Probing the circumstellar environments of supernovae with high-cadence photometry

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GOTO
GRAVITATIONAL-WAVE OPTICAL TRANSIENT OBSERVER

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Overview

1. **The curious case of SN2014J** - short timescale variability with no obvious mechanism

2. **Searching for short-timescale variability** in two CCSNe with SALTICAM and RISE

3. **Towards a systematic census** of short-timescale variability in nearby transients

The zoo of interacting transients

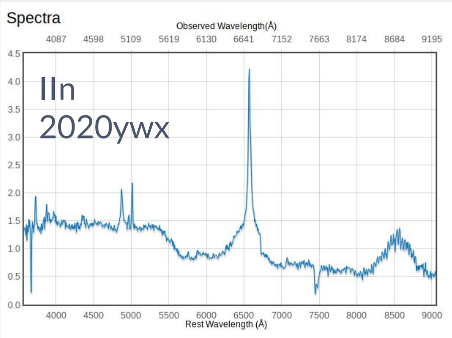
Through large-scale sky surveys, a family of transients that undergo interaction with a dense circumstellar medium has been revealed- as might be expected from mass loss towards the end of life of the most massive stars (+ a few surprises). See Fraser (2021) for an excellent review.

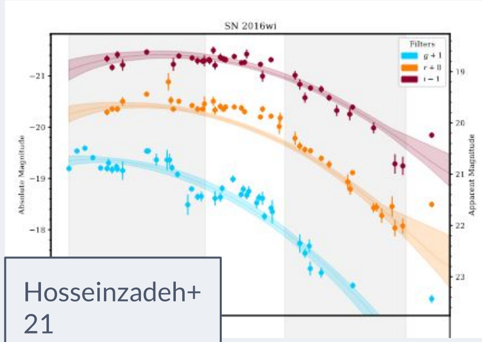
Spectroscopic

- Flash-ionised CSM close in to progenitor (flash spectroscopy, see Khazov+16)
- Interaction with massive CSM further out (e.g. SNe IIn)
- Weirder subtypes, like Ia-CSM/Ibn

Photometric

- Rise times of SNe II require some CSM to reconcile with SN explosion models
- SLSNe show bumpy light curves, most readily explained via CSM interaction (although magnetars also viable in some)





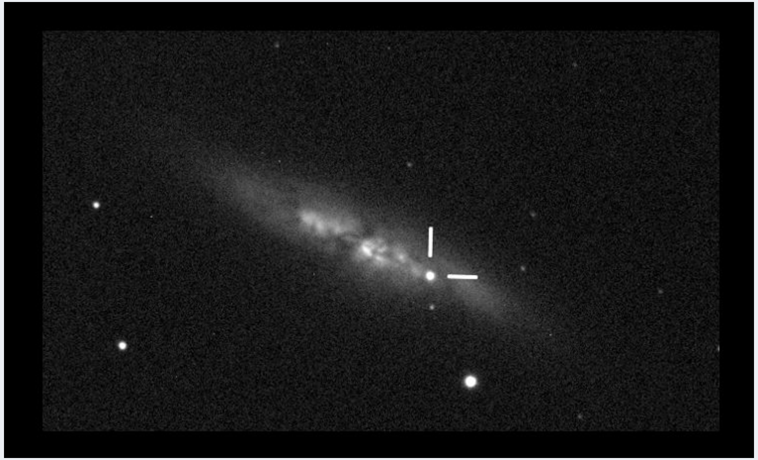
Hosseinzadeh+ 21

SN2014J - a serendipitous discovery

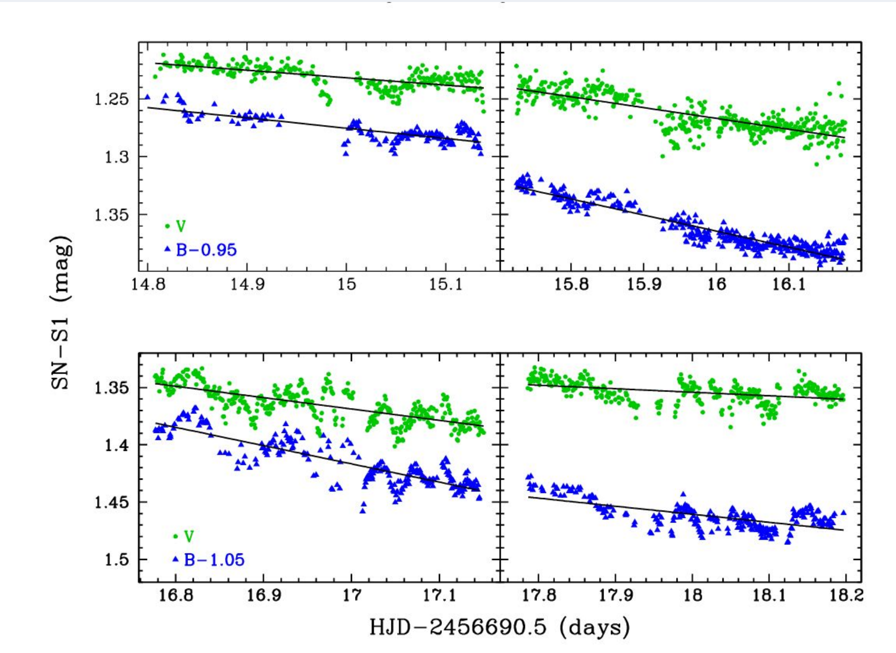
Discovered 21st January 2014 with the 0.35m UCL campus telescope - in M82 (3.5 Mpc)

Classified as SN Ia, reached peak magnitude of 10.5

208 (and counting) papers - has near-continuous INTEGRAL coverage, a rich multi-colour dataset, dust echoes, and thus is one of our best-studied SNe Ia



Short-timescale photometric variability



Reproduced from Bonanos and Boumis (2016)

Bonanos and Boumis (2016) found 20–50mmag variations in brightness over 15-60min timescales.

2 minute cadence photometry using 2.4m Aristarchus telescope

Visible across 4 different nights

Mechanisms proposed

This is a SN Ia - no engine to vary, and these timescales are far too short to accommodate this anyway. The variability must be external to the remnant.

Circumstellar interaction/clumpy ejecta

+ Can reproduce the signatures seen if we allow small-scale (~10^{12} cm) structure in the CSM/ejecta

- No radio/X-ray emission down to deep limits (VLA/Chandra)

- Don’t expect (dense) CSM around ordinary SNe Ia

+ We do see dust echoes from 2014J in HST obs

Asphericity in ejecta

+ 2014J does show high polarisation -> e.g. aspherical ejecta

- Not clear if this can explain the variability seen.

- SNe Ia typically thought to have ‘cleaner’ explosions, although this is a more circumstantial argument.

Also uncertainty around progenitor system, slight preference for double degenerate from Hβ and lack of X-rays (see Graur+19, Nielsen+21) which removes another source of CSM (stellar wind)

One of a kind?

SN2014J is an unremarkable Ia (optically at least), only really notable due to how close it is. We should see this in other bright Ia SNe if this is a real phenomenon.

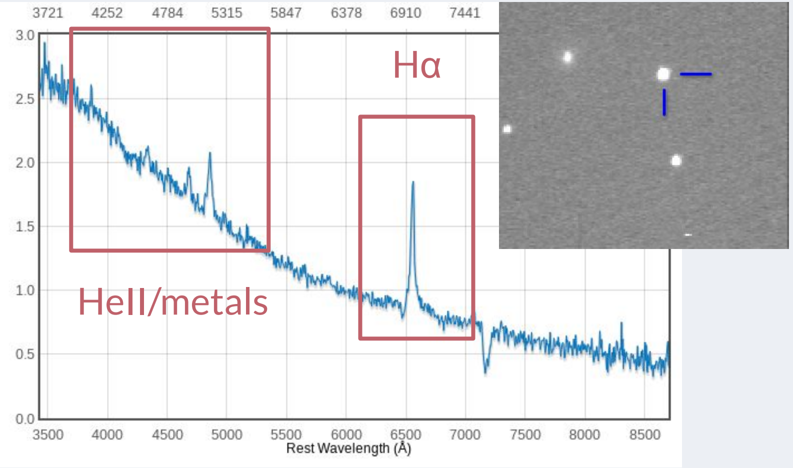
Further work *(Paraskeva+ 2021)* revealed no variability in a sample of 5 SNe, although these targets were fainter.

More observations of this kind can place limits on the rate of this phenomenon, and enable us to pin down the mechanism using different SN types.

Searches for short-timescale variability in SN2021acya and SN2022mm

SN2021acya

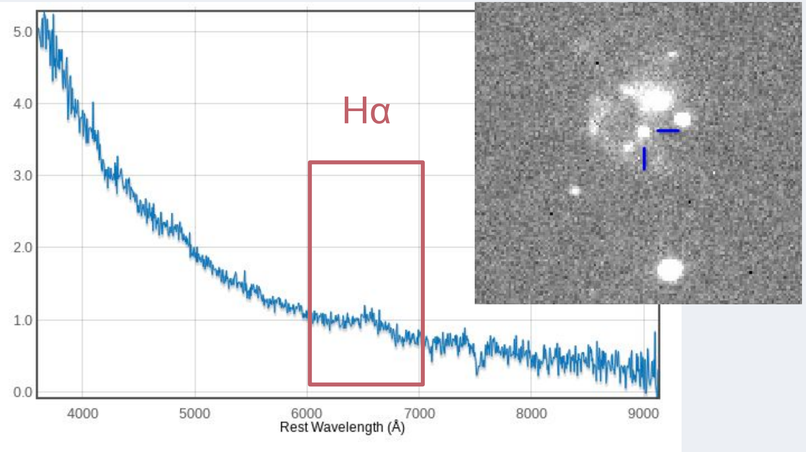
SLSN IIn discovered by ATLAS at 282 Mpc



Strong interaction signatures - observed at g = 16.5, around 1 month post-explosion due to SALT scheduling constraints.

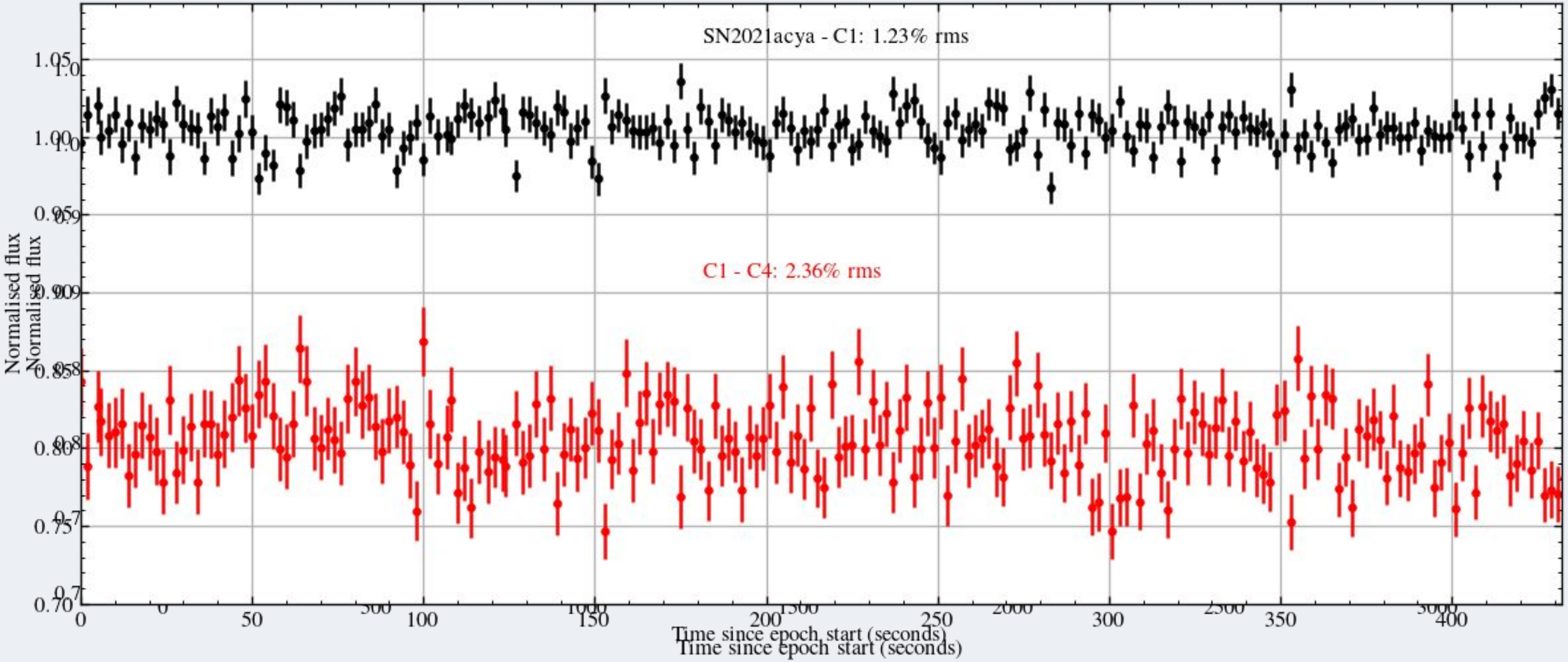
SN2022mm

SN II discovered by ATLAS at 57 Mpc, with solid 24h pre-discovery non-detection



No obvious interaction signatures - observed at g=17, around **48h post-explosion**

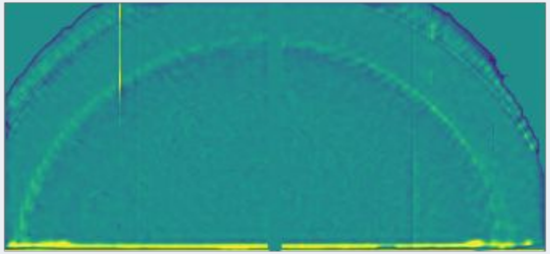
SN2021acya with SALTICAM (r’ band)



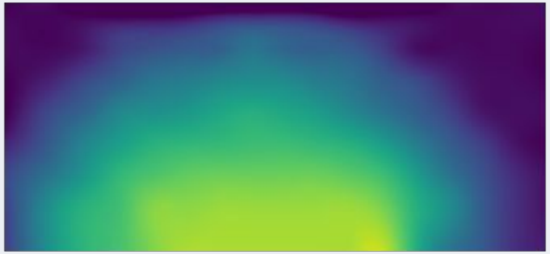
No evidence for excess variability - can rule out 2014J-like variability at 5 sigma with this.

Calibrating SALT

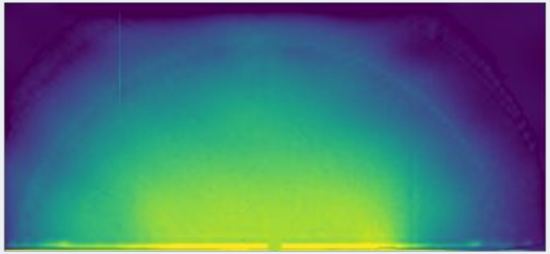
SALT has a **moving-tracker design** unlike most telescopes - this means flat-fields change as function of position on the sky. Extra calibration required.



Lamp flats: pixel response



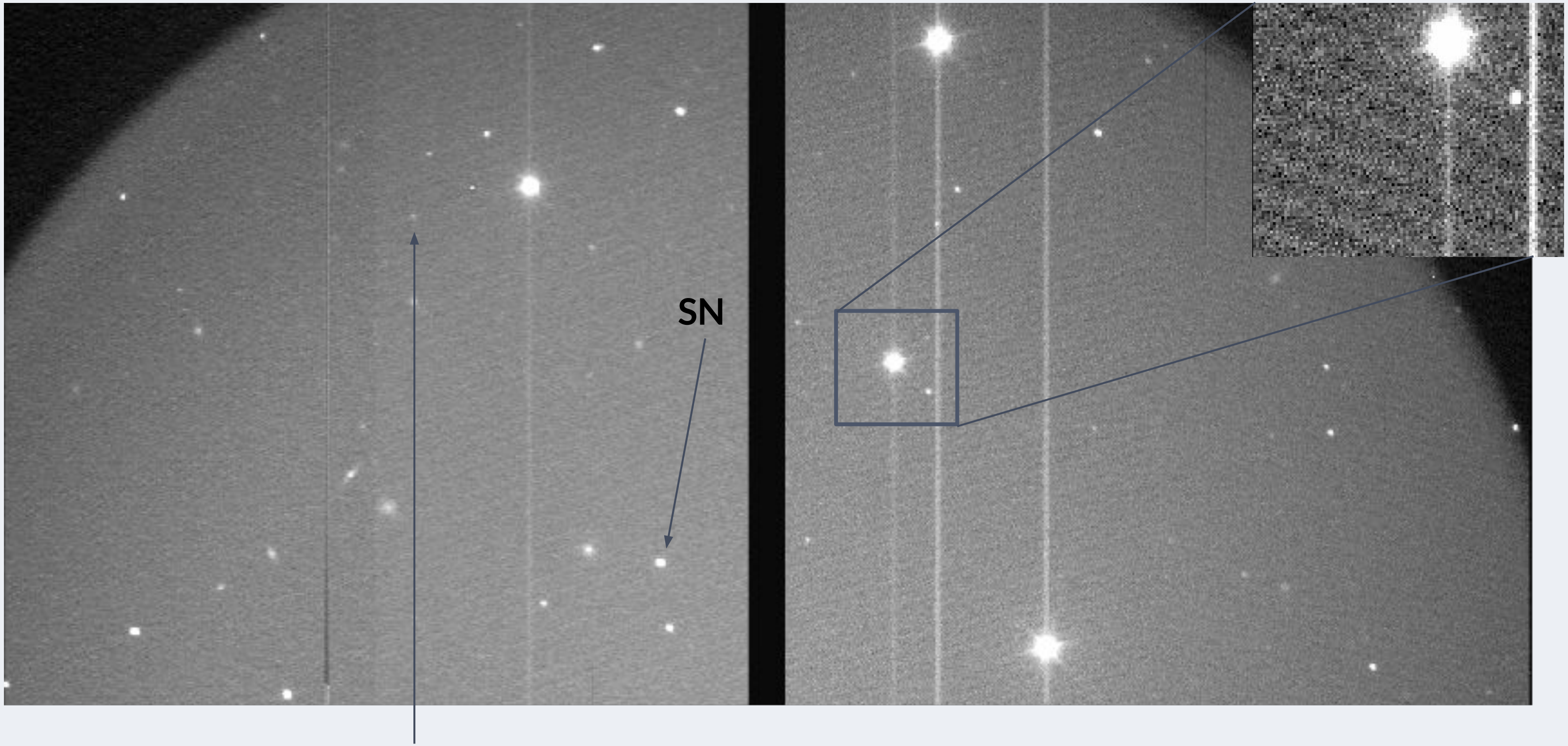
Per-frame vignette estimate



Combined ‘flatfield’

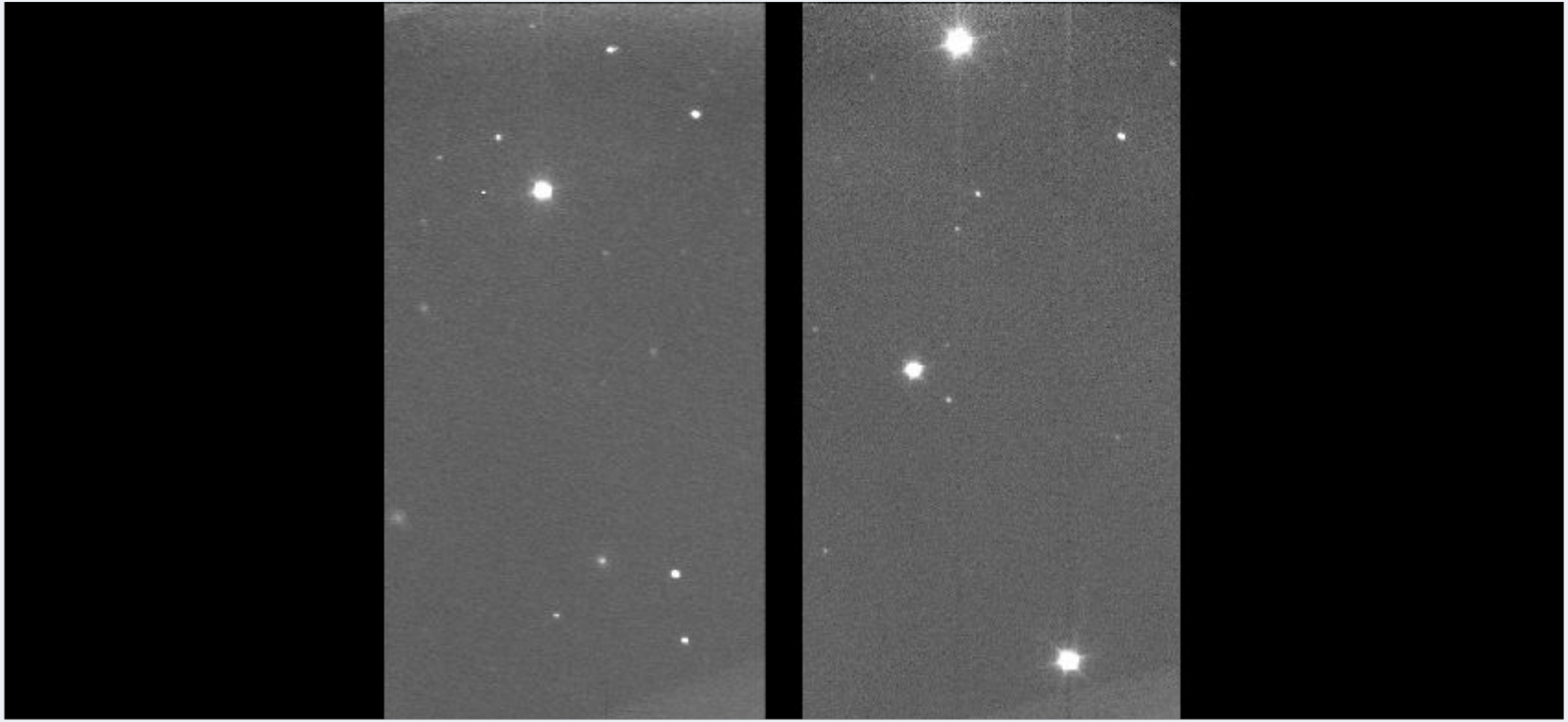
Also presence of frustrating fixed-pattern noise – difficult to correct for!

Before



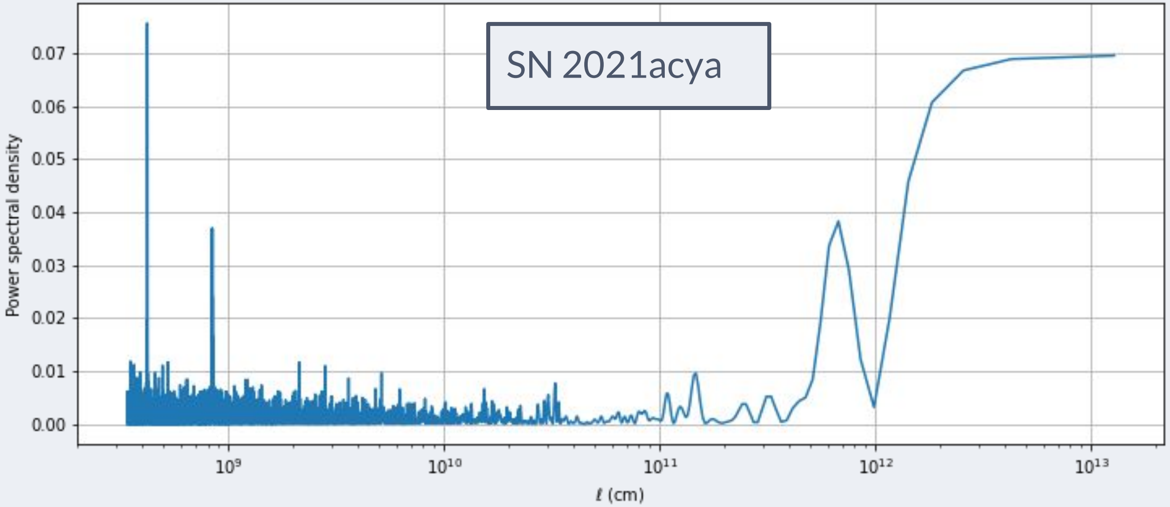
20th mag in 2s exposures!

After



Stochastic variability?

Preferential length scales (/time scales) for noise/correlation? Need data with fewer systematics and suitable cadence to sample, but:

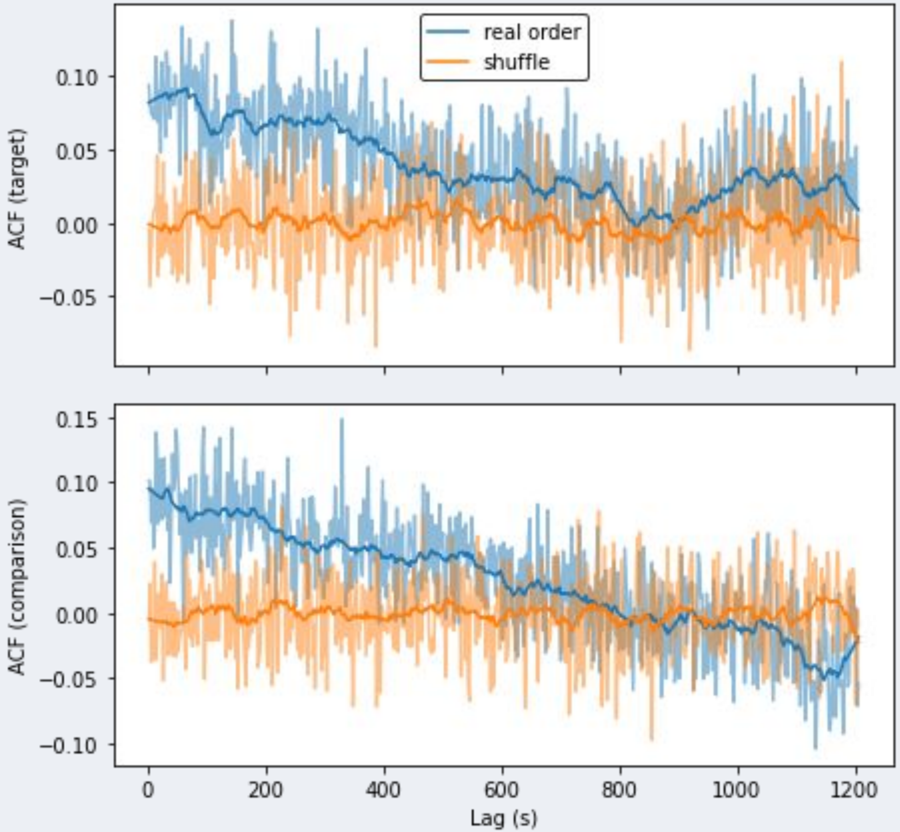


Red noise? Instrumental or intrinsic?

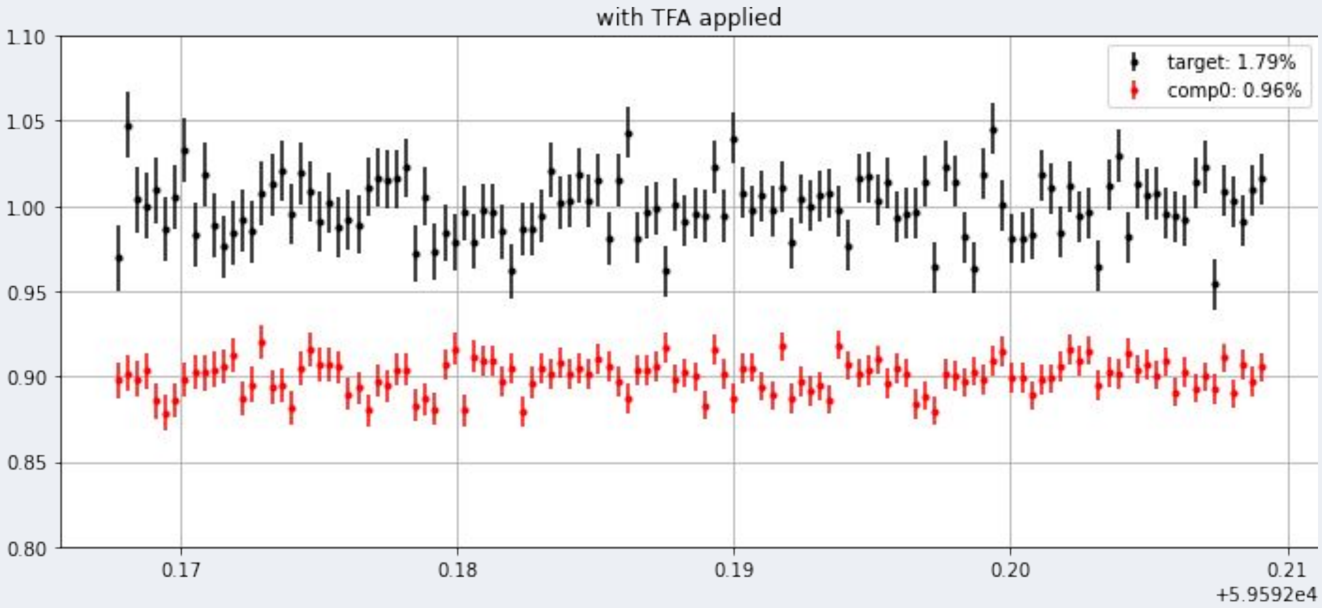
Significant residual correlation even after detrending with linear model - interesting.

Plot auto-correlation function of 2021acya light curve vs a comparison star in the field - both show characteristic excess despite having different comparison star - instrumental :(

Considering statistical uncertainties on ACF, hard to claim significance regardless!



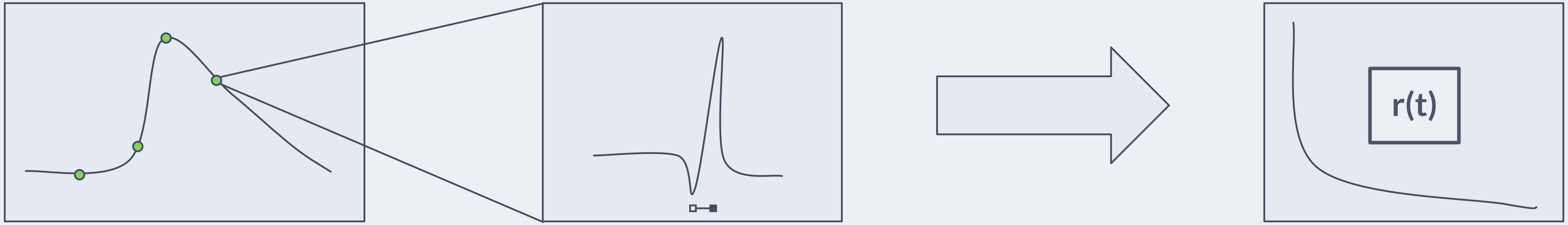
SN2022mm with RISE - just 48h post explosion!



30s cadence,
1 hour total

Target was unexpectedly fainter than anticipated (early plateau) - but still get <2% RMS - enough to place constraints on variability at epochs we haven't been able to observe before!

Environmental constraints - early work



Light curve -> gives phase

Spectral lines -> expansion velocity

Approximate radius

By converting to ‘radius’:

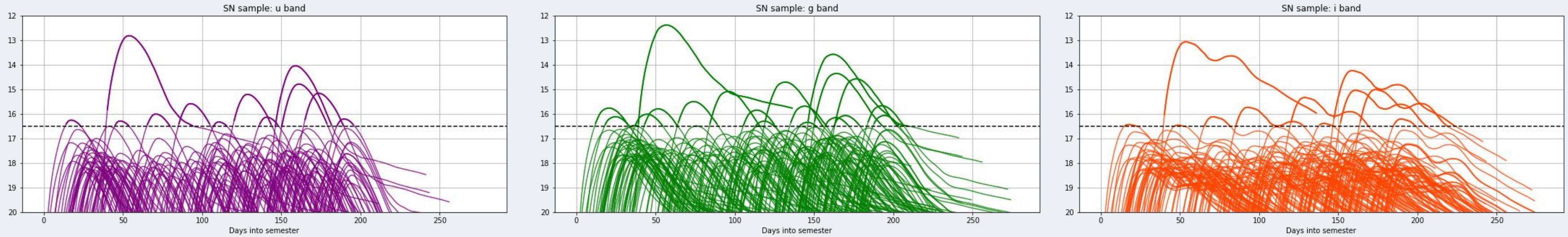
- **compare variability across supernovae** of the same class at different times
- consider this in the context of **wind density profiles (assuming CSM link)** - particularly interesting for CCSNe with their massive star progenitors (pre-explosion mass loss).

Variability model -> environment parameters. Can probe density fluctuations in CSM

A larger sample

Building a magnitude-limited sample of SNe

Using ZTF-BTS as a ~magnitude-complete sample, can synthesise expected yields of transients accessible to high-cadence photometry (r’ <= 16.5)



Simulated LCs for all ZTF-BTS SNIa discoveries one semester using ULTRACAM filters.

We expect ~70 transients per semester (per sky) to fit these criteria - there’s plenty of targets to trial this approach on.

Future plans (pending proposals)

Extend this study to a sample of ~20 nearby supernovae with r' < 16.5 - a homogeneous sample to place strong constraints on rate, and investigate this phenomenon across a wide range of SN sub-types.

High-cadence, multi-colour photometry with NTT/ULTRACAM - search for variability in u' band (not probed before!)

✔️ **Early-time searches with LT/RISE** - sampling potential CSM/interaction close-in to the remnant, on ~days timescale.

GOTO (progress and fast transients)

Conclusions

High-cadence variability is a potentially valuable probe of the explosion dynamics/*local* environment of supernovae.

A larger sample is required to place solid rate-of-occurrence constraints and investigate potential variability across SN sub-types

Paper in prep, coming later this year.

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