Carnegie Mellon University

DARK ENERGY SPECTROSCOPIC INSTRUMENT

Peculiar Velocity Improvements of Standard Siren Measurements

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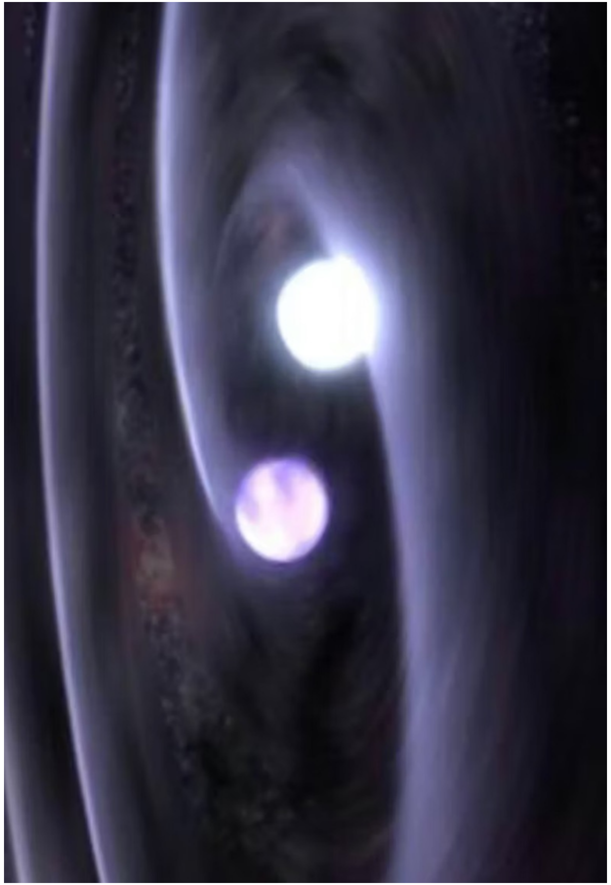
An Introduction to The Hubble Tension

Recessional Velocity → $v_r \approx H_0 \cdot \mathrm{d}$ ← Distance

- A mathematical description of universe's expansion rate.
  - Farther an objects ⇒ Faster it is moving away from us
- Why is (re-)measuring H_0 interesting?
  - 1. There's a contradiction that could lead to new physics.
    - Planck collaboration (CMB): $\mathrm{H_0} = 67.36 \pm 0.54$ km/s/Mpc
    - SH0ES (distance ladder): $\mathrm{H_0} = 73.04 \pm 1.04$ km/s/Mpc
  - 2. H_0 is ubiquitous and its uncertainty can (or will) dominate.
    - Age of universe estimation.
    - Understanding peculiar motions of celestial objects.
    - Dark matter and dark energy modeling.

Bright Standard Sirens: Two Reasons to Get Excited!

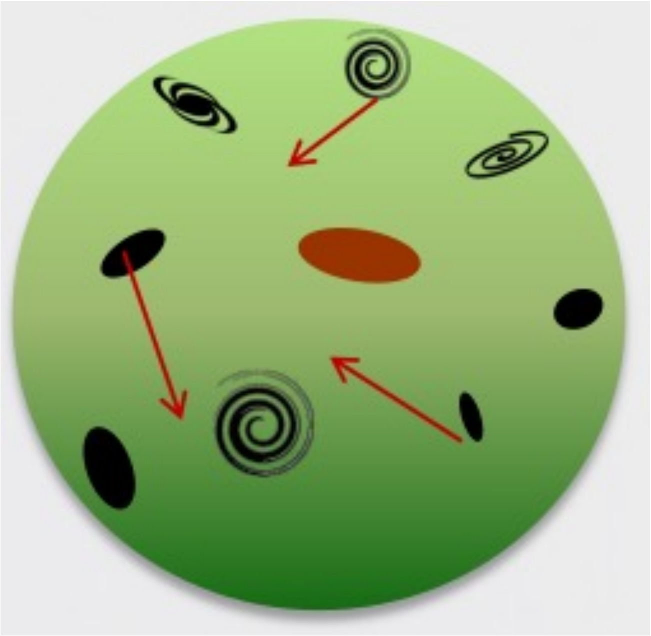
- Neutron star mergers emit *gravitational* and *electromagnetic* waves.
- From gravitational waves (GW), we measure a luminosity distance, d_L.
- If a galaxy host is identified (see crosshair), we can measure a recessional velocity, v_{rec}, from the host.
- This information is sufficient to measure H_0 via $v_r \approx H_0 \cdot d_L$.



Peculiar Velocities: What Are They and Why Do They Matter?

$$v_r \approx v_p + H_0 \cdot d$$

- Celestial objects often posses a **Peculiar Velocity (PV)** component, which is *not* attributable to the Hubble expansion but to local dynamics.
- To mitigate PV uncertainty on an object, measure PVs of **nearby objects**.
- PV uncertainty can be the **dominant uncertainty** in siren measurements (Howlett et. al. 2020, Nicolaou et. al. 2020).



https://galinc.weebly.com/blog/an-overview-on-the-status-of-the-project

This work develops a practical procedure for using the Dark Energy Spectroscopic Instrument (DESI) to measure the peculiar velocities of Bright Standard Siren hosts.

What is the Dark Energy Spectroscopic Instrument (DESI)?

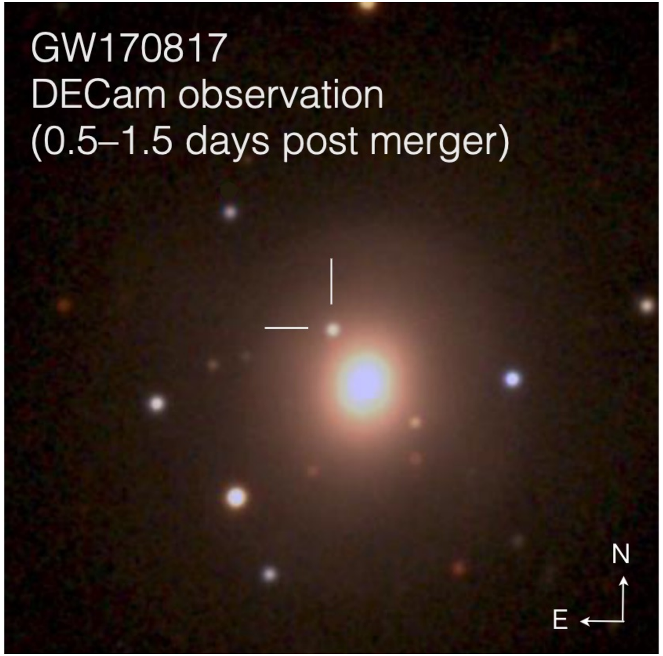
- DESI is a ground-based, optical telescope located at Kitt Peak in Arizona. It boast…
    - 5,000(!) optical fibers (some pictured at right).
    - Over 14,000 square degrees.
    - Covers large portion of the Northern Hemisphere.
    - Redshift precision $< 5 \cdot 10^{-4}(1+z)$
- One DESI objective is to perform a PV survey within the DESI footprint.
    - Ample work already done to calibrate PV measurements.

https://kipac.stanford.edu/research/projects/dark-energy-spectroscopic-instrument

GW170817: The First Standard Siren Measurement

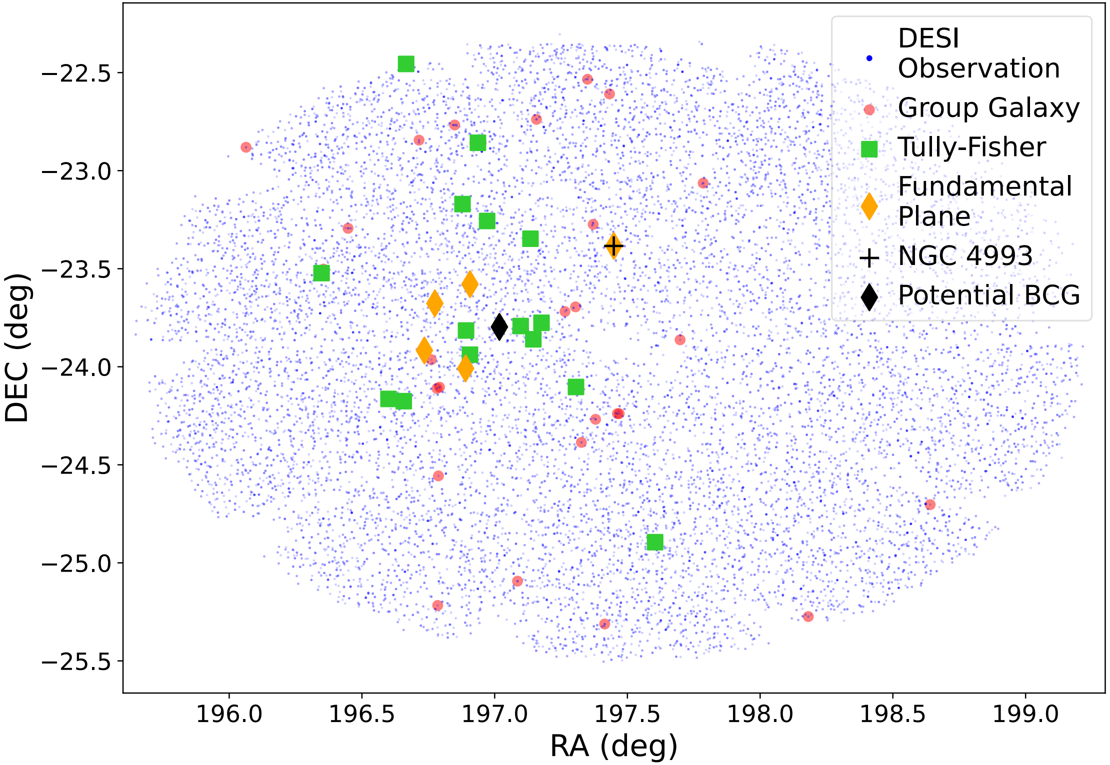
- LIGO and Virgo interferometers observe a neutron star merger event, GW170817.
- Within 12 hours, NGC 4993 is identified as the event host galaxy.
- Leads to the **first** (and, to-date, only) bright siren measurement (Abbott et al. 2017).
- Many estimations for the PV of NGC 4993 already existed using 1-3 group galaxy members. See a summary of these in Howlett et al. 2020.
- Recently, with DESI we have observed ~20 potential galaxies from which PVs can be measured.

Figure 1, Soares-Santos et al 2017

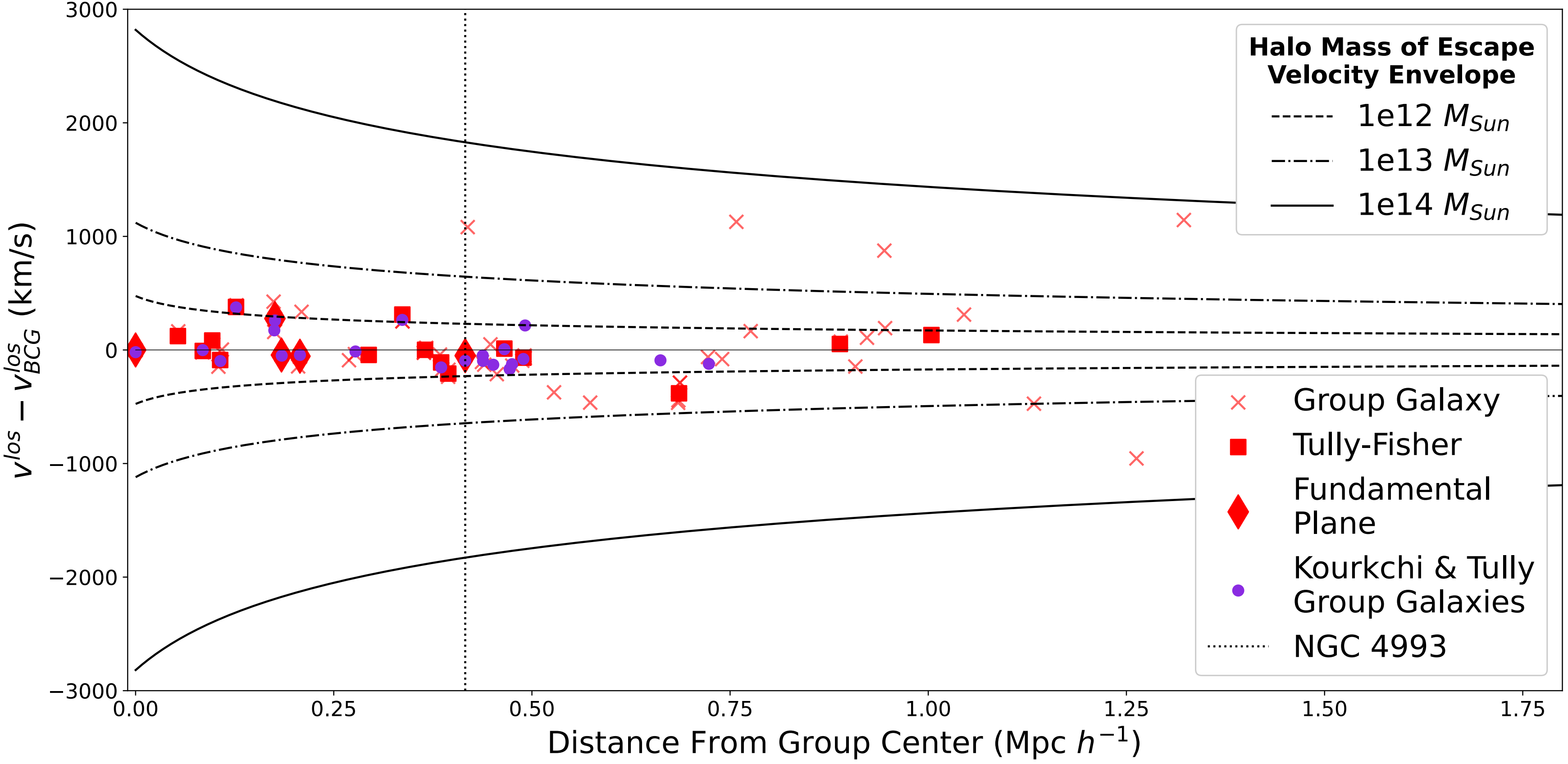


DESI Observations of the NGC 4993 Region

- Our most basic criteria for **group membership**:
  - •Redshift ∈ (0.008, 0.012).
  - •RA and DEC within observed tile.
- **78 observations** of objects in the NGC 4993 group.
- **Peculiar Velocity targets:**
  - **6 Fundamental Plane** (FP) galaxies (including NGC 4993).
  - **15 Tully-Fisher** (TF) galaxies.



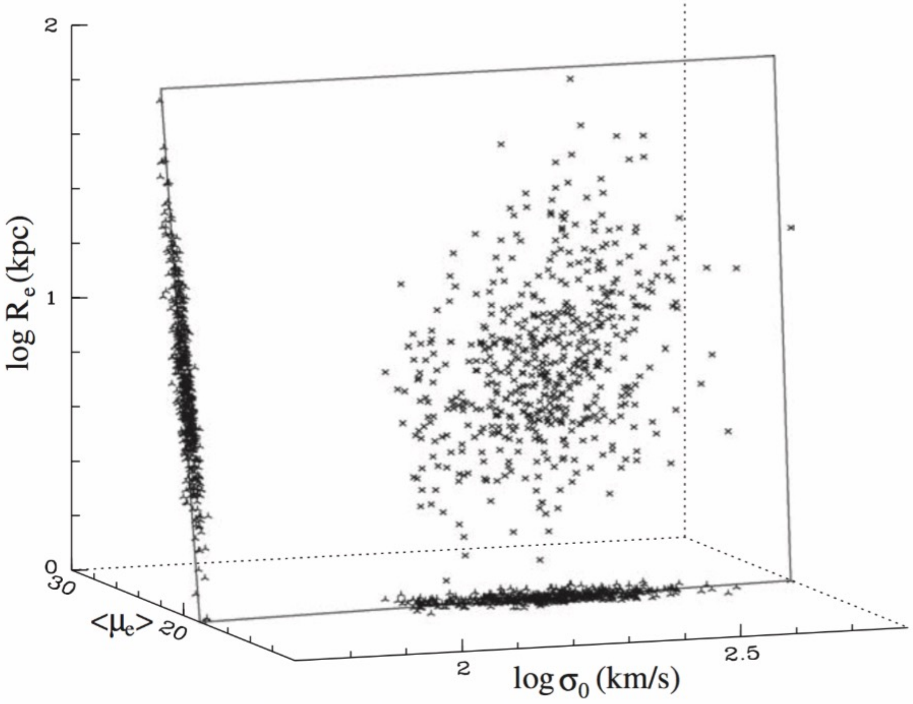
Initial Phase-Space Diagram of the NGC 4993 Group



The Fundamental Plane Relation

$$\log(R_e) = a\log(\sigma_0) + b\log(I_e) + c$$

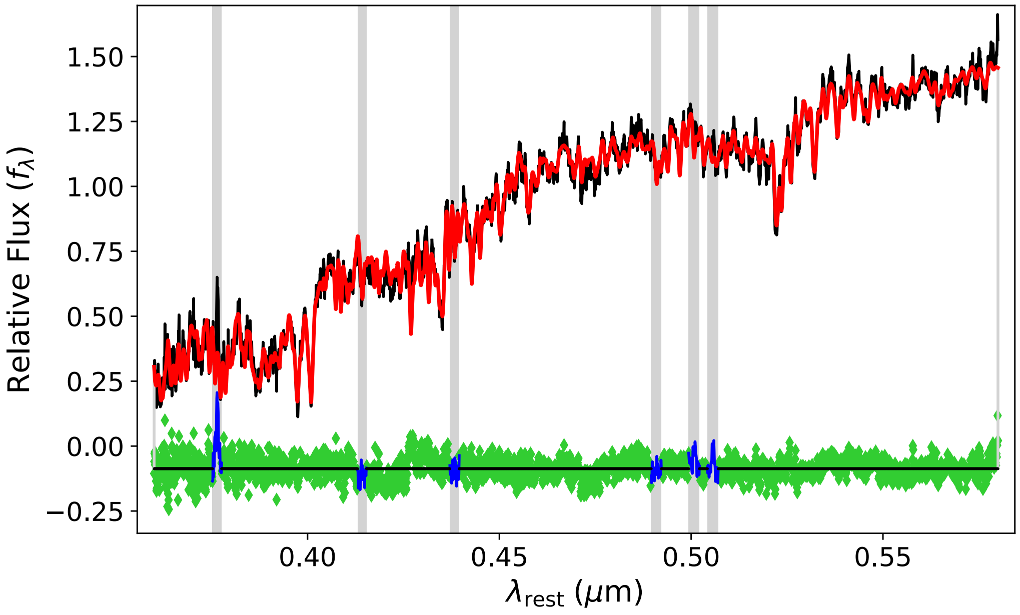
http://www.astro.yale.edu/vdbosch/astro610_lecture19.pdf



- A mostly empirical relation between the following physical observables
  - R_e: Effective Radius
  - σ_0: Velocity Dispersion
  - I_e: Mean Surface Brightness
- Adding a third axis reduces the scatter (uncertainty) on the relation (unknown parameter).
- a and b vary can vary over wavelength. We only use photometry from DECam r-band (~550-700 nm).

Measuring Fundamental Plane Parameters

- Use PPXF to fit a DESI spectrum (right) with a velocity dispersion, σ_0.
- **Measure** I_e & $R_{e,meas}$ directly from photometric quantities (from the DESI Legacy Imaging Surveys).
- **Calibrate** a value for $R_{e,cal}$, from the DESI FP calibration (Said et al. in prep), I_e, and σ_0.

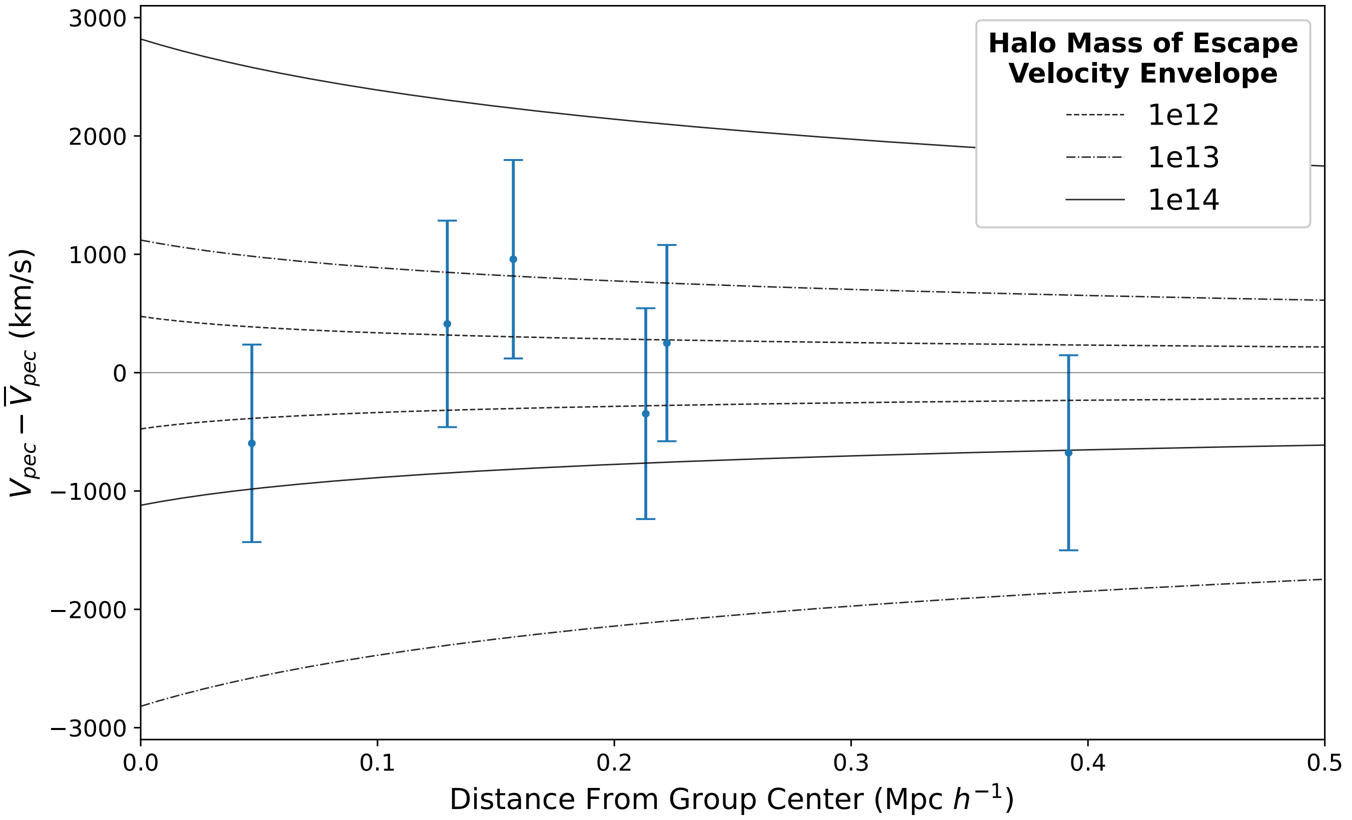


- The peculiar velocity can them be computed since $v_p \propto log_{10}\left(\frac{R_{e,meas}}{R_{e,cal}}\right)$.

Preliminary

Initial Peculiar Velocity Measurements

- Initial approximation of peculiar velocity is **640 ± 350 km/s**.
- This measurement is *already* very competitive.



Conclusion and Future Work

- Primary benefit of this work: Improved peculiar velocity **precision** from
  - 1) Increase in **number of galaxies** (from 1–3➔~20)
  - 2) Precise **DESI** redshifts and spectra
  - 3) Well-constrained distance indicator **calibrations**
- The Immediate Future:
  - Incorporate **Tully-Fisher** galaxies into our sample.
  - Calculate an H_0 posterior with new peculiar velocity samples..
- The Ultimate Goal:
  - **<u>Use DESI for similar peculiar velocity determinations for new gravitational wave events.</u>**

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