Broadband Search for Continuous-Wave Gravitation Radiation with LIGO

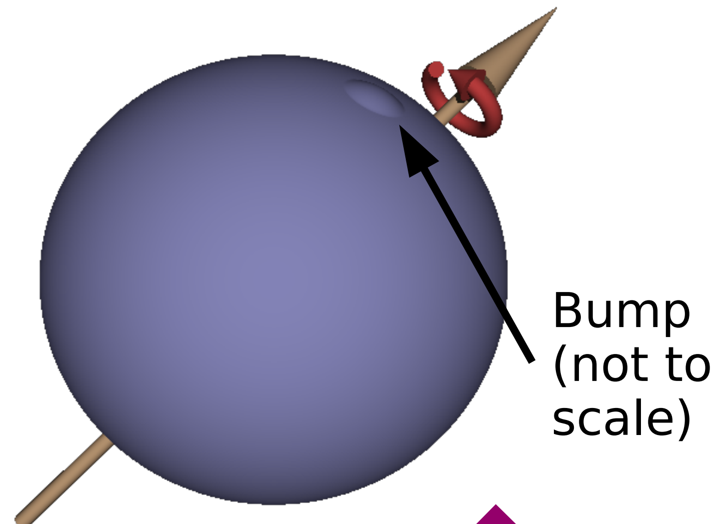
Vladimir Dergachev
(University of Michigan)
for the LIGO/Virgo scientific collaboration

April APS meeting May 1-5 2009

DCC: LIGO-G0900398-v2

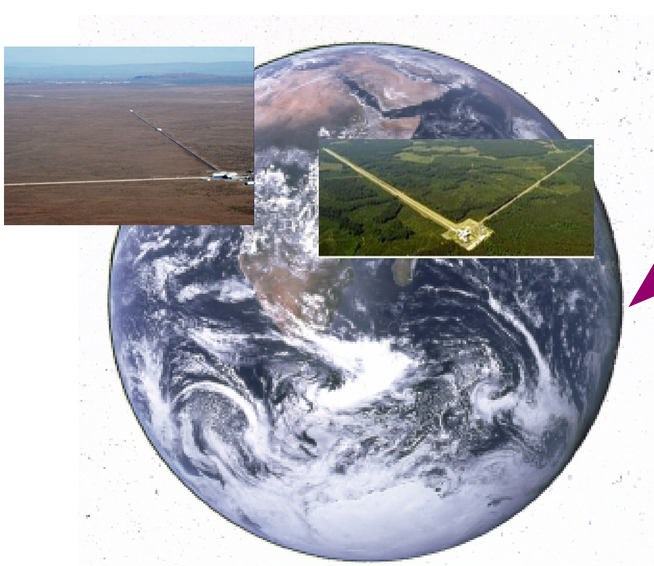
Continuous gravitational waves

Rotating neutron star



- We know of many rotating neutron stars with frequencies from below 1 Hz to more than 700 Hz
- Gravitational radiation is expected to be emitted at twice the frequency
- Not all rotating neutron stars have to emit radio waves or X rays
- Are any convenient sources nearby ?

Linearly polarized gravitational waves

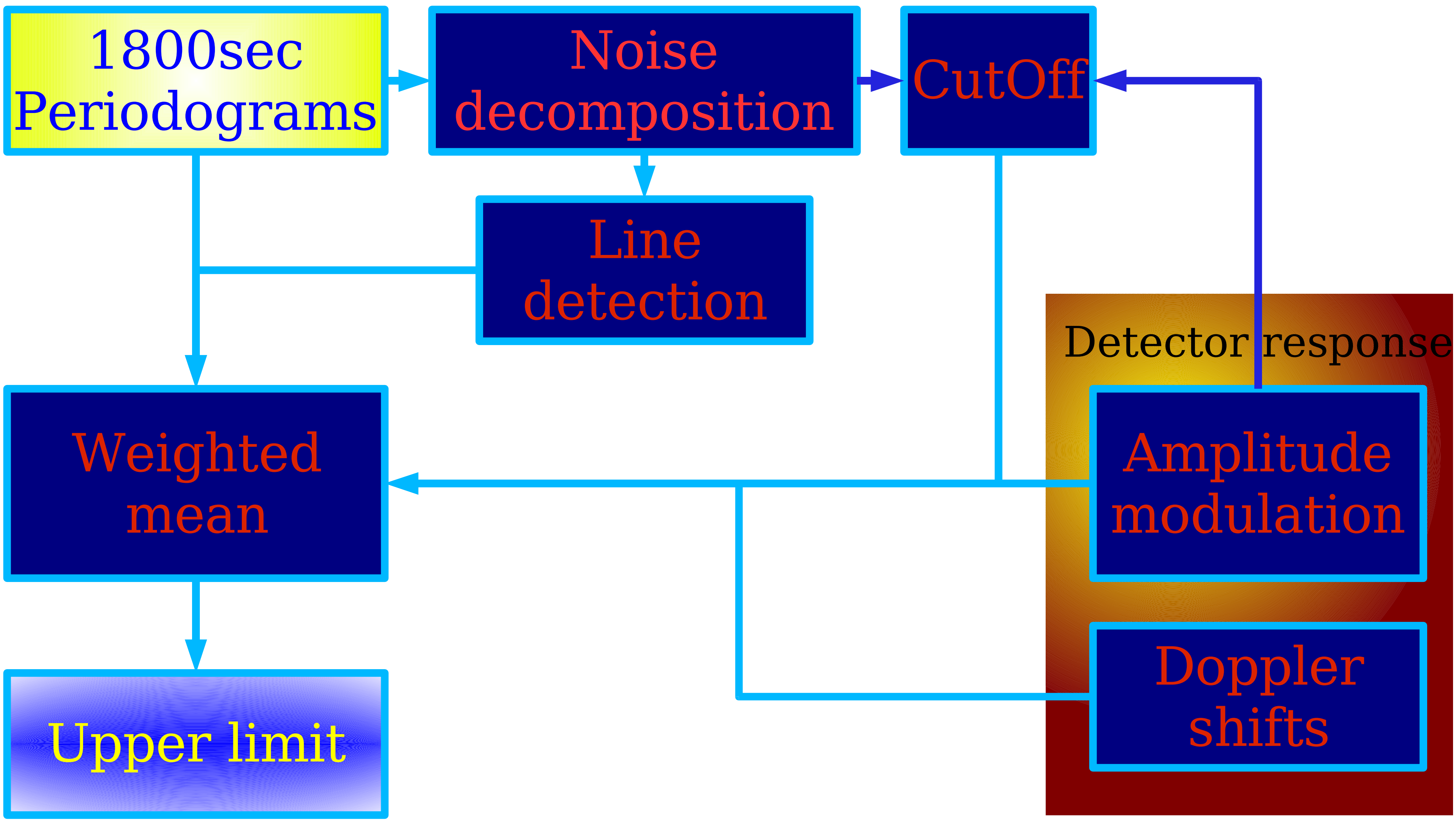


Circularly polarized gravitational waves

Challenges of search for CW gravitational waves

- Gravitational waves from spinning neutron stars are expected to be weak – need to average over long time periods
- Several parameters to search for: frequency, spindown, sky position, polarization
- Coherent methods are very sensitive, but result in enormous search space size – broadband, all sky search is impractical for large time base
- PowerFlux – place sky-dependent upper limits and detect signals by averaging power. Practical for all-sky broadband searches.

PowerFlux analysis pipeline



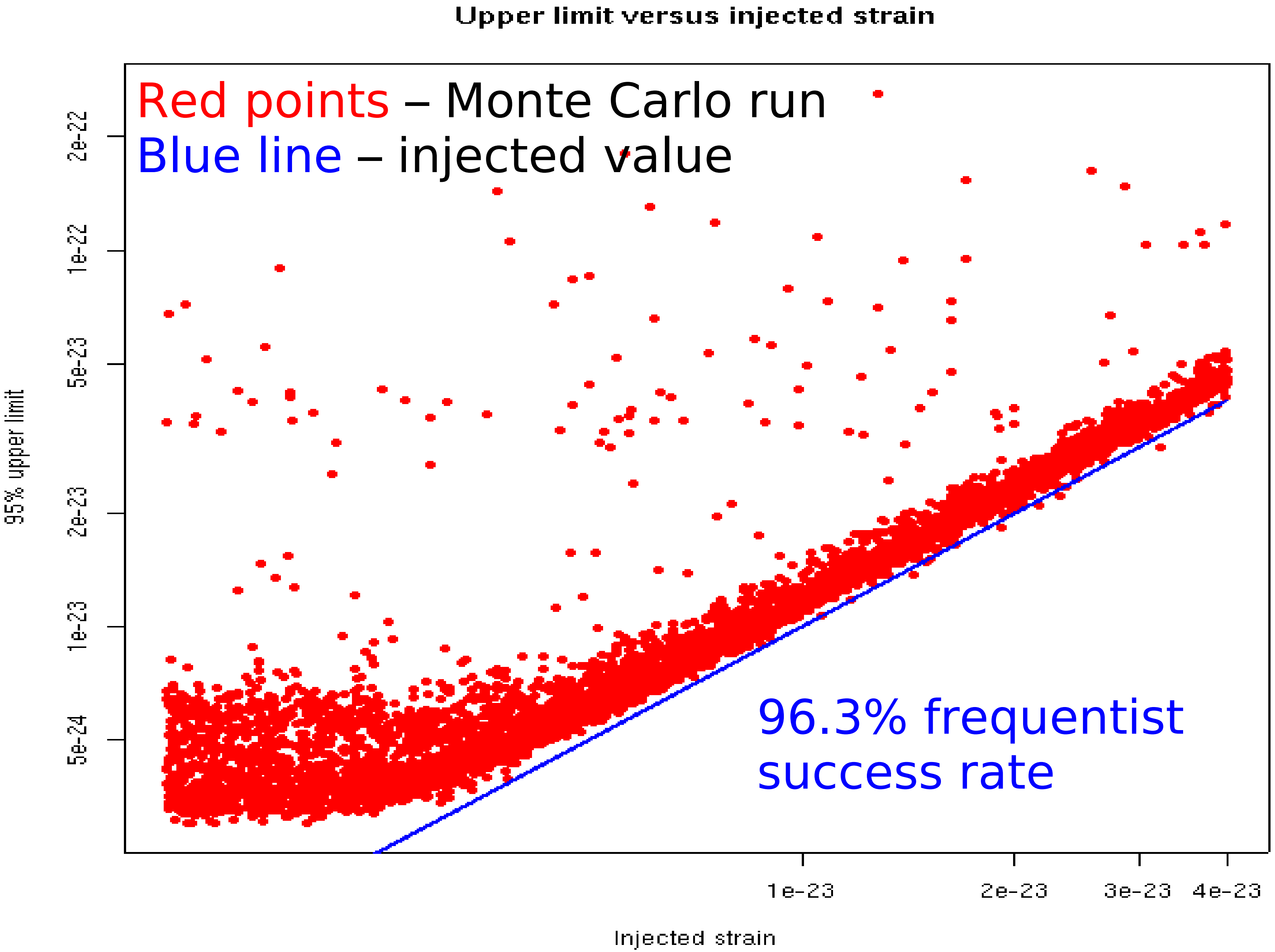
Choice of 1/1800 Hz SFT bins

- Small enough so that signal does not change appreciably from Doppler shifts.
- Large enough to have stationary noise over most of the spectrum.
- For a system of a neutron star of 1.5 solar masses and a companion of 1e-3 solar masses at 1 AU we would see ~90 degree phase shift at 1500 Hz over 30 minutes – not a problem with power based statistic.

Monte-Carlo run

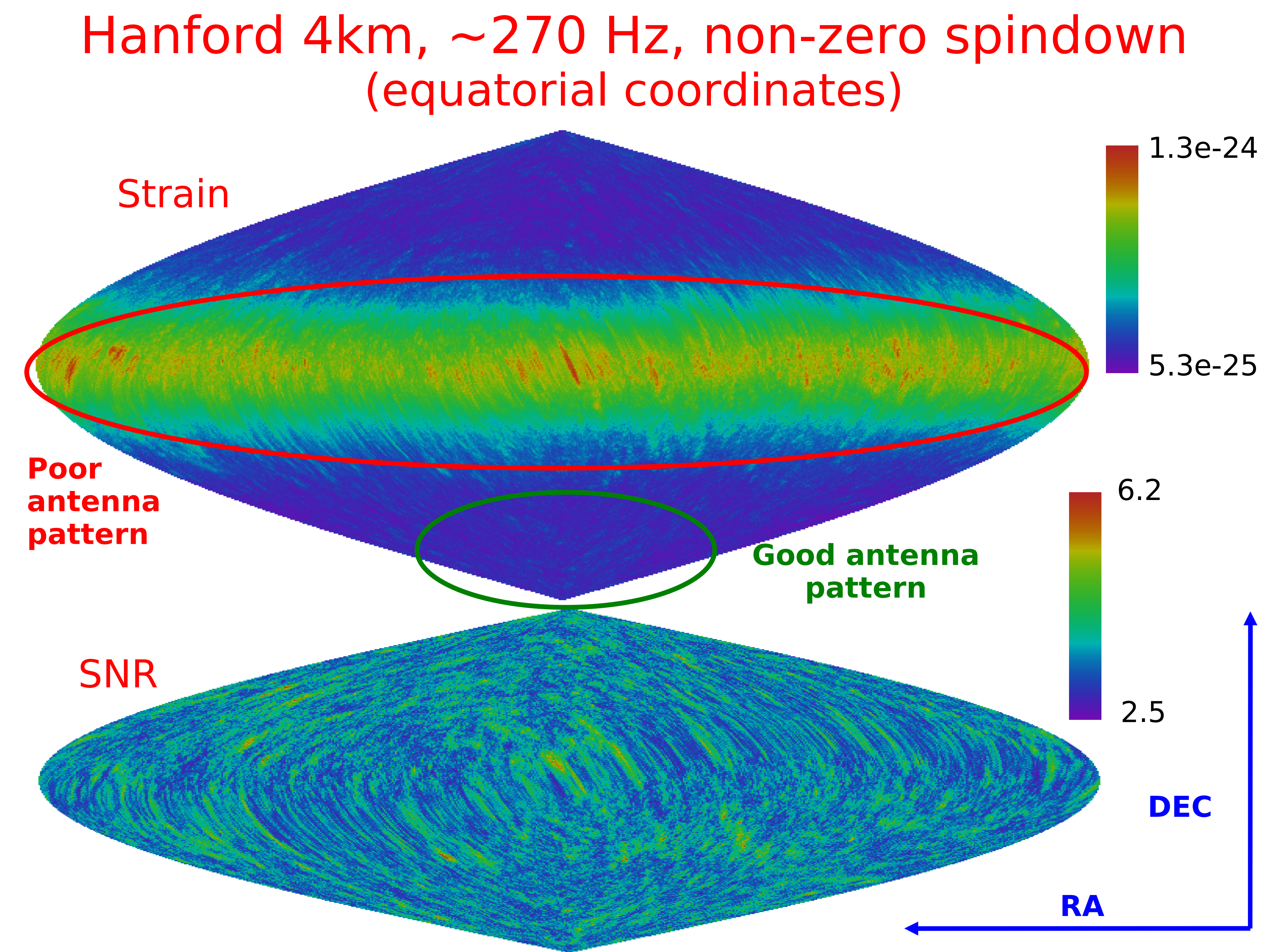
- 8000 injections between 200Hz and 300Hz using background data collected by H1 interferometer during S3 run
- 20 injections into each 0.25 Hz band
- Uniformly distributed locations on the sky and orientation of the linearly polarized injected signal
- Power-only injection – phase was assumed to be independent and uniformly distributed for each SFT
- $\log_{10}$ of injected strain values was uniformly distributed between -24 and -22.4

Upper limit versus injected strain

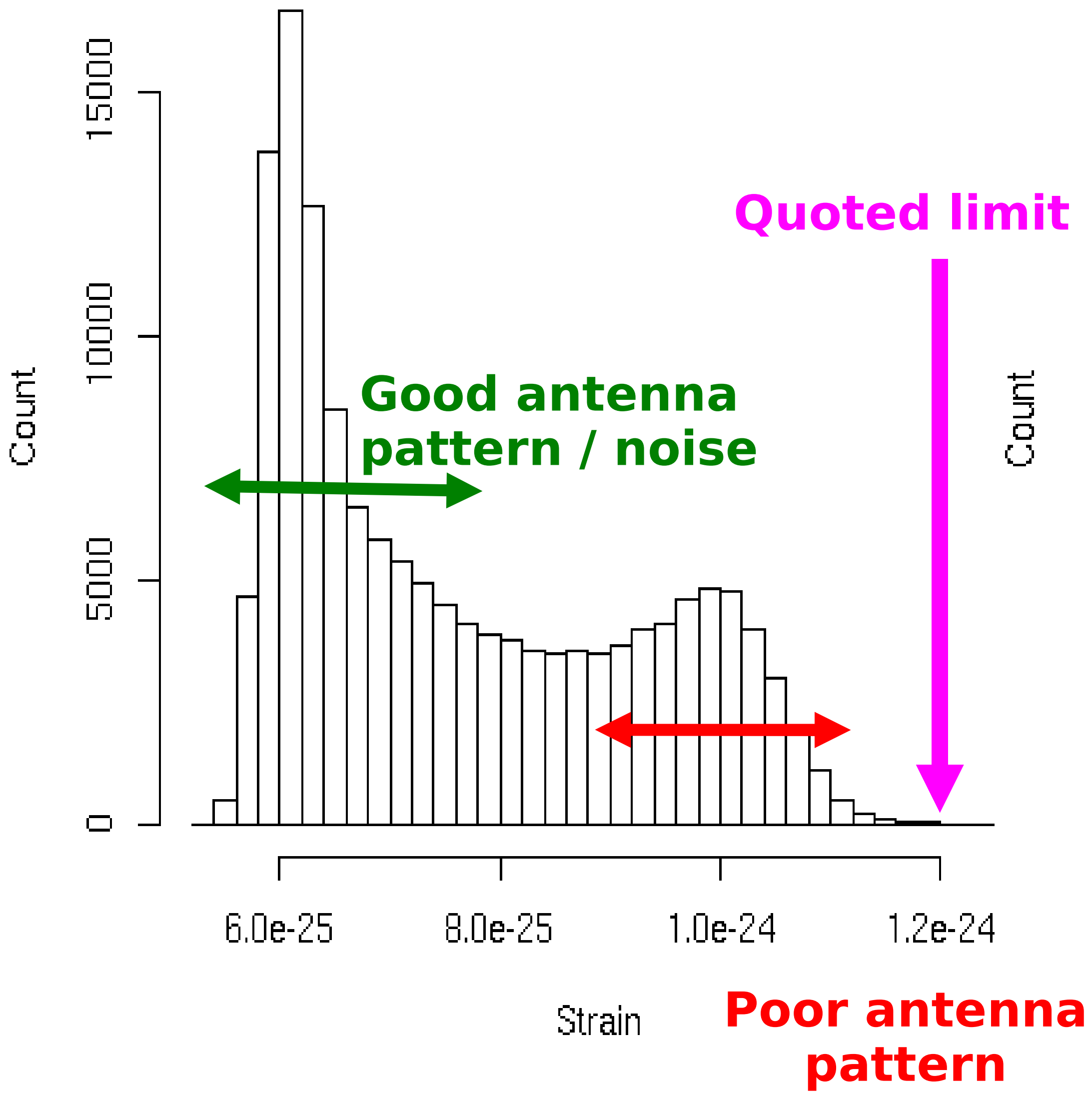


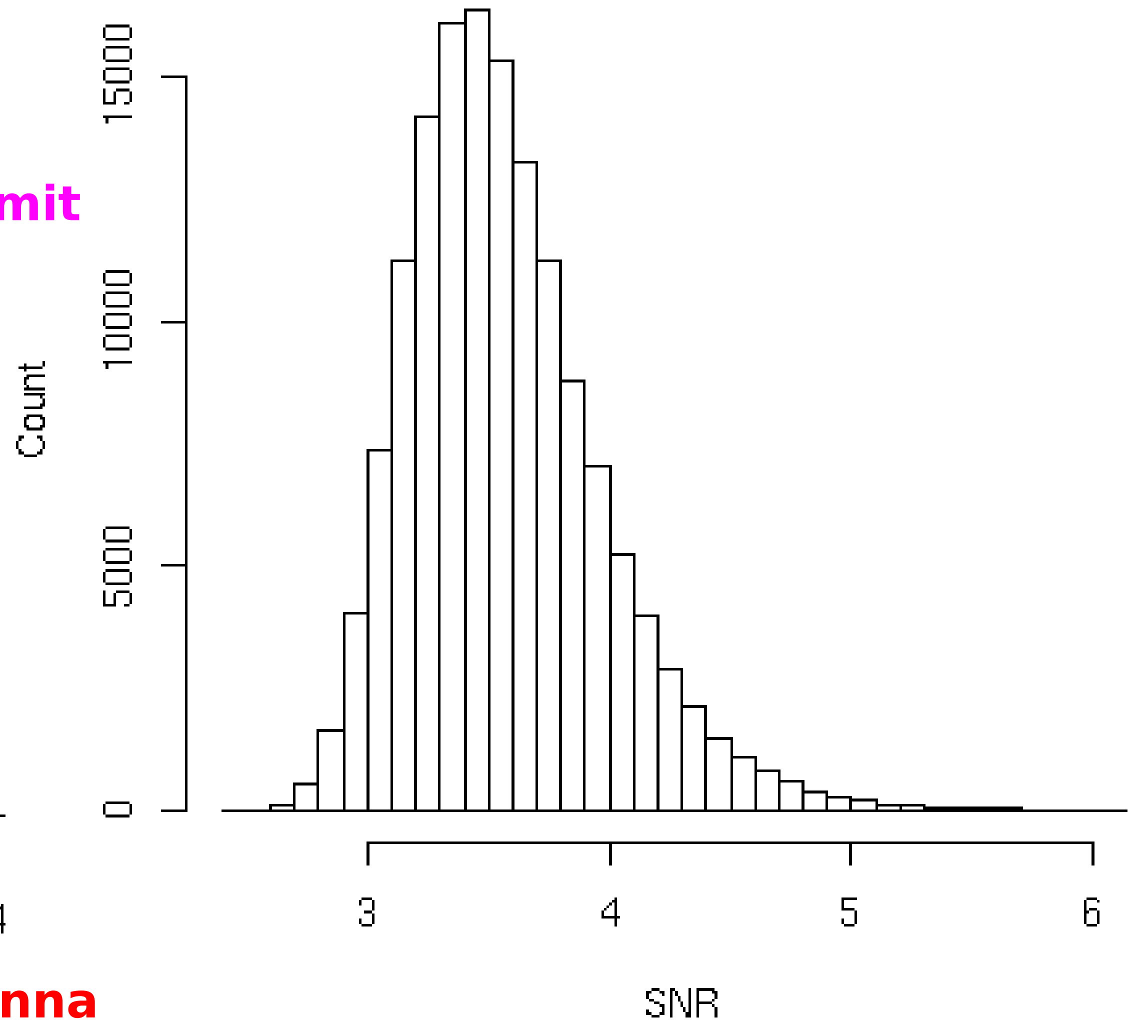
PowerFlux results

- PowerFlux produces a 95% CL upper limit for a particular frequency, sky position, spindown and polarization. One of three methods used in S4 all-sky search (arXiv:0708.3818 = Phys. Rev. D 77 (2008) 022001)
- Too much data to store, let alone present – the number of sky positions alone is ~10^5 at low frequencies and grows quadratically with frequency
- The upper limit plots show maximum over spindown range, sky and all polarizations
- Performed all-sky, multiple spindown (from 0 through -5e-9 Hz/s) searches
- Data from first 8 months of S5 science run: 7 Nov 2005 through 20 July 2006

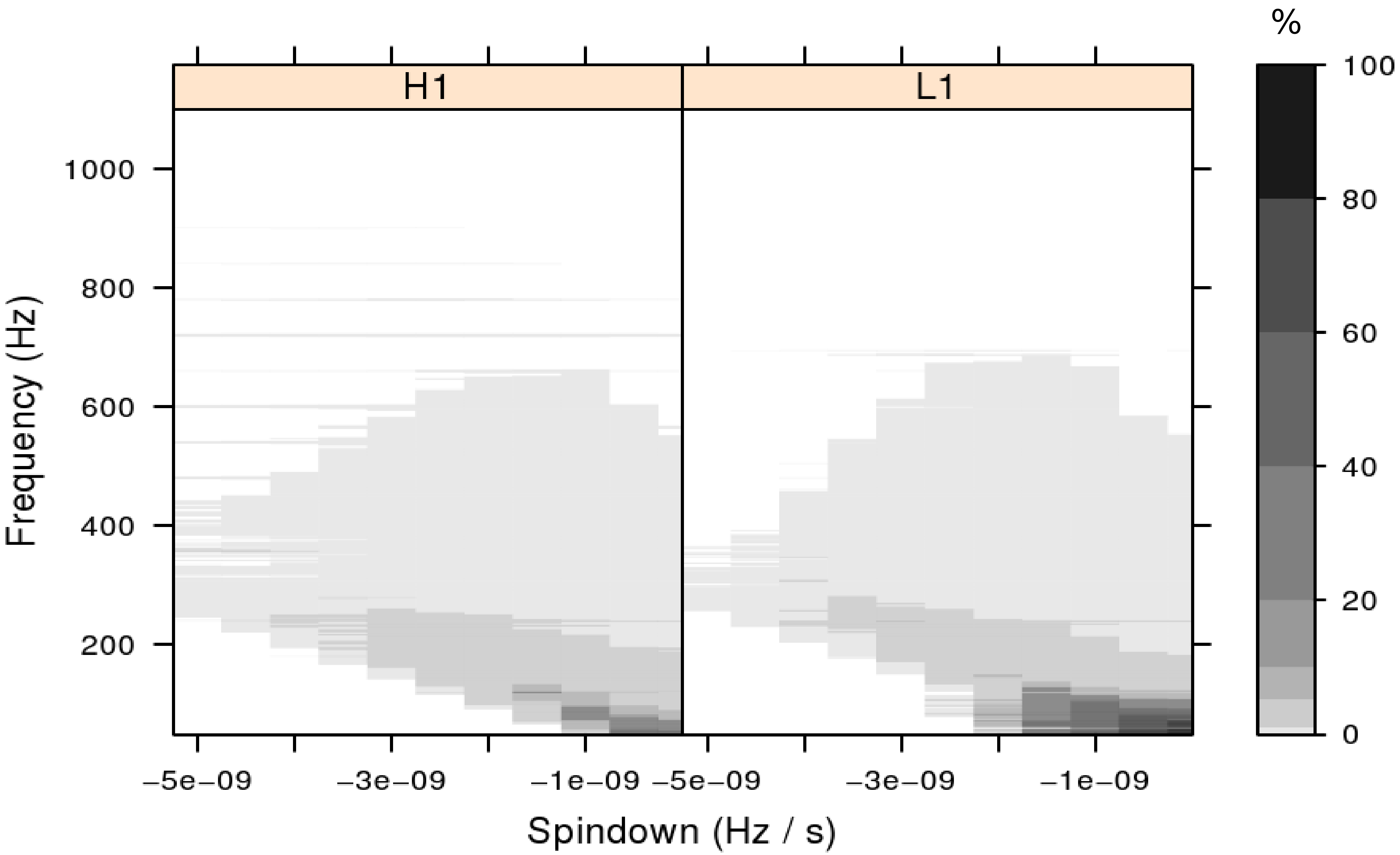

Hanford 4km, ~270 Hz, non-zero spindown
(equatorial coordinates)
Strain
1.3e-24
5.3e-25
Poor antenna pattern
Good antenna pattern
SNR
6.2
2.5
DEC
RA

Histograms
(one entry per sky point)

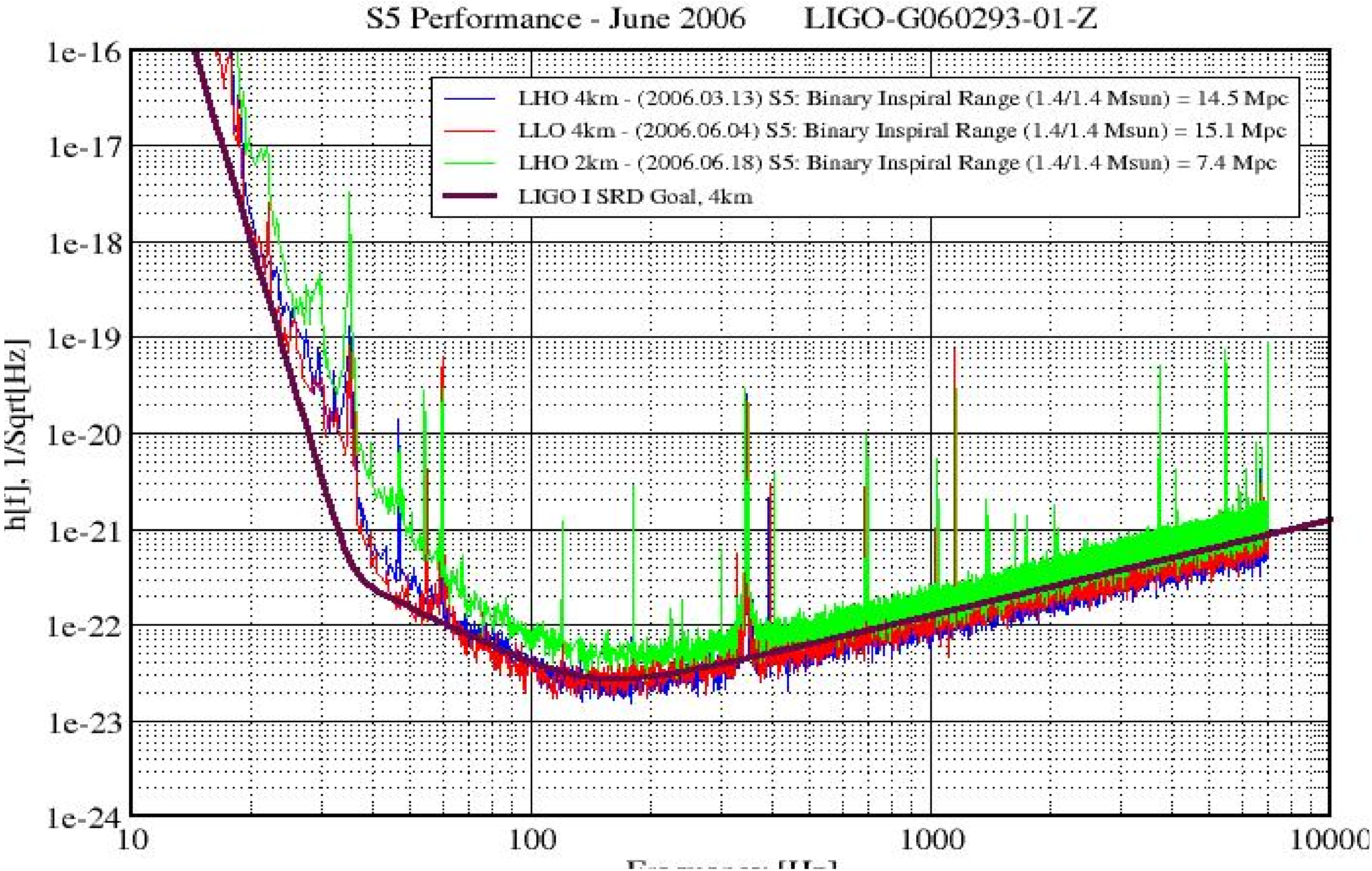




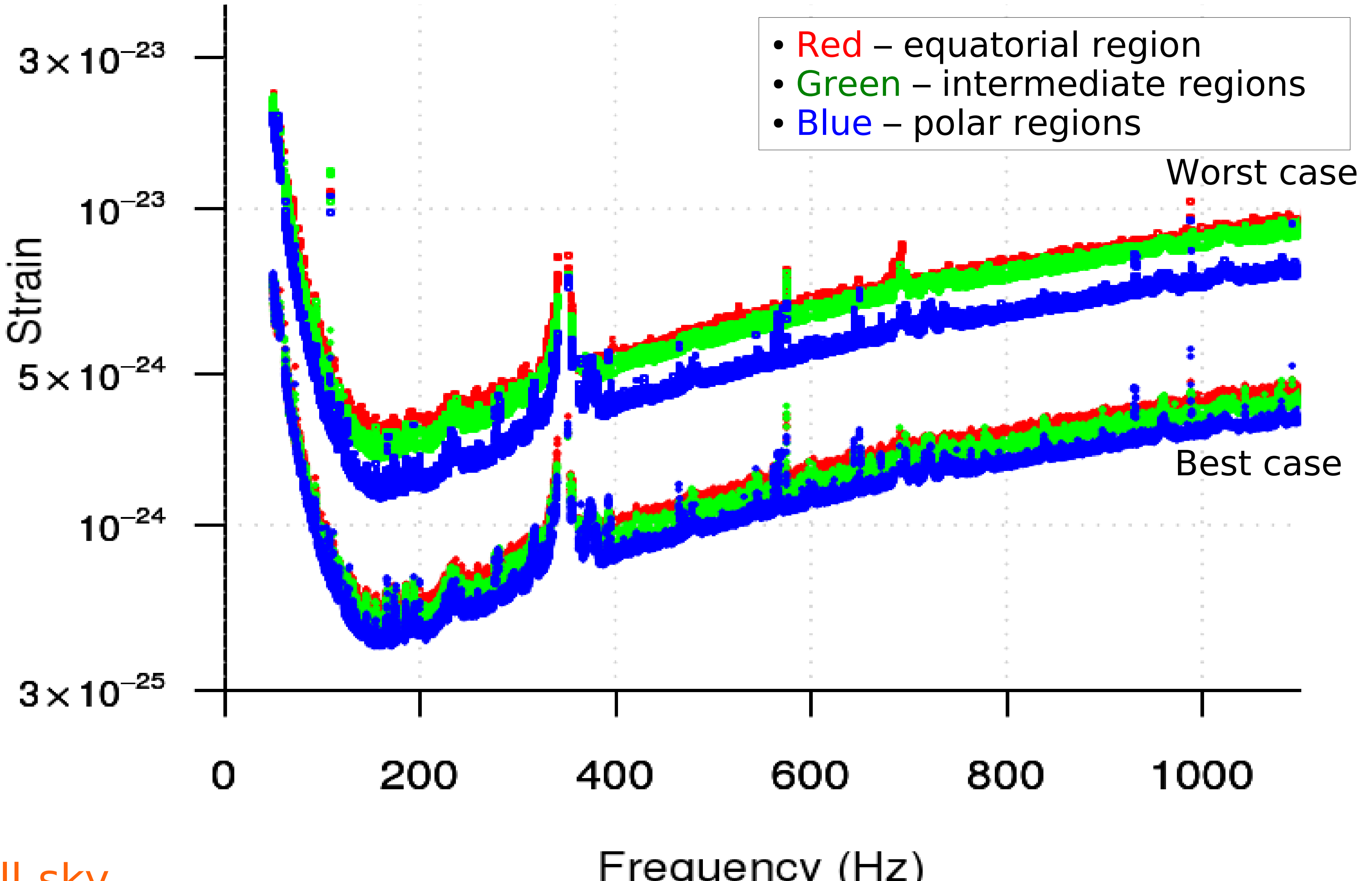
Early S5 excluded sky area



S5 science run sensitivity



Upper limits, PRL 102, 111102 (2009)



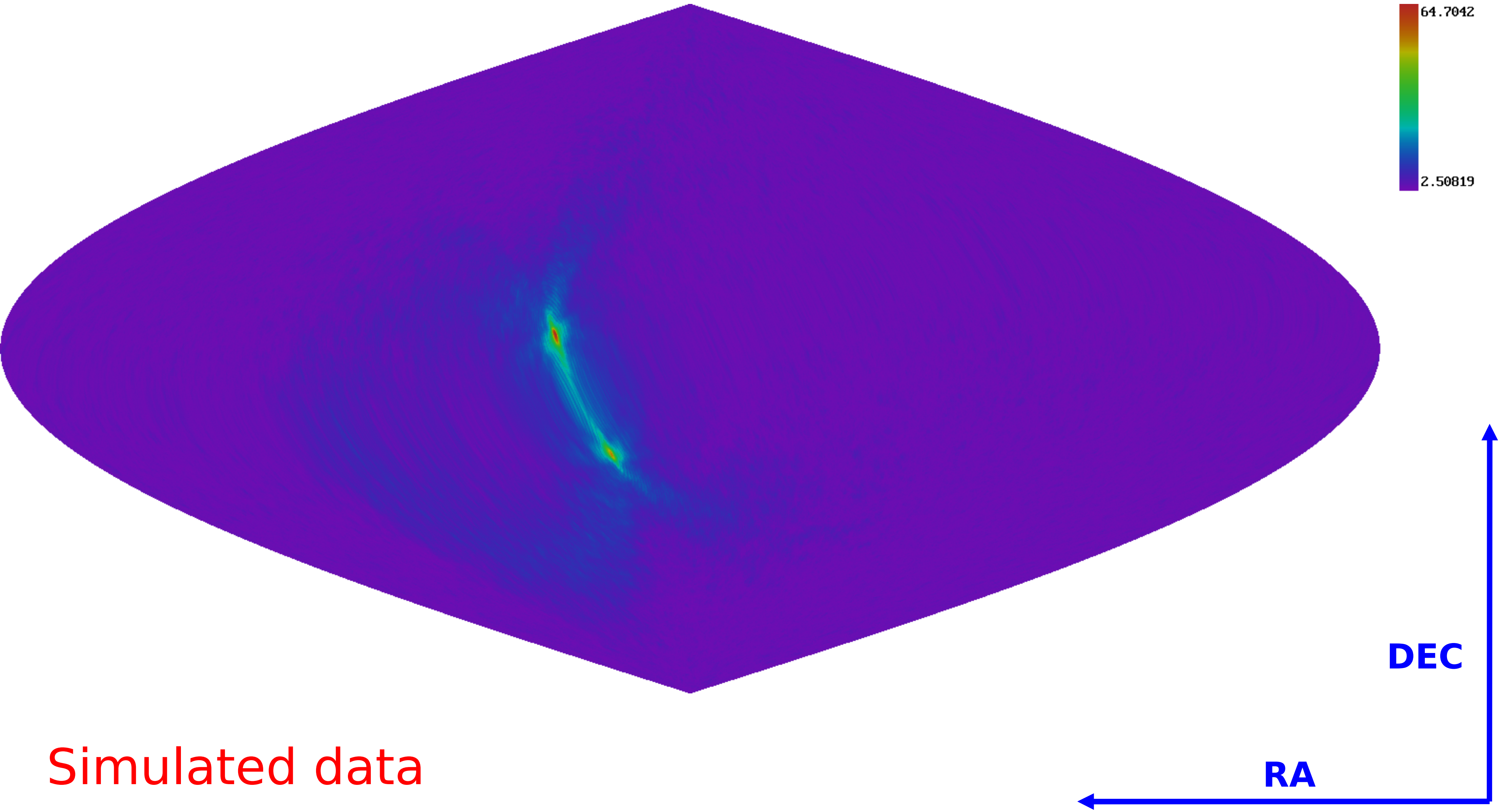
All-sky
50-1100 Hz

arXiv:0810.0283

Upper limits

- Our best sensitivity is at 153 Hz where we obtain upper limit of 4.2e-25 for circularly polarized sources in polar region.
- At a signal frequency of 1100 Hz we achieve sensitivity to neutron stars of equatorial ellipticity $\sim 1e{-}6$ at distances up to 500 pc.

Hardware injected pulsar signal

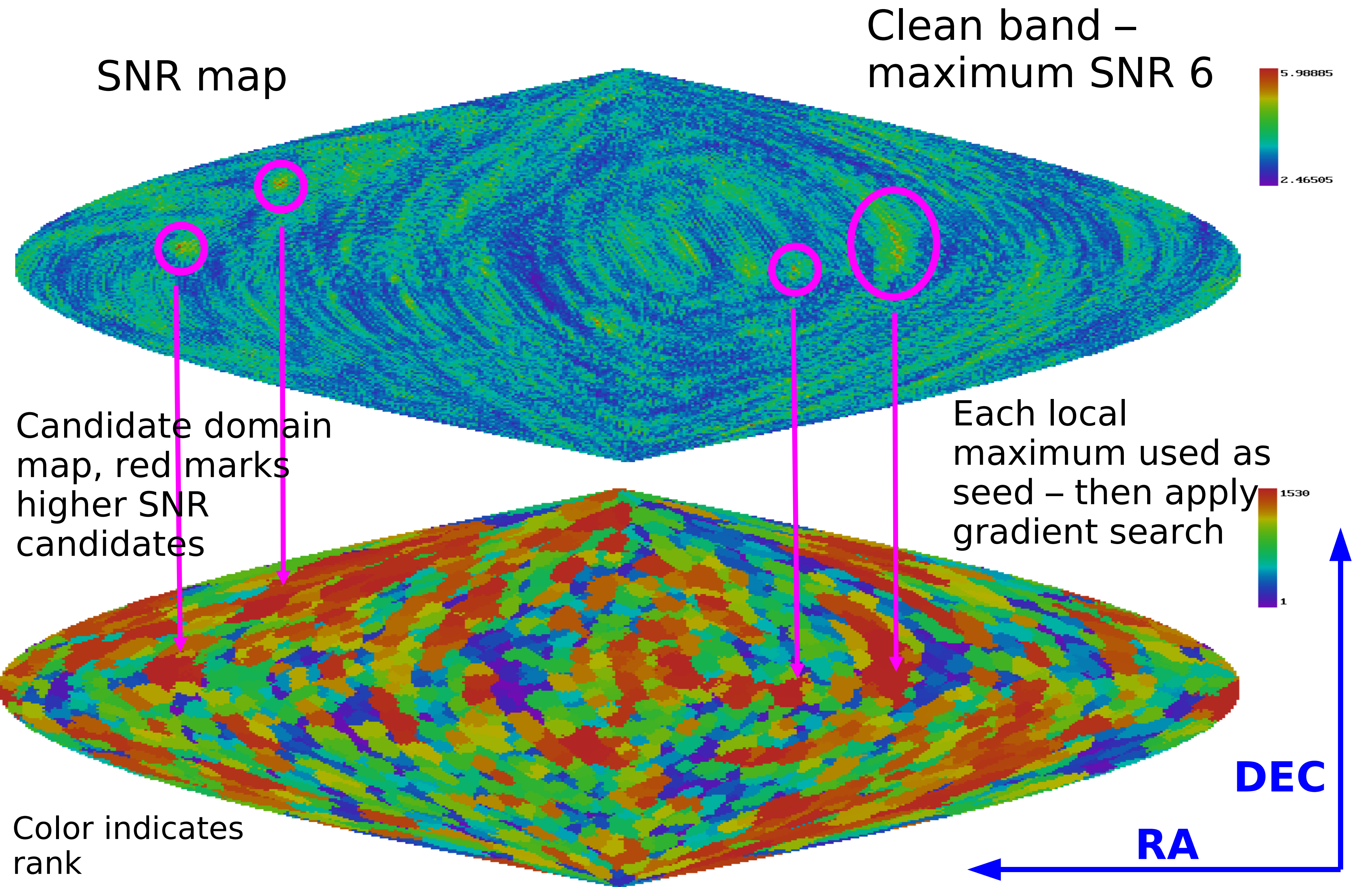


Simulated data

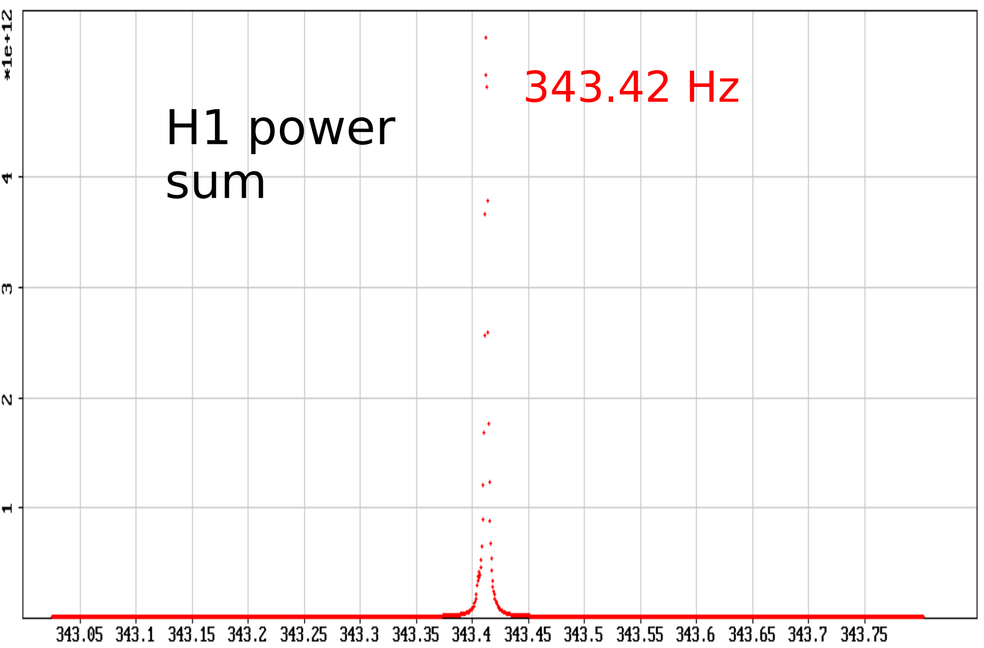
Outlier followup

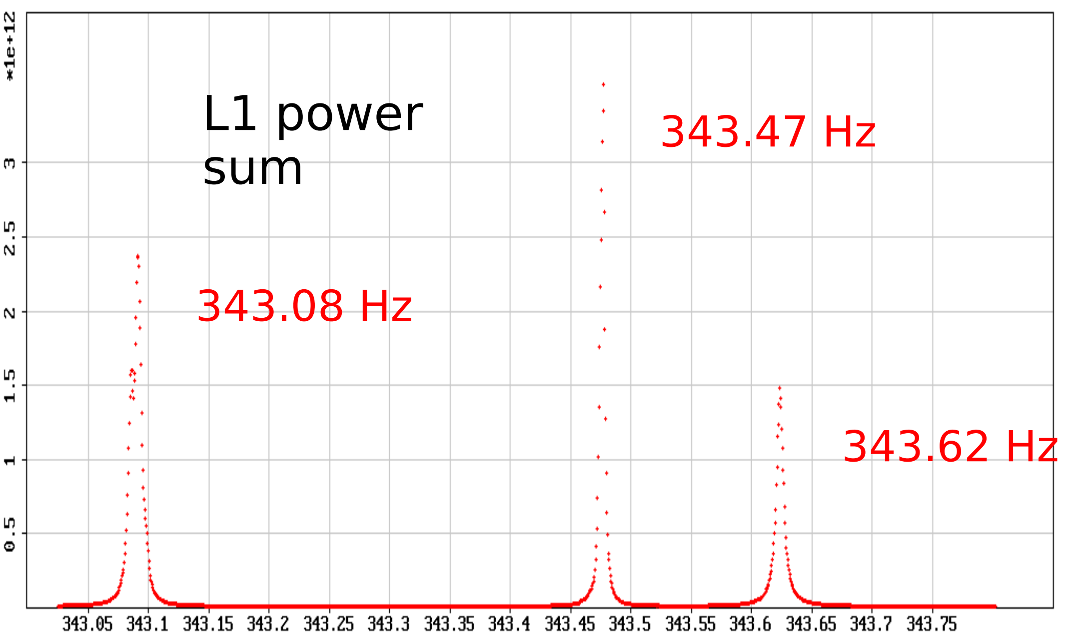
- Determine local SNR maxima, pick N highest (1000 from each of 10 sky slices)
- Apply a variation of gradient search to optimize SNR
- Look for outliers common to two interferometers:
  - SNR>6.25 for each interferometer
  - Difference in frequency less than 1/180 Hz
  - Difference in spindown of less than 4e-10 Hz/s
  - Closer than 0.14 radians (~8 degrees) on the sky
- Surviving coincidence candidates subjected to intensive followup

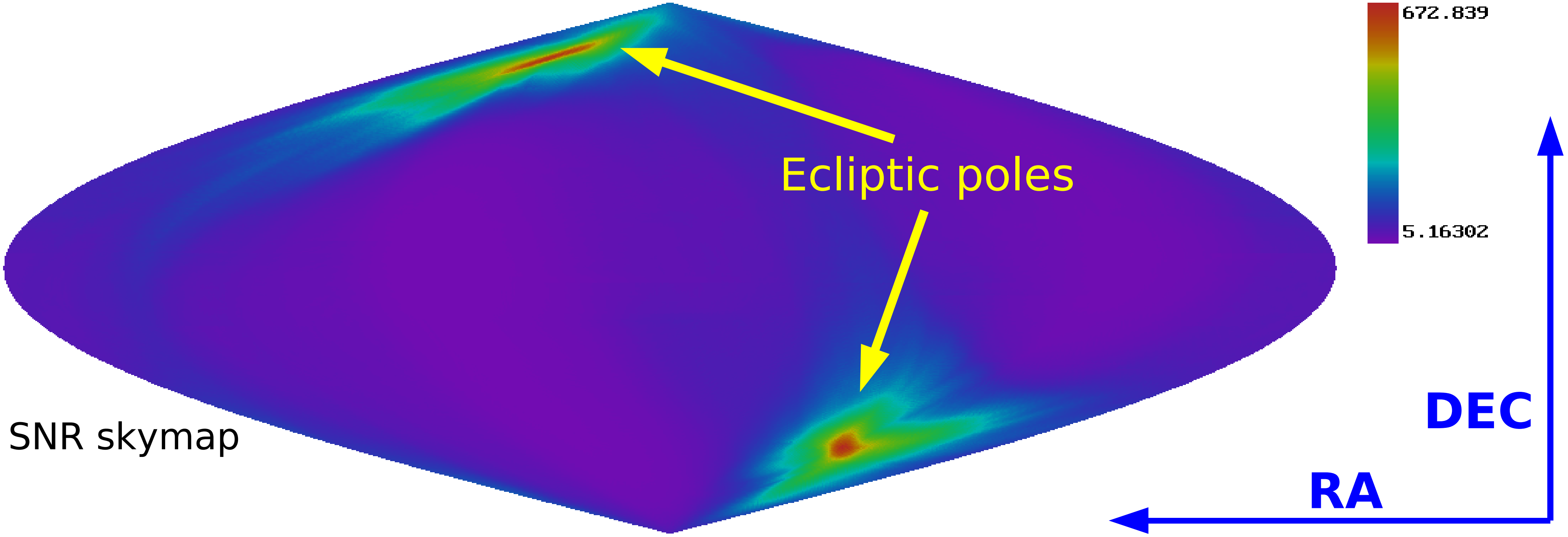
Multiple outliers



Sample outlier - caused by violin modes (5)

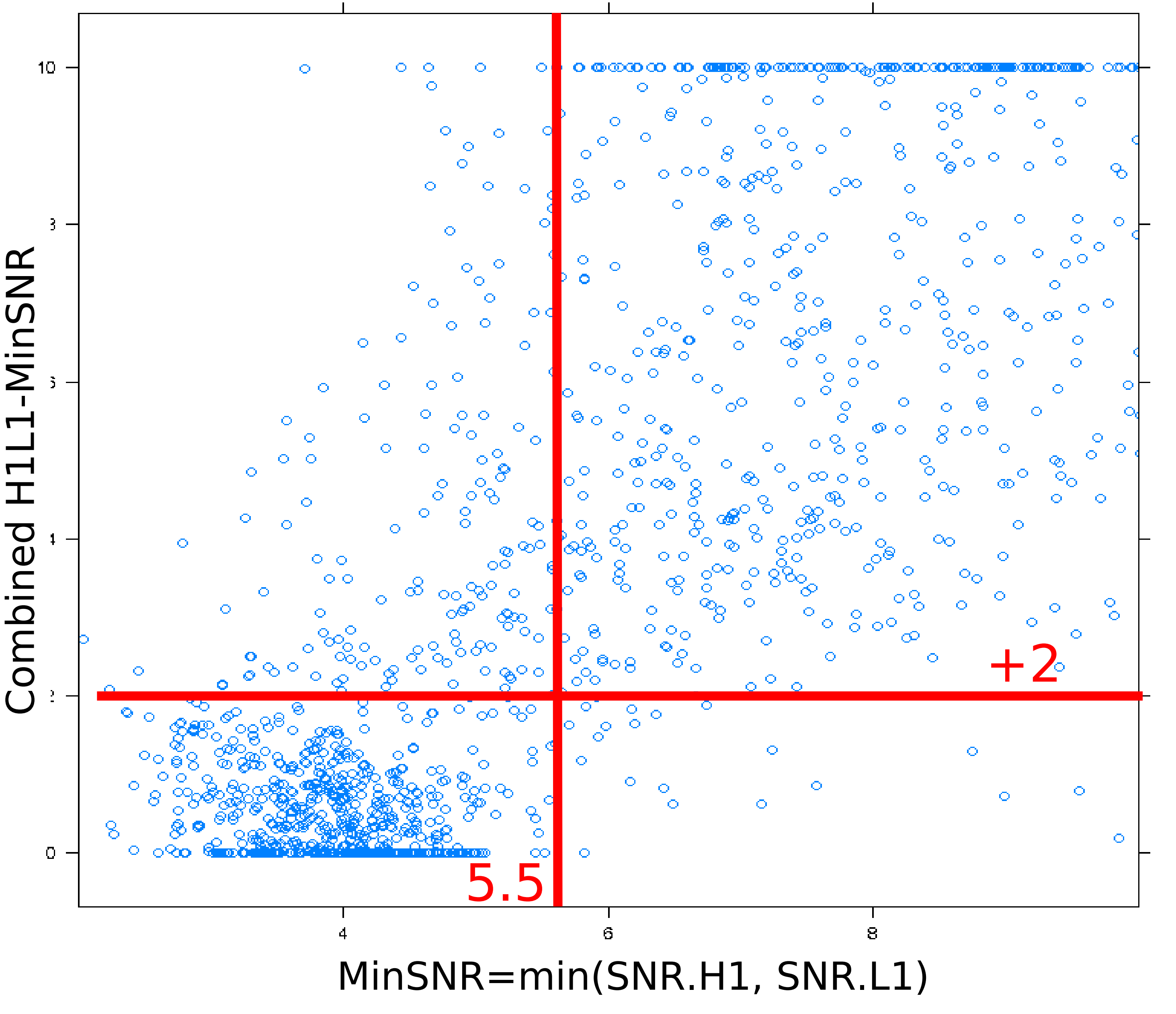






Signal injections guide followup

- 860-870 Hz
- Separate runs for H1, L1 and combined H1-L1 data
- Search in 0.3 radian disk around the injection point
- Spindown mismatch can be as large as 5e-10 Hz/s



Issues in followup

- Number of sky positions comparable with quantity of input data (especially at high frequencies) – SNR of the loudest outlier in pure noise can easily reach 6.0
- Relatively loose initial coincidence requirements are necessary not to miss real signals
- Sky partitioning that was done to reduce memory footprint introduces spurious initial coincidences – as partition boundaries are likely to be marked as local SNR maxima.
- Parameters that are narrow for a semi-coherent search are too wide for a comfortable coherent followup

Detection search results

- No credible signal found
- We encountered 6 outliers with low SNR for which we could not identify hardware source – not unexpected in this search.

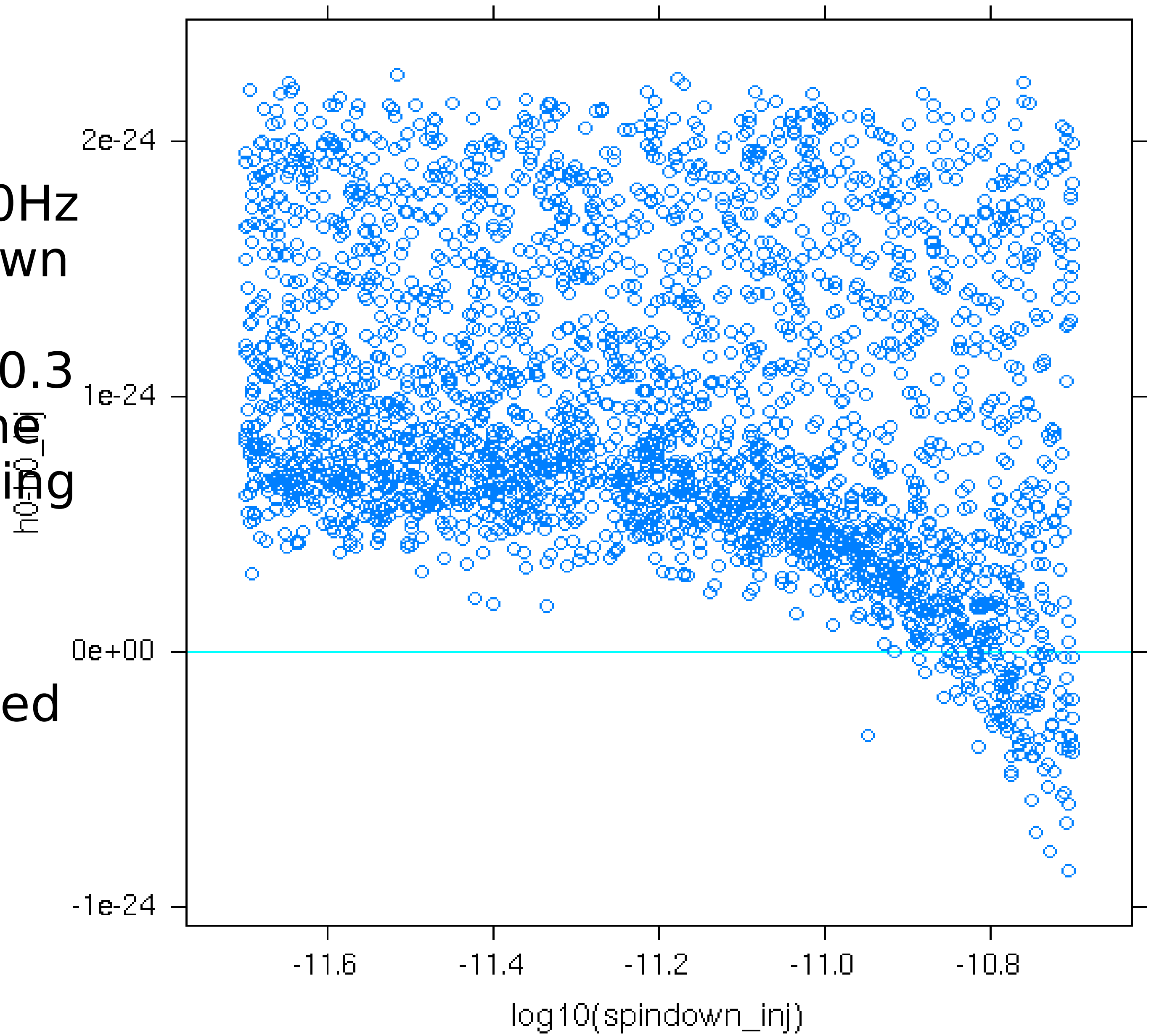
Frequency band (Hz)	Spin-down ($\mathrm{Hz\ s^{-1}}$)	H1 SNR	L1 SNR
867.2	-4.3×10^{-9}	6.27	6.30
941.0	-2.0×10^{-9}	6.50	6.67
967.8	-1.5×10^{-9}	6.26	6.33
979.5	-5.0×10^{-9}	6.40	6.29
1058.6	-5.0×10^{-10}	6.83	6.38
1070.2	-3.0×10^{-10}	6.72	6.99

Full S5

- Full S5 search is in preparation.
- The timebase spans 2 years – this provides improved sky localization, but requires much smaller spindown steps.
- New version of PowerFlux with 10x speedup when iterating over closely spaced spindown values and better statistics output.
- Run in progress iterating over 201 spindown values in steps of 3e-11 Hz/s.

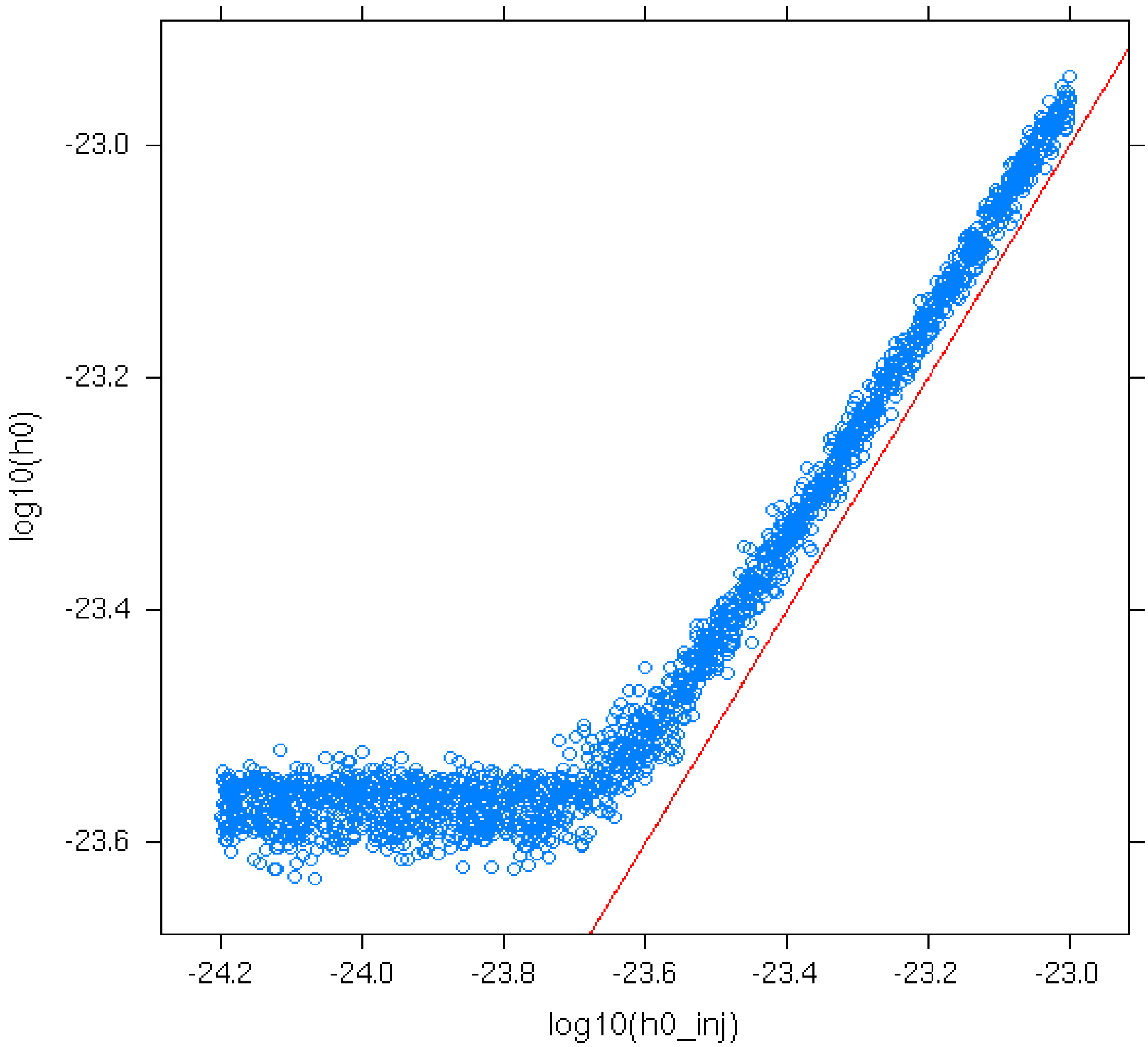
Simulation with gaussian noise

• Slightly longer timebase than full S5
• Software injections from 50 through 1500Hz with different spindown values
• PowerFlux scanned 0.3 radian area around the injection point assuming 0 spindown
• Vertical axis shows difference between upper limit and injected strain



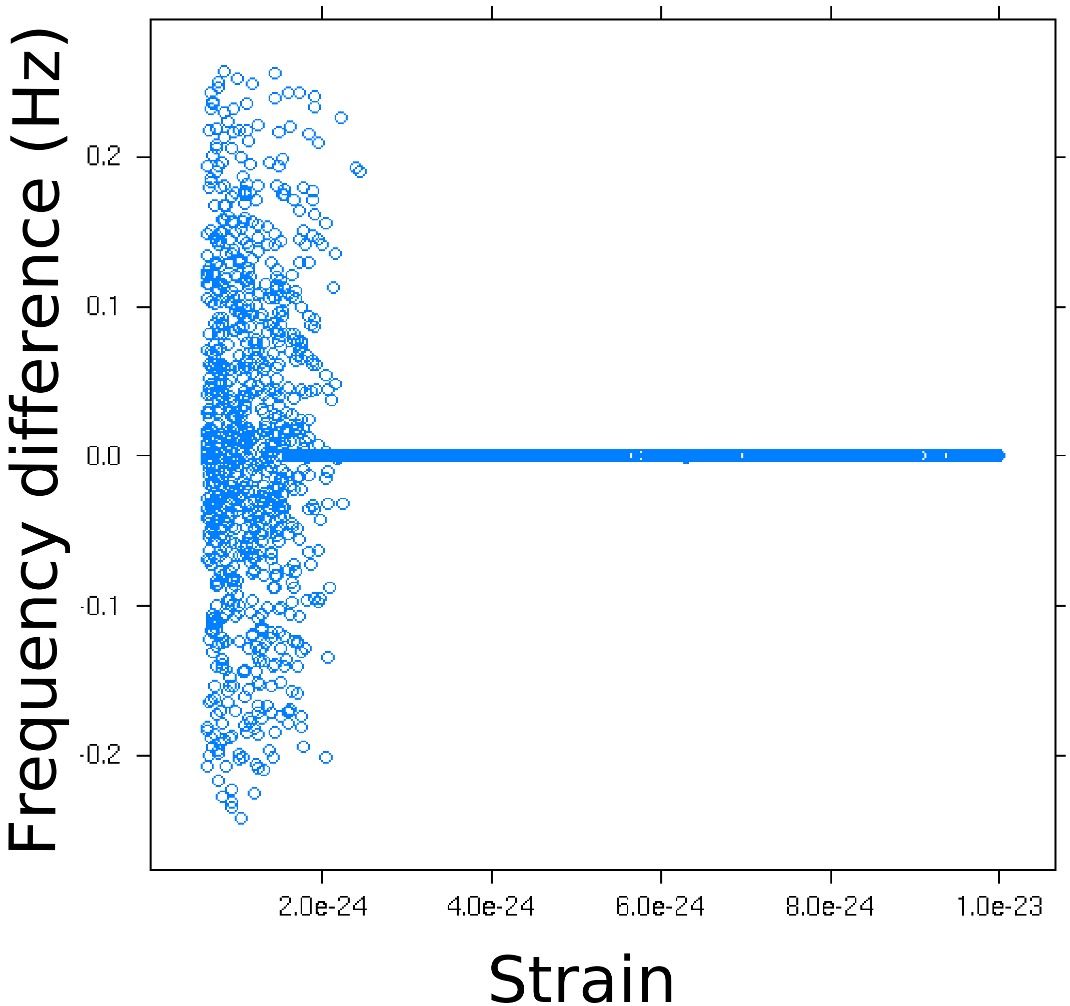
Restricting to small spindowns

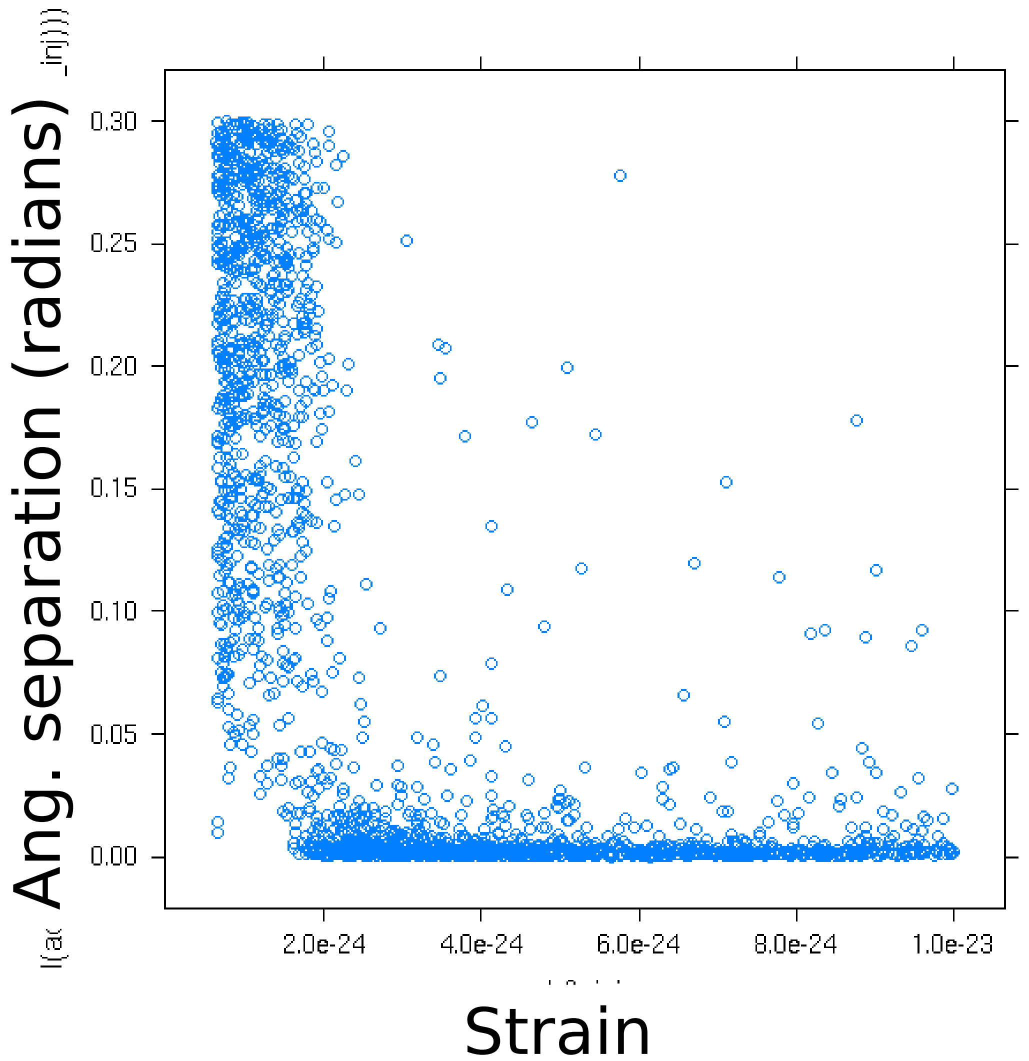
• Same data but only showing injections with spindown less than 1e-11
• Upper limit is the maximum in 0.3 radian area



Parameter reconstruction

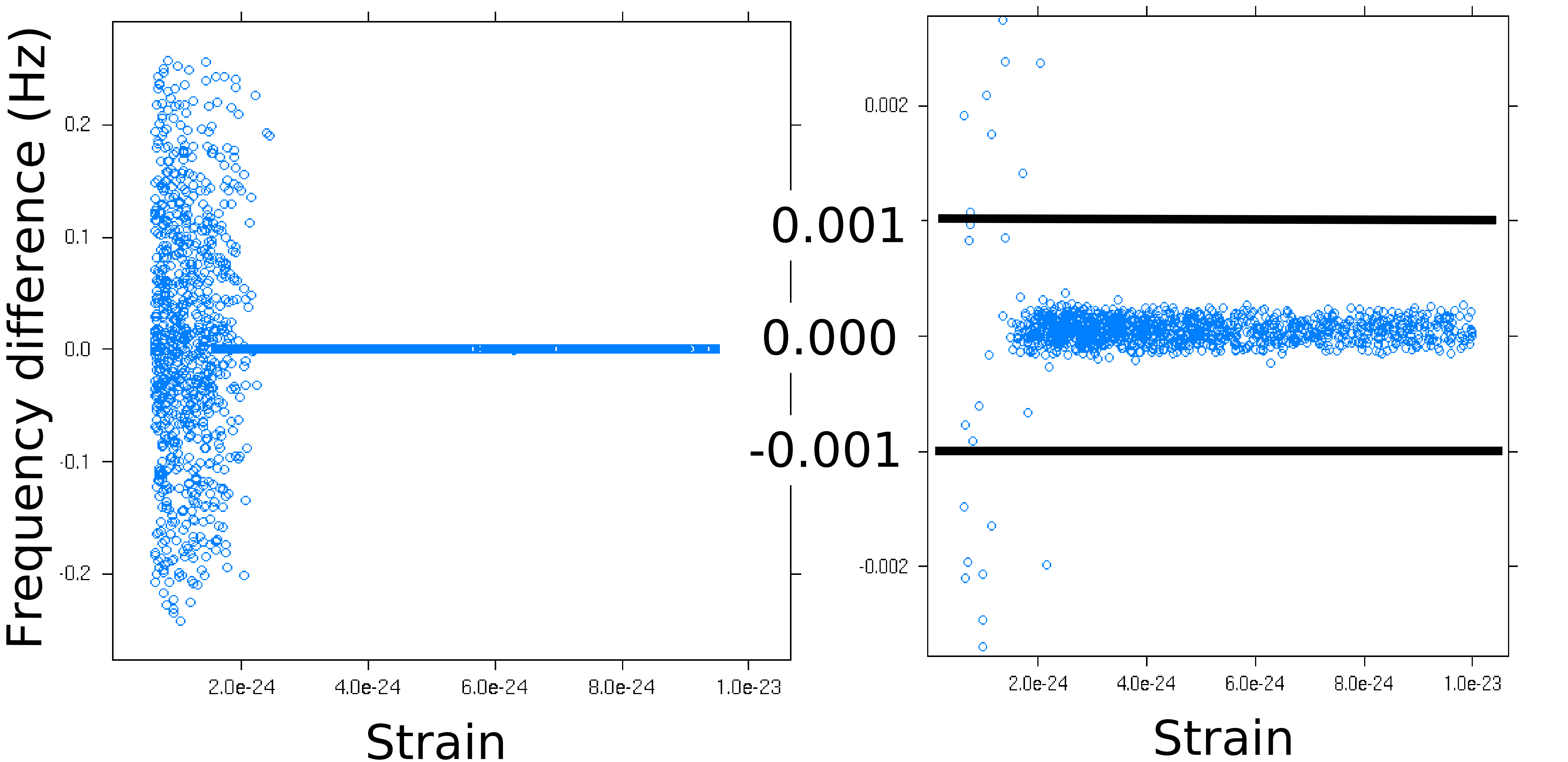
- Find highest SNR coincidences using method close to one that will be used in full S5 analysis (still fine tuning the constants)
- Plots show difference between coincidence and injection





Parameter reconstruction

- Find highest SNR coincidences using method close to one that will be used in full S5 analysis (still fine tuning the constants)
- Plots show difference between coincidence and injection



Conclusion

- All-sky multiple-spindown run over first 8 months of data complete, results available in arXiv:0810.0283, published in PRL 102, 111102 (2009)
- No credible signal found
- Full S5 data is available, more results to follow

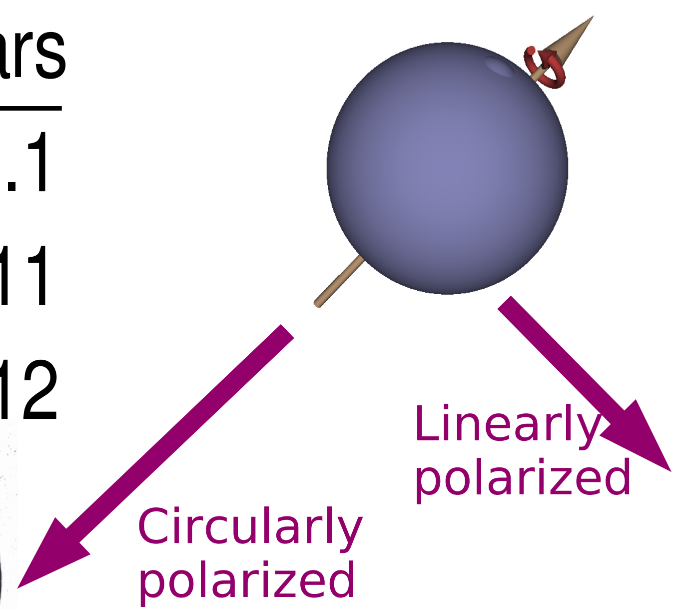
End of talk

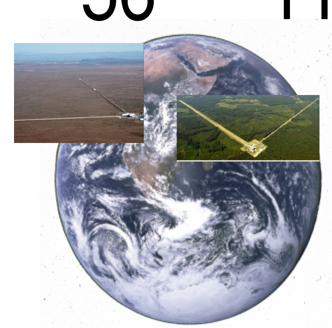
(supporting slides for questions follow)

Size of frequency shift in 1/1800 Hz bins due to different causes

	Relative	50 Hz	500 Hz	1500 Hz
Earth rotation	1e-6	0.1	1	3
Earth orbital motion	1e-4	9	90	270

	3 months	1 year	2 years
1e-11 Hz/s spindown	0.14	0.56	1.1
1e-10 Hz/s spindown	1.4	5.6	11
1e-9 Hz/s spindown	14	56	112





PowerFlux validation

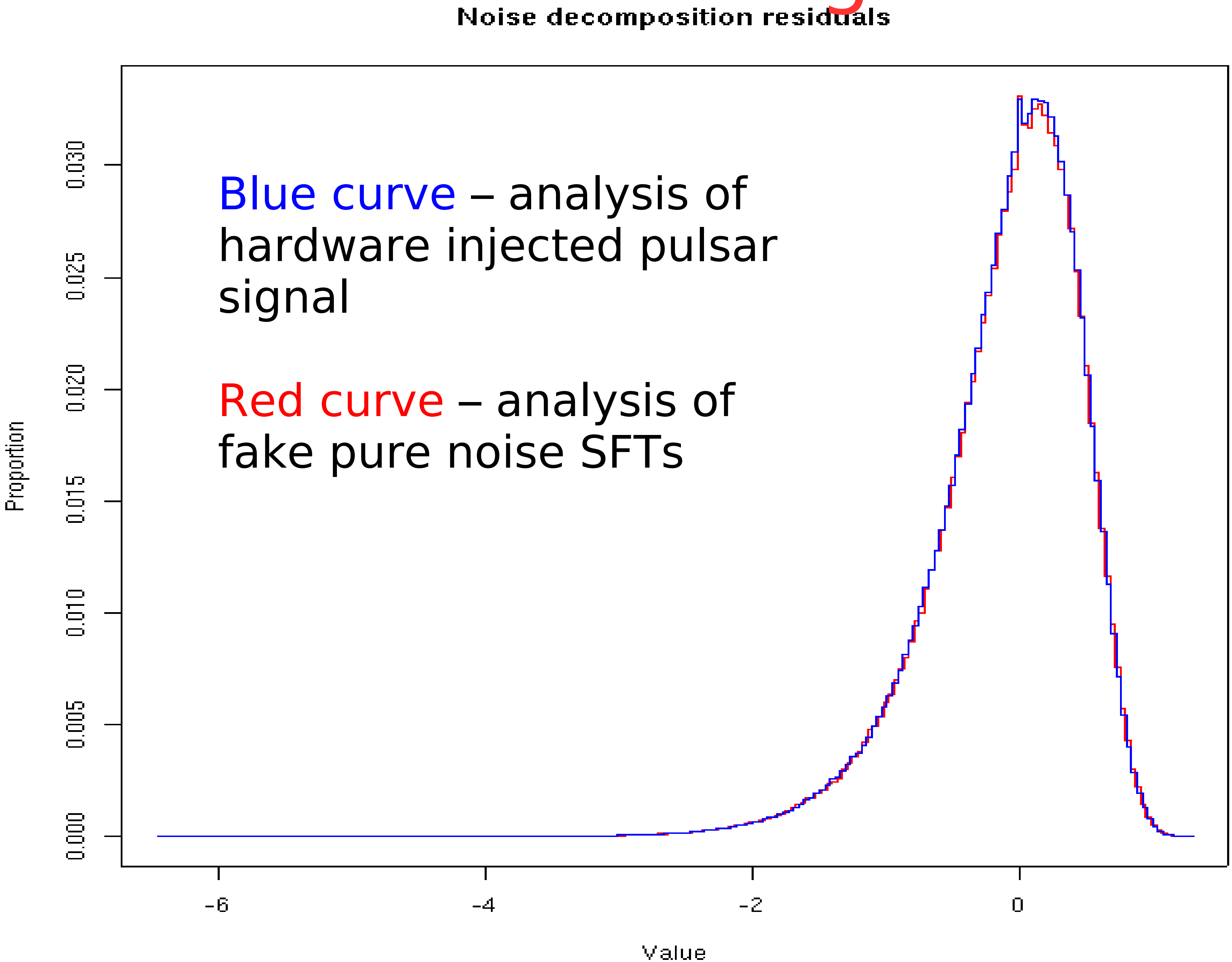
- Internal diagnostics
- Numerous software injection runs
- Analysis of hardware injected signals
- Passed code review

Noise decomposition algorithm

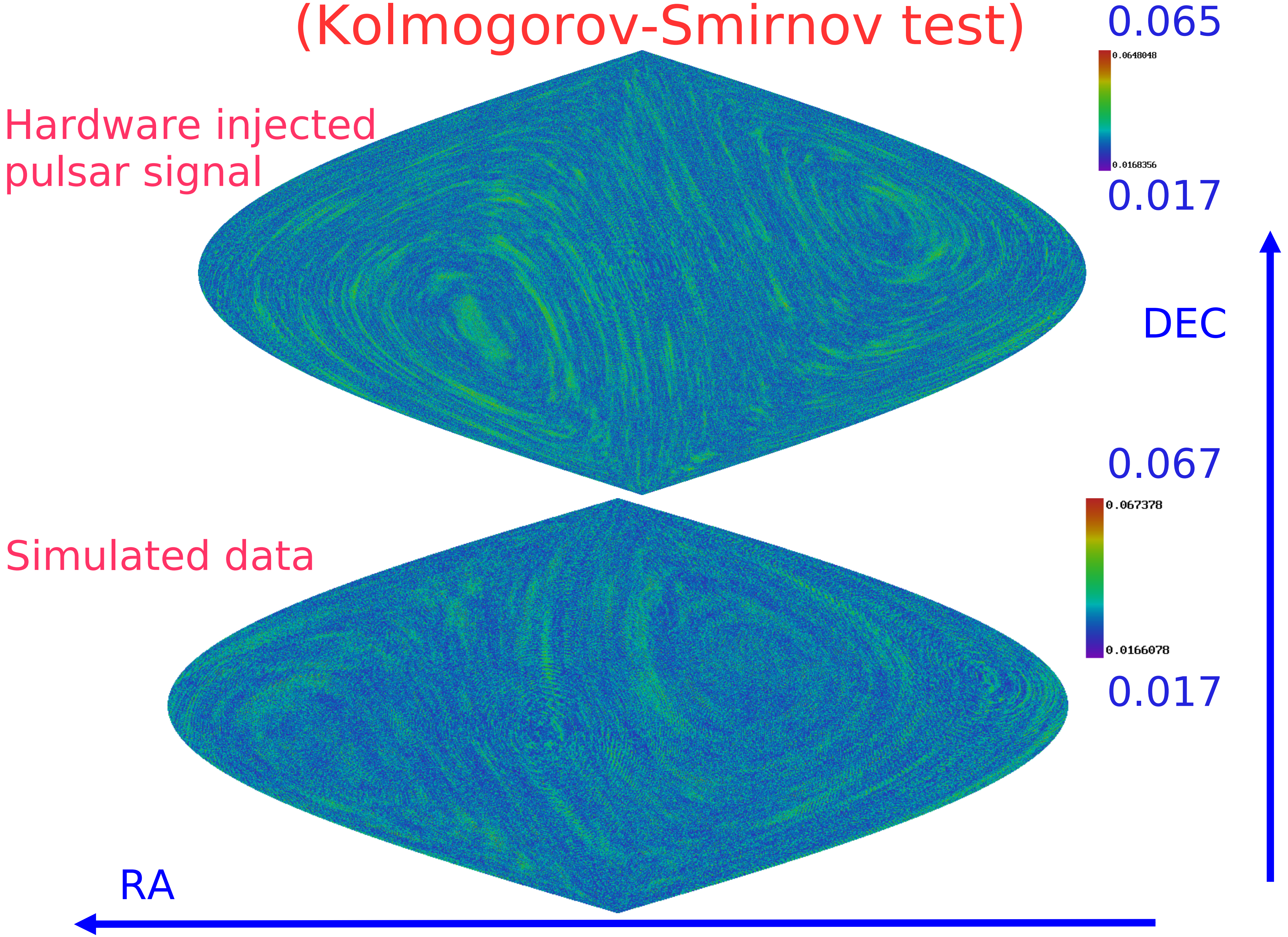
$$Power = 10^{TMedian} \cdot 10^{FMedian} \cdot 10^{Residual}$$

1. Compute log10 of each matrix entry.
2. Compute medians of each row, subtract from the matrix and add to Tmedians accumulation array.
3. Compute medians of each column, subtract from the matrix and add to Fmedians accumulation array.
4. Continue steps 2 and 3 until all medians are 0 or very small.
5. If matrix dimensions are odd always finishes in finite time with exact precision.

Residuals histograms



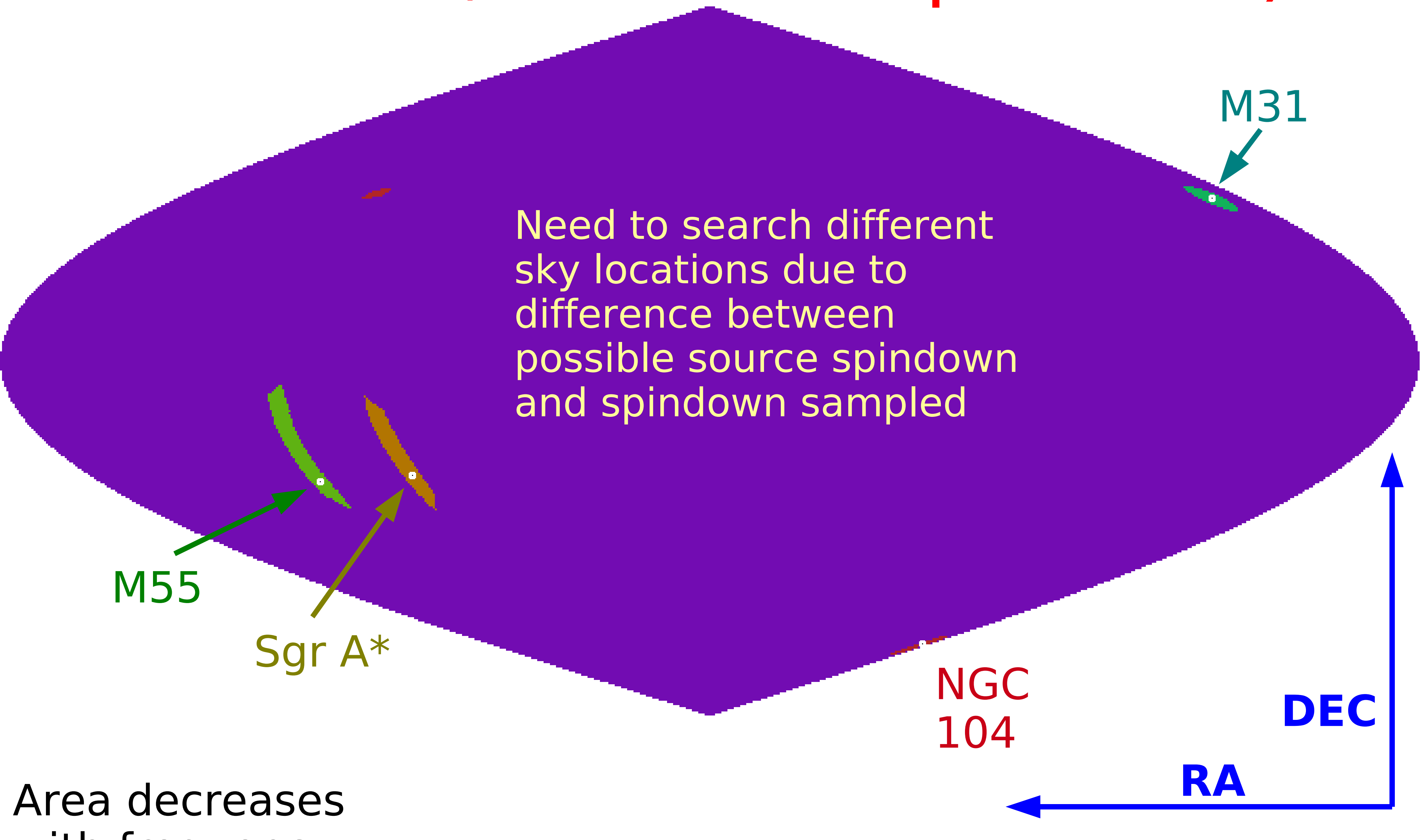
Are averaged powers gaussian ? (Kolmogorov-Smirnov test)



Sky partitioning

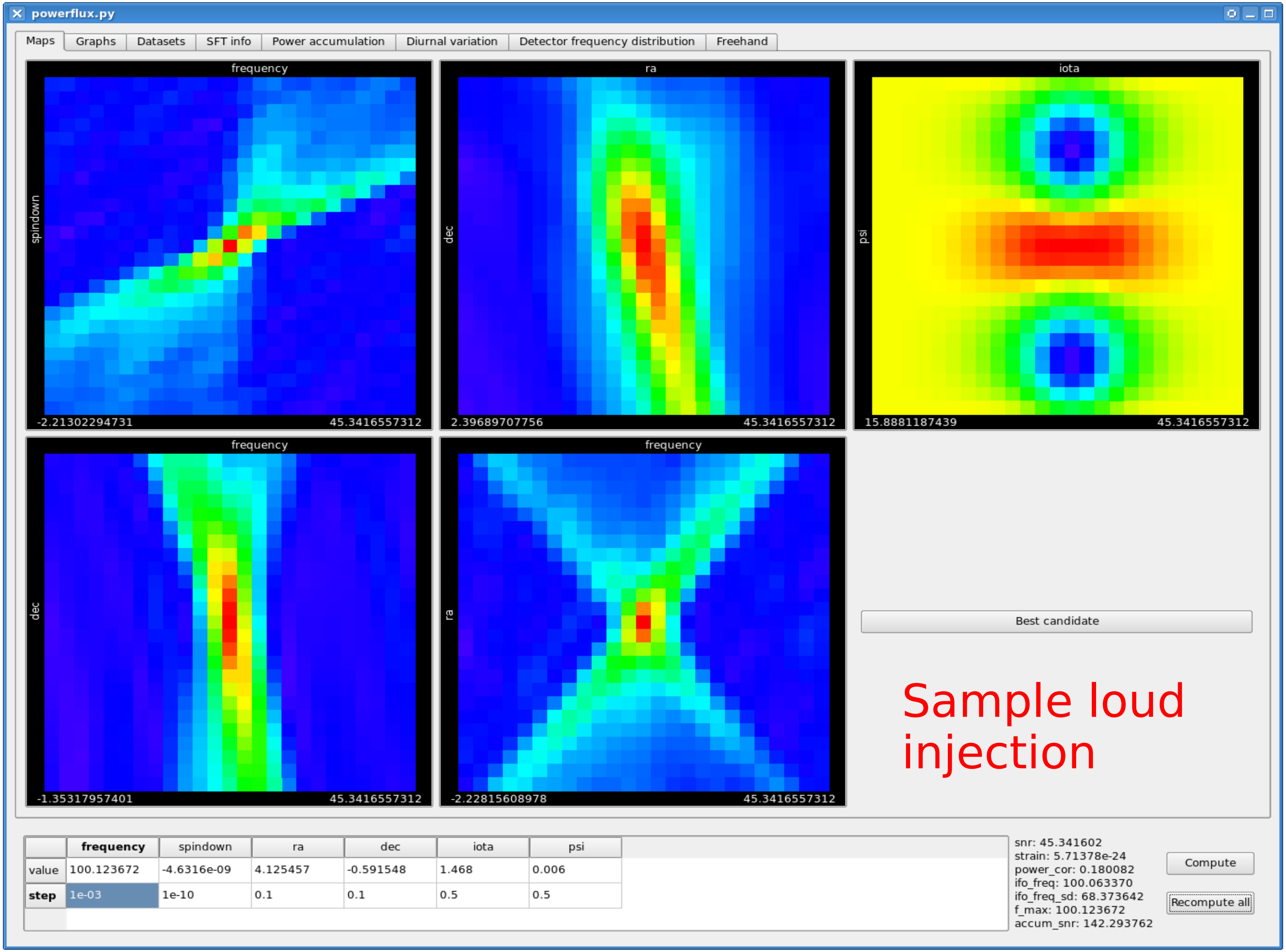
- PowerFlux can group templates based on a “sky marks” configuration file.
- Grouping can be done by sky location and by how strongly a given template will be affected by present line artifacts or by a signal injected into another template.
- A special group number indicates that template should not be processed.
- For example, one can mark regions around Sag A* and globular clusters and designate everything else as “do not process”. This search runs in the fraction of time of full sky analysis, yet shows most of the artifacts and issues of full run.
- During S5 analysis the sky was partitioned into equatorial band, two polar bands, two intermediate bands and a region strongly affected by instrumental artifacts.

Targeted search example (for ~270 Hz, non-zero spindown)

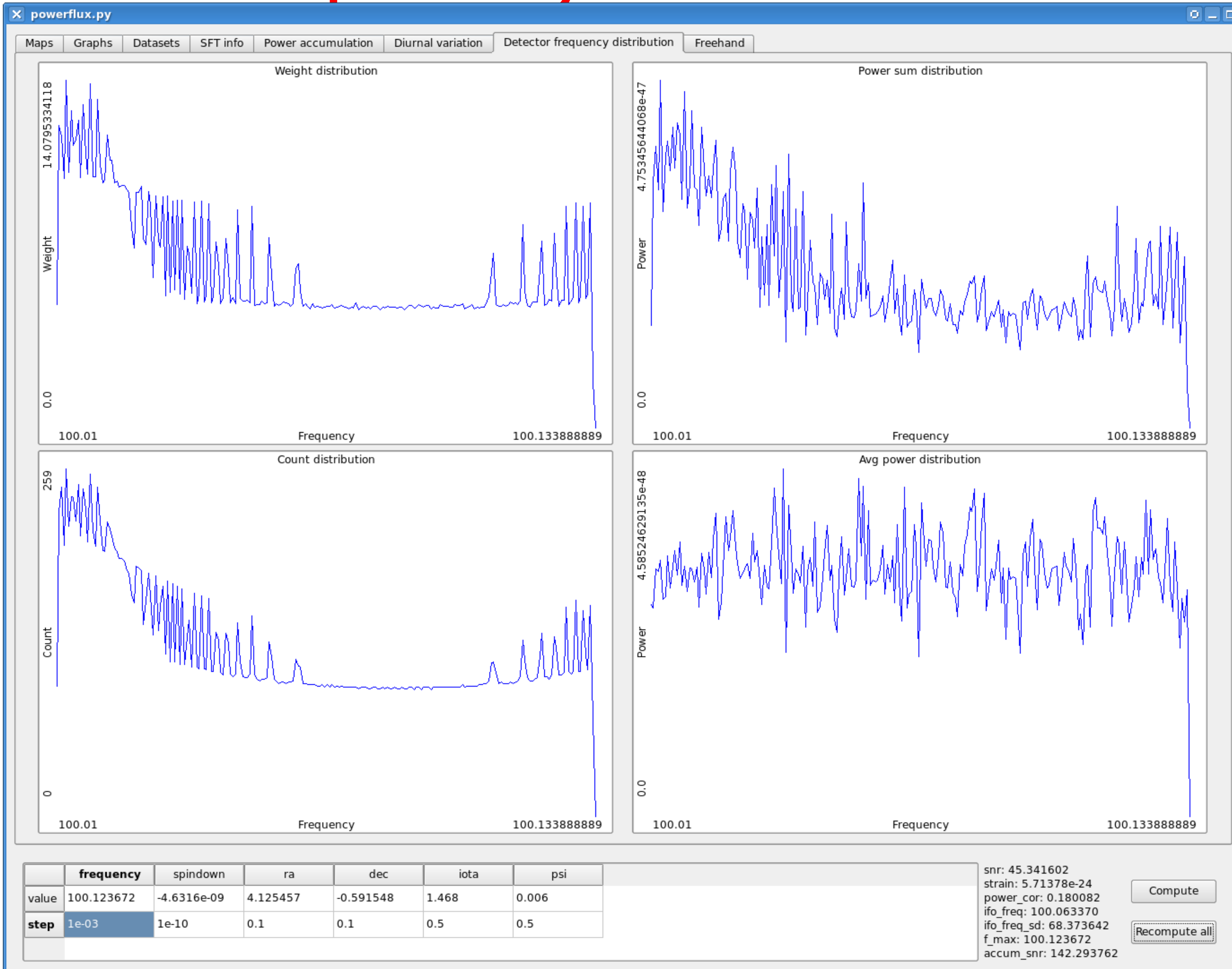


Area decreases with frequency

Interactive interface

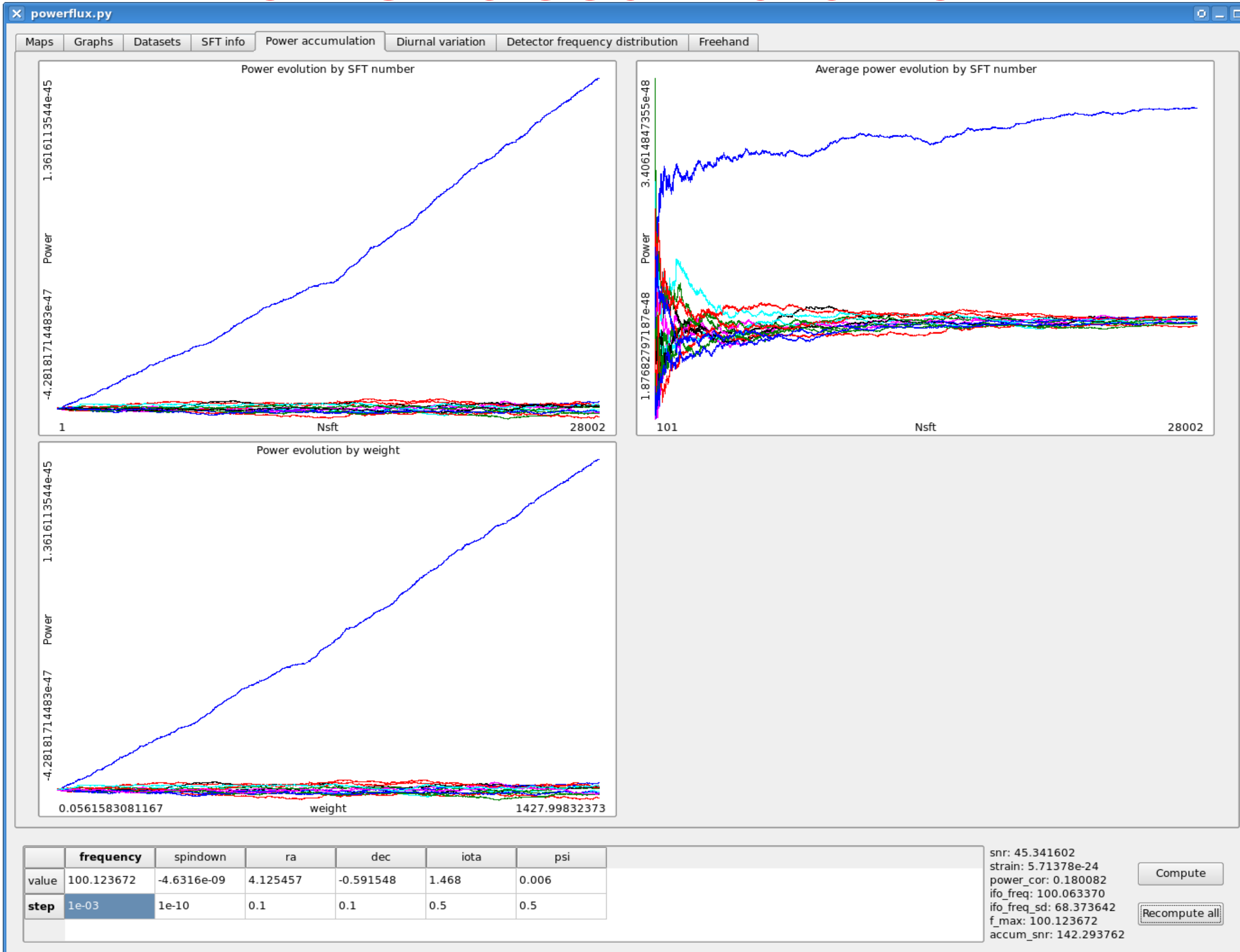


Frequency distribution

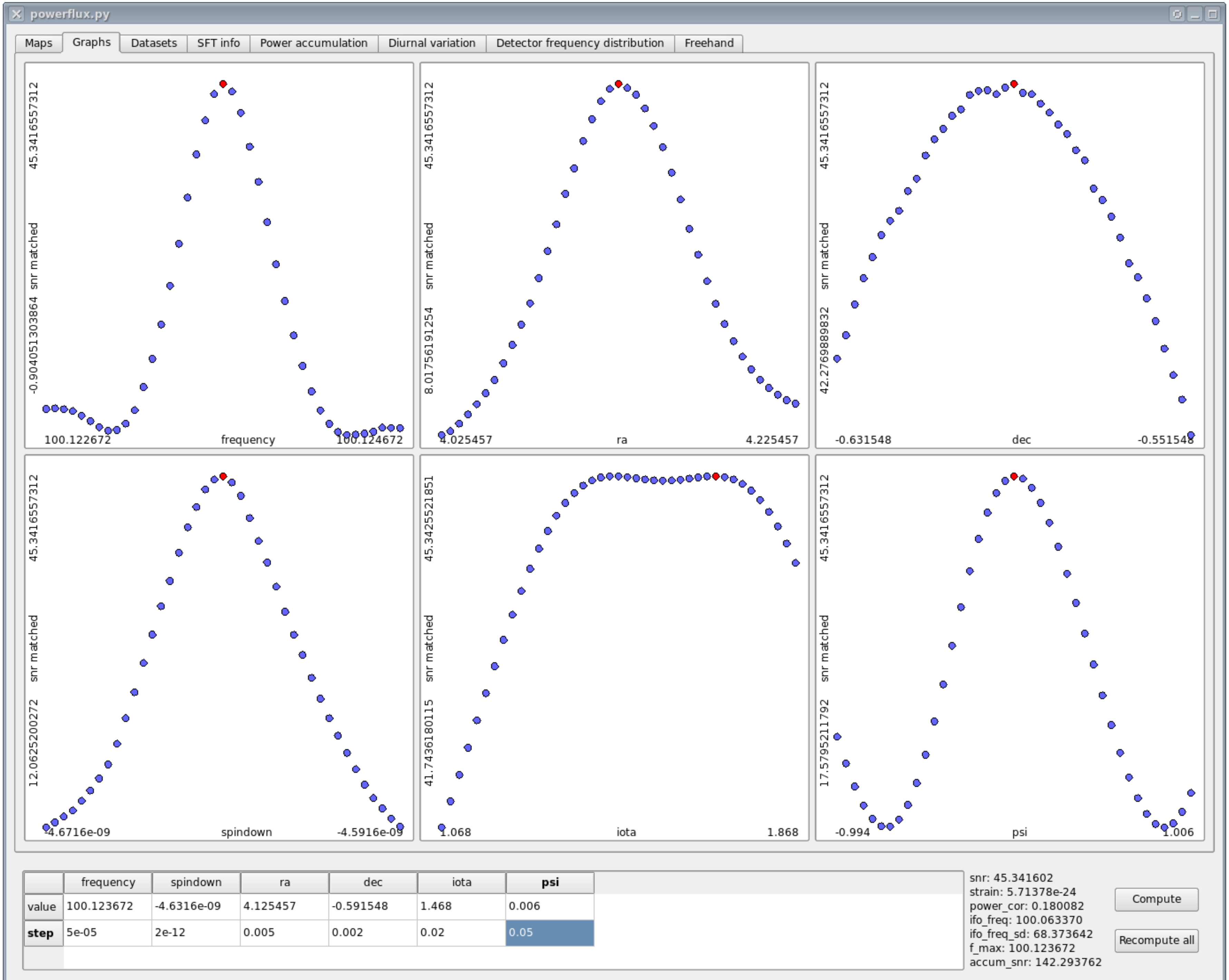


	frequency	spindown	ra	dec	iota	psi
value	100.123672	-4.6316e-09	4.125457	-0.591548	1.468	0.006
step	1e-03	1e-10	0.1	0.1	0.5	0.5

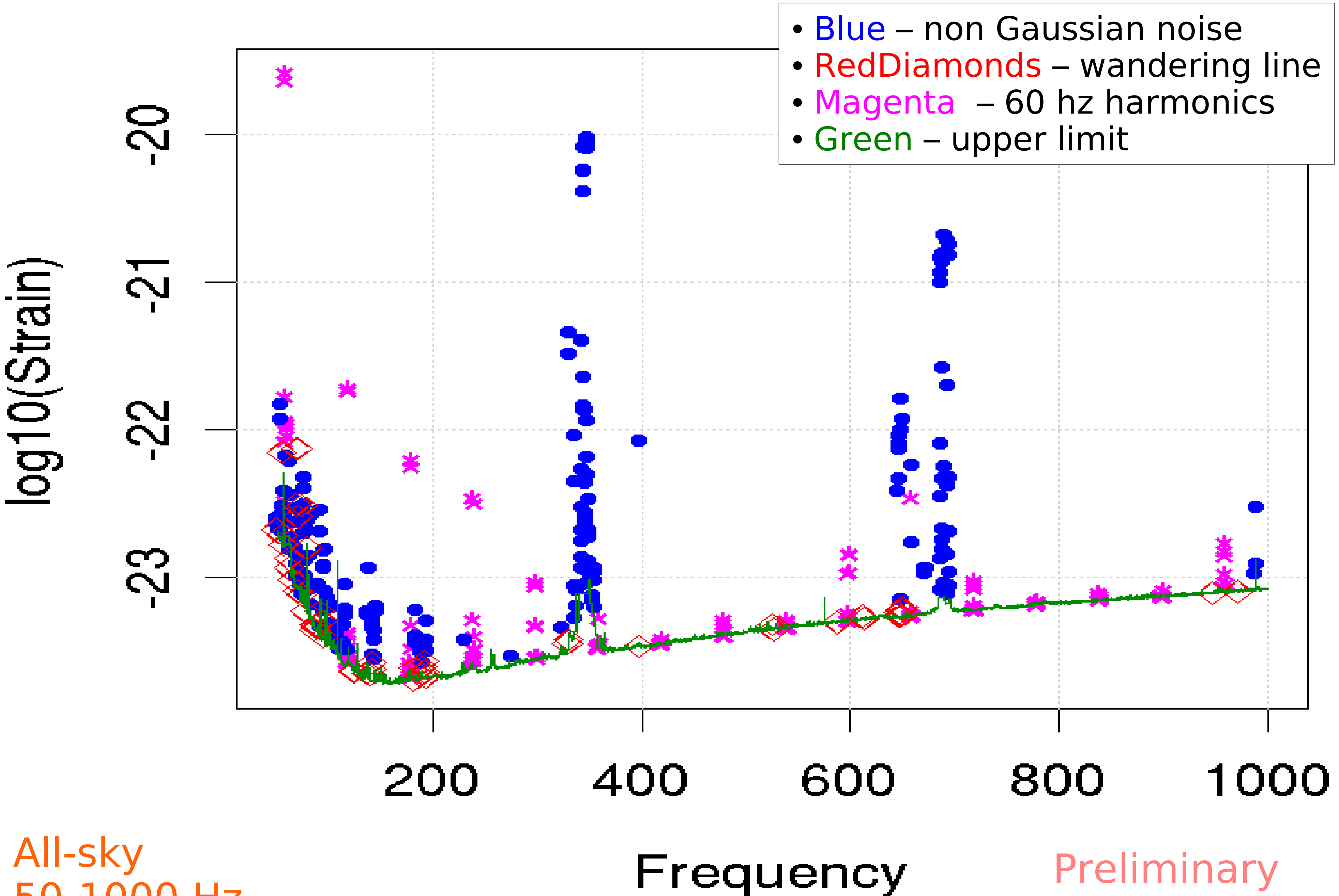
Power accumulation



Graphs


powerflux.py
Maps
Graphs
Datasets
SFT info
Power accumulation
Diurnal variation
Detector frequency distribution
Freehand
45.3416557312
snr matched
-0.904051303864
100.122672
frequency
100.124672
45.3416557312
snr matched
8.01756191254
4.025457
ra
4.225457
45.3416557312
snr matched
42.2769889832
-0.631548
dec
-0.551548
45.3416557312
snr matched
12.0625200272
-4.6716e-09
spindown
-4.5916e-09
45.3425521851
snr matched
41.7436180115
1.068
iota
1.868
45.3416557312
snr matched
17.5795211792
-0.994
psi
1.006
frequency
spindown
ra
dec
iota
psi
value
100.123672
-4.6316e-09
4.125457
-0.591548
1.468
0.006
step
5e-05
2e-12
0.005
0.002
0.02
0.05
snr: 45.341602
strain: 5.71378e-24
power_cor: 0.180082
ifo_freq: 100.063370
ifo_freq_sd: 68.373642
f_max: 100.123672
accum_snr: 142.293762
Compute
Recompute all

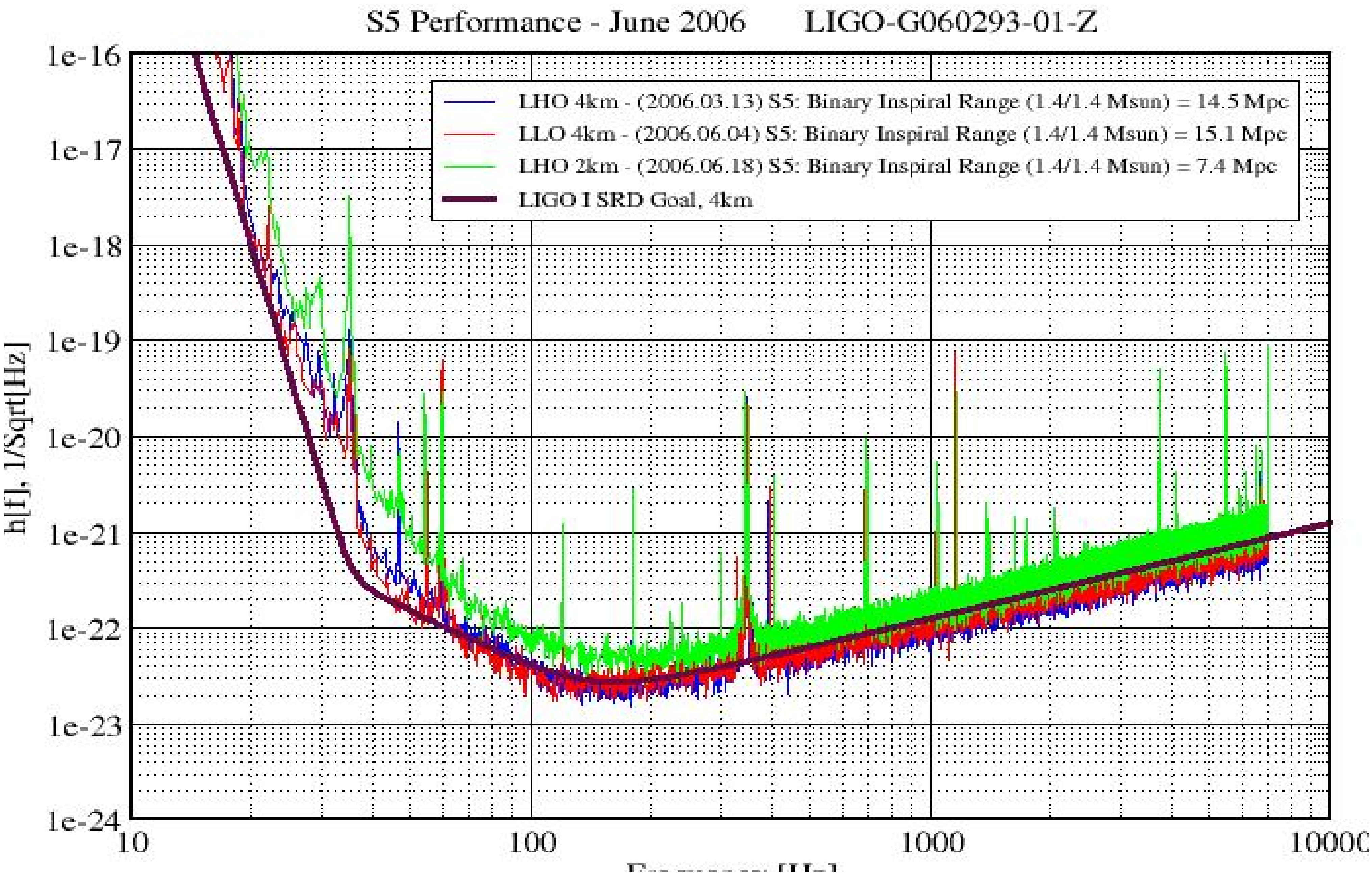
L1 S5 0-spindown run



All-sky
50-1000 Hz

Preliminary results

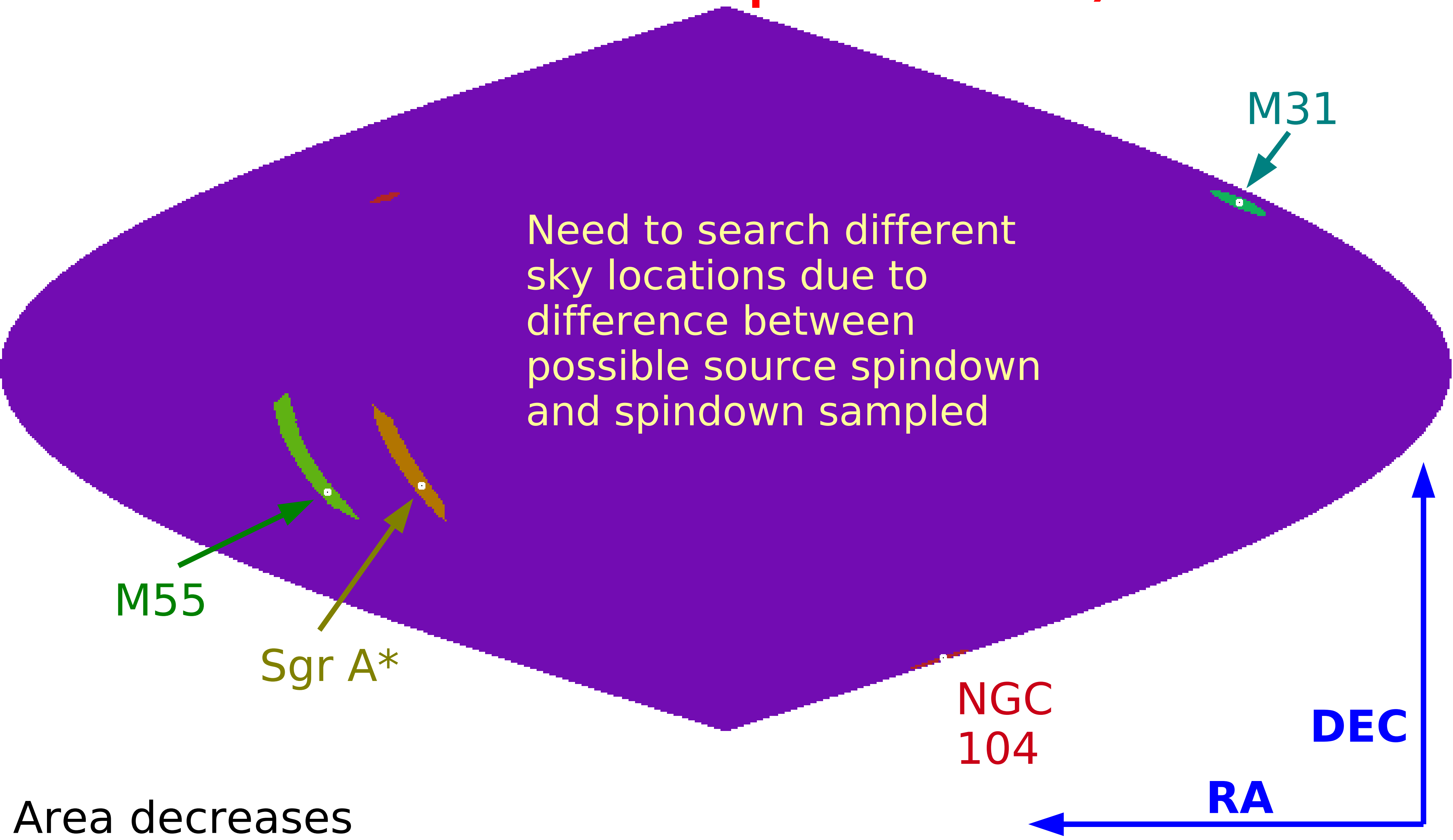
S5 science run sensitivity



Partial sky (targeted) run

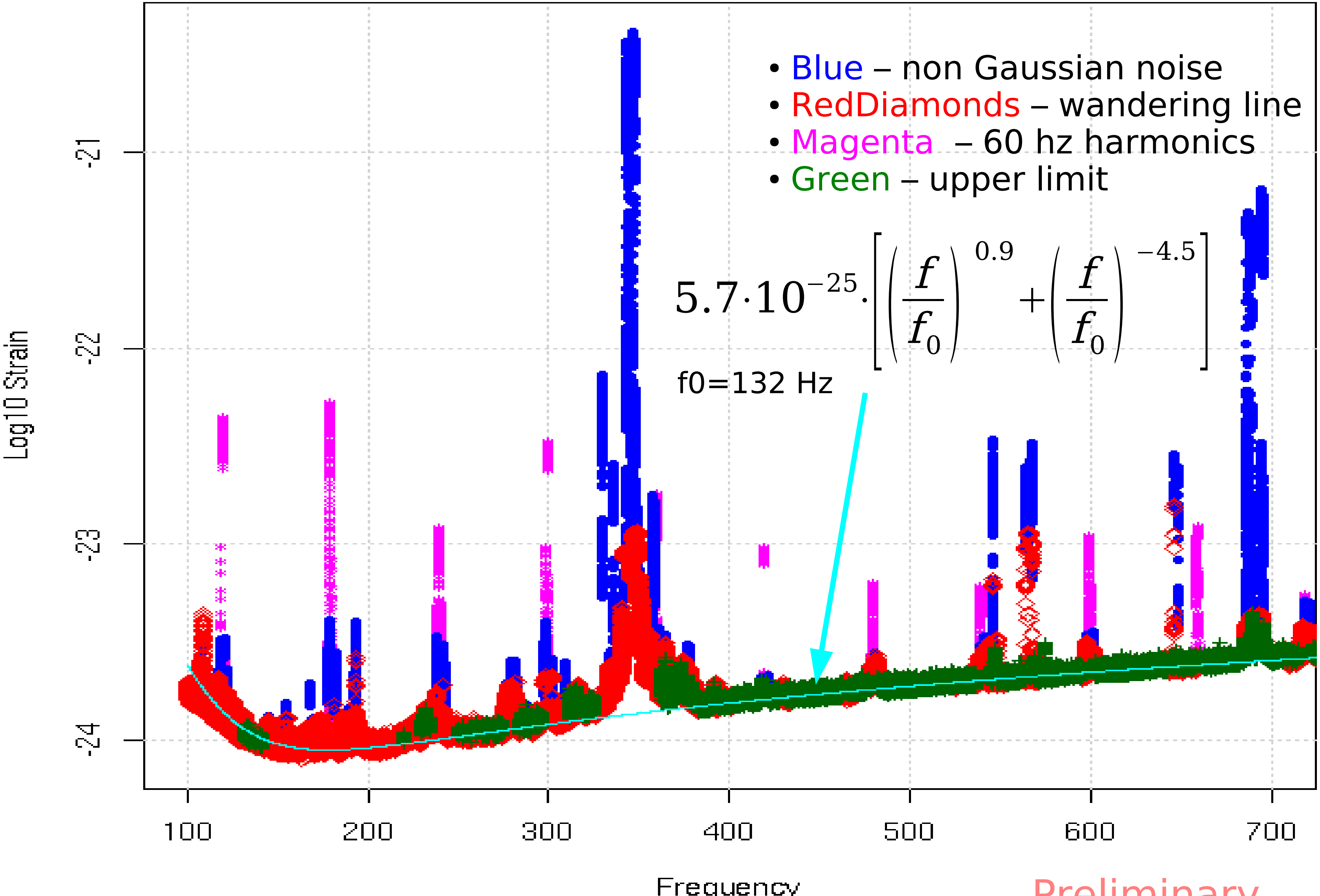
- Searched sky around
  - globular clusters M55, NGC104
  - galactic center Sgr A*
  - Andromeda M31 (control)
- 100-700 Hz
- -1.01e-8 Hz/s through 1.01e-8 Hz/s in 2e-10 Hz/s steps

Search area (for ~270 Hz, non-zero spindown)



Area decreases
with frequency

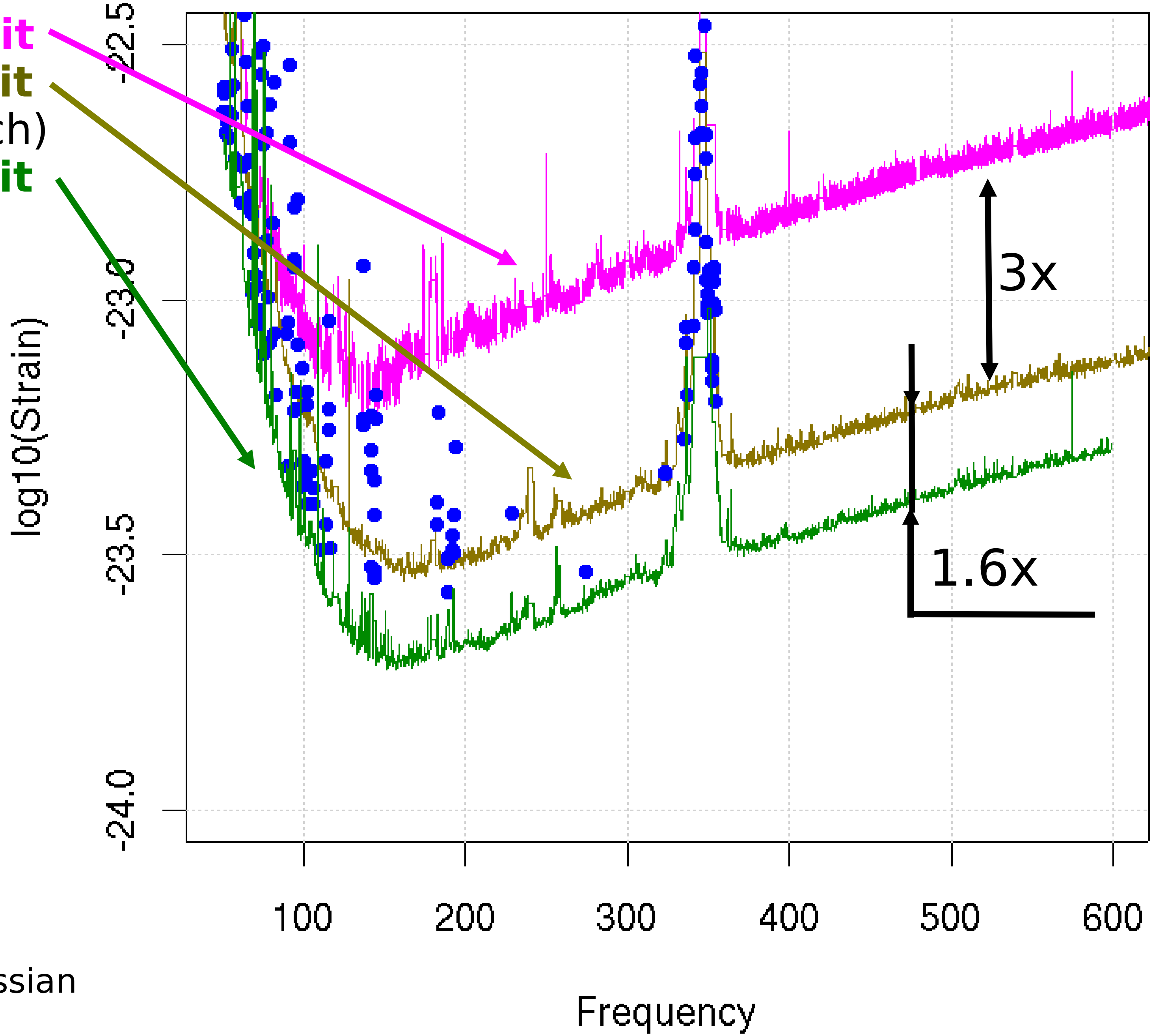
H1 Sgr A* upper limits



Preliminary results

S5 spindown-0 run

- **S4 L1 upper limit**
- **S5 L1 upper limit** (data through March)
- **S5 L1 upper limit** (data through July)



July L1 SFTs= 3x March SFTs

- 60 Hz lines excluded
- Blue points – non-gaussian noise in July run

“S parameter”

When S is closer to 0 susceptibility to stationary artifacts increases

Average detector acceleration

Average detector velocity

$$S := s + \frac{\vec{u} \times \vec{v}_{\mathrm{avg}}}{c} f \cdot \hat{\vec{r}}$$

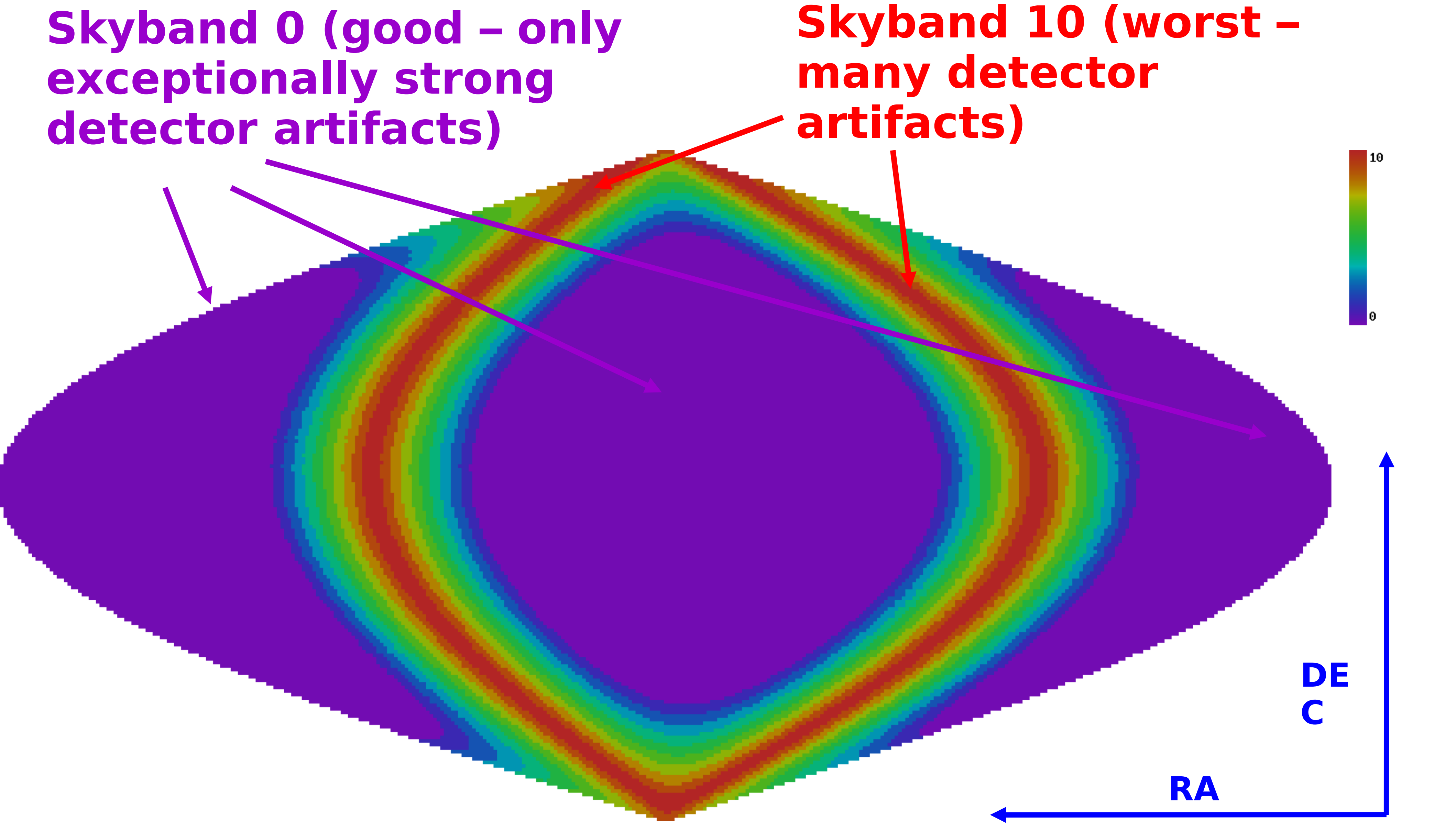
Spindown (Hz/s)

Earth orbit angular velocity

Frequency

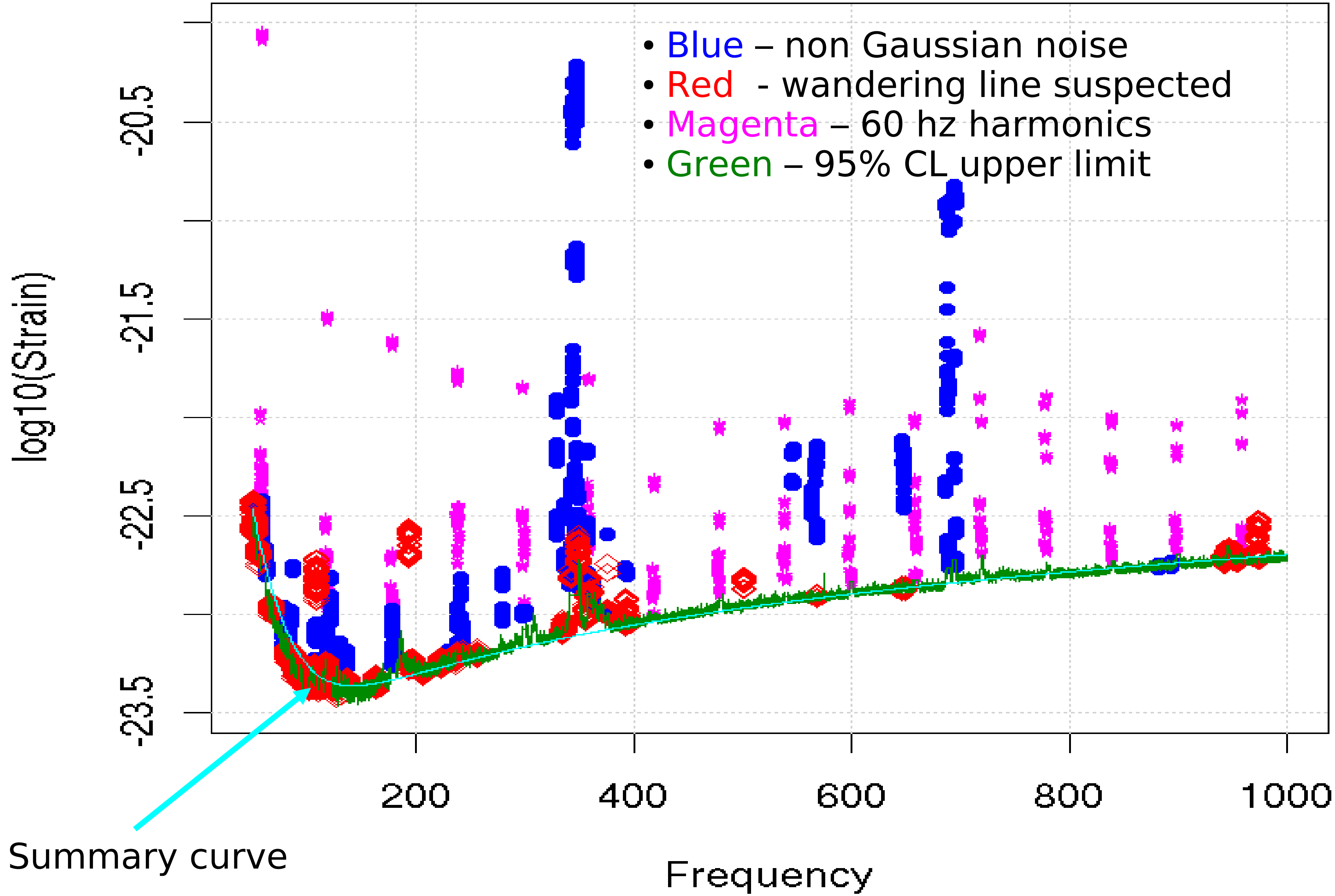
Unit sky position vector

Doppler Skybands



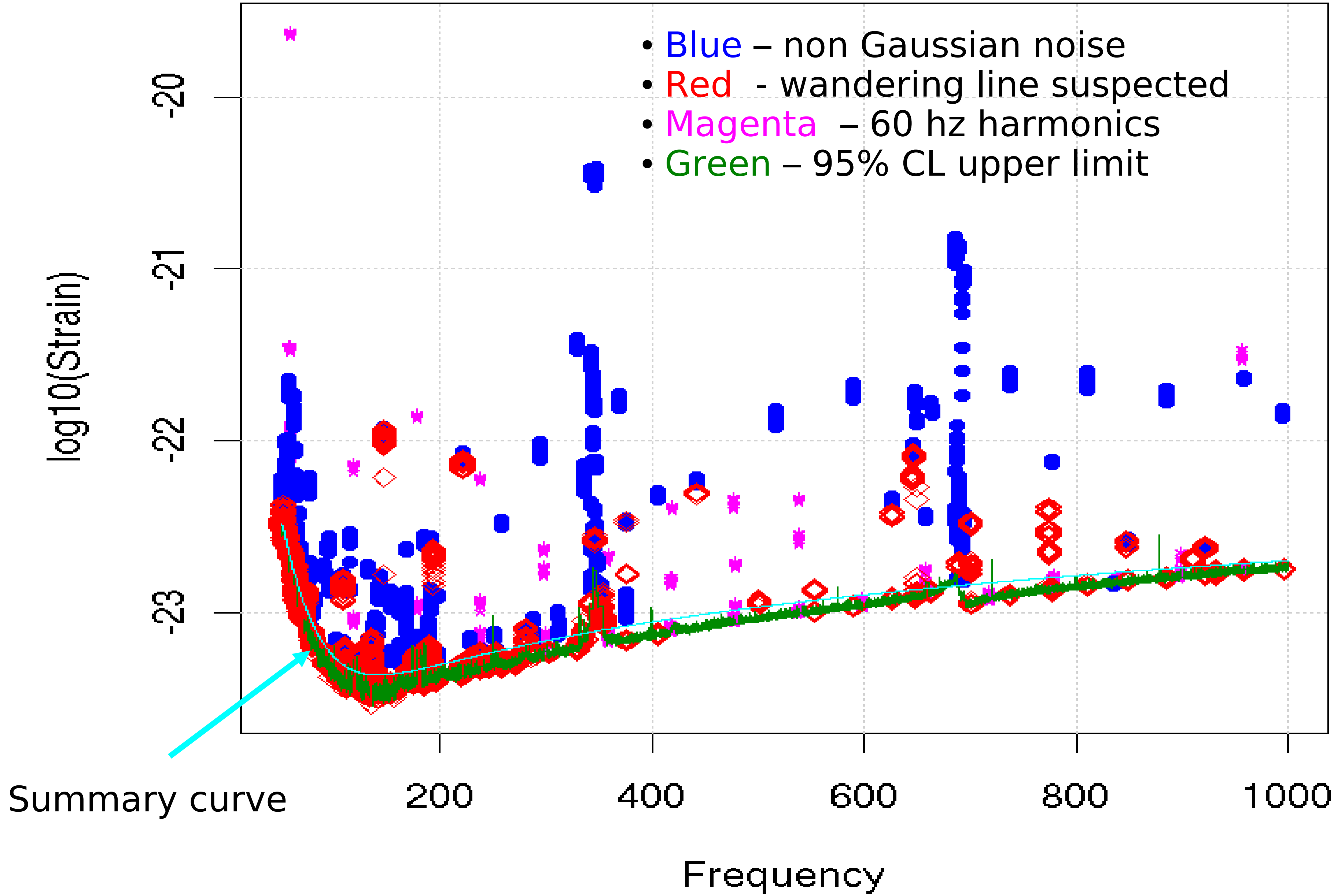
S4 run results
Hanford 4km

Hanford 4km upper limits are slightly higher than the summary curve, but much cleaner in low frequency range



S4 run results
Livingston 4km

Livingston 4km upper limits are slightly lower than the summary curve, but not as clean in low frequency range



S5 summary curve deviation