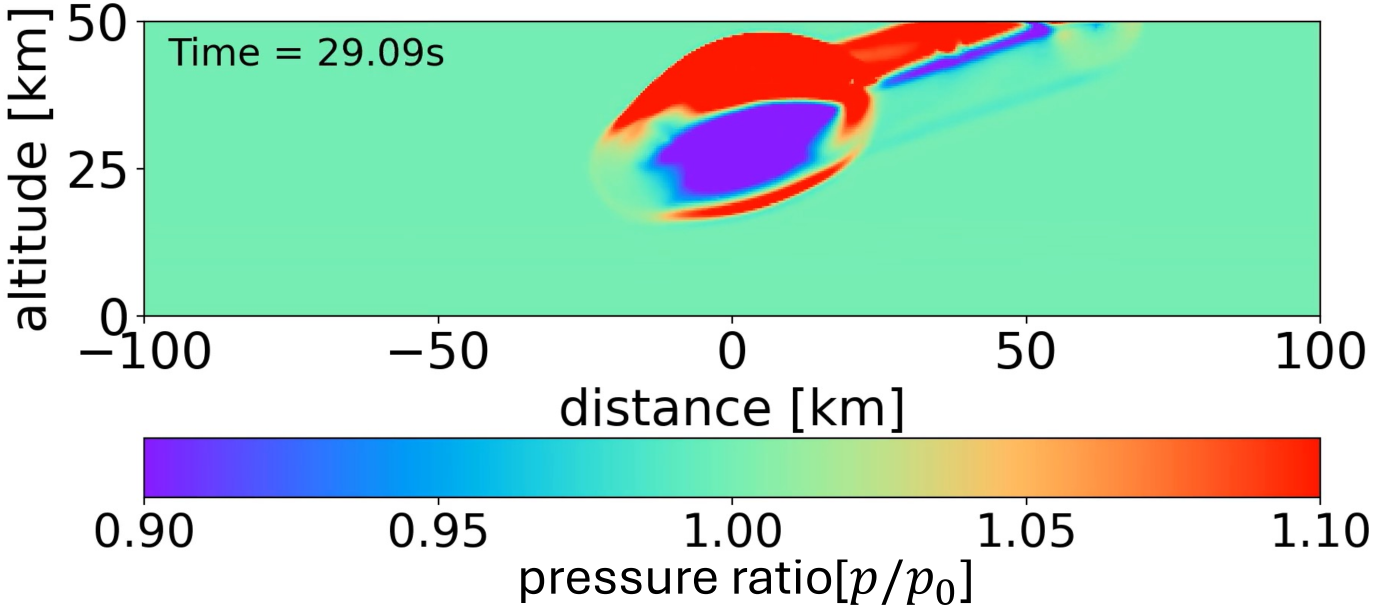
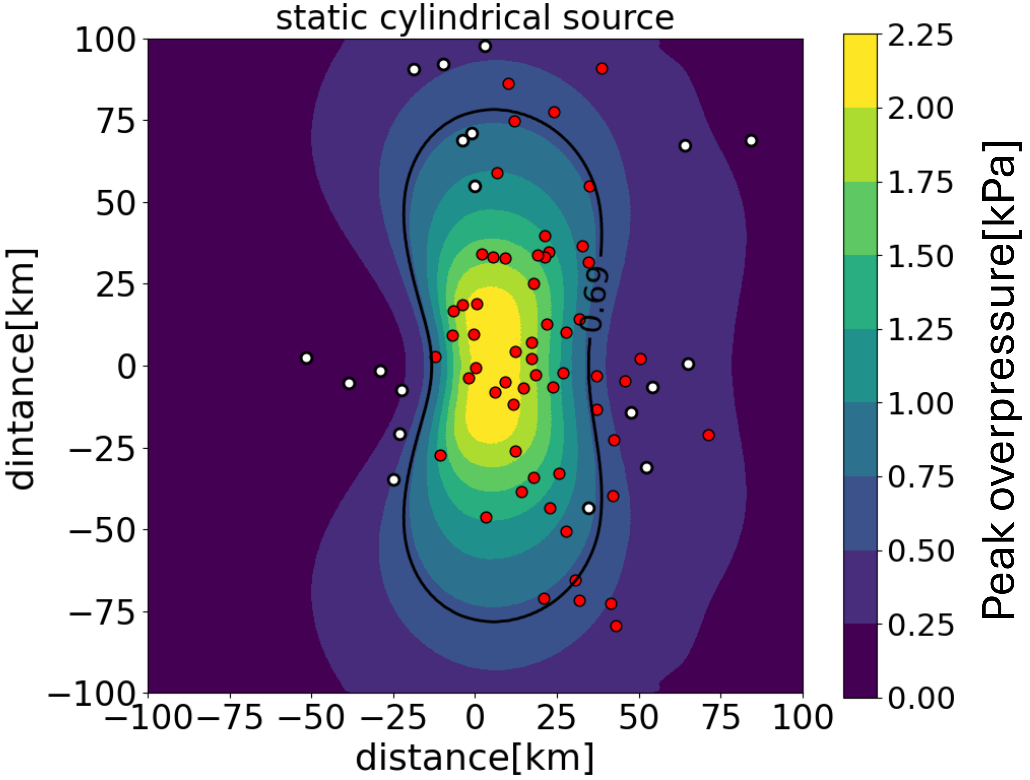
Modeling The Effects of Meteorite Atmospheric Entry on Airflow and Thermal Conditions

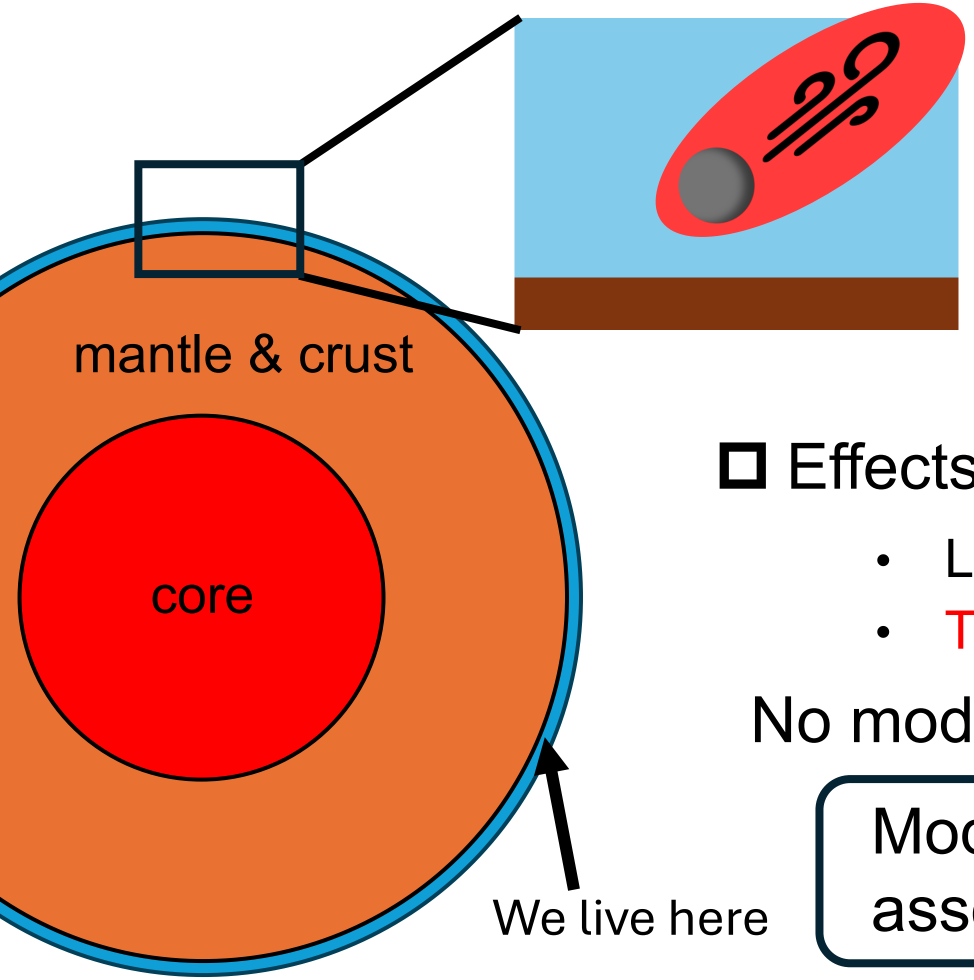




Yuji Miko Hiroshi Kobayashi, Ryushi Miyayama (Nagoya Univ.)

Introduction

■ Atmosphere on terrestrial planets



Earth
~6,400 km

≫

Atmosphere (Troposphere)
~100 km **~10 km**

Atmosphere is very thin! But…

Crucial roles on the surface environment!

Greenhouse effect, Thermal transport etc.

☐ Effects of meteorites atmospheric entry

- Local & global climate change
- Thermal & chemical evolution ➡ important for **young planets**

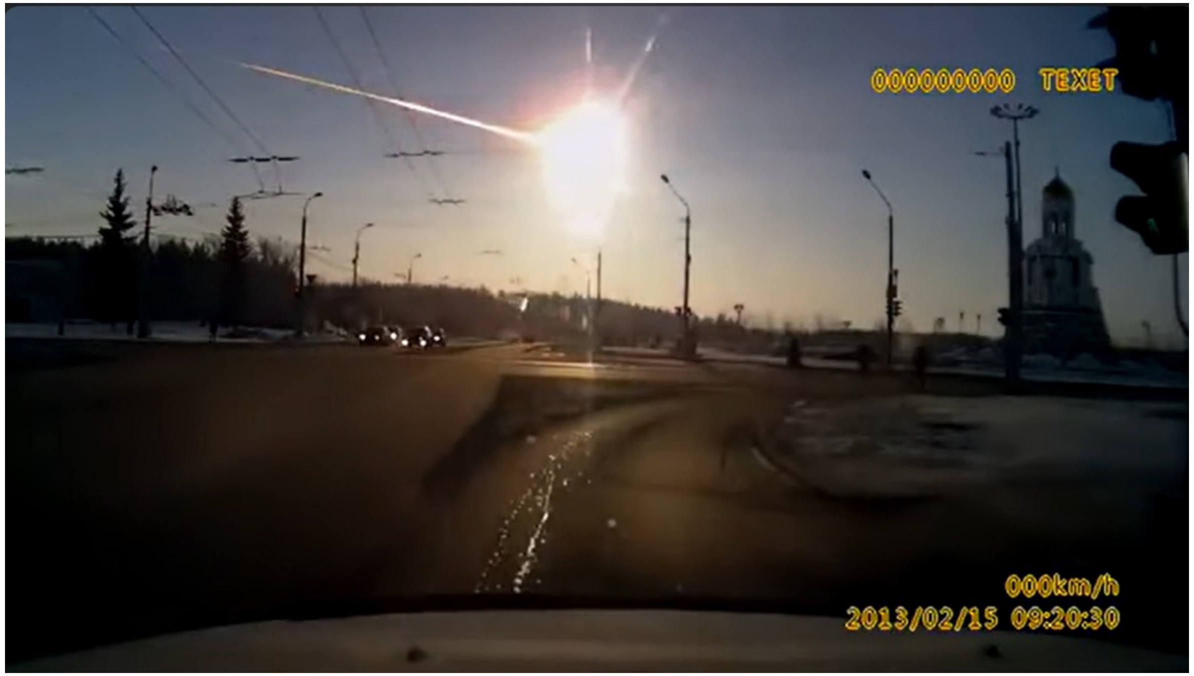
No model has been established for **impacts on atmosphere**

Modeling **thermal conditions and airflow changes**
associated with meteorite atmospheric entry

Atmospheric Entry Events on the Earth

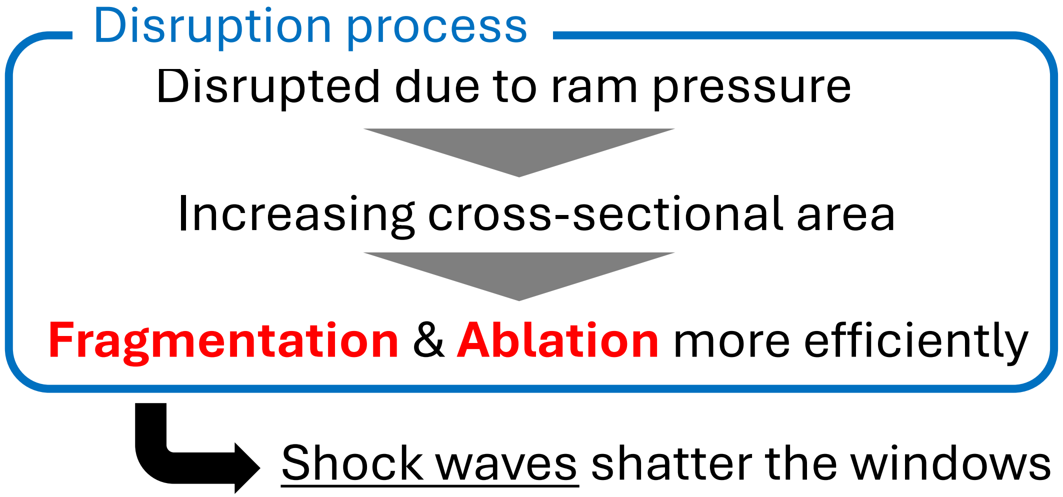
- 1908 Tunguska event ➡ Footprints on the surface (fallen trees, forest fire)
- **2013 Chelyabinsk event** ➡ Damage to buildings (glass shattering)

There are many video recordings & analysis



Ref. :https://www.youtube.com/watch?v=EhNL-YJFxOM

Meteorite was **disrupted in the sky** and **emitting enormous energy**



Disruption process

Disrupted due to ram pressure

Increasing cross-sectional area

Fragmentation & **Ablation** more efficiently

Shock waves shatter the windows

Significant impacts on thermal conditions and airflow

Setup (Background Atmosphere)

- Equations

open code :Athena++(Stone et al. 2020)
resource :XD2000 (512×512×128 mesh)

EoC

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

EoM

$$\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \nabla)\boldsymbol{v} = \boldsymbol{g} - \frac{\nabla p}{\rho}$$

energy eq.

$$\frac{\partial E}{\partial t} + \nabla \cdot \big(\boldsymbol{v}(E + p)\big) = \rho \boldsymbol{v} \cdot \boldsymbol{g}$$

EoS

$$p = (\gamma - 1)e \qquad \gamma = 1.4$$

ρ: Density
v: Velocity
p: Pressure
g: Gravity acceleration
E: Total energy
e: Internal energy

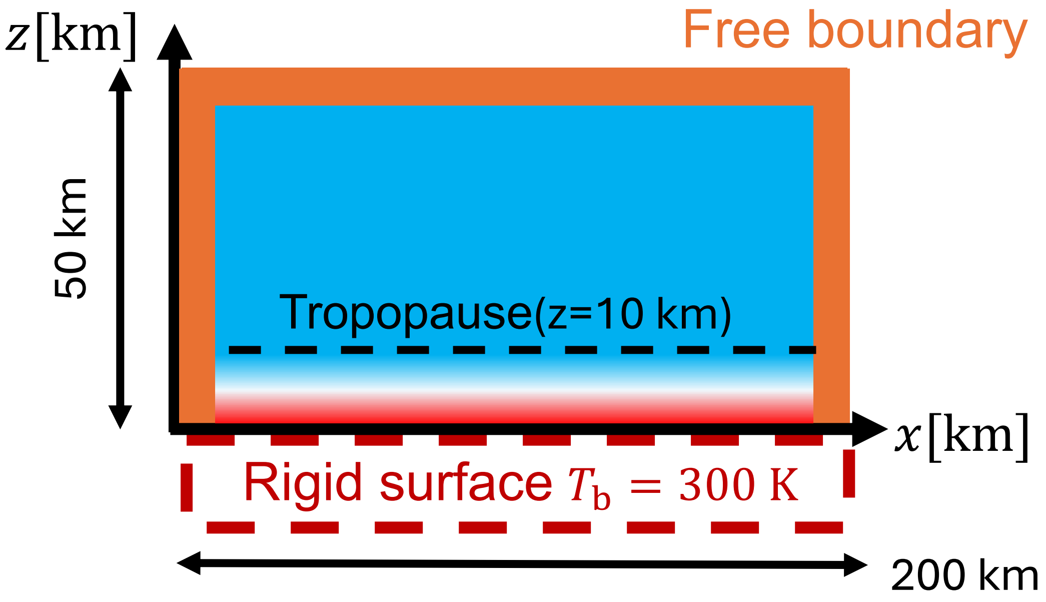
$$E = e + \frac{1}{2}\rho \boldsymbol{v}^2$$

- Initial conditions

Hydrostatic equilibrium $\frac{\partial p}{\partial z} = -\rho g$

Temperature profile

$T = 200\ \mathrm{K}\ (z > 10\ \mathrm{km})$
$T = T_b - \Gamma z\ (z < 10\ \mathrm{km}, \Gamma = 10\ \mathrm{K/km})$



Simulating the Earth-like atmosphere

Modeling the Effects of Atmospheric Entry

What happens during atmospheric entry?

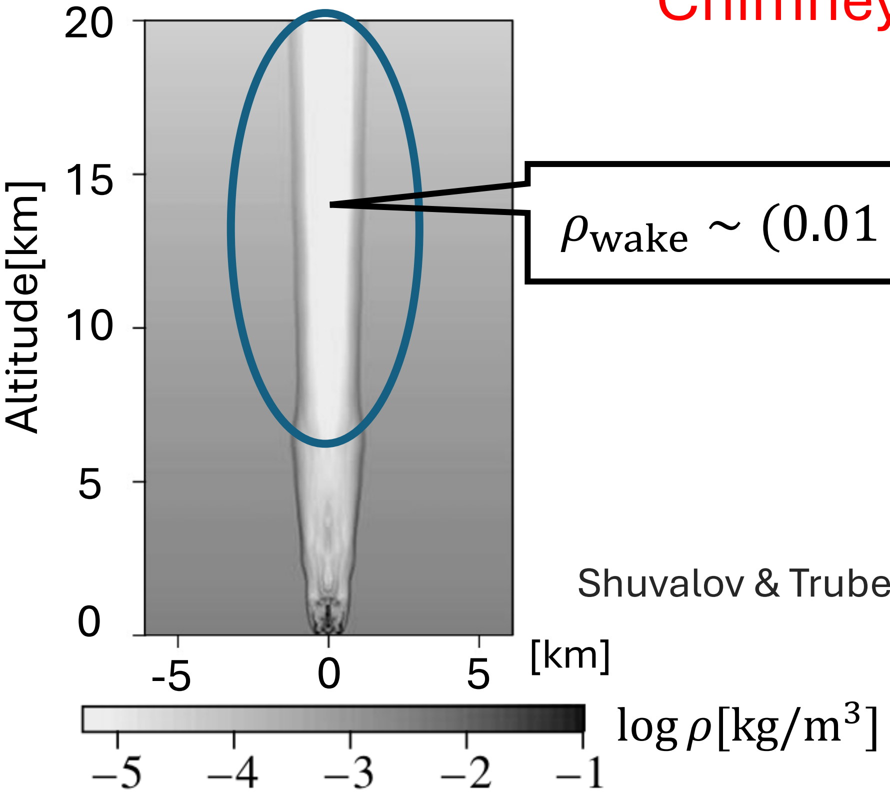
Rarefaction Region

Meteorite speed => 20 km/s

➡ Bow shock generate rarefied region behind

Ambient atmosphere flows through the rarefied region

Chimney Effect!



$$\rho_{\mathrm{wake}} \sim (0.01-0.1)\,\rho_{\mathrm{amb}}$$

Shuvalov & Trubetskaya(2007)

Rarefied Region

Generated by

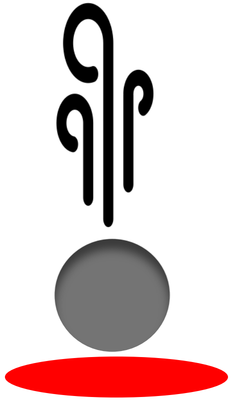
shock heating & adiabatic expansion

☐ Shock Heating

Consider 1D vertical shock

(Using Rankine-Hugoniot eq.)

$$\rho' = \frac{\gamma+1}{\gamma-1} v_{\mathrm{imp}}\,, \qquad p' = \frac{2}{\gamma+1}\rho_{\mathrm{amb}} v_{\mathrm{imp}}^2$$



☐ Adiabatic Expansion

Assume that compressed gas expand adiabatically until it reached to the ambient pressure

(Using poisson's law)

$$\rho_{\mathrm{wake}} = \left(\frac{2\rho_{\mathrm{amb}} v_{\mathrm{imp}}^2}{p_{\mathrm{amb}}(\gamma+1)}\right)^{-1/\gamma} \frac{\gamma+1}{\gamma-1}\rho_{\mathrm{amb}} \equiv \alpha\rho_{\mathrm{amb}}$$

Density ratio

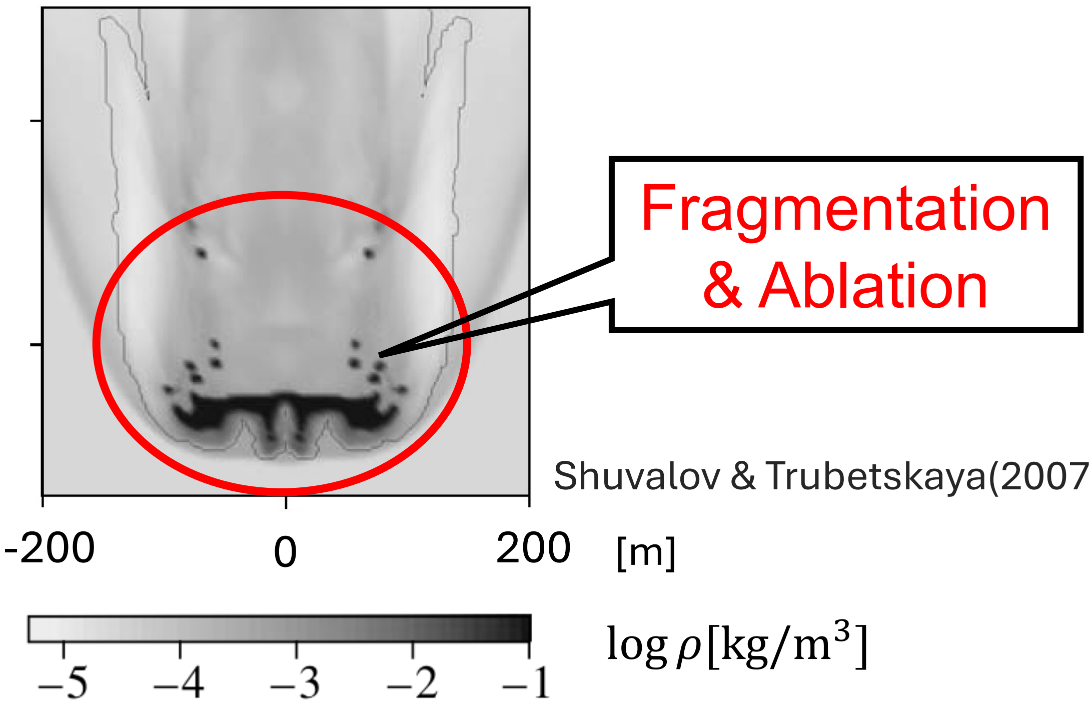
$\alpha \sim 0.01$

Energy Release Region

If the meteorite is small…(<100 m)

Disrupted in the atmosphere
and does not form huge craters

(Only small fragments reach the surface)



Shuvalov & Trubetskaya(2007)

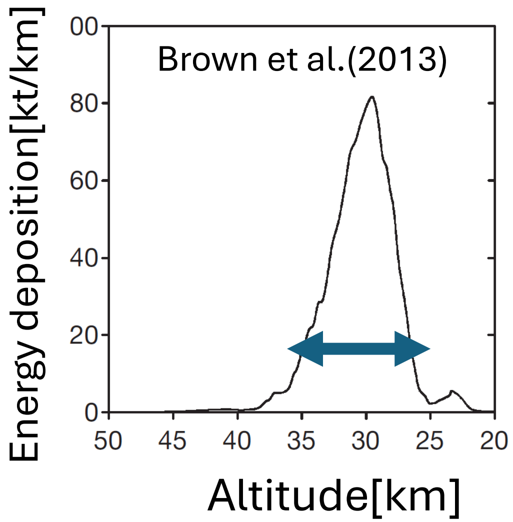
Energy Release Region

Interacting with atmosphere

- **Fragmentation** by strong ram pressure
- **Ablation** by shock heating

Release **enormous energy** into the atmosphere

☐ Chelyabinsk event



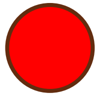
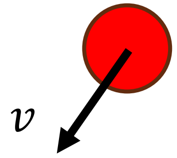
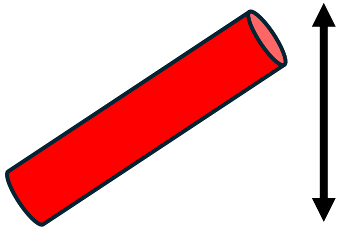
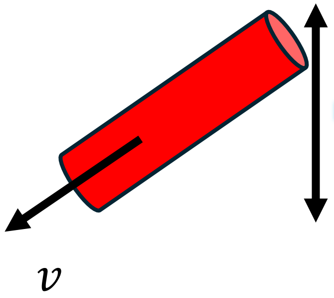
Most of the energy is released at an altitude of 35-25 km

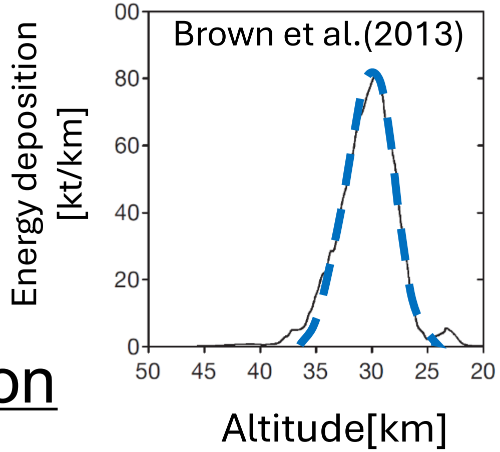
We need to consider <u>the shape of this region</u>

cylinder?

Geometry & Partition

Classify the **geometry** and **partition** of energy release region into 4 categories

	Static	Moving
Point	$E_{\mathrm{tot}} = E_{\mathrm{int}}$  Initial kinetic energy **All** converted to **thermal energy**	$E_{\mathrm{k}} : E_{\mathrm{int}} = 1:2$  Initial kinetic energy $\frac{1}{3}$ kinetic energy , $\frac{2}{3}$ **thermal energy** Collins et al. (2017)
Cylindrical	 $E_{\mathrm{tot}} = E_{\mathrm{int}}$	 $E_{\mathrm{k}} : E_{\mathrm{int}} = 1:2$



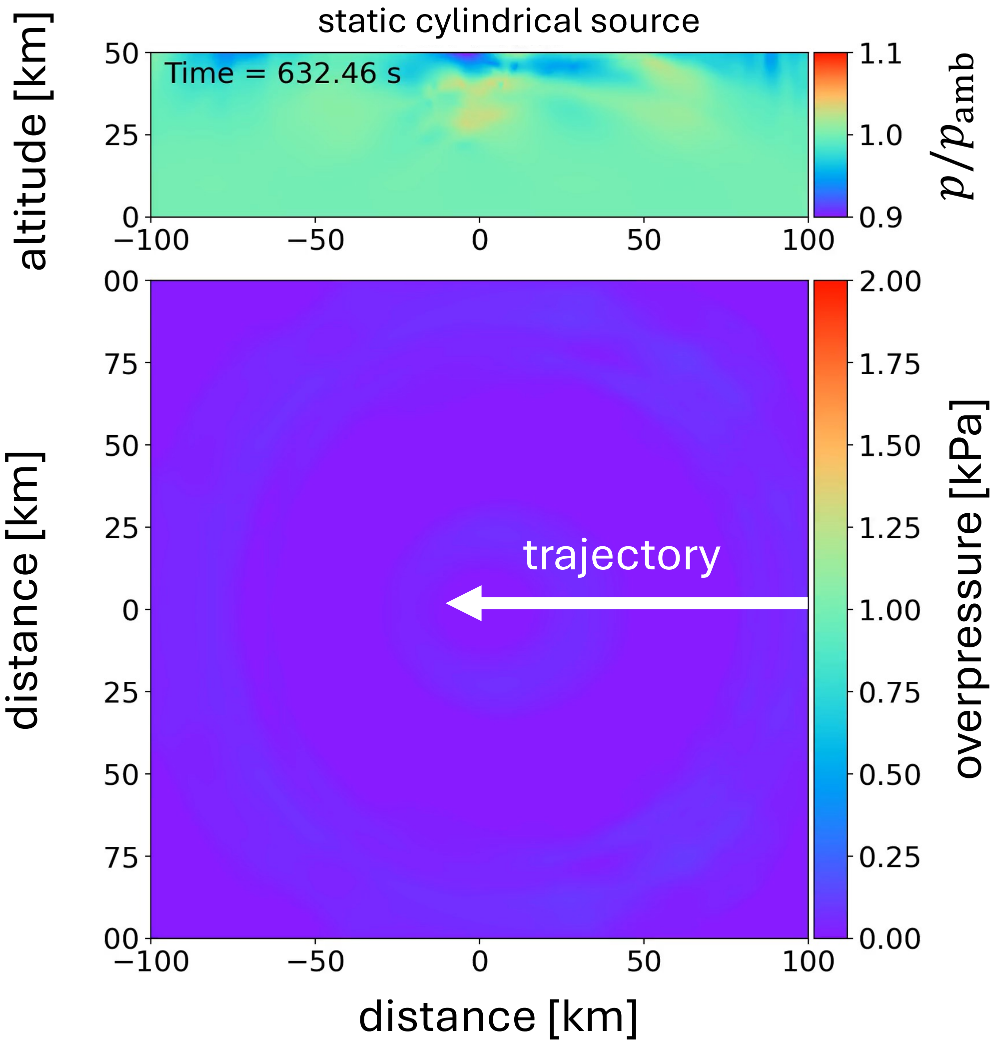
Inject internal(& kinetic) energy using a Gaussian distribution

Results

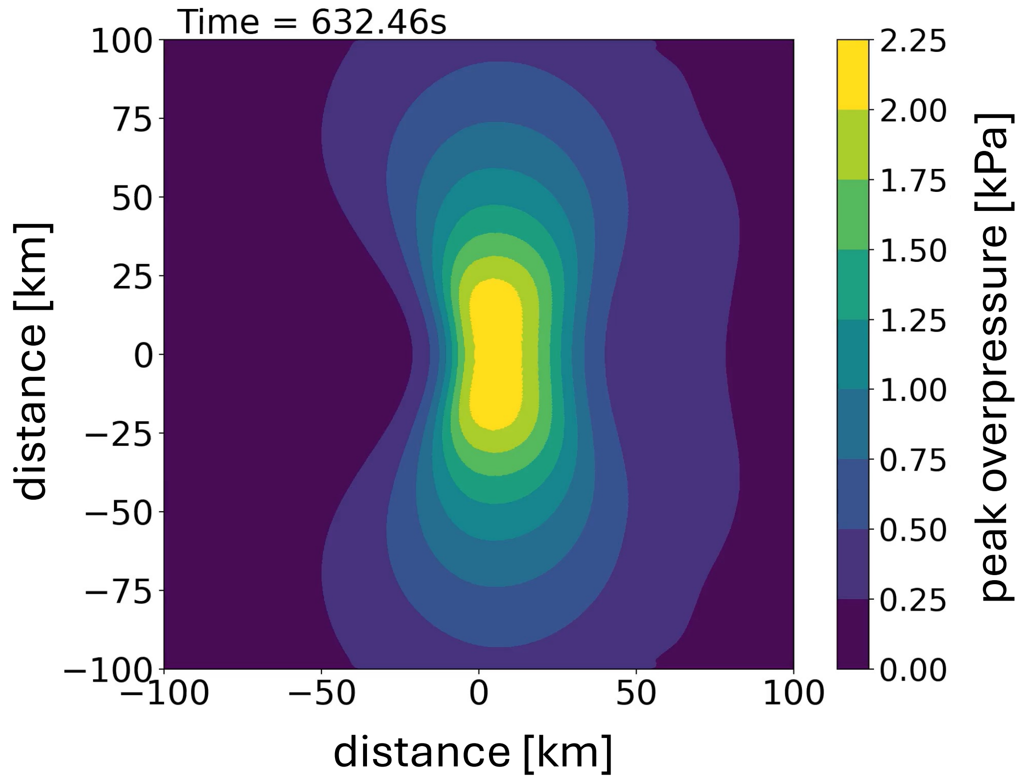
Overpressure on the Surface

Chelyabinsk meteorite data
$D = 20$ m, $v_{\mathrm{imp}} = 19$ km/s, $\theta = 18°$
$\rho = 3.3$ g/cc, break up height : 30 km

- Pressure distribution (top: side view, bottom: ground)



- Peak overpressure distribution



Damaged area spreads **elliptically**

↳ Different from point explosion

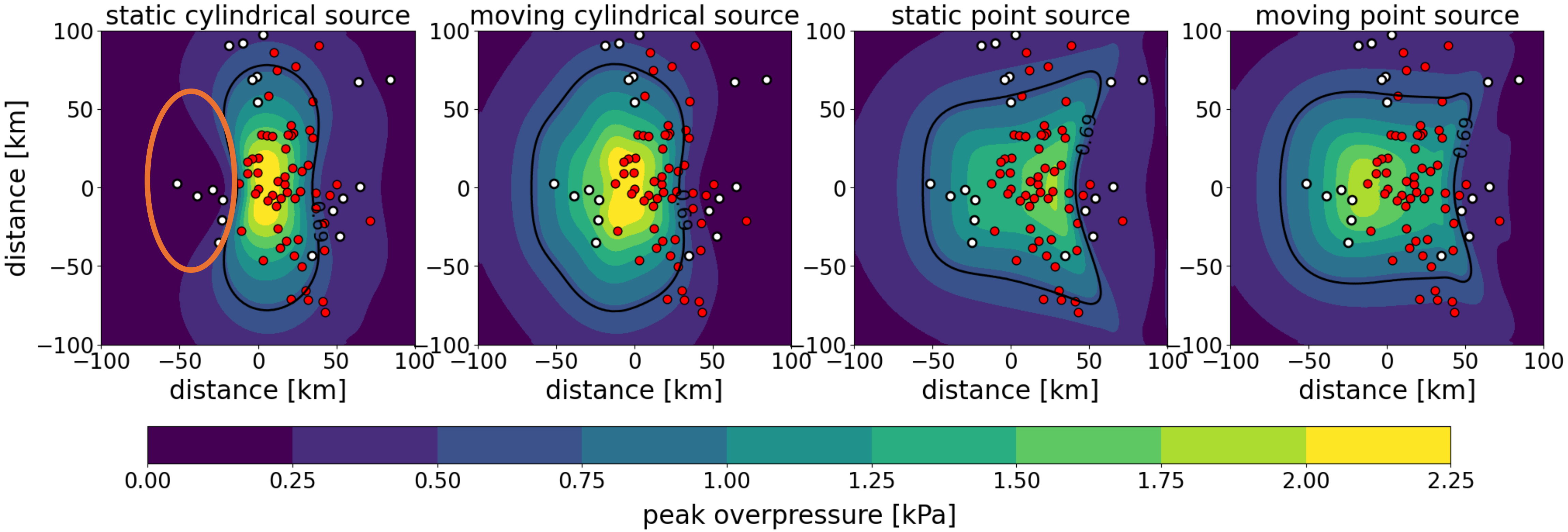
Next... Compare with the actual damage distribution

Comparison of Peak Overpressure

- Compared with actual damaged area

Contour: 0.69 kPa → 5% windows shattering (Emel’yaneko et al. 2013)

● Damaged
○ No damaged
(Popova al. 2013)



No damage reported in the area ahead of the trajectory → Effect of cylindrical shape

Static cylindrical source model is the best match with the actual damaged area

Discussion

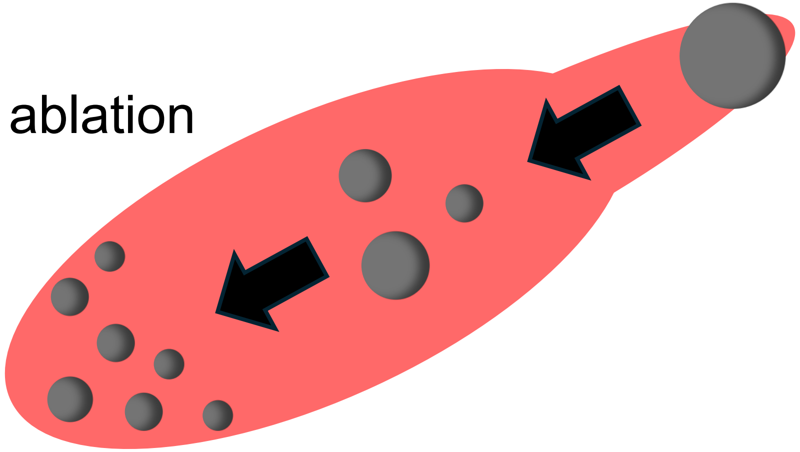
■ Disruption process

- Meteorite was disrupted in a few seconds by fragmentation & ablation

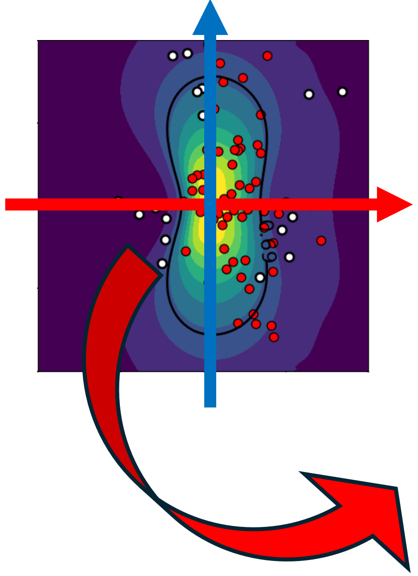
  In Chelyabinsk event ~1.7 s

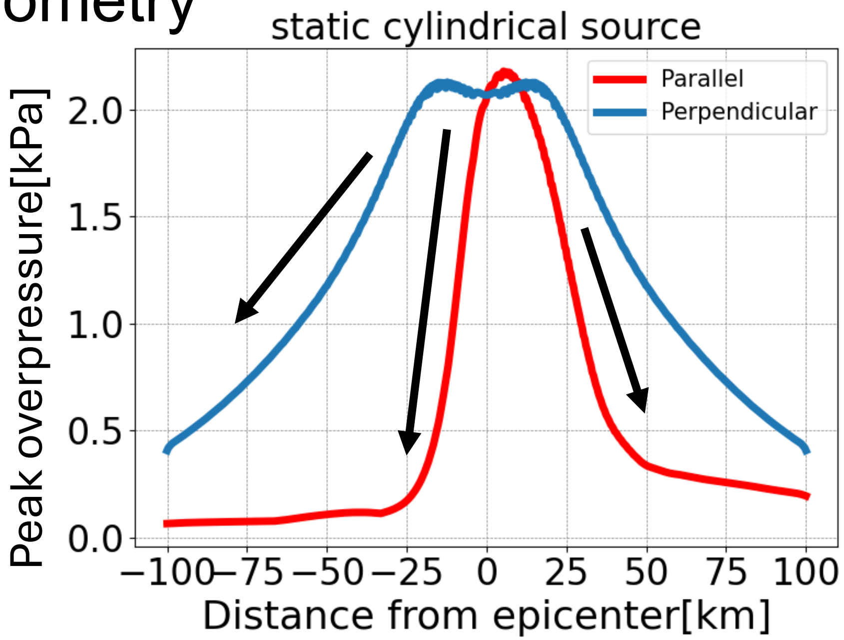
- Initial kinetic energy mostly converted to thermal energy

  The effect of dragging ambient atmosphere is small

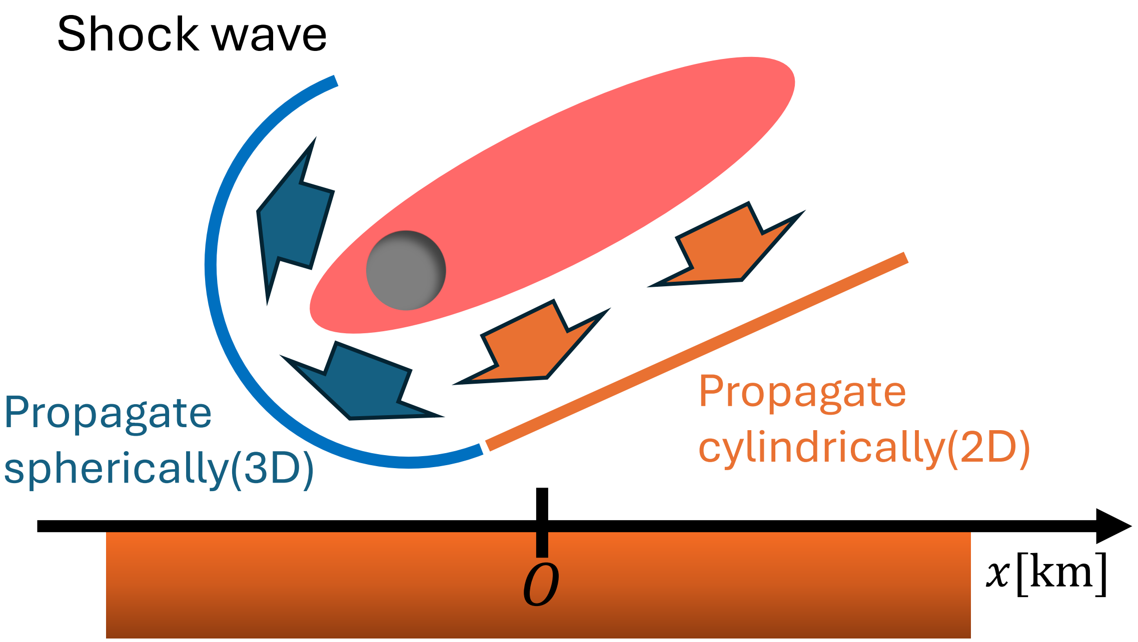


■ Effects of geometry





Slower decay perpendicular to the trajectory

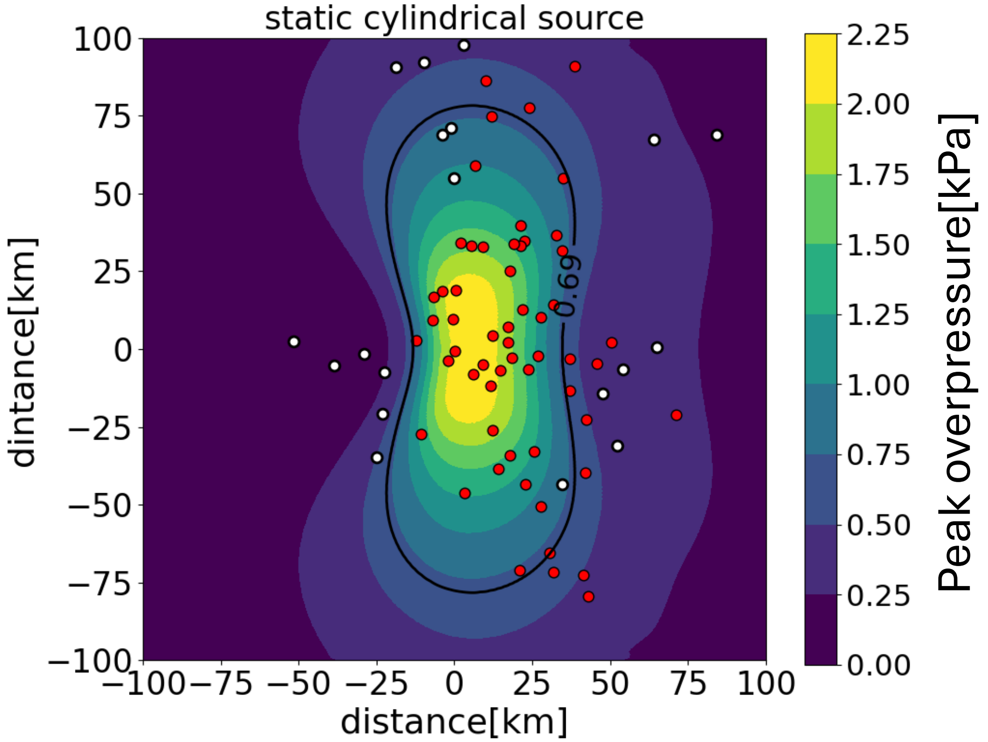


Summary & Future Works

Summary

- ✓ Developing a theoretical model to investigate the effects of **meteorite atmospheric entry**
- ✓ We performed calculations incorporating models of meteorite energy release regions and rarefied regions into atmosphere simulating the temperature structure of a planet
- ✓ By comparing the damage distribution of the Chelyabinsk meteorite, we constraints the geometry of the energy release region and the energy partition.

Static cylindrical source model is the best match!



Future Works

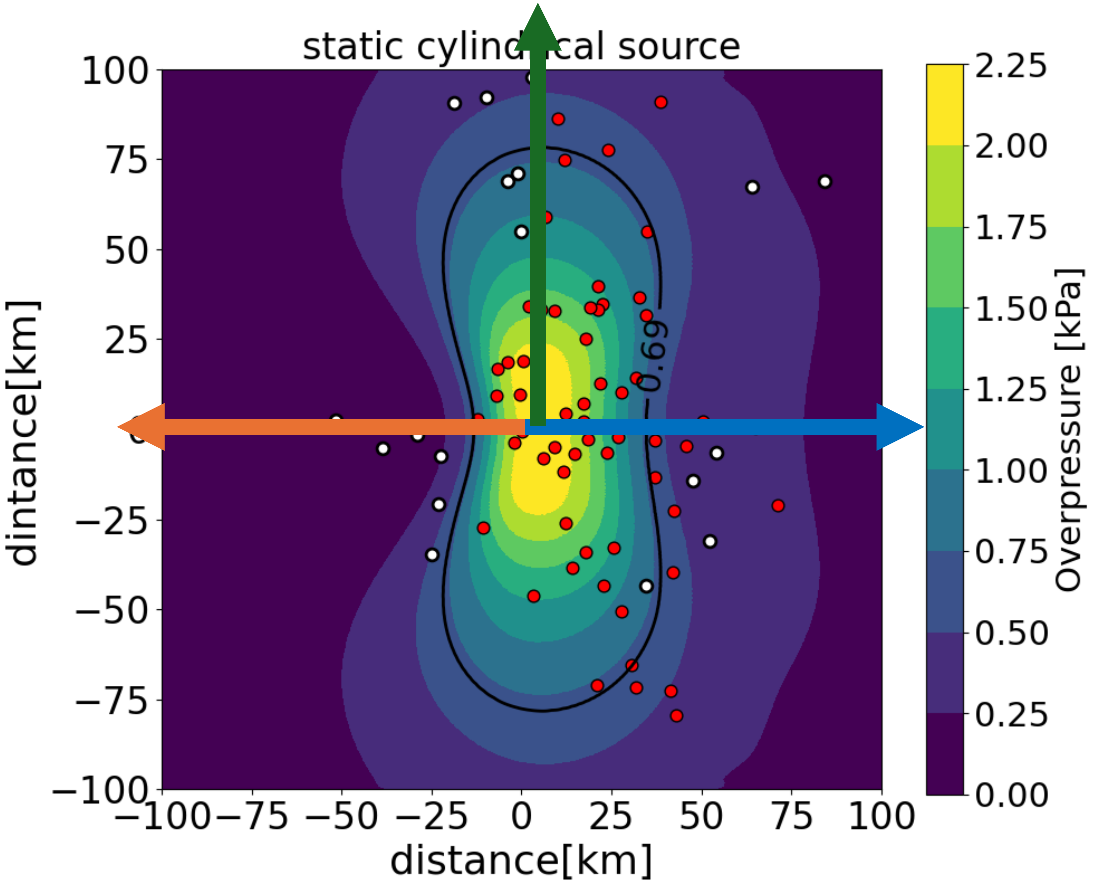
- ➢ Investigating the **chimney effect** in rarefied regions

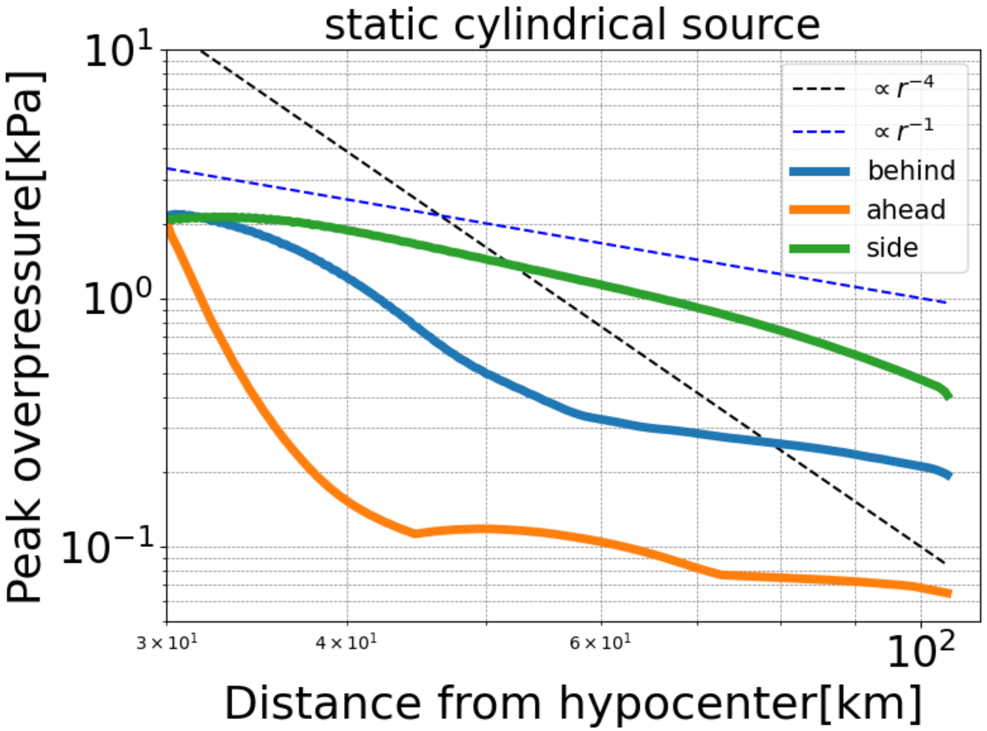
How do the chemical species generated by entries spread?

Interact with thermal convection?

Appendix

Shock Wave Decay



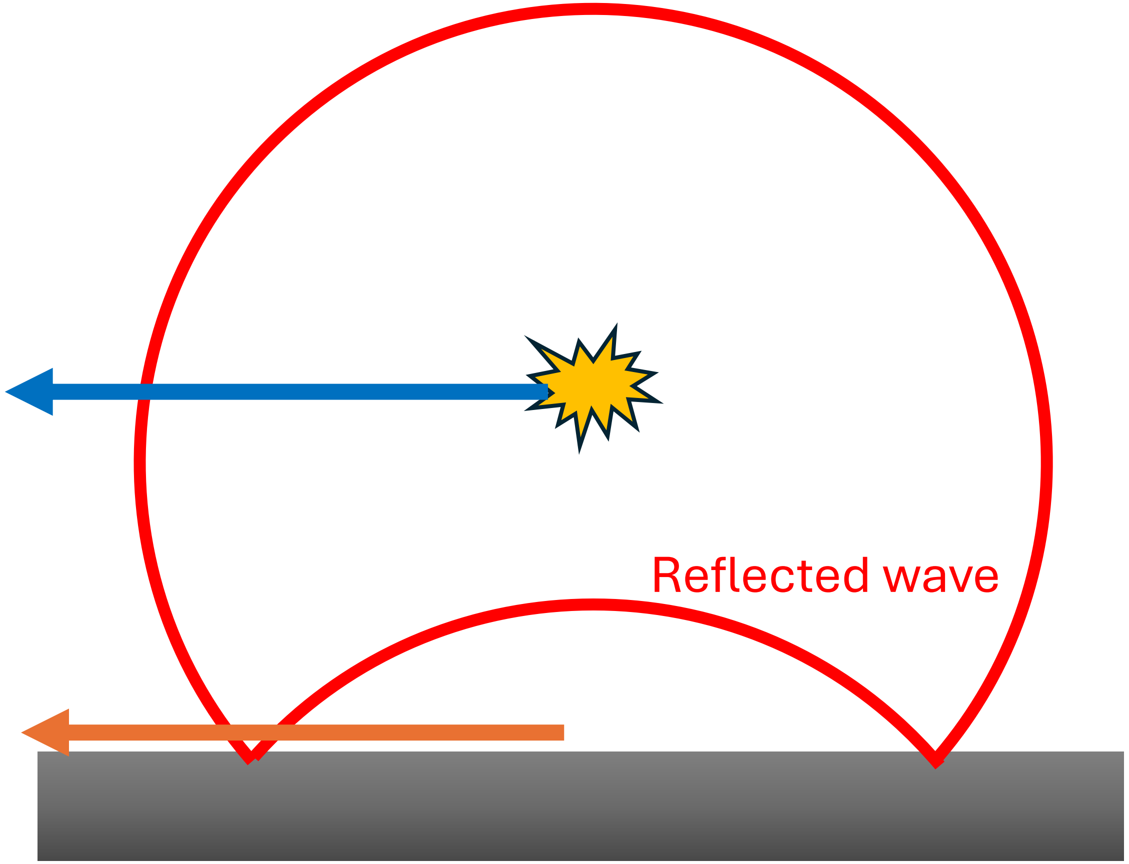


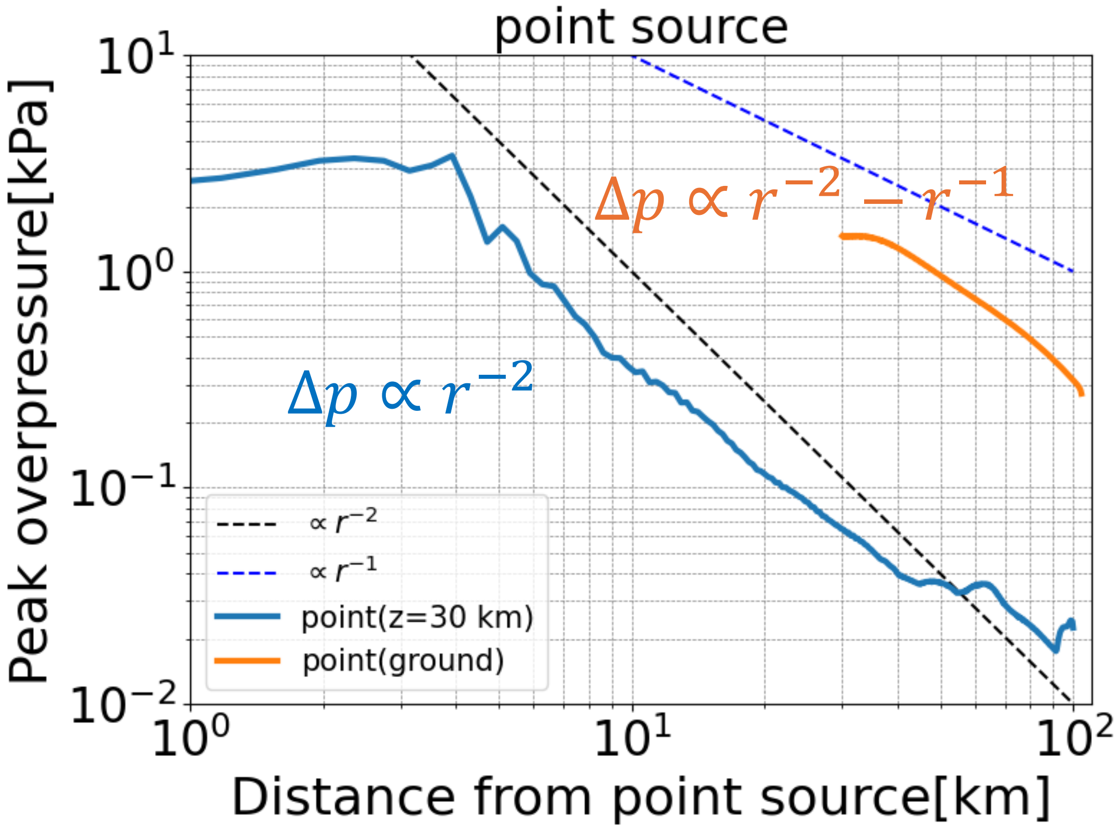
The direction perpendicular to the trajectory

Shock waves decays $\propto r^{-1}$

Effect of Surface

- Point source explosion

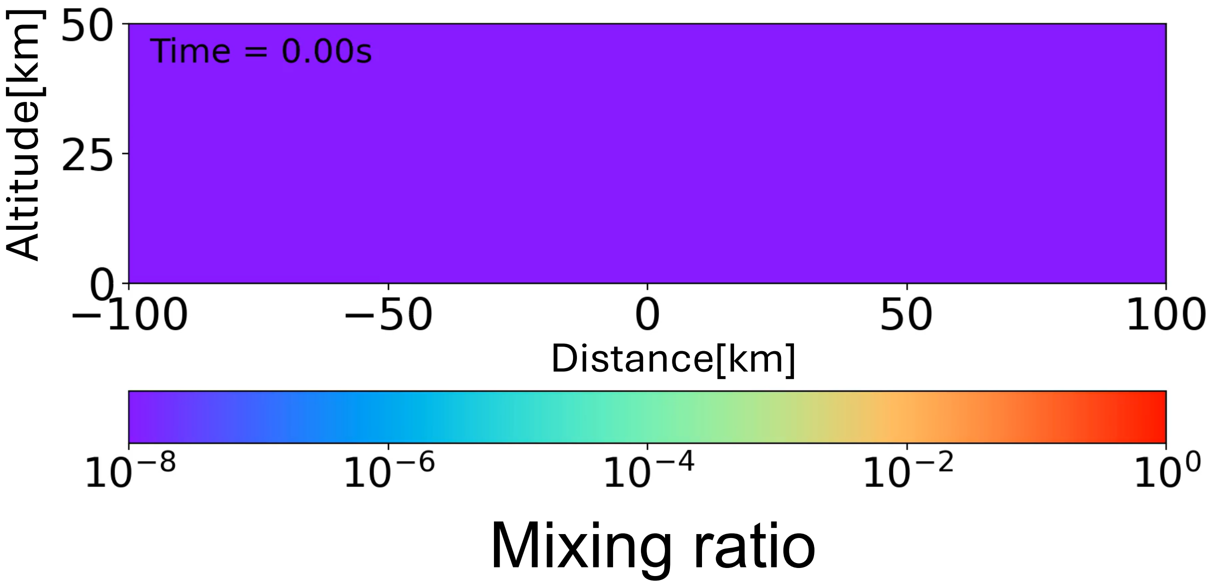


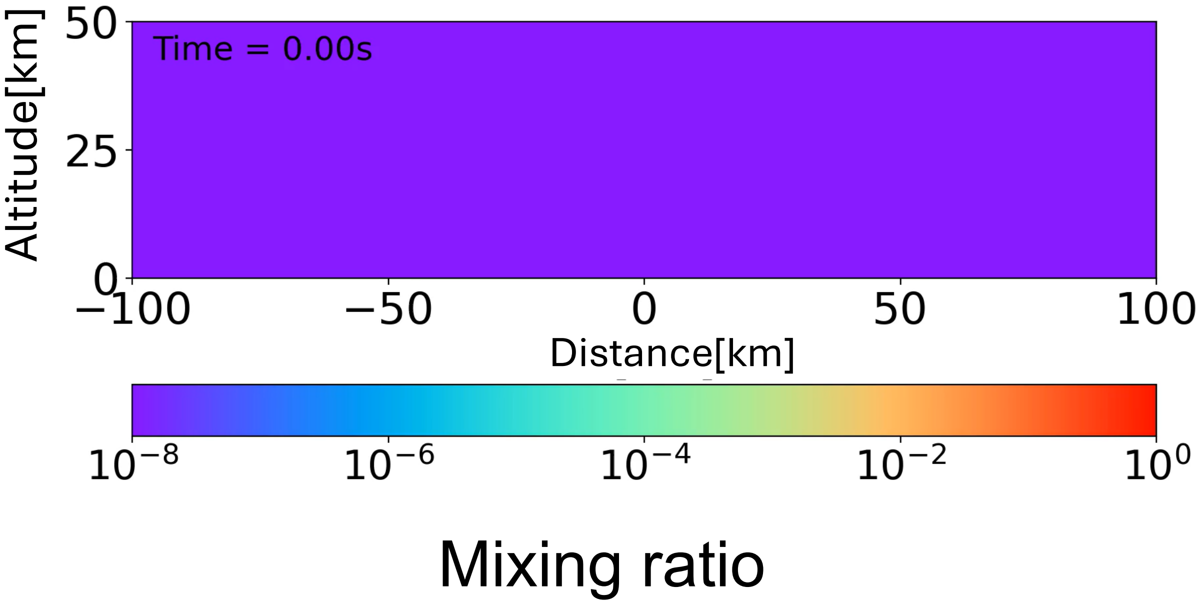


Reflected waves reinforce shock waves

Chimney Effect

Trace the gas in the energy release regions by using diffusion eq.


Include chimney


No chimney

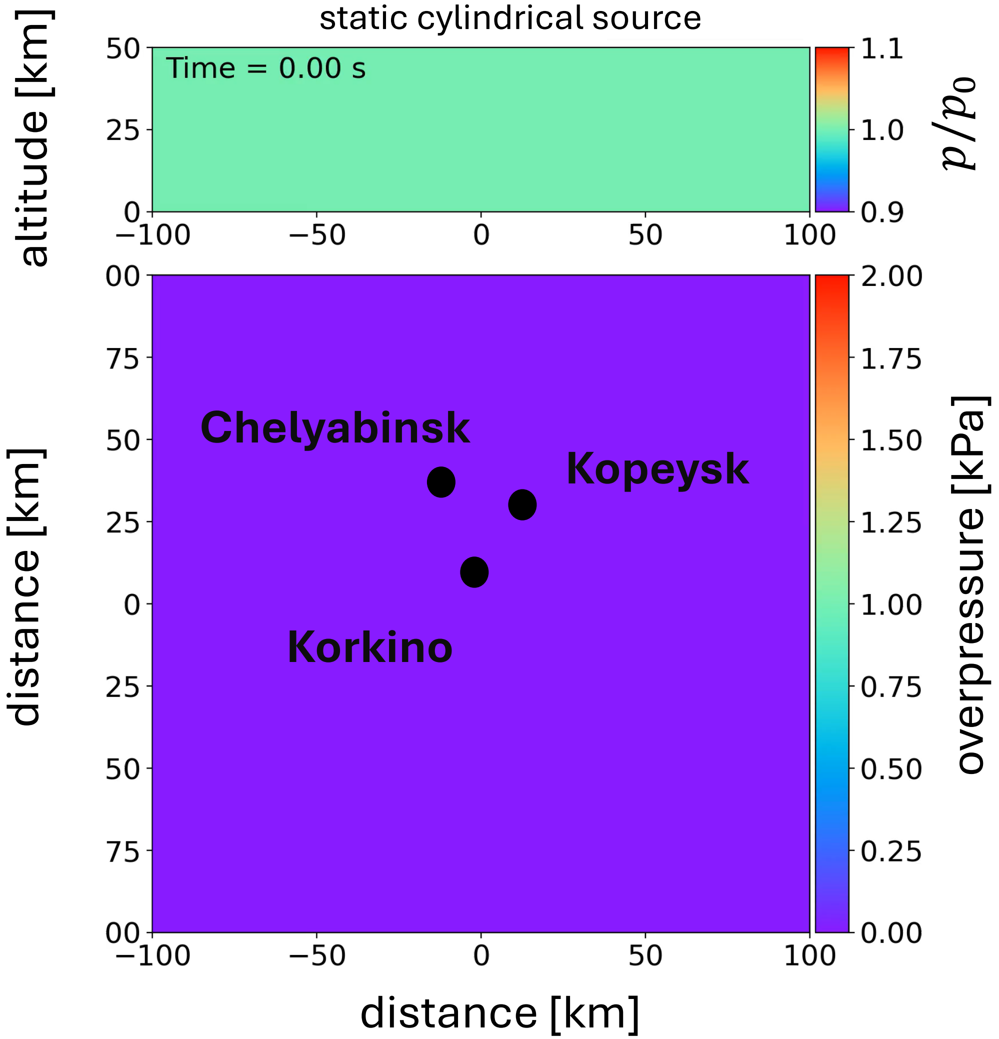
<u>The gas flows through the rarefied region</u>

(In vertical entries, this becomes even more noticeable)

→ affecting photochemical reactions

Arriving time of shock waves

- Pressure distribution



- Arriving time

Avramenko et al. (2014)

To Korkino (recorded)：**89 s**

Simulation：**~90 s**

To Kopeysk(recorded)：**127 s**

Simulation：**~130 s**

To Chelyabinsk(recorded)：**141 s**

Simulation：**~145 s**

Arriving time of shock waves
closely matches the observations!