Detection and estimation of the cosmic dipole with the Einstein Telescope and Cosmic Explorer

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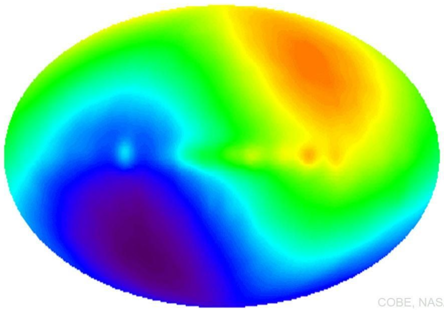
The cosmic kinematic dipole: another tension?

- Our motion with respect to the Hubble flow creates an anisotropy in temperature fluctuation of the Cosmic Microwave Bakground (CMB) *[Planck+ 2020]* and distribution of electromagnetic (EM) sources *[Colin+ 2017, Benglay+ 2018, Secrest+ 2022]*.

- The dipole estimation from the CMB and quasars at low and intermediate redshifts agrees on direction but not on amplitude (5-sigma tension).

- We expect the two dipole estimations to agree, unless a **systematic** is present or the AGN distribution **is not isotropic**. This can be due to a possible redshift evolution of EM sources *[Dalang+ 2022]*.



Quasars (AGN)

$$\frac{v_o}{c} = 6.0 \cdot 10^{-3}$$

CMB

$$\frac{v_o}{c} = 1.2 \cdot 10^{-3}$$

The effect of the observer velocity on GW detections

While the GW source is propagating from cosmological distances, the Earth is moving in the Hubble follow. GW sources will be subject to aberration and Doppler shift.

Sky position

$$d\Omega = d\bar{\Omega}\left(1 - 2\mathbf{n} \cdot \frac{\mathbf{v}_o}{c}\right)$$

Luminosity distance

$$\frac{\delta D_L}{\bar{D}_L} = -\mathbf{n} \cdot \frac{\mathbf{v}_o}{c}$$

Redshift

$$\frac{\delta z}{1+\bar{z}} = -\mathbf{n} \cdot \frac{\mathbf{v}_o}{c}$$

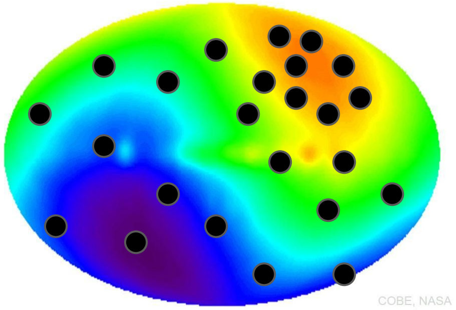
We expect to observe a distribution of sources that is “beamed” in the dipole direction

Discrete version of the estimator

$$\hat{v}_{\mathbf{n}'} = \frac{3}{2N_{\rm tot}} \sum_{i=1}^{N_{\rm sky}} N^i_{\rm det} \cdot (\mathbf{n}_i \cdot \mathbf{n}')$$

Expected value of the estimator

$$\langle \hat{v}_{\mathbf{n}'} \rangle = \frac{\alpha v_o}{2c} \cos(\theta')$$



Simulating compact binaries with XG detectors

- We simulate BBH and BNS mergers using a SFR-like GW merger rate model.

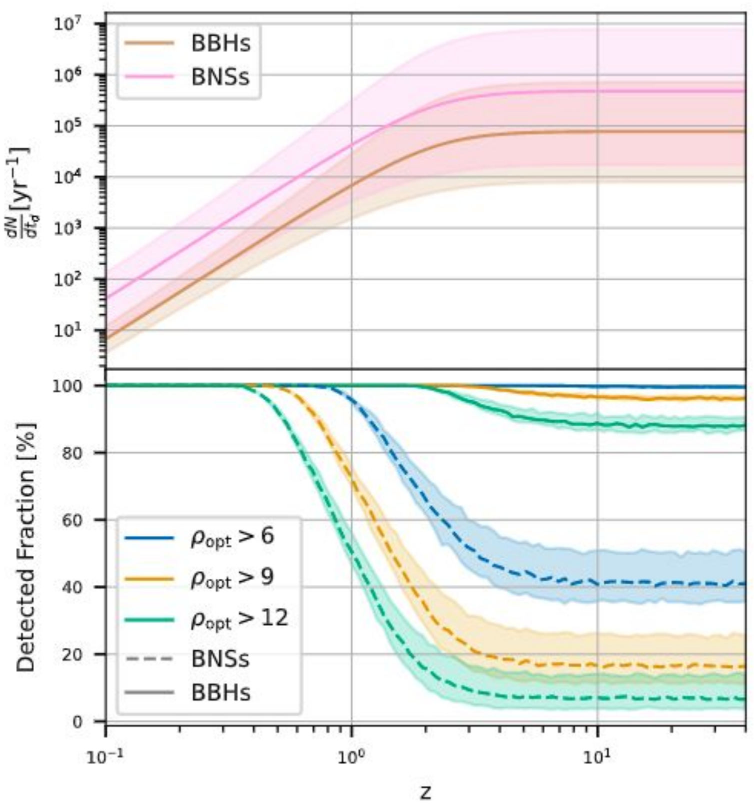
$$\frac{dN}{dt_d} = \int_0^z R(z') \frac{1}{1+z'} \frac{dV_c}{dz'} dz'$$

- The BNS and BBH mass spectrums are taken consistent with *[Iacovelli+ 2022]* and last LVK results.

- We take a network composed by ET+2CE.

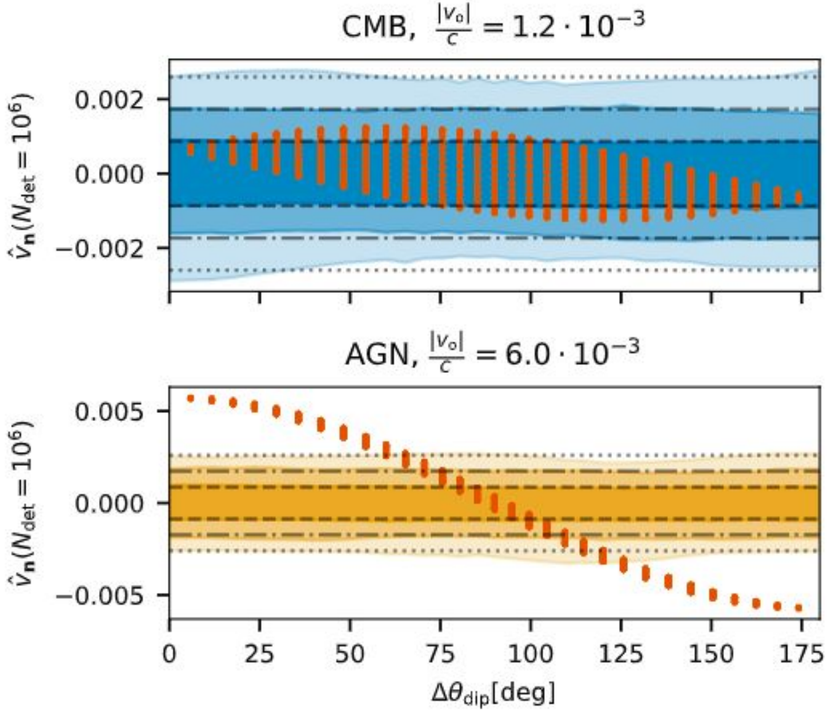
- We calculate the SNR using the 0PN approximation and considering GW frequencies above 10 Hz (pessimistic).

- The network can easily detect almost all the BBHs merging in the Universe.



Simulating compact binaries with XG detectors

- The dipole estimator maximizes when it is computed along the direction of the observer velocity.
- However, the estimator can fluctuate due to Poissonian statistic. It is important to understand if we are detecting a dipole or a noise fluctuations.
- With 1 million detections, the AGN dipole is definitely detectable but not the CMB one.



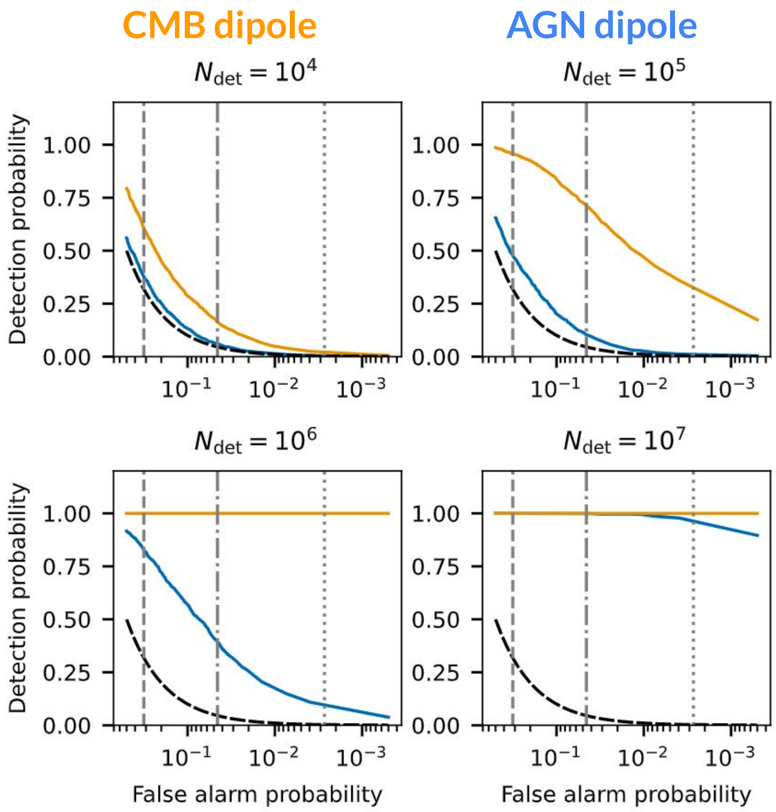
Simulating compact binaries with XG detectors

- Using Monte Carlo simulations we evaluate the detection False Alarm Rate (FAP) vs Detection probability curves for the cosmic dipole.

- Lower FAR, more confident detection but more difficult to detect the dipole.

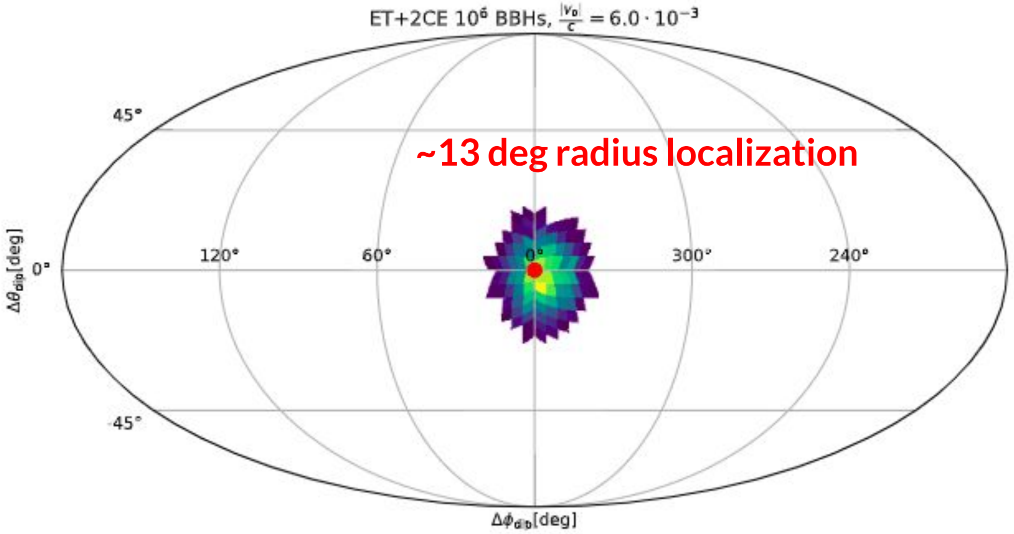
- With 1 million detections (~3 years of ET+2CE) the **AGN dipole will be detectable (3 sigma)**, while the CMB will be marginally detectable.

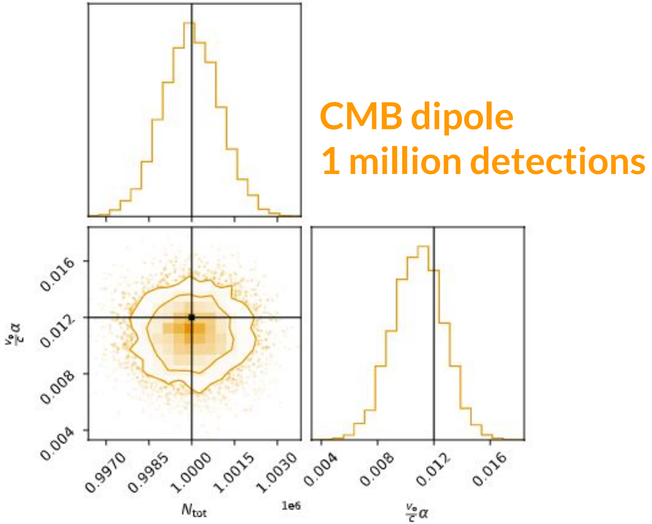
- With 10 million (~30 years of ET+2CE) detections both dipoles would be detectable.



Simulating compact binaries with XG detectors: a bayesian tool

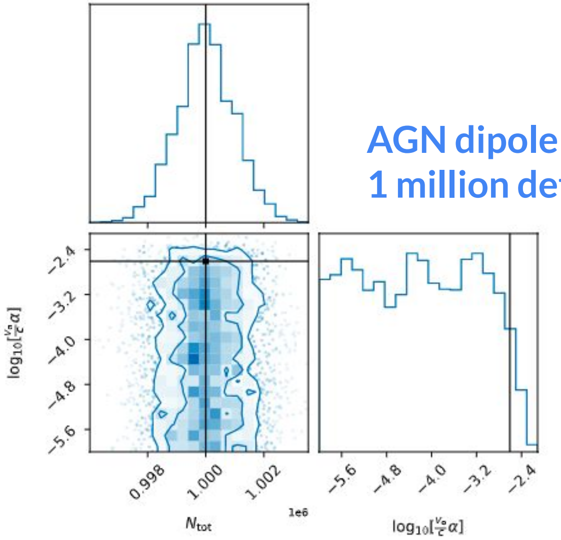
- We can also use Bayesian inference to estimate the direction and magnitude of the cosmic dipole.



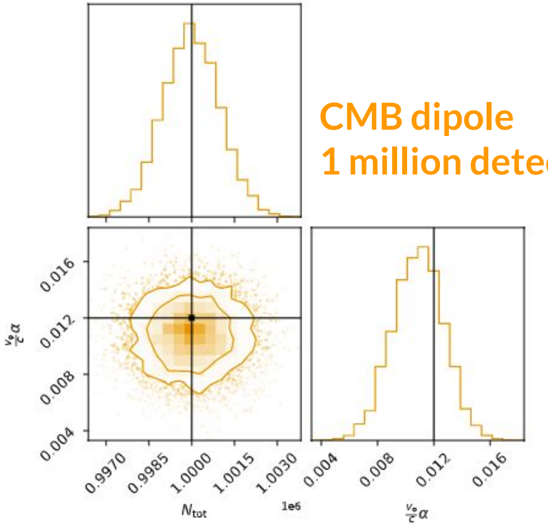


Simulating compact binaries with XG detectors: a bayesian tool

- We can also use Bayesian inference to estimate the direction and magnitude of the cosmic dipole.
- Bayesian statistic can provide also an upper-limit in case of non-detections (Bayes factors inconclusive).



AGN dipole
1 million detections



CMB dipole
1 million detections

Simulating compact binaries with XG detectors: a bayesian tool

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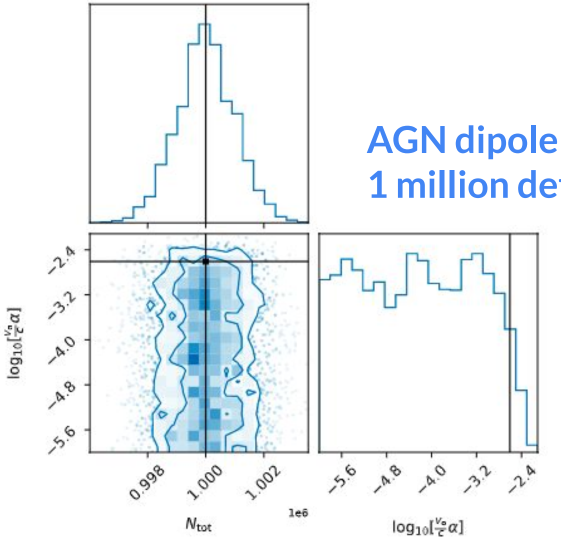
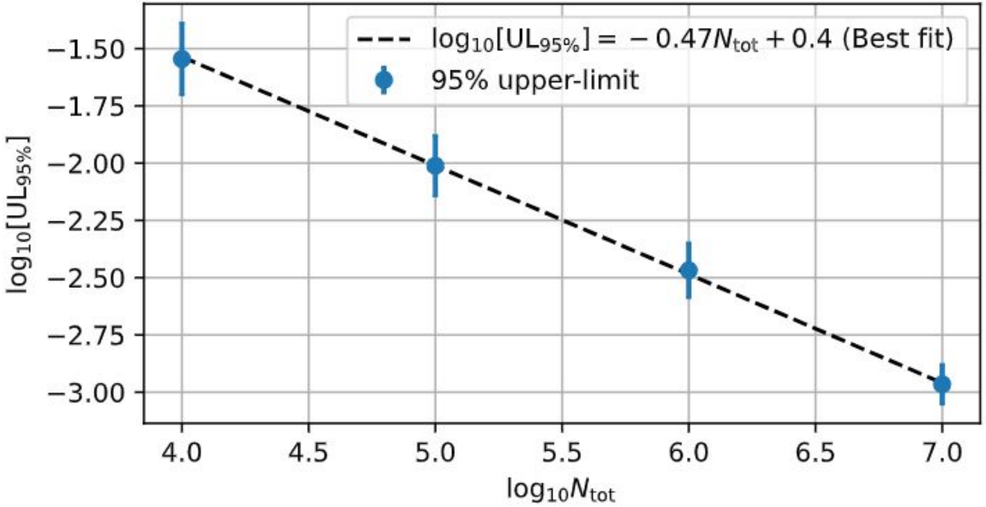


AGN dipole
1 million detections



Conclusions

- BBHs detections with XG detectors might provide a “clean” and selection bias-free channel to measure the cosmic dipole.

- We present new analysis tools to evaluate the cosmic dipole using frequentists and Bayesian techniques.

- With ~3 years of observations with XG detectors, we will be able to exclude (or detect) at least the AGN cosmic dipole with 3 sigma confidence.

- More detections can be collected to improve the sensitivity of detections of the cosmic dipole and BNSs could also be included to increase the statistics.

Conclusions

Thanks for the attention