Study of anisotropic cosmic expansion with ZTF type Ia supernovae simulations.

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Research work released under the direction of
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ZTF workshop
29 September 2026

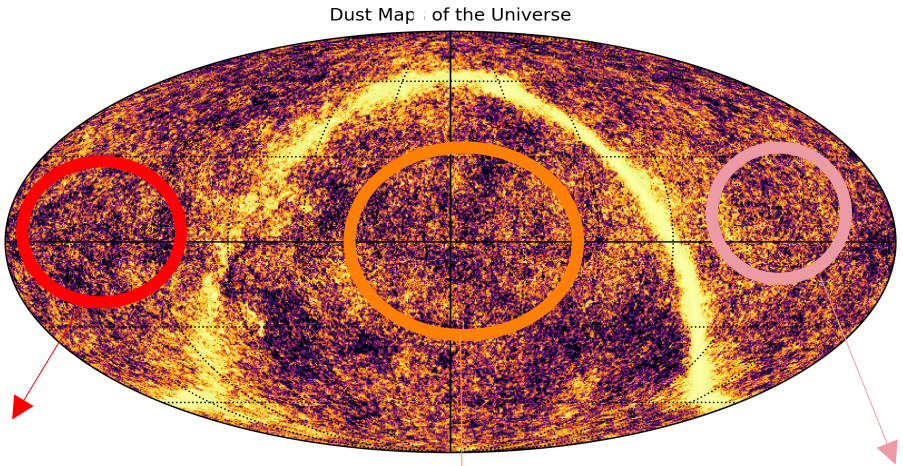
Motivation

Cosmological principle

Isotropy (large-scale) ? ? ? ?

Homogeneity (large-scale)

- This work :
- *Study anisotropy of* H_0



$H_0 = 68$ km.s^{-1}Mpc^{-1} ?

$H_0 = 73$ km.s^{-1}Mpc^{-1} ?

$H_0 = 70$ km.s^{-1}Mpc^{-1} ?

H_0 dipole studies

Anisotropies ?

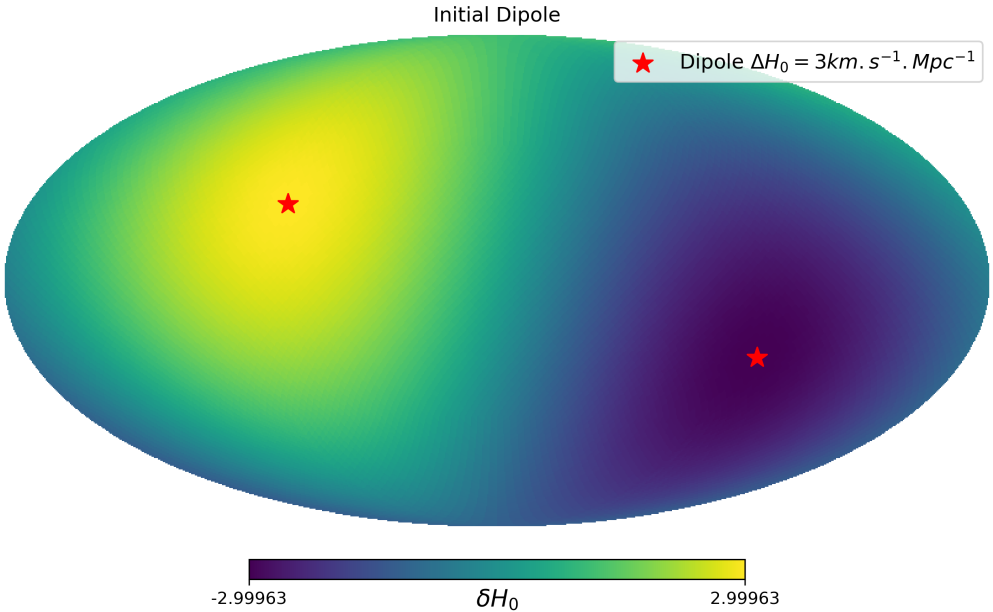
$H_0 = 67.66$ km.s^{-1}Mpc^{-1}

$$d_l = \frac{c(1+z)}{H_0'} \int_0^z \frac{d\zeta}{\sqrt{\left((1+\zeta)^3 - 1\right)\Omega_m + 1}}$$

$$H_0' = H_0 + \Delta H_0 \cos(\Delta\theta)$$

$\Delta H_0 = 3$ km.s^{-1}Mpc^{-1}

Angular distance between the dipole and SNe Ia



$$\delta H_0 = \Delta H_0 \cos(\Delta\theta)$$

H_0 dipole studies

Anisotropies ?

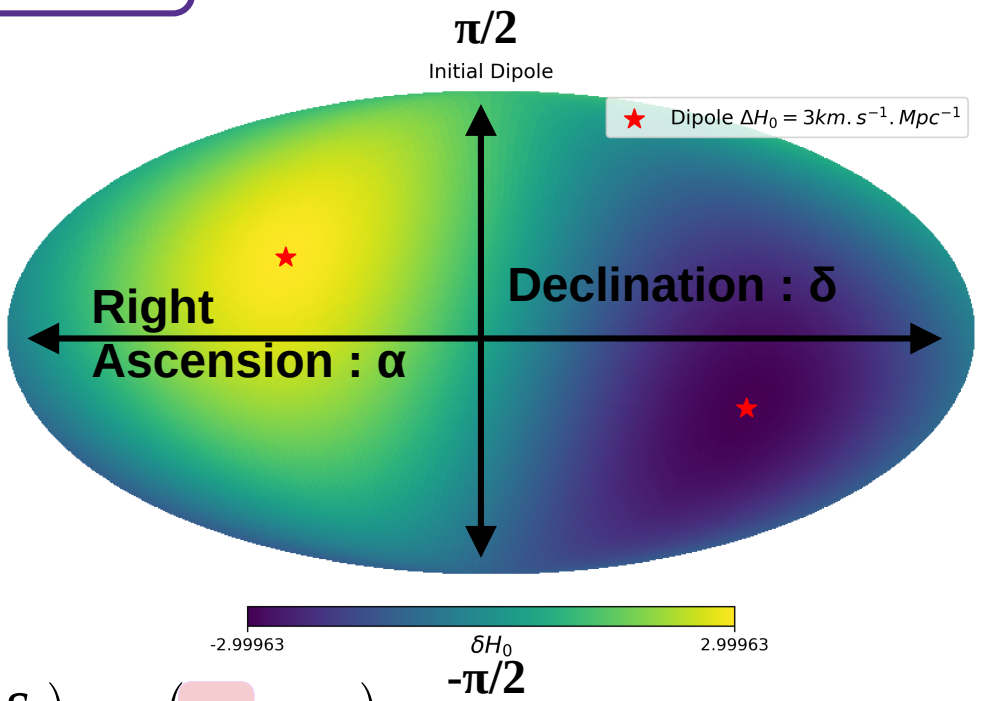
$$d_l = \frac{c(1+z)}{H_0'} \int_0^{z_i} \frac{d\zeta}{\sqrt{\left((1+\zeta)^3 - 1\right)\Omega_m + 1}} \quad \pi$$

$$H_0' = H_0 + \Delta H_0 \cos(\Delta\theta)$$

$$\cos(\Delta\theta) = \sin(\delta_0)\sin(\delta_i) + \cos(\delta_0)\cos(\delta_i)\cos(\alpha_0 - \alpha_i)$$

Parameter to fit

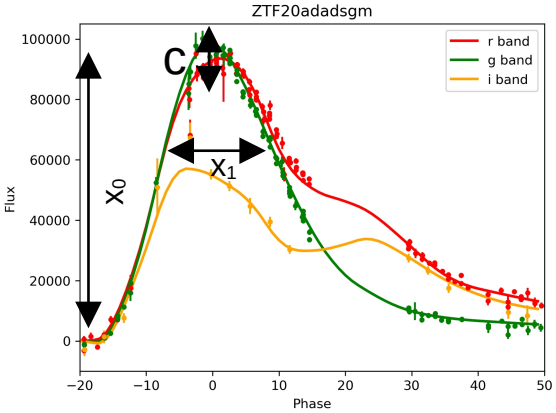
SNe la position



SNe Ia - Standardisation:

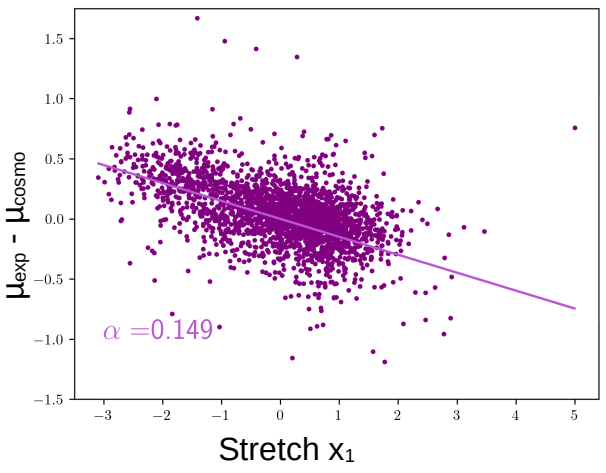
$$\mu^{exp} = m_B - M_B + \alpha\, x_1 - \beta\, c$$

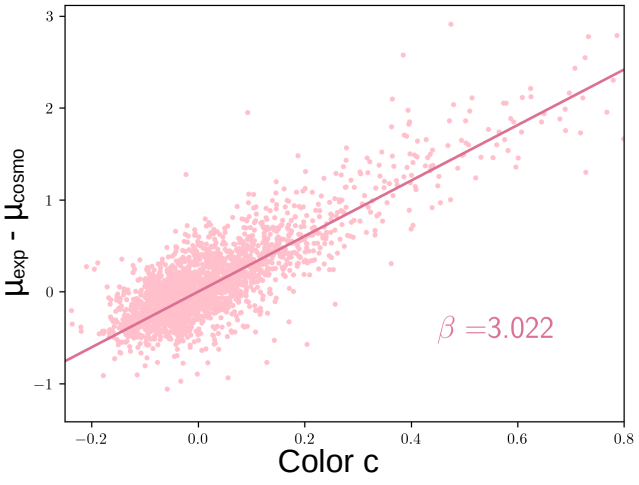
$$\mu^{cosmo} = 5\log\left(d_l(Mpc)\right) + 25$$

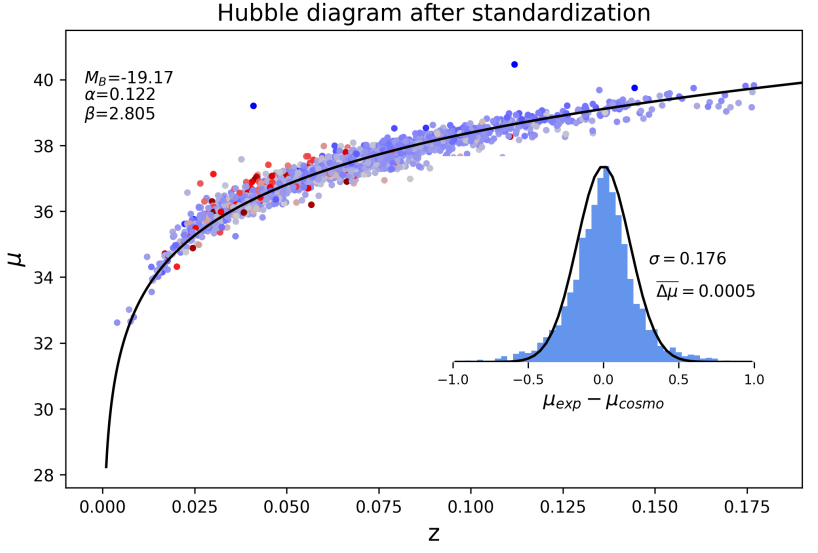


Free

$$L^2 = \frac{-1}{2}\log\left(\sum_{i=1}^{N_{SNeIa}}\left(\frac{\mu_i^{exp}\left(M_B, \alpha, \beta\right) - \mu_i^{cosmo}}{\sigma_{\mu_i}}\right)^2\right) + \log\left(2\Pi\,\sigma_{intr}{}^2\right)$$







Realistic ZTF Simulation

- Contains all observation information : maglim, field of observation, possible technical problem

ZTF observing logs

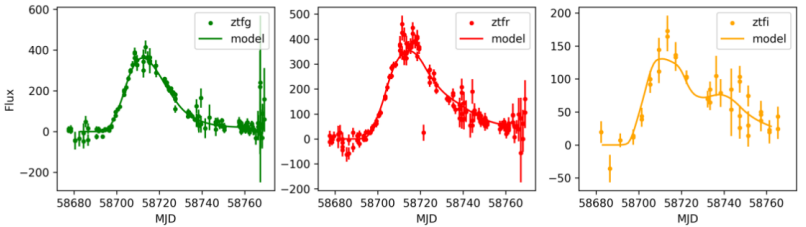
Skysurvey

- Cosmology: flat ΛCDM
  $H_0 = 67.66$ km.s^{-1}.Mpc^{-1}
  $\Omega_m = 0.30966$

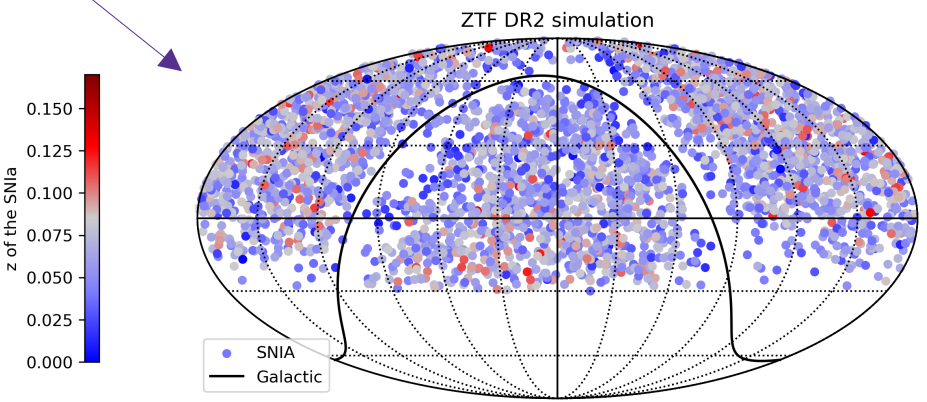
- Simulates astronomical targets as they would be observed by a survey

SN Ia model

- Sncosmo : SALT2 a python library for supernovae cosmology analysis.



M.Amenouche et al., 2025



Dipole introduced in simulation:

$H_0 = 67.66$ km.s^{-1}Mpc^{-1}

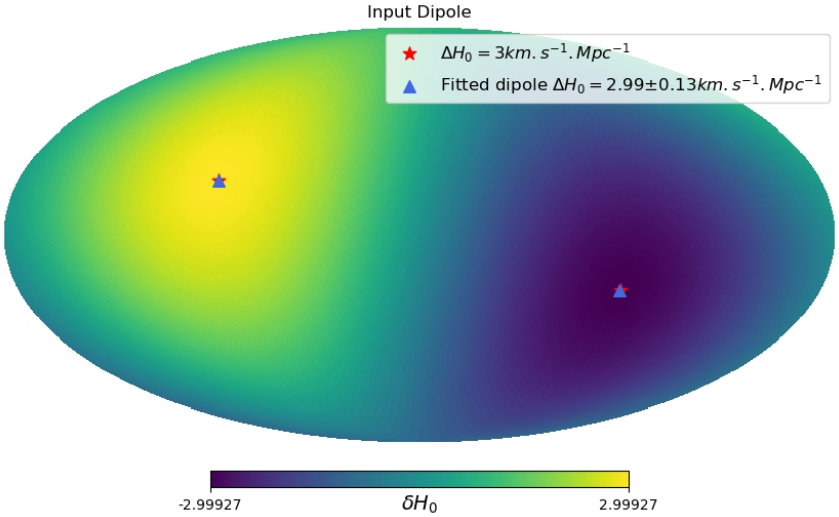
$$\mu' = 5\log(d_l') + 25 = \mu + 5\log\left(\frac{H_0}{H_0'}\right) = m_B' - M_B$$

$$m_B' = m_B + 5\log\left(\frac{H_0}{H_0'}\right)$$

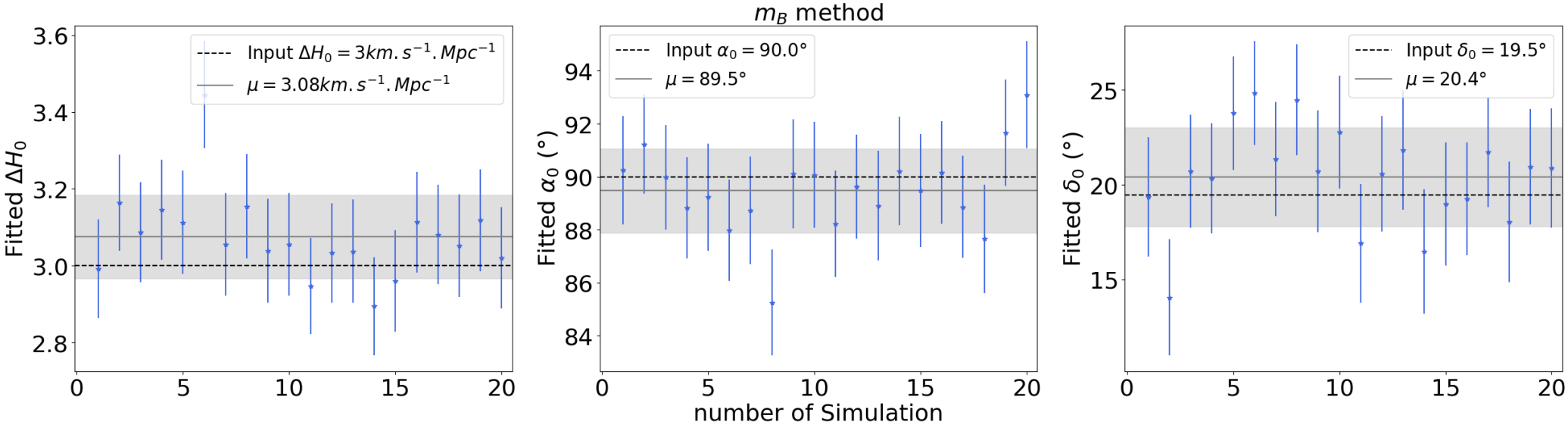
$$m_B' = m_B - 5\log\left(1 + \frac{\Delta H_0}{H_0}\cos(\Delta\theta)\right)$$

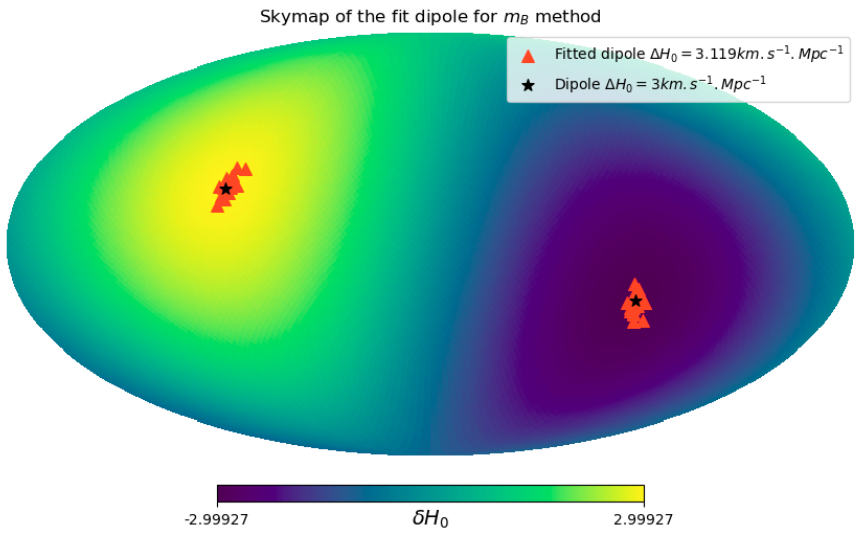
$\Delta H_0 = 3$ km.s^{-1}Mpc^{-1}

Angular distance between the dipole and Sne Ia



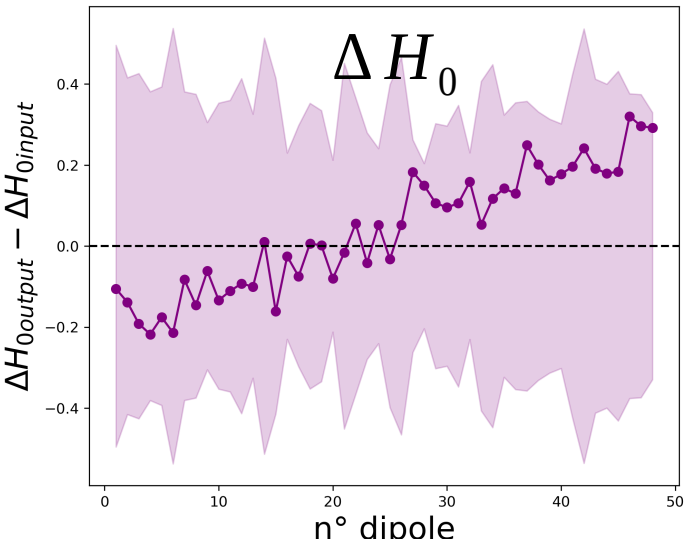
Dipole fit for 20 independent simulations for the m_B method

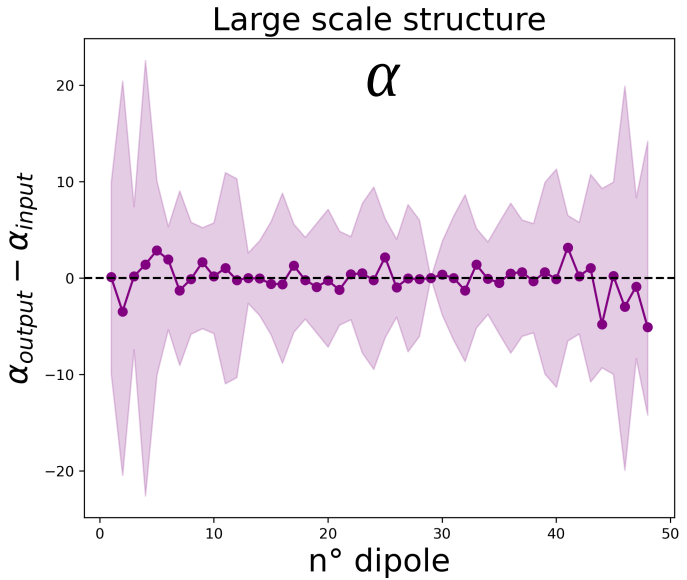


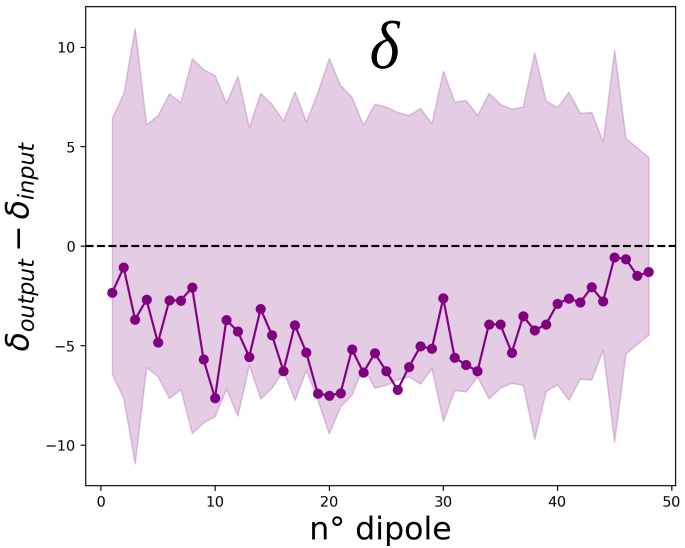


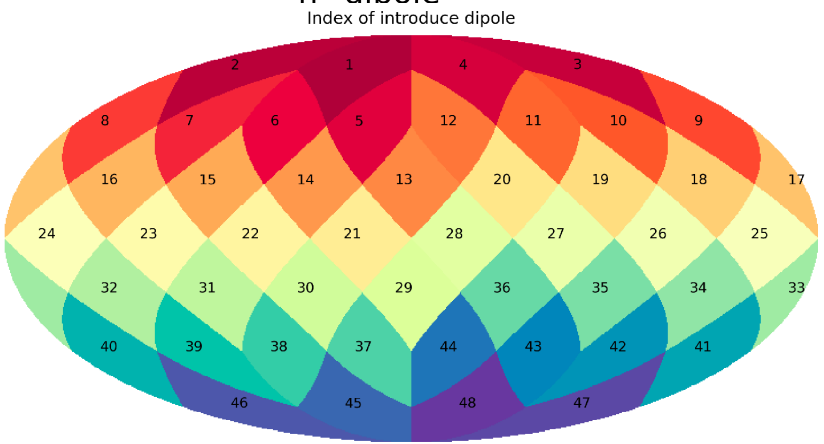
- Direction and amplitude included in 1σ uncertainty

Large scale structure



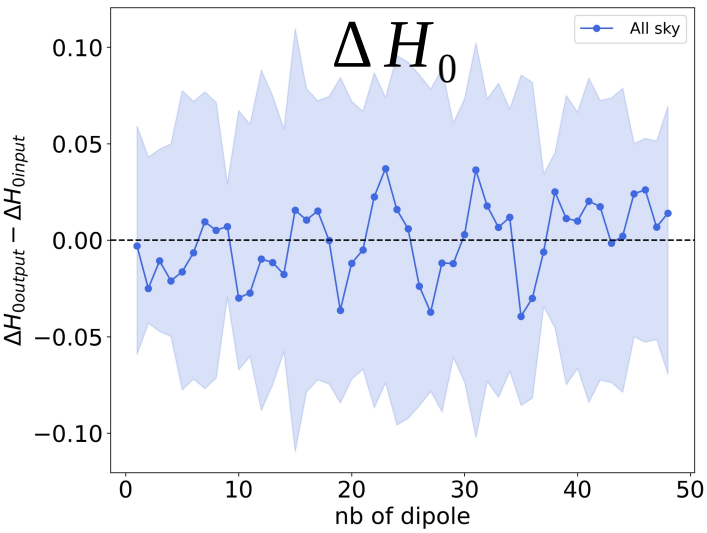


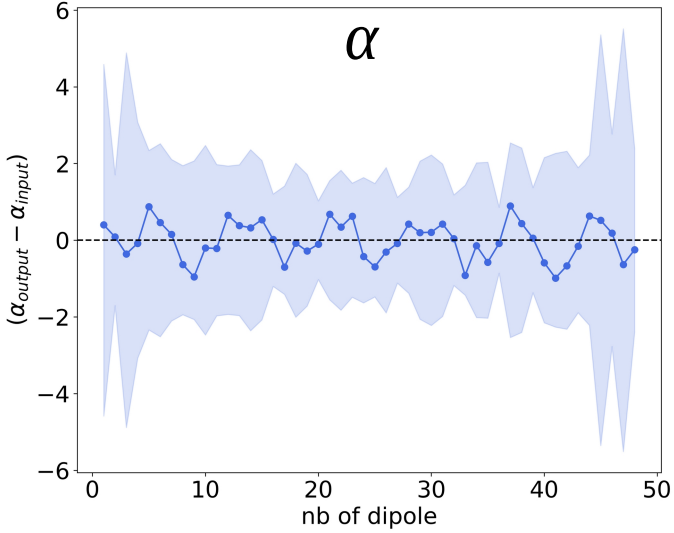


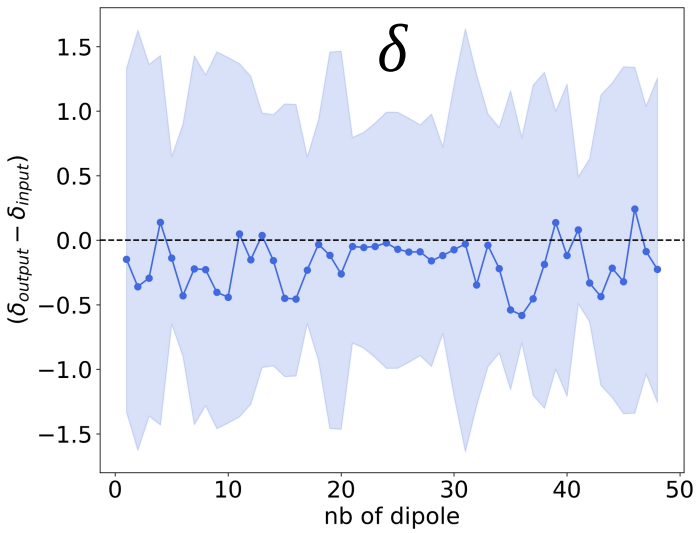


- $\sigma_{\Delta H0}$ = 0.33 km s^{-1} Mpc^{-1}
- σ_{α} = 3.4°
- σ_{δ} = 6.1°

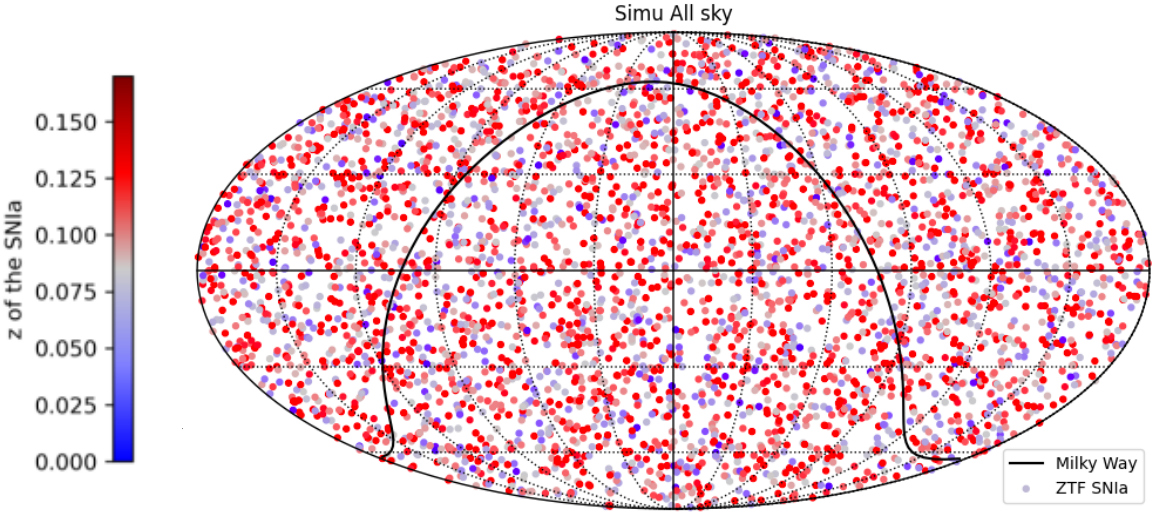
Sky coverage



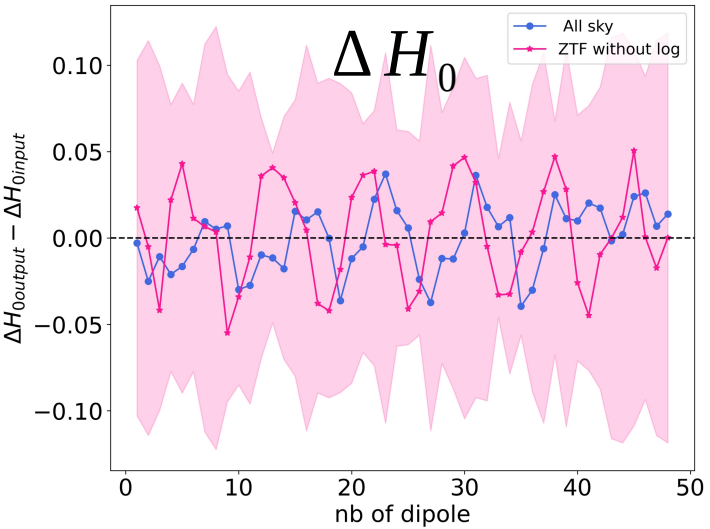


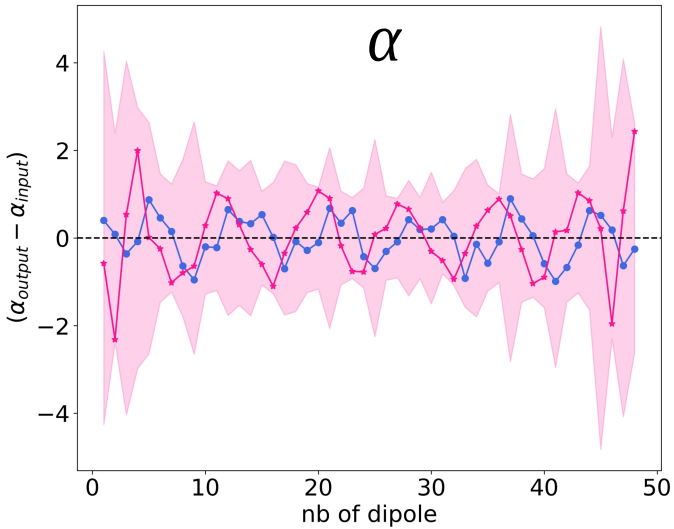


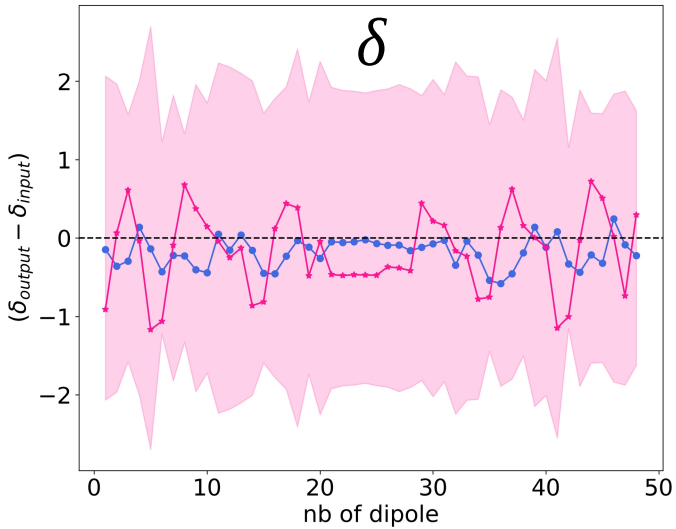
- Unbiased
- Centered around zero for the amplitude and α
- Small shift in δ (~0.15°)



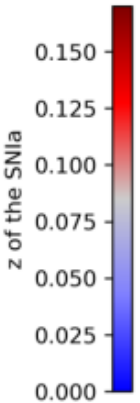
Sky coverage

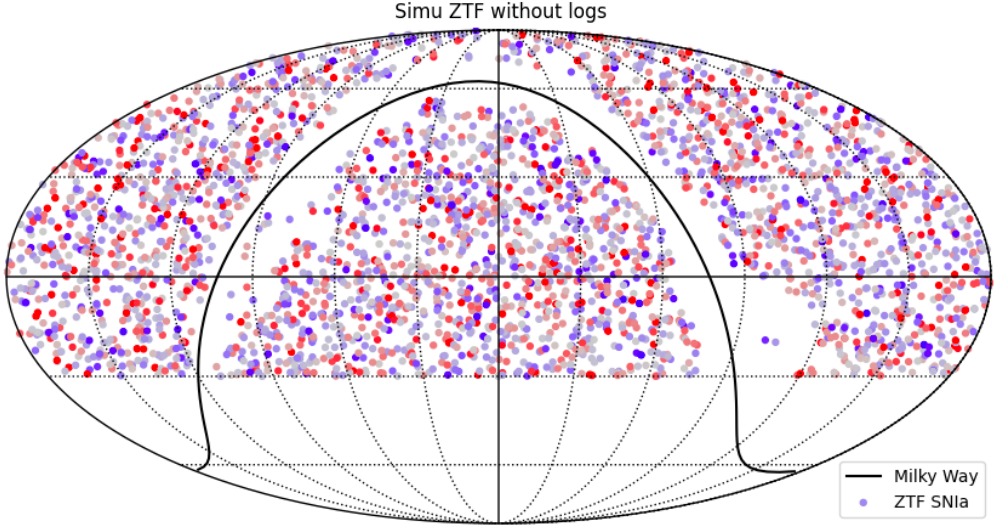




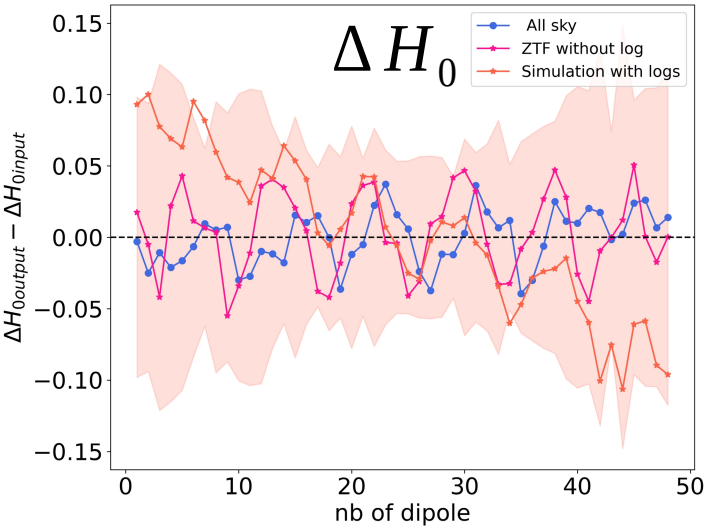


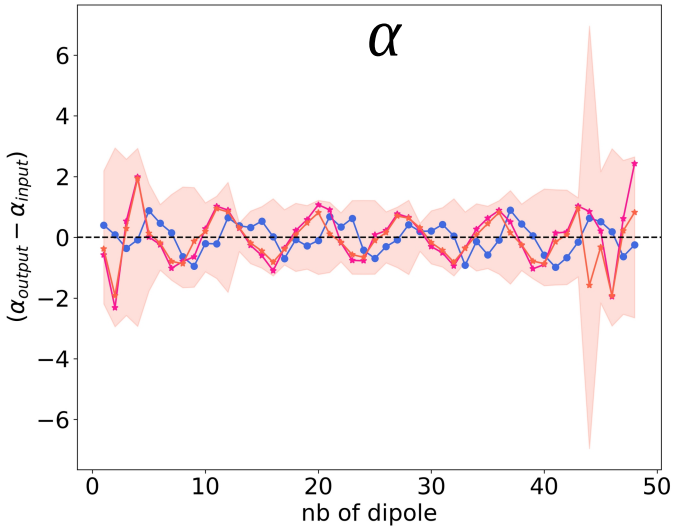
- Unbiased
- Centered around zero for the amplitude and α
- Small shift in δ (~0.10°)

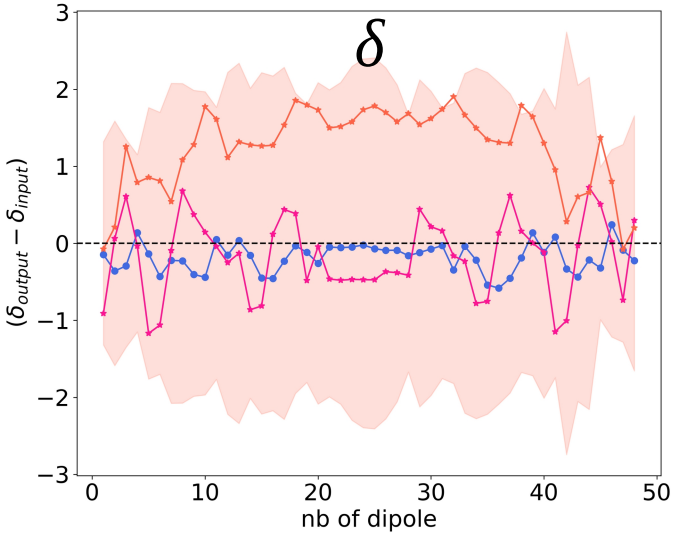




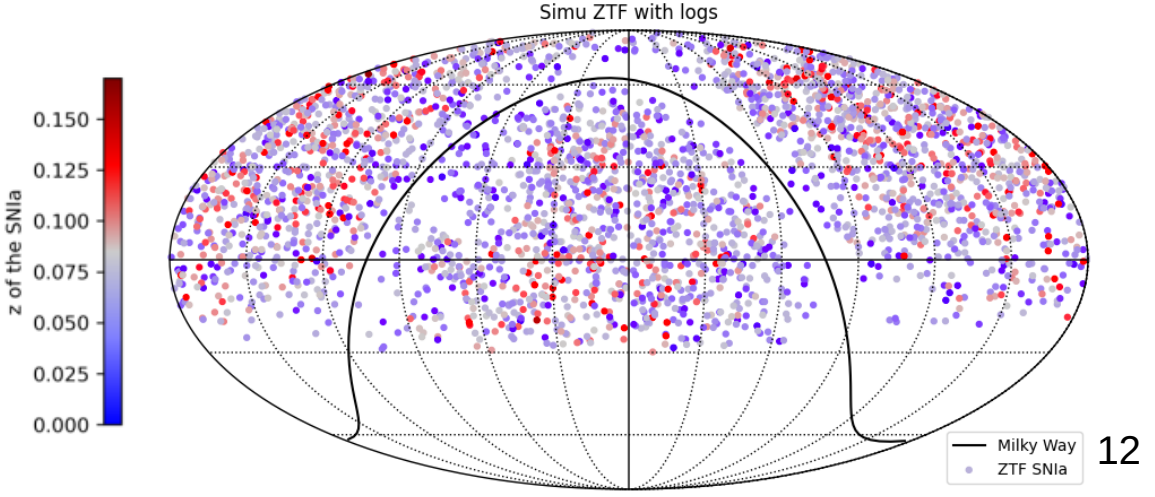
Sky coverage







- Small bias contained in incertitude
- Centered around zero for α
- A slope in the amplitude
- Shift in δ (~1.33°)
- Slope introduced with the observing log but due to a statistical effect

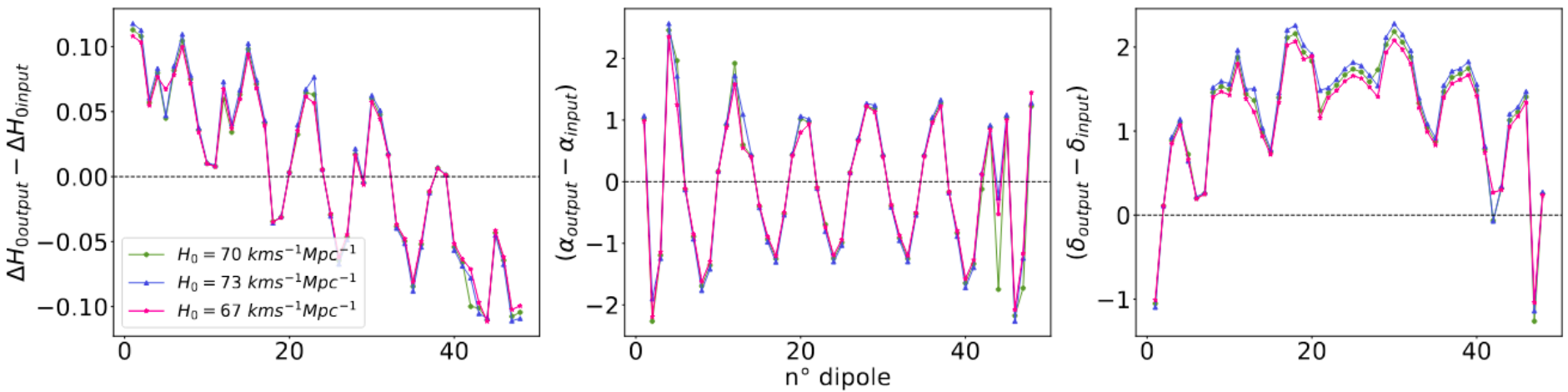


Different values of H_0

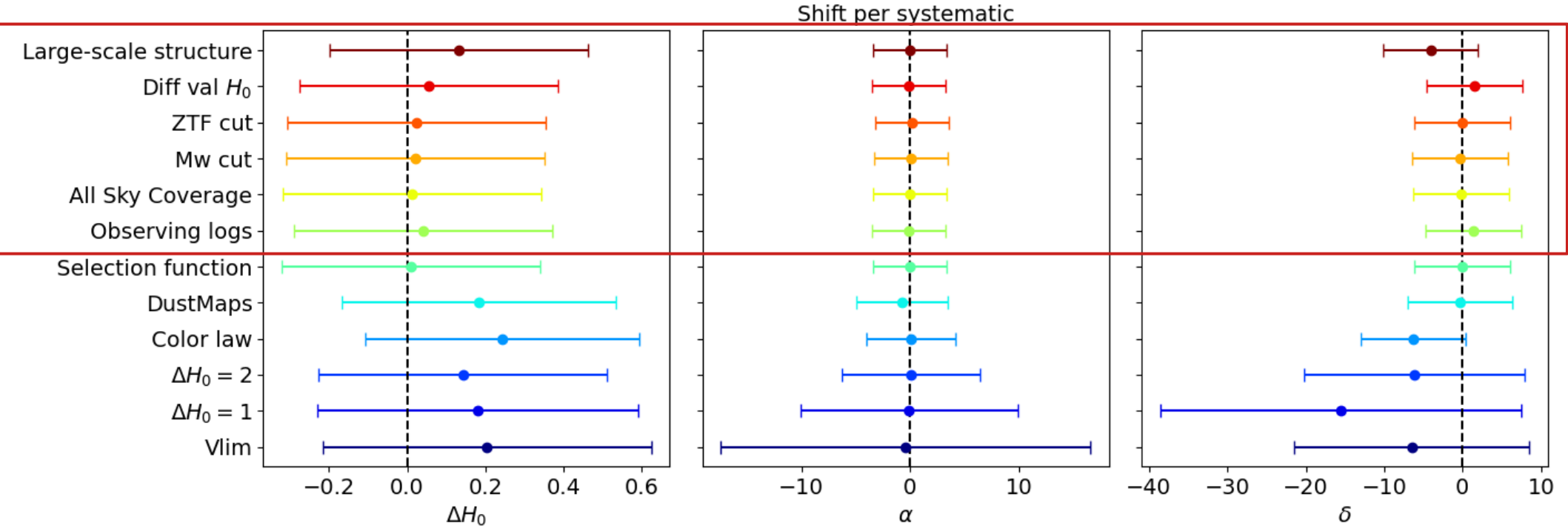
- Same results for the three different values of H_0
- **Independent on the initial value of H_0**

$$d_l = \frac{c(1+z)}{H_0'} \int_0^z \frac{d\zeta'}{\sqrt{((1+\zeta)^3 - 1)\Omega_m + 1}}$$

$$H_0' = H_0 + \Delta H_0 \cos(\Delta\theta)$$



Summary of systematics



Conclusion :

Summary :

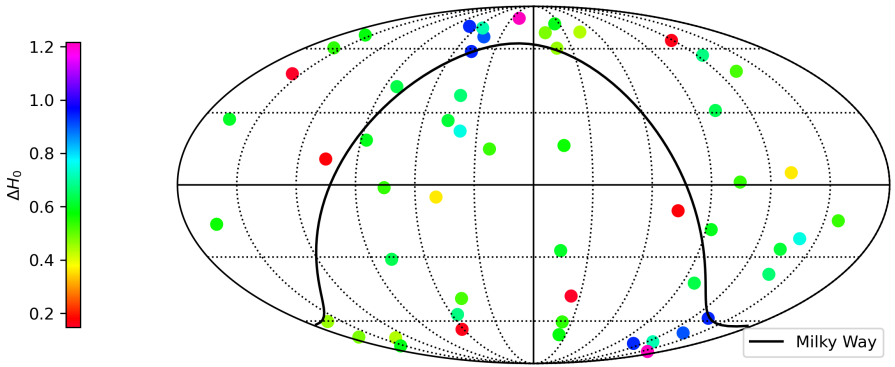
- An original method capable of fitting an H_0 dipole in the ZTF-SNe Ia-DR2.5 simulations
- We recover an initial dipole of 3 km s^{-1} Mpc^{-1} with an error of $\sigma_{\Delta H0}$ = 0.33 km s^{-1} Mpc^{-1} σ_α = 3.4° σ_δ = 6.1°
- Independante on the H_0 value
- The slop appears using the observing logs but containing in the uncertainties

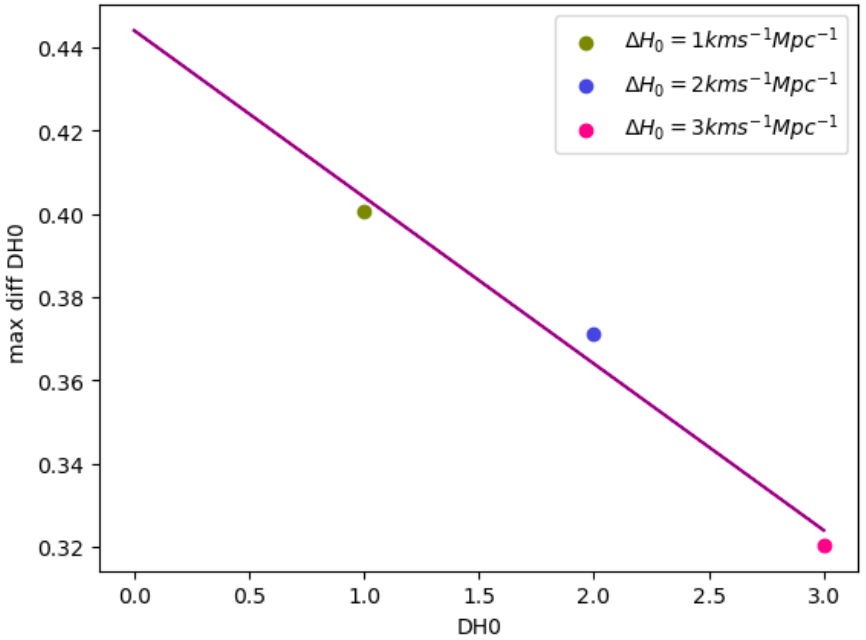
Future

- Introduce Large scale structure in the covariance matrix
- Apply the method on the data
- Introduce quadrupole and multipole

Thank You

Backup - Error model:



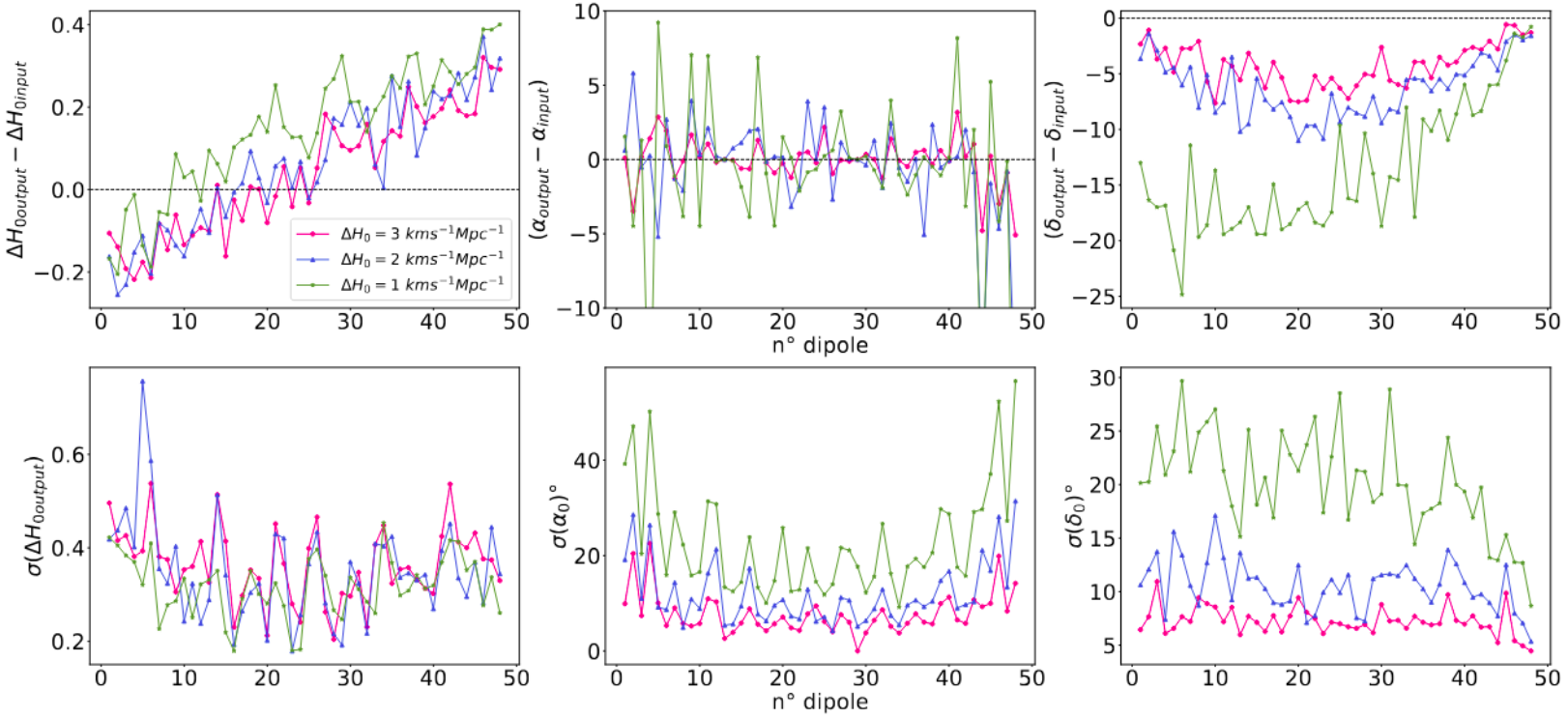


The median of the error of the 27 fits without any dipole in the simulations

$$\sigma_{tot} = \sqrt{\sigma_{stat}^{\,2} + \sigma_{sys}^{\,2}}$$

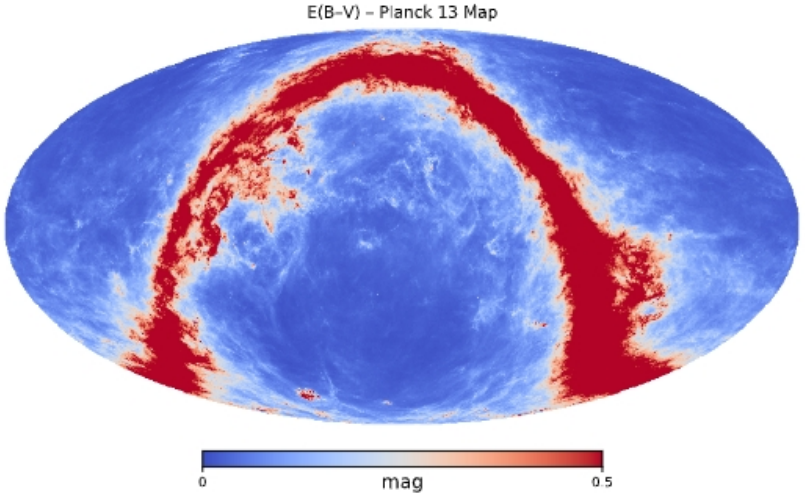
Linear function of the maximum of the slope for the three introduced amplitude dipole.

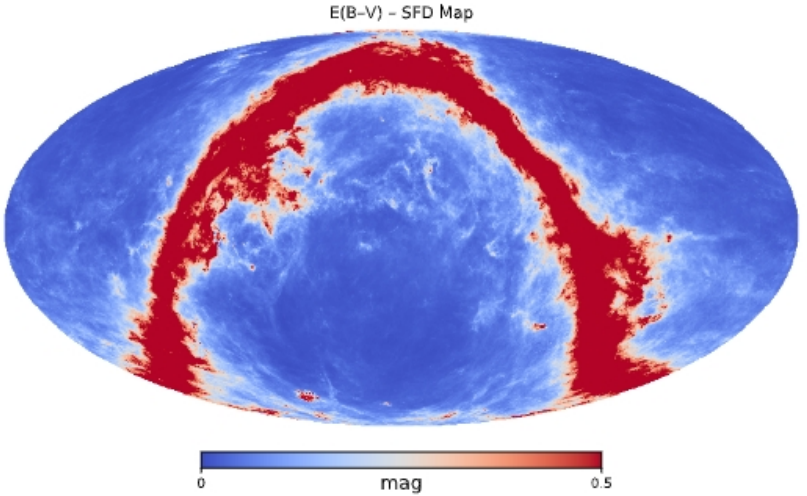
Backup- Different values of amplitude:

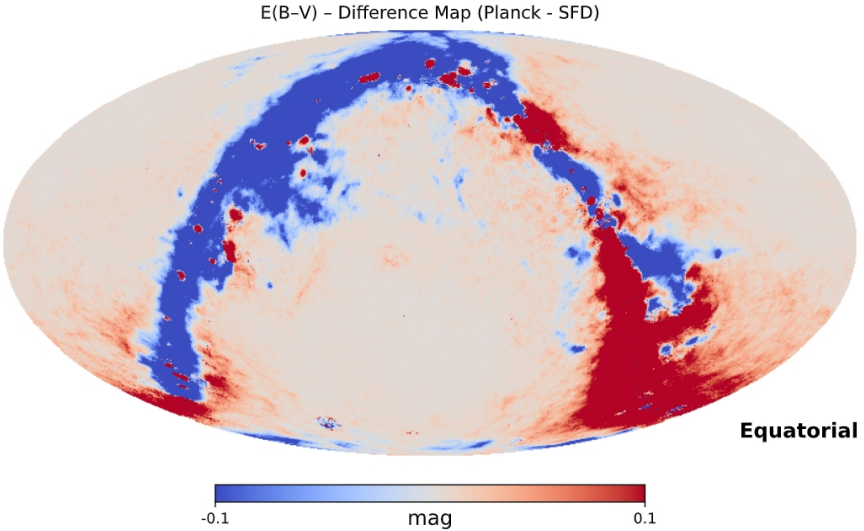


- Same behavior for the amplitude
- Largest oscillations and errors for ΔH_0=1km.s^{-1}.Mpc^{-1}
- Bigger shift for Dec
- We still recover the initial dipole for the three amplitudes

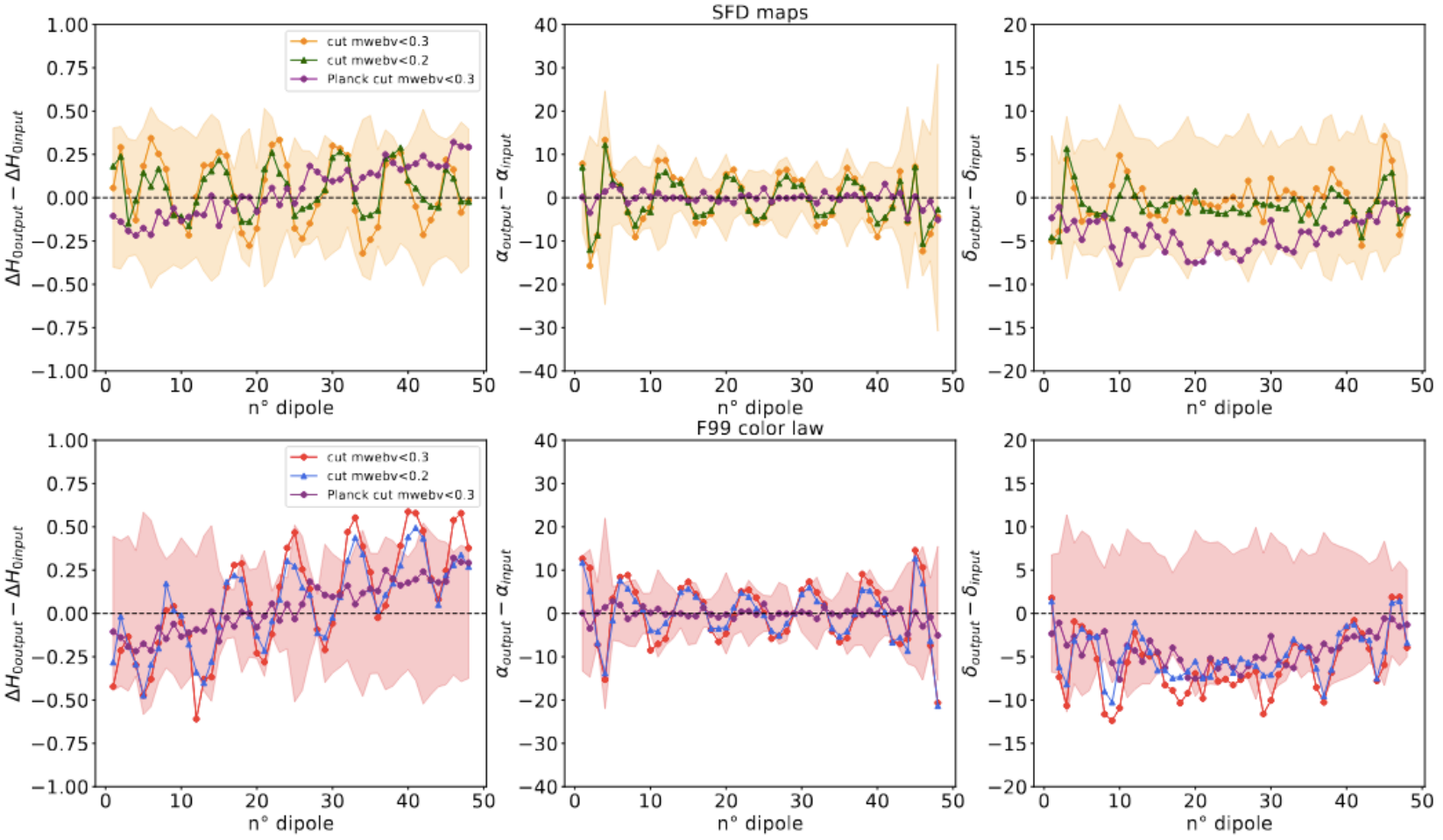
Backup DustMaps:



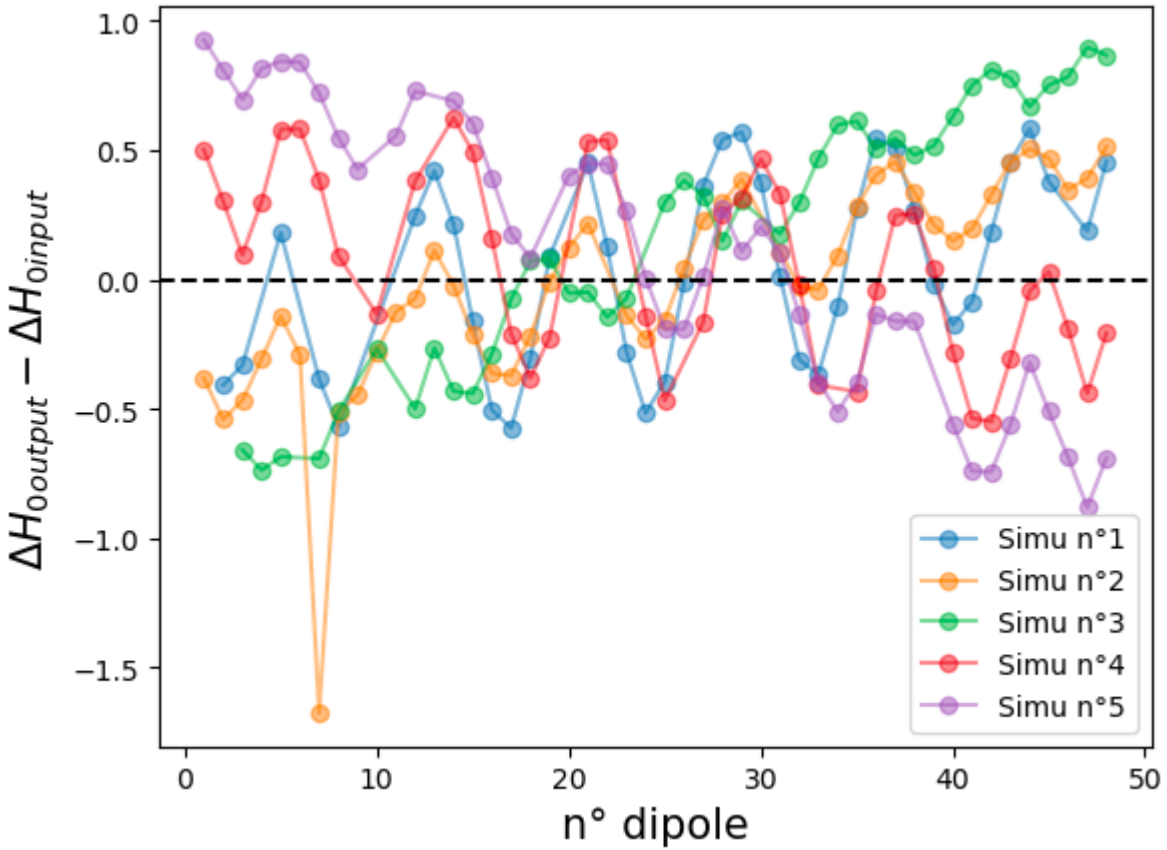




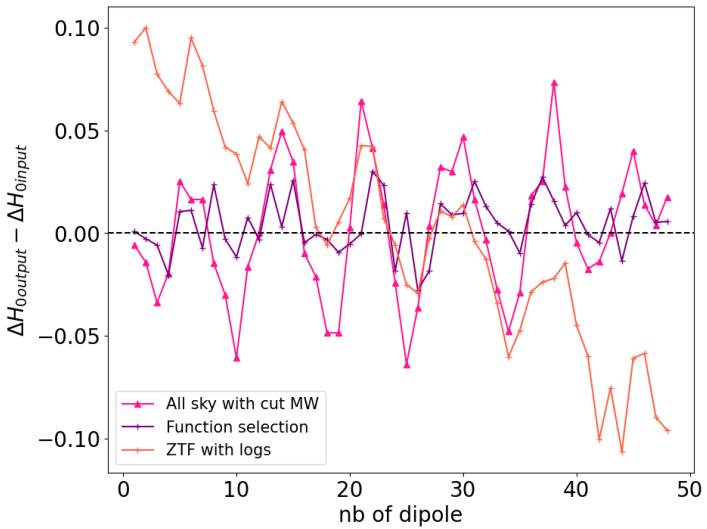
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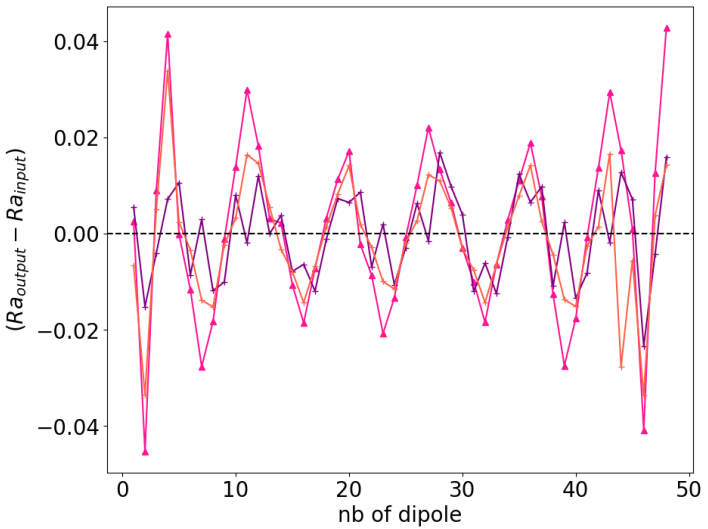


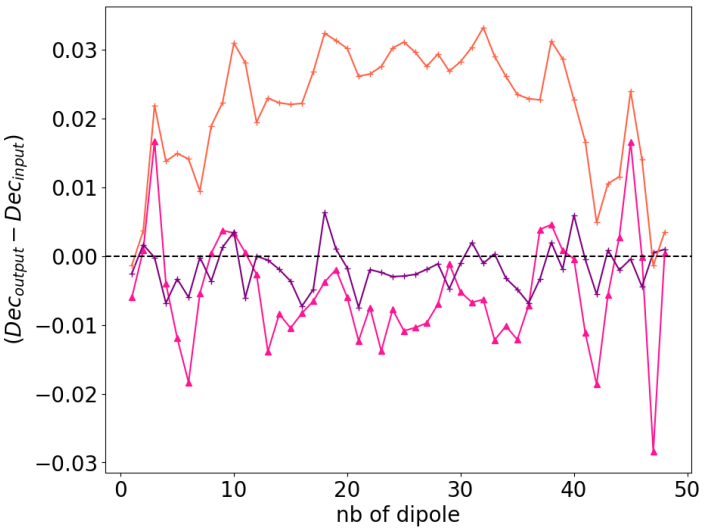
Backup 5 different simulation:



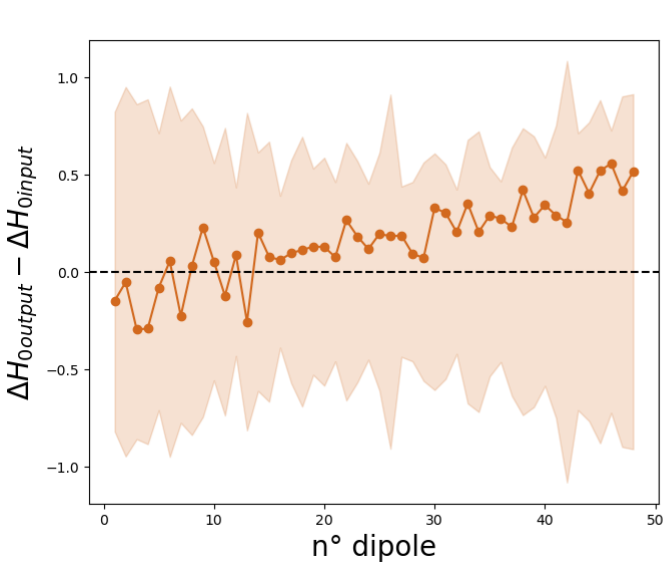
Backup sky coverage:

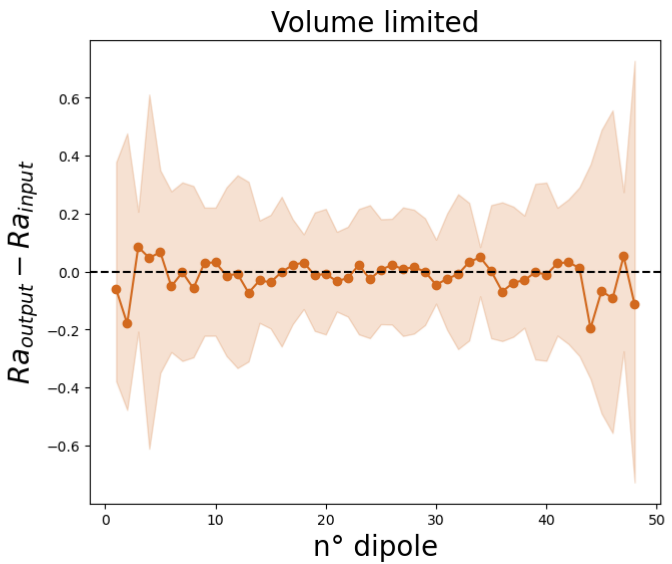


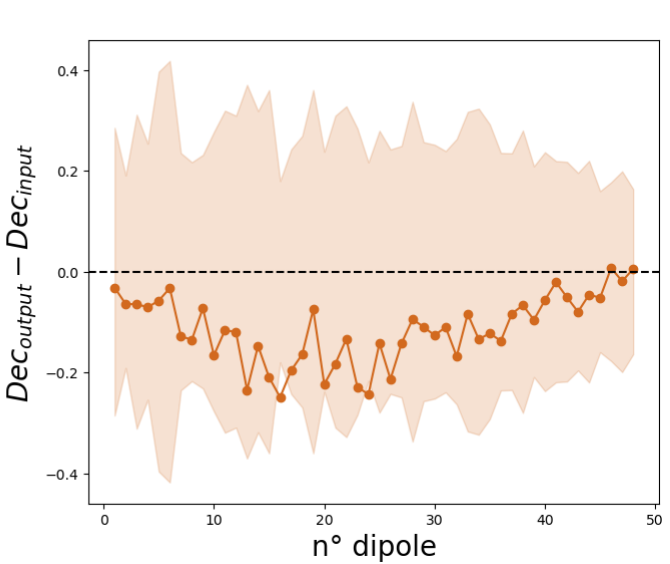




Backup Volume limited:

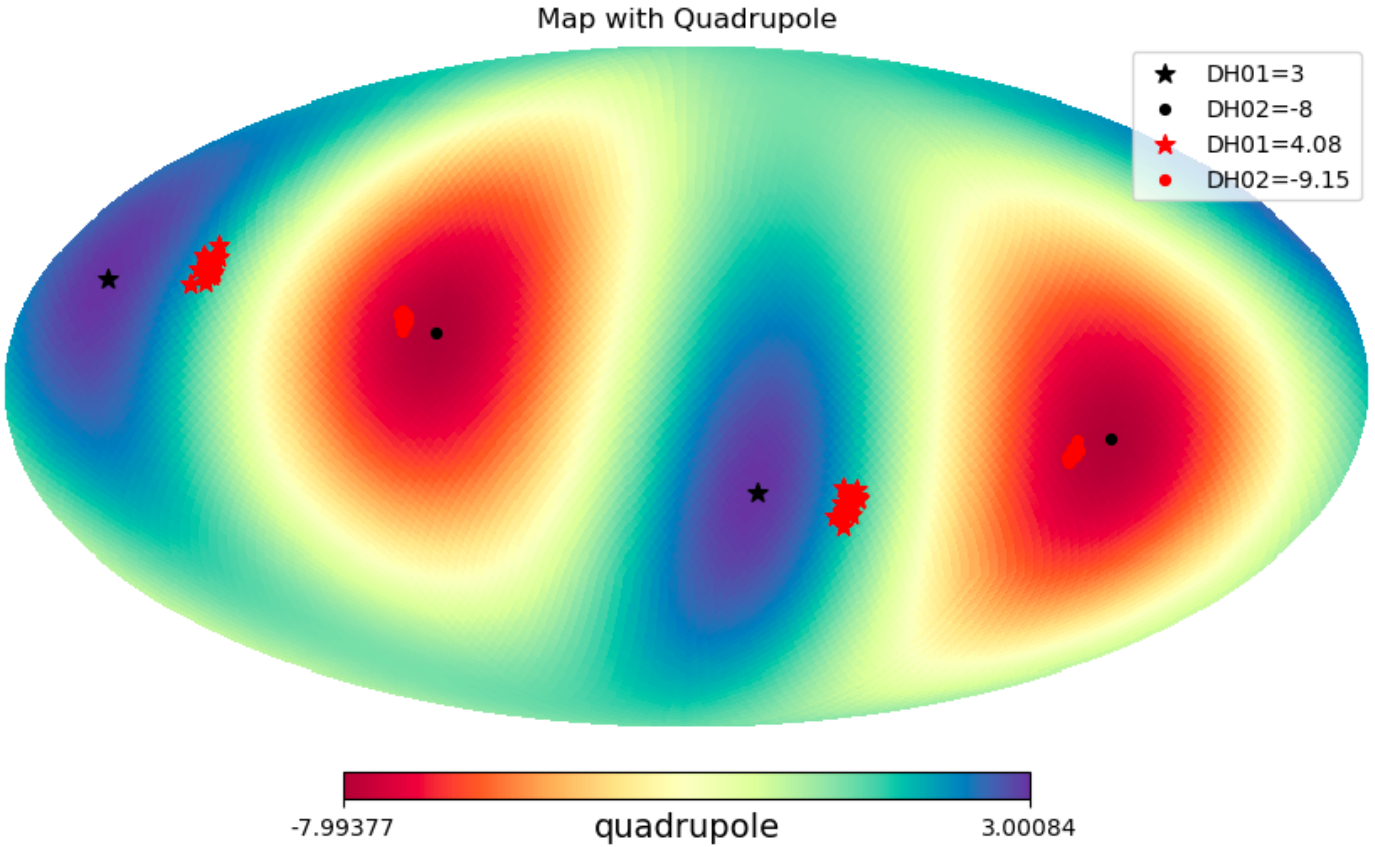




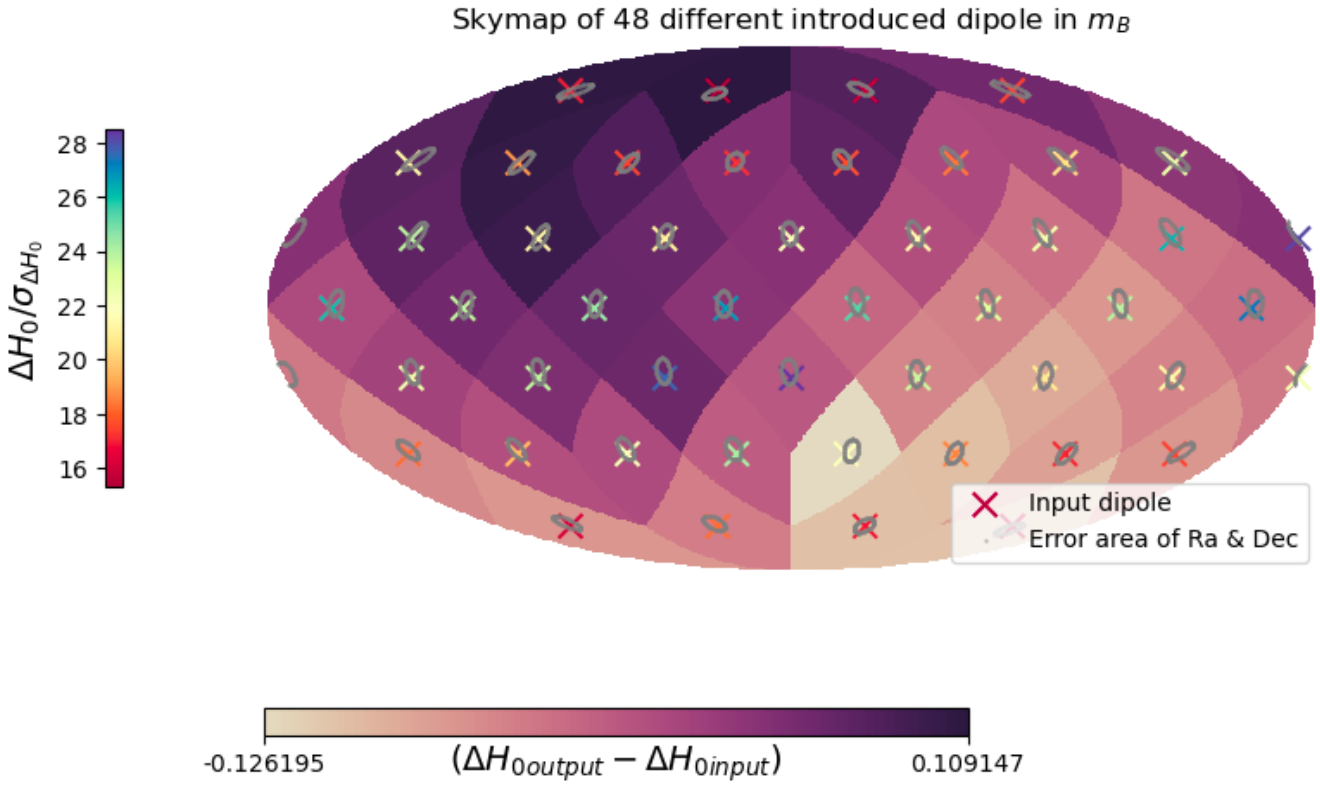


Quadrupole

$$H_0' = H_0 + \Delta H_{01}\cos(\theta_1)^2 + \Delta H_{02}\cos(\theta_2)^2 - (\Delta H_{01} + \Delta H_{02})\cos(\theta_3)^2$$



Dipole fit for 48 different directions :



- ΔH_0= 3km.s^{-1}.Mpc^{-1} for the 48 different directions
- Unbiased direction
- High ΔH0 values at top left of map

Backup - Simulations

- Contains all observation information : maglim, field of observation, possible technical problem

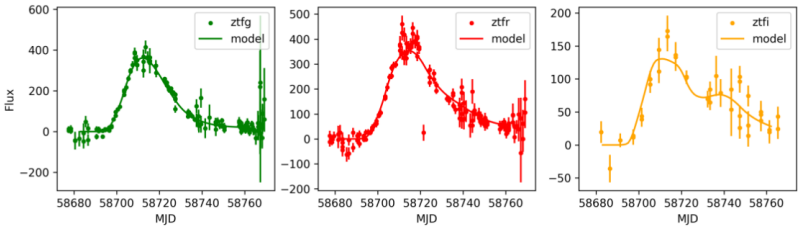
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  $\Omega_m = 0.30966$

Skysurvey

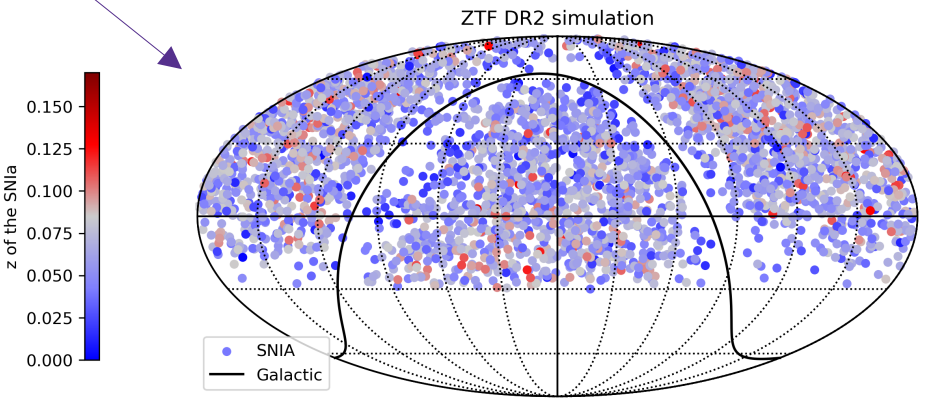
- Sncosmo : SALT2

SN Ia model



M.Amenouche et al., 2025

- Simulates astronomical targets as they would be observed by a survey



Backup SALT2

Sncosmo : A Python Library for Supernova Cosmology analysis.

Usefull for :

- Supernovae modelisation
- Light curve representation
- Simulation
- ...

sncosmo
A Python Library for Supernova Cosmology

Salt2 (T21) Spectral Adaptive Lightcurve Template version 2 : one supernovae model to modelize ligth curve parameters

$$F(p,\lambda) = X_0 \times [M_0(p,\lambda) + X_1 M_1(p,\lambda)] \times \exp[C\,\mathrm{CL}(\lambda)]$$