Real-time small-size space debris detection with Eiscat radar facilities

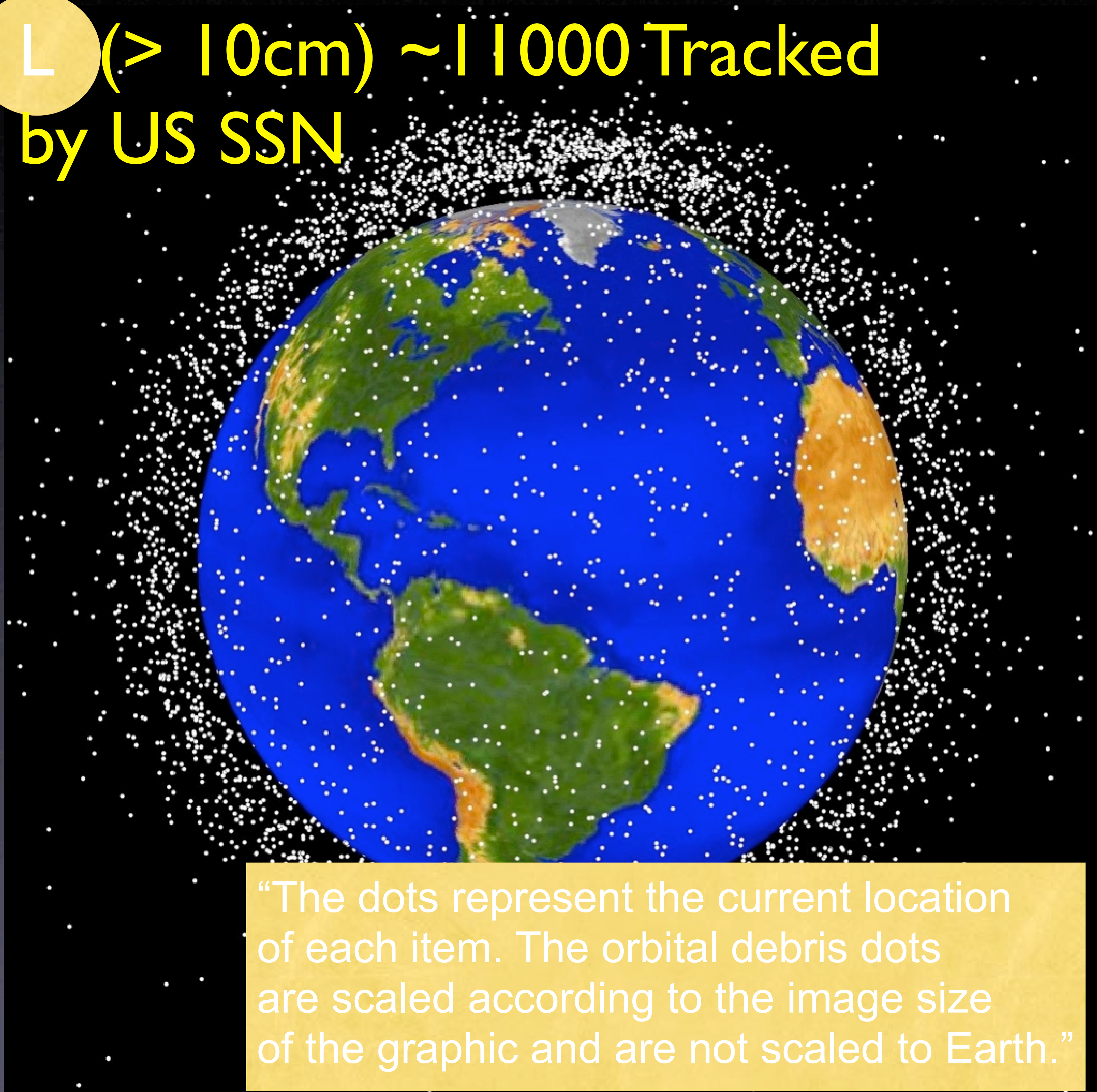
INTRODUCTION

Study objectives

- Based on developments of the precursor study,
- Develop methods to perform real-time detection of small-sized space debris objects in LEO during routine Eiscat operations,
- Demonstrate real-time detection during standard Eiscat experiment campaigns.

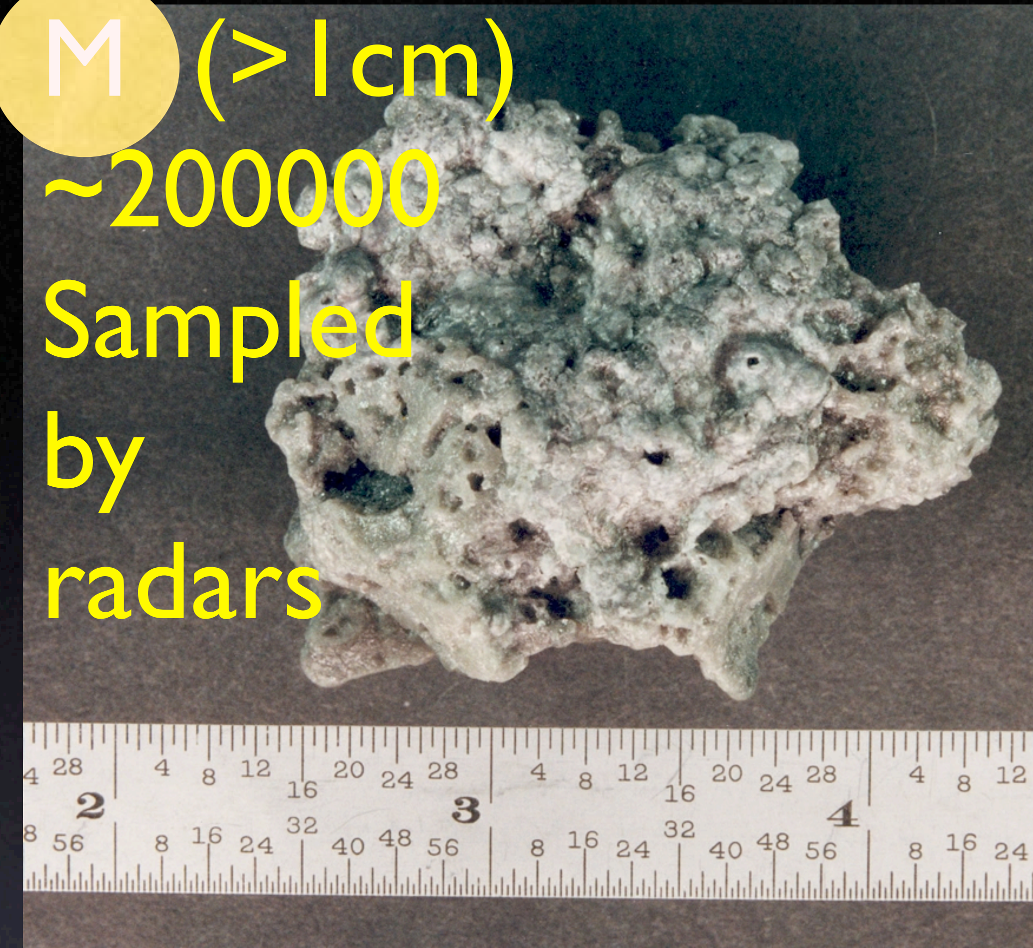
Debris

L (> 10cm) ~11000 Tracked by US SSN

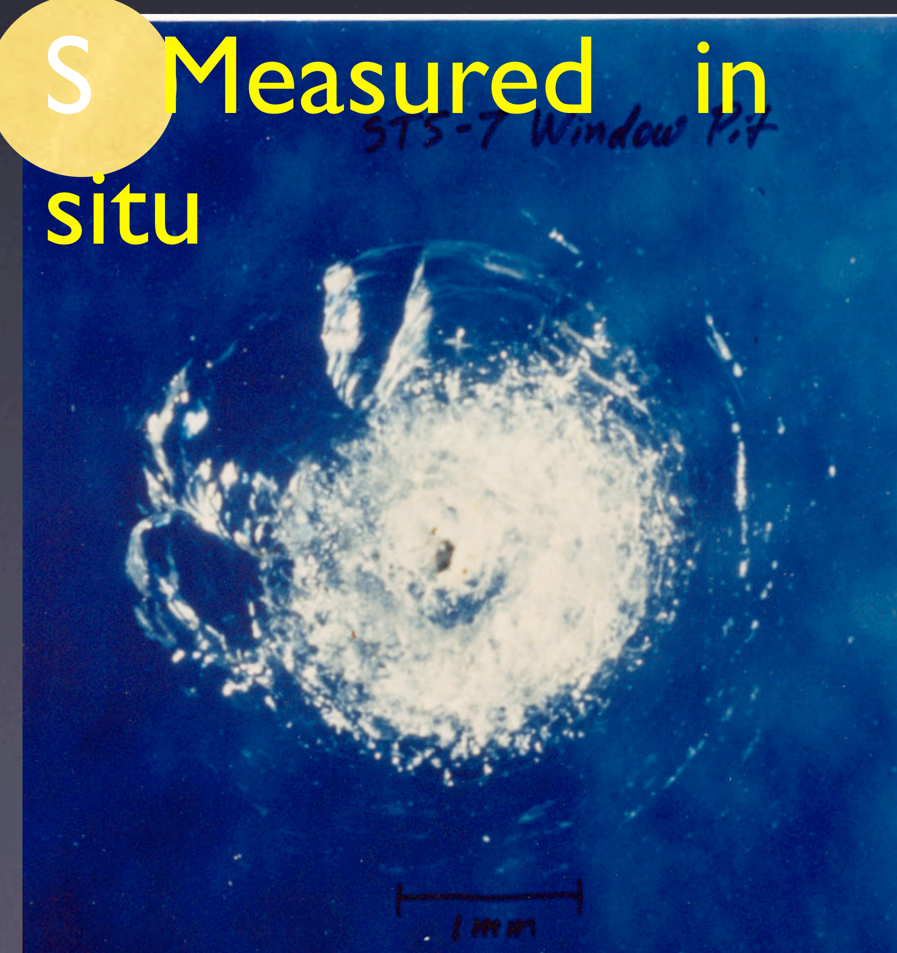


"The dots represent the current location of each item. The orbital debris dots are scaled according to the image size of the graphic and are not scaled to Earth."

M (>1cm) ~200000 Sampled by radars



S Measured in situ



Precursor study

- SGO, 2000-2001, lead by M Lehtinen.
- Matlab-based SW implements GMF method.
- Both detection and analysis done off-line.
- 4.1 h of analysed cp1lt, tau2 UHF data: 56 events.
  - “Piggy-backing” SD on Eiscat OK.
  - Sensitivity “2cm at 1000 km range”, but ...
- Coherent integration’s efficiency unknown. Etc.

Present study

- Eiscat, 2002-2003, lead by M Postila.
- c- and Matlab-based SW implements MF method.
- Detection on-line. Analysis on-line or off-line.
- Two copies of measurement HW.

Present study (cont'd)

- 157 h of analysed UHF data: 2560 events.
  - Piggy-backing SD on Eiscat routinely OK.
  - Sensitivity "2 cm at 1000 km range", but ...
- Coherent integration's efficiency unknown. Etc.

WP structure of the study

- Updating of the data processing methods and algorithms.
- Real-time detection and parameter estimation of space debris echos in raw data acquired during the precursor study.
- Real-time detection during routine operations of one selected Eiscat radar facility.
- Investigation of the Possibilities of Orbital Parameter Determination with the Eiscat radars.

Structure of this talk

- Introduction
- Hardware
- Measurement theory
- Software
- Measurement results
- Summary

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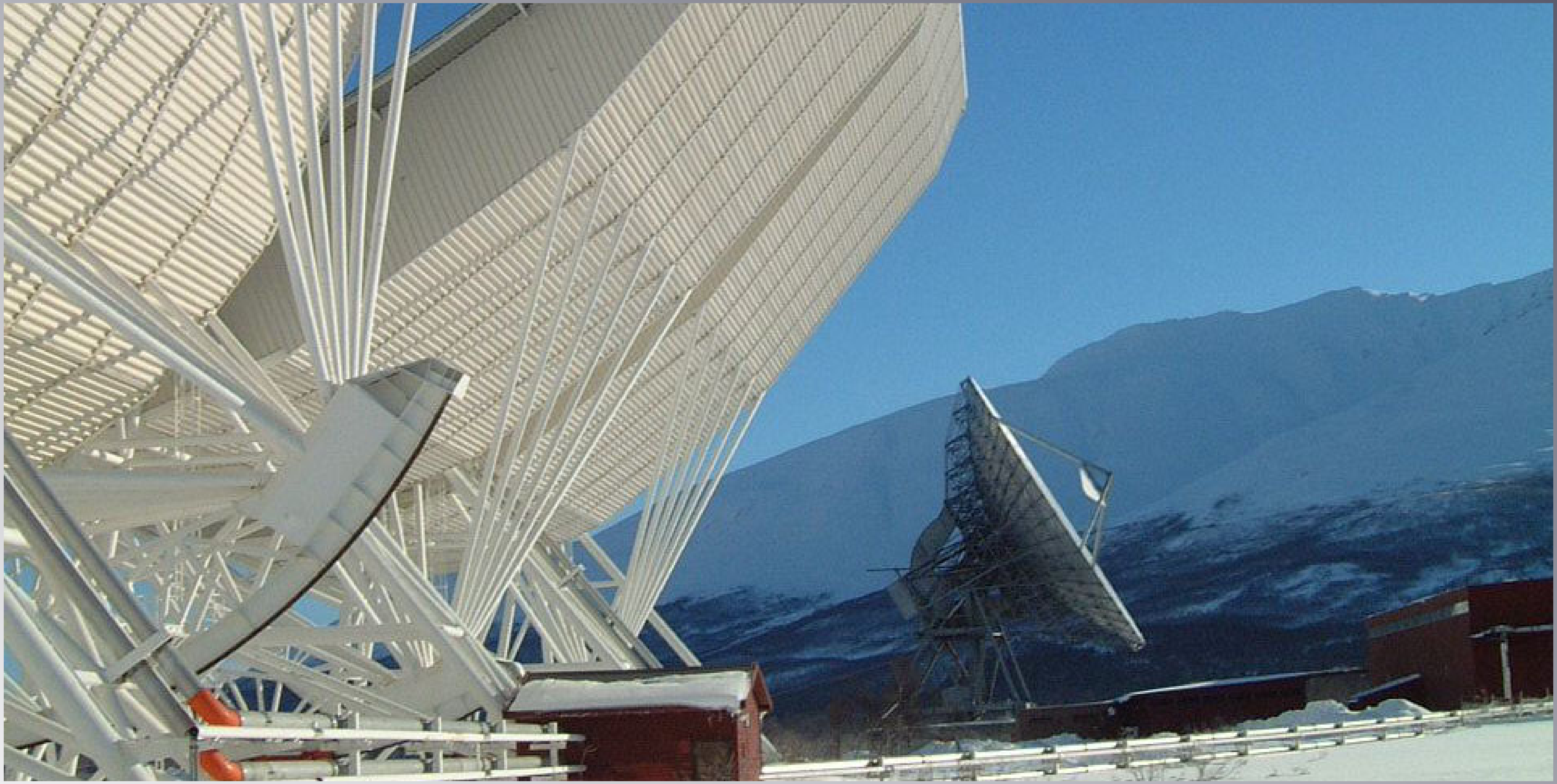
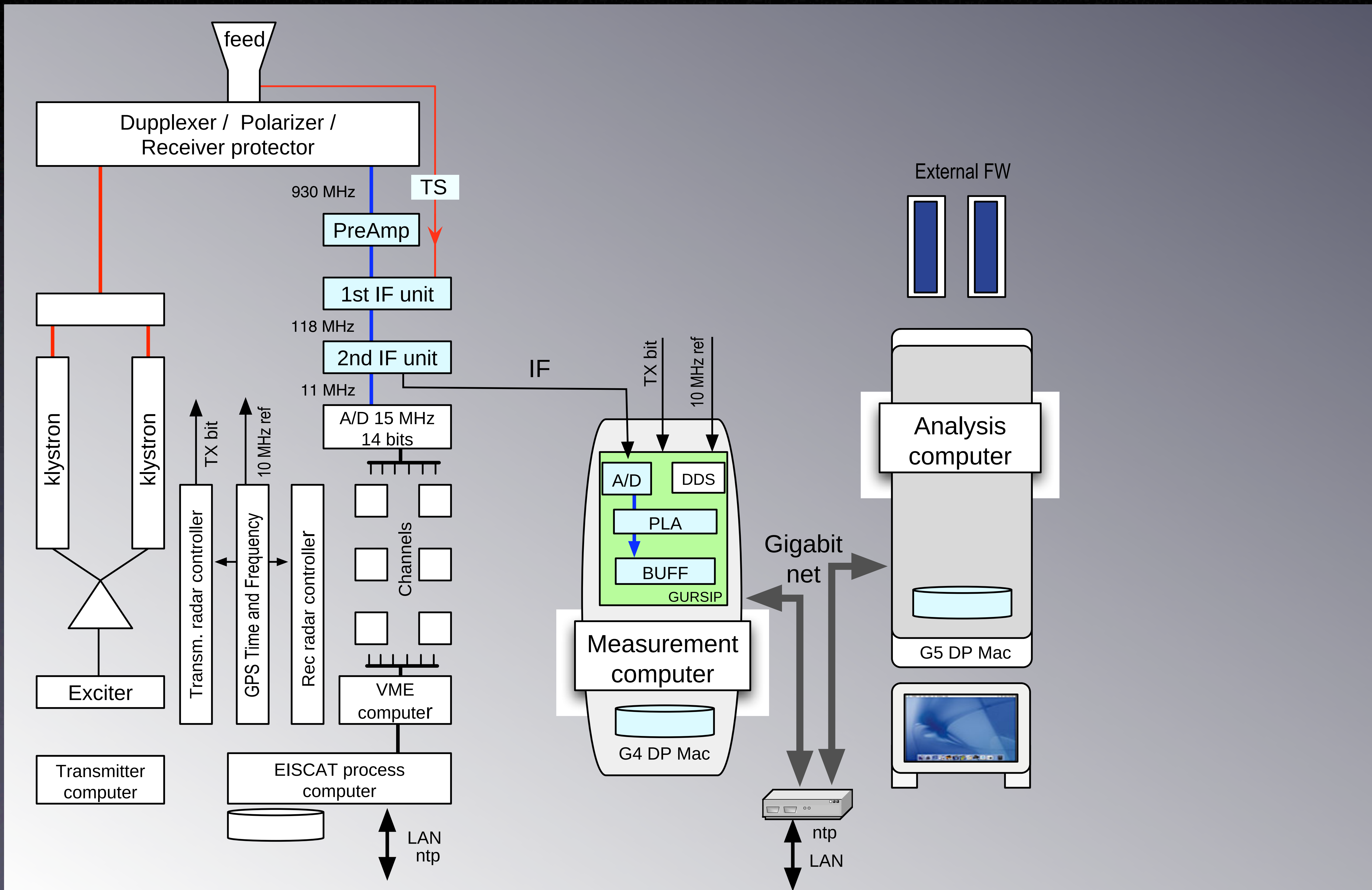
HARDWARE

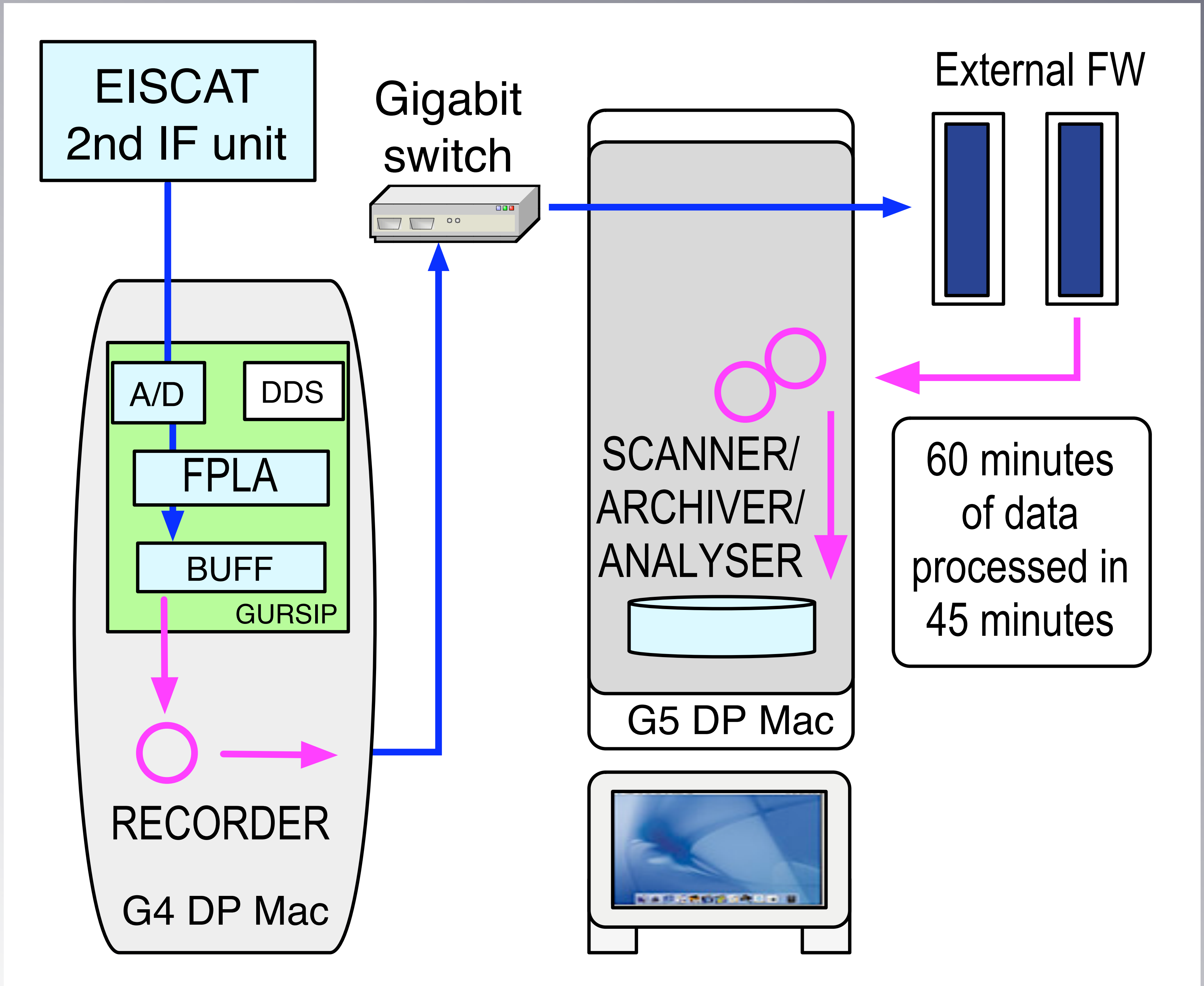
EISCAT radars



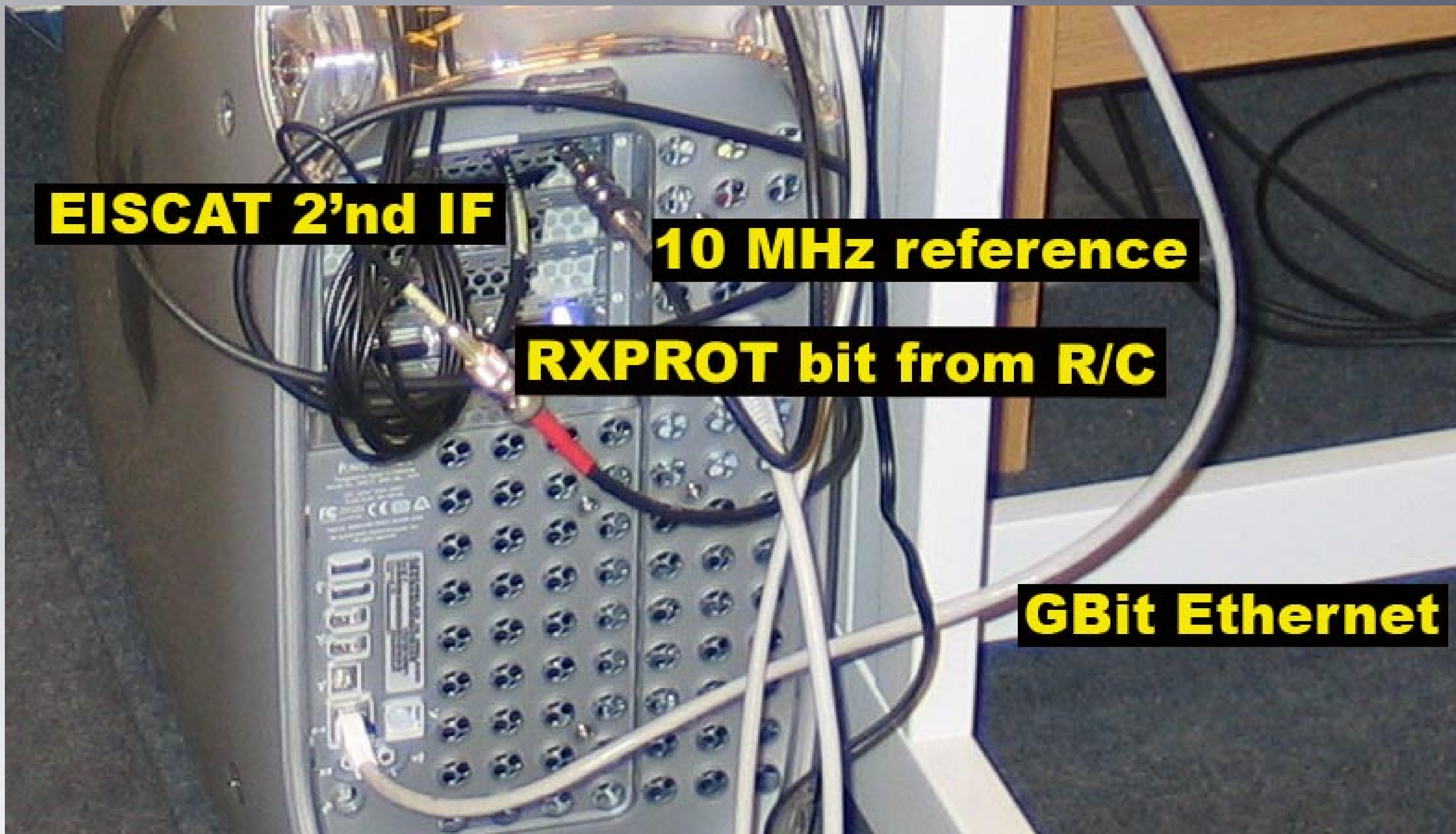
Tromsø UHF & SD receiver



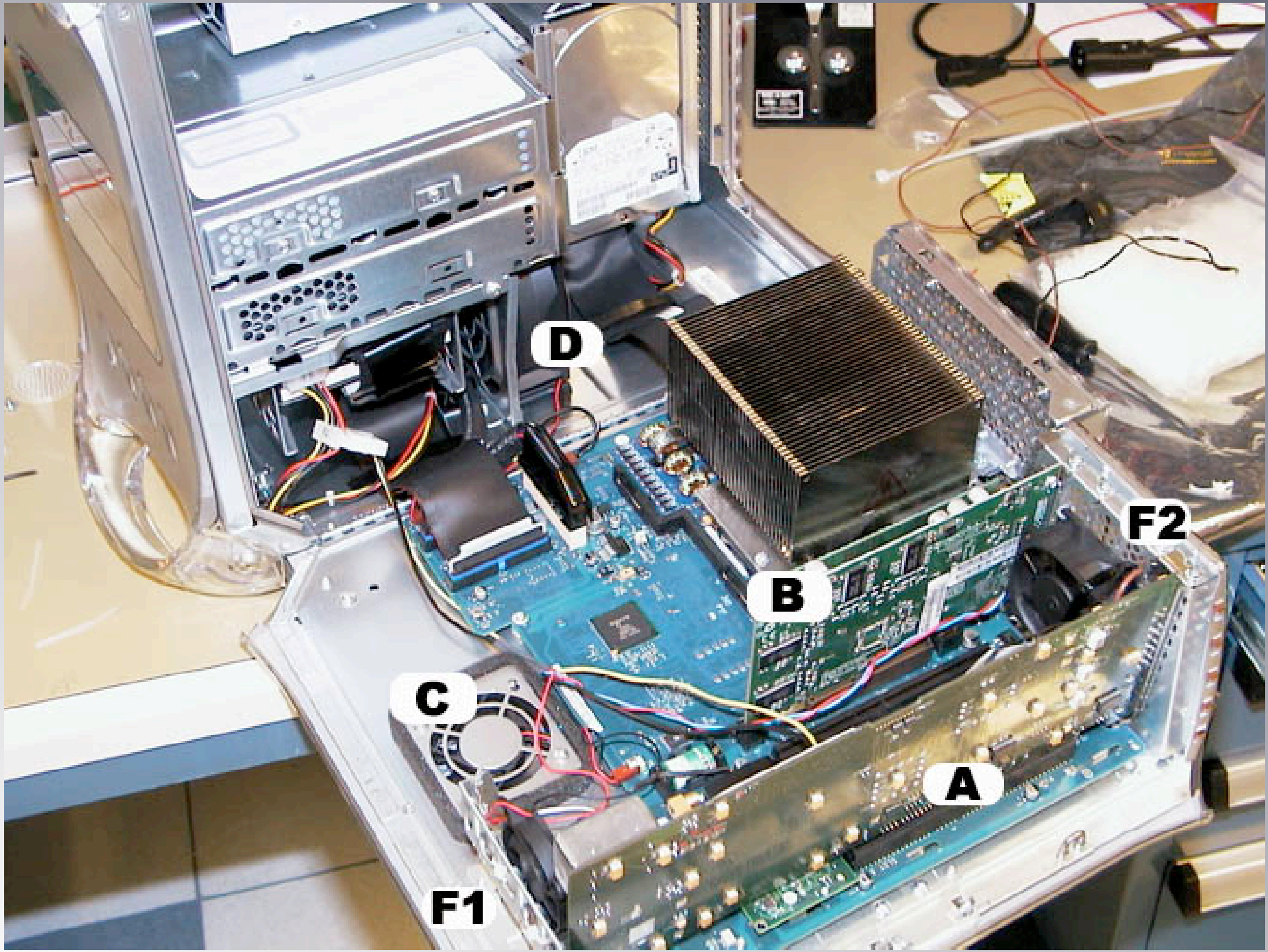
The SD receiver



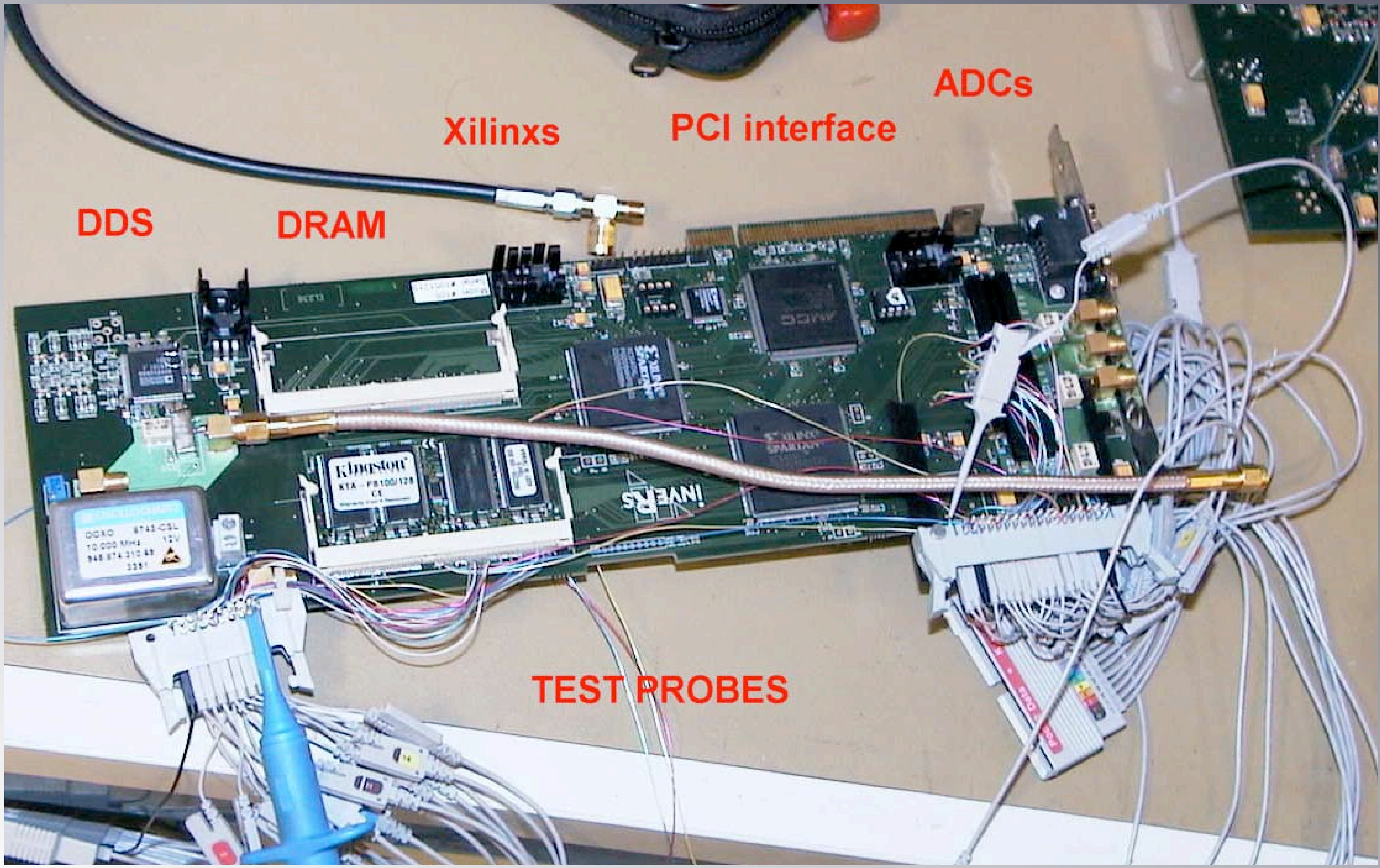
The measurement computer



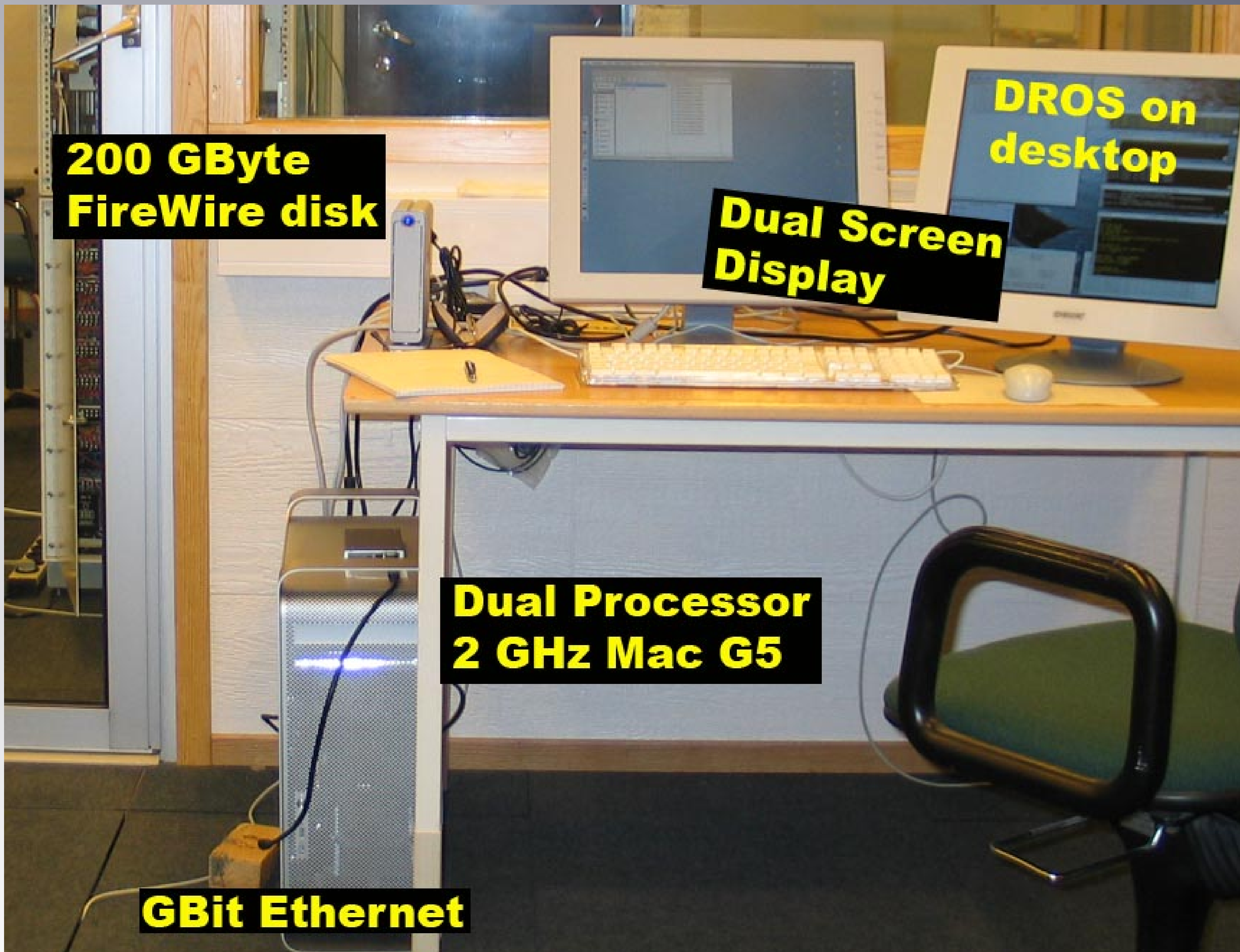
The measurement computer



The SD receiver board



The analysis computer



Real-time small-size space debris detection with Eiscat radar facilities

THEORY

Measurement theory

Requested:

$$R,\ v_r\ a_r\ W_s$$

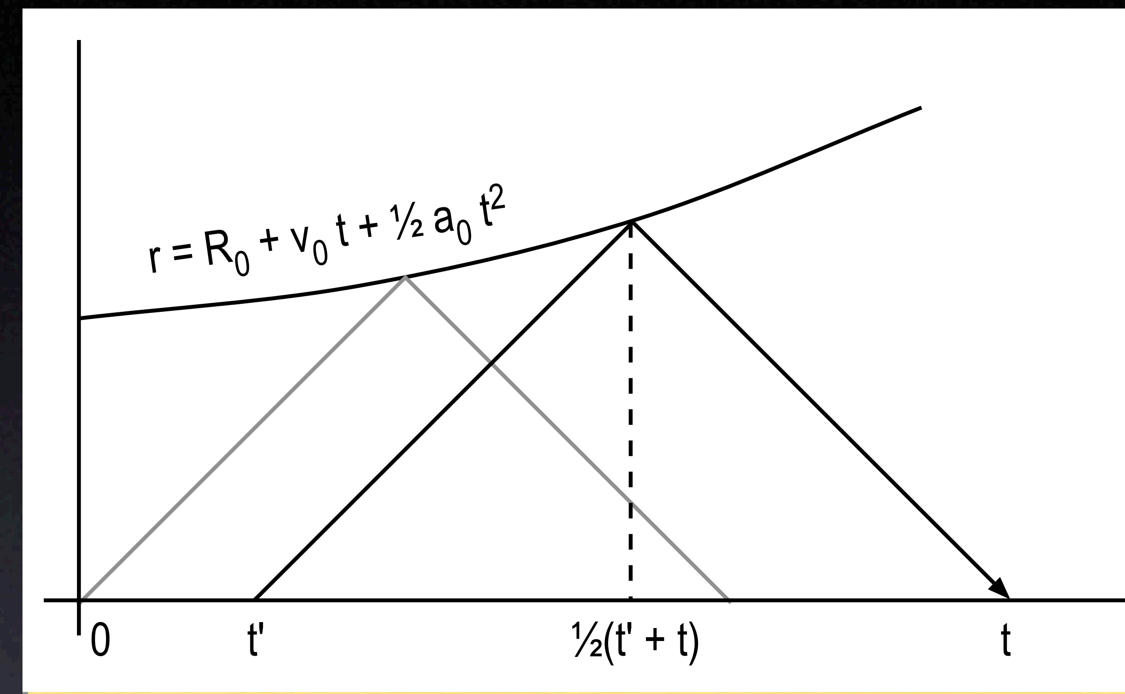
Received signal is

$$z(t) = s(t) + \gamma(t)$$

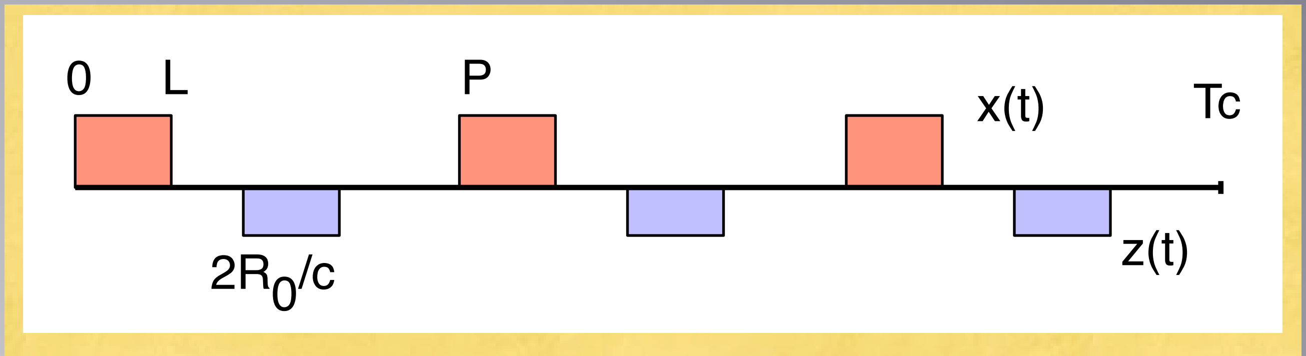
$$s(t) = b \cdot \chi(\theta; t)$$

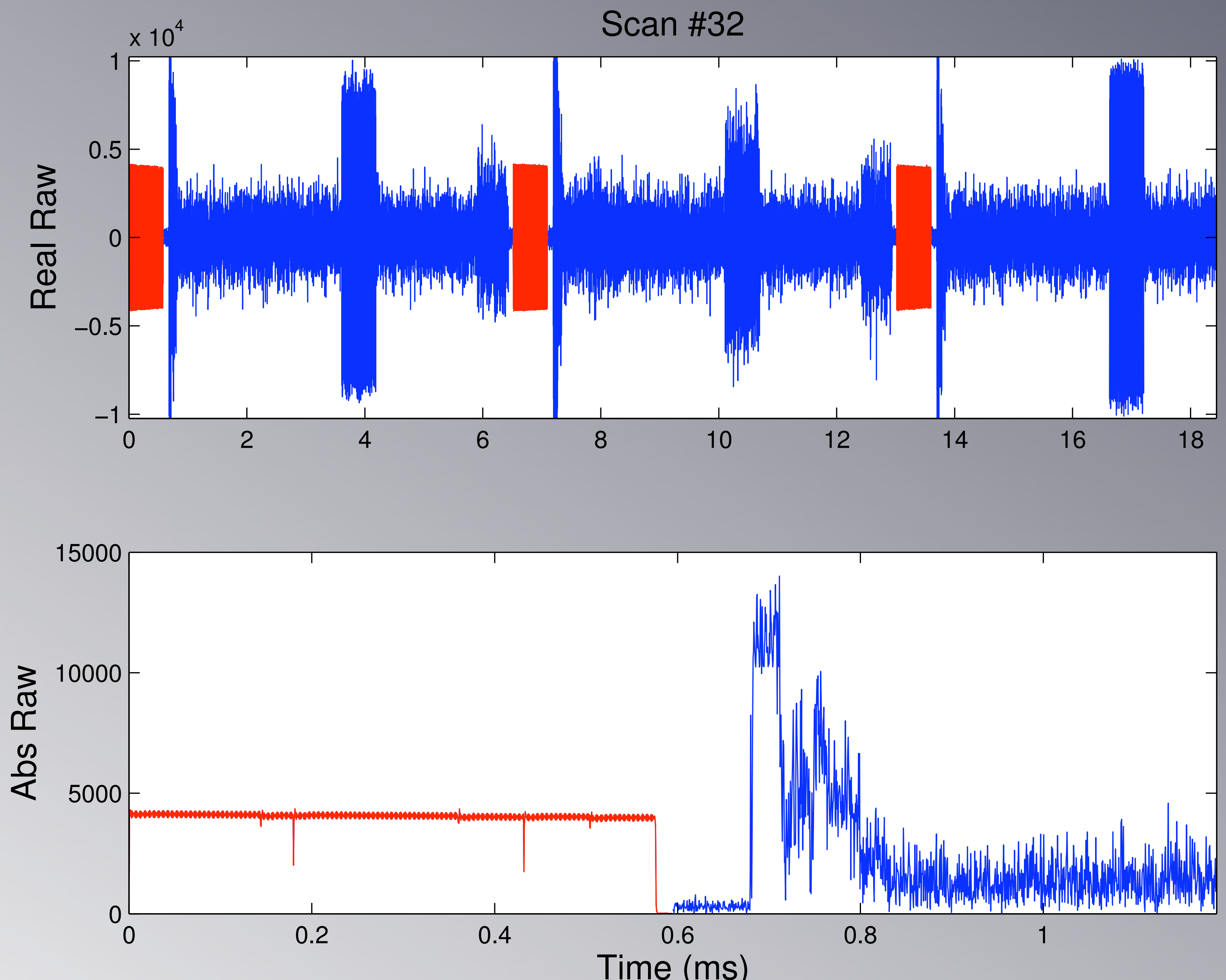
Available: sample vector

$$z_n = z(n \cdot \tau_{\mathrm{s}})\ \ , n = \ldots 10^5$$

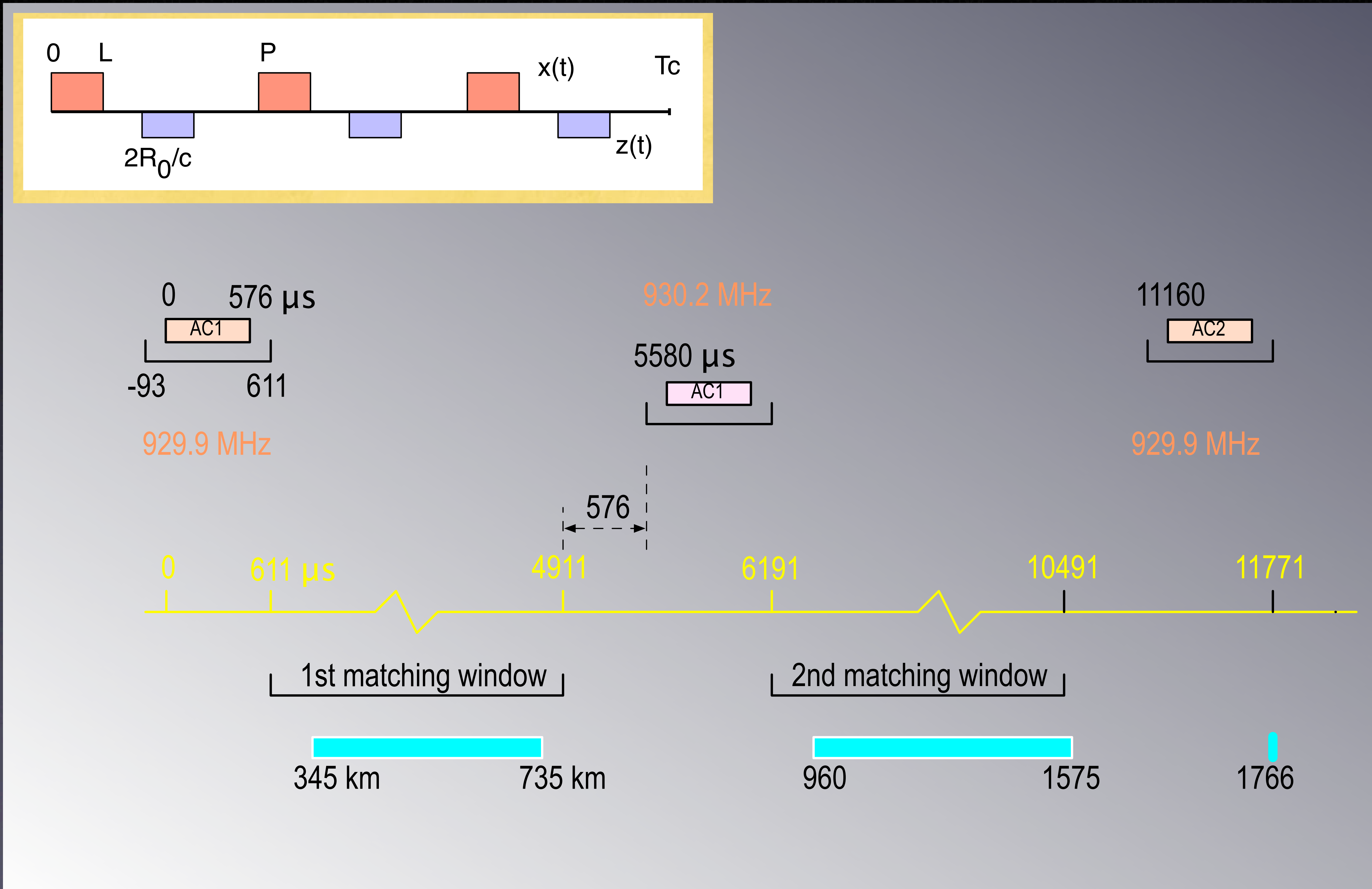


Raw data





Tau2 transmission



Inversion solution

Posteriori density (with constant prior)

$$D_{\mathrm{p}}(b, \theta | z) = C(z) \cdot \mathrm{e}^{-\frac{1}{\sigma^2}\|z - b \cdot \chi(\theta)\|^2}$$

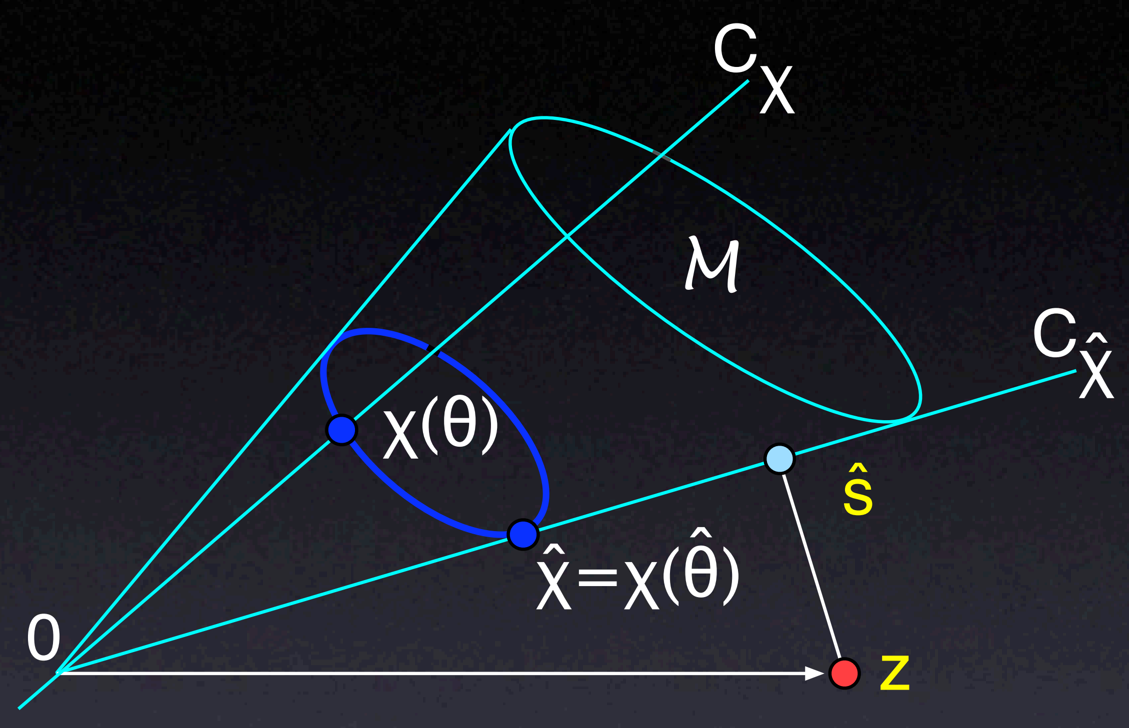
Bayesian parameter estimate

$$(\widehat{b}, \widehat{\theta}) = \arg\max_{b,\theta} D_{\mathrm{p}}(b, \theta | z)$$

In practice

Define *match function*

$$\mathrm{MF}(\theta) = \frac{|\langle z, \chi(\theta)\rangle|}{\|\chi(\theta)\|}$$



Then

$$\widehat{\theta} = \arg\max_{\theta} \mathrm{MF}(\theta)$$

The work goes here

$$\widehat{s} = \frac{\langle z, \widehat{\chi}\rangle}{\|\widehat{\chi}\|^2}\widehat{\chi}$$

$$\text{where } \widehat{\chi} = \chi(\widehat{\theta})$$

Signal energy estimate

For correctly sampled voltages x(t), energy is

$$W_x = \int |x(t)|^2 dt \approx \tau_\mathrm{s} \sum |x_n|^2 = \tau_\mathrm{s} \|x\|^2$$

Use

$$\widehat{W}_s = W_{\widehat{s}}$$

Then

$$\widehat{\mathrm{SNR}}_\mathrm{N} \equiv \frac{\widehat{W}_s}{kT_\mathrm{sys}} \approx \frac{\max \mathrm{MF}^2}{\sigma^2}$$

Target detection

Detection criterion

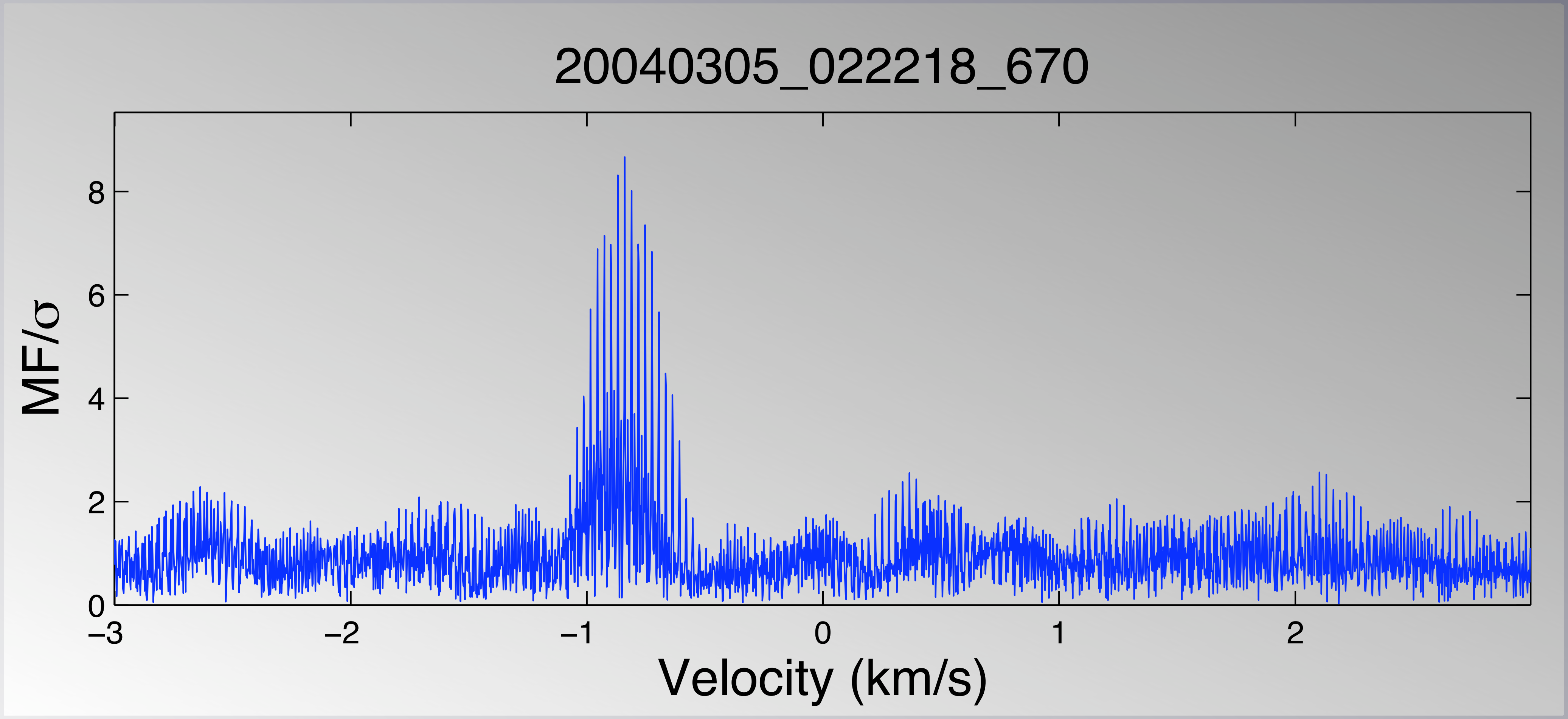
$$\sqrt{\widehat{\mathrm{SNR}}_{\mathrm{N}}} = \frac{\max \mathrm{MF}}{\sigma} > \mathrm{Threshold}$$

Note! <u>Without</u> signal, with typical data,

$$\left\langle \frac{\max \mathrm{MF}}{\sigma} \right\rangle \approx 3$$

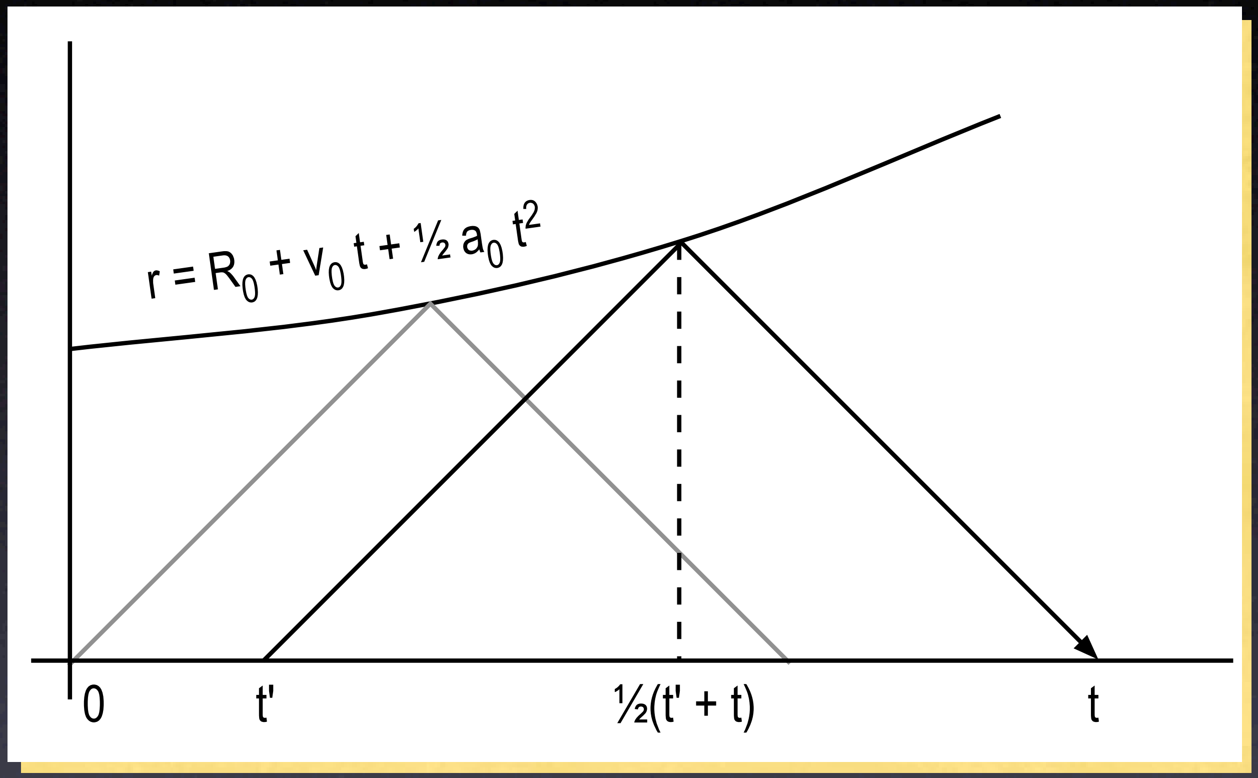
Structure of MF(R,v)

$$\max \frac{\mathrm{MF}(R,v)}{\sigma} = \frac{\|\widehat{s}\|}{\sigma}$$



Signal model x(t)

reception ∝ delayed transmission



$$s(t) = b\,\chi(t) = b\,x(t')$$

$$t - t' = \frac{2r(\frac{t'+t}{2})}{c}$$

$$t - t' = \frac{2c}{a_0}\left\{1 + \frac{v_0}{c} + \frac{a_0}{c}t - \left[1 + \frac{2v_0}{c} + \left(\frac{v_0}{c}\right)^2 + \frac{2a_0}{c}(t - \frac{R_0}{c})\right]^{\frac{1}{2}}\right\}$$

Approx. signal model

$$\chi(R, v, a; t) \approx x(t - \frac{2}{c} r(R, v, a; t - \frac{R}{c}))$$ OK

$$\approx x(t - \frac{2R}{c})\, \mathrm{e}^{i(\omega_\mathrm{D} t + \alpha_\mathrm{D} t^2)}$$?

$$\omega_\mathrm{D} = -\omega_1 \frac{2v}{c}$$

$$\alpha_\mathrm{D} = -\omega_1 \frac{a}{c}$$

Discretize

At the points

$$R_j = j \cdot \frac{c\tau_\mathrm{s}}{2}$$

$$v_k = k\frac{c}{\omega_1 T_\mathrm{c}}$$

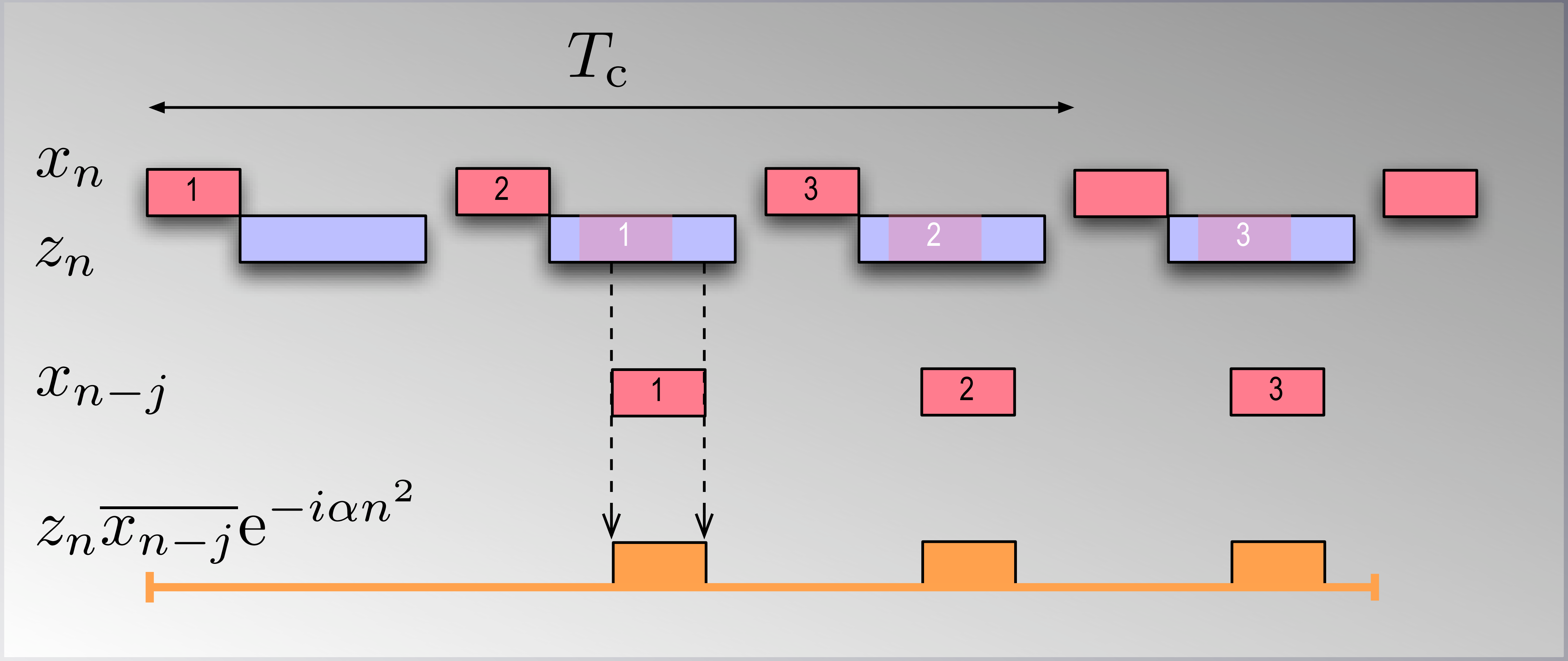
the match function becomes

$$\mathrm{MF}(R_j, v_k, a) = \frac{|\sum_{n=0}^{N-1}(z_n \overline{x}_{n-j}\mathrm{e}^{-i\alpha_\mathrm{d} n^2})\mathrm{e}^{-i\frac{kn}{N}}|}{\|x\|}$$

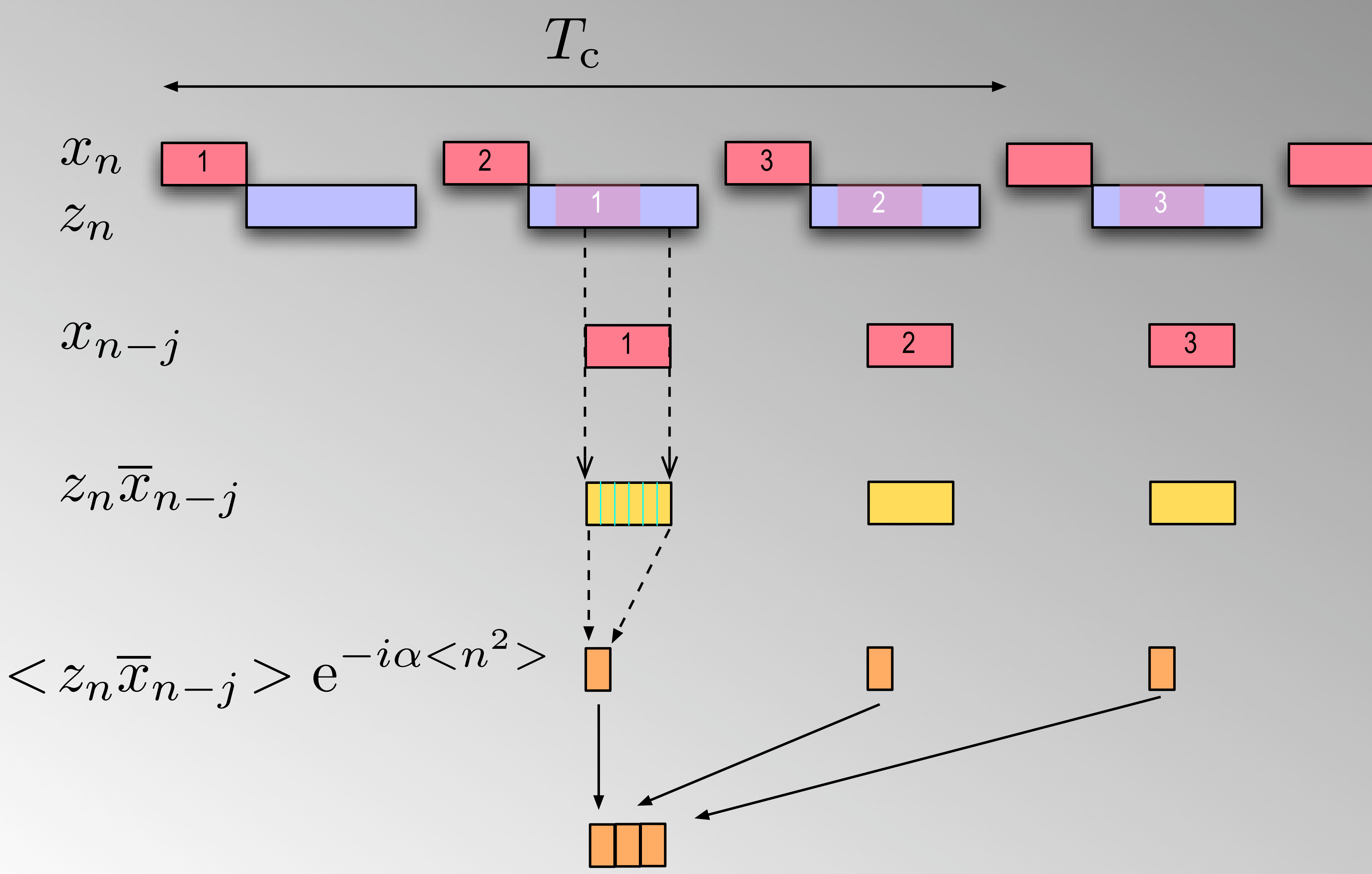
$$\alpha_\mathrm{d} = -\omega_1\tau_\mathrm{s}\frac{a\tau_\mathrm{s}}{c}$$

The MF algorithm

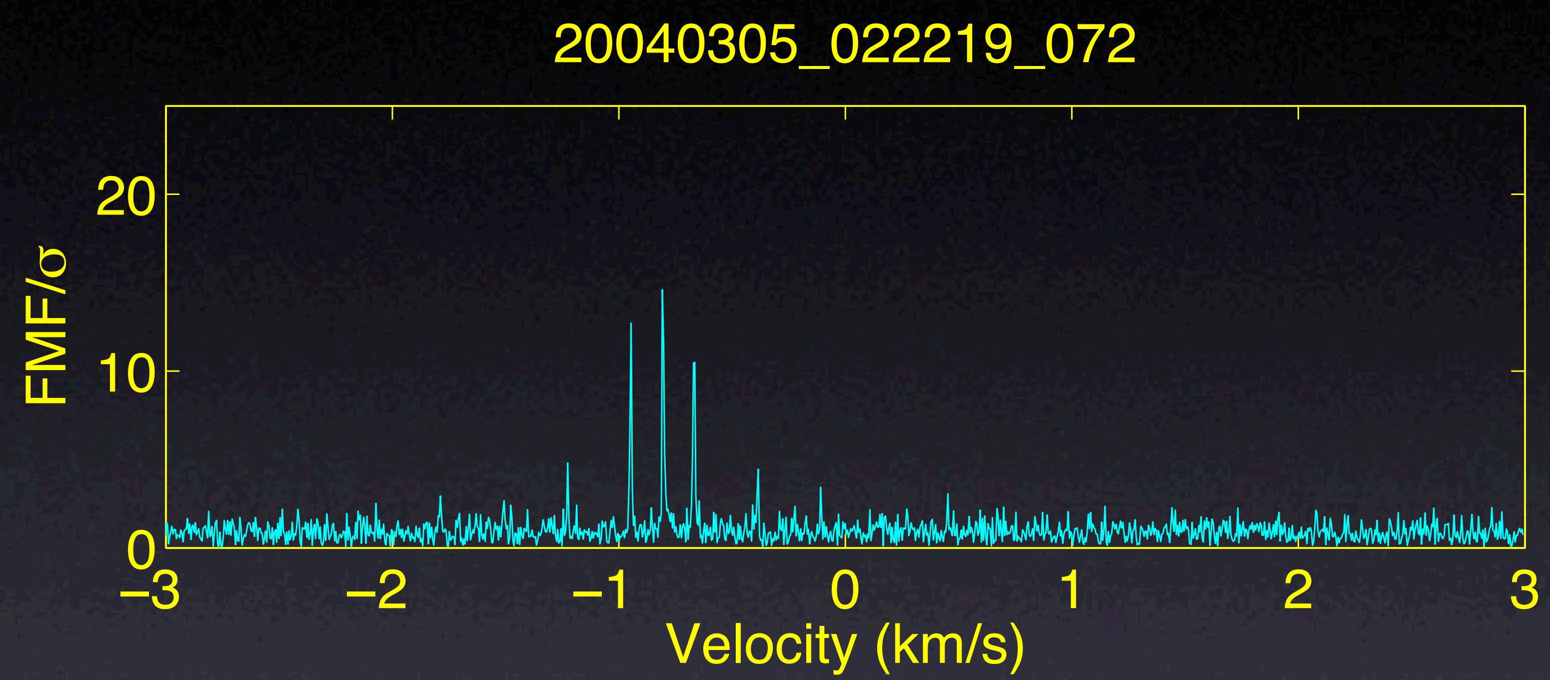
$$|\sum_{n=0}^{N-1}(z_n\overline{x}_{n-j}\mathrm{e}^{-i\alpha_{\mathrm{d}}n^2})\mathrm{e}^{-i\frac{kn}{N}}|$$



The FMF algorithm



FMF vs MF in detection



FMF

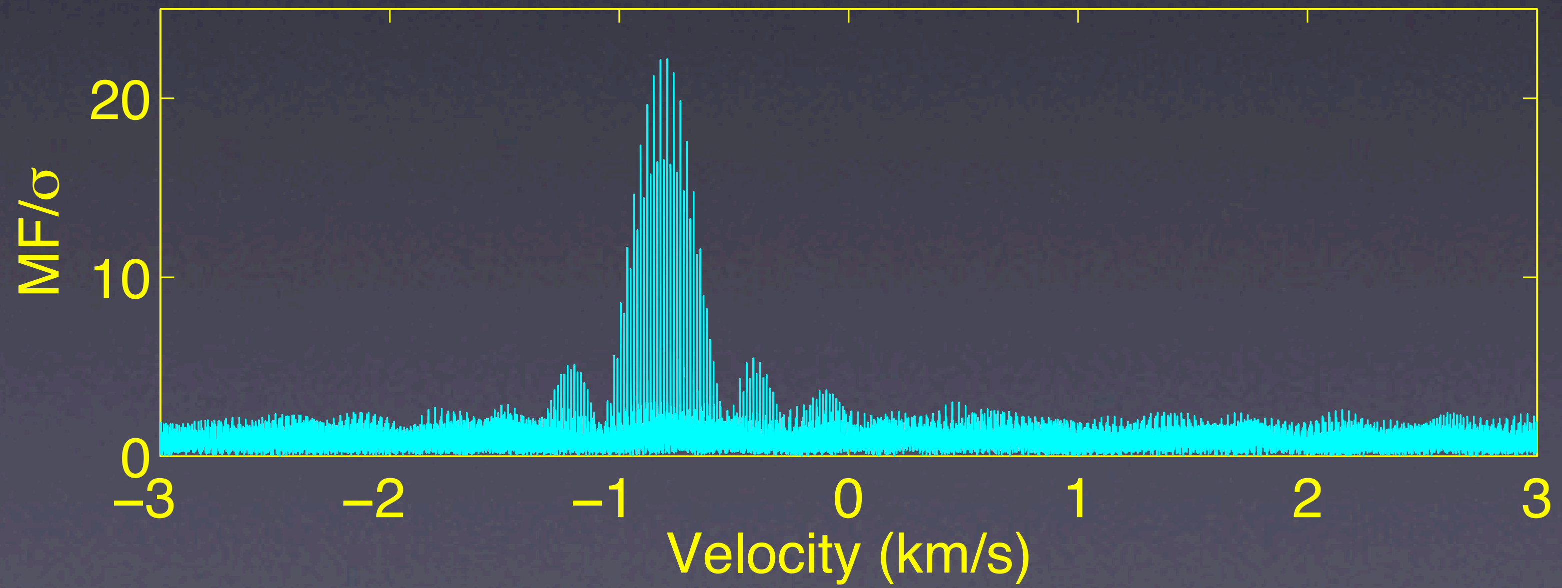
1800 Mflops /s

0.26 ms/range gate

max = 14.6

R = 1006.5 km

v = 0.802 km/s



MF

570 Mflops /s

44.9 ms/range gate

max = 22.2

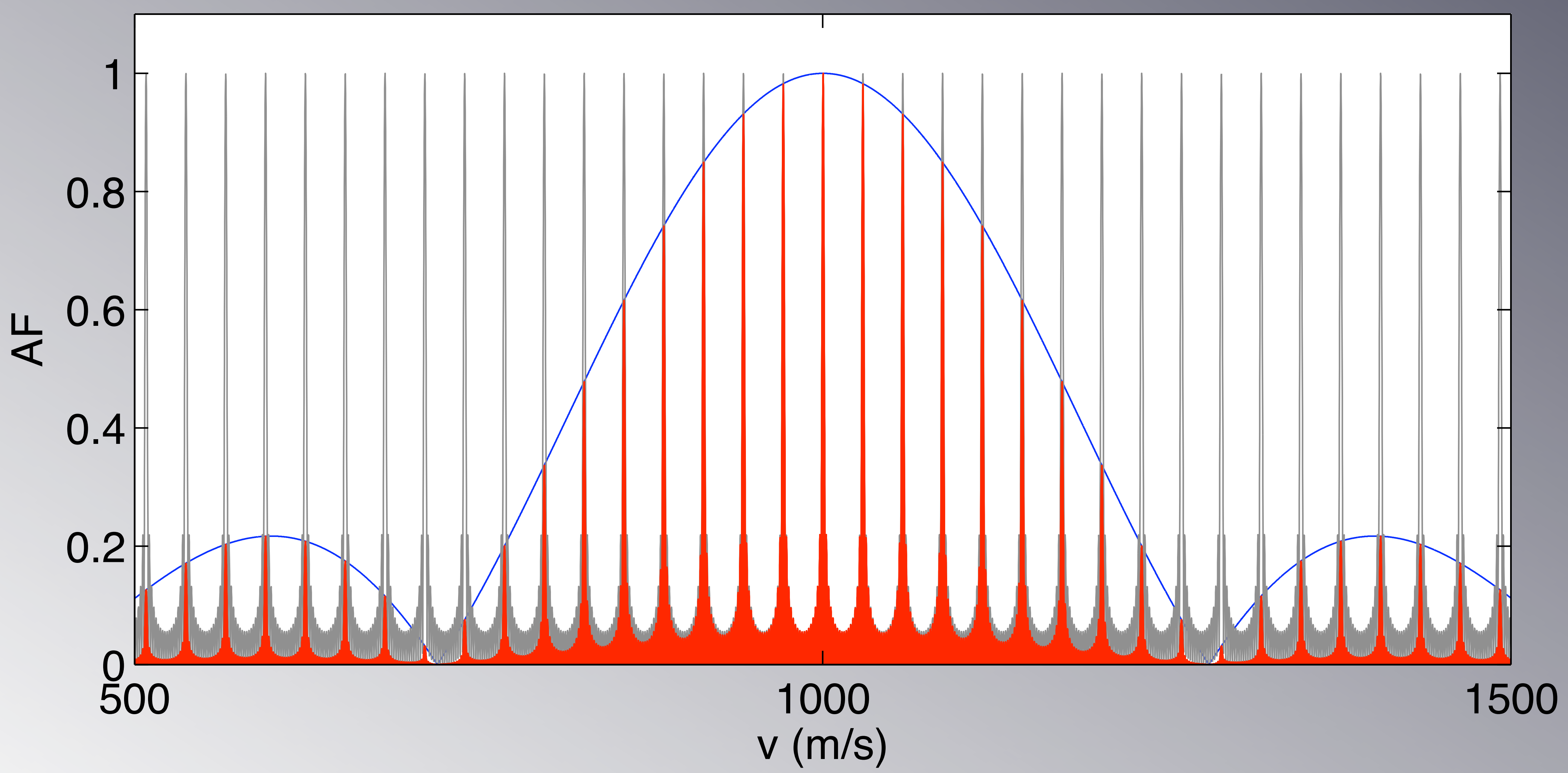
R = 1006.5 km

v = 0.791 km/s

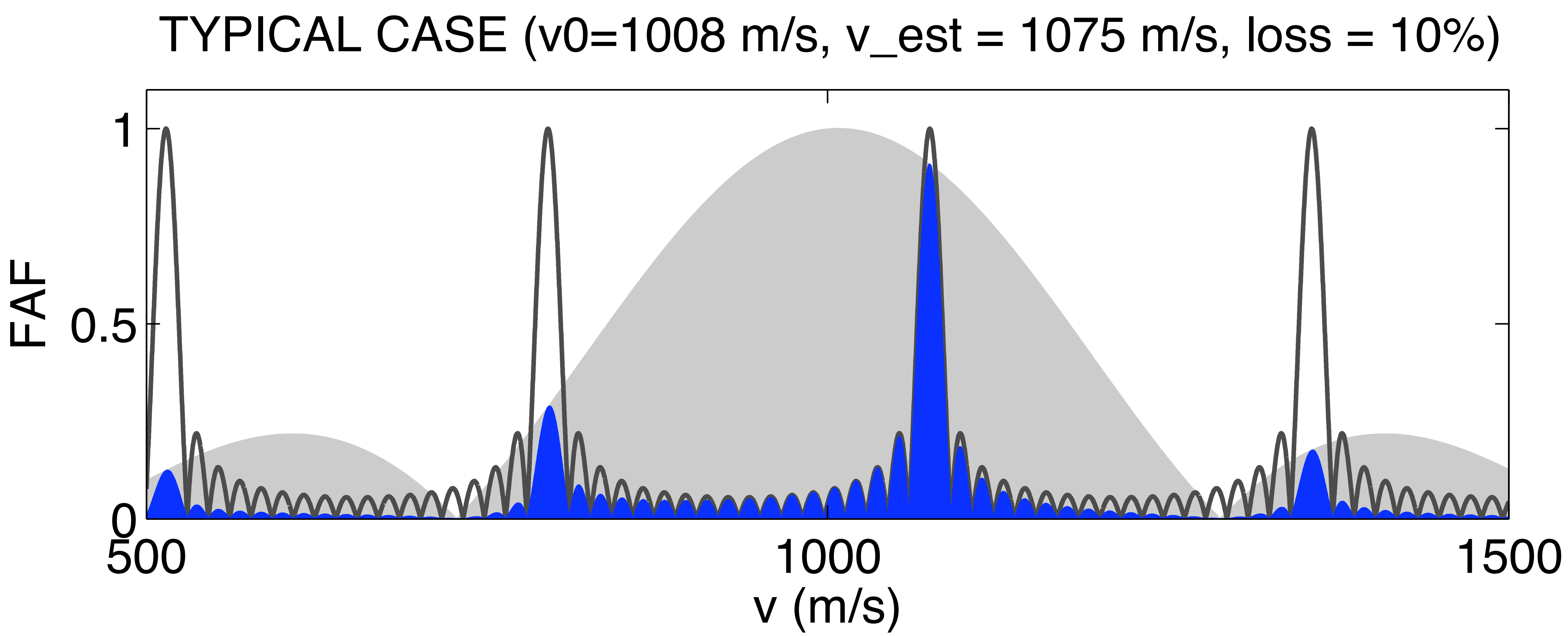
Properties of MF and FMF

- Structure of AF and FAF
- Velocity ambiguities, velocity “jumps”
- Lower bound of FMF/MF
- Effect of acceleration error
- Dual-frequency case

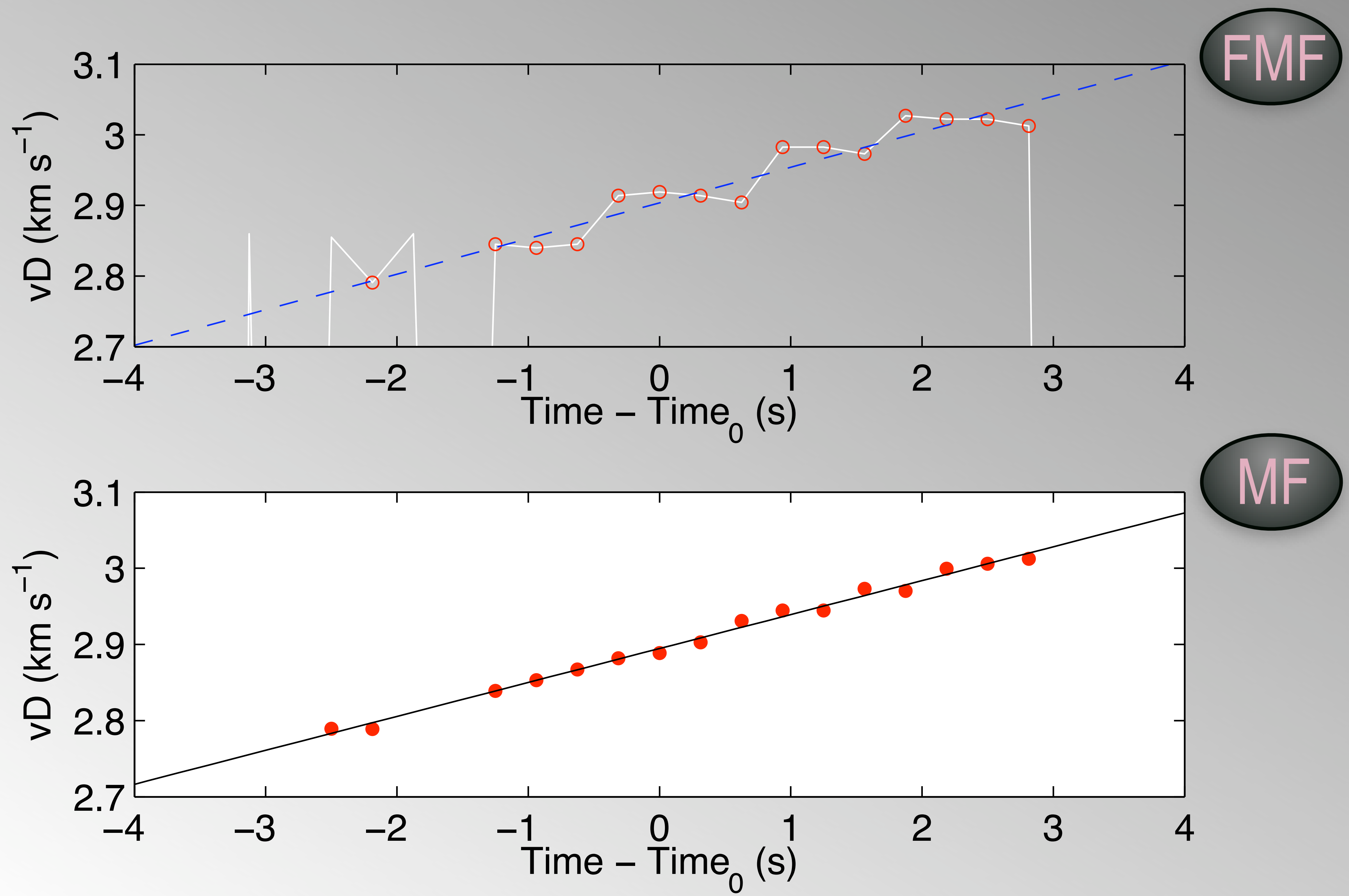
Structure of AF(R_0,v)



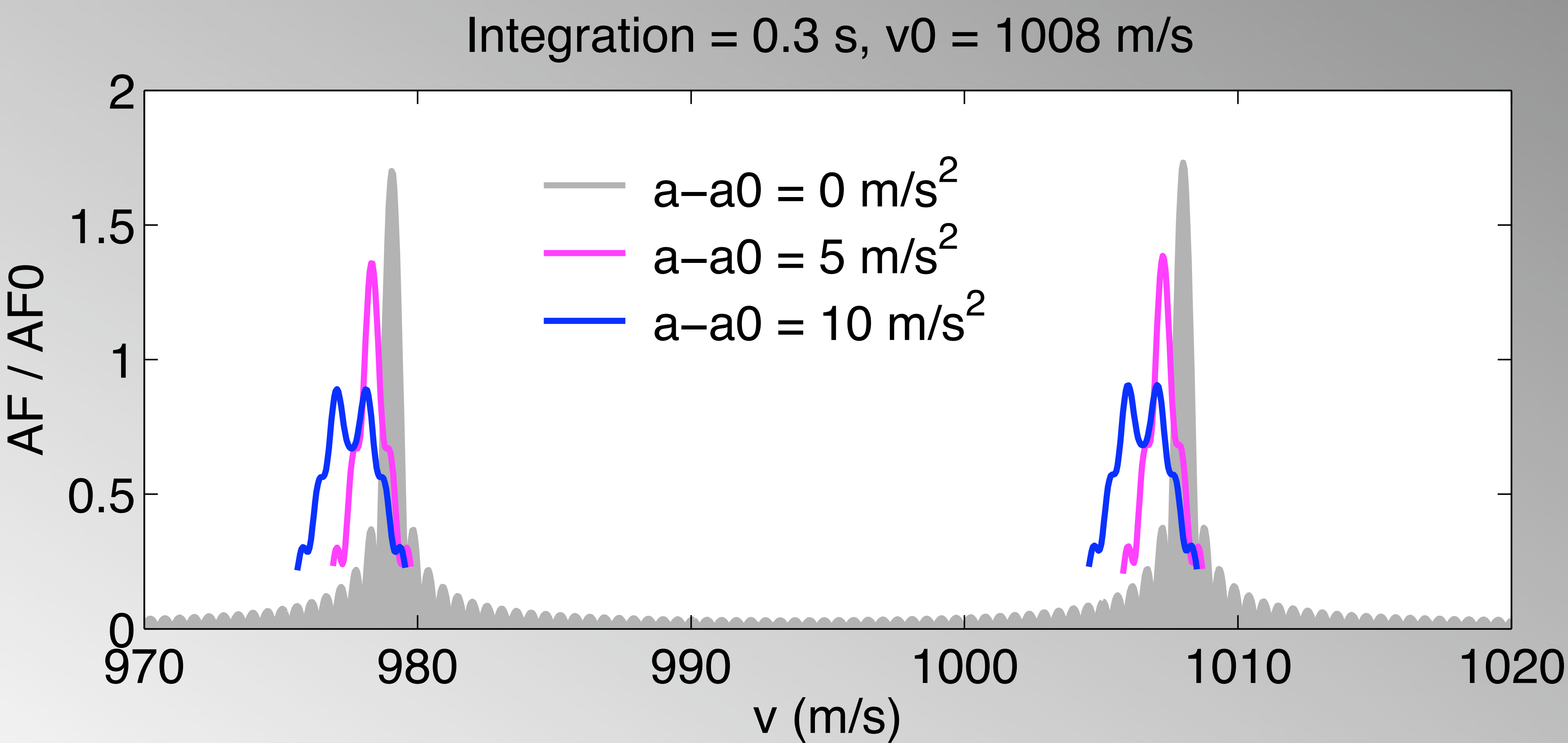
Structure of 1-freq FAF(R_0,v)



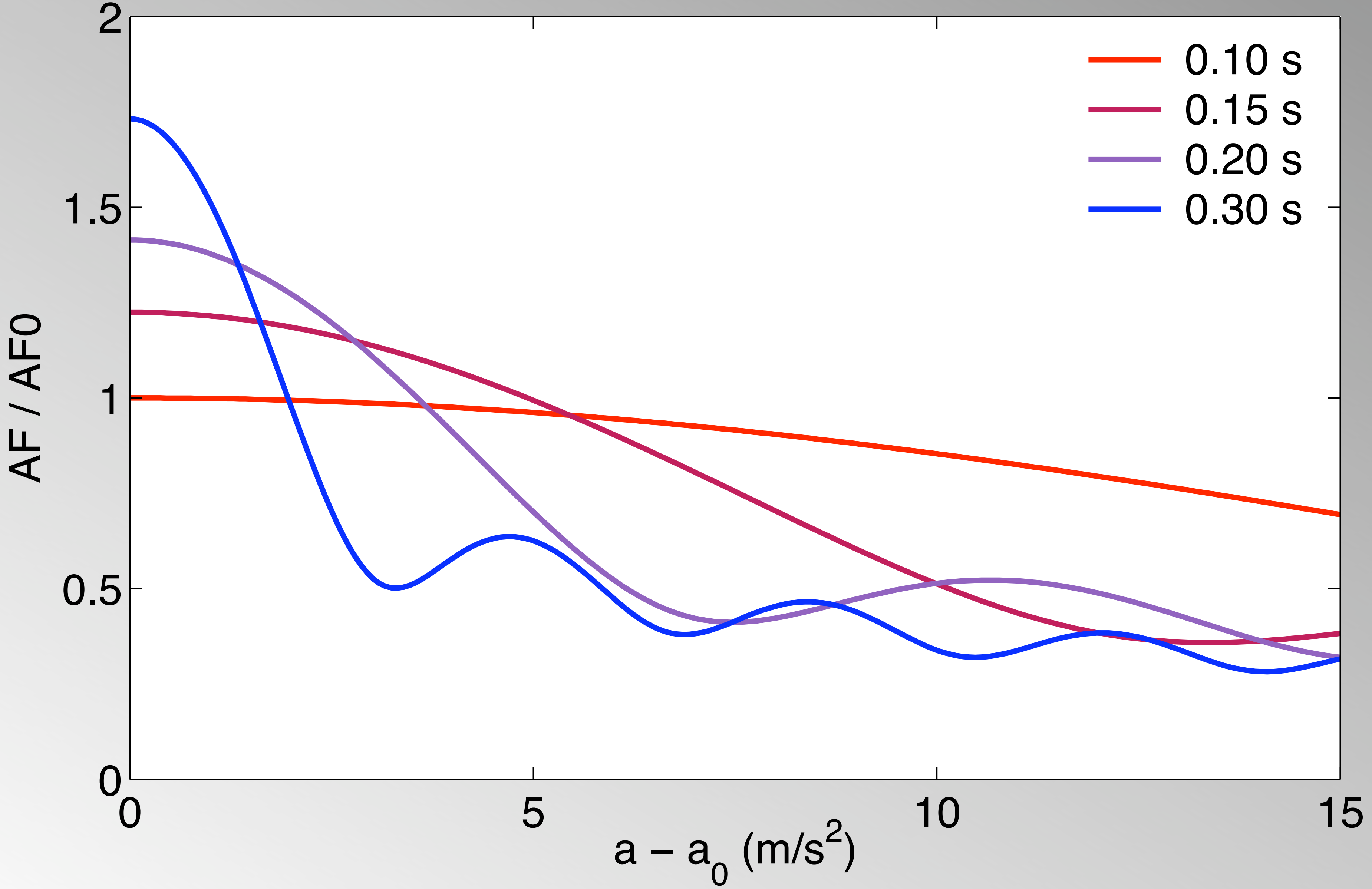
Velocity jumps



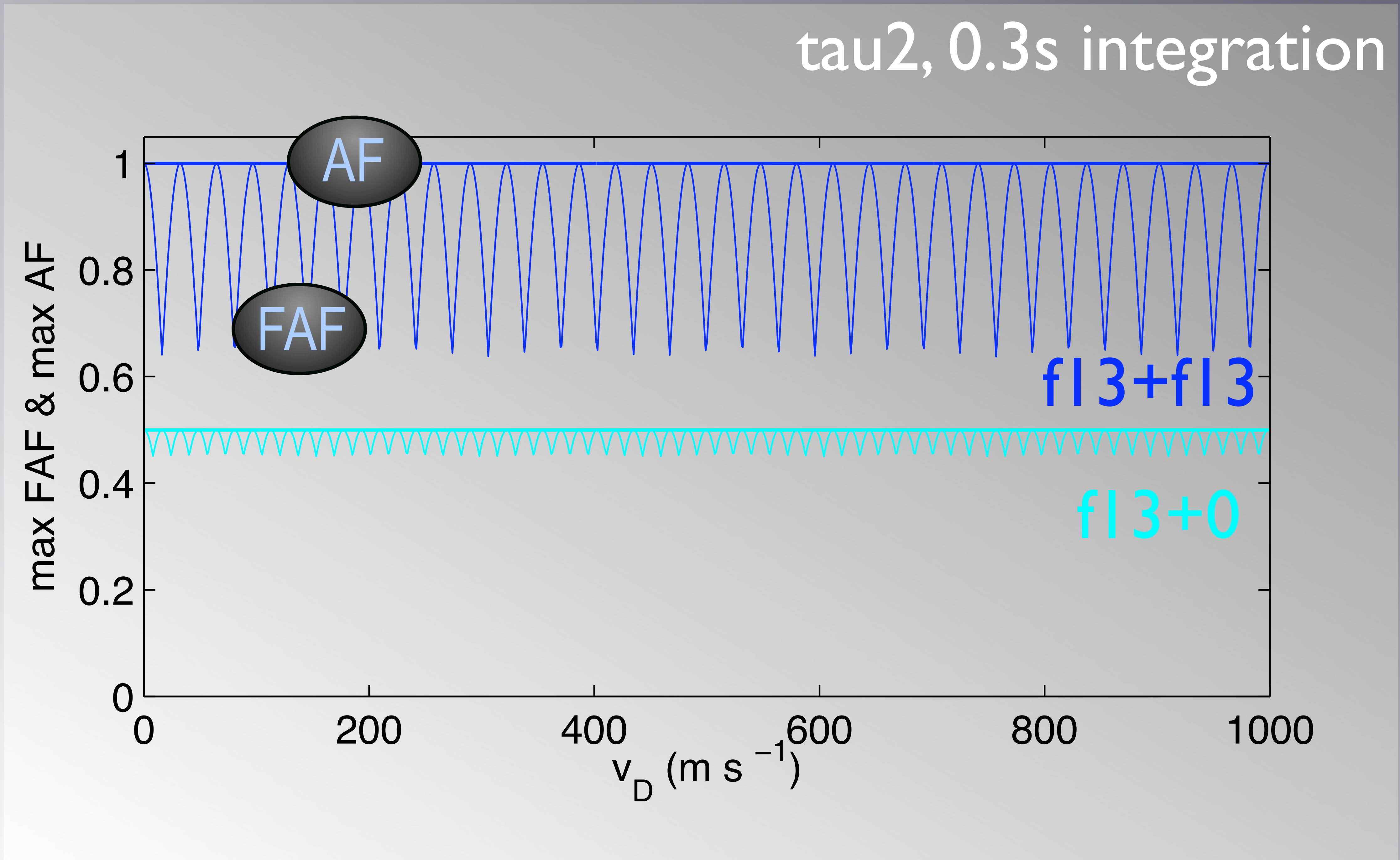
Effect of acceleration error



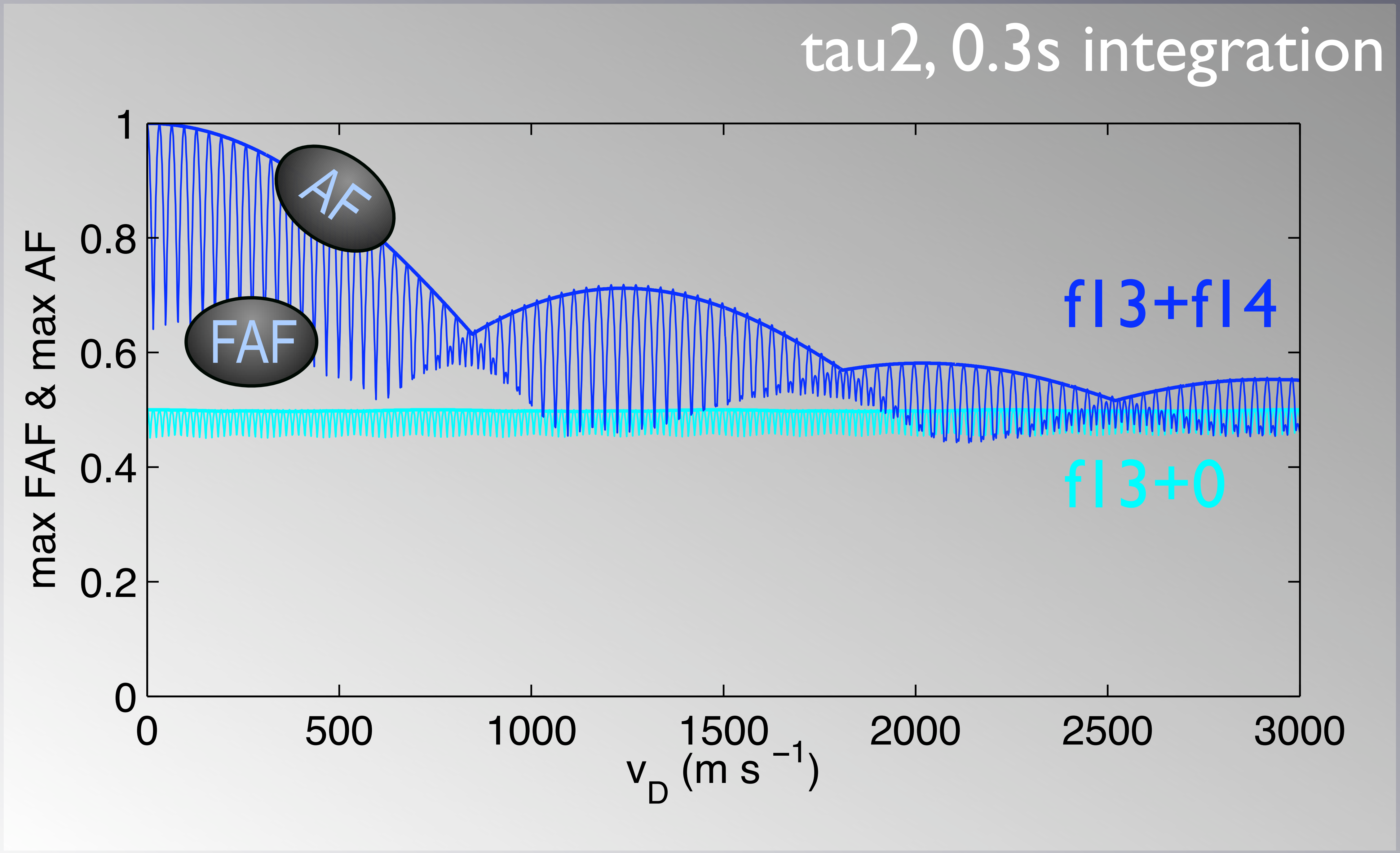
Effect of acceleration error



AF vs FAF, single freq. case



AF vs FAF, dual freq. case



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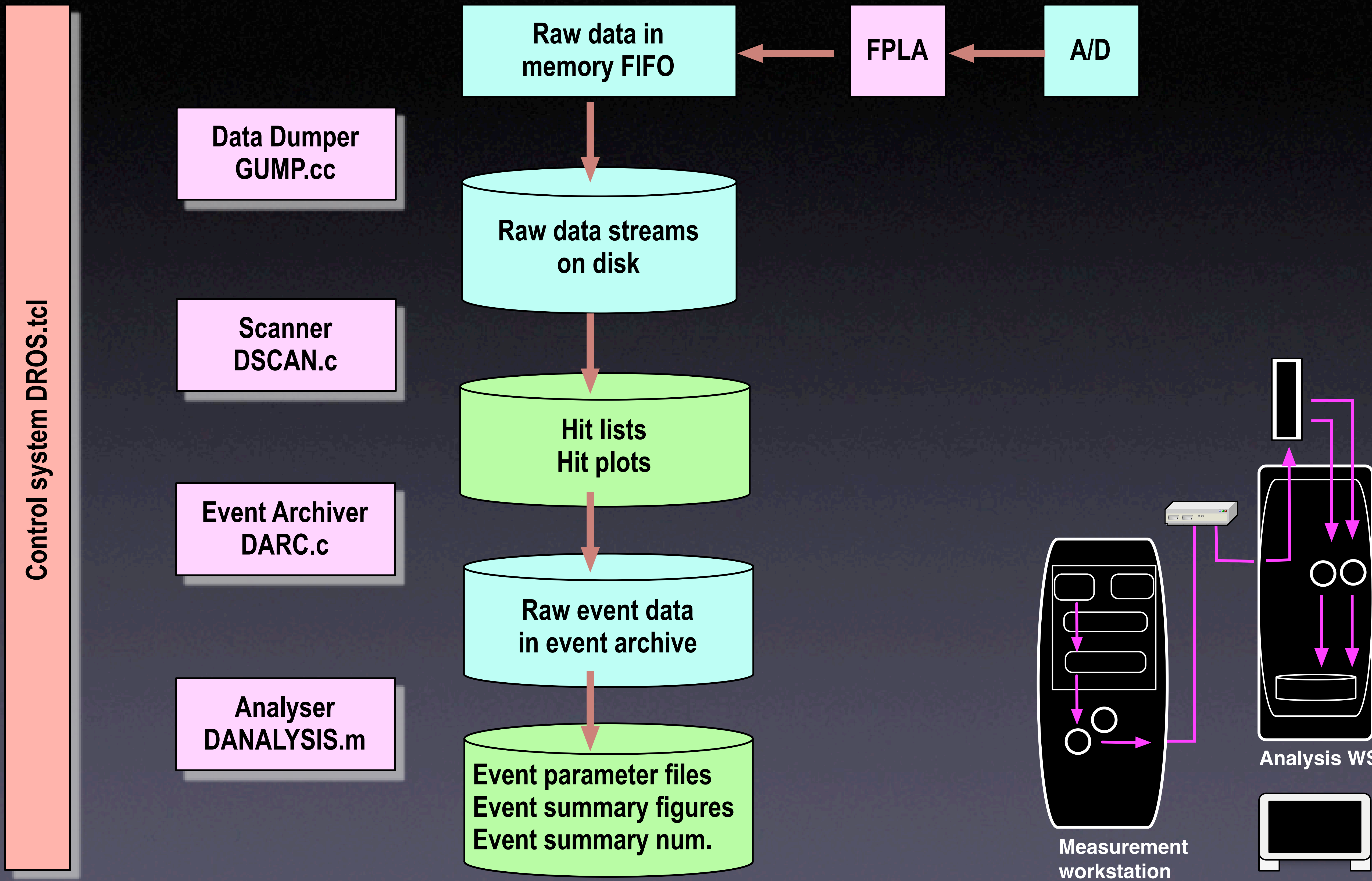
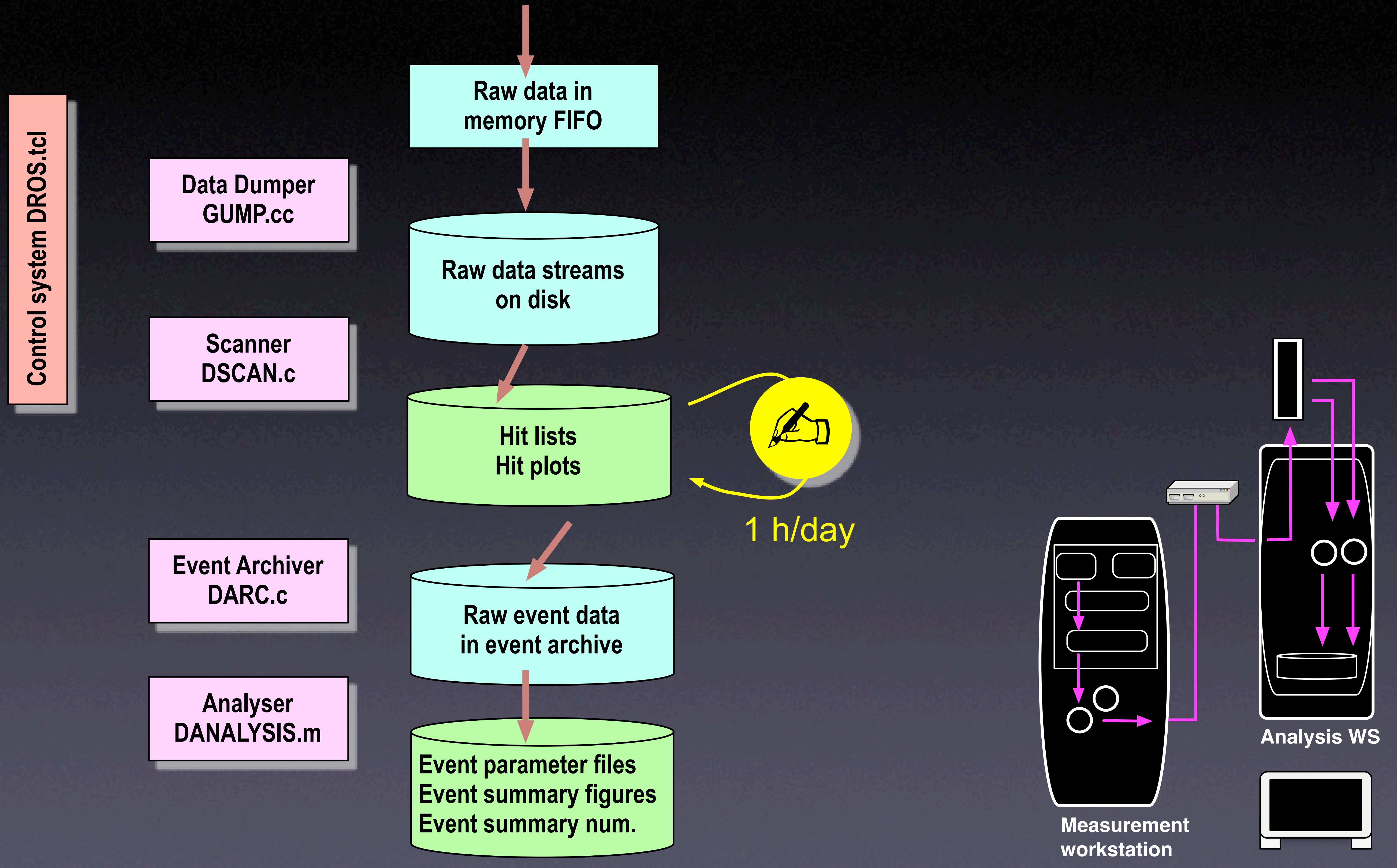
SOFTWARE

Overview

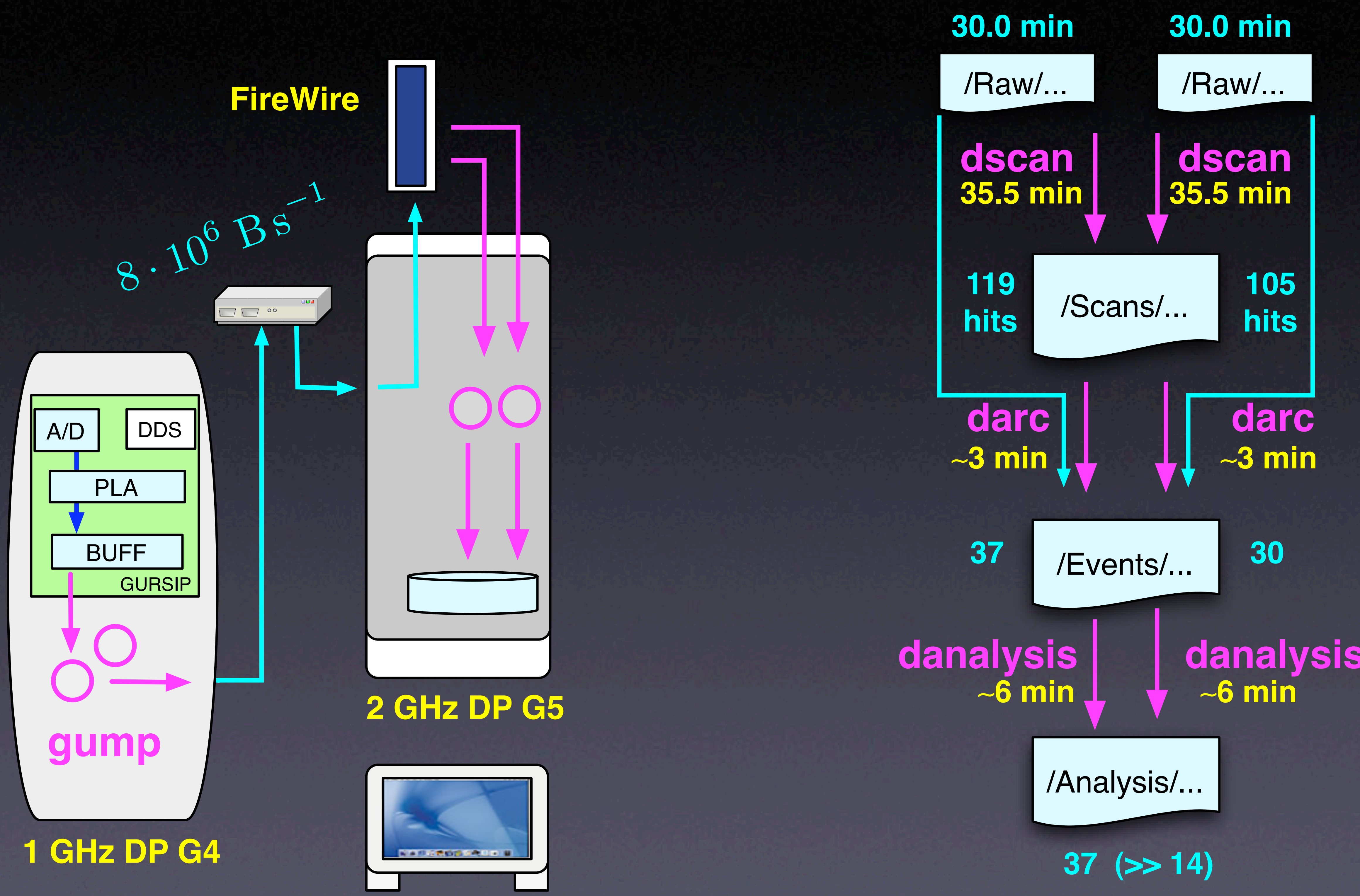


Control system DROS.tcl
Raw data in memory FIFO
FPLA
A/D
Data Dumper GUMP.cc
Raw data streams on disk
Scanner DSCAN.c
Hit lists Hit plots
Event Archiver DARC.c
Raw event data in event archive
Analyser DANALYSIS.m
Event parameter files Event summary figures Event summary num.
Analysis WS
Measurement workstation

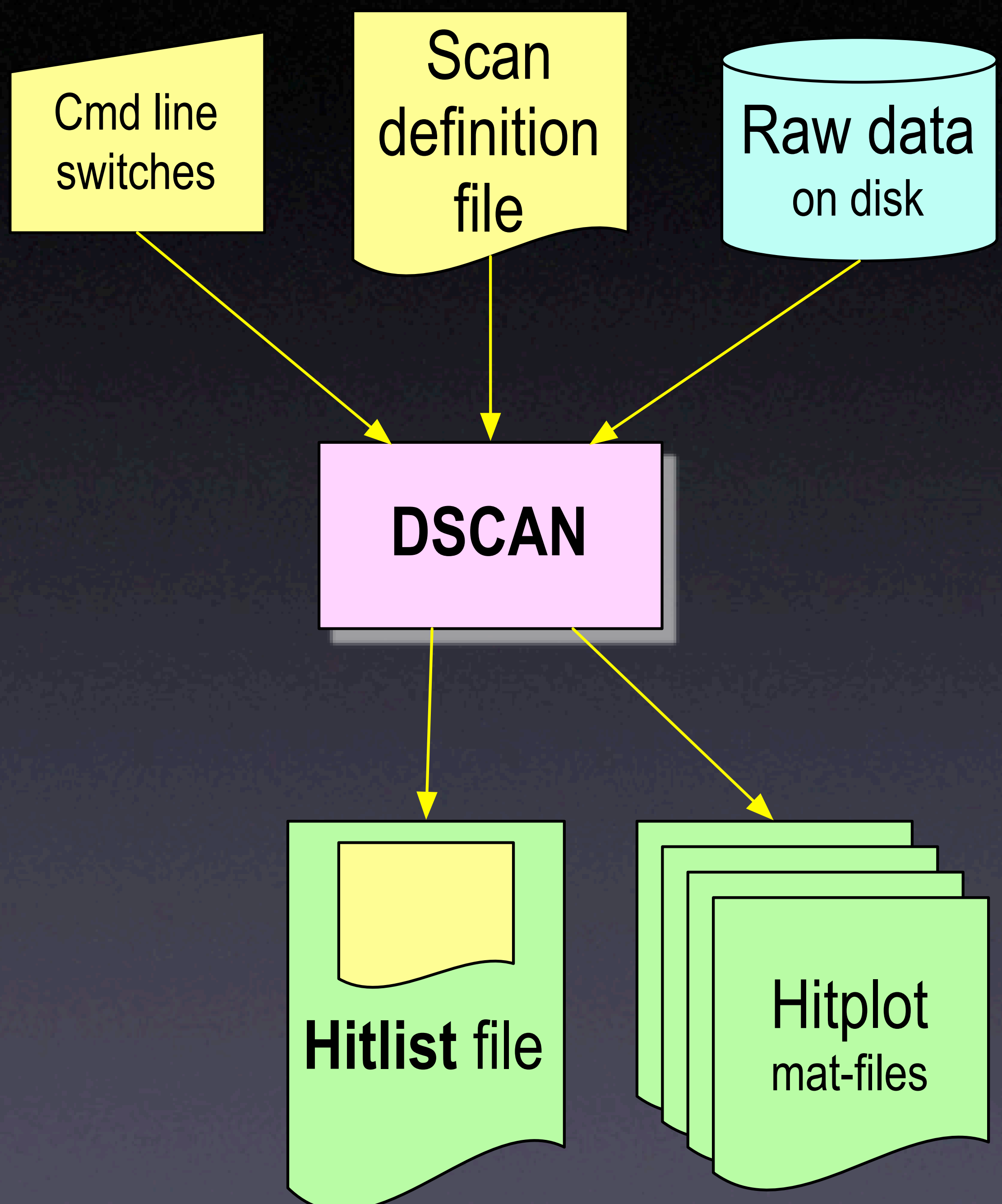
With hitlist editing

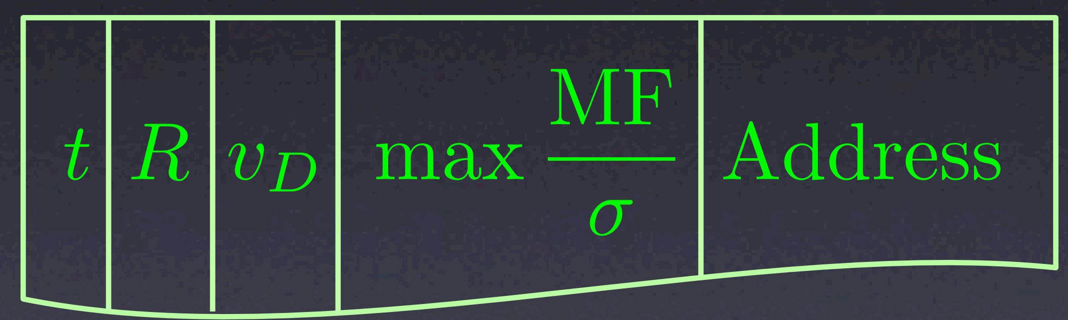


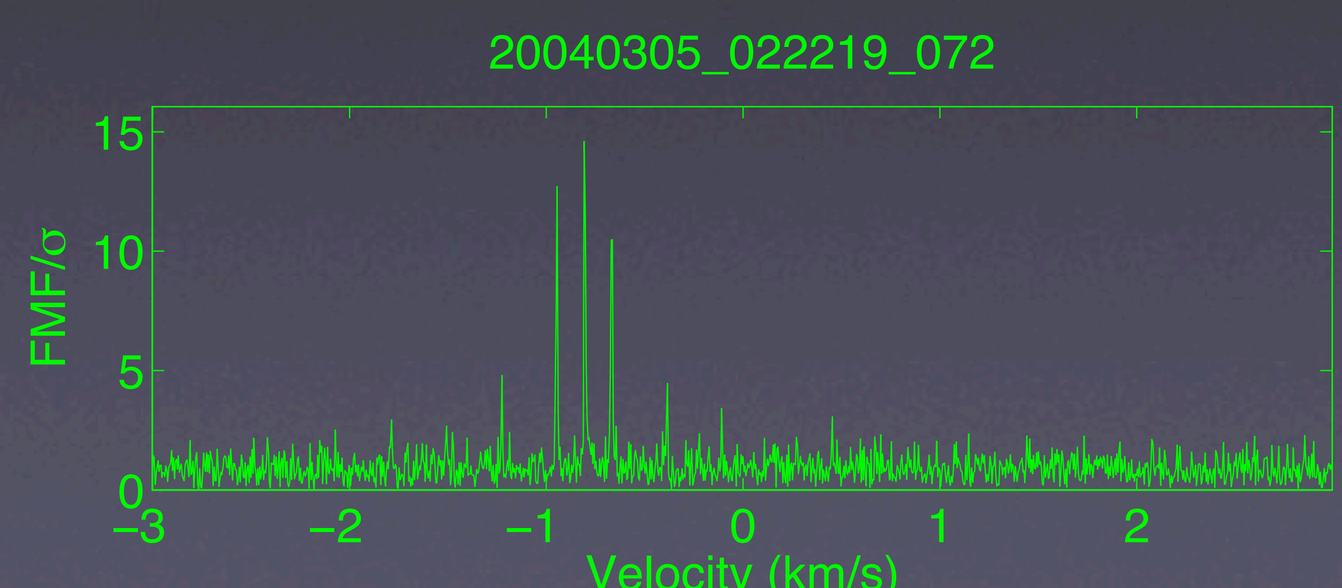
Overall processing speed



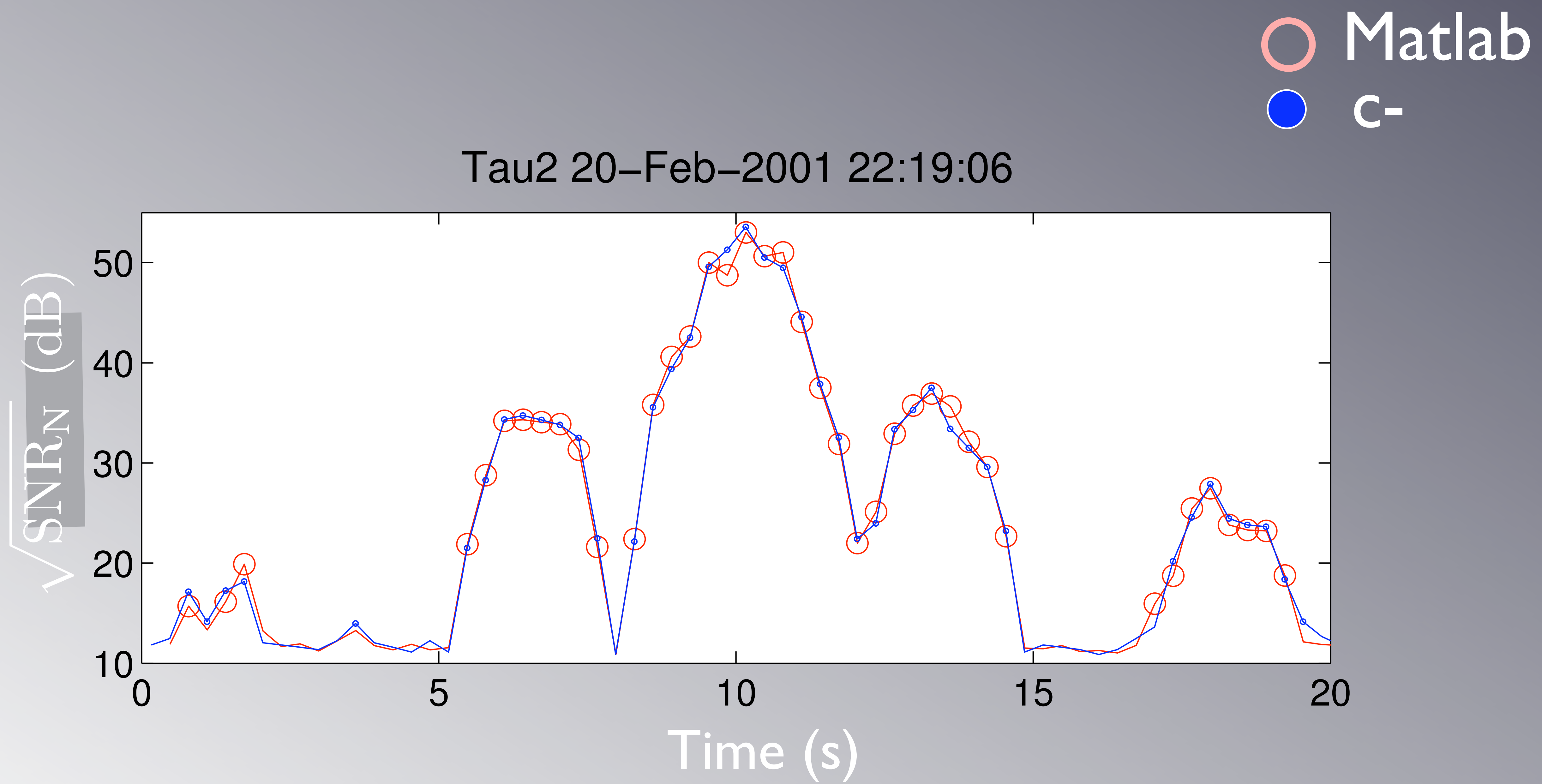
Scanner DSCAN



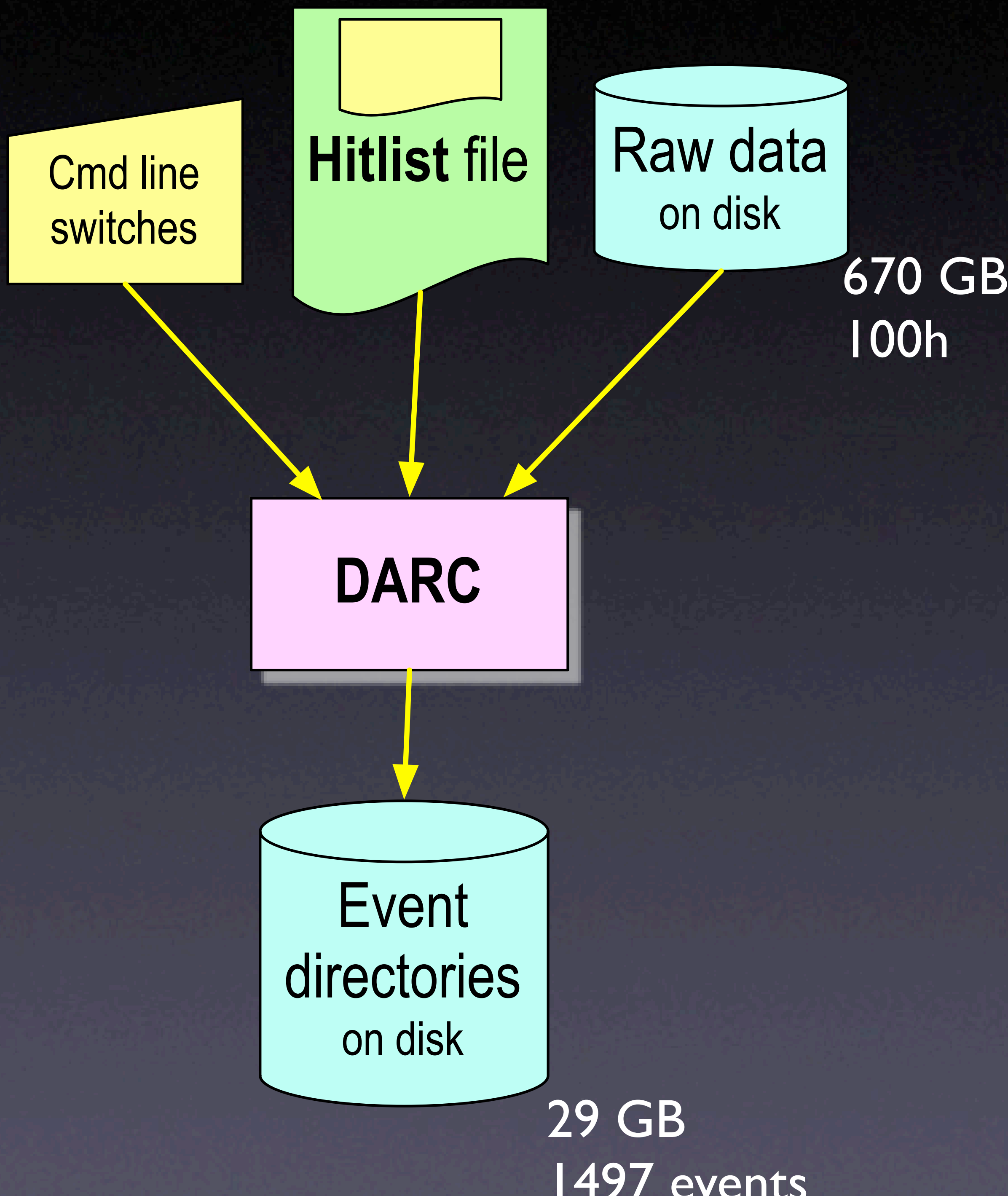




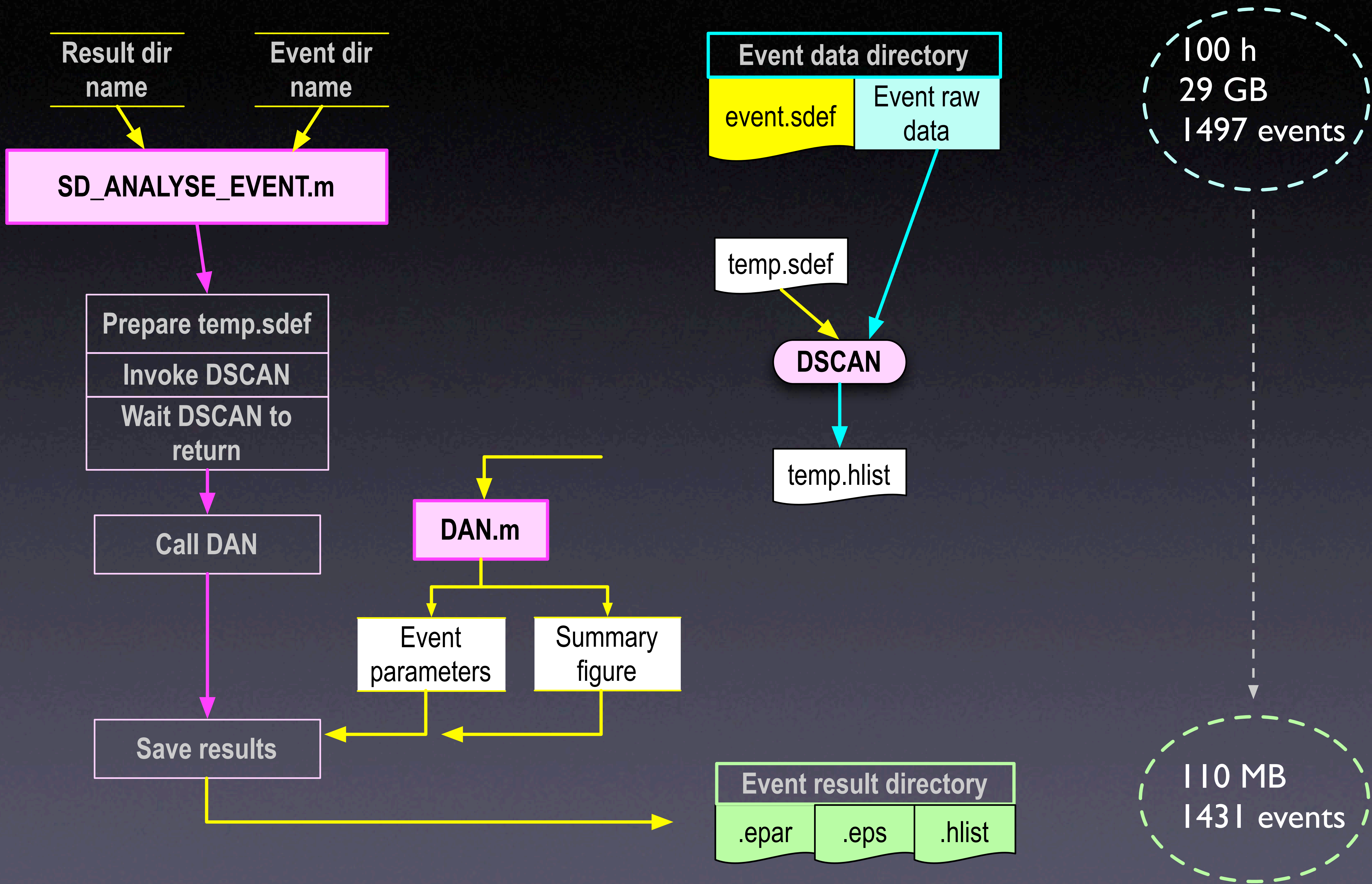
c- vs Matlab FMF



Composer/archiver DARC

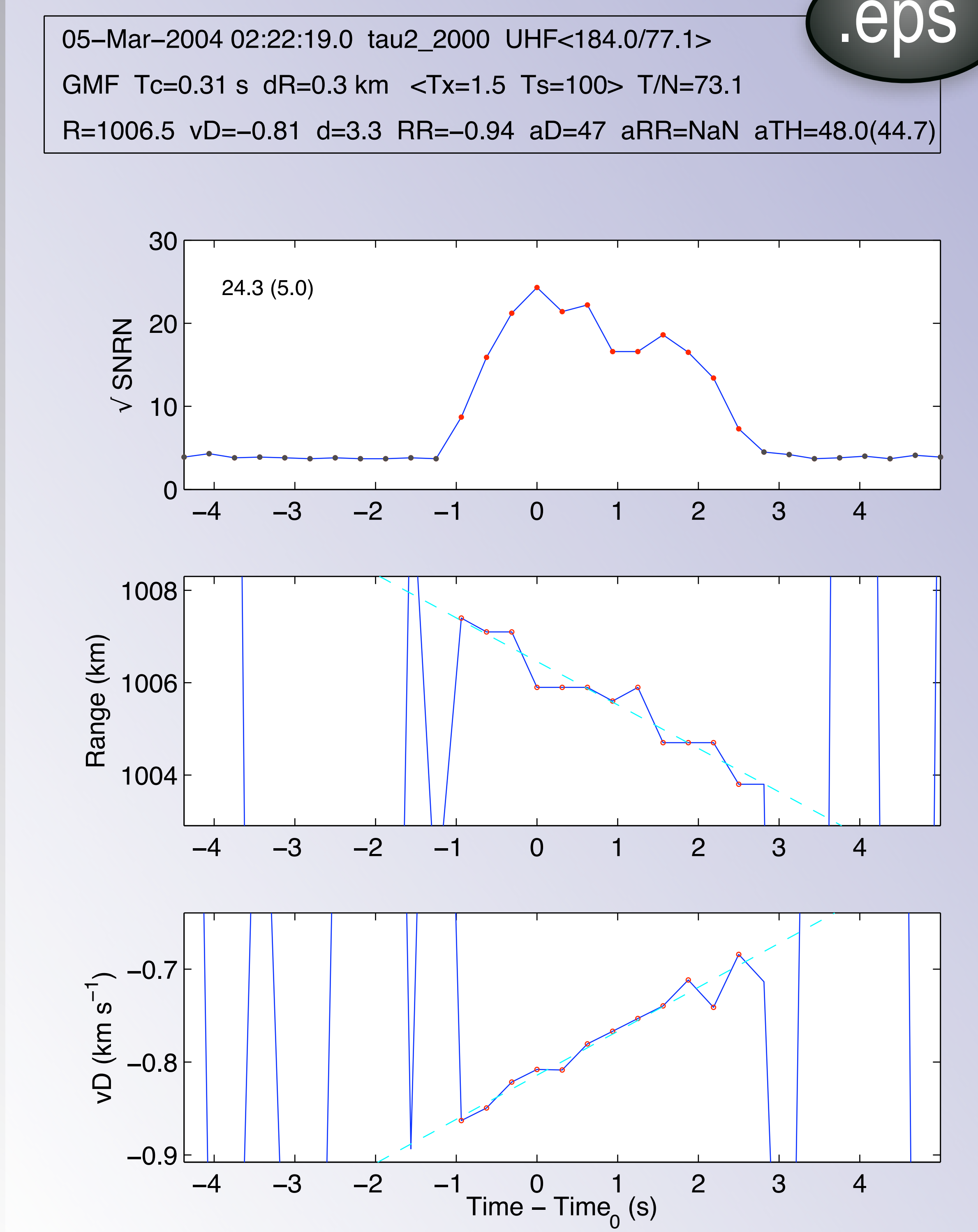


Event analyser



Event result files

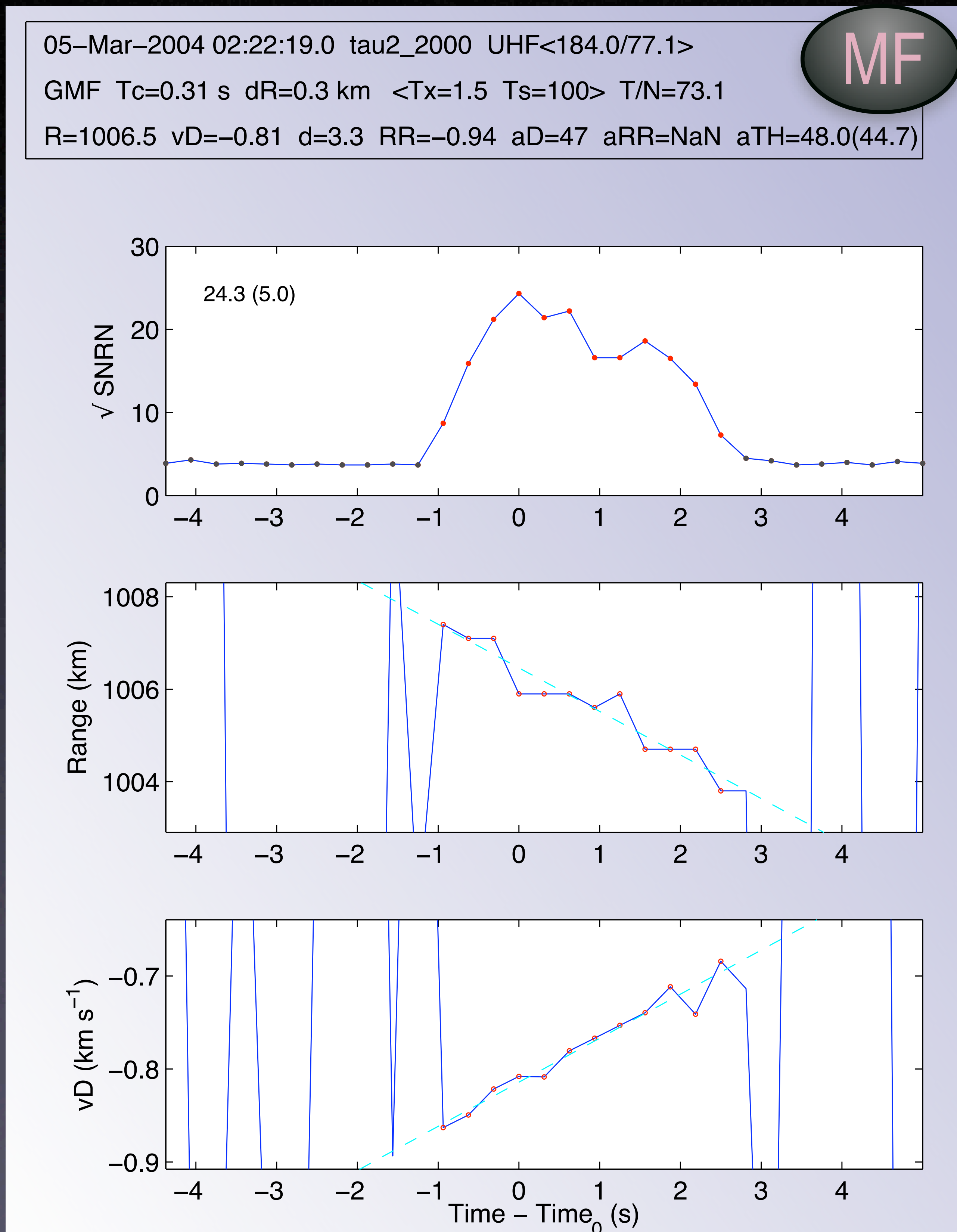
.eps

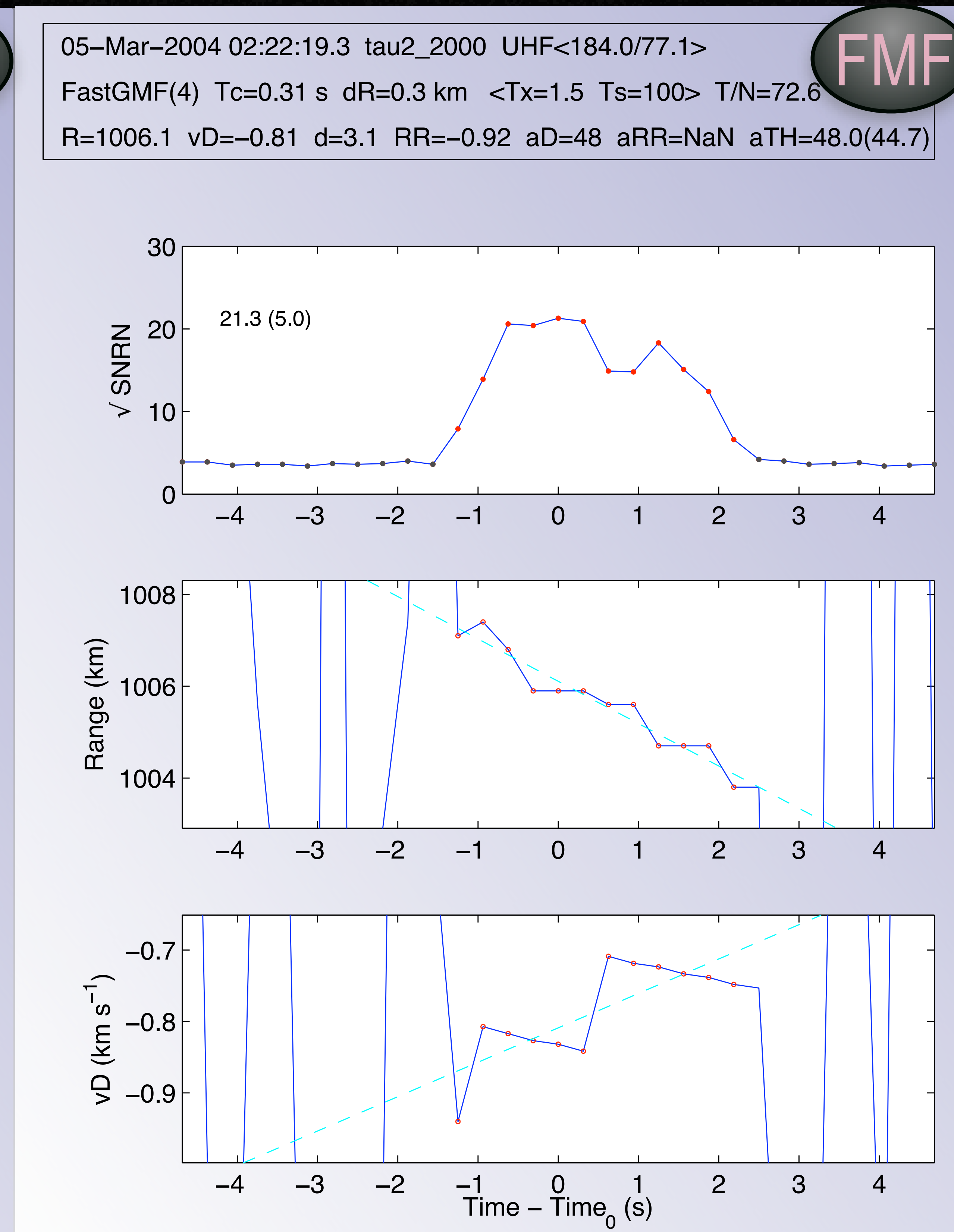


.epar

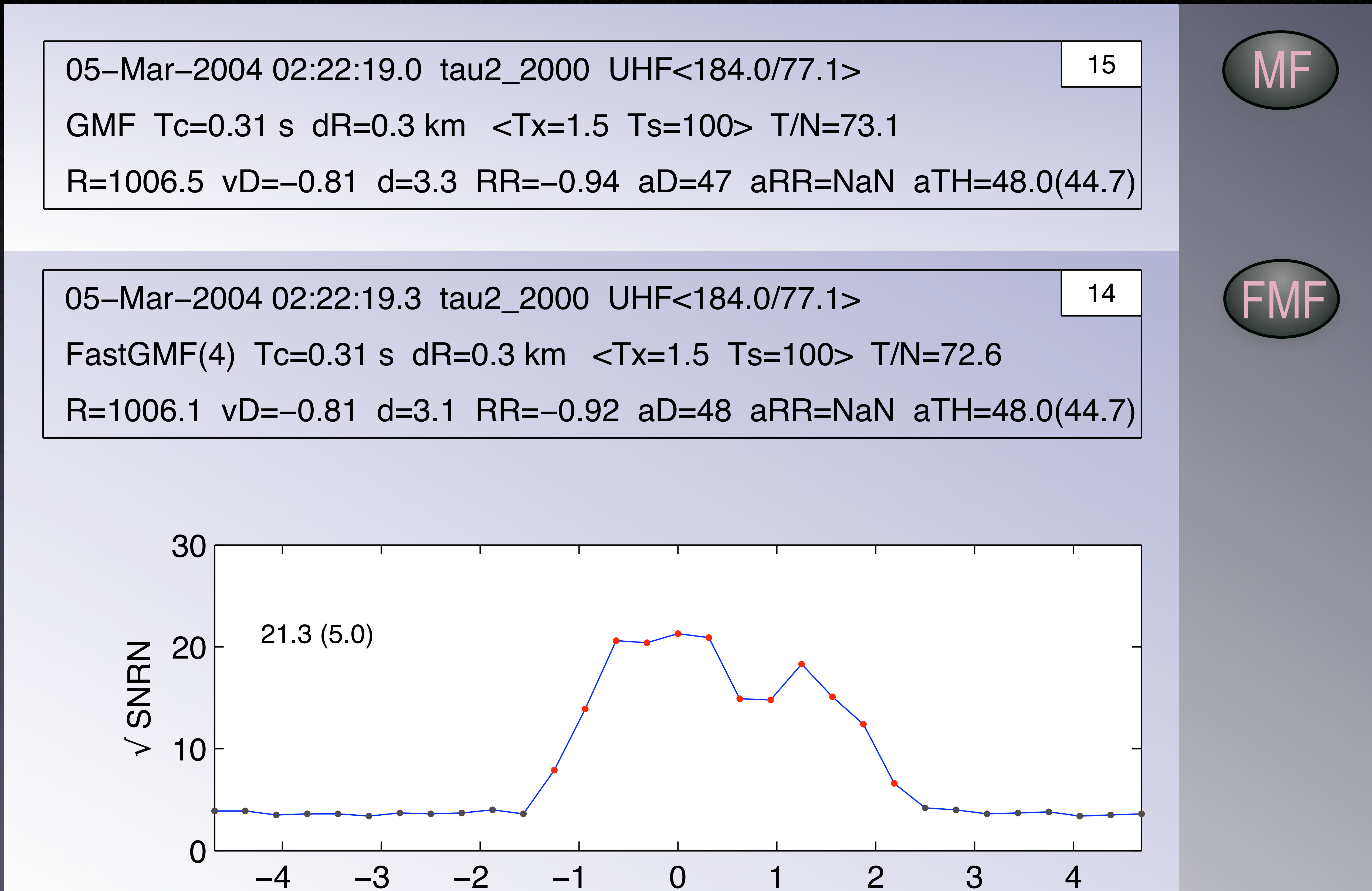
```
%       NM  Event name UT.
%       XI  Experiment ID string.
%       TM  UT of max Ratio.
%       ST  System temperature K.
%       AG  Antenna gain dB.
%       WL  Radar wavelength m.
%       PW  Transmission power MW.
%       AZ  Azimuth degr, N=0, E = 90.
%       EL  Elevation degr.
%       RT  Max Ratio ( = estimate of sqrt(SNR_N)).
%       RG  Range km.
%       RR  Range rate (km/s).
%       VD  Doppler velocity (km/s), positive away from radar.
%       AD  Acceleration from VD, m/s^2.
%       DI  Effective diameter cm.  Estimated from ST, PW, RT. RN, AG, WL.
%       CS  Lower bound of radar cross section, cm^2. Estimated as DI.
%       TS  (Transmission sample power)/(Noise power)
%       EN  Event number.
%
%       NaN = Bad.
%
%       28-Nov-2004 17:35:30
%
NM = U20040305_022214_634
XI = tau2_2000
TM = 2004   3   5   02 22 19.016
ST = 100
AG = 48.1
WL = 0.323
PW = 1.50
AZ = 184.0
EL = 77.1
RT = 24.3
RN = 1006.462
RR = -0.943
VD = -0.814
AD = 47.33
DI = 3.28
CS = 0.7891
TS = 73.10
EN = 15
```

Event result figure

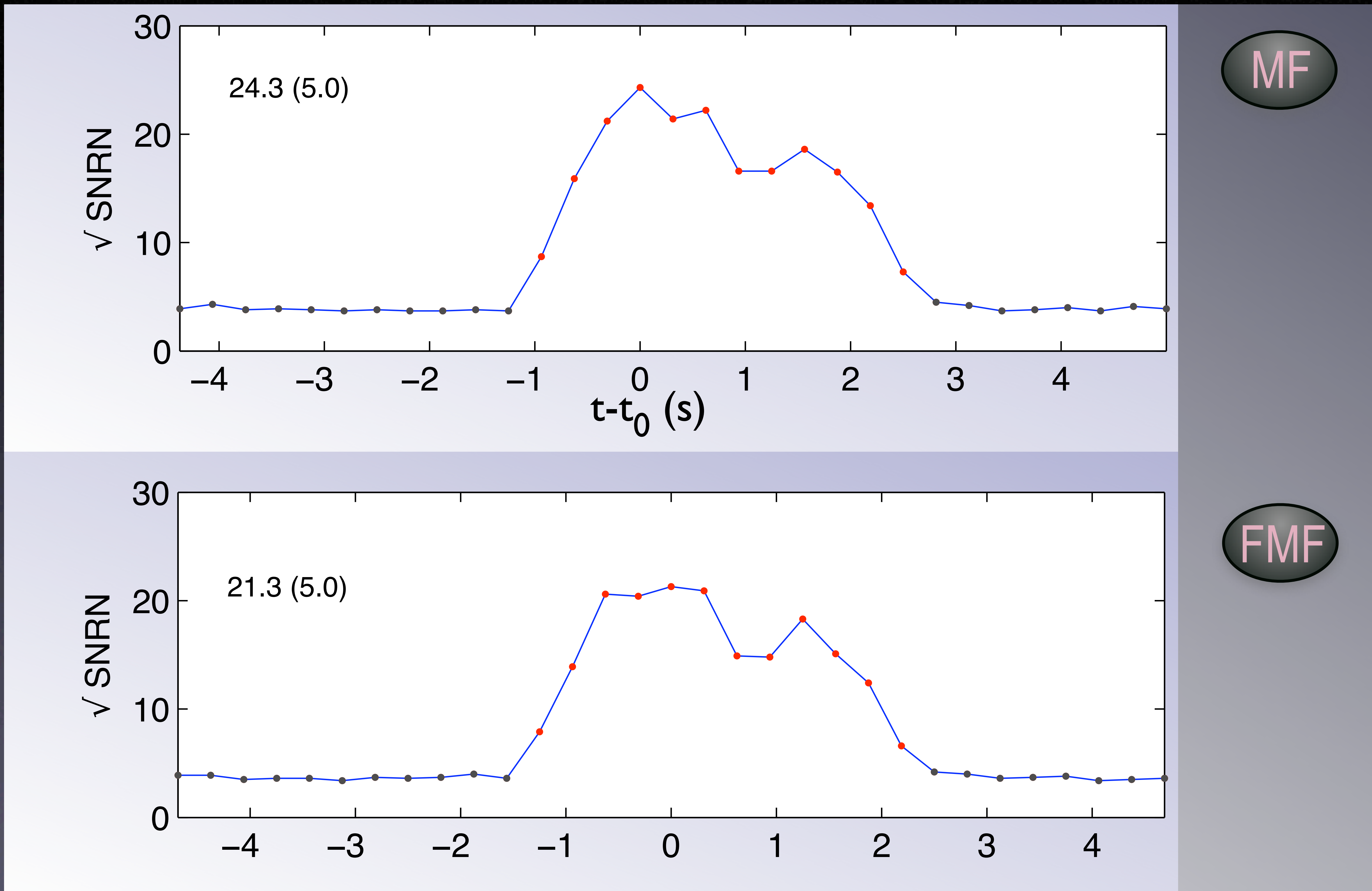




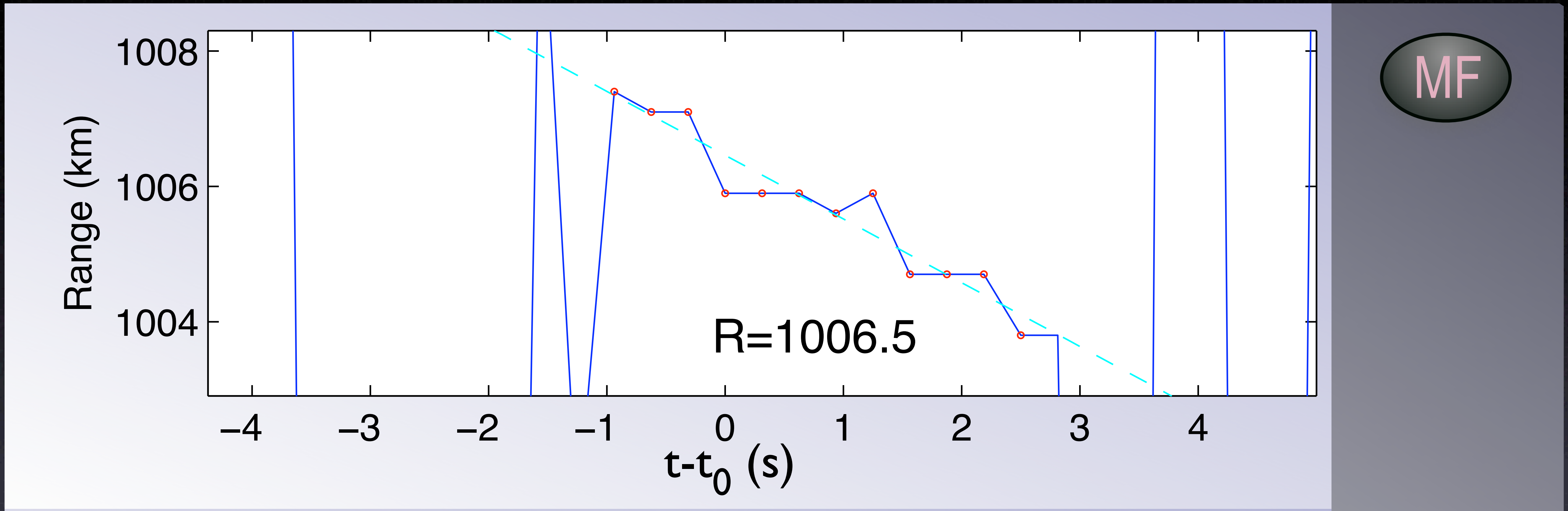
Result figure: Header

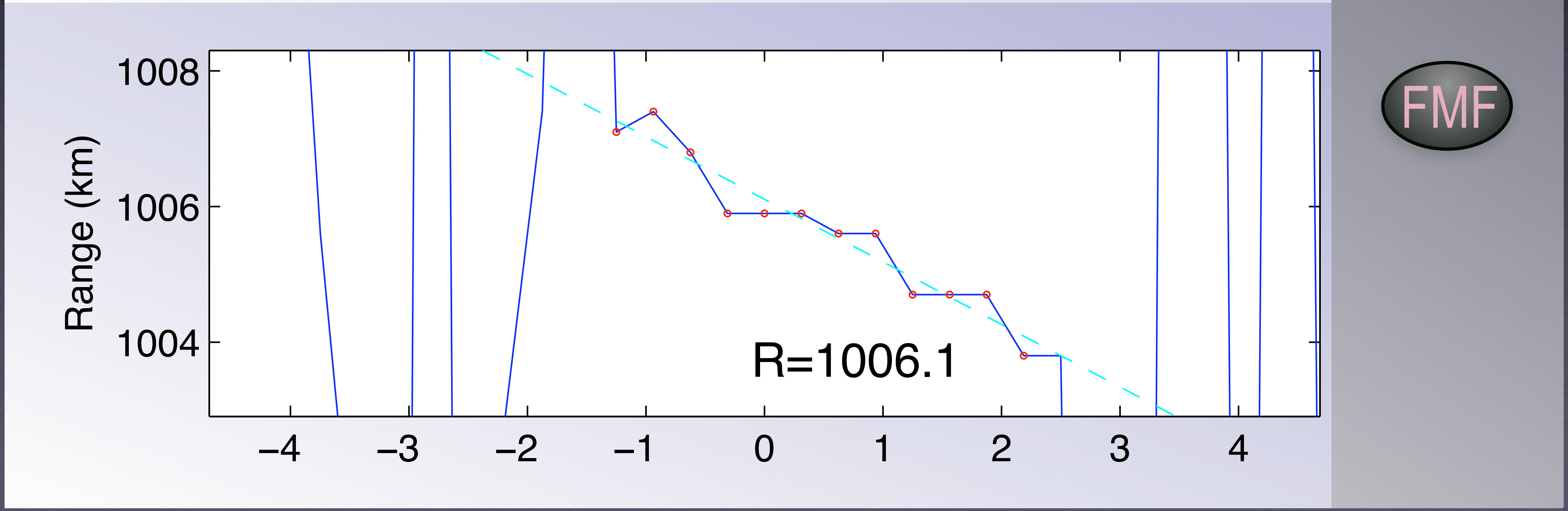


Result figure: $\sqrt{\mathrm{SNR_N}}$

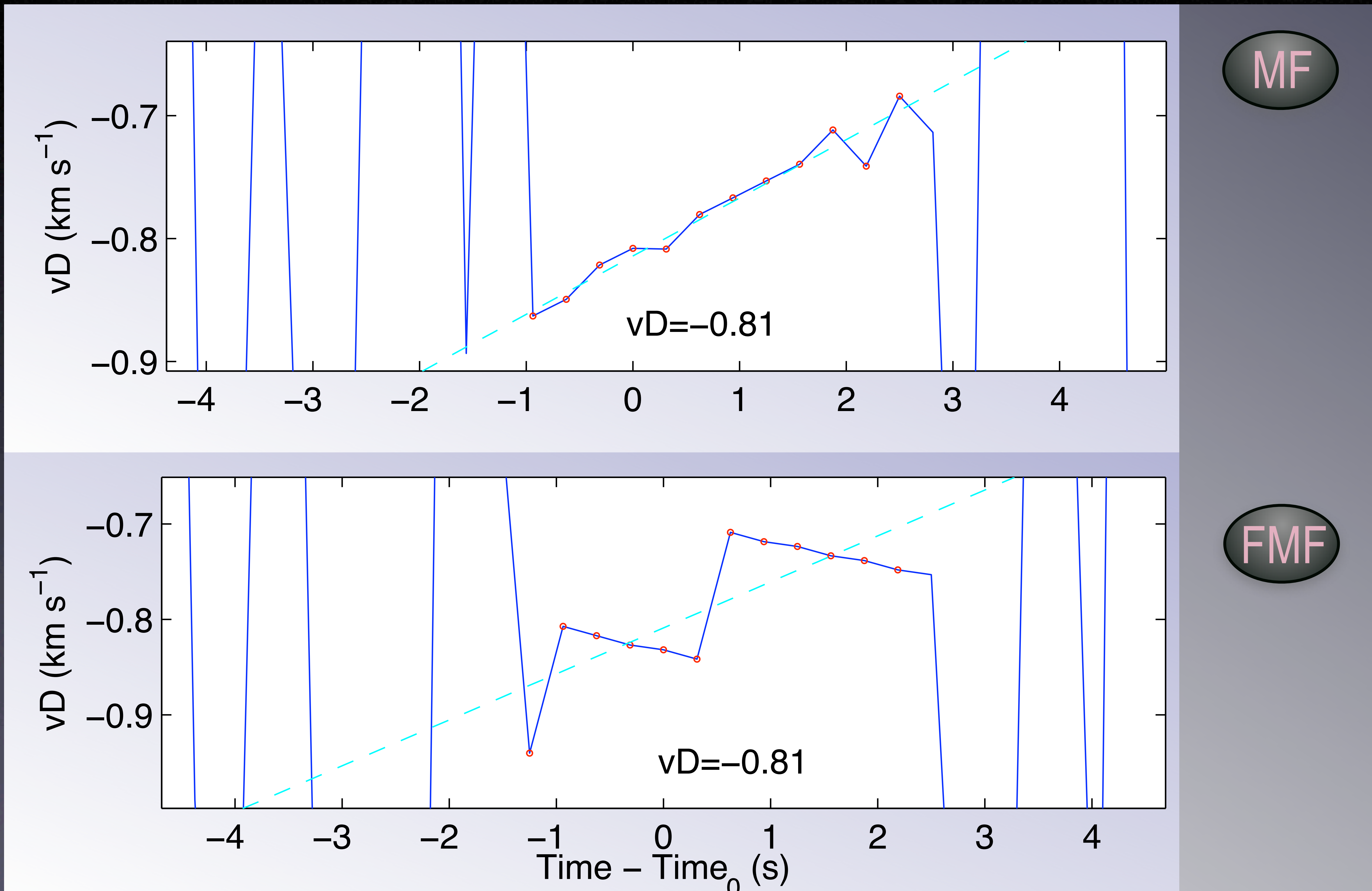


Result figure: $R = R(t)$





Result figure: $v_{\mathrm{D}} = v_{\mathrm{D}}(t)$



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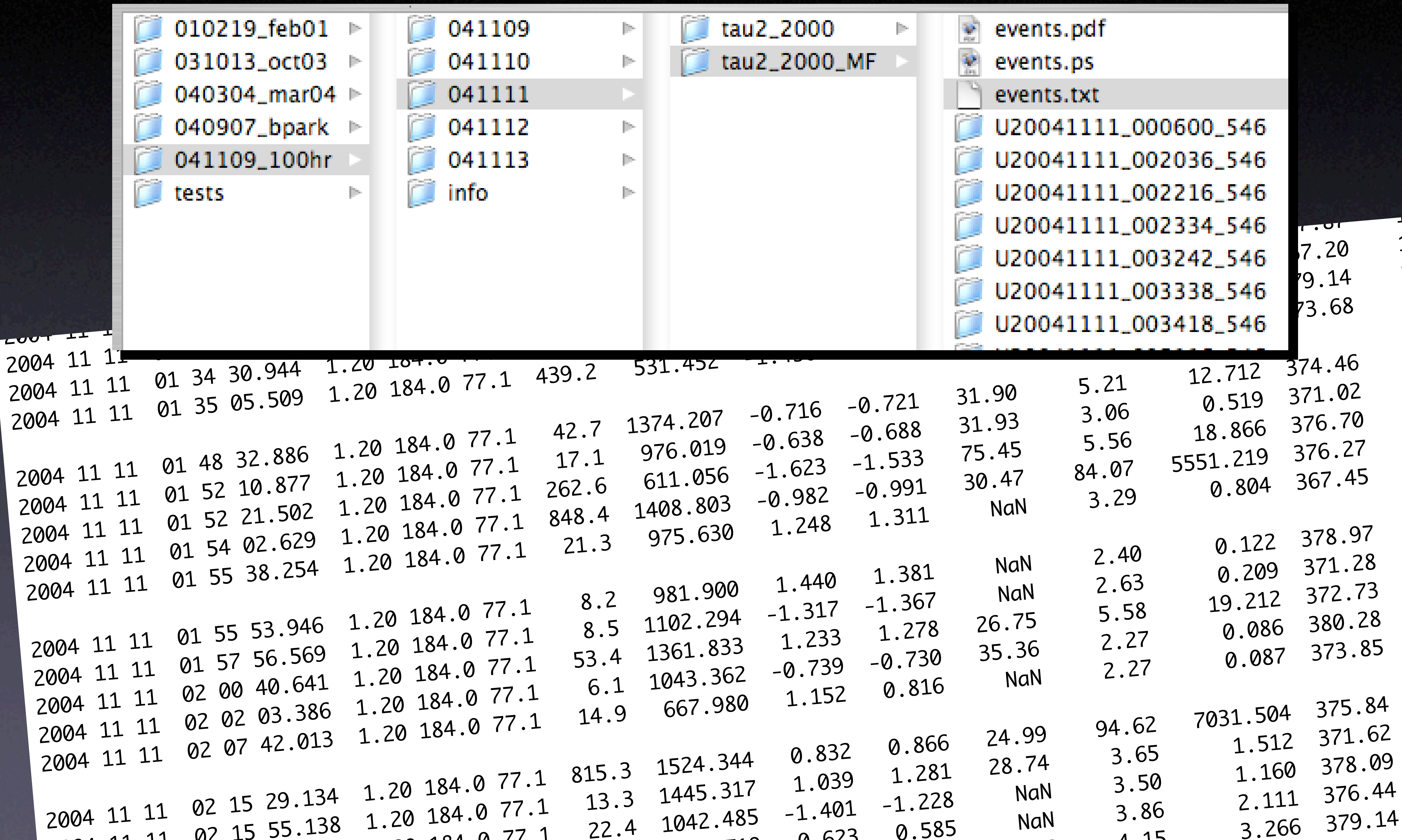
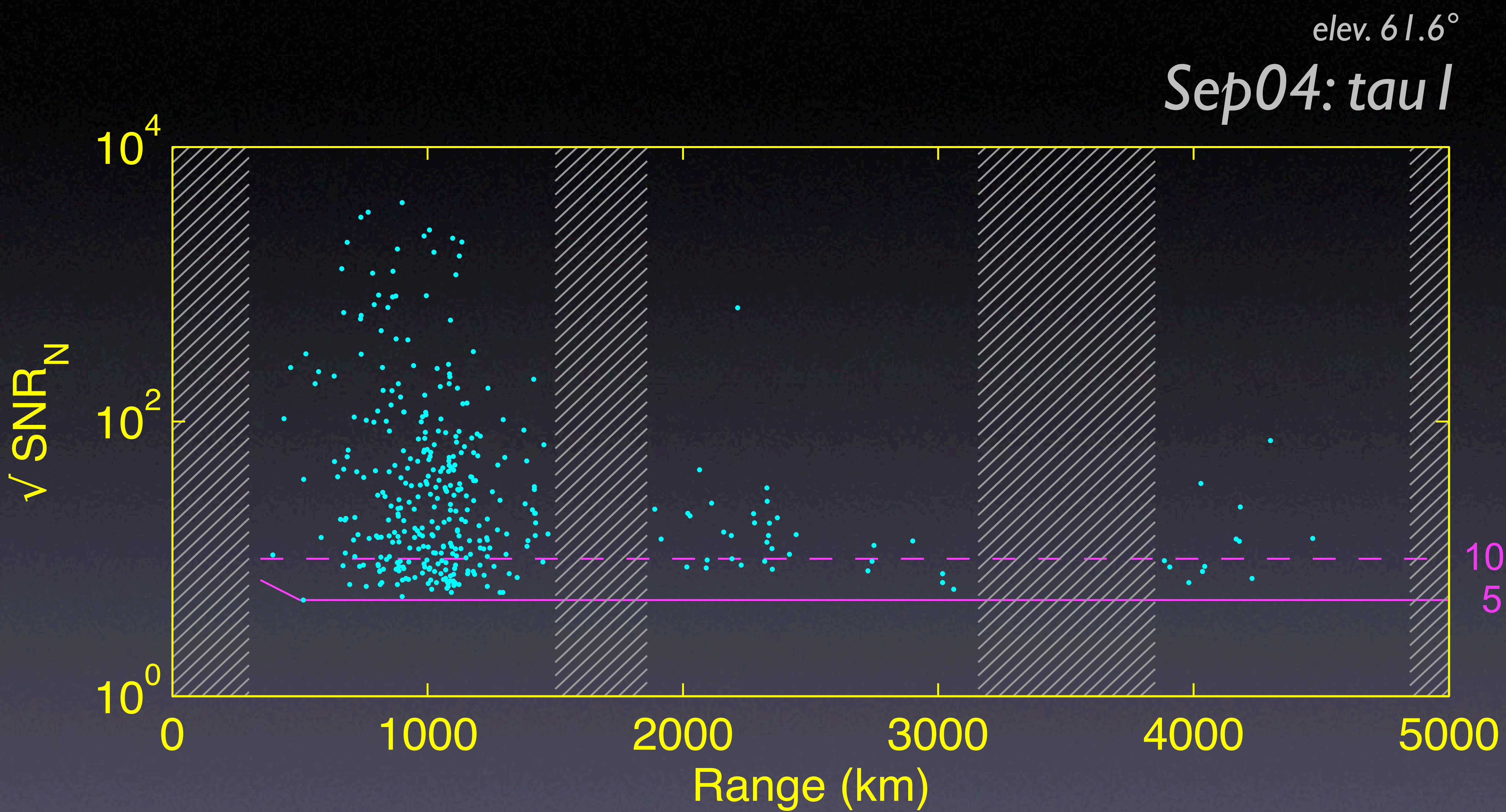
MEASUREMENTS

Campaigns and results



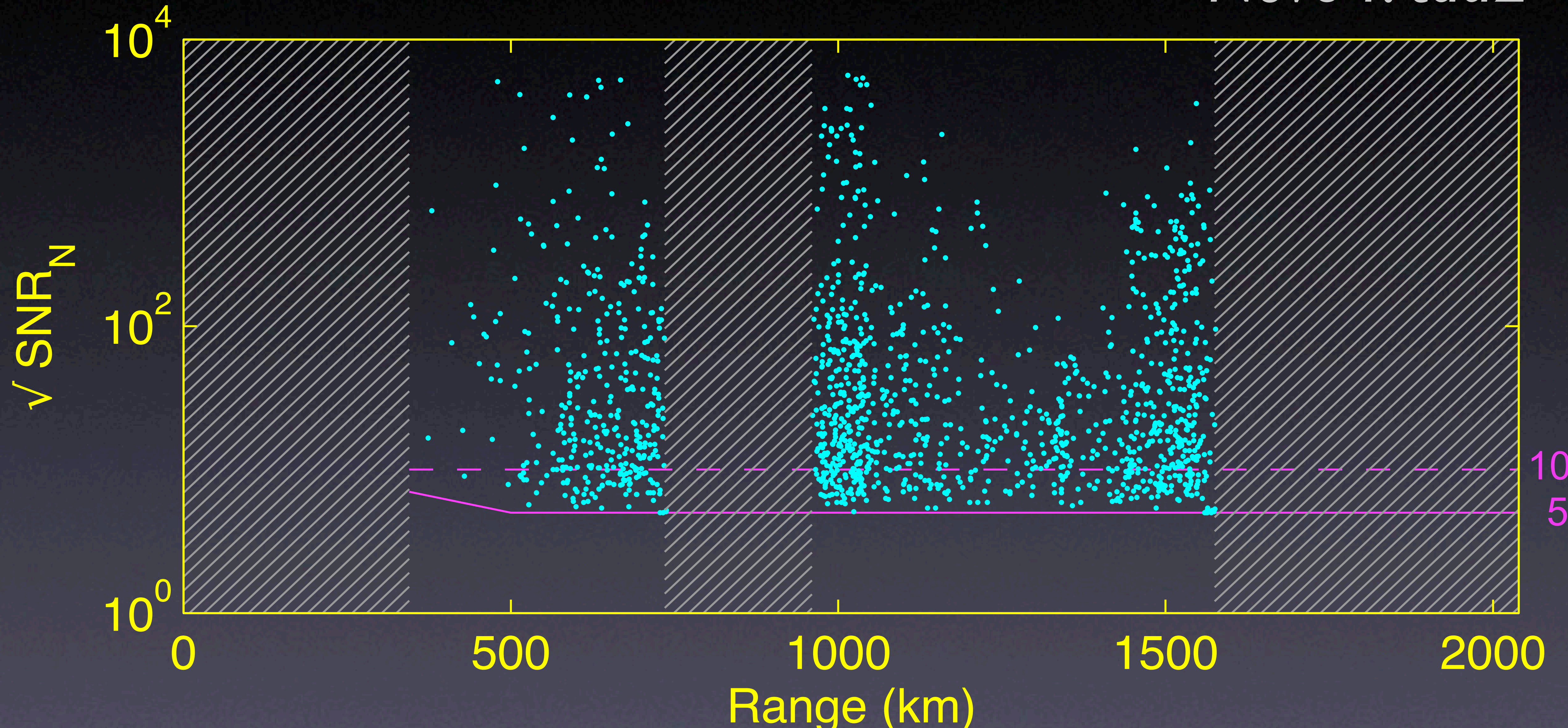
Signal strength vs range



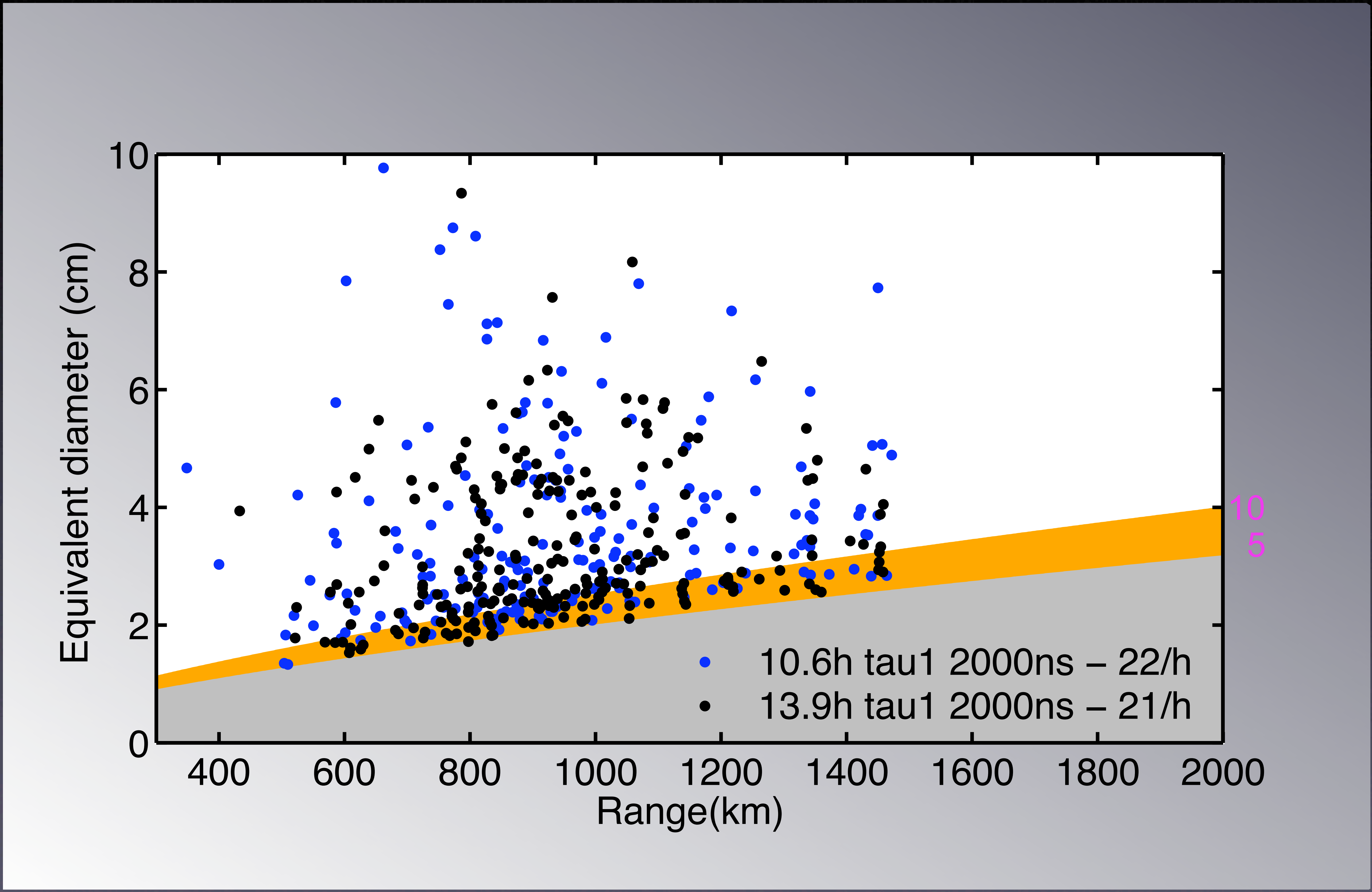
Signal strength vs range

elev. 77.1°

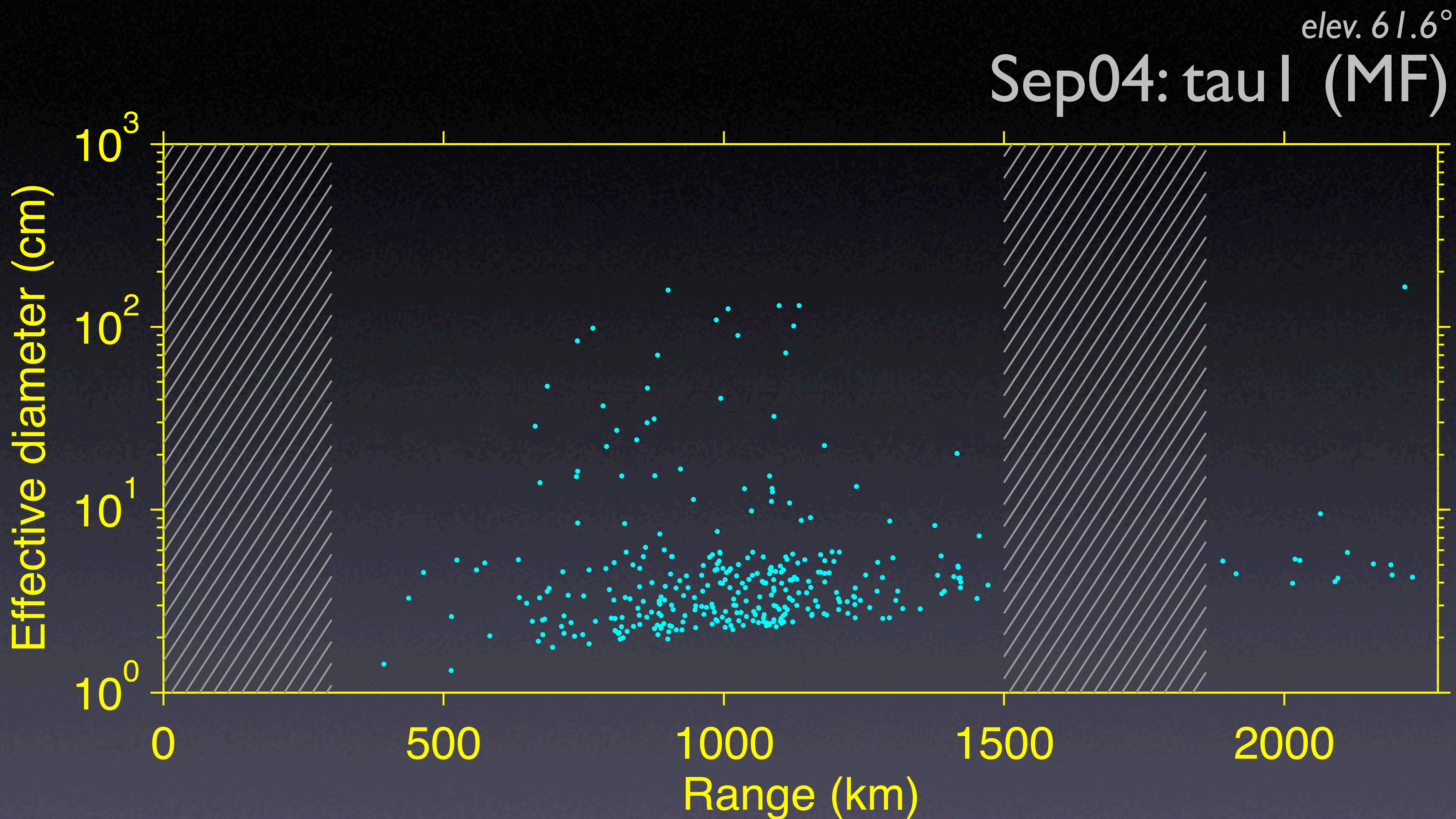
Nov04: tau2



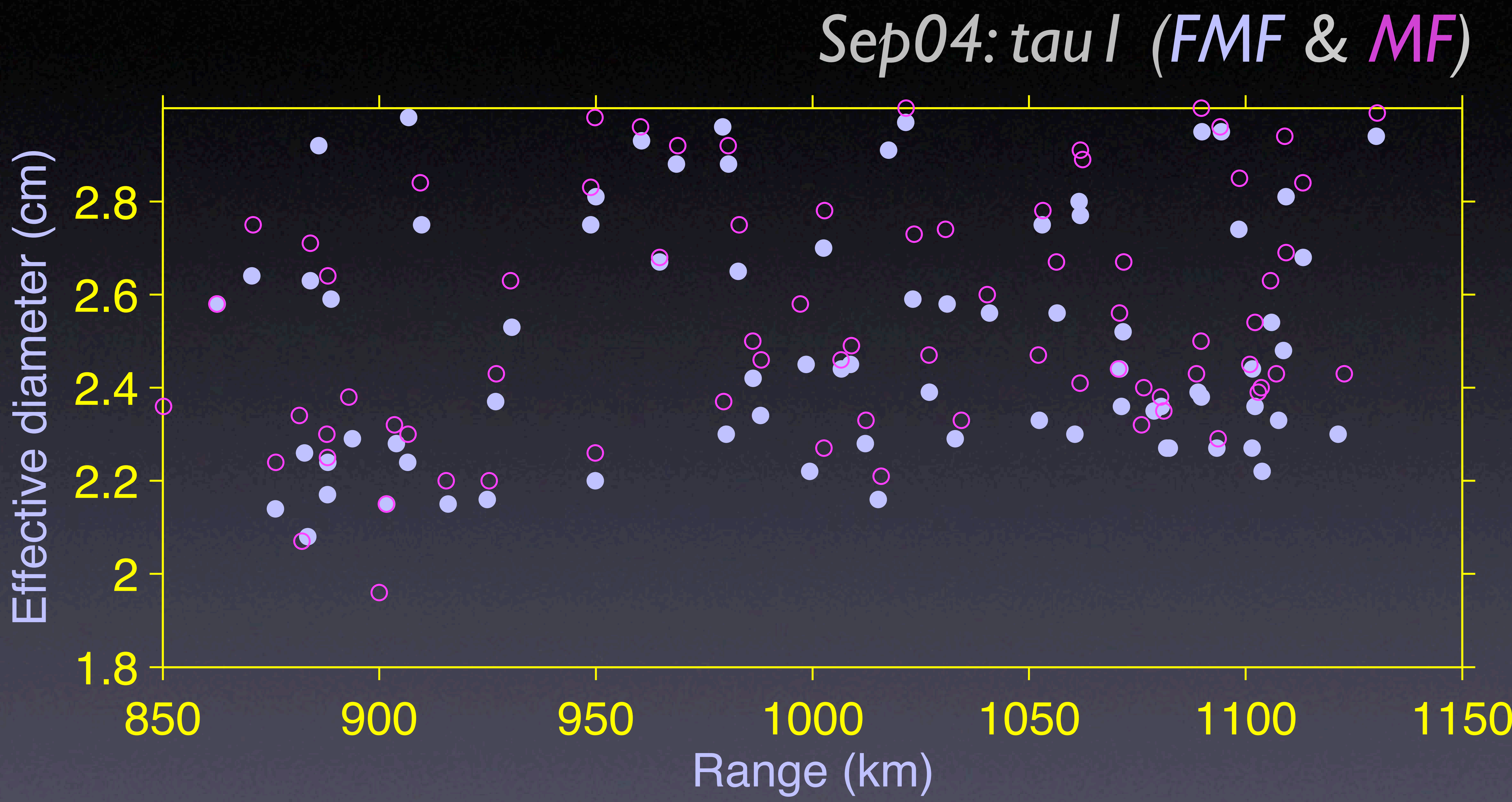
Effective diameter vs range



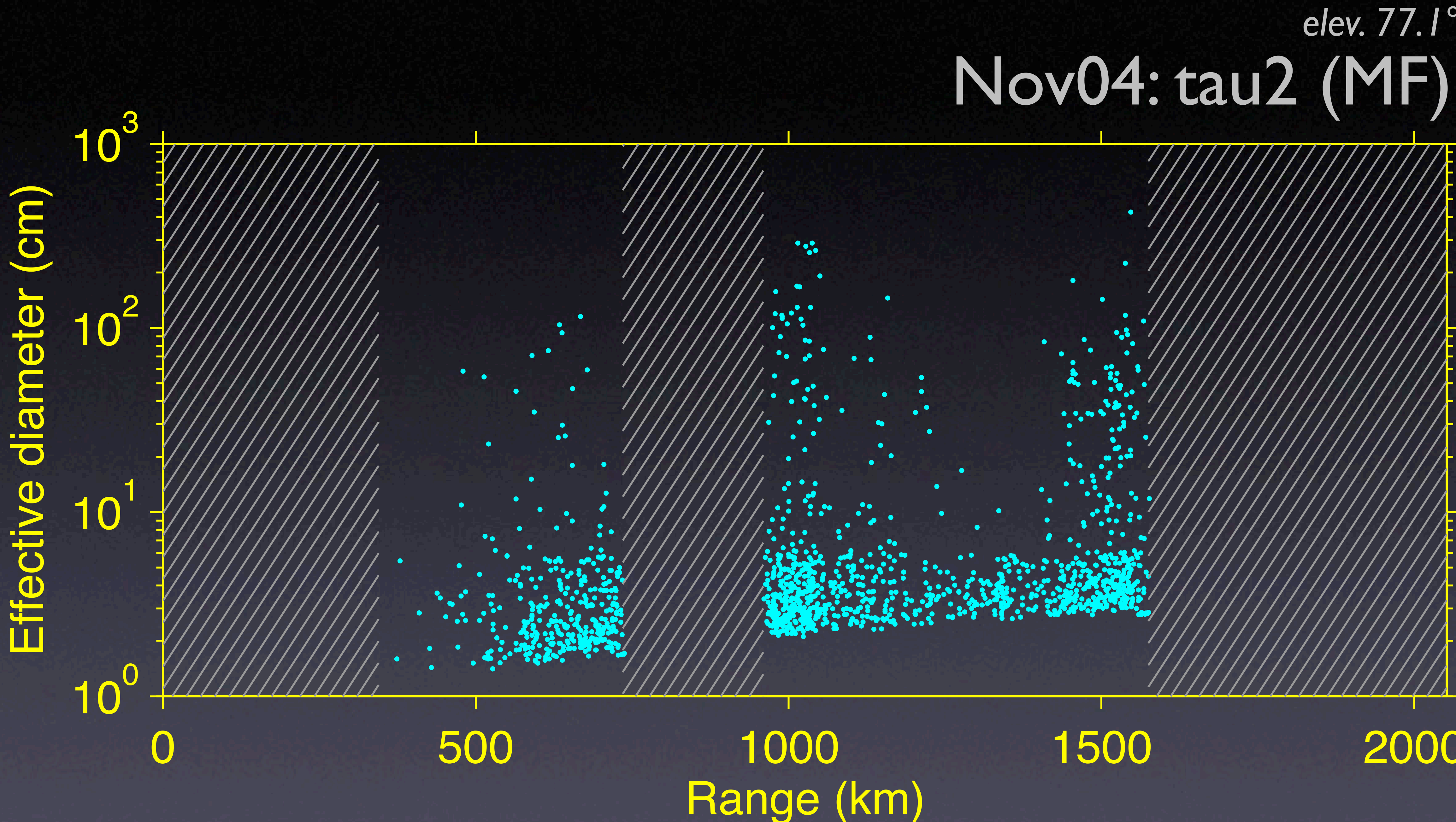
Effective diameter vs range



Effective diameter vs range

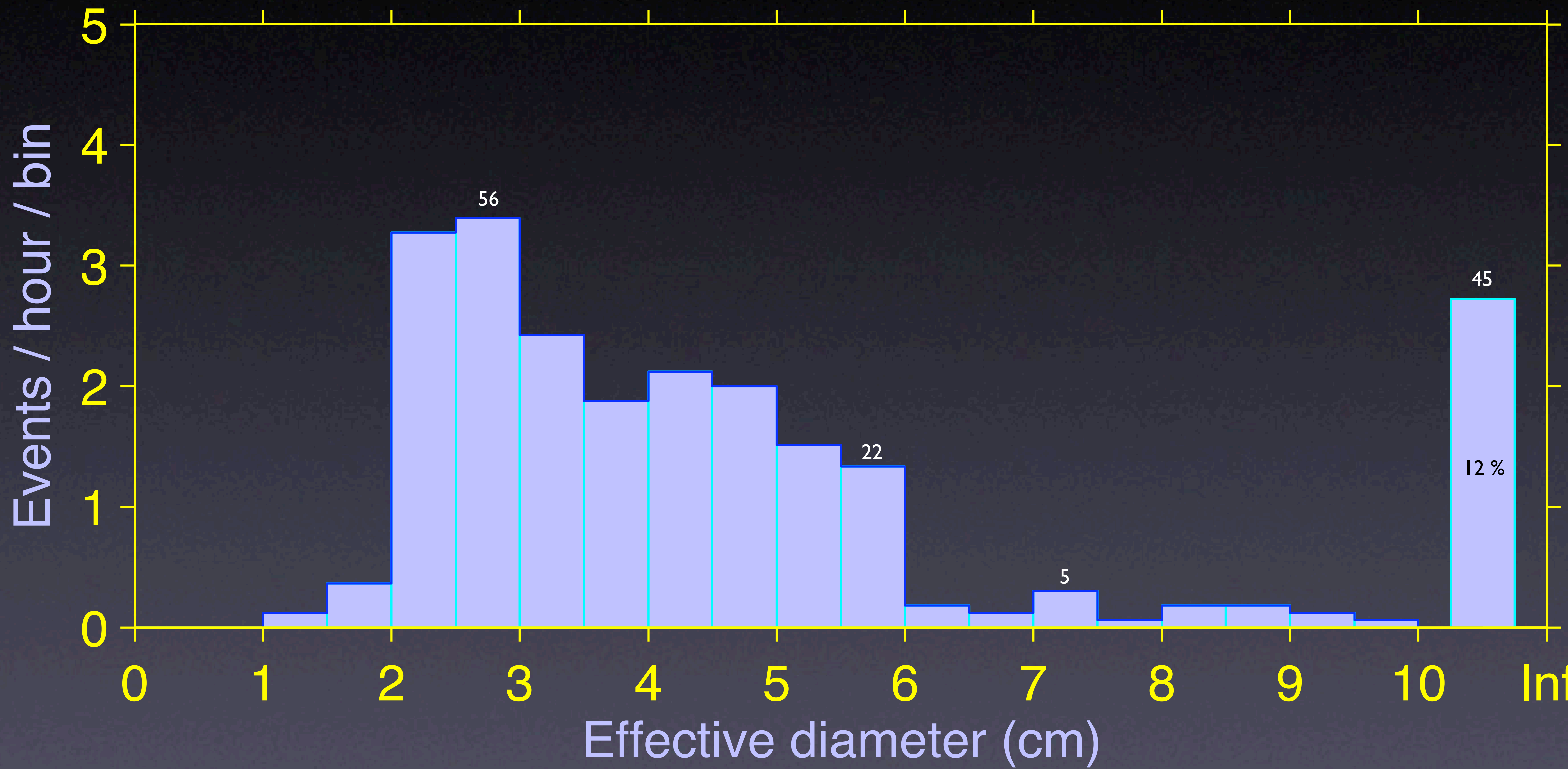


Effective diameter vs range

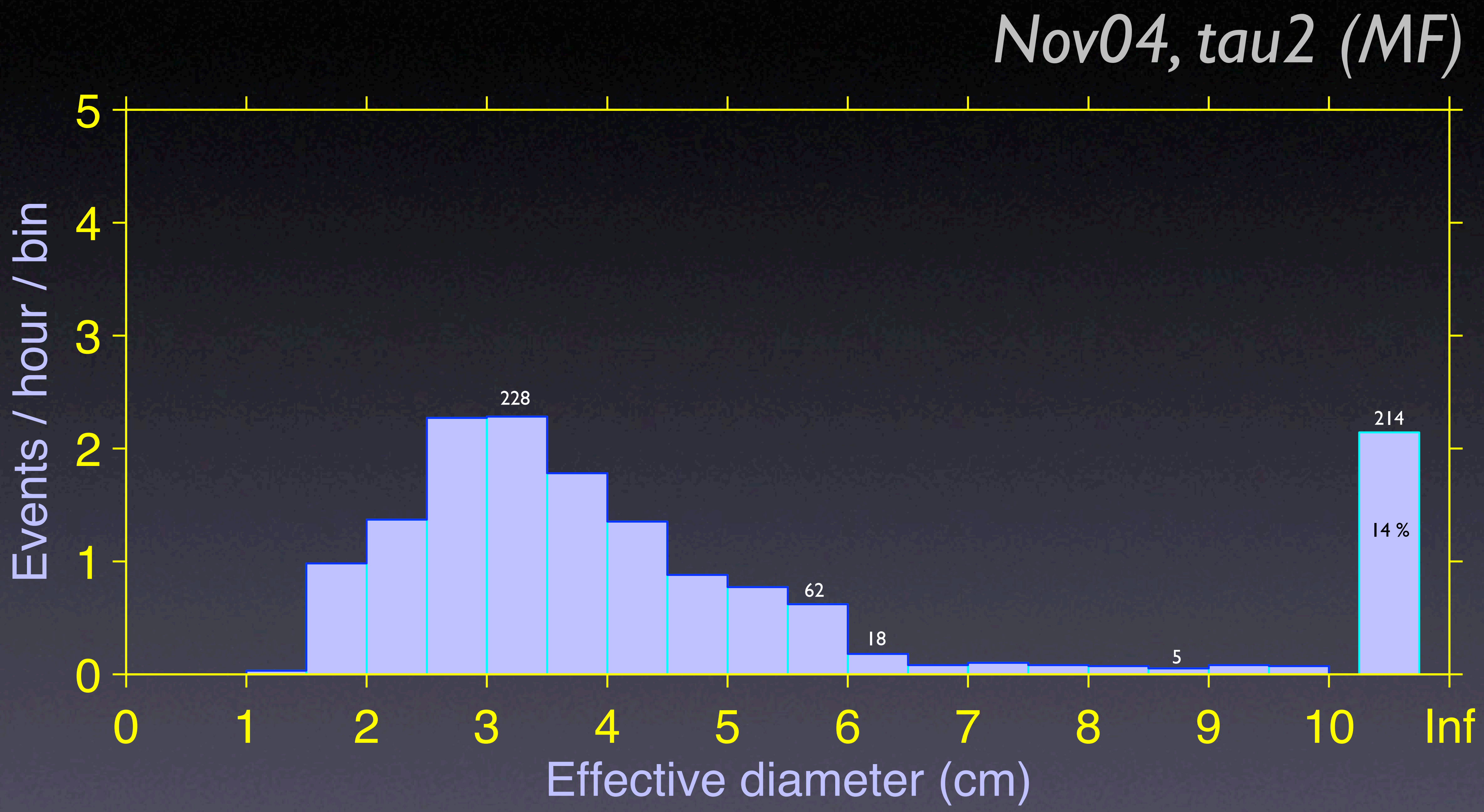


Event rate vs effective diameter

Sep04, tau1 (MF)

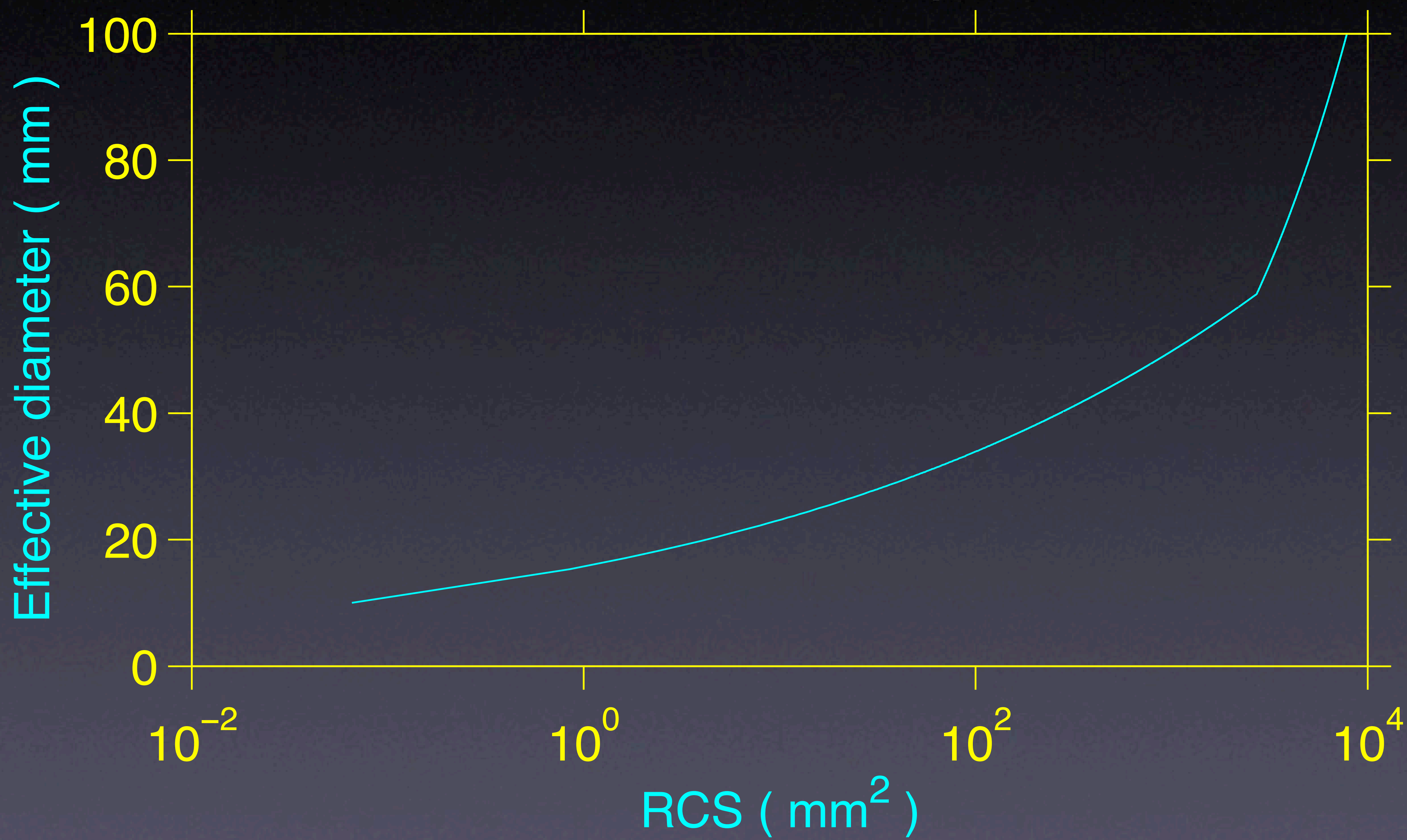


Event rate vs eff. diameter

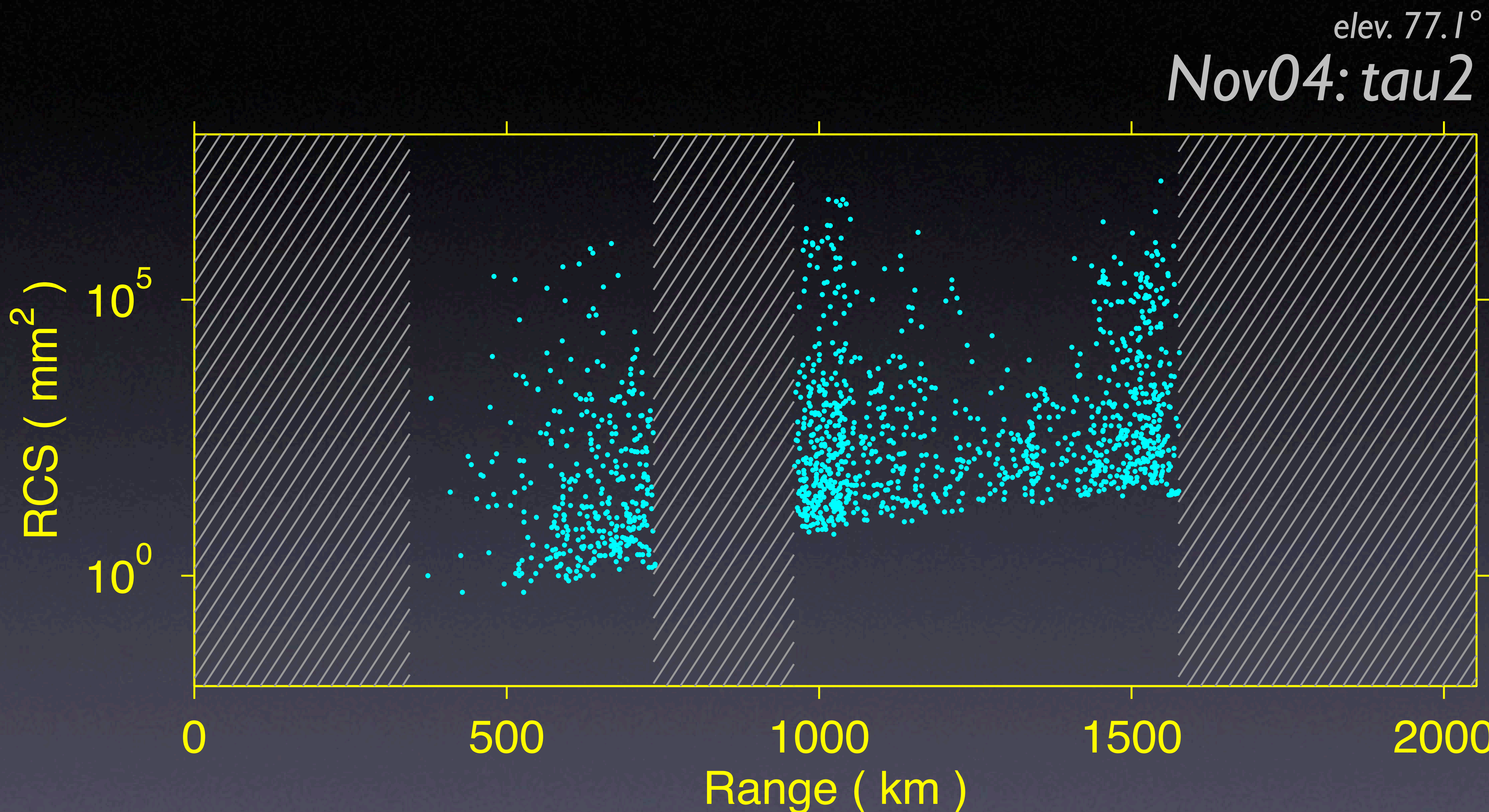


From RCS to effective diameter

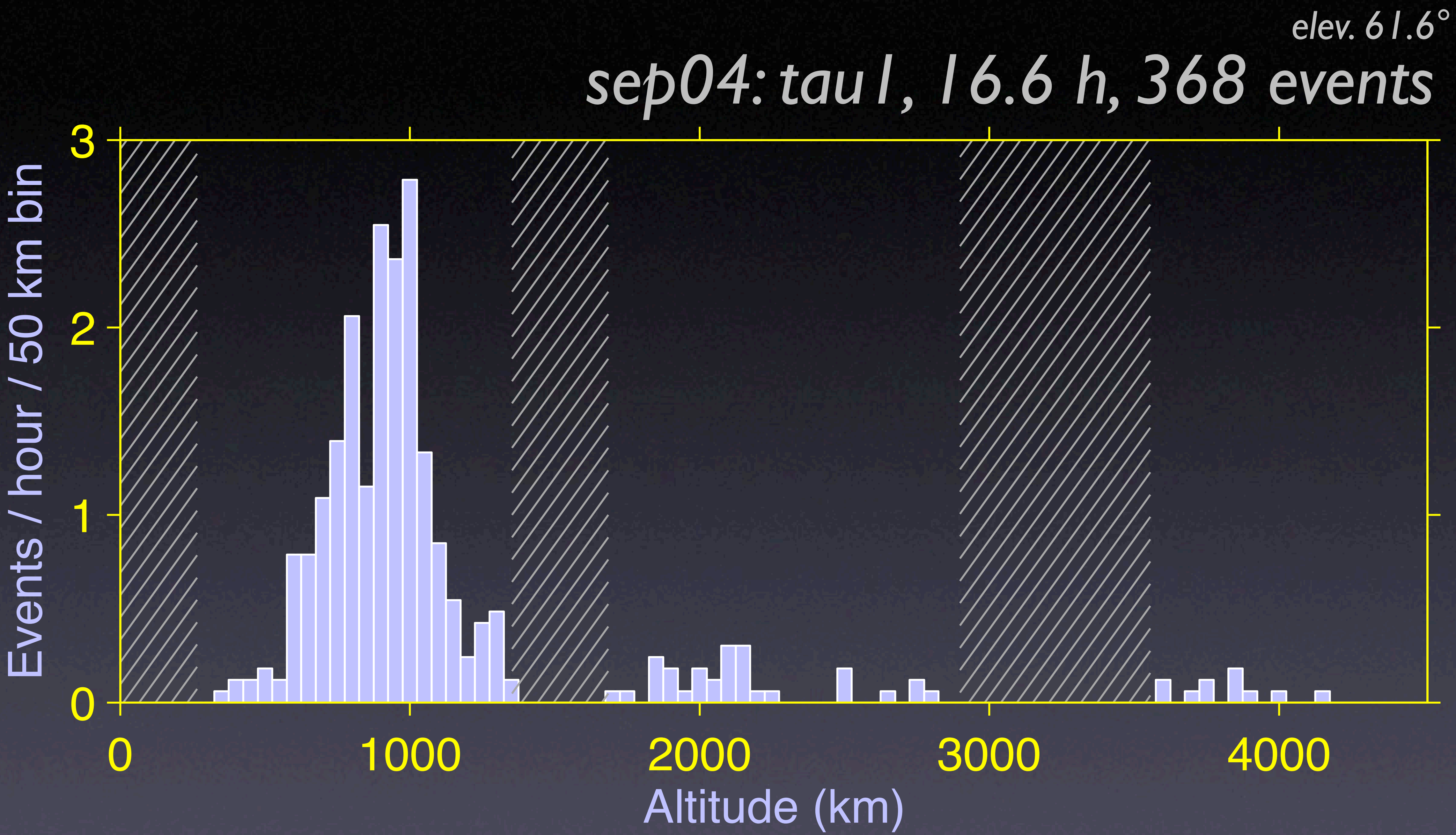
for EISCAT UHF



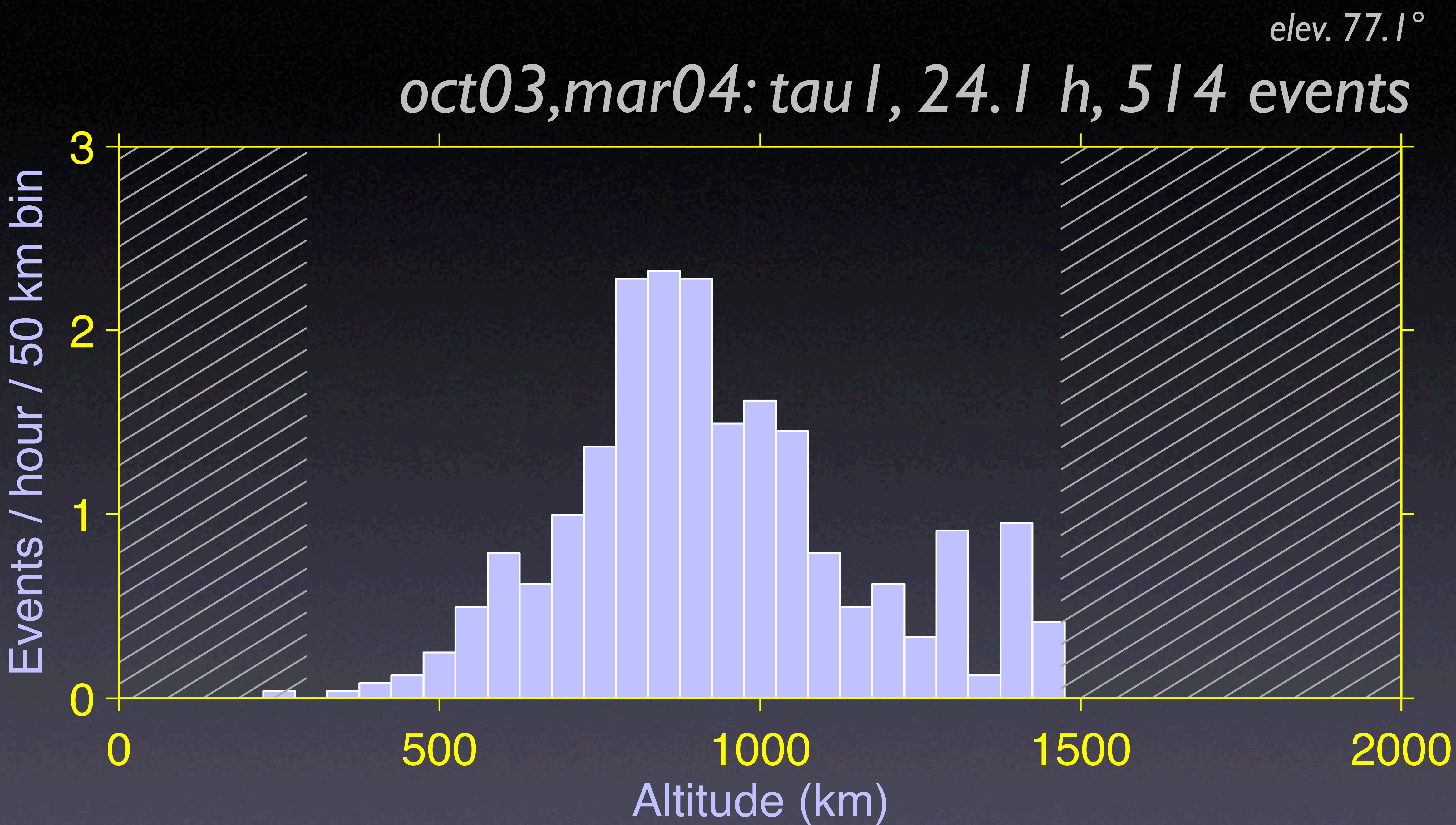
Radar cross section vs range



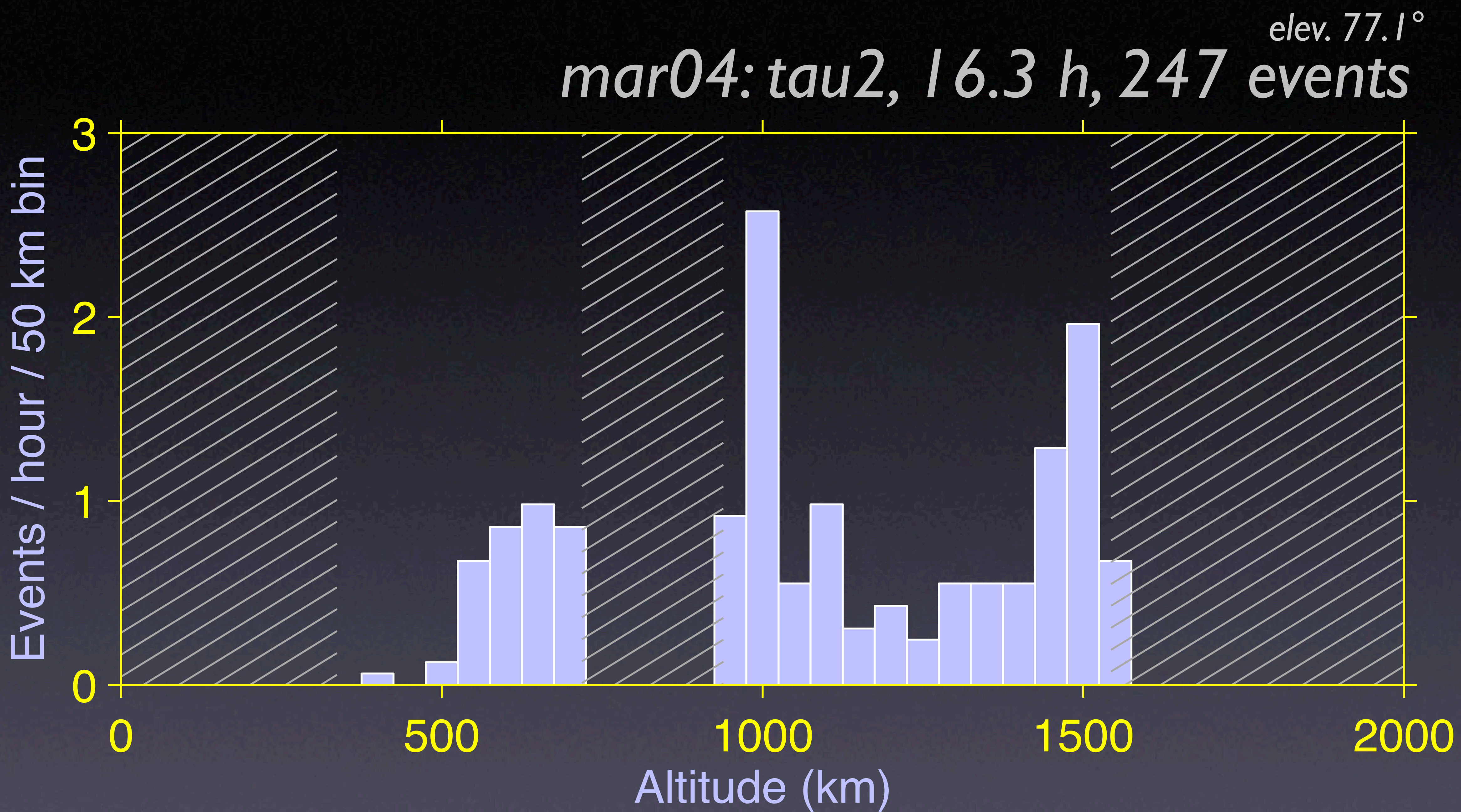
Event rate vs altitude



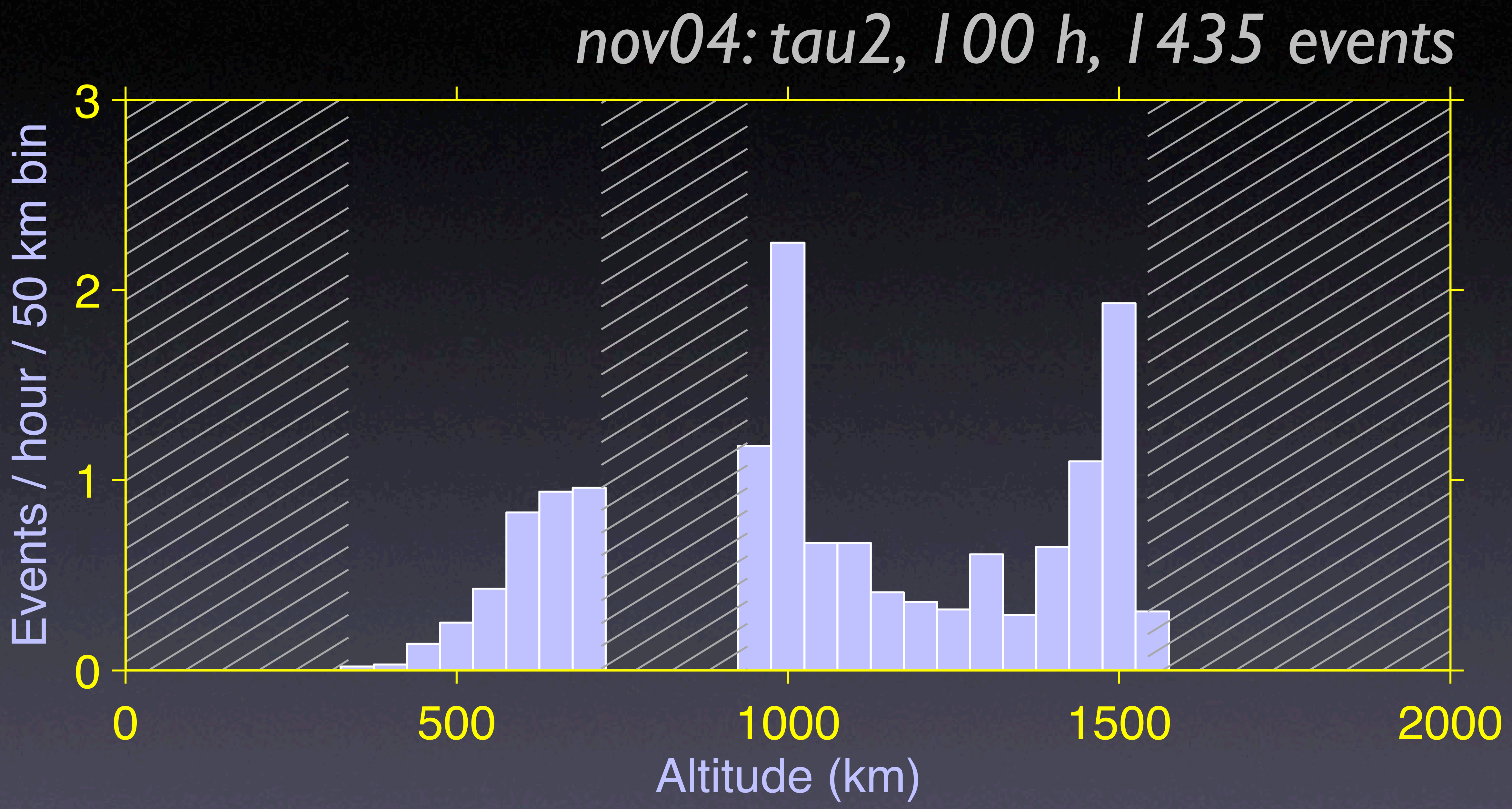
Event rate vs altitude



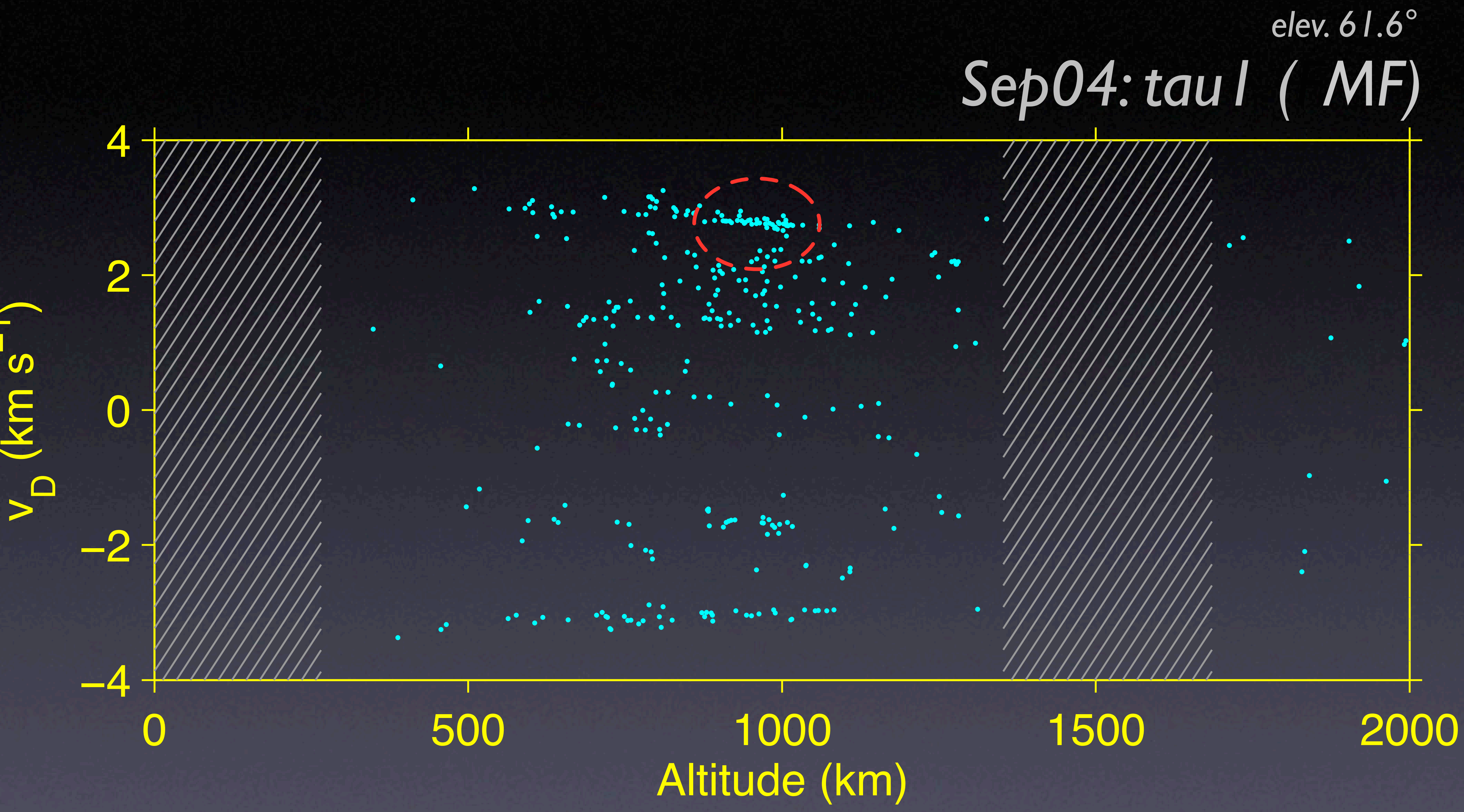
Event rate vs altitude



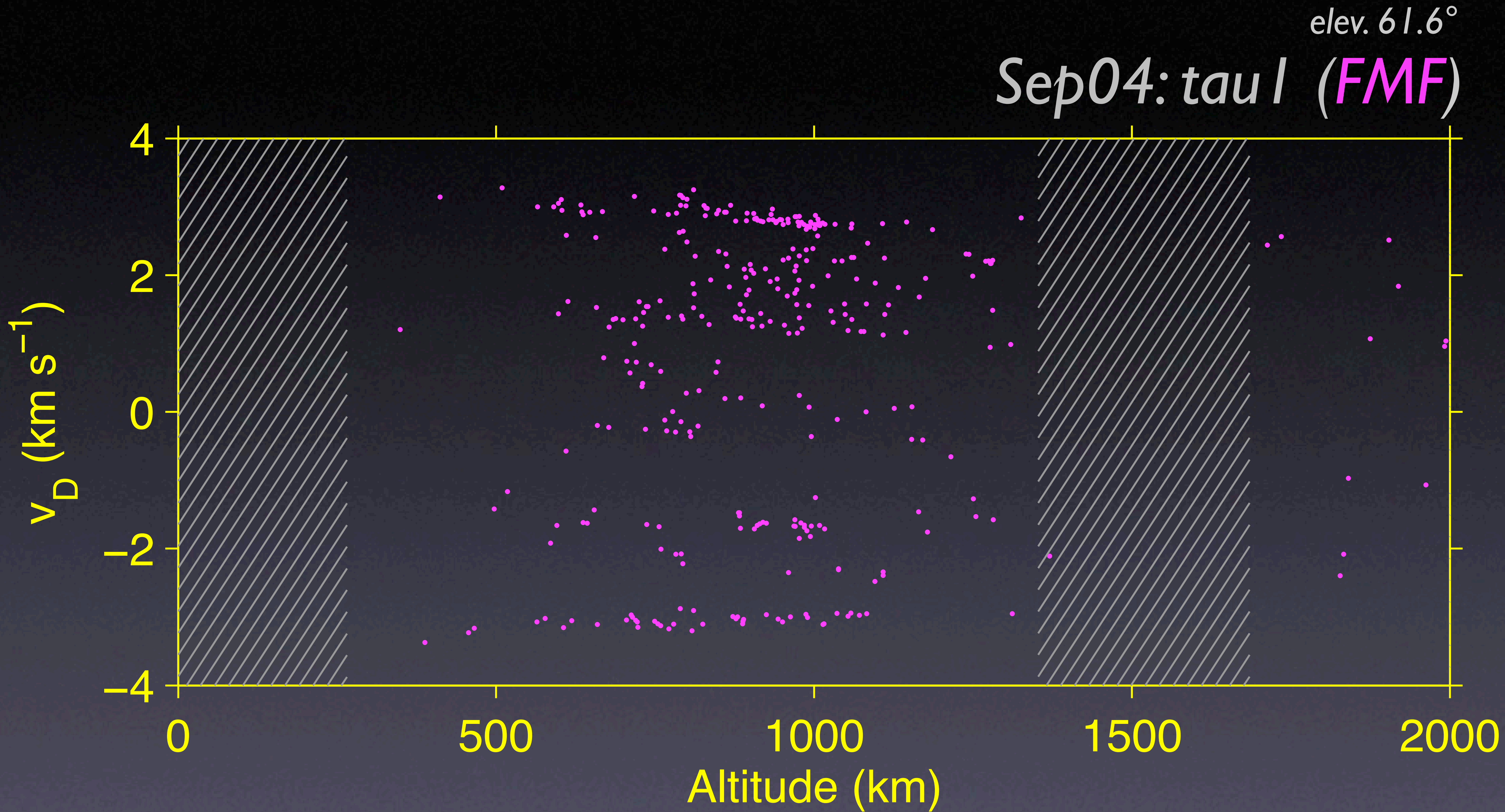
Event rate vs altitude



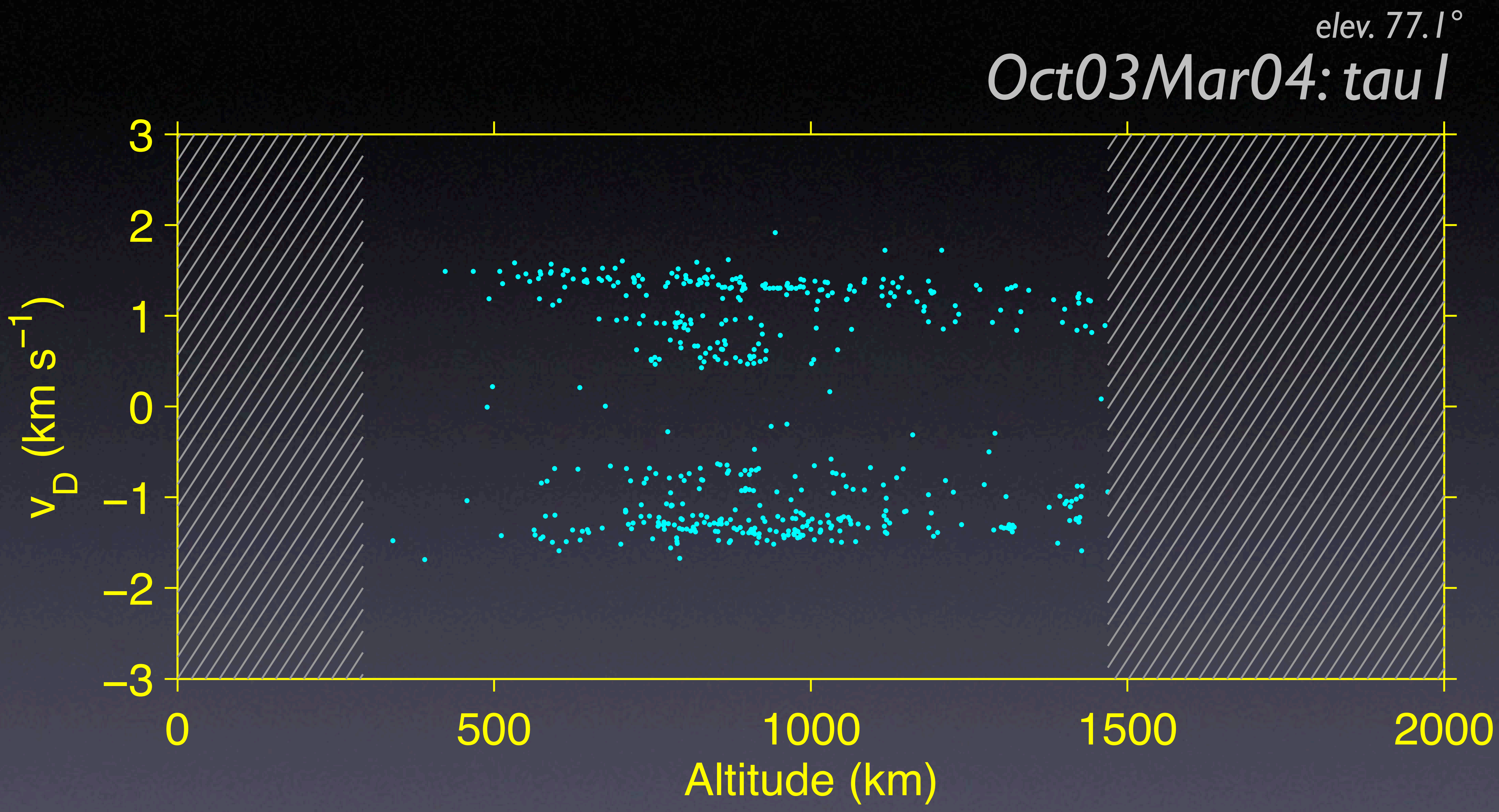
Radial velocity vs altitude



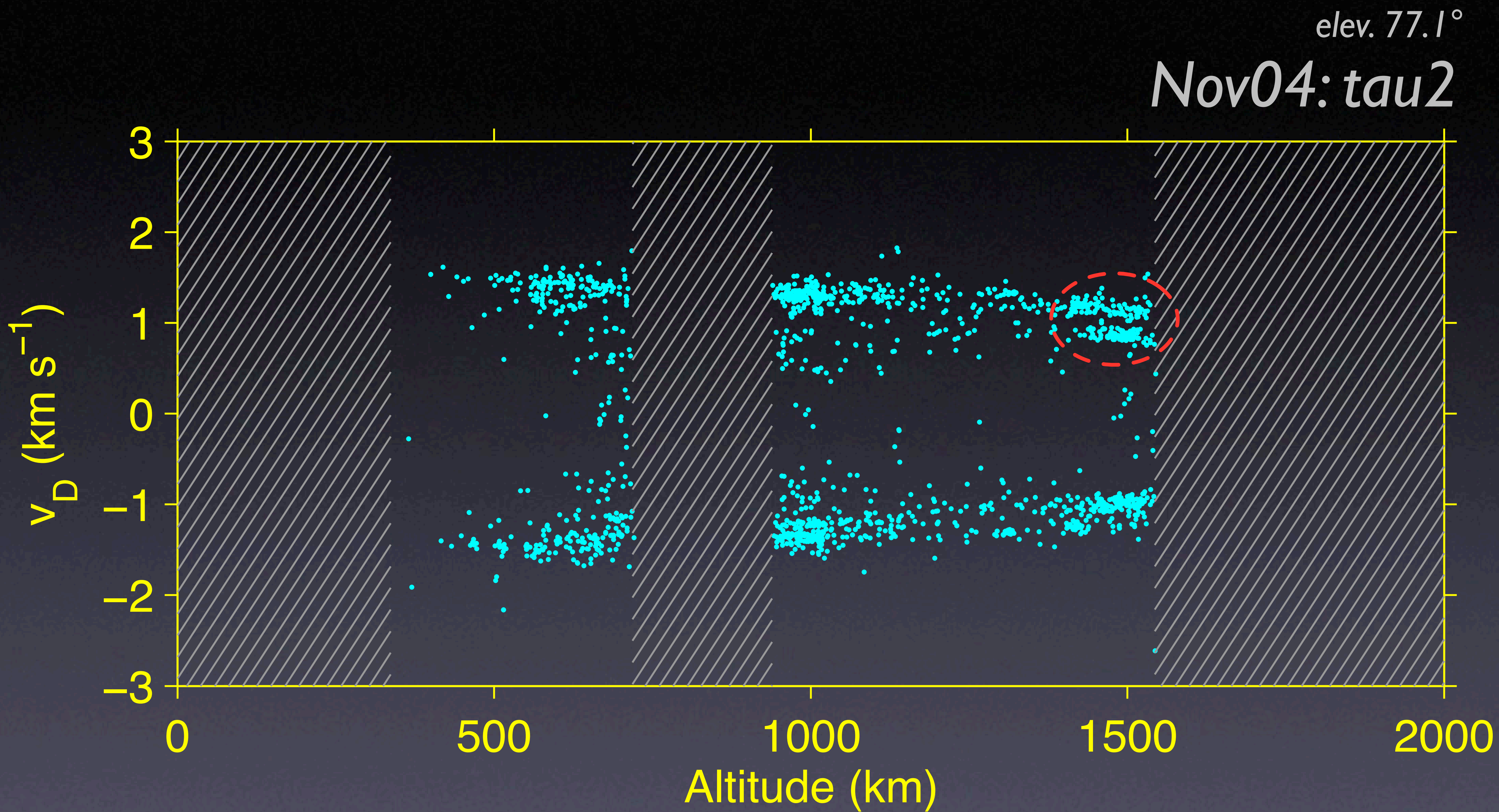
Radial velocity vs altitude



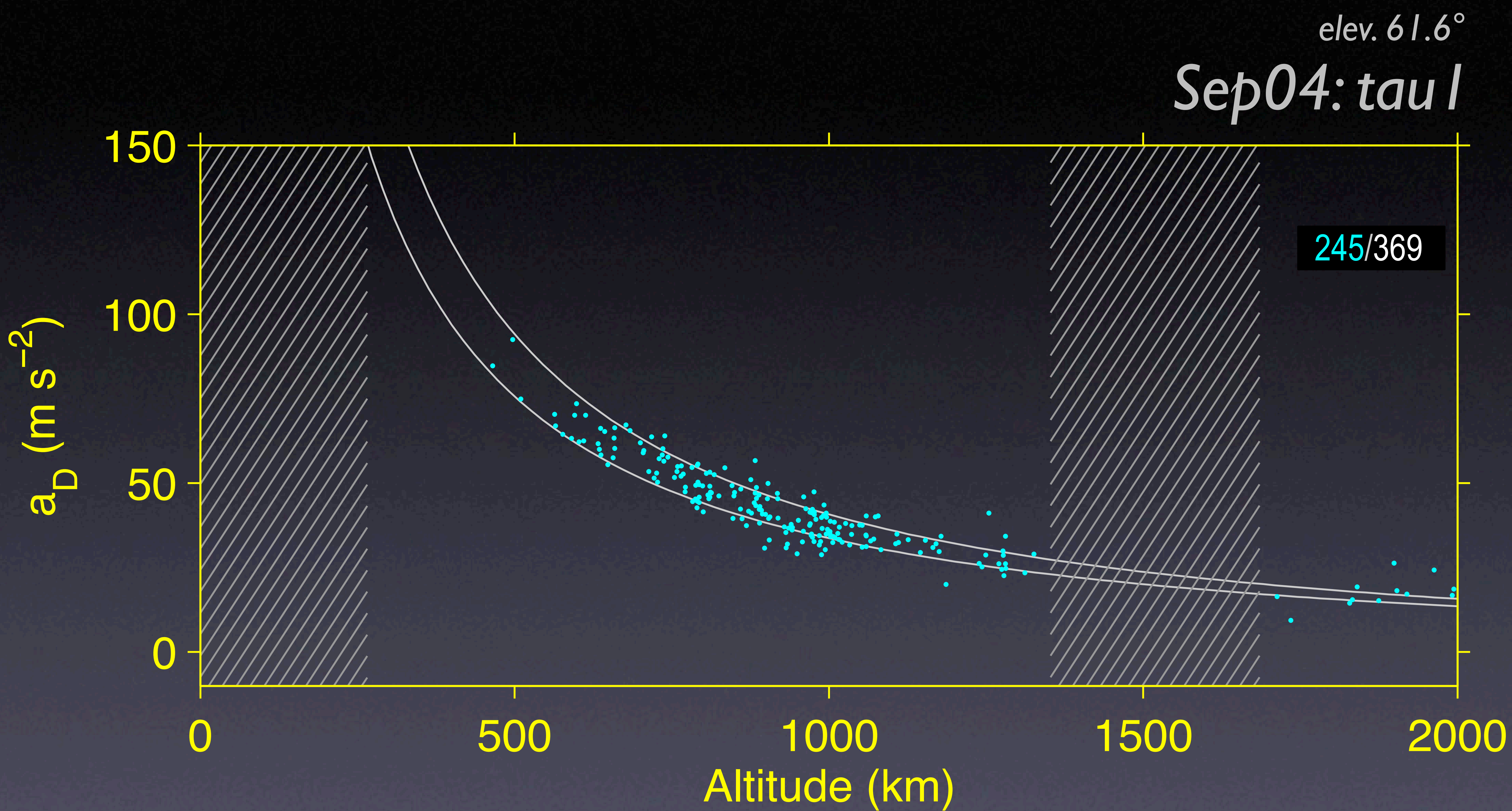
Radial velocity vs altitude



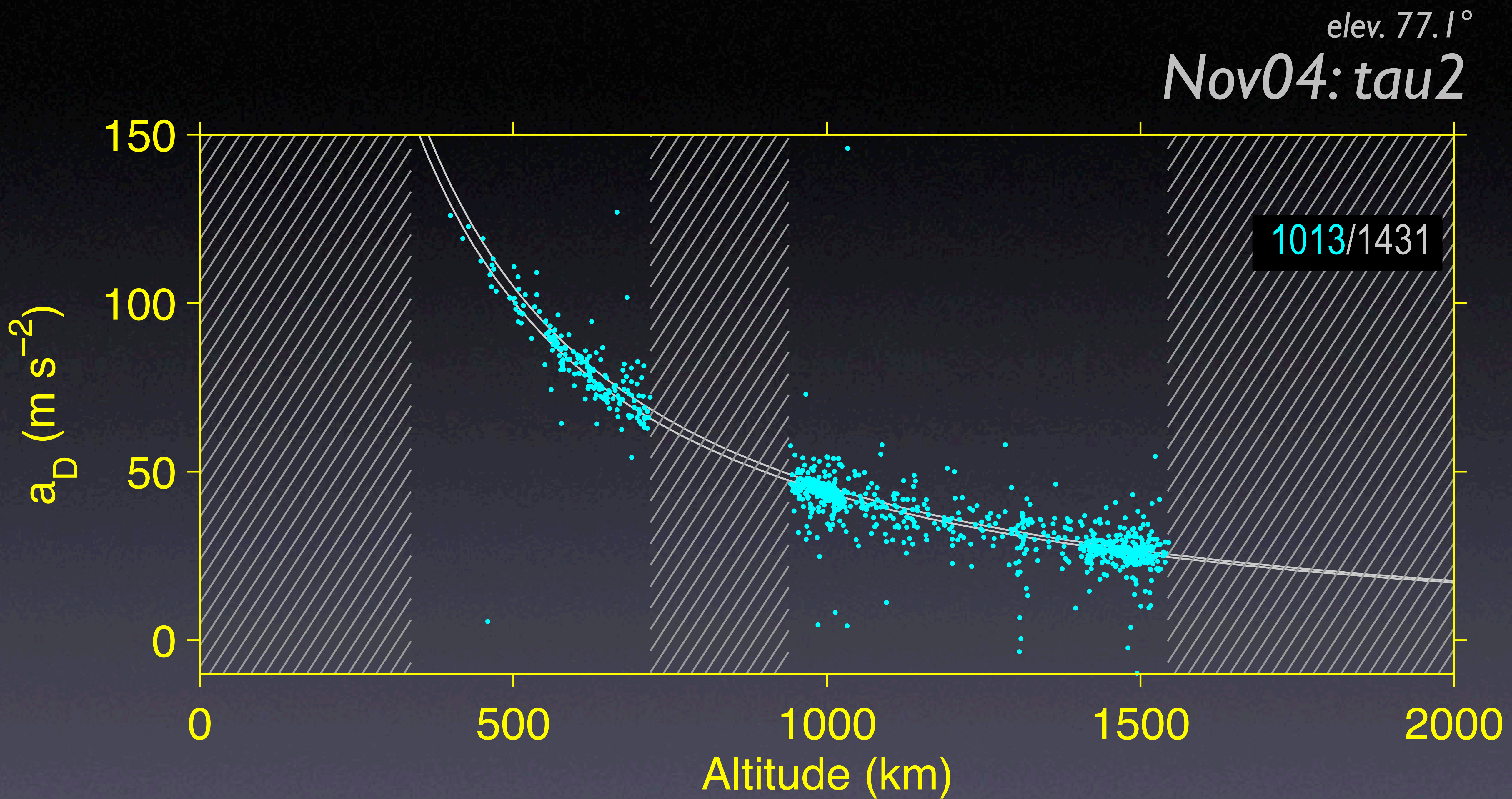
Radial velocity vs altitude



Radial acceleration vs altitude



Radial acceleration vs altitude



Real-time small-size space debris detection with Eiscat radar facilities

SUMMARY

At the moment ...

- Data collection and detection automated and RT.
- Event composing benefits of a manual step. To be included into foreseeable future.
- Analysis from events to parameters automated.
- Sensitivity as in the precursor study.
- Can handle long SD measurements in almost RT.
- SD system installed in Tromso. Ready to go.

In the future ...

- Made software more robust.
- A spare for HW exists, for now. But.
- Tackle remaining problems of the theory, including
  - What is the actual detection sensitivity?
  - How to make best use of 2-frequency data (coincidence-based detection?)
  - Can anything be done to mitigate tau2 R-gap?