Measurements of the Hubble Constant with GW170817

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KITP - Merging Visions
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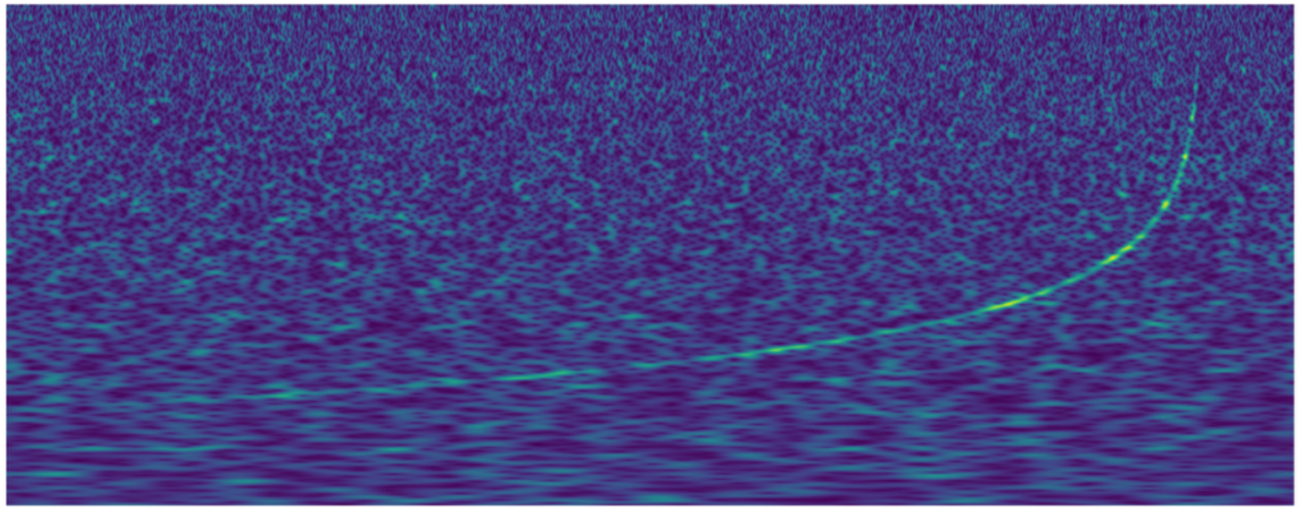
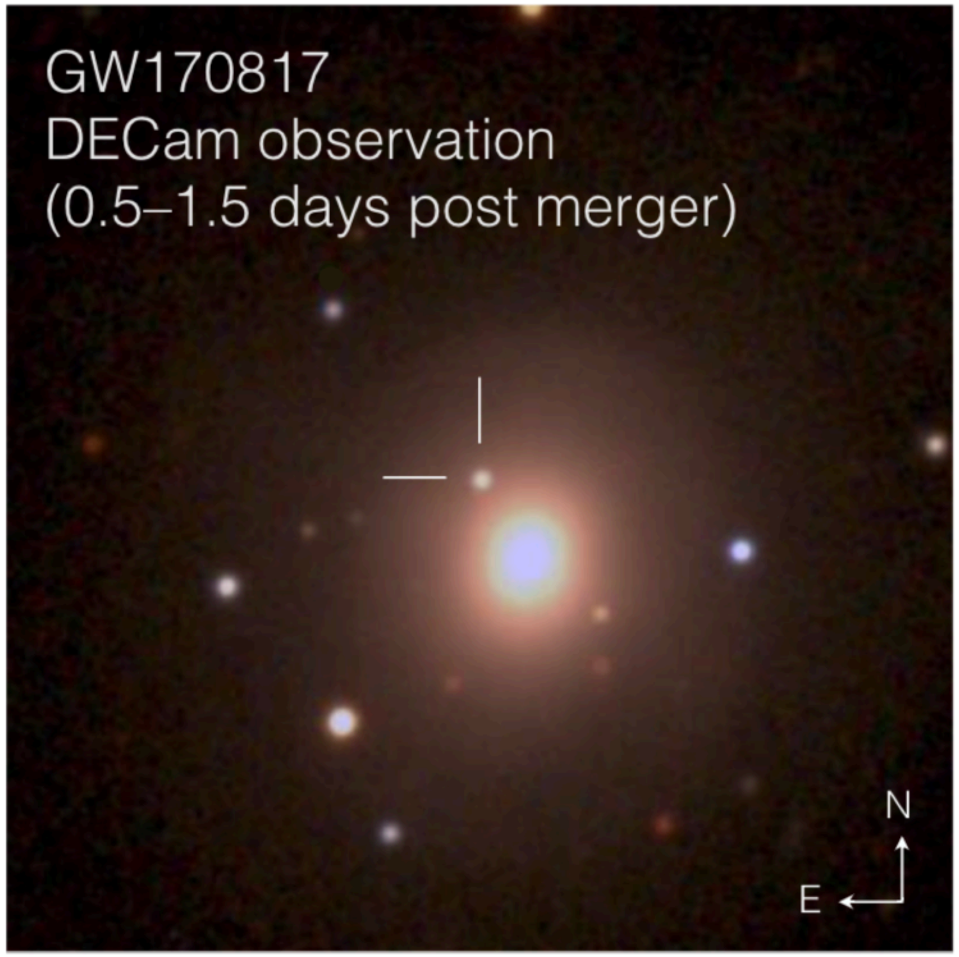
NSF

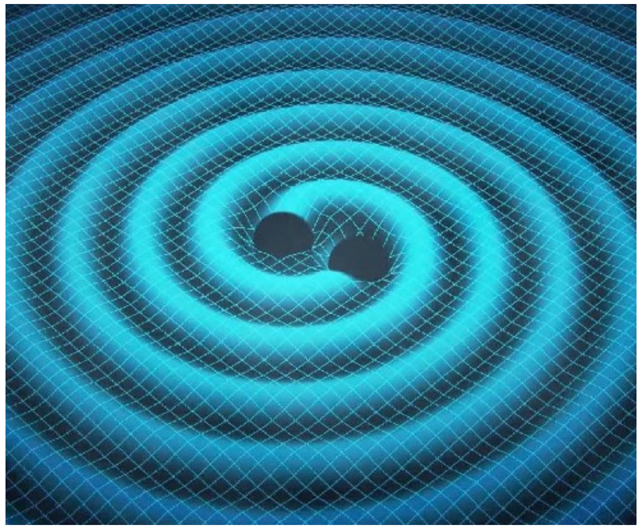
GW170817





- GW distance measurement: $43.8^{+2.9}_{-6.9}$ Mpc
- Optical counterpart allowed for an identification of a unique host galaxy, NGC 4993, with Hubble-flow velocity: 3017 ± 166 km/s

Standard Sirens



- Binary coalescences provide a direct measurement of the luminosity distance (Schutz 1986)

frequency **position and orientation**

GW strain

$$h(t) = \frac{\mathscr{M}_z^{5/3} f(t)^{2/3}}{D_L} F(\text{angles})\cos(\Phi(t))$$

phase

redshifted chirp mass **luminosity distance**

$$\mathscr{M}_z = \left(\frac{5}{96}\pi^{-8/3}\left(f(t)\right)^{-11/3}\dot{f}(t)\right)^{3/5}$$

- Need an independent measurement of the redshift to do cosmology

The Hubble velocity of NGC 4993

- *Virial velocity correction*: NGC 4993 belongs to a **group of galaxies** with center-of-mass velocity 3327 +/- 72 km/s in the CMB frame (Crook+ 2007)

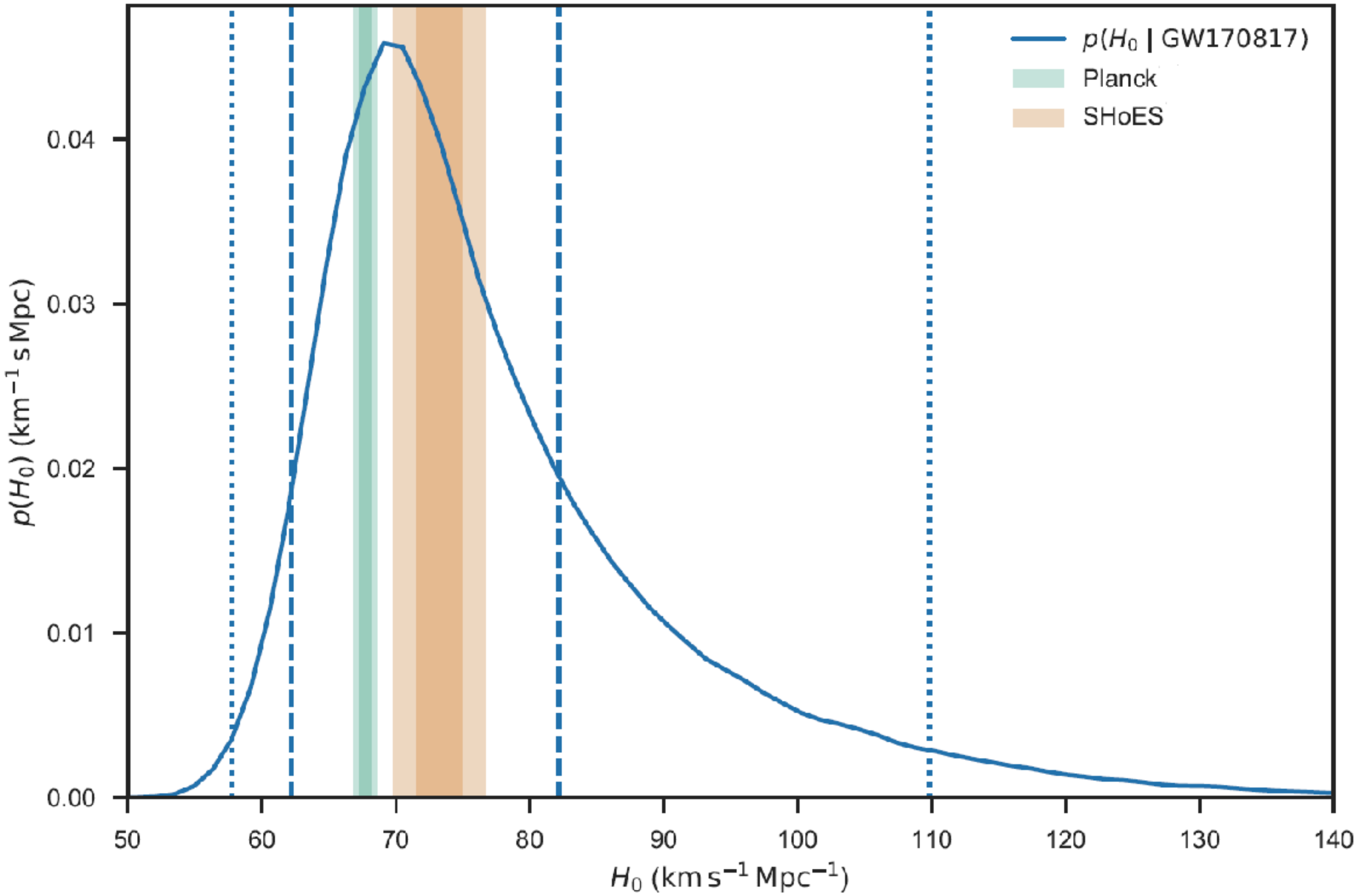
- *Bulk flow correction*: coherent bulk flow of 310 +/- 150 km/s (Springob+ 2014)

- Hubble velocity: 3017 +/- 166 km/s

compare to Hjorth+ 2017 value of 2924 +/- 236 km/s

GW170817 counterpart result (using NGC 4993 as a unique host)

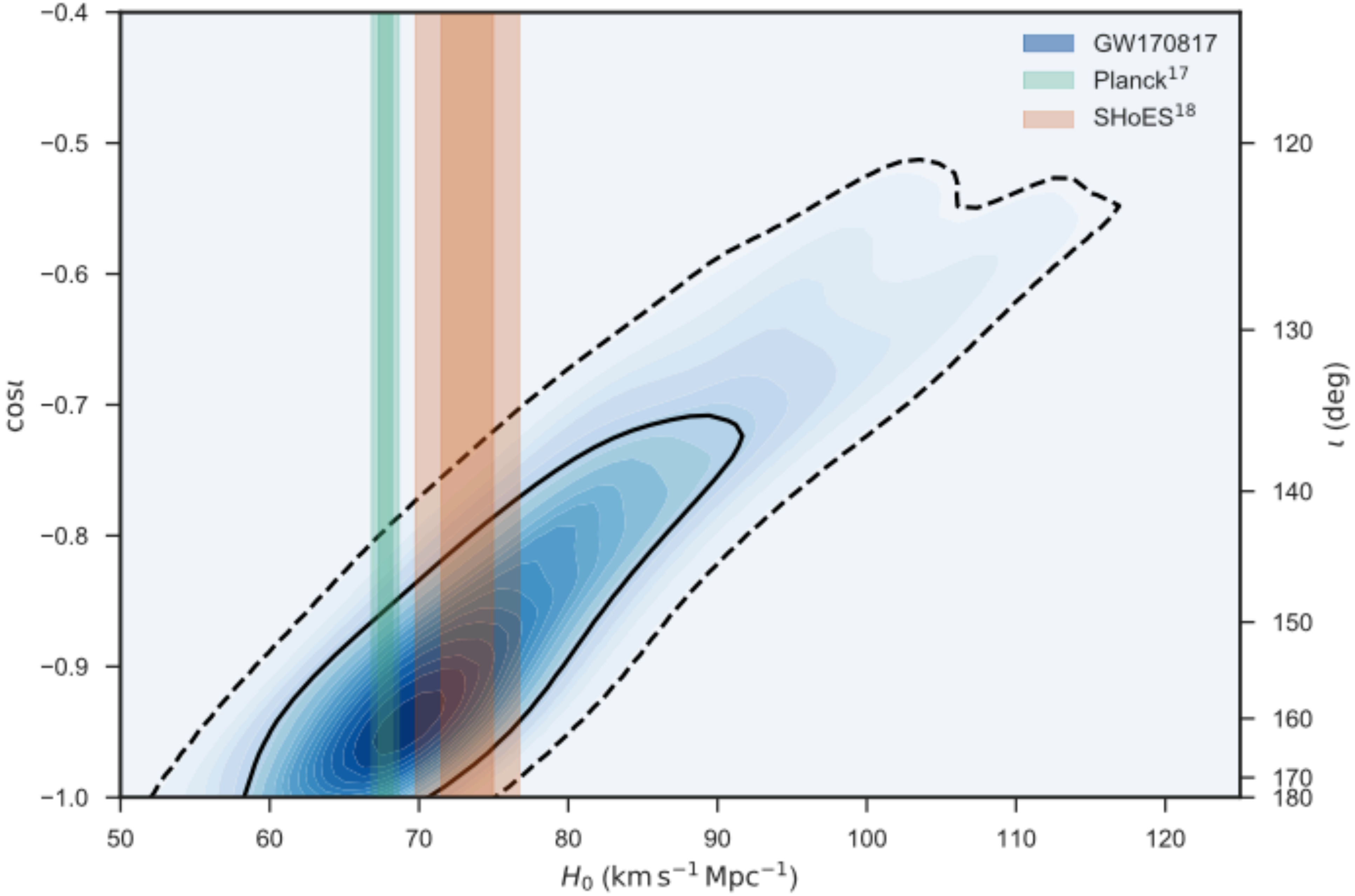
$$H_0 = 70^{+12}_{-8}\ \mathrm{km/s/Mpc}$$



Abbott et al. *Nature* 551, 85-88 (2017)

(see also PE update - Abbott et al. PRX 9, 011001 2019)

H0-inclination degeneracy



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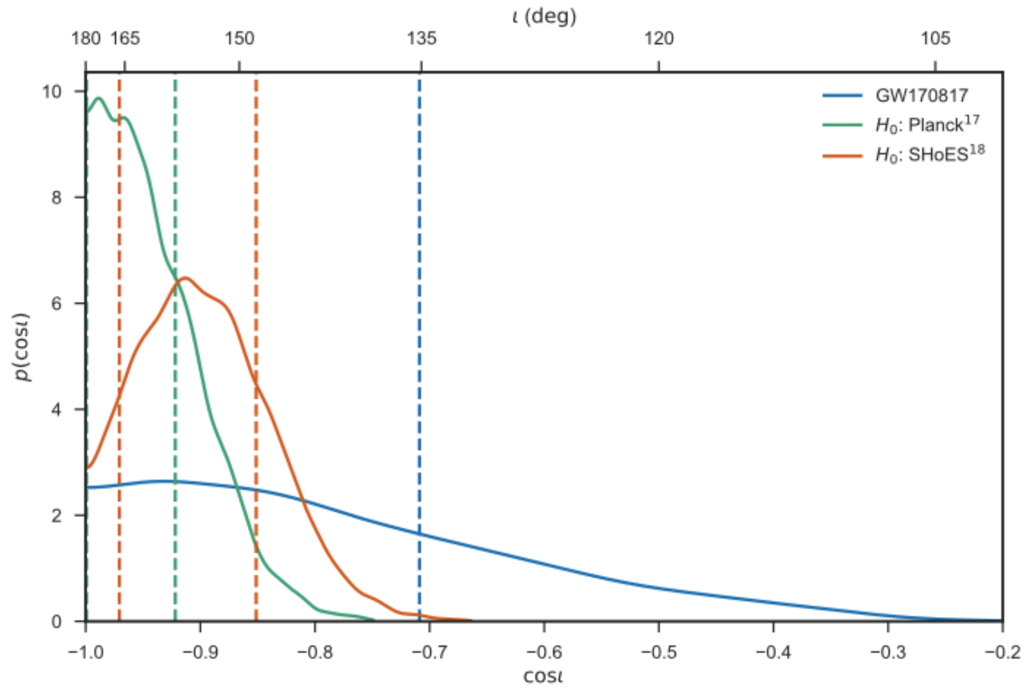
Independent H0 constraint -> improved inclination measurement



Abbott *et al* 2017 *Nature* **551**

See also Mandel 2018, Finstad+ 2018 using Cantiello+ 2018 distance measurement to NGC 4993

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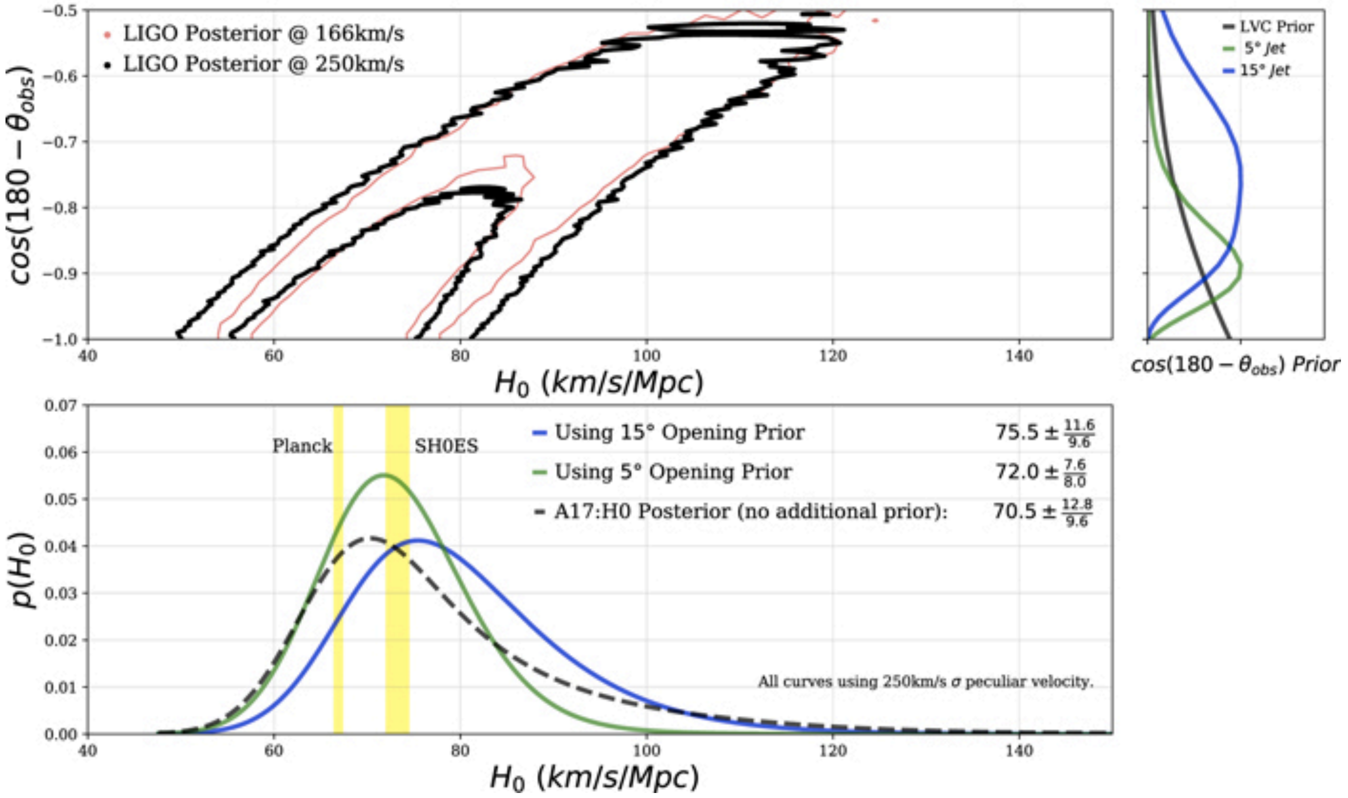


Guidorzi *et al* 2017 *ApJL* **851** L36

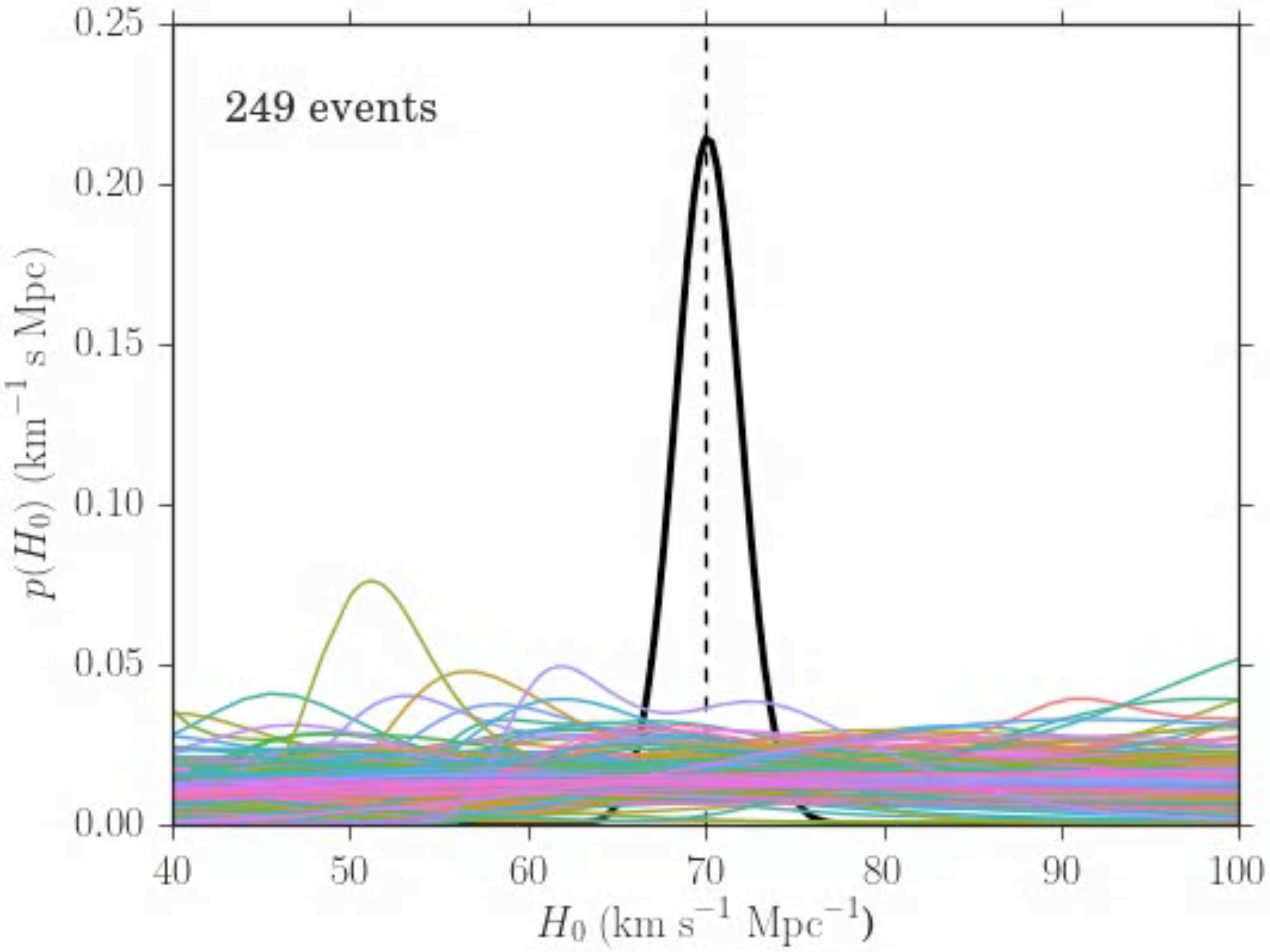
See also Hotokezaka+ 2018 using Mooley+ 2018 inclination constraints

A standard siren measurement of the Hubble constant from GW170817 without the electromagnetic counterpart

Fishbach et al. *ApJL* 871 L13 (2019); arXiv:1807.05667

Simulated Measurements:

Mock binary neutron star events (F2Y Dataset, Singer+ 2014) into mock galaxy catalog (MICE catalog, Crocce+ 2015)



Individual events usually yield very broad, only weakly informative posteriors on the Hubble constant.

MF+ *ApJL* 871 L13

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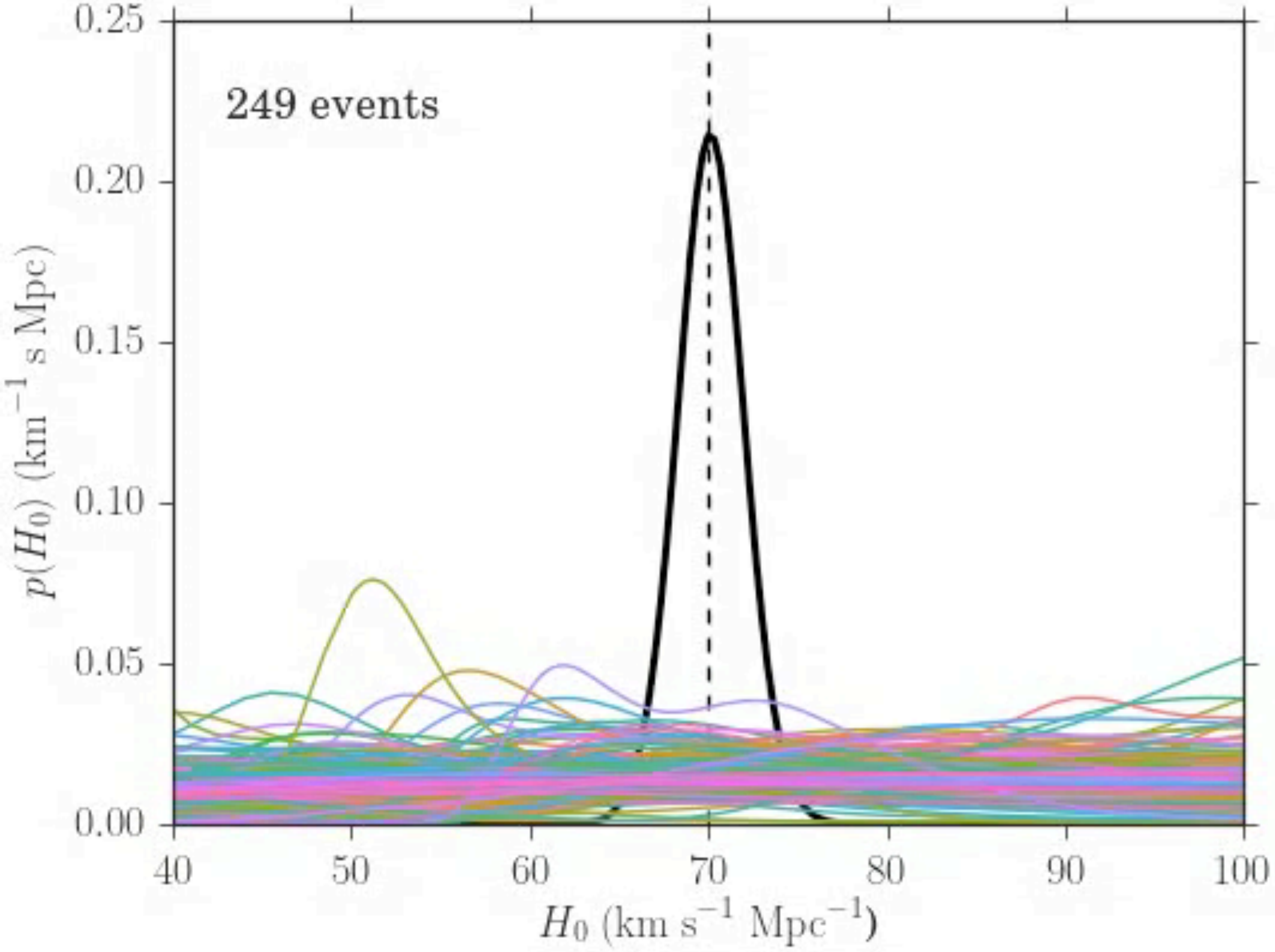

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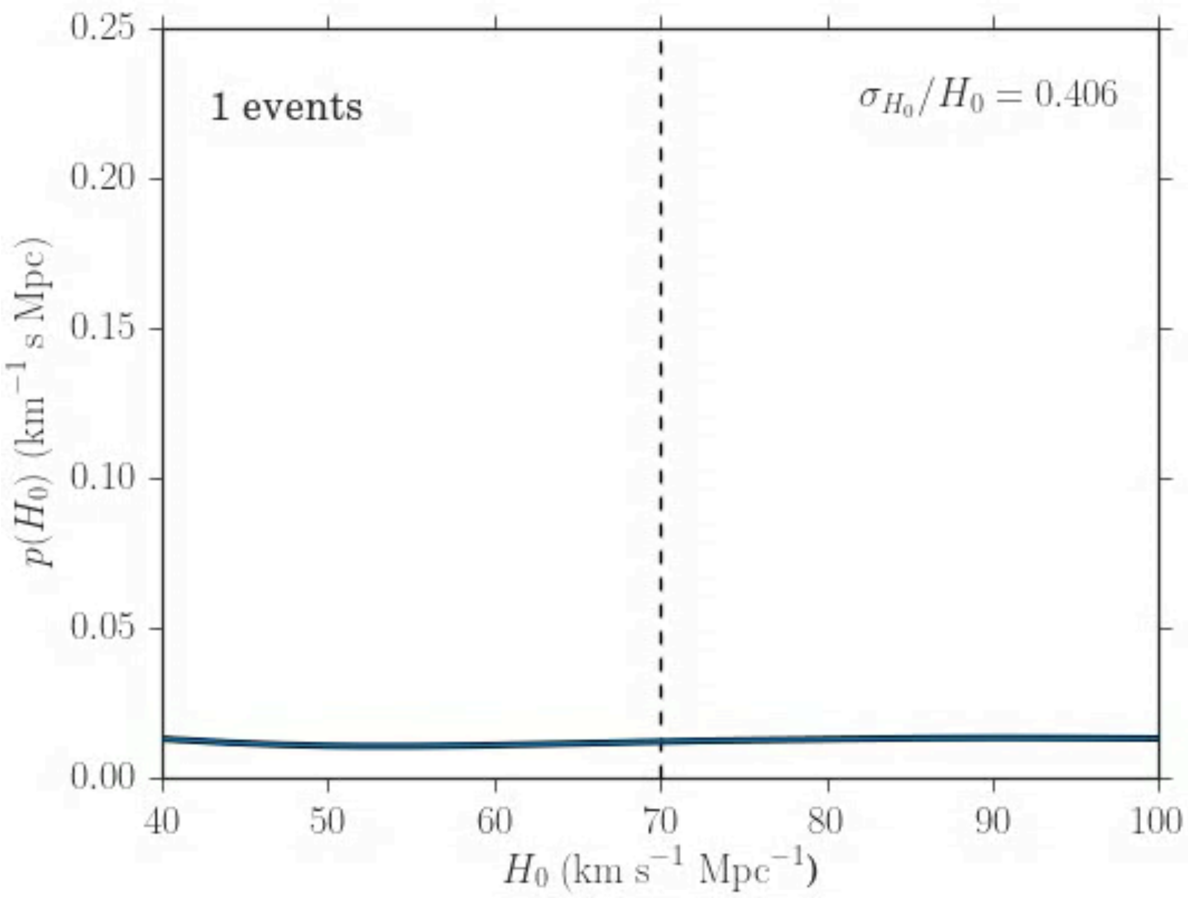
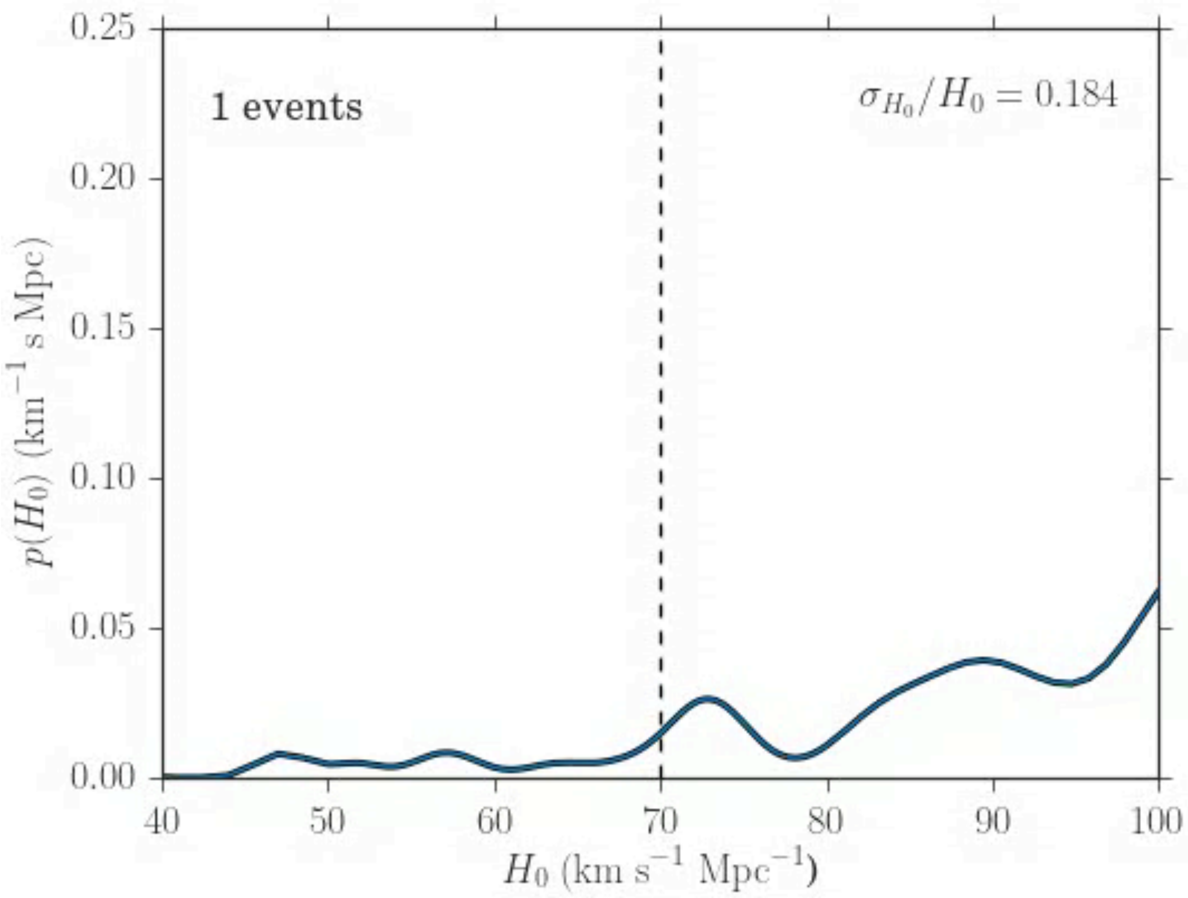
Simulated Measurements

Statistical



Counterpart



Combined measurement with *N* events converges as *~40%/√N* compared to *~15%/√N* for sources with a counterpart (see Hsin-Yu Chen's talk)

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Simulated Measurements

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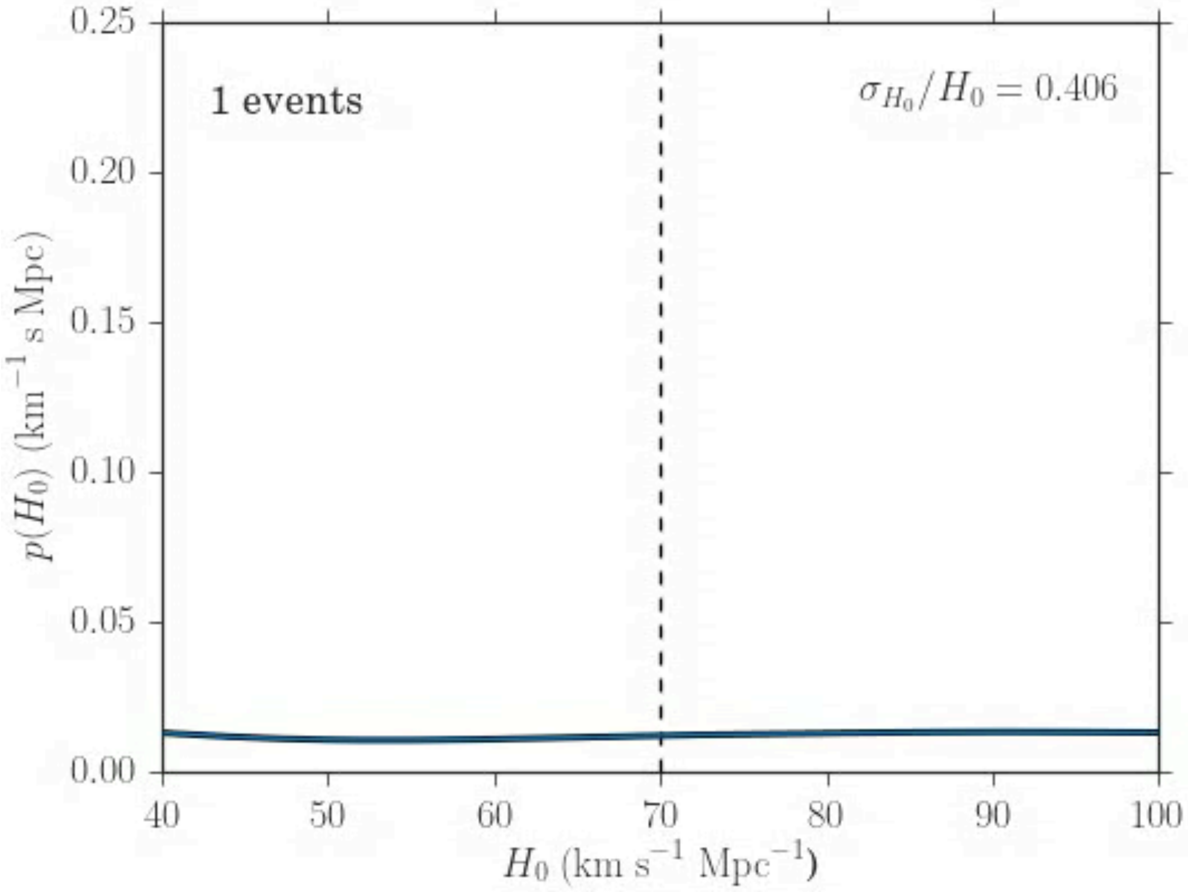

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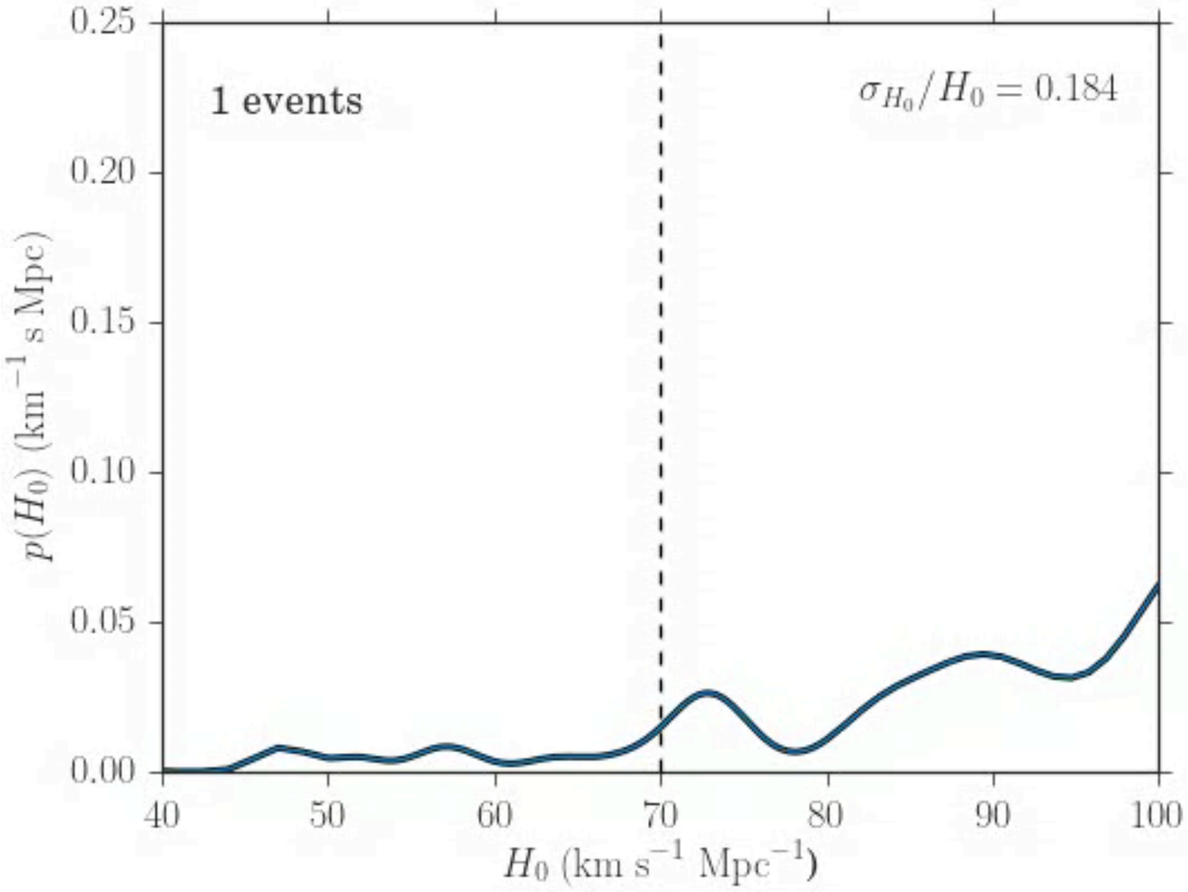

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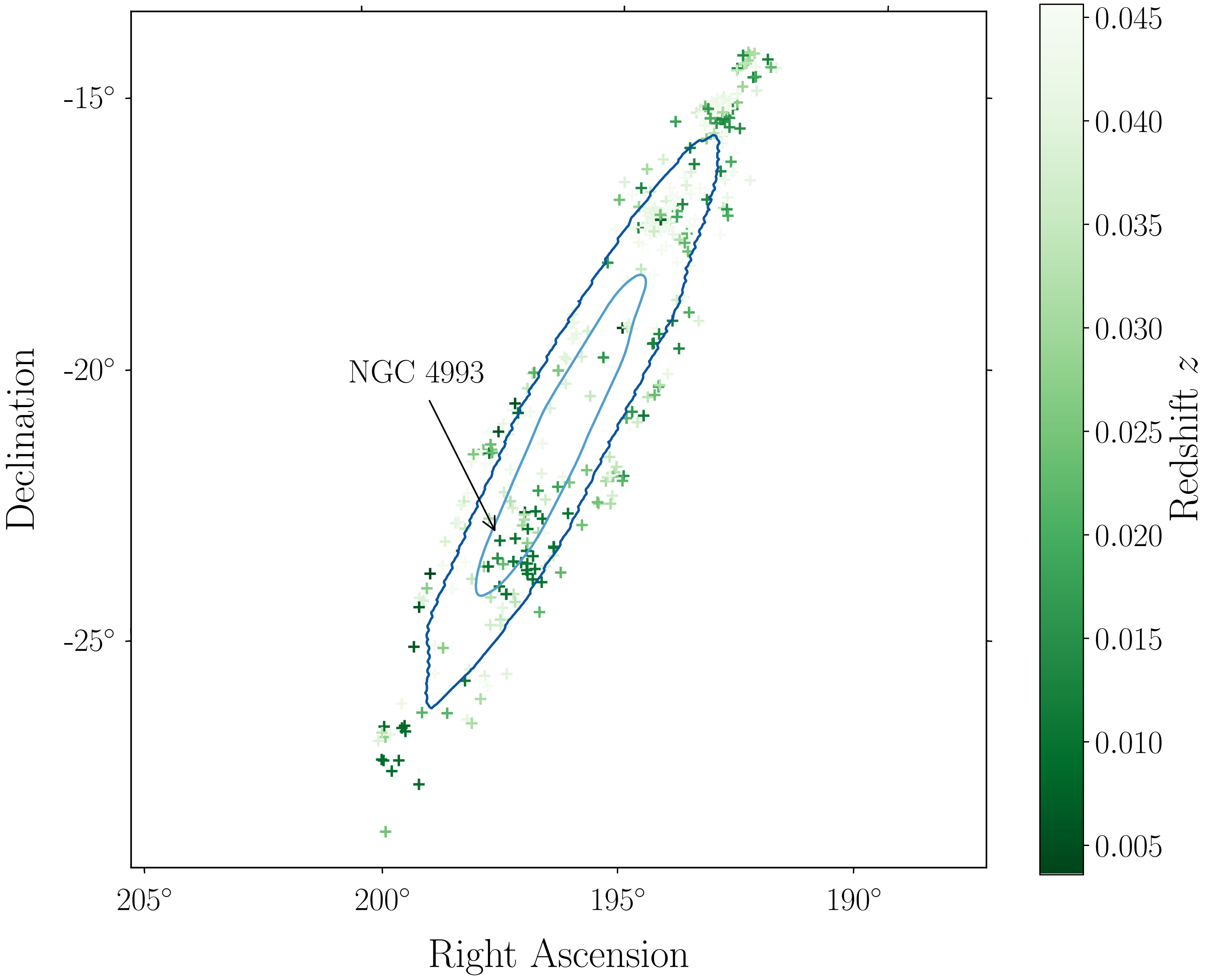
What if we didn't know GW170817's host galaxy?

- From GW data, 90% sky localization of 16 deg², 90% volume of 216 Mpc³ (assuming Planck'15 cosmology)
- Consider all ~400 galaxies in GW localization volume



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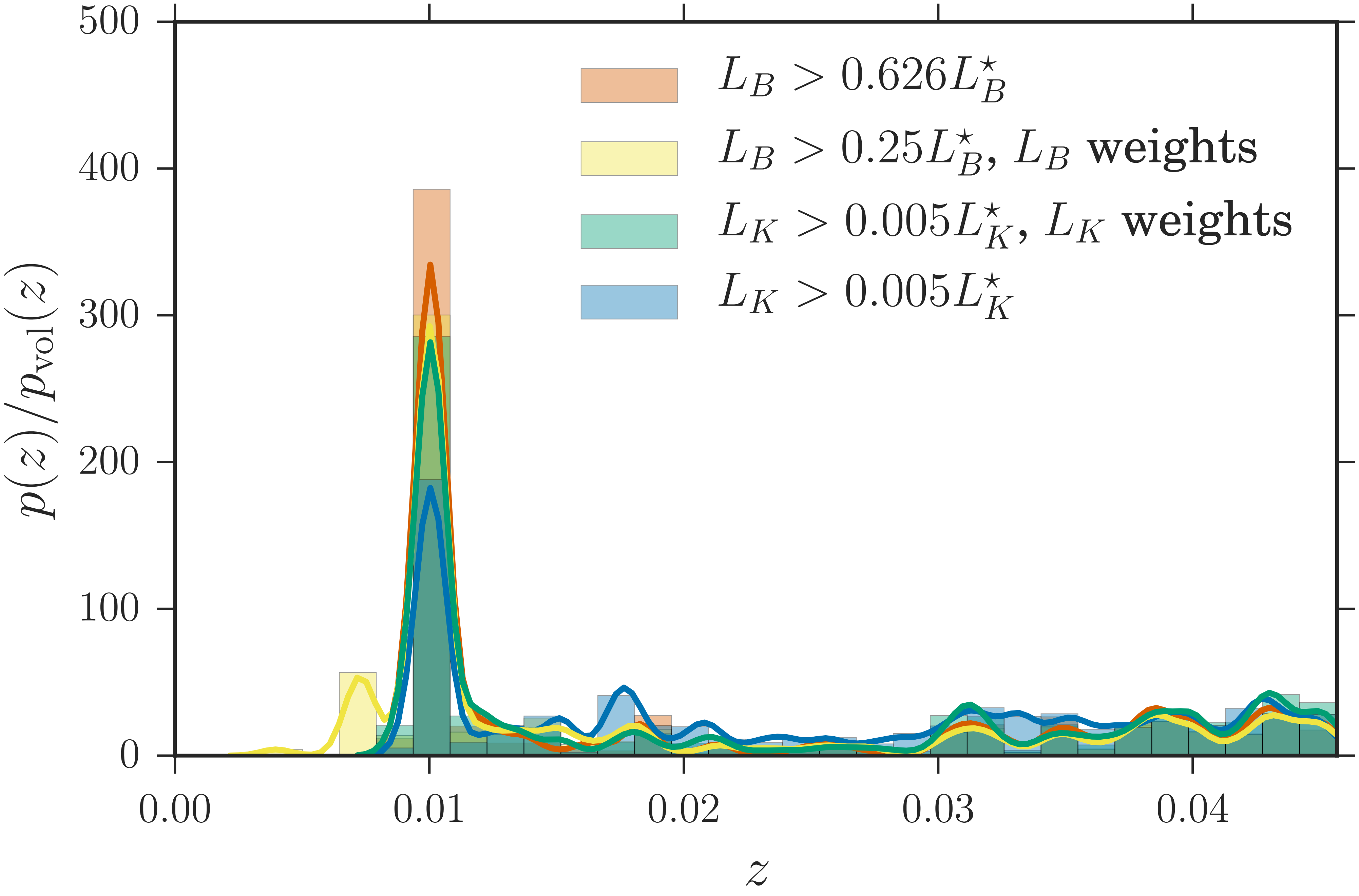
Single dominant group of galaxies (containing NGC 4993)



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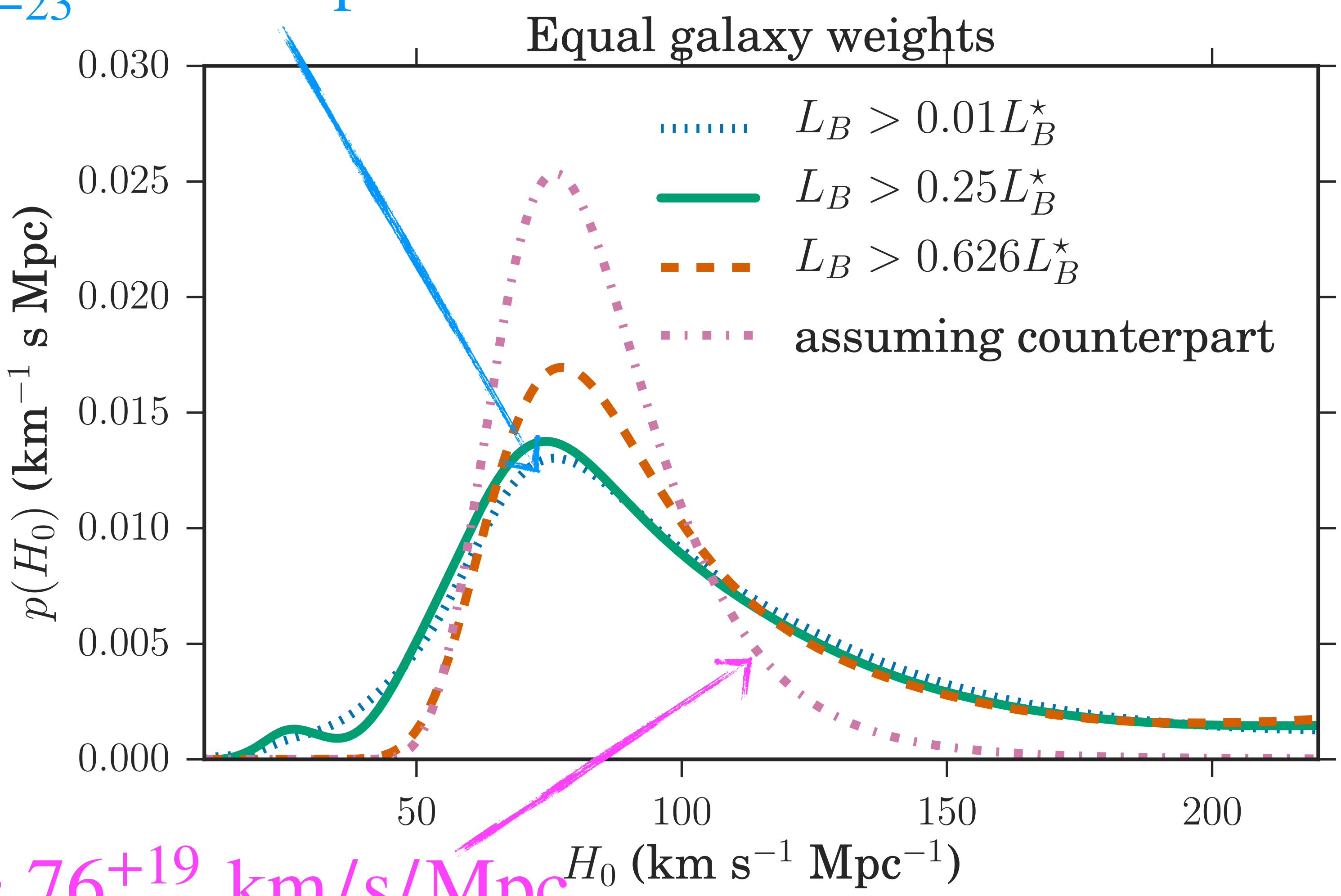
(Exceptionally) Informative Ho measurement

$H_0 = 76^{+48}_{-23}$ km/s/Mpc



$H_0 = 76^{+19}_{-13}$ km/s/Mpc

Statistical measurement is only ~2 times as broad as counterpart measurement

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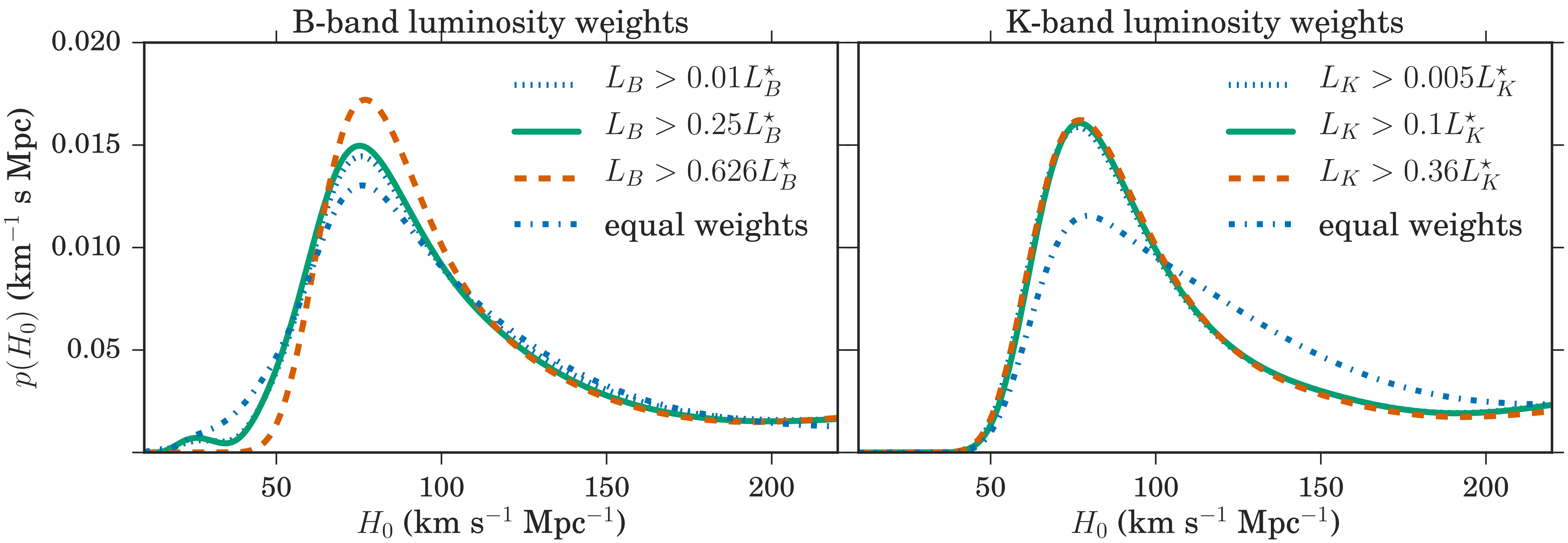
Weighting galaxies by star-formation rate or stellar mass

blue galaxies, proxy for star-formation rate

red galaxies, proxy for total stellar-mass



The peak at *z* ~ 0.01 happens to consist of bright, red galaxies. Are such galaxies more likely to host binary neutron star mergers? (We don't know yet.) With more events, we may learn what weighting is appropriate to use!

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Conclusion

- GW170817's unique host galaxy identification enabled first standard siren measurement $H_0 = 70^{+12}_{-8}\ \mathrm{km/s/Mpc}$
- Careful measurements of the peculiar velocity field can tighten this measurement, as can applying various inclination constraints (but be careful of introducing systematics)
- Because GW170817 is so well-localized, the "statistical" measurement is informative (only ~2 times less constraining than the counterpart constraint)

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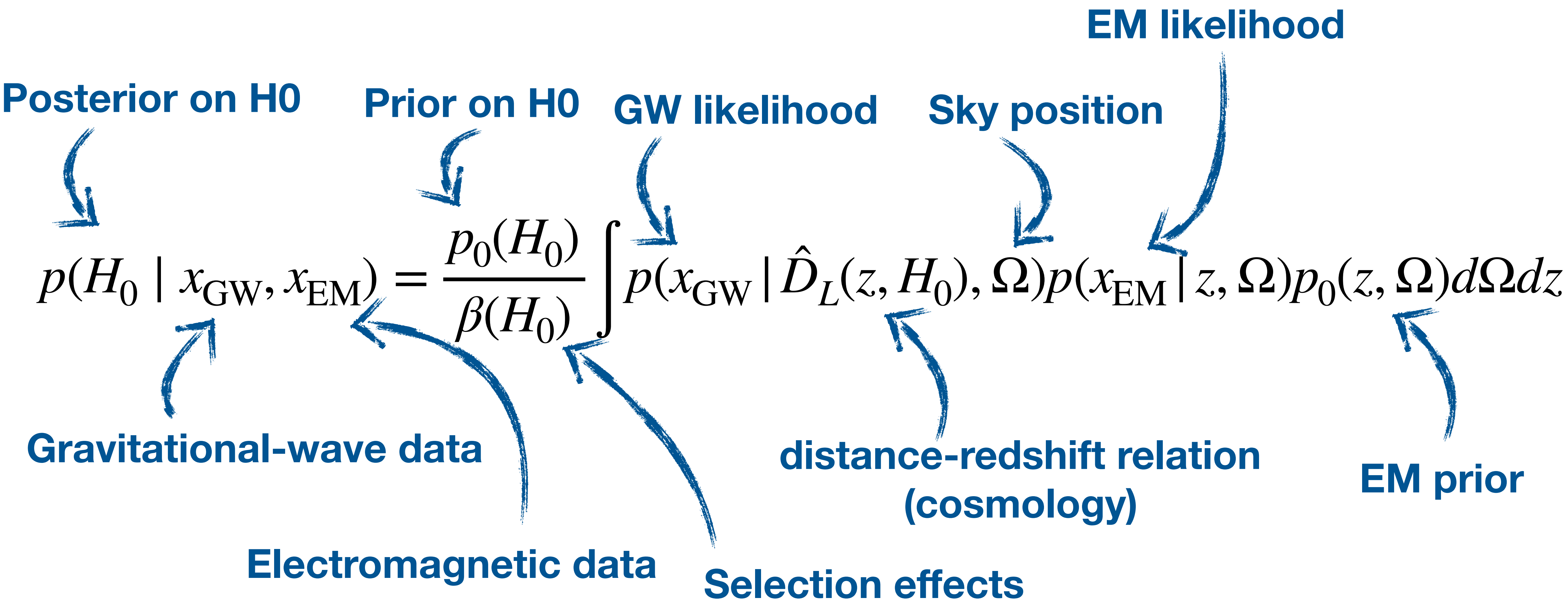
Questions?

Bayesian Analysis



EM likelihood

Posterior on H0

Prior on H0

GW likelihood

Sky position

$$p(H_0 \mid x_{\mathrm{GW}}, x_{\mathrm{EM}}) = \frac{p_0(H_0)}{\beta(H_0)} \int p(x_{\mathrm{GW}} \mid \hat{D}_L(z, H_0), \Omega) p(x_{\mathrm{EM}} \mid z, \Omega) p_0(z, \Omega) d\Omega dz$$

Gravitational-wave data

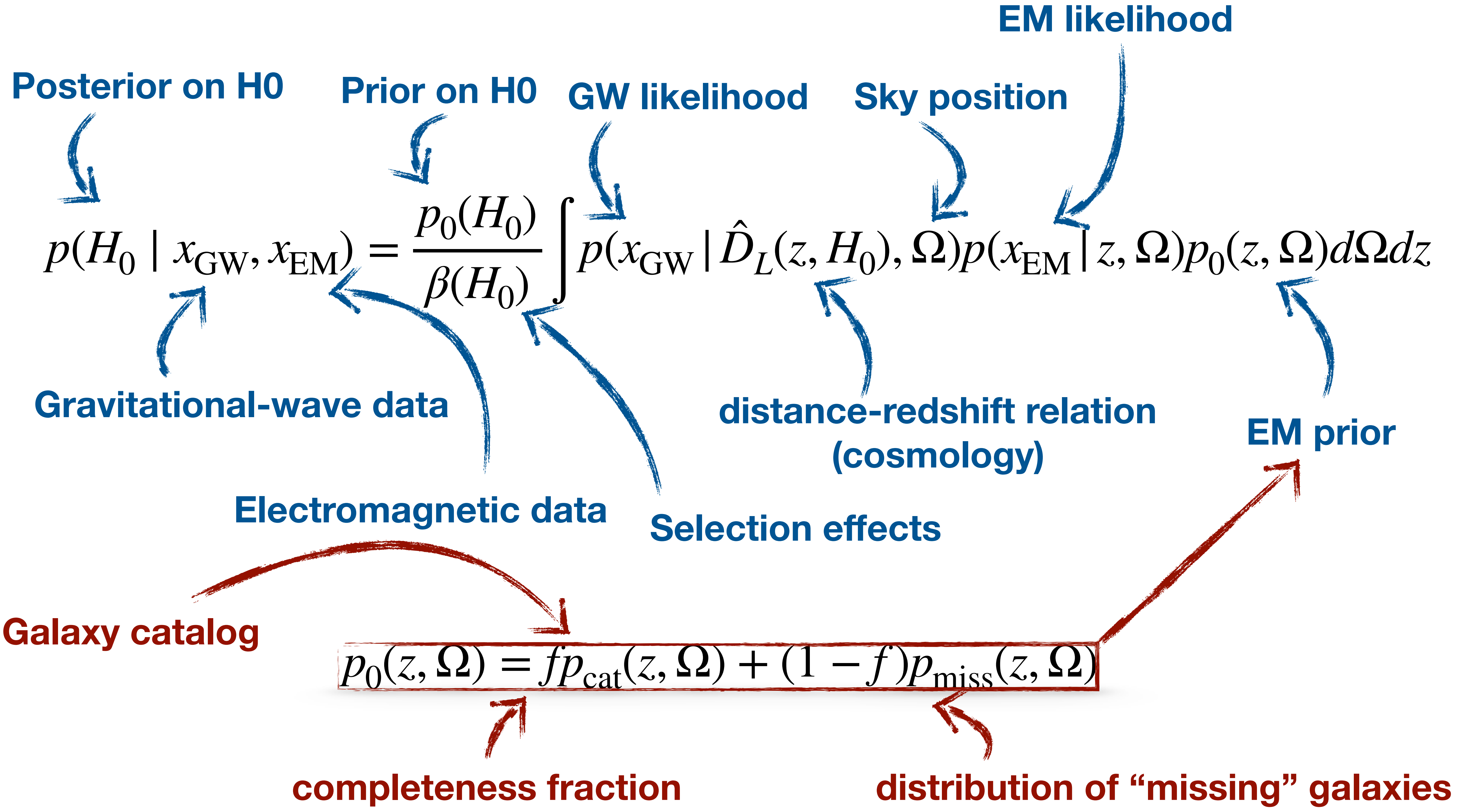
distance-redshift relation (cosmology)

EM prior

Electromagnetic data

Selection effects

Bayesian Analysis



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Galaxy catalog

$$\boxed{p_0(z, \Omega) = f p_{\rm cat}(z, \Omega) + (1 - f) p_{\rm miss}(z, \Omega)}$$

completeness fraction

distribution of “missing” galaxies