# Sample variance in the local measurements of $H_0$

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$H_0^{local} = 73.24 \pm 1.74$ km s$^{-1}$ Mpc$^{-1}$

(Riess et al. 2016)

$H_0^{CMB} = 66.93 \pm 0.62$ km s$^{-1}$ Mpc$^{-1}$

(*Planck* int. XLVI 2016)

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$$H_0^{CMB} = 66.93 \pm 0.62 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

(*Planck* int. XLVI 2016)

Can we alleviate this tension by considering **local density fluctuations** and **supernova selection**?

$H_0^{CMB} = 66.93 \pm 0.62$ km s$^{-1}$ Mpc$^{-1}$
(*Planck* int. XLVI. 2016)

- measuring the sound horizon scale at recombination, which constrains $\Omega_c h^2$
- Re-analyses (*Planck* int. LI):
  - $\ell > 800$ pulls $H_0$ down
  - $\ell < 30$ pulls $H_0$ up
- Beyond 6 parameters:
  - $N_{eff} > 3$ leads to $70.6 \pm 1.0$ (*Planck* 15 XIII)
  - unchanged when including running, running of the running (Obied+17)

$H_0^{local} = 73.24 \pm 1.74\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$

(Riess et al. 2016)

- Distance ladder
  - 4 distance anchors (geometry + Cepheids)
  - 19 distance calibrators (Cepheids + SNe Ia)
  - 217 SNe Ia at $0.023 < z < 0.15$

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- Re-analyses
  - Cardona et al. (2017): $73.75 \pm 2.11$
  - Zhang et al. (2017): $72.5 \pm 3.1 \pm 0.77$ (blind)
  - Feeney et al. (2017): $72.72 \pm 1.67$
  - Follin & Knox (2017): $73.3 \pm 1.7$

For now let's assume that the *Planck* $H_0$ is the true global value.

How much $\Delta H_0^{loc}$ can come from **sample variance**?

# Simulating $H_0$ measurement from supernovae

Take an N-body sim

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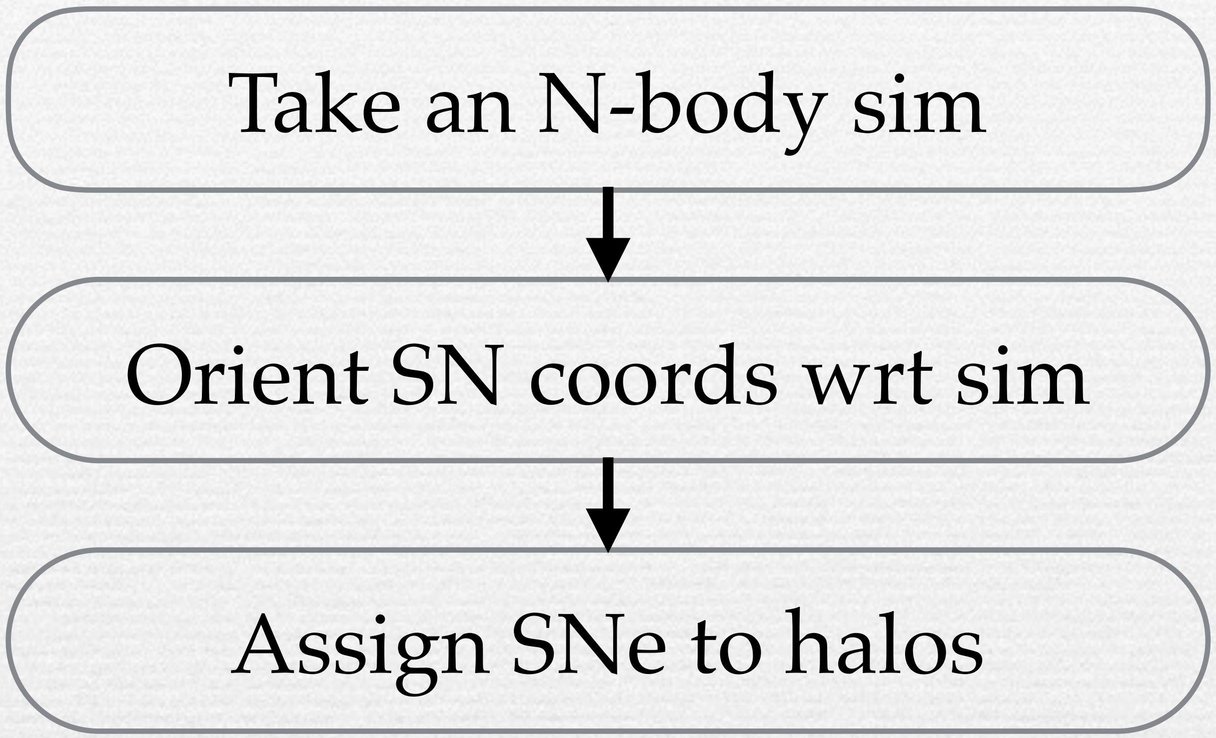
↓

Orient SN coords wrt sim

# Simulating $H_0$ measurement from supernovae



# Simulating $H_0$ measurement from supernovae

Take an N-body sim

↓

Orient SN coords wrt sim

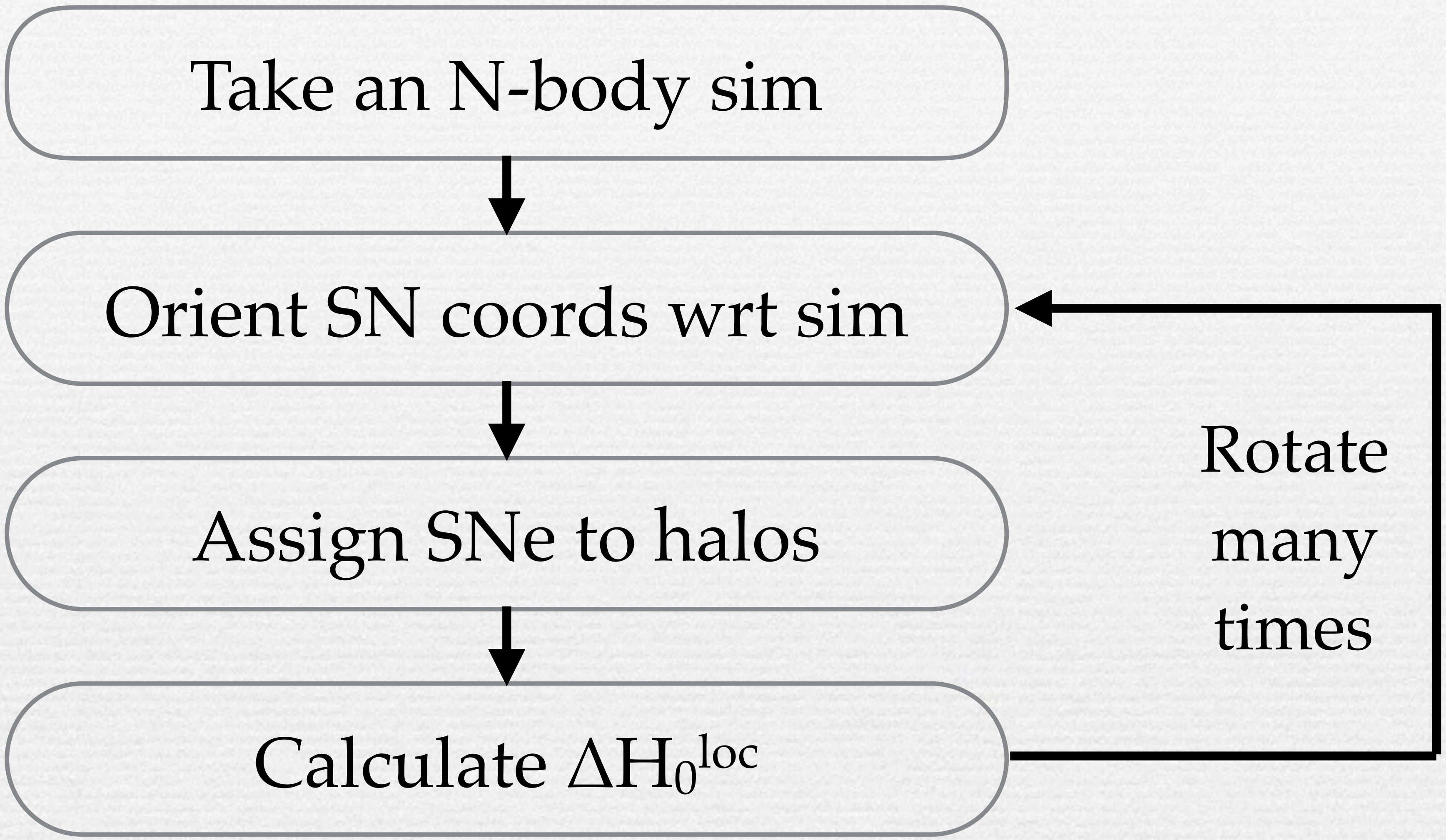
↓

Assign SNe to halos

↓

Calculate $\Delta H_0^{loc}$

# Simulating $H_0$ measurement from supernovae



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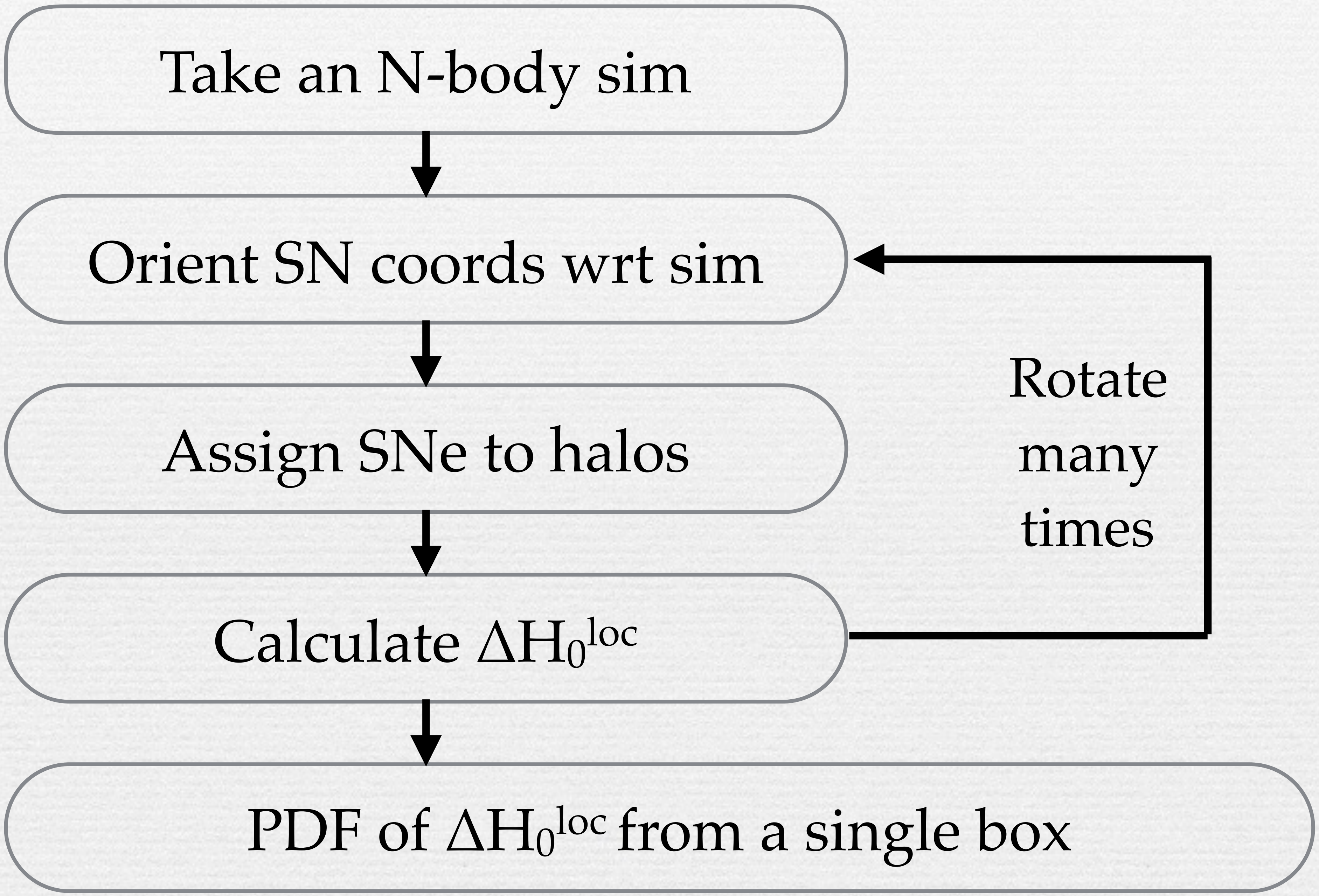

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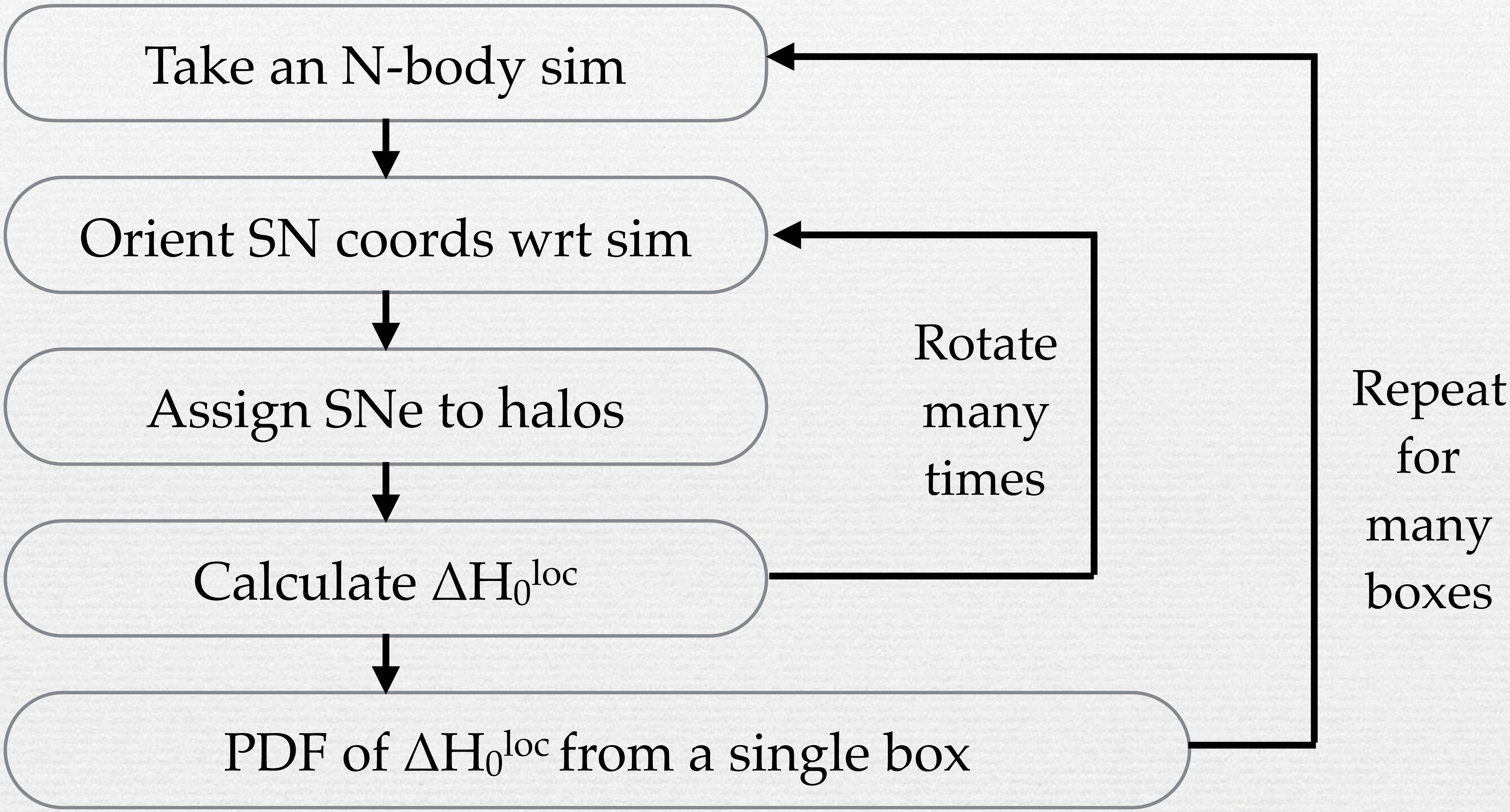
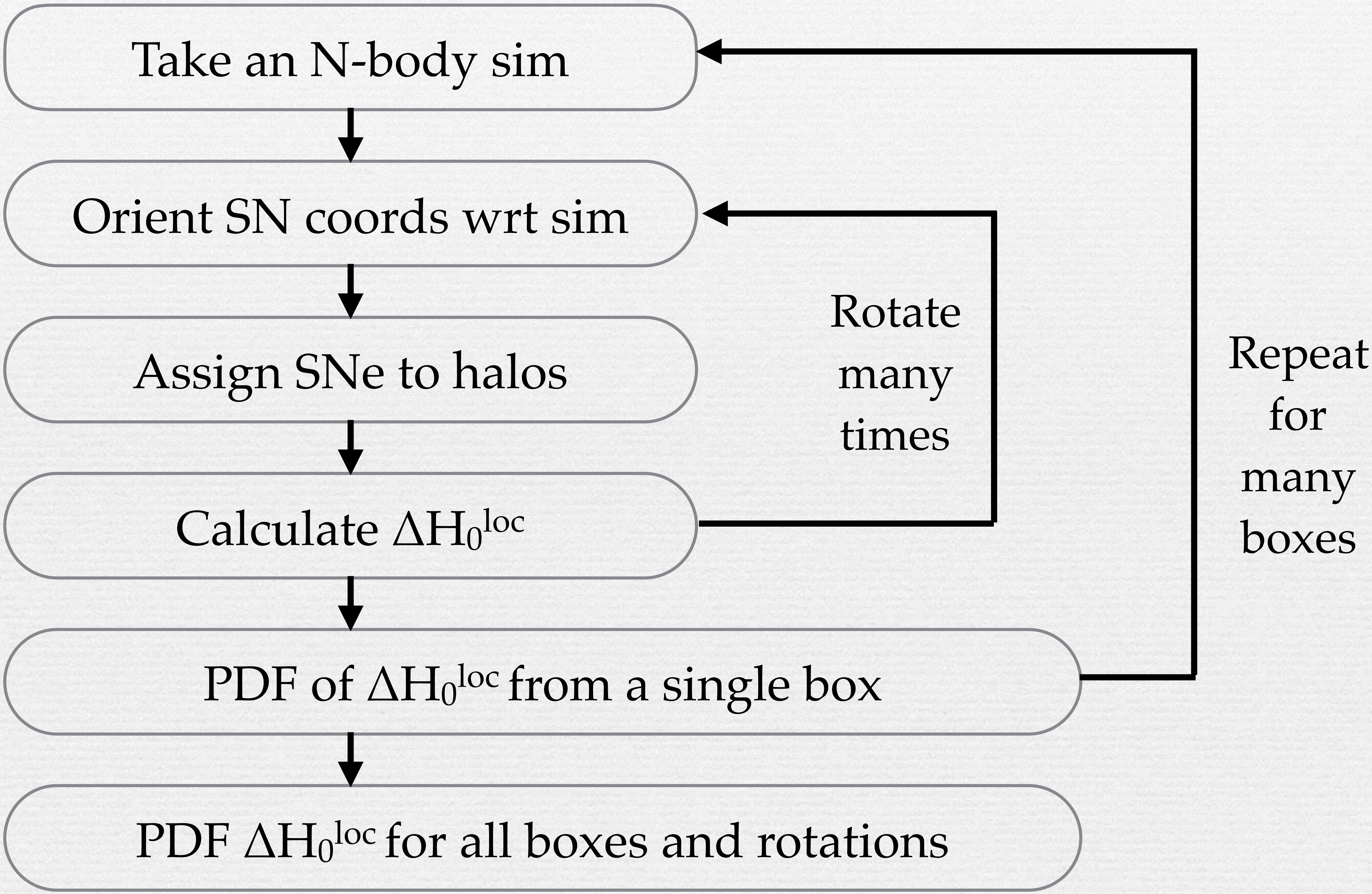


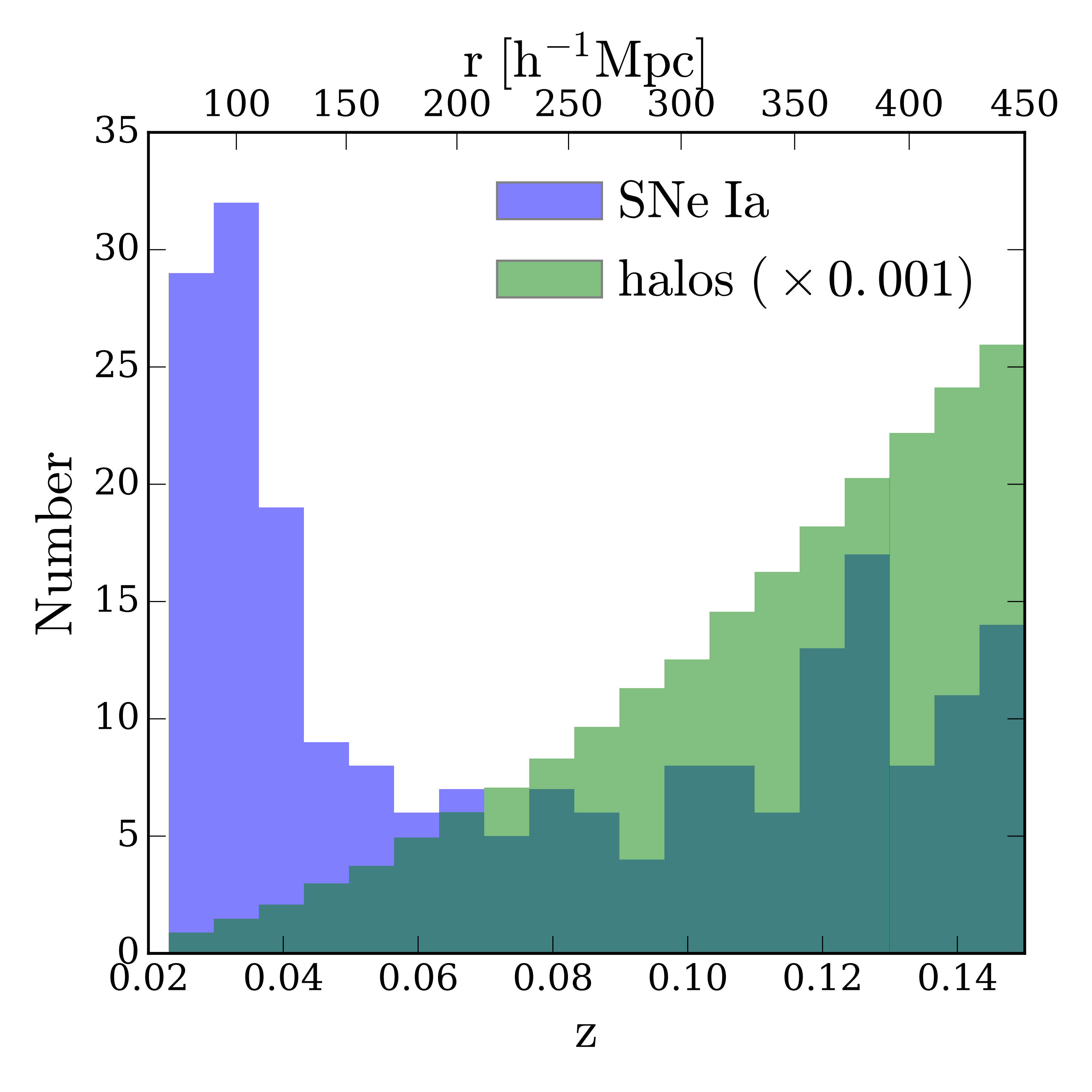
# Simulating $H_0$ measurement from supernovae



# Dark Sky Simulations (Skillman et al. 2014)

- N-body simulations (2HOT)
- 8 $h^{-1}$Gpc, divided into 512 subvolumes of 1 $h^{-1}$Gpc
- resolving $2 \times 10^{12}$ $M_{\odot}$ halos (about Milky Way mass)
- on-line database (yt + darksky.slac.stanford.edu)

# Redshift distribution 217 SNe Ia from Riess+16

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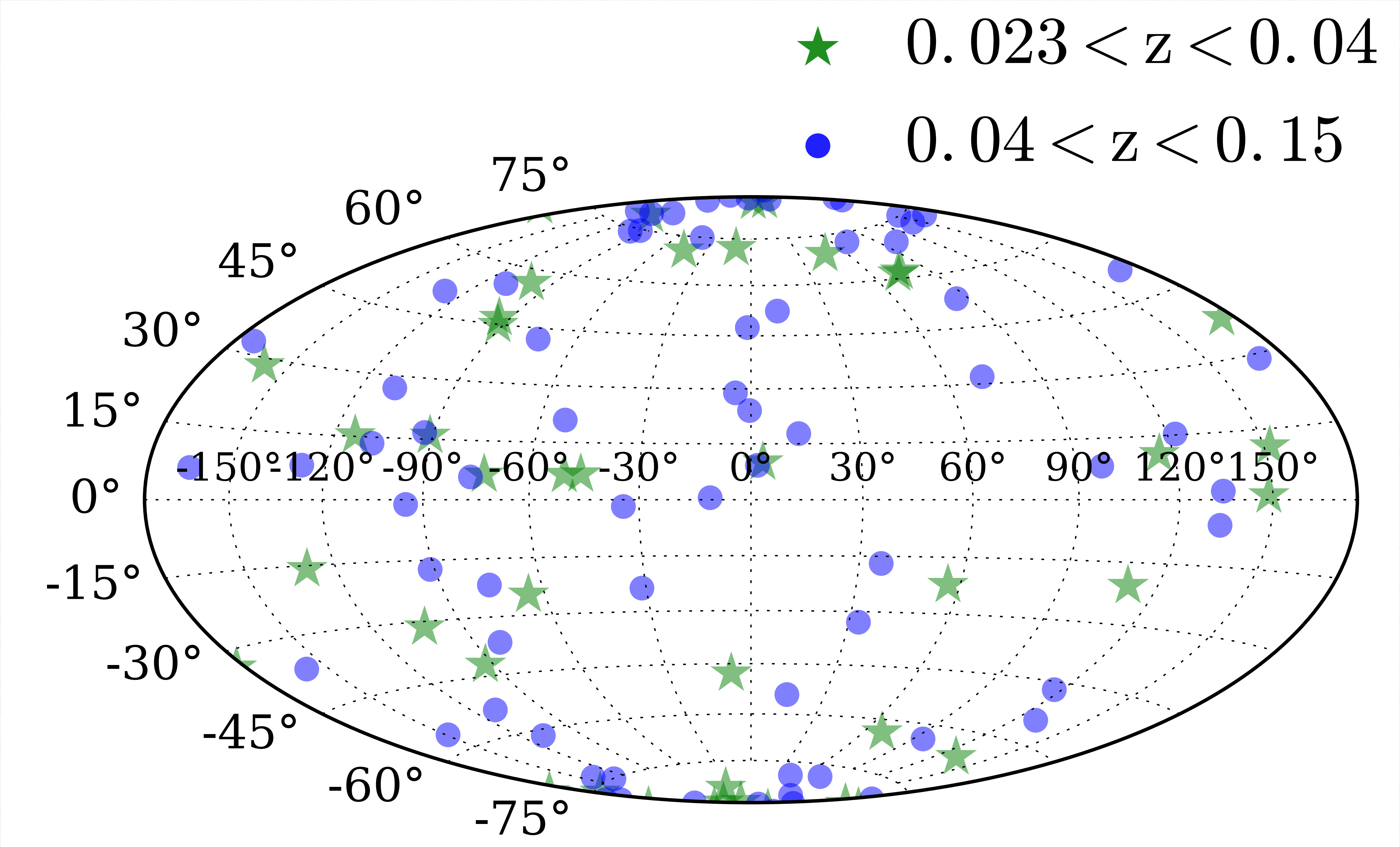
# Angular distribution 217 SNe Ia from Riess+16

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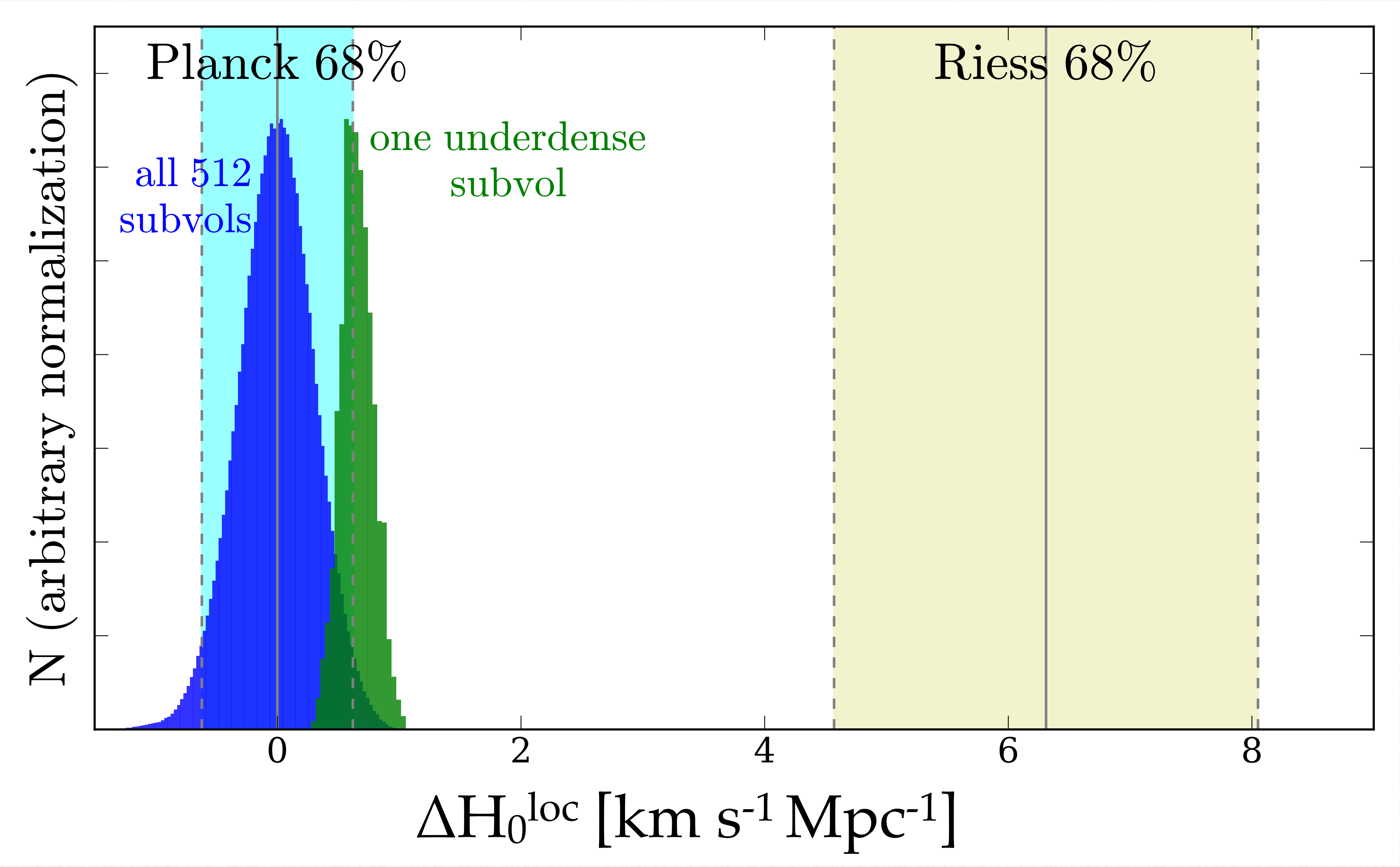
# PDF of $\Delta H_0^{loc}$ from ~1.5 million realizations

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# Sample variance of $\Delta H_0^{loc}$ is ~0.3 km s$^{-1}$ Mpc$^{-1}$

| | all halos, no weighting | SN n(z) weighting | +3D distr. +rotations | +Δmag weighting |
|---|---|---|---|---|
| σ ($\Delta H_0^{loc}$) [km s$^{-1}$ Mpc$^{-1}$] | 0.12 | 0.38 | 0.42 | **0.31** |

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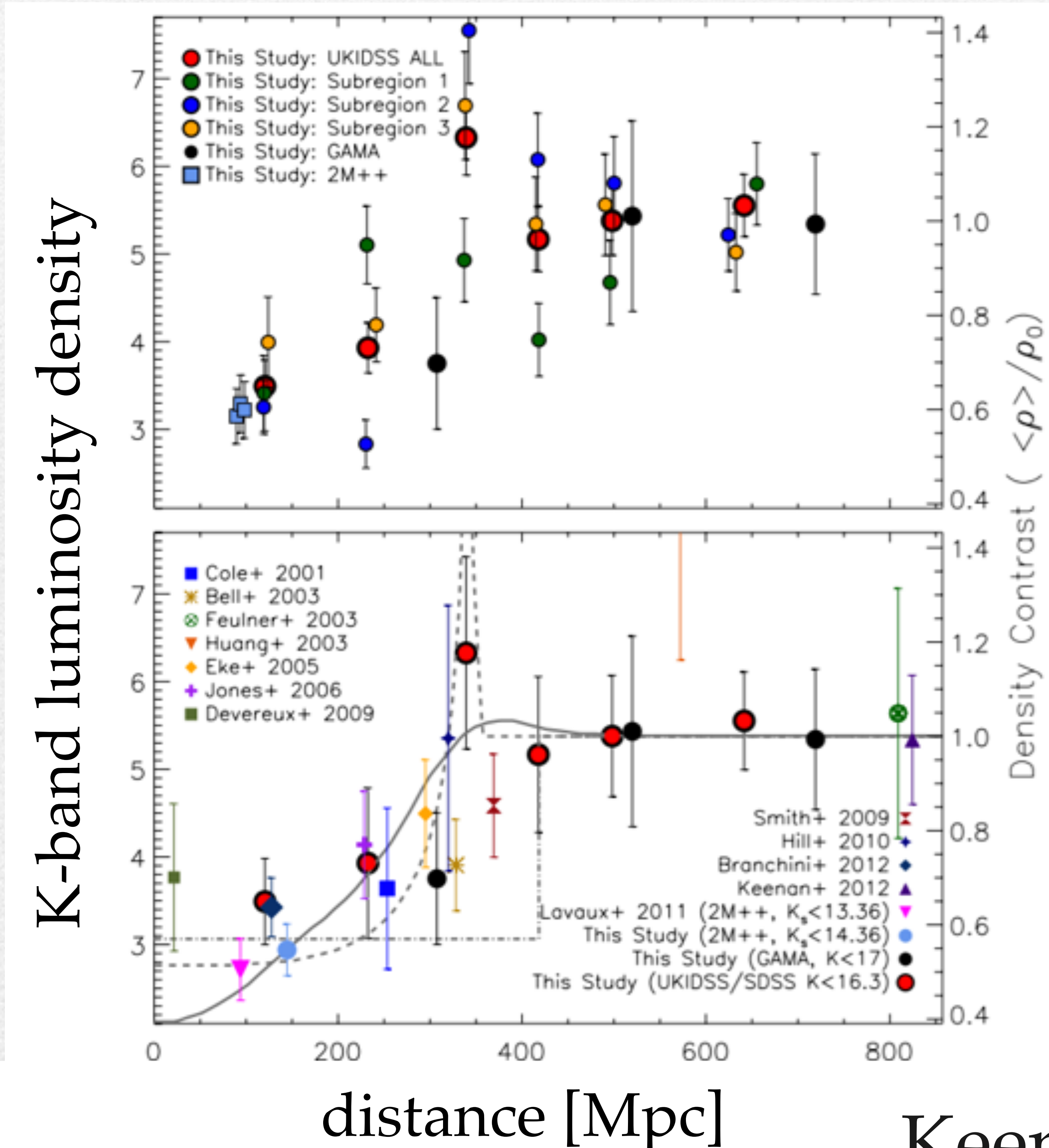
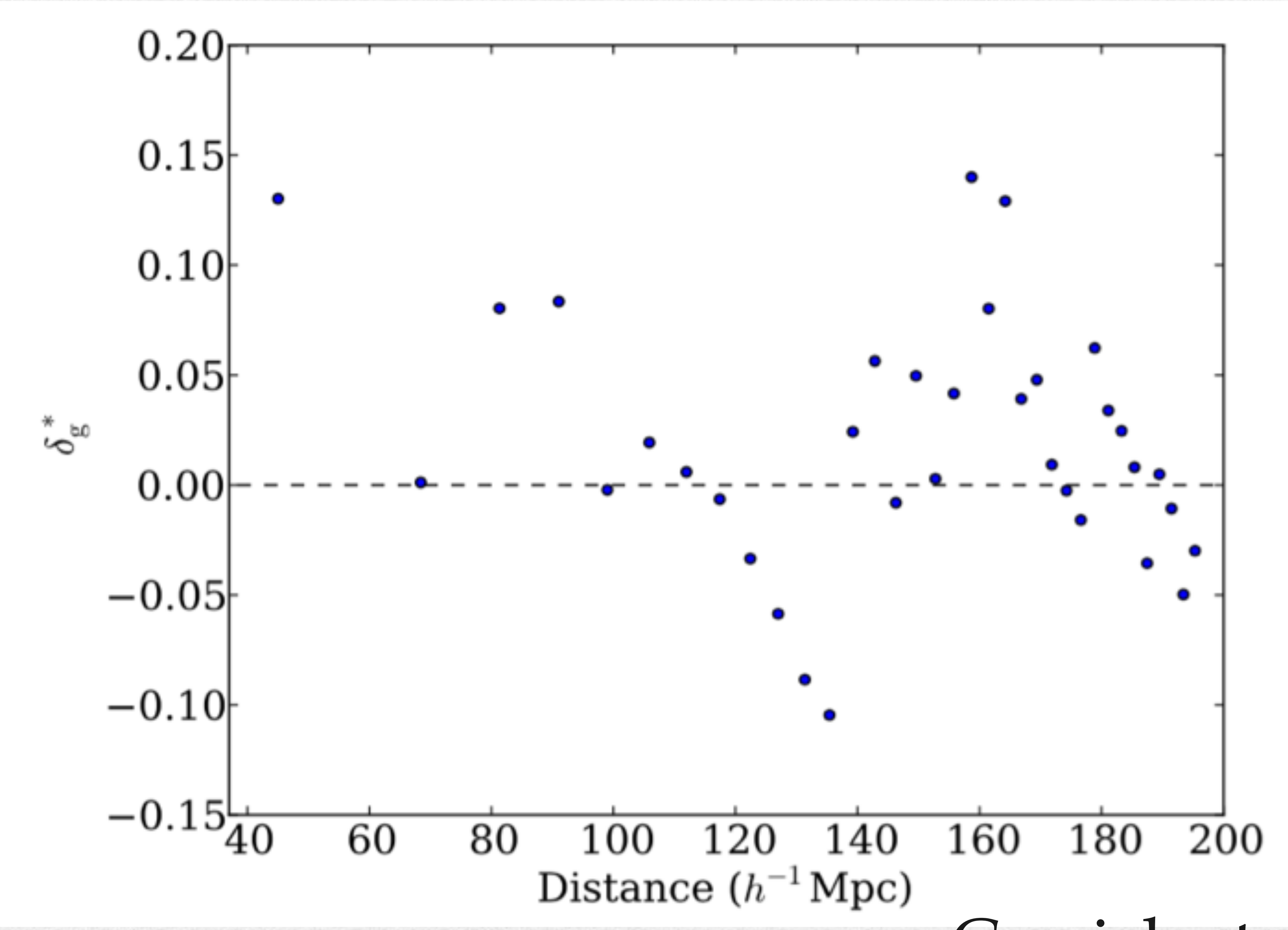
# Evidence of a local under-density?




Keenan et al. (2013)

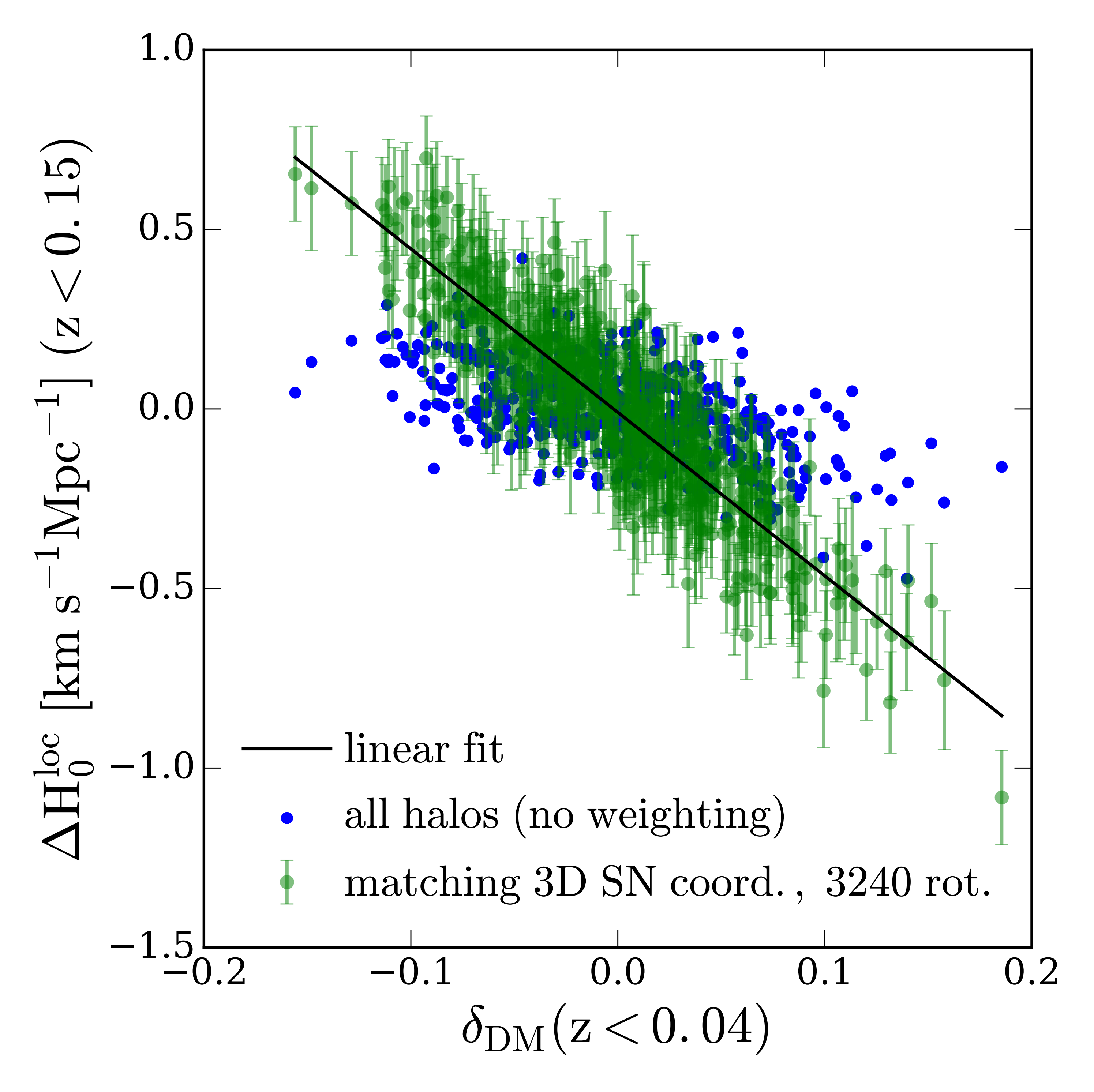
# Evidence of a local under-density?

## galaxy luminosity density from 2M++




Carrick et al. (2015)

# $\Delta H_0^{loc} \propto$ density contrast

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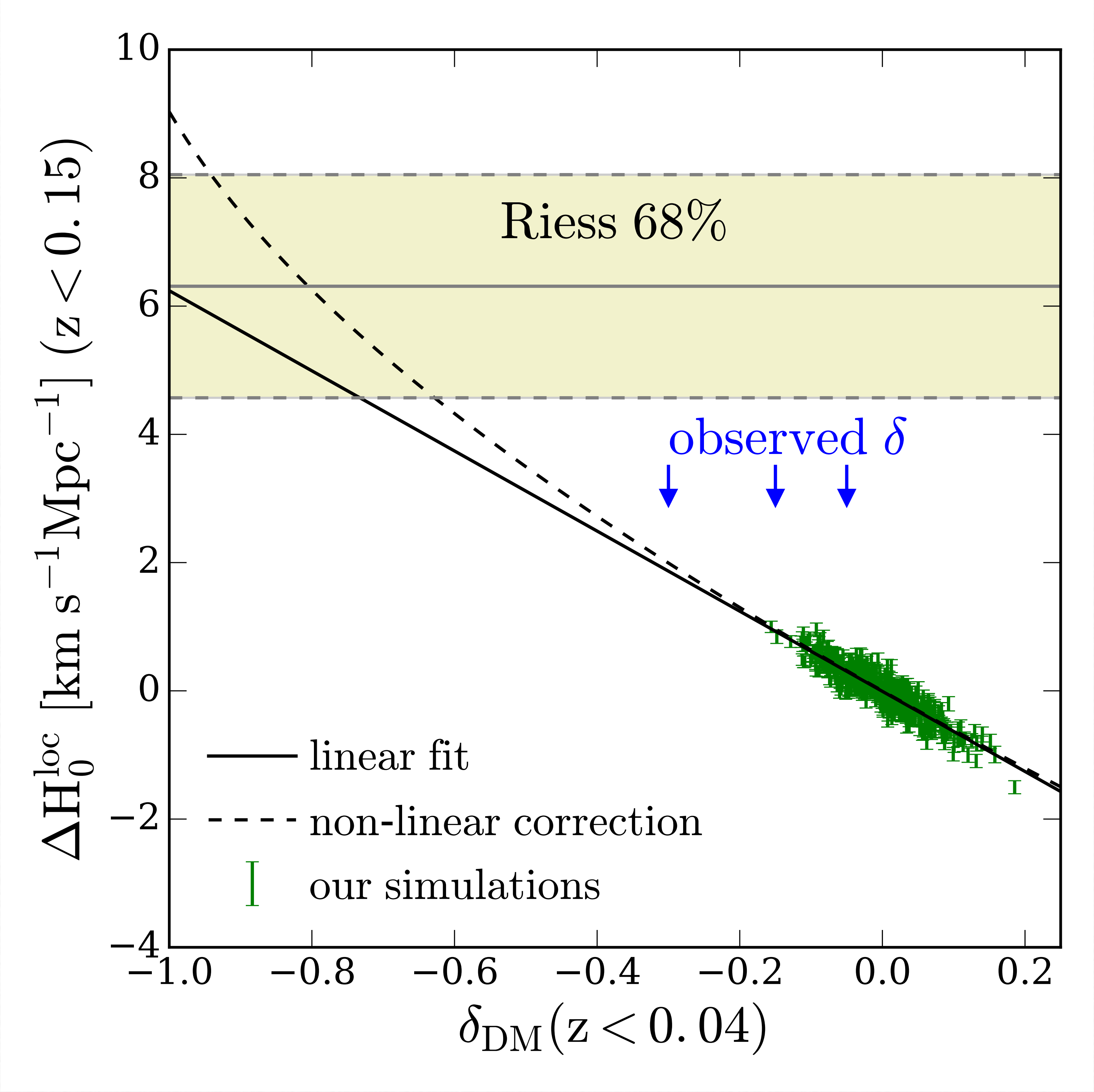
# Comparison with observations

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# Summary

- Sample variance in $H_0^{loc}$ is ~ 0.3 km $s^{-1}$ $Mpc^{-1}$, which is too small to alleviate the tension between local (~73) and CMB (~67) measurements.
- This tension would require a 80% underdensity to alleviate, which is highly unlikely in a $\Lambda$CDM universe.

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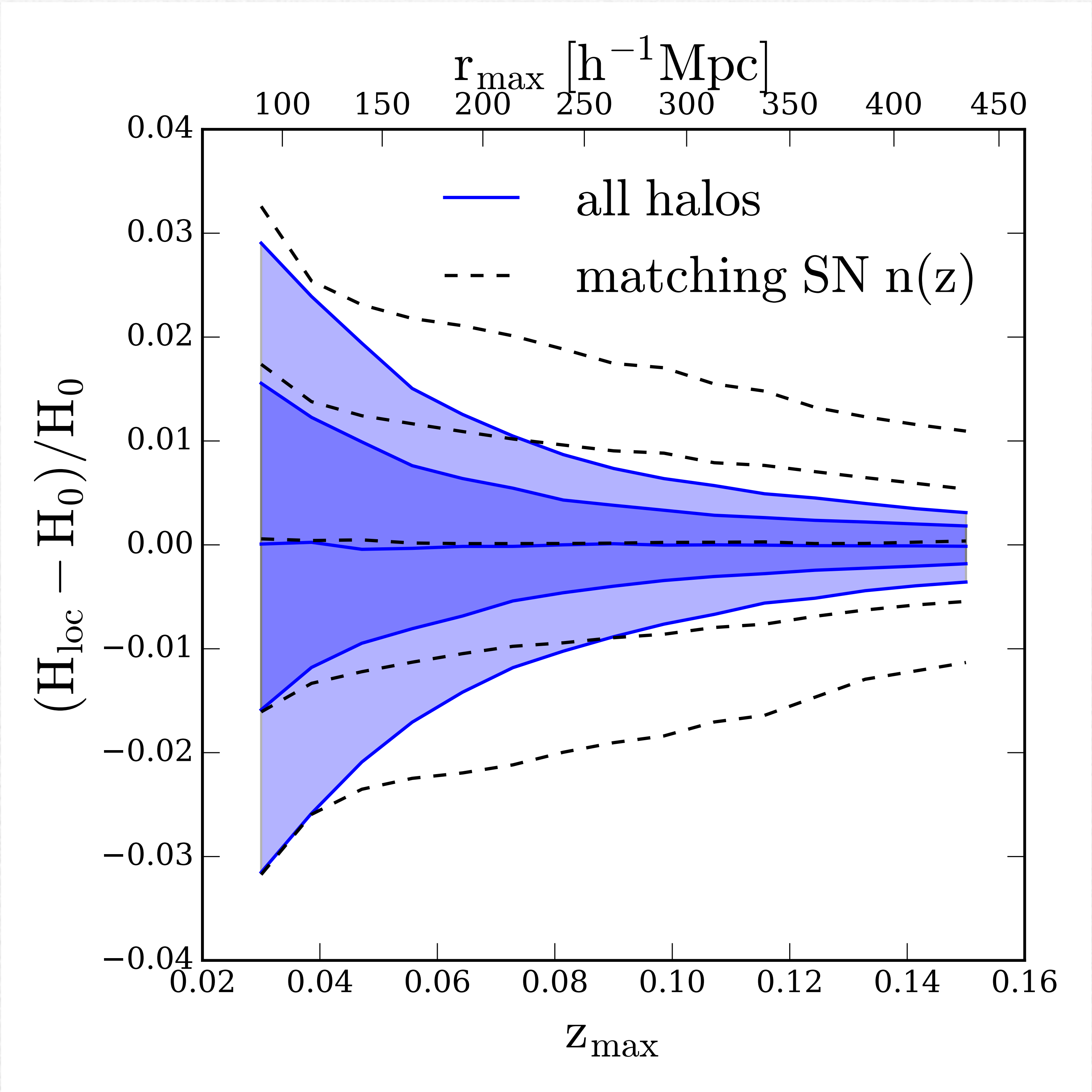
- This tension would require a 80% underdensity to alleviate, which is highly unlikely in a ΛCDM universe.

We're still not sure if there is a Hubble bubble.
Even if there is, it cannot resolve the tension.

# Sample variance of $H_0$ vs. maximum distance

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