Aligned-spin searches for compact binary coalescences

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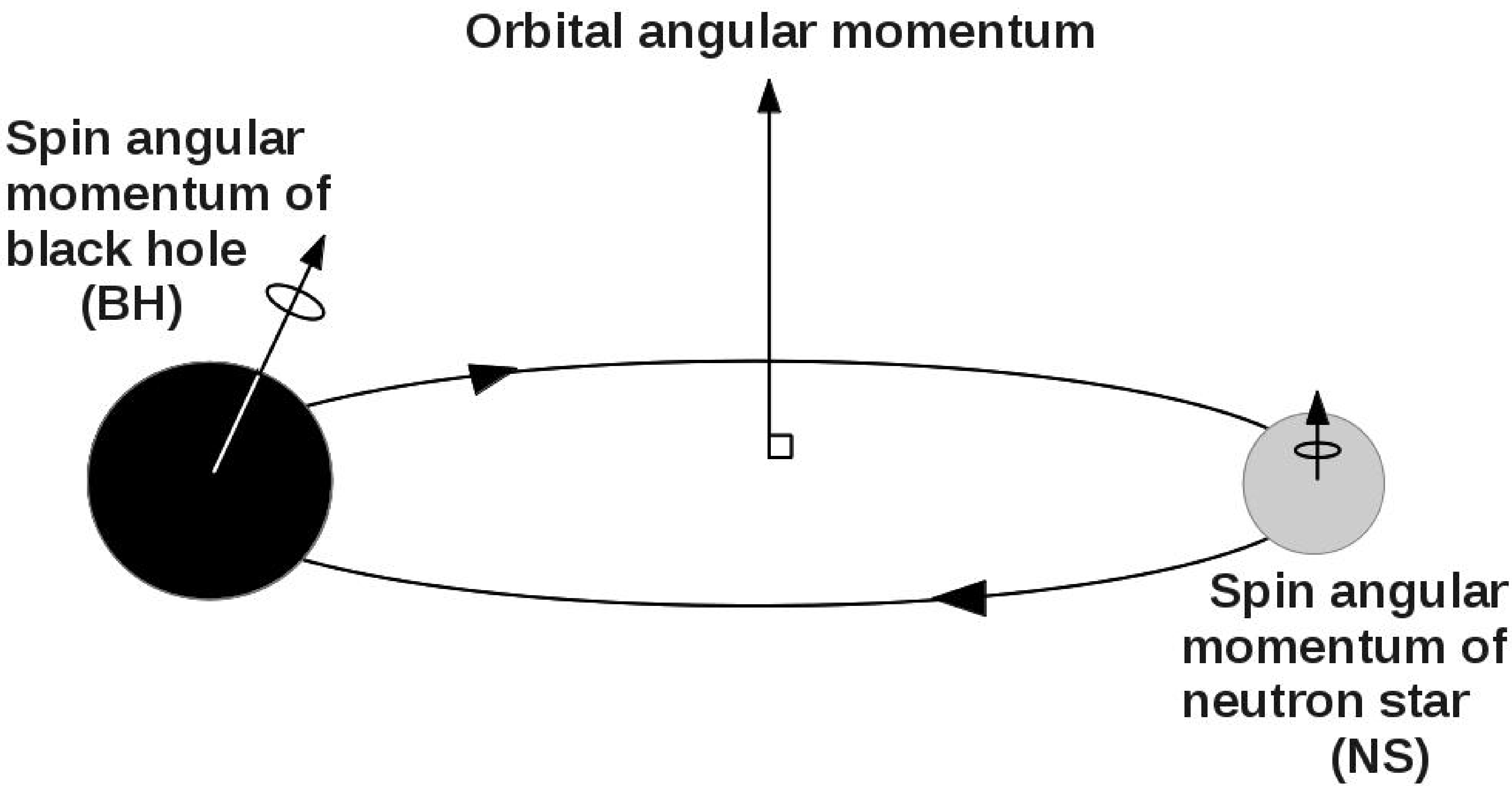
Outline

- Background
- Template banks; spin and no-spin
- Banksims
- Search method
- Missed and recovered injection plots
- ROC curves
- PyCBC and GPUs
- Conclusions


Orbital angular momentum
Spin angular momentum of black hole (BH)
Spin angular momentum of neutron star (NS)

NSBH as spinning sources

- Black holes in Neutron Star-Black Hole (NSBH) binary systems may have considerable spin.
- The neutron stars are not likely to be spinning much so we can concentrate on single exact spin on BH.
- The lightness of NSBH systems means that motion and signal are more strongly affected by spin.
- Lighter NSBH systems merge at higher frequencies so merger and ringdown can be neglected.
- The chance of neutron star tidal disruption is greatly enhanced with spinning black holes.

Main points today

- Spin of black holes in compact binaries is *likely* to be large
- The effect of ignoring it is *noticeably* detrimental to our searches
- The tools *exist* to search for aligned spinning systems and a search is computationally viable

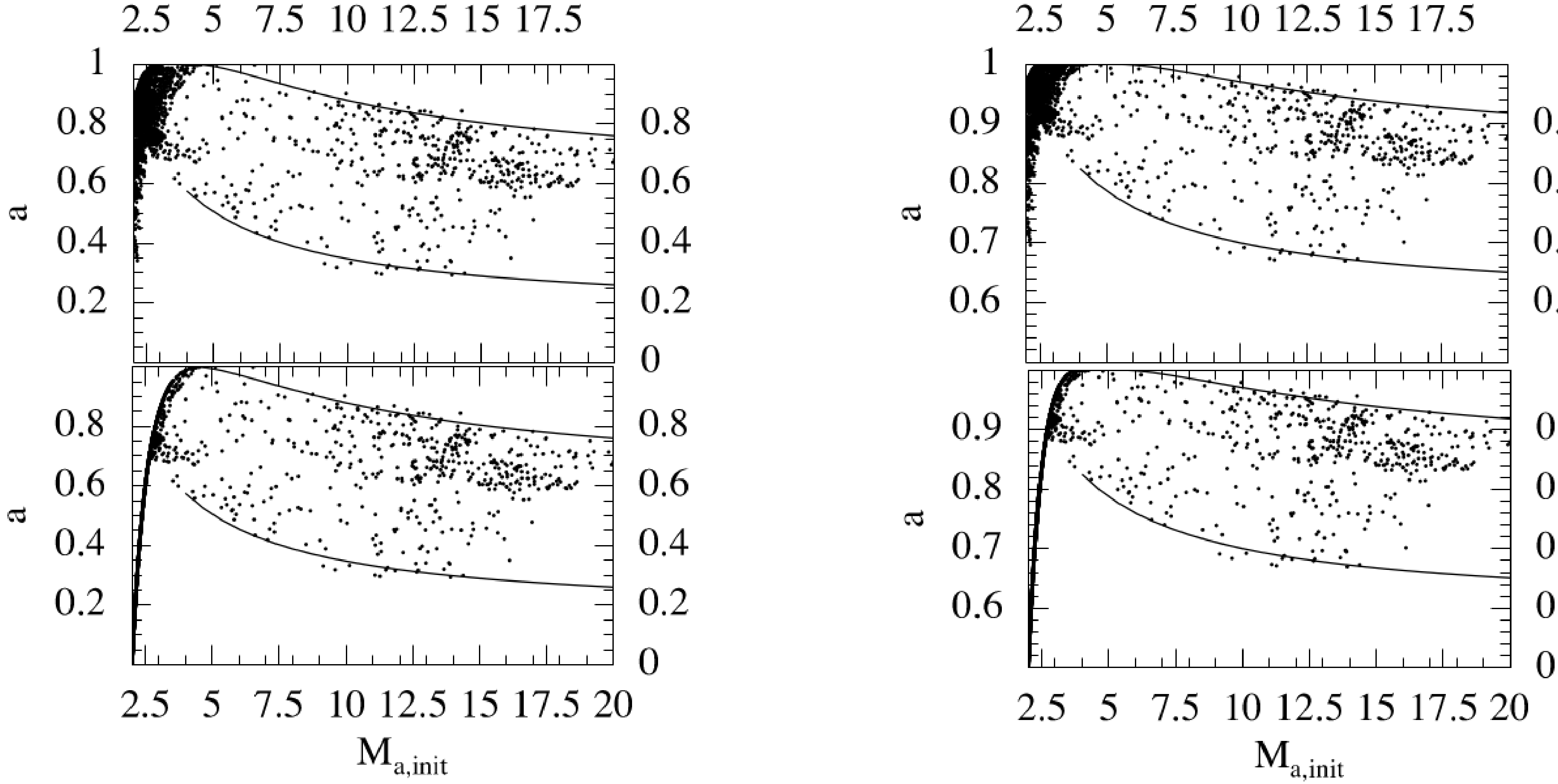
Stellar mass black hole parameters

system	binary type	M_solar	D (kpc)	method	a_*
A0620-00	LMXBT K 0.5	6.61±0.12	1.06±0.12	CF	0.12±0.18[4]
XTE J1550-564	LMXBT G or K 1.5 1.54 days	9.10±0.61	4.38±0.50	CF QPO Fe	0.34±0.28[8] 0.7±0.01[2] 0.55±0.22[8]
GRO J1655-40	LMXBT F5 2.6 days	6.30±0.27	3.2±0.5	CF QPO	0.7±0.05[4] 0.75±0.01[2]
GRS 1915+105	LMXBT KIII 30.8 days	14.0±4.4	11.0±1.0	CF QPO	>0.98[4] 0.68±0.08[2]
4U 1543-47	LMXBT Roche	9.4±1.0	7.5±1.0	CF	0.80±0.05[4]
H 1743-322	LMXBT Roche	11.3	10	QPO QPO	>0.68[1] 0.74[2]
LMC X-3	LMXB transit	10	50	CF	<0.3[4]
M33 X-7	HMXB wind	15.65±1.45	840±20	CF	0.84±0.05[4]
LMC X-1	HMXB wind	10.9	50	CF	0.92±0.07[4]
Cyg X-1	HMXB wind OB 19.2±1.9 5.6days	14.8±1.0	1.86±0.12	QPO Fe CF	0.49±0.01[5] 0.97±0.02[6] >0.983(3σ)[3,7]

Sources: *1. Mondal, ApJ 708 (2010),*
2. Mukhopadhyay, ApJ 694 (2009)
3. Gou et al., ApJ 742 (2011)
4. McClintock et al.,, CQG 28 (2011)
5. Axelsson et al., AA 438 (2005),
6. Fabian et al., 1204.5854
7. Gou et al. 1308.4760
8. Steiner et al. MNRAS 416 (2011)

Effect on spins due to common envelope phase

Black hole final spins due to HCE phase (top) and accretion after collapse (bottom) assuming BH natal spins of 0 (left) and 0.5 (right).

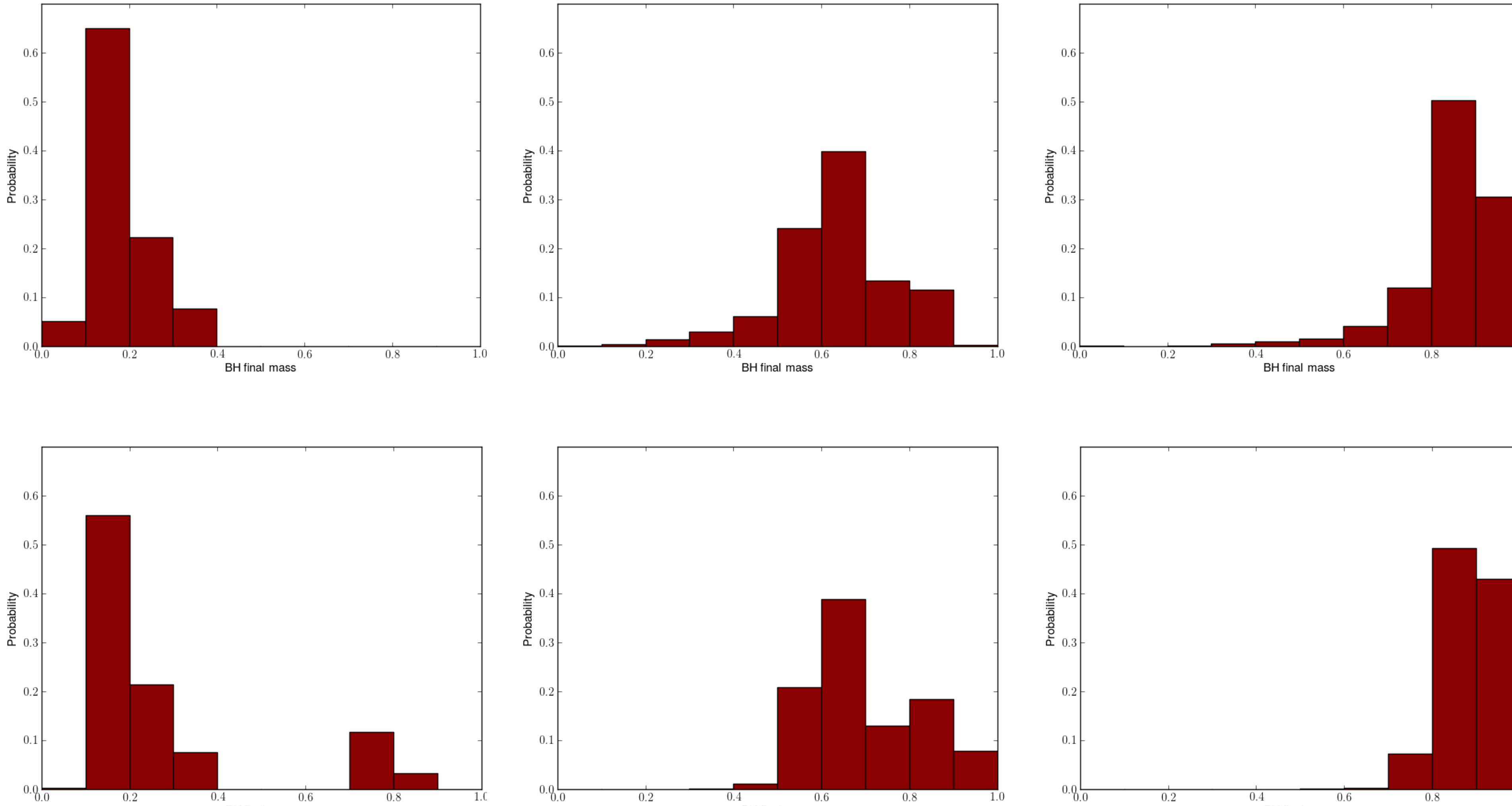


Source: O'Shaughnessy et al. ApJ 632 (2005)

HCE effect on spin distribution

0 natal BH spin

0.75 natal BH spin

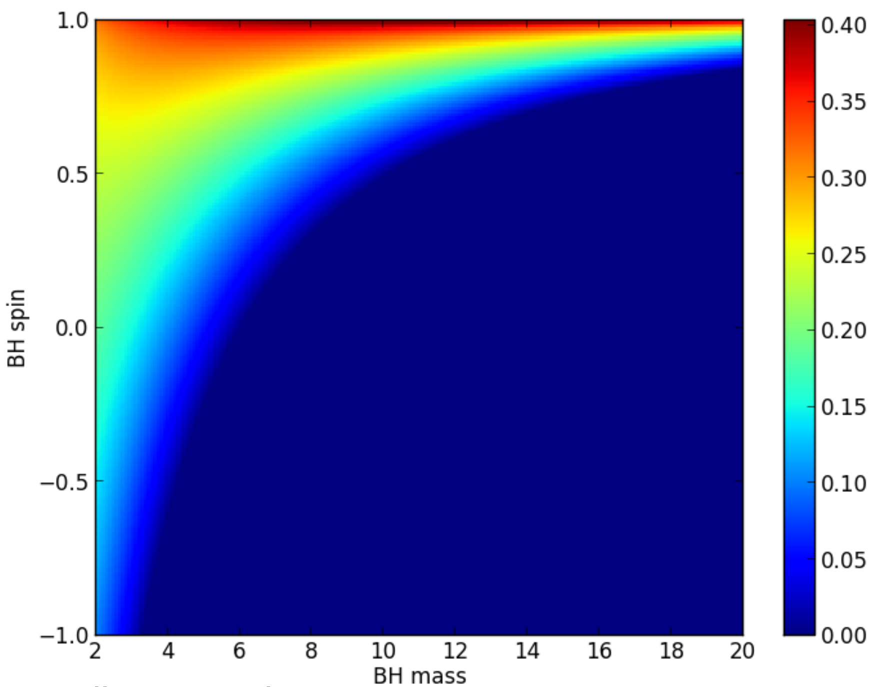


0.1 efficiency in HCE

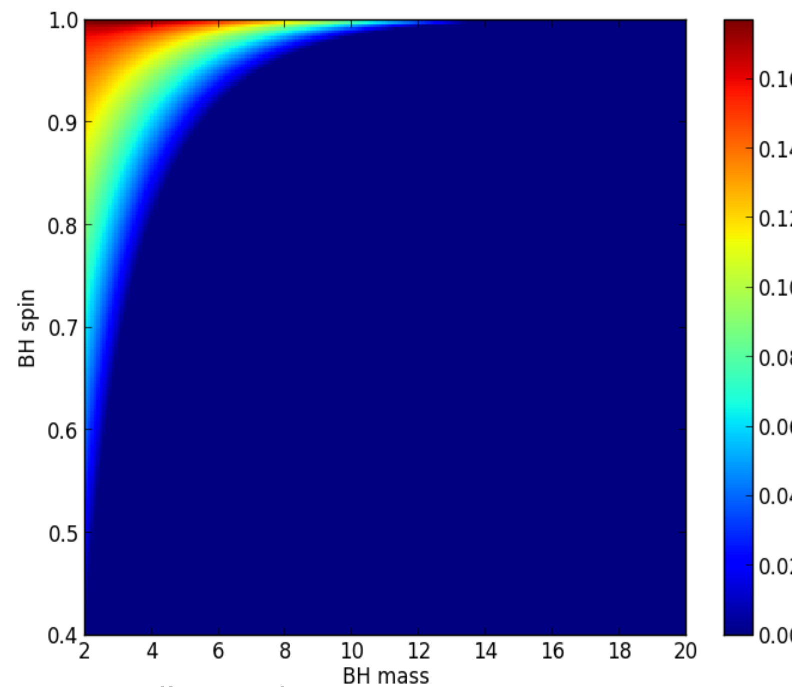
0.5 efficiency in HCE

1.0 efficiency in HCE

Tidal disruption and r-process



NS radius = 15.5km



NS radius = 9km

Previous work I

Apostolatos, Phys.Rev. D54 (1996) 2421-2437

TABLE I. This table presents the FF values for a Newtonian, a post^{1}-Newtonian, a post$^{1.5}$-Newtonian signal with maximal spin parameter β, and a post^{2}-Newtonian signal with maximal spin parameters β and σ, being searched for by the four corresponding families of templates: the Newtonian family, the post^{1}-Newtonian family, the post$^{1.5}$-Newtonian family with vanishing spins, and the post^{2}-Newtonian family with vanishing spins. For every case, two FF values are given, corresponding to a $10M_{\odot}$,$1.4M_{\odot}$ black-hole–Neutron-star (BH/NS) binary and a $1.4M_{\odot}$,$1.4M_{\odot}$ NS-NS binary. The modulational effects are absent since the spins and angular momenta are considered aligned. The numbers quoted in this table are discussed more extensively in Sec. III.

	N signal	P^{1}-N signal	$P^{1.5}$-N signal (β maximal)	P^{2}-N signal (β,σ maximal)
N templates:	1.000 (BH-NS) 1.000 (NS-NS)	0.559 (BH-NS) 0.465 (NS-NS)	0.677 (BH-NS) 0.535 (NS-NS)	0.669 (BH-NS) 0.531 (NS-NS)
P^{1}-N templates:		1.000 (BH-NS) 1.000 (NS-NS)	0.719 (BH-NS) 0.612 (NS-NS)	0.729 (BH-NS) 0.620 (NS-NS)
P$^{1.5}$-N templates: (β=0)			0.988 (BH-NS) 0.986 (NS-NS)	0.990 (BH-NS) 0.993 (NS-NS)
P^{2}-N templates: (β,σ=0)				0.979 (BH-NS) 0.989 (NS-NS)

Previous work II

- **Abbott *et al.*, Phys.Rev. D78 (2008) 042002** *"We find that our search of S3 LIGO data had good sensitivity to binaries in the Milky Way and to a small fraction of binaries in M31 and M33 with masses in the range 1.0 Msol $< m1, m2 <$ 20.0 Msol. No gravitational wave signals were identified during this search."*

- **Van Den Broeck *et al.*, Phys.Rev. D80 (2009) 024009** *"We recommend the continued use of the non-spinning stationary phase template bank until the **false alarm rate** associated with templates which include spin effects can be substantially reduced."*

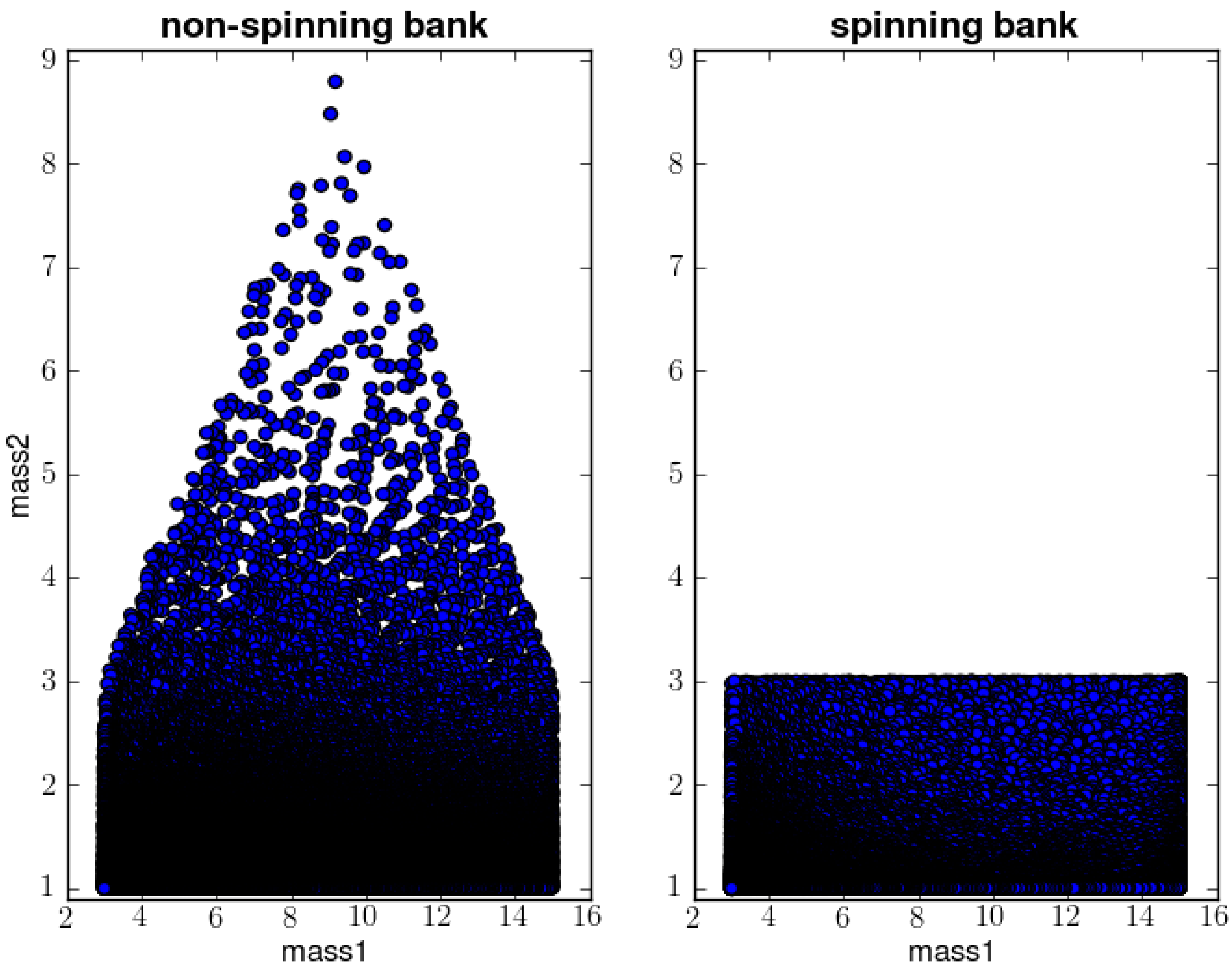
What makes this possible?

- Wider, better detector sensitivity in **aLIGO era**
- Better knowledge of spin effects at **higher pN**
- **Use signal vetoes** in non-Gaussian data; chi squared and new SNR
- Faster analysis tools, **running on GPUs**
- More **scalable database**

Template banks for comparison

- Stochastic placement
  `pycbc_aligned_stoch_bank`
- TaylorF2, 30Hz to ISCO
- non-spinning: BH mass 3-15, NS mass 1-equal
- spinning: BH mass 3-15, NS mass 1-3,
  BH spin -1 to 1, NS spin -0.4 to 0.4

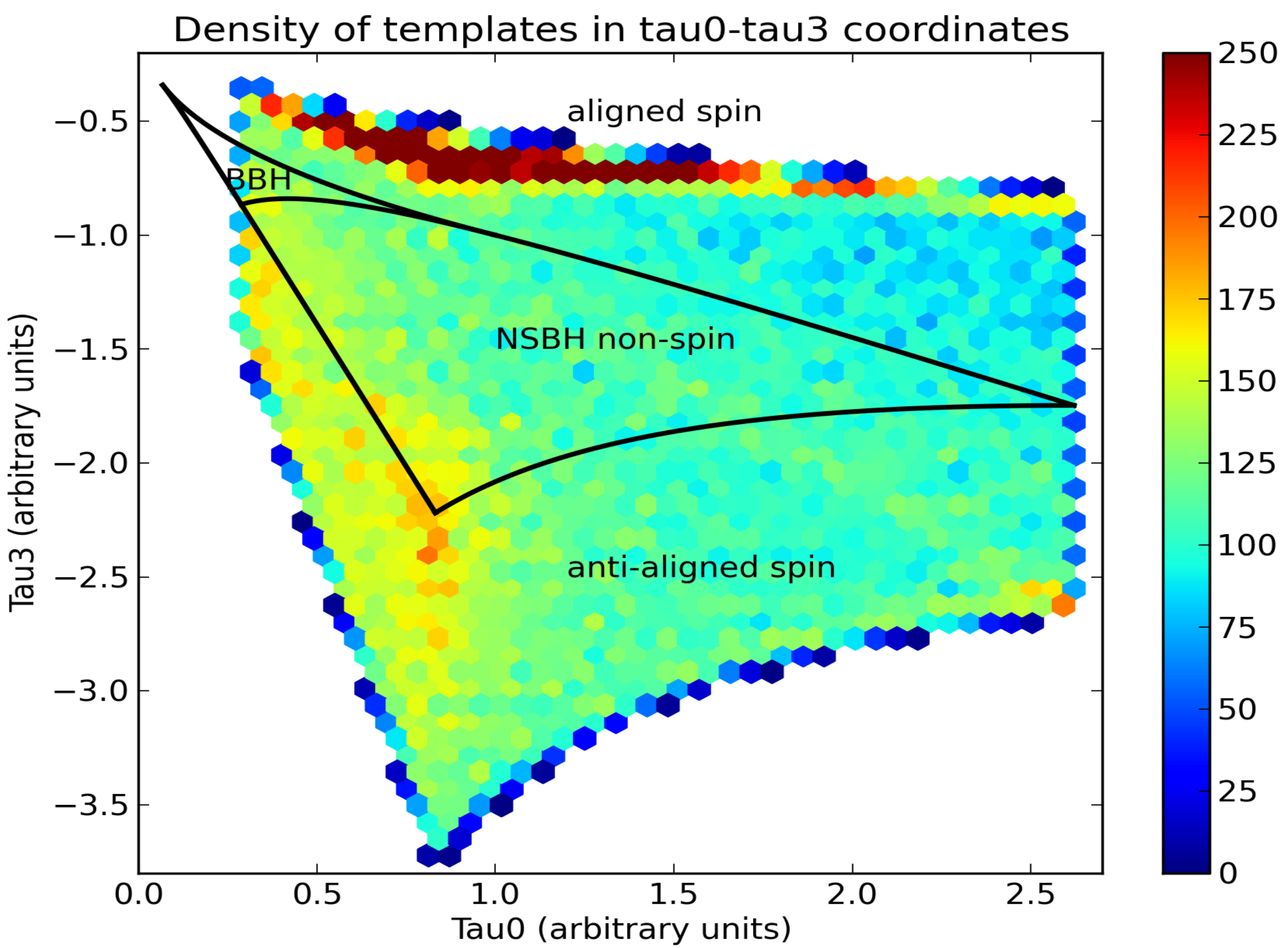
Comparison of bank mass distributions



27,752 templates **150,977 templates**

Spinning template banks for early aLIGO

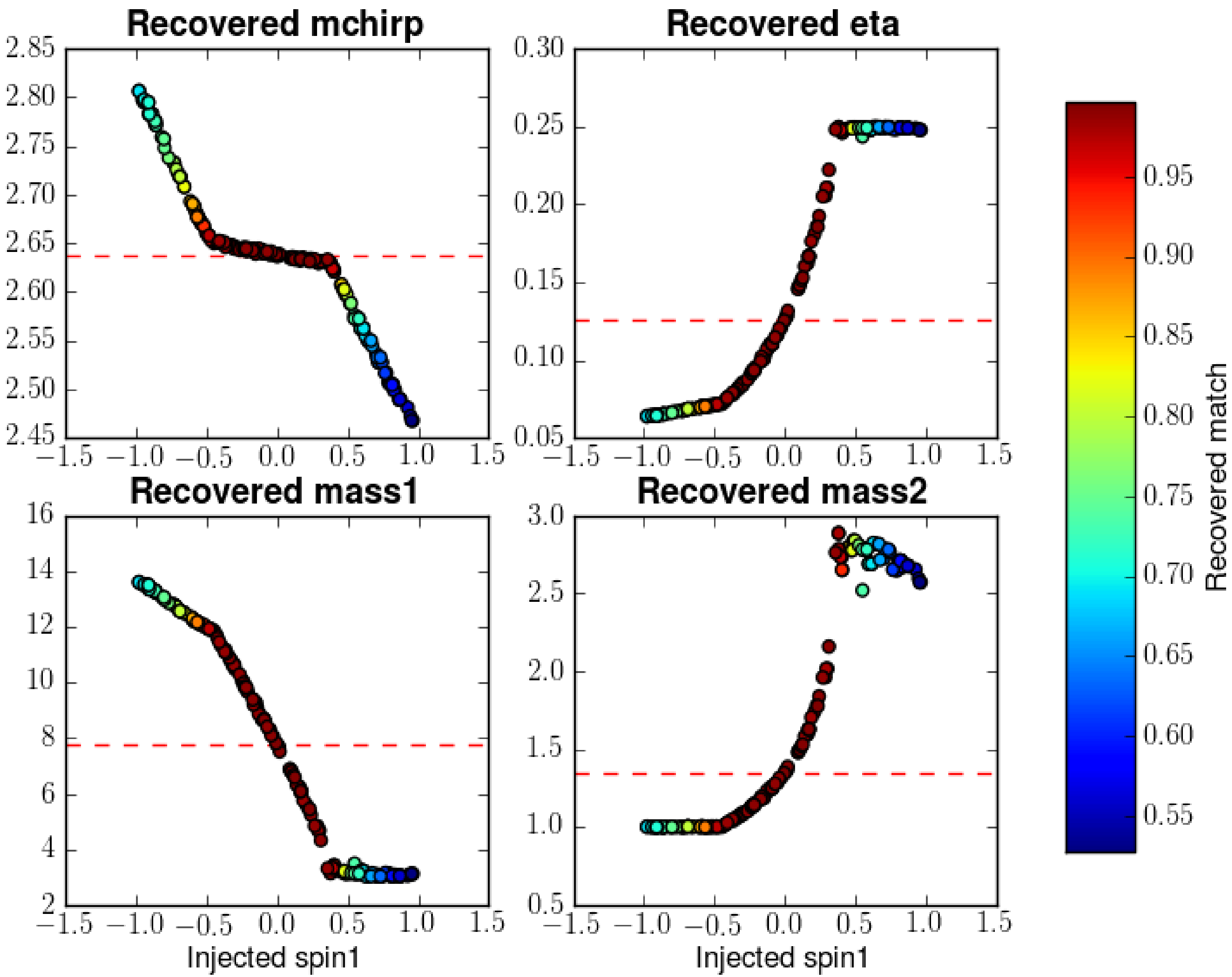
- 27,752 templates in non spinning stochastic
- 150,977 templates in spinning stochastic



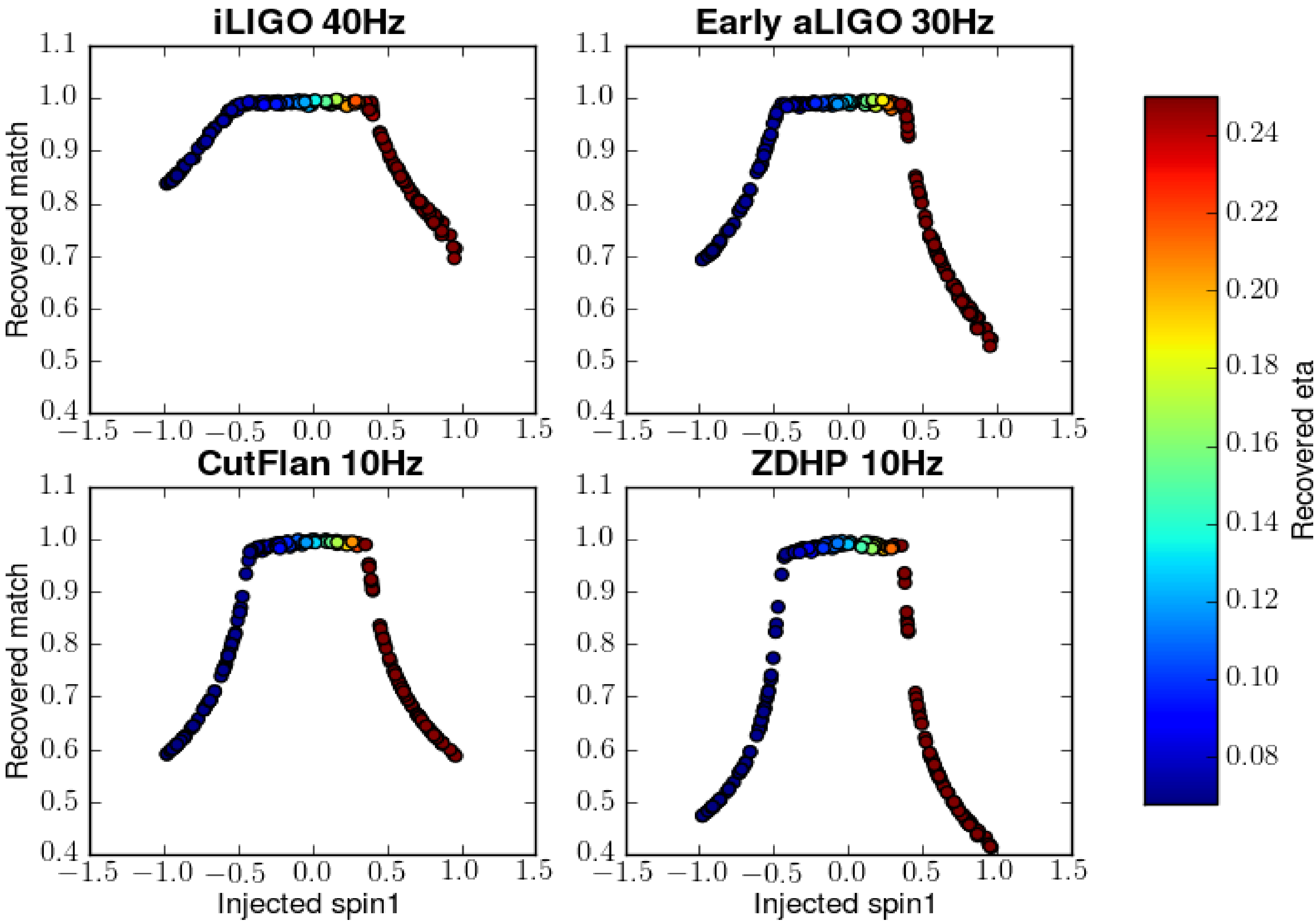
Banksims

- `pycbc_banksim`
- 7.8M_sol, 1.35M_sol, mchirp=2.637, eta=0.126
  BH spin -1 < spin1 <+1, NS spin = 0.
- Match, various sensitivities, various banks
- Recovered parameters non-spinning
- Recovered parameters spinning

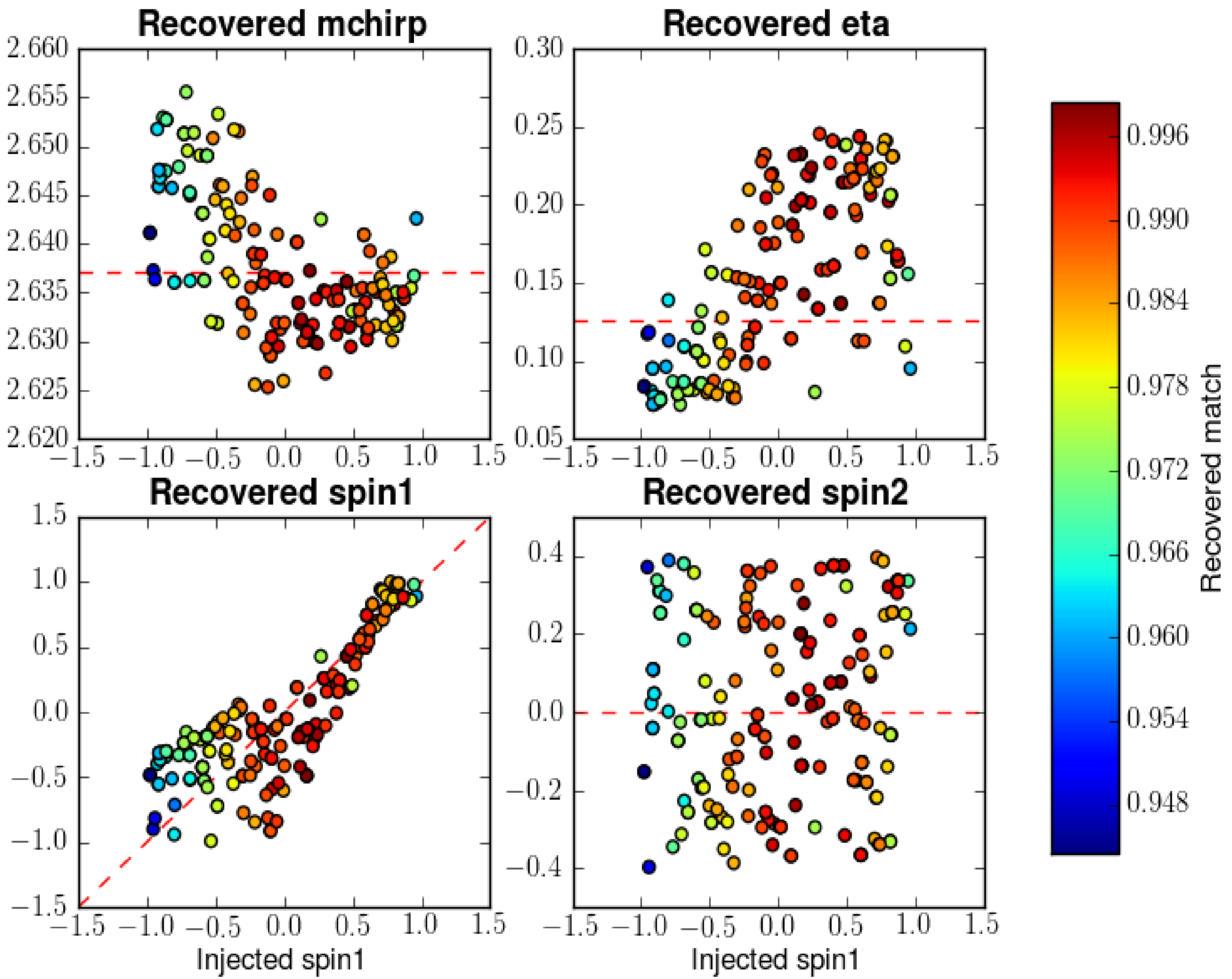
Recovered mass parameters in early aLIGO non-spinning bank



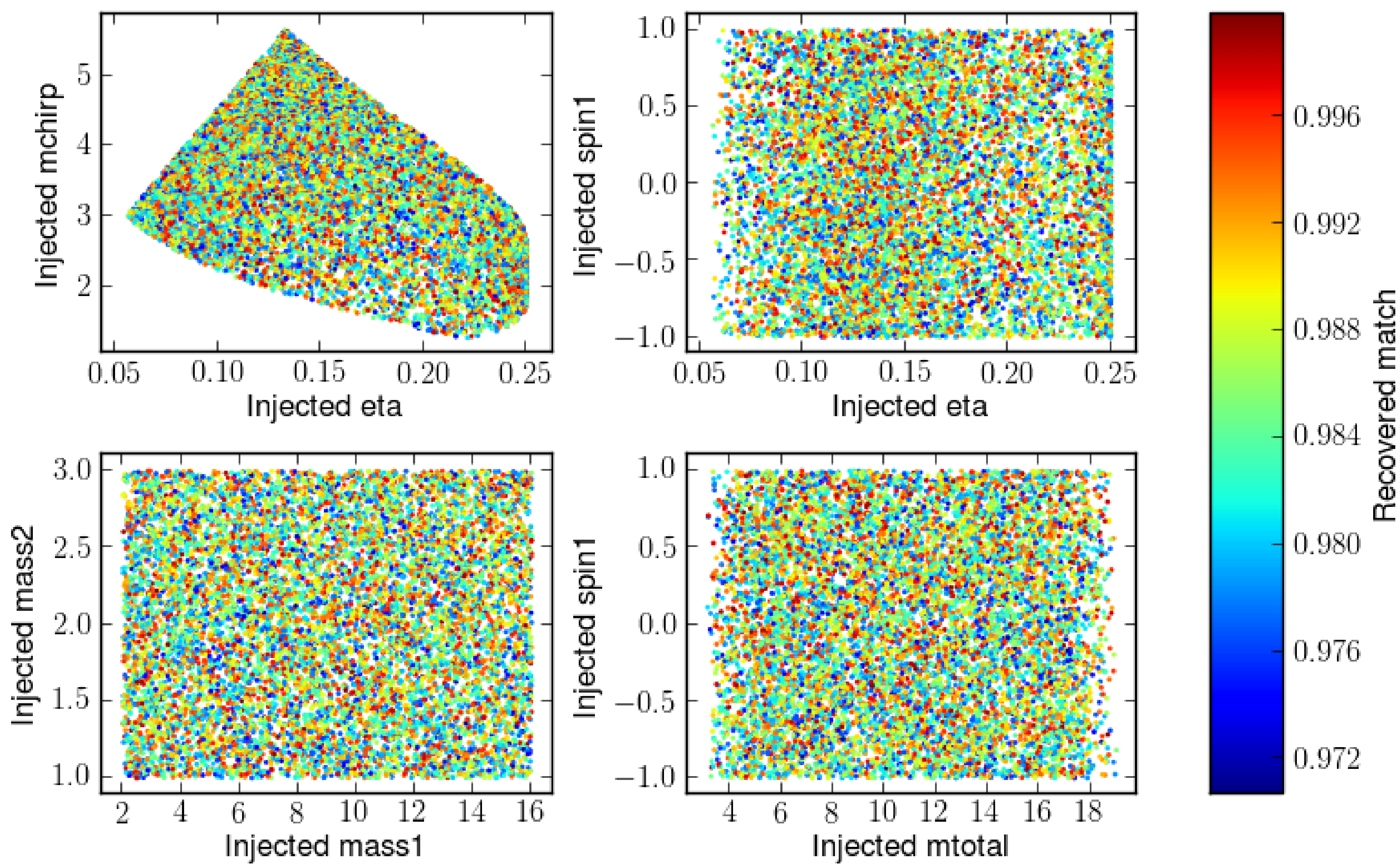
Maximised matches for different sensitivities- non-spinning



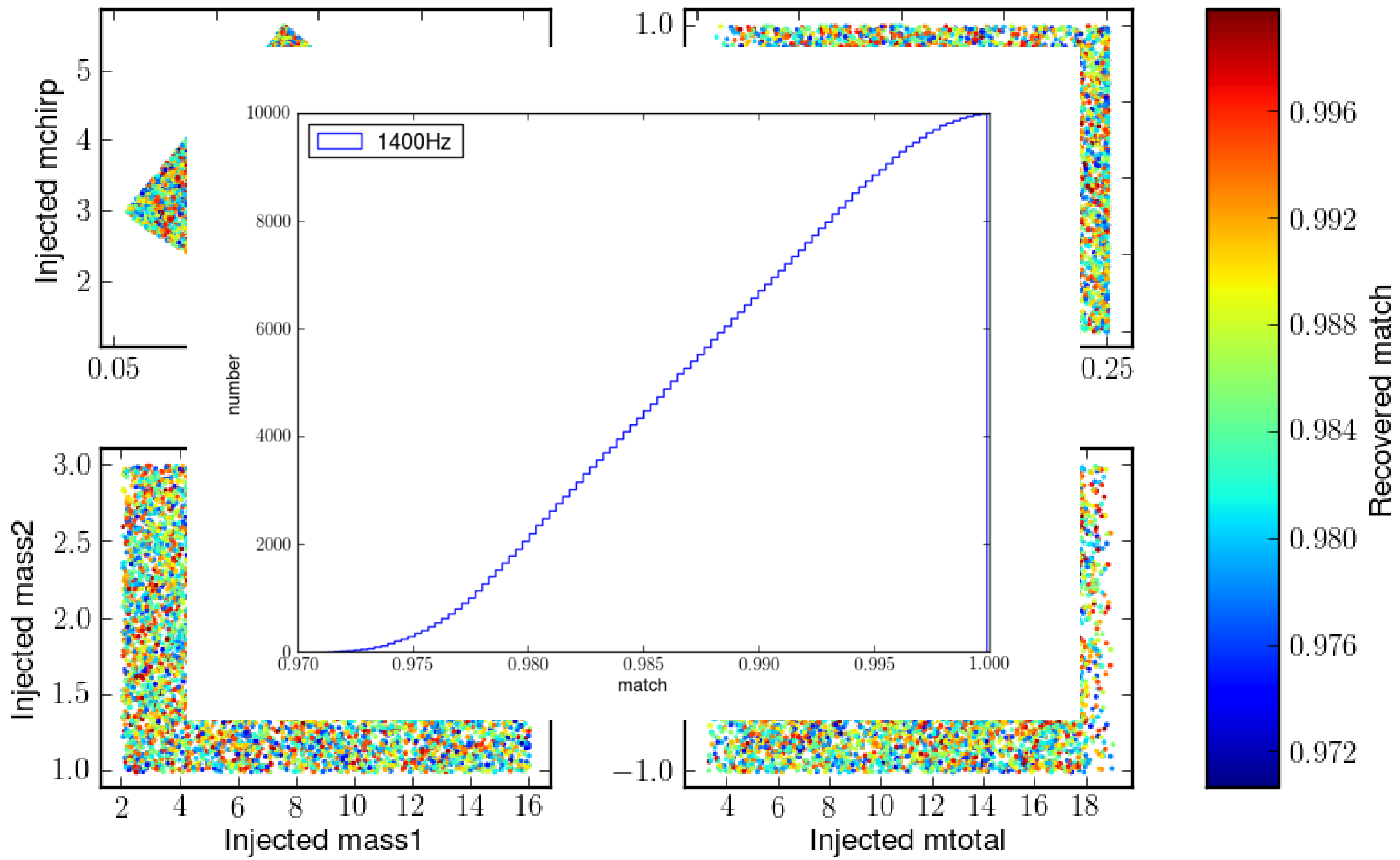
Recovered mass and spin parameters in early aLIGO spinning bank



Match with spinning bank – inspiral signals



Match with spinning bank – inspiral signals



Running a search

- Test on 2 months real (recoloured) S6 data
- Run `pycbc_inspiral`
- Cluster: Atlas, 130x NVIDIA Tesla C2050 GPUs
- Use newSNR as ranking statistic, threshold 5.9
- Database: MongoDB, 9x Intel Xeon X3220 SSDs

- Takes ~5 days

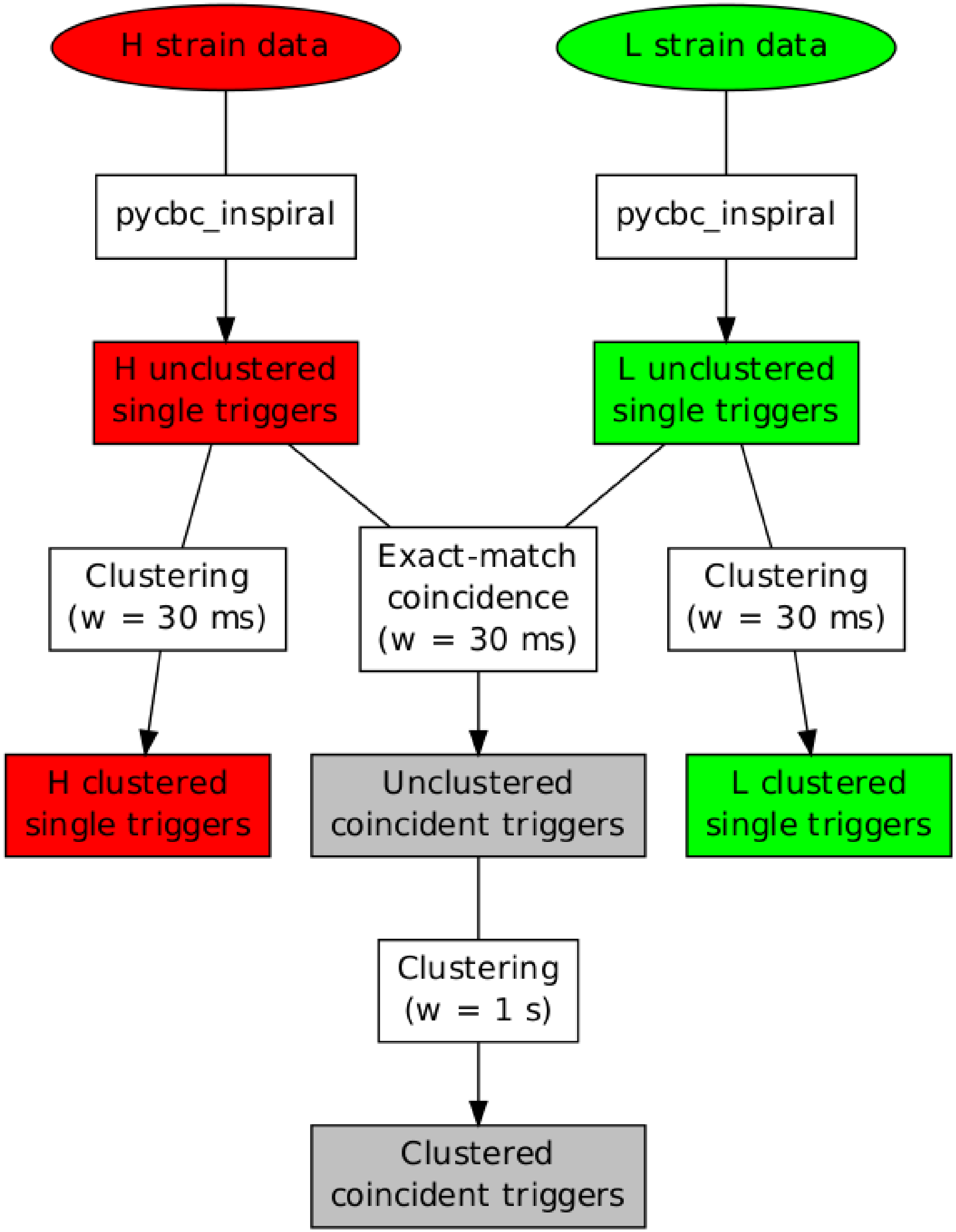
Data used for testing

- S6 recolored to early aLIGO (2016)
- H1 and L1
- Start 966388158 Aug 21, 2010 01:09:03 UTC
- End 971528001 Oct 19, 2010 12:53:06 UTC
- Data courtesy LIGO/LSC

Aligned-spin MongoDB stats

Dataset	Total trigs	H trigs	L trigs	Total clustered trigs	H clustered trigs	L clustered trigs	Total time	H time	L time
recolored_nospin_stoch_noinj	15992368	10038024	5954344	2492037	1512974	979063	72.16 d	36.62 d	35.53 d
recolored_nospin_stoch_inj	18245401	11099490	7145911	2499985	1516402	983583	72.16 d	36.62 d	35.53 d
recolored_spin_stoch_noinj	90492738	56730025	33762713	10185620	5819881	4365739	72.16 d	36.62 d	35.53 d
recolored_spin_stoch_inj	74729267	40270248	34459019	8706147	4571185	4134962	65.47 d	31.89 d	33.58 d

Generated on 2014-01-16 12:38:06 CET


H strain data
L strain data
pycbc_inspiral
pycbc_inspiral
H unclustered single triggers
L unclustered single triggers
Clustering (w = 30 ms)
Exact-match coincidence (w = 30 ms)
Clustering (w = 30 ms)
H clustered single triggers
Unclustered coincident triggers
L clustered single triggers
Clustering (w = 1 s)
Clustered coincident triggers

Using New SNR

Signal to Noise Ratio (SNR)

$$\rho = 4\,\Re \int \frac{e^{-2\pi i f t}\,\tilde{s}(f)\,\tilde{h}^*(f)}{S_n(f)}\,df$$

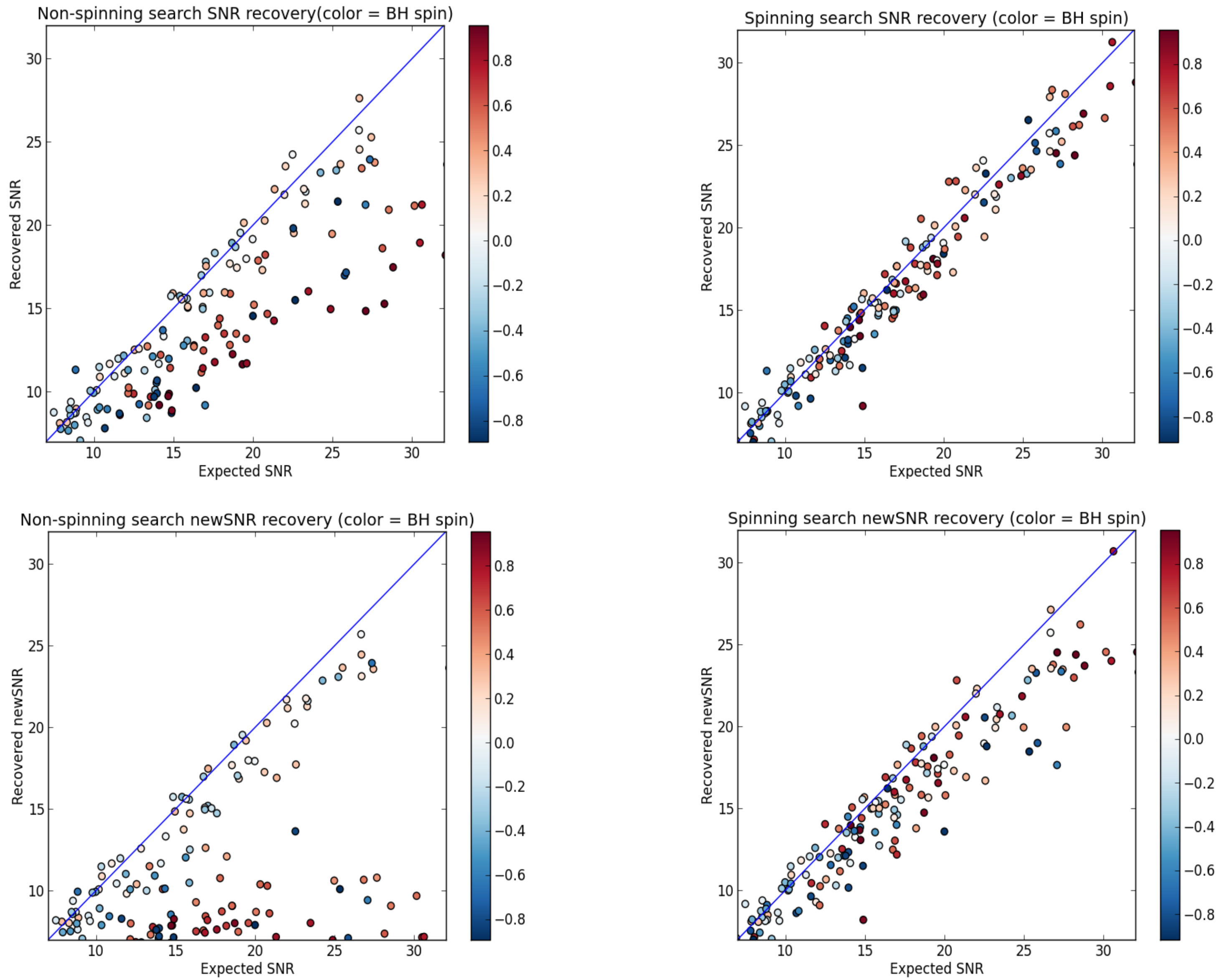
Reduced chi squared

$$\chi_r^2 = \frac{N \sum_{j=1}^{N} \left(\rho_j - \frac{\rho}{N}\right)^2}{2n-2}$$

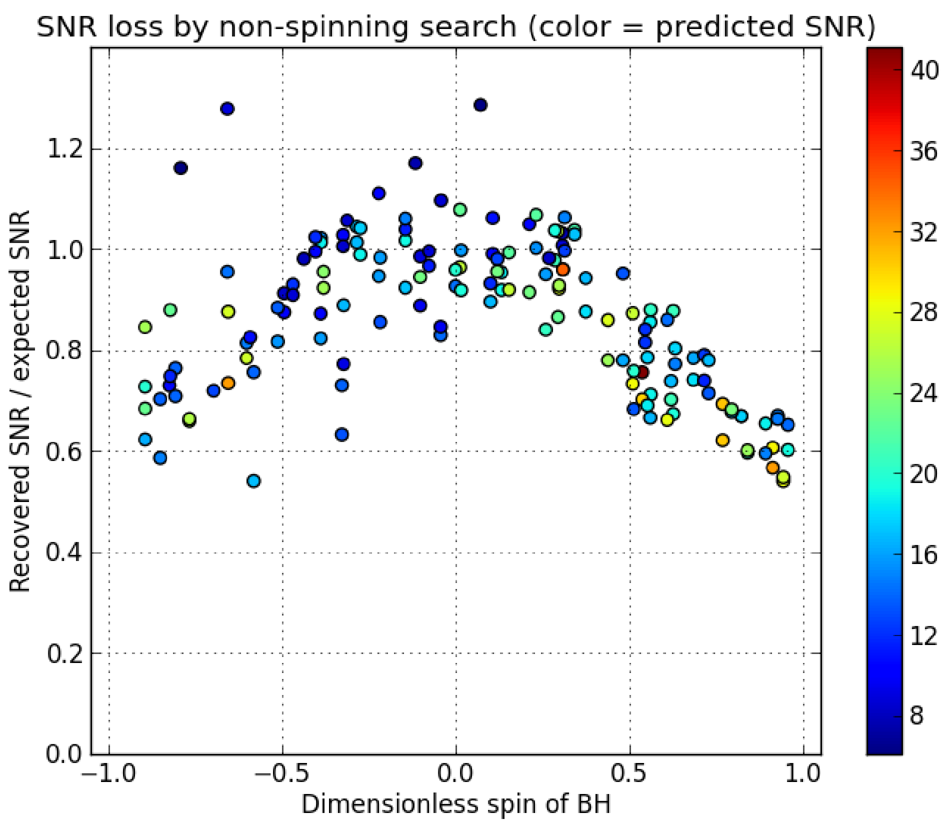
New SNR (re-weighted SNR)

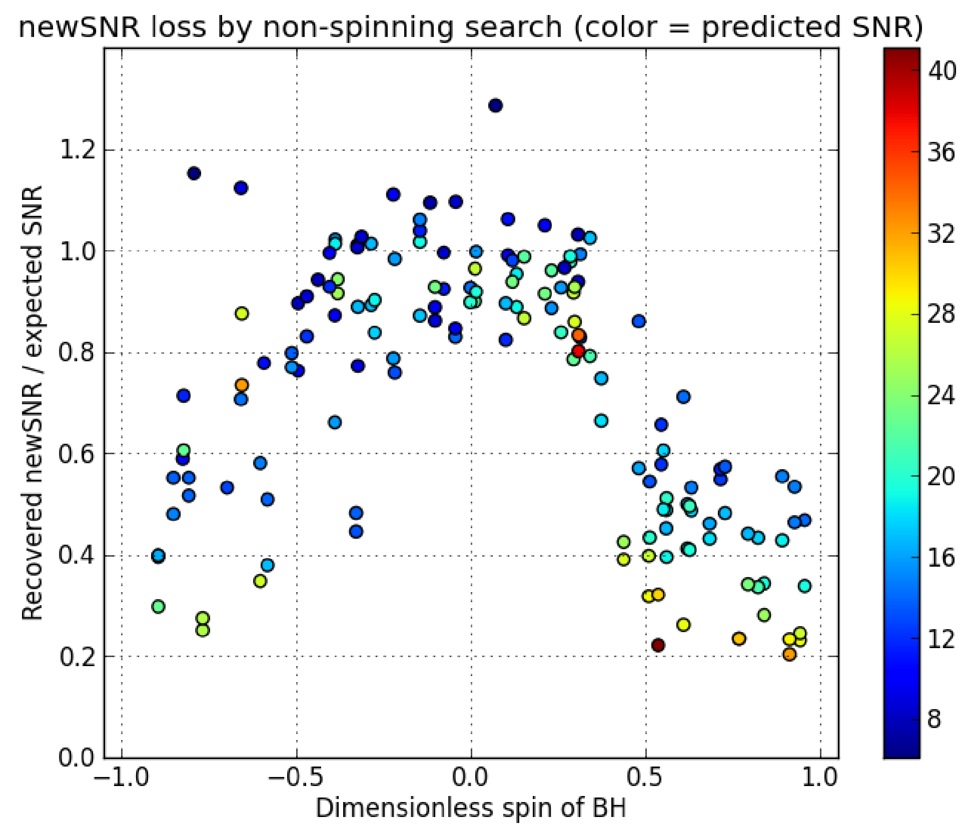
$$\hat{\rho} = \frac{\rho}{\left[\left(1+\left(\chi_r^2\right)^3\right)/2\right]^{1/6}}$$

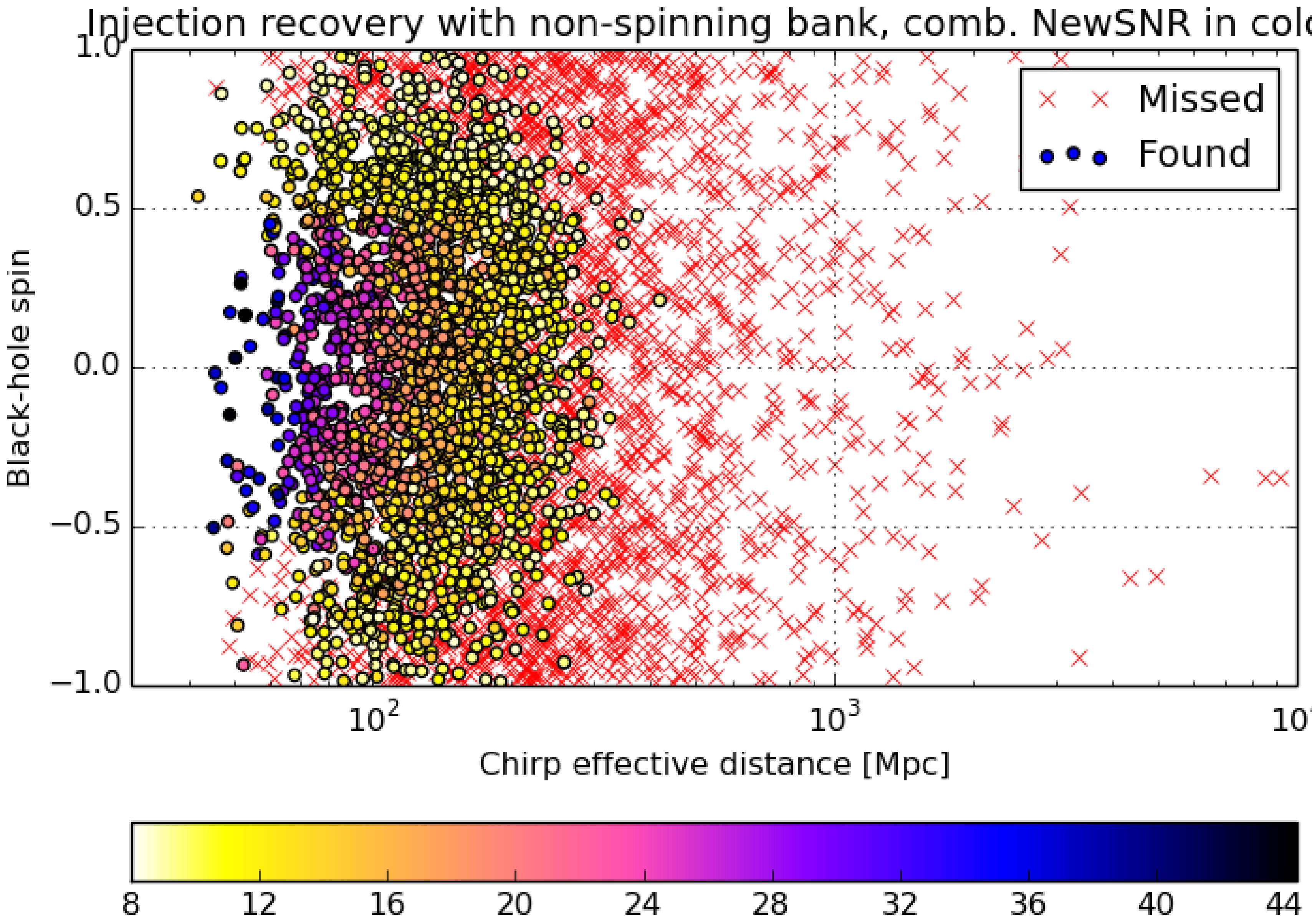
SNR vs newSNR

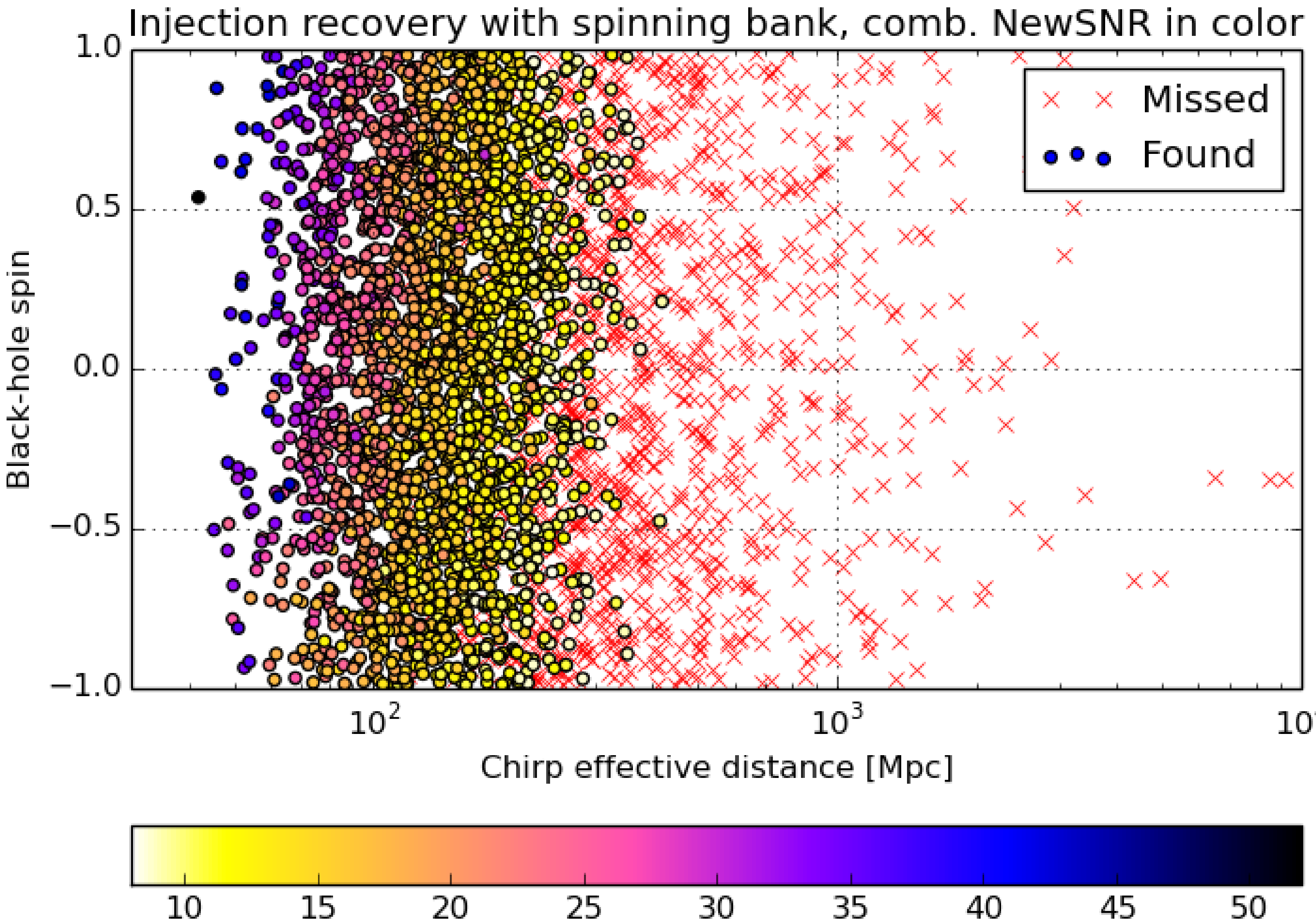


Recovered SNRs relative to expected SNRs for non-spinning templates






Injection recovery with non-spinning bank, comb. NewSNR in color
Missed
Found
Black-hole spin
1.0
0.5
0.0
−0.5
−1.0
10^2
10^3
10^4
Chirp effective distance [Mpc]
8
12
16
20
24
28
32
36
40
44

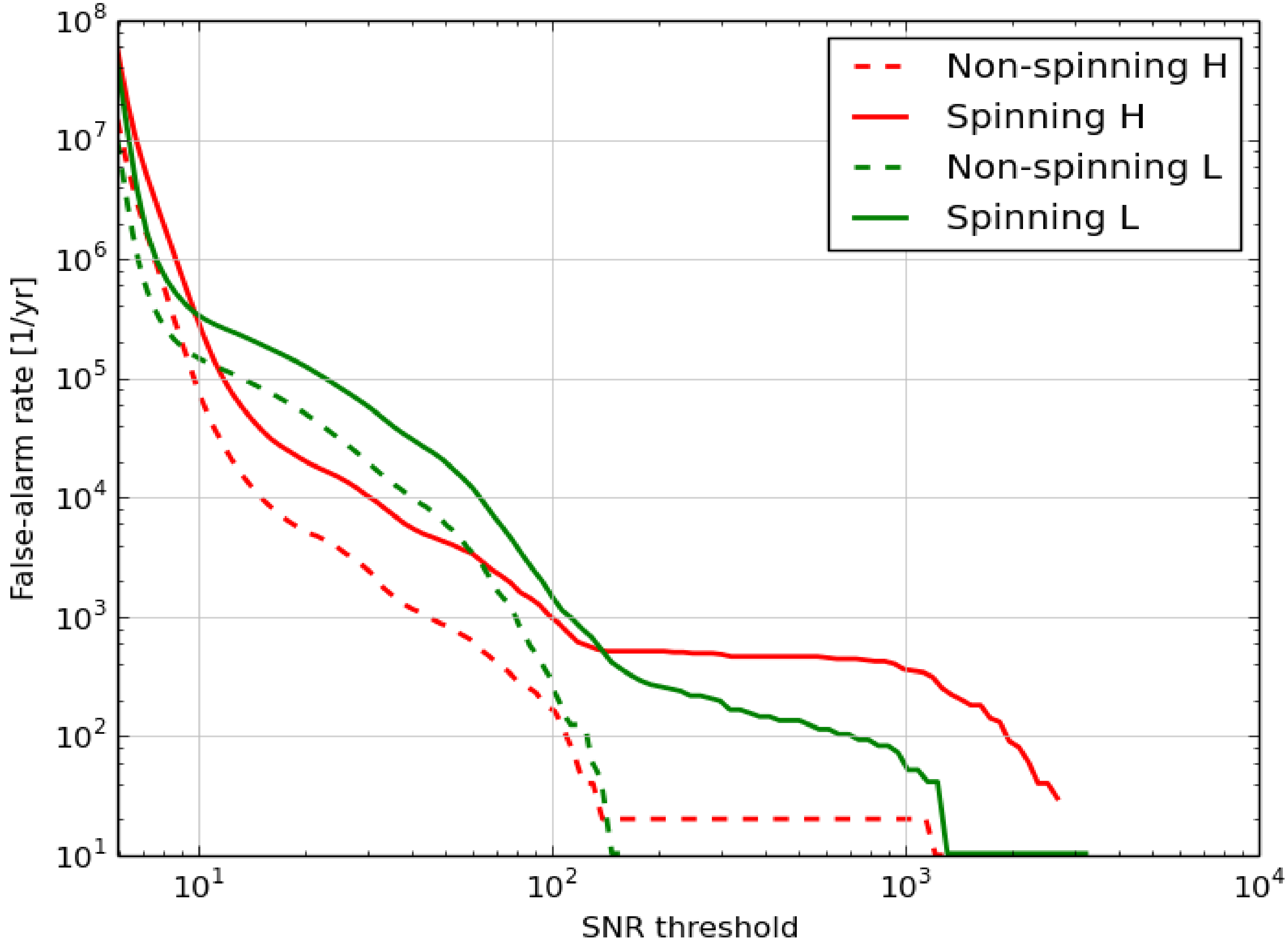


Injection recovery with spinning bank, comb. NewSNR in color
Missed
Found
Black-hole spin
1.0
0.5
0.0
−0.5
−1.0
10^2
10^3
10^4
Chirp effective distance [Mpc]
10
15
20
25
30
35
40
45
50

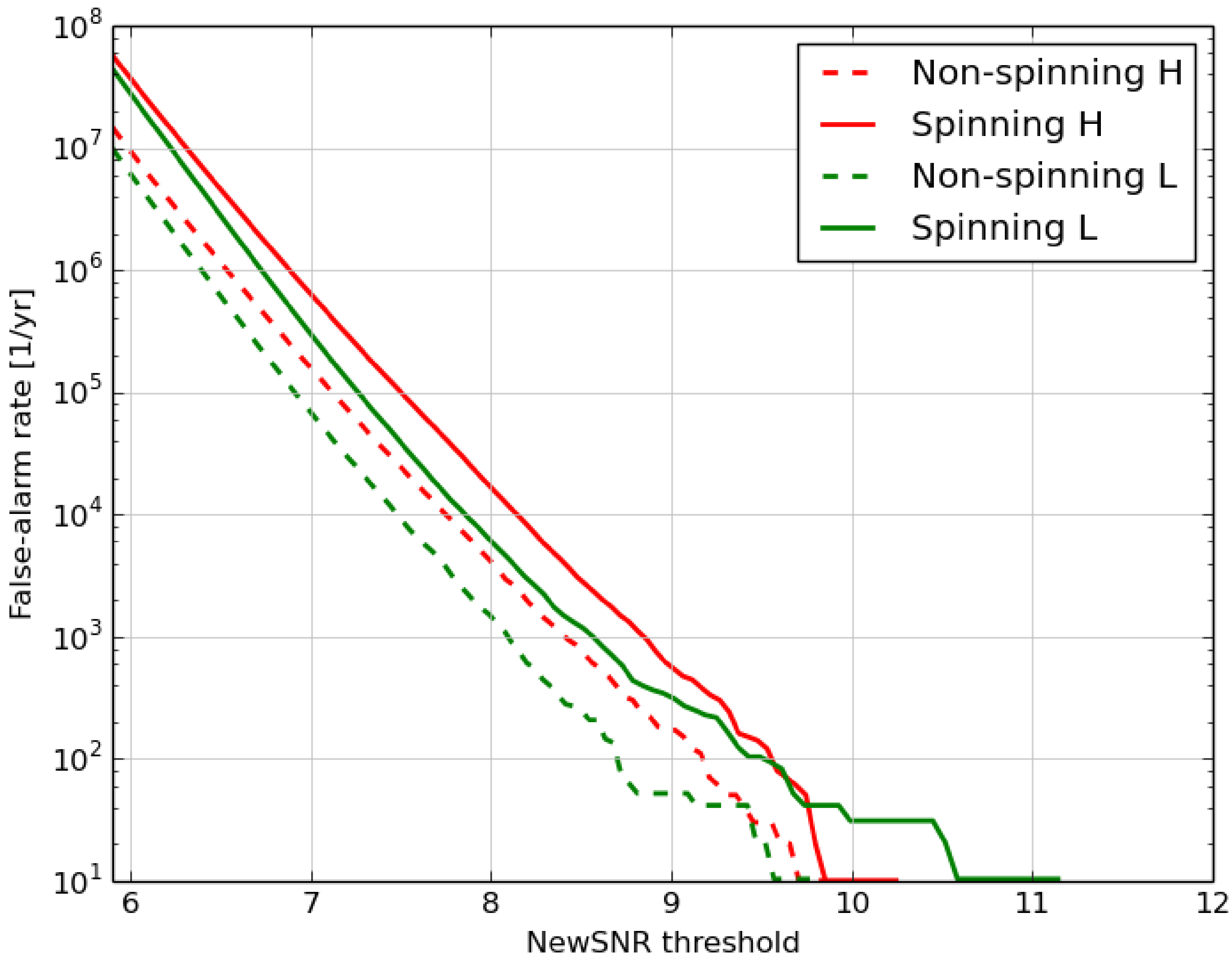
ROC curves

- Single detector
- Coincidence
- Fraction of recovered injections
- Volume vs FAR

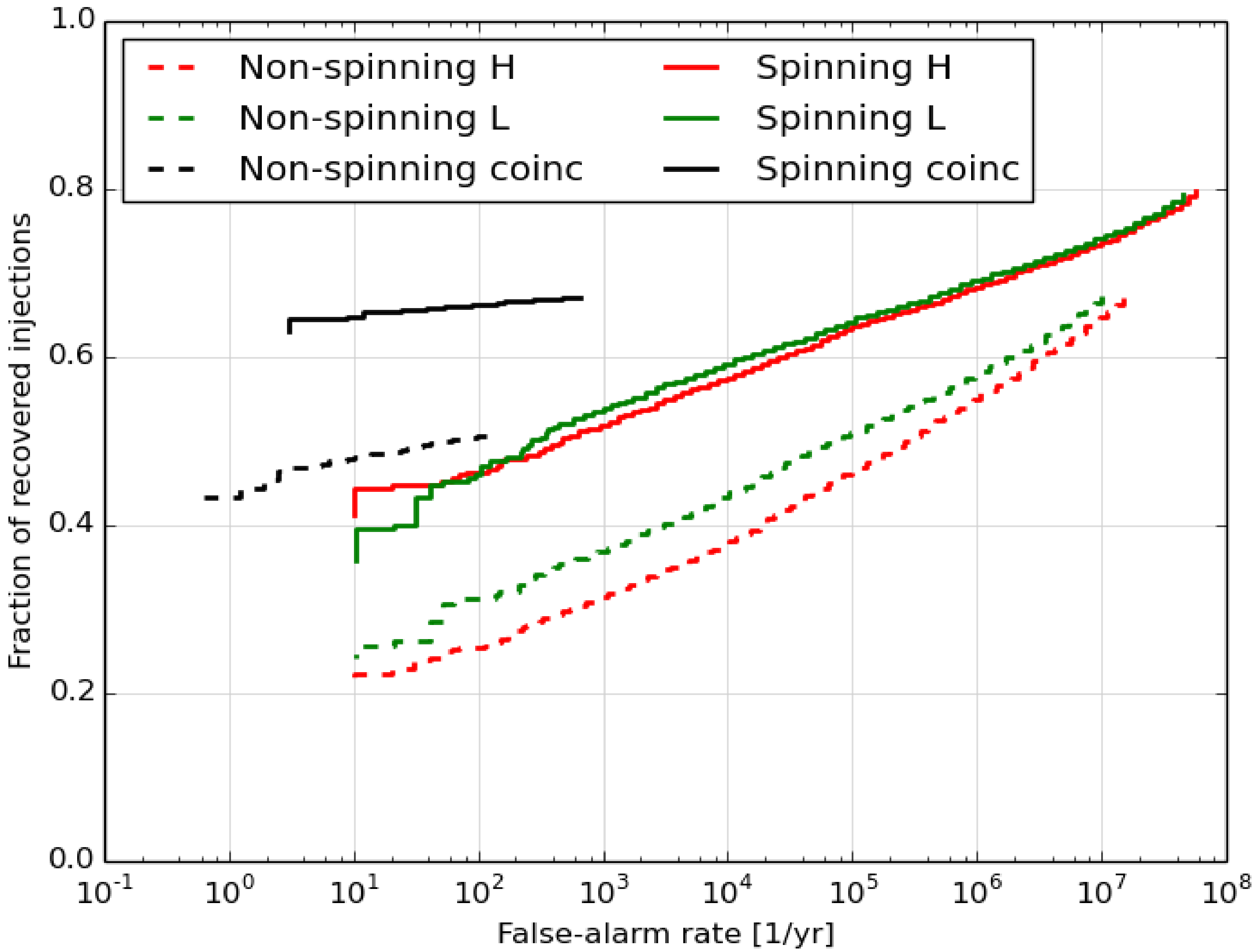
Single detector FAR with SNR



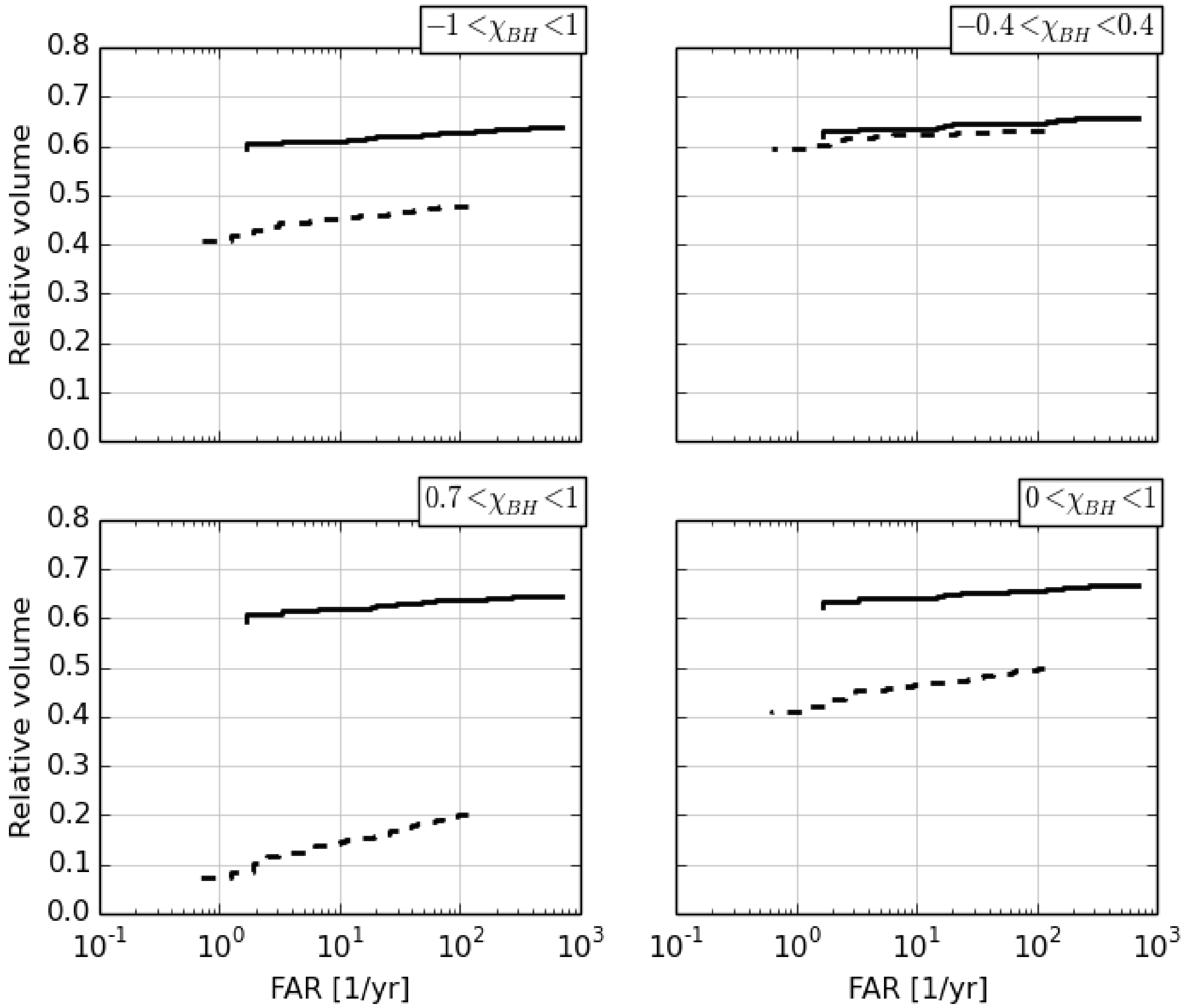
Single detector FAR with NewSNR



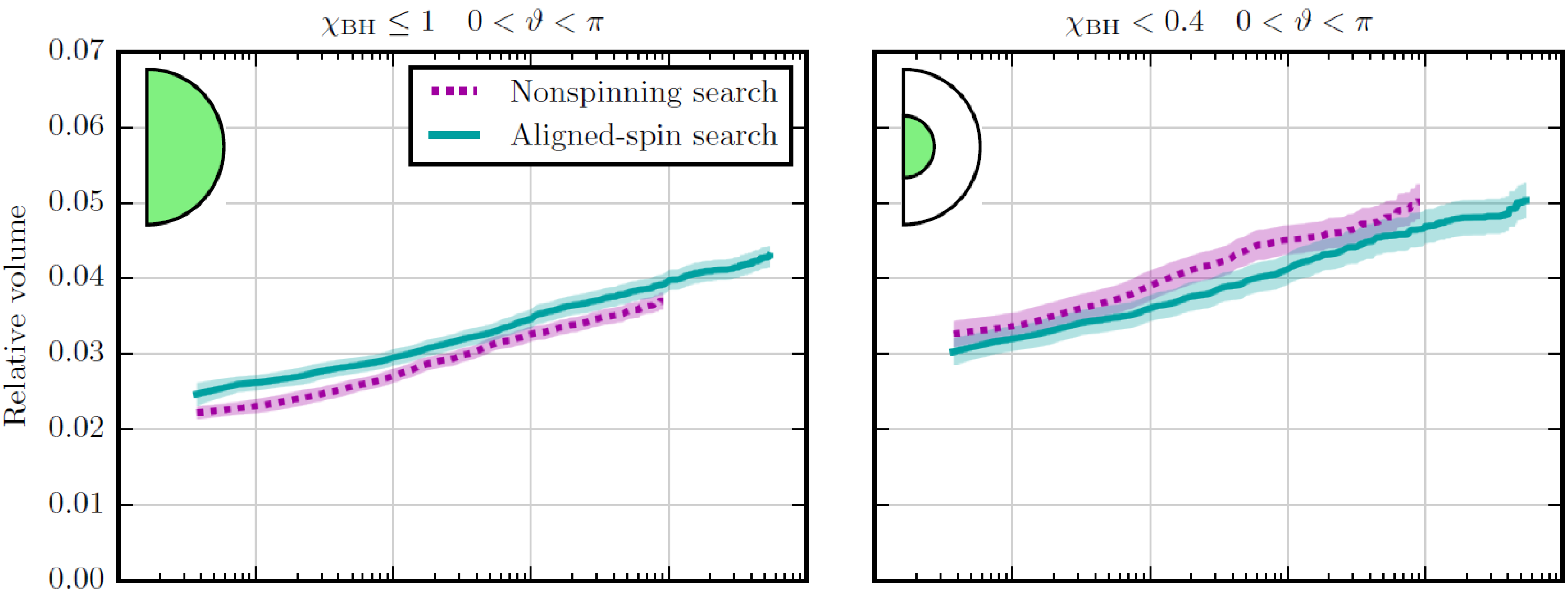
Fraction of recovered injections for single detector and coincidence



Relative volumes for different spin distributions



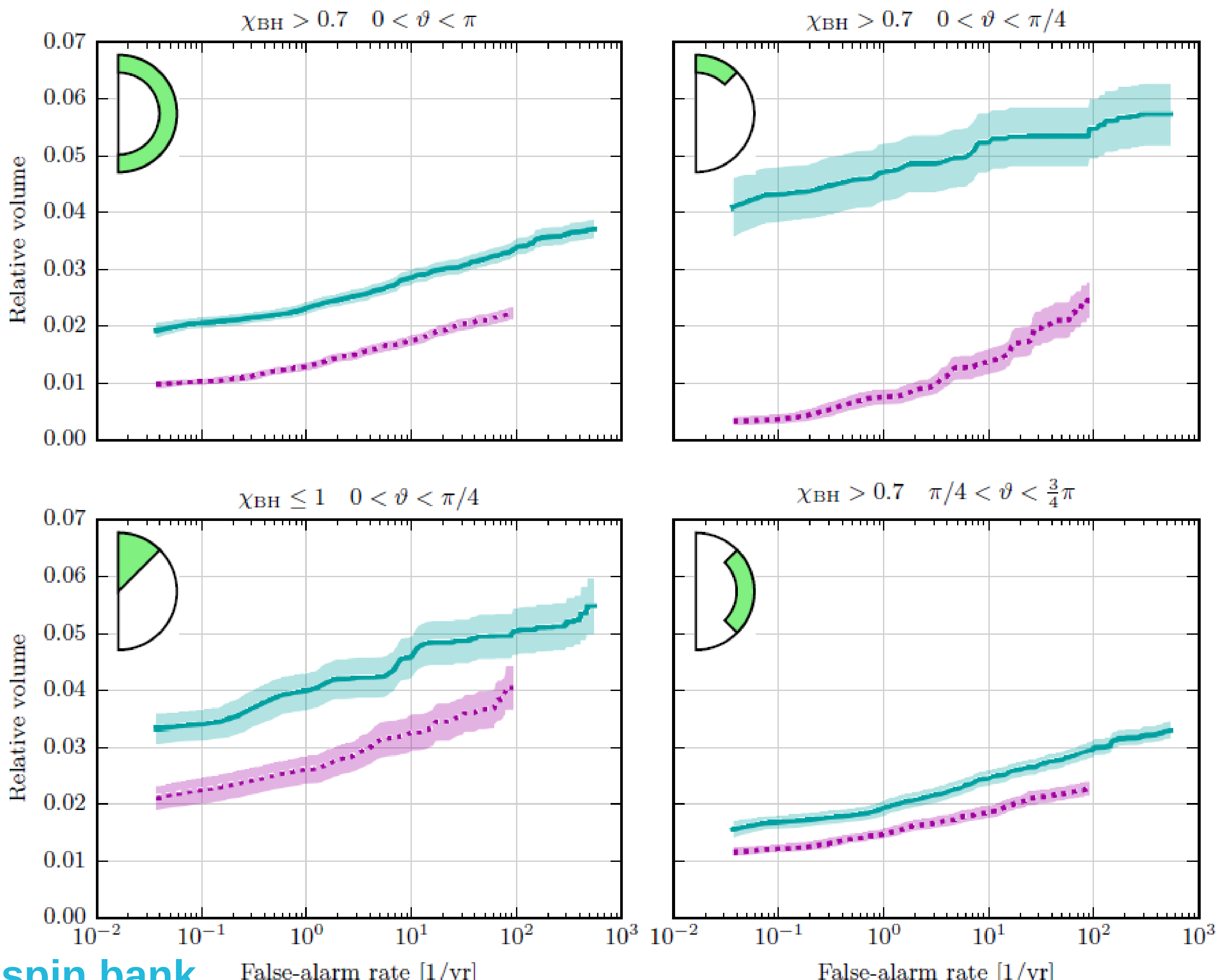
ROCs, precessing signals I



Cyan: Aligned-spin bank
Magenta: Non-spinning bank

(Dal Canton, Lundgren, AN 2014)

ROCs, precessing signals II



Cyan: Aligned-spin bank

Magenta: Non-spinning bank

(Dal Canton, Lundgren, AN 2014)

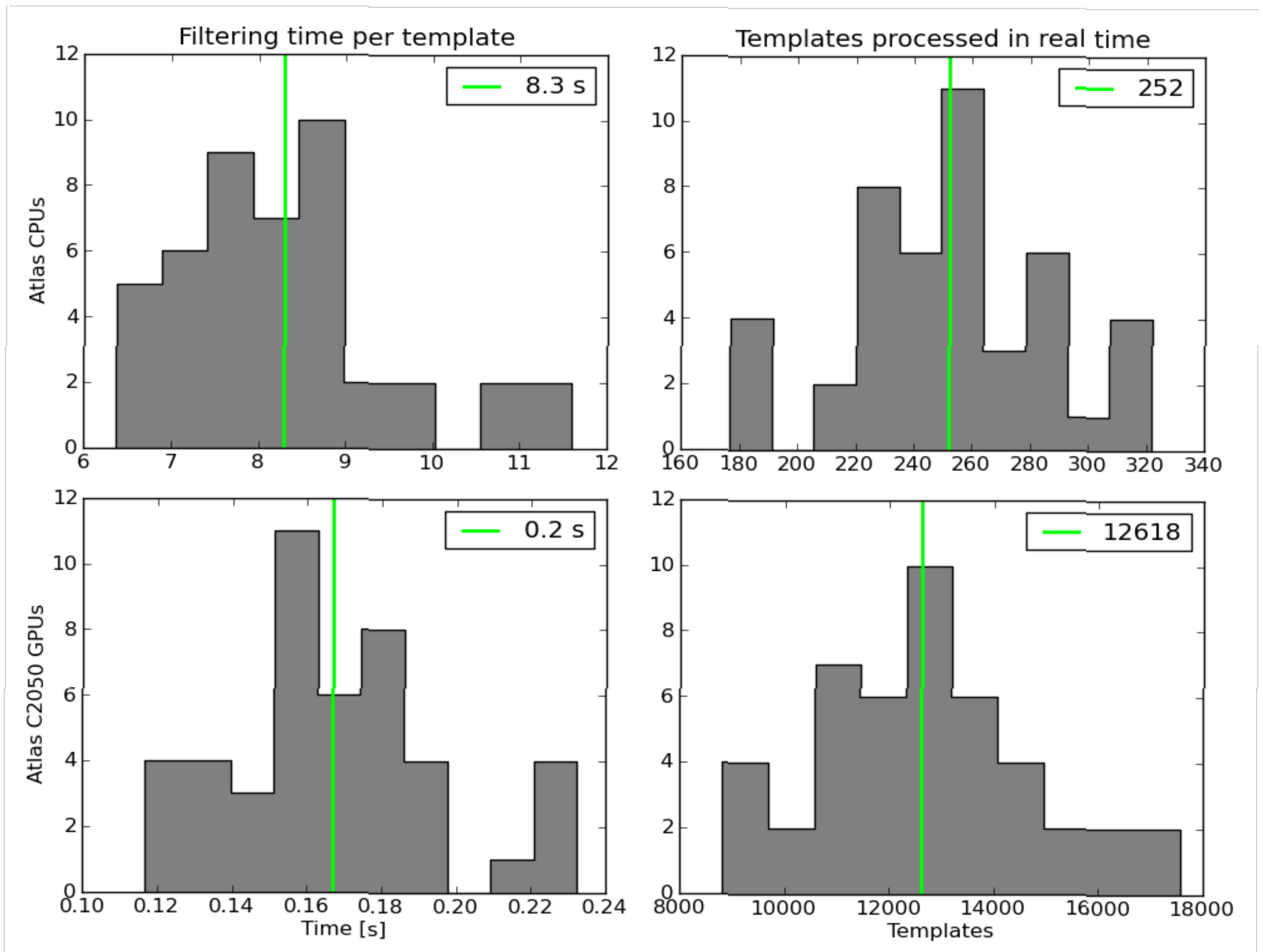
PyCBC - aims

- Python based code
- Create a flexible, extensible software for CBC analysis that can be released for the public
- Enable simple, easy and transparent access for various many-core architectures like GPUs
- Ultimately become the data analysis tool of the 'advanced era'

https://www.lsc-group.phys.uwm.edu/daswg/projects/pycbc.html

GPU running

- Identical runs ~x50 faster on **GPUs** (Nvidia Tesla C2050) compared to **CPUs** (Intel Xeon E3-1220v3) on Atlas@aei

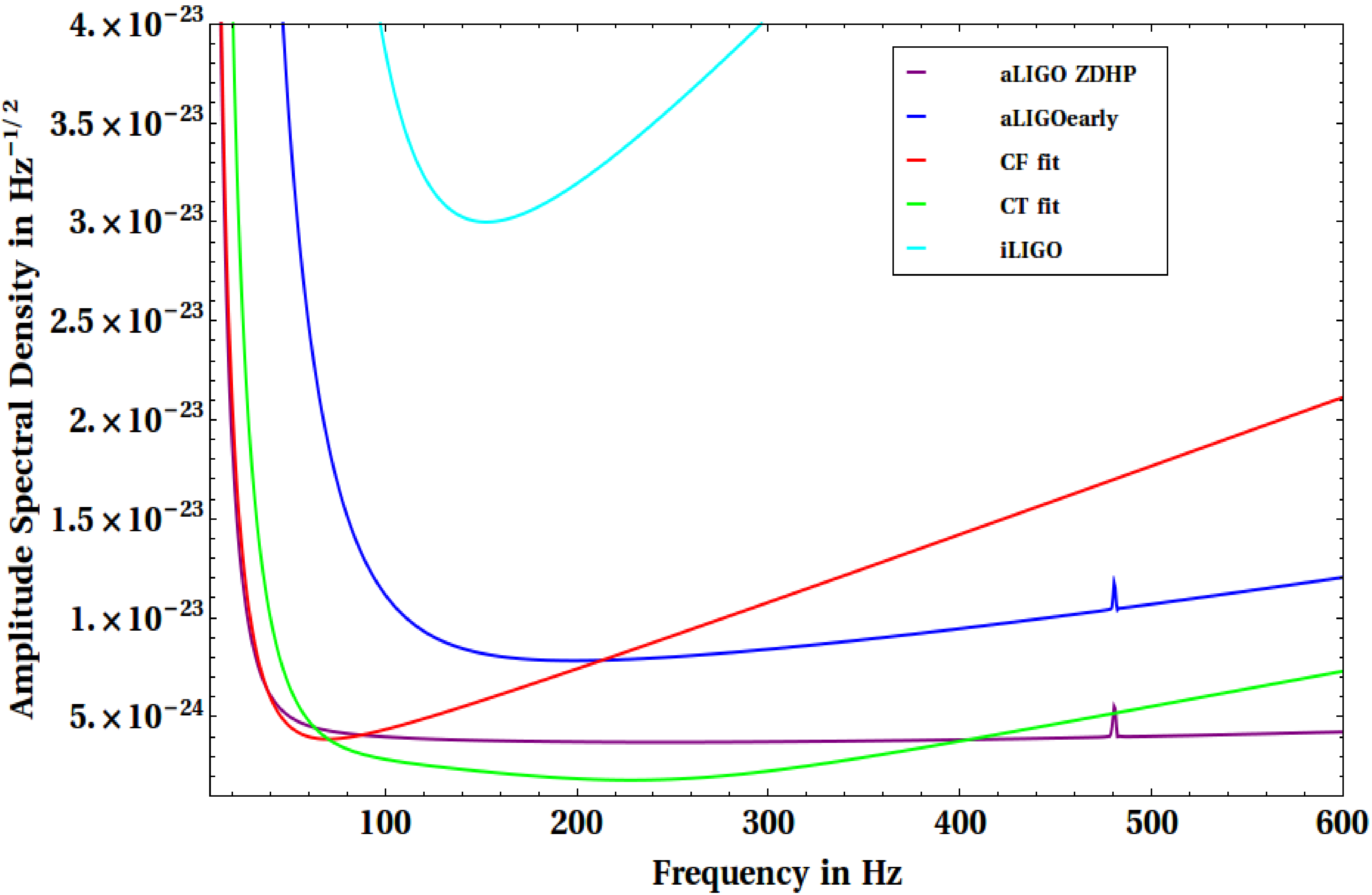


Conclusions

- **The available evidence suggests that stellar sized black holes in compact binaries may have considerable spin.**
- **Searching for these systems with spinning templates may significantly increase the detection rate, especially in multi-messenger.**
- **The challenges are largely computational; longer running times and larger trigger sets.**

Thank you

Sensitivity curves



Search parameters details

- **Data:** Early-recolored MDC, H1, L1, approx 25 hrs
- **Templates:** spins -1 to +1 (BH), -0.4 to +0.4 (NS), masses 3 to 15 M_s (BH), 1 to 3 M_s (NS), TaylorF2, 30 Hz to ISCO, pylal_aligned_stoc_bank
- **Injections:** spins flat -1 to +1 (BH), -0.05 to 0.05 (NS), masses Gaussian around 7.8M_s (BH), 1.35M_s (NS), distance 40-100Mpc, inclination face-on, 3.5 pN SpinTaylorT2 waveforms, 14 Hz to MECO, lalapps_inspinj

- **Brown *et al* Phys. Rev. D 86 (2012) 084017** “We present a new metric in a parameter space in which the template placement metric is globally flat. This new method can create template banks of signals with non-zero spins that are (anti-)aligned with the orbital angular momentum.”
- **Ajith Phys. Rev. D 84 (2011) 084037** “We also show that the secular (non-oscillatory) spin-dependent effects in the phase evolution (which are taken into account by the non-precessing templates) are more important than the oscillatory effects of precession in the comparable-mass (m_1 ~= m_2) regime. Hence the effectualness of non-spinning templates is particularly poor in this case, as compared to non-precessing-spin templates.”
- **Privitera *et al.* arXiv:1310.5633** “We find an increase in observable volume of up to 45% for systems with $0.2 \le \chi \le 0.85$ with almost no loss of sensitivity to signals with $0 \le \chi \le 0.2$.”

SNR recolored background 1day