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

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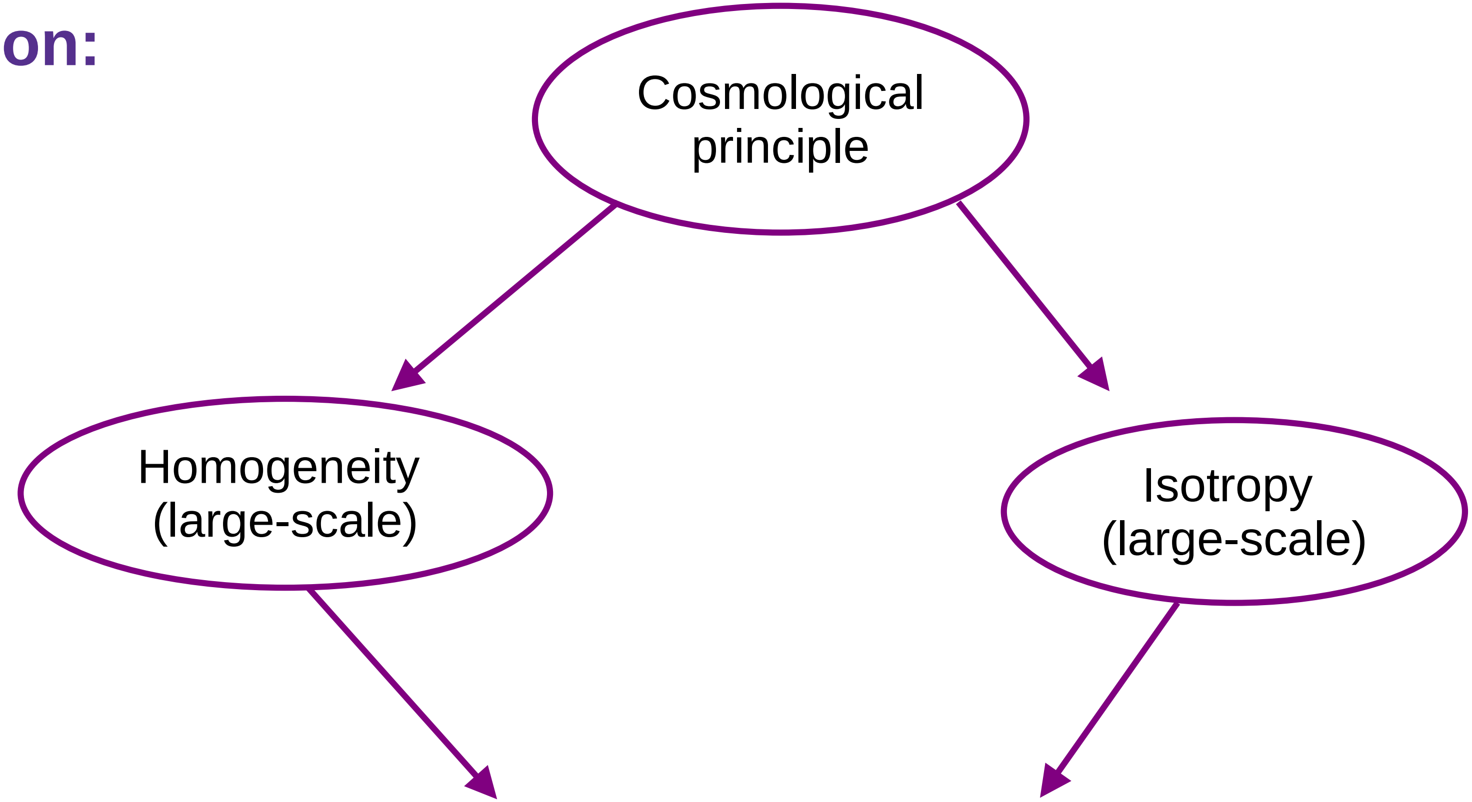
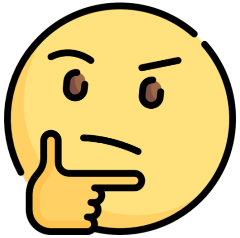
Action Dark Energy
7 Novembre 2025

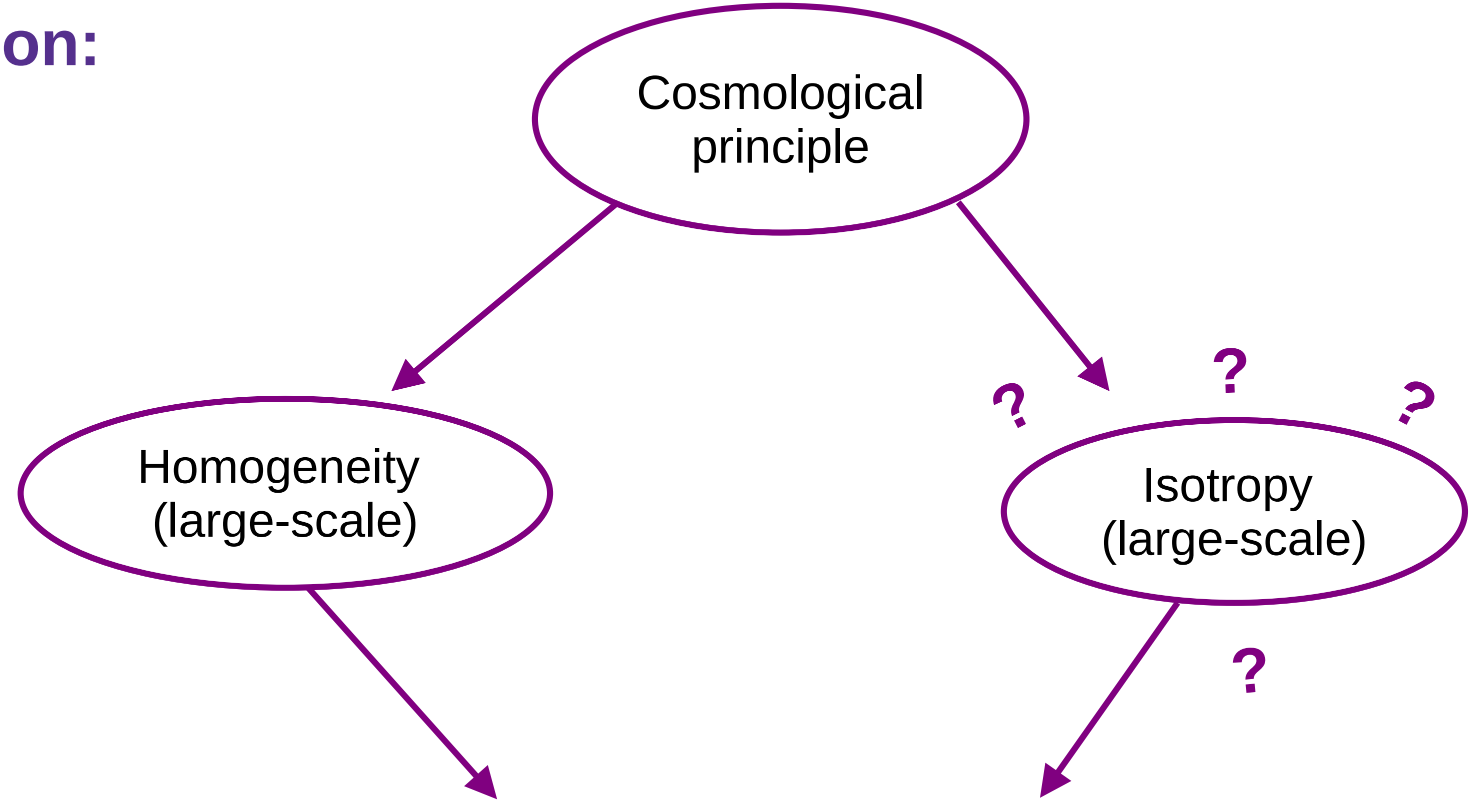
Motivation:



$$ds^2 = c^2 dt^2 - a(t)^2 (dx^2 + dy^2 + dz^2)$$

Motivation:





$$ds^2 = c^2 dt^2 - a(t)^2 (dx^2 + dy^2 + dz^2)$$

Motivation:

Anisotropic Universe

Bianchi I (spatially flat and homogenous universe) :
Hertzberg et al 2024

$$ds^2 = dt^2 - a(t)^2 dx^2 - b(t)^2 dy^2 - c(t)^2 dz^2$$

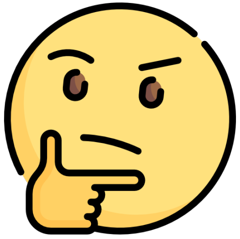
Bianchi I with residual planar symmetry (spatially flat and homogenous universe):
Verma et al 2024

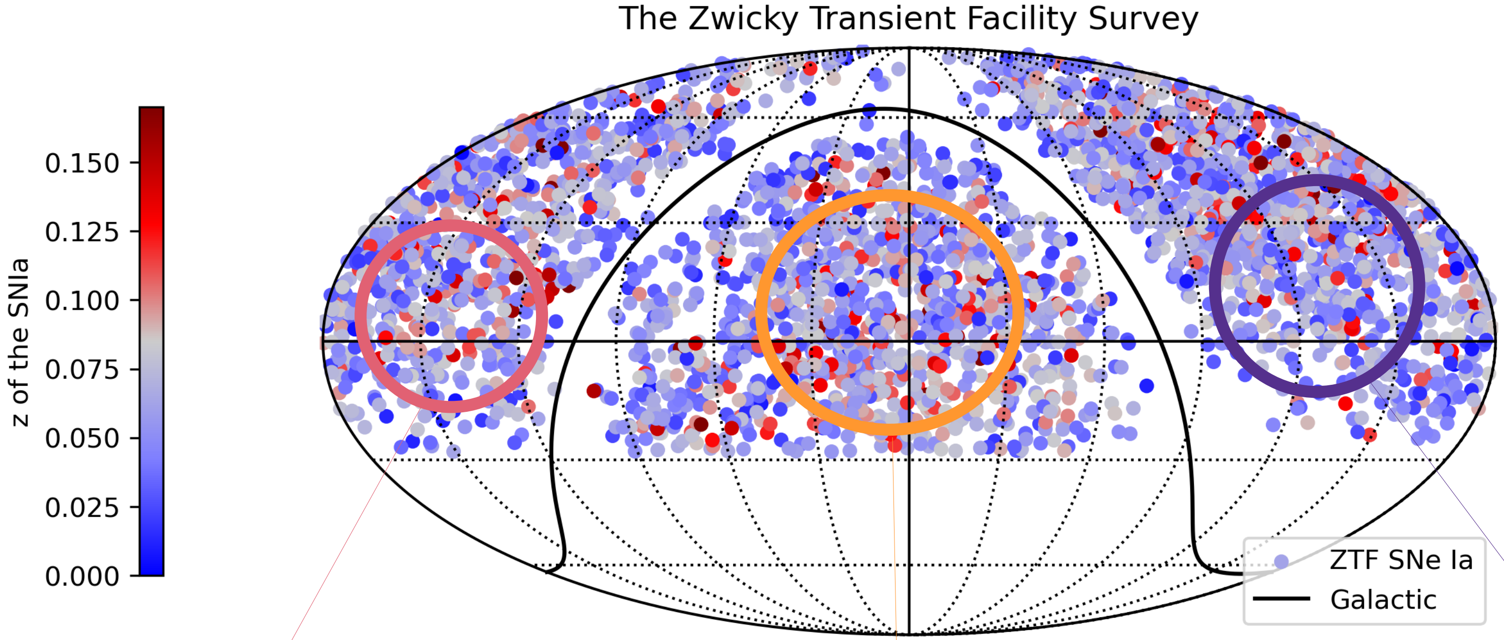
$$ds^2 = dt^2 - a(t)^2 (dx^2 + dy^2) - b(t)^2 dz^2$$

Szekeres model :
Célérier et al 2024
inhomogeneous model which imply anisotropie

Axisymmetric model :
homogenous universe with sub group of symmetry.

Motivation:





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

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

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

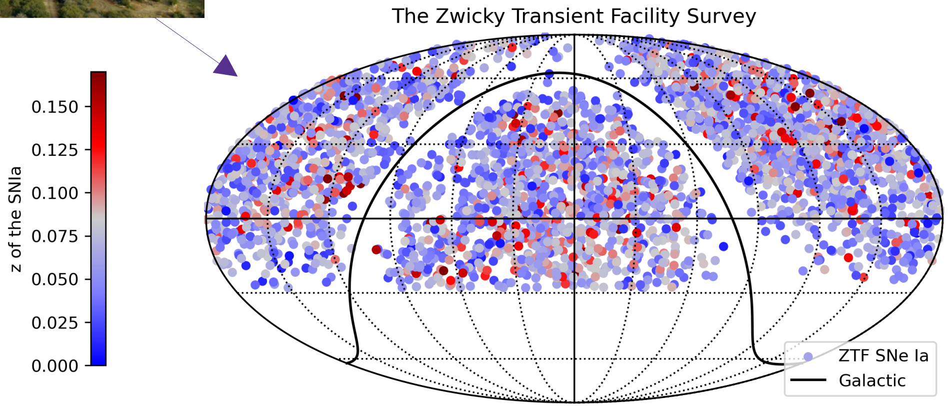
Zwicky Transient Facility (ZTF):

- Survey of the Northern sky begun in 2018 in California

- Unique survey of low redshift Sne Ia

- DR2 : second data release contains 3628 spectroscopically Sne Ia, between 2018-2020

- Simulation : Skysurvey



- *A&A special issue : https://www.aanda.org/component/toc/?task=topic&id=2090*

- Observe in three bands : g, r, i

Realistic ZTF Simulation:

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

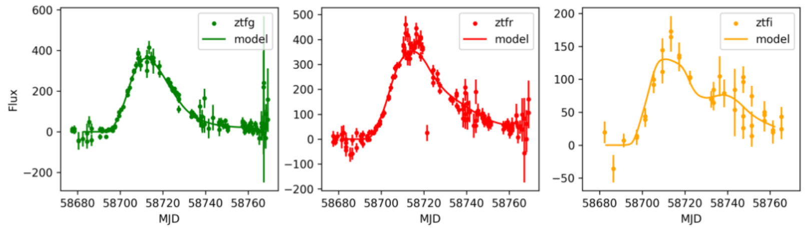
ZTF observing logs

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

Skysurvey

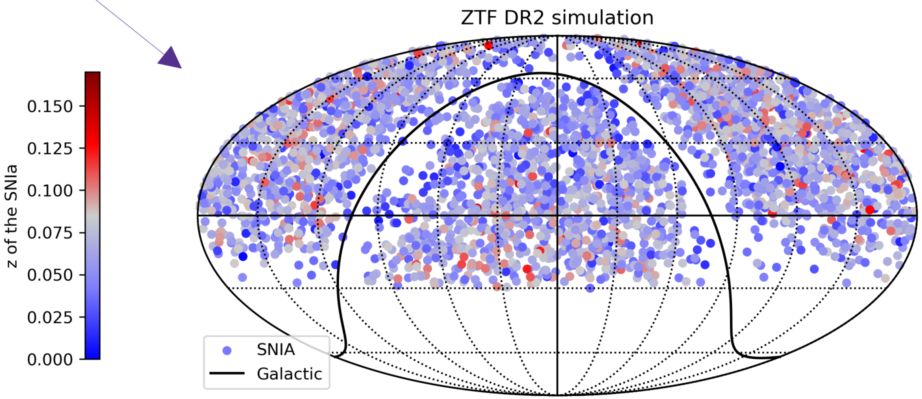
- Sncosmo : SALT2

SN Ia model



M.Amenouche et al., 2025

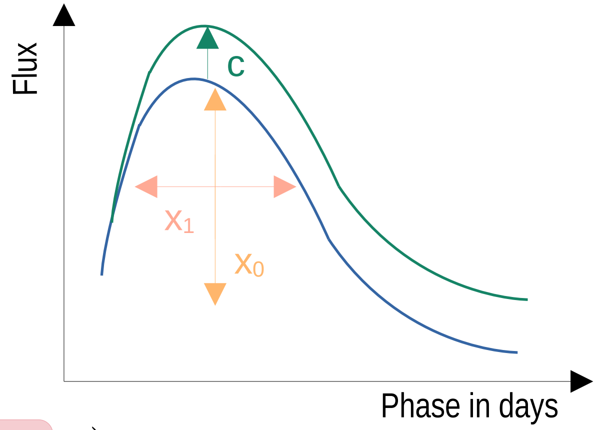
- Simulates astronomical targets as they would be observed by a survey



SNe Ia - Standardization:

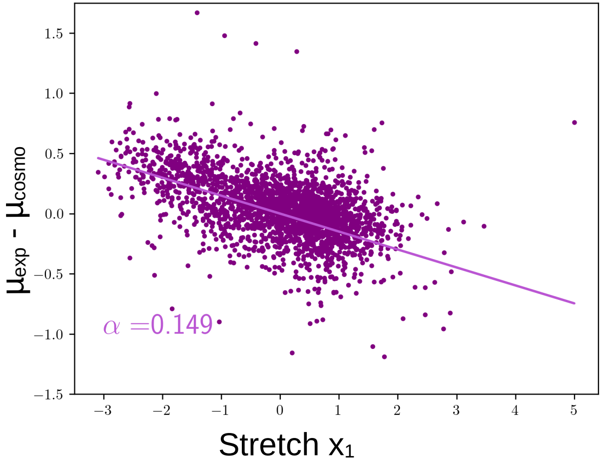
$$\mu^{exp} = m_B - M_B + \alpha\, x_1 - \beta\, c$$

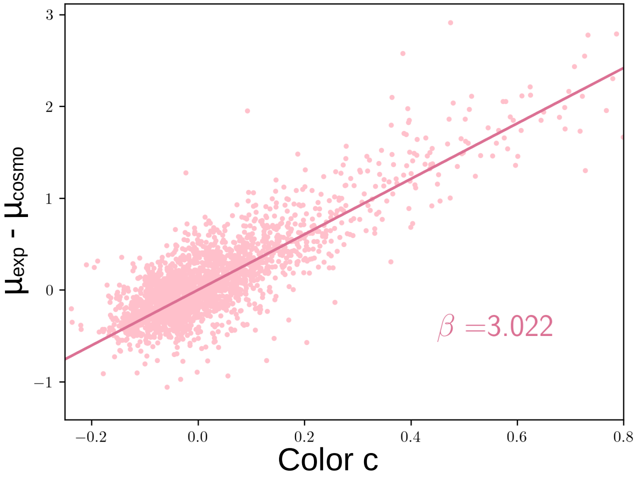
$$\mu^{cosmo} = 5\log\left(d_l(Mpc)\right) + 25$$

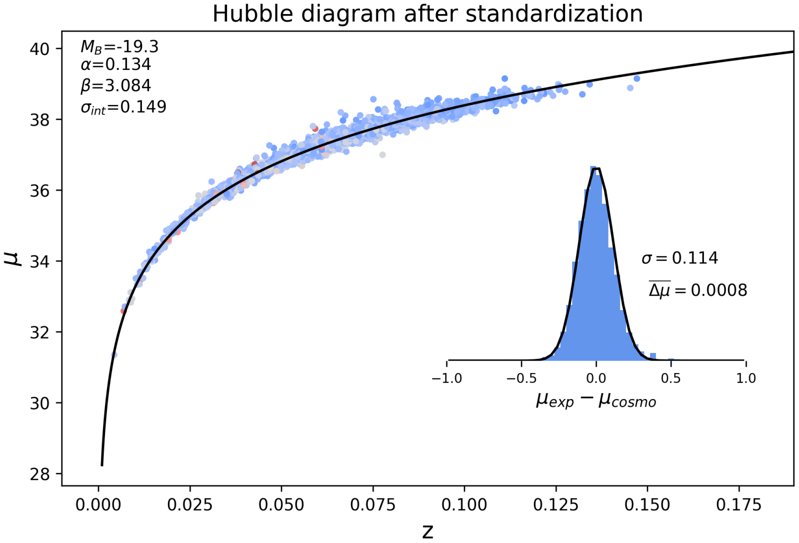


Free

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







Dipole introduced in redshift z :

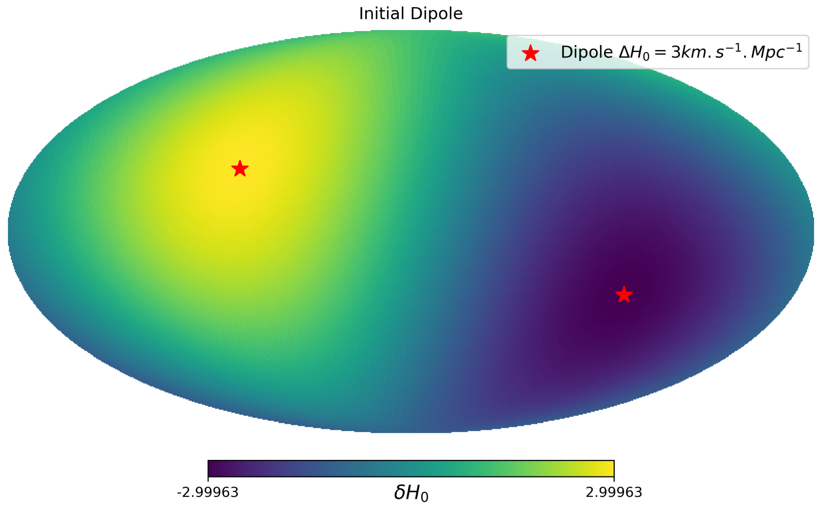
$H_0 = 67.66$ km.s^{-1}Mpc^{-1}

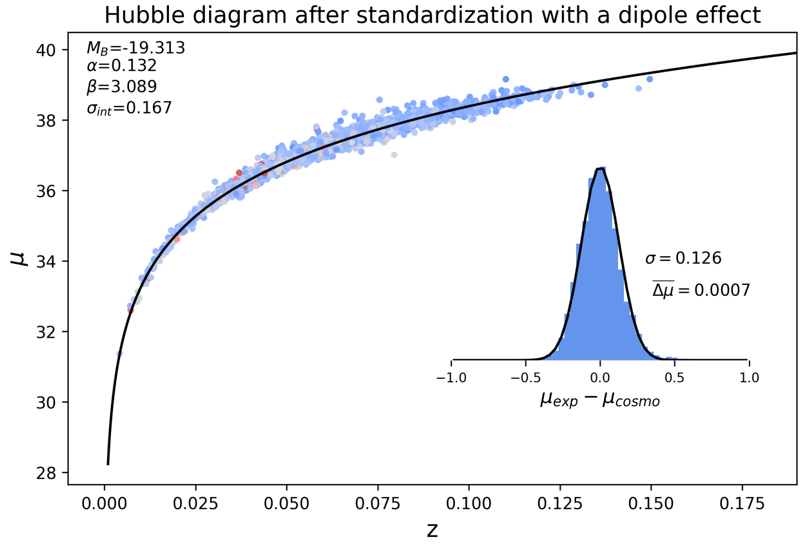
$\Delta\theta = \theta^{i}_{SNIa} - \theta_{dipole}$

$$cz' = H_0' d = \left(H_0 + \Delta H_0 \cos(\Delta\theta)\right) d$$

$$z' = \left(1 + \frac{\Delta H_0 \cos(\Delta\theta)}{H_0}\right) z$$

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





Dipole introduced in luminous distances dl :

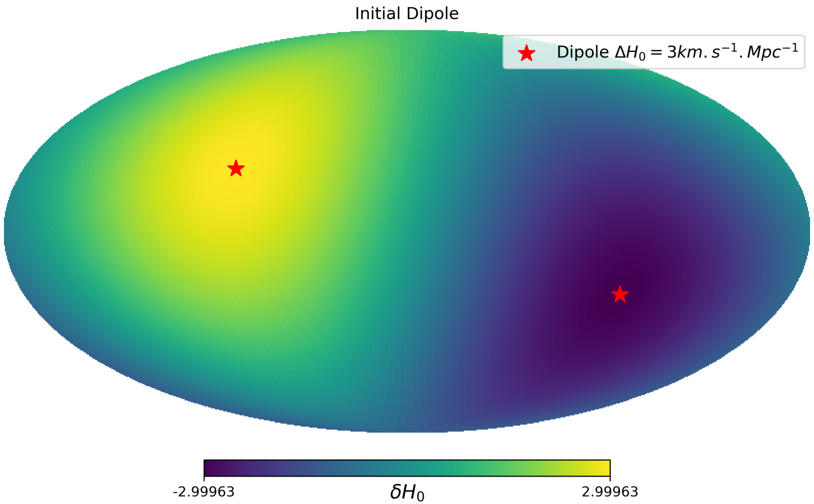
$H_0 = 67.66$ km.s^{-1}Mpc^{-1}

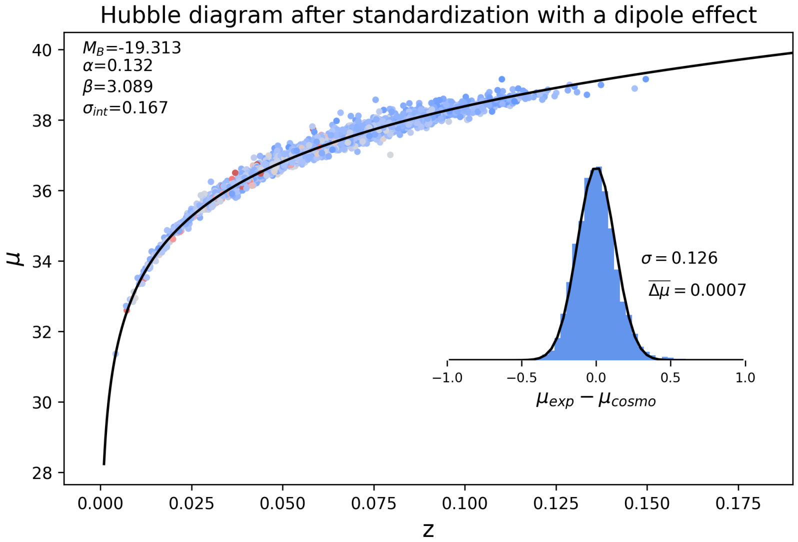
$$d_l = \frac{c(1+z)}{H_0'} \int_0^z \frac{dz'}{\sqrt{((1+z')^3 - 1)\Omega_m + 1}}$$

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

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

$\Delta\theta = \theta^i_{SNIa} - \theta_{dipole}$





Dipole introduced in magnitude m:

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

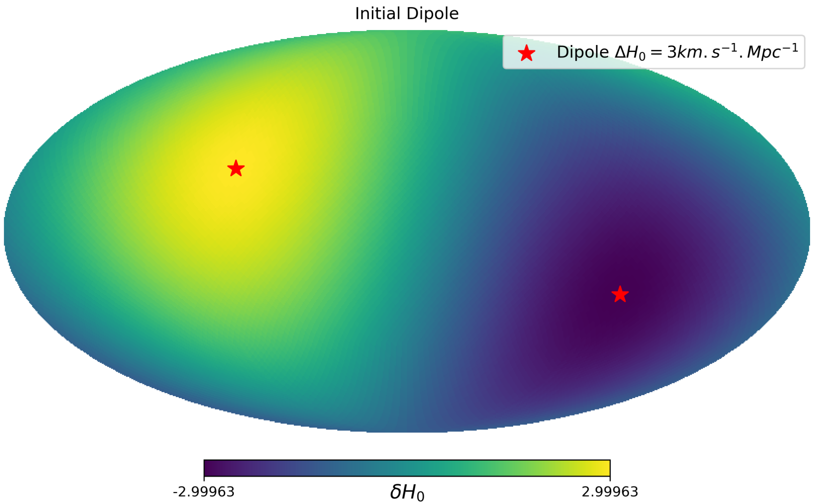
$$\mu' = 5\log(d_l') + 25 = \mu + 5\log\left(\frac{H_0}{H_0'}\right) = m_B' - M_B$$

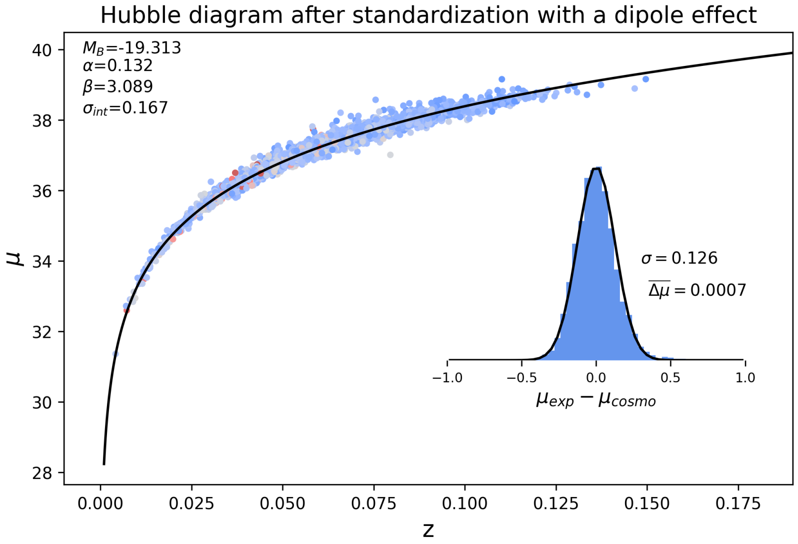
$$m_B' = m_B + 5\log\left(\frac{H_0}{H_0'}\right)$$

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

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

$\boxed{\Delta\theta = \theta^i_{SNIa} - \theta_{dipole}}$

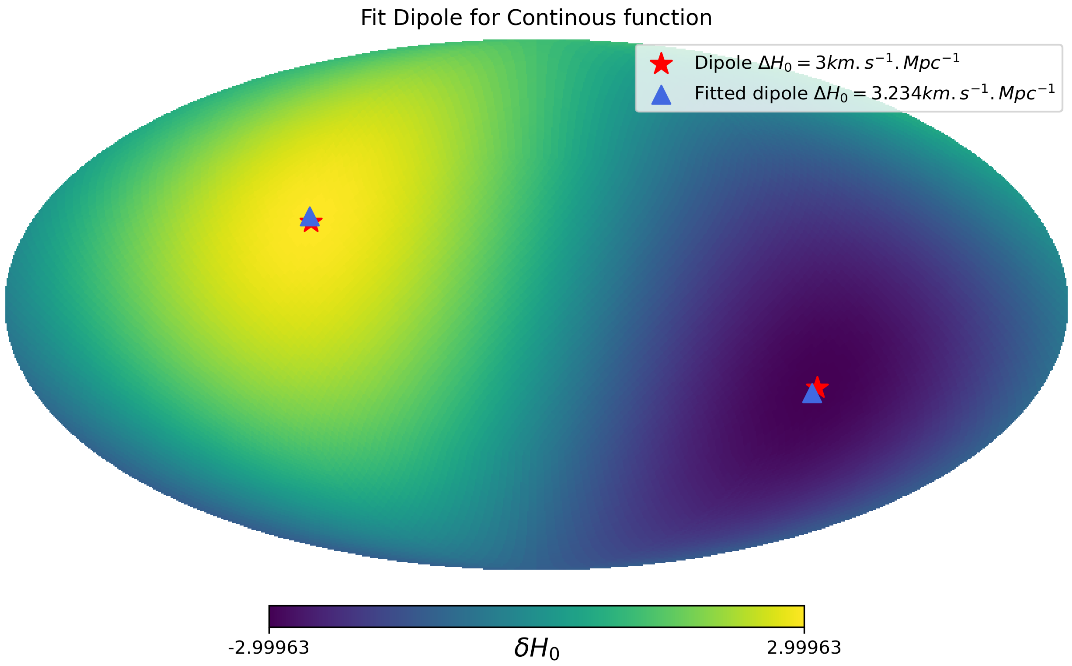




Dipole fit for one simulation for z method :

$$\left(M_B, \alpha, \beta, \sigma_{intr}\right) \longrightarrow \text{Free}$$

$$\chi^2 = \sum_{i=1}^{N_{SNeIa}} \left(\frac{\mu_i^{\exp} - \mu_i^{cosmo}\left(z_i, \theta_i, \theta_{dip}, \Delta H_0\right)}{\sigma_{\mu_i}} \right)^2$$

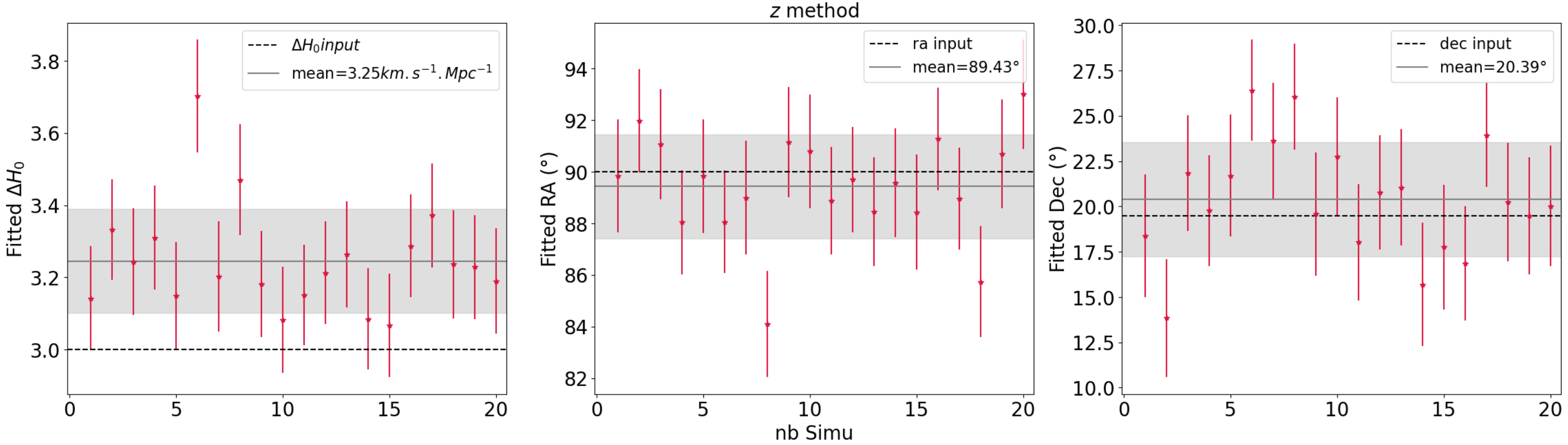


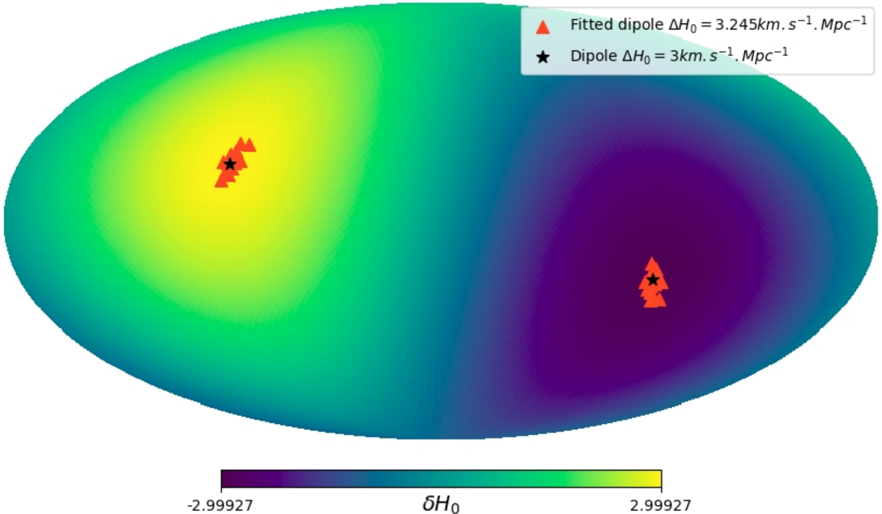
$$\mu^{cosmo} = 5\log\left(d_l(Mpc)\right) + 25$$

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

$$H_0' = H_0 + \Delta H_0 \cos\left(\theta_i - \theta_{dip}\right)$$

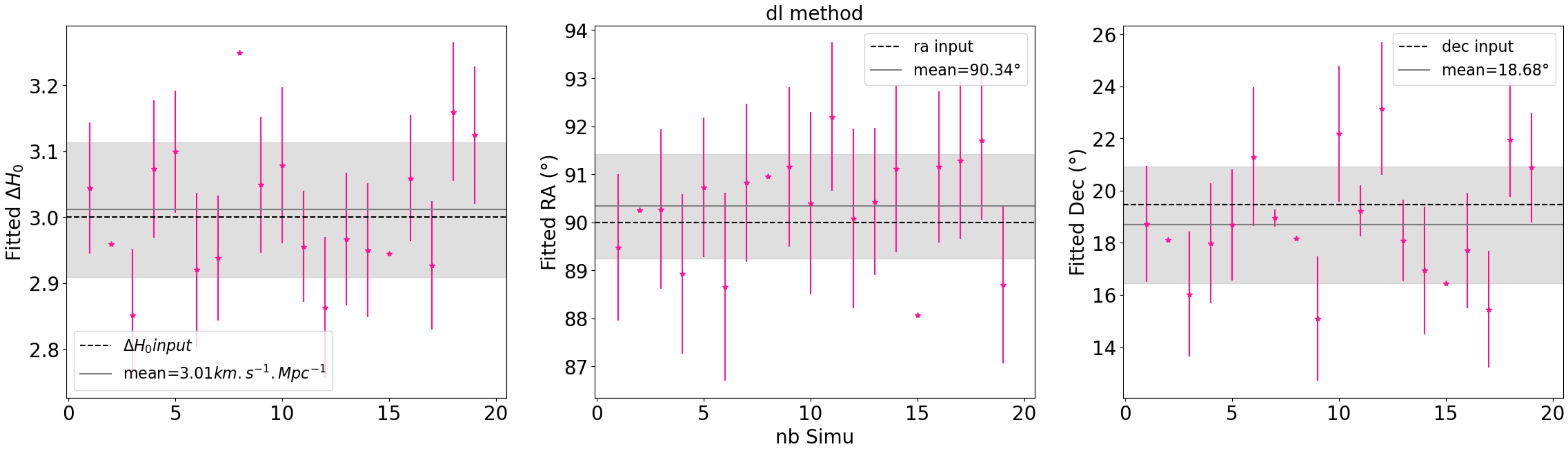
Dipole fit for 20 independent simulations for the z method :

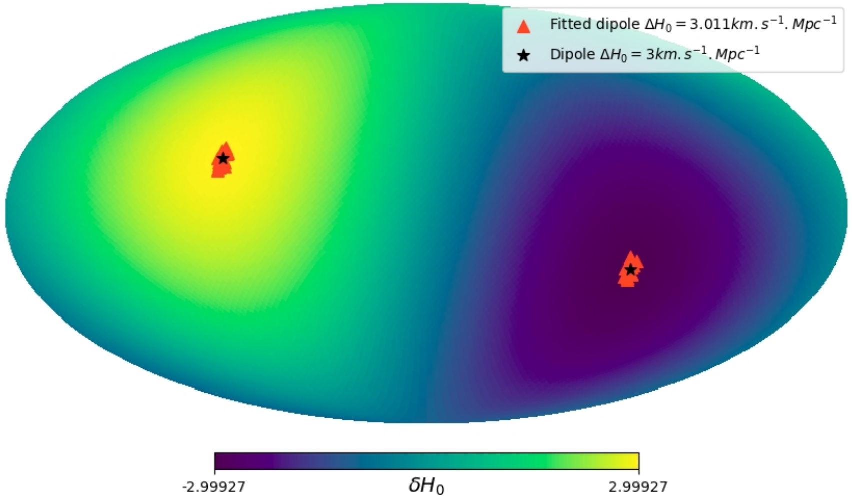




- Unbiased direction
- ~2σ ΔH_0 bias

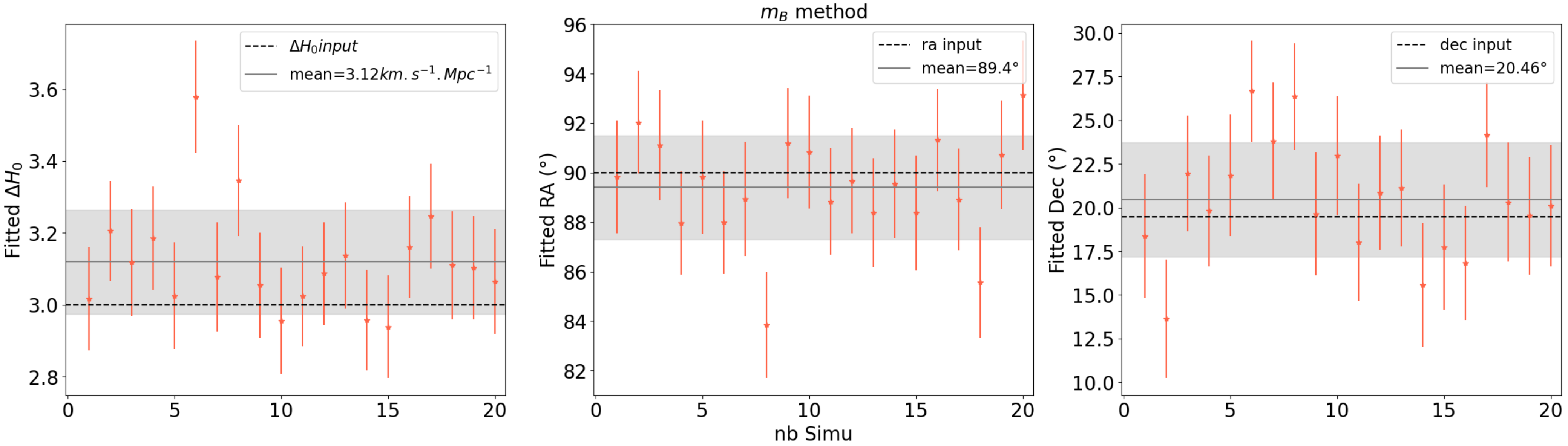
Dipole fit for 20 independent simulations for the dl method :

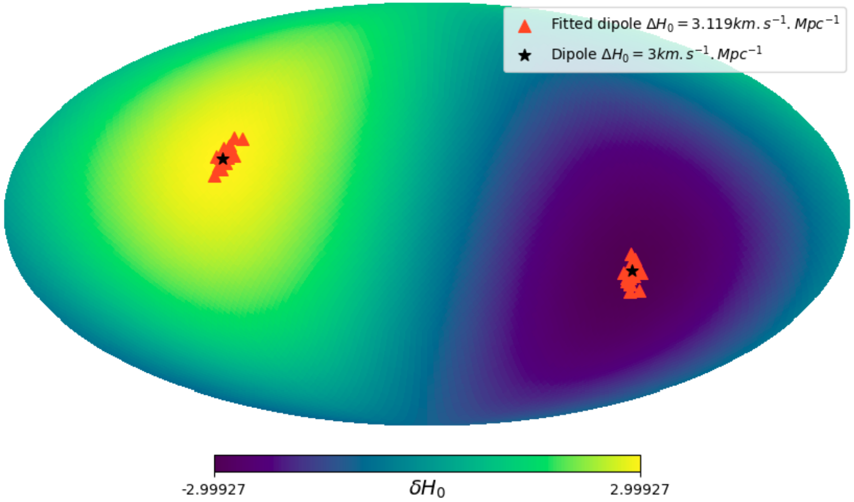




- Unbiased direction and amplitude

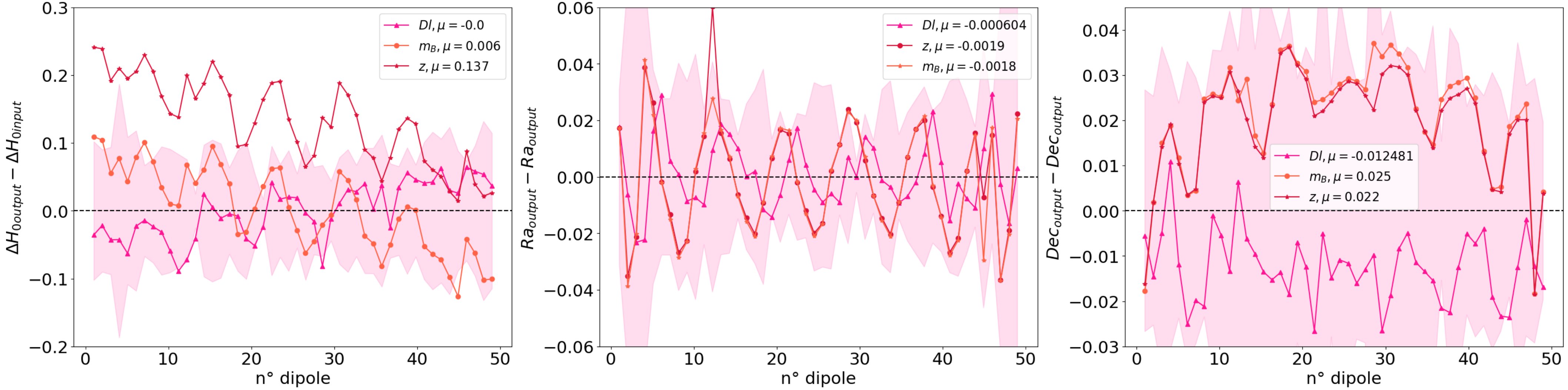
Dipole fit for 20 independent simulations for the m method :



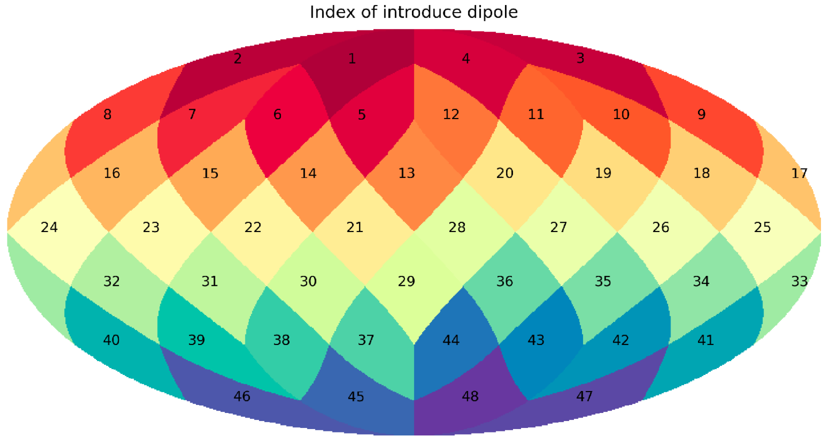


- Unbiased direction and amplitude

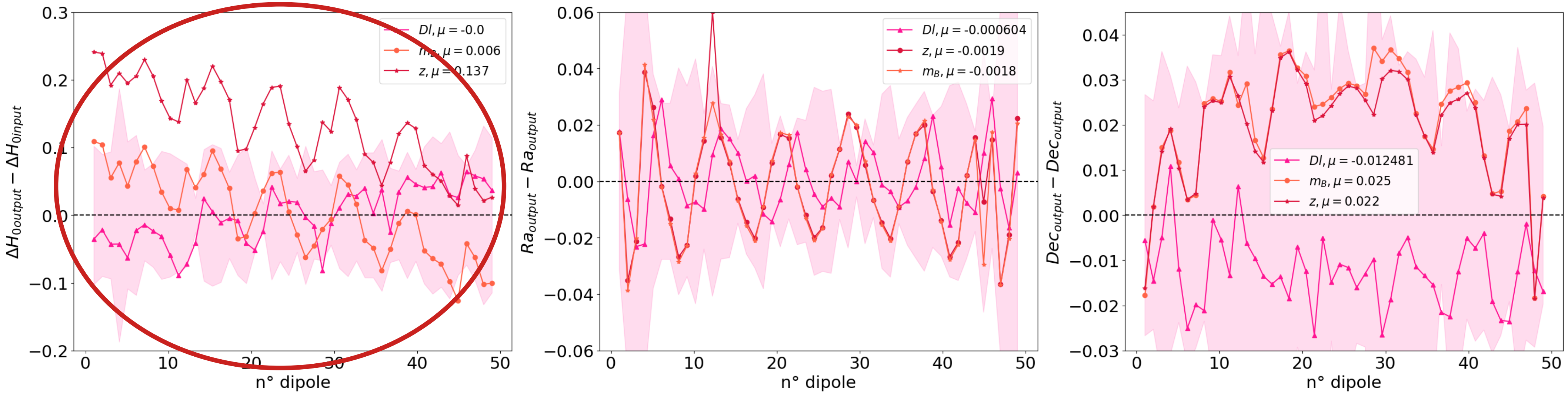
Comparison between the three methods:



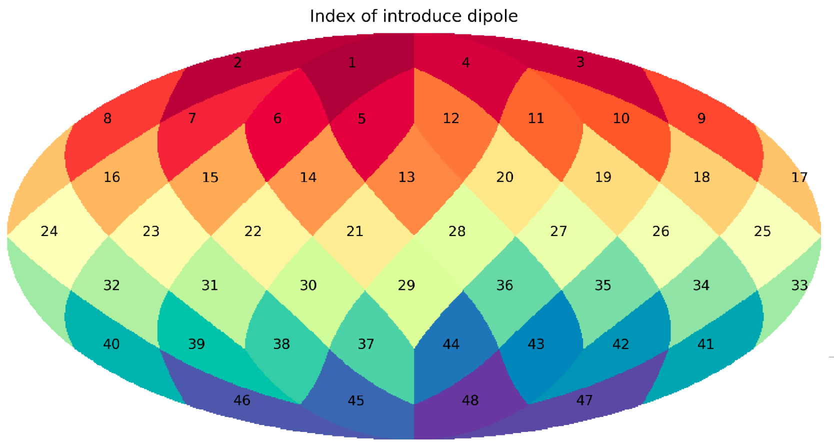
- Dl method unbiased
- M method unbiased and less costly



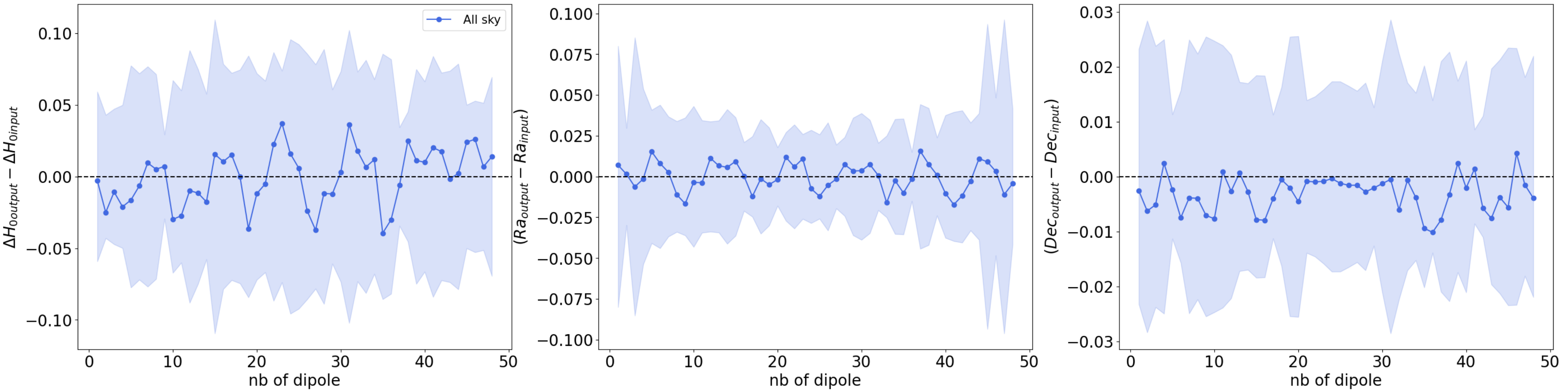
A third method to introduce the dipole:



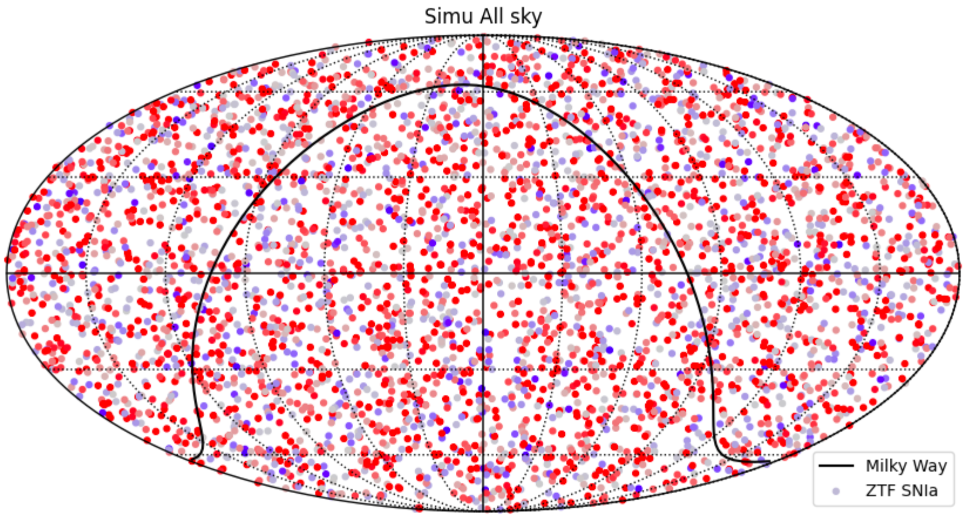
- DI method unbiased
- M method unbiased and less costly



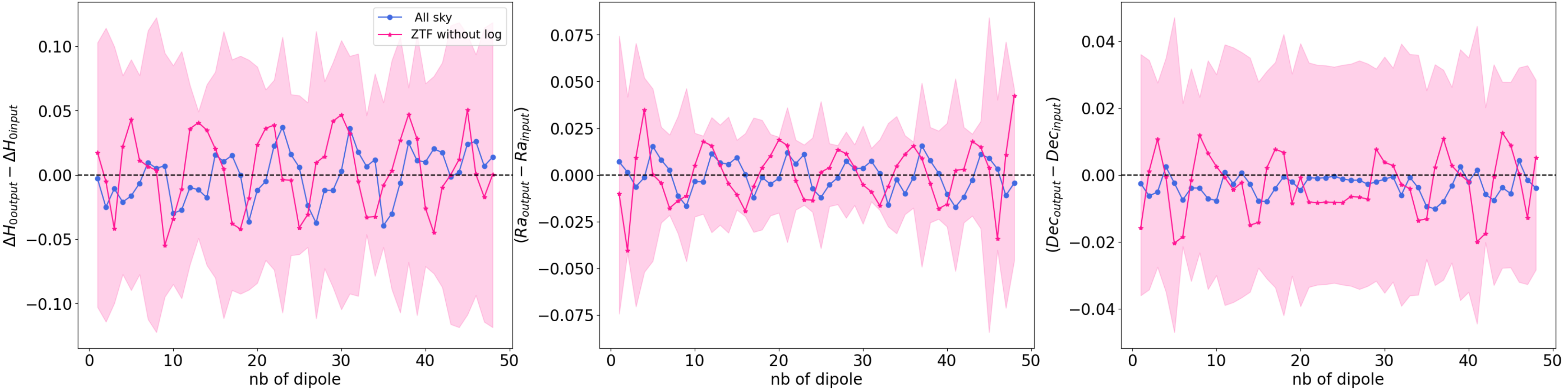
Sky coverage:



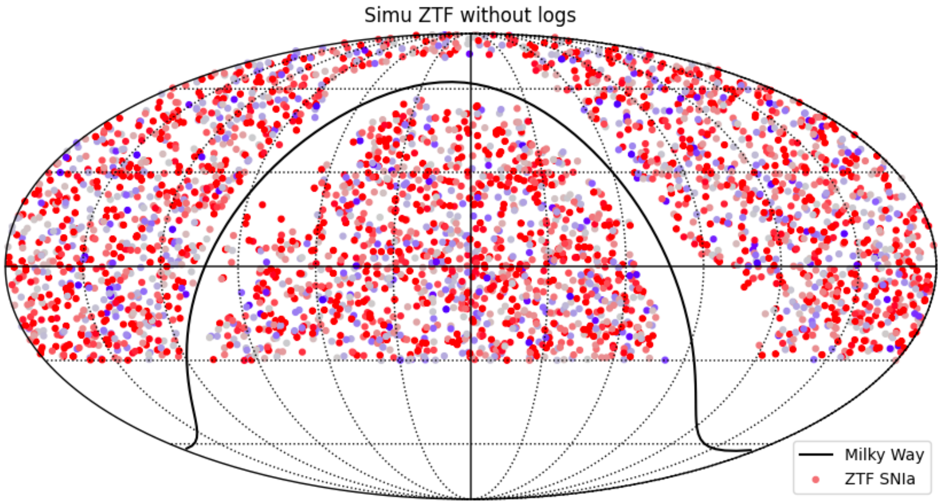
- Unbiased
- Centered around zero for the amplitude and Ra
- Small shift in Dec (~0.0027)



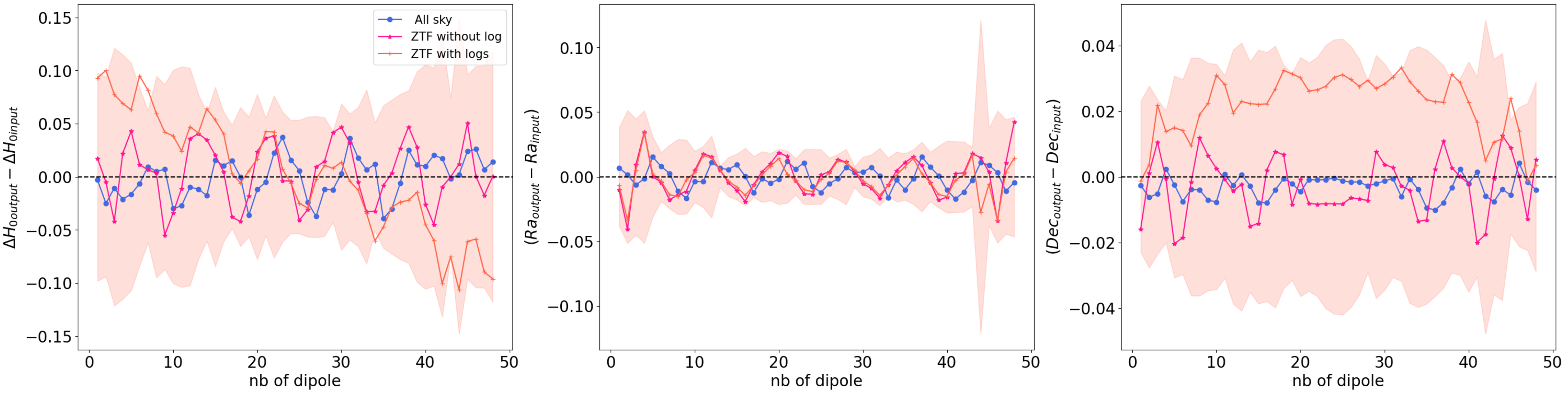
Sky coverage:



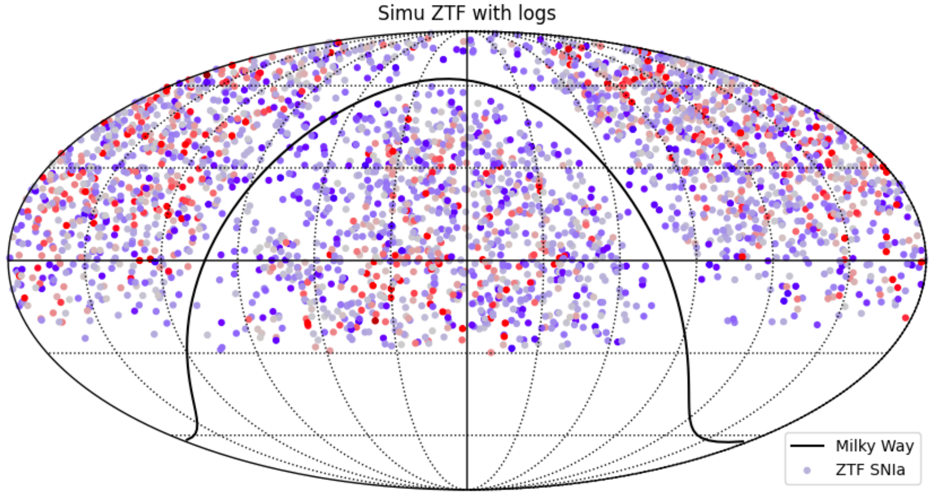
- Unbiased
- Centered around zero for the amplitude and Ra
- Small shift in Dec (~0.0018)



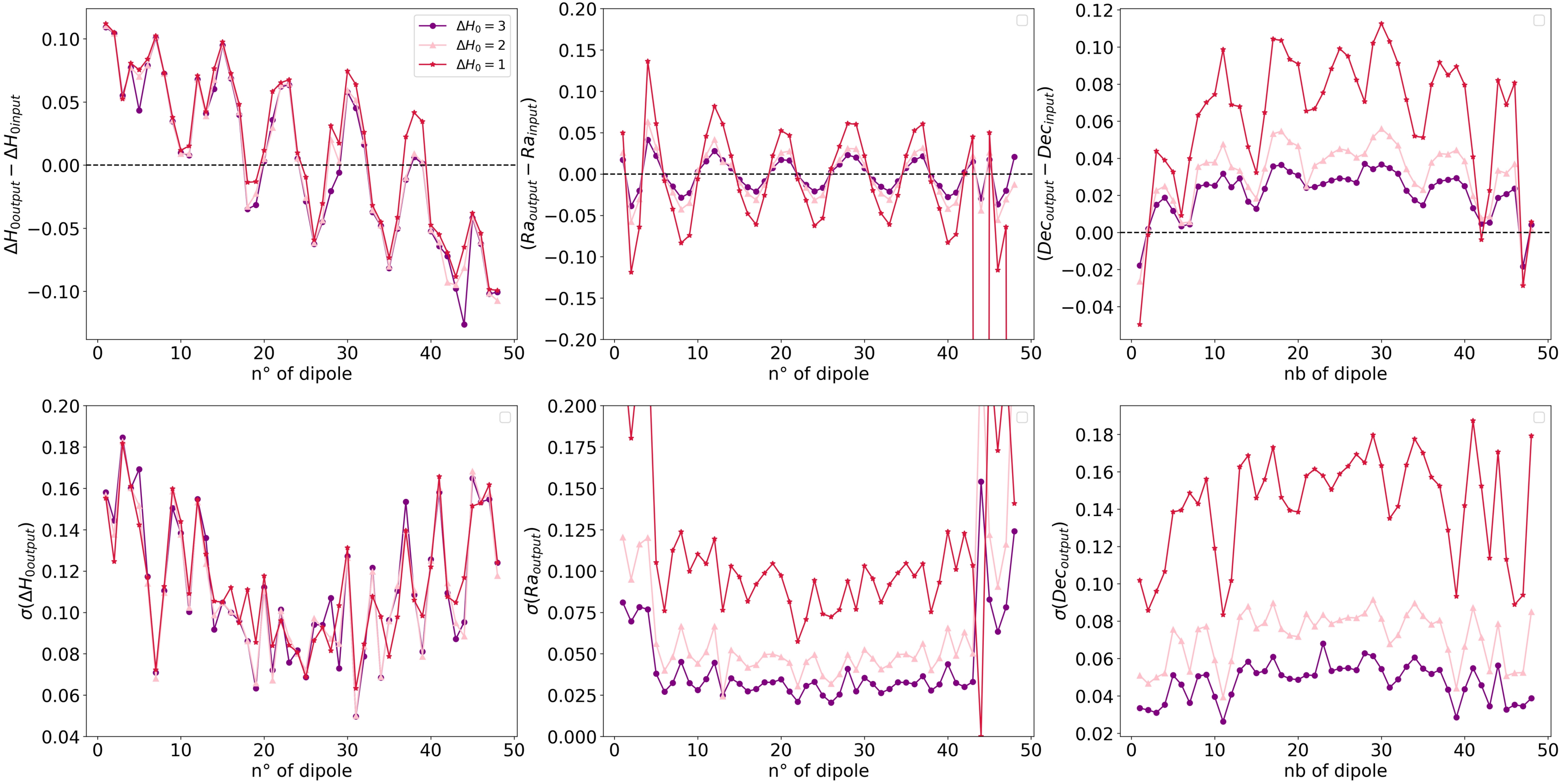
Sky coverage:



- Unbiased
- Centered around zero for Ra
- A slope in the amplitude
- Shift in Dec (~0.023)
- Slope introduced with the observing log but due to a statistical effect

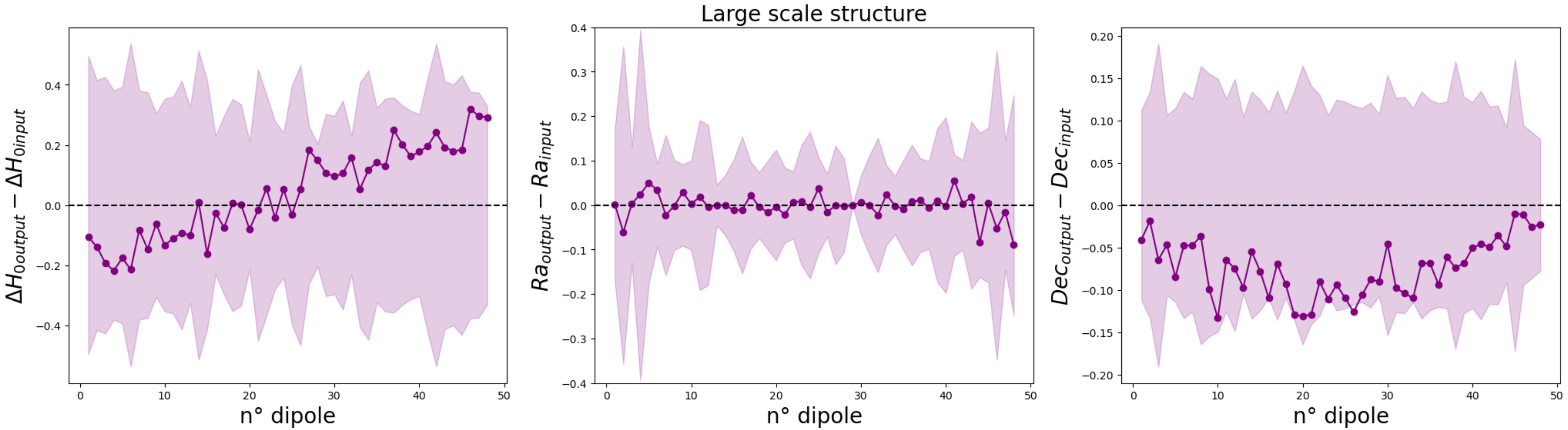


Differente values of amplitude:



- 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

Dipole fit for 48 different directions for 27 simulations with large scale structure :



- Unbiased in Ra
- Offset of ~0.13 in Dec but we remain included in the uncertainty band
- Slope for the amplitude but included at 1σ uncertaintes

- Simulation produced by R.Kebadian & M.Ginolin

Conclusion :

Summary :

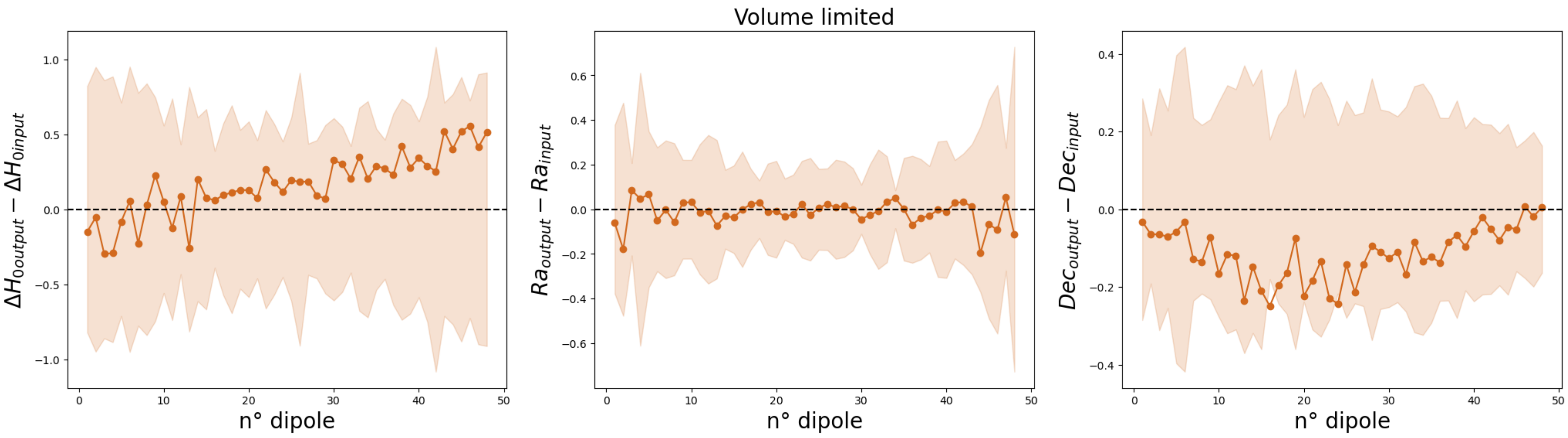
- m_B method to introduce the dipole is unbiased and the less coastly
- No change in the fit if we change the amplitude of the dipole or the H0 values.
- The slop appear using the observing log but containing in the uncertaintes
- Even for an amplitude of $1 km.s^{-1}.Mpc^{-1}$ we recover the initial dipole
- Zero comprise at 1sigma for large scale structure simulation

Futur :

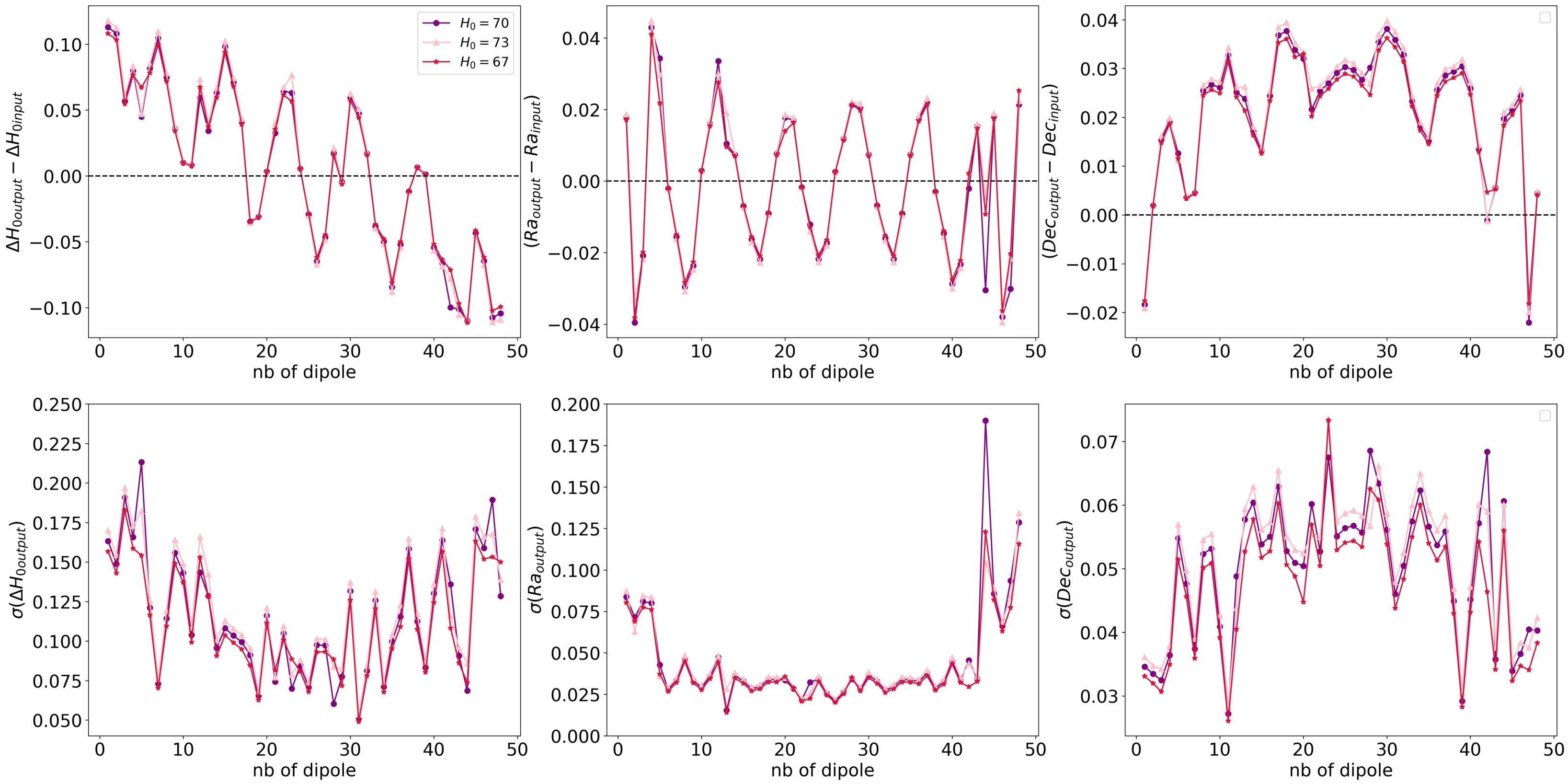
- Introduce quadrupole and multipole
- Apply the method on the data

Thank You

Backup Volume limited:

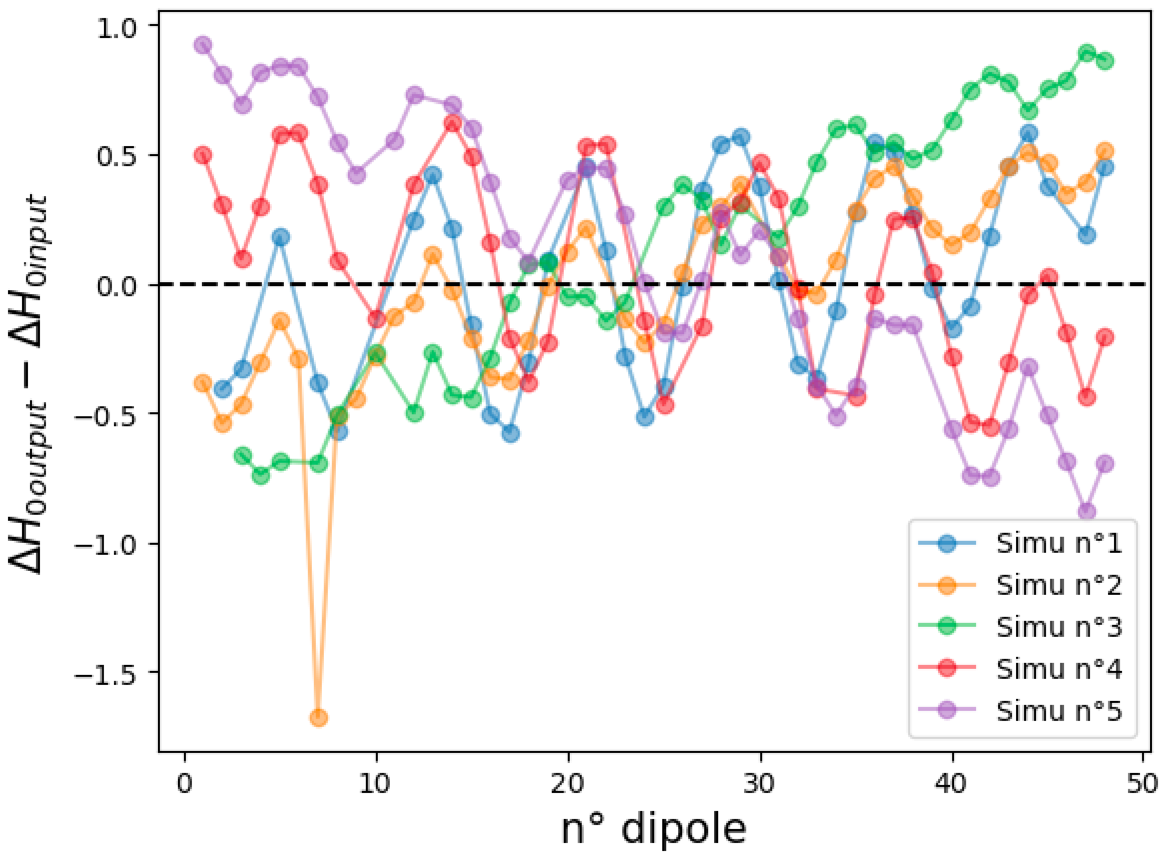


Backup- Differente values of H0:

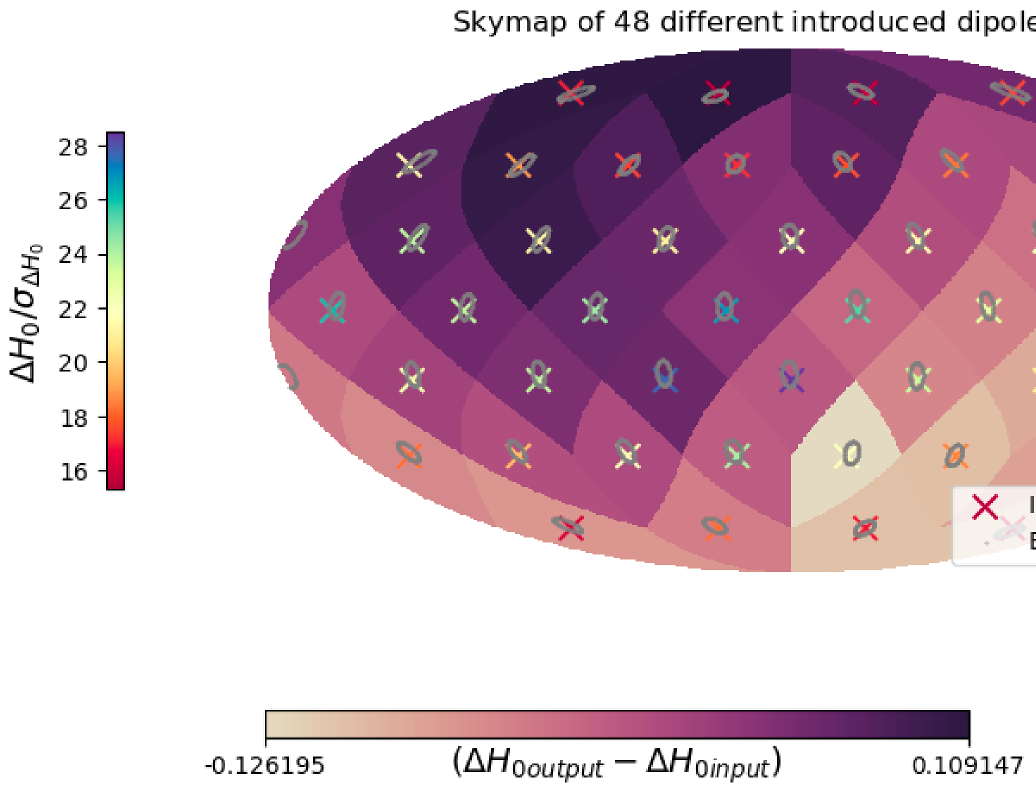


- Same results for the three differents values of H_0
- Independant of the initial value of H_0

A third method to introduce the dipole:

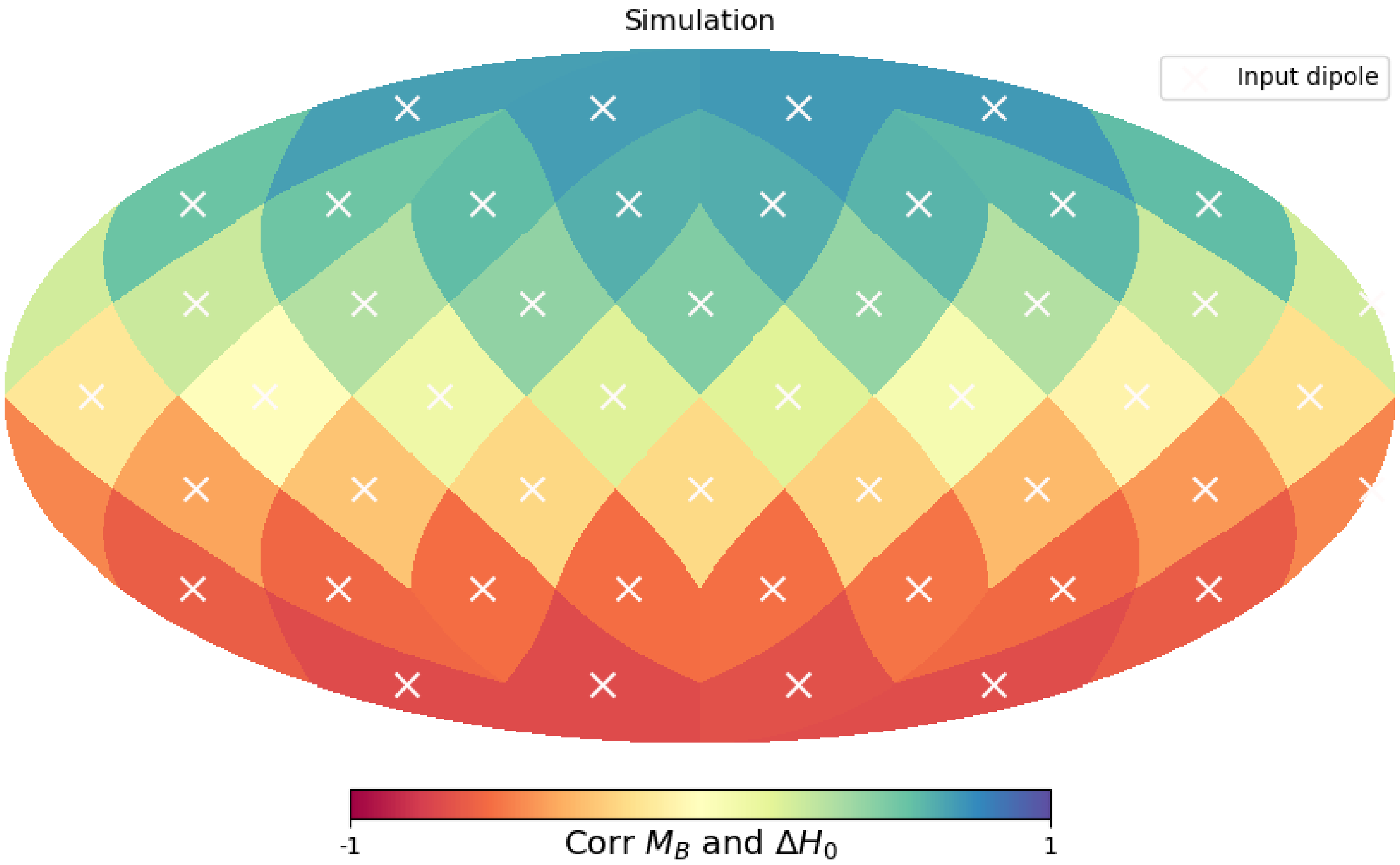


Backup- Dipole fit for 48 different directions :



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

Backup- Correlation:



Backup SALT2

sncosmo
A Python Library for Supernova Cosmology

Sncosmo : A Python Library for Supernova Cosmology analysis.

Usefull for :

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

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

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