Building a Photometric Hubble Diagram from DES-SN Data

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SN Classification Workshop
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The Dark Energy Survey

• Survey project using 4 complementary techniques:
  I. Cluster Counts
  II. Weak Lensing
  III. Large-scale Structure
  IV. Supernovae

• Two multiband imaging surveys:
  5000 deg$^2$ grizY to 24th mag
  30 deg$^2$ repeat griz (SNe)

• New 3 deg$^2$ FOV camera on the Blanco 4m telescope
  Survey 2013-2018 (525 nights)
  Facility instrument for astronomy community (DES 30% time)

• Largest optical etendue
  (FoV x mirror-area)

www.darkenergysurvey.org
www.darkenergypedetectives.org
**DES-SN Overview**

- Visit each field once per week in griz
- 8 “shallow” fields (24 deg$^2$), depth $\approx 23.5$
- 2 “deep” fields (6 deg$^2$), depth $\approx 24.5$
- Finished three `5-month’ seasons
Source of Photometry (Y1+Y2+Y3)

- **Forced Photometry** (PSF-fitted fluxes) from “Difference-Imaging Pipeline” used to discover transients
- Subtracted images from A.Becker’s hotPants
- Calibration tweaked few percent based on overlap of PS1 supercal (Scolnic et al 2015)
- More refined photometry (Scene-Modeling) in progress, but not ready yet.
Source of Redshifts

- Host Galaxy Spectroscopic redshifts, mostly from OzDES using AAT (Yuan 2015)

- Matching algorithm ($D_{LR}$) from Gupta et al, 2016 (arXiv:1604.06138)
Simulations

• Classification and HD Fitting make extensive use of SNANA simulations.

• Simulate SNIa with SALT2 model ($\alpha_{SIM}=0.14$, $\beta_{SIM}=3.20$; c,x1 population from SK16) and intrinsic scatter models that include chromatic variations.

• Simulate CC based on 42 templates (from photometric challenge, 2010). CC Rate, Ibc/II ratio, and LF from Li 2011.
Pre-Analysis Preparation: Analyze Fake SN Ia Overlaid on Images

• Are photometry errors correct?
  → Yes, after correcting for surface brightness
    (see Figs 9-10 in arXiv:1507.05137)

• Does fast SNANA sim reproduce fake SNe?
  → yes, after scaling simulated error vs. PSF
    (see Sim-validation slides to follow)
Sim-Validation: Overview

- DiffImg Pipeline (weeks)
- Analysis & fitting
- Compare DiffImg Fakes to SNANA sim

SN Ia Fakes

SNANA Simulation (minutes)
Empirical Flux-Error Adjustment for SNANA sim

Scale simulated flux-errors by black curves at left.

Purple-dash curve is prediction based on floating background in PSF fit.

forcePhoto-error excess at small-PSF is not understood.

PSF units: sigma, pixels [ = 1.6 × PSF(fwhm,arcsec) ]
Empirical Flux-Error Adjustment for SNANA sim

PSF units: sigma, pixels \[= 1.6 \times \text{PSF(fwhm,arcsec)} \]
Fake/Sim Overlays of Fitted Params

- Fake SN $\rightarrow$ DiffImg

SNANA sim

- mean $c$ vs $z_{\text{phot}}$
- mean $x_1$ vs $z_{\text{phot}}$
• Done with pre-analysis of fake SN
• Now start real analysis on data

Everything here is Extremely PRELIMINARY !!!
Photometric Selection

- **Box cuts:**
  * 3 bands with obs having SNR>5
  * at least one epoch with Trest < -2
  * at least one epoch with Trest > +10
  * |x1| < 4
  * FitProb > 0.05  
    (from SALT2 LC fit)

- **Nearest Neighbor** (Sako 2014)
  $P_{\text{la}} > 0.5$ with >1σ significance
Nearest Neighbor (NN):
3D Space of Redshift, Stretch, Color
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“NN Training” finds optimal radius of 3D sphere by maximizing Eff x Purity.
NN Performance on Simulation:

After box cuts:
SNIa Purity ≈ 90%

After $P_{NN,la} > \frac{1}{2}$:
SNIa Purity $\rightarrow$ 98% with 2% SNIa loss
Data/Sim Comparisons

- Box cuts + $P_{\text{NN,Ia}}>\frac{1}{2}$
- Sim zHost tuned to match DES data (Eff$_{\text{zHOST}}$ not known yet)
- No other sim tuning (except flux-errors to match fakes)
Data/Sim Comparisons

- Data
- Sim

- zhd
- SNRMAX1
- err_c
- SALT2-c
- SALT2-x
- err_{x1}
- SALT2-mB
- err_{mB}
- NN-P_{la}
- SNRMAX3
- P_{fit}
Data/Sim Comparisons

- Data
- Sim

DEEP Fields (24.5 mag)

Shallow Fields (23.5 mag)

DEEP	Fields

(24.5	mag)

Shallow	Fields	(23.5	mag)

NN-P_{la} 50 60 70 80 90 100

SALT2-mB 18 20 22 24 26 28

SNRMAX3 0 20 40 60 80 100

P_fit 0 0.2 0.4 0.6 0.8 1

err_{x1} 0 0.5 1 1.5 2

err_{PKMJD} 0 20 40 60 80 100

P_fit 0 0.2 0.4 0.6 0.8 1

Tuned

DEEP Fields (24.5 mag)

Shallow Fields (23.5 mag)

NN-P_{la} 0 0.1 0.2 0.3 0.4 0.5

SALT2-mB 0 20 40 60 80 100

SNRMAX3 0 20 40 60 80 100

P_fit 0 0.2 0.4 0.6 0.8 1

err_{x1} 0 0.5 1 1.5 2

err_{PKMJD} 0 0.1 0.2 0.3 0.4 0.5

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Tuned
Sim CC/Tot = 1.6% .
Data contamination is clearly few times more.
When all else Fails, Tune the CC Sim

Untuned: CC/Tot=1.6%

Double CC: CC/Tot=2.6%

CC 0.4 mag Brighter: CC/Tot=2.3%

Can tune CC to match \( \mu \)-resid tail, but cannot fix shoulder problem. See Jones talk for tests with 91bg, lax . . . .
Fitting the Hubble Diagram: Correcting for Biases and CC Contamination

DATA, \( NN(z,s,c) \)

Average Bias Corrected Distances
Fitting the Hubble Diagram: Framework

\[ \mathcal{L}_i \equiv \left[ \frac{P_{NN, Ia}^i}{P_{tot}^i} D_{Ia}(z_i, \mu_i) \right] + \left[ \frac{S_{CC}^i (1 - P_{NN, Ia}^i)}{P_{tot}^i} D_{CC}(z_i, \mu_i) \right] \]

From Hlozek 2011

\[ L = L(Ia) + L(CC) \]

\[ P_{tot} = P_{NN, Ia} + S_{CC} (1 - P_{NN, Ia}) \]
\[ D_{Ia} = \exp[-\chi^2_{Ia}/2]/(2\pi \sigma^2_\mu)^{1/2} \]
\[ D_{CC} = \text{map from simulation.} \]
Fitting the Hubble Diagram: Framework

\[
L_i = \left[ \frac{P_{NN,Ia}^i}{P_{tot}^i} D_{Ia}(z_i, \mu_i) \right] \\
+ \left[ S_{CC}^i (1 - \frac{P_{NN,Ia}^i}{P_{tot}^i}) D_{CC}(z_i, \mu_i) \right]
\]

From Hlozek 2011
\[ L = L(Ia) + L(CC) \]

Fix cosmology params \((w, \Omega_M)\) and fit for \(\mu\)-offset in redshift bins (along with \(\alpha, \beta\)):
“SALTmu” program in SNANA, Marriner 2011.

Can then fit \(\mu\)-offset vs. redshift with any cosmo program
Fitting the Hubble Diagram: Correcting for Biases and CC Contamination

\[ \mu = m_B + \alpha x_1 - \beta c - M_0 \]

\[ \mu^* = m_B^* + \alpha x_1^* - \beta c^* - M_0 \]

\[ = (m_B - \bar{\delta}_{m_B}) + \alpha(x_1 - \bar{\delta}_{x_1}) - \beta(c - \bar{\delta}_c) - M_0 \]

Avg bias corrections from simulation using color & stretch populations from SK16: Corrections binned in 3D map of \( \{ z, x_1, c \} \)
Fitting the Hubble Diagram: Correcting for Biases and CC Contamination

\[ \delta_{mB} = m_B - m_{B,\text{sim}} \]

\[ \alpha_1 = \alpha(x_1 - x_{1,\text{sim}}) \]

\[ c < -0.1 \]

\[ |x_1| < 0.4 \]

\[ |c| < 0.1 \]

\[ l \bar{c} < 0.1, \quad |x_1| < 0.4 \]

\[ l \bar{c} < 0.2, \quad |x_1| < 0.4 \]

\[ l \bar{c} < 0.1, \quad 1 < x_1 < 2 \]

\[ -3 < x_1 < -2 \]
Fitting the Hubble Diagram:
Correcting for Biases: Sim SNLa only

Unbiased results require both $\ln(\sigma)$ term + biasCor (leaving out either is bad):

$\alpha_{\text{fit}}/\alpha_{\text{SIM}} = 0.977(16)$
$\beta_{\text{fit}}/\beta_{\text{SIM}} = 1.000(8)$
Fitting the Hubble Diagram: Correcting for Biases and CC Contamination

Unbiased results
Require biasCor:
\[
\frac{\alpha_{\text{fit}}}{\alpha_{\text{SIM}}} = 0.986(20)
\]
\[
\frac{\beta_{\text{fit}}}{\beta_{\text{SIM}}} = 0.999(10)
\]
\[
S_{\text{CC}} = 0.82(10)
\]
Fitting the Hubble Diagram: Correcting for Biases and CC Contamination

DES Data: Blind Analysis

For data, SALT2mu program adds crazy $\mu$-offset in each redshift bin ... unless explicitly asked to unblind. Fitted $\alpha, \beta, \sigma_{\text{int}}$ are shown to compare with spec samples.
Final Caveat:
Bias Correction is Similar to NN Cut

- **NN cut** removes events where sim CC are majority in local \(\{z,x1,c\}\) region
- **Bias Correction** removes events where there are no sim-Ia in local \(\{z,x1,c\}\) bin (since correction cannot be made)

<table>
<thead>
<tr>
<th>Requirement after box cuts</th>
<th>True CC/Tot ratio for sim with double CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>0.11</td>
</tr>
<tr>
<td>Bias Correction (no NN)</td>
<td>0.039</td>
</tr>
<tr>
<td>NN (no bias correction)</td>
<td>0.026</td>
</tr>
<tr>
<td>NN + Bias correction</td>
<td>0.024</td>
</tr>
</tbody>
</table>
Conclusions

• Overall data/sim agreement is good.
• Fake SN → photometry pipeline is important for tuning & validating SNANA simulation.

• Simulated Hubble Residuals underestimate high-side (faint) shoulder:
  Wrong LF ?  Wrong rate ?  Missing templates?

• New HD fitting method to simultaneously account for biases and CC contamination.