Optimization of the WFIRST SN survey

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https://arxiv.org/abs/1702.01747

The SN Science Team

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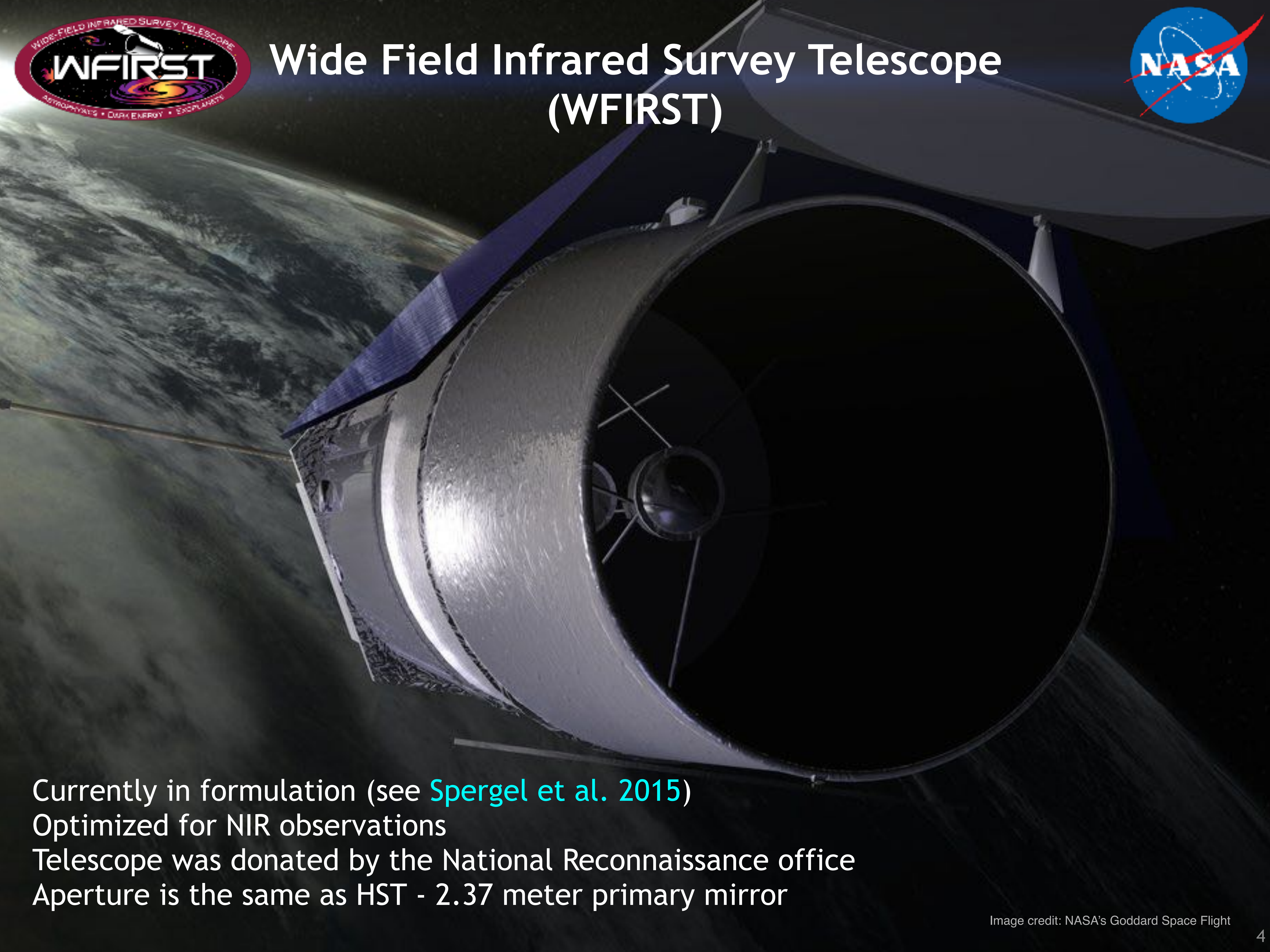
THE WFIRST MISSION

- -THE OBSERVATORY
- -SDT SURVEY DESIGN & SNANA SIMULATIONS
- -STRATEGIES INVESTIGATED
- -STATISTICAL & SYSTEMATIC UNCERTAINTIES
- -CONCLUSION

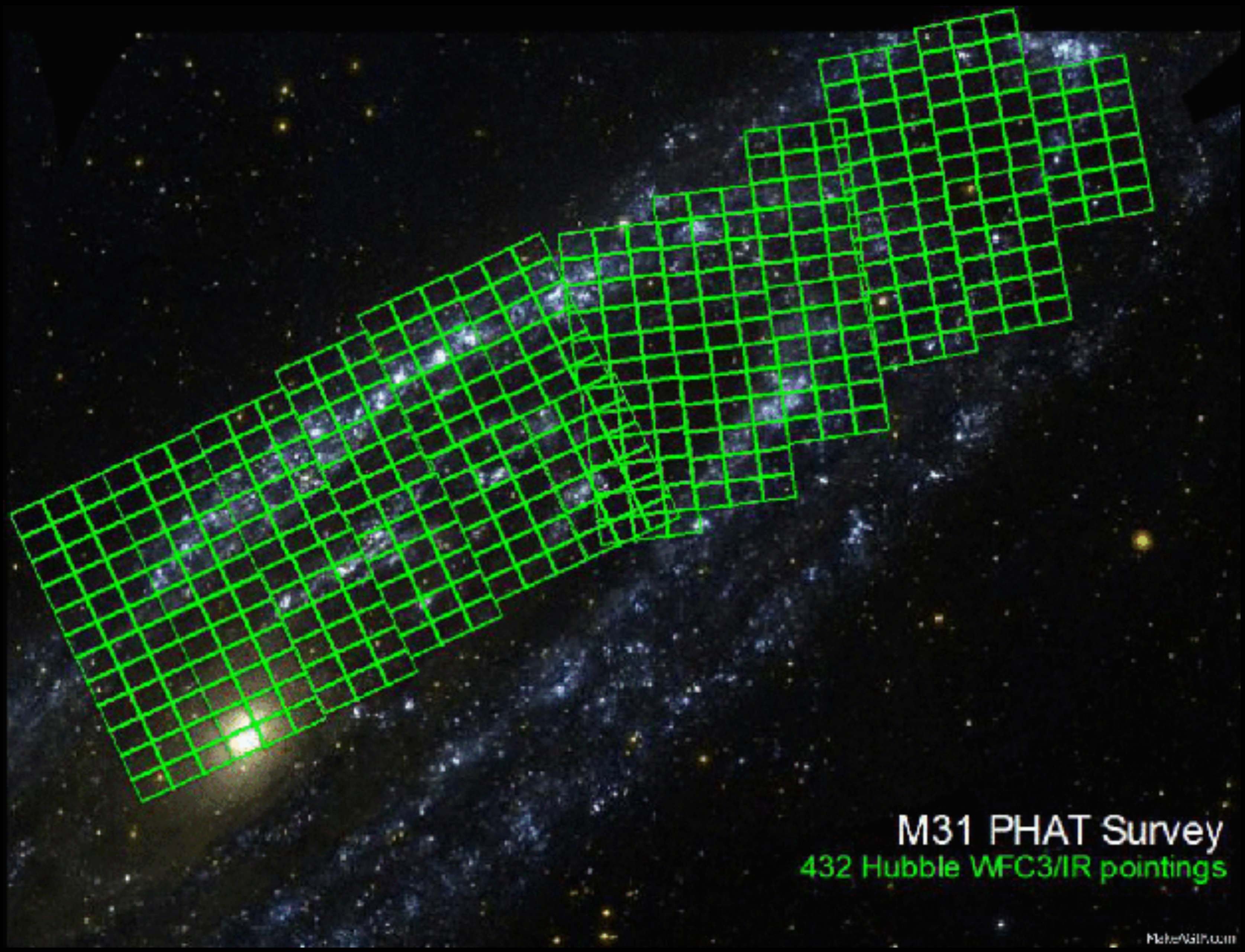
Wide Field Infrared Survey Telescope (WFIRST)



Currently in formulation (see Spergel et al. 2015)
Optimized for NIR observations
Telescope was donated by the National Reconnaissance office
Aperture is the same as HST - 2.37 meter primary mirror

Image credit: NASA's Goddard Space Flight

WIDE FIELD!



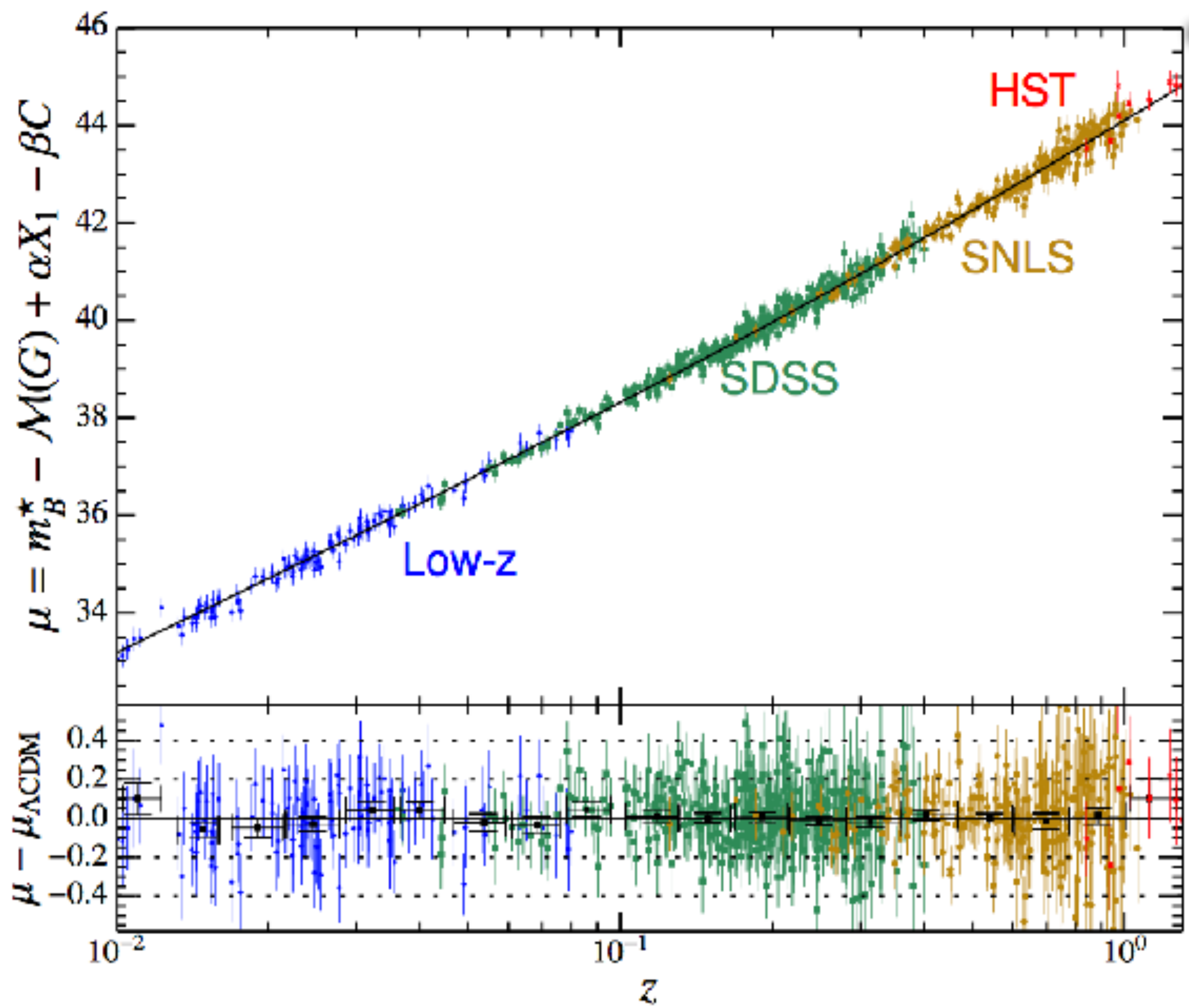
- Mission Life: ~ 6 years
- Mission Orbit: Sun-Earth L2
- Observatory: 2.4 m primary mirror Telescope
- FoV = 0.28 deg^2 - 100 x JWST

<u>Three Dark Energy Surveys</u>

- High Latitude Spectroscopic (BAO) Survey
- High Latitude Imaging (Weak Lensing) Survey
- Supernova Survey

Video credit: NASA's Goddard Space Flight

SN Ia Surveys



WFIRST z < 3.0

Hubble diagram of combined SN surveys.
Black line = best fit ΛCDM model. Bottom panel = residuals from best fit.
Image taken from Betoule et al. (2014)

Low-z: Data from multiple groups including Cfa, CSP LOSS etc.

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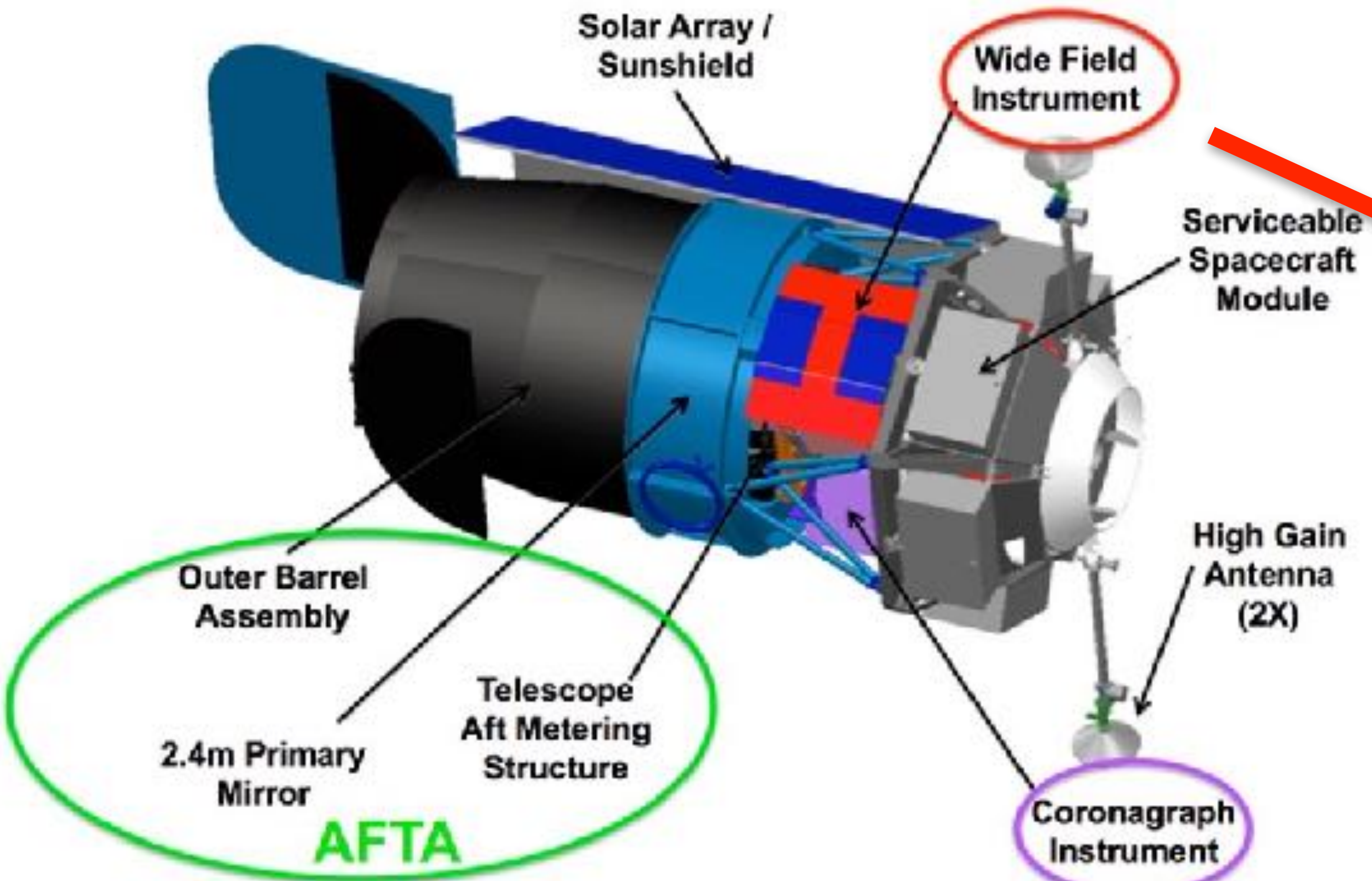
Instruments

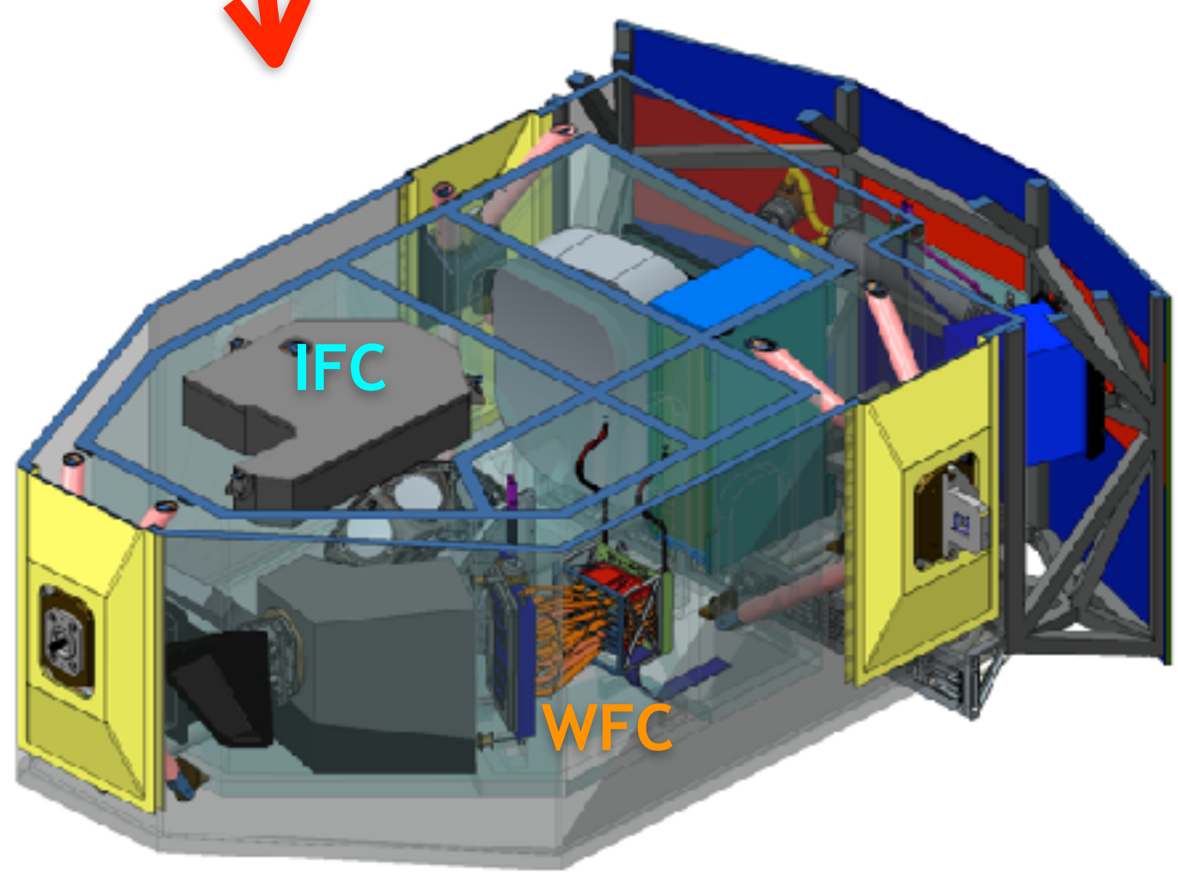


<u>Intergal Field Chanel - Supernovae (IFC-S) for spectra</u>

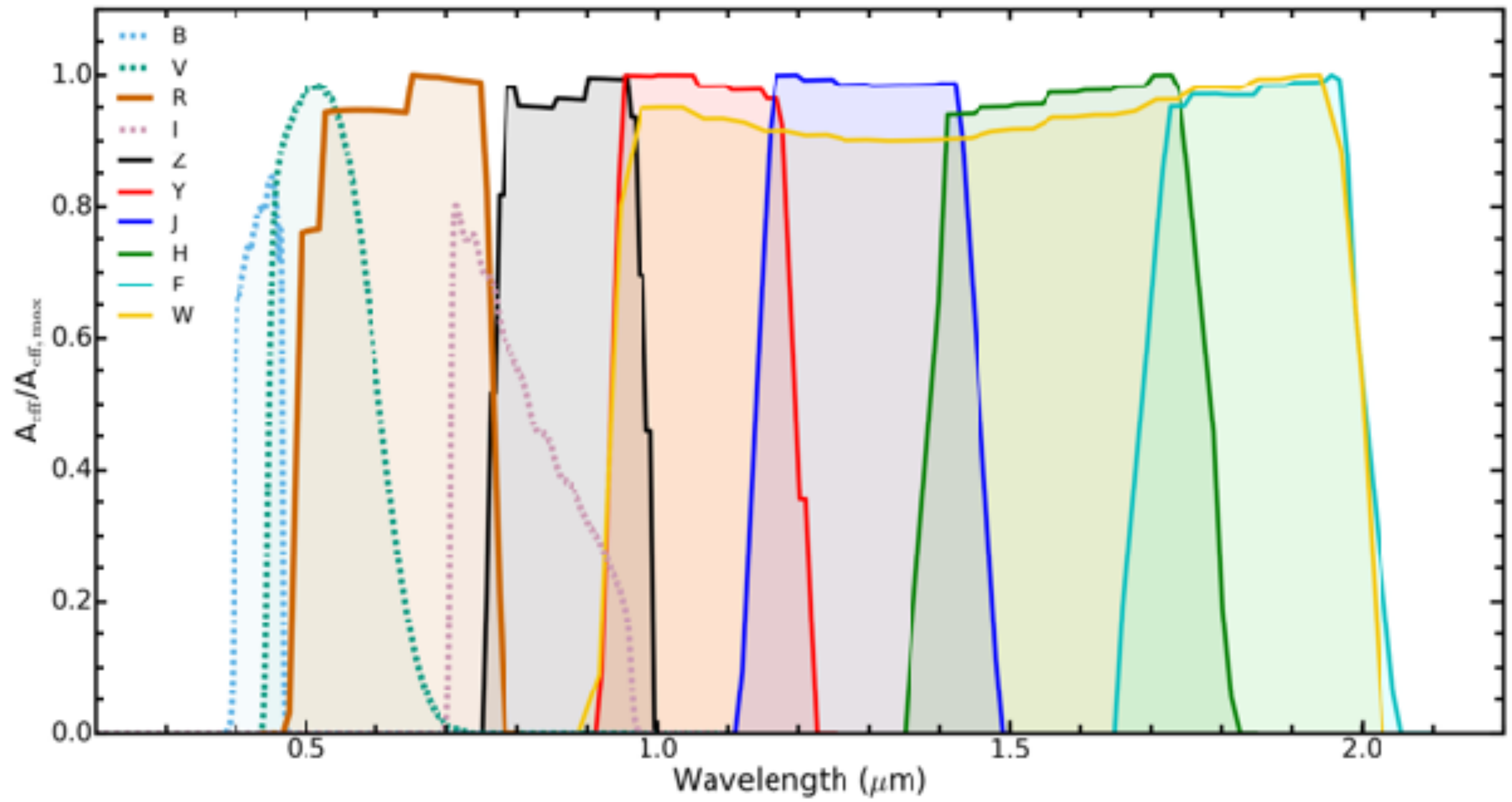
- FOV: 3 x 3 arcsec
- 0.05 arcsec/pixel
- Spectral resolution: 70 - 225
- Pass band: 0.42 - 2.0µm

<u>Wide Field Channel (WFC) Imager</u>

- FOV: 0.28 deg^2
- Resolution: 0.11 arcsec/pixel
- Pass band: 0.44 to 2.0µm
- 7 imaging filters



The Wide Field Channel (WFC)



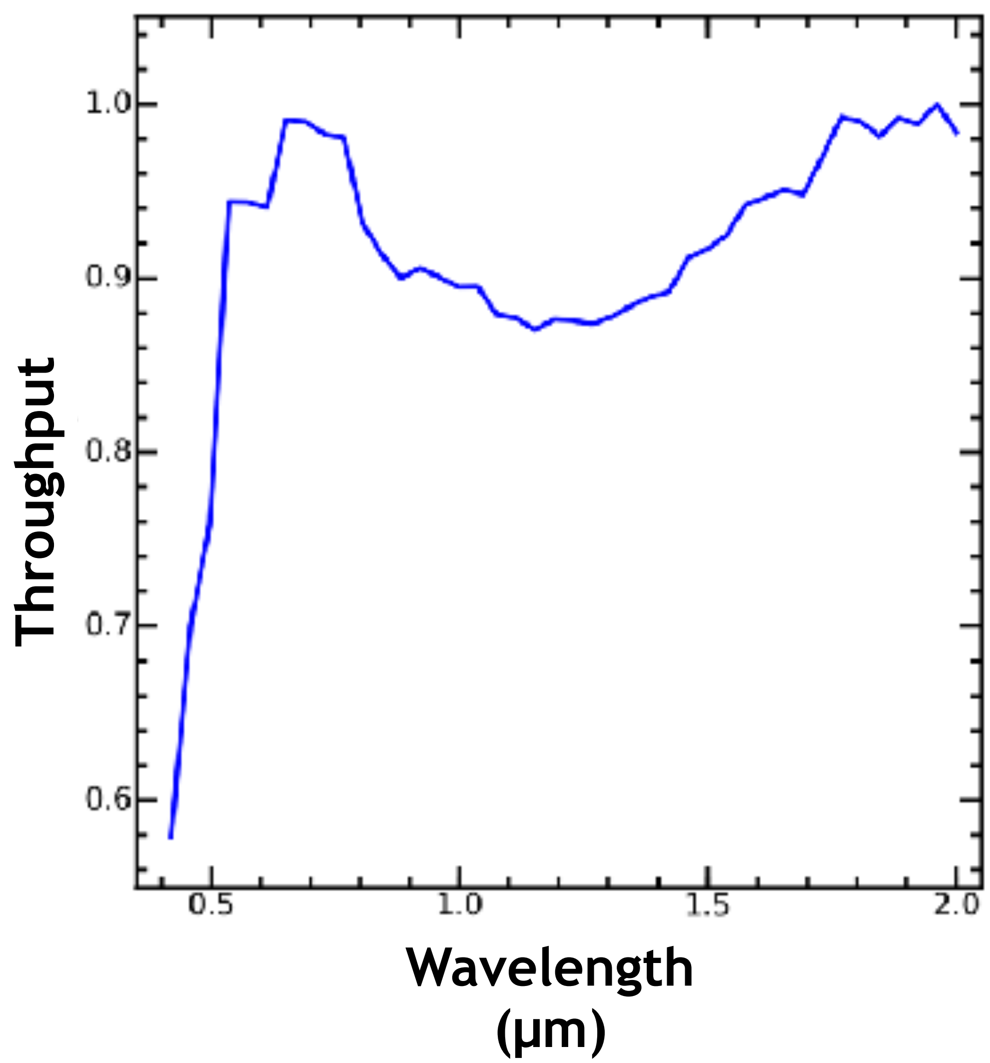
Element name	PSF FWHM (arcsec)	ZPT (AB) sec^{-1}
Z087	0.19	26.39
Y106	0.20	26.41
J129	0.23	26.35
H158	0.27	26.41
F184	0.30	25.96
W149	0.24	27.50
Rnew	0.18	26.99

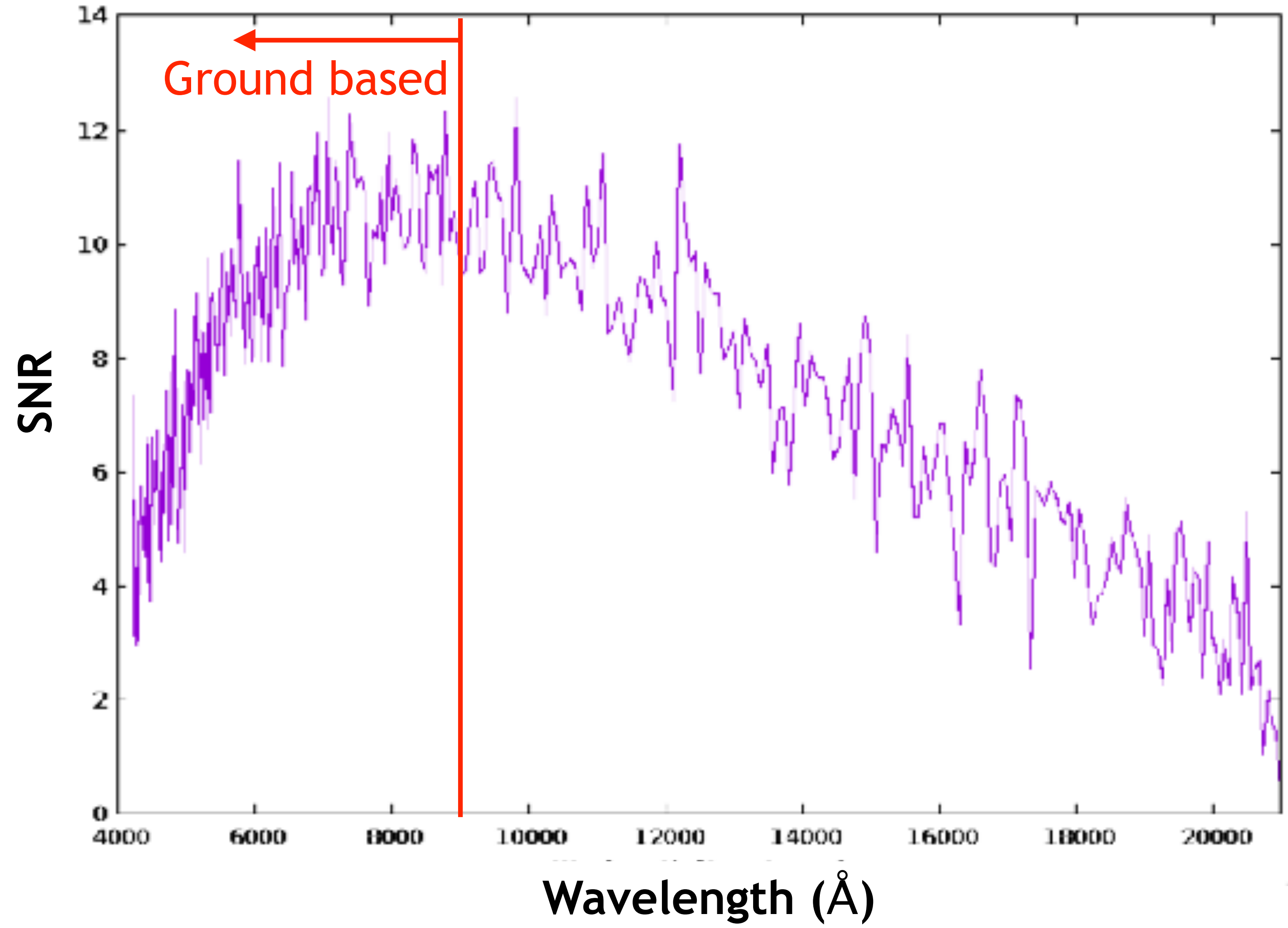
- WFIRST filters are deeper than HST/WFC3
- Filters are also redder
- Also much larger FOV!

- **Thermal:** WFIRST ETC ~ 260 K
- **Zodiacal:** G. Aldering (2001)
- **Dark Current:** 0.015 e/pix/s (Hirata & Penny 2014)
- **Read noise e/s:** Modified (Rauscher et al. (2007)

All these sources are included in our simulations

The Integral Field Channel (IFC)





- **Design:** Resolution based on Content et al. (2013)
- **Spectral bins:** 352
- **Thermal:** WFIRST ETC ~ 260 K
- **Dark Current:** 0.003 e/pix/s

All these sources are included in our simulations

An example WFIRST spectrum for a 25th magnitude source
EXP time: 5500 seconds

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Science Definition Team (SDT) Report SN Ia Survey

Report that provided initial information and preliminary designs for WFIRST surveys

Spergel et al. 2015
https://arxiv.org/pdf/1503.03757.pdf

Classification and distances from spectrophotometric time series!

Duration: 6 month survey over a 2 yr duration
Instruments: Spectra + discovery imaging

Each confirmed SN Ia will have 10 spectra: Cadence of 5 rest frame days
Imaging for discovery and SN peak brightness only!

Tier Name	Approximate Redshift Range	FOV (deg^2)	Filters	Depth per Exposure (mag)
Shallow	0.1 – 0.4	27	Y, J	~22
Medium	0.4 - 0.8	9	J, H	~25
Deep	0.8 – 1.7	5	J, H	~26

SuperNova ANAlysis (SNANA & CosmoMC)

SN Model

SN Ia and SN CC Volumetric Rates
Lensing, Extinction, Intrinsic Scatter, Color, Host properties

INSTRUMENT PARAMETERS

Filter Band-passes + Zero Points
Spectral Table
Areas
PSF FWHM
Sources of noise

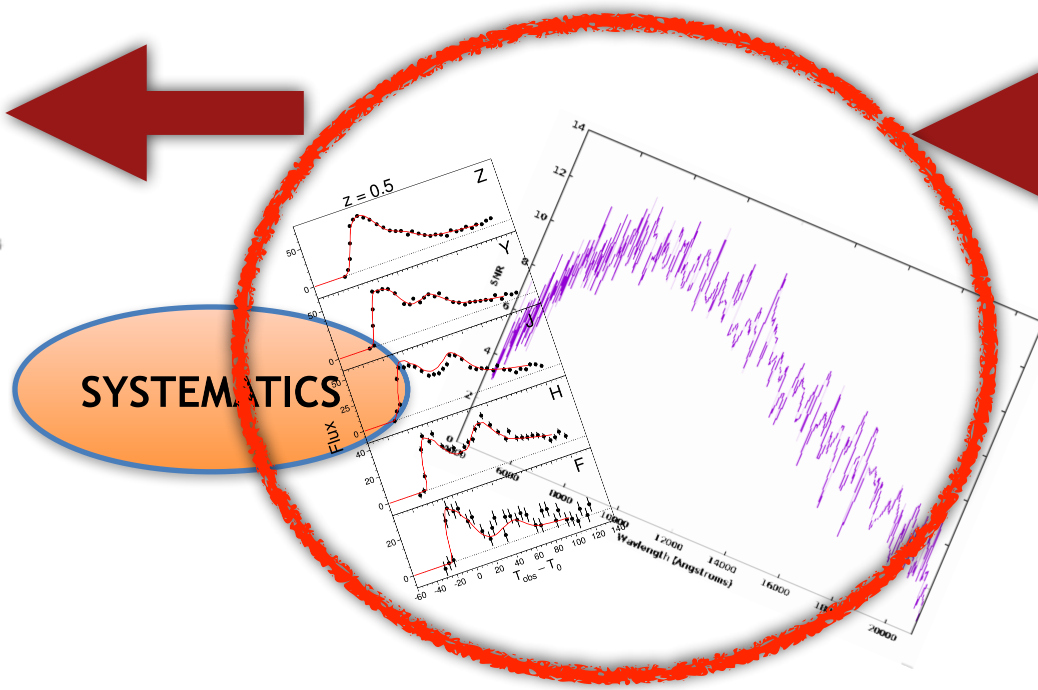
SCHEDULING & SELECTION

Cadence of observations
Selection criteria and cuts

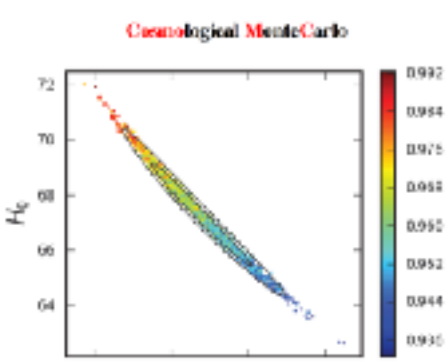
SIMULATION

SNANA

ANALYSIS & FITTING



COSMOLOGY



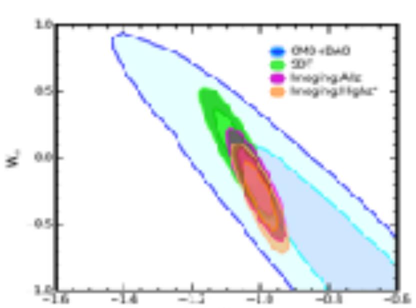
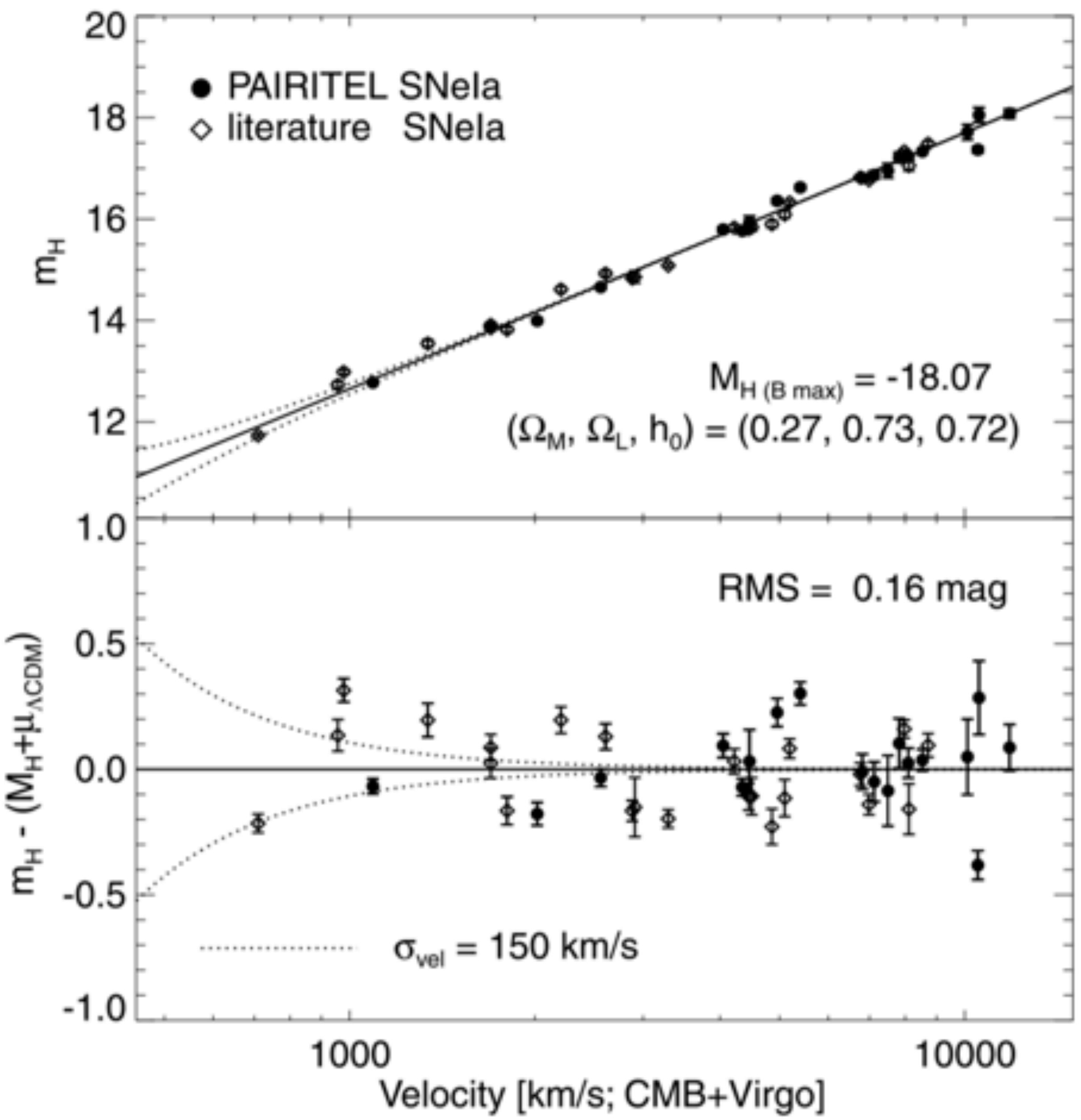


Image credits: CFA Harvard, NASA, solarviews.com, clipartbest.com

Are NIR SNe Ia better standard candles?



NIR H-band SN Ia Hubble diagram with an RMS of 0.15 mag. SN Ia that are diamonds are from the literature, filled circles from Wood Vasey et al (2008) paper.

- Work by Wood-Vasey et al., (2008), Mandel et al., (2009), Barone-Nugent (2012), Kattner (2013), and Stanishev et al., (2018) indicate that nearby SN Ia are excellent standard candles in the NIR.
- By combining information from both the NIR and optical light curves it may be possible to reduce scatter and obtain better distances by improving our understanding of,
  - Dust Absorption
  - Spectroscopic Variation
  - Host galaxy properties
- Simulations by Krisciunas et al., (2007) indicate that distance modulus errors are improved by factors of 2.7 and 3.7 by adding J and JHK bands respectively, to UBVIR data.

The SALT2 model

Type Ia SN flux F is given as a function of phase φ and λ

$$F(\varphi, \lambda) = [x_0 M_0(\varphi, \lambda) + x_1 M_1(\varphi, \lambda)] \times \exp[c \times CL(\lambda)]$$

Key components M_0, M_1, CL

Original SALT2 wavelength range is from 2000-8500Å.

Training is only reliable over 3400-8000Å (Guy et al., 2007)

The current SALT2 model has been extended into the NIR: 1700-25,000Å

Used new synthetic Type Ia SEDs from Arturo Avelino.
SED templates based on the Hsiao SN Ia spectrophotometric model.
Templates warped (see Avelino (2018, in prep)) to match NIR photometric observations from low-z SN Ia (Friedman et al., (2015), Hicken et al., (2012), Contreras et al., (2010), Stritzinger et al., (2011)).

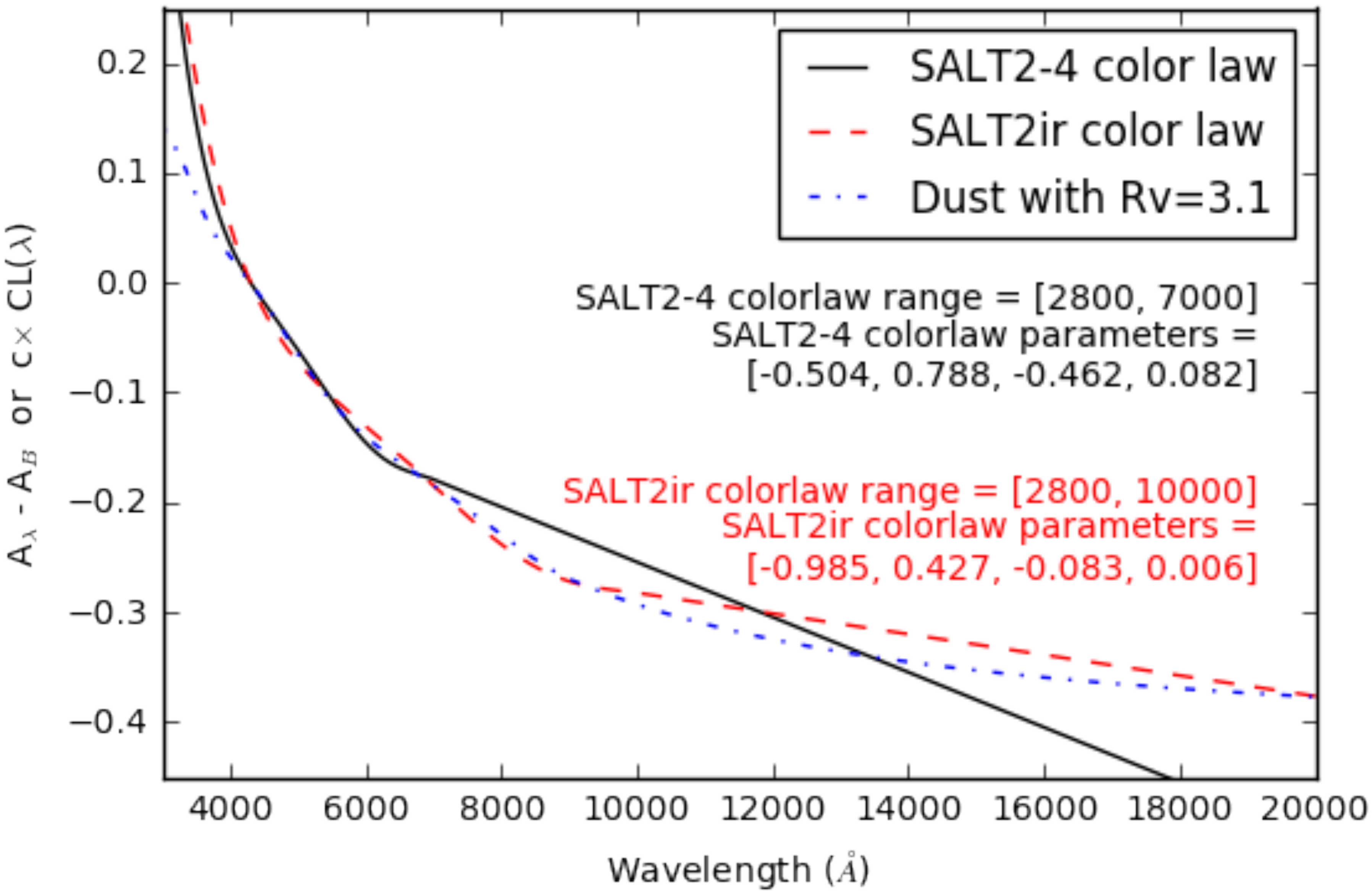
<u>The extension is crude</u>
Can be used for simulations and 1st order photometric classifications

Work by Justin Roberts-Pierel and Steve Rodney

SALT2ir - Extended Model

Extrapolating the SALT2 Color Law

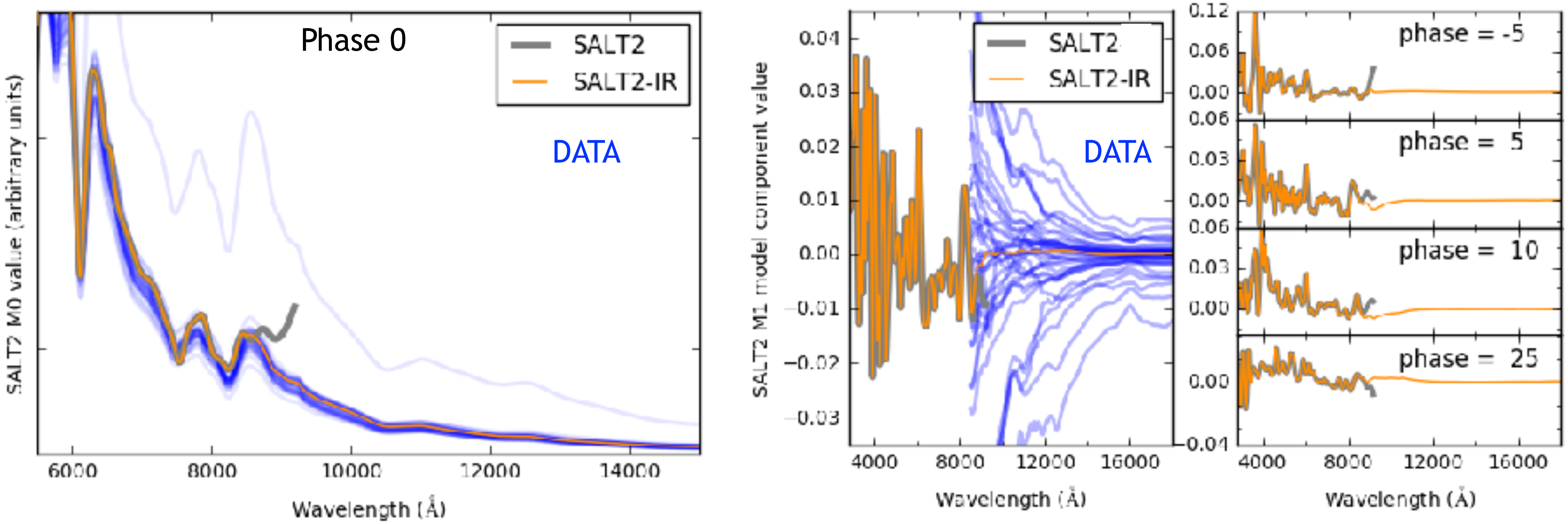
- SALT2 color law is a polynomial in λ
- To extend - updated coefficients of polynomial with a given constraint
    - The phase-independent SN Ia color variation at NIR is dominated by dust extinction (not intrinsic scatter).



For a SN with c = 0.1 you get an extinction factor c × CL(λ) that behaves like the Milky Way dust extinction curve from Cardelli et al. (1989) and O'Donnell (1994)

Work by Justin Roberts-Pierel and Steve Rodney

SALT2ir - Extended Model



Extrapolating the M_0 and M_1 components

SED templates then de-reddened to correct for redshift and dust.

M_0: Using new SEDs take the median flux at each wavelength
M_1:For every SED, use the new M_0 value in combination with the best-fit values for the x_0, x_1 and c, and solve SALT2 model equation (+ additional smoothing)

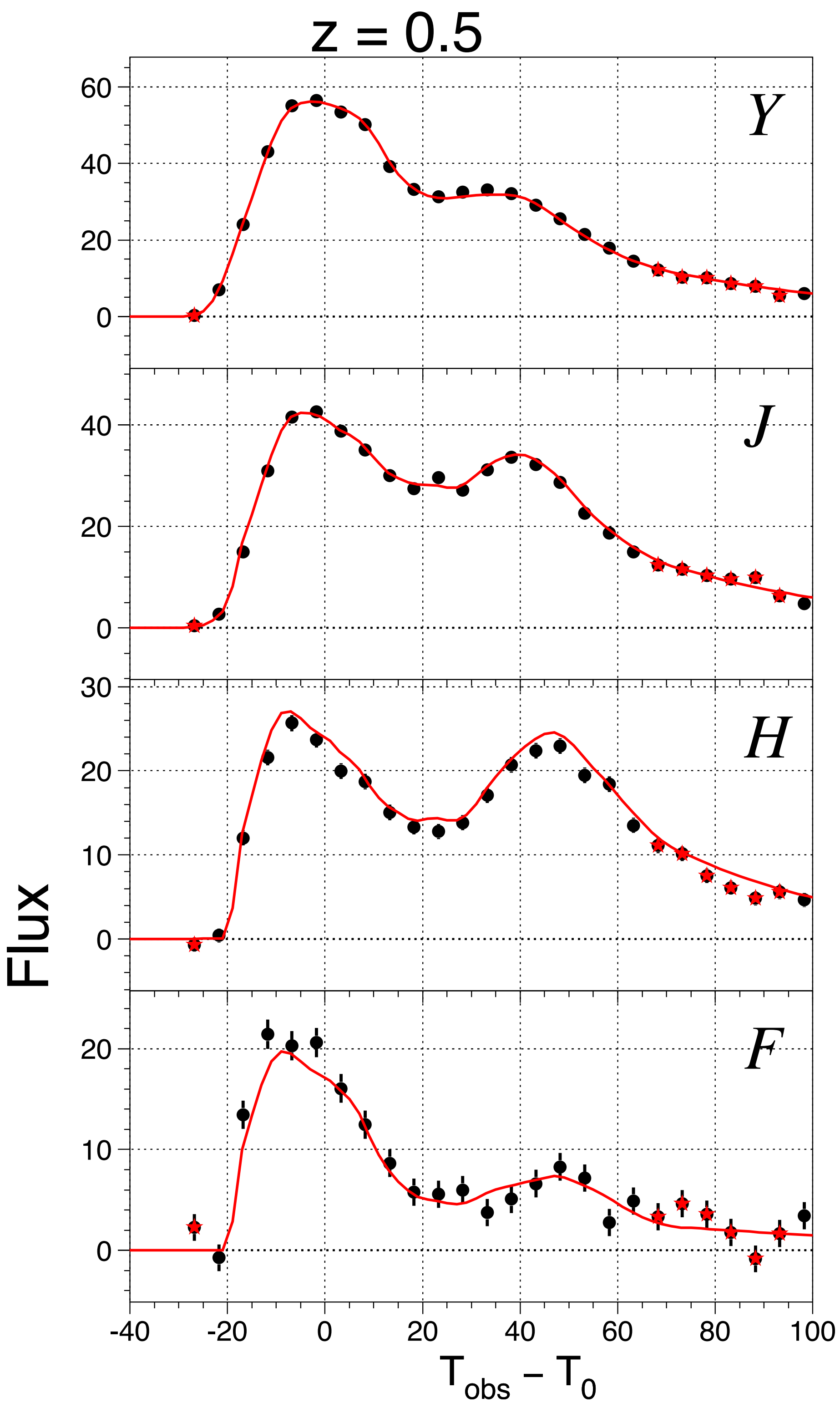
Work by Justin Roberts-Pierel and Steve Rodney

Work to be done!

A SALT2-ir model that can be used for fitting real data?

To modify SALT2 for light curve fitting a full training of the model, with a large sample of NIR Type Ia SN light curves, would be required.

Analysis: Light Curve Fitting



- ● Simulated WFIRST SNANA light curves
- ▬ Fitted SALT2 templates

We obtain stretch and color from light curve fits

The Tripp (1998) formulation

$$\mu = m_B - M + (\alpha \times \mathcal{X}_1) - (\beta \times c)$$

μ = distance modulus

m_B & M = apparent & absolute B band mag

$\mathcal{X}_1$ = Light-curve shape parameter

c = color law parameter

α, β = hyper parameters ~ 0.14, 3.2

Selection effect introduce a redshift dependent bias - use MC to correct

$$\mu \longrightarrow \mu + \Delta\mu_{MC}$$

SN Uncertainties Included

Wavelength Dependent Calibration Uncertainty

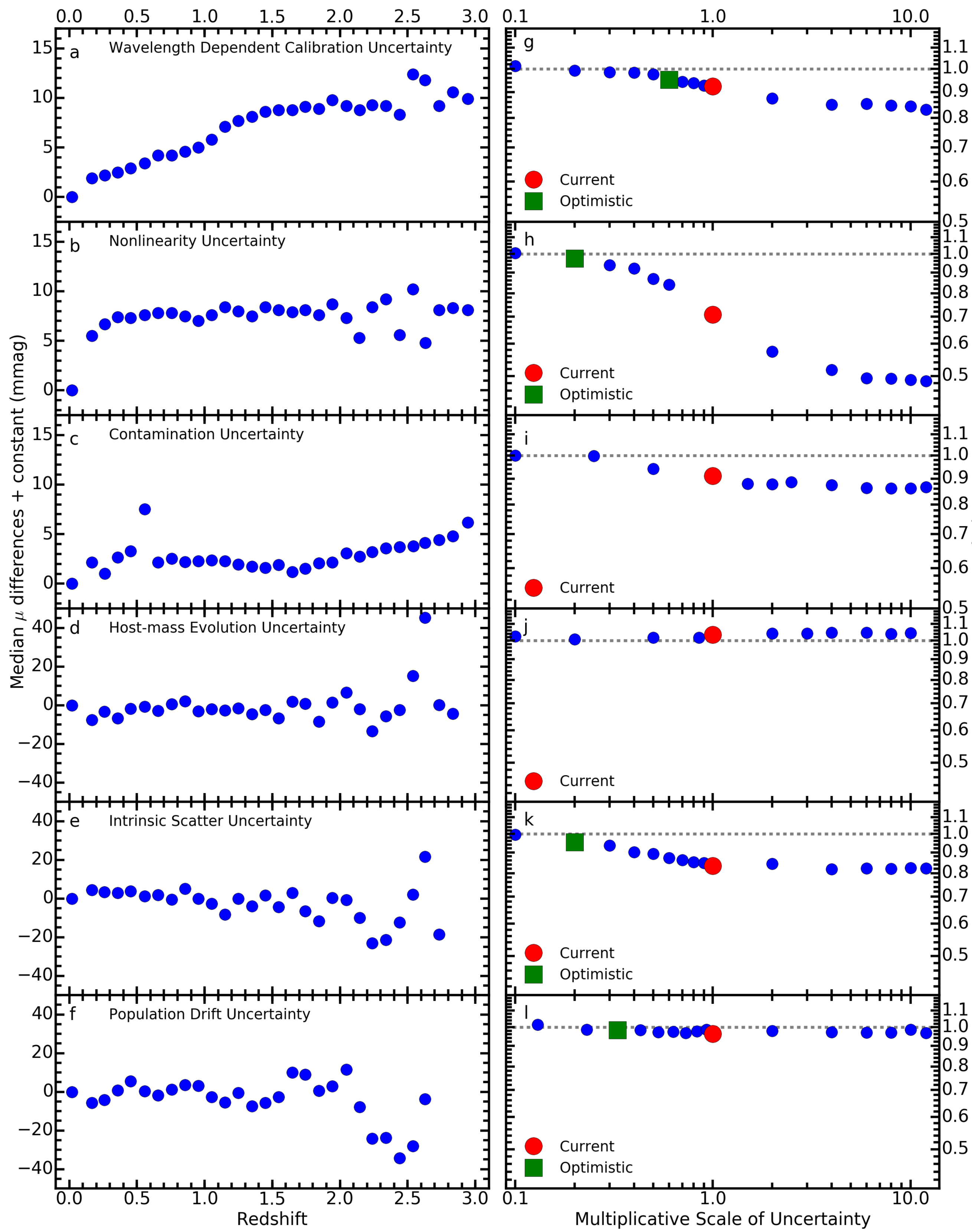
Nonlinearity Uncertainty

Core Collapse Contamination Uncertainty

Host-Mass Evolution Uncertainty

Intrinsic Scatter Uncertainty

Population Drift Uncertainty



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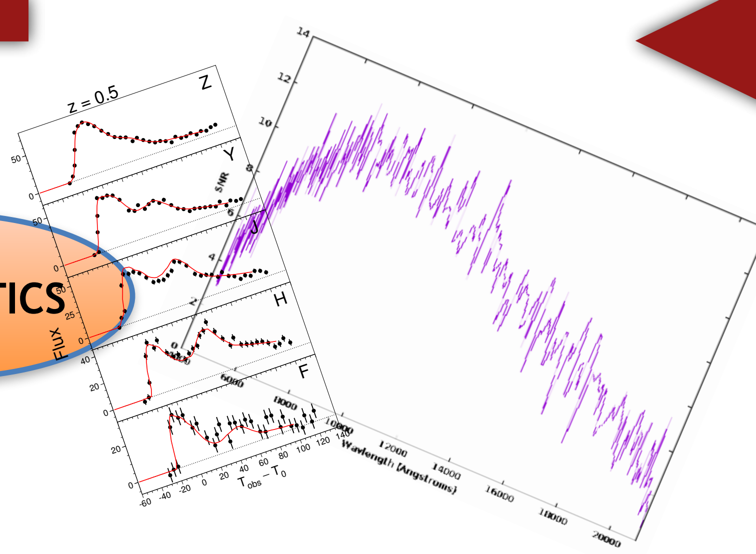

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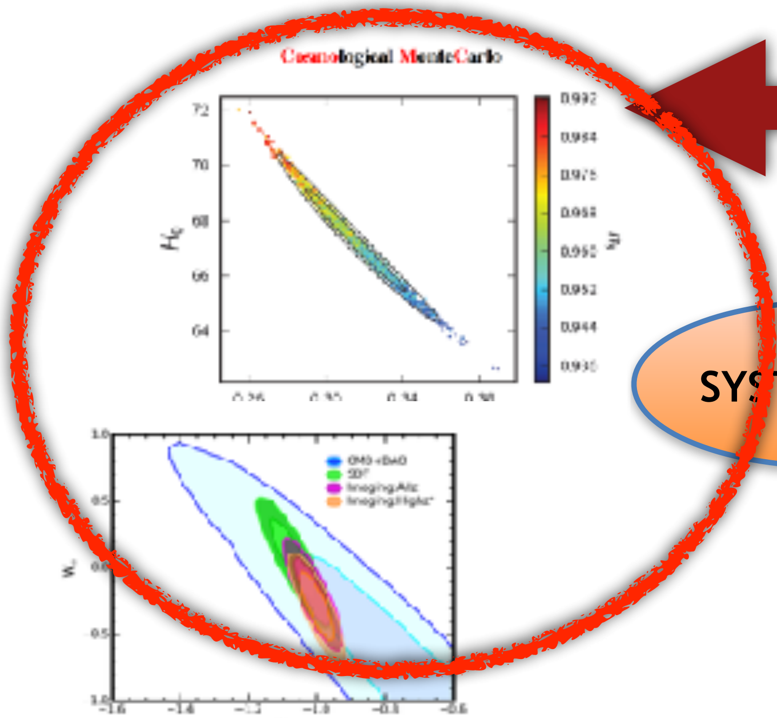

SYSTEMATICS

Image credits: CFA Harvard, NASA, solarviews.com, clipartbest.com

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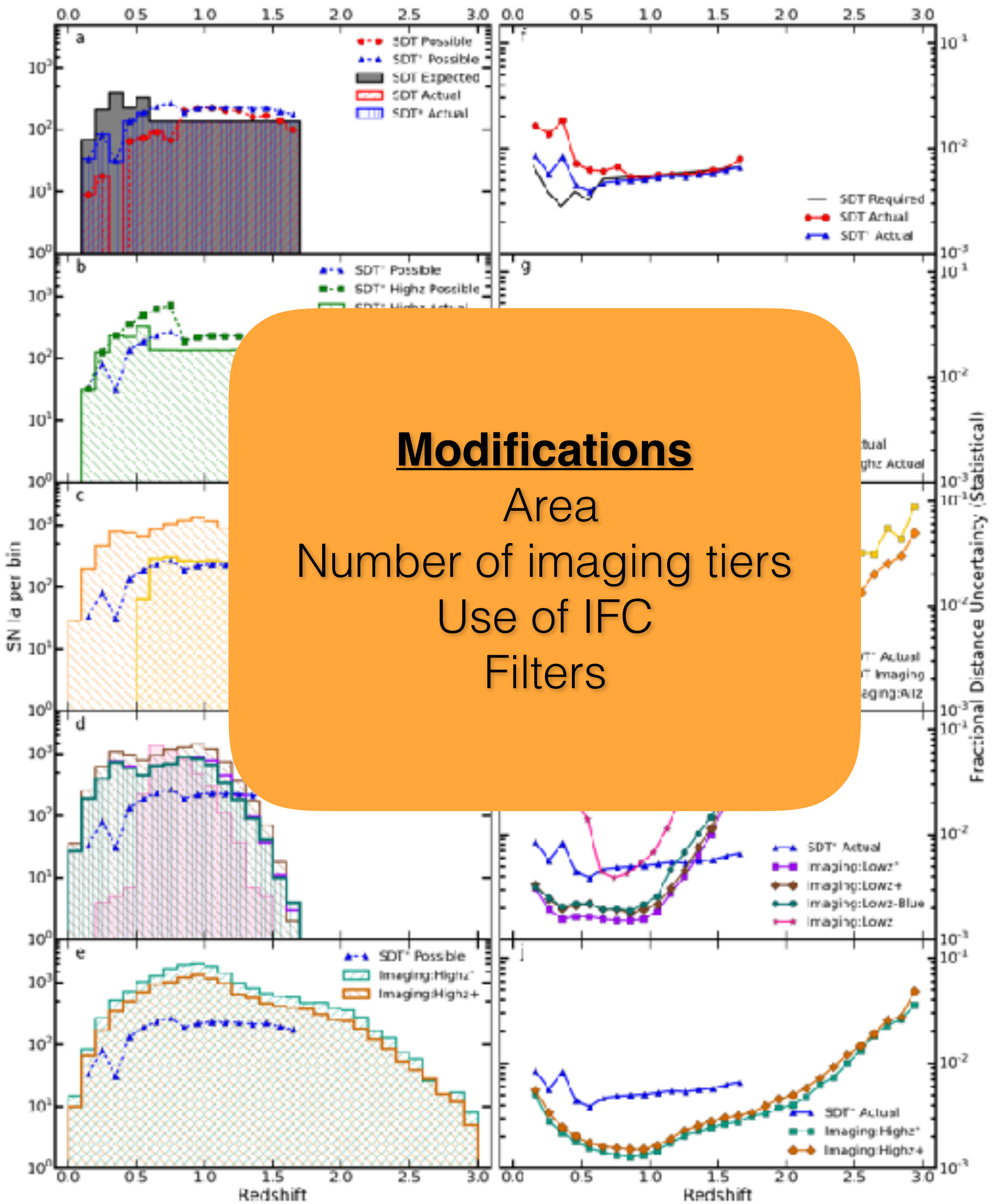
Multiple Strategies Investigated

IFC + IMAGING

IMAGING ONLY



Modifications

Area

Number of imaging tiers

Use of IFC

Filters

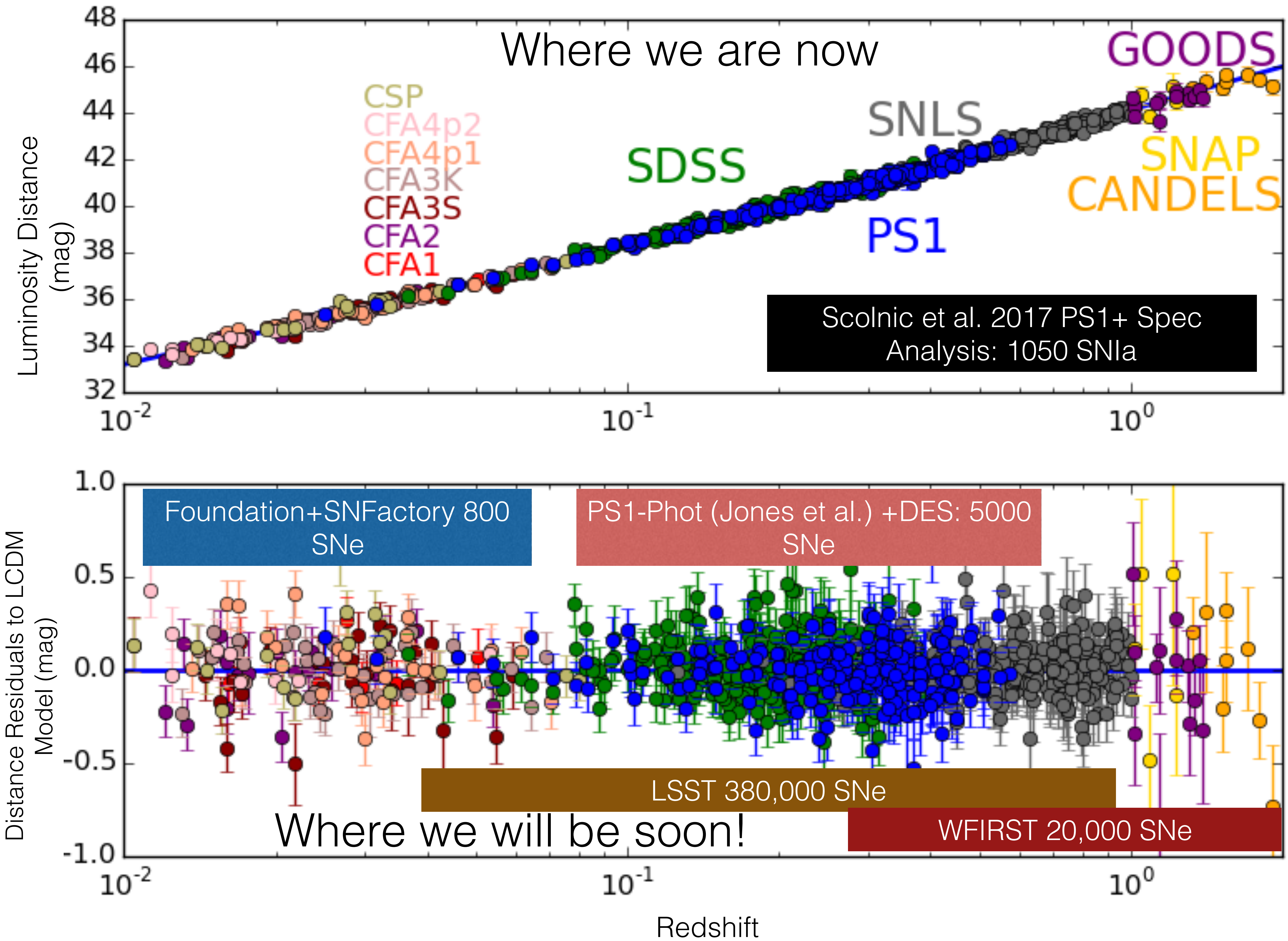
3 Tier Survey

2 Tier Survey

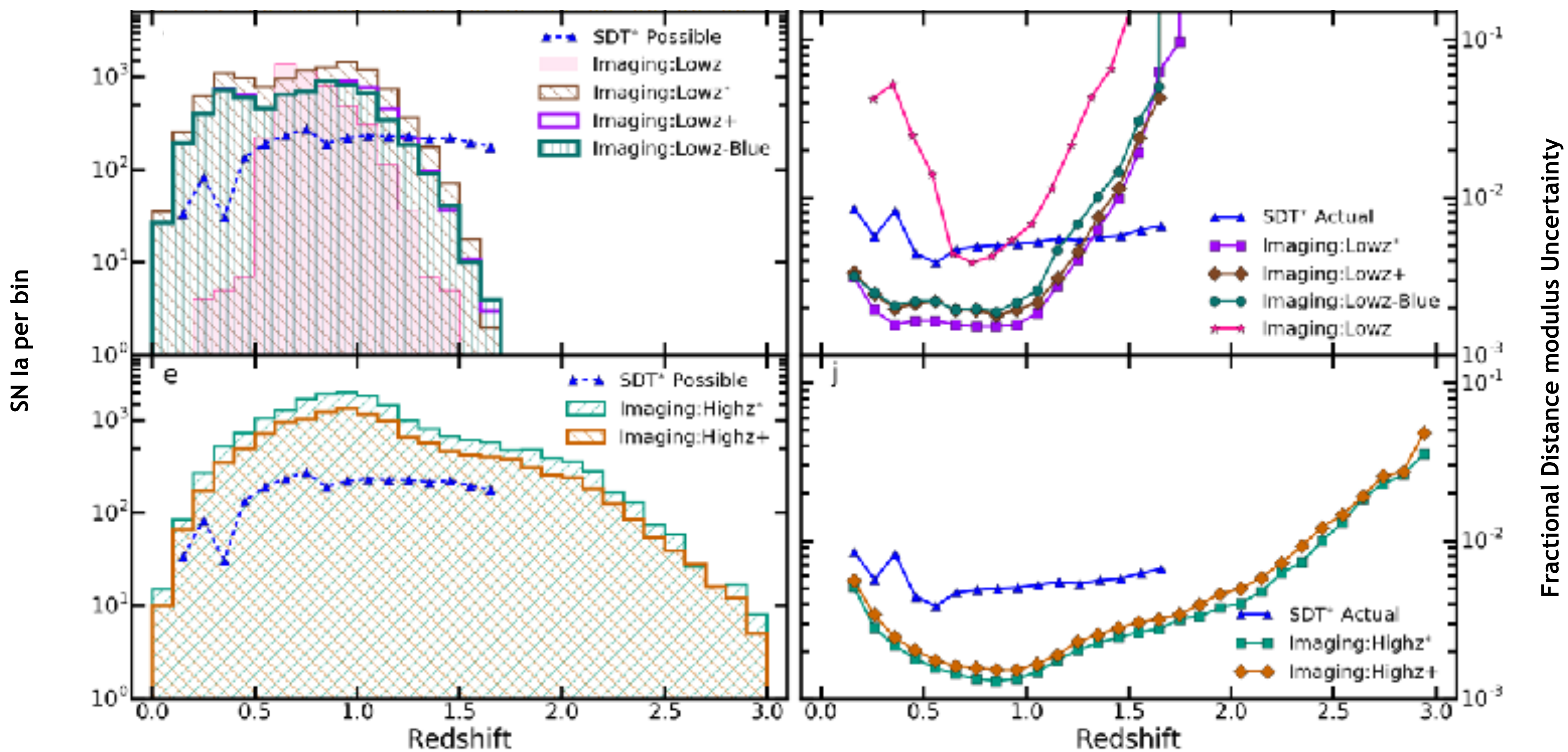
3 Tier Surveys

2 Tier Surveys
Shallow + Medium

2 Tier Surveys
Medium + Deep


Where we are now
GOODS
CSP
CFA4p2
CFA4p1
CFA3K
CFA3S
CFA2
CFA1
SNLS
SDSS
SNAP
CANDELS
PS1
Scolnic et al. 2017 PS1+ Spec Analysis: 1050 SNIa
Luminosity Distance (mag)
Foundation+SNFactory 800 SNe
PS1-Phot (Jones et al.) +DES: 5000 SNe
LSST 380,000 SNe
WFIRST 20,000 SNe
Where we will be soon!
Distance Residuals to LCDM Model (mag)
Redshift

Where should we focus our time?



1. A deeper survey: NIR data for high redshift rest-frame optical light curves
2. A shallow survey: Lower redshift SNe but with rest-frame NIR light curves.

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Systematics

We incorporate all top systematics from recent analyses

Systematic Uncertainty	*Description*
Wavelength dependent calibration	The accuracy of the HST Calspec system (Bohlin et al. 2014) is described as a linear function with a slope of roughly 5 mmag per 7000Å. **WFC: 5 mmag per 7000Å. IFC: 50 mmag per 7000Å** Childress et al. (2016).
Non-linearity	Detector response non-linearity can severely impact photometric precision in astronomical observations. Riess (2010) measured a non-linearity in WFC3-IR data as **1% per dex over a range of 10 mag (4 dex).**
Zero-point offset	Zero-point uncertainty can effect color term in SN distance equation. Space-based zero-point uncertainty expected to be at **5 mmag or less**
CC SN Contamination	For IFC expected to be negligible. For imaging only surveys we use photometric selection methods from DES & PS1.
Intrinsic scatter	How does bias depend on different models of intrinsic scatter.
Color + Stretch Population	Redshift dependent changes.
Host galaxy - SN luminosity	Correction to SN distances based on host-galaxy mass (e.g., Betoule et al. 2014). We introduced redshift dependent variation.

How much effort should go into reducing each systematic?

To date we have been assuming systematics based on optical studies.

How do we incorporate NIR knowledge?

Systematics

We incorporate all top systematics from recent analyses

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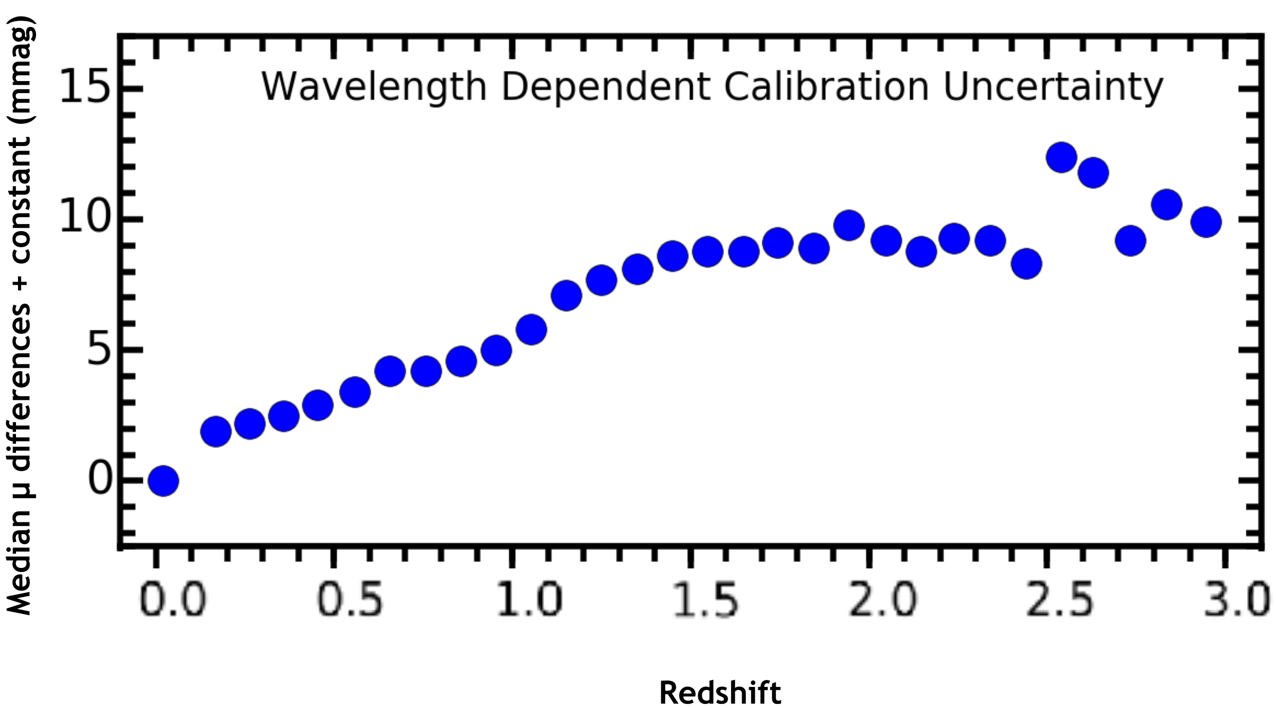
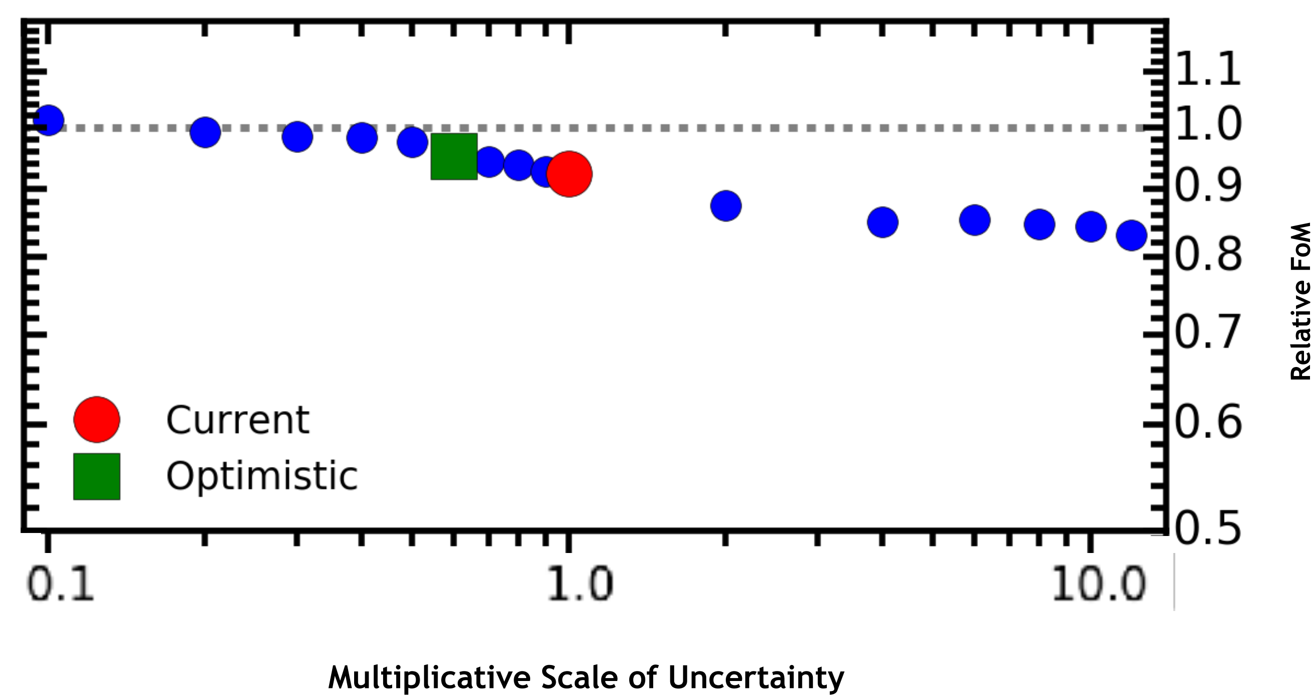
Wavelength dependent calibration	The accuracy of the HST Calspec system (Bohlin et al. 2014) is described as a linear function with a slope of roughly 5 mmag per 7000Å. **WFC: 5 mmag per 7000Å. IFC: 50 mmag per 7000Å** Childress et al. (2016).



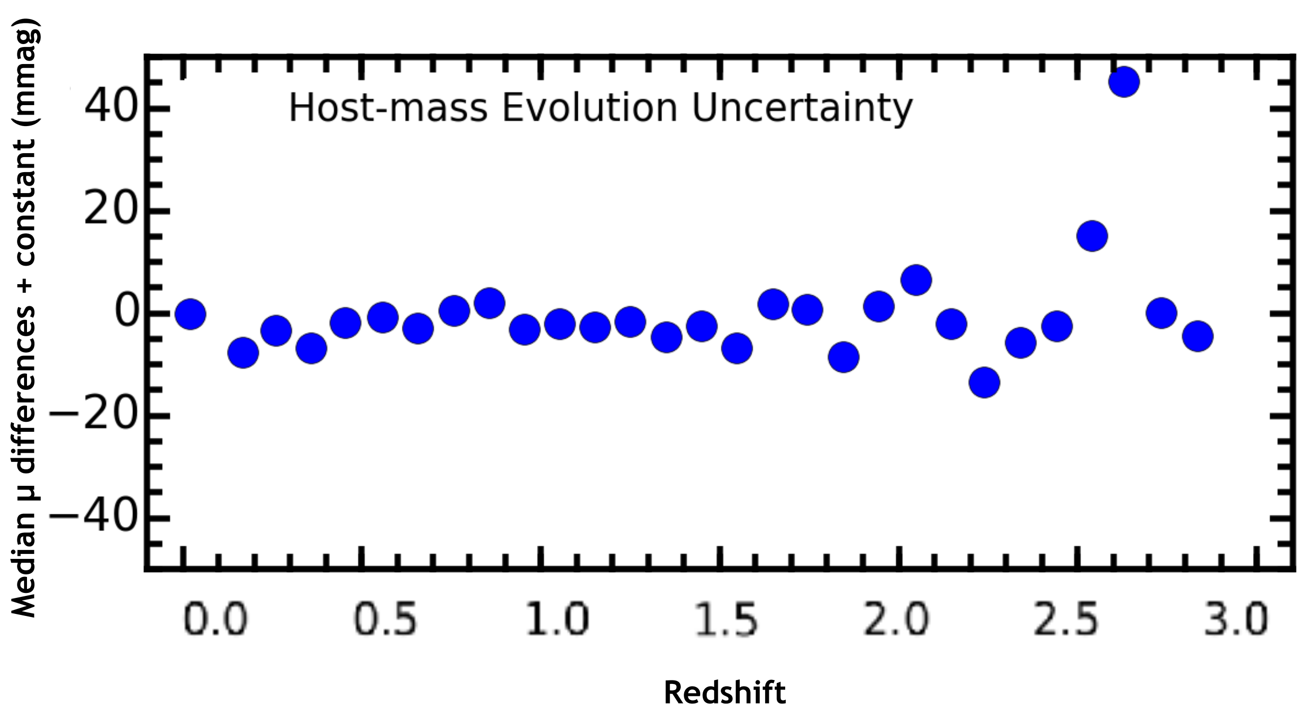


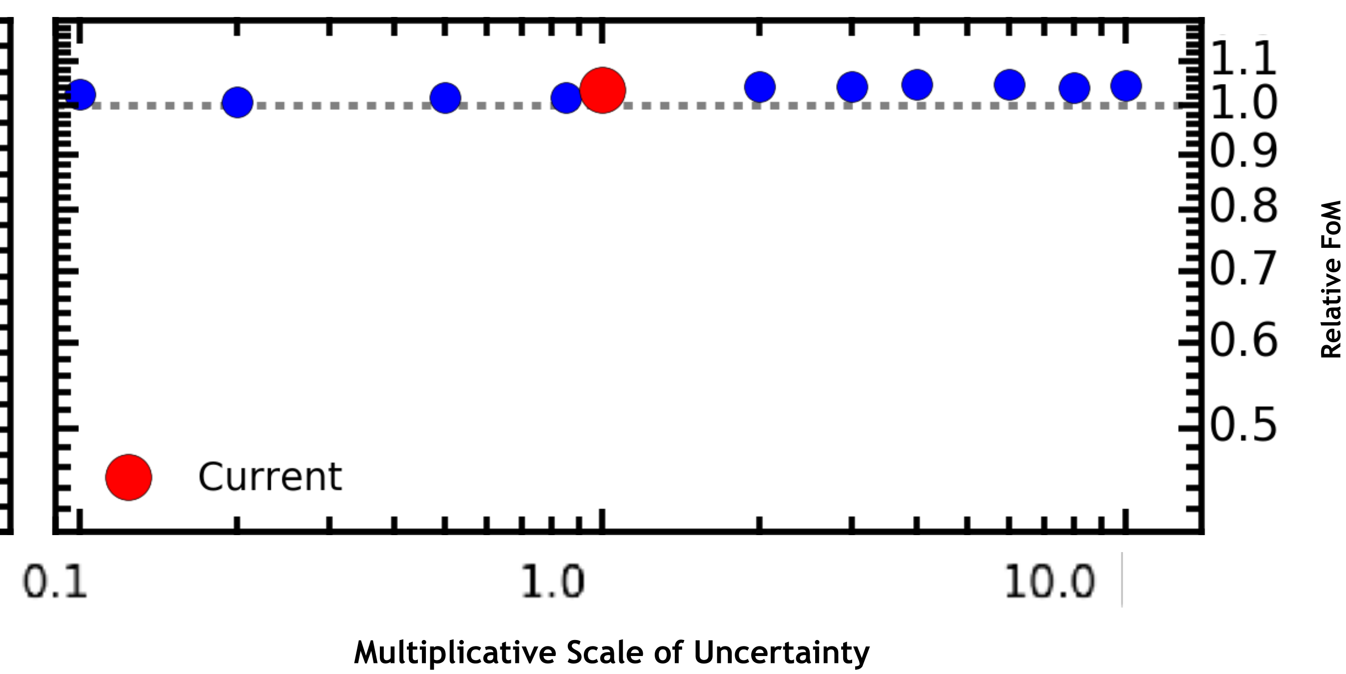
- Optimistic uncertainty is taken as 3 mmag per 7000Å.

Gautham?

Host galaxy - SN luminosity Relation

Systematic Uncertainty	*Description*
Host galaxy - SN luminosity	Correction to SN distances based on host-galaxy mass (e.g., Betoule et al. 2014). We introduced redshift dependent variation.



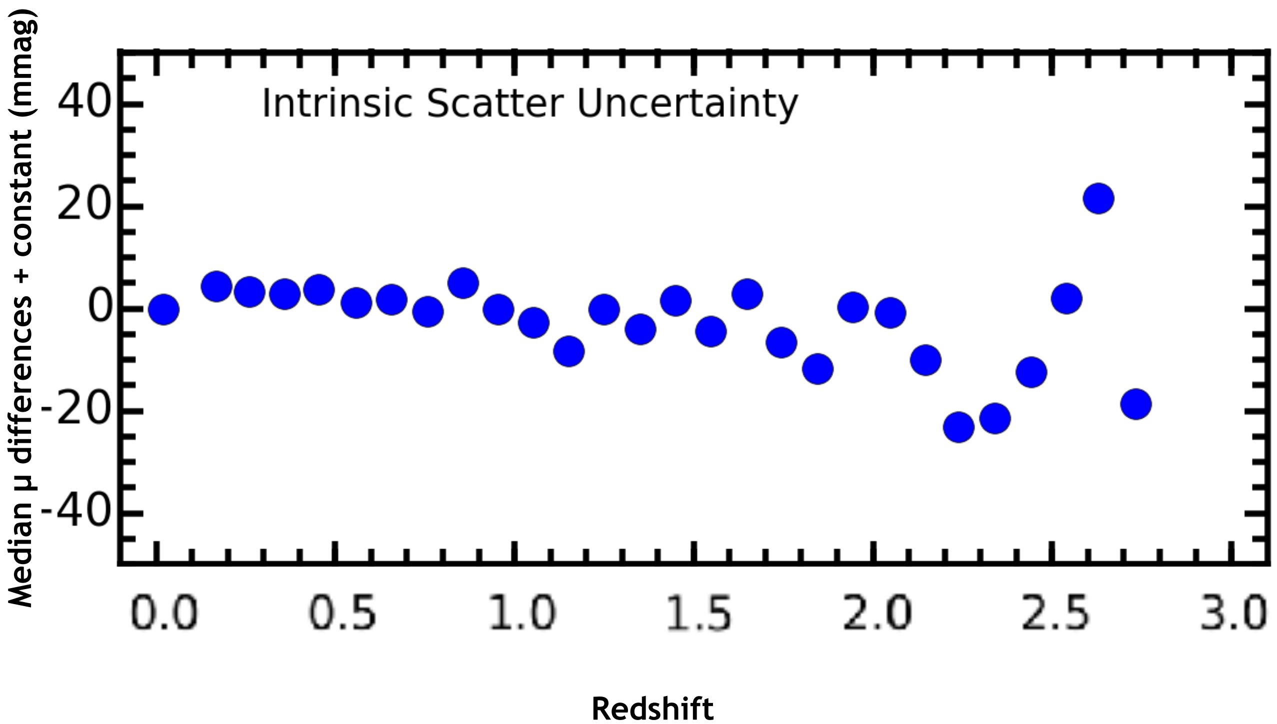


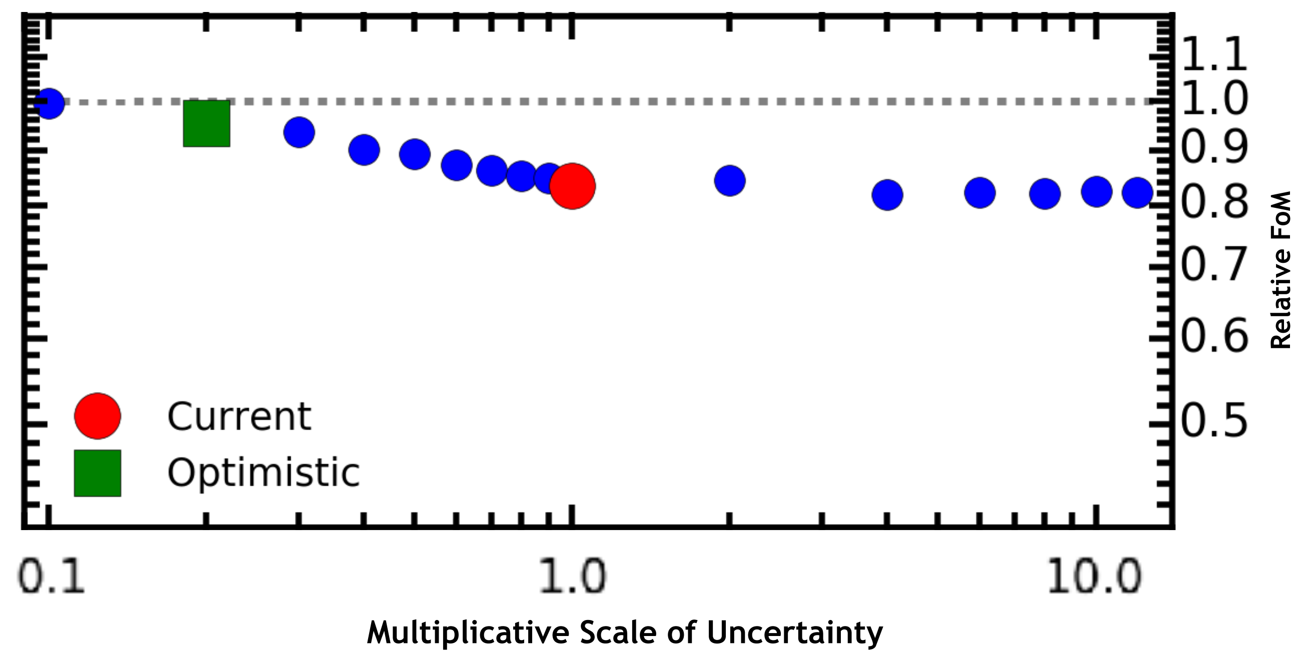
- The exact functional form of this correction is still poorly constrained
- The magnitude of this correction and the form could change with redshift (e.g., Rigault et al., 2013, 2015; Childress et al., 2014)

Chris, Kara, & Suhail?

Intrinsic Scatter

Systematic Uncertainty	*Description*
Intrinsic scatter	How does bias depend on different models of intrinsic scatter.





- There is still some uncertainty in relative proportion of color and luminosity variation in the intrinsic scatter model (Scolnic & Kessler 2016)
- Distance bias corrections applied depend on intrinsic scatter model assumptions
- Simulated data with both G10 (Guy et al 2010) and C11 (Chotard et al. 2011)

  G10: 70% luminosity variation, 30% color variation
  C11: 25% luminosity variation, 75% color variation
- Optimistic uncertainty is assumed as 5 x better due to improved models in the IR

Chris + Kaisey: Smaller scatter in NIR, but how do we describe the color or spectral variation of these models ?

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Concluding Remarks

If the future is NIR we need to fully understand how to use it.

- JWST will have the capabilities to observe the rest-frame NIR out to high-z
  - But limited number of SNe!
- LSST, WFIRST will provide SNe with well-sampled rest-frame B and V light curves out to redshift ~1.5, <3.0 respectively - Much larger sample of SNe i.e., 100,000s for LSST, ~10,000s for WFIRST!
- WFIRST will allow us to analyze SNe within the rest-frame NIR (lower z).
- Data from the combined RZYJHF filters may allow us to reduce certain systematics.
- We are currently incorporating the new NIR extended SALT2 models into our work.
- Many of our systematic assumptions are based on optical data and NIR considerations need to be made.
- To date we have produced realistic simulations of the WFIRST SN Survey and are continuing optimization.

Thank you