

Time-frequency approach to long-lived signals of LISA: an application to stellar-mass black hole binaries and EMRIs

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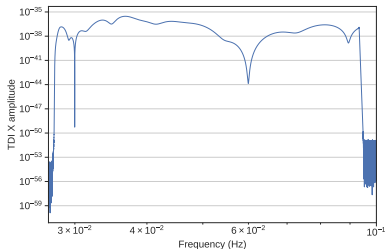
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Astroparticule & Cosmologie, CNRS, Université Paris-Cité

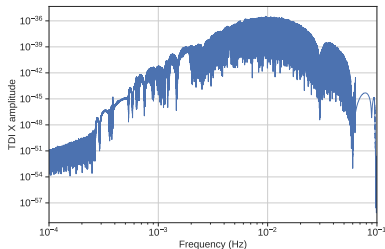
Time-Frequency Methods

Why time-frequency ?

- Useful for **overlapping** and **long** signals.
- Inclusion of noise **non-stationarities**.
- Analysing **noisy data**.
- **Sparse** representation in time-frequency domain.



(a) SOBHB

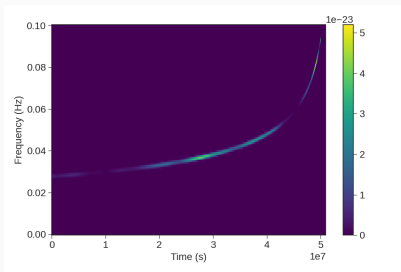


(b) EMRI

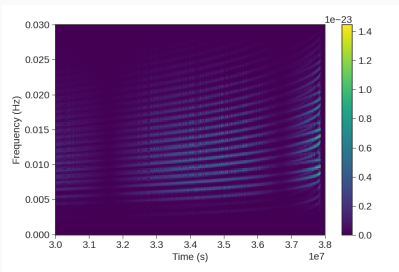
Figure 1: Example of frequency map in LISA data.

Why time-frequency ?

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(a) SOBHB



(b) EMRI

Figure 2: Example of time–frequency map of LISA data.

Principles

- Idea: compute waveform/TDI in time-frequency plane from the knowledge of mode-by-mode amplitudes and phases of the waveform:

$$h = \sum_{\ell, m} {}_{-2}Y_{\ell m} h_{\ell m}, \quad h_{\ell m} = A e^{-i\Phi} \quad (1)$$

- Taylor expansion of amplitude and phase:

(a) Time domain:

$$A(t) \approx A(\tau) \quad (2)$$

$$\Phi(t) \approx \Phi(\tau) + 2\pi f(\tau)(t - \tau) + \pi \dot{f}(\tau)(t - \tau)^2 \quad (3)$$

(b) Frequency domain:

$$A(\nu) \approx A(f) \quad (4)$$

$$\Phi(\nu) \approx \Phi(f) + 2\pi\tau(f)(\nu - f) + \pi\tau'(f)(\nu - f)^2 \quad (5)$$

- Analytical maps $(A, \Phi) \mapsto (h_+, h_\times)$ and $(A, \Phi) \mapsto (\text{TDI})$

Features

- Computes STFT with rectangular window.
- Time-frequency track localisation using phase.
- LISA response implemented therein, applied directly in t-f domain.
- Use of sparse t-f representation to accelerate computation.
- Implementation in tfwaves package¹.
- Numpy and JAX² versions.

¹<https://gitlab.in2p3.fr/lisa-apc/tfwaves>

²<https://gitlab.in2p3.fr/servignat/jaxtfwaves>

Mojito Lite Data validation: SOBHB

Tools

Short Time Fourier Transform:

$$D(\tau, f) = \text{STFT} \{d(t)\}(\tau, f) = \int_{\mathbb{R}} d(t)w(t - \tau)e^{-2i\pi ft} dt, \quad (6)$$

Inner product:

$$\langle d|h \rangle = 4\text{Re} \left\{ \int \frac{D(\tau, f)H^*(\tau, f)}{S_n(\tau, f)} d\tau df \right\}, \quad (7)$$

Overlap:

$$\begin{aligned} \mathcal{O}(d, h) &= \max_{\phi} \langle d|he^{i\phi} \rangle \\ &= 4 \left| \int \frac{D(\tau, f)H^*(\tau, f)}{S_n(\tau, f)} d\tau df \right|. \end{aligned} \quad (8)$$

SOBHB plots

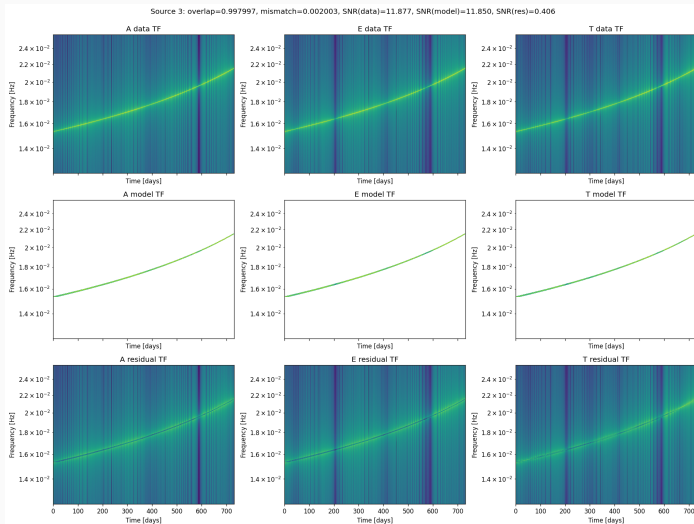


Figure 3: Source n°3, t-f plane comparison.
Using **IMRPhenomD** (ripplegw), **TDI2**.

SOBHB summary: overlaps & SNR

Table 1: SBHB validation summary.

Source	Overlap	Mismatch	SNR_{data}	$\text{SNR}_{\text{model}}$	N_{bins}
0	0.9755	0.0245	15.17	15.14	12547
1	0.9754	0.0246	18.90	18.87	7654
2	0.9490	0.0510	11.68	11.66	6904
3	0.9980	0.0020	11.88	11.85	7978
4	0.9695	0.0305	9.74	9.72	7645
5	0.9554	0.0446	8.23	8.22	7124

Mojito Lite Data analysis: SOBHB

Tools (the return)

Bayes' theorem (equation):

$$p(\theta|d) = \frac{p(d|\theta)p(\theta)}{p(d)} \quad (9)$$

Bayes' theorem (words):

$$\text{posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{evidence}} \quad (10)$$

Log-likelihood function:

$$\log(\text{likelihood})(\theta) = -\frac{1}{2} \langle d|d \rangle - \frac{1}{2} \langle h(\theta)|h(\theta) \rangle + \langle d|h(\theta) \rangle \quad (11)$$

SOBHB data analysis: plot (preliminary)

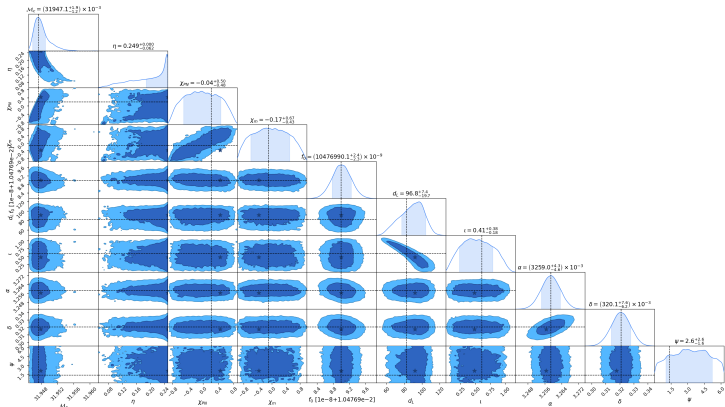


Figure 4: Corner plot of Mojito Lite source n°1, noiseless data.

SOBHB data analysis: plot (preliminary)

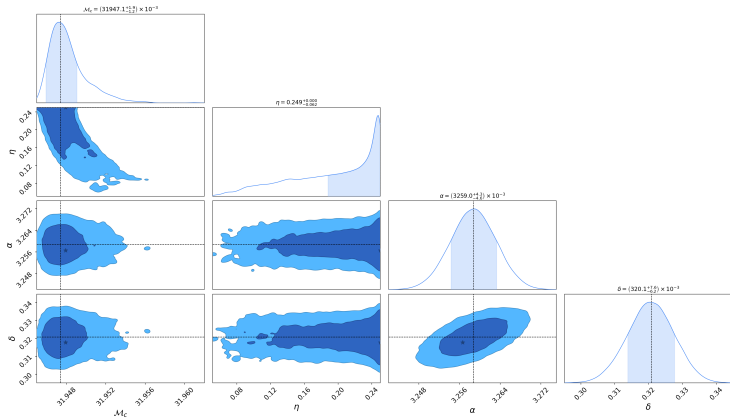


Figure 5: Corner plot of Mojito Lite source n°1, noiseless data (masses + sky localisation).

SOBHB data analysis: plot (preliminary)

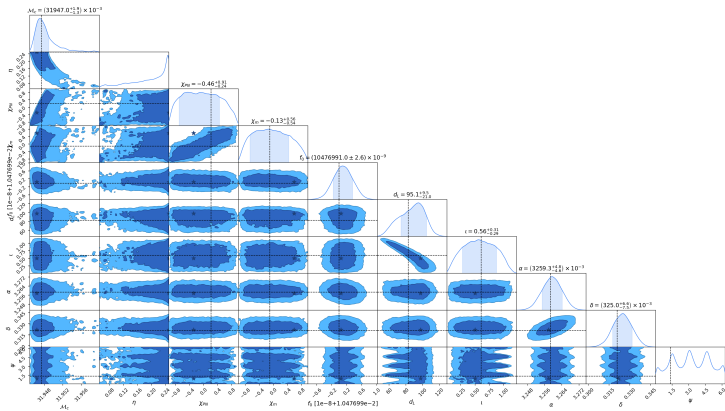


Figure 6: Corner plot of Mojito Lite source n°1, noisy data.

SOBHB data analysis: plot (preliminary)

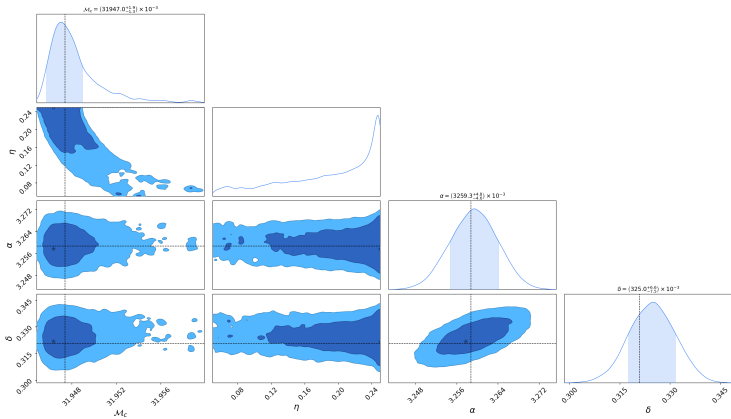


Figure 7: Corner plot of Mojito Lite source n°1, noisy data (masses + sky localisation).

Mojito Lite Data validation: EMRI

EMRI plots (Credits @Saptarshi Ghosh), ongoing

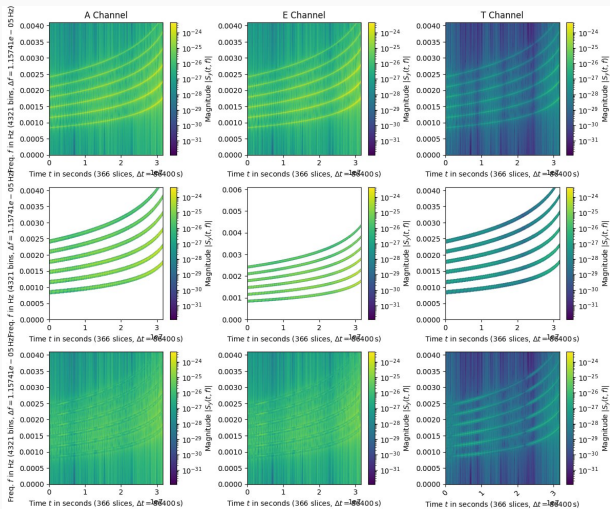


Figure 8: Source n°3, t-f plane comparison.

Using **FEW** (Kerr background), **TDI2**. A/E overlap 98%, T overlap 72%

Summary

Conclusions

- SOBHB validated, EMRI validation ongoing.
- Combining time-frequency and JAX/GPU acceleration.
- Framework implemented in `tfwaves`³ and `jaxtfwaves`⁴ packages.
- To be incorporated in globalfit pipeline Gee-Moo (APC): stay tuned!

³<https://gitlab.in2p3.fr/lisa-apc/tfwaves>, not public yet

⁴<https://gitlab.in2p3.fr/servignat/jaxtfwaves>, not public yet.

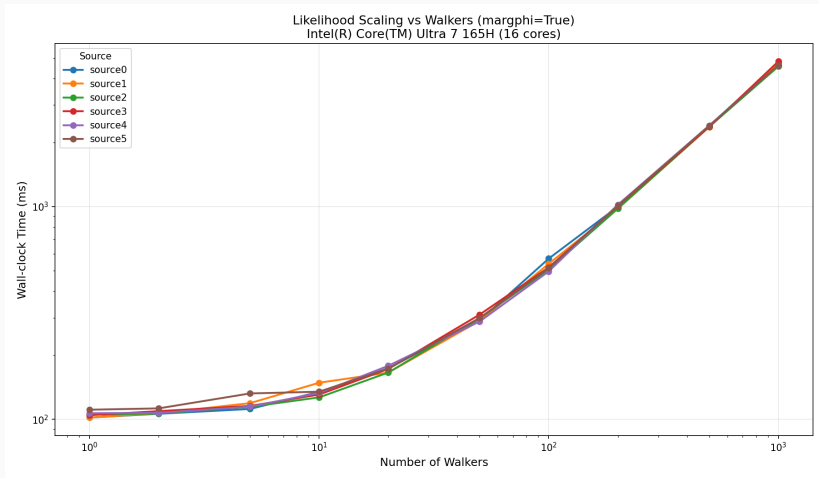
Thank you!

SOBHB catalogue

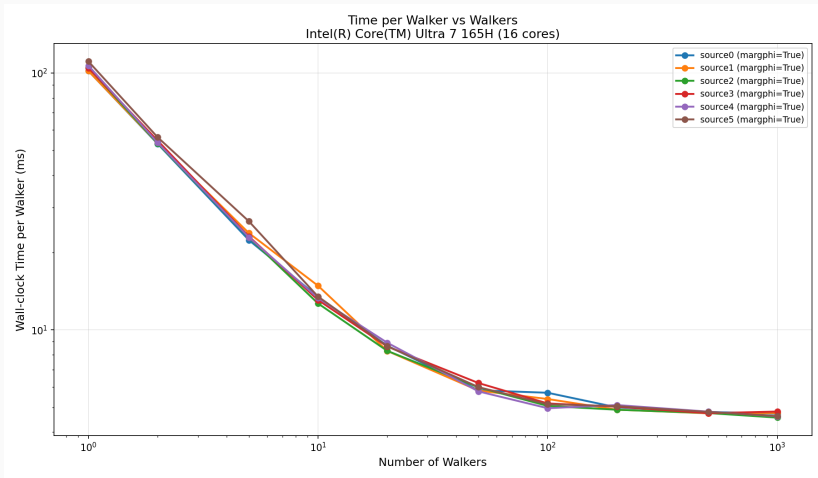
Parameter	Source 0	Source 1	Source 2	Source 3	Source 4	Source 5
Mass1 [M_{\odot}]	71.058	37.410	76.848	43.586	94.328	58.449
Mass2 [M_{\odot}]	66.194	36.002	72.149	43.316	73.448	51.926
Spin1	0.039909	0.14328	0.33789	0.21125	0.20595	-0.19450
Spin2	0.82517	0.36002	0.21199	0.090458	0.044782	0.052145
Distance [Mpc]	368.64	82.589	170.46	148.50	547.12	273.64
InitialFrequency [Hz]	0.015265	0.010477	0.0055310	0.015292	0.0070279	0.0070259
RightAscension [rad]	6.0494	3.2587	3.1718	0.97136	5.9279	3.0426
Declination [rad]	1.3000	0.32080	0.44918	0.11873	-0.00052213	-1.2281
Polarization [rad]	2.1162	1.3289	2.0693	1.1379	1.9066	1.7773
InitialPhase [rad]	-3.0522	-1.0761	-1.4310	-0.70866	3.1113	1.0714
Inclination [rad]	2.7664	0.60480	2.0371	2.0362	2.7961	2.6773
Redshift	0.078677	0.018403	0.037454	0.032740	0.11404	0.059196
AzimuthalAnglePrimarySpin [rad]	2.3533	5.9735	4.5993	3.7615	0.98029	0.98014
AzimuthalAngleSecondarySpin [rad]	0.36495	5.4423	3.7769	4.4490	0.12934	6.0941
PolarAnglePrimarySpin [rad]	0	0	0	0	0	0
PolarAngleSecondarySpin [rad]	0	0	0	0	0	0

Mojito Lite Data analysis: likelihoods

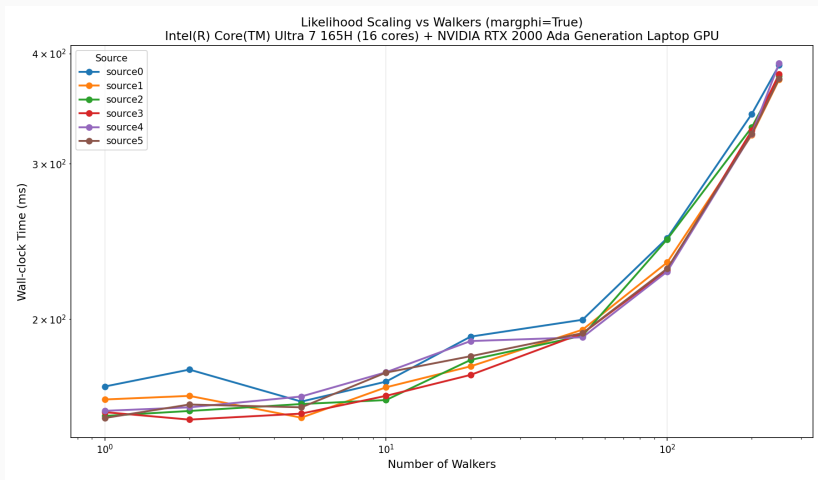
JAX Likelihood benchmark: CPU



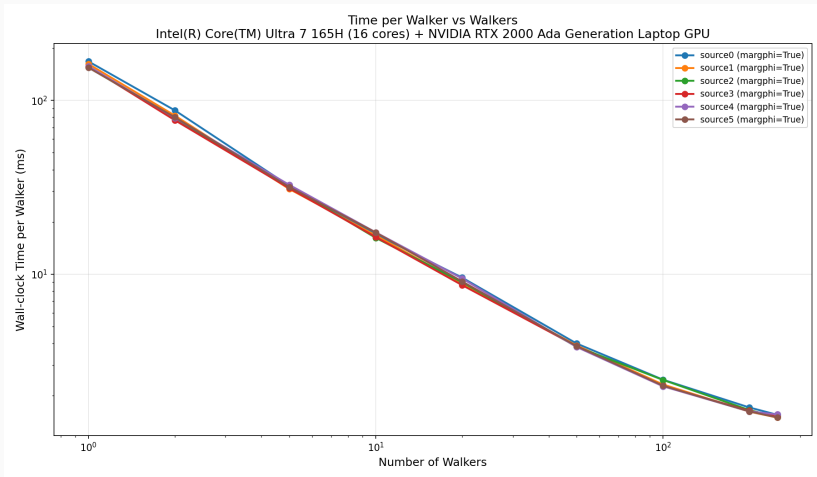
JAX Likelihood benchmark: CPU



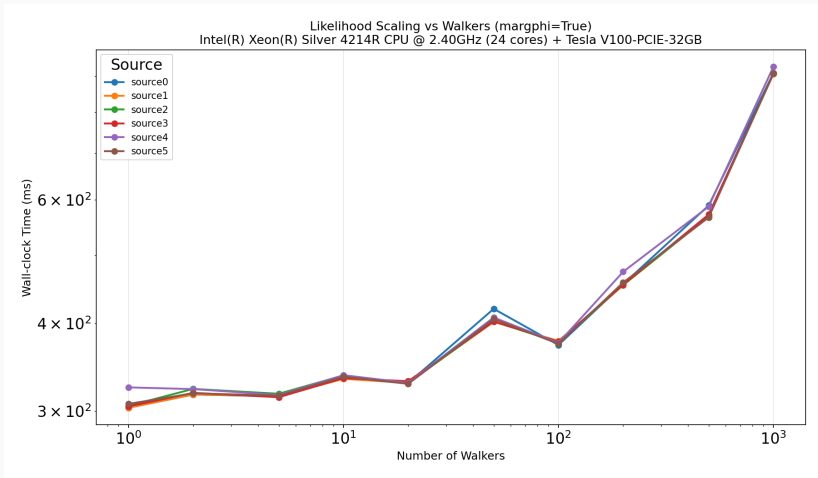
JAX Likelihood benchmark: GPU



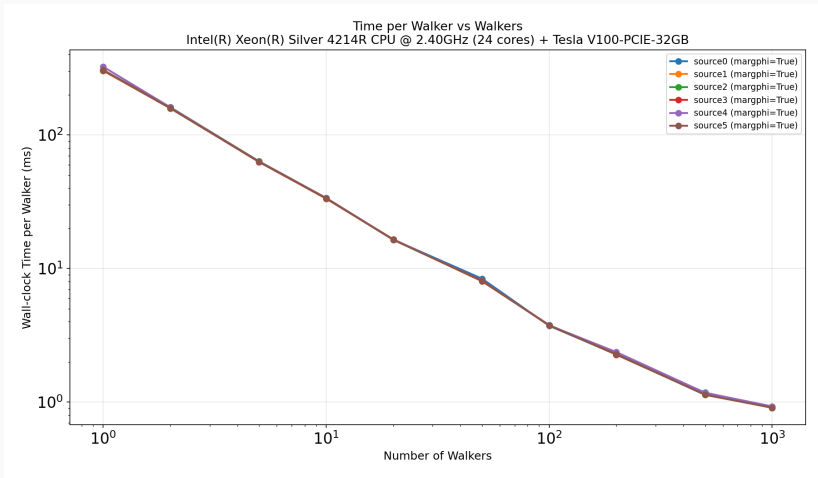
JAX Likelihood benchmark: GPU



JAX Likelihood benchmark: CCIN2P3 V100 GPU

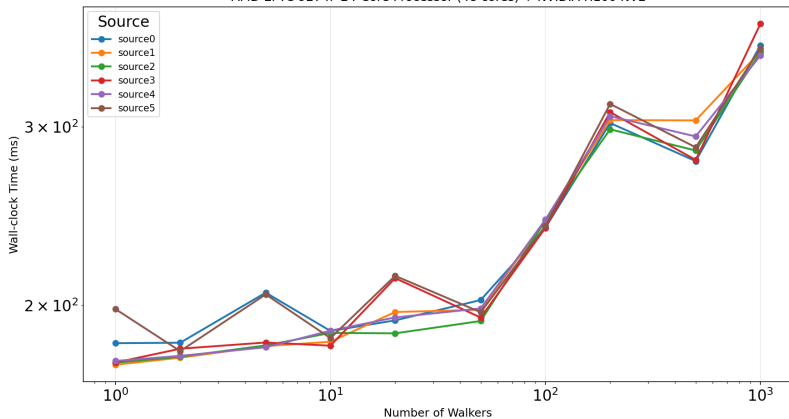


JAX Likelihood benchmark: CCIN2P3 V100 GPU

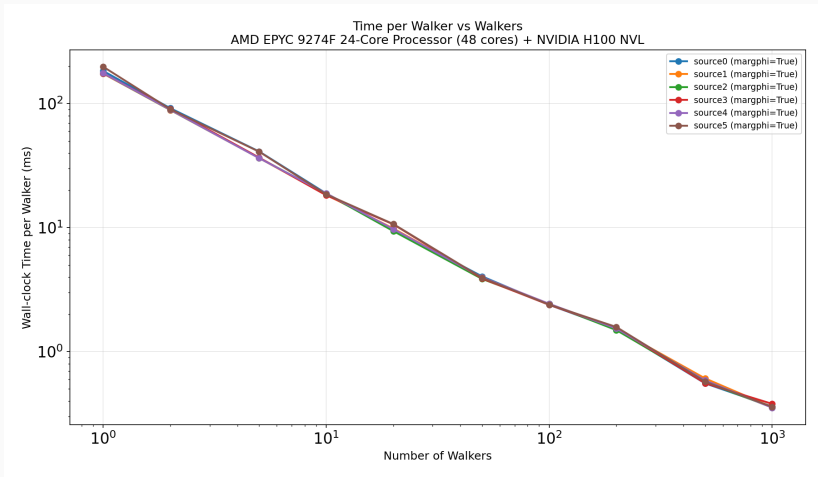


JAX Likelihood benchmark: CCIN2P3 H100 GPU

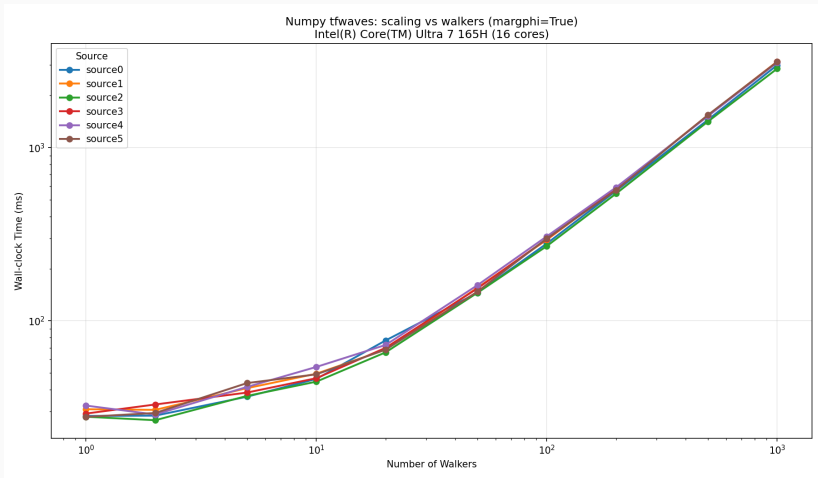
Likelihood Scaling vs Walkers (margphi=True)
AMD EPYC 9274F 24-Core Processor (48 cores) + NVIDIA H100 NVL



JAX Likelihood benchmark: CCIN2P3 H100 GPU



Numpy Likelihood benchmark



Numpy Likelihood benchmark

