How do more realistic nanoflare distributions affect thermal nonequilibrium in model loops?

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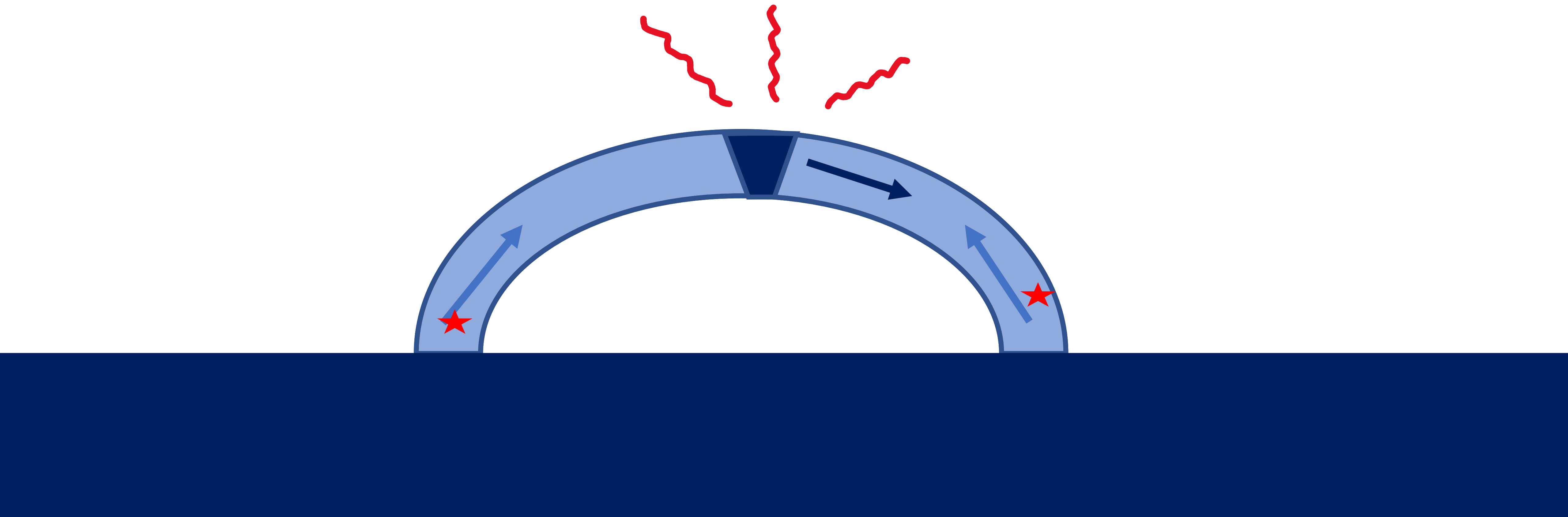
Outline

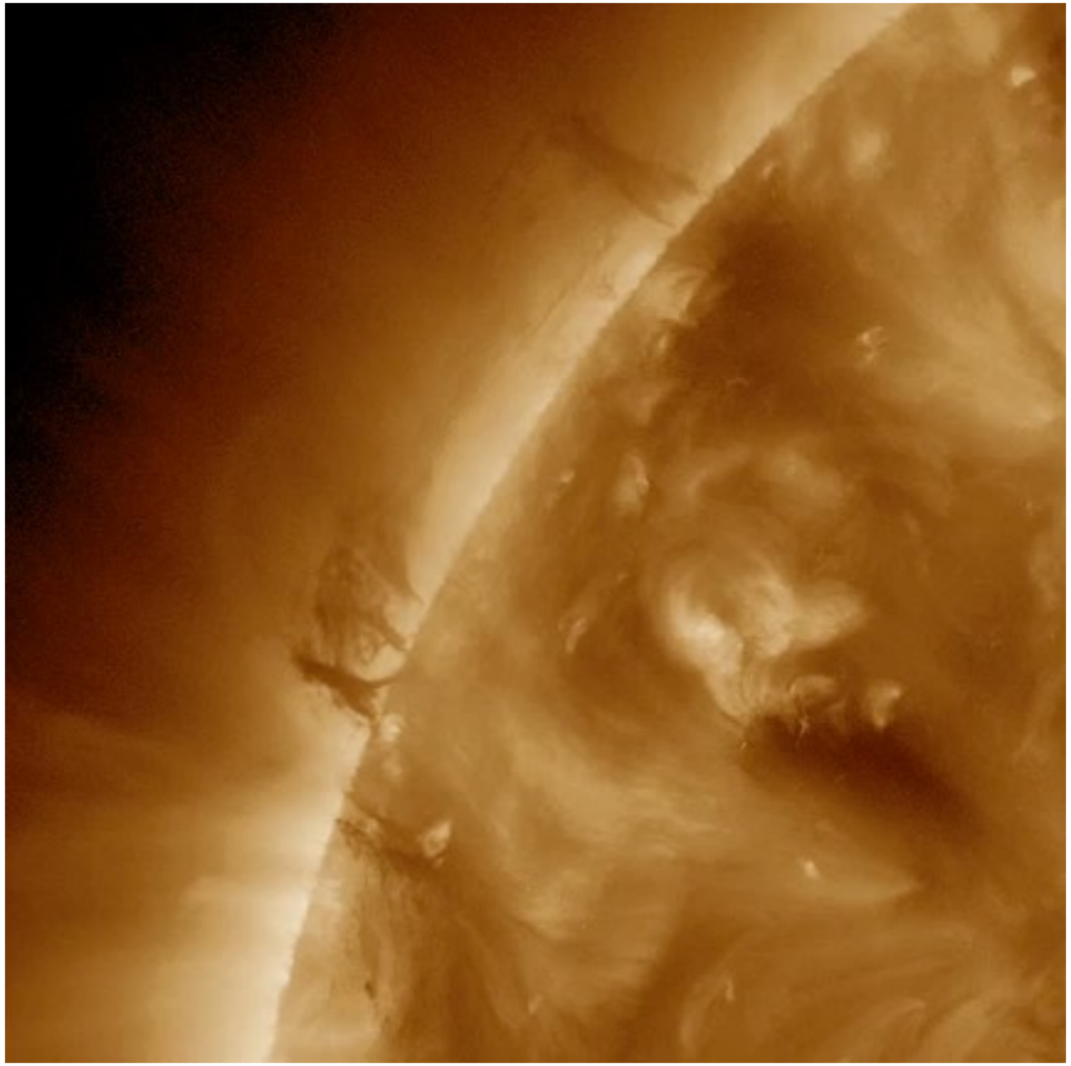
- Intro to Thermal NonEquilibrium (TNE)
- 1D modeling of TNE using discrete nanoflares
- What we already know about TNE in model loops
- Variations in nanoflare timing and intensity
- Variations in nanoflare location
- Summary of results and future plans

Thermal NonEquilibrium

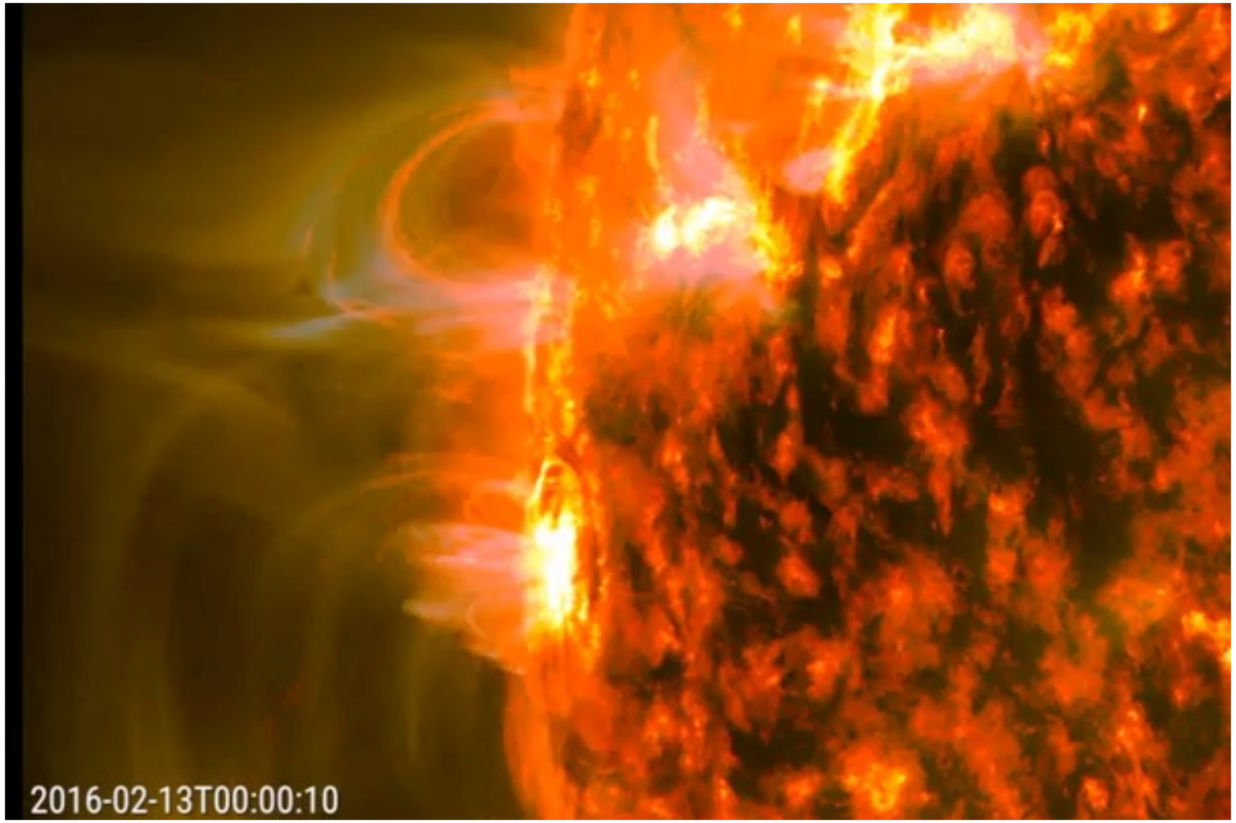
TNE is a process under which heated plasma from the chromosphere enters a coronal loop and if it becomes sufficiently dense undergoes catastrophic radiative cooling to chromospheric temperatures, forming a condensation.



TNE is important in prominences and some coronal loops.



SDO/AIA



SDO/AIA, Mason et al 2019

Goals:

- Understand conditions leading to TNE in coronal loops
  - Determine how these are affected by using various distributions of intensity, timing and location, especially more realistic scenarios with randomly distributed nanoflares.
- Understand how TNE effects diagnostics of coronal loops and thus our understanding of coronal heating
- Determine how common TNE is in coronal loops.
- Ultimately feeds into ability to model EUV irradiance of corona

ARGOS

- Antiochos et al. 1999
- Adaptive Mesh calculation
- 1-D hydro equations for mass, momentum, and energy

$$\frac{\partial \rho}{\partial t} + \frac{1}{A}\frac{\partial}{\partial s}(Av\rho) = 0,$$

$$\frac{\partial(v\rho)}{\partial t} + \frac{1}{A}\frac{\partial(Av^2\rho)}{\partial s} + \frac{\partial p}{\partial s} = \rho g_{\|},$$

$$\frac{\partial E}{\partial t} + \frac{1}{A}\frac{\partial[A(E+p)v]}{\partial s} = \rho v g_{\|} + \frac{1}{A}\frac{\partial}{\partial s}\left(A\kappa_0 T^{5/2}\frac{\partial T}{\partial s}\right) - n^2\Lambda(T) + Q(s),$$

$$E = \frac{1}{2}\rho v^2 + \frac{p}{\gamma - 1}.$$

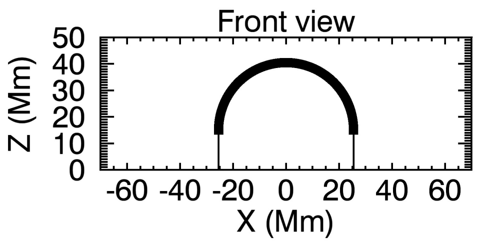
- Klimchuk & Cargill (2001) radiative loss function

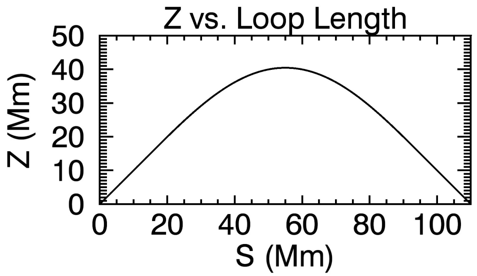
Loop Geometric Parameters

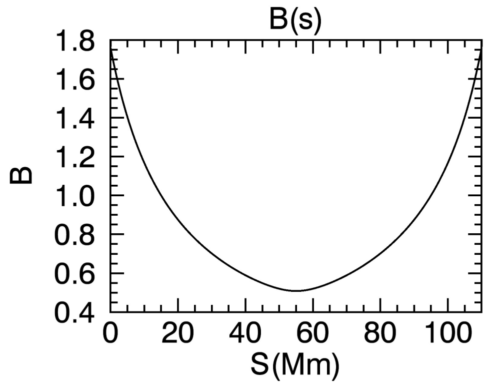
Full Length 110 Mm

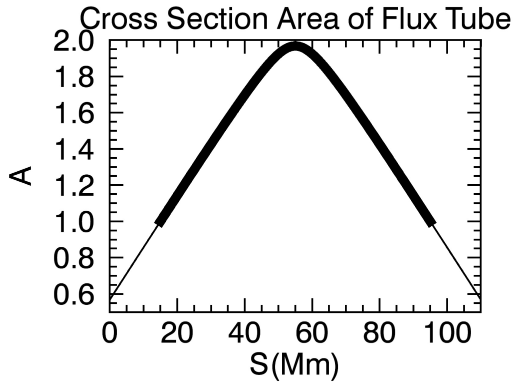
- 80 Mm initial coronal loop
- 15 Mm potential transition region at each end

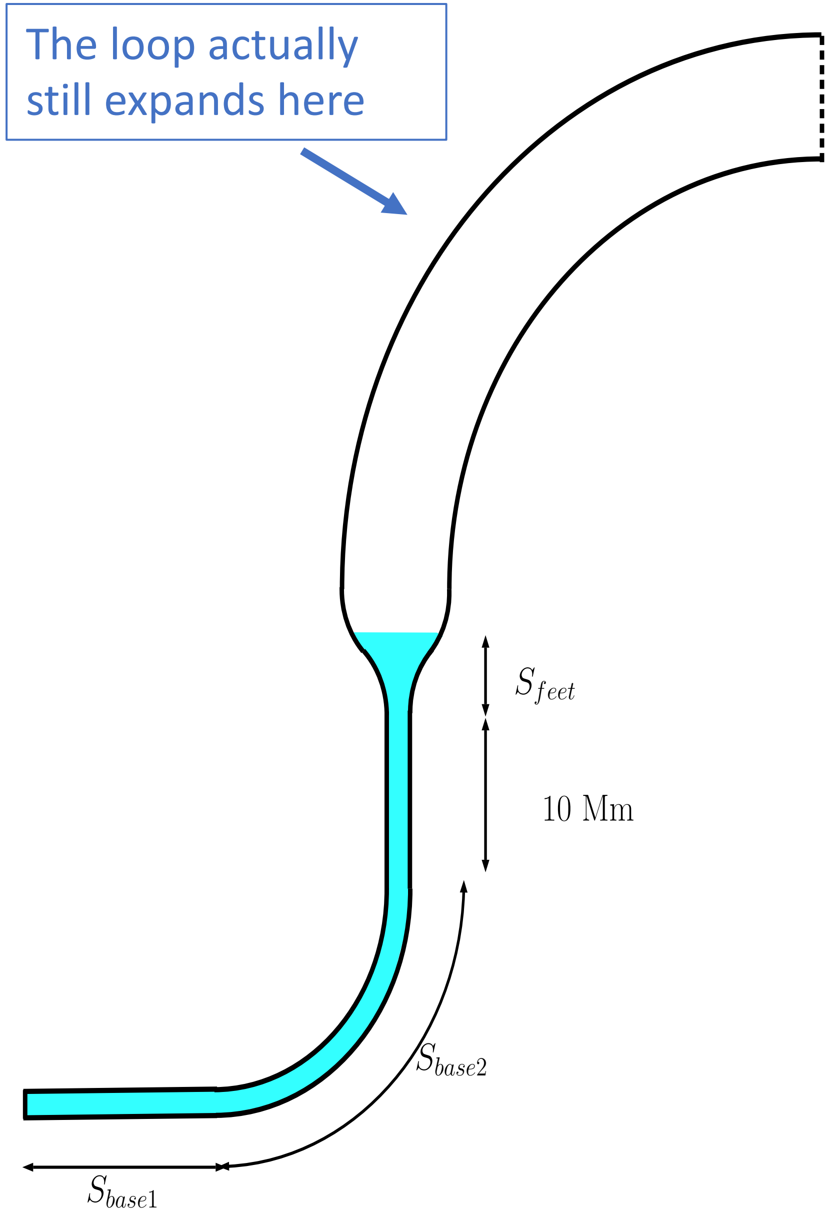
Hyperbolic cross section





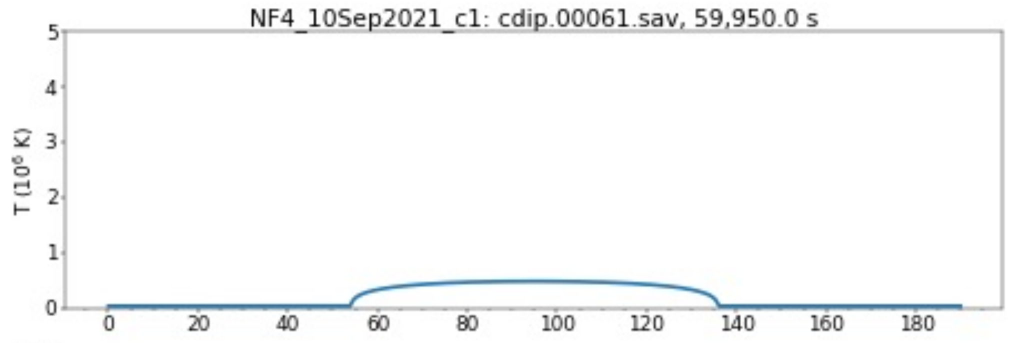






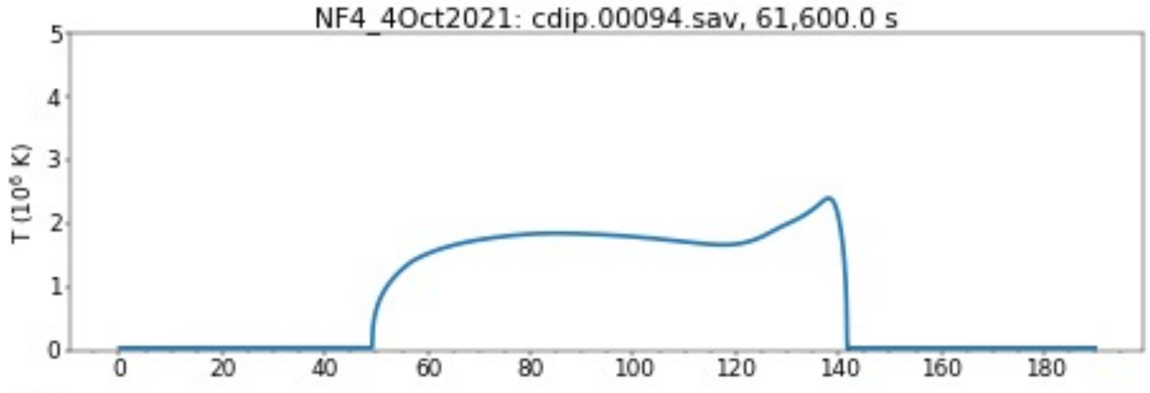
Initial equilibrium state

- Initial peak temperature 477,000 K.
- This amount of heating maintained through the runs.

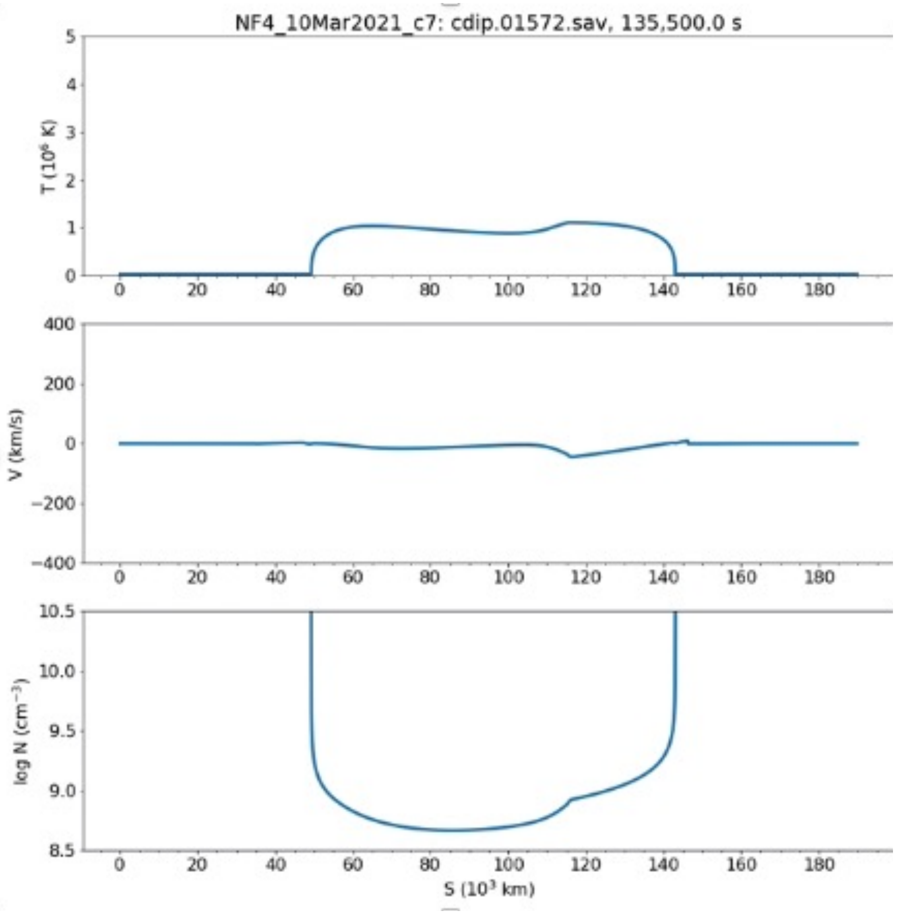


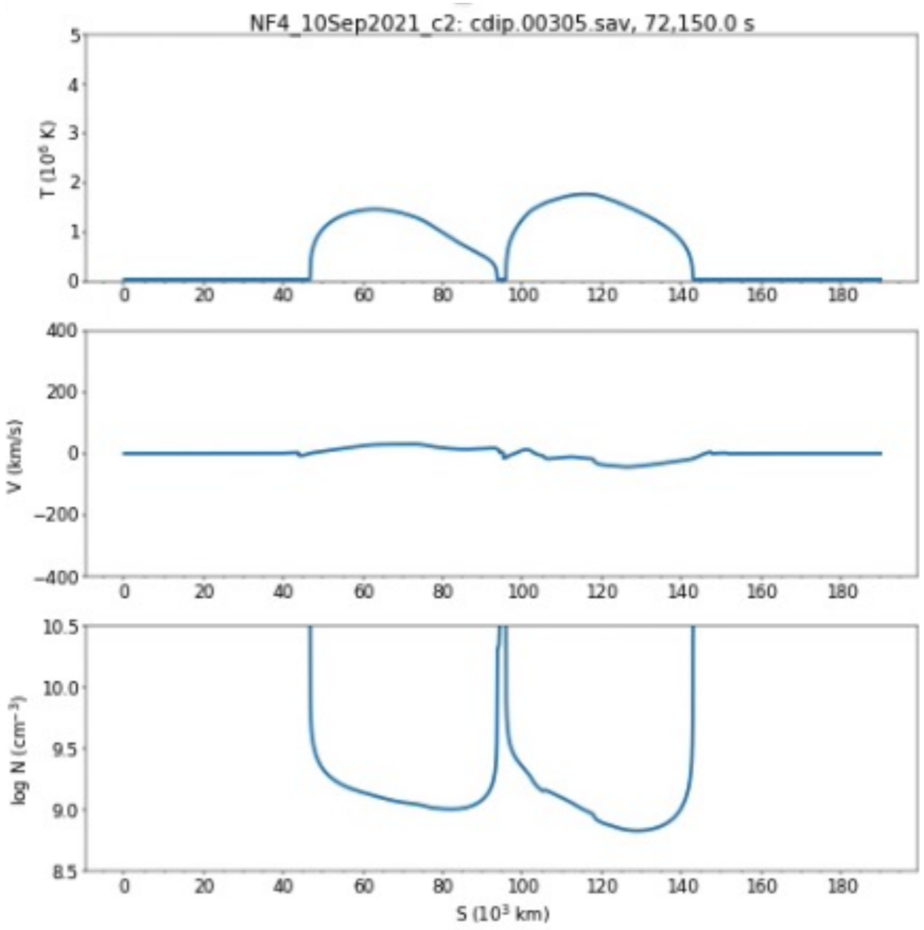
Nanoflares

- Timing, intensity, & locations adjustable
- Triangular in space and time (duration 100 s, size 5 Mm)



Under what conditions do you get TNE?



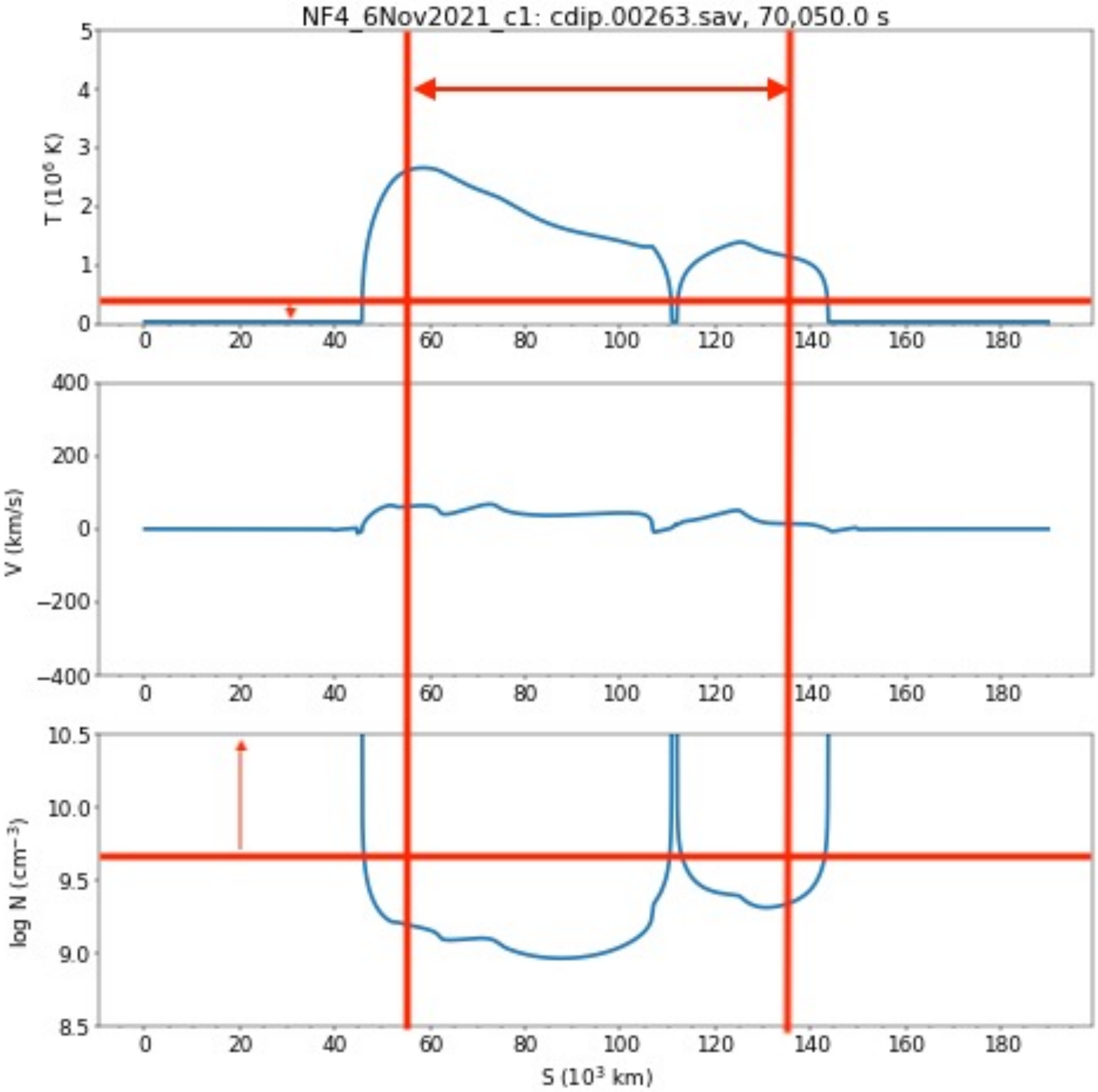


The following conditions *encourage* TNE:

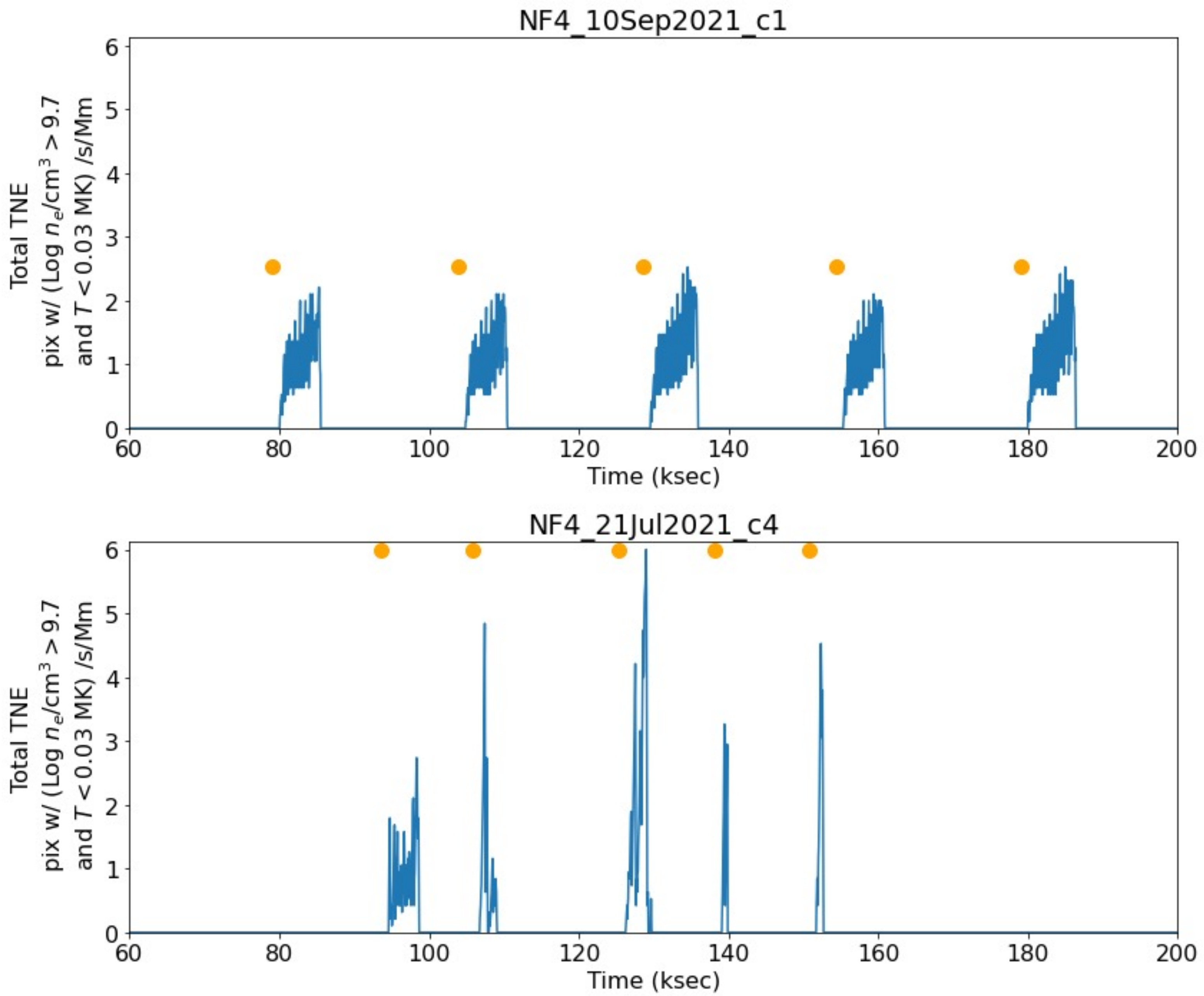
- **Timing:** Delay between nanoflares must be < time it takes for loop to return to initial state (includes both cooling and draining) ✓ *
- **Location:** Energy release must be as close to the foot points as possible without actually being in the chromosphere ✓
- **Symmetry** in nanoflare energy and loop cross section ✓
- **Loop Cross Section:** Large loop expansion encourages TNE

TNE Metrics

- TNE Rate - Number of pixels exhibiting TNE
- Presence/Absence of TNE
- Number of Condensations per Time Interval
- Average Duration of Condensations
- Average Maximum Size of Condensations



TNE characteristics vary strongly depending on nanoflares characteristics



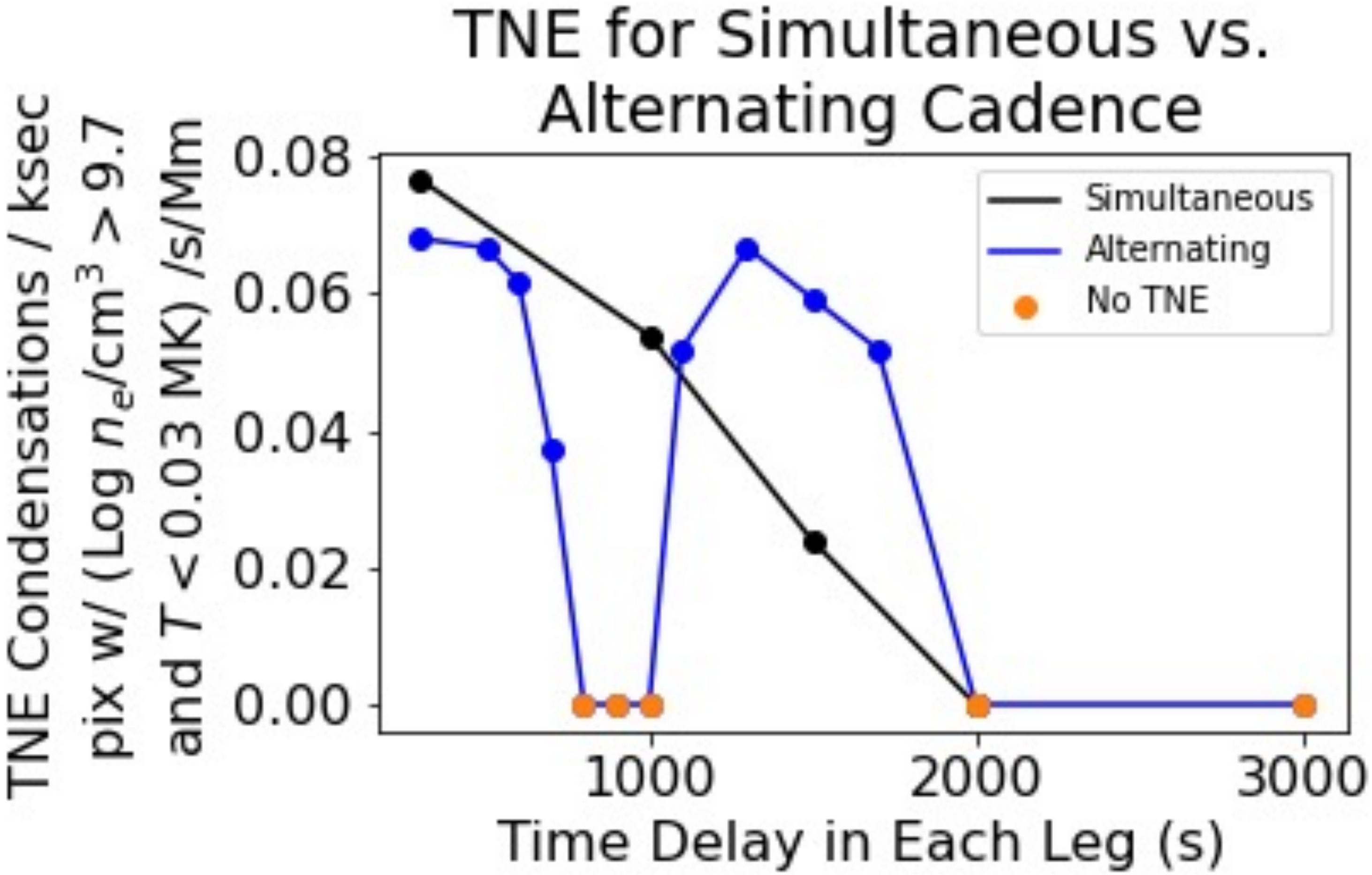
Variations in Delay Time

- Regularly repeating nanoflares
  - Simultaneously in each leg
  - Alternating in each leg
- Nanoflares random in intensity/time with power-law distribution
- 15 Mm from the footpoint

Questions:

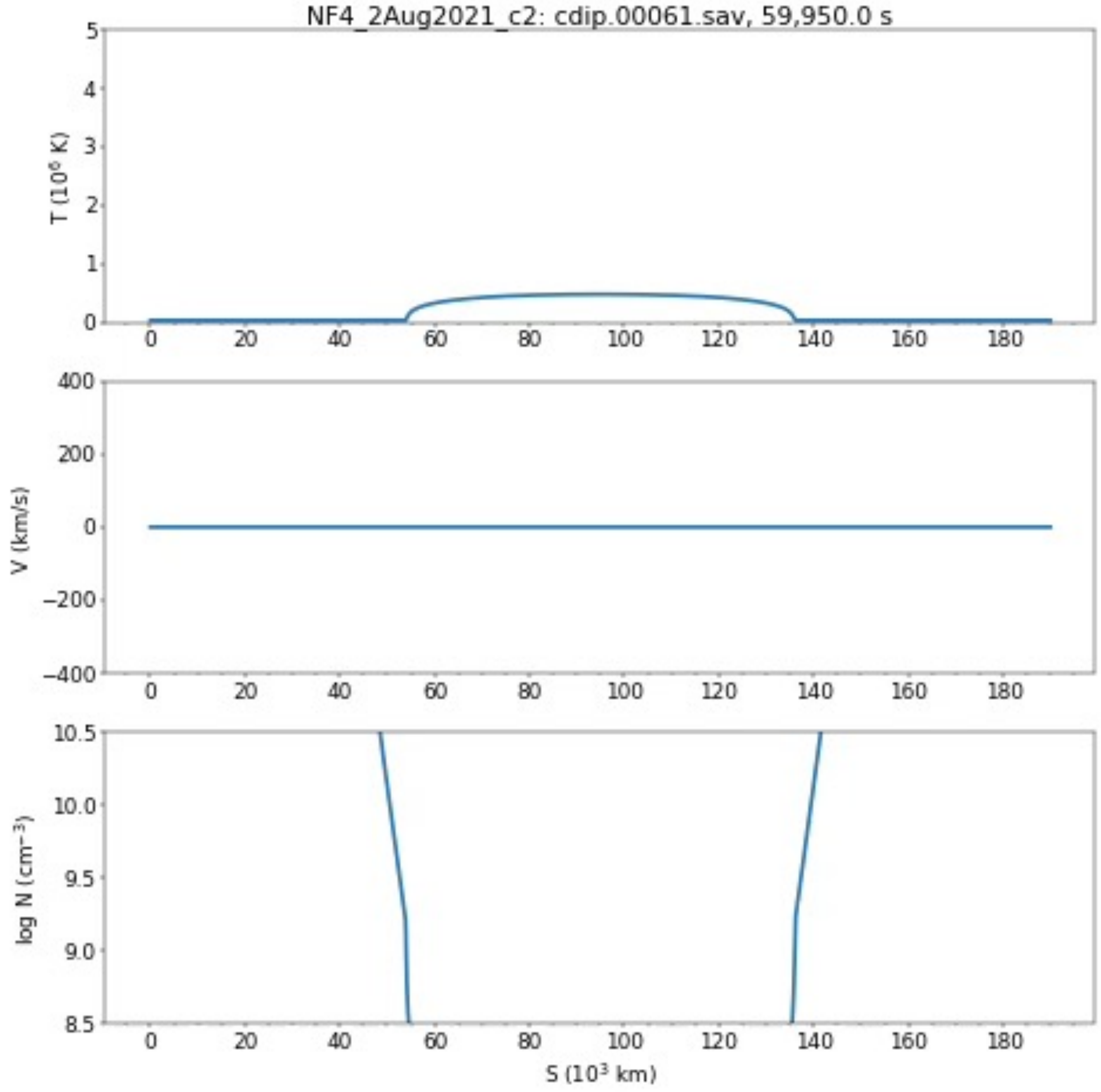
- Do we confirm the maximum delay time (minimum frequency) for TNE?
- What are the differences in TNE between alternating symmetric nanoflare?
- How do random nanoflare distributions affect TNE occurrence?

Symmetric and alternating nanoflares show maximum delay time, but alternating nanoflares more complex

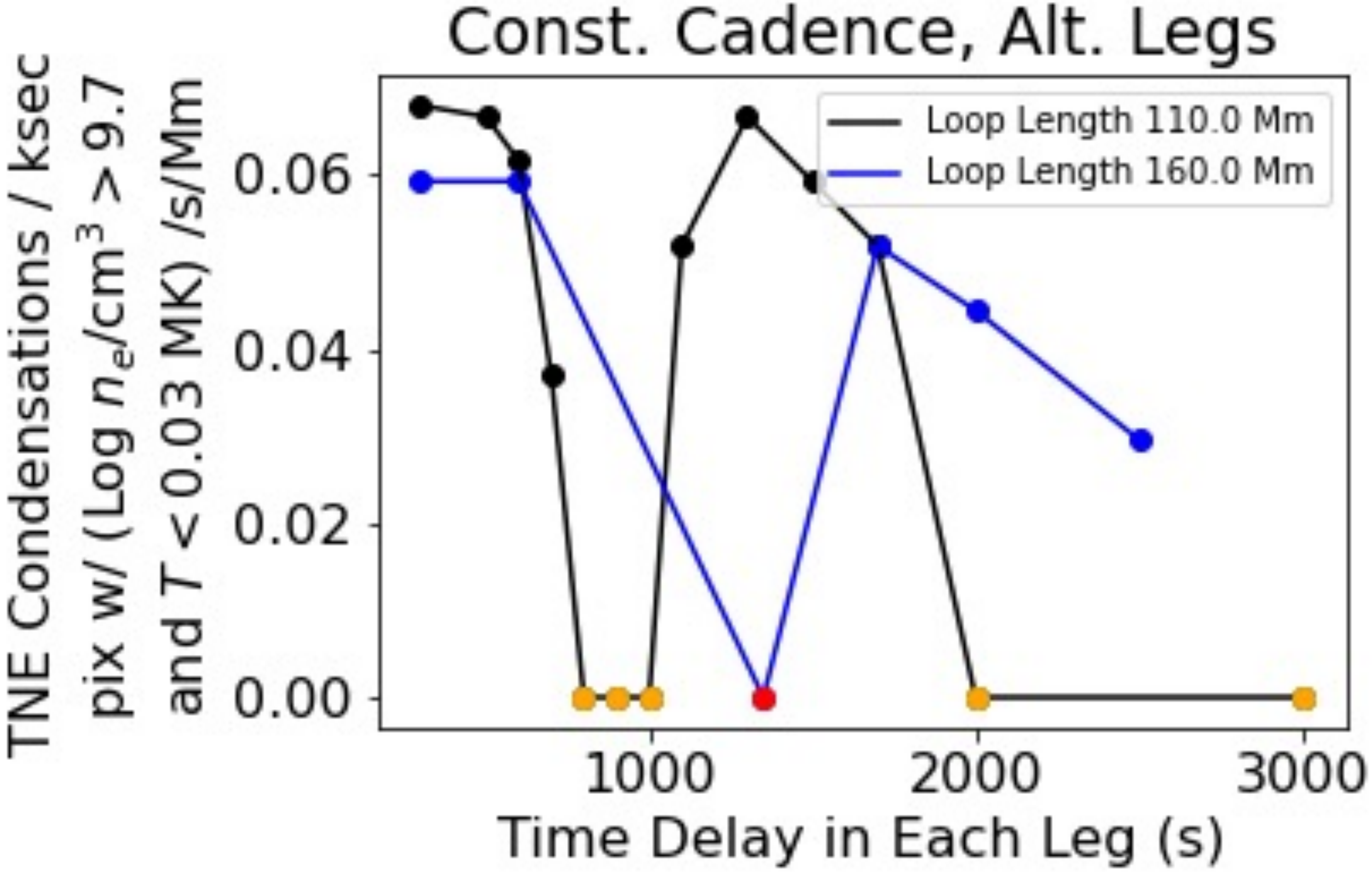


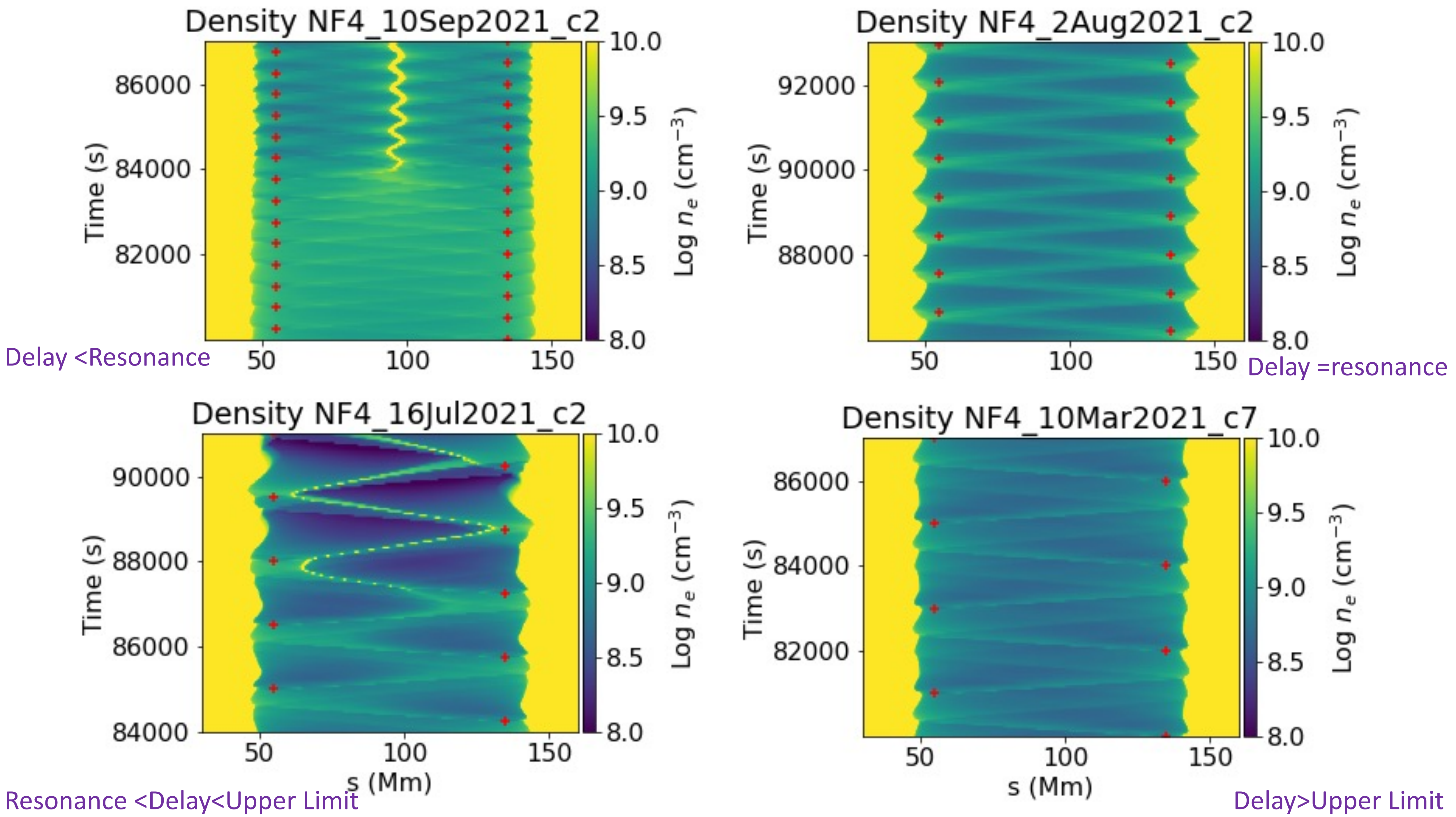
Nanoflares 15 Mm from loop footpoints

Lack of TNE for delays ≈ 900 s seems related to the time for the pulse associated with a nanoflare to cross the loop.



The delay at which this “resonance” occurs increases with loop length




Density NF4_10Sep2021_c2
Density NF4_2Aug2021_c2
Density NF4_16Jul2021_c2
Density NF4_10Mar2021_c7
Time (s)
s (Mm)
Log n_e (cm^{-3})
Delay <Resonance
Delay =resonance
Resonance <Delay<Upper Limit
Delay>Upper Limit

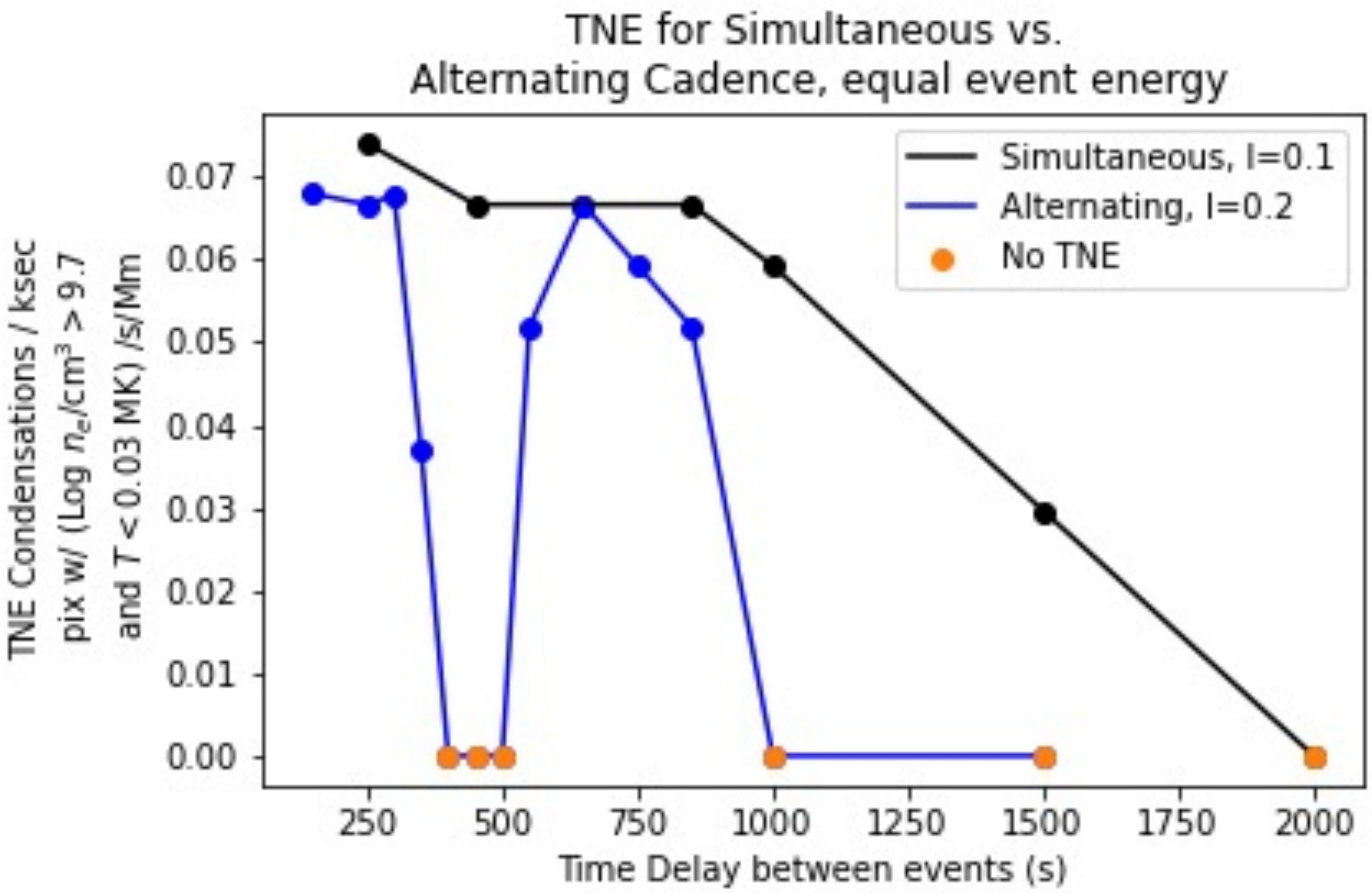
Why is this resonance interesting?

- Unlikely to happen in the real corona
- Insight into requirements for TNE
- Points out importance of sampling a range of parameters

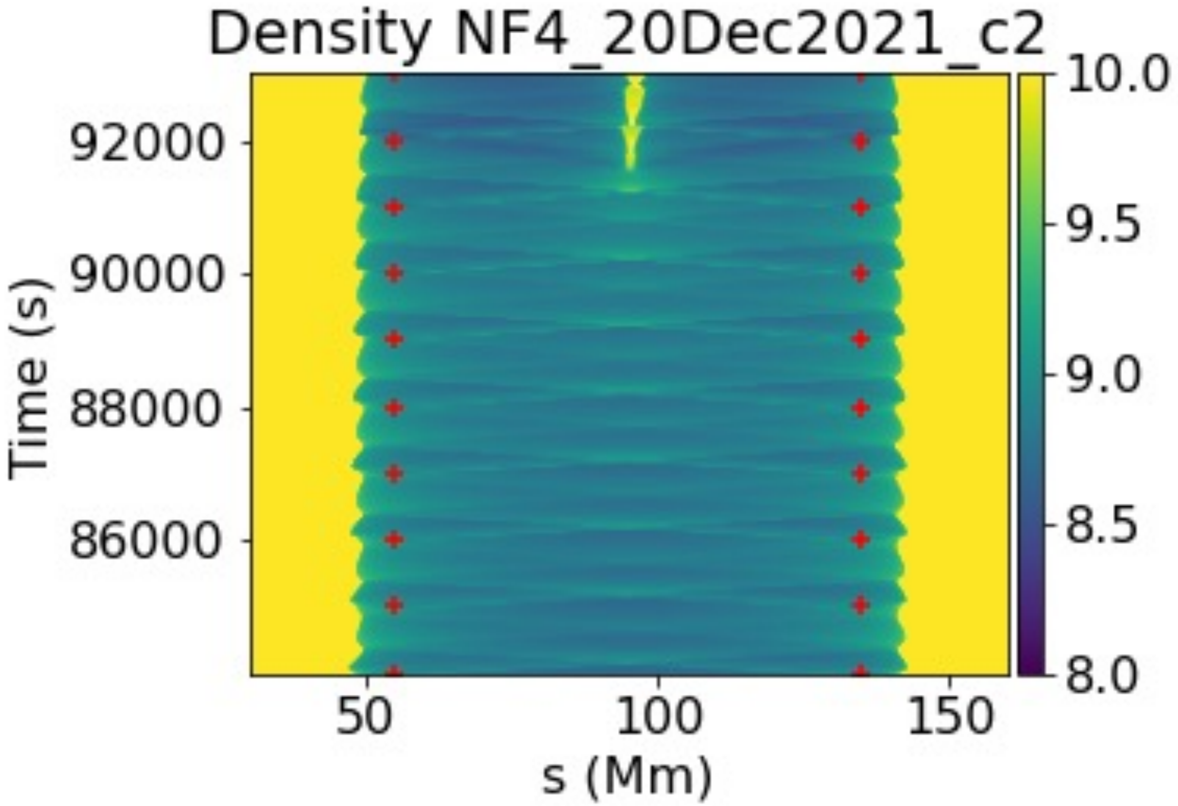
As a function of *global event time* the symmetric case produces condensations for much higher delay times

Energy and cadence per *global event* equal

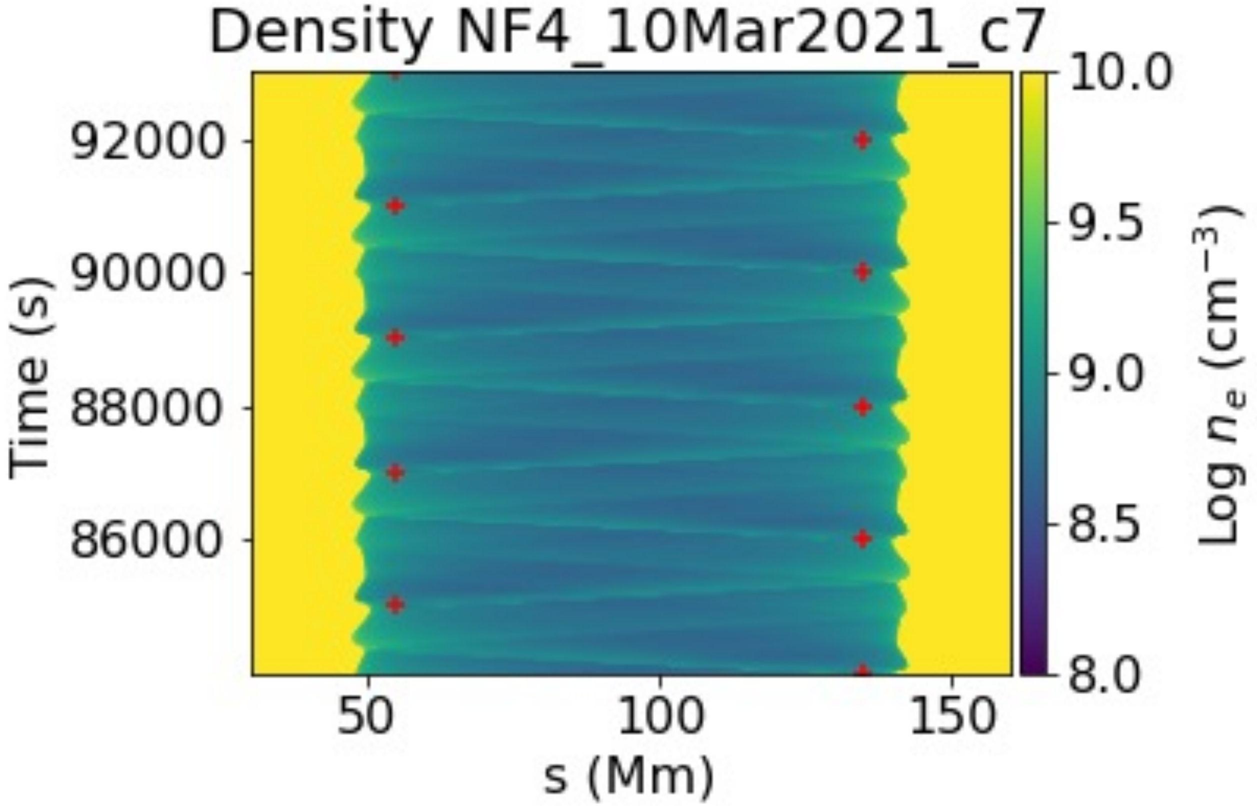
- Simultaneous case: split between two legs
- Alternating case: all in one nanoflare



Symmetric nanoflares result in an increase in density at the center of the loop, which encourages TNE



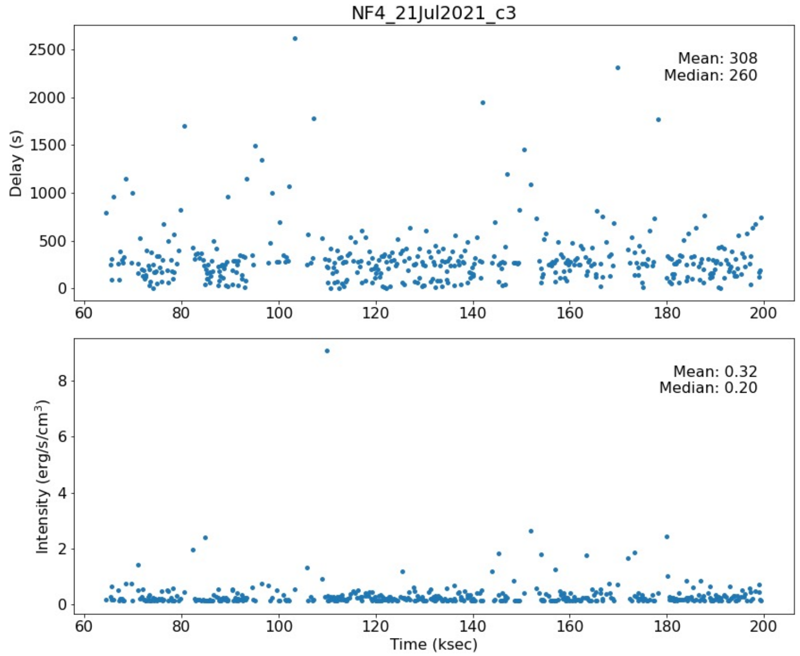
Symmetric nanoflares
(delay in each leg=1,000 s, global delay =1,000 s)

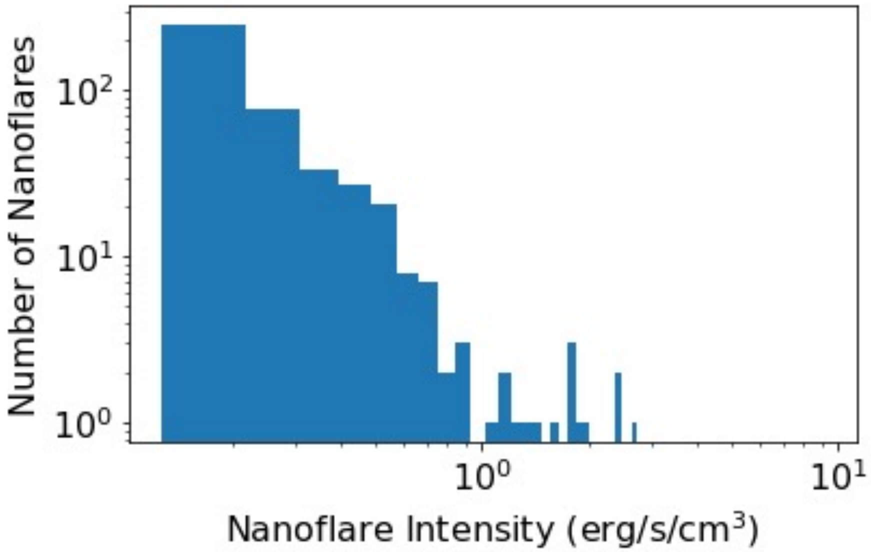


Alternating nanoflares
(delay in each foot=2,000, global delay=1,000 s)

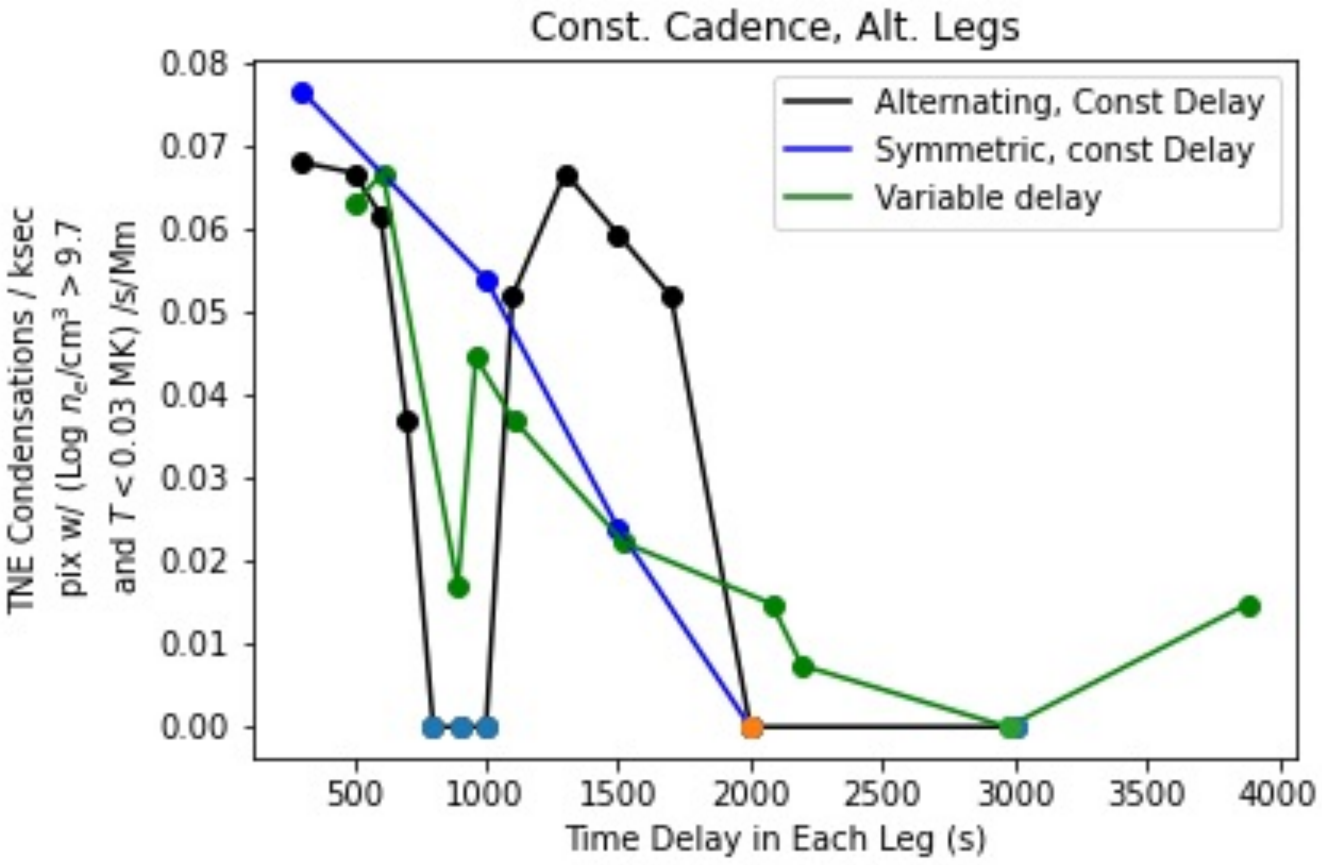
More Realism: Power-law intensity and delay distribution

- The peak heating rates are from a power law distribution with assumed slope and range in intensity.
- The delay between events is proportional to the magnitude of the first event, so these are also a power-law.
- Intensity normalized so median equals the intensity normally used on the runs with regular cadence.

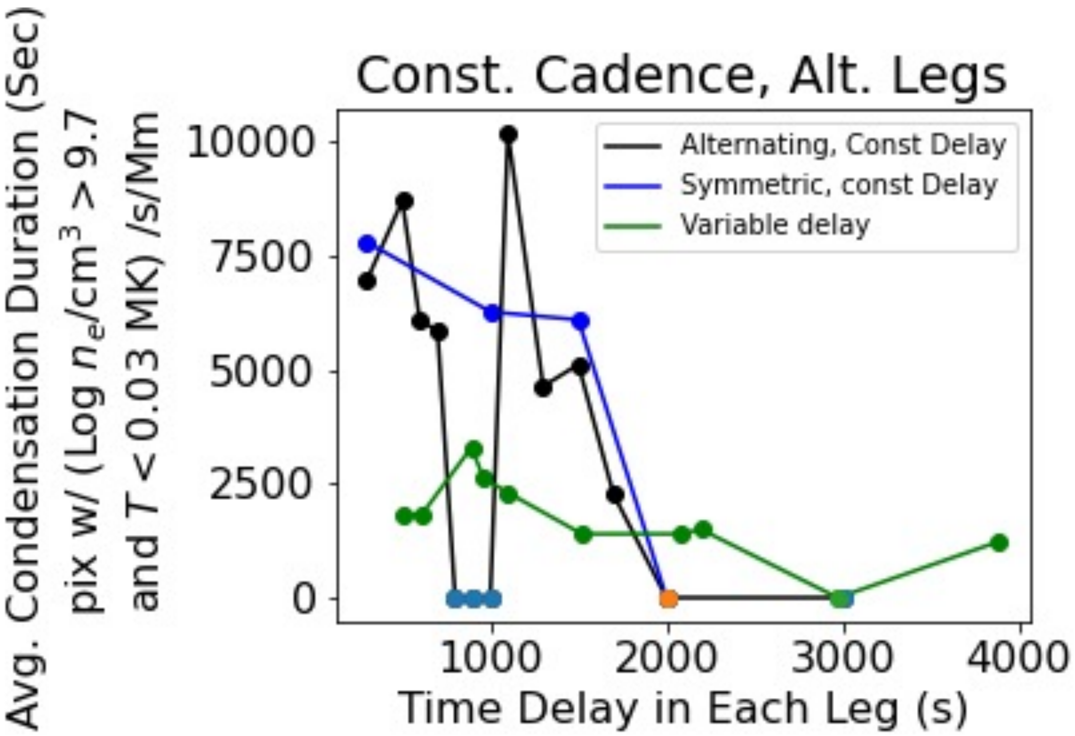


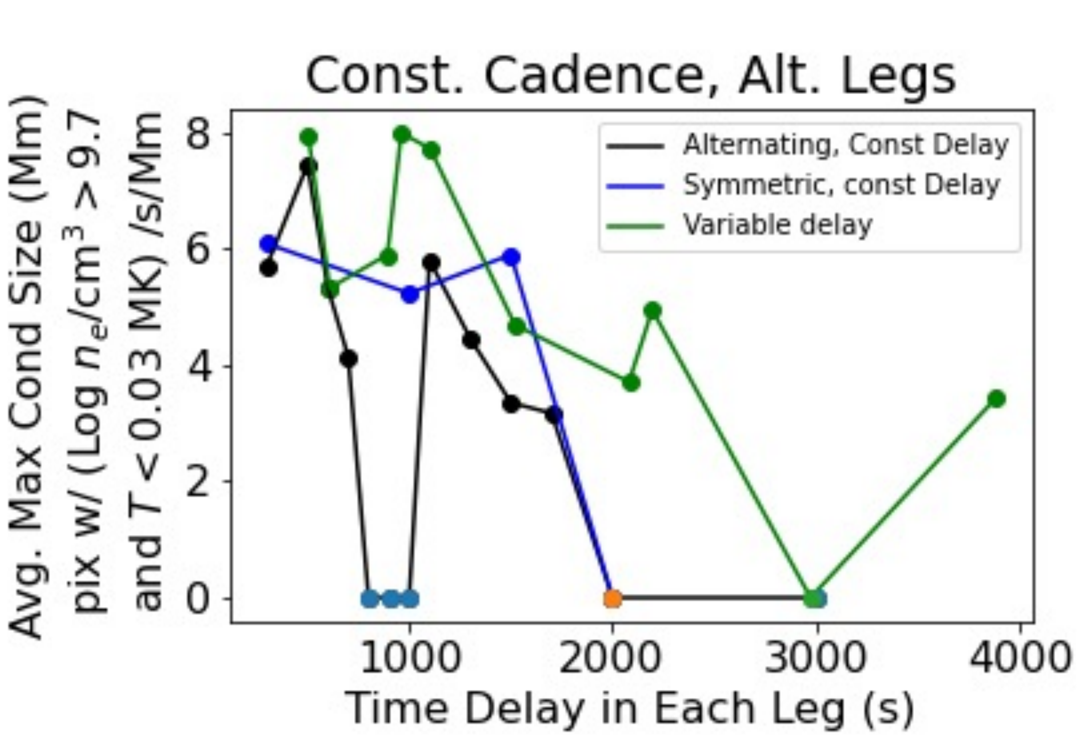


Variable delay case shows higher delay time limits on TNE formation than the symmetric and alternating cases



The random size/delay nanoflares produce condensation which stay in the loop a shorter amount of time





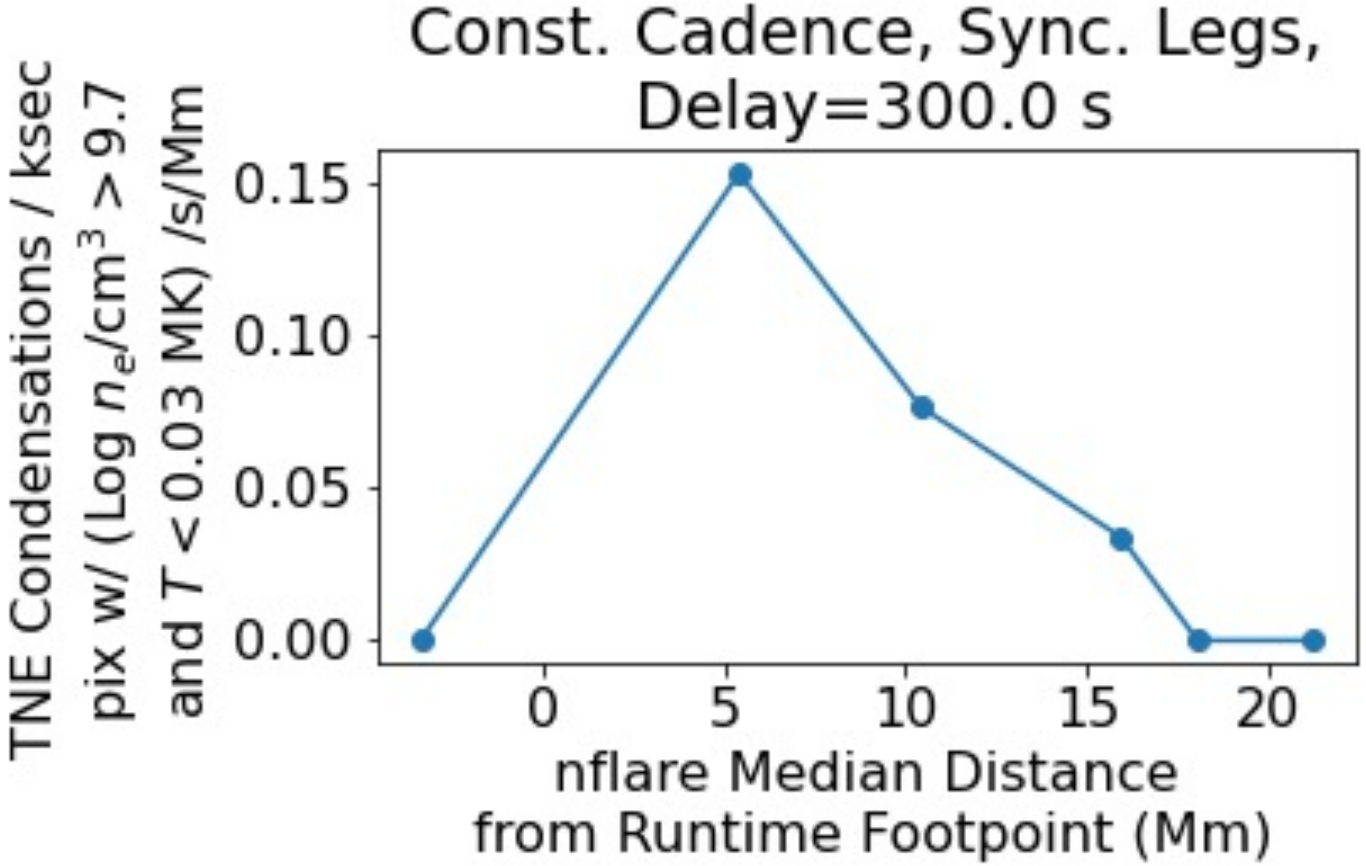
Variations in nanoflare location

- Regularly repeating nanoflares
  - Symmetric and alternating
  - Delay =300 s, Intensity =0.2 erg/s/cm^3

Questions:

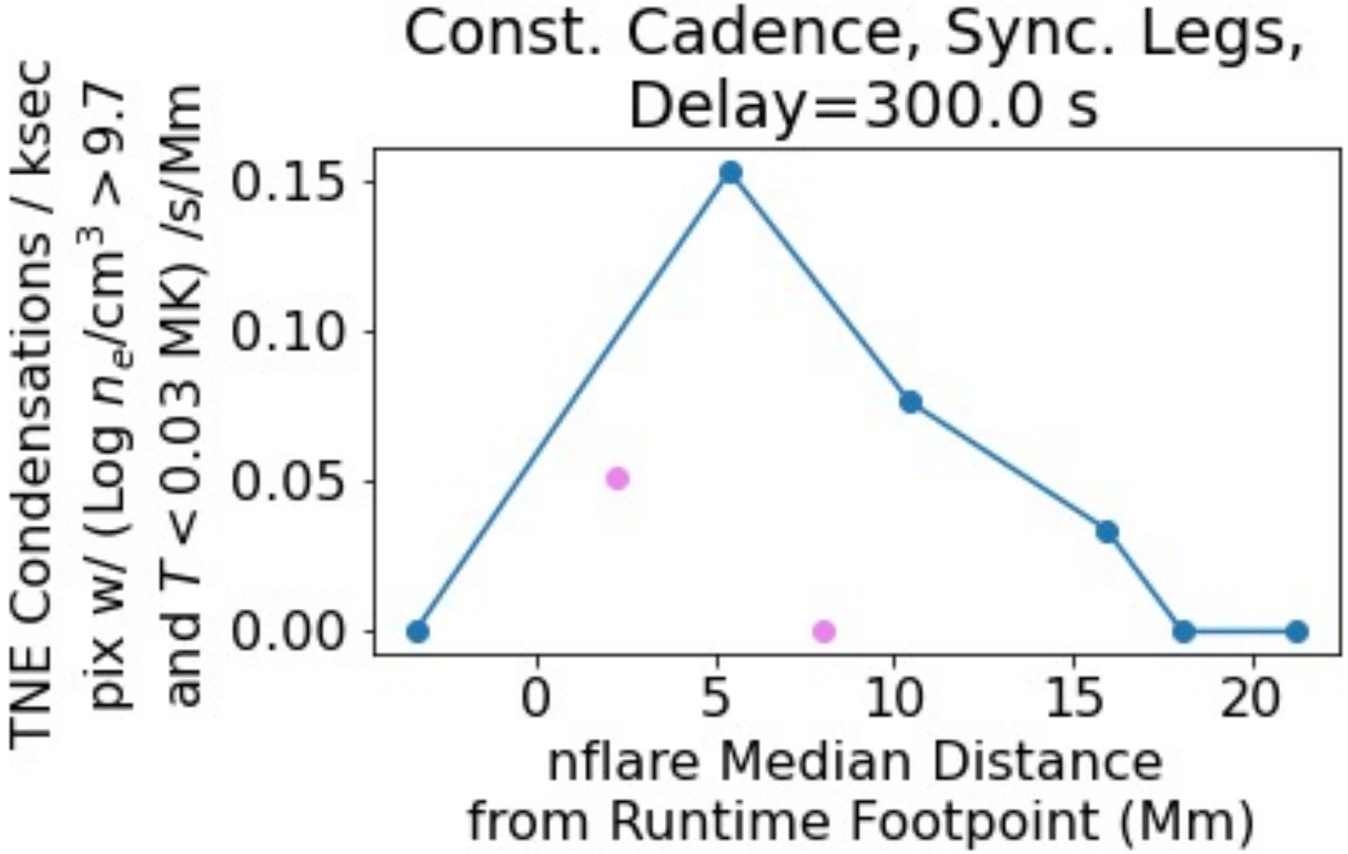
- Do we confirm that nanoflares closest to the loop footpoints produce more TNE?
- How do nanoflares with randomly distributed locations affect TNE occurrence?

Effects of Location: Number of condensations decreases with distance from footpoints

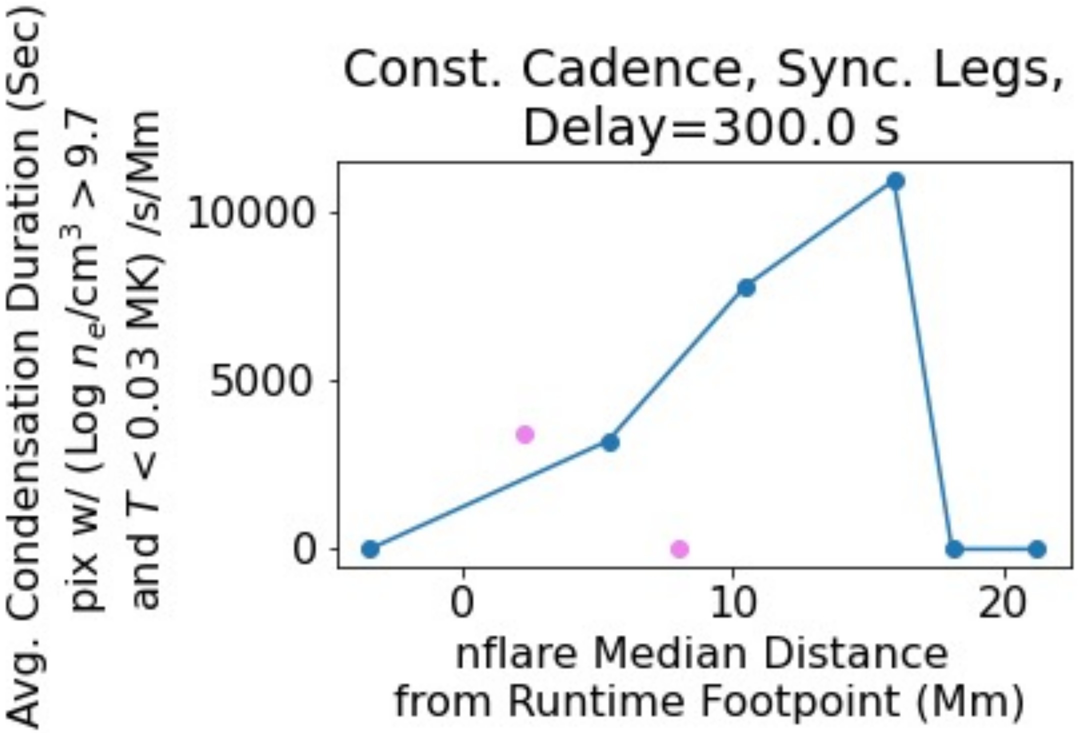


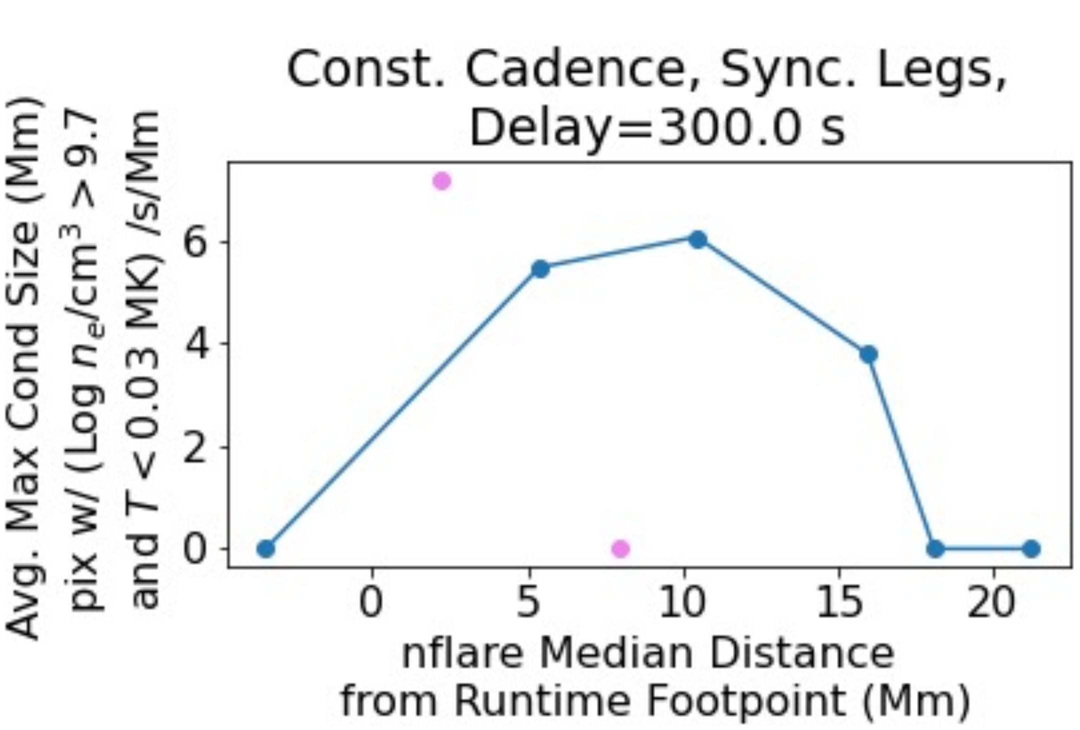
Simultaneous nanoflare in each leg, Delay = 300 s

Symmetric nanoflares can produce TNE at higher altitudes than alternating nanoflares

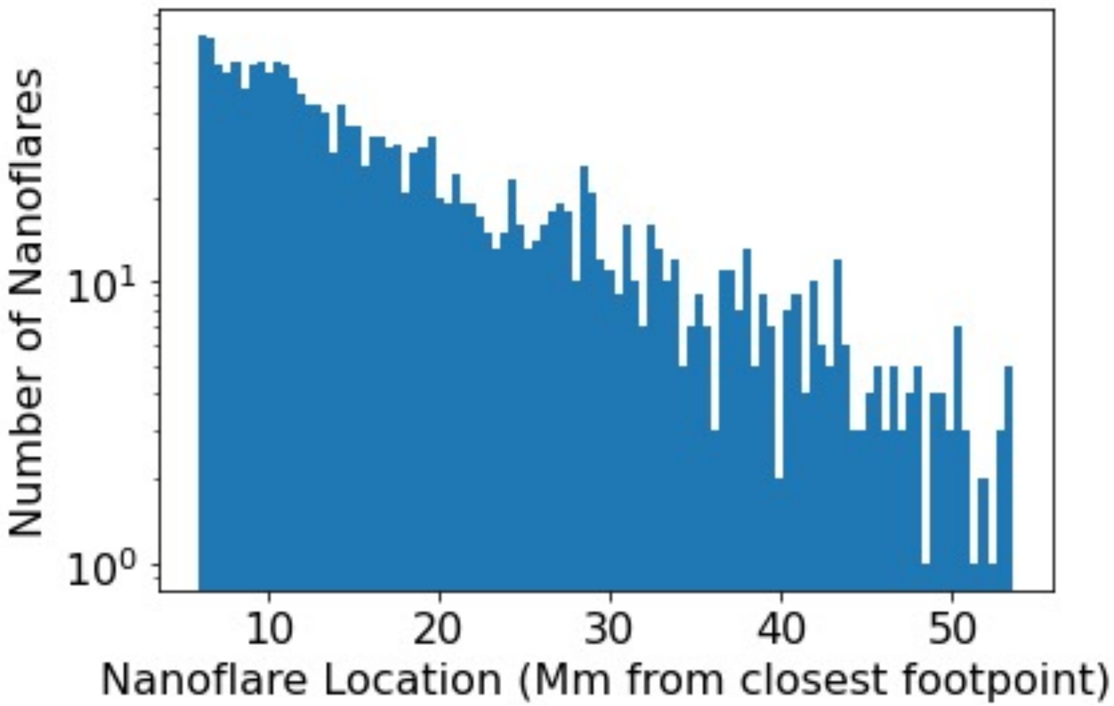


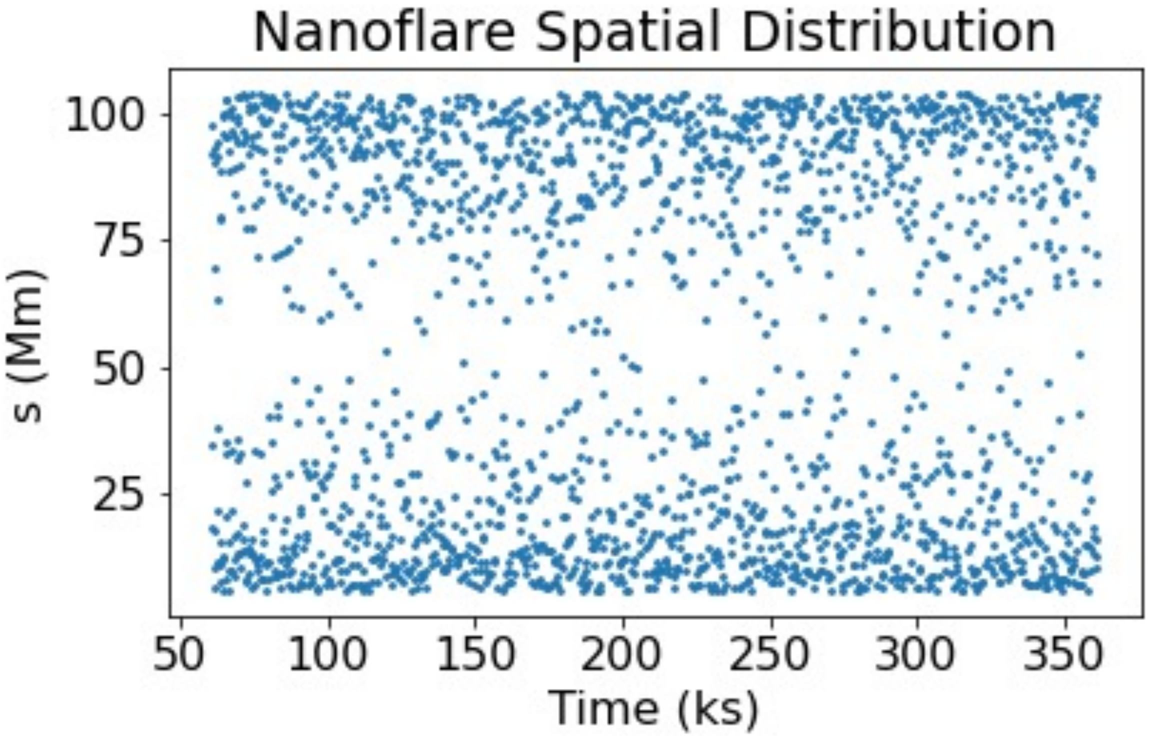
Duration of condensations increases with distance from footpoints (for symmetric case, anyway)





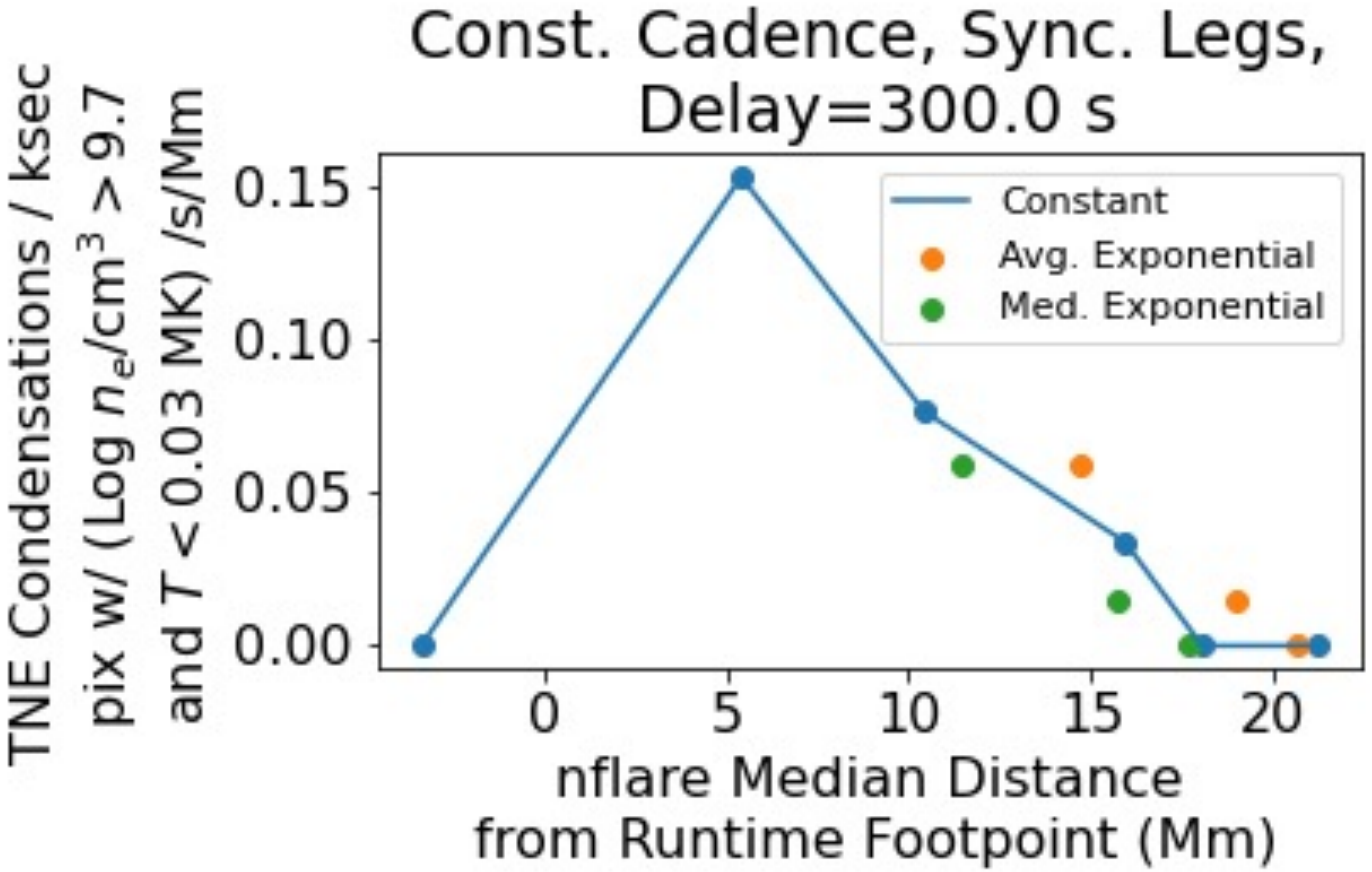
More realism: Exponential Spatial Distributions





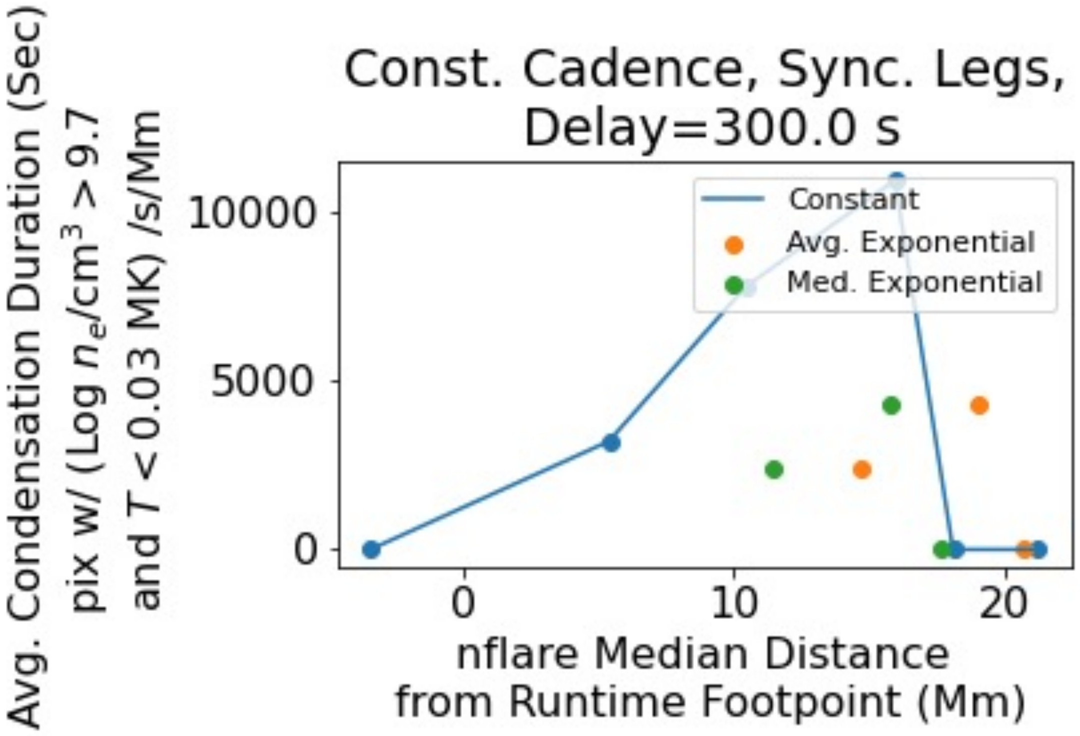
A separate distribution is run in each leg, with symmetric, simultaneous timing

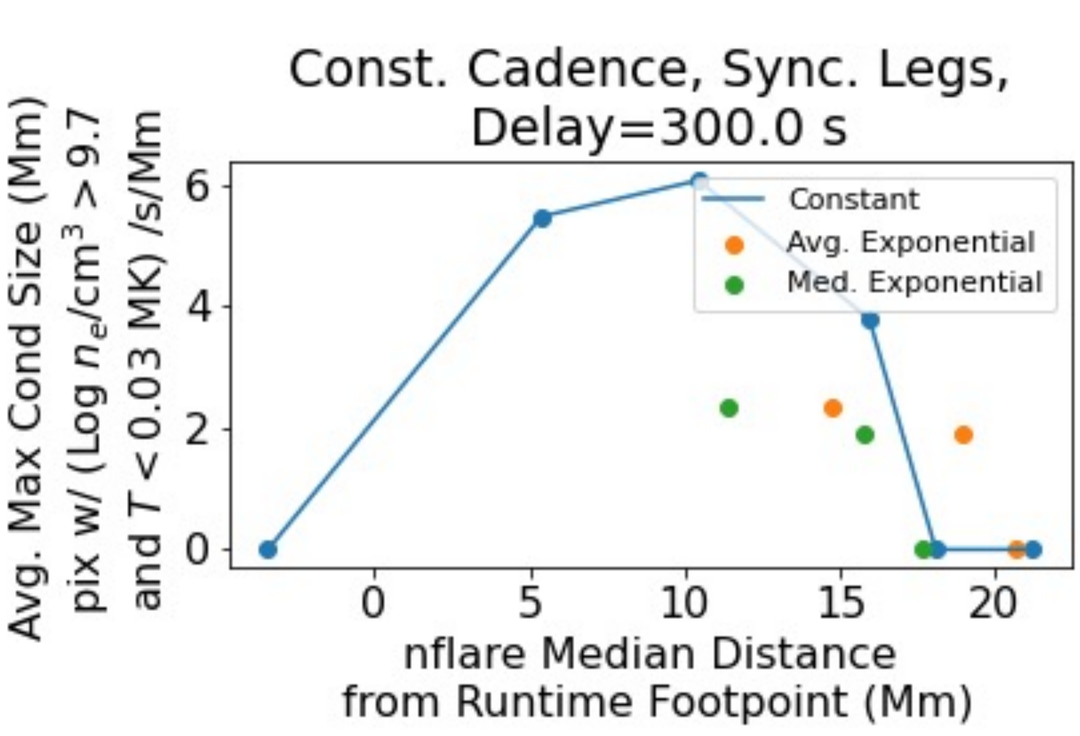
The exponential distributions give similar results to the even cadence in both legs runs.



Simultaneous in both legs, Delay =300 s

The dependence of duration and size do not hold for the random exponential distributions





Summary

- Delay variation
  - Confirms maximum delay (minimum frequency) requirement for TNE for regularly occurring nanoflares based on time needed for loop to return to initial state.
  - Find suppression of TNE in alternating case based on velocity of front across loop.
  - For regularly recuring nanoflares with the same global cadence and energy symmetric, simultaneous nanoflares the critical delay is higher than for alternating nanoflares.
  - With randomized nanoflares in intensity/time it is possible to get TNE for longer average delays, but the condensations stay in the corona a shorter amount of time.

- Location variation
  - Confirms that TNE more likely if nanoflares near foot points
  - Exponential distributions seem to give similar results with respect to the condensation rate

Next Steps

- Consider nanoflares randomized in **both** location and intensity/time
- Eventually consider effect of randomized nanoflares on diagnostics like DEM and time lags