



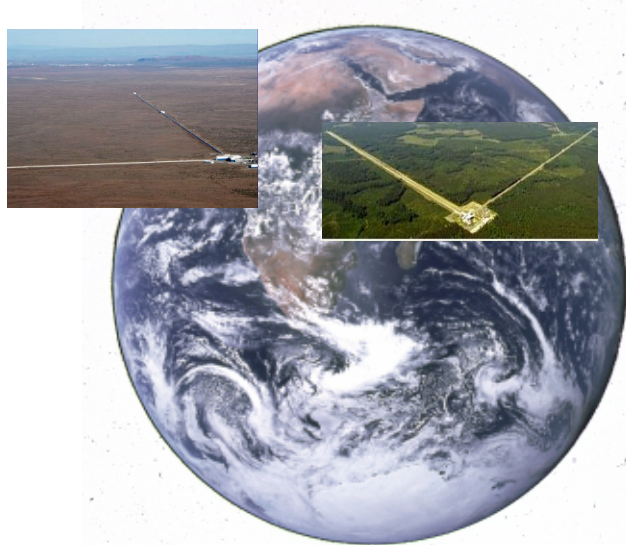
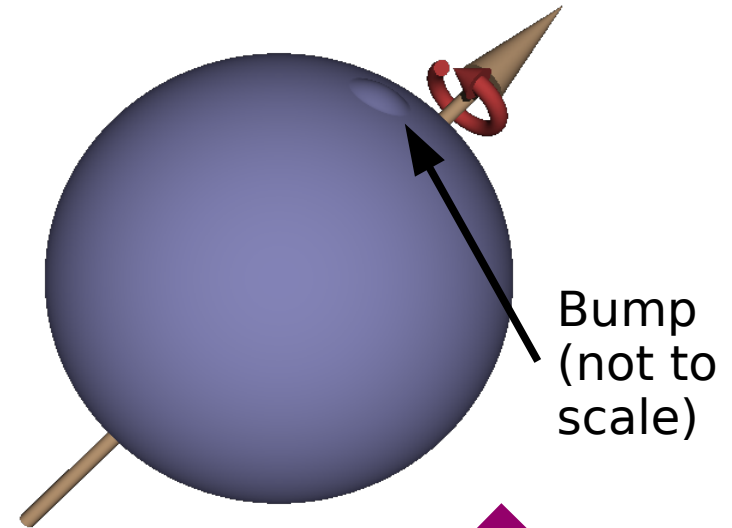
Broadband Search for Continuous-Wave Gravitation Radiation with LIGO

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

Continuous gravitational waves

- 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 ?

Rotating neutron star



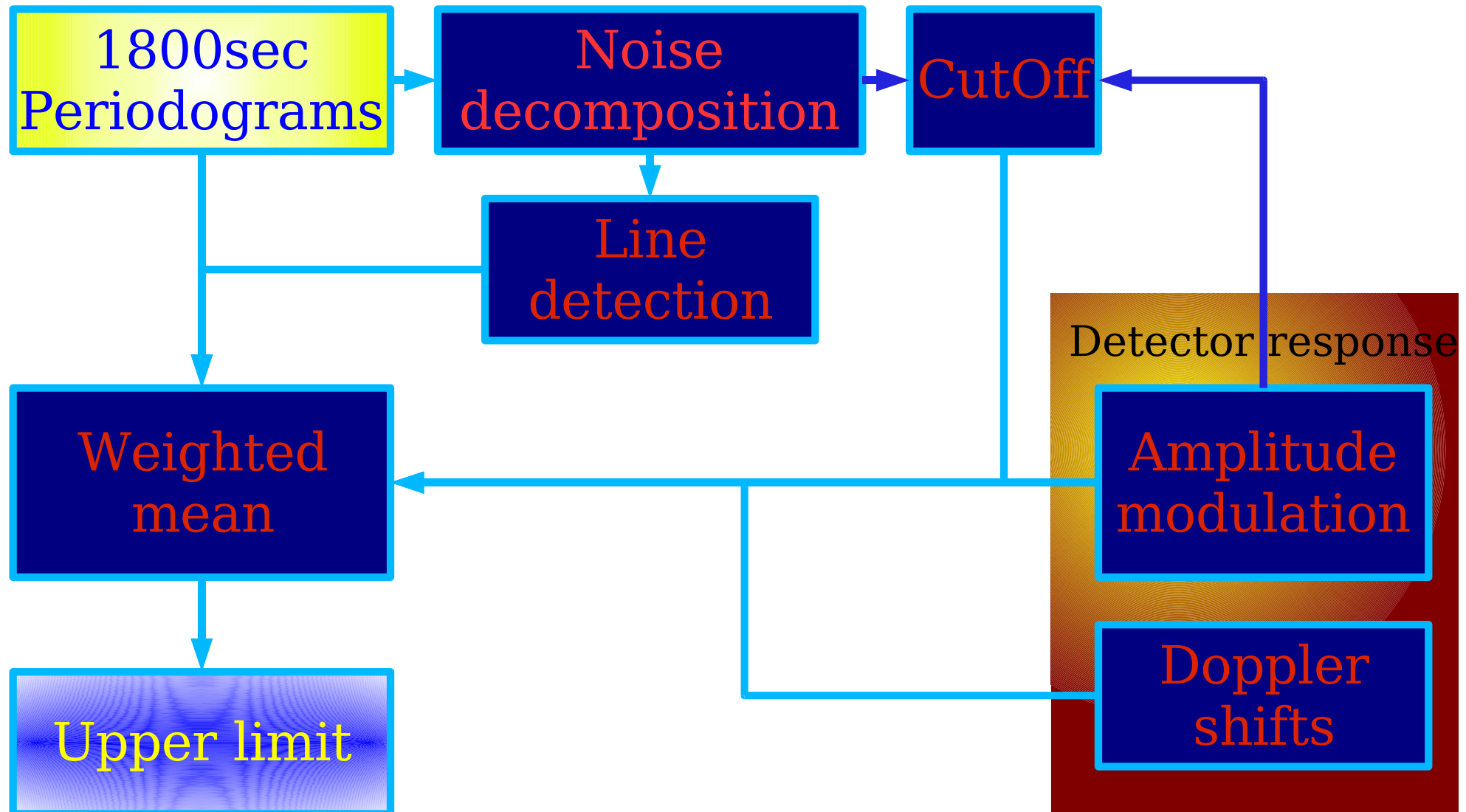
Circularly polarized gravitational waves

Linearly 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



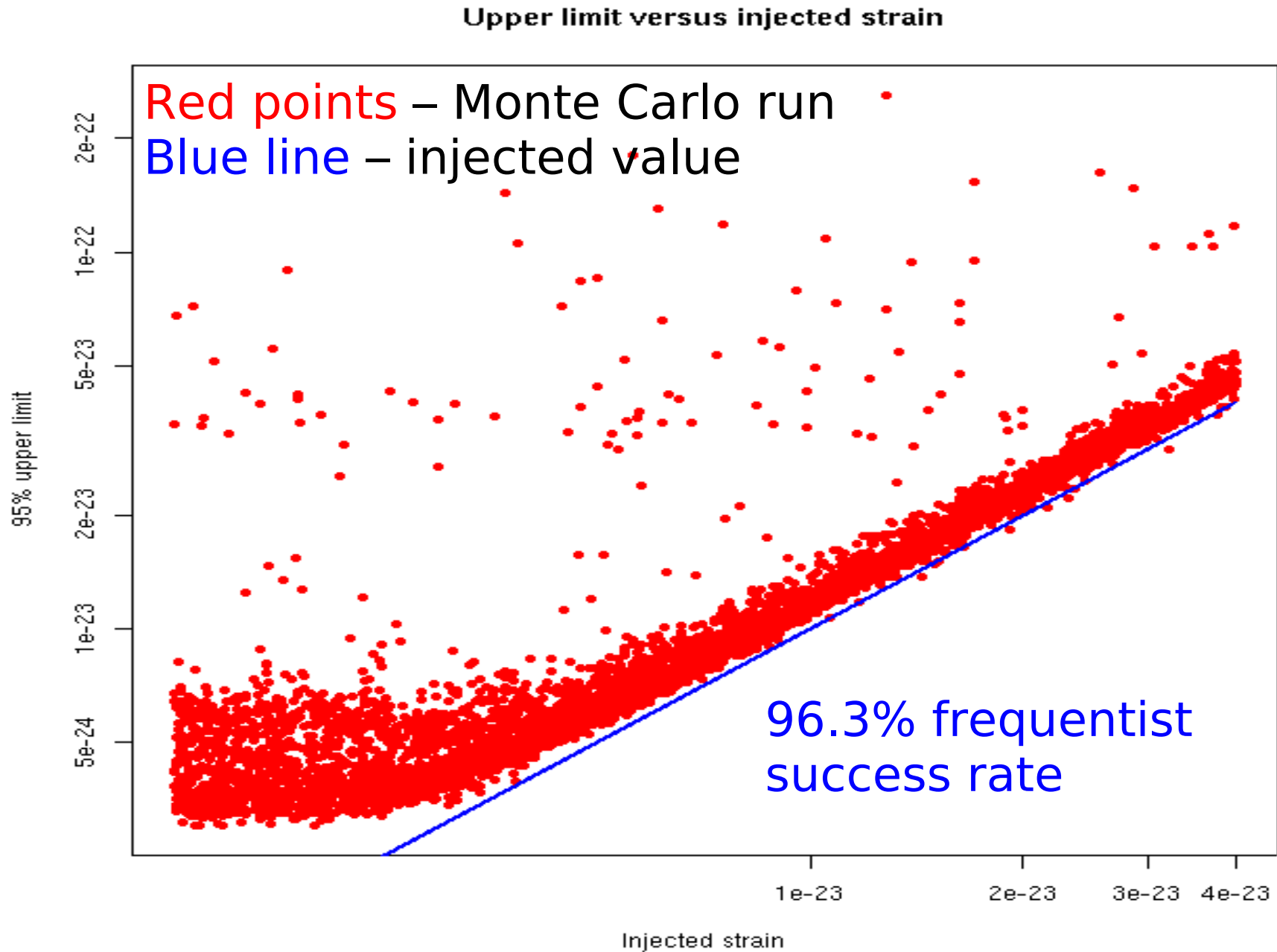
Choice of 1/1800 Hz SFT bins

- 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

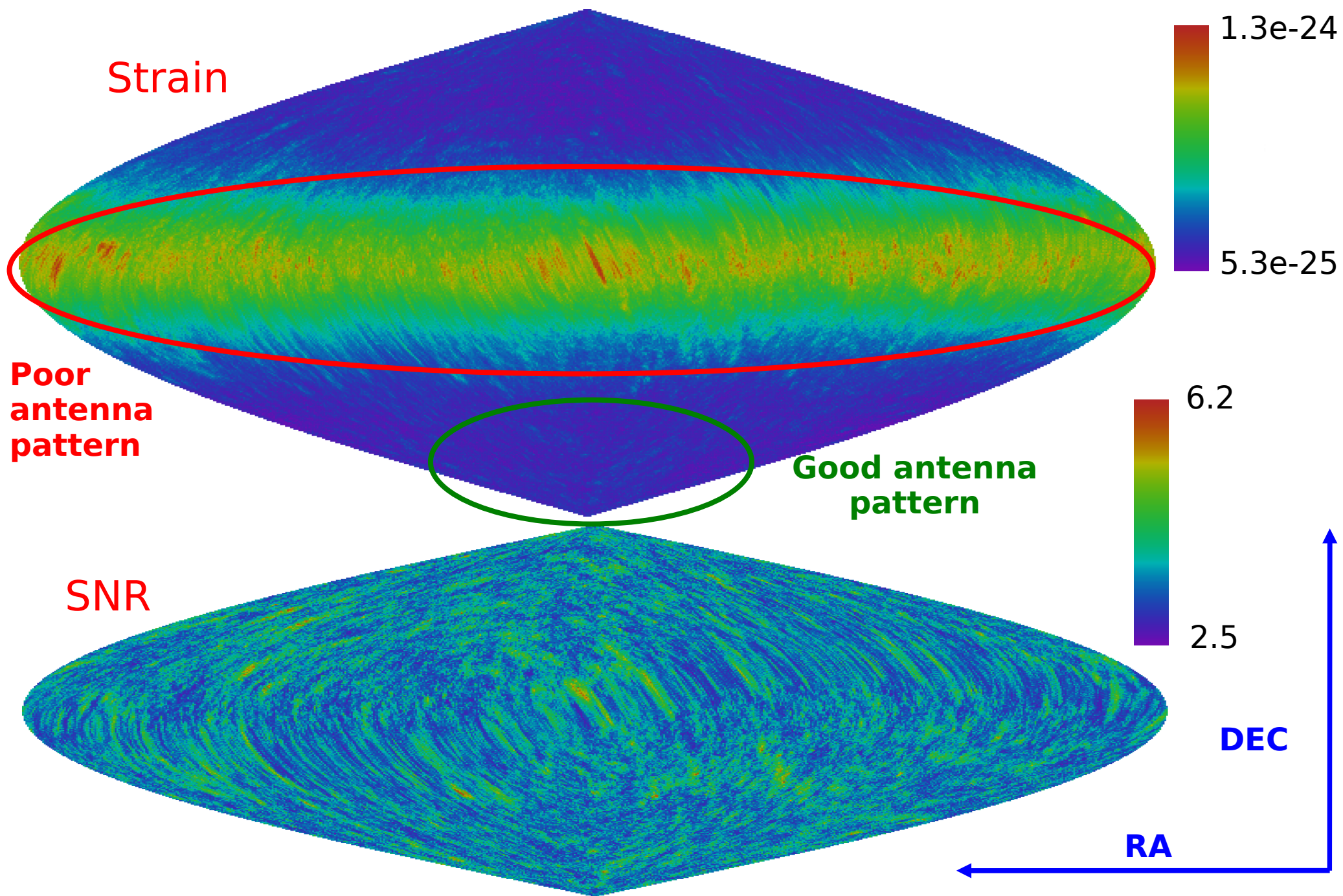
Upper limit versus injected strain



PowerFlux results

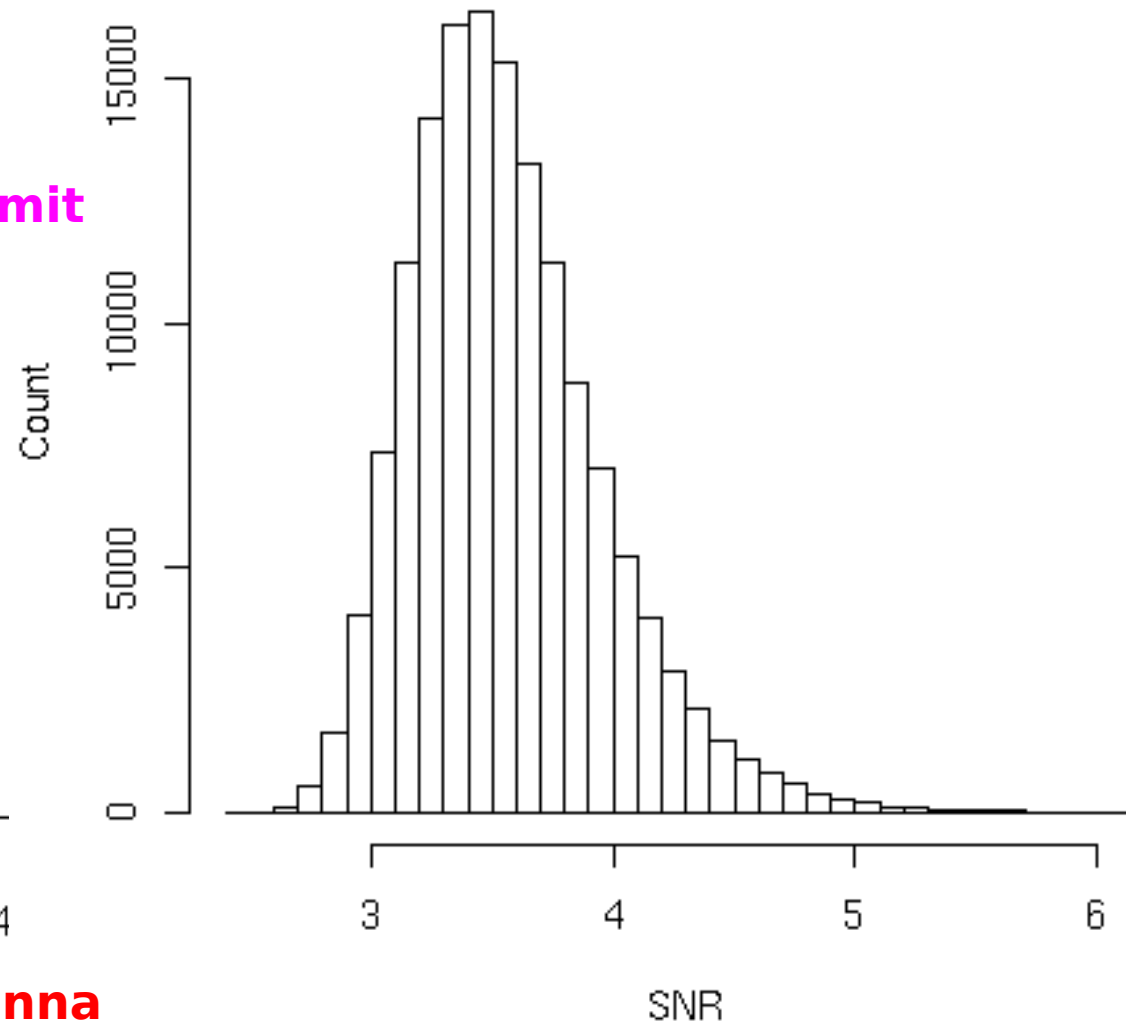
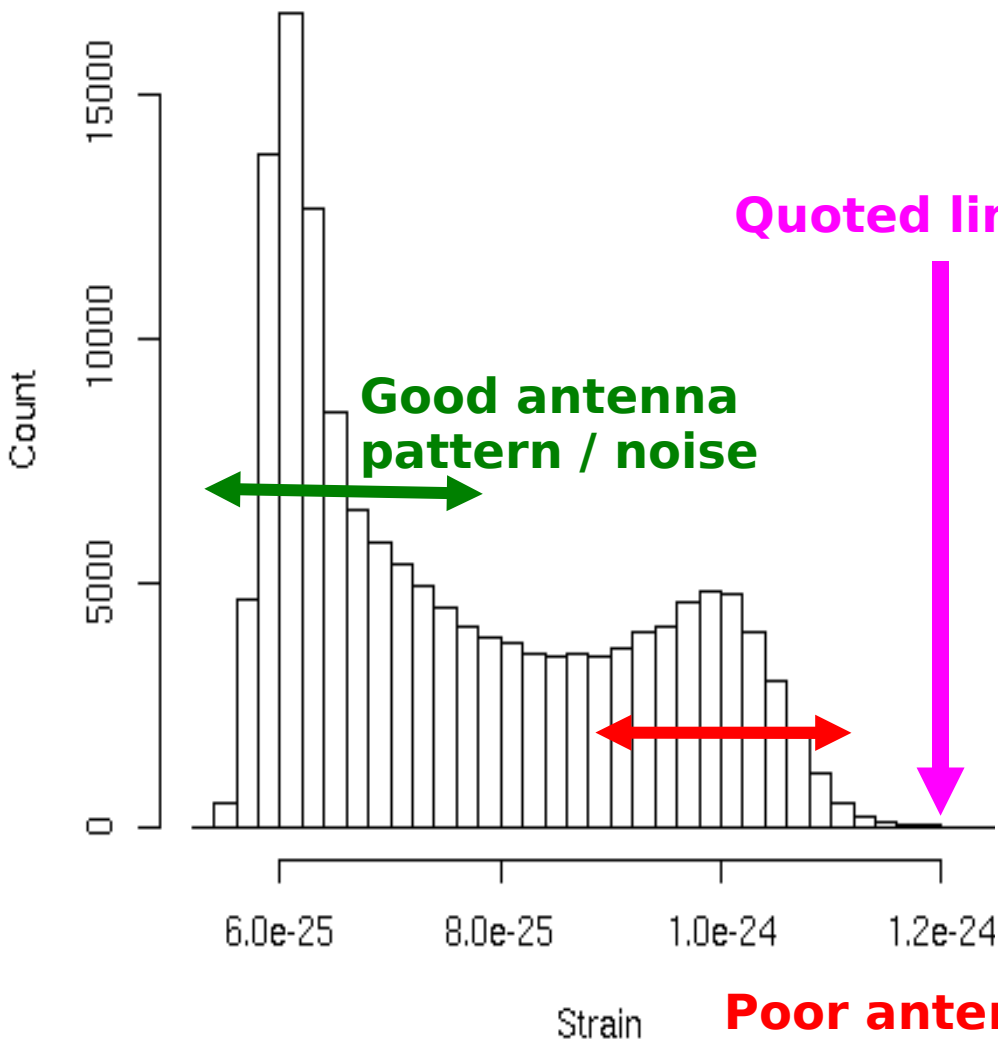
- PowerFlux produces a 95% CL upper limit for a particular frequency, sky position, spindown and polarization. One of three methods used in S4 all-sky search (arXiv:0708.3818 = Phys. Rev. D 77 (2008) 022001)
- Too much data to store, let alone present – the number of sky positions alone is $\sim 10^5$ 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)

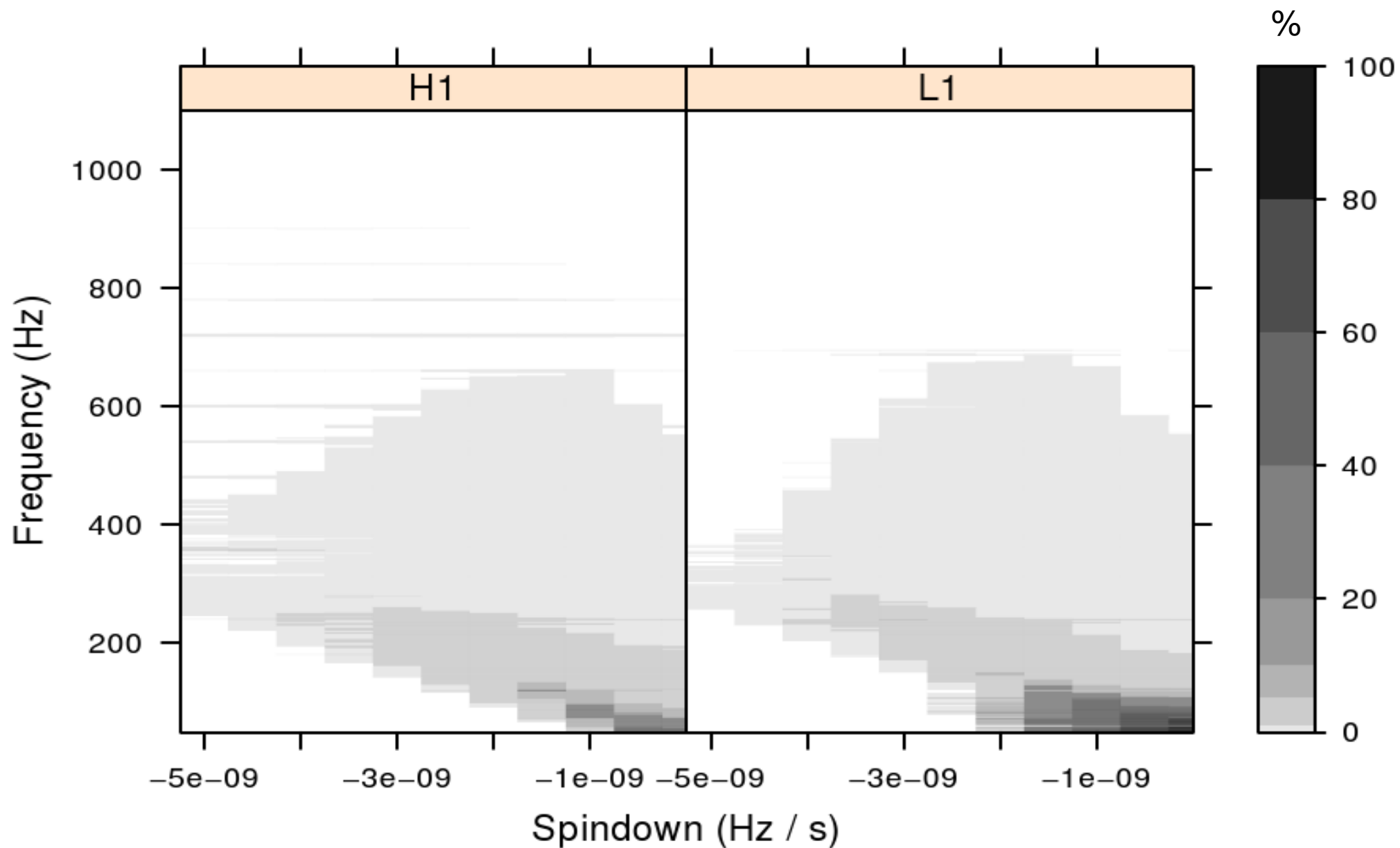


Histograms

(one entry per sky point)



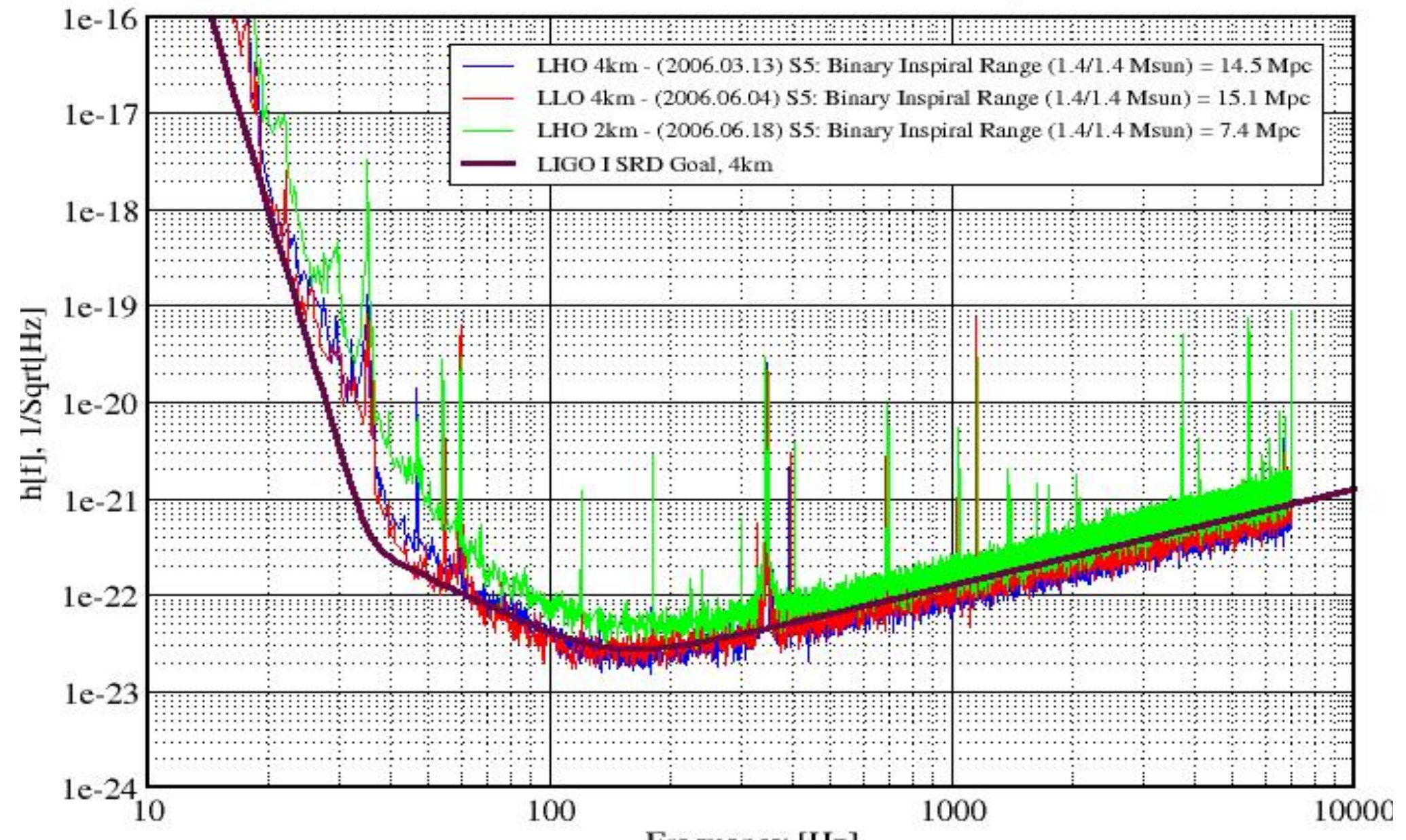
Early S5 excluded sky area



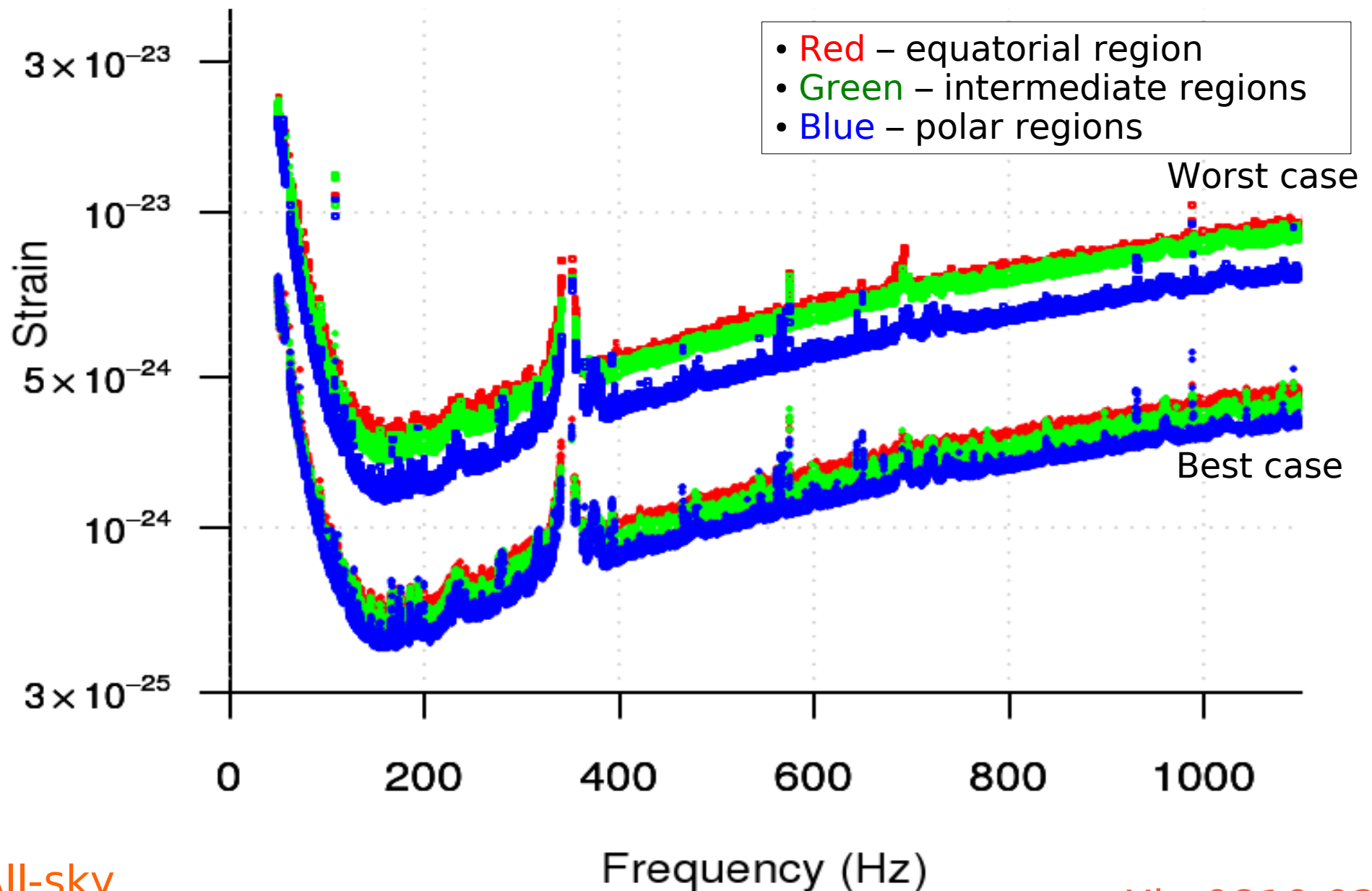
S5 science run sensitivity

S5 Performance - June 2006

LIGO-G060293-01-Z



Upper limits, PRL 102, 111102 (2009)



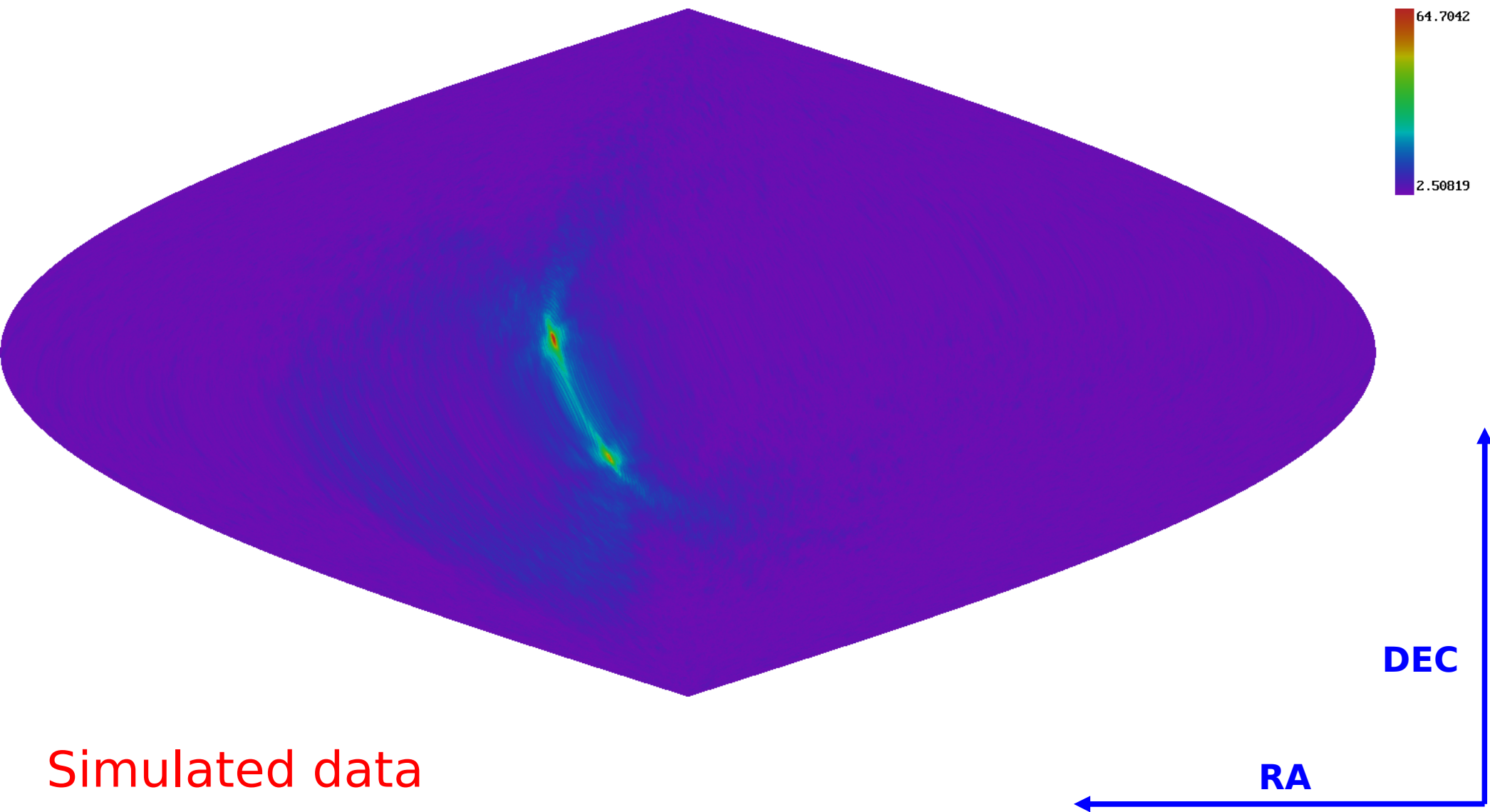
All-sky
50-1100 Hz

arXiv:0810.0283

Upper limits

- Our best sensitivity is at 153 Hz where we obtain upper limit of 4.2×10^{-25} for circularly polarized sources in polar region.
- At a signal frequency of 1100 Hz we achieve sensitivity to neutron stars of equatorial ellipticity $\sim 1 \times 10^{-6}$ at distances up to 500 pc.

Hardware injected pulsar signal



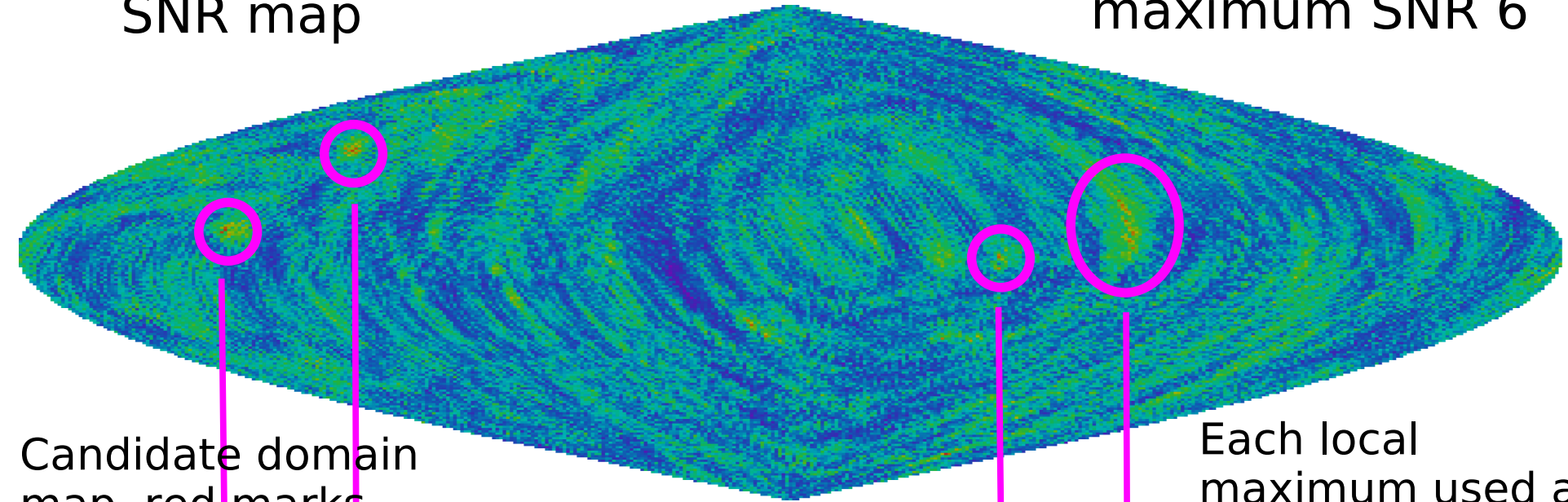
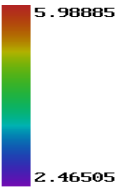
Outlier followup

- 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:
 - $\text{SNR} > 6.25$ 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

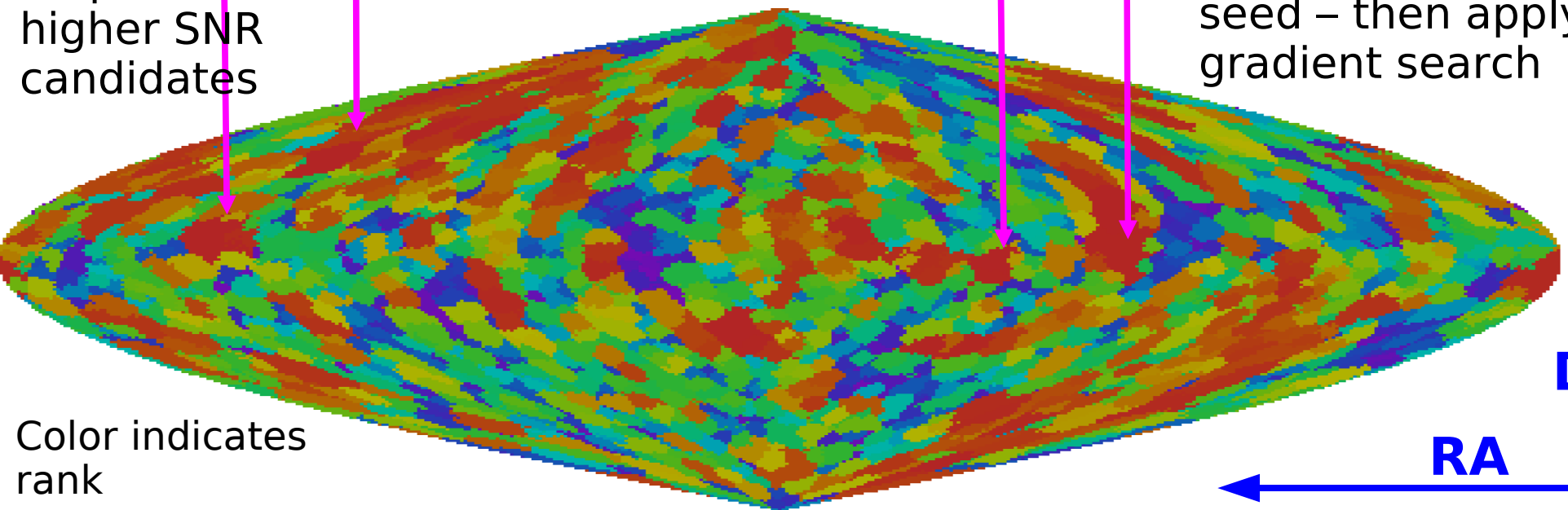
SNR map

Clean band –
maximum SNR 6



Candidate domain
map, red marks
higher SNR
candidates

Each local
maximum used as
seed – then apply
gradient search

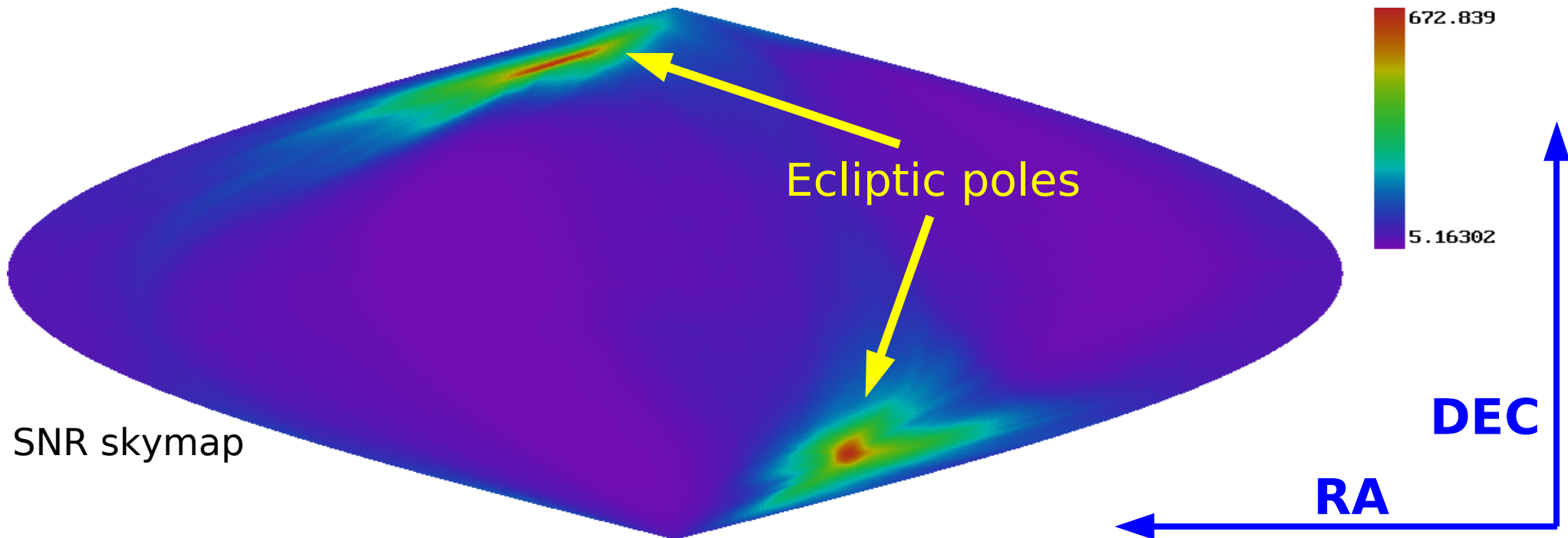
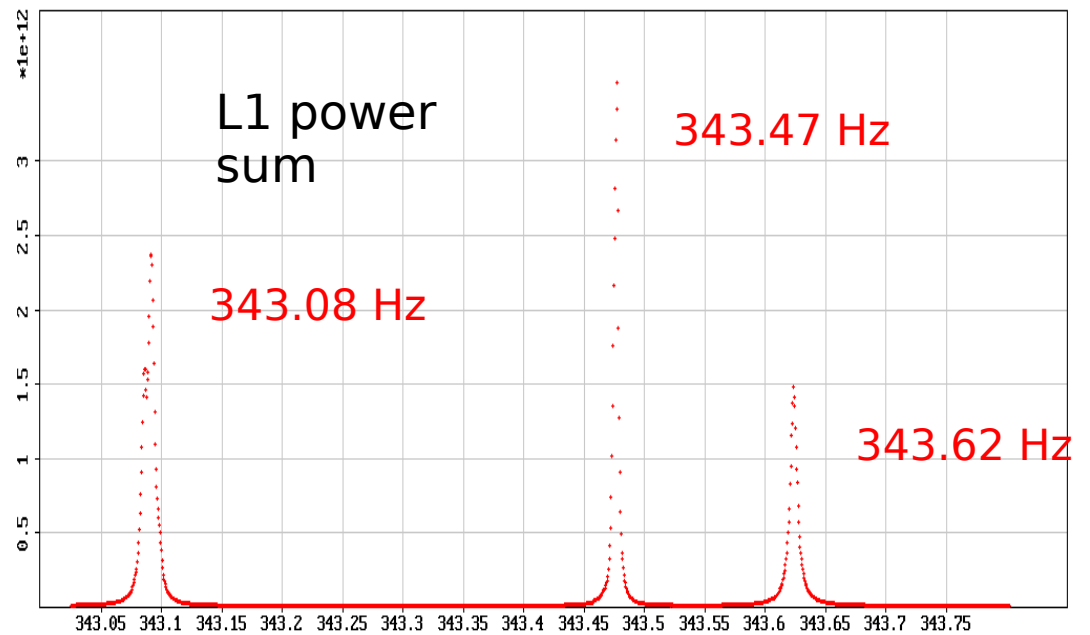
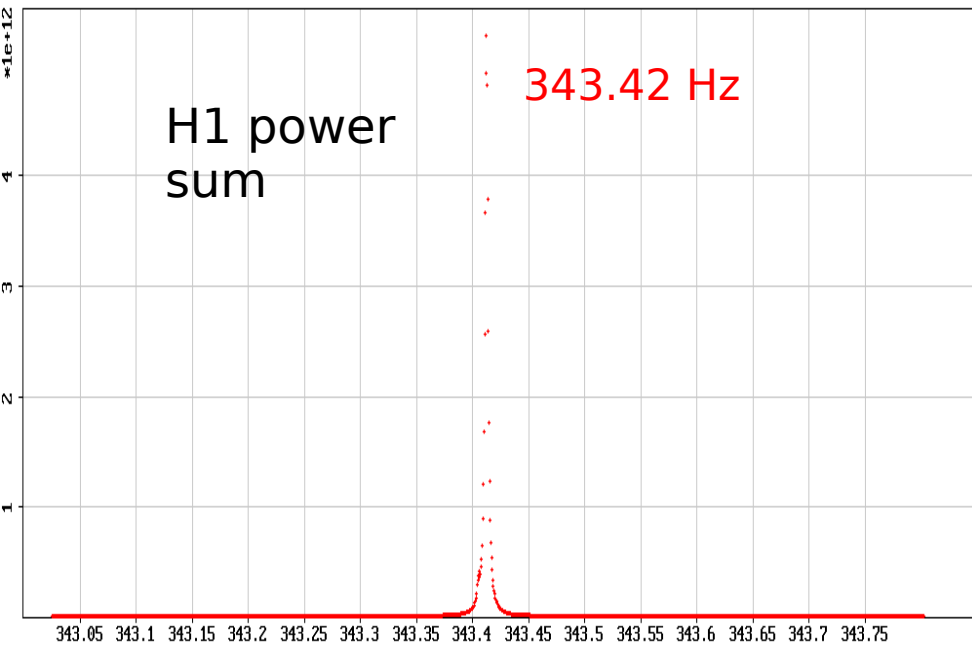


Color indicates
rank

RA

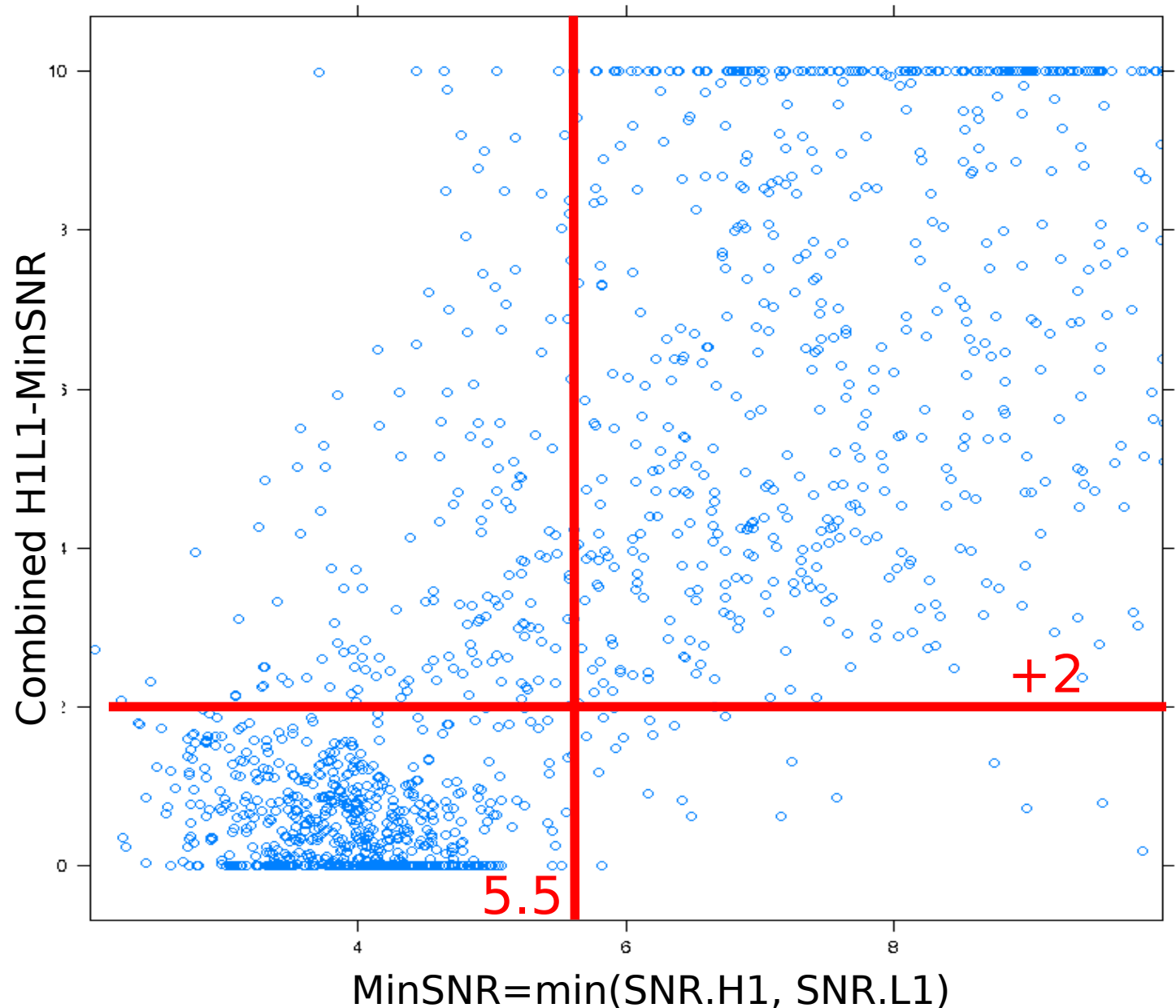
DEC

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 $5\text{e-}10$ 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.

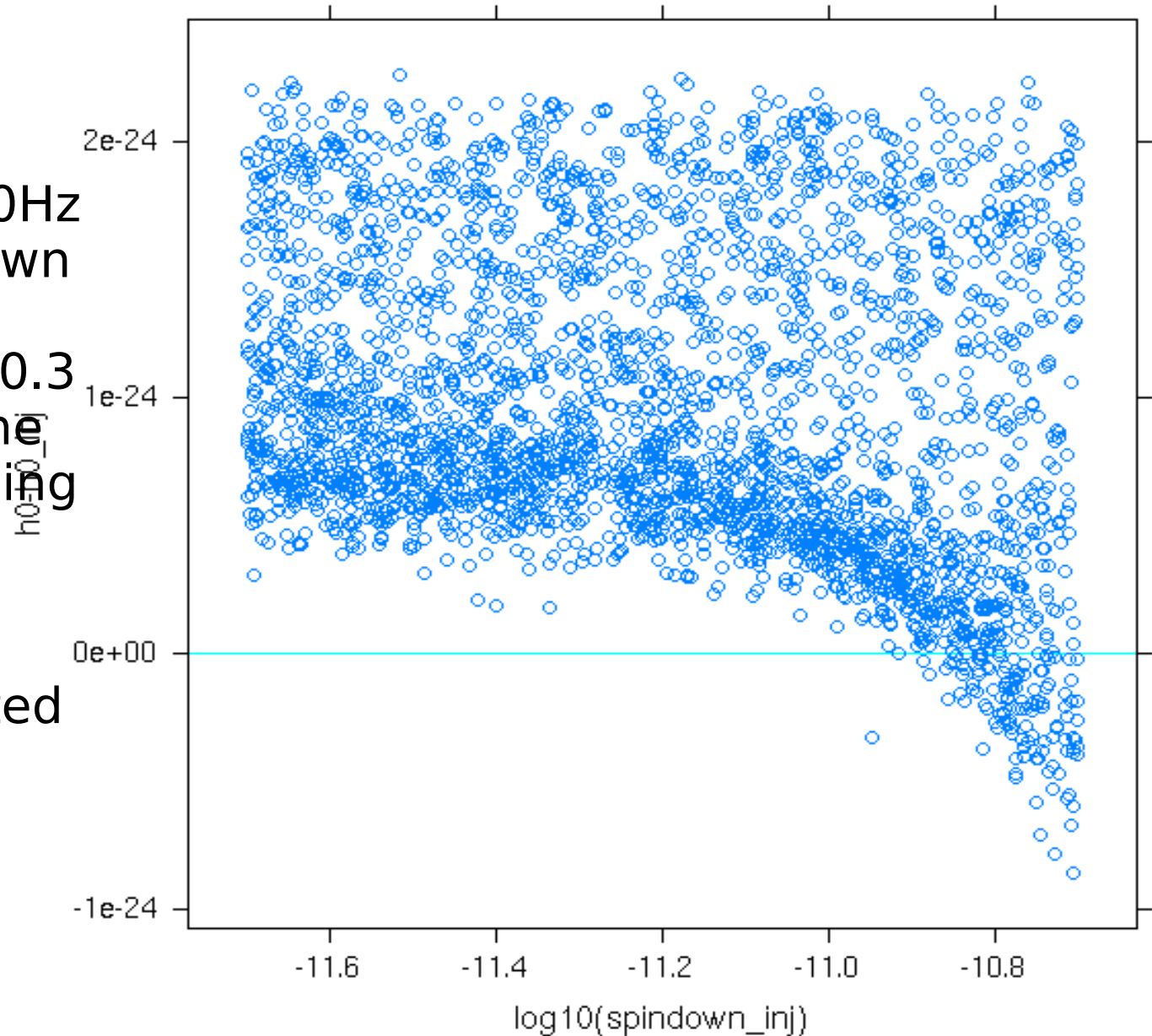
Frequency band	Spin-down		
(Hz)	(Hz s ⁻¹)	H1 SNR	L1 SNR
867.2	-4.3×10^{-9}	6.27	6.30
941.0	-2.0×10^{-9}	6.50	6.67
967.8	-1.5×10^{-9}	6.26	6.33
979.5	-5.0×10^{-9}	6.40	6.29
1058.6	-5.0×10^{-10}	6.83	6.38
1070.2	-3.0×10^{-10}	6.72	6.99

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.

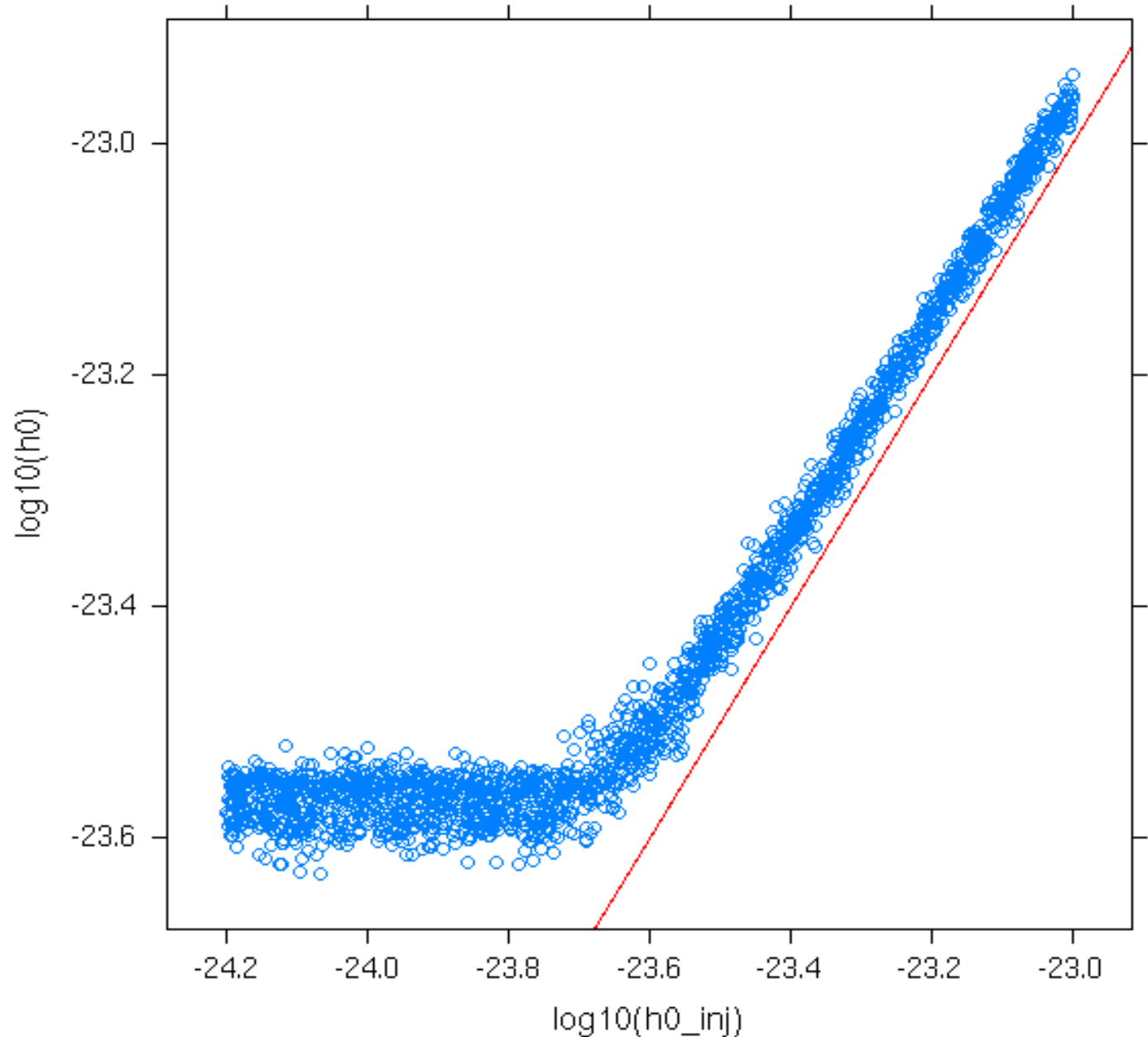
Simulation with gaussian noise

- 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



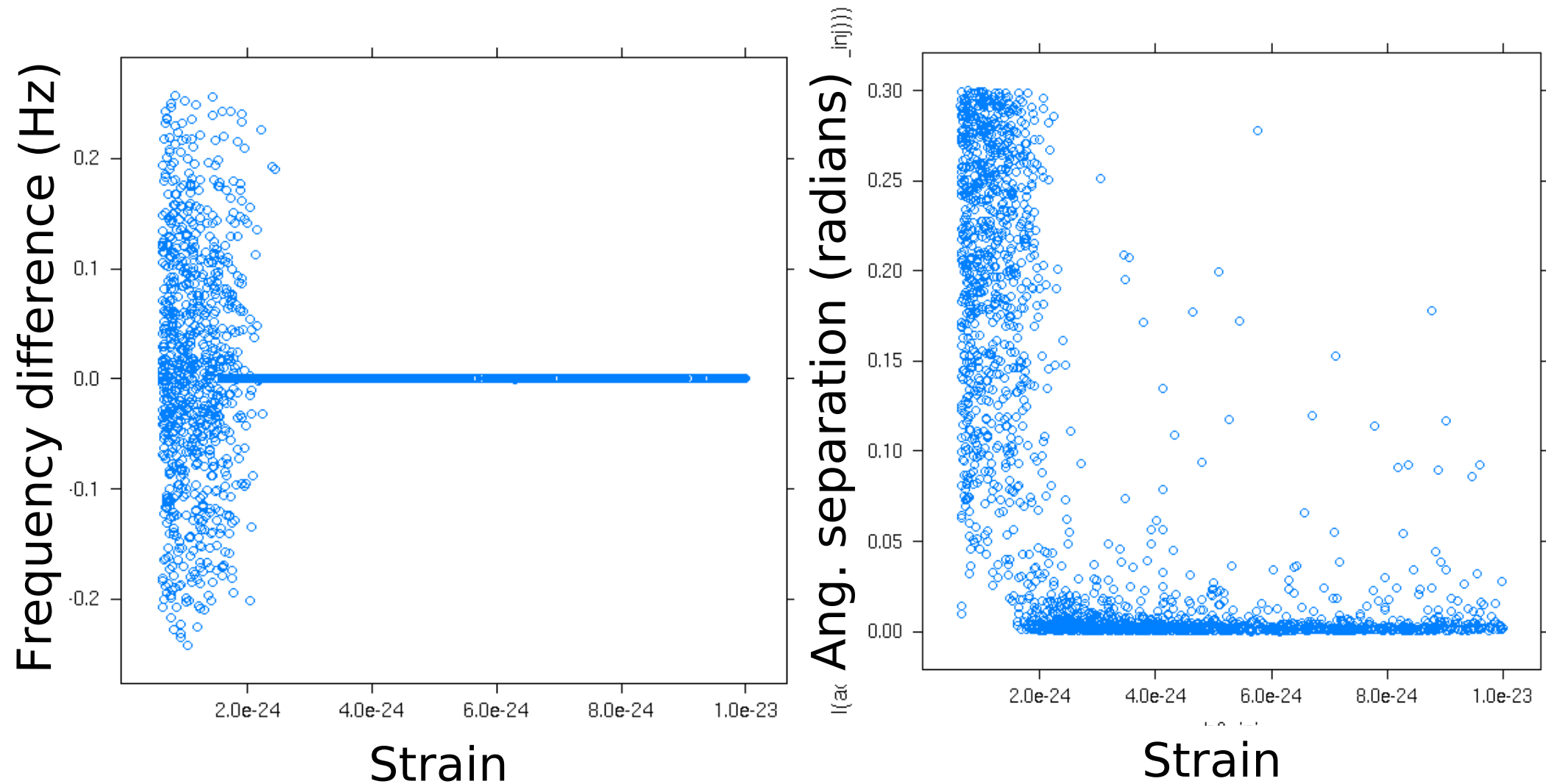
Restricting to small spindowns

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



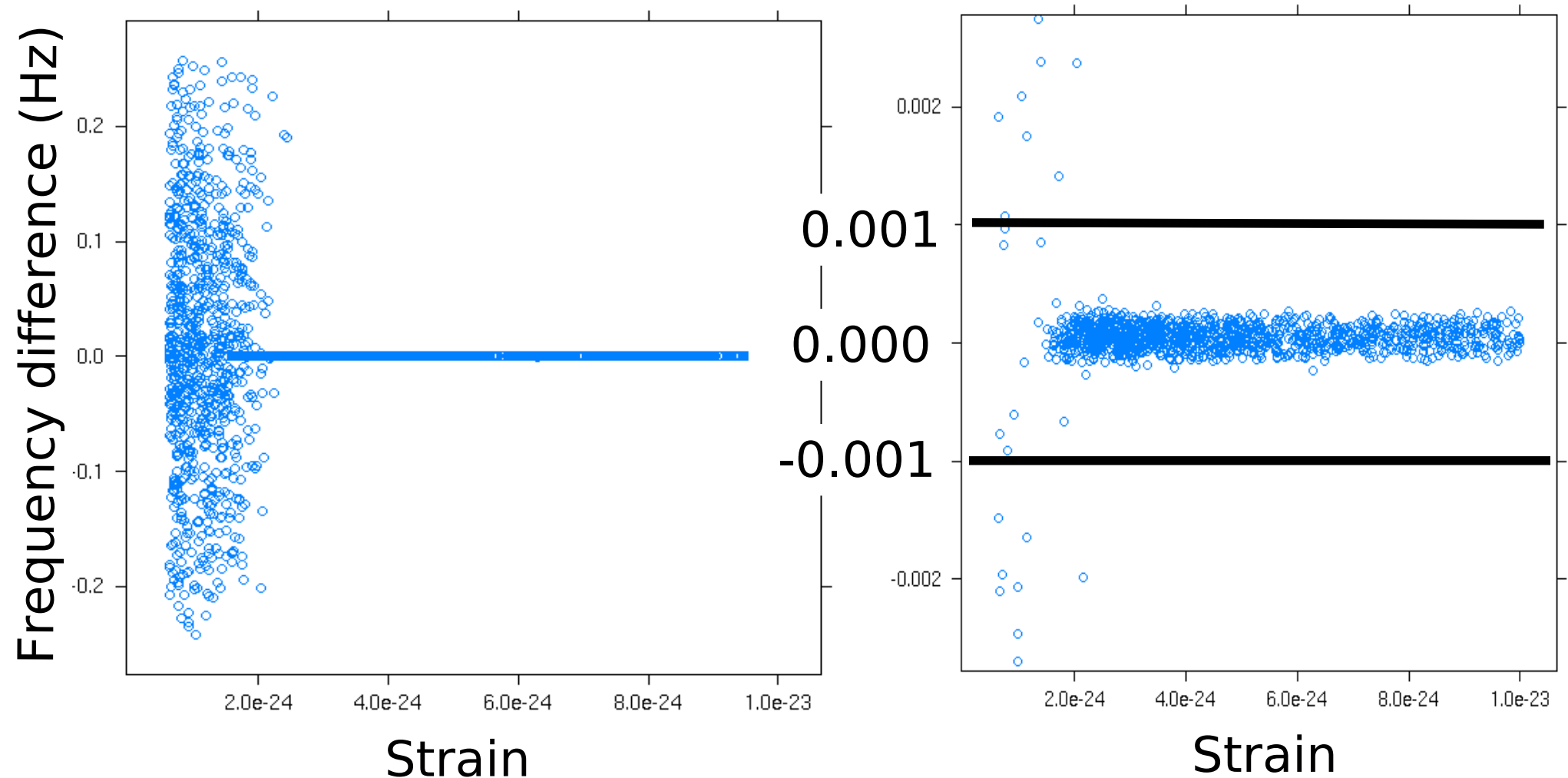
Parameter reconstruction

- 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

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- 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

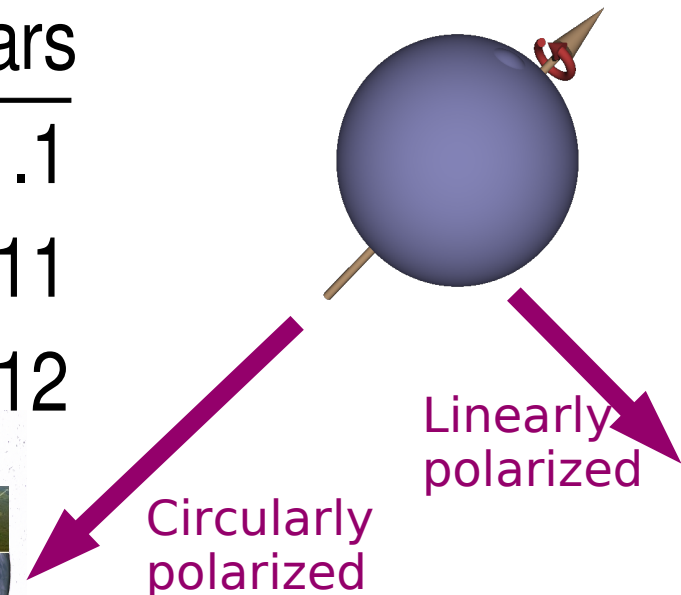
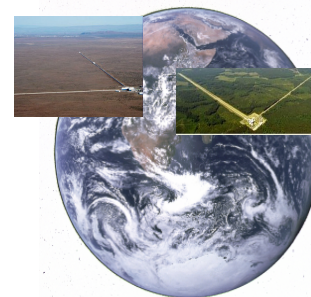
End of talk

(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

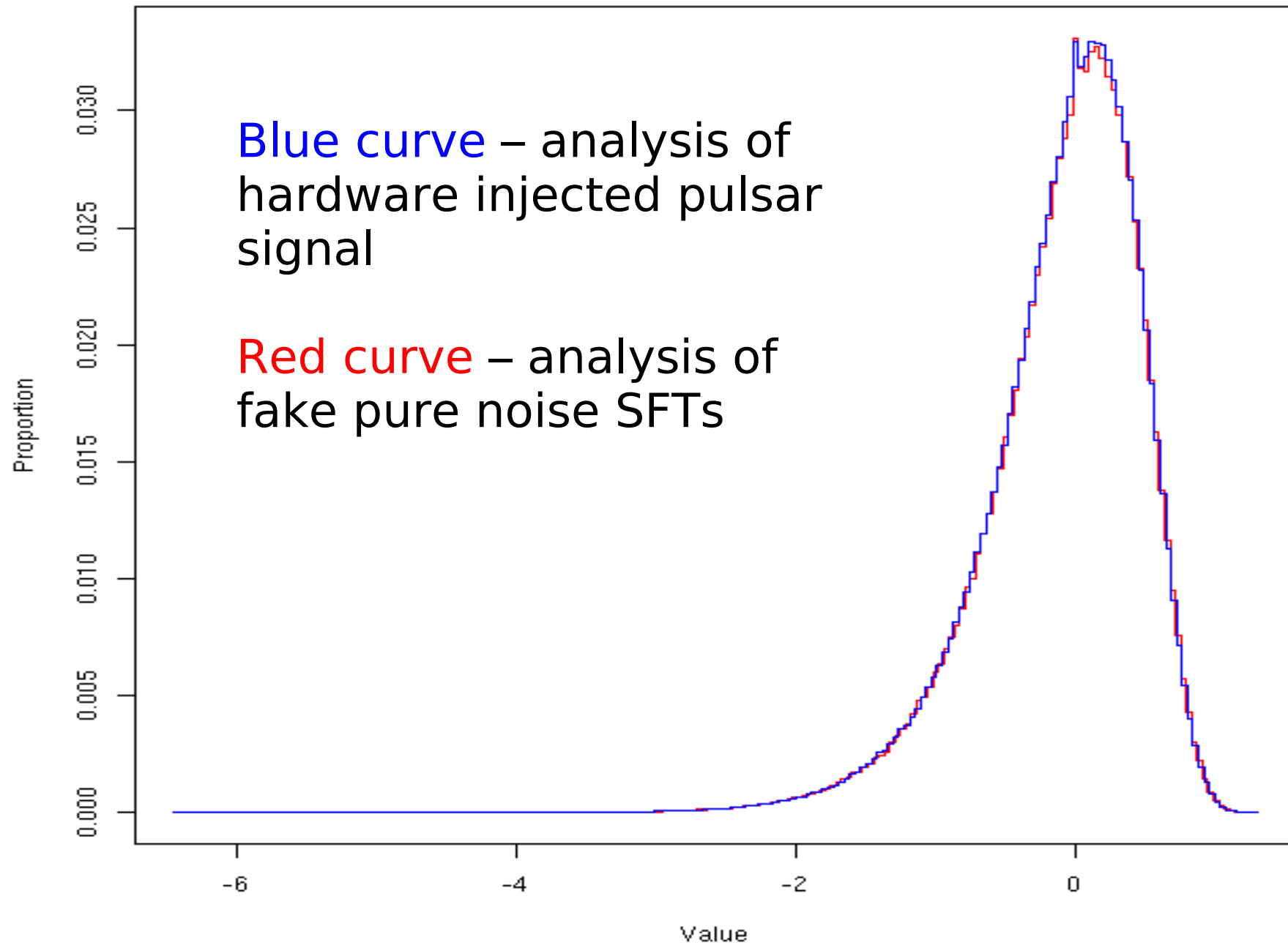
Noise decomposition algorithm

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

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.

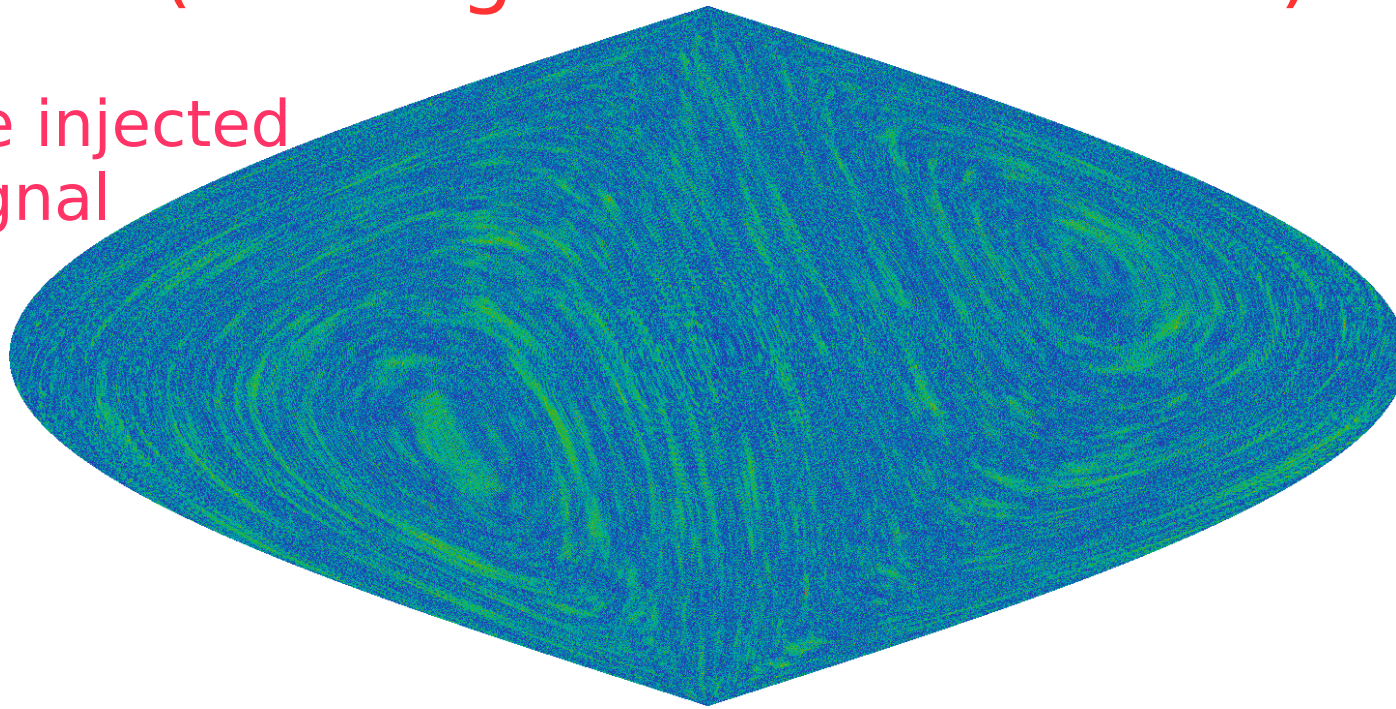
Residuals histograms

Noise decomposition residuals

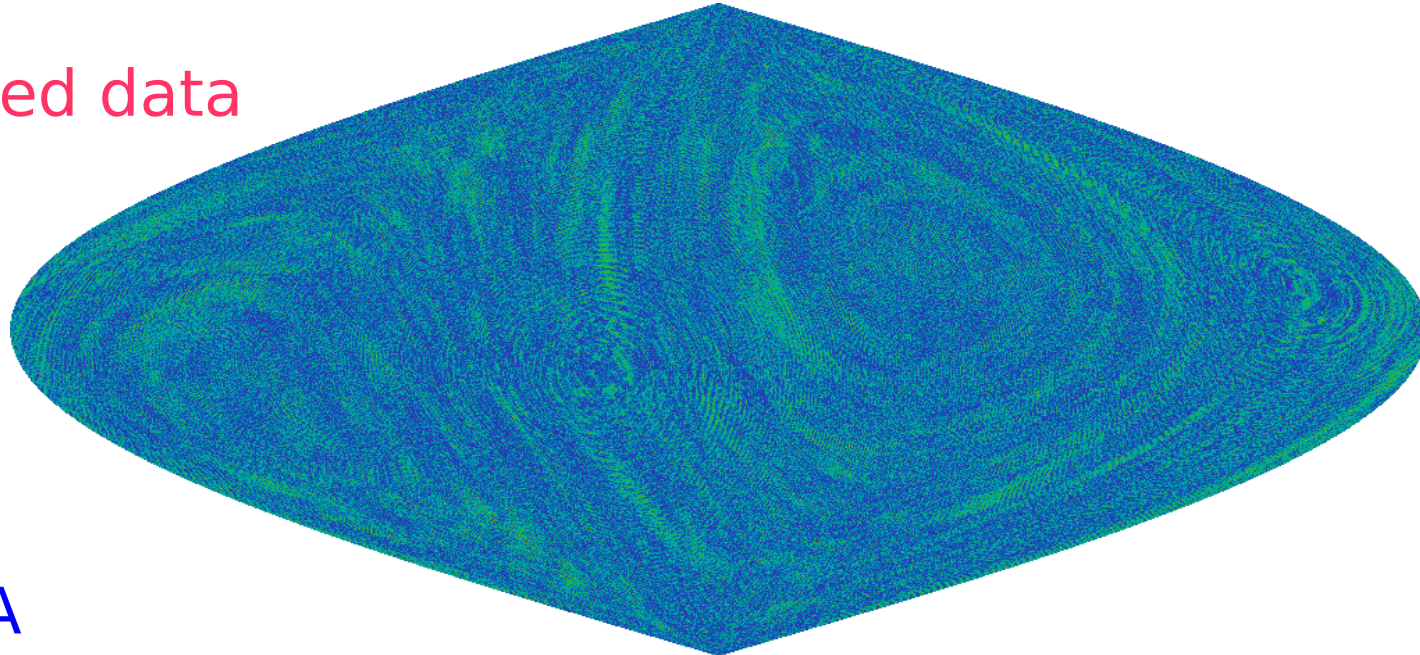


Are averaged powers gaussian ? (Kolmogorov-Smirnov test)

Hardware injected
pulsar signal



Simulated data



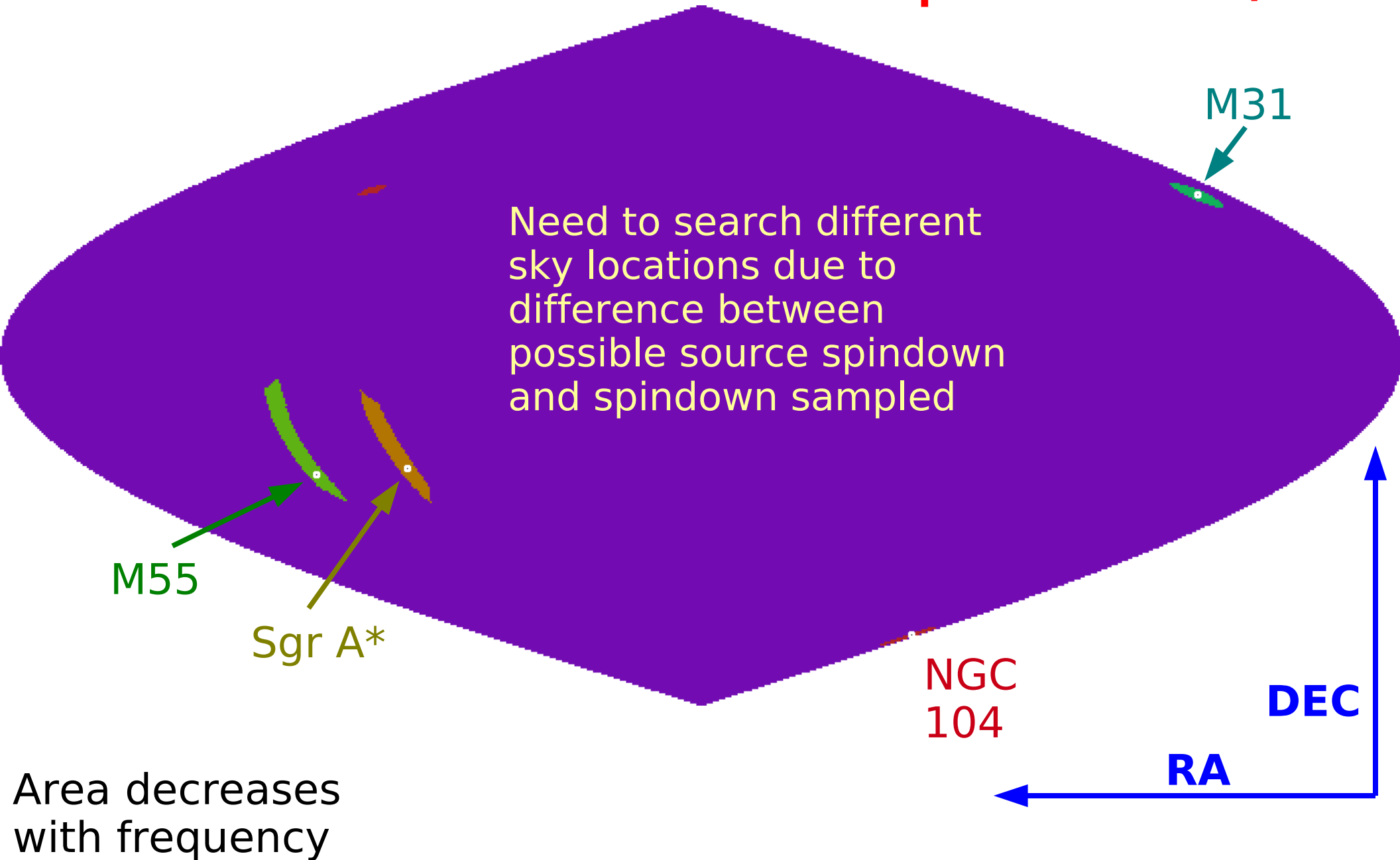
RA

DEC

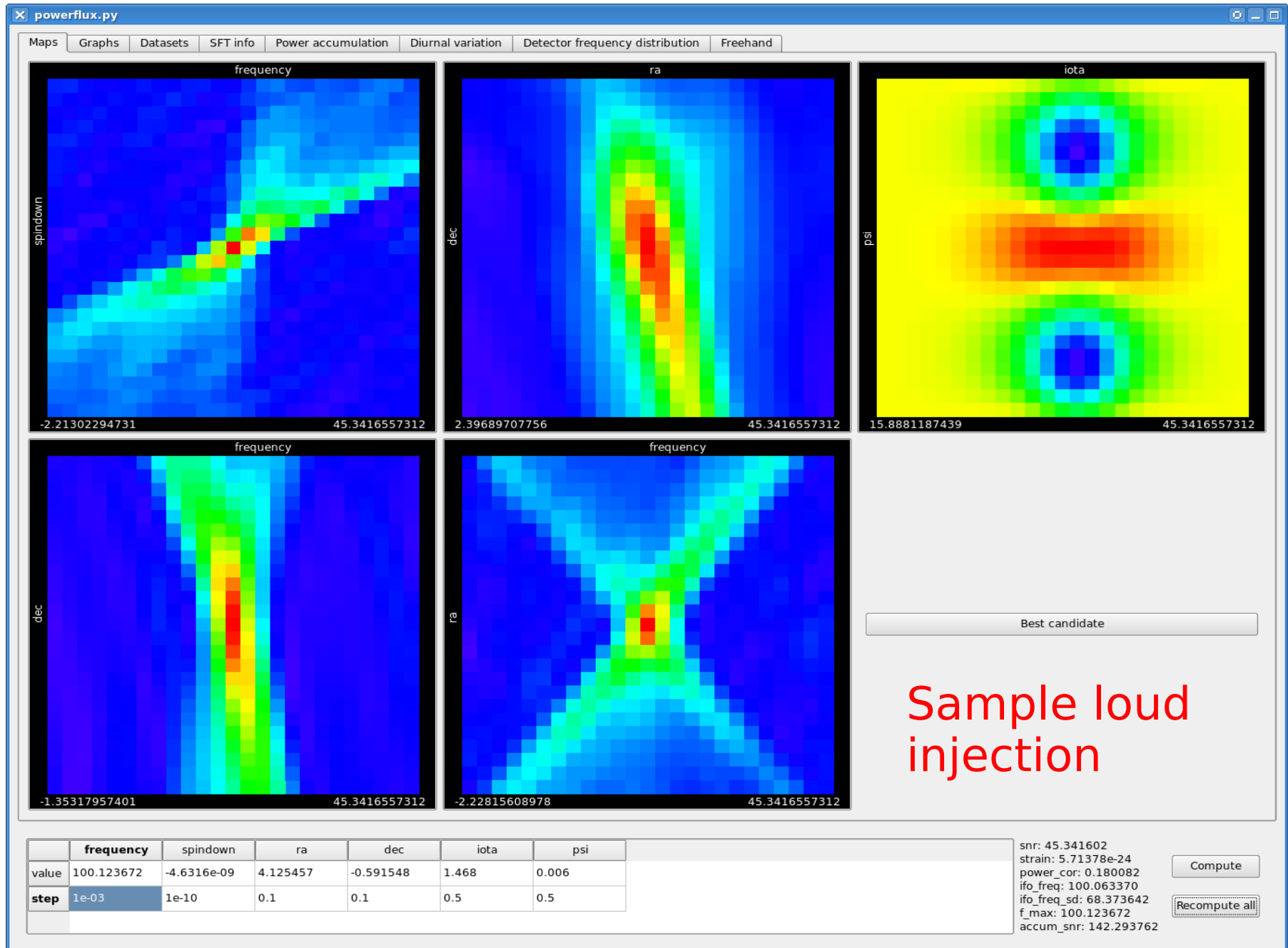
Sky partitioning

- 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.

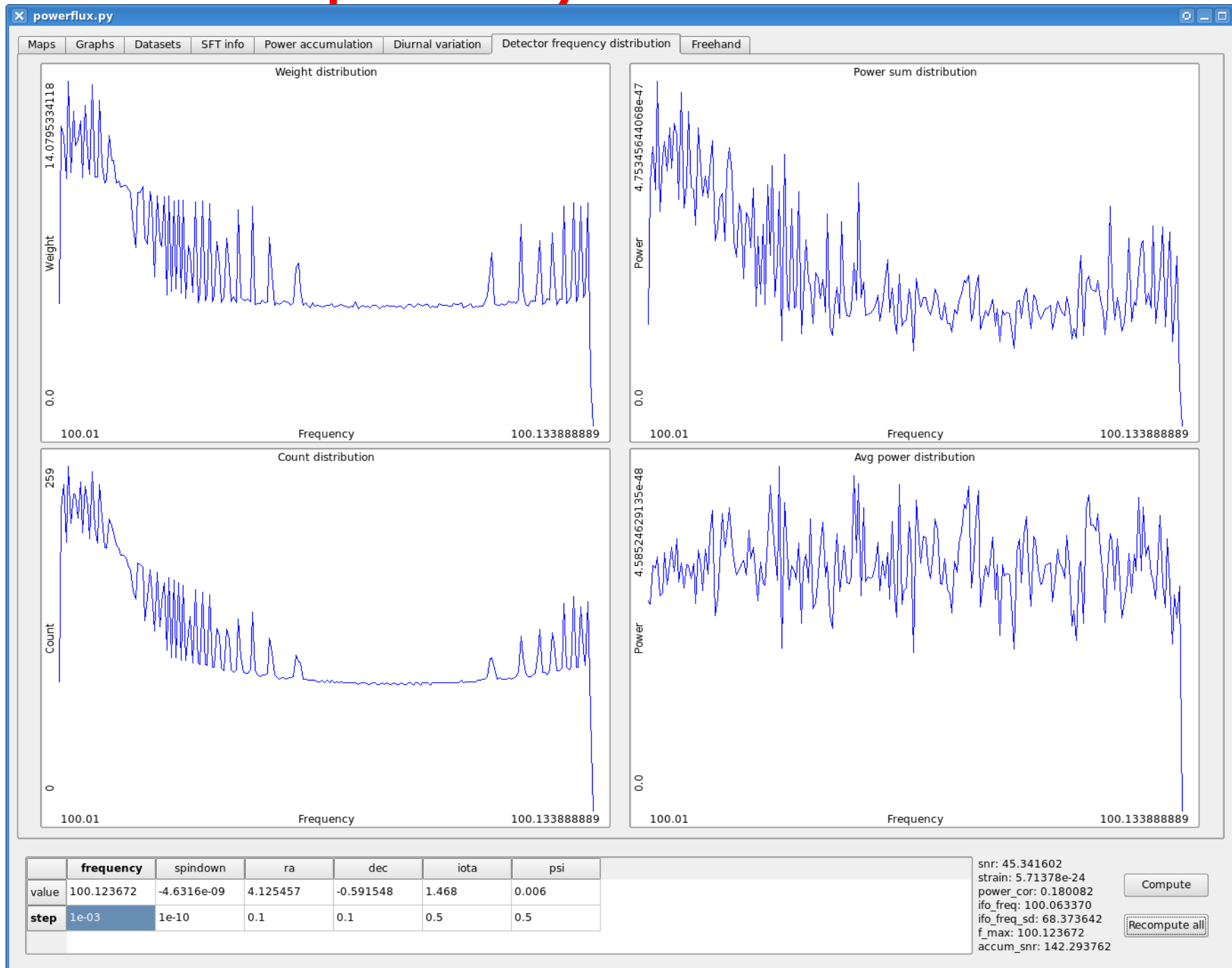
Targeted search example (for ~270 Hz, non-zero spindown)



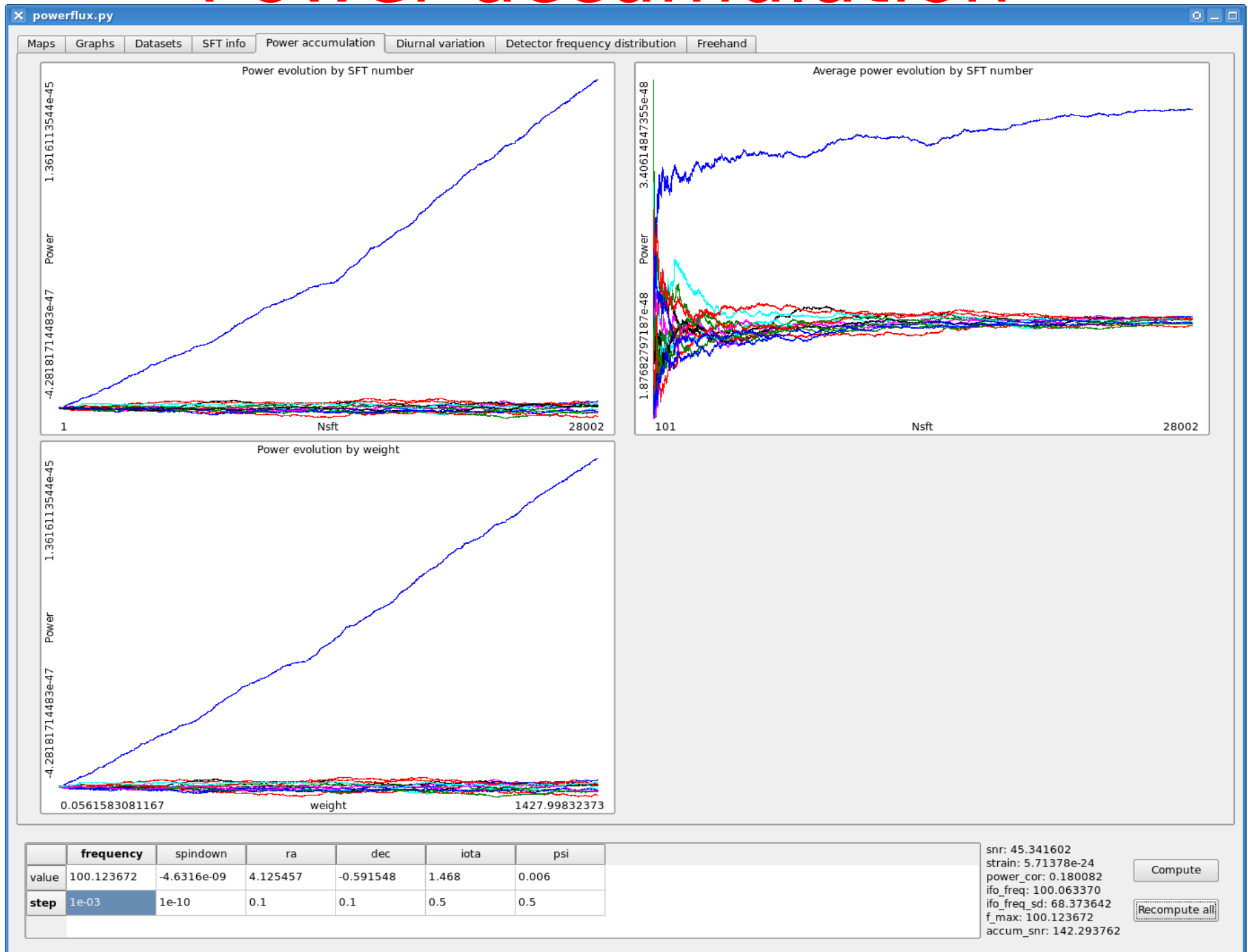
Interactive interface



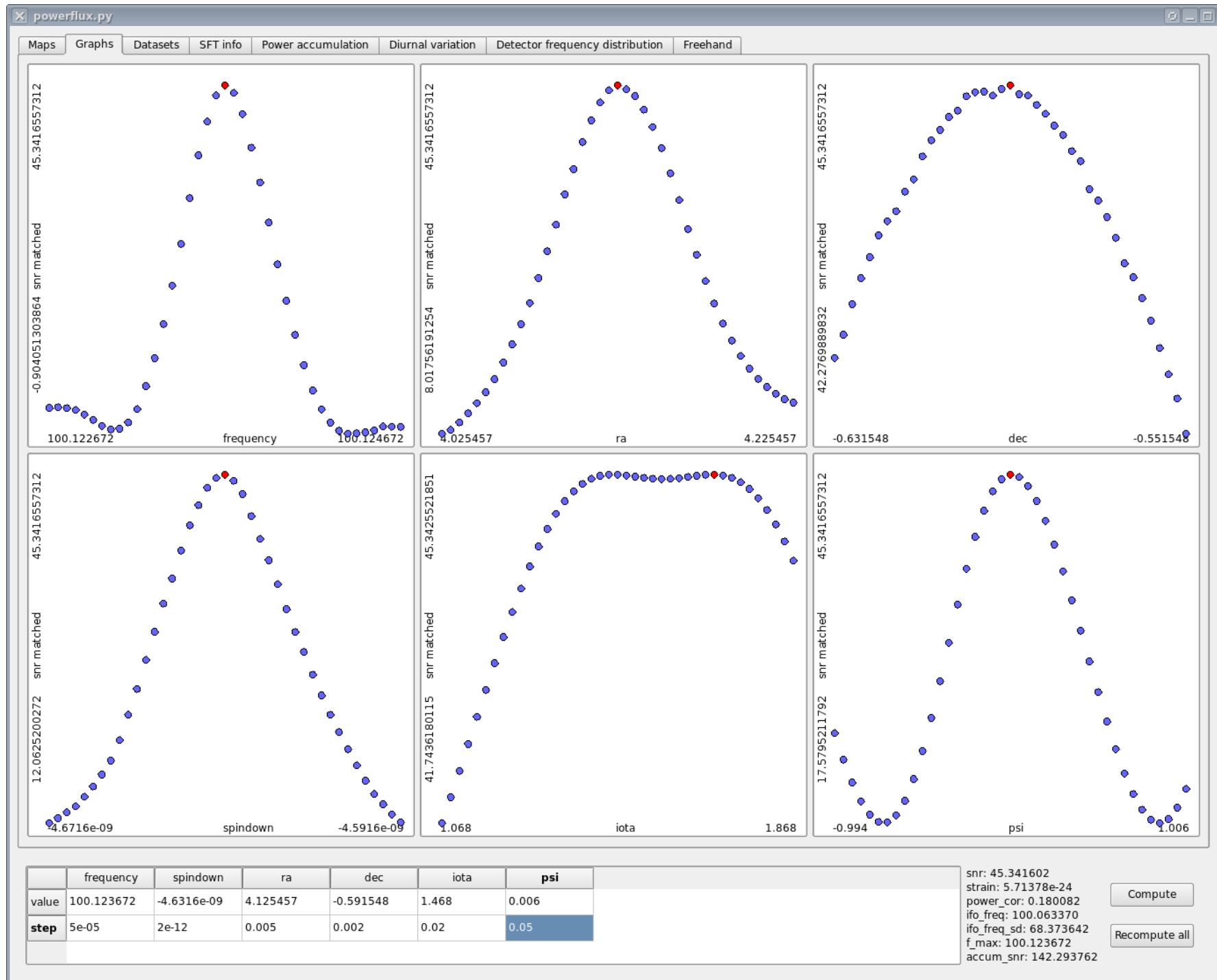
Frequency distribution



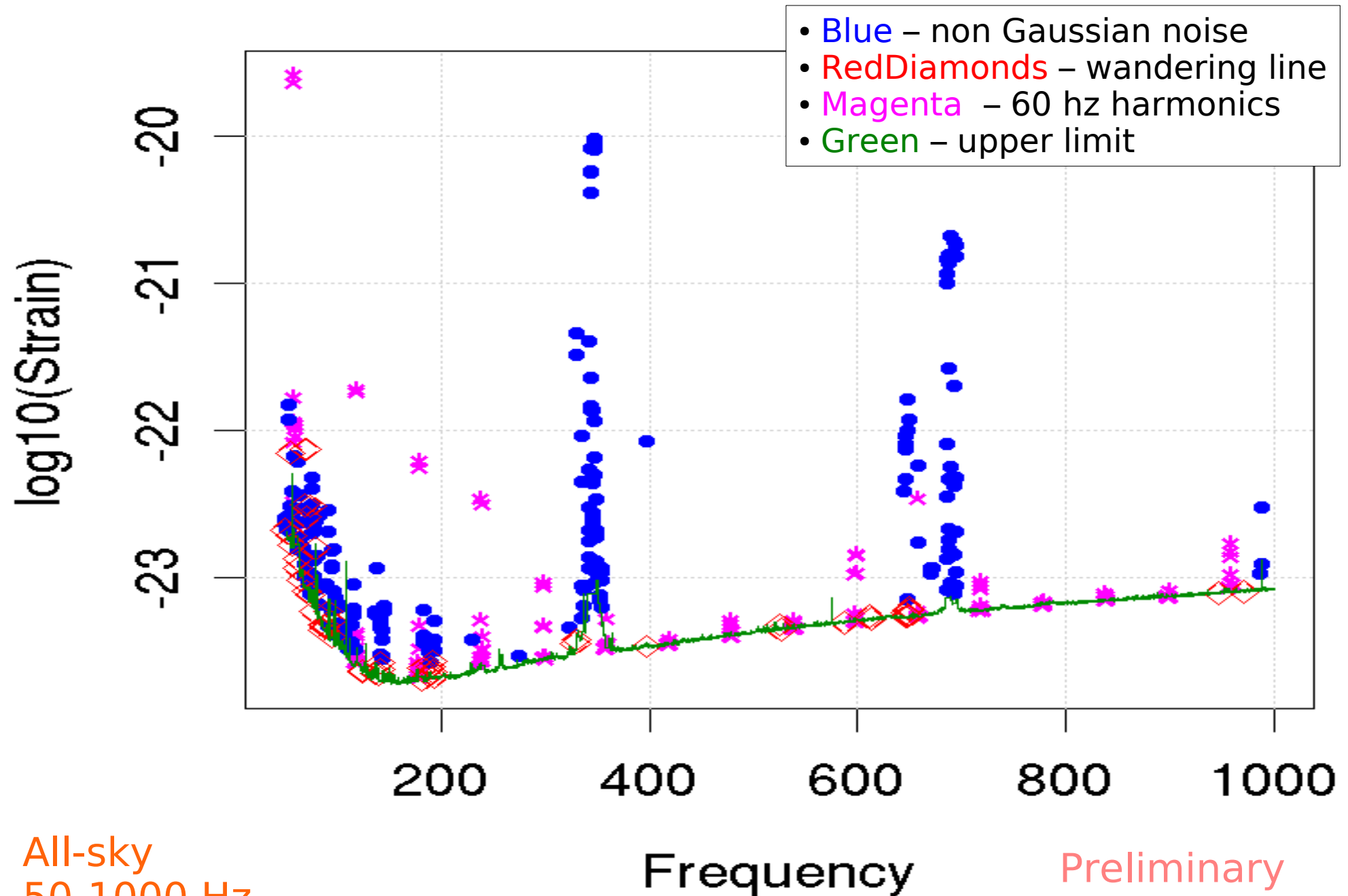
Power accumulation



Graphs



L1 S5 0-spindown run



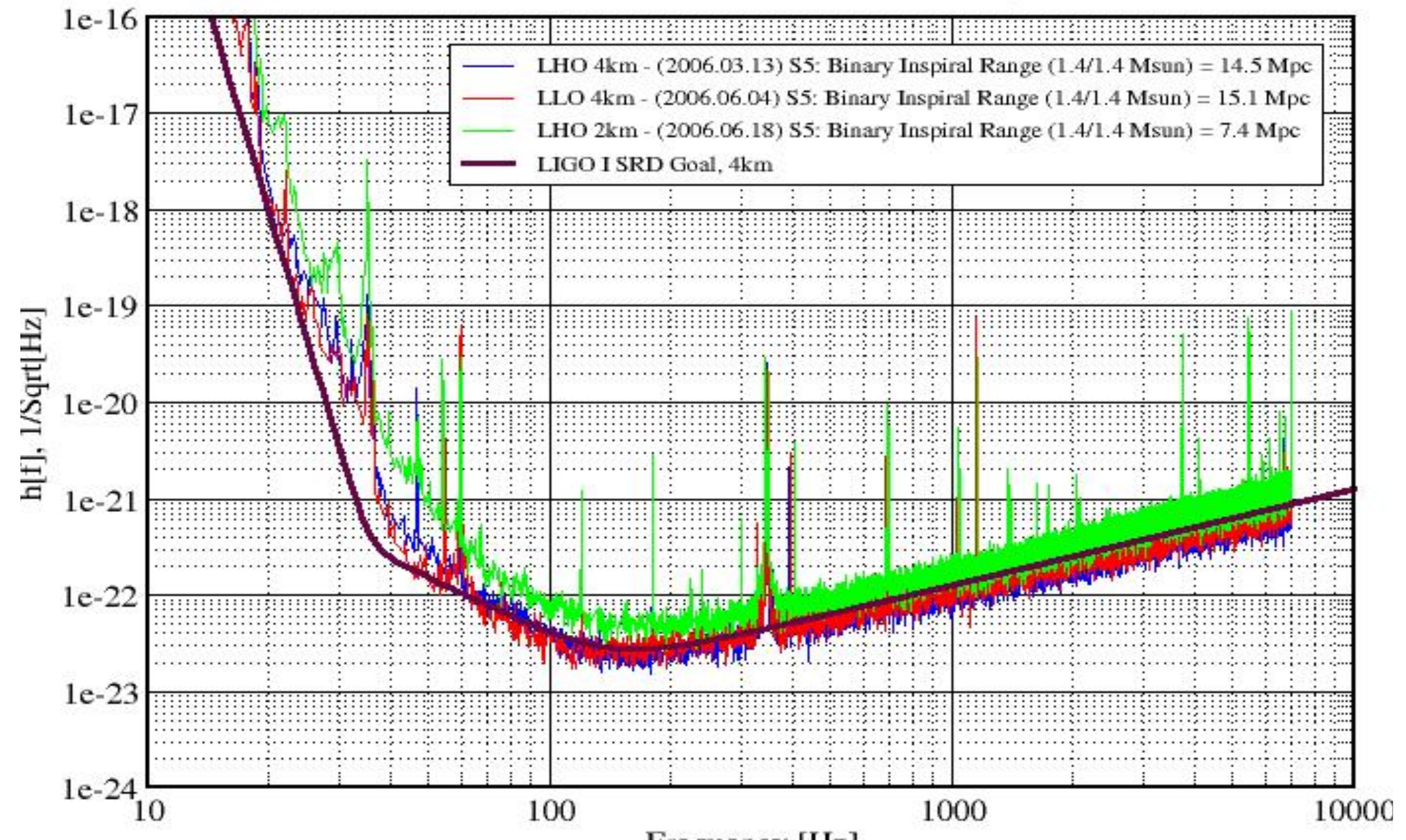
All-sky
50-1000 Hz

Preliminary
results

S5 science run sensitivity

S5 Performance - June 2006

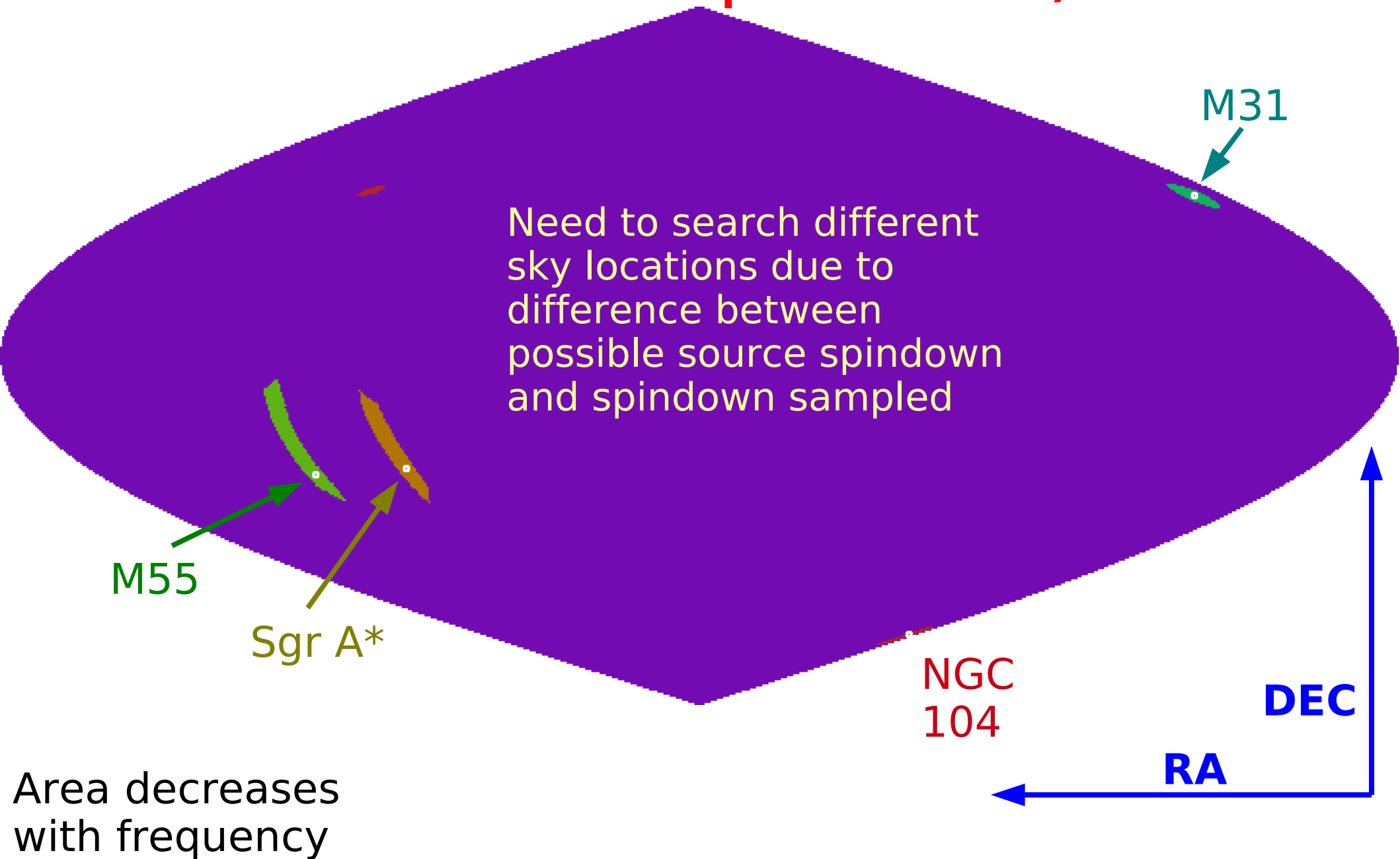
LIGO-G060293-01-Z



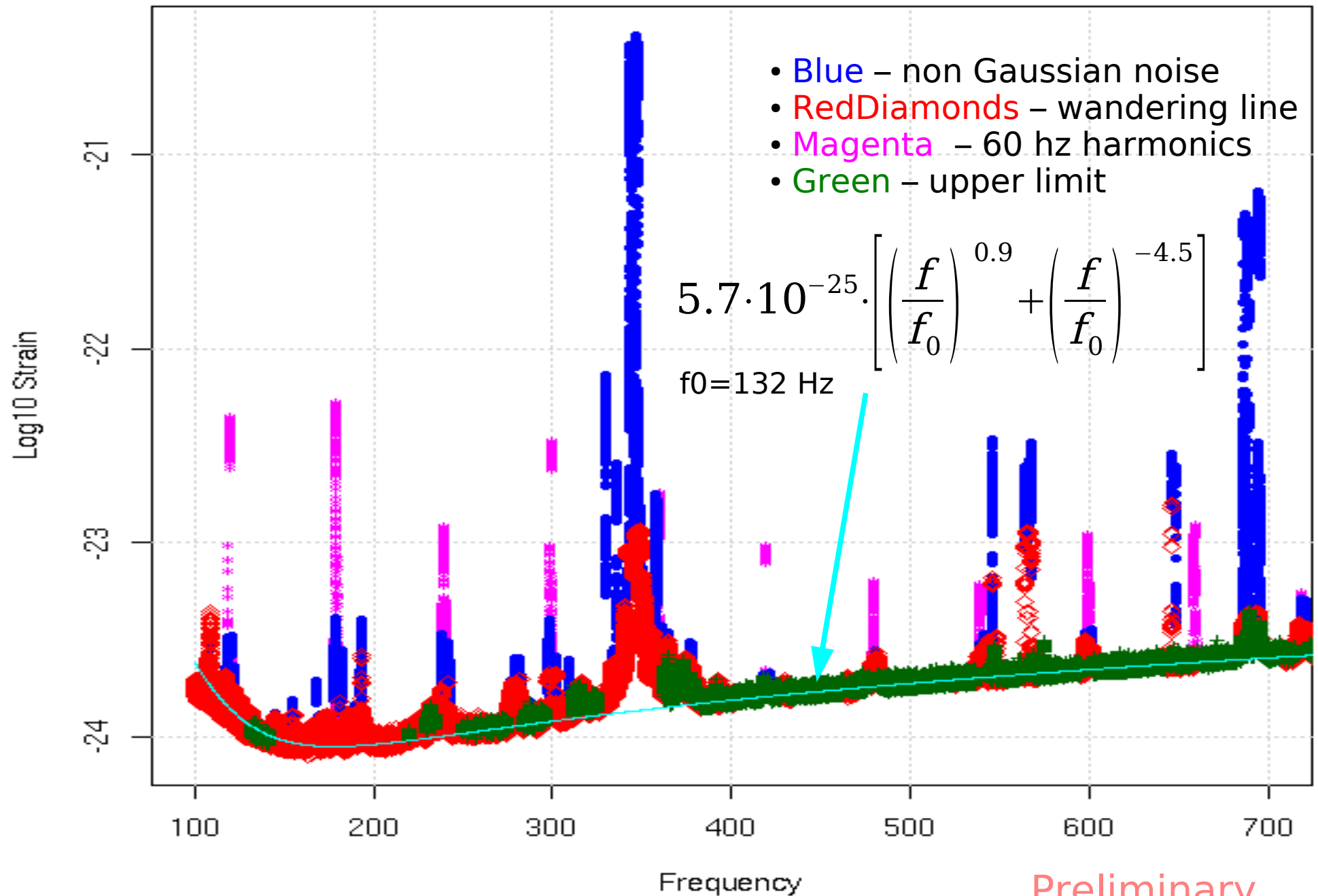
Partial sky (targeted) run

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

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



H1 Sgr A* upper limits

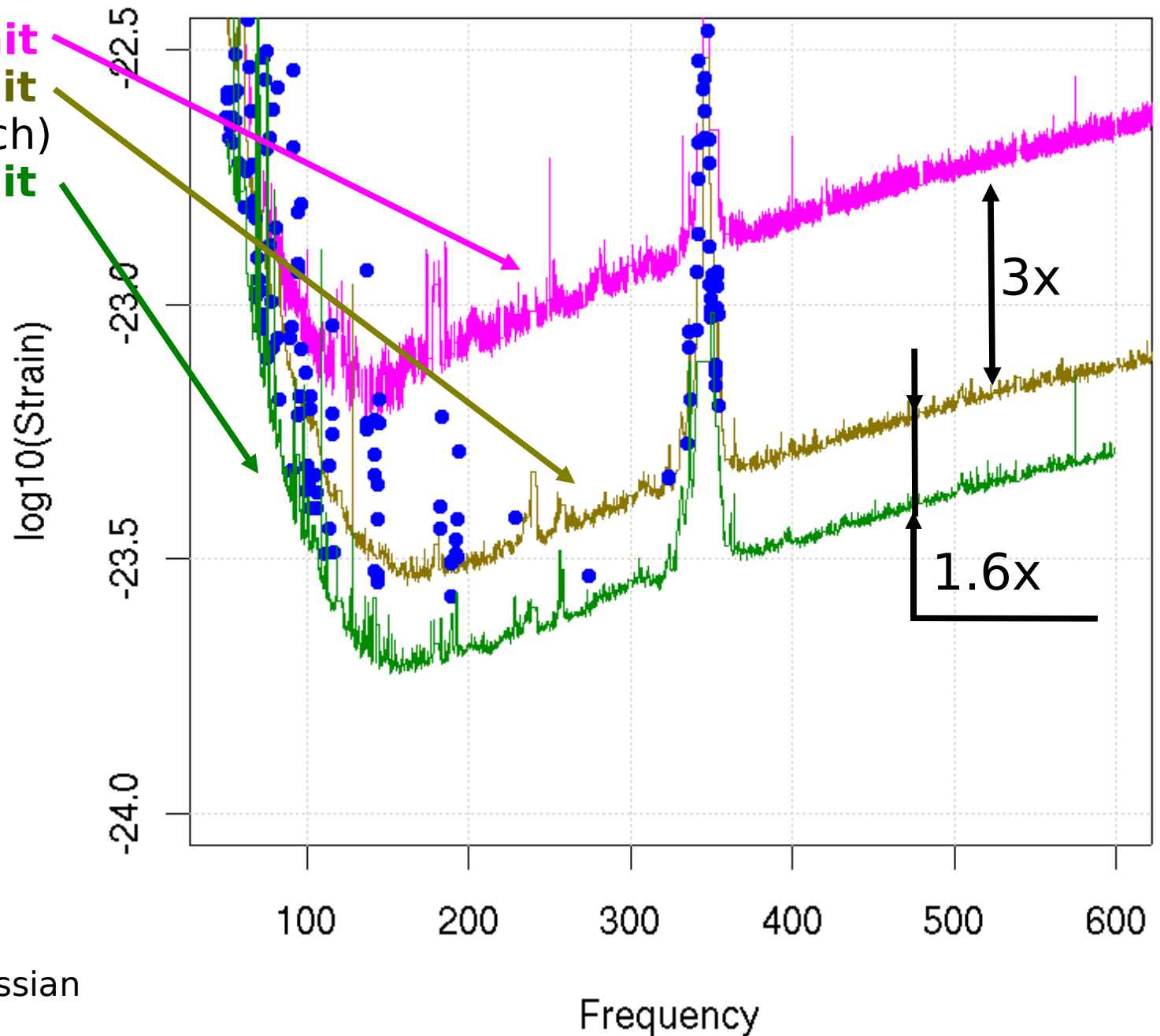


Preliminary
results

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

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

Average detector acceleration

Average detector velocity

Spindown (Hz/s)

Earth orbit angular velocity

Frequency

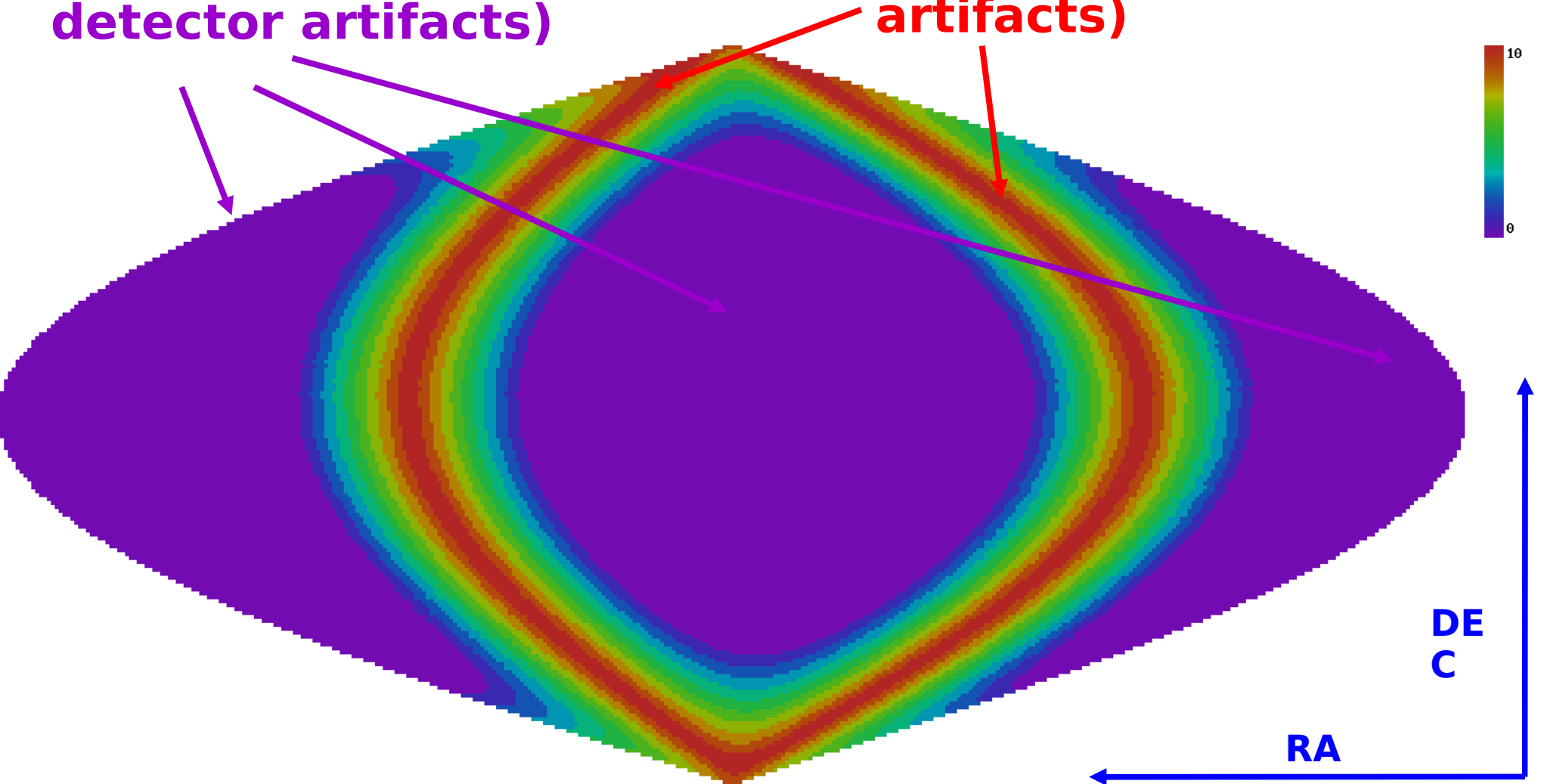
Unit sky position vector

The diagram shows the equation $S := s + \frac{\vec{u} \times \vec{v}_{\text{avg}}}{c} f \cdot \hat{r}$. Green arrows point from descriptive text labels to the variables in the equation: 'Spindown (Hz/s)' points to s ; 'Earth orbit angular velocity' points to $\vec{u}$; 'Average detector acceleration' points to the cross product $\vec{u} \times \vec{v}_{\text{avg}}$; 'Average detector velocity' points to $\vec{v}_{\text{avg}}$; 'Frequency' points to f ; and 'Unit sky position vector' points to $\hat{r}$. A green bracket is also placed over the cross product term.

Doppler Skybands

Skyband 0 (good – only exceptionally strong detector artifacts)

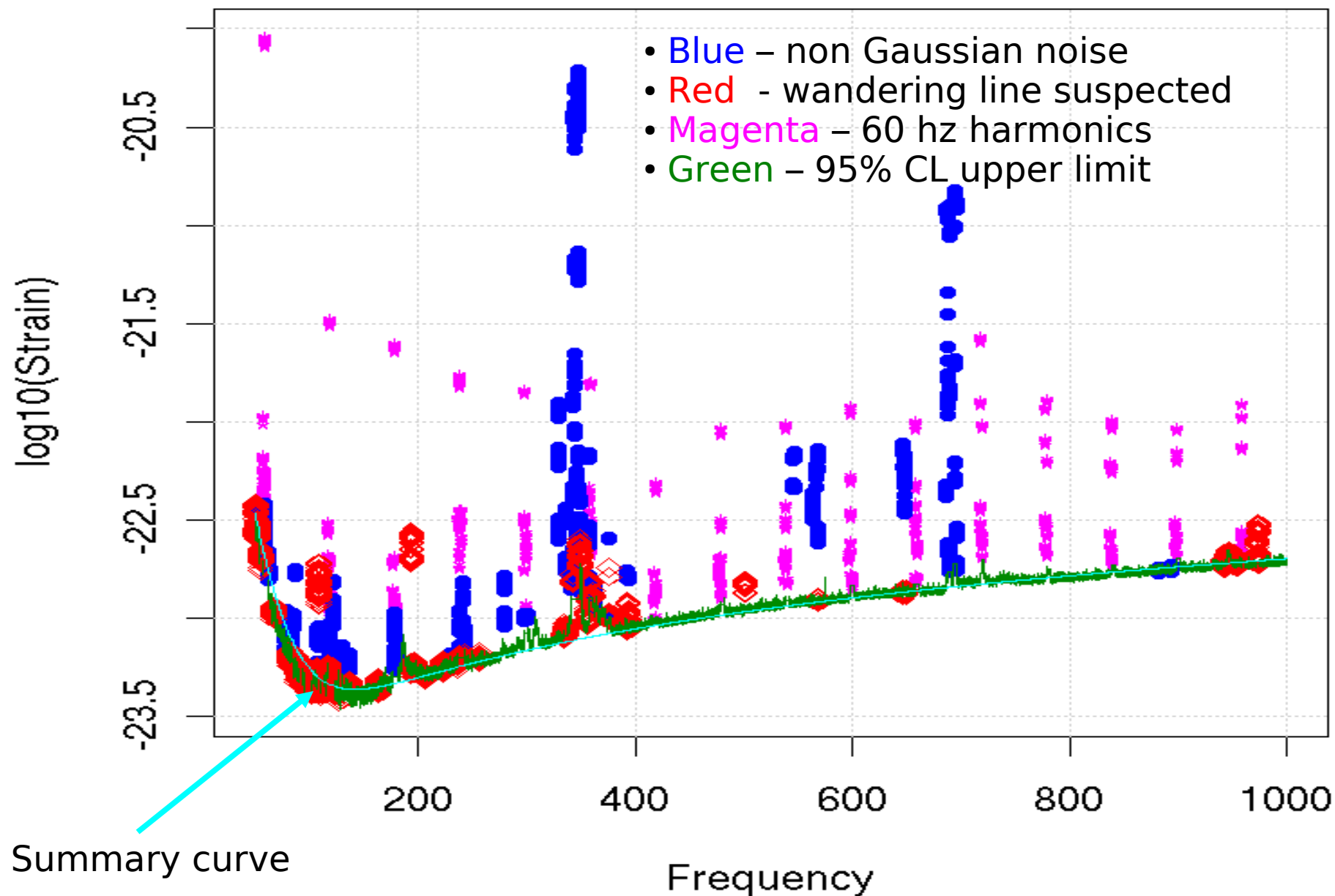
Skyband 10 (worst – many detector artifacts)



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

S4 run results

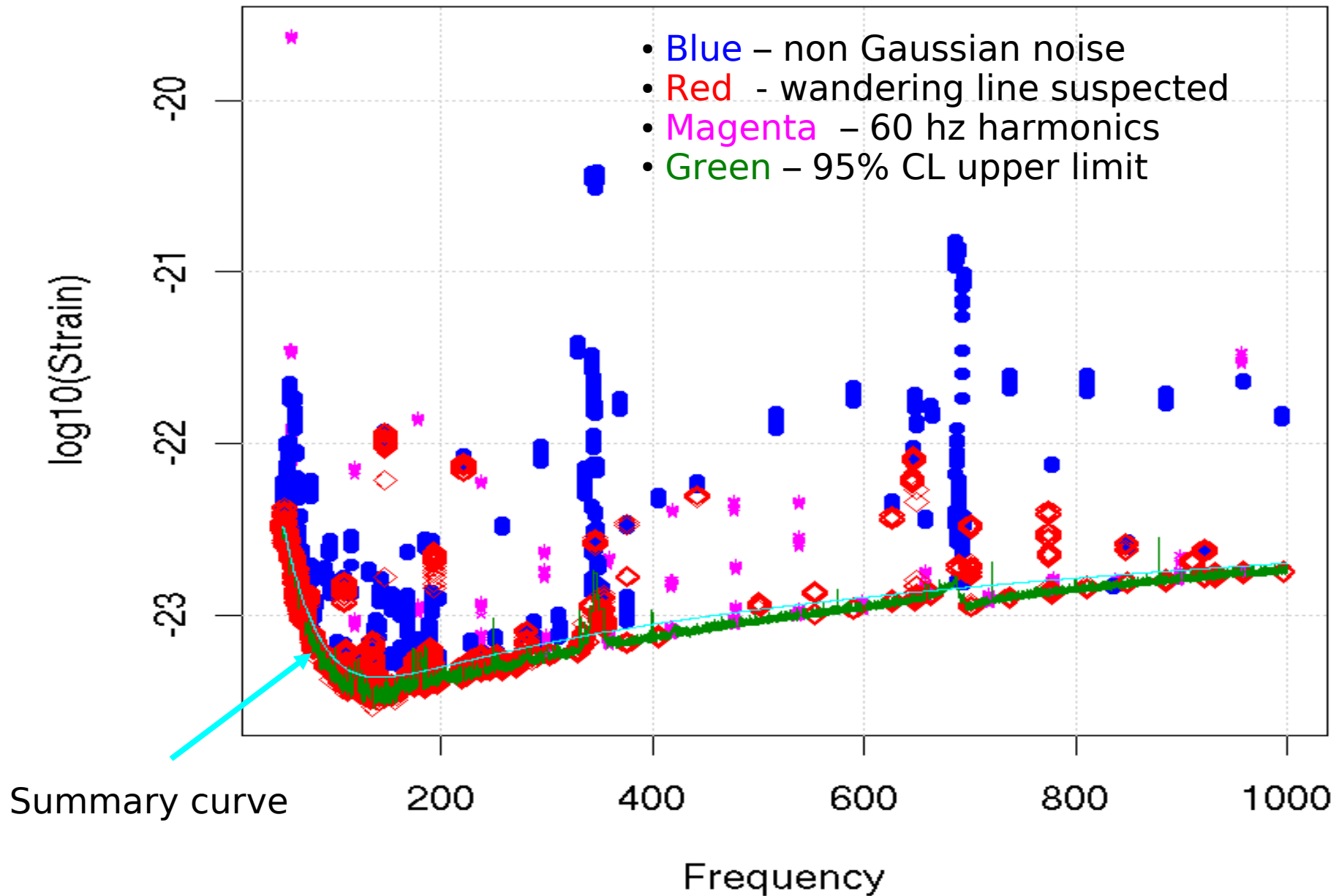
Hanford 4km



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

S4 run results

Livingston 4km



S5 summary curve deviation

