Measuring the cosmic dipole with golden dark sirens

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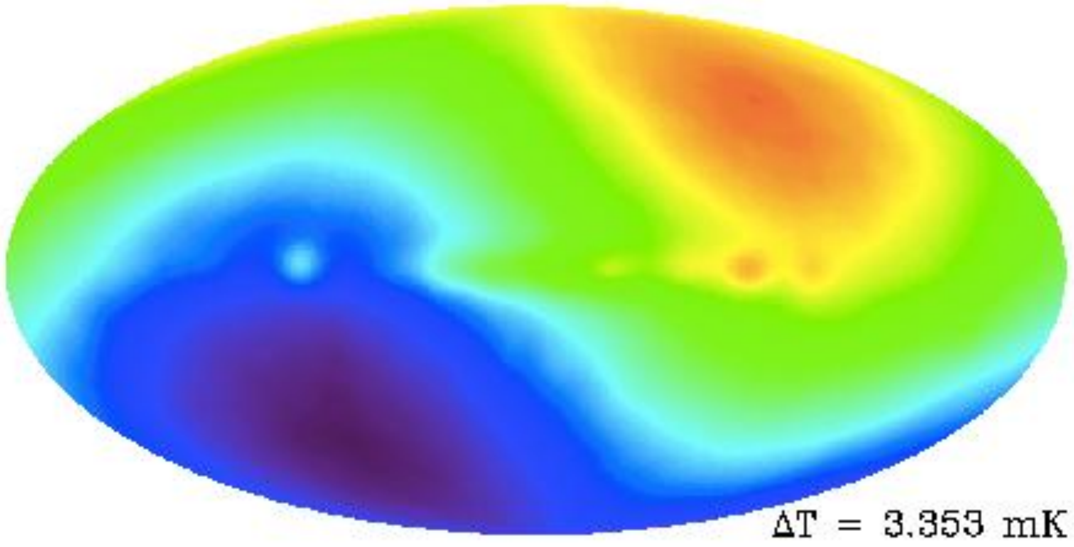
What is cosmic dipole?

- The cosmic dipole is caused by observer's velocity relative to the background (kinetic dipole).
- Or perhaps by intrinsic anisotropy of the universe, which could mimic dark energy.

Kinetic dipole measured from CMB observation: $|\vec{v}_o|/c = 1.2 \times 10^{-3}$



Credit: Lloyd Knox

Cosmic dipole tension

- There exists a tension up to ~5σ between the cosmic dipole measured from CMB and source number counting (~ twice of CMB result).
- Number counting for mutiple galaxy surveys supports the existence of tension.

dipole anisotropy	type	redshift	amplitude	$l°$	$b°$	significance
CMB solar dipole [1]	K	N/A	$1.23 \pm 0.00036 \times 10^{-3}$	264.02 ± 0.01	48.253 ± 0.005	N/A
CMB temperature asymmetry* [2]	I	N/A	$2.3^{+0.8}_{-0.4} \times 10^{-2}$	220 ± 25	-5 ± 25	$\sim 2.7\sigma$
SNe [9] (CMB frame)	K	$0.01 - 1$	$8 \pm 1.7 \times 10^{-4}$	242 ± 16	59 ± 19	68% C.L.
SNe [10] (heliocentric frame)	K/I	$0.01 - 1$	$5 \pm 1.6 \times 10^{-3}$	252 ± 12	65 ± 9	3.3σ
TGSS radio galaxies [7]	K/I	$0.01 - 4$	$7.0 \pm 0.4 \times 10^{-2}$	243 ± 12	45 ± 3	99.5% C.L.
NVSS radio galaxies [7]	K/I	$0.01 - 4$	$2.3 \pm 0.4 \times 10^{-2}$	253 ± 11	27 ± 3	99.5% C.L.
quasars [8]	K/I	$0 - 3.6$	1.5×10^{-2}	238	28	4.9σ
α [11]	I	$0.2 - 7.1$	$0.72 \pm 0.16 \times 10^{-5}$	325 ± 17.5	-11 ± 10.3	3.9σ
H_0 via galaxy clusters [12]	I	$0.004 - 0.839$	9% variation	273 ± 40	-11 ± 27	5.4σ

Credit: Cousins et al., 2024

- 10^7 GW event number counting in the 3G era can constrain the cosmic dipole to the CMB level (Grimm et al., 2023).

Cosmic dipole effects

- Denote the dipole amplitude along the line-of-sight $\hat{z}(\phi, \theta)$ as $g(\hat{n} \cdot \hat{z})$.

  Dipole magnitude g , direction $\hat{n}(\phi^{dip}, \theta^{dip})$

  For kinetic dipole, $g^{kin} = -|\vec{v}_o|/c$

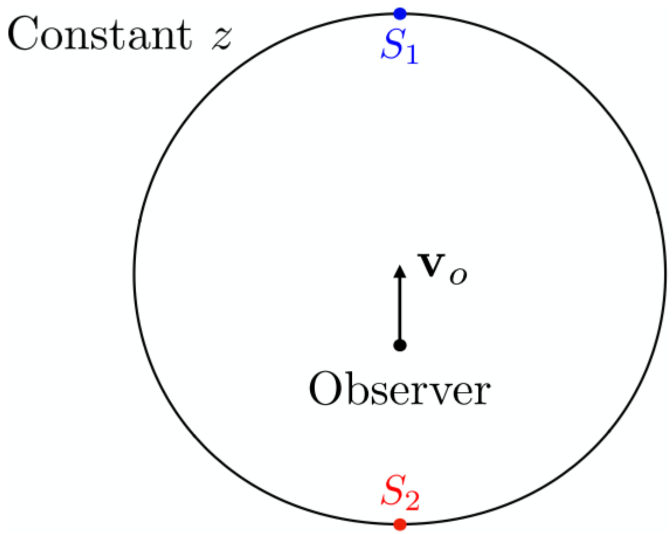
- Modification to luminosity distance and redshift

$$d_L^{\mathrm{obs}} = d_L^0[1 + g(\hat{n} \cdot \hat{z})]$$

$$1 + z^{obs} = (1 + z^0)[1 + g(\hat{n} \cdot \hat{z})]$$

- Modification to observed binary mass

$$m^{obs} = m^s(1 + z^0)[1 + g(\hat{n} \cdot \hat{z})]$$

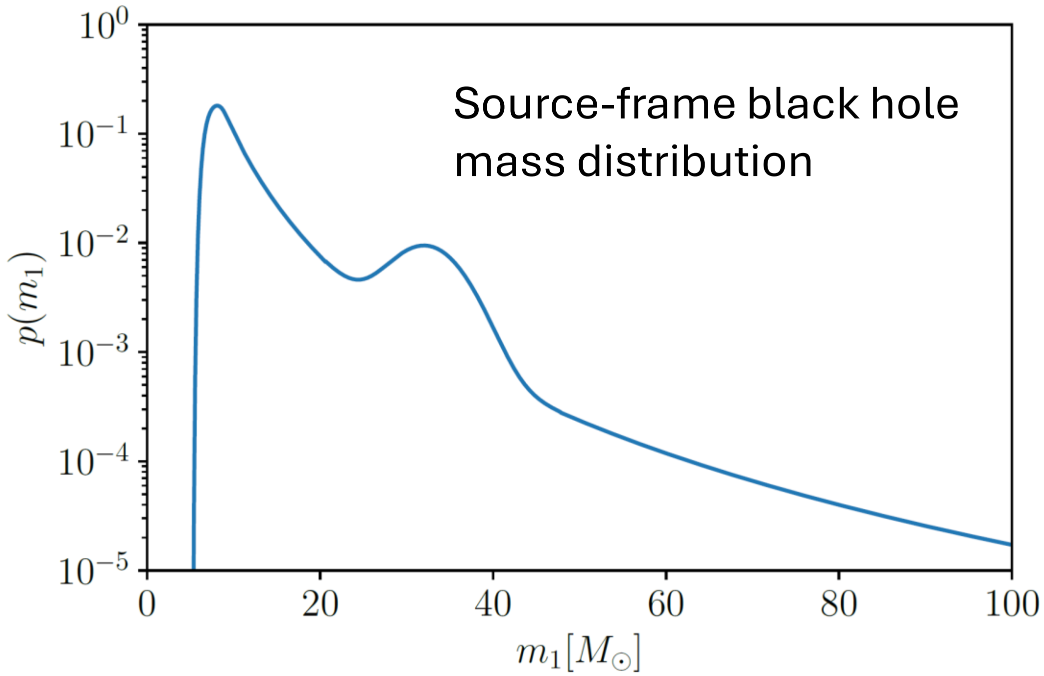


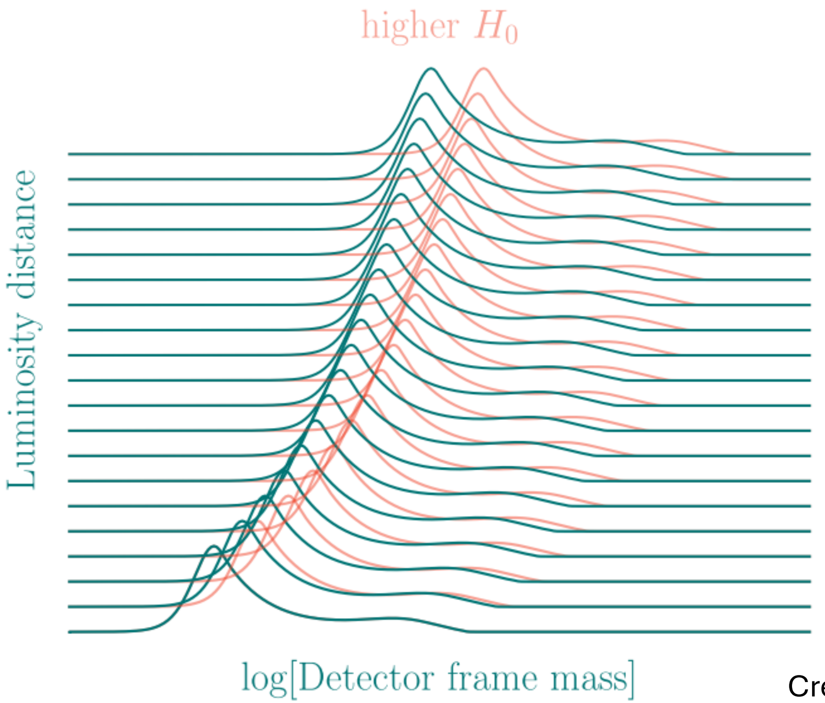
Credit: Dalang & Bonvin, 2021

How does it affect GW cosmology?

Spectral siren analysis

- A Bayesian statistical method to measure cosmological parameters using features in BBH population model.
- Obtain $z(d_L, H_0)$ from GW events, then obtain source-frame black hole masses $m^s = m^{det}/(1+z)$.
- $P(H_0)$ is obtained by the position of the peak in mass distribution.



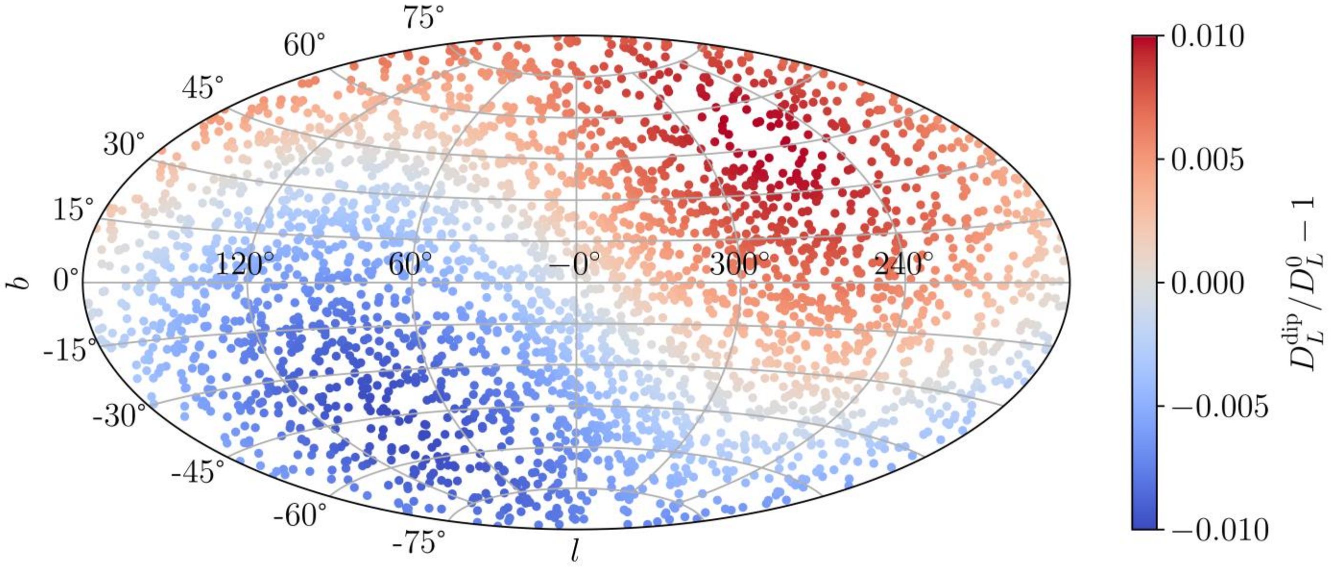


Credit: Chen et al, 2024

Effects in spectral siren analysis

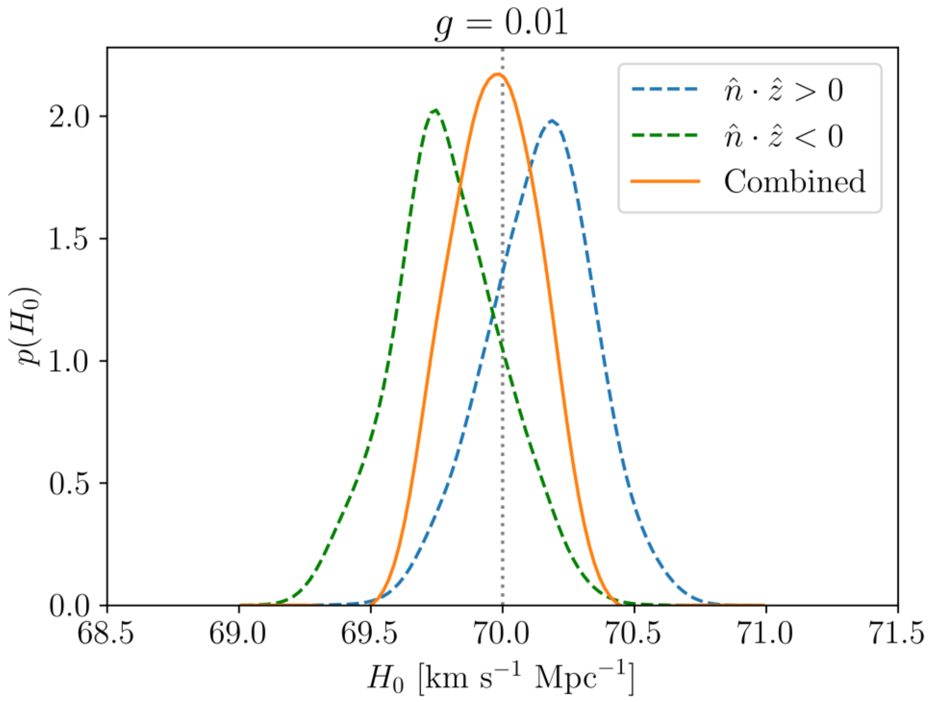
- We generate mock BBH events detected by LVK under designed sensitivity with SNR>11.
- We use Powerlaw + Peak population model and Madau merger rate redshift evolution model using GWTC-3 estimation values.
- d_L^{obs} is computed from z^0 with $H_0 = 70\ \mathrm{km\ s^{-1} Mpc^{-1}}$, $\Omega_{m0} = 0.3$ with an injected dipole.
- We generate posterior samples for $(m_1^{\mathrm{obs}}, m_2^{\mathrm{obs}}, d_L^{\mathrm{obs}}, \iota, \phi, \theta)$ for each event with Fisher likelihood inference.

Cosmic dipole effects for O5 events with *g*=0.01 pointing at $(264°, 48°)$.



O5 test

- We compute $p(H_0)$ with the spectral siren method with 5-year mock O5 events.
- Combined posterior has little deviation, but there is ~1σ deviation between posteriors from hemispheres for opposite directions of the cosmic dipole.
- Such deviation could be larger in the 3G era as the detected event number difference increases for two hemispheres.



How can we measure it with GWs?

Golden dark sirens

- Schechter function: galaxy number density in relation to luminosity.

$$\phi(L) = \left(\frac{\phi^*}{L^*}\right)\left(\frac{L}{L^*}\right)^{\alpha} e^{-L/L^*}$$

- Areal density of galaxies at distance *r* with luminosity greater than *L*:

$$N_{\mathrm{gal}} \approx 0.28\ \mathrm{deg}^{-2}\left(\frac{r}{100\mathrm{Mpc}}\right)^3\left(\frac{\phi^*}{4\times10^{-3}\mathrm{Mpc}^{-3}}\right)\Gamma\left(1+\alpha,\frac{L}{L^*}\right)$$

- Using B-band parameters:

$$\alpha = 1.25, \qquad \phi^* = 1.2\times10^{-2}h^3Mpc^{-3}, \qquad L^* = 1.2\times10^{10}h^{-2}L_{\odot}$$

Only one galaxy with $L > L^*$ can be found within a sky area of ~$0.06\ \mathrm{deg}^2$ for $z < 0.1$.

It is potentially the host galaxy of a well-locallized dark siren.

Detection forecast

1. Obtain $d_L^{\rm obs}, z^{\rm obs}, m_1^{\rm obs}, m_2^{\rm obs}$ for different values of g and create GW injections at z<0.1.
2. Compute the uncertainties for $(m_1^{\rm obs}, m_2^{\rm obs}, d_L^{\rm obs}, \iota, \phi, \theta)$ with Fisher matrix using GWDALI.
3. Check for the golden dark siren criteria of $0.06\ \mathrm{deg}^2$ with 90% sky area from $\delta\phi$ and $\delta\theta$.

We consider 10-year observation by Einstein Telescope (ET) and LIGO detectors with Cosmic Explorer (CE) or A# sensitivity.

Detector network	Golden dark siren number			
	BBH	NSBH	BNS	Total
1ET+2A#s	13	0	0	13
1ET+1CE+1A#	31	2	2	35
1ET+2CEs	33	3	3	39

Dipole measurements

- We construct the likelihood as

$$\log \mathcal{L} = -\frac{1}{2}\sum_{i}^{N_{\mathrm{obs}}}\left\{\frac{d_{L,i}^{\mathrm{obs}} - d_L^0\left[z^0\left(z_i^{\mathrm{obs}}, g, \hat{n}\right), H_0\right][1 + g(\hat{n}\cdot\hat{z}_i)]}{\delta d_{L,i}^{\mathrm{obs}}}\right\}^2$$

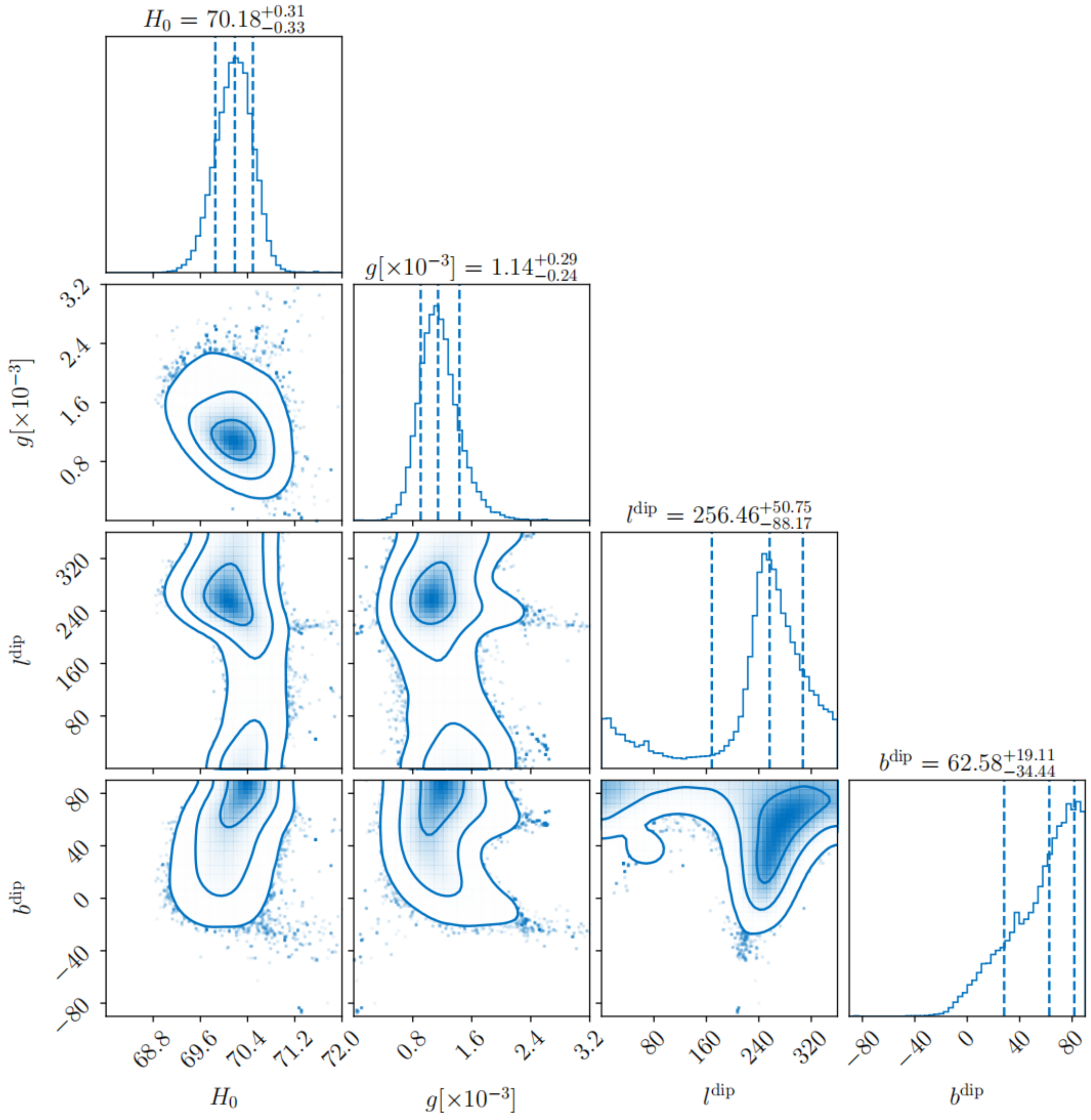
- Rest-frame redshift

$$z^0\left(z_i^{\mathrm{obs}}, g, \hat{n}\right) = \frac{1 + z_i^{\mathrm{obs}}}{1 + g(\hat{n}\cdot\hat{z}_i)} - 1$$

- We run MCMC sampling to jointly constrain $H_0, g, l^{\mathrm{dip}}, b^{\mathrm{dip}}$.

Results

- 1ET + 2LIGOs (A#)
- Injected $g = 10^{-3}$, $(l^{\mathrm{dip}}, b^{\mathrm{dip}}) = (264°, 48°)$.
- $\sim 0.5\%$ constraint on H_0.
- $\sim 27\%$ constraint on the dipole magnitude g.
- Weak constraint on the dipole direction.



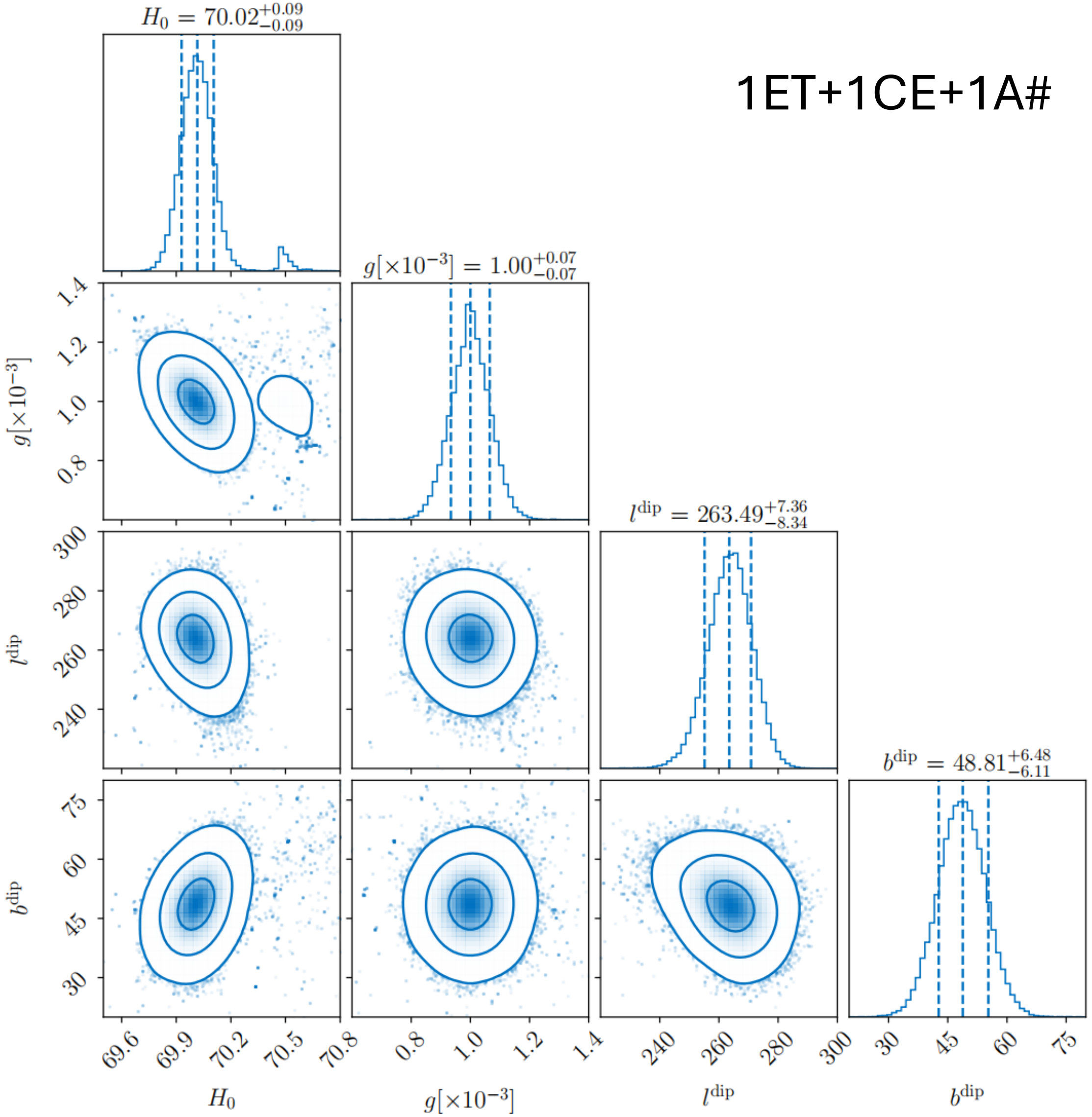
Results

- Injected $g = 10^{-3}$, $(l^{\rm dip}, b^{\rm dip}) = (264°, 48°)$.

Detector network	1σ uncertainty			
	H_0	g	$l^{\rm dip}$	$b^{\rm dip}$
1ET+2A#s	0.46%	27%	69°	27°
1ET+1CE+A#	0.13%	7%	8°	6°
1ET+2CEs	0.11%	6%	6°	5°

- At least two 3G detectors in a three-detector network can constrain the cosmic dipole well.

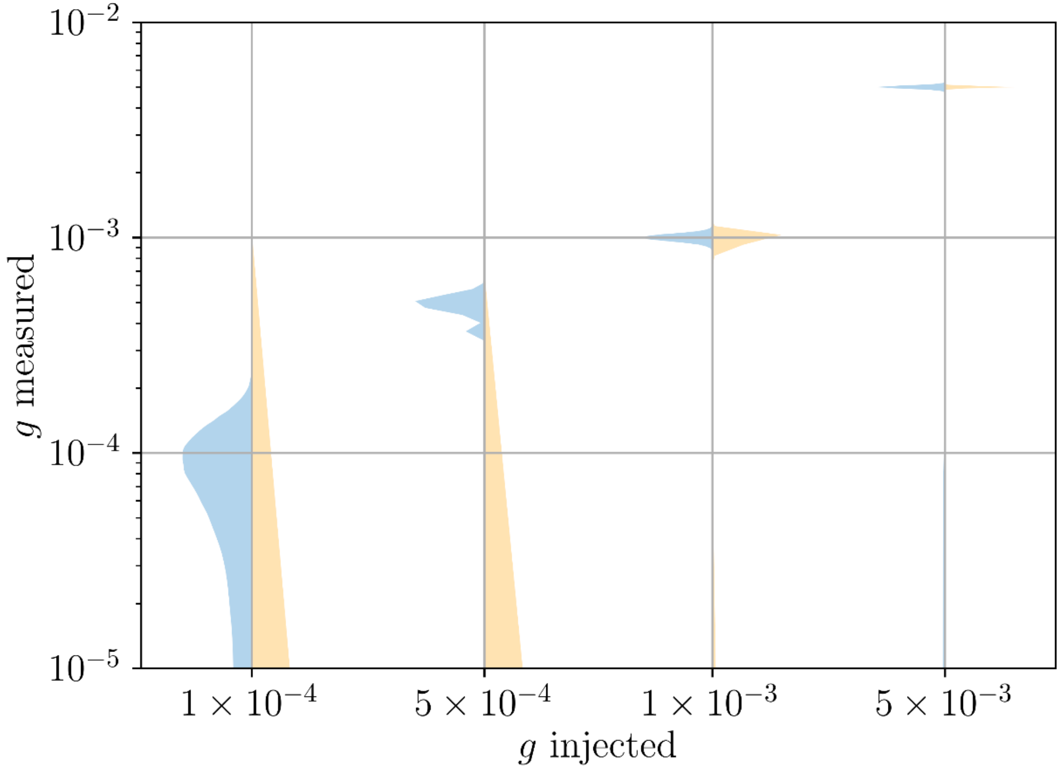
1ET+1CE+1A#



Results

- We check constraints for different injected values of g.

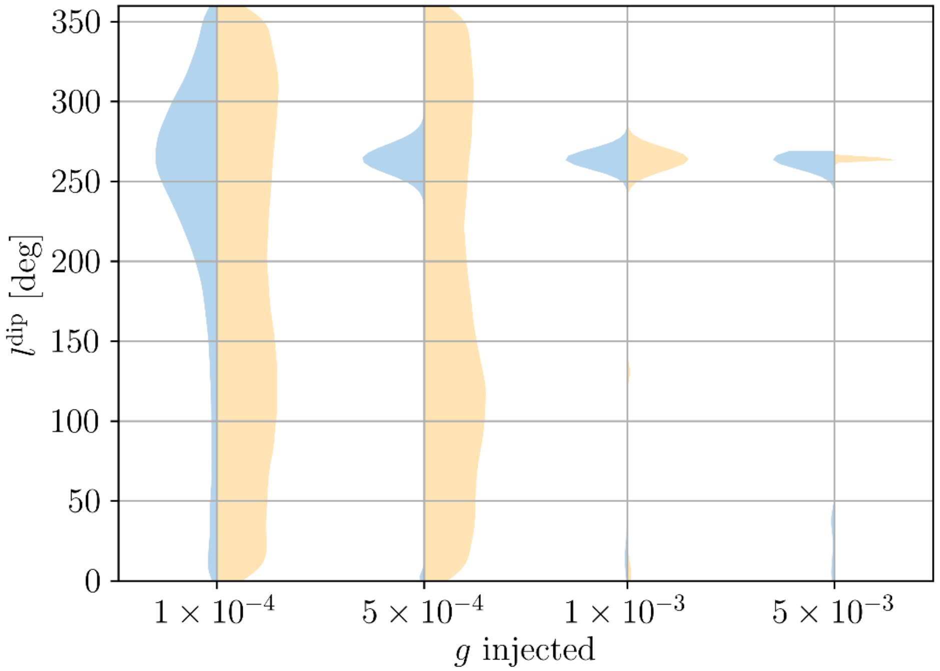
- g cannot be constrained in order of 10^{-4} when jointly measured with H_0, but it can be constrained when fixing H_0.

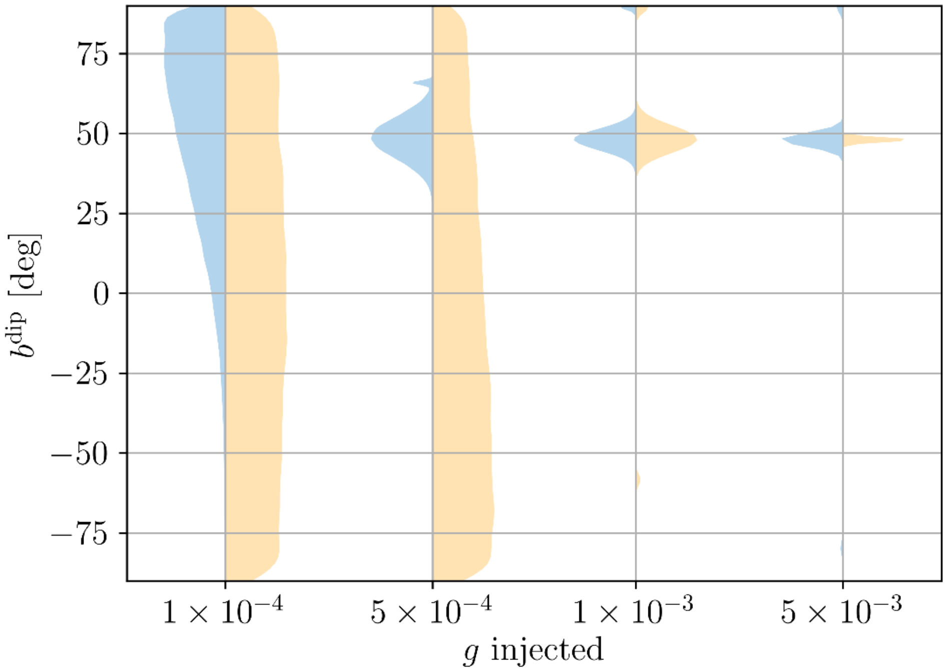


Blue: fixing H_0
Orange: jointly measured with H_0

Results

- Constraints on $(l^{\mathrm{dip}}, b^{\mathrm{dip}})$ can be obtained down to $g \sim 10^{-4}$ when fixing H_0.





Blue: fixing H_0
Orange: jointly measured with H_0

Conclusions

- The cosmic dipole may cause biases in precise H_0 measurement with spectral siren analysis for future detections.
- ~35 golden dark sirens observed by a three-detector network that includes more than one 3G detector can constrain $g = 10^{-3}$ (CMB level) with ~7% error, and jointly constrain H_0 with <0.2% error at the same time.
- Constraint on the dipole can be enhanced by an order of magnitude when fixing H_0.

Thank you!

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