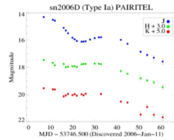

PAIRITEL
PETERS AUTOMATED INFRARED IMAGING TELESCOPE

CfAIR2: 100 Type Ia Supernova Light Curves from PAIRITEL

Andrew Friedman
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www.cfa.harvard.edu/pairitel www.pairitel.org
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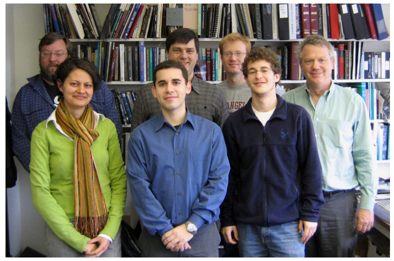
Massachusetts Institute of Technology
VE RI TAS
NSF
NASA
Fred Lawrence Whipple Observatory

Hello, I'm Andrew Friedman, a Ph.D. candidate in Astronomy at Harvard University working with Bob Kirshner.
I'll talk briefly about the work I've been involved with for the past several years, following up Type Ia Supernovae at Near-Infrared wavelengths with the PAIRITEL 1.3m telescope at Mt. Hopkins in Arizona.
We present a large data set of infrared data that is the largest, homogeneously observed and processed kind of its date, matched only by the recently published data set by the Carnegie Supernova project.

Part of a coherent program to observe SN at NIR and optical wavelengths. The combination with optical data for the same objects adds considerable value to my thesis data set, as I will show.

I will discuss previous results from this data set that we have obtained.

COLLABORATORS



Collaborators:
Kaisey Mandel,
Pete Challis, Howie Marion,
Malcolm Hicken,
Gautham Narayan, Bill Wyatt,
Ryan Foley, Armin Rest (Harvard/CfA)

Joshua Bloom, Dan Starr,
Chris Klein, Adam Miller,
Adam Morgan (Berkeley)
Maryam Modjaz (NYU)
Cullen Blake (Princeton)
Stephane Blondin (ESO)
Ori Fox, Neil Gehrels (NASA GSFC)
Mike Skrutskie (UVA)

Thesis Advisor:
Robert Kirshner

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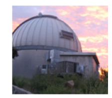
Research Exam Advisor:
Joshua Bloom



Thesis Committee:
Robert Kirshner, Edo Berger, Alicia Soderberg,
Daniel Eisenstein (CfA), Michael Wood-Vasey (Pitt)

This work has been done in collaboration with many others at Harvard and other institutions.
I'd especially like to thank Bob Kirshner, my thesis advisor and collaborators at Harvard and Josh Bloom and collaborators at UC Berkeley for giving me the opportunity to work on Near-Infrared data from PAIRITEL, which I will be talking more about.
To put things in perspective, Bob Kirshner actually did the first work on IR light curves for SN1972E in 1973, - we've come a long way from single pixel detectors!
Bob has been a wonderful and supportive advisor. He cares about you not just as a scientist but as a human being.

This was all made possible by Josh Bloom roboticizing the telescope in 2004, and the many people involved in the hardware and software end.
Thank Michael Wood-Vasey, who took the lead on analyzing the first data we published back in 2008.
Michael has been my closest technical collaborator in the past year. A great sounding board figuring out how to best implement our improvements to the photometry.

In our group, I've been mainly responsible for the NIR data and Kaisey Mandel has done some really amazing work analyzing the previously published subset of my thesis data.
Thank Kaisey Mandel has developed sophisticated statistical methods to analyze SN Ia LCs in the NIR and optical and use
them to produce the most accurate and precise distance estimates. I'll be presenting some of his results
This work is all part of a larger effort at the CfA to observer supernovae
of all types at optical and NIR wavelengths, with optical spectroscopy as well.
Maryam Modjaz started working with PAIRITEL before I joined the group.
Pete Challis does a little bit of everything, including helping me manage the IR Q
Howie Marion has taken over the daily management of the NIR observations
Malcolm and Gautham have been a huge help with photometry and technical questions in general
To put together a large data set like this you need a lot of help, and I've been fortunate to be at a place with so much local expertise.

OUTLINE: INFRARED LCS OF SN IA

1. The Big Picture: SN Ia & Cosmology

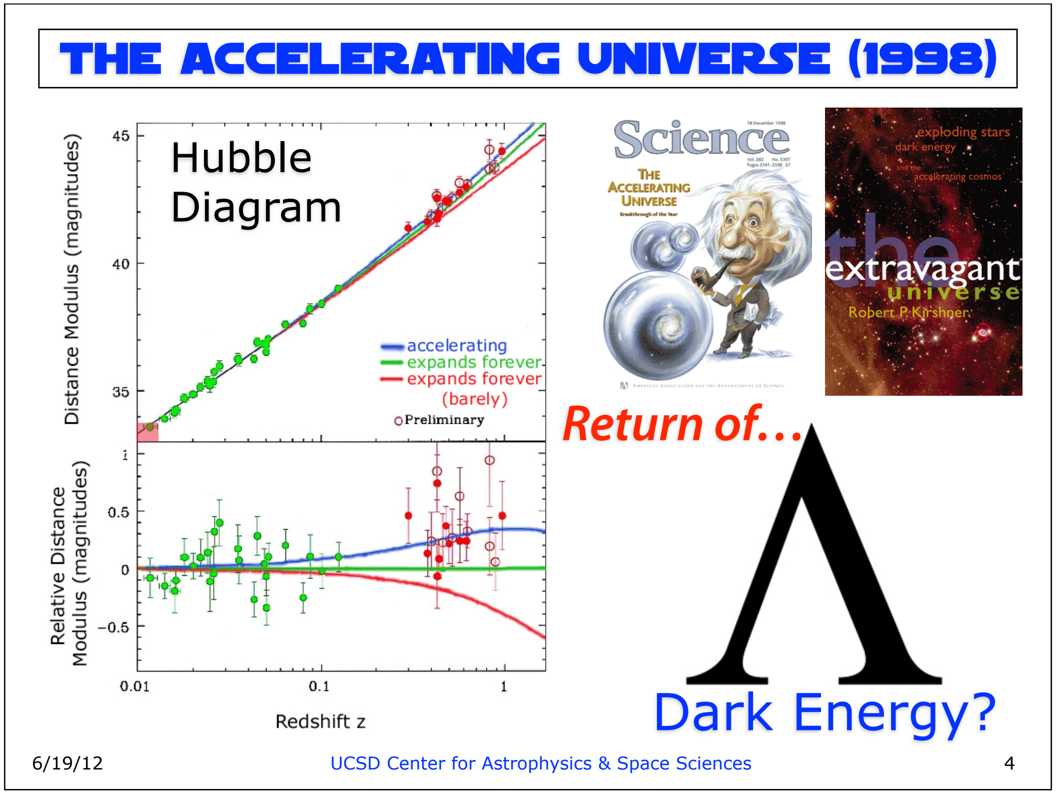
2. CfAIR2 Data Set: PAIRITEL SN Project

Wood-Vasey, Friedman+08 (WV+08)
Friedman+12 in prep. (F+12)

3. Previous Results & Future Work

Wood-Vasey, Friedman+08 (WV+08)
Mandel, Wood-Vasey, Friedman, & Kirshner 09
Mandel, Narayan, & Kirshner 11
Friedman+12 in prep. (F+12)
Mandel+12 in prep.

Here is the outline
I'll briefly review the motivations for studying SN Ia in the NIR (mainly for cosmology). I'll do my best to introduce some of the major concepts for the benefit of the non-astronomers.
I'll discuss our program of supernova follow up observations with PAIRITEL, the data reduction and photometry, which is really the major contribution of mine.
In our research group, we had a division of labor where I have been largely responsible for the observations, data reduction and photometry, but Kaisey has taken the lead on the analysis.
I'll then discuss published results from this work and end by outlining ongoing work in progress.
And I will refer a lot to results obtained by Kaisey Mandel along with earlier work led by Michael Wood-Vasey.



Dark energy. and the acceleration of the expansion of the universe.
Hubble diagram. Distance vs. redshift.
To put things in perspective, Hubble's original diagram fits in the tiny red square. So how have we been able to measure the expansion history so far into the past with such distant objects?
We needed something brighter and better than Cepheids.

Best fit is a universe with a cosmological constant. Is dark energy a cosmological constant or something else?

Bob's book is a fascinating account of the discovery from someone who was there from the beginning.

The standard picture of the Hubble diagram.
Redshift is related to velocity.
Distance modulus is a logarithmic measure of distance that astronomy likes to use.

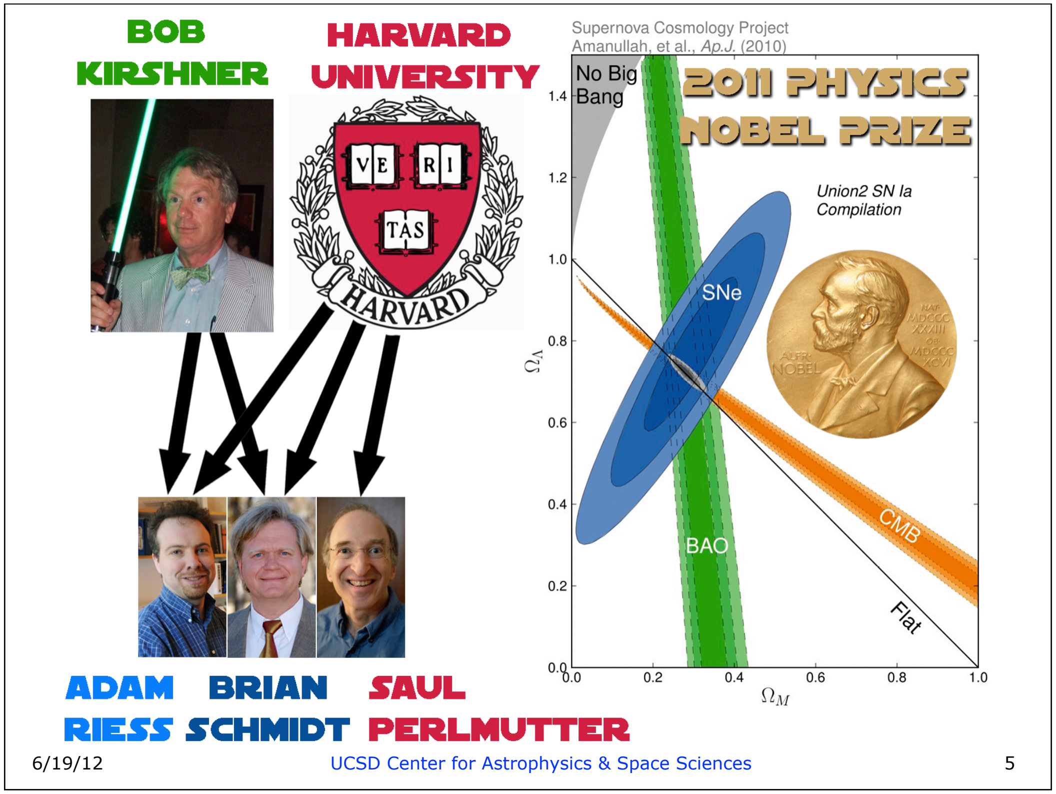
The unexpected 1998 discovery by 2 independent teams, the High-z SN Search Team (HZT) and the Supernova Cosmology Project (SCP).

only the HZT results are shown here

The expansion history is encoded into the relationship between distance and redshift.
For each possible expansion history, we can draw a curve that relates distance to redshift.
We then use our supernova distance and redshift measurements and find the curve that fits the data best.

It's easiest to see in the bottom plot, where every curve is compared to the green curve by subtracting the green curve from it.

Surpisingly, this turned our to be an expansion history where the universe is accelerating.

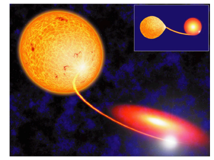


Notes.
Physics nobel 2011 has harvard legacy.
Adam and Brian were students supervised by Bob in the 1990s. Saul was a Harvard undergrad.
This is the standard diagram showing the dark energy result. Matter density fraction. Dark energy density fraction.
Concordance of other cosmological techniques - they all line up! -ave supported the original SN results including measurements from the CMB and
techniques like BAO pioneered by researchers including our own Daniel Eisenstein

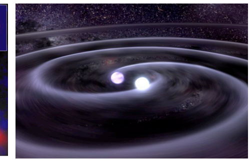
TYPE IA SUPERNOVAE

- Thermonuclear explosions of White Dwarf stars in binary systems.
- Very bright.
  Can detect in distant galaxies.
- Explode at ~1.4 solar masses →
  Similar peak intrinsic luminosities
- Standardizable candles:
  Intrinsic brightness (L) varies, but we can correct for this to infer L.
- Distance: Given L, get d from apparent brightness (F).

WD accretes mass



WD-WD merger



Inverse Sq. Law

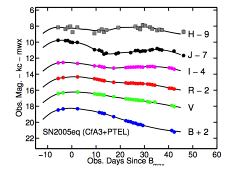
$$\boxed{F = \frac{L}{4\pi d^2}}$$

Artist's conception vs. actual picture!
As most of you are aware, a decade ago, 2 teams (HZT, SCP) presented evidence for the acceleration of the expansion of the universe based on optical observations of SN Ia.
Optical SN Ia cosmology is now the most mature cosmological method we have to study dark energy, and numerous ground based surveys, and potential space surveys are planned in the near future to better constrain dark energy.
However, it has long been know that there are many potential advantages from observing SN in the NIR
-dust
-standard
-only recently have we developed the required NIR array detector technology to do observations comparable to optical CCD observations

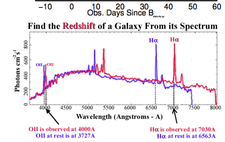
So why aren't we doing SN Ia cosmology in the NIR already?
NIR detector technology only in the past decade or so.
Thermal radiation from telescope & surroundings becomes an issue beyond 2microns. Passive cooling or cryogenics is required.
Observations of high-z NIR and optical SN Ia necessary to probe dark energy must be done from space because rest-frame JHK band light for high-z objects is redshifted to longer wavelengths largely absorbed by the earth's atmosphere or drowned out by the NIR atmospheric sky background.
Sky brightness increases toward longer wavelength.
Observation of SN Ia at z > 0.8 essentially requires a space telescope with near-IR (NIR) instrumentation.

SN IA COSMOLOGY

- Observe multi-band optical/UV + NIR SN Ia light curves (LCs)

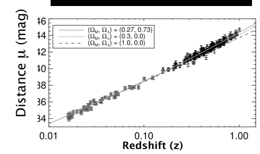


- Measure redshift z from spectrum



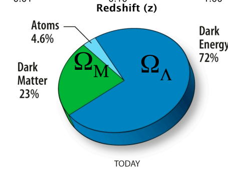
- Infer distances μ to SN Ia from observed LCs + models (e.g. MLCS, SALT, BayeSN)

distance=?



- Measure μ, z for many SN Ia

- Compare to theoretical model $\mu(z,\Omega)$
  → constrain cosmo params $\Omega=(\Omega_M,\Omega_\Lambda,w)$



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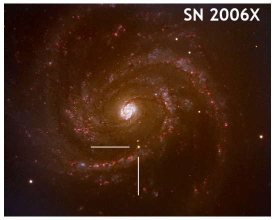
DUST BUSTED

- Extinction: Dims apparent brightness (some dimming due to intrinsic luminosity variation)

- Reddening: Preferentially absorbs bluer light (some redder colors from intrinsic color variation)

- Ignore dust → systematic distance overestimate
- Measure dust inaccurately → systematic distance error



http://messier.seds.org/more/m100_sn2006X.htm

Makes object appear further away
Dust along the line of sight to the SN
Color = difference in brightness between pairs of wavelengths.
Because dust can only make an object look further away, ignoring it leads to a systematic error on distance
In any case, a poor measurement of dust leads to a systematic error on distance
This turns out to be very important for SN cosmology.
Perhaps the most important systematic error.

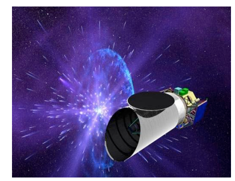
INFRARED VS. OPTICAL

Optical SN Ia Cosmology

- **Reddening**
  Dust extinction + intrinsic color variation
  Dominant systematic distance error

Advantages of NIR

- ~2-12 times less sensitive to dust
- NIR SN Ia intrinsically more standard
- Ground-based JHK obs at low-z



- Rest-frame high-z SN Ia NIR obs
  must be done from space
  (HST, JWST, EUCLID, WFIRST)

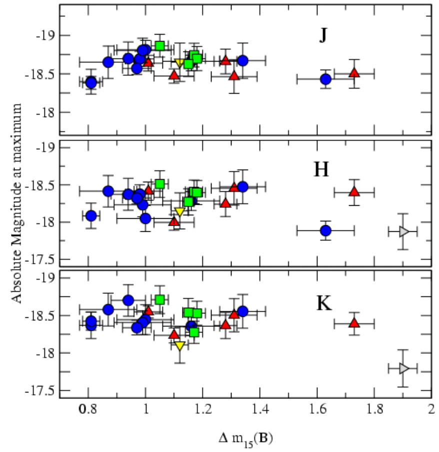
Advantages of NIR. Most previous results have been obtained using optical observations of SN Ia in the nearby and distant universe. The ability to observe large numbers of objects at NIR wavelengths is new, within the past 5 years or so.

IR light penetrates dust better than optical.
NIR SN Ia are intrinsically more standard. So you don't have to do as much to standardize them.
We can already make the LC measurements with ground based telescopes like the telescope PAIRITEL, that I use, to be discussed in more detail later.

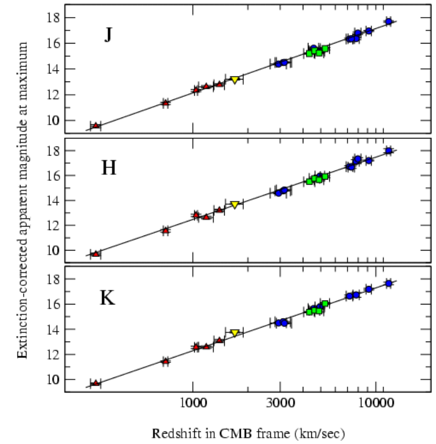
Nearby data alone can not constrain cosmology, so we need distant data that tell us about the history of the universe. Rest-frame NIR light is redshifted to longer wavelengths by cosmic expansion, so that by the time it gets to Earth, its light is blocked by our atmosphere. So we need a space telescope to observe very distant NIR SN Ia.

WFIRST NASA missions. Observe NIR SN Ia in the distant universe. Artist's conception of future planned mission.

STANDARD CANDLES IN NIR?



Krisciunas 2005



Krisciunas+2004

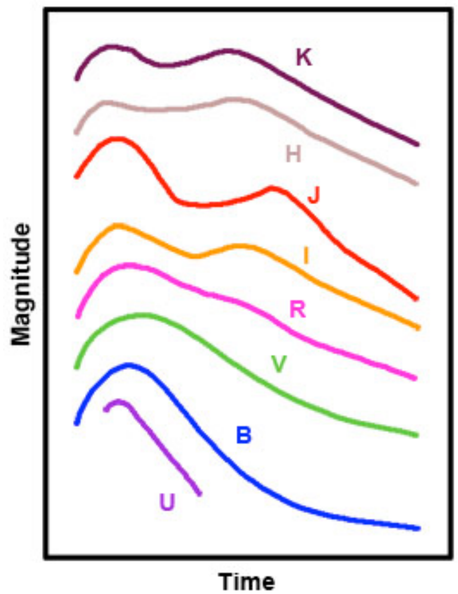
Absolute mags of SN Ia at max. light vs. Δm_{15} (B)
Lack of decline rate relations, small intrinsic scatter
~ 0.15-0.2 mag in JHK. (First NIR Hubble diagram right)

make JHK SN Ia promising cosmological distance indicators

Towards longer wavelengths the slope of abs Mag vs. delta m15 shrinks to zero. Seen through the optical out into the NIR.

Notice the small scatter. 22 SN with varying quality LC's. The small scatter is reflected in the very well behaved low-z Hubble diagram.

OPTICAL+INFRARED SN IA LC SHAPES



Second hump emerges toward longer λ

UBVRI Optical

JHK Near-Infrared

Dromedary **Bactrian**

UBV R IJHK

http://astronomy.swin.edu.au/cms/astro/cosmos/t/Type+Ia+Supernova+Light+Curves

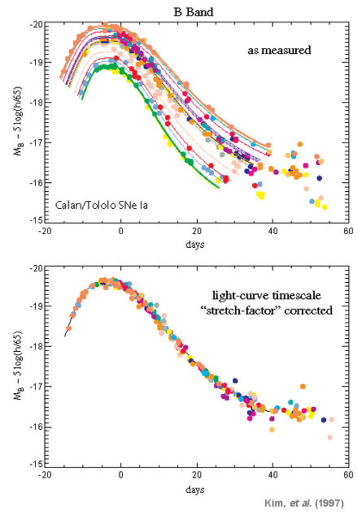
NIR LCs have different LC shapes. NIR LCs have second peak or hump, which emerges at late times starting a little bit in the R band and clearly in the I.

Crayon drawings of SN Ia LCs.

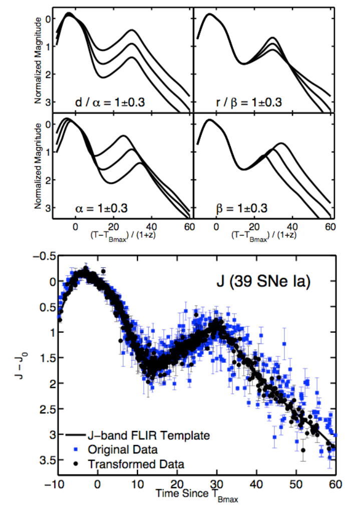
J is the bactrianist of them all. The J-band LC is what happens when the bactrian camel finds an oasis.

SN IA: STANDARDIZEABLE CANDLES

Optical B-Band (1 parameter) NIR J-Band (4 parameter)



J. Frieman 2008 (FIG 12)
(from Kim 2004)



Mandel, Wood-Vasey, Friedman, & Kirshner+2009 (FIG 4,5)

SN Ia not perfect standard candles. But we can measure their LC shape, a property which doesn't depend on distance, and correct for the fact that the intrinsic luminosities are not all the same.

peak intrinsic V-band brightness varies by ~3.5 (~1.4 mag)
peak instrinsic H-band brightness varies by factor of ~2 (0.7-0.8 mag)

But, brightest ones decline slower →correct for LC shape
NIR LC shape is more complicated, you can't correct with 1 parameter, you need more like 4 parameters, but you can account for the variation in the trough and secondary maximum.

H -band light curve was observed to exhibit small scatter from [−10, +40] days.

The J -band aggregate light curve has small scatter about the template from [−10, +10] days but begins to show variations in the time and flux of the secondary maximum for individual supernovae.

The K-band data from our PAIRITEL observations is not as good as the J - and H -band data due to increased sky background in K. Our template in the K band shows significantly more scatter with fewer objects. We draw no firm conclusions in this paper with regard to K-band SN Ia light curves.

Less late time K coverage…faintest in K, worst sky noise.

Dashed lines indicate how standard the template is.

Variance is illustrated more clearly in next slide.

We constructed J H Ks templates using the IR light curves from the PAIRITEL observations
the MLCS2k2.v004 (Jha+2006) values fit to our own CCD observations (Hicken+2008) for the time of B-band maximum light, tBmax
and an initial guess for the H -band magnitude at tBmax , Hbmax

The IR light curves for the remaining 17 SN Ia were registered to a common phase by subtracting tBmax and accounting for time dilation based on the heliocentric redshift, zhelio (Leibundgut+1996; Goldhaber+2001). The SN Ia lightcurves were then registered to a common magnitude scale by subtracting the initial guess for HBmax determined by rough visual inspection of the light curve (the fitting process is insensitive to the determination of the initial HBmax guess to within 7̄0.5 mag). Unlike Krisciunas+(2004a), we do not further adjust this phase by the optical light-curve width parameter. No K-cor.

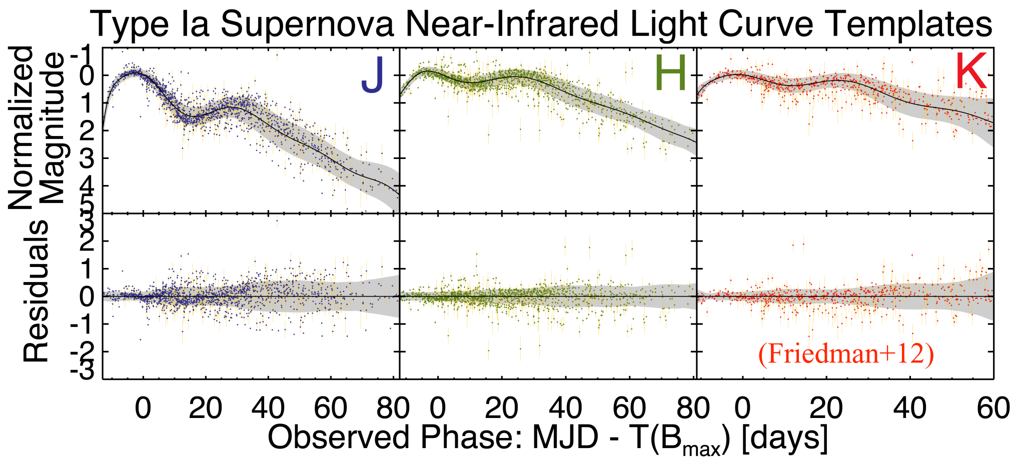
We found that compensating for the light-curve width gave no improvement in the template fits or in the resulting dispersion of absolute magnitudes determined between -10 and +20 days in phase.
However, the position of the second IR maximum is variable, and may be related to intrinsic luminosity. In larger data sets it will be worth exploring whether a width-correction parameter would produce a more effective template for fitting the second maximum at later times.

This initial set of standardized light curves was sampled on a daily basis from –20 to +80 days and then fit with the IDL routine ÒINTERPOLÓ. This interpolation was smoothed twice with a boxcar of length 5 days. The smoothing has very little effect near maximum light because of our dense sampling at those epochs. Varying the smoothing length between 1 and 5 days did not substantially affect the template near maximum. However, at late times (+30 days), we found some smoothing necessary because we had fewer points from which to construct the template.

To refine this template, we determined the magnitude value at tBmax that minimized the χ2 of the template versus the data over the span from [−10, +20] days. These new magnitude offsets were then used to seed the process above where we had previously used the initial guesses for HBmax . The procedure was iterated twice more to construct final values at tBmax for each SN Ia, and the final template was constructed based on these values. We found that three iterations were sufficient to reach convergence.

The uncertainty in the template is the standard deviation of the residuals of the SN Ia light-curve points around the mean template in a moving 5-day window.

SN Ia: Infrared Light Curves



- SN Ia essentially JHK standard candles at first peak
- **~0.15-0.2 mag** scatter *without* LC shape corrections!
- As good as optical *after* LC shape corrections!

Still, Near the first peak, NIR LCs of SN Ia are so standard, even if you do no LC shape corrections at all, they are already as standard as optical LCs after correction.

You can go pretty far estimating distances with NIR data without any LC shape corrections.

As good as optical even without corrections!

Some are brighter than others at the peak.

so we can correct for the fact that peak luminosities are different.

SCIENTIFIC GOALS

- Study NIR properties of large, homogeneous, ground-based, low-z, bright SN Ia data set
- NIR+Optical→ more accurate & precise distances
- Understand dust in other galaxies
- High-z cosmology (HST, JWST, EUCLID, WFIRST)
- <u>Thesis</u>: Largest homogeneous NIR SN Ia sample
  ~double published NIR SN Ia LCs (~120→ ~200)
  ~more than triple # of observations

Given the motivations for studying NIR SN Ia, these are the goals of the thesis.

Then I'll briefly review the motivations for studying SN Ia in the NIR (mainly for cosmology)

NIR data is the most important component of the growing low-z sample. Adding more optical data is great, but adding NIR data packs more punch for distances and cosmology.

OUTLINE: INFRARED LCS OF SN IA

1. The Big Picture: SN Ia & Cosmology

2. CfAIR2 Data Set: PAIRITEL SN Project

Wood-Vasey, Friedman+08 (WV+08)
Friedman+12 in prep. (F+12)

3. Previous Results & Future Work

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Mandel, Wood-Vasey, Friedman, & Kirshner 09
Mandel, Narayan, & Kirshner 11
Friedman+12 in prep. (F+12)
Mandel+12 in prep.

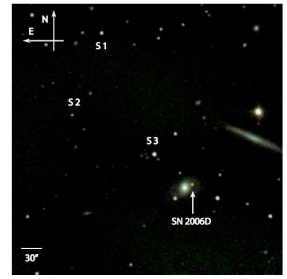
This is the meat of the talk and my primary scientific contribution.

Peters Automated InfraRed Imaging TELescope

- PAIRITEL 1.3m: 2MASS telescope
- Roboticized in 2004: **(Bloom+06)**
- Autonomous queue scheduled obs
- 20+ science projects + SN follow-up

PAIRITEL SN Project

- ~30% time since 2005
- Homogeneous data set, tested camera
- Simultaneous JHK, ~nightly cadence
- Photometric calibration → 2MASS
- Optical Phot, Spectra (1.2m, 1.5m)



PAIRITEL JHKs: SN2006D
Wood-Vasey, Friedman+2008 (FIG 1)

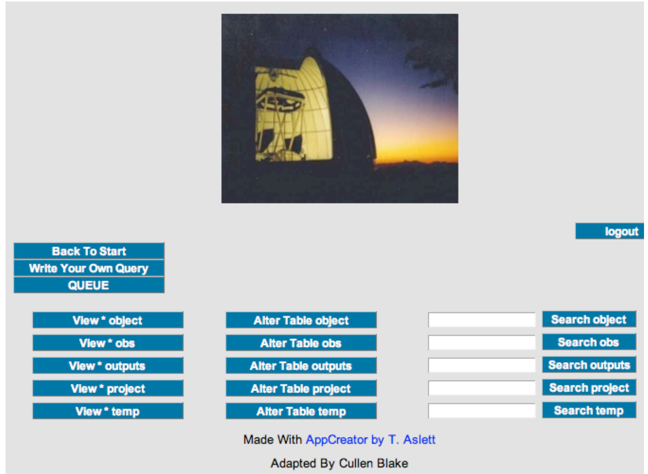
PAIRITEL at Mount Hopkins in Arizona.

Autonomous queue scheduled observing
...

We've been fortunate to be awarded 30% of time since 2005. This ends up being more than 6 months of time on the sky. This is an unheard of amount of data for a thesis. Students at other institutions who are not as fortunate to have the observational resources that we have might get 4 nights on a telescope that constitutes the entire data set for their thesis. So I am luck to be swimming in data. This of course, creates other problems which I will discuss.

Part of a larger follow-up effort at the CfA of concurrent optical photometry and spectroscopy

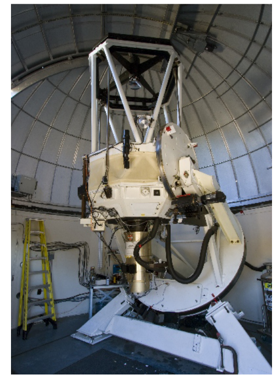
PAIRITEL IS A ROBOT



PAIRITEL MySQL Database Interface

http://192.33.141.15/sked/datasked/tablmgr/index.php

1.3-meter PAIRITEL→



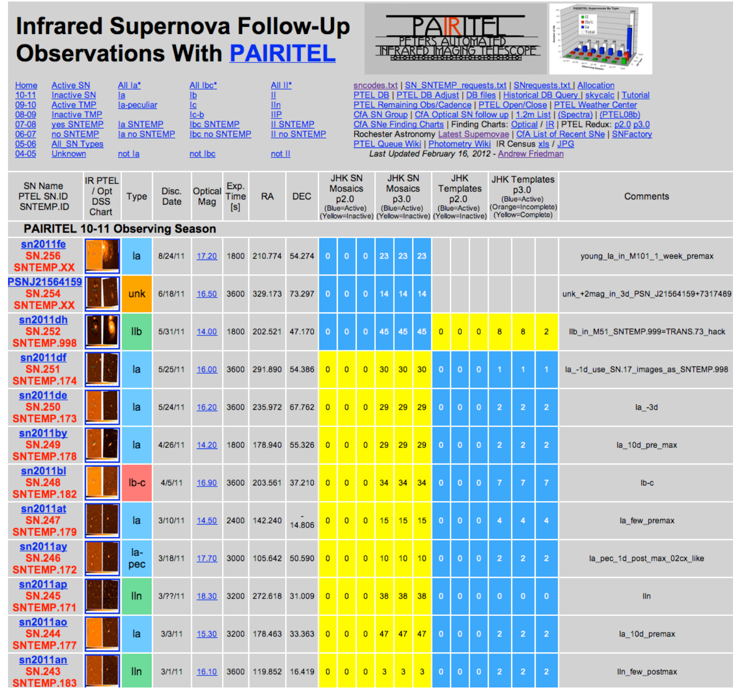
Allows me to be a lazy astronomer, imaging supernovae from the comforts of my uncomfortable office chair.

But this is not the full story. In reality, managing the observations requires constant attention and effort spanning many years.

We don't discover these SN. We follow up those discovered by optical searches, so we have to keep a constant lookout through the IAU circulars and other notices to see if there are interesting SN worth following up. we then put them in the PAIRITEL queue, which is managed by intelligent queue scheduling software which tries to optimize all the observations for all the objects for all PAIRITEL projects. So there is no 100% guarantee that an SN we put in the Q will get observed on any given night. Once its in the Q, the images are reduced automatically at Berkeley, and we have to look at them to make sure the telescope is doing what it is supposed to do. Sometimes the telescope has bad pointing and the SN is not in the FOV. Sometimes the image creation code fails. Sometimes there is bad weather or the SN was interrupted by a higher priority GRB observation. Sometimes the telescope breaks! We also monitor the observing parameters to see if we need to change the exposure time or the time between observations. We also need to make sure we input the coords properly. We need to monitor the SN to see if it has faded below detection and then deactivate it.

This is done in a coordinated fashion with concurrent optical observations and spectra. The spectra often tell us the SN is not of the right type that we want to follow or that it was discovered too late, so sometimes we deactivated it based on that information.

The bottom line is that even though this is a robotic telescope, managing the observations requires constant daily energy and effort. So obtaining the data, even before we do anything with it is sometimes more than half of the battle.



Infrared Supernova Follow-Up Observations With PAIRITEL

Home | Active SN | All Ia* | All Ibc* | All II*
10-11 | Inactive SN | Ia | Ib | II
09-10 | Active TMP | Ia-peculiar | Ic | IIn
08-09 | Inactive TMP | | Ic-b | IIP
07-08 | yes SNTEMP | Ia SNTEMP | Ibc SNTEMP | II SNTEMP
06-07 | no SNTEMP | Ia no SNTEMP | Ibc no SNTEMP | II no SNTEMP
05-06 | All_SN Types
04-05 | Unknown | not Ia | not Ibc | not II

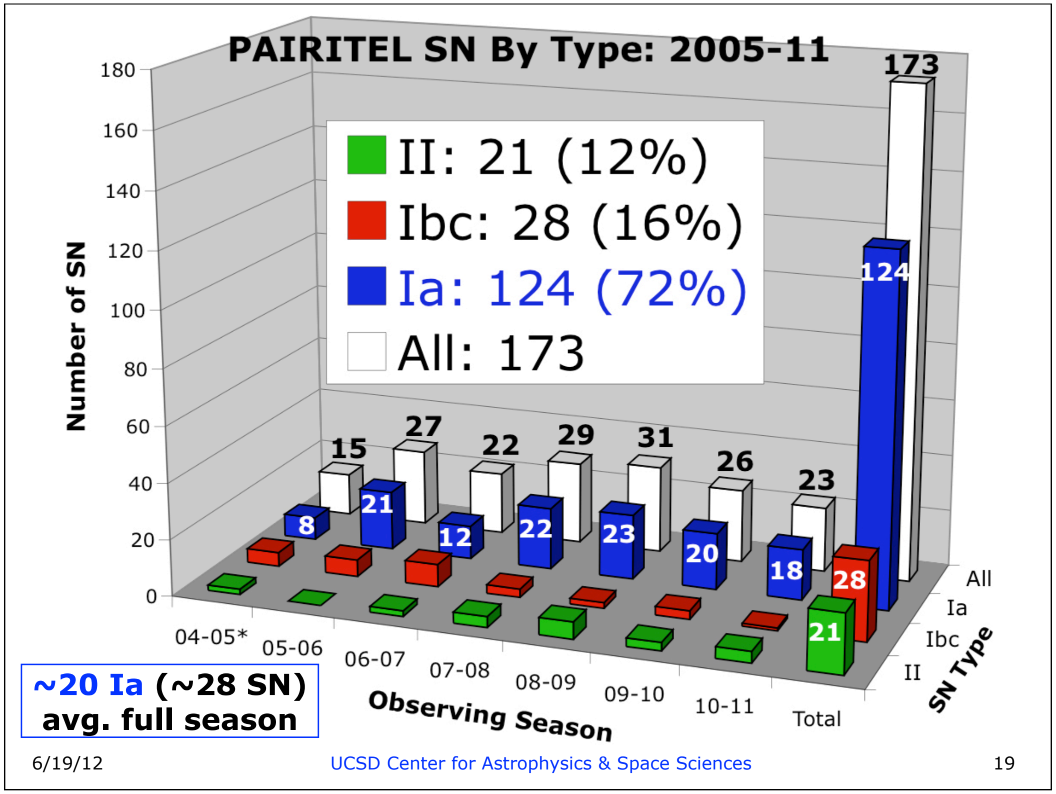
sncodes.txt | SN_SNTEMP_requests.txt | SNrequests.txt | Allocation
PTEL DB | PTEL DB Adjust | DB files | Historical DB Query | skycalc | Tutorial
PTEL Remaining Obs/Cadence | PTEL Open/Close | PTEL Weather Center
CfA SN Group | CfA Optical SN follow up | 1.2m List | (Spectra) | (PTEL08b)
CfA SNe Finding Charts | Finding Charts: Optical / IR | PTEL Redux: p2.0 p3.0
Rochester Astronomy Latest Supernovae | CfA List of Recent SNe | SNFactory
PTEL Queue Wiki | Photometry Wiki IR Census xls / JPG
Last Updated February 16, 2012 - Andrew Friedman

SN Name PTEL SN.ID SNTEMP.ID	IR PTEL / Opt DSS Chart	Type	Disc. Date	Optical Mag	Exp. Time [s]	RA	DEC	JHK SN Mosaics p2.0 (Blue=Active) (Yellow=Inactive)			JHK SN Mosaics p3.0 (Blue=Active) (Yellow=Inactive)			JHK Templates p2.0 (Blue=Active) (Yellow=Inactive)			JHK Templates p3.0 (Blue=Active) (Orange=Incomplete) (Yellow=Complete)			Comments
PAIRITEL 10-11 Observing Season																				
sn2011fe SN.256 SNTEMP.XX		Ia	8/24/11	17.20	1800	210.774	54.274	0	0	0	23	23	23							young_Ia_in_M101_1_week_premax
PSNJ21564159 SN.254 SNTEMP.XX		unk	6/18/11	16.50	3600	329.173	73.297	0	0	0	14	14	14							unk_+2mag_in_3d_PSN_J21564159+7317489
sn2011dh SN.252 SNTEMP.998		IIb	5/31/11	14.00	1800	202.521	47.170	0	0	0	45	45	45	0	0	0	8	8	2	IIb_in_M51_SNTEMP.999=TRANS.73_hack
sn2011df SN.251 SNTEMP.174		Ia	5/25/11	16.00	3600	291.890	54.386	0	0	0	30	30	30	0	0	0	1	1	1	Ia_-1d_use_SN.17_images_as_SNTEMP.998
sn2011de SN.250 SNTEMP.173		Ia	5/24/11	16.20	3600	235.972	67.762	0	0	0	29	29	29	0	0	0	2	2	2	Ia_-3d
sn2011by SN.249 SNTEMP.178		Ia	4/26/11	14.20	1800	178.940	55.326	0	0	0	29	29	29	0	0	0	2	2	2	Ia_10d_pre_max
sn2011bl SN.248 SNTEMP.182		Ib-c	4/5/11	16.90	3600	203.561	37.210	0	0	0	34	34	34	0	0	0	7	7	7	Ib-c
sn2011at SN.247 SNTEMP.179		Ia	3/10/11	14.50	2400	142.240	-14.806	0	0	0	15	15	15	0	0	0	4	4	4	Ia_few_premax
sn2011ay SN.246 SNTEMP.172		Ia-pec	3/18/11	17.70	3000	105.642	50.590	0	0	0	10	10	10	0	0	0	2	2	2	Ia_pec_1d_post_max_02cx_like
sn2011ap SN.245 SNTEMP.171		IIn	3/??/11	18.30	3200	272.618	31.009	0	0	0	38	38	38	0	0	0	0	0	0	IIn
sn2011ao SN.244 SNTEMP.177		Ia	3/3/11	15.30	3200	178.463	33.363	0	0	0	47	47	47	0	0	0	2	2	2	Ia_10d_premax
sn2011an SN.243 SNTEMP.183		IIn	3/1/11	16.10	3600	119.852	16.419	0	0	0	3	3	3	0	0	0	2	2	2	IIn_few_postmax

http://www.cfa.harvard.edu/pairitel/

For example, here is a snapshot of the webpage I maintain for the database of NIR observations

Since 2005, I have observed over 135 SNe of all types including over 90 SN Ia.
We typically observe 2-6 objects per night and try to follow up objects with nearly nightly cadence, weather and telescope permitting.
The plot above is color coded by type. The 04-05 season was partial and the 09-10 season is still underway, but we typically observe 20-30 SN / season and 15-20 SN Ia.
These only include SN with more than 3 epochs. Not all of these data are viable. Some objects are too faint, problems with sky subtraction, galaxy subtraction, data quality impaired due to weather, processing issues, etc…
About 70% Ia, 20% Ib/c, and the rest Type II core collapse objects.
Often we'll go after a target before it is typed and de-activate it if it turns out to be well past max or a Type II that we haven't commited to.



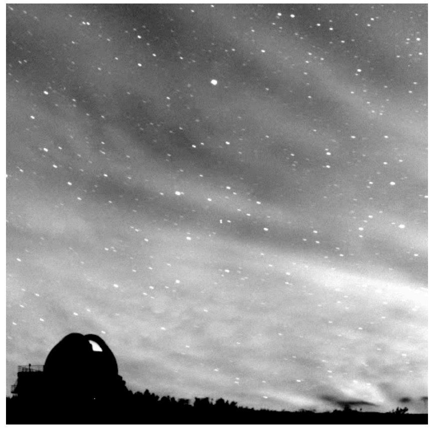
Census. Managing all this.
Maryam in the beginning. Help from Howie in past year. Help from Pete Challis throughout.
This is a significant effort.

Talk about observing strategy. We follow mostly Ia's but we also observe SN of other types with PAIRITEL. These are not in my thesis but the data have been reduced and the photometry done in the same way as the Ia's.

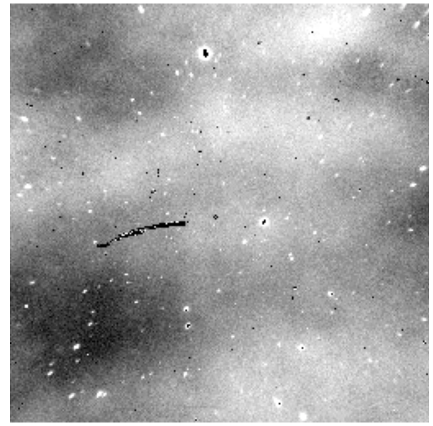
About 70% Ia, 20% Ib/c, and the rest Type II core collapse objects.
Often we'll go after a target before it is typed and de-activate it if it turns out to be well past max or a Type II that we haven't commited to.

Since 2005, I have observed over 170 SNe of all types including over 90 SN Ia.
We typically observe 2-6 objects per night and try to follow up objects with nearly nightly cadence, weather and telescope permitting.
The plot above is color coded by type. The 04-05 season was partial and the 09-10 season is still underway, but we typically observe 20-30 SN / season and 15-20 SN Ia.
These only include SN with more than 3 epochs. Not all of these data are viable. Some objects are too faint, problems with sky subtraction, galaxy subtraction, data quality impaired due to weather, processing issues, etc…

THE DARK SIDE OF THE BRIGHT IR SKY



Observatoire de Haute-Provence



2MASS H-Band (FLWO)

INFRARED AIRGLOW FROM
THE NIGHT SKY. AT NIGHT!

http://www.obs-besancon.fr/nirsky/,
http://www.astro.virginia.edu/~mfs4n/2mass/airglow/adams/airglowpage.html

Probably the most important feature of NIR observing that makes this different than the optical is the NIR sky.

These Infrared movies show airglow.

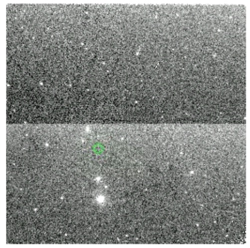
Doesn't necessarily have anything to do with clouds. You'll see this phenomenon even on a cloudless night.

The sky is so bright, in fact, that it can saturate our exposures in under 10 seconds! How the heck do you observe faint objects through that?

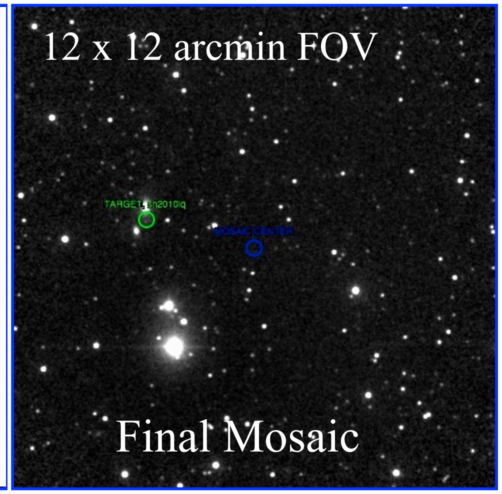
In the optical, in many cases, you can just point and shoot and get longer exposures to observe fainter objects. In the NIR you need another solution.

Note the bad pixels on the right. How do we get rid of those too?

IR MOSAICS DITHER PATTERN



each 8.5 x 8.5 arcmin FOV



PAIRITEL Mosaic Code: Automated Reductions @ Berkeley, CfA

- p1.0-p3.5: Josh Bloom, Cullen Blake, Dan Starr, Chris Klein (Berkeley)
- p3.6: Andrew Friedman, Bill Wyatt (Harvard/CfA)

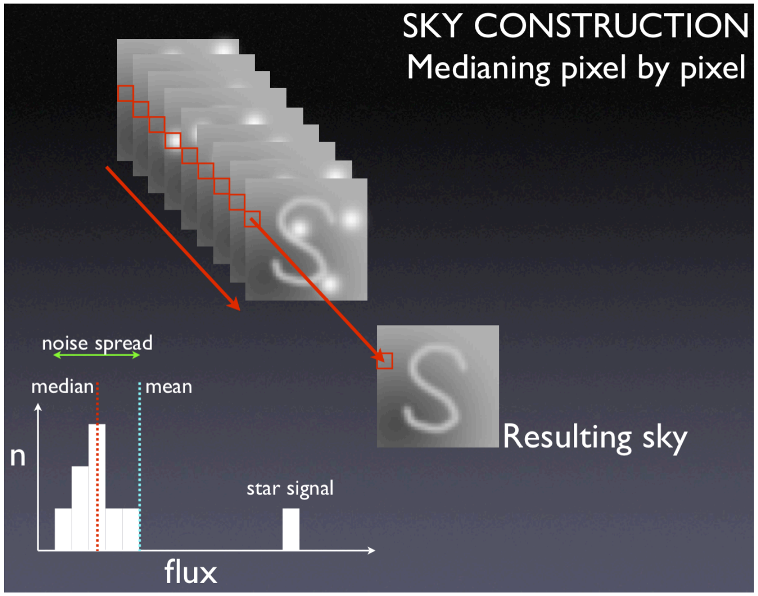
The answer is to combine multiple smaller exposures that have also been dithered to different positions on the sky, as shown in this movie. Our exposures are about 8 seconds in length. We take 3 at each dither position (shown left).

They are eventually combined into a final mosaic image on the right.

Mosaics automatically reduced nightly at UC Berkeley. We get a friendly e-mail from the PAIRITEL robot saying the images are done.

Various versions of the mosaic code were developed at UC Berkeley by these folks. Recently, Bill Wyatt helped me get a version running at the CfA and I added a couple of features that are particularly important for Supernova data which I will discuss. We don't have a parallel, automated version running here yet but that remains a near-term goal.

DITHERING & SKY SUBTRACTION



PAIRITEL

10 minute
time window
+/- 5 minutes
around image

Pixel-by-pixel
median through
un-registered
stack of
dither images

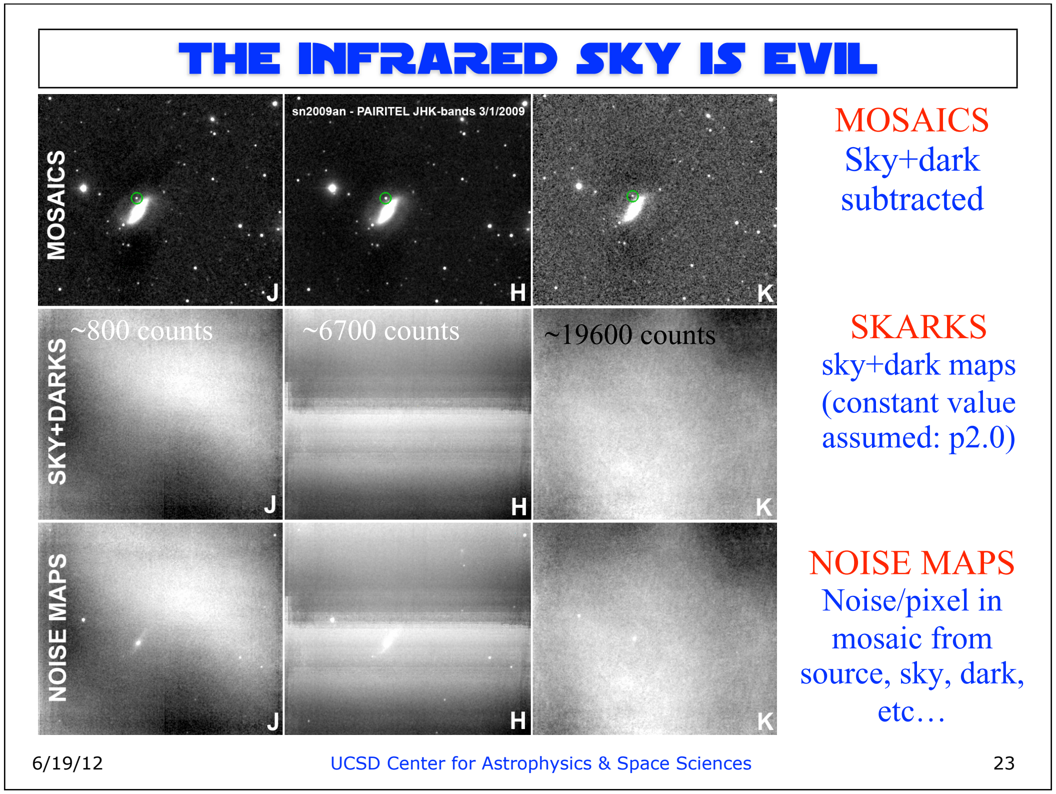
http://cfht.hawaii.edu/Instruments/Imaging/WIRCam/pics.WIRCam/NIRlecture_ASIAA_2007_part2.pdf

dithering helps you estimate sky.

did not have to sacrifice observing time to on-off pointings to estimate sky

We make the approximate assumption that sky is constant on 10 minute timescales (but not necessarily spatially constant in the 8.5x8.5 arcmin FOV). So we stack all dithered images and do a pixel by pixel median through the stack.

Since the dithering allows different patches of sky to fall on different mosaic pixels and most pixels are empty sky, the median gives a good estimate for the sky value in that pixel.



Mosaics, Sky+darks, noise maps

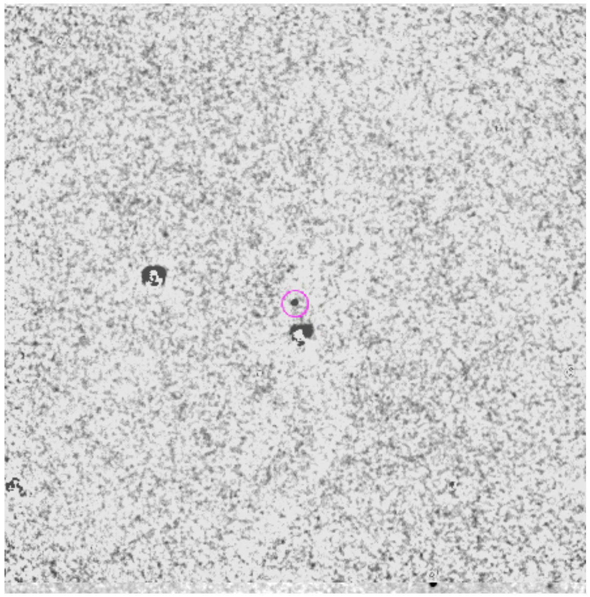
This is the main new feature I added to the mosaic pipeline adapted the mosaic code to include sky+dark mosaics and noise mosaics

Pairitel has no shutter, so we can't measure the dark current (background thermal photons from the heat of the detector) independently. So they are added together in the sky counts. Dark current patterns are fairly stable and get smeared out across the detector

Emphasize sky background counts. Which get worse as you go to longer wavelenght, for example, more than 20 times more sky counts from J to K.

Emphasizes the difficulty of K band measurements.

GALAXY SUBTRACTION



SEND
THE GALAXY
FAR FAR AWAY!

SN 2009an
SN Image: 3/1/2009

NGC 4332
SNTEMP Image:
5/5/2010

Difference Image
SN - SNTEMP

PAIRITEL H-Band Images

Also want to get rid of other light we are not interested in from the galaxy.

We want to measure the SN brightness.

The actual process of PSF matching and convolving one image to the seeing conditions of the other is more complex than just subtracting the images, but this gives a rough idea.

Because PAIRITEL detector is undersampled, PSF matching is hard to do, so we can incur biases for individual subtractions.

NNTEMP

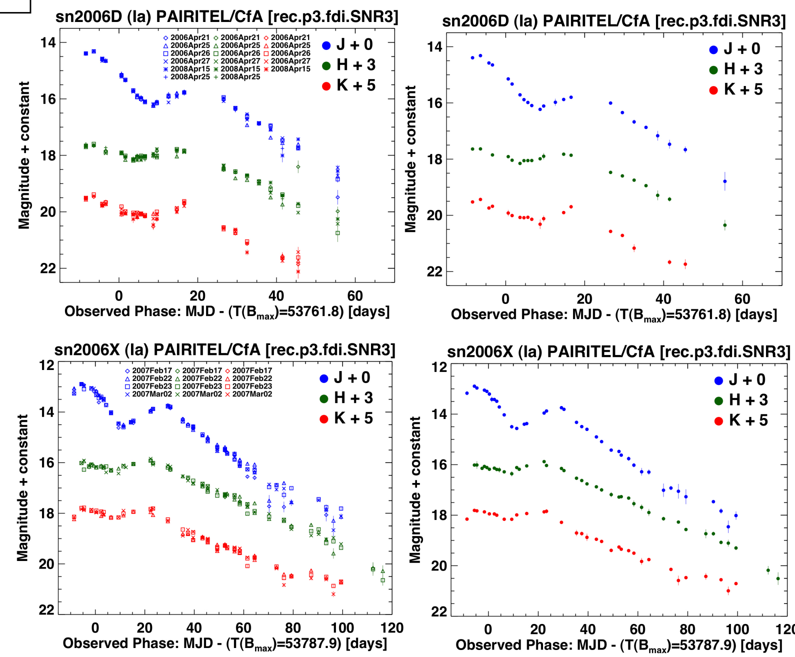
N~2-10 host galaxy SNTEMP images

N LCs: One for each subtraction

NNTEMP Weighted Average of N LCs

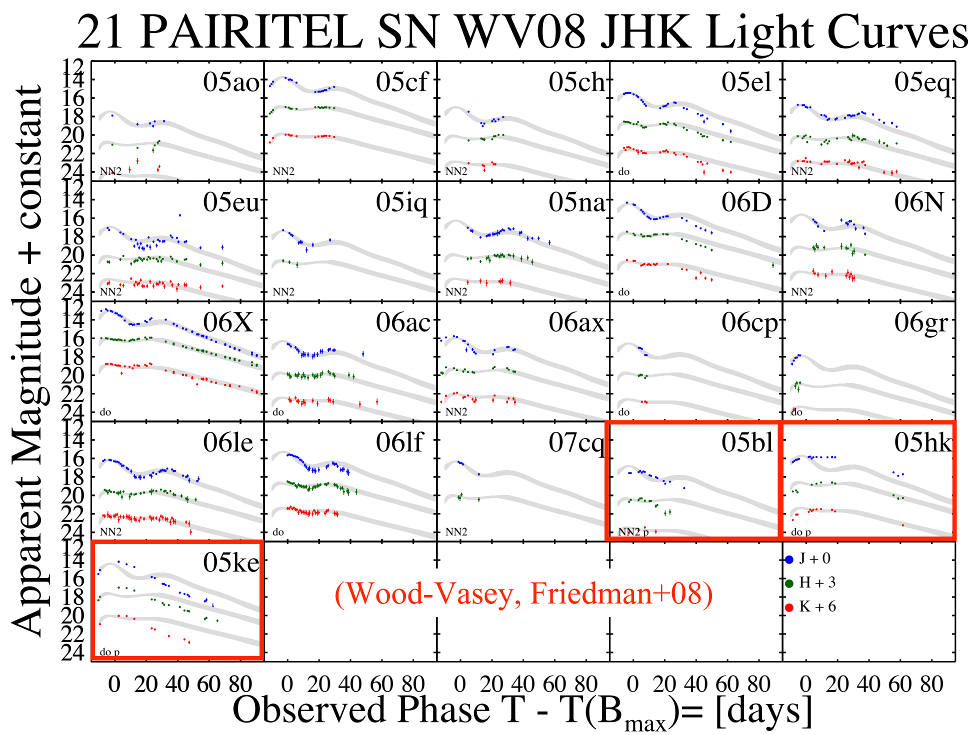
Before NNTEMP

After NNTEMP



One way to limit that bias is to observe many host galaxy template images and average the LCs from each of their subtraction.

This helps limit systematic bias, if you have enough good template images, but adds additional scatter, which we need to include in our final photometric errors.



UCSD Center for Astrophysics & Space Sciences

Here is the data set of light curves we published in 2008 in a paper led by Michael Wood-Vasey.
18 normal Ia.
3 peculiar objects which clearly have different LCs with respect to the mean LC template for normal Ia shown in gray.

IMPROVEMENTS SINCE WV08

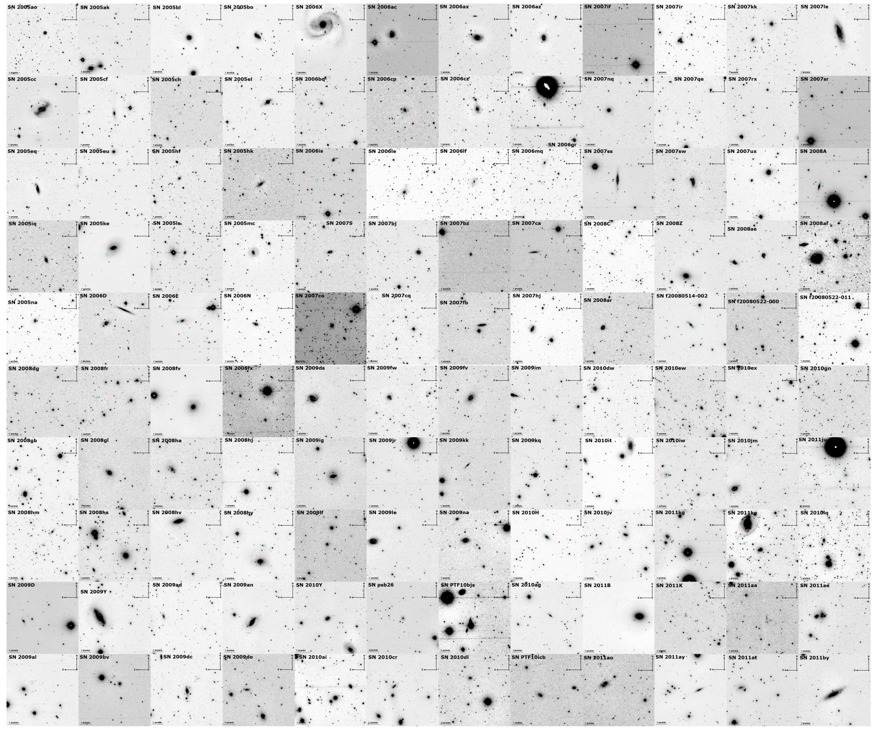
DATA	SN Ia	JHK Obs	SN Coords	Mosaics	Noise Mosaics	Mosaic Success
WV08	21	1087	IR	p2.0	No	---
CfAIR2	**~100***	**~7000**	**Opt**	**p3.6**	**Yes**	▲ **15-20%**

*Includes revised photometry for 21 WV08 SN Ia

LCS	Cluster	Photpipe success	Galaxy sub	DoPHOT Corrections	Gal sub Errors	CSP Agree?
WV08	Hydra	---	NN2	No	No	OK
CfAIR2	**Odyssey**	▲ **20-40%**	**NNT**	**Yes***	**Yes** **	**Good*****

* DoPHOT errors calibrated with 2MASS star tests
** Galaxy subtraction errors included
*** Better agreement - 19 overlap CSP SN Ia

Why redo WF+08 photometry - improvements



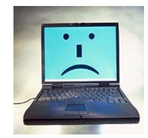
~120 PAIRITEL SN Ia Fields

JHK

~35 LC pts

photometry
~15000 SN images

We need A bigger Computer!



Gallery of PAIRITEL J band images for 120 SN fields we observed. Lots of Images.

We have a complicated photometry pipeline originally developed for optical images for the ESSENCE and SuperMacho projects which we have adapted to the NIR.

The pipeline has many computational steps, some of which can be quite computationally intensive.

We need computing power to modify the pipeline and test it efficiently.

Enter the Harvard Odyssey cluster. We moved our pipeline over there about years ago. It took a year or so to get it working and add new features to get it to work with the newer IR mosaics.

the day after I gave my thesis talk, they kicked our group off of the queue we had been using for several years, evidently we had been freeloading by accident.

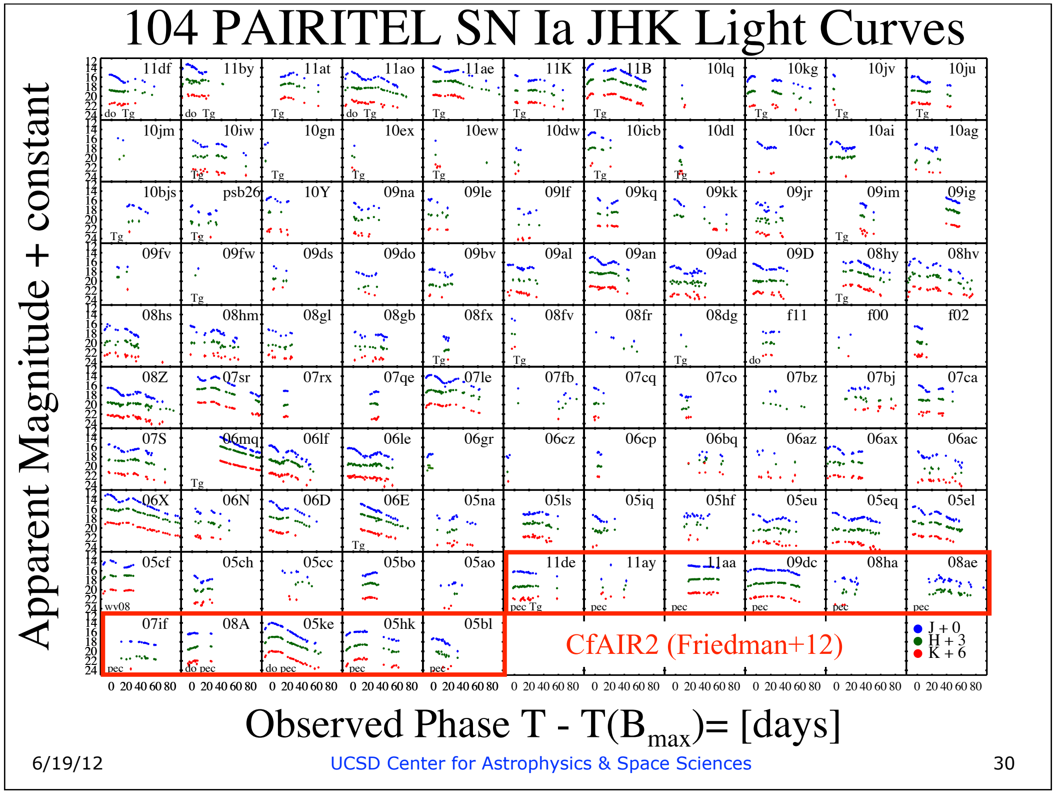
I wrote some software to use the Odyssey LSF queue system to automate the photometry pipeline so it partitions up the pipeline into the smallest possible computational sub tasks so they can be farmed out to different nodes on the cluster, executed in parallel, and in the right order.

With this setup, we can make a change to the photometry pipeline and re-run photometry for all objects in ~5-7 hours, overnight, depending on node availability.

This would have taken several weeks with the setup we had as of a few years ago, when we published a first subset of my thesis data.

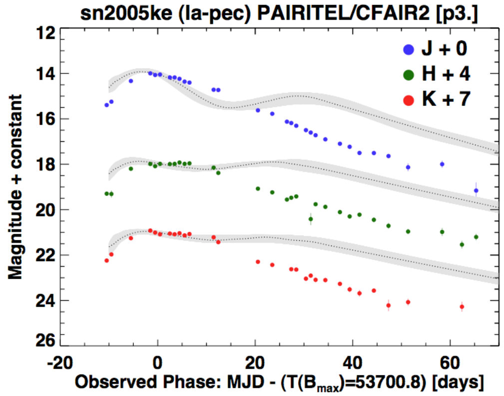
After having spent so much time poking around the inner workings of Odyssey, I can tell you that this is what it actually looks like on the inside.

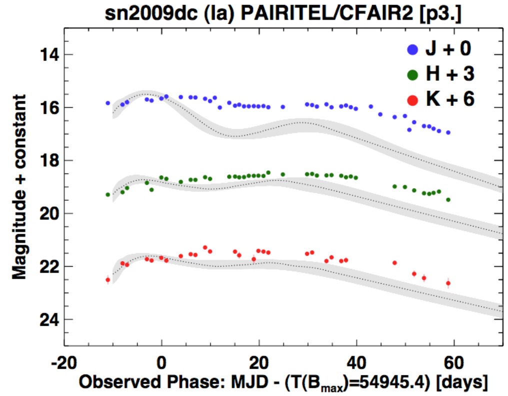
And if the cluster keeps assimilating nodes at its current rate, in a few years, its going to look like this.



Gallery of SN Ia LCs. We also have 9 more objects that are peculiar Ia's. Some of these are strange too.

EXCLUDING PECULIAR SN IA



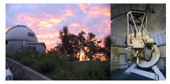


sn2005ke:
fast-declining LC,
single NIR peak

sn2009dc:
slowly-declining LC,
suppressed NIR peaks

(Friedman+12)

Templates help you to indentify peculiar objects based on LC shape alone, which should not be included in the construction of the template or the hubble diagra,



CfAIR2 vs. CSP

19 overlap SN Ia		Individual Observations				Phot. Errors
	SN Ia	**Y**	**J**	**H**	**K**	σ_{mag}
CfAIR2	**~100**	0	**~1583**	**~1514**	**~1172**	~0.02-0.10
CSP	74	**826**	739	674	103	**~0.01-0.03**

	Telescope	**Camera**	**Pixel size**	**FOV**	**Image FWHM**
CfAIR2	PAIRITEL 1.3m	*2MASS South Camera*	2”	8.53’	~2.5-3.0”
CSP	Swope 1.0m duPont 2.5m	*RetroCam* *WIRC*	**0.54”** **0.196”**	**3.4’** **3.3’**	**~1.0-2.0”** **~0.5-0.8”**

Recently published CSP data set is natural comparison set.

the only other sample comparable to CfAIR2. Each set has its own advanatages.

Complementary set of objects. Although we do have 19 overlap SN Ia which allows us to compare photometry.

We have more data. They have ~2-3 x smaller errors. We understand why.
They have better seeing conditions at the Las Campanas observatory and a higher resolution camera. Our telescope is undersampled, which makes galaxy subtraction more difficult. This, for PAIRITEL is the dominant source of error.

OUTLINE: INFRARED LCS OF SN IA

1. The Big Picture: SN Ia & Cosmology

2. CfAIR2 Data Set: PAIRITEL SN Project

Wood-Vasey, Friedman+08 (WV+08)
Friedman+12 in prep. (F+12)

3. Previous Results & Future Work

Wood-Vasey, Friedman+08 (WV+08)
Mandel, Wood-Vasey, Friedman, & Kirshner 09
Mandel, Narayan, & Kirshner 11
Friedman+12 in prep. (F+12)
Mandel+12 in prep.

Give special emphasis to the work Kaisey has done. I've been responsible for the data. He has done most of the analysis.

SN IA H-BAND STANDARD CANDLES

Fig 6: Wood-Vasey, Friedman+08

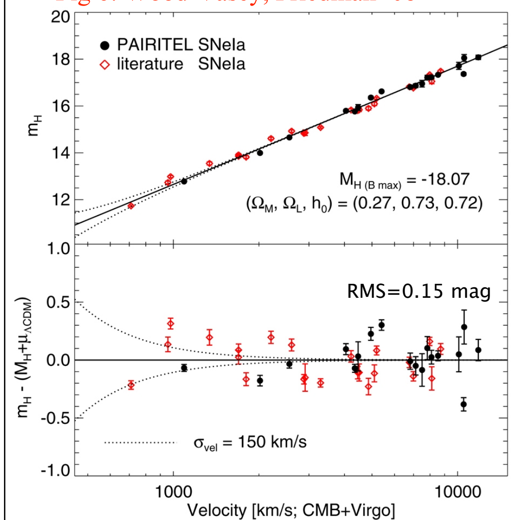
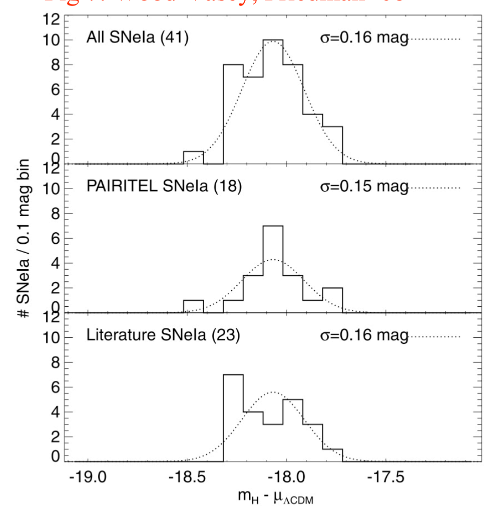


Fig 7: Wood-Vasey, Friedman+08



- H-band Hubble Diagram: 0.15 mag
- Optical MLCS: 0.18 mag (Jha+07)
- H-band PTEL Absolute Mags
- Observed scatter 0.15 mag

In WV08, we made the simple assumption that IR Ia are perfect standard candles at maximum light in H

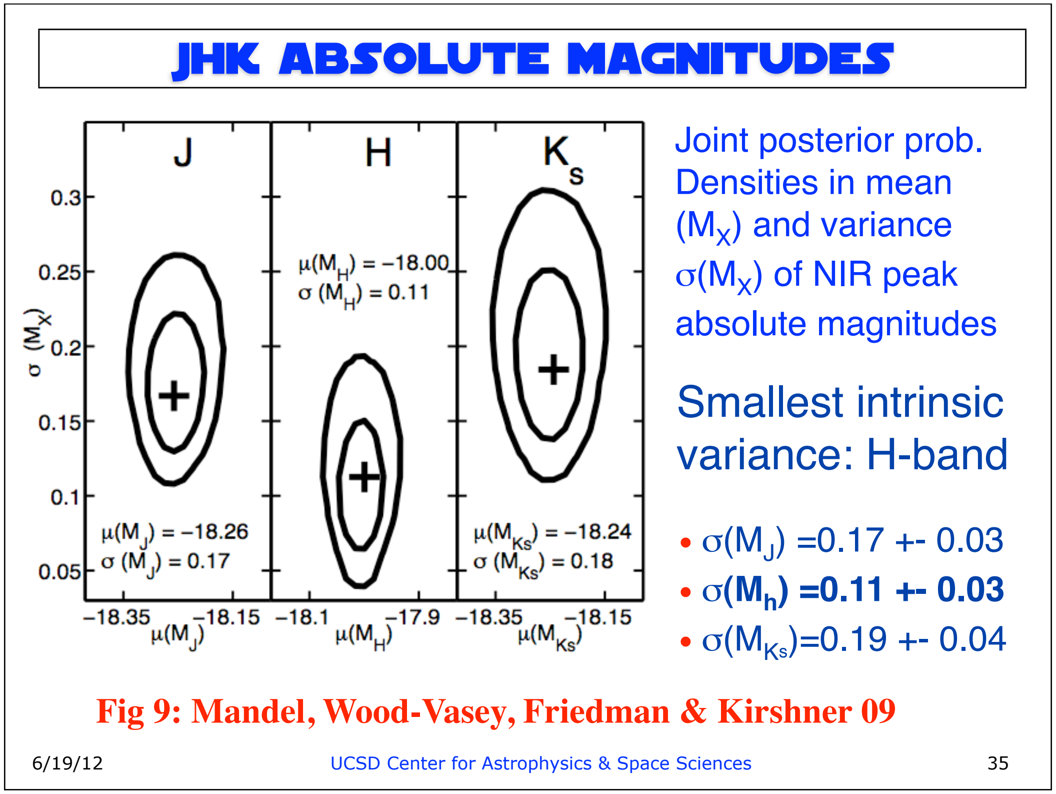
0.15 mag of scatter. No LC shape corrections.

Only used optical data to infer reddening.

Hubble residual (Absolute mag) distributions are consistent from PTEL and LIT samples.

Confirms and strengthens Krisciunas 2004 results
Histograms of H band absolute magnitudes
at time of B-band max light
(ΛCDM, ho = 0.72)
34 SN Ia
17 PAIRITEL SN Ia
17 literature SN Ia
SN Ia excellent NIR standard candles, even without correction for LC shape or reddening
H-band absolute magnitudes from 18 SN Ia have an uncorrected intrinsic RMS of only 0.15 mag
(comparable to corrected optical scatter)
(dotted line) Overlaid Gaussian
of width σ=0.15 mag
normalized to # of SN Ia

Hubble Diagram
Uncertainties from fit to
H-band template (not including peculiar velocites)



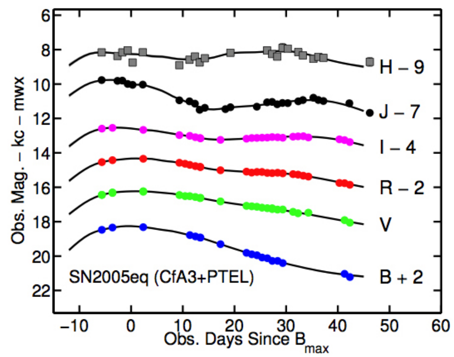
Adapted from Fig. 15 of Kasen 2006.Predicteddispersioninpeak magnitude (measured at the first light curve maximum) as a function of wavelength band for the models of Fig. 10 of Kasen 2006 with 56Ni masses between 0.4 and 0.9 solar masses. Note that the theoretically predicted dispersion is smallest in the rest-frame H- band. We confirm this with our sample of SN Ia data from PAIRITEL and the literature, finding an intrinsic variance in the H-band absolute brightness of 0.15-0.16 mag (Wood-Vasey & Friedman+2008) and 0.11 mag with a more sophisticated analysis method (Mandel+2009; see Fig. 3 below). This work strengthens the evidence that SN Ia are excellent NIR standard candles.

Joint posterior prob. Densities in mean (MX) and variance σ(MX) of NIR peak absolute magnitudes X=JHKs
+ = mode of bivariate density

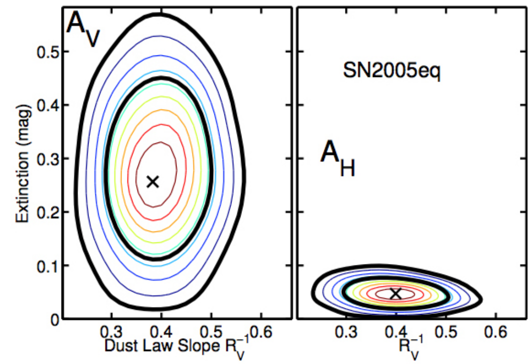
Univariate marginal variance estimates
σ(MJ) =0.17 +- 0.03
σ(Mh) =0.11 +- 0.03
σ(MKs)=0.19 +- 0.04

Stability of 1st peak mag, minimum persists even when changing other parameters like the abundance of e- capture elements
Minimum between peaks, especially in J, may be the most stable standard candle, for a variety of Ni masses
Minimum actually more stable. If so, SN caught late enough for dip between 1st and 2nd maximum are still very useful.
We find that missing the first peak is a reality for our data, so it will be interesting to see if the data show the stability of this minimum.
Fainter and harder to observe with accurate photometry, but 1st and 2nd peak data can constrain it.

Extinction and Dust with BayeSN



NIR (WF+08) + Opt (CfA3) LCs of SN2005eq fit w/ multi-band LC model
→ observed colors



Posterior probability contours of A_v, R_v for SN2005eq given observed colors and population parameters

Adapted from: Fig 3 of Mandel, Narayan, & Kirshner 11

kaisey has taken this question of estimating extinction and host galaxy dust properties using multiband LCs and colors and applied it to the previously published subset of my thesis data and NIR and optical data from the literature.

The right slide shows that the extinction by dust in the infrared H band about 5 times smaller than in the optical V band.

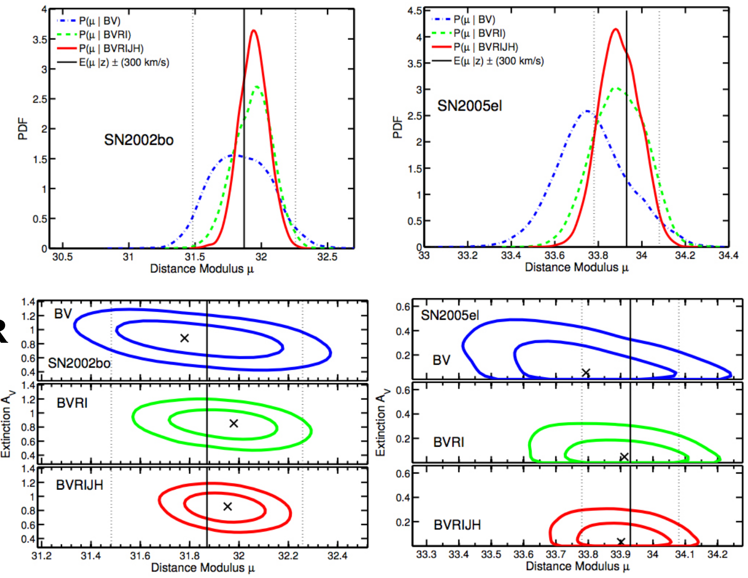
IMPROVED DISTANCES NIR+OPTICAL

JH + BVRI →
SN distance estimates more: accurate (top) & precise (bottom)

Mandel+11
conditions on NIR +Opt SN Ia LCs

PTEL, CSP, CfA, & literature

BAYESN



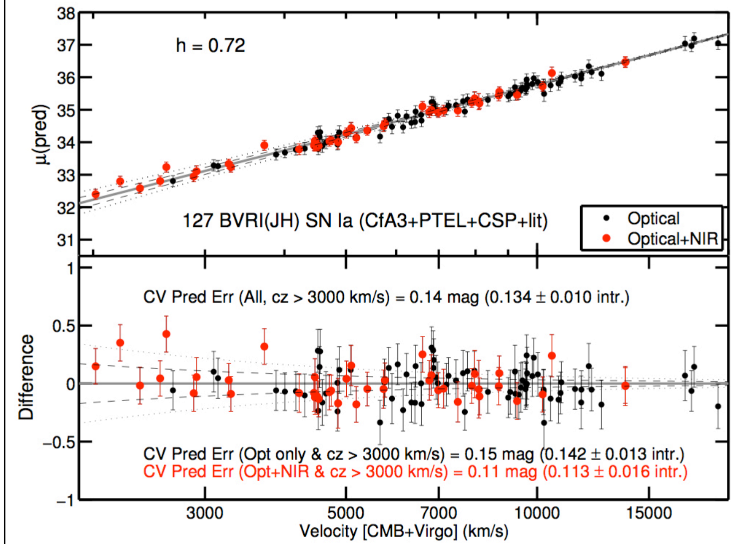
Figs 17-18: Mandel, Narayan, & Kirshner 11

Using the published subset of my thesis data (WF+08),

Most crucially, when you combine OIR data together, you get more precise distances estimates, as shown by the decreasing uncertainty contours.

You also get more accurate distances. See above compared to what you get using the Hubble law, black line.

NIR+OPTICAL HUBBLE DIAGRAM



127 SN Ia BVRI + JH

RMS scatter:

Optical only
0.15 mag
(7% in distance)

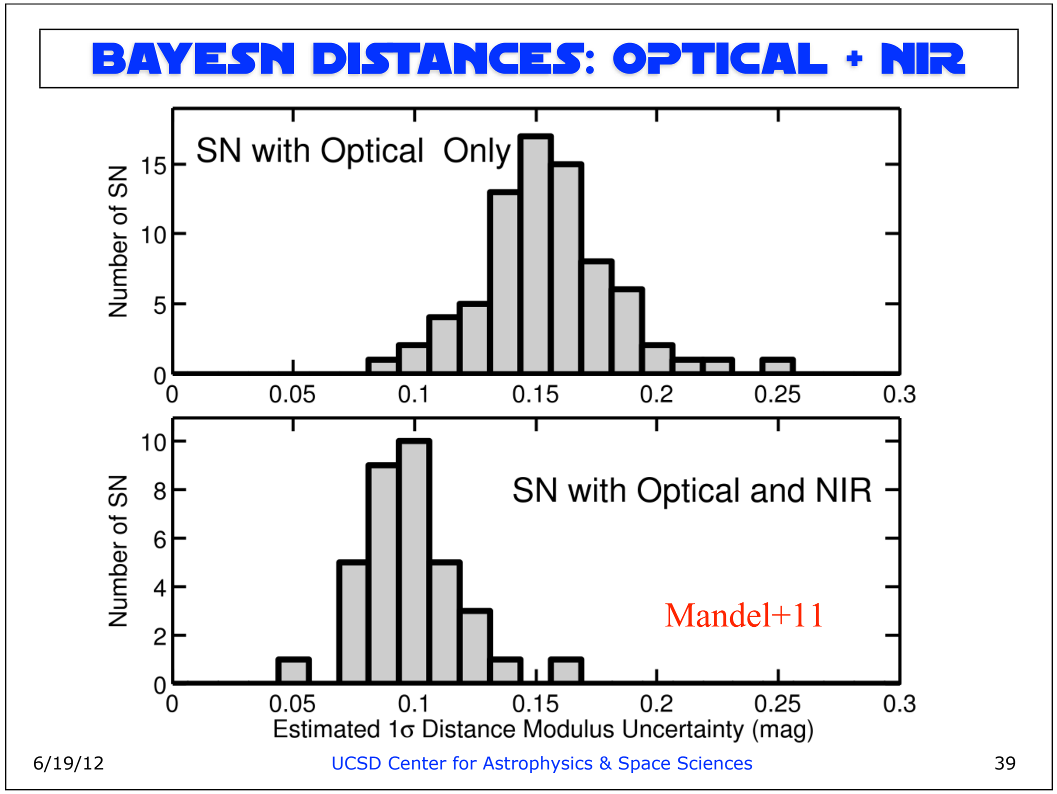
NIR+Optical
0.11 mag
(5% in distance)

Fig 16: Mandel, Narayan, & Kirshner 11

BAYESN

Kaisey constructed Hubble diagrams and found an RMS scatter 0.15 with optical data and 0.11 mag with OIR data.

This shows the power of the data.

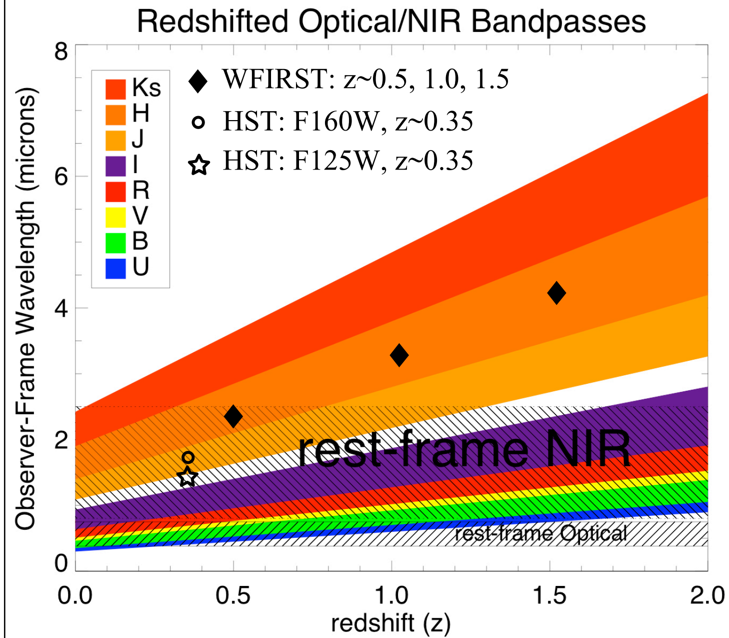


Using the published subset of my thesis data (WF+08),

Most crucially, when you combine OIR data together, you get more precise distances estimates, as shown by the decreasing uncertainty contours.

You also get more accurate distances. See above compared to what you get using the Hubble law, black line.

INFRARED SPACE OBSERVATIONS



WFIRST should consider going to longer wavelength

To observe rest-frame H-band Ia @ z~0.5, 1.0, 1.5, need detectors with coverage to: λ~2.4, 3.2, 4μm

HST z~0.35, rest-frame YJ F125W, F160W

Friedman+12

SN Ia in the near-IR may be superior distance indicators than in the optical bands.
At least ~3.6 μm to catch rest frame J band at z~2.
Expensive, but it might be worth it to really constrain w, where photometric errors and extinction errors must be small.

RAISIN: TRACERS OF COSMIC EXPANSION WITH SN IA IN THE IR

HST Cycle 20: 100 orbits approved!

25 rest-frame YJ-band SN Ia at z~0.35 with WFC3/IR.

Follow up on PanSTARRS discoveries ~10 days pre max.

3 epochs per SN x 25 SN = 75 orbits
(2500 sec = 900 sec F125W + 1600 sec F160W)
host galaxy templates = 25 orbits

Estimated statistical uncertainty of 6% on w.
Smaller systematic errors than current approaches

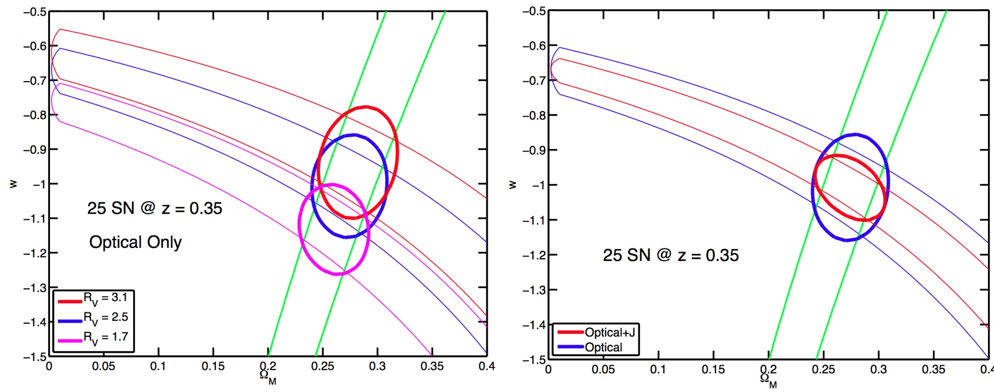
PI: Robert Kirshner

Using the published subset of my thesis data (WF+08),

Most crucially, when you combine OIR data together, you get more precise distances estimates, as shown by the decreasing uncertainty contours.

You also get more accurate distances. See above compared to what you get using the Hubble law, black line.

RAISIN: Simulate 25 Ia at z=0.35



Optical Only
w depends sensitively on Rv
Large systematic error

Optical+J vs. Optical Only
Rv fit w/ multi-band Ia LCs dw~0.10 to dw~0.06

BAO constraints (Percival+10)

Kirshner+2012 (HST proposal - from K. Mandel)

Using the published subset of my thesis data (WF+08),

Most crucially, when you combine OIR data together, you get more precise distances estimates, as shown by the decreasing uncertainty contours.

You also get more accurate distances. See above compared to what you get using the Hubble law, black line.

Conclusions: Past

Wood-Vasey, Friedman+08

(No NIR LC shape correction, Reddening from Optical)

- Ia H standard candles~0.15 mag (MLCS Opt 0.18 mag)

Mandel, Wood-Vasey, Friedman & Kirshner 09

(No HK LC shape corrections, R_V=3.1 fixed)

- J-band LC shape model: JHK Abs mag intrinsic variances
  $\sigma(M_J)$ =0.17+-0.03, **$\sigma(M_h)$ =0.11 +- 0.03,** $\sigma(M_{Ks})$=0.19 +- 0.04
- JHK Hubble diagram 0.10-0.15 mag scatter. No Opt data.

Mandel, Narayan, & Kirshner 11

(Correction for Opt+NIR LC shape & reddening. A_V, R_V fit)

- JHBVRI vs. BV data improves accuracy (dust extinction systematics) & precision (distance errors ~60% smaller)
- Hubble diagram RMS: NIR+Opt: 0.11 mag, Opt: 0.15 mag

Conclusions: Future

Friedman+12

- CfAIR2: PAIRITEL JHK LCs of ~100 SN Ia
- Nearly doubles world sample of objects
- More than triple NIR observations

Mandel+12

- BayeSN Distances, Hubble Diagrams: Opt+NIR SN Ia LCs
  Optical (CfA4: Hicken+12) + NIR (CfAIR2: Friedman+12)

HST: RAISINS

- HST rest-frame YJ data (3 epochs) for 25 SN Ia @ z~0.35
- PanSTARRS optical LCs
- Competitive Dark Energy constraints:
  Statistical: dw~0.10 (Optical) dw~0.06 (Optical+IR)
  Smaller systematics

REFERENCES

Wood-Vasey, Friedman+2008, ApJ, 689, 377-390 (WF+08)
Mandel, Wood-Vasey, Friedman, & Kirshner 2009, ApJ, 704, 629-651
Mandel, Narayan, & Kirshner 2011, ApJ, 701, 120

Bloom+06, ASPC, 351, 751B
Burns+11, AJ, 141, 19
Cohen+03, ApJ, 126, 1090
Contreras+10, AJ, 139, 519
Stritzinger+11, AJ, 142, 156
Elias+81, ApJ, 251, L13
Elias+85, ApJ, 296, 379
Filippenko+05, ASPC, 332, 33
Folatelli+10, AJ, 139, 120
Hamuy+06, PASP, 118, 2
Hicken+09a, ApJ, 700, 1097
Hicken+09b, ApJ, 700, 331
Jha+07, ApJ, 659, 122
Kasen 06, ApJ, 649, 939
Kattner+12, arXiv:1201.2913
Meikle 00, MNRAS, 314, 782
Kirshner+73, ApJ, 180, L97
Kirshner+04, *The Extravagant Universe*
Krisciunas+04, ApJL, 602, L81
Krisciunas 05, ASPC V. 339, p75
Krisciunas+07, ApJ, 133, 58
Perlmutter+99, ApJ, 517, 565
Phillips 93, ApJ, 413, L105
Phillips 11, arXiv:1111.4463
Riess+96, ApJ, 473, 88
Riess+98, AJ, 116, 1009
Schmidt+98, APJ, 507, 46
Skrutskie+06, AJ, 131, 1163

SN Ia in the near-IR may be superior distance indicators than in the optical bands.

If future data confirms this, IR SN Ia may prove ideal for cosmology.