



Broadband Search for Continuous-Wave Gravitation Radiation with LIGO

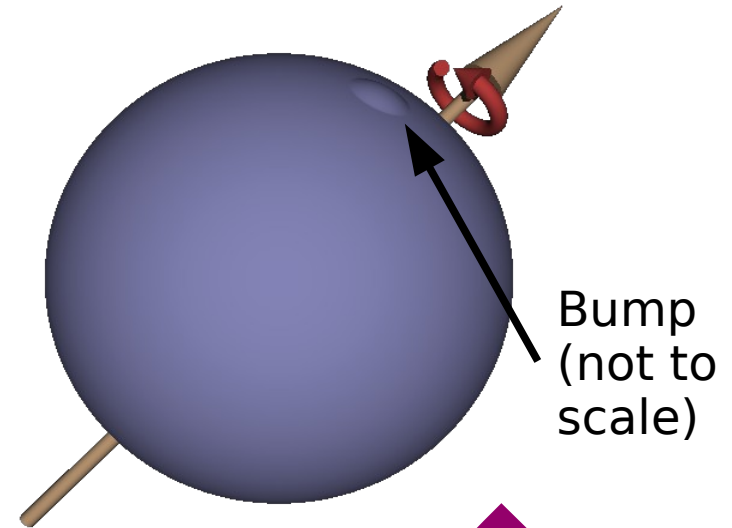
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(Caltech)

for the LIGO Scientific Collaboration and the
Virgo Collaboration

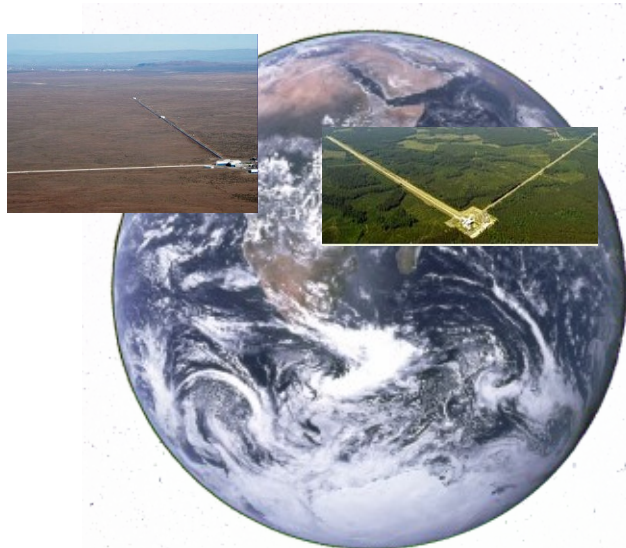
Continuous gravitational waves

- 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



Bump
(not to
scale)



Circularly polarized
gravitational waves

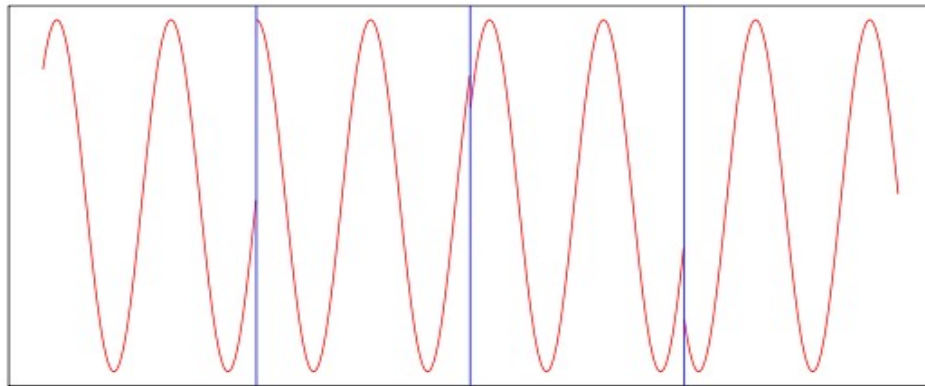
Linearly
polarized
gravitational
waves

Known neutron stars

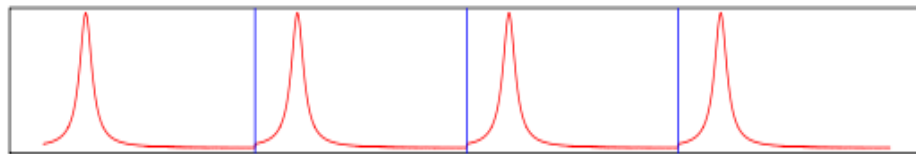
- There are over 2000 known neutron stars, with estimates of $1e8$ to $1e9$ in our galaxy.
- PSR J0108-1431 – 130 parsecs away.
- PSR B1508+55 – 1100 km/s velocity.
- PSR J1748-2446ad – rotation frequency of 716 Hz (if gravitational waves are emitted they will likely be at 1432 Hz).
- PSR B1257+12 has three planets, closest at 0.19 AU.
- PSR B1620-26 has a 2.5 Jupiter mass planet that orbits both it and a white dwarf companion.
- What else is out there ?

Detection methods

Semi-coherent



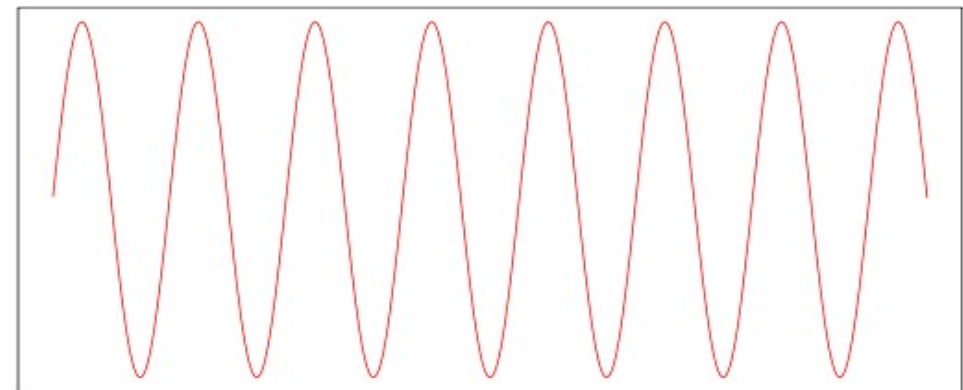
Time



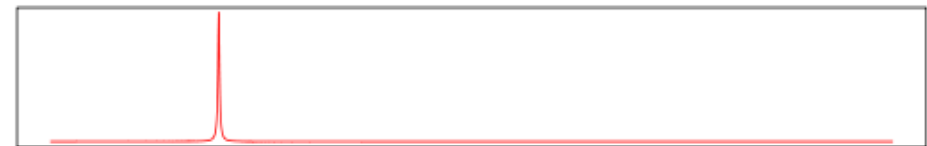
Frequency

- Chop data into equal size (30 min) chunks
- Sum powers from all chunk
- Ignores phase information between chunks
- Sensitivity scales $1/T^{0.25}$
- CPU cycles scale as T^4

Coherent



Time



Frequency

- Use matched filter to achieve high sensitivity
- Need to know exact signal form
- Sensitivity scales as $1/T^{0.5}$
- CPU cycles scale as T^6 or faster

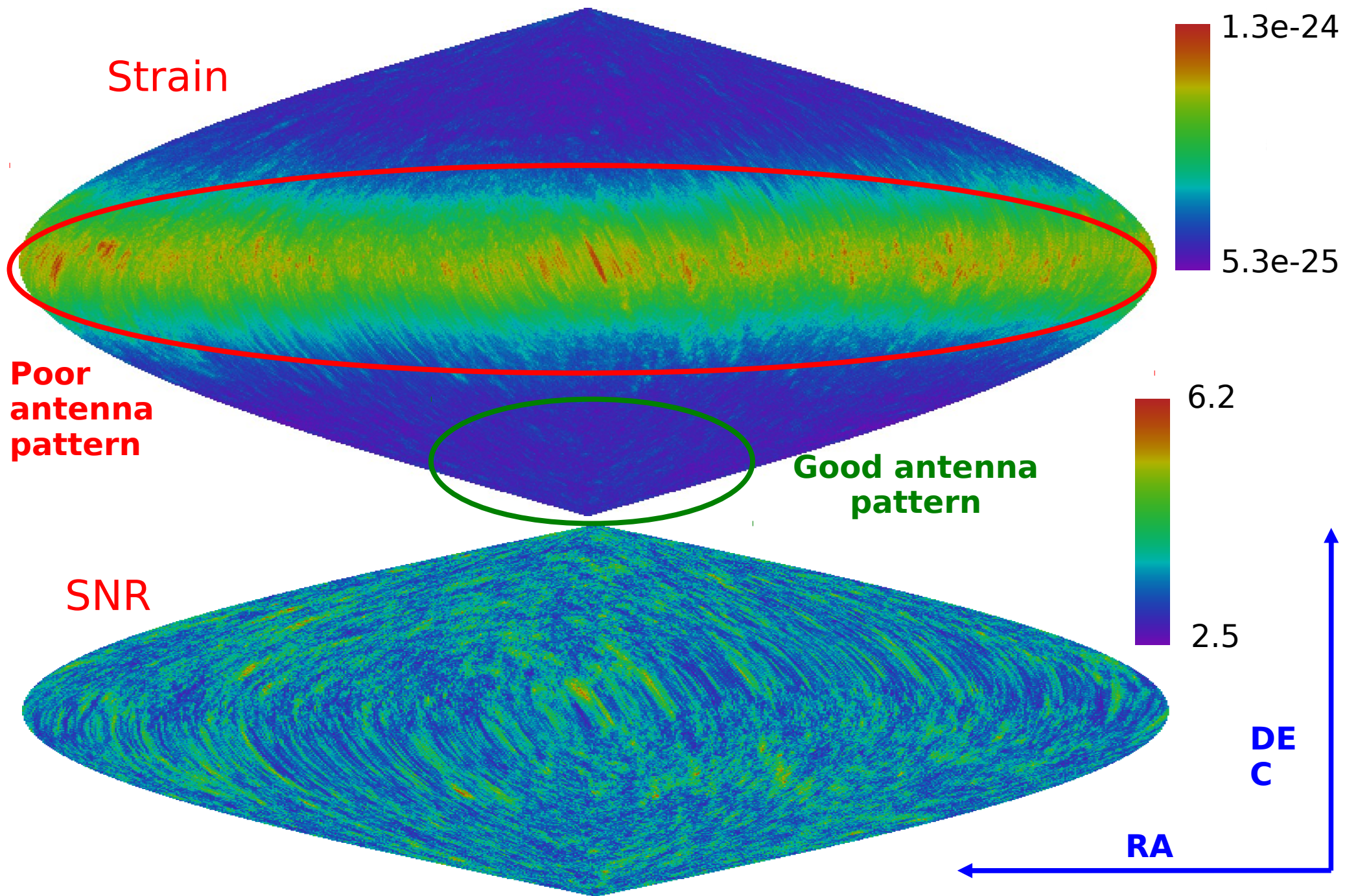
Challenges of search for CW gravitational waves

- 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 results

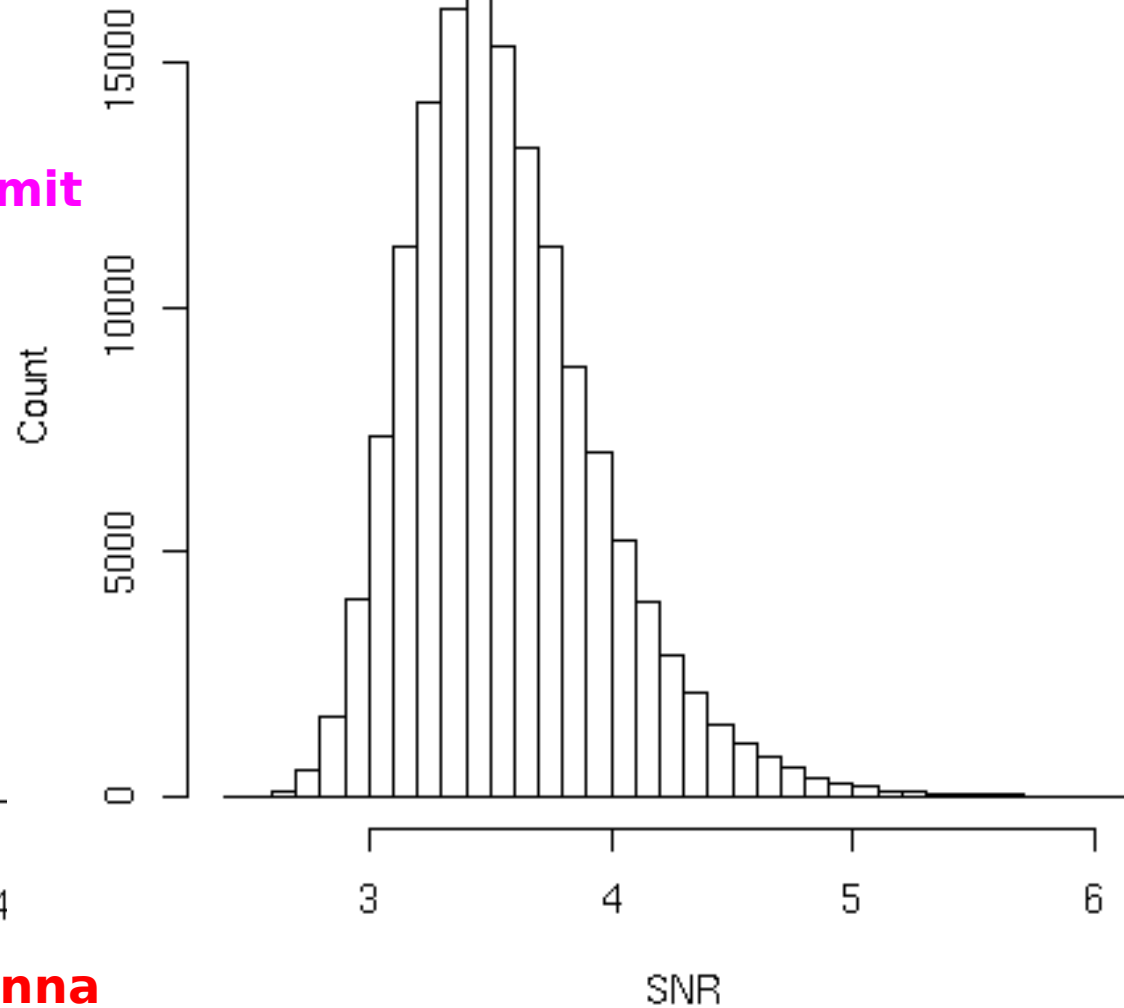
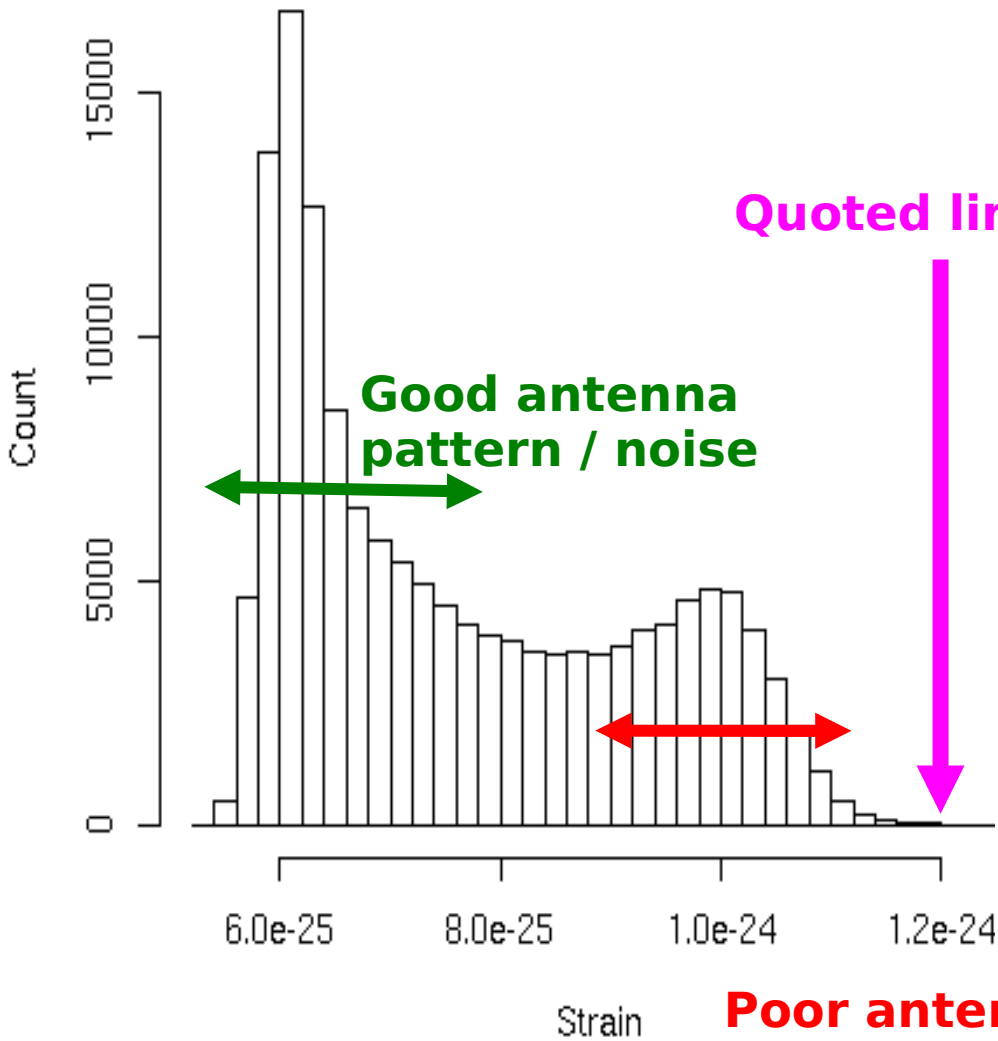
- PowerFlux produces a 95% CL upper limit for a particular frequency, sky position, spindown and polarization. One of three methods used in S4 all-sky search (arXiv:0708.3818 = Phys. Rev. D 77 (2008) 022001)
- Too much data to store, let alone present – the number of sky positions alone is $\sim 10^5$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

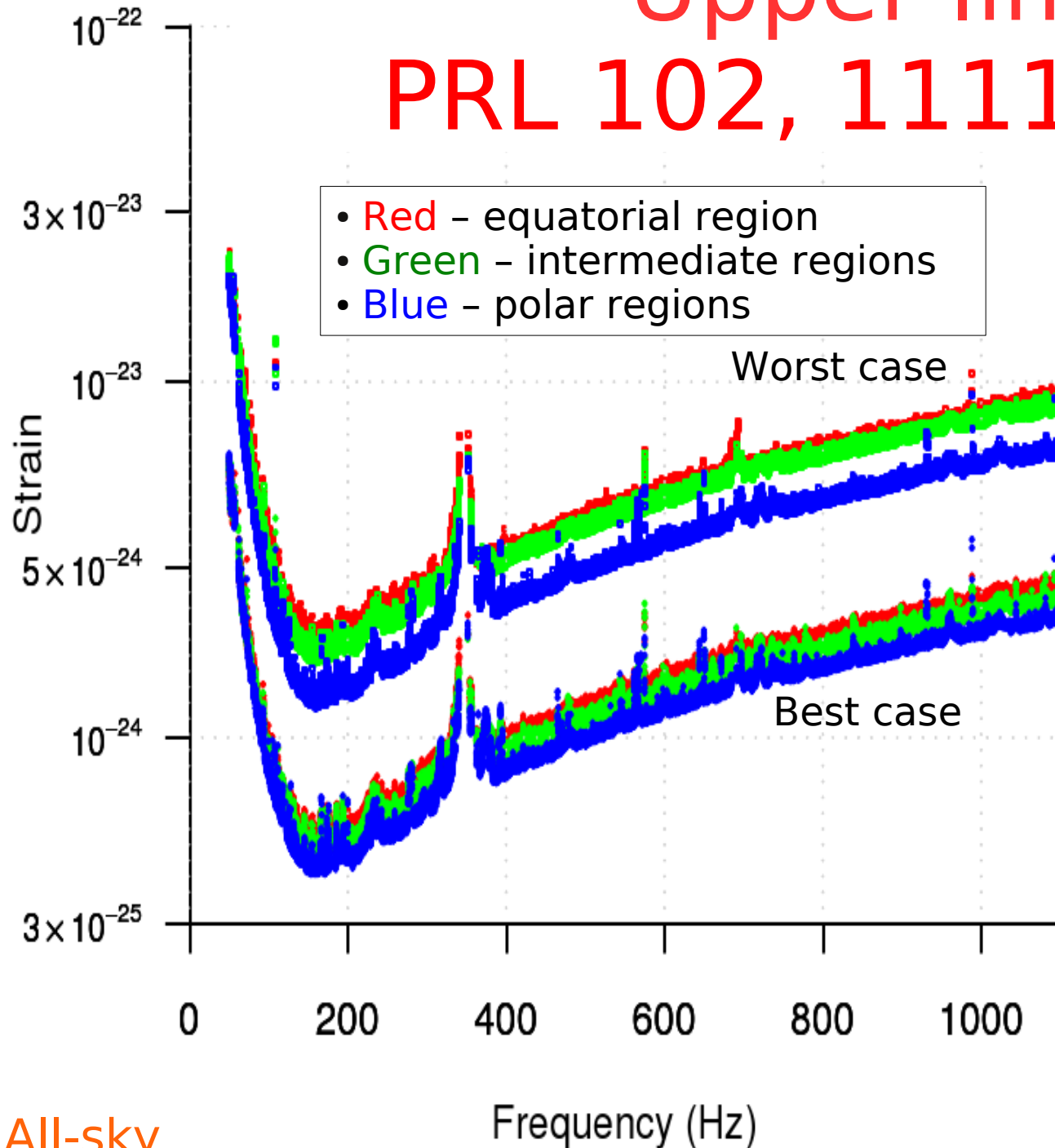


Histograms

(one entry per sky point)



Upper limits, PRL 102, 111102 (2009)



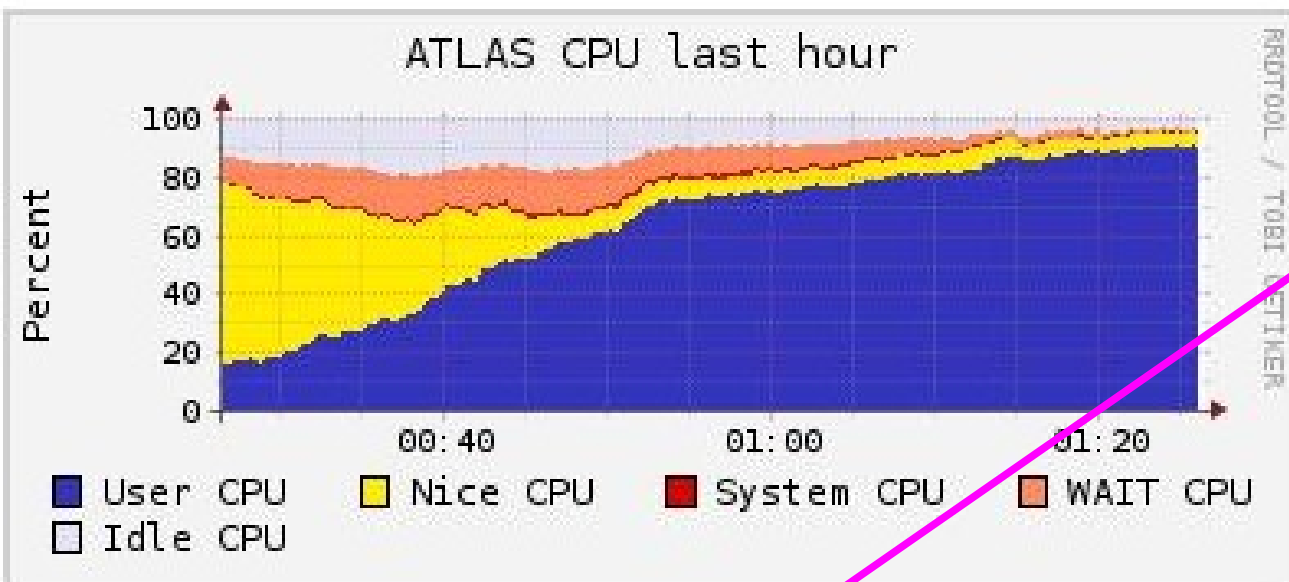
- Our best sensitivity is at 153 Hz where we obtain upper limit of 4.2×10^{-25} for circularly polarized sources in polar region.
- At a signal frequency of 1100 Hz we achieve sensitivity to neutron stars of equatorial ellipticity $\sim 1 \times 10^{-6}$ at distances up to 500 pc.

Full S5

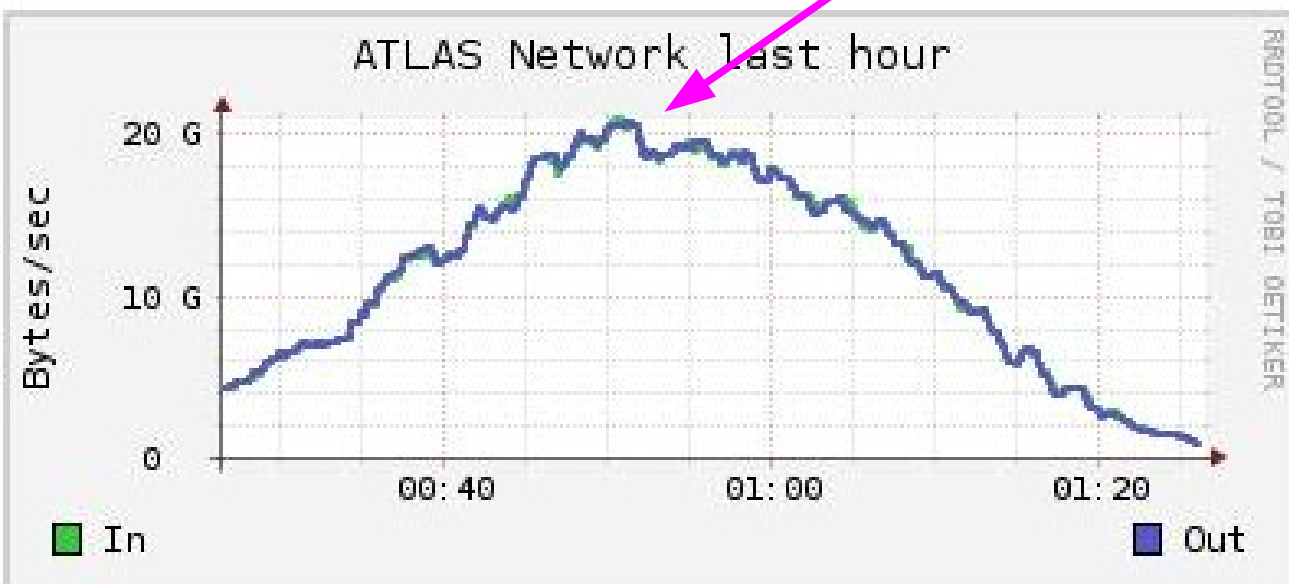
- Full S5 search is in progress.
- The timebase spans 2 years - this provides improved sky localization, but requires much smaller spindown steps.
- New version of PowerFlux with 10x speedup when iterating over closely spaced spindown values and better statistics output.
- Sample 201 spindown values in steps of $3e-11$ Hz/s, from 0 to $-6e-9$ Hz/s.

One of Full S5 runs starting on ATLAS cluster

(Albert Einstein Institute - Hannover)



- One of less busy days - cluster was initially idle
- **20 GB/sec** read rate from disk
- This is within a factor of 5 of maximum throughput of ATLAS network
- Big thanks to ATLAS support crew !

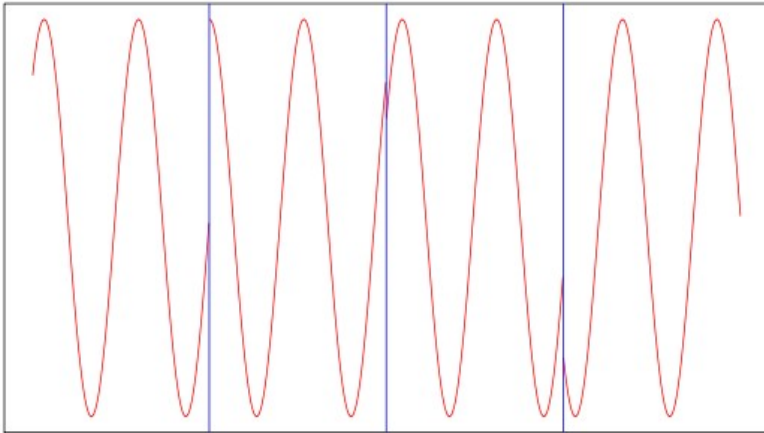


Loosely coherent search

- It is likely that the brightest CW object is extreme in some way and has a special reason (like a companion star or gas giant) for large quadrupole moment.
- This can cause phase evolution different from perfect monochromatic emitter model.
- Semi-coherent searches are robust against large variations in phase, but are limited in sensitivity.
- Fully coherent searches assume very close adherence to monochromatic emitter model.
- Need *Loosely coherent search* that is sensitive to signals with slow phase evolution.

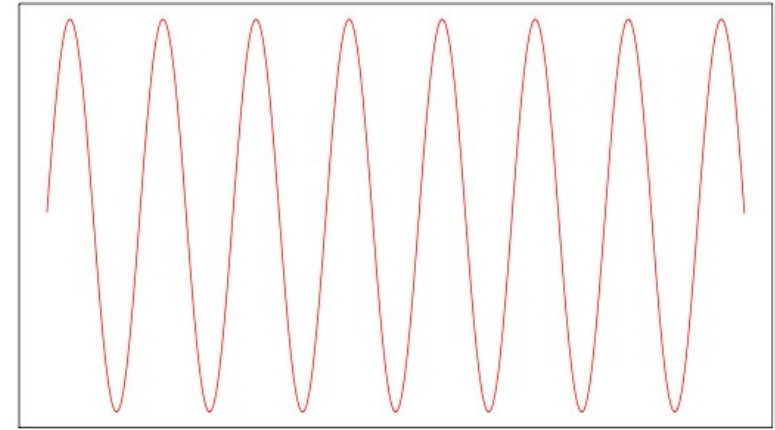
Loosely coherent search

Semi-coherent



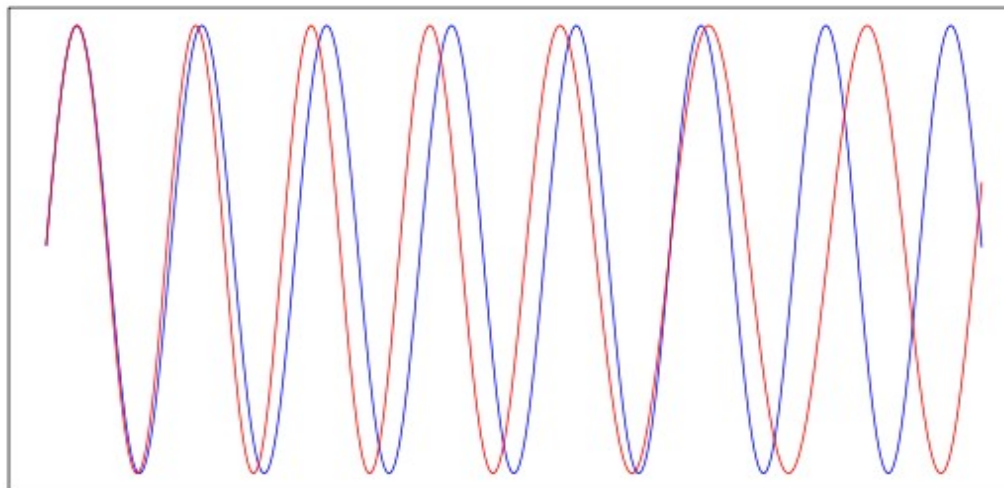
Time

Coherent



Time

Loosely coherent



Time

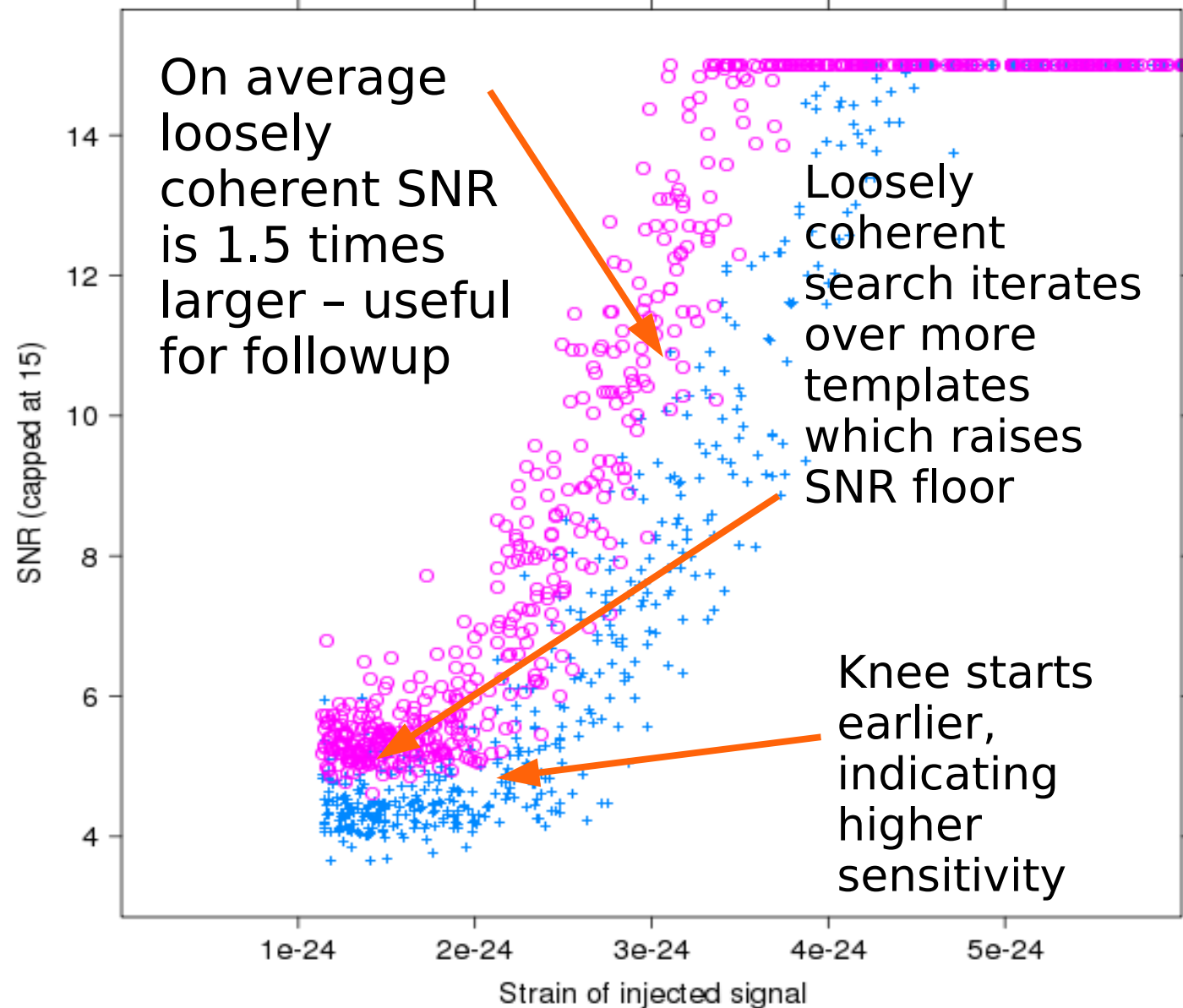
Preliminary study with simulated Gaussian noise

semicoherent search +
 $\pi/2$ loosely coherent search ○

- There are many different ways to construct a loosely coherent search
- Our present code computes power using Lanczos kernel:

$$P = \sum_{i,j} a_i K_{ij} a_j$$

- The kernel is parametrized by δ which limits allowed phase shift
- Plot on the right uses $\delta = \pi/2$



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 analysis is close to completion, more results to follow.
- Coincidences from Full S5 will be analysed using a coherent followup pipeline as well as new [loosely coherent](#) search code.

End of talk

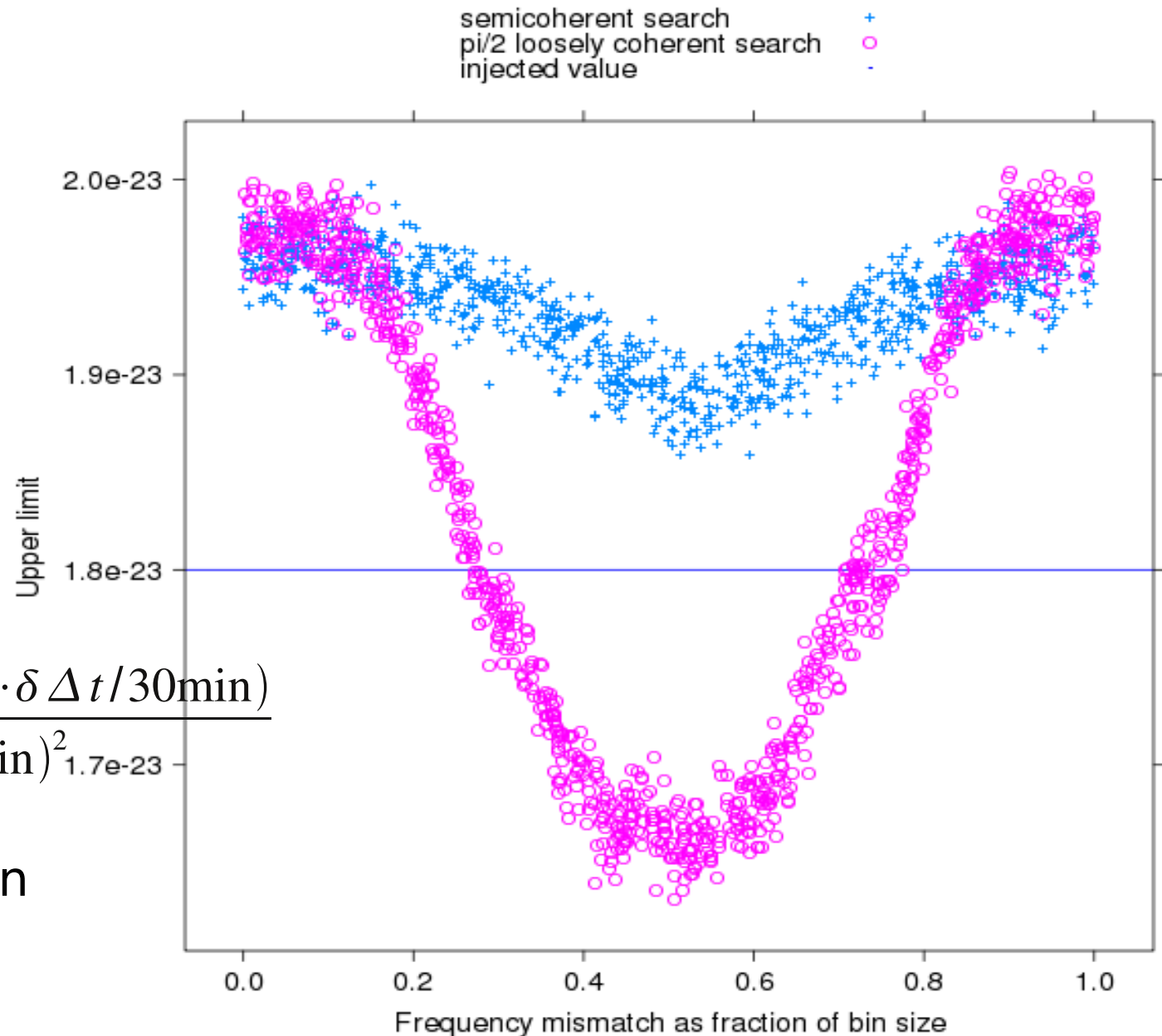
(supporting slides for questions follow)

Response to frequency mismatch

- Linearly polarized injections with $h_0=1.8e-23$ into Gaussian data
- Fixed sky location
- Frequencies within 400-410 Hz
- Loosely coherent search with Lanczos kernel

$$\frac{\sin(\delta \Delta t/30\text{min}) \sin(0.333 \cdot \delta \Delta t/30\text{min})}{0.333 \cdot \delta^2 \cdot (t/30\text{min})^2}$$

(zero when $\delta\Delta t/30\text{min}$ exceeds 3π)



Coincidence requirements

- An outlier with $\text{SNR} > 7$ from combined H1L1 data must have nearby outliers with $\text{SNR} > 5$ for both of H1-only and L1-only data sets with the following tolerances:
 - Frequency within 1 mHz
 - Spindown within $2e-11$ Hz/s
 - Location within 0.03 radians (1.7 degrees)
 - These could change based on further tests

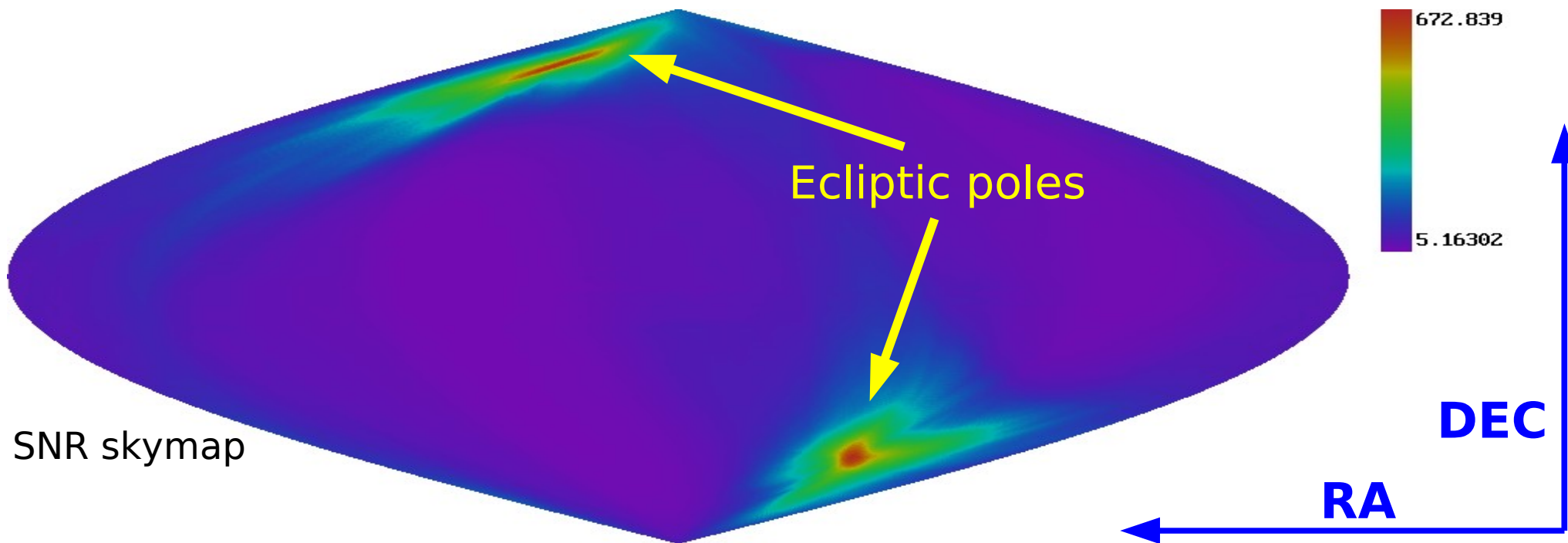
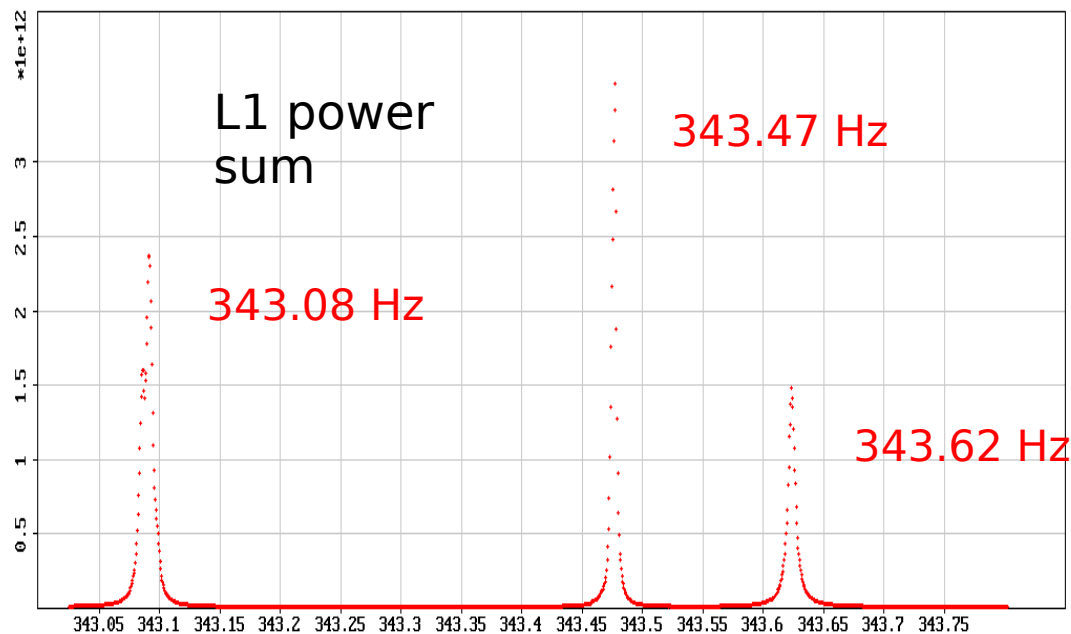
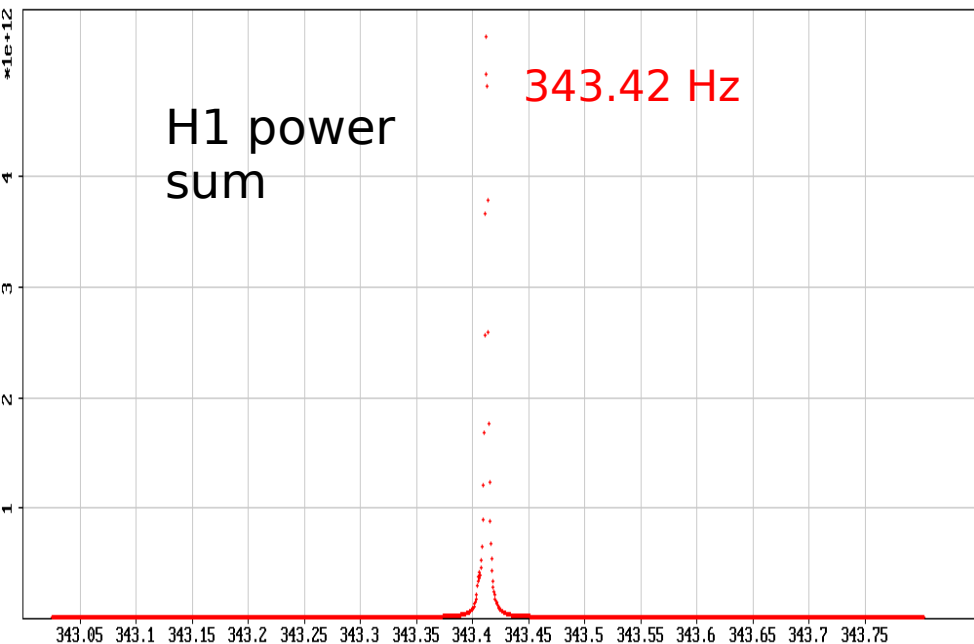
PowerFlux validation

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

Outlier followup

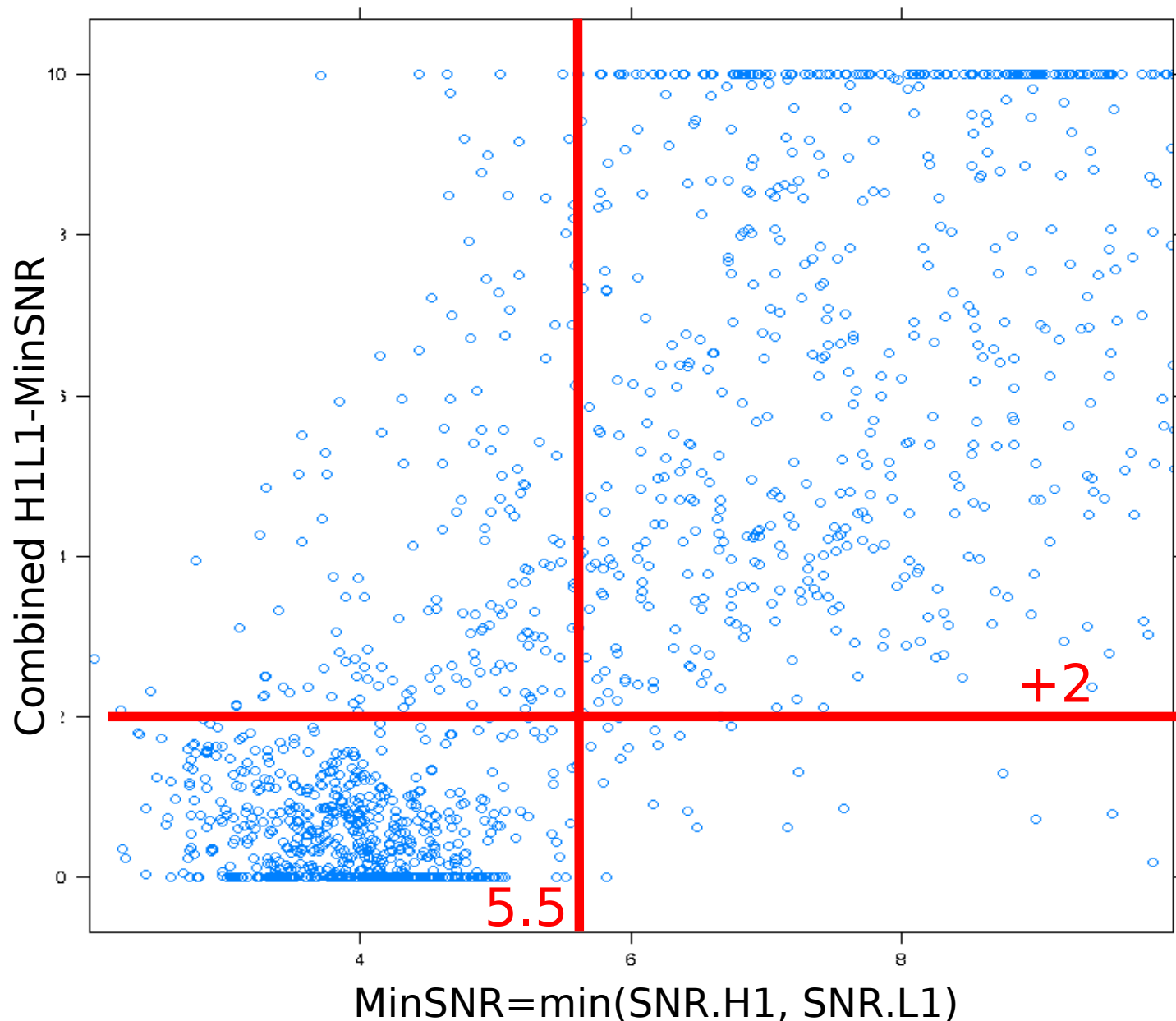
- Determine local SNR maxima, pick N highest (1000 from each of 10 sky slices)
- Apply a variation of gradient search to optimize SNR
- Look for outliers common to two interferometers:
 - $\text{SNR} > 6.25$ for each interferometer
 - Difference in frequency less than $1/180$ Hz
 - Difference in spindown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

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



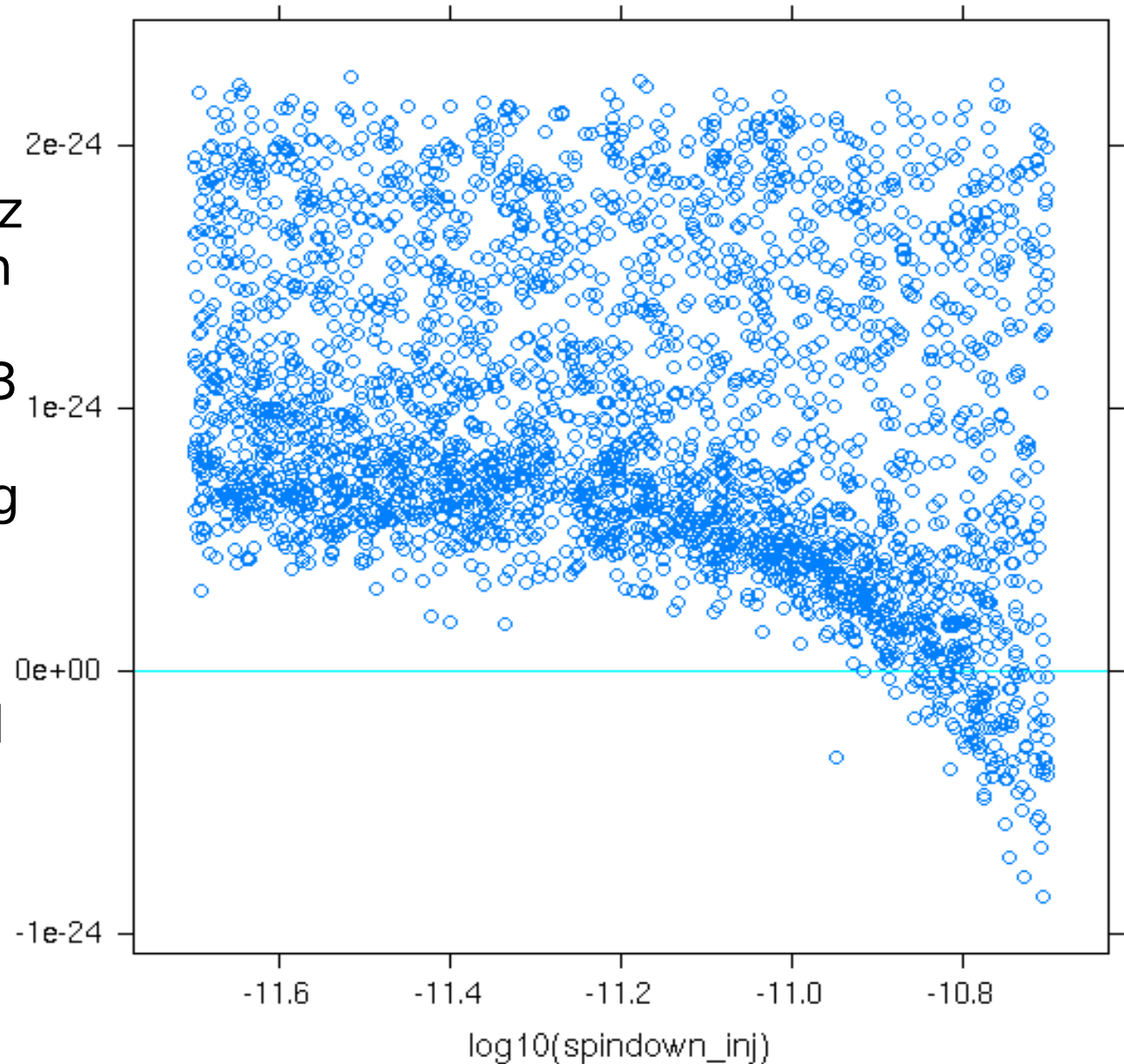
Detection search results

- 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 (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

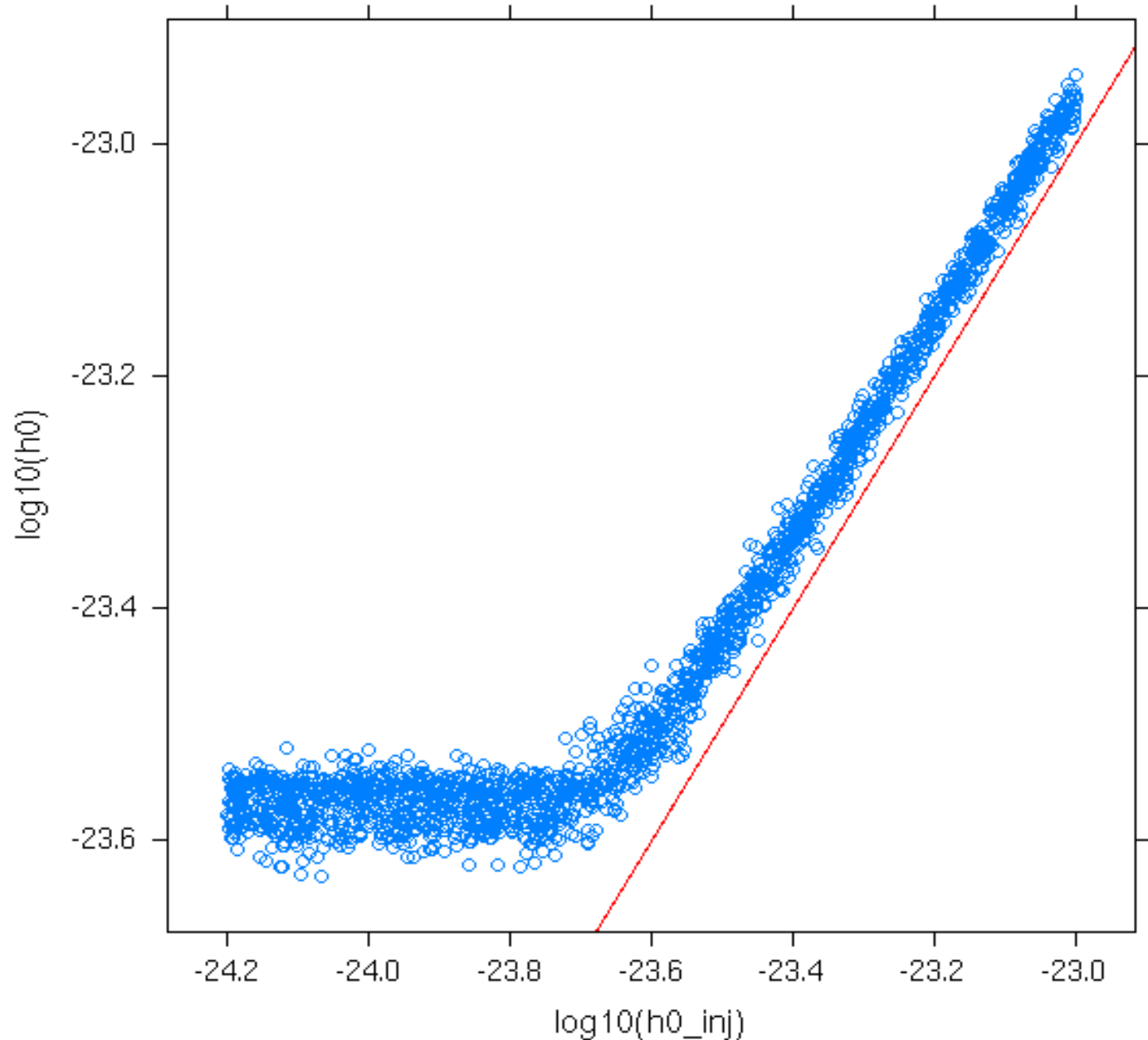
Simulation with Gaussian noise

- 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



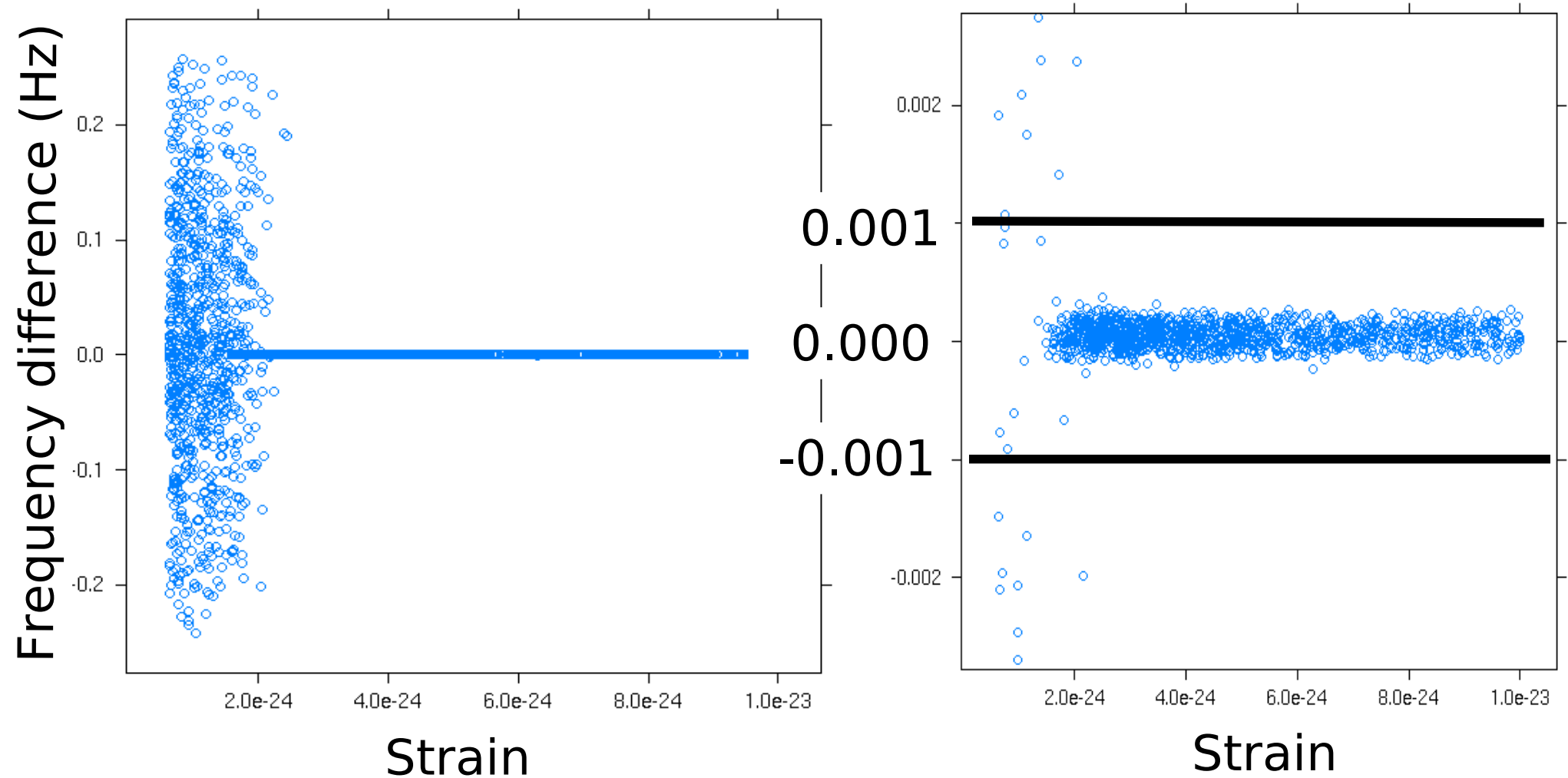
Restricting to small spindowns

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

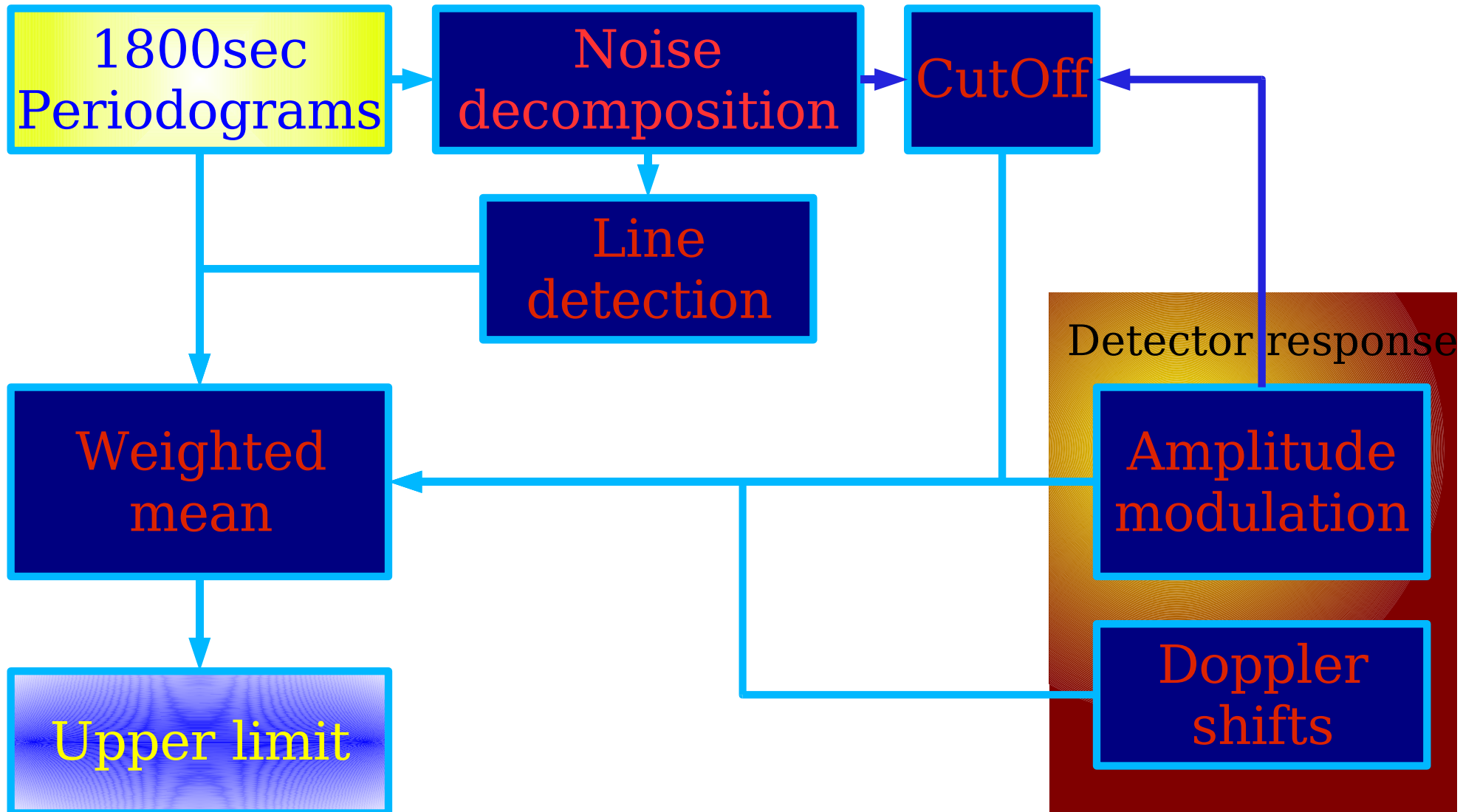


Parameter reconstruction

- 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



PowerFlux analysis pipeline

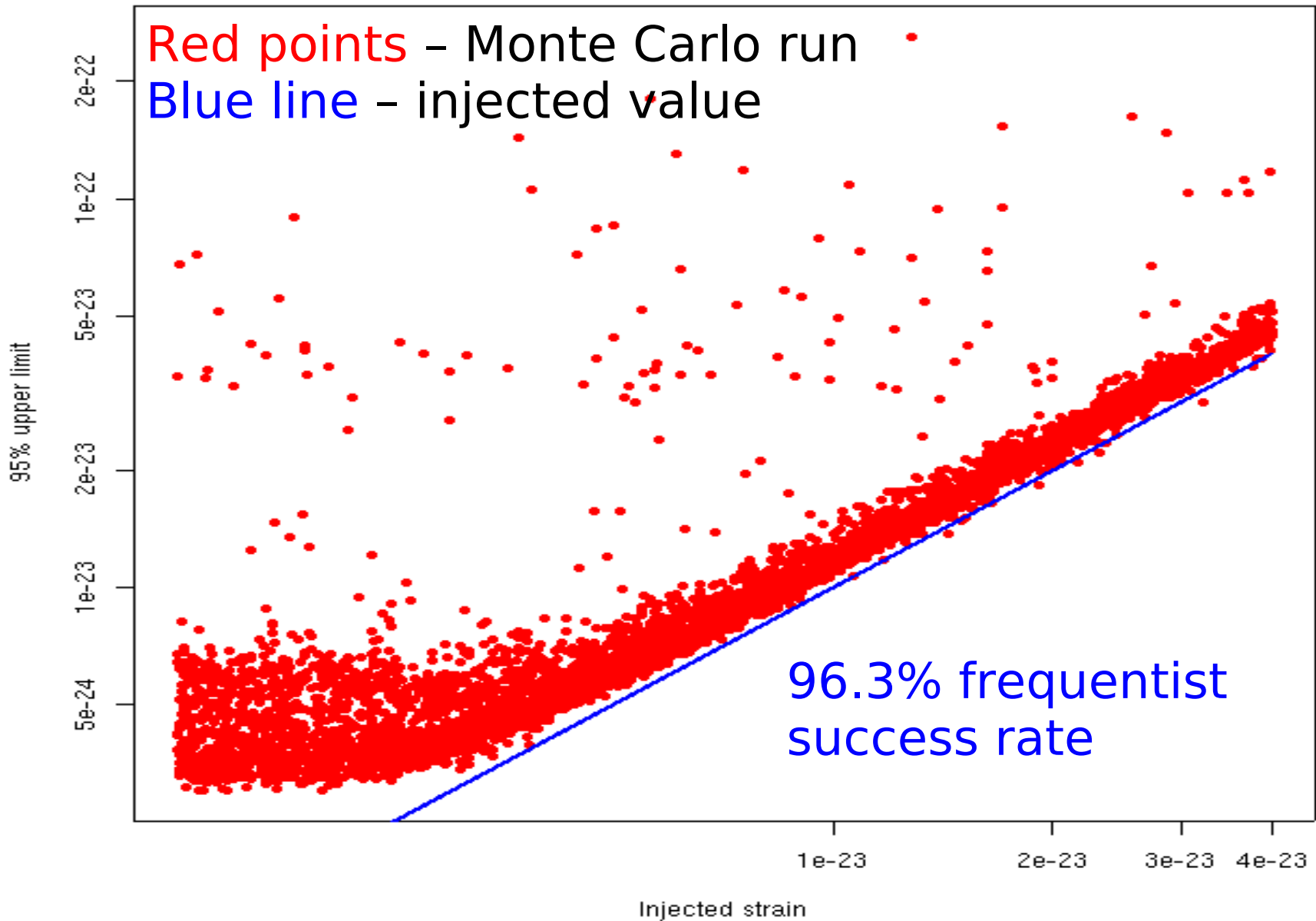


Monte-Carlo run

- 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

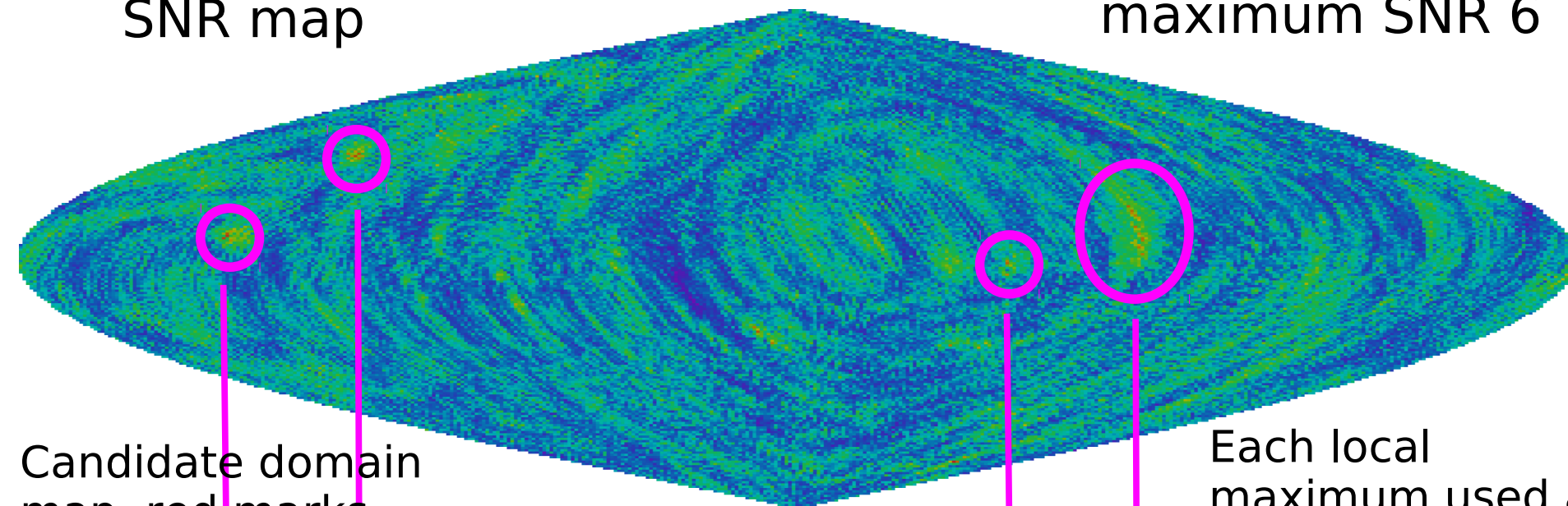
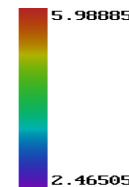
Upper limit versus injected strain



Multiple outliers

Clean band -
maximum SNR 6

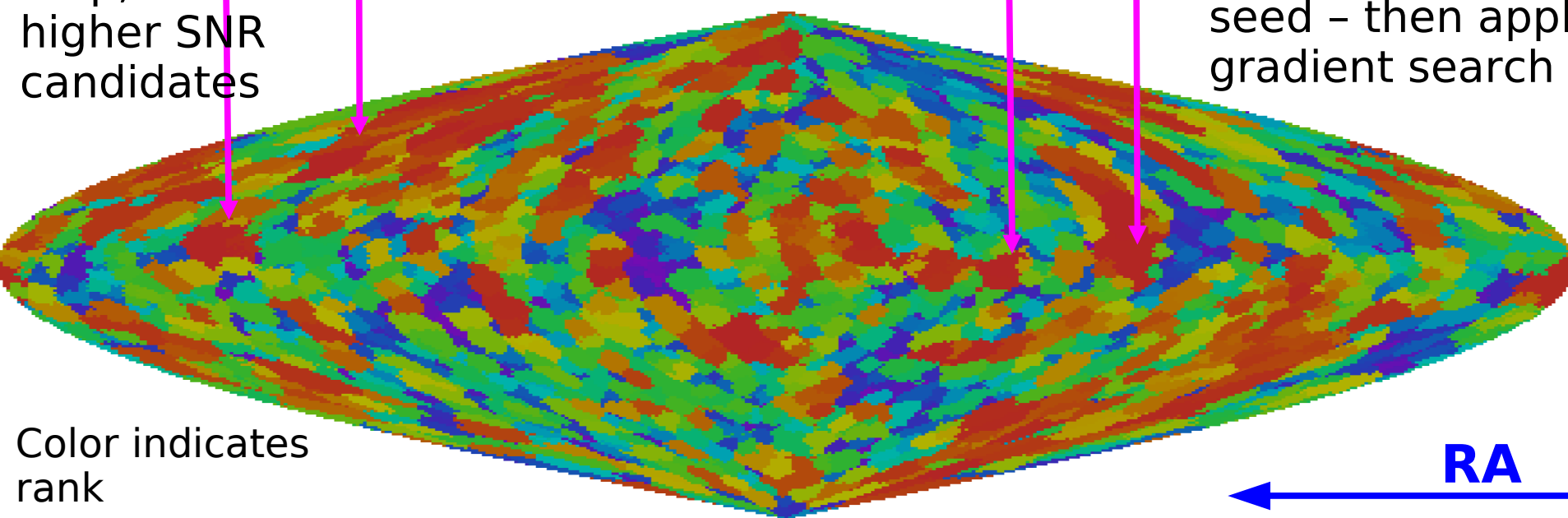
SNR map



Each local
maximum used as
seed - then apply
gradient search



Candidate domain
map, red marks
higher SNR
candidates



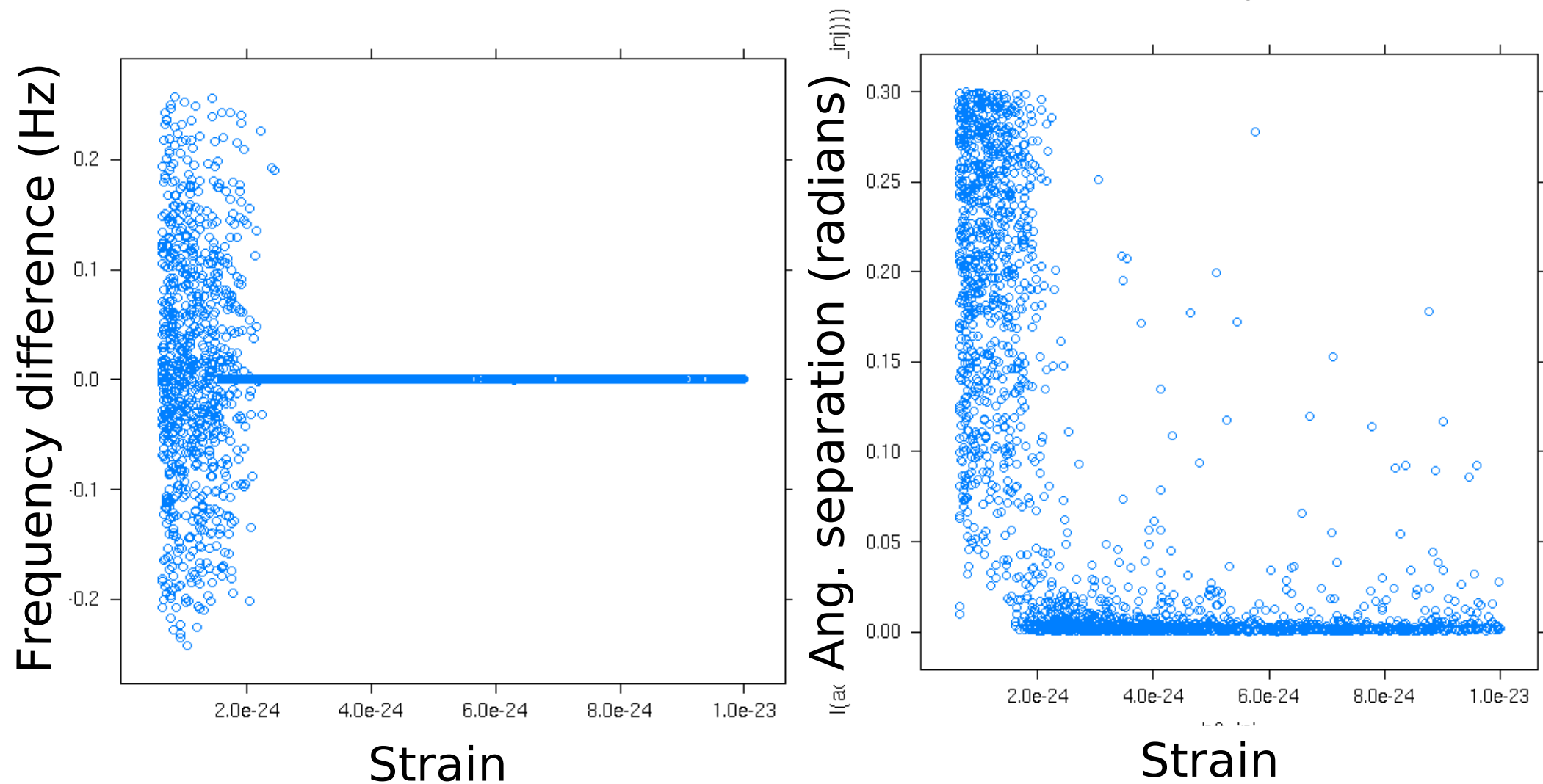
Color indicates
rank

DEC

RA

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



Example

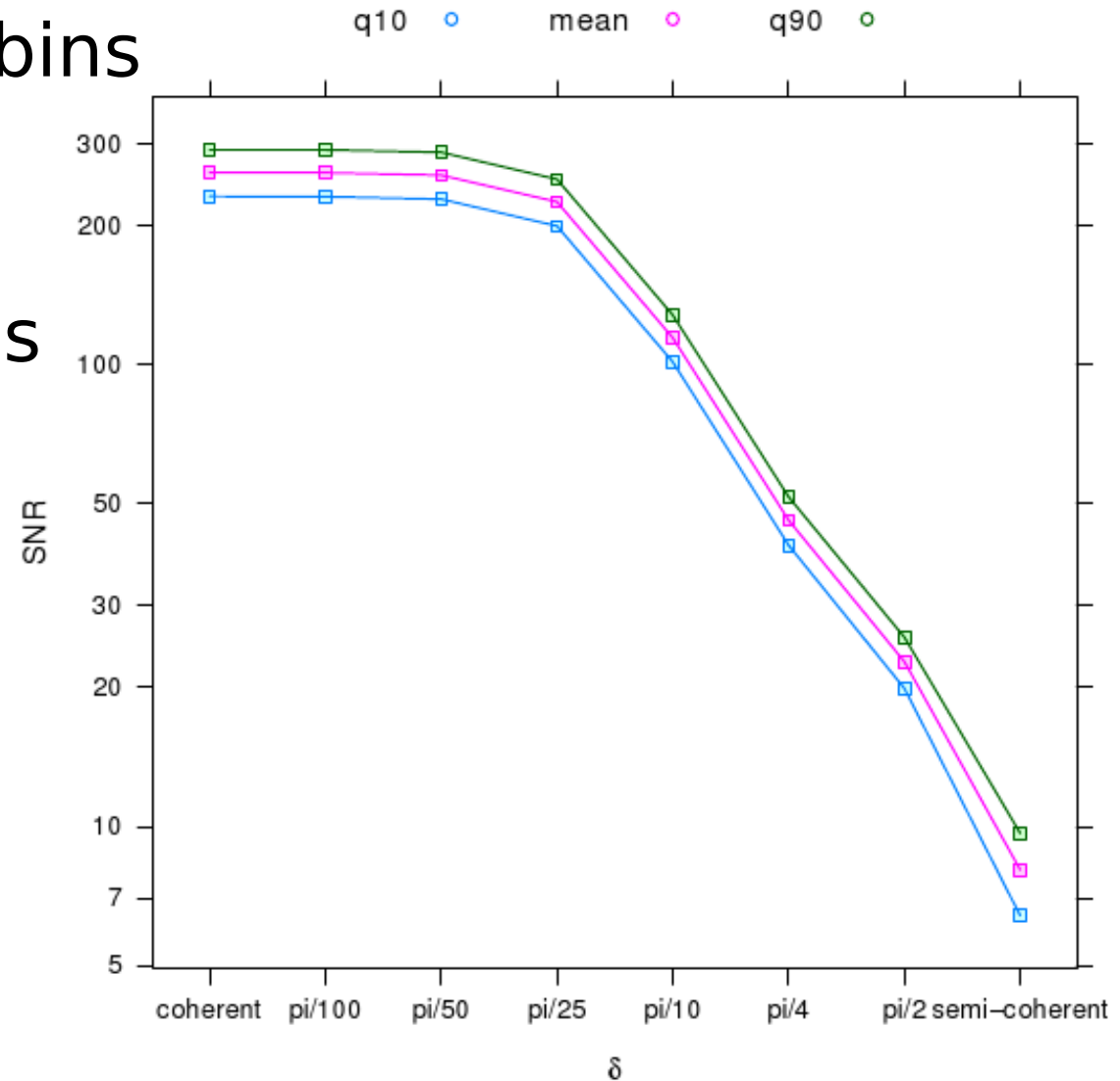
- Start with a fully coherent sum of a series of SFT bins (one bin from each SFT)

$$P = \left| \sum a_k e^{i\phi_k} \right|^2$$

- Average over all phases such that $|\phi_k - \phi_{k+1}| \leq \delta$

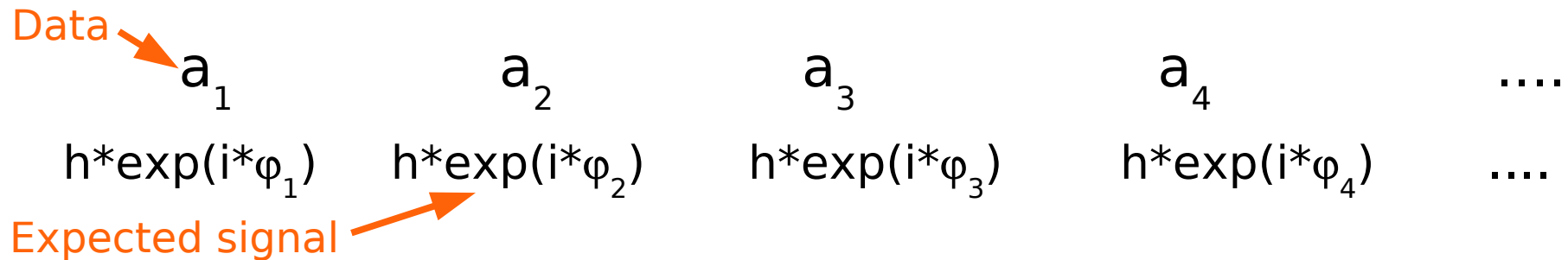
- Obtain statistic with reduced sensitivity to phase drift:

$$P' = \sum \bar{a}_k a_l \left(\frac{\sin(\delta)}{\delta} \right)^{|k-l|}$$



Another point of view

Assume that SFT bins have already been corrected for Doppler shift (resampled):



Since phases vary slowly $|\varphi_k - \varphi_{k+1}| < \delta$ we can use a low-pass filter to reject rapidly varying noise and then compute the power sum as usual.

This performs especially well under frequency mismatch.

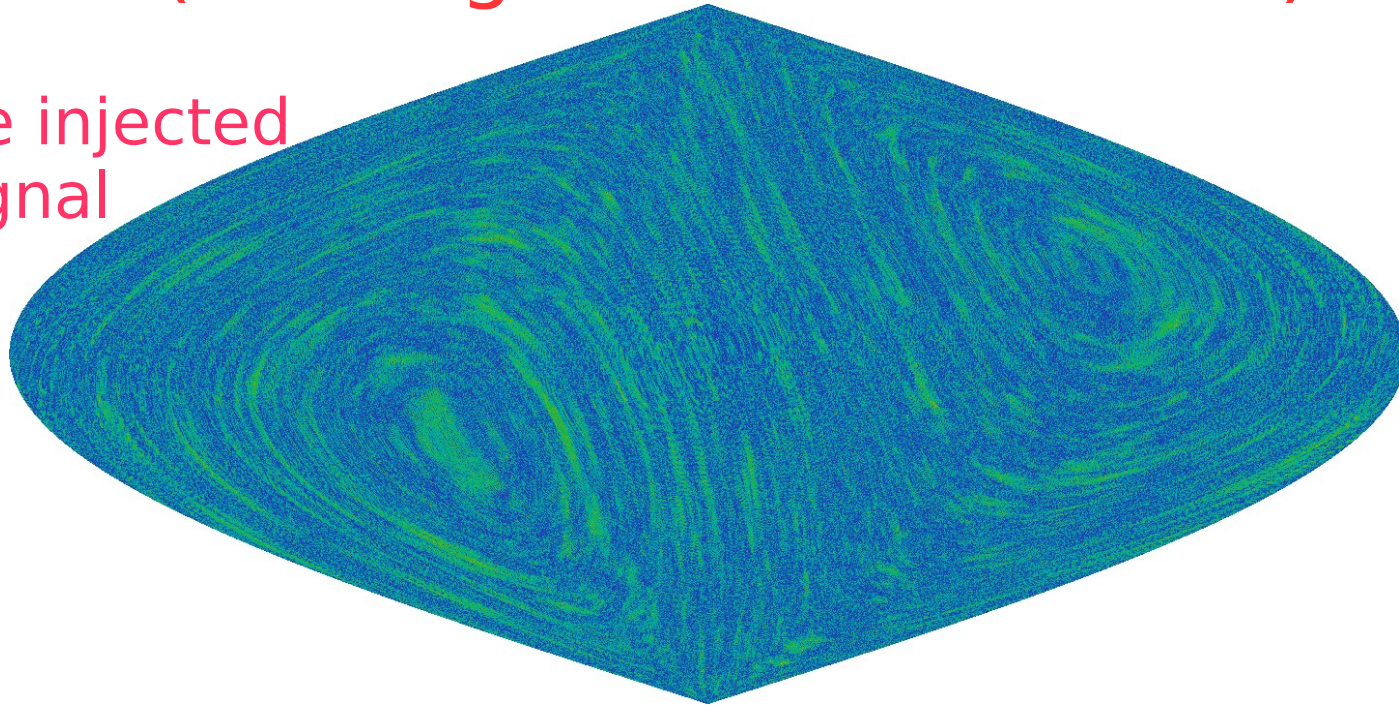
This method is optimal if all slowly varying signals are physically valid – which is the case for very small δ .

Technical details

- For large values of δ (such as $\pi/2$) one can avoid summing over the entire matrix by discarding small entries. This brings the search closer to cross-correlation search.
- For small values of δ it makes sense to do a Fourier transform first, which makes most entries in the matrix small enough to be discarded.
- We have a large δ test implementation based on PowerFlux code (still being tweaked).
- Small δ implementation aimed at doing targeted searches is in the queue (joint with Joe Betzweizer)

Are averaged powers Gaussian ? (Kolmogorov-Smirnov test)

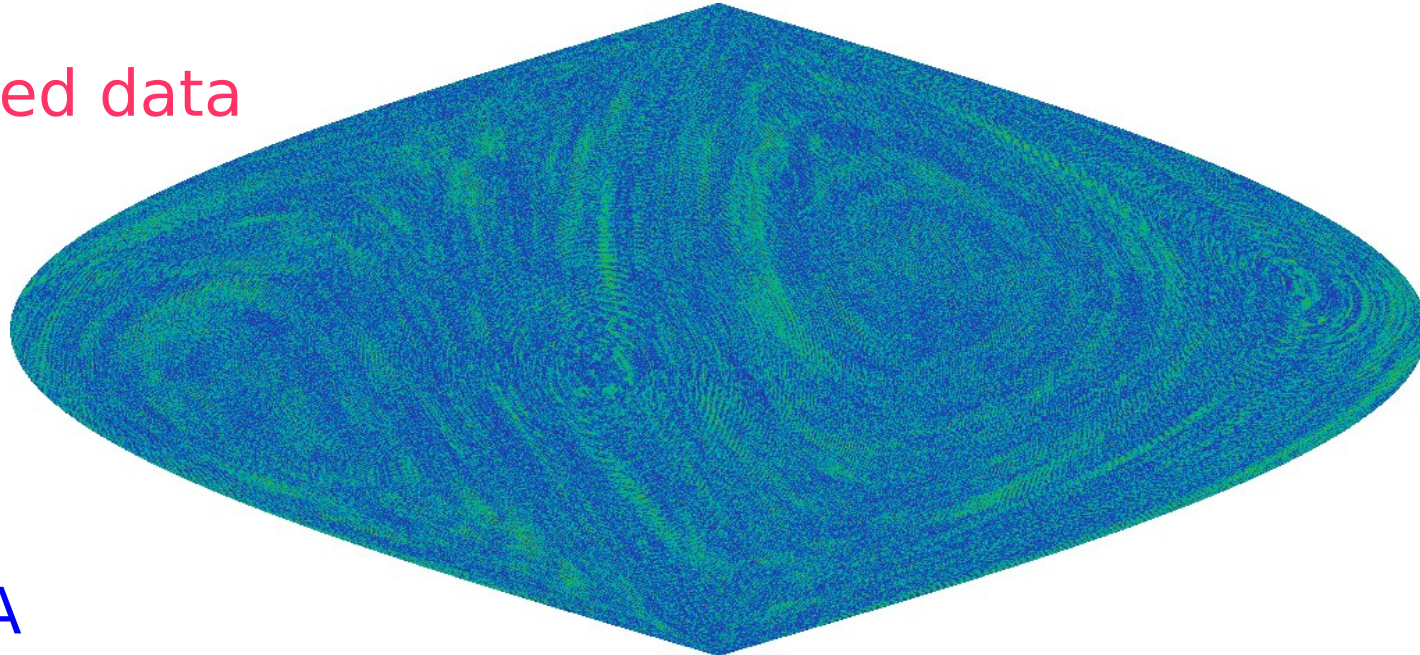
Hardware injected
pulsar signal



0.065
0.0648048
0.017
0.0168356

DEC

Simulated data



0.067
0.067378
0.017
0.0166078

RA



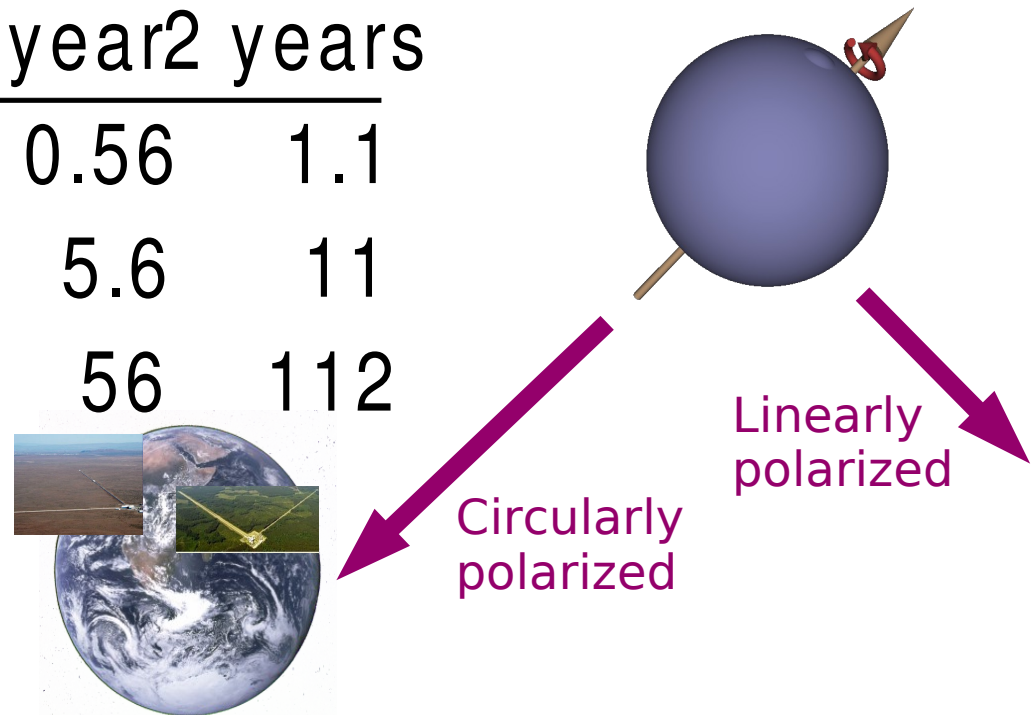
Choice of 1/1800 Hz SFT bins

- 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 1 Jupiter mass at 1 AU we would see ~ 90 degree phase shift at 1500 Hz over 30 minutes – not a problem with power based statistic.

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

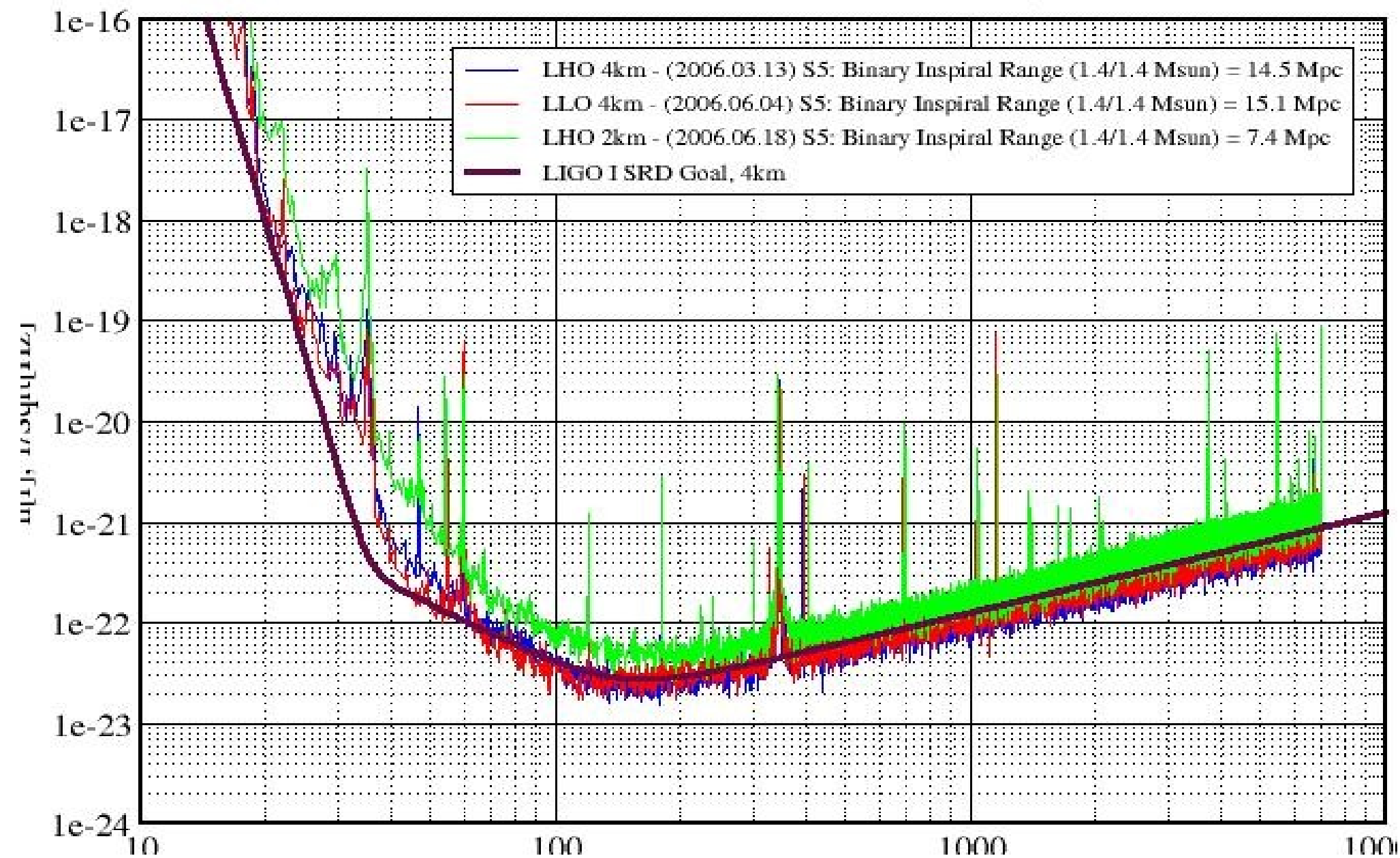
	3 months	1 year	2 years
1e-11 Hz/s spindown	0.14	0.56	1.1
1e-10 Hz/s spindown	1.4	5.6	11
1e-9 Hz/s spindown	14	56	112



S5 science run sensitivity

S5 Performance - June 2006

LIGO-G060293-01-Z



Dedicated loosely coherent code

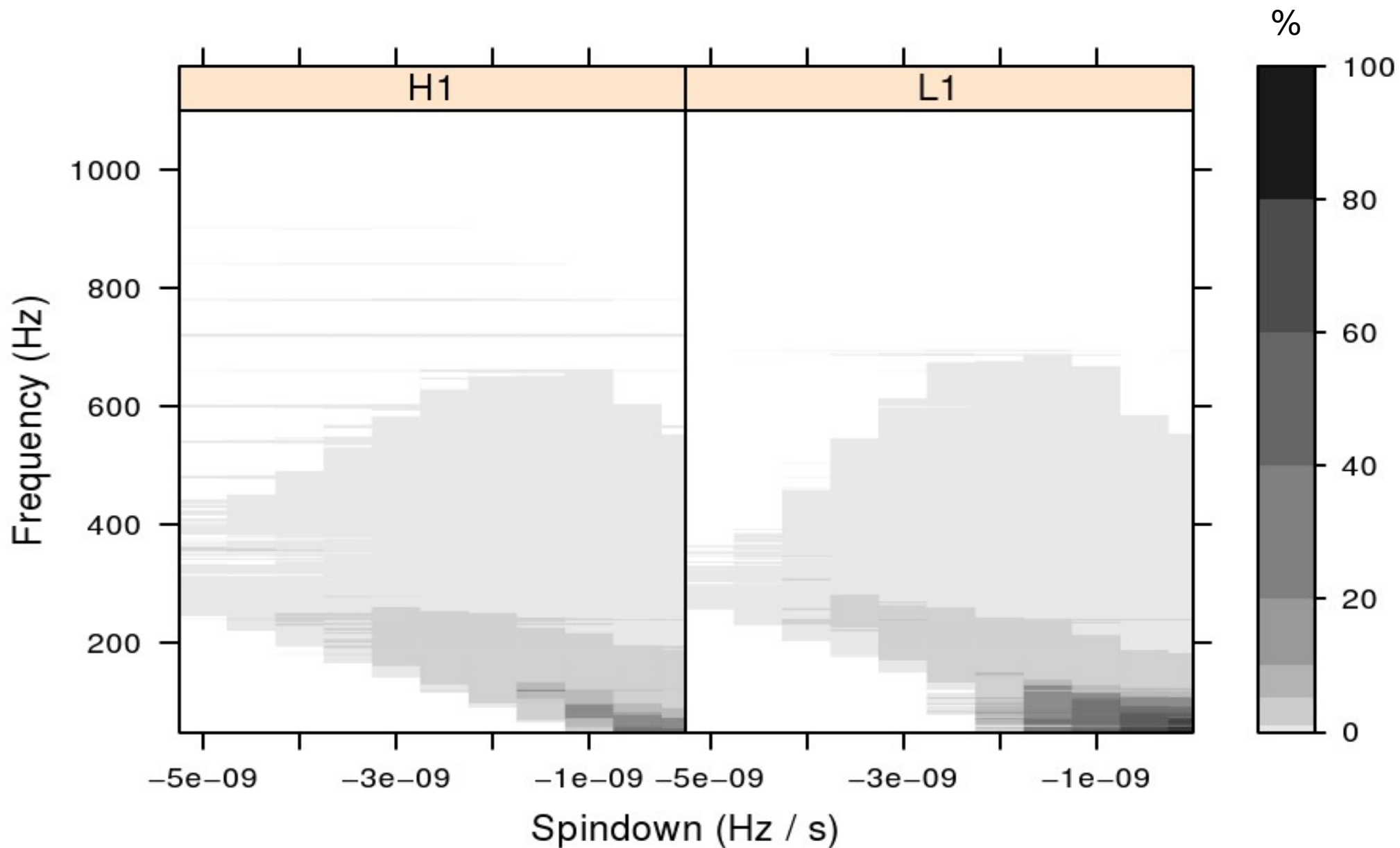
- We would like to develop dedicated loosely coherent code for the case of small δ .
- Purpose: wide- and narrow-band searches of small sky regions with long coherence times and control of phase evolution.
- We envision code built on top of very short SFTs with bins on the order of 0.1-2 Hz, such that relative to central sky point the Doppler shifts result in phase evolution only and no actual shift of the bin.
- Explore δ resulting in phase wrap around of 10-100 times over S5/S6 run.
- Produce upper limits and perform detection search similar to PowerFlux (and reusing PowerFlux infrastructure).

Noise decomposition algorithm

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

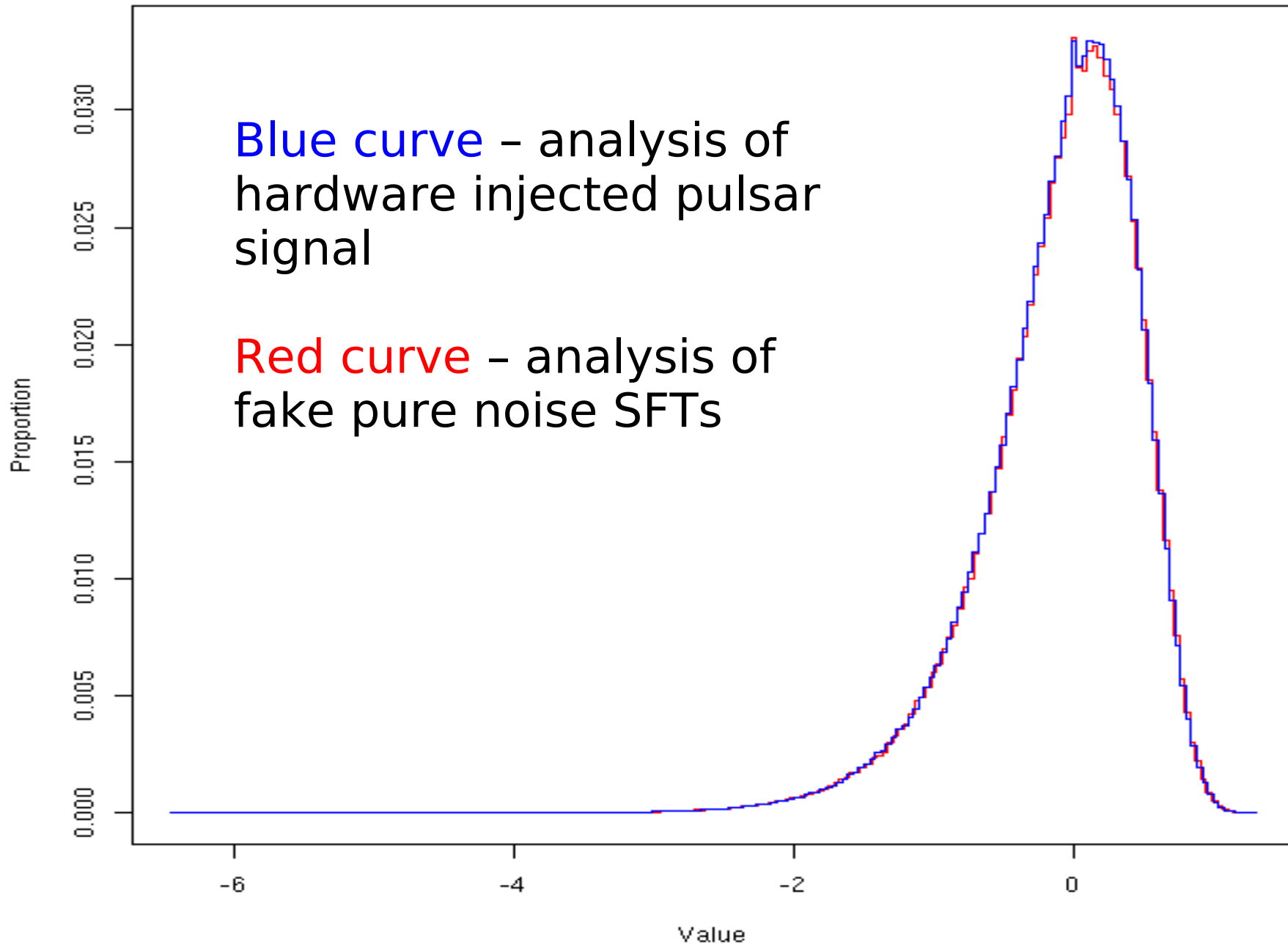
1. Compute log10 of each matrix entry.
2. Compute medians of each row, subtract from the matrix and add to Tmedians accumulation array.
3. Compute medians of each column, subtract from the matrix and add to Fmedians accumulation array.
4. Continue steps 2 and 3 until all medians are 0 or very small.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

Early S5 excluded sky area



Residuals histograms

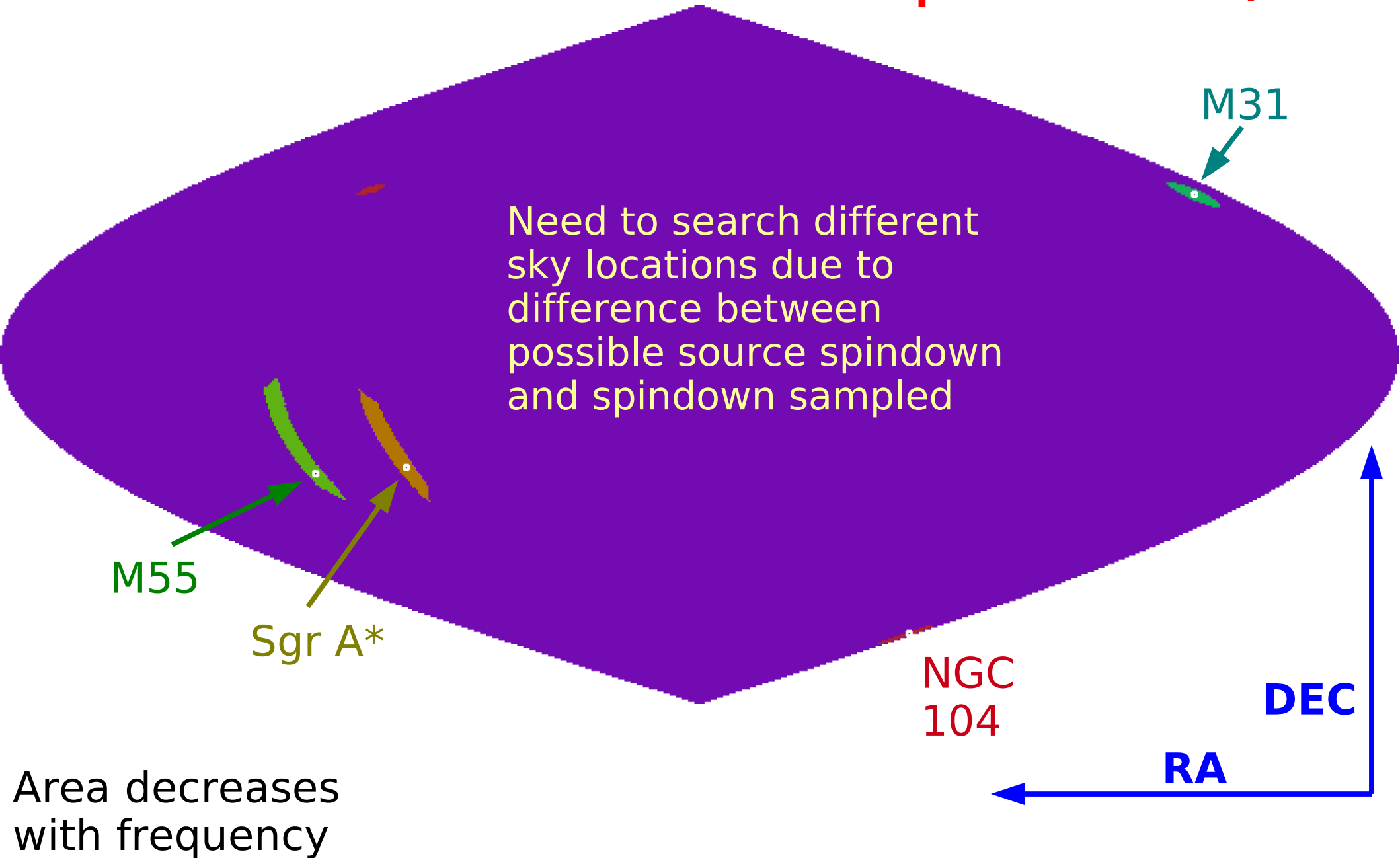
Noise decomposition residuals



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.

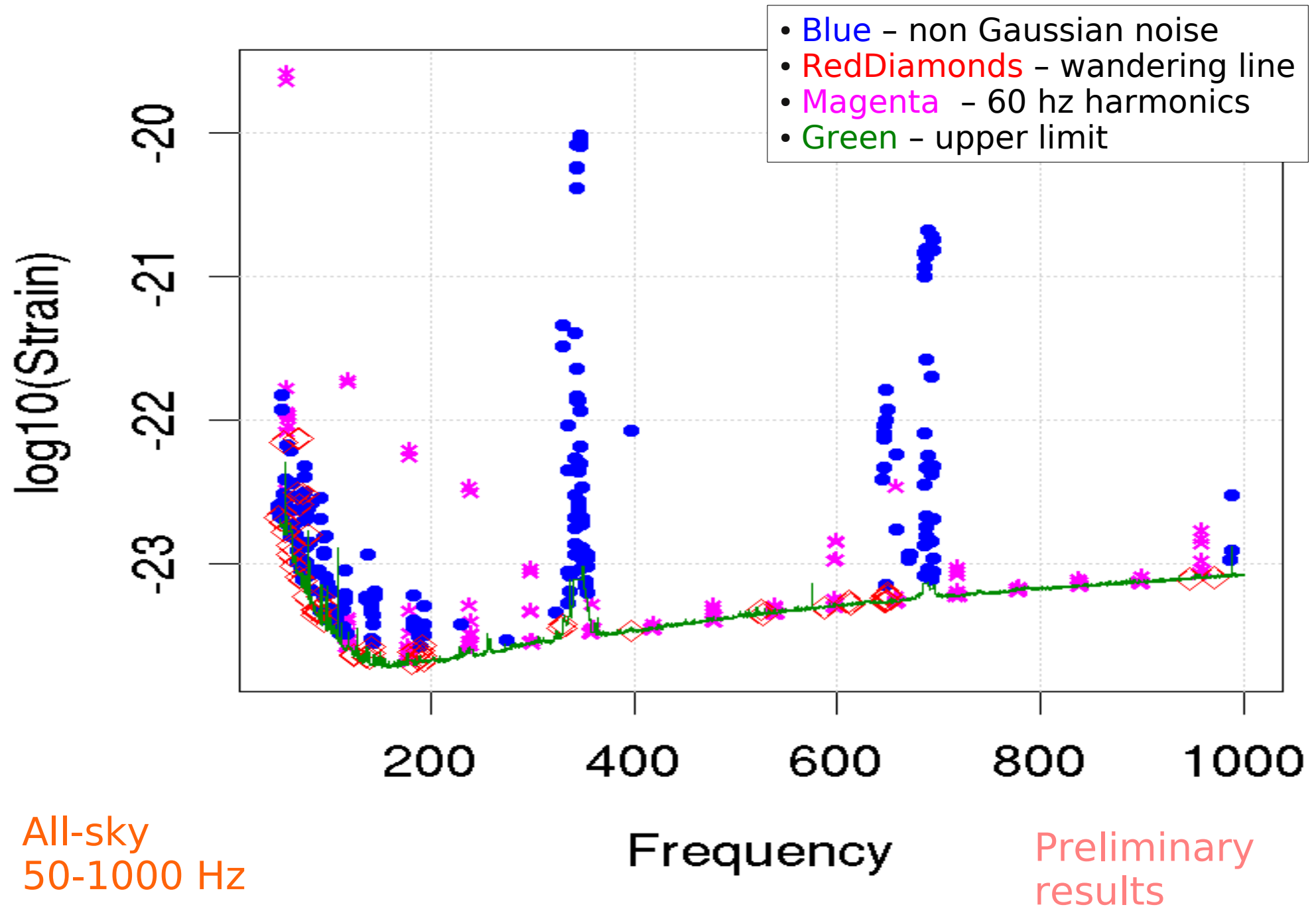
Targeted search example (for ~270 Hz, non-zero spindown)



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

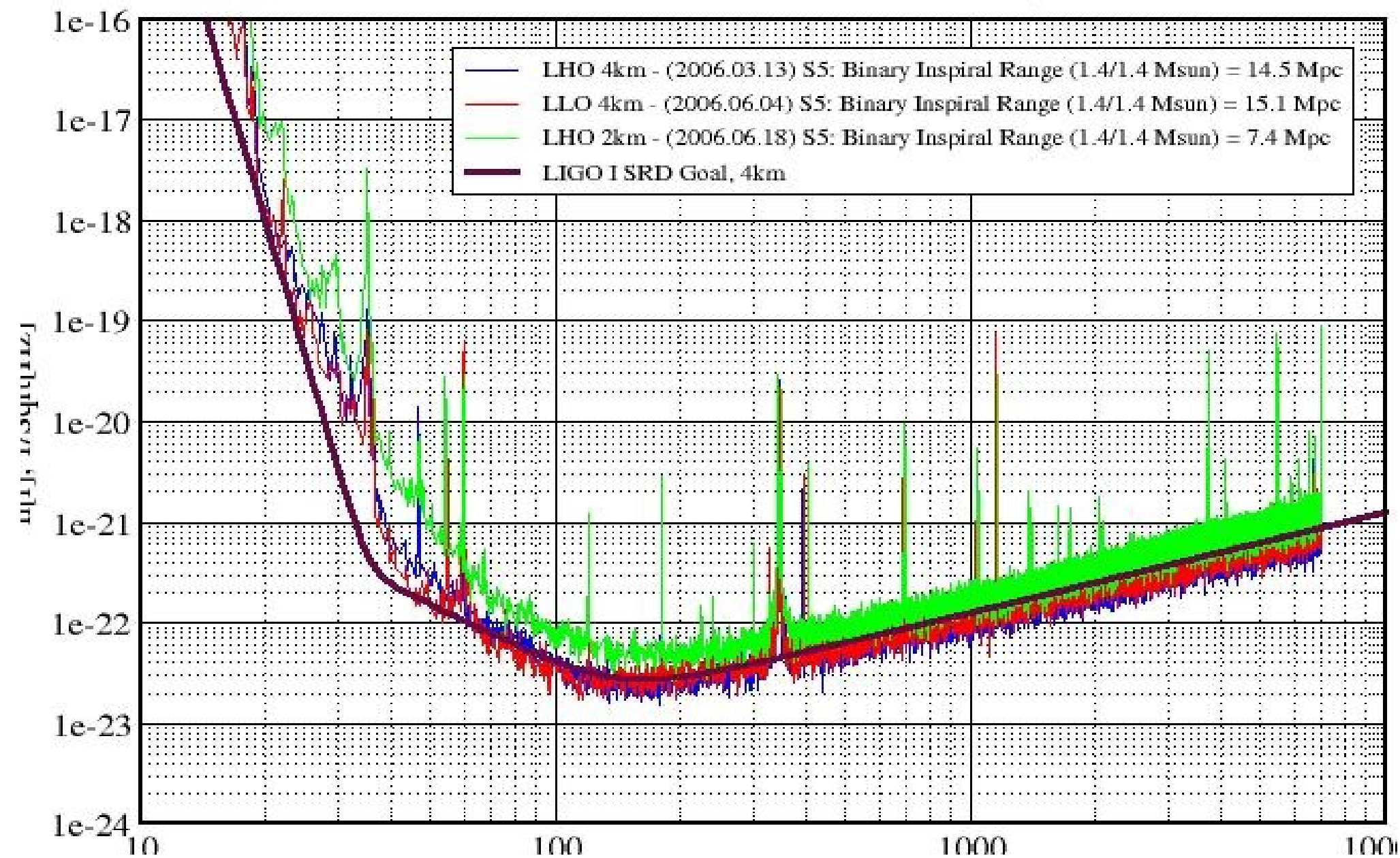
L1 S5 0-spindown run



S5 science run sensitivity

S5 Performance - June 2006

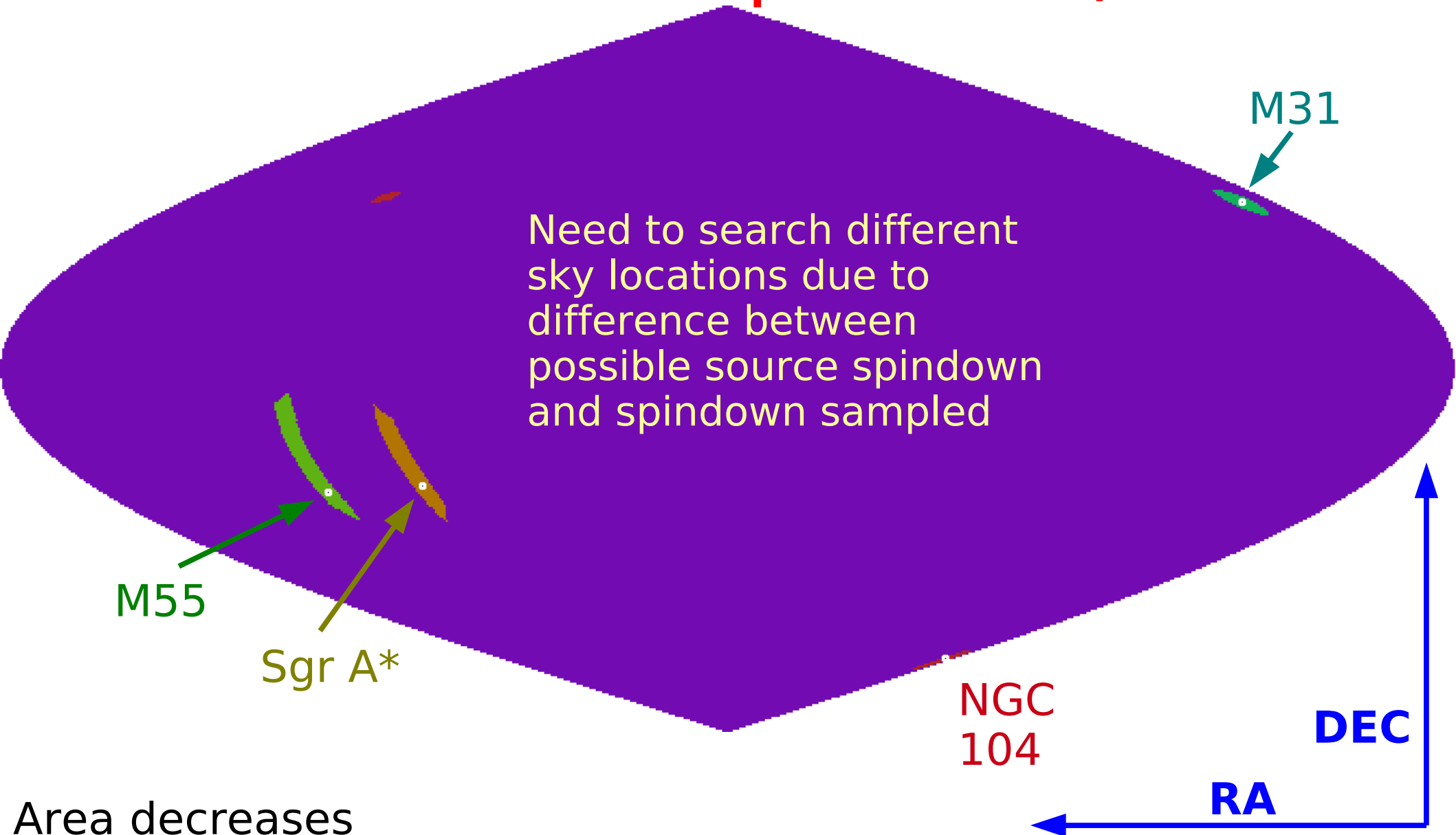
LIGO-G060293-01-Z



Partial sky (targeted) run

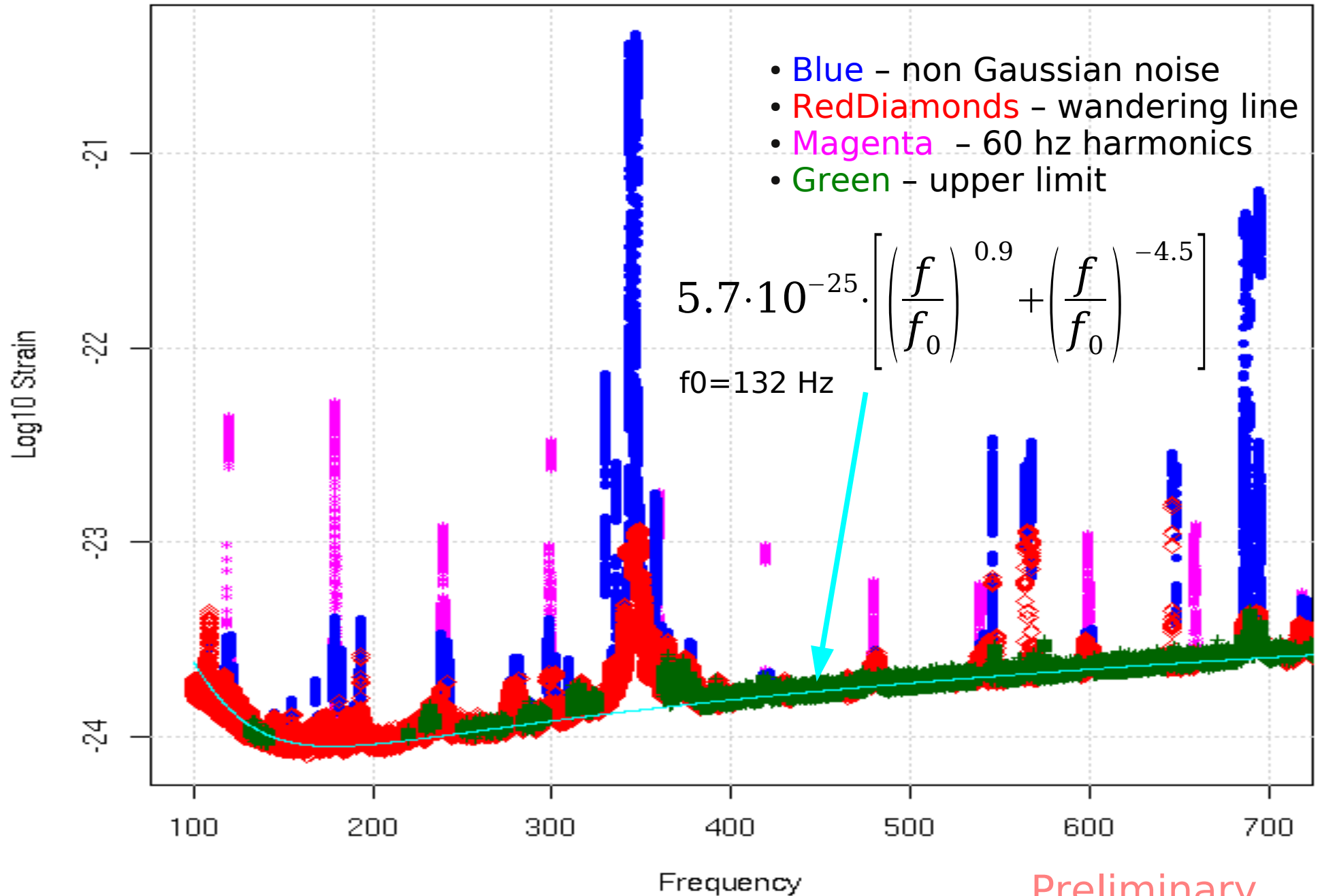
- Searched sky around
 - globular clusters M55, NGC104
 - galactic center Sgr A*
 - Andromeda M31 (control)
- 100-700 Hz
- $-1.01e-8$ Hz/s through $1.01e-8$ Hz/s in $2e-10$ Hz/s steps

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



Area decreases with frequency

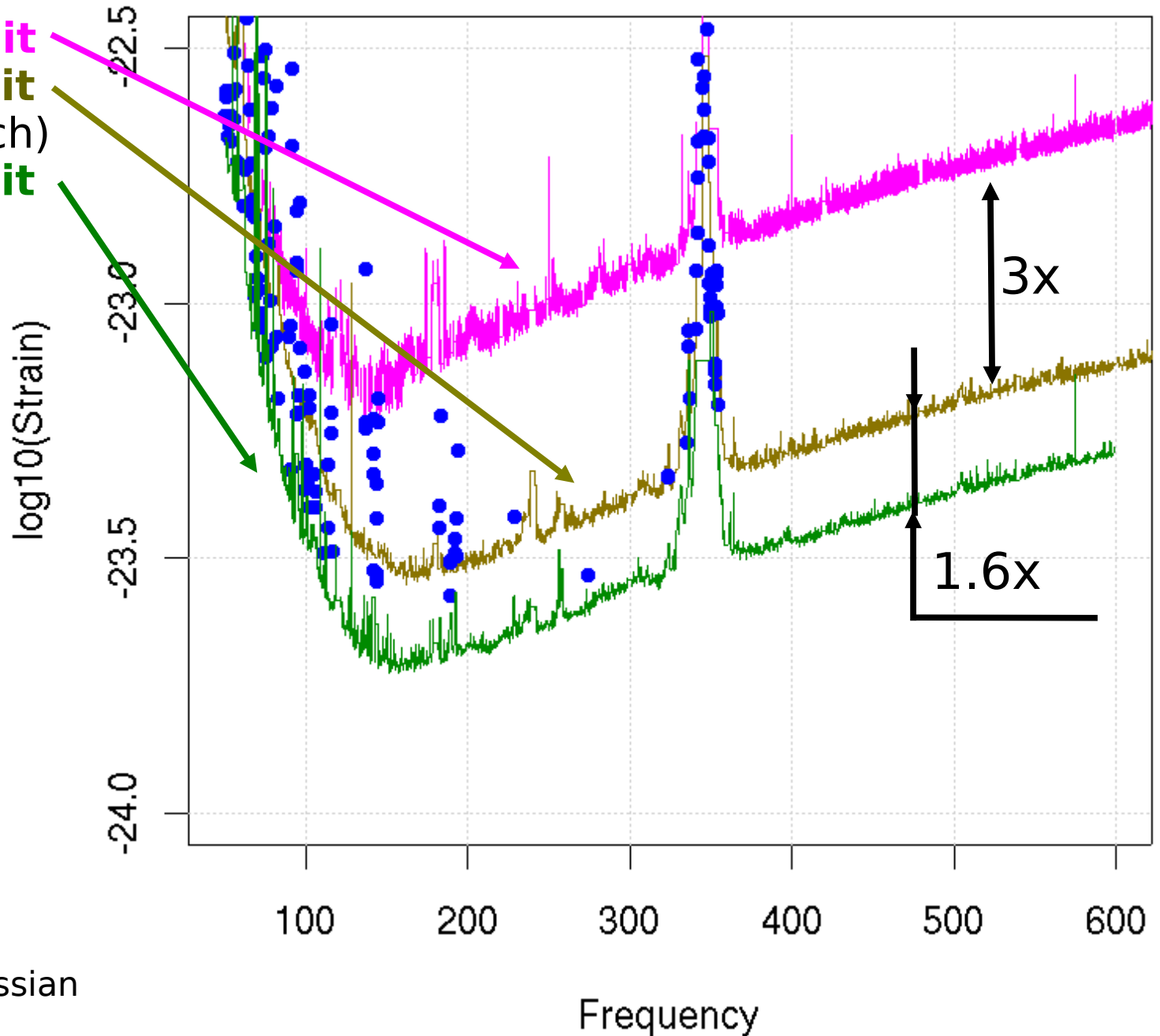
H1 Sgr A* upper limits



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

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

Average detector acceleration

Average detector velocity

Spindow n (Hz/s)

Earth orbit angular velocity

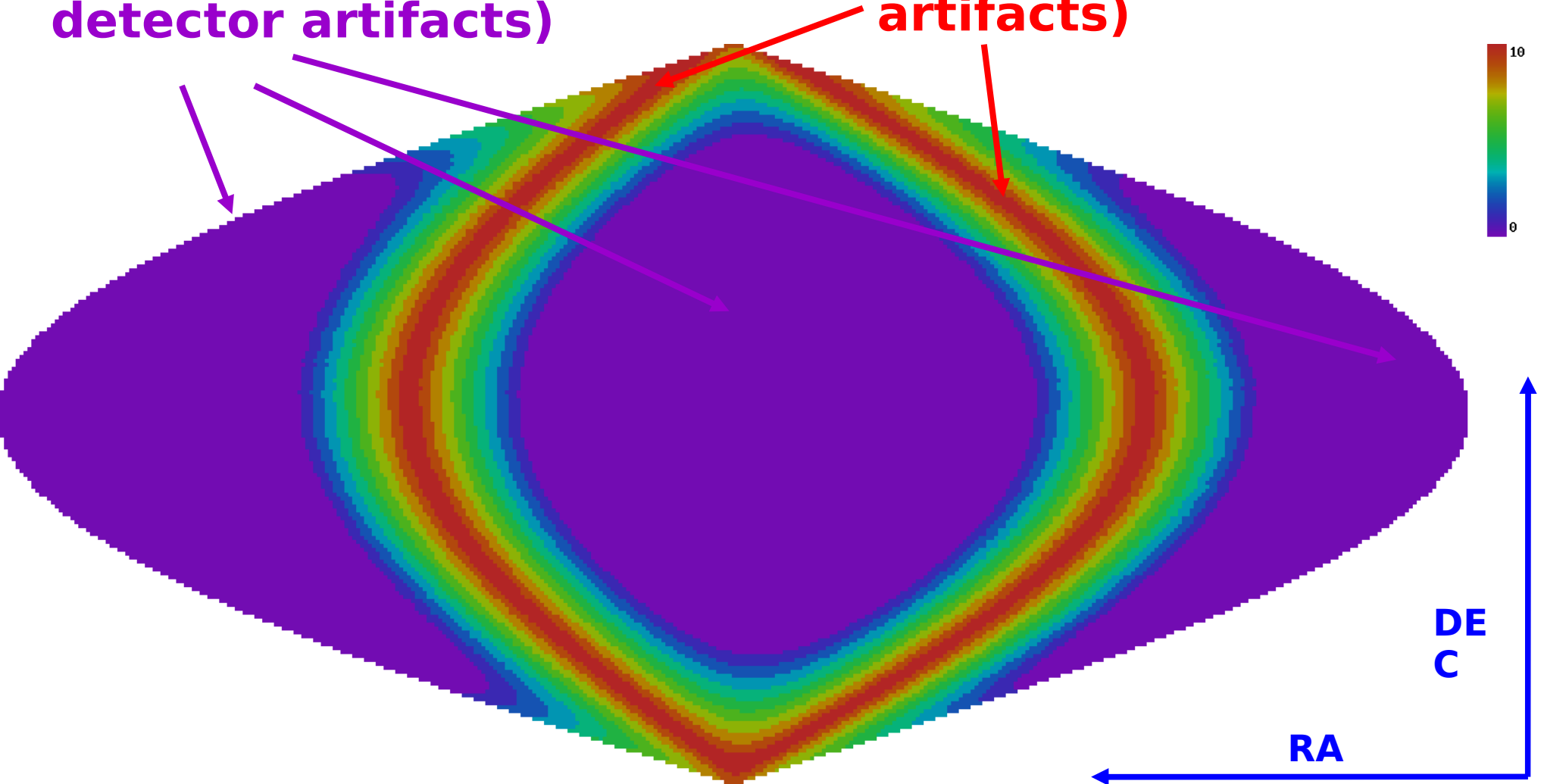
Frequency

Unit sky position vector

Doppler Skybands

Skyband 0 (good - only exceptionally strong detector artifacts)

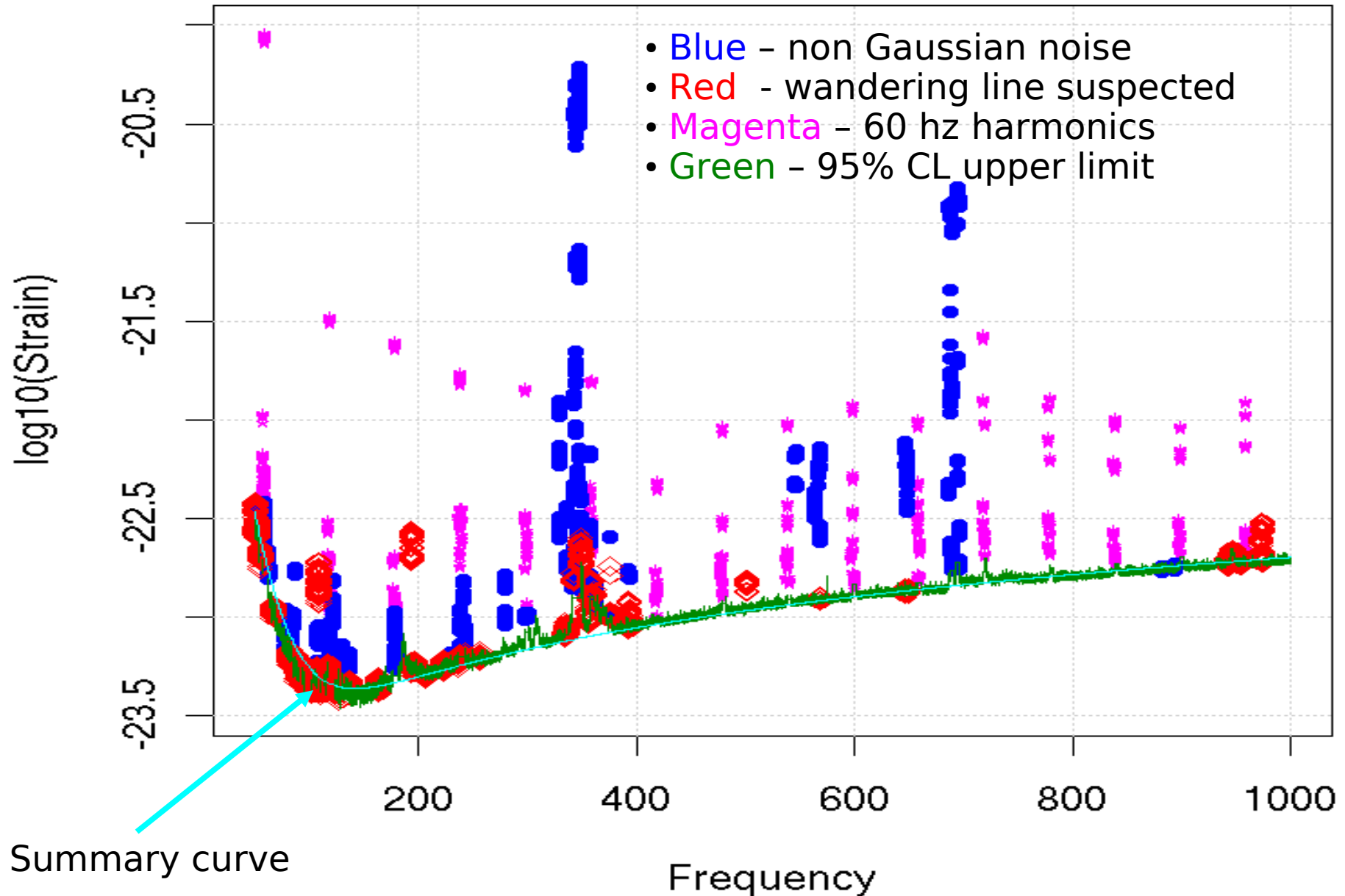
Skyband 10 (worst - many detector artifacts)



S4 run results

Hanford 4km

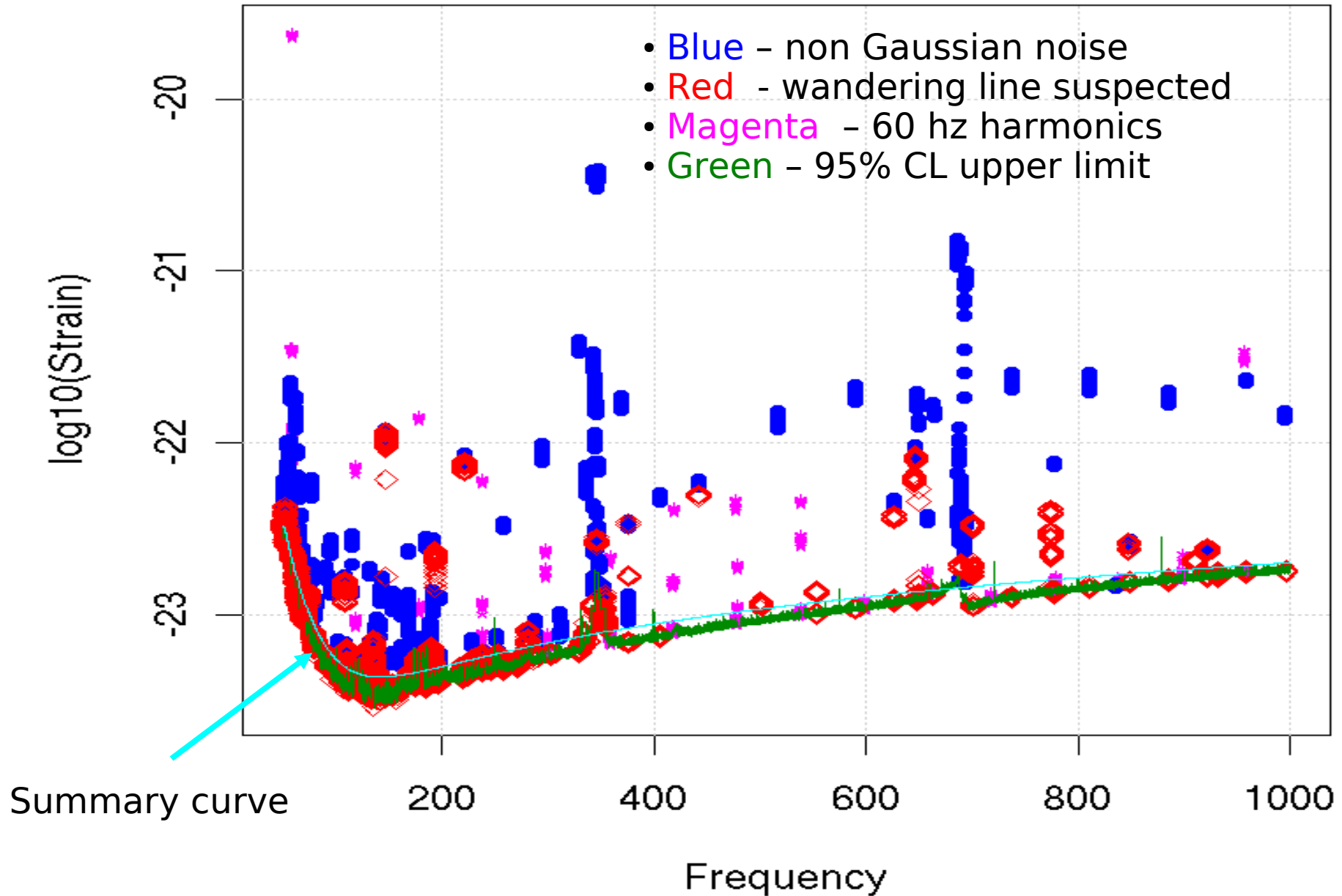
Hanford 4km upper limits are slightly higher than the summary curve, but much cleaner in low frequency range



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

