OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery

ANU CENTRE FOR GRAVITATIONAL ASTROPHYSICS

NATURAM PRIMUM COGNOSCERE RERUM
Australian National University

LIGO VIRGO KAGRA

Gravitational Waves and Ultralight Bosons: observations from Spinning Black Holes

New Horizons for Psi - Lisbon, Portugal

Ornella J. Piccinni
3 July 2024
ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav) and
Centre for Gravitational Astrophysics,
The Australian National University, Canberra, Australia

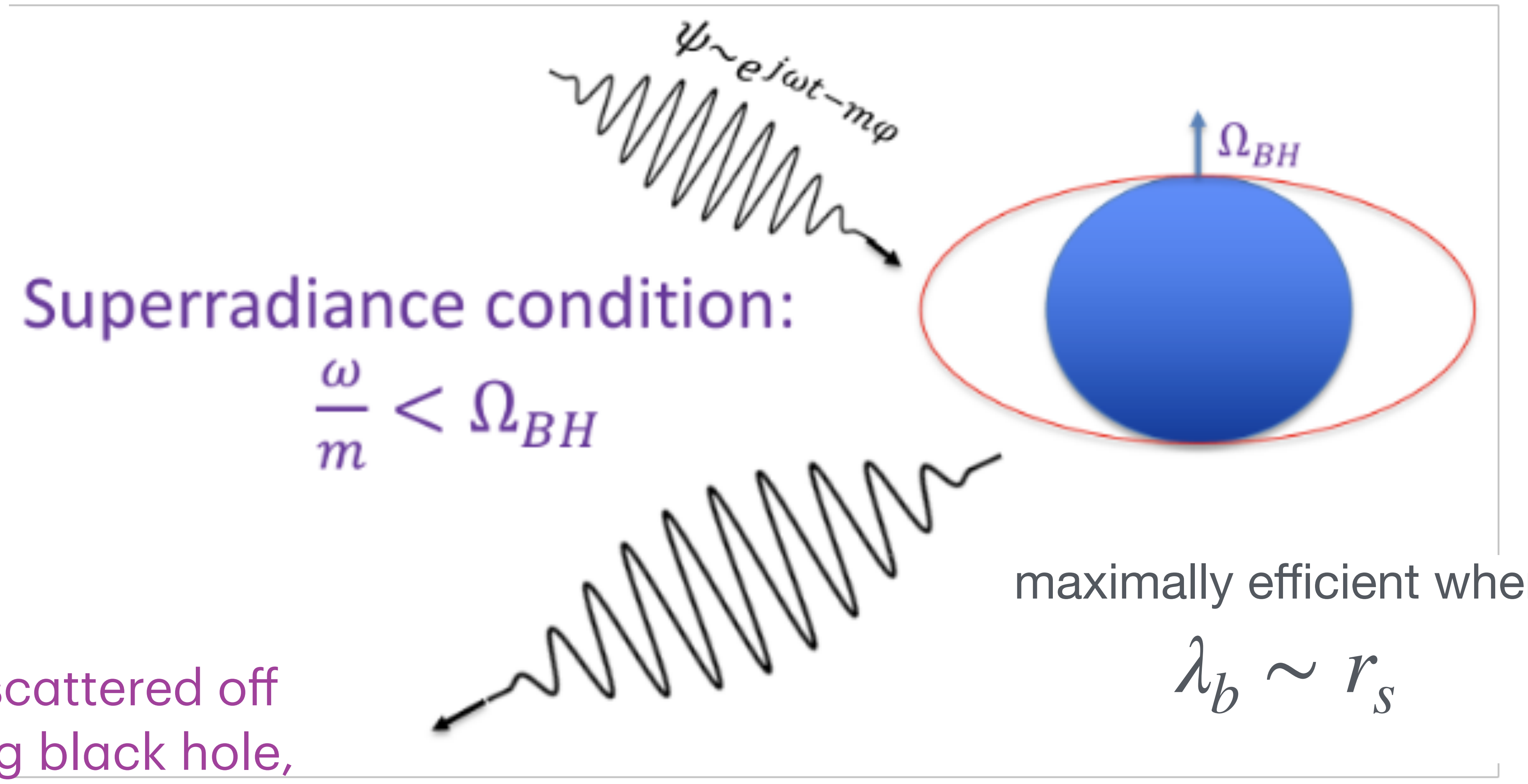
See the extensive literature:
Arvanitaki et al., PRD 81, 123530 (2010); PRD 83, 044026 (2011); PRD 91, 084011 (2015)
Brito et al., Lect. Not. Phys. 971 (2020); PRL 124, 211101 (2020)
Baryakhtar et al. PRD 96, 035019 (2017); PRD 103, 095019 (2021)
Siemonsen &. East, 101, 024019 (2020)
...

Boson clouds

(see Sam Dolan Lectures; Will East talk)

- Ultralight bosonic particles (scalar, vector or tensor fields; QCD axion, axion-like particles) can clump around spinning BHs due to ***superradiance***
- Given a BH with $(M_{\mathrm{BH}}, \chi_i)$ and a boson particle of m_{b}, the superradiance instability is maximized if the **confinement conditions** are satisfied $\hbar c/m_b \sim 2GM_{\mathrm{BH}}/c^2$
- Astrophysical black holes could match well with boson masses ranging from 10^{-20} to 10^{-10} eV
- Potentially observable through their effects on the BH's ***dynamics*** and the ***gravitational waves*** they emit
- The gravitational wave **frequency f_{GW}** is mainly determined by the **boson mass**
- LIGO/Virgo/KAGRA are sensitive to a mass range of **10^{-14} to 10^{-11} eV** (10-2000 Hz)

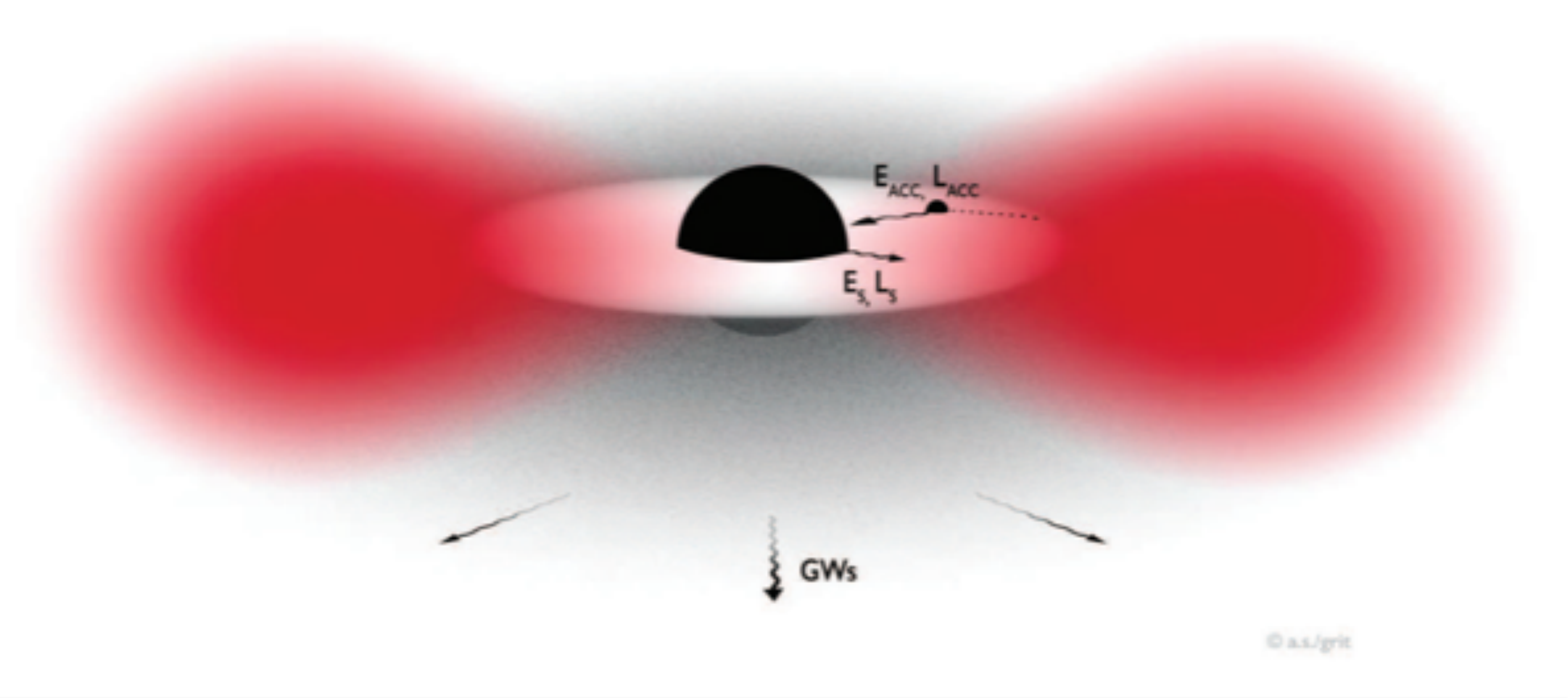
Boson clouds: scalar case



maximally efficient when

$$\lambda_b \sim r_s$$

wave is scattered off
a rotating black hole,
energy and angular momentum are extracted from a BH
leading to the amplification of these fields.



[Picture credit: Ana Sousa Carvalho]

- We need: boson angular frequency < BH's outer horizon angular frequency for the growth
- field bosons condensate, occupying the same (quantum) state with huge occupation numbers
- This process (~days) subtracts energy from the BH momentum -> The BH slows down

$$\tau_{\rm inst} \approx 20 \left(\frac{M_{\rm BH}}{10 M_\odot}\right)\left(\frac{\alpha}{0.1}\right)^{-9}\left(\frac{1}{\chi_i}\right) \text{days},$$

- The superradiance stops (at saturation) and the cloud dissipates through GWs (~years)

$$\tau_{\rm gw} \approx 6.5 \times 10^4 \left(\frac{M_{\rm BH}}{10 M_\odot}\right)\left(\frac{\alpha}{0.1}\right)^{-15}\left(\frac{1}{\chi_i}\right) \text{years}.$$

The boson cloud signal characterization

- The BH-boson cloud system resembles the hydrogen atom = *gravitational atom*

fine structure constant

$$\alpha = \frac{G M_{\rm BH}}{c^3}\frac{m_b}{\hbar}$$

- The strain amplitude decays $h(t) = \frac{h_0}{1+\frac{t}{\tau_{\rm gw}}}$

$$h_0 \approx 6\times10^{-24}\left(\frac{M_{\rm BH}}{10M_\odot}\right)\left(\frac{\alpha}{0.1}\right)^7\left(\frac{1\,{\rm kpc}}{D}\right)(\chi_i-\chi_c)$$

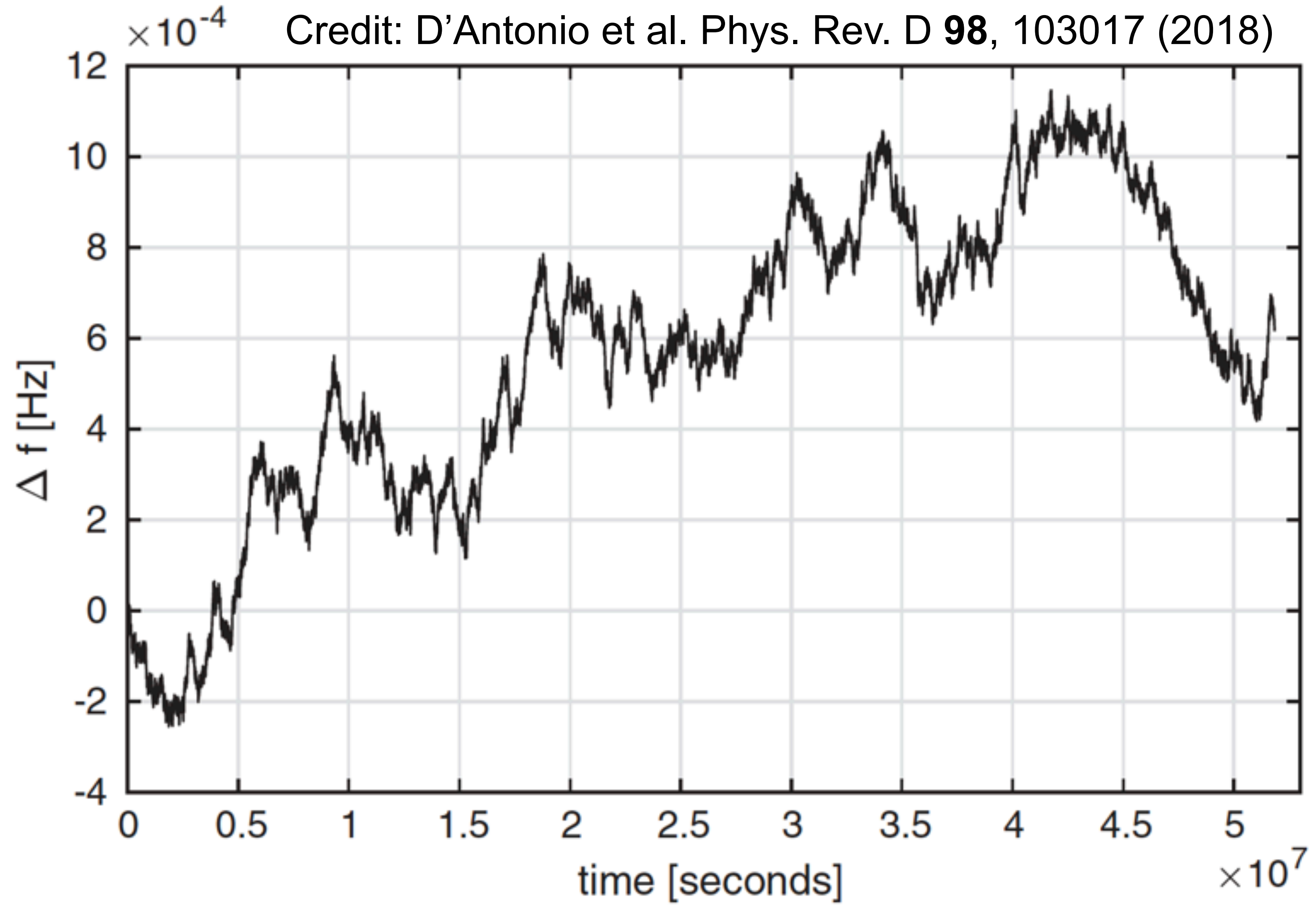
- The GW frequency is twice the field frequency

$$f_{\rm gw} \simeq 483\ {\rm Hz}\left(\frac{m_{\rm b}}{10^{-12}{\rm eV}}\right)\left[1-7\times10^{-4}\left(\frac{M_{\rm BH}}{10M_\odot}\frac{m_{\rm b}}{10^{-12}{\rm eV}}\right)^2\right]$$

- A small spin-up due to annihilation is present

$$\dot{f}_{\rm gw} \approx 7\times10^{-15}\left(\frac{m_{\rm b}}{10^{-12}{\rm eV}}\right)^2\left(\frac{\alpha}{0.1}\right)^{17}\ {\rm Hz/s}$$

We do not consider the effect due to transition levels



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

(when self interaction is negligible)

see Collaviti et al. in prep for obs. prospect of self-interacting scalars DCC: P2400284

Scalar vs Vector: timescales and h0

Scalar bosons

$$\tau_{\rm inst} \approx 20\ \text{days} \left(\frac{M_{\rm BH}}{10\ M_\odot}\right)\left(\frac{0.1}{\alpha}\right)^9 \frac{1}{\chi_i}$$

$$\tau_{\rm GW} \approx 10^5\ \text{yr} \left(\frac{M_{\rm BH}}{10\ M_\odot}\right)\left(\frac{0.1}{\alpha}\right)^{15} \left(\frac{0.5}{\chi_i - \chi_f}\right)$$

$$h_0 \approx 6 \times 10^{-24} \left(\frac{M_{BH}}{10\ M_\odot}\right)\left(\frac{\alpha}{0.1}\right)^7 \left(\frac{1\ \text{kpc}}{d}\right)\left(\chi_i - \chi_f\right)$$

Vector bosons

$$\tau_{\rm inst} \approx 2\,\text{mins} \left(\frac{M_{\rm BH}}{10\ M_\odot}\right)\left(\frac{0.1}{\alpha}\right)^7 \frac{1}{\chi_i}$$

$$\tau_{\rm GW} \approx 8\ \text{days} \left(\frac{M_{\rm BH}}{10\ M_\odot}\right)\left(\frac{0.1}{\alpha}\right)^{11} \left(\frac{0.5}{\chi_i - \chi_f}\right)$$

$$h_0 \approx 3 \times 10^{-26} \left(\frac{M}{10\ M_\odot}\right)\left(\frac{\alpha}{0.1}\right)^5 \left(\frac{1\ \text{Gpc}}{d}\right)\left(\chi_i - \chi_f\right)$$

Valid in the non relativistic regime

Scalar vs Vector: Frequency

Scalar bosons

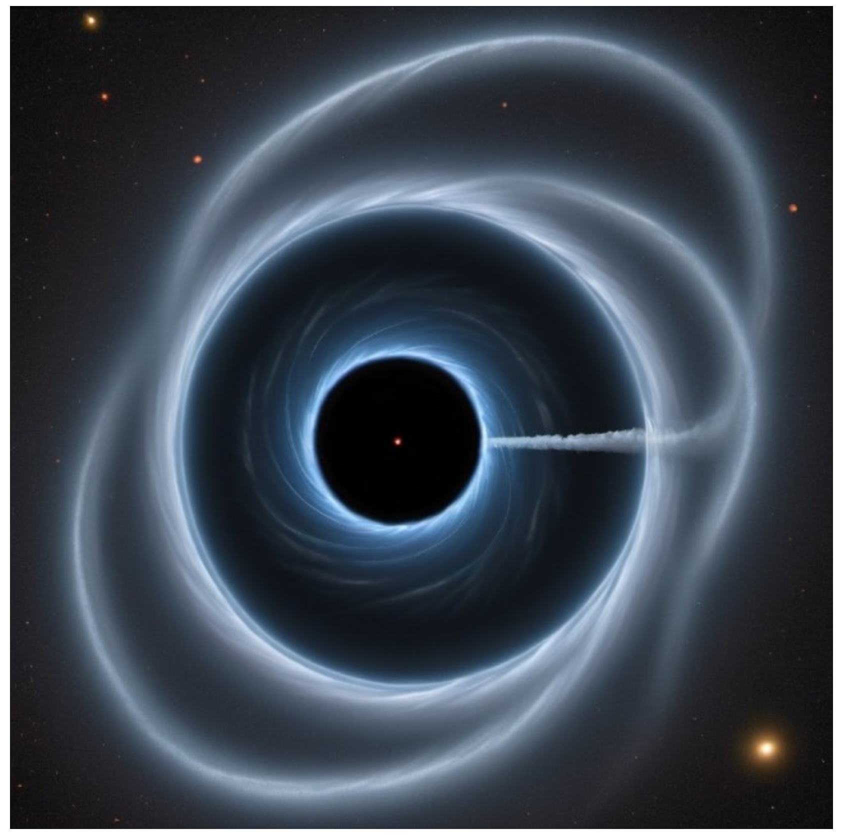
Vector bosons

$$f_{\mathrm{GW}} \approx 645\ \mathrm{Hz} \left(\frac{10\ M_\odot}{M_{\mathrm{BH}}}\right)\left(\frac{\alpha}{0.1}\right)$$ (at 1st order)

$$\dot{f} \approx 3 \times 10^{-14}\ \mathrm{Hz/s} \left(\frac{10\ M_\odot}{M_{\mathrm{BH}}}\right)^2 \left(\frac{\alpha}{0.1}\right)^{19} \chi_i^2$$

$$\dot{f} \approx 1 \times 10^{-6}\ \mathrm{Hz/s} \left(\frac{10\ M_\odot}{M_{\mathrm{BH}}}\right)^2 \left(\frac{\alpha}{0.1}\right)^{15} \chi_i^2$$

weak signals that are longer-lived



loud signals that are shorter-lived

Data analysis POV

(See also MAP's Lectures)

- The variety of methods reflects the different ways it is possible to look for these long-lasting signals, choosing the right balance between:
  - ✦ **Sensitivity:** digging as deed as possible in the noisy data
  - ✦ **Robustness:** to deviations of the signal from the assumed model and being able to take noise into account
  - ✦ **Computational efficiency:** try to explore as much parameter space as possible with reduced resources available
- Quite often, CW data analysis techniques can be directly applied or easily adapted to search for dark matter signatures in gravitational wave data.
- **Studying the noise** is important to discriminate between real astrophysical signals and instrumental mimickers
- Discrimination among **different signals** in case of detection or parameter estimation might not be a trivial task

Searches of BC with Earth-based interferometers (with CW methods)

Scalar boson clouds:

- First **all-sky survey** dedicated to GW signals emitted by ultralight scalar boson clouds. Frequency range 20–610 Hz of the O3 LIGO data. A small range around zero is considered as a spin-up parameter - Abbott et al. PRD 105, 102001 (2022) (see also Palomba et al. PRL 123 171101 (2019) - O2 data; Dergachev and Papa PRL 123 101101 (2019) - O1 data)
- Ensemble of signals, characterization and impact on CW analyses: Zhu, et al., PRD 102, 063020 (2020); Pierini, et al., PRD 106, 042009 (2022)
- Directed:
  - ✦ targeting the **Galactic Center** in O3 data: no priors on BH mass, spin or ages - Abbott et al. PRD 106, 042003 (2022)
  - ✦ targeting known **galactic BHs:** Cygnus X-1 O2 - rely on the mass, spin and age estimates of the target - Sun et al. PRD 101, 063020 (2020)

Methods for scalars:
All-sky semi-coherent method: D'Antonio PRD 98, 103017 (2018); - used for the all-sky search in O3
Hidden Markov model tracking (directed) Isi et al. PRD 99 084042 (2019); - used for the Cygnus X-1 O2 search
Sidereal amplitude modulation, i.e. semi-coherent 5-vector (directed): D'Antonio, et al., PRD 108, 122001 (2023)

Vector boson clouds:

- (method) Directed **post-merger remnant BHs** from compact binaries: Jones et al., PRD 108, 064001 (2023) - Expected to be used for promising O4 events

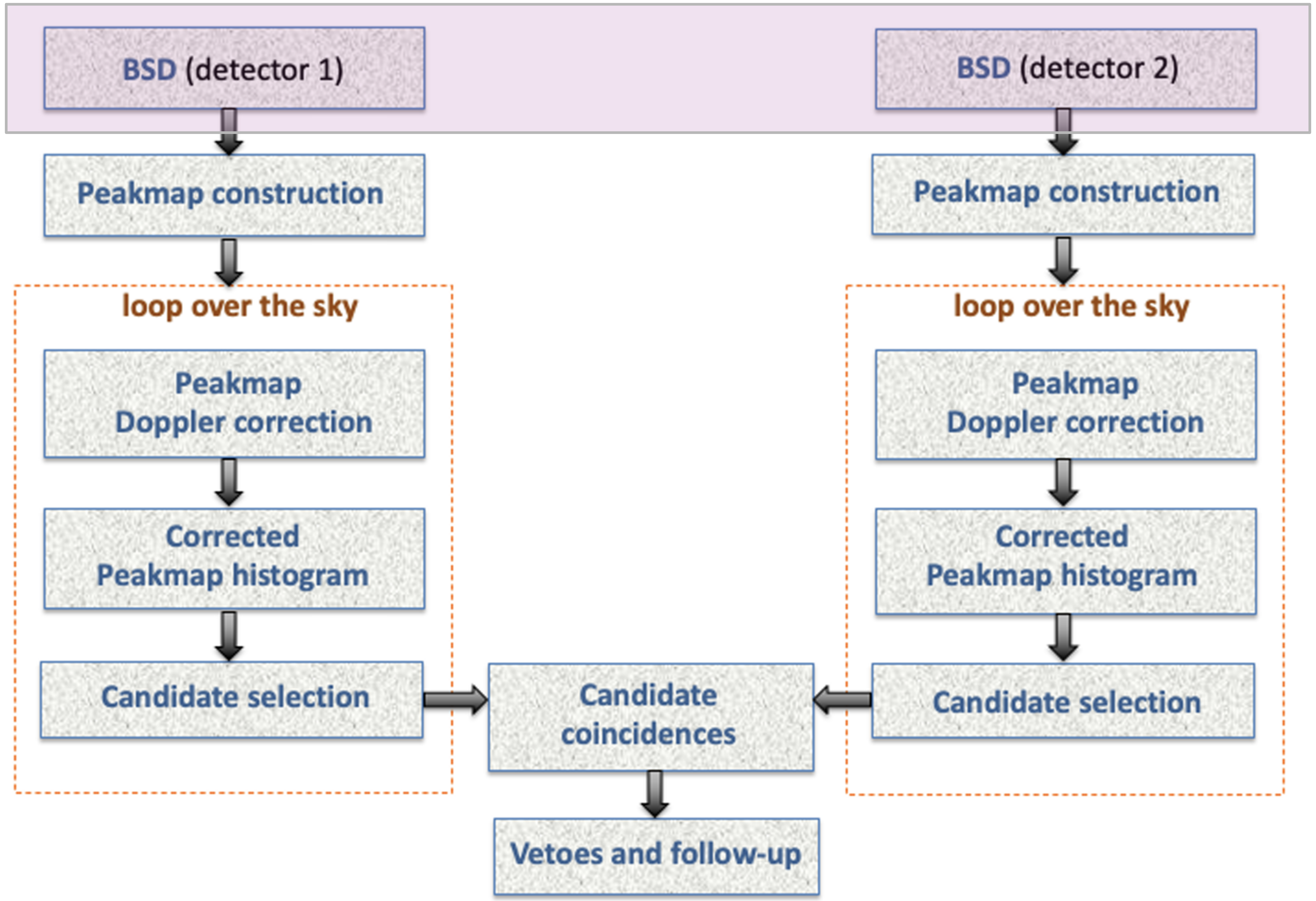
Other ways to look for BC evidence

other than CW methods

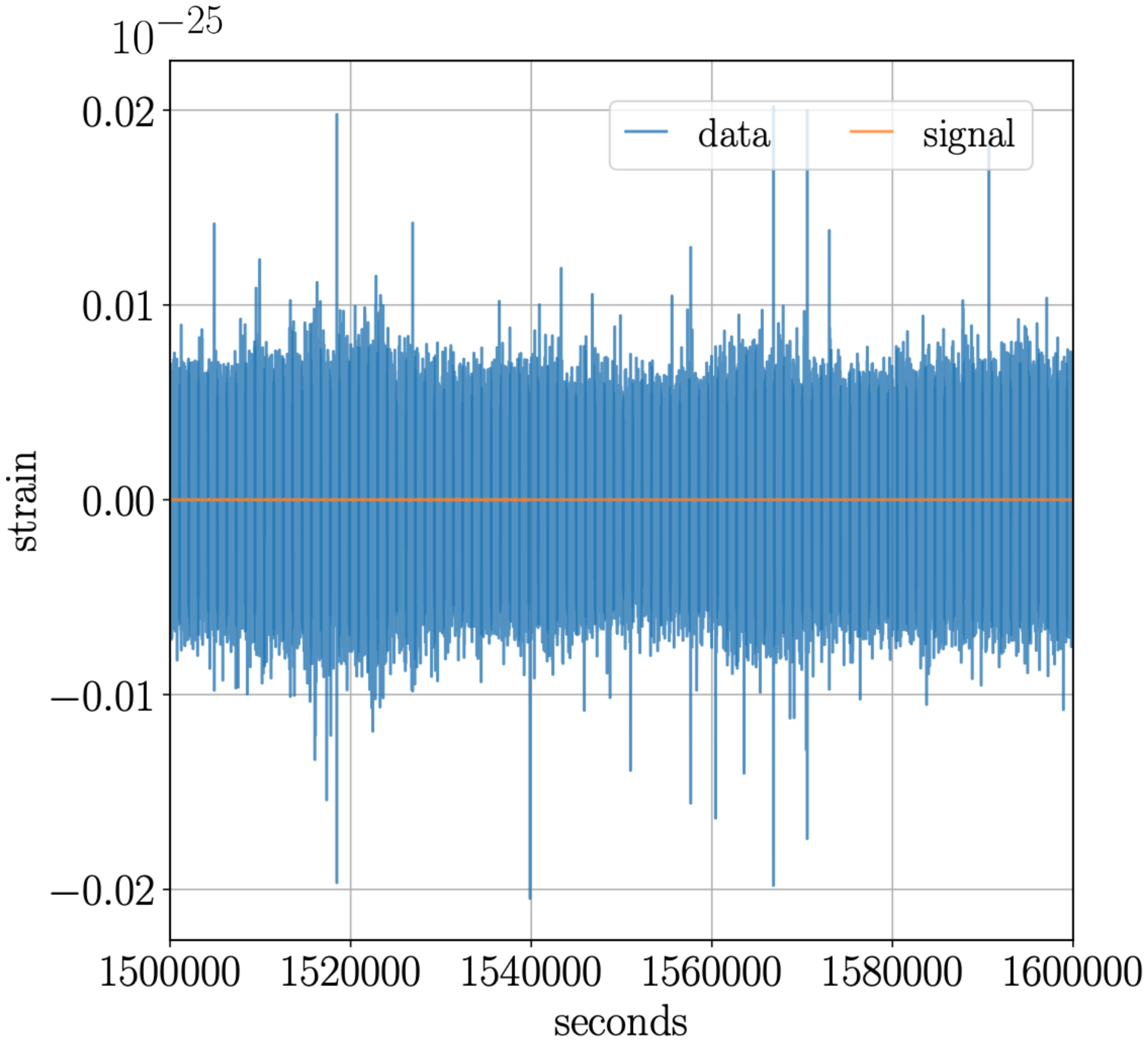
- Impact of DM on **binary dynamics** - Baumann et al., PRD99, 044001 (2019); Hannuksela et al. Nature Astron. 3 447 (2019); Xue, Huang, Sci. China Phys., Mech. & Astro., 67 210411 (2024)
- **Stochastic background** generated by the superposition of all signals from **scalar or vector** boson cloud; Assume BH spin distribution and merger rate - Tsukada et al., PRD 103, 082005 (2021): Vector boson clouds (O1+O2); Yuan et al., PRD106, 023020 (2022): Scalar boson clouds (O1+O2+O3)
- SGWB from **tensor** boson clouds - Guo et al. Arxiv 2312.16435
- Constraints from **BH spin distributions** (spin limited by superradiance) - Ng et al., PRL 126, 151102 (2021)
- Effects on the GW waveform due to **boson transfer** BBH system - Guo et al. 2309.07790
- Checking the rates of **hierarchical black hole mergers** in nuclear star clusters - Payne et al 2022 ApJ 931 79 (2022)

Case study: all-sky boson cloud search in O3 - Abbott et al. PRD 105, 102001 (2022)

Search method: all-sky

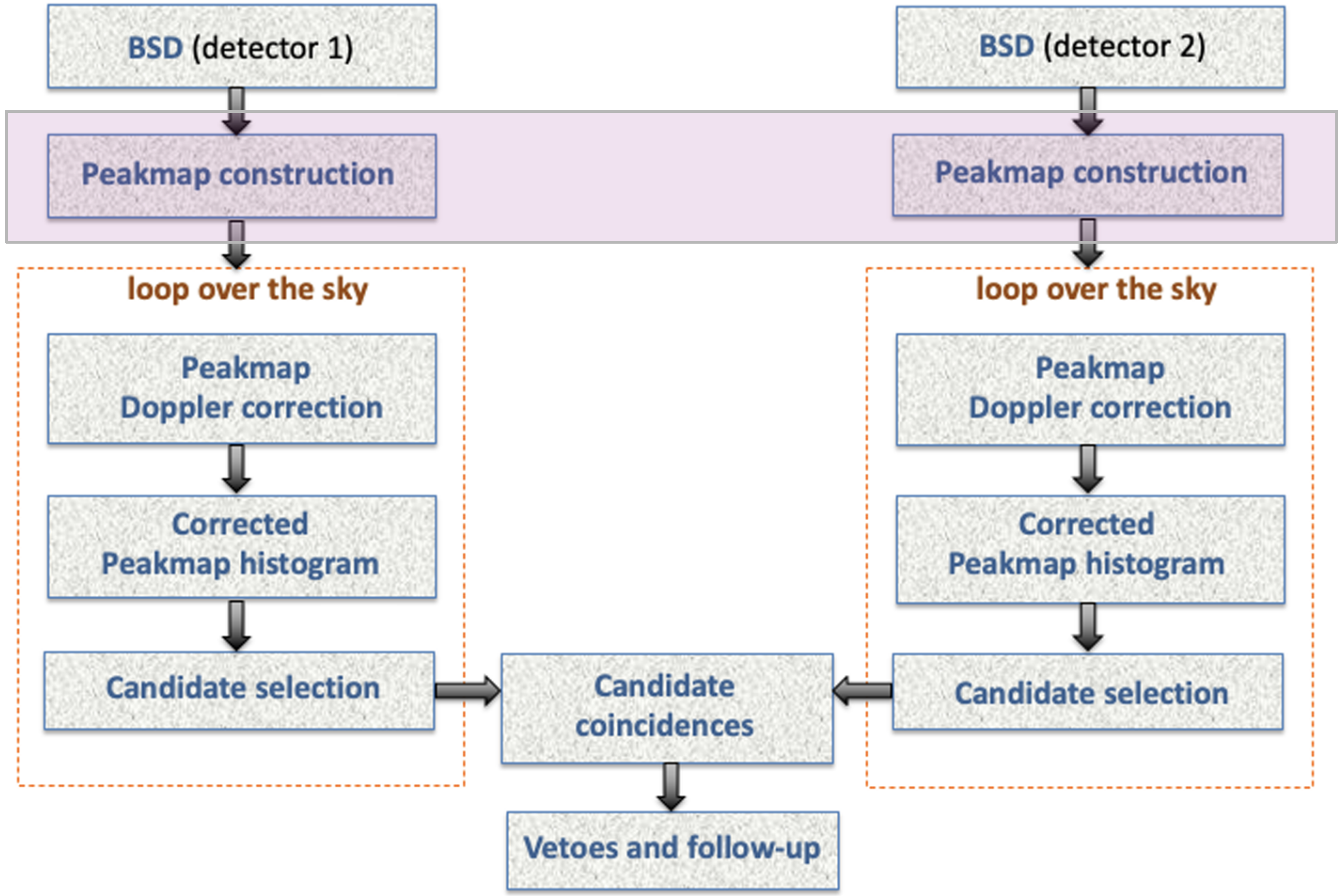

BSD (detector 1)
BSD (detector 2)
Peakmap construction
Peakmap construction
loop over the sky
Peakmap Doppler correction
Corrected Peakmap histogram
Candidate selection
loop over the sky
Peakmap Doppler correction
Corrected Peakmap histogram
Candidate selection
Candidate coincidences
Vetoes and follow-up

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



Data framework from Piccinni et al CQG 36 015008 (2019)

Search method



BSD (detector 1)

Peakmap construction

loop over the sky

Peakmap Doppler correction

Corrected Peakmap histogram

Candidate selection

BSD (detector 2)

Peakmap construction

loop over the sky

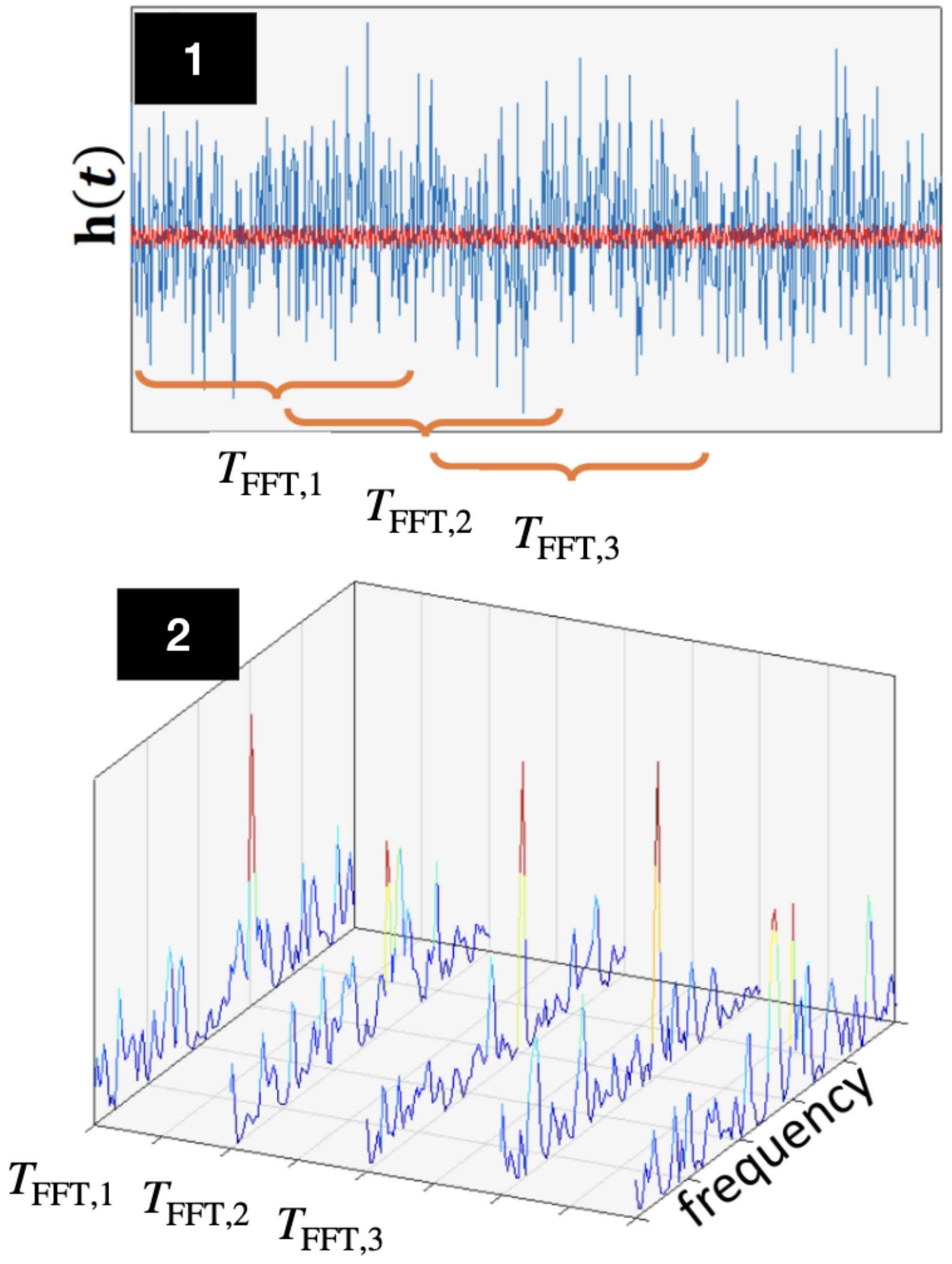
Peakmap Doppler correction

Corrected Peakmap histogram

Candidate selection

Candidate coincidences

Vetoes and follow-up

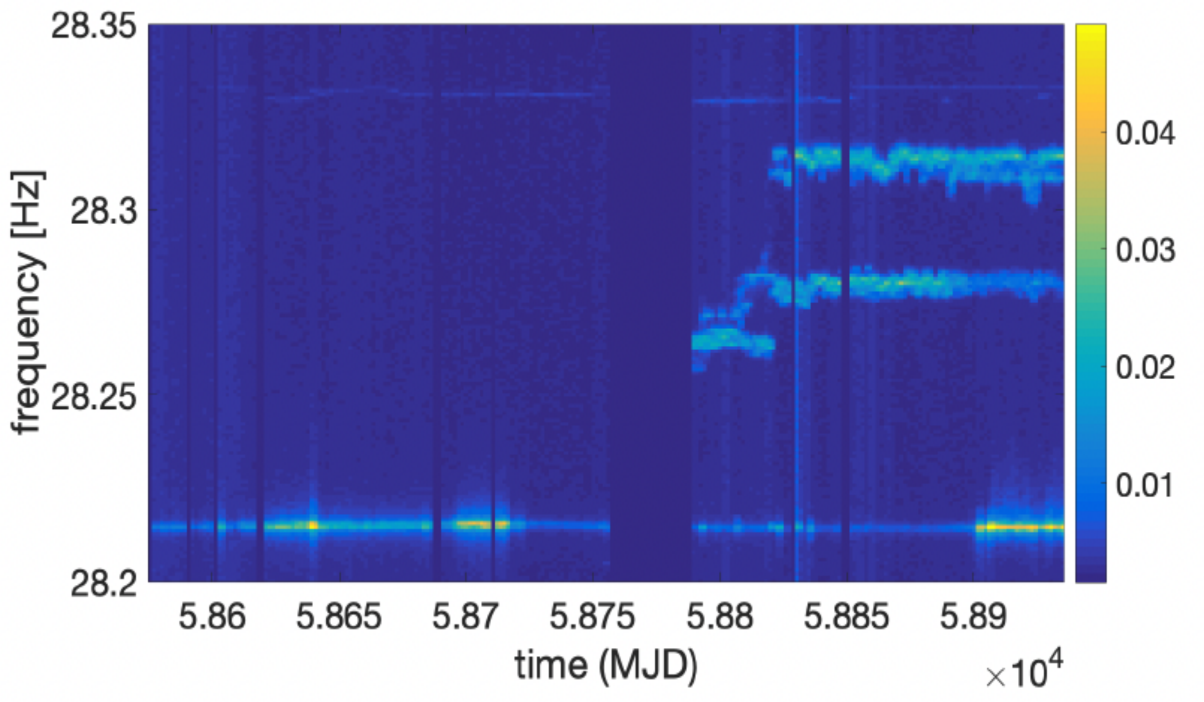


Credit: L. Pierini

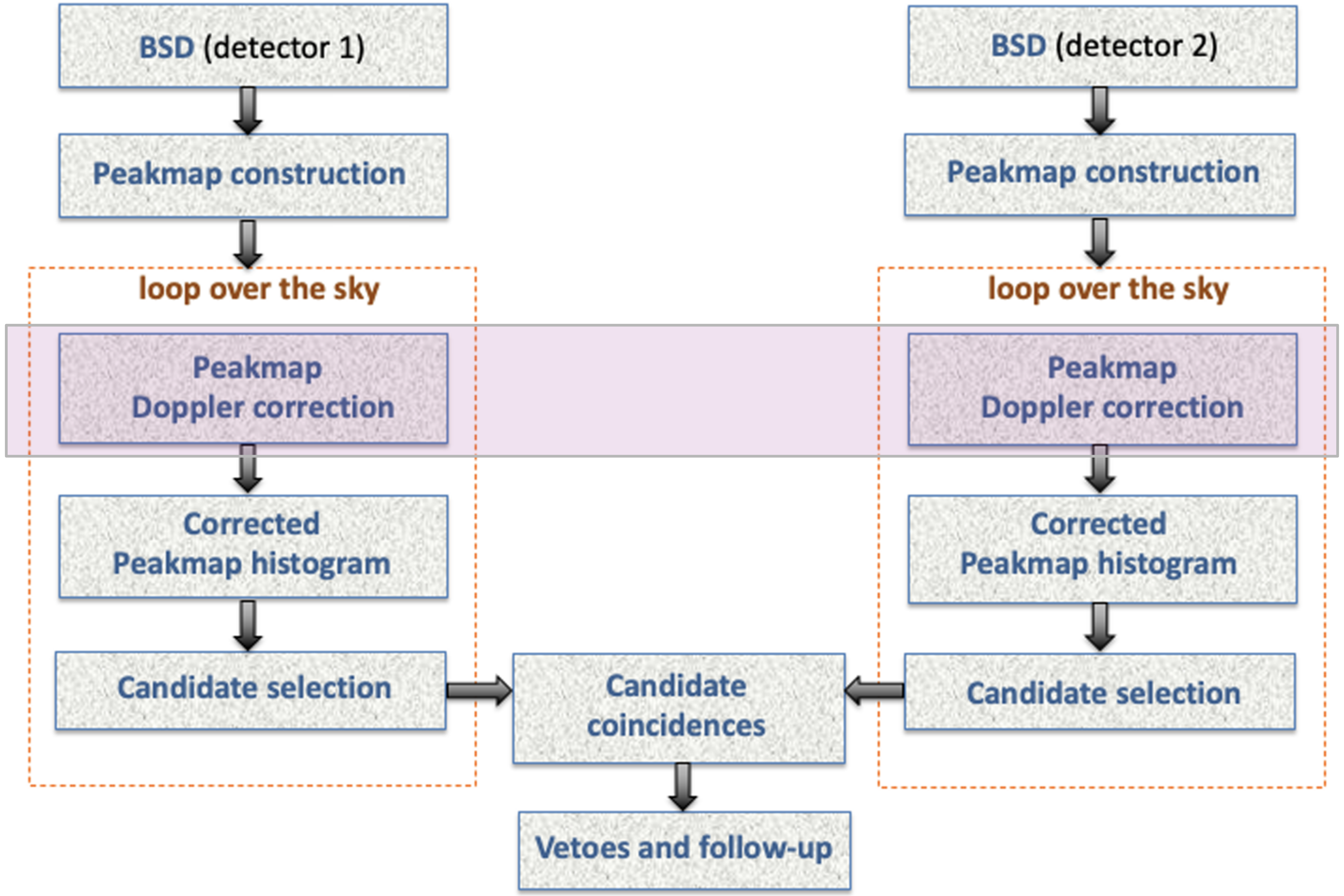
$$T_{\mathrm{FFT}} = \frac{1}{\Omega_{\mathrm{rot}}}\sqrt{\frac{c}{2 f_{10} R_{\mathrm{rot}}}}$$

Using different resolutions (T_{FFT}) in each 10 Hz

20-610 Hz



Search method: modulation effects



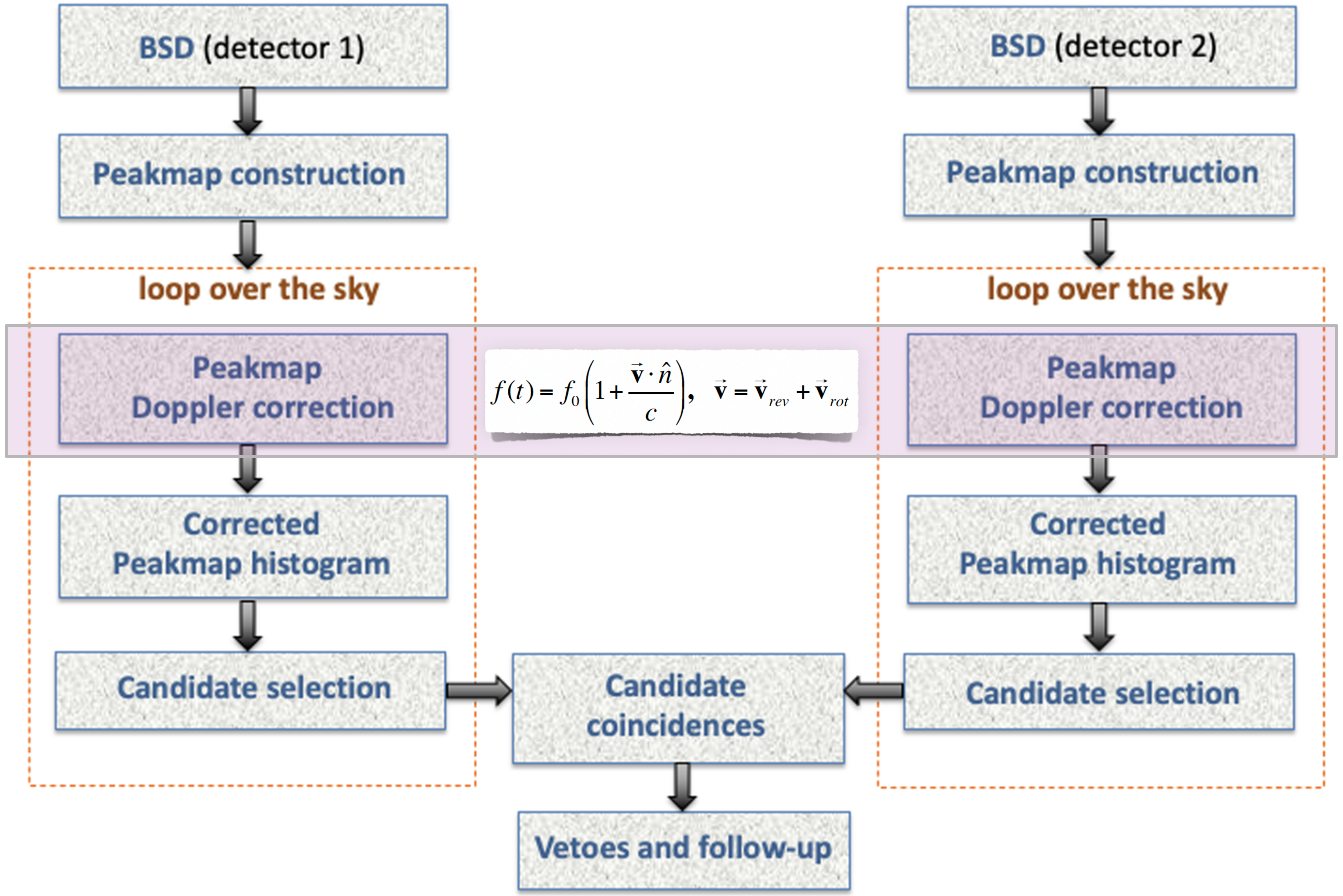
Doppler effect, which depends on frequency and source position

$$f(t) = f_0\left(1 + \frac{\vec{\mathbf{v}} \cdot \hat{n}}{c}\right), \quad \vec{\mathbf{v}} = \vec{\mathbf{v}}_{rev} + \vec{\mathbf{v}}_{rot}$$

Amplitude modulation (for signals longer than ~ 1 sidereal day) due to the response of the antenna

Relativistic effects (Einstein delay)

Search method



BSD (detector 1)

Peakmap construction

loop over the sky

Peakmap Doppler correction

$$f(t) = f_0\left(1 + \frac{\vec{\mathbf{v}} \cdot \hat{n}}{c}\right), \quad \vec{\mathbf{v}} = \vec{\mathbf{v}}_{rev} + \vec{\mathbf{v}}_{rot}$$

Corrected Peakmap histogram

Candidate selection

BSD (detector 2)

Peakmap construction

loop over the sky

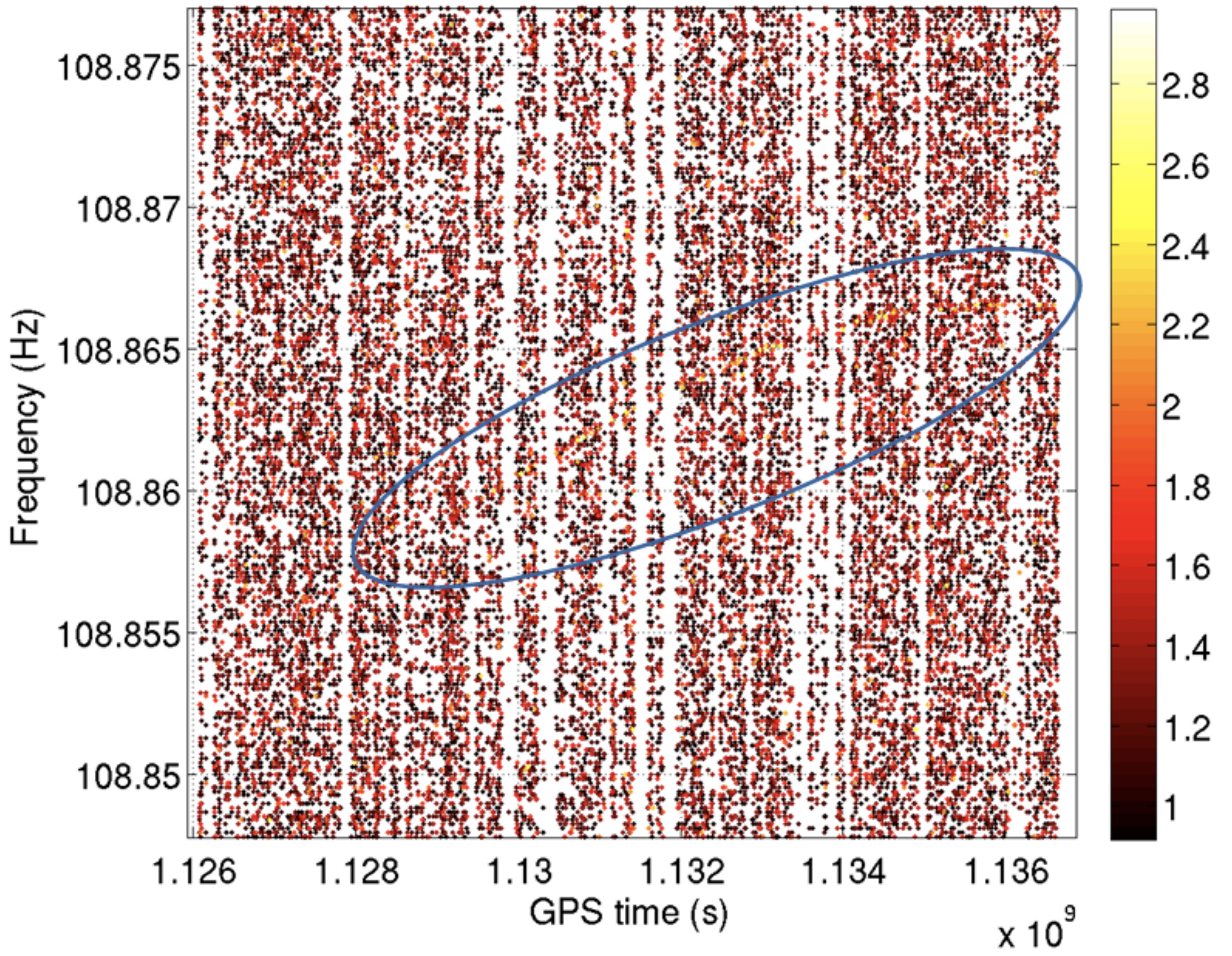
Peakmap Doppler correction

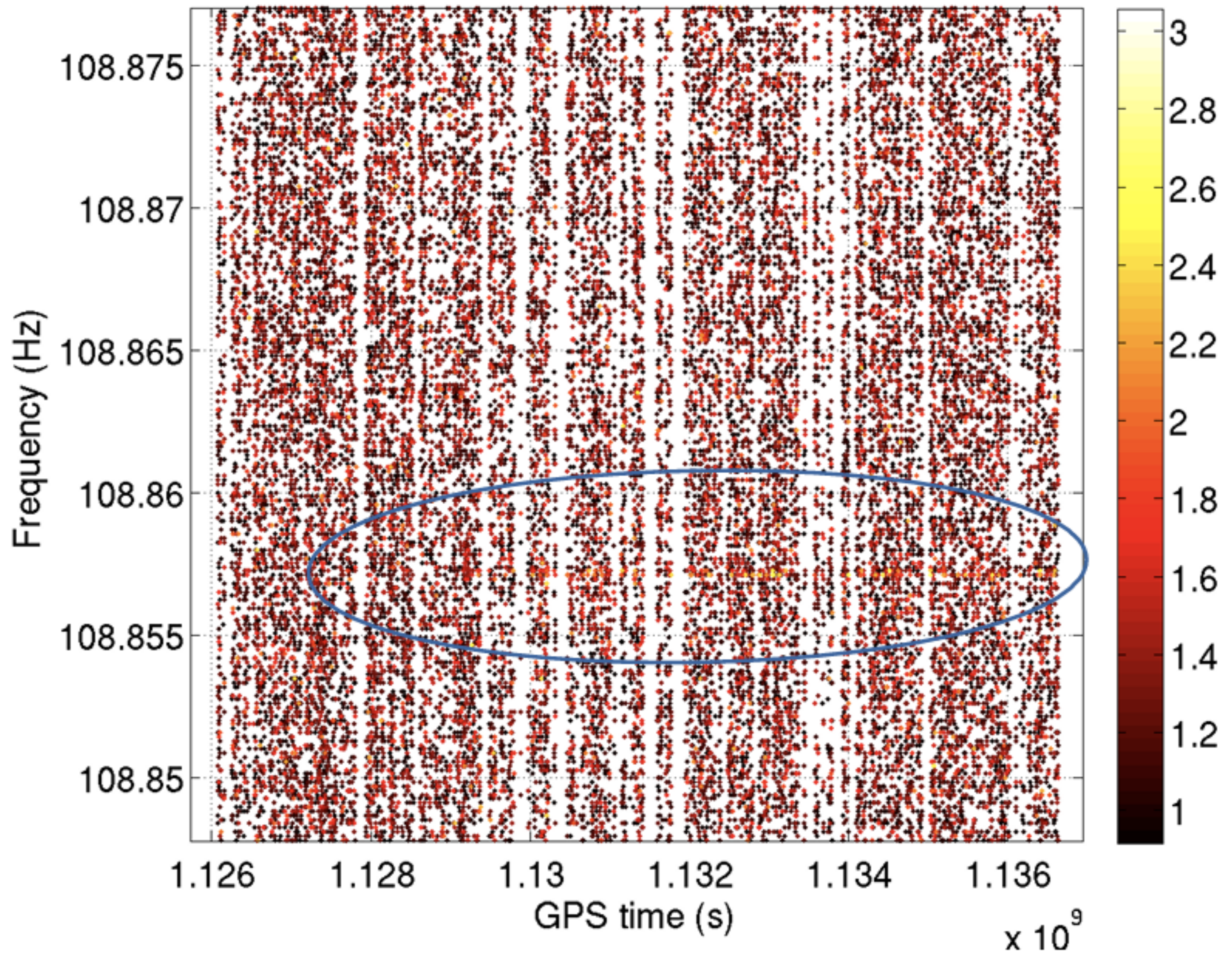
Corrected Peakmap histogram

Candidate selection

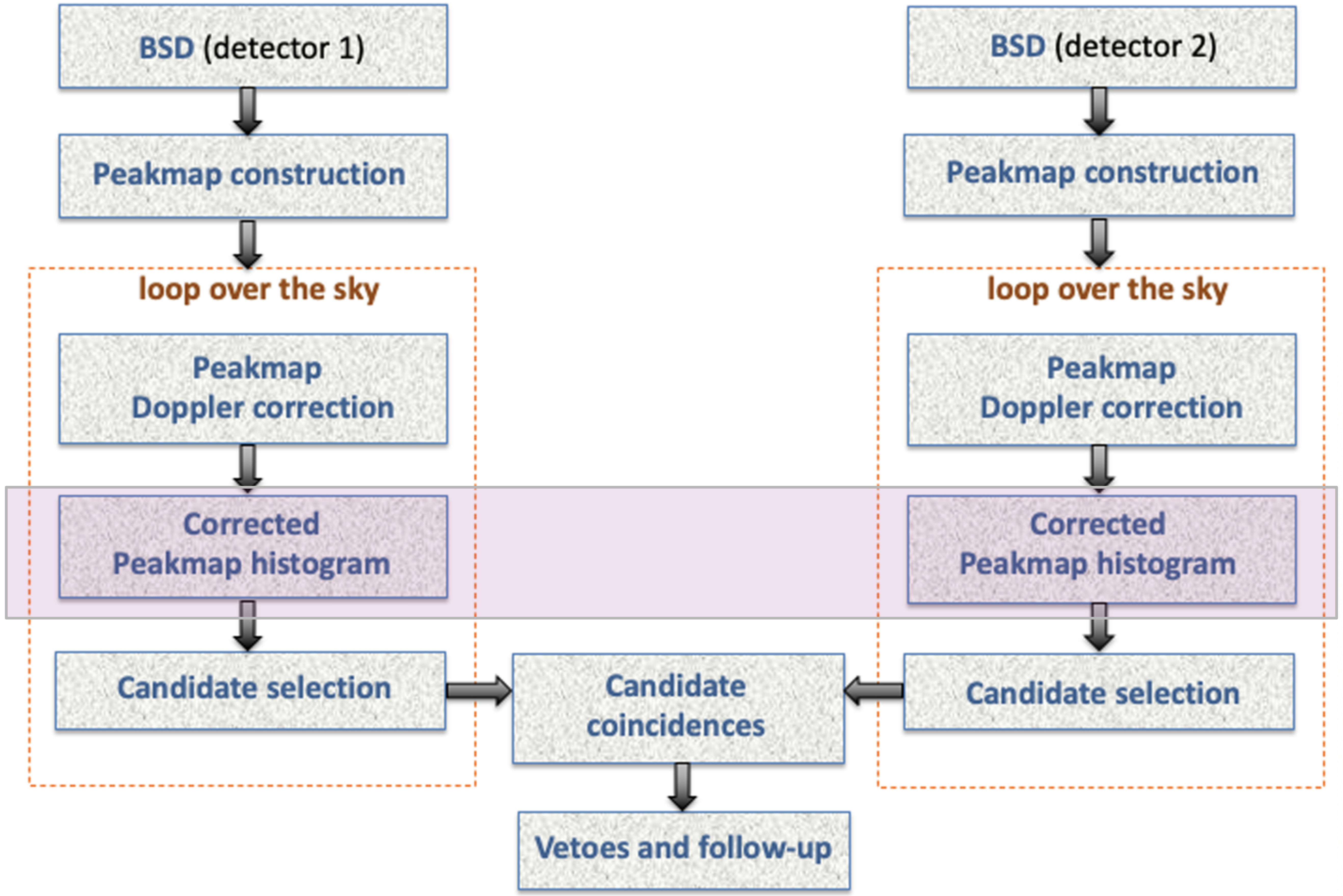
Candidate coincidences

Vetoes and follow-up





Search method



BSD (detector 1)

Peakmap construction

loop over the sky

Peakmap Doppler correction

Corrected Peakmap histogram

Candidate selection

BSD (detector 2)

Peakmap construction

loop over the sky

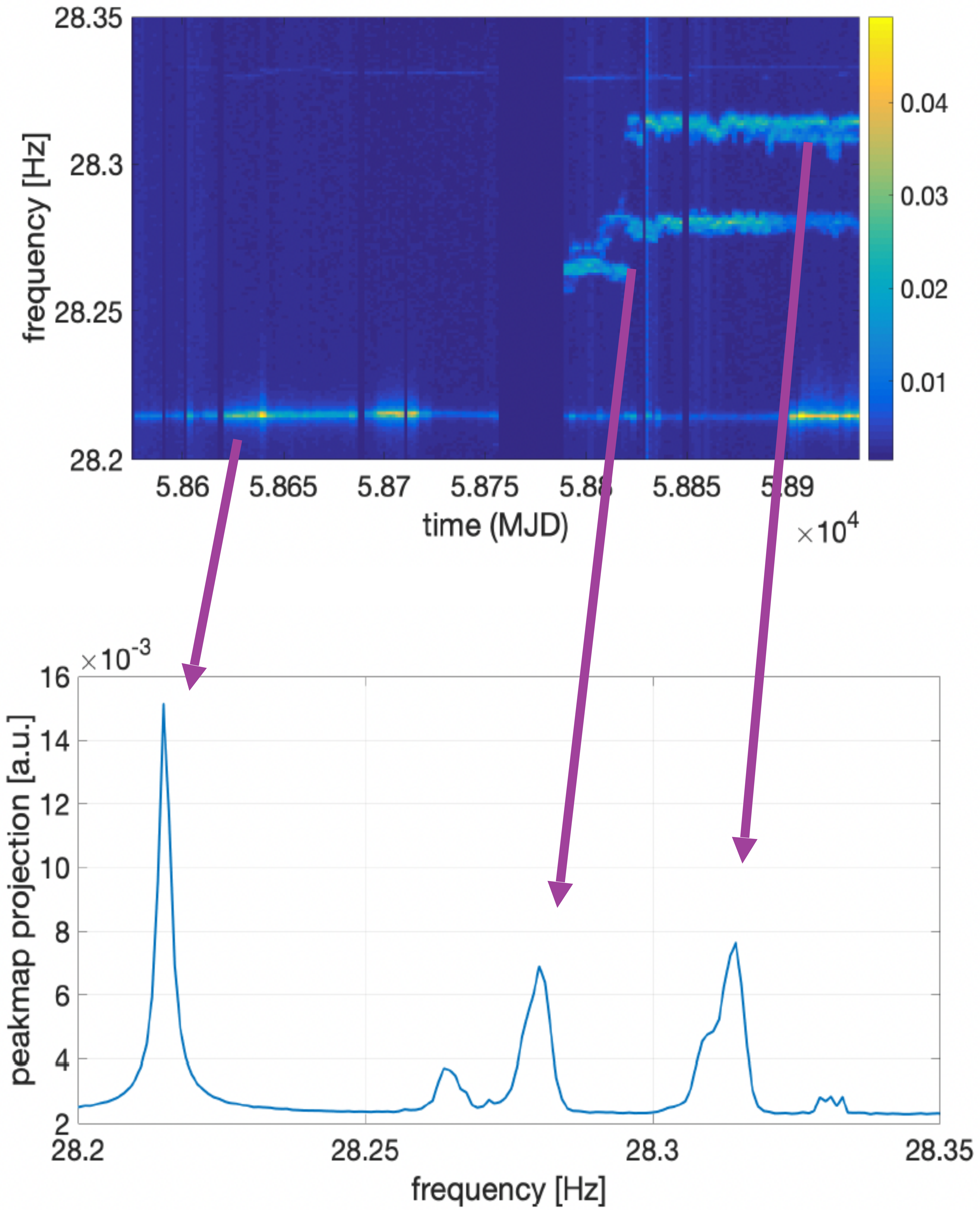
Peakmap Doppler correction

Corrected Peakmap histogram

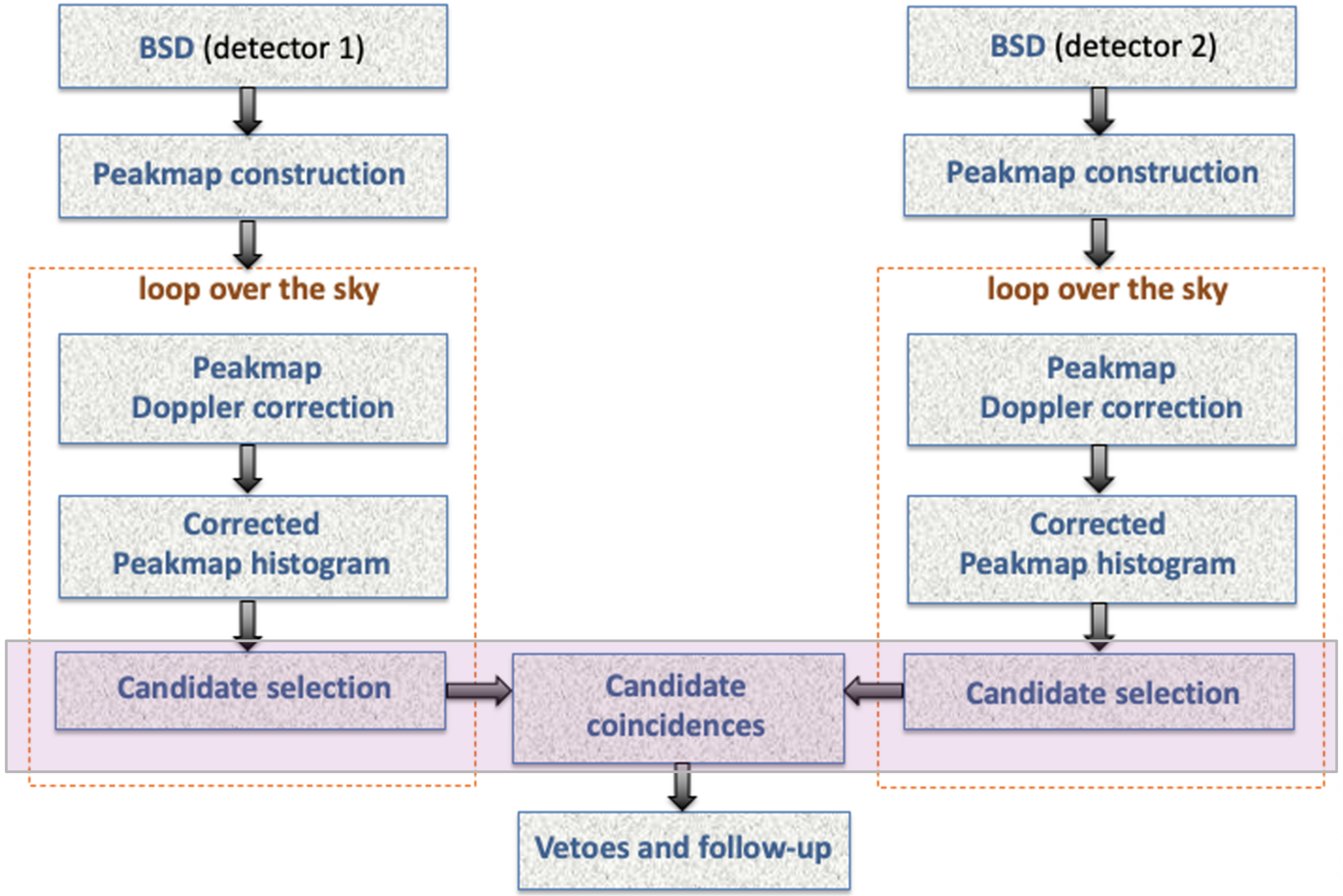
Candidate selection

Candidate coincidences

Vetoes and follow-up



Search method



BSD (detector 1)

Peakmap construction

loop over the sky

Peakmap Doppler correction

Corrected Peakmap histogram

Candidate selection

BSD (detector 2)

Peakmap construction

loop over the sky

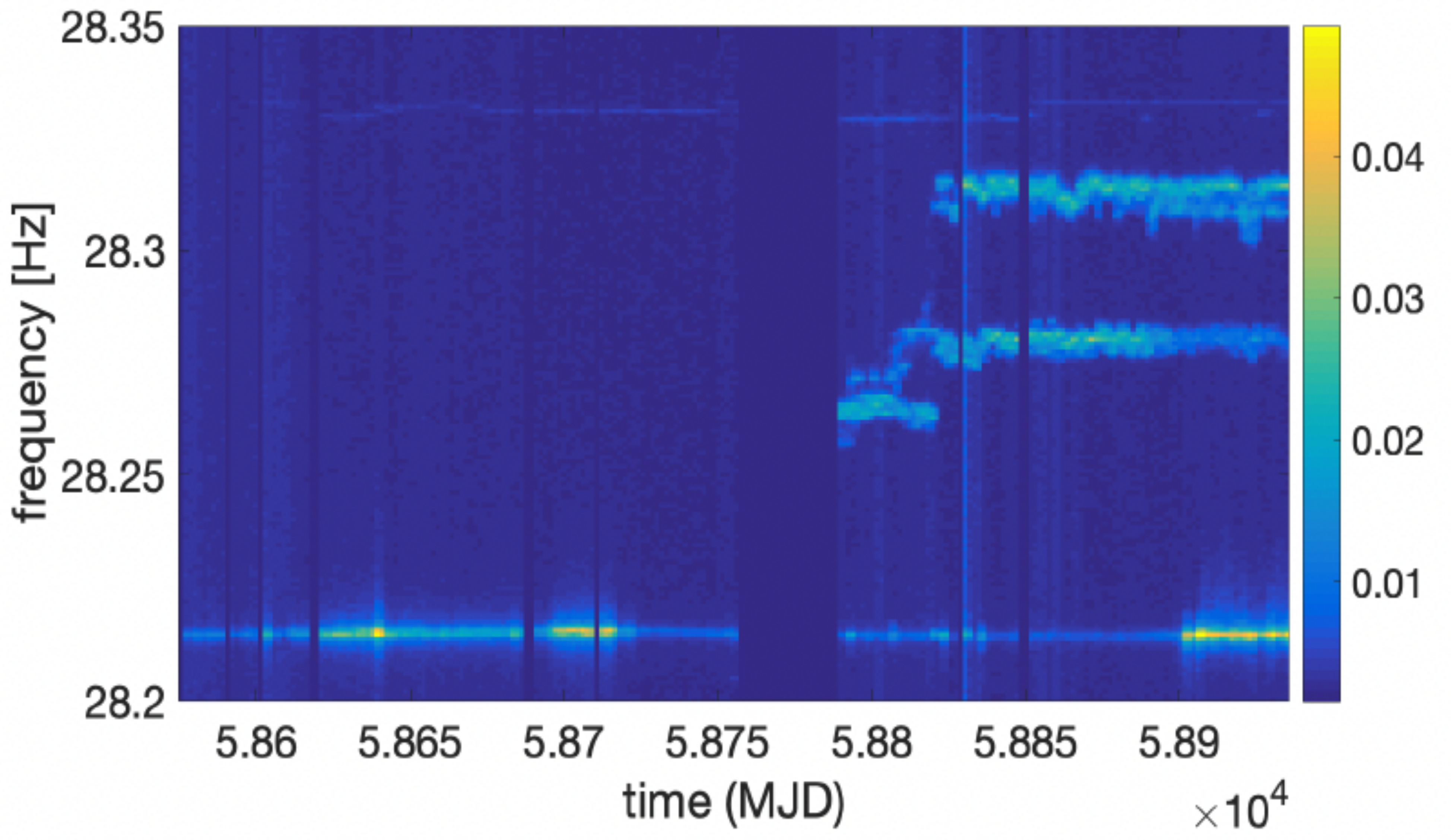
Peakmap Doppler correction

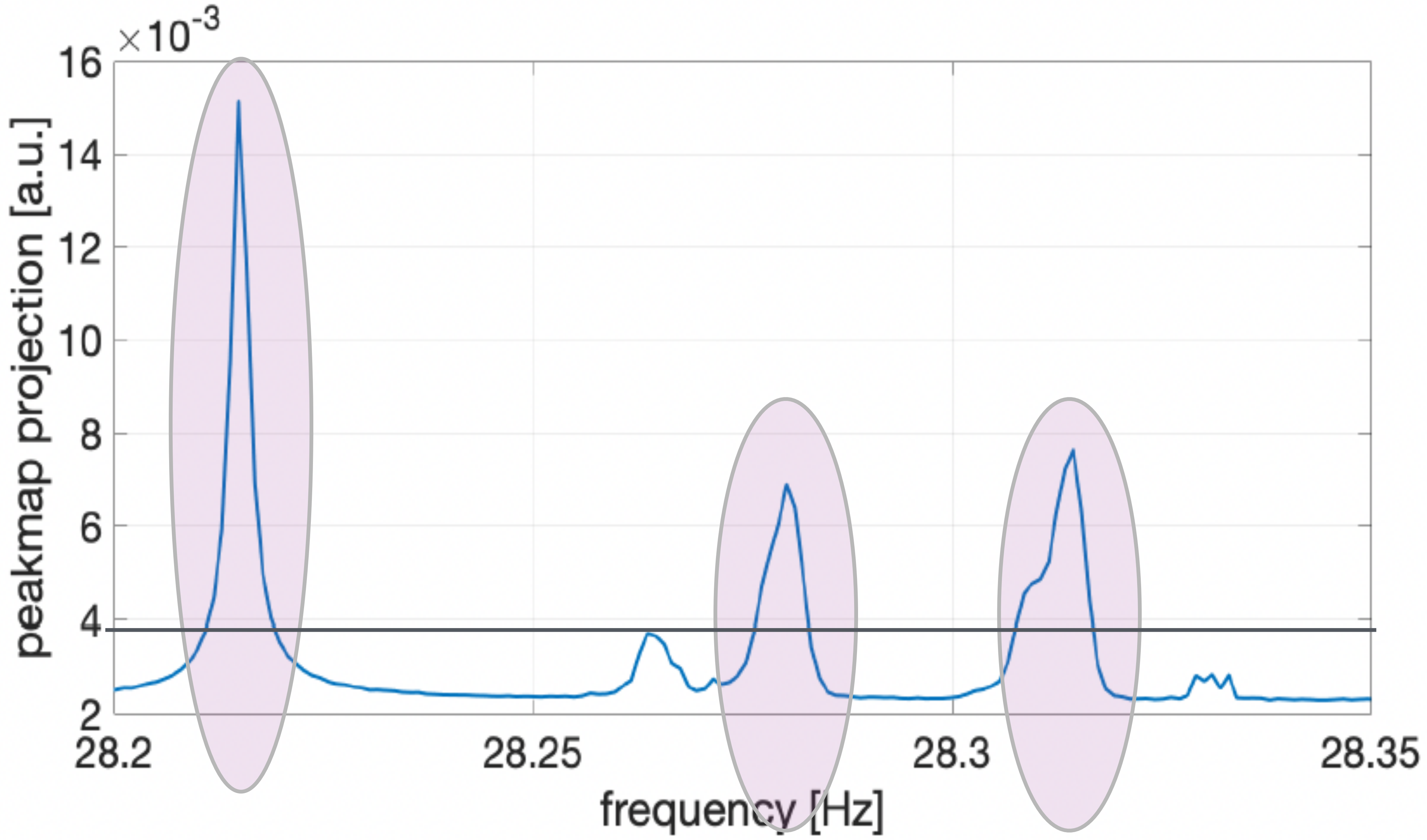
Corrected Peakmap histogram

Candidate selection

Candidate coincidences

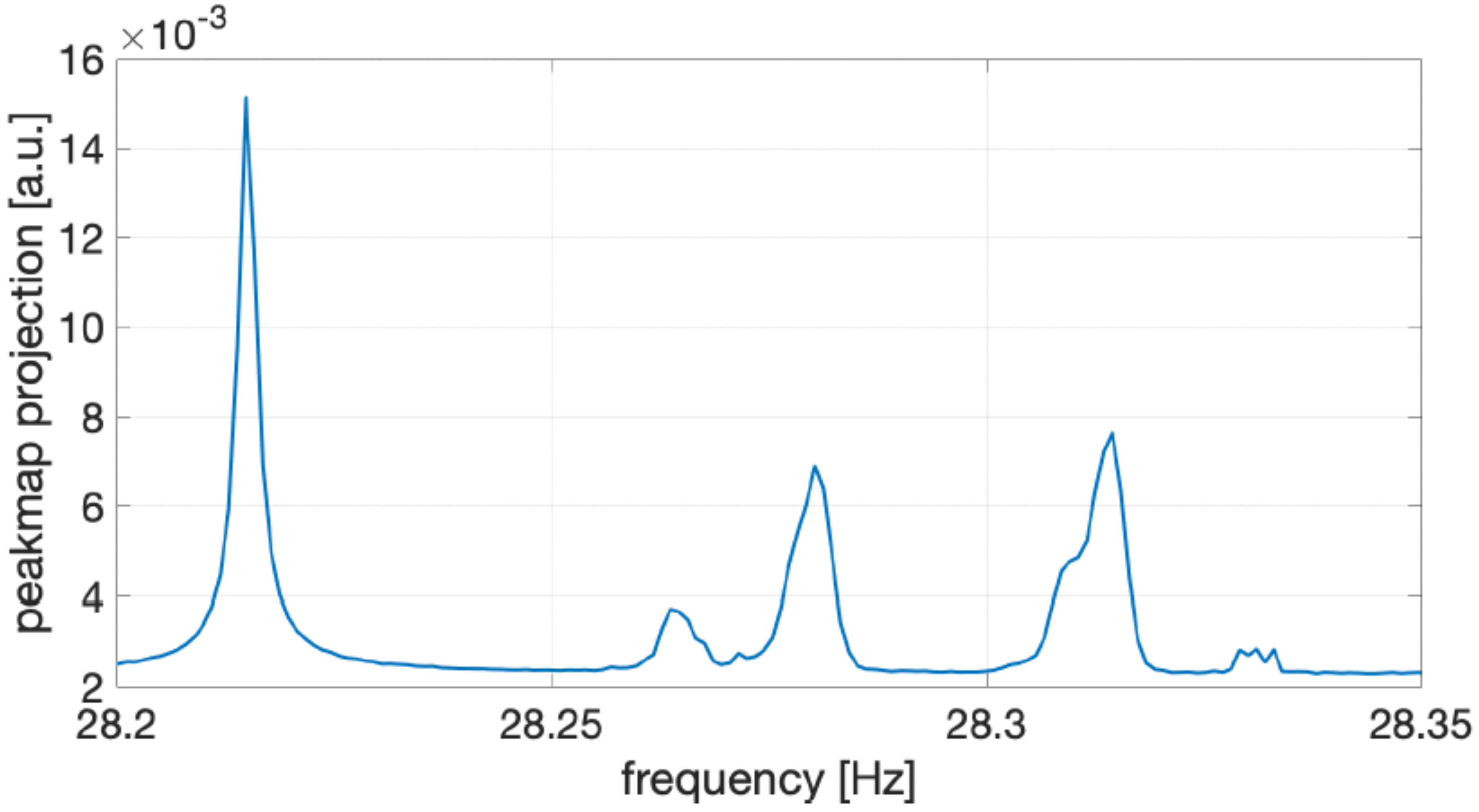
Vetoes and follow-up





Candidate selection

- Histograms: moving average over a window W=1,..,10 bins (1 bin=1/T_{FFT})
- Equivalent and more efficient than building peakmaps with shorter chunks T_{FFT}/W
- Allows for robustness
- 2 candidates for each 0.05 Hz/sky position selected



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

Check for coincidences in 2 detectors, follow up the most significant candidates with 2 methods:

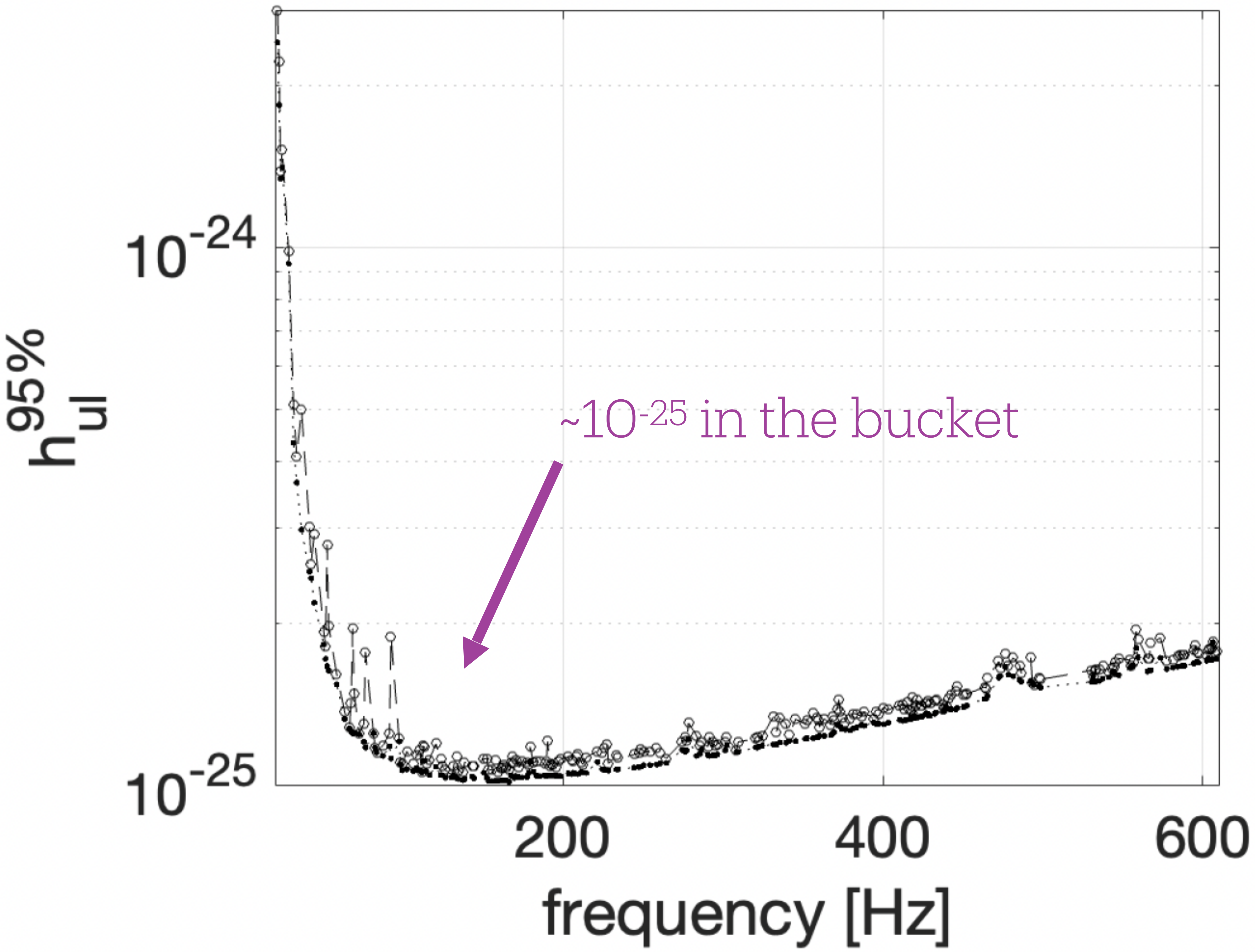
- FrequencyHough – tuned for standard monochromatic signals (W=1)
- Viterbi – more robust against deviations (W>1)

Results: upper limits

- No potential candidate remains after the follow-up

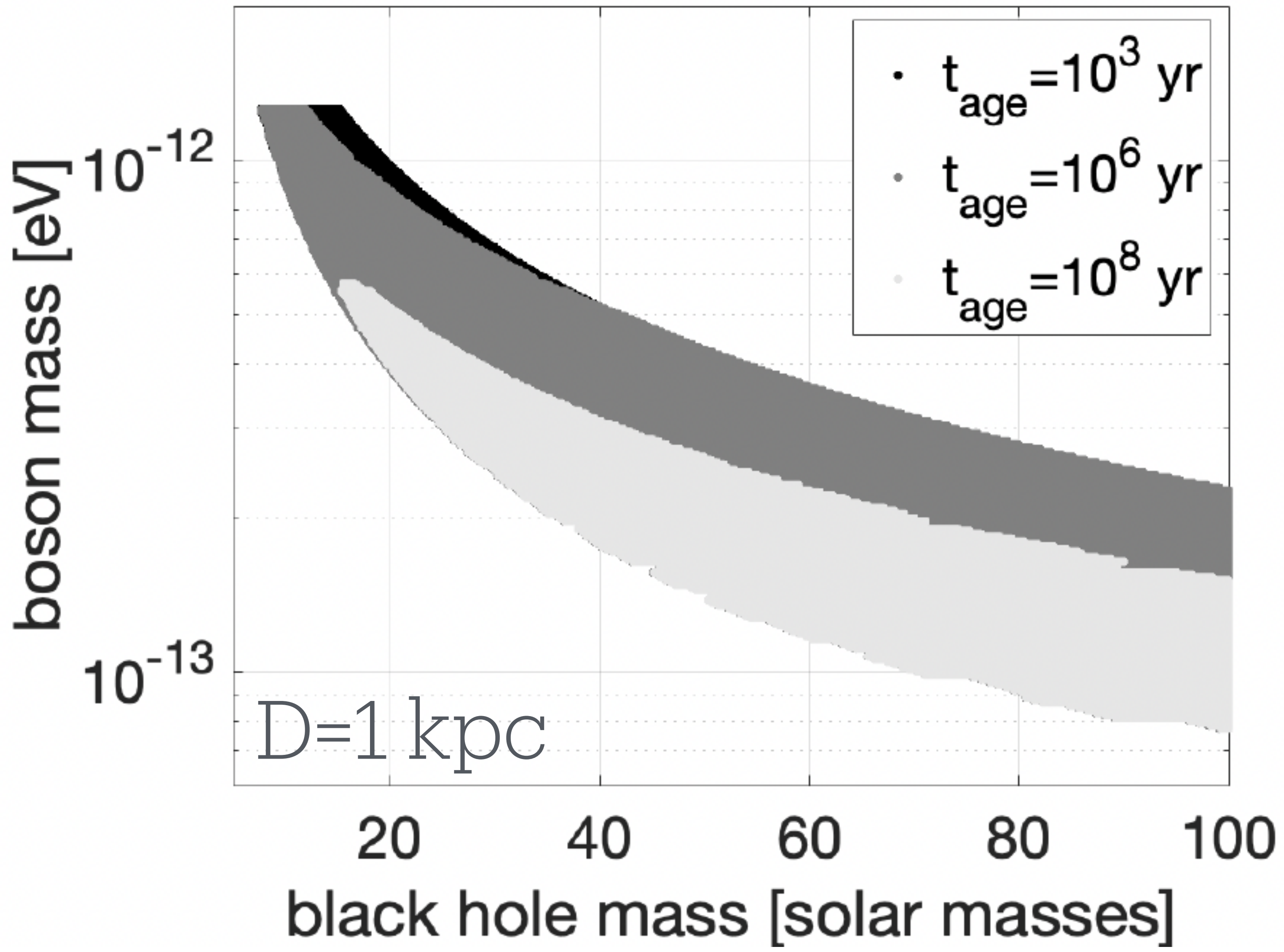
  → *upper limits on the signal strain*

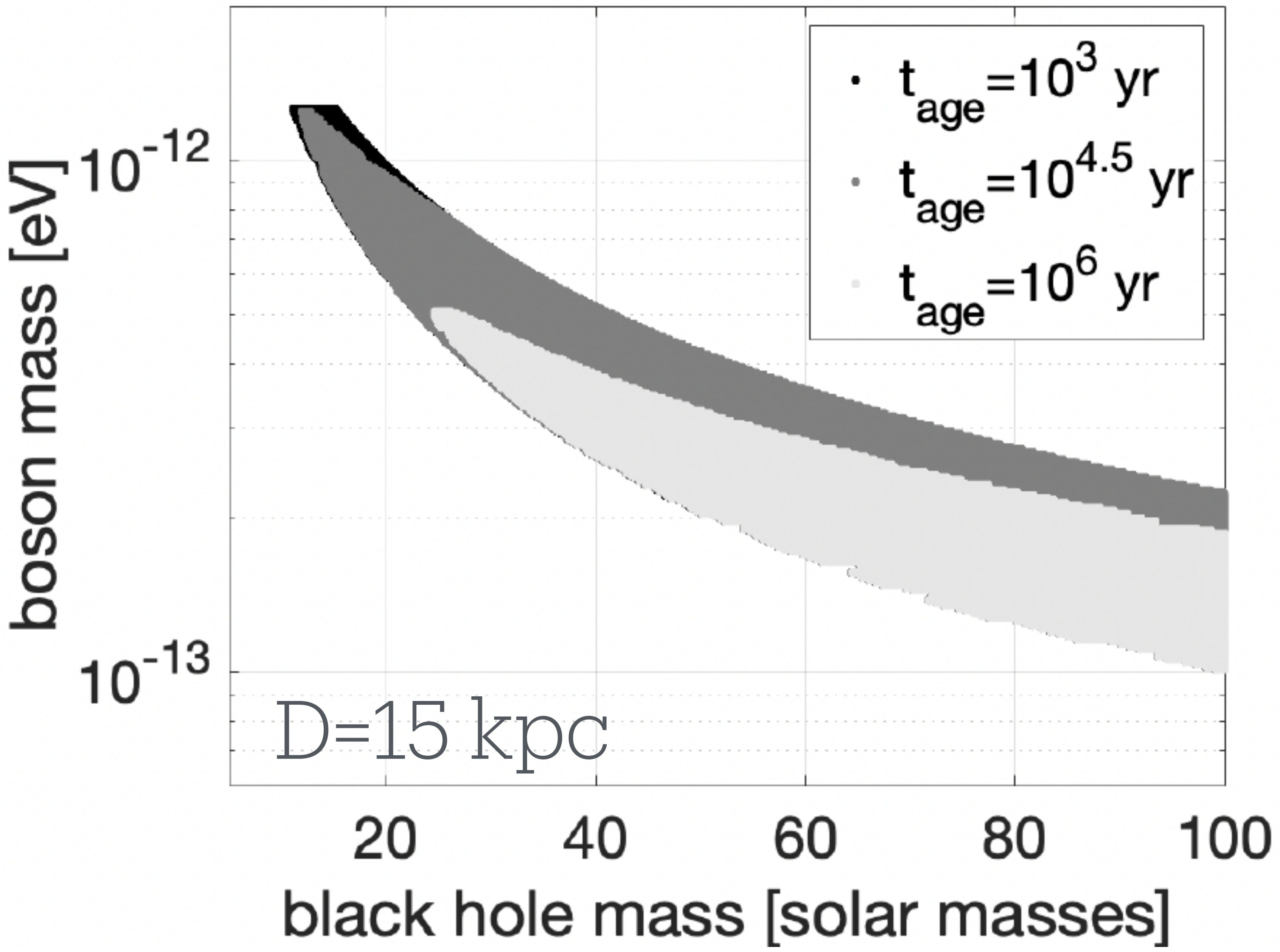
- Astrophysical implications:
  - **exclusion regions** in the BH-boson mass plane
  - **distance reach** of the search: how far we can exclude the presence of an emitting system given the null detection results



~10^{-25} in the bucket

Exclusion regions





BH spin = 0.9

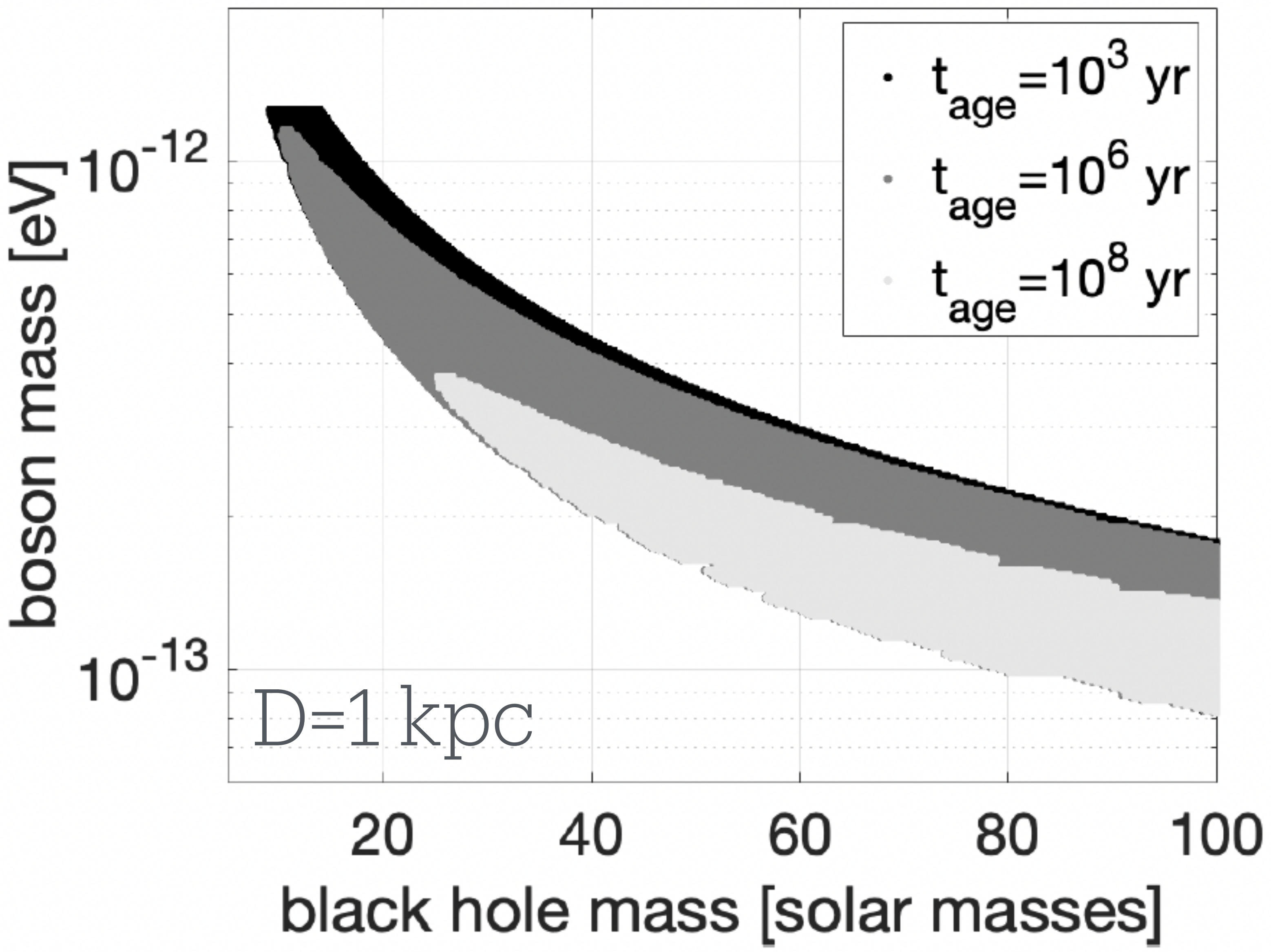
$$h_0 \approx 6\times10^{-24}\left(\frac{M_{\rm BH}}{10M_\odot}\right)\left(\frac{\alpha}{0.1}\right)^7\left(\frac{1\,{\rm kpc}}{D}\right)(\chi_i-\chi_c)$$

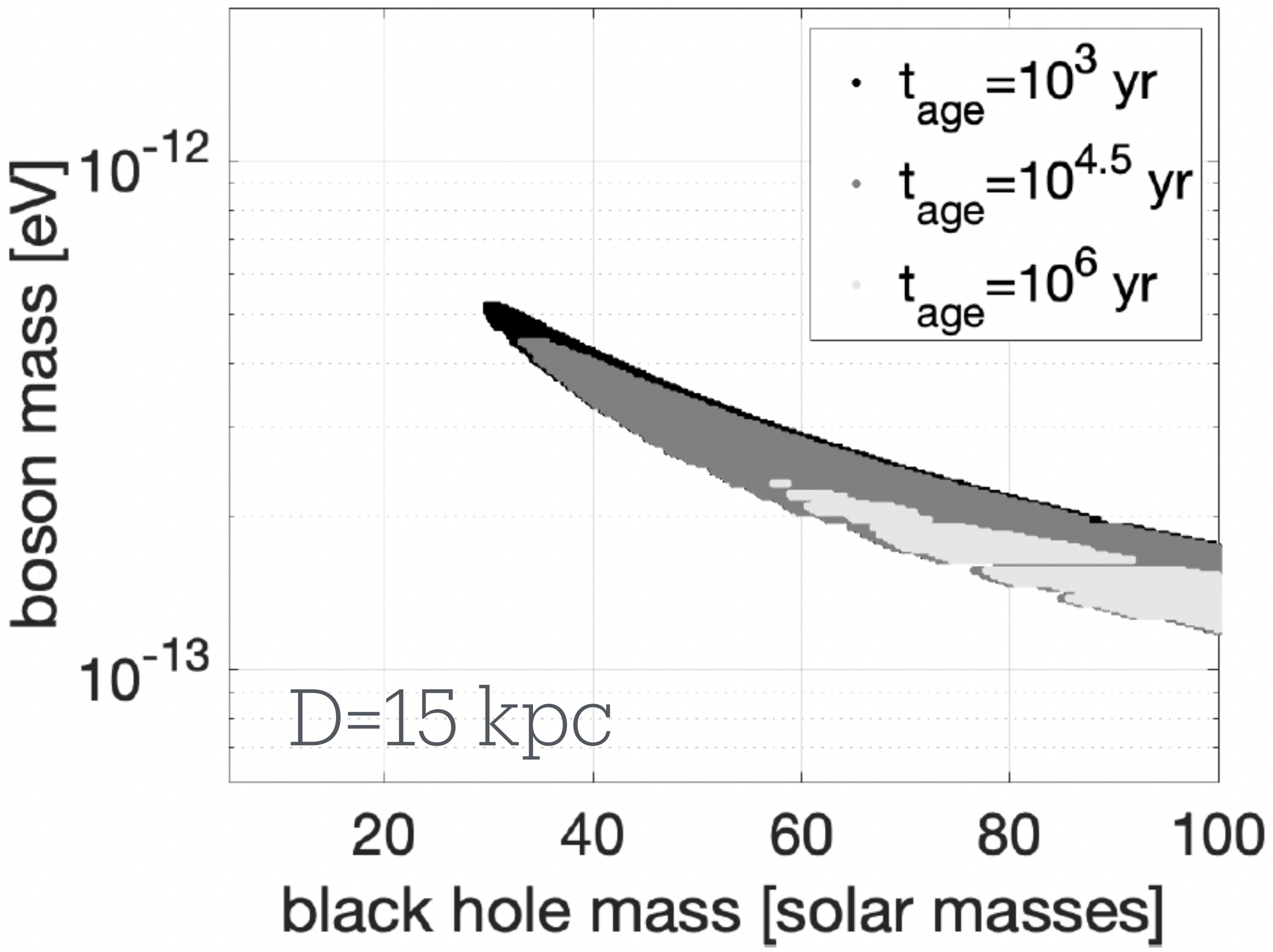
$$h(t)=\frac{h_0}{1+\frac{t}{\tau_{\rm gw}}}$$

assuming a BH with a given spin, distance and age

↓

we exclude some BH-boson masses combination

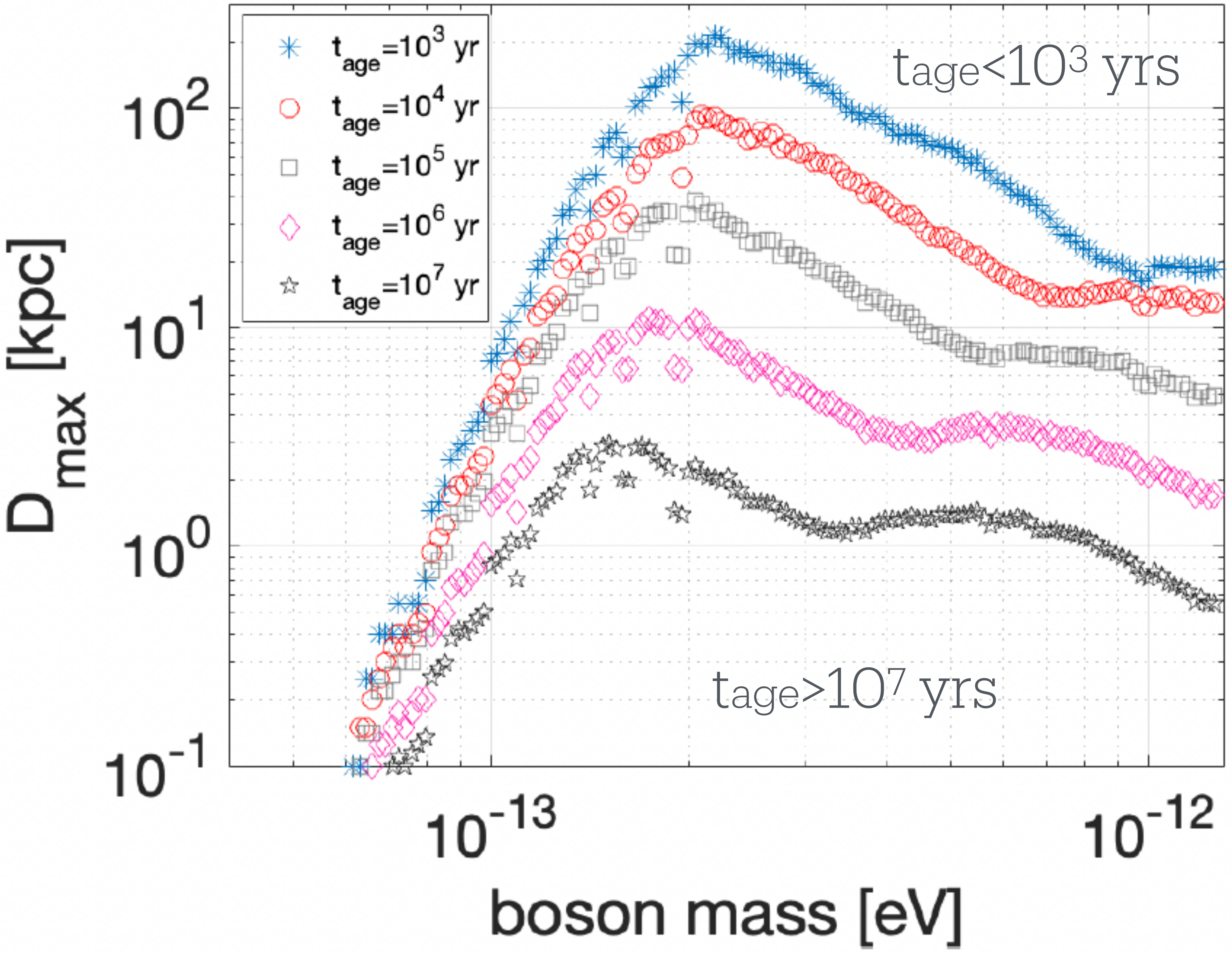




BH spin = 0.5

Astrophysical reach of the search

maximum distance at which a given BH–boson cloud system, with a certain age, is not emitting CWs, as a function of the boson mass



Simulating a BH population with:

- Kroupa mass distribution [5, 100] $M_\odot$
- uniform spin distribution [0.2, 0.9].

The maximum distance corresponds to the distance at which at least 5% of the simulated signal have $h_0 > h_{ul}$ → are detected.

Similar behaviour for a simulated BH population of [5, 50] $M_\odot$.

Results depend on the properties of the simulated BH population.

Directed and post-merger

O3 GC search

Best h_0 UL 7.6×10^{-26} at 140 Hz

Abbott et al PRD 106, 042003 (2022)

Frequency range: $[10 - 2000]$ Hz

min spin-down: -1.8×10^{-8} Hz/s

spin-up: 1×10^{-10} Hz/s

Data: full O3 clean data (April 2019 - March 2020)

Sky position (Sgr A*):

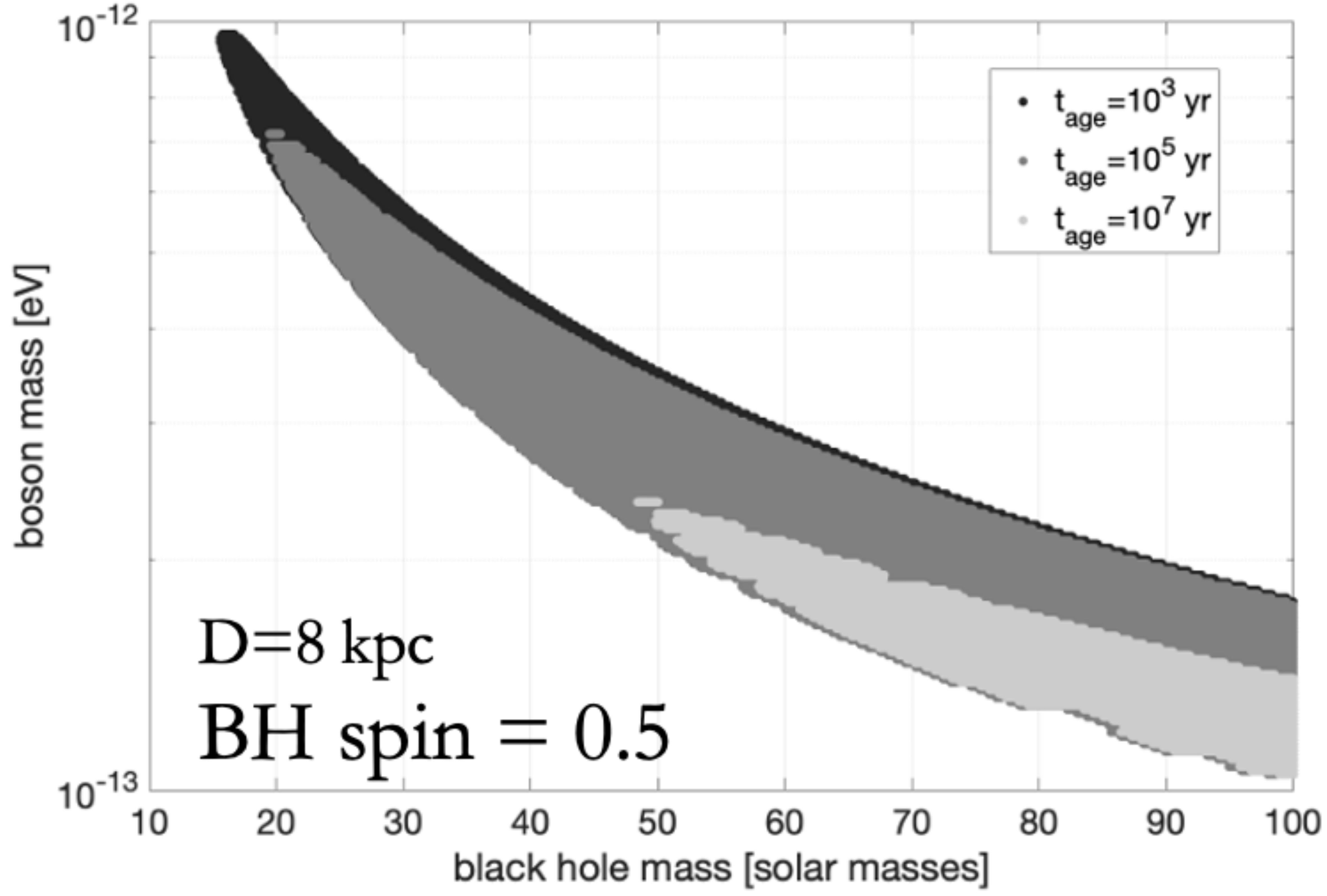
$\alpha = 4.650$ rad $\delta = -0.506$ rad

- 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)

NS or DM?

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

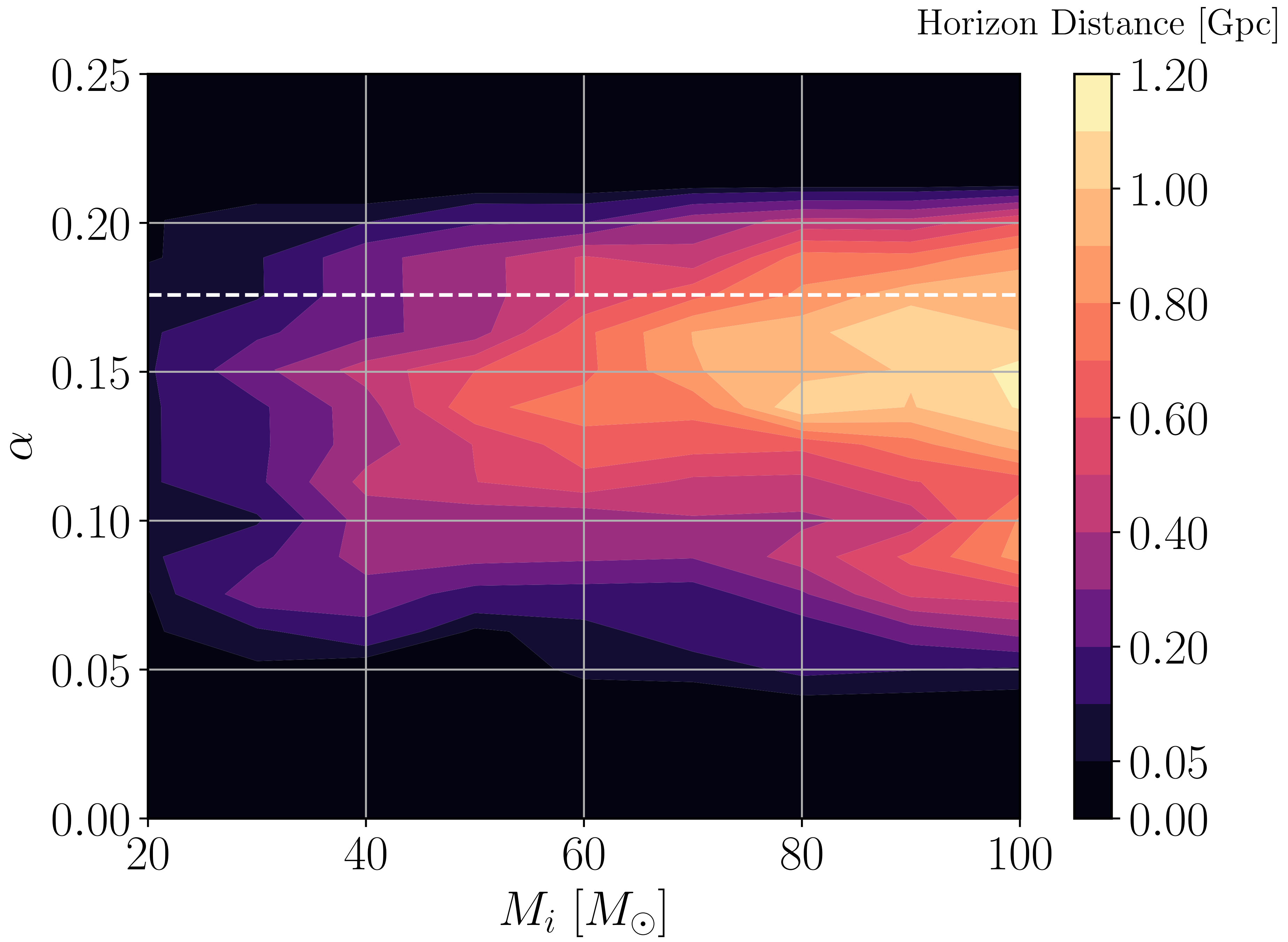


Semi-coherent method + spin-up range: boson clouds exclusion regions

Horizon distances

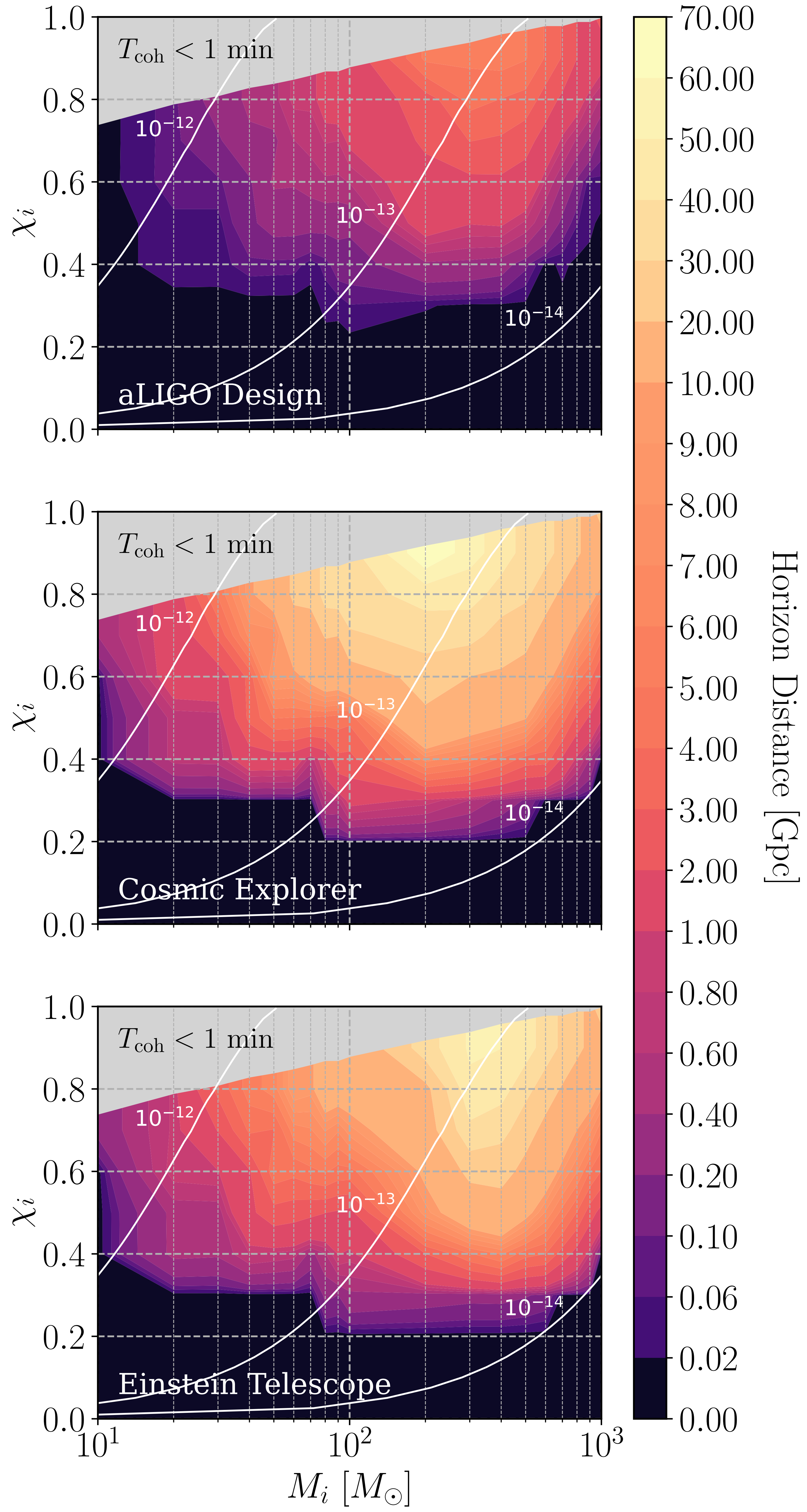
Directed vector boson case: CBC remnants

- **hidden Markov model** tracking signals on timescales from hours to months. Jones et al., PRD 108, 064001 (2023)



Able to reach signals at a luminosity distance above ~1 Gpc (in current gen.)

Scalar clouds in CBC remnant are not promising in current gen. detectors

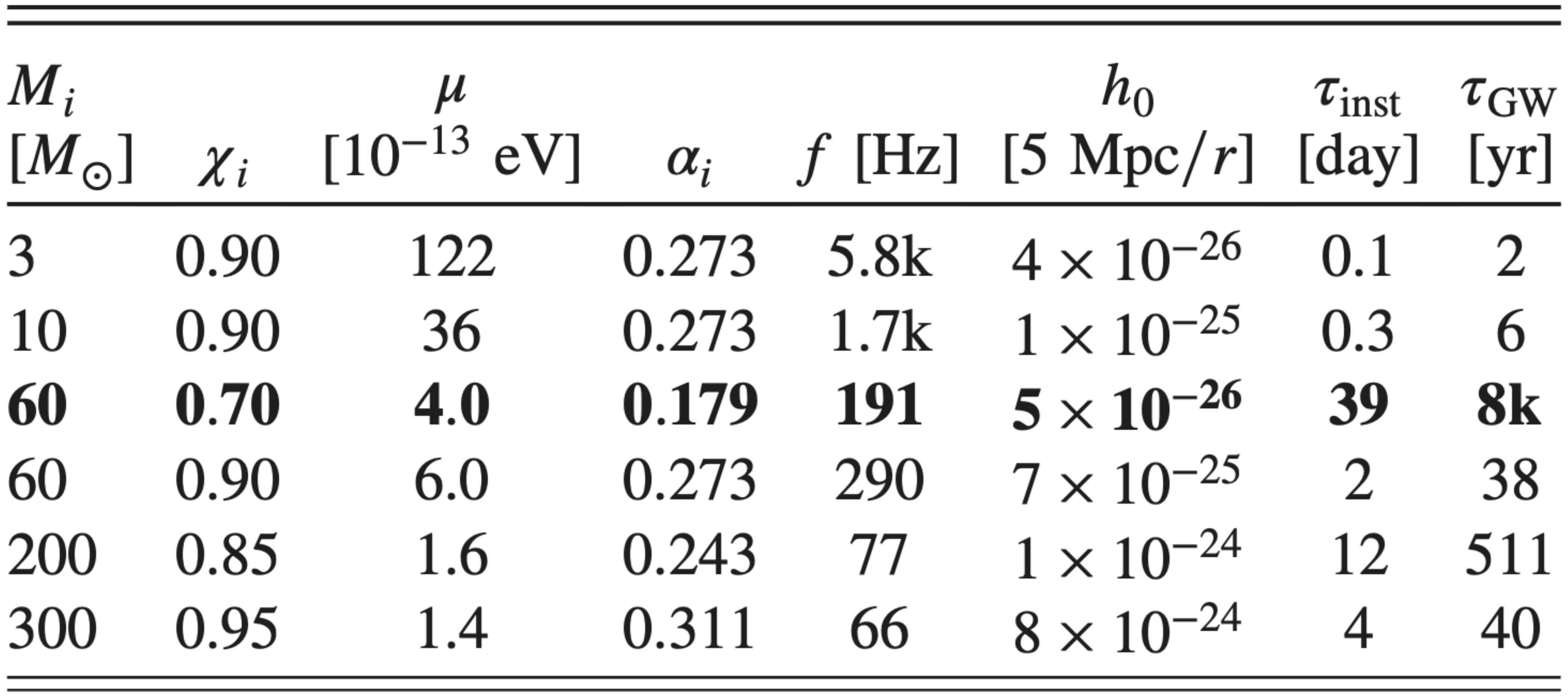


Conclusion

- Earth-based interferometers can be used to look for BC evidence
- Searches in GW data are already providing **interesting constraints** in the ultralight mass range
- New DA techniques are under development, improving also in the **signal modeling**
- There is a wide margin of improvement if we consider second-order effects, different self-interaction regimes, etc…
- We might get to the point where it might be difficult to **distinguish between sources** (e.g. NS or BC?) and **between signal models** (scalar, vector, tensor, self-interaction or not, relativistic regime, …)
- We look forward to the upcoming O4 run!

Backup

Isi+ PRD 99, 084042 (2019)



M_i $[M_\odot]$	χ_i	μ $[10^{-13}$ eV$]$	α_i	f [Hz]	h_0 $[5$ Mpc$/r]$	τ_{inst} [day]	τ_{GW} [yr]
3	0.90	122	0.273	5.8k	4×10^{-26}	0.1	2
10	0.90	36	0.273	1.7k	1×10^{-25}	0.3	6
60	**0.70**	**4.0**	**0.179**	**191**	$\mathbf{5 \times 10^{-26}}$	**39**	**8k**
60	0.90	6.0	0.273	290	7×10^{-25}	2	38
200	0.85	1.6	0.243	77	1×10^{-24}	12	511
300	0.95	1.4	0.311	66	8×10^{-24}	4	40