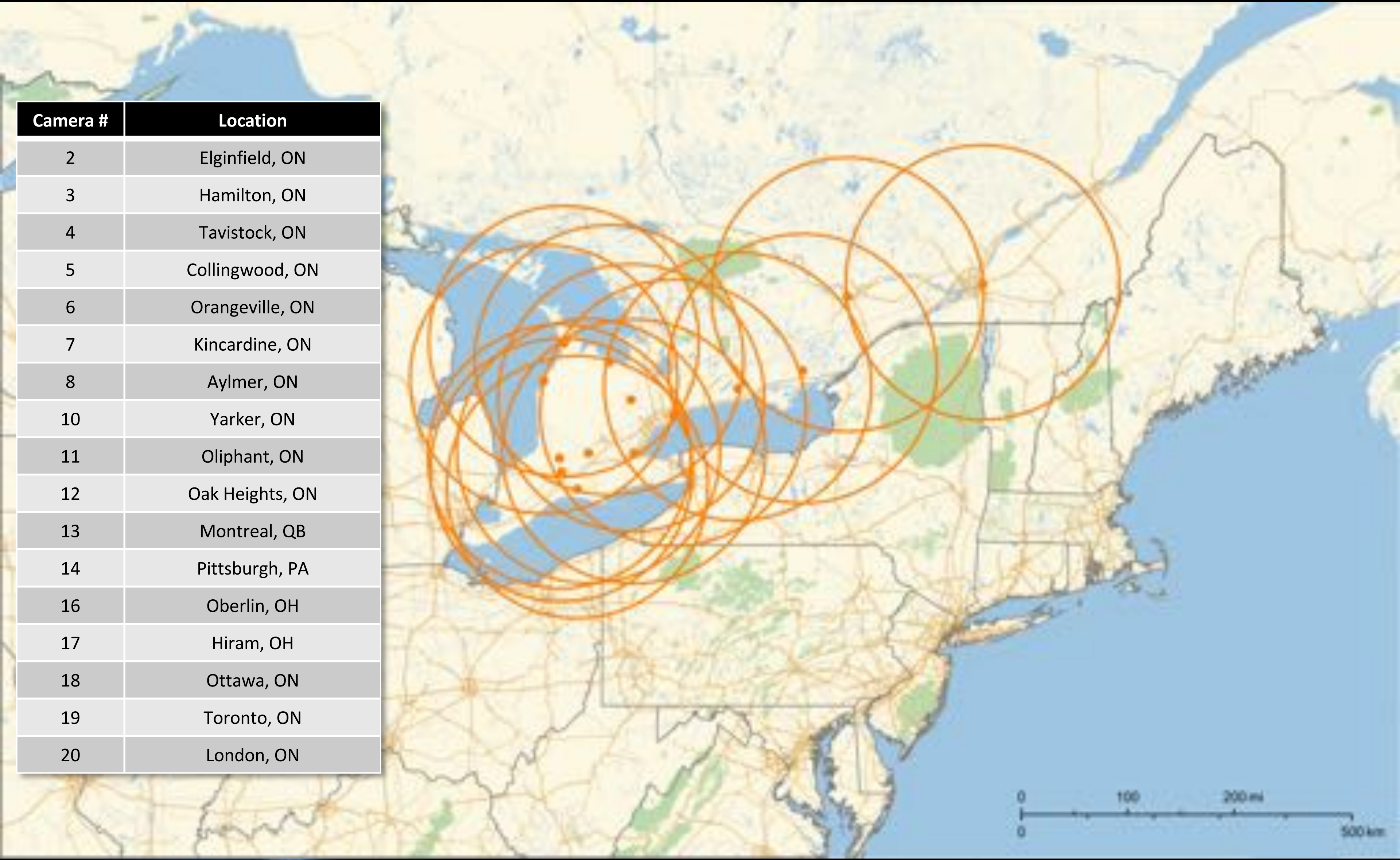

DFNEXT000
Laptop / eth0
Network / eth1

The Desert Fireball Network (DFN)

- Established with the primary goal of finding meteorites
- Operates ~50 automated stations in Australia; started working with NASA SSERVI (Solar System Exploration Research Virtual Institute) in 2018 to create a “global fireball observatory”
- Cameras take 30 second exposures throughout the night; meteor events have the time encoded on the trail in a De Bruijn sequence (messes up photometry/mass determinations)
- Events are tagged and correlated on central server; analysis of correlated events is done manually using specialized software
- Camera stations are serviced 1-2 times per year; data on replaced drives is archived

Southern Ontario Meteor Network (SOMN)

Camera #	Location
2	Elginfield, ON
3	Hamilton, ON
4	Tavistock, ON
5	Collingwood, ON
6	Orangeville, ON
7	Kincardine, ON
8	Aylmer, ON
10	Yarker, ON
11	Oliphant, ON
12	Oak Heights, ON
13	Montreal, QB
14	Pittsburgh, PA
16	Oberlin, OH
17	Hiram, OH
18	Ottawa, ON
19	Toronto, ON
20	London, ON



The NASA all sky fireball network

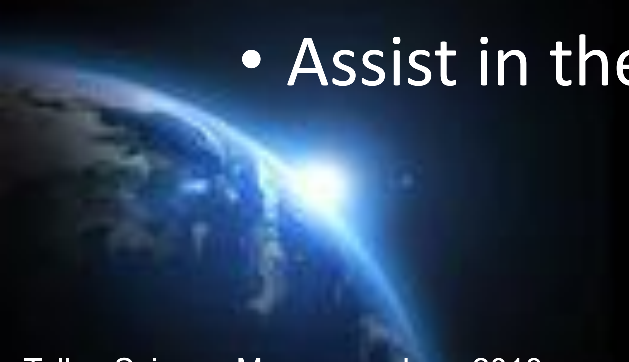
Camera #	Location
1	Huntsville, AL
2	Chickamauga, GA
3	Tullahoma, TN
4	Cartersville, GA
5	Las Cruces, NM
6	Mayhill, NM
7	Rosman, NC
8	Dahlonega, GA
9	Kitt Peak, AZ
10	Mt. Lemmon, AZ
11	Mt. Hopkins, AZ
14	Pittsburgh, PA
16	Oberlin, OH
17	Hiram, OH
18	Daytona Beach, FL
19	Orlando, FL
20	Cape Canaveral, FL

Goals of SOMN

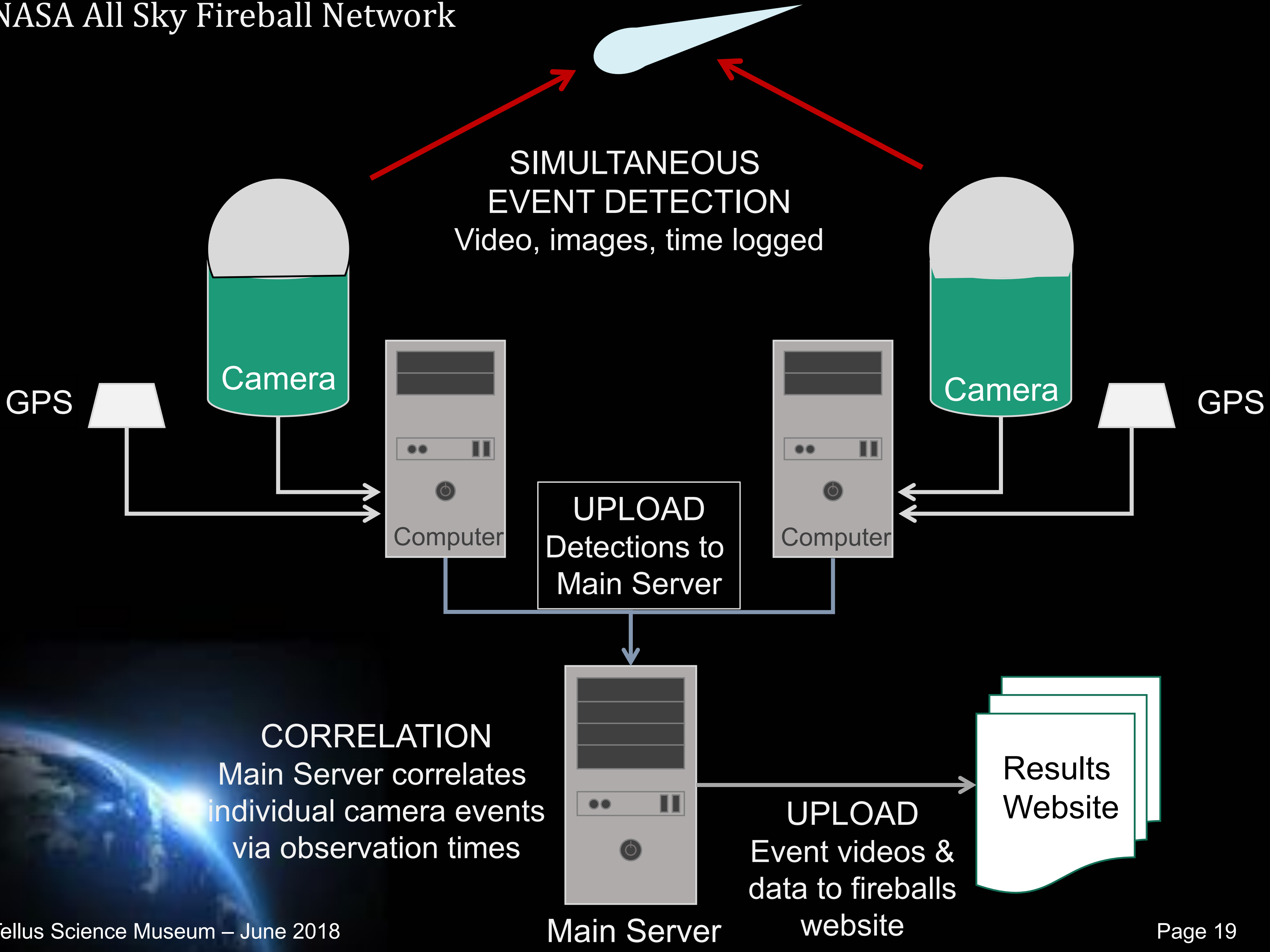
- Multi-sensor calibration of relative meteoroid mass/energy scales: video, radar, infrasonic, seismic
- Probe of observational biases in meteor observations
- Detailed ablation modeling as a proxy for physical structure
- Flux of small NEOs
- Meteorite fall observations

Goals of the NASA Network

- Establish the speed distribution of cm size meteoroids
- Determine which sporadic sources produce large particles
- Determine (low precision) orbits for bright meteors
- Attempt to discover the size at which showers begin to dominate the meteoroid flux
- Monitor the activity of major meteor showers
- Assist in the location of meteorite falls



NASA All Sky Fireball Network



SIMULTANEOUS
EVENT DETECTION
Video, images, time logged

UPLOAD
Detections to
Main Server

CORRELATION
Main Server correlates
individual camera events
via observation times

UPLOAD
Event videos &
data to fireballs
website

Camera

- Watec 902-H2 Ultimate or Sony HiCam HB-710E
  - monochrome 8bit CCD video cameras
  - 1/2” CCD chip, effectively 768x494 px
  - Interleaved 30 fps video
- F1.4, 1.6-3.4mm Rainbow L163VDC4P fisheye lens
- Weatherproof PVC enclosure with twilight sensor, thermostat, heater, fan
- Flat-roof or pole mounted

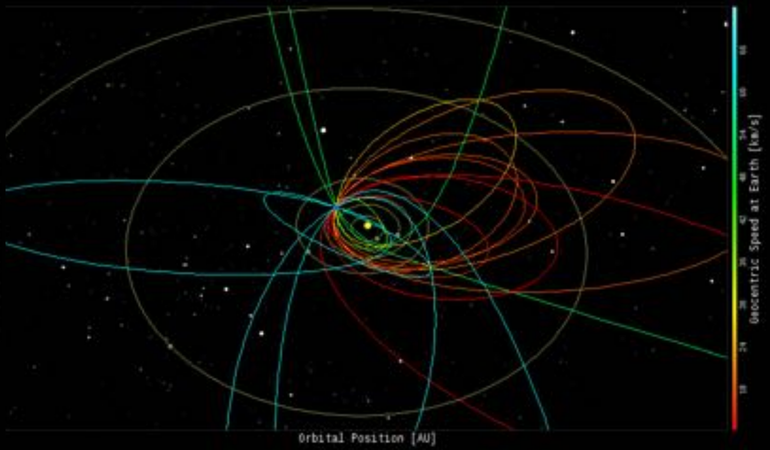
Computer

- Standard desktop computer running Debian Linux
  - Frame-grabber card
  - Large disk storage for streaming video buffer
  - ASGARD (All Sky and Guided Automatic Real-time Detection) software for meteor detection, correlation, analysis, and storage
  - USB GPS for time synchronization
- Network link

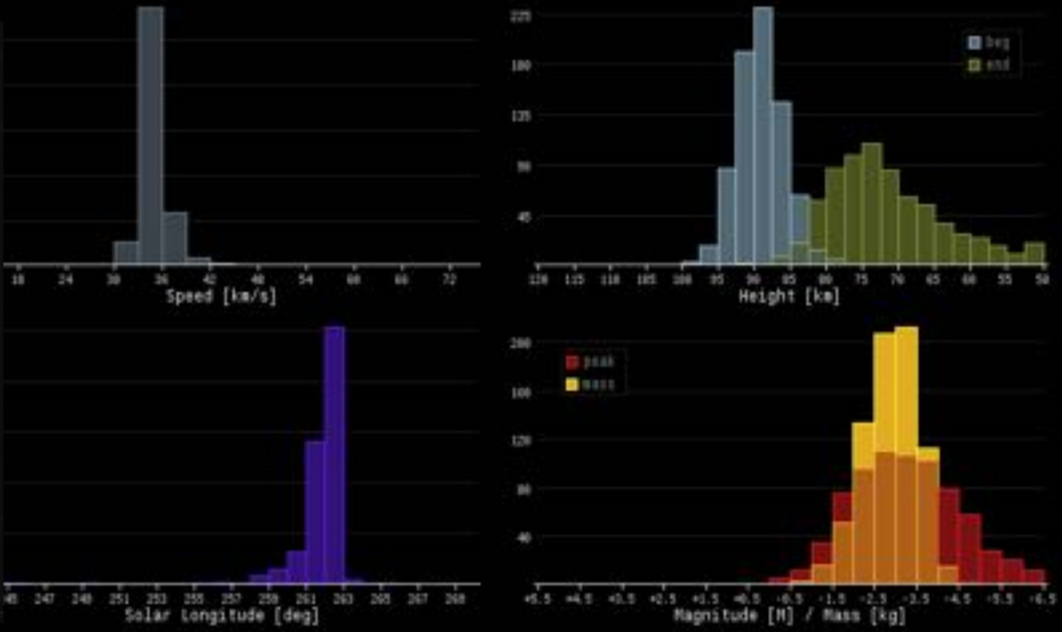
FoV and detections

FoV and detections


Latitude [deg]
Longitude [deg]
Average Speed [km/s]


Orbital Position [AU]
Geocentric Speed at Earth [km/s]


20180304 05:30:23.973 UTC (0)
Chickamauga (02A)


Speed [km/s]
beg
end
Height [km]
Solar Longitude [deg]
peak
mass
Magnitude [M] / Mass [kg]

Results website

http://fireballs.ndc.nasa.gov

Daily weblog of events seen by the camera network

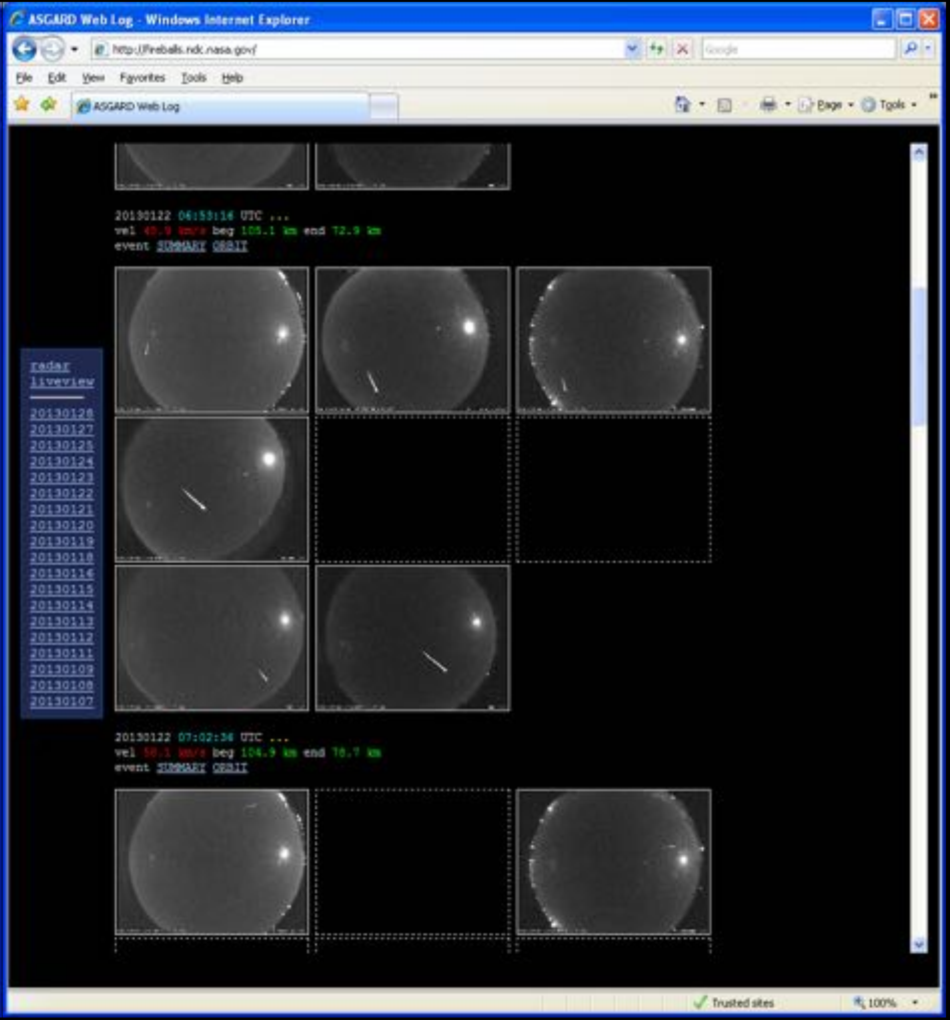
NASA's All Sky Fireball Network

"What was that bright light in the sky last night?"

Intro: The NASA All-sky Fireball Network is a network of cameras set up by the NASA Meteoroid Environment Office (MEO) with the goal of observing meteors brighter than the planet Venus, which are called fireballs. The collected data will be used by the MEO in constructing models of the meteoroid environment, which are important to spacecraft designers.

Network: The network currently consists of 8 cameras, 6 of which are placed in locations in north Alabama, north Georgia, southern Tennessee, and southern North Carolina. The remaining 2 are located in southern New Mexico. The network is growing all the time, with plans to place a total of 15 cameras in schools, science centers, and planetaria in the United States, predominantly east of the Mississippi River, where there are few such systems.

radar
liveview
20130128
20130127
20130125
20130124
20130123
20130122
20130121
20130120
20130119
20130118
20130116
20130115
20130114
20130113
20130112
20130111
20130109
20130108
20130107



radar
liveview
20130128
20130127
20130125
20130124
20130123
20130122
20130121
20130120
20130119
20130118
20130116
20130115
20130114
20130113
20130112
20130111
20130109
20130108
20130107

```
20130122 06:53:16 UTC ...
vel [illegible] km/s beg 105.1 km end 72.9 km
event SUMMARY ORBIT
```

```
20130122 07:02:36 UTC ...
vel 58.1 km/s beg 104.9 km end 76.7 km
event SUMMARY ORBIT
```

Images, movies sorted by date

Meteor speed, trajectory, orbit, brightness, mass

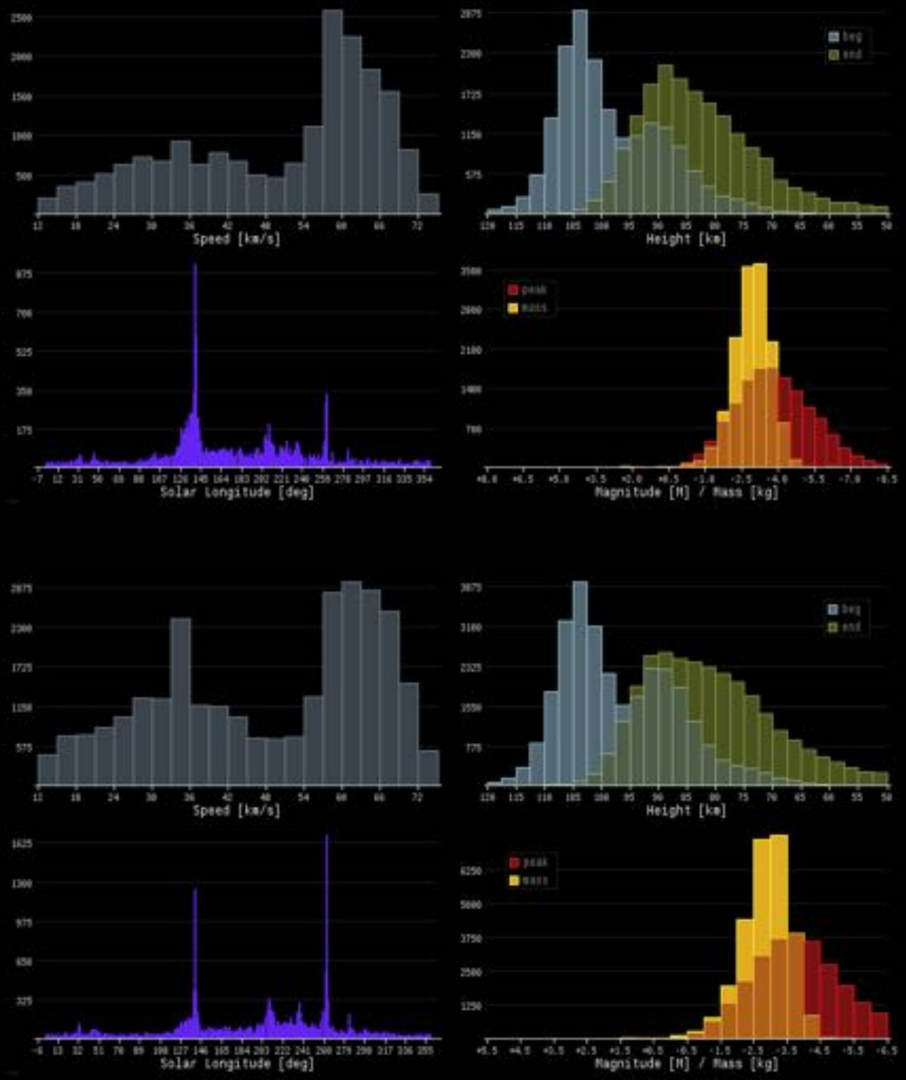
Results to Date

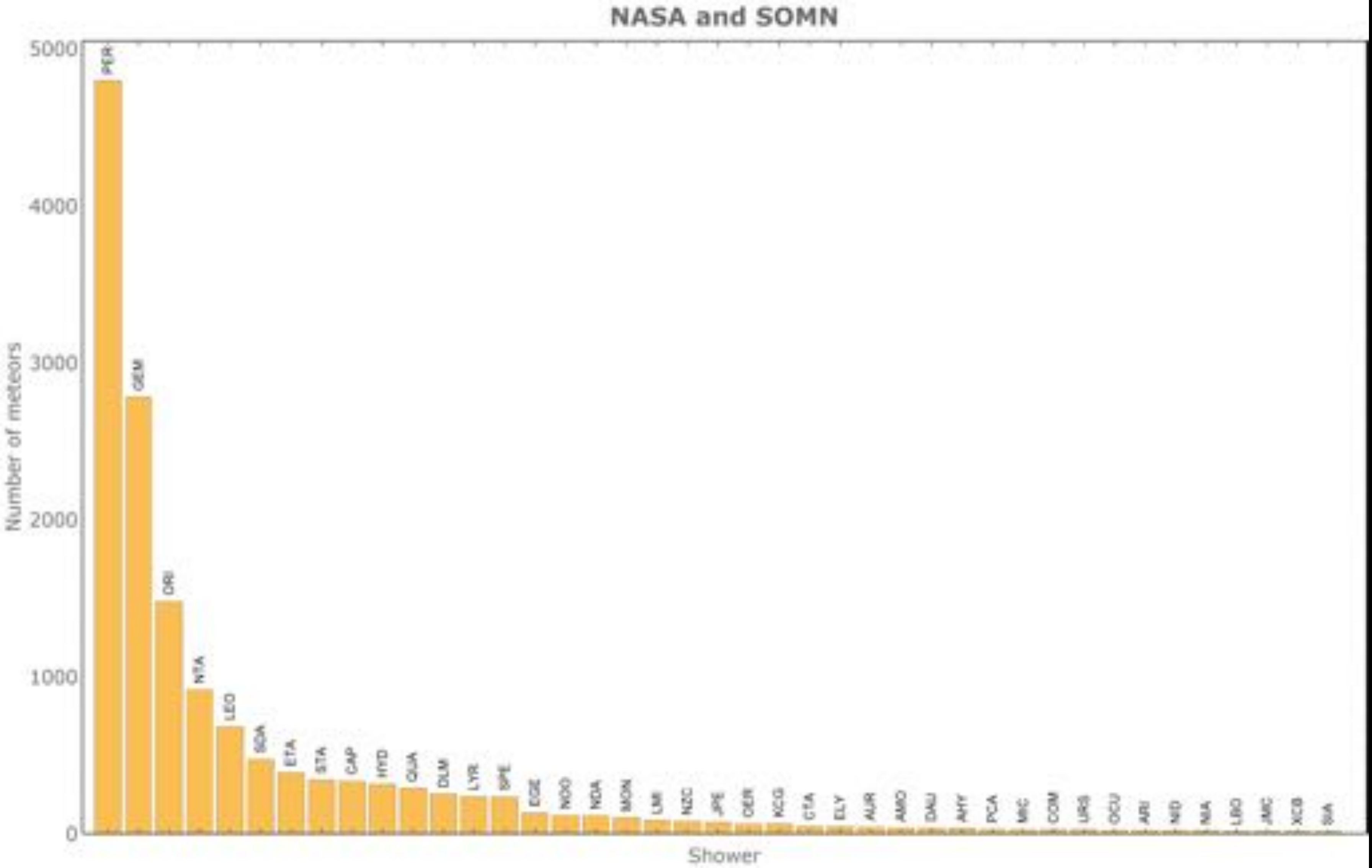
SOMN

Time period: early 2006 to present
meteors: 17,000+ multi-station
Lim meteor mag: -2.0 (Jupiter)
meteorite falls: 7

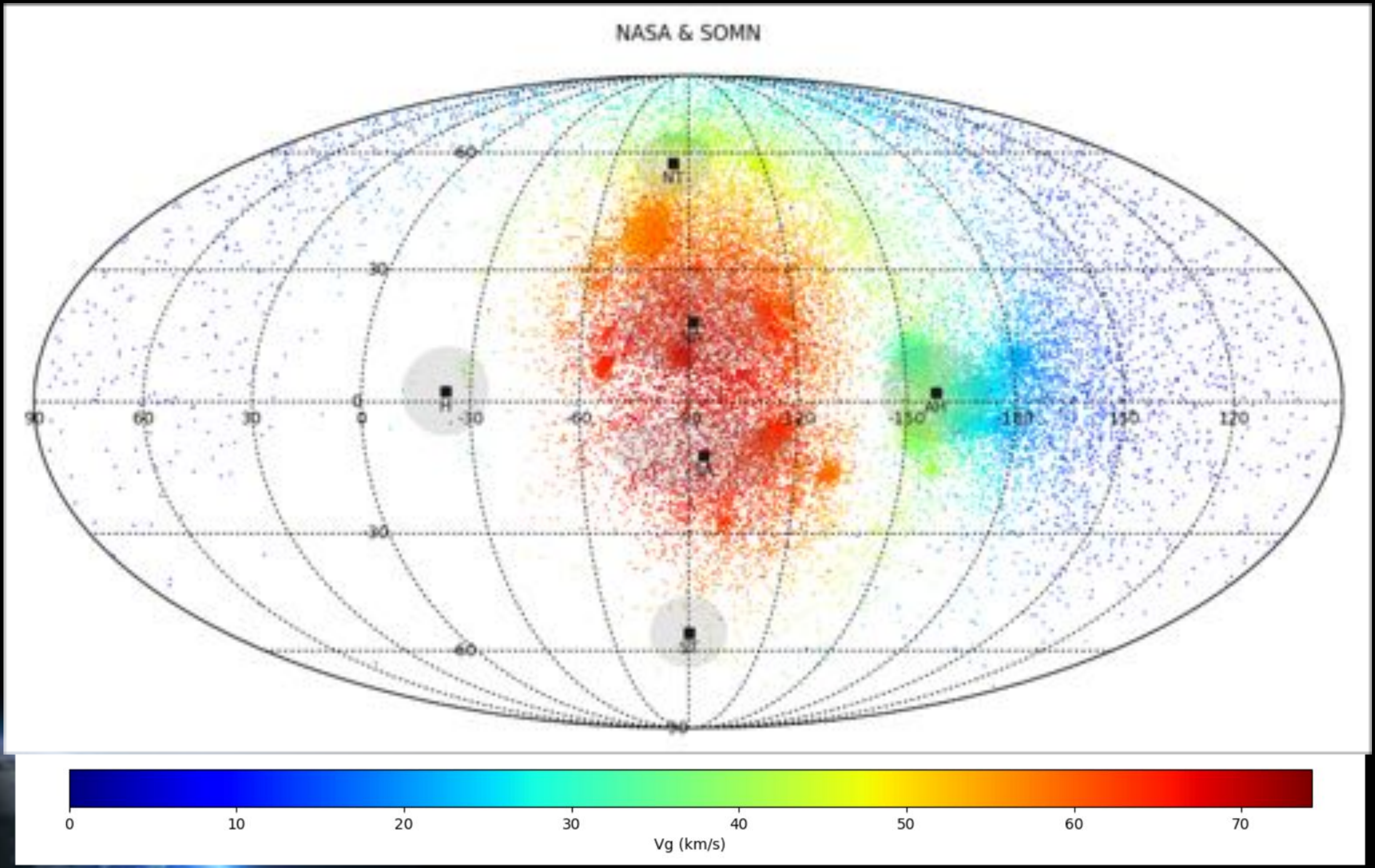
NASA

Time period: late 2008 to present
meteors: 27,000+ multi-station
Lim meteor mag: -2.0 (Jupiter)
public interest: ~1/week avg
meteorite falls: 2



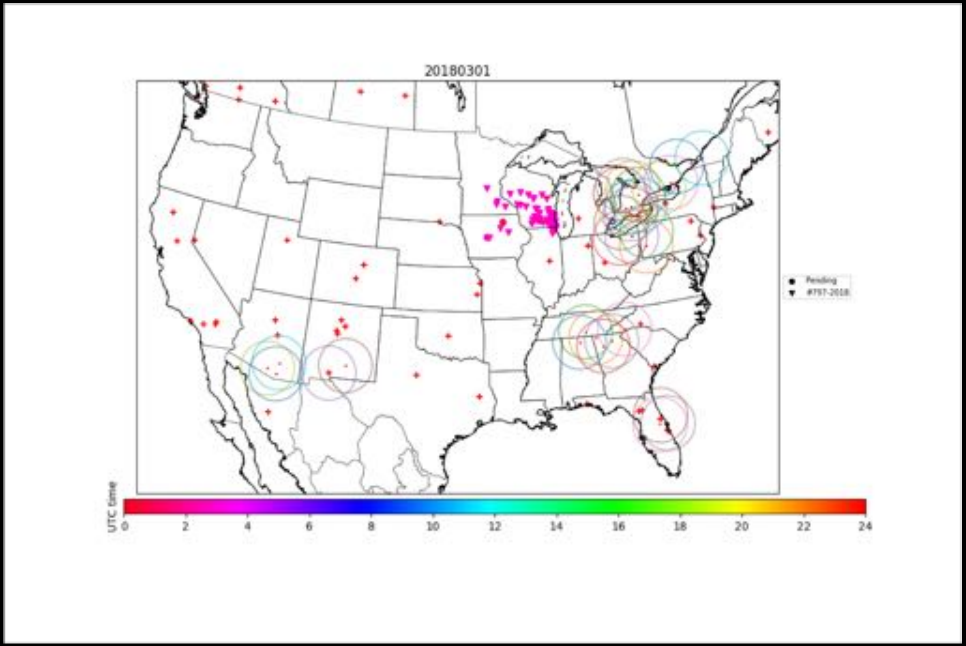


For 3-letter meteor shower abbreviations, see https://www.ta3.sk/IAUC22DB/MDC2007

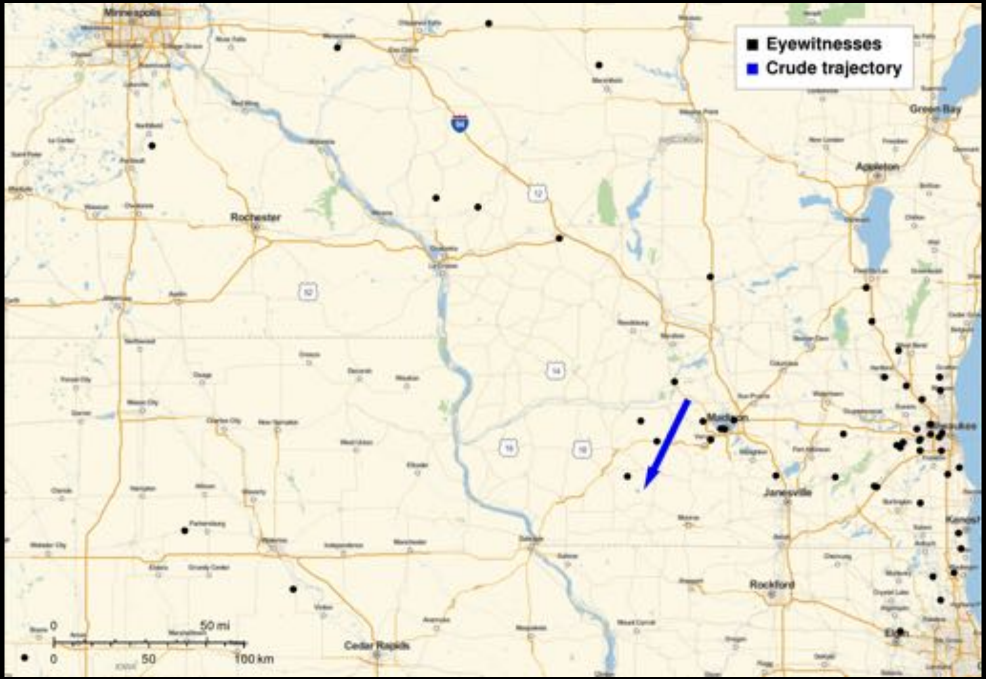

NASA & SOMN
60
30
0
-30
-60
-90
90
60
30
0
-30
-60
-90
-120
-150
180
150
120
NT
H
AH
0
10
20
30
40
50
60
70
Vg (km/s)

Skyfalls

- The MEO has to prepare a quick response to NASA HQ whenever there are ”large” numbers of reports about a bright object in the night sky.
- We have software tools (“Chicken Little”) that enable us to do a rapid analysis of the eyewitness accounts, establishing a crude trajectory that permits the searching of data from cameras, weather radar, etc. in the area.
- The summary is due to HQ within a few hours (typically by 11 AM CST) for events that happened the previous night.

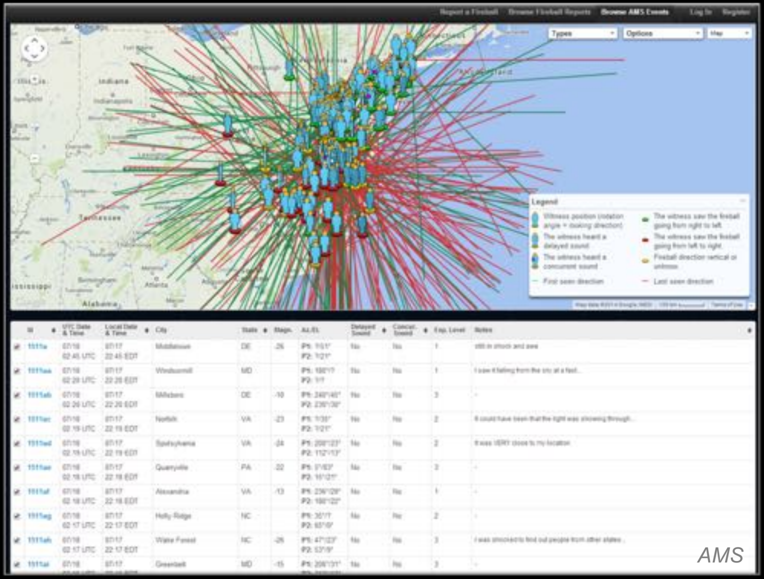

20180301
● Pending
▼ #797-2018
UTC time
0
2
4
6
8
10
12
14
16
18
20
22
24


20:47:25 Wed Feb 28 2018
UW-Madison SSEC/AOS

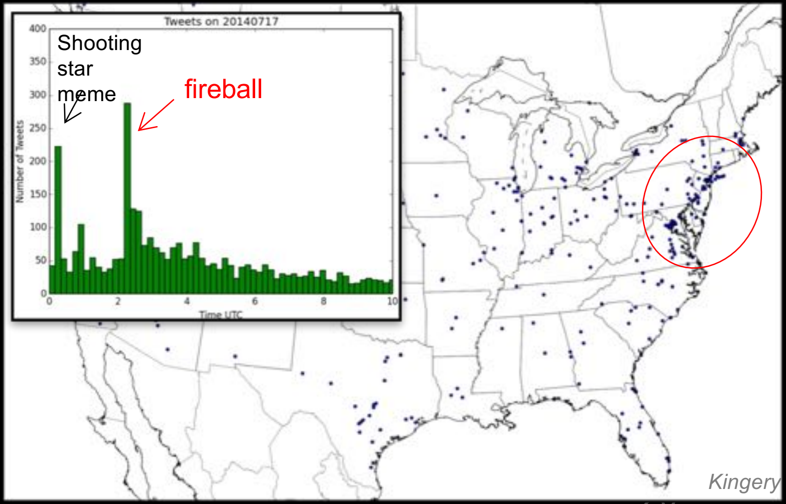

■ Eyewitnesses
■ Crude trajectory
Minneapolis
Rochester
Green Bay
Appleton
Madison
Janesville
Milwaukee
Kenosha
Rockford
Elgin
Cedar Rapids
0
50 mi
0
50
100 km

Sites we monitor for info

- Major news outlets
- American Meteor Society (*www.amsmeteors.org*)
- Latest Worldwide Meteor/Meteorite News (*lunarmeteoritehunters.blogspot.com/*)
- MeteorObs e-mail list (*www.meteorobs.org*)
- Facebook (*www.facebook.com/NasaMeteorWatch*)
- Twitter

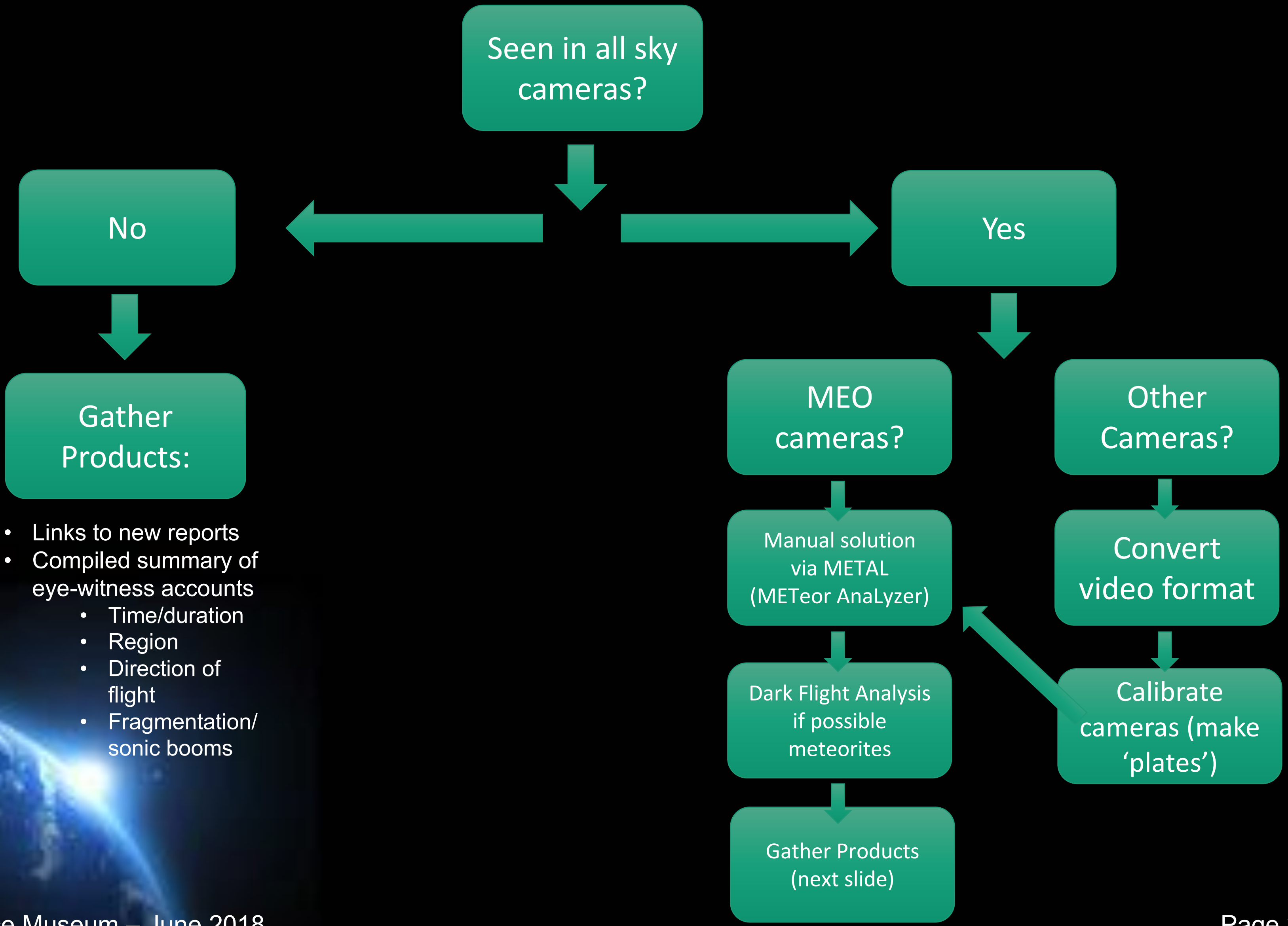


American Meteor Society fireball log



Data-mining Twitter

Procedures



Seen in all sky cameras?

No

Gather Products:

- Links to new reports
- Compiled summary of eye-witness accounts
    - Time/duration
    - Region
    - Direction of flight
    - Fragmentation/ sonic booms

Yes

MEO cameras?

Manual solution via METAL (METeor AnaLyzer)

Dark Flight Analysis if possible meteorites

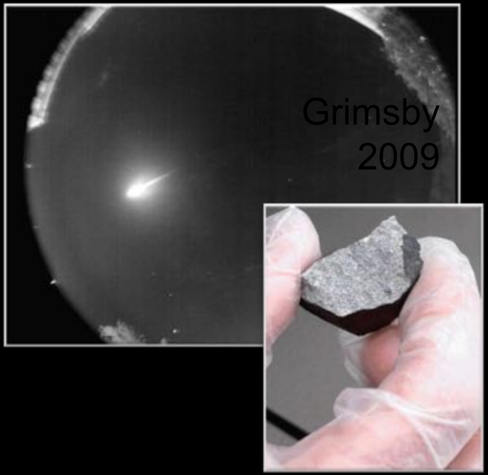
Gather Products (next slide)

Other Cameras?

Convert video format

Calibrate cameras (make ‘plates’)

Meteorite Terminology



Grimsby
2009

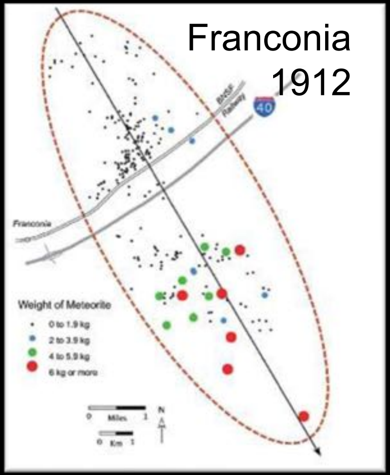
Meteorite fall

- A meteorite collected after it was observed travelling through the atmosphere.
- Observation made by people or instruments
- Just above 20 worldwide.

Image courtesy of the 2011-2012 ANSMET team.

Meteorite find

- A meteorite collected with no record of its fall.
- Thousands worldwide.



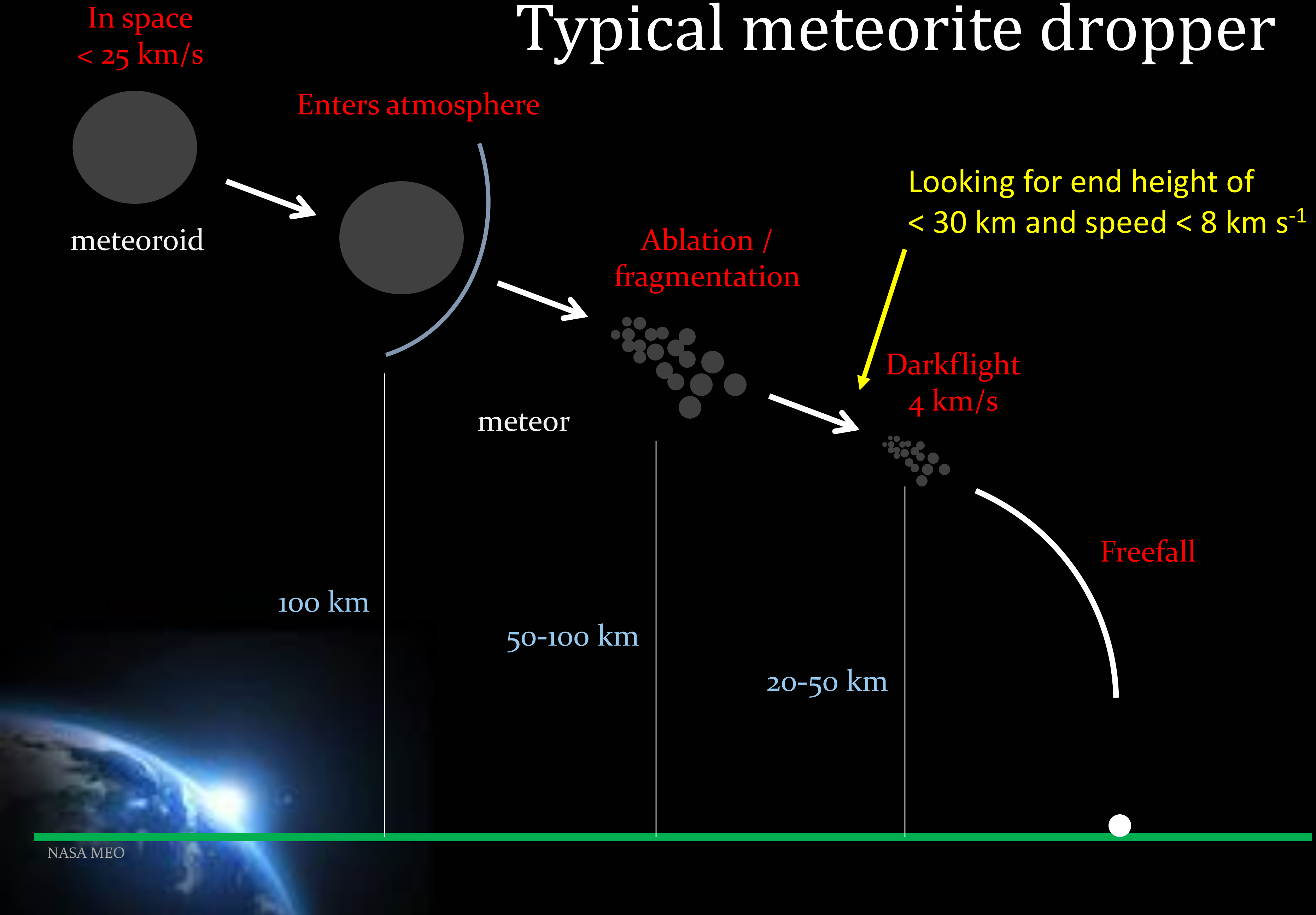
Franconia
1912

Nuggetshooter.com

Strewn field

- The area where meteorites from a single fall are dispersed.
- Bigger meteorites are found down range.

Typical meteorite dropper



In space
< 25 km/s

meteoroid

Enters atmosphere

meteor

Ablation /
fragmentation

Looking for end height of
< 30 km and speed < 8 km s^{-1}

Darkflight
4 km/s

Freefall

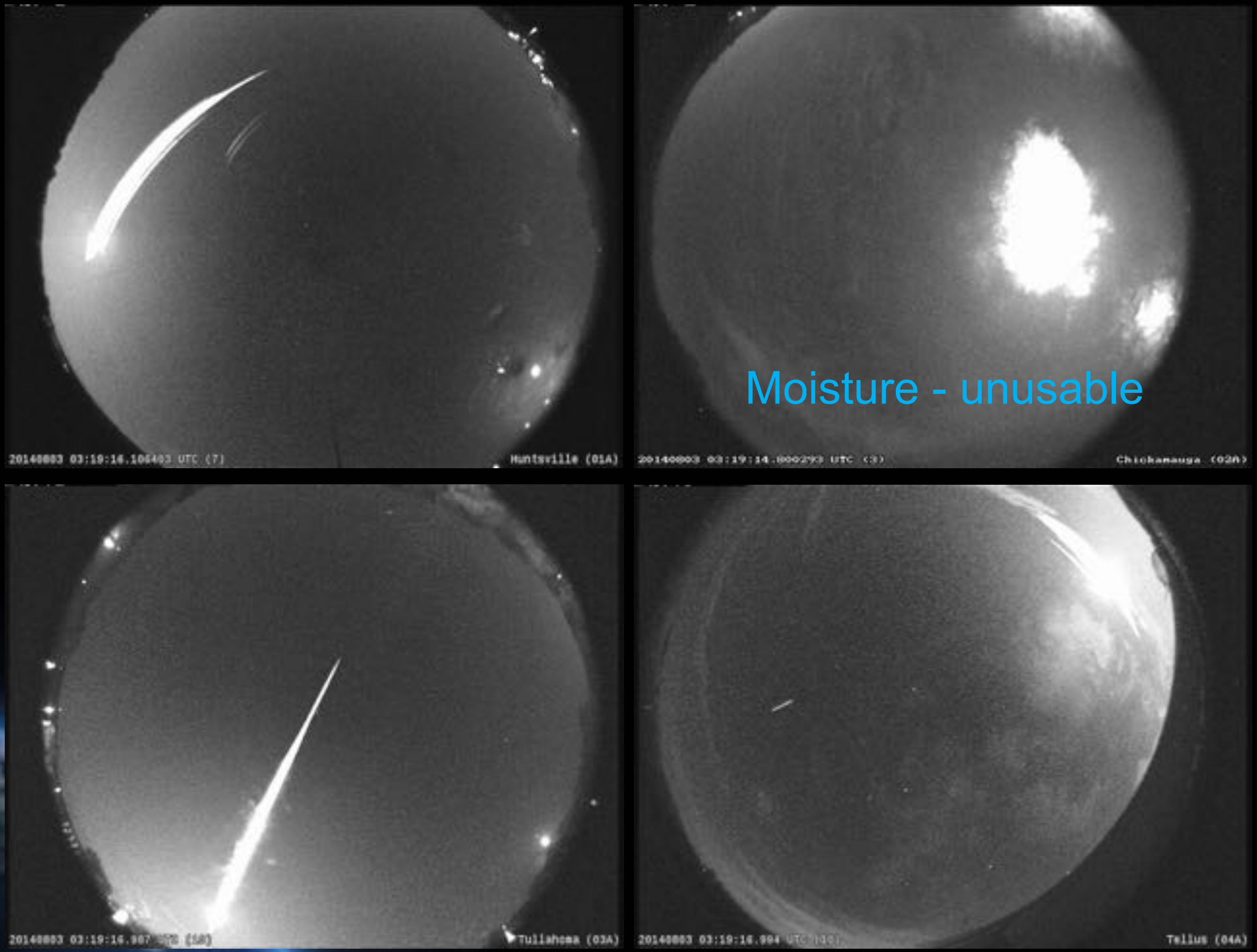
100 km

50-100 km

20-50 km

NASA MEO

Case study: Alabama Fireball



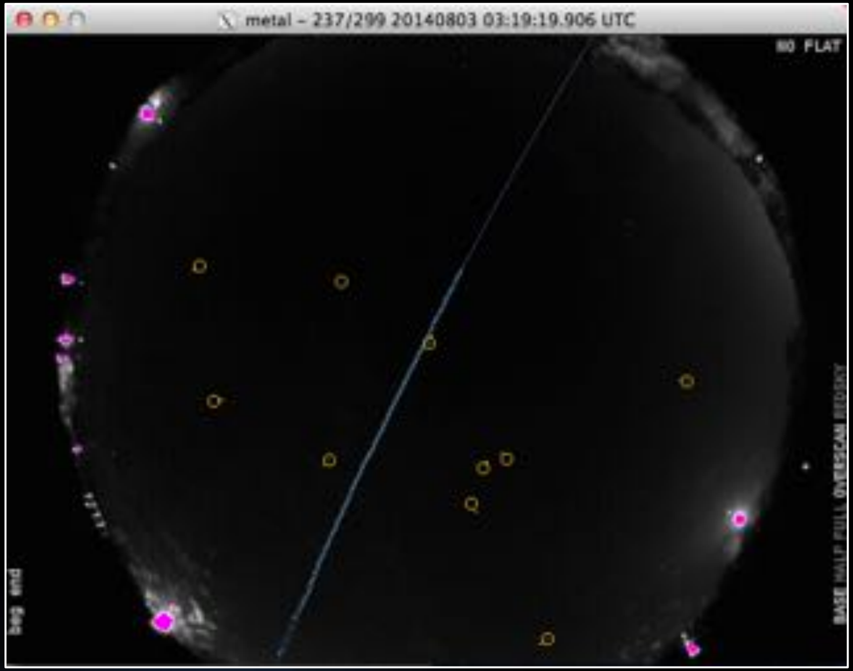
Moisture - unusable

Seen in 4 NASA cameras

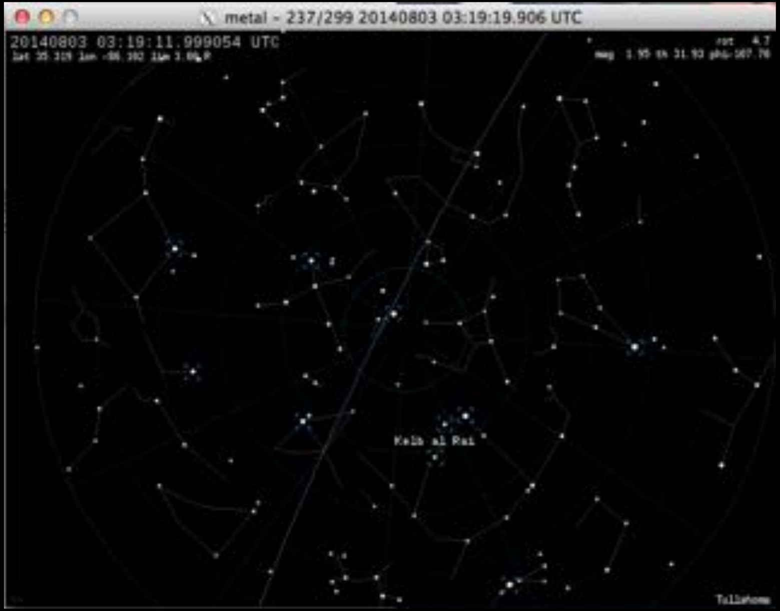
3 videos useable for manual analysis

Automated solution poor due to saturation and flaring

METAL (METeor AnaLyzer)

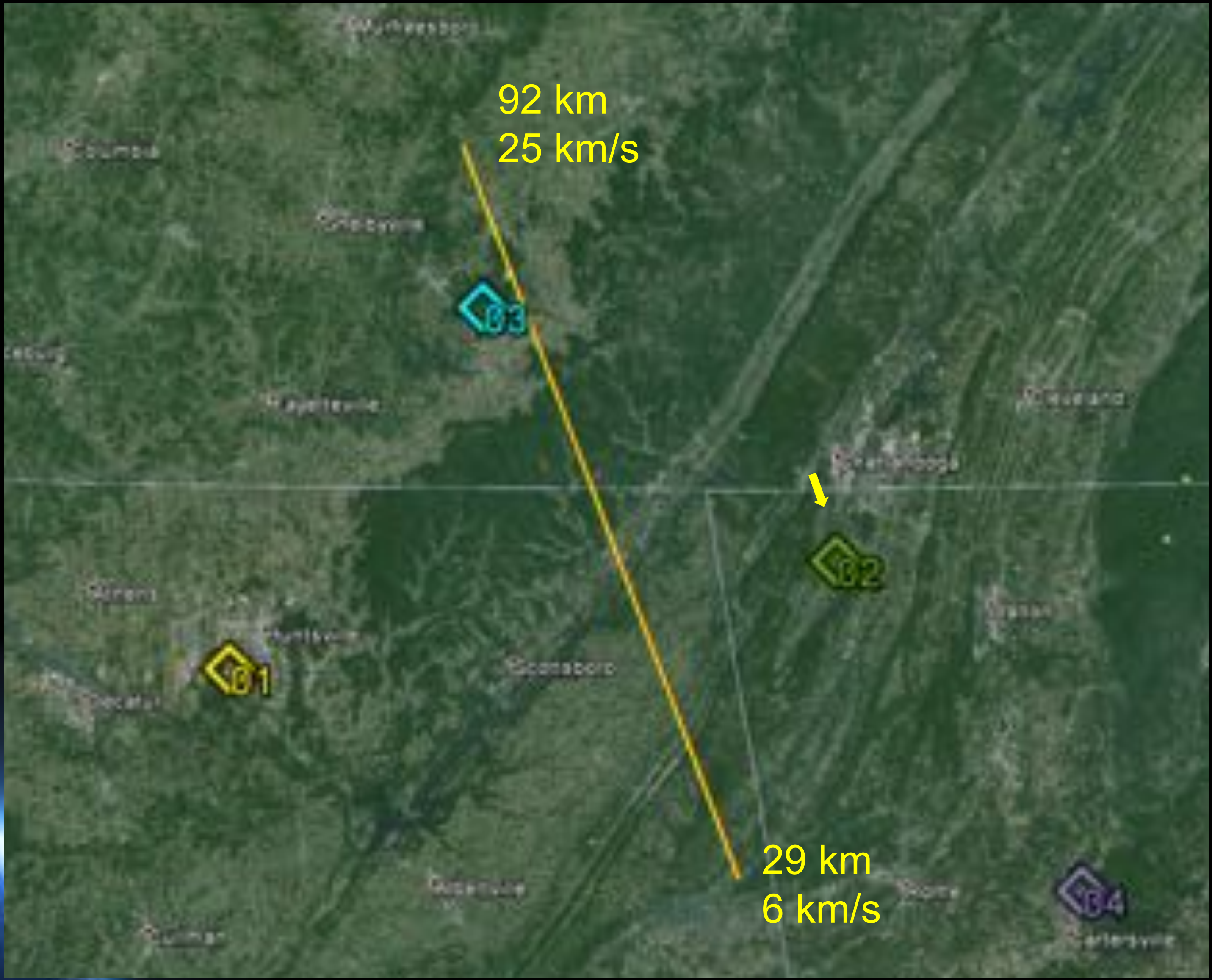


Images Calibrated + trajectory mapped

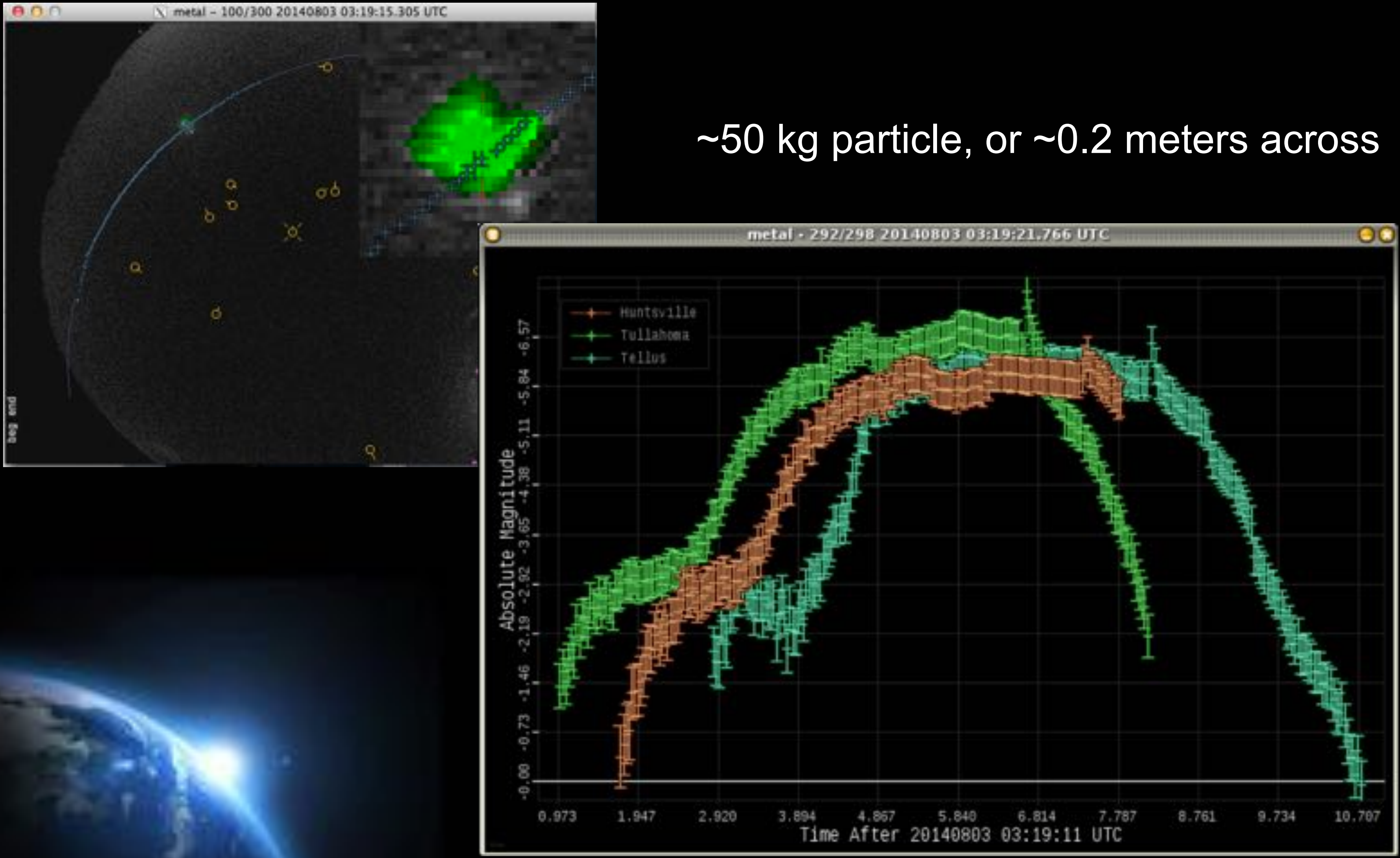


Trajectory

20140803 03:19:11.0 UTC

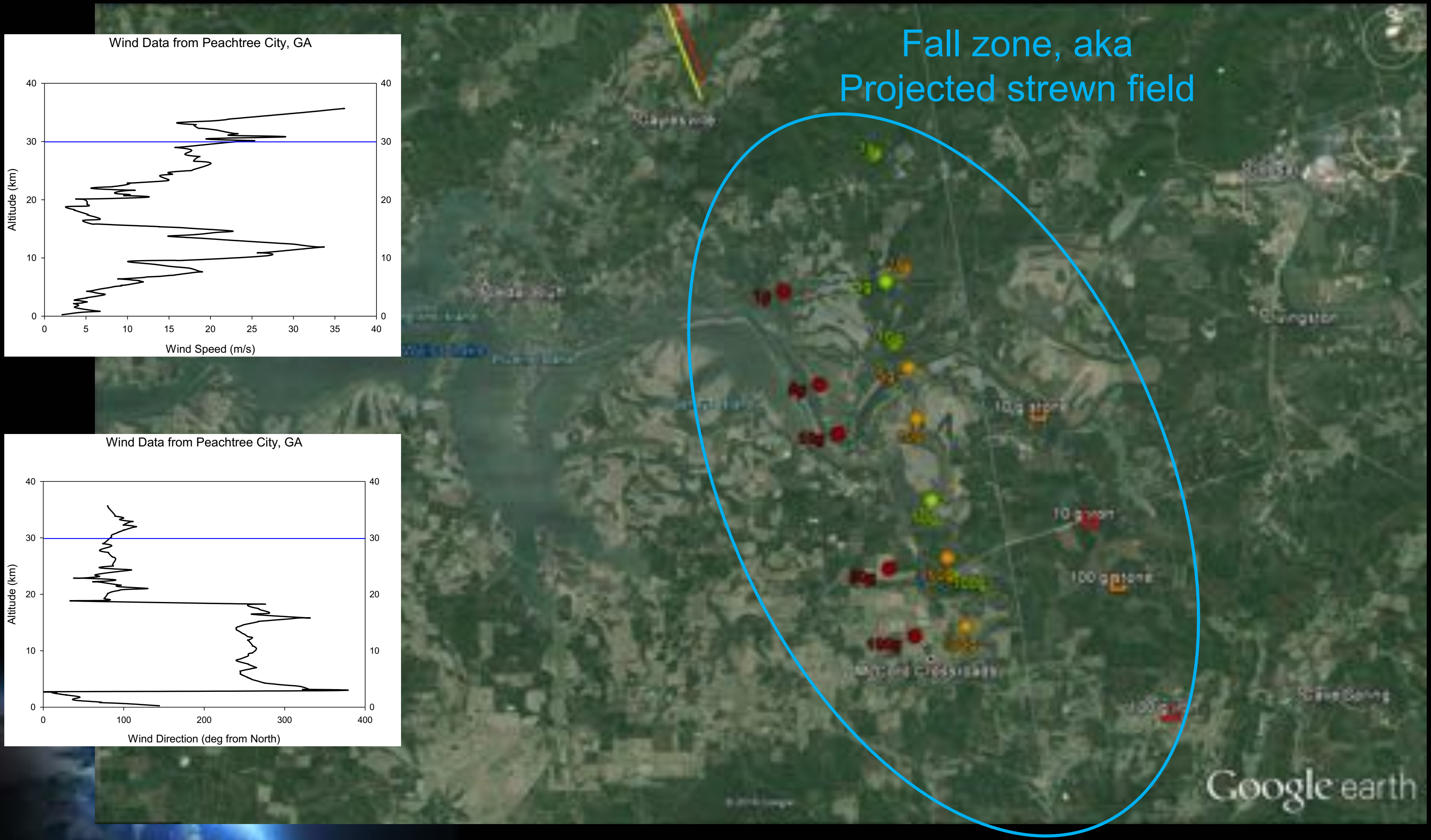


Photometry



~50 kg particle, or ~0.2 meters across

Dark flight modeling



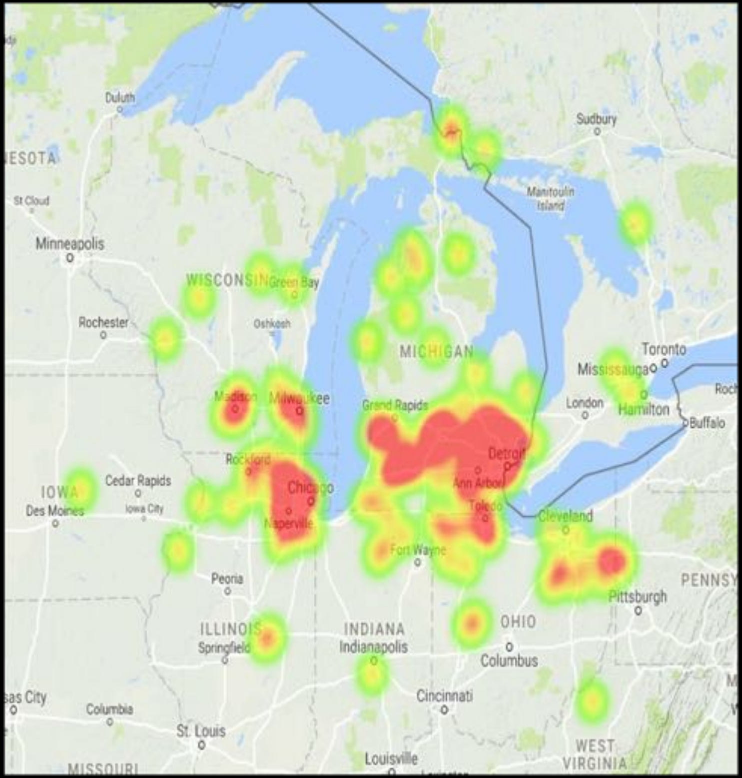
NASA model (stone): ● No wind ● Average wind ● Approx wind

Fries model: ☐ Stone ☐ Iron

Meteorite hunting expedition

Michigan event – January, 2018

- Occurred on January 17, 2018 at 01:08:30 UTC (2018 January 16 7:08:30 PM CST)
- Over 600 eyewitness accounts
- Caught on security and dash cameras throughout the region
- Detected by the NASA all sky meteor camera at Oberlin College
- Superbolide class event



American Meteor Society (AMS) observer heat map

CAM6

01/16/2018 20:14:30

Windsor,


RailStream, LLC. - MH Tower (Chicago, IL) 2018-01-16 19:08:26

Rochester Hills

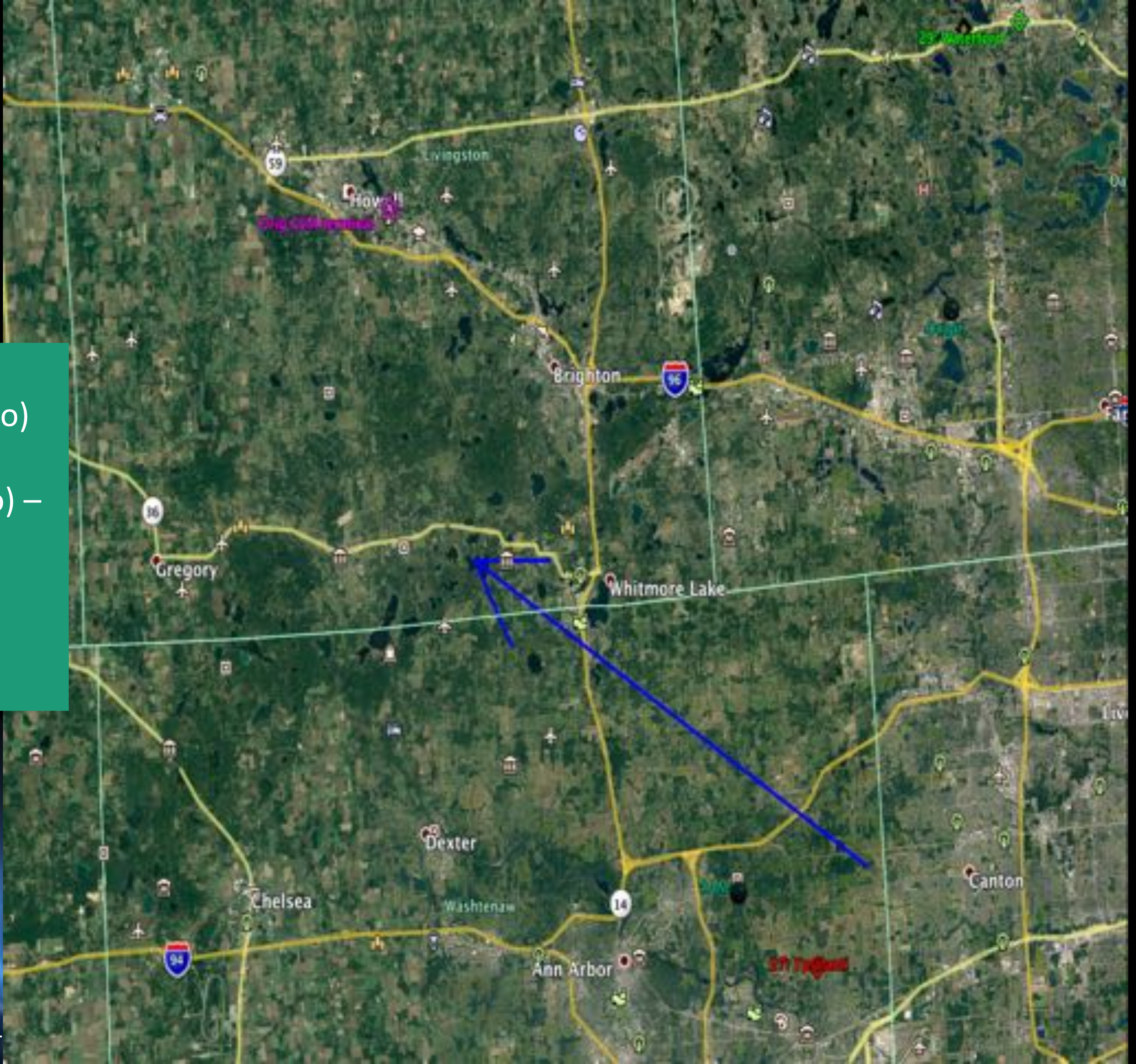
What we know

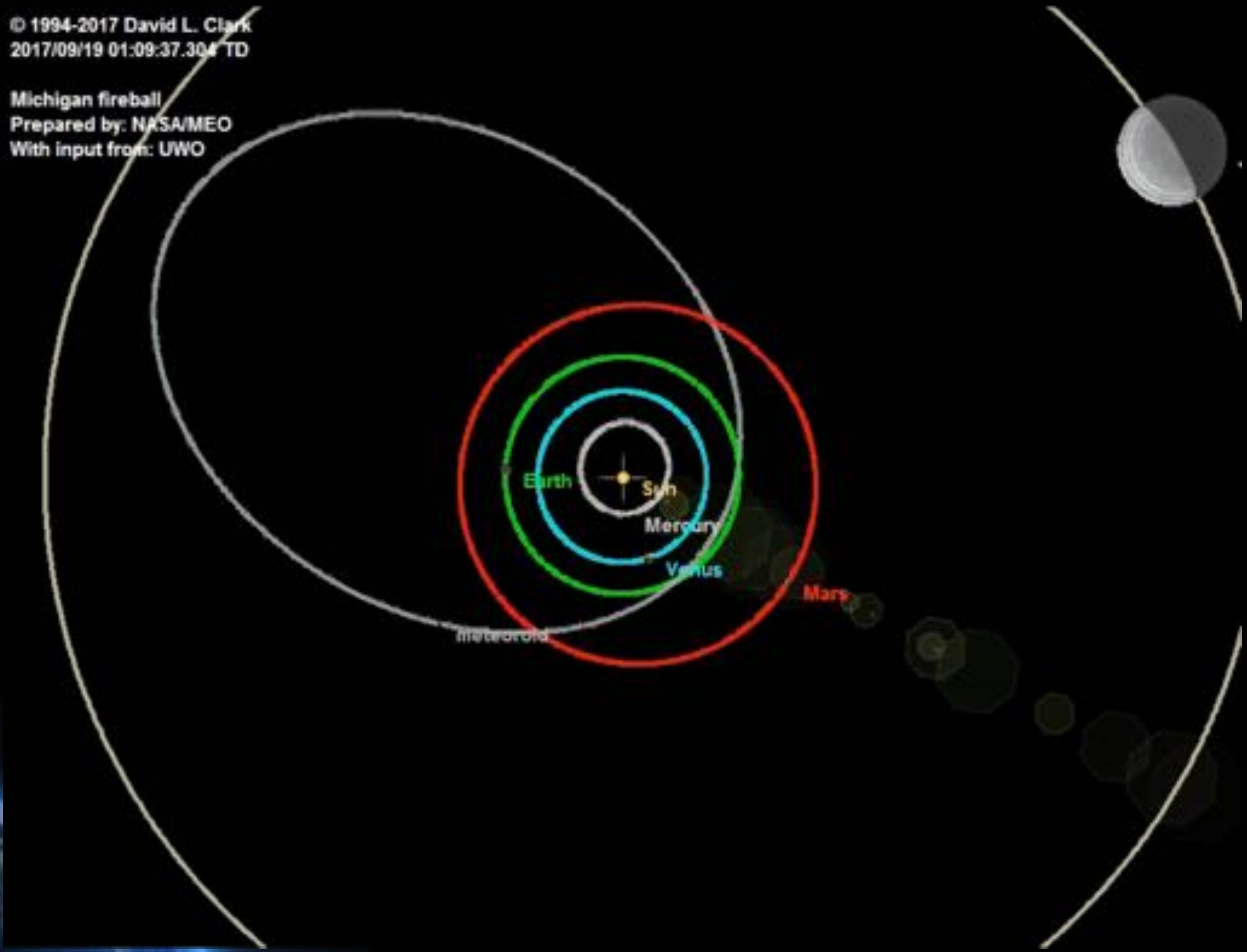
Speed – 15 km/s

Start height (video) – 86 km

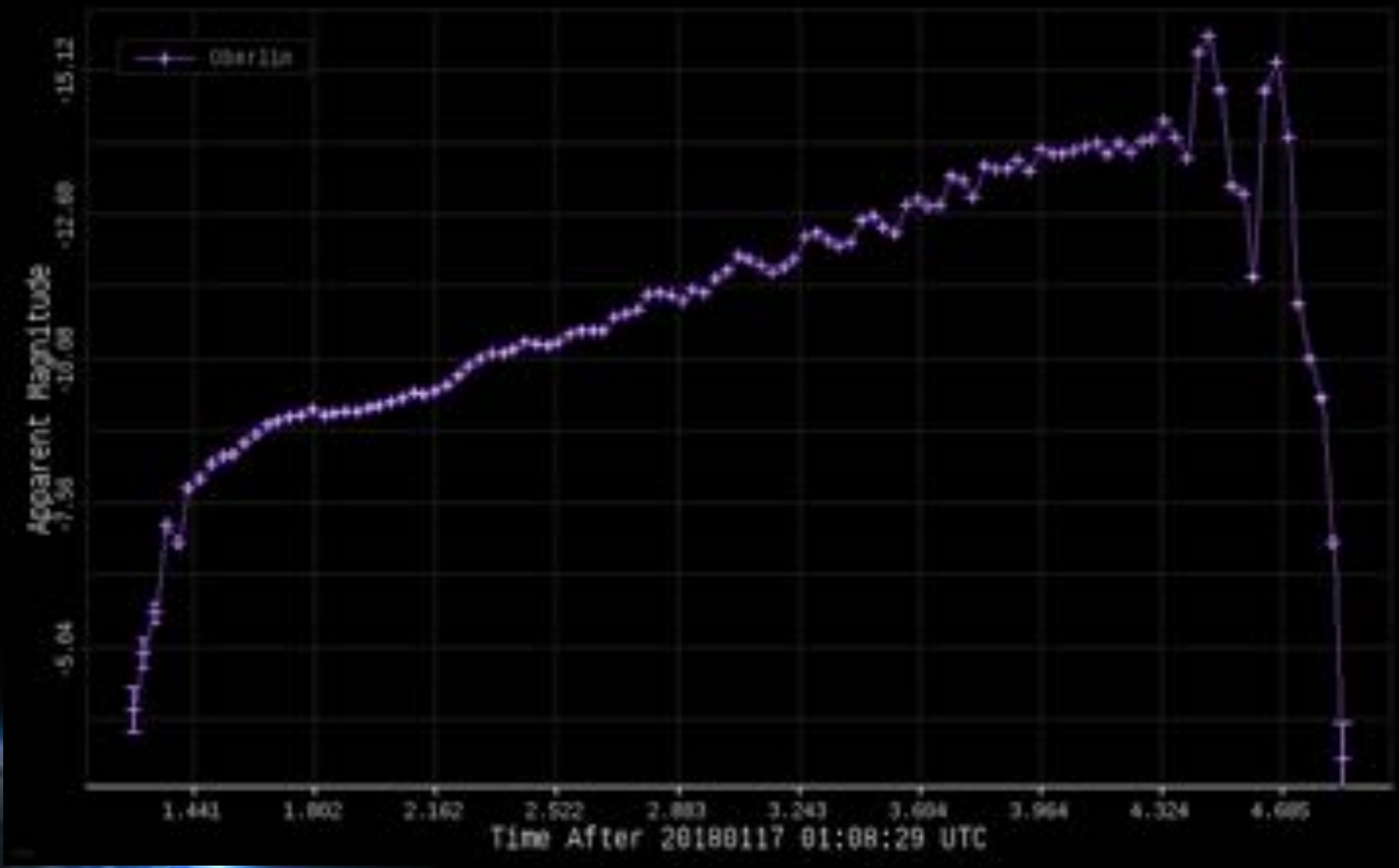
End height (video) – 18 km

Very steep entry angle – 22° from vertical

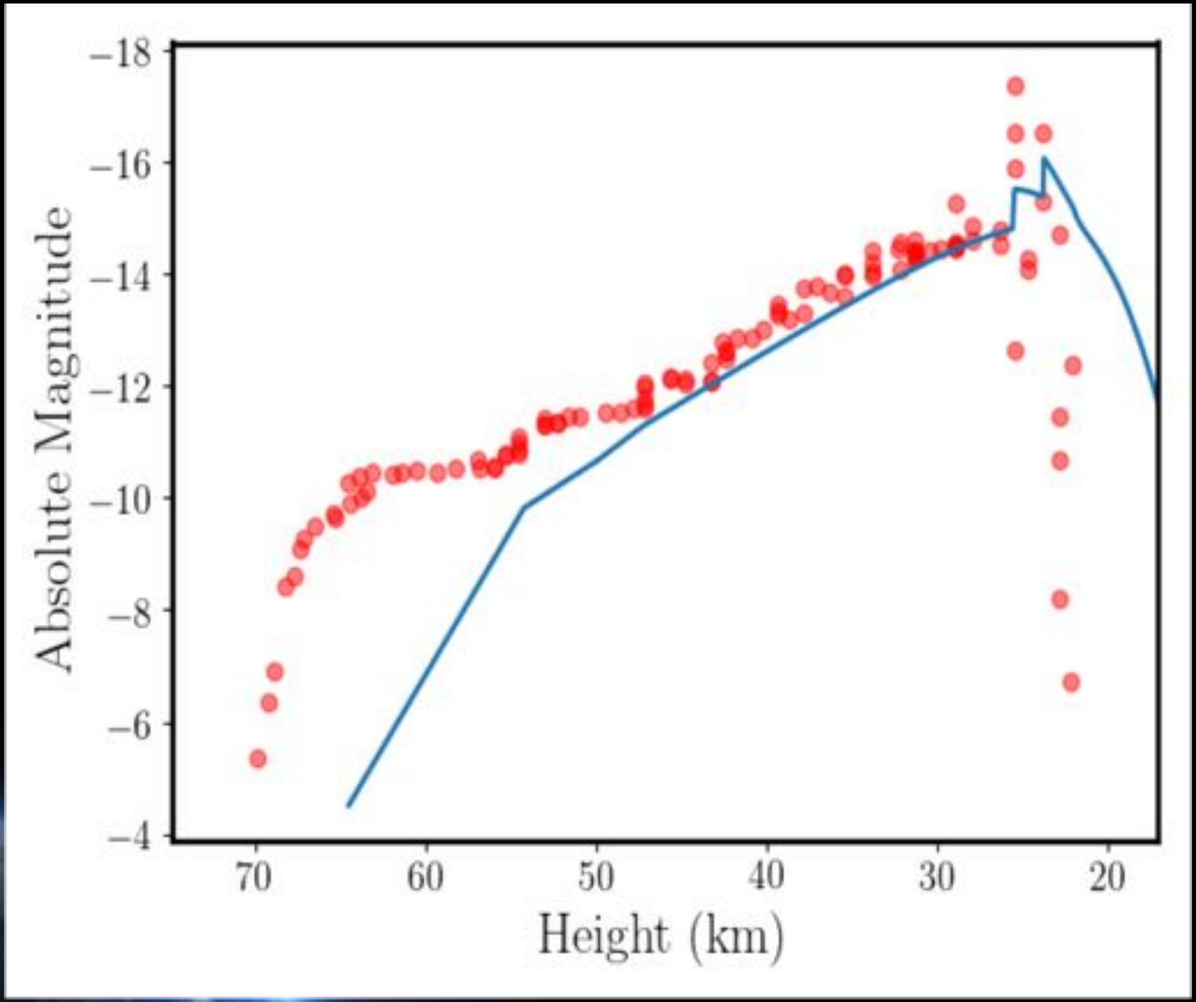



© 1994-2017 David L. Clark
2017/09/19 01:09:37.304 TD
Michigan fireball
Prepared by: NASA/MEO
With input from: UWO
Earth
Sun
Mercury
Venus
Mars
Meteoroid

Light curve


Oberlin
Apparent Magnitude
-15.12
-12.60
-10.08
-7.56
-5.04
1.441
1.802
2.162
2.522
2.883
3.243
3.604
3.964
4.324
4.685
Time After 20180117 01:08:29 UTC

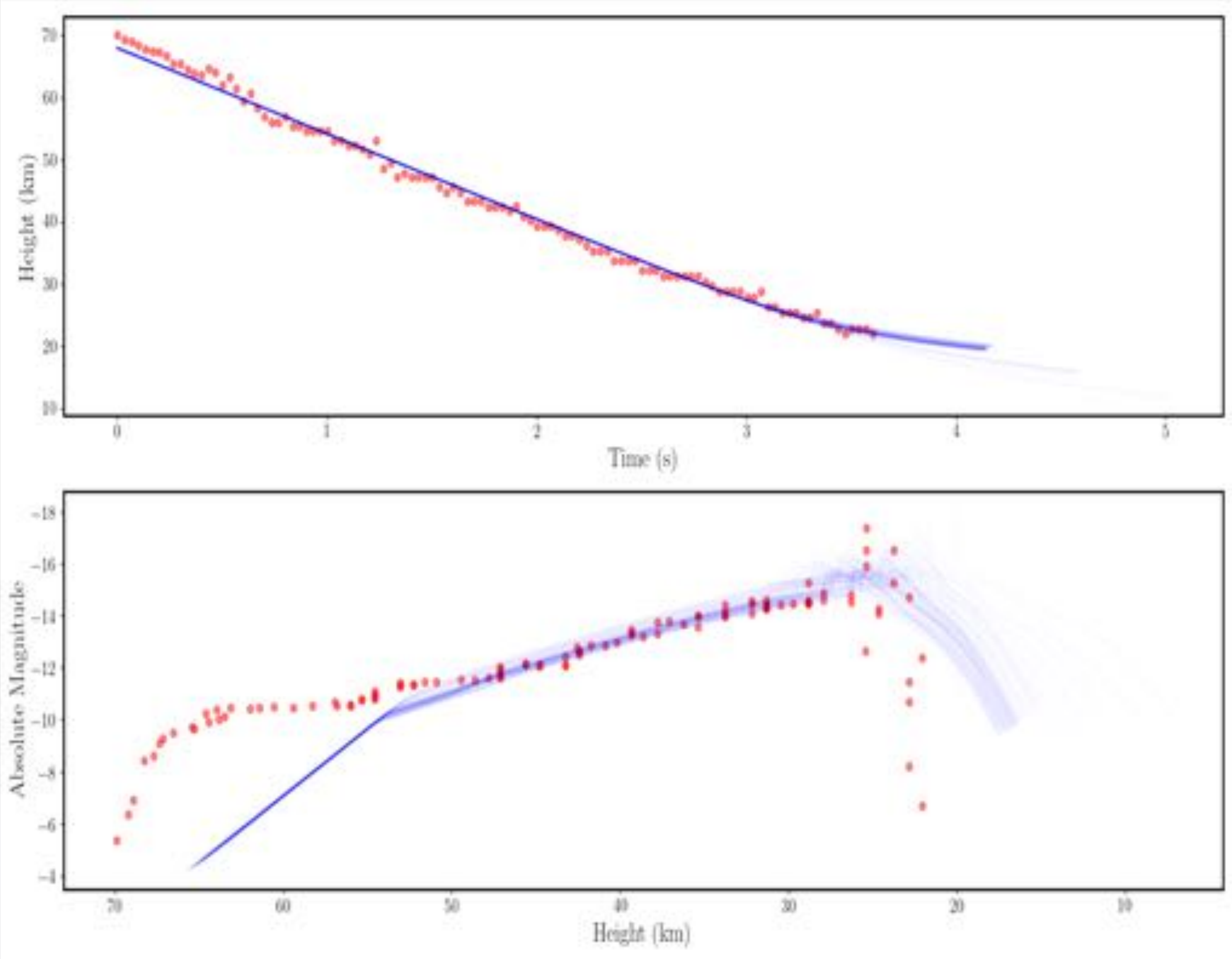
Manual TPFM Model Fit



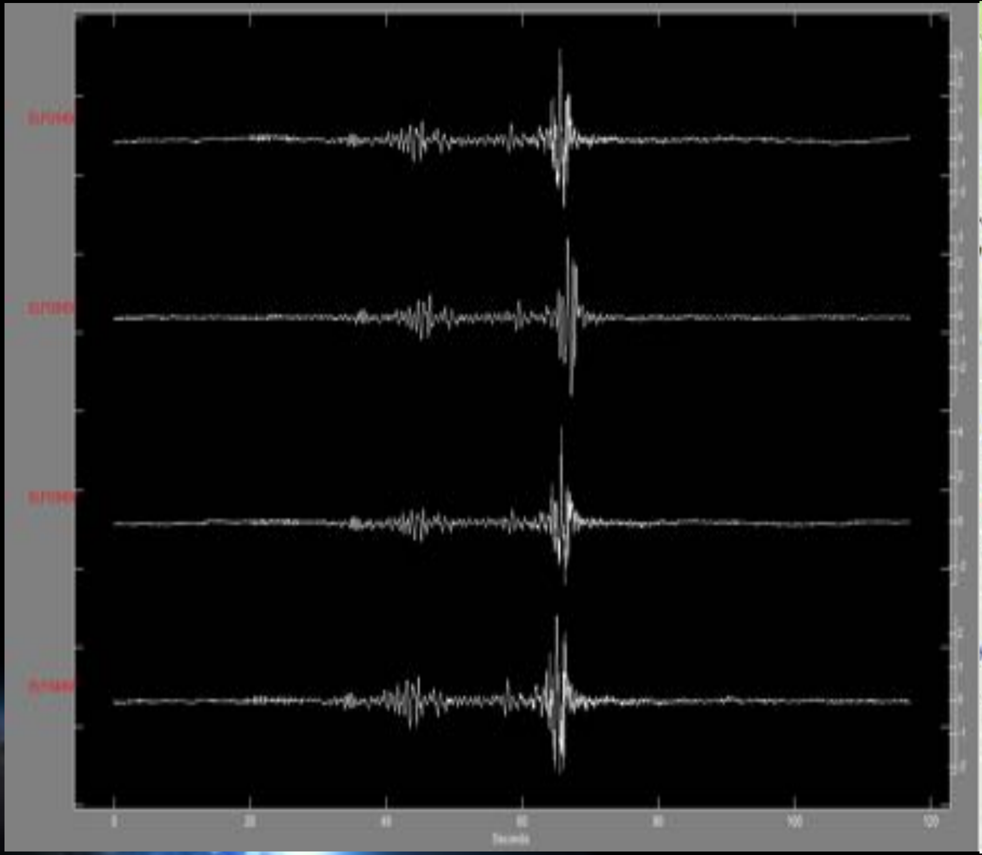
Diameter = 68 cm
Strength = 2.7 Mpa
Bulk density = 3700 kg m^{-3}
Mass = 609 kg
KE = 16.4 tons TNT

Mcmc tpfm results

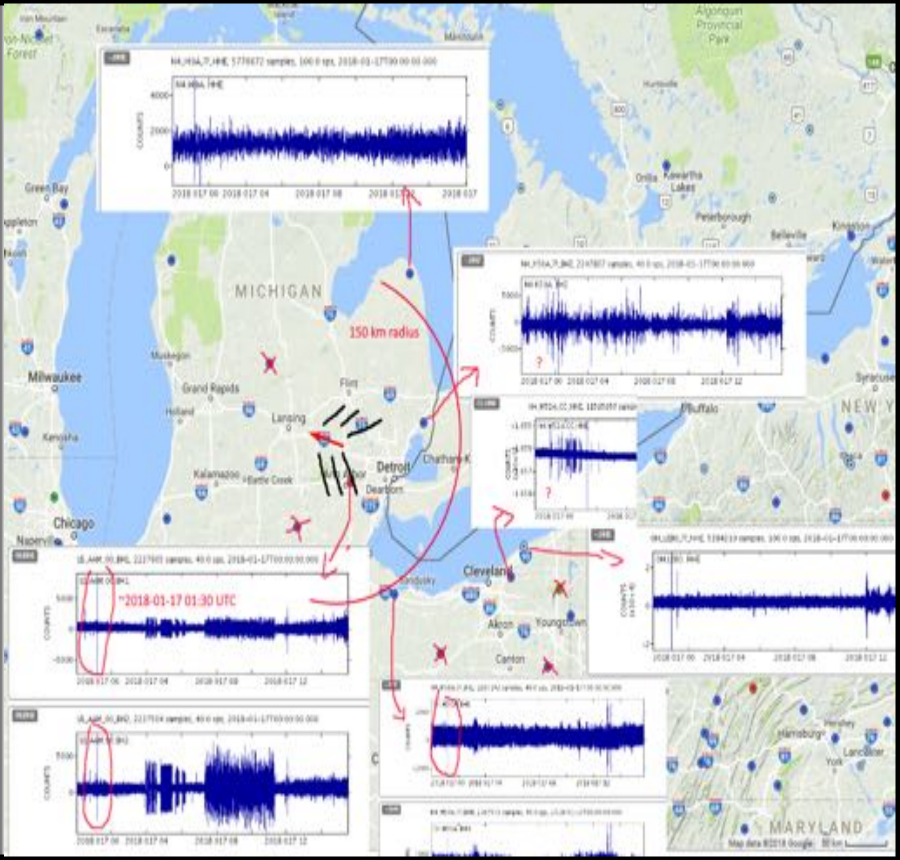
RINF: 0.311 - -0.020 + 0.039 (meters)
VINF: 14.904 - -0.006 + 0.004 (km/s)
ZR: 22.479 - -0.003 + 0.008 (degrees)
NUMBMAX: 256.000 - 0.000 + 0.000
SFINF: 1.209 - -0.005 + 0.007
MU: 0.667 - -0.008 + 0.007
POR CLASS: 1 (ordinary chondrite)
STRMOD: 1.267 - -0.171 + 0.140
TSTROVER: 2.583e+06 - -6.071e+05 + 1.230e+06 (Pascals)
SIGMA_HEIGHT: 1.125 - -0.070 + 0.082 (km)
SIGMA_MAG: 1.260 - -0.184 + 0.168 (magnitude)



Infrasound and seismic signature

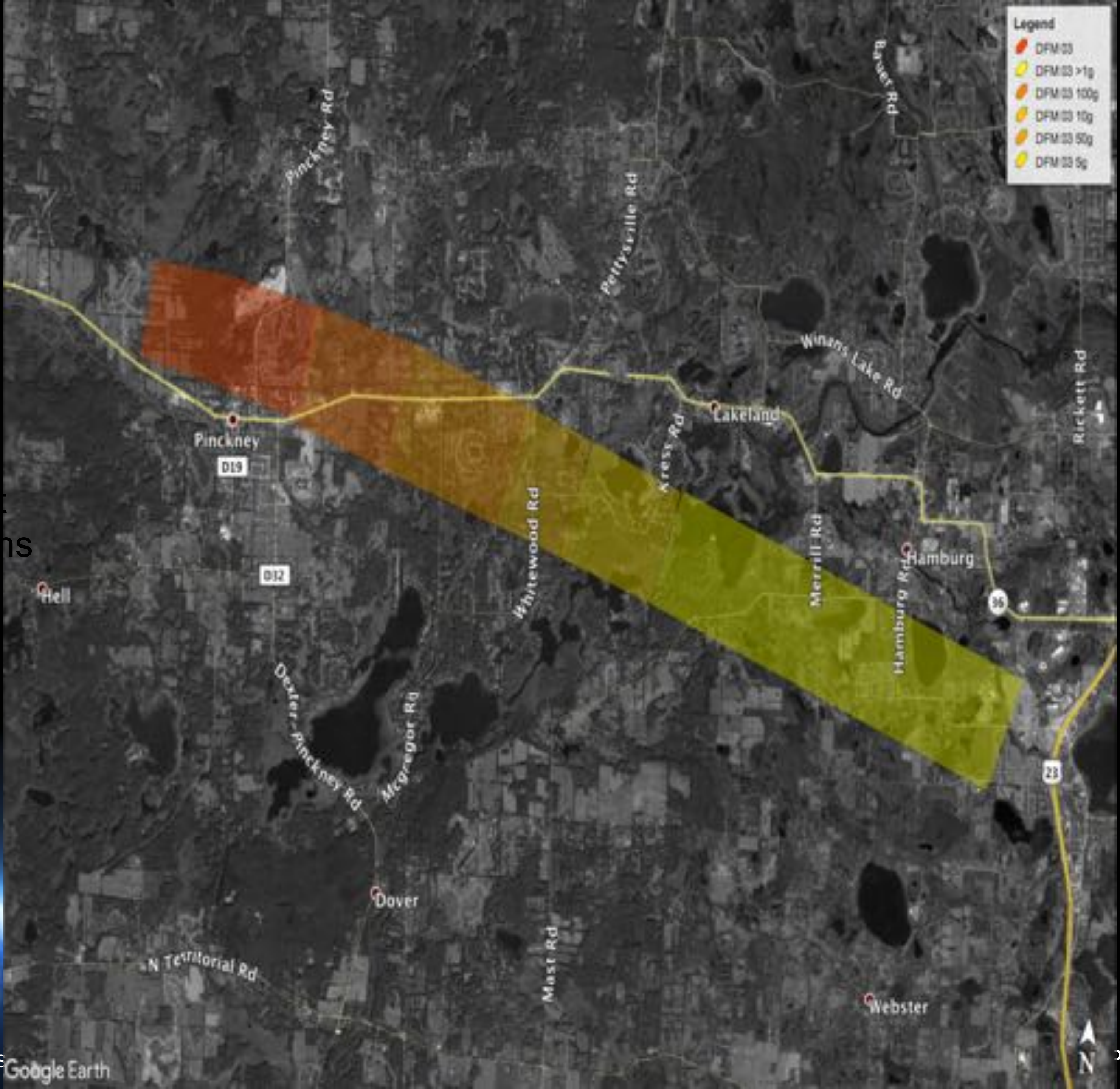


Energy upper limit of 50 tons TNT; nominal close to 10 tons TNT



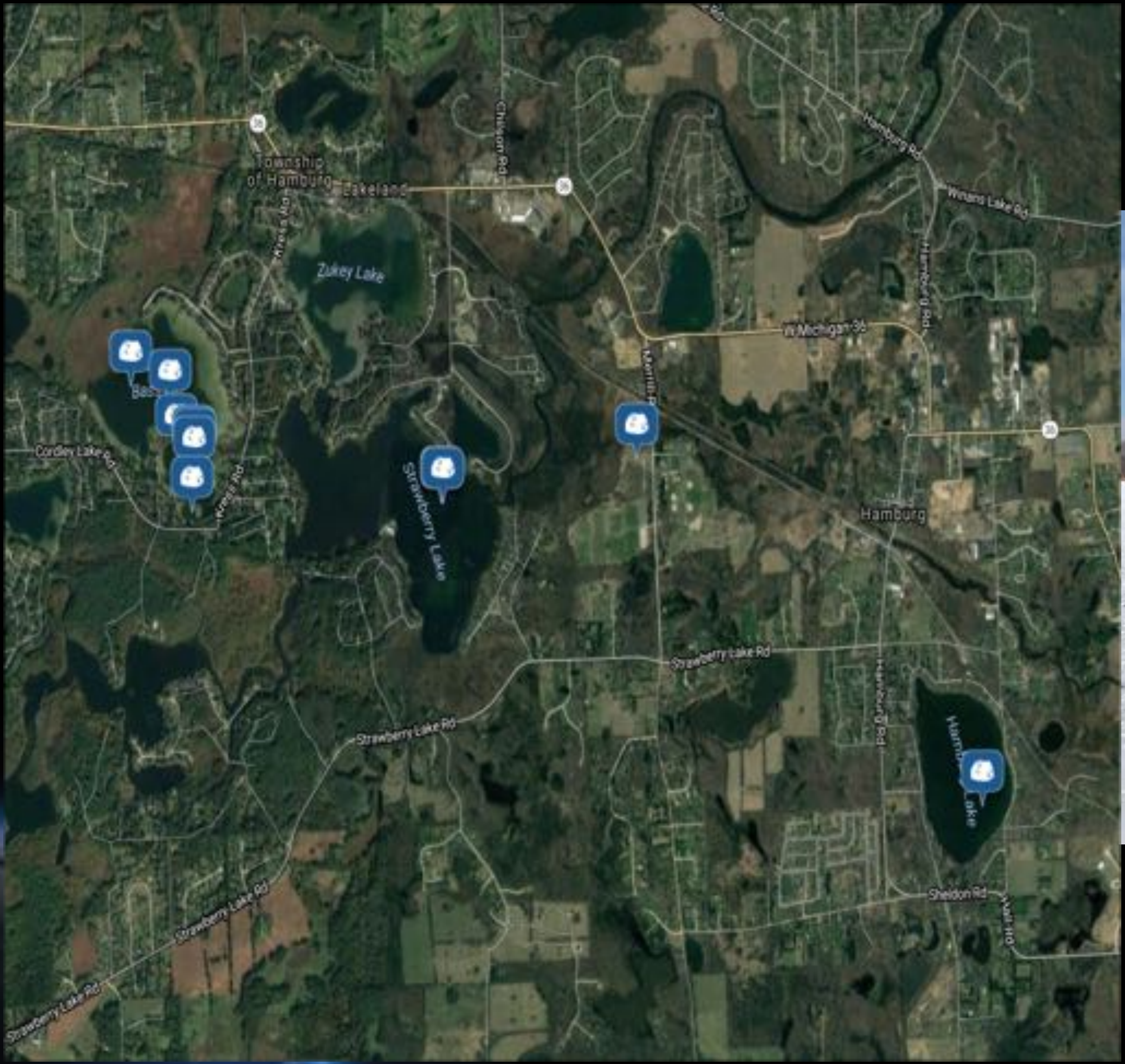
Event caused a magnitude 2 tremor

Dark flight calculations



Doppler radar signature of falling meteoritic dust

Meteorite finds



Final remarks

- The goals of the network determine pretty much everything…

A. Type of equipment
  - Video or DSLR

B. Placement of cameras
  - Dense or scattered network

C. Software
  - Automated or manual or mixed?

D. Plan of operations
  - Fast turnaround or leisurely academic pace

- Establish your network goals up front!