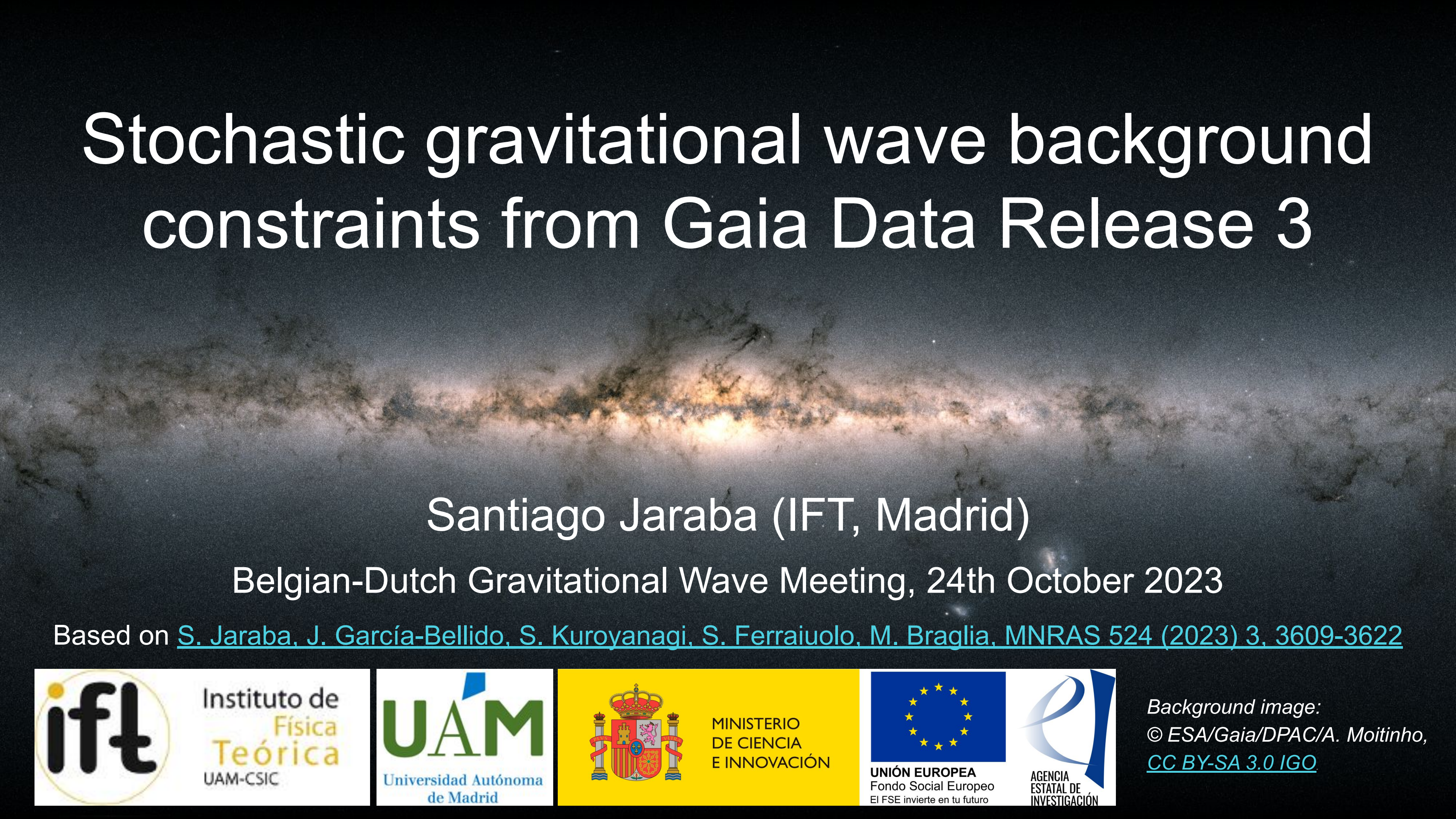

Stochastic gravitational wave background constraints from Gaia Data Release 3

Santiago Jaraba (IFT, Madrid)

Belgian-Dutch Gravitational Wave Meeting, 24th October 2023

Based on S. Jaraba, J. García-Bellido, S. Kuroyanagi, S. Ferraiuolo, M. Braglia, MNRAS 524 (2023) 3, 3609-3622

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Background image:
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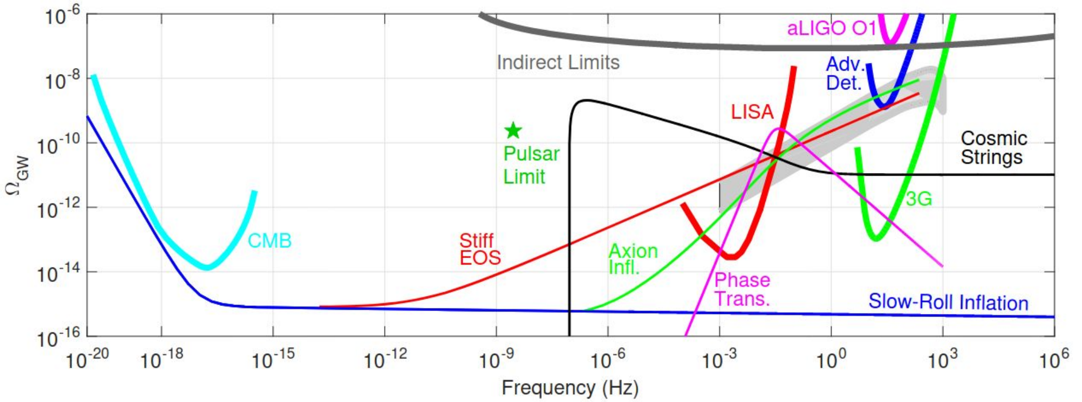
The stochastic gravitational wave background

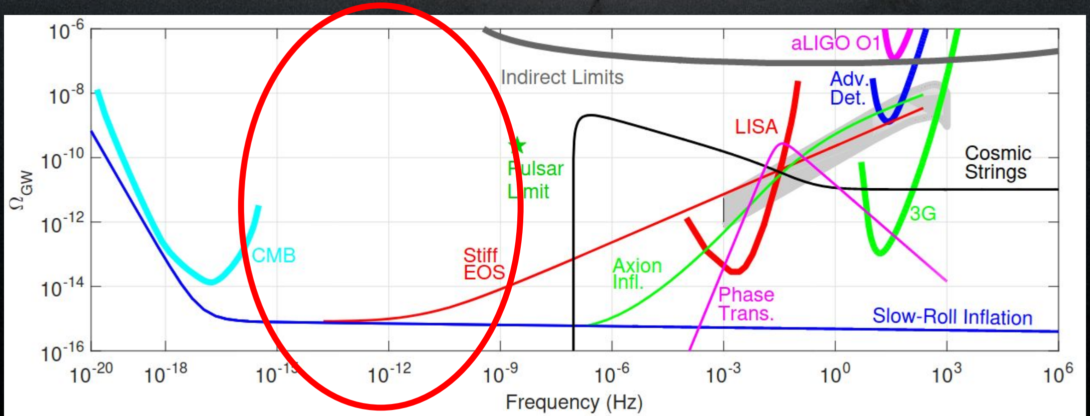
- Detectors as LVK detect intense GW signals from individual BBH.
- Weaker, unresolved signals would form a continuous background: SGWB.
- Lots of sources would also leave an imprint in this background: very rich field!
  - Also close hyperbolic encounters (J. García-Bellido, S. Jaraba, S. Kuroyanagi, arXiv:2109.11376).
- Important to look for this background in all possible frequencies.



LIGO and Virgo collaborations, arXiv:0910.5772

The stochastic gravitational wave background

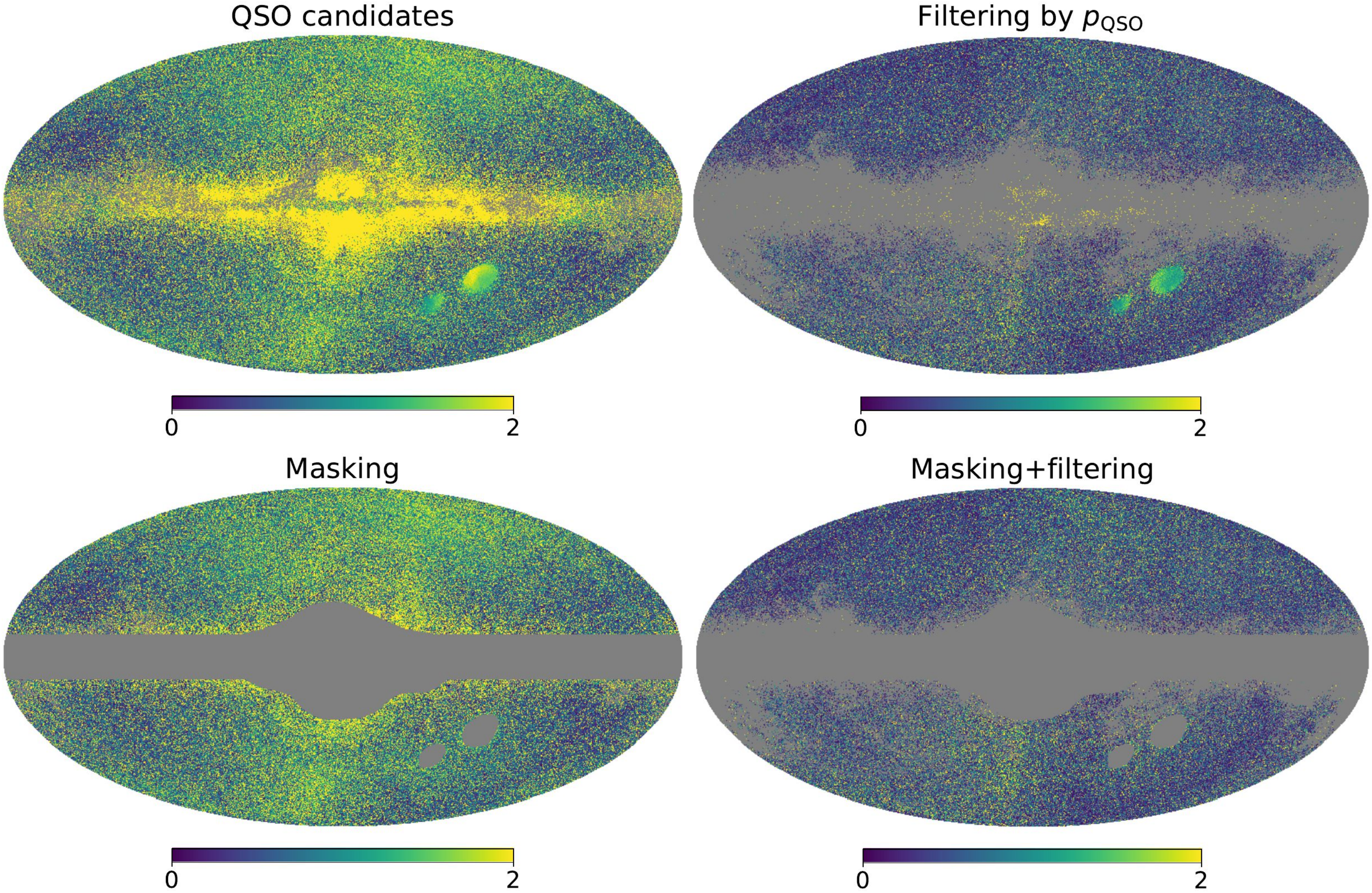
We can use astrometry to constrain this region!



[LIGO and Virgo collaborations, arXiv:0910.5772](arXiv:0910.5772)

Overview of Gaia mission

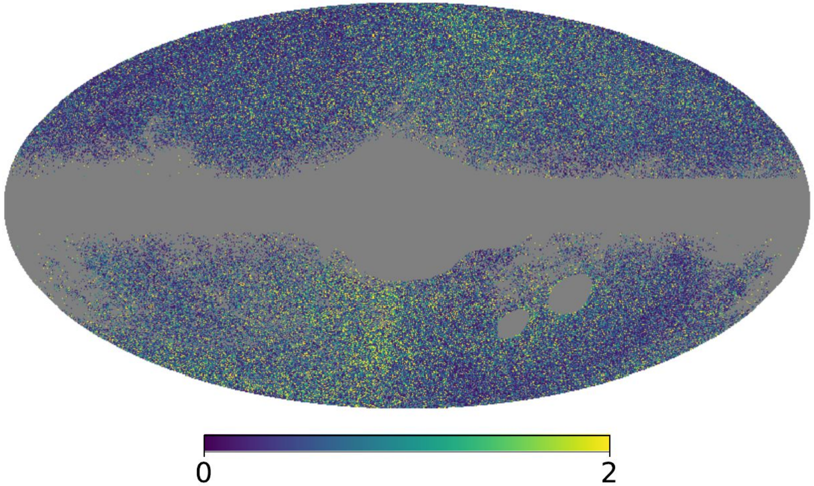
- Launched by ESA in December 2013, expected to operate until 2025.
- Data Release 3 (June 2022): 1.81 billion objects, 34 months of operation.
- Low intrinsic proper motions needed → focus on Quasi Stellar Objects (QSO).
- No “official” Gaia QSO catalog, but “QSO candidate” list provided.
- By cleaning this sample, we can get purer datasets.

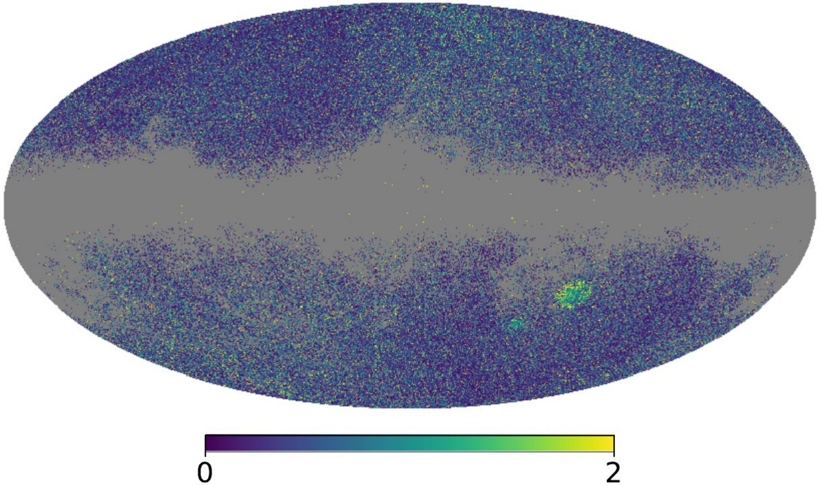

QSO candidates

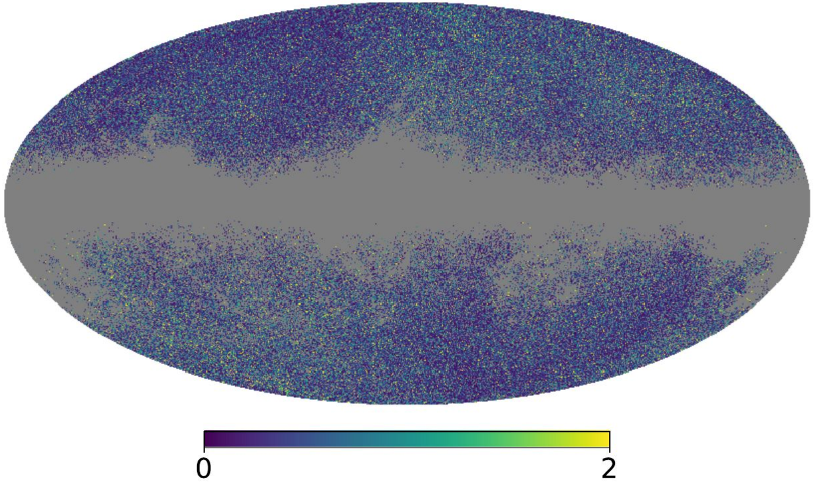
Filtering by p_{QSO}

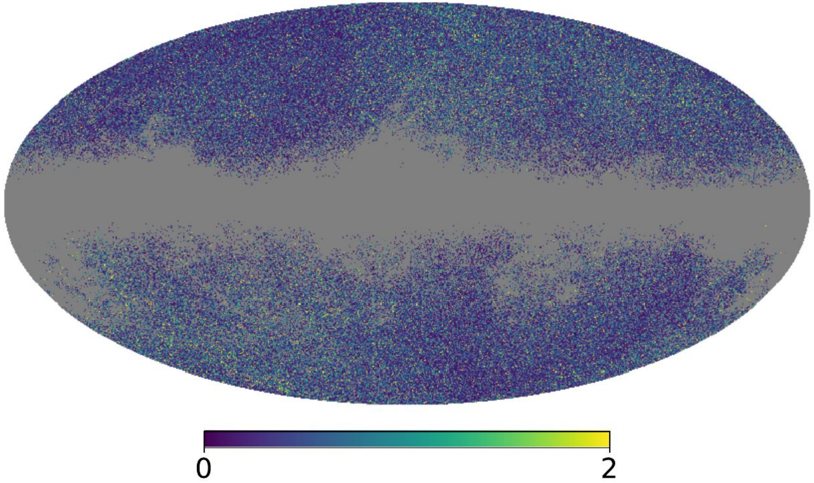
Masking

Masking+filtering

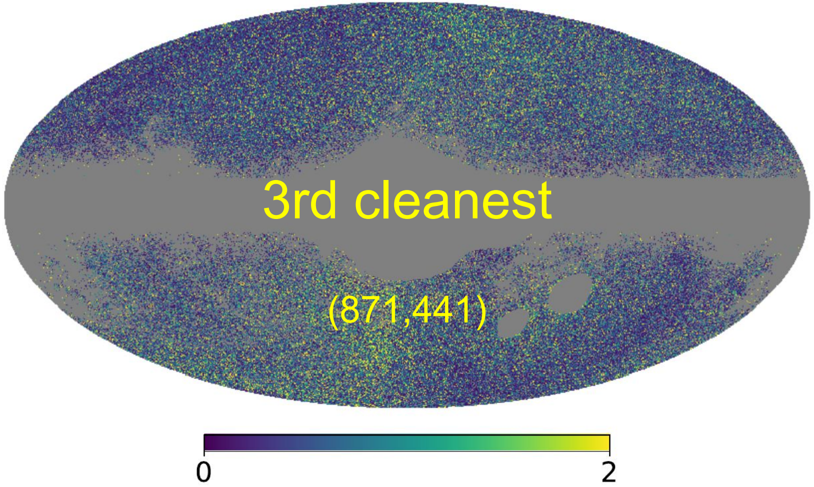

Masking+filtering


Pure


Astrometric


Pure and astrometric intersection

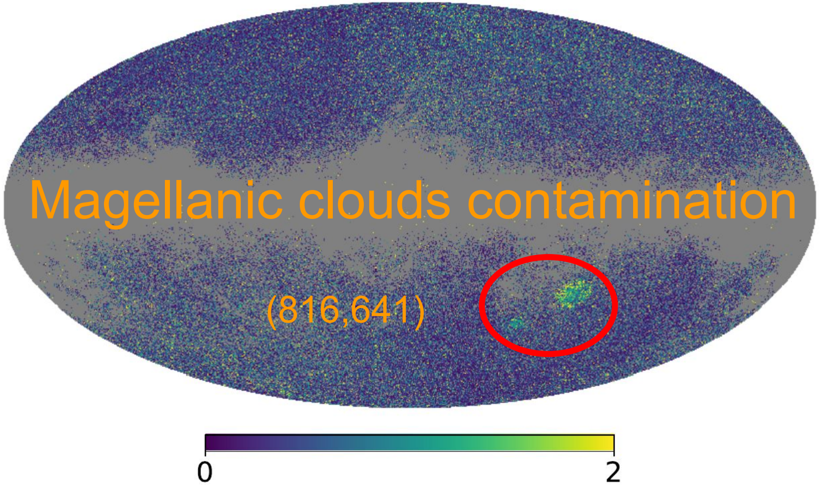
Masking+filtering



3rd cleanest

(871,441)

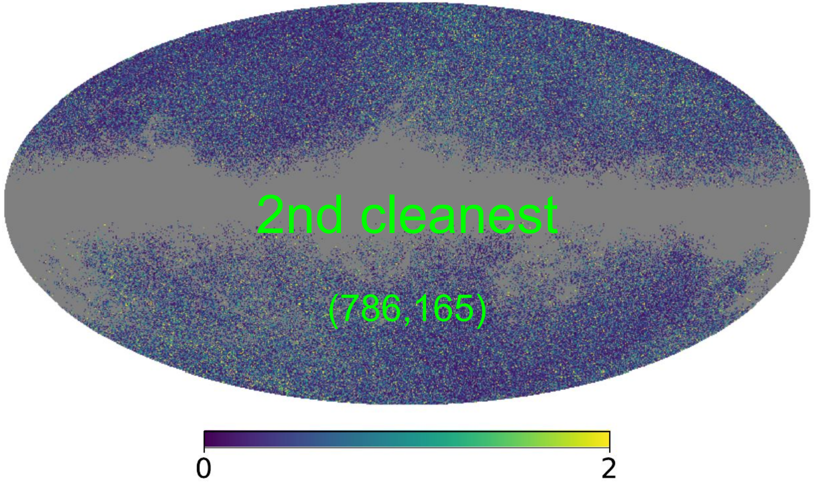
Pure



Magellanic clouds contamination

(816,641)

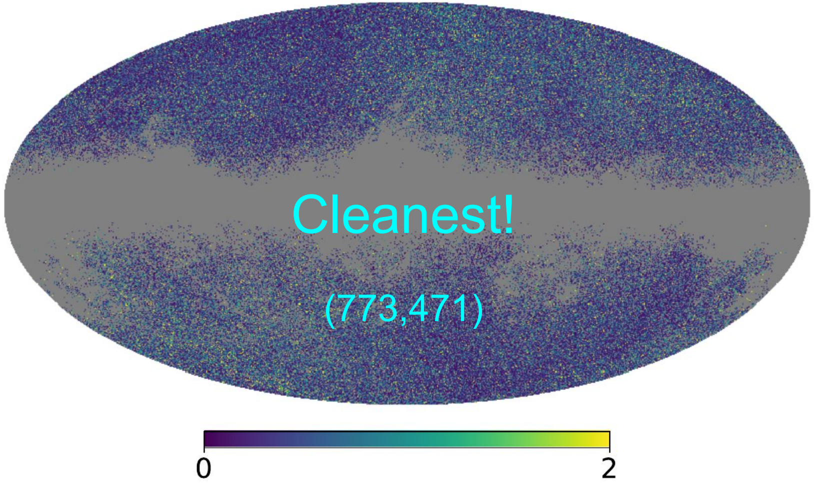
Astrometric



2nd cleanest

(786,165)

Pure and astrometric intersection



Cleanest!

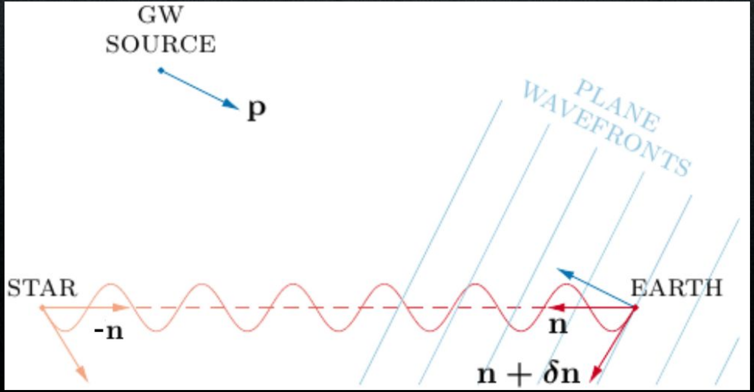
(773,471)

We have our data ready.

Now, how to use it to set constraints on SGWB amplitude?

Gravitational waves from astrometry

- Studied in the 1980s and 90s (E. V. Linder 1986, Braginsky et al. 1990, Pyne et al. 1995, Gwinn et al. 1996, etc.).
- Recent review by Book & Flanagan 2010, arXiv:1009.41920.
- We observe light from distant stars.
- The passage of a GW can alter the observed position.



D. P. Mihaylov et al., arXiv:1804.006608 (modified to match Book&Flanagan notation)

Angular deflection spectrum from a SGWB

$f_{\rm min}$

- Under distant source limit assumption (distance to source >> GW wavelength),

$$\langle \delta\mathbf{n}(\mathbf{n},t)^2\rangle = \theta^2_{\rm rms} = \frac{1}{4\pi^2}\int d\ln f \left(\frac{H_0}{f}\right)^2 \Omega_{\rm gw}(f)$$

- Differentiating,

$$\langle \delta\dot{\mathbf{n}}(\mathbf{n},t)^2\rangle = \int d\ln f\, H_0^2\,\Omega_{\rm gw}(f)$$

- $f_{\rm max} \lesssim T^{-1}$. For Gaia DR3, T = 2.84 years.
- In our case, 4×10^{-18} Hz $\lesssim f \lesssim 1 \times 10^{-8}$ Hz.

$$\Omega_{\rm GW}(f) \sim \langle \mu(f)^2\rangle / H_0^2$$

Multipole decomposition

$$\vec{S}_{lm}(\alpha,\delta) = \frac{1}{l(l+1)}\nabla Y_{lm}(\alpha,\delta)$$

$$\vec{T}_{lm}(\alpha,\delta) = -\frac{1}{l(l+1)}\hat{n}\times\nabla Y_{lm}(\alpha,\delta)$$

- A vector field needs two basis: spheroidal/electric and toroidal/magnetic.
- We run MCMCs to fit proper motion data to a generic vector field up to l = 2.

$$\vec{V}(\alpha,\delta) = \sum_{\substack{r=s,t\\R=S,T}} \sum_{l=1}^{\infty} \left[r_{l0}\vec{R}_{l0} + 2\sum_{m=1}^{l} \left(r^{\mathrm{Re}}_{lm}\vec{R}^{\mathrm{Re}}_{lm} - r^{\mathrm{Im}}_{lm}\vec{R}^{\mathrm{Im}}_{lm} \right) \right]$$

- Power per multipole and mode

$$P^r_l = \sum_{m=-l}^{l} |r_{lm}|^2 = r^2_{l0} + 2\sum_{m=1}^{l} (r^{\mathrm{Re}}_{lm})^2 + (r^{\mathrm{Im}}_{lm})^2$$

$$\Omega_{\mathrm{GW}} = \frac{6}{5}\frac{1}{4\pi}\frac{P_2}{H_0^2} = 0.000438\frac{P_2}{(1\ \mu\mathrm{as/yr})^2}h_{70}^{-2}$$

$$P_l = P^s_l + P^t_l$$

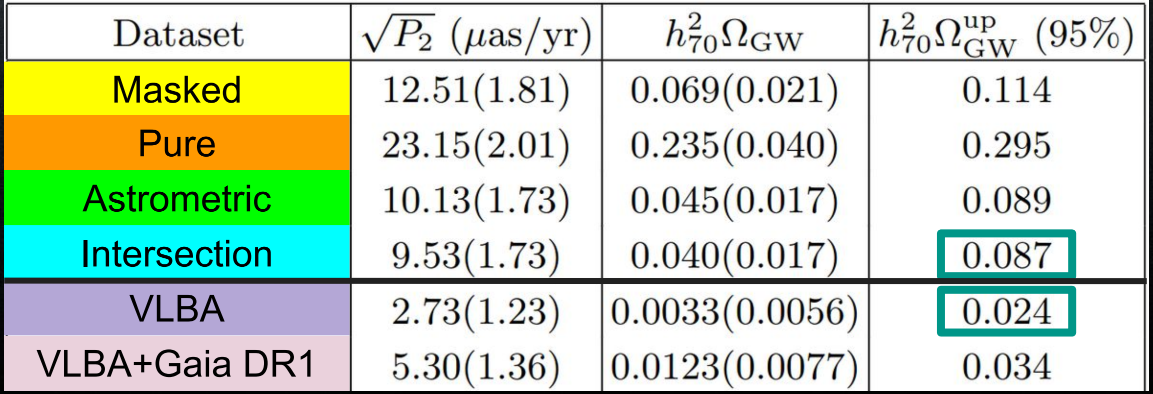
$$H_0 = 70h_{70}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

Previous work (Darling, Truebenbach, Paine, arXiv:1804.06986)

- Darling et al. followed a very similar procedure to ours to get $\Omega_{GW} \lesssim 0.0064$.
- Two datasets: quasars from VLBA, combination of VLBA + Gaia DR1.
- Only 711 and 508 sources (1000 times less than our datasets).
- However, much better resolution! A factor 30-40 better than ours.
  - The combination of both makes the expected results comparable.
- Main differences with our analysis:
  - They fit the dipole and quadrupole separately. This produces a less conservative result.
  - Their code underestimates the errors in a factor ~2.
- We thus decided to reanalyse their work for a better comparison.

Results

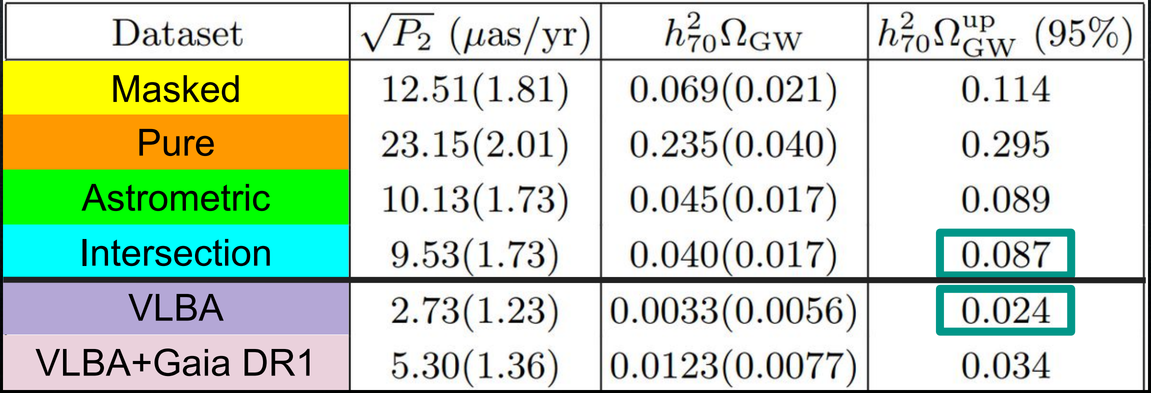
- For the intersection dataset, quadrupole power of order 100 (µas/yr)^2.
- No evidence for detection → we provide 95% upper bound $\Omega_{GW} \lesssim 0.087$.
- Our other datasets behave as expected:
  - The astrometric is similar but slightly more contaminated.
  - The masked behaves a bit worse, but still within 30%.
  - The pure one does much worse due to contamination. Still, within the order of magnitude.
- We conclude that our results are robust under dataset choice within the Gaia DR3 QSO candidates sample.



Dataset	$\sqrt{P_2}$ (μas/yr)	$h_{70}^2\Omega_{\rm GW}$	$h_{70}^2\Omega_{\rm GW}^{\rm up}$ (95%)
Masked	12.51(1.81)	0.069(0.021)	0.114
Pure	23.15(2.01)	0.235(0.040)	0.295
Astrometric	10.13(1.73)	0.045(0.017)	0.089
Intersection	9.53(1.73)	0.040(0.017)	$\boxed{0.087}$
VLBA	2.73(1.23)	0.0033(0.0056)	$\boxed{0.024}$
VLBA+Gaia DR1	5.30(1.36)	0.0123(0.0077)	0.034

Results

- For VLBA and VLBA+Gaia datasets, we worsen a bit the results by Darling et al. (0.0064 and 0.011).
  - Expected due to the differences in our works.
- Still, VLBA places better constraints than Gaia DR3.
- Also expected due to the much better resolution in VLBA, caused by the larger observing period (22.2 years vs 2.84).



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Conclusions and future prospects

- Gaia DR3 (2.84 yr) → $\Omega_{GW} \lesssim 0.087$ for 4×10^{-18} Hz $\lesssim f \lesssim 1 \times 10^{-8}$ Hz.
- VLBA update → $\Omega_{GW} \lesssim 0.024$ for 6×10^{-18} Hz $\lesssim f \lesssim 1 \times 10^{-9}$ Hz.
- Gaia improves proper motion resolution like $T^{3/2}$: 2.7 and 6.6 improvement factors for DR4 (5.5 yr) and DR5 (10 yr) → 7.2 and 44 improvement for Ω_{GW}.
- Extrapolating our constraints, $\Omega_{GW} \lesssim 0.012$ (DR4) and $\Omega_{GW} \lesssim 0.0020$ (DR5).
  - Conservative prediction: number of sources will likely increase.
  - For DR5, we will also have the full time series, which will help further cleaning the data.
- Proposed mission Theia with 60 better angular resolution & 100 more sources → $O(10^{-10})$!
- More modest constraints than standard GW detectors, but completely different freq. range.
  - Necessary for signals such as supermassive black hole binaries or looking for new physics.

Thank you for your attention!

Backup: angular deflection spectrum from a SGWB

- Assuming pure Gaussian fluctuations and equal distribution of sources in the sky, it is usually assumed we can get root mean square proper motions of order

  $$\Delta\theta/(T\sqrt{N})$$

  so we could set constraints

  $$\Omega_{\mathrm{gw}}(f) \lesssim \frac{\Delta\theta^2}{NT^2H_0^2}$$

  - Δθ angular resolution, T observing period, N number of sources.

- These estimations tend to be optimistic. However, good to have them in mind.
- Ω_{GW} scales like N^{-1}, while the resolution enters squared.