Constraining the Hubble Constant using Cross-Correlation of Gravitational-Wave Events with Galaxies

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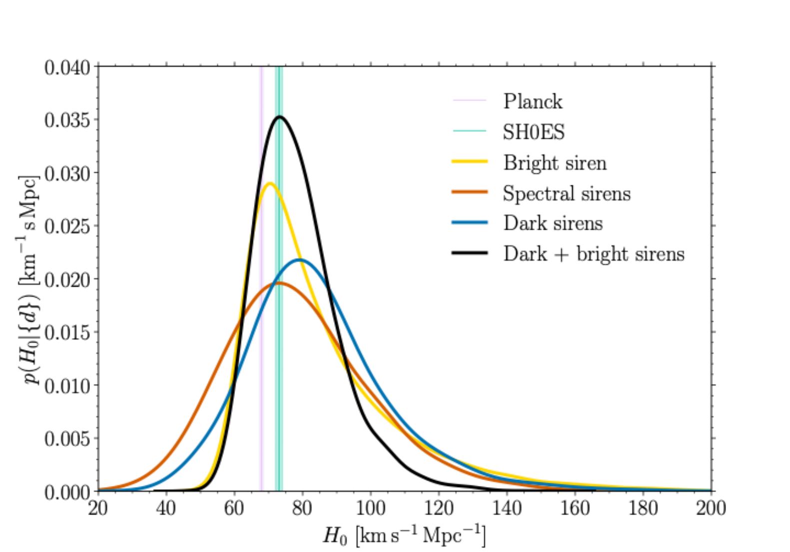
GW Cosmology

- GW from compact binary coalescence (CBC) is a new probe to study the expansion of the Universe.

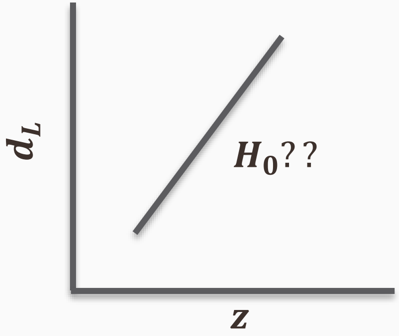


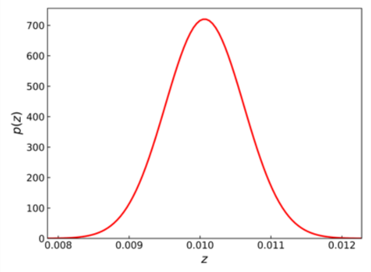
Ref.: LVK (arXiv: 2509.04348)

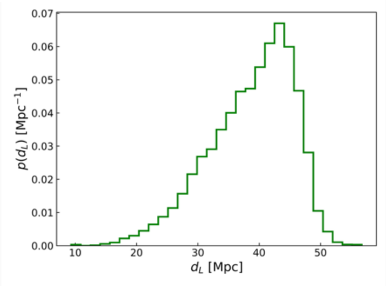
GW Cosmology: Bright Sirens

- GW from compact binary coalescence (CBC) is a new probe to study the expansion of the Universe.
- **Bright Siren:** Identification of unique host galaxy.

$$d_L = \frac{c(1+z)}{H_0} \int \frac{dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}}$$







Ref.: LVK (Nature 2017)

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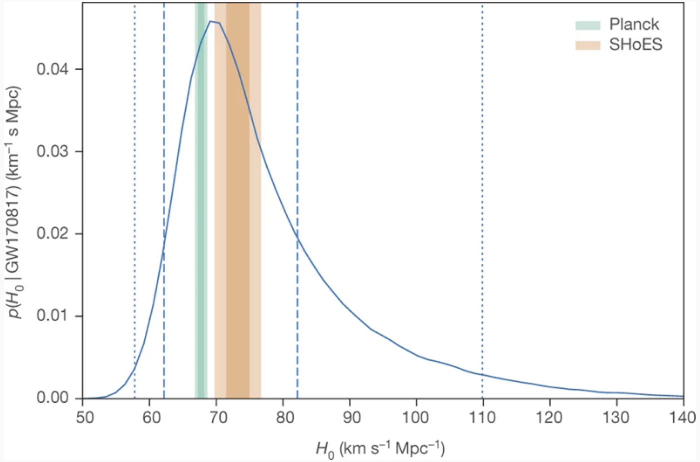
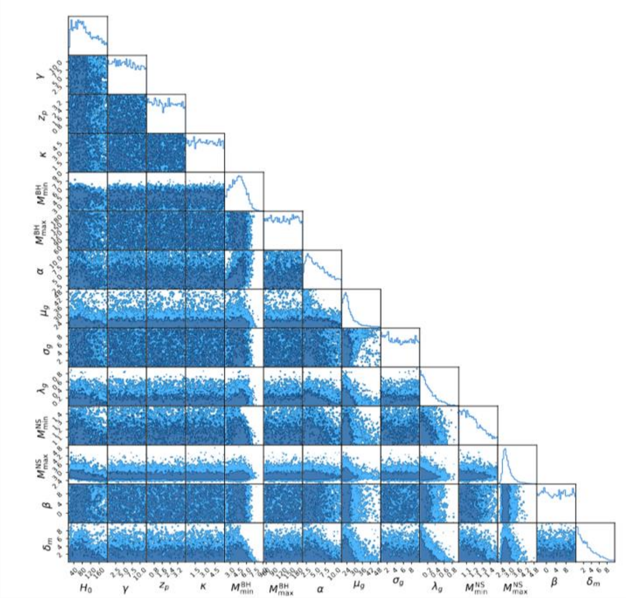


Ref.: LVK (Nature 2017)

GW Cosmology: Dark Sirens

- GW from compact binary coalescence (CBC) is a new probe to study the expansion of the Universe.
- **Dark Sirens:**
  - LVK pipelines: gwcosmo+, icarogw2.0
  - Based on galaxy catalog + cbc population.
  - Main Challenges: Incompleteness of the galaxy catalog.
  - Primarily constraint from population.
- Do not utilize large-scale information explicitly.



Refs.: Mastrogiovanni *et al.* (PRD 2023), Gray *et al.* (JCAP 2023)

GW Cosmology with BBHs using *GW-Galaxy Clustering*

References:

- *Bayesian framework to infer the Hubble constant from the cross-correlation of individual gravitational wave events with galaxies*, **T. Ghosh**, S. More, S. Bera, and S. Bose, *Phys. Rev. D 111, 063513 (2025).*

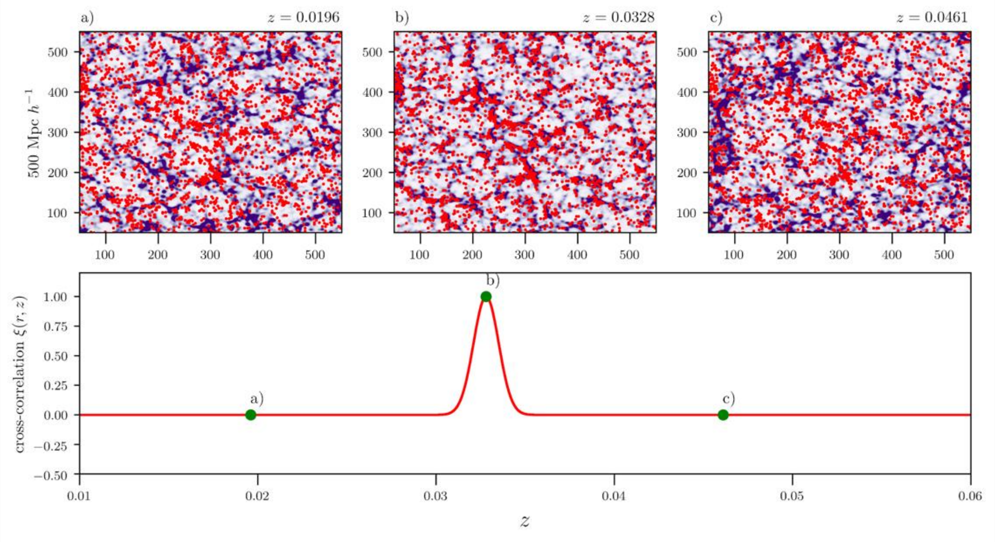
- *Constraining the Hubble constant using cross-correlation of gravitational wave events with flux-limited galaxy catalog*, **T. Ghosh** and S. More, *arXiv:2510.22187.*

Redshift from Cross-Correlation

- Binary black hole (BBH) mergers share the same large-scale structure as the galaxies.
- Possible to obtain redshift from **cross-correlation**.

BBH events fixed at unknown redshifts

Galaxy distribution at different redshift slices



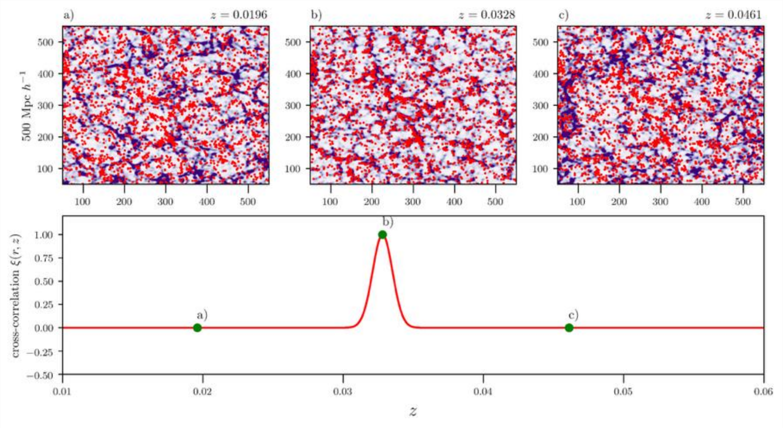
Credit: Bera *et al.* (ApJ 2020)

Cross-Correlation

- 2 point cross-correlation: Measure of probability of finding a galaxy in volume element dV from a distance r of another galaxy

$$dP = \bar{n}[1 + \xi(r)]dV$$

BBH events fixed at unknown redshifts



Galaxy distribution at different redshift slices

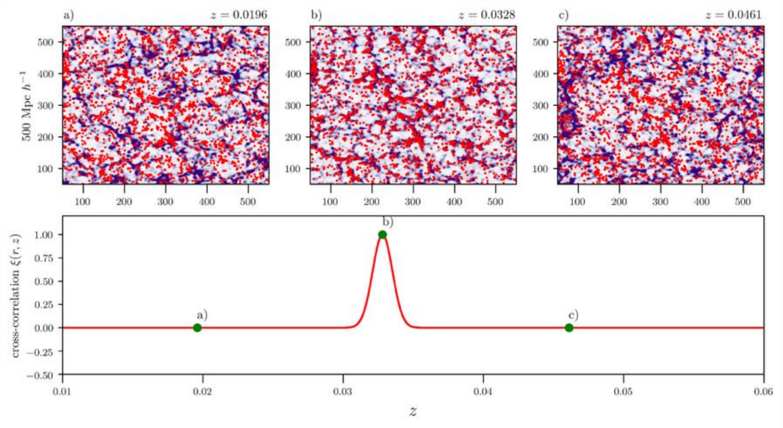
Refs.: Newman (ApJ 2008), Oguri (PRD 2016), Mukherjee *et al.* (PRD 2021), Bera *et al.* (ApJ 2020), **Ghosh** *et al.* (PRD 2025)

Cross-Correlation

- 2 point cross-correlation: Measure of probability of finding a galaxy in volume element dV from a distance r of another galaxy

$$\xi_{\mathrm{gw,g}} = b_{\mathrm{gw}} b_{\mathrm{g}} \xi_{\mathrm{m}}$$

BBH events fixed at unknown redshifts



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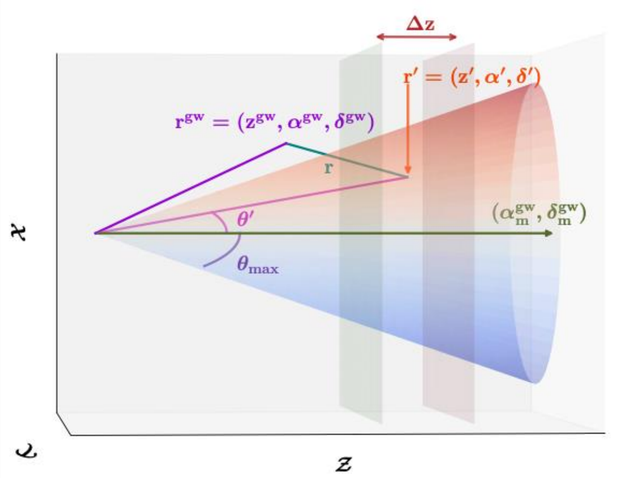
Galaxy Overdensity (Observed)

- Compared **observed** galaxy overdensity with the **modeled** galaxy overdensity around an individual GW event.
  - Observed galaxy overdensity

$$\delta_{\mathrm{g}}^{\mathrm{obs}}(z) = \frac{n(z \mid \delta_{\mathrm{m}}^{\mathrm{gw}}, \alpha_{\mathrm{m}}^{\mathrm{gw}})}{\bar{n}(z)} - 1$$



- $n(z \mid \delta_{\mathrm{m}}^{\mathrm{gw}}, \alpha_{\mathrm{m}}^{\mathrm{gw}})$: number of galaxies within a specific redshift bin along a particular direction.
- $\bar{n}(z)$: average number of galaxies at that particular bin.
- $\theta_{\max}$: angular radius which is considered to calculate the above quantities.

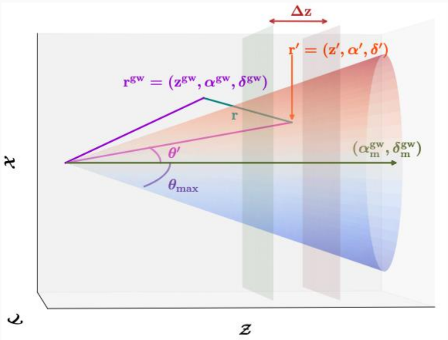
Ref.: **Ghosh** *et al.* (PRD 2025)

Galaxy Overdensity (Modeled)

- Compared **observed** galaxy overdensity with the **modeled** galaxy overdensity around an individual GW event.
  - Modeled galaxy overdensity

$$\delta_{\mathrm{g}}^{\mathrm{mod}}(z \mid \boldsymbol{r}^{\mathrm{gw}}) = \frac{\int_{z-\Delta z/2}^{z+\Delta z/2} \int_0^{\theta_{\max}} \int_0^{2\pi} \bar{n}_V(z')\xi_{\mathrm{gw,g}}(|\boldsymbol{r}(\boldsymbol{r}^{\mathrm{gw}}, \boldsymbol{r}')|)\, \sin\theta' d_c'^2 J\left(\frac{d_c'}{z'}\right) d\alpha' d\theta' dz'}{\int_{z-\Delta z/2}^{z+\Delta z/2} \int_0^{\theta_{\max}} \int_0^{2\pi} \bar{n}_V(z')\, \sin\theta' d_c'^2 J\left(\frac{d_c'}{z'}\right) d\alpha' d\theta' dz'}$$

- $\xi_{\mathrm{gw,g}}$: 3D Cross-correlation function
- r : comoving distance in h^{-1} unit
- $J\left(\frac{d_c'}{z'}\right)$: Jacobian $\left(= \frac{\partial d_c'}{\partial z'}\right)$
- $\bar{n}_V$: number density in comoving volume



Ref.: **Ghosh** *et al.* (PRD 2025)

Methodology

- Bayesian inference of H_0 by comparing the observed and modeled galaxy overdensity.

$$\boldsymbol{p}\left(\boldsymbol{H_0} \mid \boldsymbol{d}_{\text{strain}}, \boldsymbol{d}_{\text{g}}^{\text{obs}}\right) \propto \boldsymbol{p}(\boldsymbol{H_0}) \int \boldsymbol{\mathcal{L}}\left(\boldsymbol{d}_{\text{g}}^{\text{obs}} \mid \boldsymbol{d}_{\text{gw}}\right) \boldsymbol{\mathcal{L}}\left(\mathbf{d}_{\text{strain}} \mid \boldsymbol{H_0}, \boldsymbol{d}_{\text{gw}}\right) \mathbf{p}(\mathbf{d}_{\text{gw}}) \mathbf{d}\boldsymbol{d}_{\text{gw}}$$

  - Galaxy overdensity likelihood: $\mathcal{L}\left(d_{\text{g}}^{\text{obs}} \mid d_{\text{gw}}\right) \propto \exp\left(-\frac{1}{2}\sum_z \frac{(\delta_{\text{g}}^{\text{obs}} - \delta_{\text{g}}^{\text{mod}})^2}{\sigma_\delta^2}\right)$

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$$p(H_0 \mid d_{\rm strain}, d_{\rm g}^{\rm obs}) \propto p(H_0) \int \mathcal{L}(d_{\rm g}^{\rm obs} \mid d_{\rm gw}) \mathcal{L}(d_{\rm strain} \mid H_0, d_{\rm gw}) p(d_{\rm gw}) dd_{\rm gw}$$

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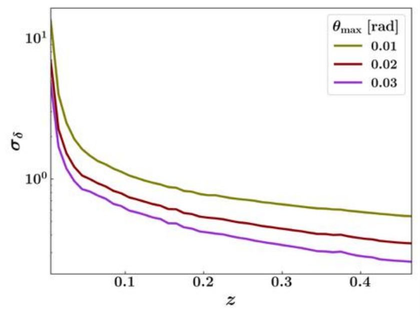
  - σ_δ : Fluctuation in galaxy overdensity



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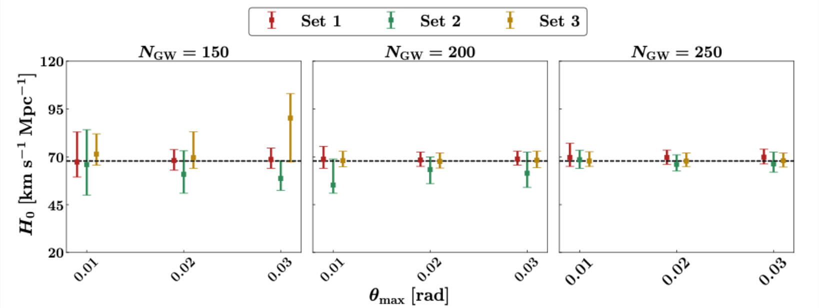
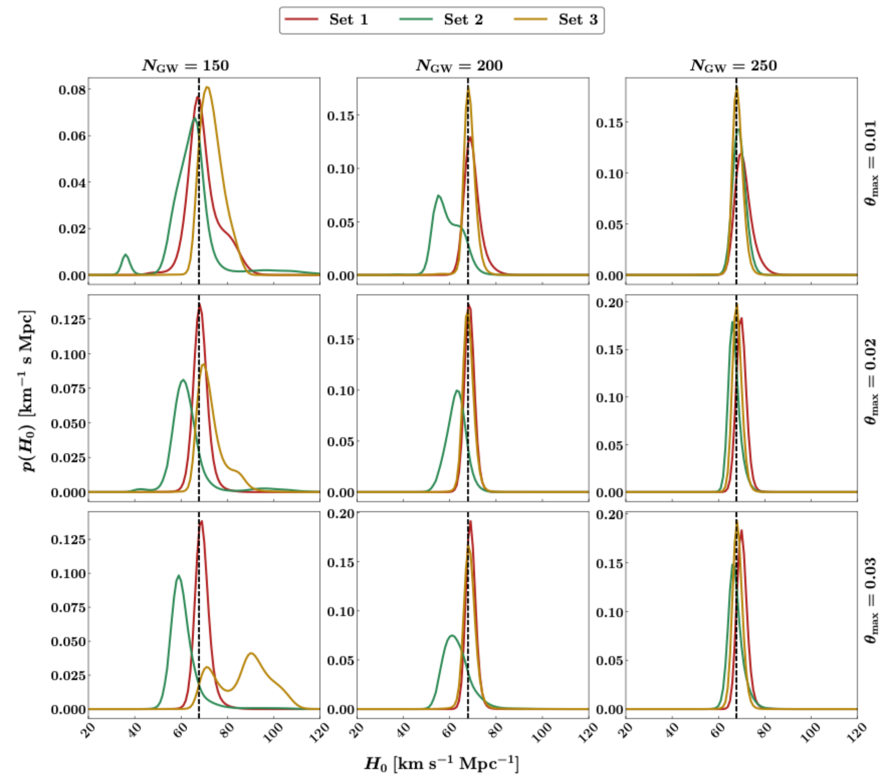
Mock Catalog

- Use a mock galaxy catalog constructed from Big Multi Dark Planck simulation.
- Populate GW events randomly to the galaxies, ensuring they are distributed with 1 Gpc.
- True cosmology: Flat ΛCDM cosmology with $H_0 = 67.8$ km/s/Mpc and $\Omega_m = 0.3$.
- Mass model: Power law + Peak model (mass hyperparameters are consistent with GWTC 3).
- Inject BBH signal (IMRPhenomD) in stationary Gaussian noise, colored with O4 sensitivity of the LIGO-Virgo detectors.
- Detected GW events with network SNR $\rho_{\text{net}} \geq 12$.

Ref.: **Ghosh** *et al.* (PRD 2025)

Results



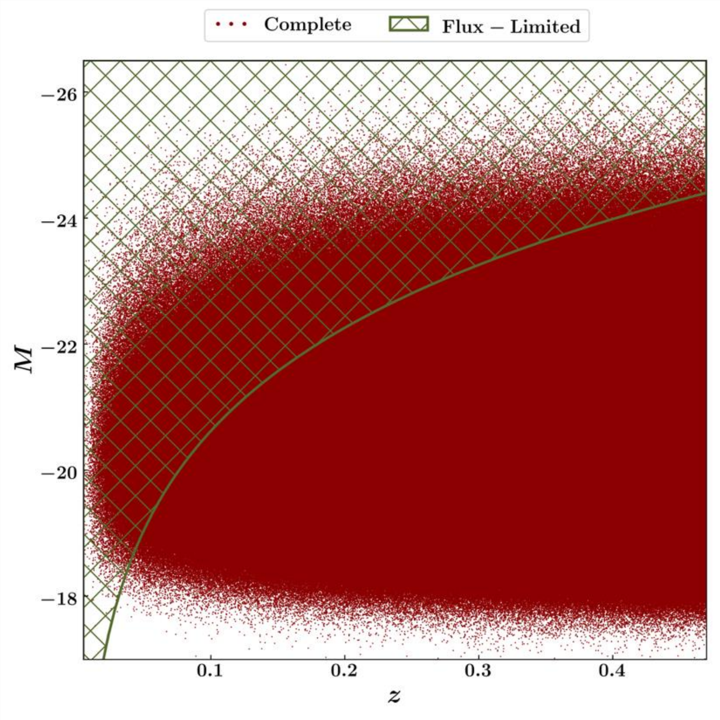


Estimated H_0 using 250 GW events with precision $\lesssim 8\%$

Ref.: **Ghosh** *et al.* (PRD 2025)

Flux Limited Galaxy Catalog

- So far used complete galaxy catalog, which is not realistic.
- Flux-limited galaxy catalog with $m \leq 17.77$.
- Study the H_0 posteriors, inferred by using the complete and the flux-limited galaxy catalog.



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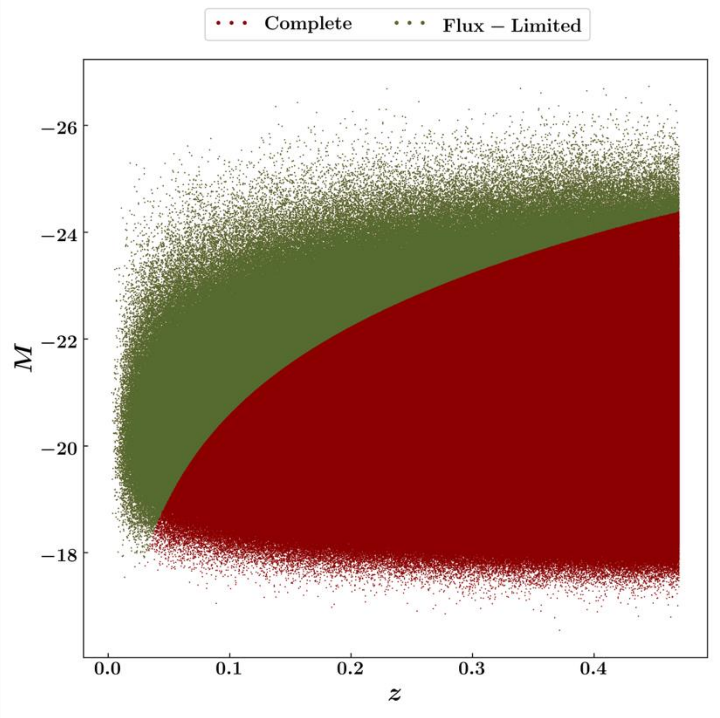

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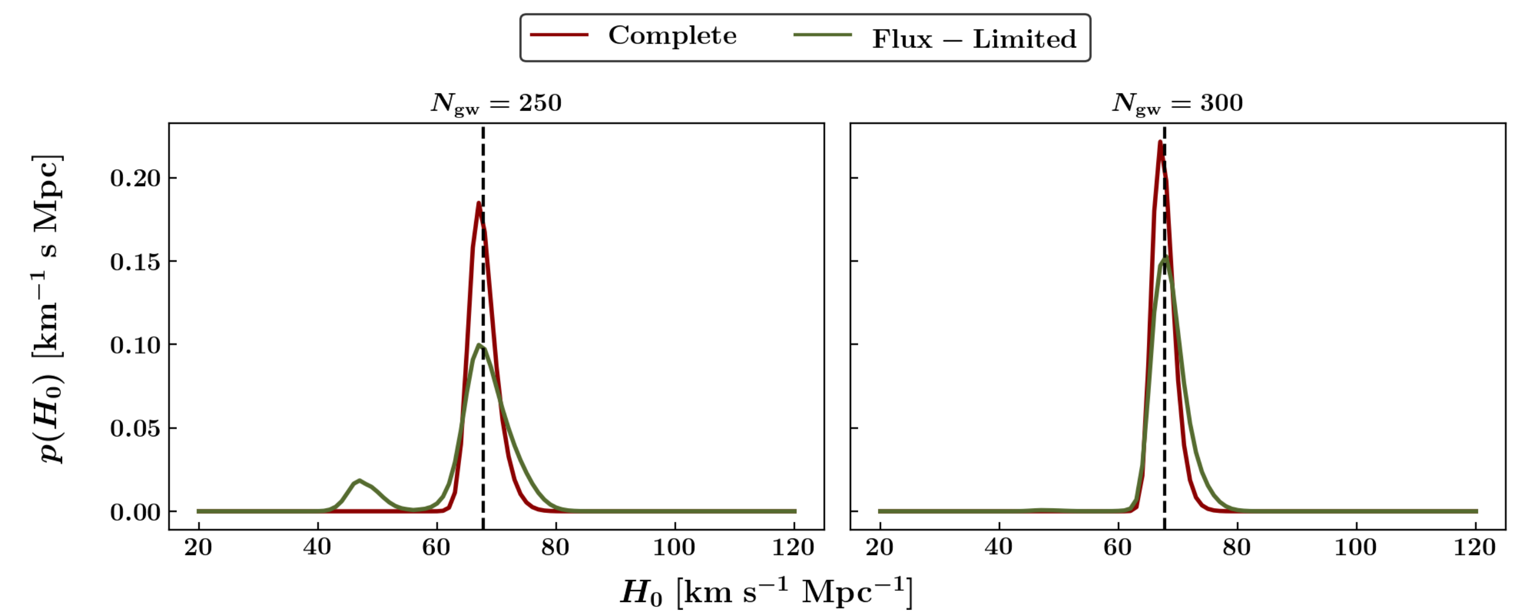

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Conclusion

- Developing a Bayesian framework to infer the Hubble constant utilizing the cross-correlation of GW events with galaxies.
- Test the efficacy and robustness of the method with 3 independent sets of GW events.
- Inferred H_0 with 250 GW events within 1 Gpc, achieving a precision of $\leq 8\%$ (90% highest density interval).
- There are other important applications of GW-galaxy clustering in GW cosmology:
    - Large-scale structure information can also be utilized to model the incompleteness of the galaxy catalog. [**Ghosh** and More (in prep.)]
    - Galaxy-GW cross-correlation may be able to detect BAO with the next generation GW detectors. [Bhuyan, **Ghosh**, and More (in prep.)]

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Thanks for Listening !