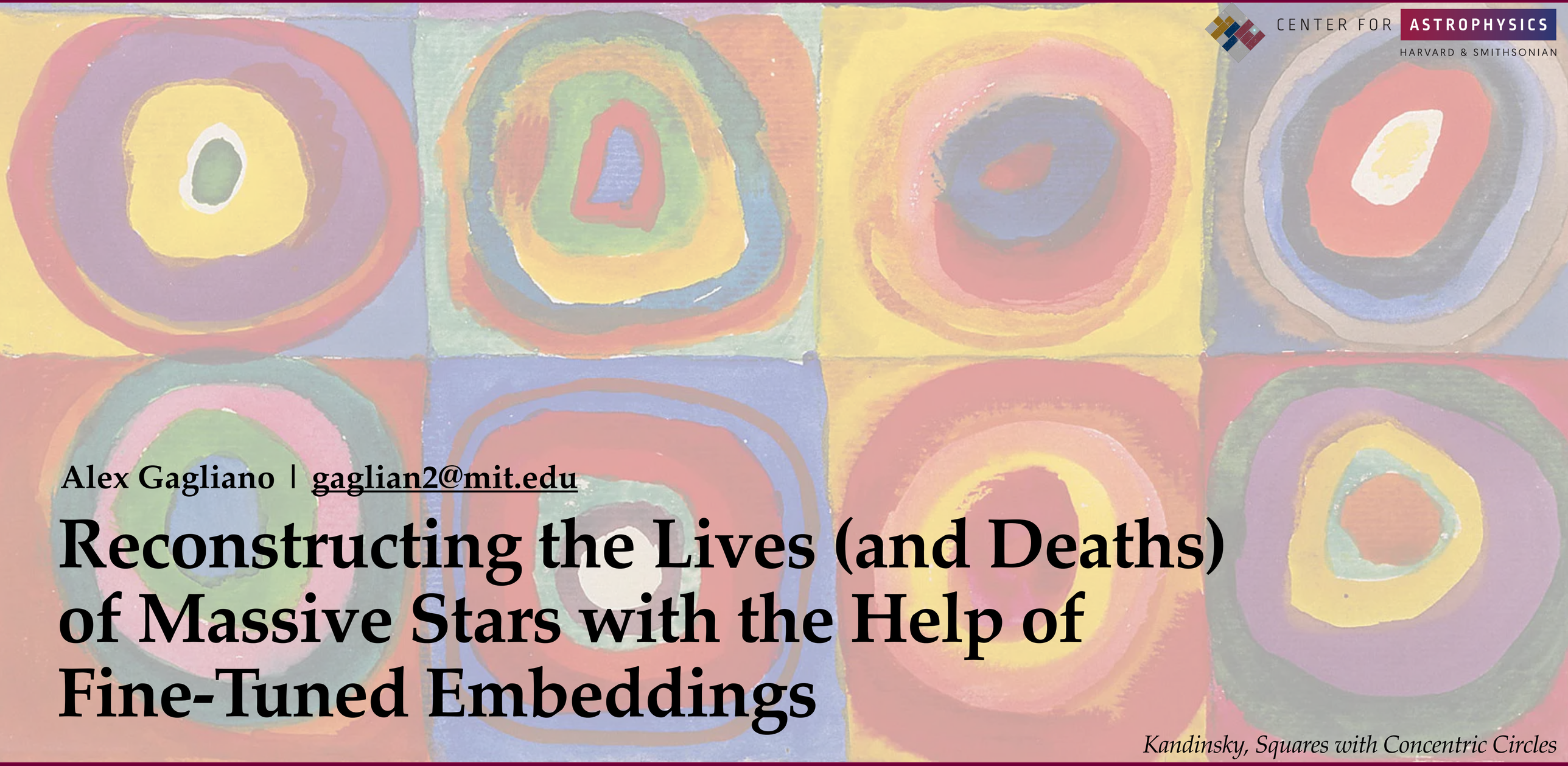

Alex Gagliano | gaglian2@mit.edu

Reconstructing the Lives (and Deaths) of Massive Stars with the Help of Fine-Tuned Embeddings

Kandinsky, Squares with Concentric Circles

IAIFI Seminar, March 8th 2024

Talk Outline

I. A Primer on Supernova Classification

II. The Value of Circumstellar Interaction

III. Finding Interaction Signatures, Faster

Supernovae: The Explosive Deaths of Stars

SN 1994D; NASA/ESA

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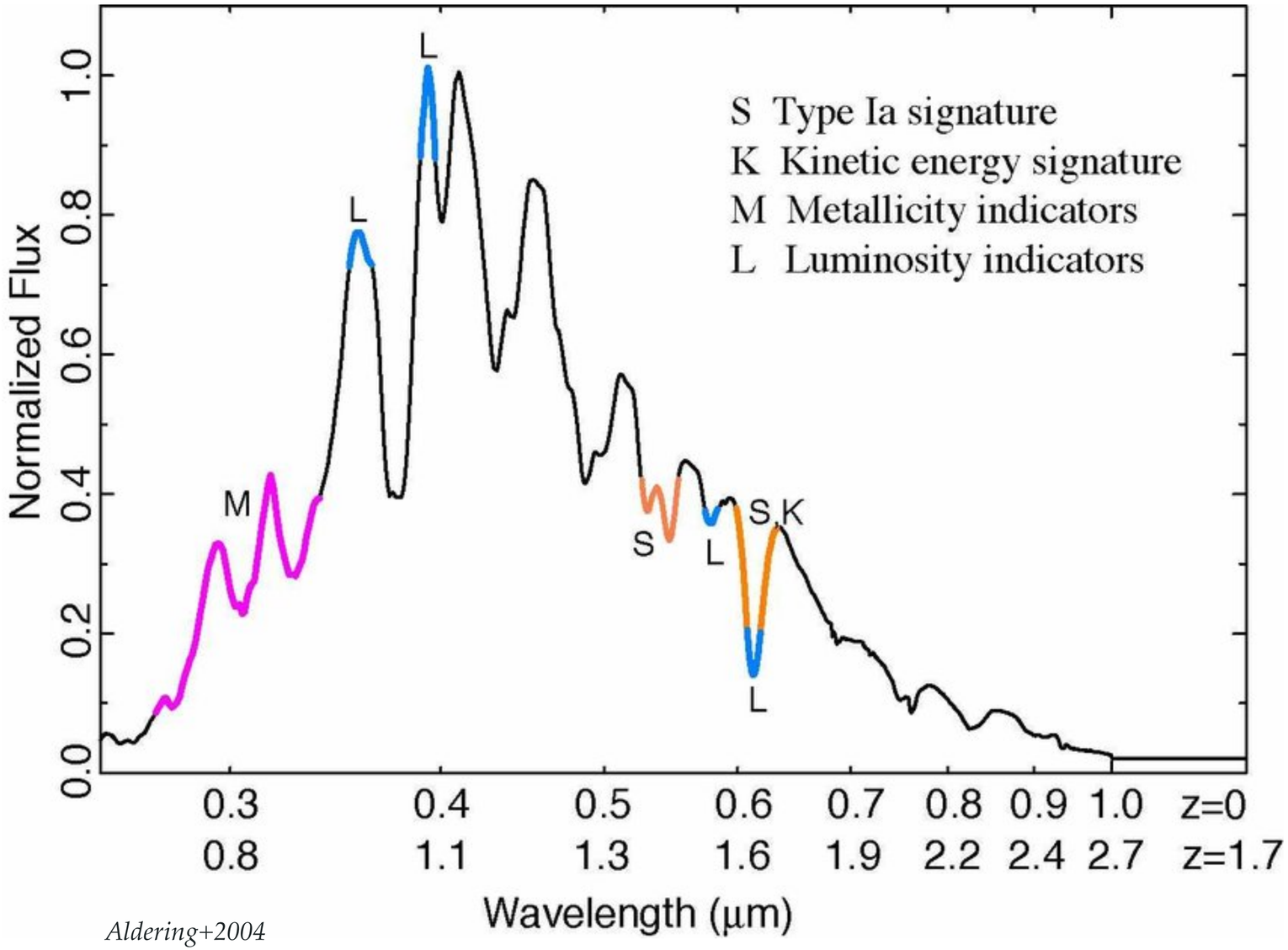
Spectroscopy: An SN's Rosetta Stone

A supernova is fully described by its composition, density profile, and velocity structure.

All of these are constrained with spectroscopy.



Aldering+2004

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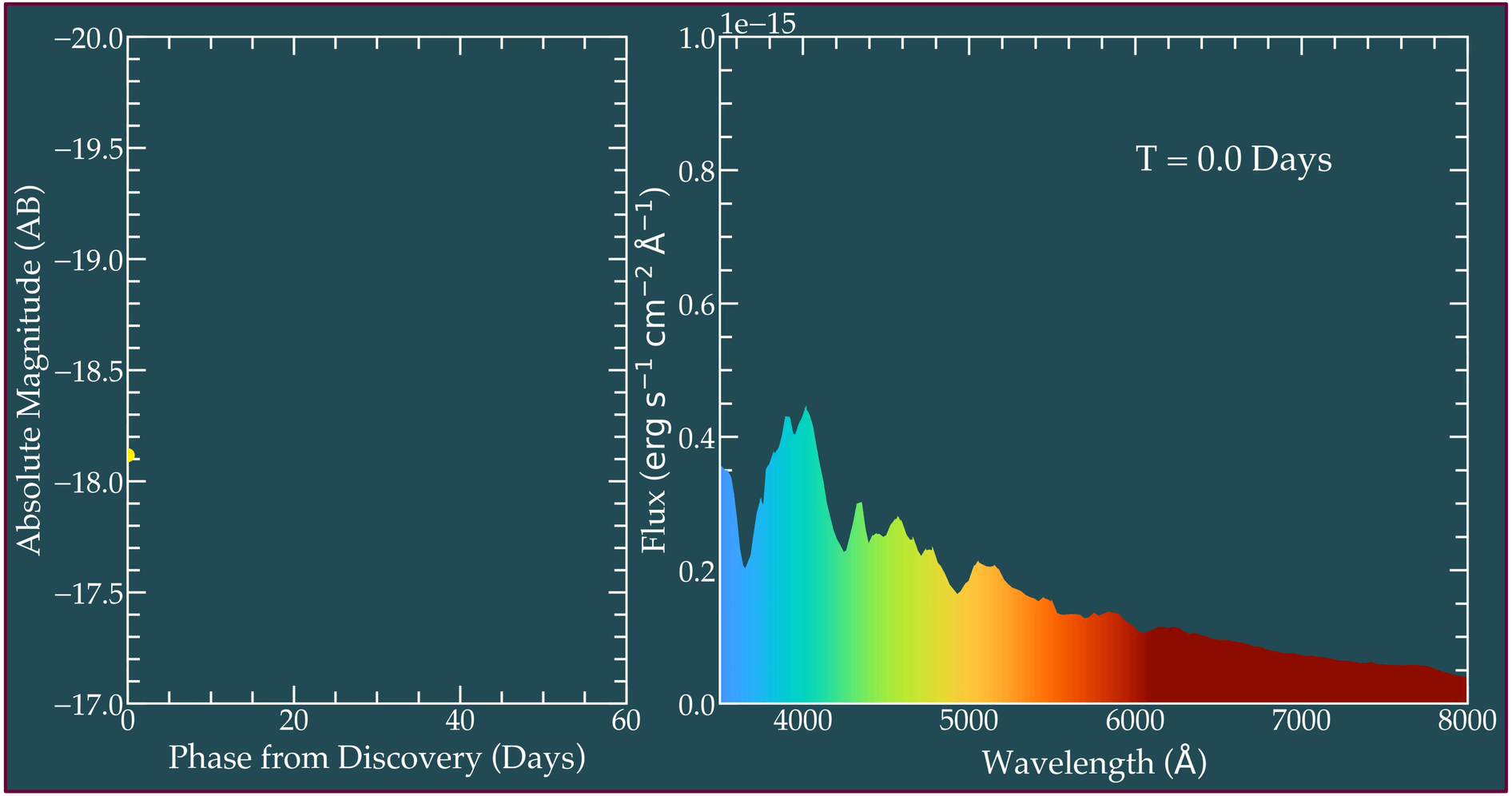
From Spectroscopy to Photometry

Optical Spectral Sequence of a Type Ia Supernova



Multi-band **photometric features** (peak light, decline) are a weak proxy for underlying spectral evolution.

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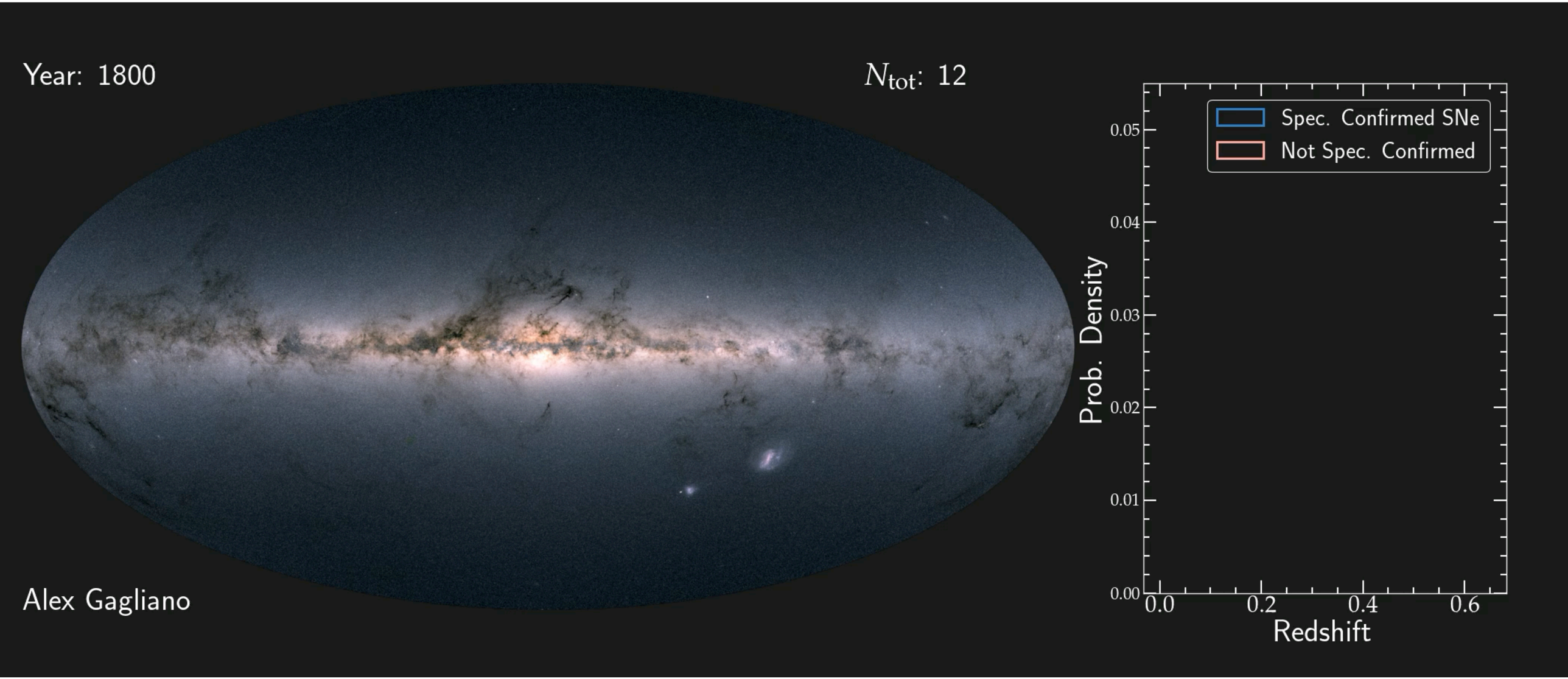
Trading Data Quality for Quantity



Photometric Classification

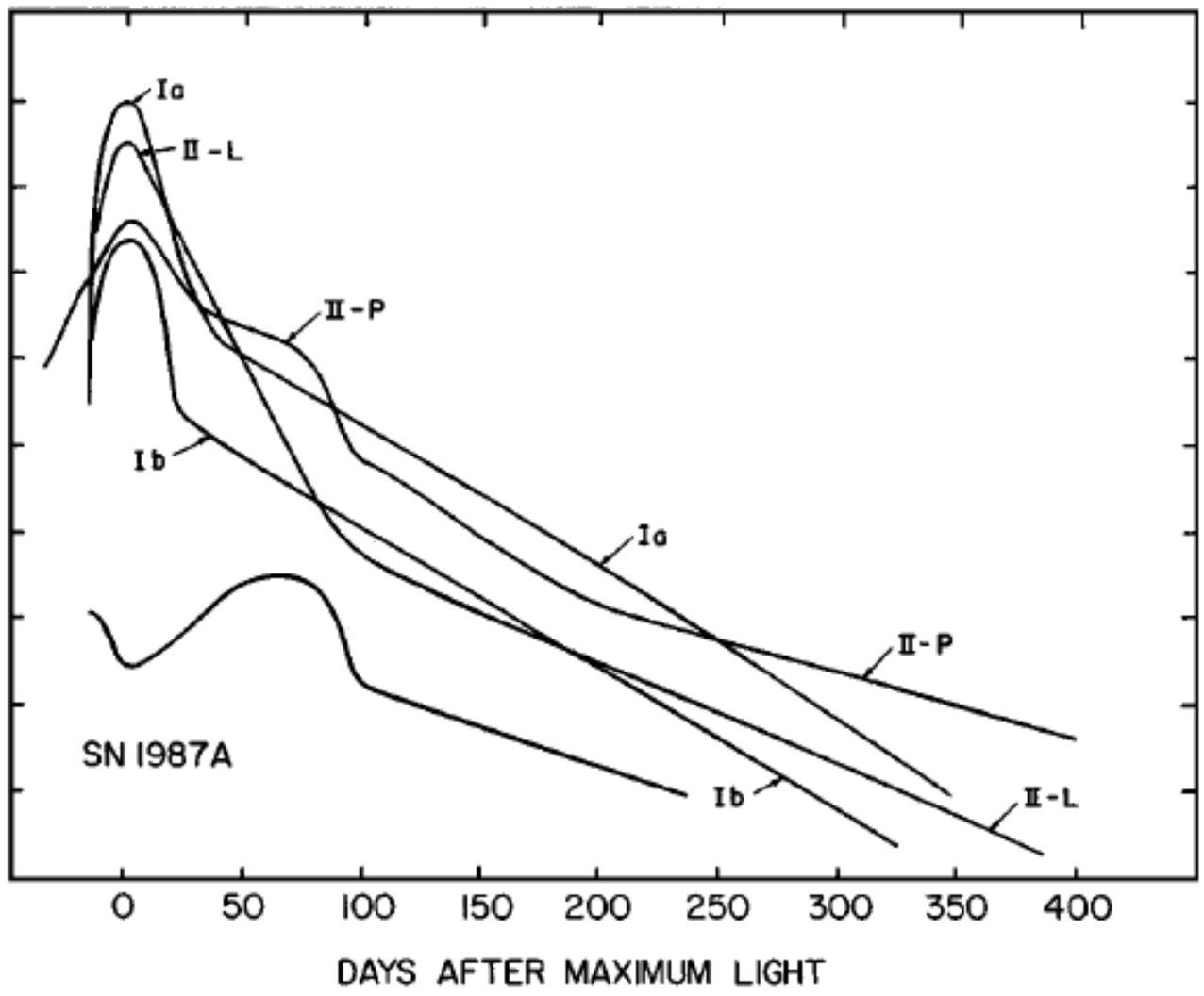
Increasing **discovery rates & sims** drove classifier development:

Brute-force template matching
(*Sako+08, Rodney+09*)

Decision trees on LC features
(*Möller+16, Lochner+16, Boone+18, Leoni+22*)

NNs on raw / interpolated photometry
(*Karpenka+13, Charnock+17, Muthukrishna+19, Villar+19, Qu+21, Pimentel+22, Gagliano+23*)

Filippenko (1997)



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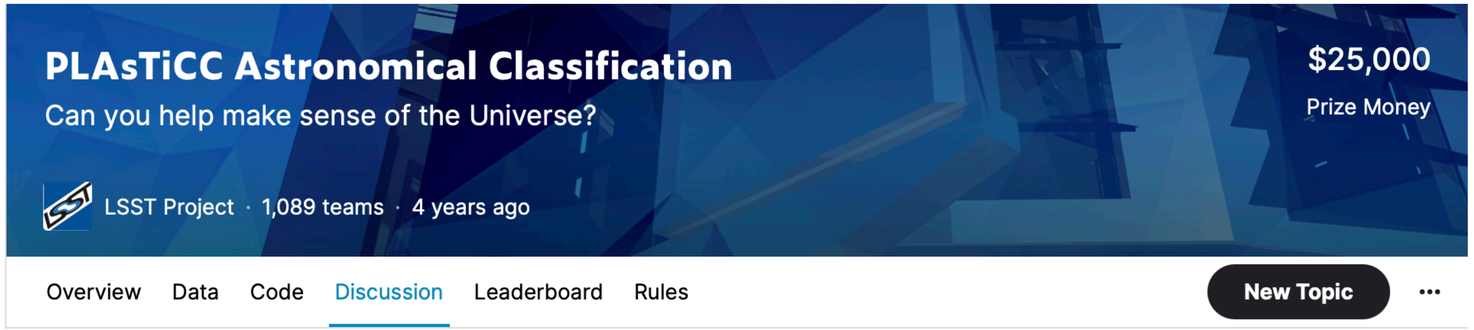

Objective: To foster development of machine learning algorithms for photometric classification of transients.

Name	Boosted Decision Trees			Neural Nets			
	LightGBM	CatBoost	XGBoost	NN	CNN	RNN	MLP
Kyle Boone	✓	✗	✗	✗	✗	✗	✗
Mike & Silogram	✓	✗	✗	✗	✗	✓	✗
Major Tom, mamas & nyanp	✓	✓	✗	✗	✓	✗	✗
Ahmet Erdem	✓	✗	✗	✓	✗	✗	✗
SKZ Lost in Translation	✓	✗	✗	✗	✗	✓	✓
Stefan Stefanov	✗	✗	✗	✓	✗	✗	✗
rapids.ai	✓	✗	✗	✗	✗	✓	✓
Three Musketeers	✓	✓	✓	✗	✓	✗	✗
Simon Chen	✓	✗	✗	✗	✗	✗	✗
Go Spartans!	✓	✗	✓	✗	✗	✗	✗

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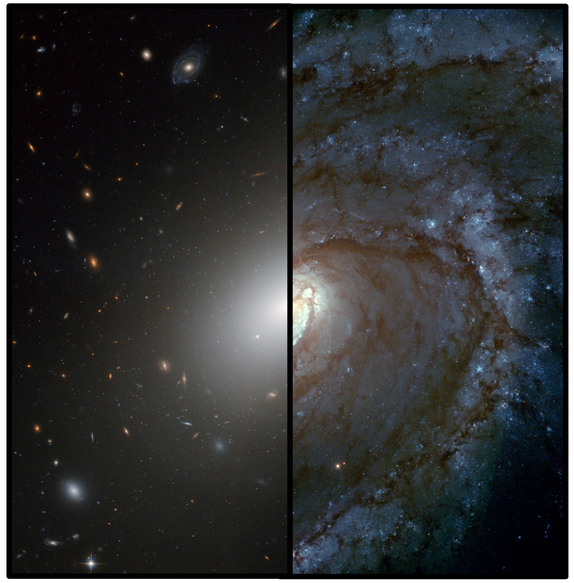
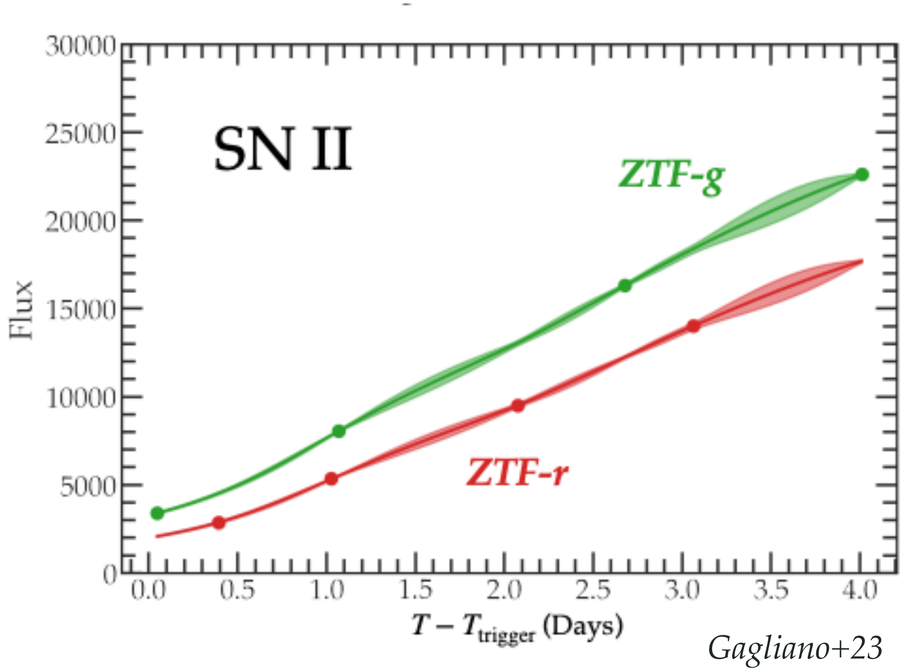
Host-Enabled Early-Time Classification

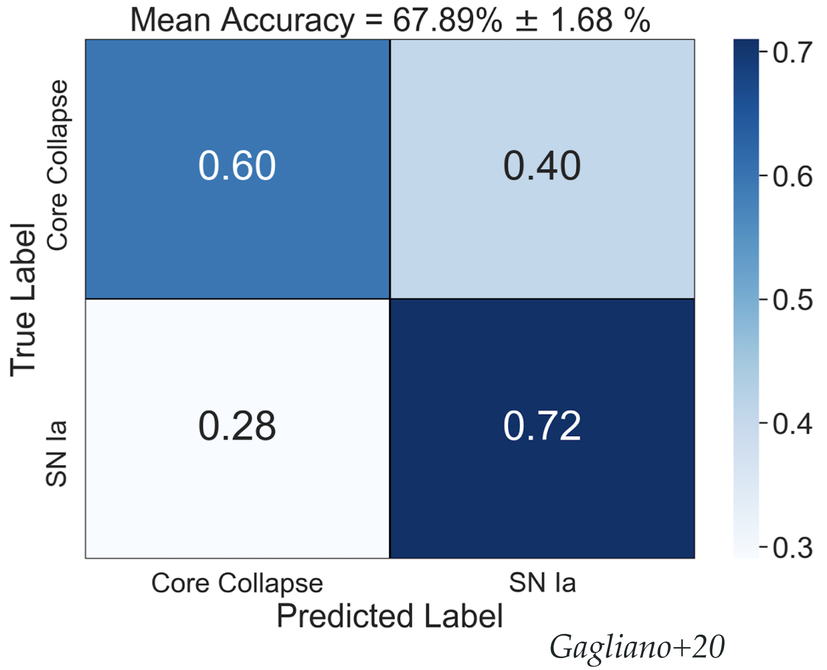
How well can we do with the **explosion site**?



NGC 1132,4321; *NASA/ESA/Hubble*



Gagliano+23



Gagliano+20

~70% accuracy from host galaxy photometry alone, with further improvements from partial-phase SN photometry.

(Gagliano+20,23)

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What's the Value of Classification?

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What's the Value of Classification?

1. Linking Observations to Underlying Explosion Physics

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What's the Value of Classification?

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2. Finding & Observing Transients that Challenge Existing Models

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What's the Value of Classification?

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Circumstellar Interaction

Kandinsky, Squares with Concentric Circles

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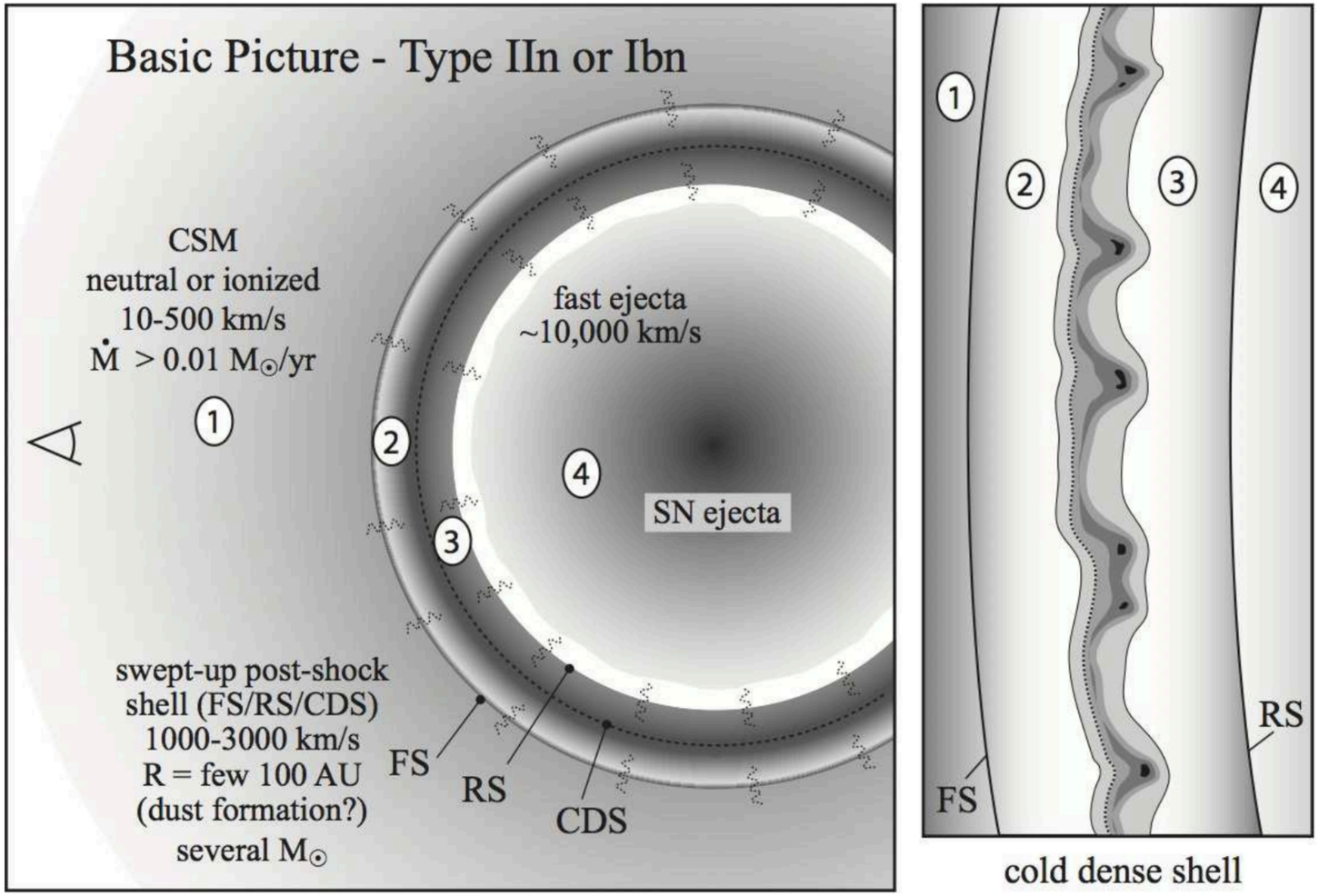
Circumstellar Material (CSM) and Its History



Smith+2014

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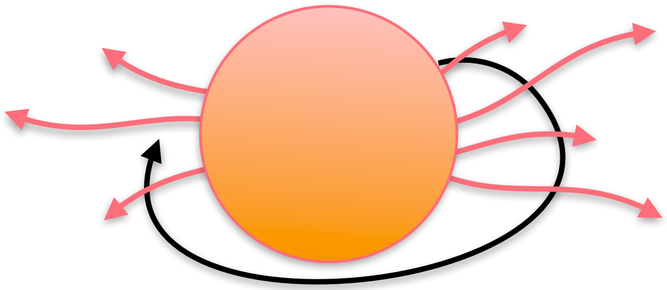
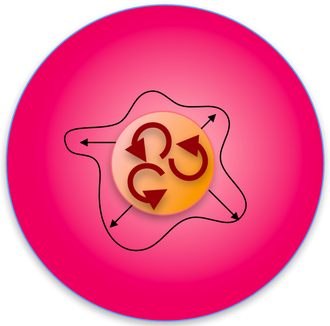
Where Does CSM Come From?

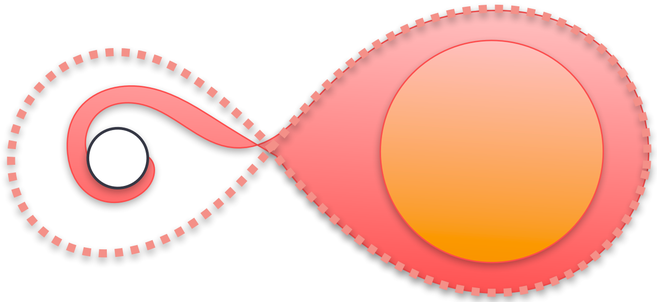
Centrifigully-induced mass-loss in rapidly rotating stars.
(Aguilera-Dena+18)



Energy deposition from convection-driven gravity waves.
(Quataert & Shiode+12; Wu & Fuller+22)



Mass transfer onto stellar companion.
(Sun+20)



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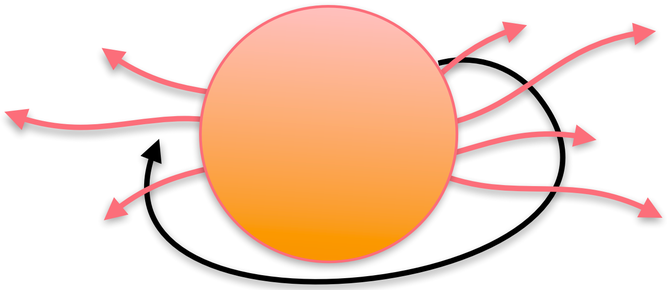

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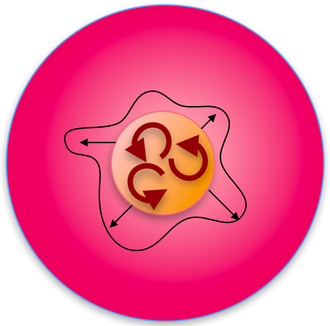

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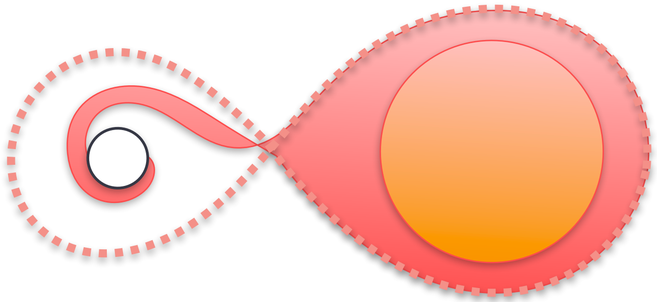
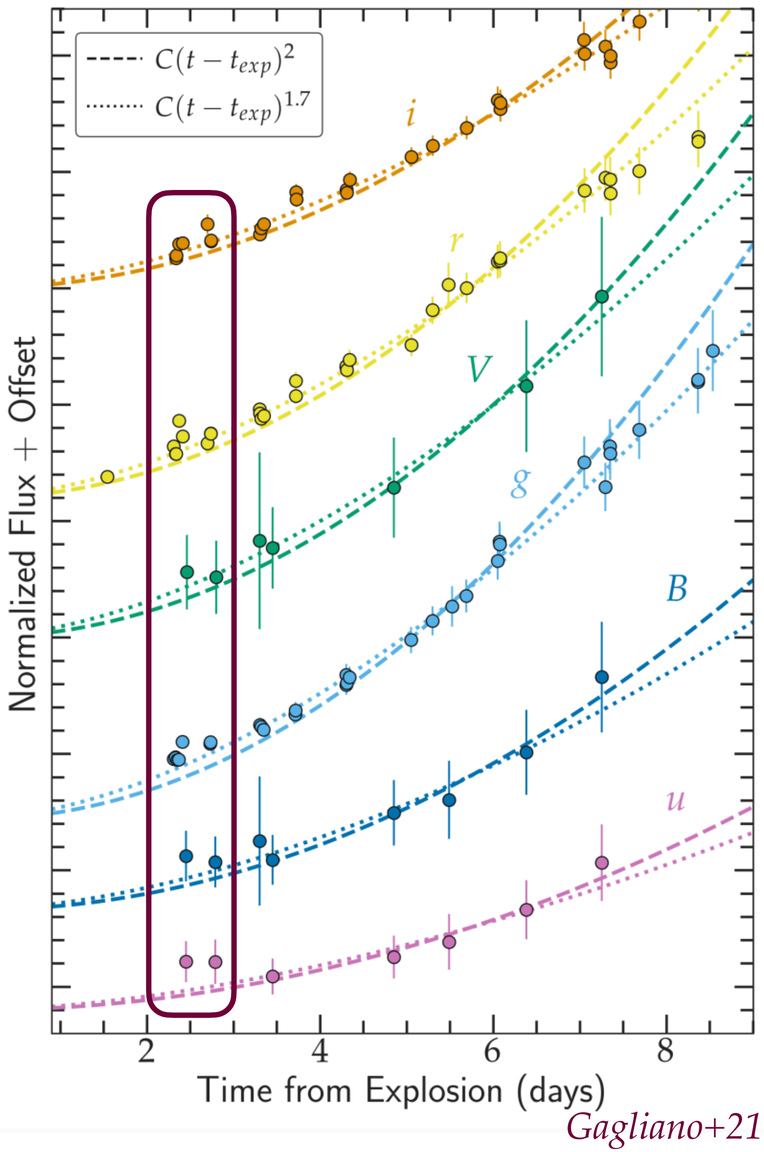


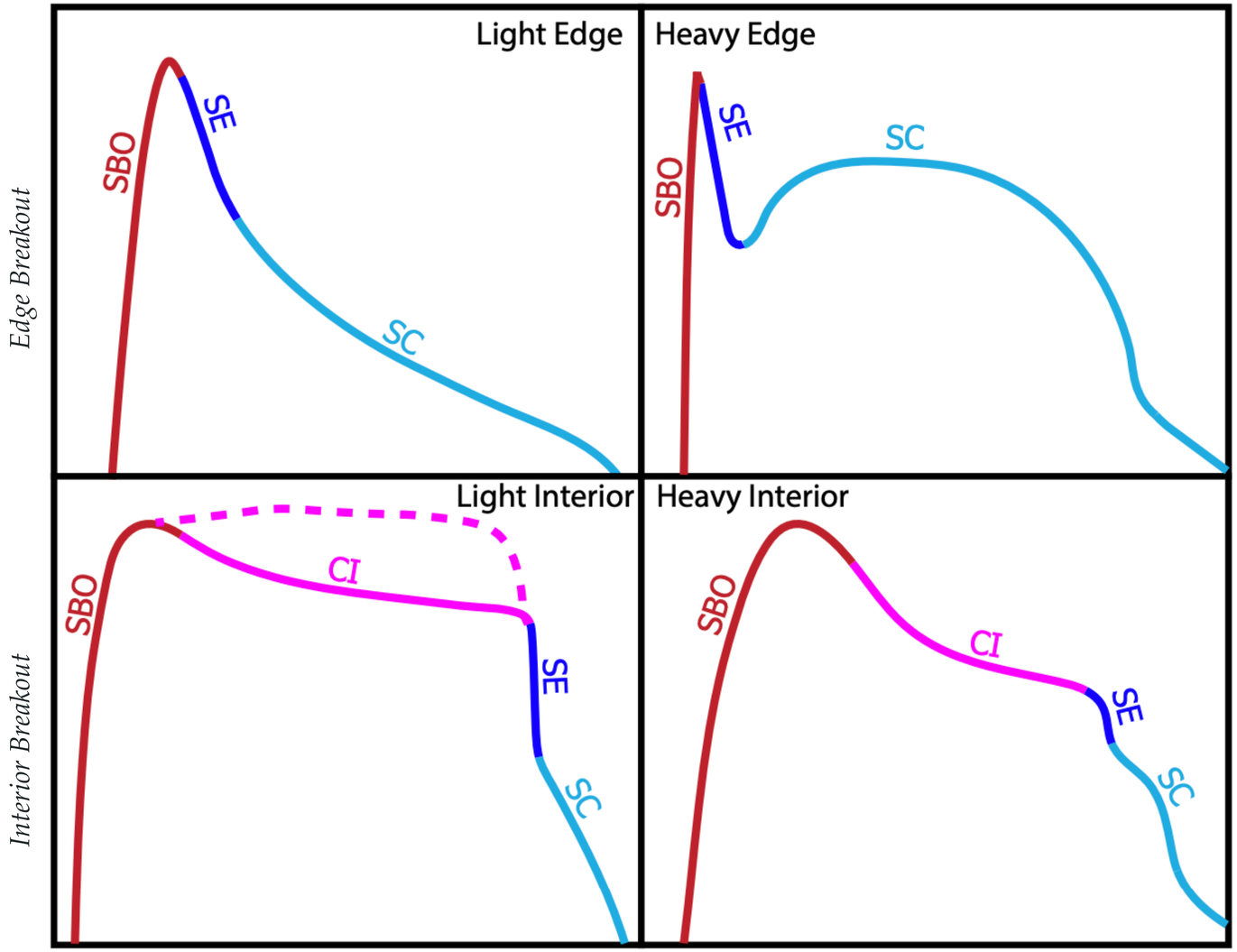
Infrared (>100 yr) *Optical (0.1 - 100 yr)* *Radio (<0.1 yr)*

CSM Breeds Persistent Anomalous Behavior



Gagliano+21

Khatami & Kasen+23



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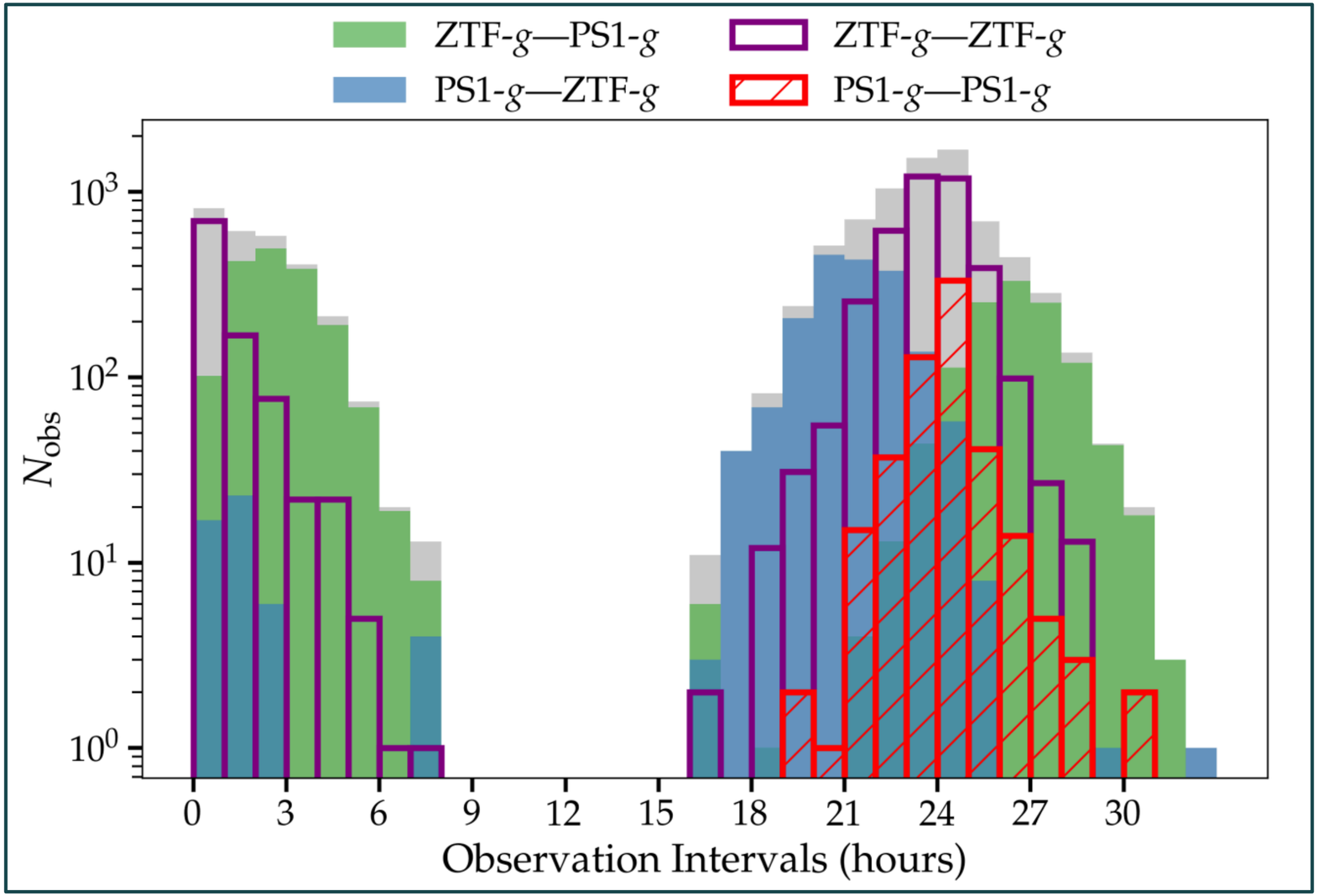
The Young Supernova Experiment

https://www2.ifa.hawaii.edu/research/Pan-STARRS.shtml

7% of time on Pan-STARRS1, 7% of time on Pan-STARRS2

3-day cadence + overlap with public photometry yields **highest effective cadence** of any ongoing transient survey.



(Aleo+23)

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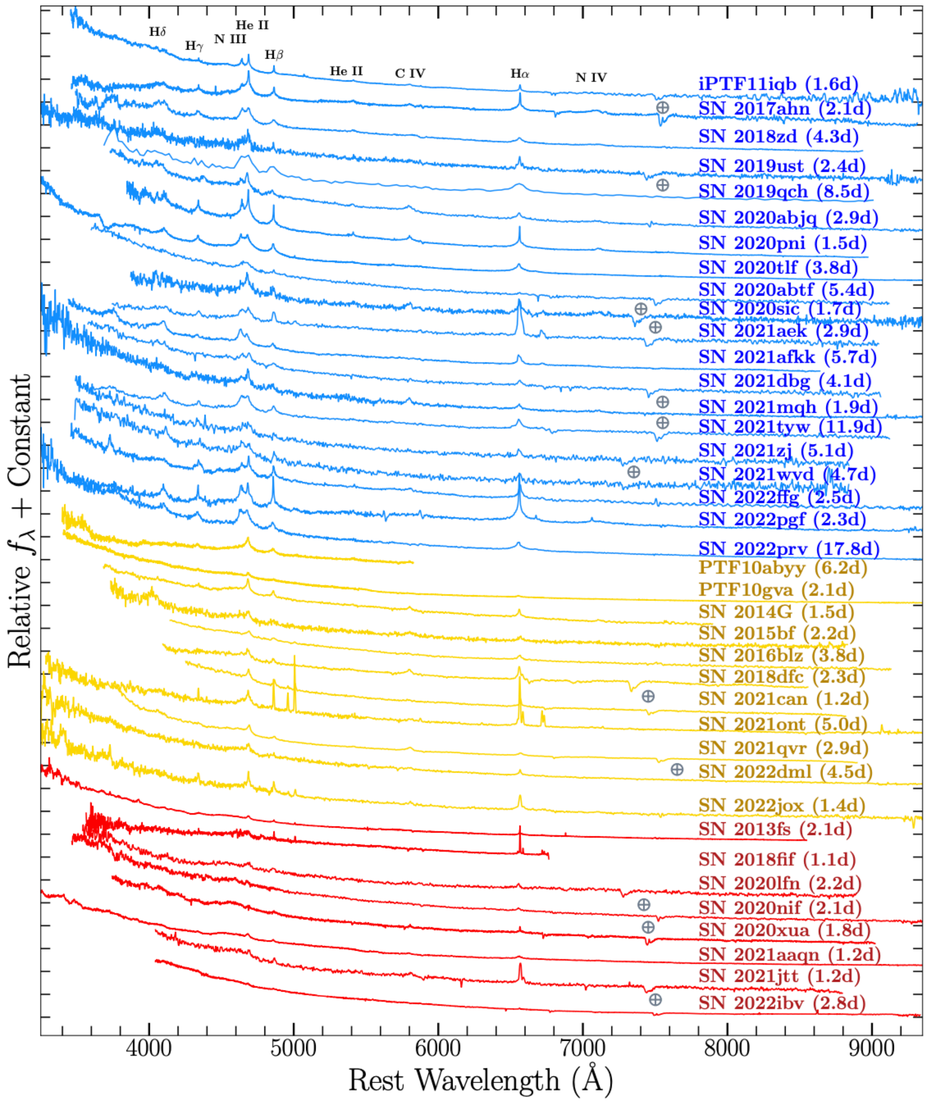
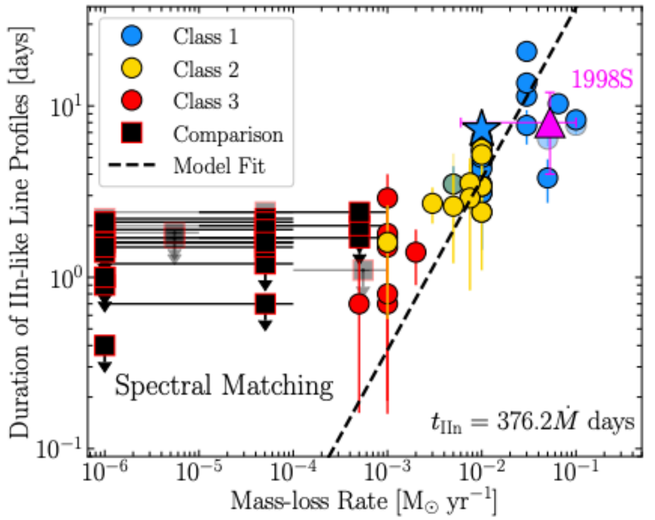
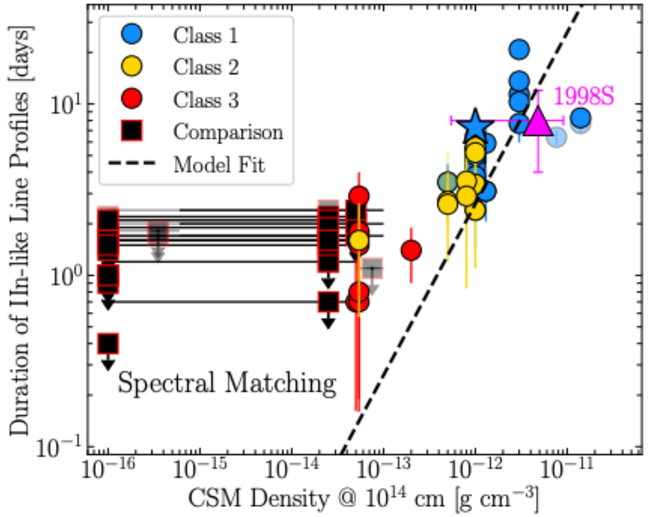
Constraints on Phases and Mass-Loss Rates



(Jacobson-Galán+24)

Early YSE spectroscopy provides new constraints on **CSM density profiles** for 39 supernovae (largest to date)!





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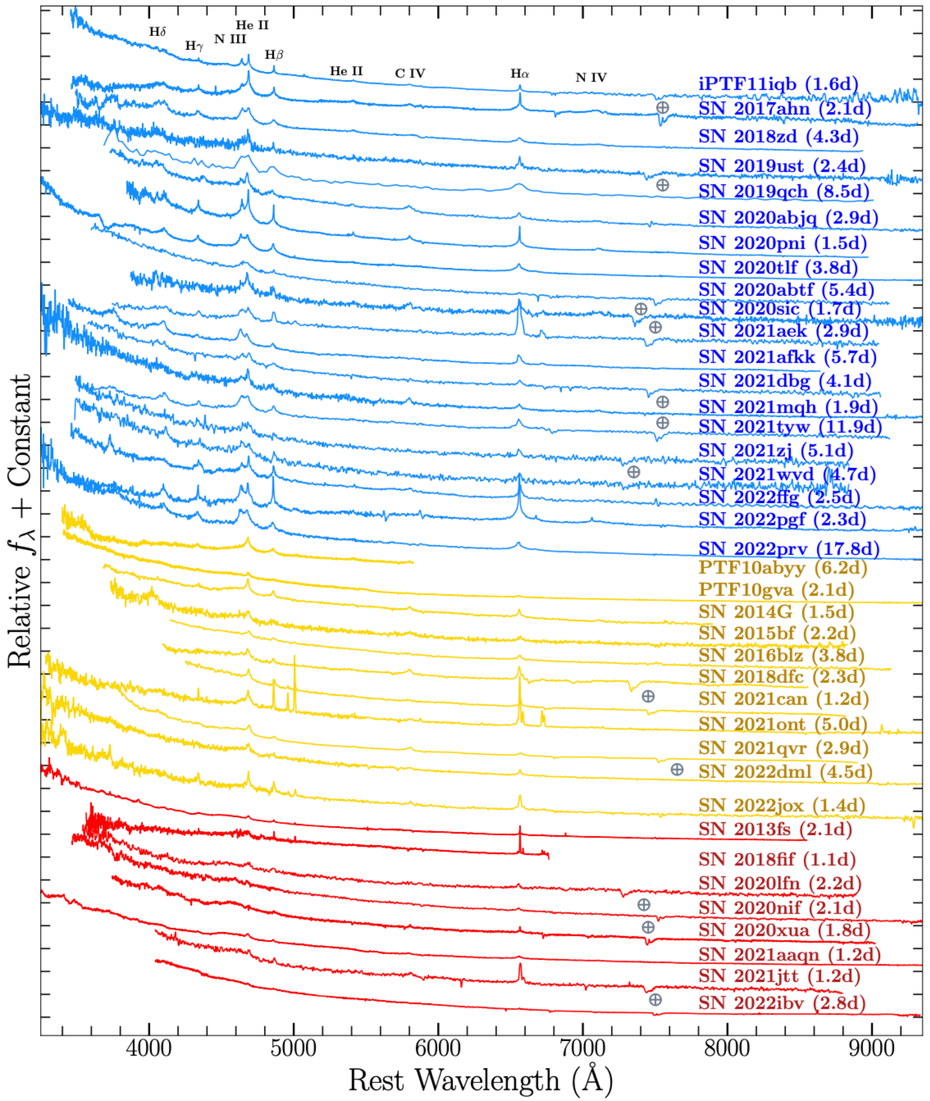
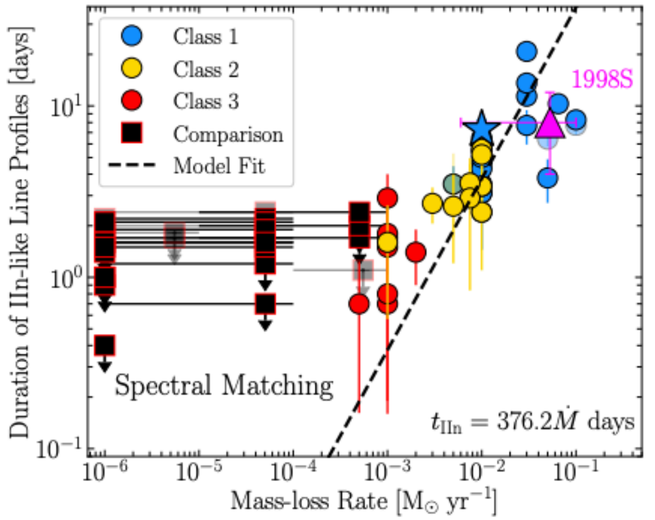
Constraints on Phases and Mass-Loss Rates

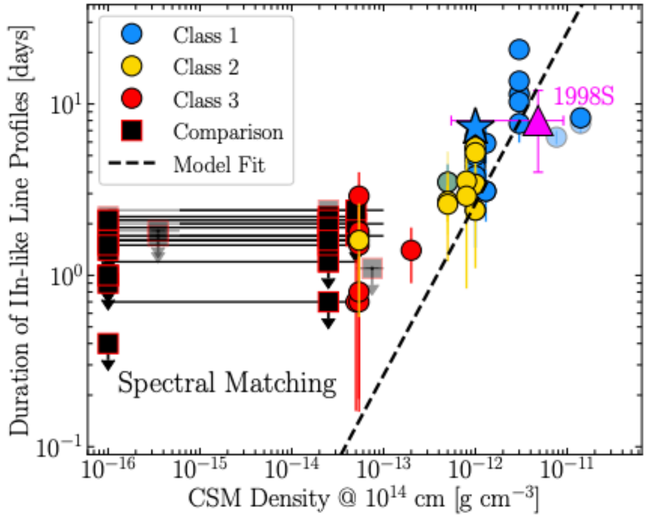


(Jacobson-Galán+24)

Early YSE spectroscopy provides new constraints on **CSM density profiles** for 39 supernovae (largest to date)!

Can we look for them directly?





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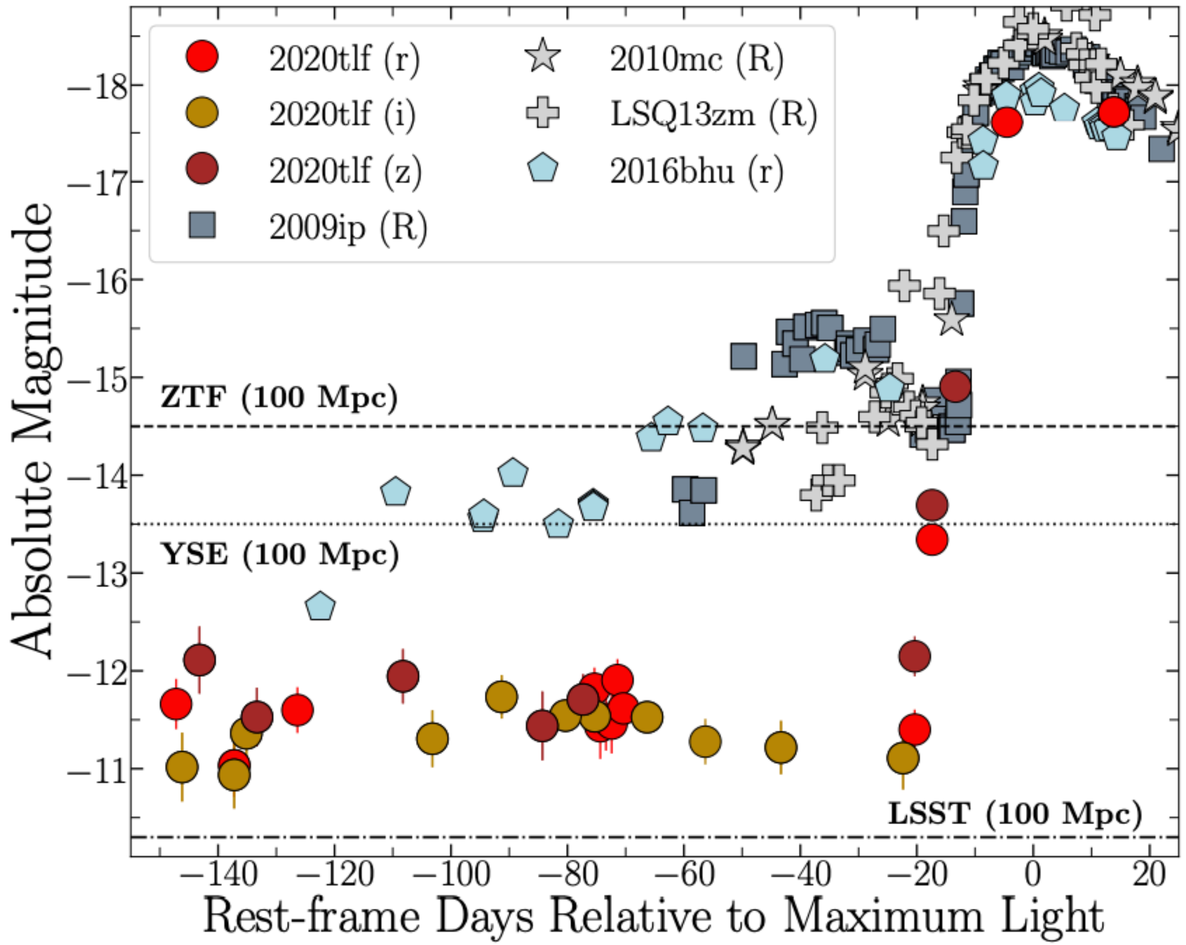
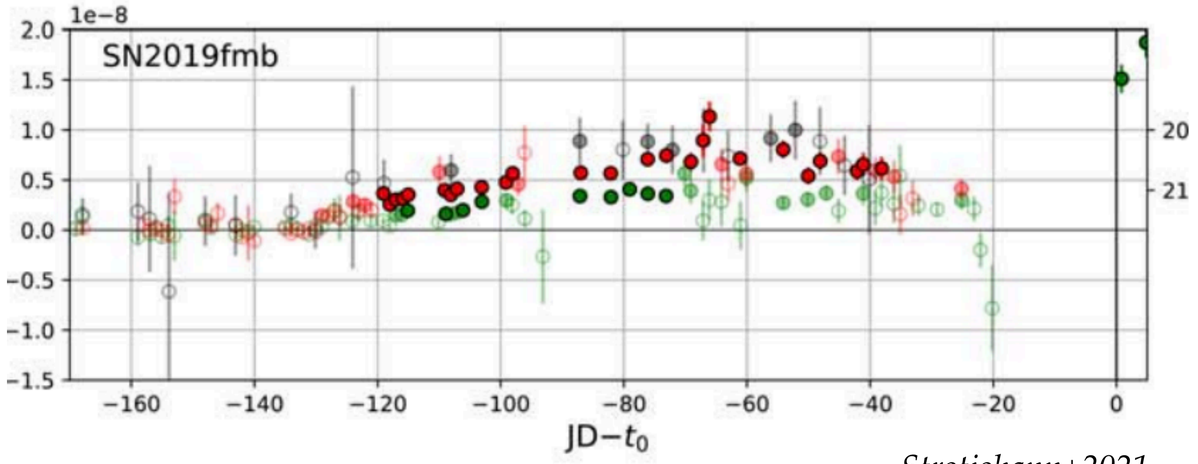
Yes!



(*Jacobson-Galán+2022*)



Strotjohann+2021

Precursor eruptions are a **direct, independent probe** of CSM formation.

But we can't make population statements with 10 events.

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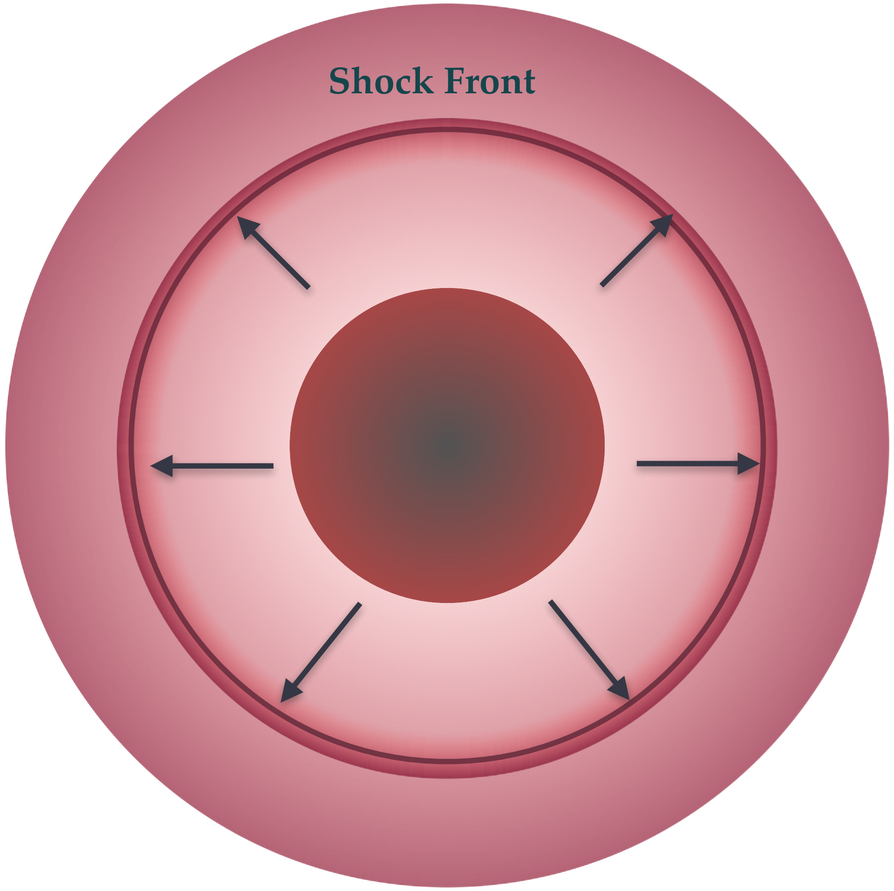
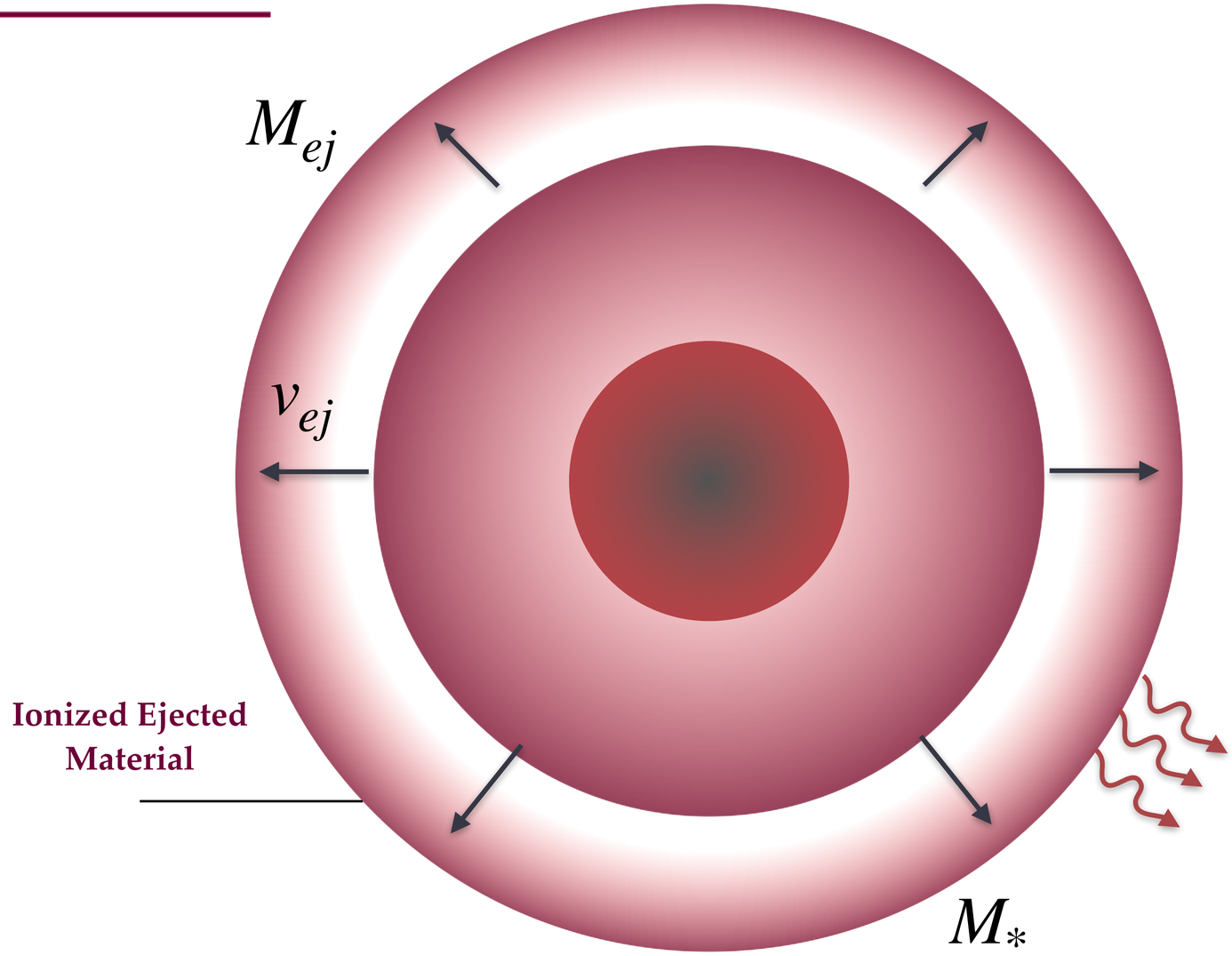
Modeling an Eruptive Precursor





(Matsumoto & Metzger, 2022)

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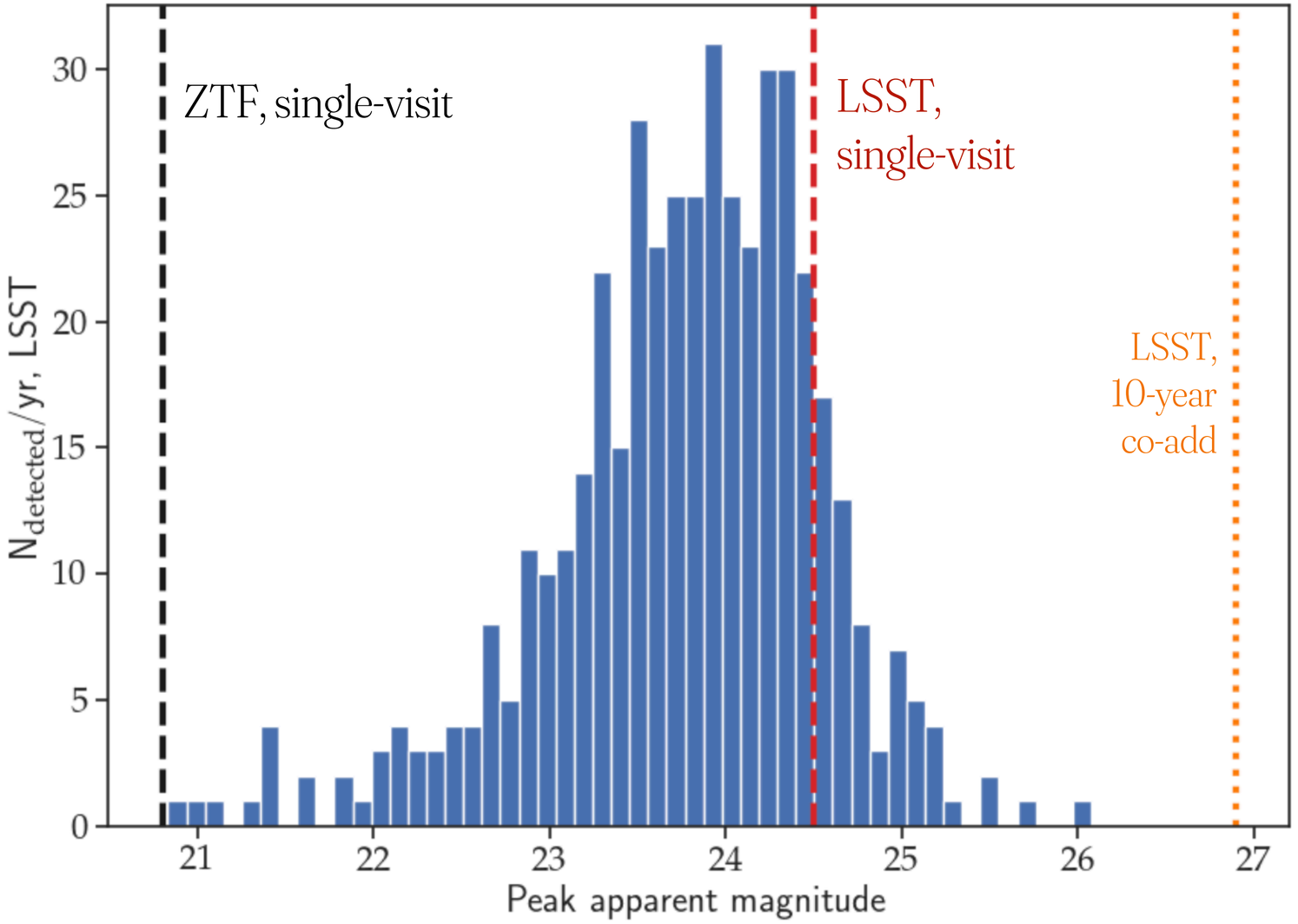
Preliminary Results for LSST

The Rubin Observatory may directly detect **~100 eruptive precursors/yr** *(Gagliano & Berger+24, in prep)*.

Scores more will fall out of image stacking.



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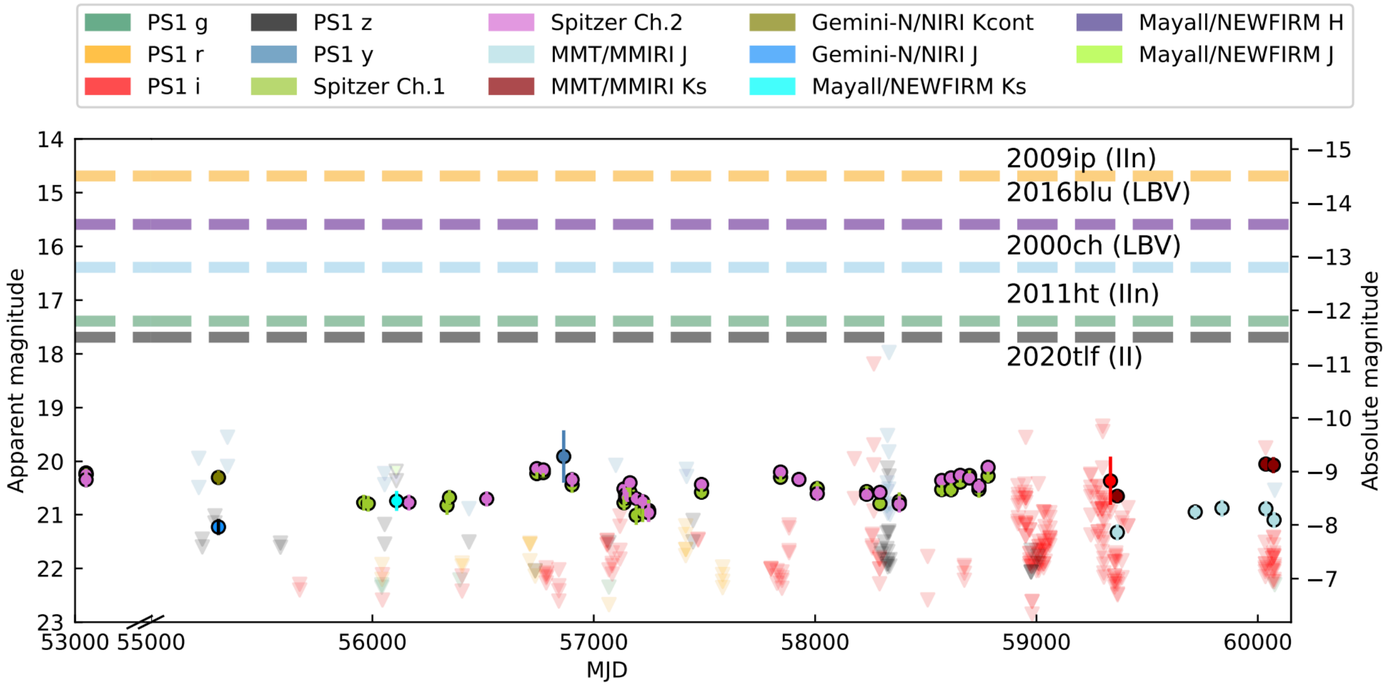
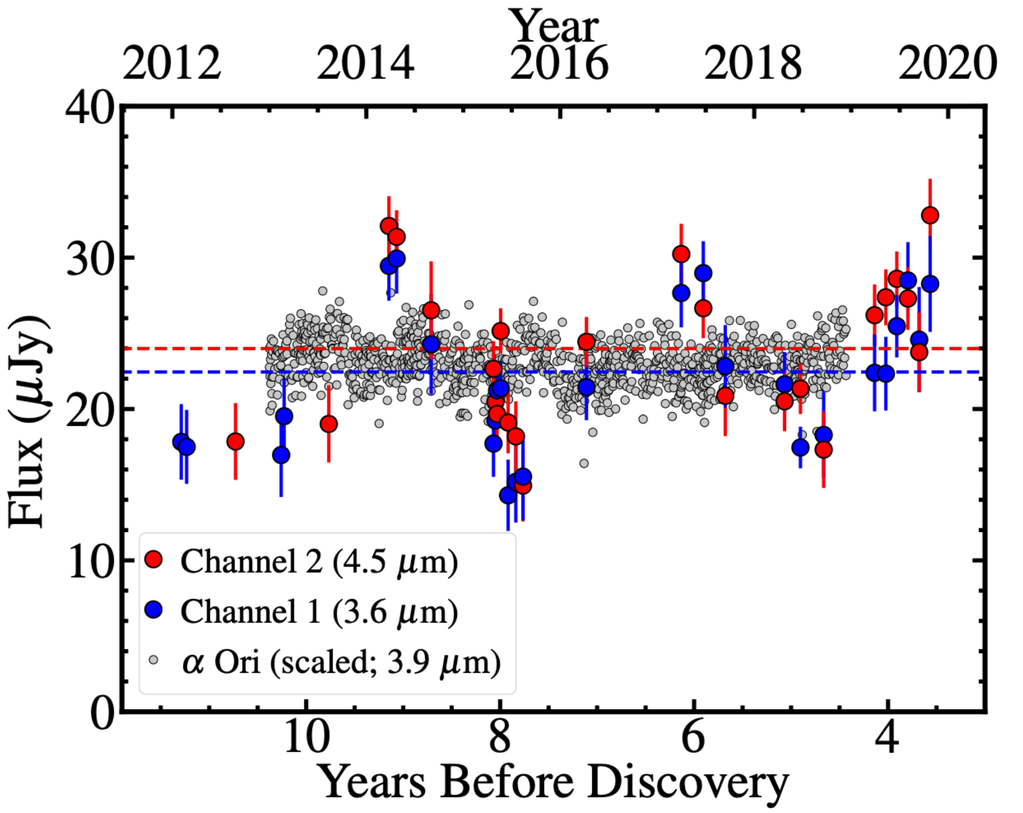
Dust Puts a Damper on the Situation



Ransome+2023



Kilpatrick+2023 (incl. A. Gagliano)

Dust can condense from the cooling CSM, **obscuring optical** emission.

Infrared missions like *Roman* (2027) offer a complementary view!

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Building Population Statistics, Photometrically

1. Does the SN's galaxy host massive stellar populations?

2. Does the light curve show prominent variability beyond radioactive decay? (e.g., phases of re-brightening?)

Benefits of Host Galaxy Characterization

A New Class of Fast Transients Has Emerged in an Unlikely Place

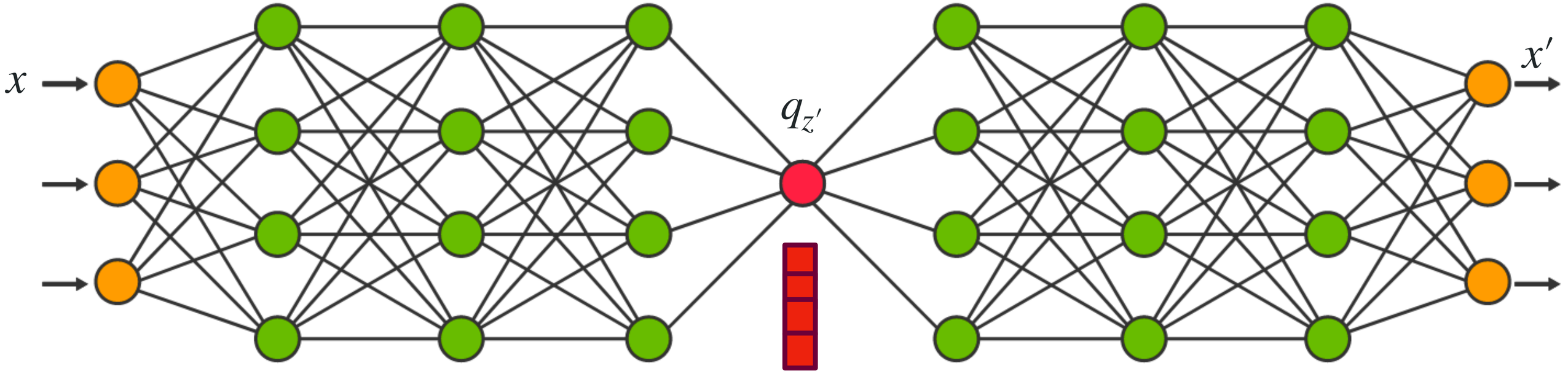
By Kerry Hensley on 15 September 2023 FEATURES Share:

Nicholl+23

1. Some **rare transient classes** correlate with **rare galaxies:**
   - SLSNe-I
     (Perley+16, Ørum+20, Cleland+23)
   - TDEs
     (*French+17, Bortolas+22, Wang+23*)
2. **Contextual anomalies** point to distinct formation channels.

Image Compression via Variational Autoencoders

Weights optimized to minimize distance of decoded values to input values.



$$\text{ELBO Loss} = MSE(x, x') + KL(q_{z'}||N)$$

Image Reconstruction Error

KL-Divergence

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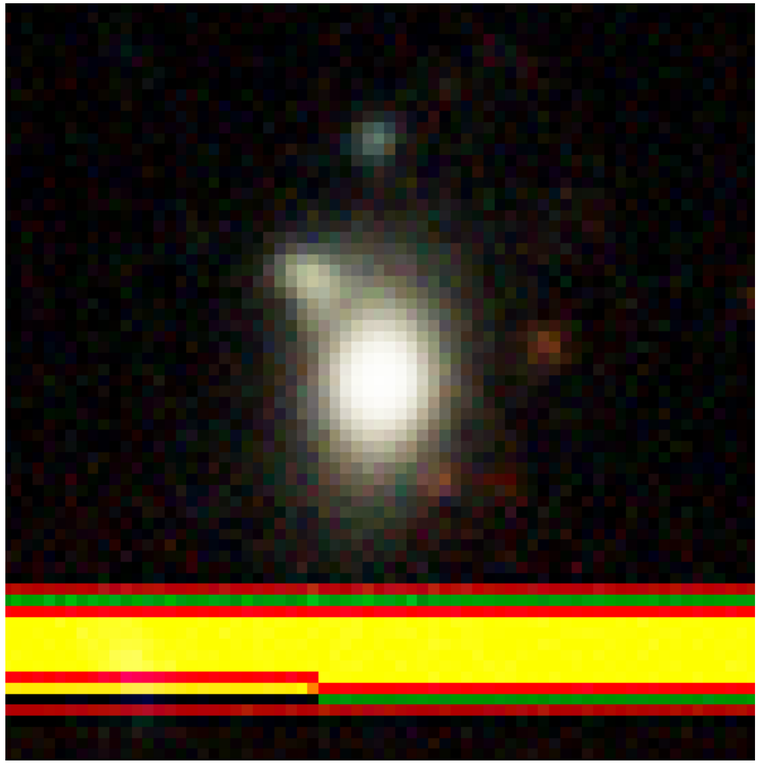
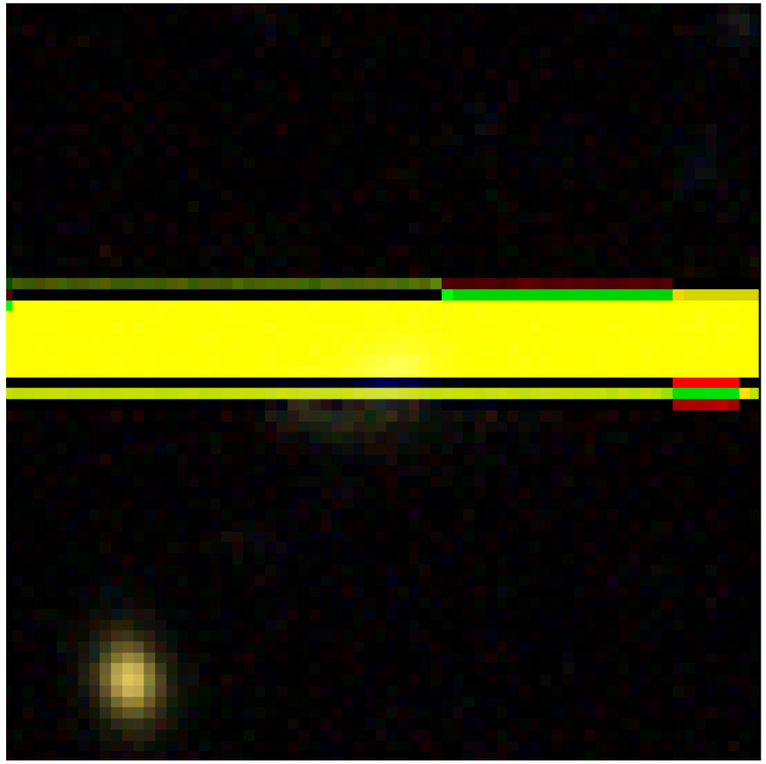
‘Galaxy’ Anomalies in the VAE Latent Space

Trained for ***grz*-band imaging of ~26k galaxies** from the Dark Energy Camera Legacy Survey (DECaLS).

Isolation forest on the latent space returns:





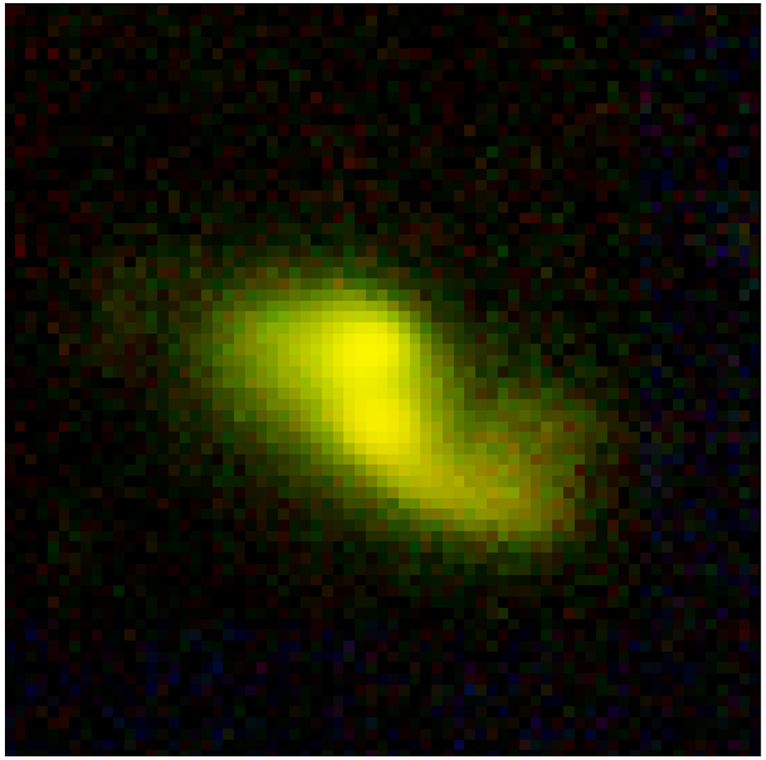


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Image Compression via Variational Autoencoders

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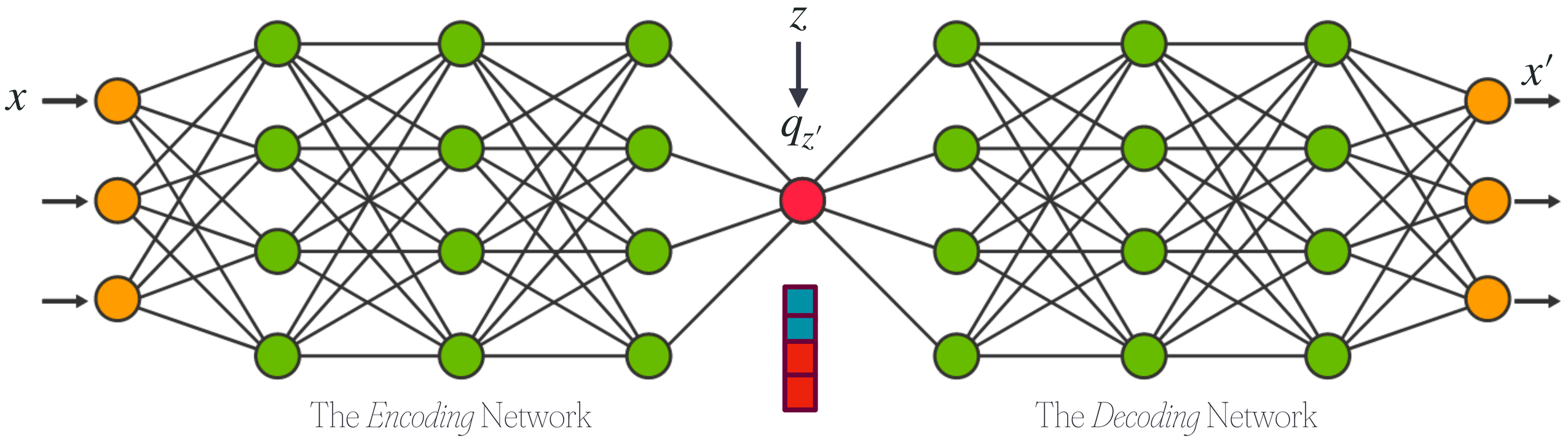

$$\text{ELBO Loss} = MSE(x, x') + KL(q_{z'}||N) + MSE(z, z')$$

Image Reconstruction Error | **KL-Divergence** | **Physical Parameter Reconstruction Error**

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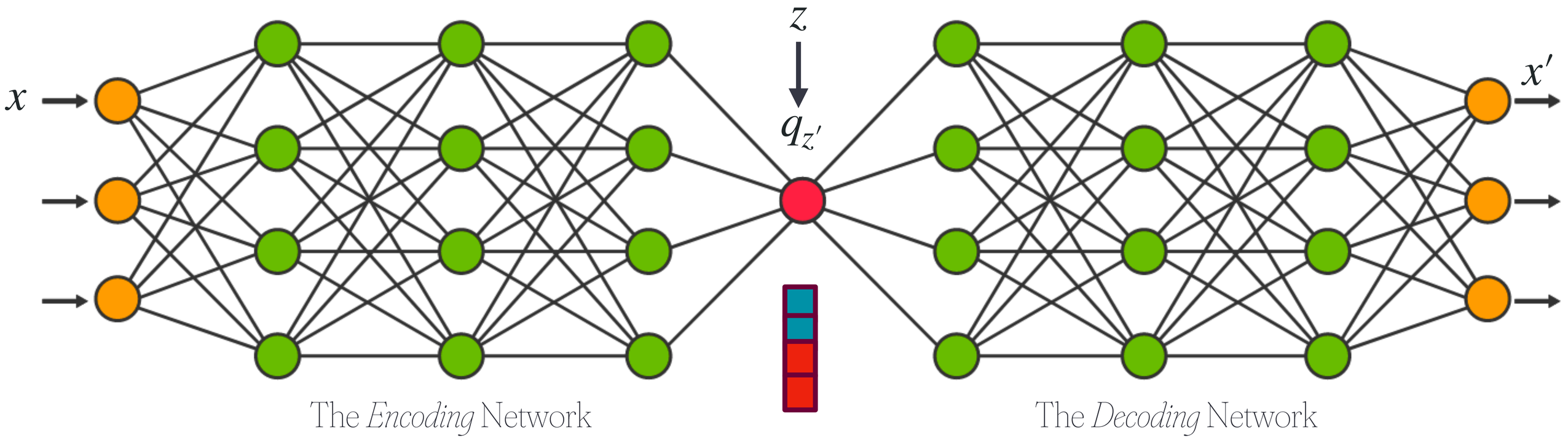
Image Compression via Variational Autoencoders

Weights optimized to minimize distance of decoded values to input values.



$$\text{ELBO Loss} = \beta_0 MSE(x, x') + KL(q_{z'}||N) + \beta_1 MSE(z, z')$$

Image Reconstruction Error | **KL-Divergence** | **Physical Parameter Reconstruction Error**

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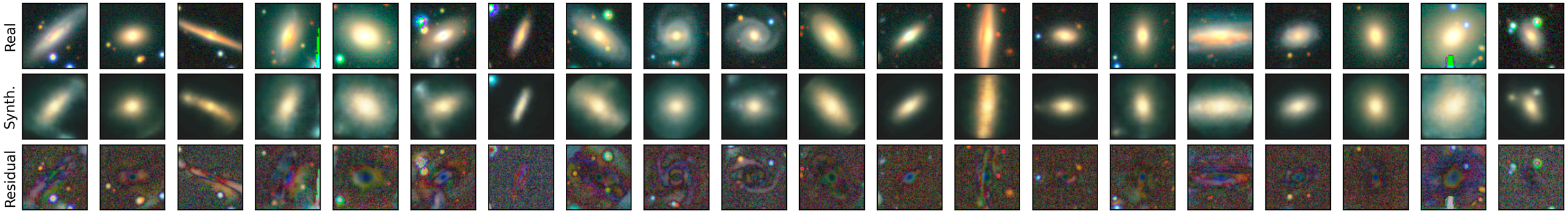
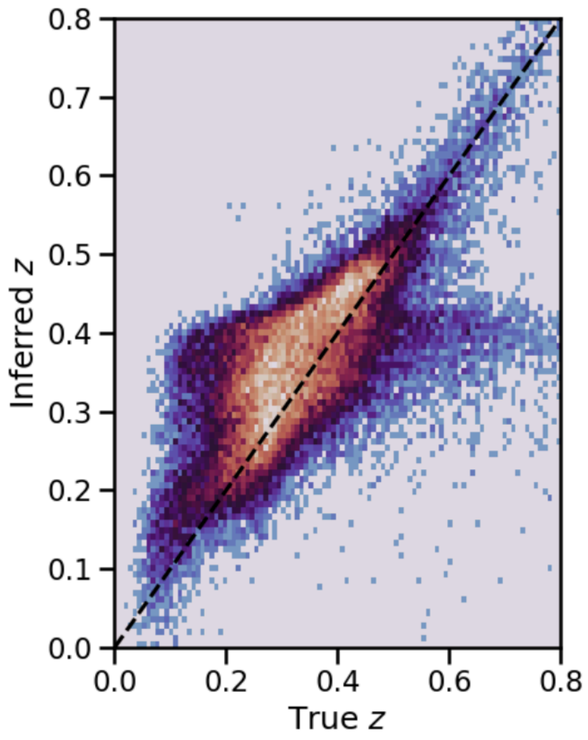
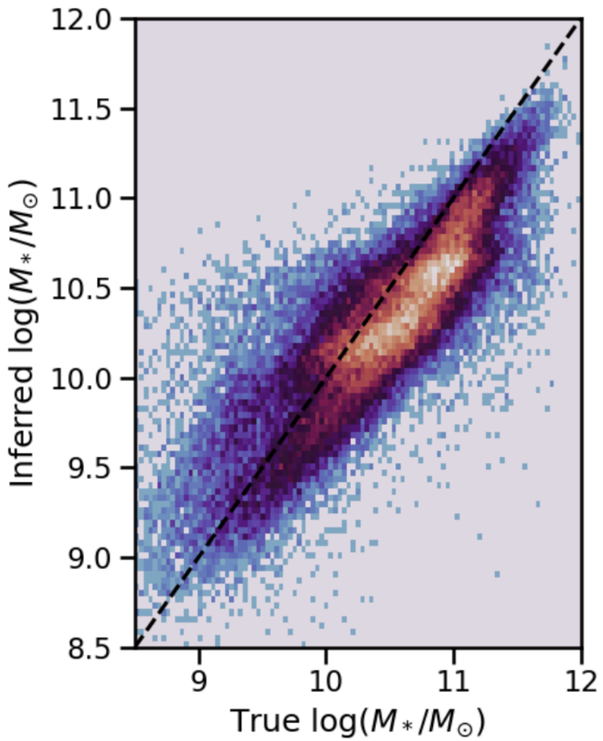
Galaxy Reconstructions: Images and Parameters



(Gagliano & Villar+24, in prep)





Scaled to **2M DECaLS galaxies**, with SED-derived z and stellar mass from *Zou+19*.

Trained for 200 epochs on 4 Cannon A100 GPUs.

Method	Redshift R^2	Stellar Mass R^2
(r, g, z) Photometry + MLP [11]	0.69	0.65
Image Embedding + MLP [16]	0.39	0.45
Image Embedding + MLP [11]	0.63	0.57
Image Embedding + kNN [11]	0.71	0.66
Image Embedding (ours)	**0.83**	**0.75**

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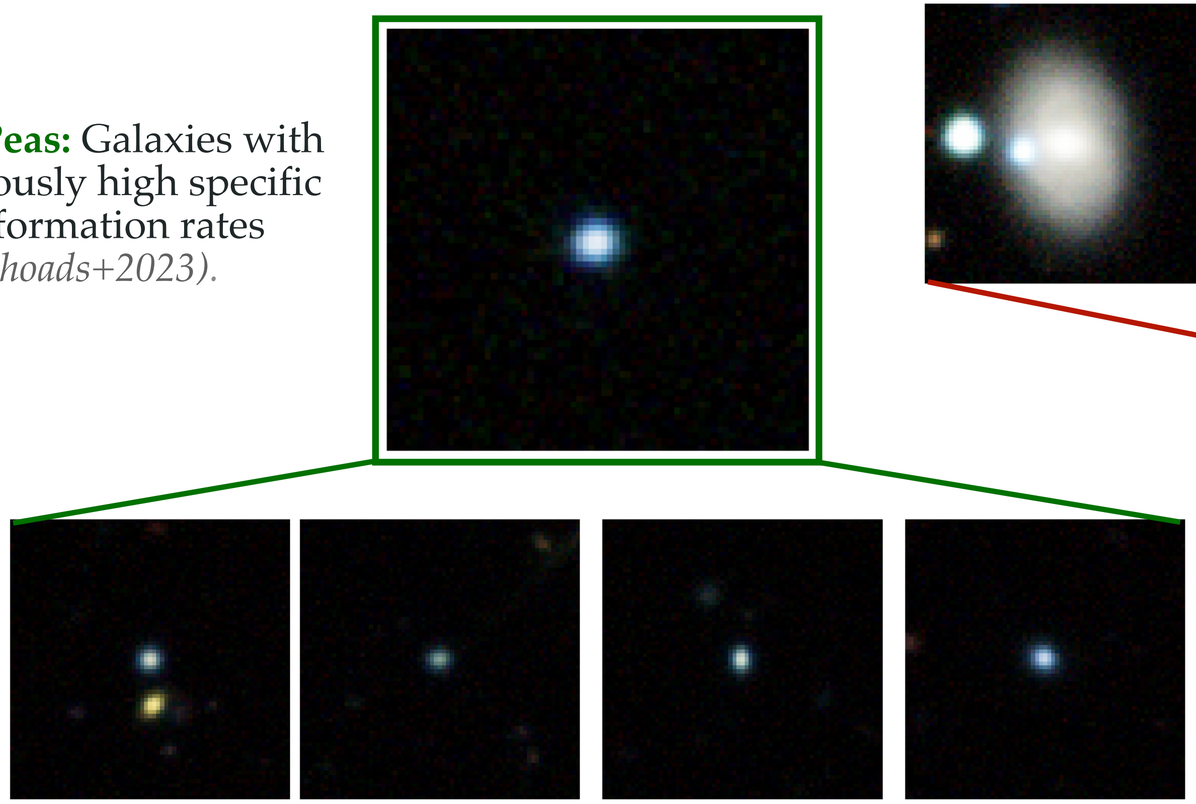
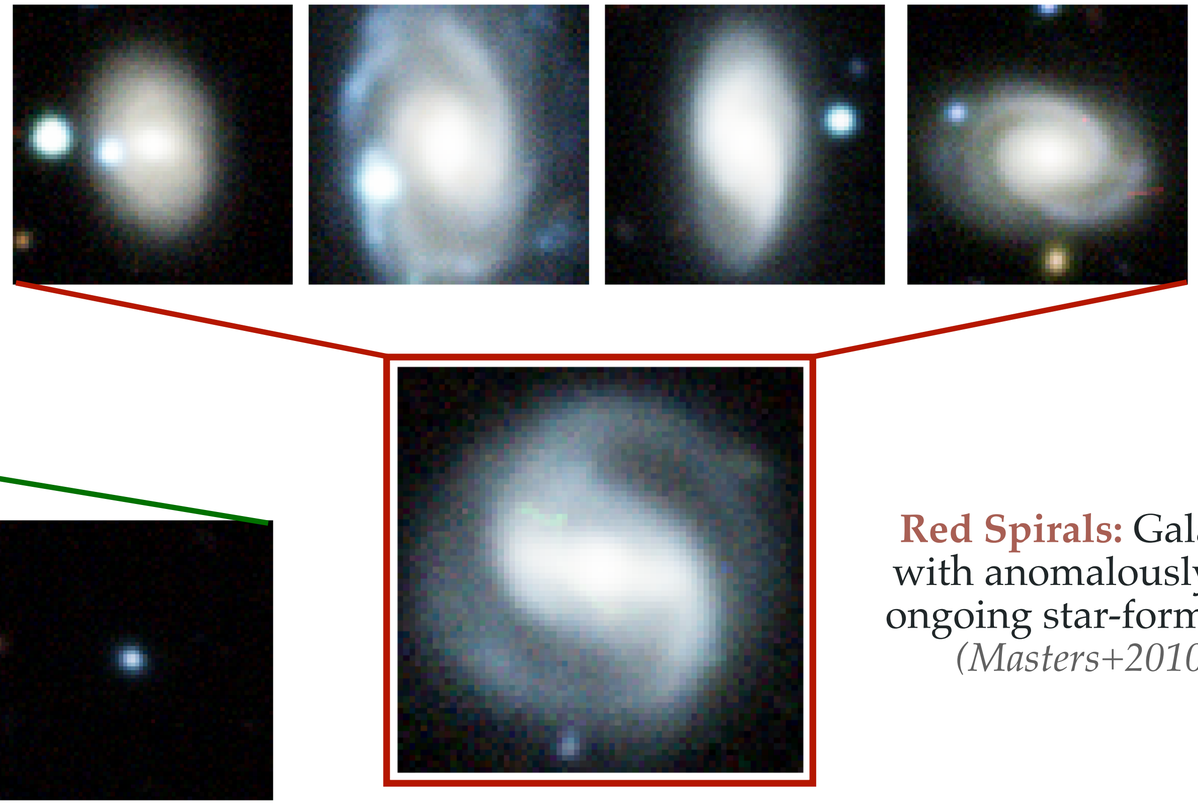
Recovering Galaxy Anomalies in the Latent Space

Green Peas: Galaxies with anomalously high specific star-formation rates *(Rhoads+2023)*.





Red Spirals: Galaxies with anomalously low ongoing star-formation *(Masters+2010)*.

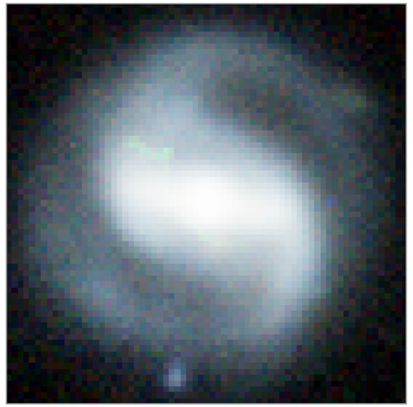
(Gagliano & Villar+23 NeurIPS)

Soon-to-be applied to the SN problem - stay tuned!

Combining SN and Host-Galaxy Properties

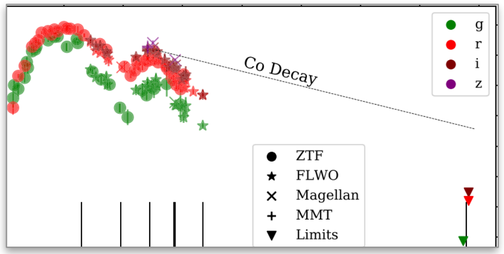
Multi-band imaging of supernova location

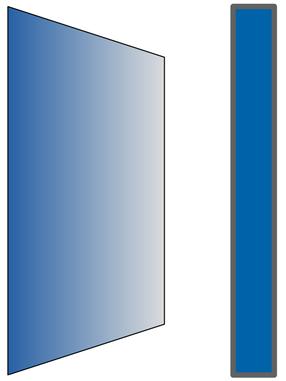
x

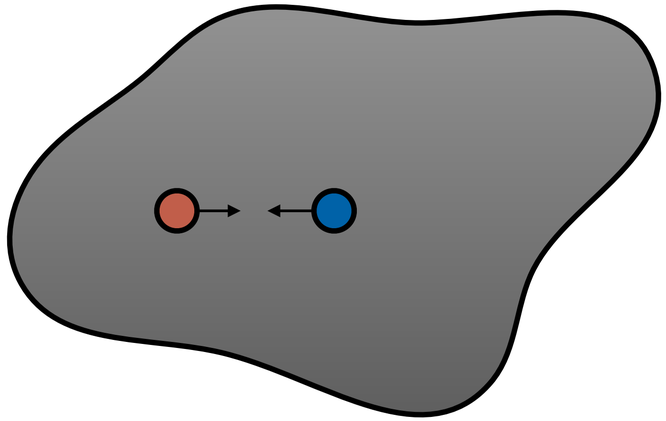


Supernova **photometry**

y







Contrastive loss allows for **embedding and aligning** multiple modalities, e.g.,

$$\mathscr{L} = -\frac{1}{|B|}\sum_{i=1}^{|B|}\sum_{j=1}^{|B|}\log\frac{1}{1+e^{z_{ij}(-tx_i\cdot y_j+b)}}$$

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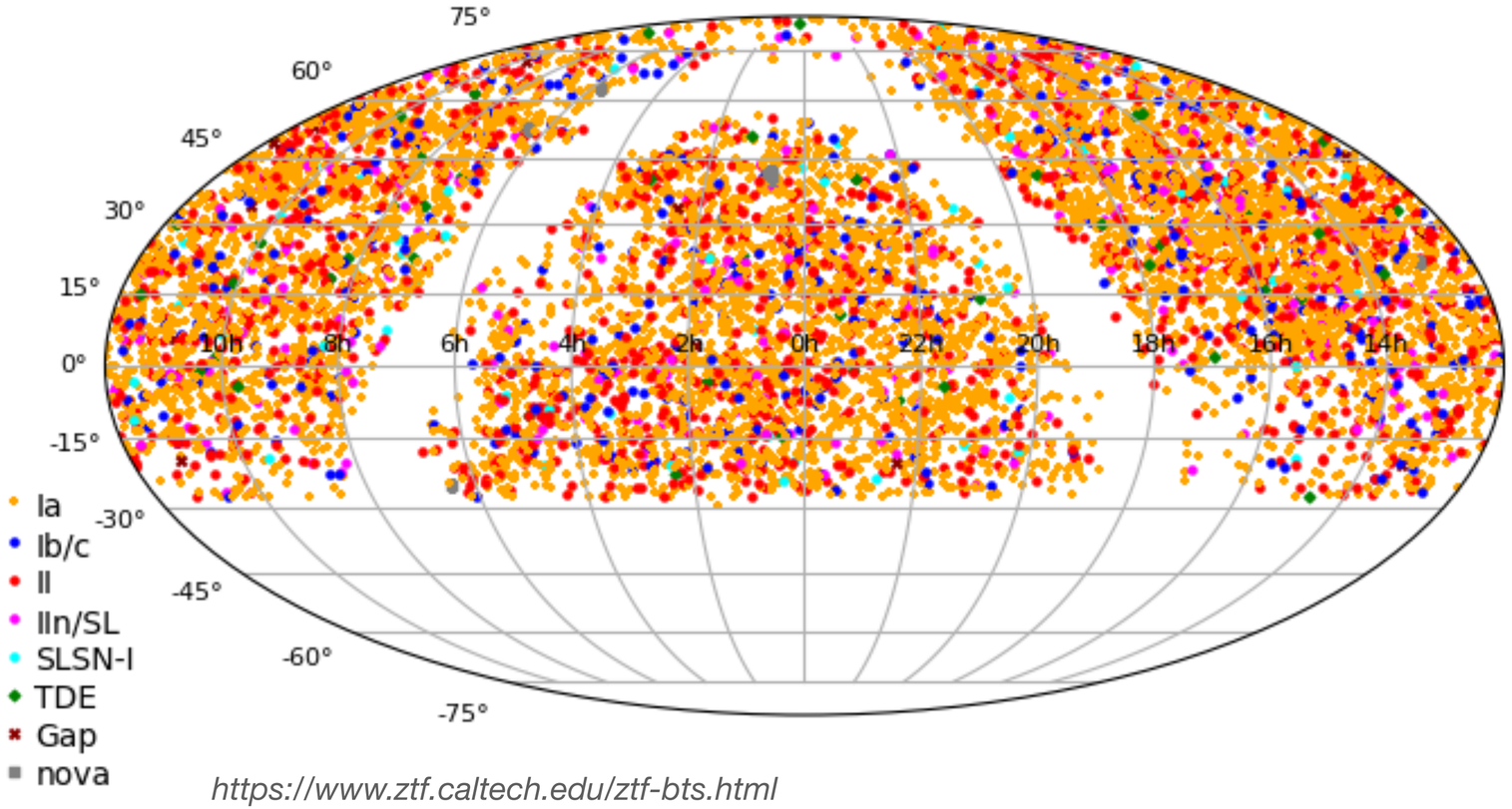
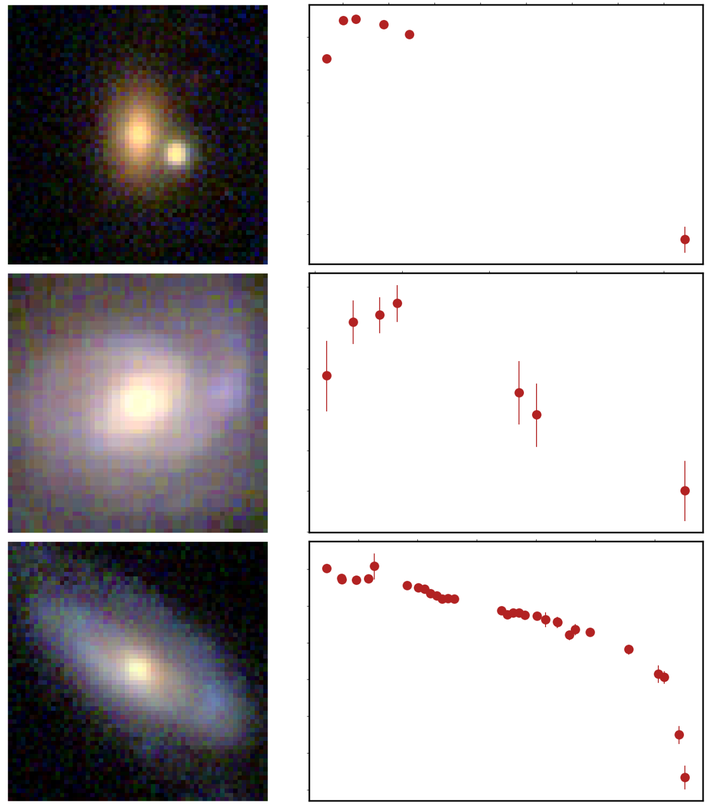
The Dataset: ZTF Bright Transient Sample



https://www.ztf.caltech.edu/ztf-bts.html



https://github.com/smsharma/iaifi-hackathon-2024/tree/main/multimodal_ssl

Scanned the Northern sky every ~2 nights in *g,r* since 2018.

>5,000 spectroscopic SNe with consistently-calibrated photometry & spectra!

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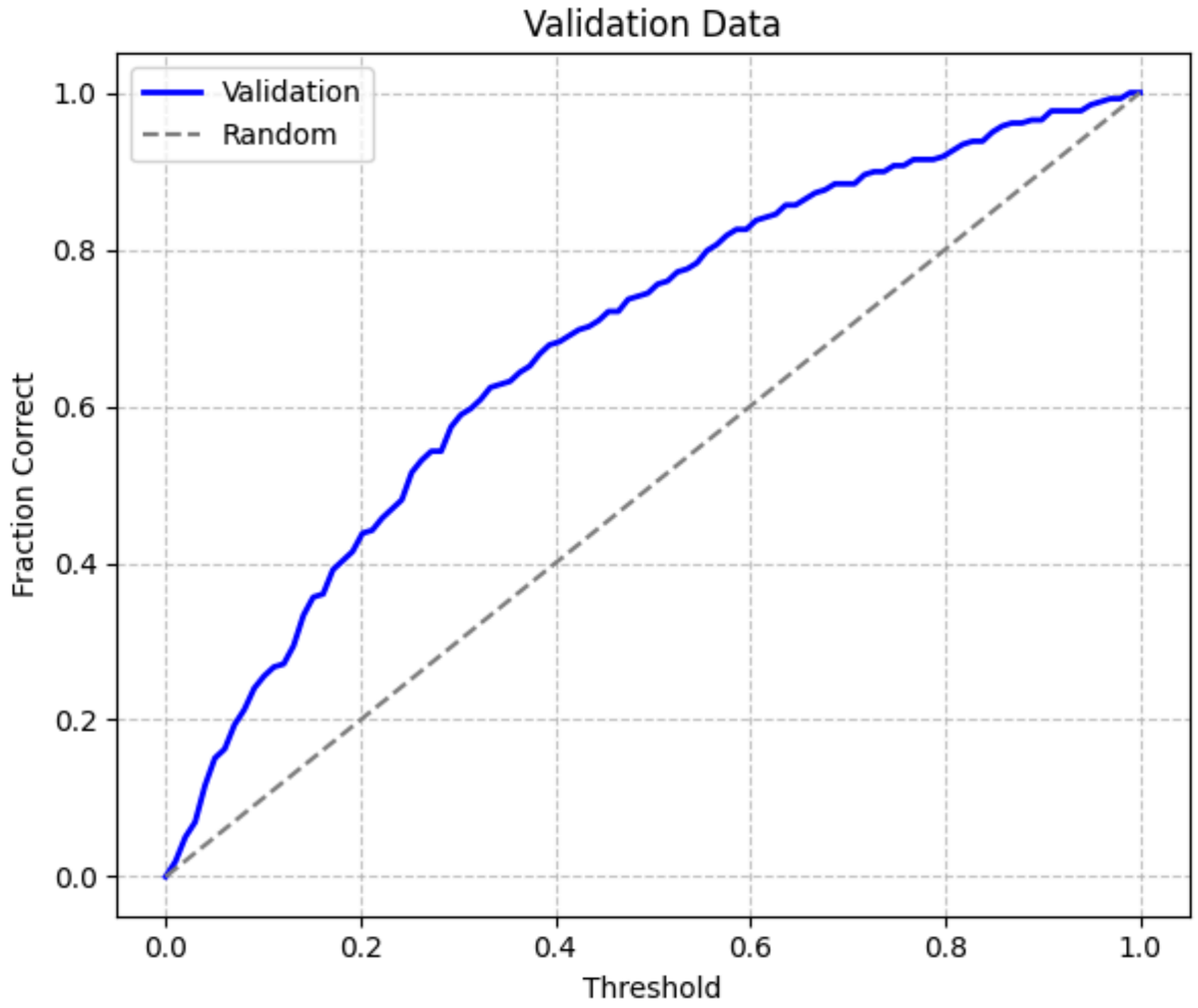
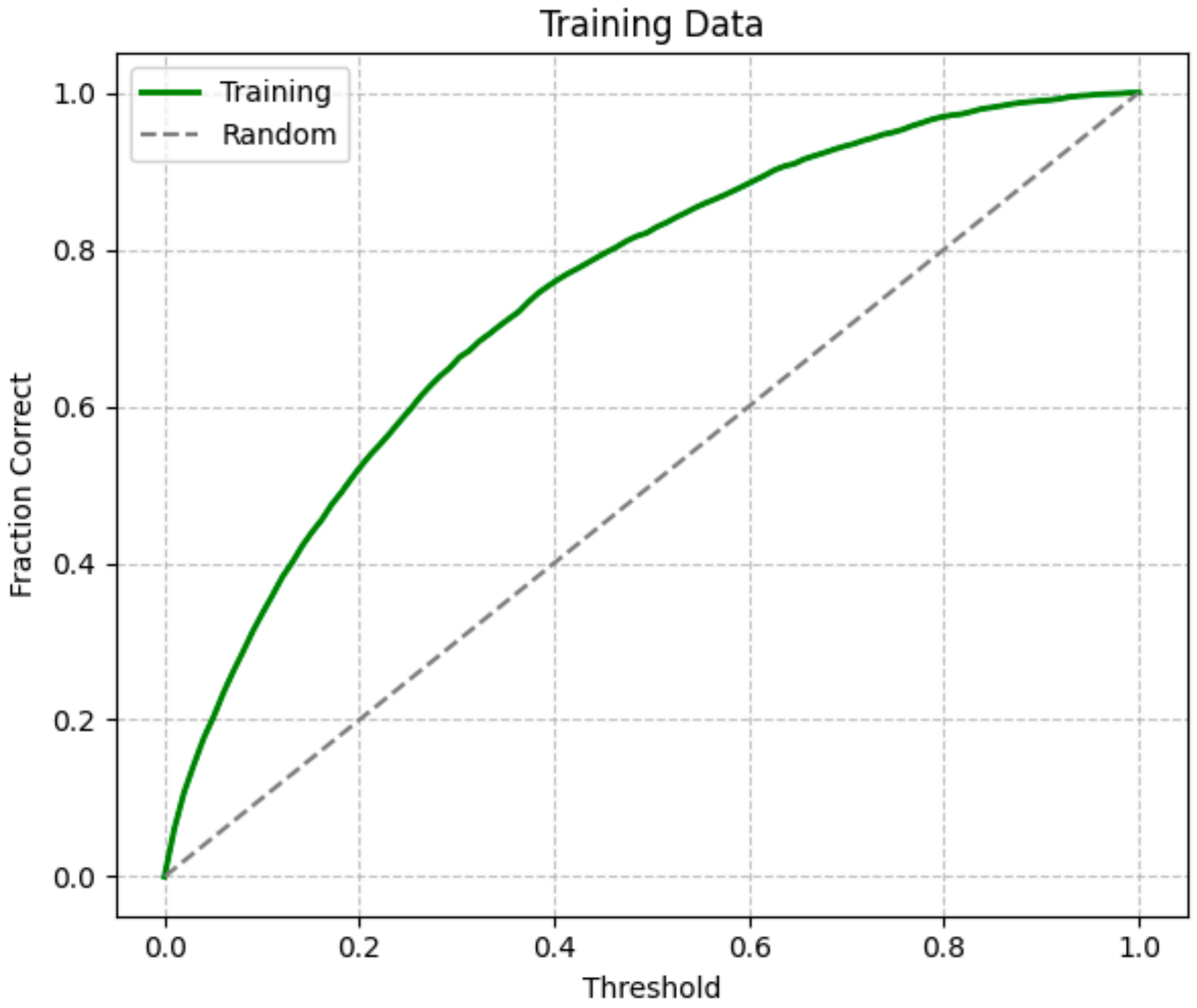
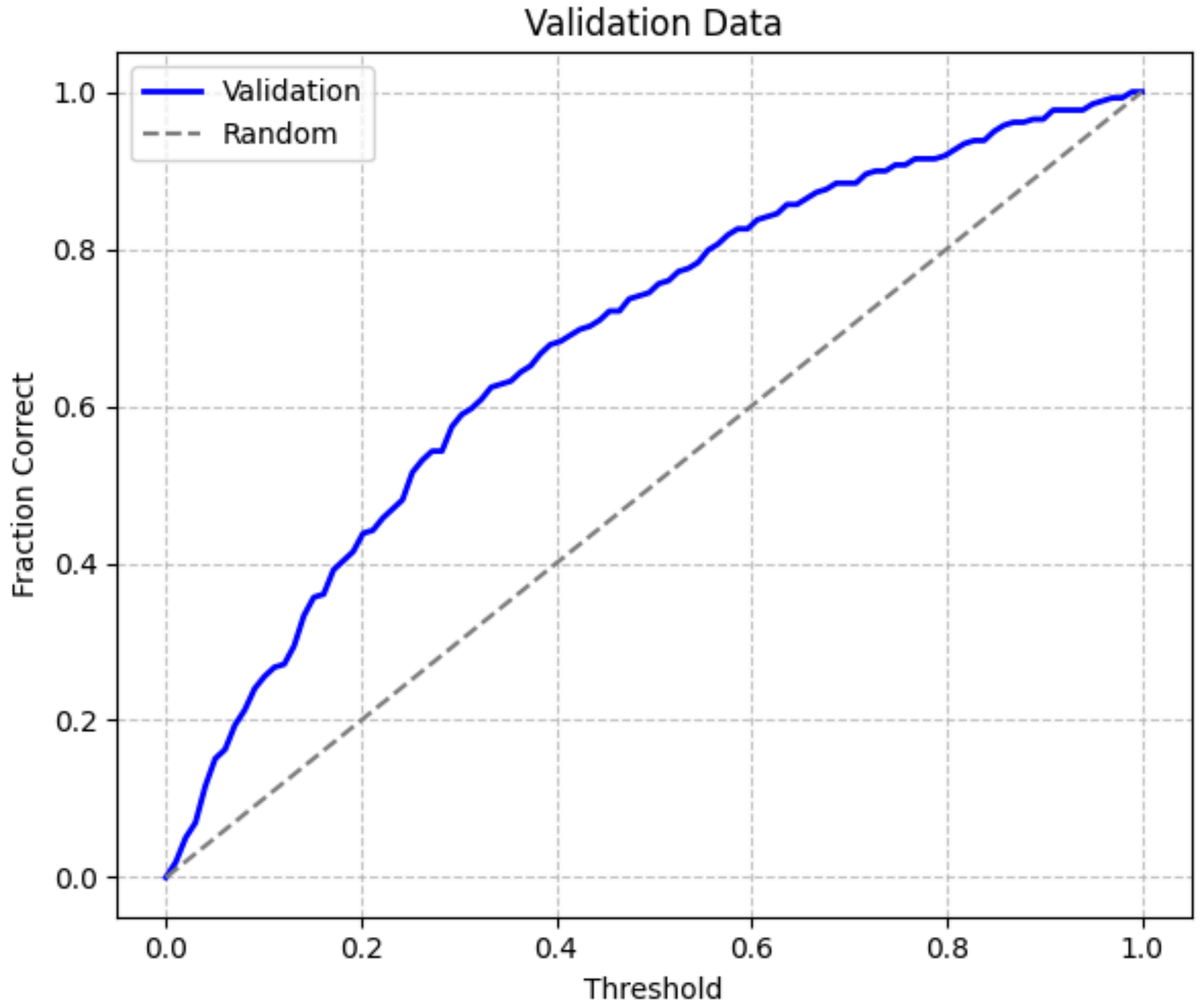
Galaxy Image and SN Light Curves: Training!





Gemma Zhang, Thomas Helfer, Siddharth Mishra-Sharma, Alex Gagliano

Galaxy Image and SN Light Curves: Training!



Gemma Zhang, Thomas Helfer, *Siddharth Mishra-Sharma, Alex Gagliano*

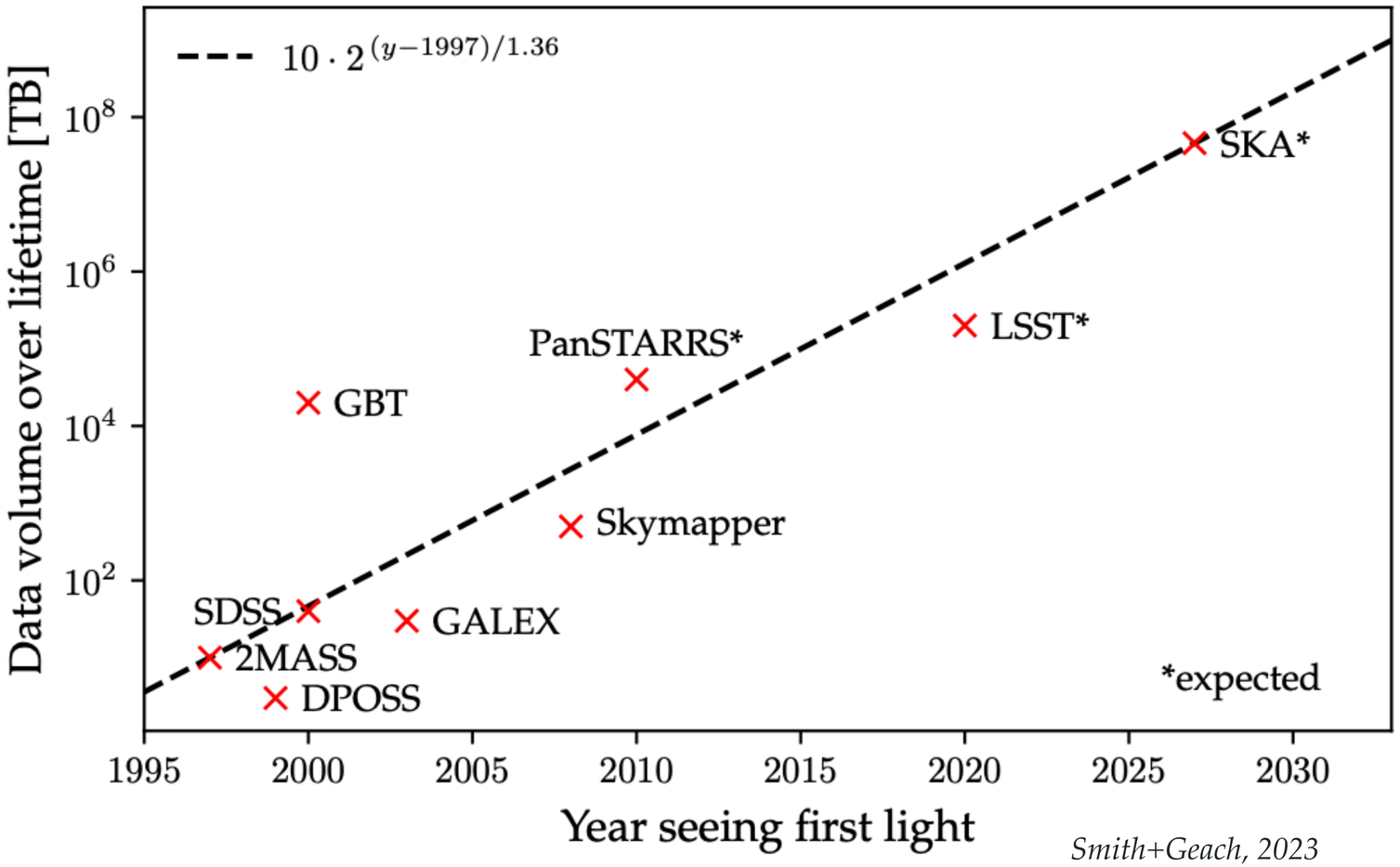
Downstream Tasks

Neighbor retrieval / identification of long-duration CSM interactions

Improved photometric redshifts / classifications

Cross-survey generalization / inference

Forecasting the Vera C. Rubin Observatory



Smith+Geach, 2023

20 TB/night

Alert Brokers

Value-added scientific alerts

How to mitigate covariate shift (composition & redshift distribution)?

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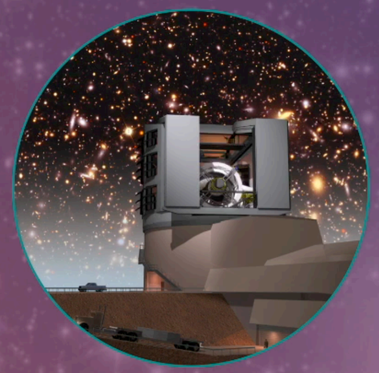

Time-Domain Needles in Rubin's Haystack

Harvard Center for Astrophysics, Cambridge, MA | April 17-19, 2024

About | Registration | Program | Getting Around

https://rubin-anomalies-workshop.github.io/

Conclusions

Circumstellar interaction offers a tracer of late-stage stellar evolution that is **anomalous** among SNe and **robust** to drops in observing cadence.

Finding these events (using ML) will inform where we hunt for **precursor emission**, to stitch together the final years of a massive star's life.

10-year light curves of 10M supernovae with the Rubin Observatory (2025-2035) will revolutionize these studies.

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