Autonomous real-time science-driven follow-up of survey transients

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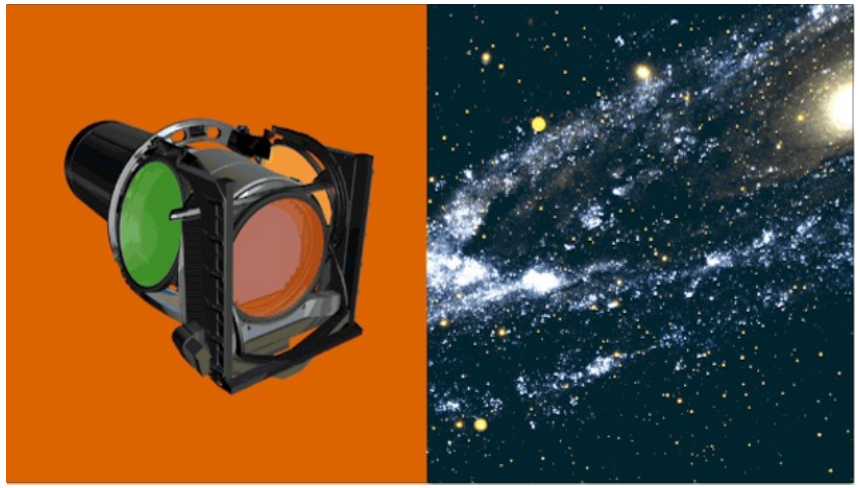
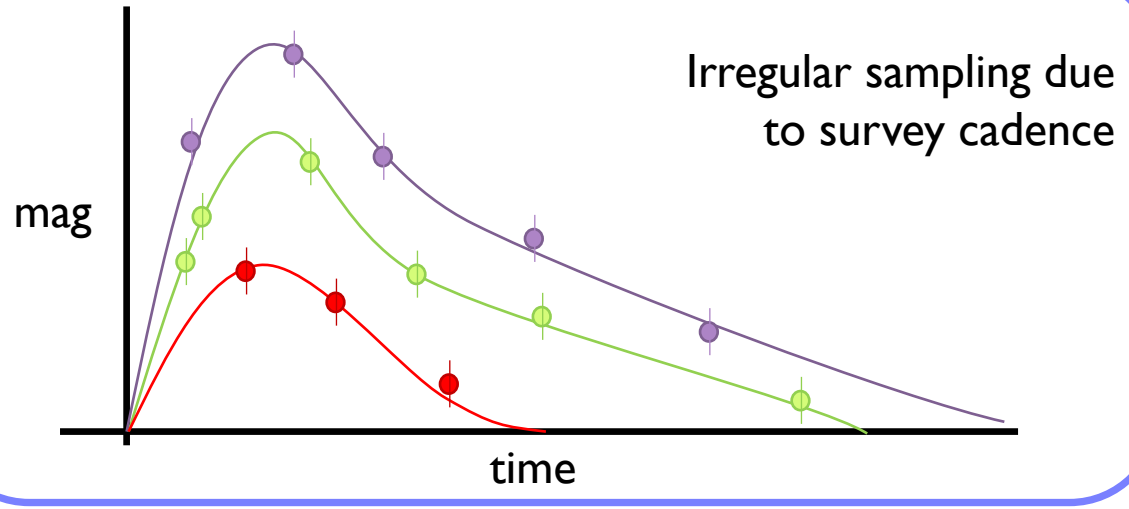
Caltech

Multi-color Light curves

(Multi-channel time series)



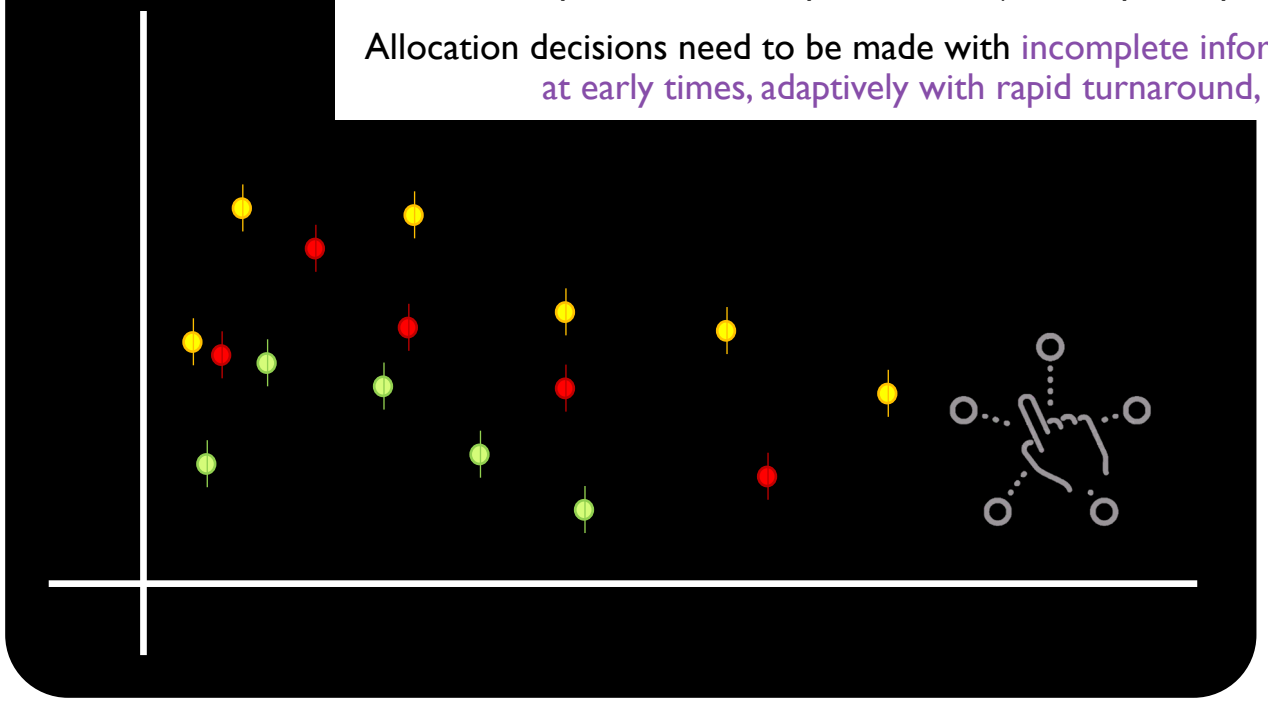


Optimal Follow-up

Data determined by survey schedule

Limited/expensive follow-up resources (UV/IR space, spectra, …)

Allocation decisions need to be made with incomplete information, at early times, adaptively with rapid turnaround, at scale



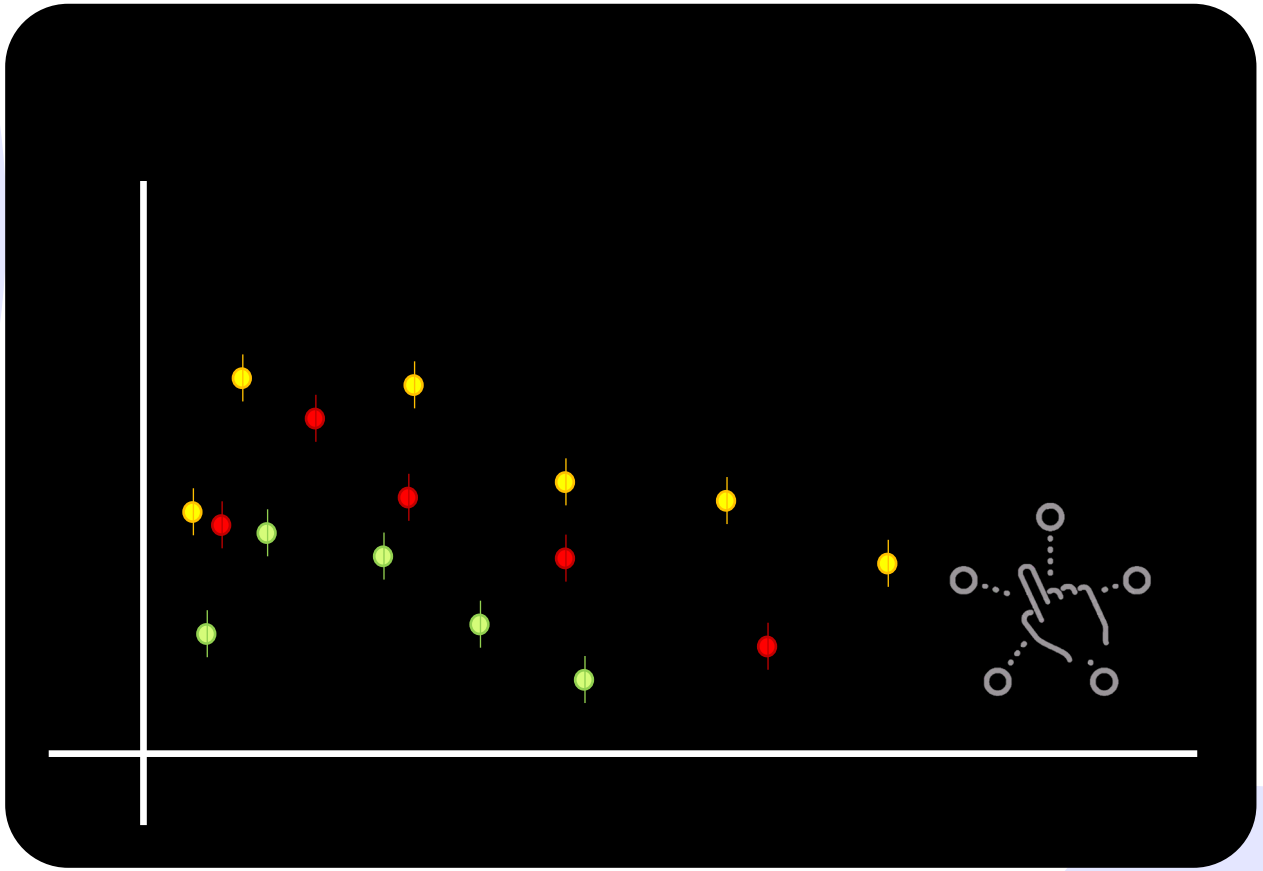
Optimal Follow-up

PROBLEM:

What sequence of actions (now and future), subject to a budget, maximize objective

CAVEATS:

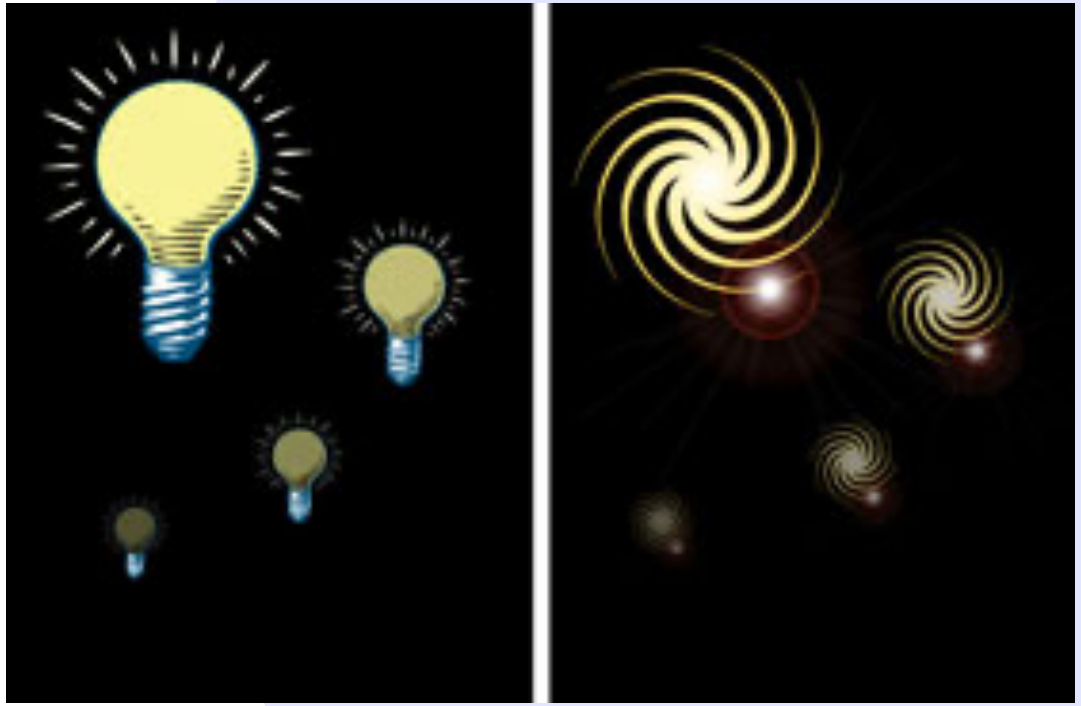
Only current actions will yield true outcomes
Cannot undo
May not know if action was good until later (delayed consequences)
Need to adapt to new information



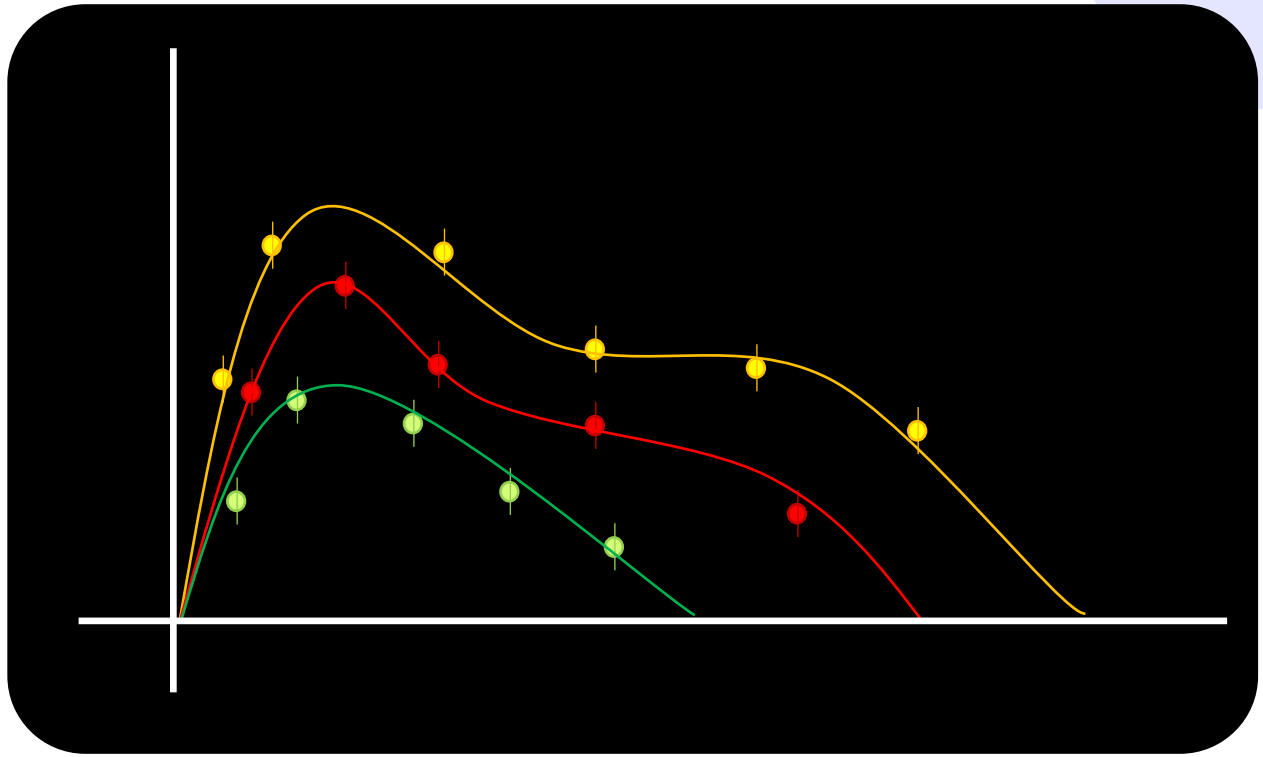
Type Ia Supernovae

Constrain cosmological parameters:
Hubble constant, Dark Energy equation of state, …

Low redshift samples constrain local large-scale structure properties:
growth rate, velocity flows



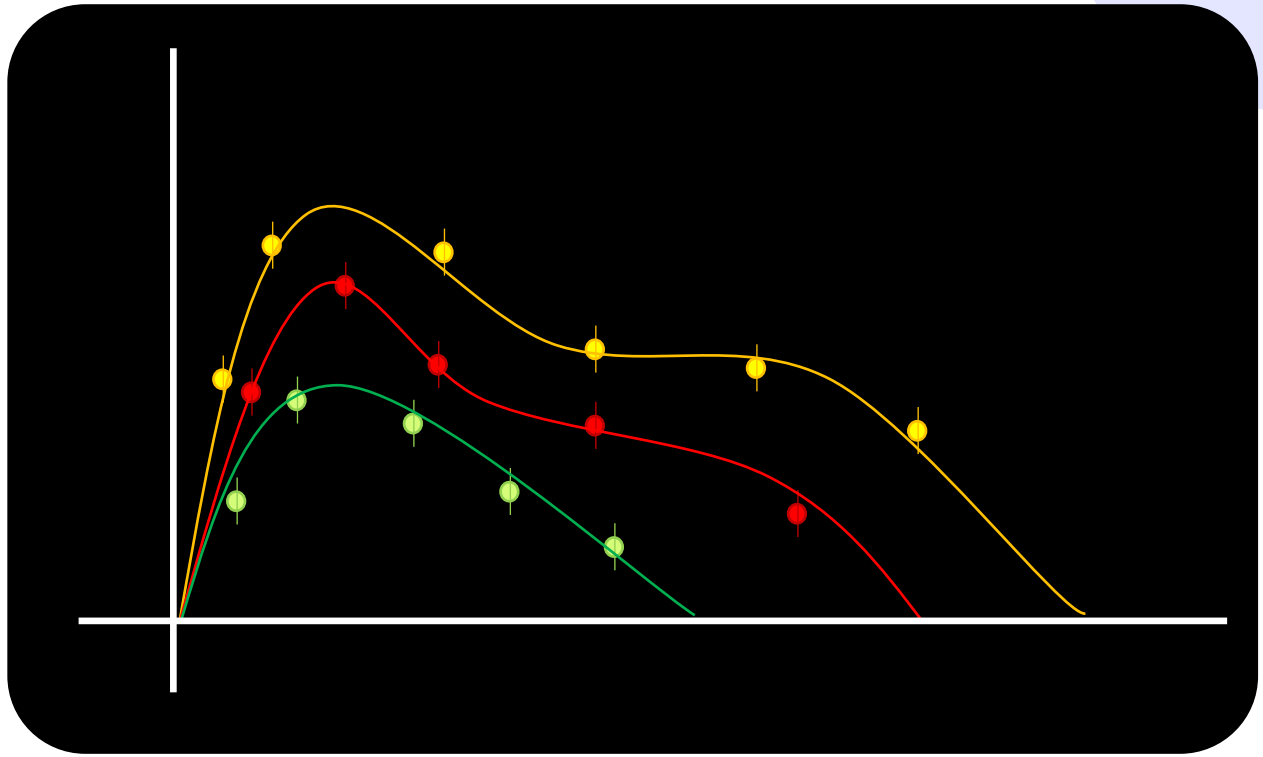
Real-time SN Ia LC augmentation to maximize cosmology



x_0, x_1, c, z are light curve fit parameters

Cosmology is $f(x_0, x_1, c, z)$ for a sample of SNe

Real-time SN Ia LC augmentation to maximize cosmology



Minimize uncertainty on light curve fit parameters (in quadrature)

Minimize uncertainty on cosmology

Problem statement:

Augment photometry to branch-normal SN Ia light curves from ZTF-I public survey (g and r) in g,r, and i to minimize net uncertainty on SALT2 parameters

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i-band important for precisely estimating H_0 (Burns+ 2018)

Second peak could help probe SN Ia explosion mechanisms (Folatelli+ 2010)

Data in UV or IR can help better calibrate models (Milne+ 2015)

Algorithm

Non-stationary MDP with finite horizon (60 day episodes)

State space: Observed photometry and expected data from survey (stochastic, 10x monte carlo). Remaining budget allocated randomly*

Action space: {no action, g, r, i, gr, ri, ig, gri}

Deterministic reward model: SALT2 + photo z A-optimality**

Deterministic dynamics model

Upper limit using 2-D Gaussian Process regression over full LC

For real time estimated with encoder-decoder LSTM trained on 10^5 simulated ZTF SNe Ia (slightly lower performance)

New state simulated using 2-D Gaussian Process fit to full LC and fed back the next day

Deterministic off-policy, fixed budget and unit cost

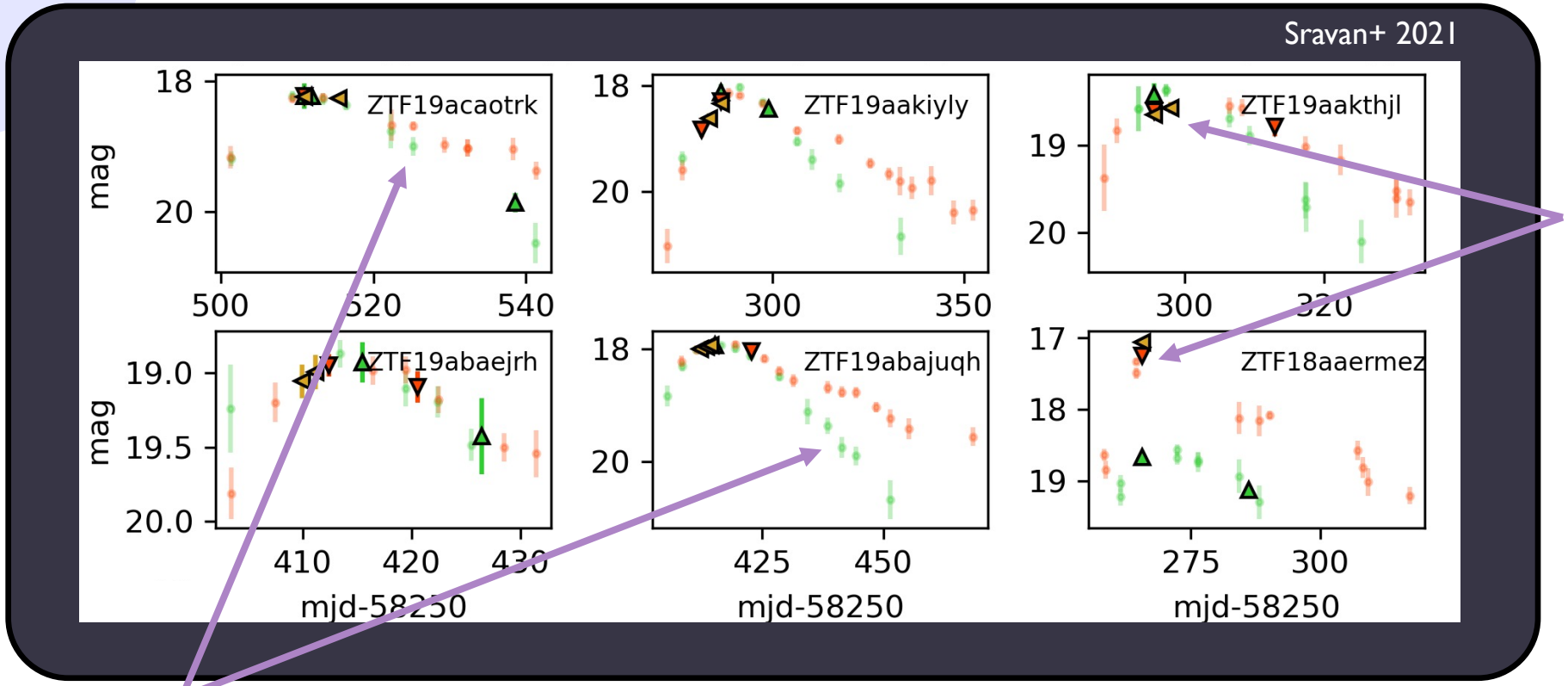
Take modal action with maximum reward and least cost across all rollouts. Threshold ϵ over no action (hyperparameter)

* substitutes expected **optimal** actions for expected **naïve** actions

** Distance error in quadrature. Note: min $\chi 2$ $\neq$ max liklihood

Gap filling

Resolves phase with high variability (first and second peaks+valleys)



Augmented photometry to minimize uncertainty on cosmology

Survey light curve

Improvement in SALT2 parameters over naïve** strategy

2-5% more improvement for faint SNe Ia (peak>18.5 mag)

Due to gap filling, strong prospects for Rubin

Budget	Usage	$\delta(\sigma_{x0})$	$\delta(\sigma_{x1})$	$\delta(\sigma_c)$	$\delta(\sigma_z)$
3	2	2%	3%	5%	6%
6	5	3%	5%	4%	6%
9	7	5%	6%	5%	11%

Sravan+ 2021

**Adding data itself can lead to improvement!

Summary and outlook

Algorithm interpretable

Data acquisition failure tolerant

- Latency intolerant

Need to perform optimal set of actions

Consider

- Variable observing cost, observing season based budget
- Other choices of utility incl prior building, model discrimination
- Diverse science cases – spectra, MW/MM astronomy