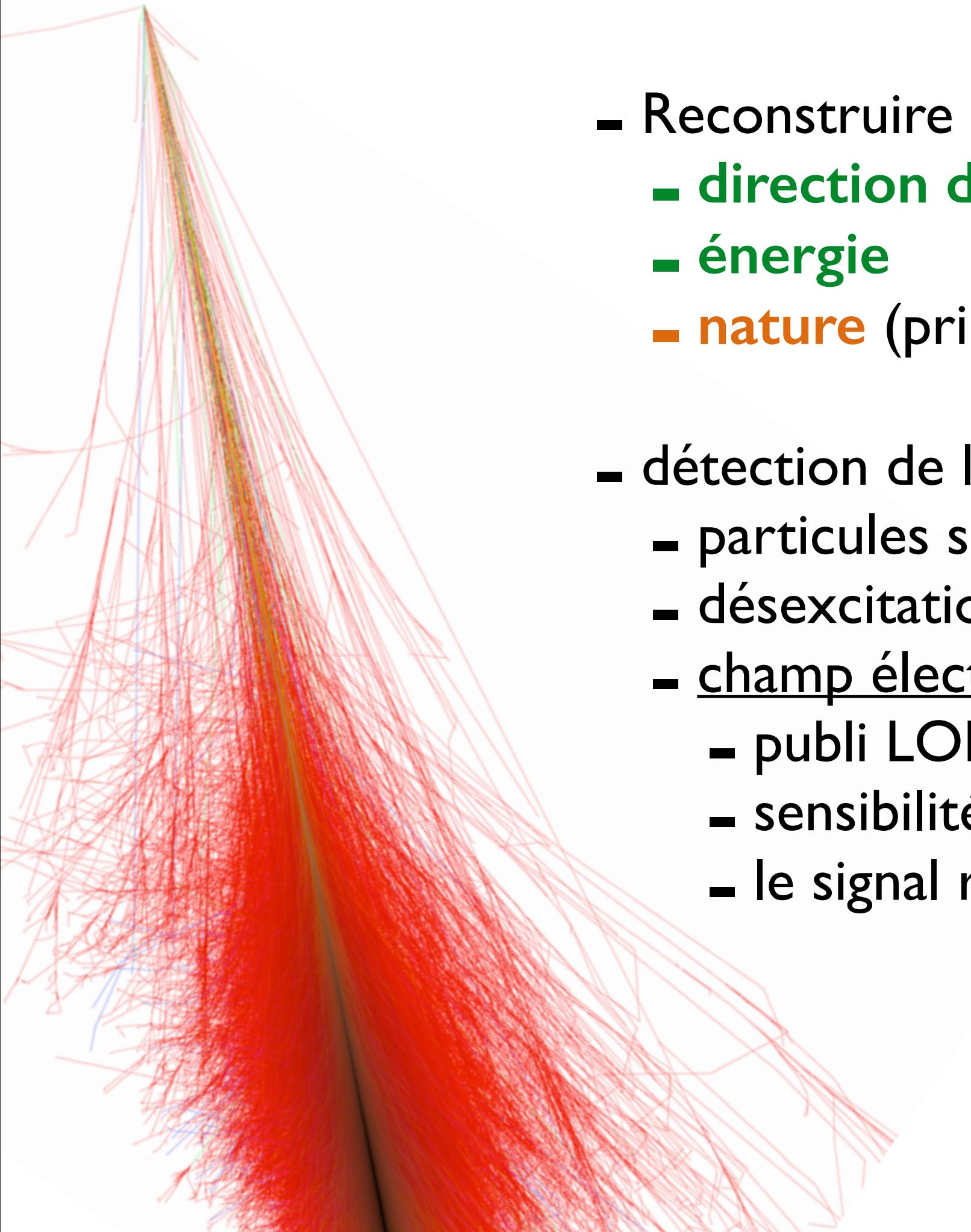


**EXTASIS:**  
**EXTinction of Air Shower Induced Signal**  
**Coherent radio emission from the**  
**air shower sudden death**

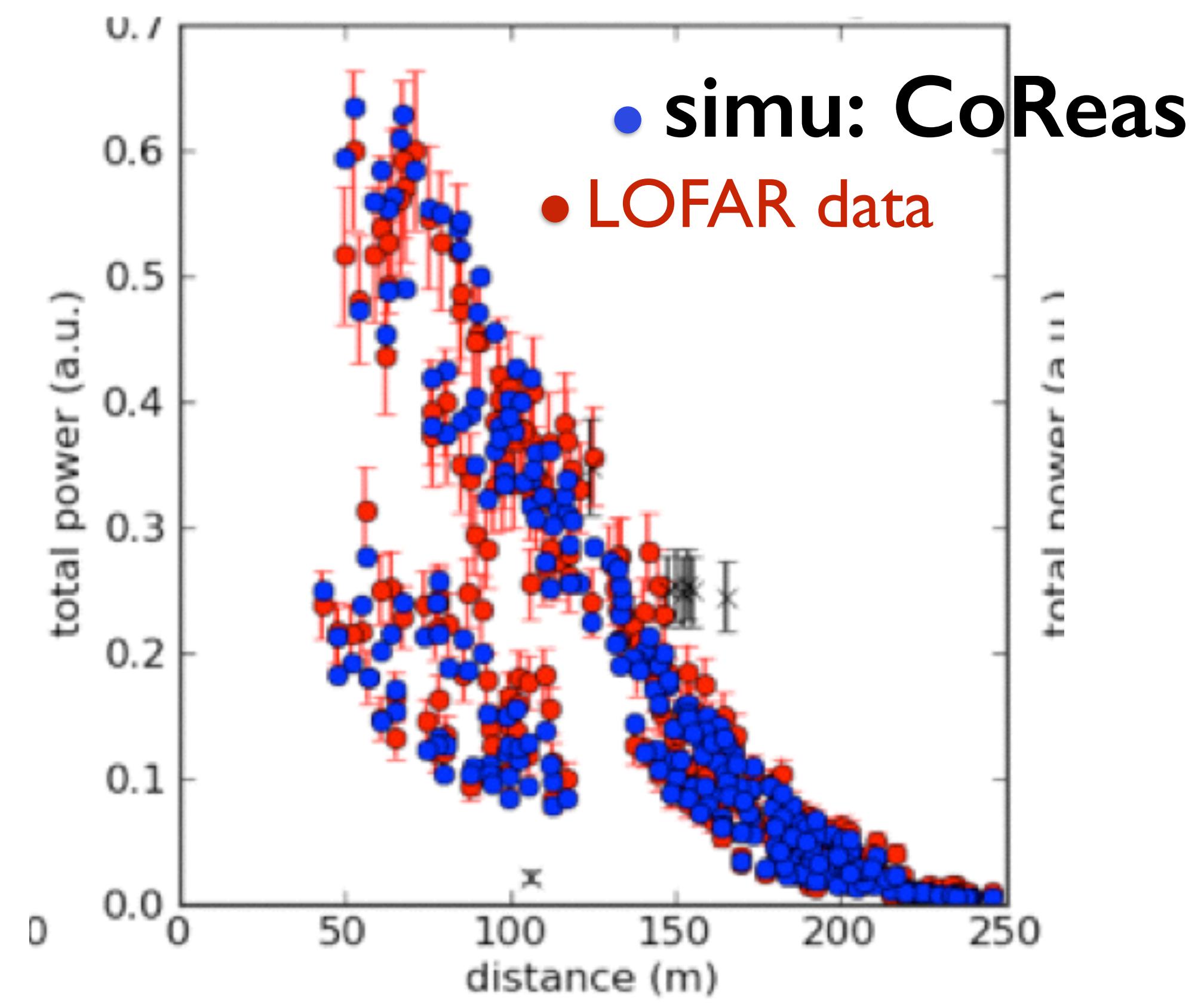
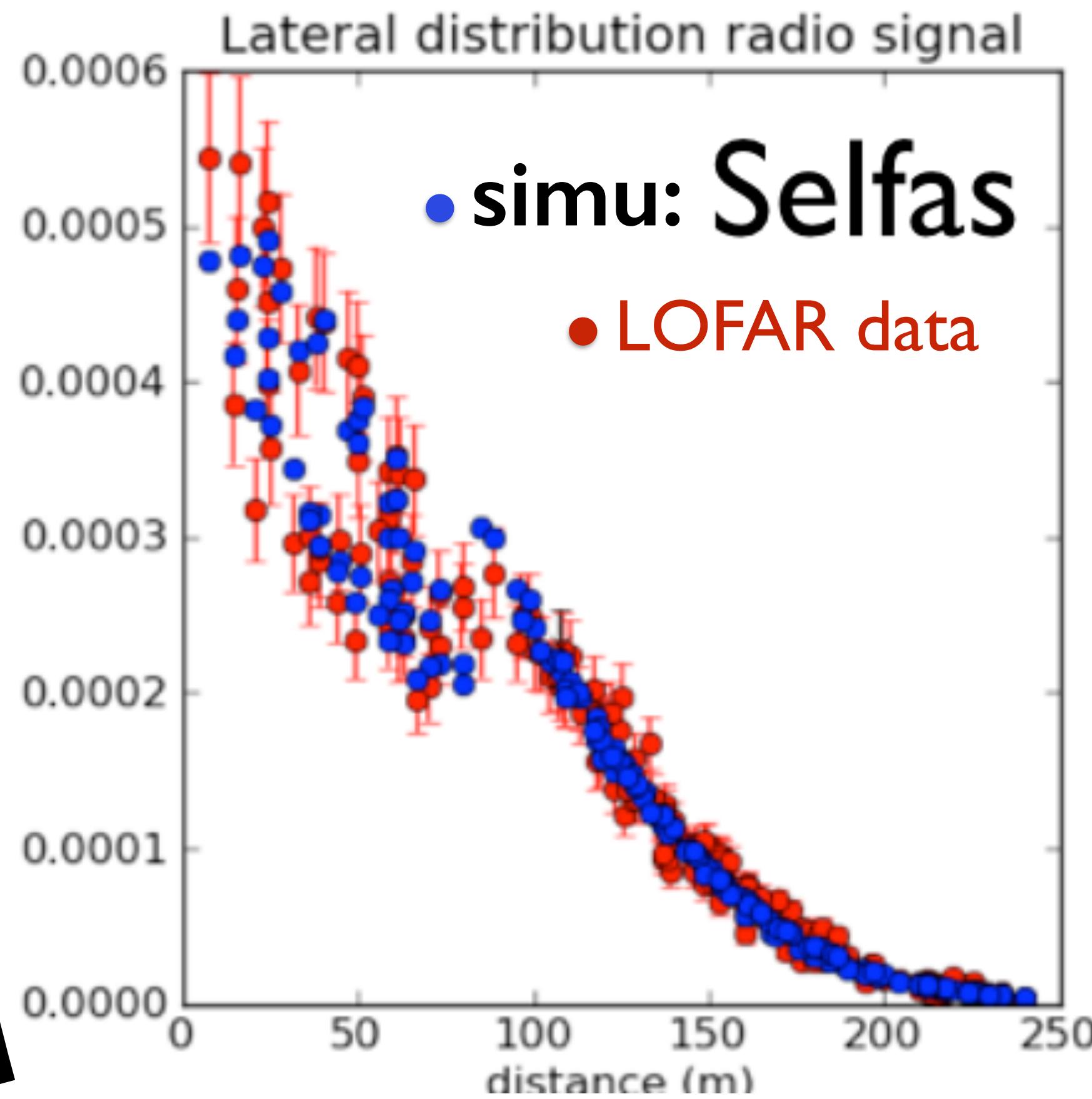
SUBATECH  
École des Mines de Nantes  
Université de Nantes  
CNRS/IN2P3

# Rayons cosmiques d'ultra-haute énergie

- 
- Reconstruire les caractéristiques du rayon cosmique :
    - **direction d'arrivée**
    - **énergie**
    - **nature** (principal moteur des upgrades d'Auger)
  - détection de la gerbe atmosphérique via 3 observables :
    - particules secondaires atteignant le sol
    - désexcitation du N<sub>2</sub> atmosphérique suite au passage de la gerbe (fluorescence)
    - champ électrique radio émis par la gerbe
      - publi LOFAR en gestation, composition entre 10<sup>17</sup> eV et 10<sup>18</sup> eV
      - sensibilité à la composition similaire à la technique de fluorescence
      - le signal radio est un indicateur de la nature du primaire, c'est un **fait**

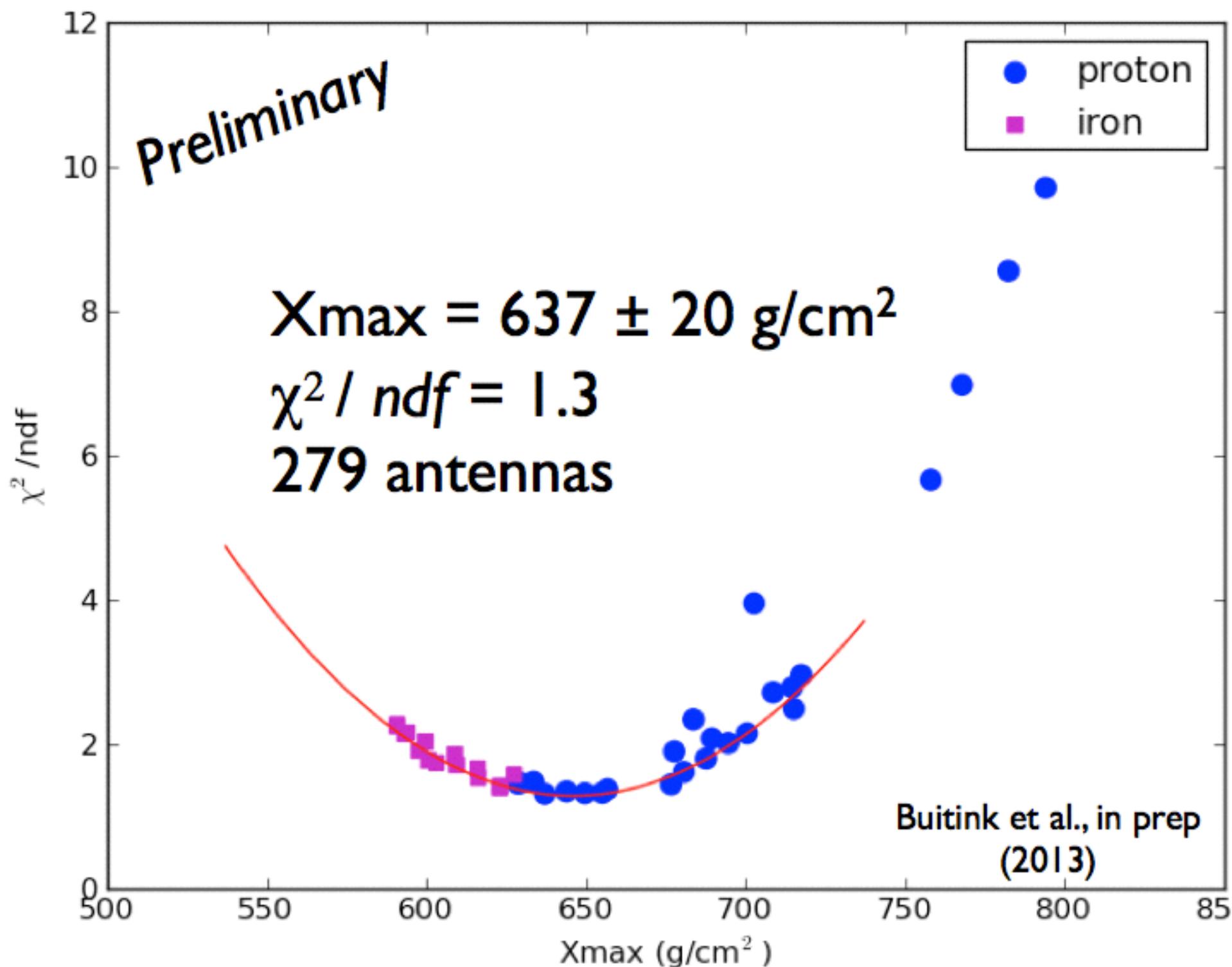
# The radio signal

understood in great details since  $\sim 1$  year  
interference of 2 different polarization patterns produced by 2 different mechanisms

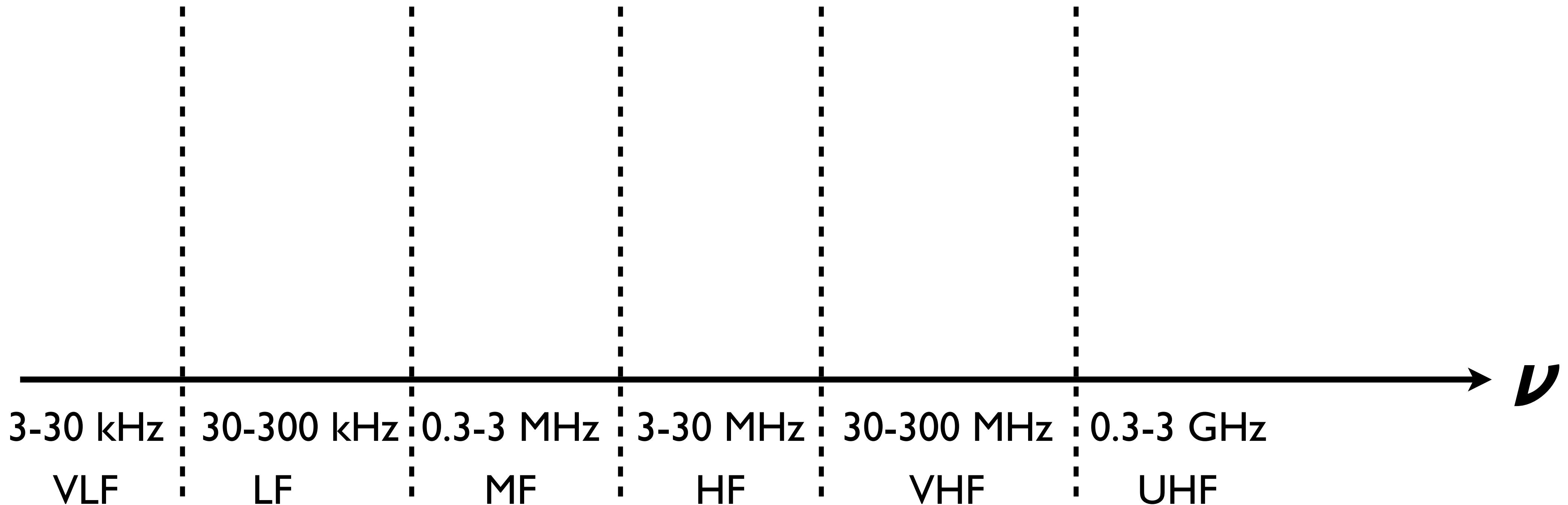


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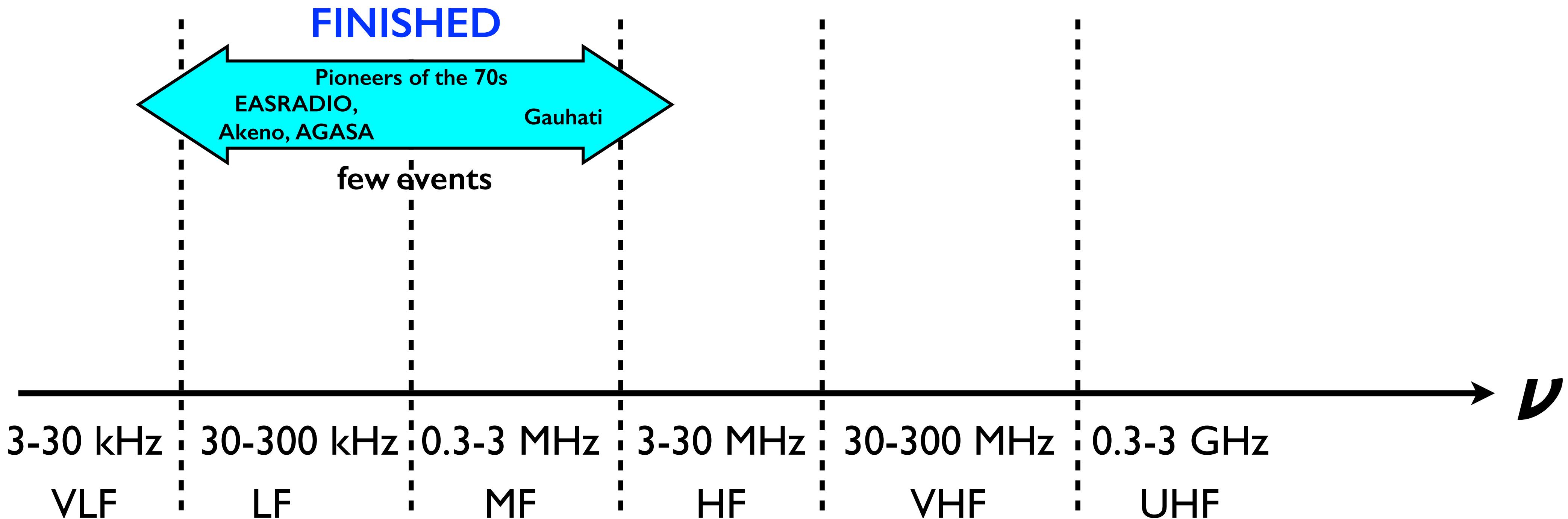
Sensitivity to the nature of the primary cosmic ray:  
 $X_{\max}$  is measured with an uncertainty of  $\sim 20 \text{ g/cm}^2$   
(Buitink et al, ICRC 2013)



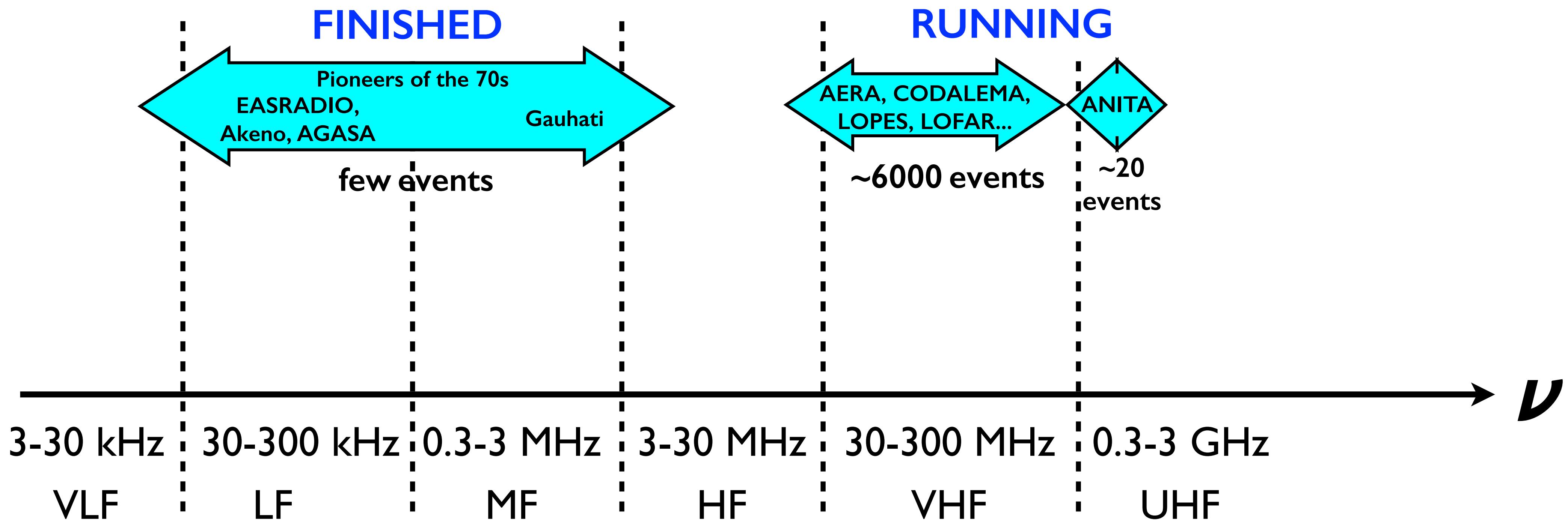
# Radio emission of EAS



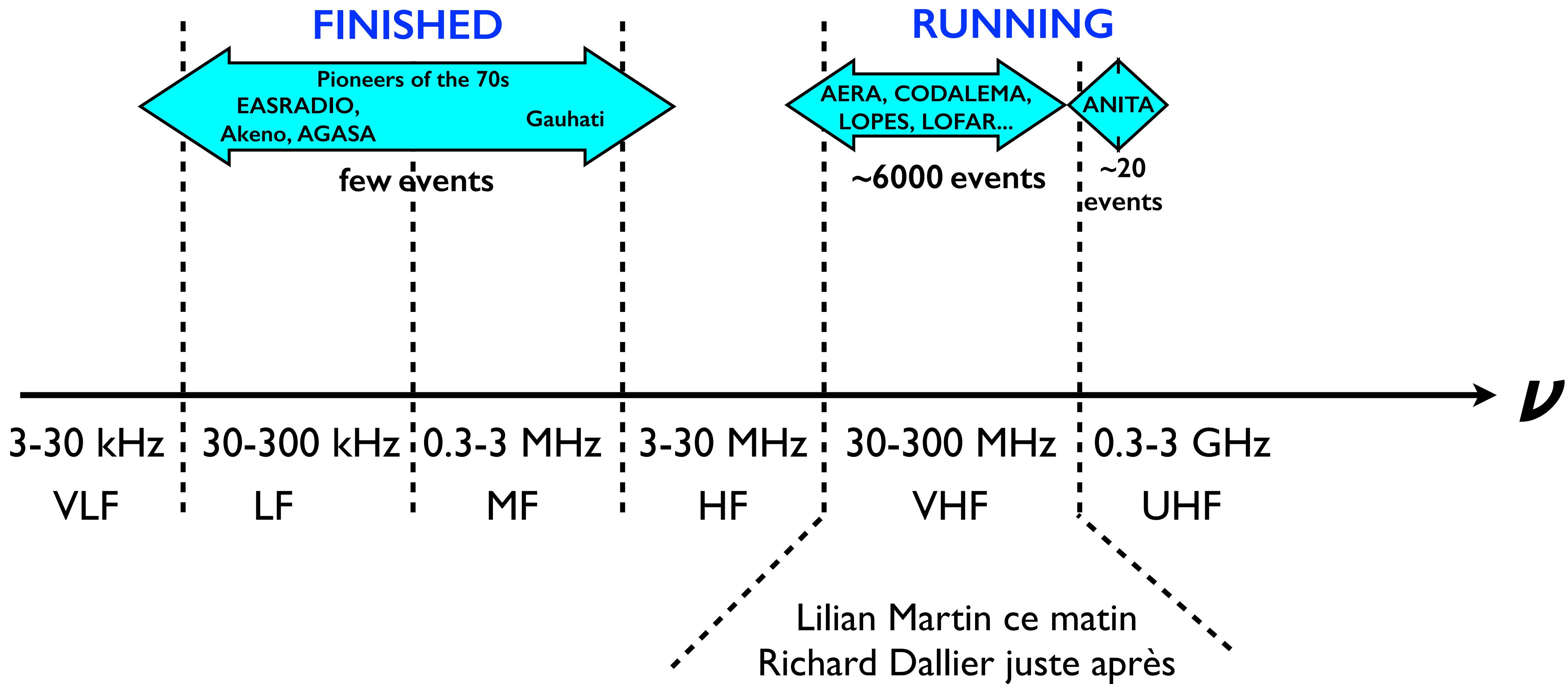
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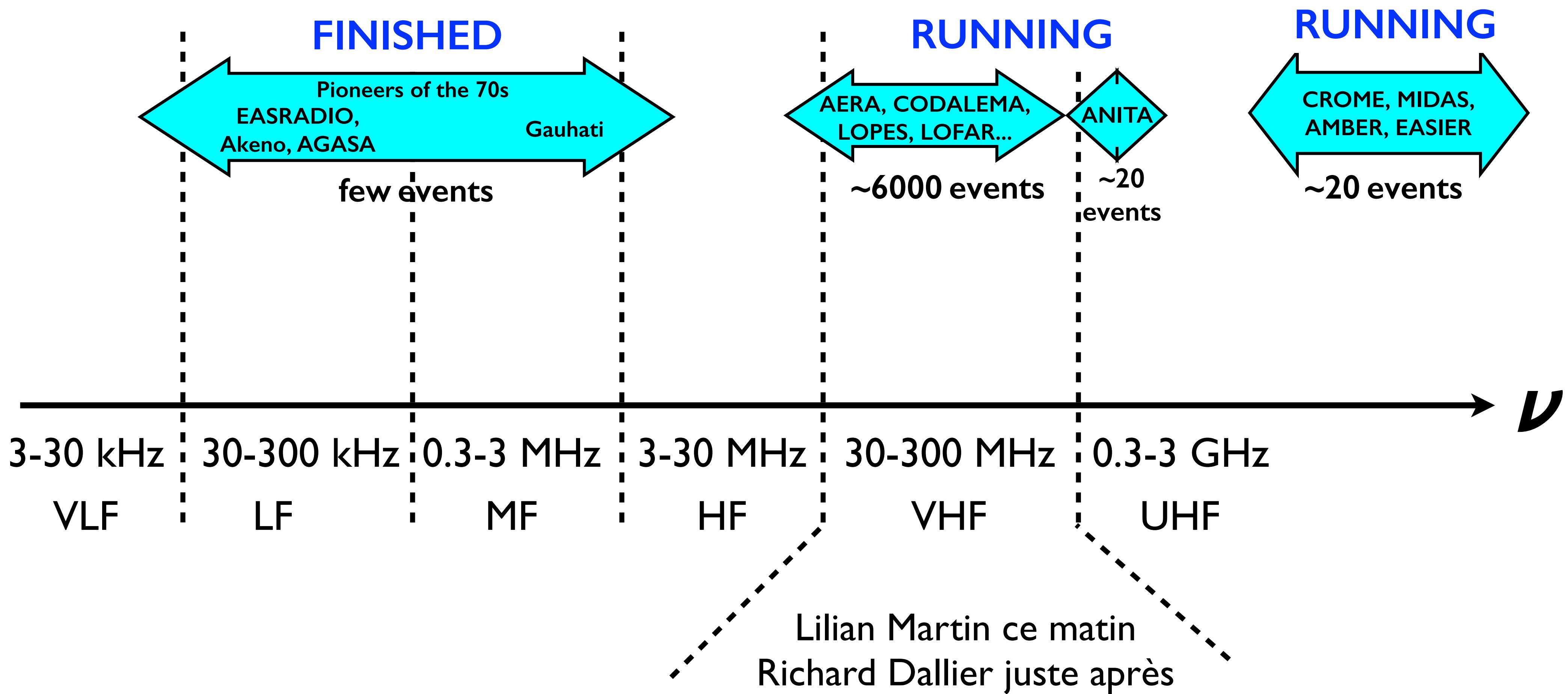
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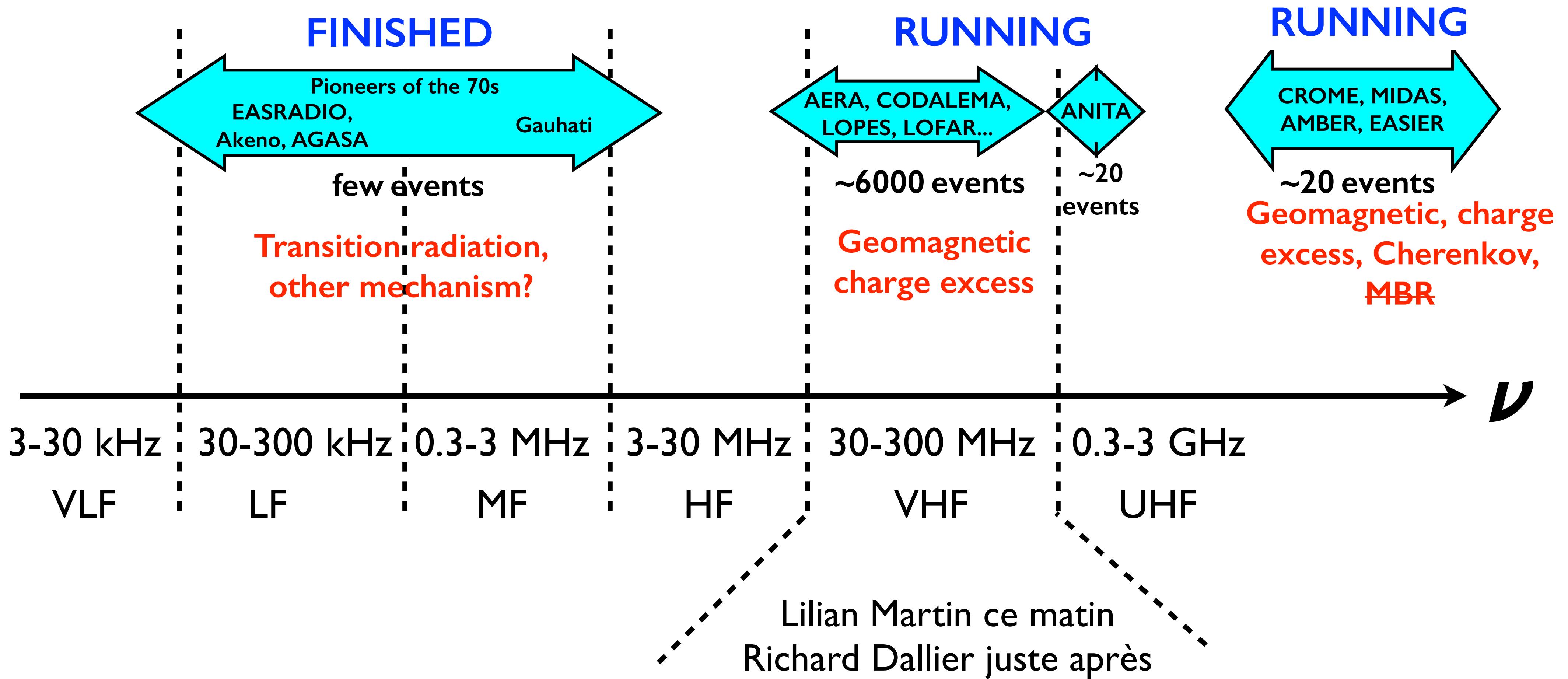
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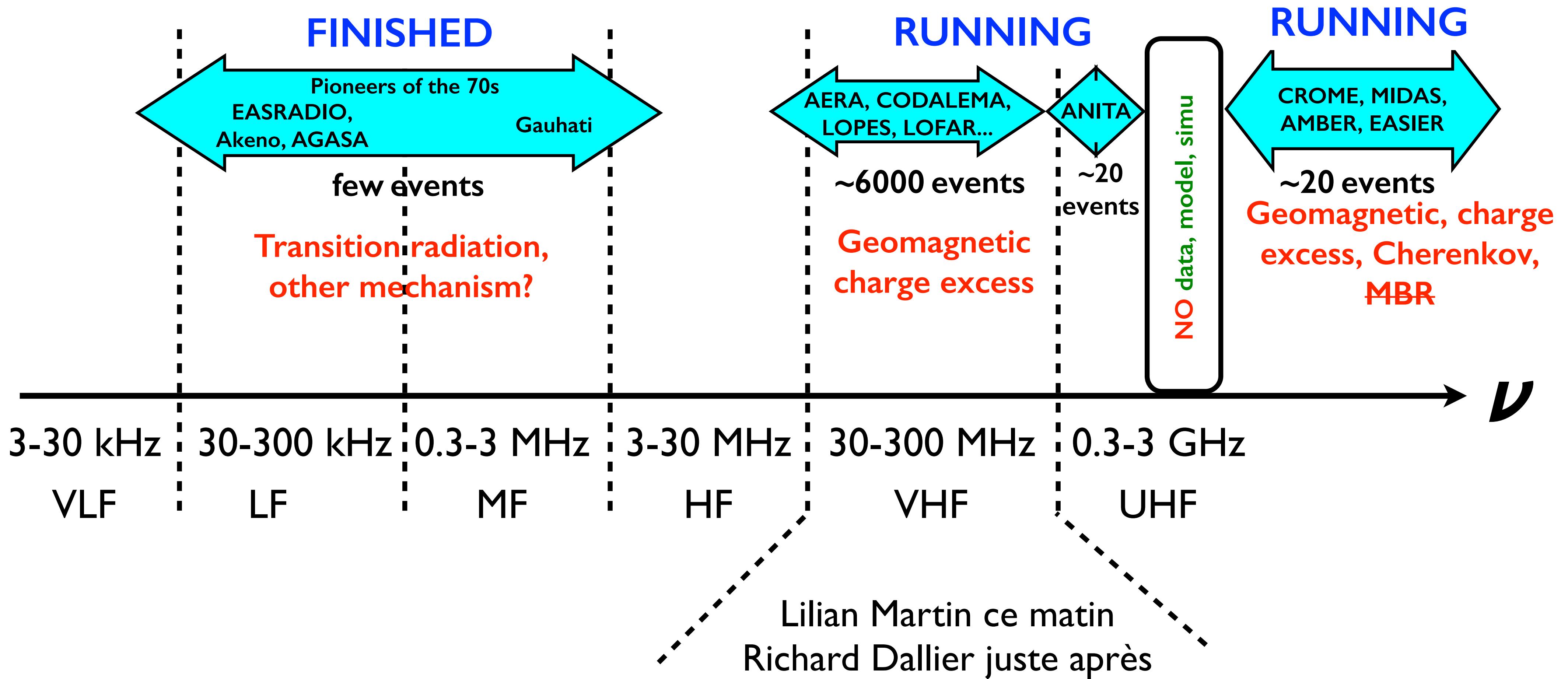
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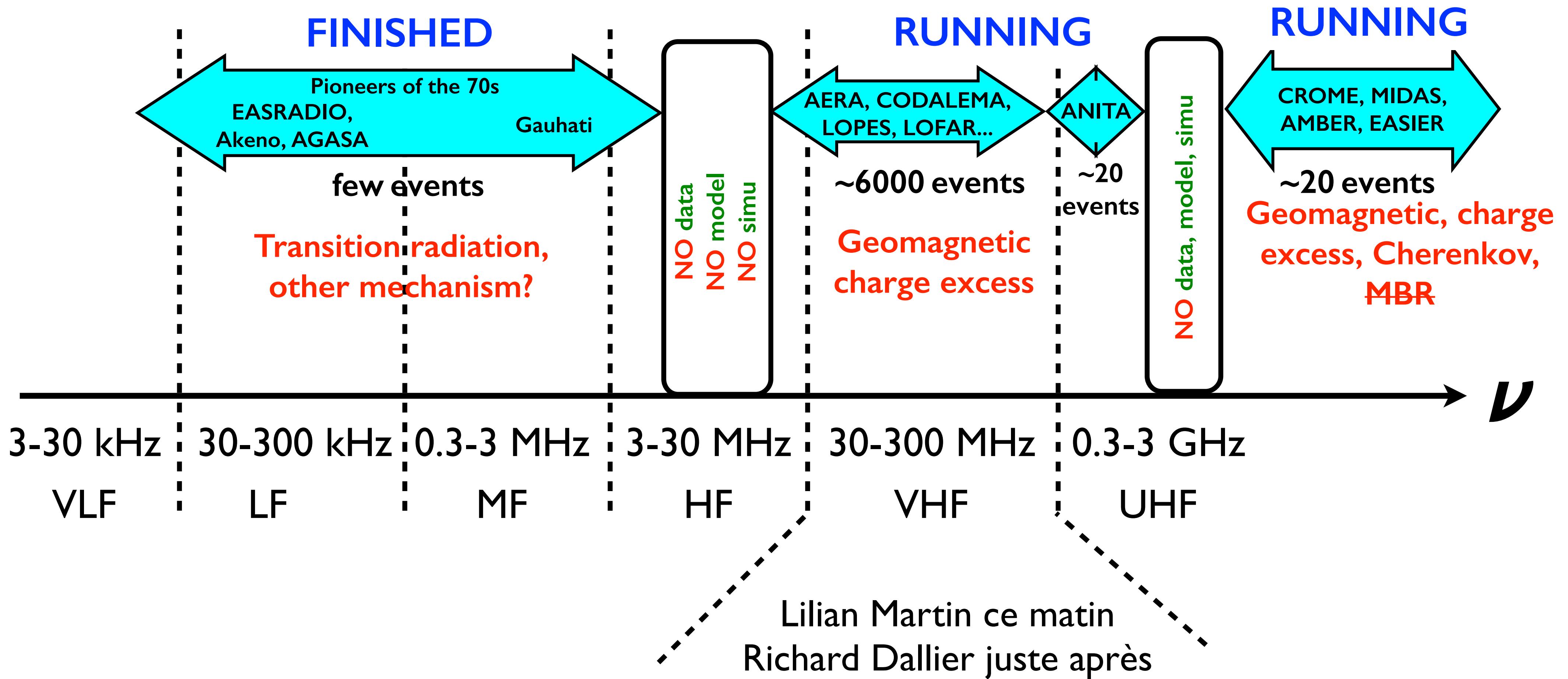
# Radio emission of EAS



# Radio emission of EAS



# Radio emission of EAS



# Radiodetection of EAS in the kHz-MHz range

year	reference	frequency	message
1970	Allan, Clay, Nature 225, 253	2 MHz	100 times higher than at 32 MHz
1970	Prescott et al, 11th ICRC 3, 717	3.6 MHz, 10 MHz	higher than geomagnetic, no detection at 10 MHz
1971	Stubbs, Nature 230, 172	2 MHz	250 times higher than at 44 MHz
1971	Hough et al, Nature 232, 14	3.6 MHz	10 times higher than geomagnetic in 20-60 MHz
1972	Felgate, Stubbs, Nature 239, 151	6 MHz	two polarizations, not only geomagnetic
1973	Clay et al, 13th ICRC 4, 2420	100 kHz	$\varepsilon_\nu \propto \nu^{-1.5}$
1973	Gregory et al, Nature 245, 86	100 kHz	large SNR, not only geomagnetic
1985	Suga et al, 20th ICRC 7, 268	50 kHz, 170 kHz, 1.6 MHz	Akeno, huge field strength vs geo-magnetic/electric
1987	Nishi, Suga, 20th ICRC 6, 125	26-300 kHz	Akeno, monopolar, I/d, 2.5 km
1991	Castagnoli et al, 22nd ICRC 4, 363	470 kHz, 2.6 MHz	EASTOP/EASRadio, amplitude ↗ when freq ↘
1992	Baishya et al, NCimC 16, 17	2 MHz, 9 MHz	TR is not the only mechanism
1993	Kadota et al, 18th ICRC 4, 262	30 kHz-3 MHz	AGASA, mono/bi polar

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# Emission mechanisms in the kHz-MHz range

year	reference	mechanism
1957	Wilson, Phys. Rev. 108, 155	geoelectric
1968	Charman, J. Atm. Terr. Phys. 30, 195	geoelectric
1972	Allan, Nature 237, 384	maximum coherence
1983	Kaneko et al, 18th ICRC 11, 428	charge-excess in air and at the ground
1985	Nishimura, 20th ICRC 7, 308	TR of electrons on the ground
1985	Suga et al, 20th ICRC 7, 268	TR of electrons on the ground

## Summary

- extensive air showers emit a strong electric field at low frequencies (< MHz)
- clear evidence of a strong increase of the radio pulses amplitude with decreasing frequencies
- no definitive conclusion, not enough data, no proper atmospheric monitoring
- no satisfactory underlying mechanism
- low frequency band unsued since 20 years

# Air shower sudden death

Proposed mechanism (TR not considered):

the sudden death of the shower front when reaching the ground level generates a coherent electric field at low frequency

macroscopic

$$\mathbf{E}(\mathbf{x}, t) = \frac{1}{4\pi\epsilon_0} \int d^3x' dt' \left\{ \frac{\mathbf{n}}{R^2} [\rho(\mathbf{x}', t')]_{\text{ret}} + \frac{\mathbf{n}}{cR} \left[ \frac{\partial\rho(\mathbf{x}', t')}{\partial t'} \right]_{\text{ret}} - \frac{1}{c^2 R} \left[ \frac{\partial\mathbf{J}(\mathbf{x}', t')}{\partial t'} \right]_{\text{ret}} \right\} \delta \left\{ t' - \left( t - \frac{|\mathbf{x} - \mathbf{x}'|}{c} \right) \right\}$$

very strong time variation of  $\mathbf{J}$  and  $\rho$ !

~ instantaneous at low frequencies (< 20 MHz, > 15 m): coherence

microscopic

the coherent deceleration, ie Bremsstrahlung, of the electrons is responsible for the strong electric field

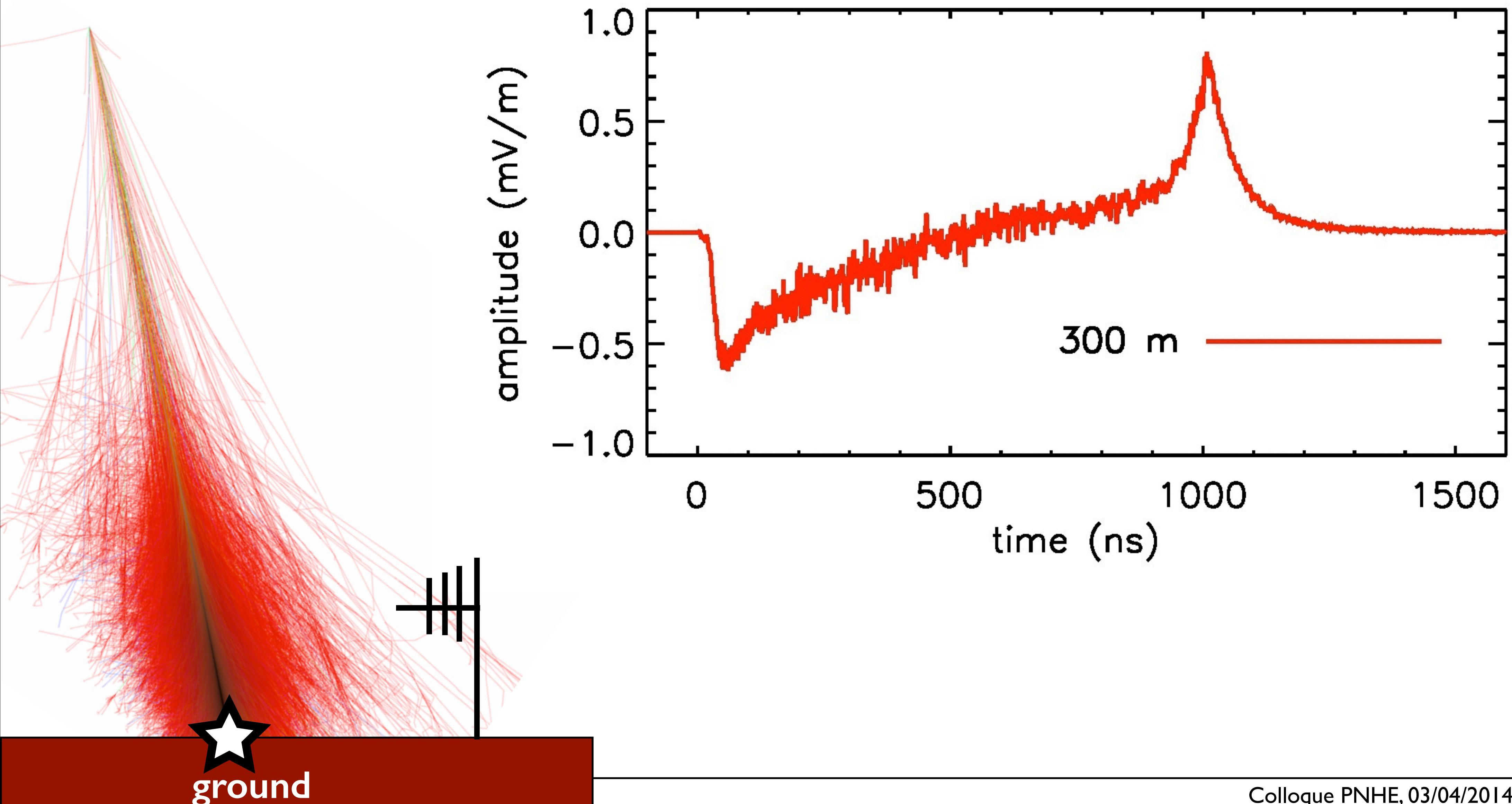
$$\begin{aligned} \mathbf{J}(x, y, z, t) \\ \rho(x, y, z, t) \end{aligned}$$



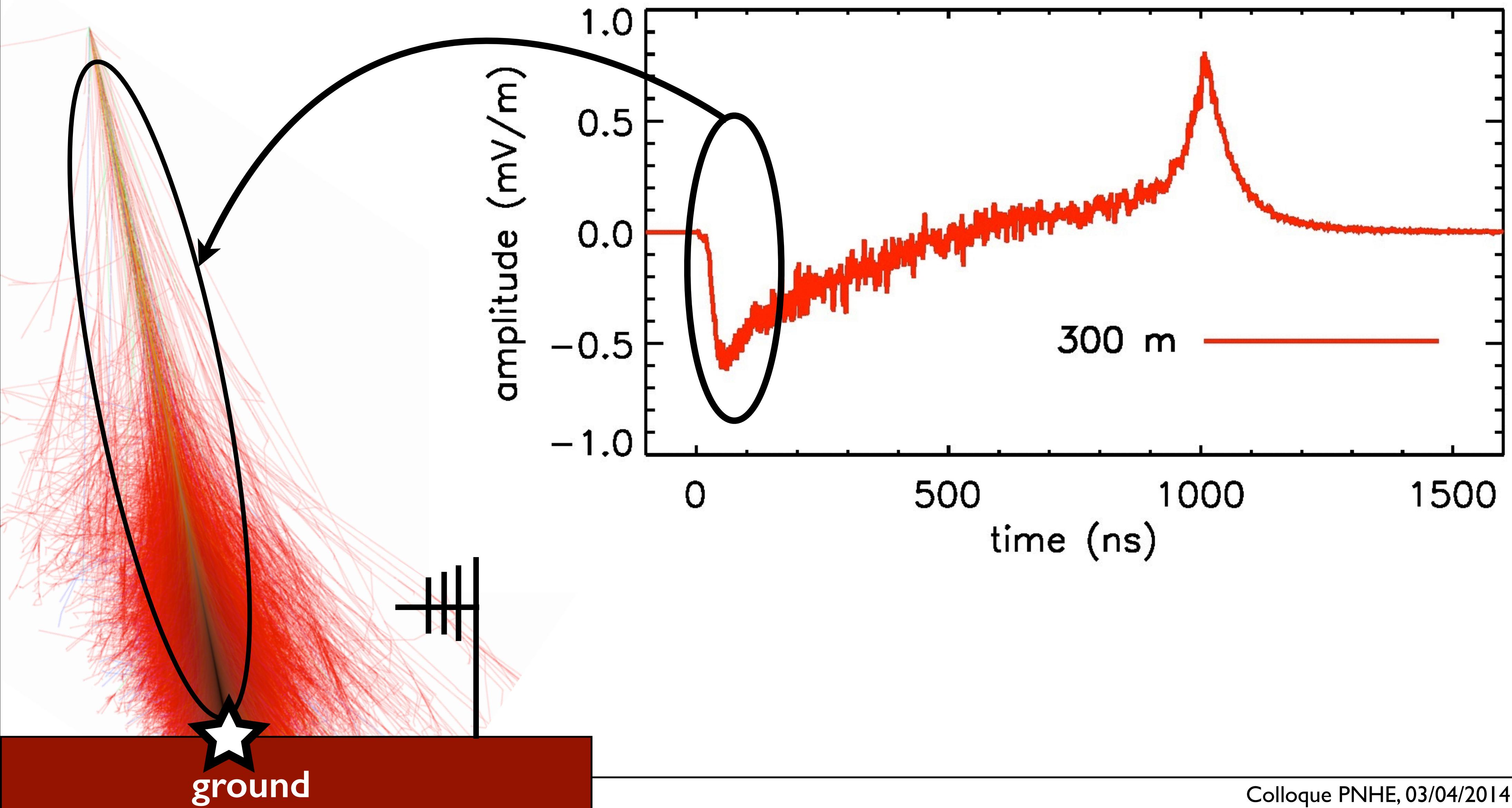
ground

Characterize the sudden death signal with the simulation (code SELFAS)

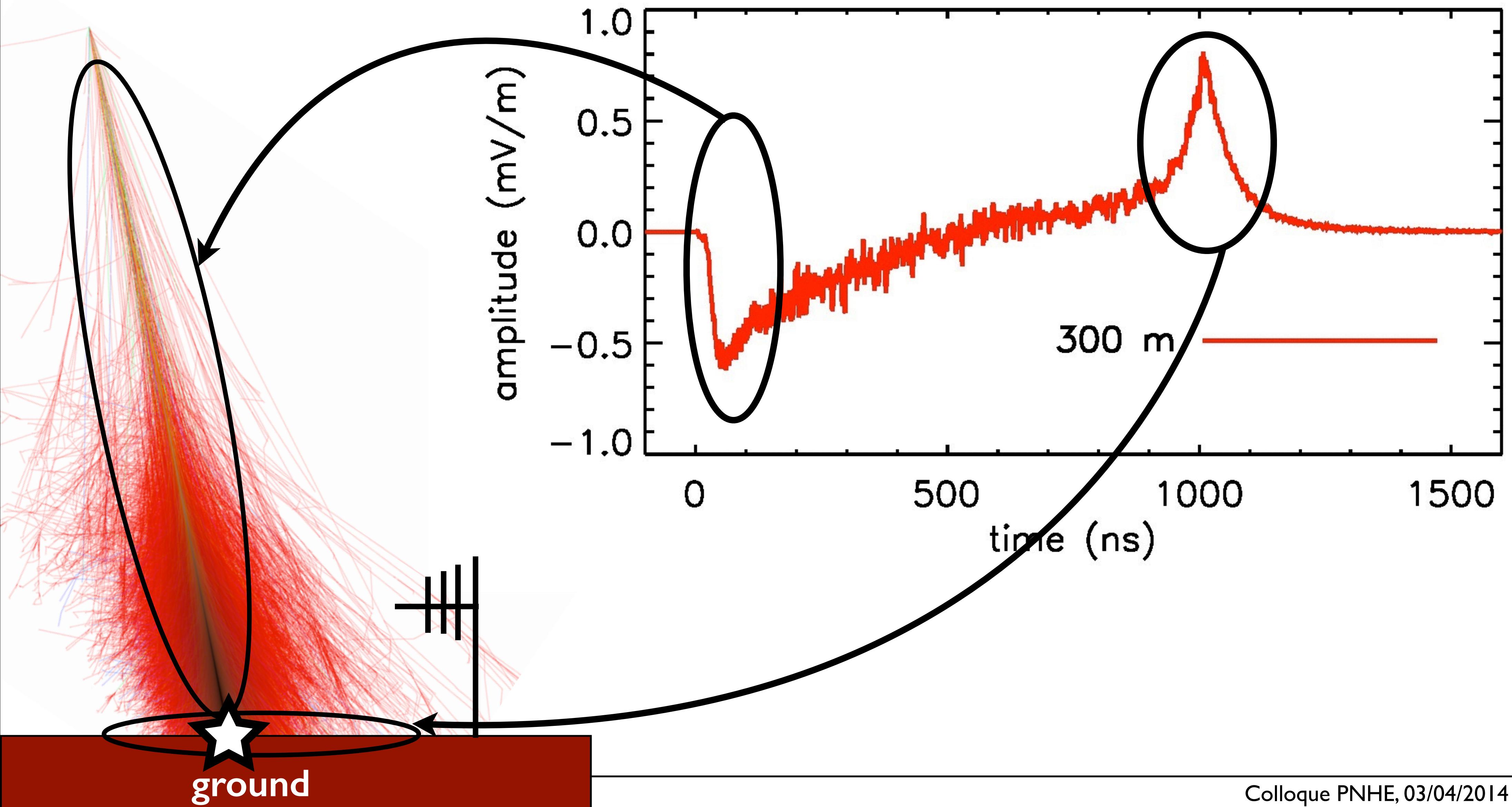
# Sudden death pulse



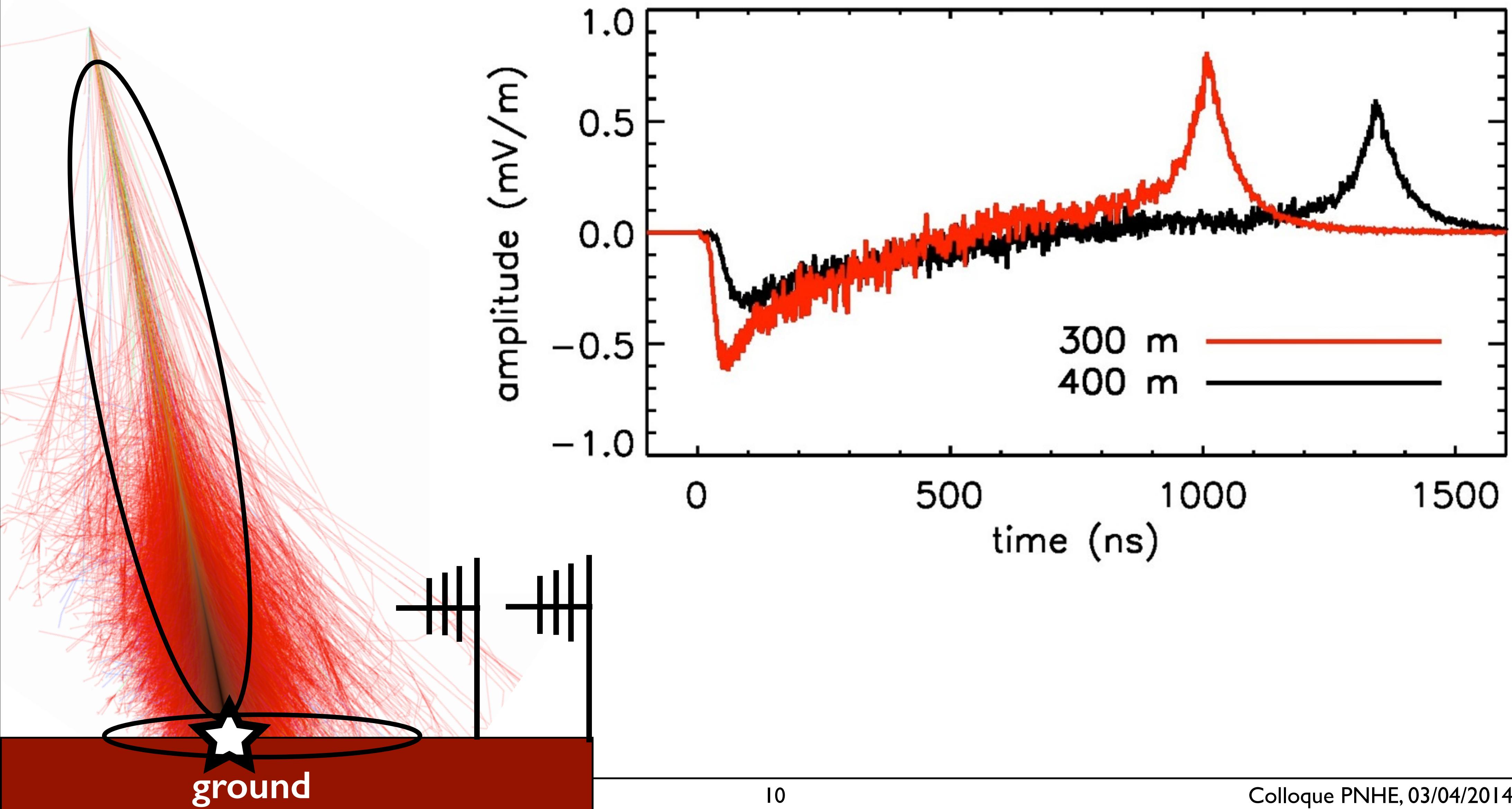
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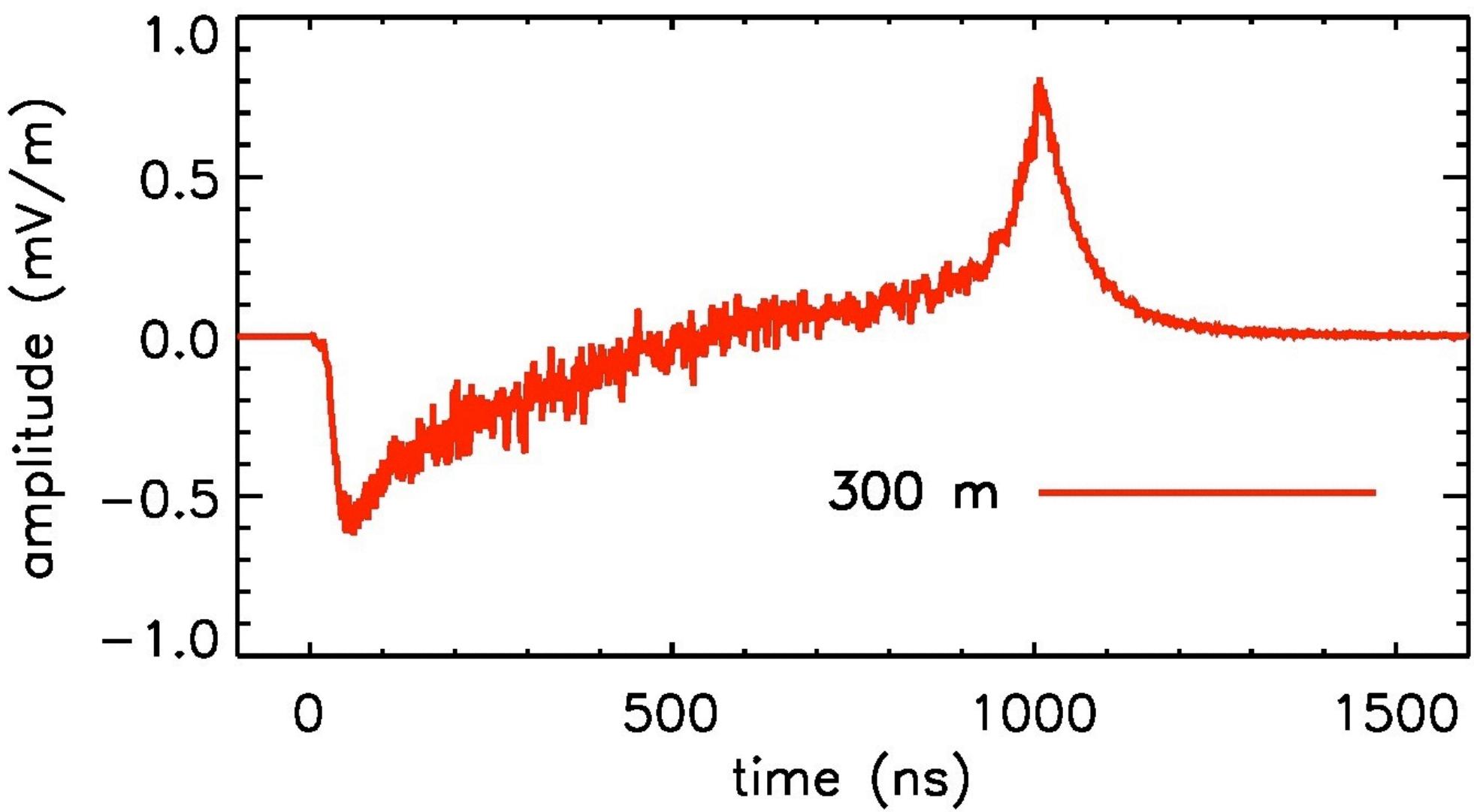
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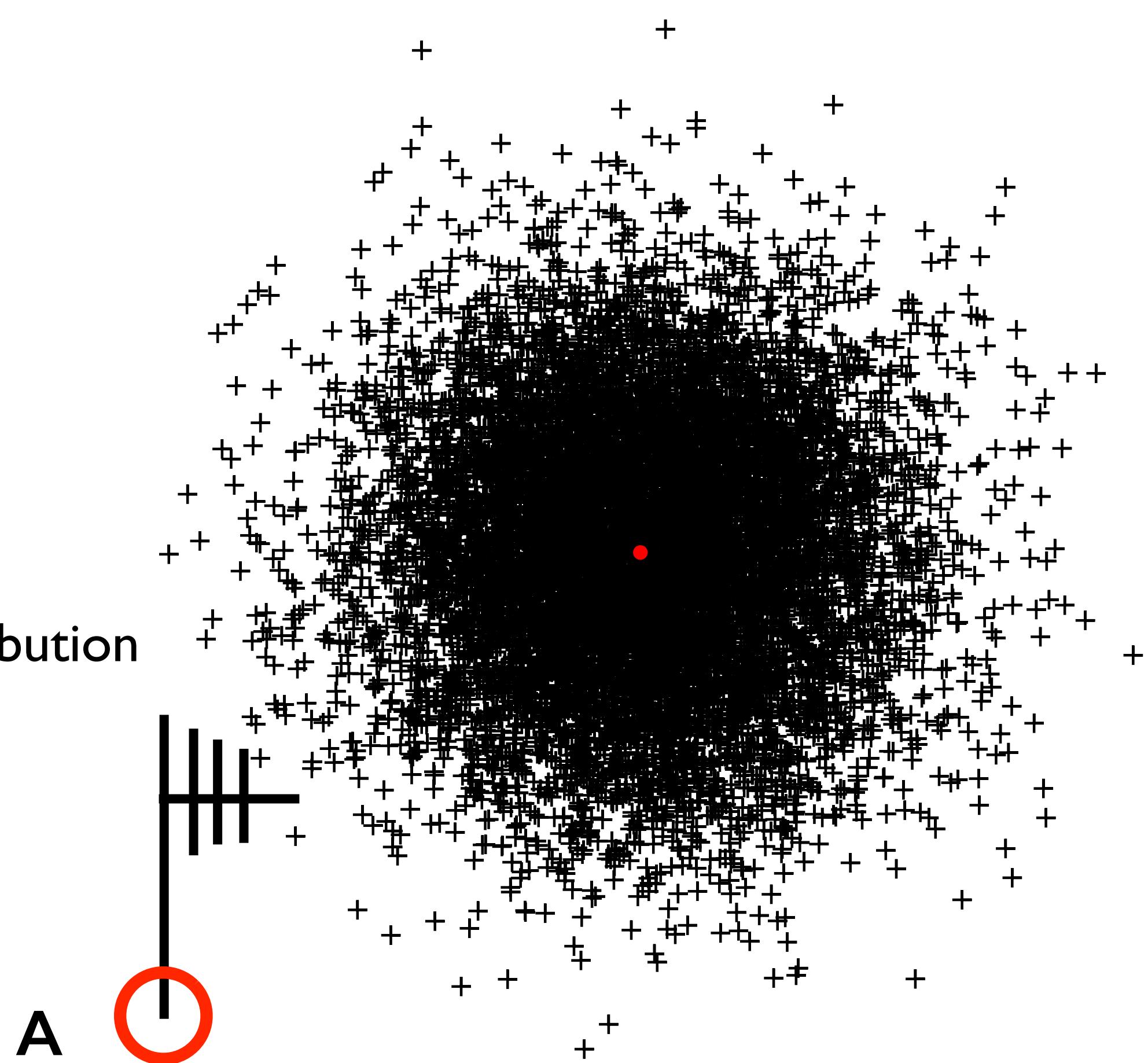
# Sudden death model: amplitude, time structure



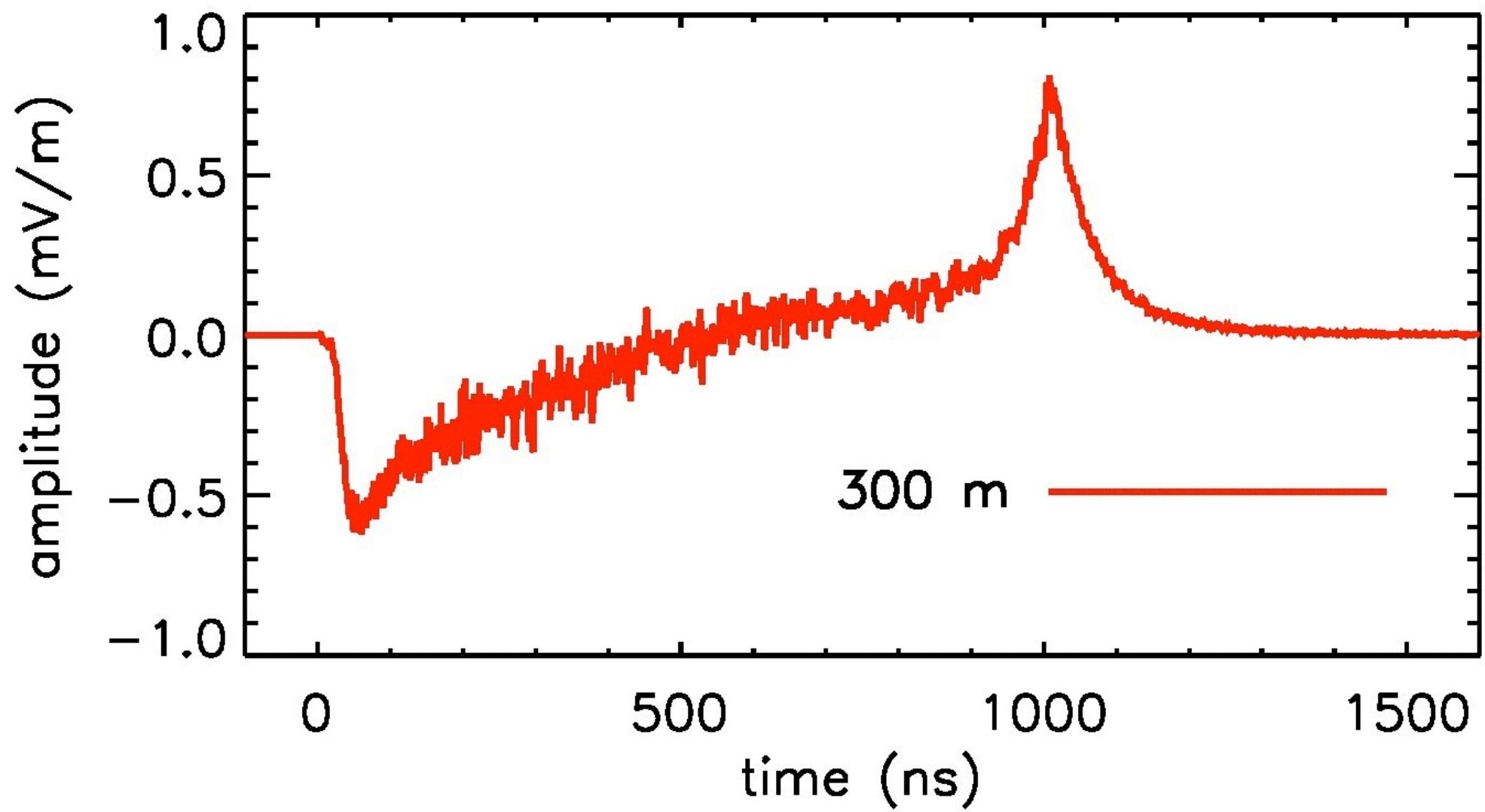
- simple model based on the ground particles distribution
- validated for vertical and inclined showers

$$s(t = r/c) \propto \int_0^{2\pi} \mathcal{L}(\rho) d\phi$$

correlated to the total  
number of  $e^-/e^+$



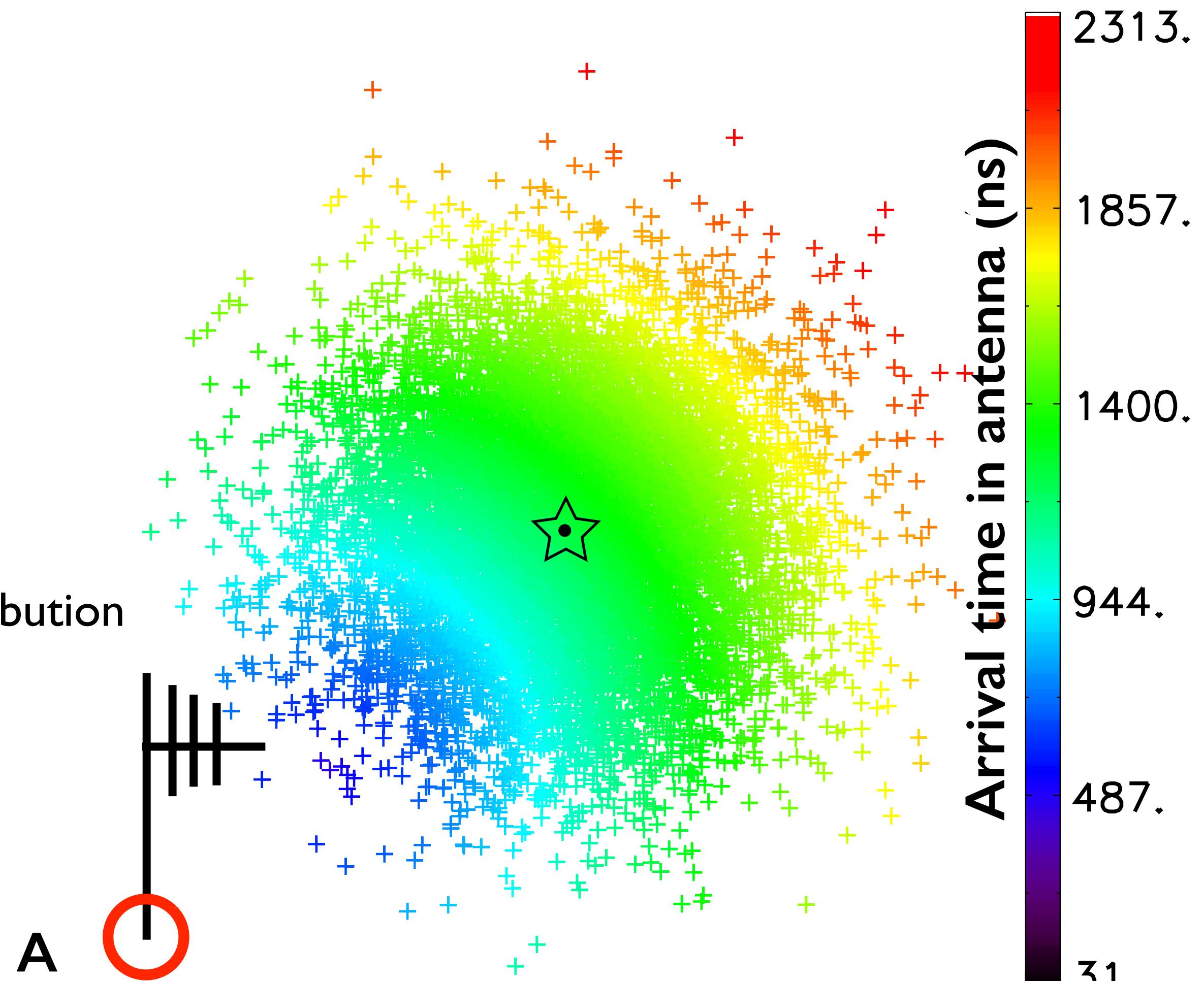
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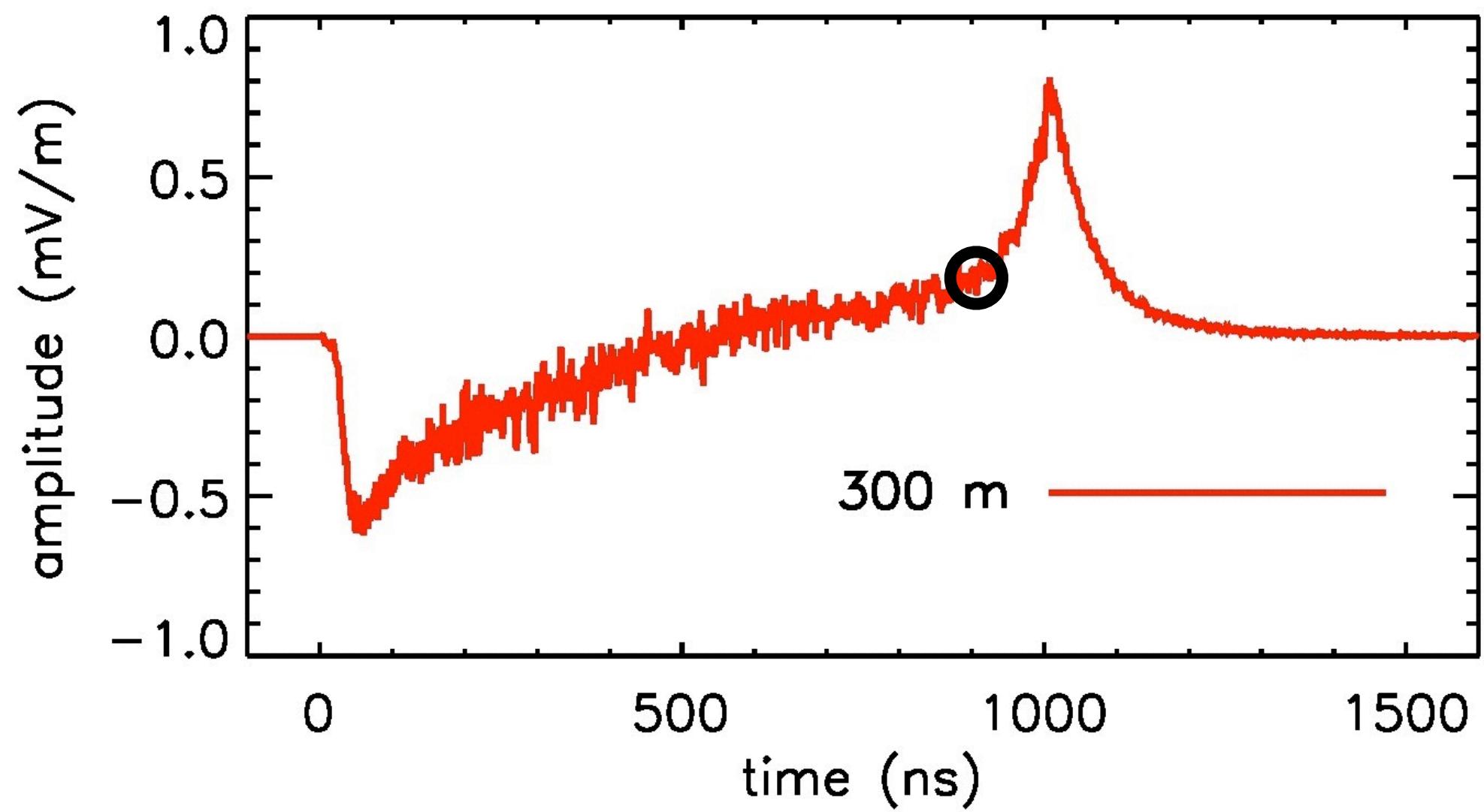
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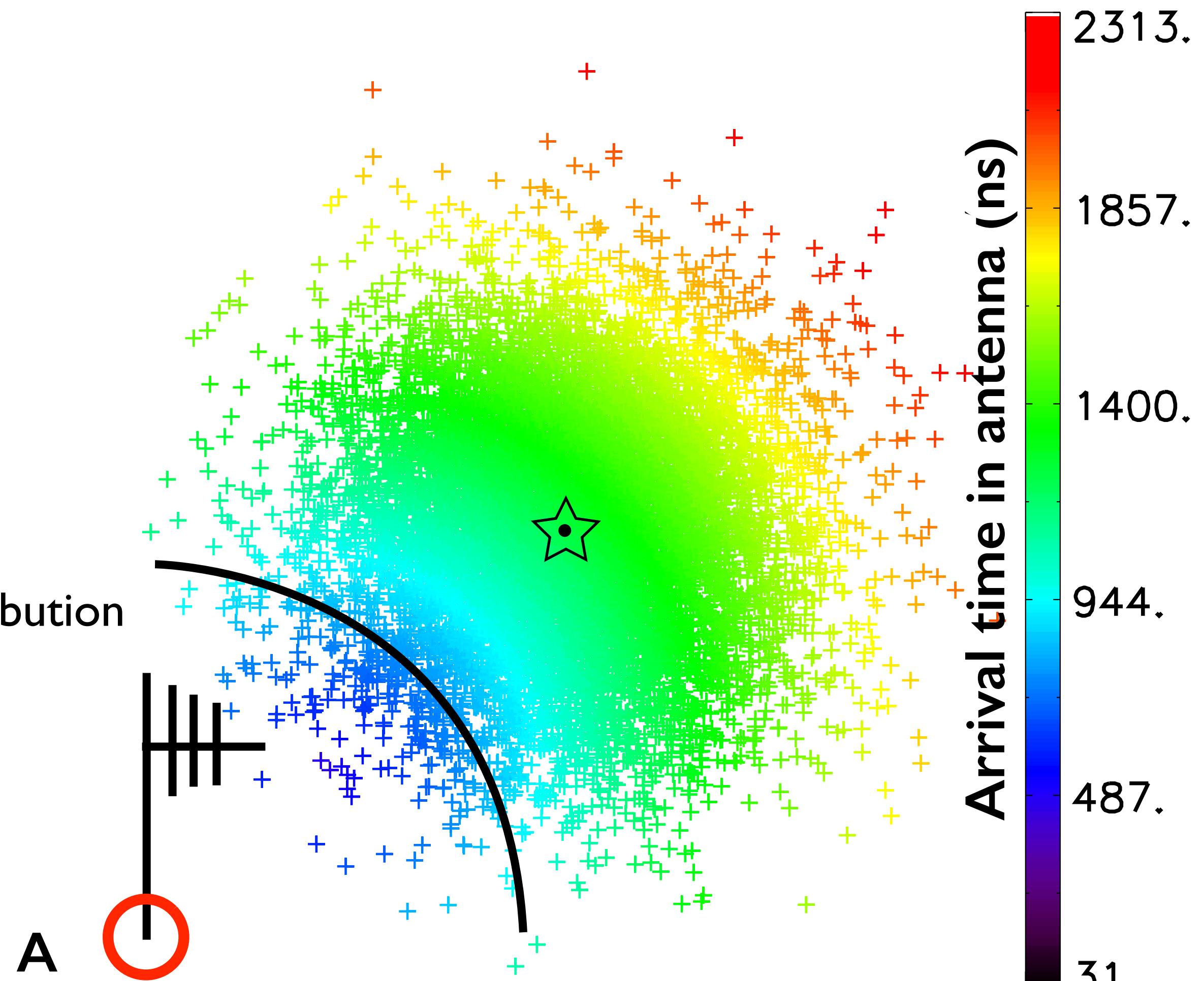
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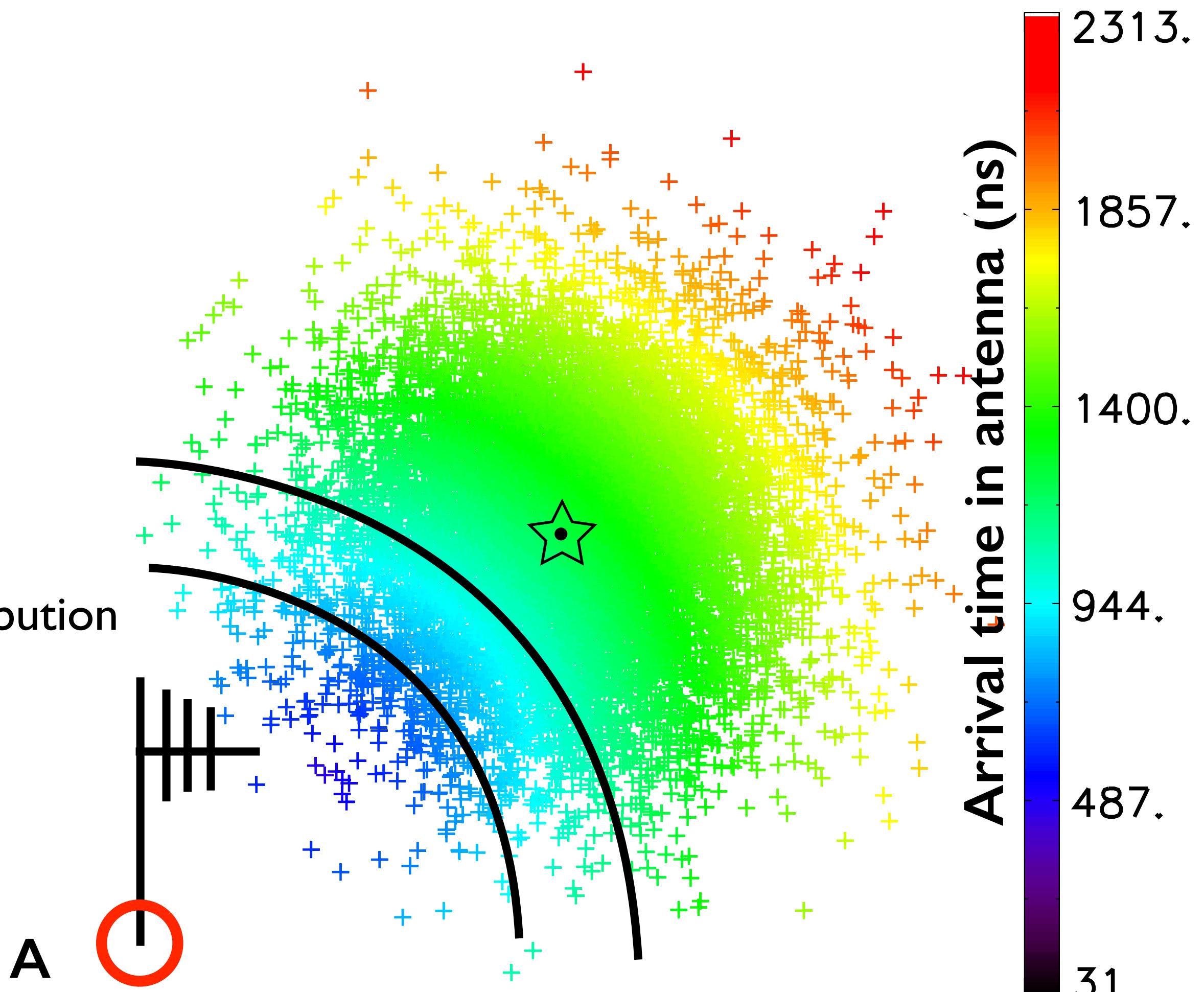
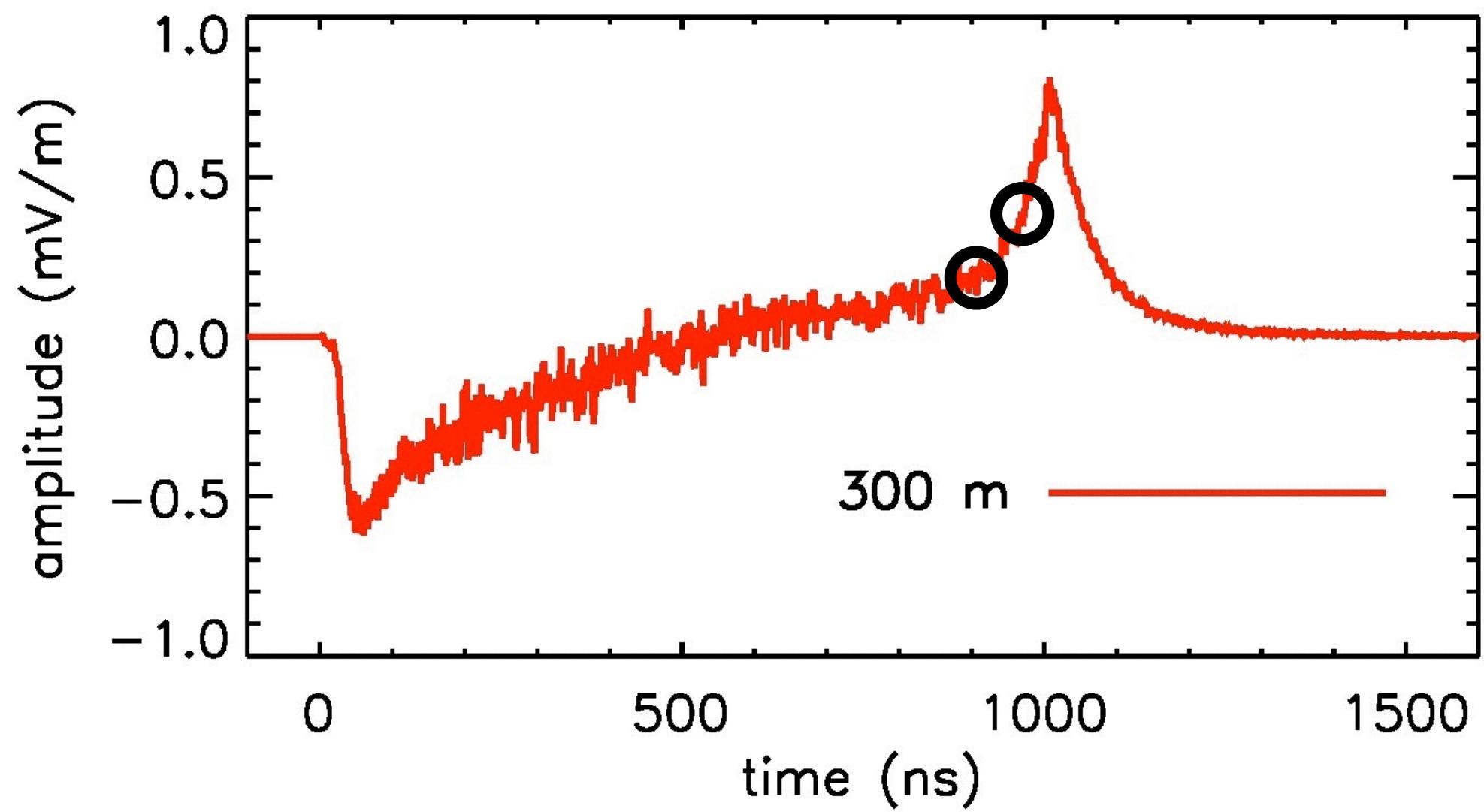
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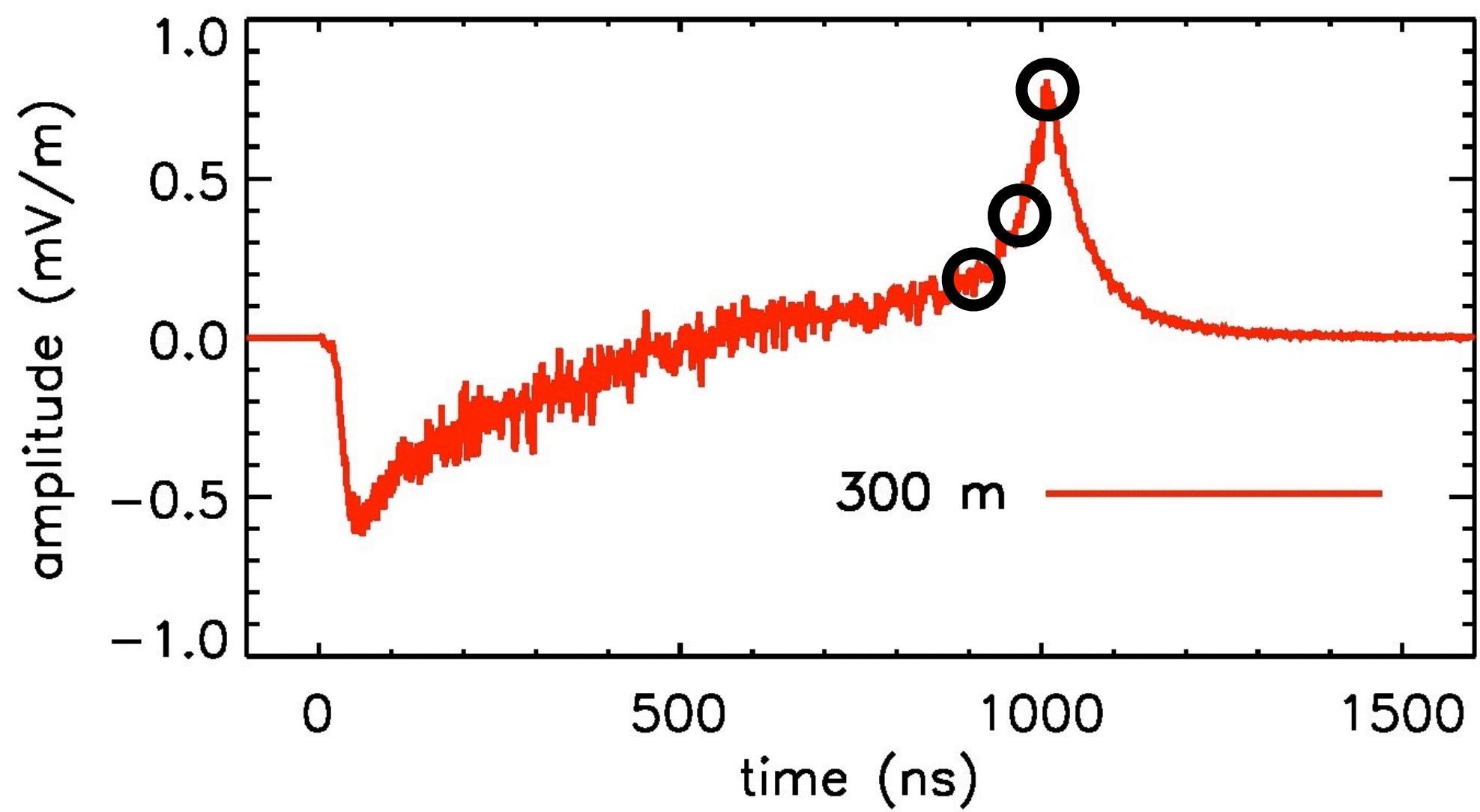


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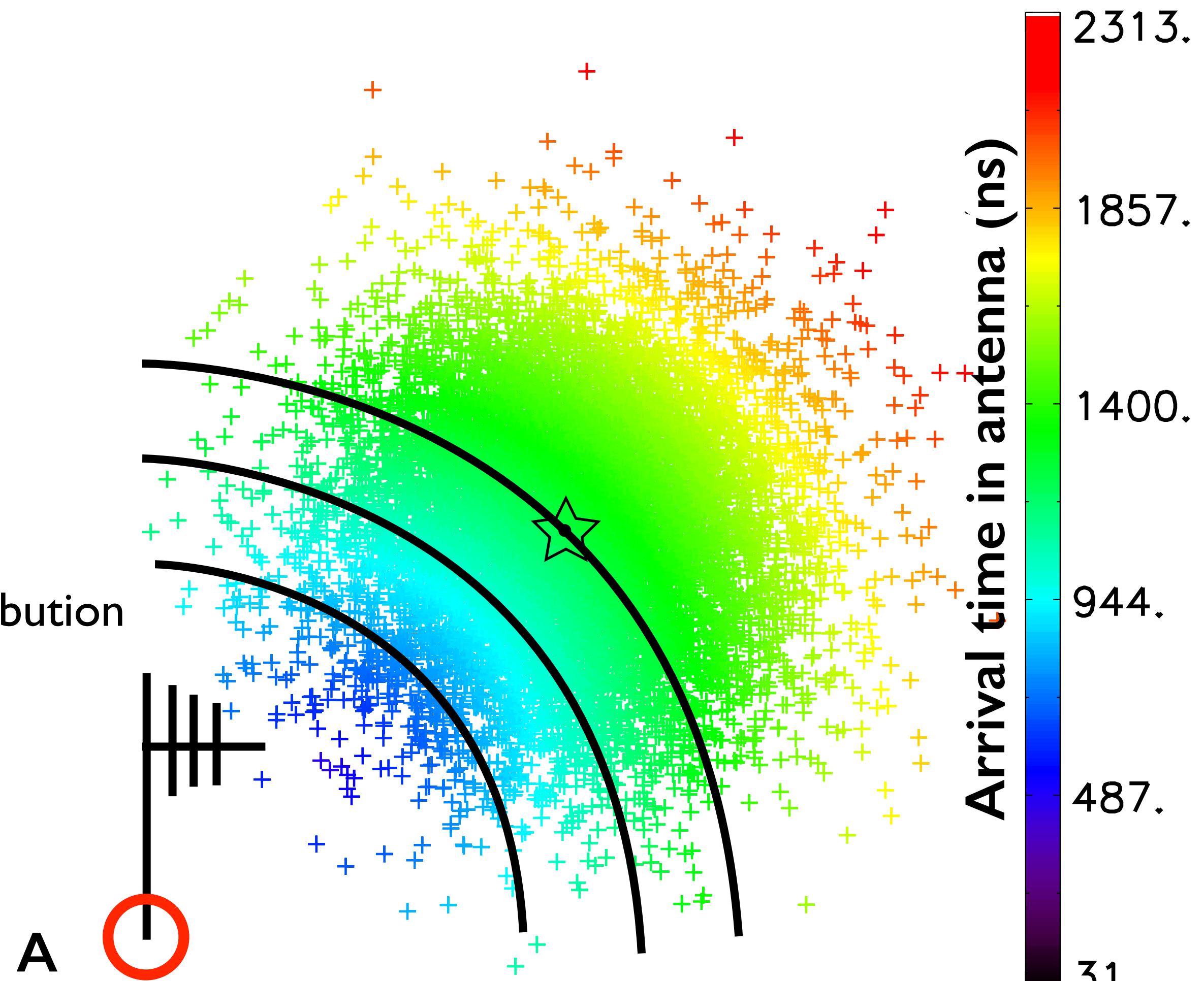
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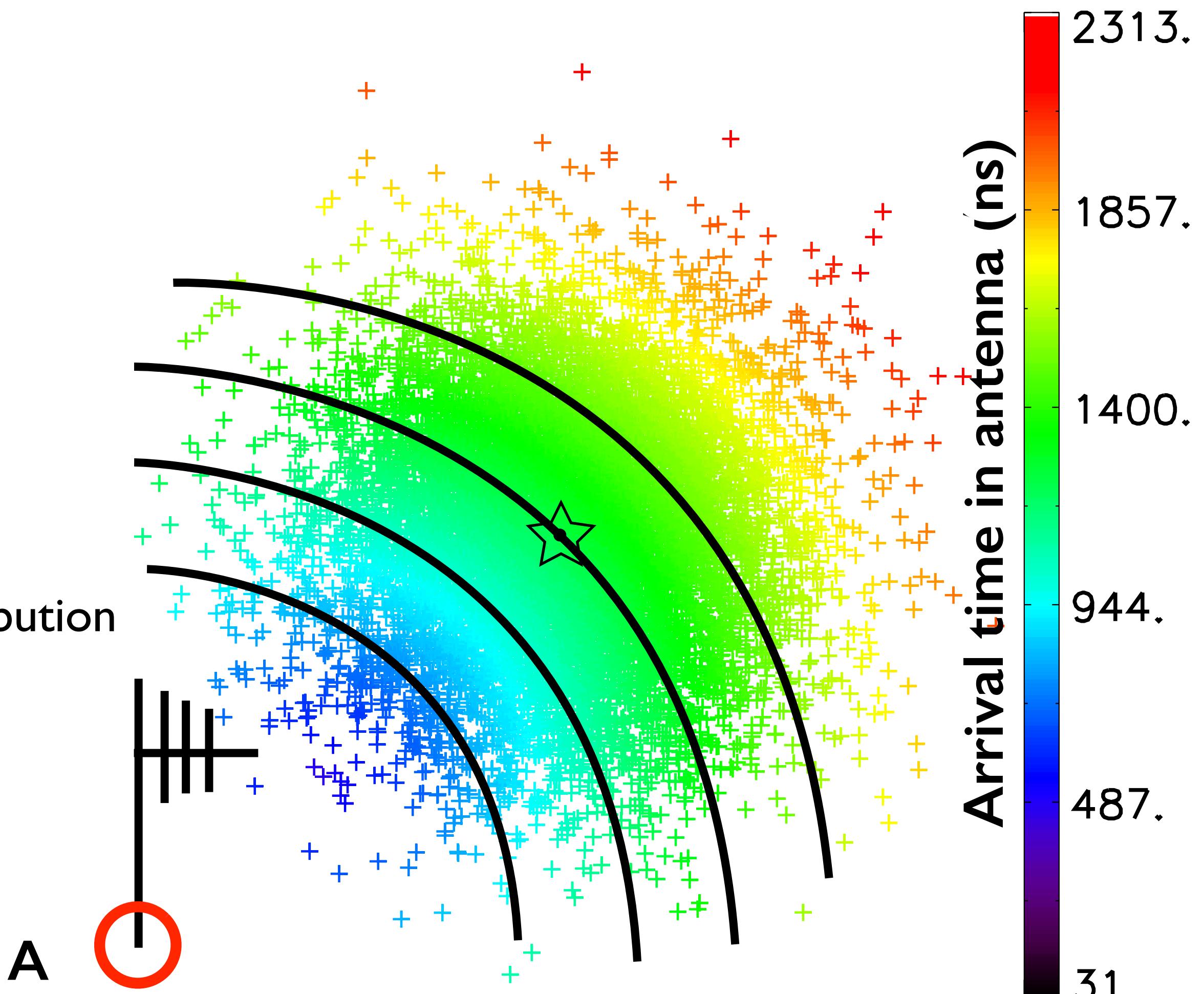
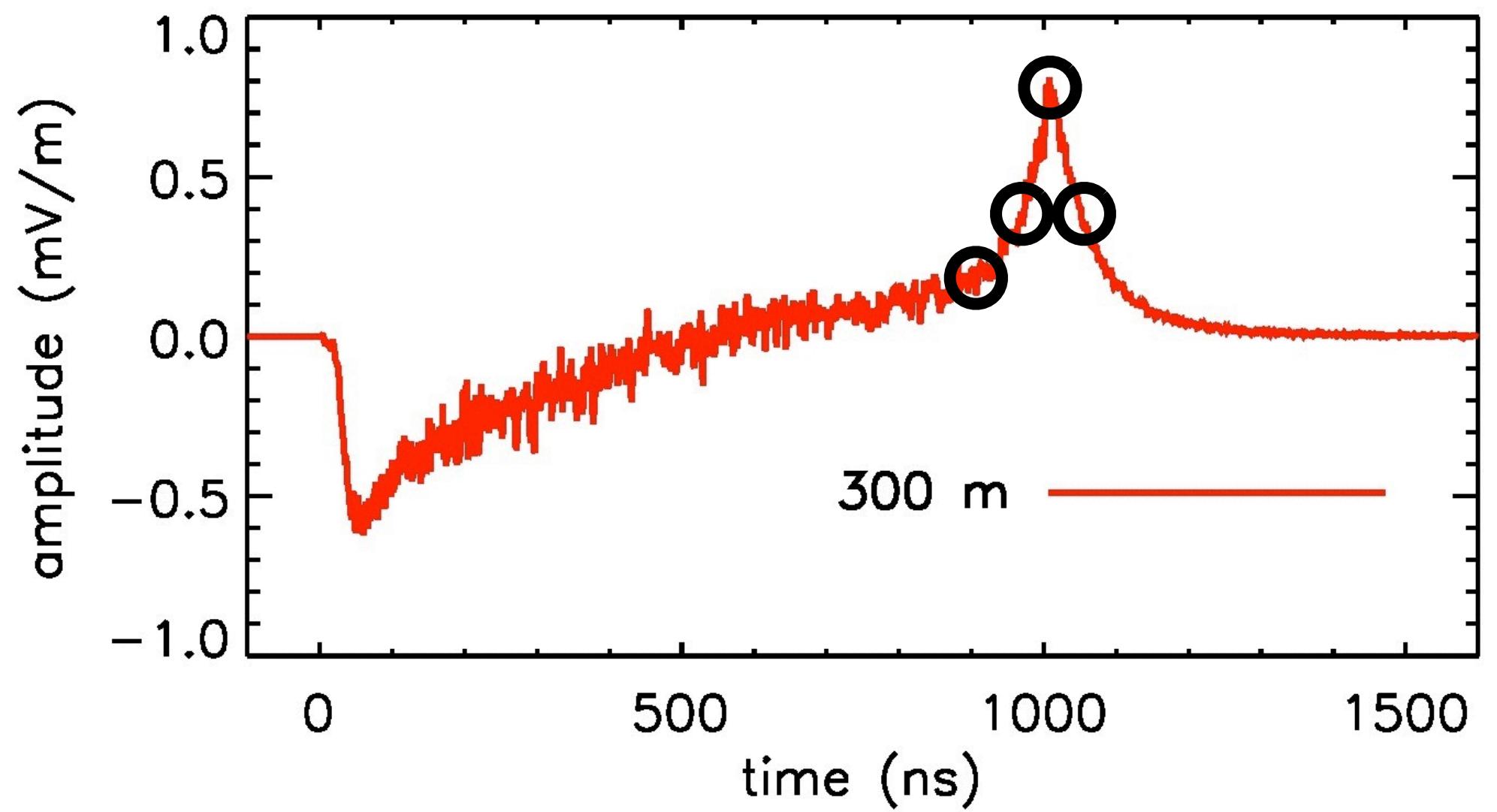
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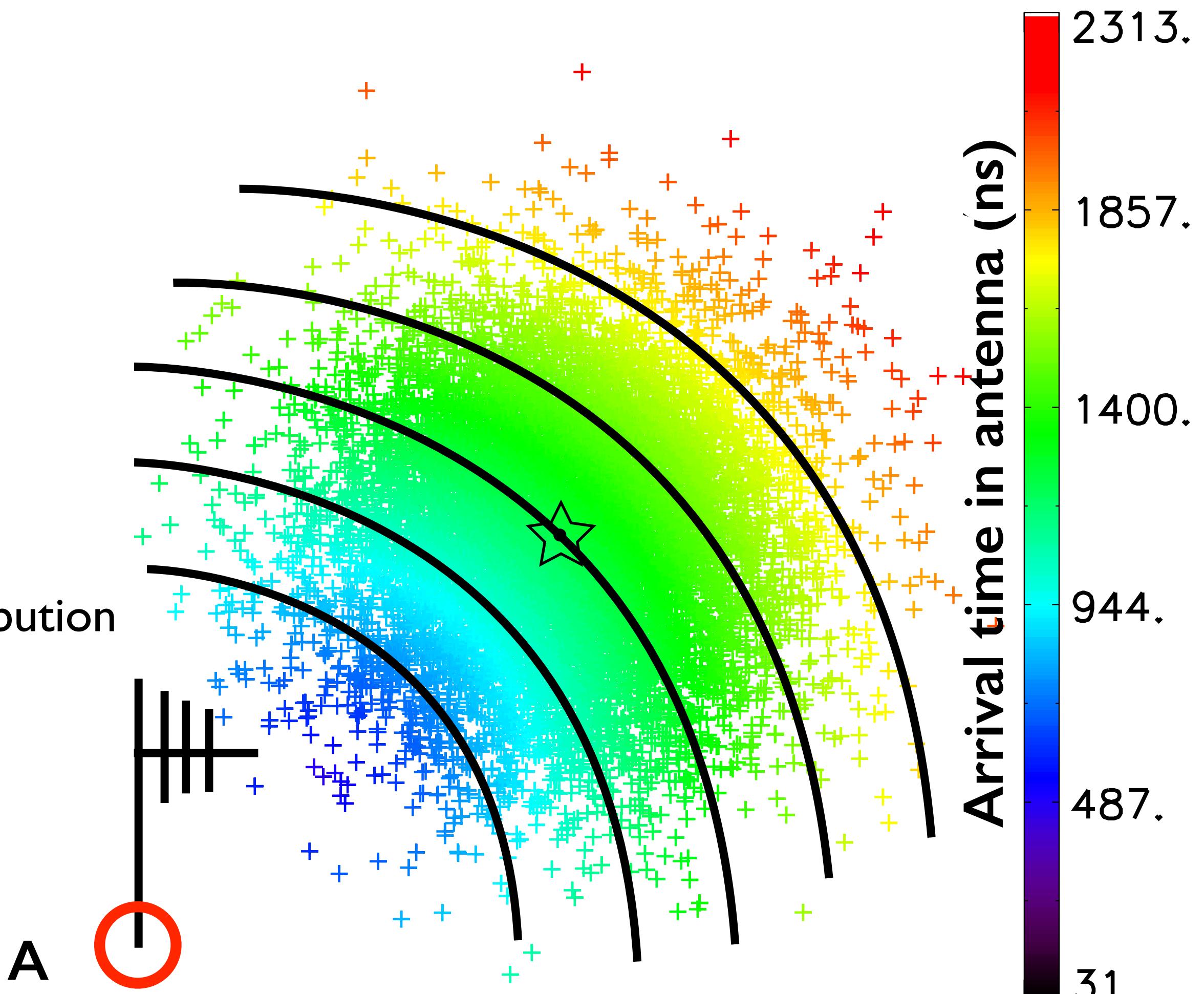
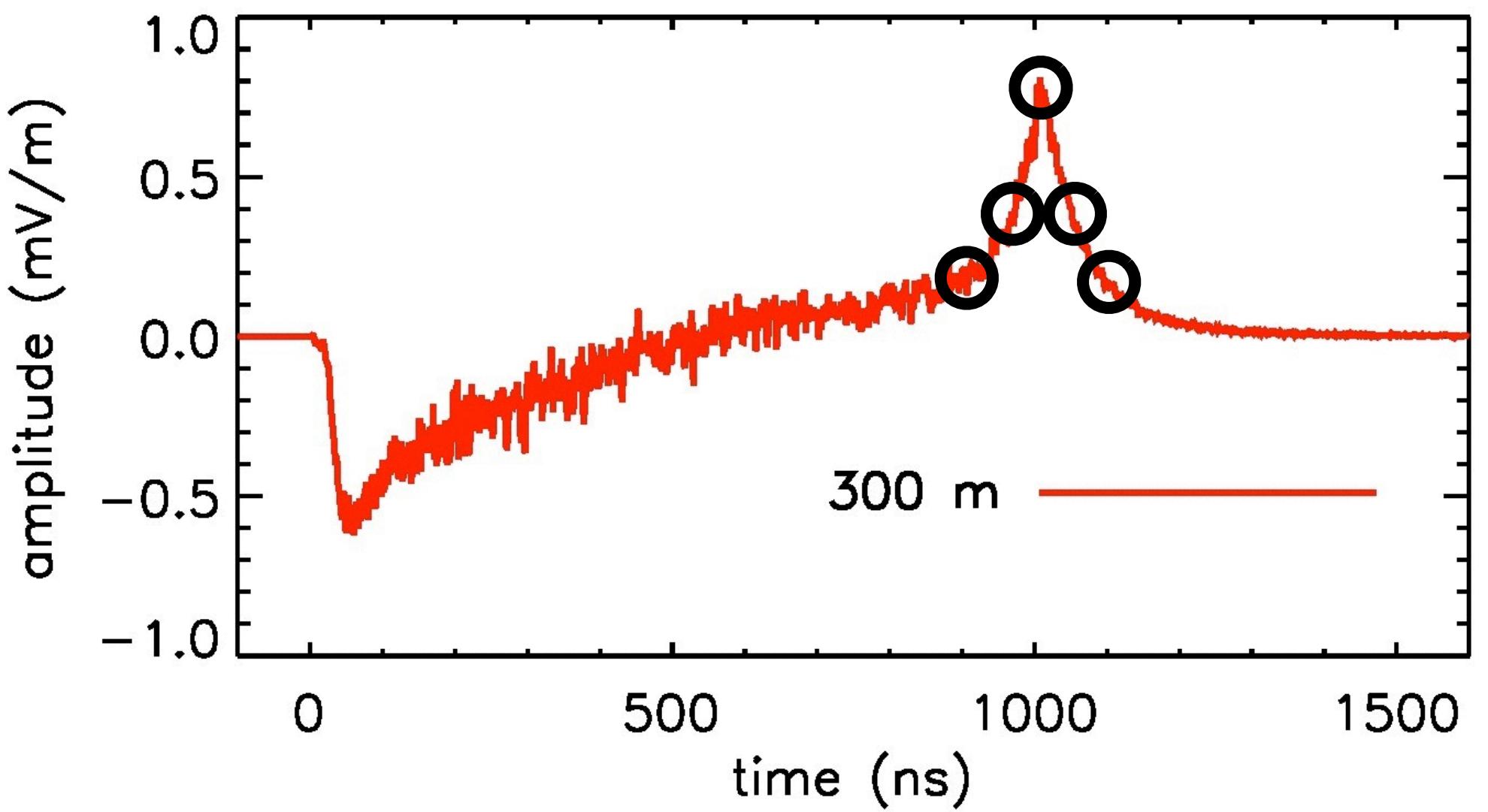


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# Sudden death pulse: some characteristics

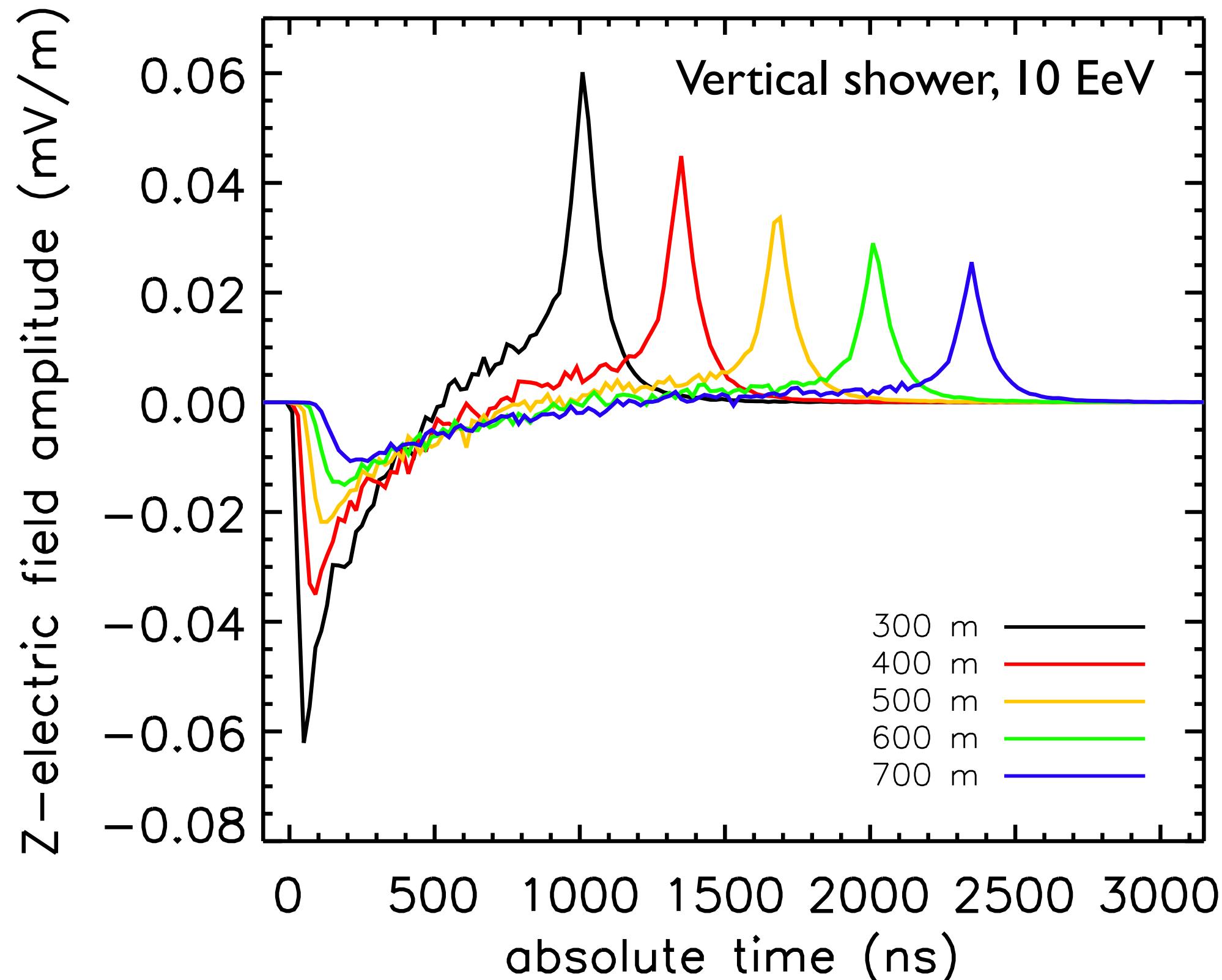
**Amplitude:** scales as  $E$

**Polarization:** lies in the plane transverse to the direction observer-shower core, vertical component

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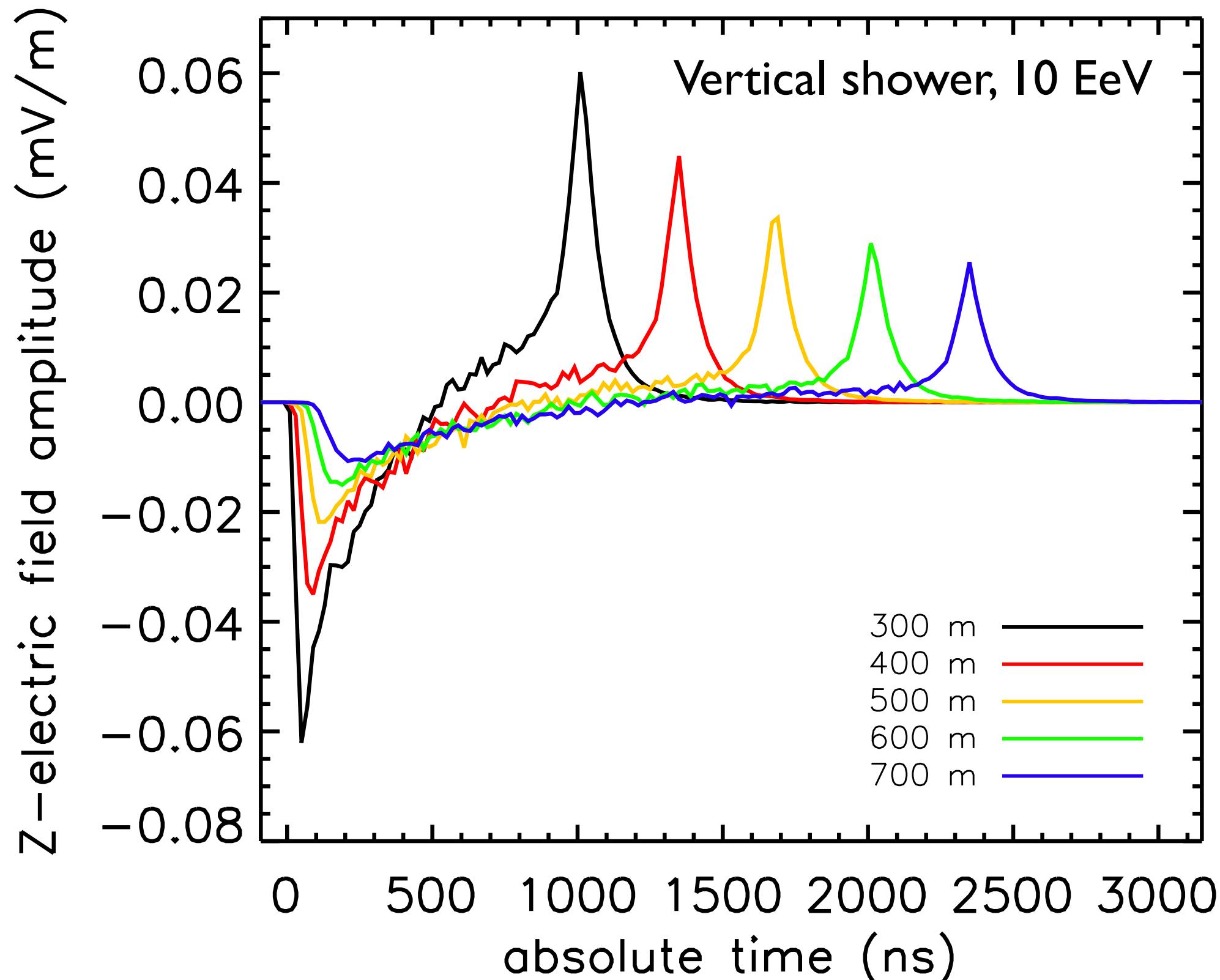


Principal pulse amplitude decreases exponentially,  
SDP amplitude decreases as  $1/d_{\text{core}}$

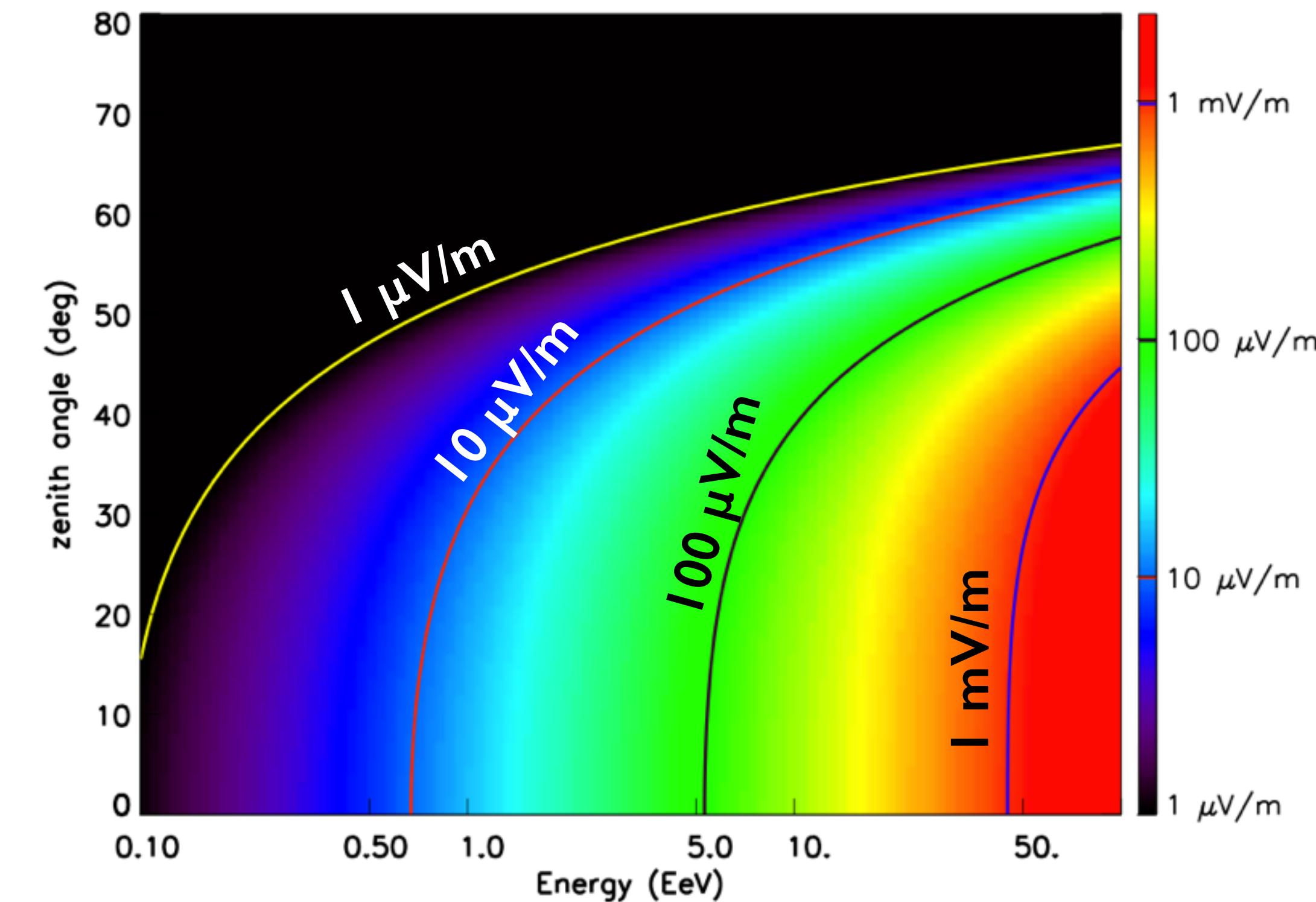
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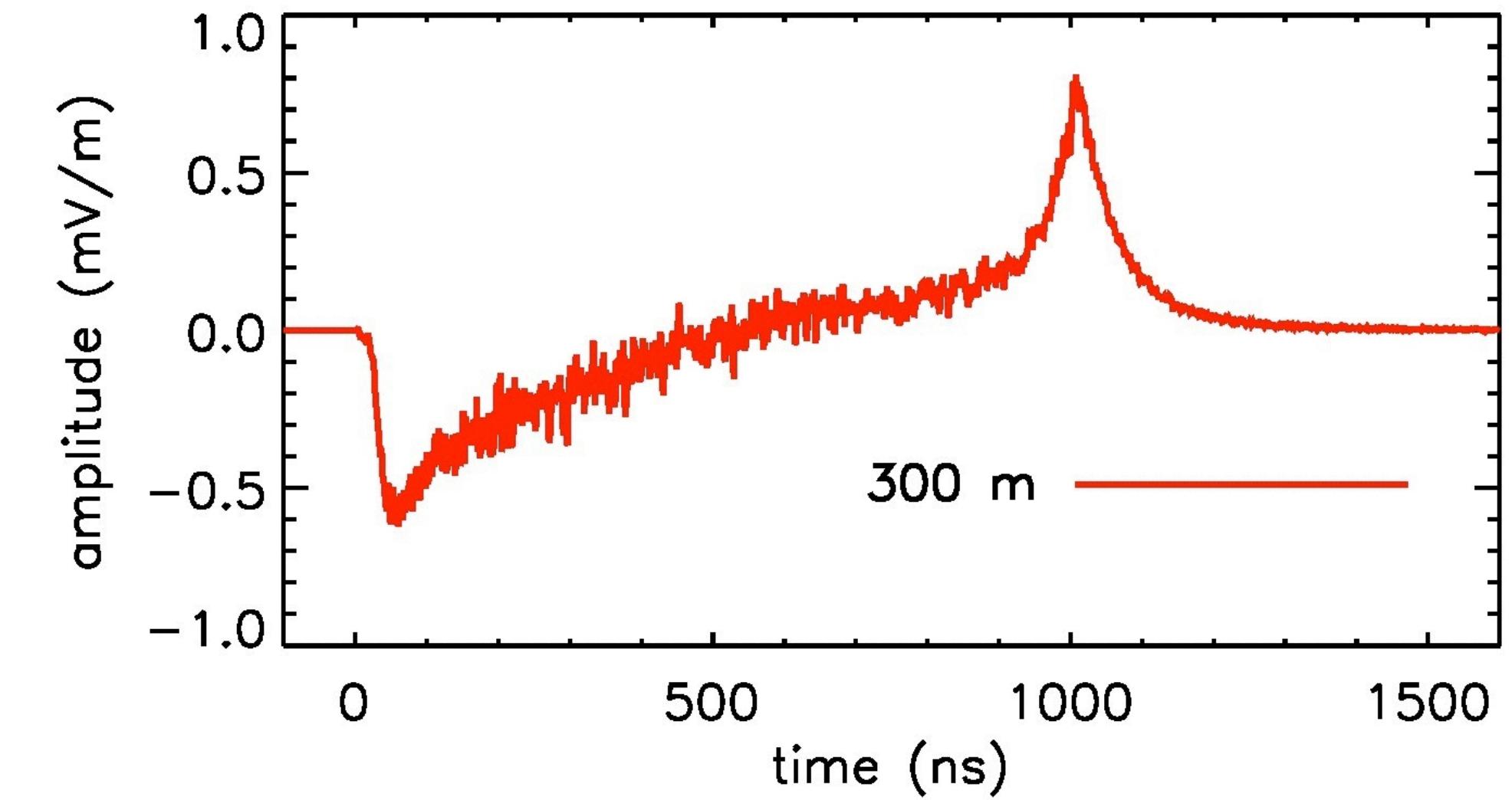
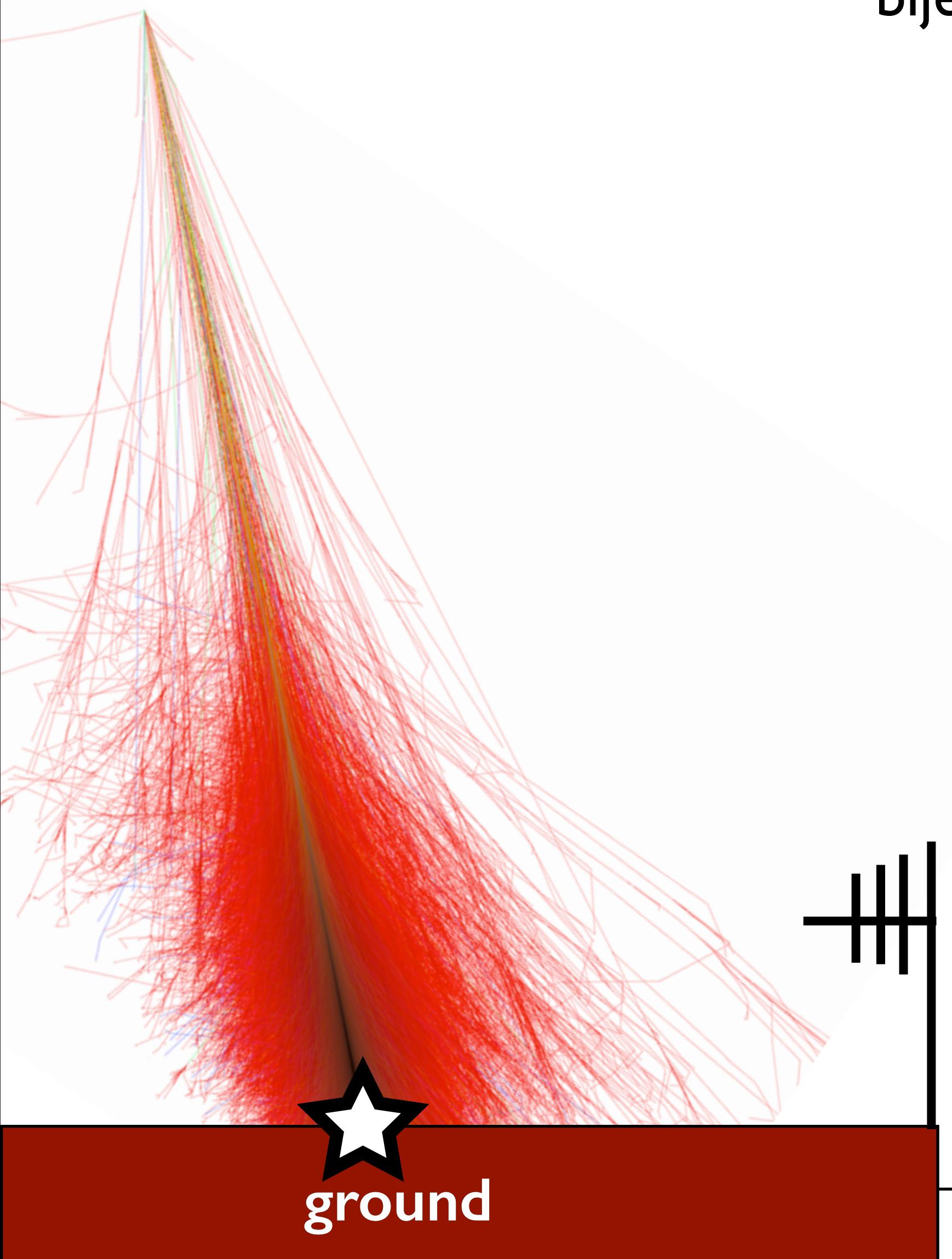
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Expected amplitude as a function of the primary characteristics detectable for a wide range of shower parameters

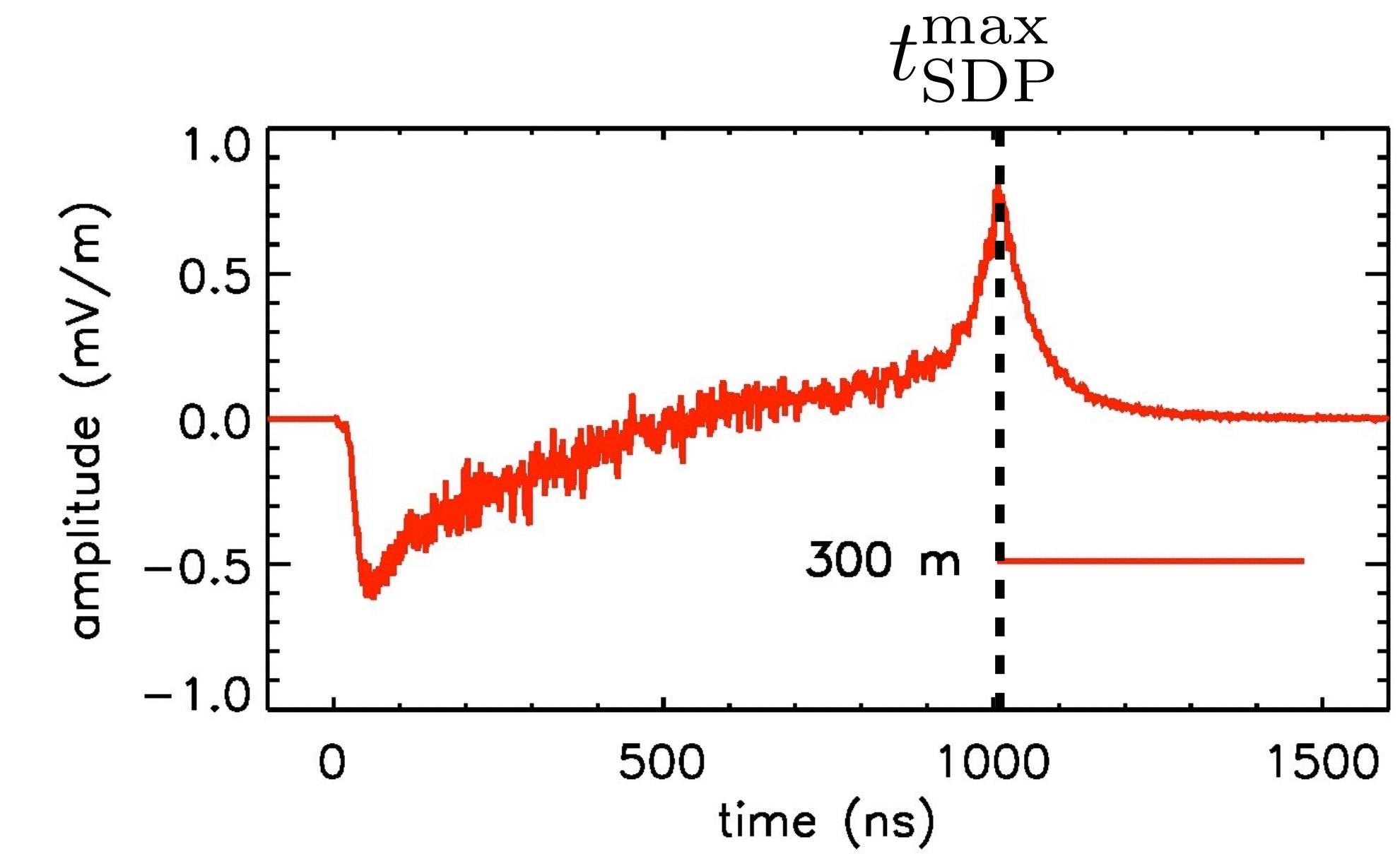
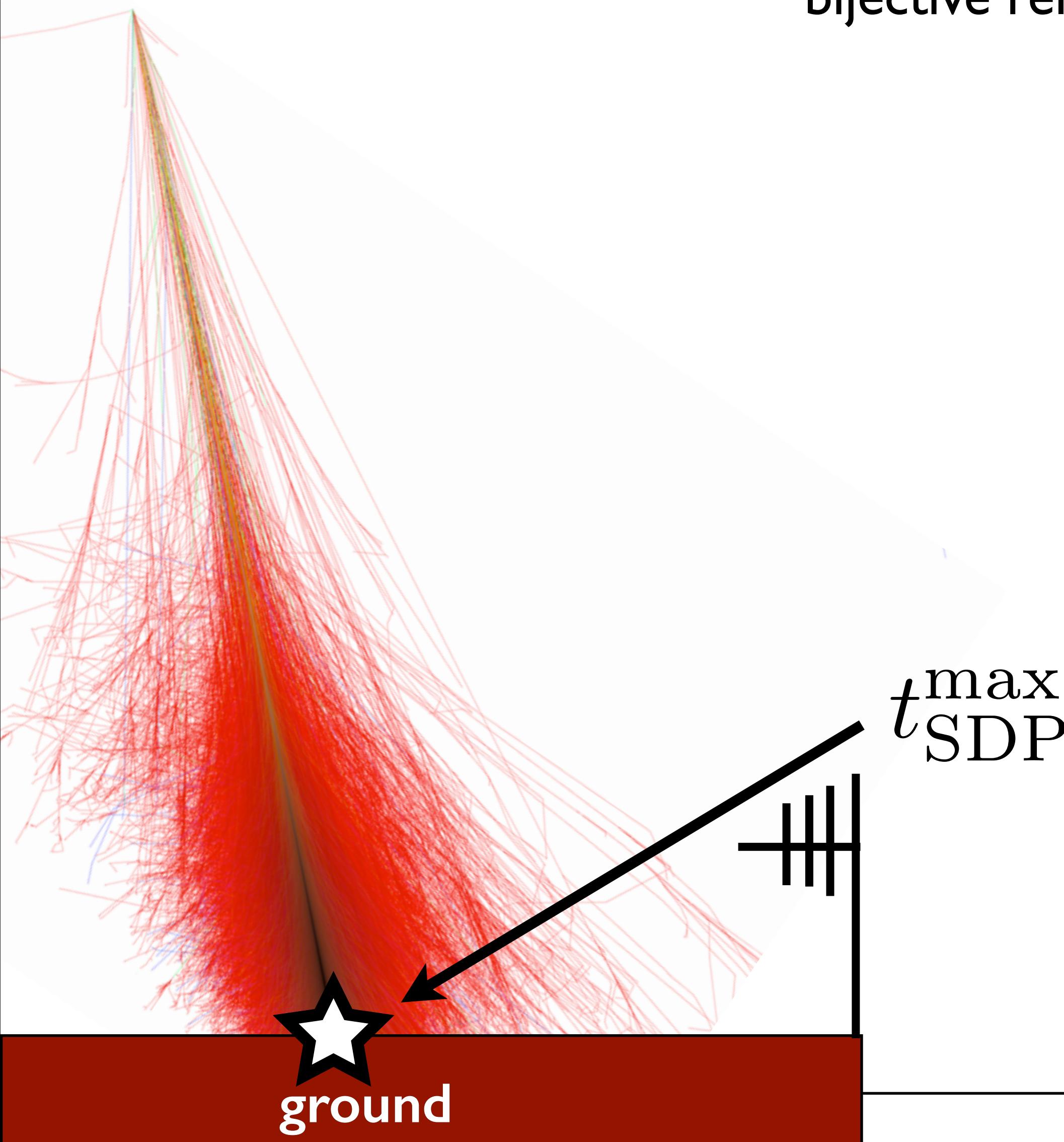
# Sudden death signal: absolute timing

bijective relation between the time in the antenna and the shower development



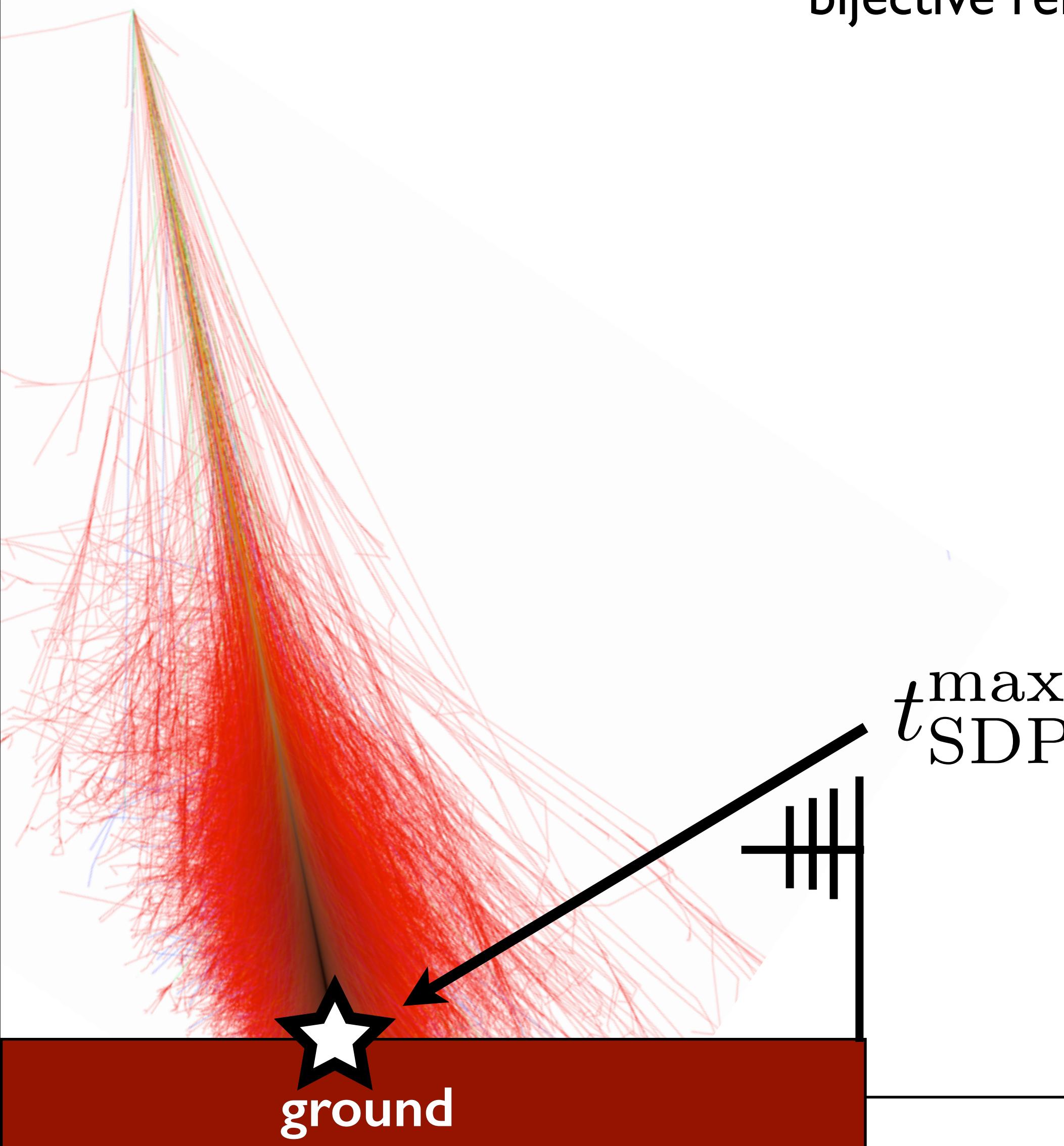
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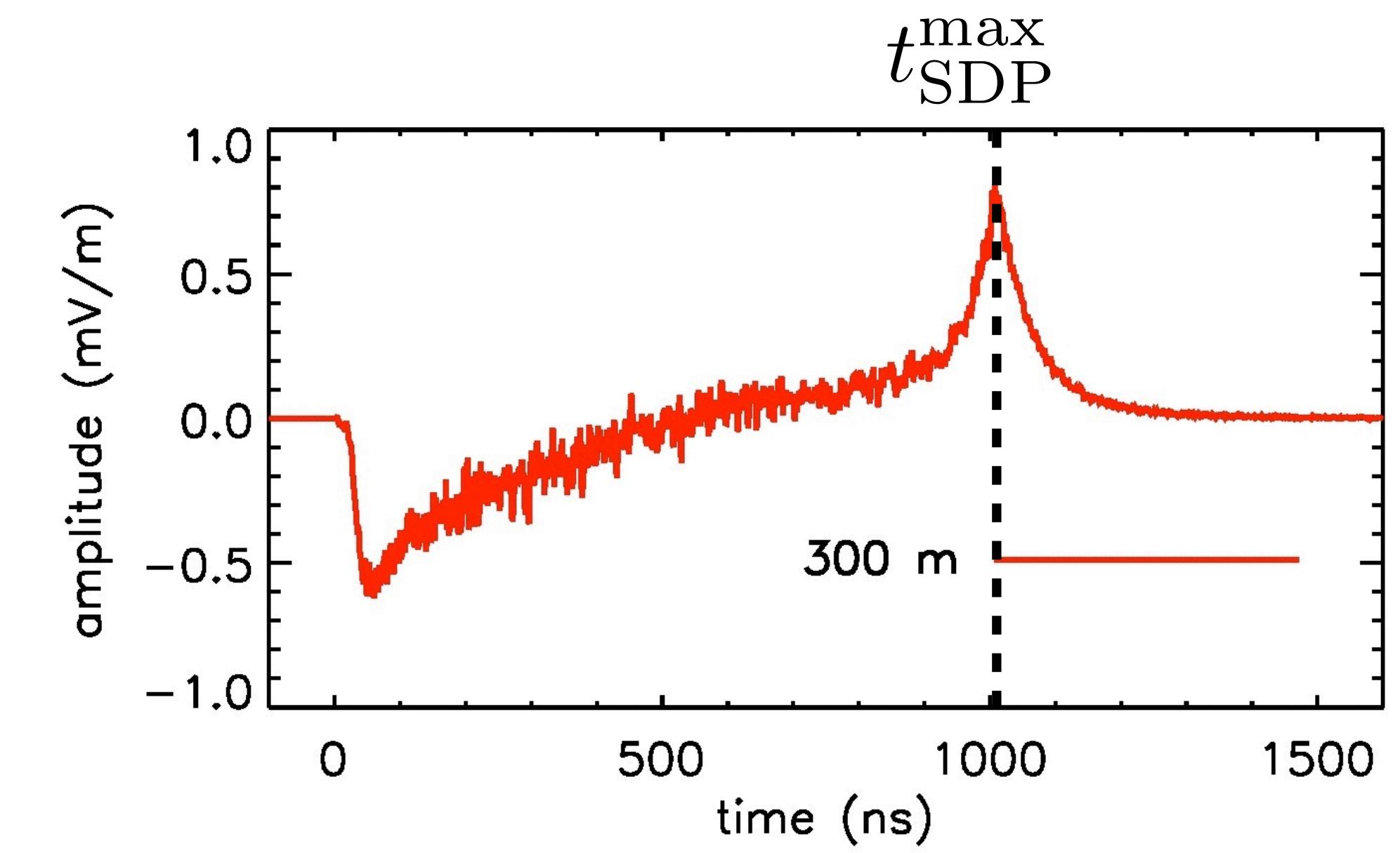


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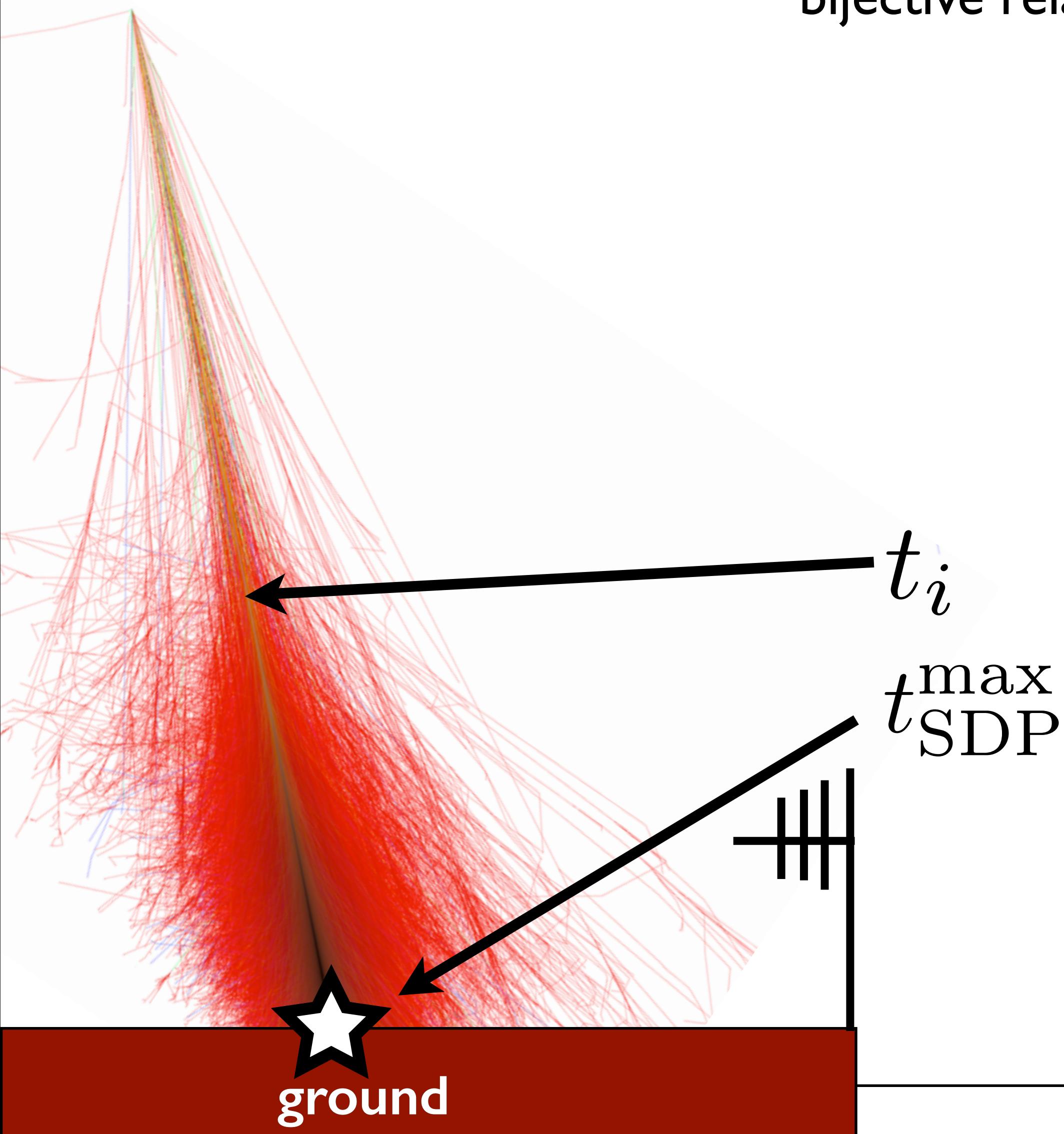


$t_i$

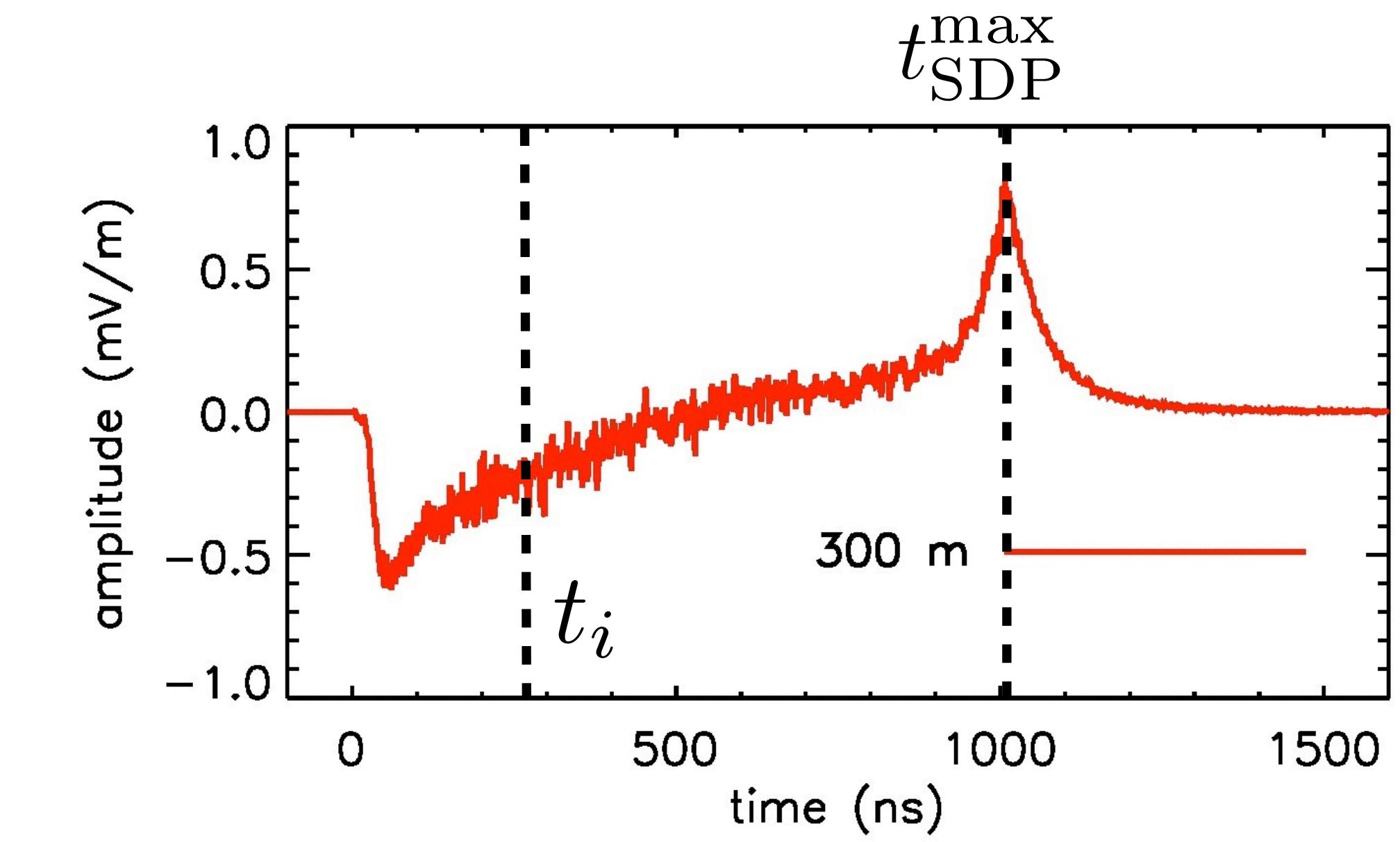


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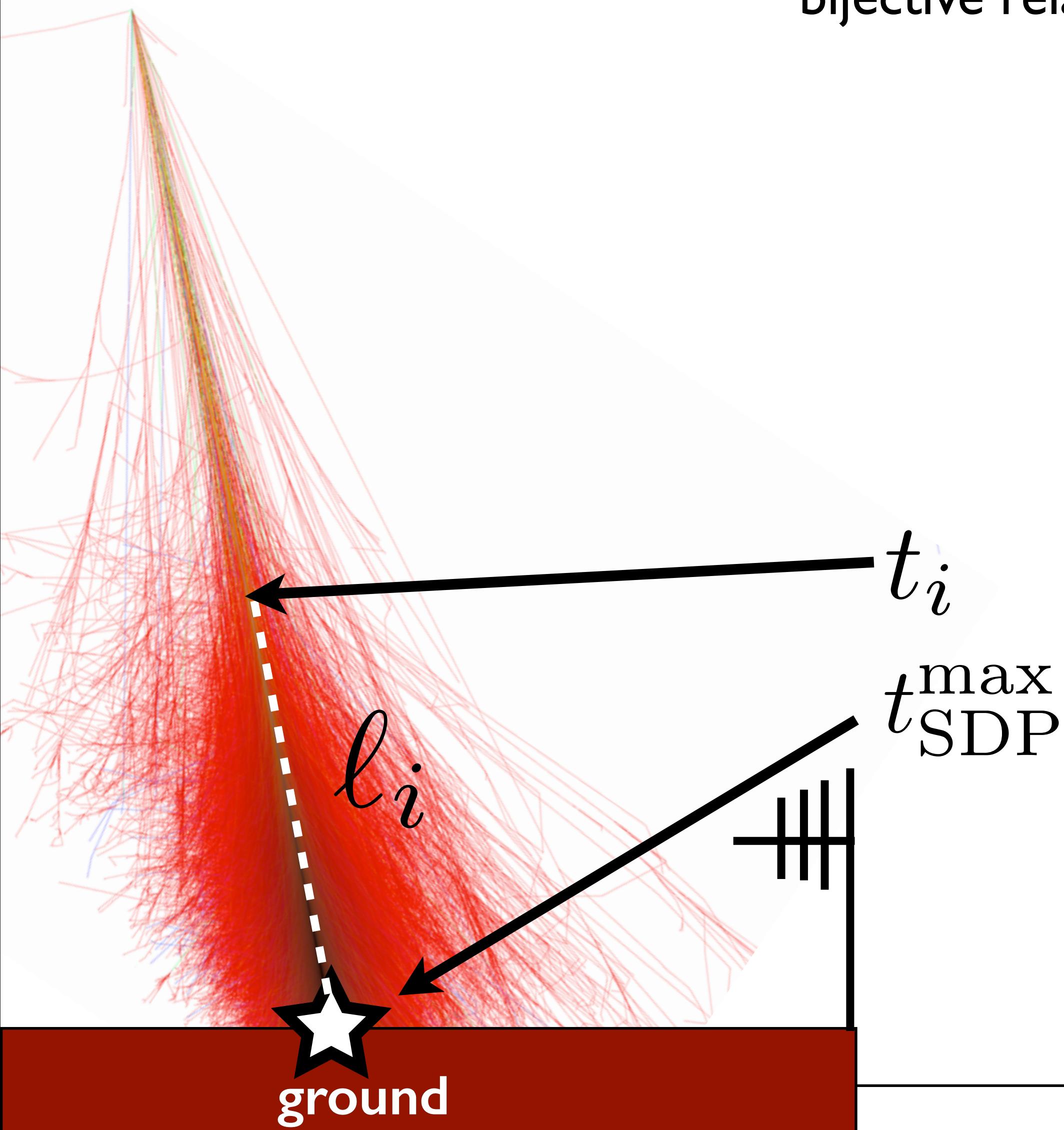


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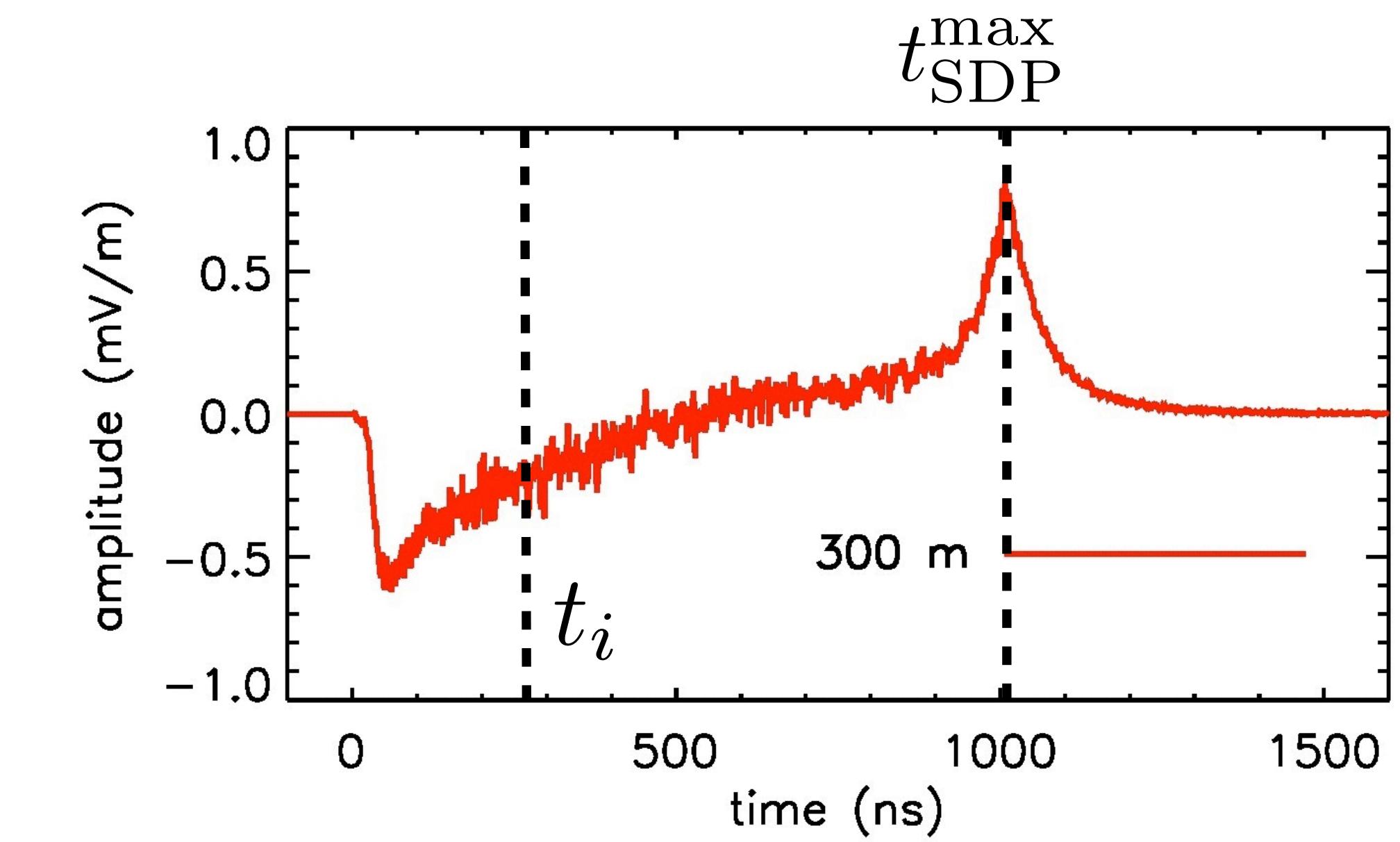


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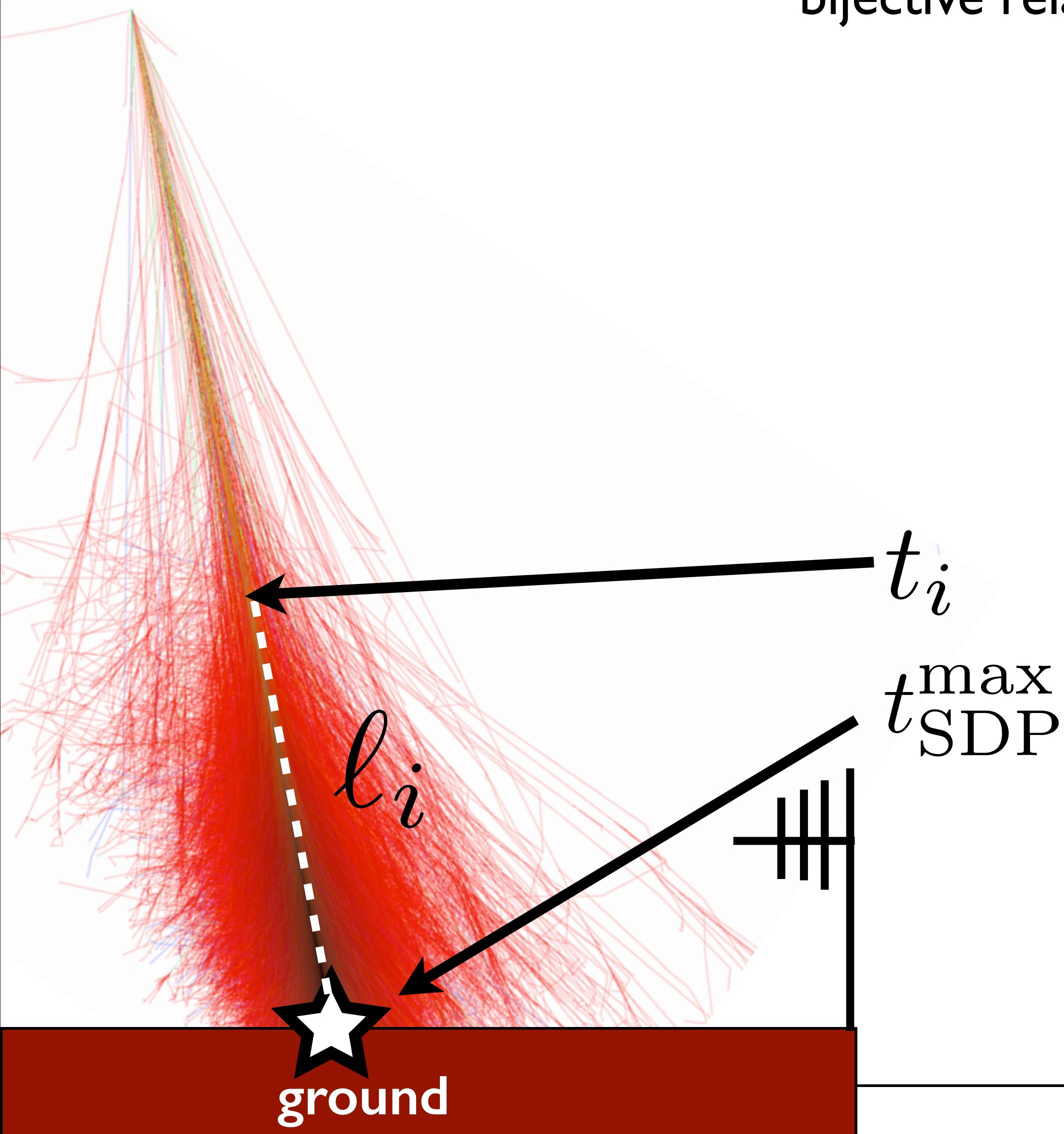


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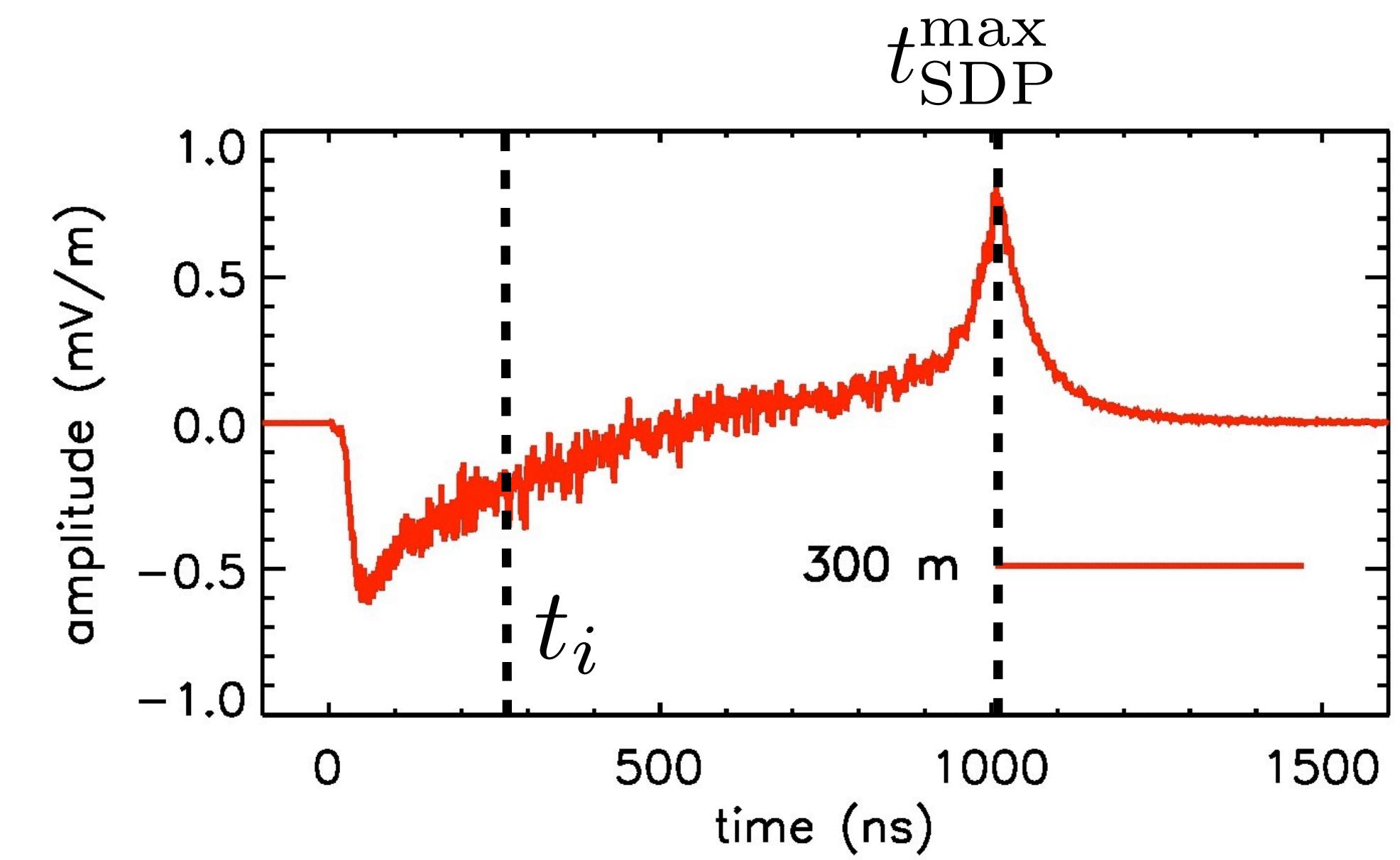


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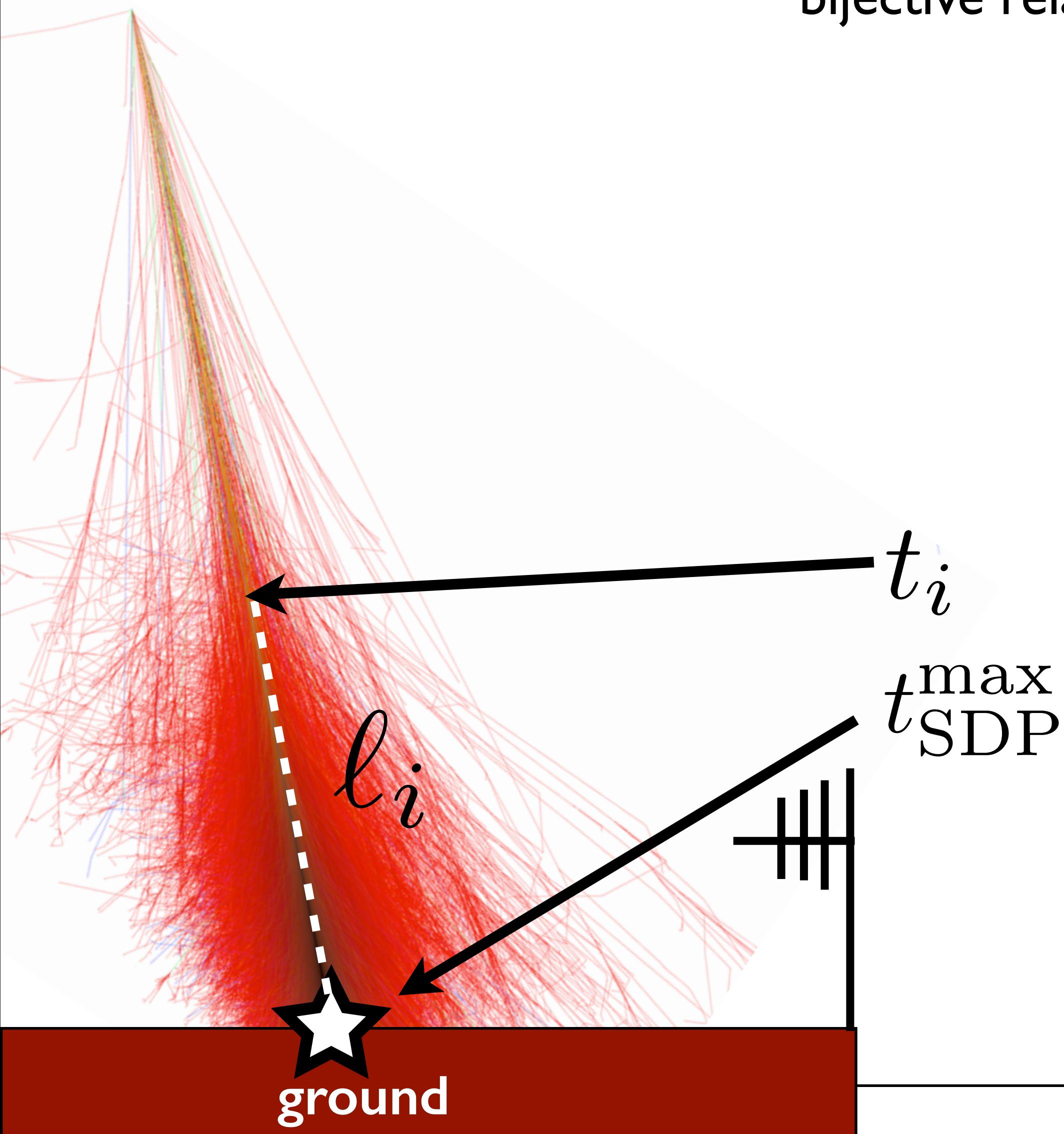


$$t_i \mapsto \ell_i$$

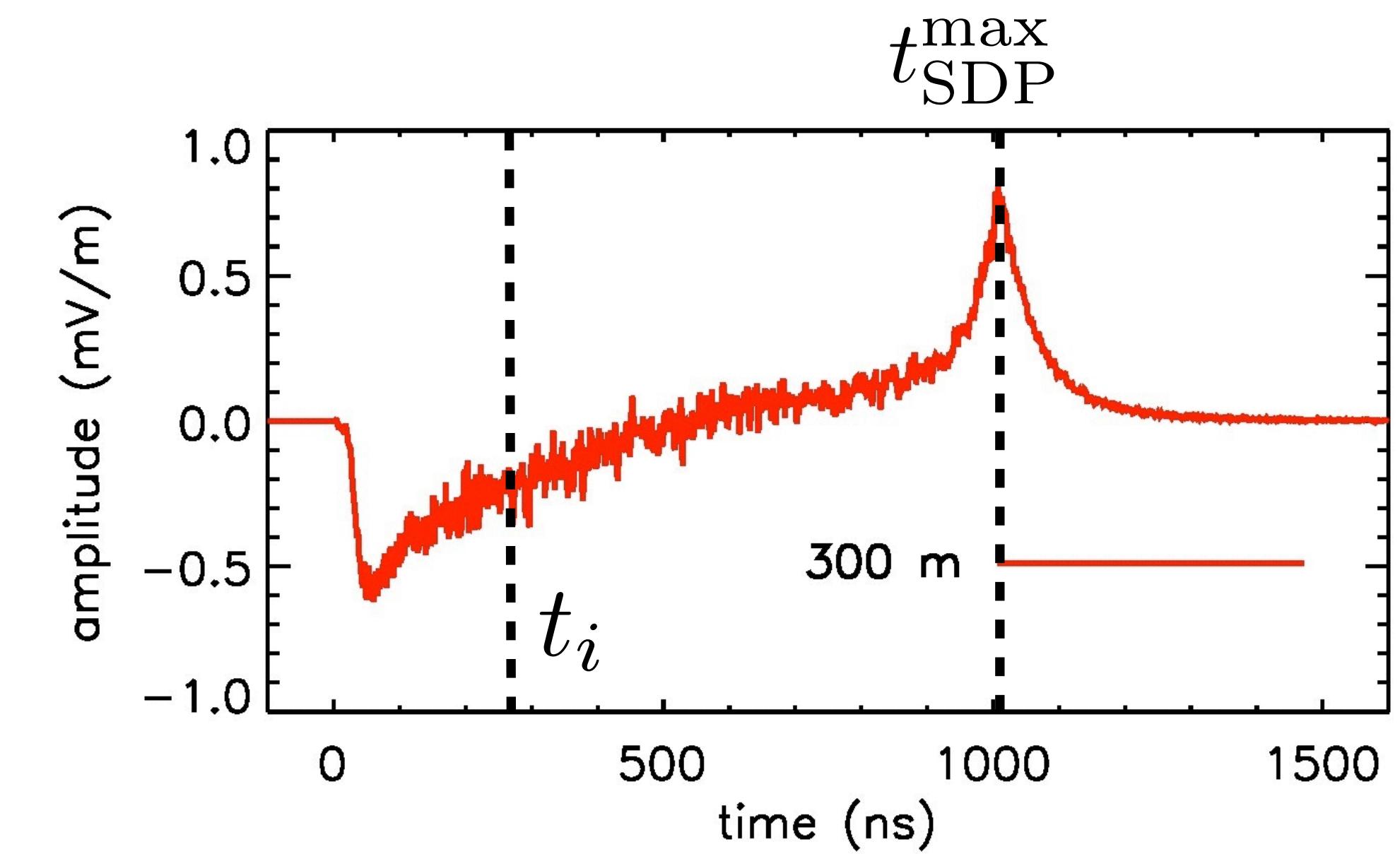


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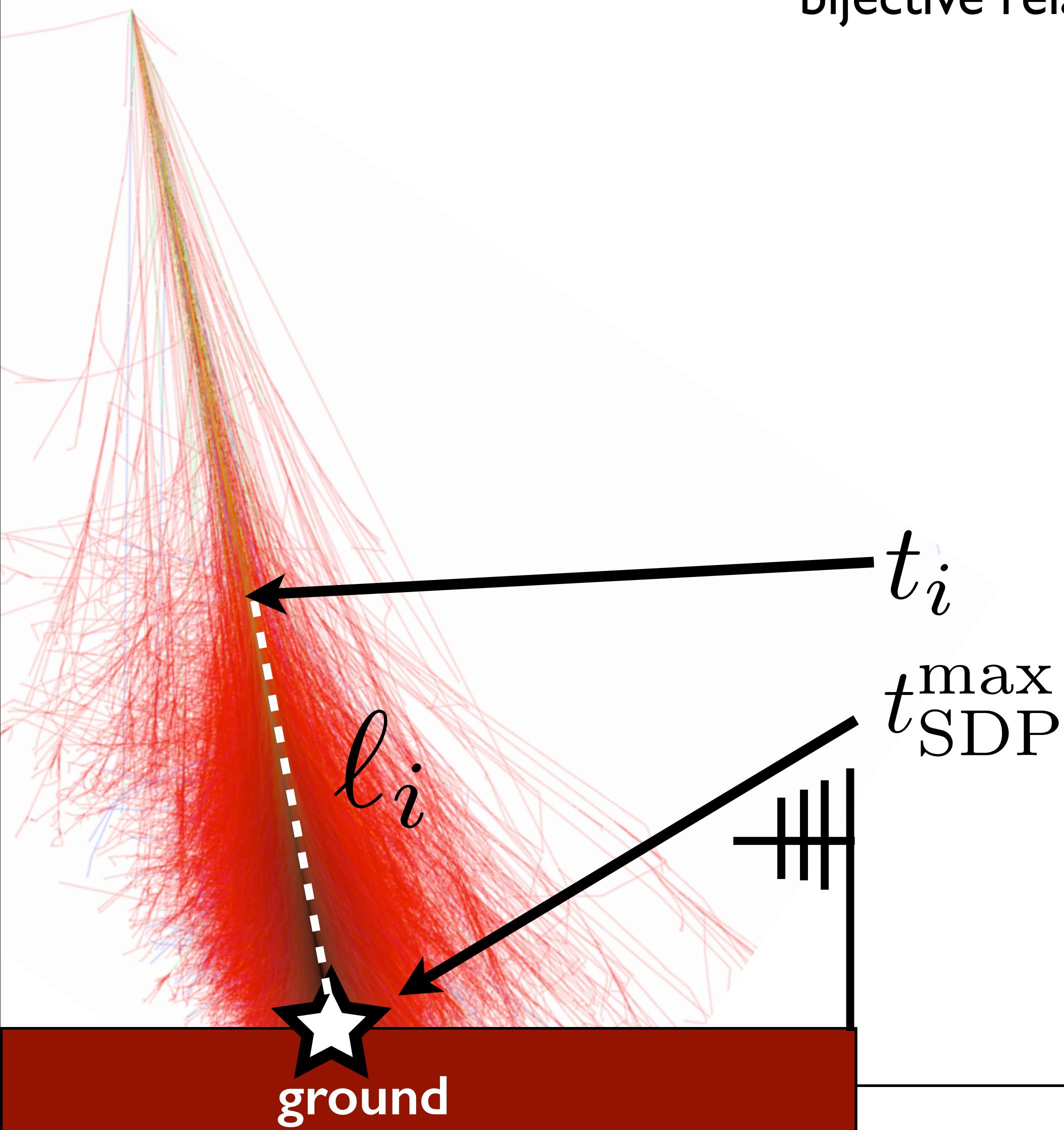


$$t_i \mapsto \ell_i \mapsto X_i$$

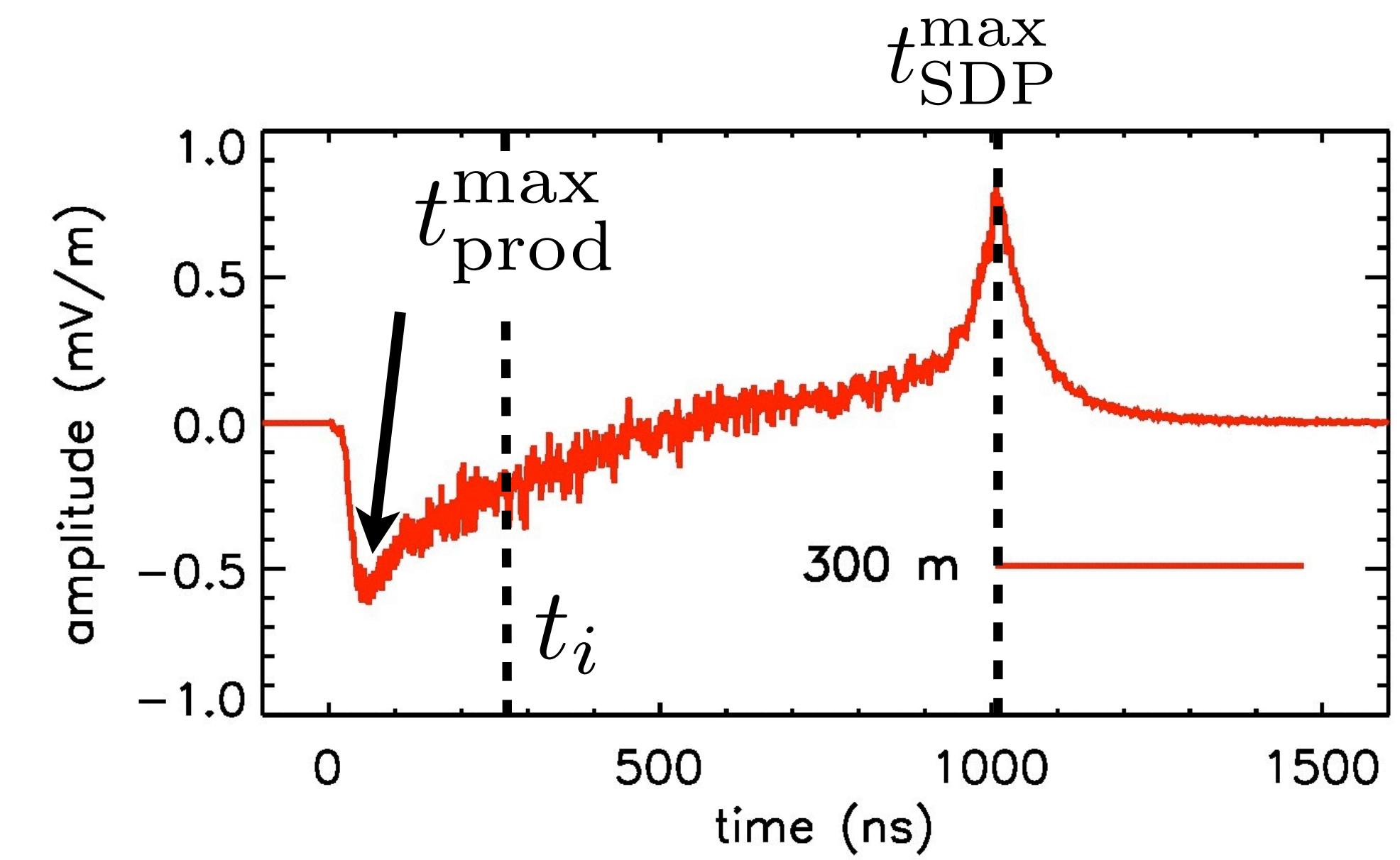


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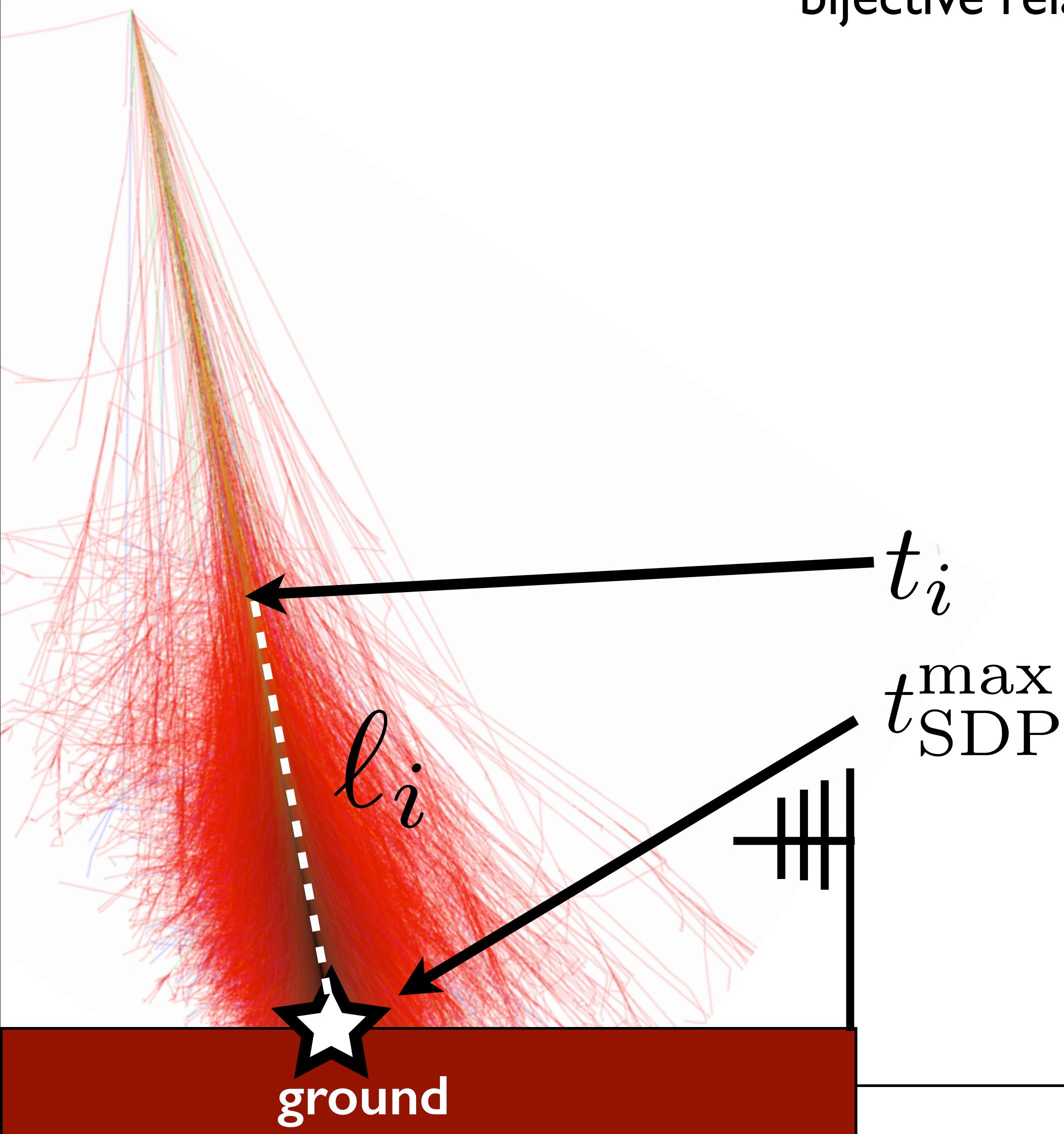


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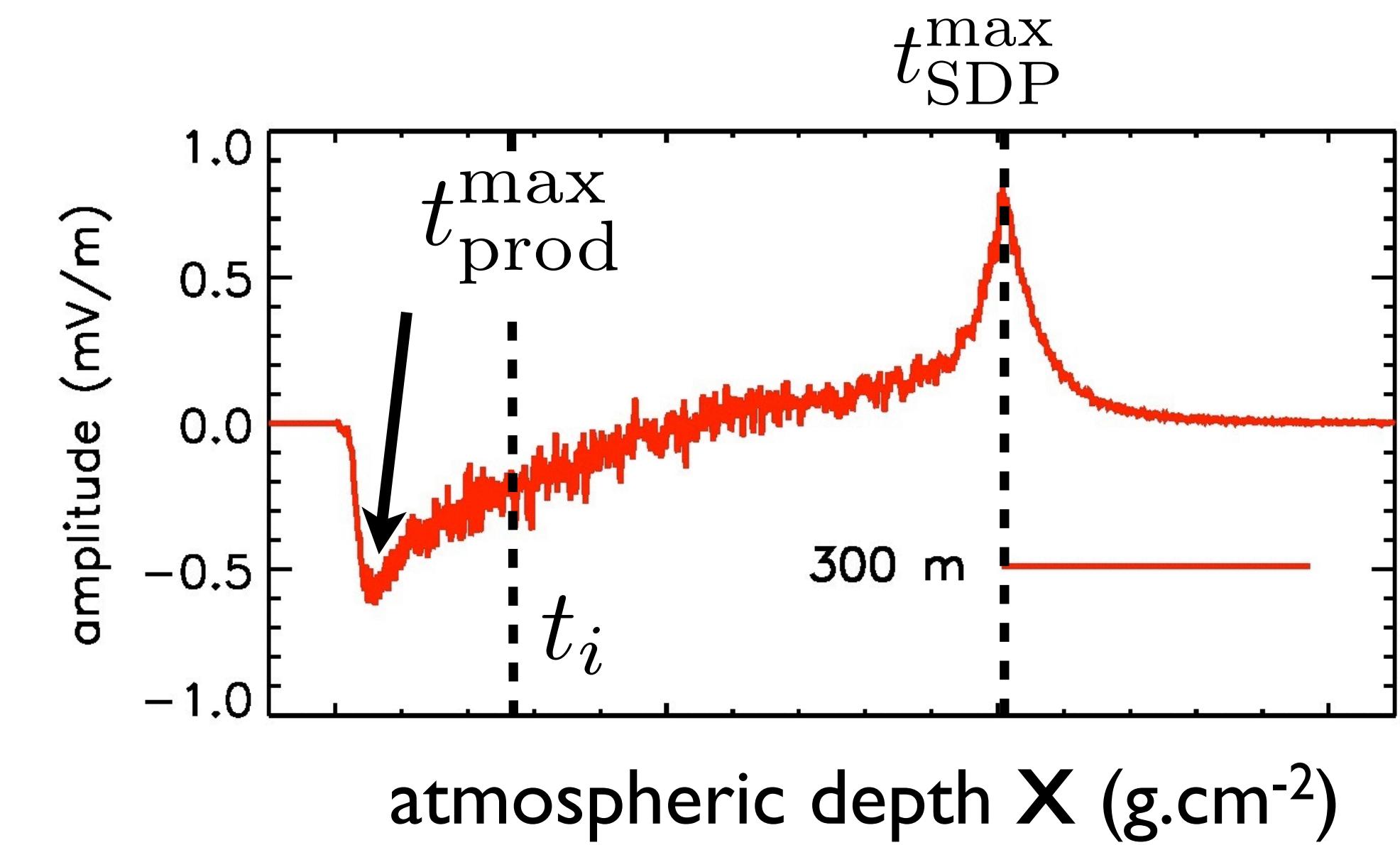


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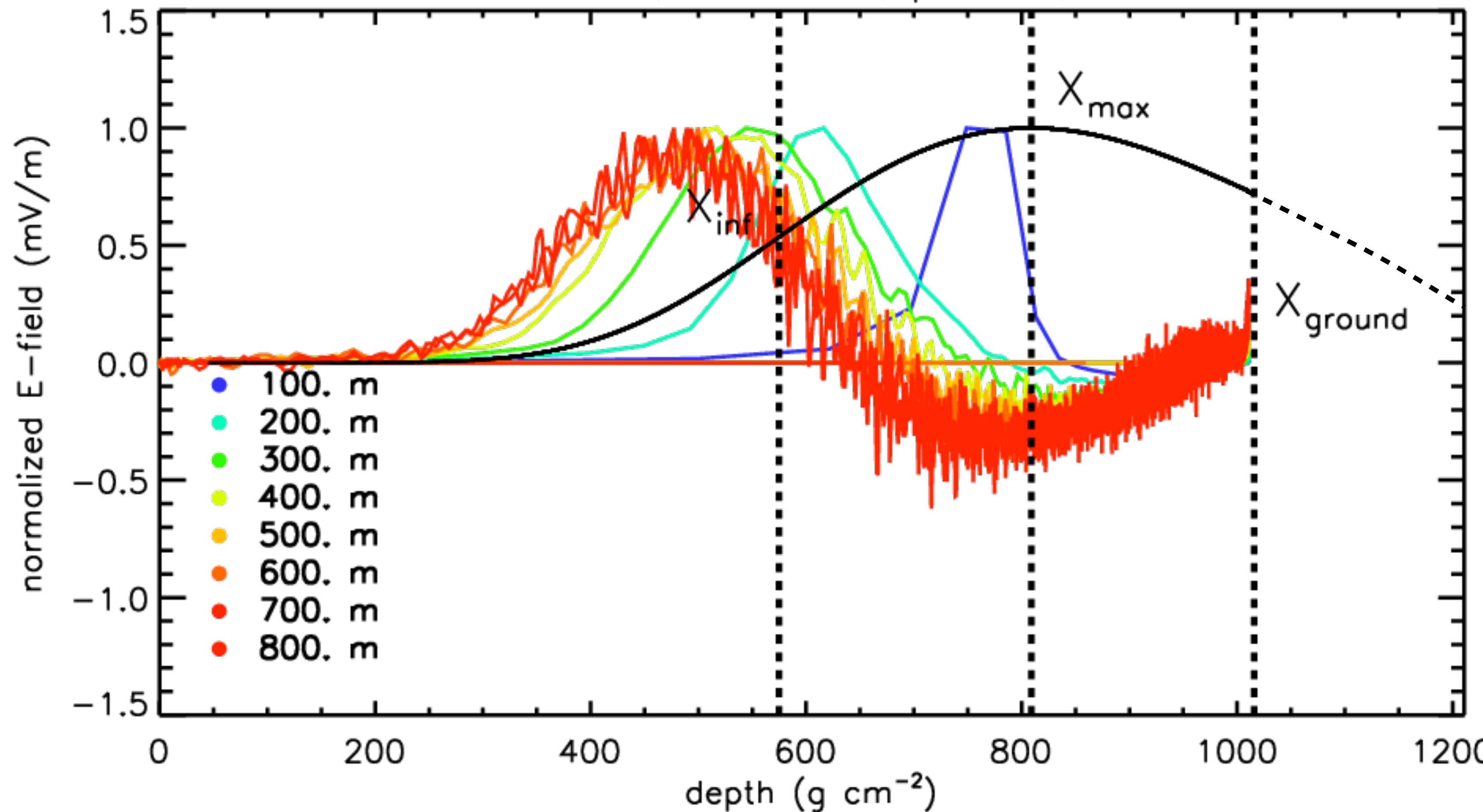


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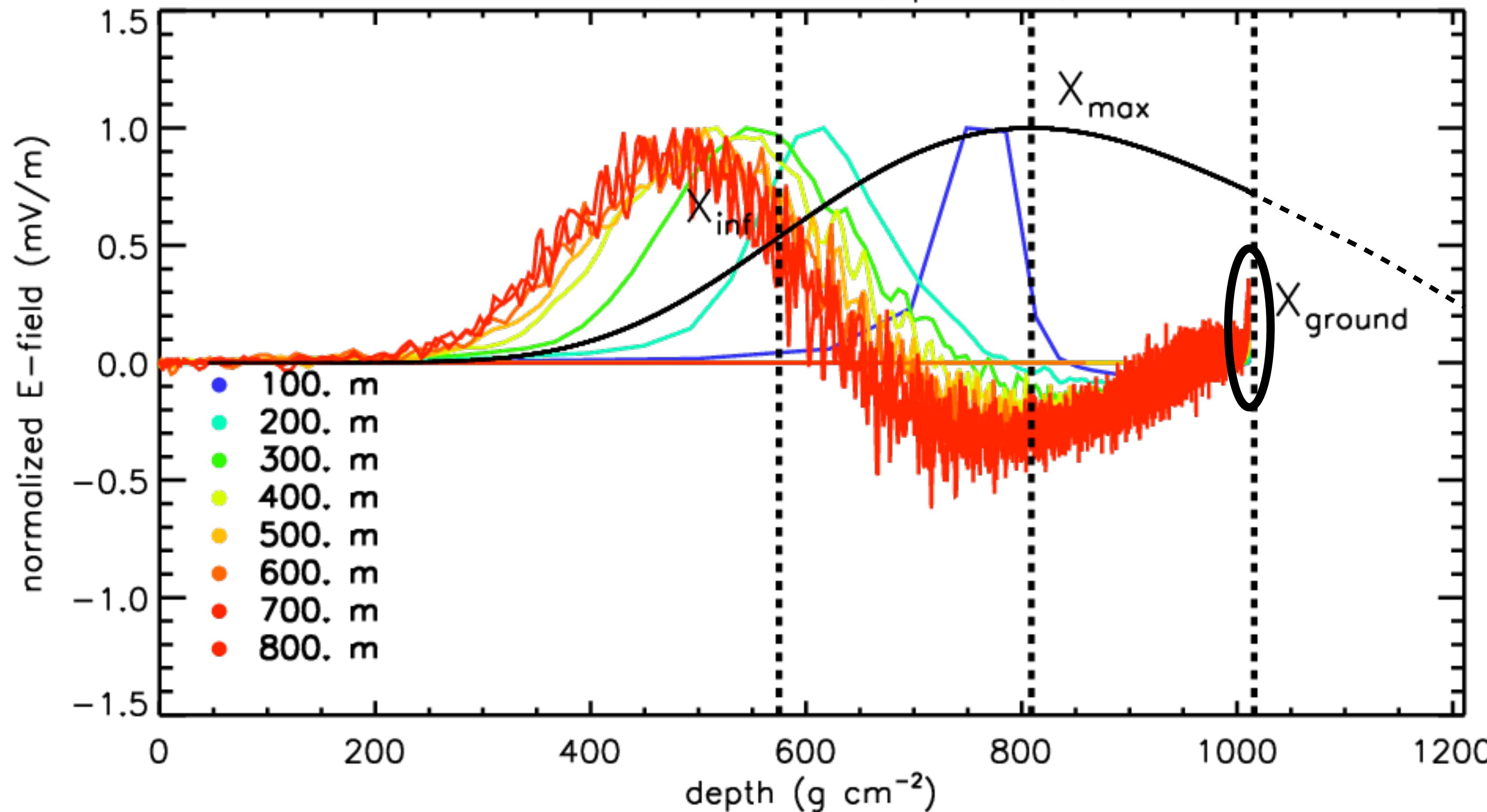
10 EeV, theta=30, phi=45, V



The production of maximum electric field occurs  
well before  $X_{\max}$ , close to  $X_{\text{inf}}$

# Sudden death: absolute timing

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The production of maximum electric field occurs  
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# Summary

from the simulations, the SDP contains many informations on the shower, in particular an indication that the maximum of emission of the electric field occurs well before  $X_{\max}$

The signal gives a measurement of the total number of  $e^+e^-$  that reached the ground:

very important for composition studies

The amplitude scales as  $I/d_{\text{core}}$ , providing a signal detectable up to large distances from the shower core (as already seen in Akeno in 1987)

need a dedicated antenna, sensitive to:

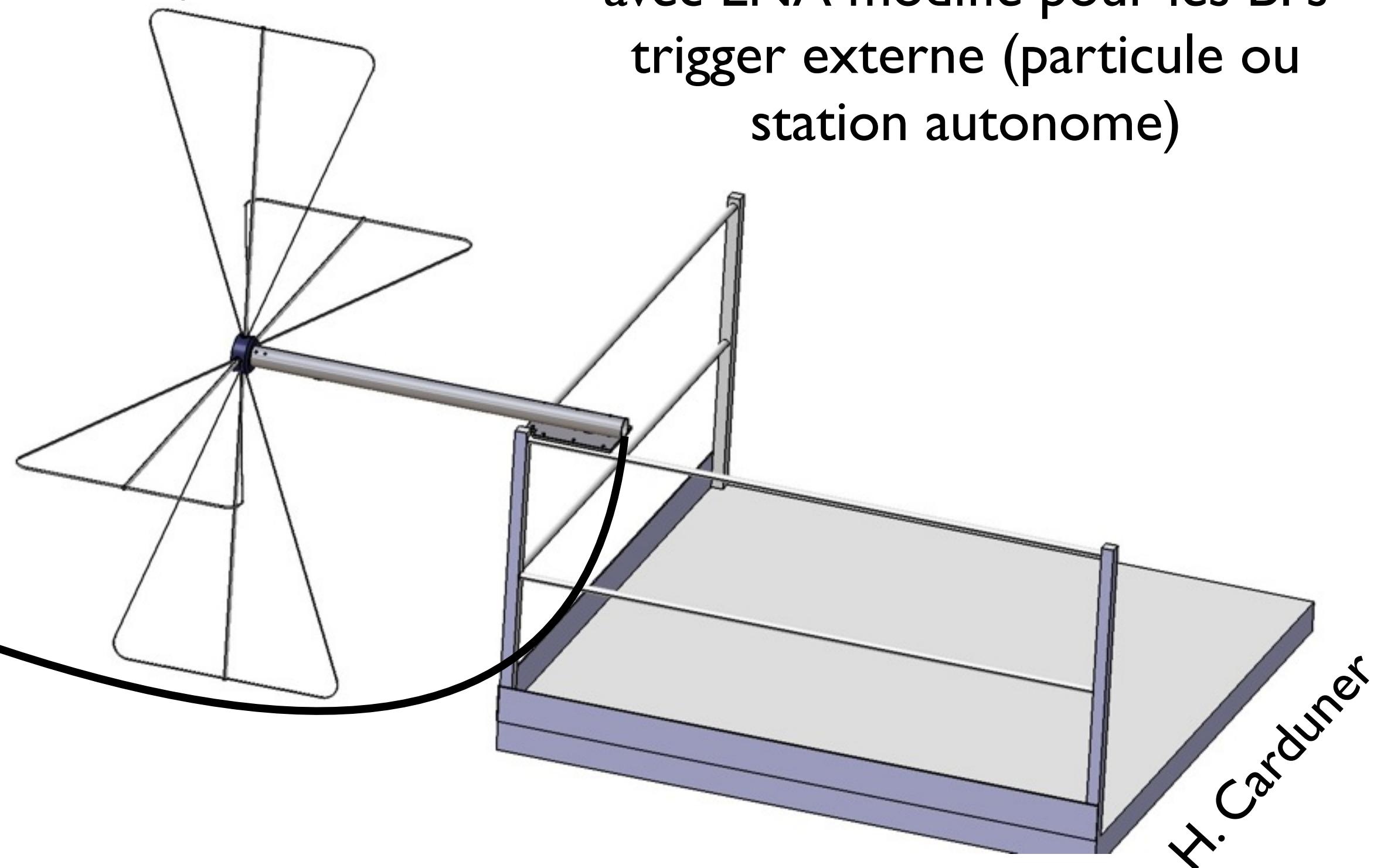
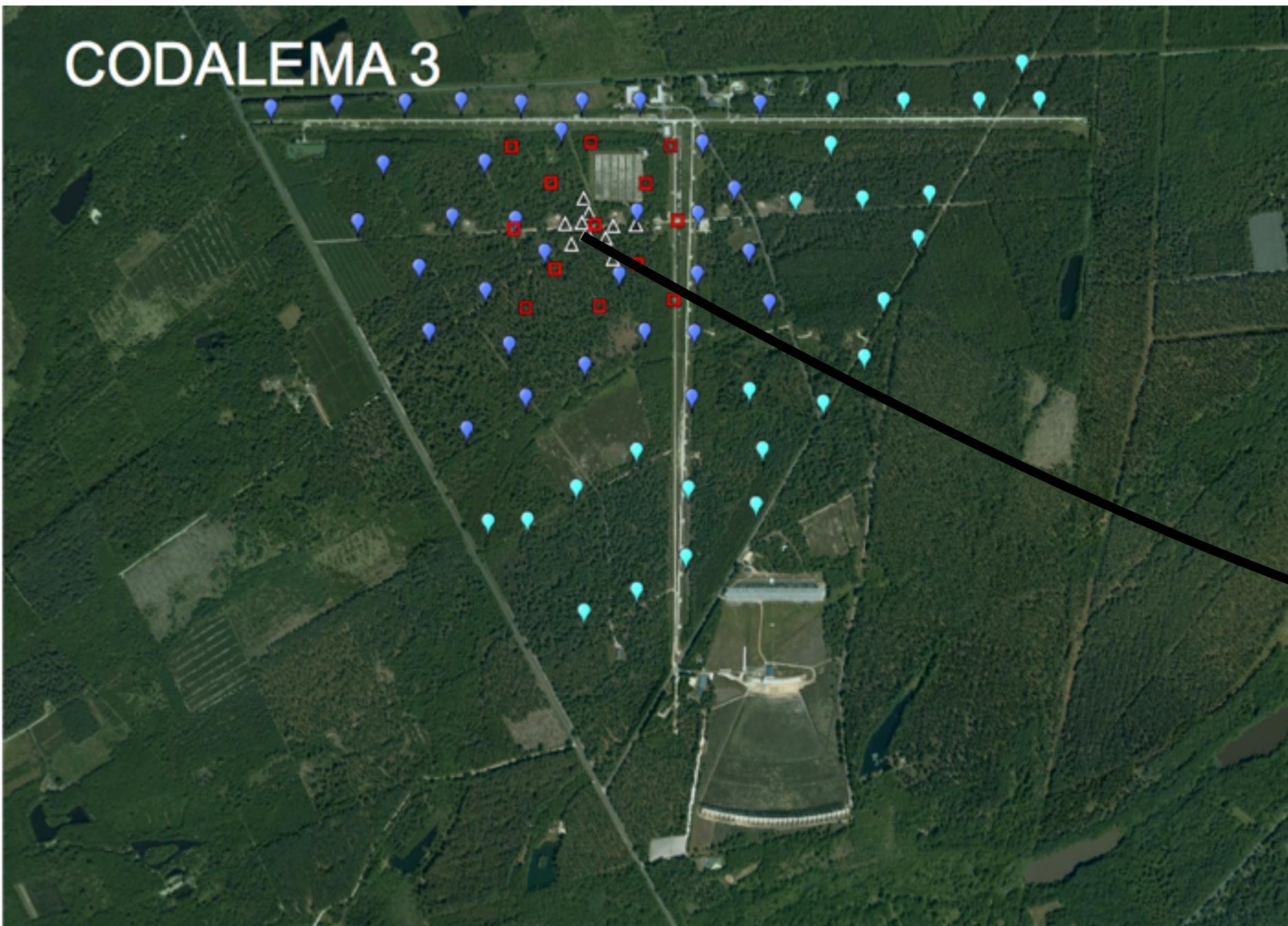
- low frequencies (below 20 MHz)
- vertical polarization
- horizontal incoming directions

# EXTASIS

## EXTinction of Air Shower Induced Signal

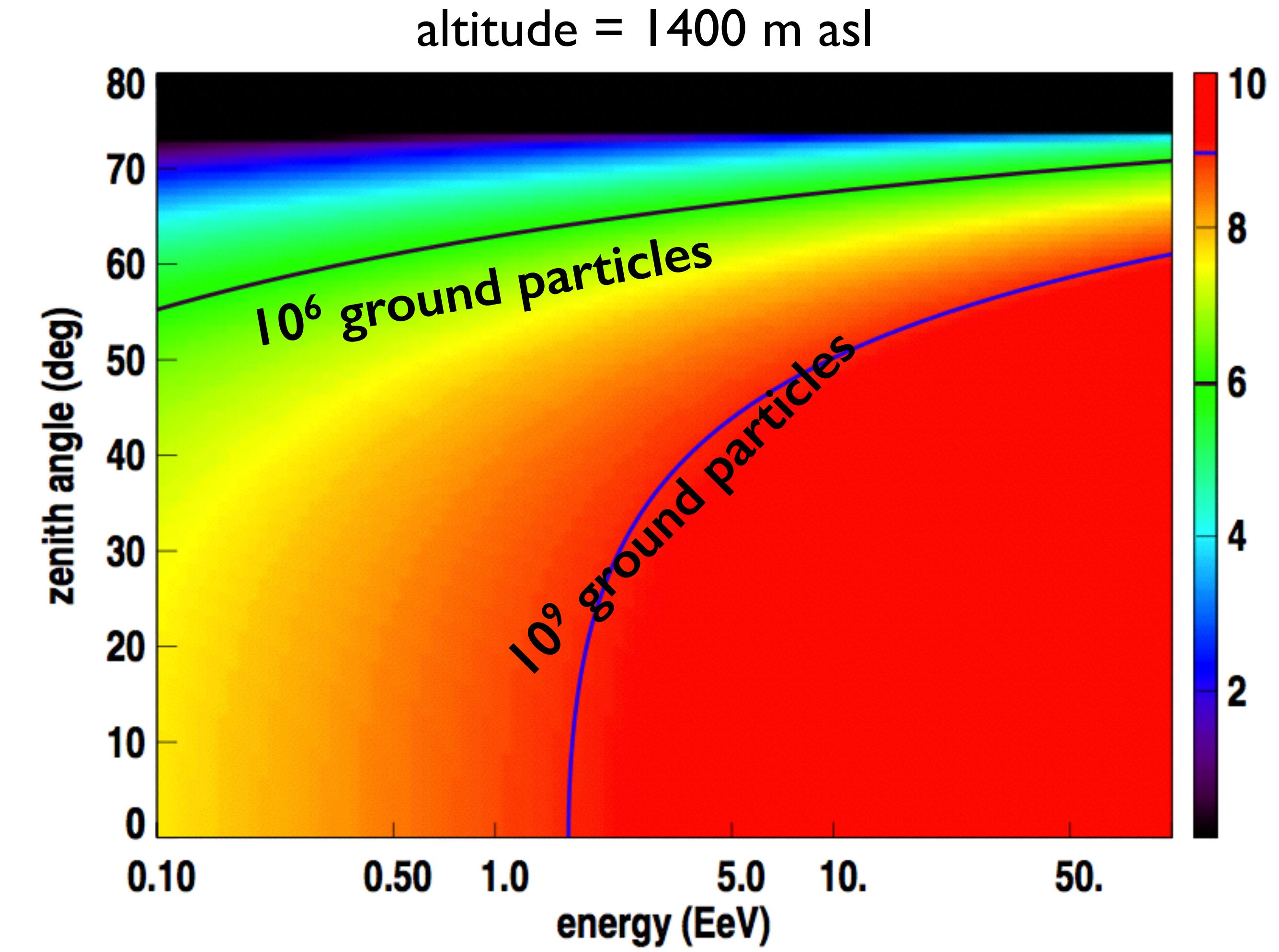
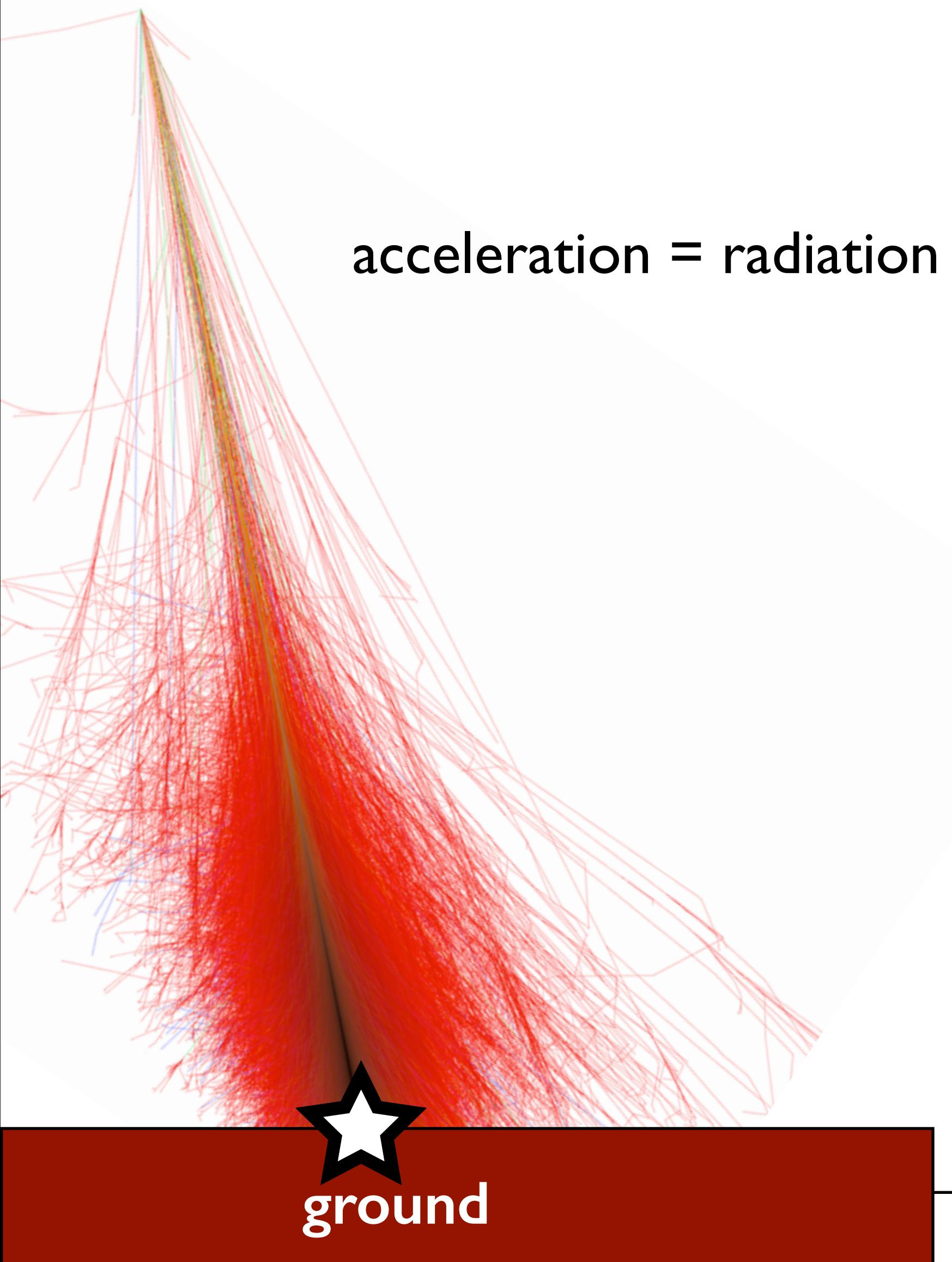
- Financé par la Région Pays de la Loire, depuis fin 2013, pour 4 ans
- soutien du PNHE
- site choisi : Nançay, au cœur de CODALEMA3
- équipe : SUBATECH, LESIA, US Nançay (13 personnes)
- 1 postdoc, 1 thèse

Avril-mai 2014  
Antenne Butterfly  
(CODALEMA3,AERA...)  
avec LNA modifié pour les BF  
trigger externe (particule ou  
station autonome)





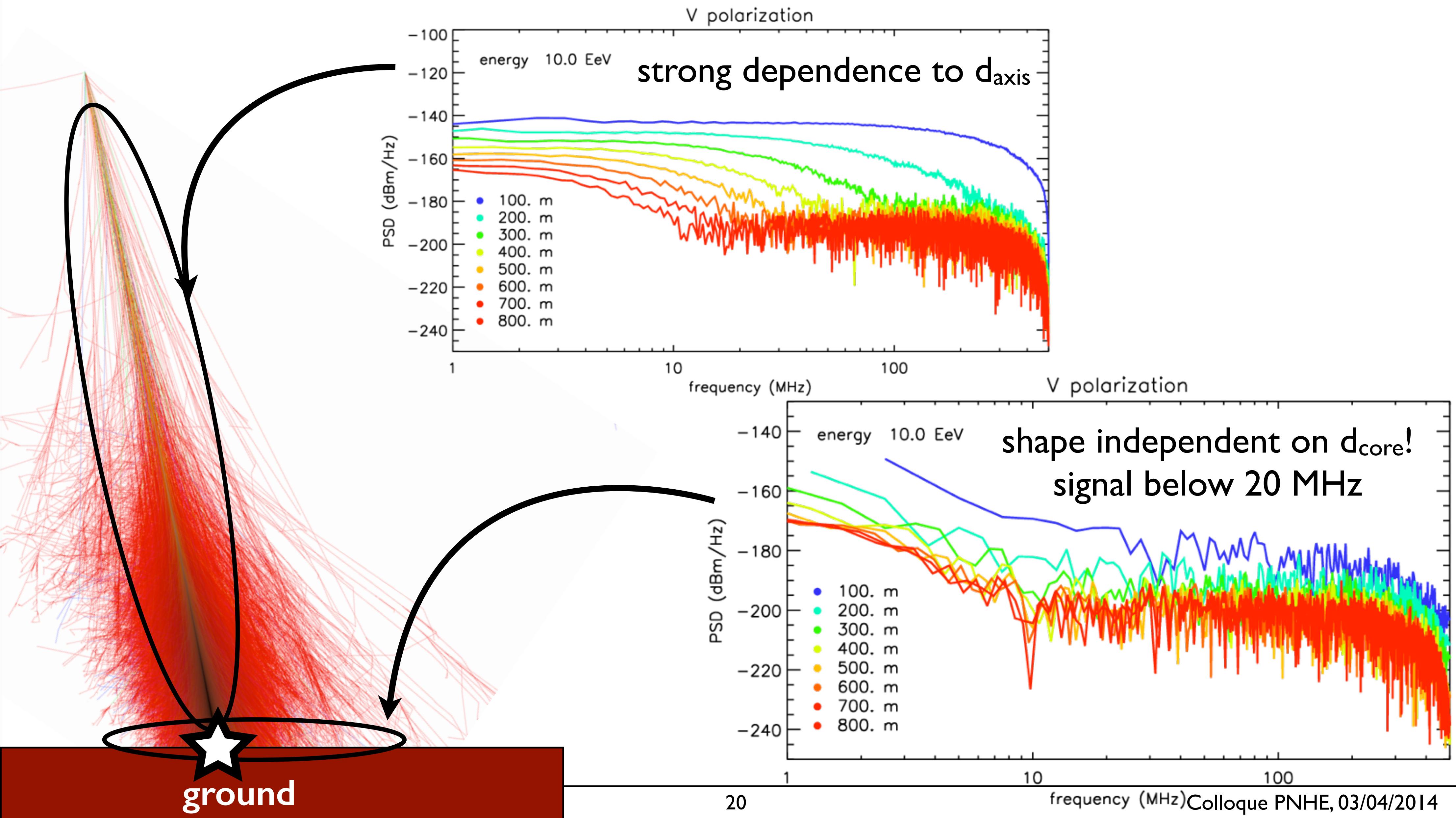
# Air shower sudden death



# Sudden death: summary

pulse	<b>main (<math>n \times B</math>)</b>	<b>sudden death</b>
<b>geometry</b>	depends on the <b>axis distance</b>	depends on the <b>core distance</b>
<b>polarization</b>	polarization along $n \times B$ at 1st order	polarization in the plane $\perp AC$
<b>frequency</b>	between 1 MHz and $\sim$ GHz	below 20 MHz
<b>spectrum</b>	shape depends on $d$	same shape, coherent below 20 MHz
<b>timing</b>	relative timing	<b>absolute timing</b>
<b>E-production</b>	X	X
<b>LDF</b>	$\sim$ exp decrease of the LDF	amplitude scales as $1/d$
<b>amplitude</b>	amplitude scales as $E$	amplitude scales as $E$
<b>core position</b>	radio core $\neq$ particle core (interference)	finds the true core

# Sudden death: PSD



# Sudden death: PSD

