Gravitational wave searches with the Band-Sampled-Data framework

a ~5-year summary for the "Continuous gravitational waves and neutron stars workshop"
AEI Hannover, Germany

The main outcome of my PhD project supervised by **Sergio Frasca** + many inputs from the Rome Virgo group

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Files formats for CW analysis

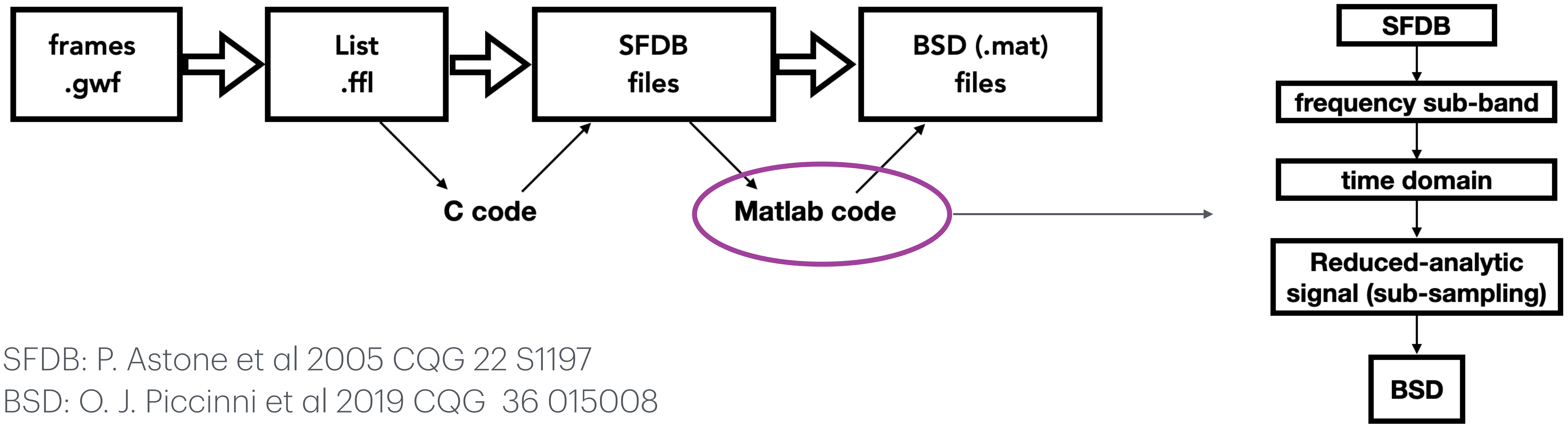
SFT, SFDB, BSD

- Some of the analyses carried out by the LIGO-Virgo CW groups do not use the LIGO version of the SFT files
- The main starting data products are the so-called **SFDB** files (Short-Fourier Transform DataBase)
- The **Band-Sampled-Data files** (BSD) are sub-products of the SFDB files
- A version of these input files is produced using both Virgo and LIGO data (BSD and SFDB)
- For O4 analyses, several groups (Rome1 and 2, IFAE, UCLouvain, Nikhef, Manitoba, ANU) will use BSD-based pipelines

From SFDB to BSD

A simple scheme

- The starting point to produce these files are the frames files (.gwf) of the main channel

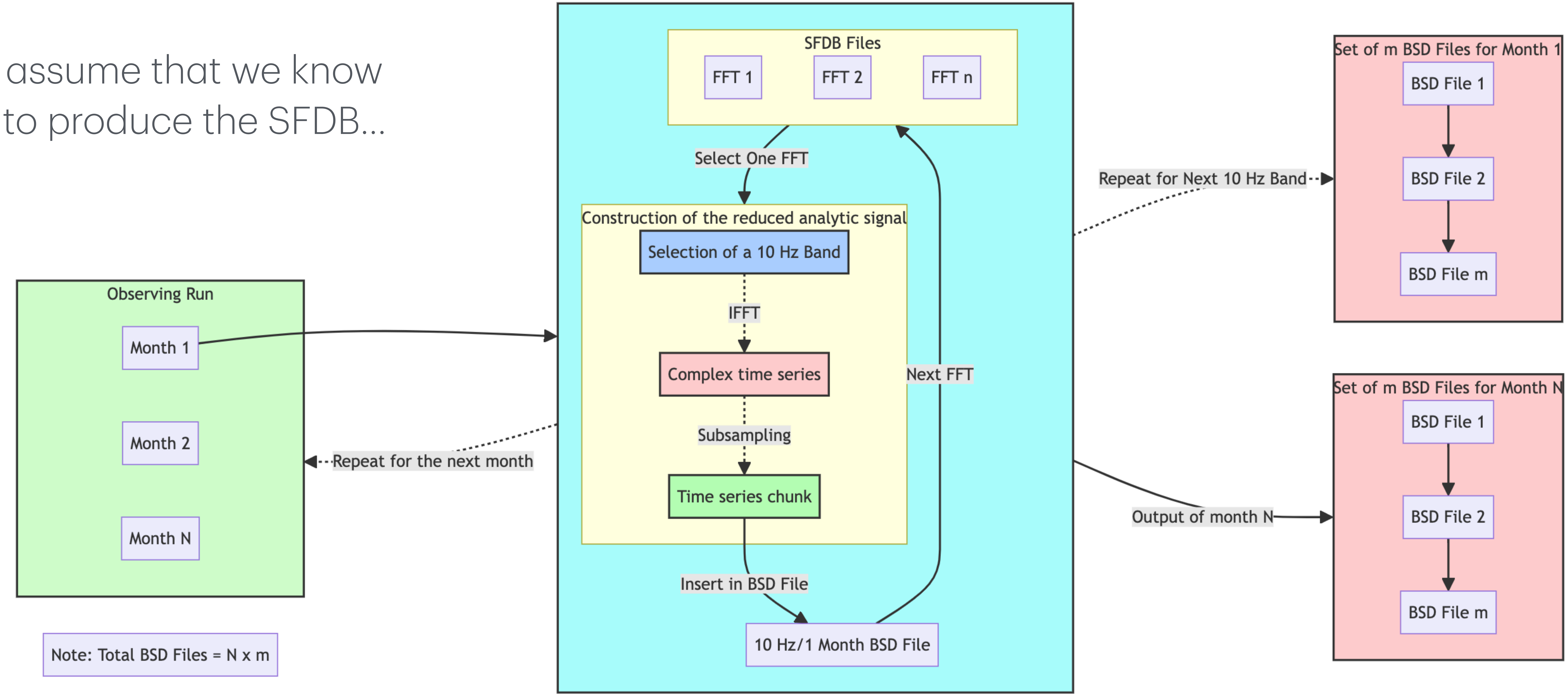


SFDB: P. Astone et al 2005 CQG 22 S1197
BSD: O. J. Piccinni et al 2019 CQG 36 015008

From SFDB to BSD

A (less) simple scheme

- Let's assume that we know how to produce the SFDB...



BSD features

O. J. Piccinni et al 2019 CQG 36 015008

Adds-on

- Extra time-domain cleaning procedure (in addition to the "Rome-gating" - F. Acernese et al 2009 CQG 26 204002) for very high disturbances (<3%)

- Basic information ready for diagnosis and analyses:

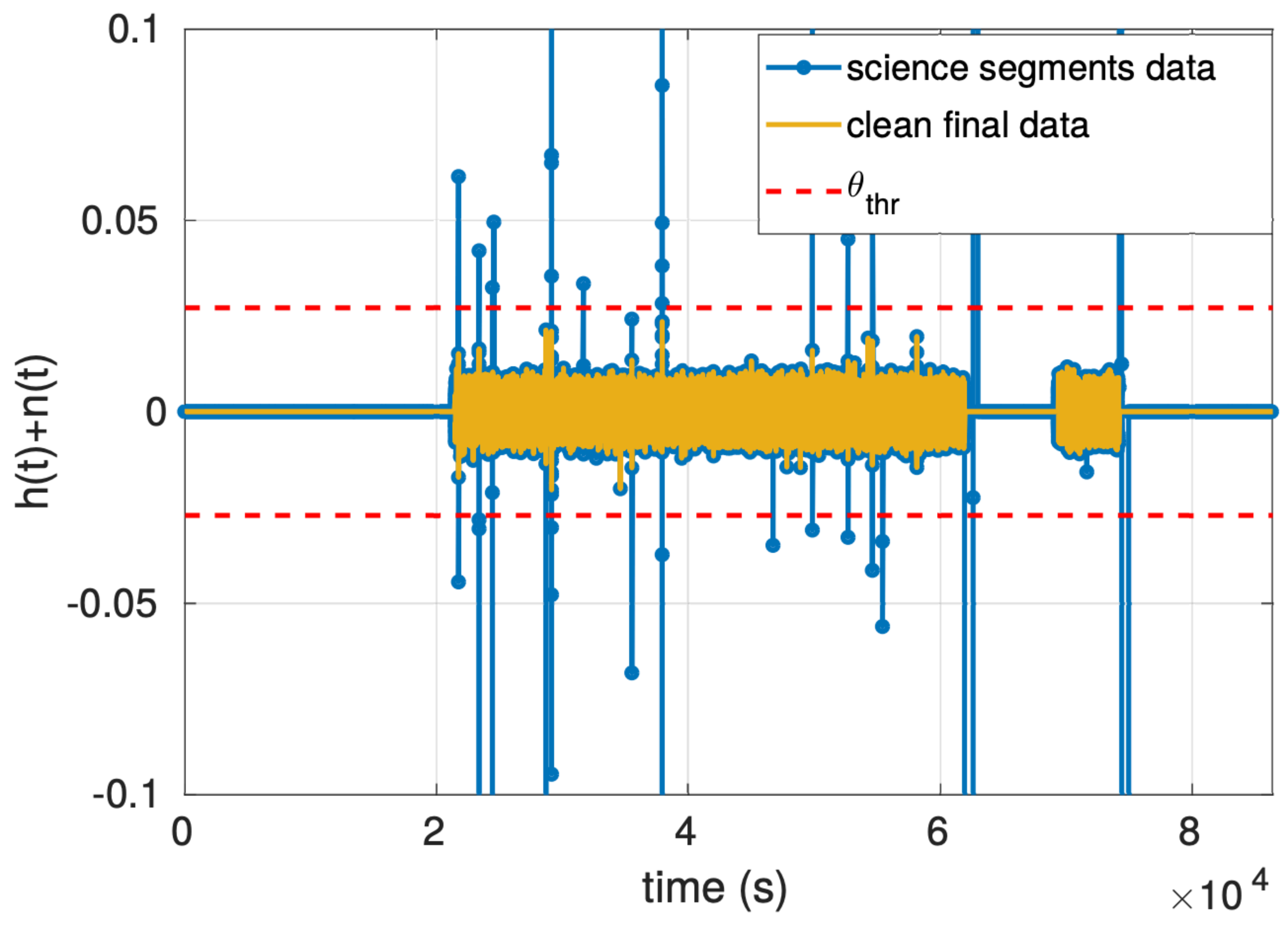
  ✓ time-frequency maps (*peakmaps*)

  ✓ persistency

  ✓ time-frequency histograms

  ✓ ASDs, spectrograms

  ✓ info about the files, detector position and velocity (SSB)



The BSD bricks

the fundamental bsd_lego function

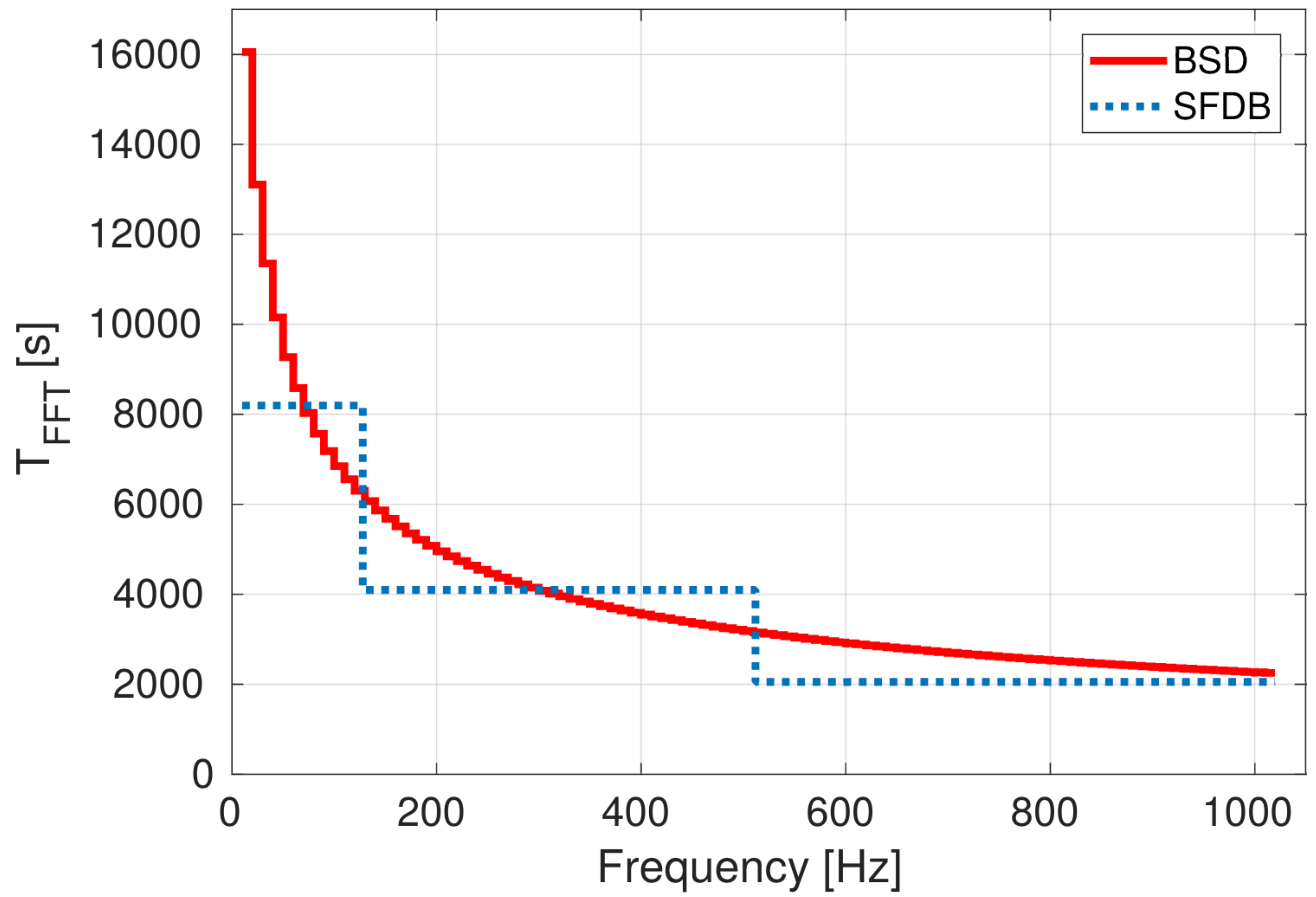
- possibility to combine the data in a lego way (starting from bricks of 10Hz/1 month)
  - For targeted searches, the preferable combination is a *small frequency band* and whole run
  - For long transients, *wider frequency bands* and *shorter times*
  - Directed searches can use the *standard* 10 Hz configuration
- New configurations are being tested: e.g. overlapping bands between two months
- Some configurations are limited for sampling reasons and should be handled with care (or after a systematic study of these cases)

What's the advantage

- The SFDB are built with fixed FFT lengths

Band	Sampling	TFFT
[10-128] Hz	512 Hz	8192 s
[128-512] Hz	1024 Hz	4096 s
[512-1024] Hz	2048 Hz	2048 s
[1024-2048] Hz	4096 Hz	1024 s

- The BSD can be easily manipulated allowing the use of **any FFT length** in a more straightforward way

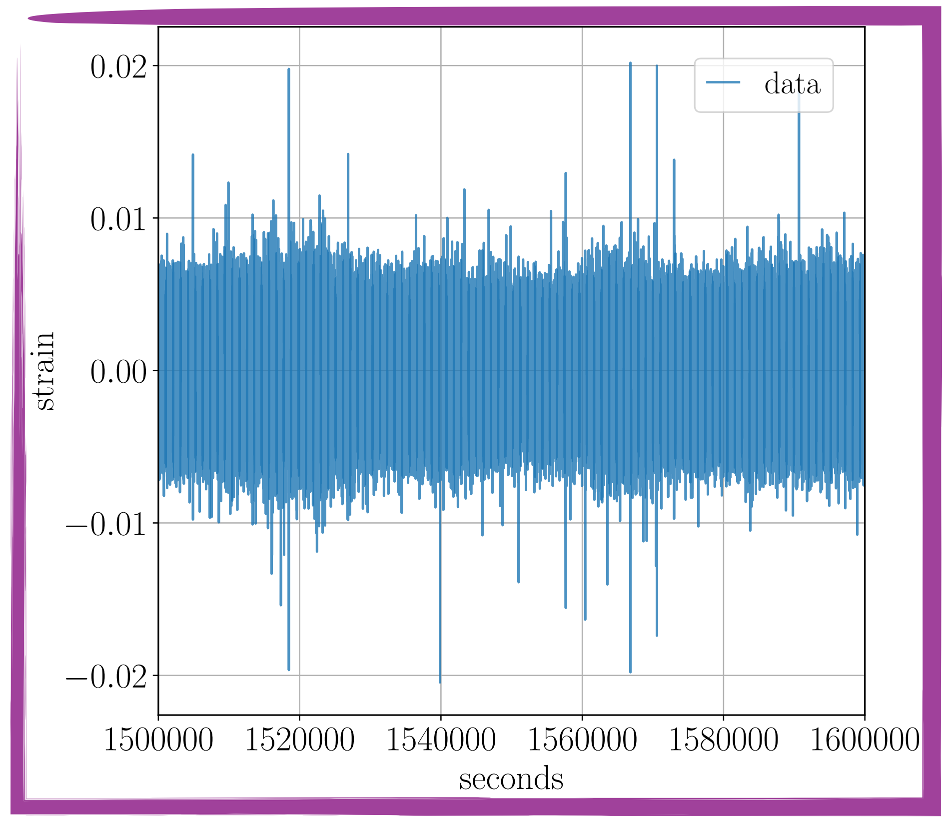


The (reduced-)analytic signal

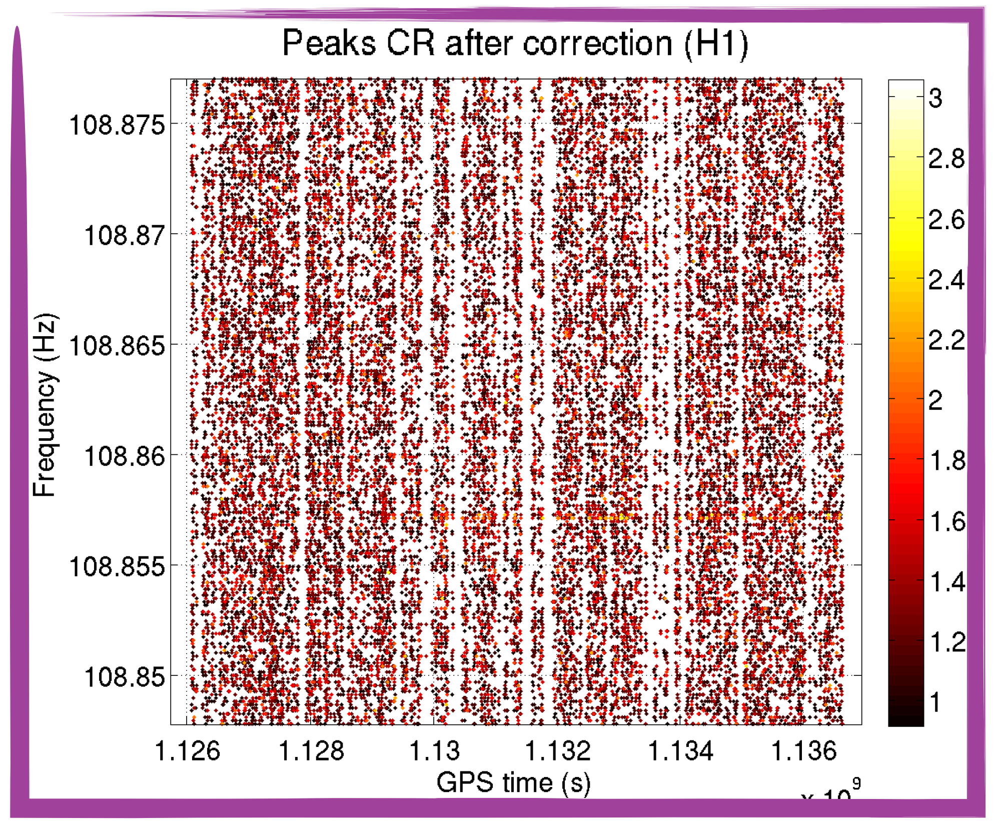
- One of the secrets of the BSD files: we are manipulating a complex and (reduced-)analytic signal
- This allows us to apply the so-called heterodyne corrections just by multiplying the data with exponential complex phase
- any modeled frequency variation can be turned into a heterodyne correction e.g.
  - spin-down: $\phi_{sd}(t) = 2\pi \int_{t_0}^{t} \left[\dot{f}_0(t'-t_0) + \frac{1}{2}\ddot{f}_0(t'-t_0)^2 + \ldots \right] dt'.$
  - doppler: $\phi_d(t) = 2\pi \int_{t_0}^{t} f_0(t') \frac{\vec{v}\cdot\hat{n}}{c} dt' \approx \frac{2\pi}{c} p_{\hat{n}}(t) f_0(t).$
- This can be applied to the (complex) data as $h_{corr}(t) = h(t)e^{i\phi(t)}$
- After the demodulation, we can increase the coherence time of a hierarchical search

A prototype search

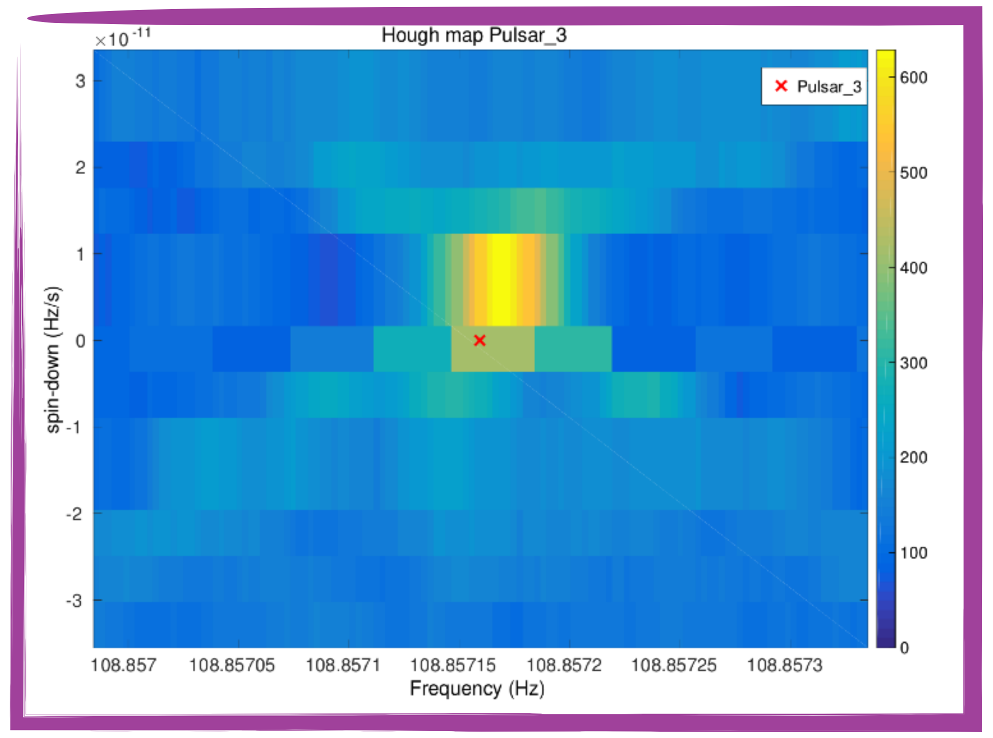
- A generic BSD pipeline might use a combination of the following steps:
  - bsd_lego: to eventually **combine the data** in time or frequency domain



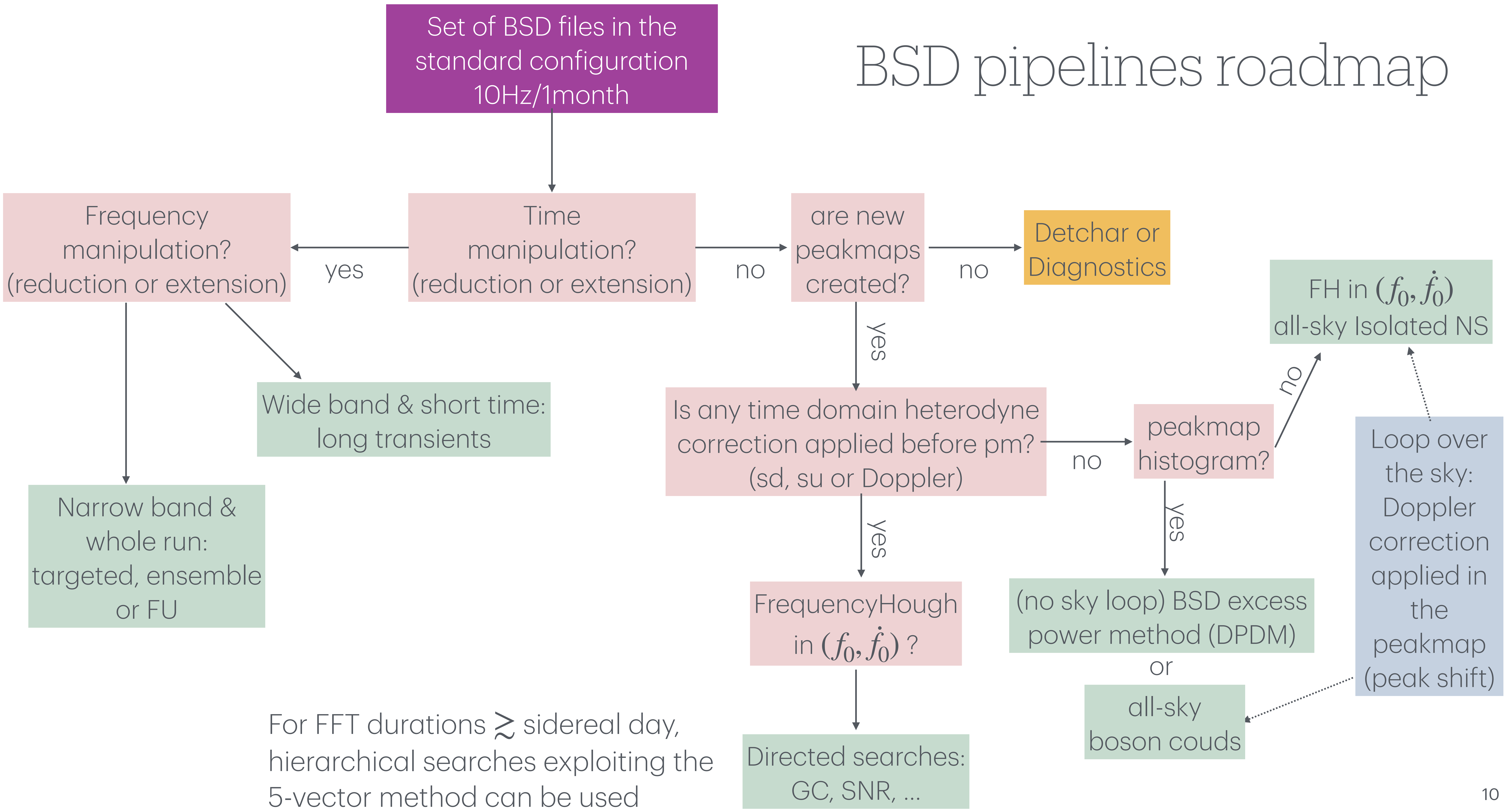
  - heterodyne: to **demodulate the signal** and e.g. increase the coherence time (also as an FU step)
    Targeted BSD methods (5-vec, ensembles)



  - bsd_peakmap: to **build the time-frequency map** with the desired FFT length
    - peakmap projection (histogram over frequency)
      BSD excess power methods (PBHs, DPDM, BC)
  - bsd_hough: to **map the peakmap into** $(f_0, \dot{f}_0)$
    BSD FH methods (GC, SNR, all-sky NS)



BSD pipelines roadmap



For FFT durations $\gtrsim$ sidereal day, hierarchical searches exploiting the 5-vector method can be used

BSD pipelines references

- GC (directed): Abbott et al. PRD 106, 042003 (2022); Piccinni et al. PRD 101, 082004 (2020)
- SNR (directed): Abbott et al. ApJ 921 80 (2021);
- Scalar boson clouds (all-sky): Abbott et al. PRD 105, 102001 (2022); D'Antonio PRD 98, 103017 (2018)
- Excess power DPDM (all-sky): Abbott et al. PRD 105, 063030 (2022); Miller et al. PRD 103, 103002 (2021)
- BSD COBI - PBH (all-sky & directed) - **see Marc's talk on Wednesday**
- 5-vector semi-coherent (directed): D'Antonio et al. PRD 108, 122001 (2023)
- 5-vector ensemble (targeted): D'Onofrio et al. PRD 108, 122002 (2023) & PRD 105,063012 (2022)
- 5-vector (targeted) - adapted to the BSD framework: Abbott et al. ApJL 902 L21 (2020) & ApJ 935 1 (2022)
- FH isolated NS (all-sky) - adapted to the BSD framework: paper in preparation

Some O3 results

O3 scalar boson clouds

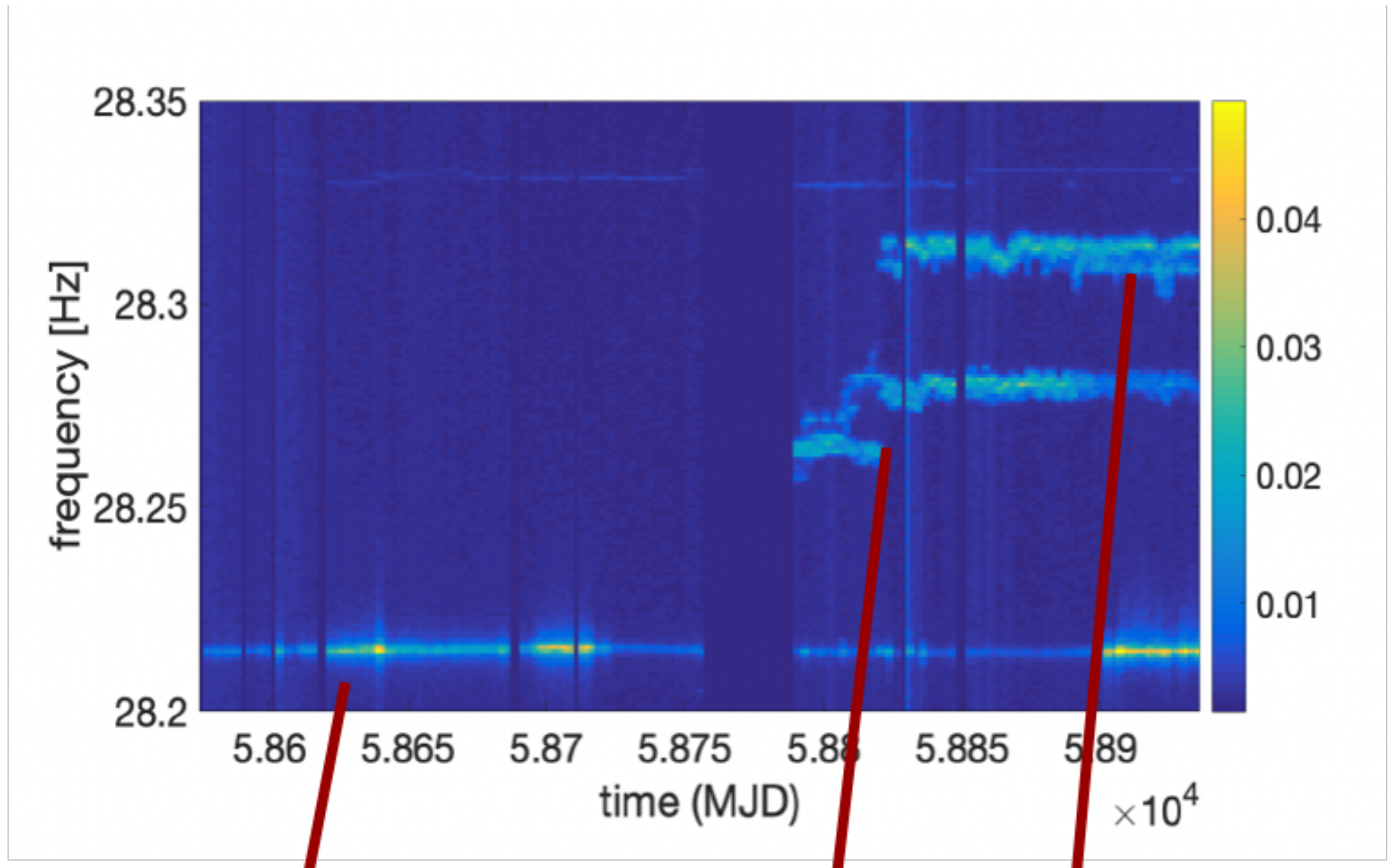
Abbott et al. - PRD 105, 102001(2022)

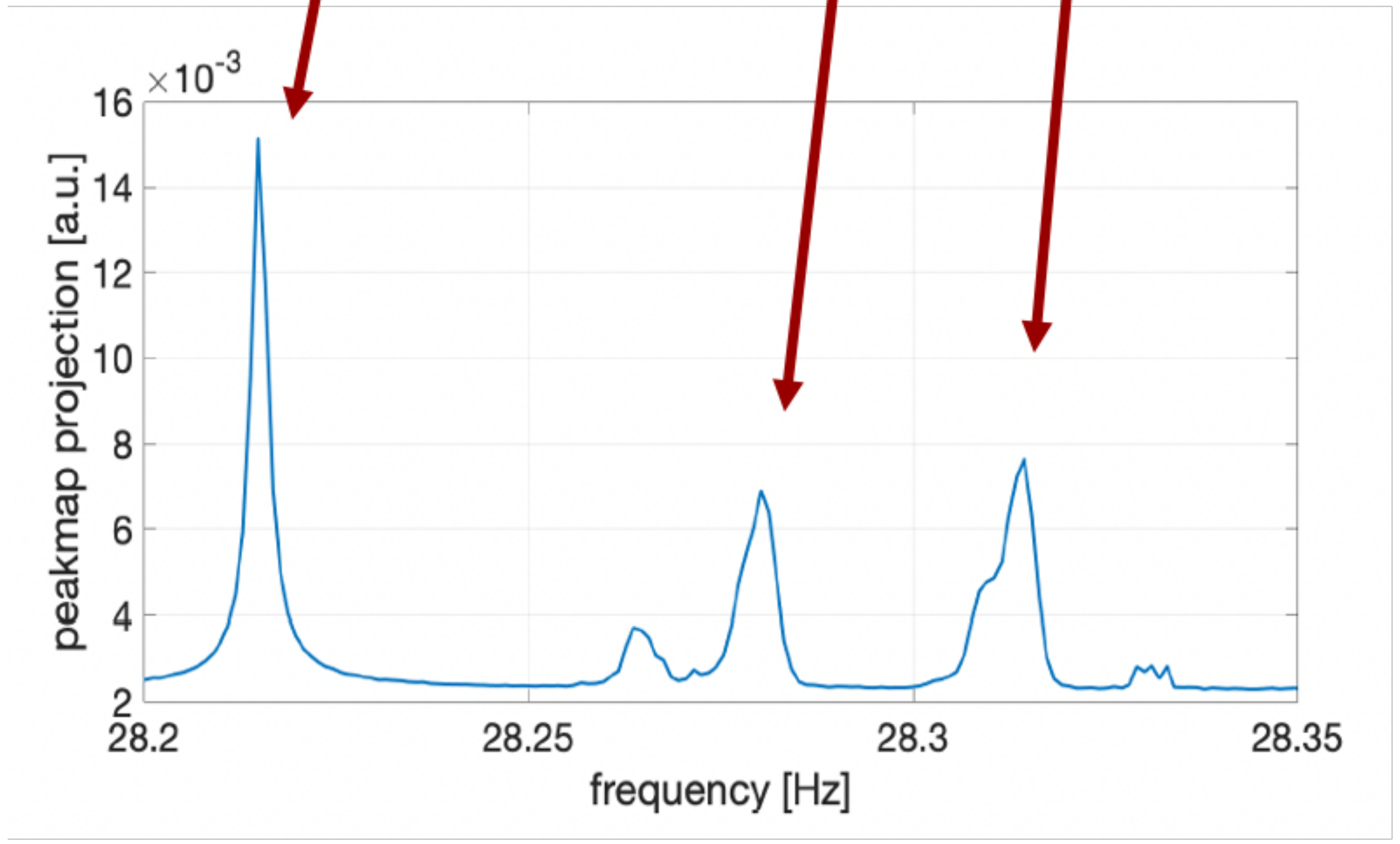
Frequency range: $[20 - 610]$ Hz
spin-down/up range: 1 bin around zero
Data: full O3 clean data (April 2019 - March 2020)

all-sky

- standard BSD configuration 10Hz/1month
- Peakmap creation new FFT length
- Peakmap correction (peaks shifts, loop over sky)
- Peakmap histogram (moving average)

D'Antonio et al. Phys. Rev. D 98, 103017 (2018)

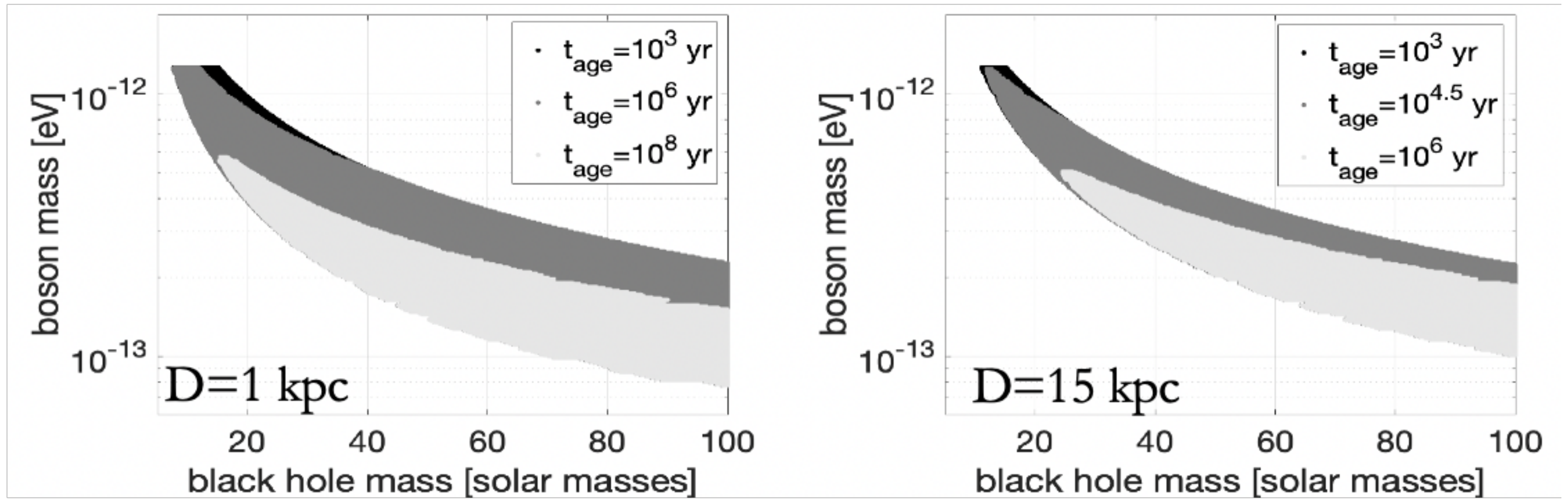




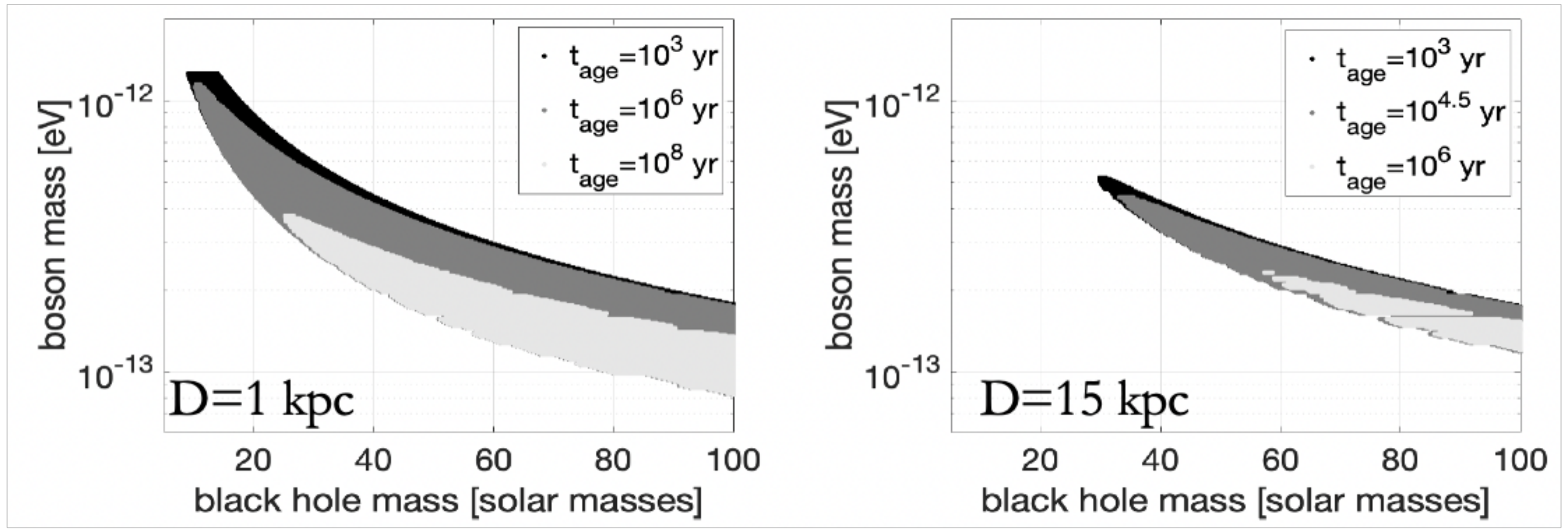
O3 scalar boson clouds

Astrophysical interpretation of null results:

- exclusion regions in the BH-boson mass plane

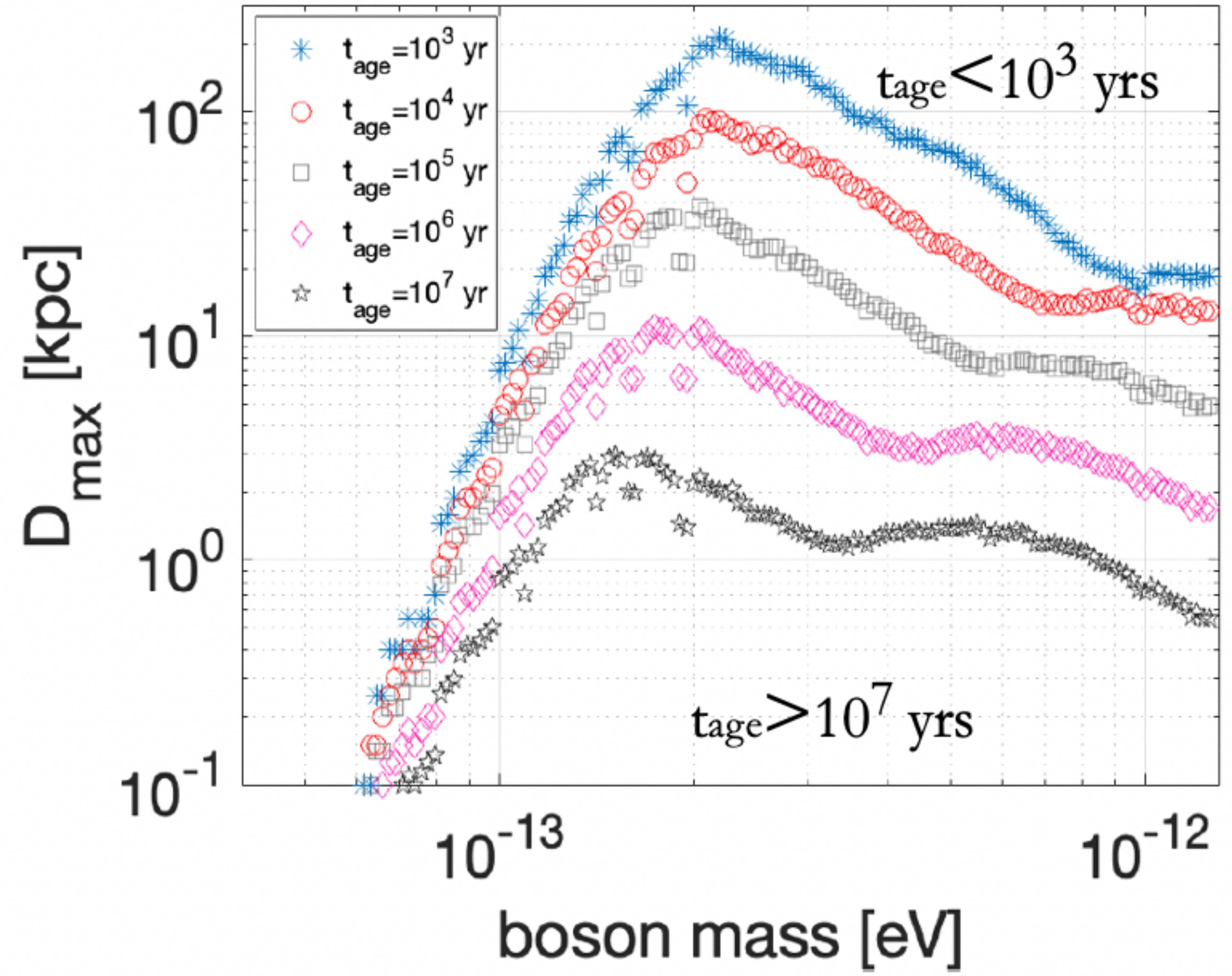


BH spin = 0.9



BH spin = 0.5

- distance reach of the search: how far we can exclude the presence of an emitting system given the null detection results



O3 GC search - setup

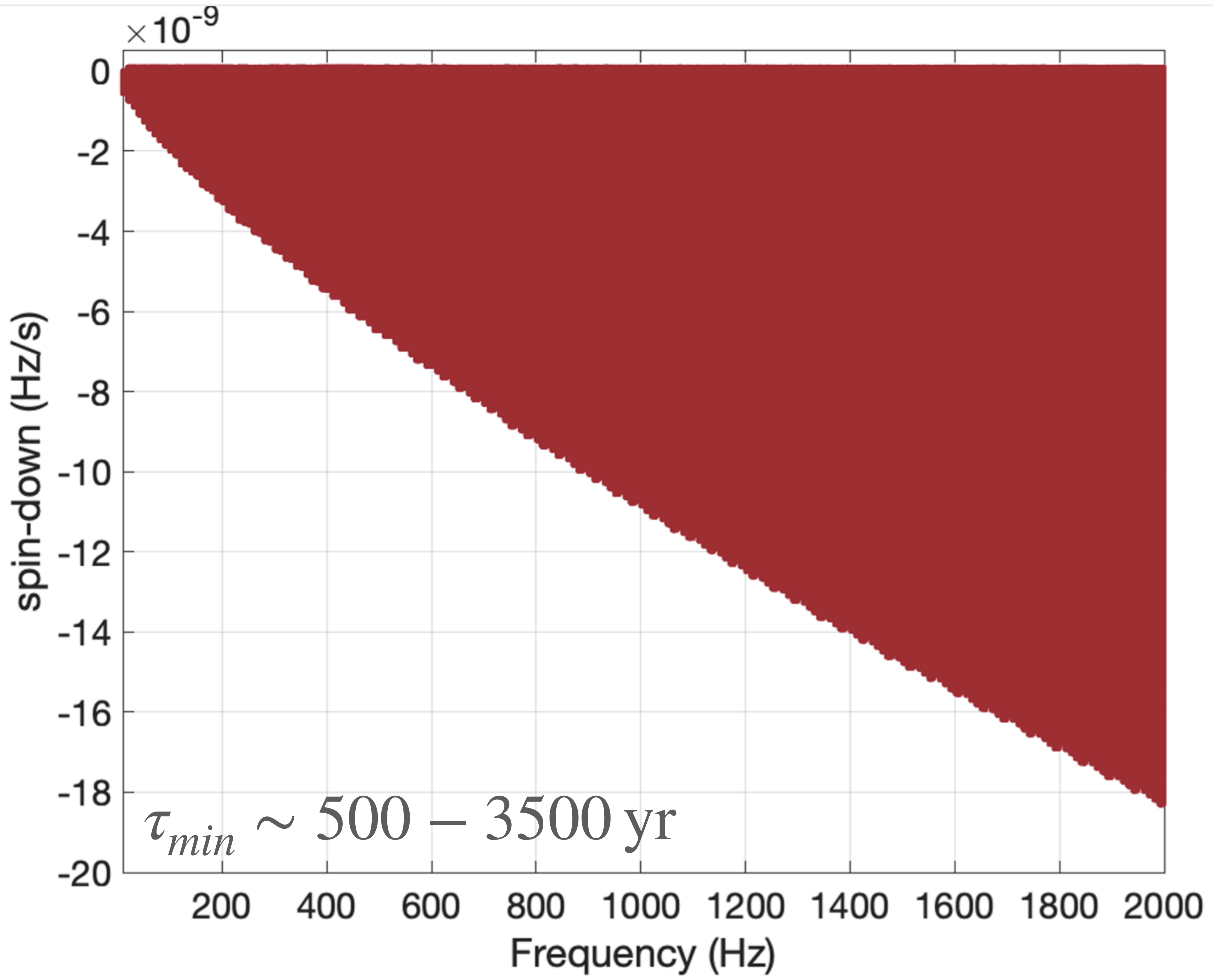
Abbott et al PRD 106, 042003 (2022)

Frequency range: $[10 - 2000]\,\mathrm{Hz}$
min spin-down: $-1.8 \times 10^{-8}\,\mathrm{Hz/s}$
spin-up: $1 \times 10^{-10}\,\mathrm{Hz/s}$
Data: full O3 clean data (April 2019 - March 2020)

Sky position (Sgr A*):
$\alpha = 4.650$ rad $\delta = -0.506$ rad

- standard BSD configuration 10Hz/1month
- Partial heterodyne Doppler correction
- new peakmap + FH based method
- Sum of monthly FH of 10 Hz each

Piccinni et al., PRD, 101, 082004 (2020)

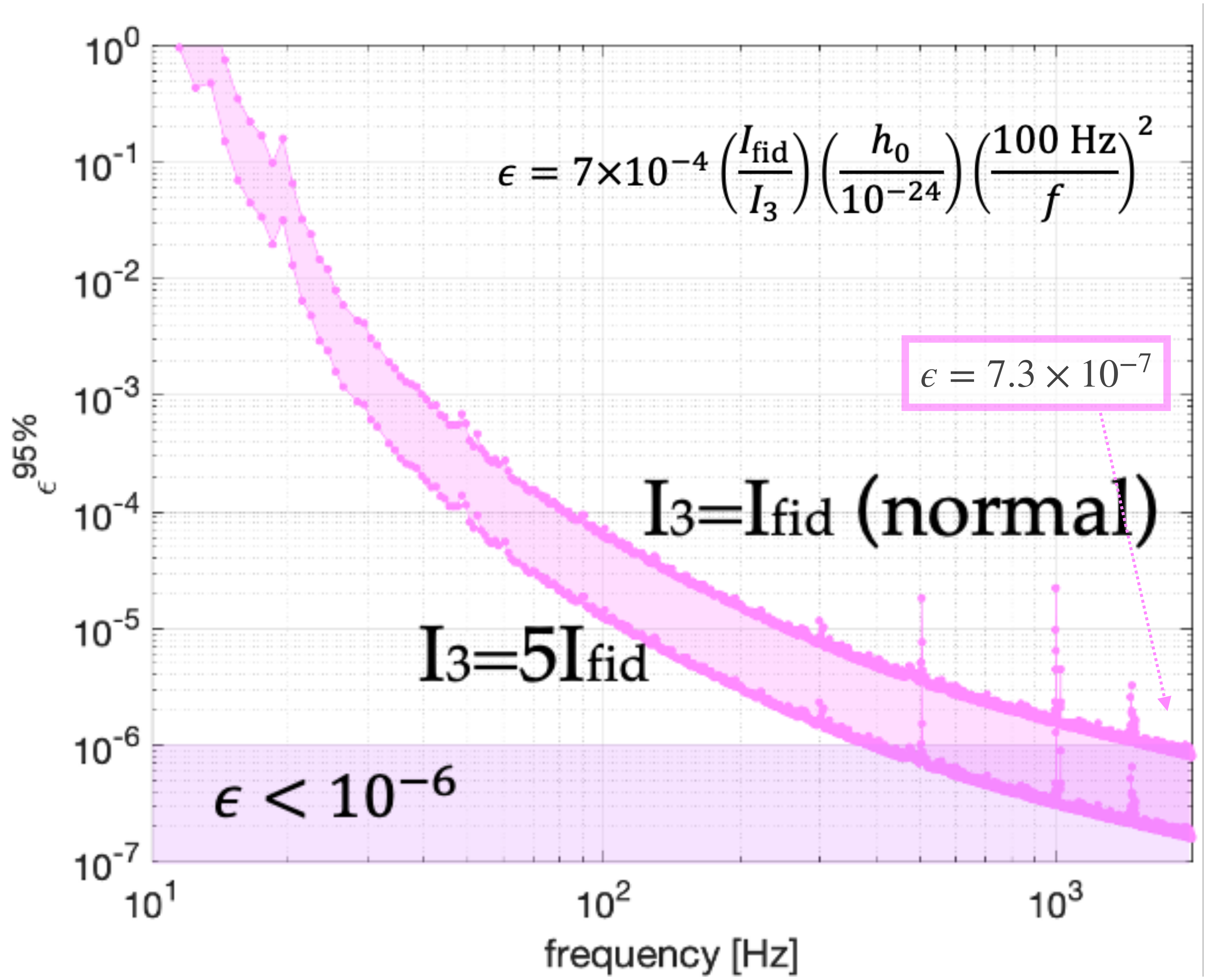


O3 GC search

Best h_0 UL 7.6×10^{-26} at 140 Hz

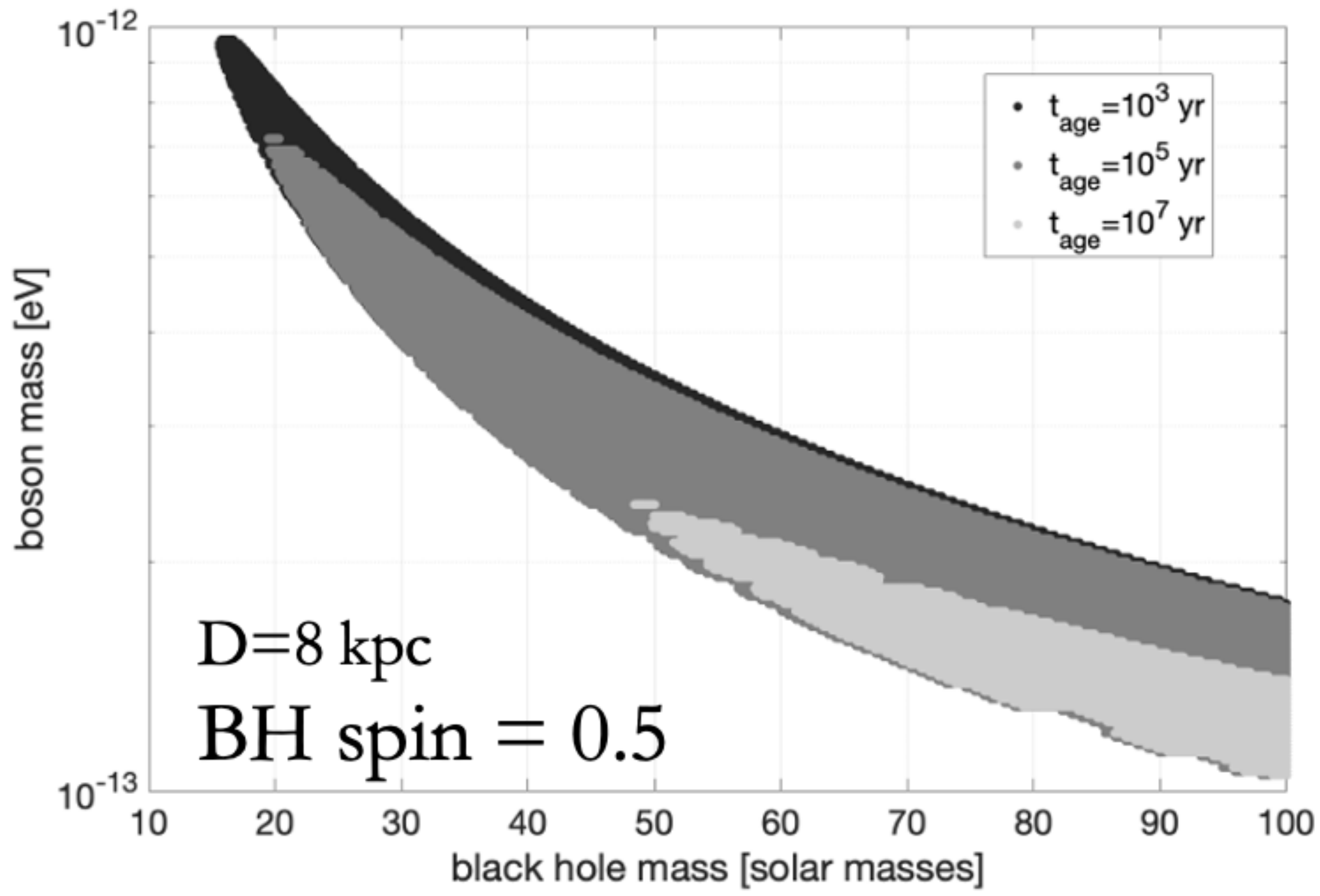
Disclaimer: Interpretation depends on the BH population in the GC and actual ages and/or formation rates

NS population?



Limits more stringent than max theoretical expectations

or DM?



Semi-coherent method + spin-up range: boson clouds exclusion regions

Conclusions

- The Band-Sampled-Data (BSD) framework has emerged as a powerful tool in the search for GW signals
- The tool has been instrumental in various searches for both standard CW signals and dark matter candidates
- One of the key strengths of the BSD framework lies in its ability to handle data effectively
- Over the past five years, it has evolved significantly, offering a comprehensive suite of functions for analyzing GW data
- Its foundational functions provide a solid basis for implementing search methods tailored to specific research goals
- The framework is still far from being perfect and some limitations need to be overcome
- Of course, there is plenty of room for improvement!

Backup

SFDB cleaning

- SFDB have a different sampling/duration than LIGO SFT
- Furthermore an extra cleaning technique is used:
  - Removal of glitches using a bilateral high-pass filter
  - identify the presence of "events" in the high-passed data (using a threshold and AR procedure to estimate mean and standard deviation of the data)
  - subtract from the original data the high-passed data corresponding to the glitch times
- Cleaning is also described in this paper and in the FH review page
- Time-domain glitches affect the whole frequency band!

The SFDB cleaning and the SFTs

- An extensive study of the impact of this cleaning on LIGO data has been done by Paola Leaci and Pep Covas
- the cleaning has been integrated into some of the SFT-production software (see Leaci)
- Also the SFT seem to benefit from this cleaning procedure (~5 noise floor level)
- Test by Covas show a significant increase of the detection efficiency in the SkyHough (at depth 32: 0.87 -> 0.93 efficiency)
- SFDB can be read by LAL: XLALReadSFDB