Astrometric Redshifts of Supernovae

Jaemyoung (Jason) Lee, Masao Sako, Rick Kessler, and the LSST Collaboration

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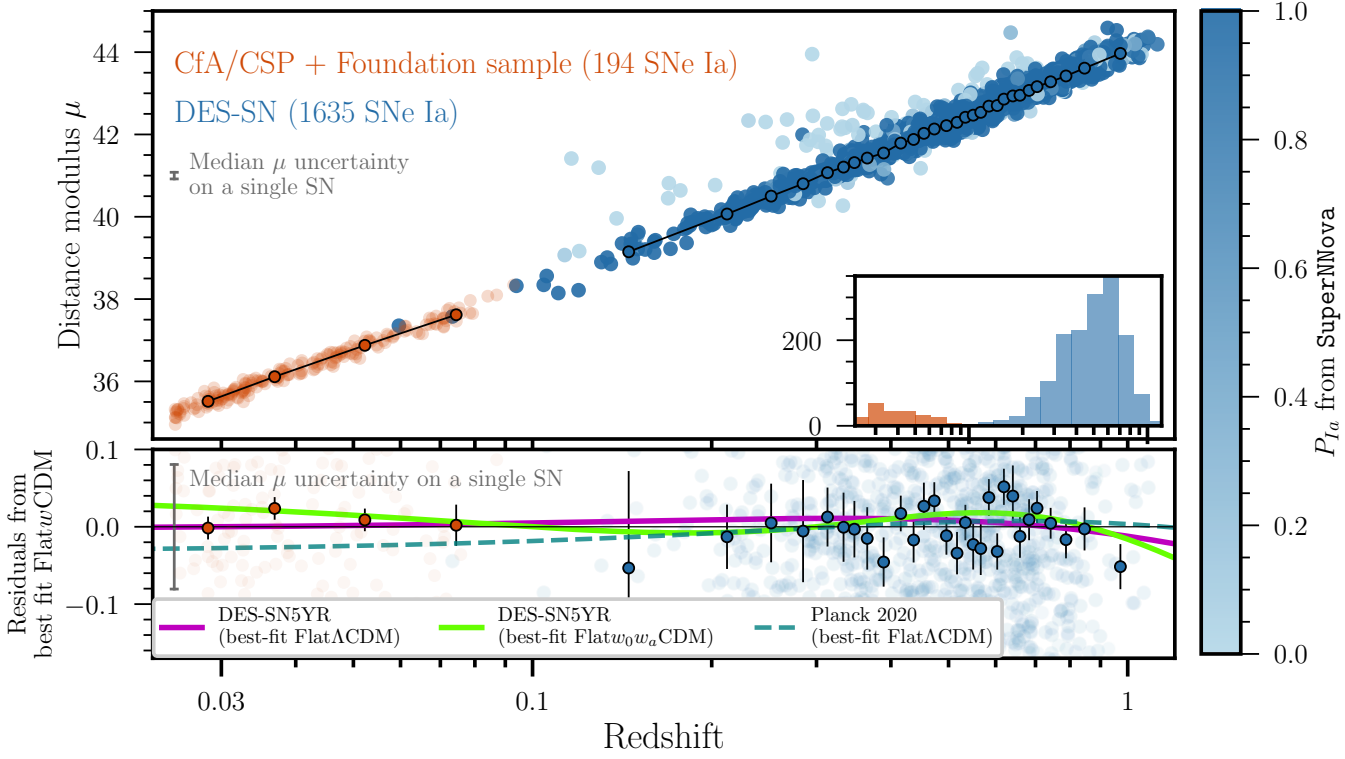
Fink-Brazil Workshop

DESC Project 319 (PUBID:149)

arXiv:2405.04522

Redshifts in SN Ia Cosmology



From the DES Collaboration, arXiv:2401.02929

Motivation

- Too many Rubin (LSST) SNe Ia for spectroscopic follow-up => non-spectroscopic redshift measurements (photo-z's) crucial

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- **(Nearly) independent** redshift measurement from conventional photo-z's

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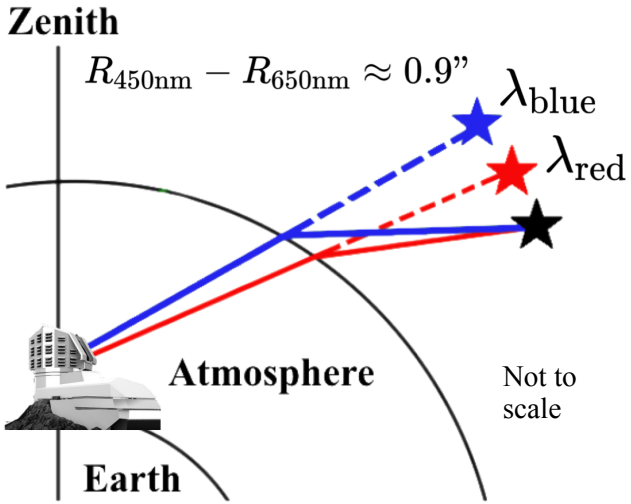
- No additional measurements needed

Differential Chromatic Refraction (DCR)

Atmospheric refractive index: λ-dependent



More DCR shift at higher air mass (AM),
or amount of air along the line of sight (AM: 1.0 at zenith)

DCR shift by redshift

$$\bar{R}_{\mathrm{DCR}} = \frac{\int_0^\infty R_0(\lambda) \tan z_a F(\lambda) S(\lambda) d\lambda}{\int_0^\infty F(\lambda) S(\lambda) d\lambda}$$

$S(\lambda)$: Source Flux, $F(\lambda)$: Filter Function

$R_0(\lambda) : f(n(\lambda))$, z_a : zenith angle

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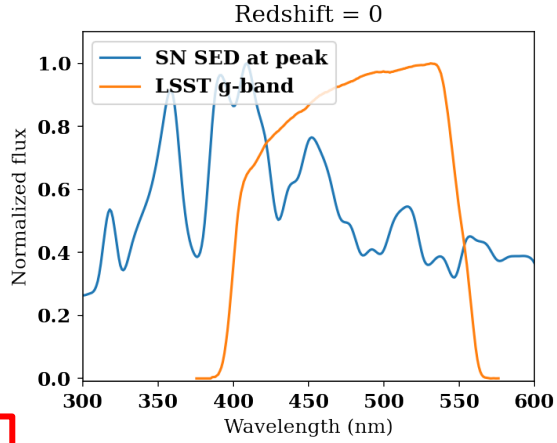

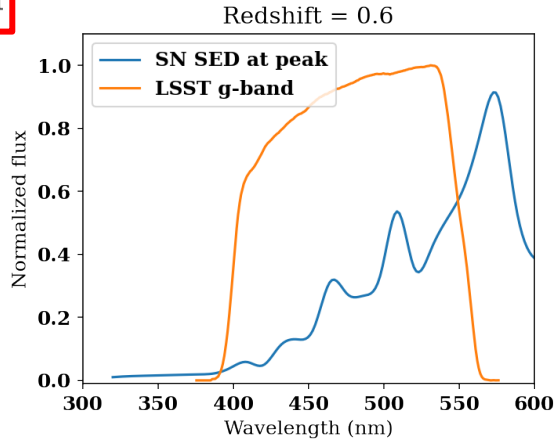

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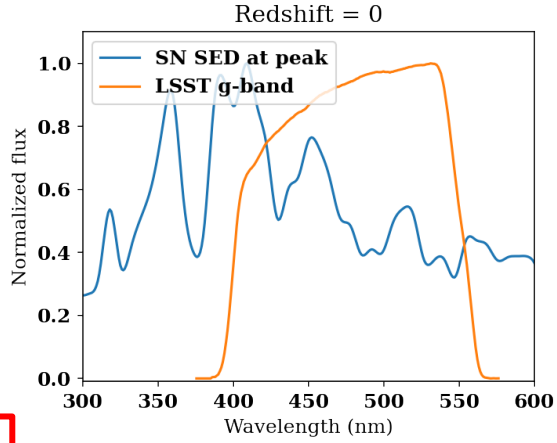

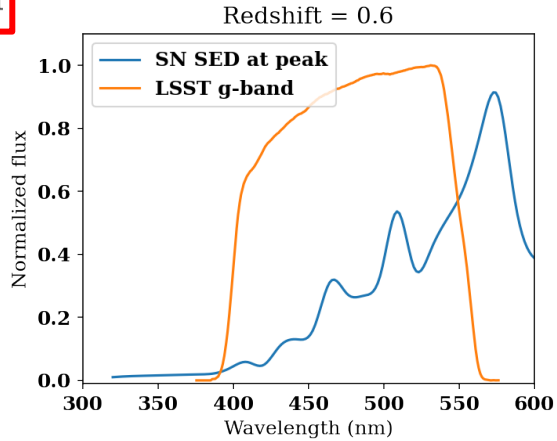

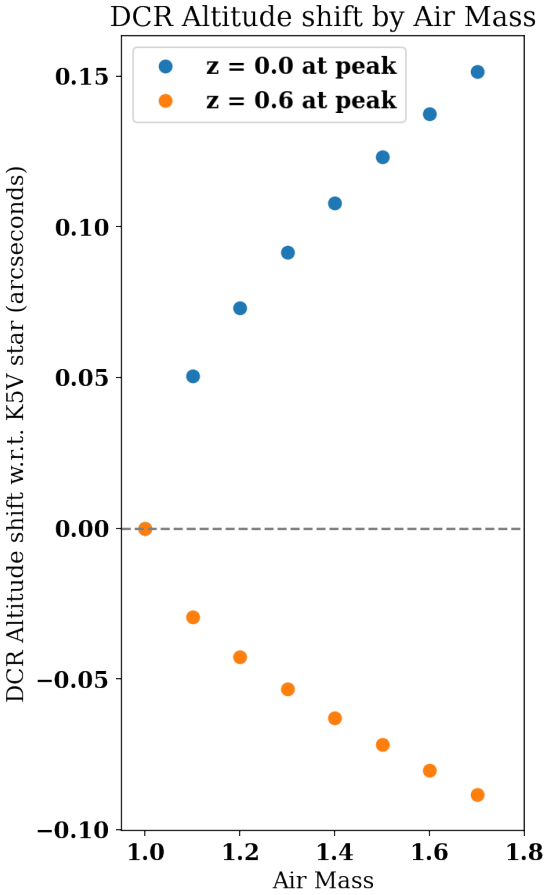

Methodology

- SNANA simulations (ELAsTiCC) for realistic astrometric simulations (OBS)
- SED (spectral energy distribution) from underlying model to calculate DCR shifts according to [z, AM, color (c), stretch (x_1)] analytically for *ugriz* bands (MODEL)

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- $\chi^2 = \sum \frac{(\Delta_{\mathrm{OBS}} - \Delta_{\mathrm{MODEL}})^2}{\sigma^2_{\mathrm{stat}} + \sigma^2_{\mathrm{syst}}}$, $P(z, x_1, c) = e^{-\frac{\chi^2}{2}}$
- Construct PDF => marginalize over c, x_1

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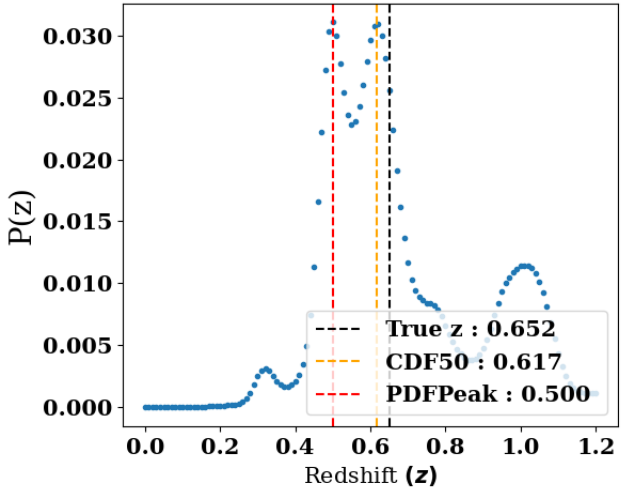
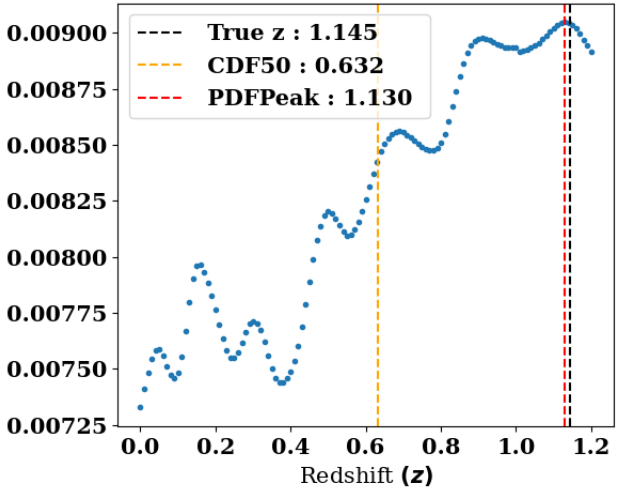
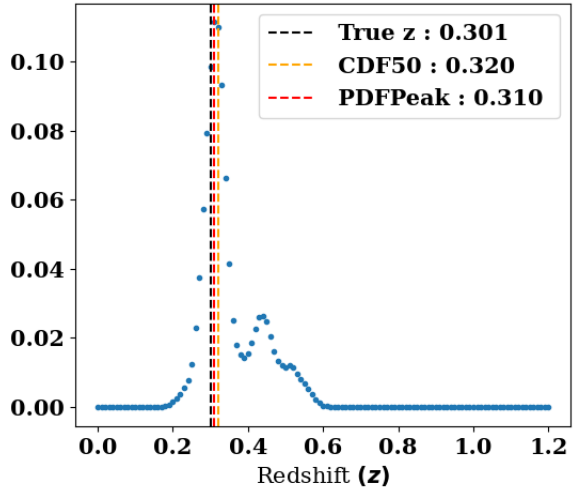
- **Two methods to get astro-z (z_{DCR}):**
  - **CDF50: 50th percentile of CDF $\pm 1\sigma$, PDFPeak: Peak of PDF $\pm 1\sigma$**

Two methods of z_{DCR} estimation: CDF50 vs. PDFPeak







Selection Cuts (for cosmology quality SNe)

- Light-curve requirements: $T_{\text{rest}} < -3$ & $T_{\text{rest}} > 10$ (69% of candidates remaining)

- 3 bands with S/N > 8 for Realistic SIMs (43% of candidates remaining)

- LCFIT+z convergence + FITPROB > 0.01 when combining with SN photo-z's (33 ~ 37% of candidates remaining)

Performance metrics

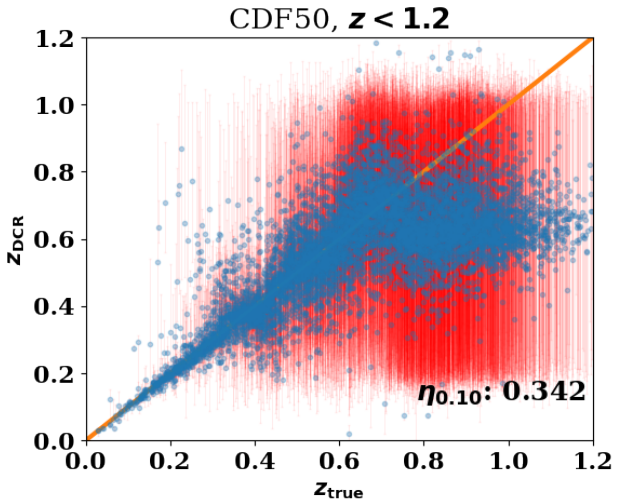
- Residuals $\Delta z \equiv \frac{z_{\text{estimate}} - z_{\text{true}}}{1 + z_{\text{true}}}$, Bias $\equiv \langle \Delta z \rangle$

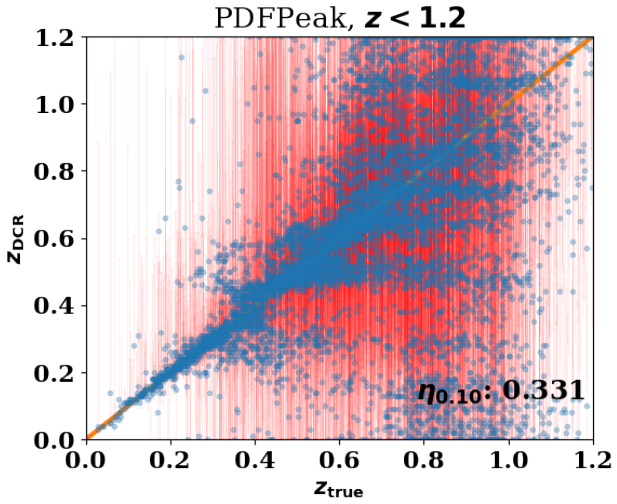
- (Accuracy) Outlier fraction η_x, fraction of candidates where $|\Delta z| > x$ (Default: $x = 0.10$)

- (Precision) MAD (Median absolute deviation) deviation
  $\sigma_{\text{MAD}} = 1.4826 \times \text{Median}|\Delta z - \text{Median}(\Delta z)|$

Realistic SIMs

- $\sigma_{\text{syst}} = 5$ mas
- Realistic T_{obs} (epoch), marginalized over x_1, c
- Degradation at high-redshifts
- $$\Delta z \equiv \frac{z_{\text{estimate}} - z_{\text{true}}}{1 + z_{\text{true}}}$$
- η_x: fraction of candidates where $|\Delta z| > x$





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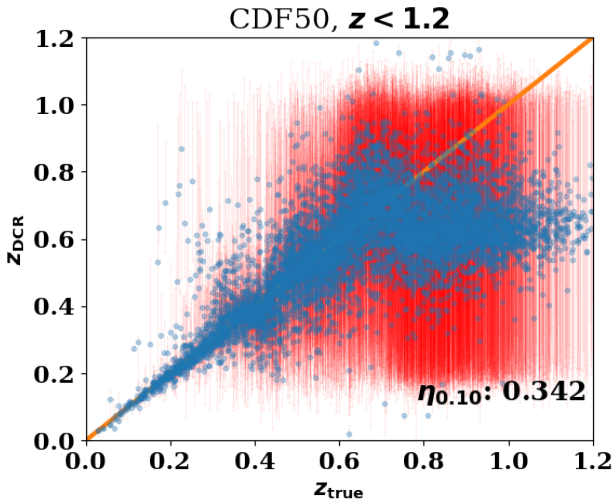
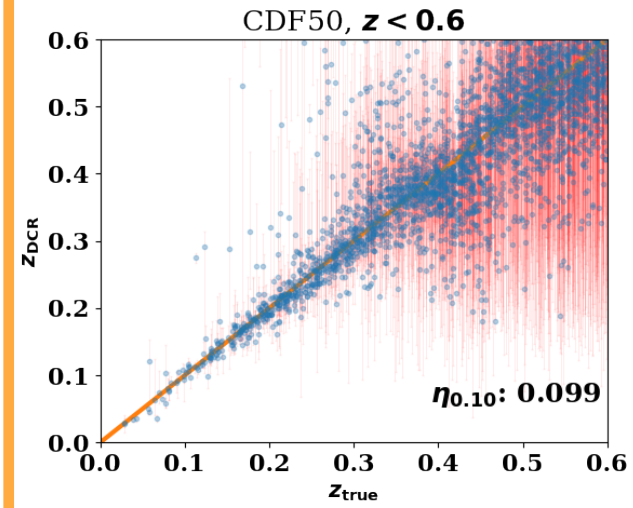
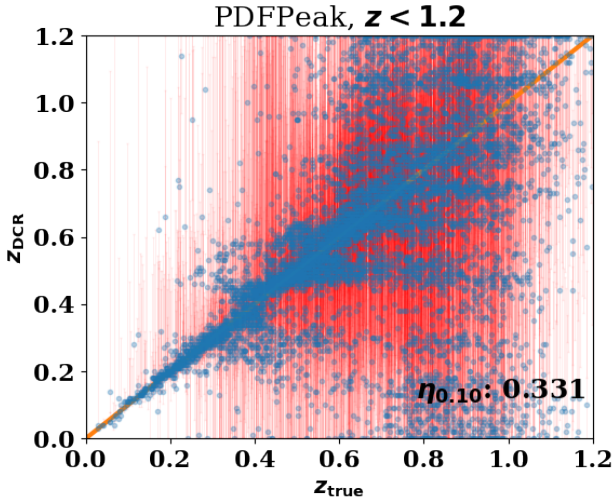
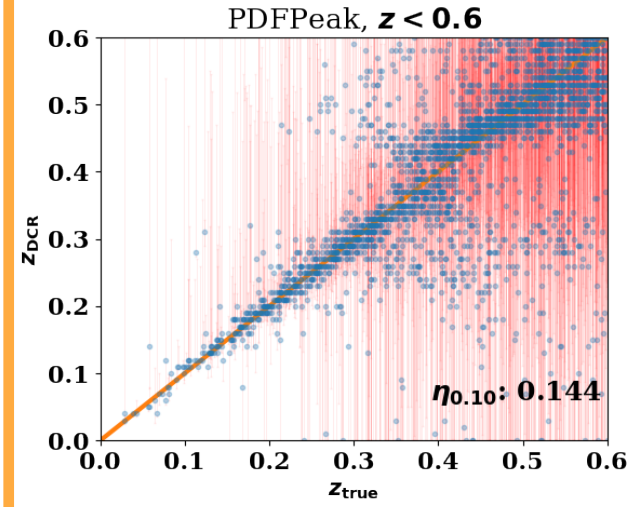
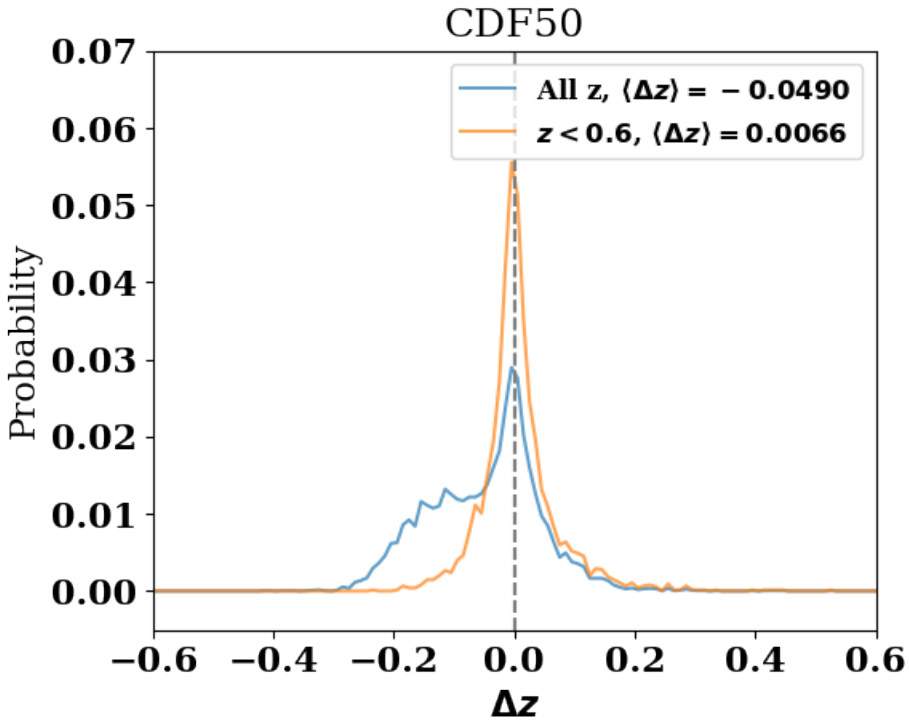


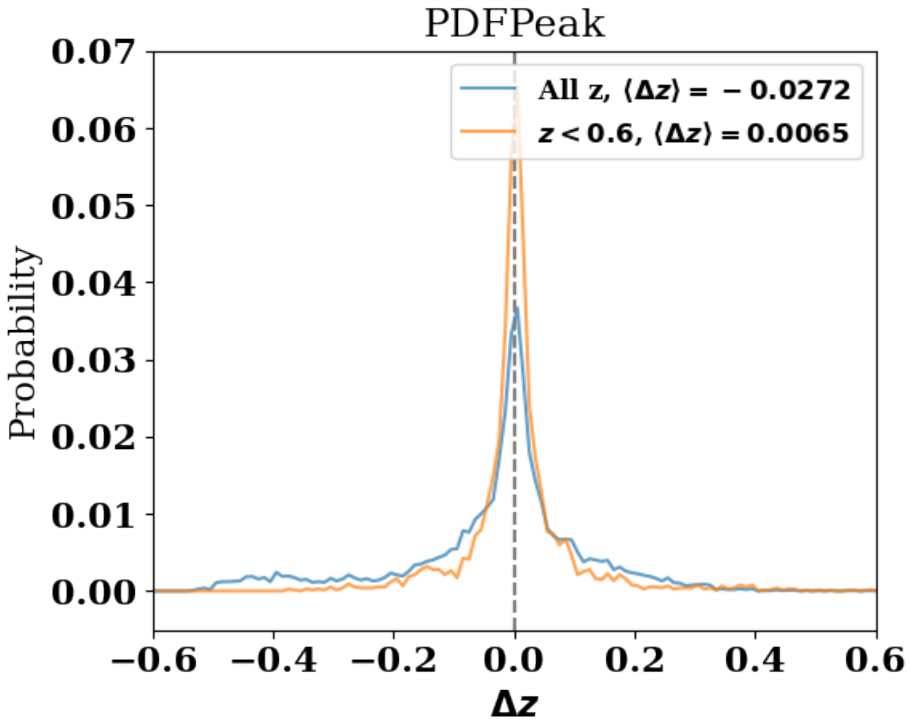






Realistic SIMs (Histograms)

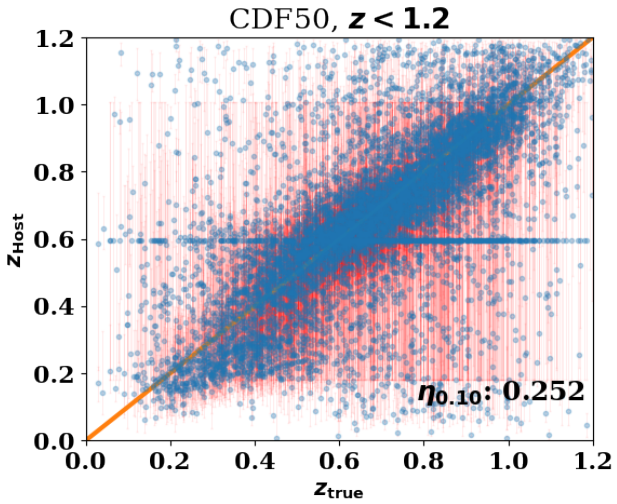


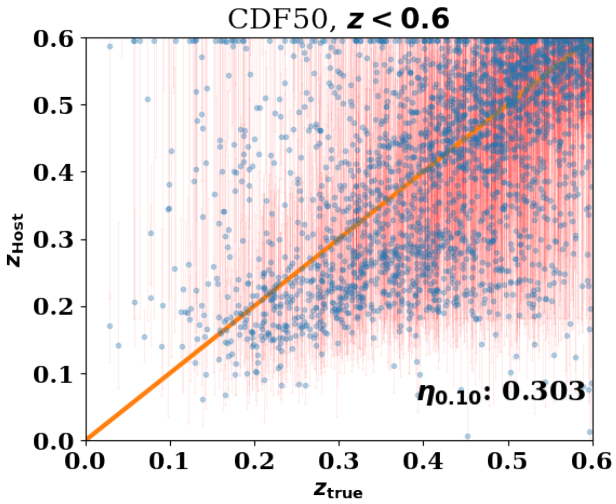


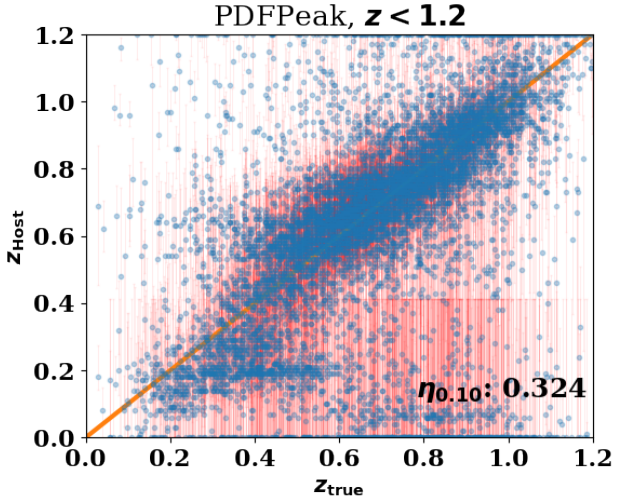
Combining with photo-z's

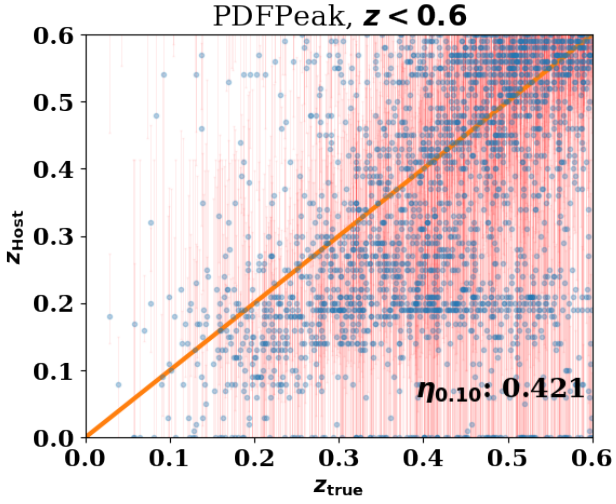
Host photo-z (z_{Host})

- From RAIL, better performance at high-redshifts



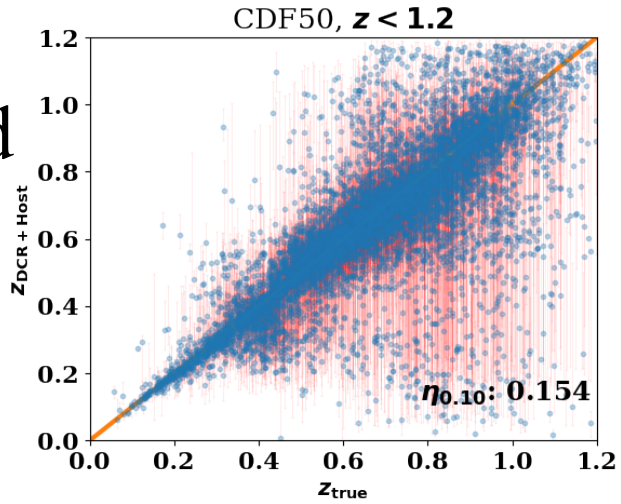


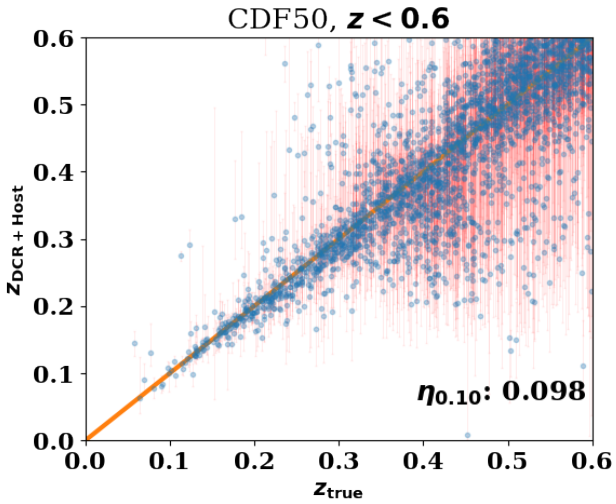


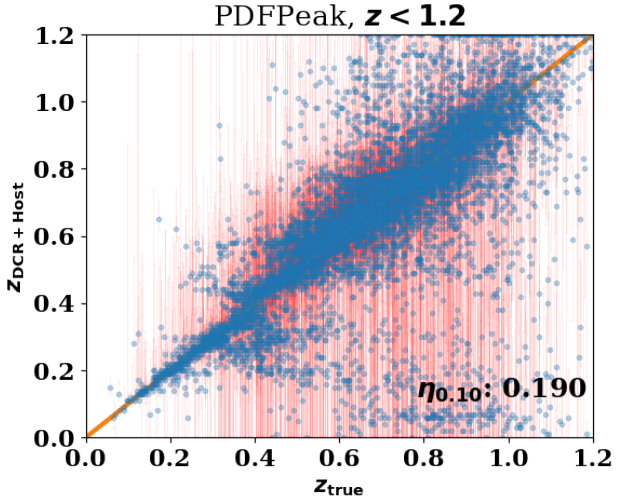


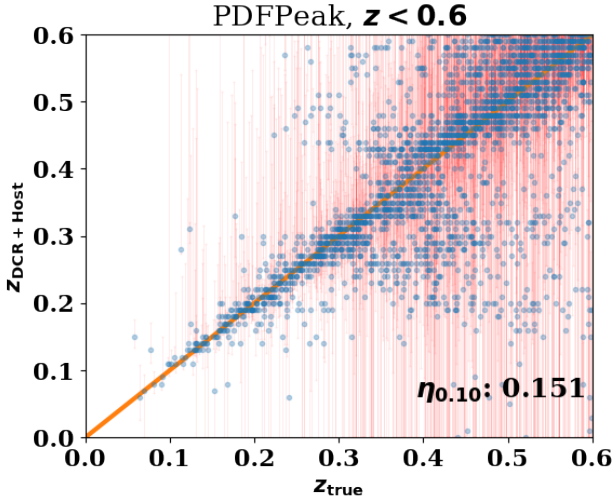
Astro-z Combined ($z_{\mathrm{DCR+Host}}$)

- Noticeably better performance at low-redshifts

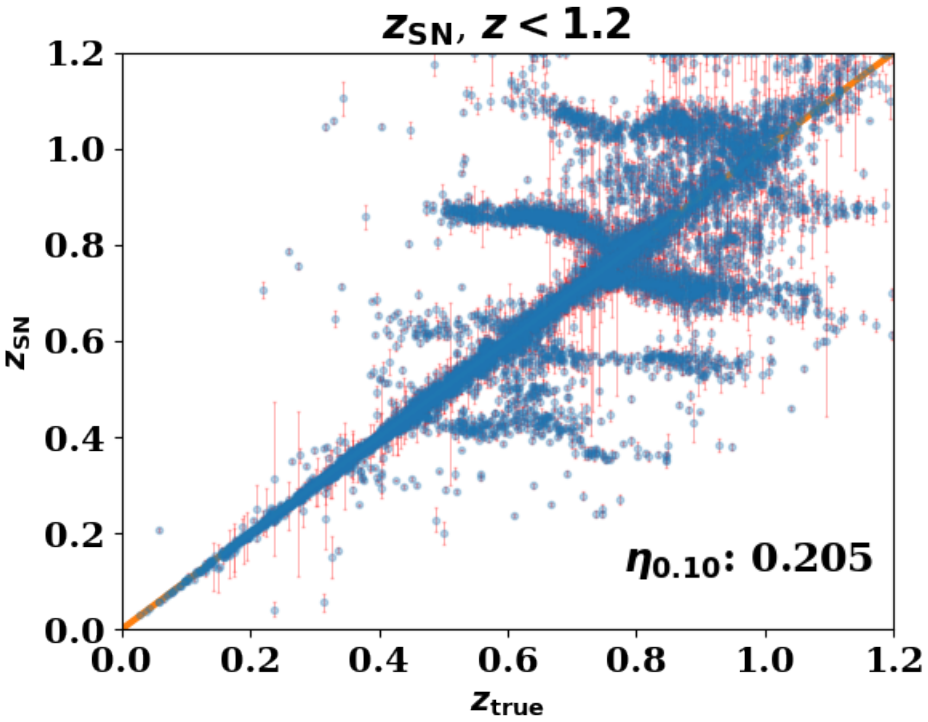


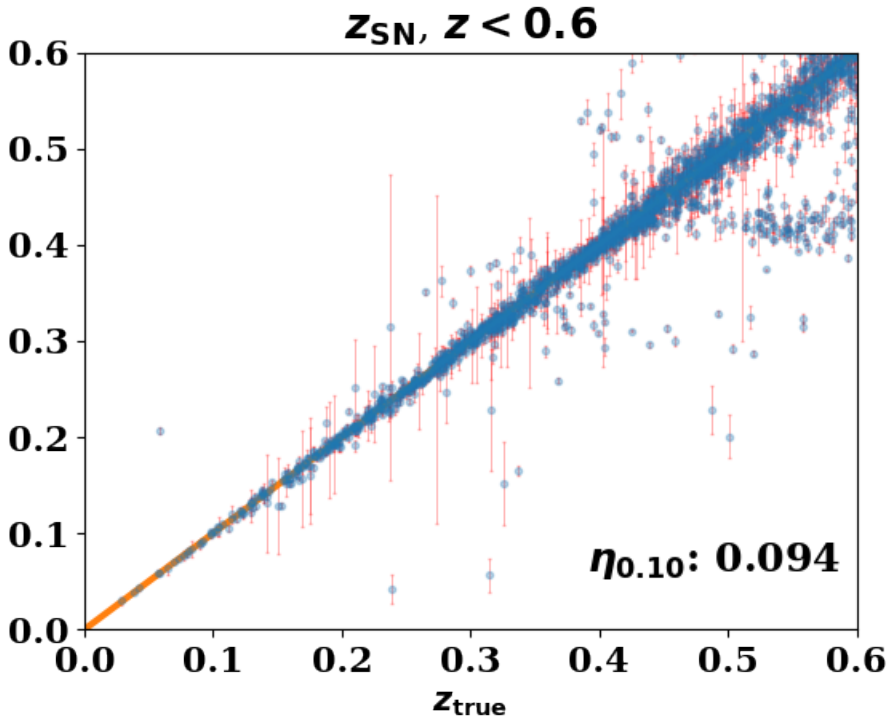






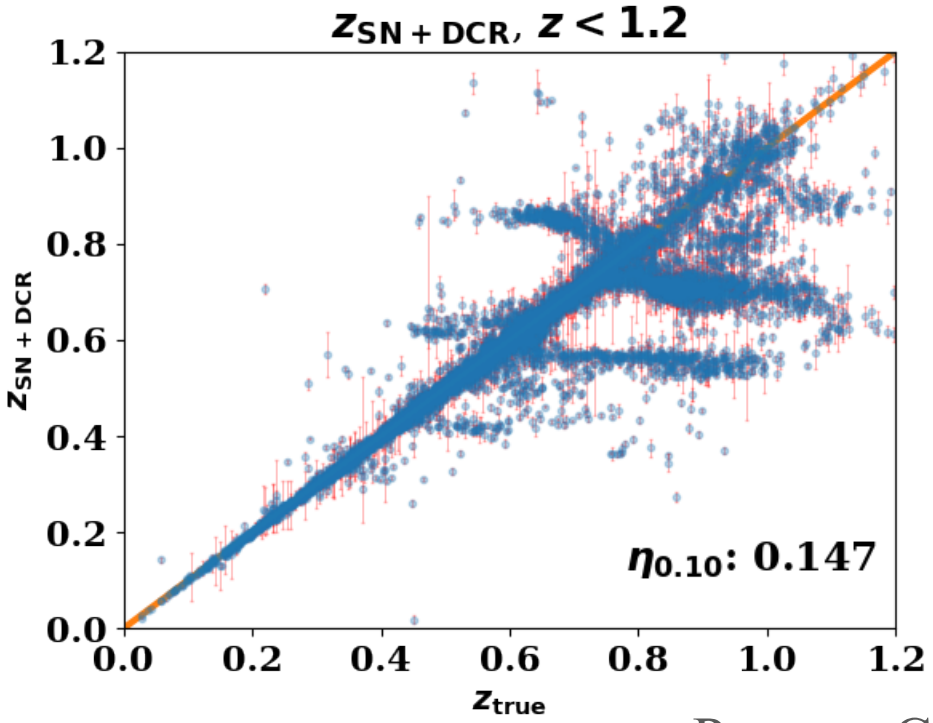
SN photo-z (z_{SN})

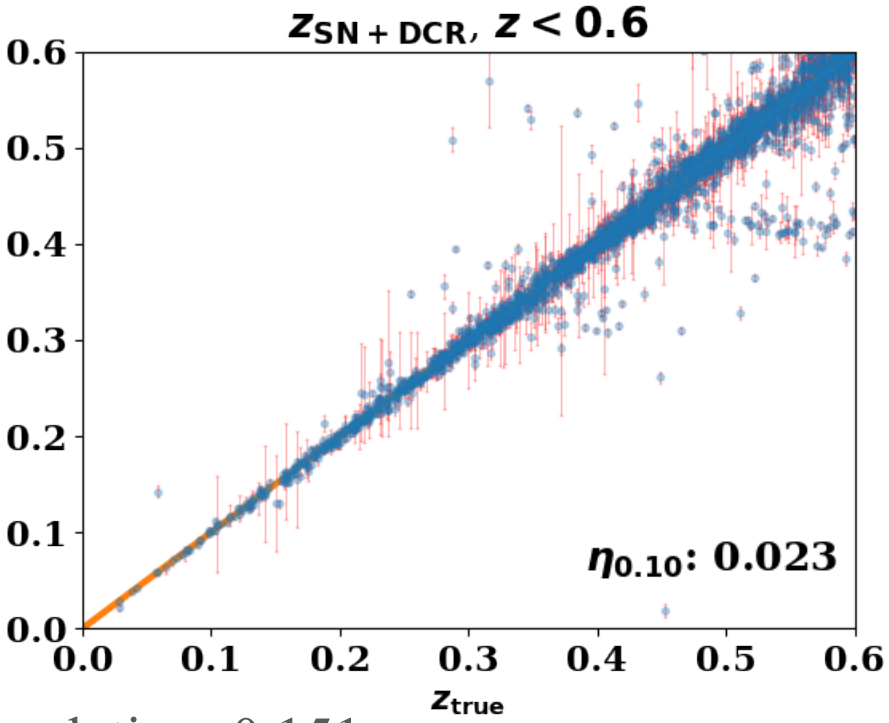




- Using LCFIT+z: Fits LC parameters + z simultaneously

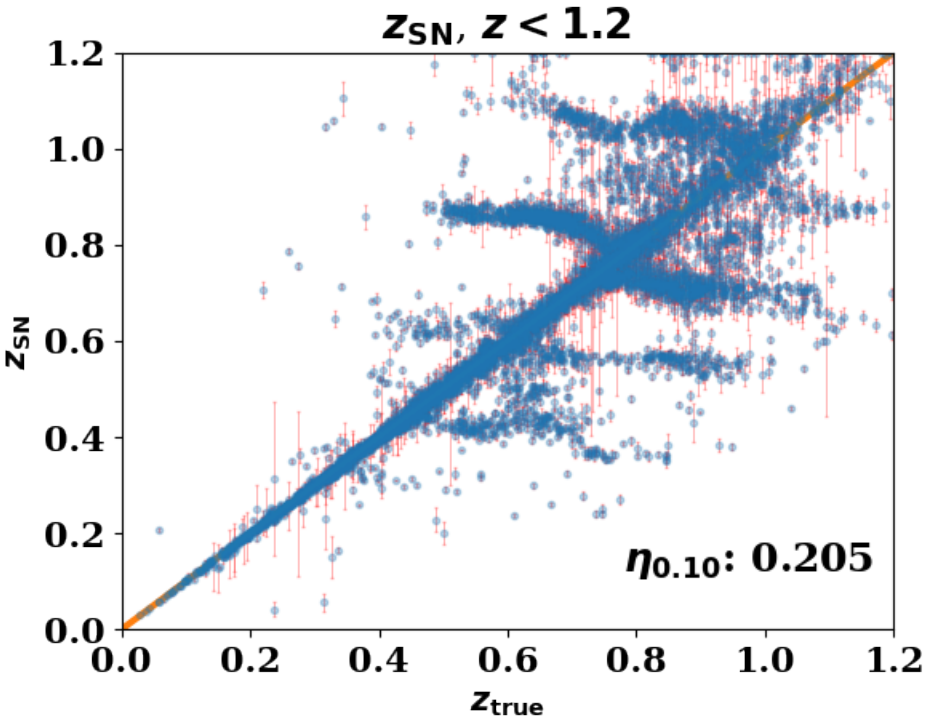
SN photo-z + Astro-z ($z_{\mathrm{SN+DCR}}$)

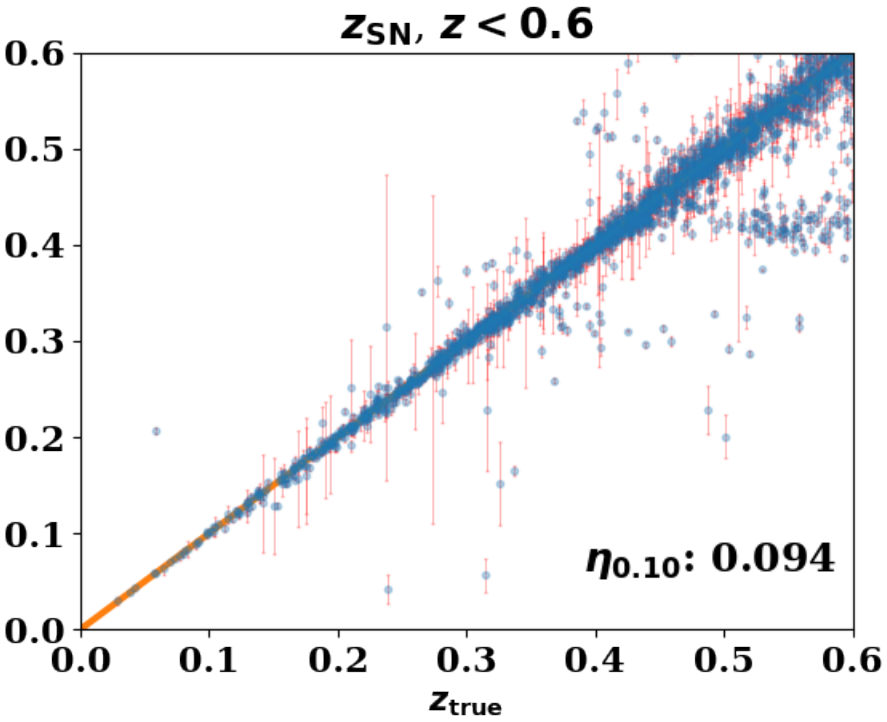




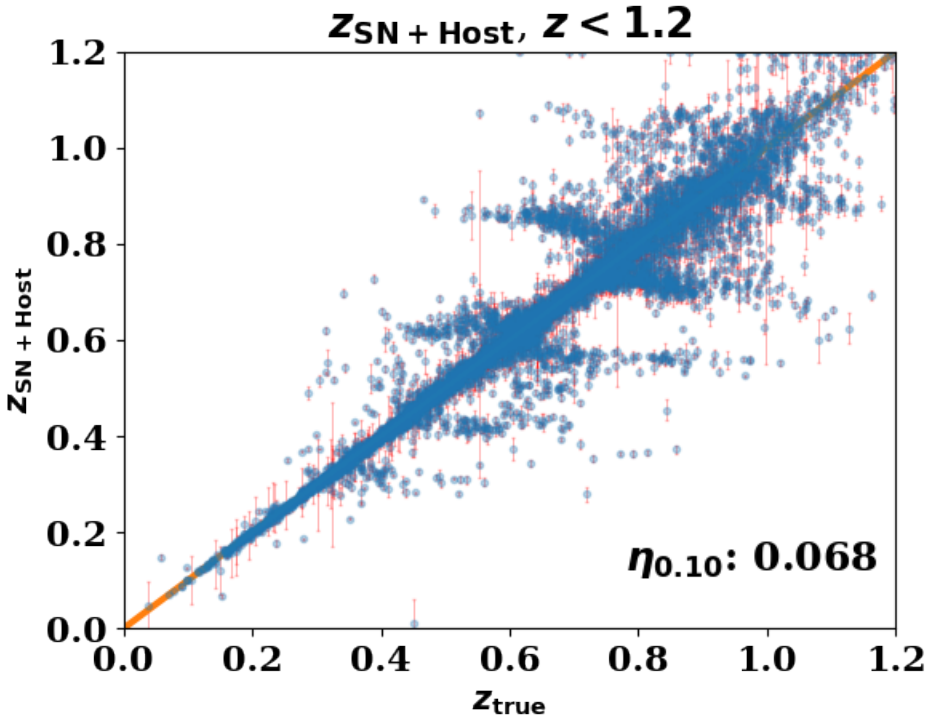
- Pearson Correlation: 0.151

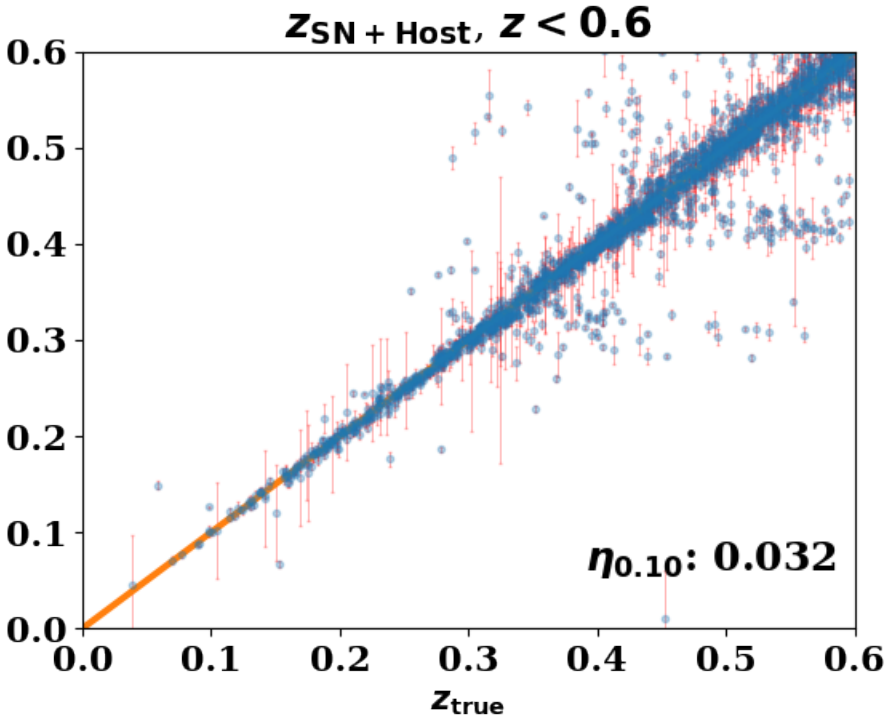
SN photo-z (z_{SN})



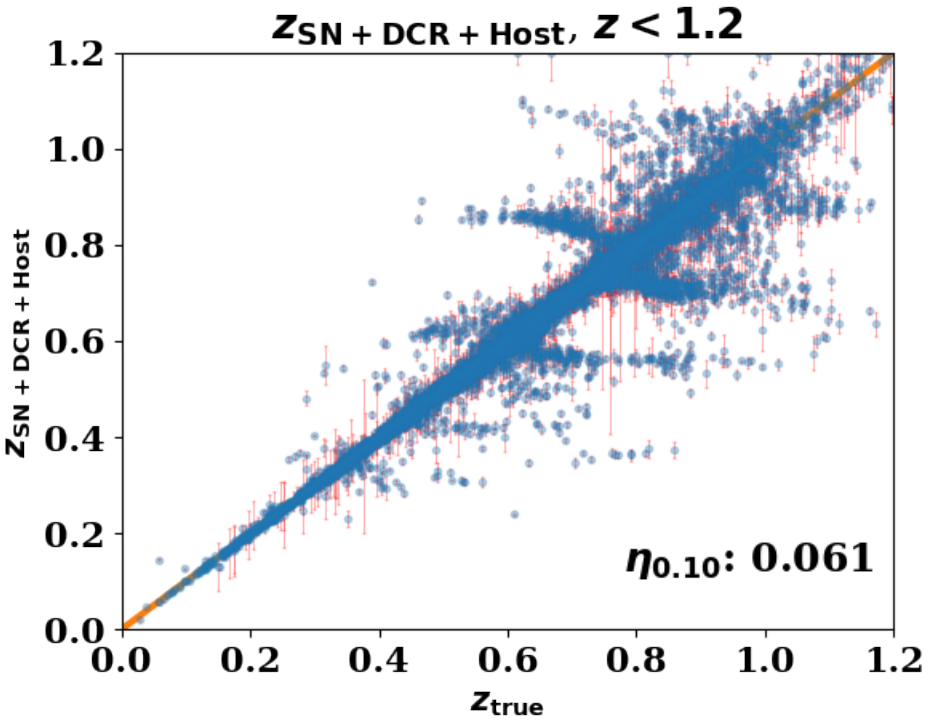


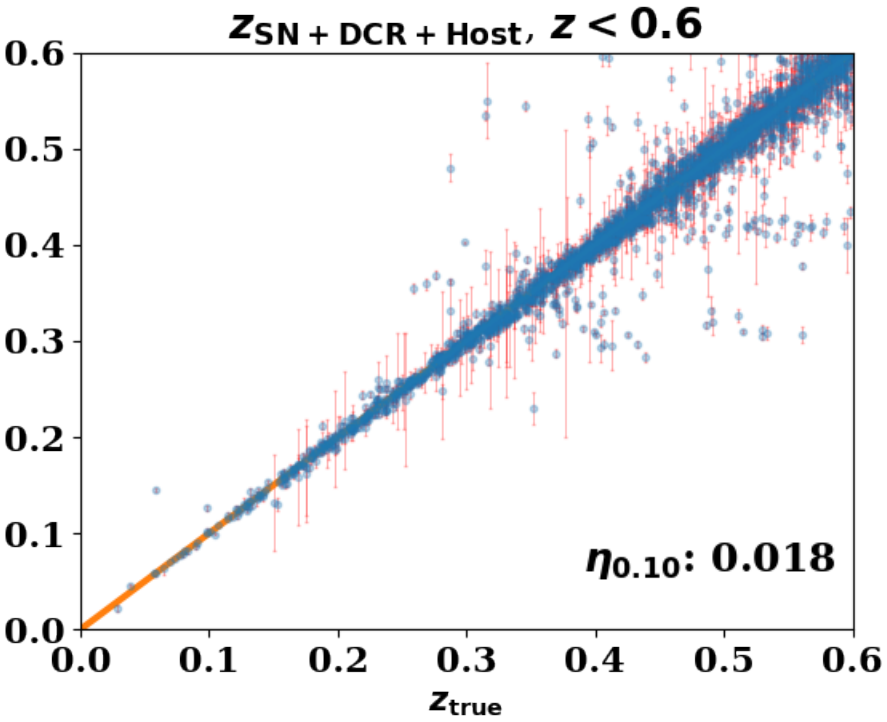
SN photo-z + Host photo-z ($z_{\mathrm{SN+Host}}$)





SN photo-z + Host photo-z + Astro-z ($z_{\mathrm{SN+DCR+Host}}$)



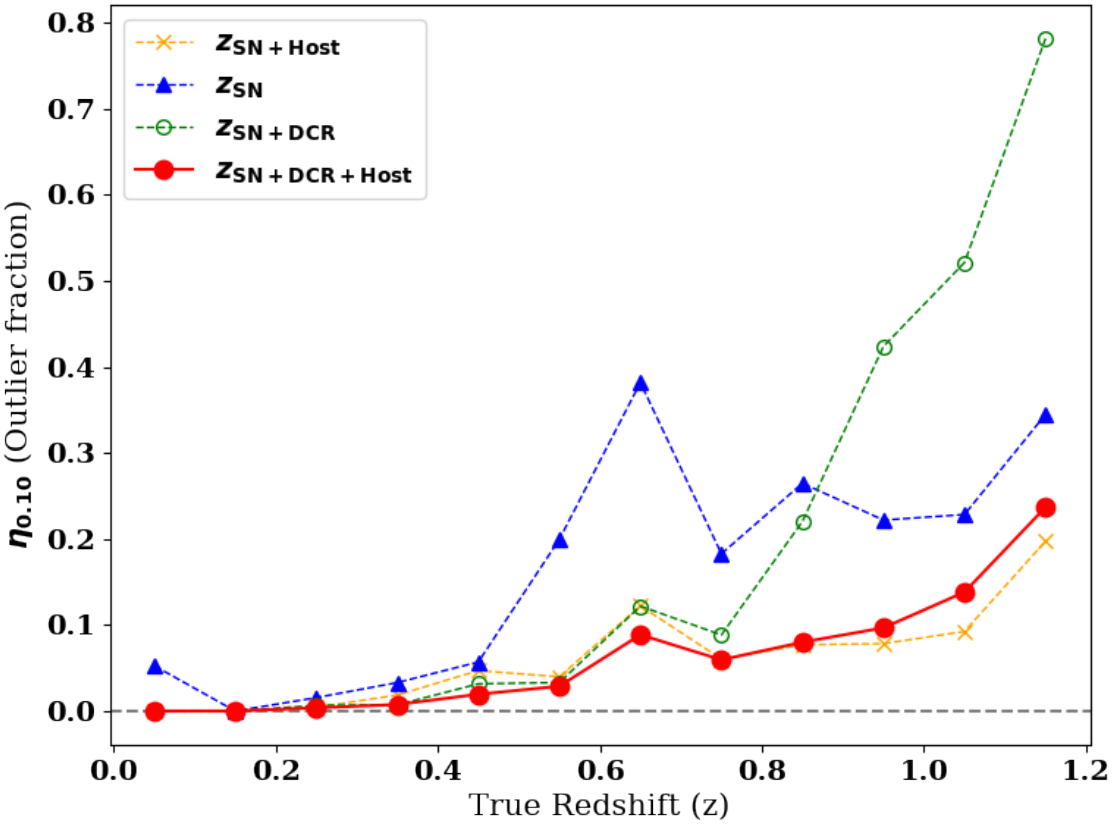


Events with LCFIT+z convergence

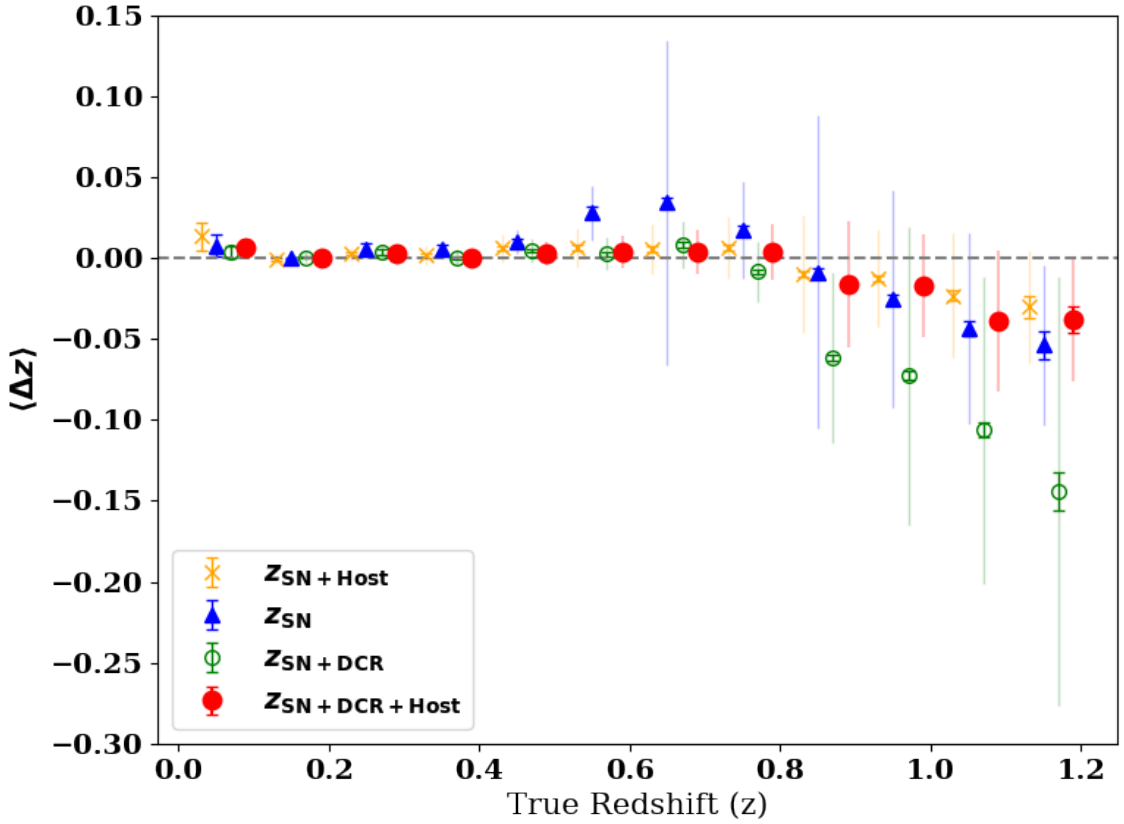
Type	Number of LCFIT+z events with: No cuts	Default cuts	Default + FITPROB cuts
z_{SN}	12,589	7,295	6,657
$z_{\mathrm{SN+Host}}$	12,324	7,176	6,615
$z_{\mathrm{SN+DCR}}$	12,246	7,660	7,255
$z_{\mathrm{SN+DCR+Host}}$	12,779	7,568	7,215

- Combining with z_{DCR} recovers about 600 candidates or 9%!

Outlier Fractions by True Redshift



Bias and MAD Deviation by True Redshift



Systematic Effects

Type	Bias (CDF50)	Bias (PDFPeak)	$\eta_{0.10}$ (CDF50)	$\eta_{0.10}$ (PDFPeak)	$\sigma_{\rm MAD}$ (CDF50)	$\sigma_{\rm MAD}$ (PDFPeak)
Perfect	-0.003±0.000	-0.003±0.000	0.016	0.016	0.008	0.008
$\sigma_{\rm syst} = 2$ mas	-0.007±0.000	-0.003±0.000	0.015	0.016	0.009	0.009
$\sigma_{\rm syst} = 5$ mas	-0.010±0.000	-0.004±0.000	0.028	0.024	0.011	0.011
$\sigma_{\rm syst} = 10$ mas	-0.019±0.000	-0.007±0.000	0.065	0.046	0.019	0.015
c marginalized	-0.004±0.000	-0.004±0.000	0.018	0.018	0.007	0.007
x_1 marginalized	-0.003±0.000	-0.003±0.000	0.015	0.015	0.008	0.008
realistic $T_{\rm obs}$	-0.002±0.000	-0.002±0.000	0.041	0.041	0.010	0.010
All syst. for realistic	-0.010±0.001	-0.004±0.001	0.064	0.073	0.016	0.014

Table 9. Bias, outlier fractions, and $\sigma_{\rm MAD}$ for various systematics. The impact of $\sigma_{\rm syst} = 2$ or 5 mas, marginalization over c and x_1 is small, while using realistic $T_{\rm obs}$ results in more degradation. Larger $\sigma_{\rm syst}$ results in substantially larger degradation compared to other systematics. 'All syst. for realistic' means using realistic $T_{\rm obs}$, marginalizing over c and x_1, and assuming $\sigma_{\rm syst} = 5$ mas.

Conclusion

- **Developed methodology** for SN Ia astro-z's using DCR
- **Reasonable** z_{DCR} **at** $z_{\mathrm{true}} < 0.6$ for LSST-like simulations
- **Combining** z_{DCR} with z_{Host} and z_{SN} substantially **improves** z_{SN}

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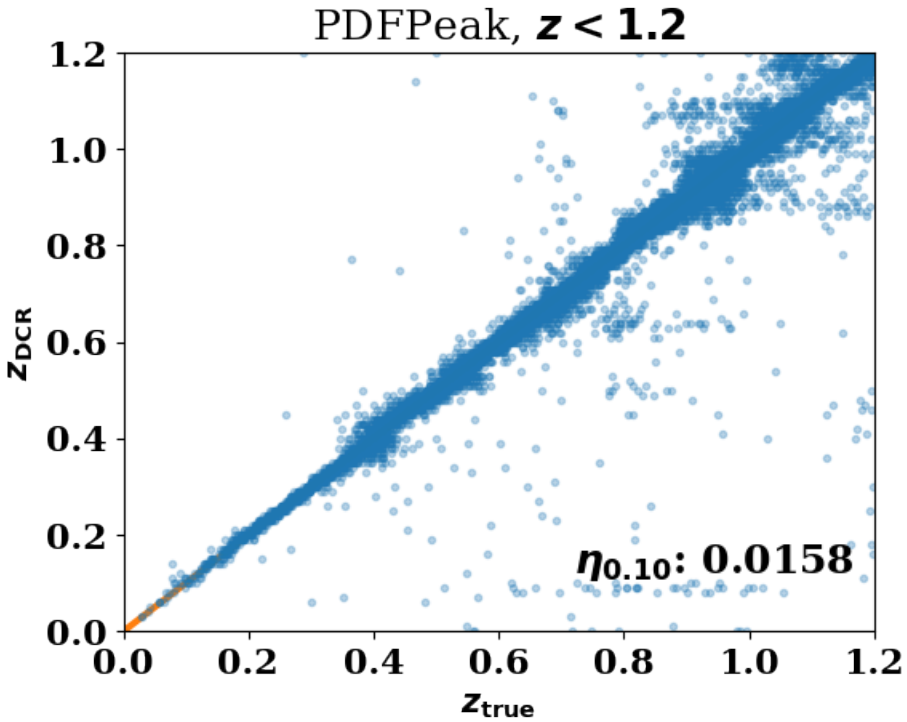
- 1st time astro-z's were applied to SNe Ia and constructed the full PDF for astro-z's
- Can be adapted for other sources with distinct emission lines like SNe II

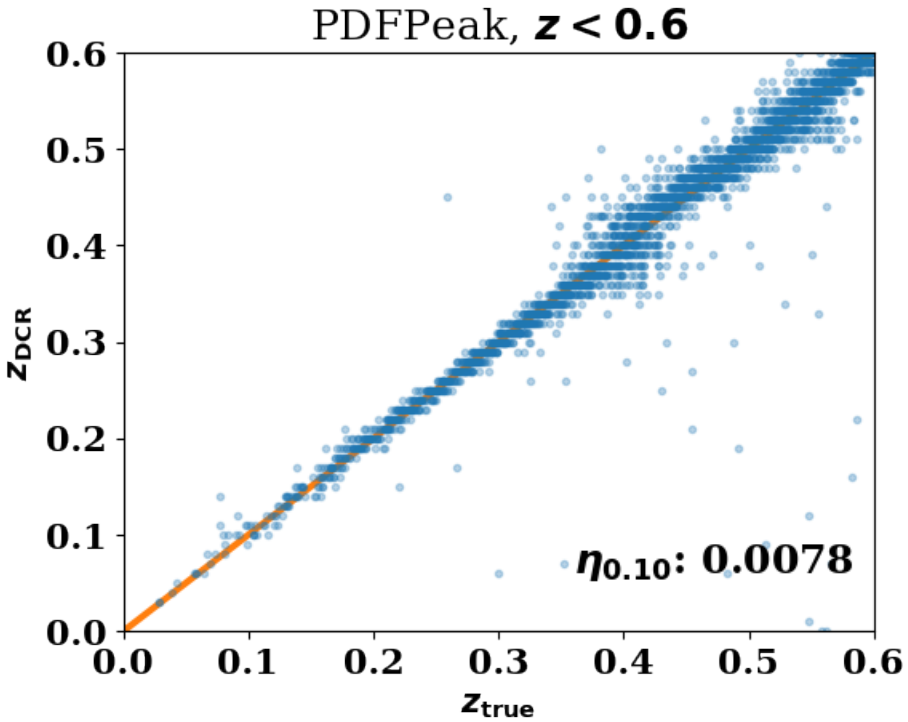
Thank you very much!

Questions?

Extra Slides

Perfect SIMs





- $\sigma_{\text{stat}} = \sigma_{\text{syst}} = 0$ & assuming we know T_{obs} (epoch), x_1, c

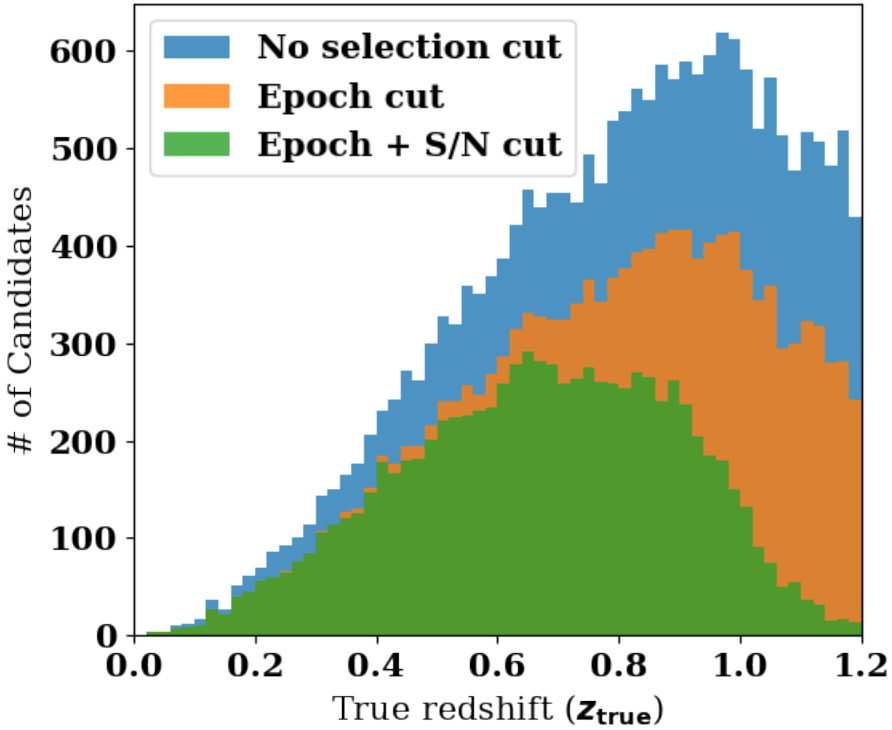
Various Metrics

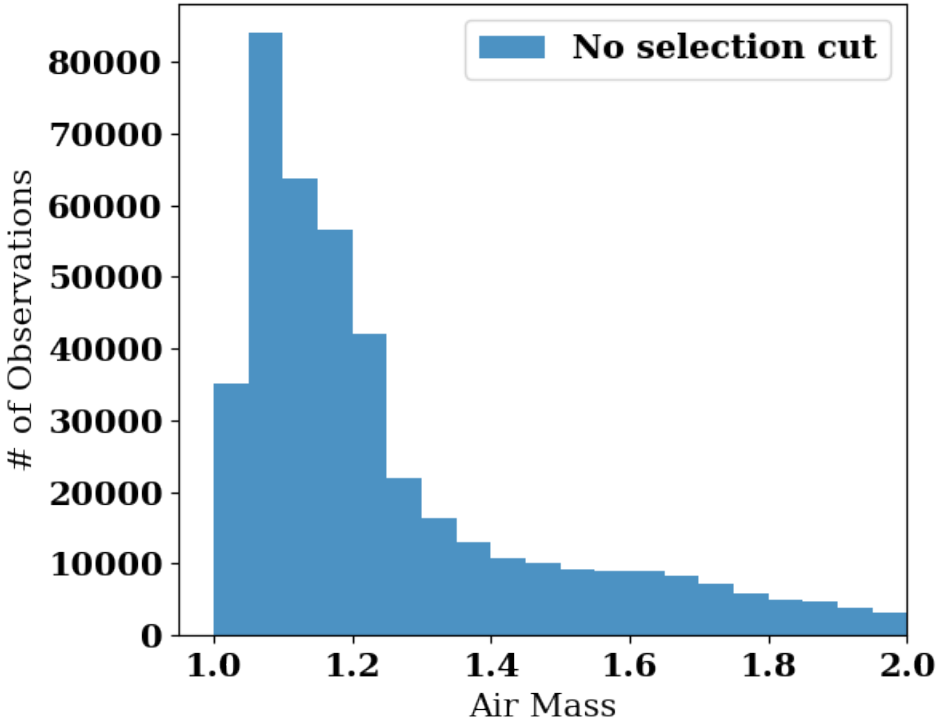
- low-z: $z_{\rm true} < 0.6$, high-z: $z_{\rm true} > 0.6$

Type	Bias (low-z)	Bias (high-z)	$\eta_{0.10}$ (low-z)	$\eta_{0.10}$ (high-z)	$\sigma_{\rm MAD}$ (low-z)	$\sigma_{\rm MAD}$ (high-z)
$z_{\rm DCR}$	0.006±0.002	-0.047±0.002	0.144	0.439	0.031	0.121
$z_{\rm Host}$	0.012±0.003	-0.052±0.002	0.421	0.268	0.123	0.066
$z_{\rm DCR+Host}$	0.005±0.001	-0.025±0.002	0.151	0.212	0.039	0.057
$z_{\rm SN}$	0.014±0.001	0.002±0.001	0.094	0.265	0.007	0.064
$z_{\rm SN+Host}$	0.005±0.001	-0.004±0.001	0.032	0.089	0.008	0.024
$z_{\rm SN+DCR}$	0.003±0.001	-0.036±0.001	0.023	0.224	0.007	0.044
$z_{\rm SN+DCR+Host}$	0.003±0.001	-0.008±0.001	0.018	0.087	0.007	0.023

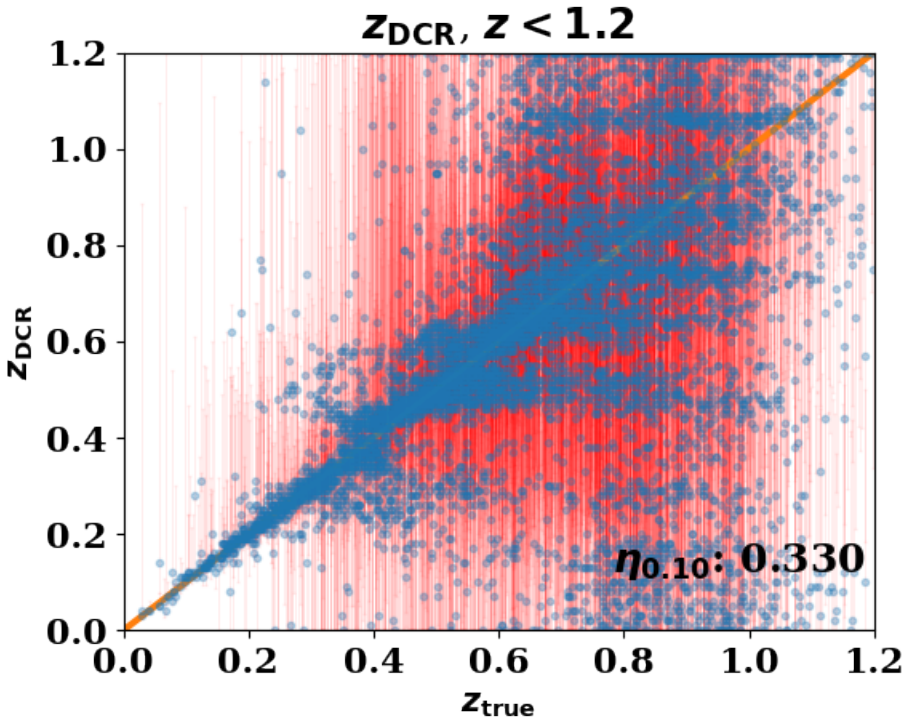
Table 8. Bias and error on the mean, $\eta_{0.10}$, and $\sigma_{\rm MAD}$ for low-z ($z_{\rm true} < 0.6$) and high-z ($z_{\rm true} > 0.6$) for various combinations of the three methods discussed in this work. For $z_{\rm DCR}$, $z_{\rm Host}$, and $z_{\rm DCR+Host}$, we show the PDFPeak values. $z_{\rm DCR}$ shows good performance at low-z while $z_{\rm Host}$ shows good performance at high-z, which leads to $z_{\rm SN+DCR}$ being significantly improved at low-z compared to $z_{\rm SN}$ and $z_{\rm SN+Host}$ being significantly improved at high-z. $z_{\rm SN+DCR+Host}$ show similar performance to $z_{\rm SN+DCR}$ and $z_{\rm SN+Host}$ at low-z and high-z respectively.

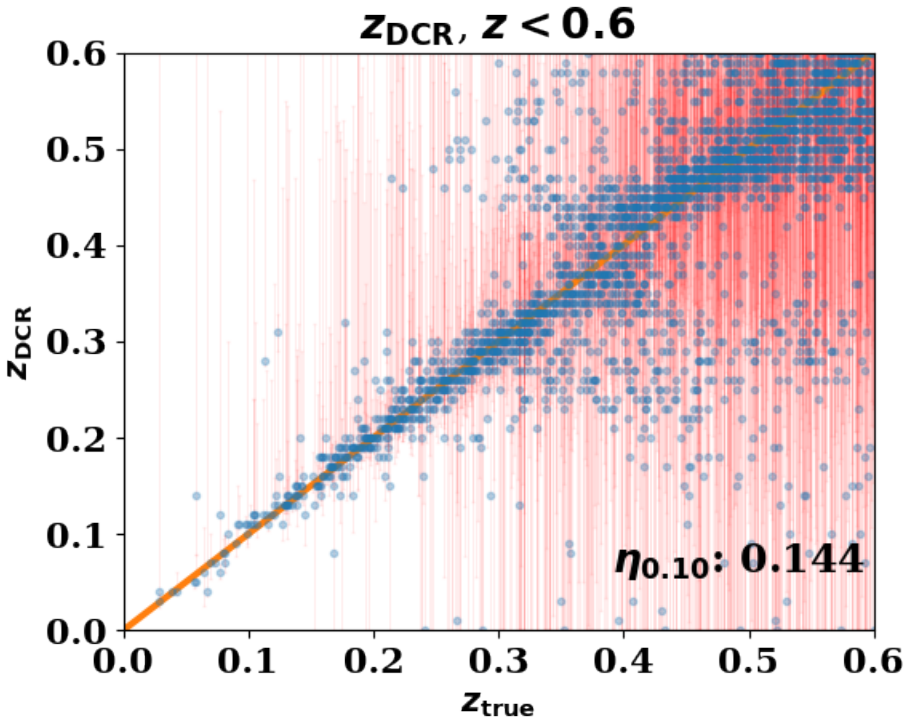
Redshift and AM distributions (maybe get rid of this)





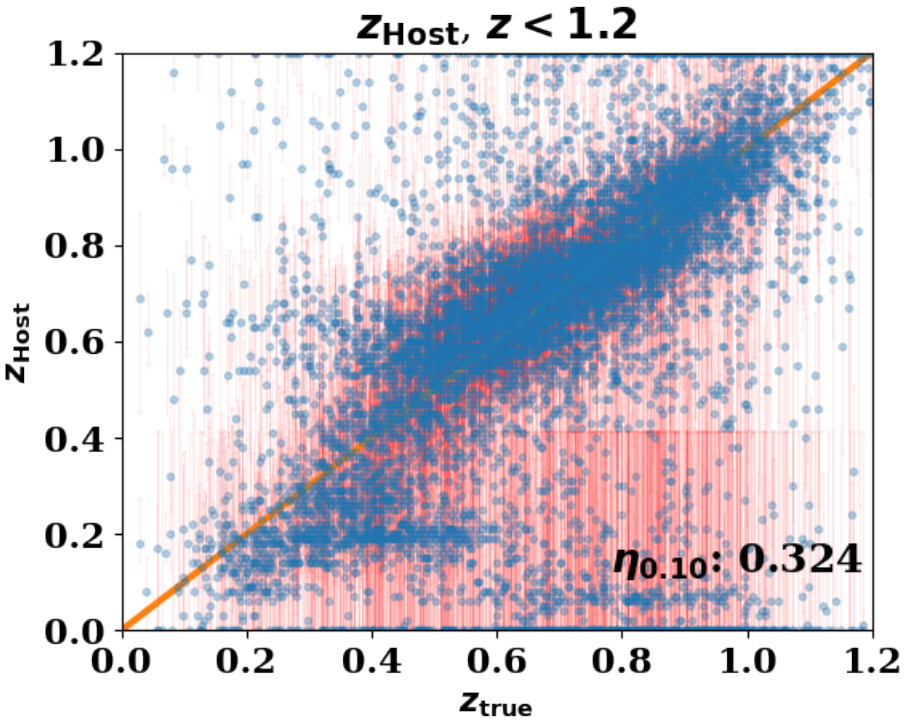
Astro-z (z_{DCR})

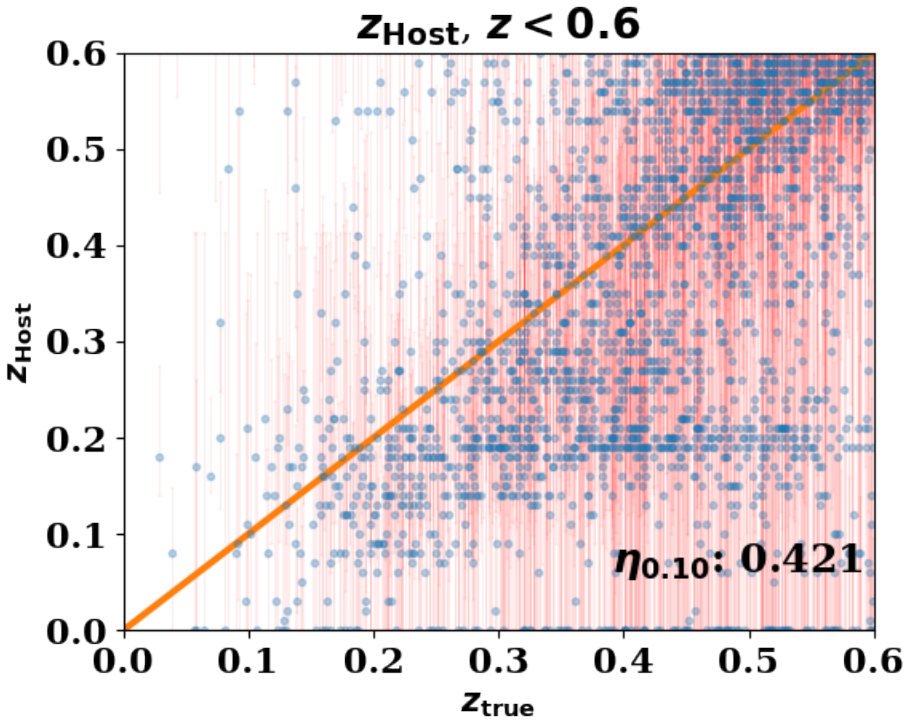




- $\sigma_{\mathrm{syst}} = 5$ mas, Realistic T_{obs} (epoch), marginalized over x_1, c, better at low-z

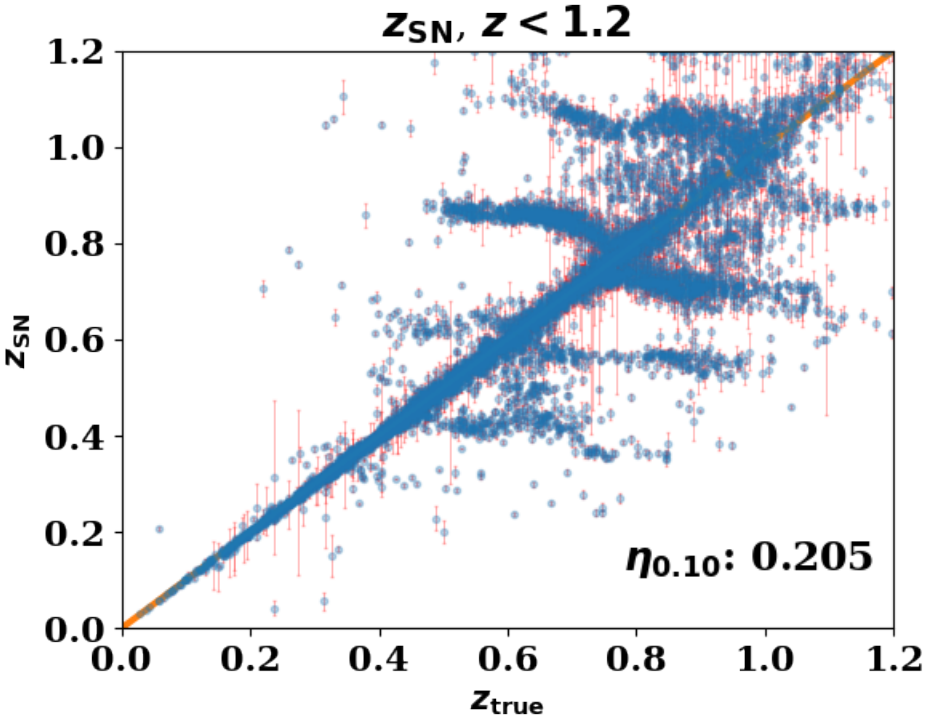
Host photo-z (z_{Host})

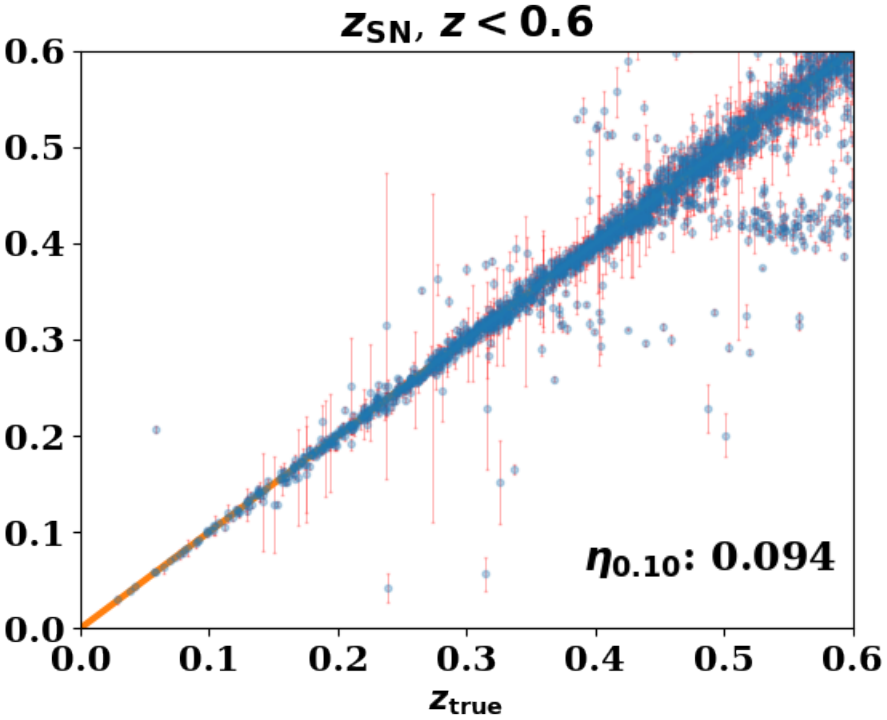




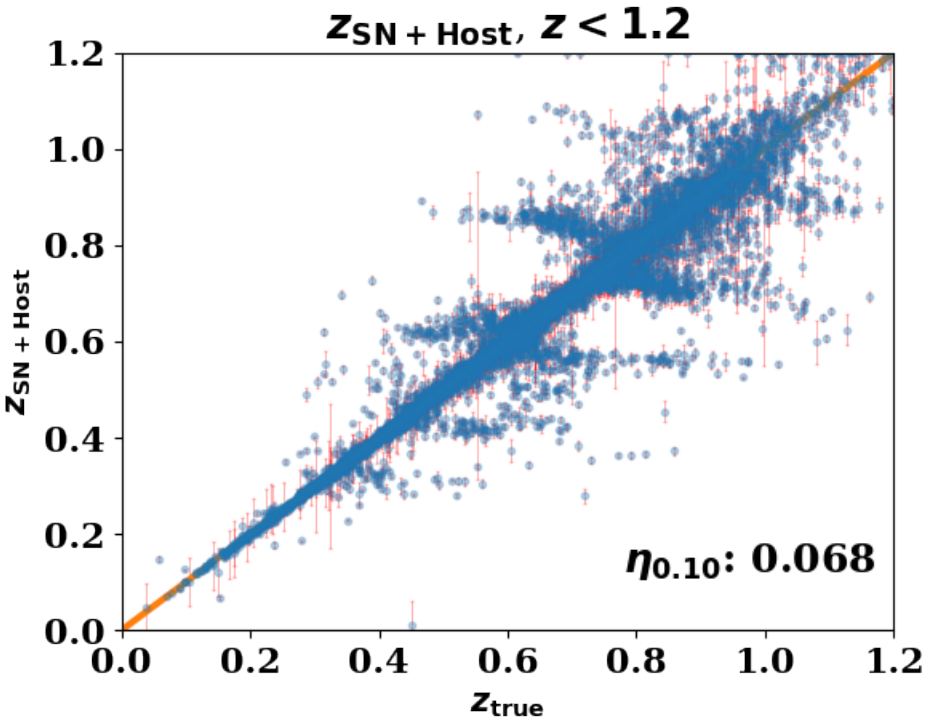
- Better performance at high-z

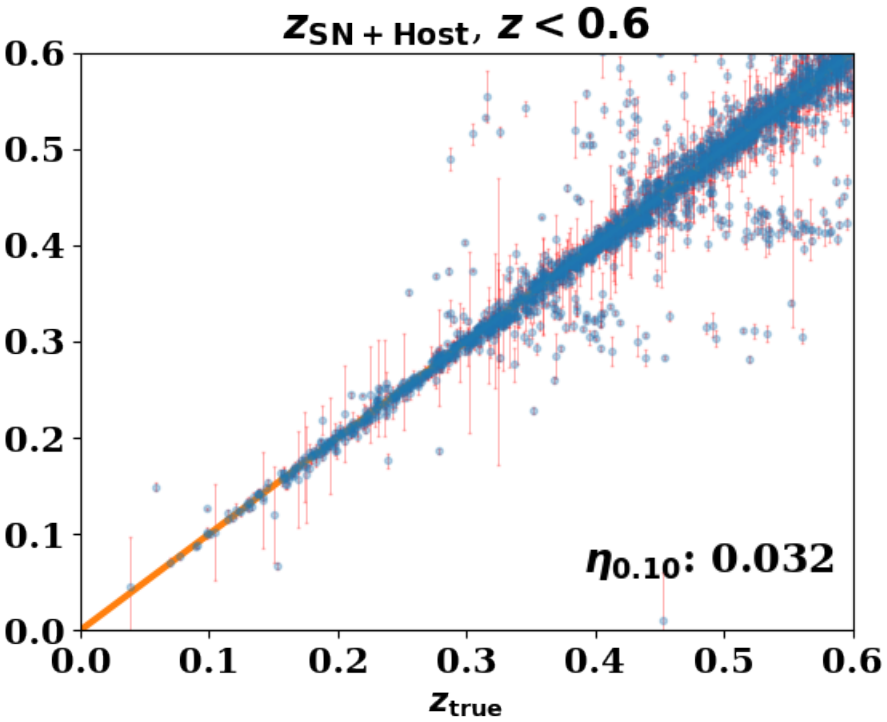
SN photo-z (z_{SN})



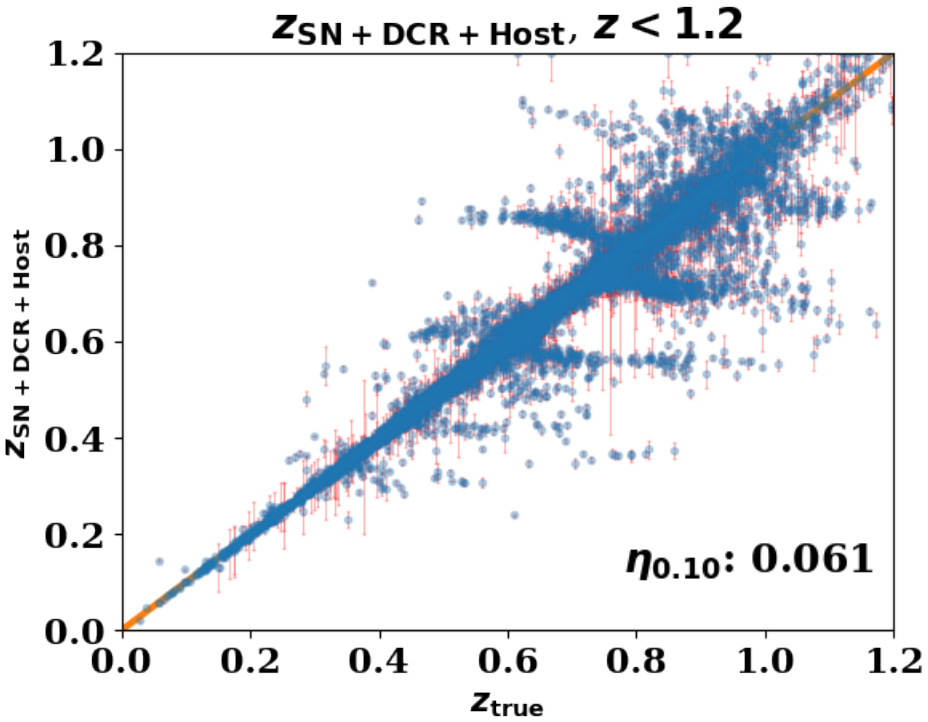


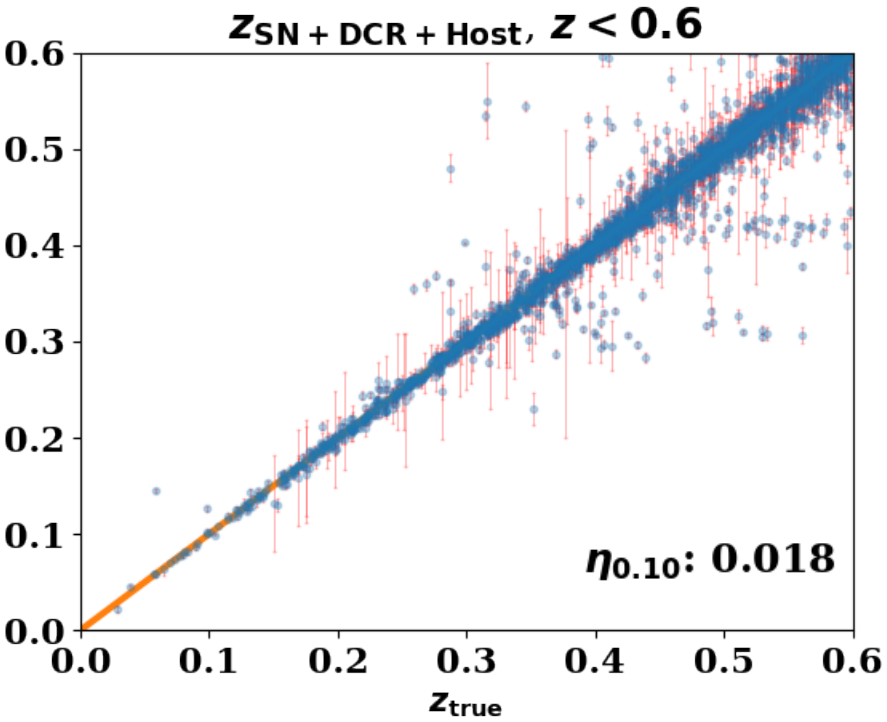
SN photo-z + Host photo-z ($z_{\mathrm{SN+Host}}$)



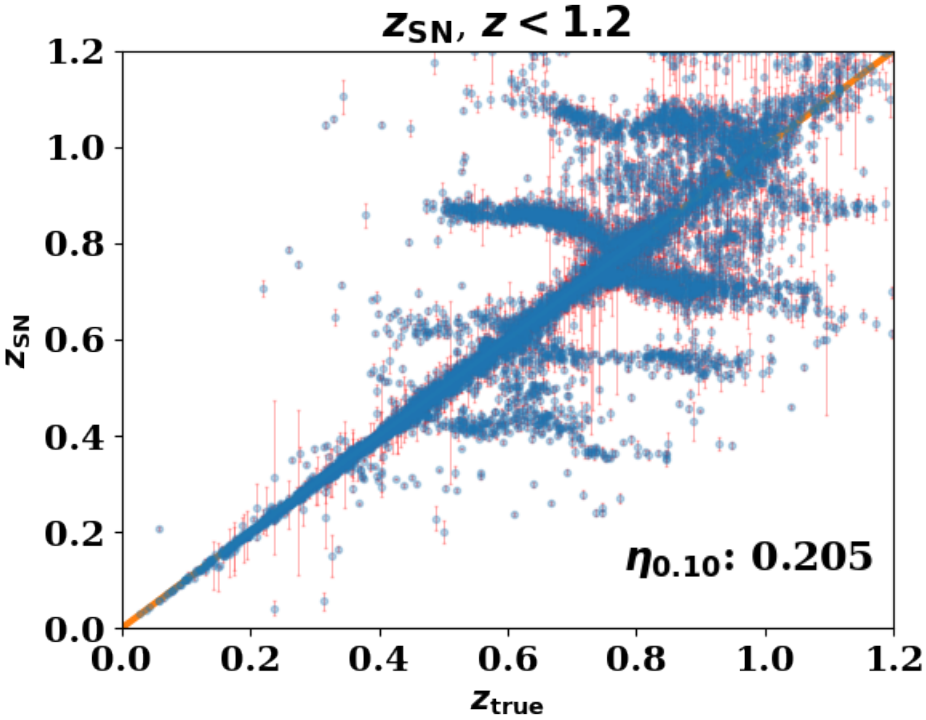


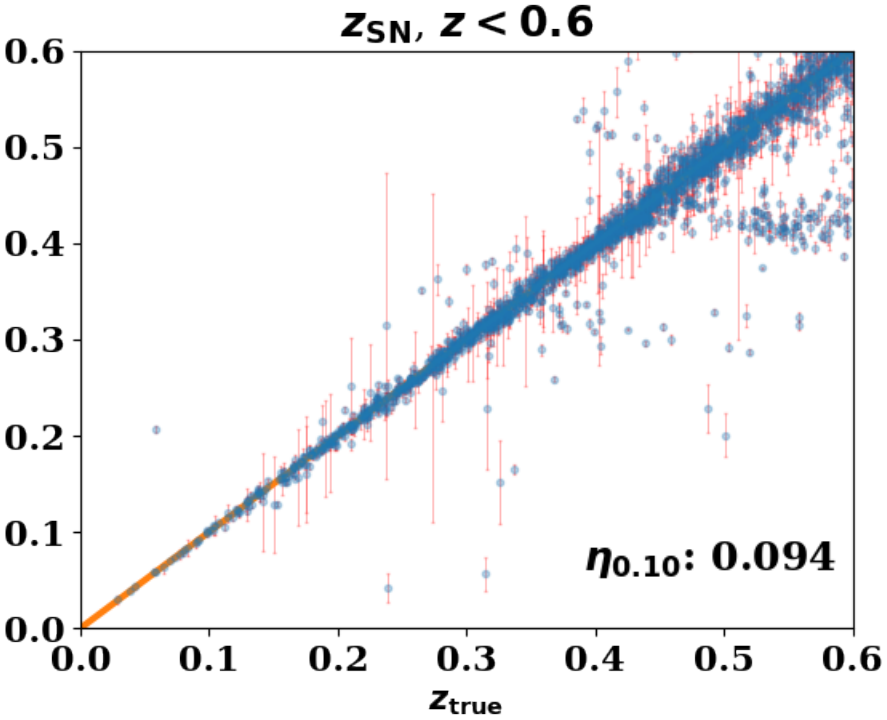
SN photo-z + Host photo-z + Astro-z ($z_{\mathrm{SN+DCR+Host}}$)



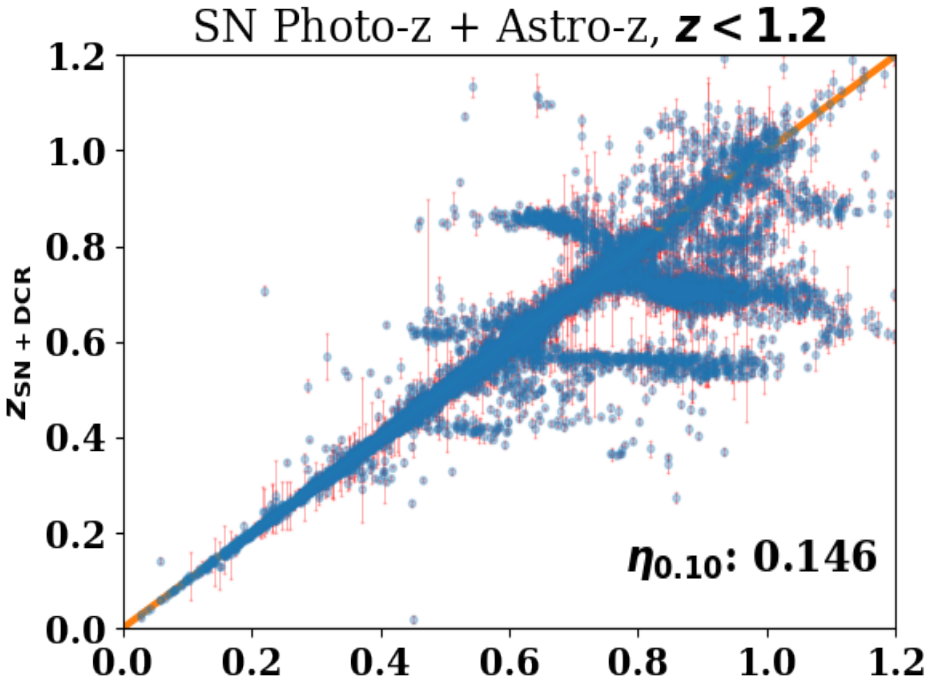


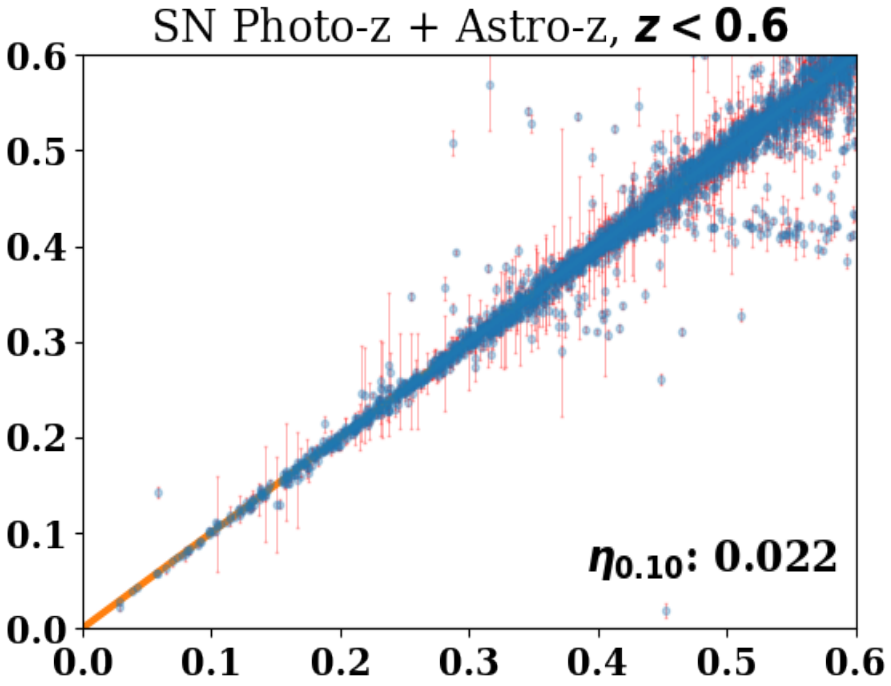
SN photo-z (z_{SN})





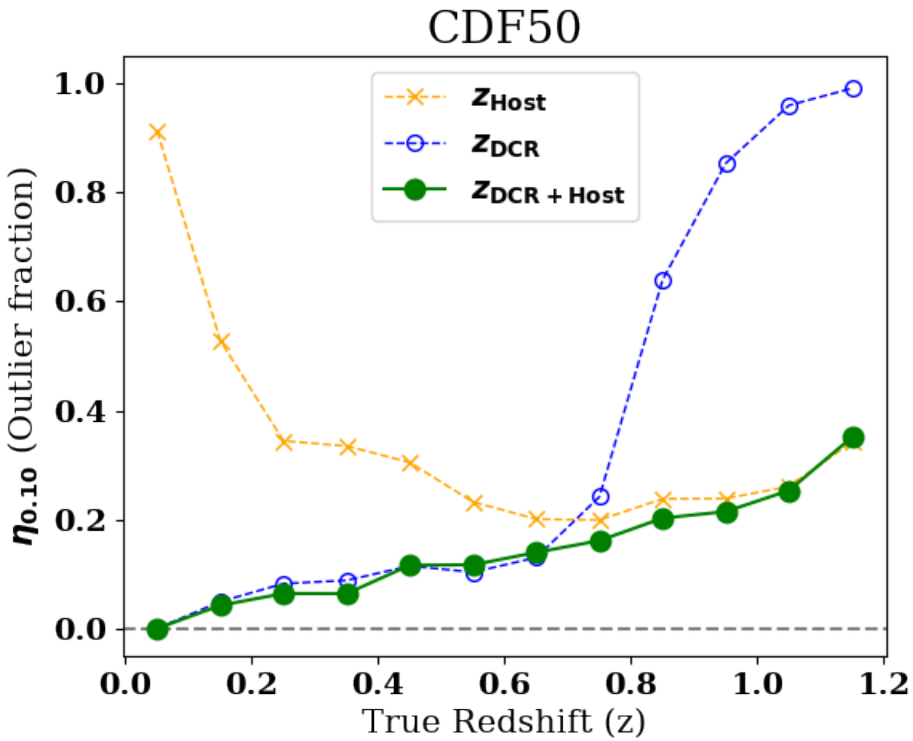
SN photo-z + Astro-z ($z_{\mathrm{SN+DCR}}$)

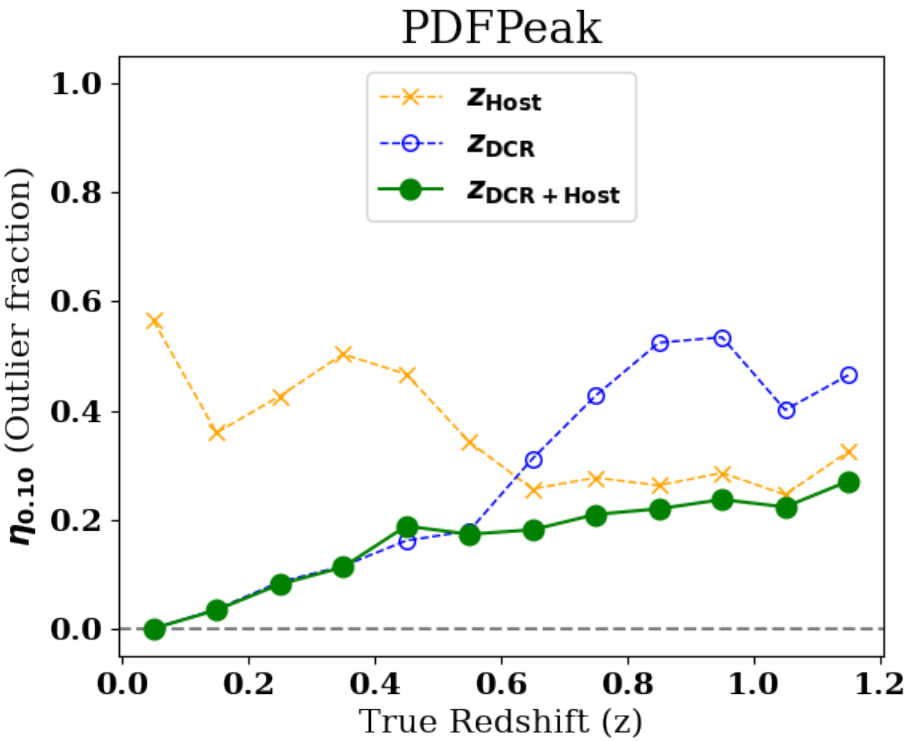




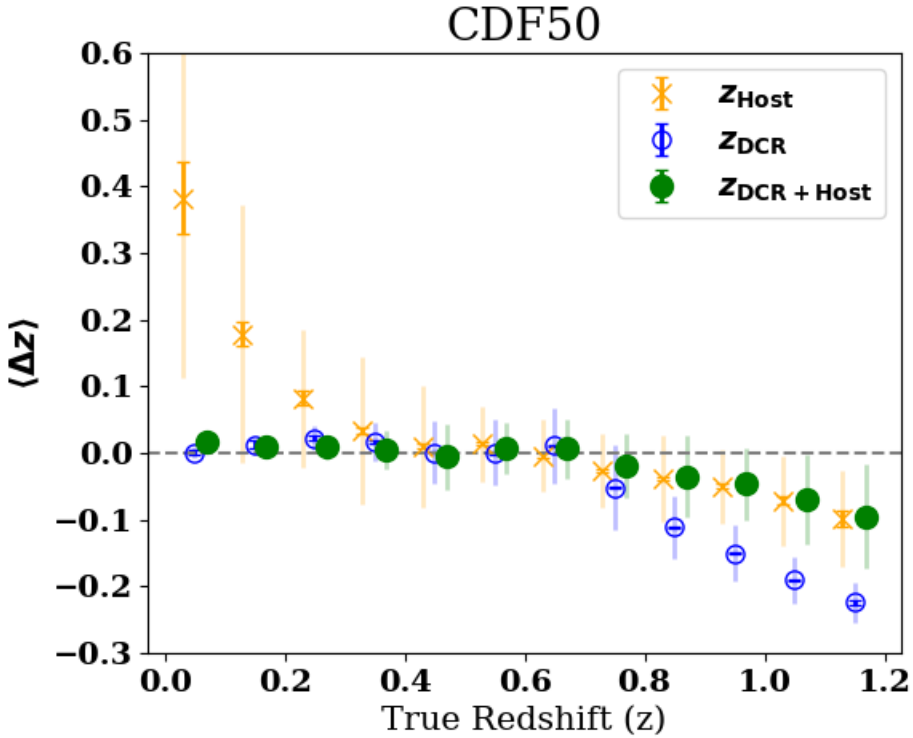
- Pearson Correlation: 0.154

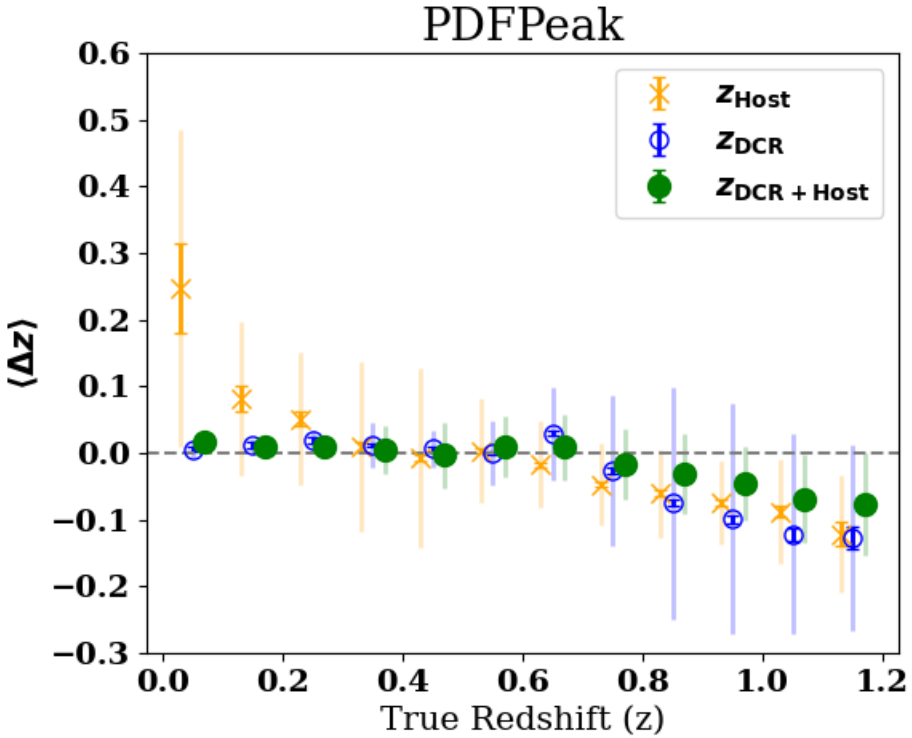
Outlier Fractions by True Redshift





Bias and MAD Deviation by True Redshift

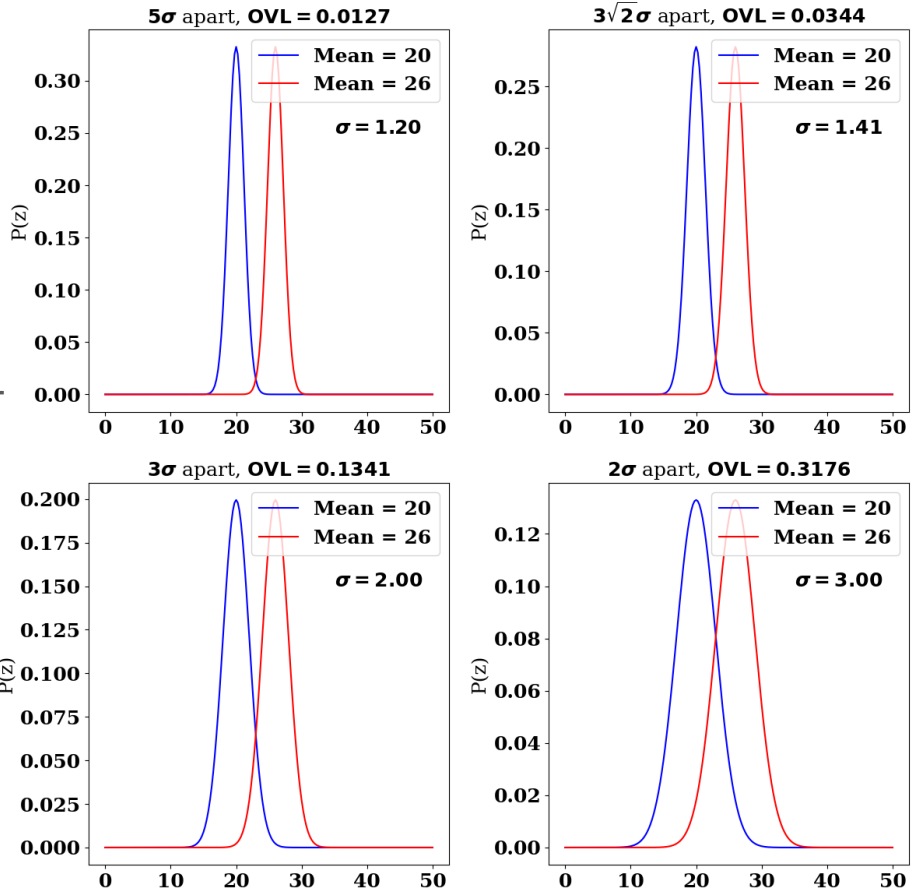




Treatment of Incompatible Priors

$$\mathrm{OVL}(p_0, p_1) = \int \min(p_0(x), p_1(x)) dx$$

➢ Only combine priors when OVL > 0.0344



Various Metrics

- low-z: $z_{\rm true} < 0.6$, high-z: $z_{\rm true} > 0.6$

Type	Bias (low-z)	Bias (high-z)	$\eta_{0.10}$ (low-z)	$\eta_{0.10}$ (high-z)	$\sigma_{\rm MAD}$ (low-z)	$\sigma_{\rm MAD}$ (high-z)
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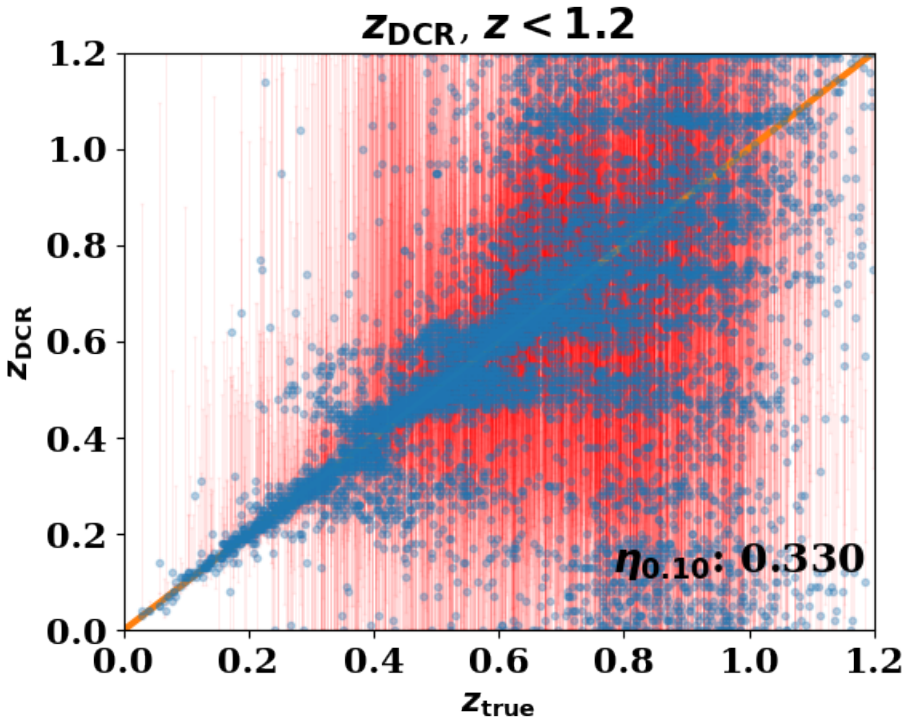
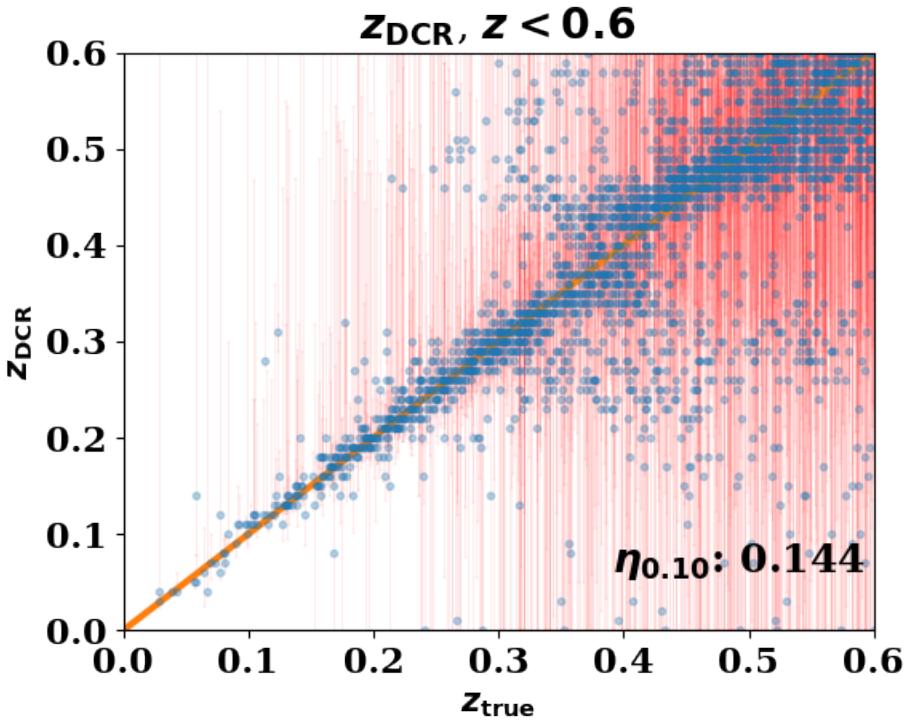
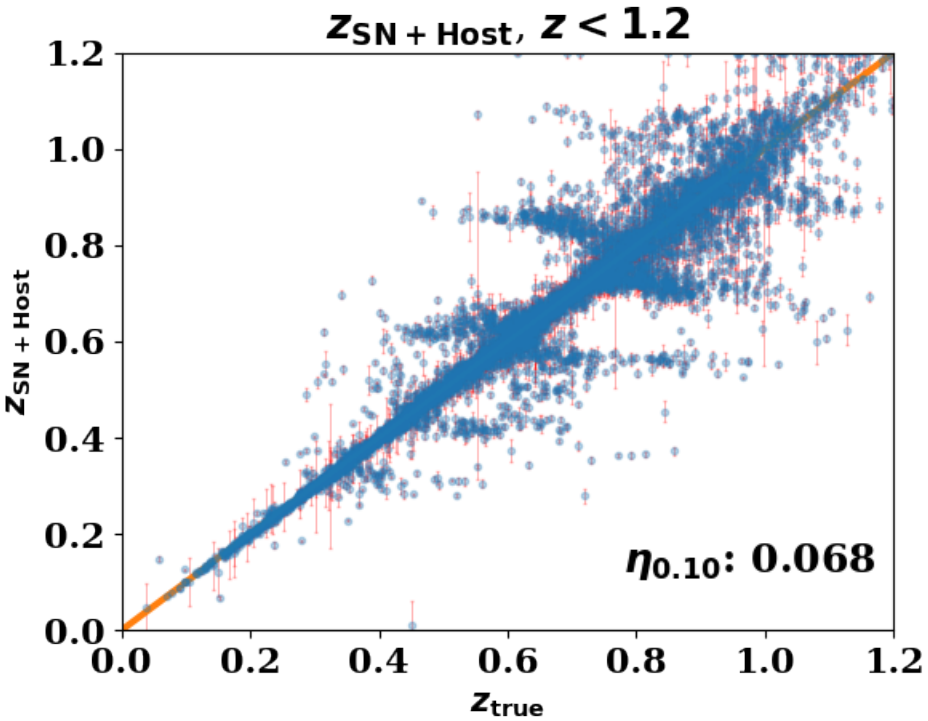
Astro-z (z_{DCR})

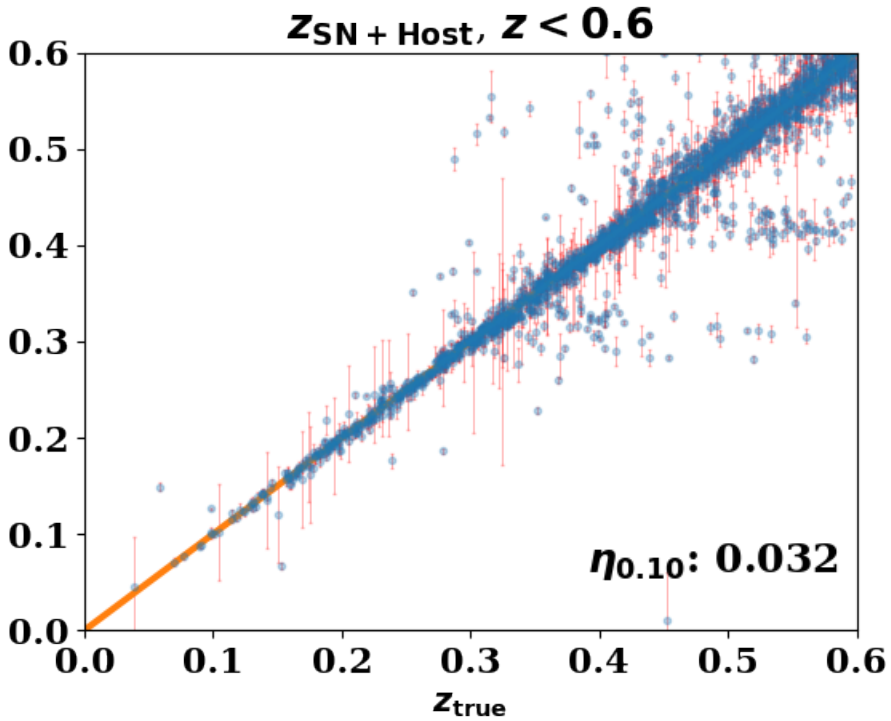




- $\Delta z \equiv \frac{z_{\mathrm{estimate}} - z_{\mathrm{true}}}{1 + z_{\mathrm{true}}}$ & η_x: fraction of candidates where $|\Delta z| > x$

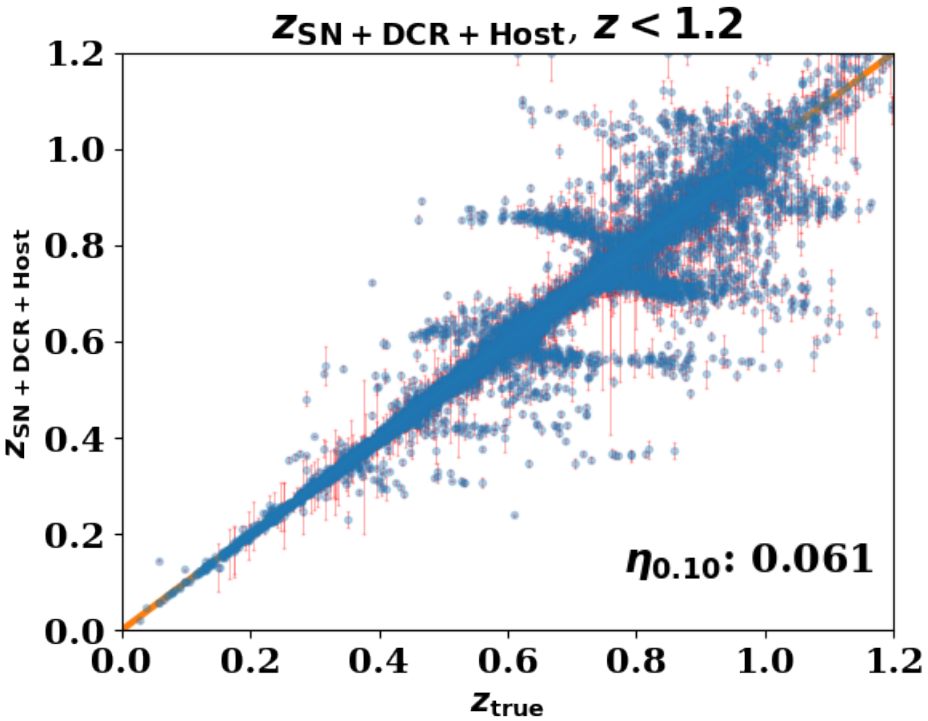
SN photo-z + Host photo-z ($z_{SN+Host}$)

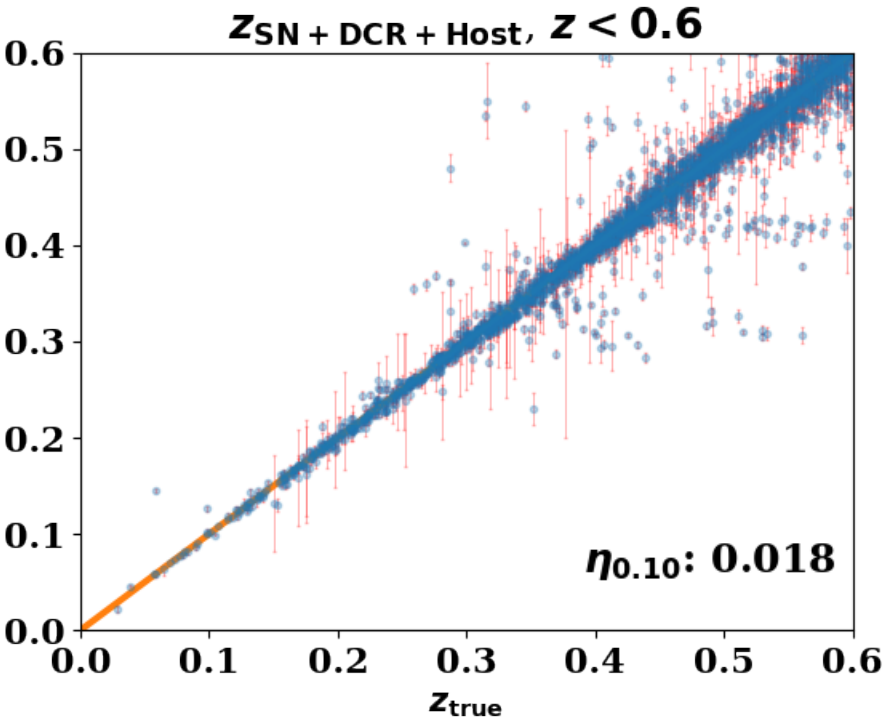




- Using LCFIT+z, z_{Host} from RAIL

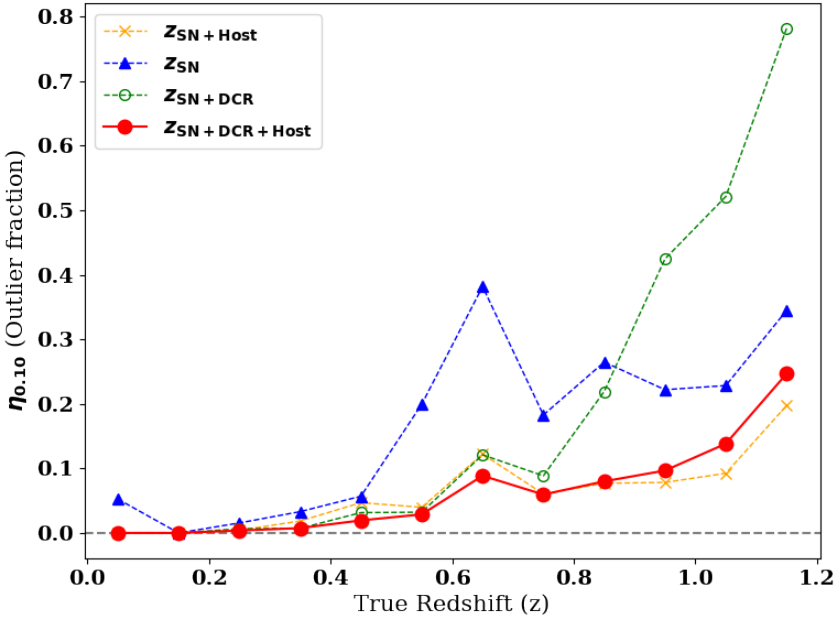
SN photo-z + Host photo-z + Astro-z ($z_{\mathrm{SN+DCR+Host}}$)

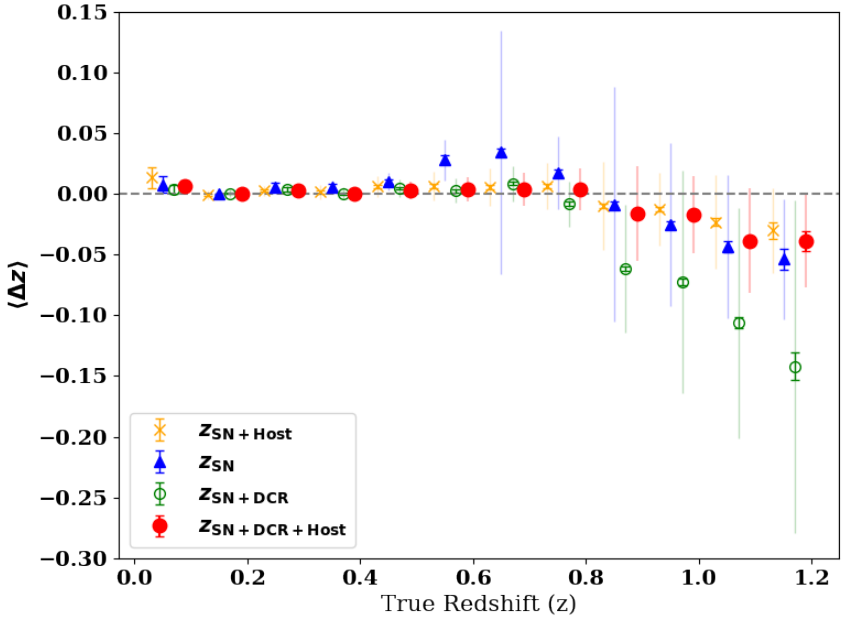




- 8 ~ 9% more LCFIT+z converged candidates that pass selection cut

Outlier Fractions, Bias and MAD Deviation by True Redshift





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