Airburst Modeling

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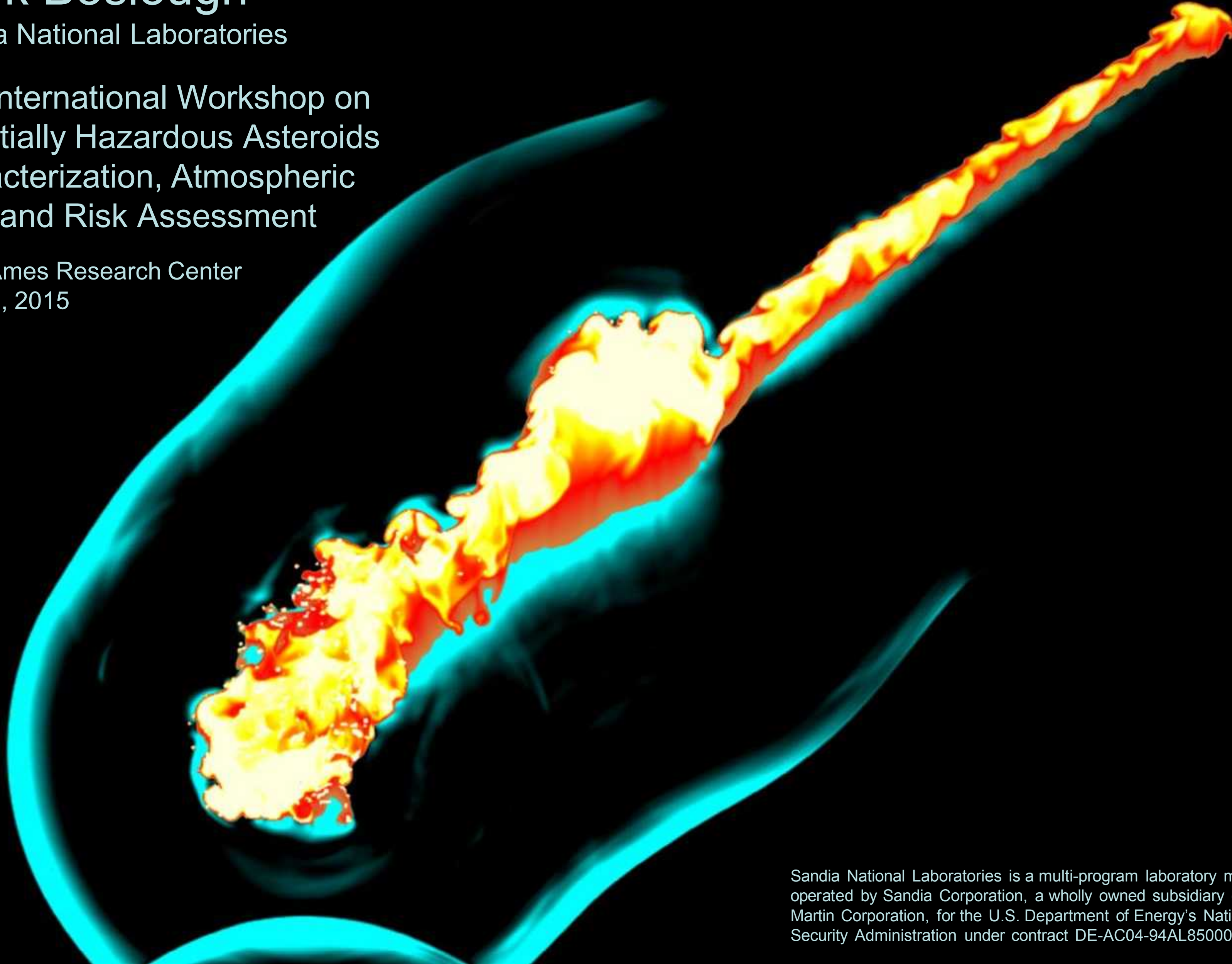
Sandia National Laboratories

First International Workshop on Potentially Hazardous Asteroids Characterization, Atmospheric Entry and Risk Assessment

NASA Ames Research Center
July 7-9, 2015



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Sandia's Airburst Modeling: Recent Work

- Focused on observable & risk-related effects, not process
- New insertion method for Chelyabinsk simulation (2013)
- Four table top exercises (2 FEMA, 2 PDC in last 2 years)
- Capability development for mapping damage zones
- Efficiency improvements (AMR indicators, domain size)
- Output and visualization improvements
- Convergence analysis
- Robustness analysis
- Airburst-coupled tsunami

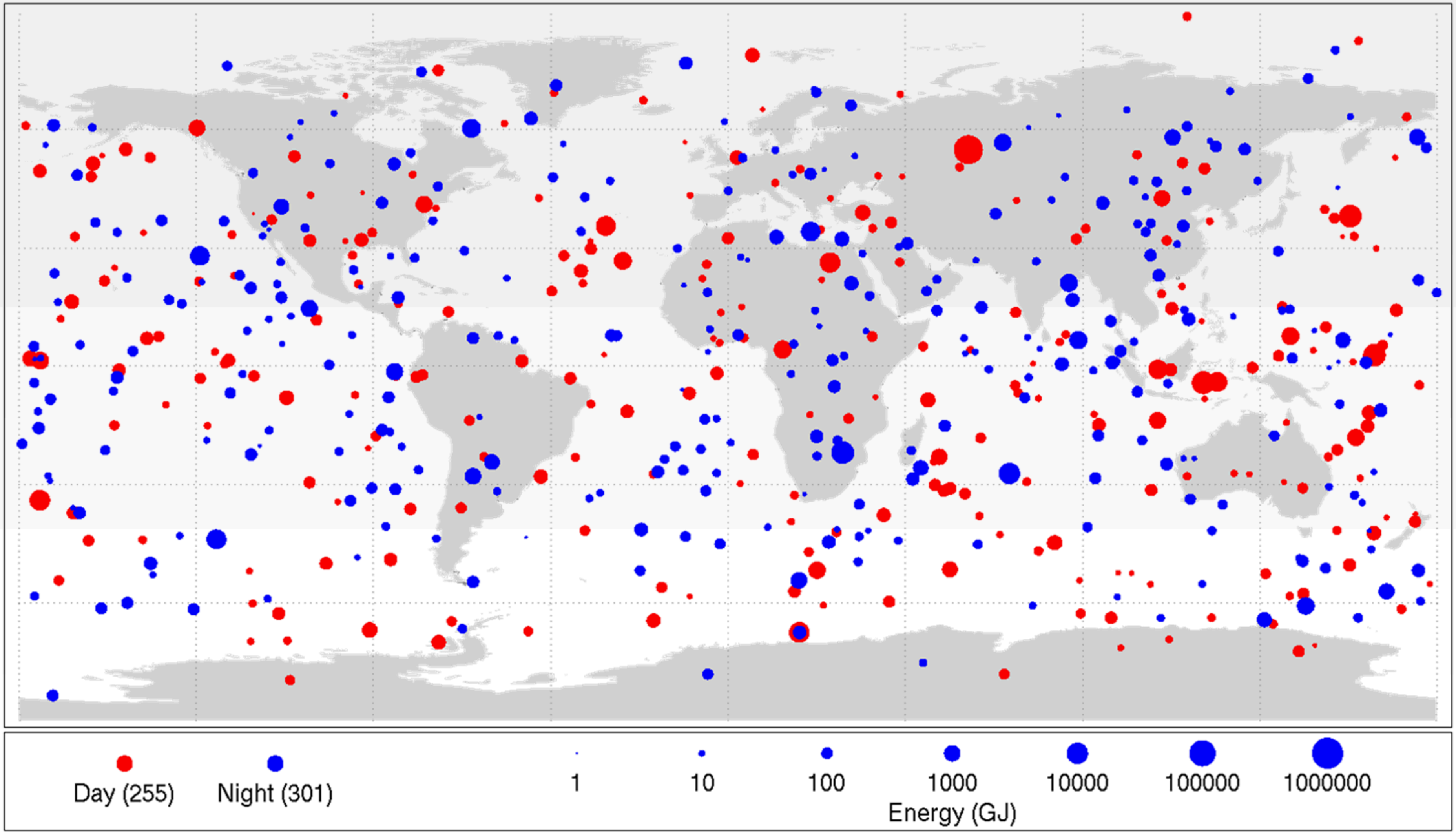
Outline

1. Why are airbursts important?
2. Modeling Tunguska
3. Tabletop Excercises
4. Modeling Chelyabinsk
5. Airburst-generated tsunami

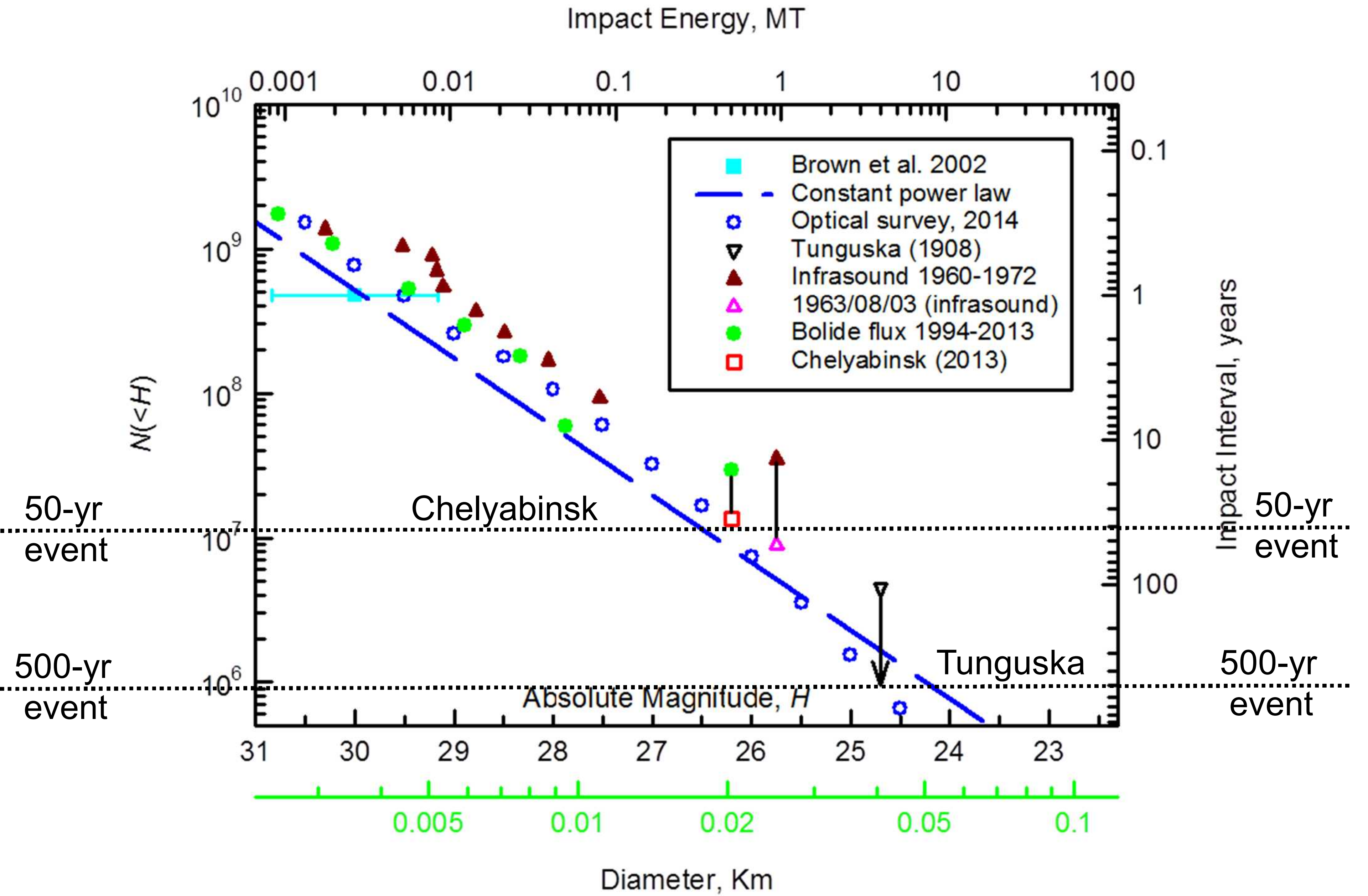
1. Why are Airbursts Important?

- Risk will be dominated by airbursts after completion of the George E. Brown survey
- Virtually certain that the next destructive NEO event will be an airburst
- Full-scale “validation”: Tunguska, SL9, Chelyabinsk
- Small cratering events accompanied by airbursts
- More efficient than craters at generating tsunami?
- Plume-forming airbursts may put satellites at risk
- Important surface process on Venus & Mars?

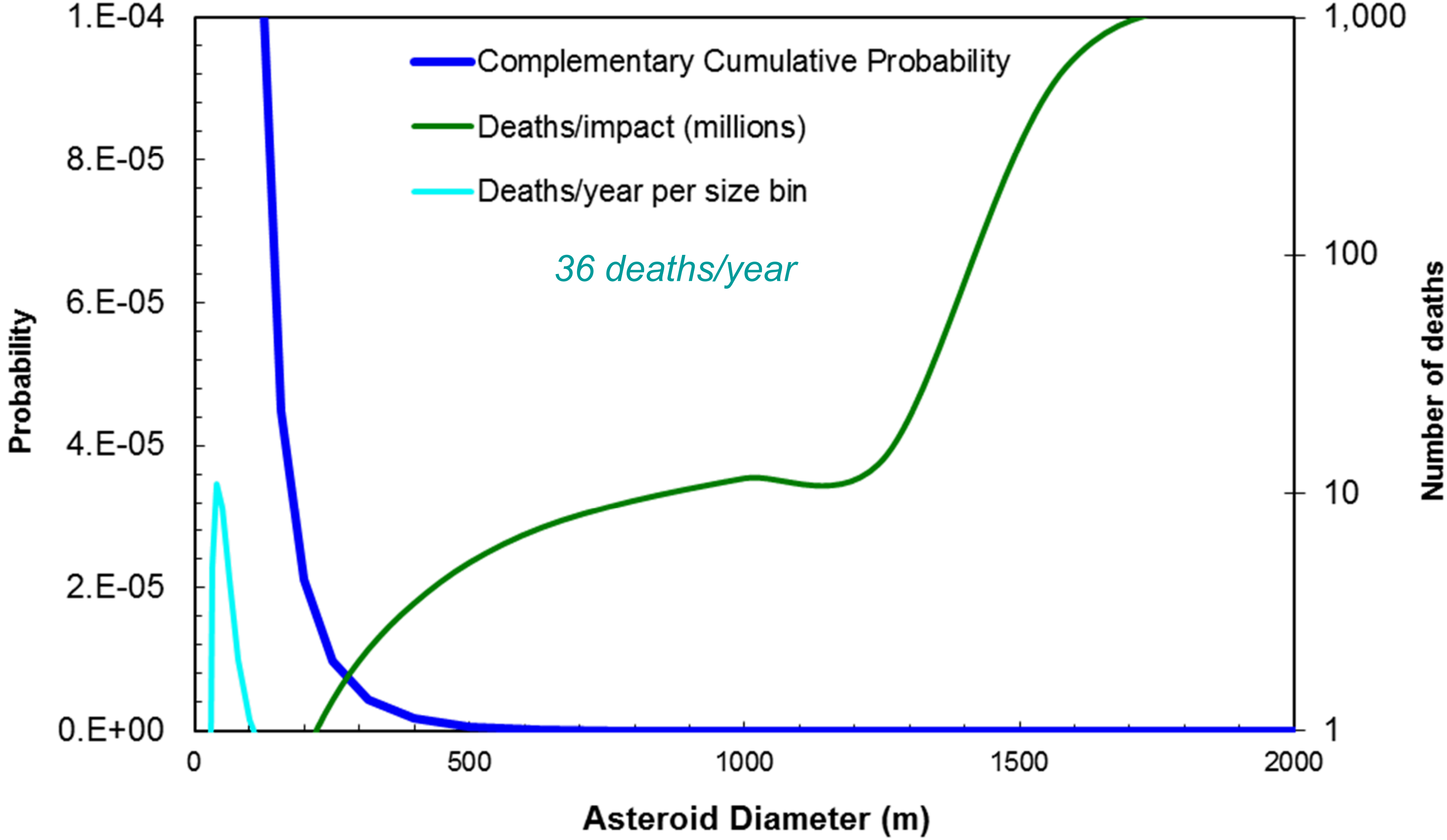
Recorded Bolide Events 1994 - 2013



Boslough, M., Brown, P., and Harris, A., "Updated Population and Risk Assessment for Airbursts from Near-Earth Objects (NEOs)," *2015 IEEE Aerospace Conference*, March 2015.



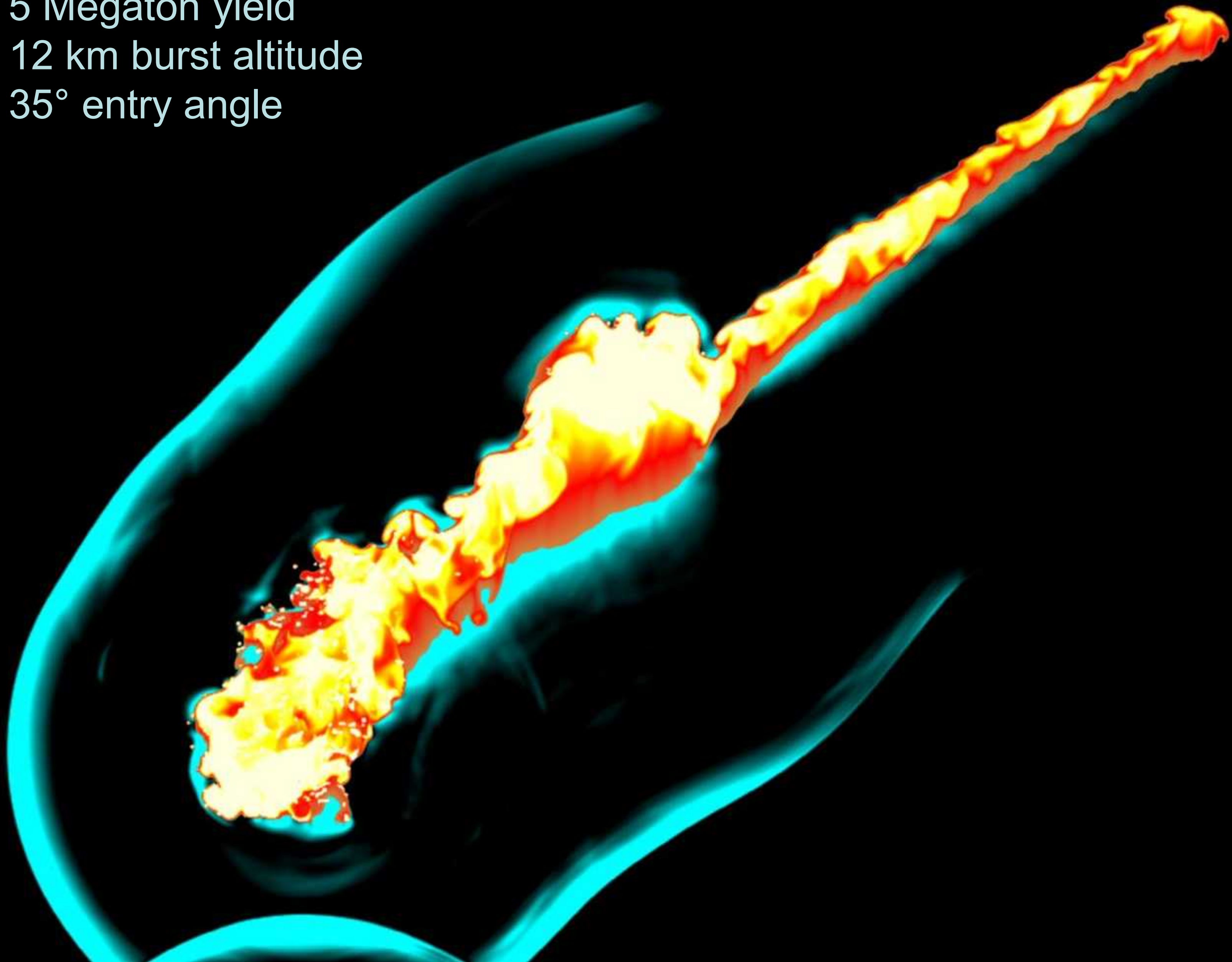
Kill curve with directed airbursts (green curve)
Population as of 2014 (blue curve)
Total probabilistic risk = 36 deaths /year (after G Brown survey)



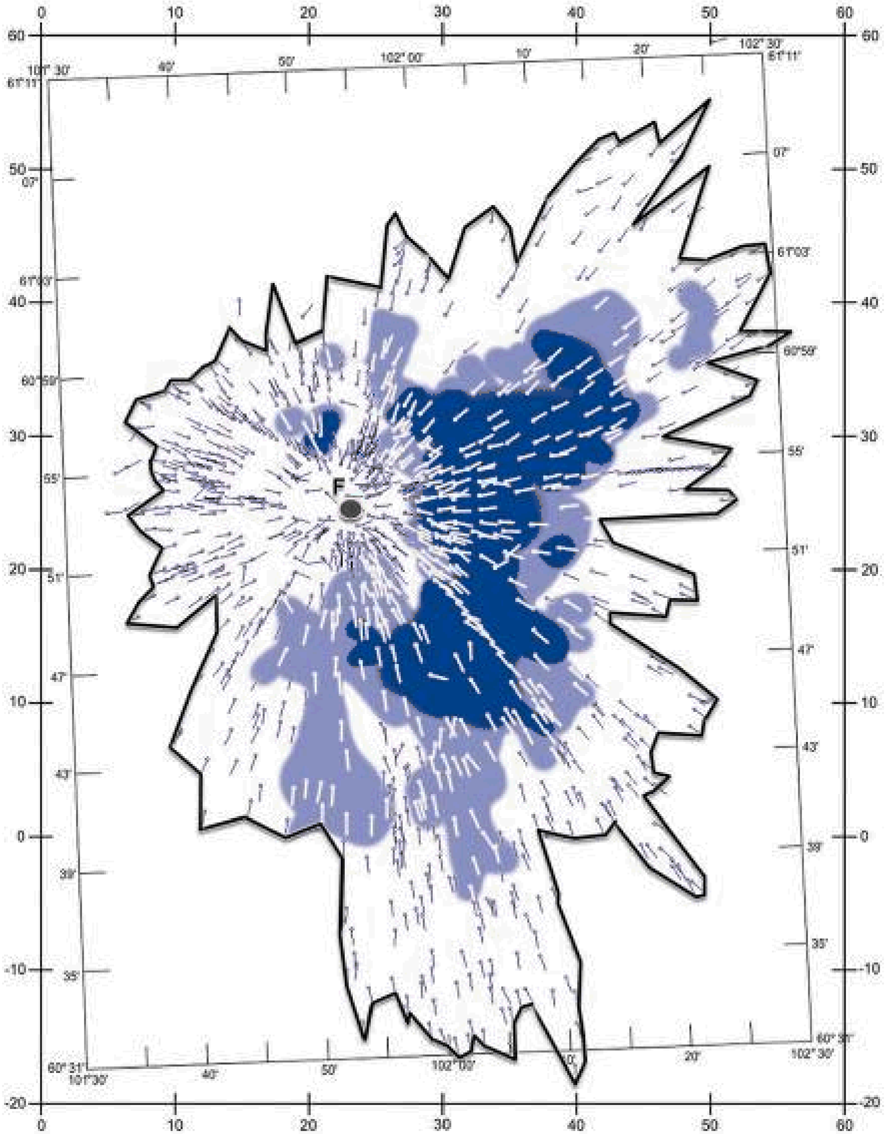
2. Modeling Tunguska

"Canonical Tunguska"

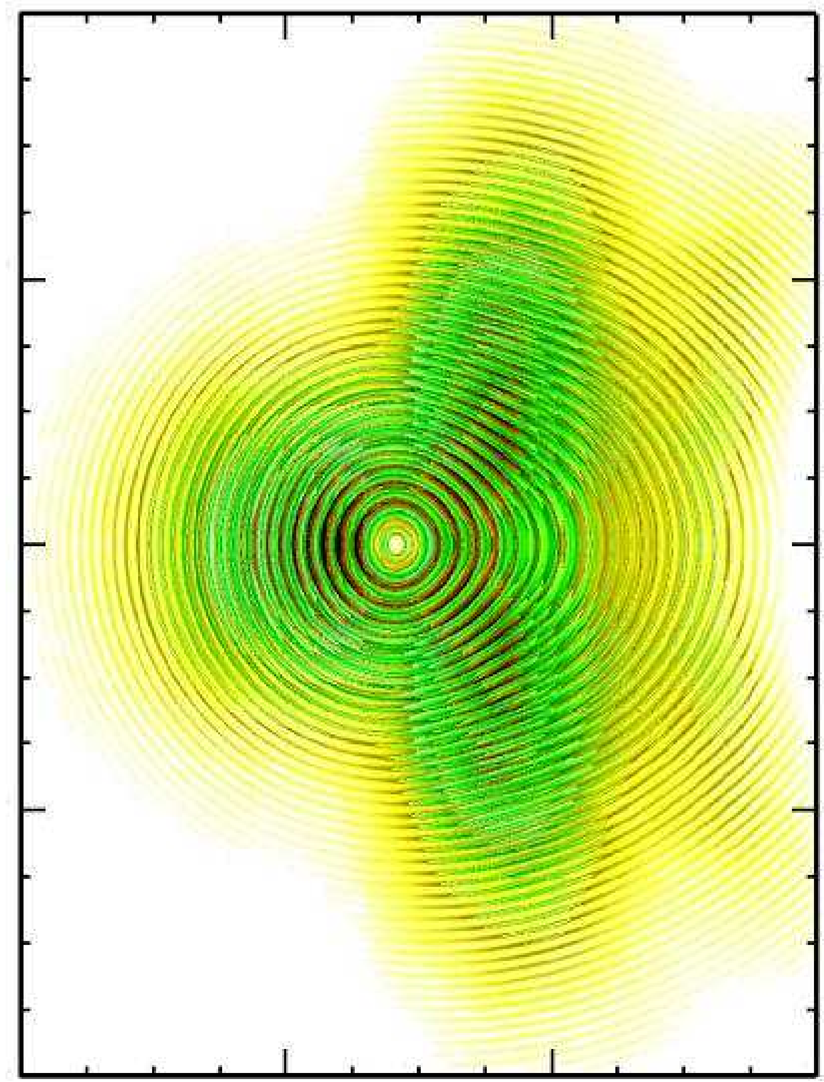
- 5 Megaton yield
- 12 km burst altitude
- 35° entry angle



5 Mt explosion at 12 km above surface, 35° entry angle



Tunguska treefall map (Longo et al, 2005)



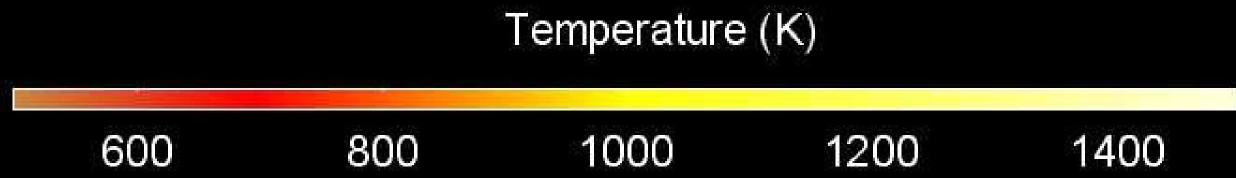
Wind speed map

Convergence Analysis

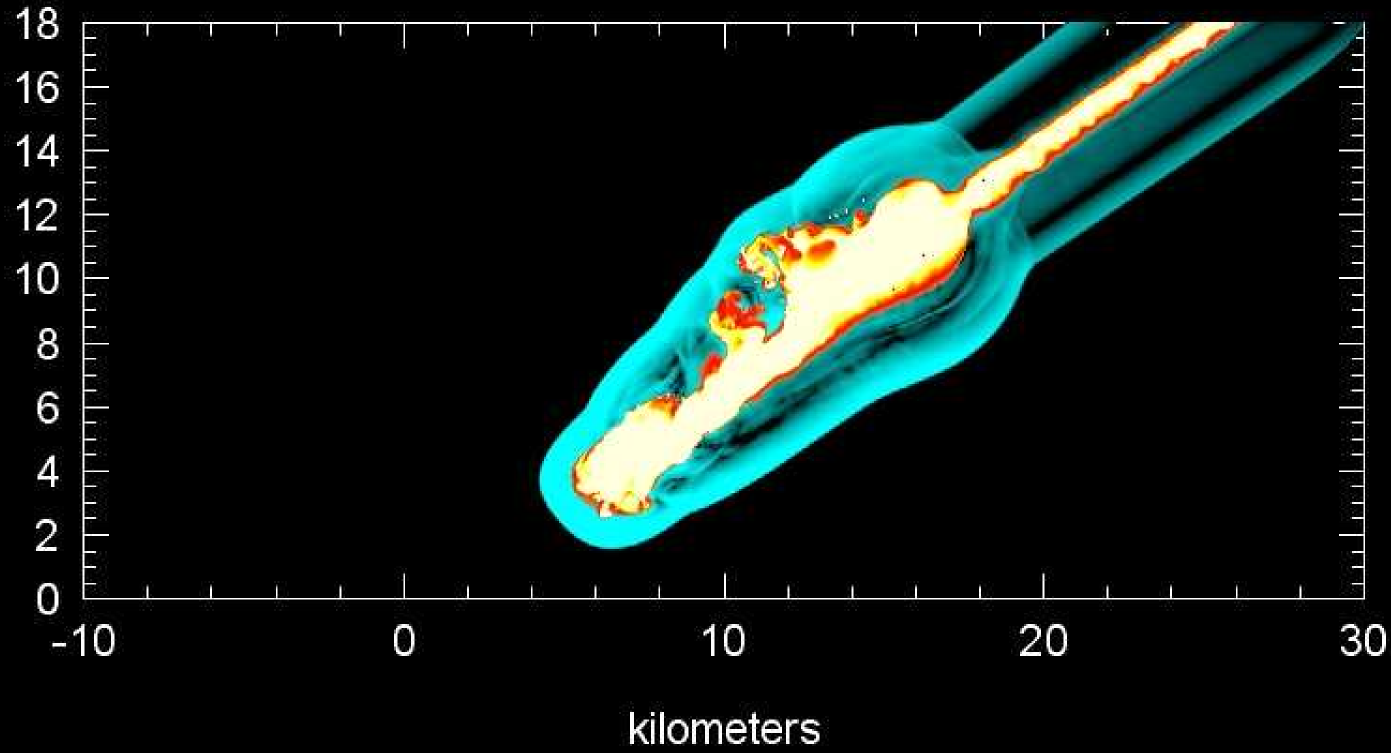
Low res: 4 refinement levels = 32 m (original)
Mid res: 5 refinement levels = 16 m
High res: 6 refinement levels = 8 m

Yield = 5 Mt

Entry angle = 35°



32-meter cells (original 2007 input deck)

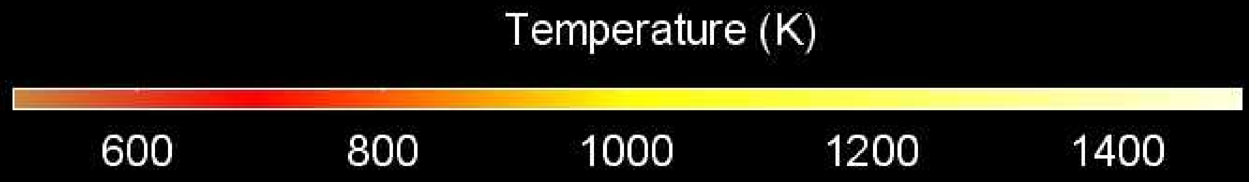


Time = 6.5 s

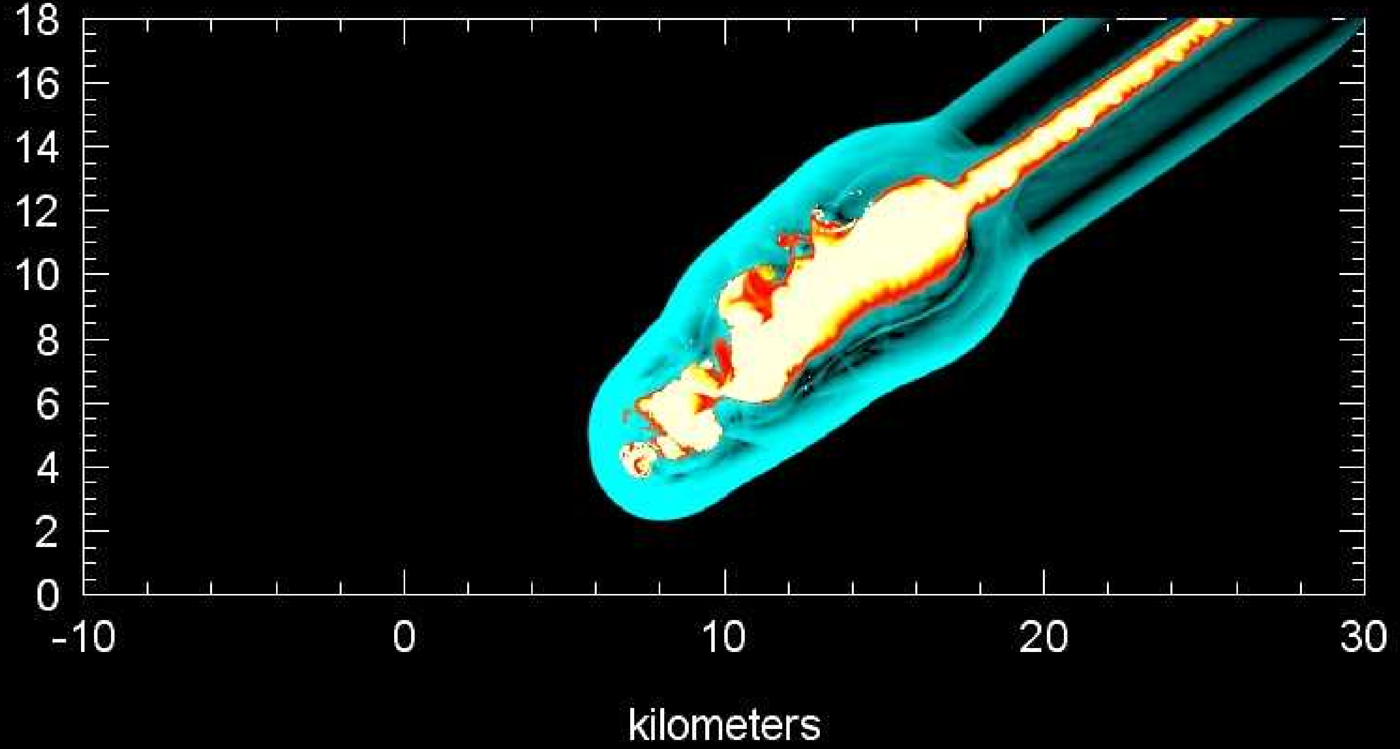
Burst height = 12 km

Yield = 5 Mt

Entry angle = 35°



32-meter cells (mesh refined on 1 m/s motion)



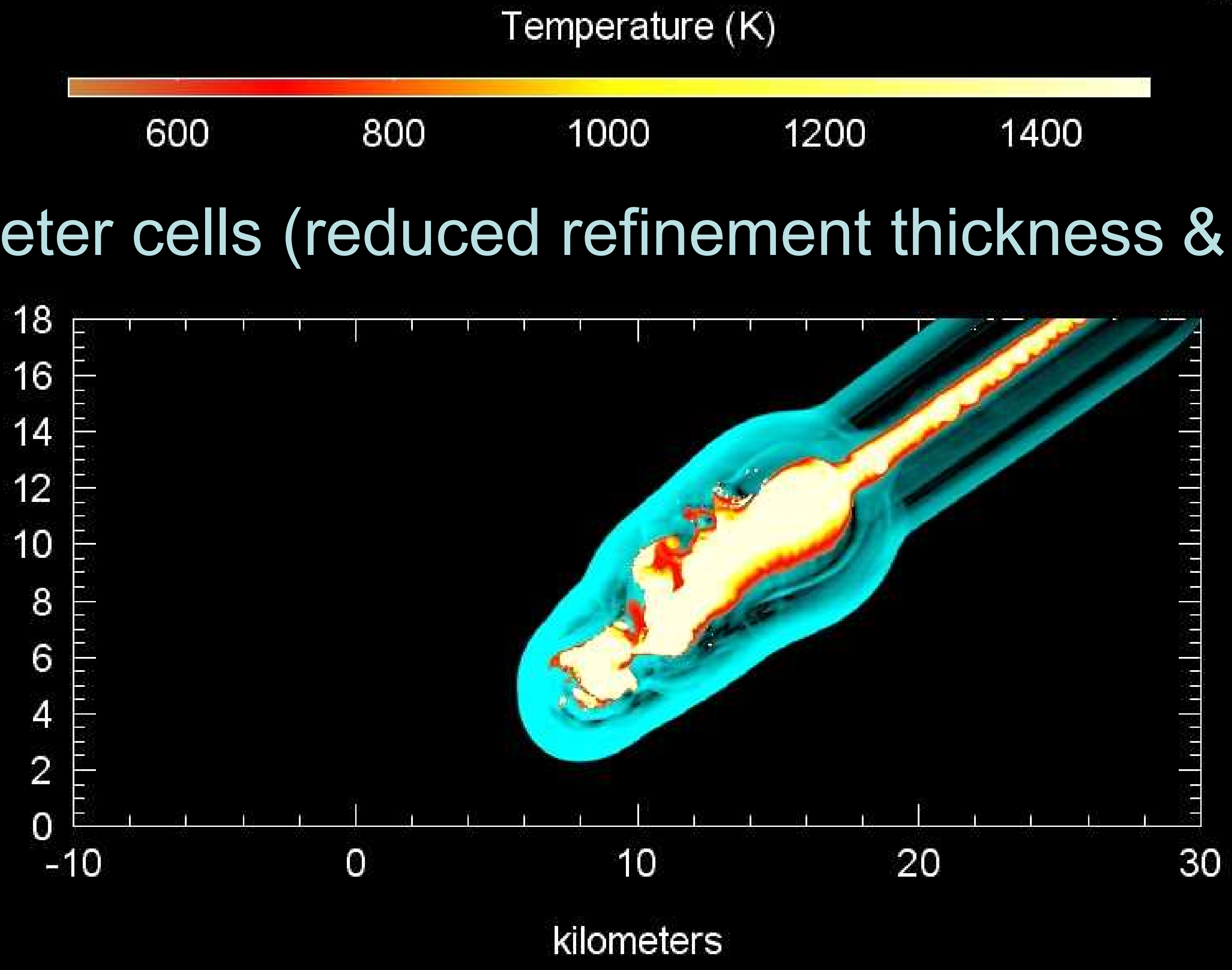
Time = 6.5 s

Burst height = 12 km

Yield = 5 Mt

Entry angle = 35°

32-meter cells (reduced refinement thickness & 1 m/s)



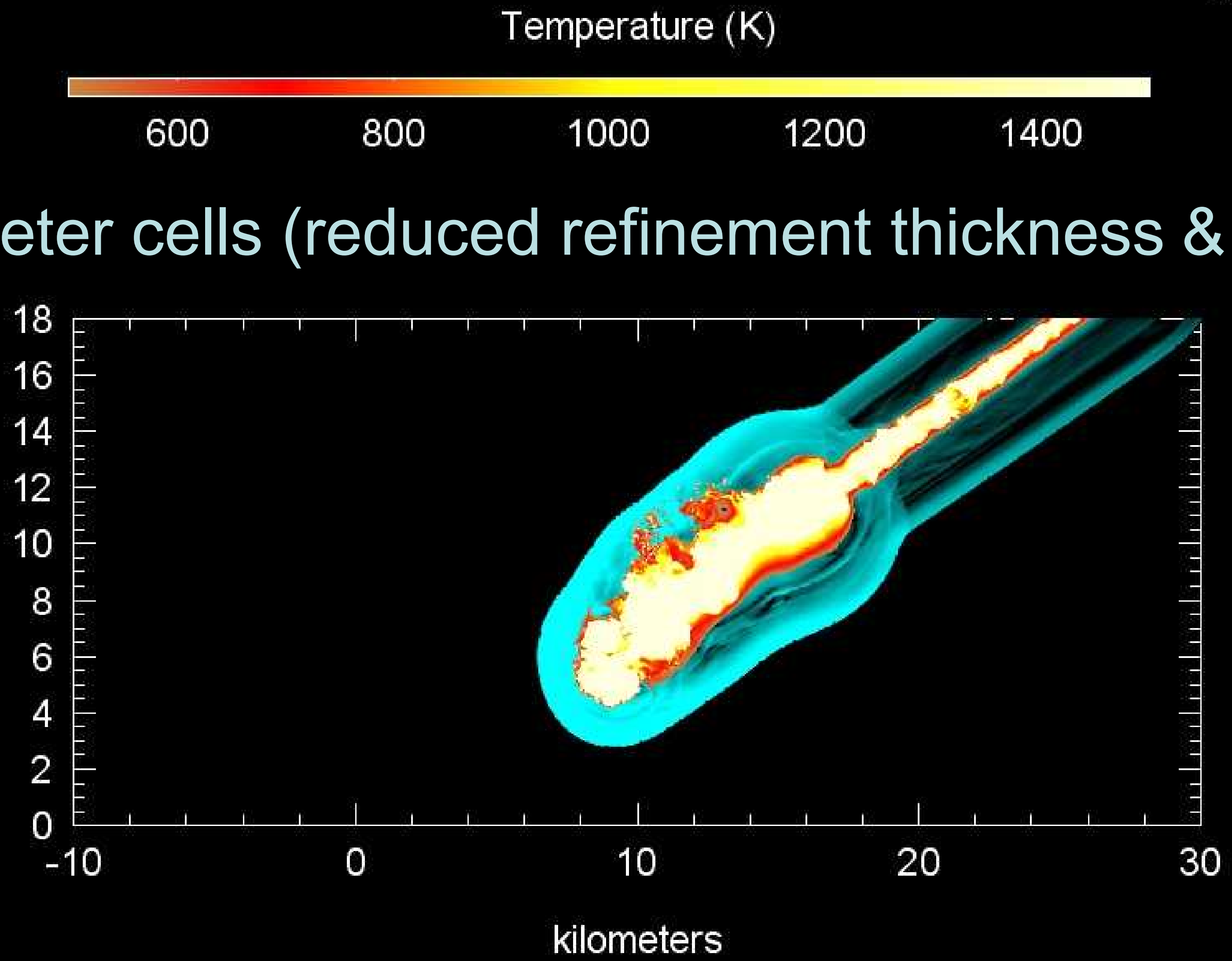
Time = 6.5 s

Burst height = 12 km

Yield = 5 Mt

Entry angle = 35°

16-meter cells (reduced refinement thickness & 1 m/s)

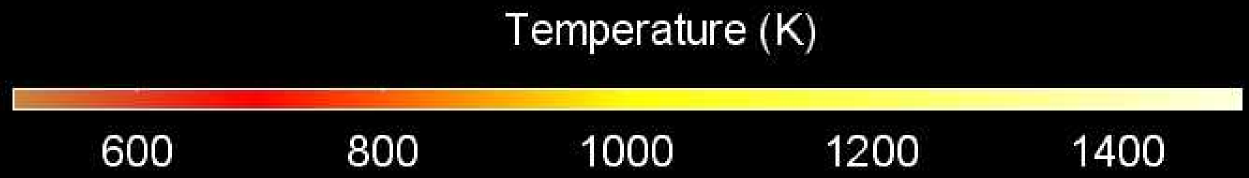


Time = 6.5 s

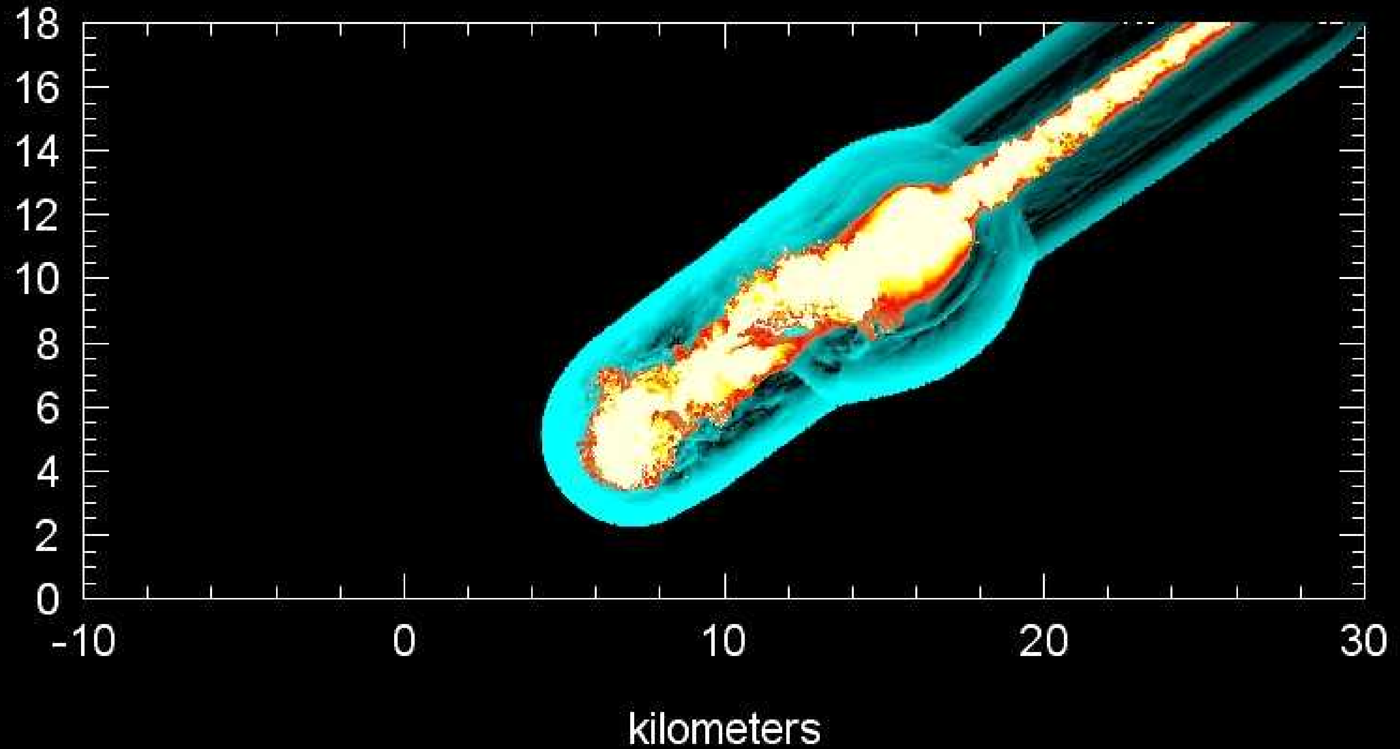
Burst height = 12 km

Yield = 5 Mt

Entry angle = 35°



8-meter cells (reduced refinement thickness & 1 m/s)



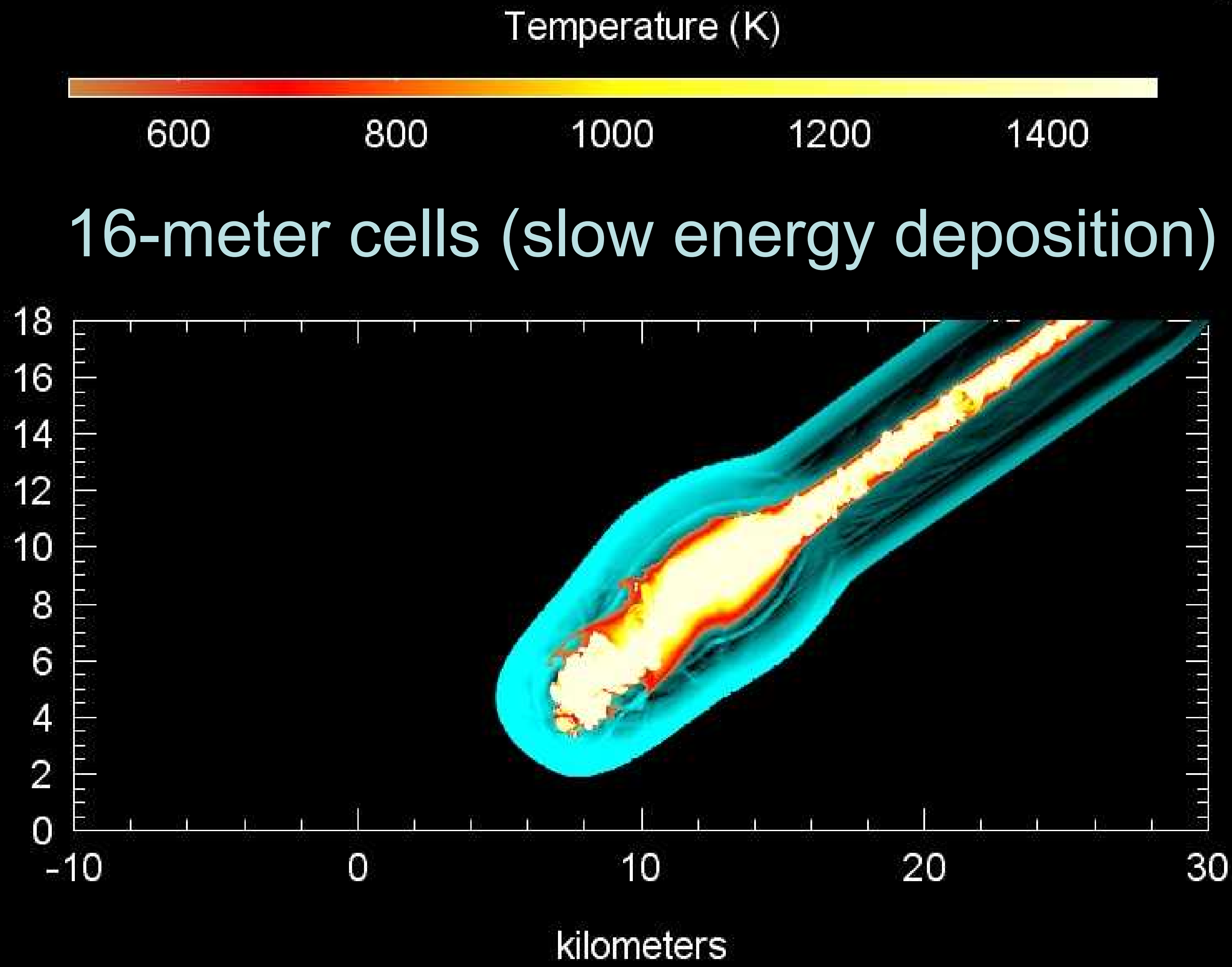
Time = 6.5 s

Burst height = 12 km

Yield = 5 Mt

Entry angle = 35°

16-meter cells (slow energy deposition)



Time = 6.5 s

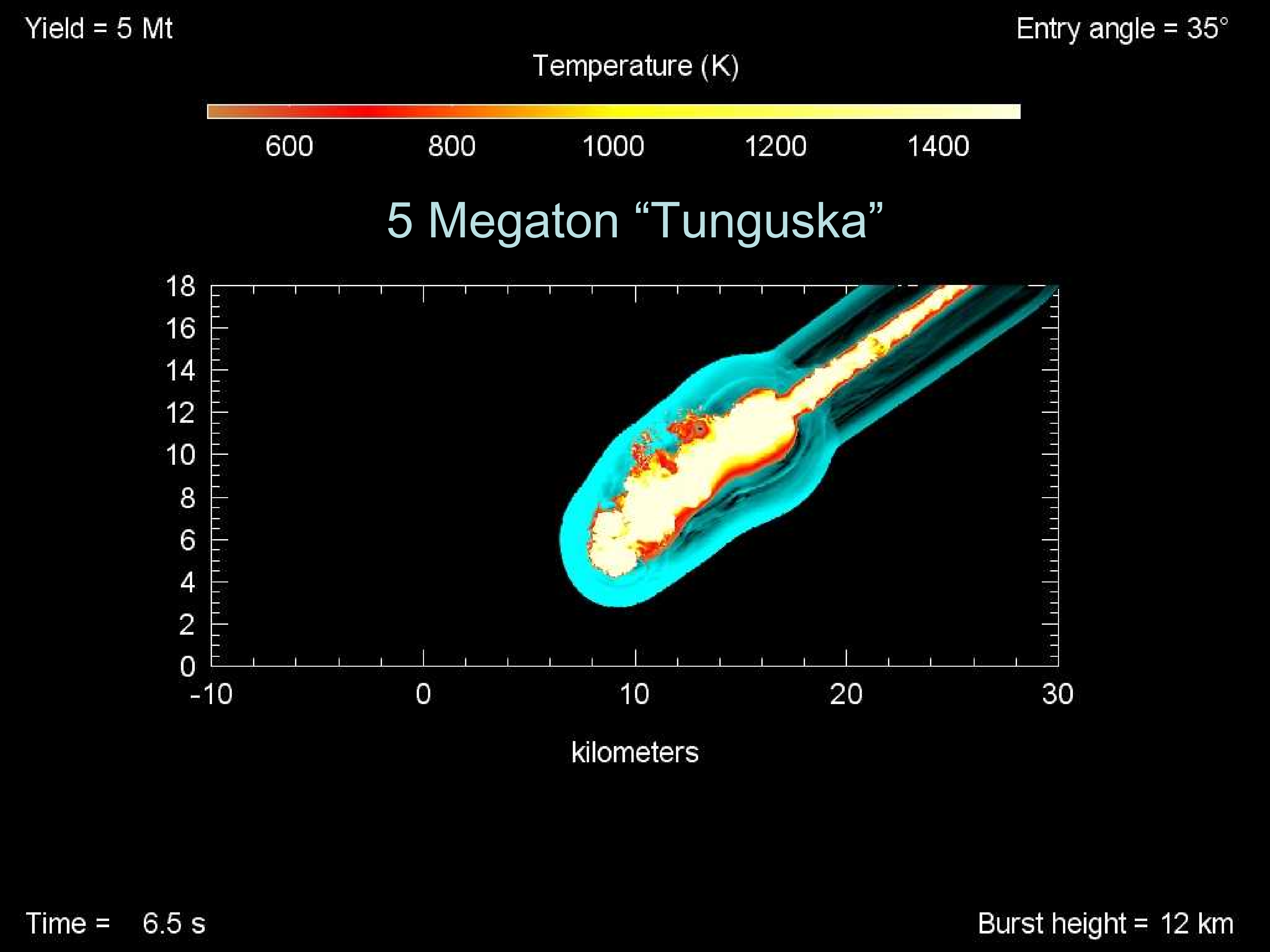
Burst height = 12 km

Convergence Analysis

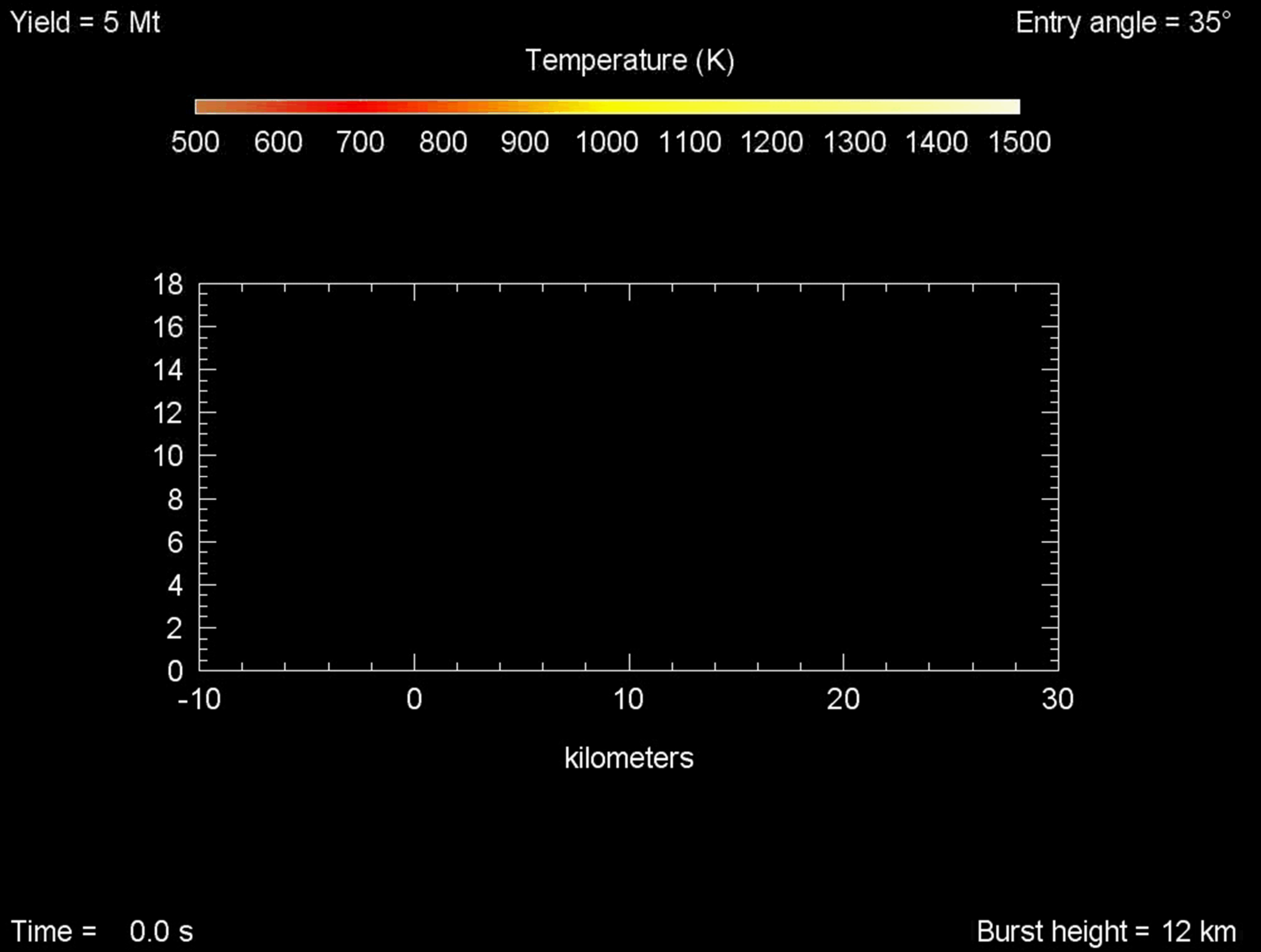
- Domain size and AMR criteria appear more important than more resolution
- Slower energy deposition more realistic
- Effective burst height depends on mesh, even if actual burst height is exactly prescribed
- Small differences in jet penetration efficiency can have large effects on damage at surface
- Jet penetration uncertainty still smaller than airburst height uncertainty

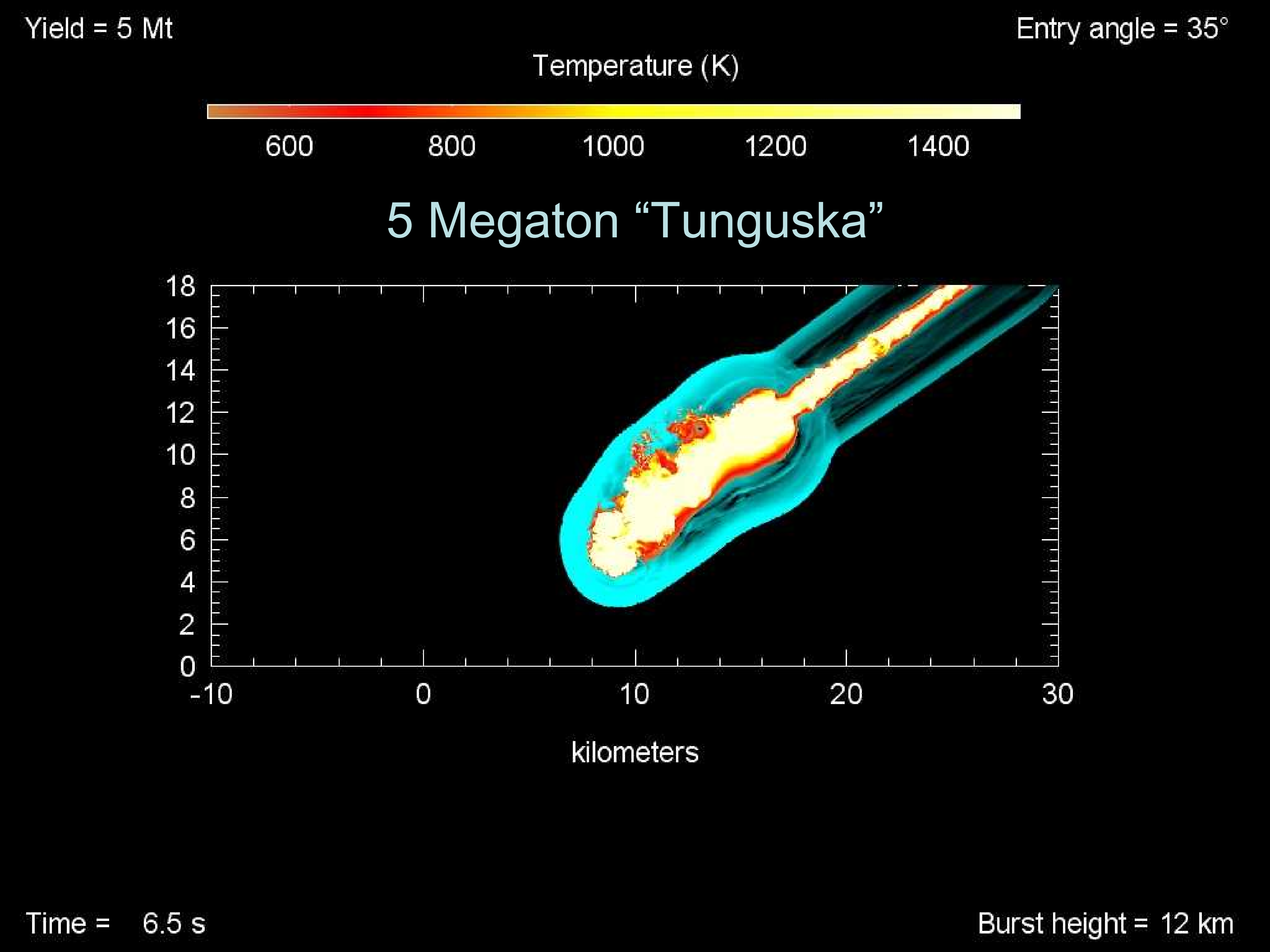
Other Cases

Yield = 5 Megatons (strong core)
Yield = 15 Megatons

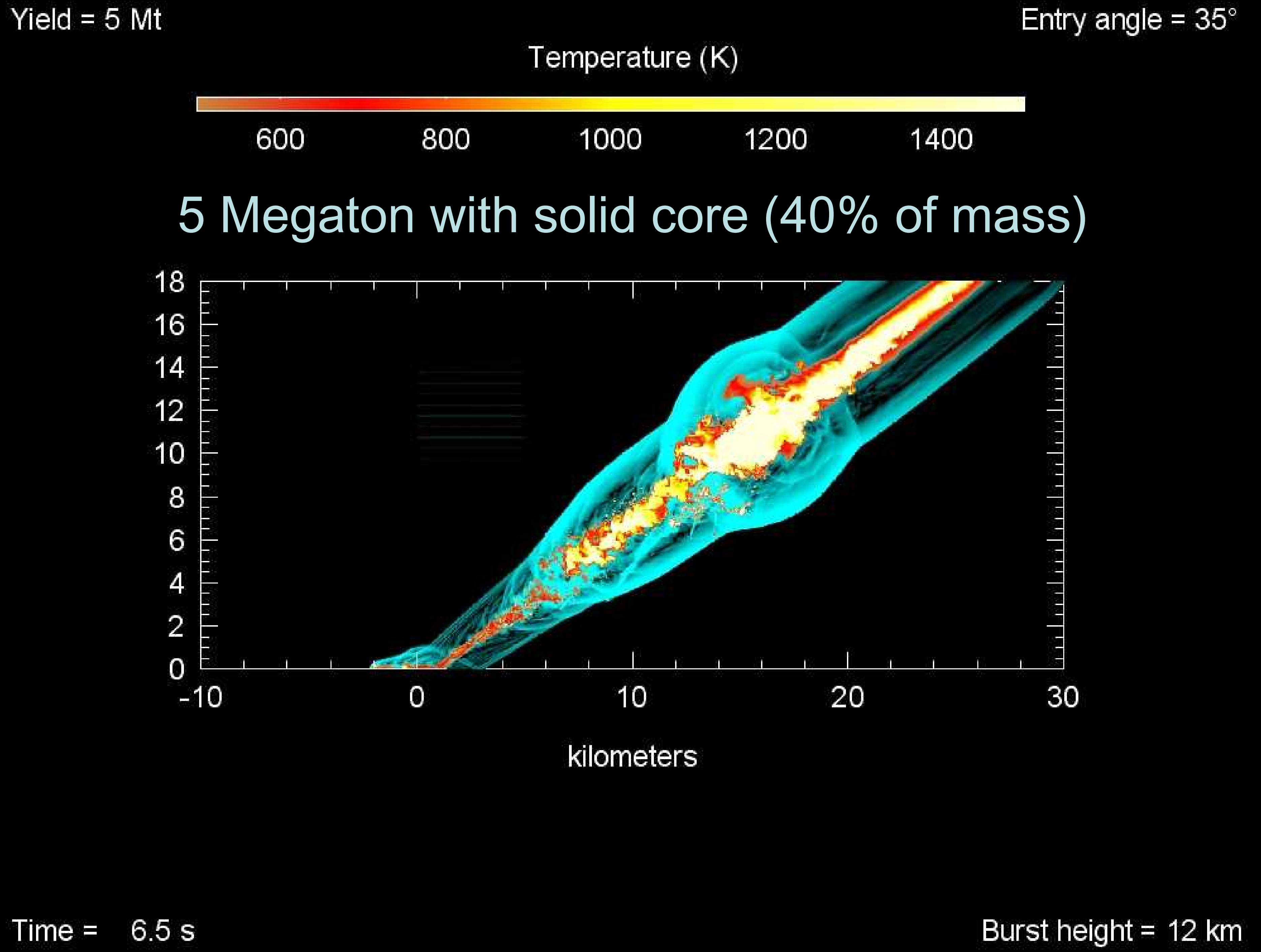


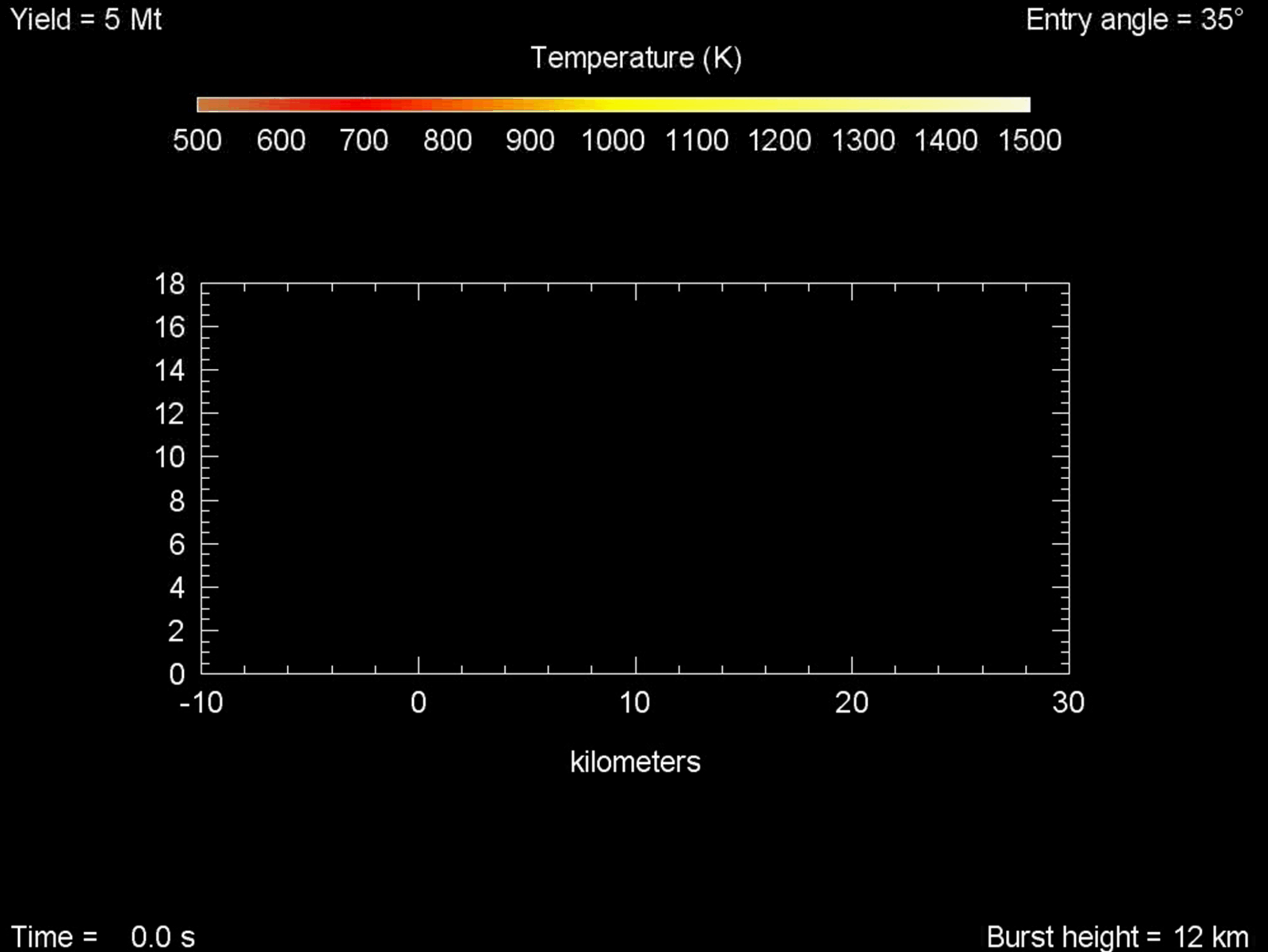
Yield = 5 Mt
Entry angle = 35°
Temperature (K)
600
800
1000
1200
1400
5 Megaton "Tunguska"
18
16
14
12
10
8
6
4
2
0
-10
0
10
20
30
kilometers
Time = 6.5 s
Burst height = 12 km


Yield = 5 Mt
Entry angle = 35°
Temperature (K)
500 600 700 800 900 1000 1100 1200 1300 1400 1500
18
16
14
12
10
8
6
4
2
0
-10
0
10
20
30
kilometers
Time = 0.0 s
Burst height = 12 km


Yield = 5 Mt
Entry angle = 35°
Temperature (K)
600
800
1000
1200
1400
5 Megaton "Tunguska"
18
16
14
12
10
8
6
4
2
0
-10
0
10
20
30
kilometers
Time = 6.5 s
Burst height = 12 km

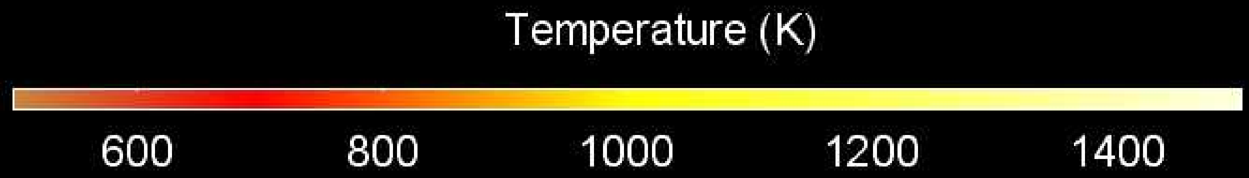
5 Megaton with solid core (40% of mass)



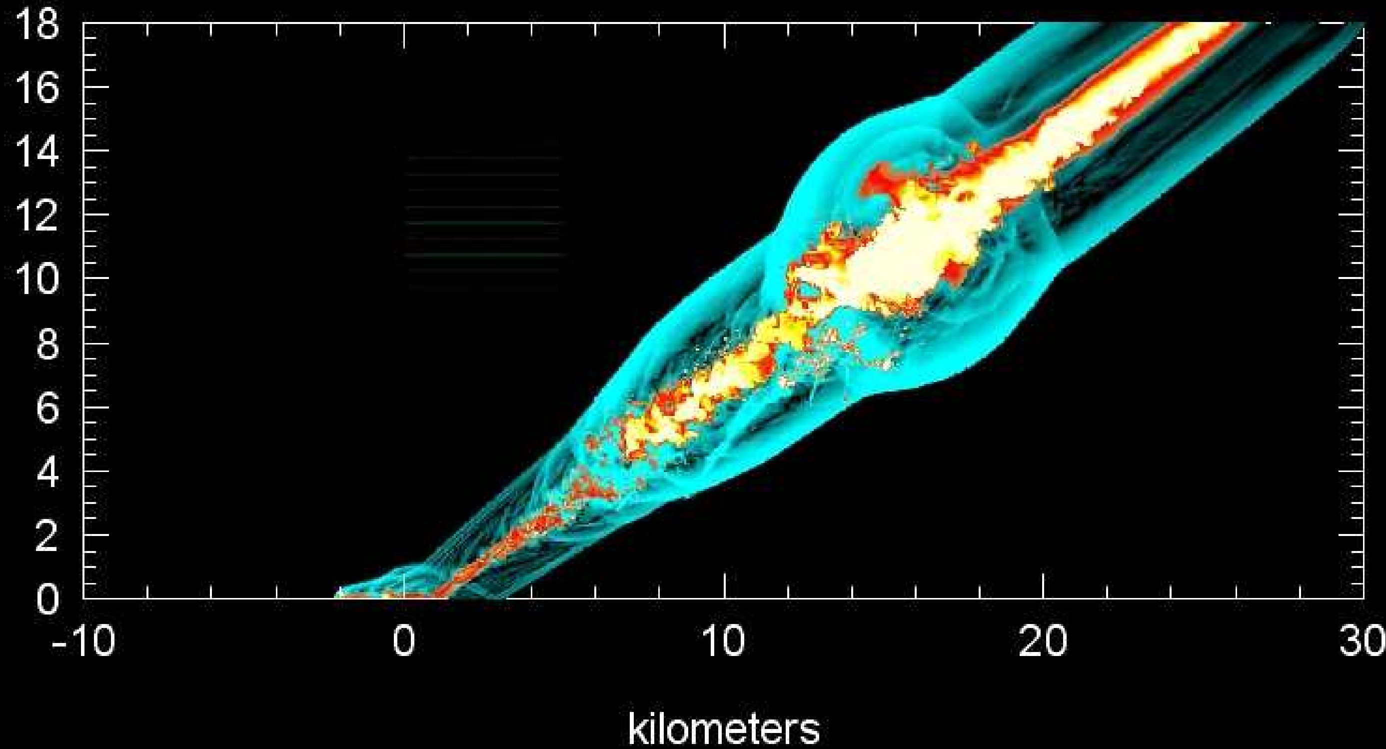

Yield = 5 Mt
Entry angle = 35°
Temperature (K)
500 600 700 800 900 1000 1100 1200 1300 1400 1500
0 2 4 6 8 10 12 14 16 18
-10 0 10 20 30
kilometers
Time = 0.0 s
Burst height = 12 km

Yield = 5 Mt

Entry angle = 35°

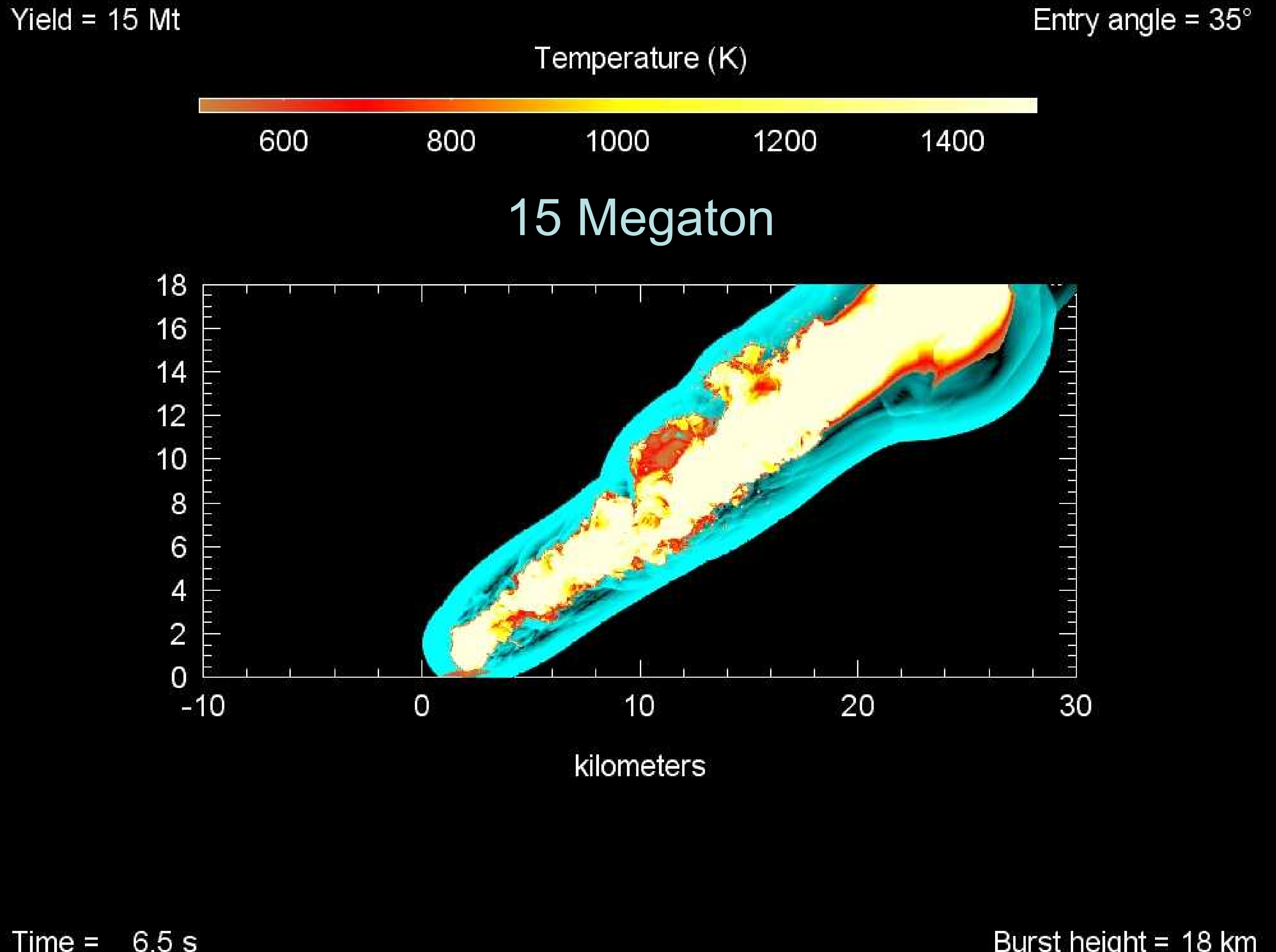


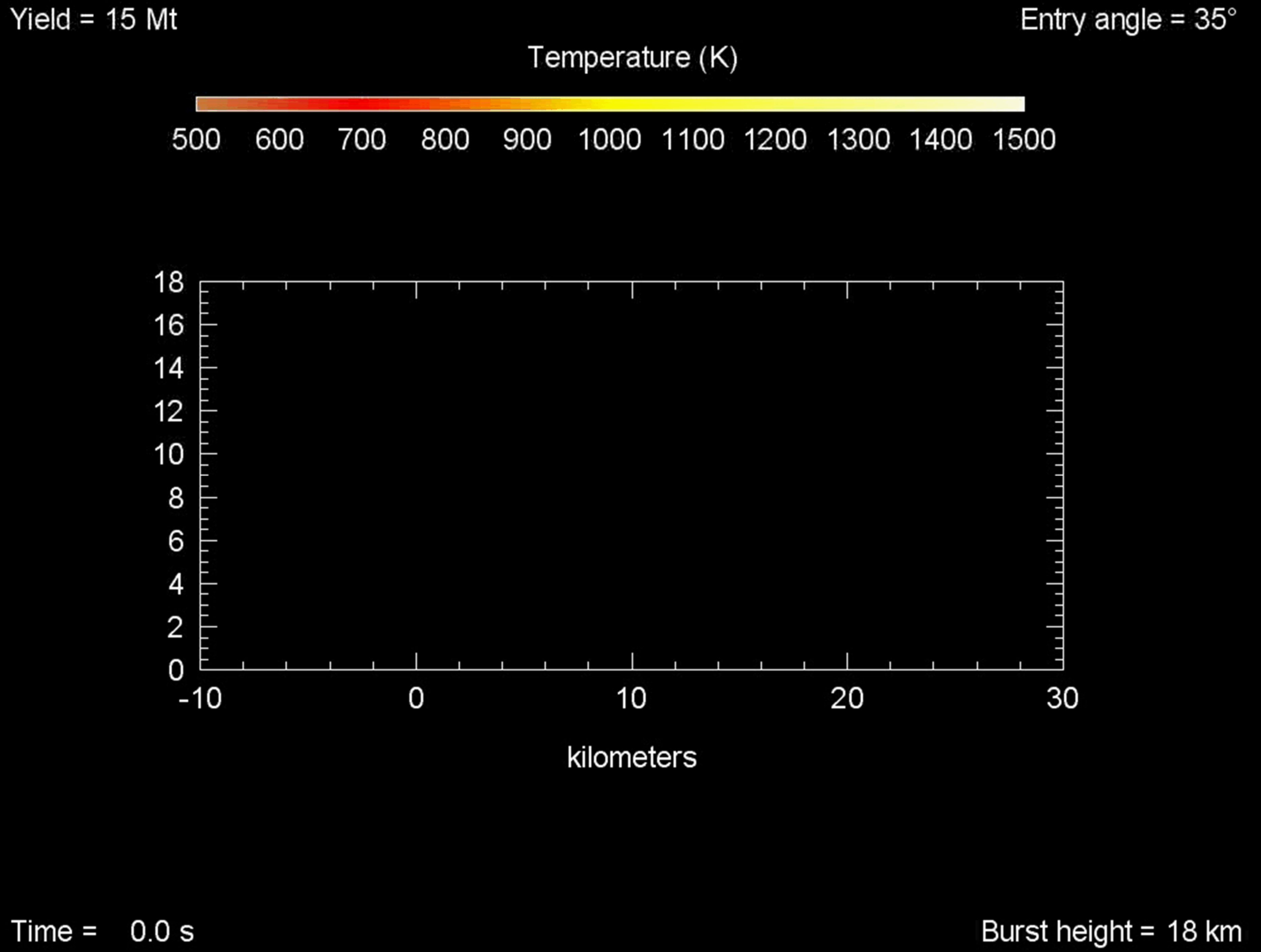
5 Megaton with solid core (40% of mass)

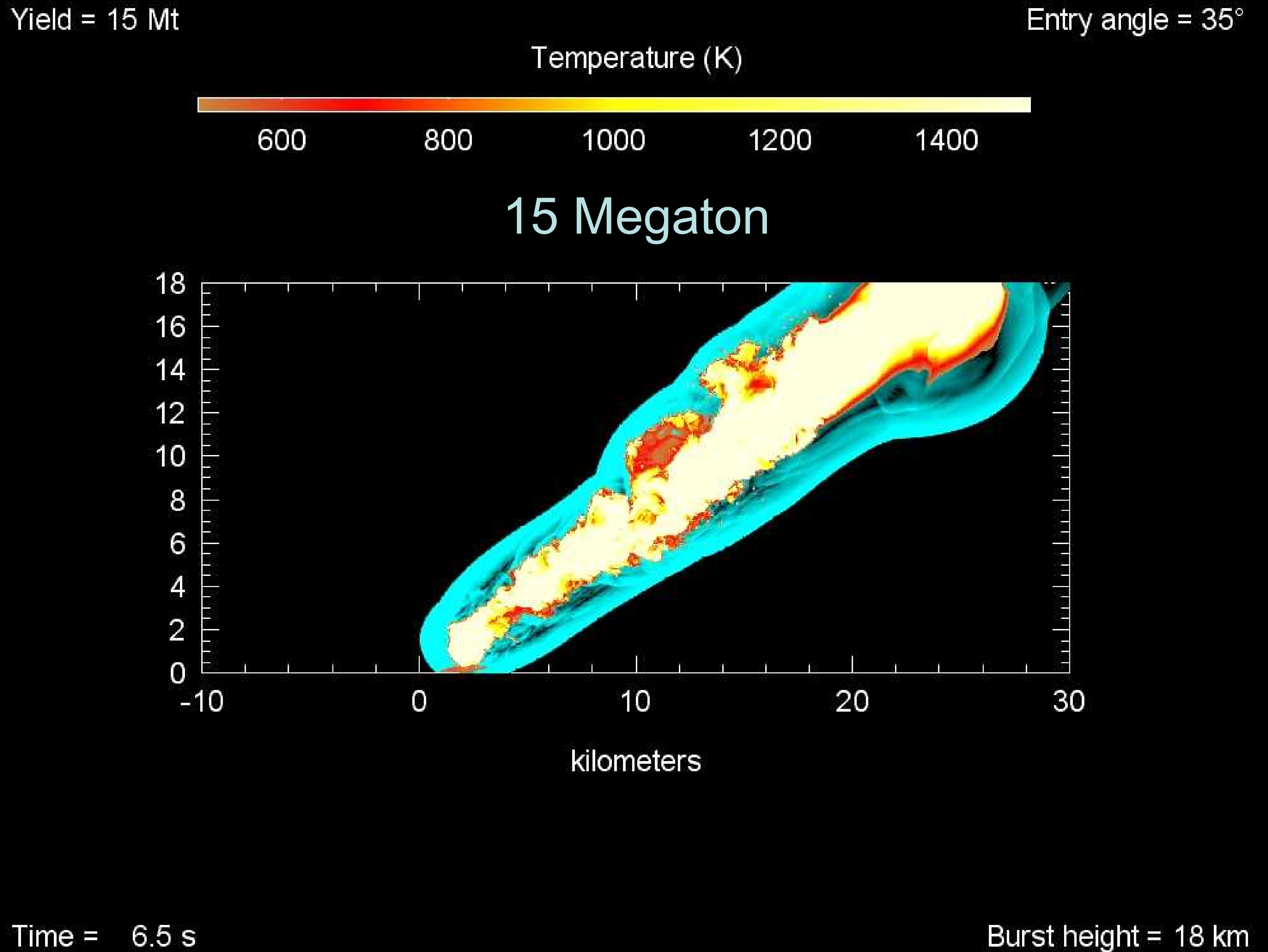


Time = 6.5 s

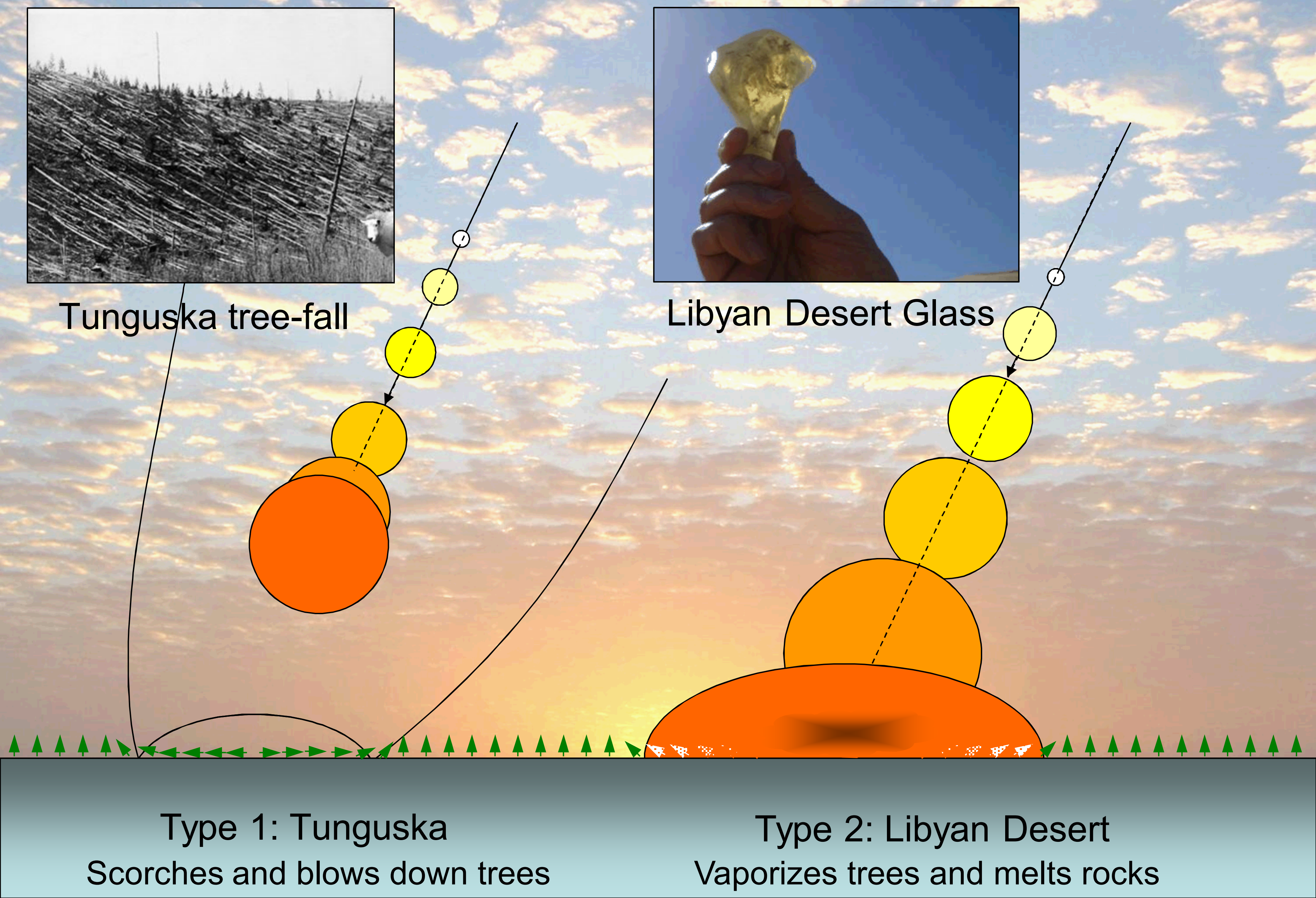
Burst height = 12 km


Yield = 15 Mt
Entry angle = 35°
Temperature (K)
600
800
1000
1200
1400
15 Megaton
18
16
14
12
10
8
6
4
2
0
-10
0
10
20
30
kilometers
Time = 6.5 s
Burst height = 18 km


Yield = 15 Mt
Entry angle = 35°
Temperature (K)
500 600 700 800 900 1000 1100 1200 1300 1400 1500
18
16
14
12
10
8
6
4
2
0
-10 0 10 20 30
kilometers
Time = 0.0 s
Burst height = 18 km


Yield = 15 Mt
Entry angle = 35°
Temperature (K)
600
800
1000
1200
1400
15 Megaton
18
16
14
12
10
8
6
4
2
0
-10
0
10
20
30
kilometers
Time = 6.5 s
Burst height = 18 km

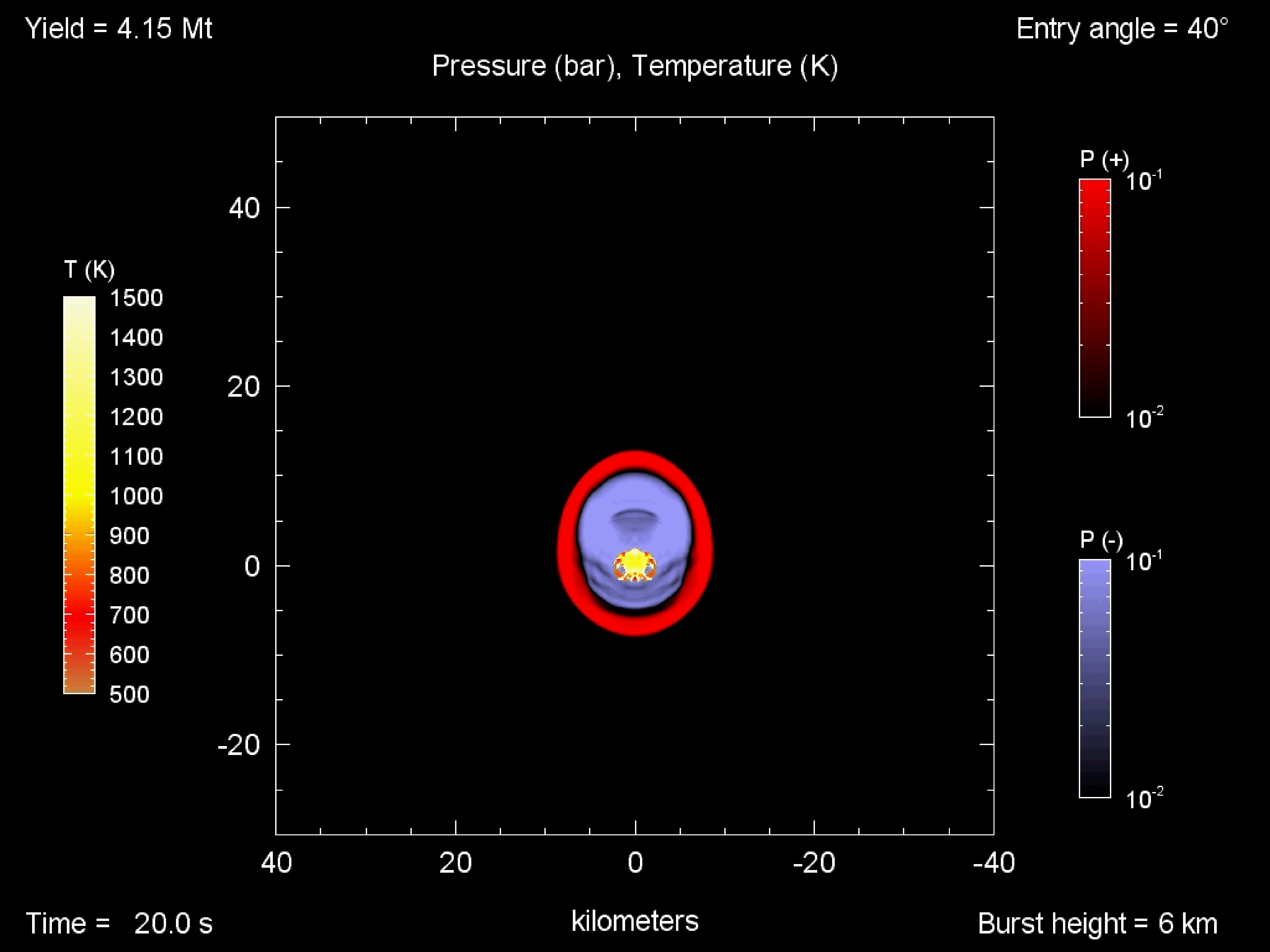
Two types of Low-Altitude Airburst



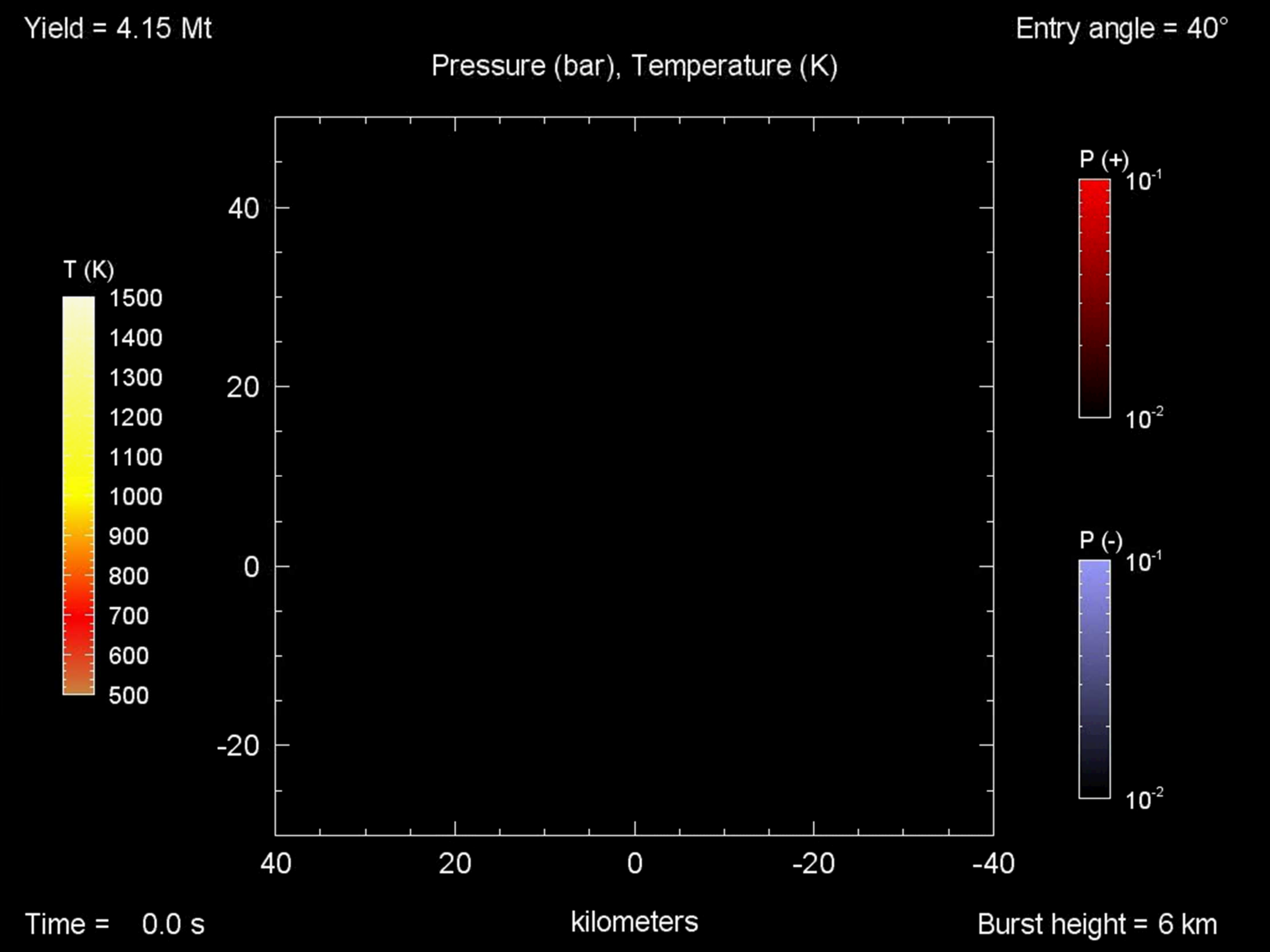
3. Tabletop Exercises

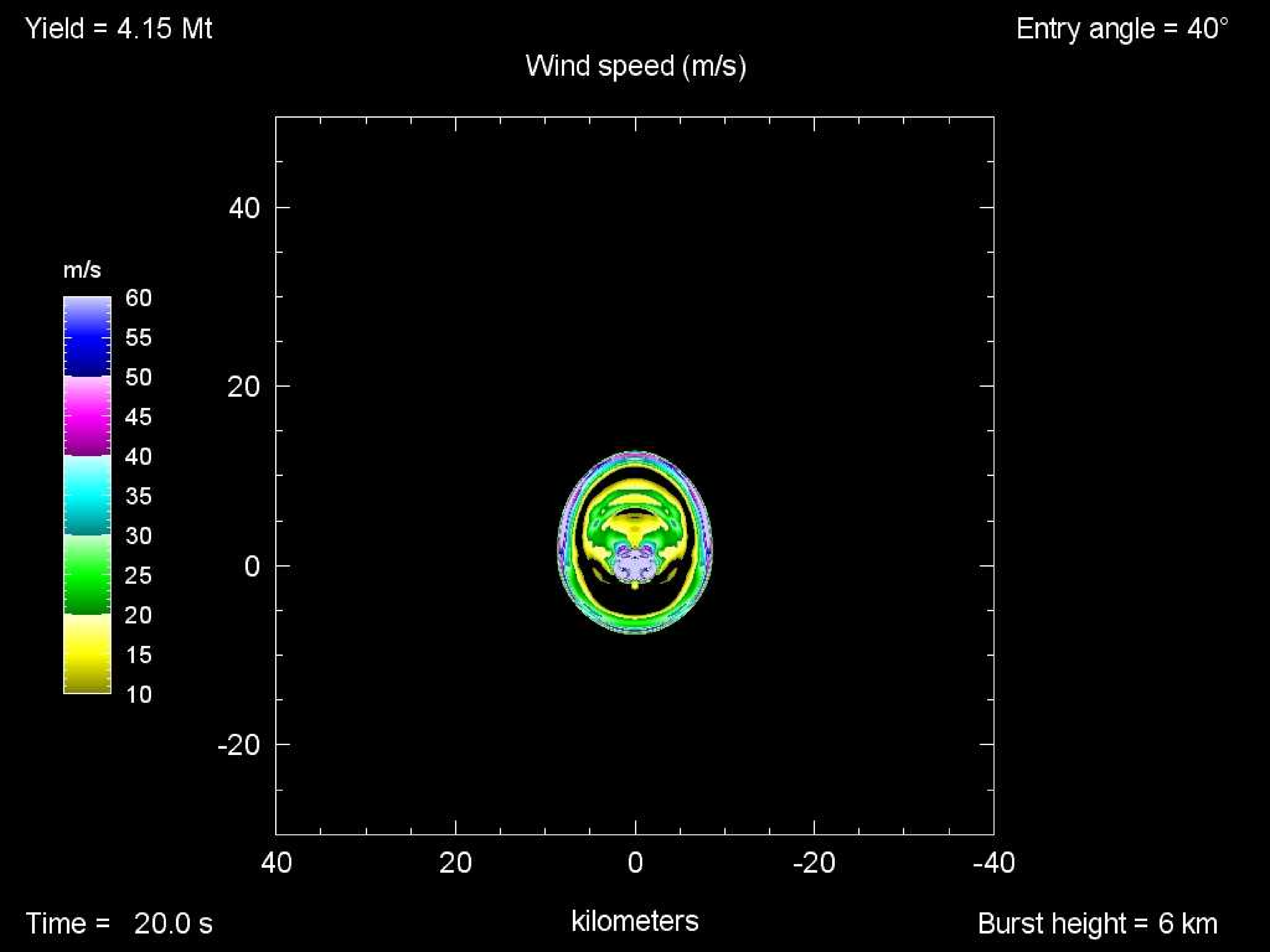
- FEMA, 2013
- PDC Flagstaff, 2013
- FEMA, 2014
- PDC Frascati, 2015

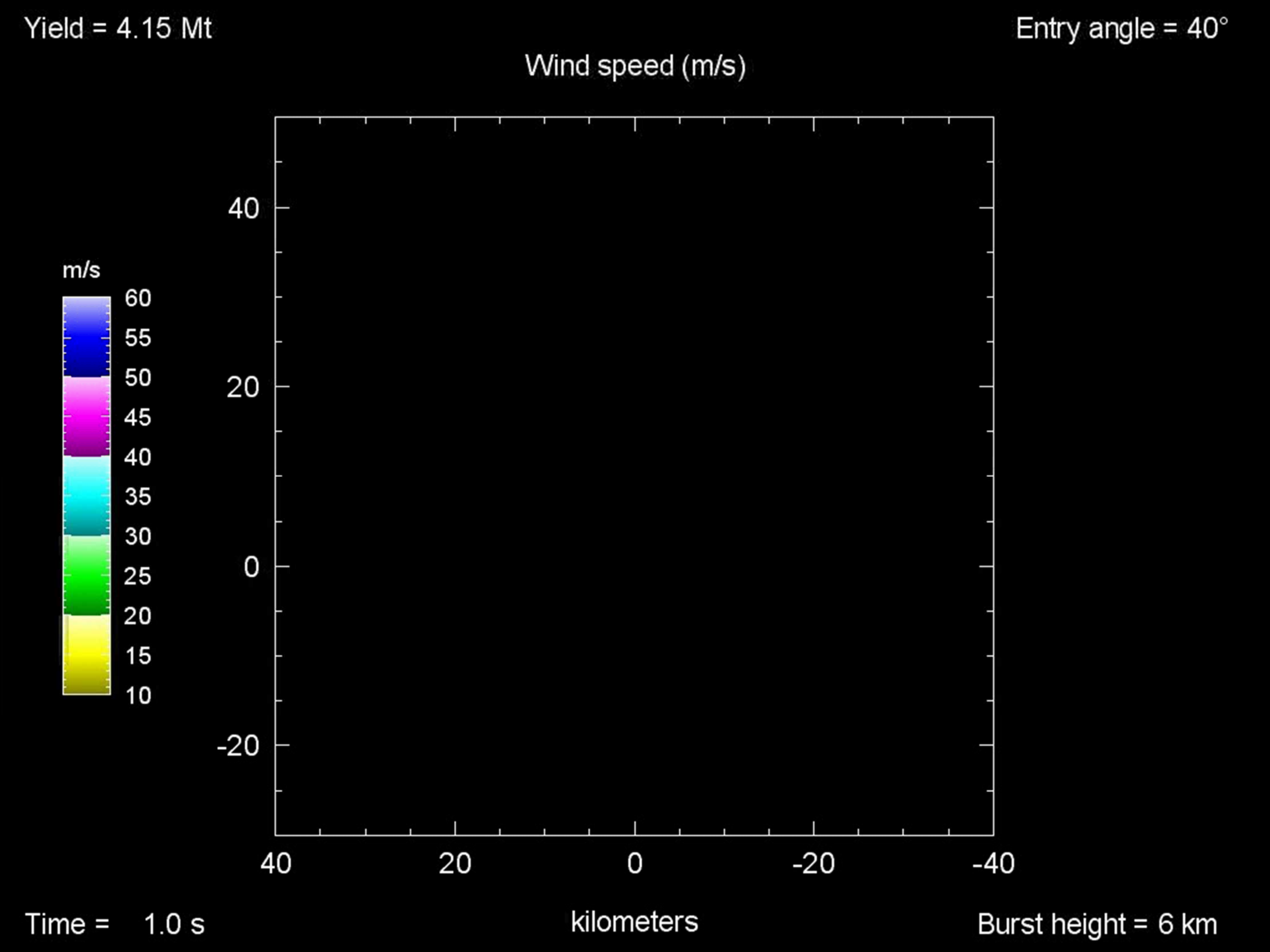
- FEMA, 2013
- PDC Flagstaff, 2013
- **FEMA, 2014**
- PDC Frascati, 2015

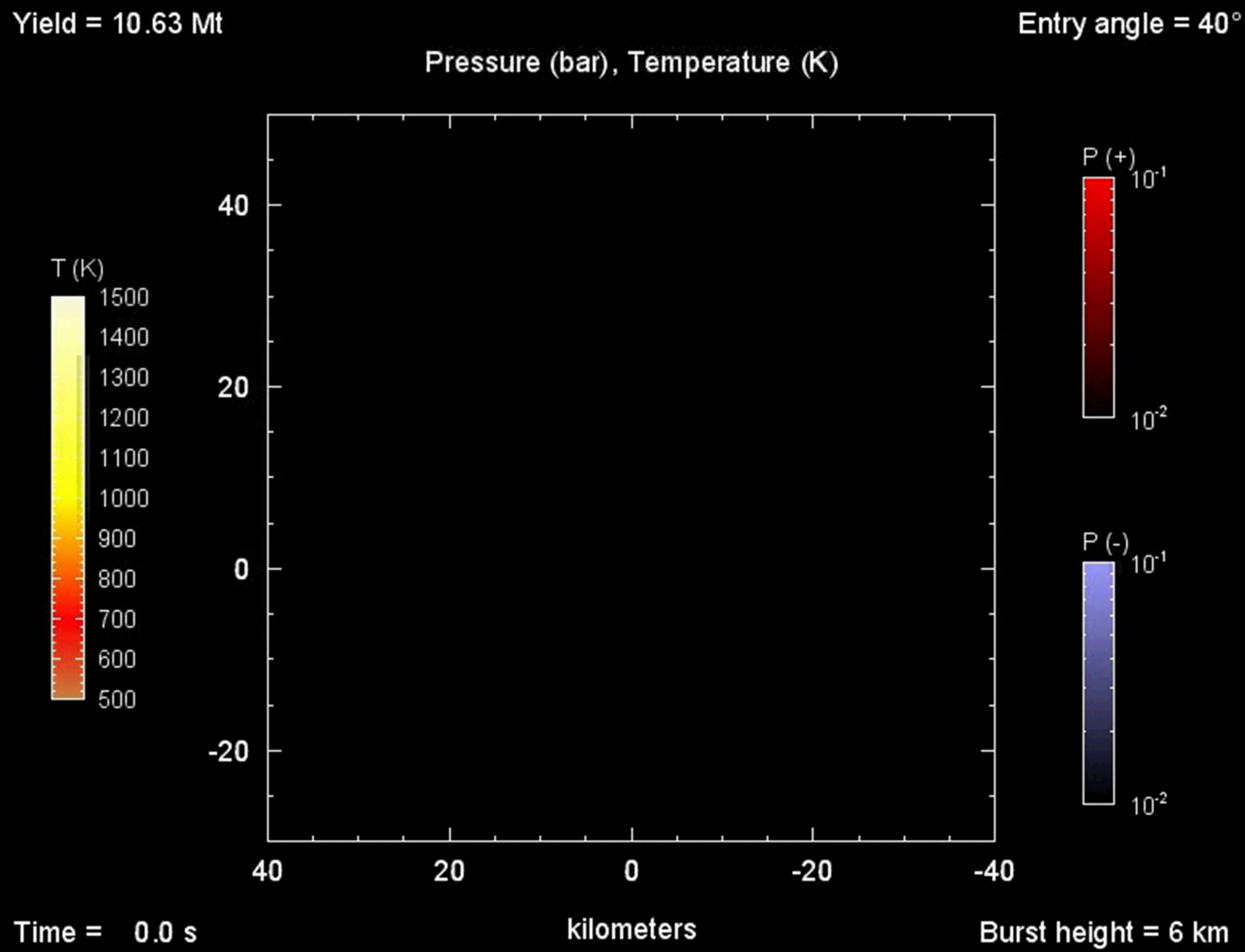


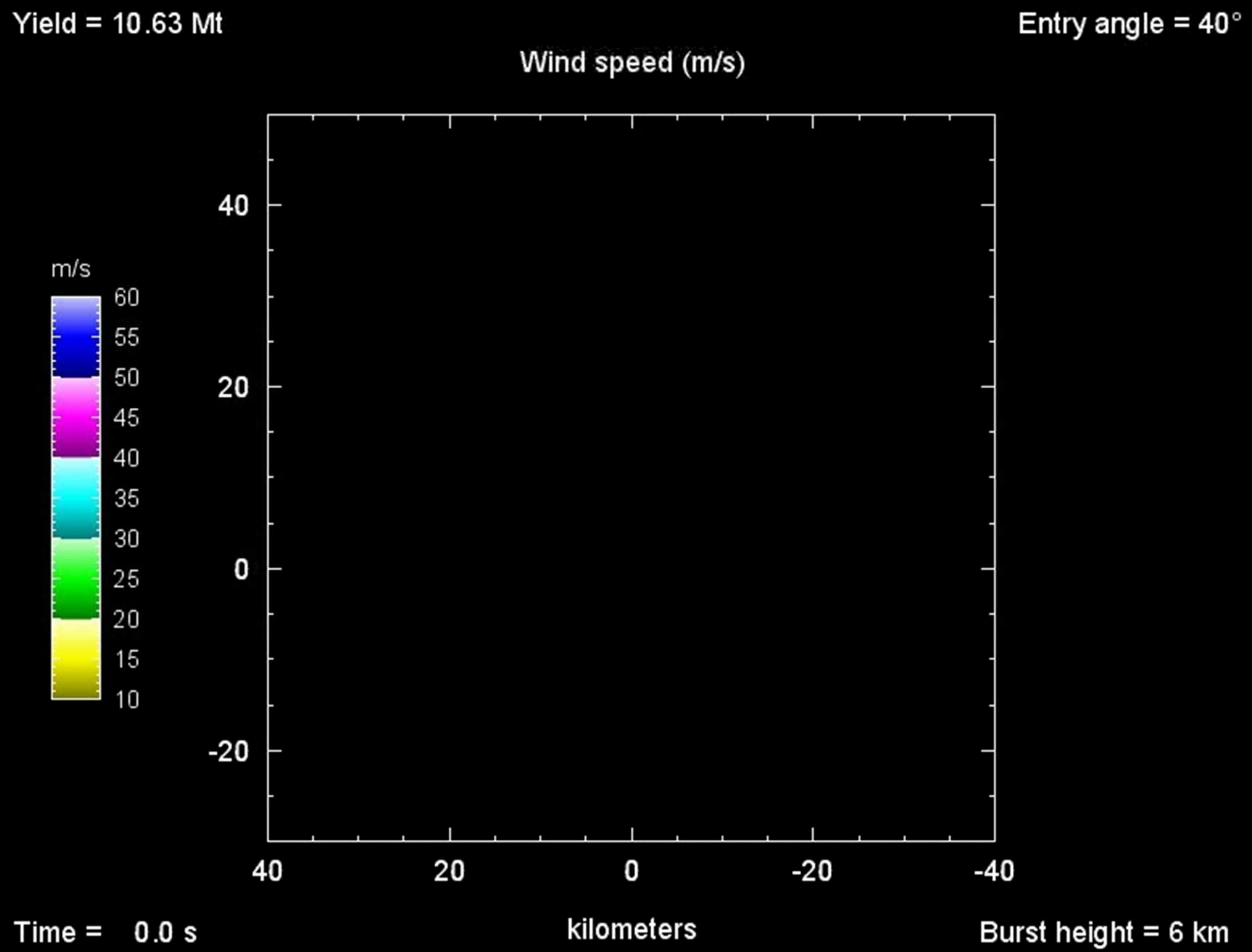
Yield = 4.15 Mt
Entry angle = 40°
Pressure (bar), Temperature (K)
T (K)
1500
1400
1300
1200
1100
1000
900
800
700
600
500
P (+)
10-1
10-2
P (-)
10-1
10-2
40
20
0
-20
40
20
0
-20
-40
kilometers
Time = 20.0 s
Burst height = 6 km


Yield = 4.15 Mt
Entry angle = 40°
Pressure (bar), Temperature (K)
T (K)
1500
1400
1300
1200
1100
1000
900
800
700
600
500
P (+)
10-1
10-2
P (-)
10-1
10-2
40
20
0
-20
40
20
0
-20
-40
kilometers
Time = 0.0 s
Burst height = 6 km

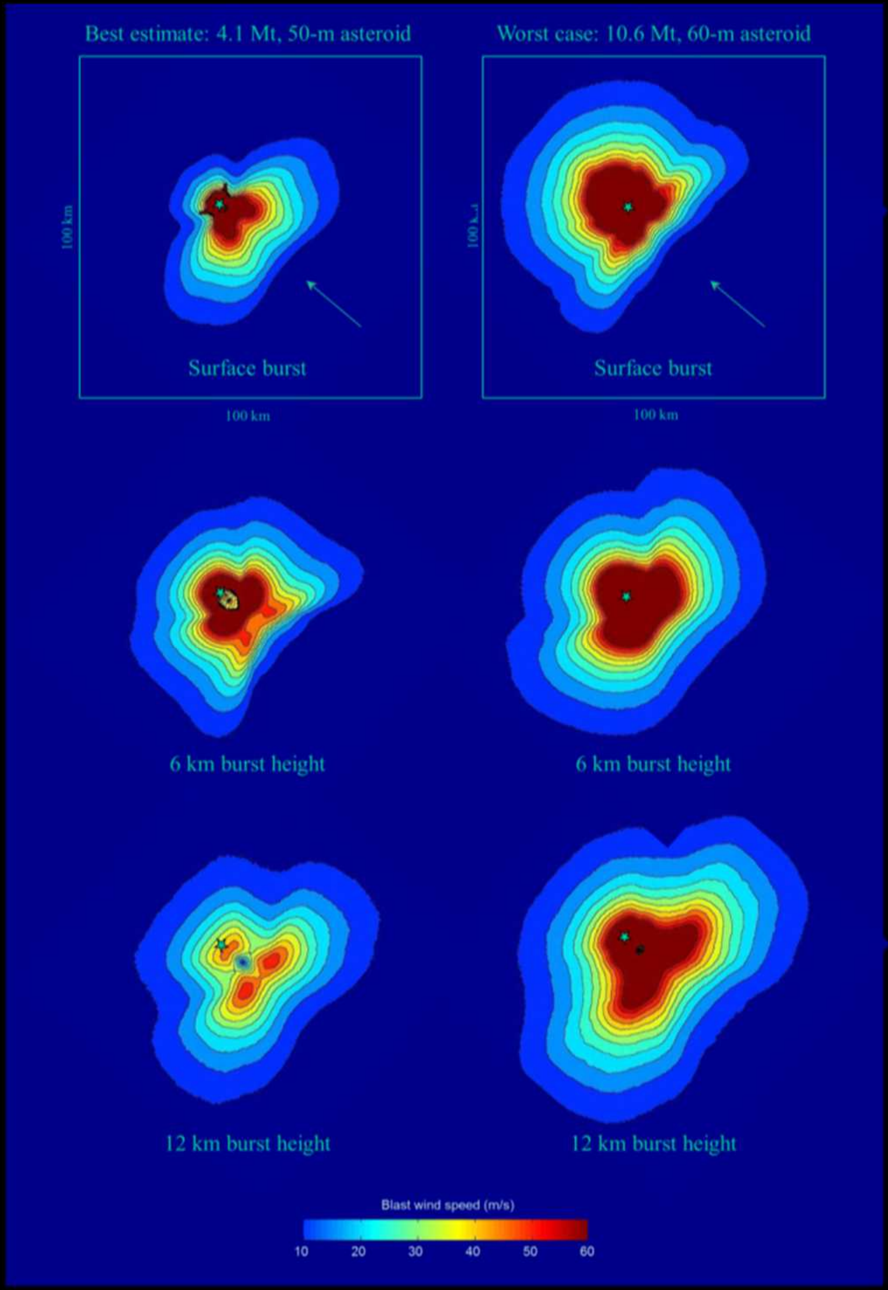

Yield = 4.15 Mt
Entry angle = 40°
Wind speed (m/s)
m/s
60
55
50
45
40
35
30
25
20
15
10
40
20
0
-20
40
20
0
-20
-40
Time = 20.0 s
kilometers
Burst height = 6 km

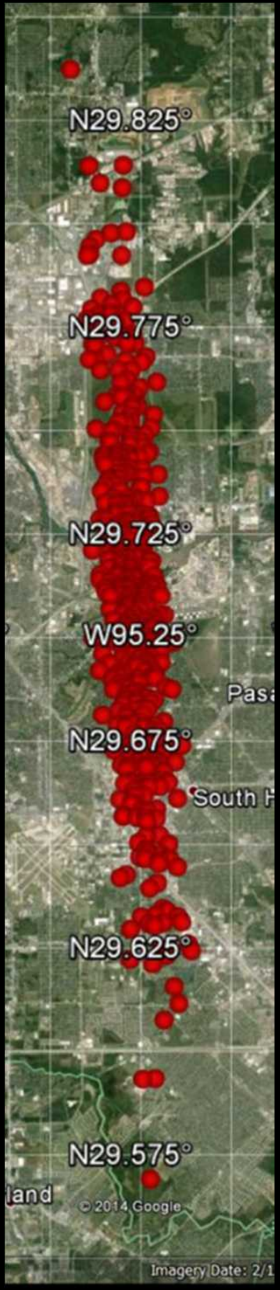

Yield = 4.15 Mt
Entry angle = 40°
Wind speed (m/s)
m/s
60
55
50
45
40
35
30
25
20
15
10
40
20
0
-20
40
20
0
-20
-40
kilometers
Time = 1.0 s
Burst height = 6 km

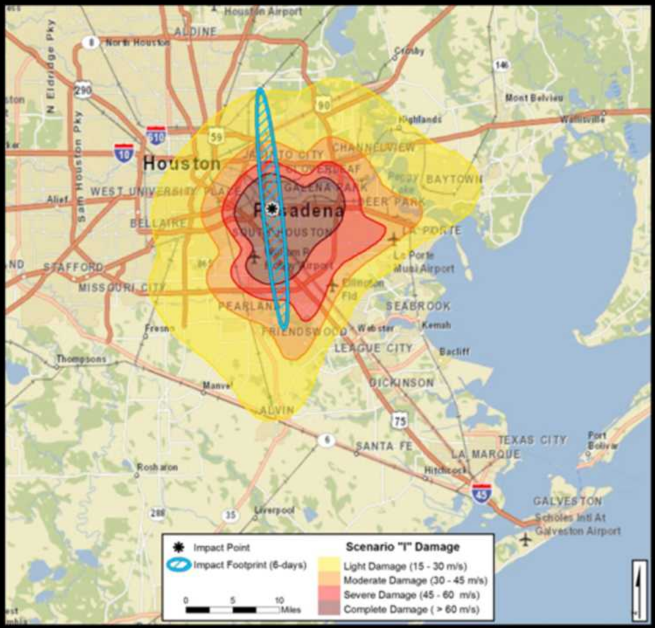

Yield = 10.63 Mt
Entry angle = 40°
Pressure (bar), Temperature (K)
T (K)
1500
1400
1300
1200
1100
1000
900
800
700
600
500
P (+)
10^{-1}
10^{-2}
P (-)
10^{-1}
10^{-2}
40
20
0
-20
40
20
0
-20
-40
kilometers
Time = 0.0 s
Burst height = 6 km

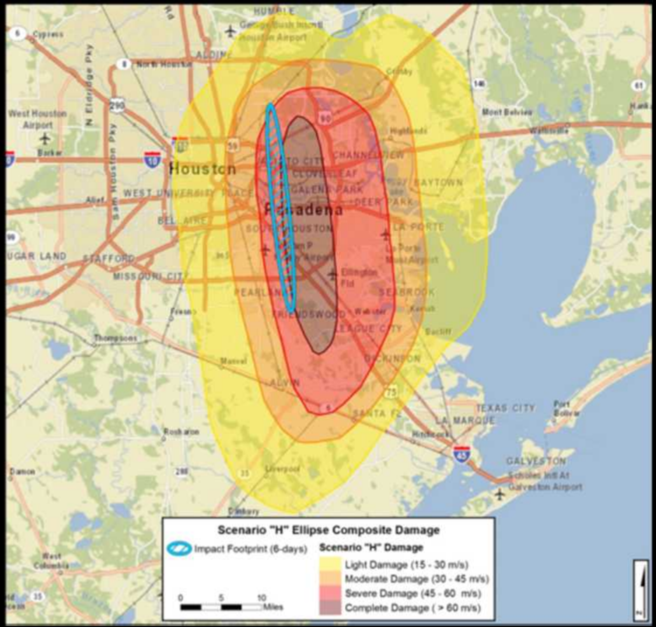

Yield = 10.63 Mt
Entry angle = 40°
Wind speed (m/s)
m/s
60
55
50
45
40
35
30
25
20
15
10
40
20
0
-20
40
20
0
-20
-40
Time = 0.0 s
kilometers
Burst height = 6 km

FEMA Tabletop Exercise, 2014

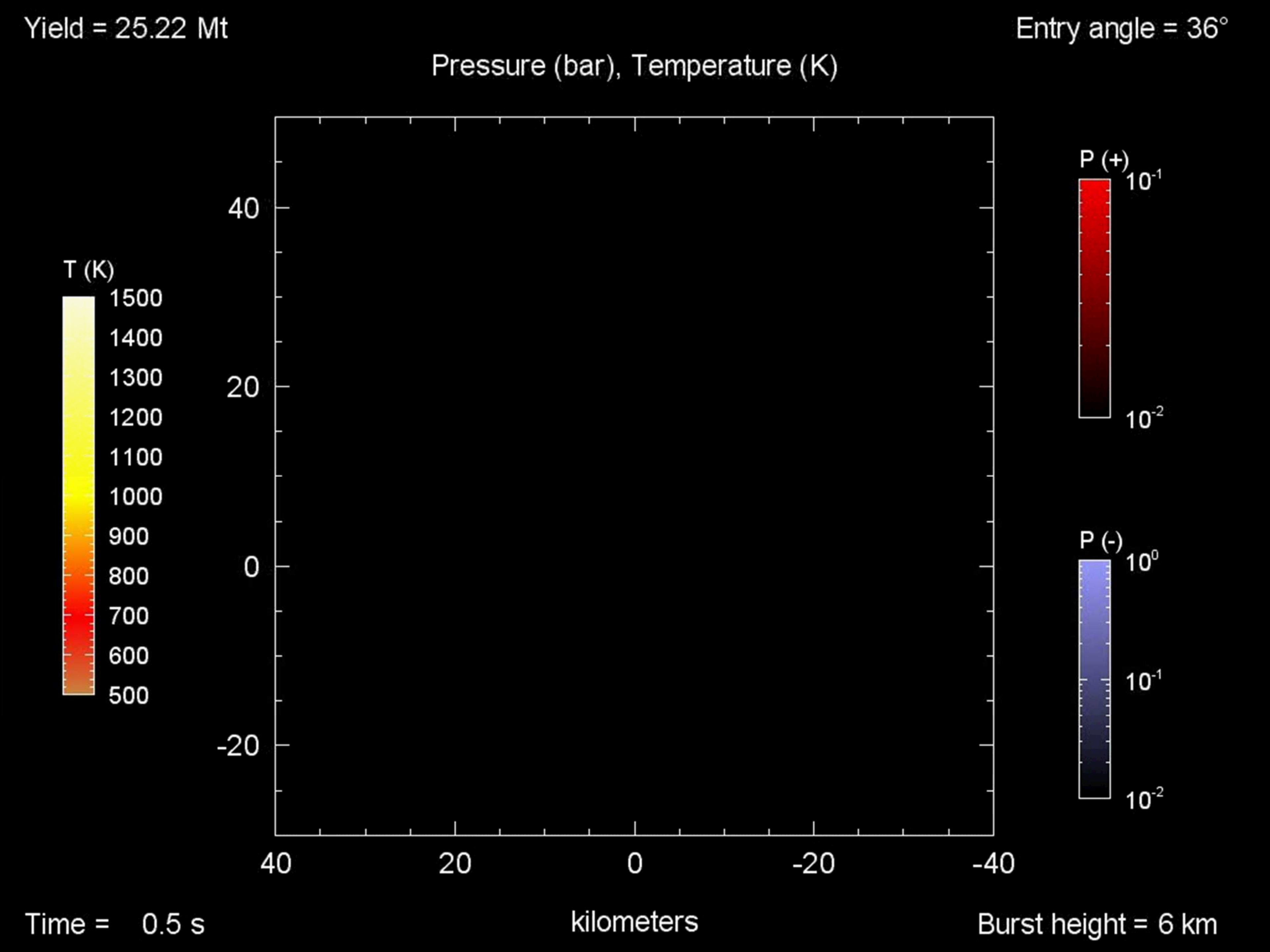


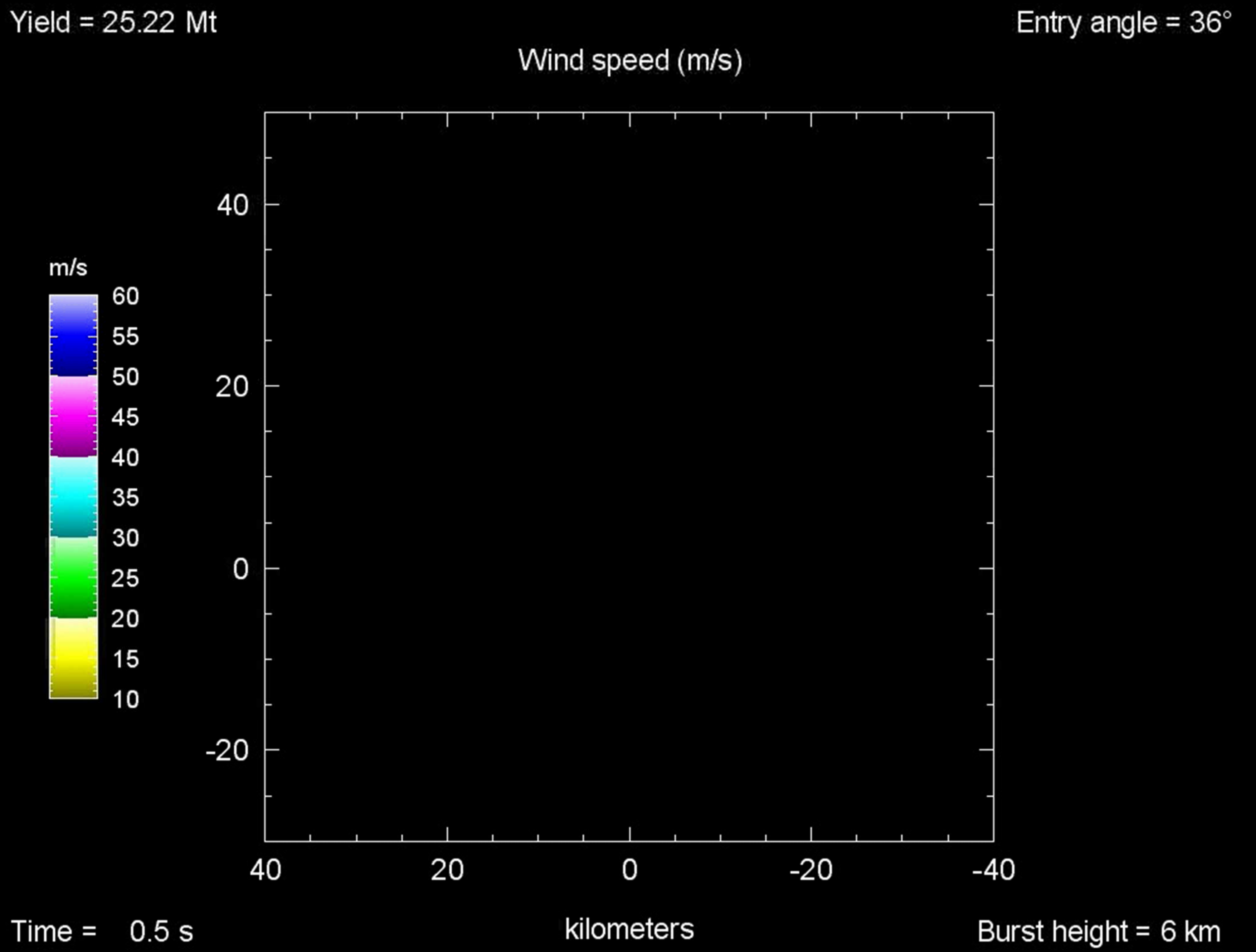




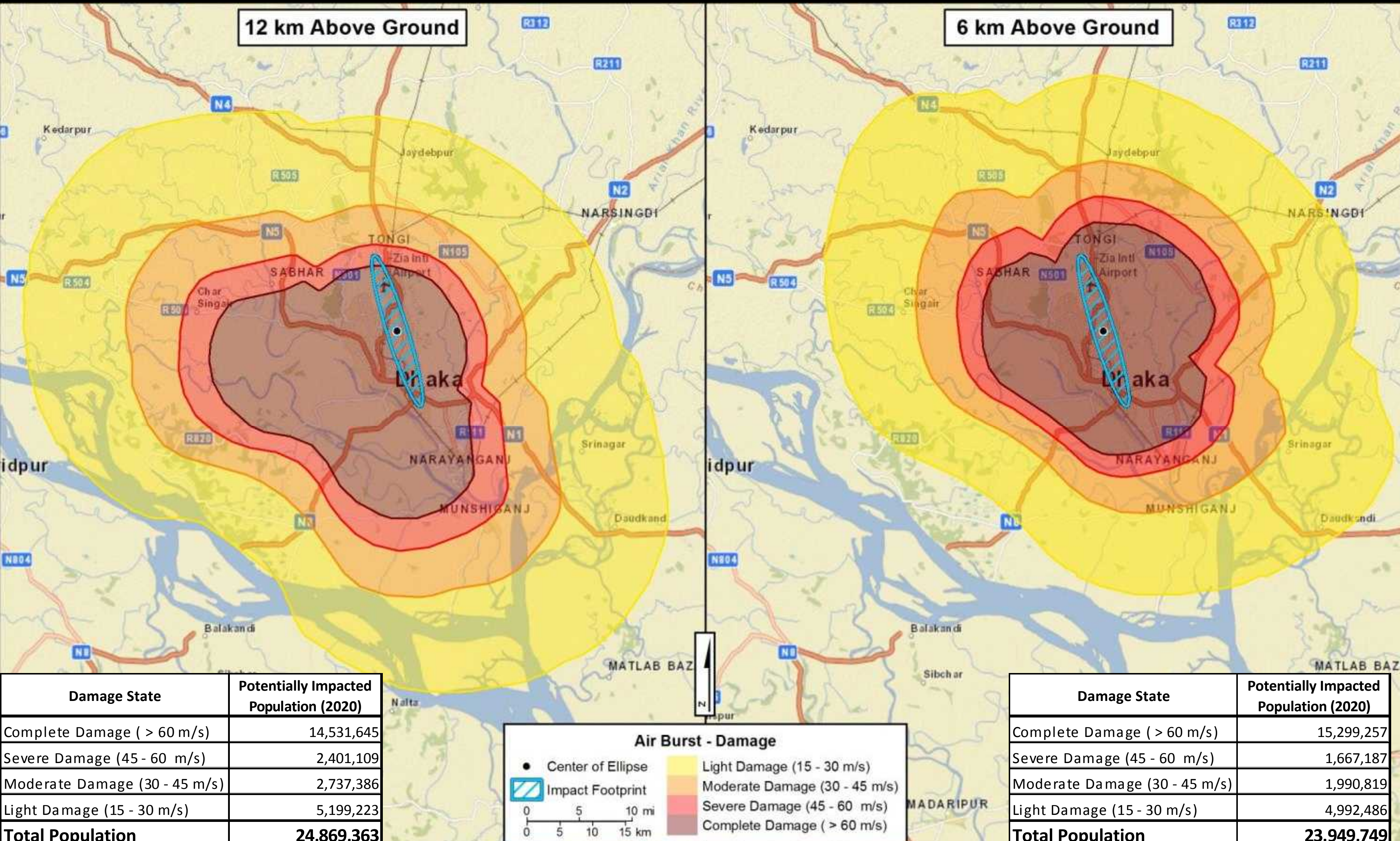


- FEMA, 2013
- PDC Flagstaff, 2013
- FEMA, 2014
- **PDC Frascati, 2015**


Yield = 25.22 Mt
Entry angle = 36°
Pressure (bar), Temperature (K)
T (K)
1500
1400
1300
1200
1100
1000
900
800
700
600
500
40
20
0
-20
P (+)
10^{-1}
10^{-2}
P (-)
10^{0}
10^{-1}
10^{-2}
40
20
0
-20
-40
Time = 0.5 s
kilometers
Burst height = 6 km


Yield = 25.22 Mt
Entry angle = 36°
Wind speed (m/s)
m/s
60
55
50
45
40
35
30
25
20
15
10
40
20
0
-20
40
20
0
-20
-40
kilometers
Time = 0.5 s
Burst height = 6 km

Planetary Defense Conference, 2015



12 km Above Ground:

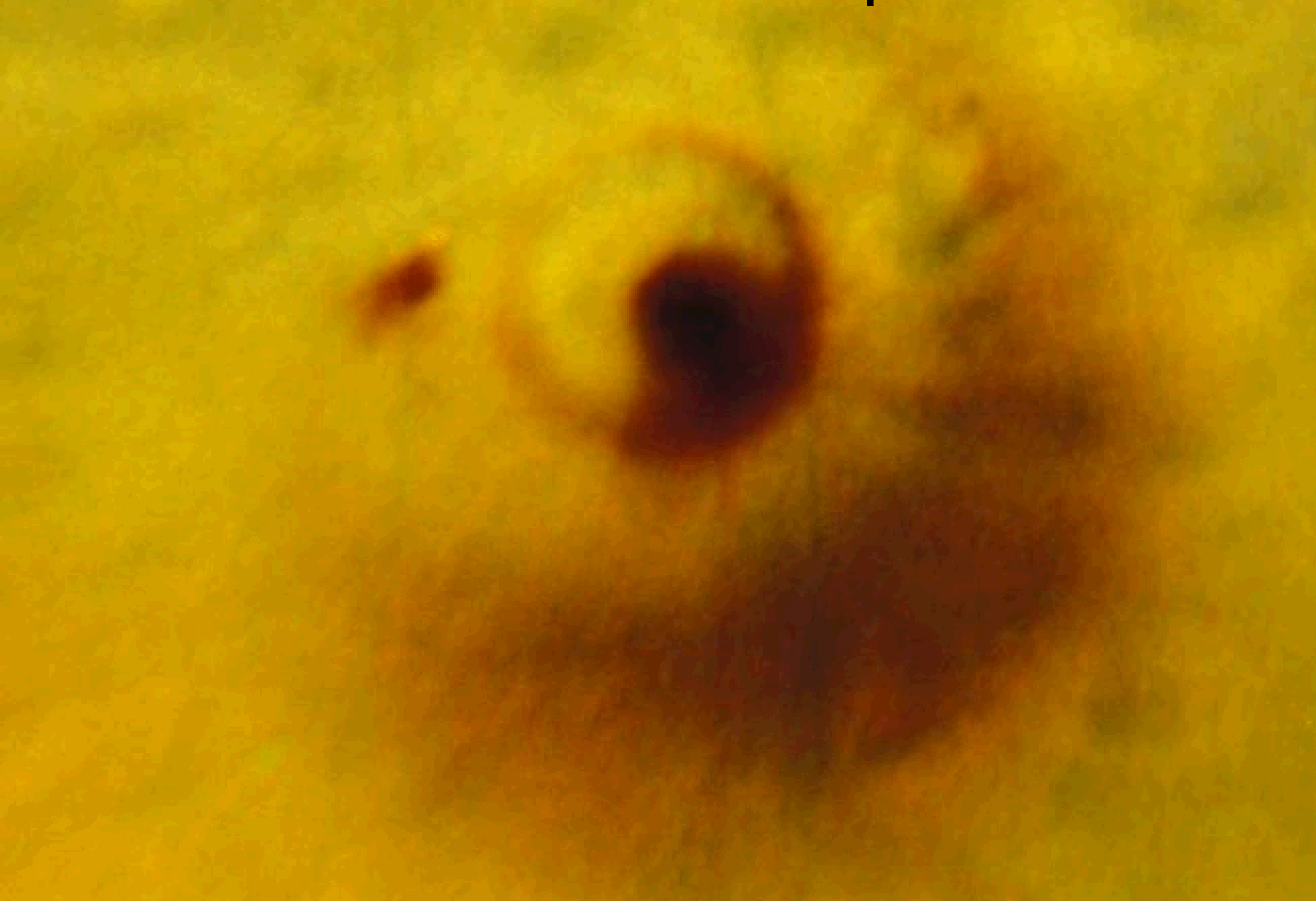
Damage State	Potentially Impacted Population (2020)
Complete Damage (> 60 m/s)	14,531,645
Severe Damage (45 - 60 m/s)	2,401,109
Moderate Damage (30 - 45 m/s)	2,737,386
Light Damage (15 - 30 m/s)	5,199,223
Total Population	**24,869,363**

6 km Above Ground:

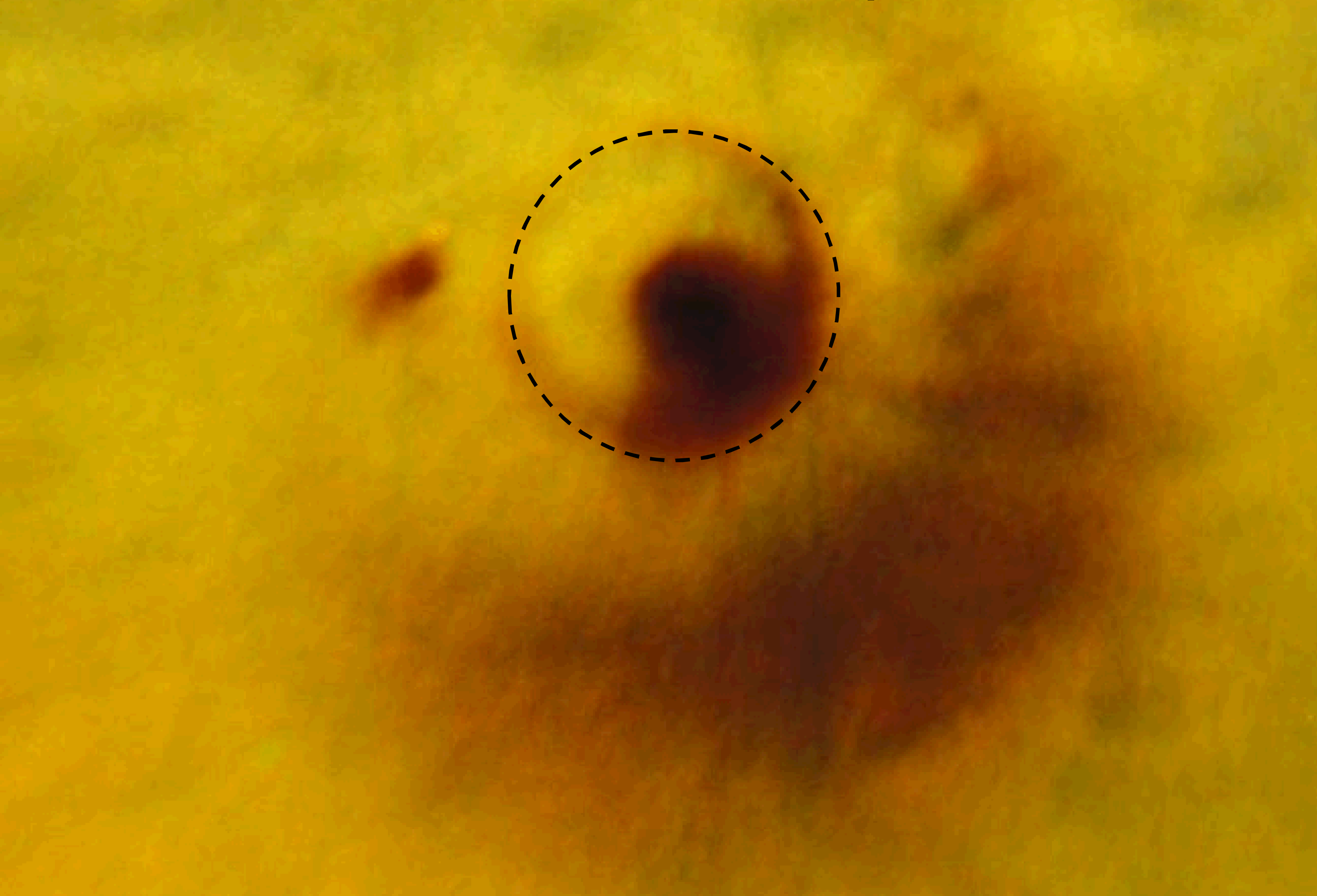
Damage State	Potentially Impacted Population (2020)
Complete Damage (> 60 m/s)	15,299,257
Severe Damage (45 - 60 m/s)	1,667,187
Moderate Damage (30 - 45 m/s)	1,990,819
Light Damage (15 - 30 m/s)	4,992,486
Total Population	**23,949,749**

4. Airburst-generated tsunami

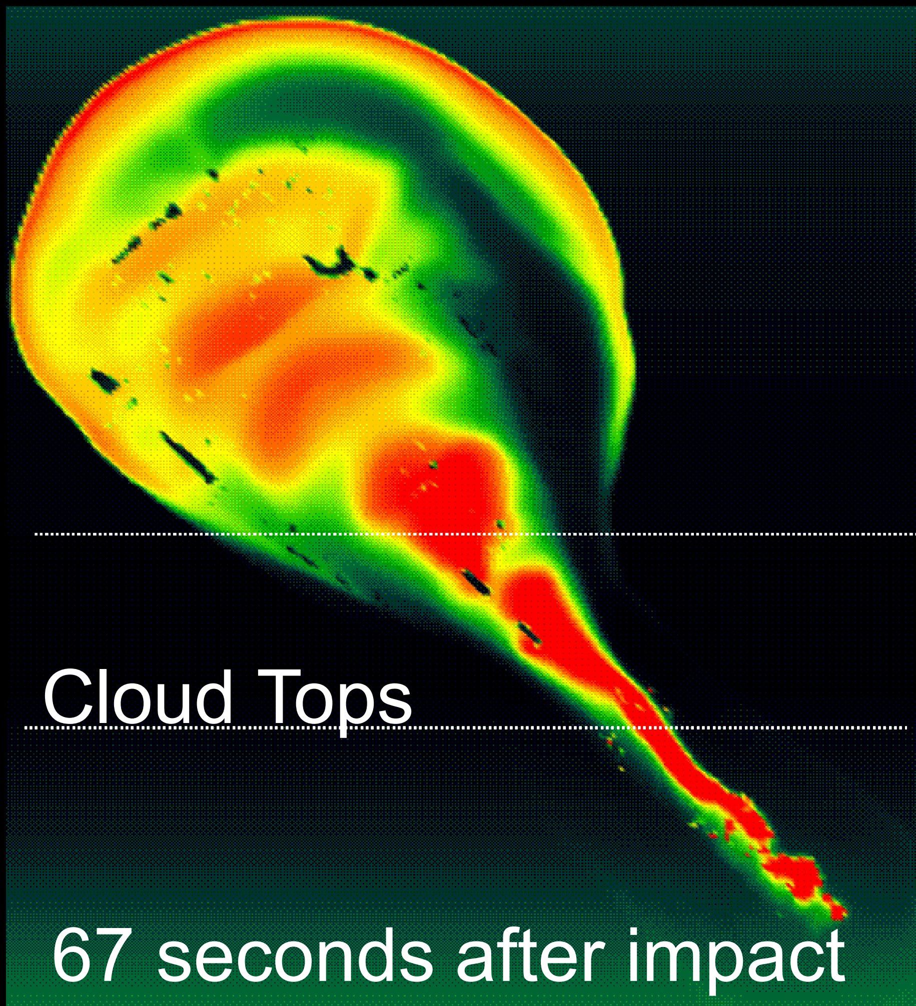
“Tsunami” on Jupiter



“Tsunami” on Jupiter

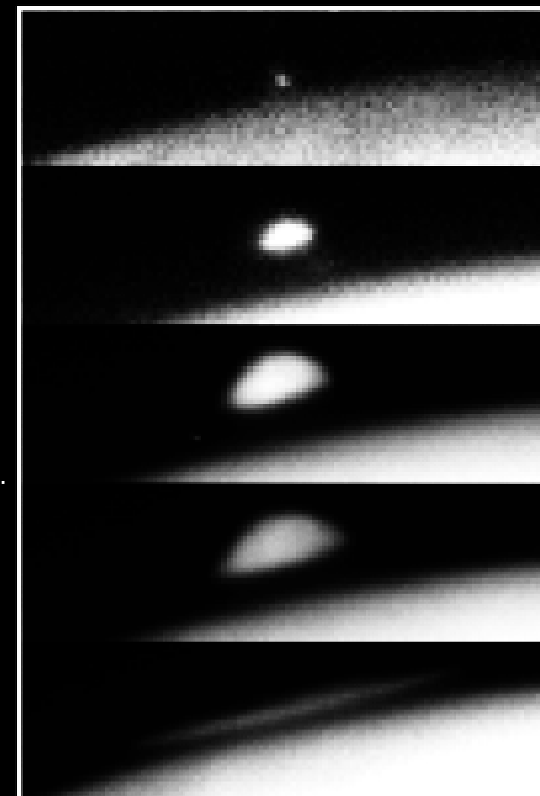


Airburst is a line explosion that ejects a plume: Observational validation by Shoemaker-Levy 9 impact



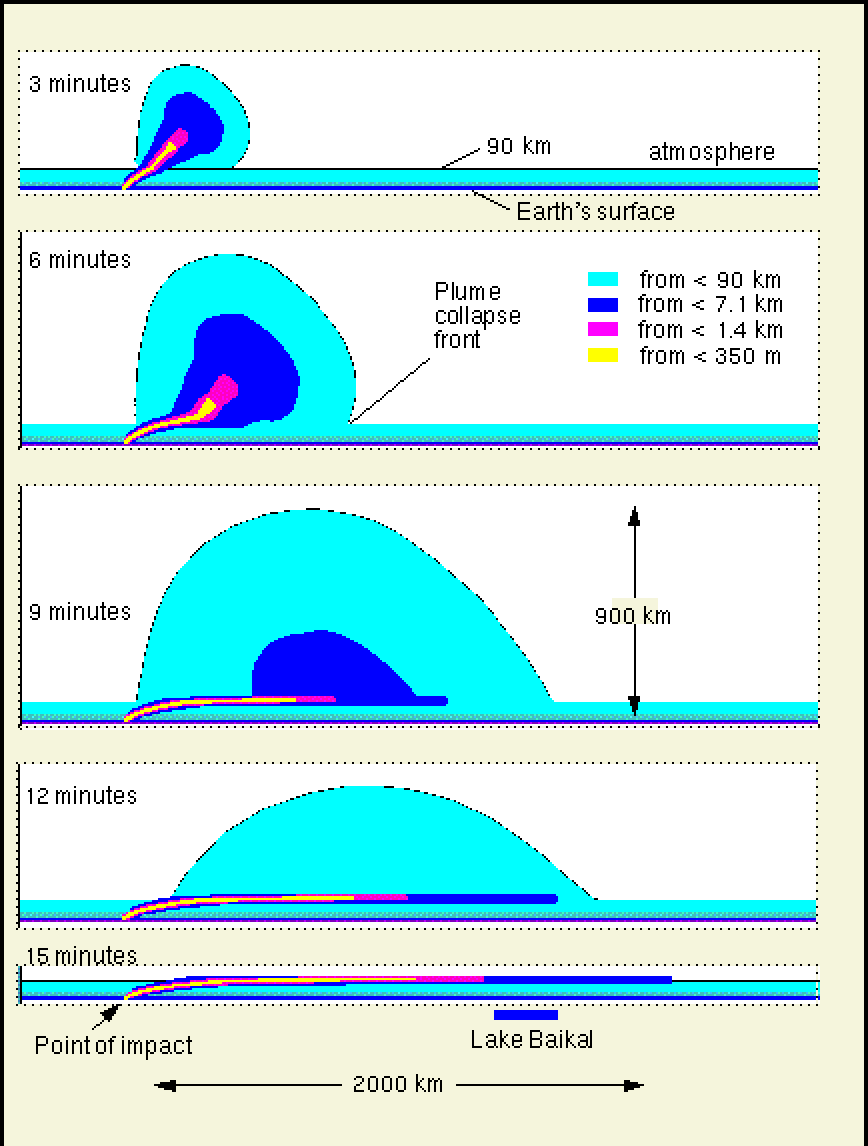
1000 km

Impact G



Hubble Space Telescope Image

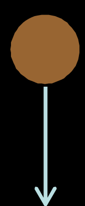
Distribution of bright night skies,
June 30 – July 1, 1908
(I.T Zotkin & A.L. Tchijevsky)



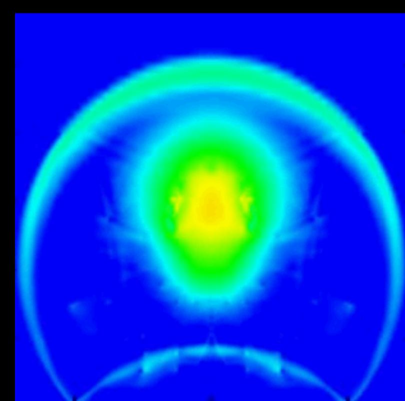
Tunguska Yield Estimates

Three ways to generate seismic impulse: 7×10^{18} dyne-cm

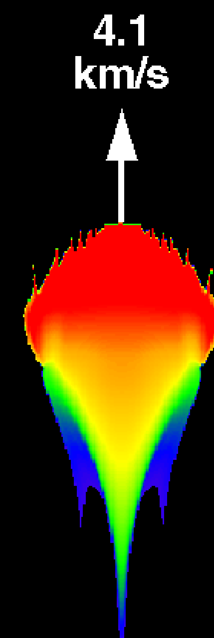
The earth has a β for seismic coupling time scale



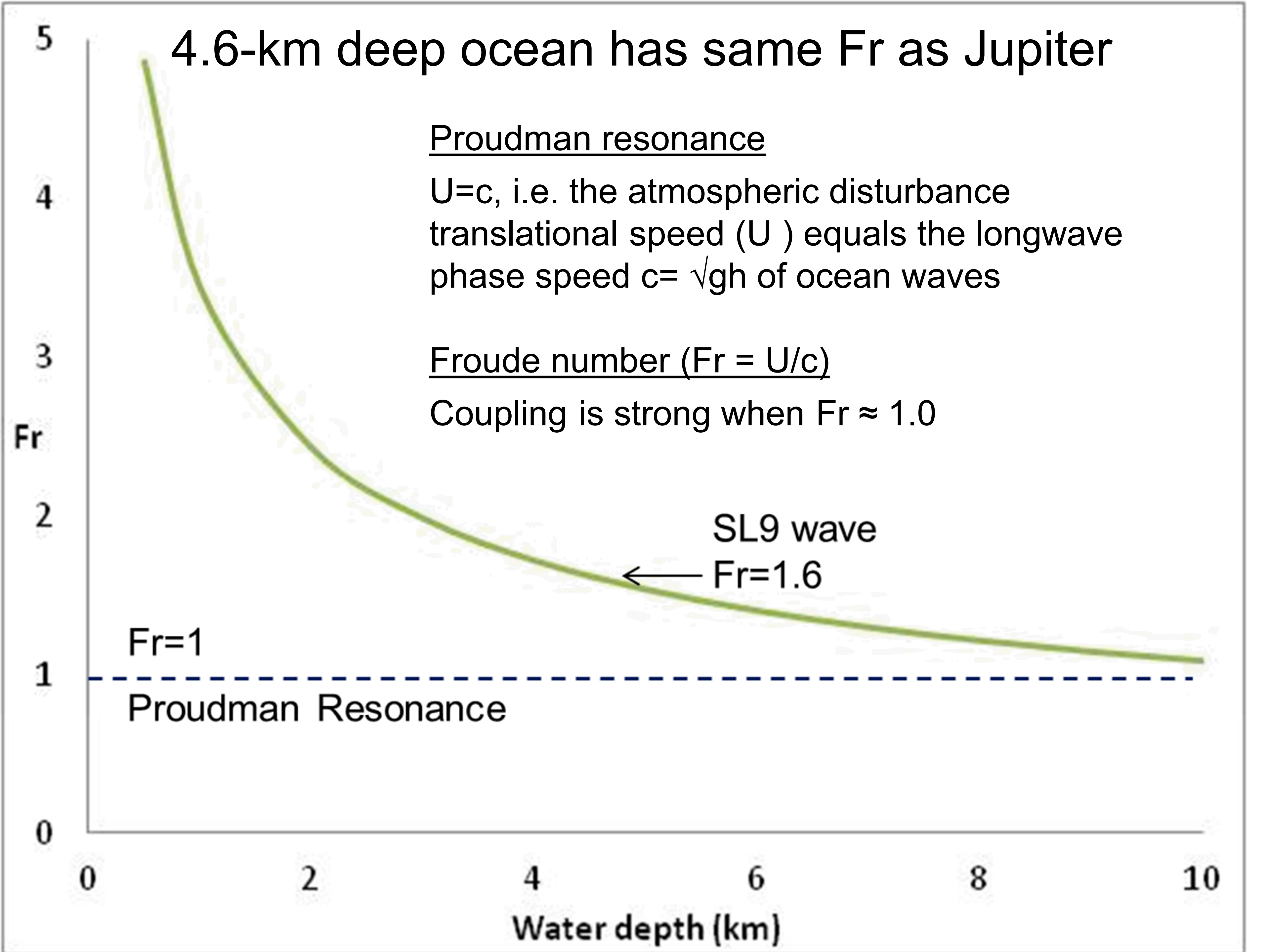
1000 Mton   β = 1
Turco et al., 1982



12.5 Mton   β ≈ 80
Ben-Menahem, 1975



3 Mton   β ≈ 300
Boslough & Crawford, 1997



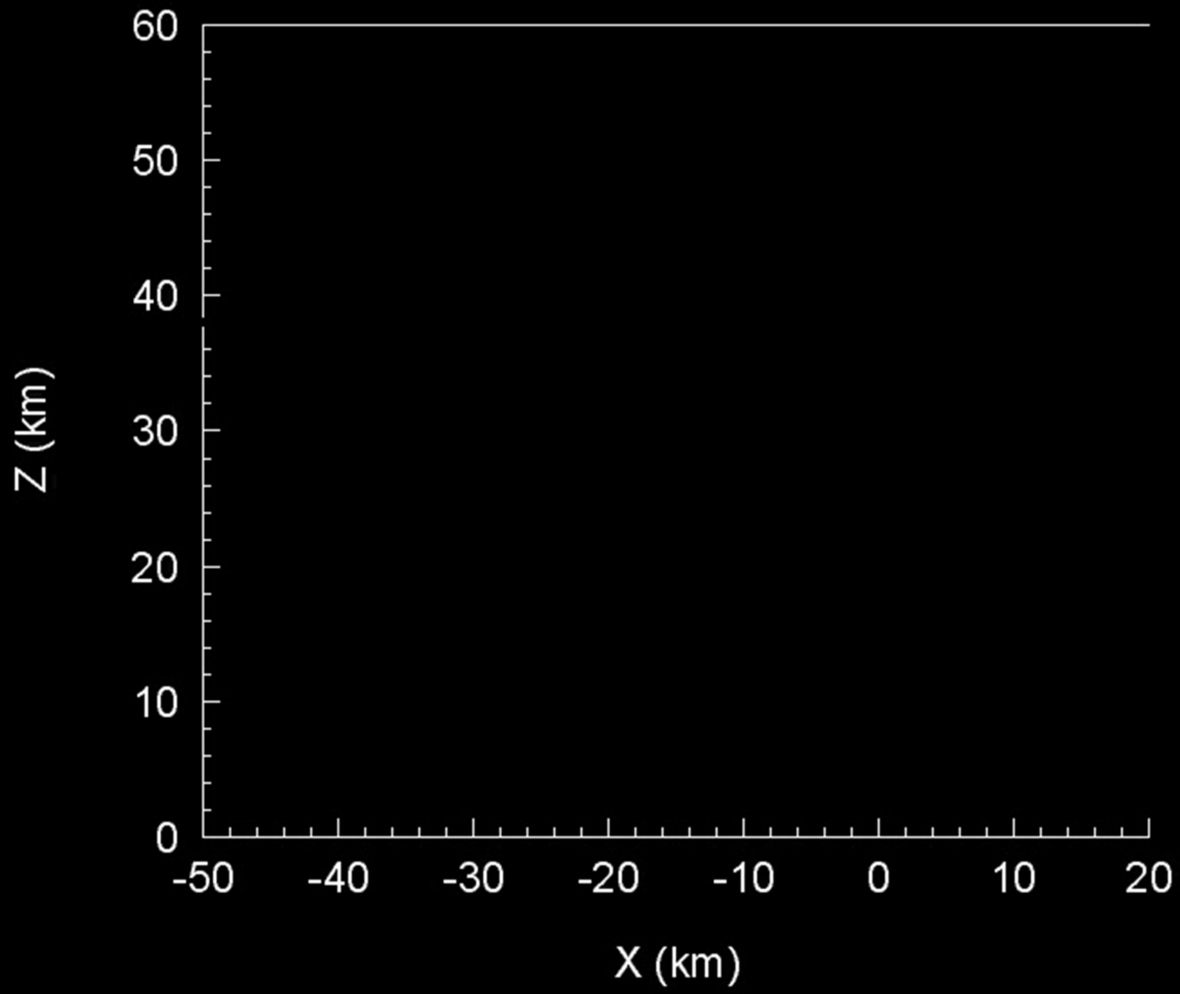
4.6-km deep ocean has same Fr as Jupiter
Proudman resonance
U=c, i.e. the atmospheric disturbance translational speed (U) equals the longwave phase speed c= √gh of ocean waves
Froude number (Fr = U/c)
Coupling is strong when Fr ≈ 1.0
SL9 wave
Fr=1.6
Fr=1
Proudman Resonance
Fr
0
1
2
3
4
5
0
2
4
6
8
10
Water depth (km)

5. Modeling Chelyabinsk

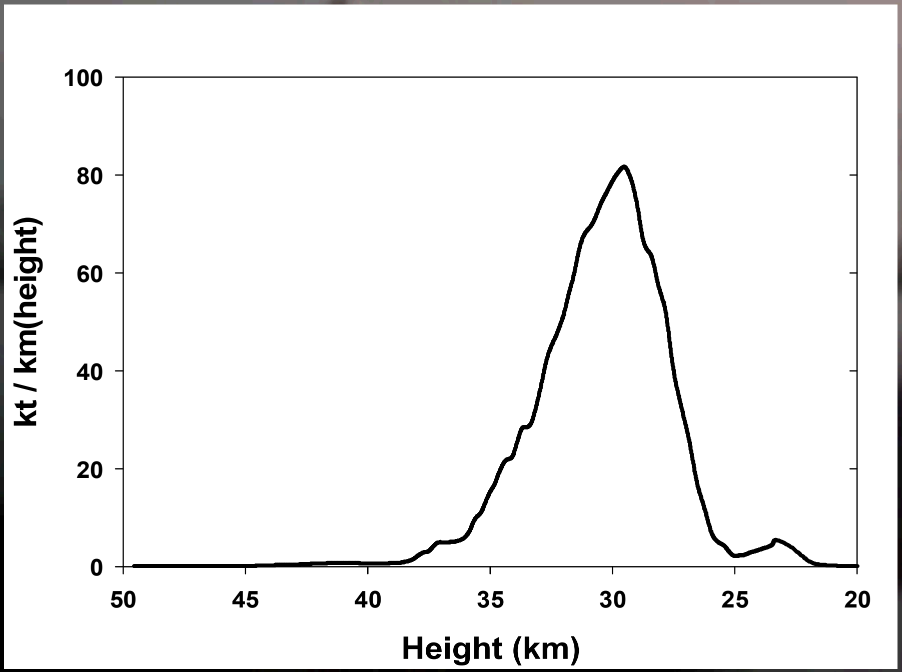
Cr

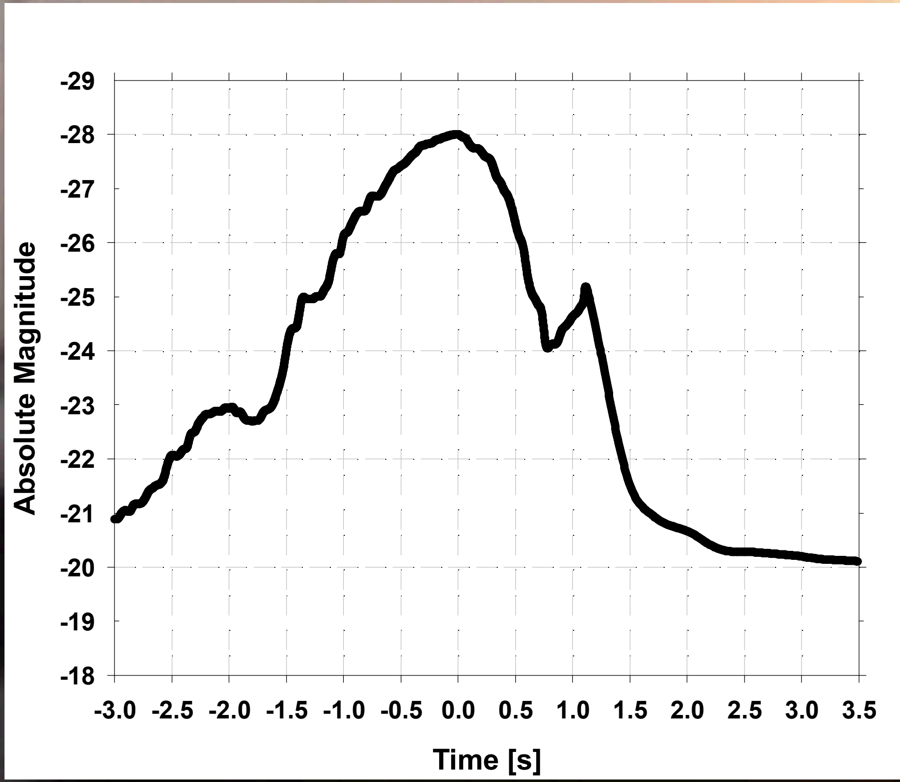
0.00 seconds

Mt



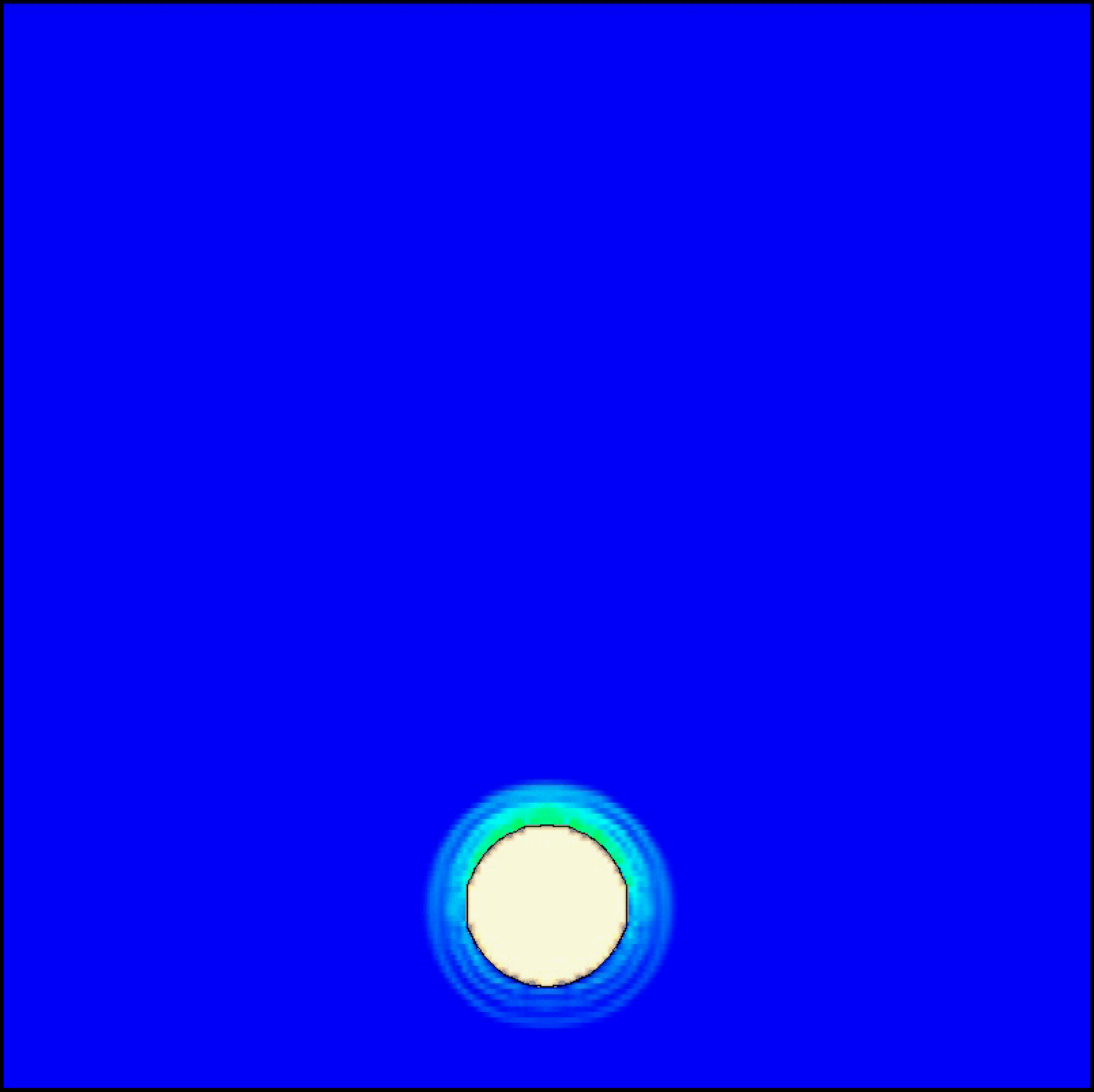
Video Calibrations - Lightcurve





- Uses indirect scattered light and corrected for autogain
- Calibrated using both meteorite-fireball events and kiloton class and larger airbursts
- Total deposited energy assuming η = 17% is >471 kT

2D wake simulation



Near-future work

- Optimize Chelyabinsk model to match obs
- Optimize Tunguska model to match obs
- Include thermal radiation
- Couple airburst model to tsunami wave propagation code
- Recalculate risk with improved kill curve