LOOKING FOR NEUTRON STARS AS CW-EMITTERS IN THE GALACTIC CENTER USING LIGO/VIRGO O3 DATA

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LIGO VIRGO KAGRA

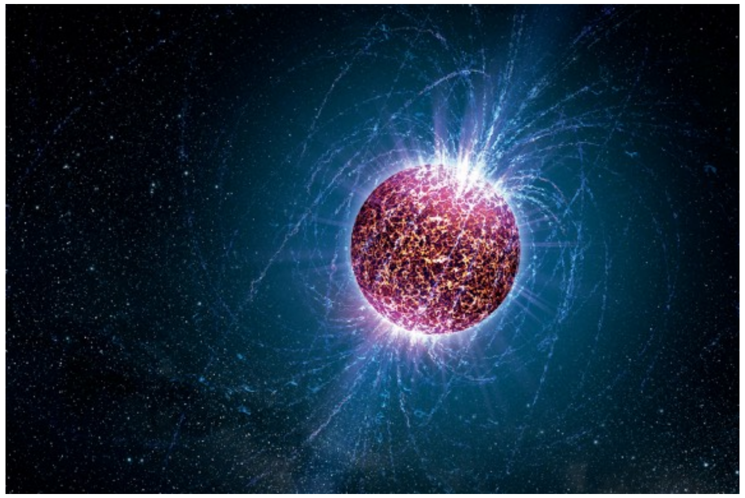
AMALDI RESEARCH CENTER

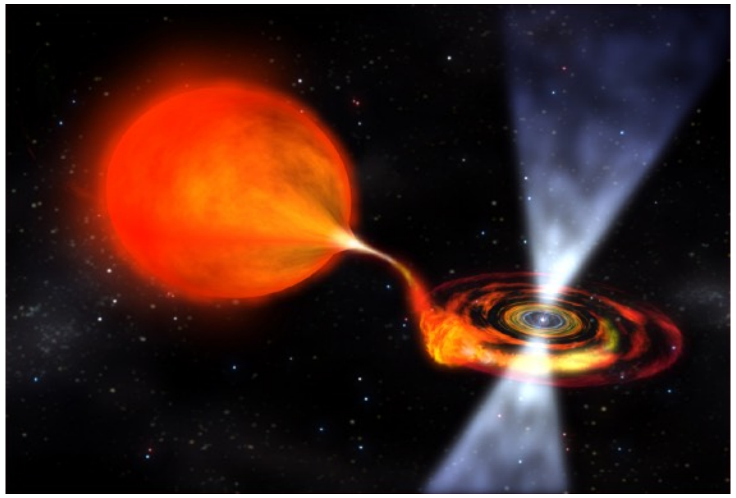
11th IGWM, 11 June 2021

OVERVIEW

- Continuous gravitational waves (CW) signals and sources
  - standard isolated neutron star (NS)
- The Galactic Center (GC) search
- Pipeline technicalities: the Band-Sampled-Data (BSD)
- Candidates and followup
- Final remarks and perspectives

WHAT IS A CONTINUOUS WAVE (CW)?





Credit: C. Reed, Penn State/Mc Gill University

Persistent signal (long-lived)

Produced by a periodic mass quadrupole moment variation

Expected sources

Non-axisymmetric isolated neutron stars (NS)

NSs in binary systems (e.g. in accreting systems)

More objects: bosons clouds around spinning BH, newborn NSs

Expected strain

$$h_0 \cong 10^{-27} \left(\frac{I_{zz}}{10^{38}\ \mathrm{kg\ m^2}} \right) \left(\frac{10\,\mathrm{kpc}}{d} \right) \left(\frac{f}{100\ \mathrm{Hz}} \right)^2 \left(\frac{\epsilon}{10^{-6}} \right) \ll h_{0_{CBC}}$$

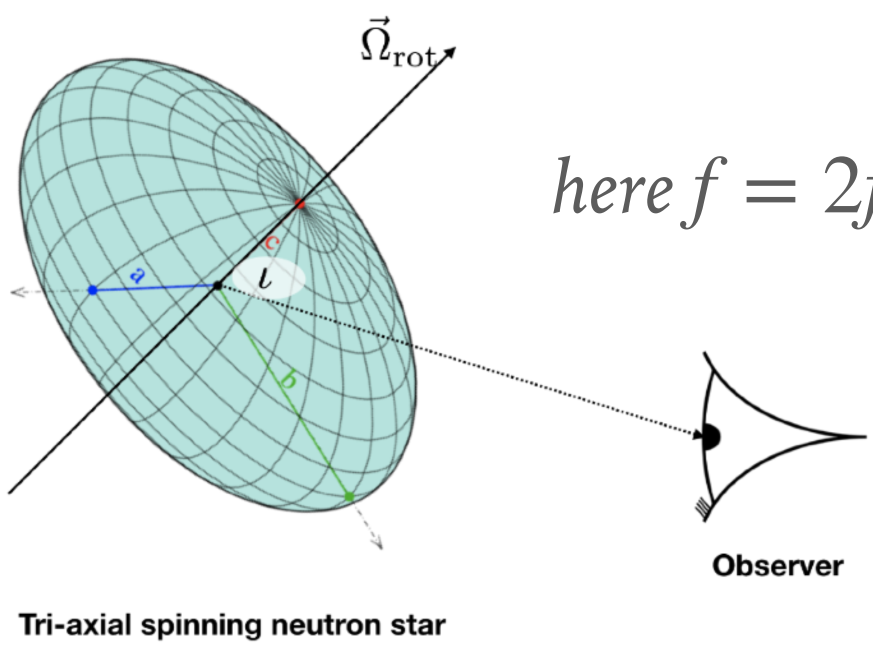
[For a CW review: Lasky PASA 32, pp. 34 (2015), Riles Mod Phys Lett A 32, No. 39, 1730035 (2017)]

EASY CASE: ISOLATED NEUTRON STAR

Expected strain

$$h_0 \cong 10^{-27} \left(\frac{I_{zz}}{10^{38}\ \mathrm{kg\ m^2}} \right) \left(\frac{10\,\mathrm{kpc}}{d} \right) \left(\frac{f}{100\ \mathrm{Hz}} \right)^2 \left(\frac{\epsilon}{10^{-6}} \right) \ll h_{0_{CBC}}$$

non-precessing, rotating around z



here $f = 2f_{spin}$

$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I_{zz} f^2}{d} \epsilon$$

I_{zz}: moment of inertia

ϵ: ellipticity

$$\epsilon = \left| \frac{I_{xx} - I_{yy}}{I_{zz}} \right|$$

Credit: S. Mastrogiovanni

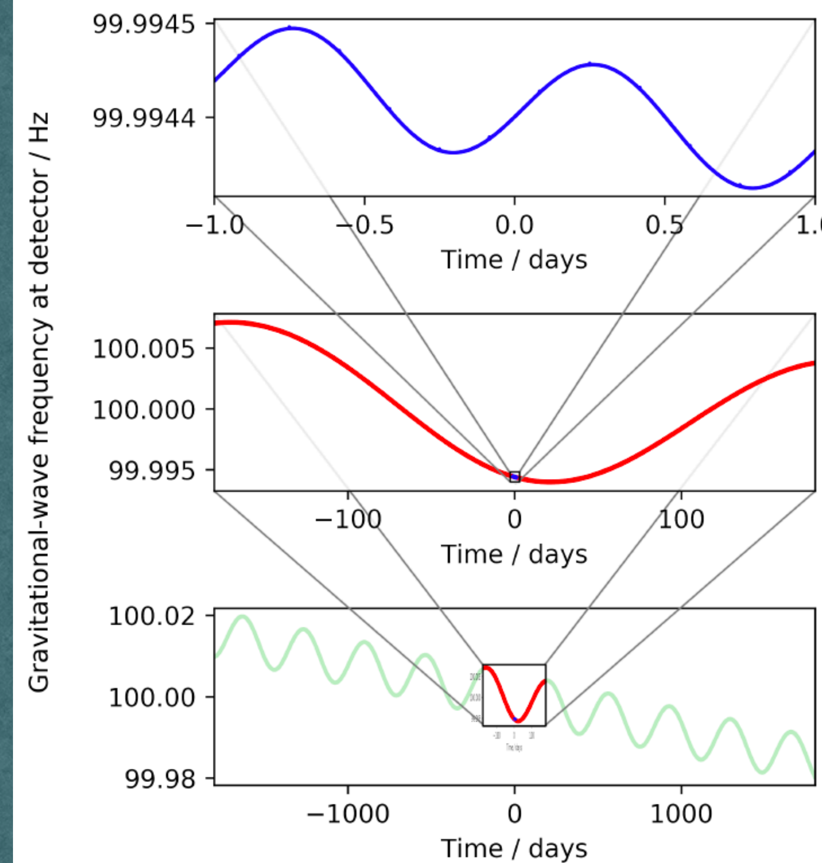
What is the actual value of ϵ*?*

$10^{-9} \leq \epsilon \leq 10^{-4}$

from previous estimates

WHAT THE SIGNAL LOOKS LIKE

Credit: K. Wette



A CW received at the detector is NOT exactly monochromatic

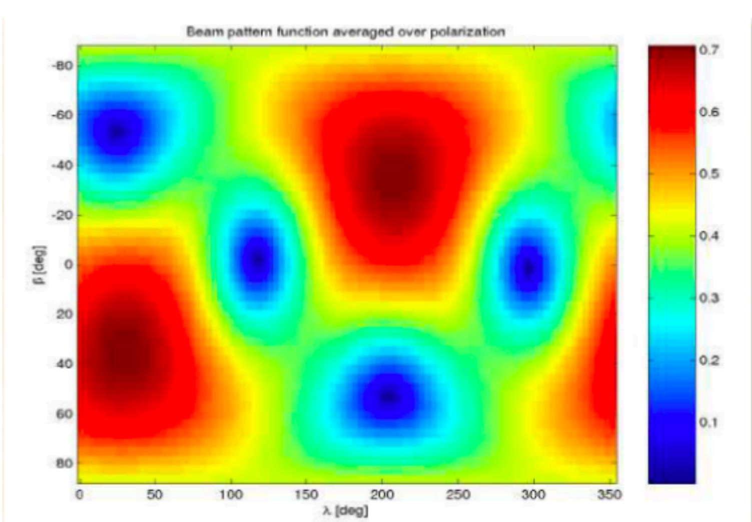
- SPIN-DOWN due to the loss of energy of the star

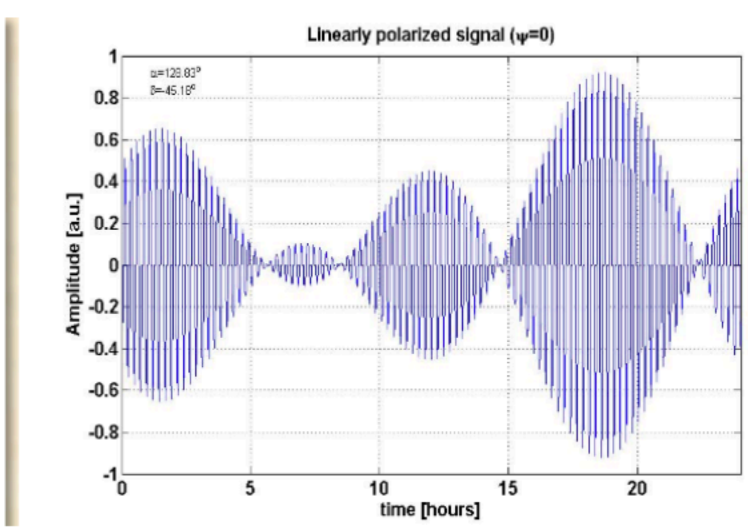
$$f_0(t) = f_0 + \dot{f}_0\left(t - t_0\right) + \frac{\ddot{f}_0}{2}\left(t - t_0\right)^2 + \ldots$$

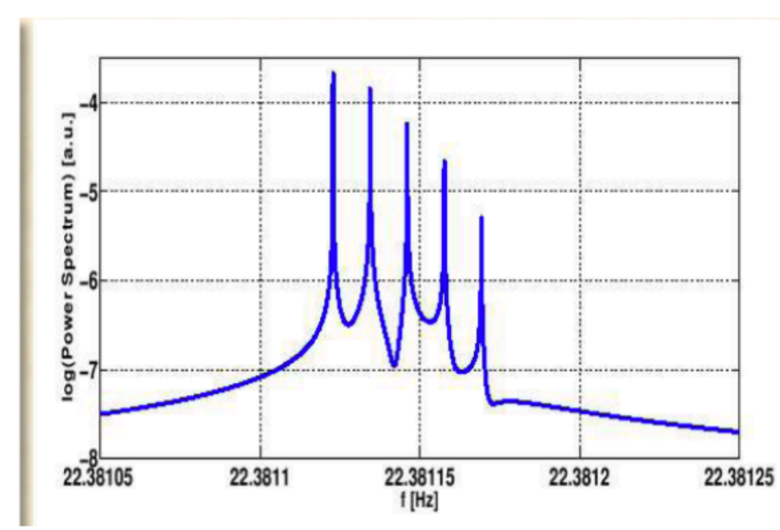
- DOPPLER shift due to the motion of the Earth

$$f(t) = \frac{1}{2\pi}\frac{d\Phi(t)}{dt} = f_0(t)\left(1 + \frac{\overrightarrow{v}\cdot\widehat{n}}{c}\right)$$

- SIDEREAL VARIATION of the amplitude

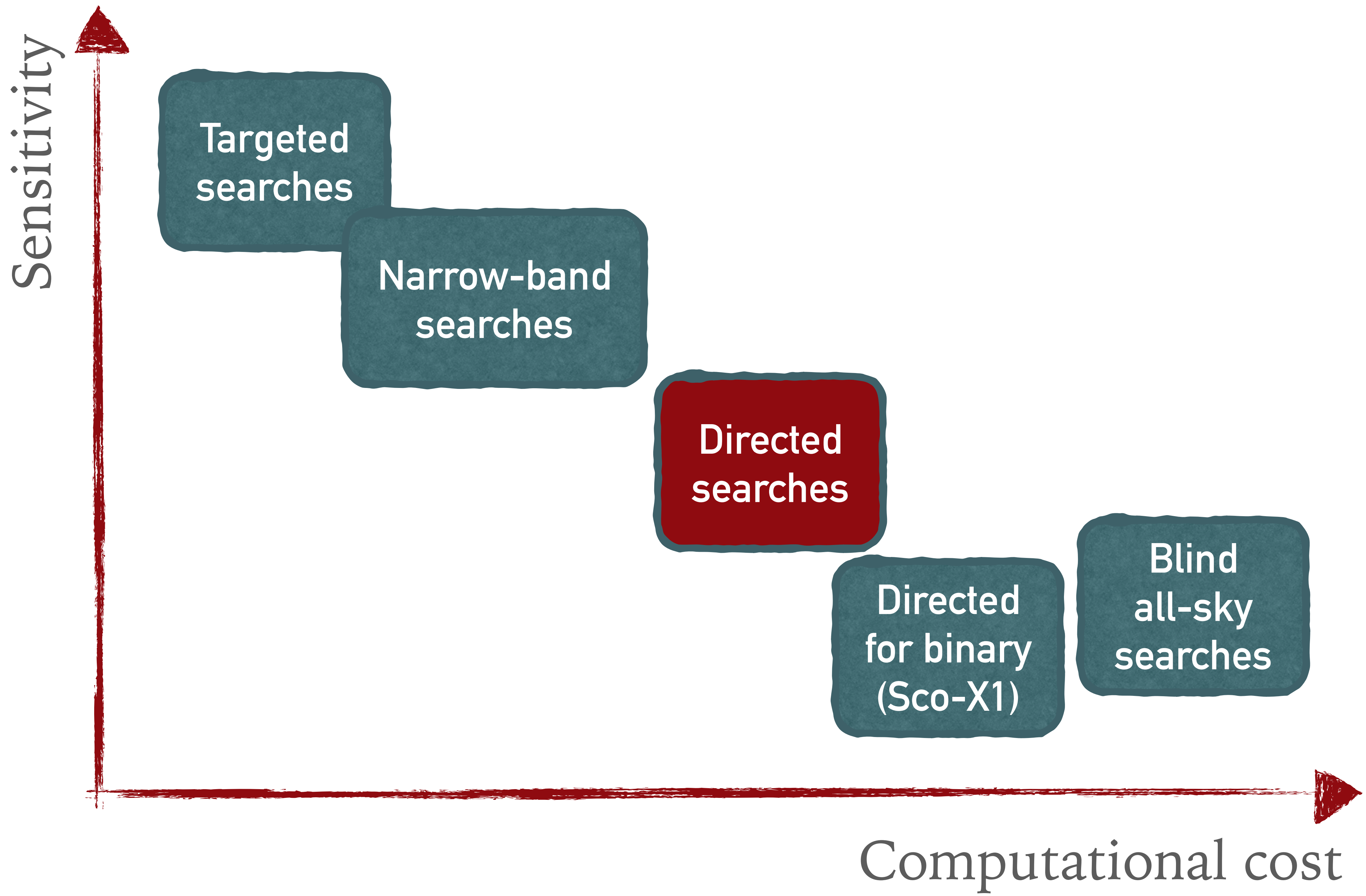






Credit: C. Palomba

TYPE OF CW SEARCHES



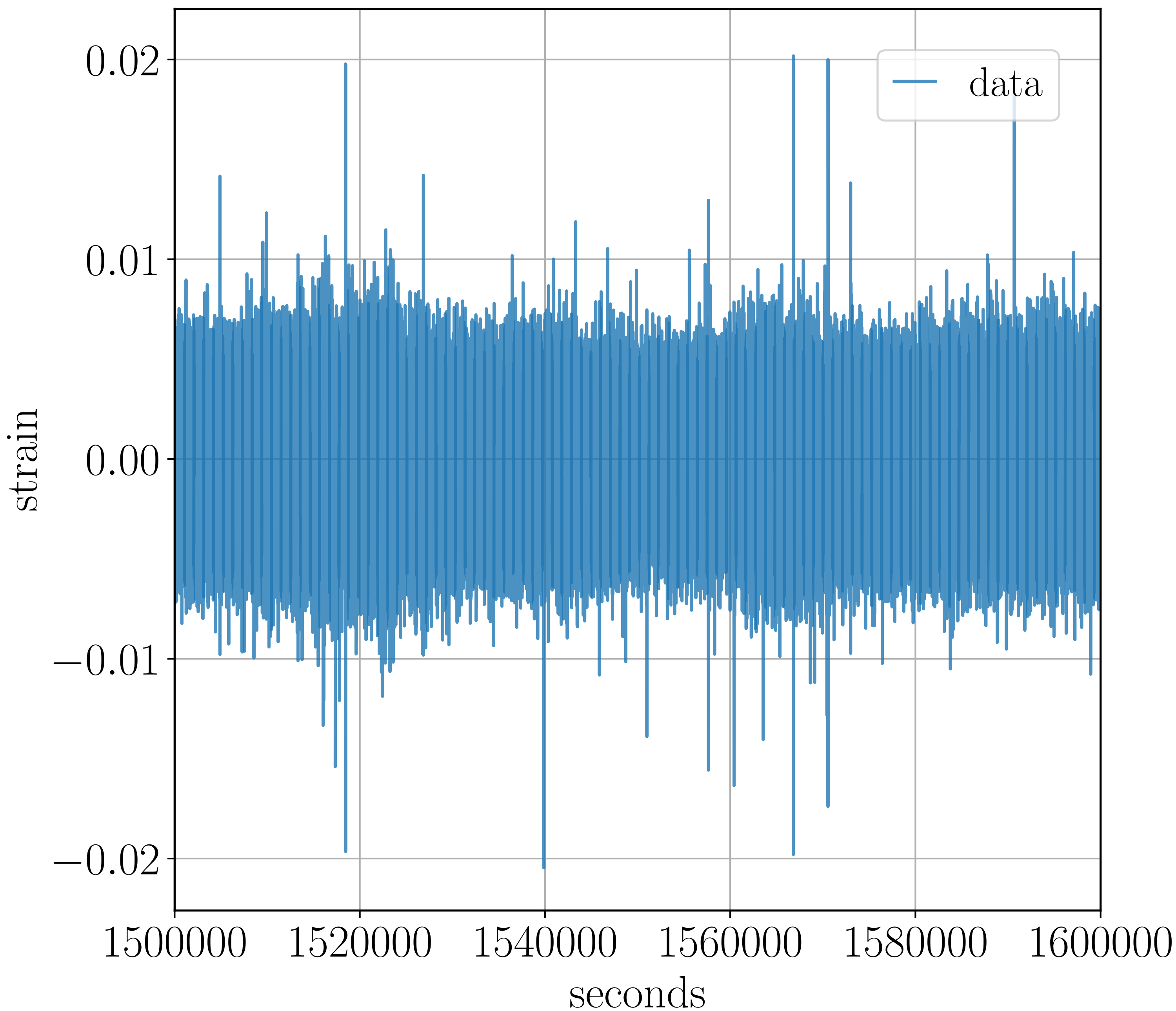
WHY THE GC

- Several independent lines of evidence predict a sizable population of NSs in the region ($O(10^8 - 10^9)$ expected in the full Galaxy, only a fraction observed $\sim$3000)
- Given the large number of massive stars, the central parsec likely hosts a large NS population (mostly millisecond pulsars (MSP) [Macquart, J.P. et al. 2015])
- The size of the potentially EM observable population (i.e. those beaming towards us) could include up to 50 canonical pulsars and 10000 millisecond pulsars [Rajwade et al. 2016]
- A GC pulsar population could explain the GC GeV excess measured by Fermi and H.E.S.S. [Bartels et al. 2016, Lee et al. 2016, Fermi-LAT coll. 2017]
- Potentially solve the debate about the presence (or not) of dark matter (DM) in the GC

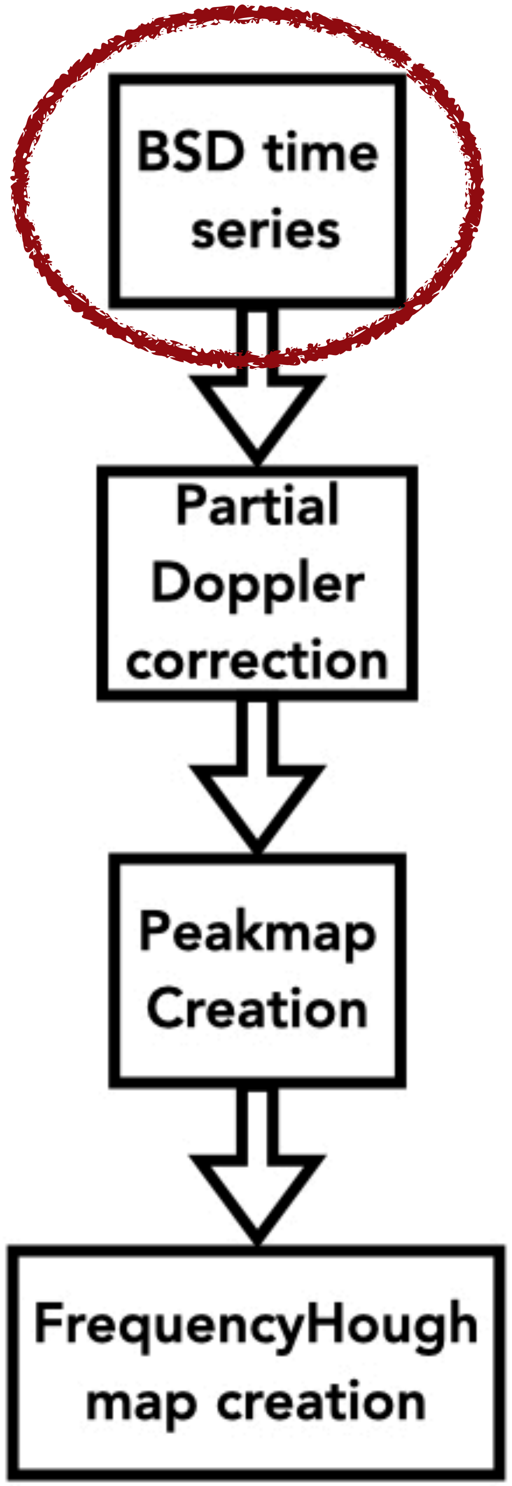
The Galactic center is a good place to look for CWs since it is likely to host several candidates

THE BSD PIPELINE – A DIRECTED SEARCH

➤ *We use data in the BSD format*

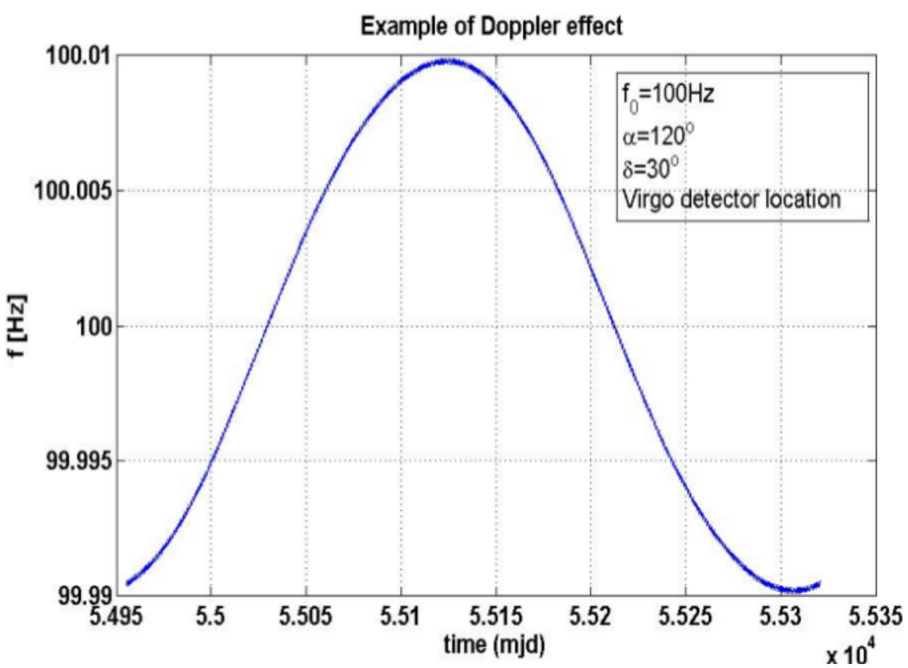


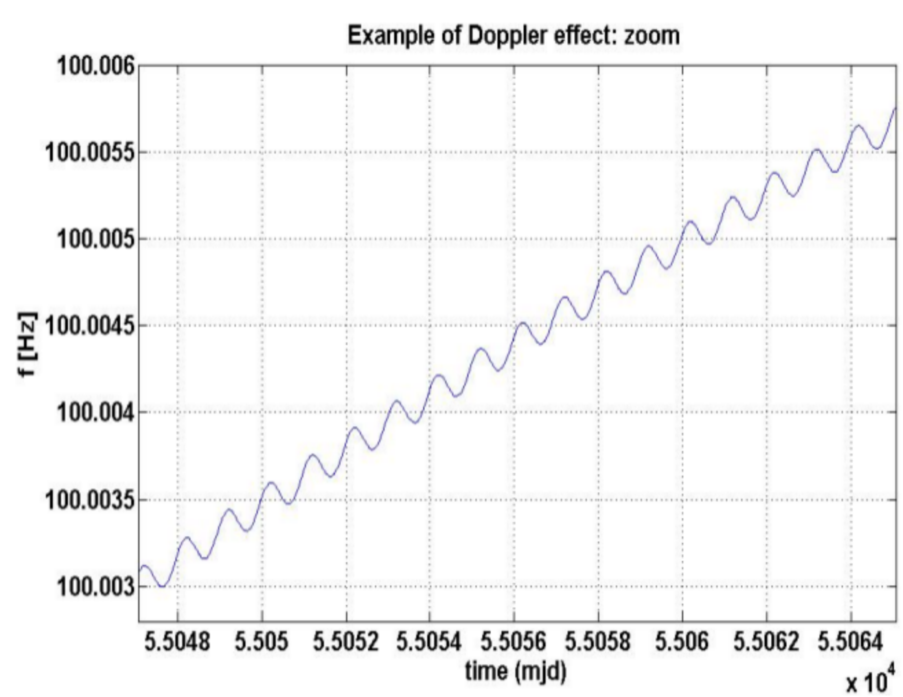
Piccinni et al., CQG 36, 1 (2018)

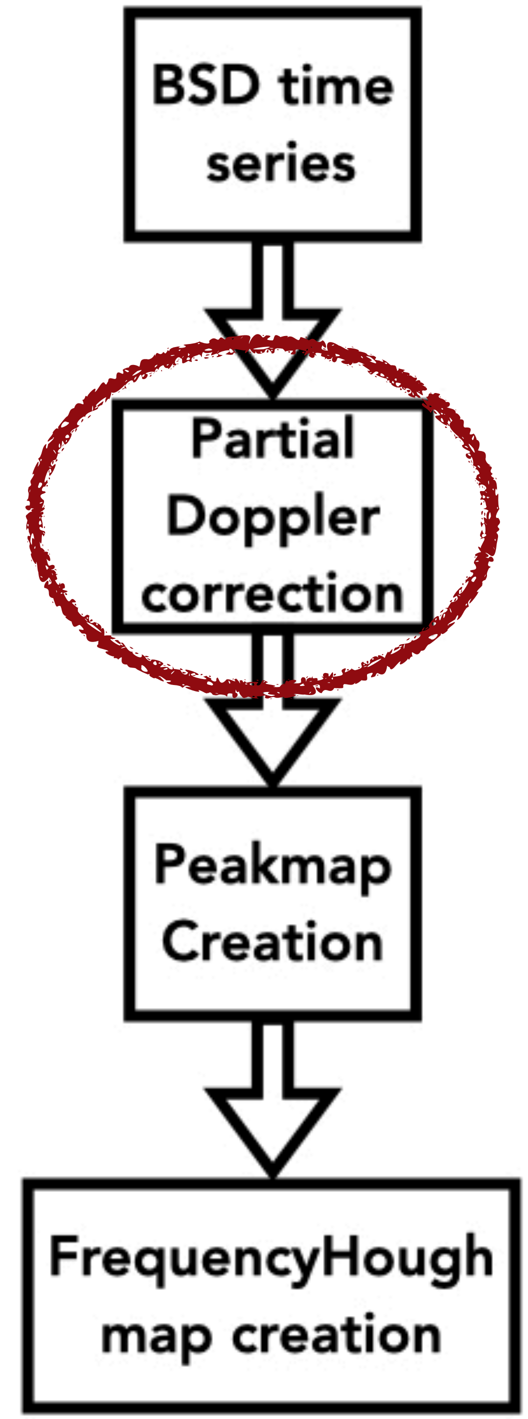


THE BSD PIPELINE – A DIRECTED SEARCH

- *Given a sky position: apply barycentric correction*

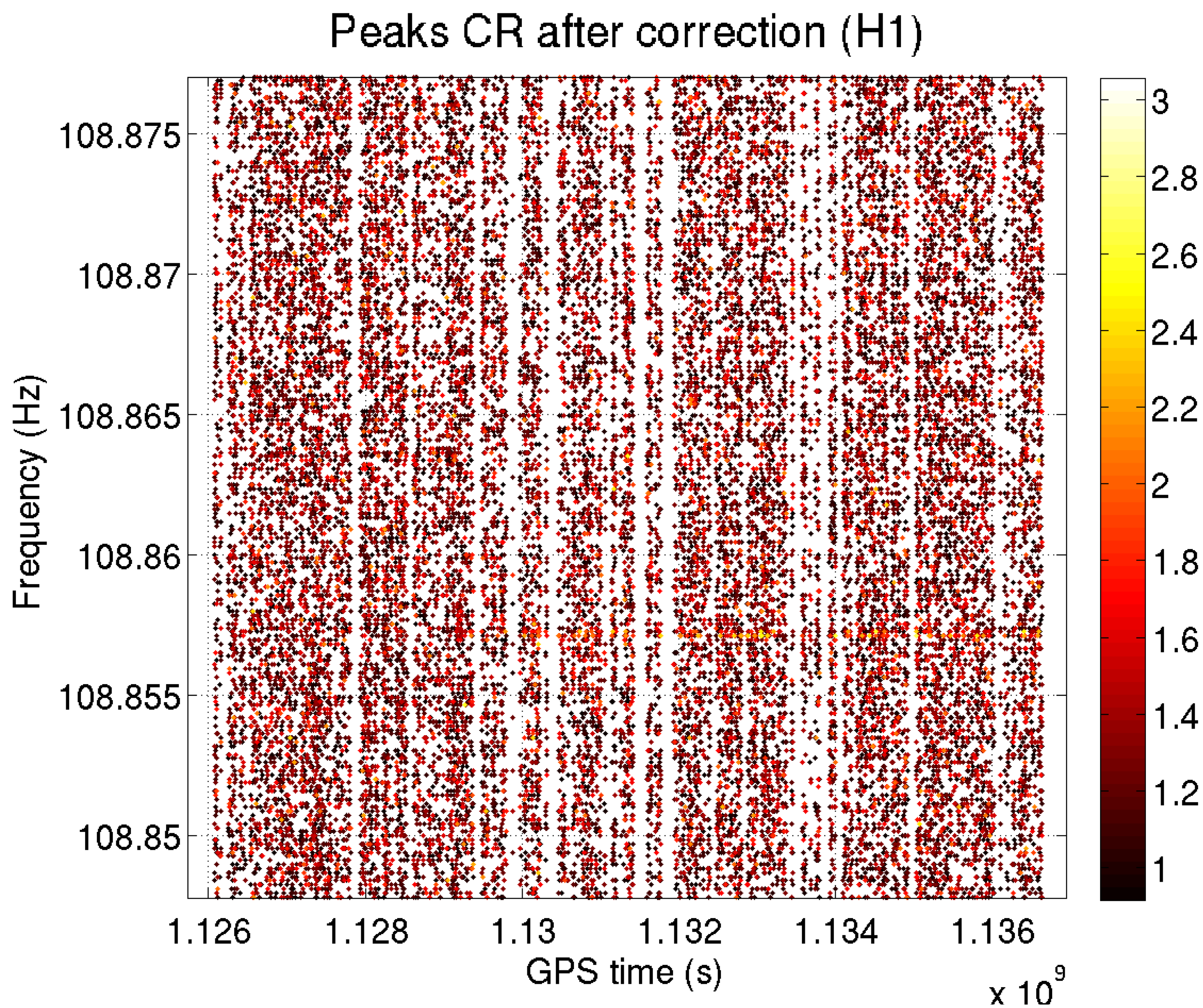




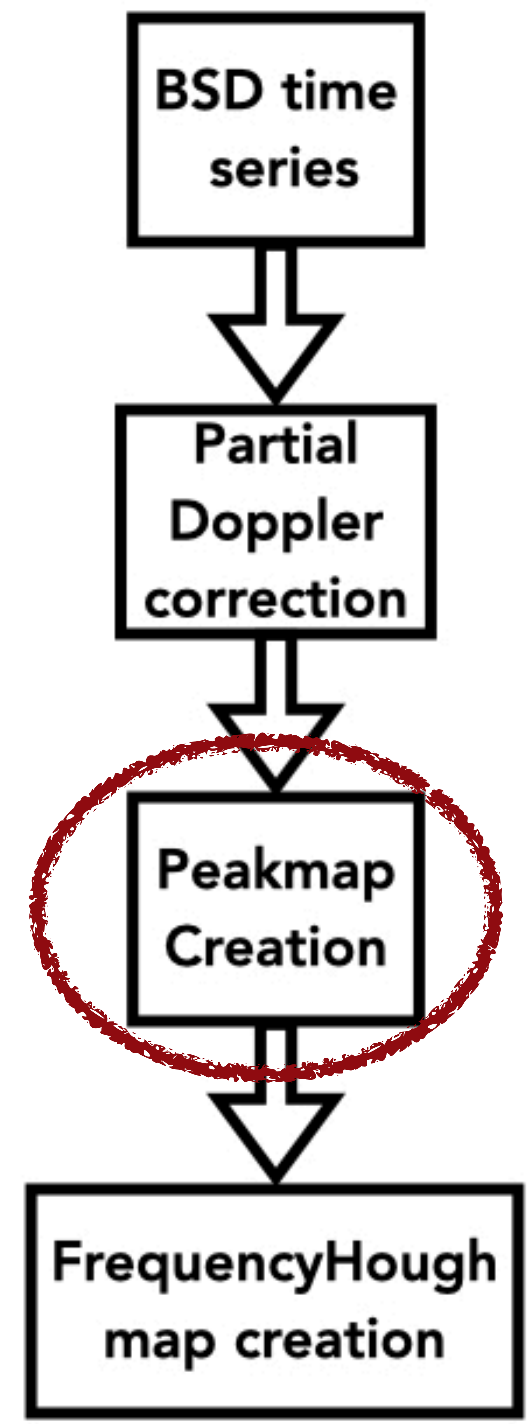


THE BSD PIPELINE – A DIRECTED SEARCH

- *Selection of time frequency peaks using a T_{coh}*

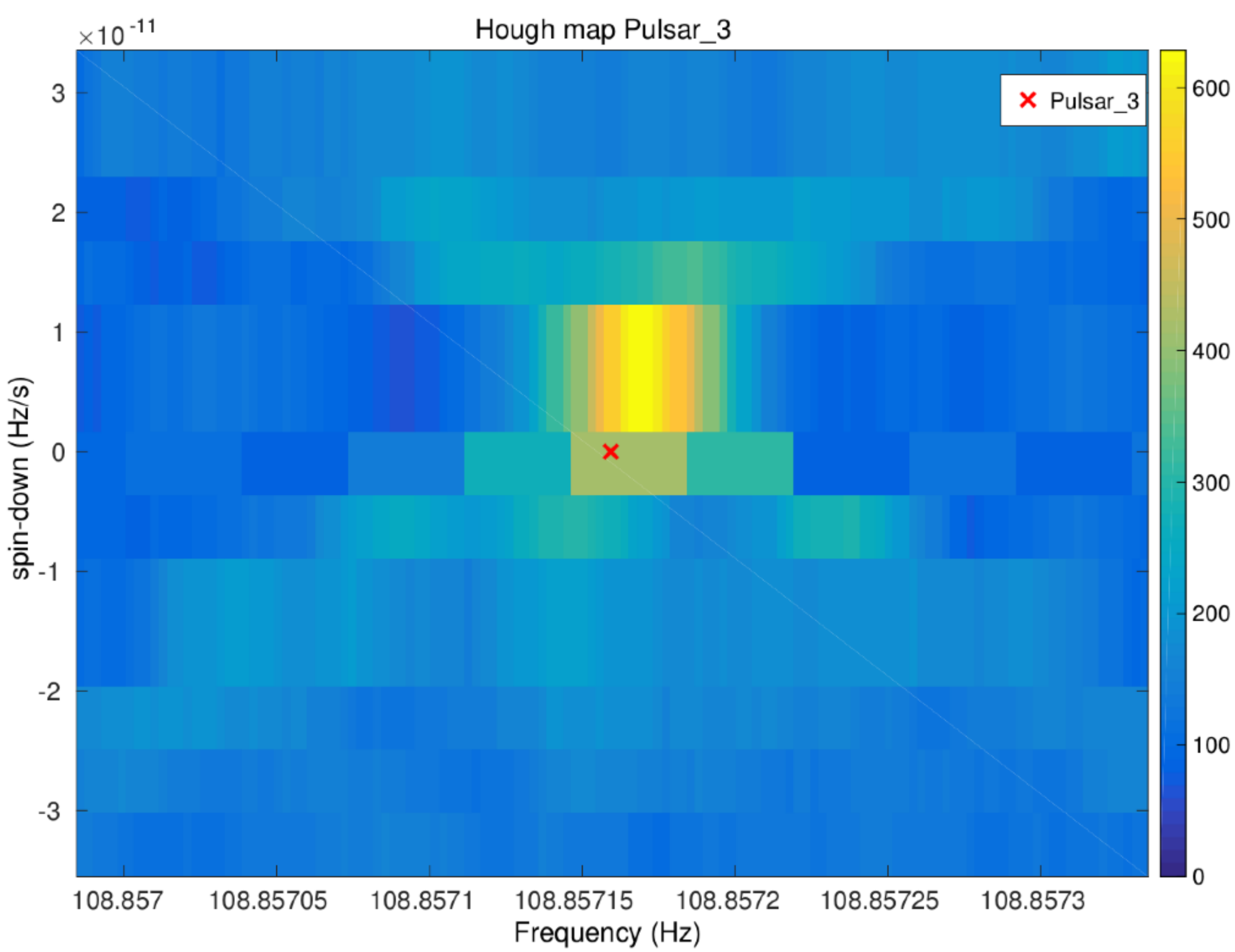


(Astone+ CQG 22, S1197, 2005)

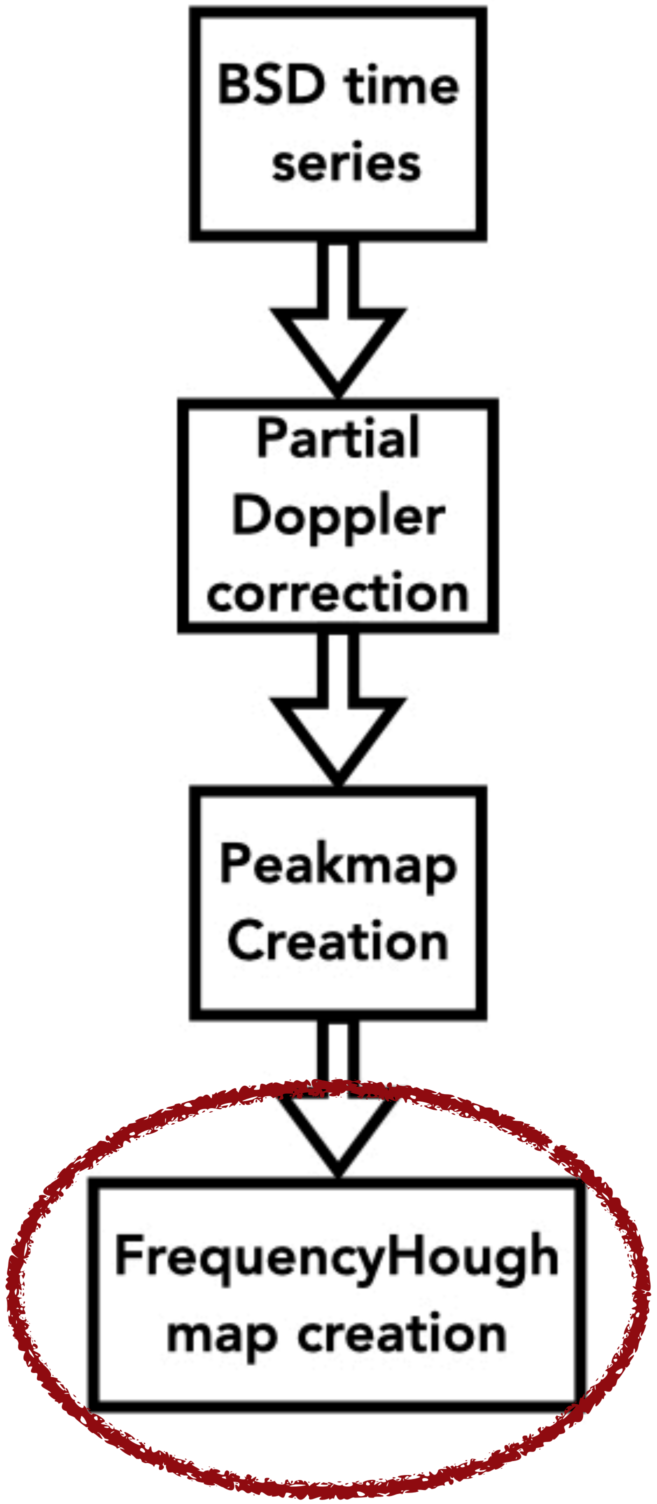


THE BSD PIPELINE – A DIRECTED SEARCH

- *The peakmap will be the input for the FrequencyHough map.*
- *A peak becomes a line in the $(f_0, \dot{f}_0)$ plane*

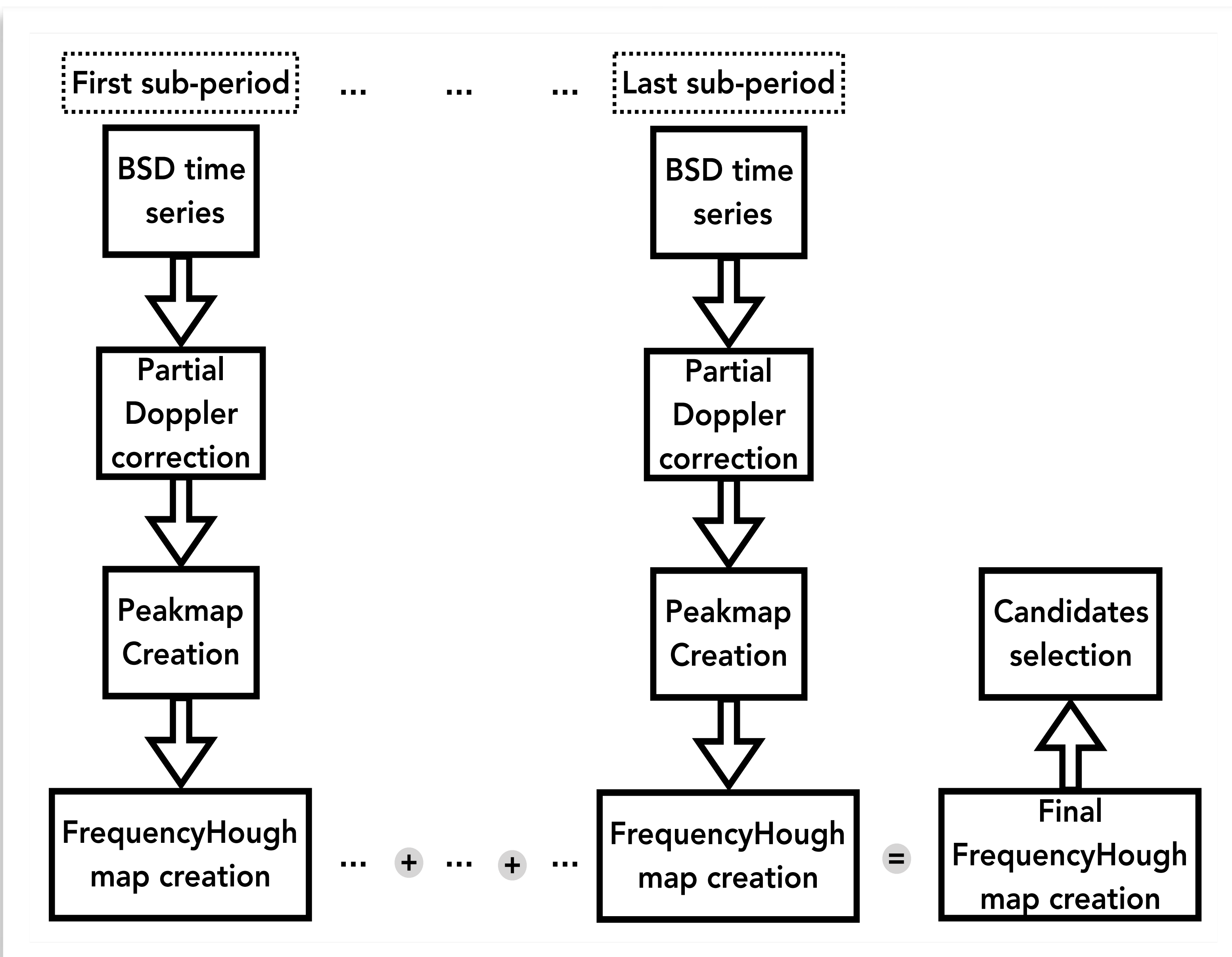


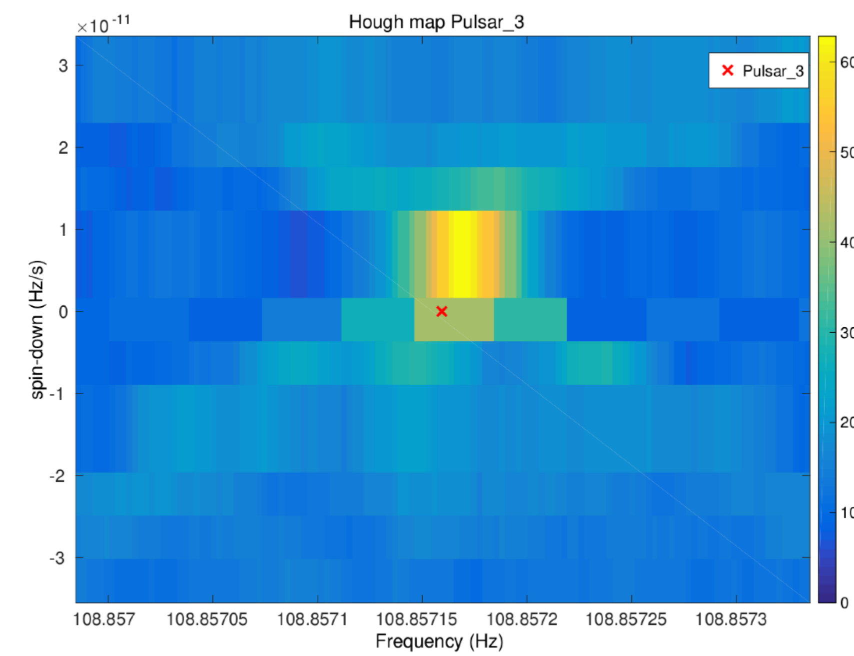
(Astone+ PRD 90, 042002, 2014)



THE BSD PIPELINE – A DIRECTED SEARCH

➤ *Candidates selected on a final FH map, sum of the montly-based FH maps*





Candidates are selected with a ranking procedure over the Critical Ratio computed from the FH number counts

Piccinni et al., Phys. Rev. D 101, 082004 (2020)

GC SEARCH SETUP - FULL O3 LVK in preparation

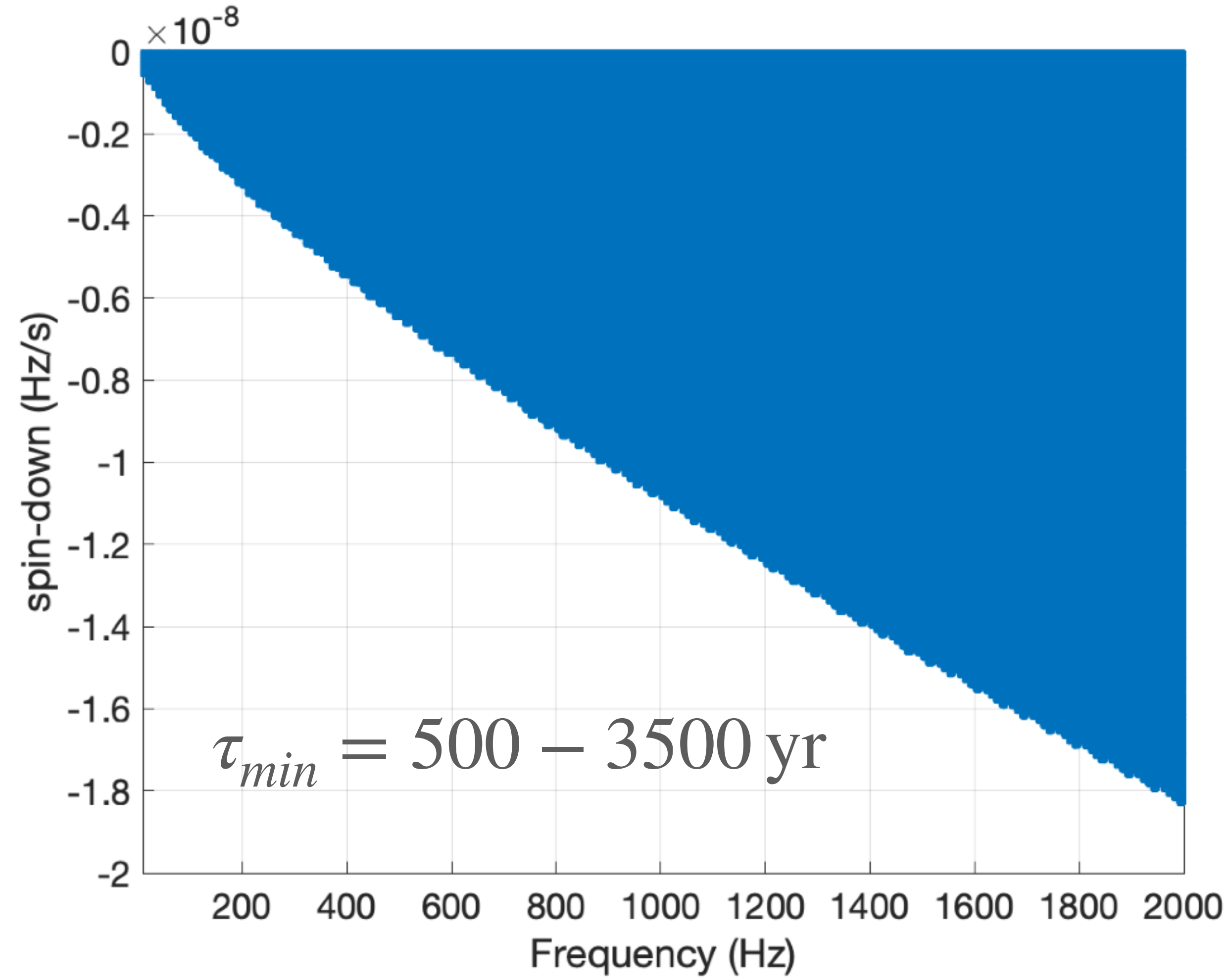
Using the BSD-directed search pipeline on O3 data from LIGO and Virgo interferometers we can search for CWs *in the direction of* Sgr A*

Frequency range: $[10 - 2000]\,\mathrm{Hz}$

min spin-down range:
$-1.8 \times 10^{-8}\,\mathrm{Hz/s}$

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

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



Assuming that $f_{start} \gg f_{today}$, the decay time gives an estimate of the age as $\tau \sim -f/\dot{f}$

Parameter space:
Frasca et al. *Class.Quant.Grav.* 22 (2005) S1013-S1019

GC SEARCH – FIRST RESULTS LVK in preparation

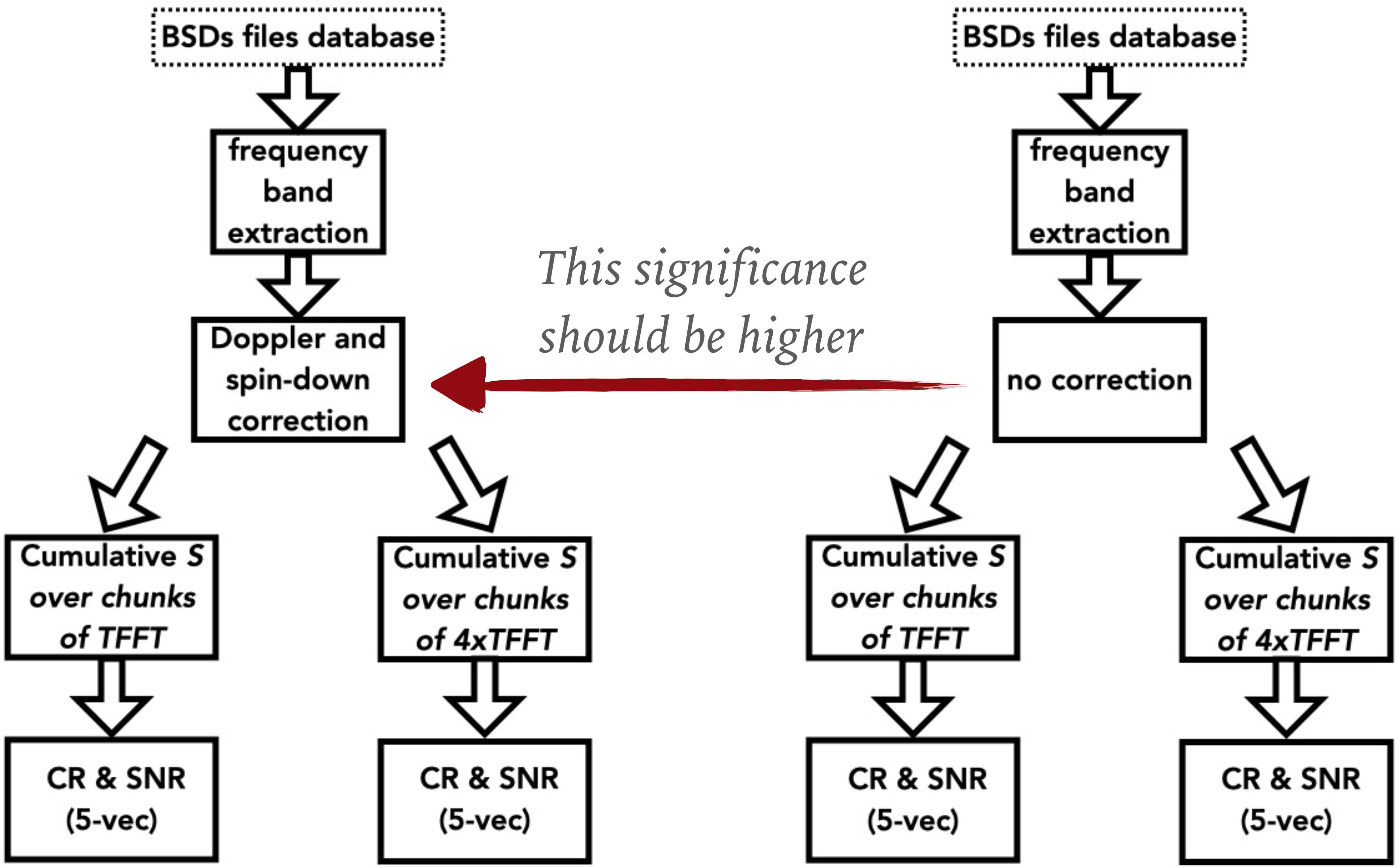
- Candidates selected per detector.
- First level of vetoes are applied (e.g. removal of candidates near known lines).
- Coincidences between the datasets.
- Selection based on the significance (Critical Ratio).
- Remaining candidates need to be investigated.

	H, L, V
starting (per det)	$\sim 3 \times 10^6$
excluded by known lines veto (per det)	$\sim$10k

	LH/HV/LV	HLV
coincidences	$\sim$15k	$\sim$100
significance selection	$\sim$300	$<$10

FOLLOWUP OF SURVIVING CANDIDATES – ONGOING

Assuming a phase evolution of the signal, $\phi(f_0, \dot{f}_0)$, as fully described by the frequency and spin-down parameters of the candidate, given by f_0 and $\dot{f}_0$, respectively.



5-vector statistics: Astone et al. *Class.Quant.Grav*, 27, 194016 (2010), Phys. Rev. D, 89, 062008 (2014)

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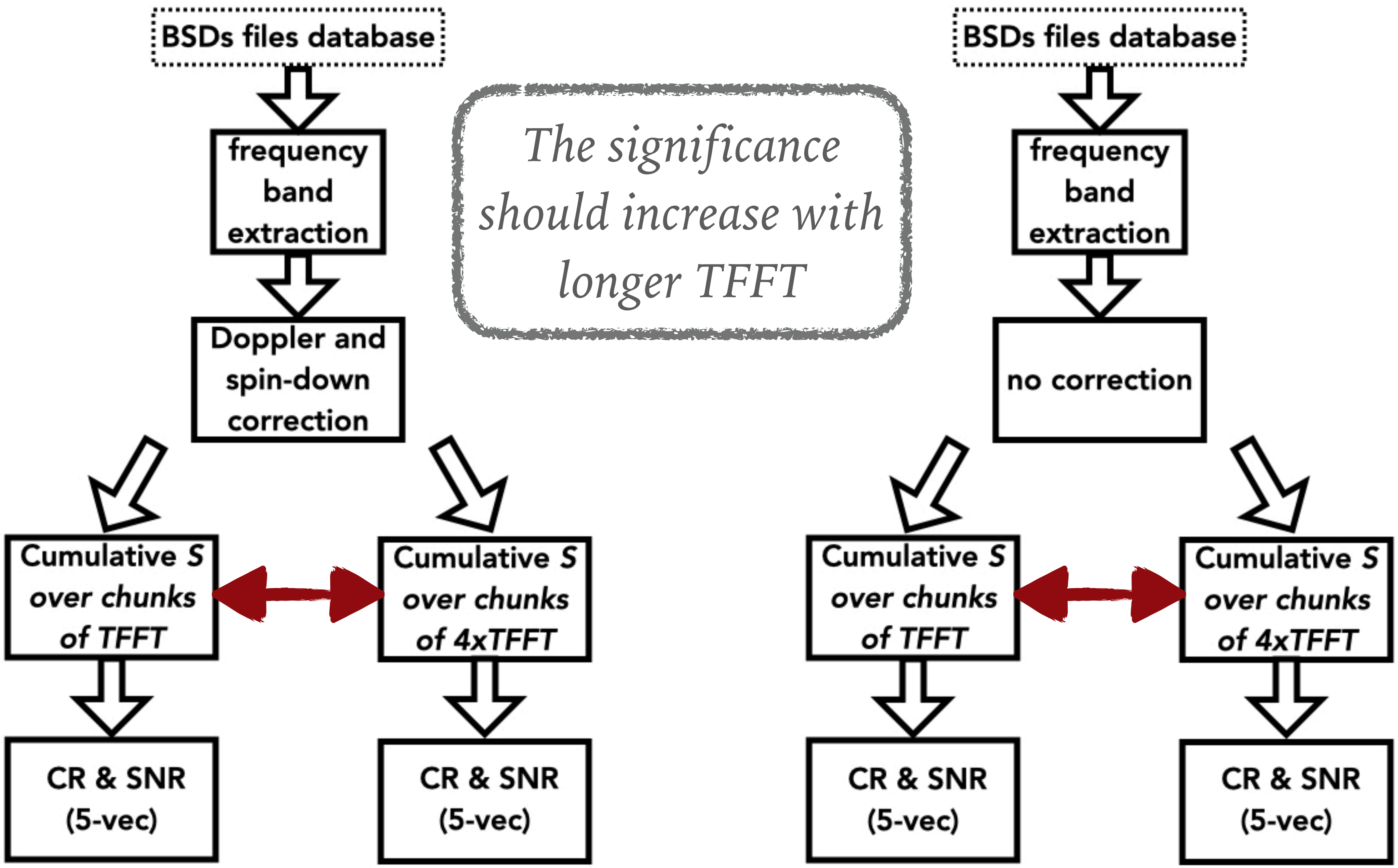

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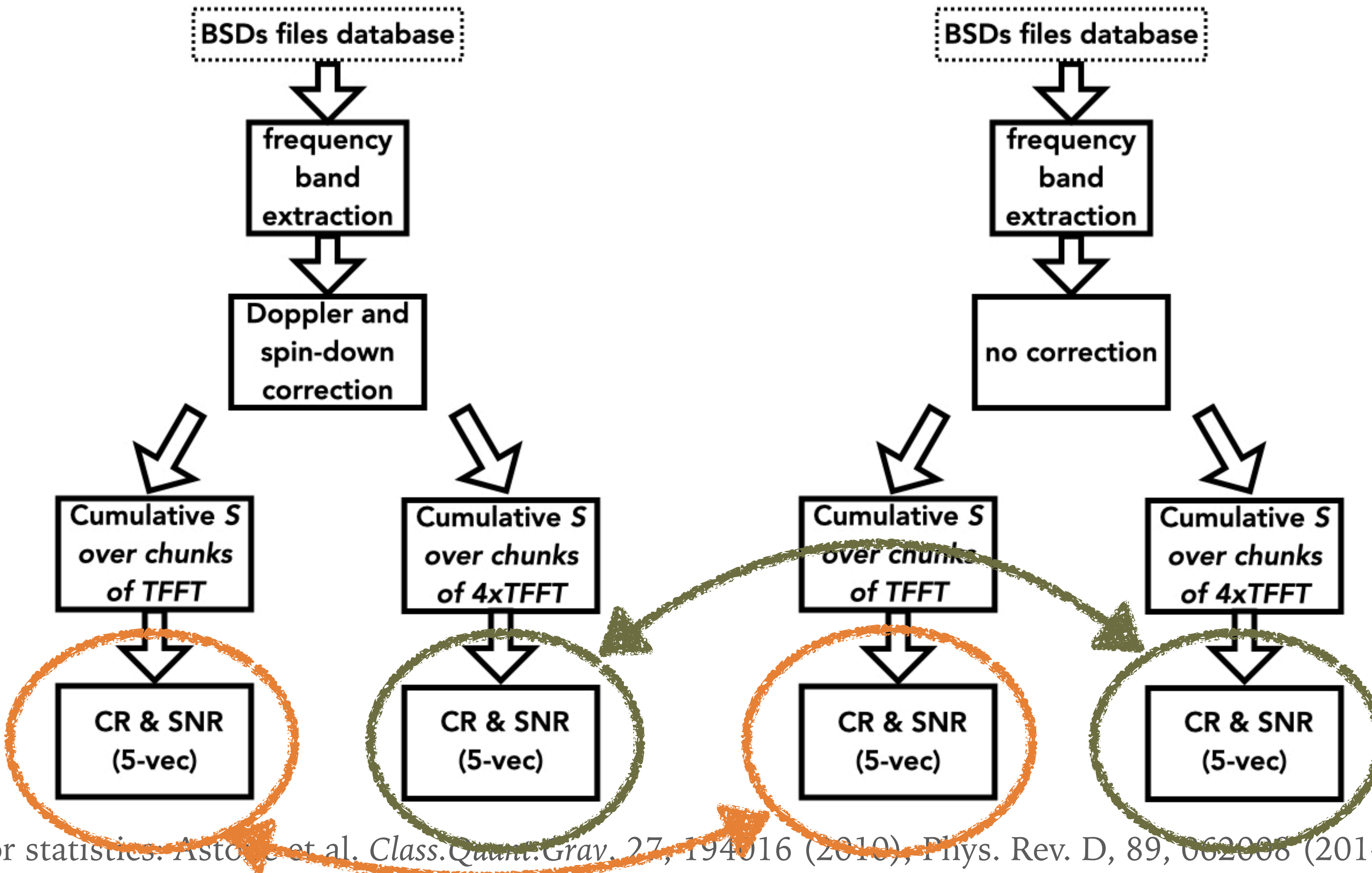

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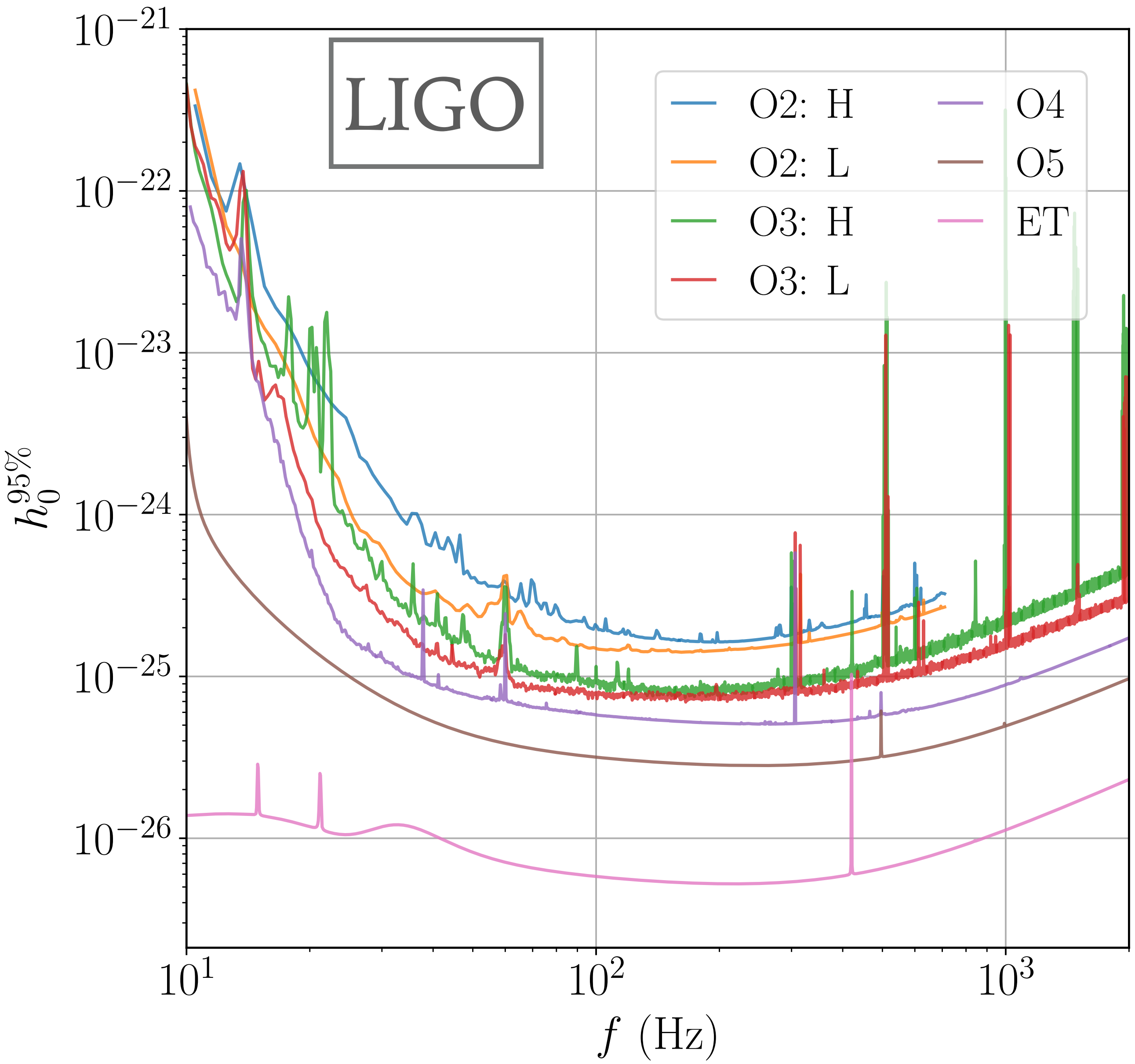
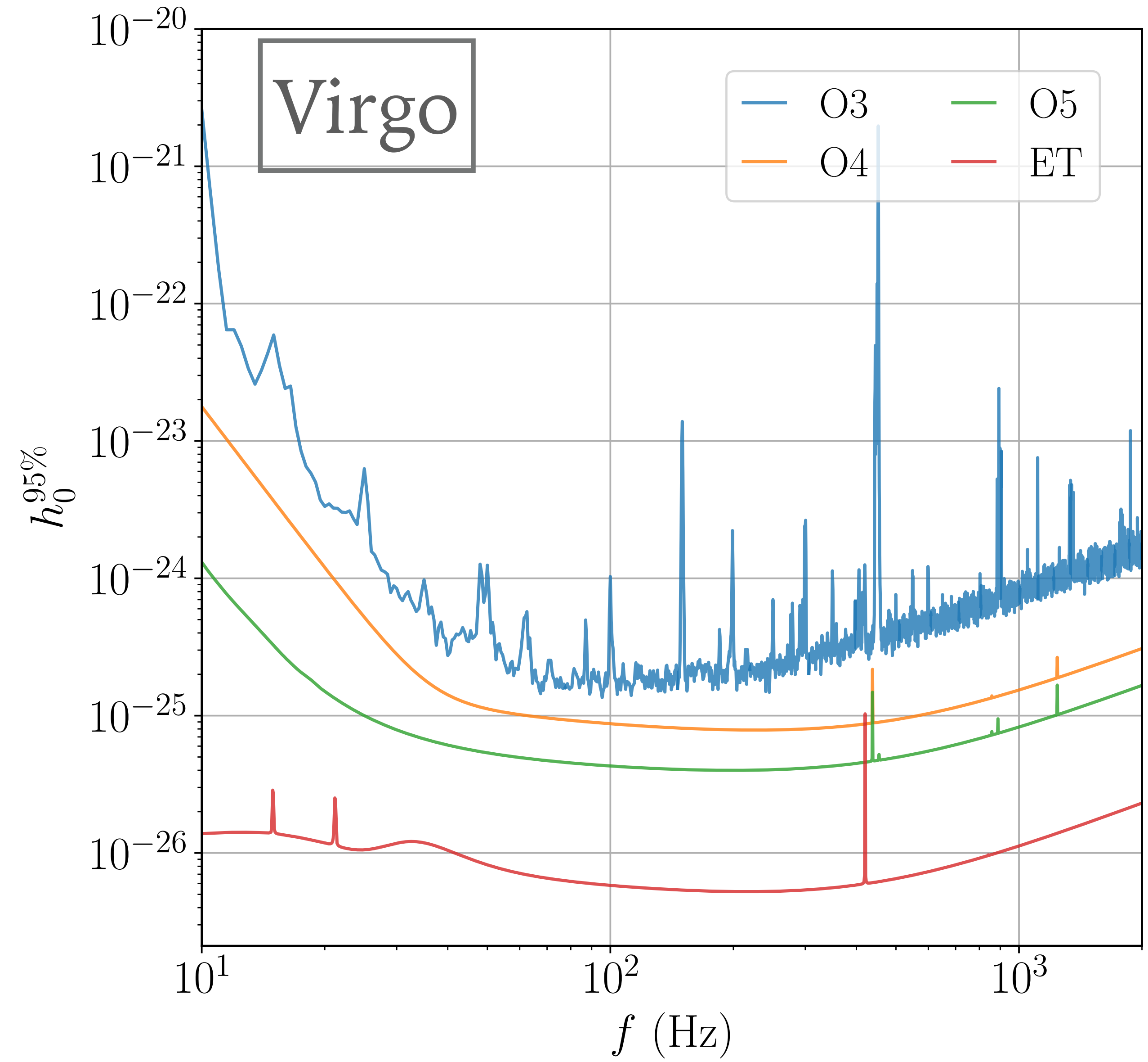
FUTURE PROSPECTS: GC SEARCH SENSITIVITY

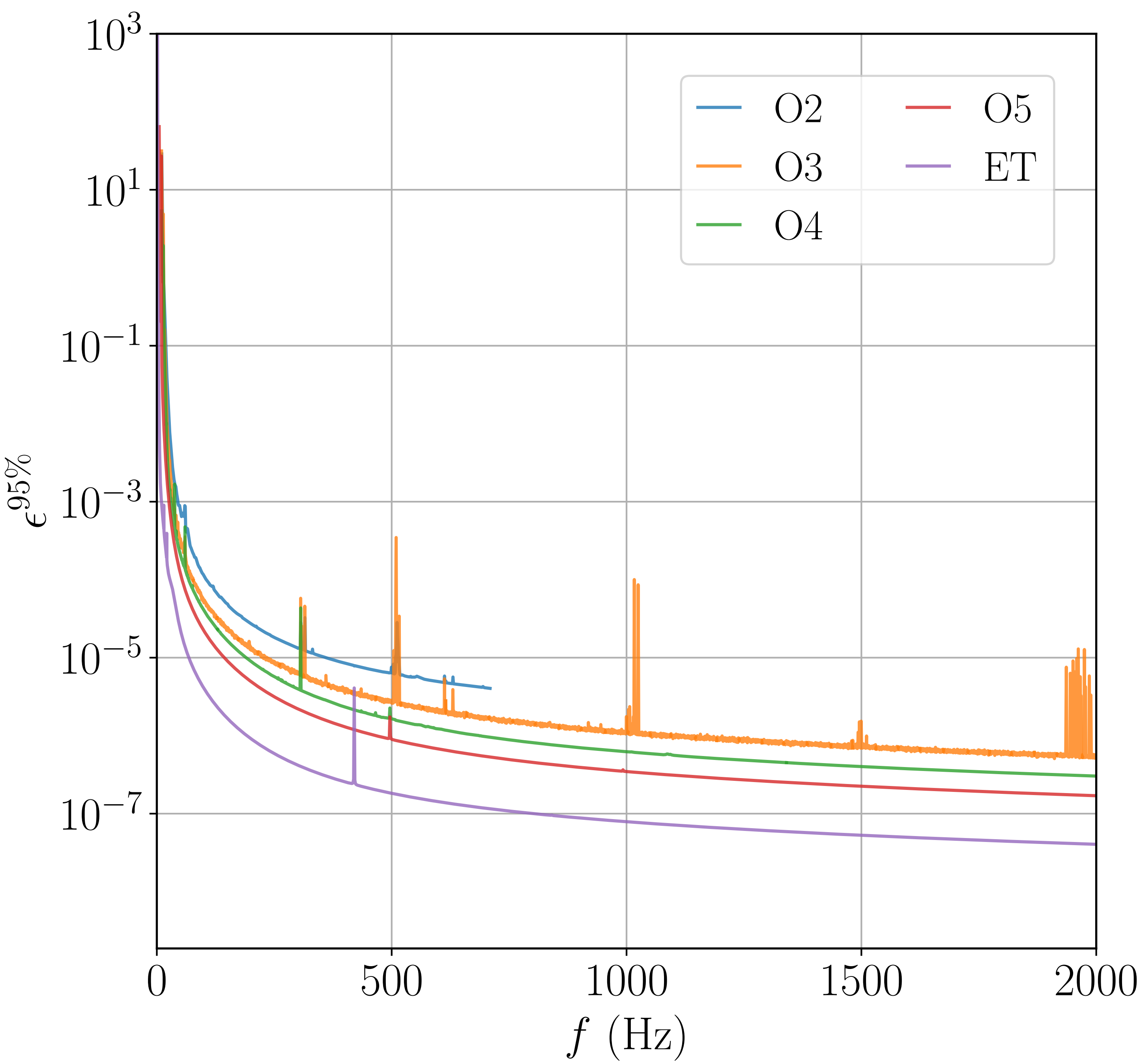




$$h_{0,\,\mathrm{min}} \approx \frac{4.02}{N^{1/4}\theta_{thr}^{1/2}}\sqrt{\frac{S_n(f)}{T_{FFT}}}\left(\frac{p_0\,(1-p_0)}{p_1^2}\right)^{1/4}\sqrt{CR_{thr}-\sqrt{2}\,\mathrm{erfc}^{-1}(2\Gamma)} = \frac{\Lambda}{N^{1/4}}\sqrt{\frac{S_n(f)}{T_{FFT}}}$$

O2: 9 months, O3: 10 months, O4, O5, ET: 1 year

FUTURE PROSPECTS: GC SEARCH ELLIPTICITY



$$h_0 \propto \frac{I_{zz}}{d}\epsilon f^2 \rightarrow \epsilon = \frac{c^4}{4\pi^2 G}\left(\frac{d}{I_{zz}}\right)\frac{h_0}{f^2}$$

Galactic center distance d=8 kpc

$I_{zz} = I_{fid} = 10^{38}$ kg m^2

$$10^{-9} \leq \epsilon \leq 10^{-4}$$

from previous estimates

CONCLUSION

- CW could be the next surprise in GW astronomy given the enhanced sensitivity of the detectors
- Noise characterization is fundamental for the removal of potential outliers
- The GC search could shed light on the actual main components of the neighboring region of Sgr A* (debated to be DM)
- For the standard NS case scenario we are probing ellipticities very close to the lowest estimates
- Exciting times especially if a joint CW and EM observation occurs (constraints on NS interior), remarking the importance of multi-messenger astronomy
- We expect (and hope) to find several surprises in O3/O4