Covariances Between ISM and Timing Parameters in Millisecond Pulsars

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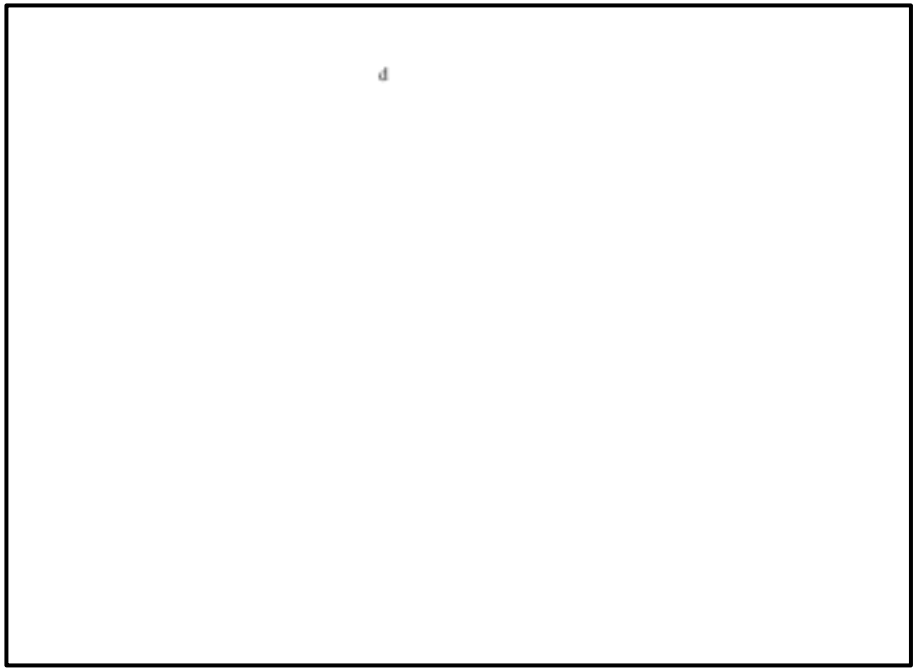
Refractive effects in the ISM



From Shannon 2011 (PhD Dissertation)

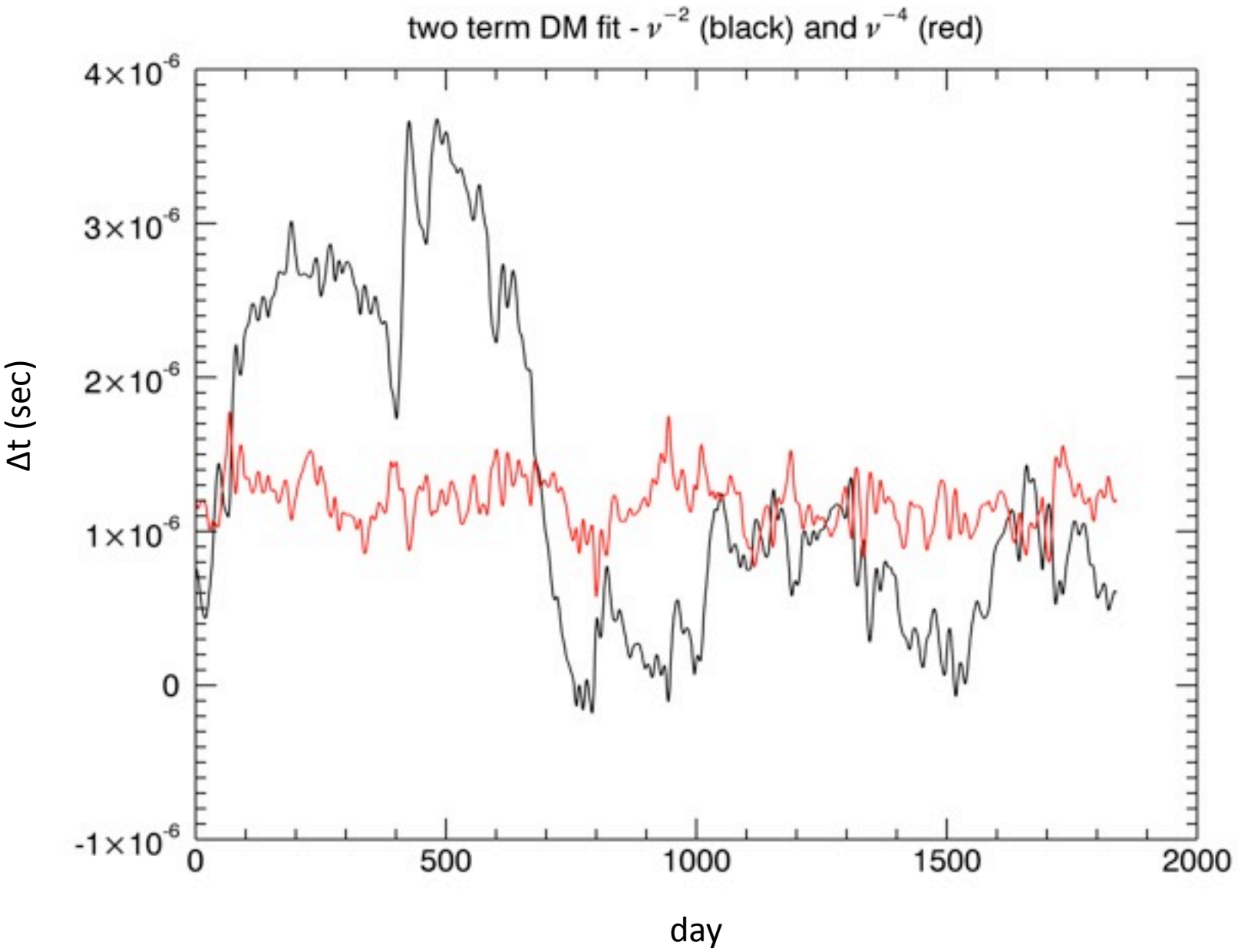
- Time delay due to angle-of-arrival $\boldsymbol{\theta}$ is $\propto \boldsymbol{\theta^2}$
- Frequency dependence: $\boldsymbol{\theta} \propto \boldsymbol{\nu}^{-2}$
- $\Delta t_{AOA} \propto \boldsymbol{\nu}^{-4}$
- Here we assume Kolmogorov power spectrum for (isotropic) spatial fluctuations in refractive screen
- Focus here on refractive effects – time delays due to diffraction as well
- Result – varying DM as well as refractive component

Model for timing residuals

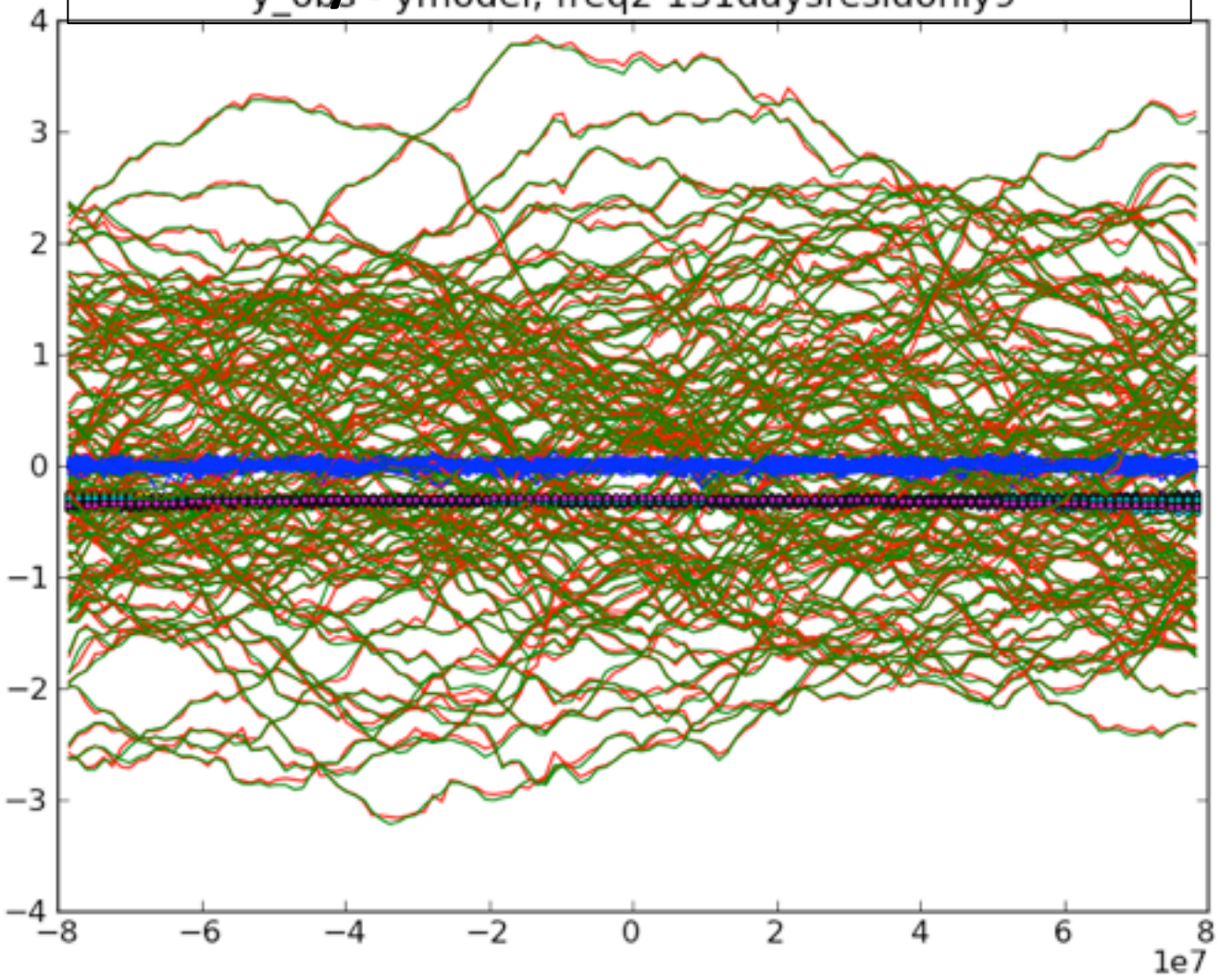
- N_{days} = 128 (about every 2 weeks over 5 yr)
- Linear least squares – no iterations

$$\Delta_t(\nu) = A + Bt_i + Ct_i^2 + DM(t_i)$$

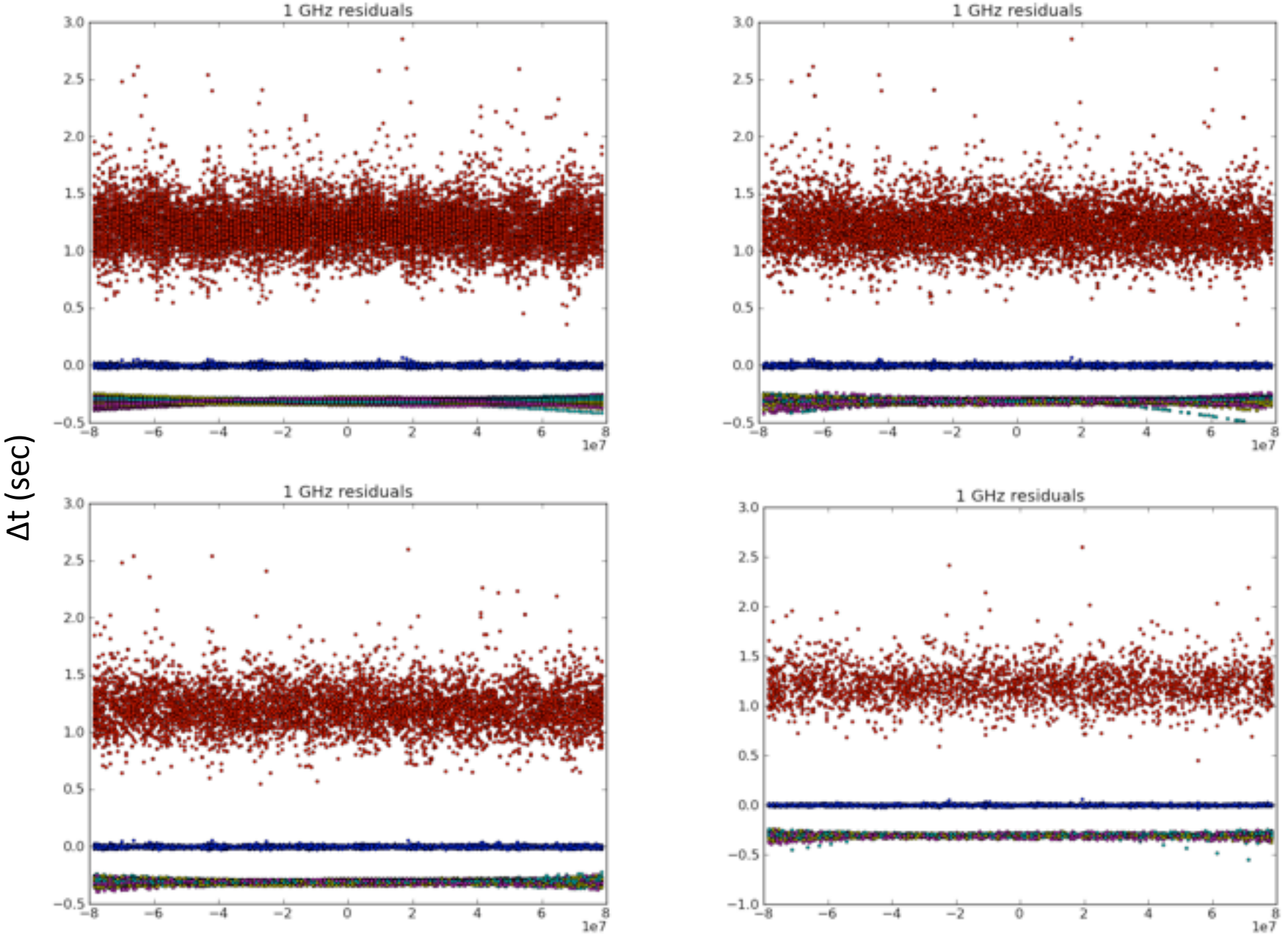
- DM at each time is a separate parameter for the model – 131 parameters total
- Time cadence is varied to be more and more "Poisson" -like


two term DM fit - ν^{-2} (black) and ν^{-4} (red)
4×10-6
3×10-6
2×10-6
1×10-6
0
-1×10-6
Δt (sec)
0
500
1000
1500
2000
day

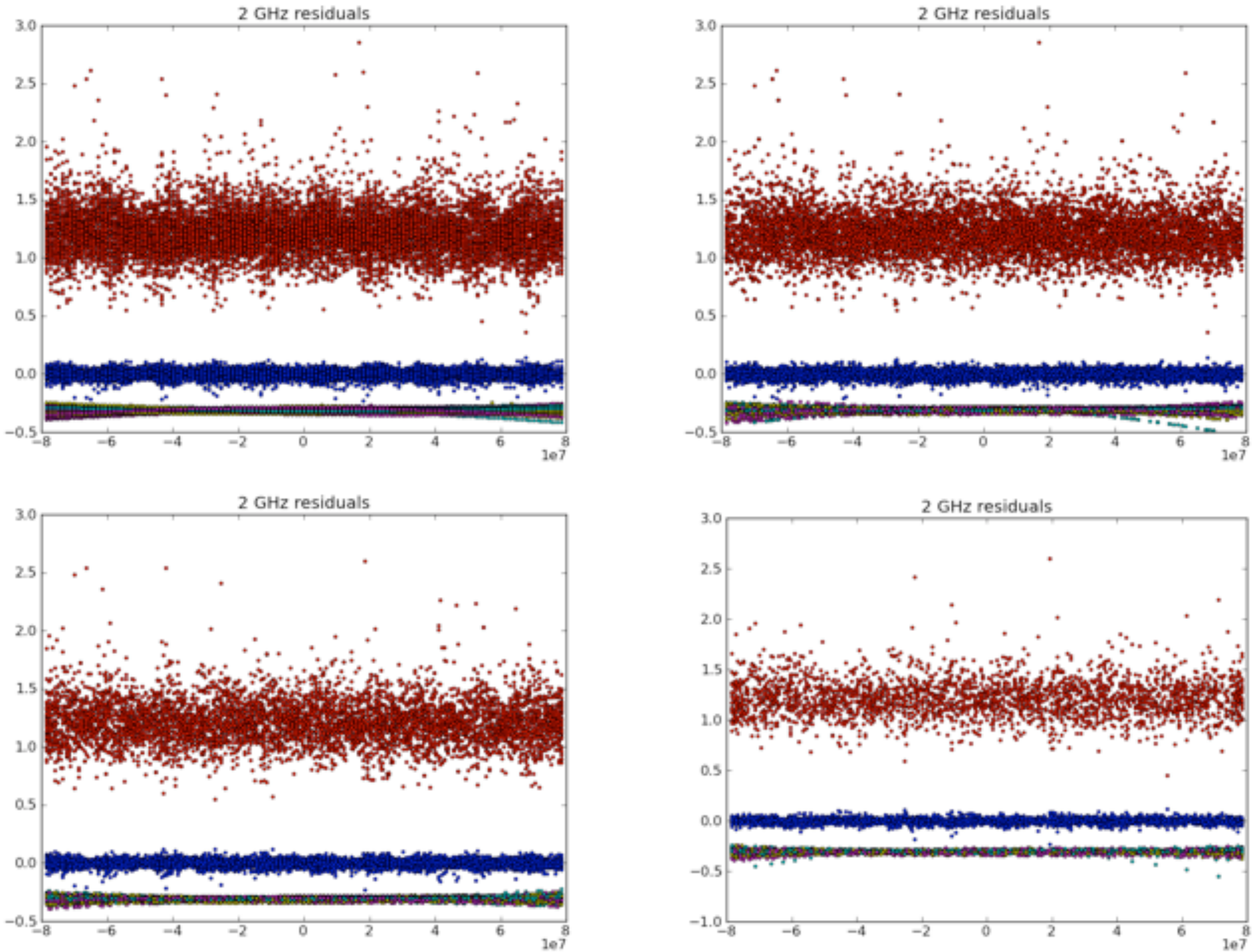
Time Delays due to ISM: DM and Refraction



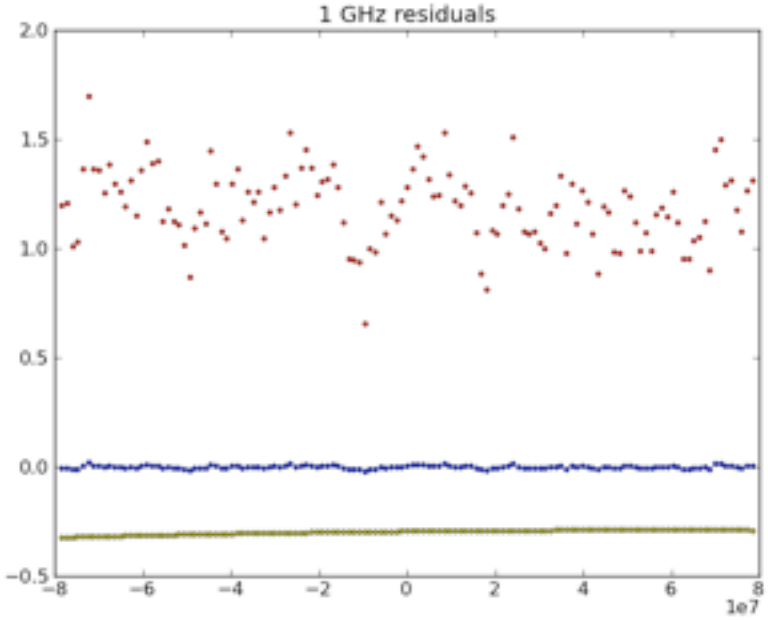
Residuals after DM term removed: 1GHz

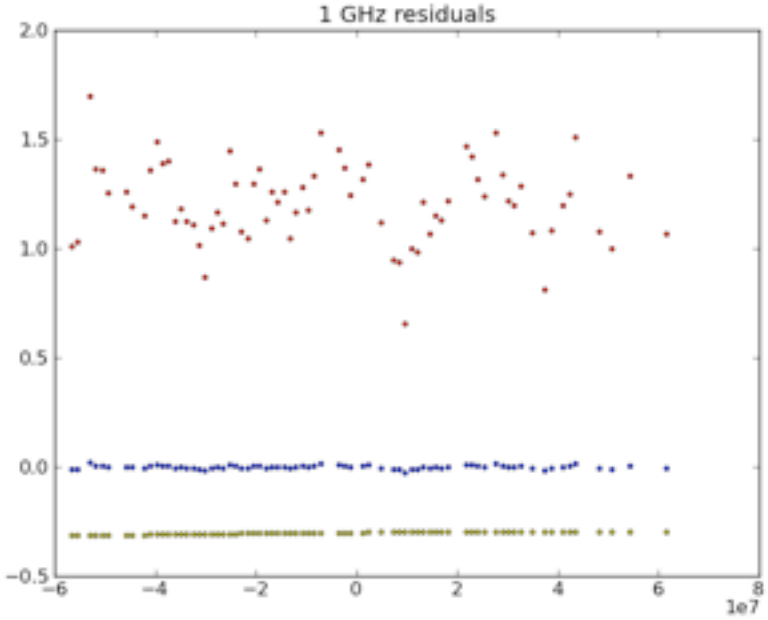


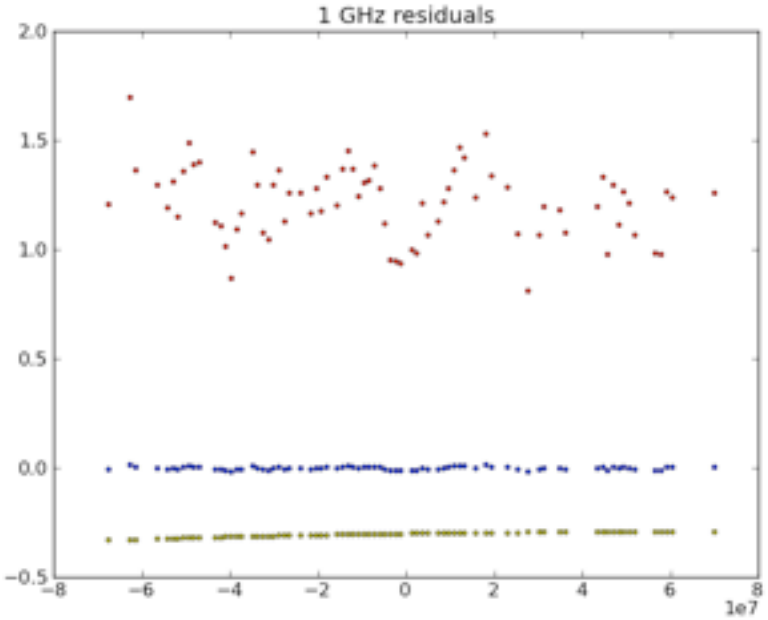
Residuals after DM term removed: 2GHz



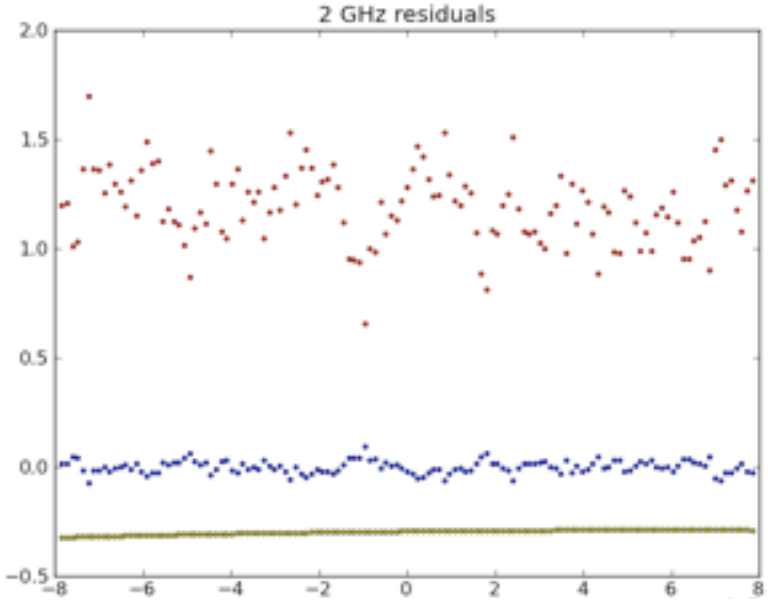
Single iteration residuals after DM term removed: 1 GHz

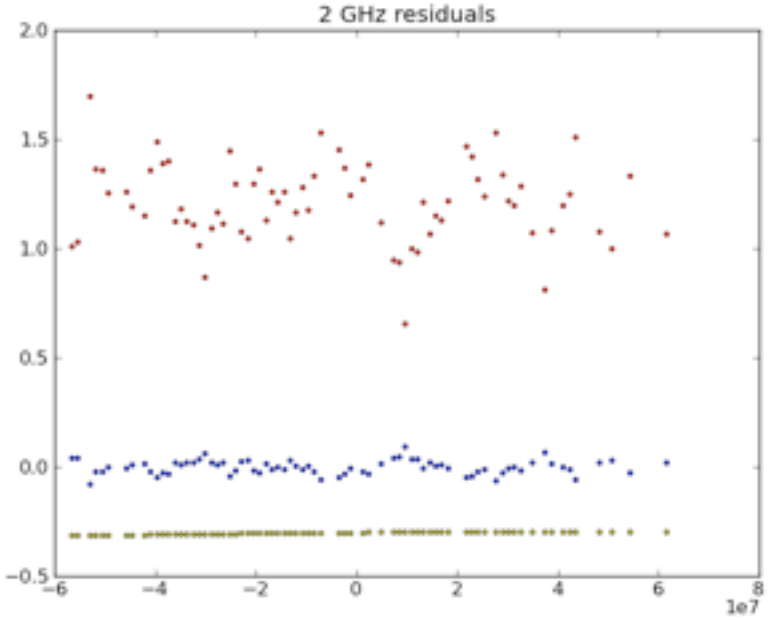


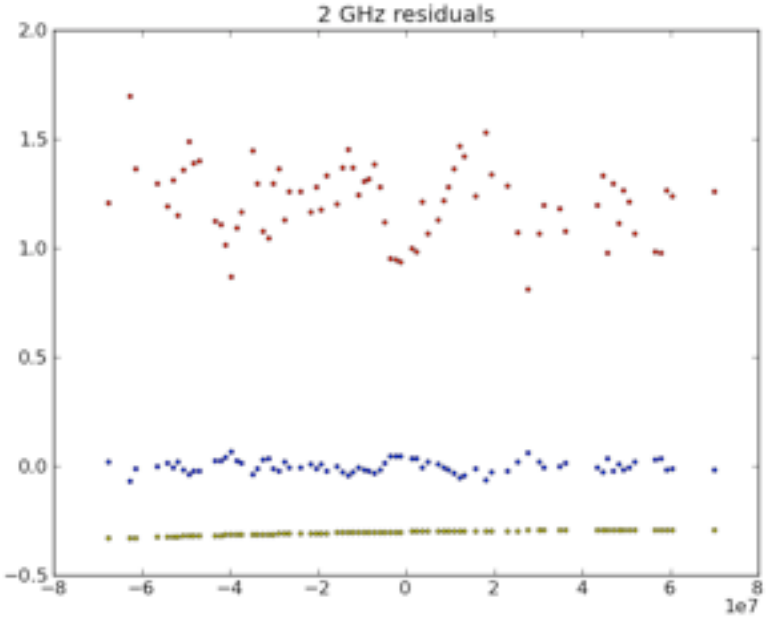




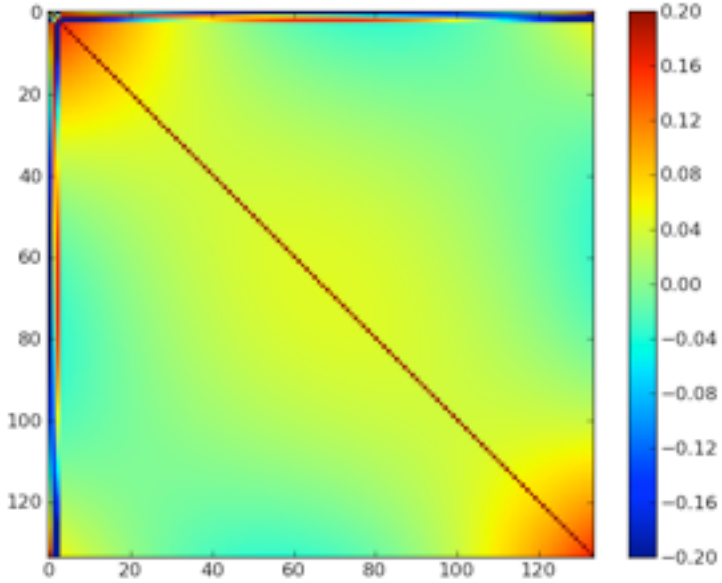
Single iteration residuals after DM term removed: 2 GHz

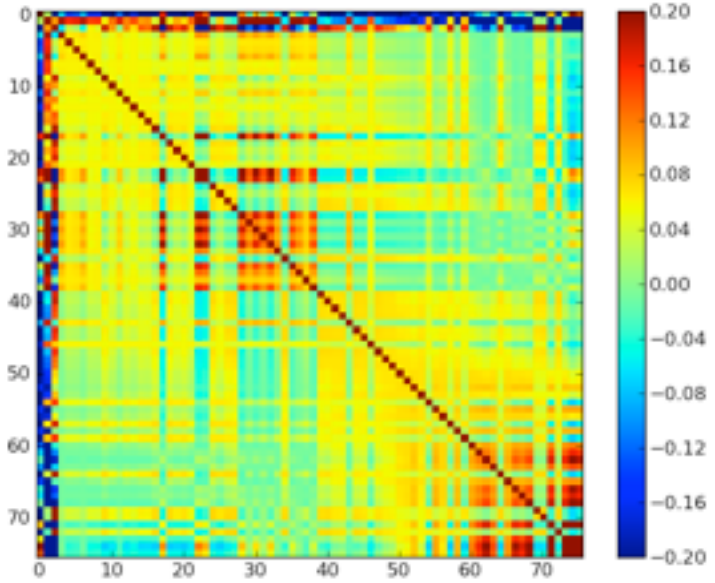


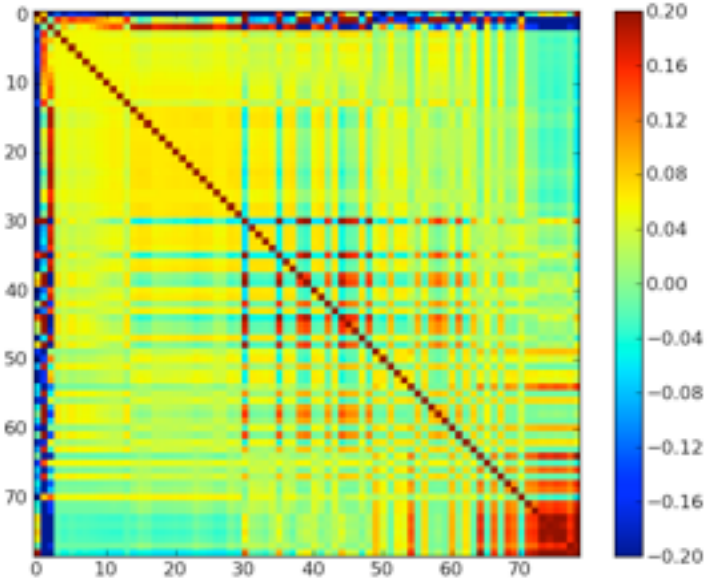




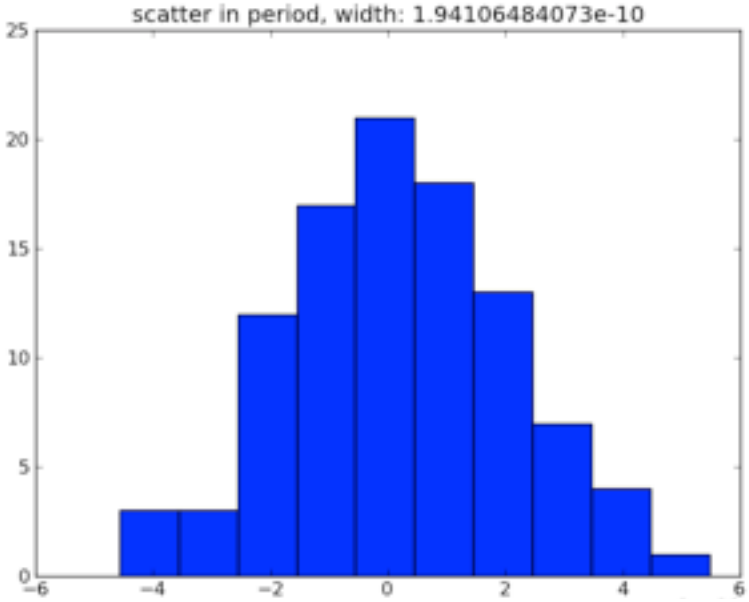
Covariance Matrix of Model Parameters

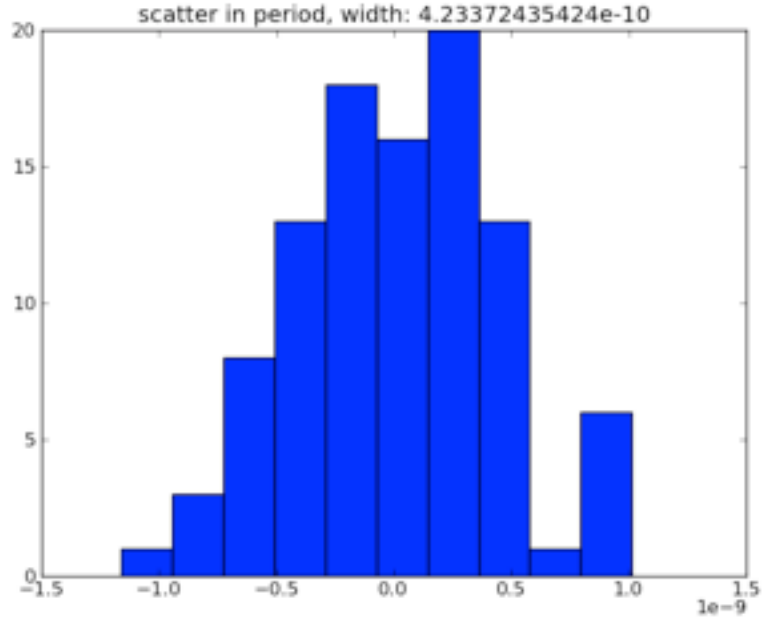


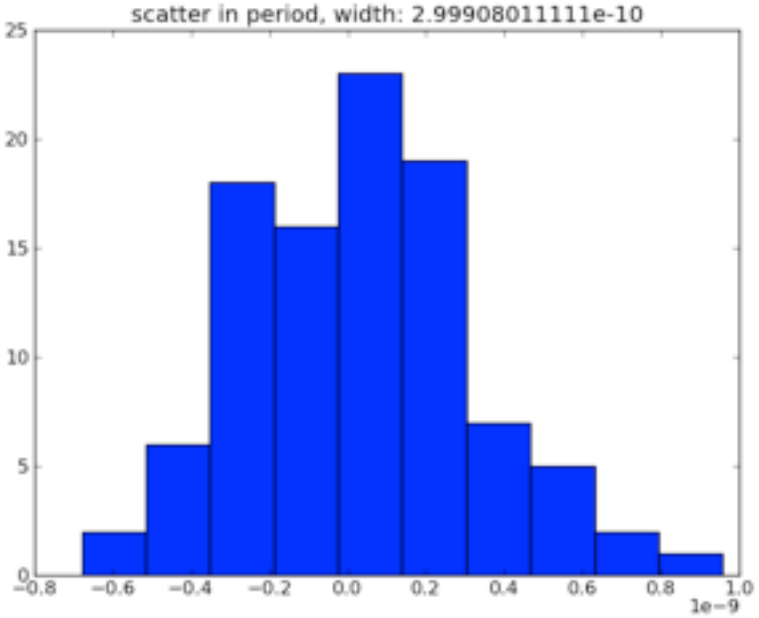




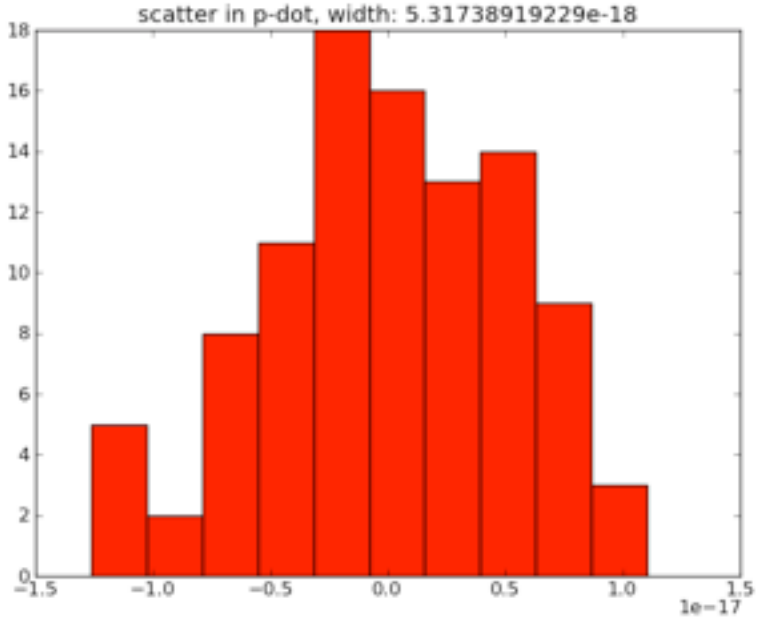
Scatter in B Parameter

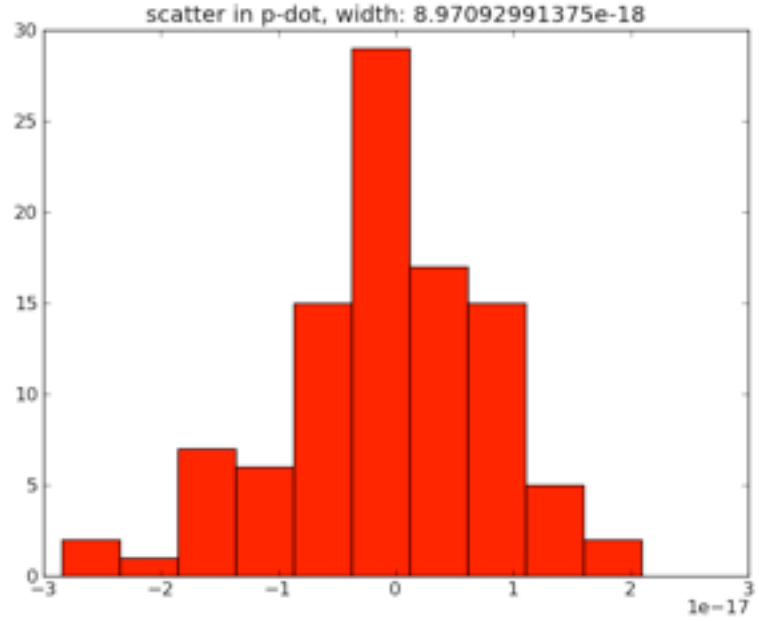


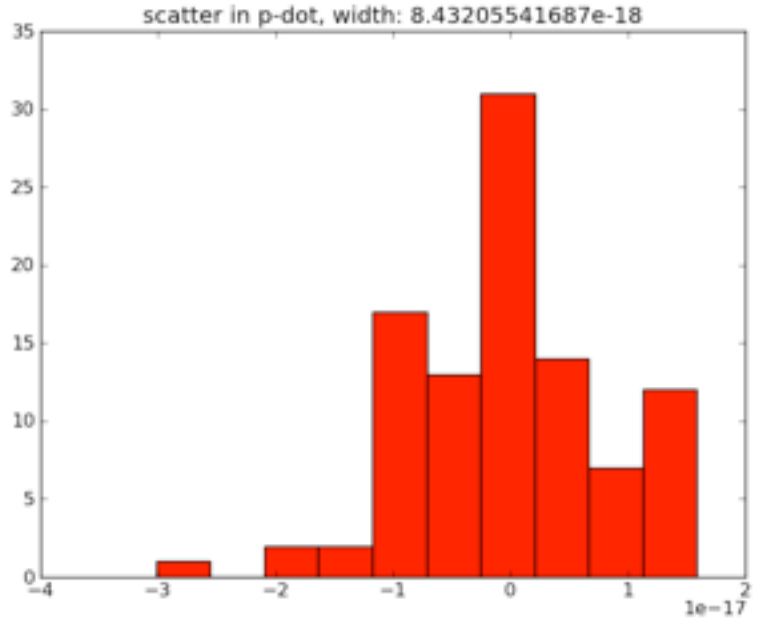




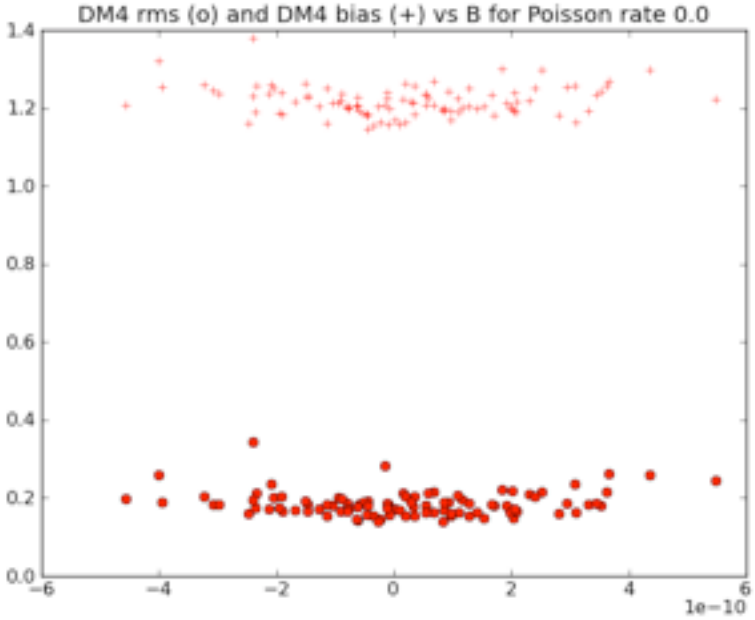
Scatter in C Parameter

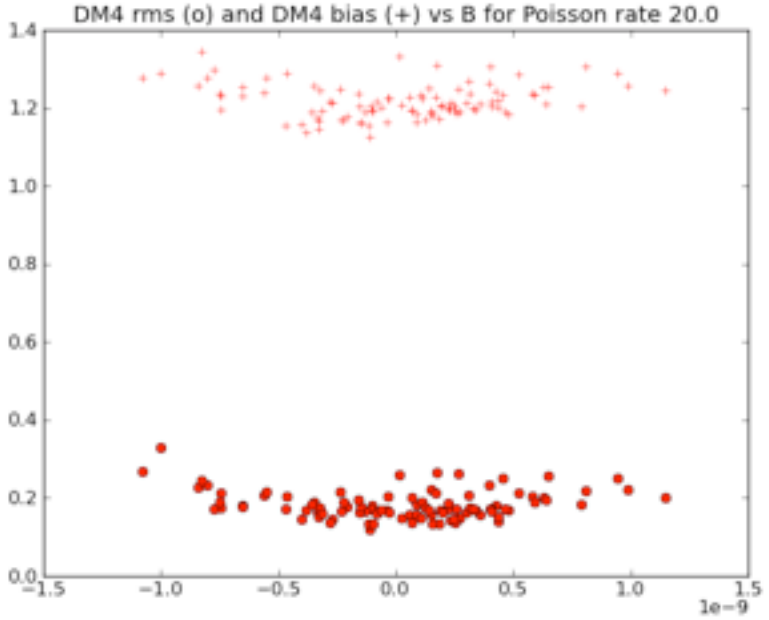


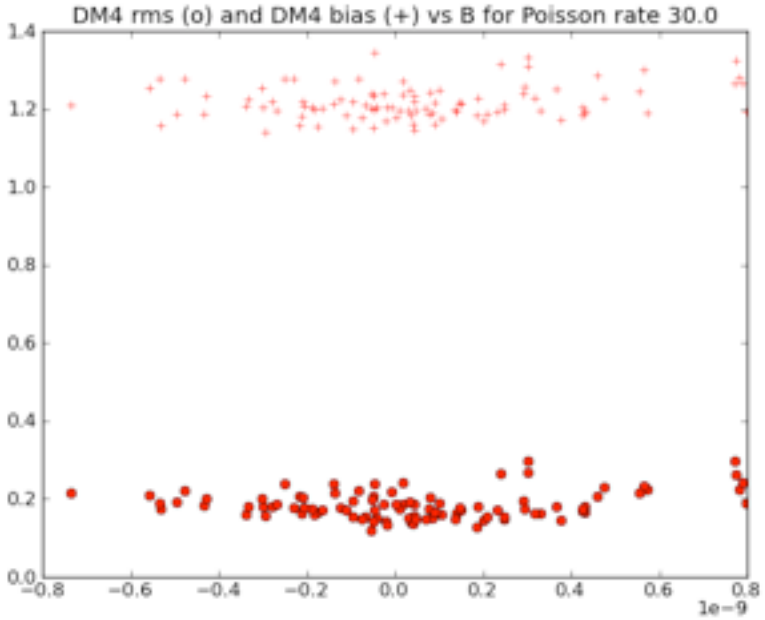




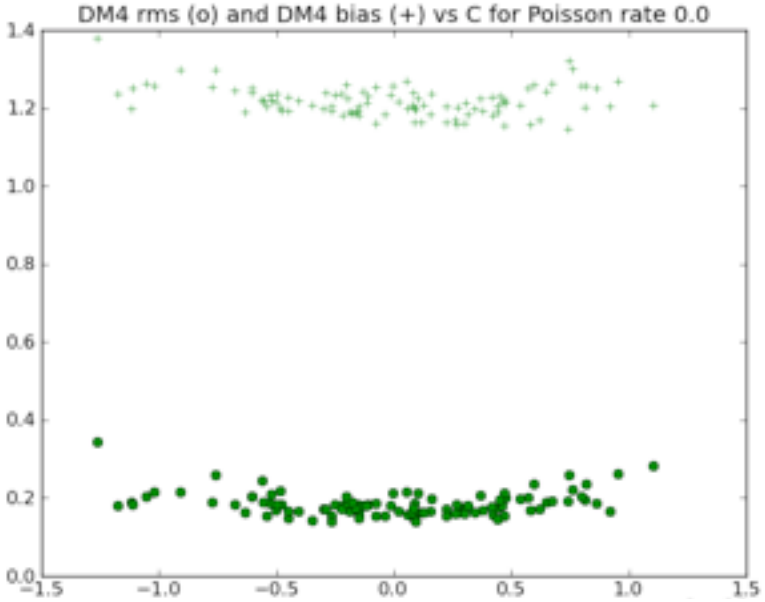
Scatter in Refractive Time Delay

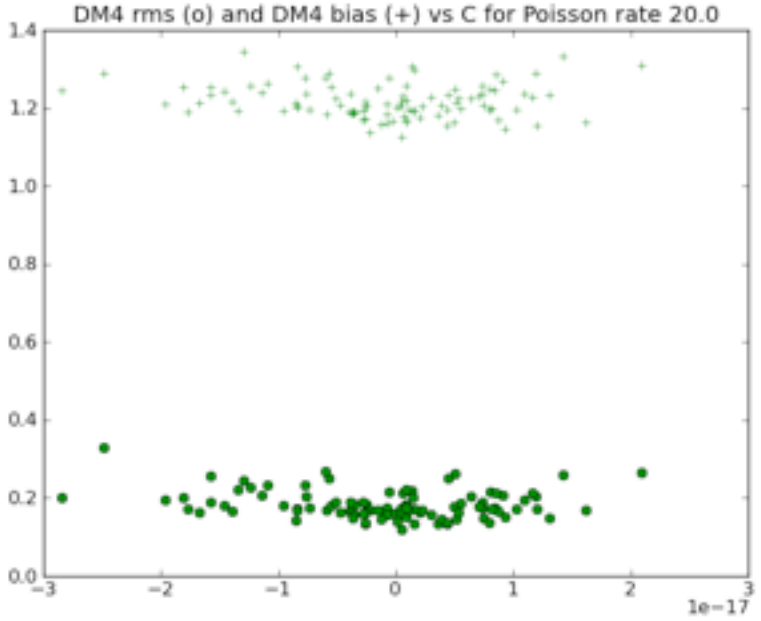


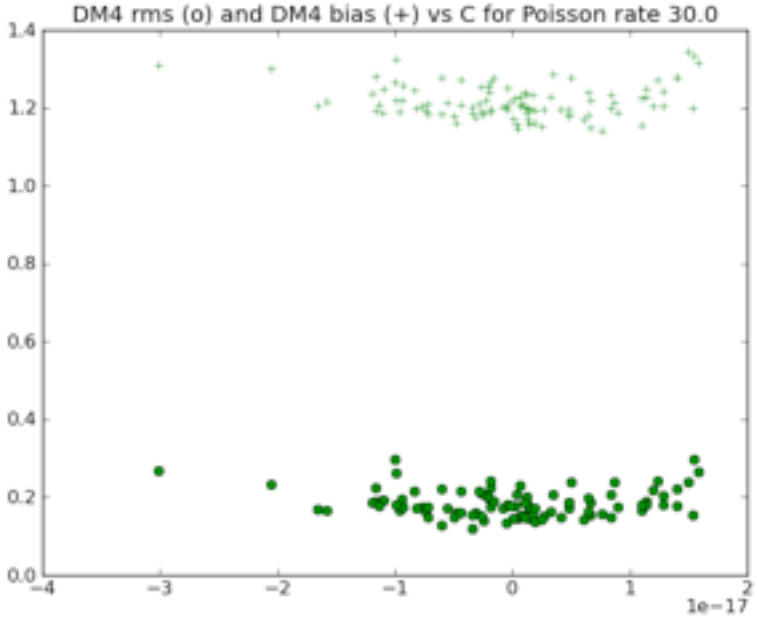




Scatter in Refractive Time Delay

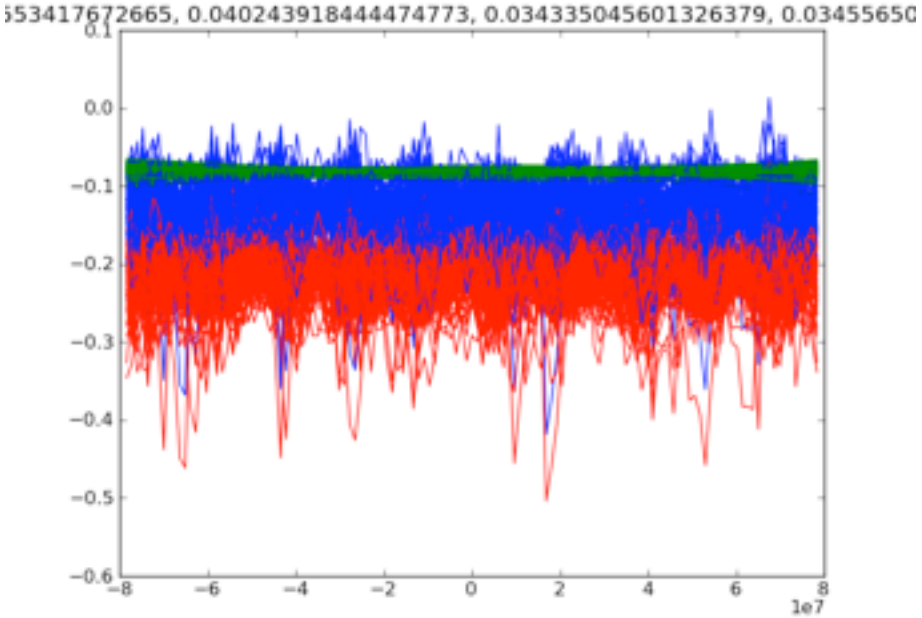


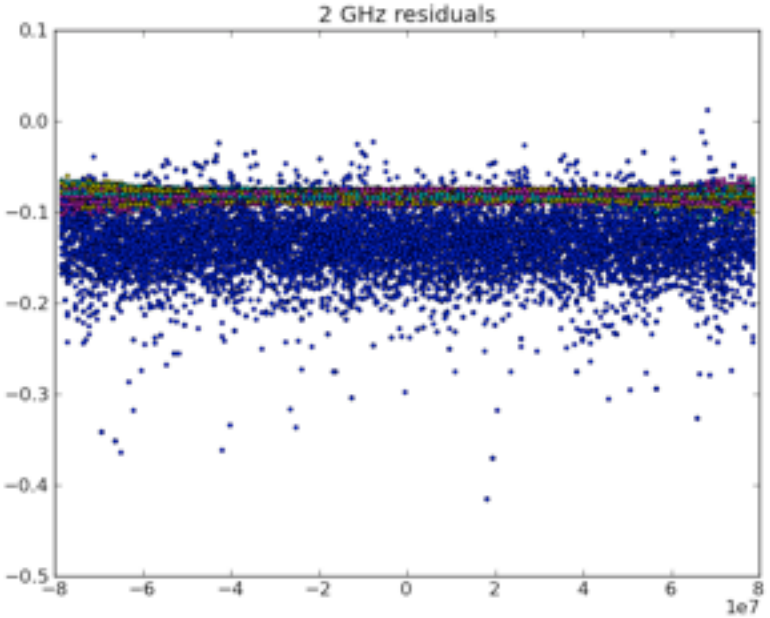


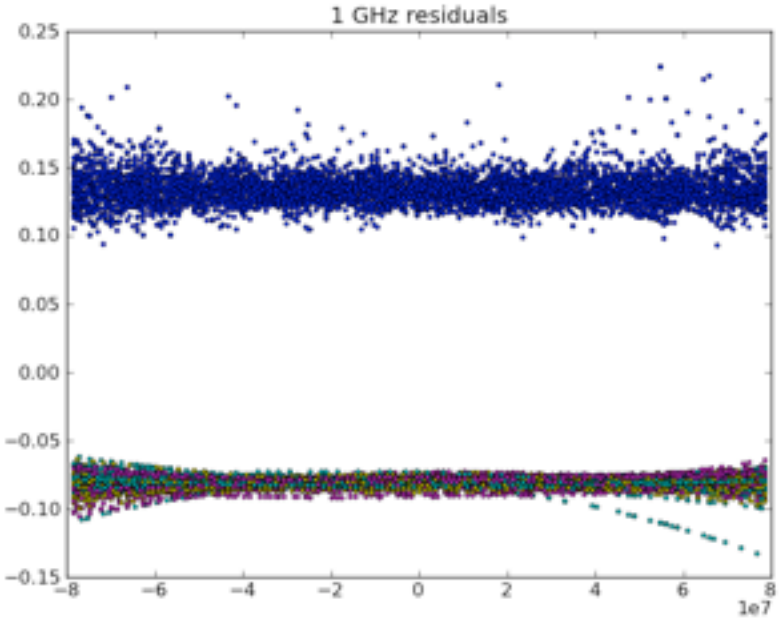


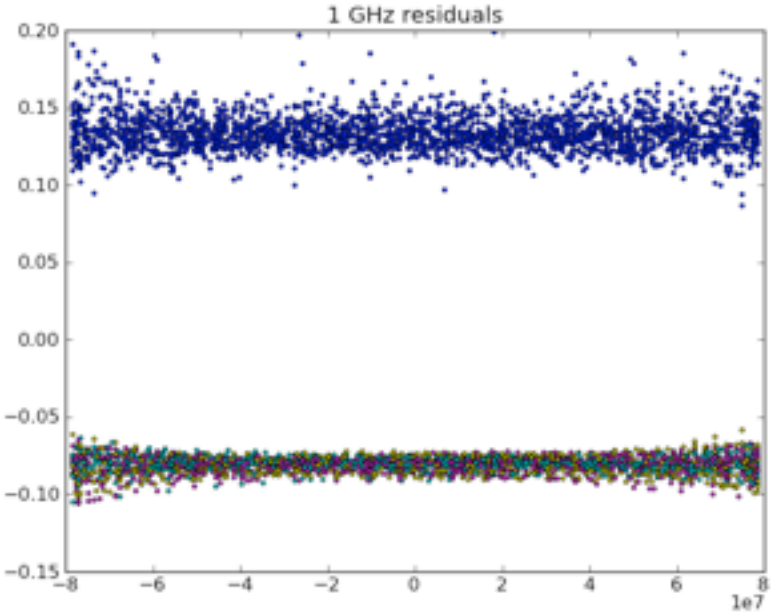
Towards modeling the ISM beyond DM

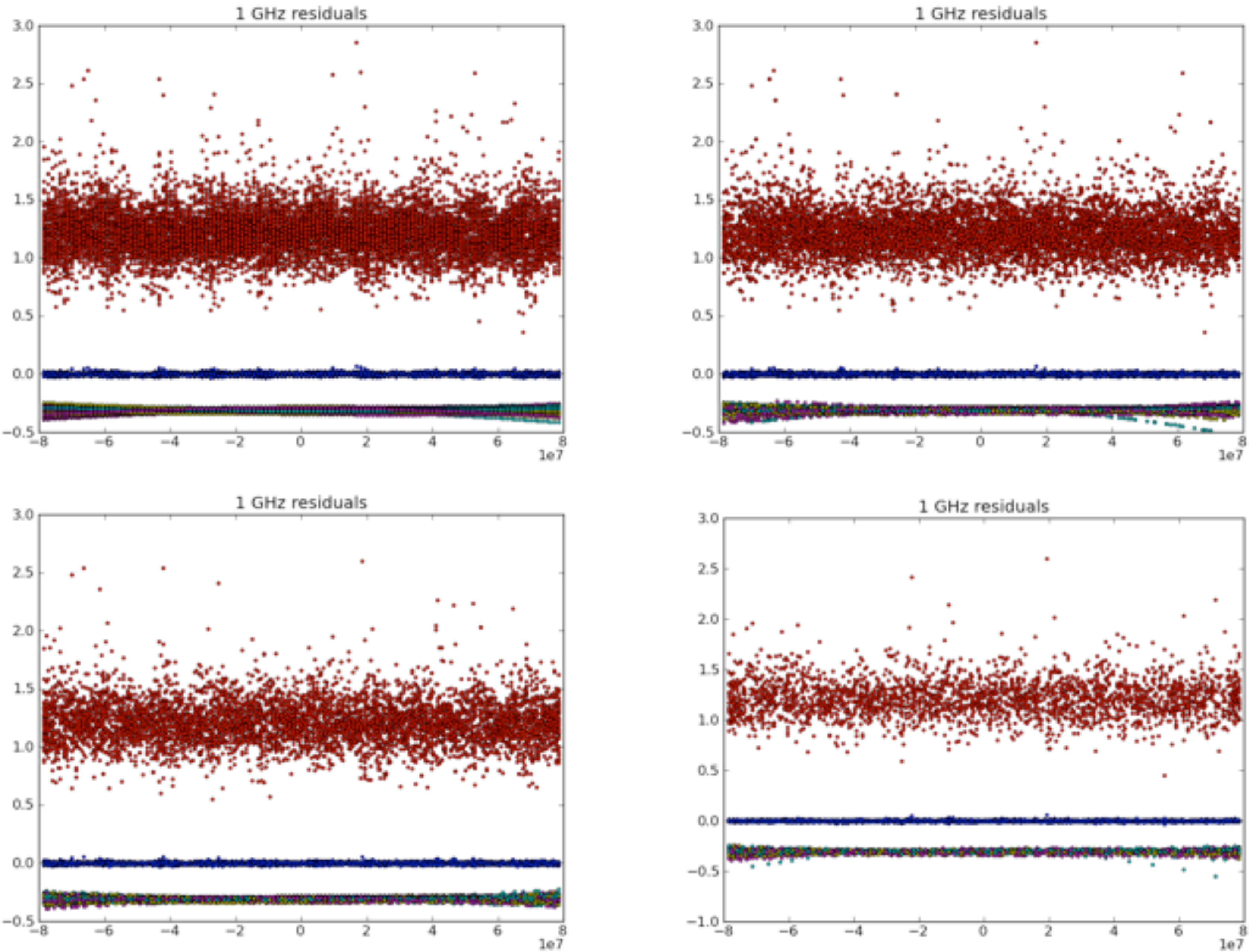
- Beyond Kolmogorov fluctuation spectrum
- Introduction of anisotropies
- as timing residuals approach 10ns, explicit modeling of refractive and diffractive effects should be employed in addition to DM variations

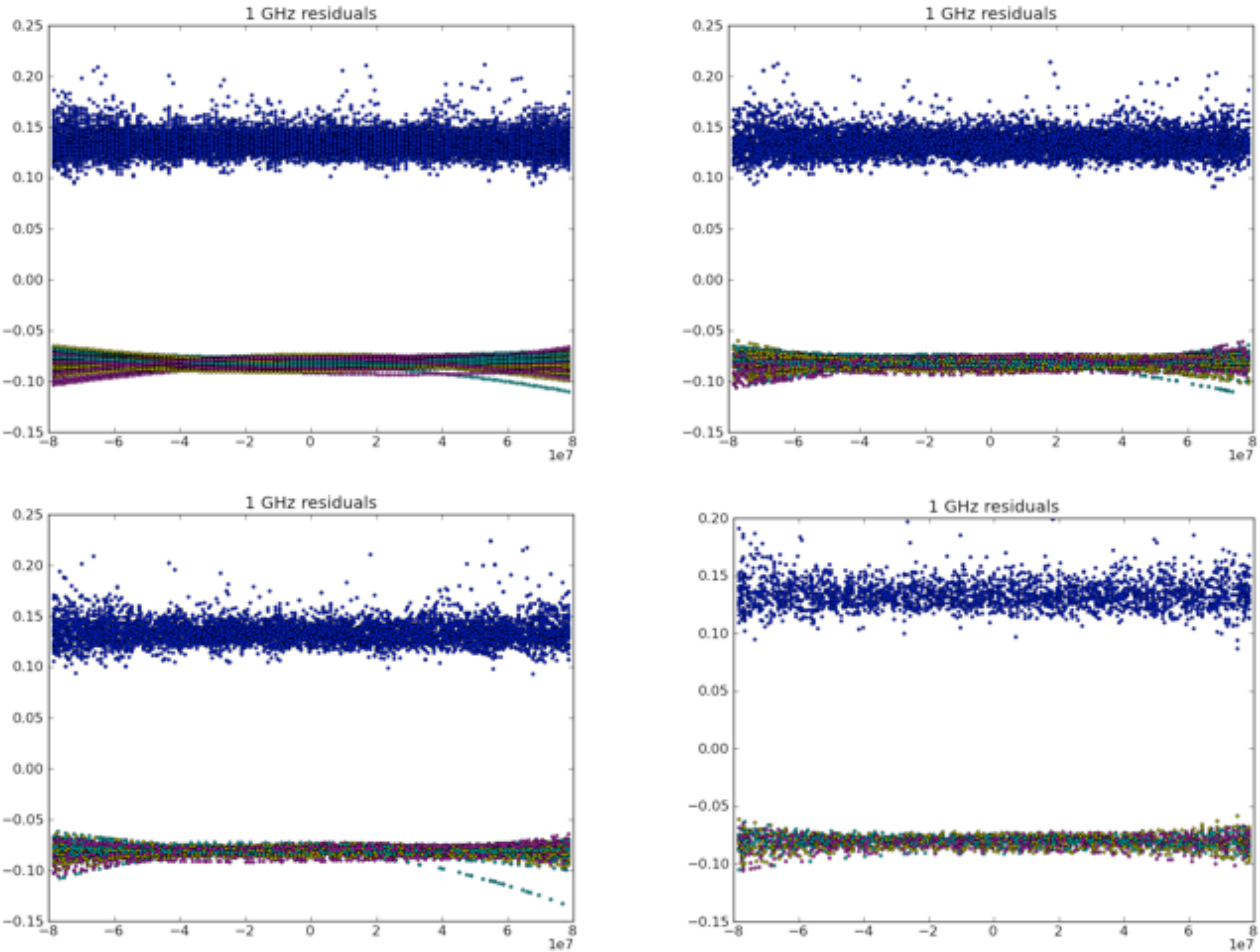

553417672665, 0.040243918444474773, 0.034335045601326379, 0.03455650
1e7

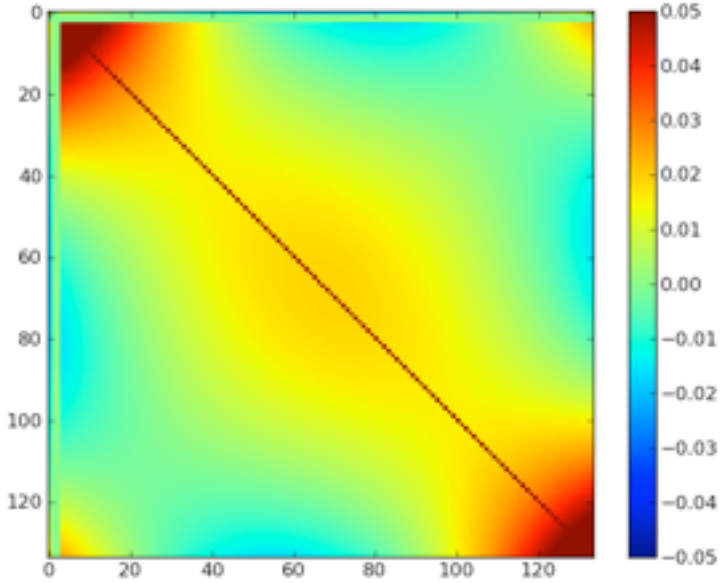

2 GHz residuals
1e7

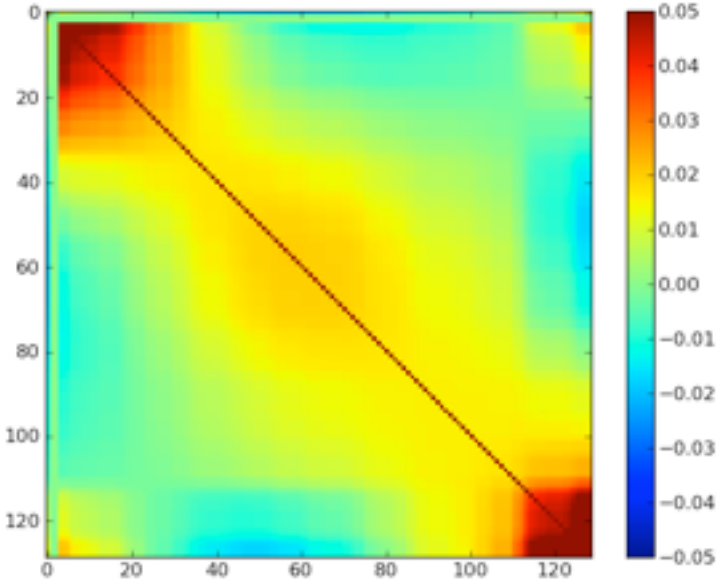

1 GHz residuals
1e7

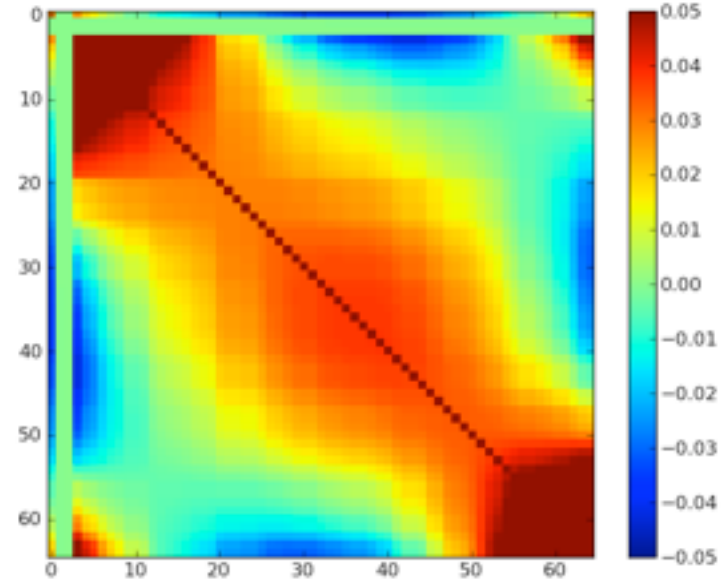

1 GHz residuals
1e7

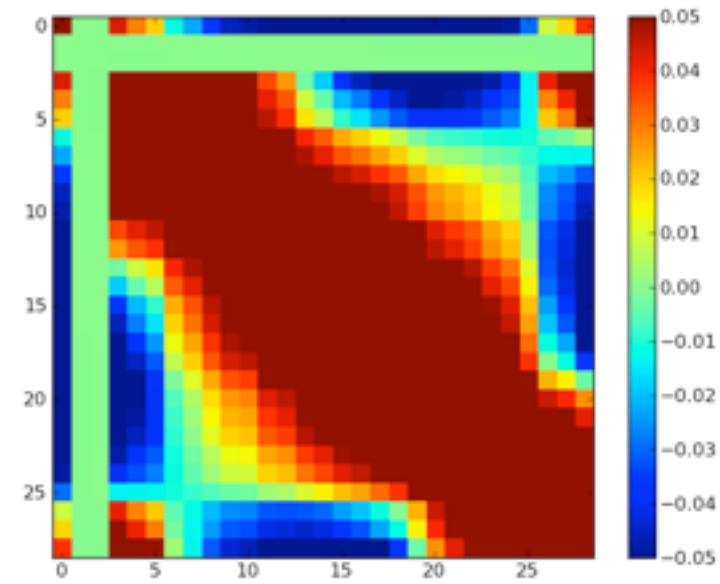

1 GHz residuals
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−8
−6
−4
−2
0
2
4
6
8
1e7
1 GHz residuals
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−8
−6
−4
−2
0
2
4
6
8
1e7
1 GHz residuals
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−8
−6
−4
−2
0
2
4
6
8
1e7
1 GHz residuals
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−8
−6
−4
−2
0
2
4
6
8
1e7

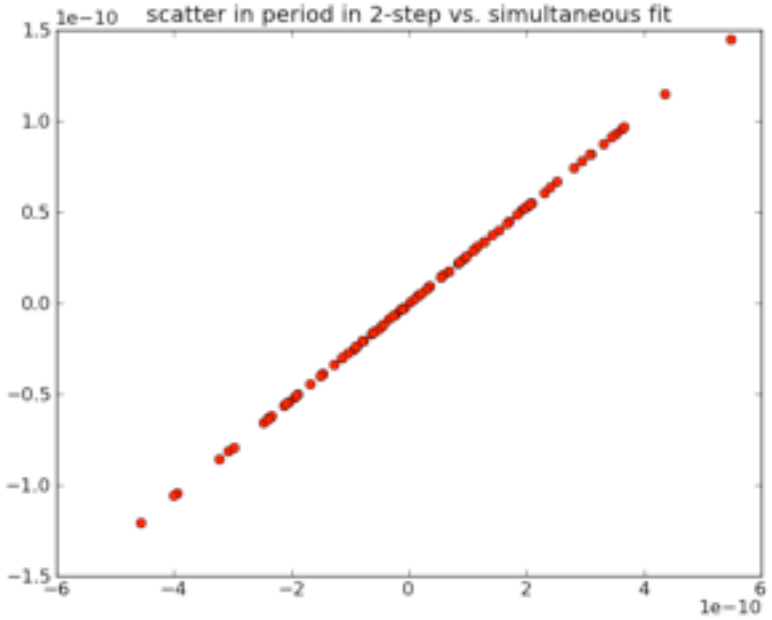

1 GHz residuals
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−8 −6 −4 −2 0 2 4 6 8
1e7
1 GHz residuals
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−8 −6 −4 −2 0 2 4 6 8
1e7
1 GHz residuals
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−8 −6 −4 −2 0 2 4 6 8
1e7
1 GHz residuals
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−8 −6 −4 −2 0 2 4 6 8
1e7

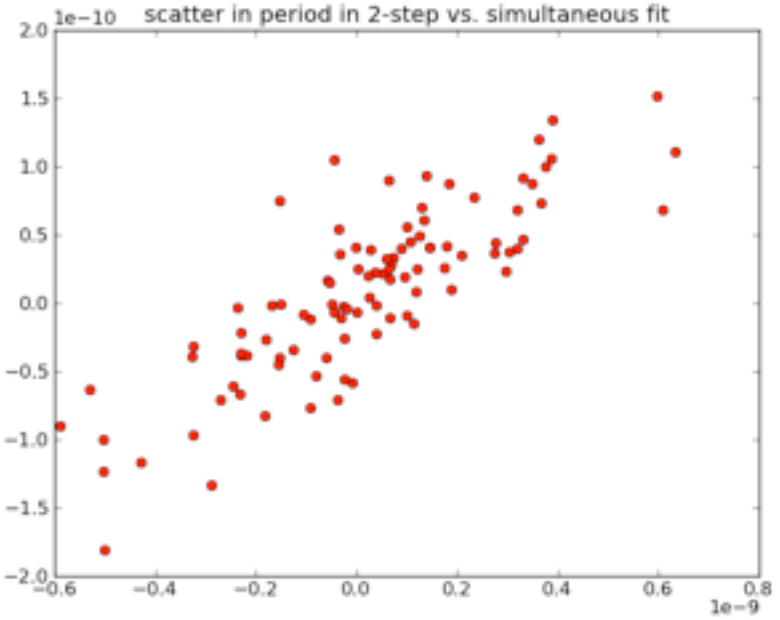

0
20
40
60
80
100
120
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
−0.05

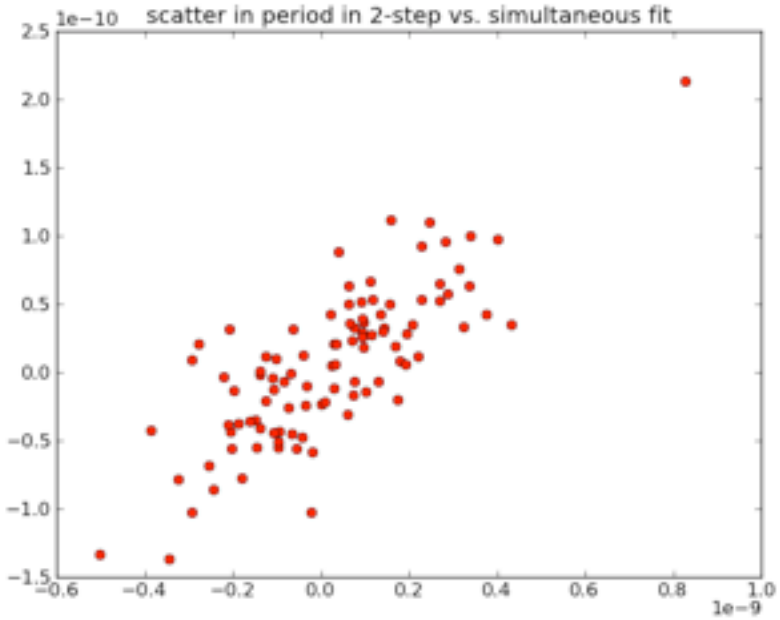

0
20
40
60
80
100
120
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
−0.05

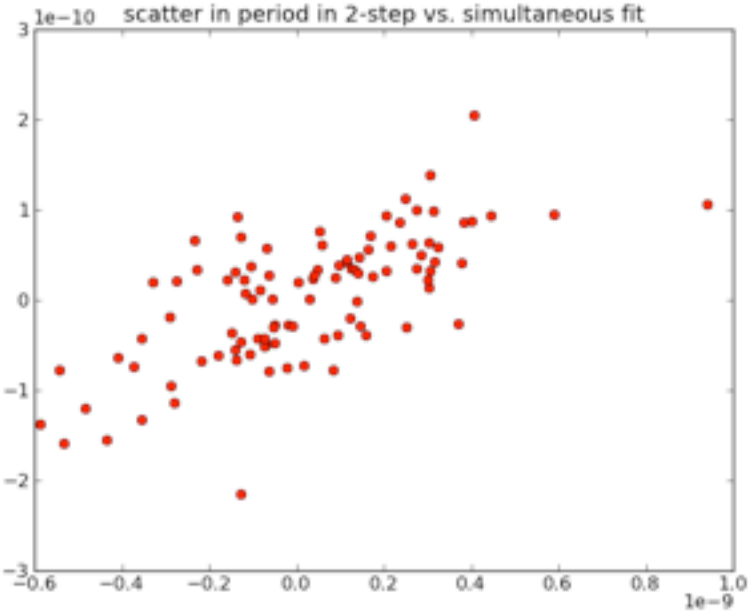

0
10
20
30
40
50
60
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
−0.05

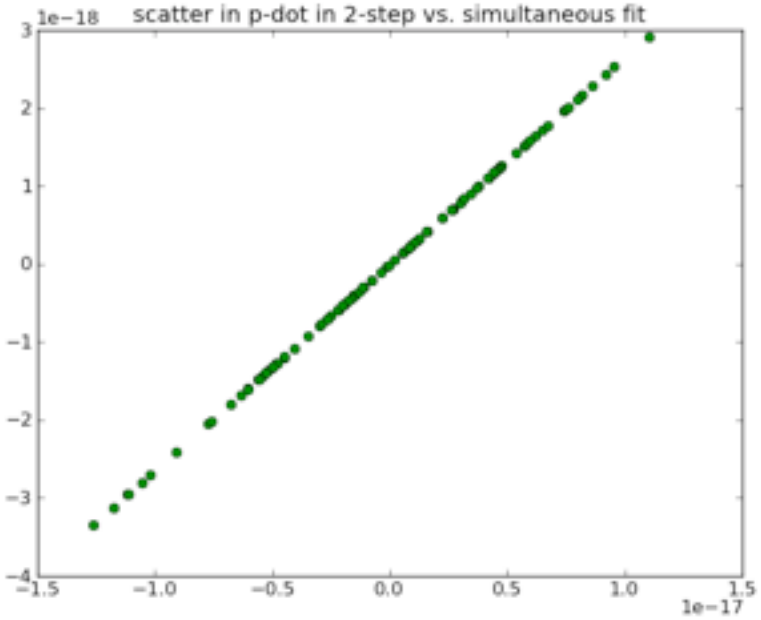

0
5
10
15
20
25
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
−0.05

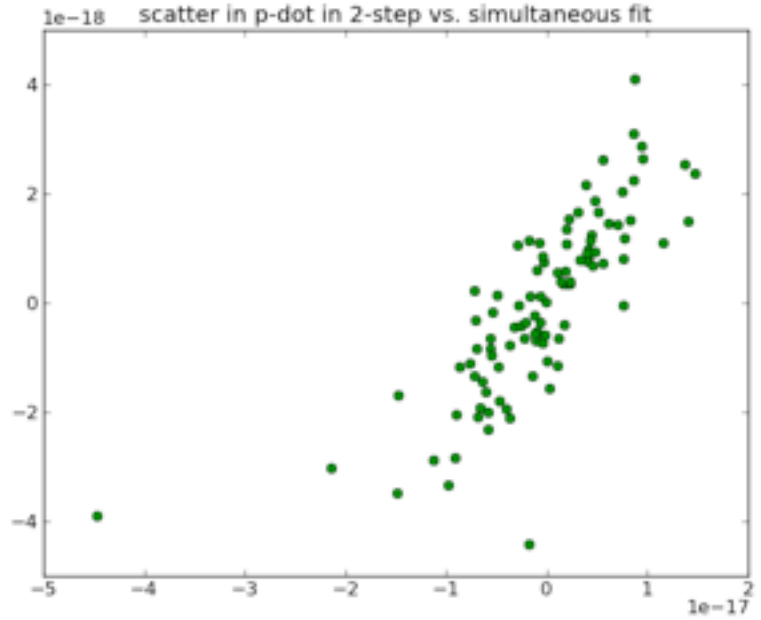

scatter in period in 2-step vs. simultaneous fit
1e−10
1e−10

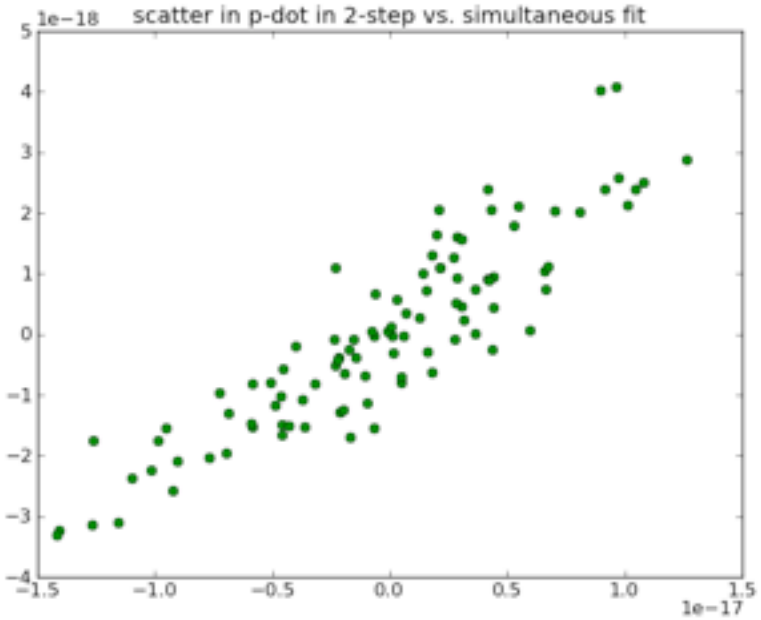

scatter in period in 2-step vs. simultaneous fit
1e−10
1e−9

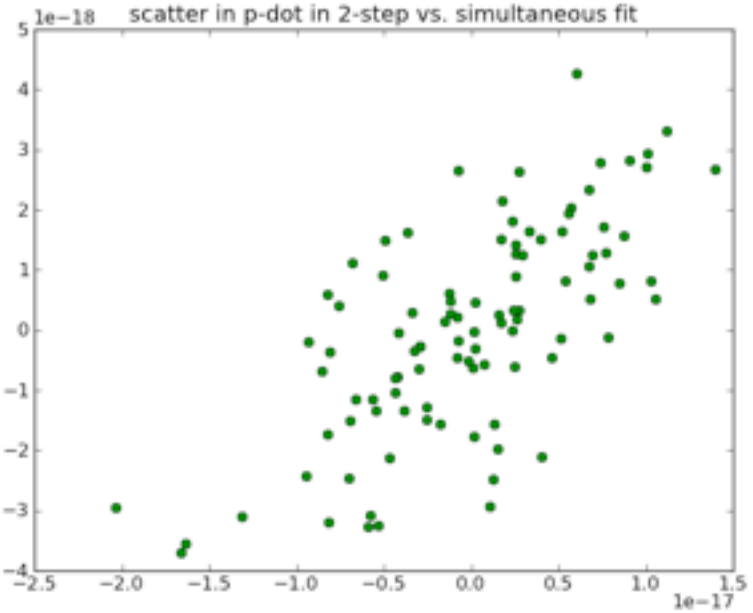

scatter in period in 2-step vs. simultaneous fit
1e−10
1e−9


scatter in period in 2-step vs. simultaneous fit
1e−10
1e−9


scatter in p-dot in 2-step vs. simultaneous fit
1e−18
3
2
1
0
−1
−2
−3
−4
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
1e−17


scatter in p-dot in 2-step vs. simultaneous fit
1e−18
4
2
0
−2
−4
−5
−4
−3
−2
−1
0
1
2
1e−17


scatter in p-dot in 2-step vs. simultaneous fit
1e−18
5
4
3
2
1
0
−1
−2
−3
−4
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
1e−17


scatter in p-dot in 2-step vs. simultaneous fit
1e−18
5
4
3
2
1
0
−1
−2
−3
−4
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
1e−17