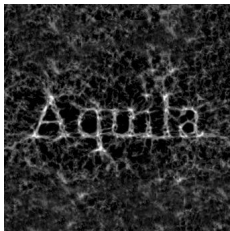
Spatial inhomogeneities in the ZTF DR2 SNe Ia sample

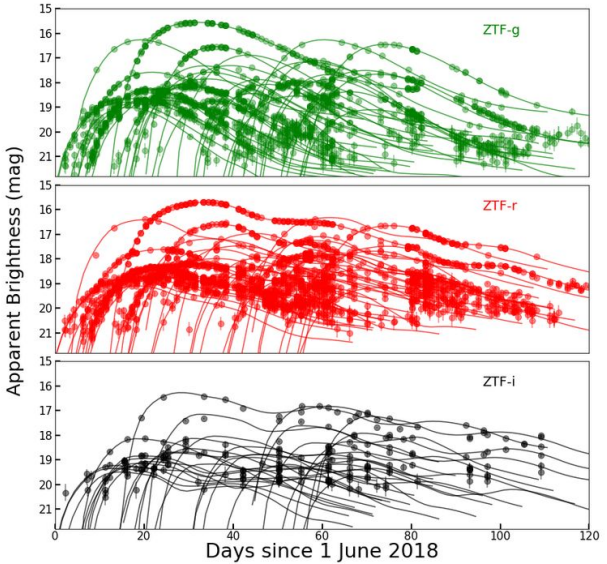
Antoine Gilles Lordet, Ariel Goobar
Jens Jasche, Stuart McAlpine

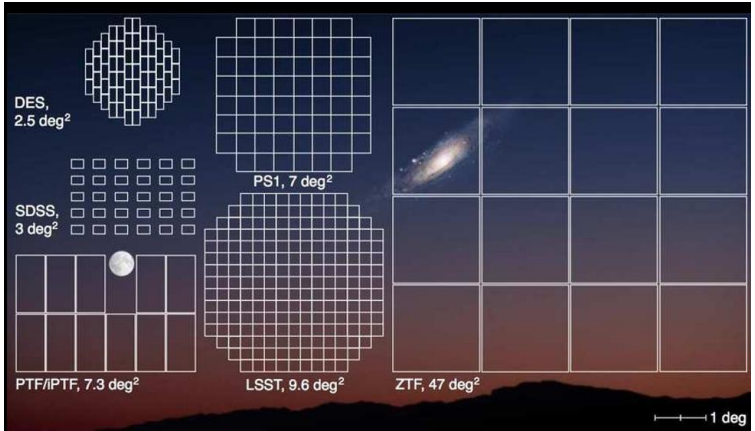
arXiv:2604.12714



The Zwicky Transient Facility

- 48-inch Samuel Oschin Telescope at Palomar Observatory, 47 deg² field of view
- Covers the Northern sky on an averaged 3 days cadence cycle
- 3 filters: g, r, i





See Rigault et al. (2025)

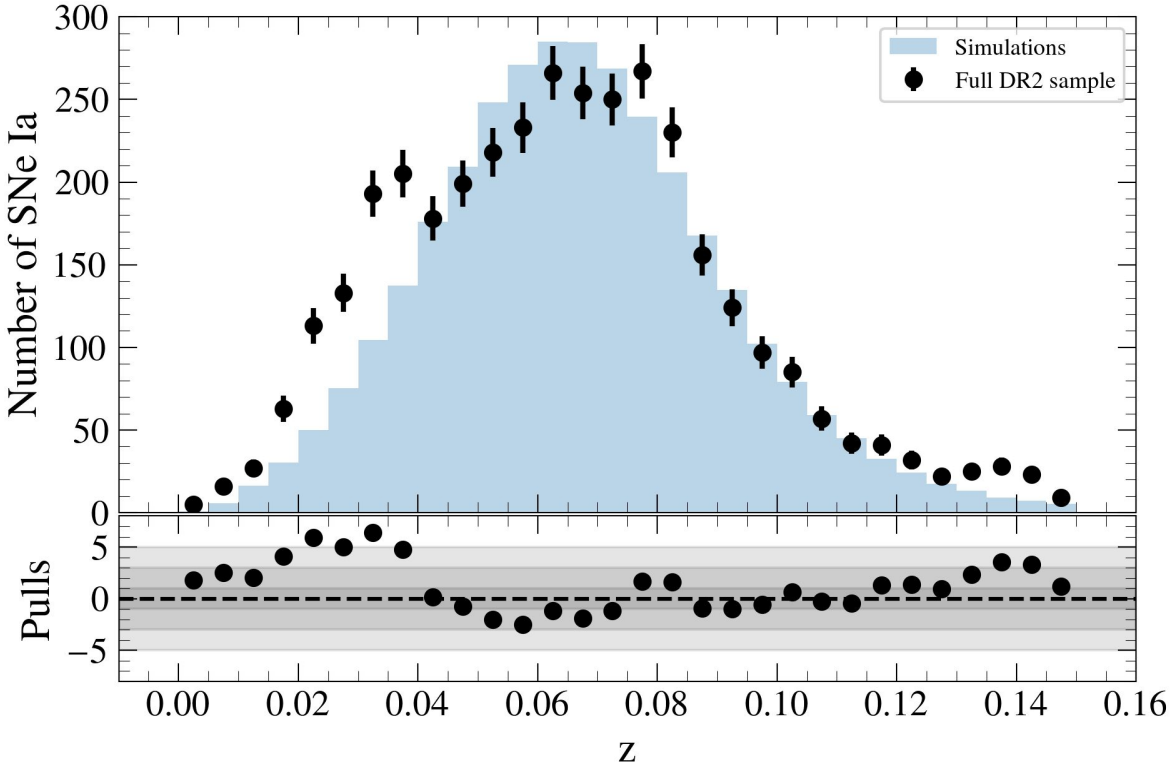
The SN Ia Second Data Release (DR2) sample

- SNe Ia peaking between March 2018 and December 2020 (~2.53 years)

- 3628 spectroscopically confirmed events, 2667 suited for cosmology analysis (lightcurve sampling and parameter quality cuts)

- Volume limited sample up to z~0.06: excellent description of our cosmic neighbourhood

ZTF DR2 SNe Ia redshift distribution



- Simulations using the comoving average SN Ia rate inferred by Perley et al. (2022):
  2.35×10^4 SNe $\mathrm{Gpc^{-3}\ yr^{-1}}$
- Uniform spatial prior
- Sigmoid selection function on the peak observed magnitude in ZTF r-band

$$S(m_{\mathrm{obs}}; m_{\mathrm{lim}}, s_{\mathrm{lim}}) = \frac{1}{1 + e^{s_{\mathrm{lim}}(m_{\mathrm{obs}} - m_{\mathrm{lim}})}}$$

$$m_{\mathrm{lim}} = 18.8\ \mathrm{mag} \quad s_{\mathrm{lim}} = 4.5\ \mathrm{mag}^{-1}$$

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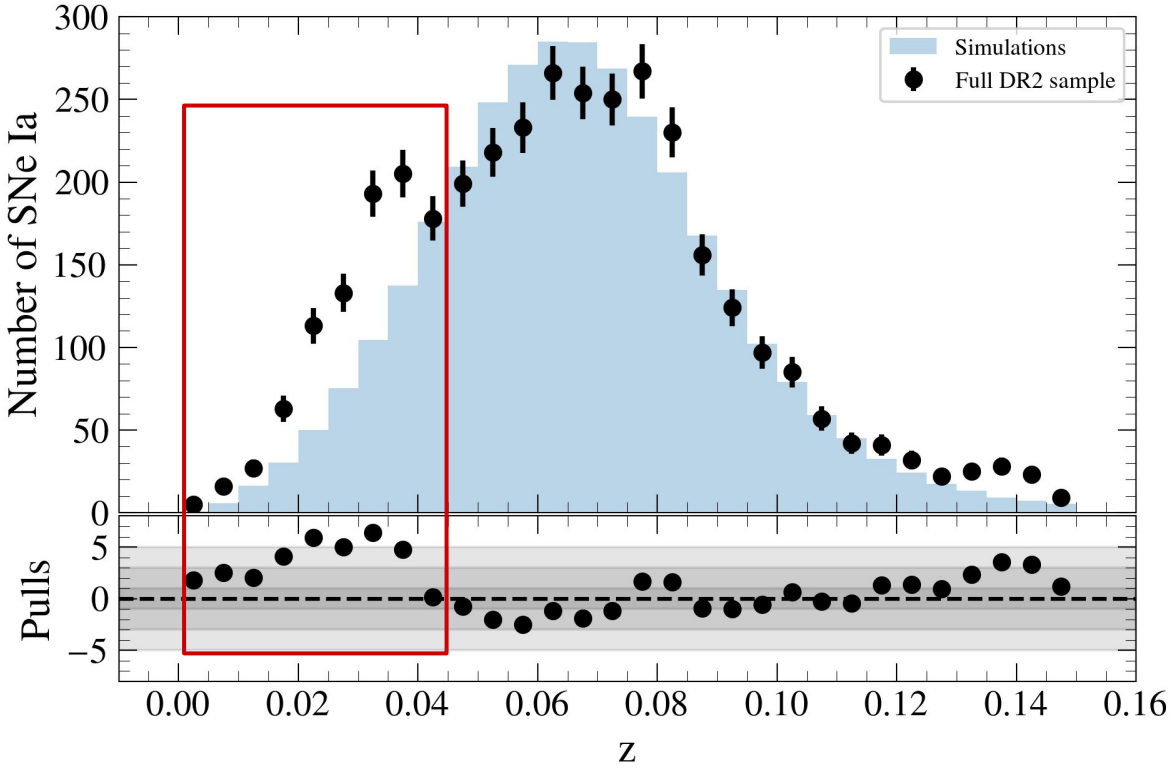

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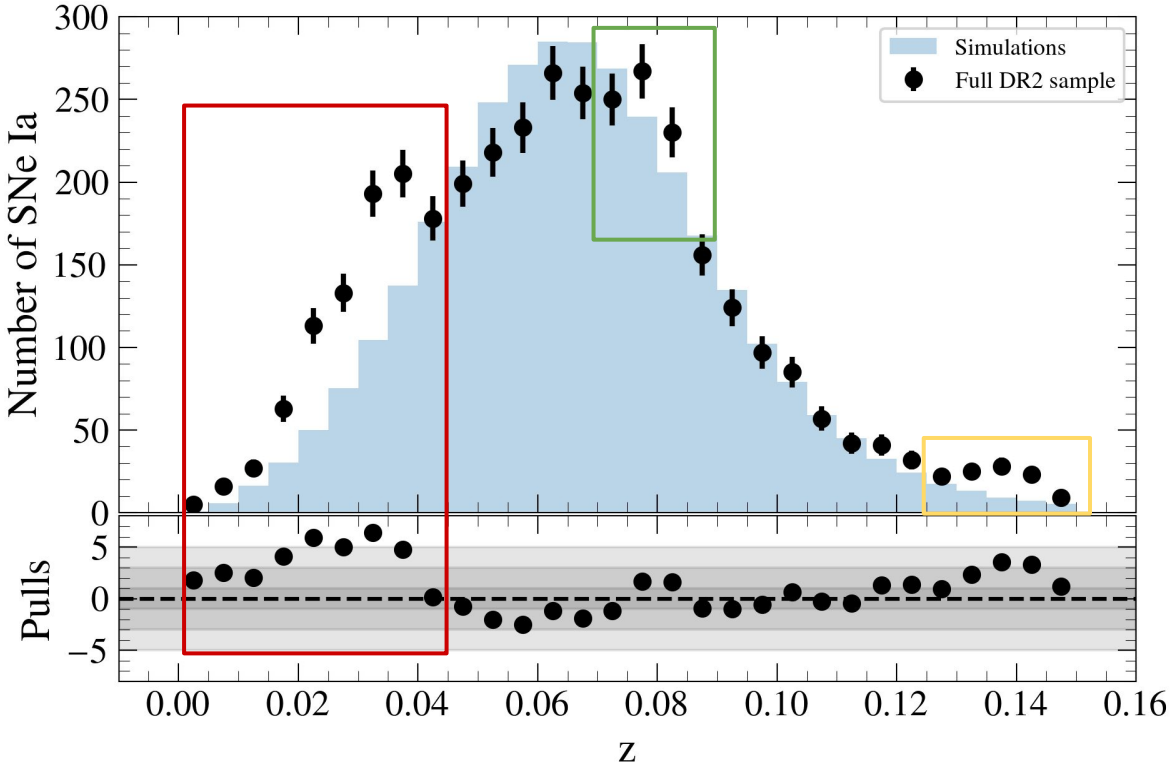

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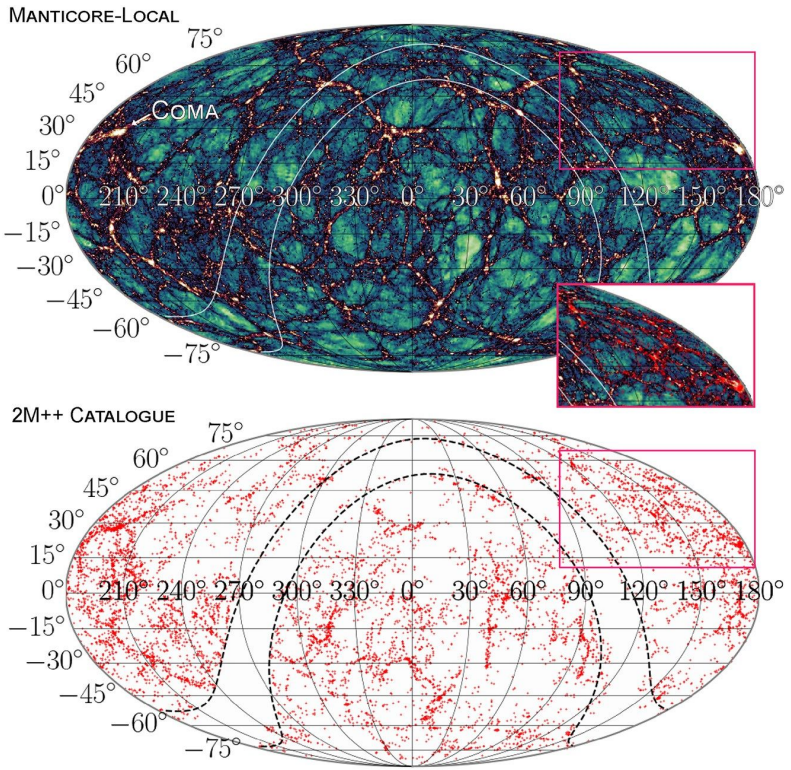
Adding structures in the prior: Manticore halos

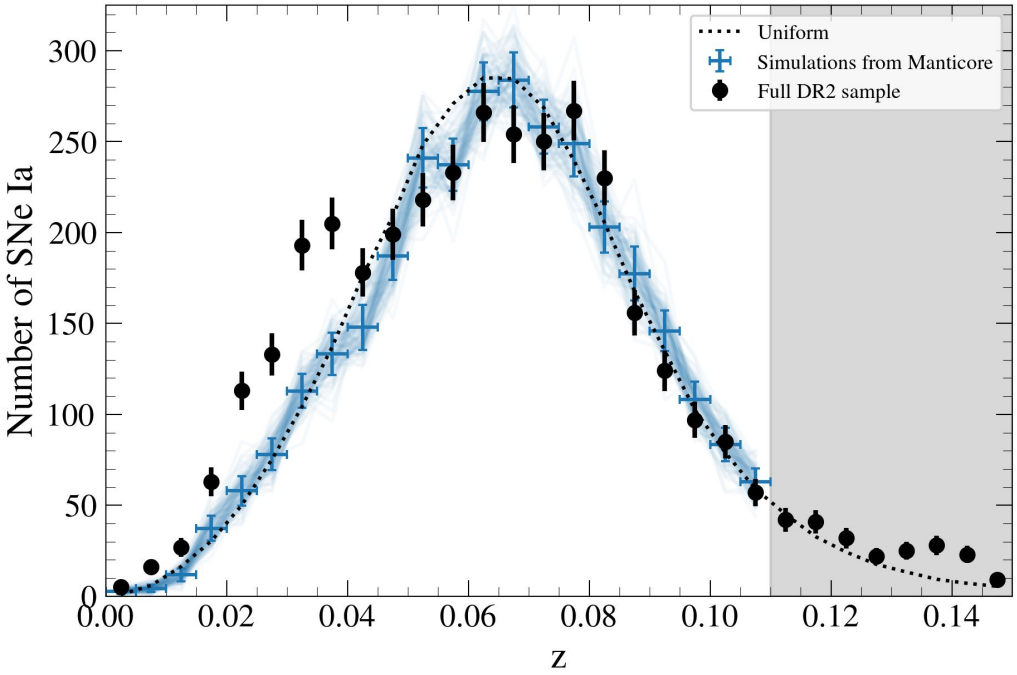
- Inference of the DM field by evolving initial conditions with the BORG algorithm with a fixed cosmology
- Constrained on the 2M++ galaxy catalog (2MASS, 6dFGS, SDSS DR7)
- 1Gpc³ box
- Halos catalogue obtained from the particle meshes



McAlpine et al. (2025), 95–125 Mpc slice https://doi.org/10.1093/mnras/staf767

Adding structures in the prior: Manticore halos

- Instead of sampling positions uniformly, they are drawn from DM halos
- Total number of SNe fixed by the rate
- Weighting proportional to the halo mass



Adding structures in the prior: Manticore halos

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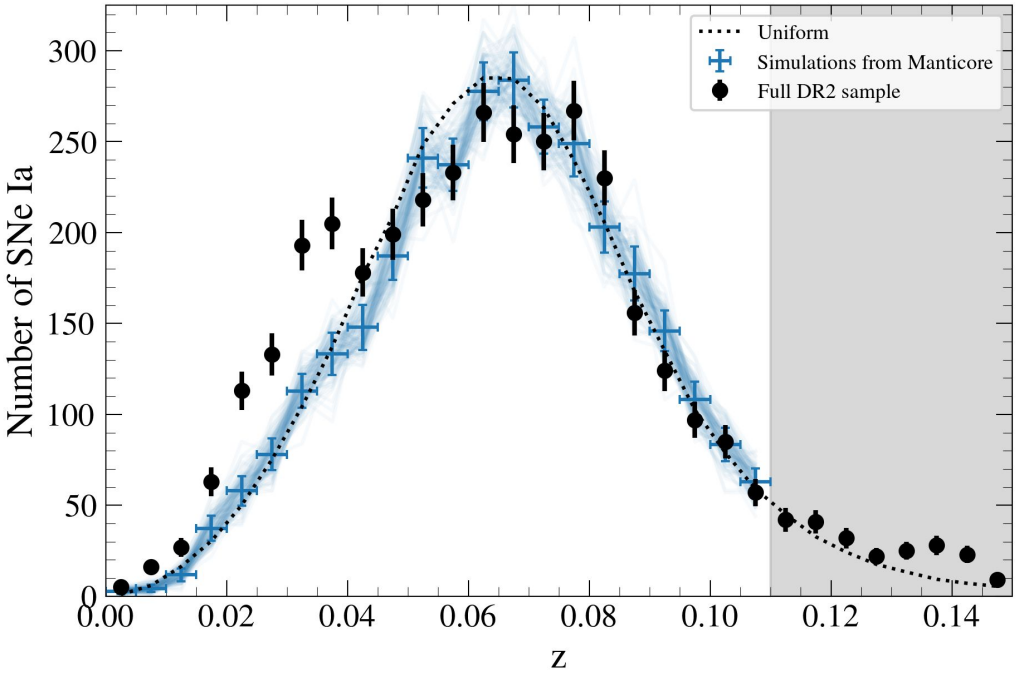
- Some inhomogeneities start appearing but not the full story



Measuring a volumetric rate: rate model

Fraction of the sky covered by ZTF

Total time duration of the DR2

Sum over all the SNe in the redshift slice

Restframe time-dilation correction

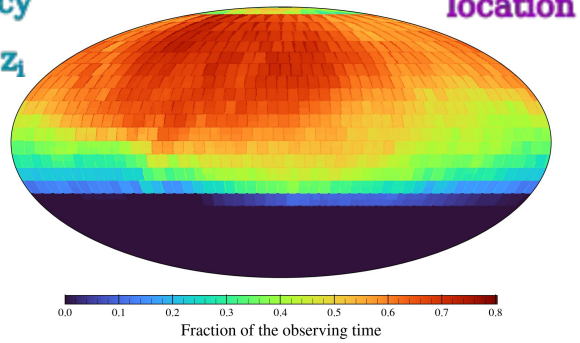
$$R_k = \frac{1}{f_{\mathrm{skyarea}} f_{\mathrm{ext}} \Delta V_k T} \sum_{i=1}^{N_k} \frac{1+z_i}{\varepsilon(z_i) f_{\mathrm{obstime},i}}$$

Restriction to $A_V \leq 1$

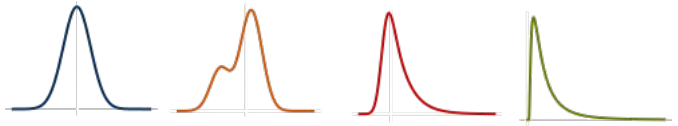
Comoving volume in the shell

Theoretical efficiency for ZTF at redshift z_i

Fraction of the time duration covering the SN location



Measuring a volumetric rate: Efficiency model



$$\varepsilon(z) = \iiint S(M - \alpha x_1 + \beta c + \mu(z) + K(z, x_1, c) + A_r; m_{\rm lim}, s_{\rm lim}) \frac{1}{\sqrt{2\pi}\sigma_{\rm int}} e^{\frac{1}{2}\frac{(M-M_0)^2}{\sigma_{\rm int}^2}} \mathrm{d}M \; f(x_1)\,\mathrm{d}x_1 \; g(c)\,\mathrm{d}c \; h(A_r)\,\mathrm{d}A_r$$

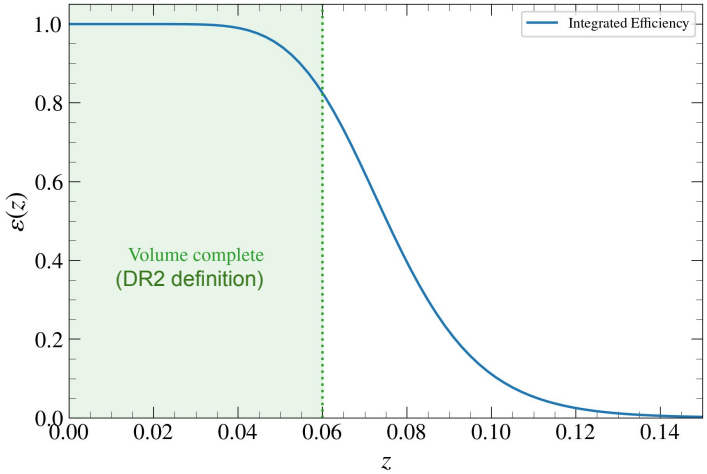
K-correction from Bessell B band to ZTF r band

Tripp standardisation

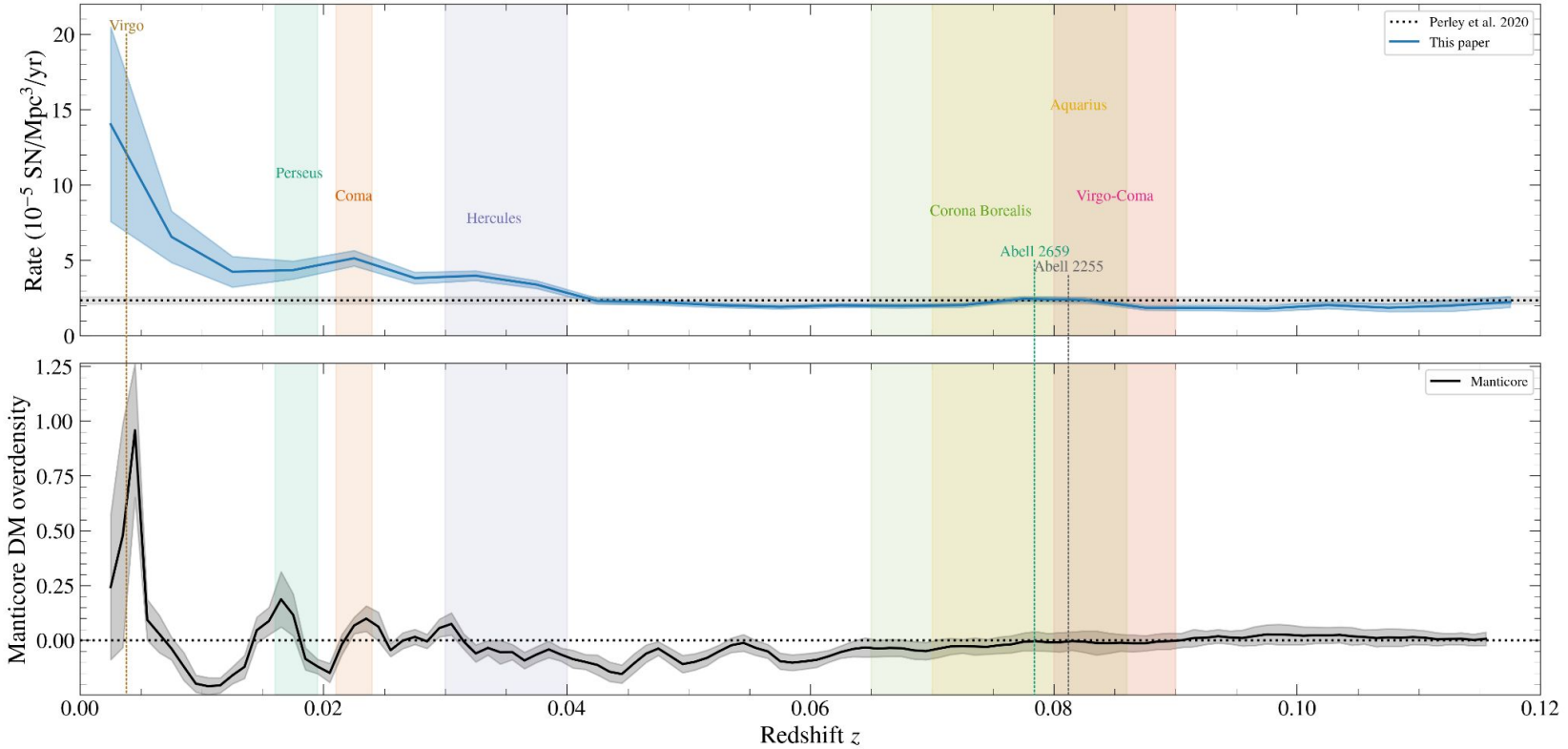
Distance modulus (Planck 2018 prior)

MW extinction in ZTF r band

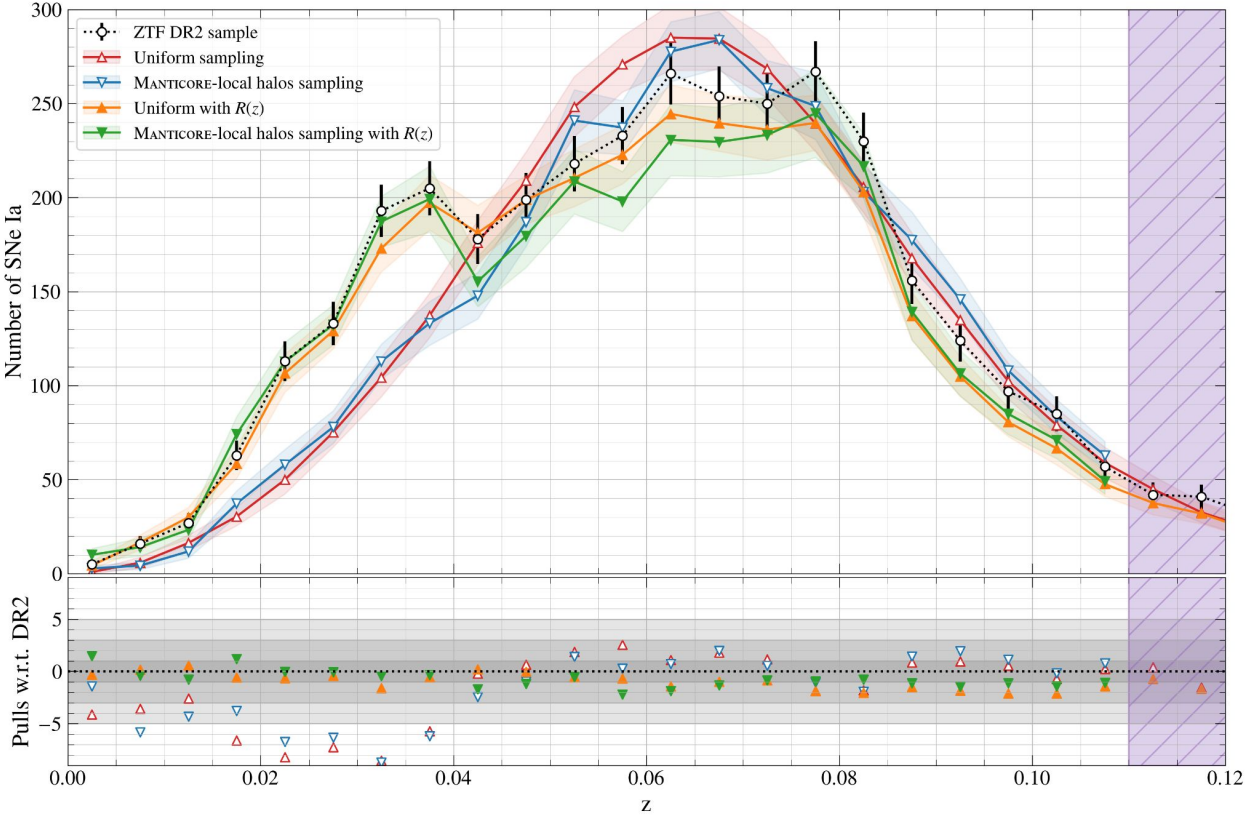
Restframe absolute B band magnitude



Obtained rate



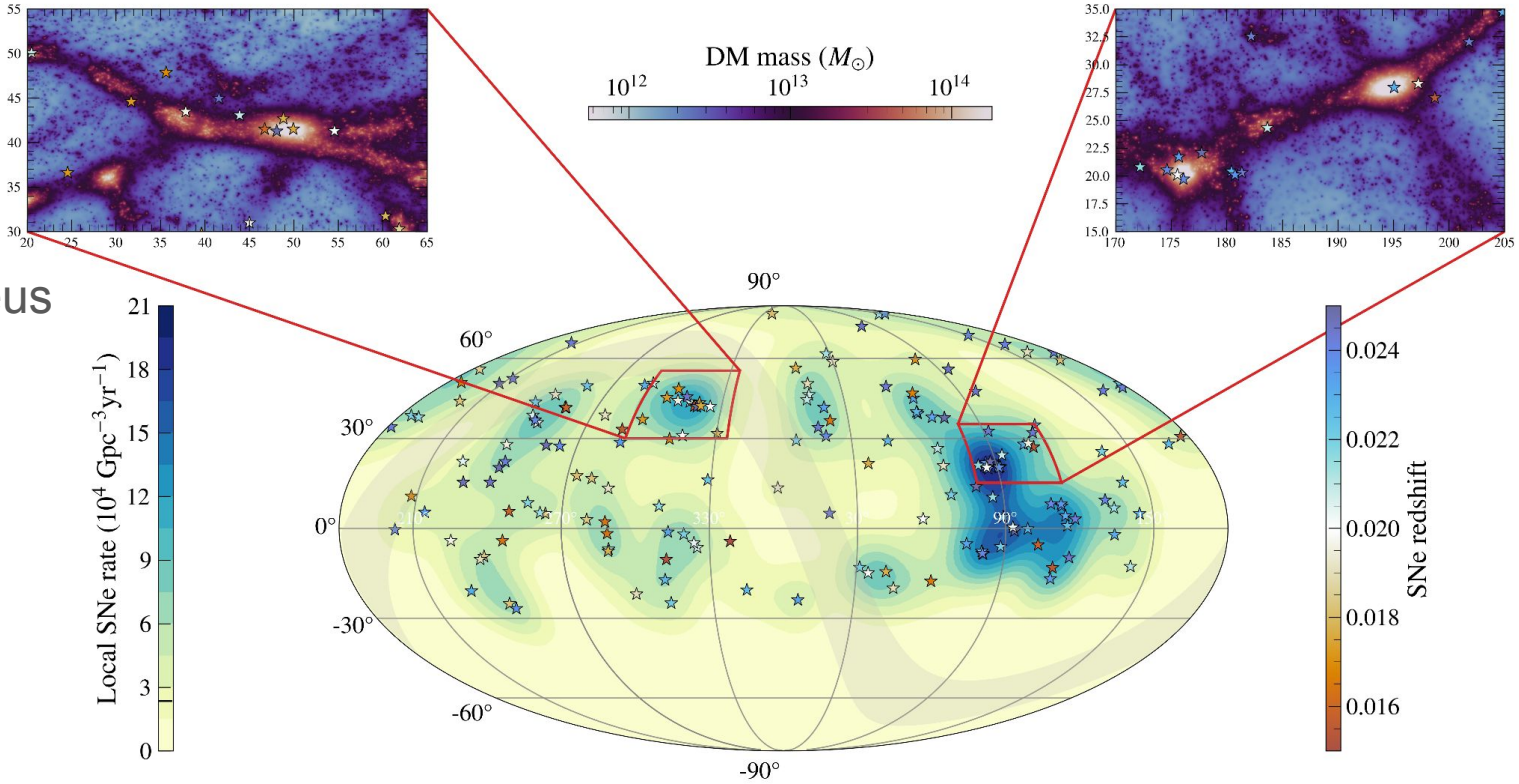
Resimulations with evolving rate



Local rate for z~0.015-0.025

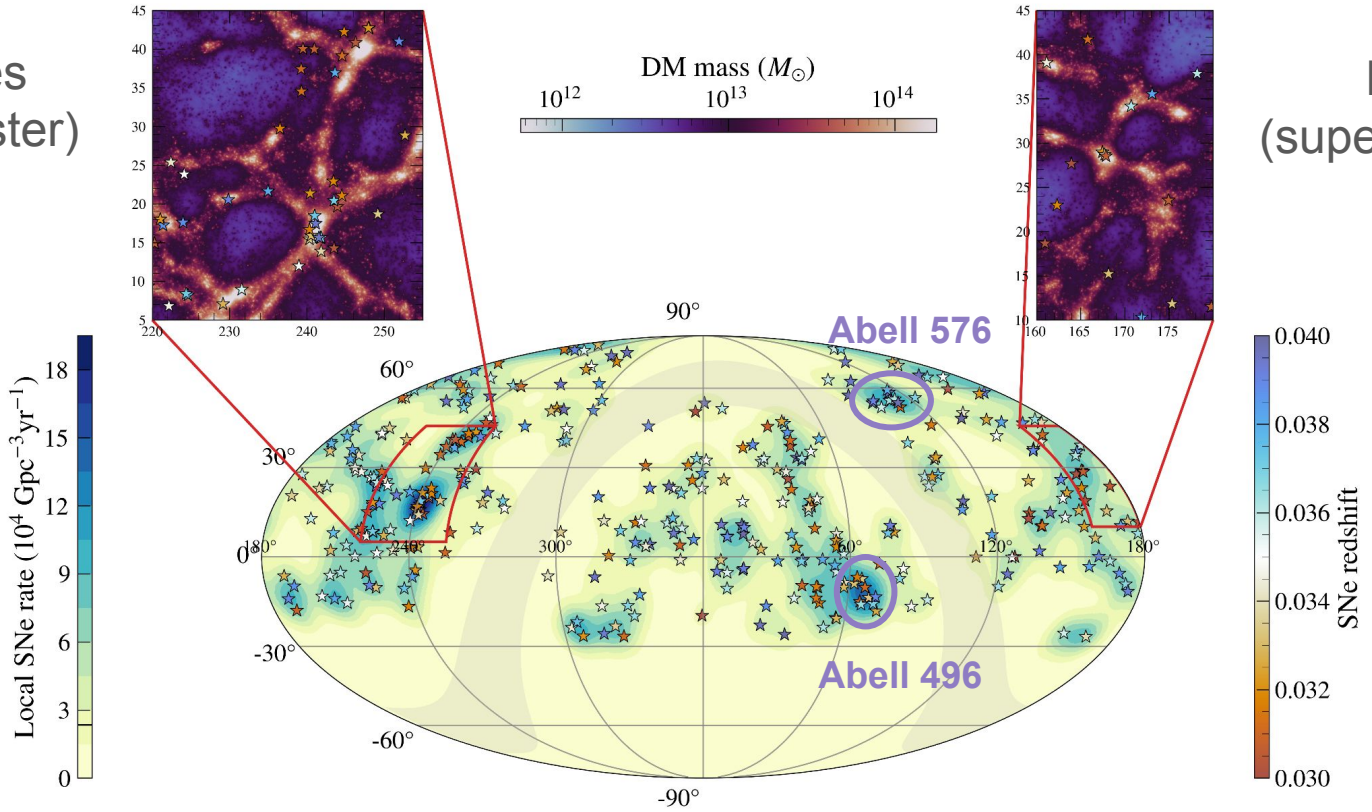
Coma (supercluser)

Perseus



Local rate for z~0.03-0.04

Hercules (supercluster)



Leo (supercluster)

Observations

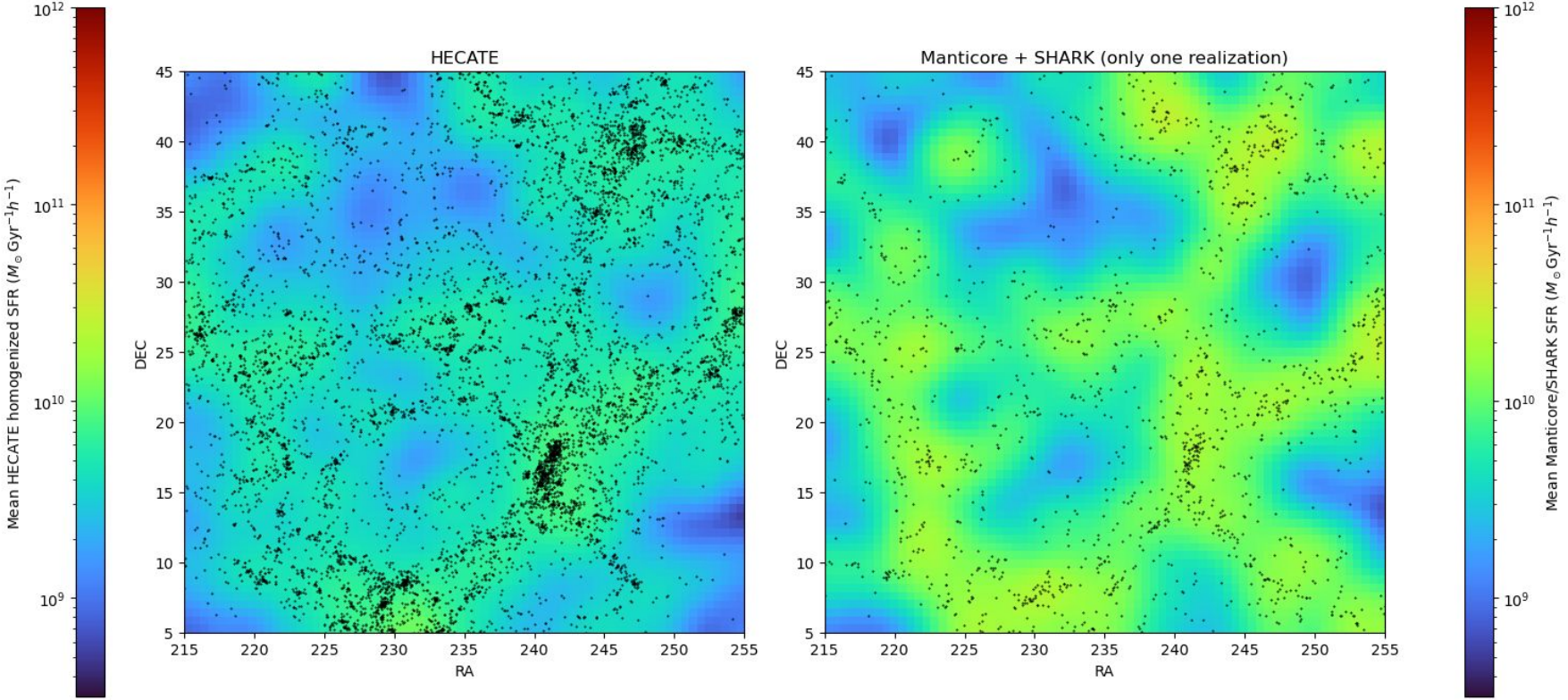
- Local rate depends strongly on the environment, 5-6 times higher than average in some clusters
- Follow the overall structures, but there are discrepancies with DM scaling
    - SN Ia are a highly biased tracer of structures
- Hard to explain the increase in clusters:
    - If it's not mass it should be SFR (A+B model)...
    - …but clusters contain in general more elliptical galaxies with low SFR
    - Hercules has a larger fraction of elliptical than Leo, but is somehow more efficient at producing SNe
- Probably linked to the dynamic state of the cluster (e.g. A2255)
- Heiger et al. (2026): Dwarf spheroidal galaxies have a 5 times yield compared to field galaxies and steeper delay-time distribution

The second suspect: SFR

- Heraklion Extragalactic Catalogue (HECATE): homogenized SFR from different surveys/methods
  - Galaxies up until z~0.05
  - Can’t be used directly as a prior for SNe Ia simulations: no completeness model

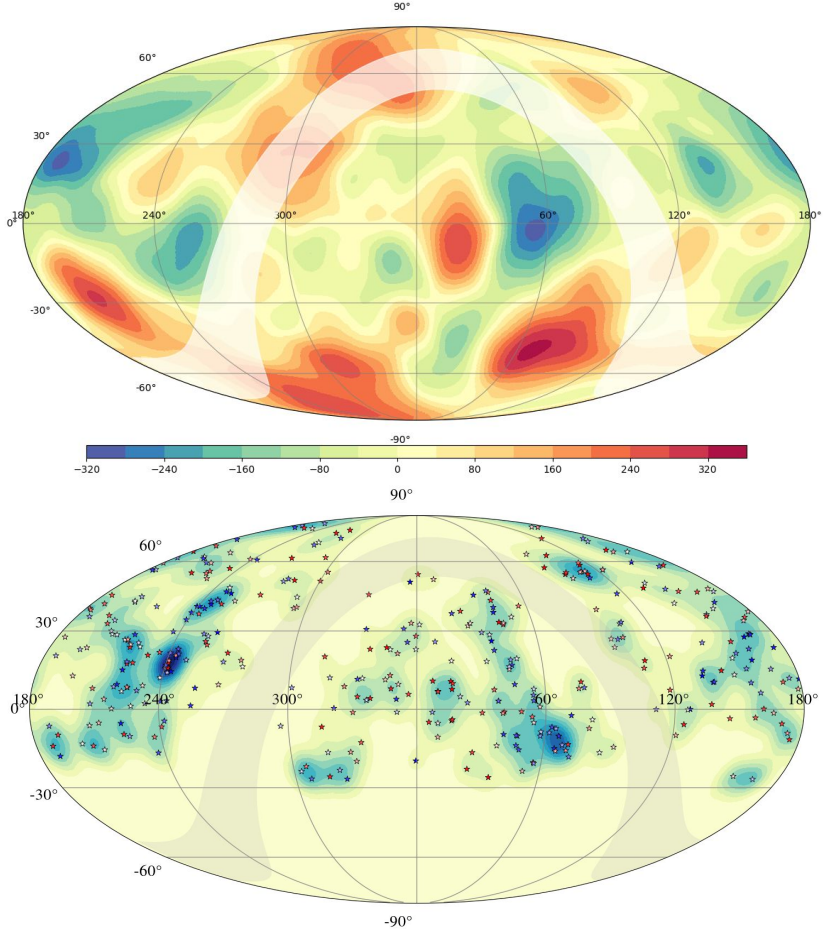
- Use Semi-Analytic Models of galaxy formation and evolution on Manticore merger trees
  - Need to tune the SAM to match observation
  - Low mass halos and galaxy not accurately reproduced

The second suspect: SFR (Work In Progress)



Implications for Cosmology

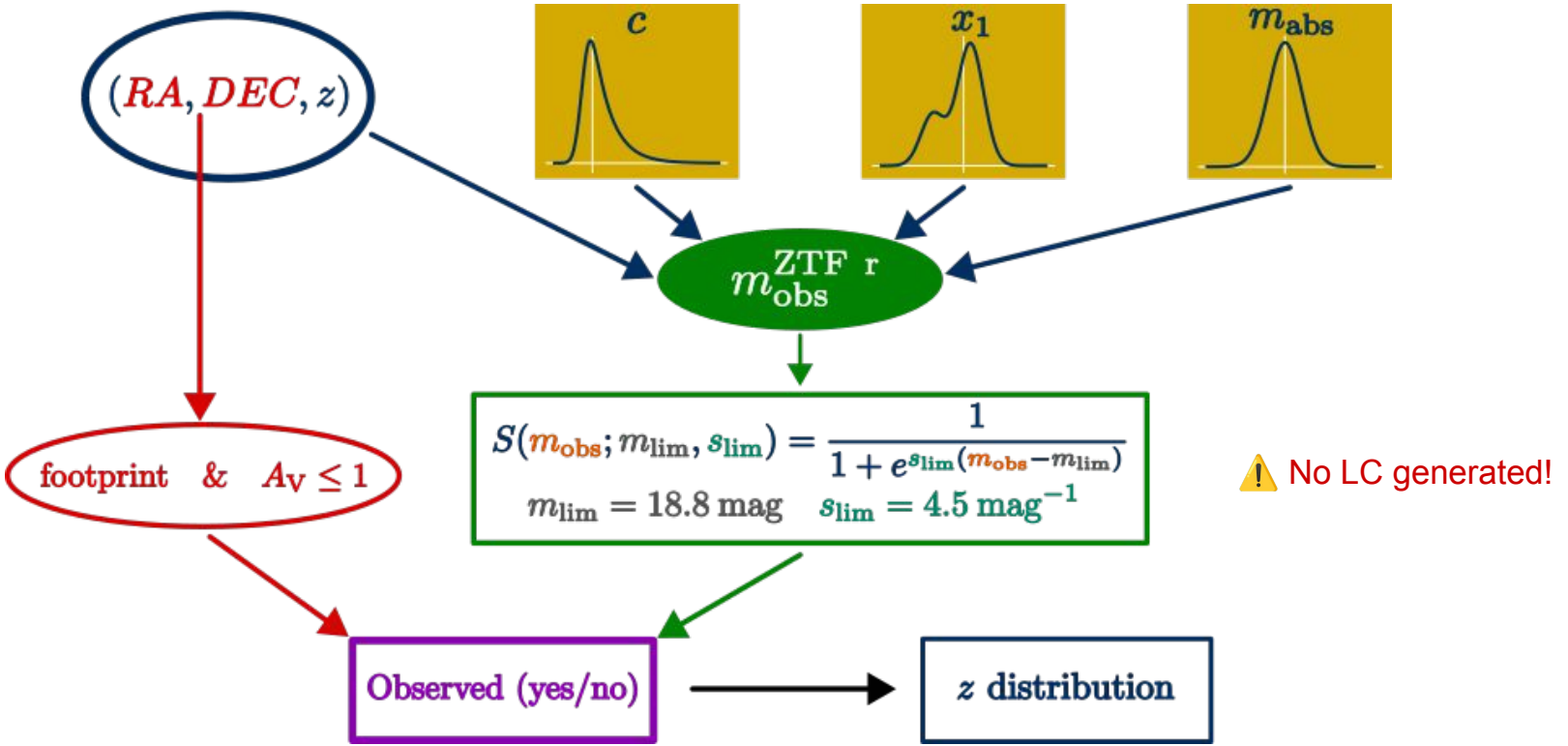
- Additional correlations that are not taken into account:
  - Bulk vpec of structures
  - Shared environmental properties
- Intrinsic parameter distributions can be biased at low redshift



Conclusion

- Cosmological analysis rely on simulations that do not reproduce the observations at low redshift
  - Need to move away from comoving averaged rate as it is not physical
  - The impact needs to be investigated
- Nice statistics for analysis on the impact of environment on SN Ia physics and progenitor channels

Model for simulations



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