

SiPM Single Photon Extraction allows for Novel IACT Event Representation

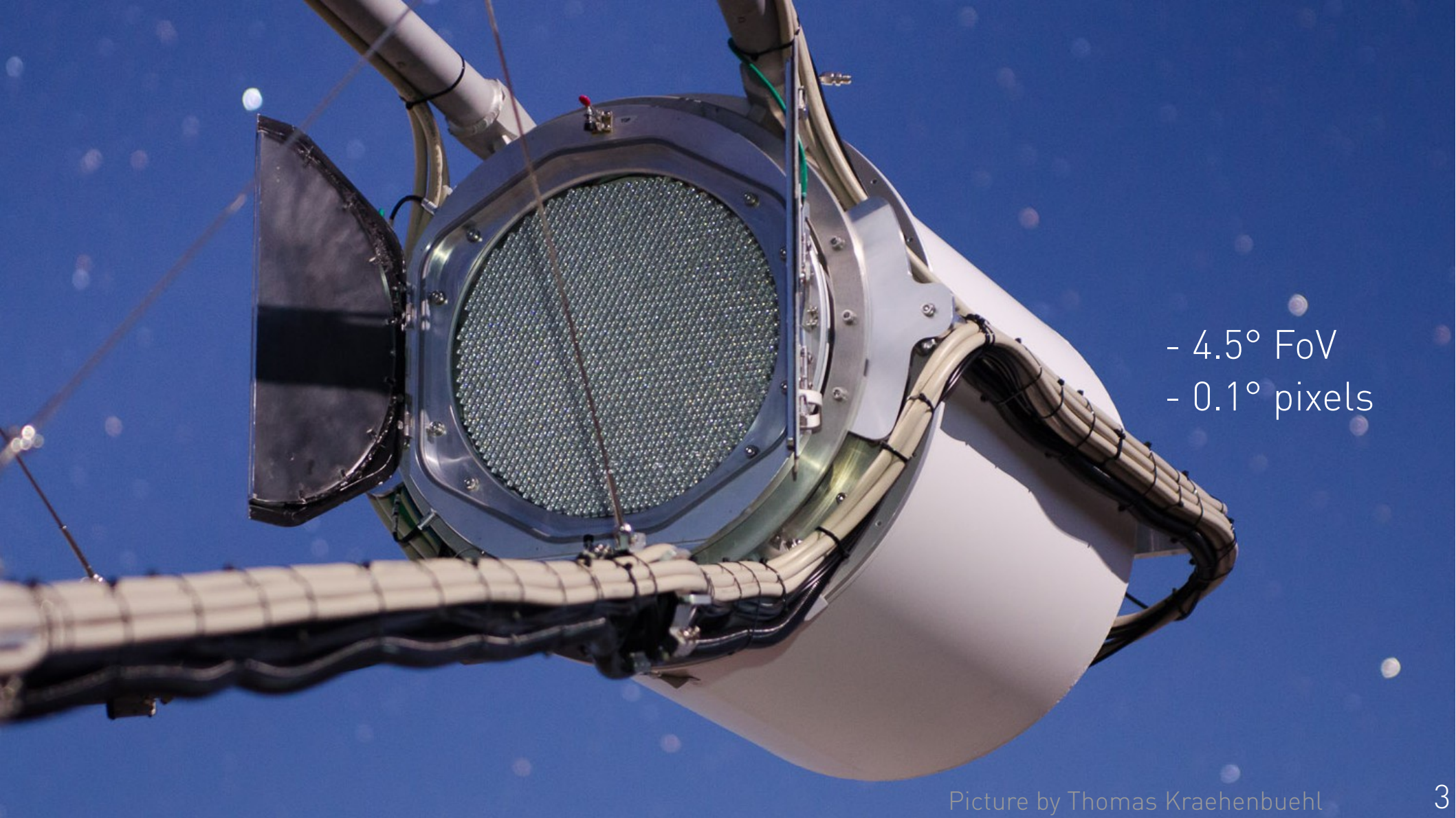


Sebastian Achim Mueller
Dominik Neise
ETH Zurich

Picture by Thomas Kraehenbuendli

- 9.5m^2 mirror area
- 4.9m focal length



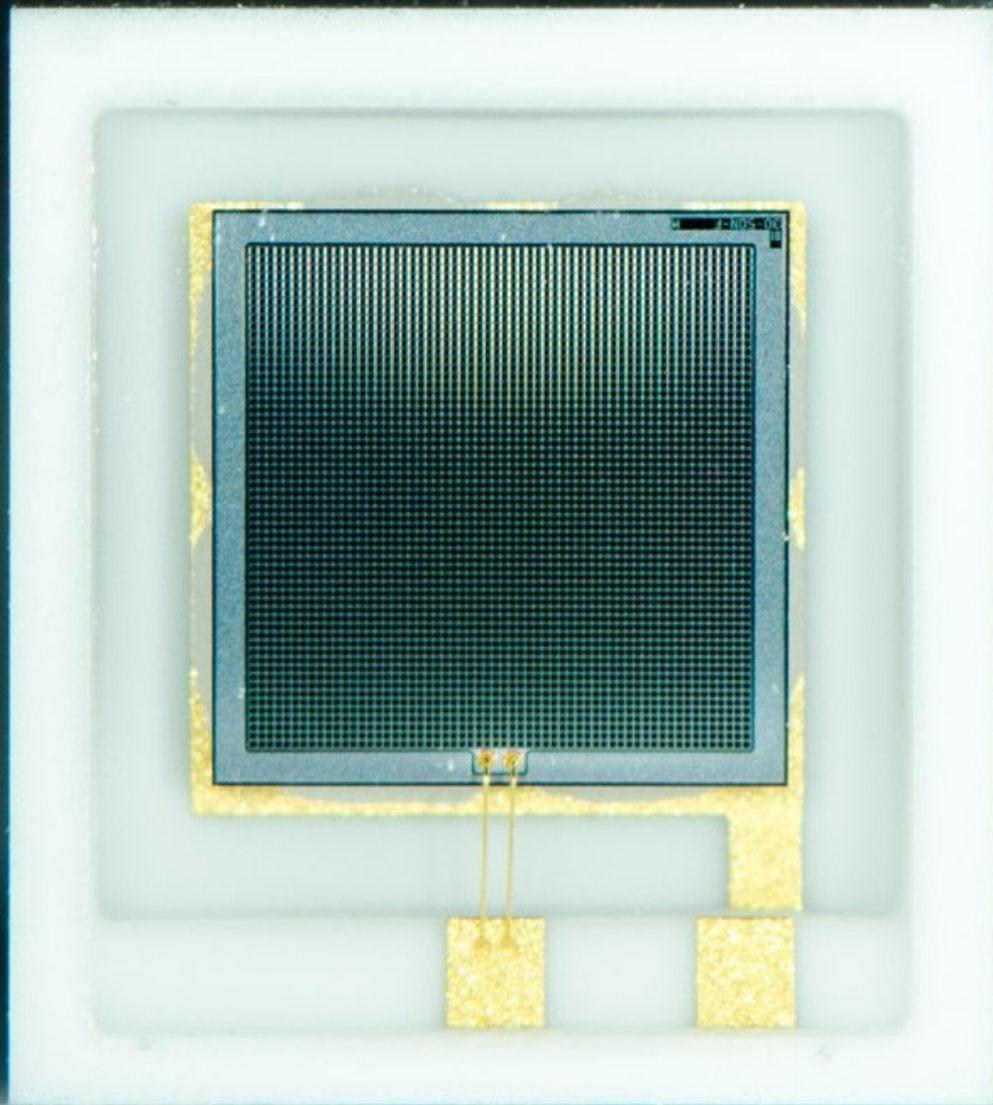


- 4.5° FoV
- 0.1° pixels



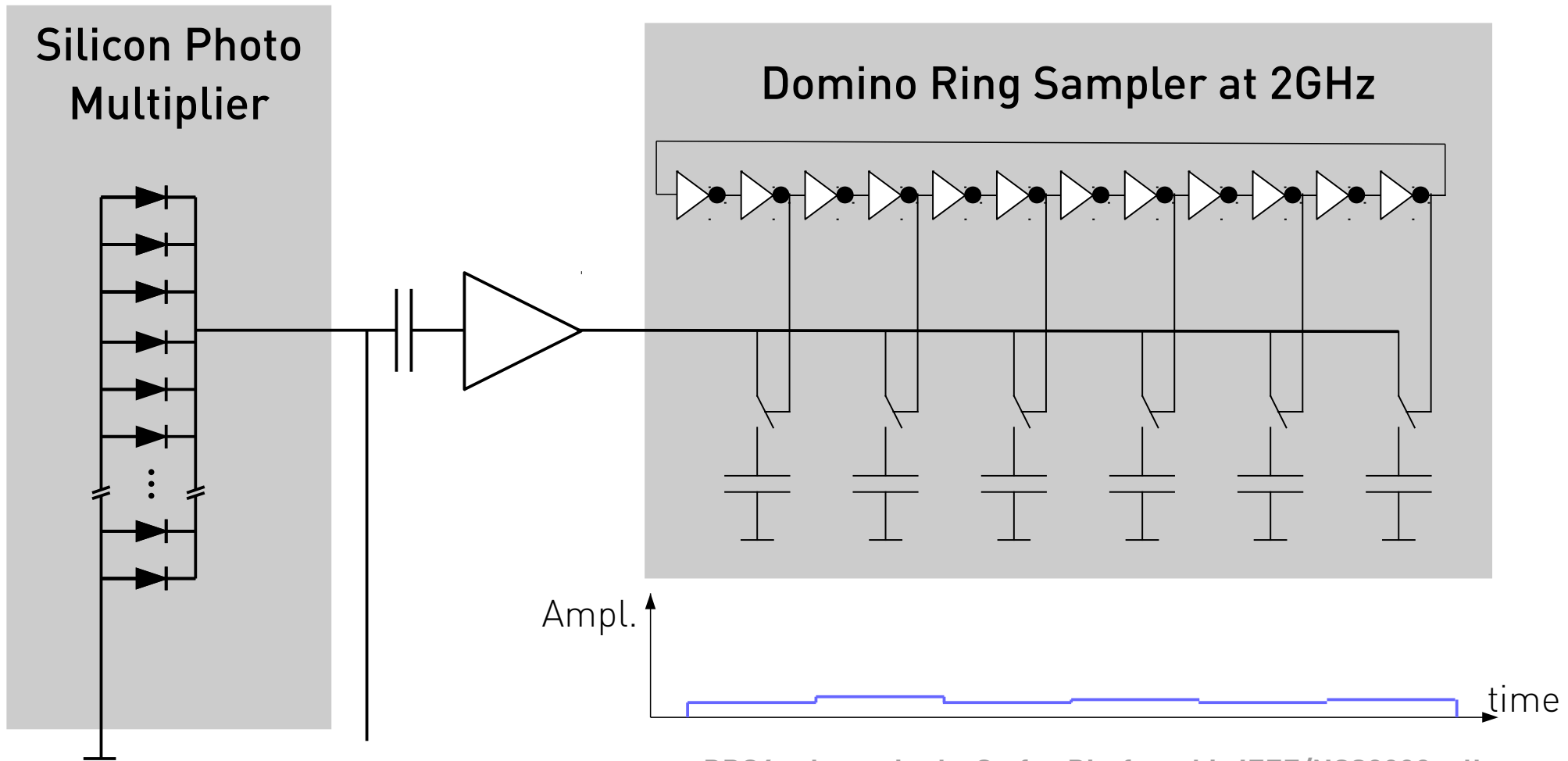
1 FACT camera
1440 SiPM pixels

- 4.5° FoV
- 0.1° pixels

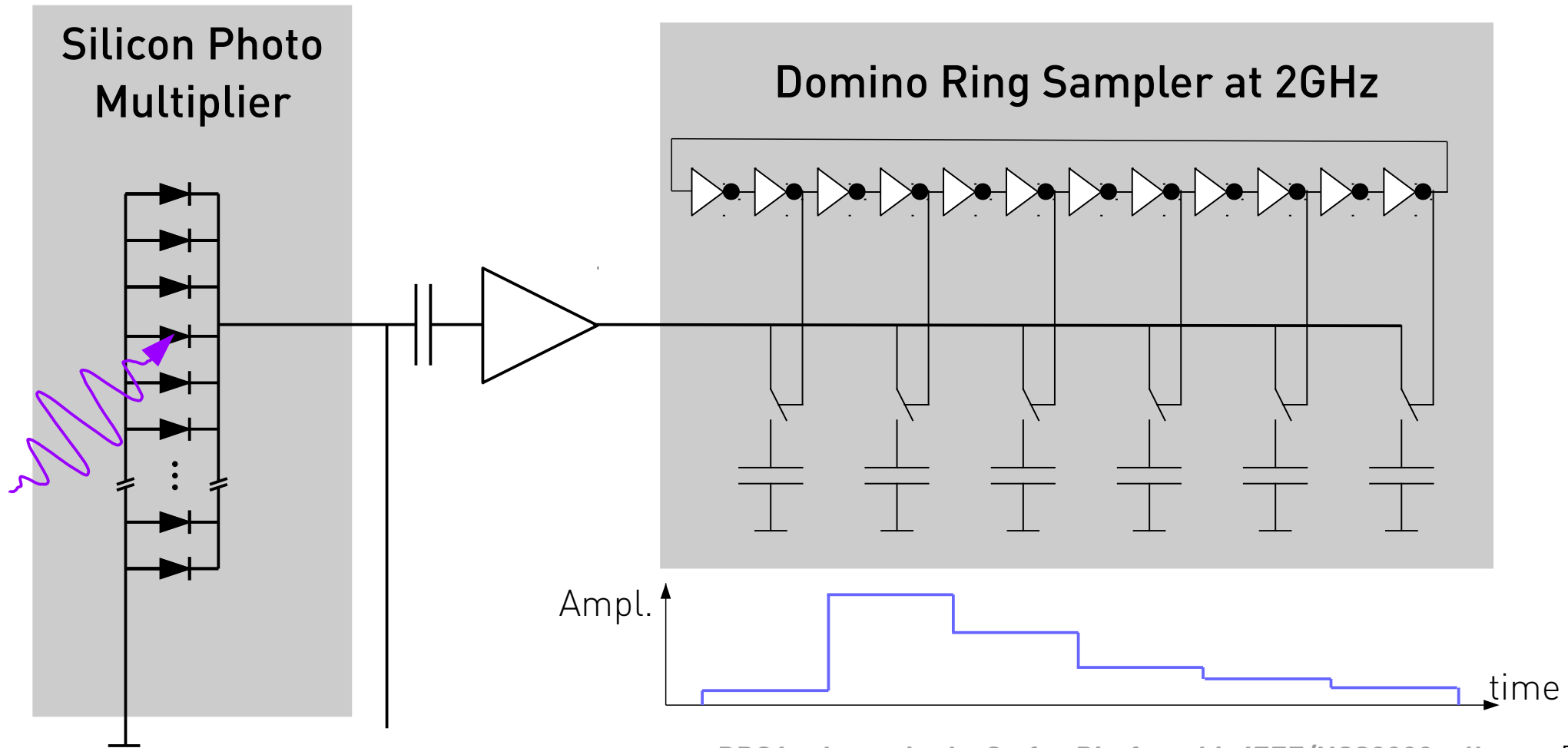


**1 SiPM pixel
3600 identical G-APDs
in parallel**

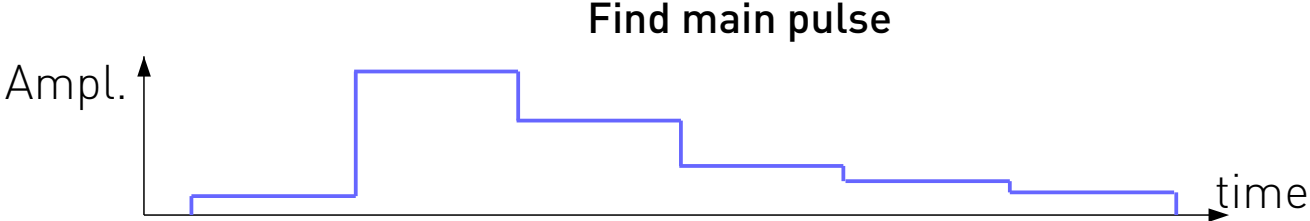
Readout of 1 pixel



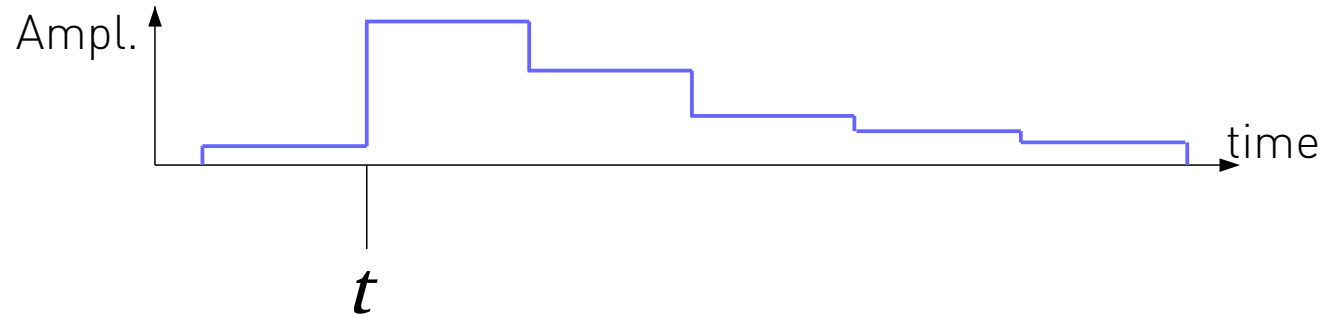
Readout of 1 pixel



Classic extraction for 1 pixel

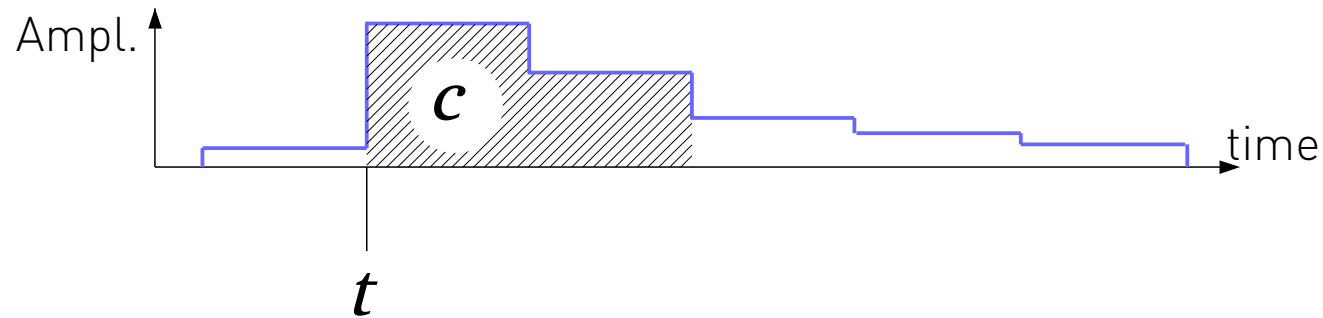


Classic extraction for 1 pixel



1) Arrival time of main pulse, t

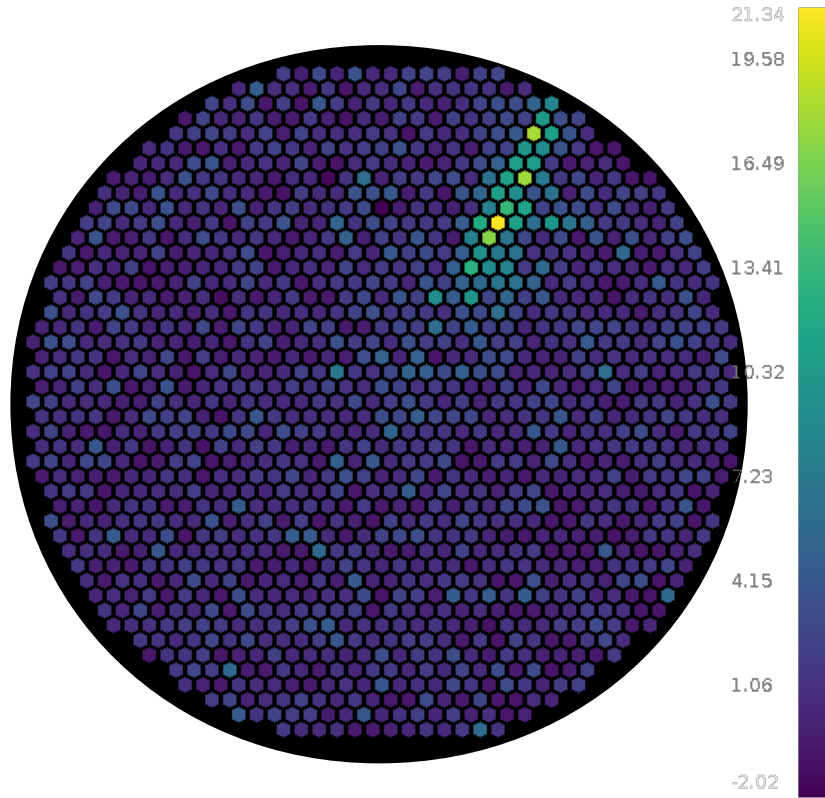
Classic extraction for 1 pixel



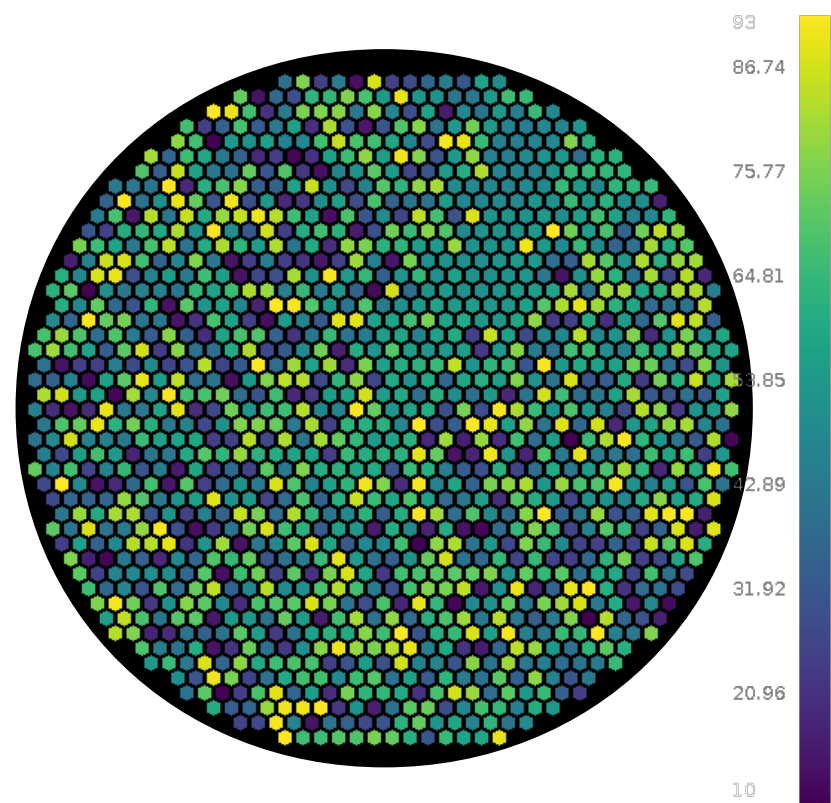
1) Arrival time of main pulse, t

2) Photon-equivalent of main pulse, c

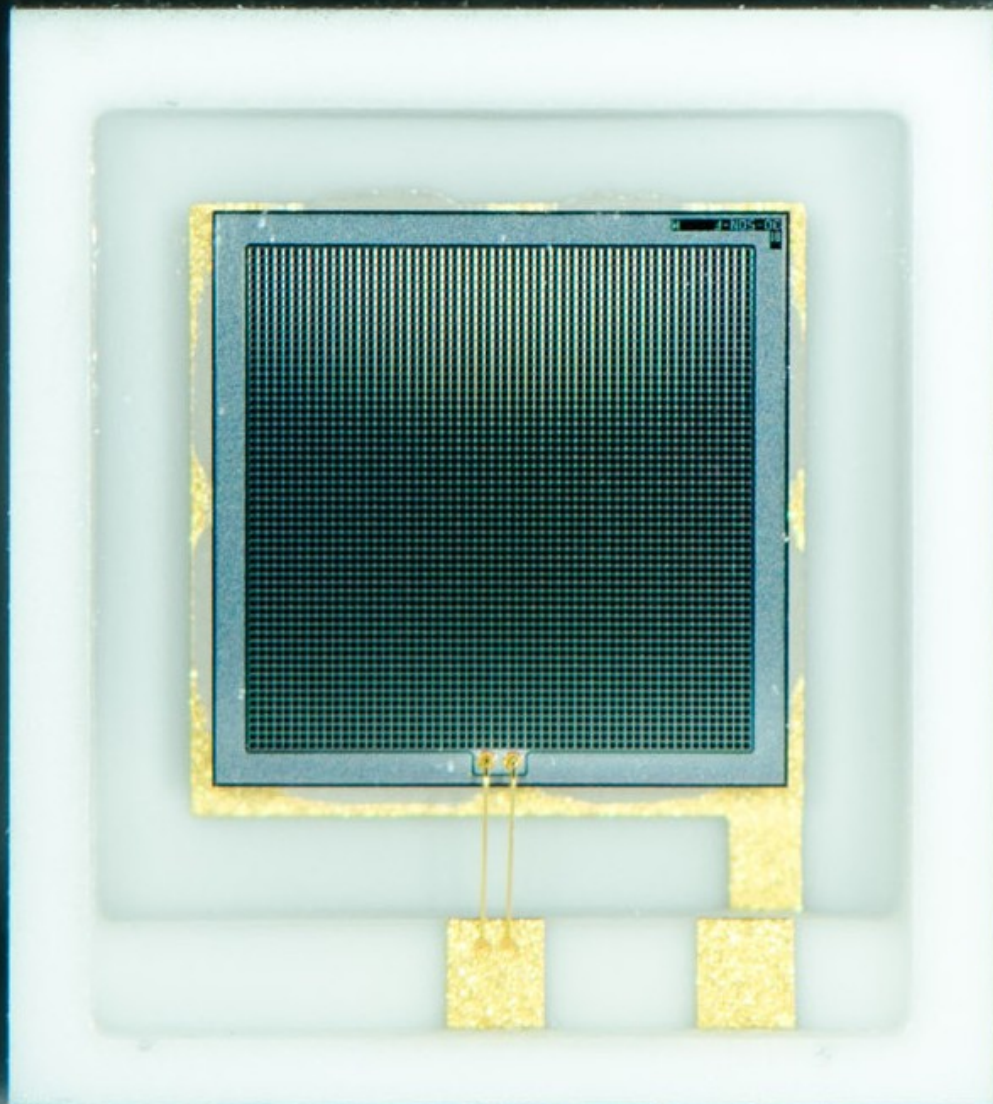
Classic Event Representation



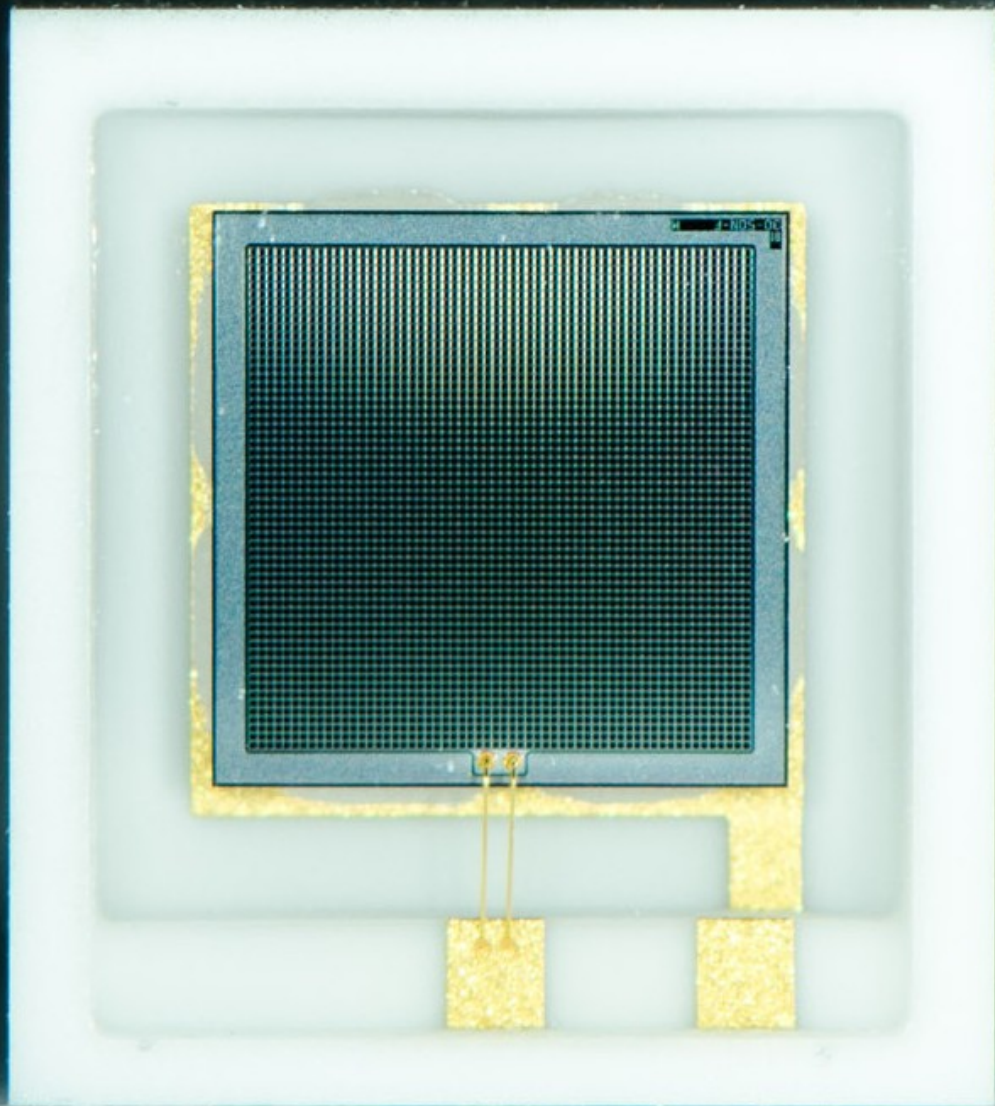
Photon-equivalents of main pulses
 c /p.e.



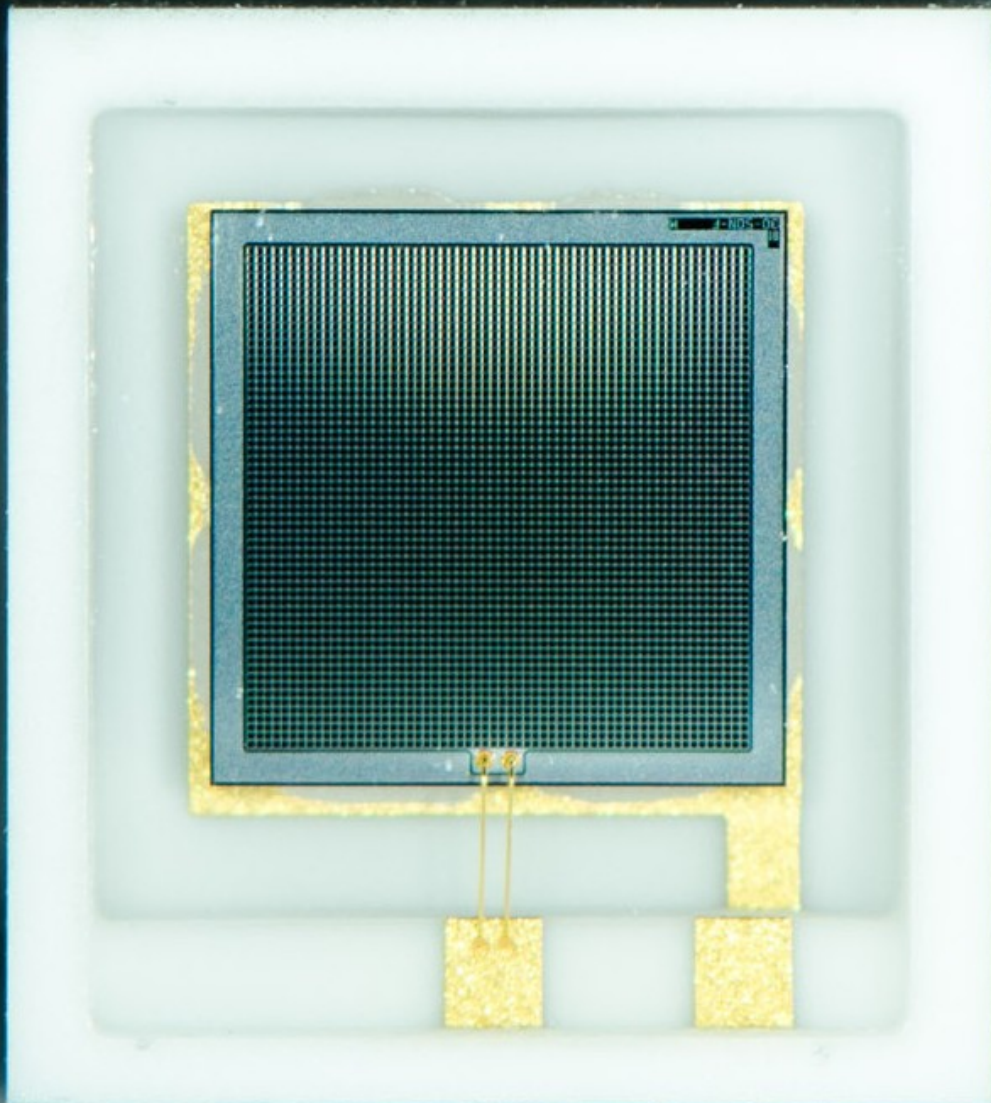
Arrival times of main pulses
 t /ns



Now we challenge our
classic signal extraction



Photon-Stream for FACT



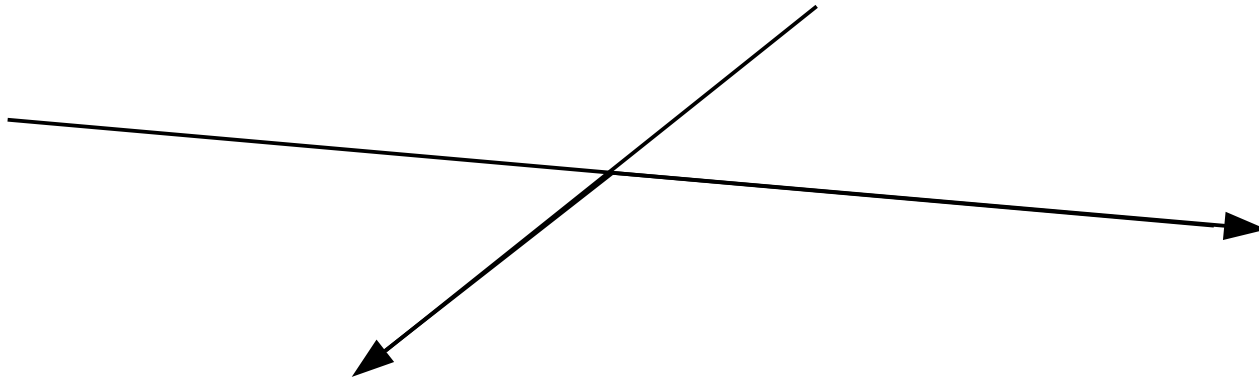
Photon-Stream for FACT

beyond the PMT heritage

A list of single photon
arrival times for each
pixel.

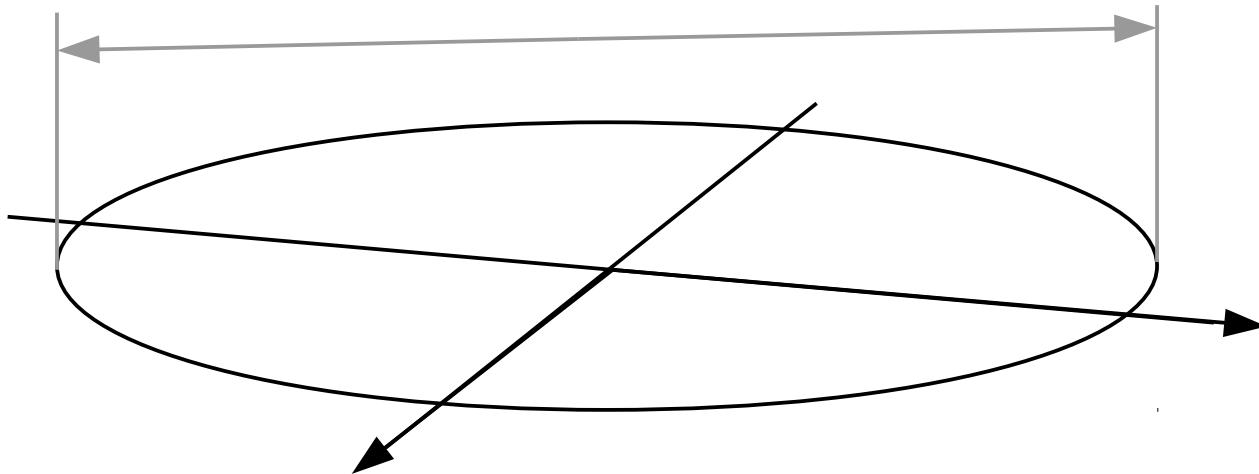
Photon-Stream in 3D

Pixel directions on the 2D sky dome

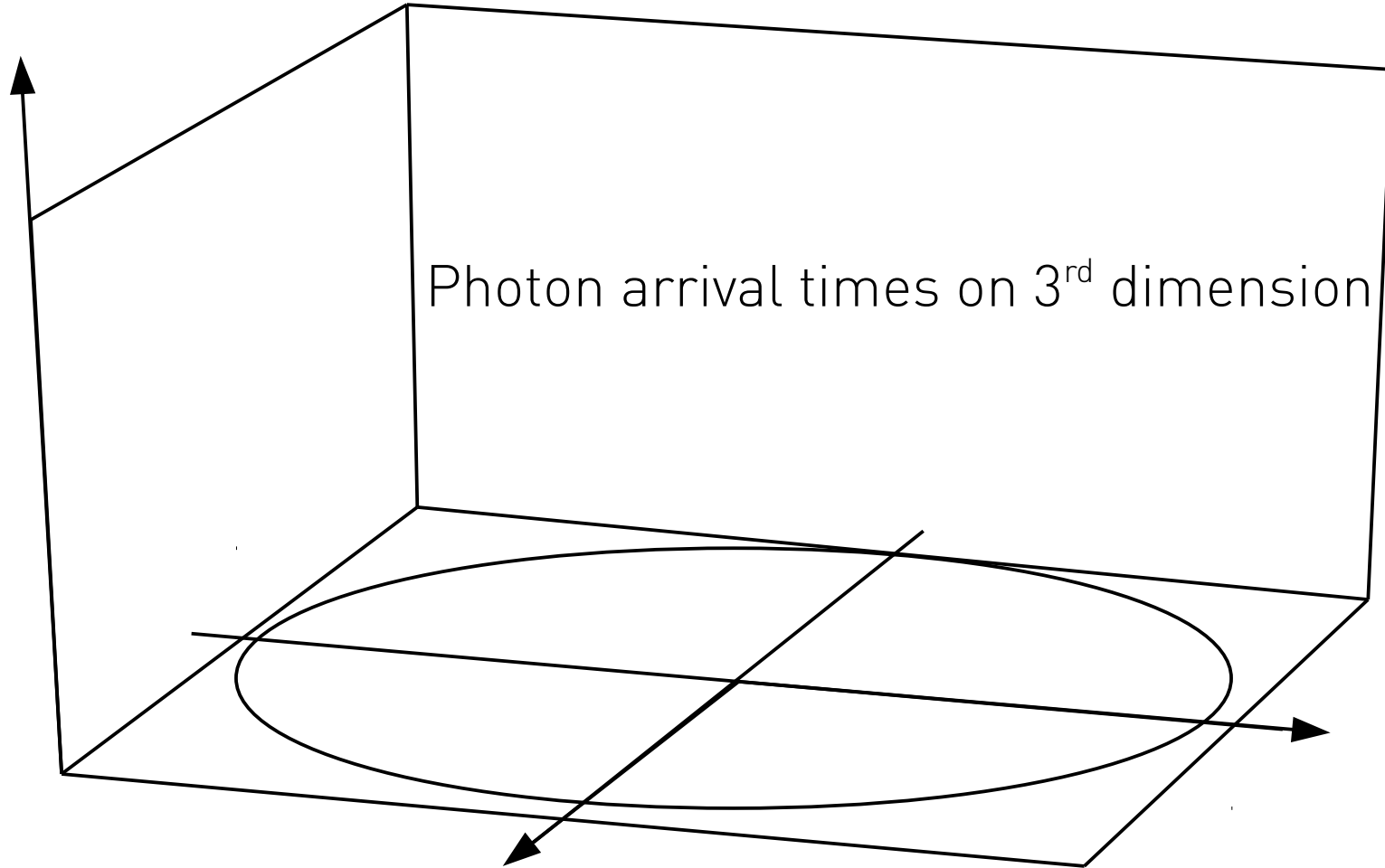


Photon-Stream in 3D

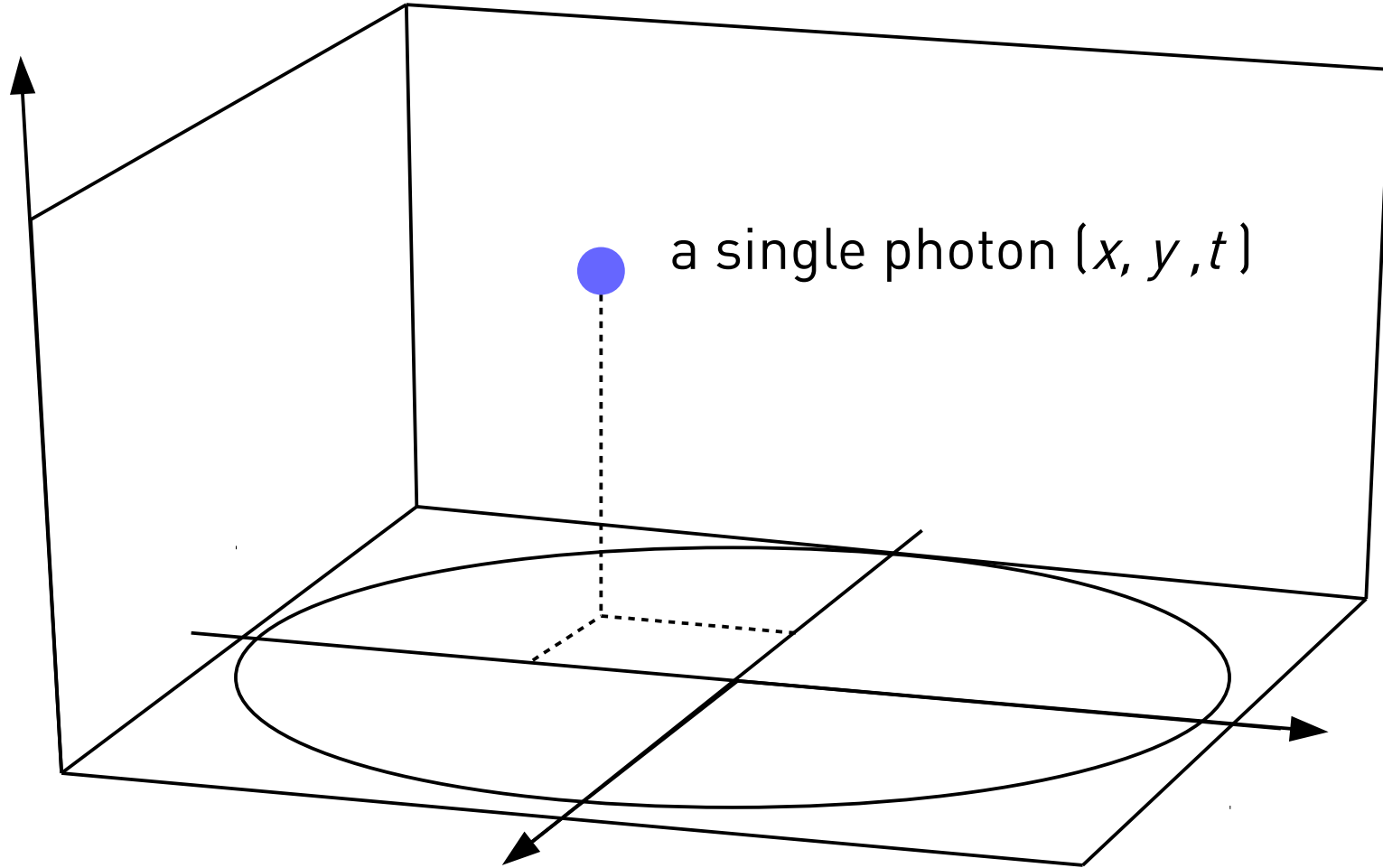
4.5° field of view



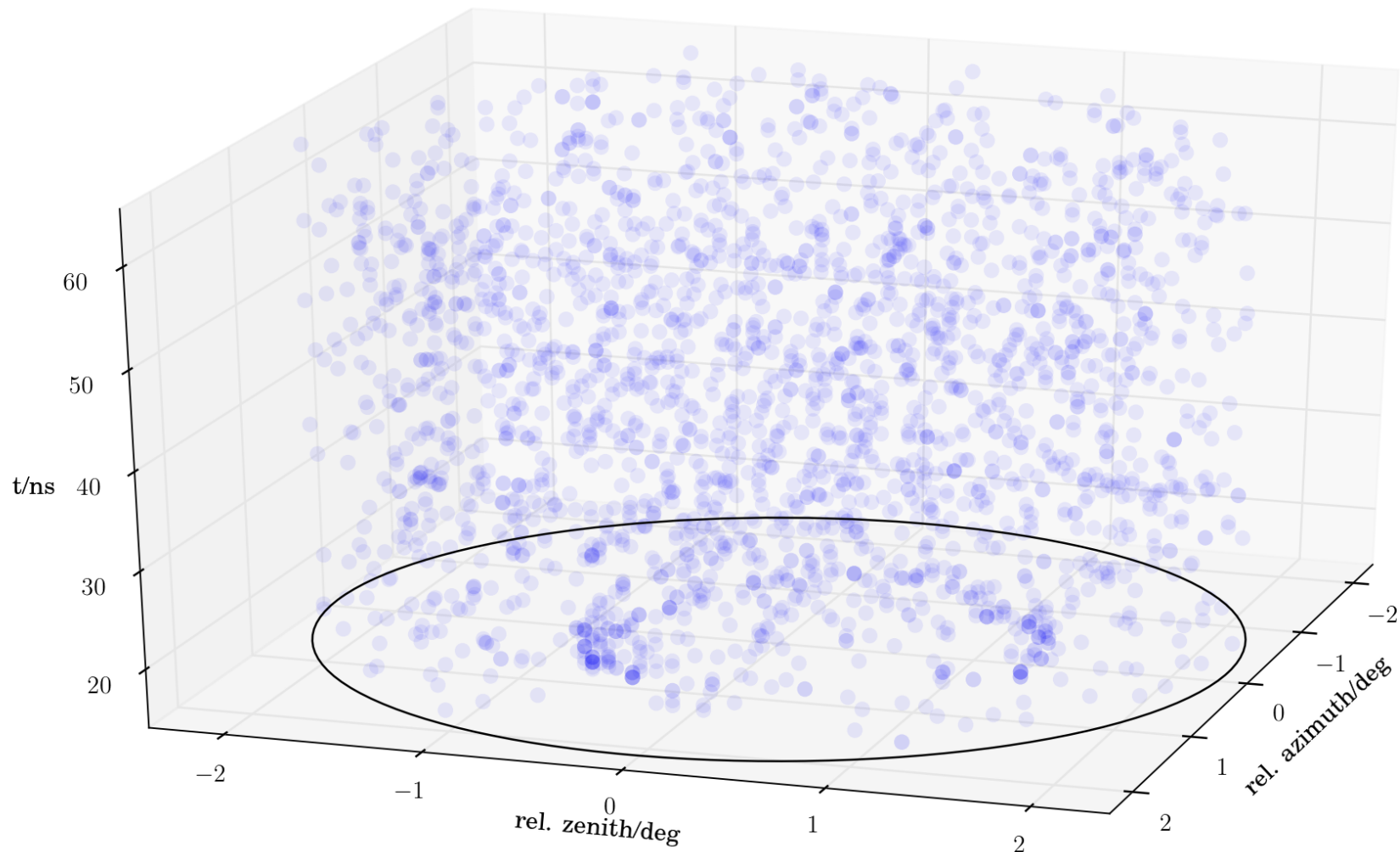
Photon-Stream in 3D



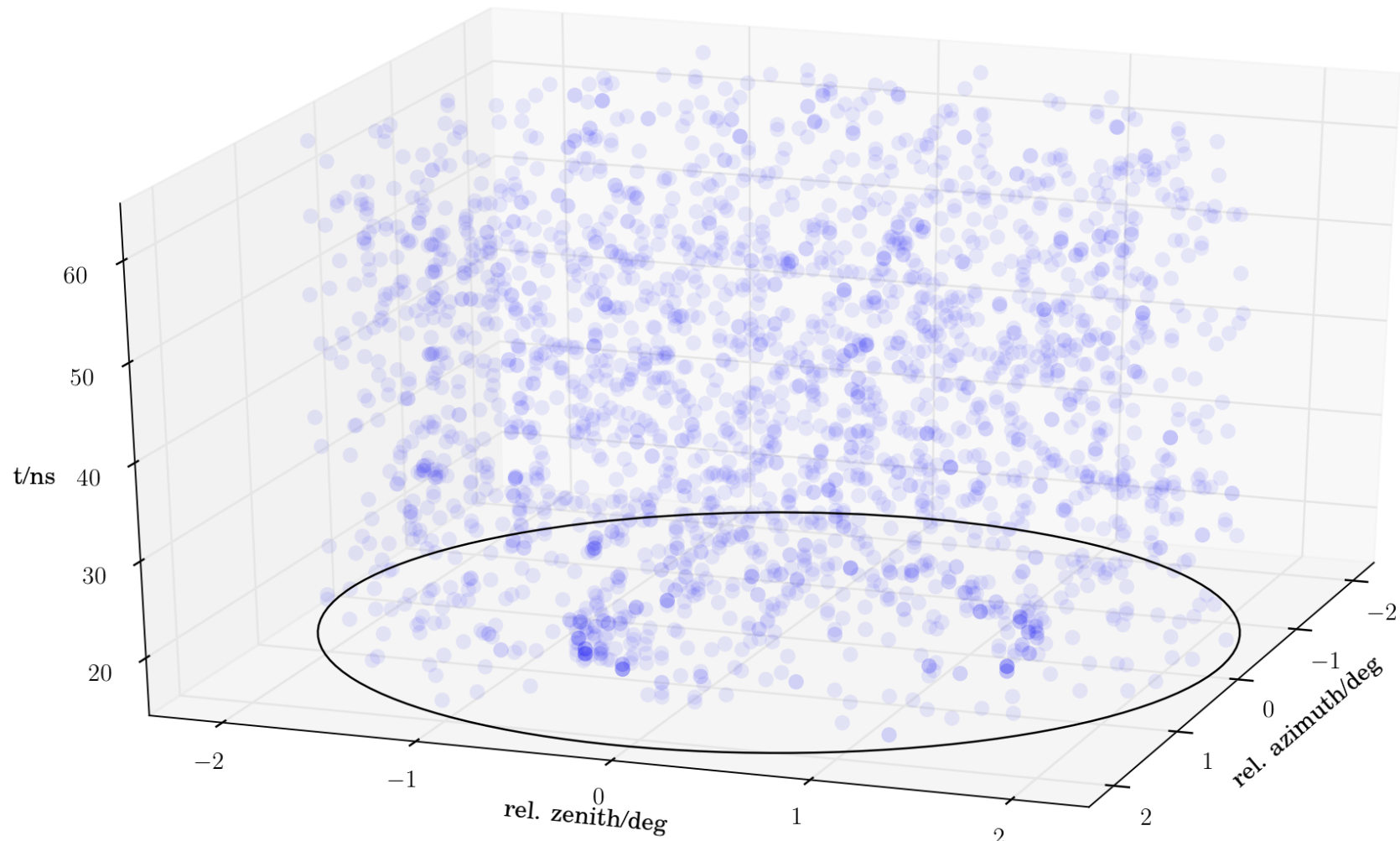
Photon-Stream in 3D



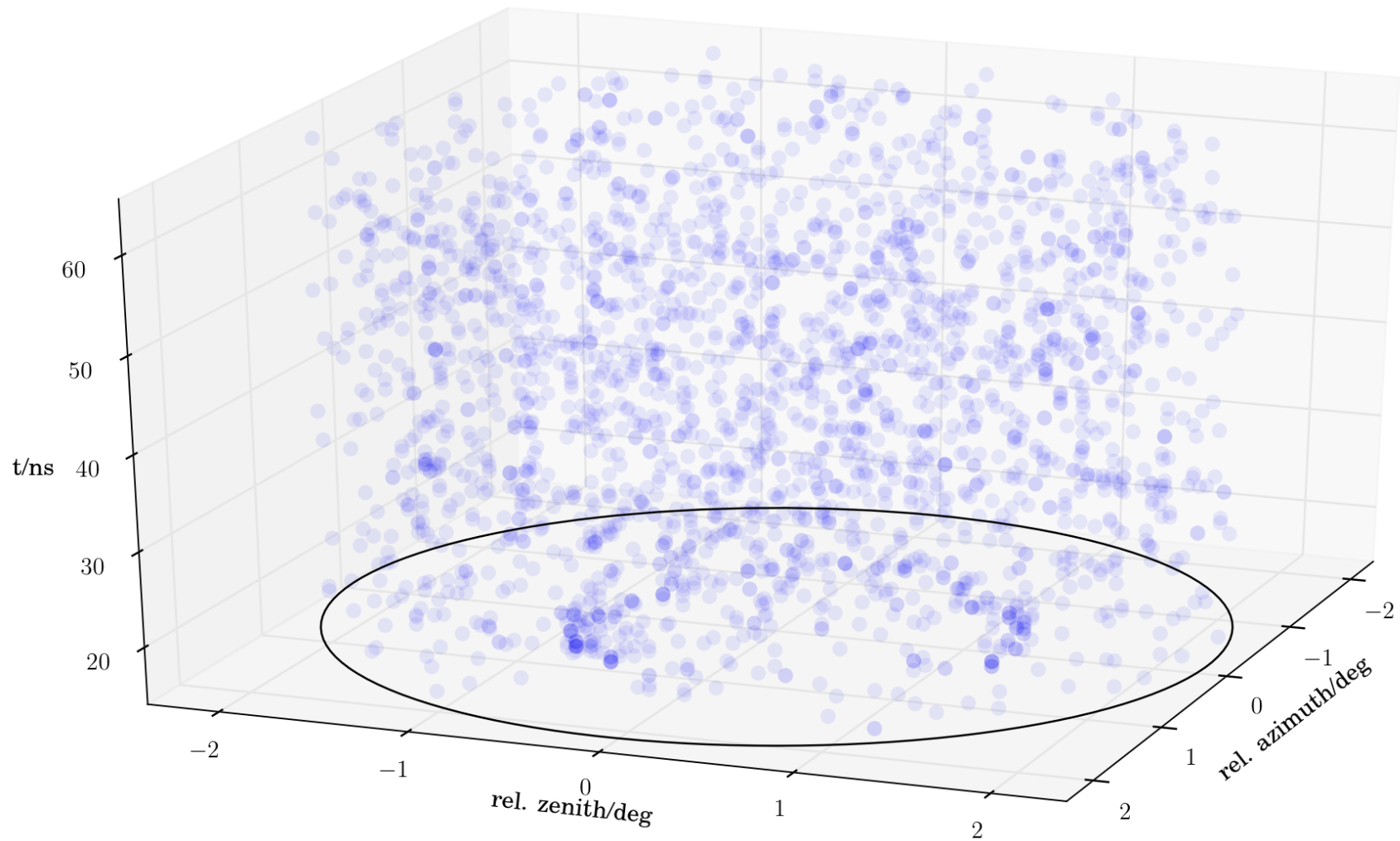
Night 20151113, Run 109, Event 18



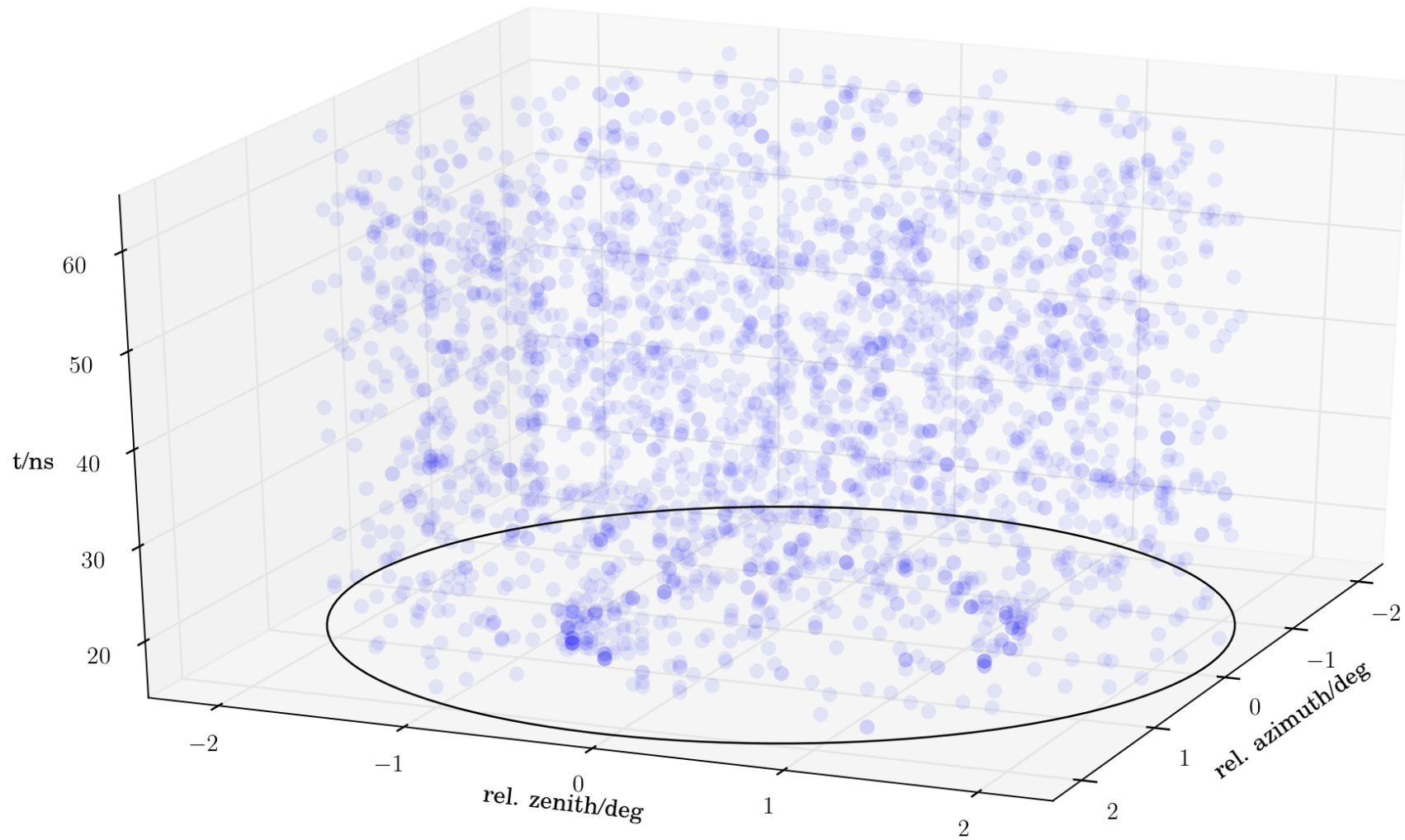
Night 20151113, Run 109, Event 18



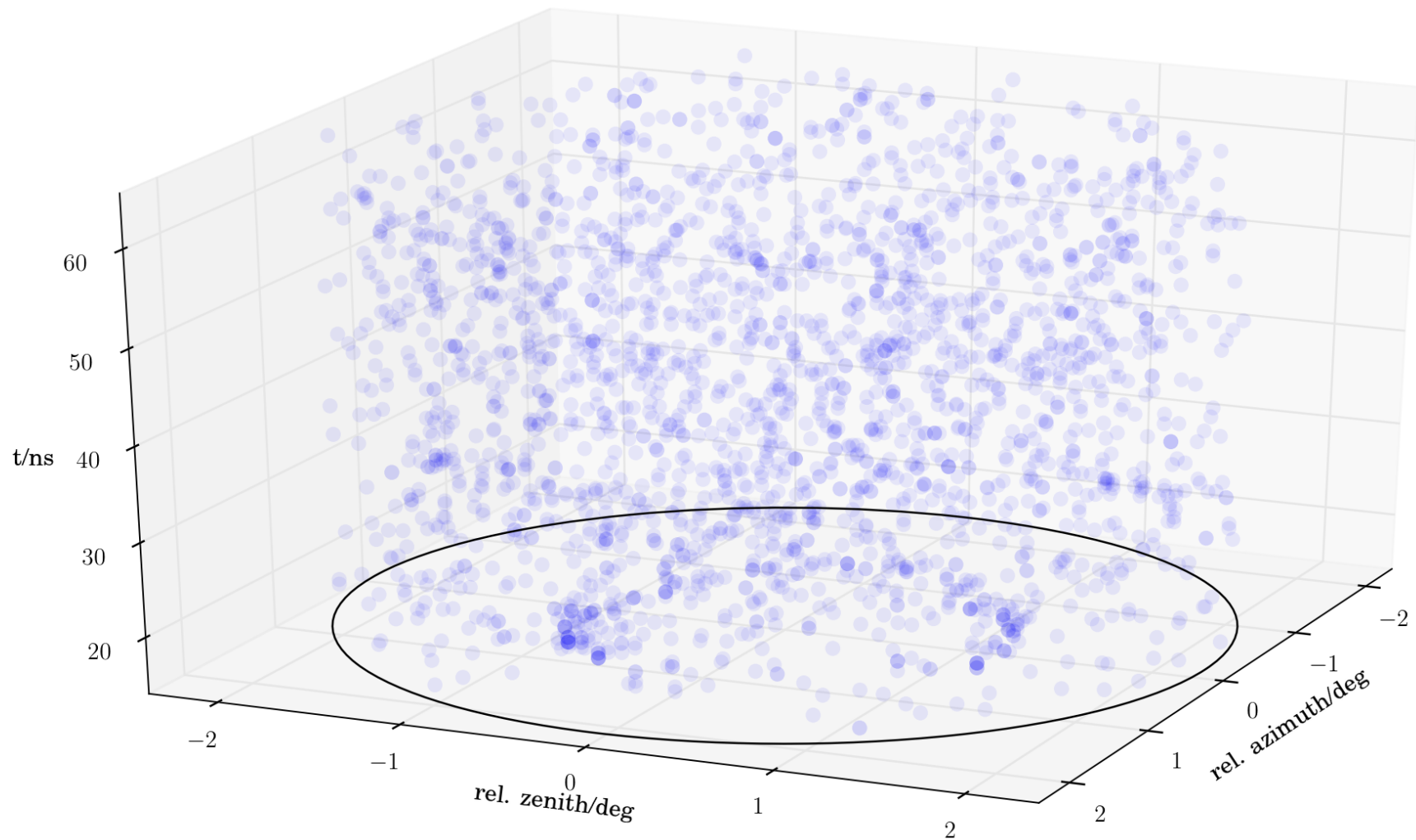
Night 20151113, Run 109, Event 18



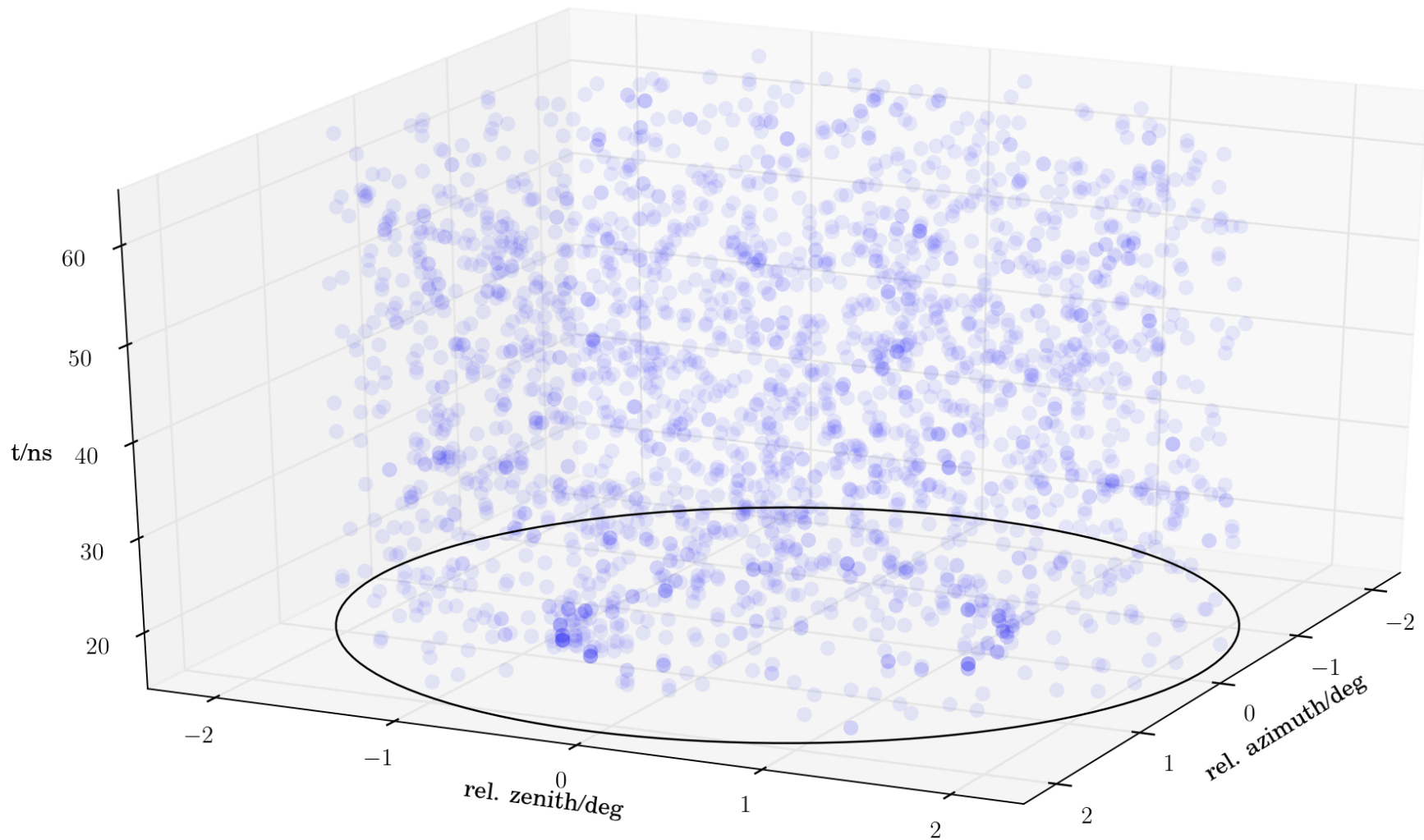
Night 20151113, Run 109, Event 18



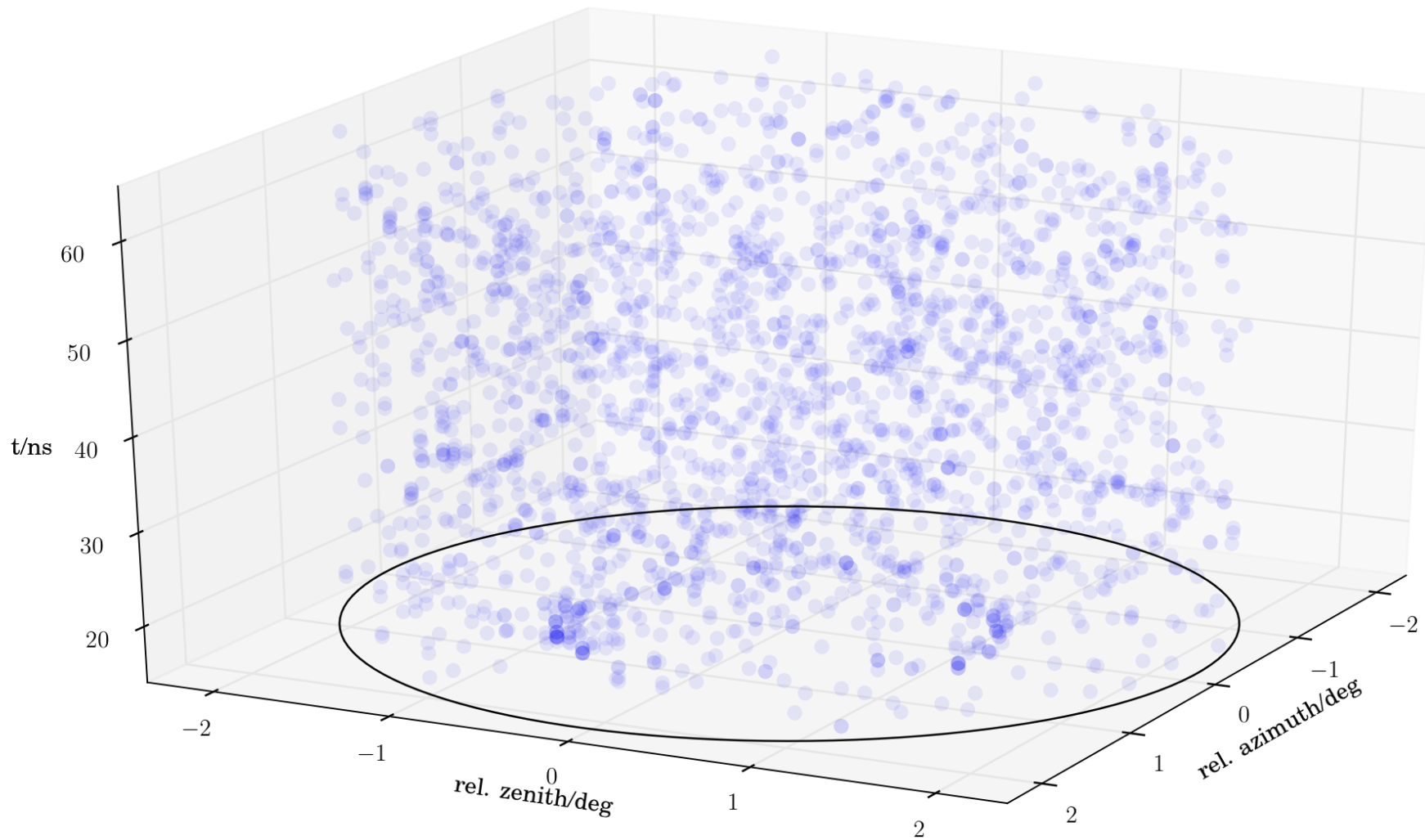
Night 20151113, Run 109, Event 18



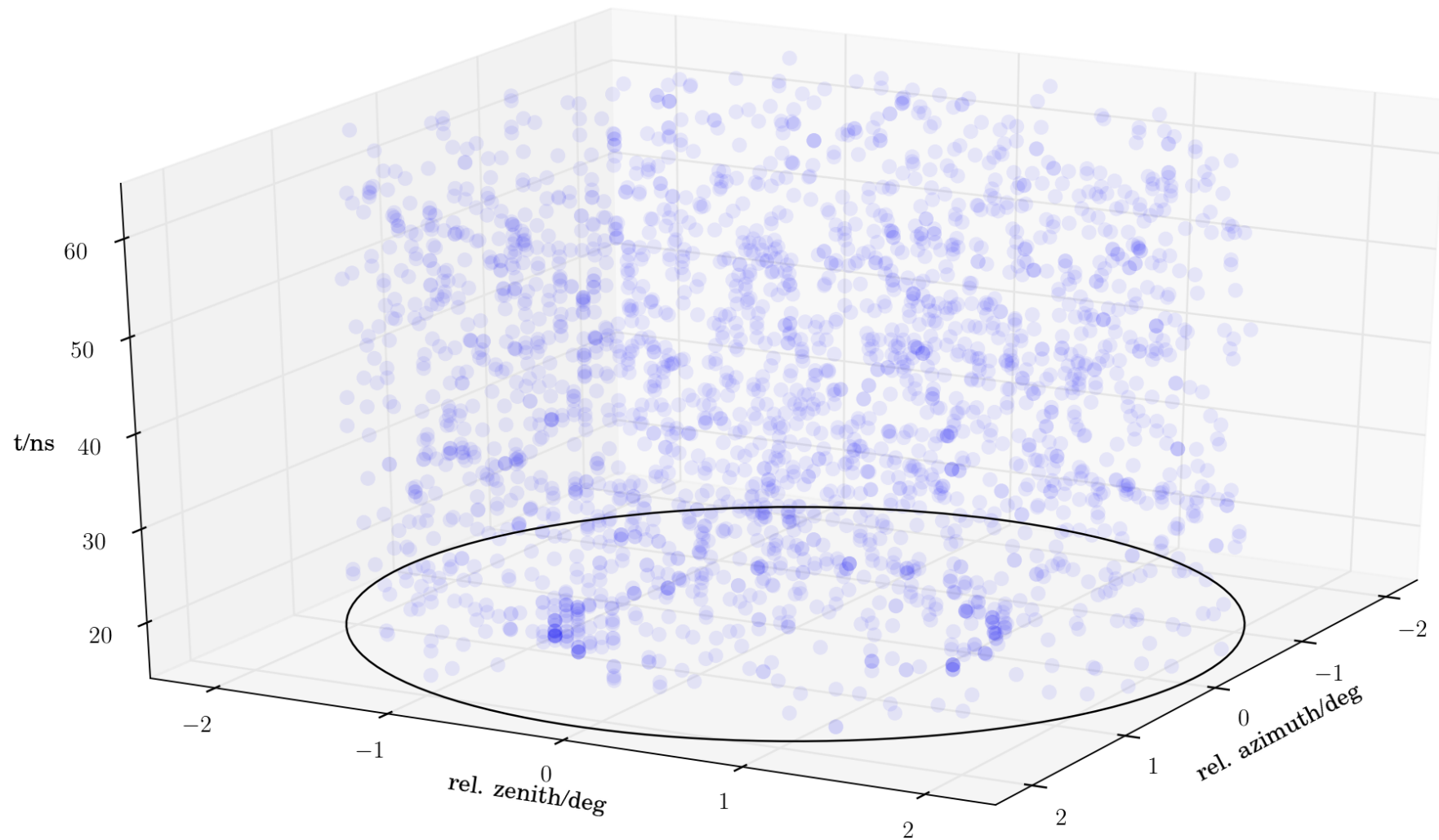
Night 20151113, Run 109, Event 18



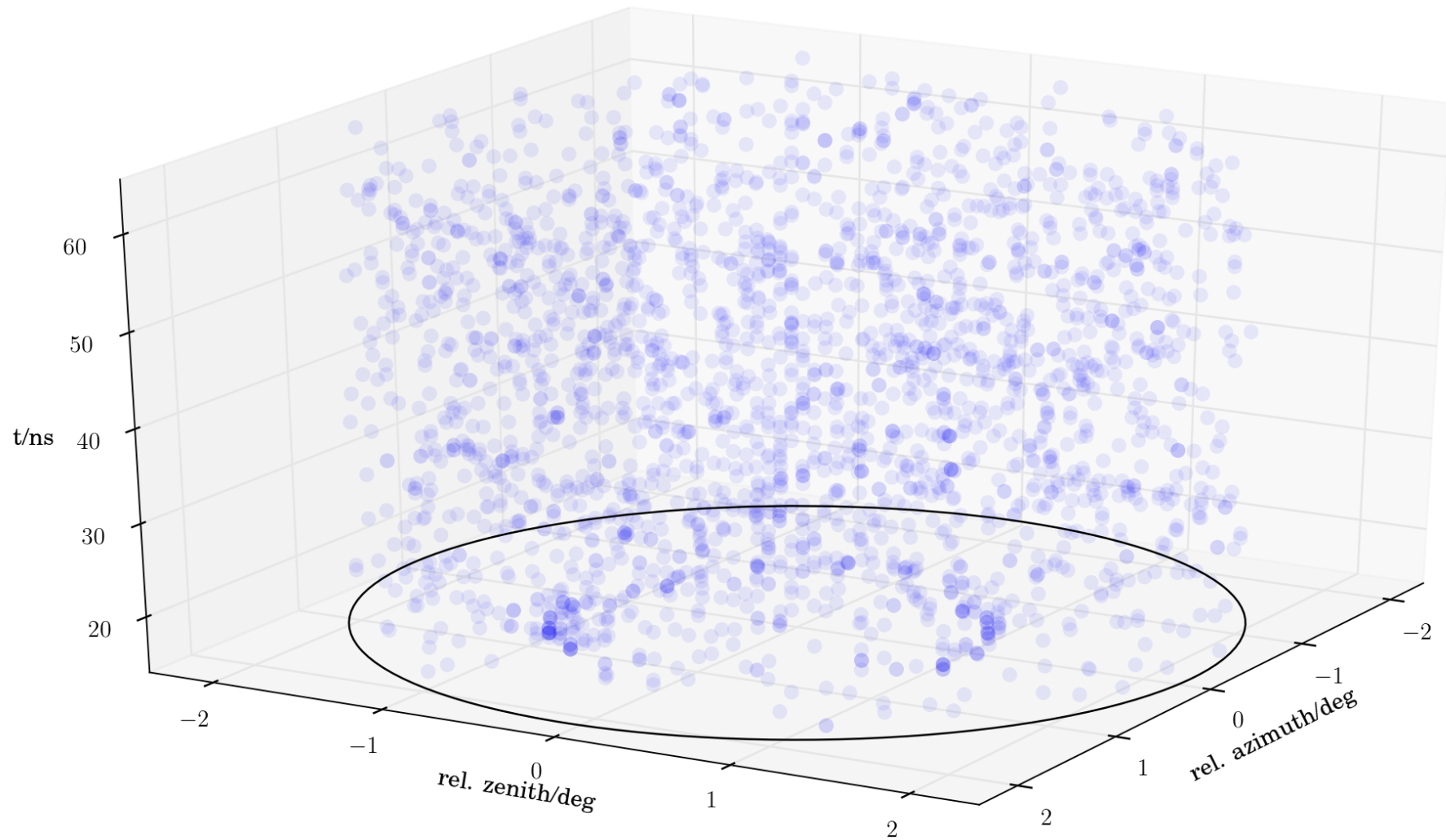
Night 20151113, Run 109, Event 18



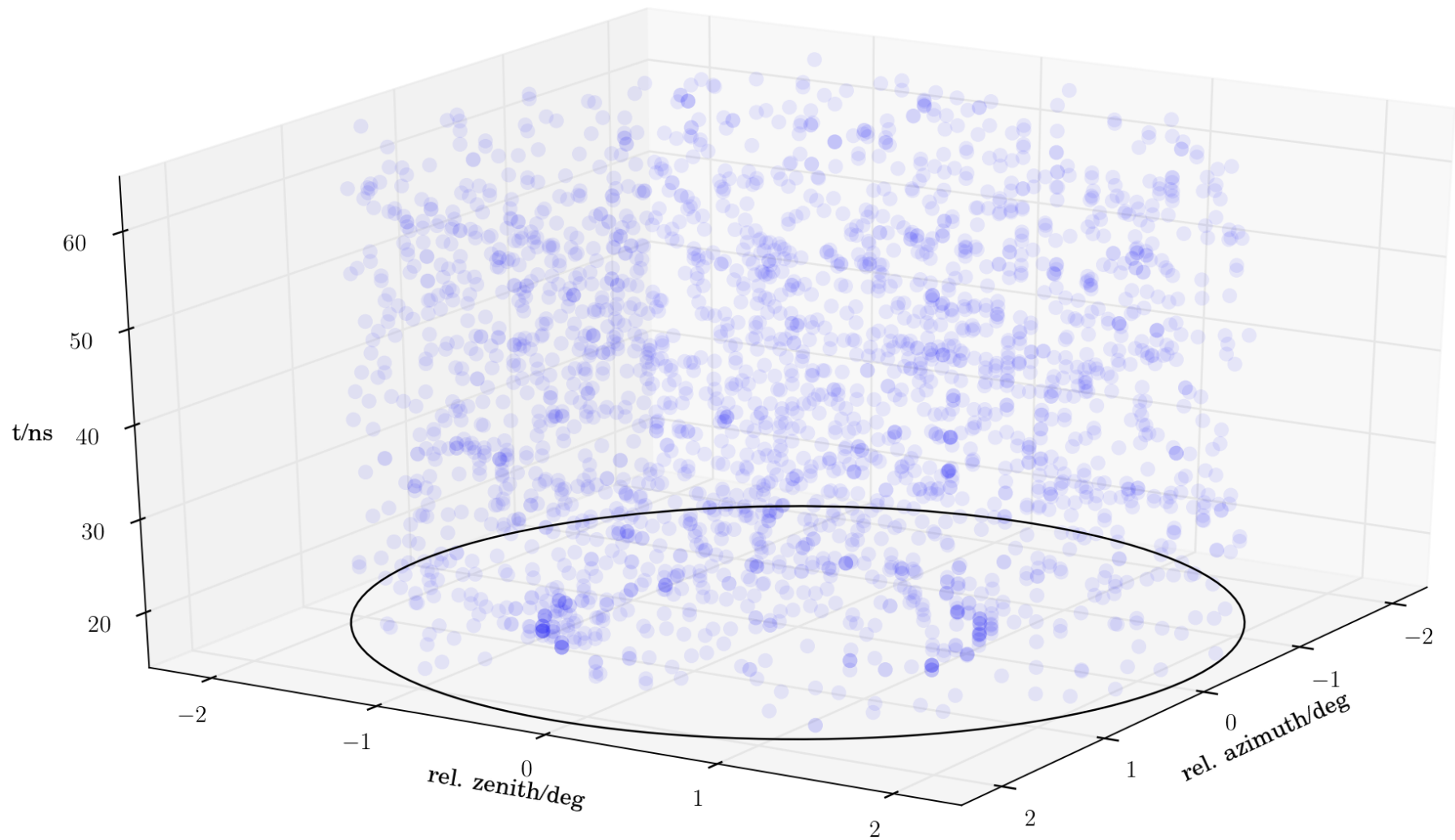
Night 20151113, Run 109, Event 18



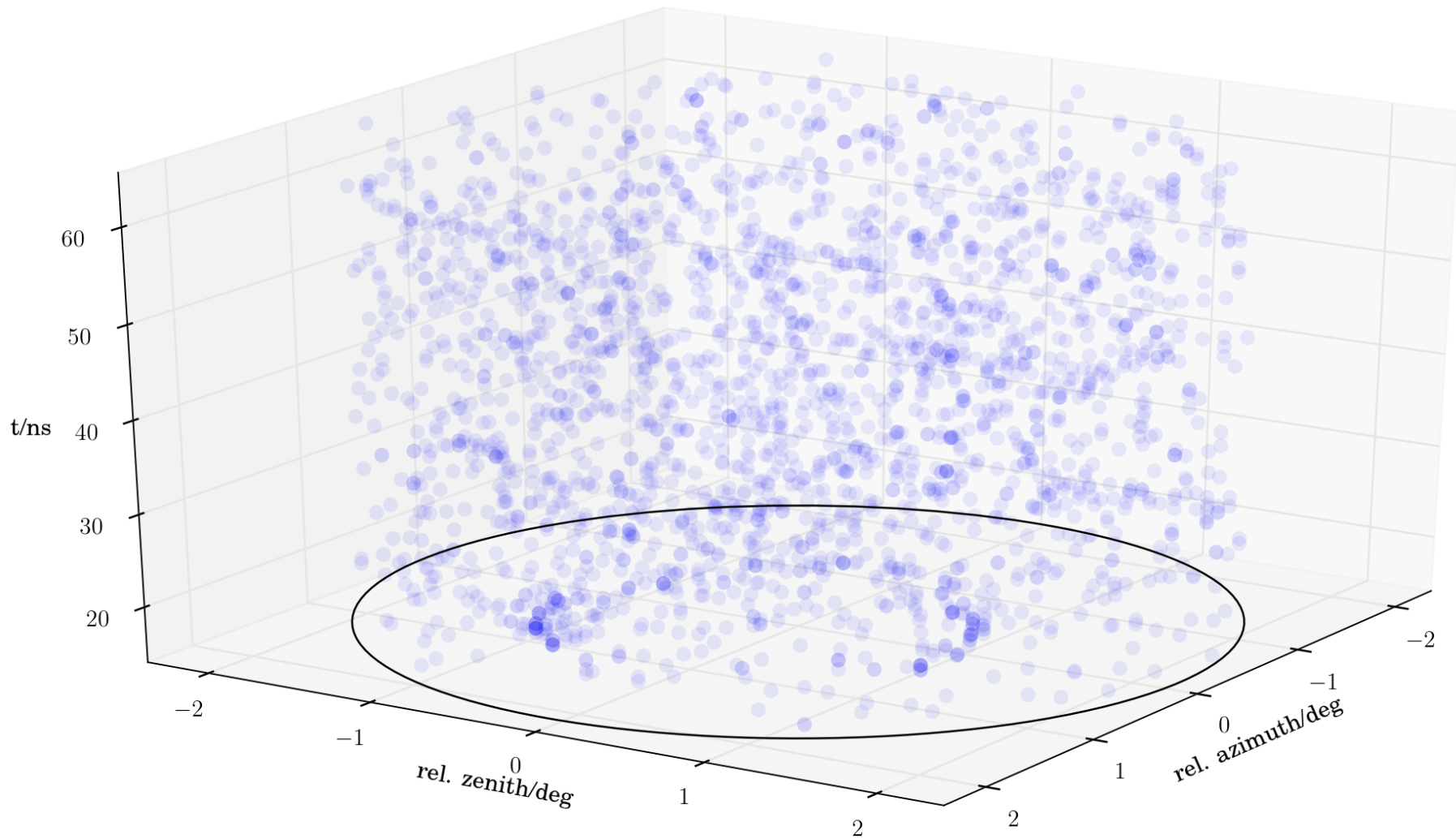
Night 20151113, Run 109, Event 18



Night 20151113, Run 109, Event 18

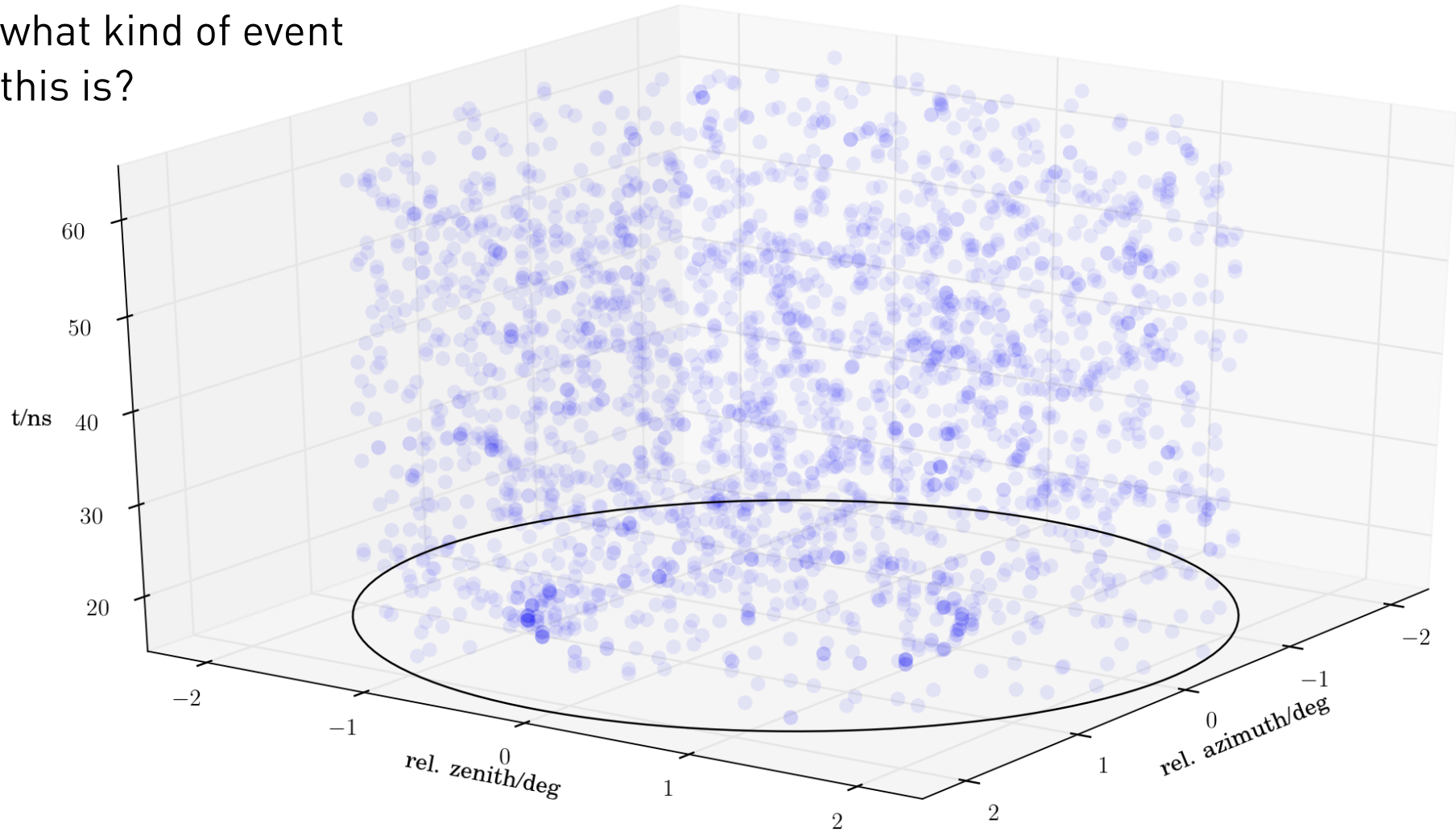


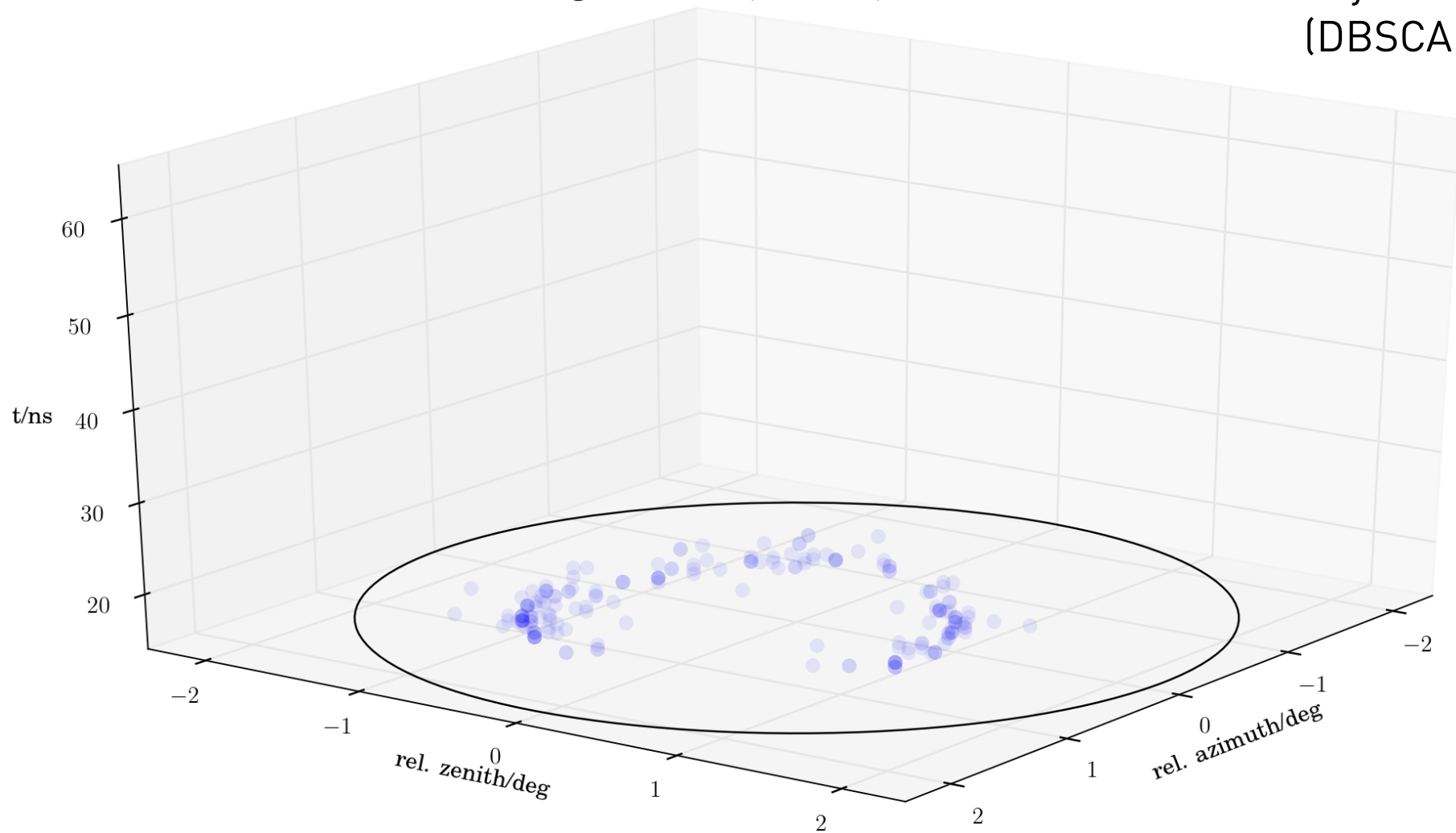
Night 20151113, Run 109, Event 18

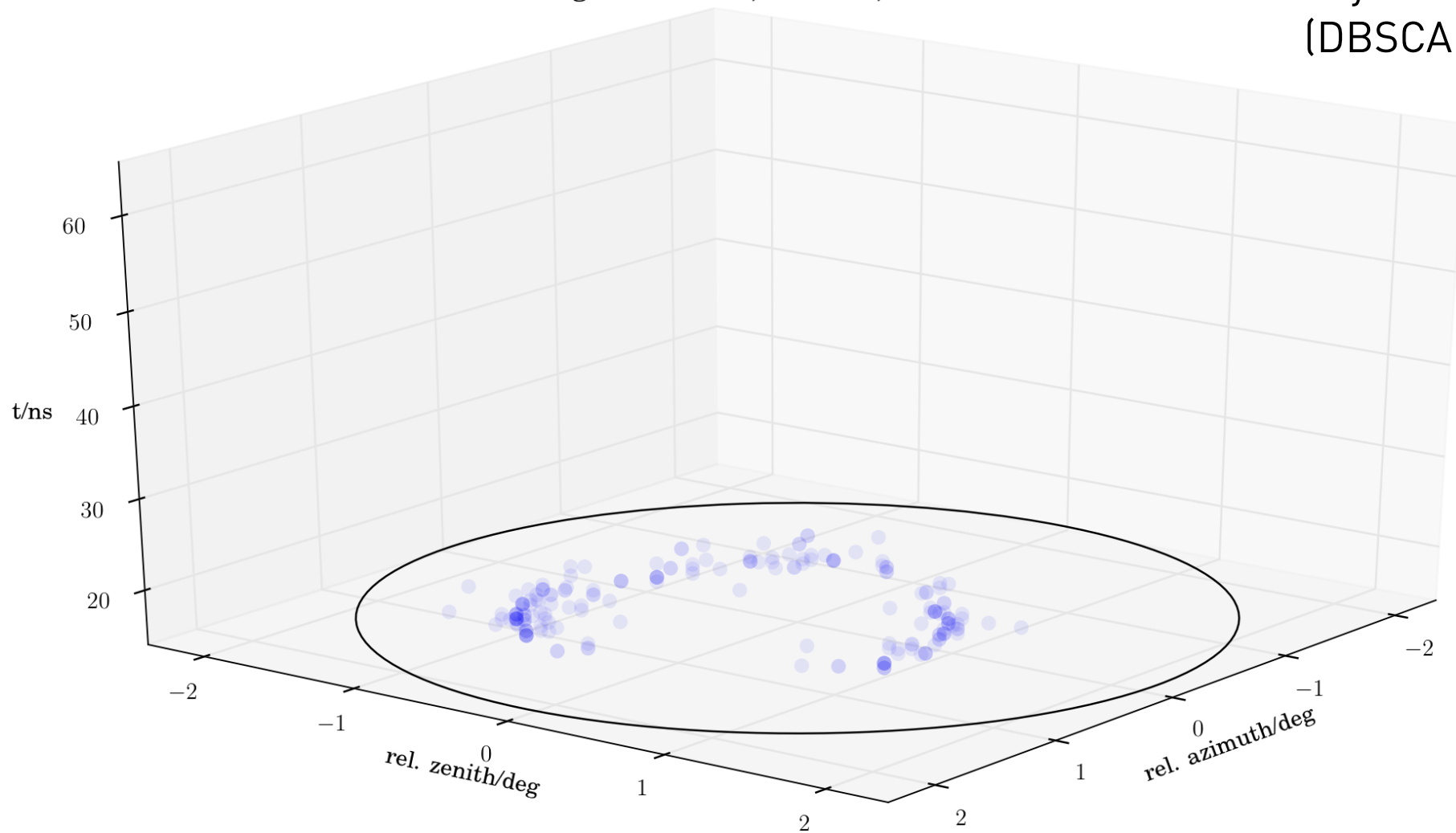


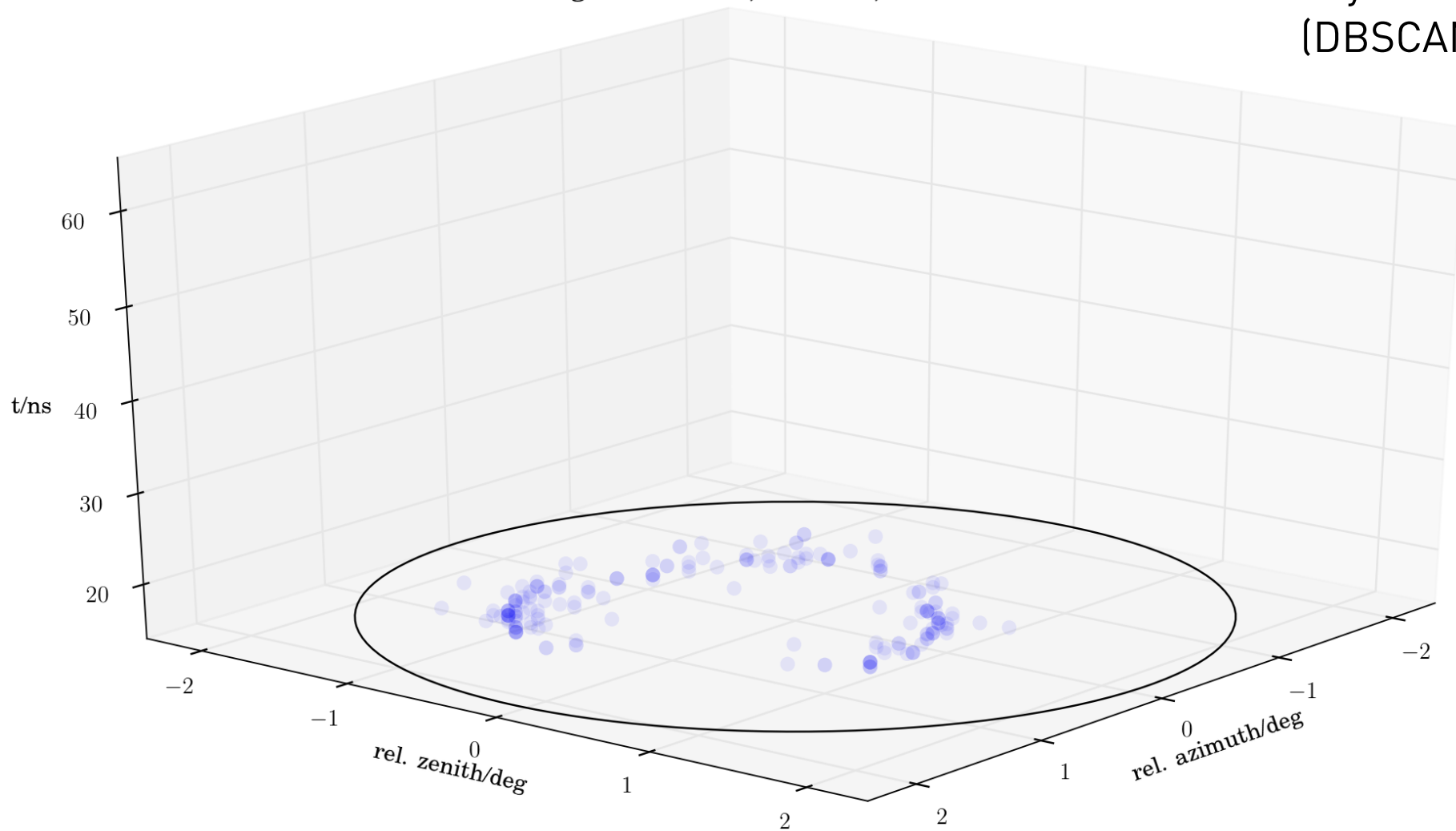
Do you already see
what kind of event
this is?

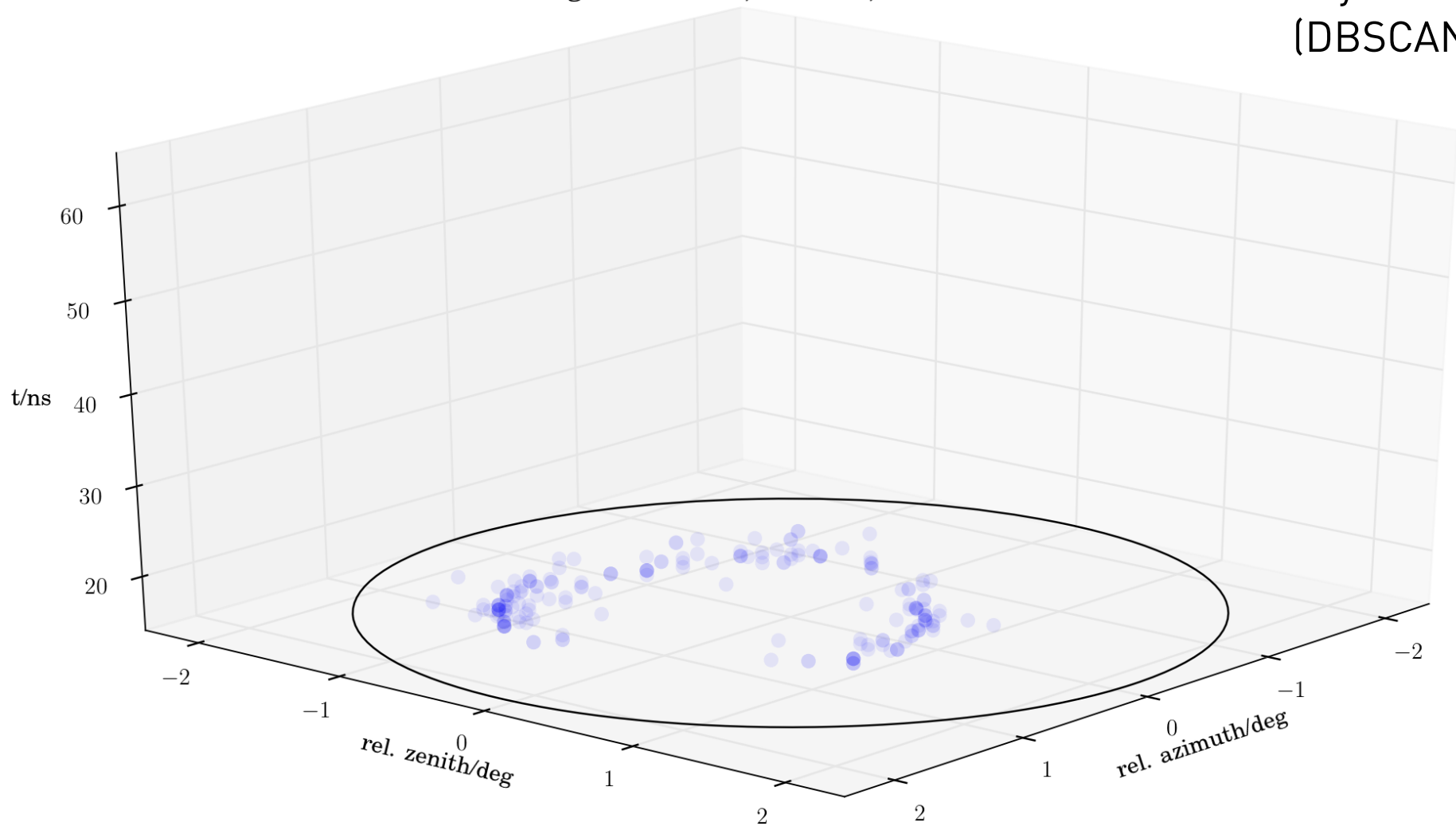
Night 20151113, Run 109, Event 18

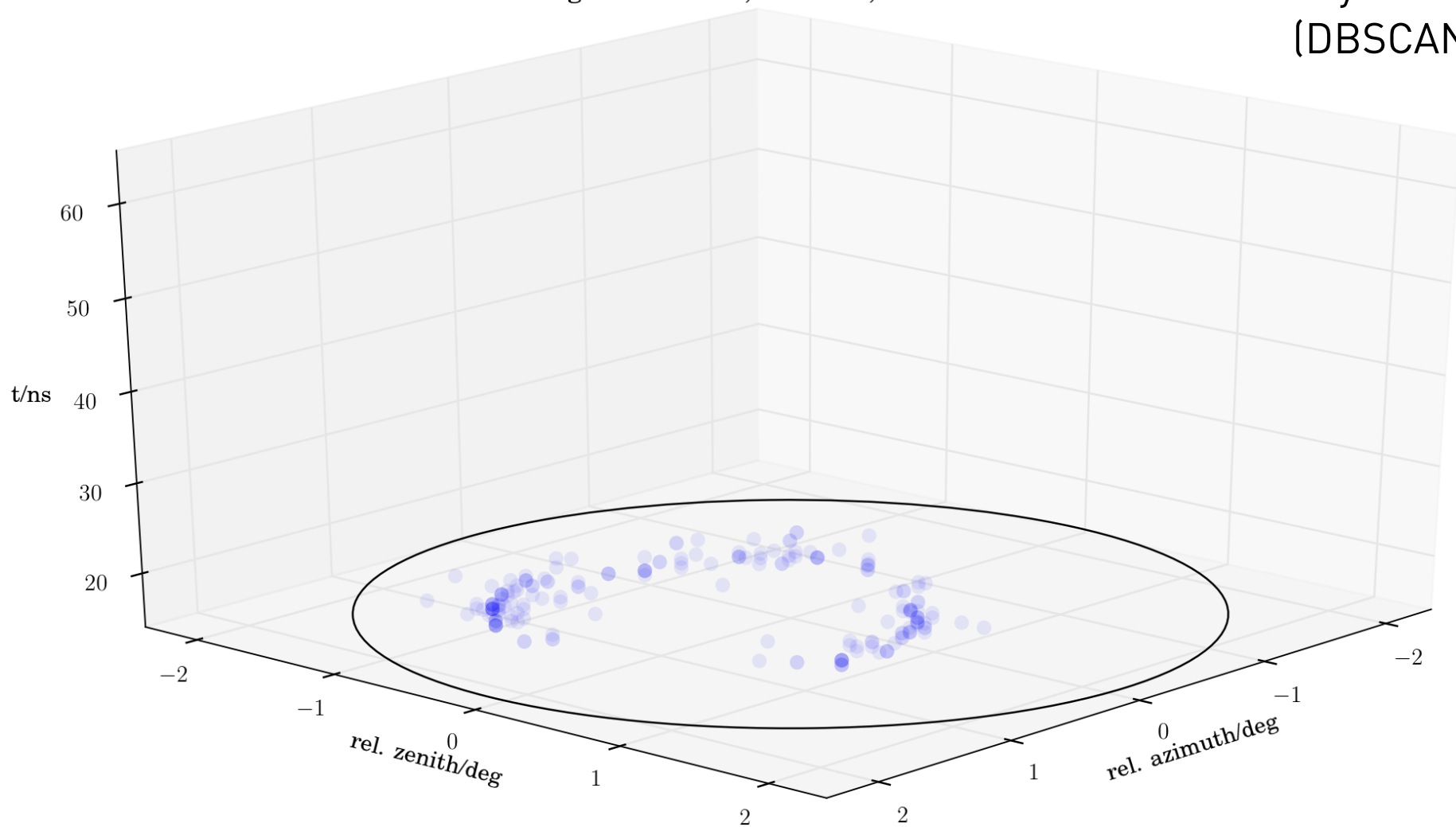


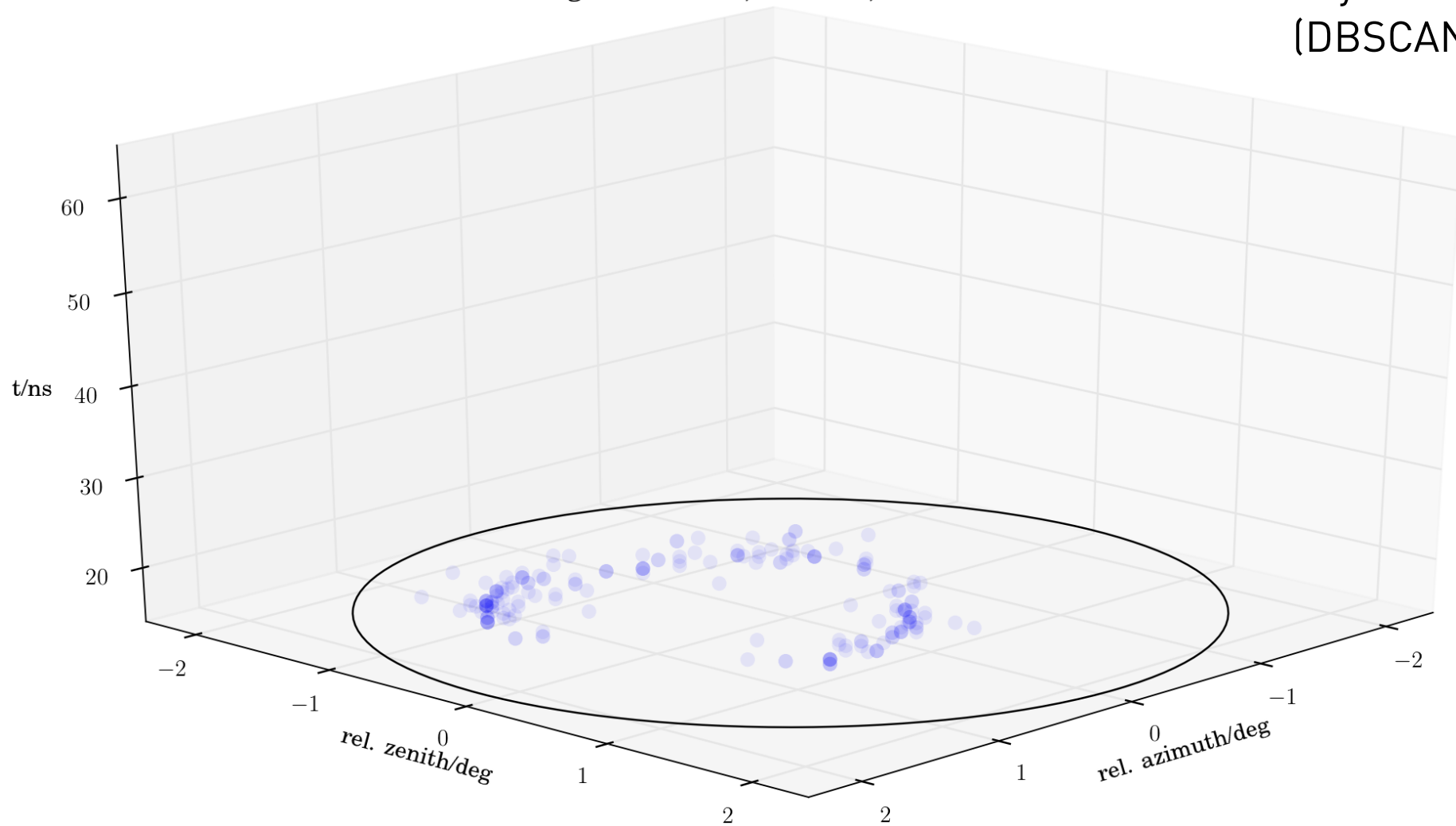


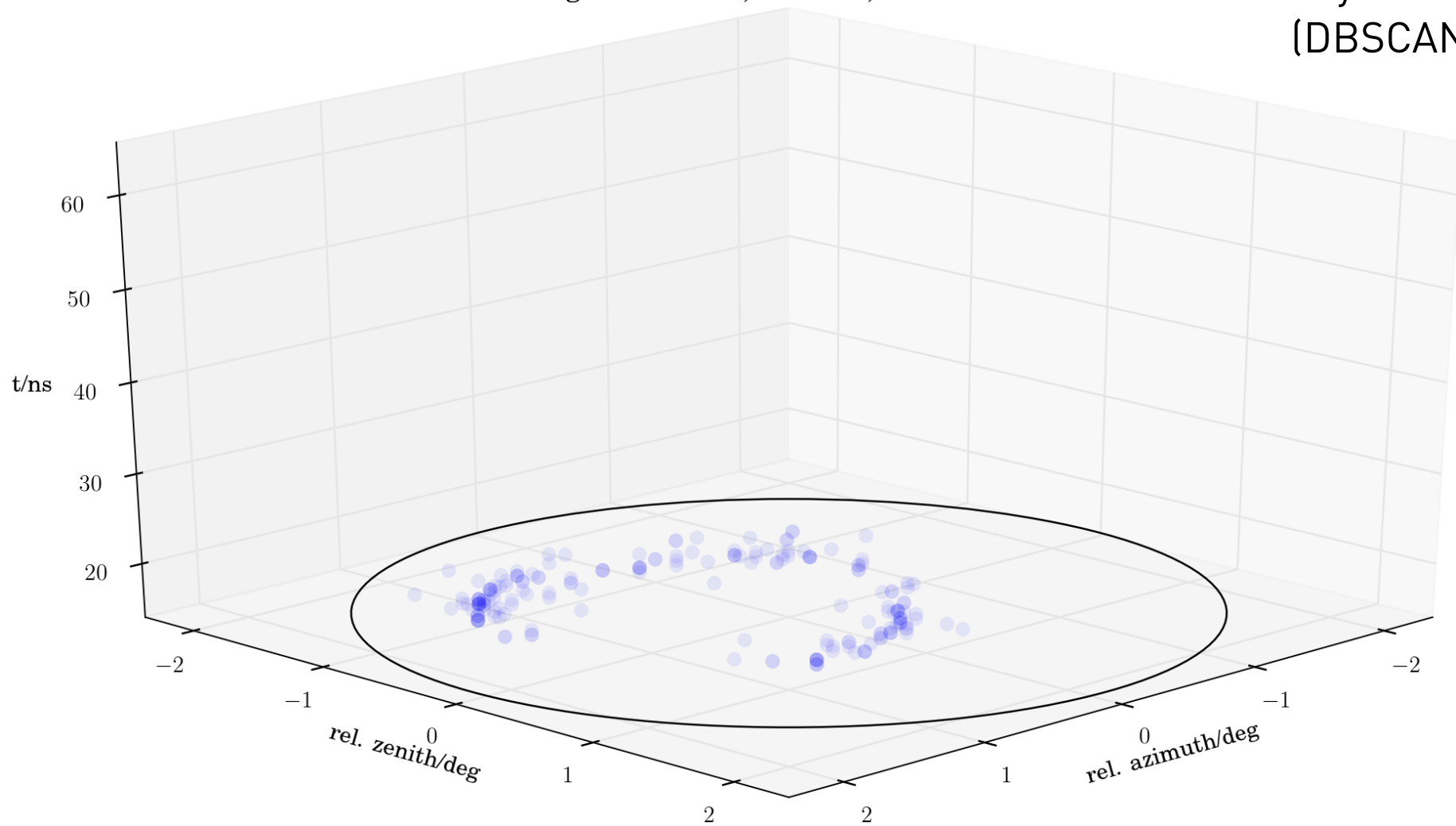


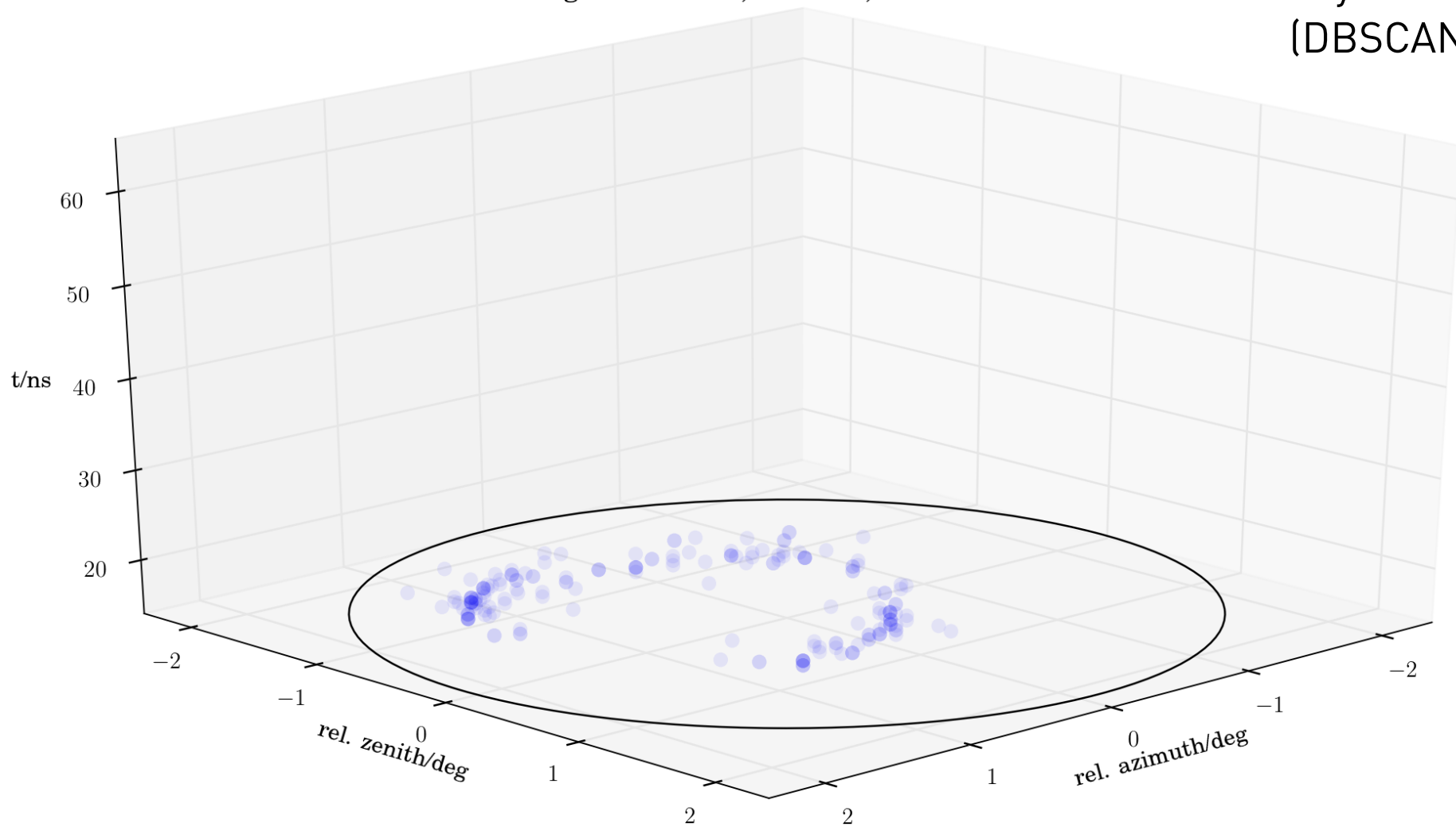


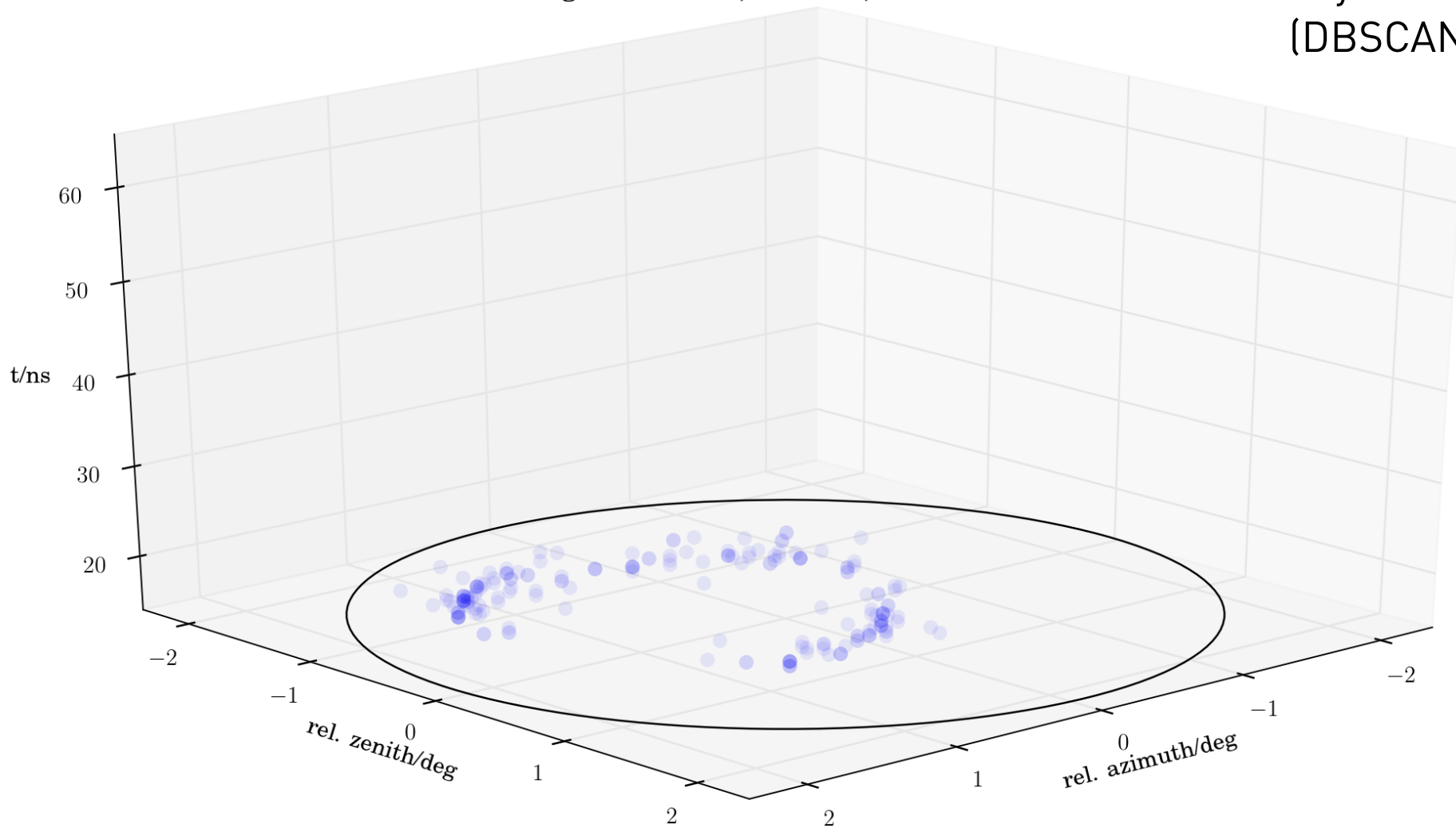






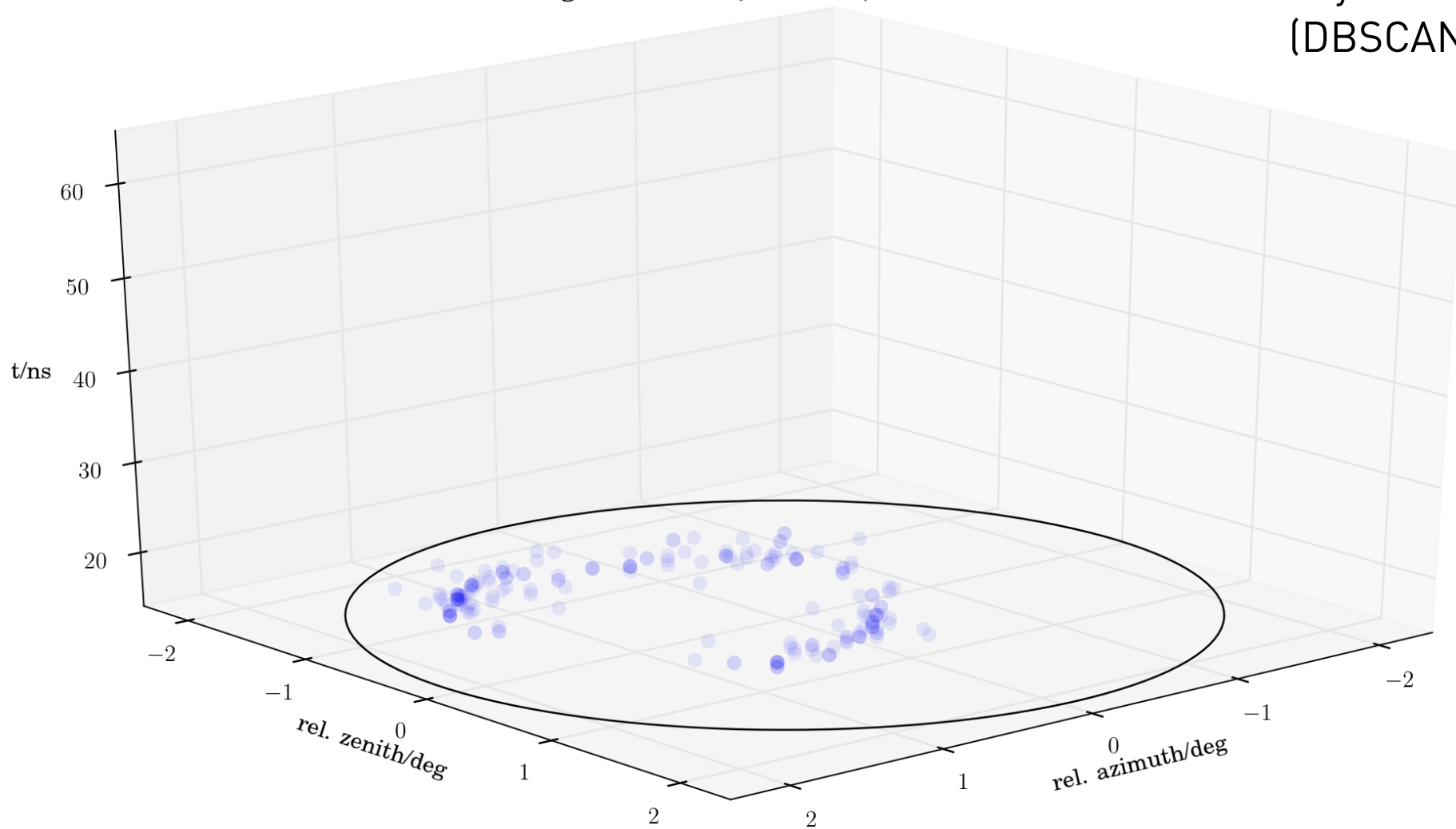


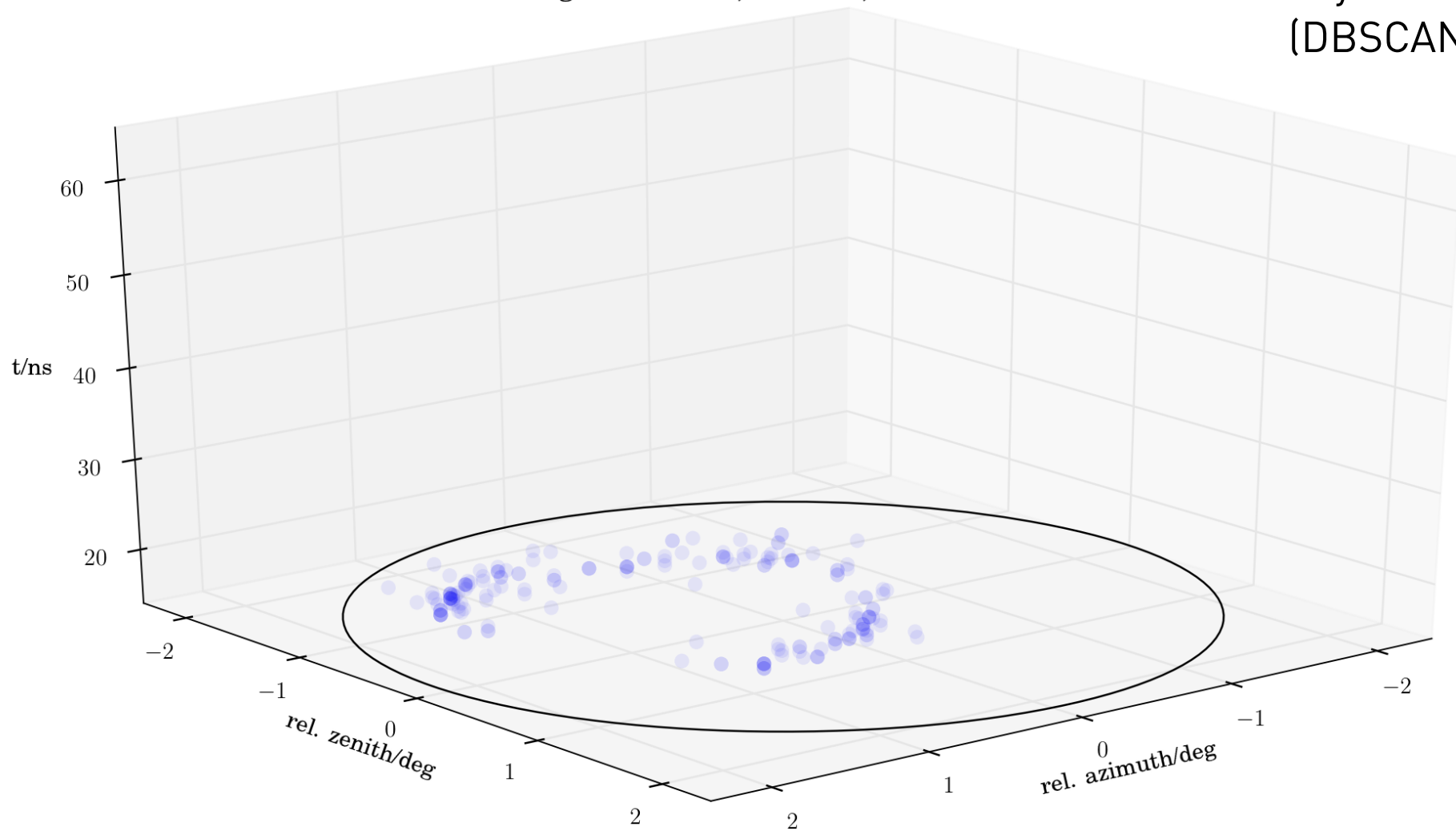


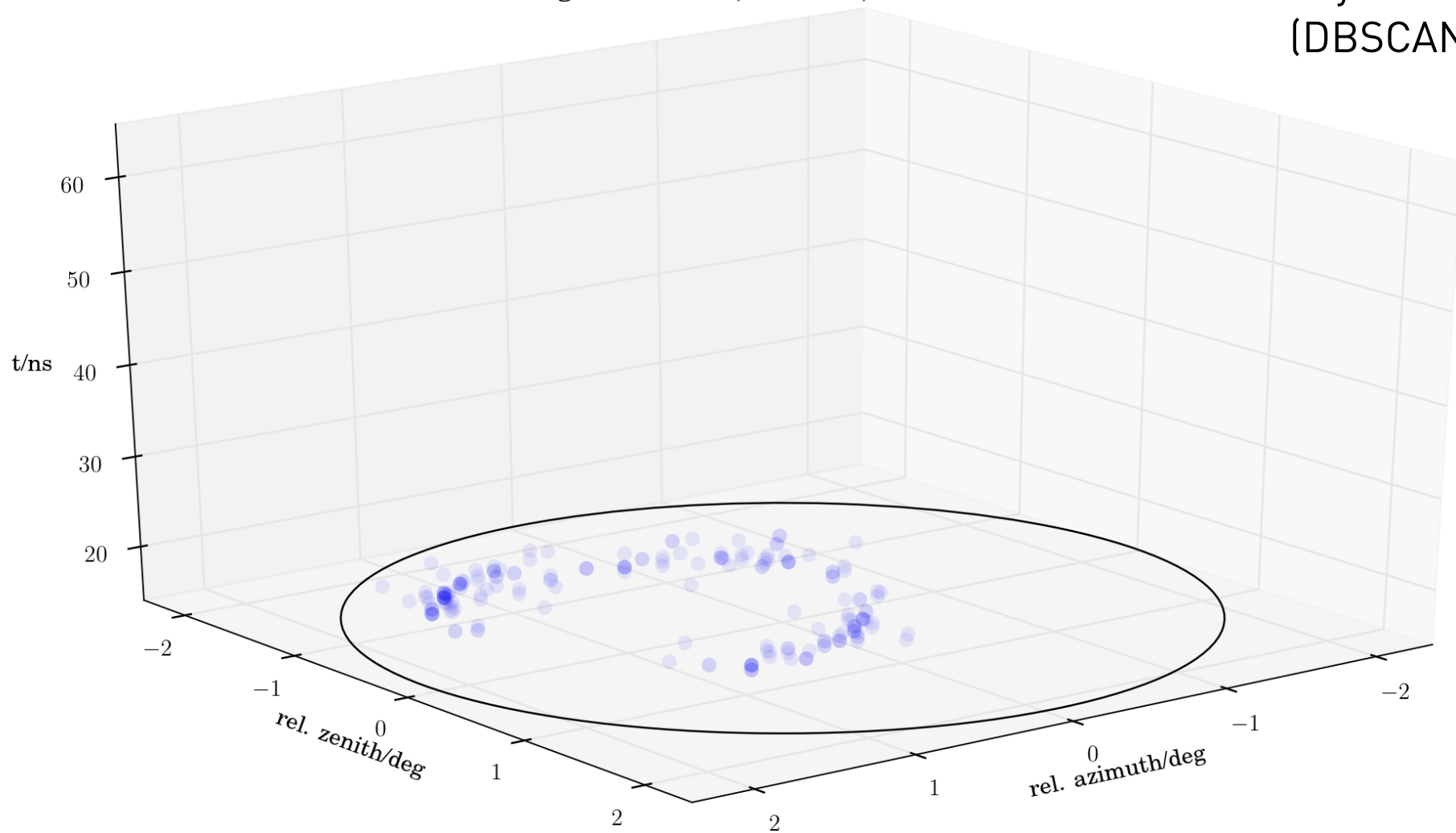


Night 20151113, Run 109, Event 18

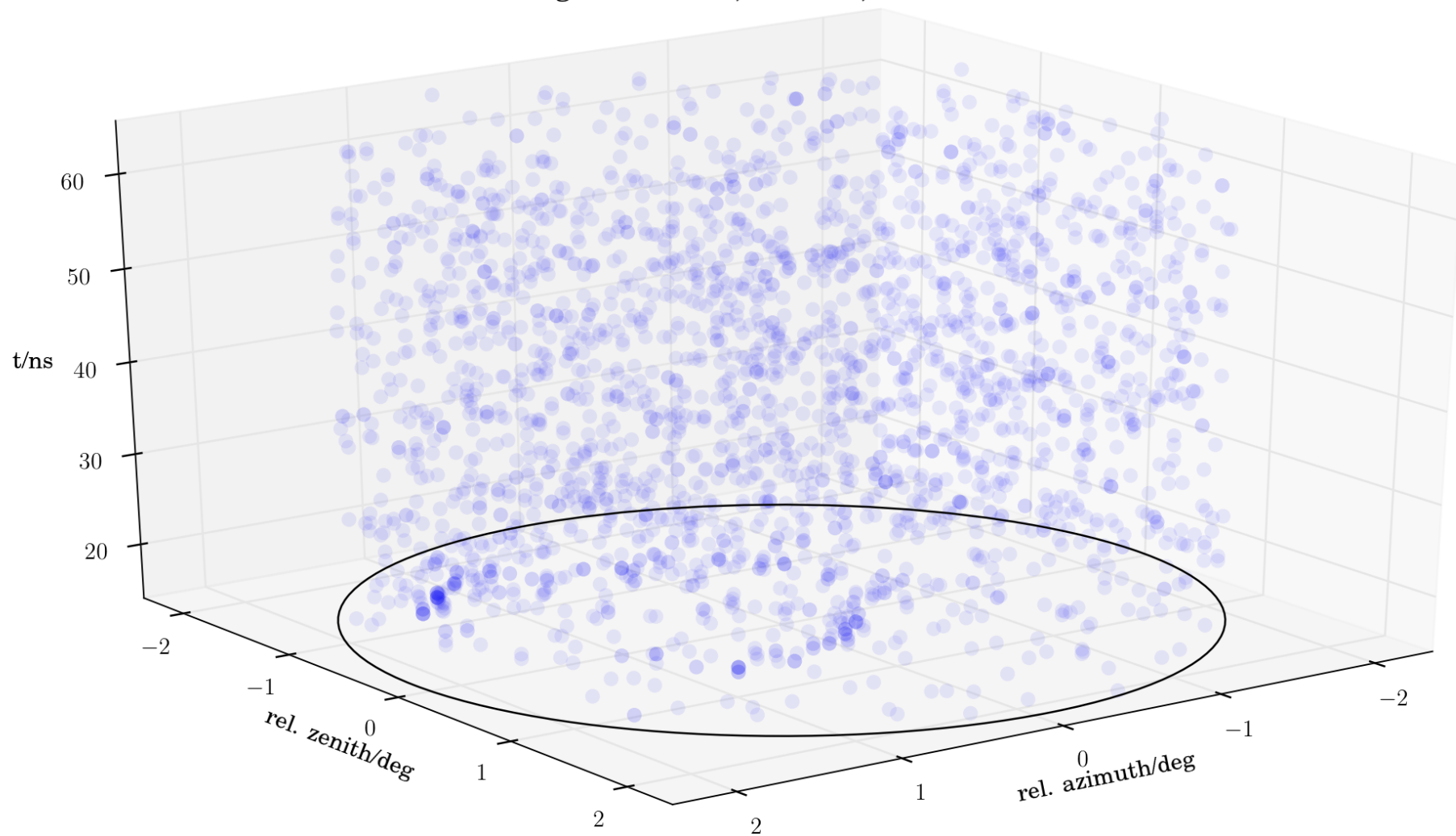
Density clustering
(DBSCAN)



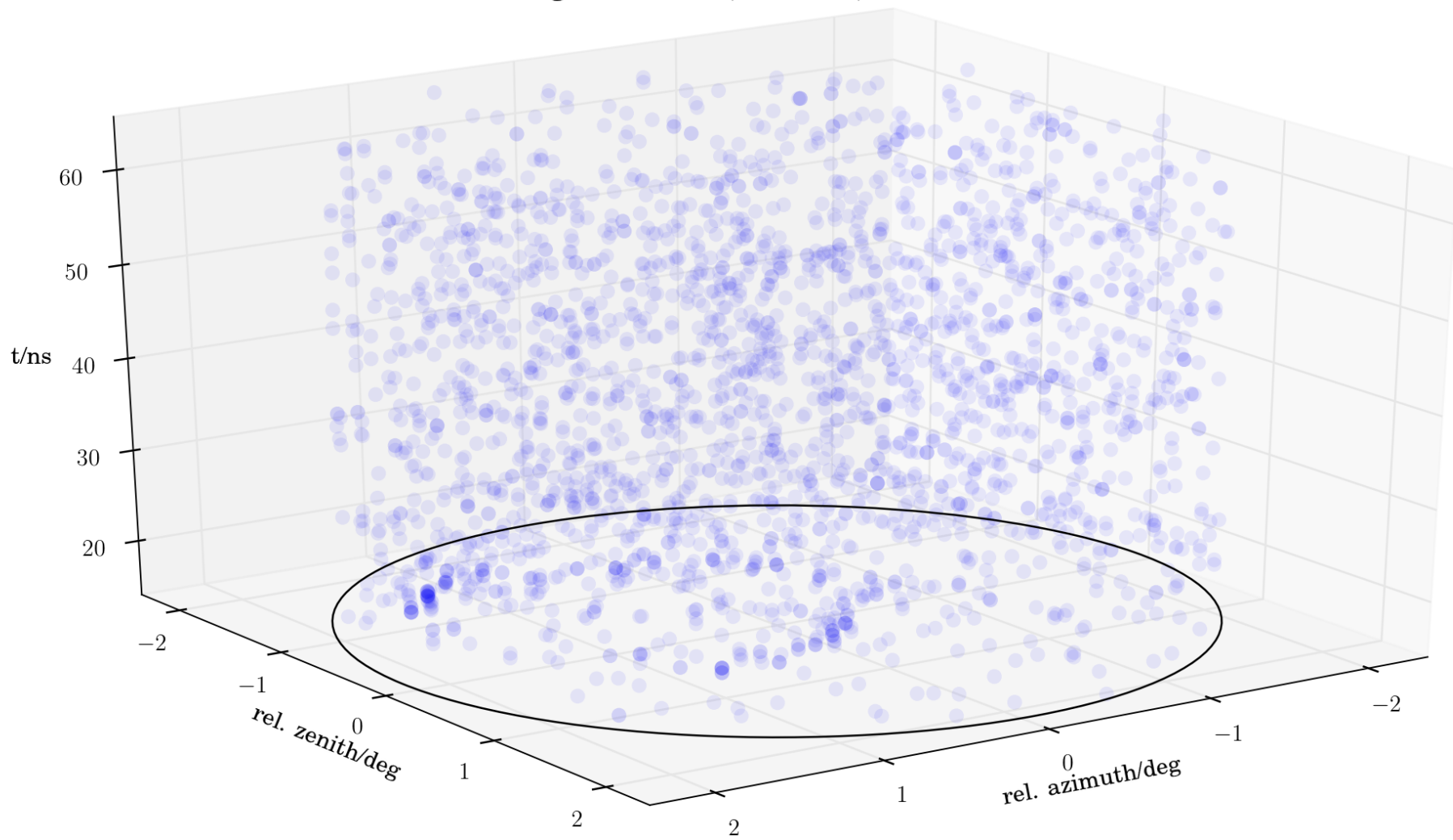




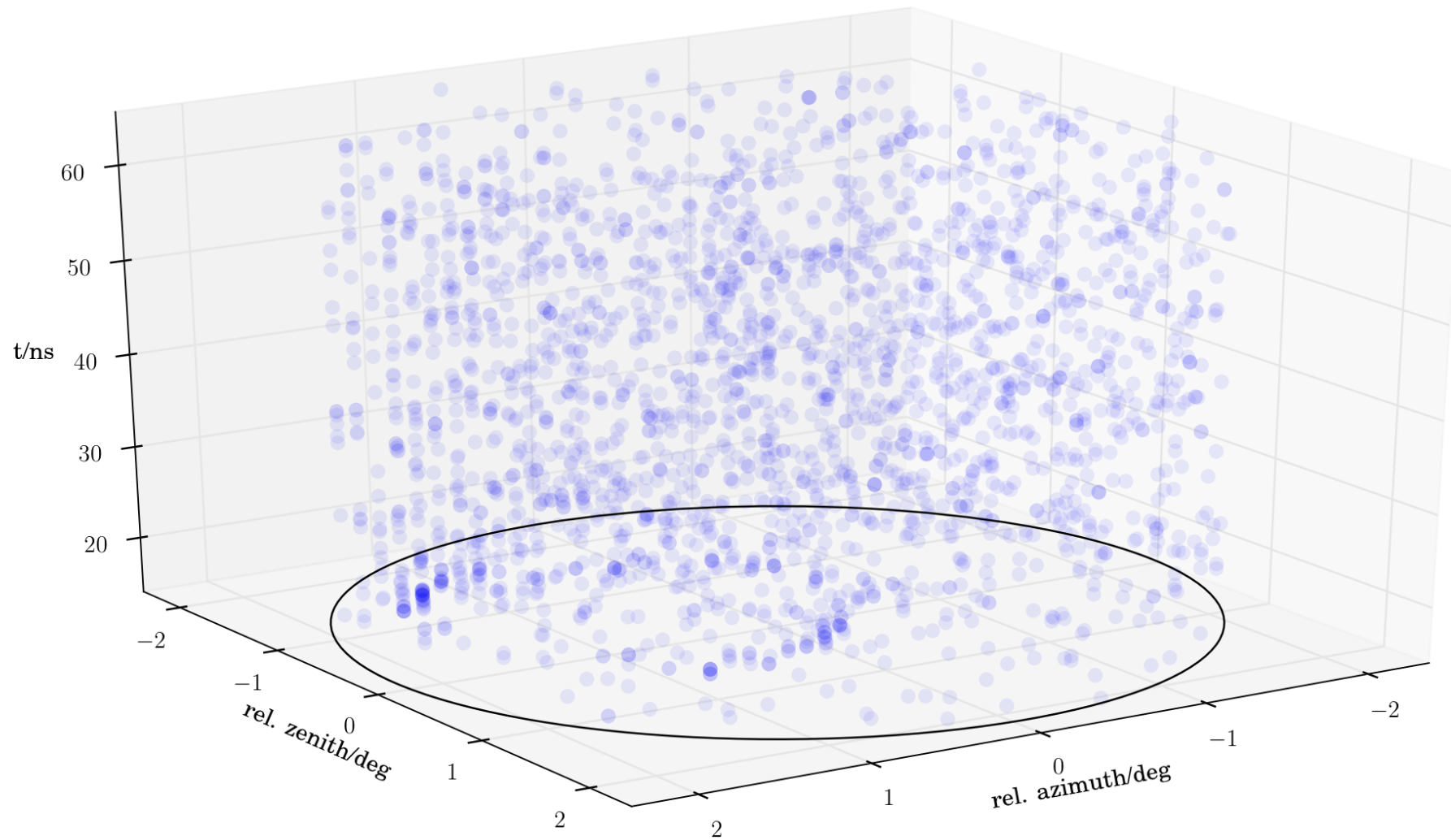
Night 20151113, Run 109, Event 18



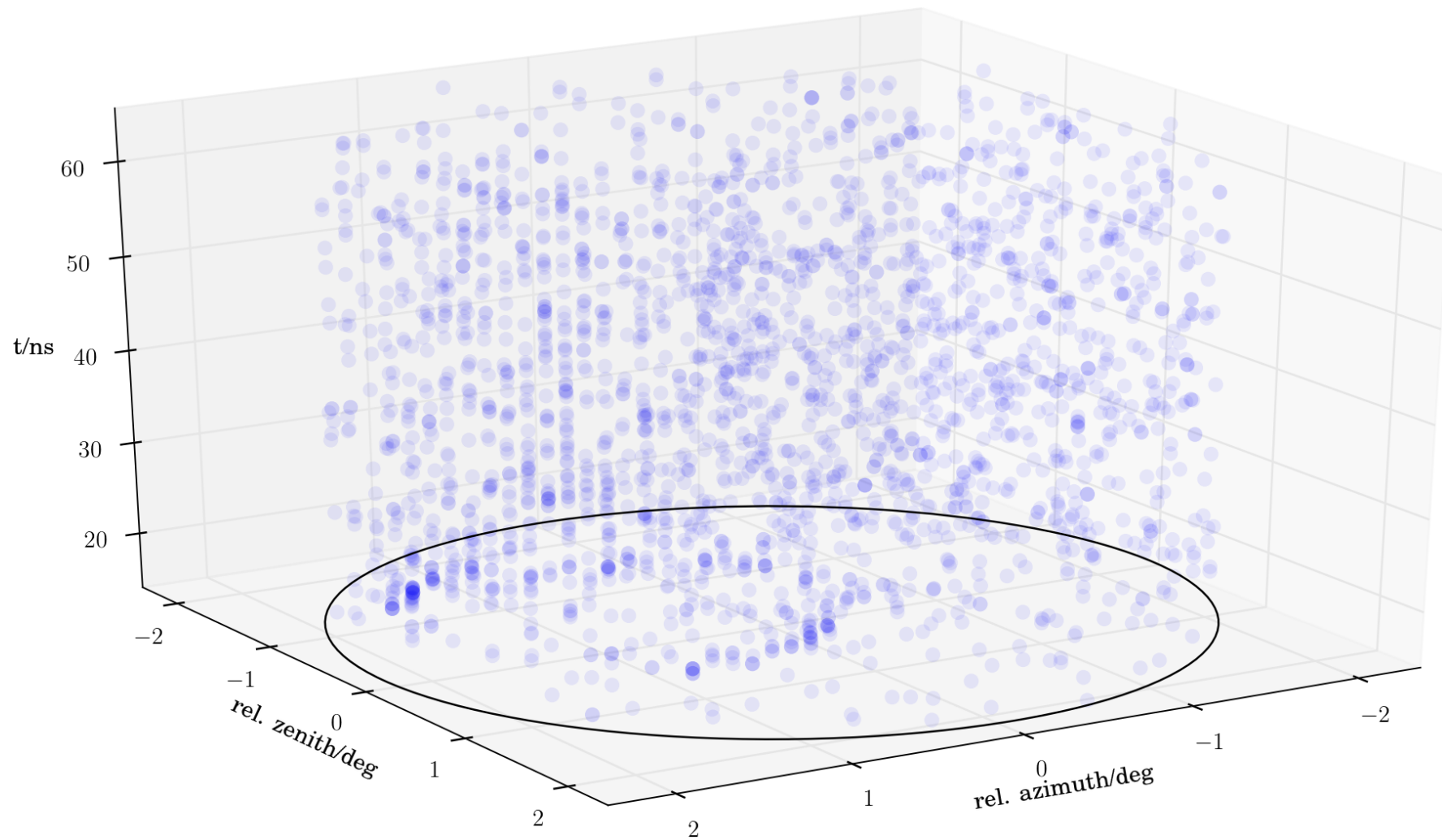
Night 20151113, Run 109, Event 18



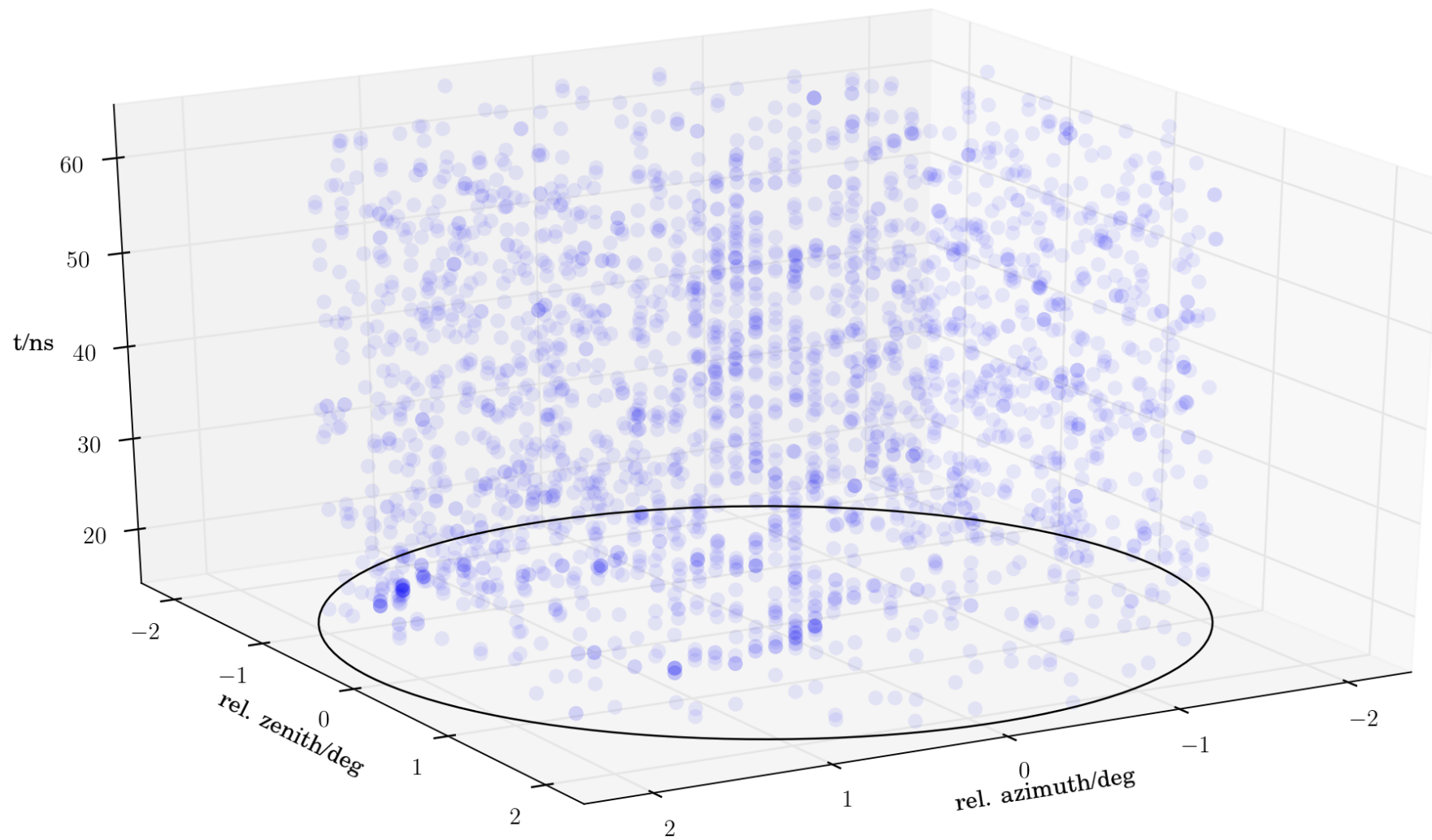
Night 20151113, Run 109, Event 18



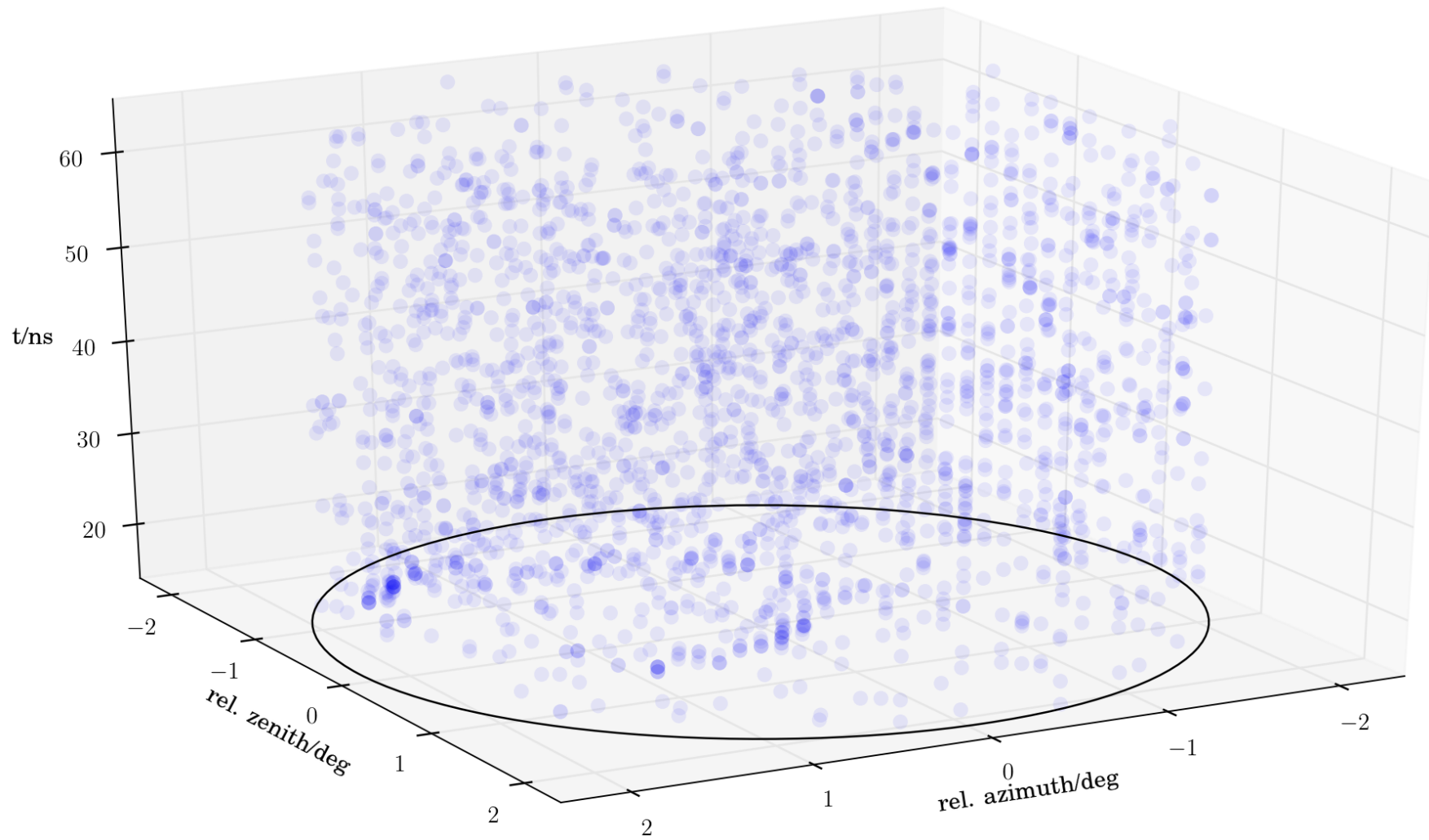
Night 20151113, Run 109, Event 18



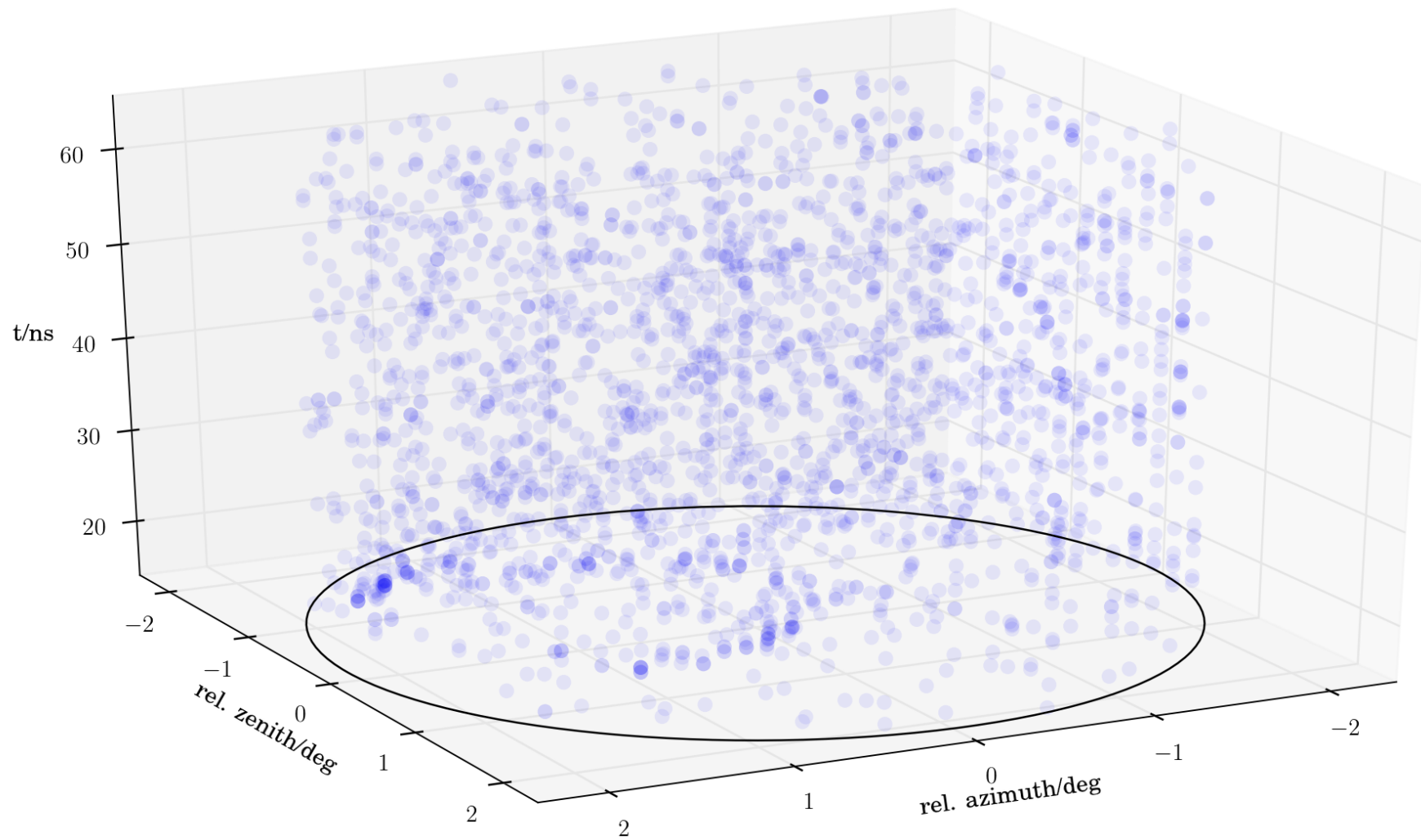
Night 20151113, Run 109, Event 18



Night 20151113, Run 109, Event 18



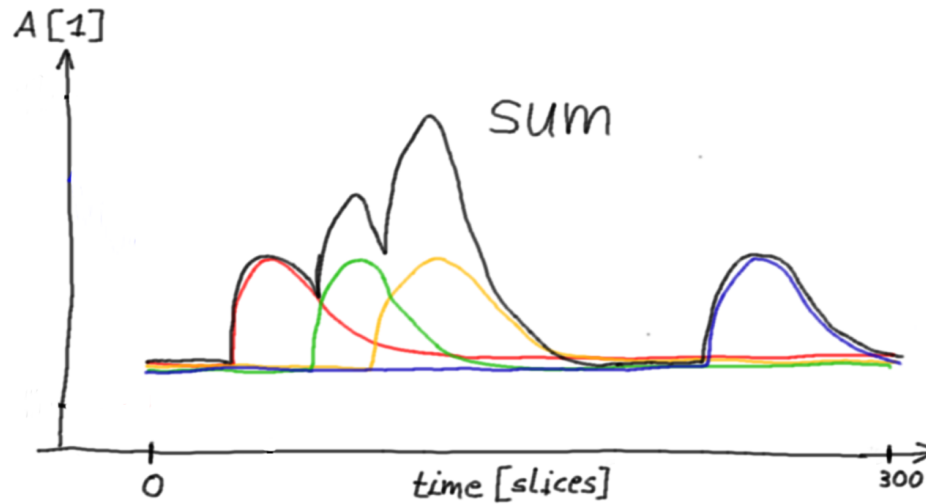
Night 20151113, Run 109, Event 18



Single Pulse Extraction

Assumption

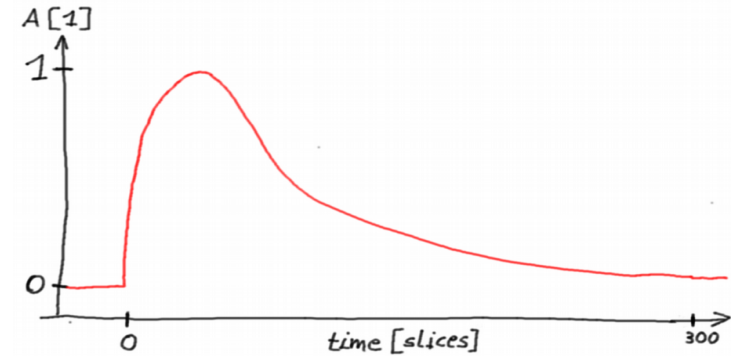
- The amplitude of a pixel is only the sum of individual G-APD pulses
- Individual G-APD pulses are the same for all pixels and for all epochs



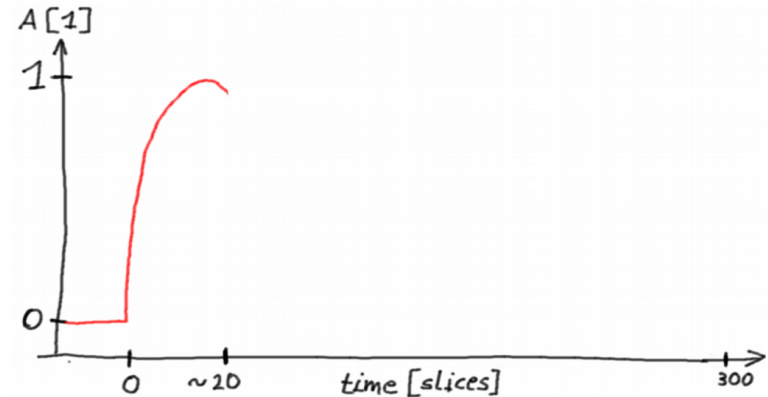
Single Pulse Extraction

- **Initiate**
 - **Template Pulse time lines**
- Input time line
- do {
 - correlate input and template pulse
 - find max response in correlation
 - store arrival time of max response
 - subtract template pulse from input
- } while(
 - has max response in correlation)
- return arrival times

Template Pulse
(full)

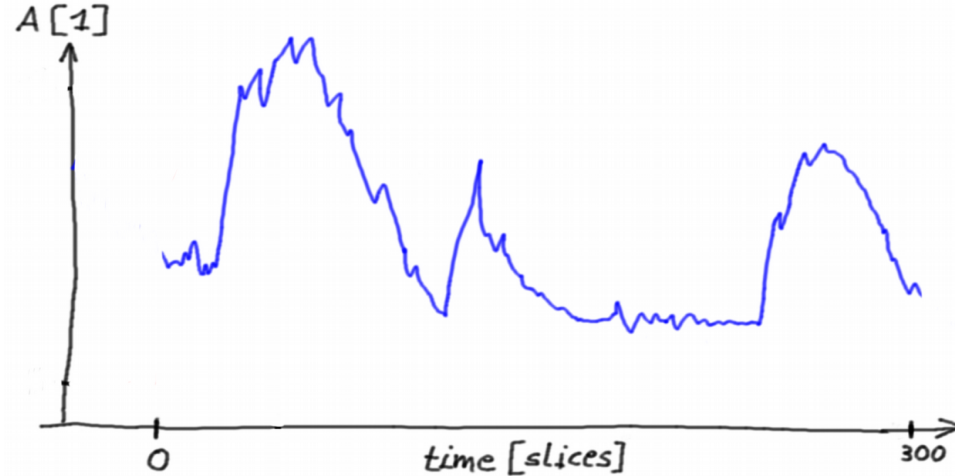


Template Pulse
(only rising edge)



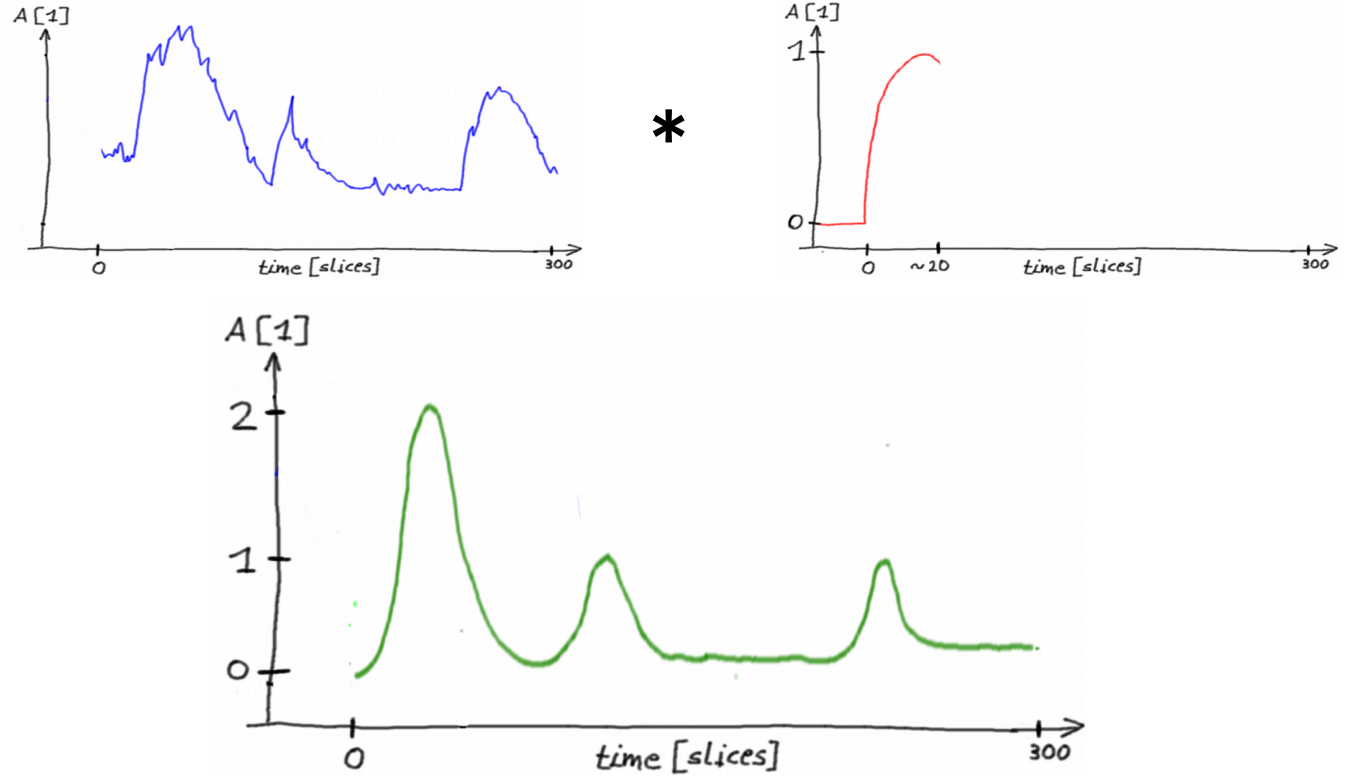
Single Pulse Extraction

- Initiate
 - Template Pulse time lines
- **Input time line**
- do {
 - correlate input and template pulse
 - find max response in correlation
 - store arrival time of max response
 - subtract template pulse from input
- } while(
 - has max response in correlation)
- return arrival times



Single Pulse Extraction

- Initiate
 - Template Pulse time lines
 - Input time line
- **do** {
 - **correlate input and template pulse**
 - find max response in correlation
 - store arrival time of max response
 - subtract template pulse from input
- } **while** {
 - has max response in correlation
- }
- return arrival times

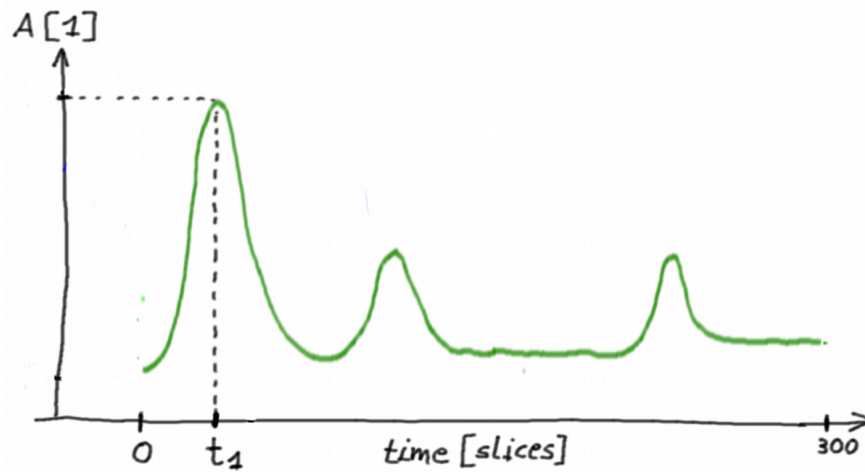


Very smooth response

Single Pulse Extraction

- Initiate
 - Template Pulse time lines
- Input time line
- **do** {
 - correlate input and template pulse
 - **find max response in correlation**
 - store arrival time of max response
 - subtract template pulse from input
- } **while** {
 - has max response in correlation
- }
- return arrival times

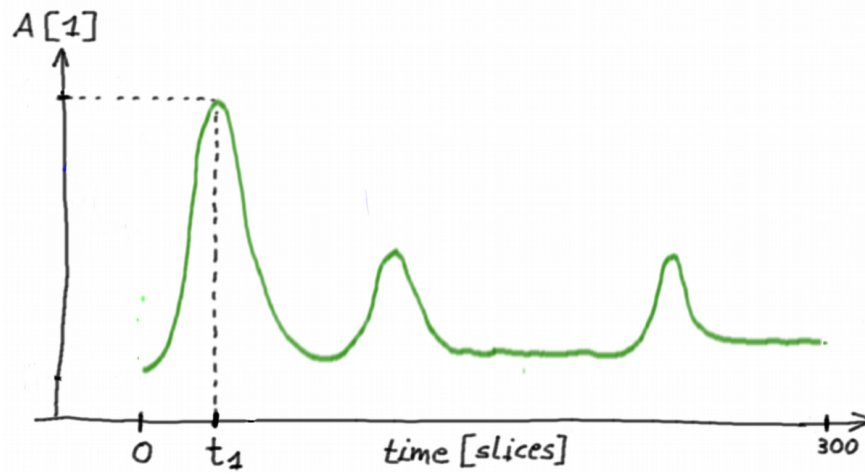
Easy to find the peaks



Single Pulse Extraction

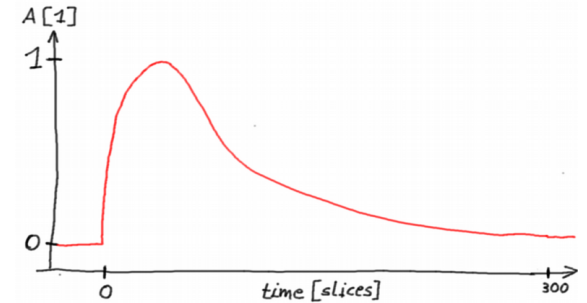
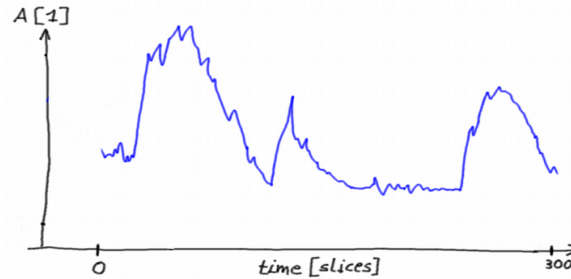
- Initiate
 - Template Pulse time lines
- Input time line
- **do** {
 - correlate input and template pulse
 - find max response in correlation
 - **store arrival time of max response**
 - subtract template pulse from input
- } **while** {
 - has max response in correlation
- }
- return arrival times

Append arrival time t_1 of largest response to arrival time list

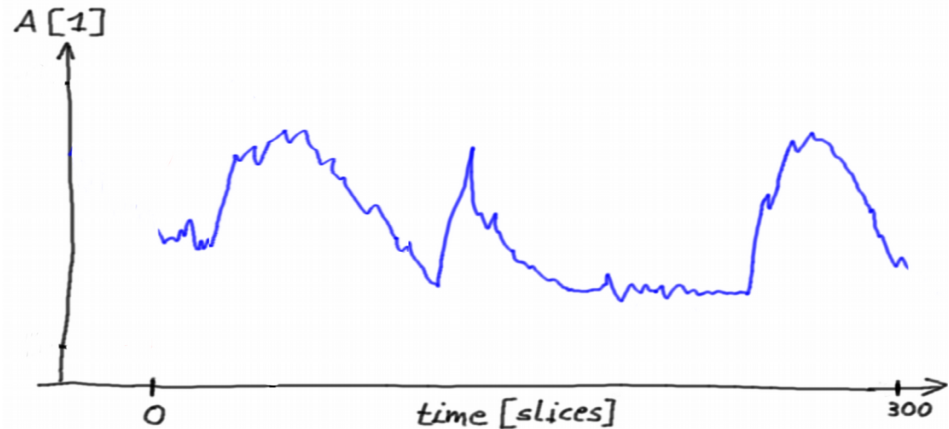


Single Pulse Extraction

- Initiate
 - Template Pulse time lines
- Input time line
- **do** {
 - correlate input and template pulse
 - find max response in correlation
 - store arrival time of max response
 - **subtract template pulse from input**
- } **while** {
 - has max response in correlation
- }
- return arrival times



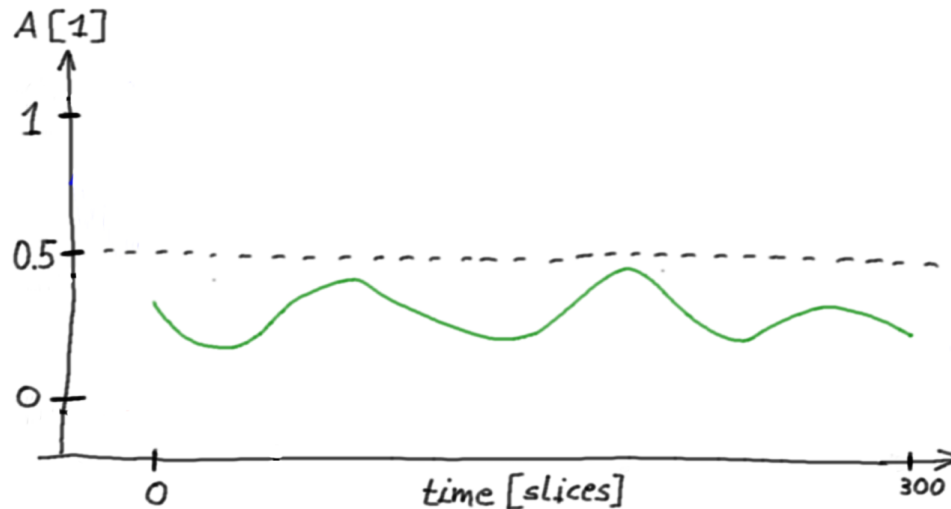
Subtract full template at time t_1



Single Pulse Extraction

- Initiate
 - Template Pulse time lines
- Input time line
- **do** {
 - correlate input and template pulse
 - find max response in correlation
 - store arrival time of max response
 - subtract template pulse from input
- } **while**{
 - has max response in correlation**
- }
- return arrival times

Repeat until response below 0.5 p.e.

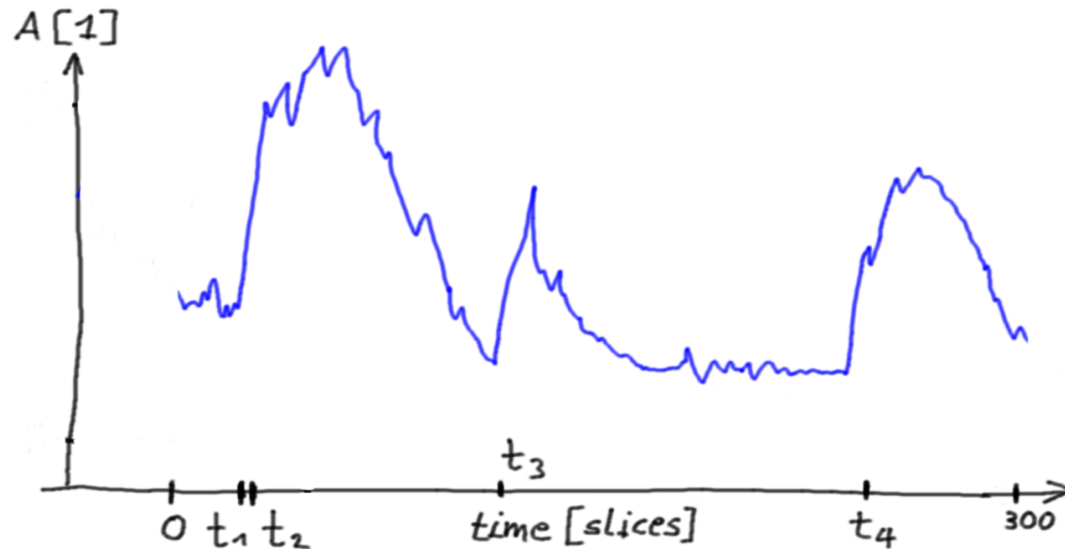


Single Pulse Extraction

- Initiate
 - Template Pulse time lines
- Input time line
- do {
 - correlate input and template pulse
 - find max response in correlation
 - store arrival time of max response
 - subtract template pulse from input
- } while(
 - has max response in correlation)
- **return arrival times**

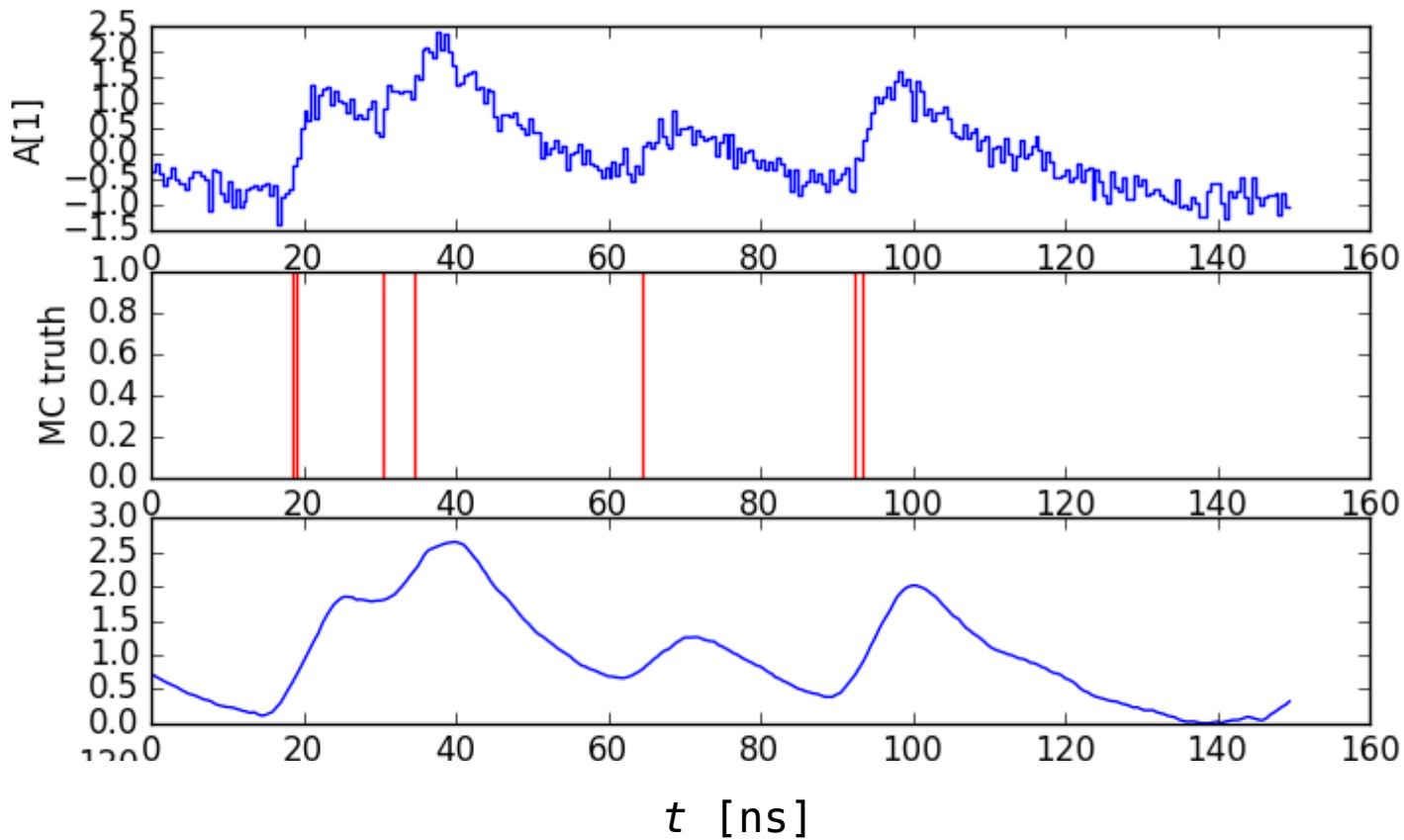
Return a list of arrival times

$[t_1, t_2, t_3, t_4]$



Example

Found at:



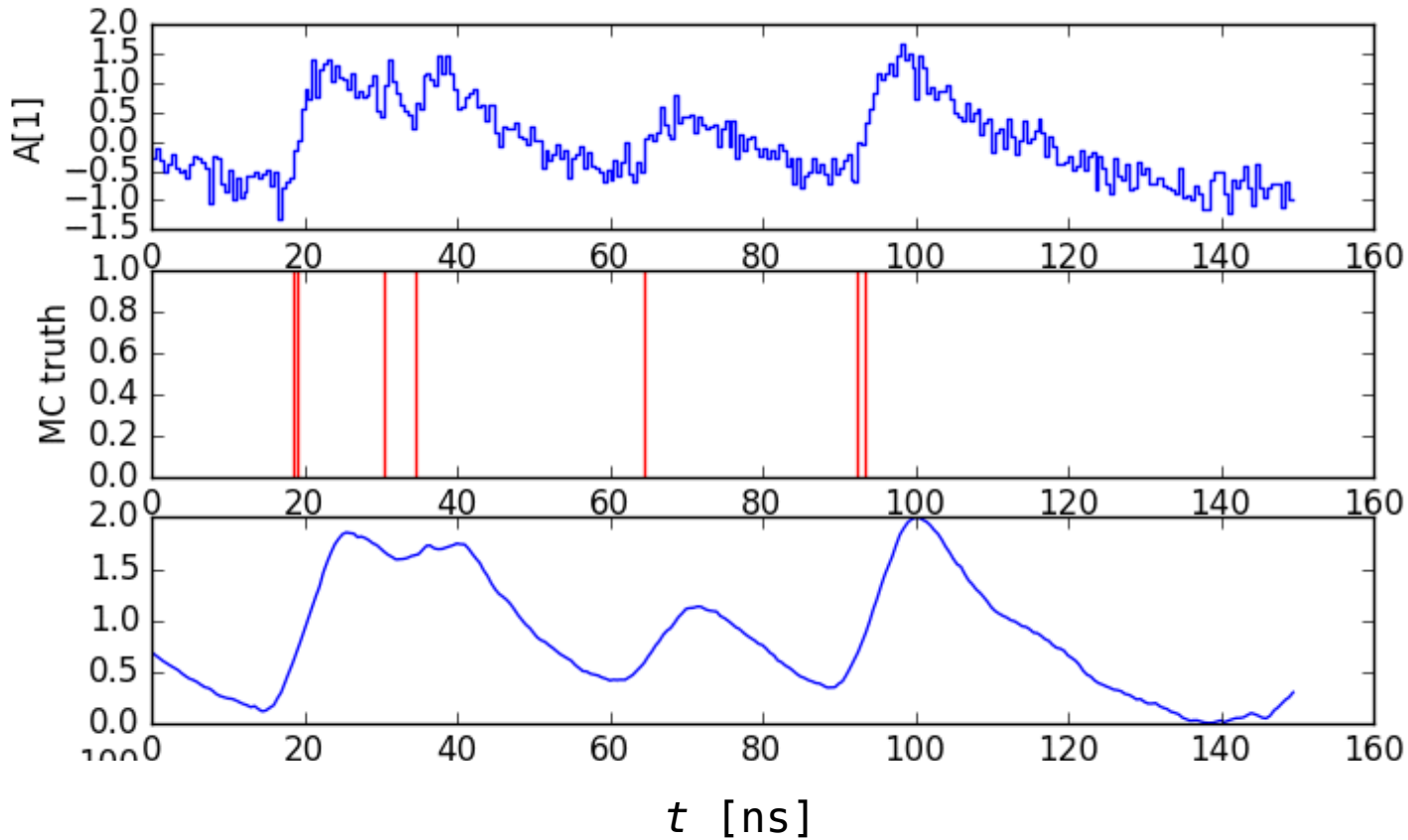
photons found: 0

photons injected: 7

Example

Found at:

31.5ns



photons found: 1

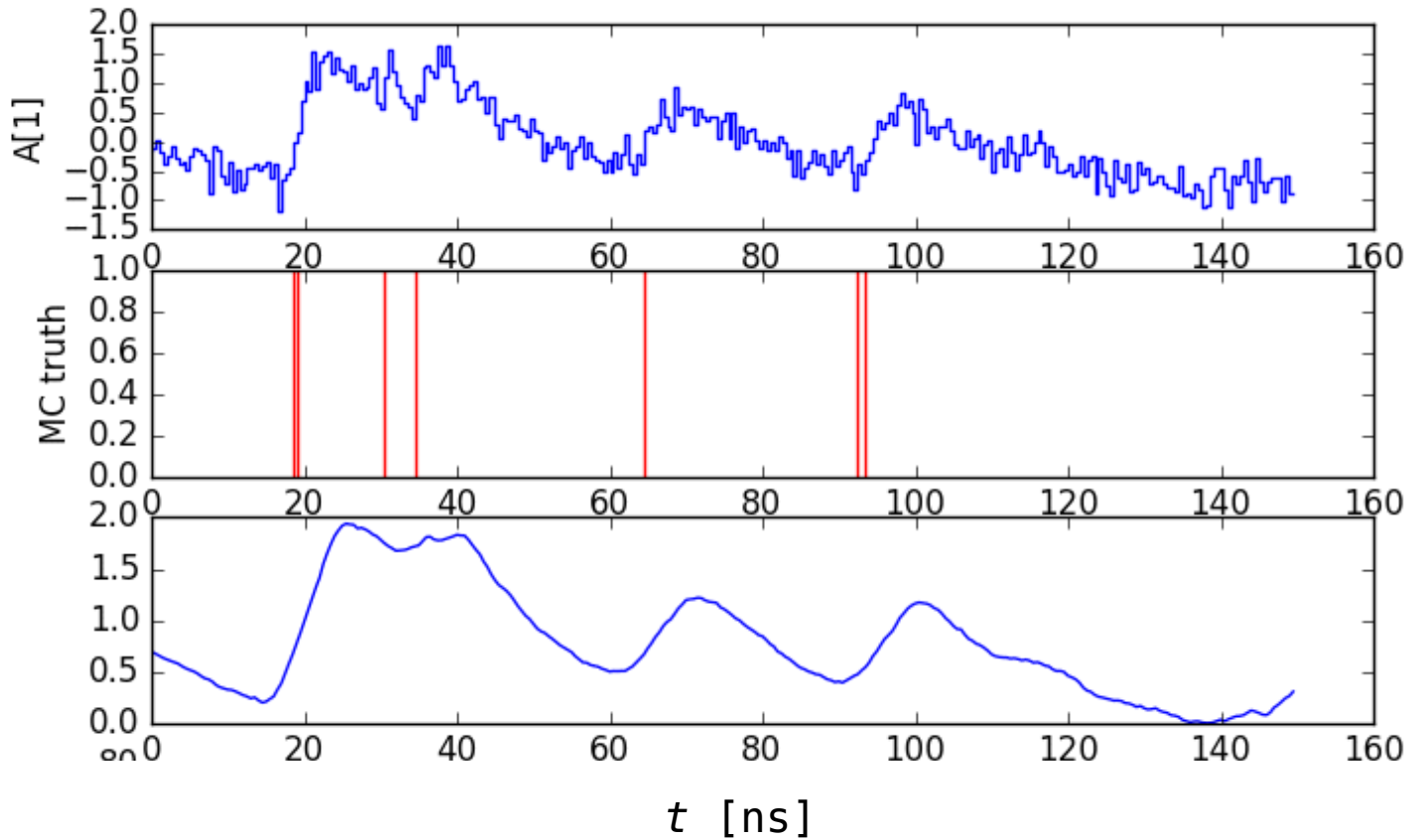
photons injected: 7

Example

Found at:

31.5ns

92.0ns



photons found: 2

photons injected: 7

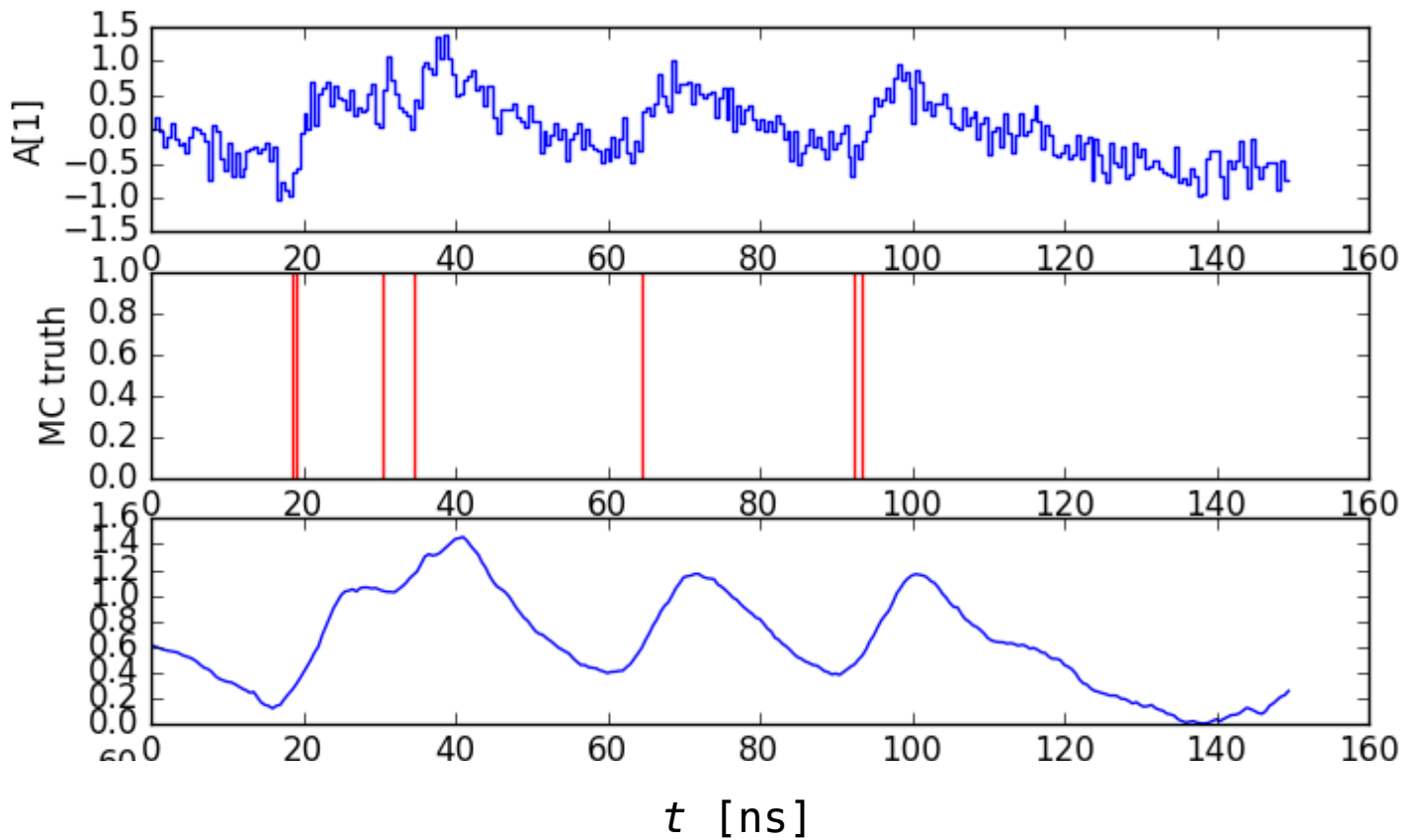
Example

Found at:

31.5ns

92.0ns

17.0ns



photons found: 3

photons injected: 7

Example

Found at:

31.5ns

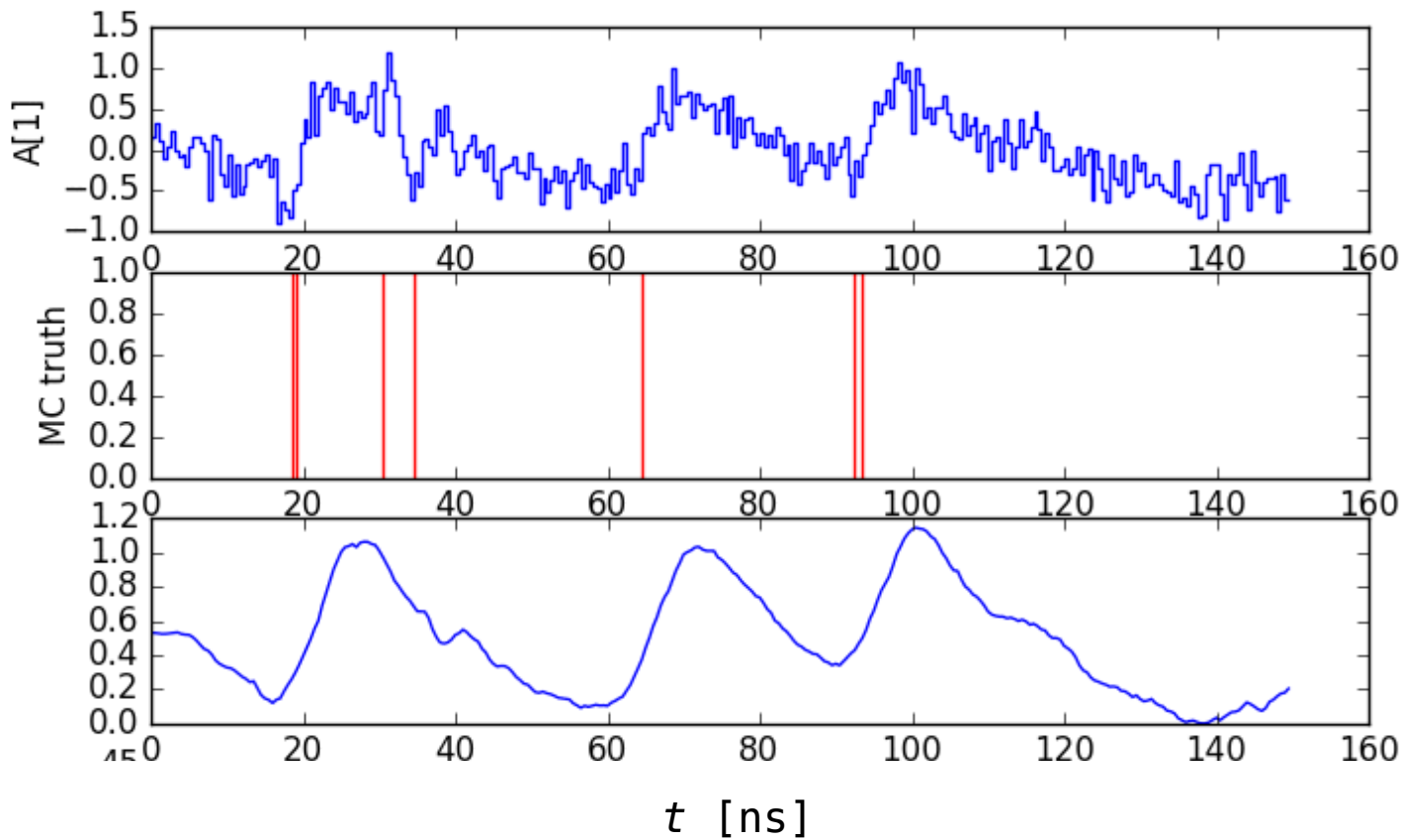
92.0ns

17.0ns

32.5ns

photons found: 4

photons injected: 7



Example

Found at:

31.5ns

92.0ns

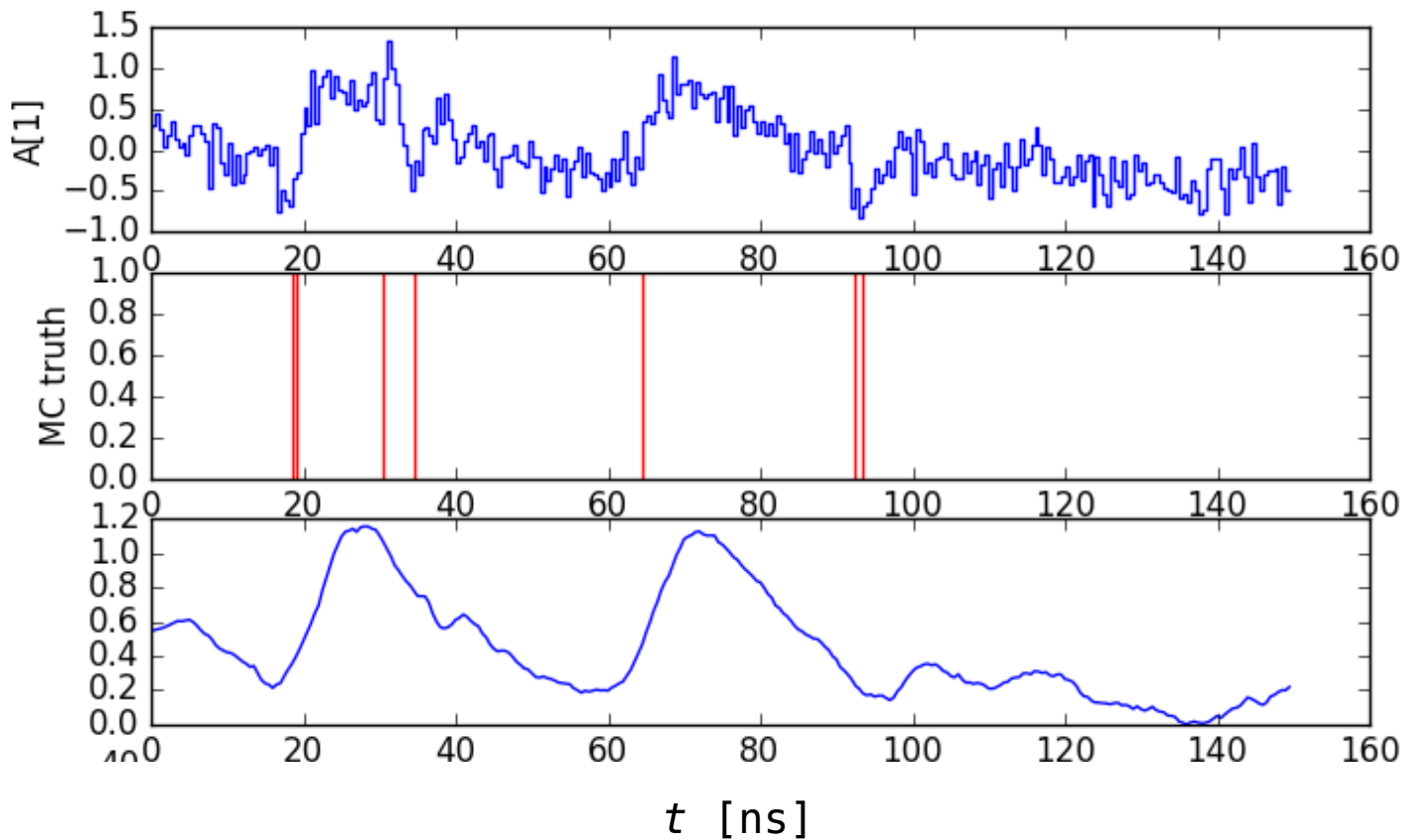
17.0ns

32.5ns

92.0ns

photons found: 5

photons injected: 7



Example

Found at:

31.5ns

92.0ns

17.0ns

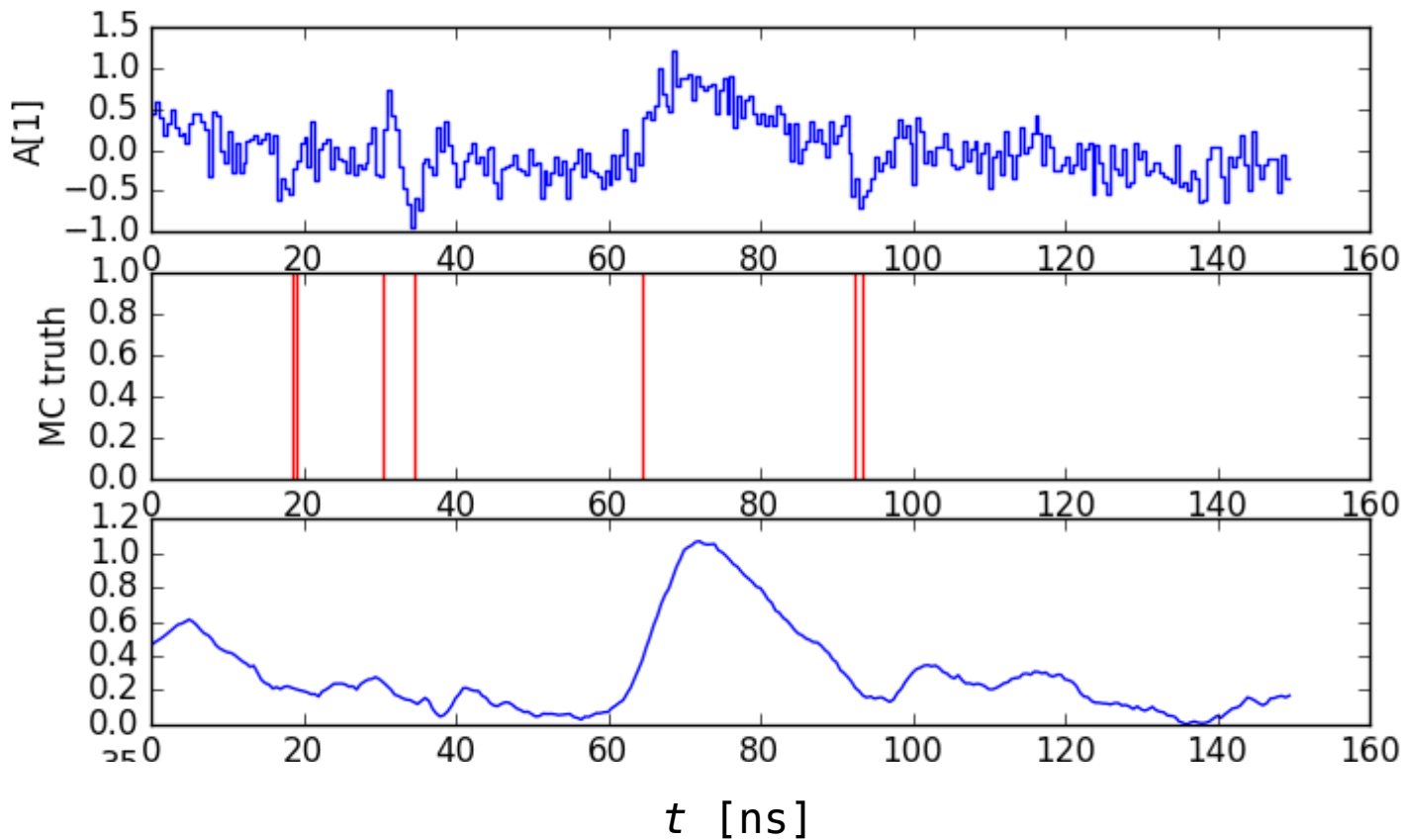
32.5ns

92.0ns

19.5ns

photons found: 6

photons injected: 7



Example

Found at:

31.5ns

92.0ns

17.0ns

32.5ns

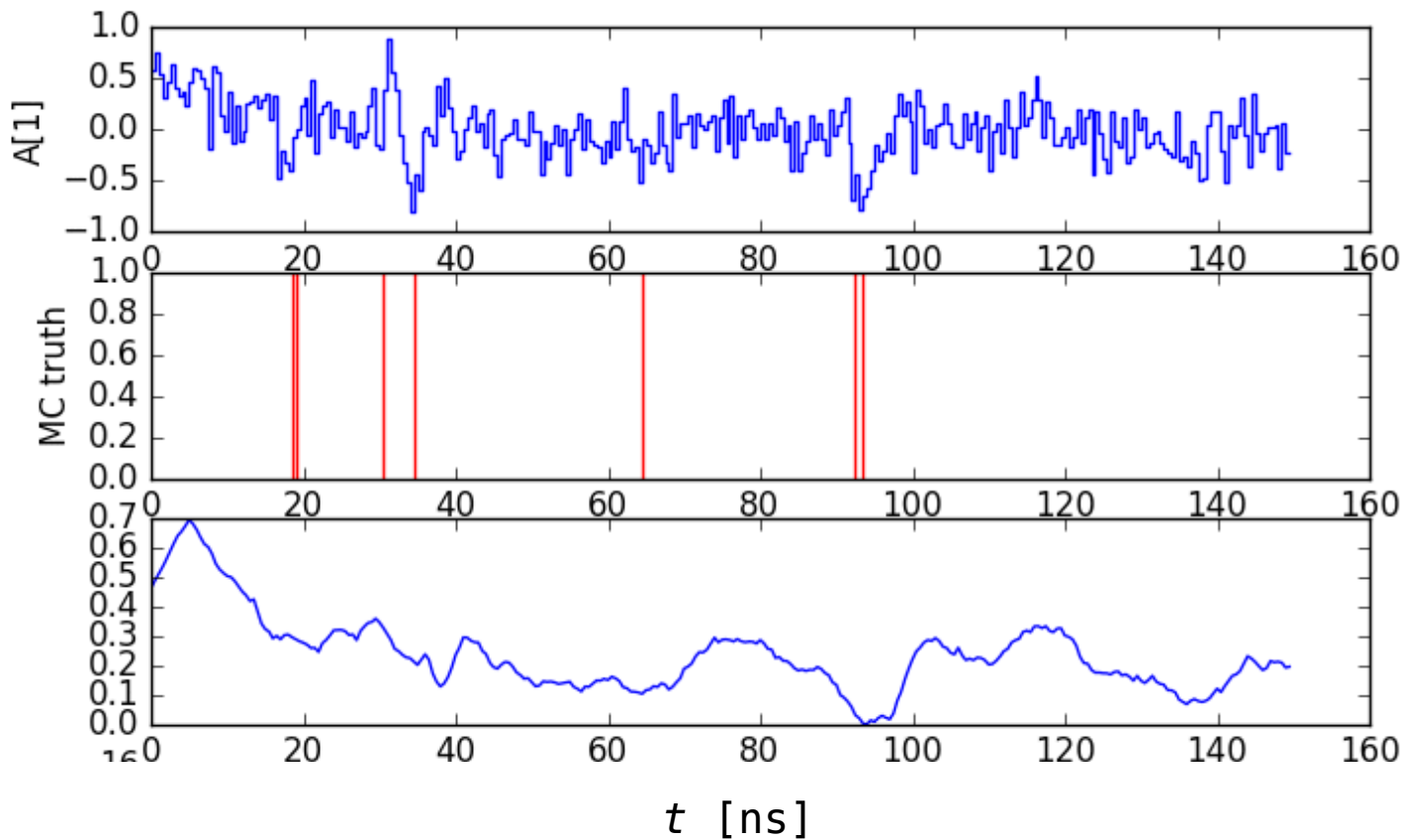
92.0ns

19.5ns

63.5ns

photons found: 7

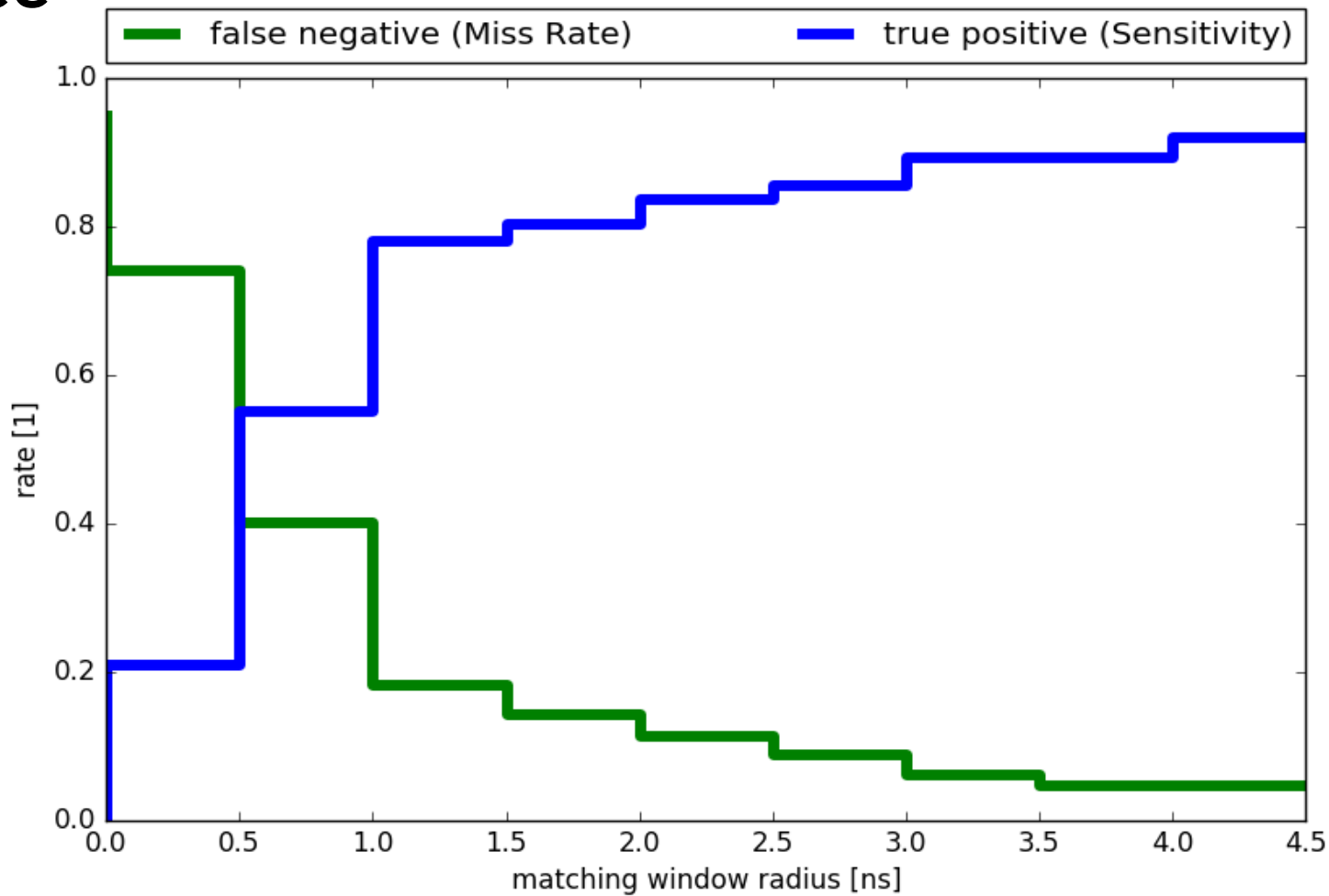
photons injected: 7



Performance

Dark night
50MHz NSB
per pixel

(1000 time lines/bin)



Compare

novel

Single Pulse Extractor

over full time line of 150ns

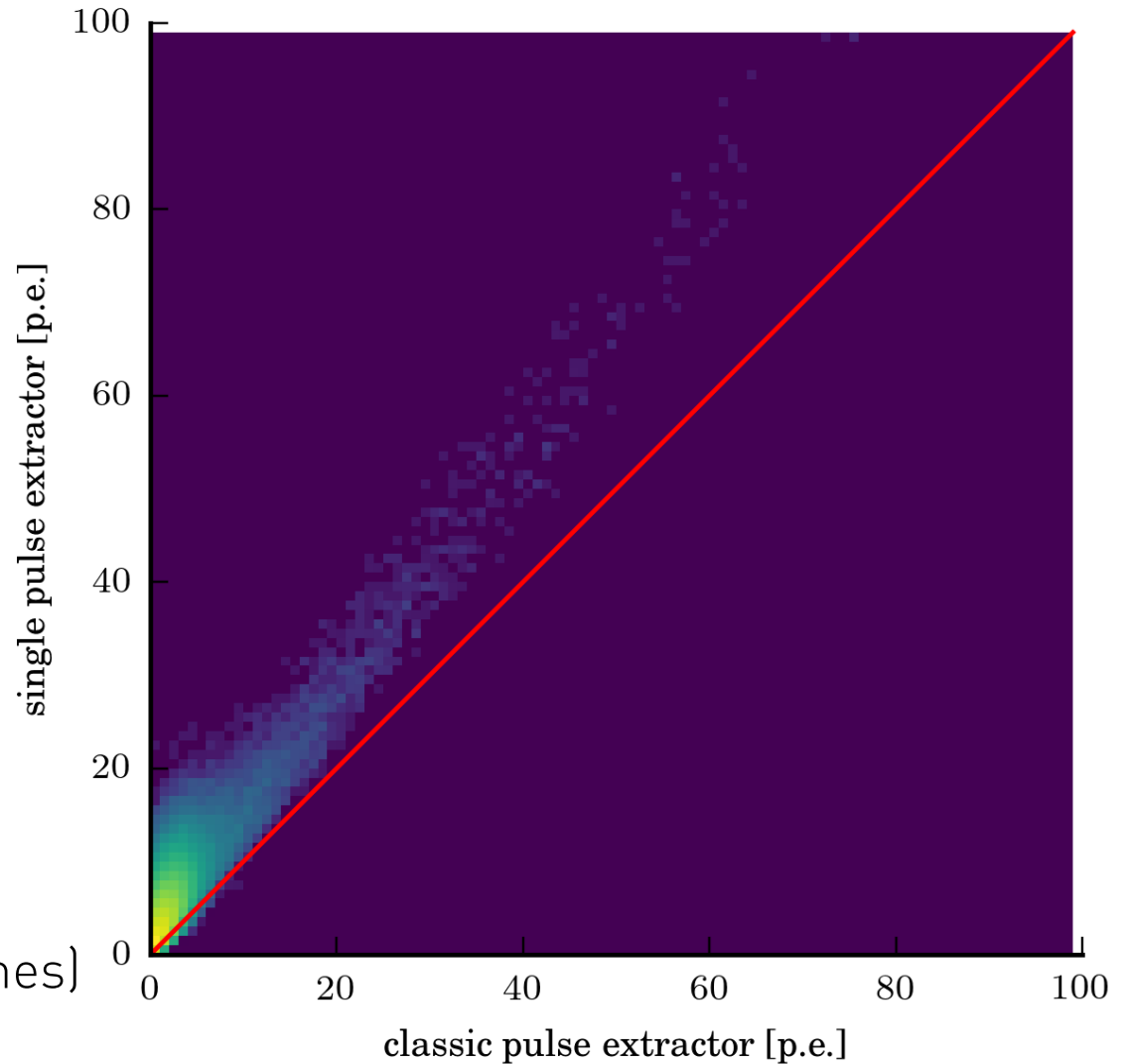
VS

classic

Photon Charge Integration

only of the 'main pulse'

(sample size is 455k pixel time lines)



Photon-Stream as a Raw Event Format



```
[  
  [],  
  [46,45,44,53],  
  [],  
  [122,83,121],  
  [35],  
  [],  
  [76,84],  
  [],  
  [],  
  [116,56],  
  [],  
]
```

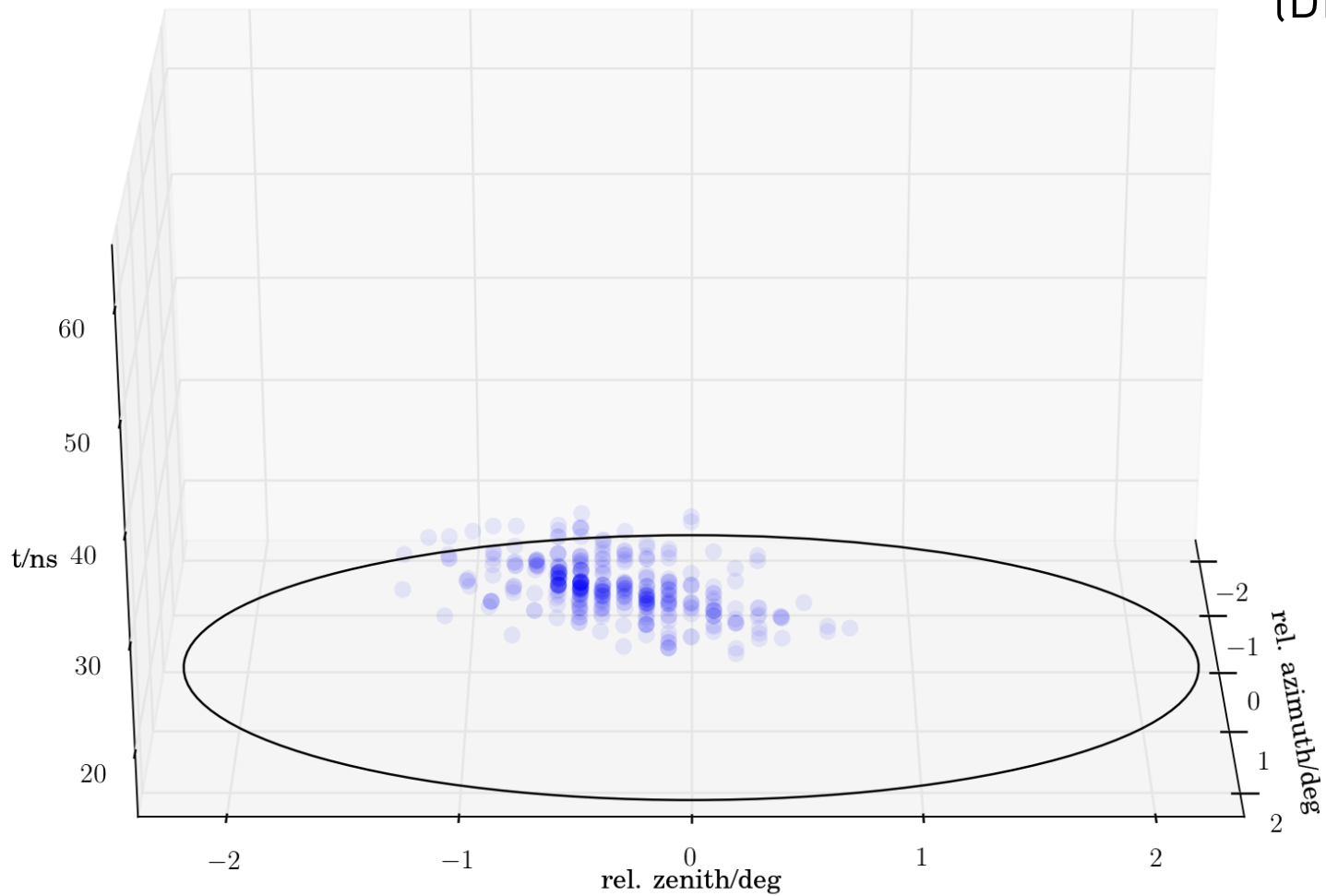
Only store the arrival times
of individual photons.

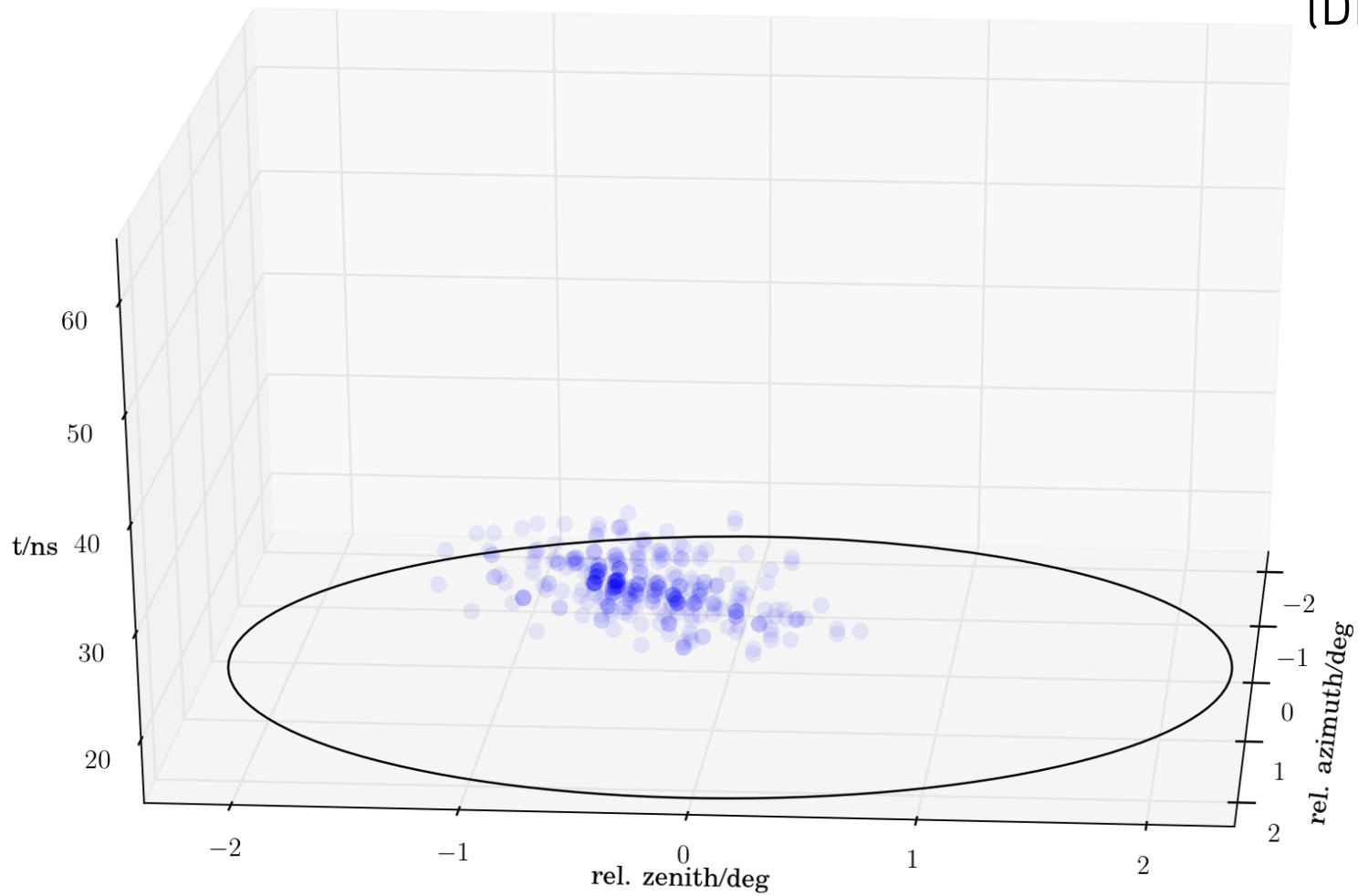
Only ~ 3.7kByte/event (for dark nights)
Only photons. No noise.

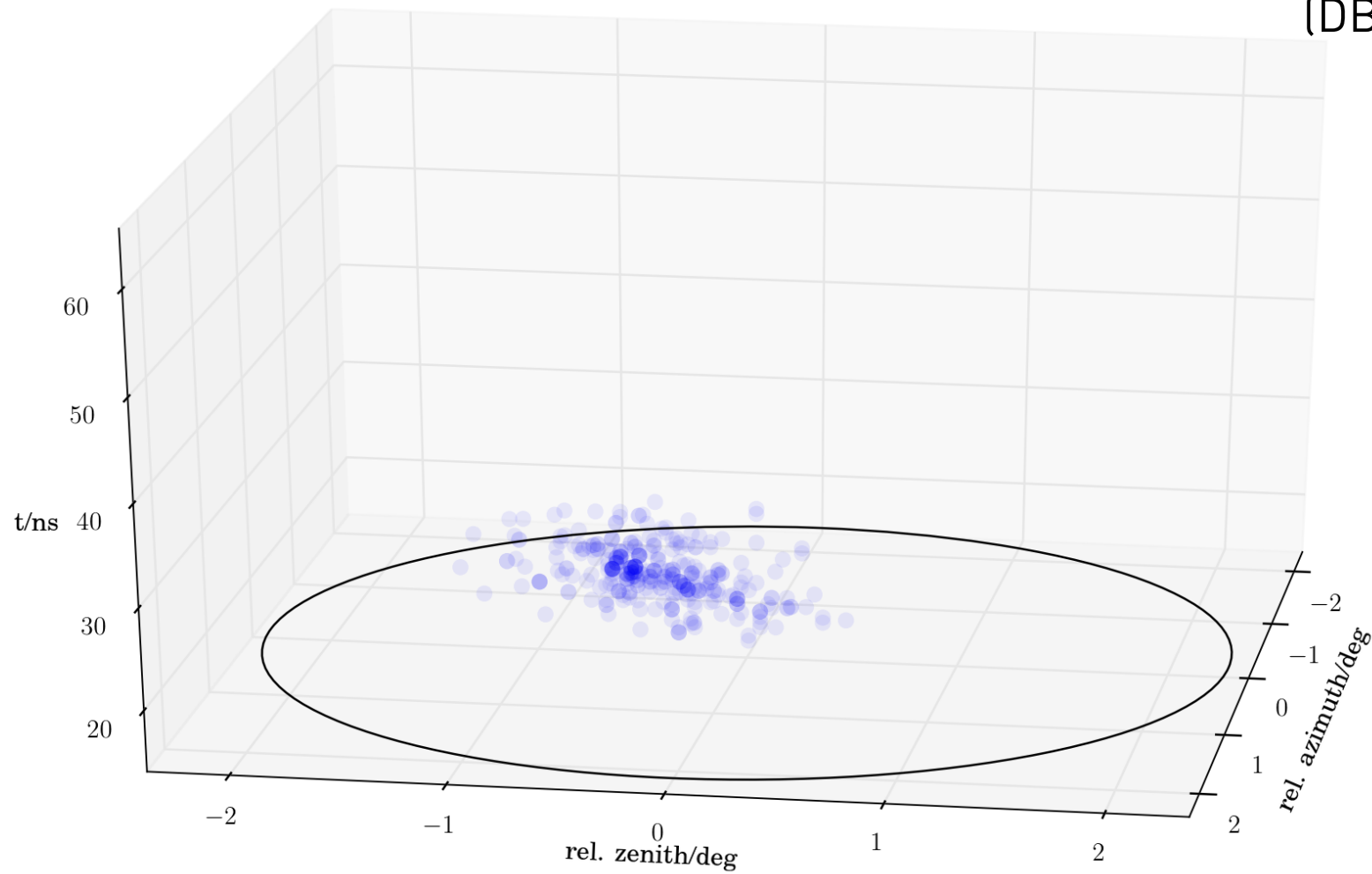
Example Photon-Stream Event

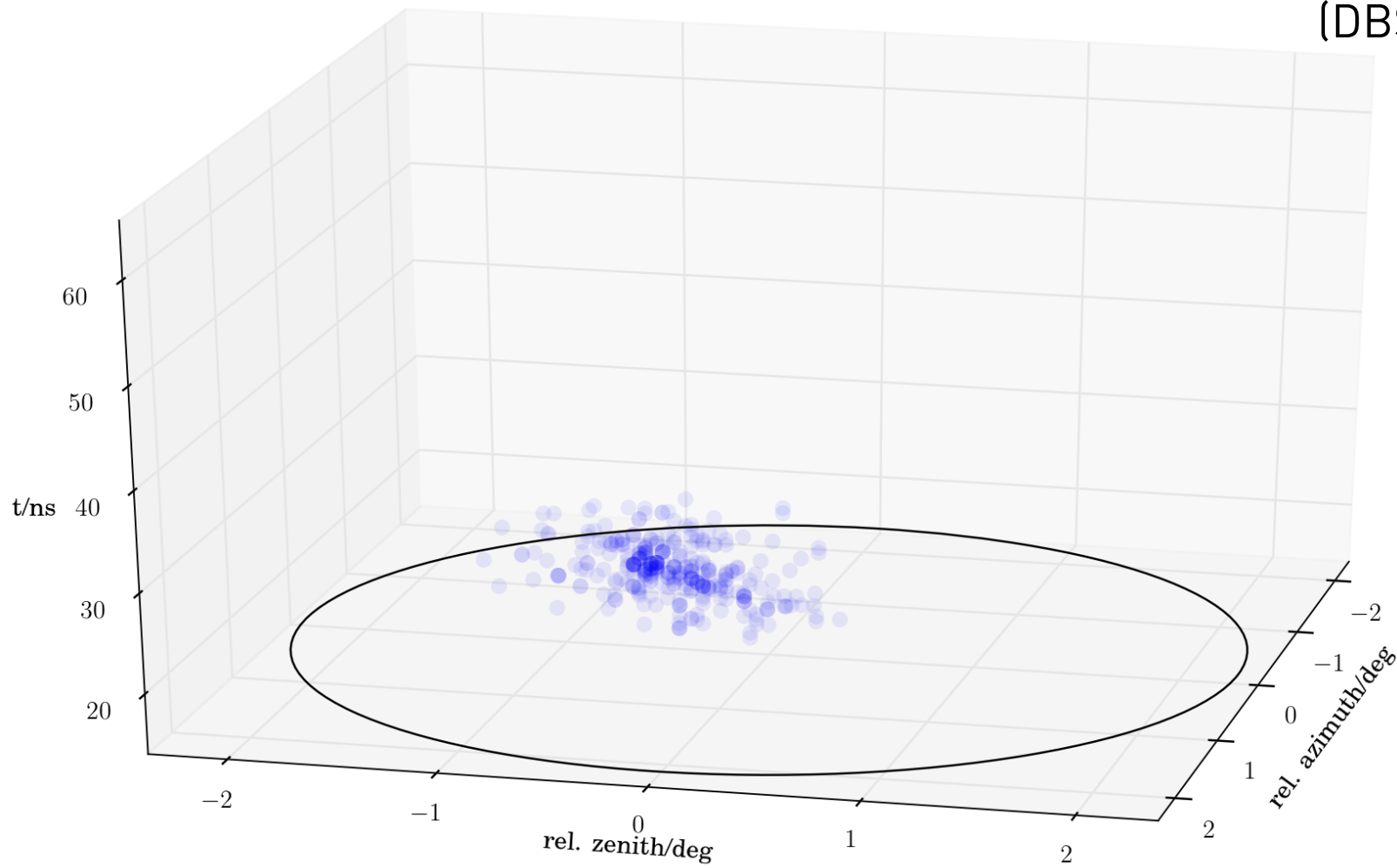
1

FACT 2015 Nov 13
faint shower

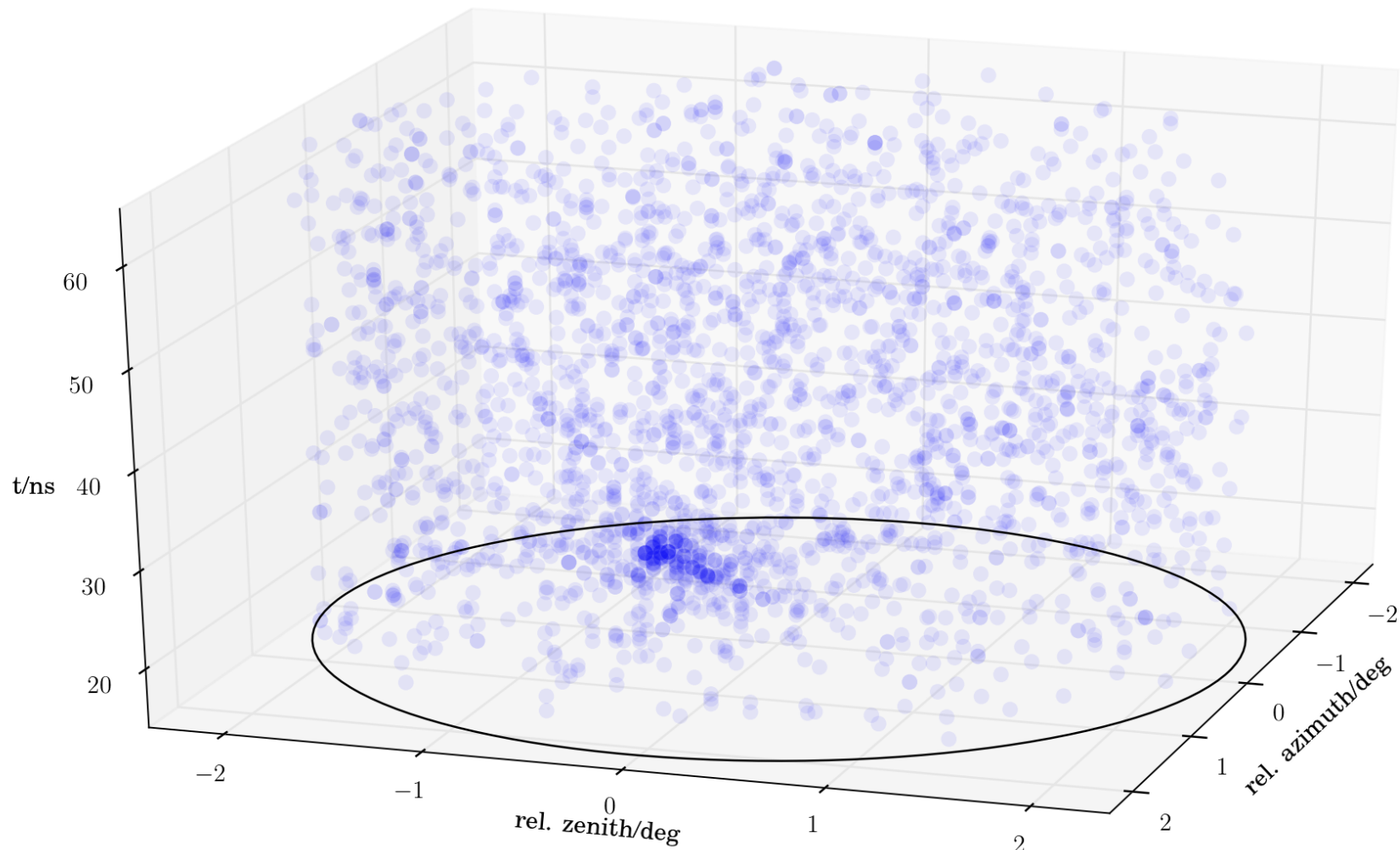




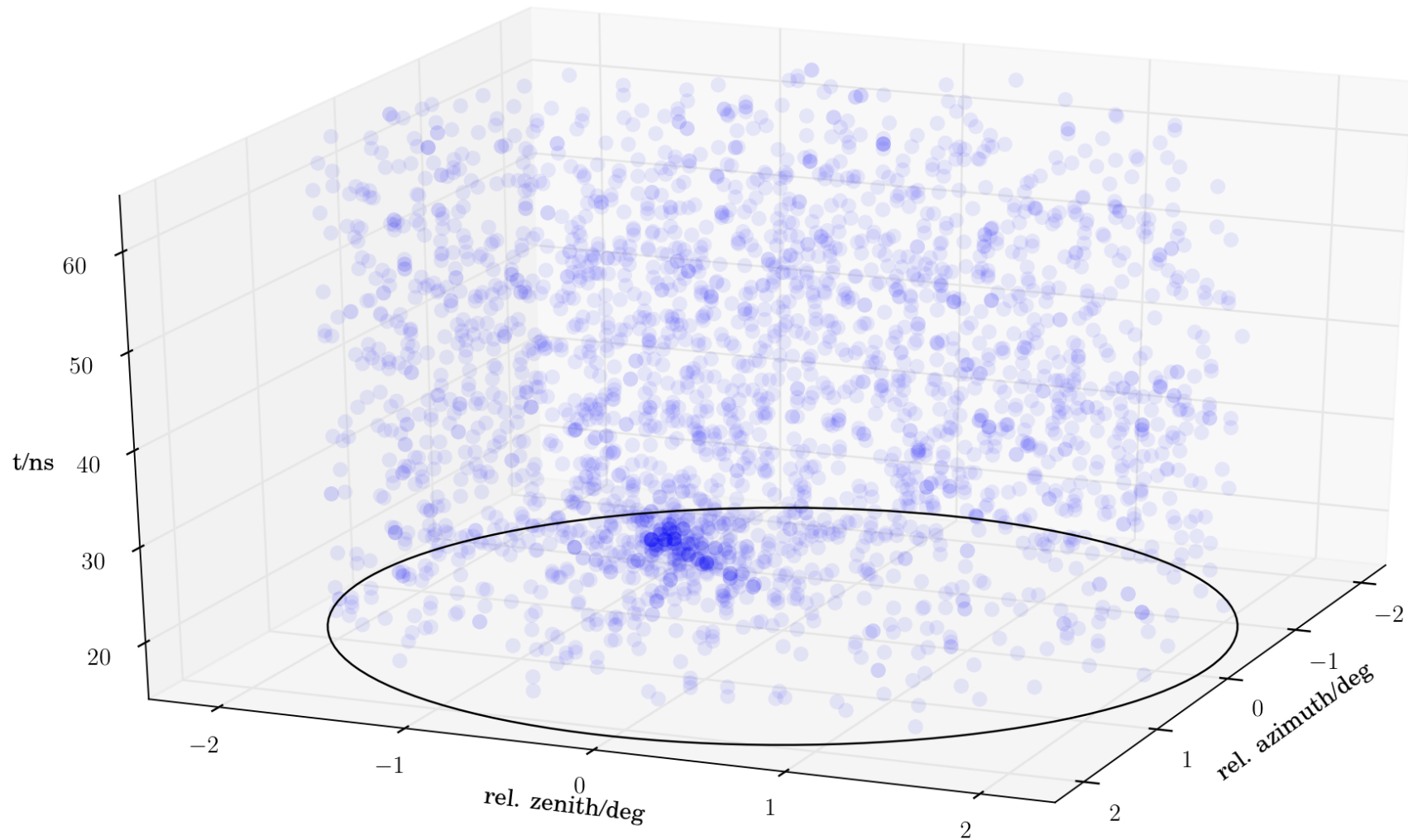




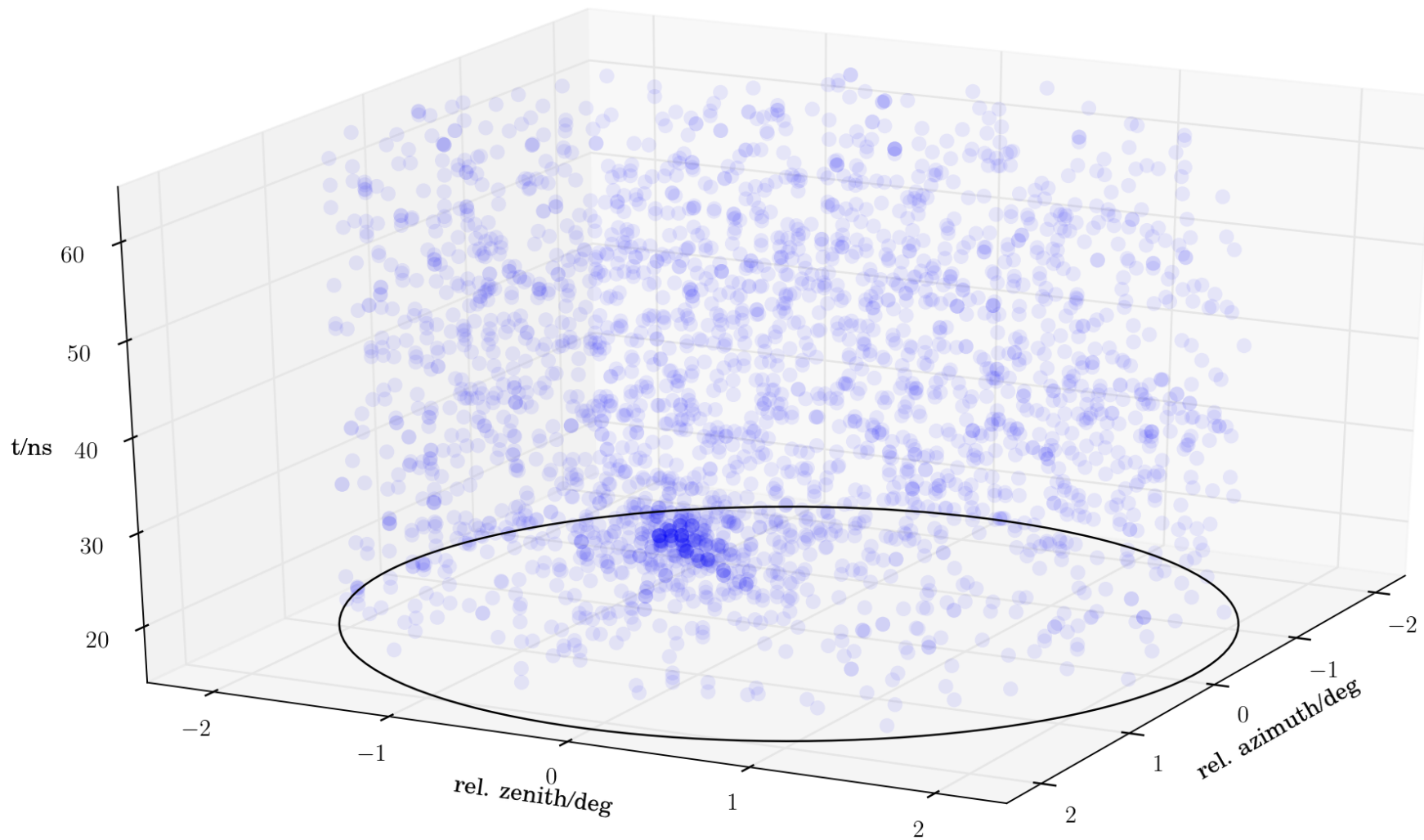
Night 20151113, Run 109, Event 99



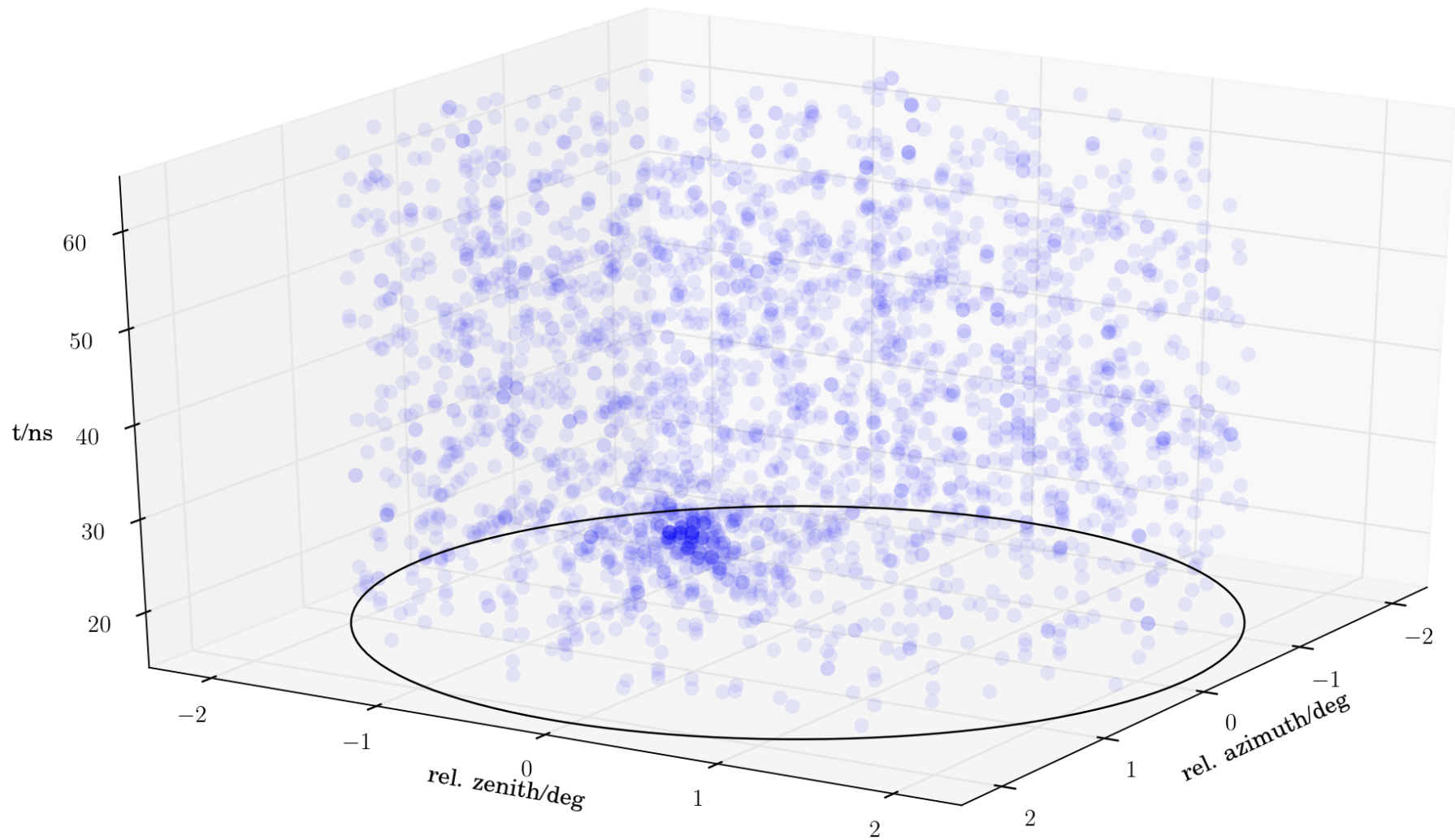
Night 20151113, Run 109, Event 99



Night 20151113, Run 109, Event 99

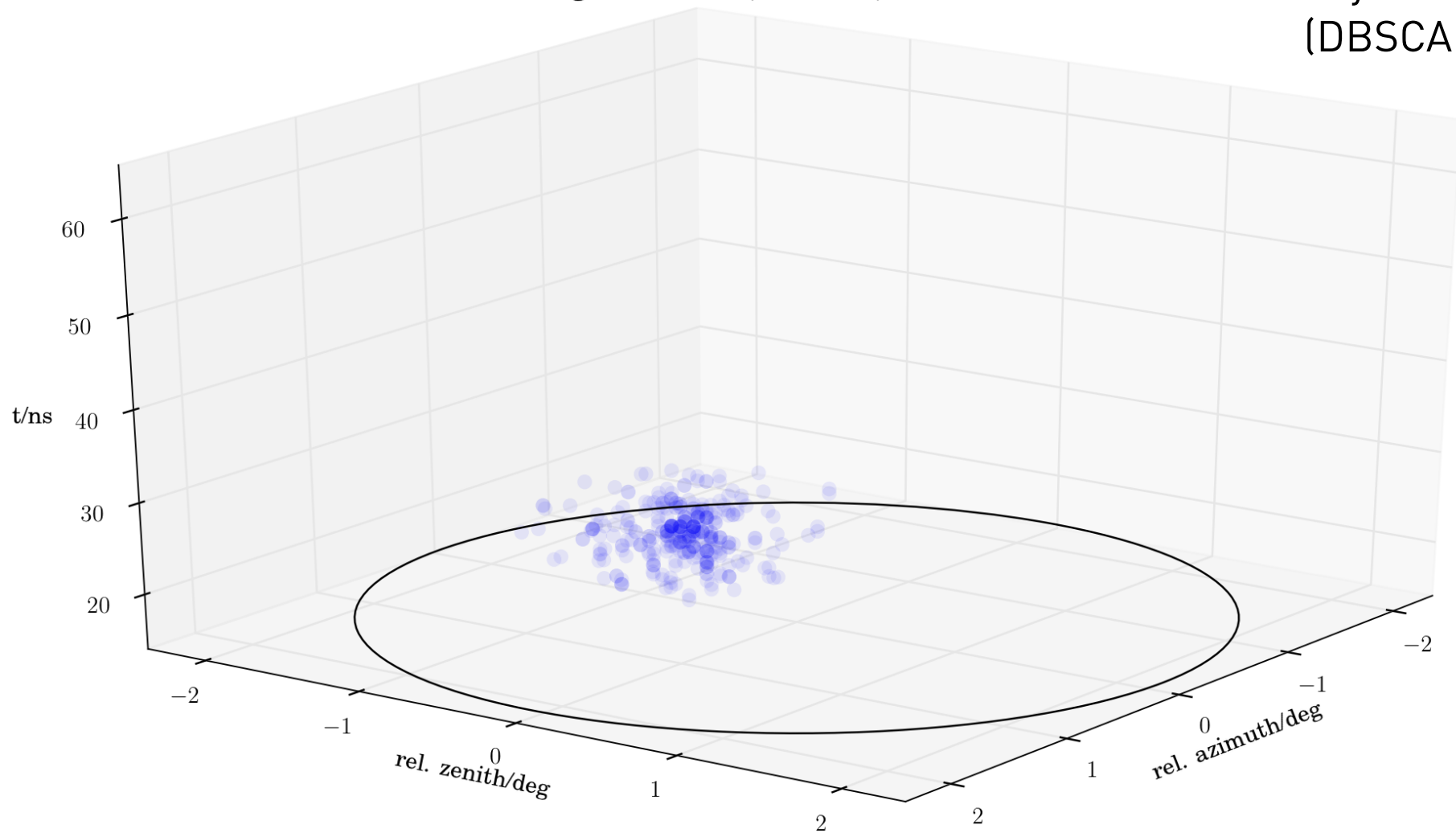


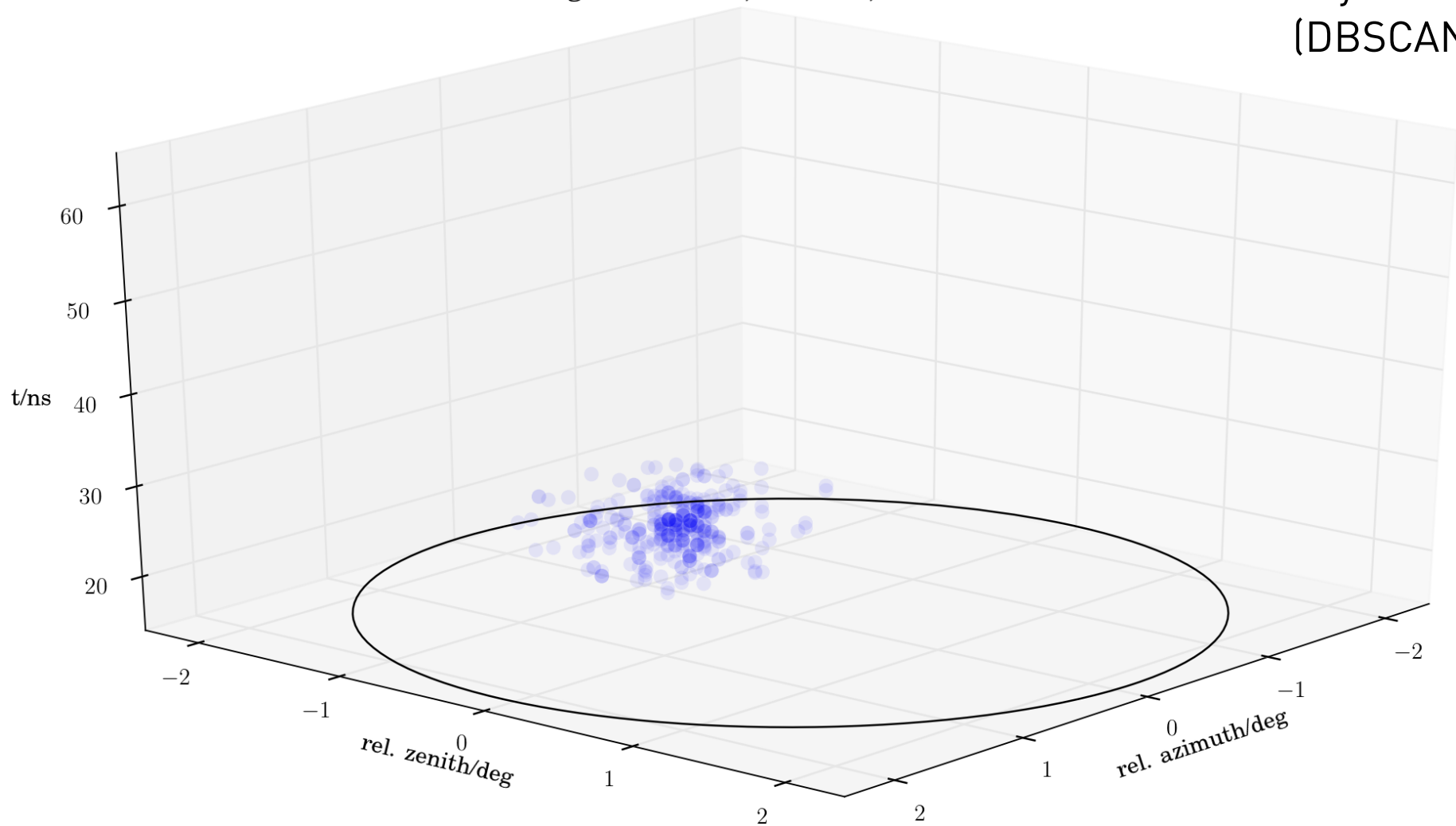
Night 20151113, Run 109, Event 99

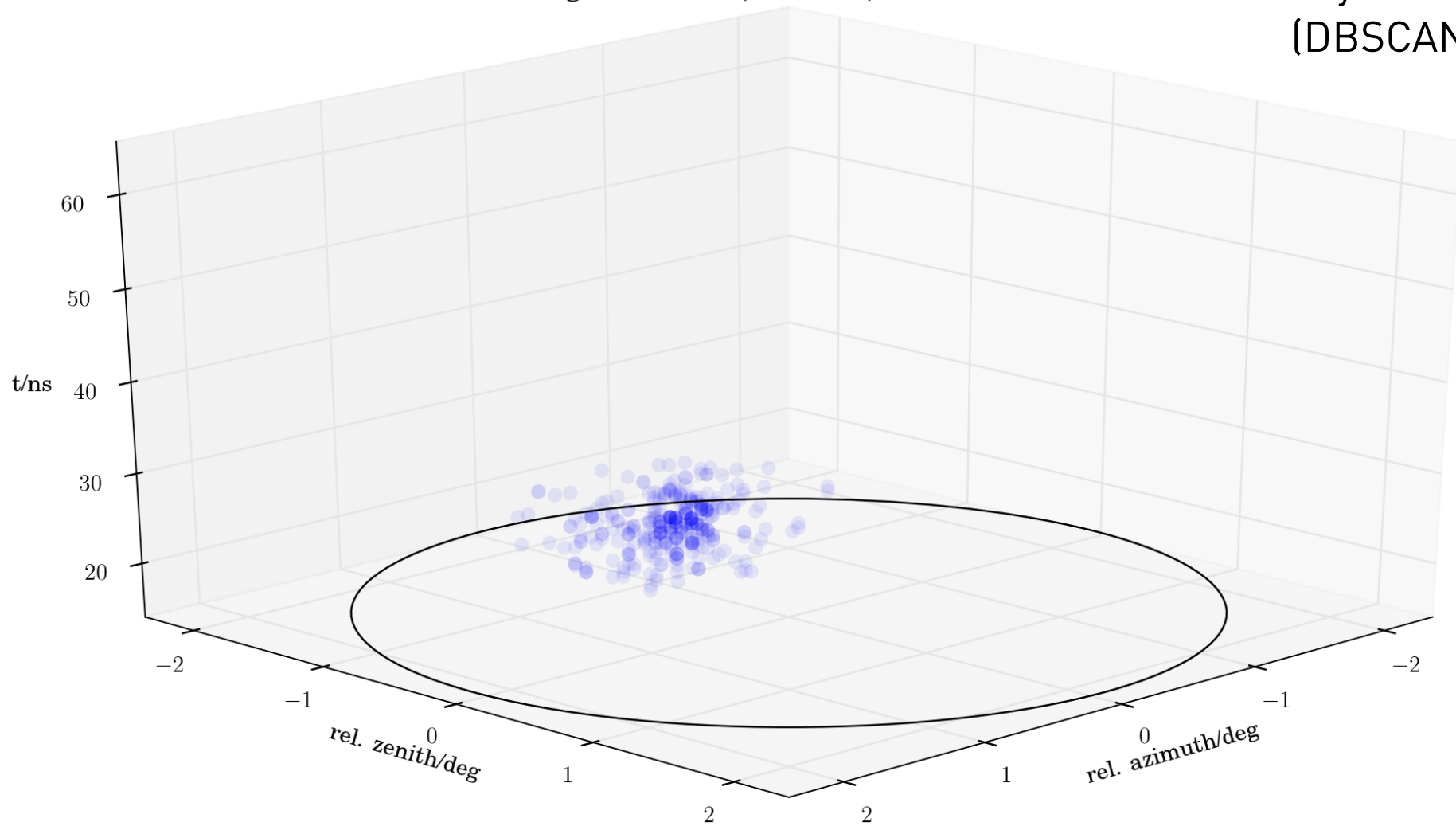


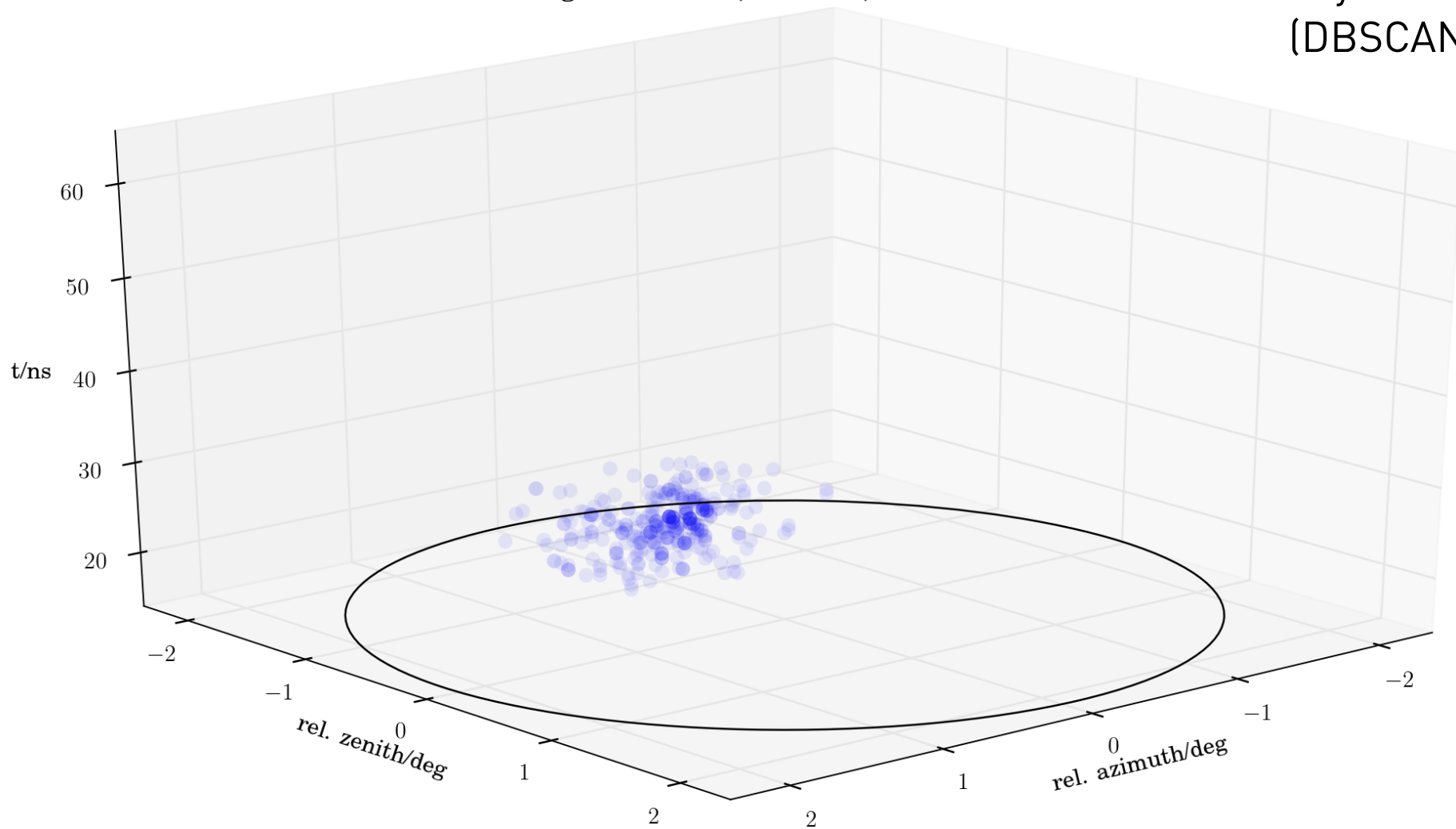
Night 20151113, Run 109, Event 99

Density clustering
(DBSCAN)

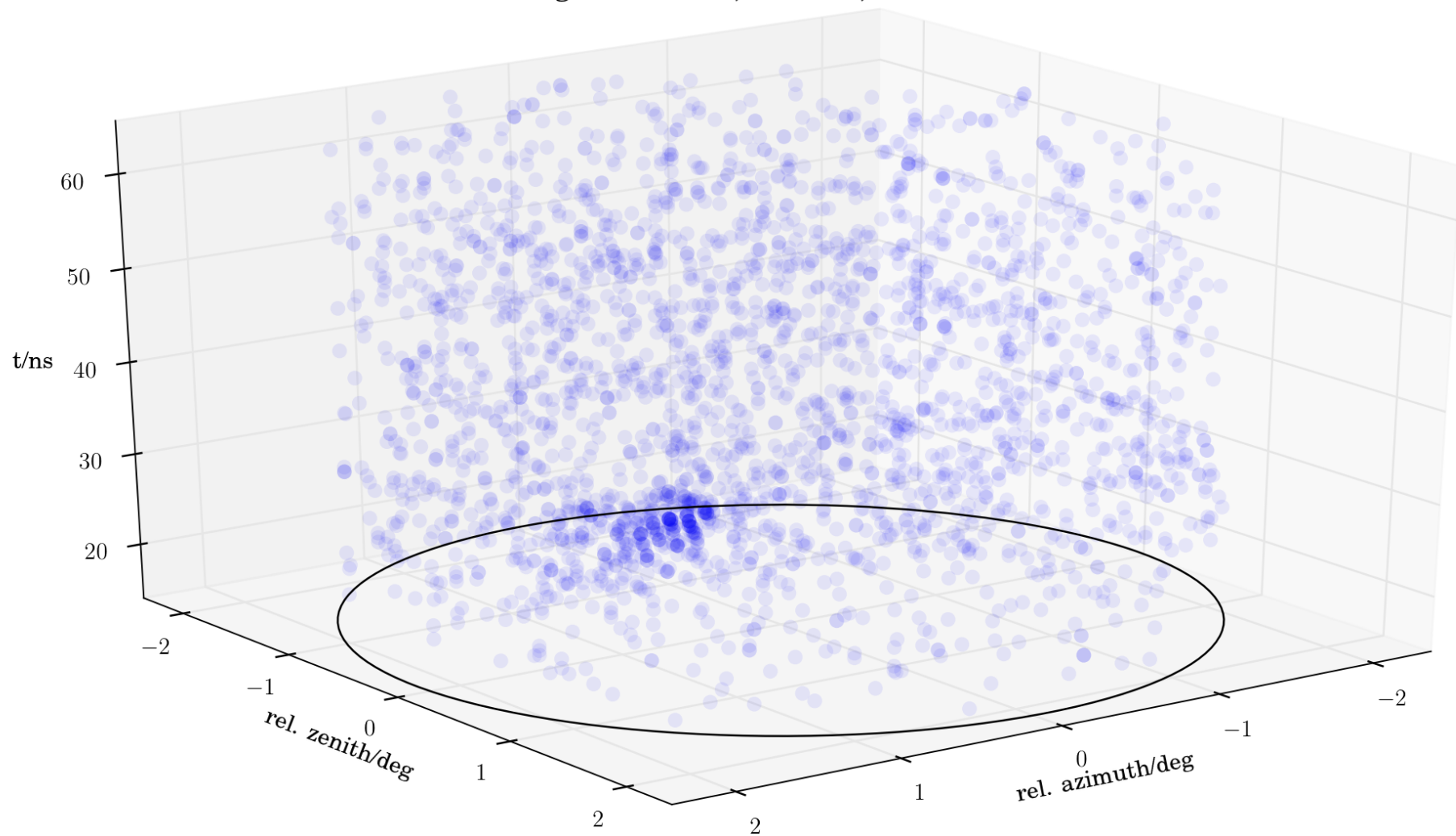




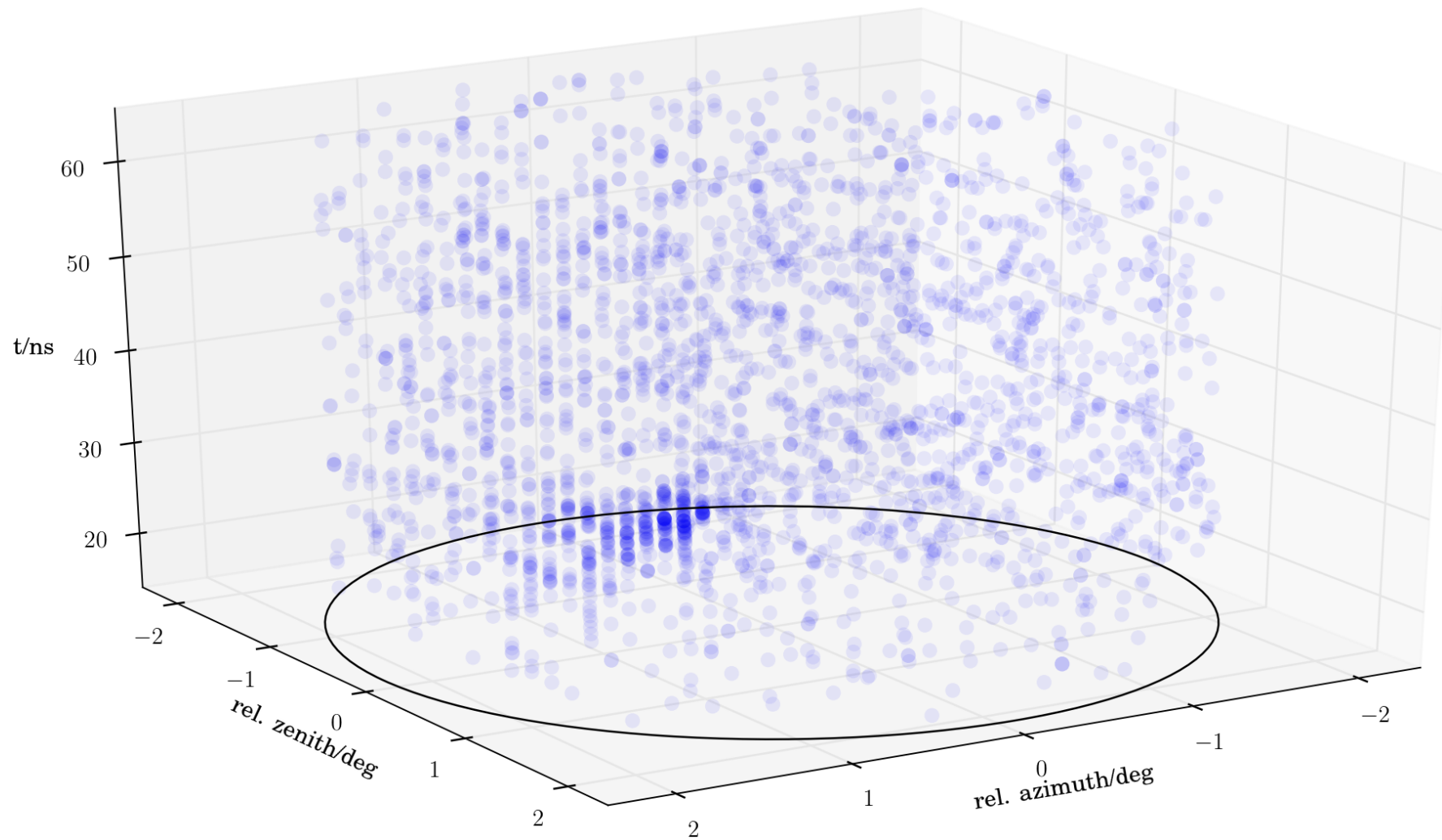




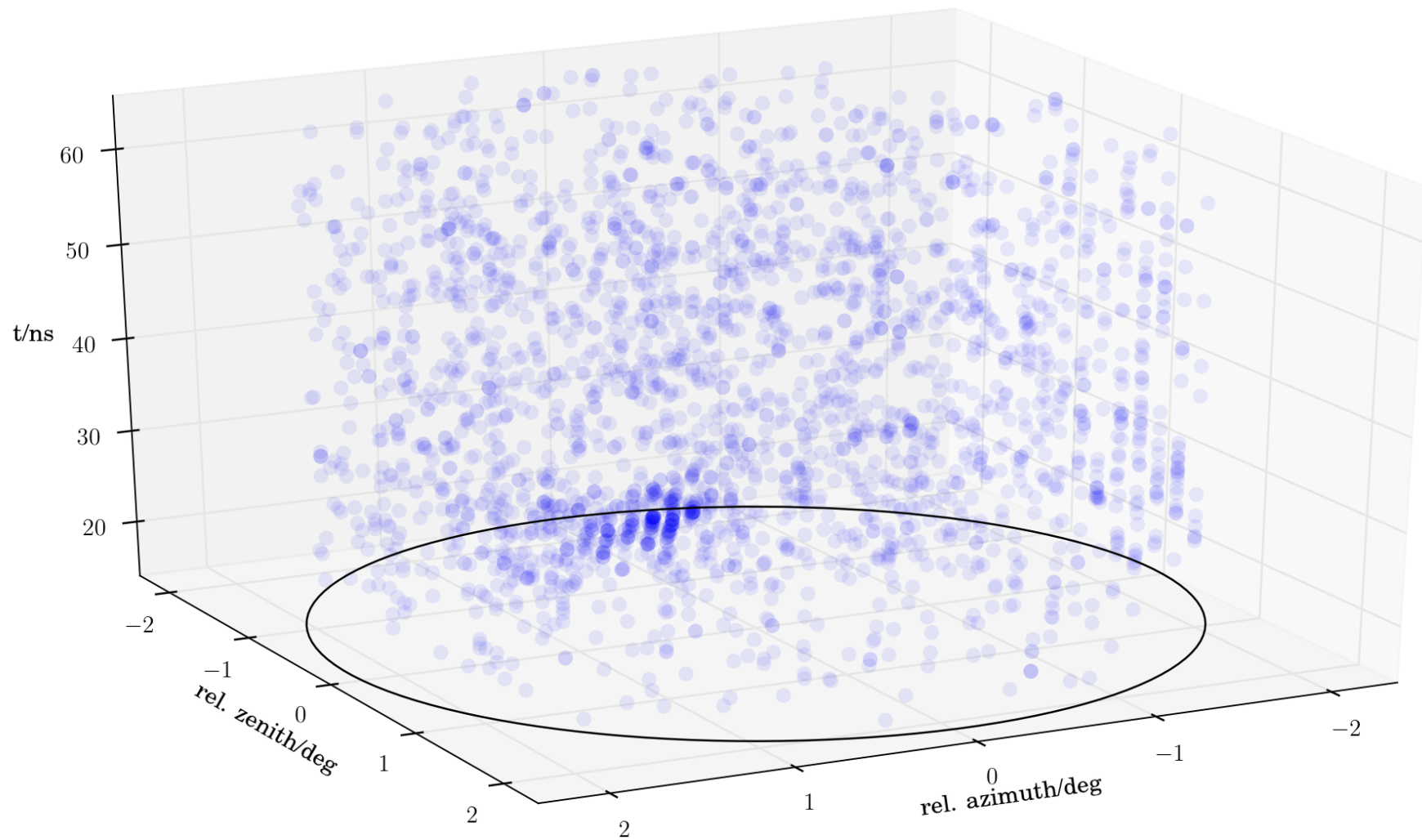
Night 20151113, Run 109, Event 99



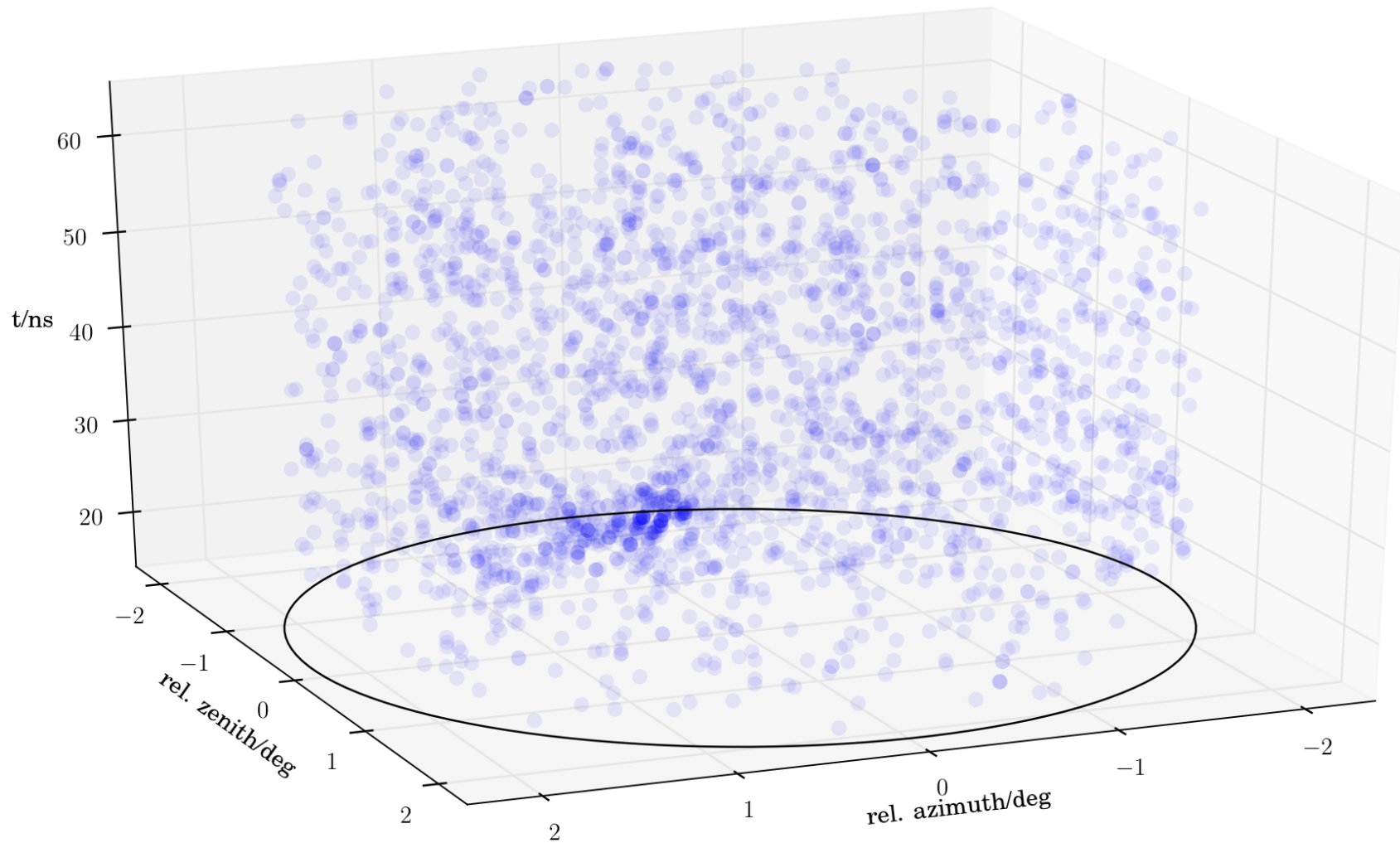
Night 20151113, Run 109, Event 99

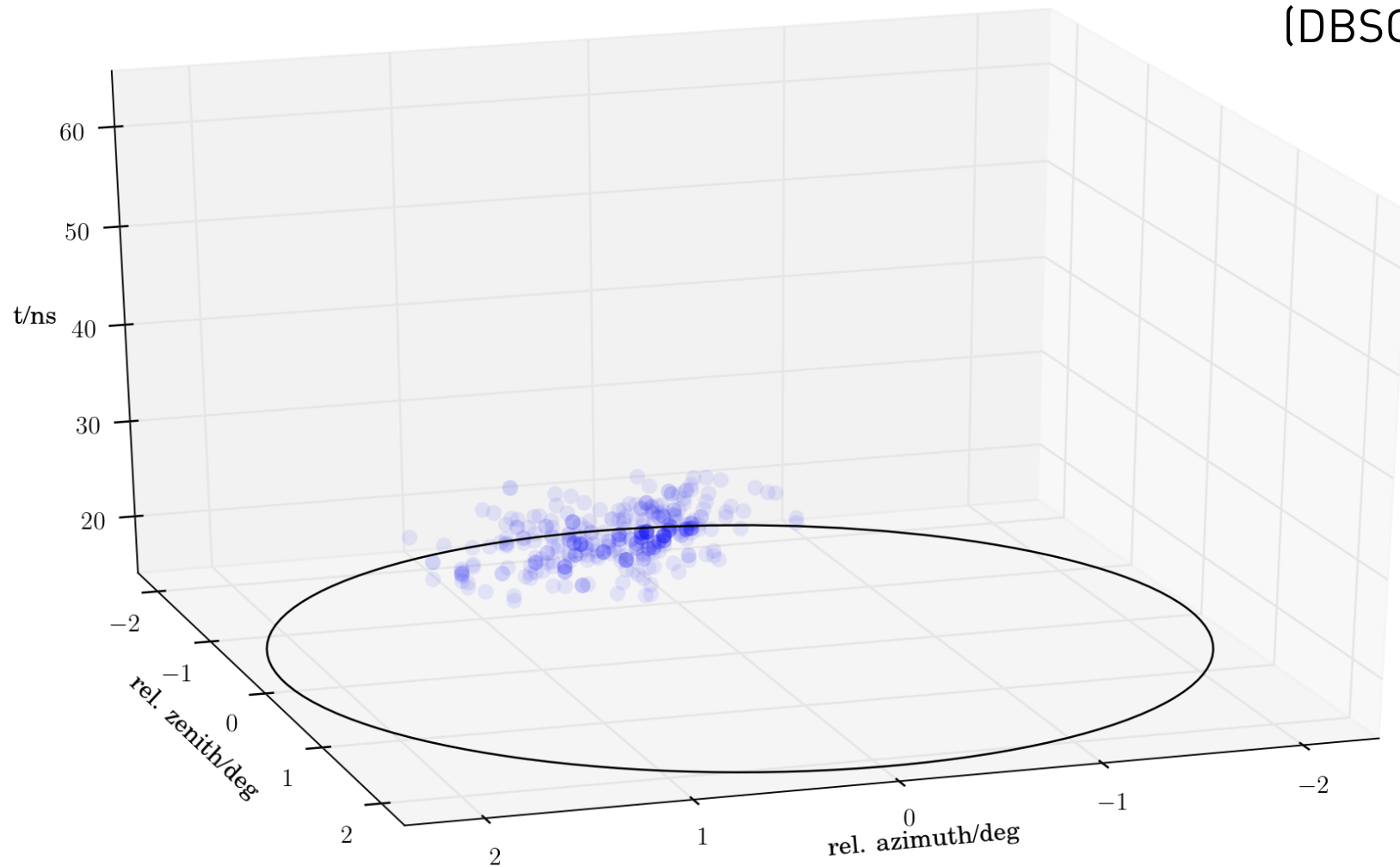


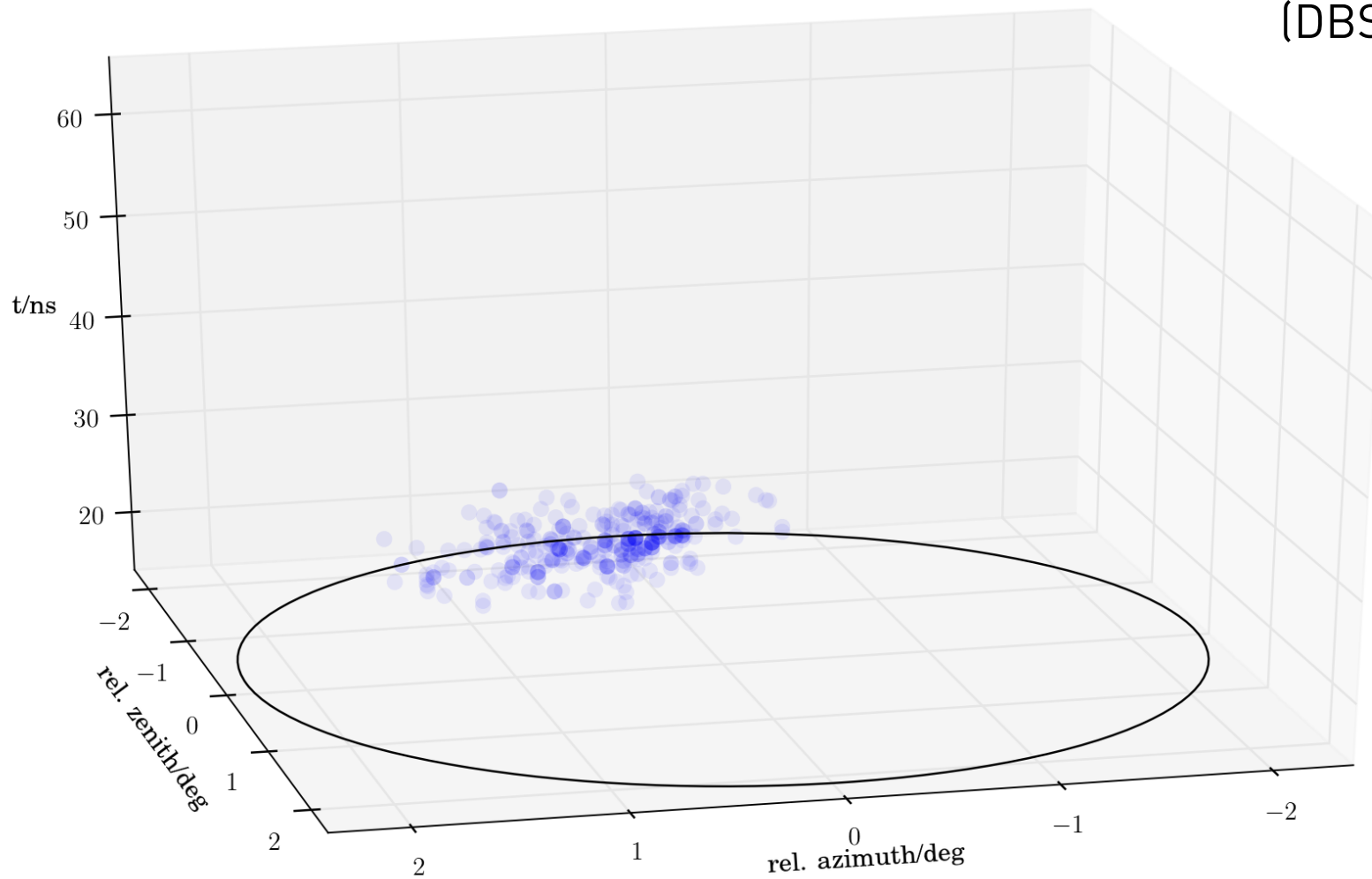
Night 20151113, Run 109, Event 99

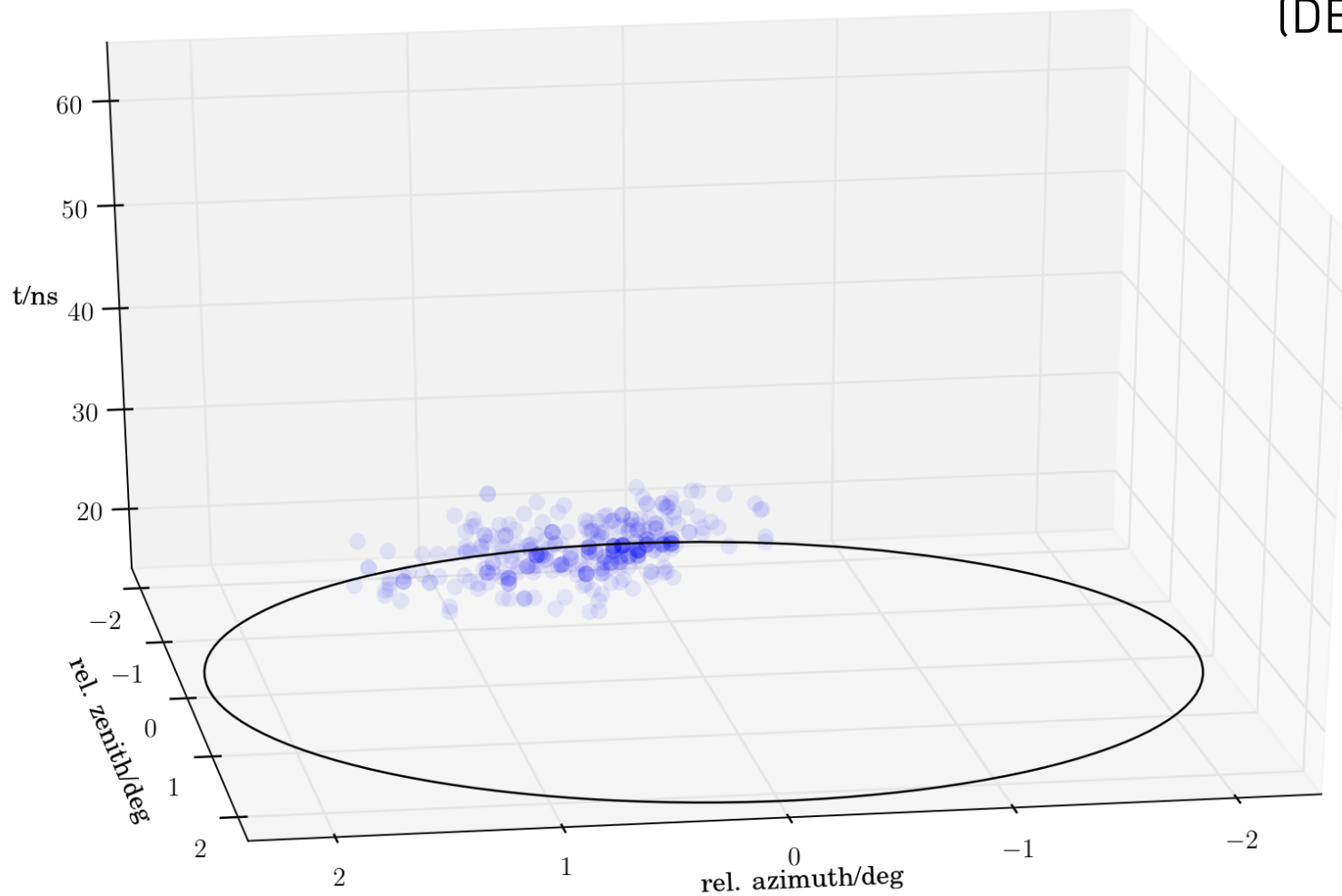


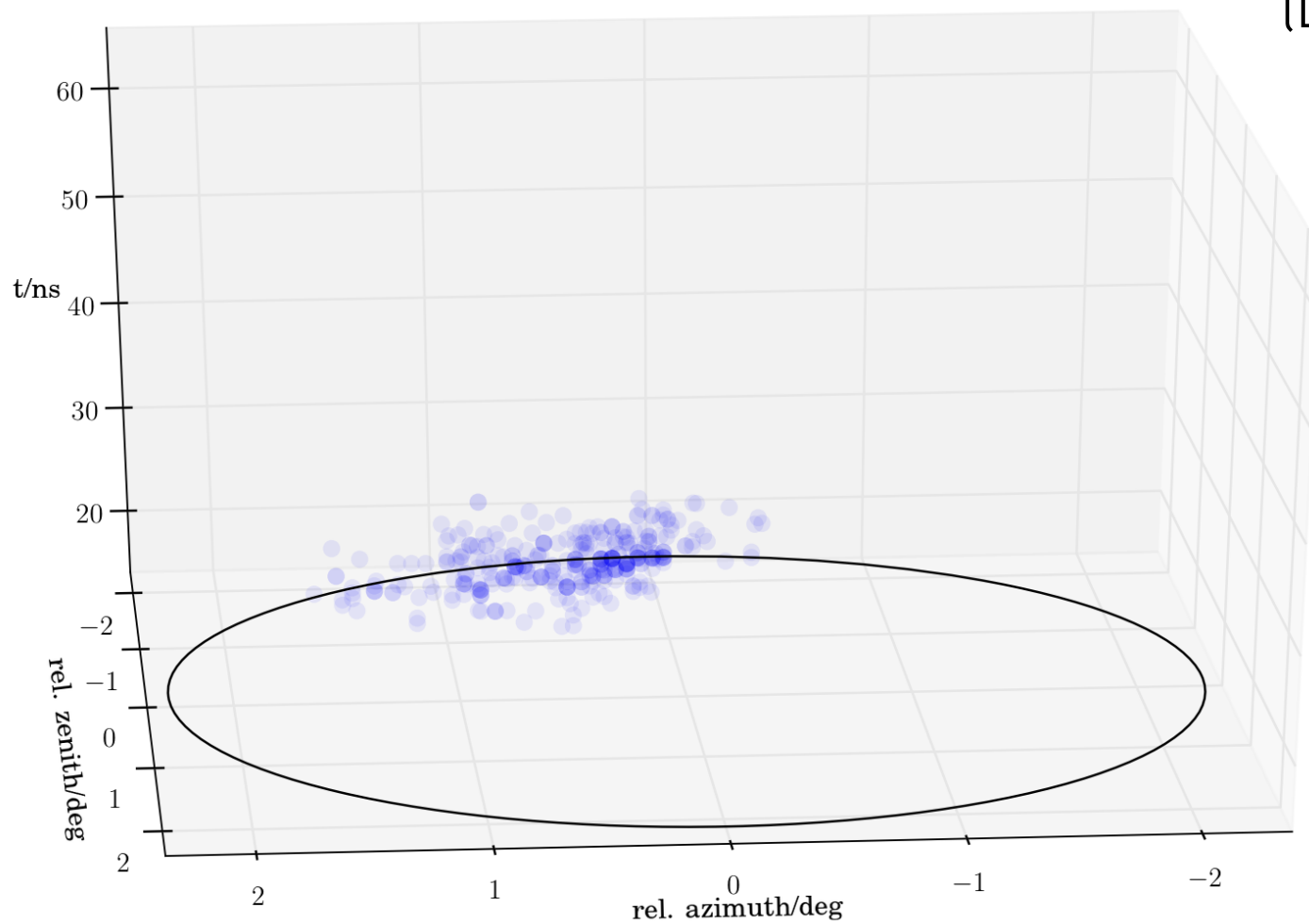
Night 20151113, Run 109, Event 99



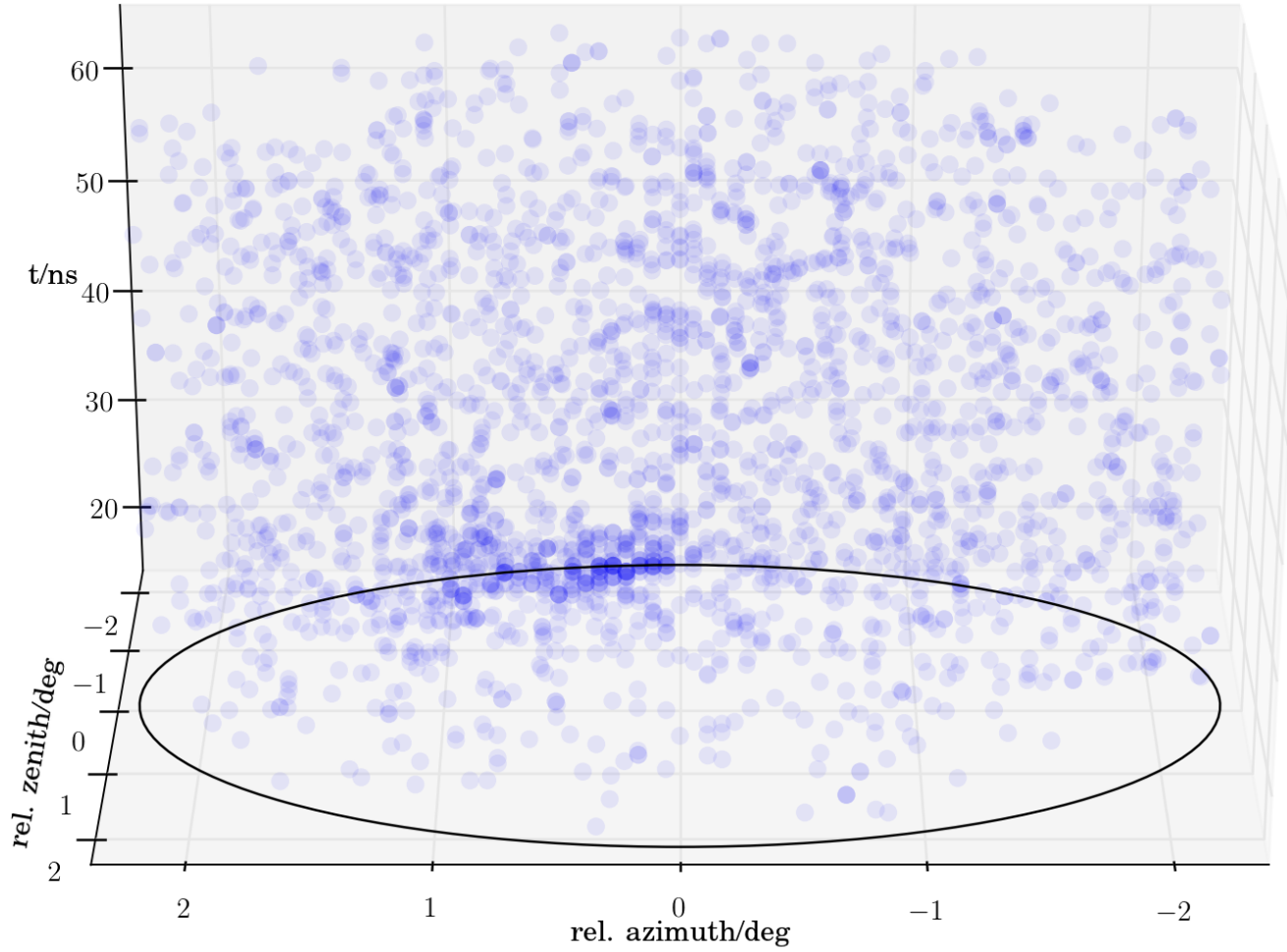




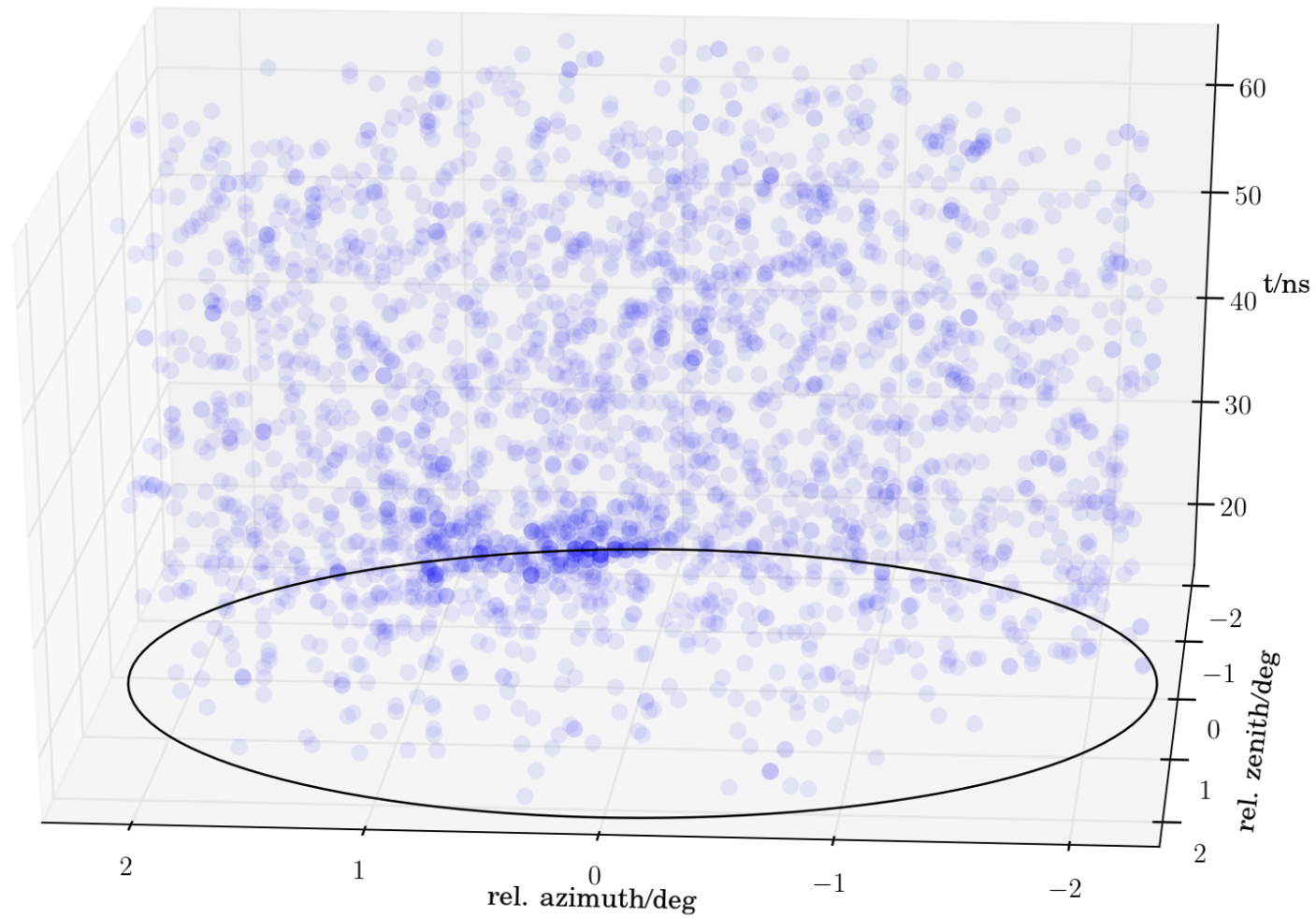




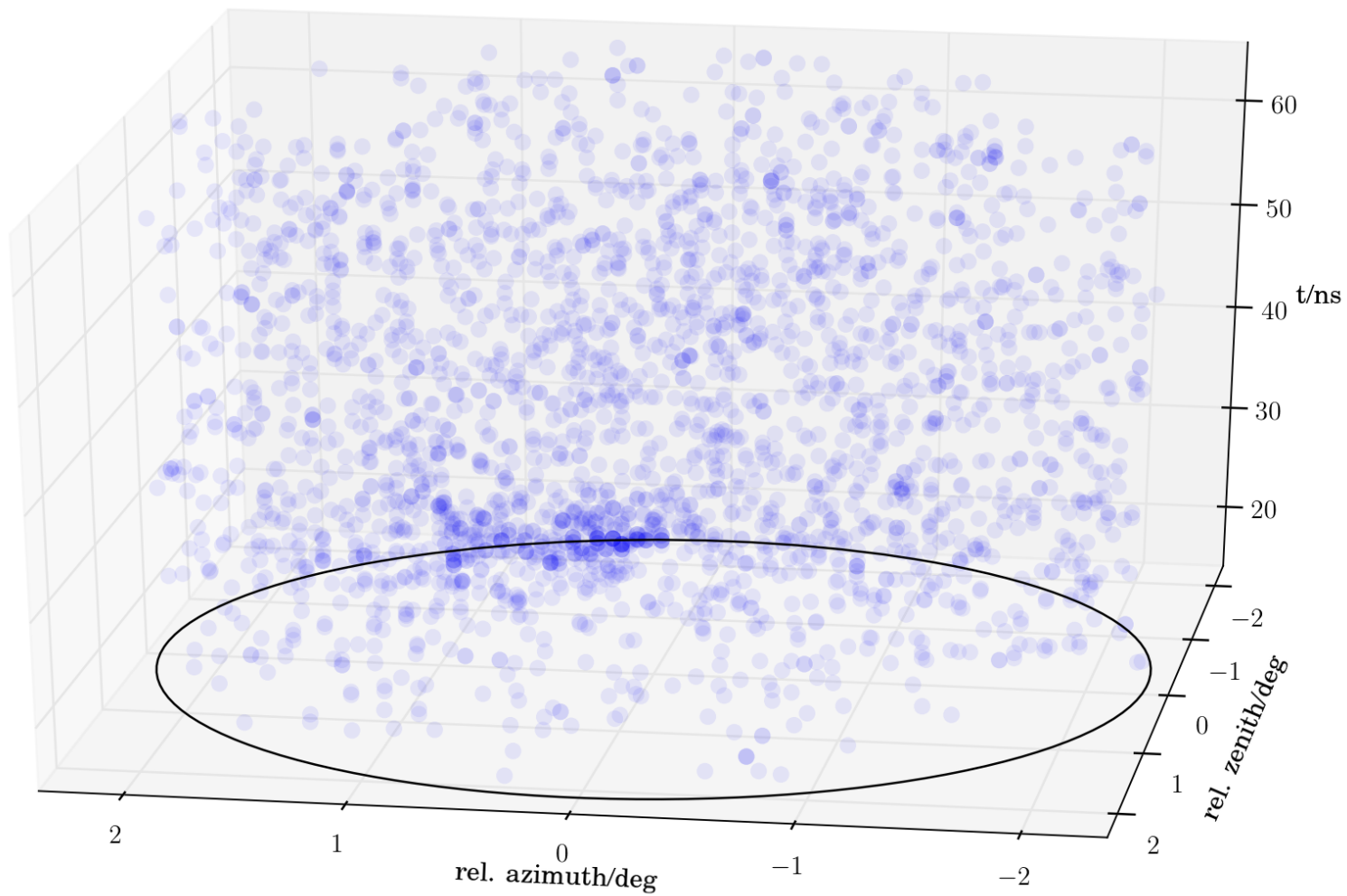
Night 20151113, Run 109, Event 99



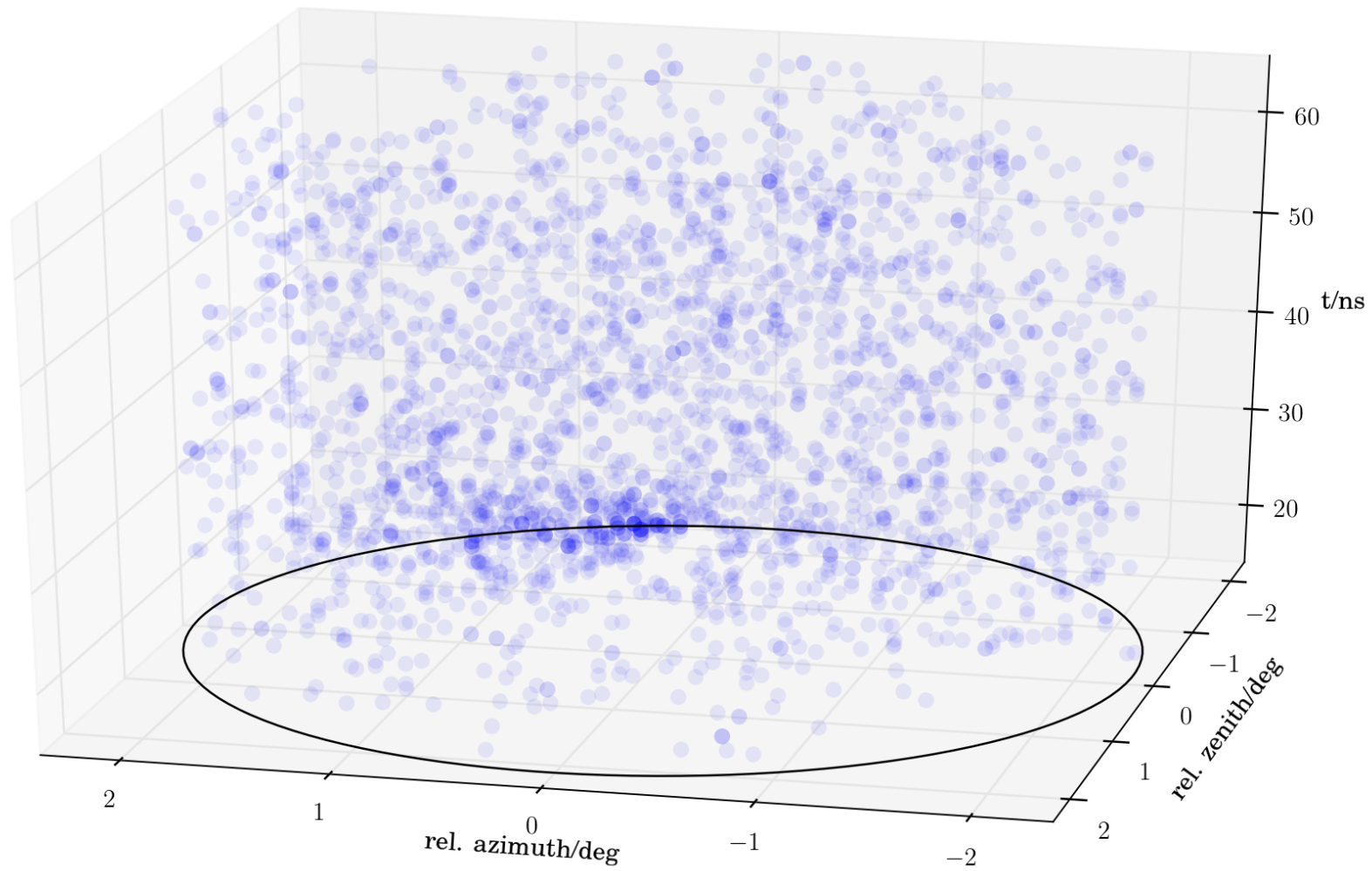
Night 20151113, Run 109, Event 99



Night 20151113, Run 109, Event 99

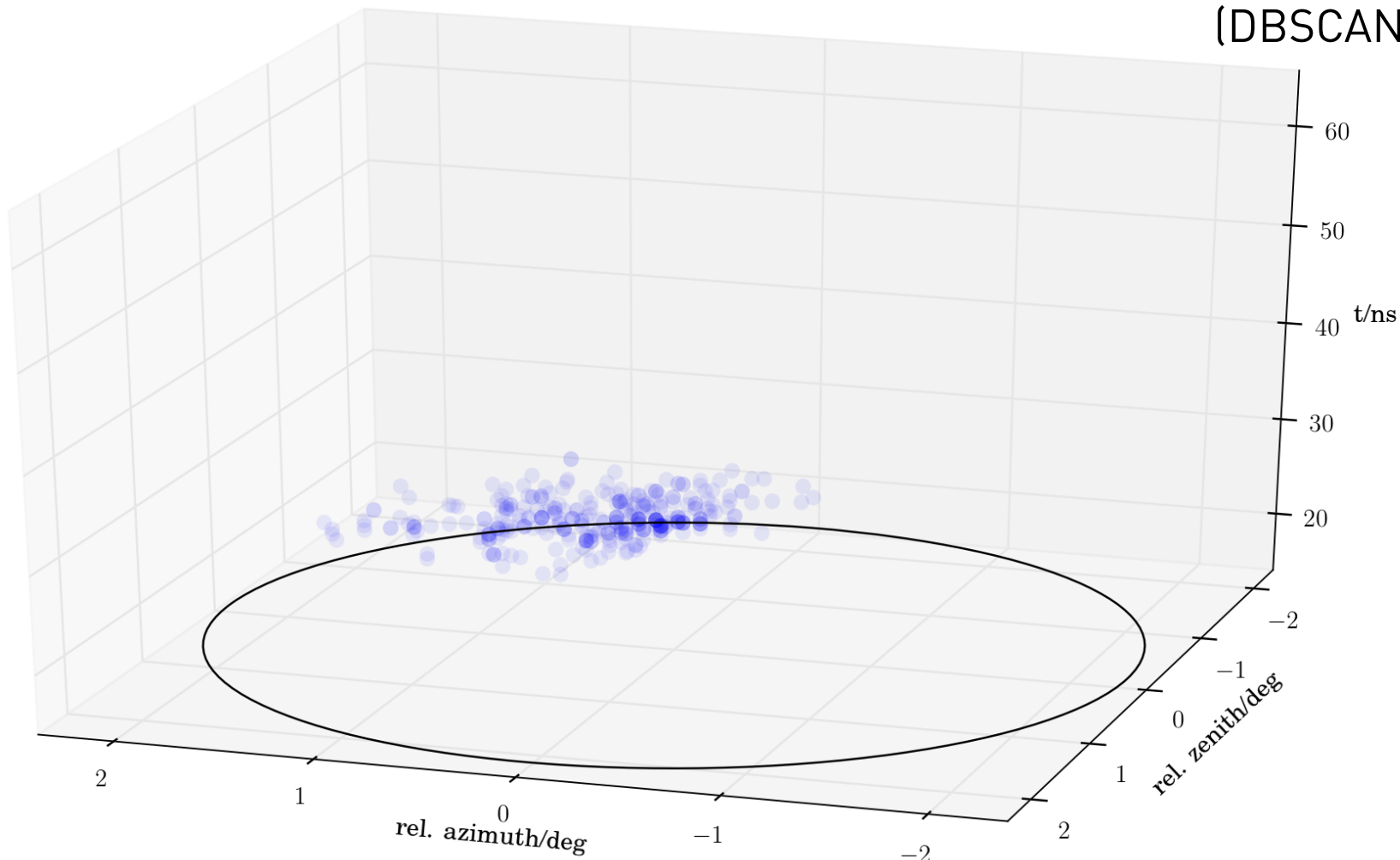


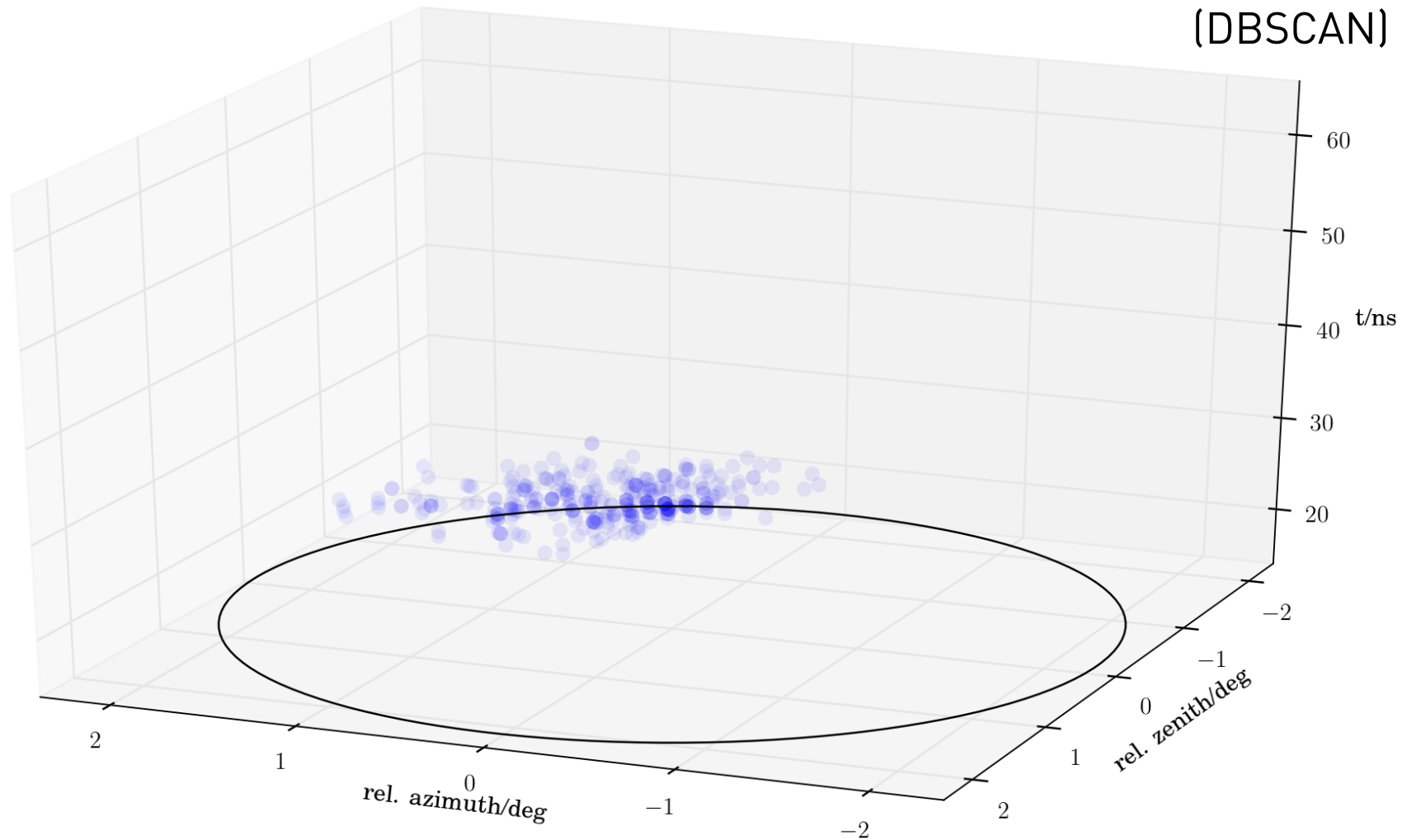
Night 20151113, Run 109, Event 99



Night 20151113, Run 109, Event 99

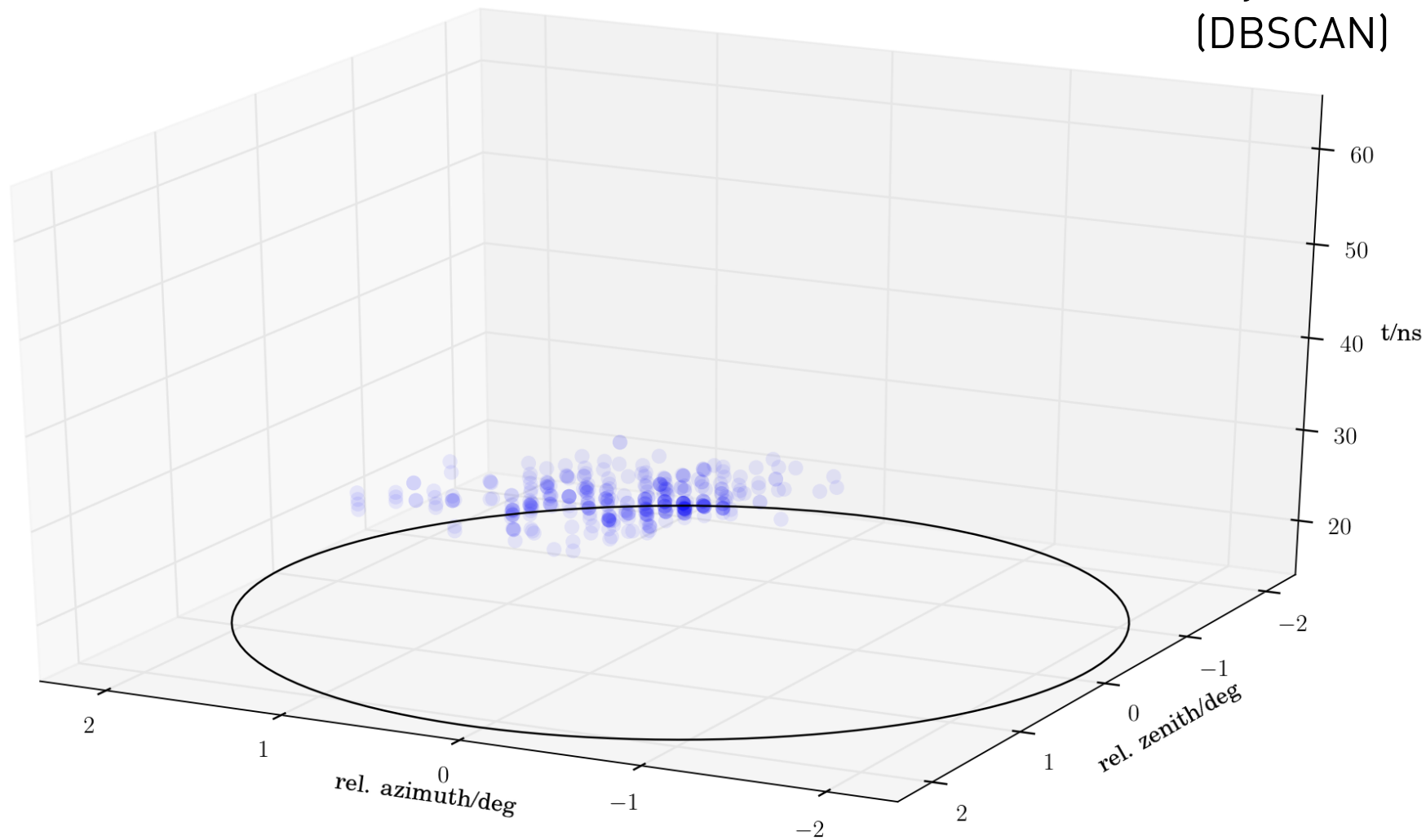
Density clustering
(DBSCAN)





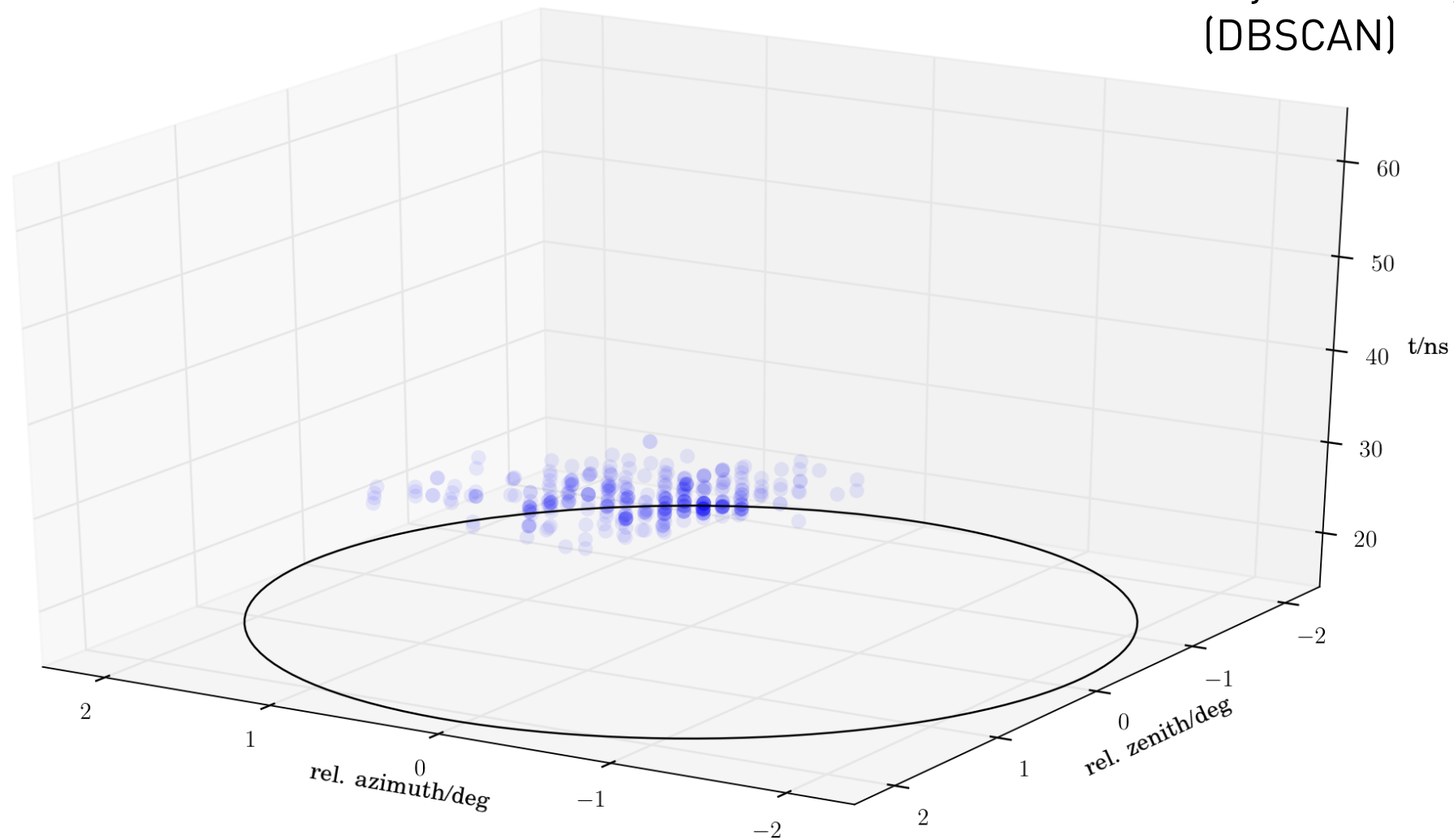
Night 20151113, Run 109, Event 99

Density clustering
(DBSCAN)

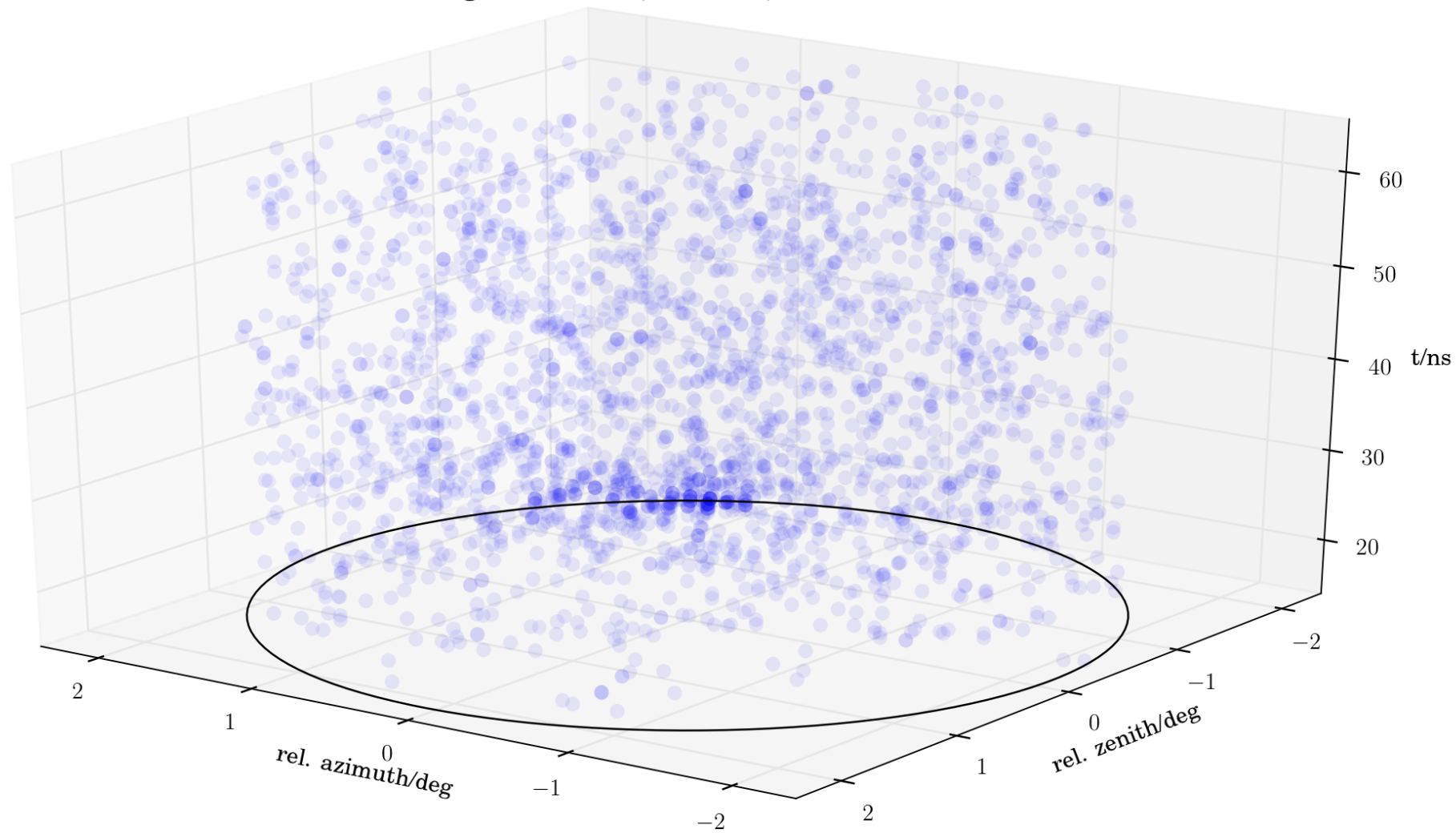


Night 20151113, Run 109, Event 99

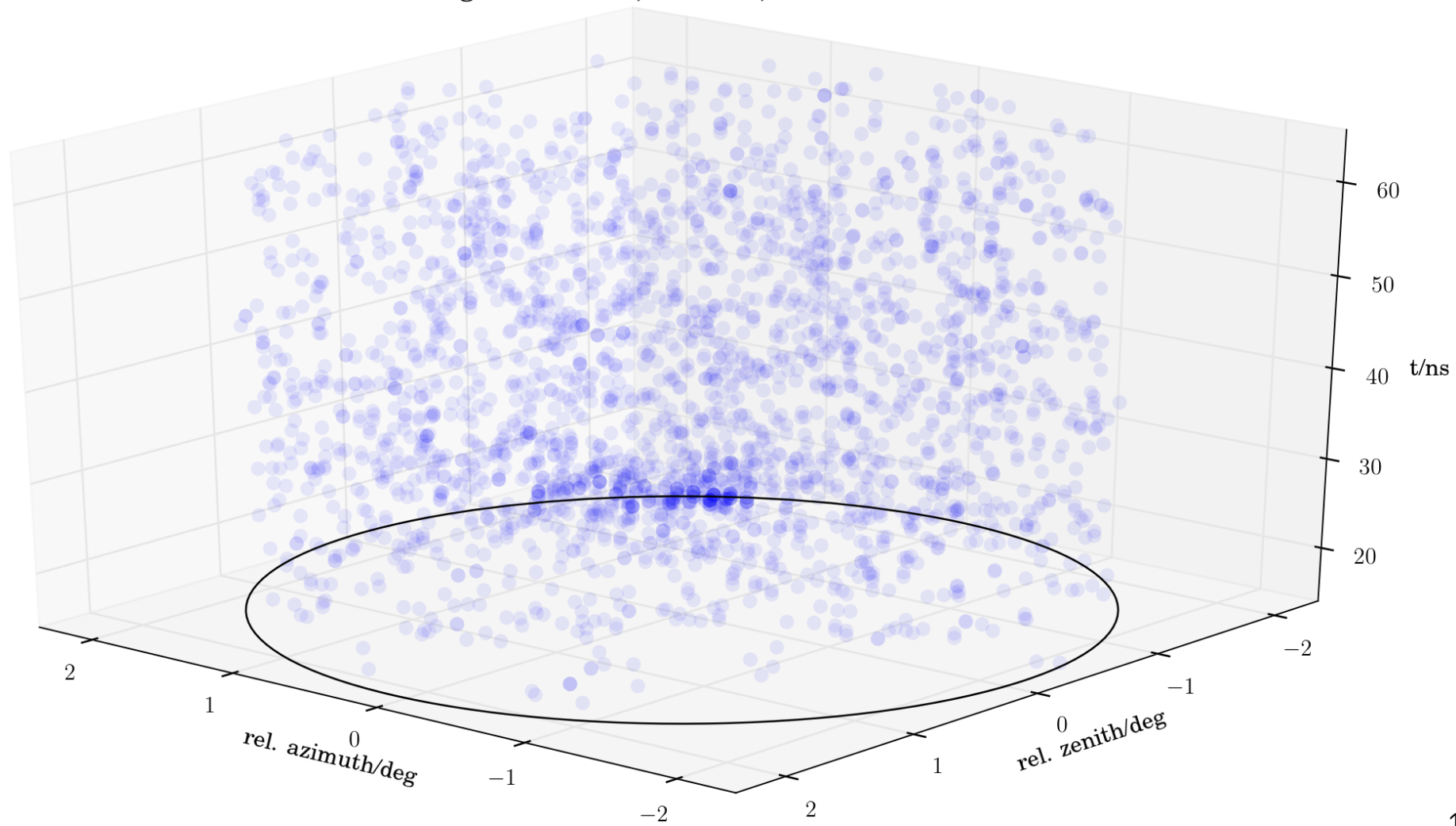
Density clustering
(DBSCAN)



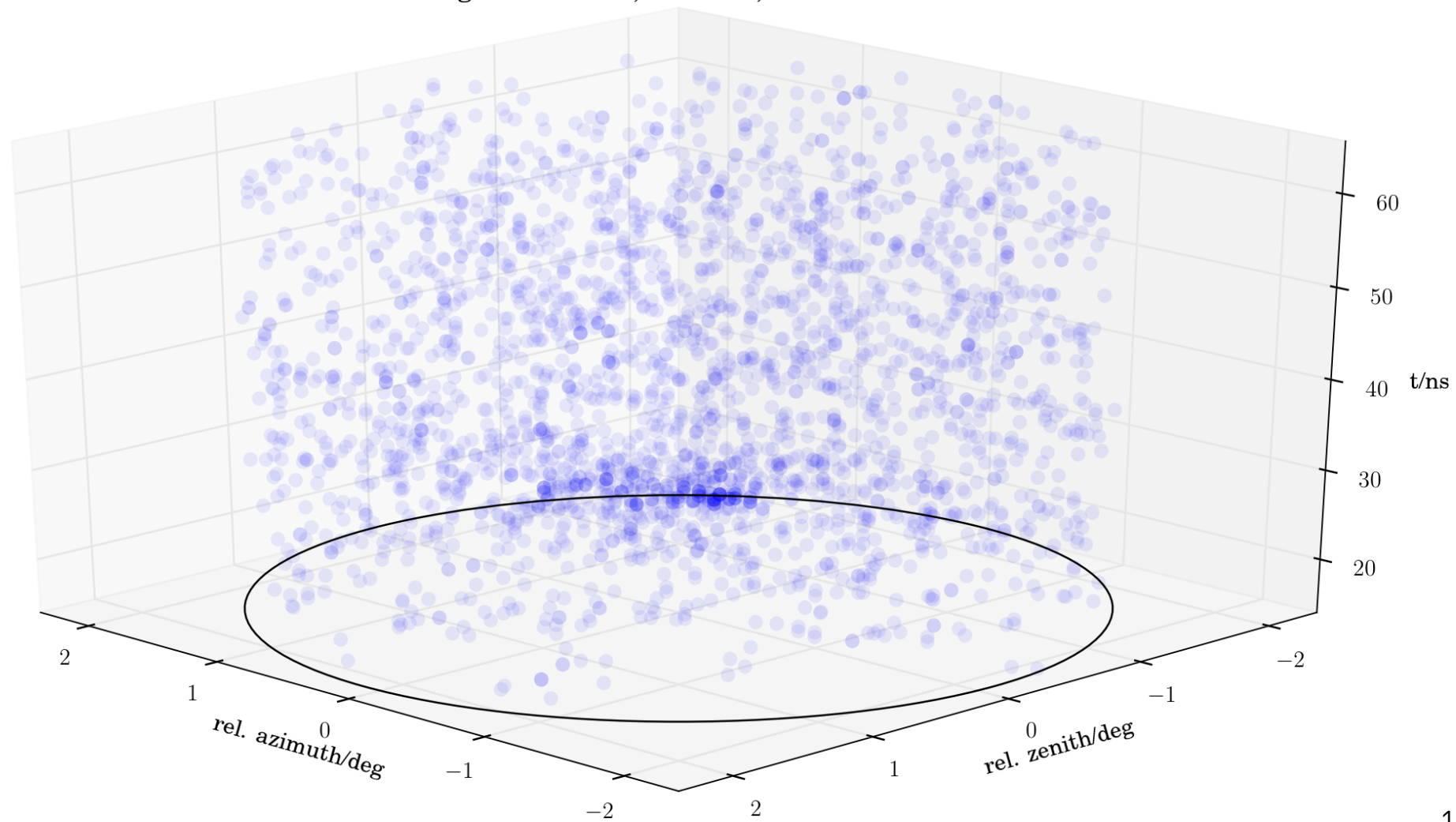
Night 20151113, Run 109, Event 99



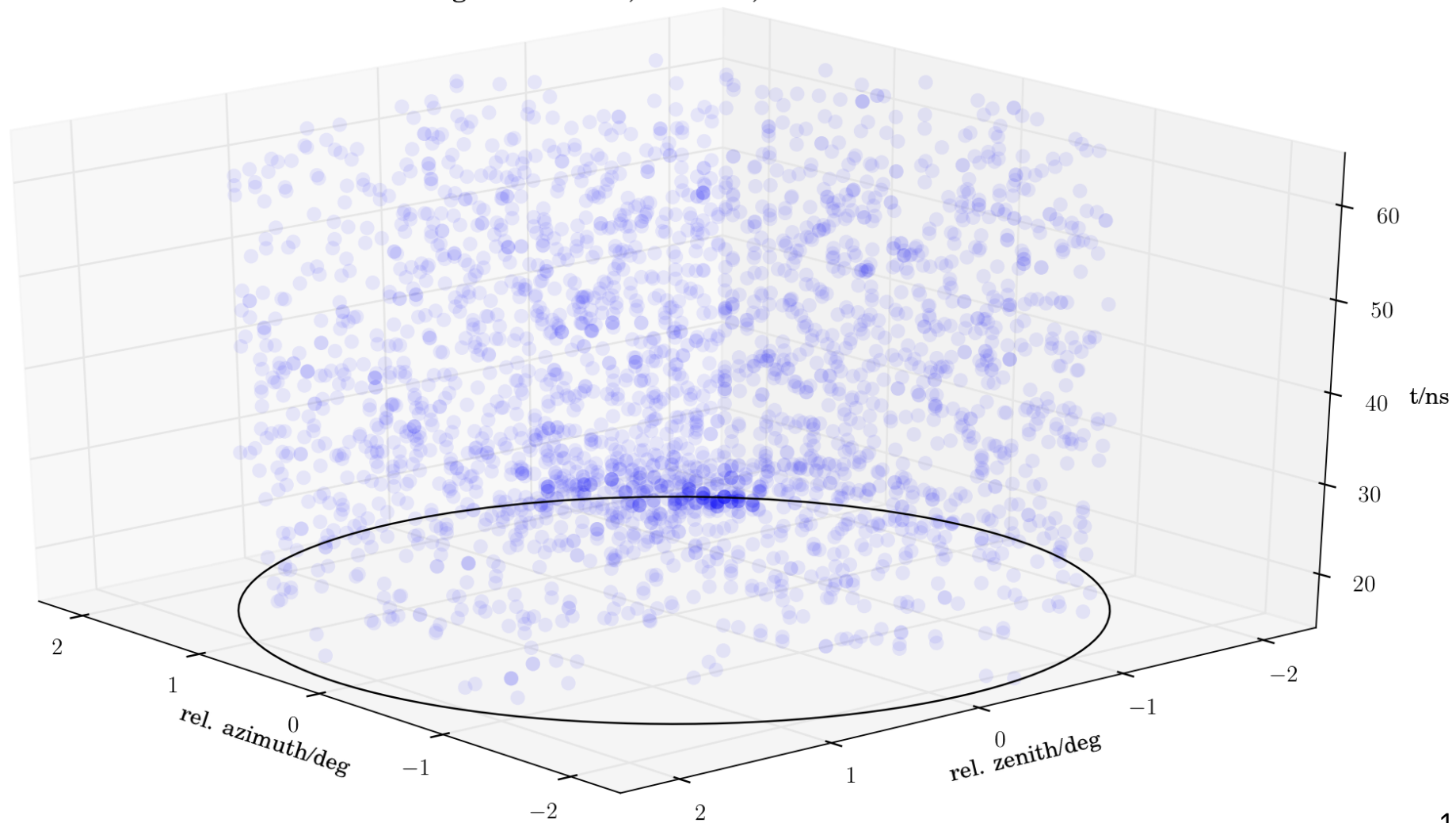
Night 20151113, Run 109, Event 99



Night 20151113, Run 109, Event 99

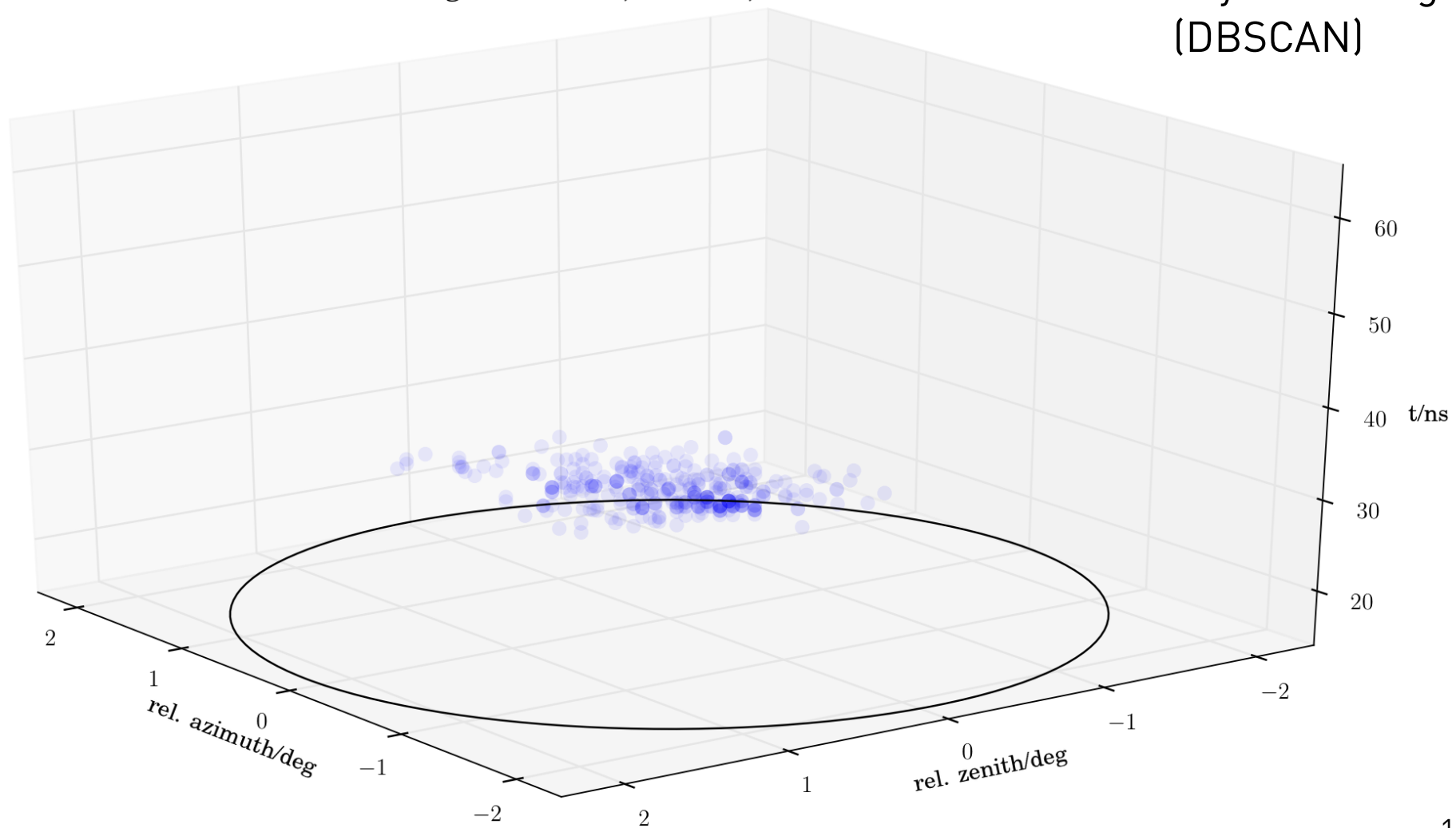


Night 20151113, Run 109, Event 99



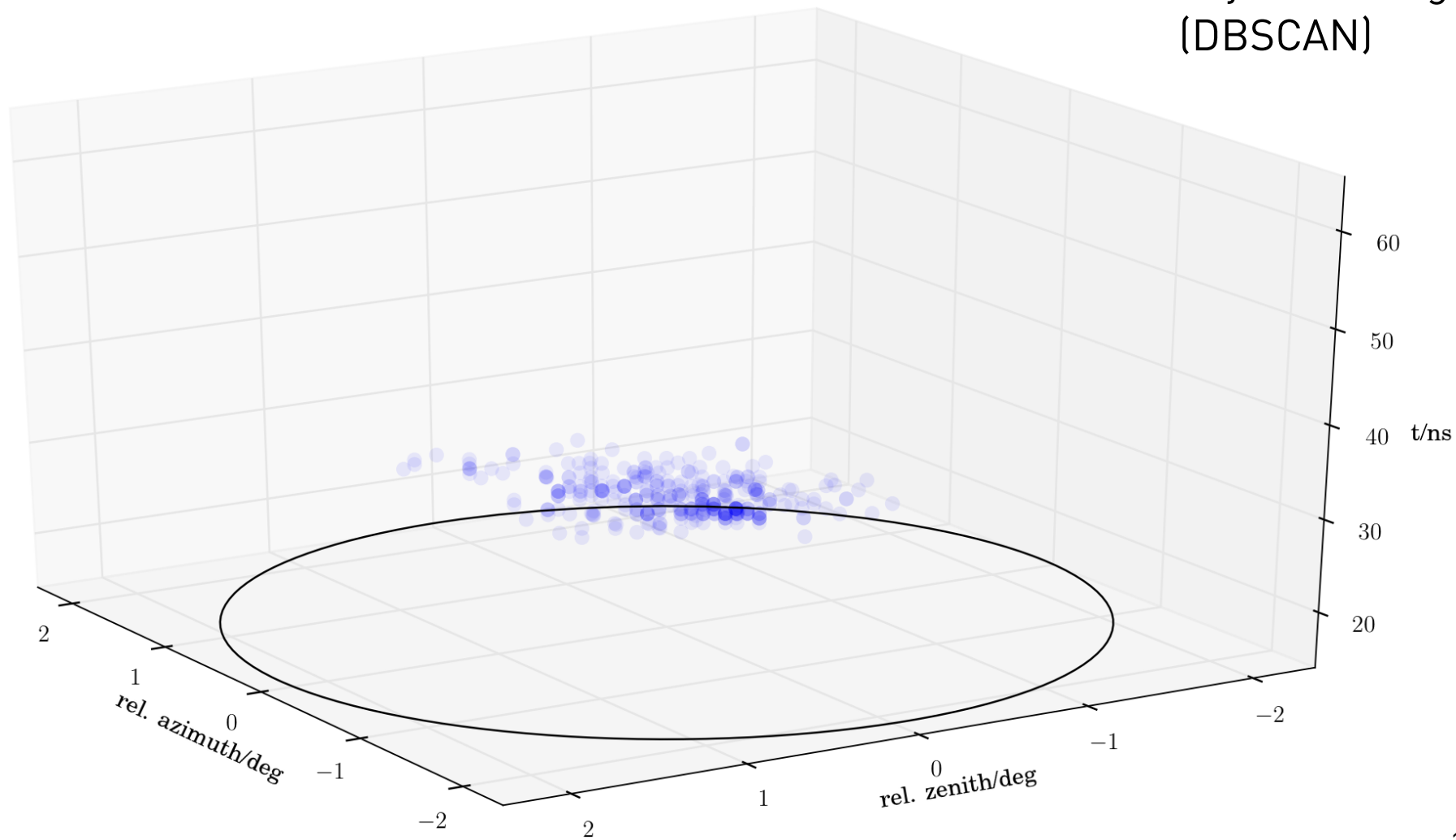
Night 20151113, Run 109, Event 99

Density clustering
(DBSCAN)



Night 20151113, Run 109, Event 99

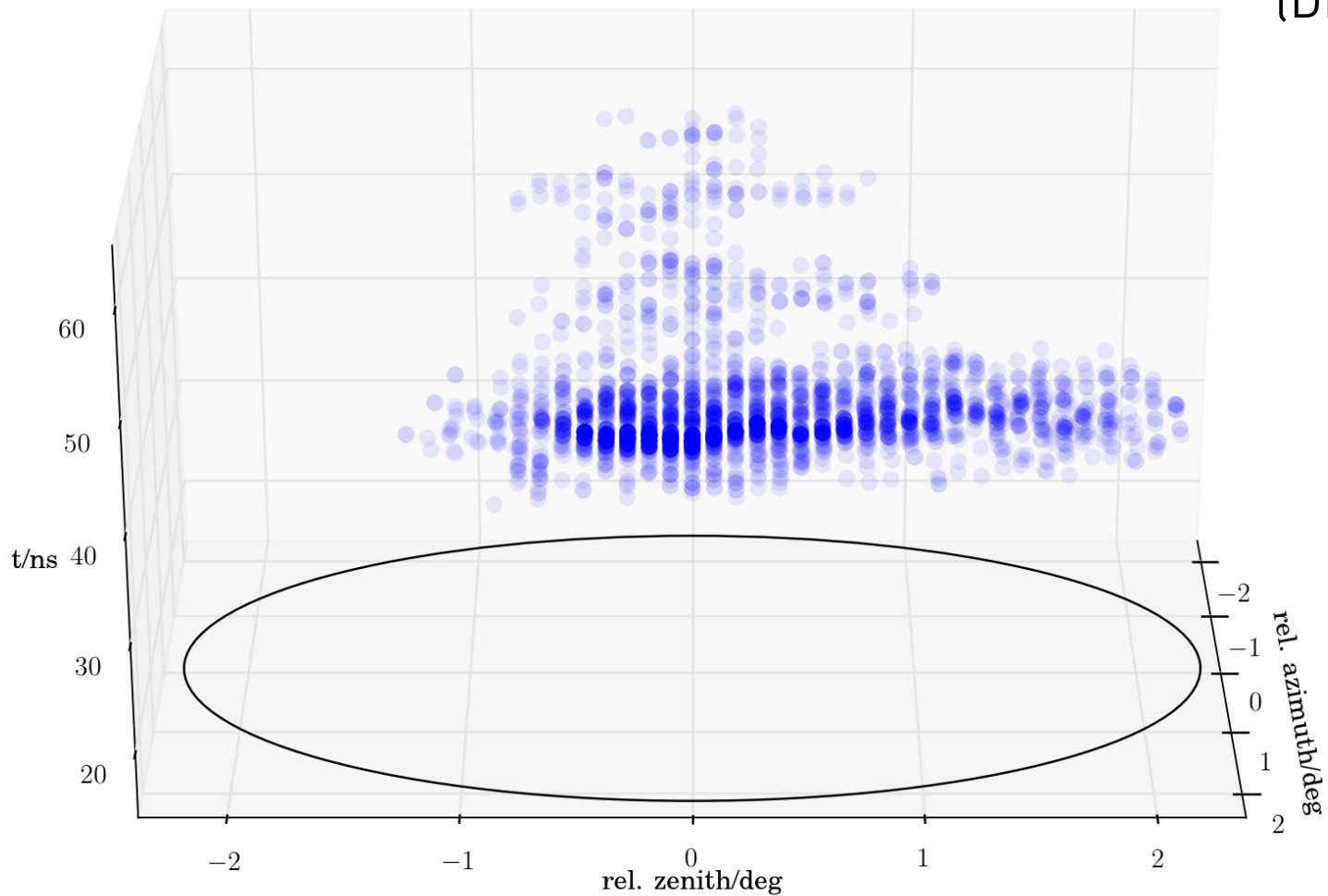
Density clustering
(DBSCAN)

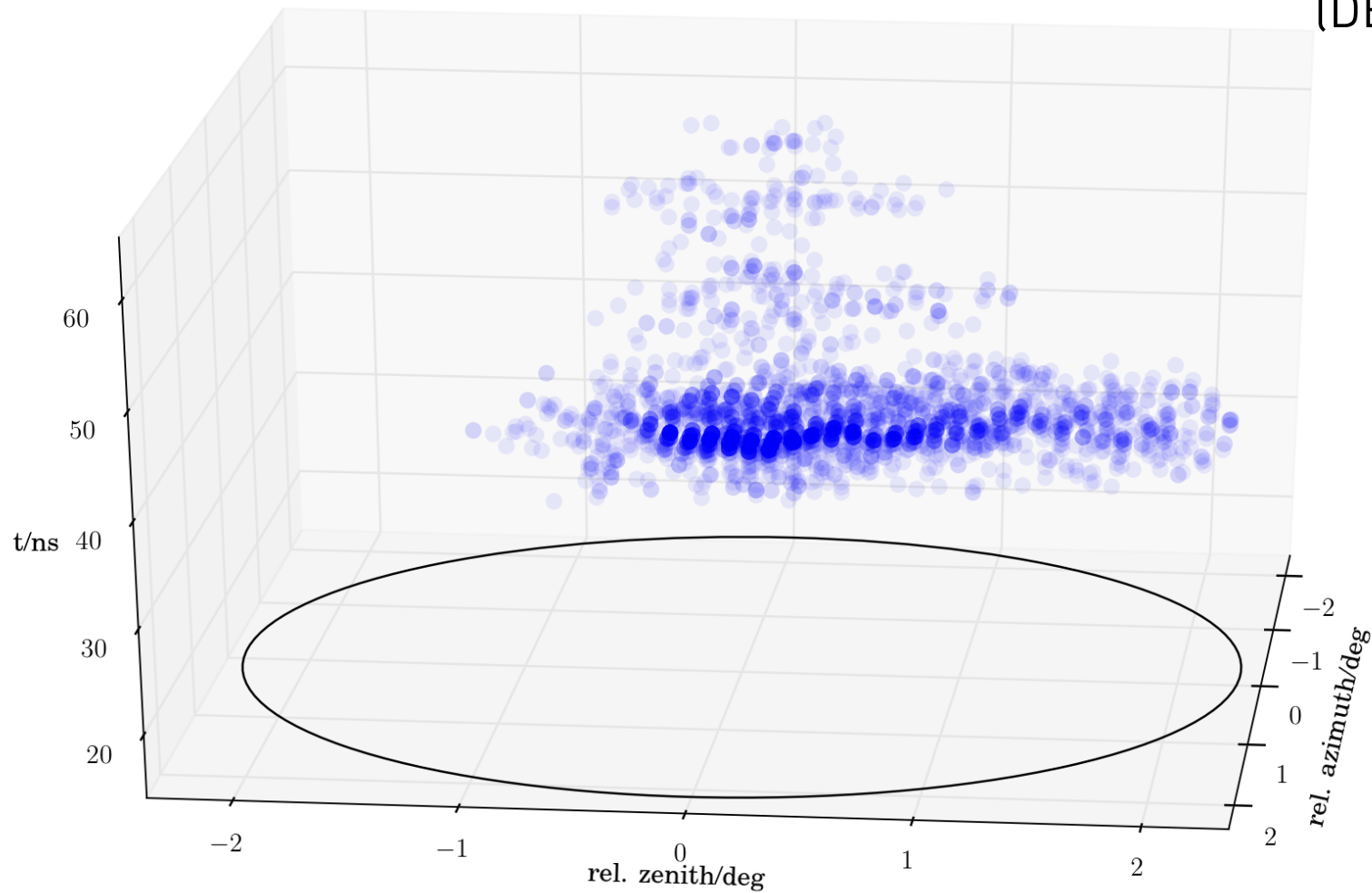


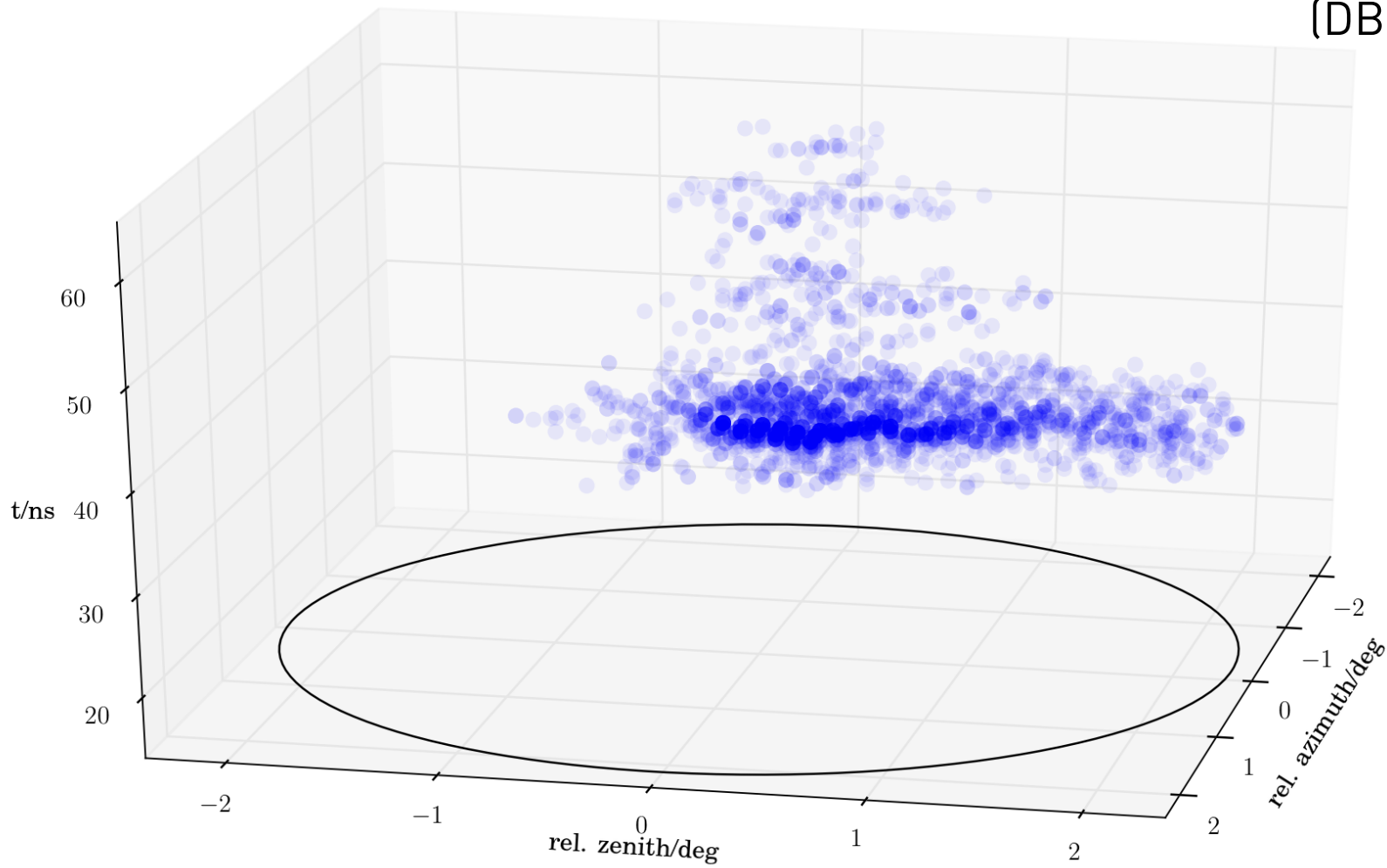
Example Photon-Stream Event

2

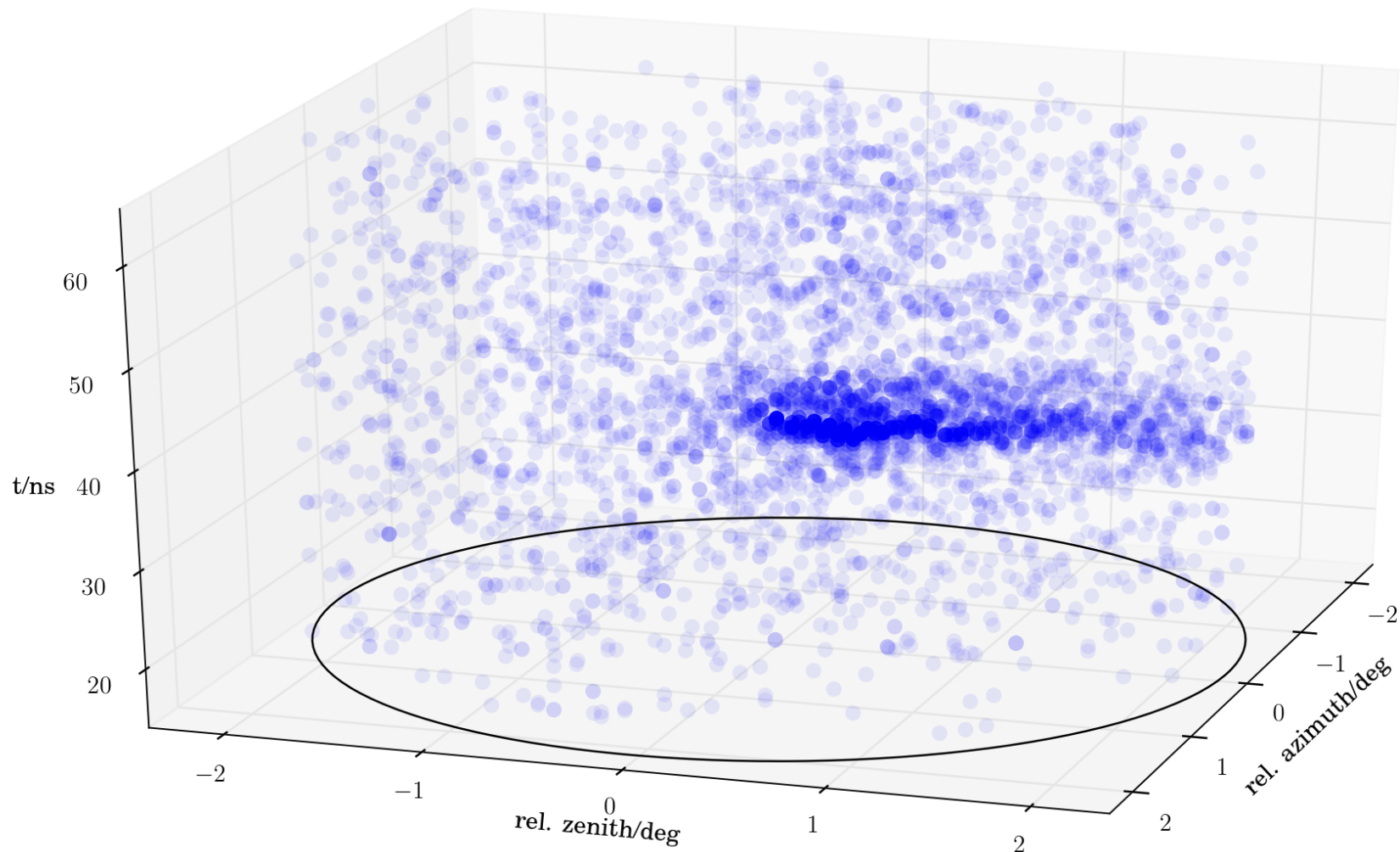
FACT 2015 Nov 13
bright shower



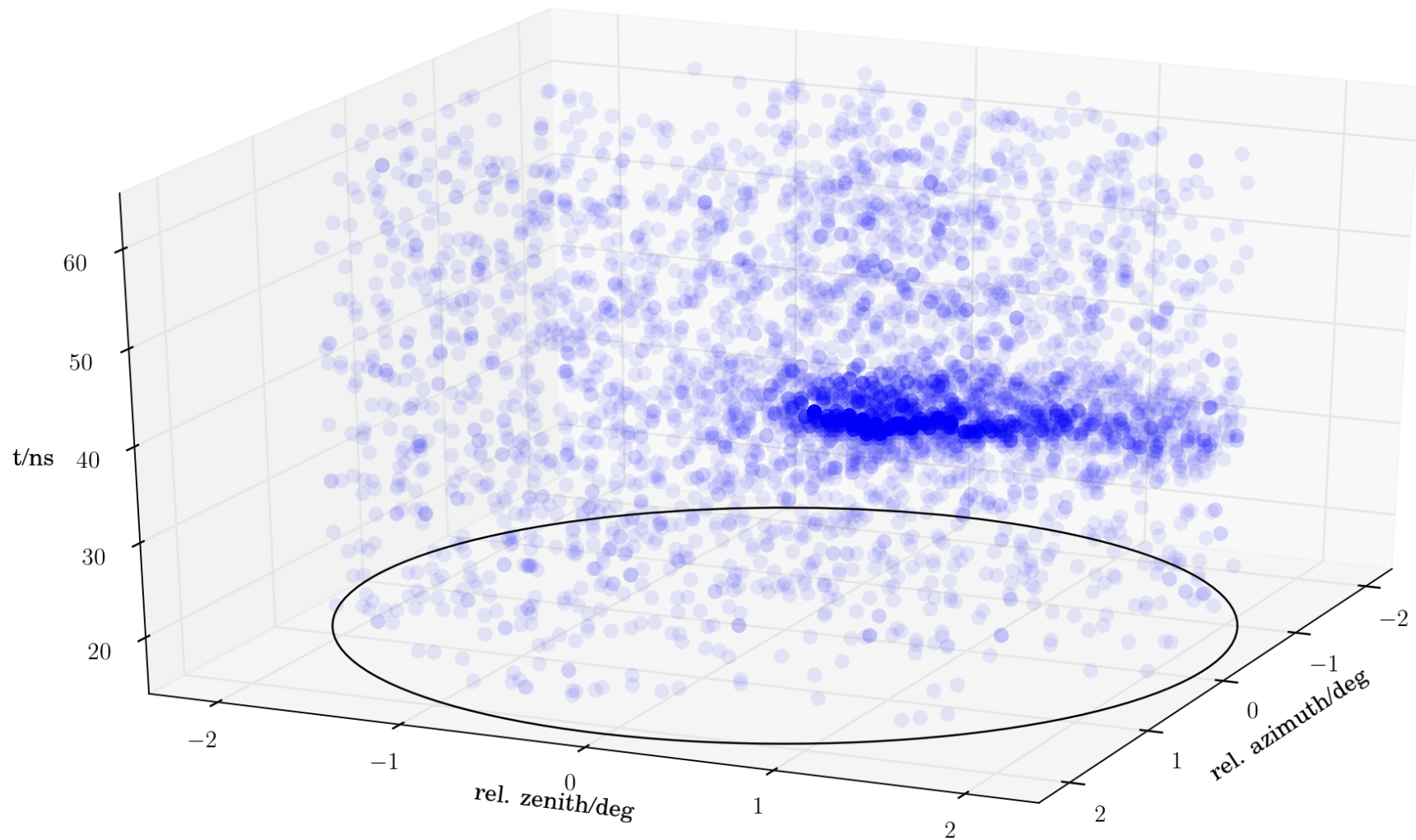




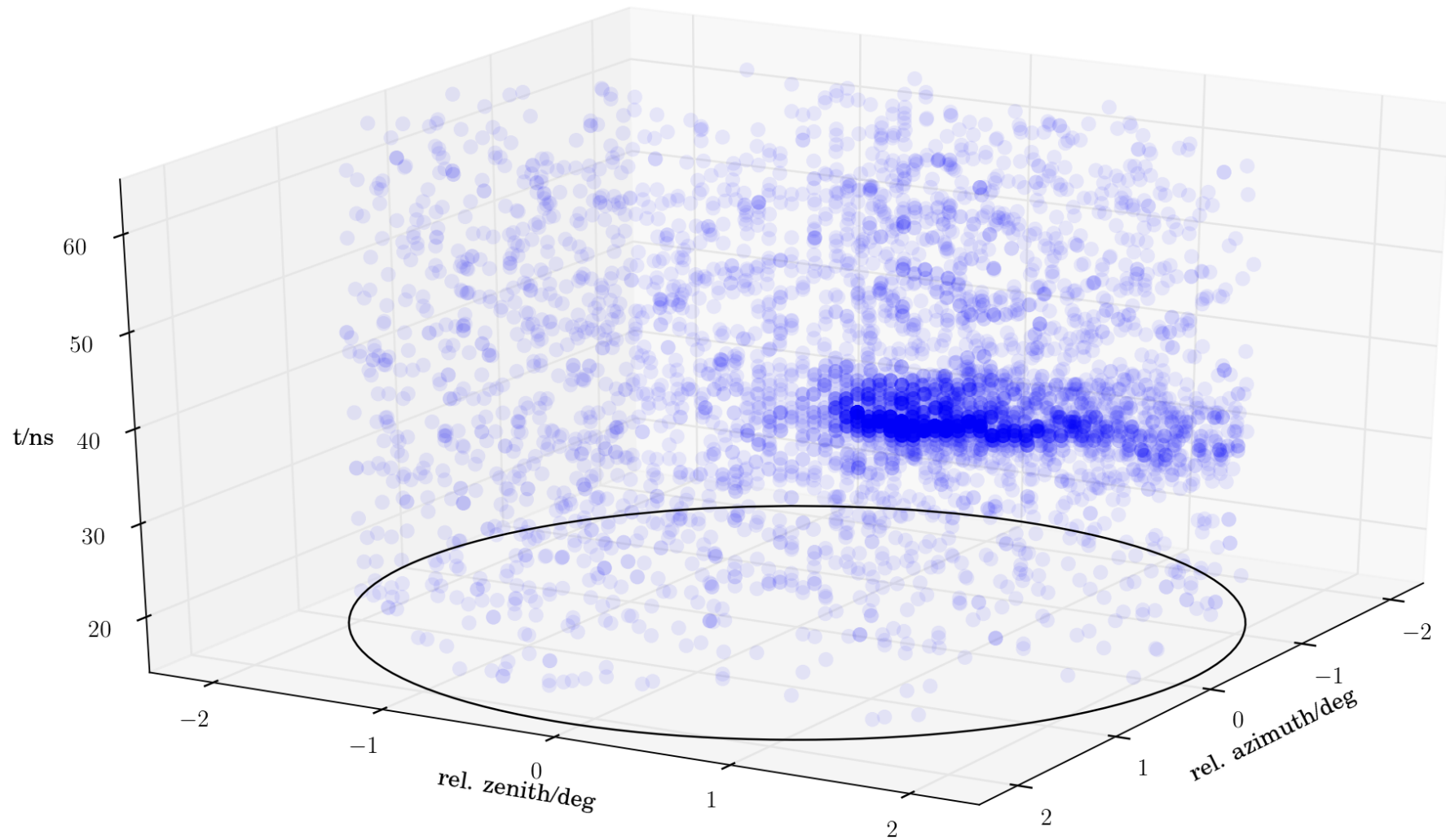
Night 20151113, Run 109, Event 159

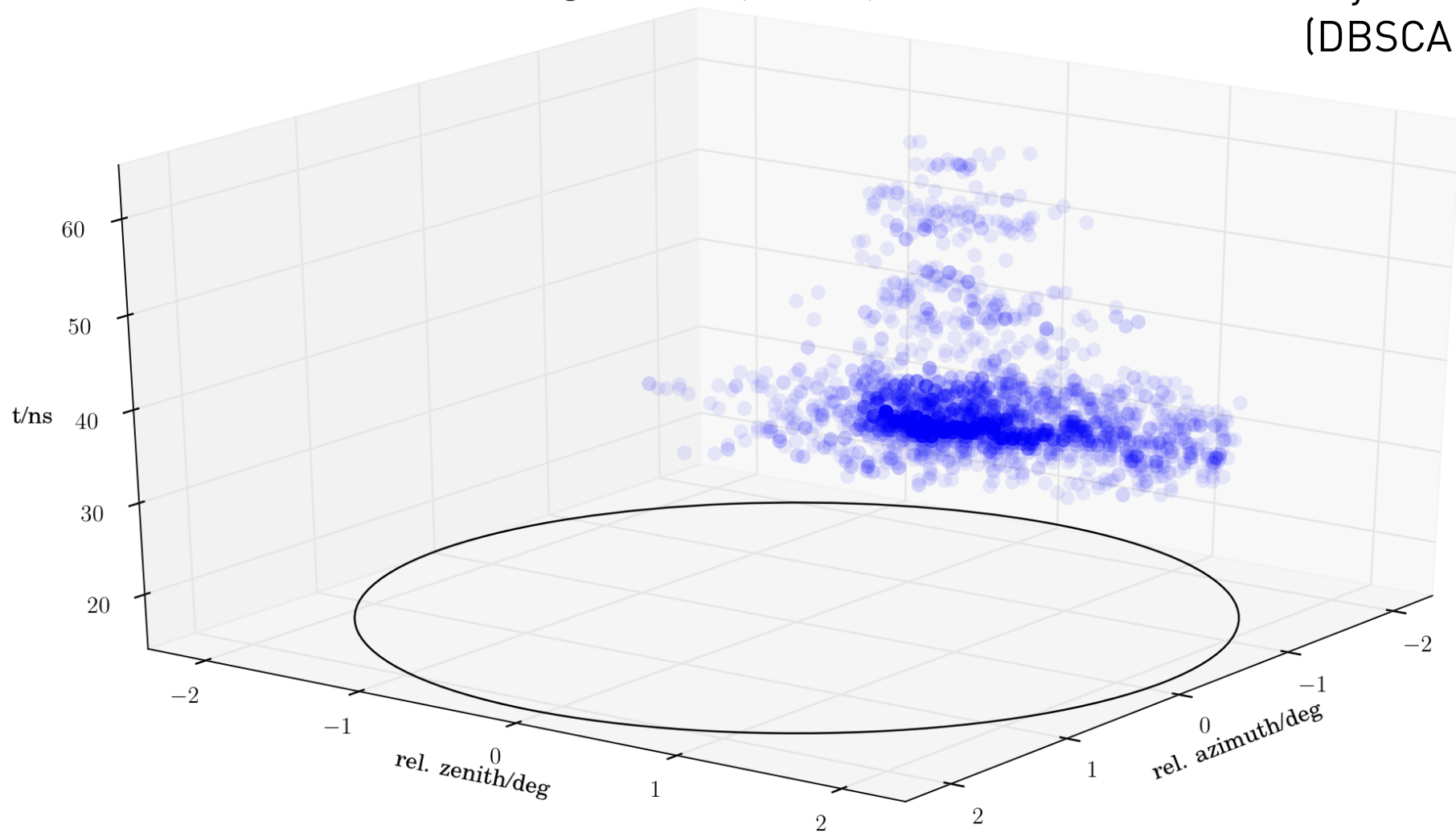


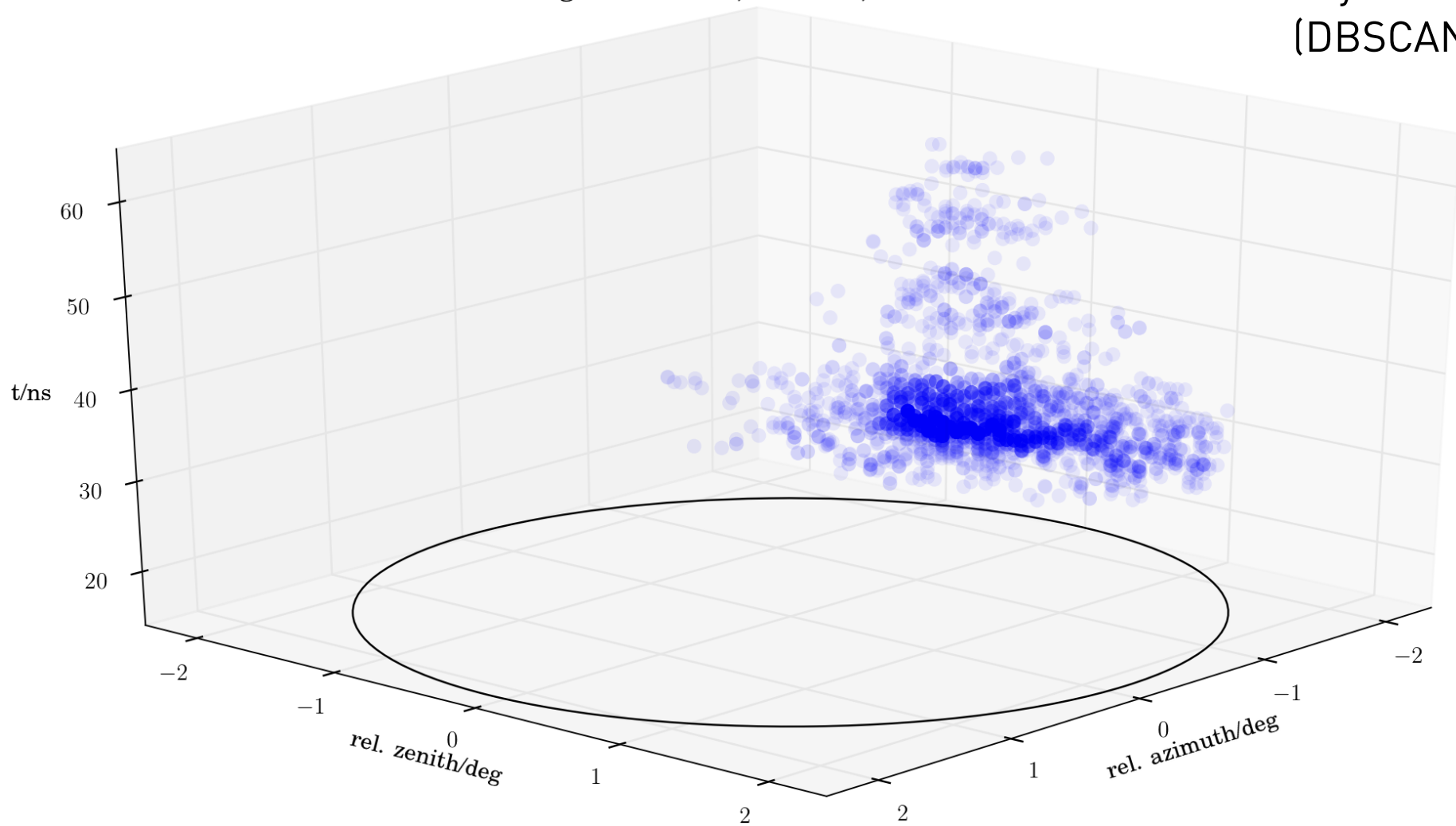
Night 20151113, Run 109, Event 159

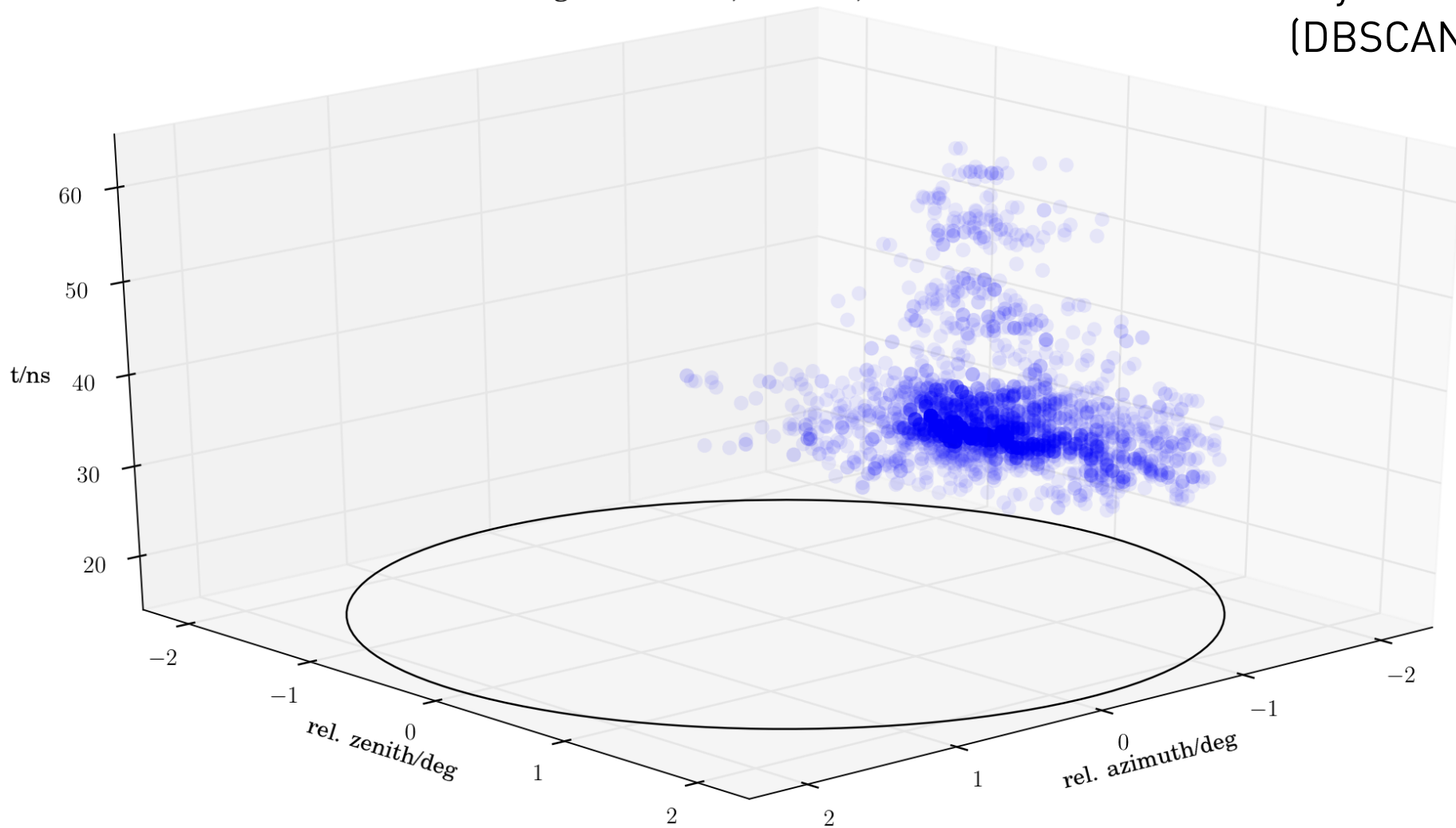


Night 20151113, Run 109, Event 159

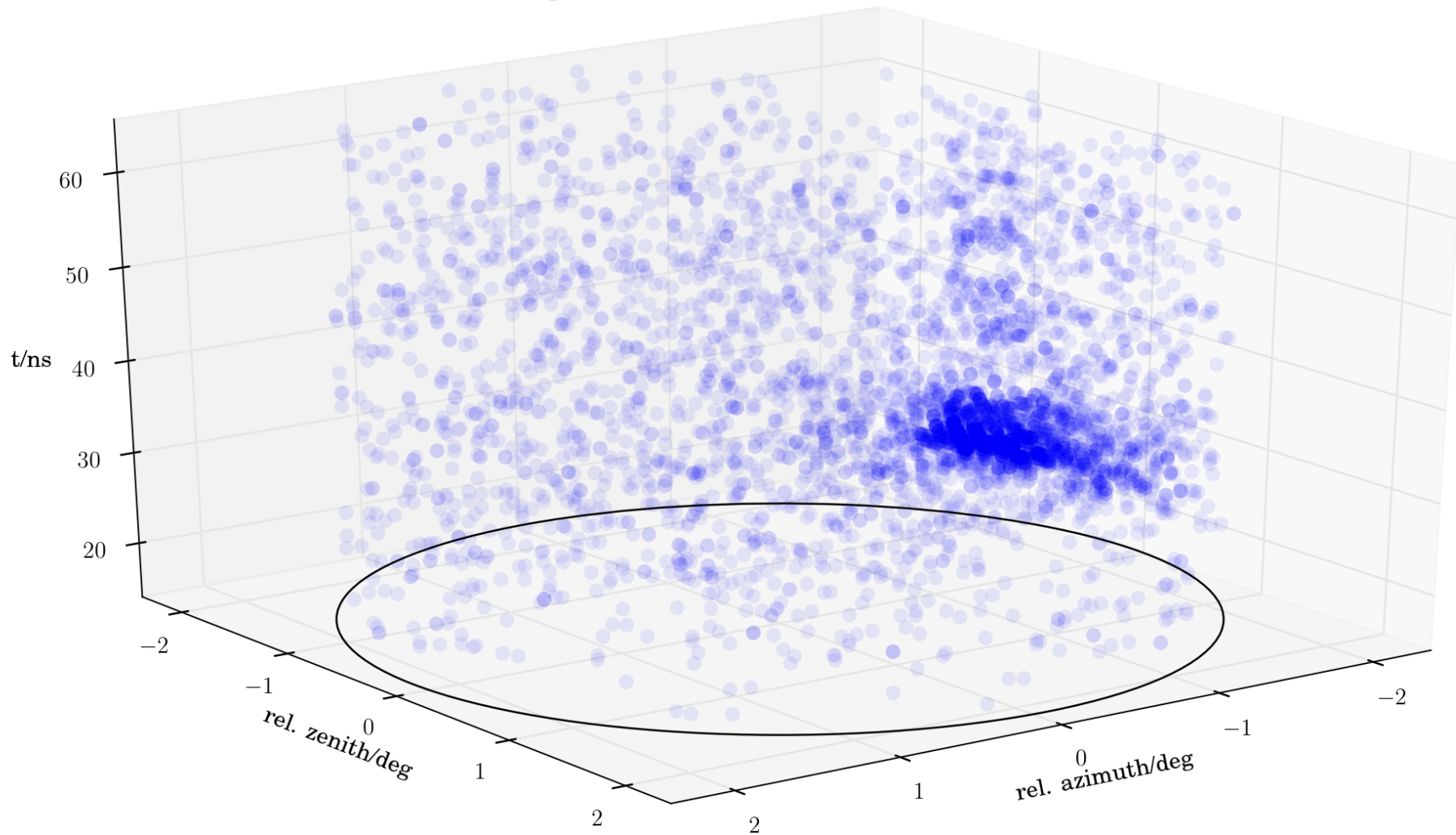




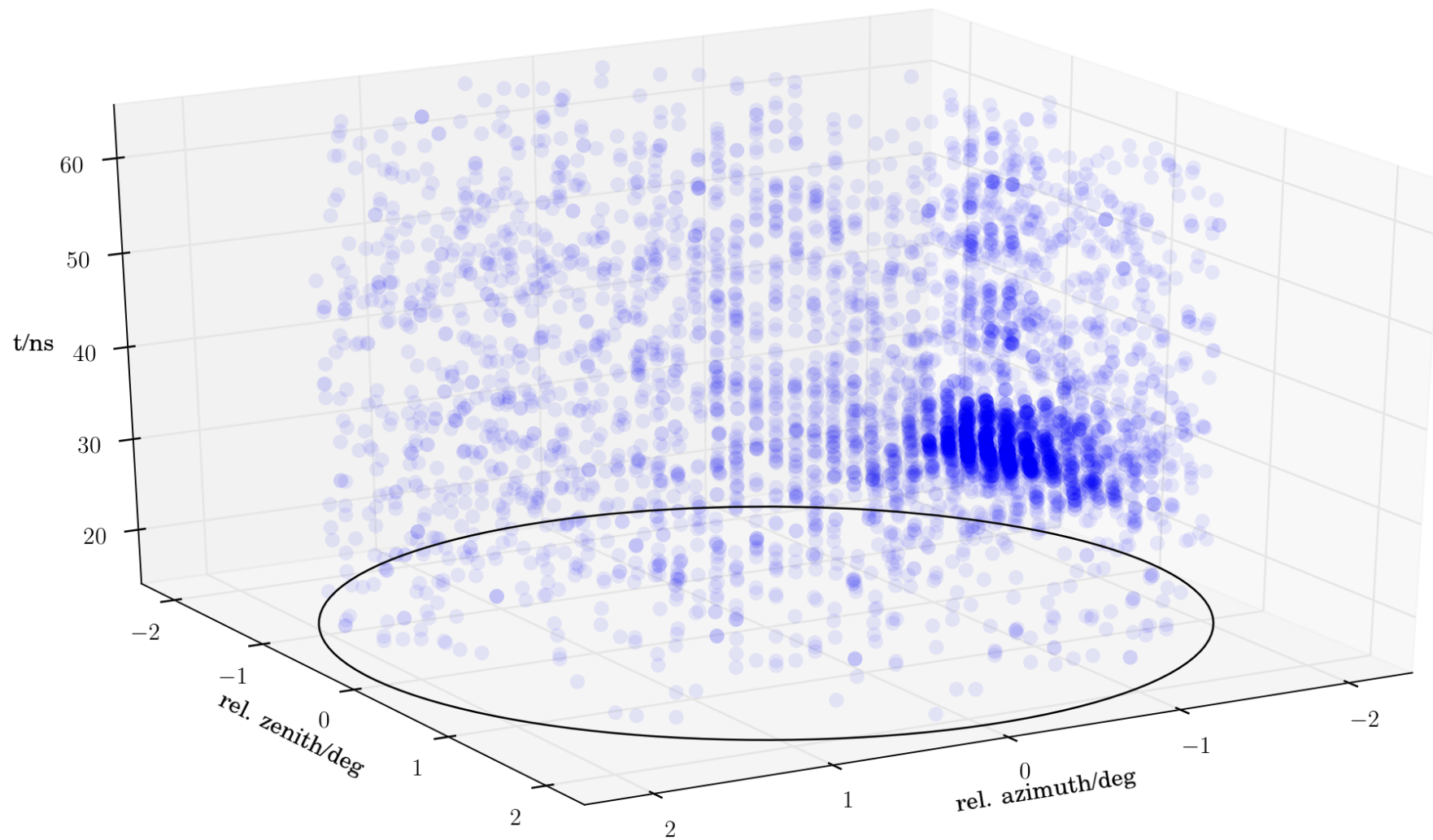




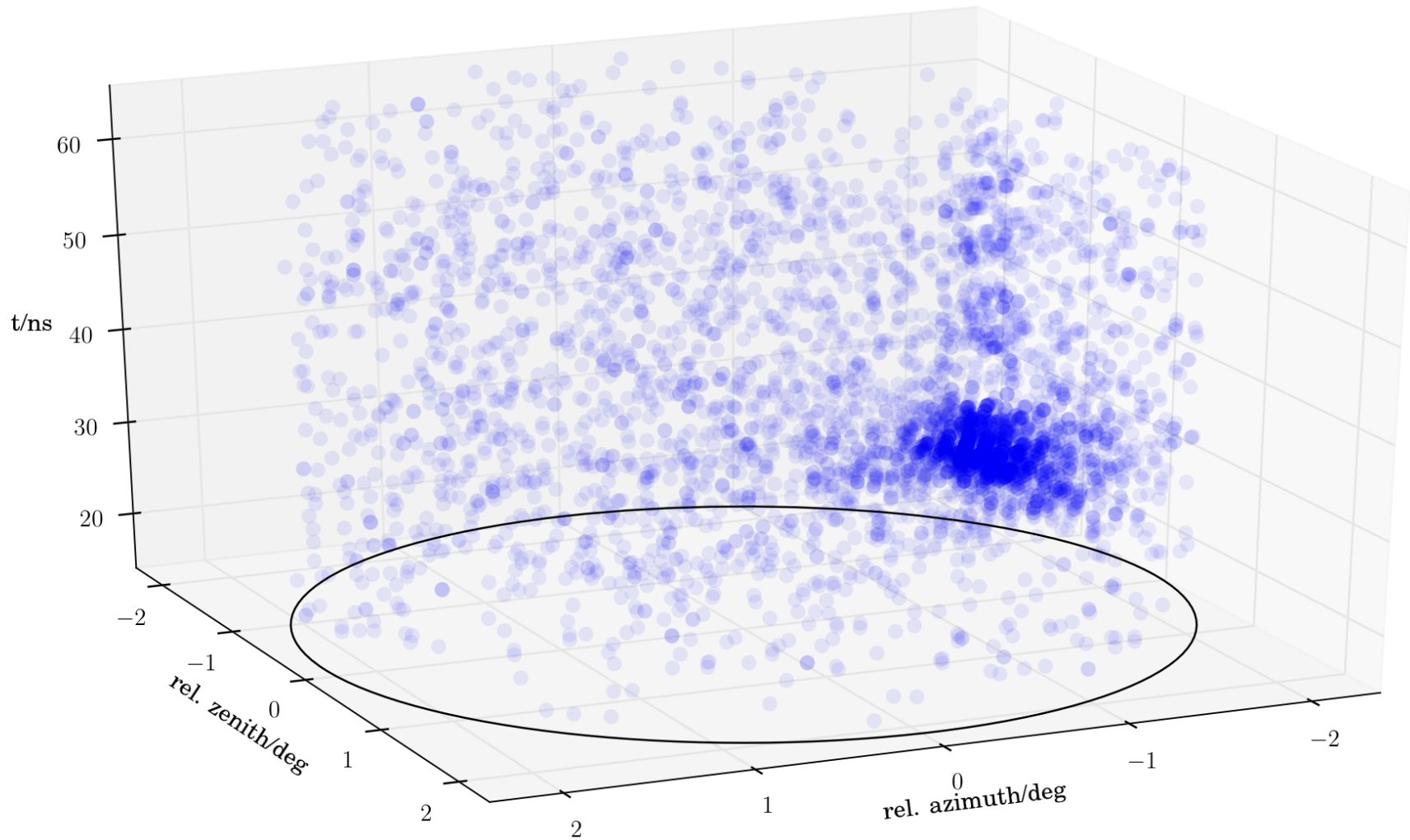
Night 20151113, Run 109, Event 159

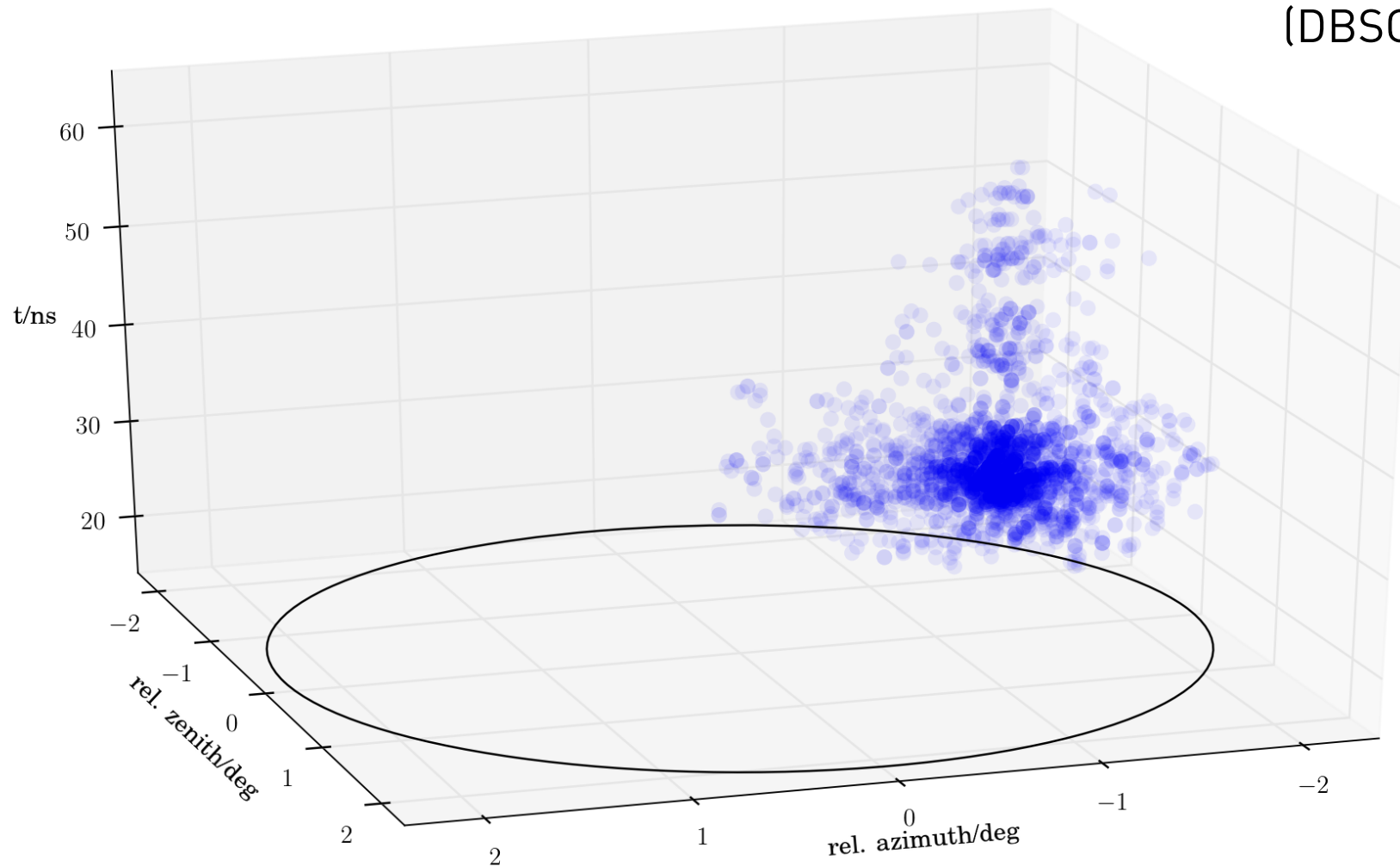


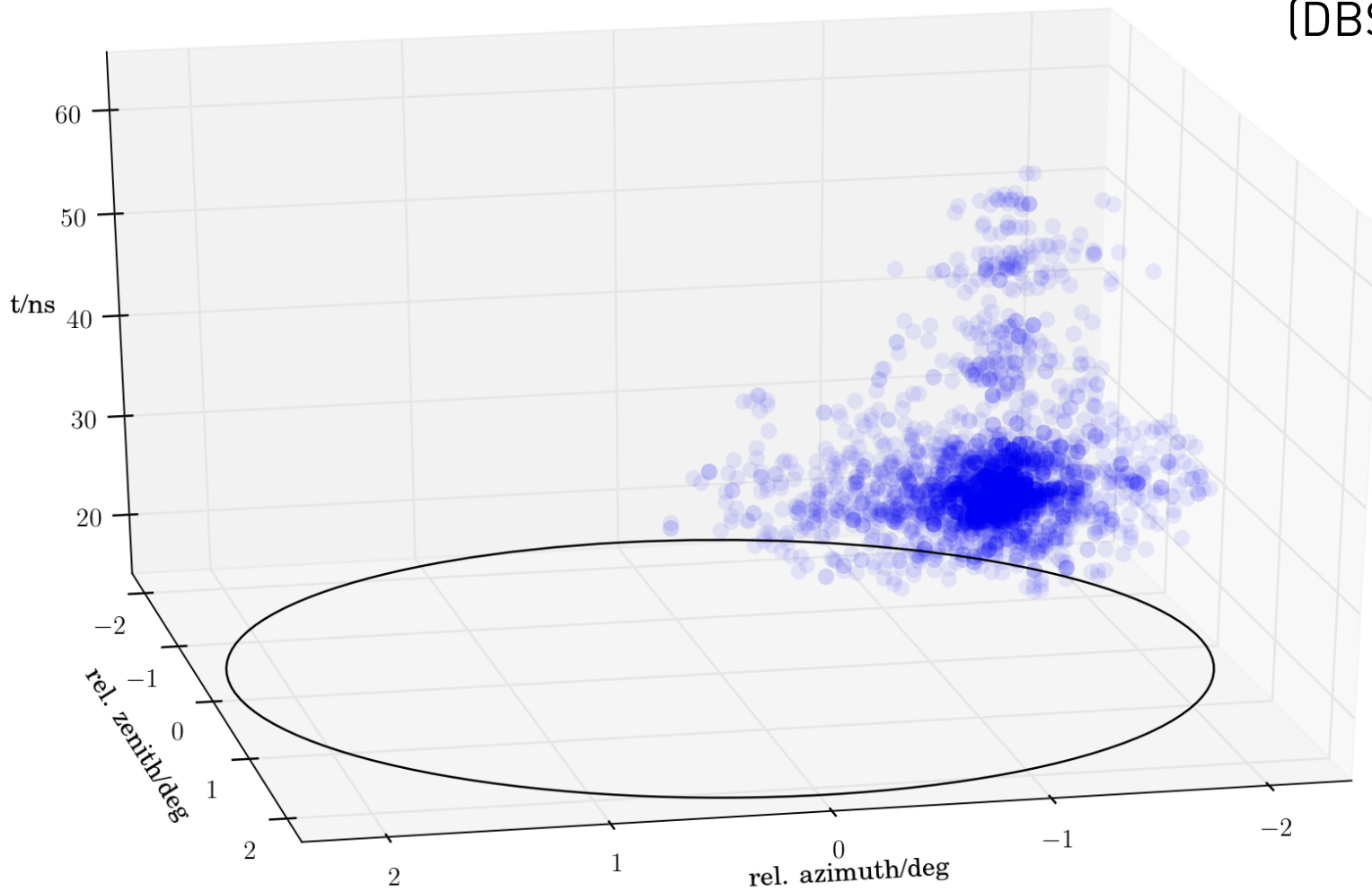
Night 20151113, Run 109, Event 159

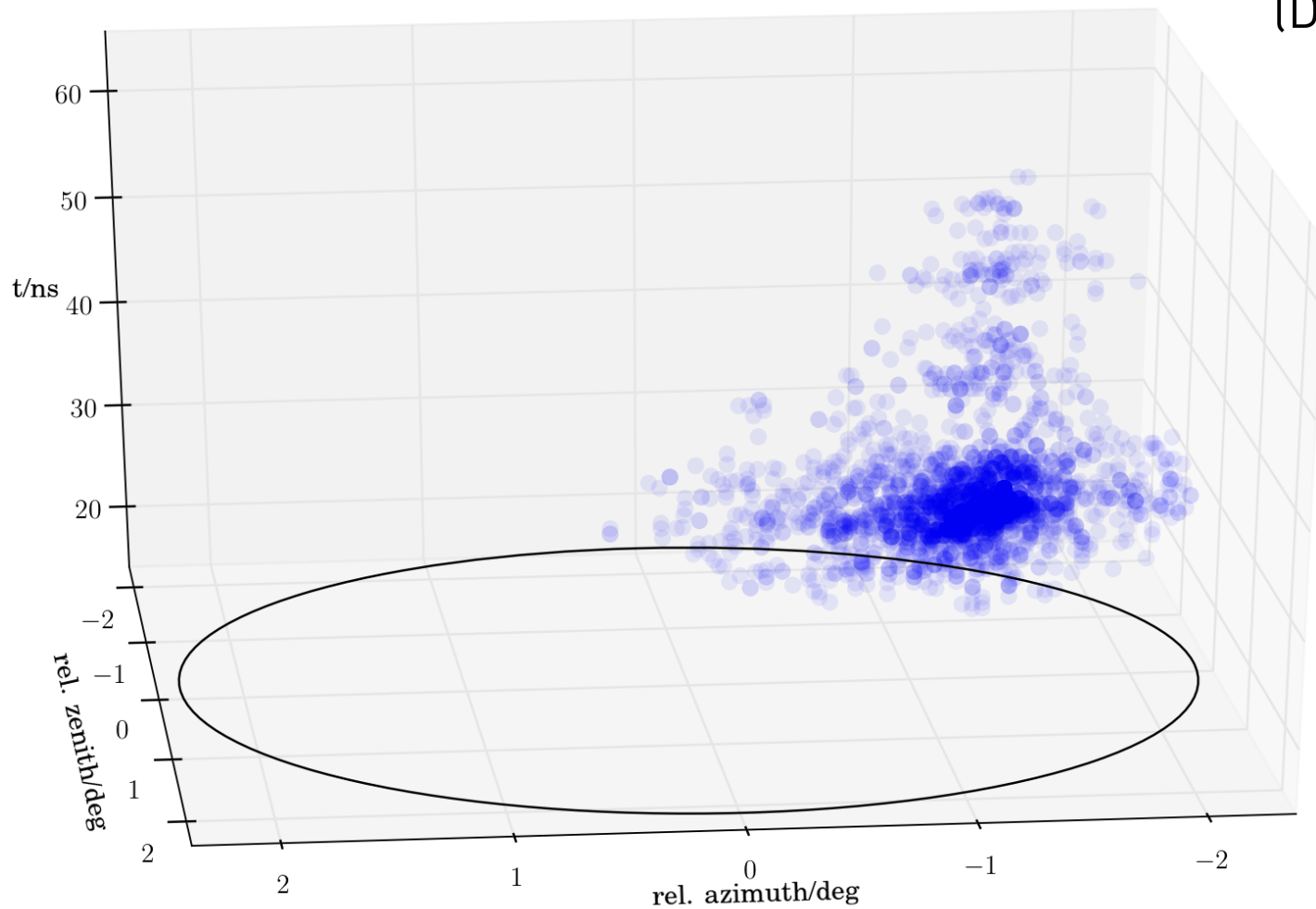


Night 20151113, Run 109, Event 159

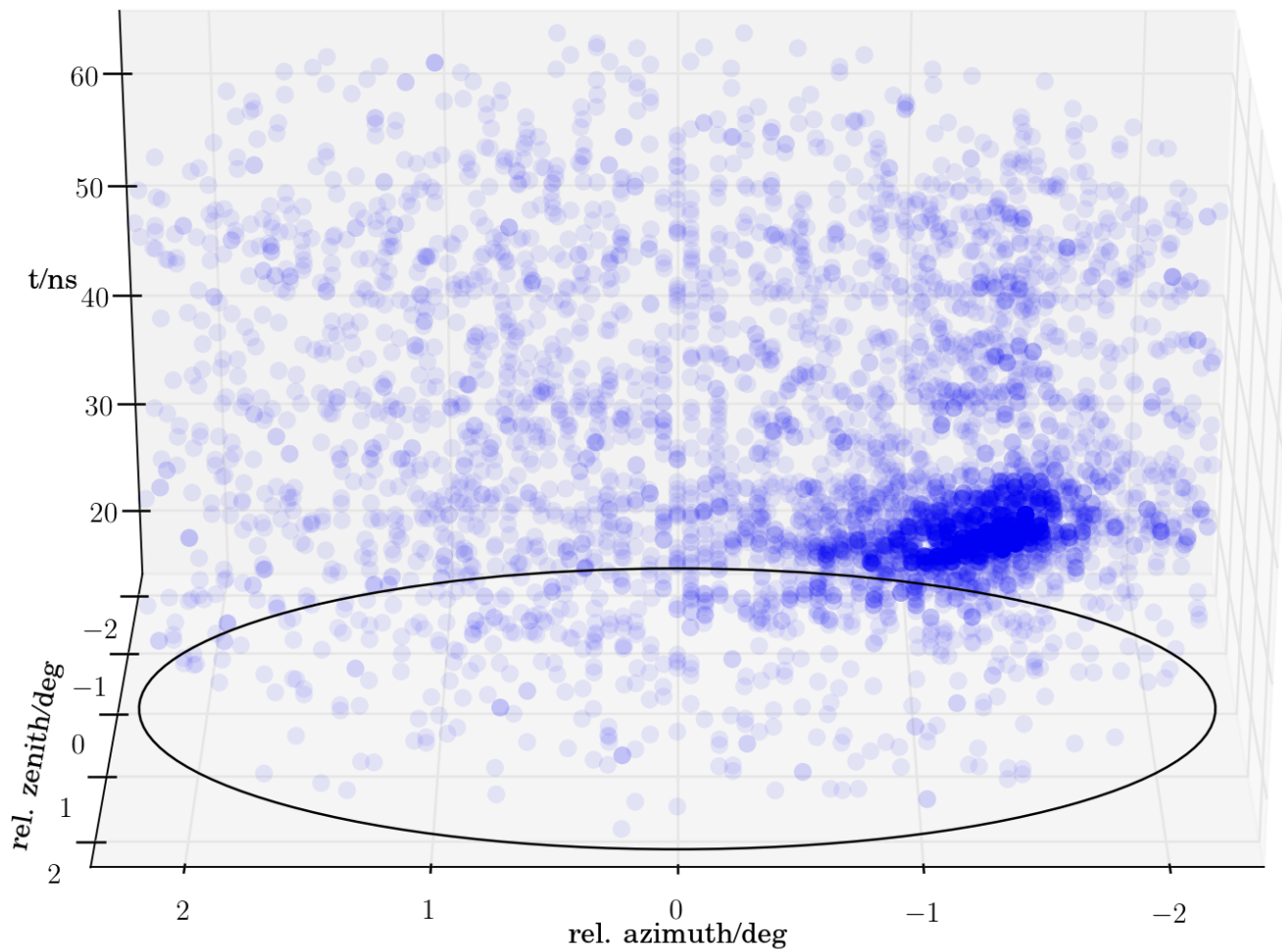




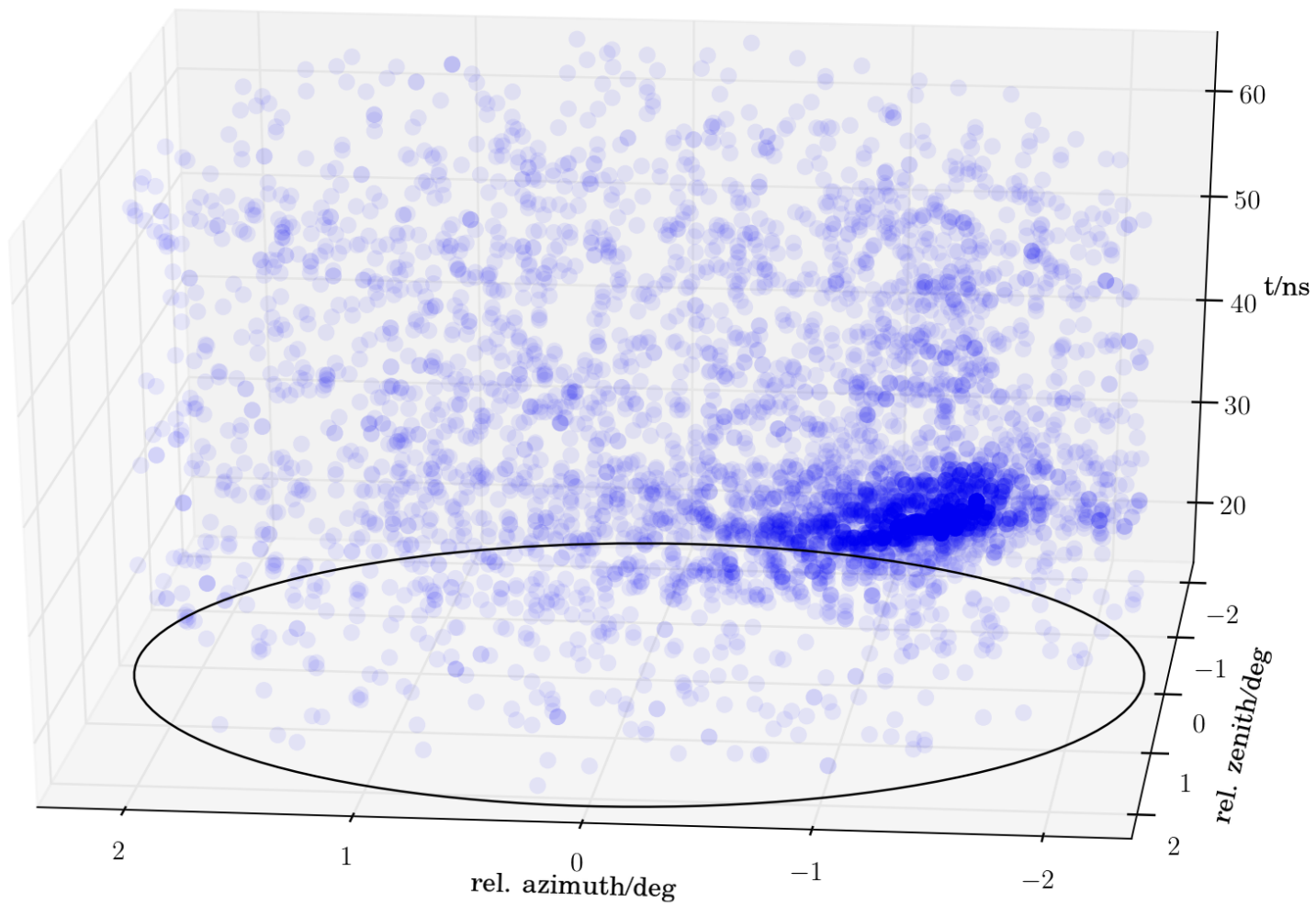




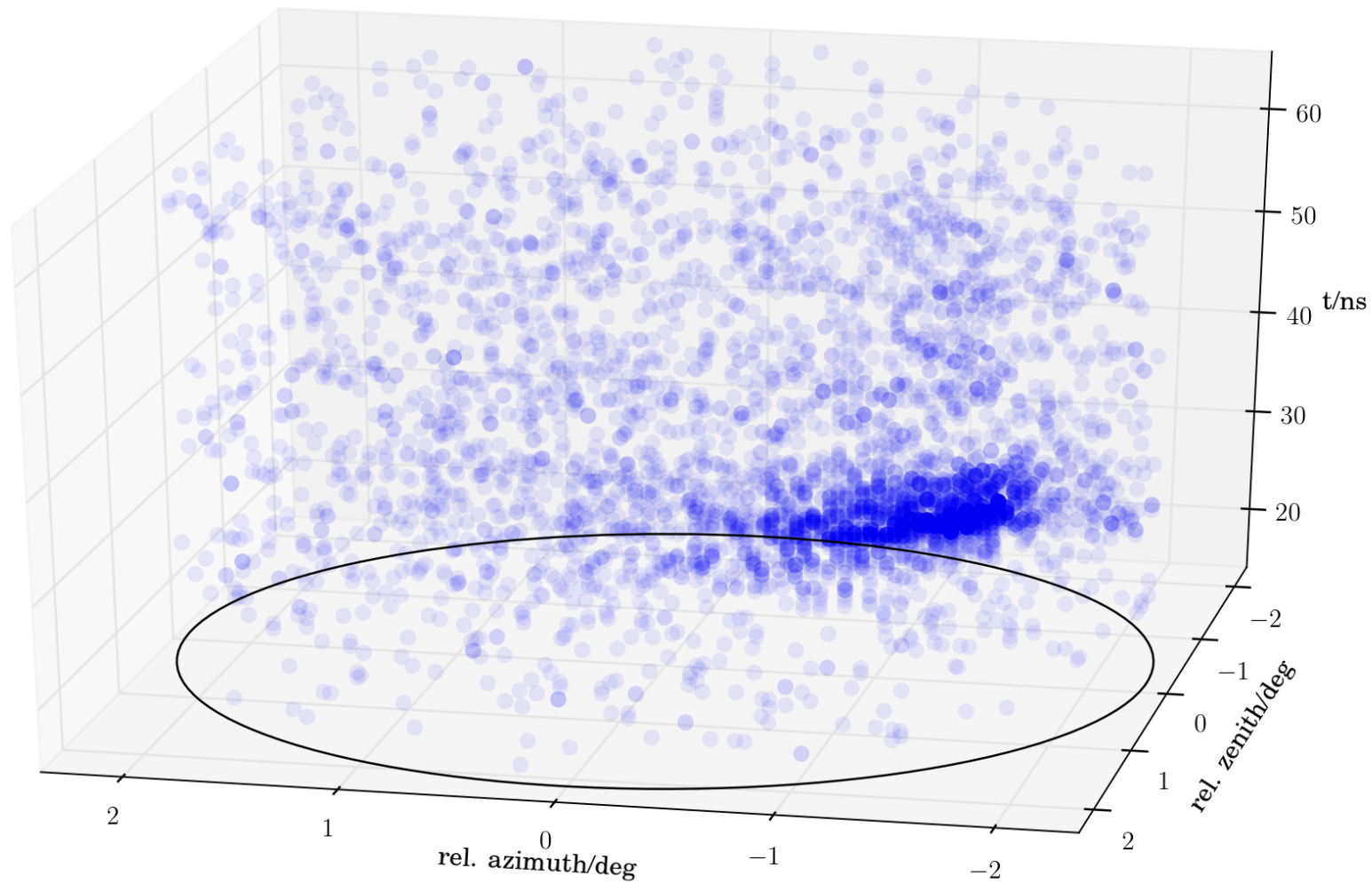
Night 20151113, Run 109, Event 159

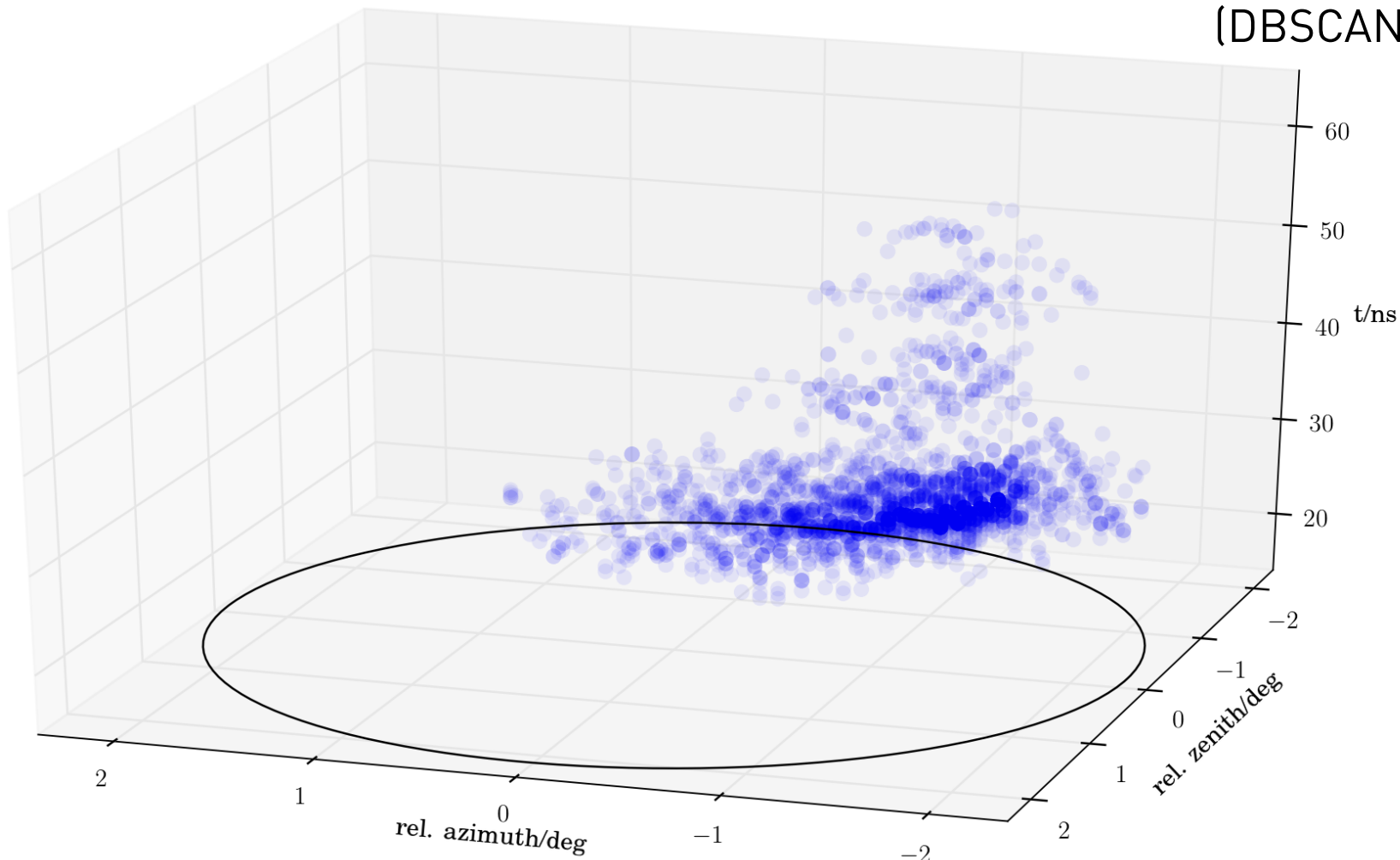


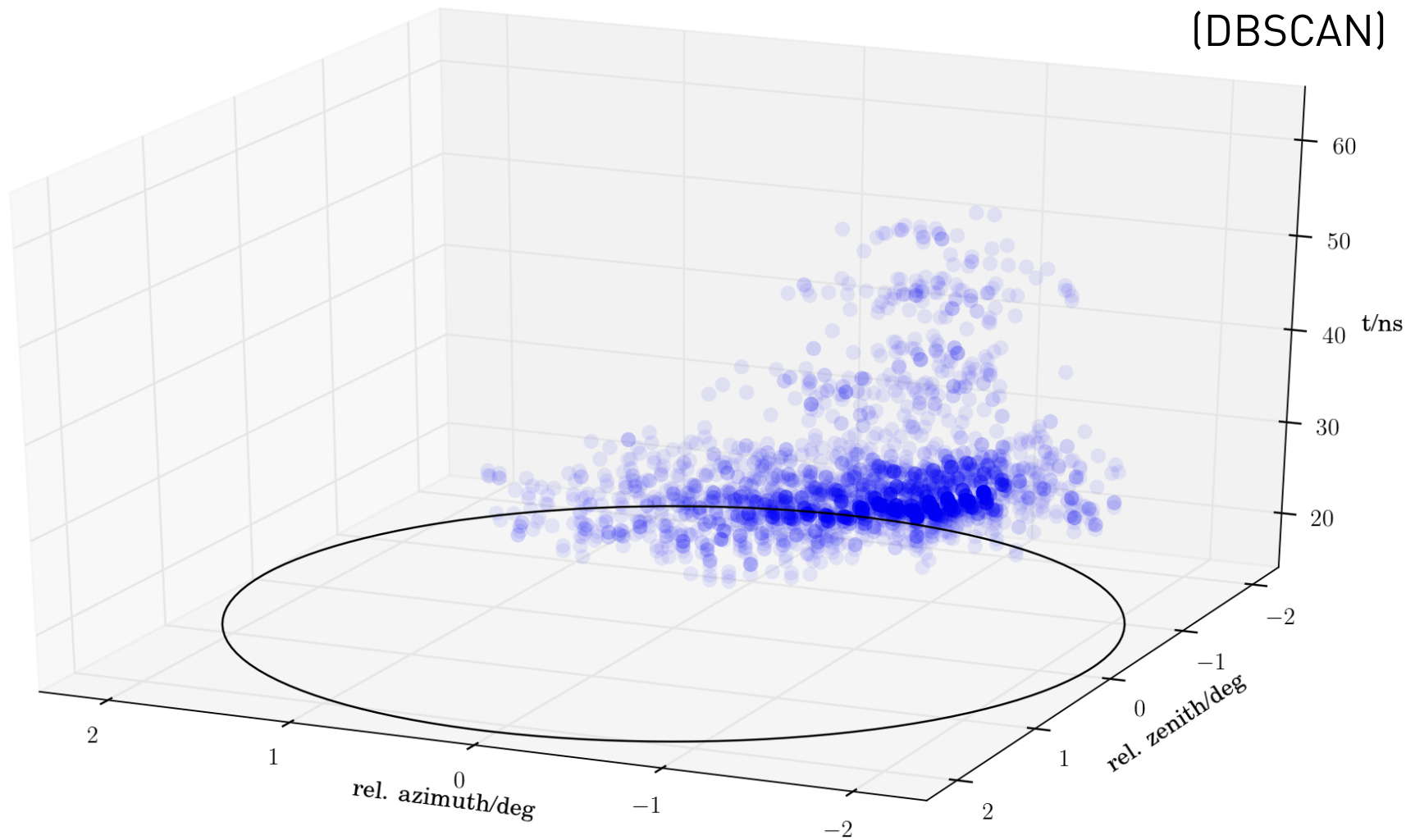
Night 20151113, Run 109, Event 159

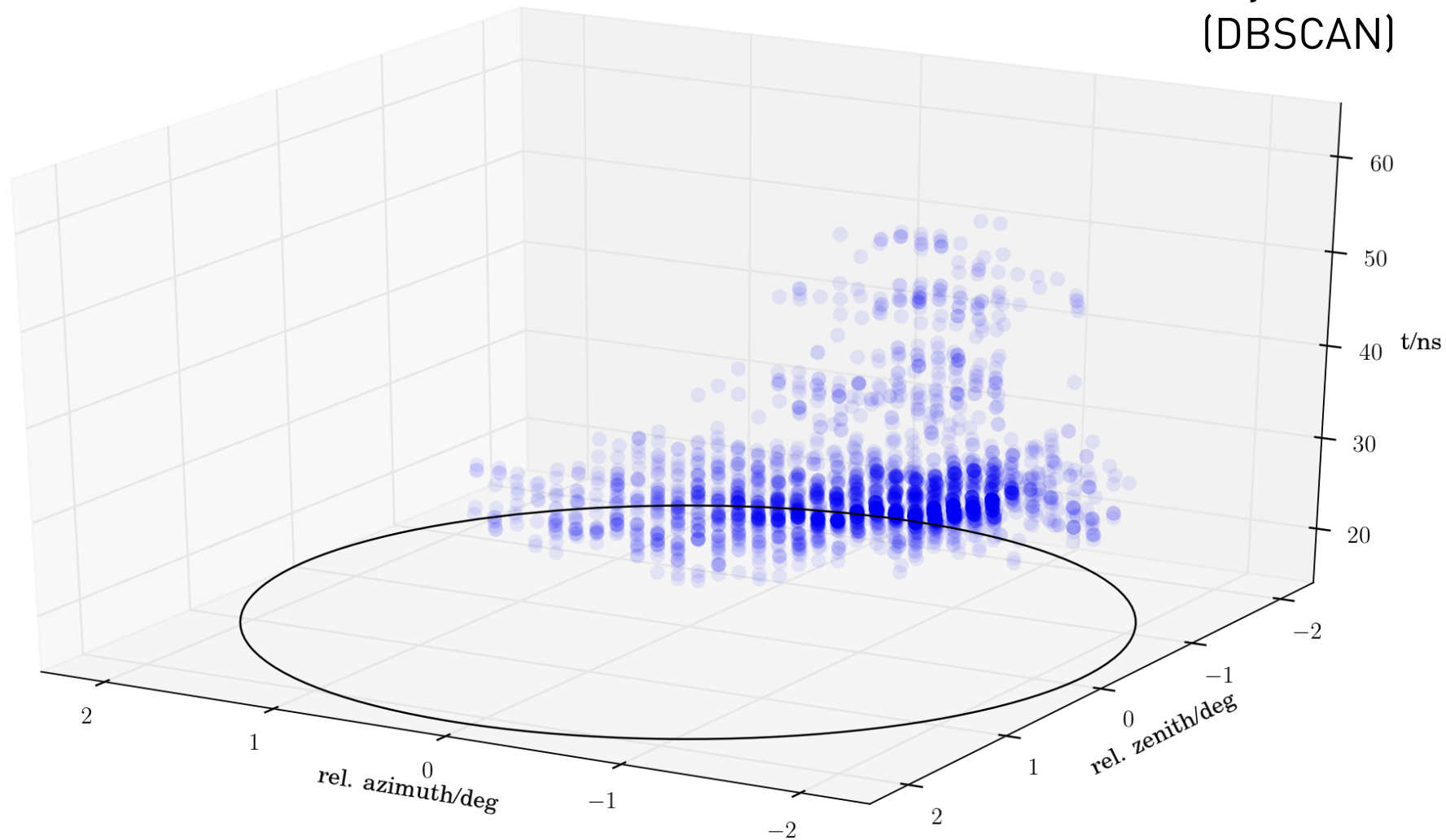


Night 20151113, Run 109, Event 159

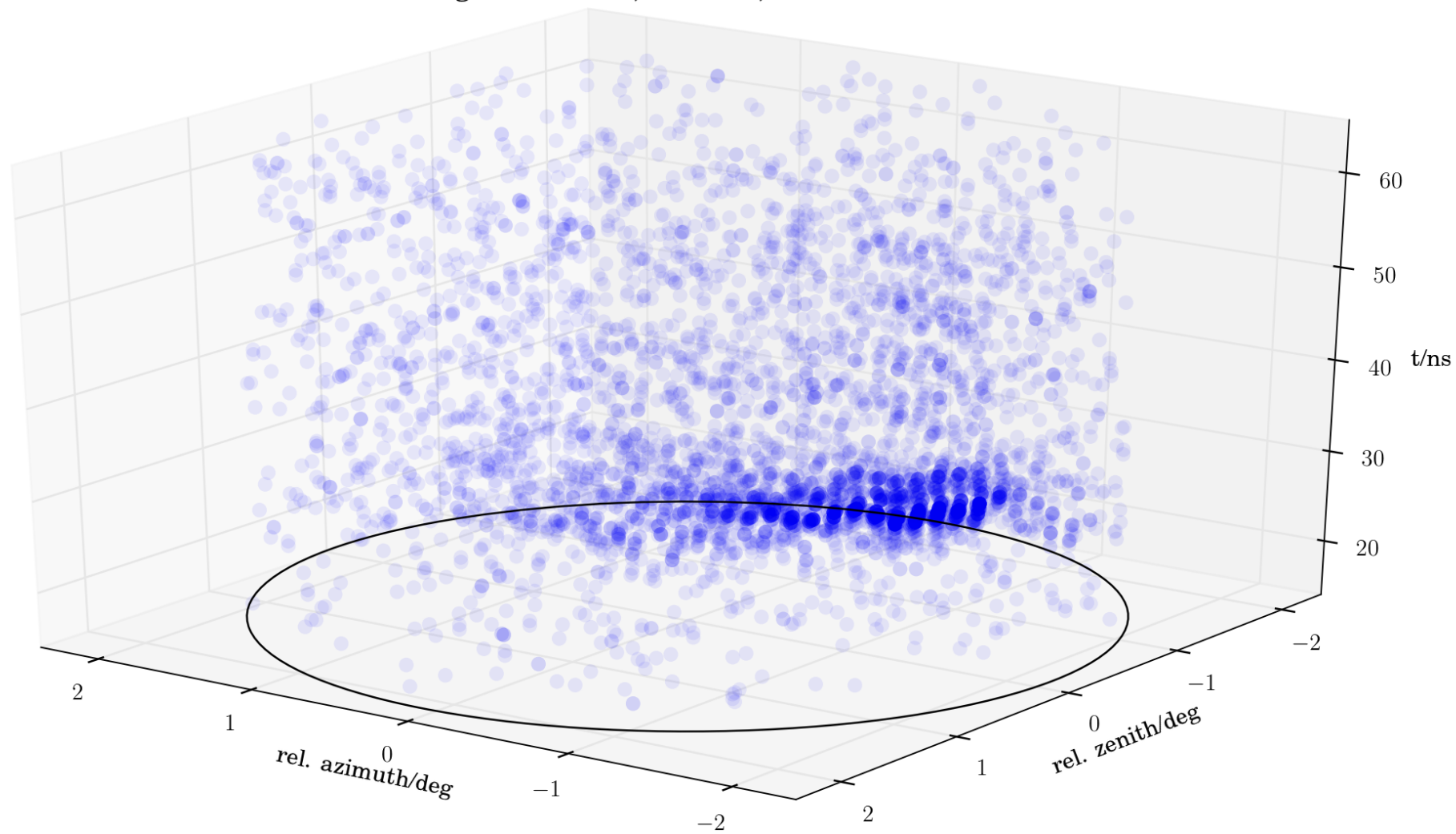




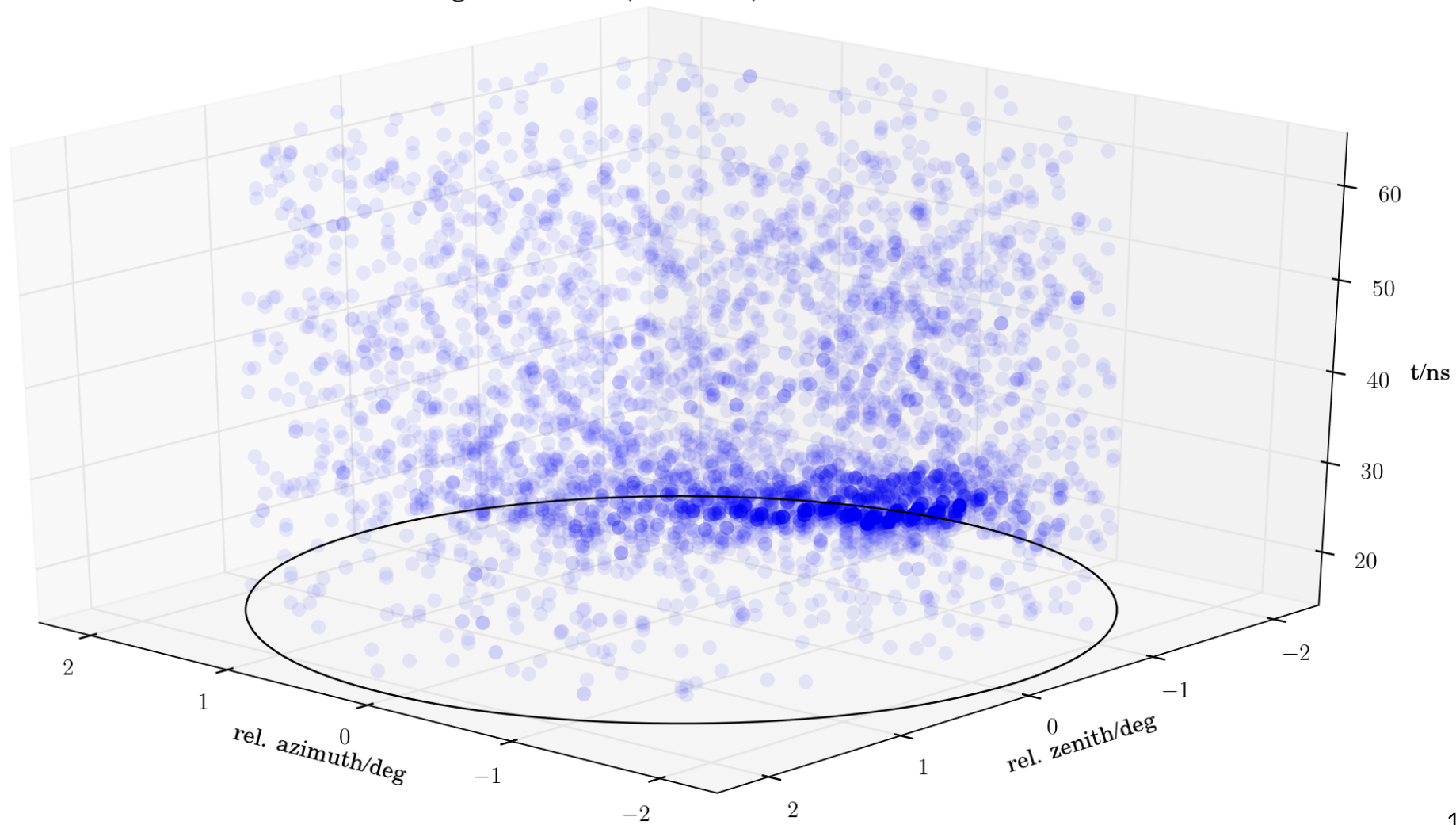




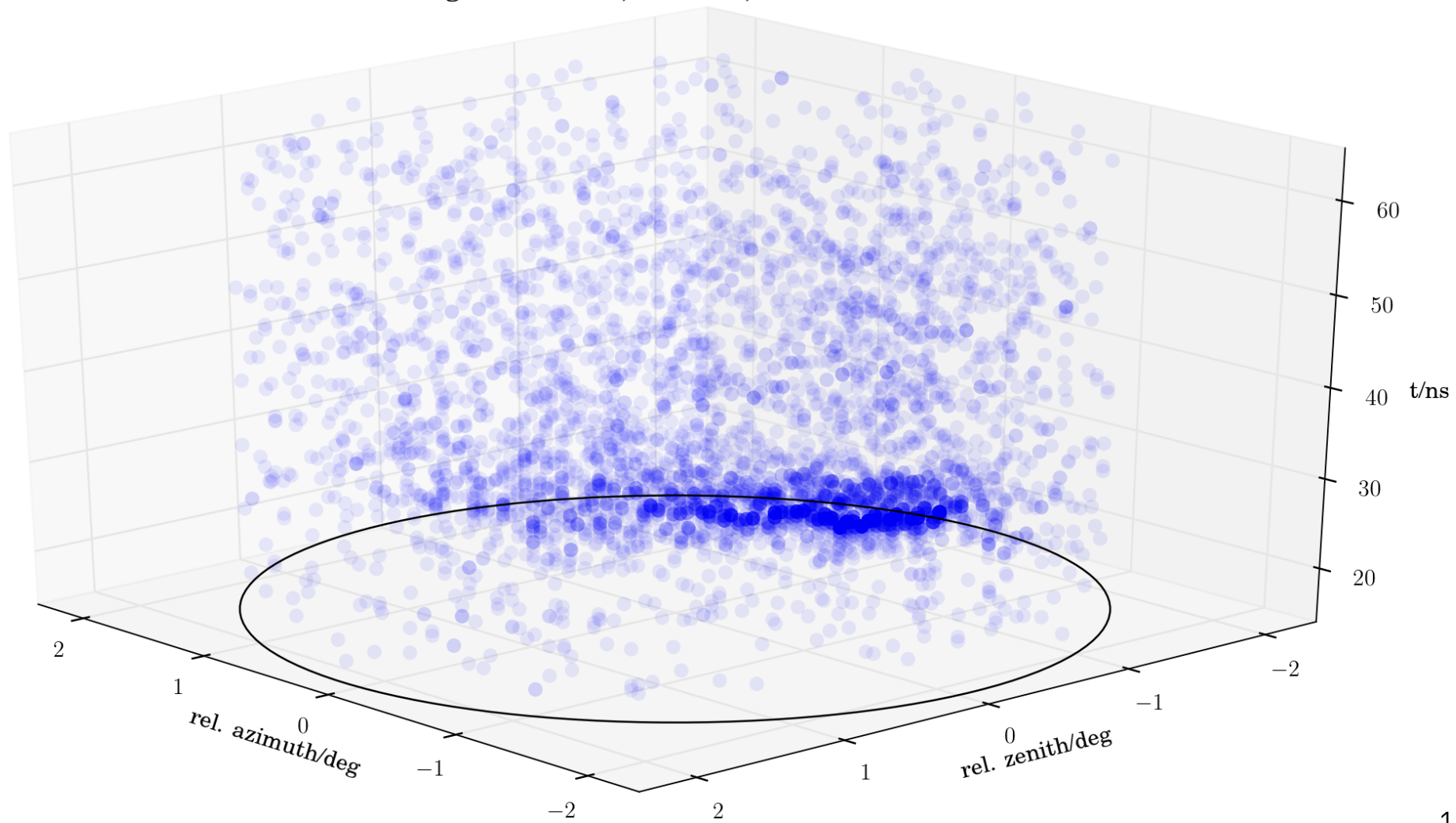
Night 20151113, Run 109, Event 159

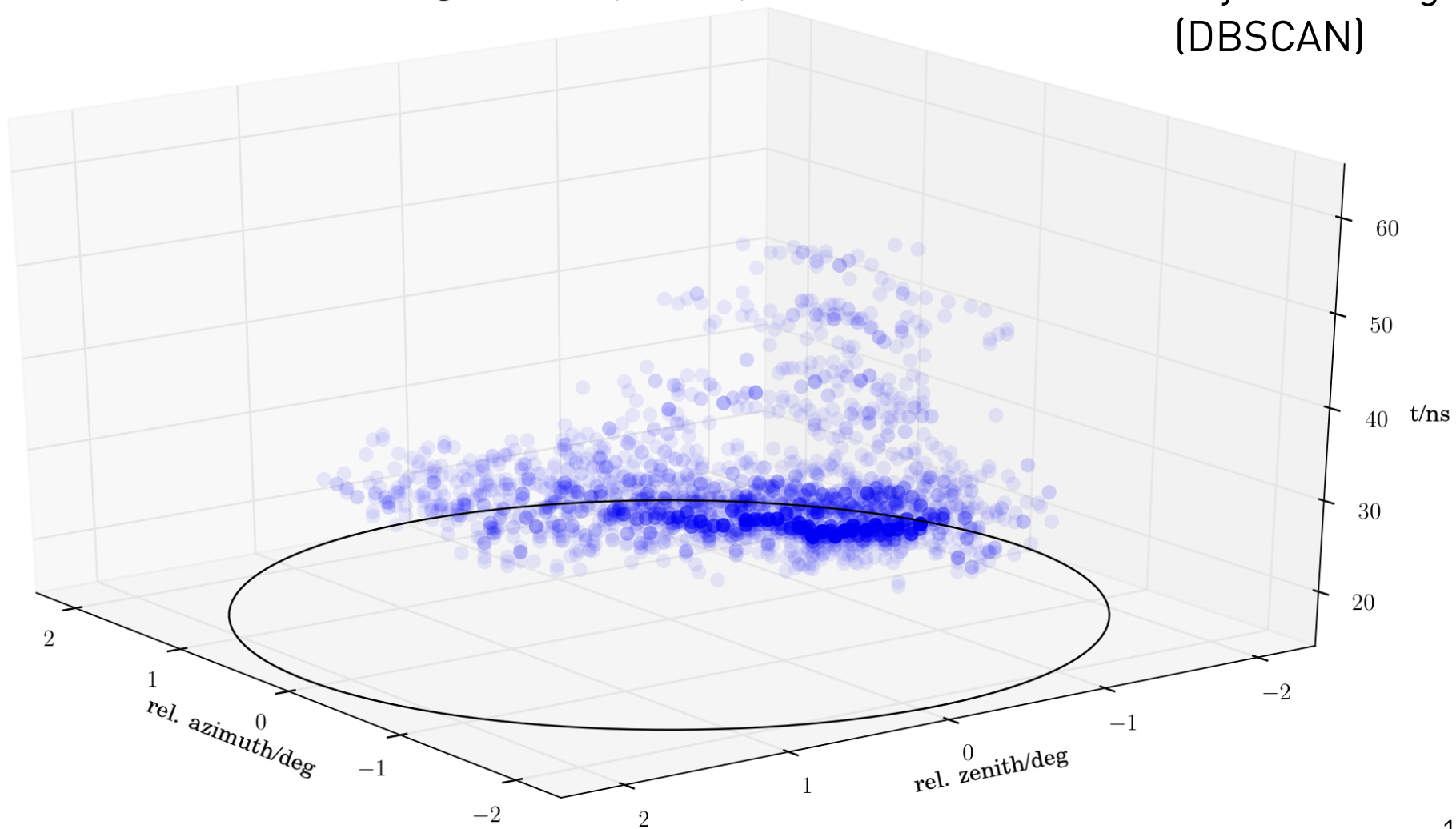


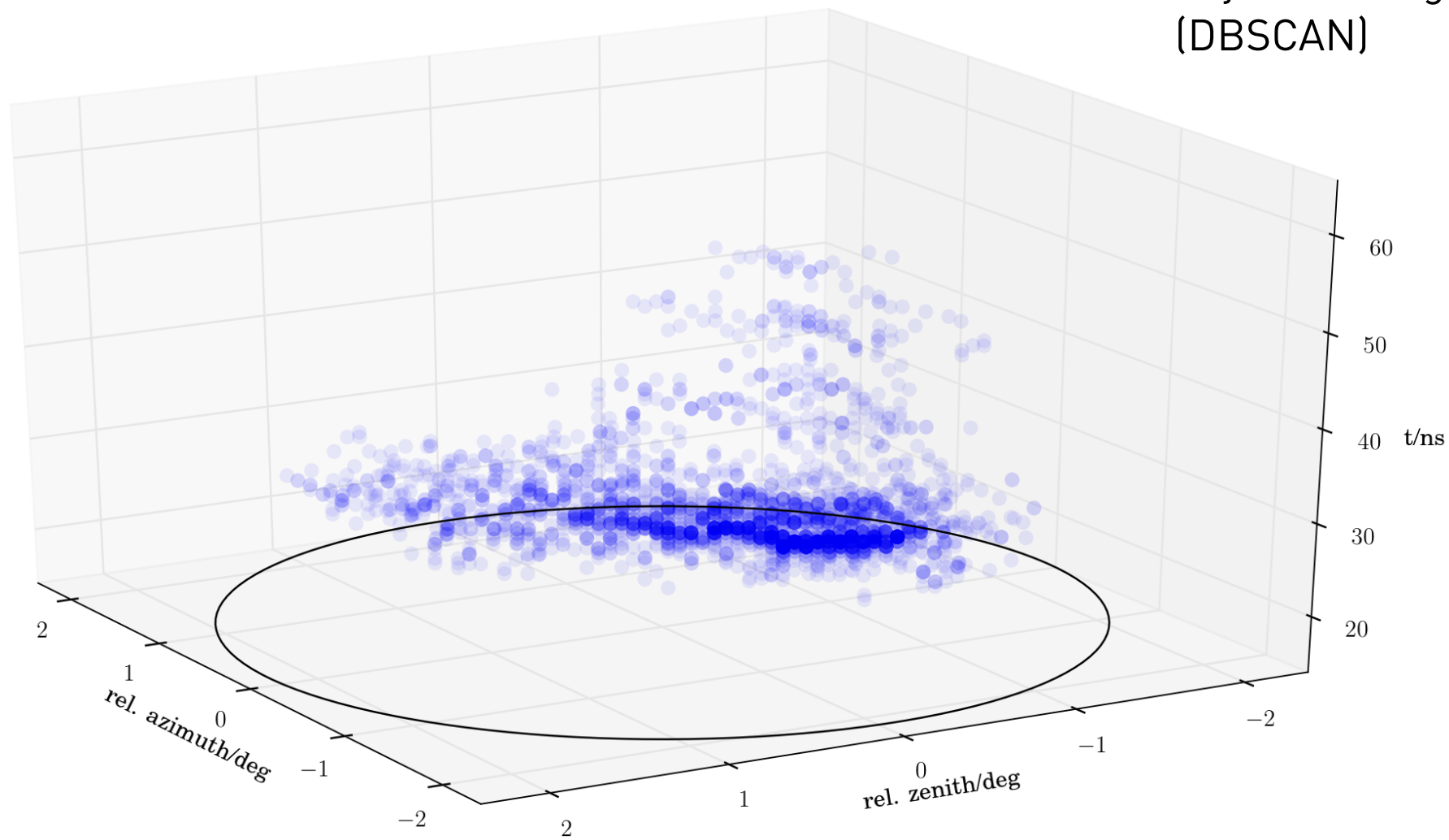
Night 20151113, Run 109, Event 159

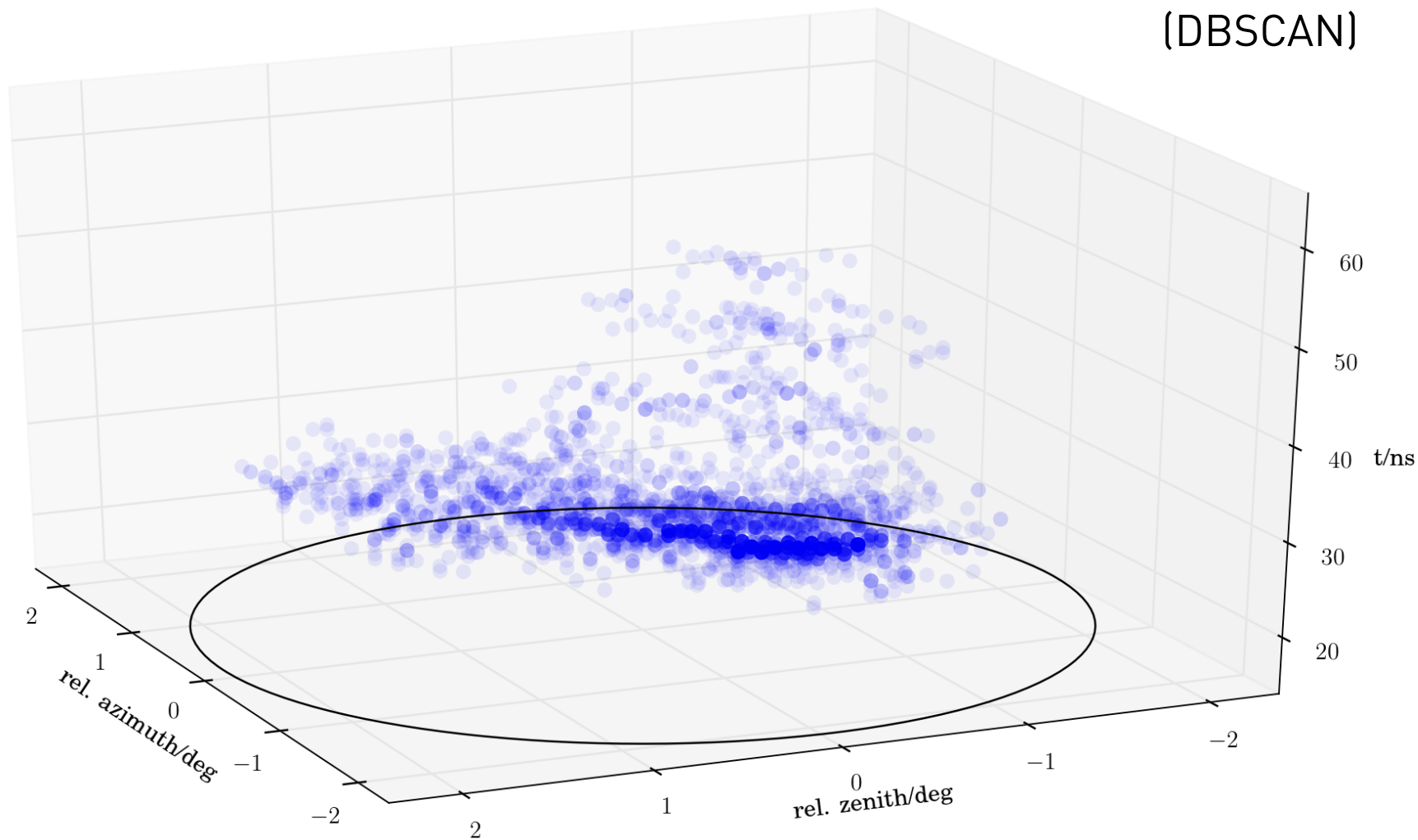


Night 20151113, Run 109, Event 159

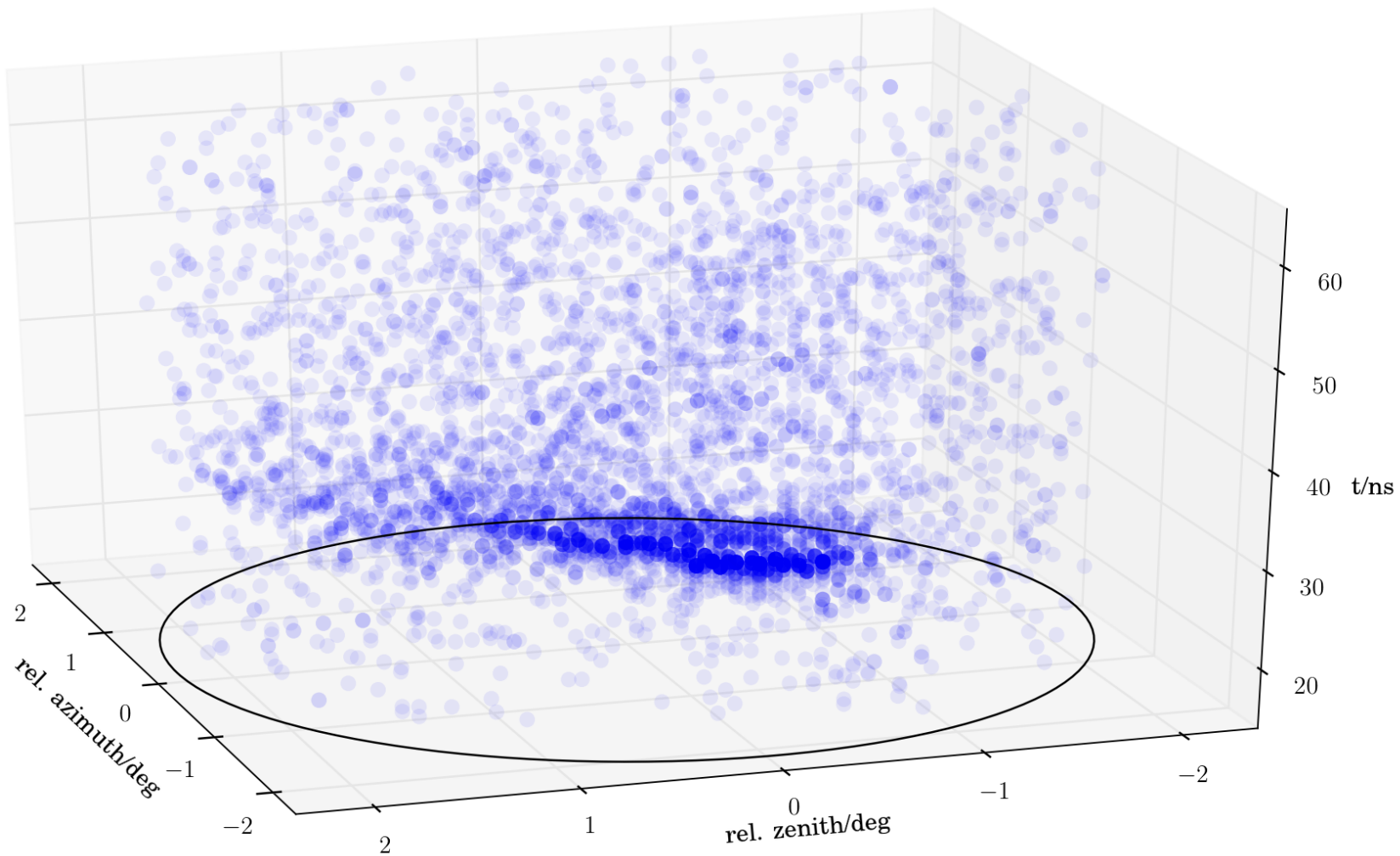




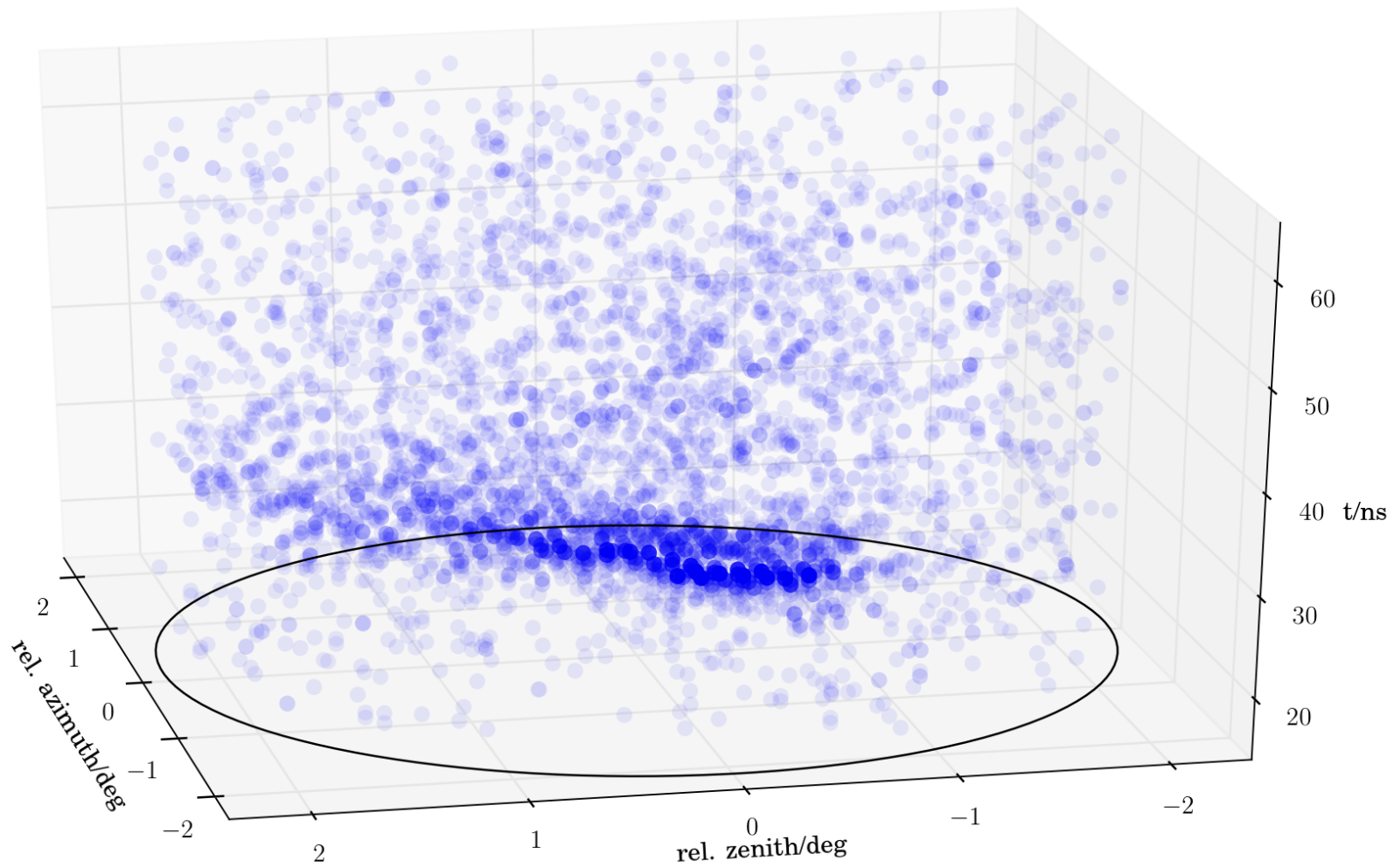




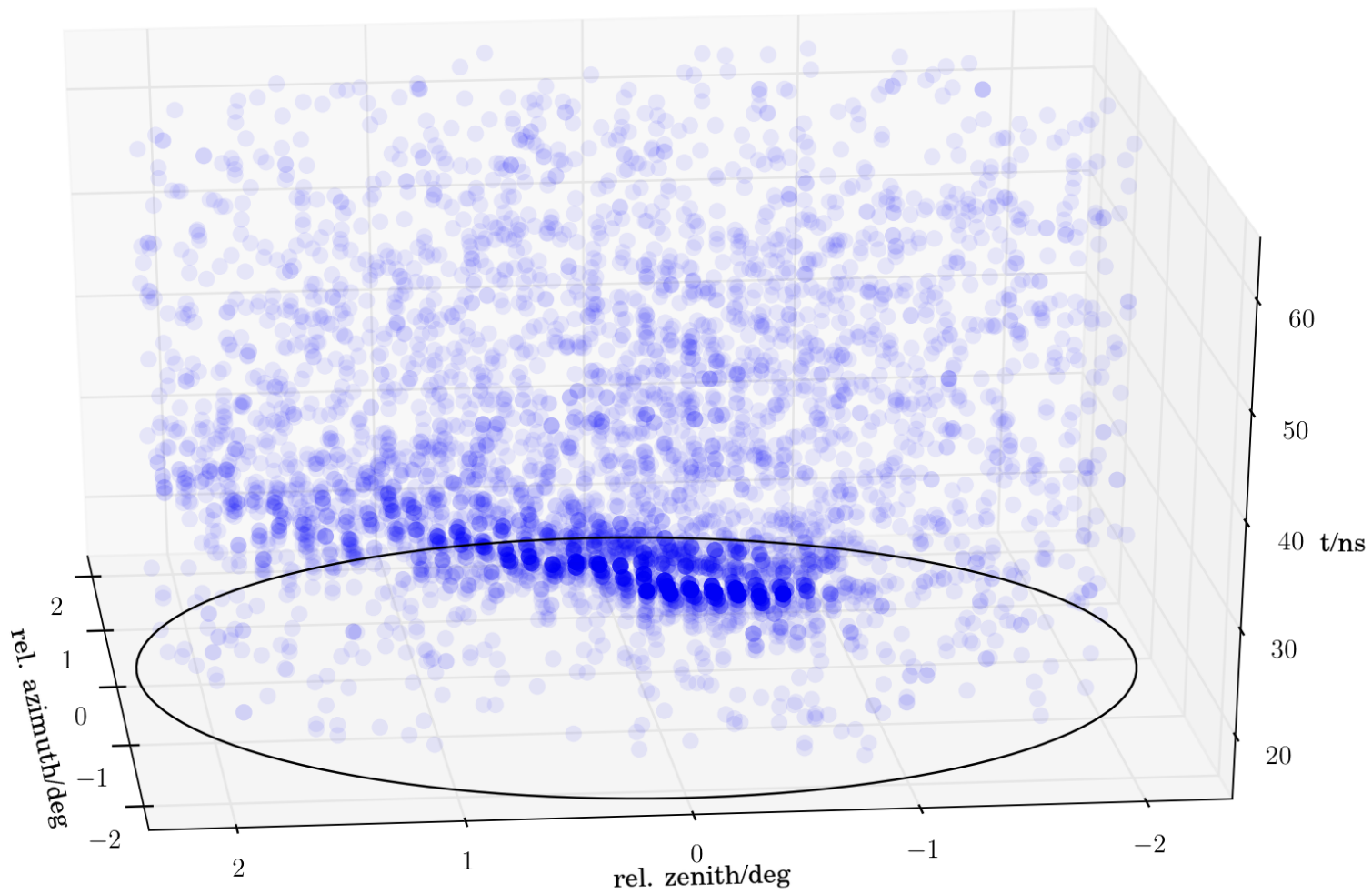
Night 20151113, Run 109, Event 159

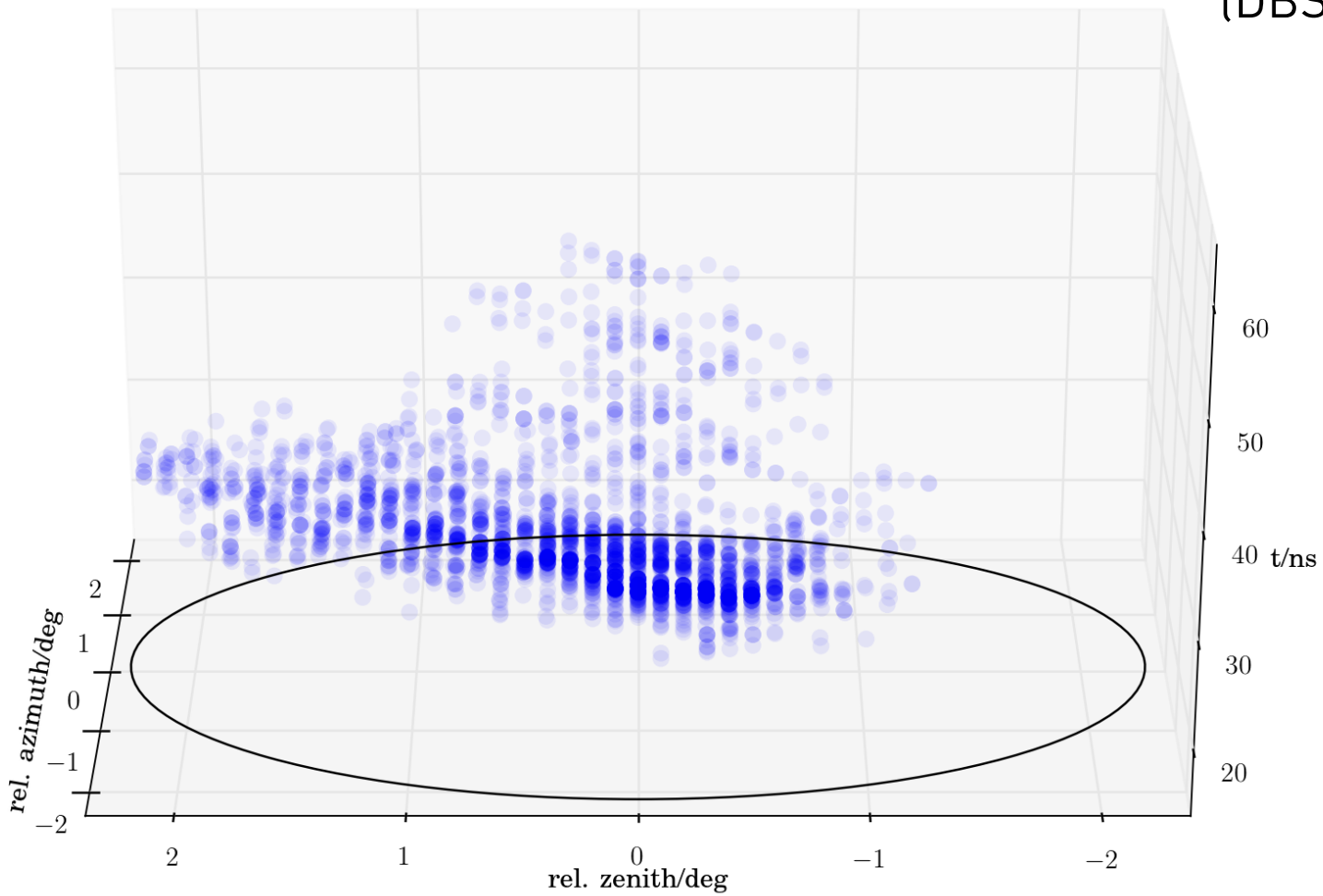


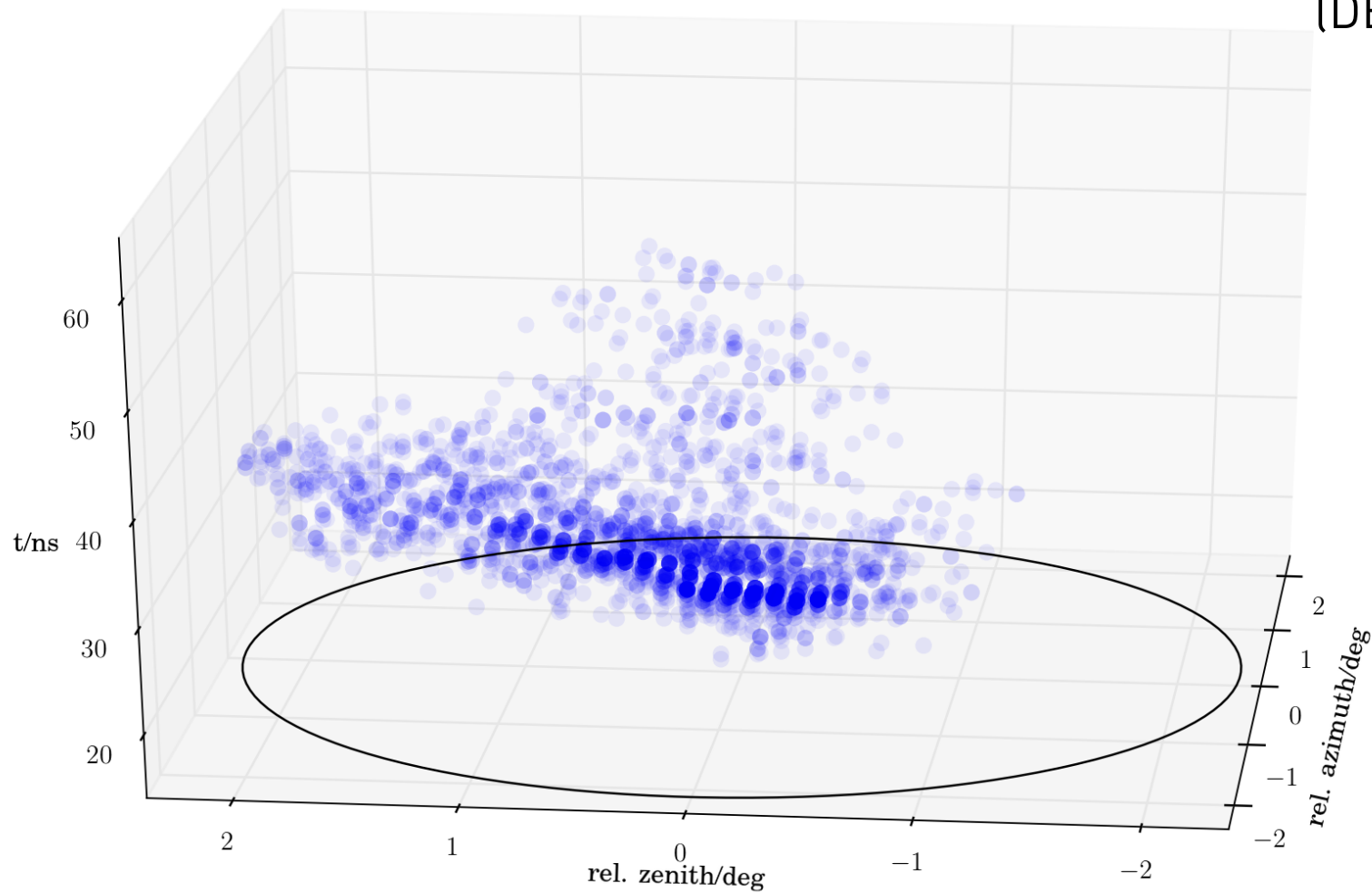
Night 20151113, Run 109, Event 159

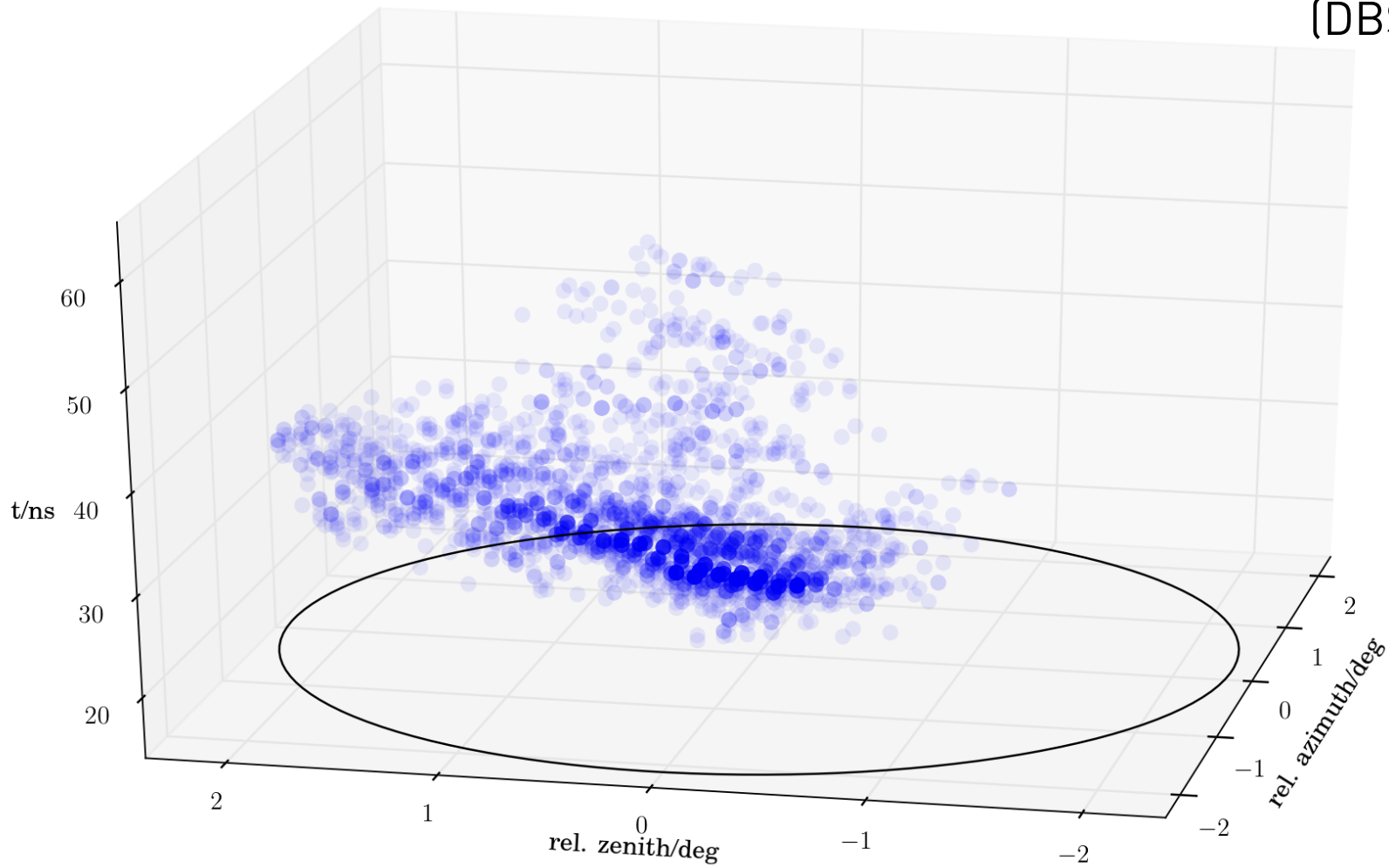


Night 20151113, Run 109, Event 159

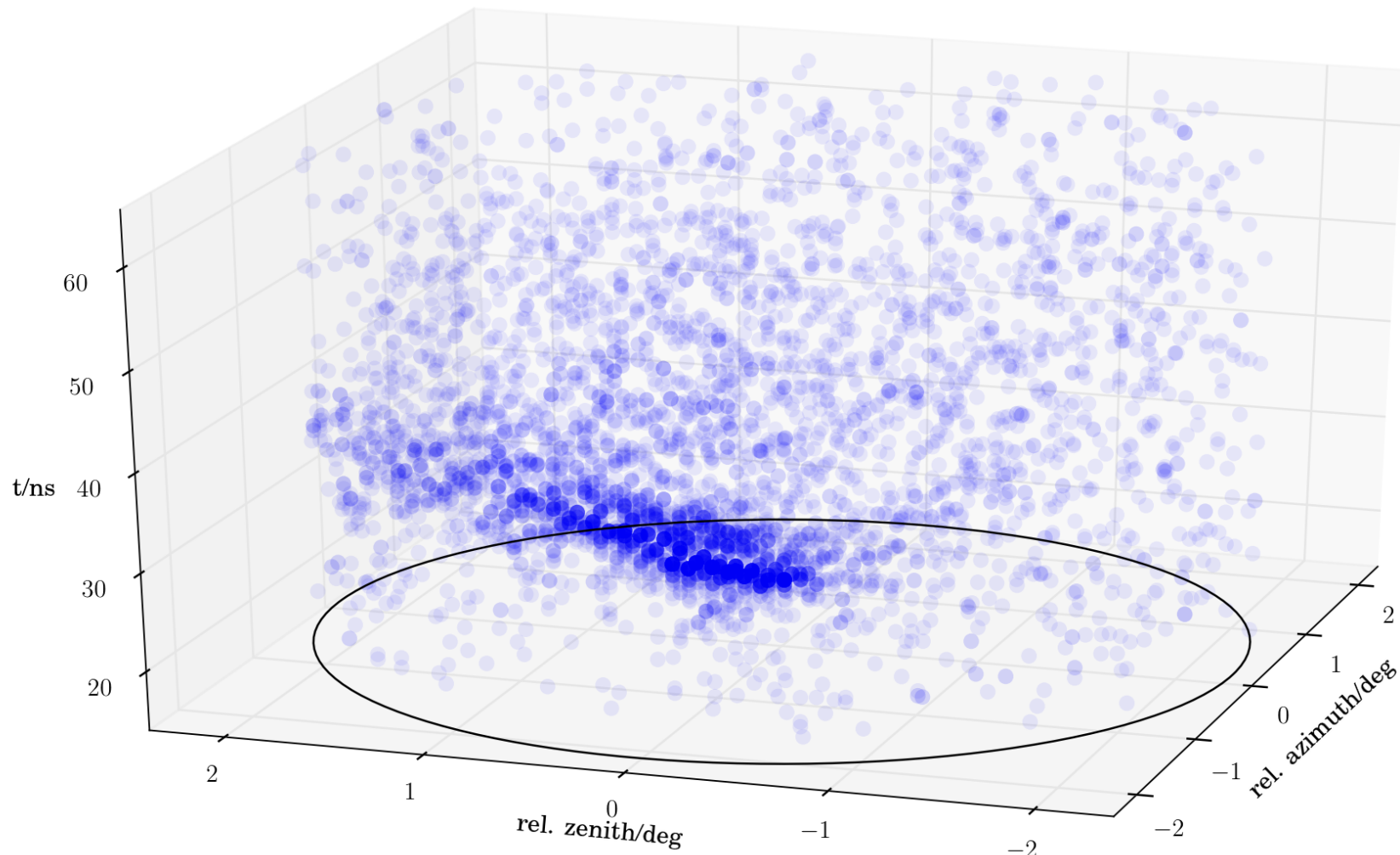




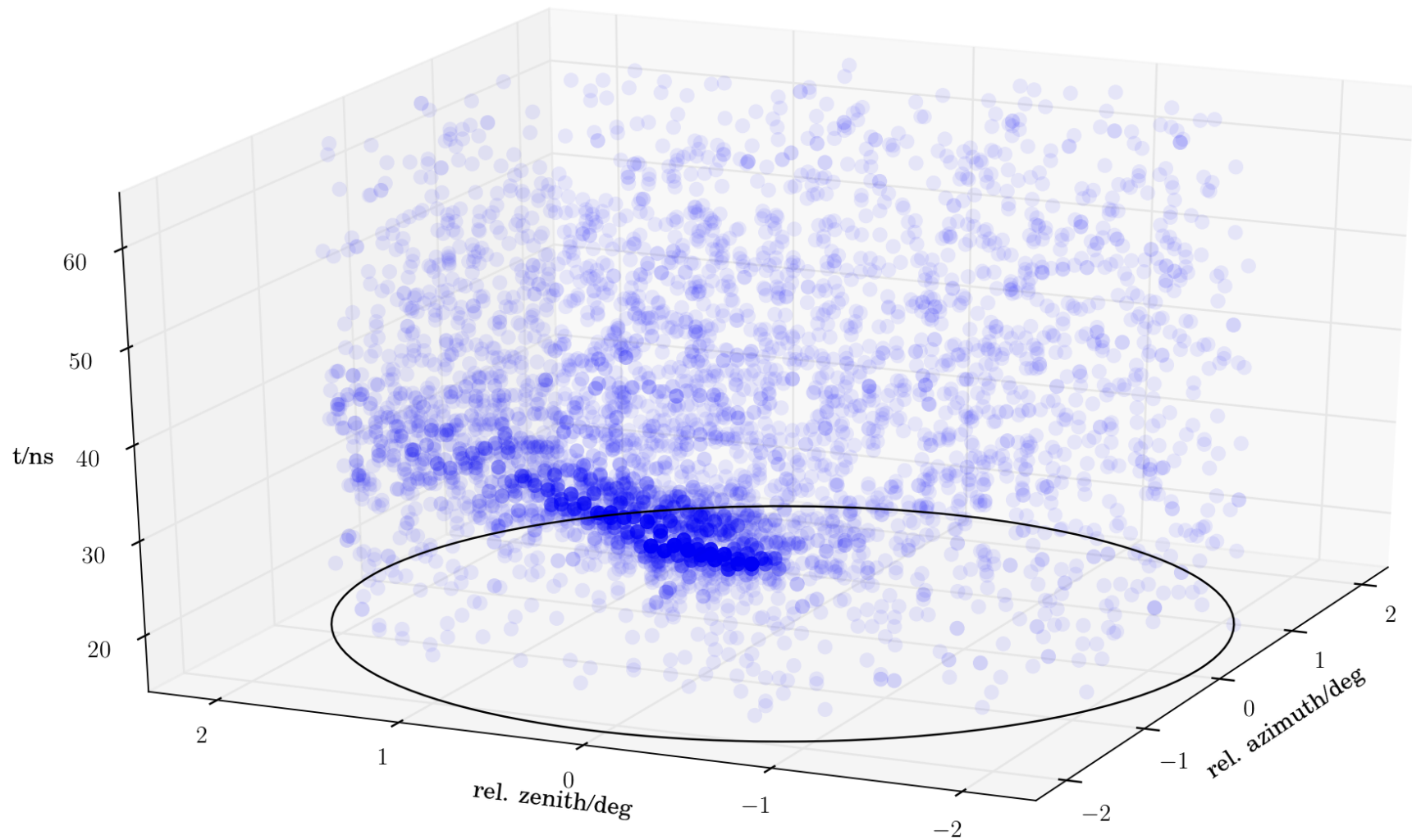




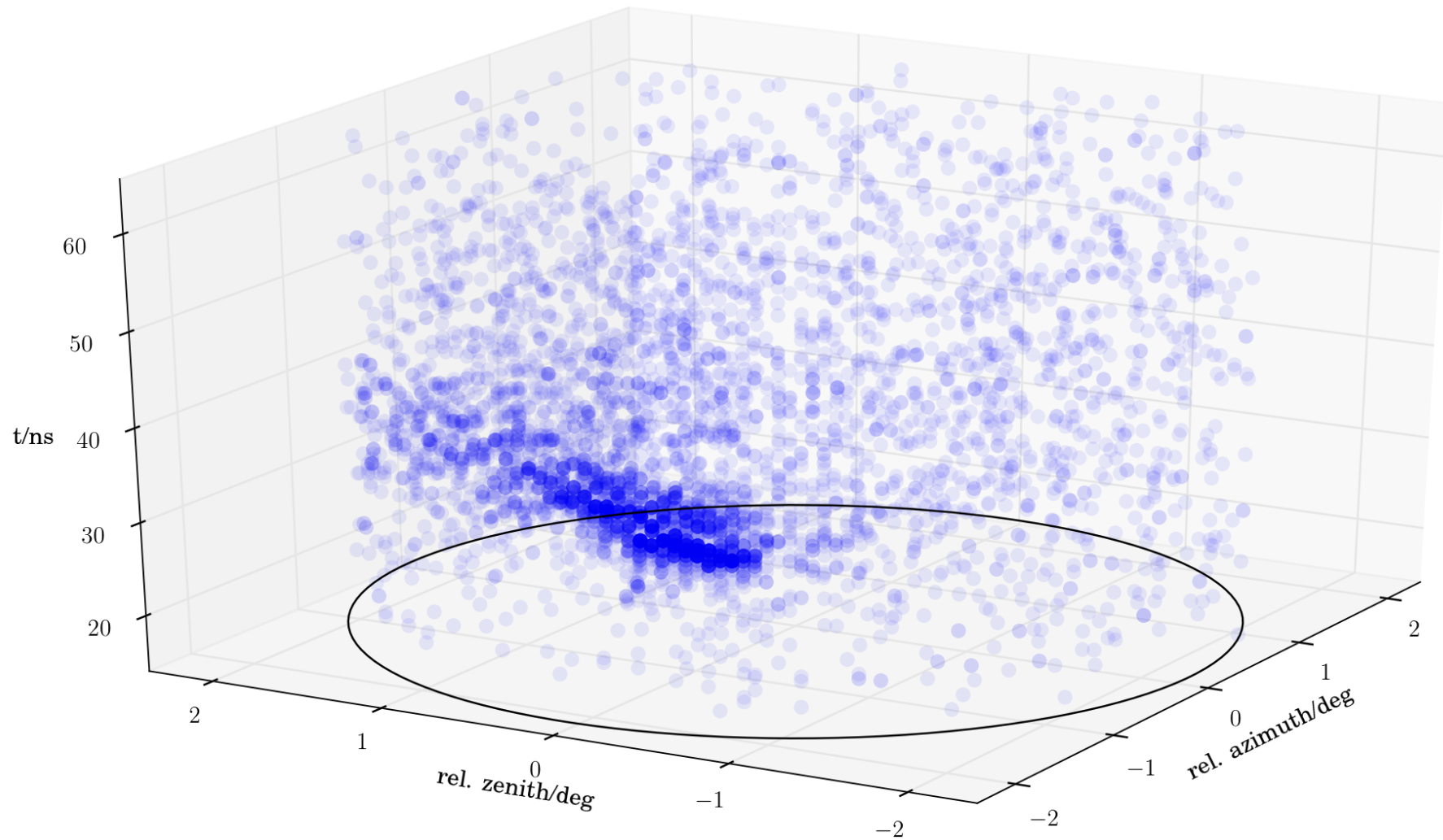
Night 20151113, Run 109, Event 159

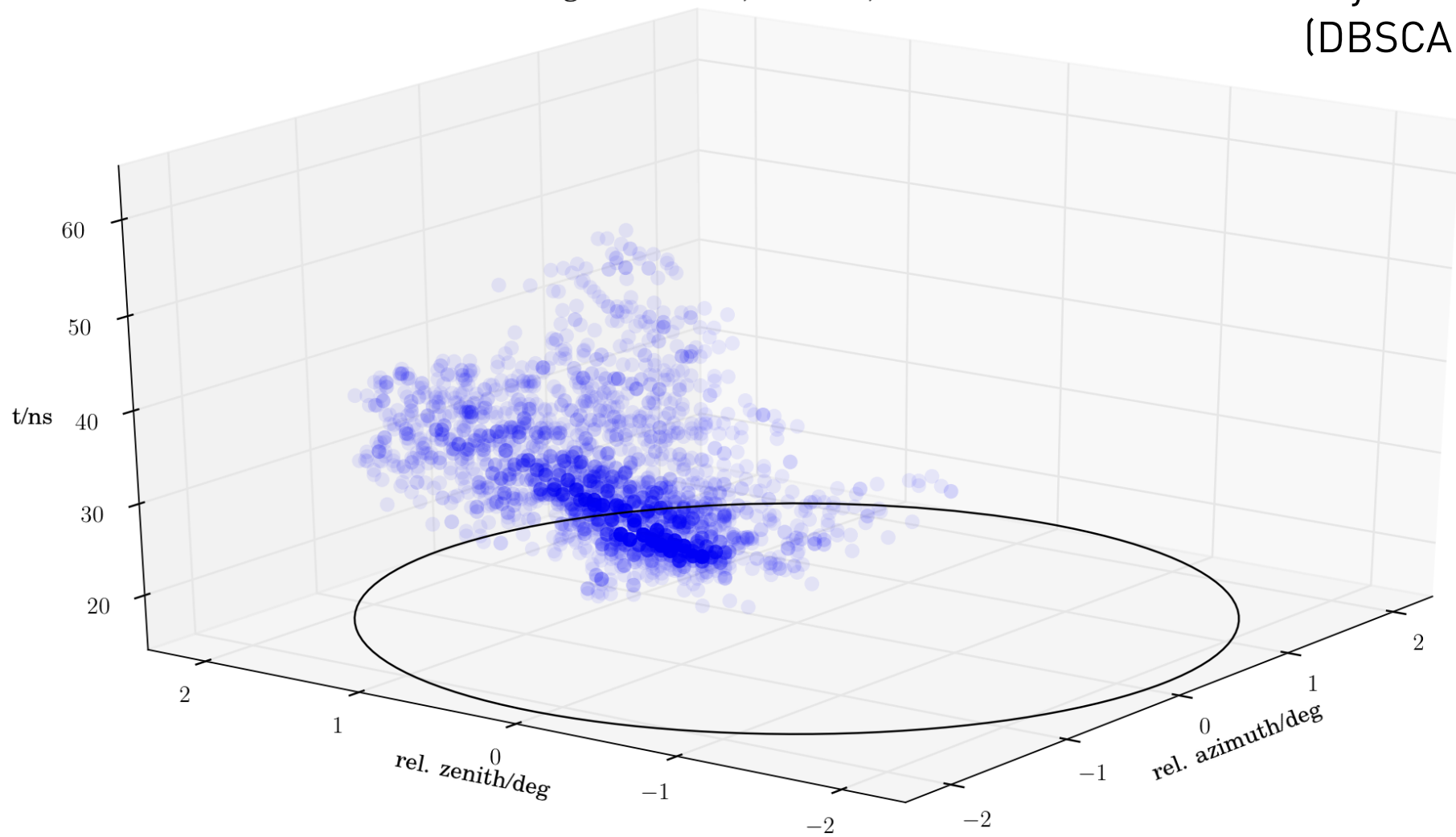


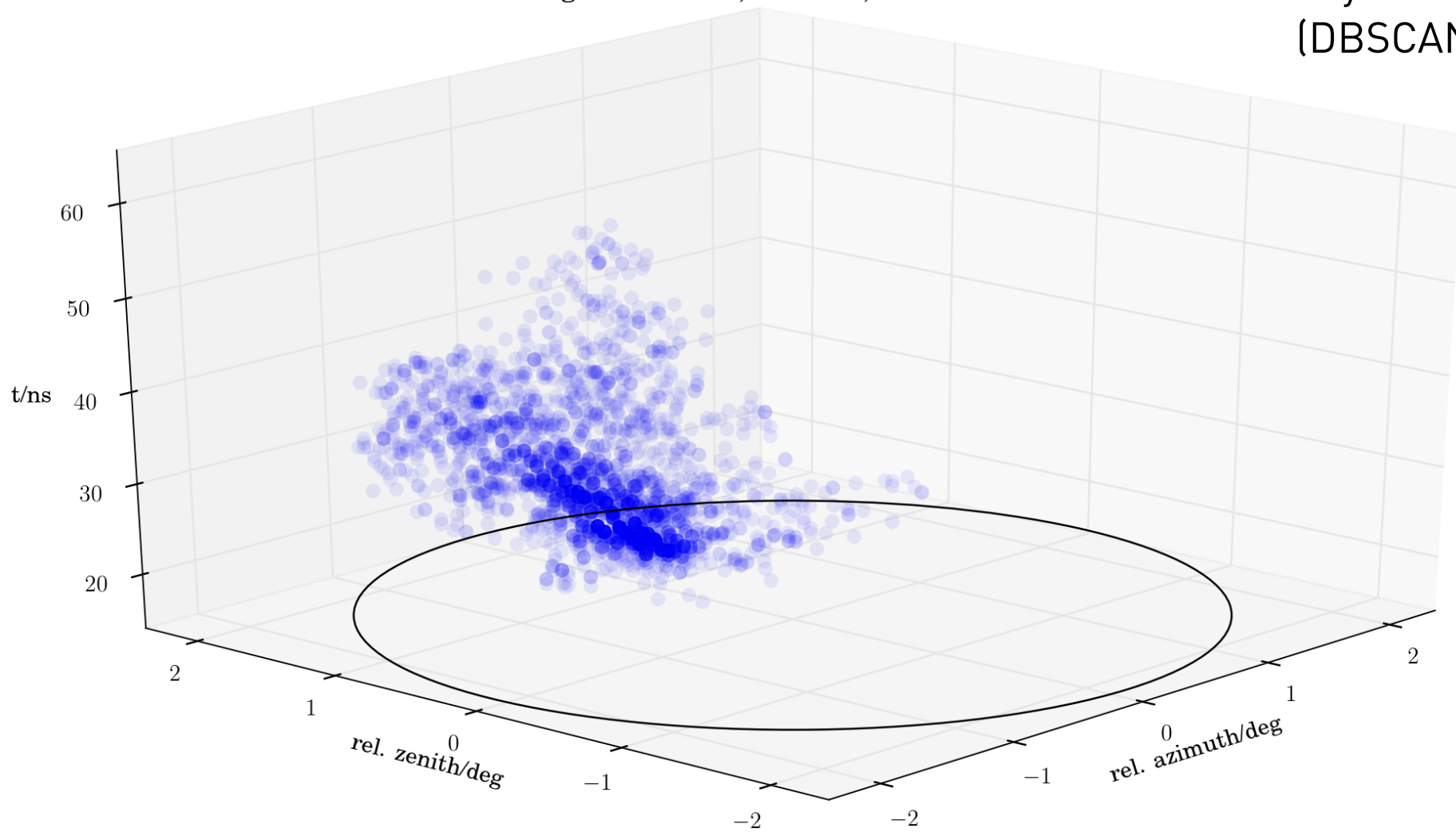
Night 20151113, Run 109, Event 159

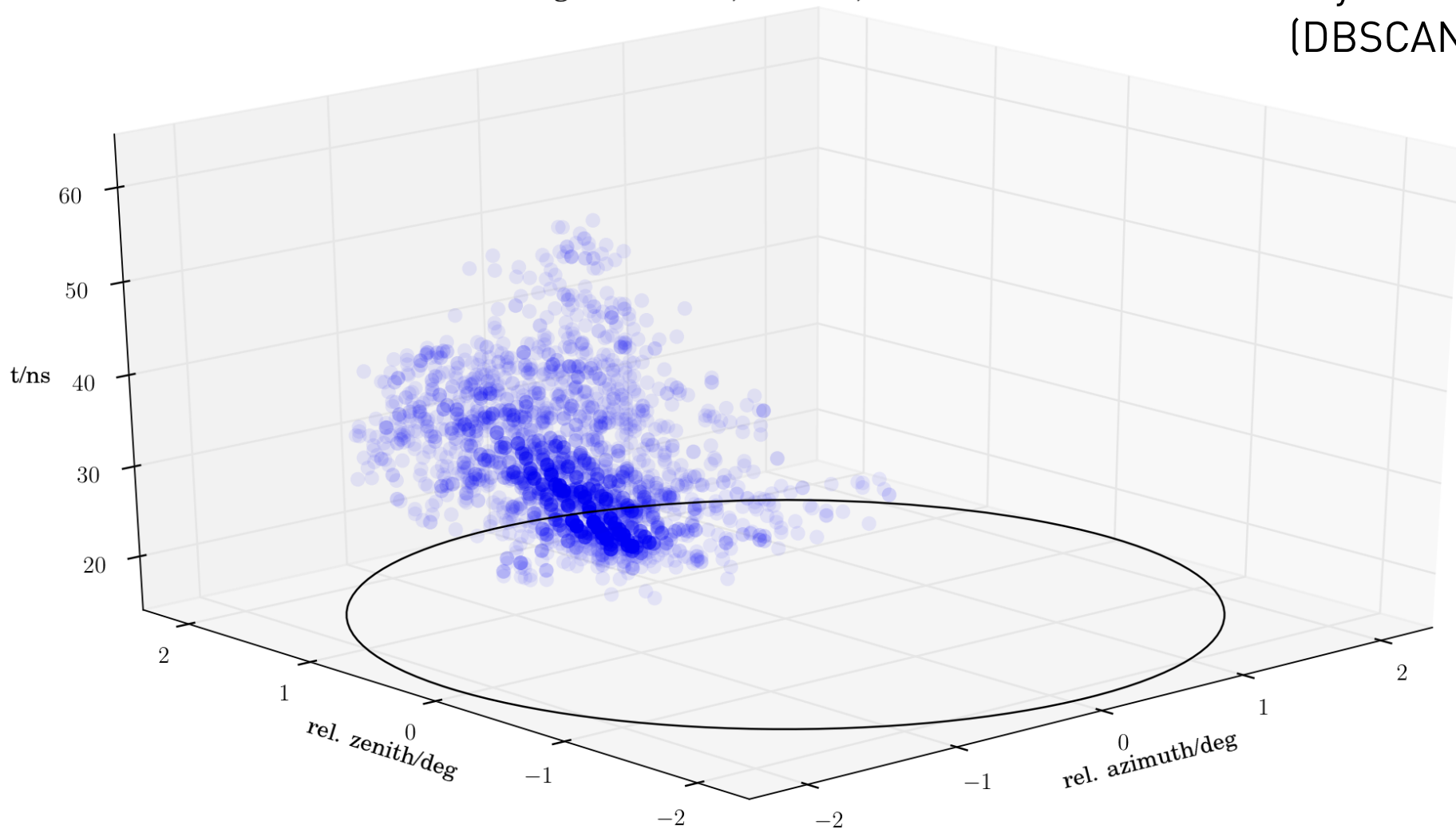


Night 20151113, Run 109, Event 159

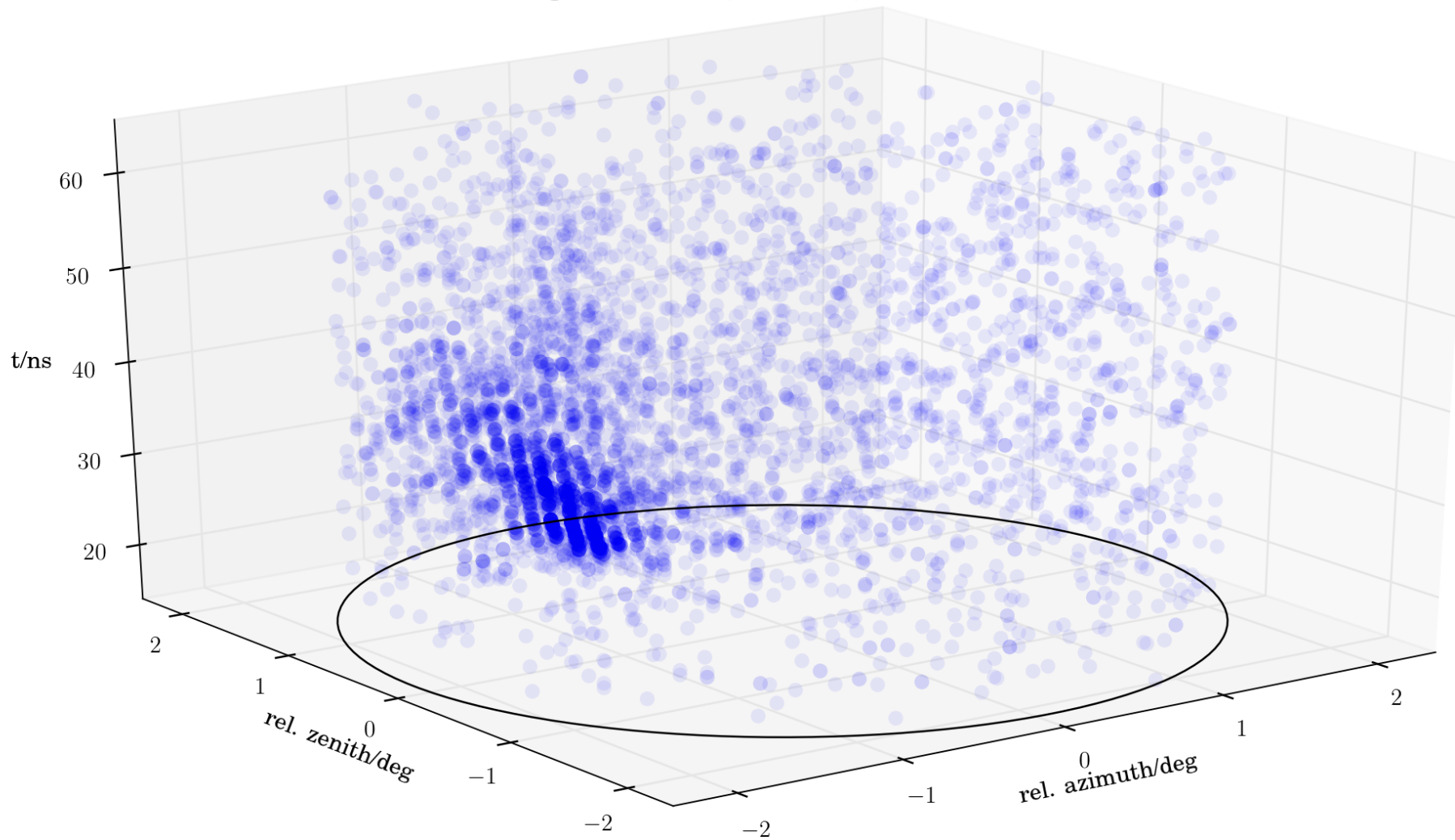




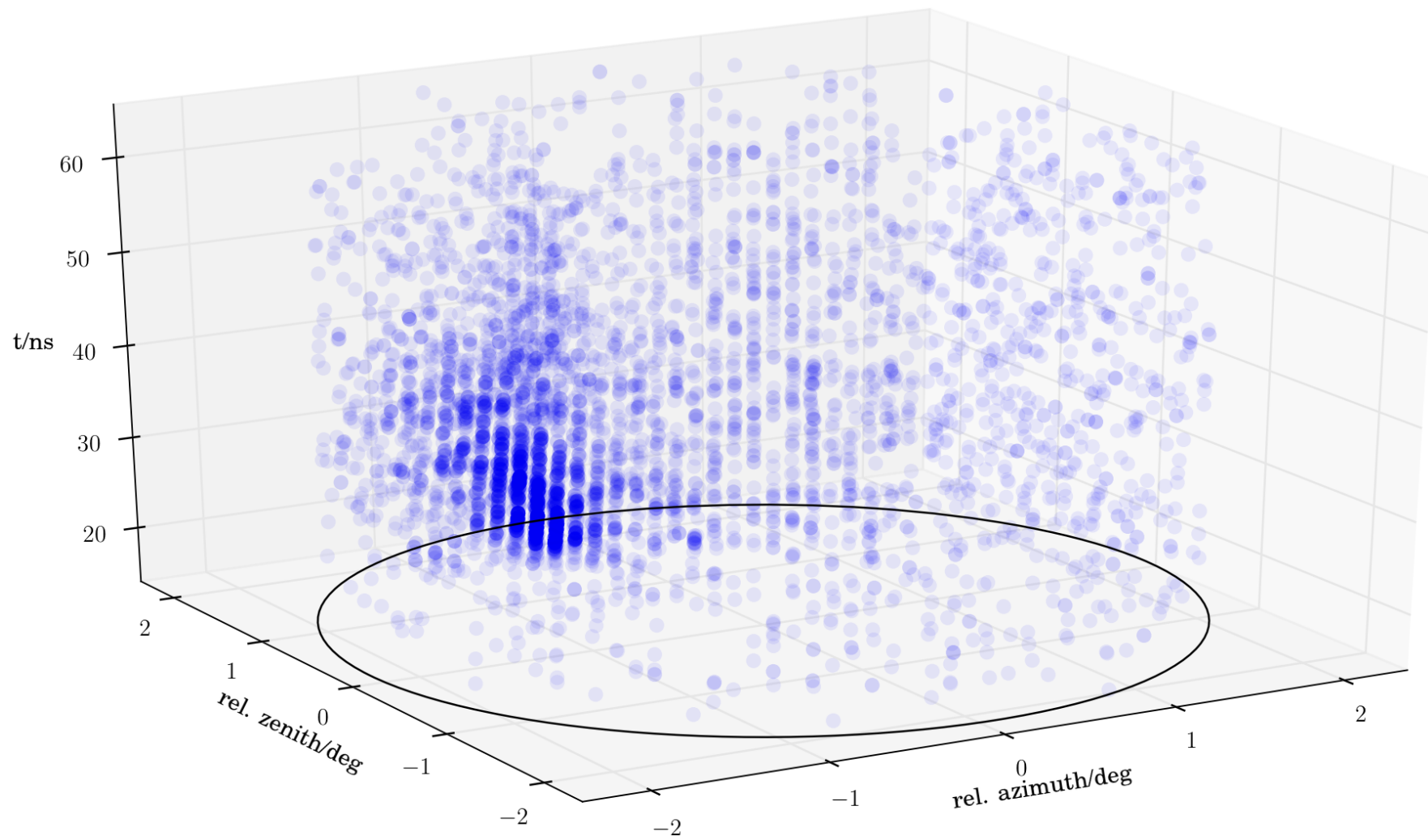




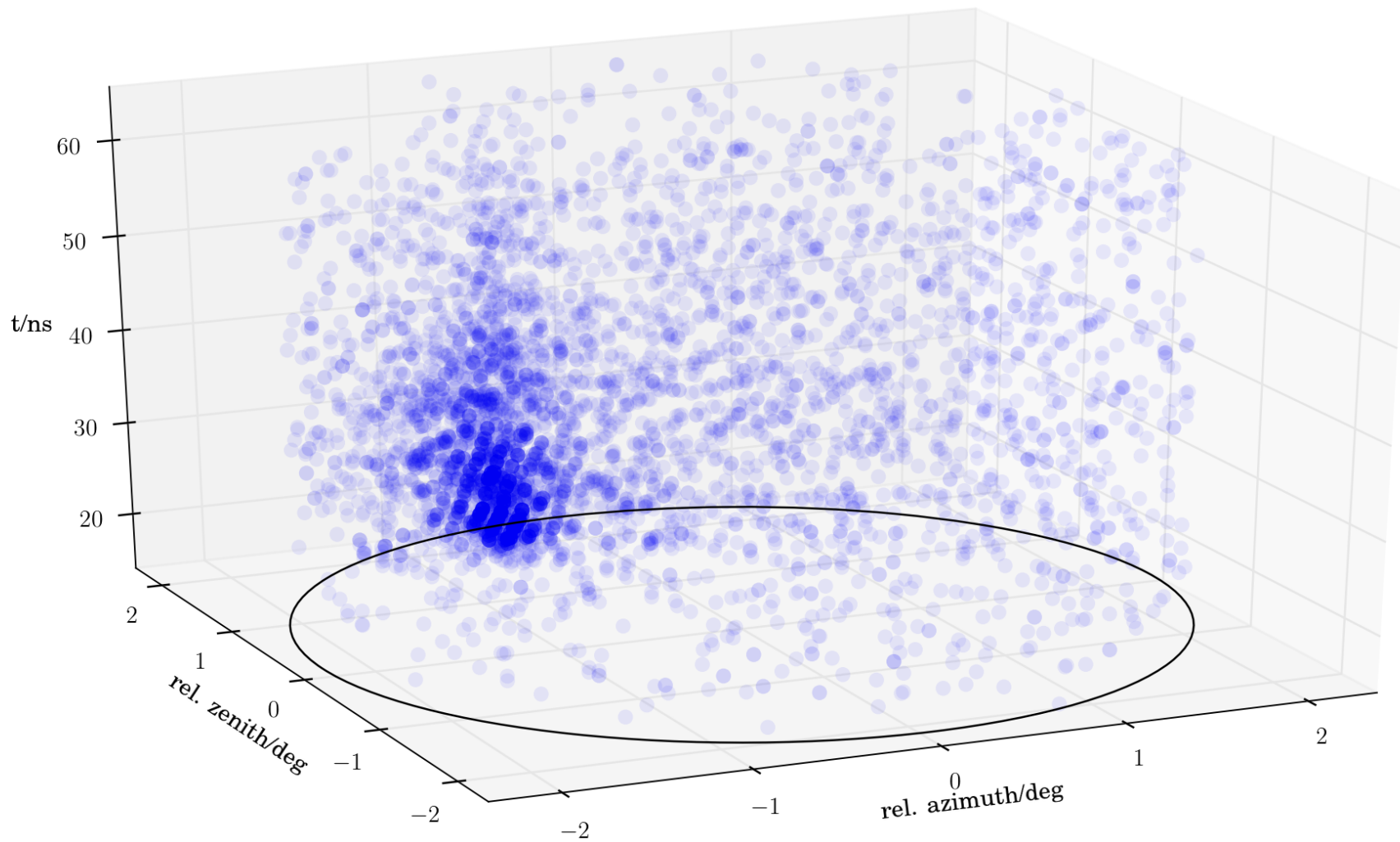
Night 20151113, Run 109, Event 159

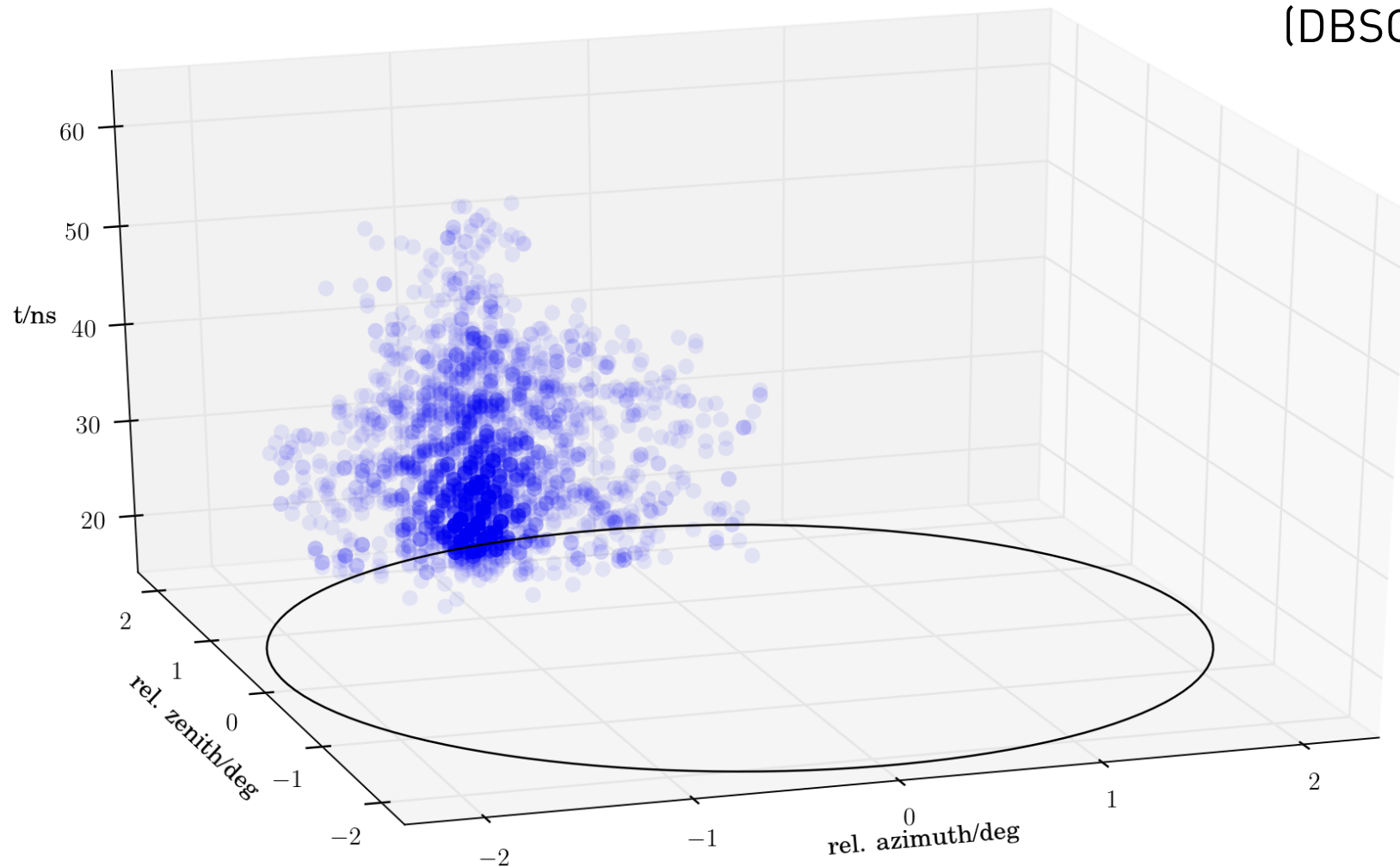


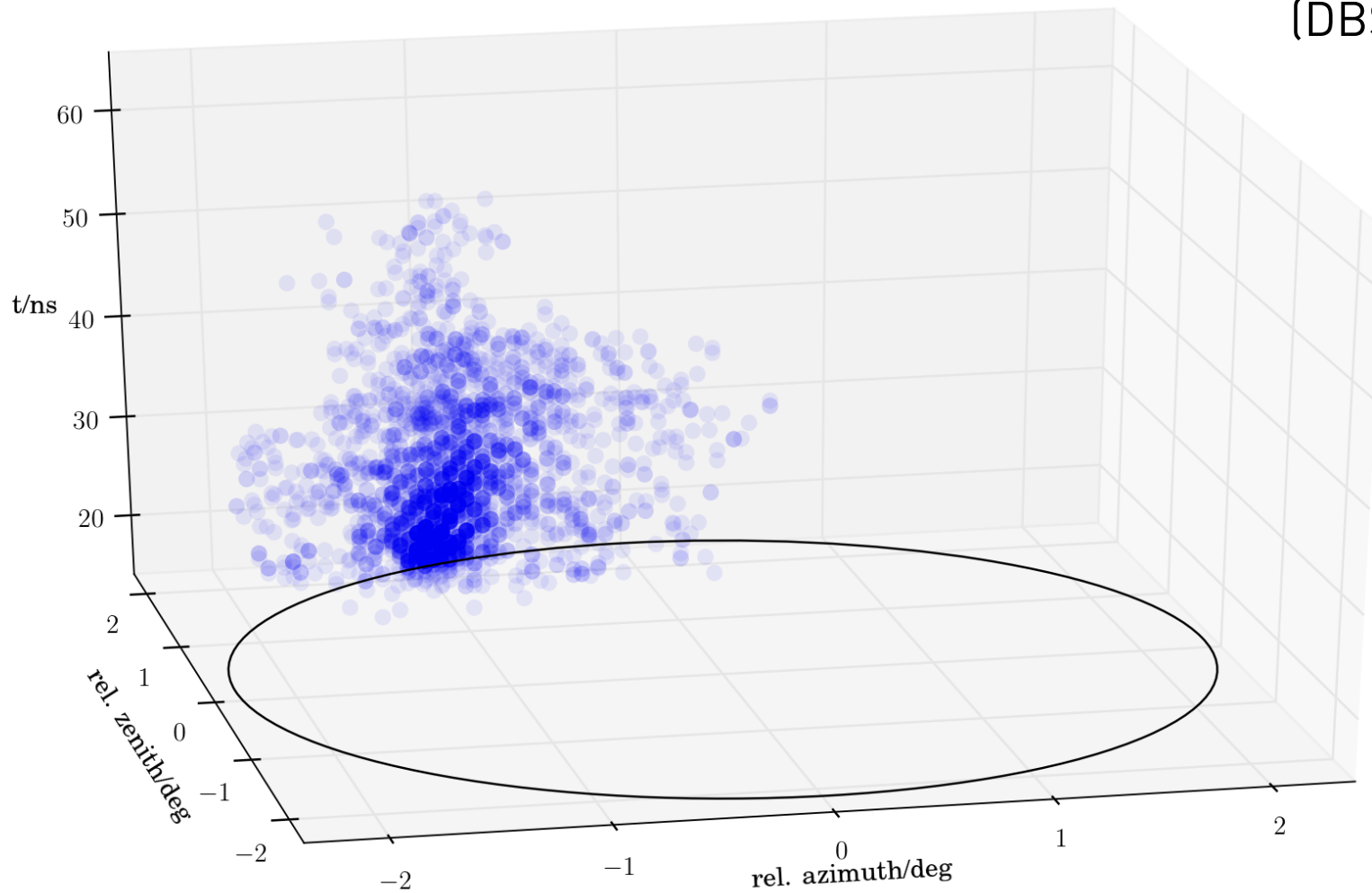
Night 20151113, Run 109, Event 159

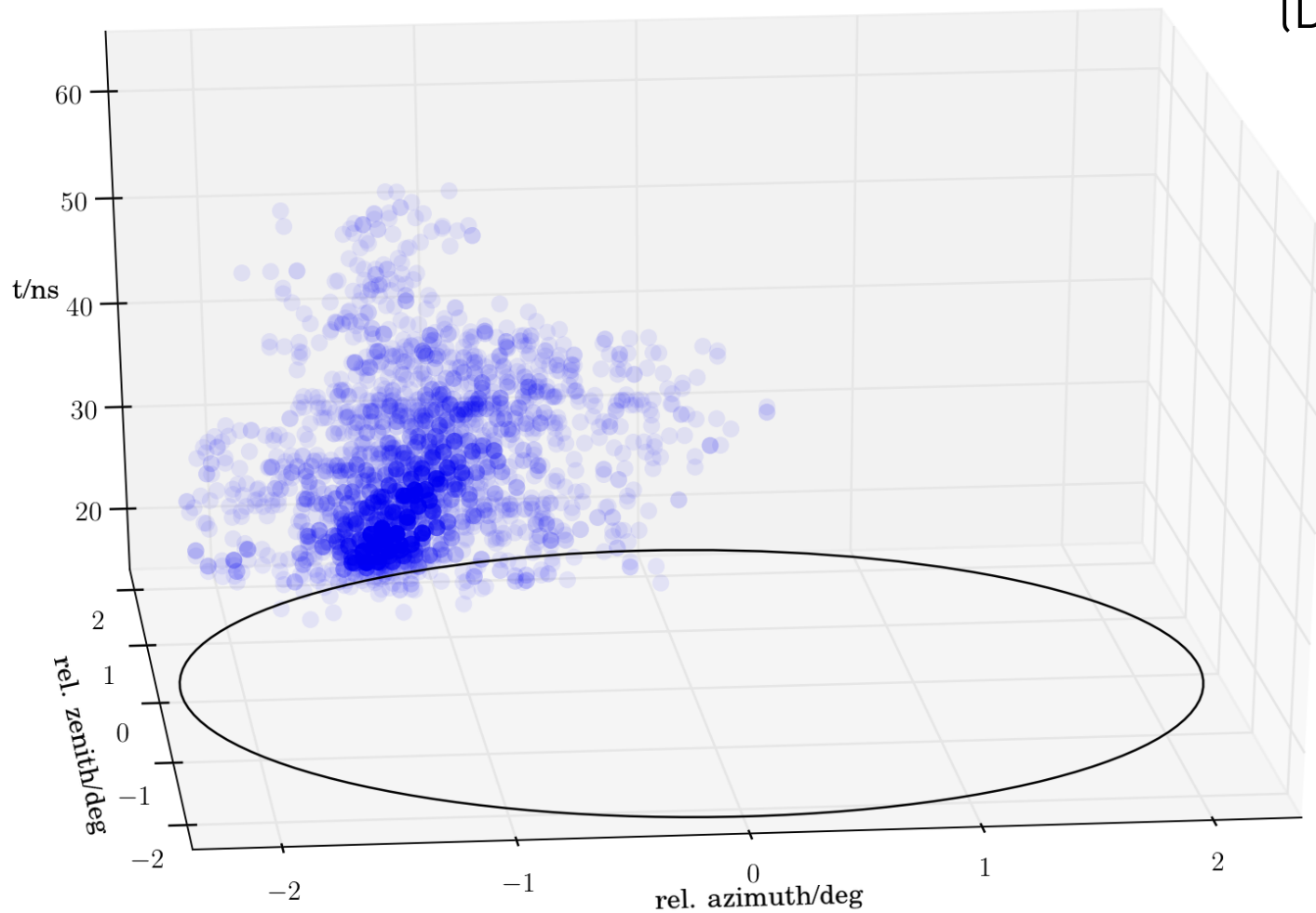


Night 20151113, Run 109, Event 159

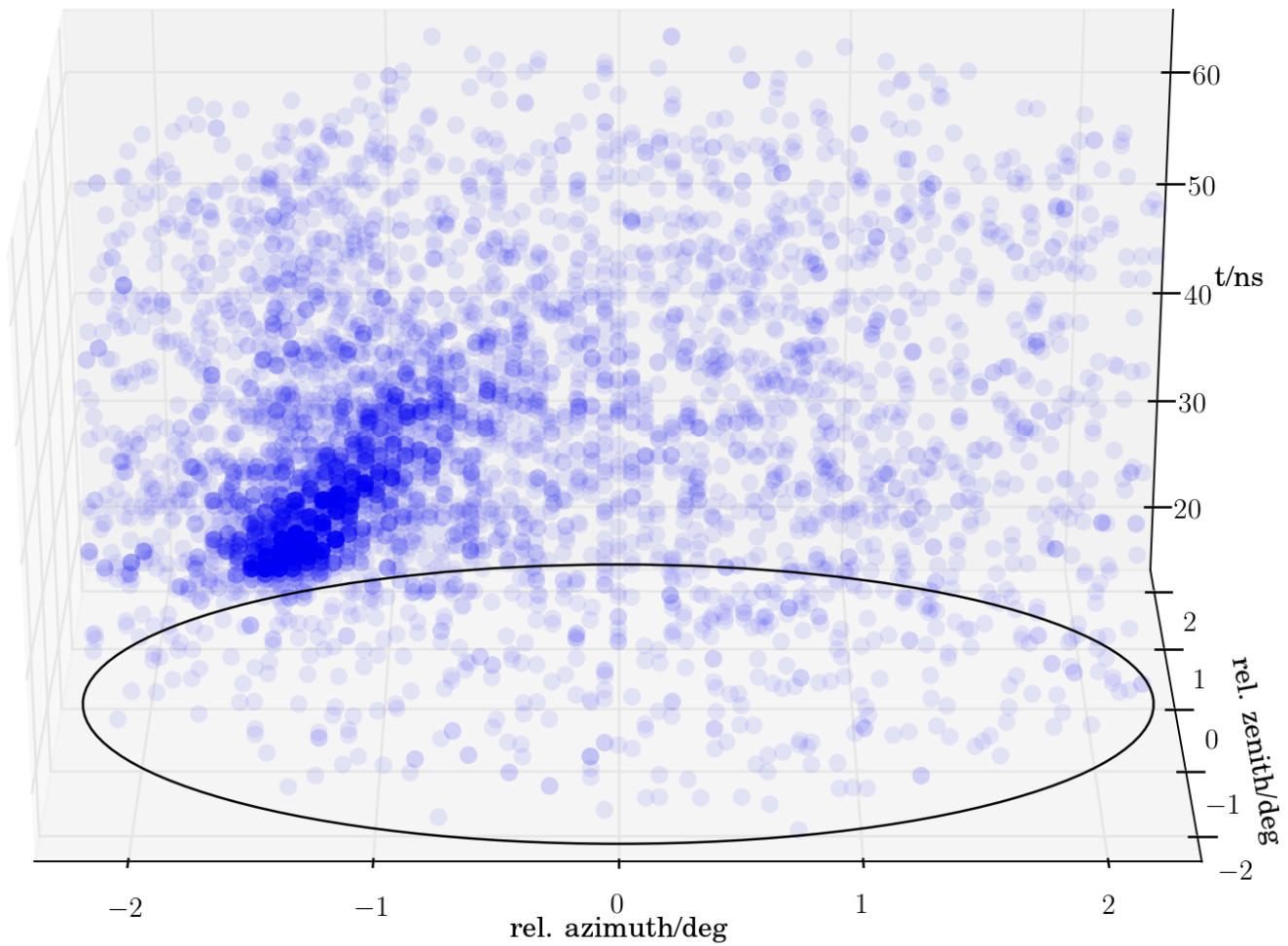




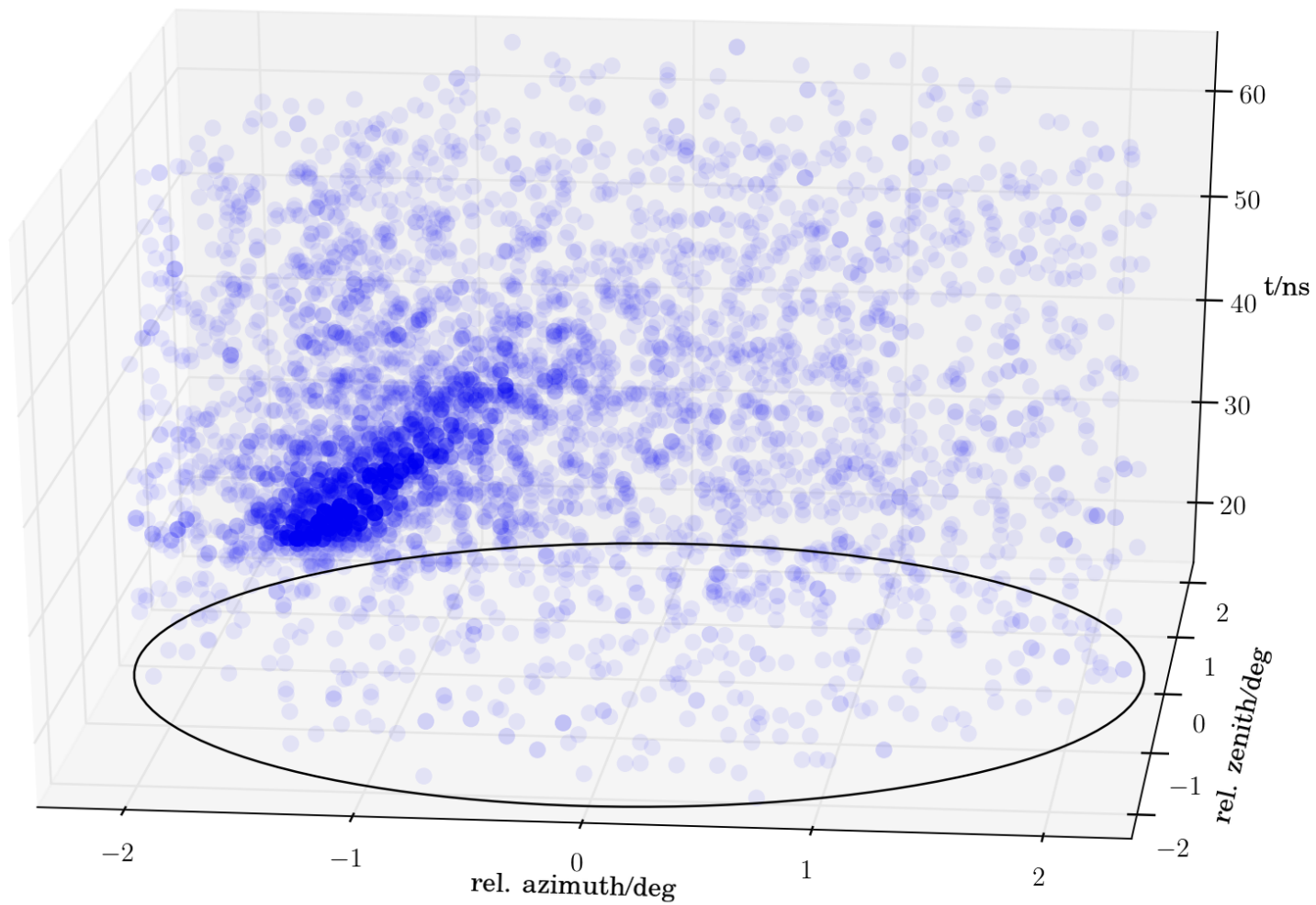




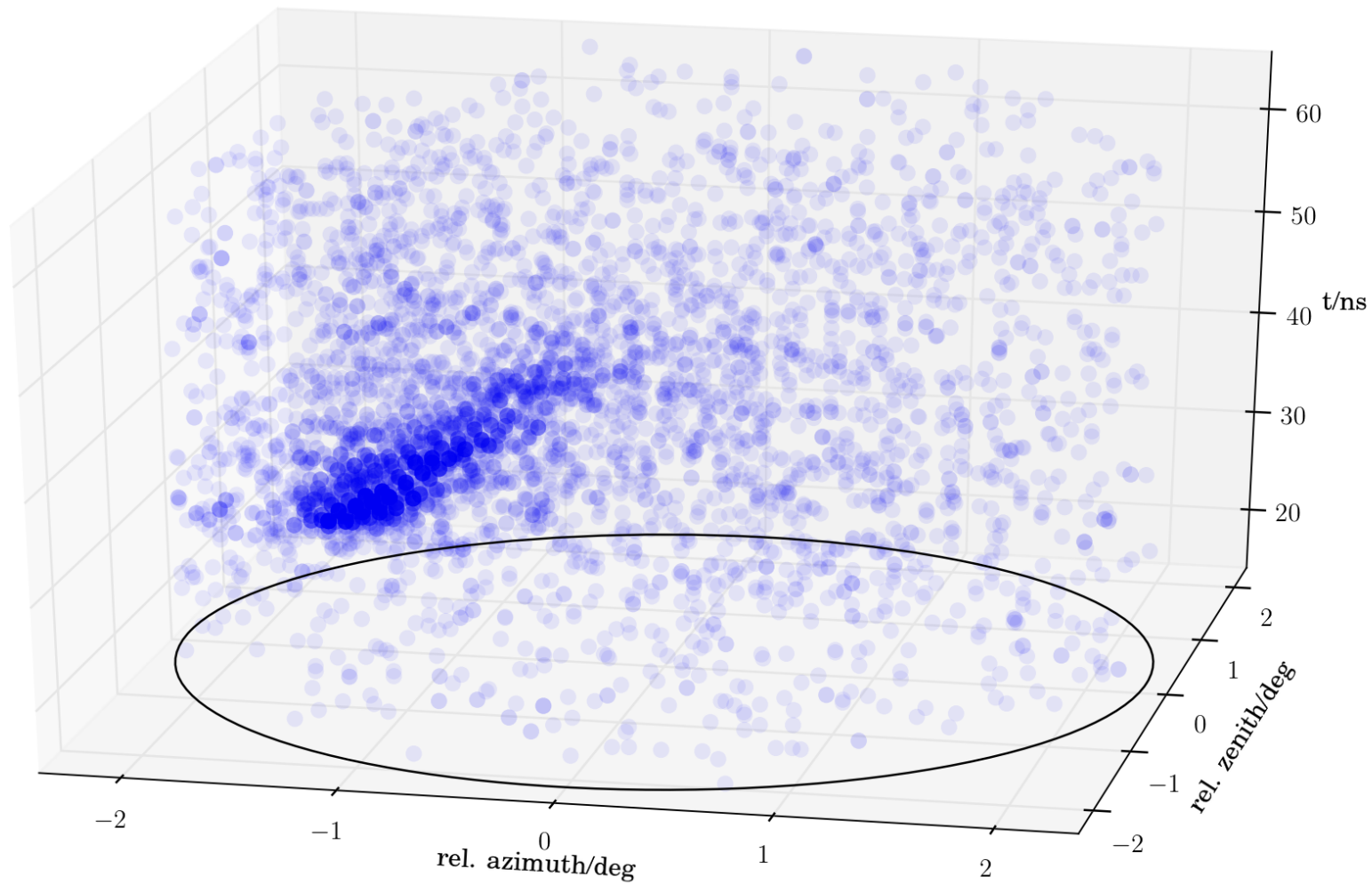
Night 20151113, Run 109, Event 159

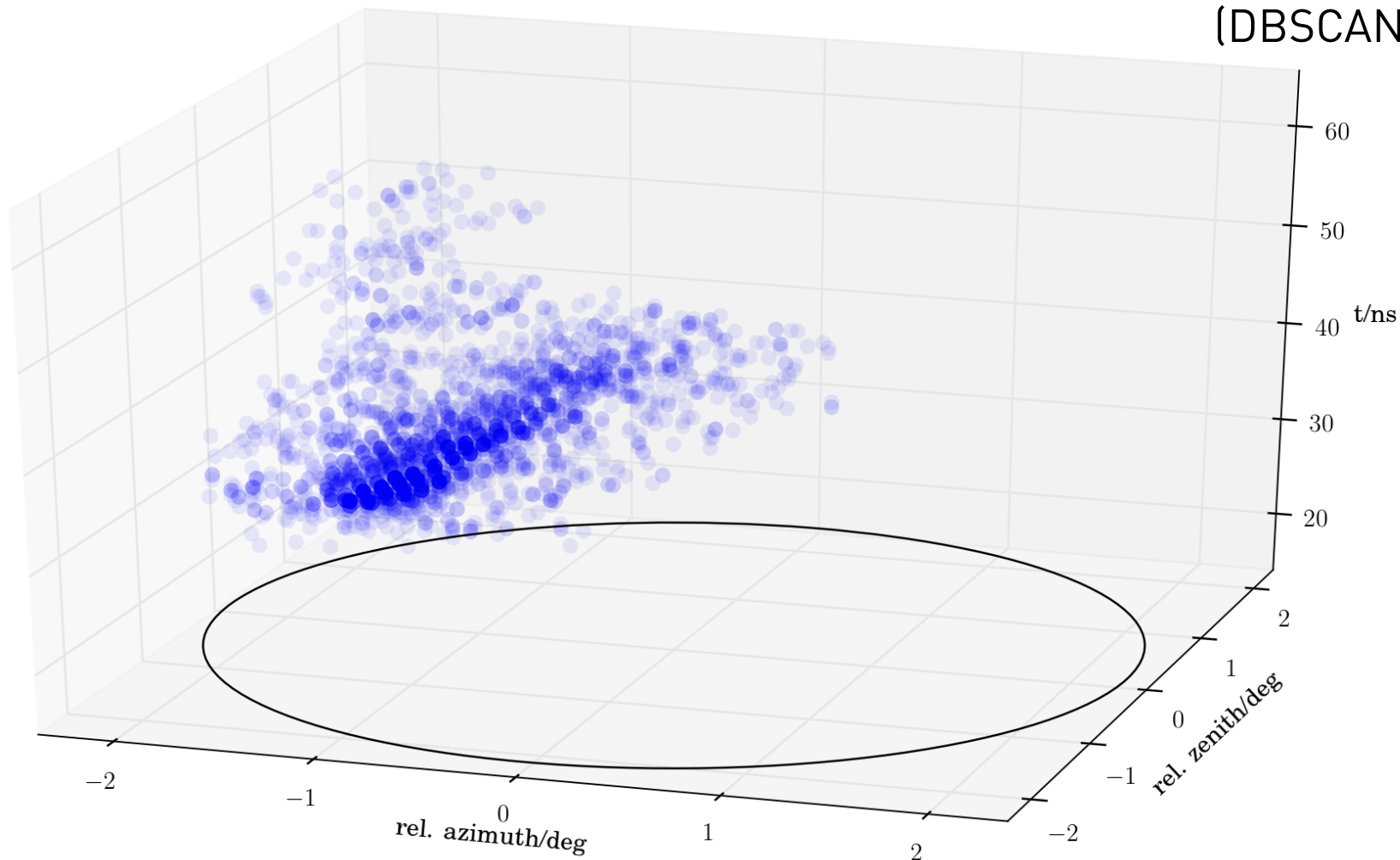


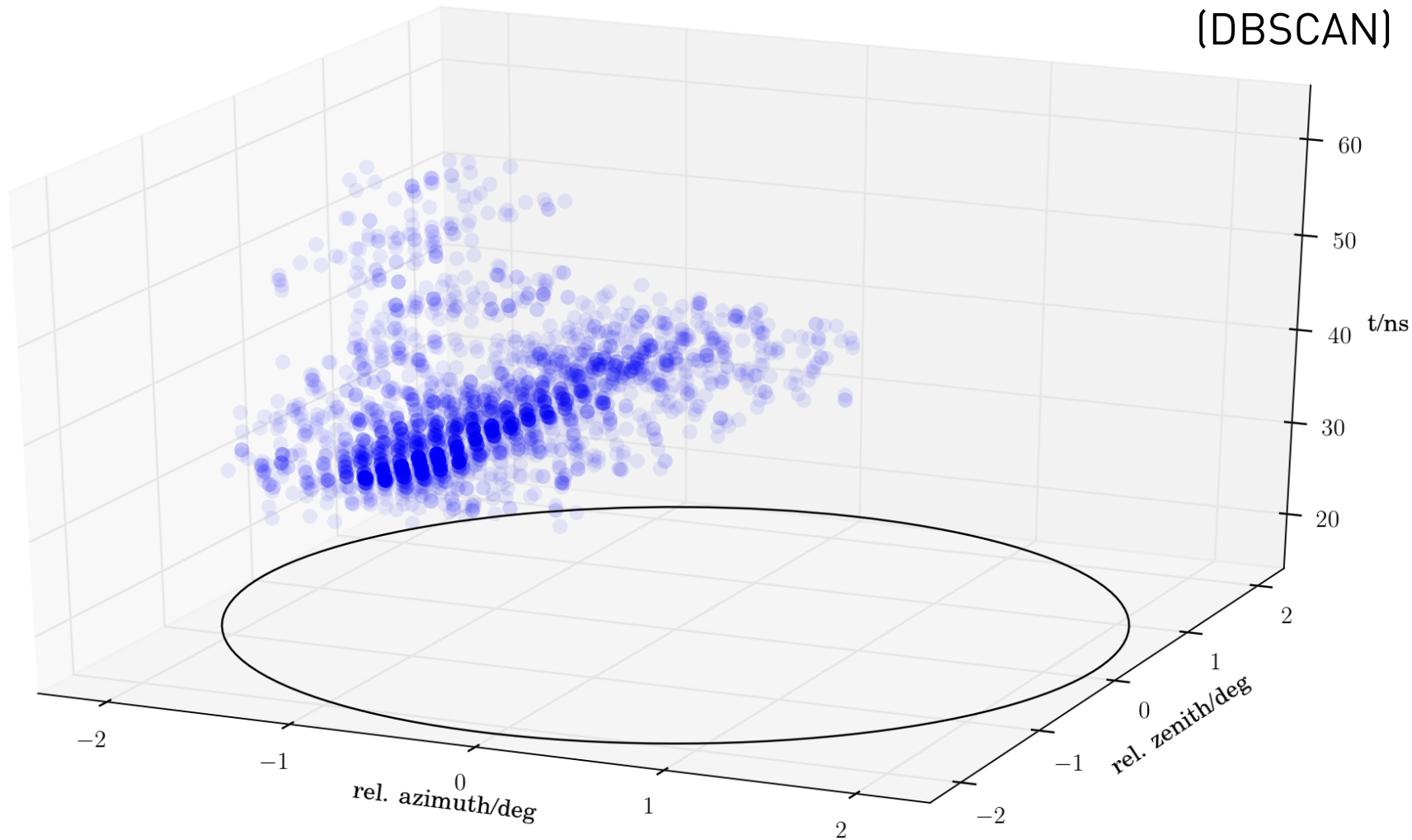
Night 20151113, Run 109, Event 159

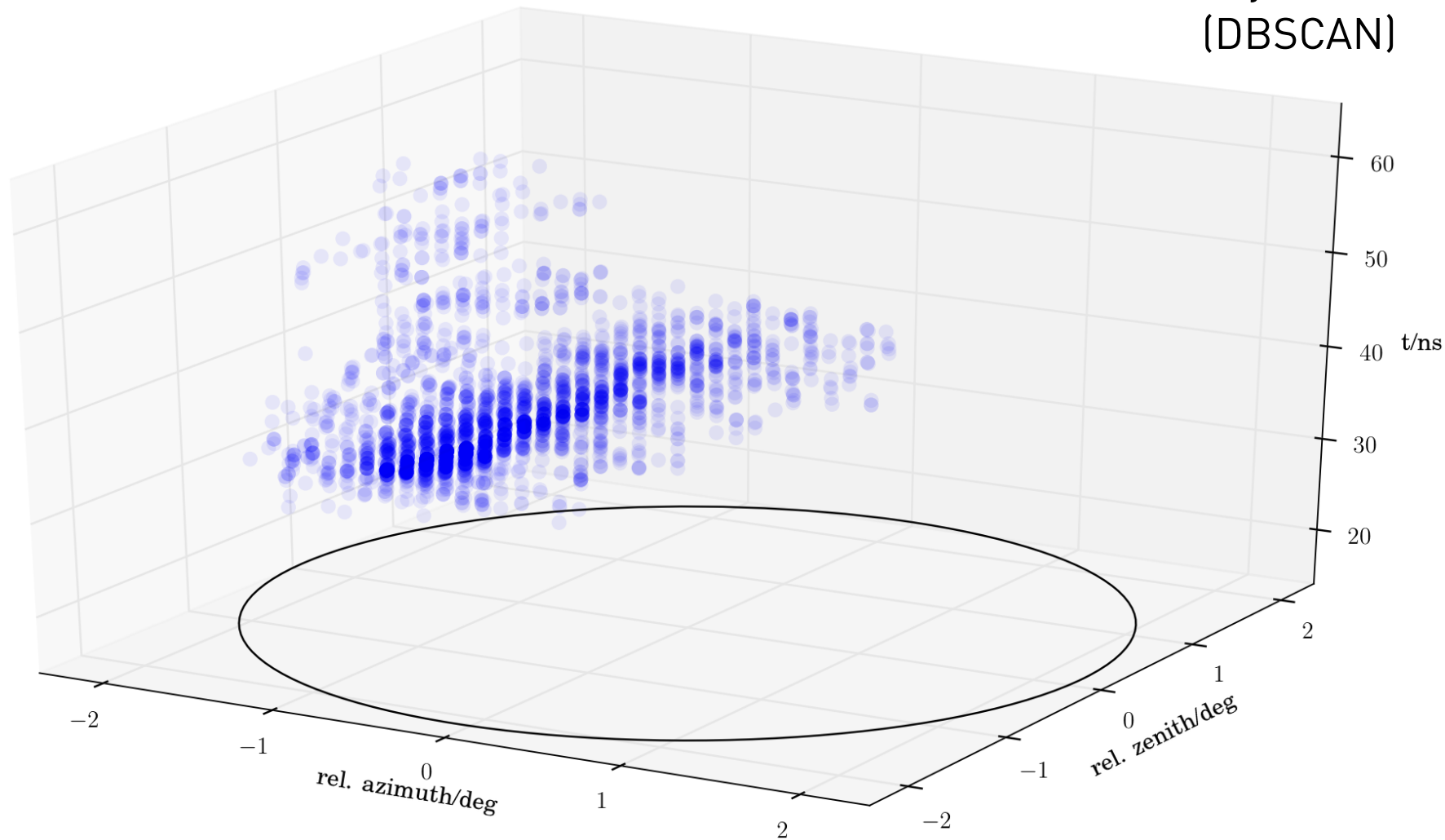


Night 20151113, Run 109, Event 159

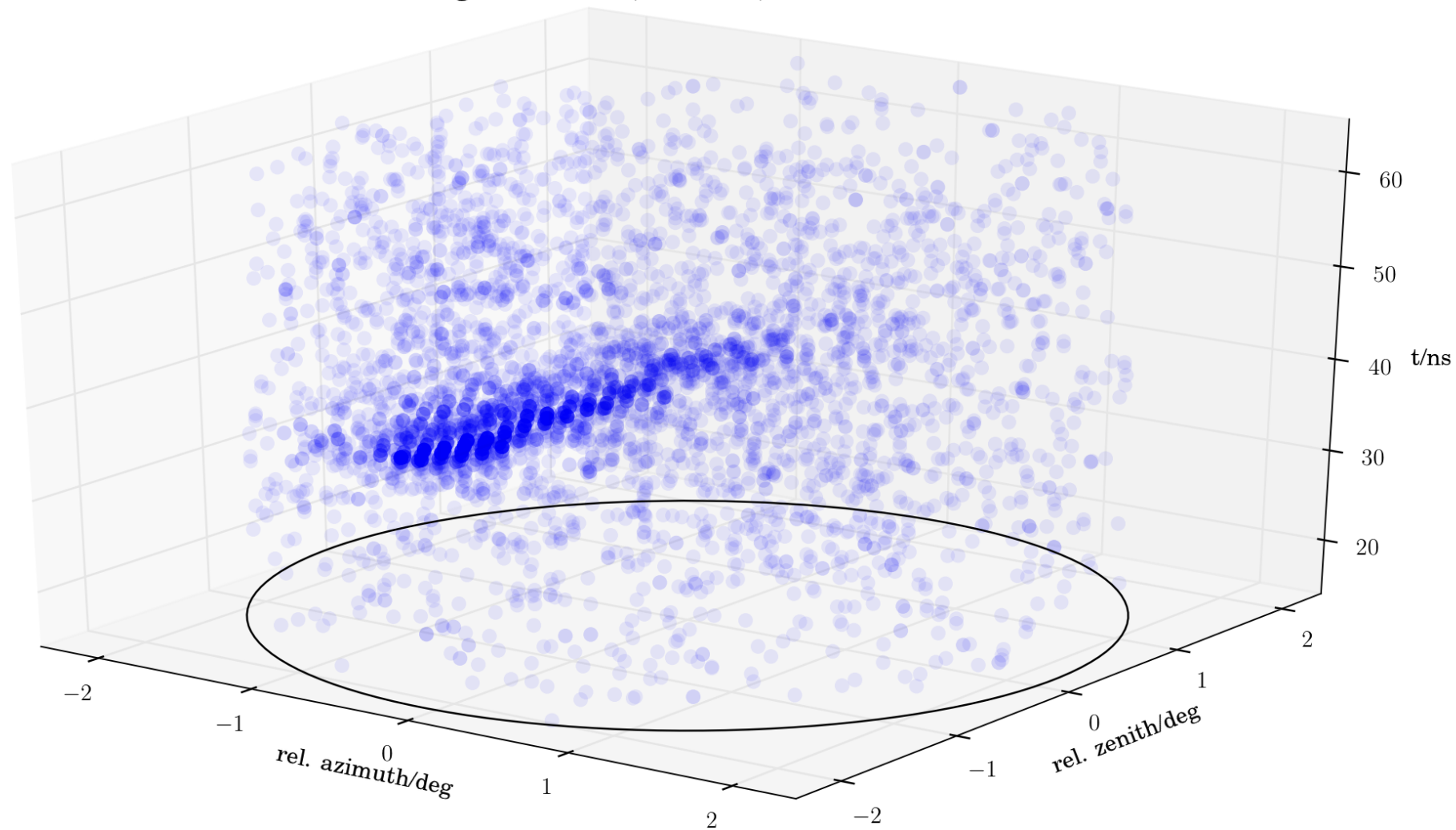




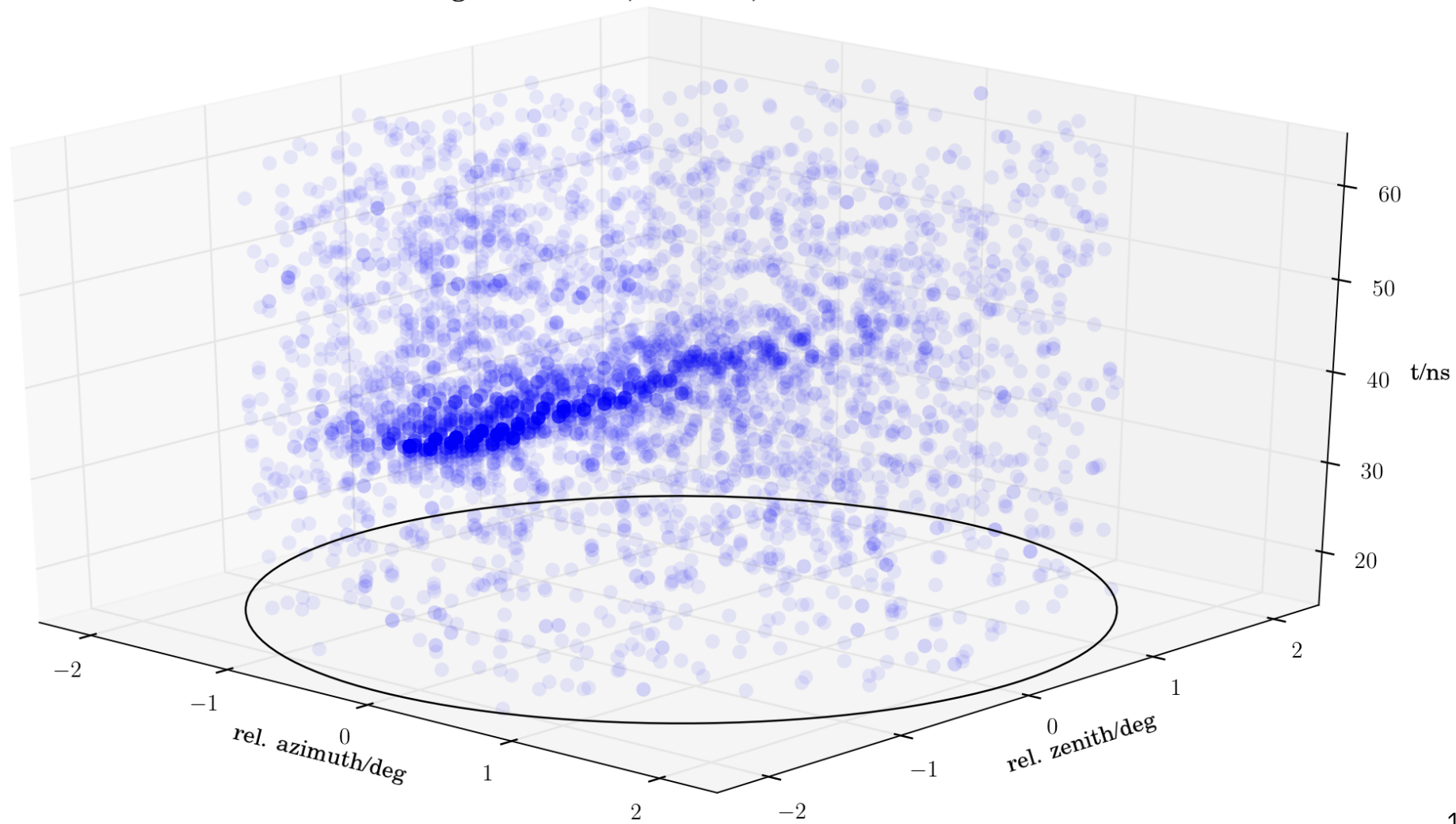




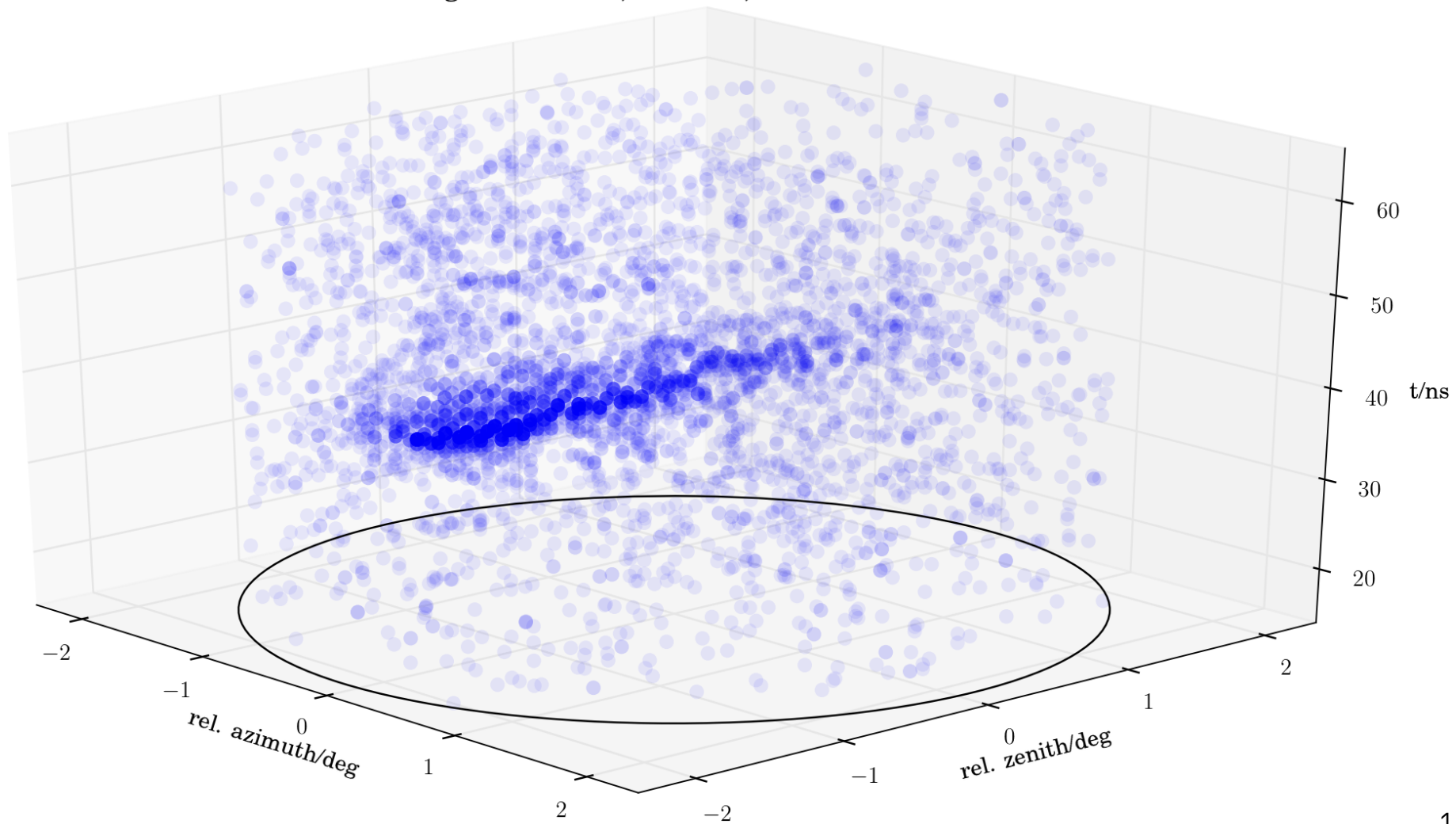
Night 20151113, Run 109, Event 159

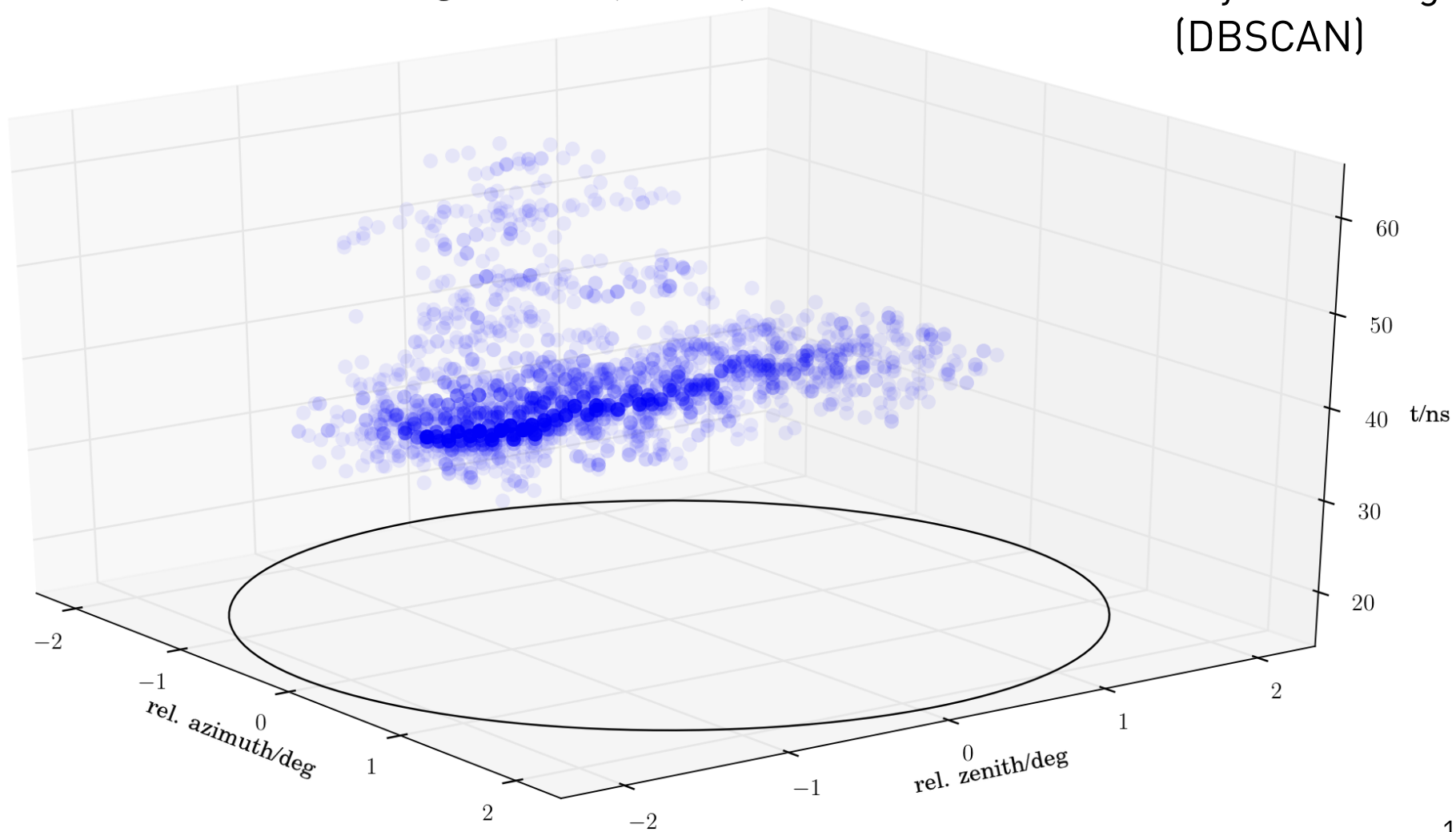


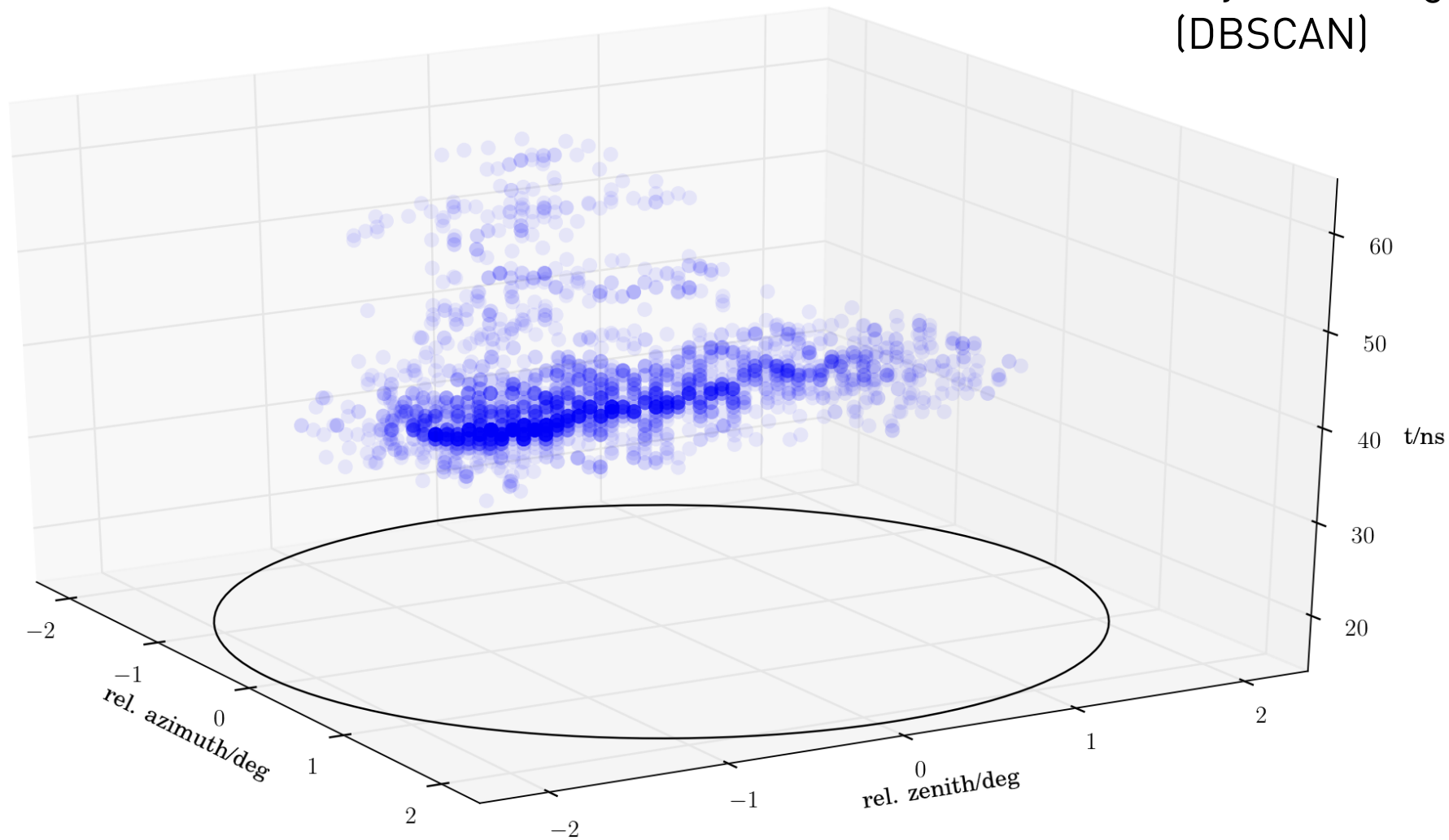
Night 20151113, Run 109, Event 159

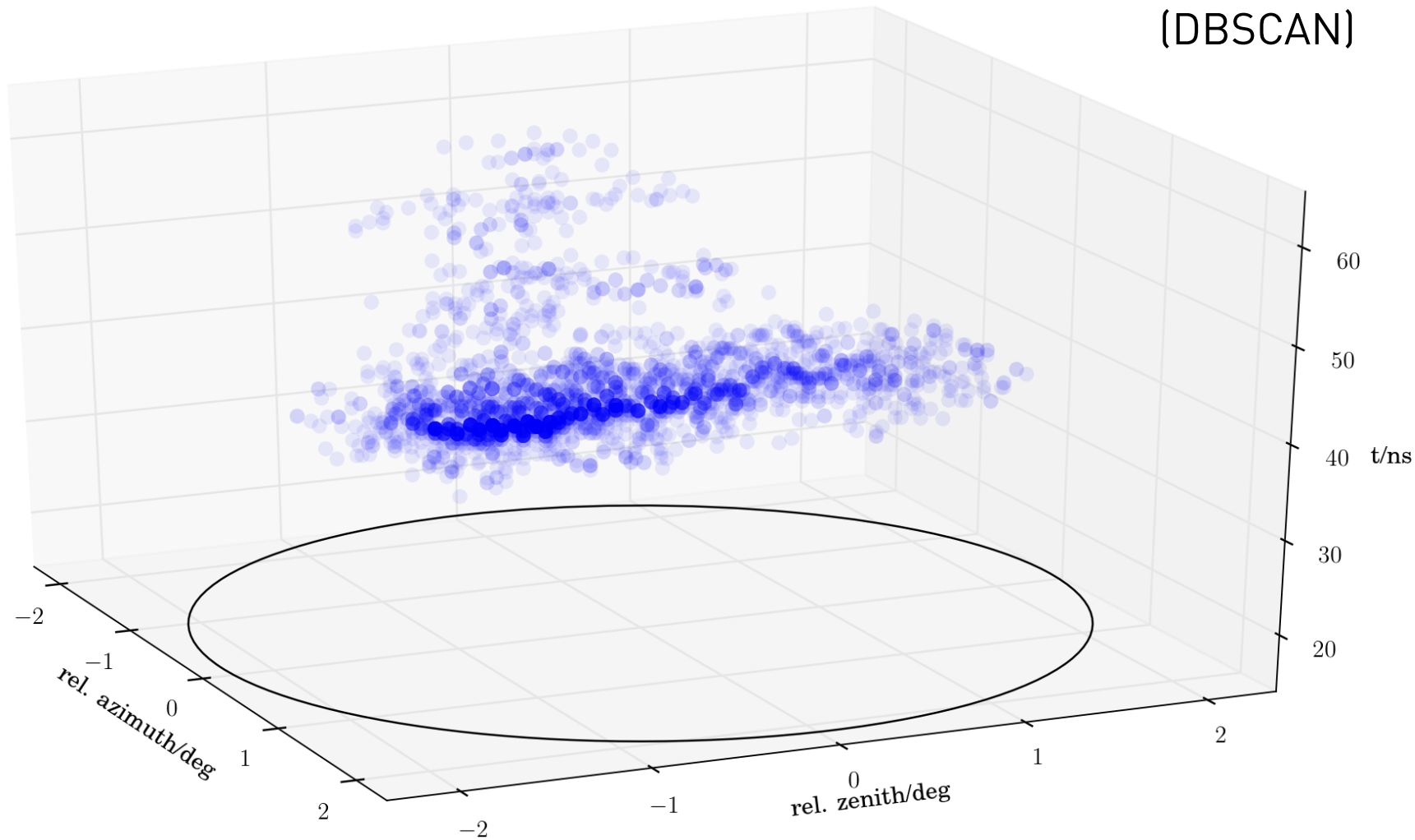


Night 20151113, Run 109, Event 159

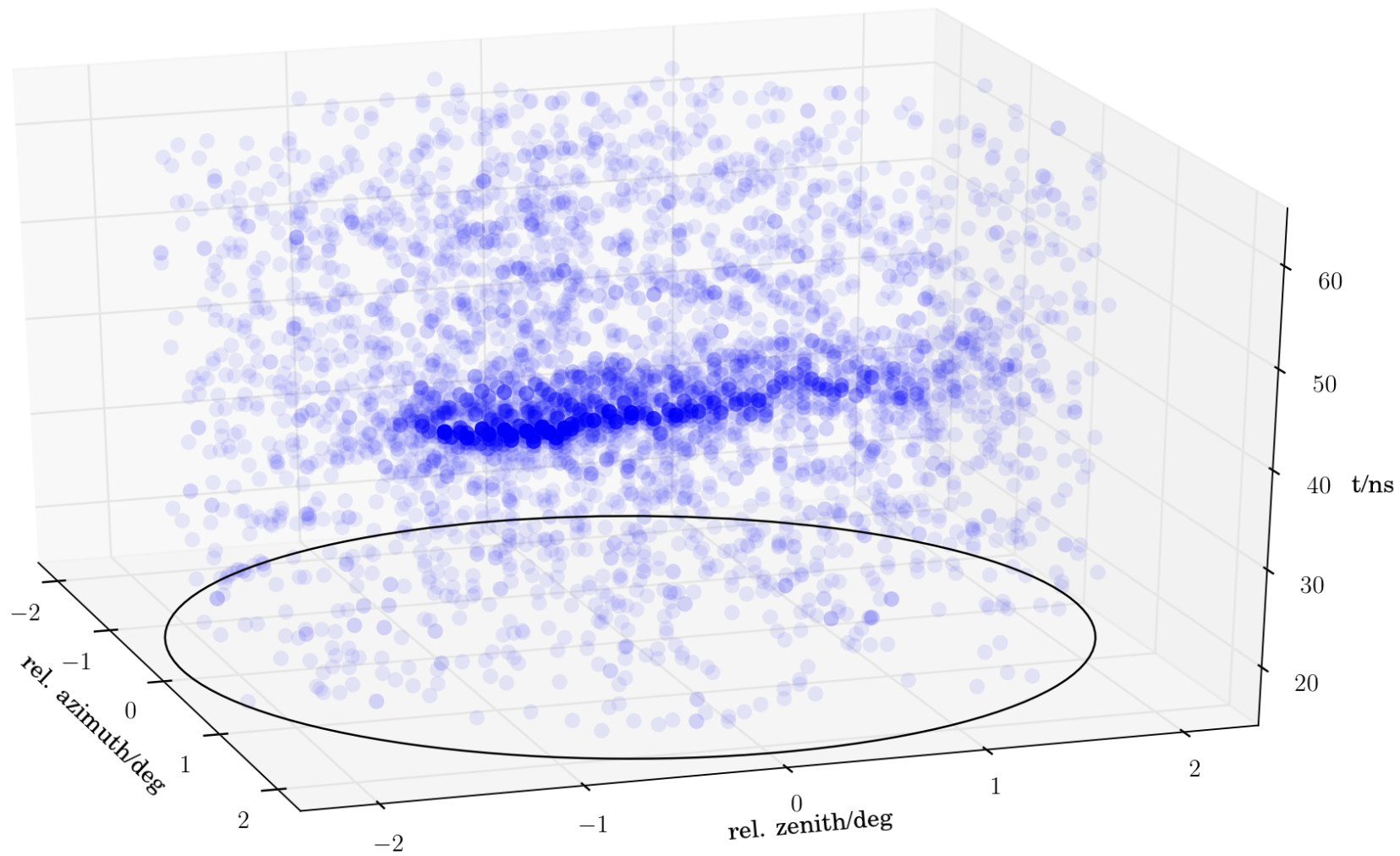




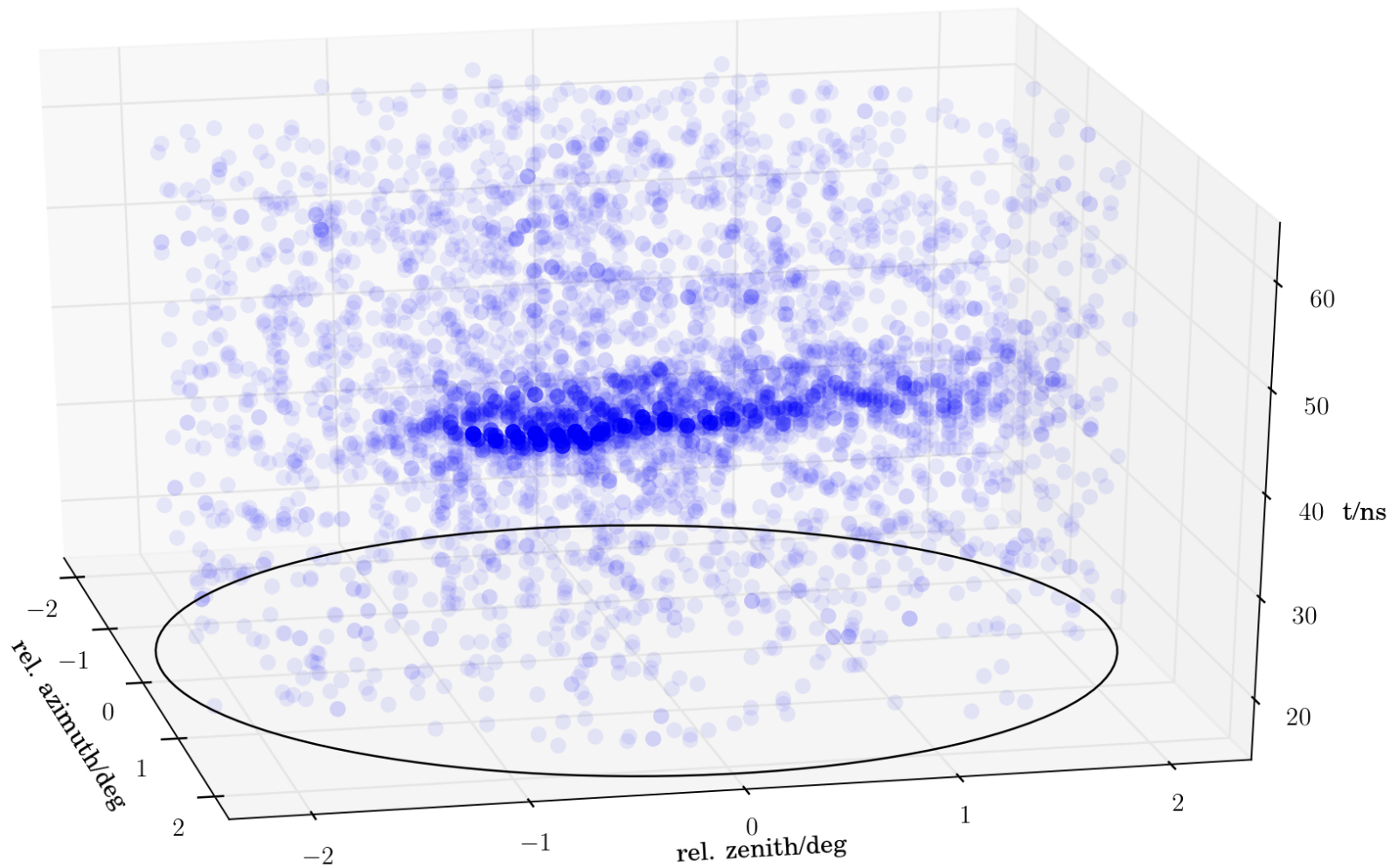




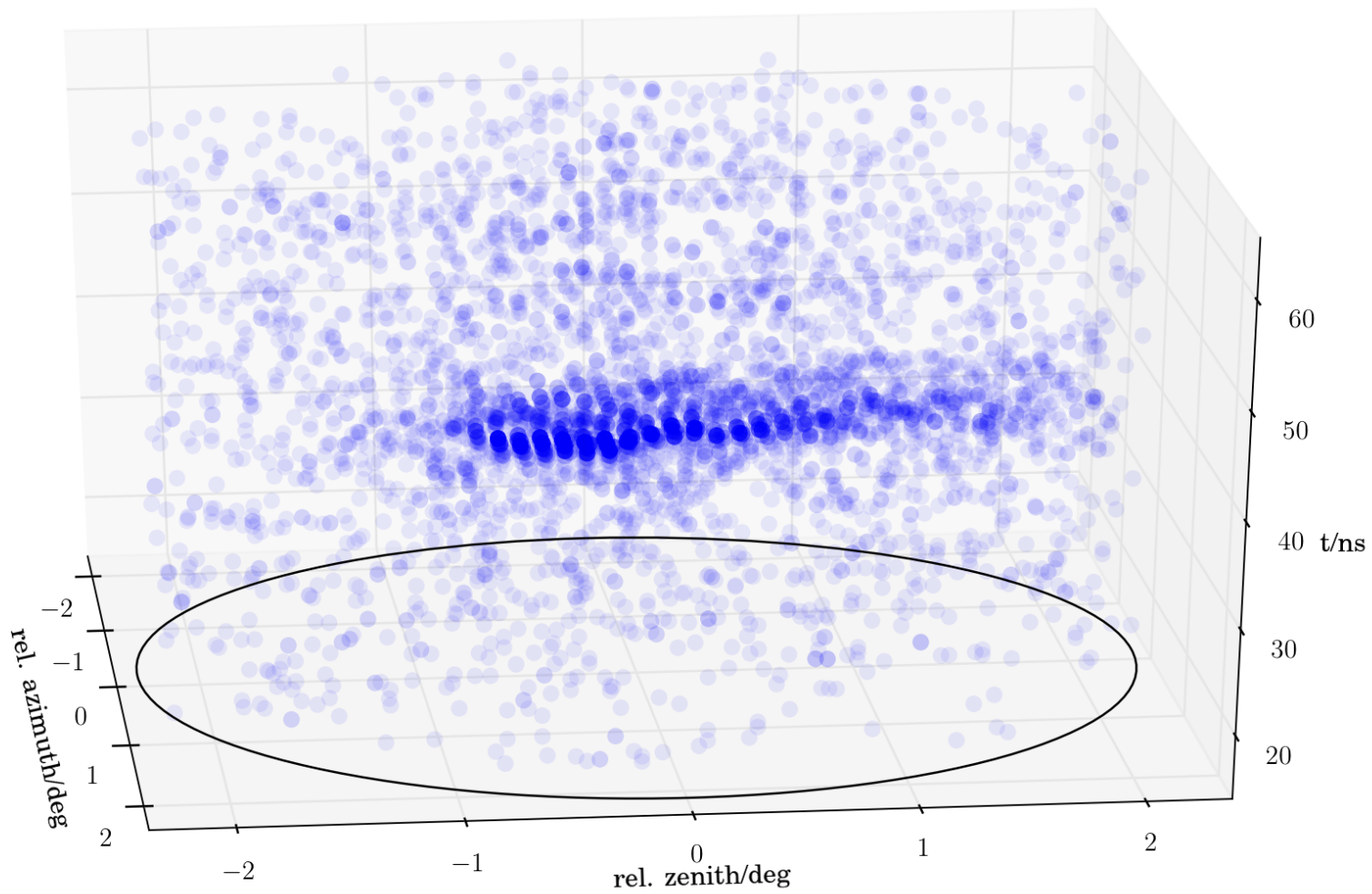
Night 20151113, Run 109, Event 159



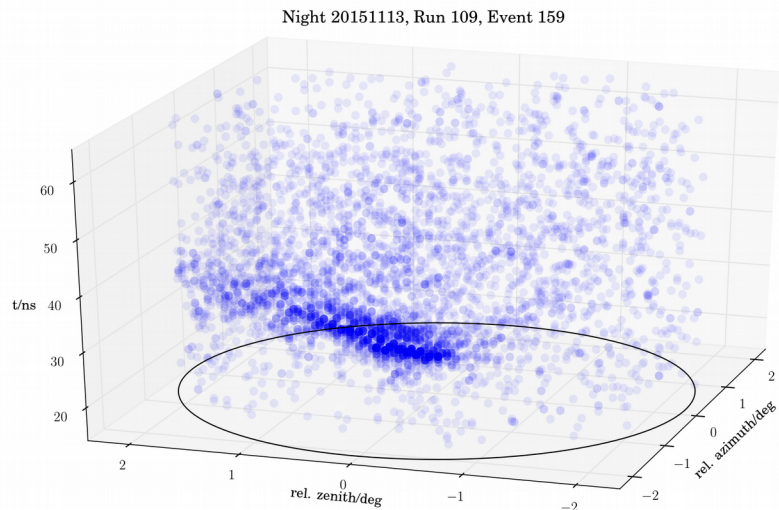
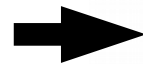
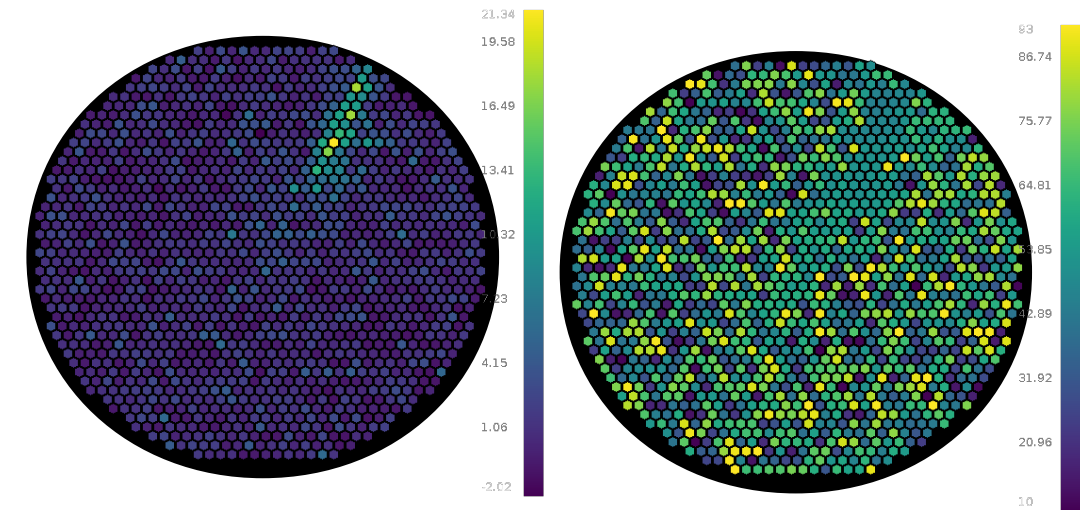
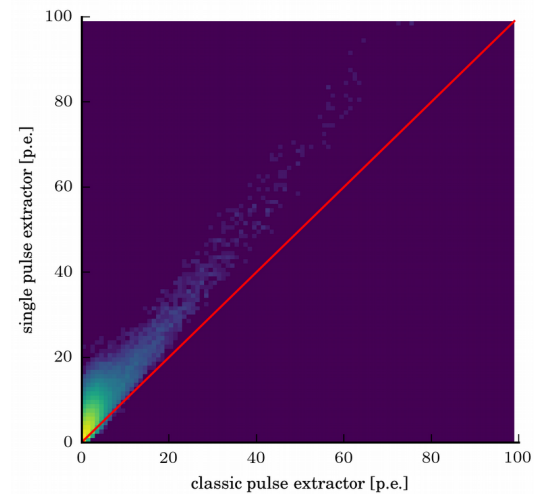
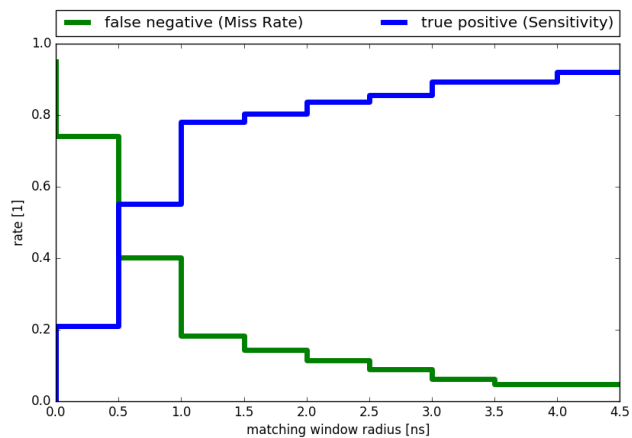
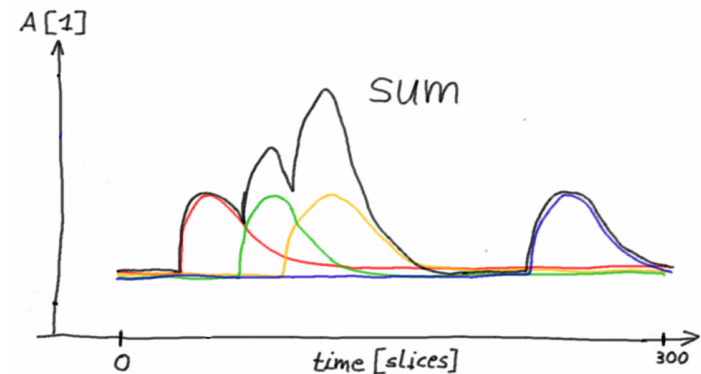
Night 20151113, Run 109, Event 159



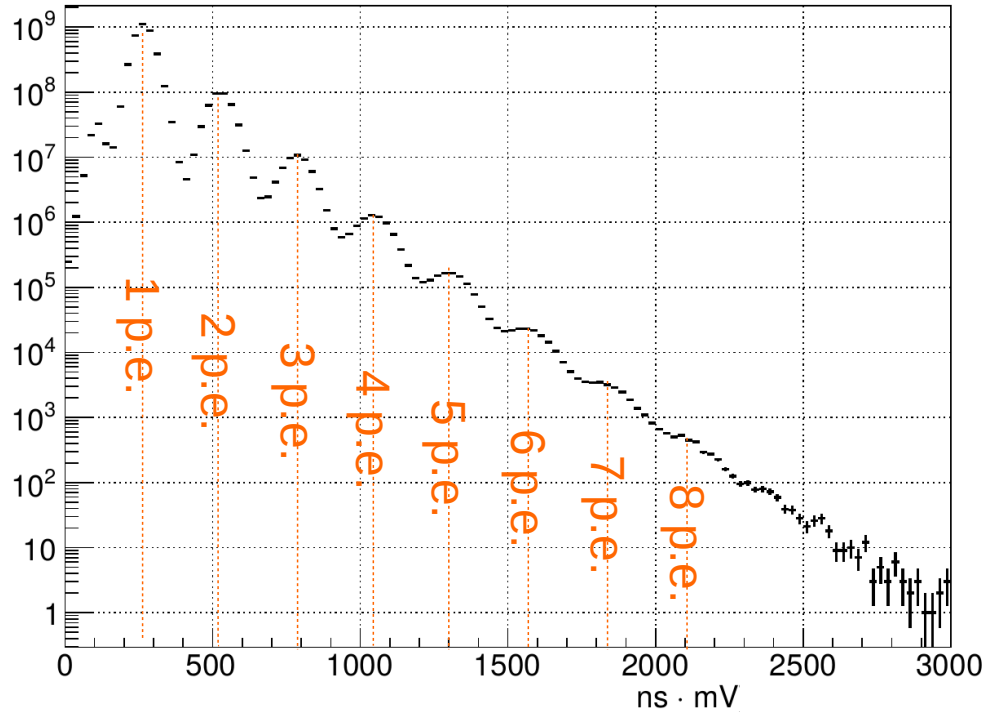
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Conclusion

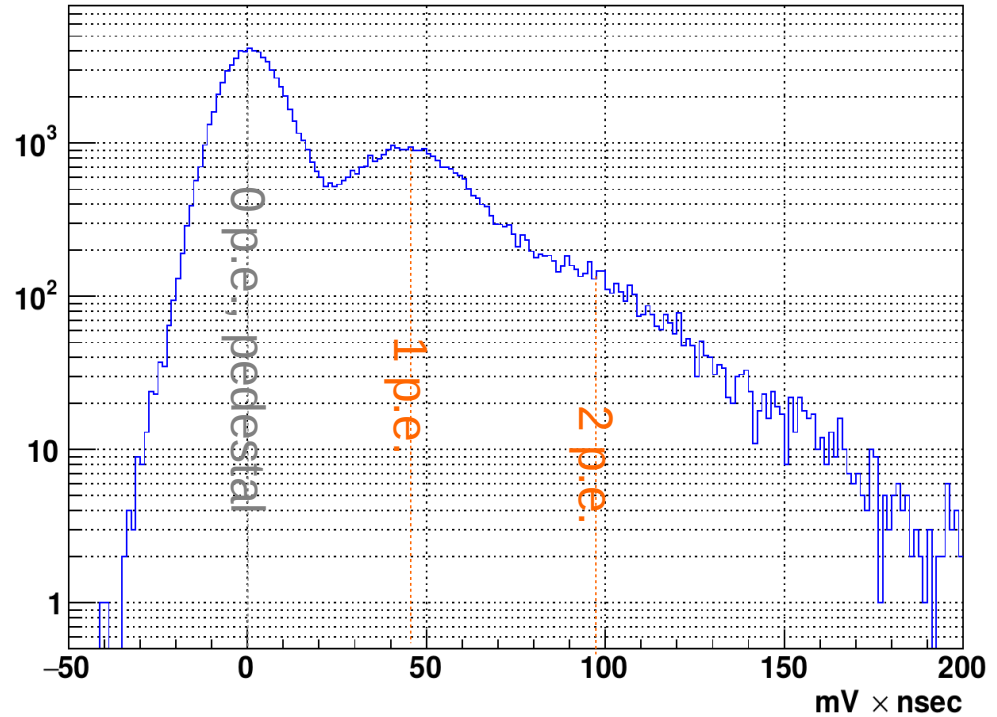


FACT, SiPM



'Calibration and performance of the photon sensor response of FACT – the first G-APD Cherenkov telescope', Biland et al., Journal of Instrumentation, Volume 9, Number 10, 2014

CTA LST, PMT



'Development of the photomultiplier tube readout system for the first Large-Sized Telescope of the Cherenkov Telescope Array', by Masuda et al., The 34th International Cosmic Ray Conference, arXiv preprint arXiv:1509.00548, 2015