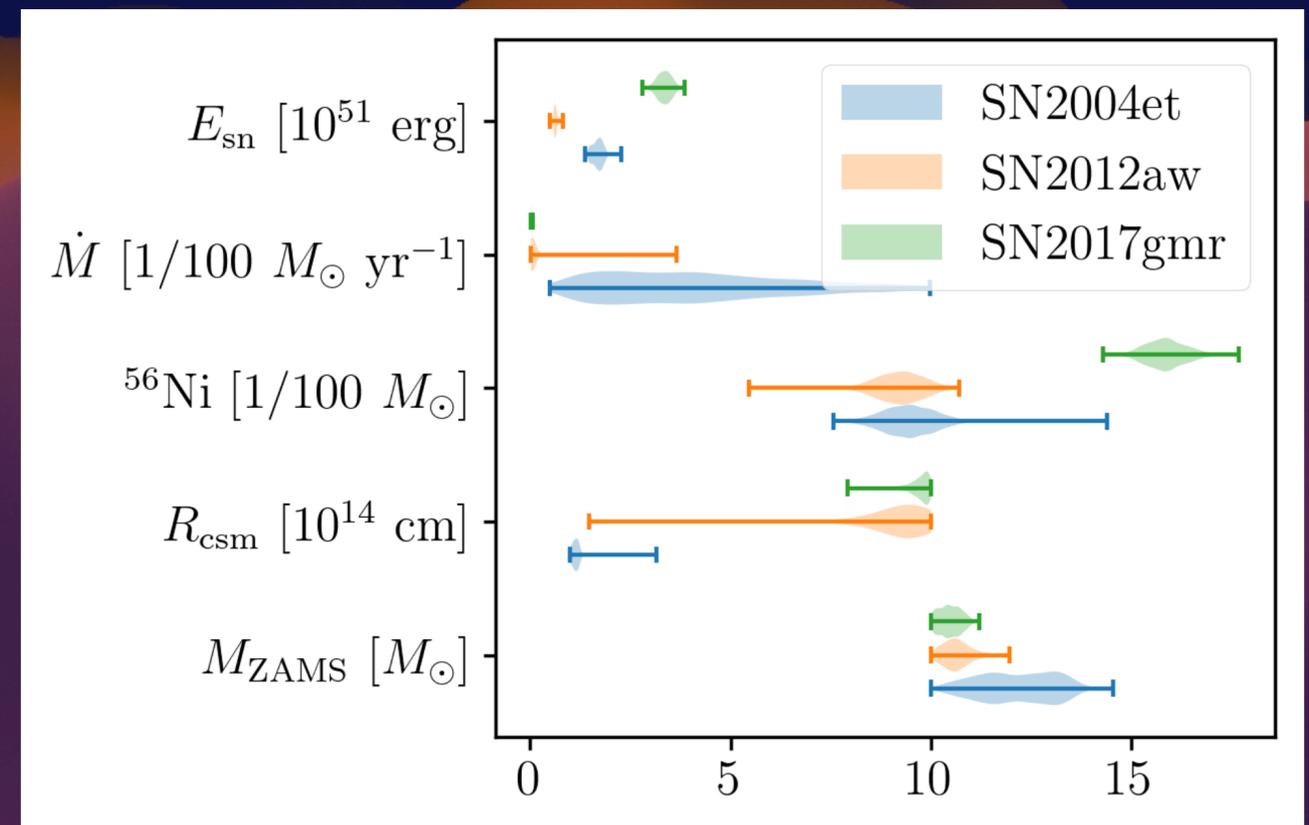
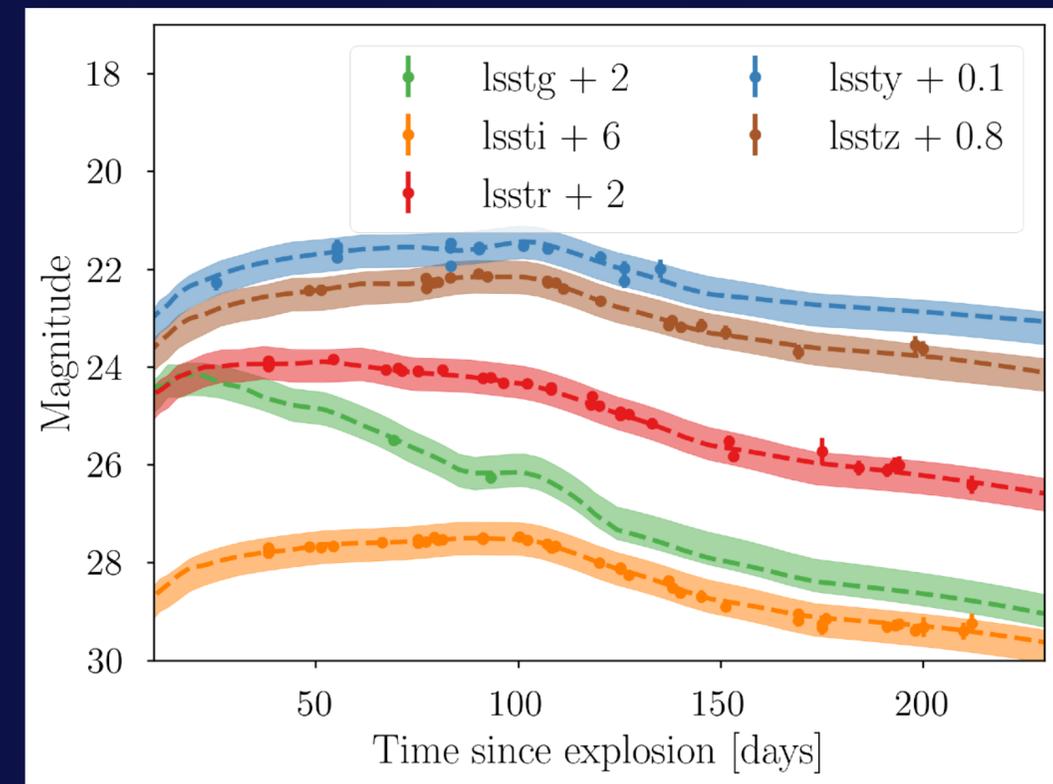


TOWARDS TRANSIENT LIGHTCURVE MODELING AT SCALE: SOME PEDAGOGY AND TYPE IA IN DR2

NIKHIL SARIN

- ▶ Why do we want to do inference?
 - ▶ Because data itself is not intrinsically *interesting*.
 - ▶ *What the data tells us is.*
- ▶ We want to confront observations with models.
 - ▶ Theoretical, empirical or both.
 - ▶ Ideally also a continuum.
 - ▶ Simple → complex models.
- ▶ We want to do this in detail but also at scale.



Sarin+2025

$$T_{\text{runtime}} \propto T_{\text{model}} \times T_{\text{likelihood}} \times f_{\text{sampler}} \times D_{\text{KL}} \times n_{\text{samples}}$$

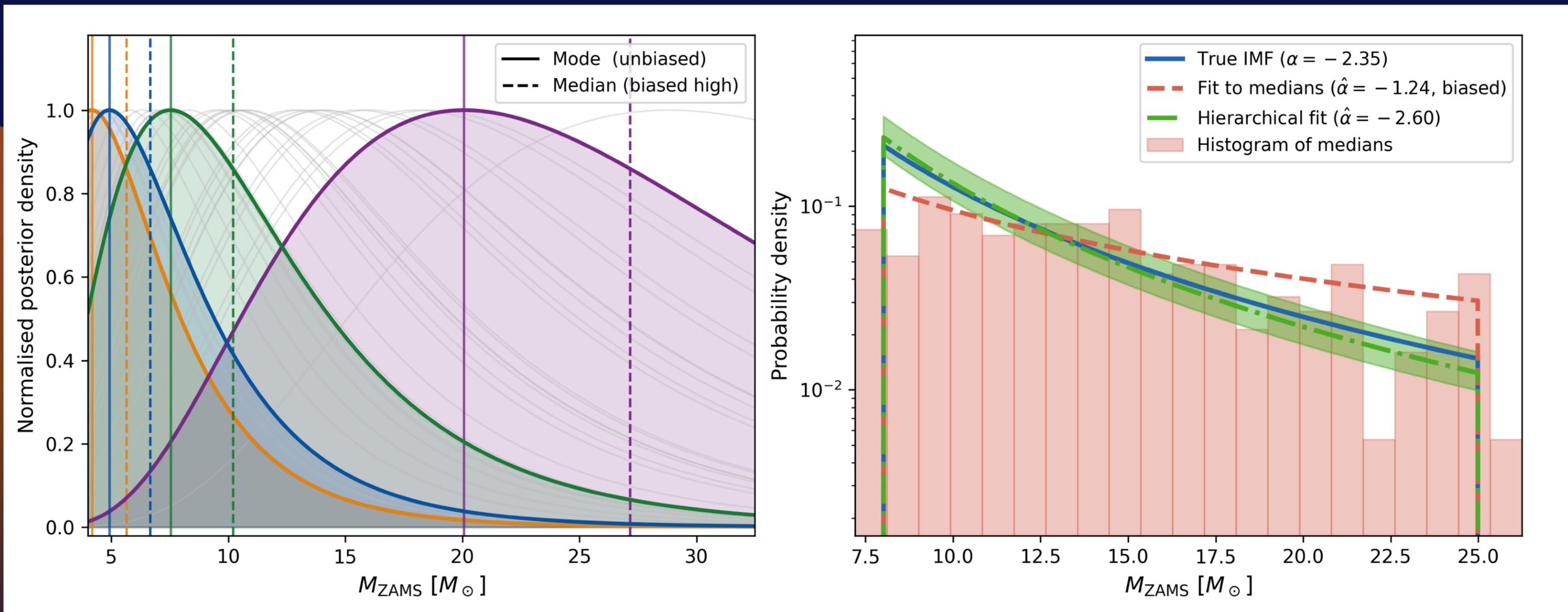
- ▶ It does not matter if you 'fit' by eye, or fit with a sampler. Your "runtime" is always expressed this way.
 - ▶ Empirical models are cheaper.
 - ▶ Simple data is easier to model.
 - ▶ Some 'samplers' are more efficient than others.
 - ▶ More informative data takes longer to 'fit'.
 - ▶ And the more 'samples' or 'estimates' you want, the longer it takes.
- ▶ Different tools try to change some parts of this equation.



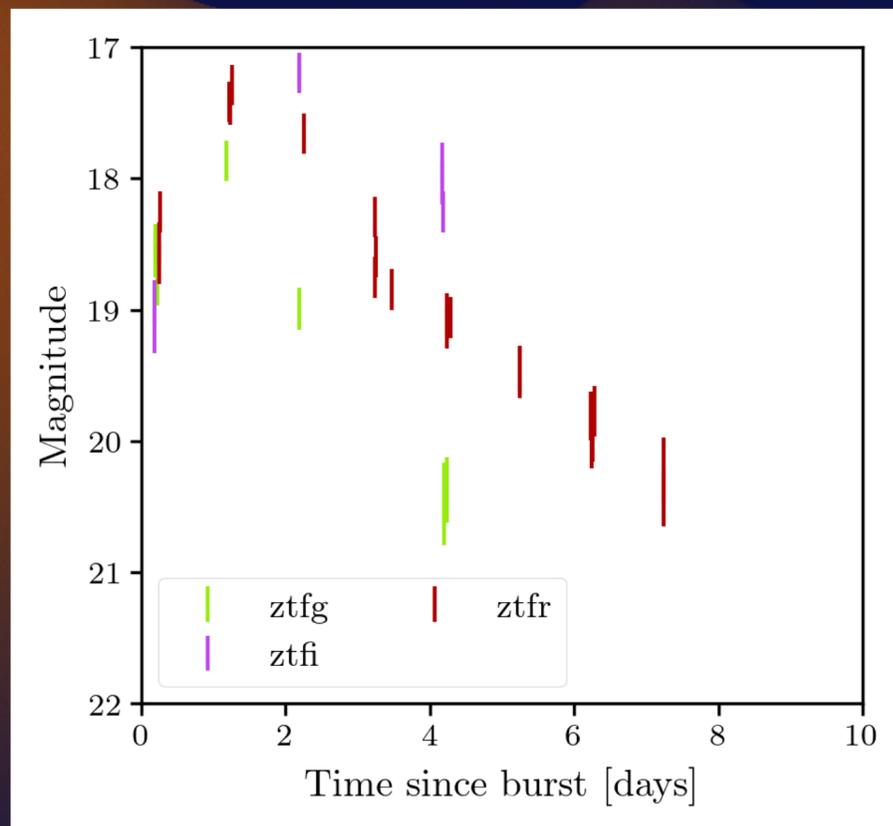
$$T_{\text{runtime}} \propto T_{\text{model}} \times T_{\text{likelihood}} \times f_{\text{sampler}} \times D_{\text{KL}} \times n_{\text{samples}}$$

- ▶ Less complex models $\rightarrow T_{\text{model}} \downarrow$
- ▶ Human finding a fit manually $\rightarrow f_{\text{sampler}} \uparrow \uparrow \uparrow$
- ▶ Empirical model + One max-likelihood sample $\rightarrow T_{\text{model}} \downarrow + f_{\text{sampler}} \downarrow + n_{\text{samples}} \downarrow$
- ▶ Newer/faster models + better samplers? $T_{\text{model}} \downarrow + f_{\text{sampler}} \downarrow + T_{\text{likelihood}} \downarrow$
- ▶ Full transient fitting, i.e., full posteriors, takes $\approx 10^4 - 10^6$ model evaluations.
 - ▶ The fastest models based on real physics are $\approx 10\text{ms} \approx 100 - 10,000\text{s}$ to get a final fit.
 - ▶ You have to do this for every event.
- ▶ As the data gets more informative, the same model requires more evaluations \rightarrow LSST+ era, inference will be tougher at a per-object level.

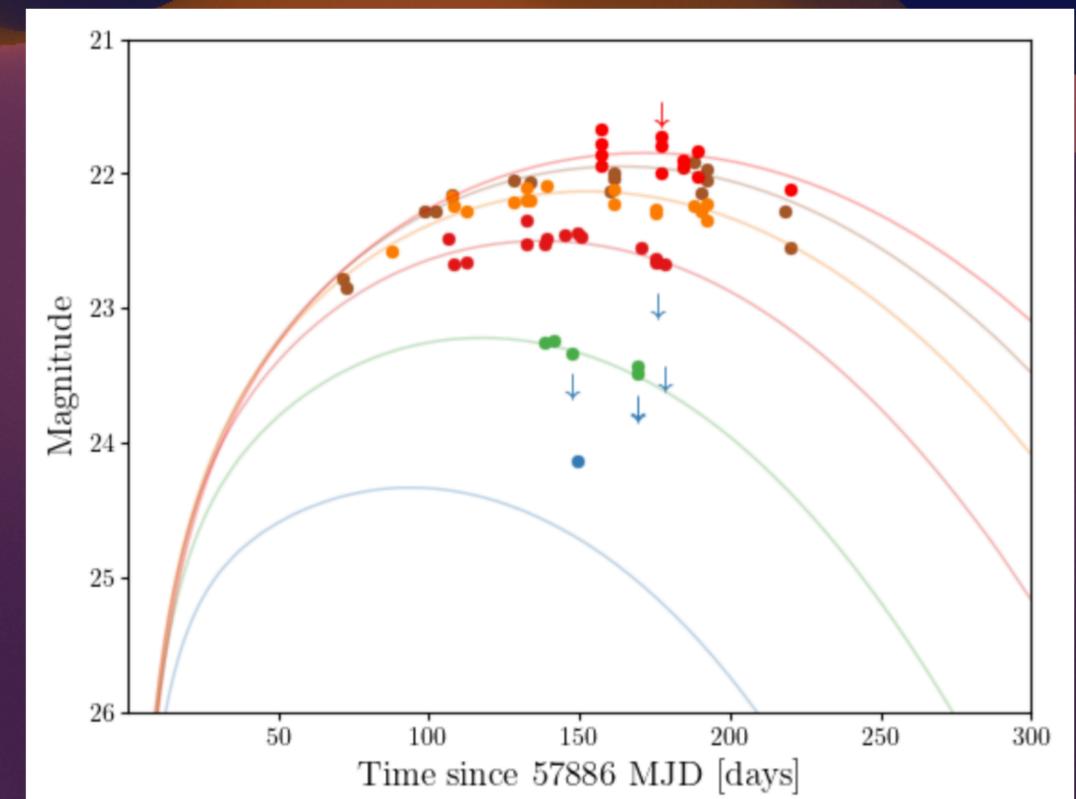
- ▶ As the data gets more informative, the same model requires more evaluations to produce a posterior.
- ▶ Point-estimates e.g., max-likelihood/max posterior estimates become increasingly less useful.
 - ▶ The models are intrinsically uncertain. Degeneracies are not symmetric.
 - ▶ A median is useful to quote in a paper but it washes uncertainty and combining medians produces biased inferences.



- ▶ Hierarchical inference is a solved problemTM.
 - ▶ But as a transient community we barely use the technique.
- ▶ Need to understand selection + a have a good simulator 'engine'.
 - ▶ The simulators that now exist are good enough for everything we do in transients other than precision cosmology.
 - ▶ Selection is also a solvable problem. Provided theorists/inference people work with observers.

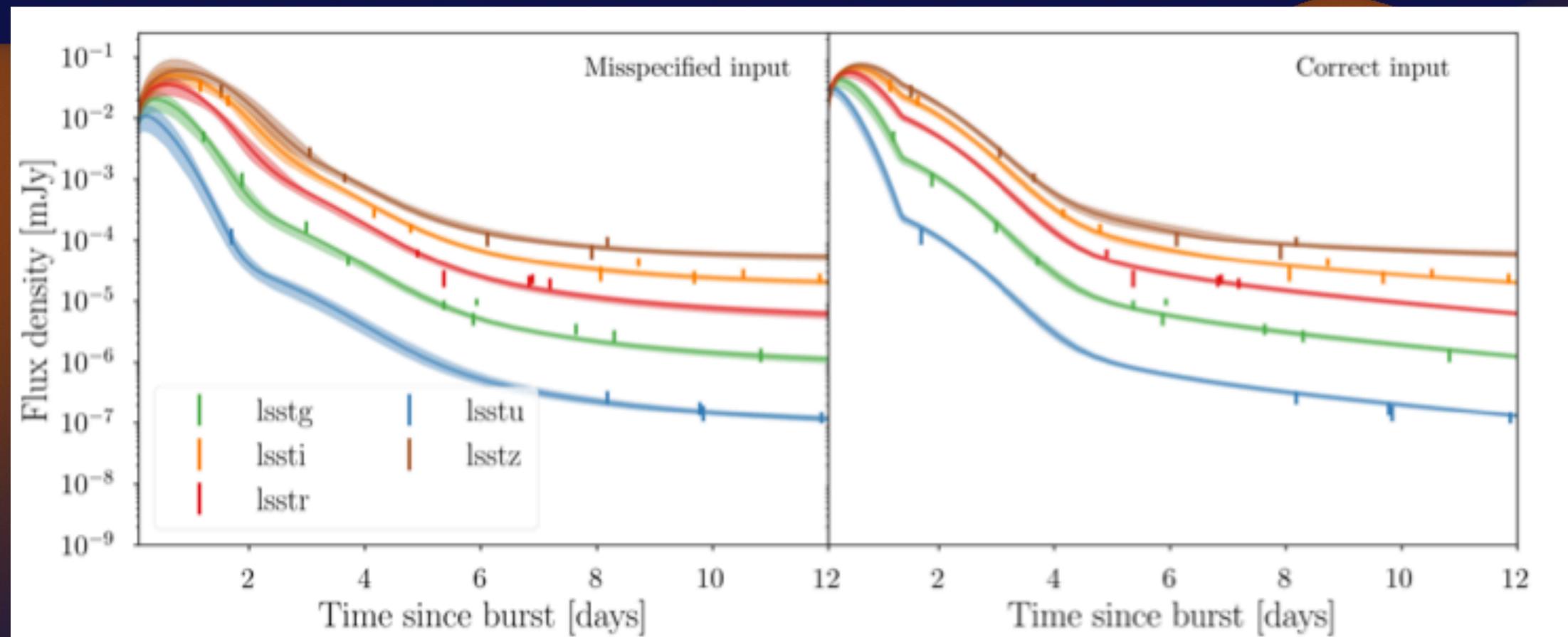


Simulated Kilonova in ZTF



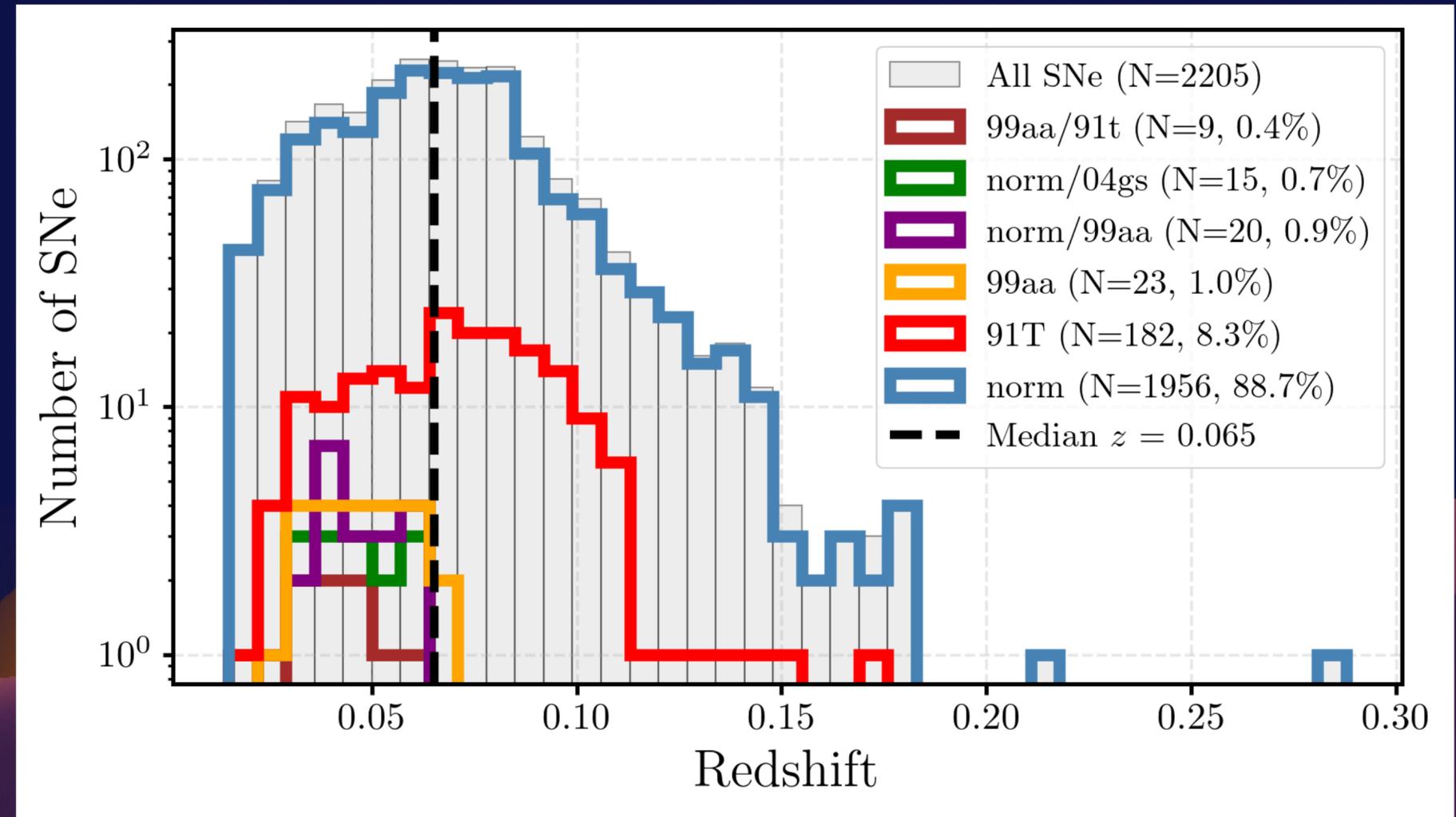
Simulated supernova in LSST with Rubin baseline v3.0 survey.

- ▶ End-to-end simulations are the best way to understand systematics/biases.
 - ▶ Or whether the “sampler” was an unbiased estimator.
- ▶ You could historically somewhat rely on most samplers/tools out of the box to recover a transients with typical data quality.
 - ▶ Increasingly not true. And LSST+ will break things even more.
 - ▶ Traditional MCMC, e.g., emcee is only useful in a rare set of circumstances.
- ▶ As the data get's better, we are also more and more susceptible to model misspecification.



Sarin and Rosswog+2024.

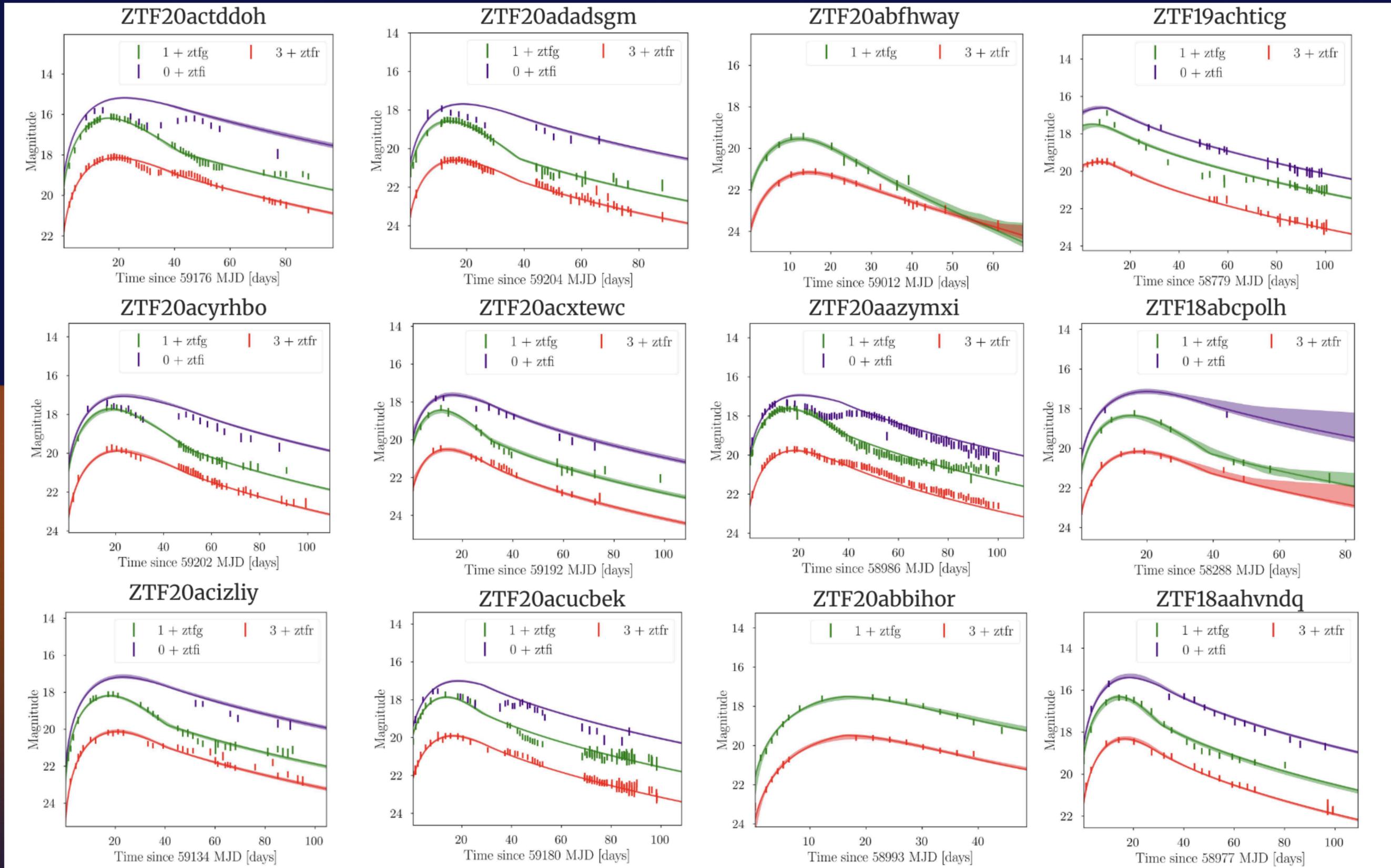
- ▶ ZTF DR2
- ▶ The largest homogeneous sample of Type Ia ever.
- ▶ 3628 events with spectroscopic classification.
- ▶ A lot of awesome science.
- ▶ Light curve analysis restricted to empirical SALT (or similar) models.
 - ▶ For good reason.
 - ▶ Basic models don't fit well.
 - ▶ Take ~100,000 of CPU hours for a sample of this size to not fit well.



Sarin+2026.

- ▶ The cosmology-class of Type Ia should be described only by radioactive decay of ^{56}Ni .
- ▶ The simplest physical model you could apply here is:
 - ▶ One zone of material of mass M_{ej} with some fraction f_{nickel} of ^{56}Ni expanding homologously at v_{ej} .
 - ▶ Diffusion approximation is reasonable around peak phase,
 - ▶ The continuum is blackbody-ish.
- ▶ This is the basic 'arnett' model for supernovae.
- ▶ Implemented in publicly-used software such as MOSFiT and Redback.
 - ▶ Both tools incorporate gamma-ray leakage.
 - ▶ But make different assumptions/defaults.

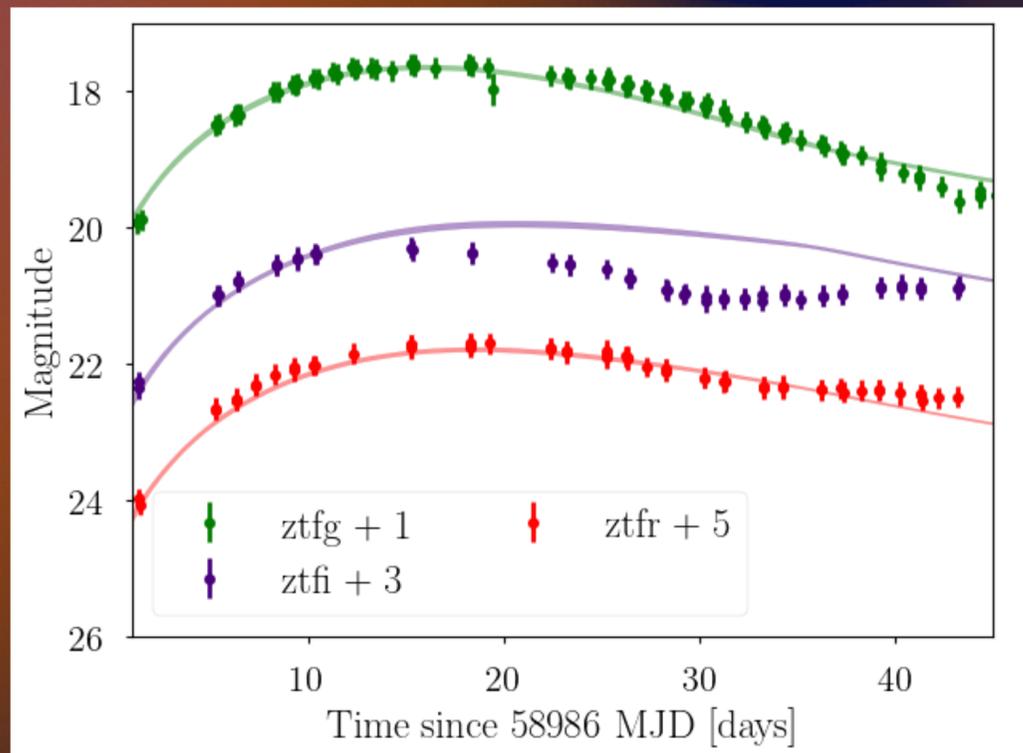
► Generally works but falls apart in ZTF-i band.



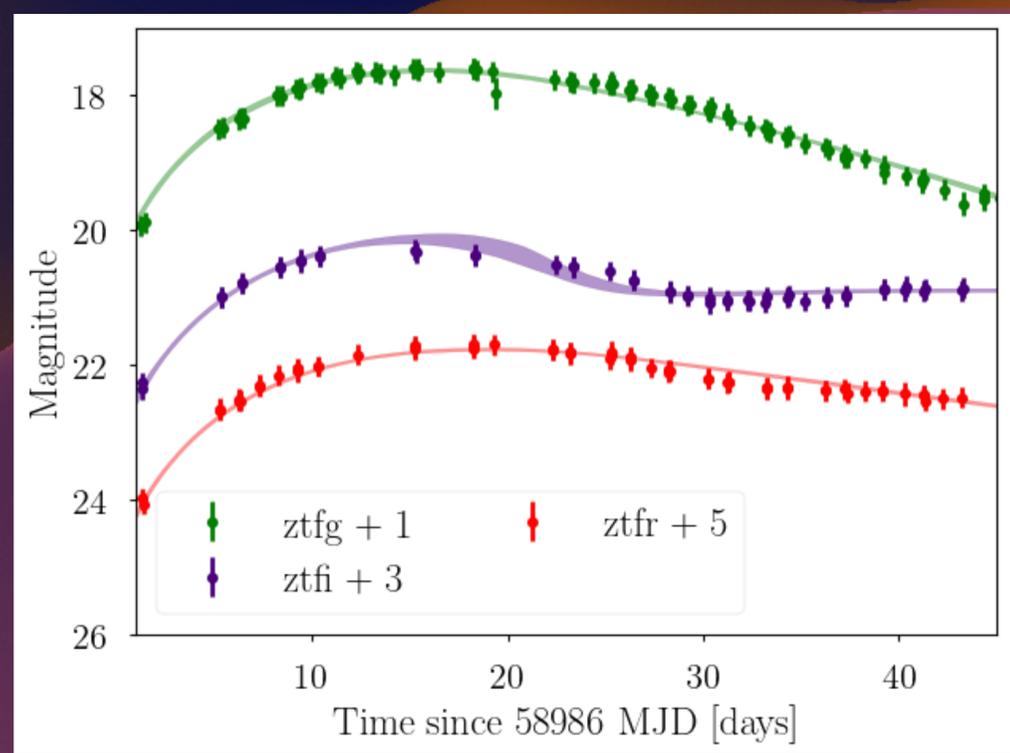
▶ What happens in the I-band?

- ▶ Secondary 'bump' is proposed to be due to Iron group recombination, Kasen 2006.
- ▶ Introduces strong wavelength (and time) dependent "opacity" that redistributes flux from UV/blue to longer wavelengths.
- ▶ So we extend the model...
 - ▶ We put in a time and wavelength-dependent opacity (phenomenologically, this is not radiative transfer)

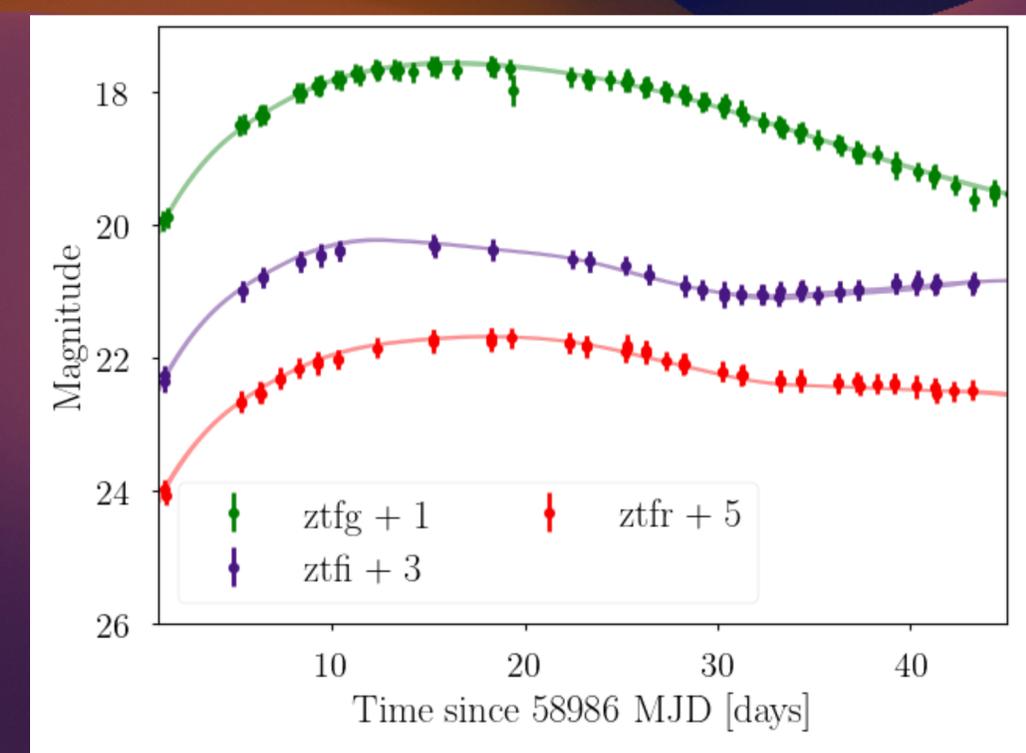
ZTF20aazymxi



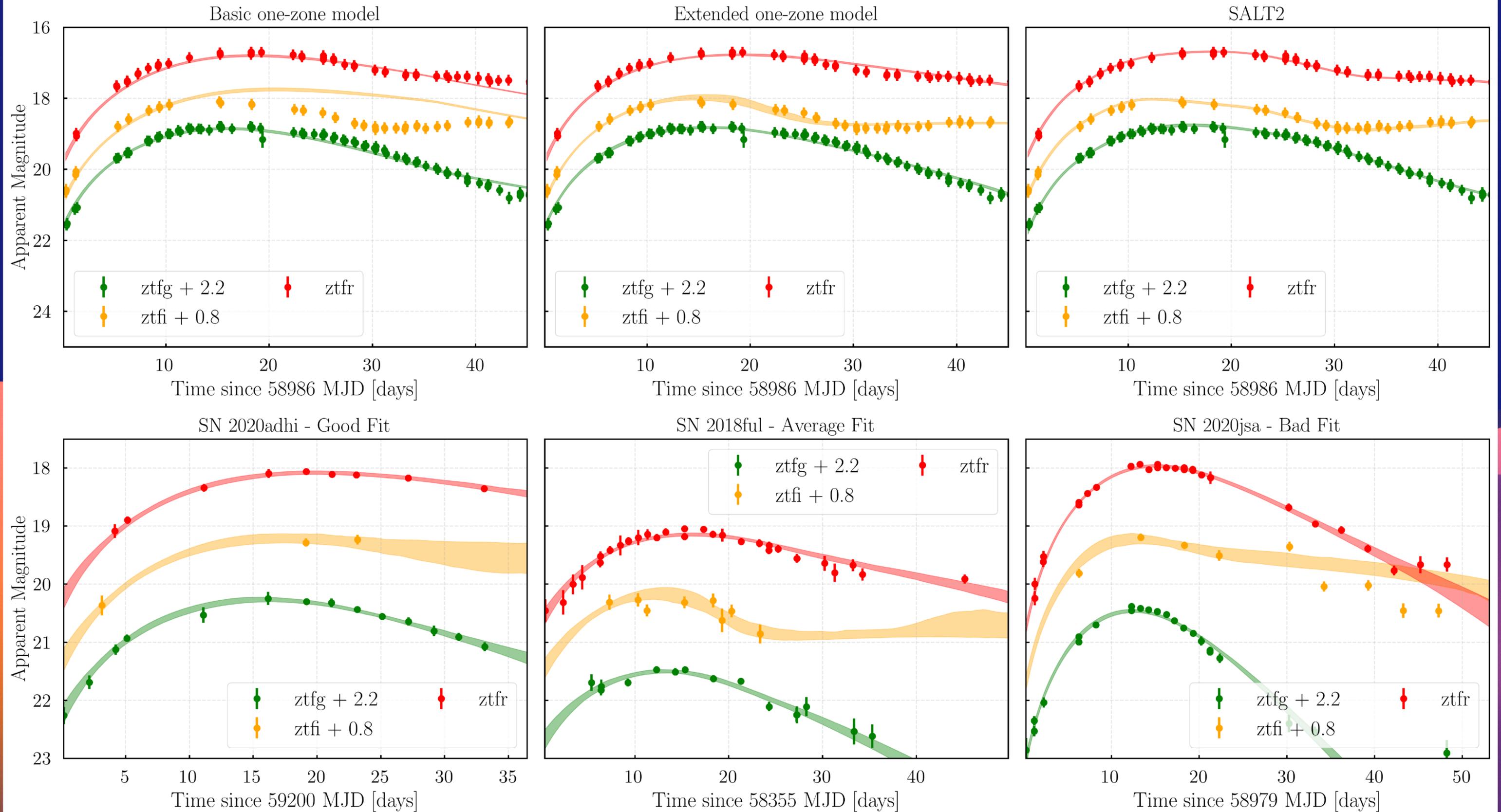
Basic one-zone model

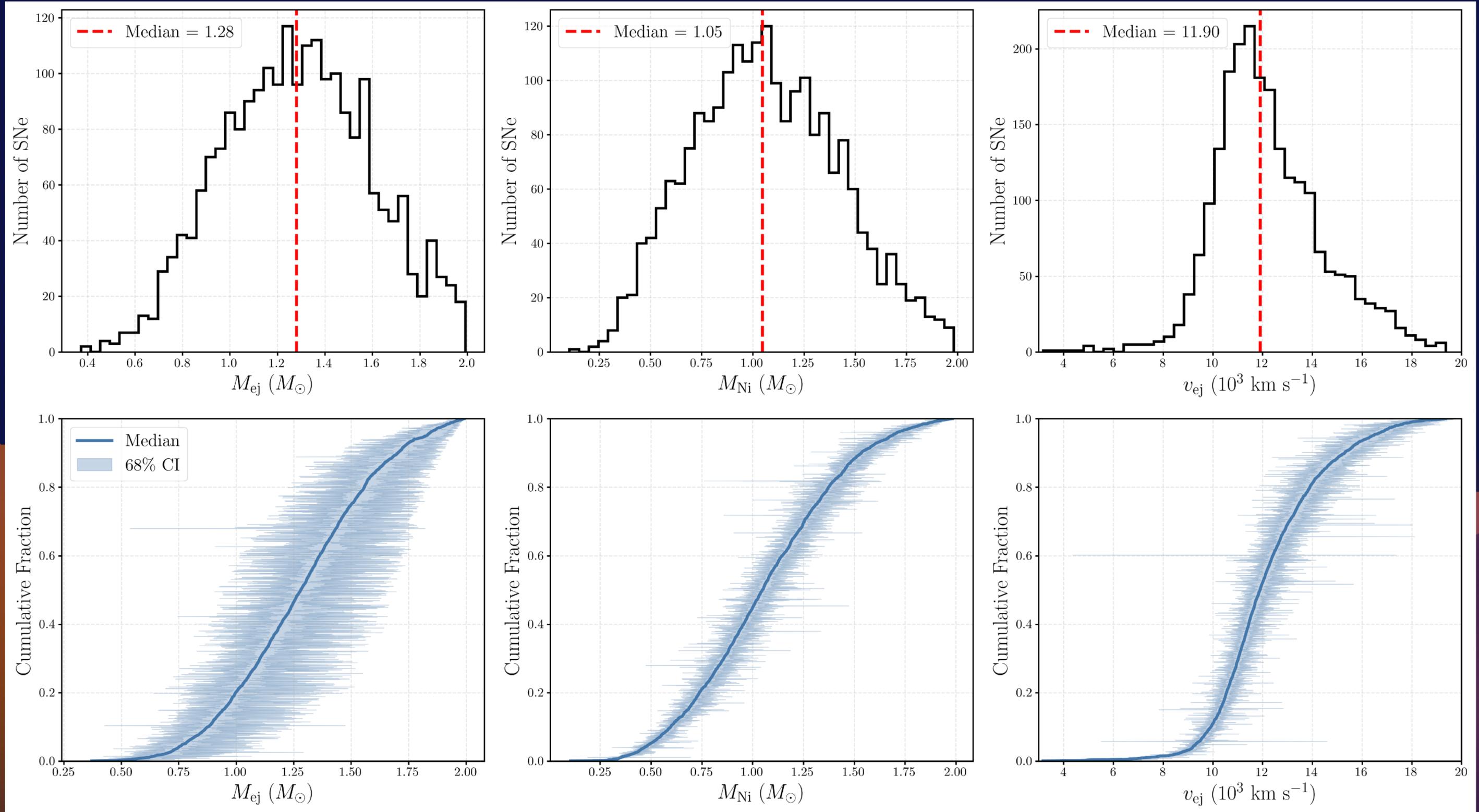


Extended model

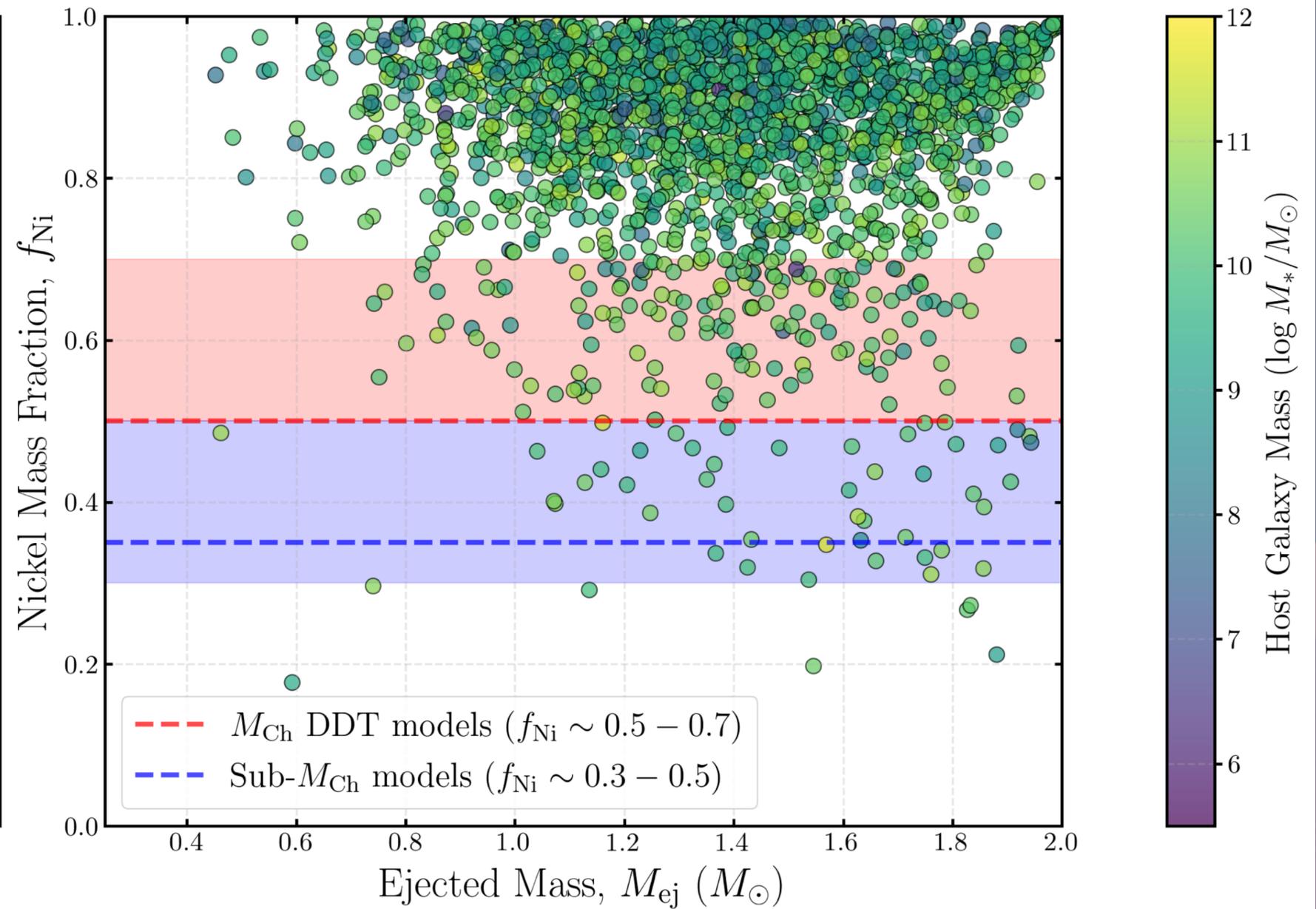
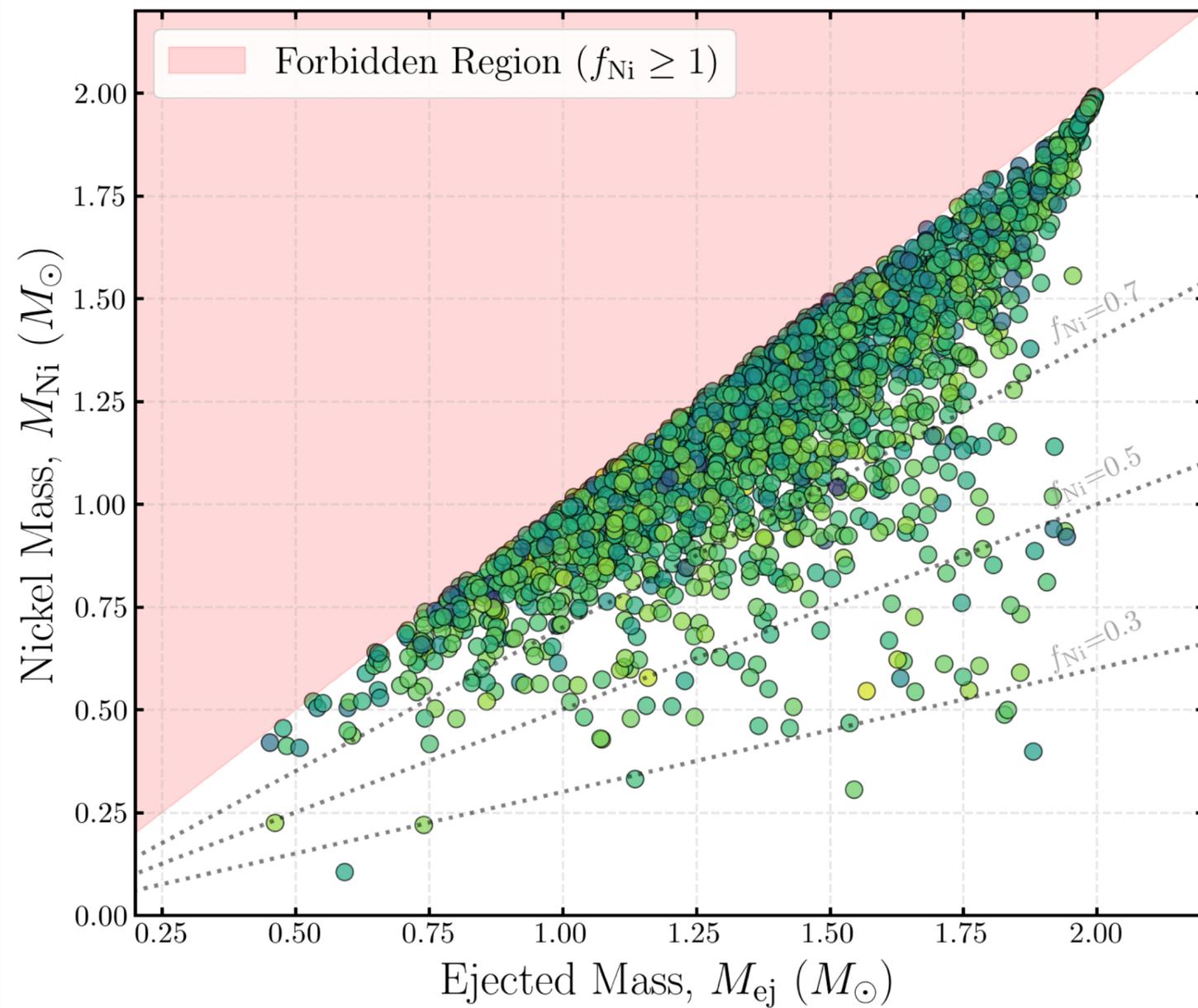


SALT2

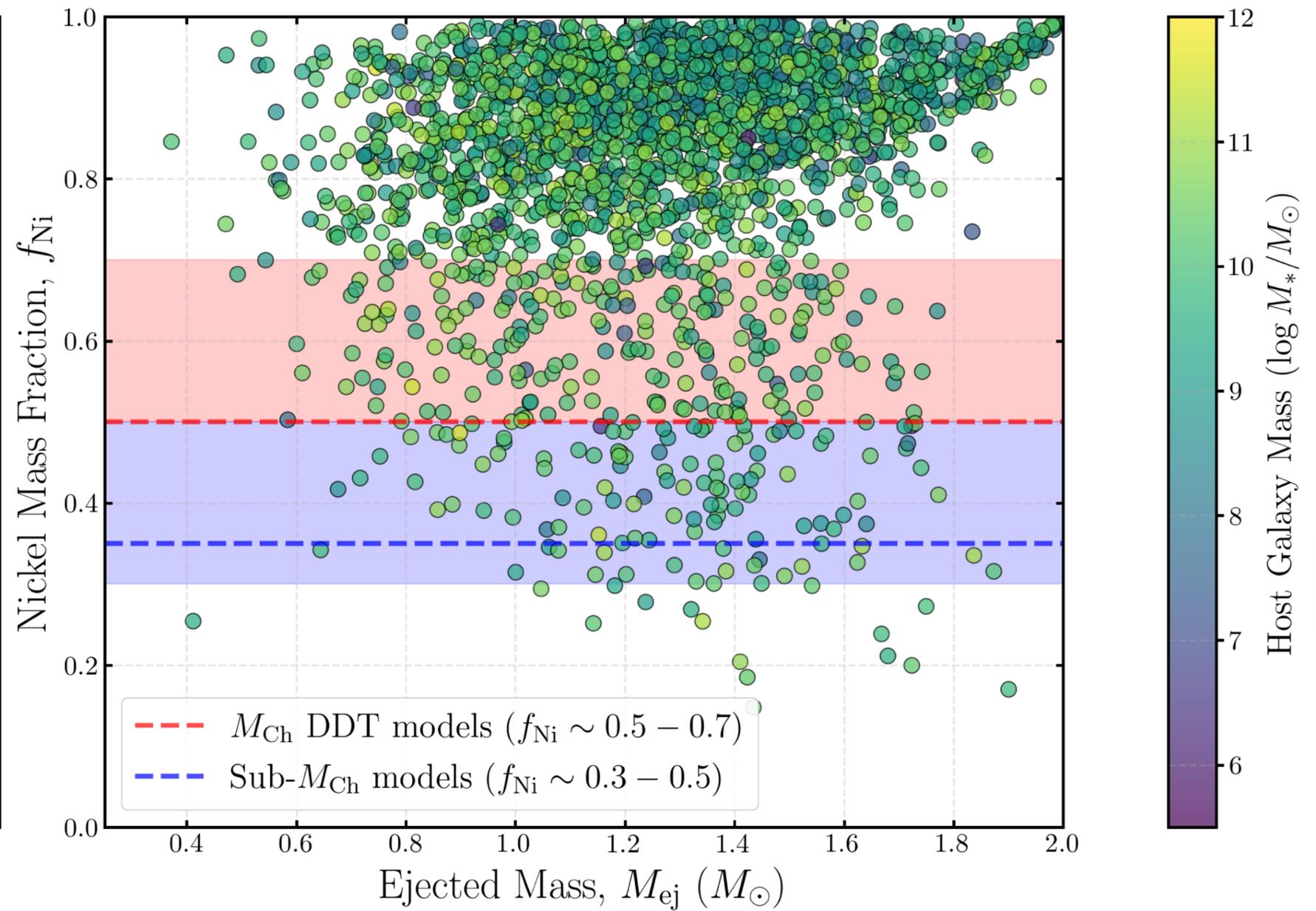
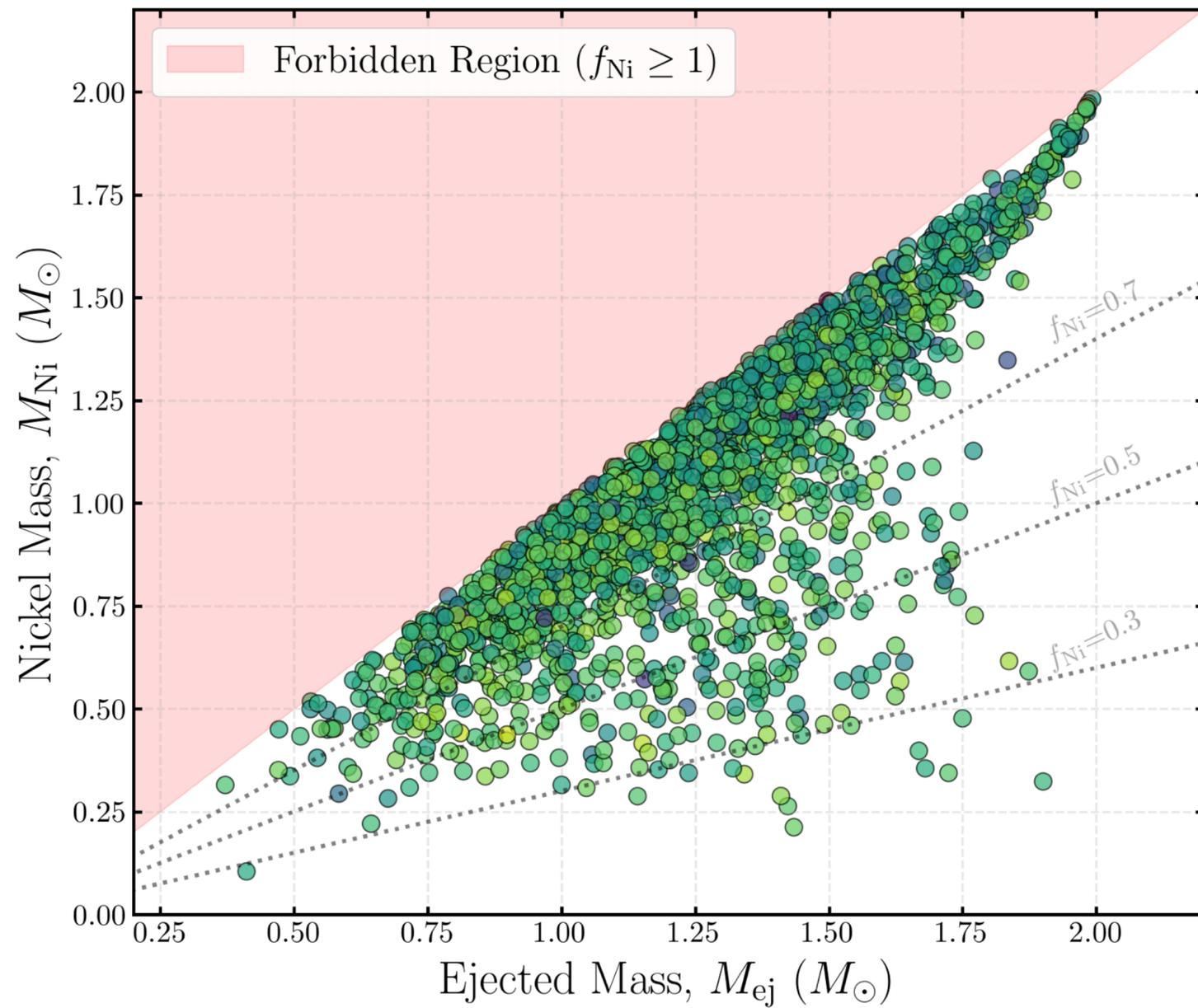




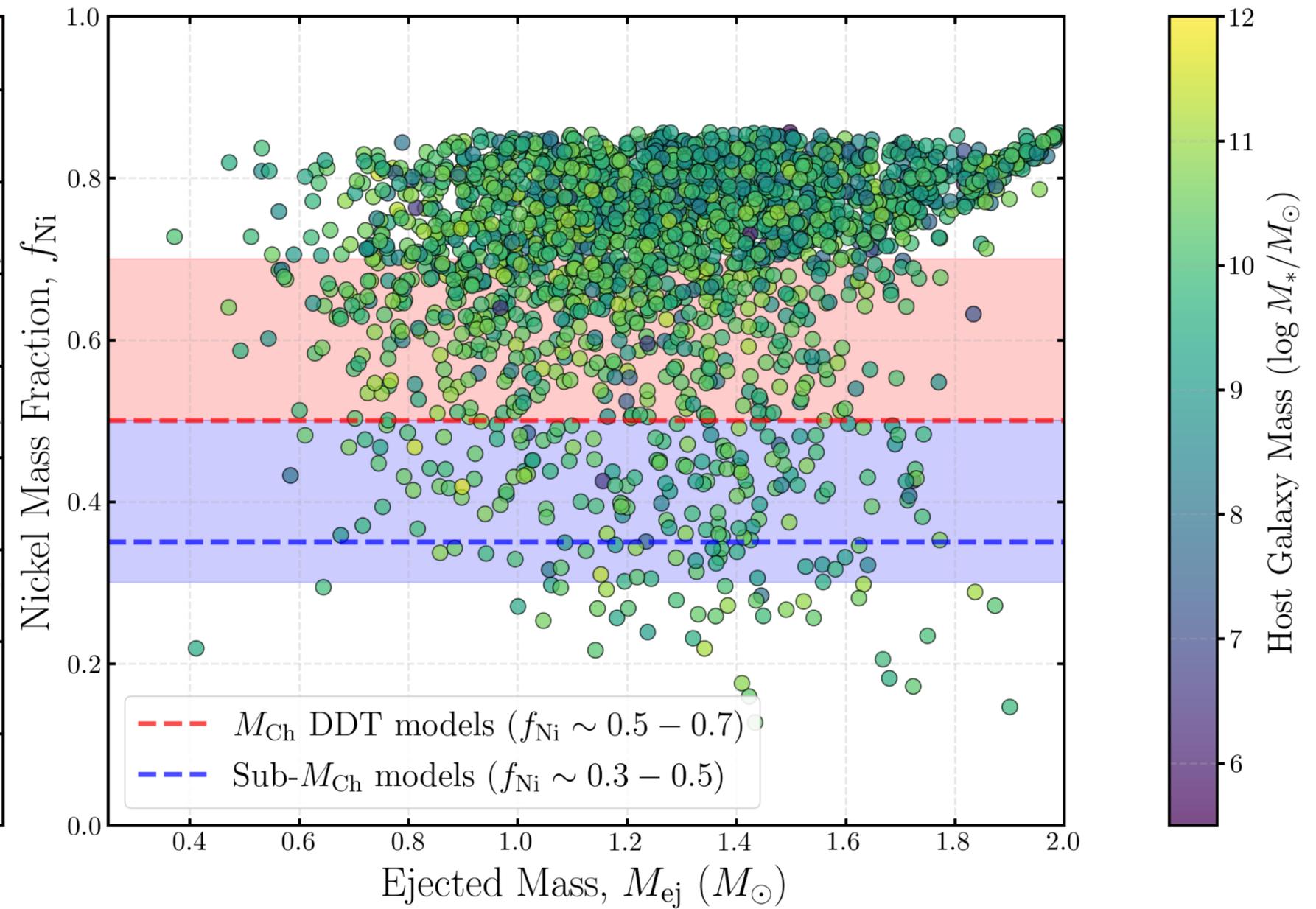
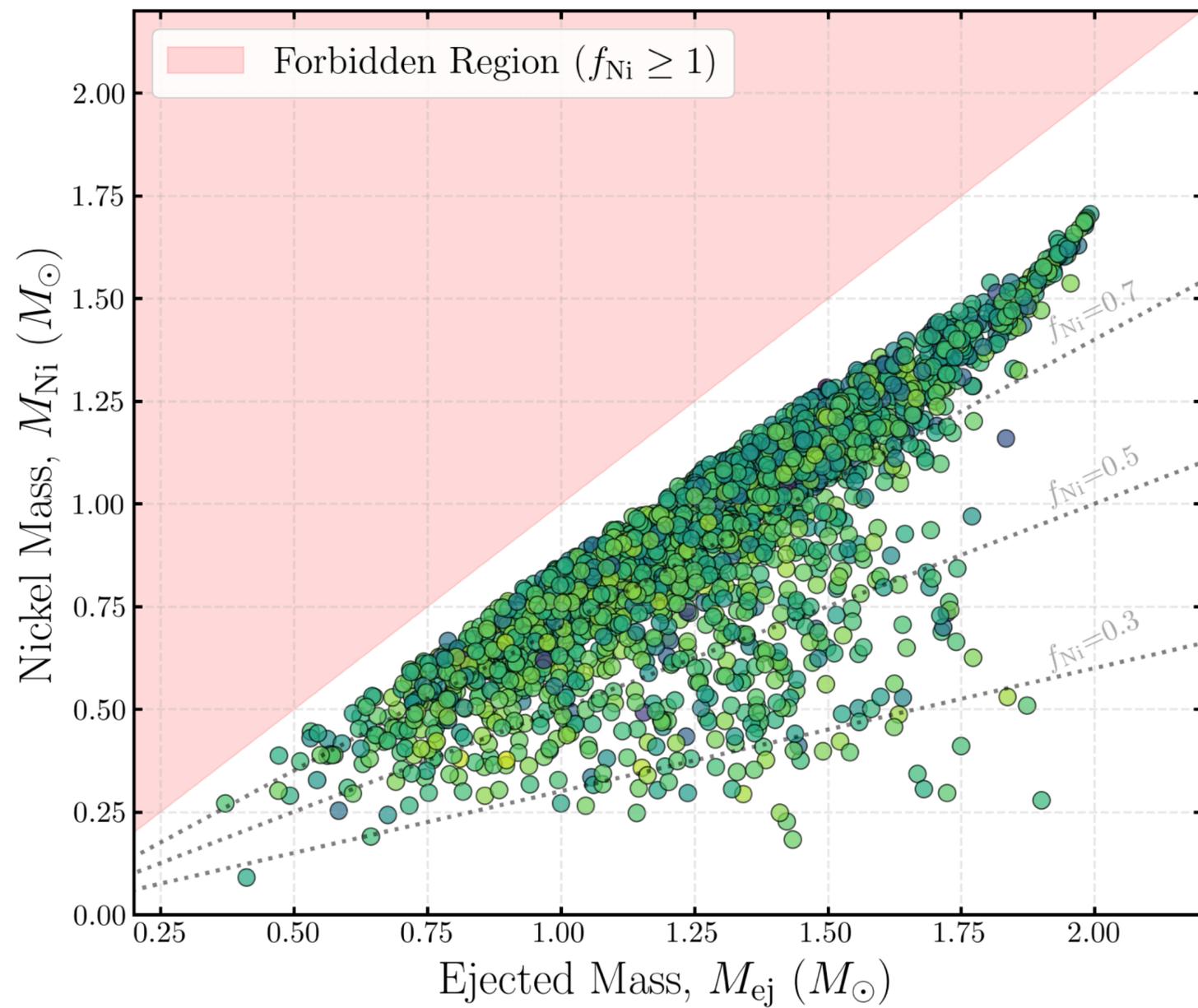
- ▶ No strong sign of bimodality in the COSMO sample. Reasonably homogeneous population of Ia.



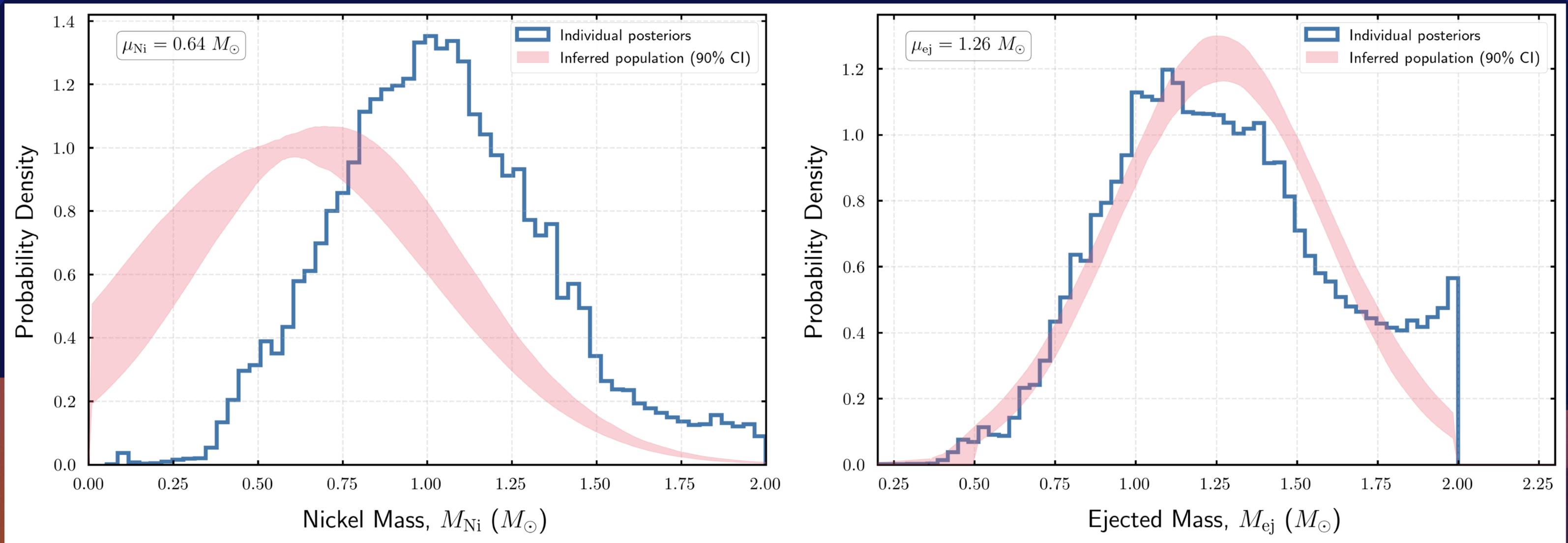
- ▶ COSMO sample Ia are clustered around very interesting parts of the parameter space. High burning efficiency not predicted by DDT models. Too high?



- ▶ Medians are misleading....
- ▶ Degeneracies are large/Posteriors are broad.

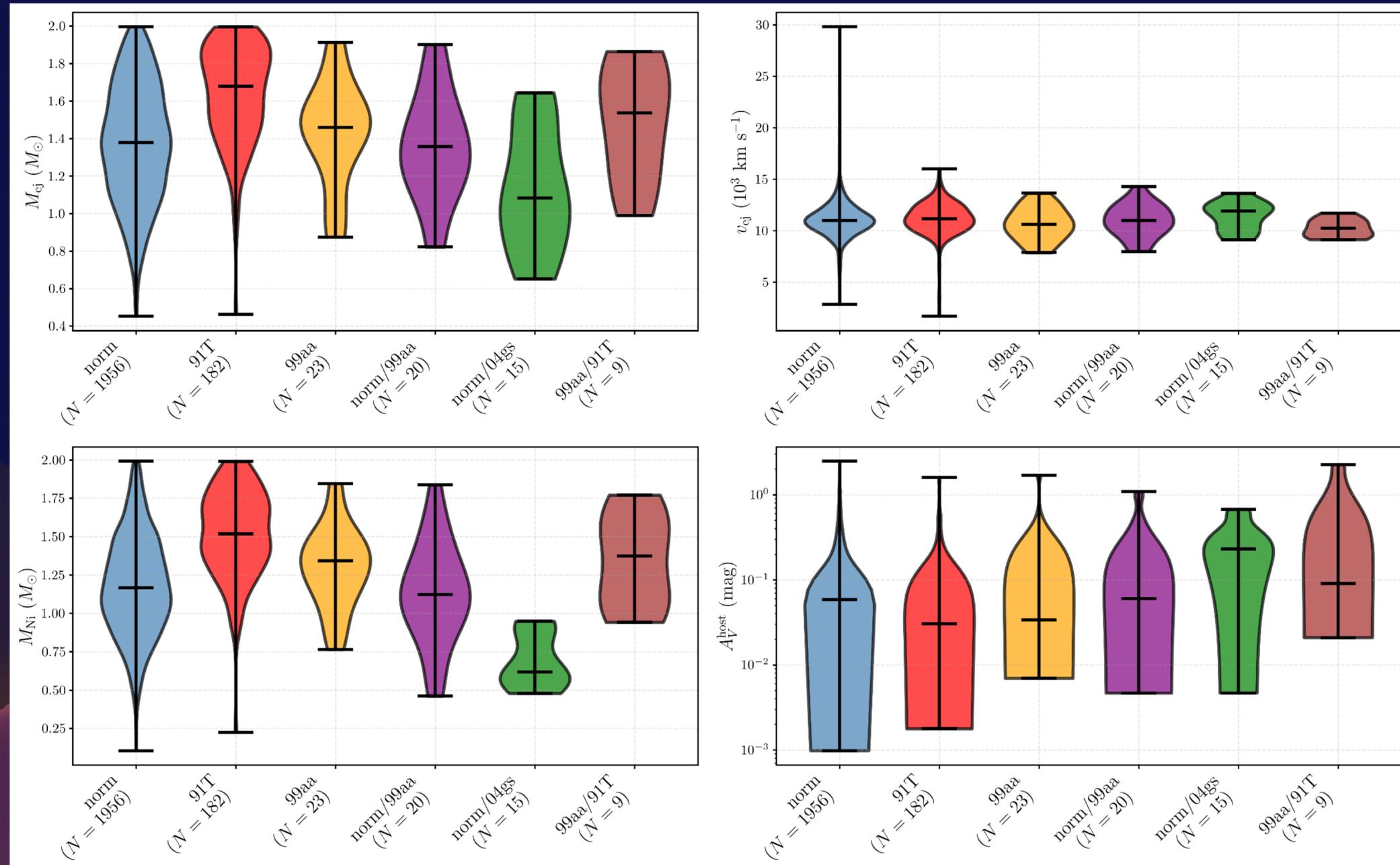


- ▶ Medians are misleading....
- ▶ Degeneracies are large/Posteriors are broad.

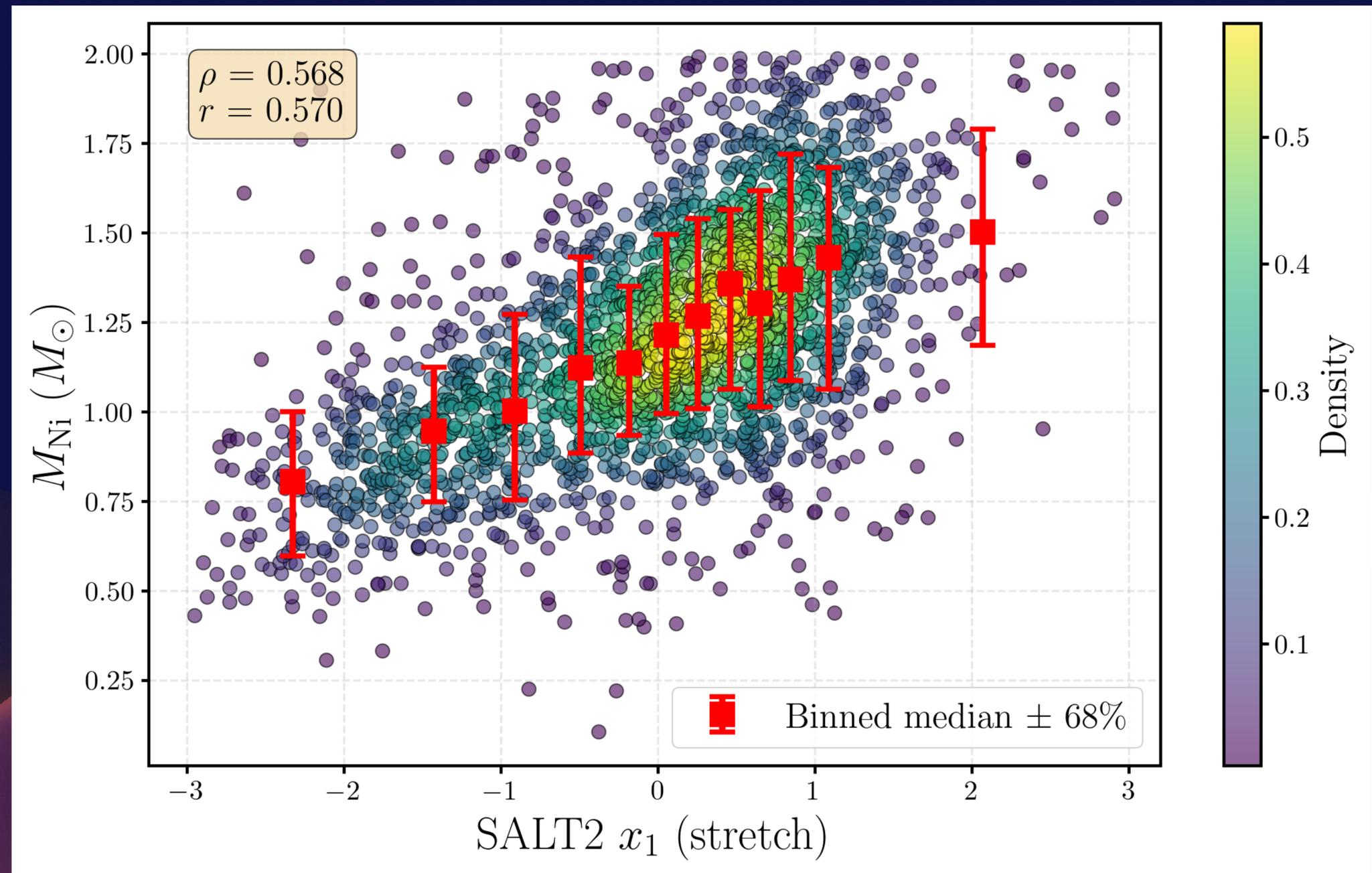


- ▶ Nickel mass distribution becomes much more consistent with expectations, $\mu_{\text{Ni}} = 0.64 \pm 0.06$.
- ▶ 43 % (78%) of Type Ia have $M_{\text{ej}} \leq 1.2M_{\odot}$ ($1.5M_{\odot}$)
- ▶ Burning efficiencies compatible with DDT channel, $f_{\text{Ni}} = 0.5 \pm 0.3$.

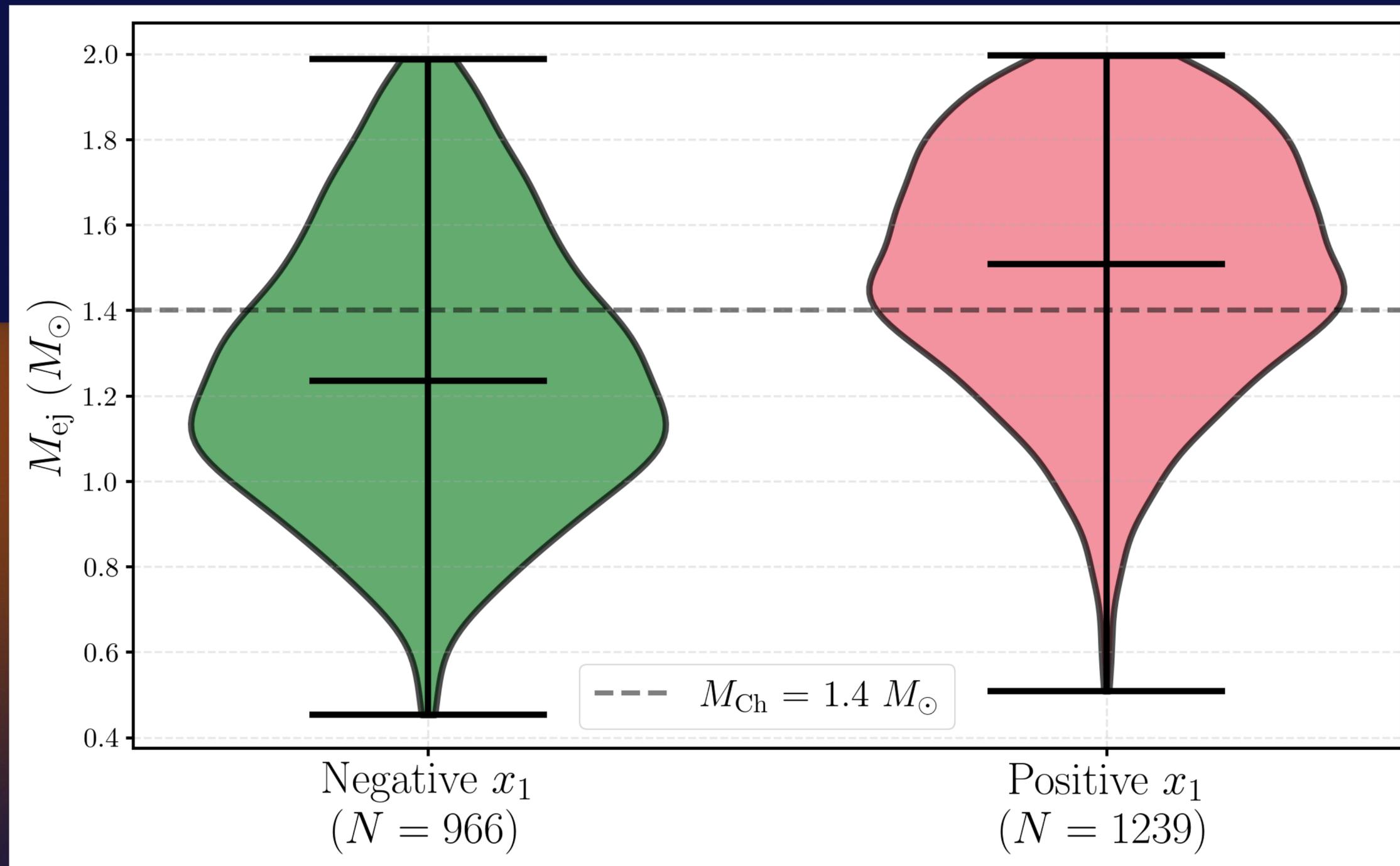
- ▶ Some variation between subtypes...
- ▶ Strong support that 91T-like have systematically higher ejecta.
 - ▶ 1.4 vs 1.64 M_{\odot}
 - ▶ Produce ~30% more ^{56}Ni .
- ▶ 04gs-like are usually underluminous compared to the rest of the sample.
 - ▶ ~1.0 vs 0.6 M_{\odot} of ^{56}Ni "median".



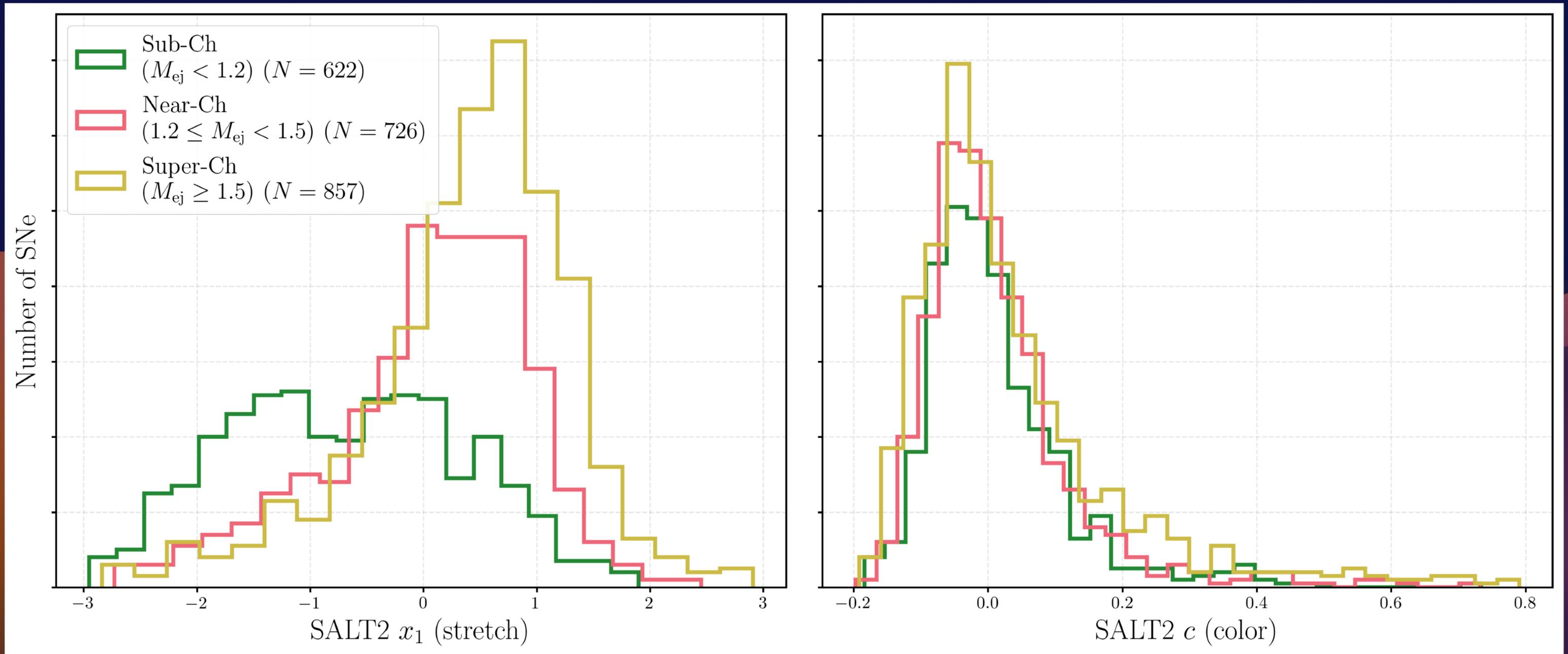
- ▶ ^{56}Ni well correlated with stretch.
- ▶ Supernova with more ^{56}Ni have a larger width.
- ▶ Higher ^{56}Ni = brighter.
- ▶ In the simple one-zone model, M_{ej} = larger diffusion time = longer lightcurve.
- ▶ Empirical Phillips relation, but from physics.



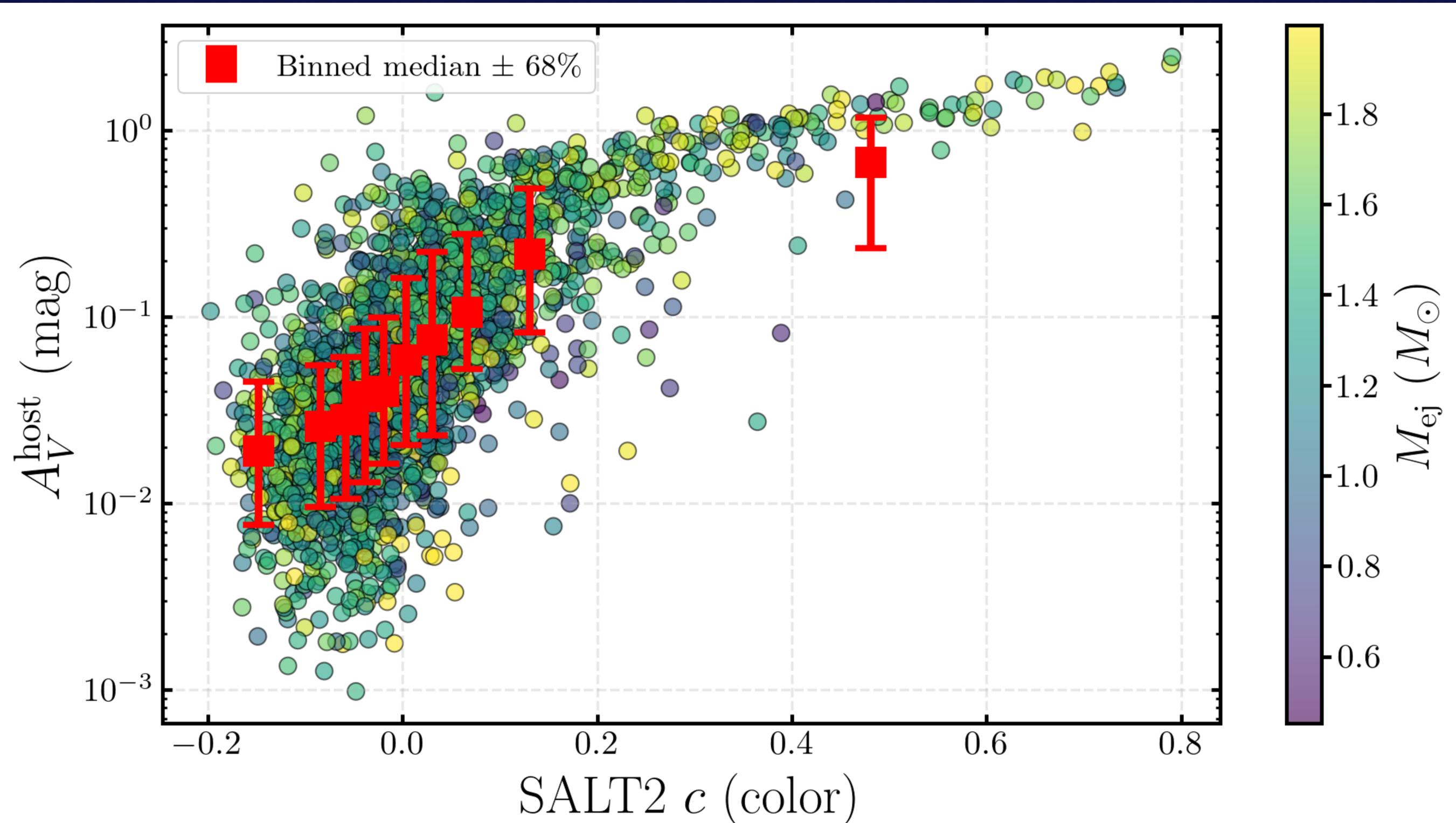
- ▶ Ejecta mass also correlated with stretch.
- ▶ Systematically larger M_{ej} for positive stretch vs negative.



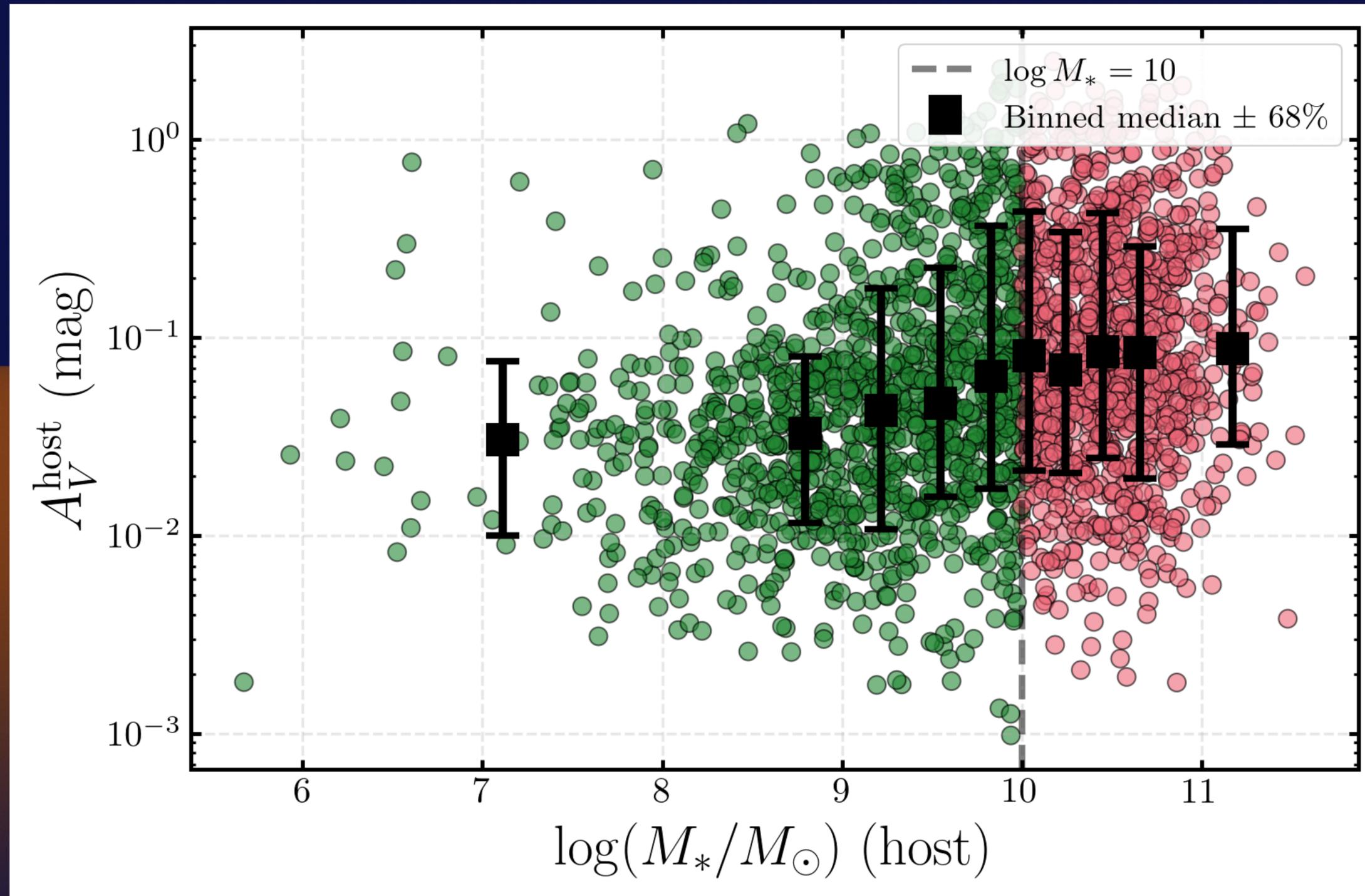
- ▶ Stretch distributions are different for different M_{ej} bins.



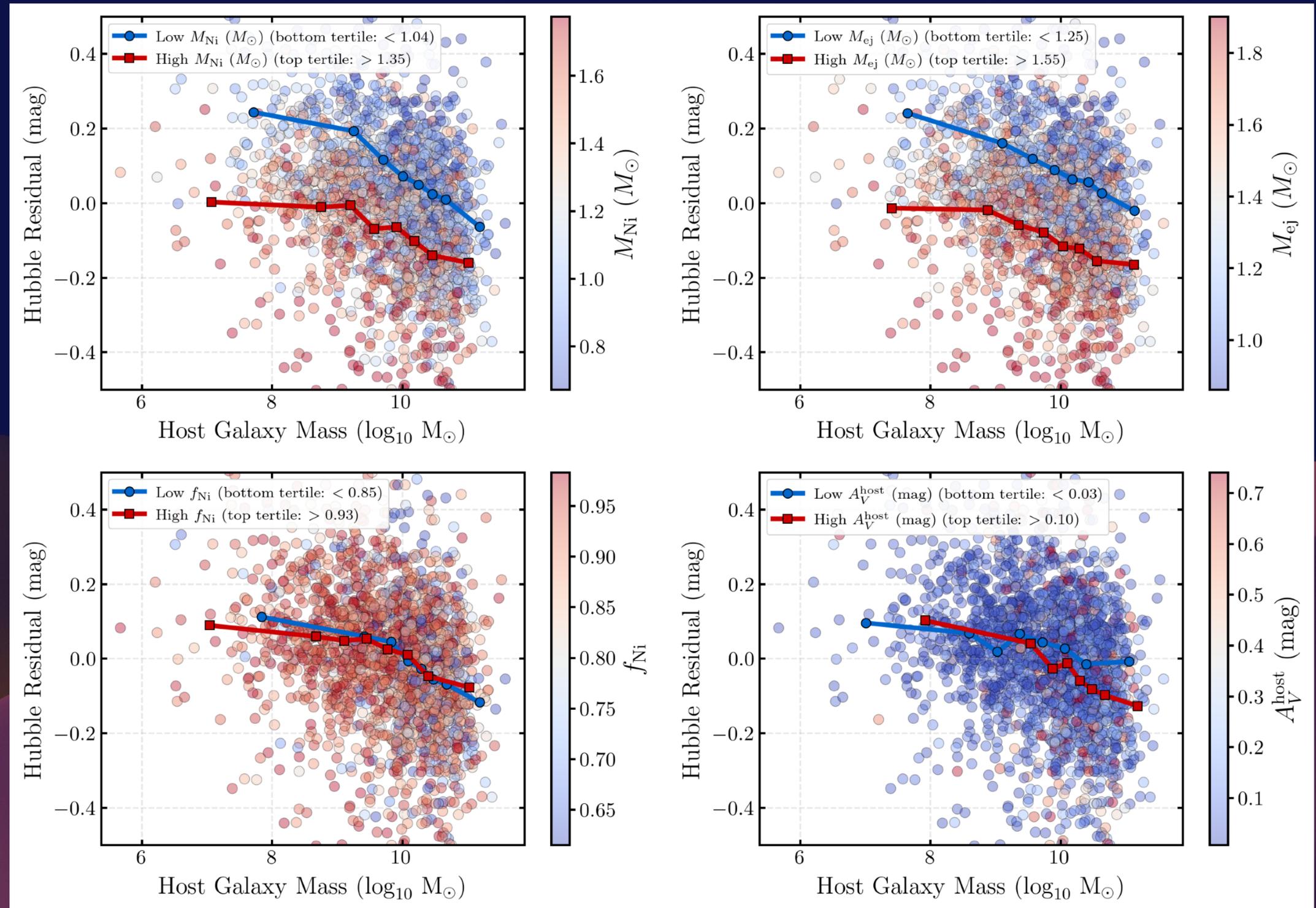
- ▶ SALT color also highly correlated with inferred host galaxy extinction.



- ▶ Host extinction does not change too much, basically the same distribution above $M_{\text{gal}} > 10^{9.5} M_{\odot}$, maybe lower at lower galaxy mass.



- ▶ Host mass-step seen in physical parameters.
 - ▶ Mass step is rooted in ^{56}Ni production?
 - ▶ Standardisation fails to account for the sub-population of cosmo events with lower ^{56}Ni yield.
 - ▶ Suggests dependence on host-galaxy metallicity or something else affecting the burning efficiency?



- ▶ As the data becomes better, D_{KL} will kill many existing models/and many 'sampling algorithms'.
 - ▶ Lessons from GW...
- ▶ Population-era analyses with Bayesian posteriors should ideally use Bayesian hierarchical modelling techniques.
 - ▶ Summary statistics are not useful beyond summaries...
- ▶ End-to-end simulations are possible and should become a standard part of the pipeline.
 - ▶ Individual object or full survey level e.g., cadence/realistic noise.
- ▶ We have performed an analysis of the largest sample of Type Ia with a physical but still wrong model.
- ▶ An analysis that would have previously taken ~50000 CPU hours can now be done in ~300 CPU hours. GPUs brings this down to ~minutes.
- ▶ The Ia population as seen through a one-zone model is quite homogeneous, and mostly consistent with one channel, with near Chandrasekhar mass dominating.
 - ▶ Physics-based standardisation may remove the biggest systematic in Ia cosmology.

TOWARDS TRANSIENT LIGHTCURVE MODELING AT SCALE: SOME PEDAGOGY AND TYPE IA IN DR2

NIKHIL SARIN

- ▶ Host mass-step.
- ▶ ^{56}Ni seems to be different between galaxies with low and high mass.
 - ▶ $^{56}\text{Ni} \sim 1.2$ in $M_{\text{gal}} < 10^{10} M_{\odot}$
 - ▶ $^{56}\text{Ni} \sim 1.1$ in $M_{\text{gal}} > 10^{10} M_{\odot}$

