ML in Astronomy:
classification of cosmic explosions

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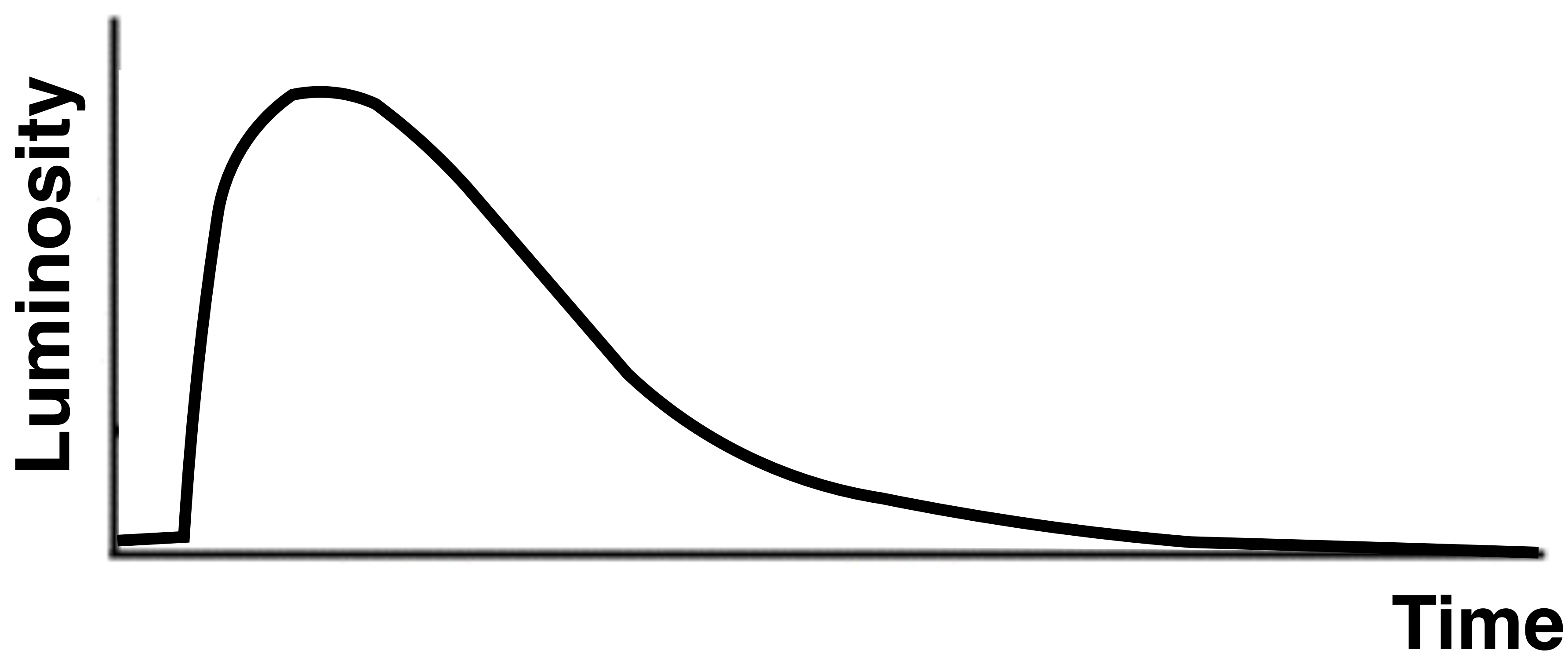
Institute of Cosmology and Gravitation

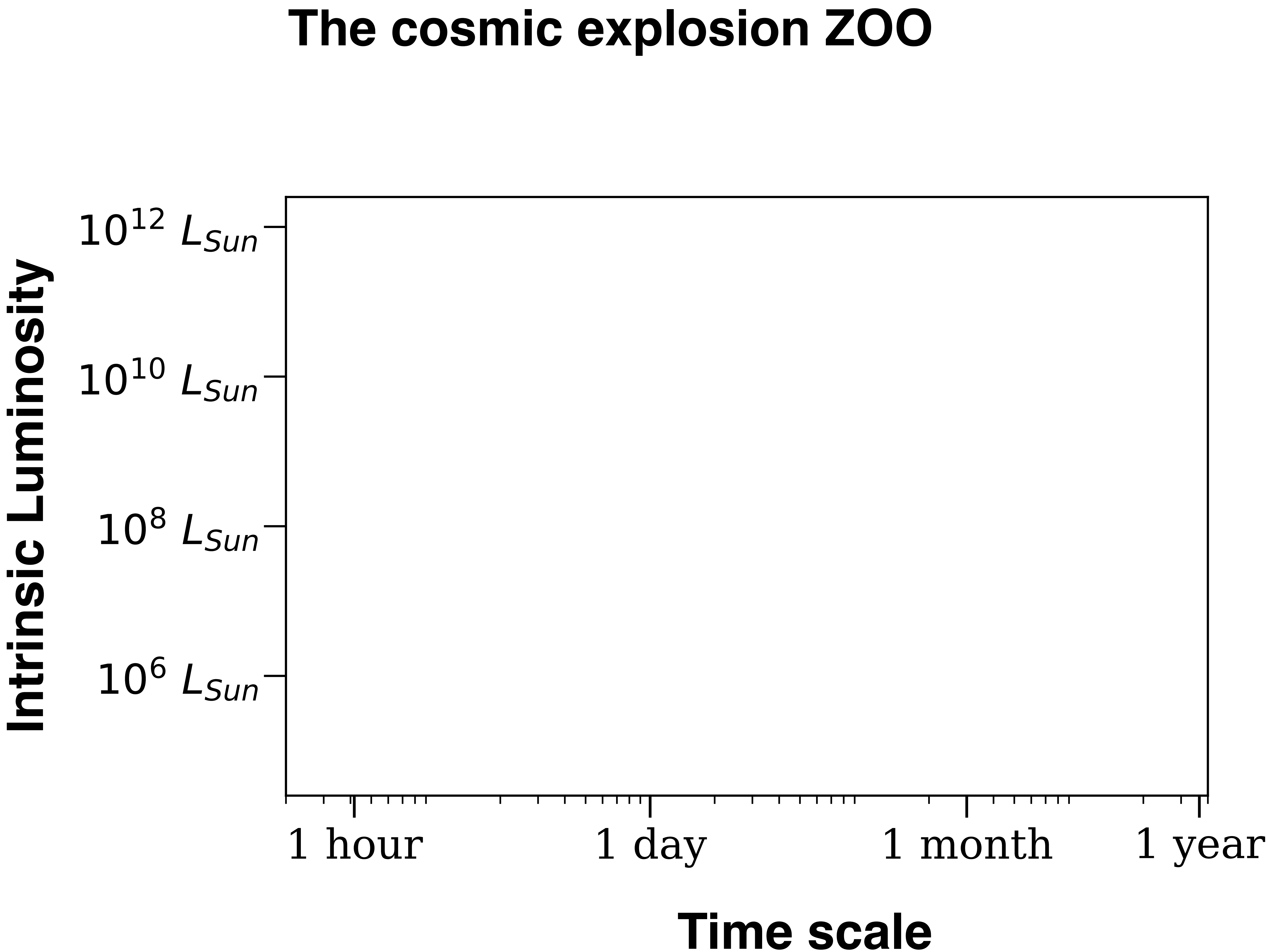
Supervisors: Mark Sullivan, Bob Nichol

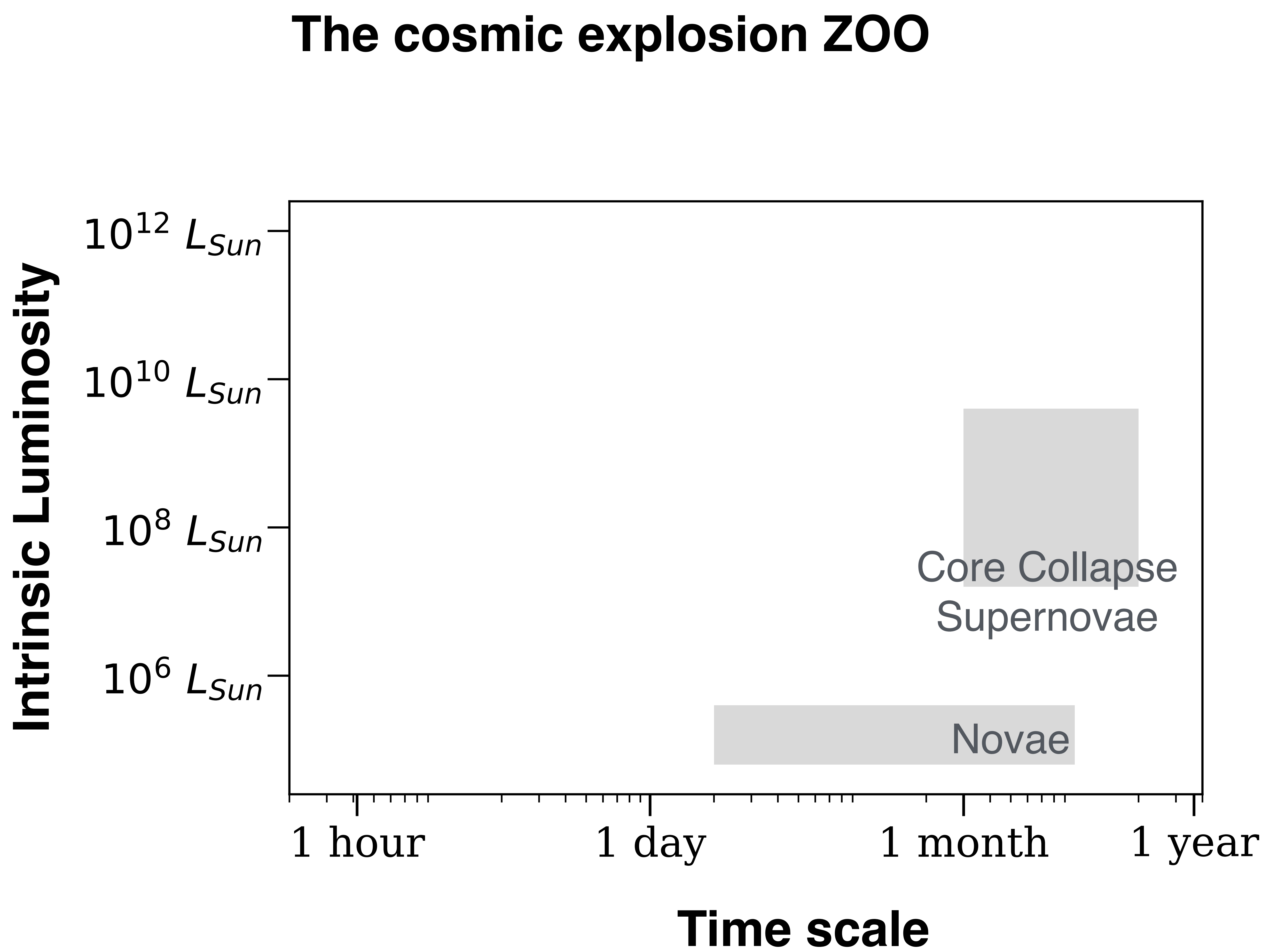
Outline

- What are **cosmic explosions** and why we study them?
- How we **detect** them,
- How we **classify** them,
- What people have done on this classification problem,
- What I have done for this classification problem.

What are cosmic explosions and why we study them?




The cosmic explosion ZOO
Intrinsic Luminosity
$10^{12}\ L_{Sun}$
$10^{10}\ L_{Sun}$
$10^{8}\ L_{Sun}$
$10^{6}\ L_{Sun}$
1 hour
1 day
1 month
1 year
Time scale



The cosmic explosion ZOO
$10^{12}\ L_{Sun}$
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Intrinsic Luminosity
Core Collapse Supernovae
Novae
1 hour
1 day
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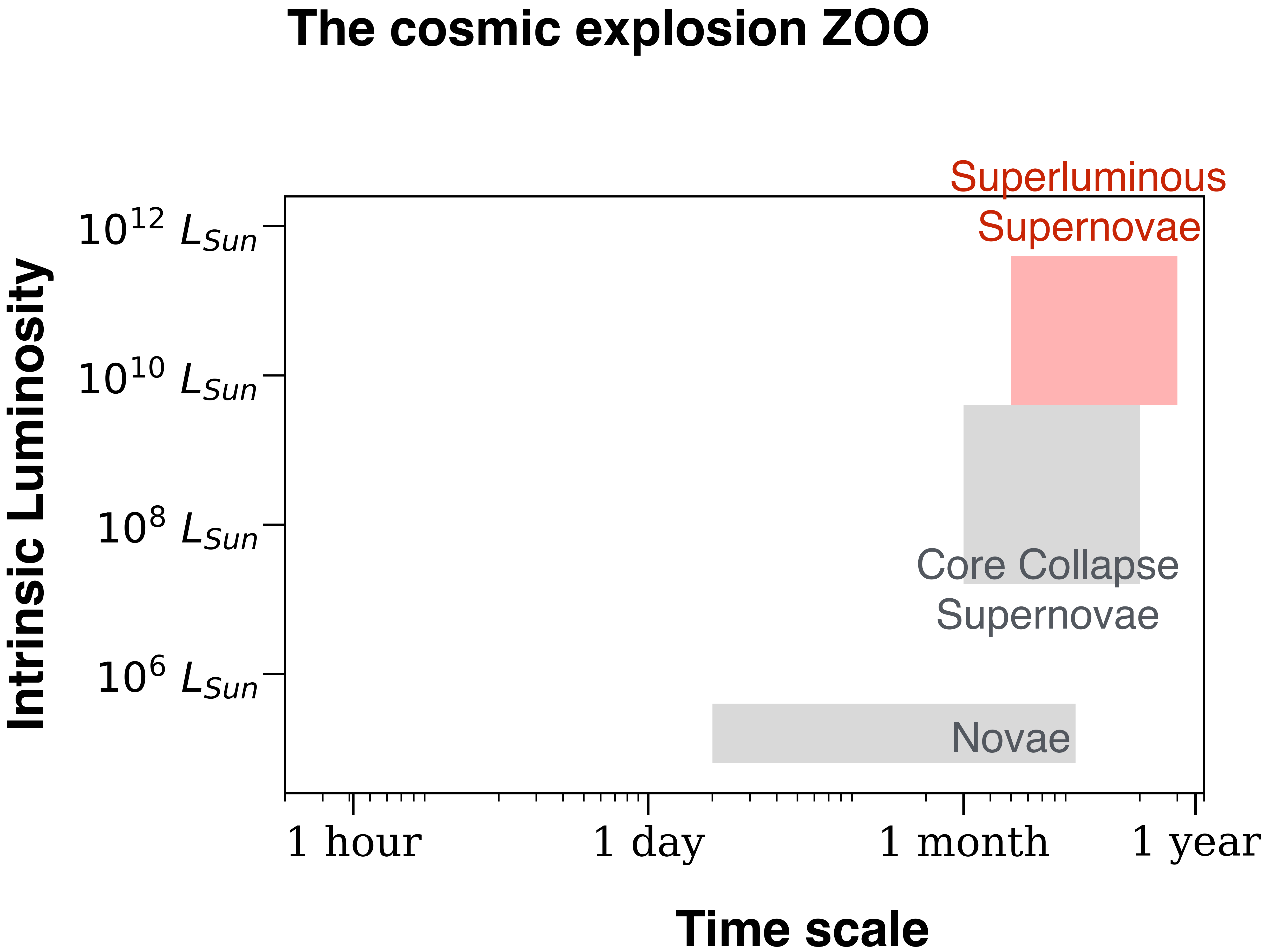
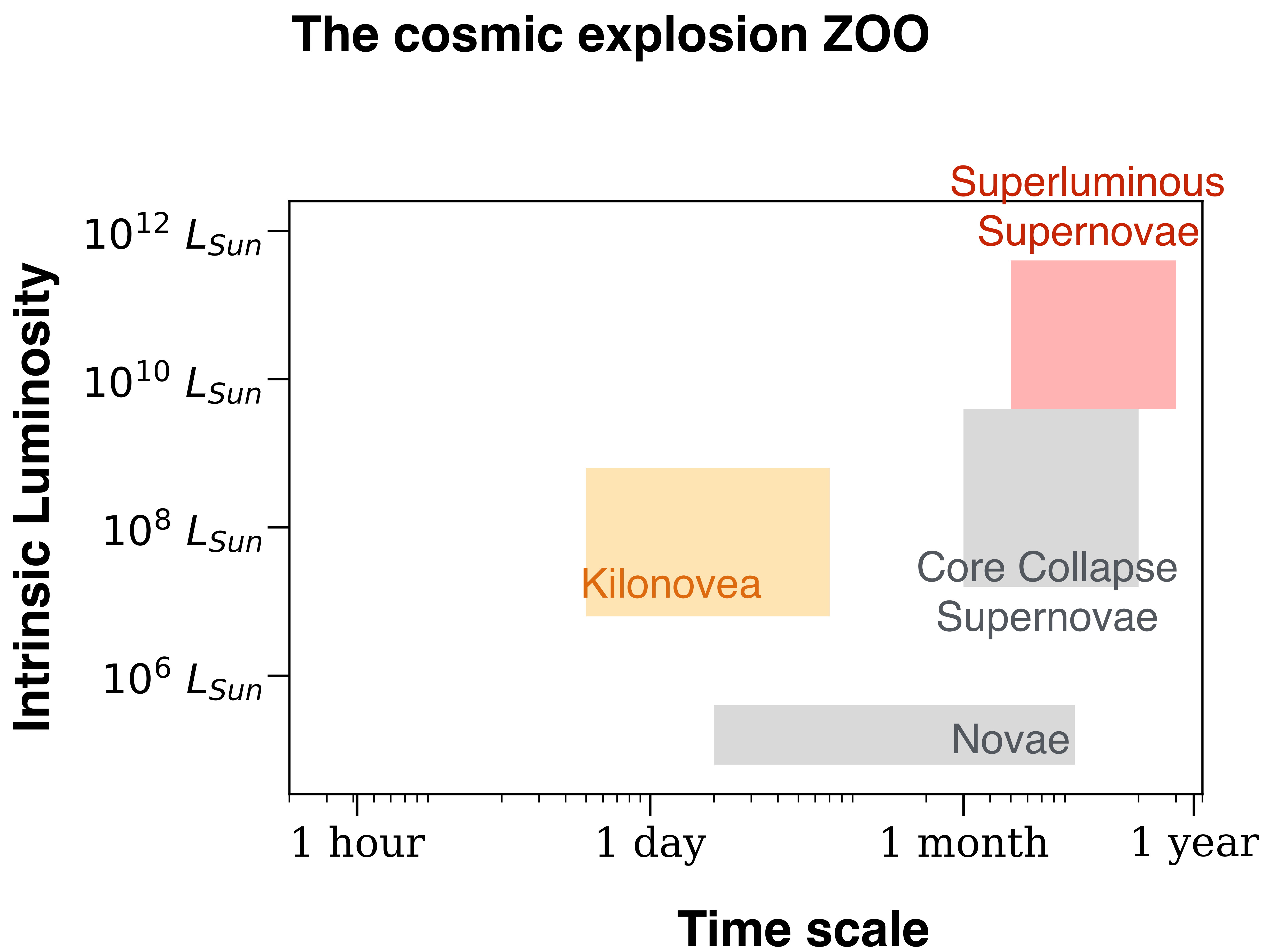
1 year
Time scale


The cosmic explosion ZOO
Superluminous Supernovae
Core Collapse Supernovae
Novae
10^{12} L_{Sun}
10^{10} L_{Sun}
10^{8} L_{Sun}
10^{6} L_{Sun}
Intrinsic Luminosity
1 hour
1 day
1 month
1 year
Time scale


The cosmic explosion ZOO
Superluminous
Supernovae
Kilonovea
Core Collapse
Supernovae
Novae
$10^{12}\ L_{Sun}$
$10^{10}\ L_{Sun}$
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Intrinsic Luminosity
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1 day
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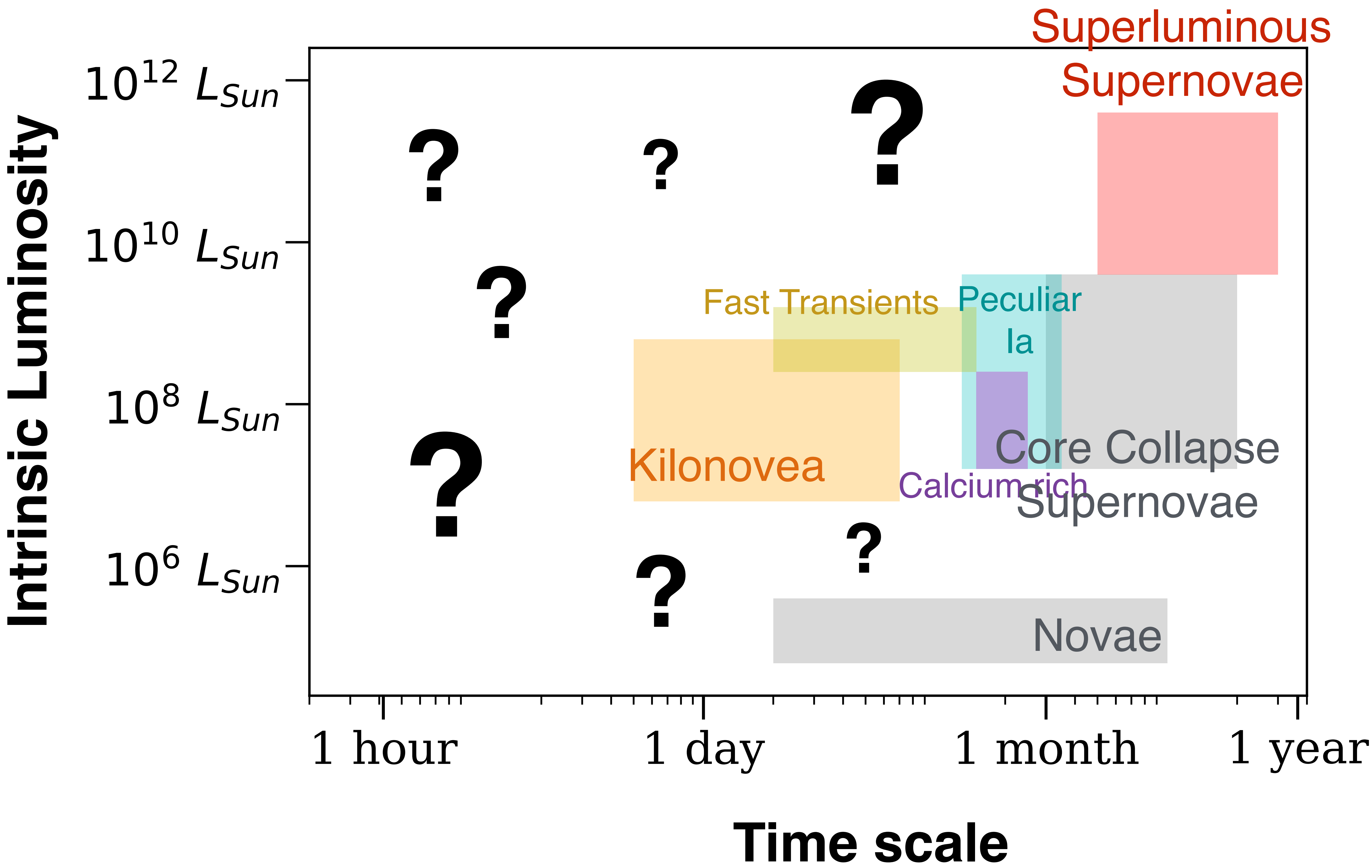
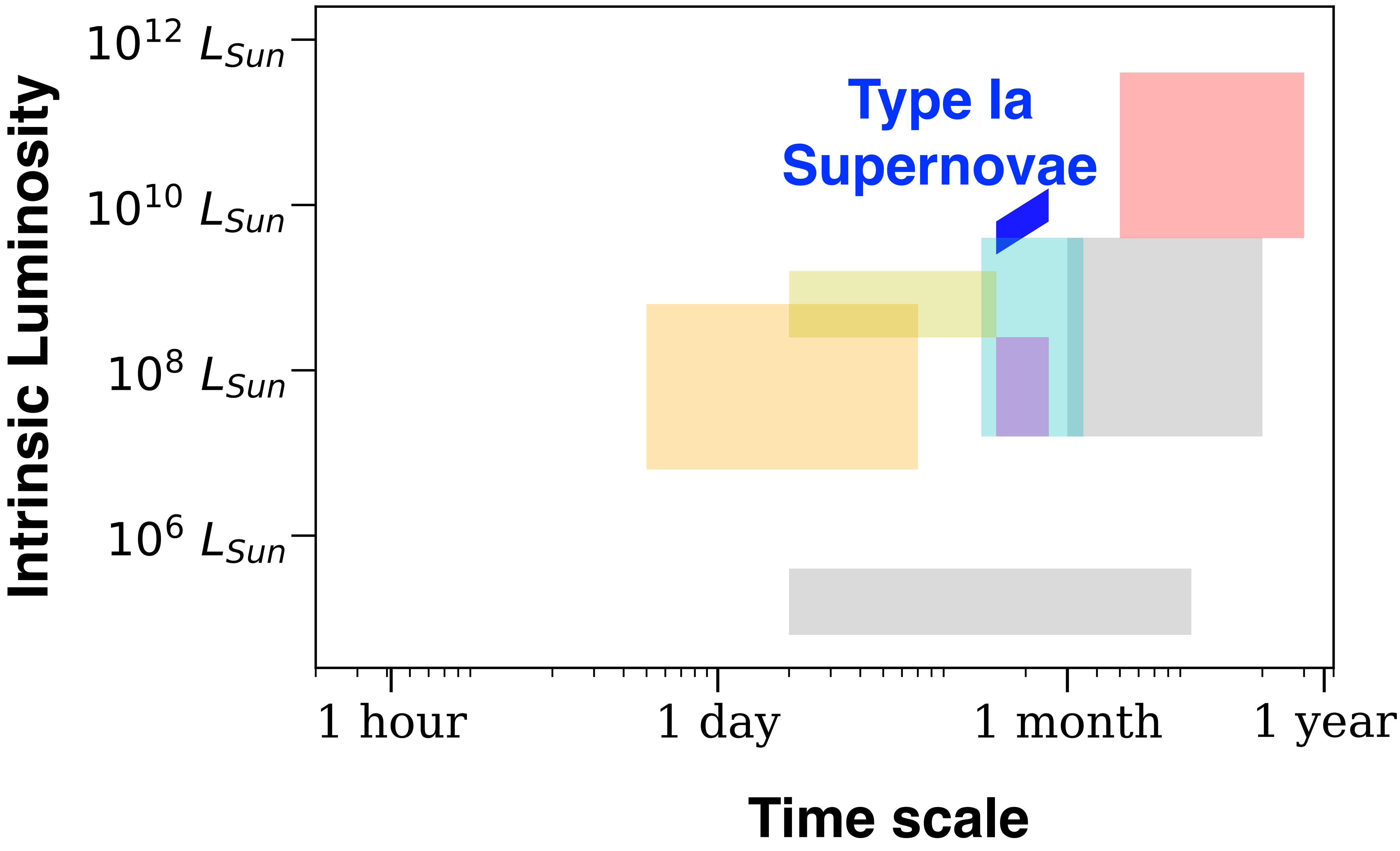


The cosmic explosion ZOO



Type Ia Supernovae

Thermonuclear explosions of dwarf stars made of Carbon and Oxygen

Critical Mass = 1.4 M_{Sun}

Standard evolution and brightness!

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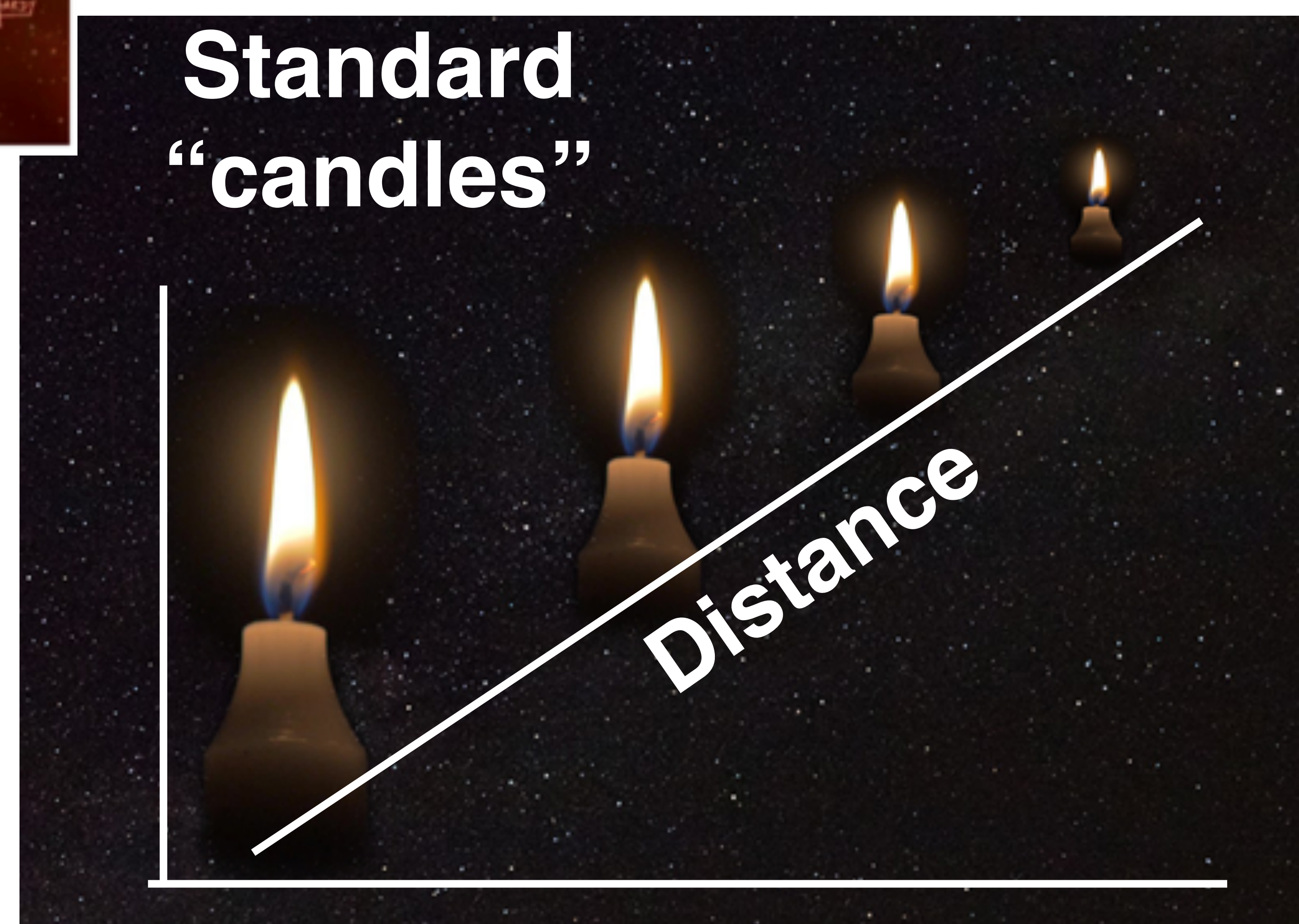
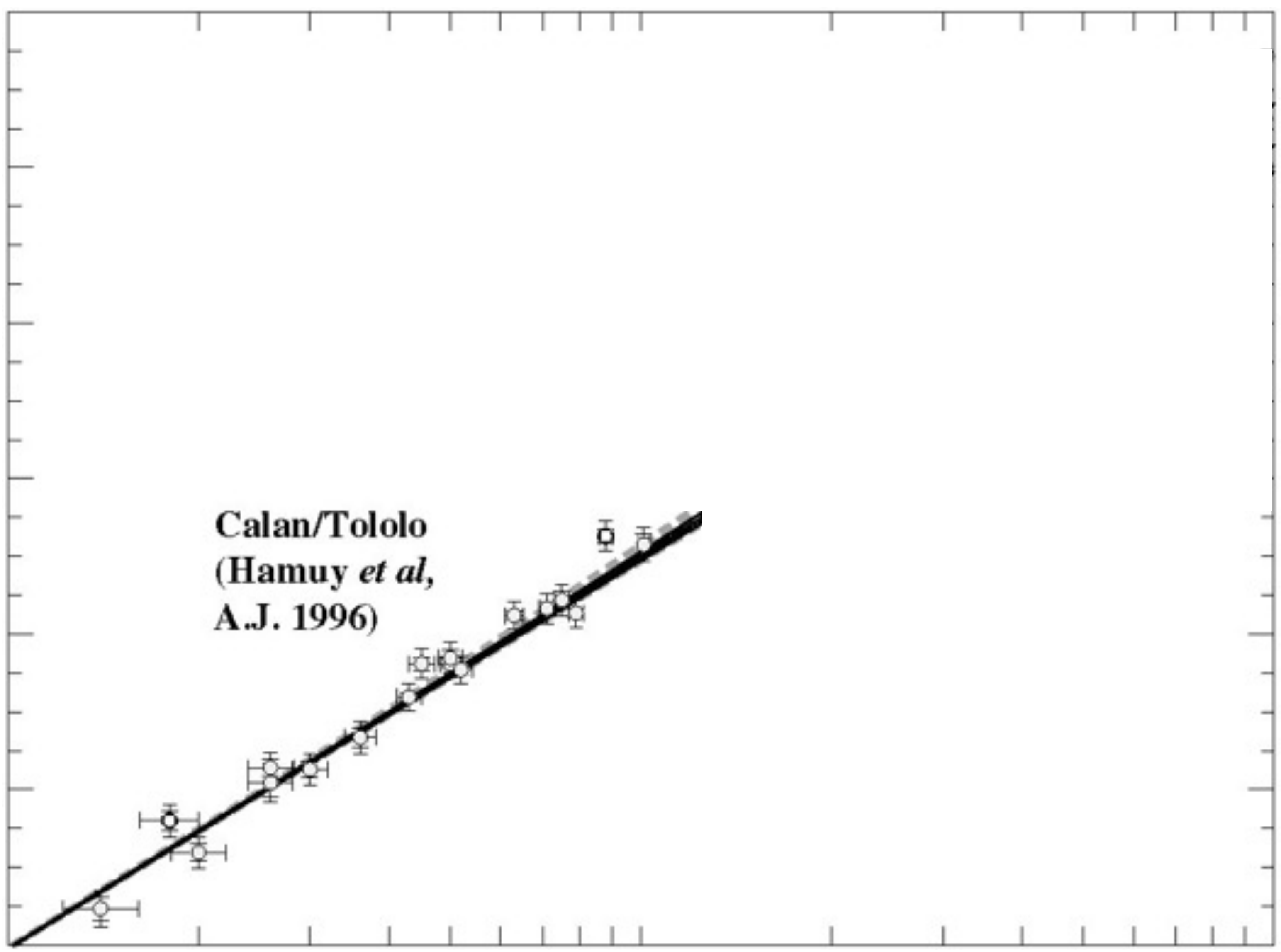


Excellent objects to measure distances! (< 5% accuracy)

Type Ia Supernovae

The expansion of the Universe is…..

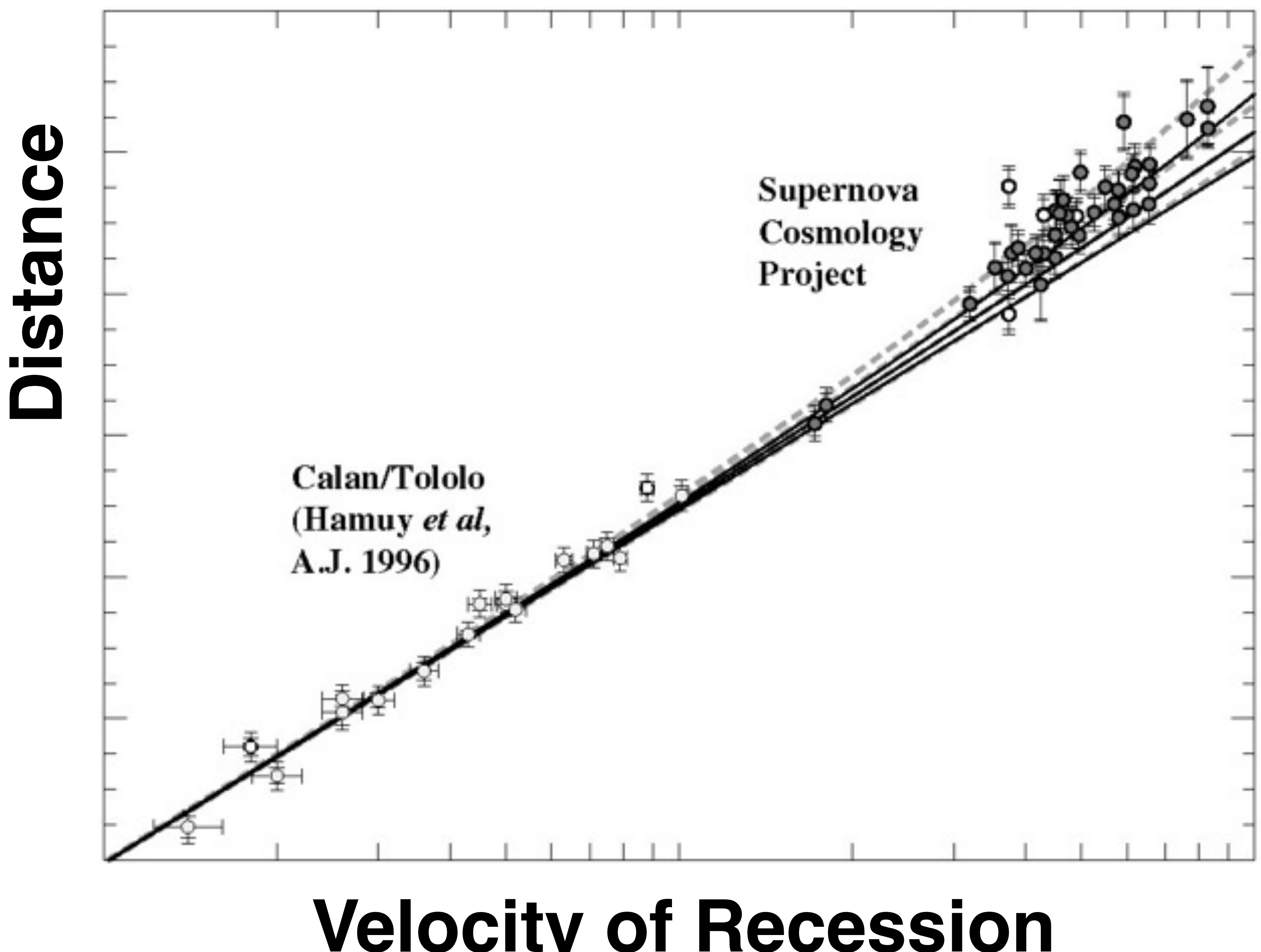
Distance



Velocity of Recession

Type Ia Supernovae

The expansion of the Universe is **ACCELERATING** !!



Perlmitter et al. 1999, Riess et al. 1998

Type Ia Supernovae

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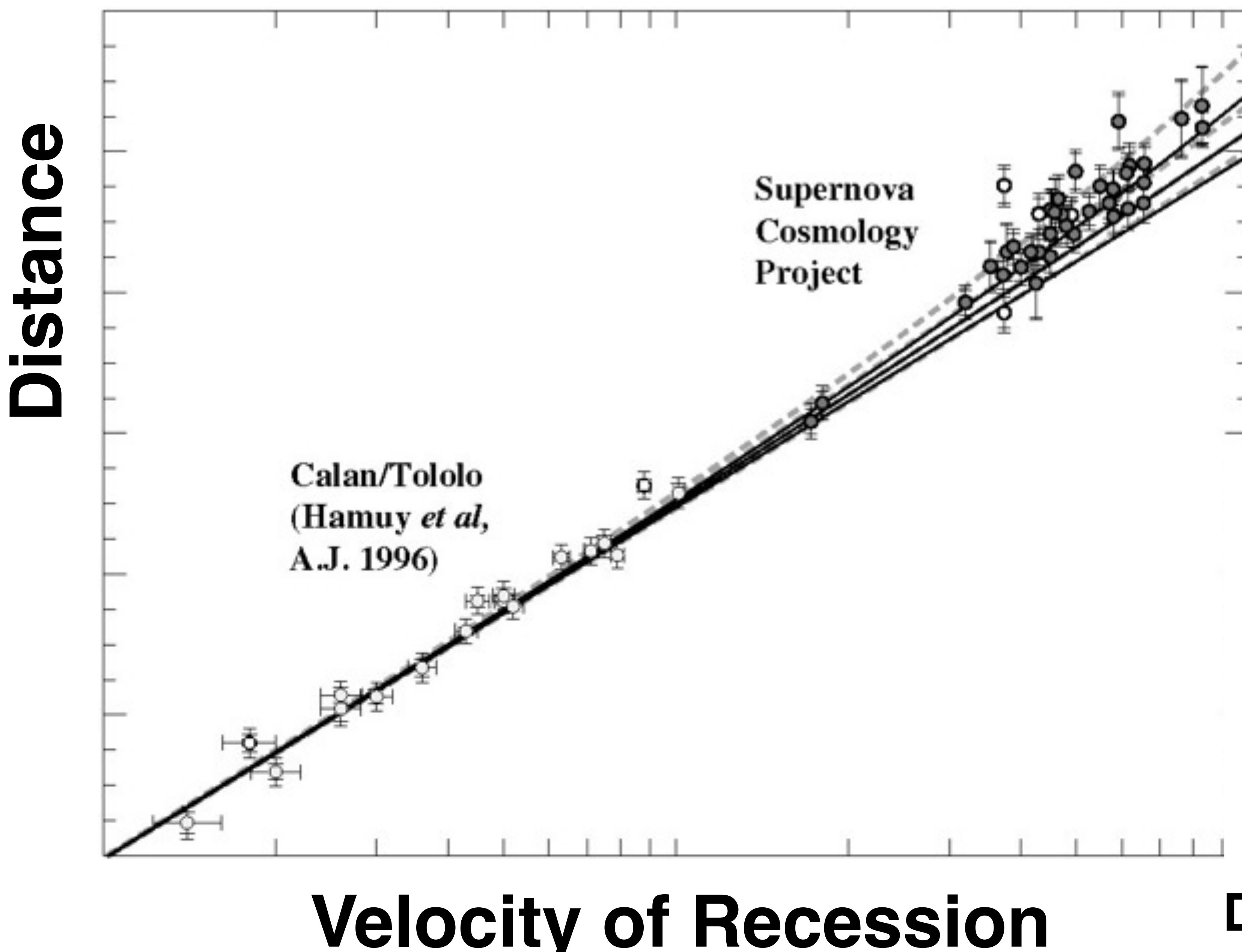
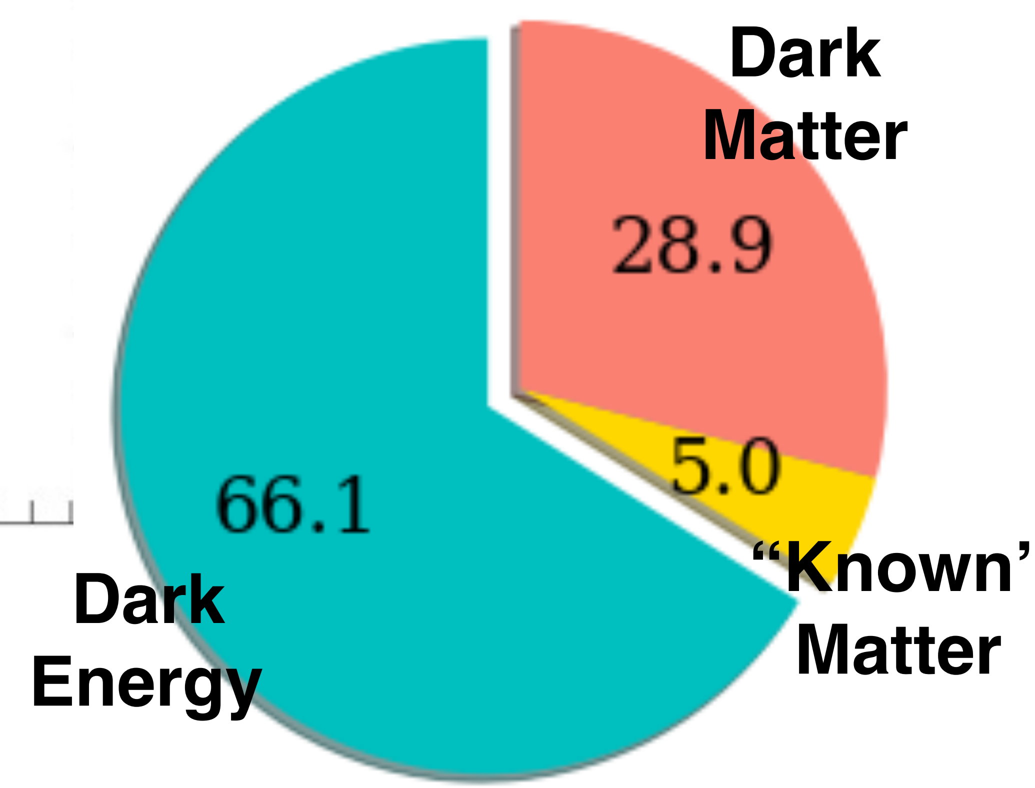


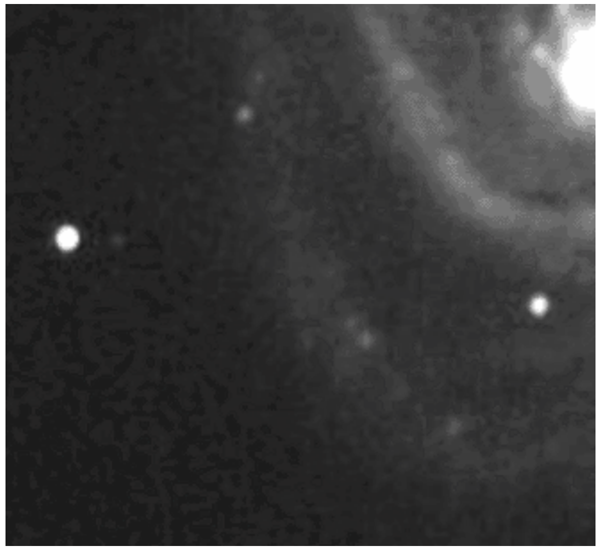
Dark Energy?
“Wrong” gravity theory?

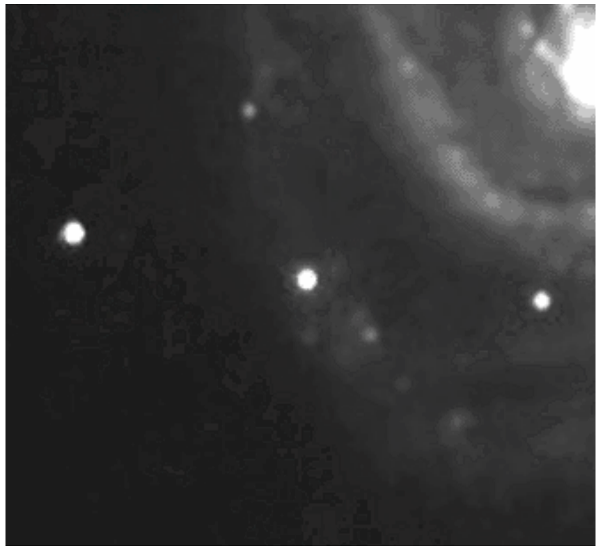


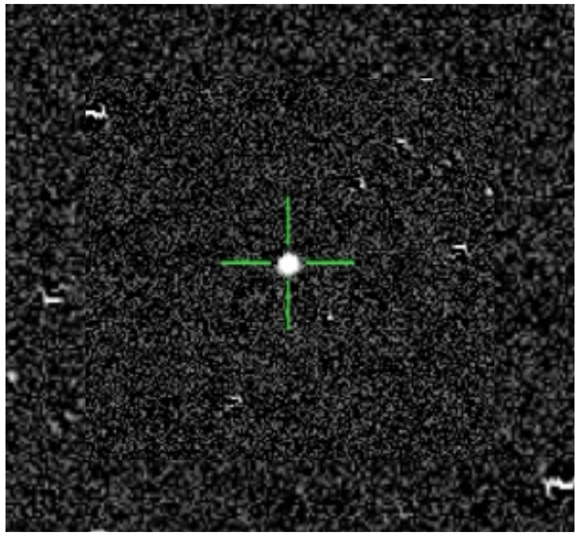
Perlmitter et al. 1999, Riess et al. 1998

Detection

Detection

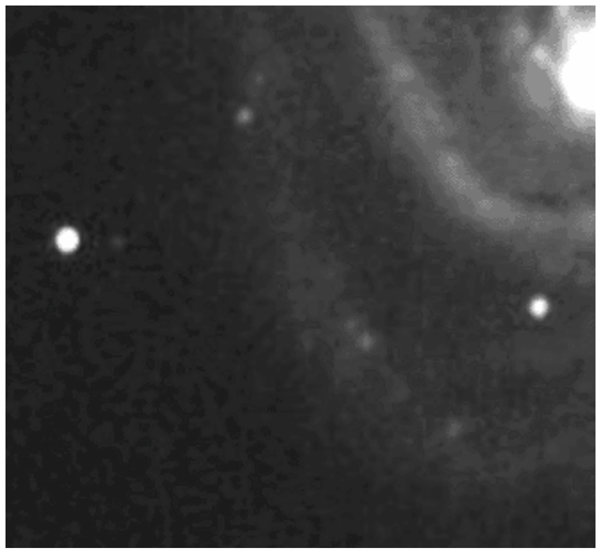

Reference Image


New Image

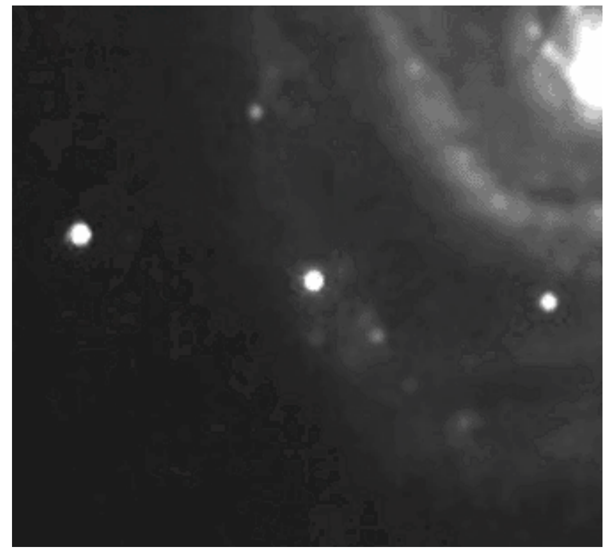

Difference Image

New detection!

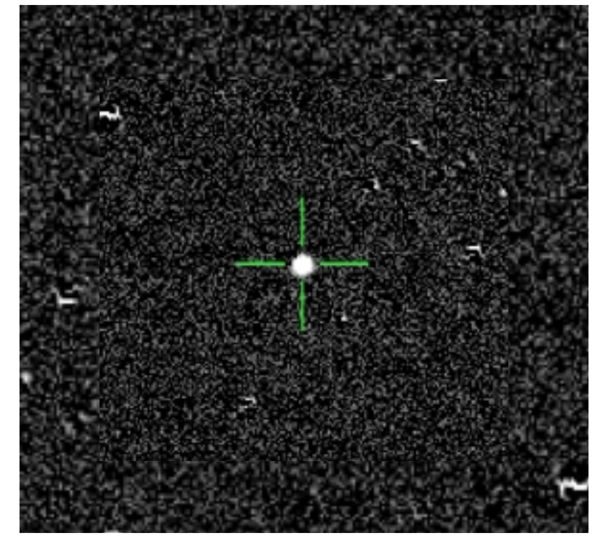
Detection



Reference
Image

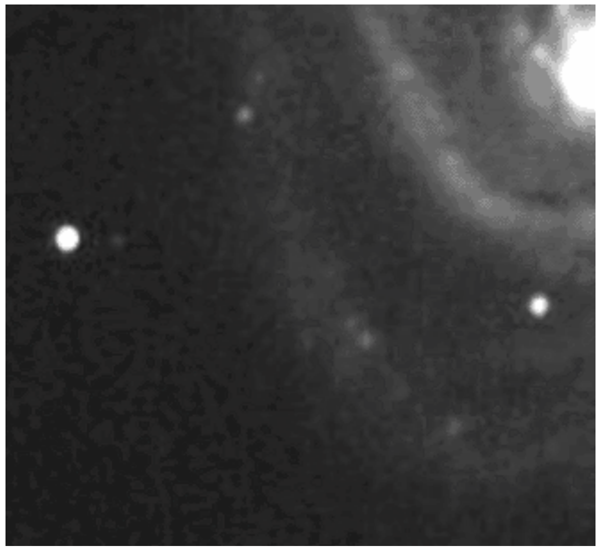


New
Image



Difference
Image

Detection



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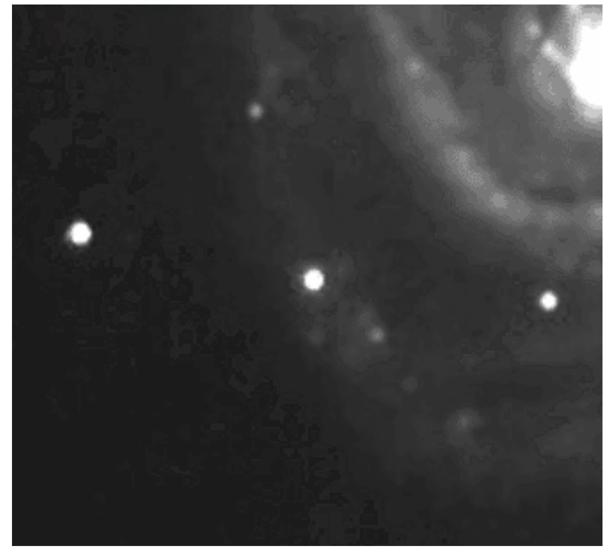
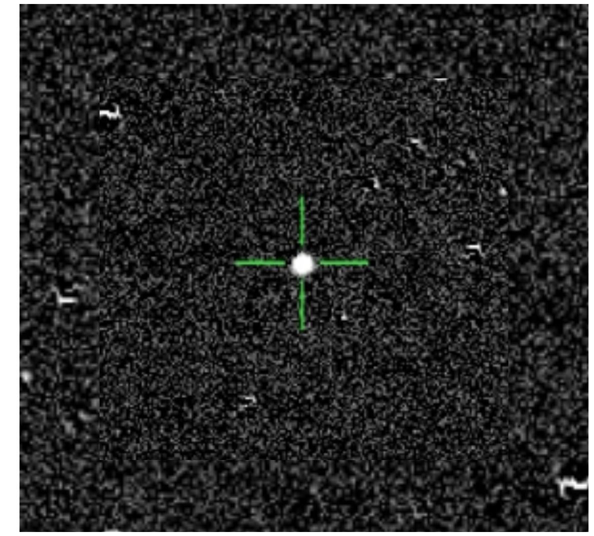
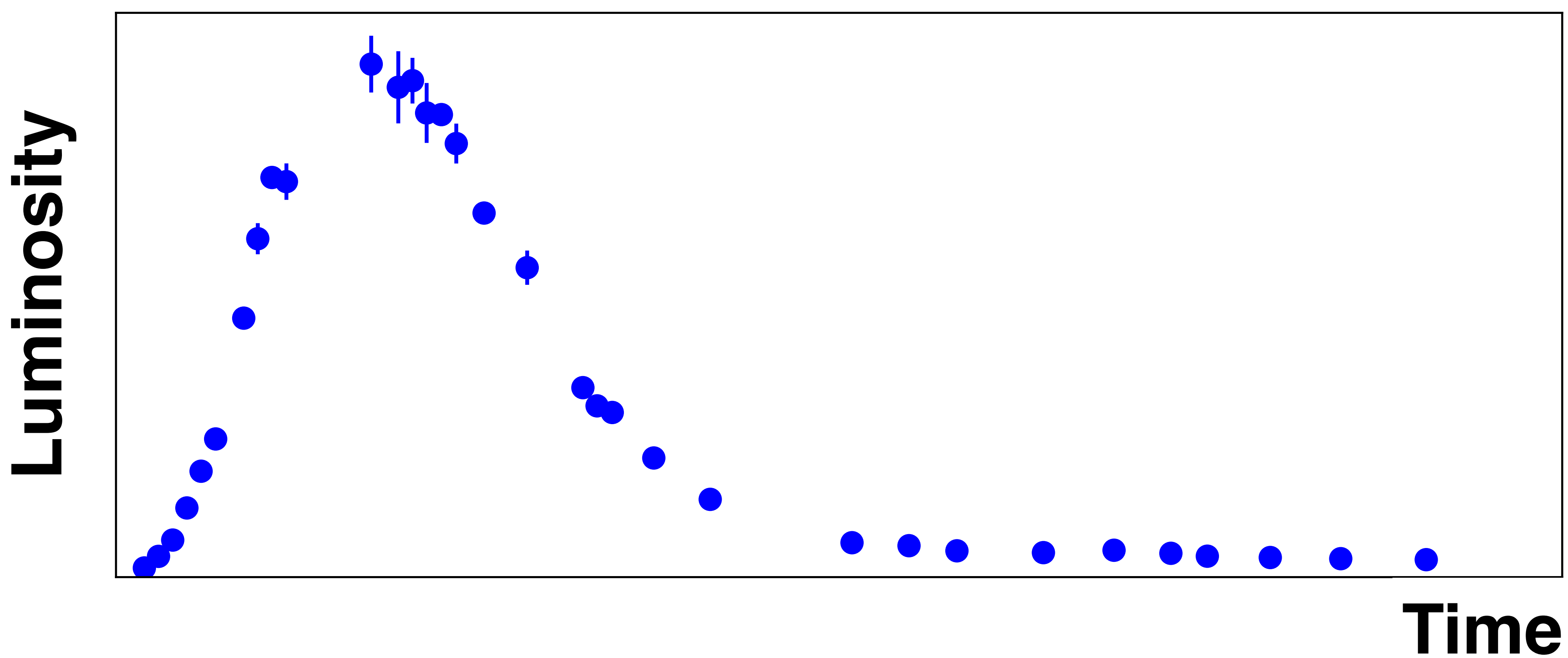


New Image



Difference Image



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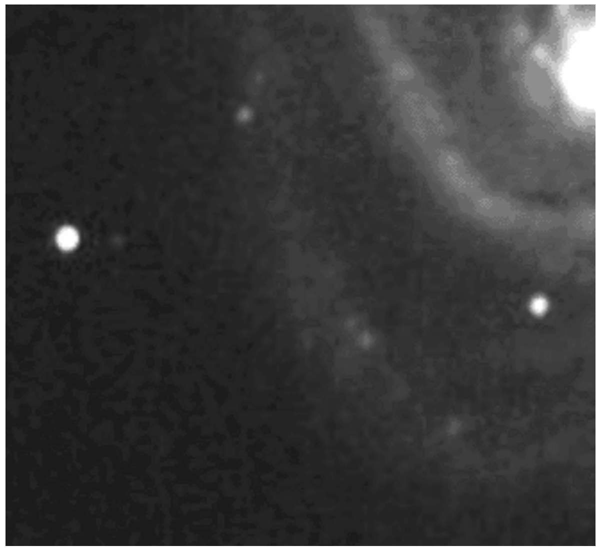

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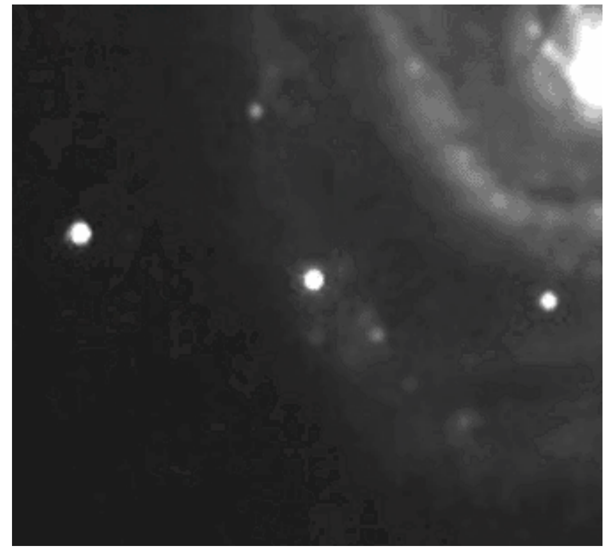

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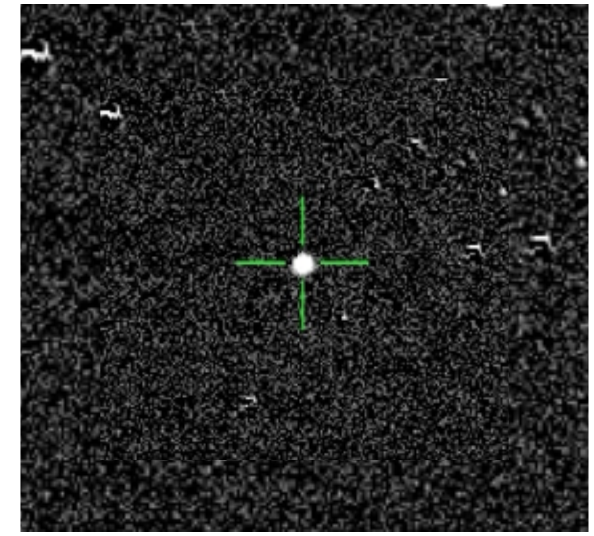
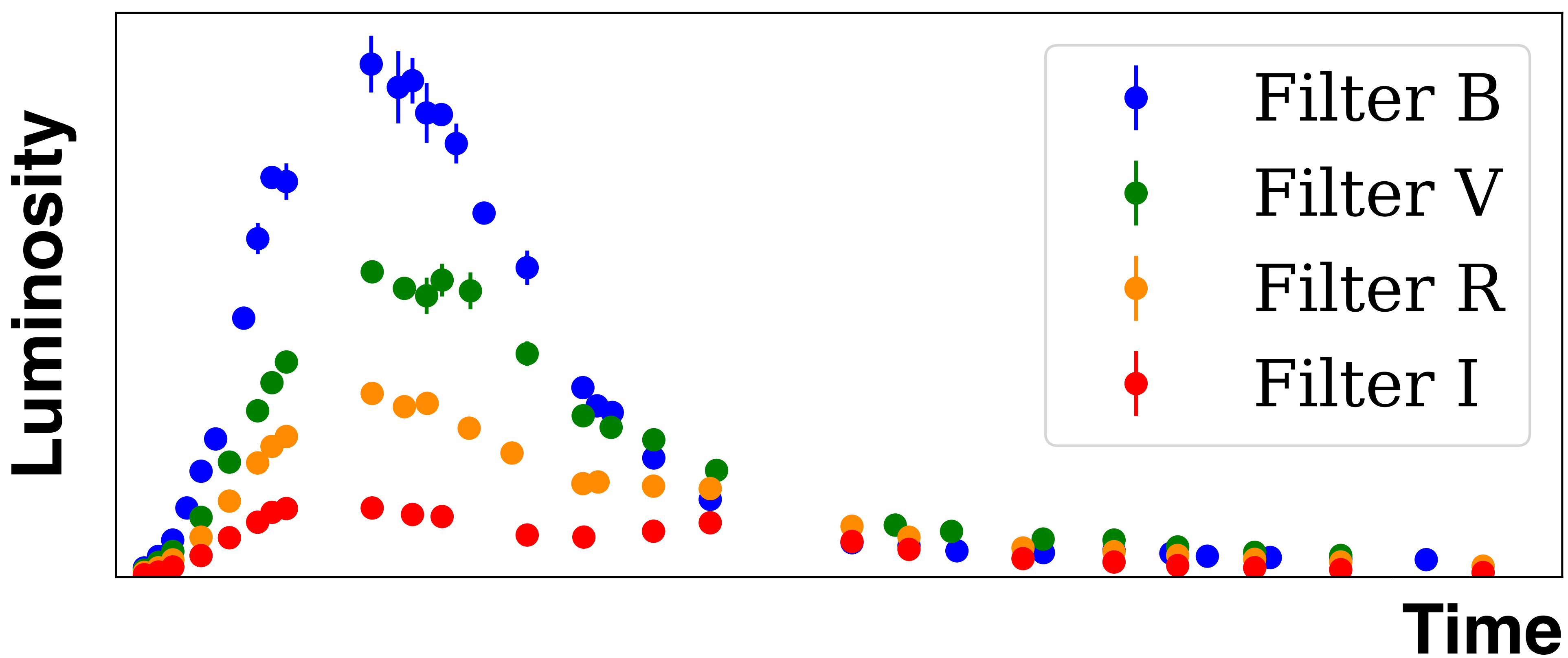
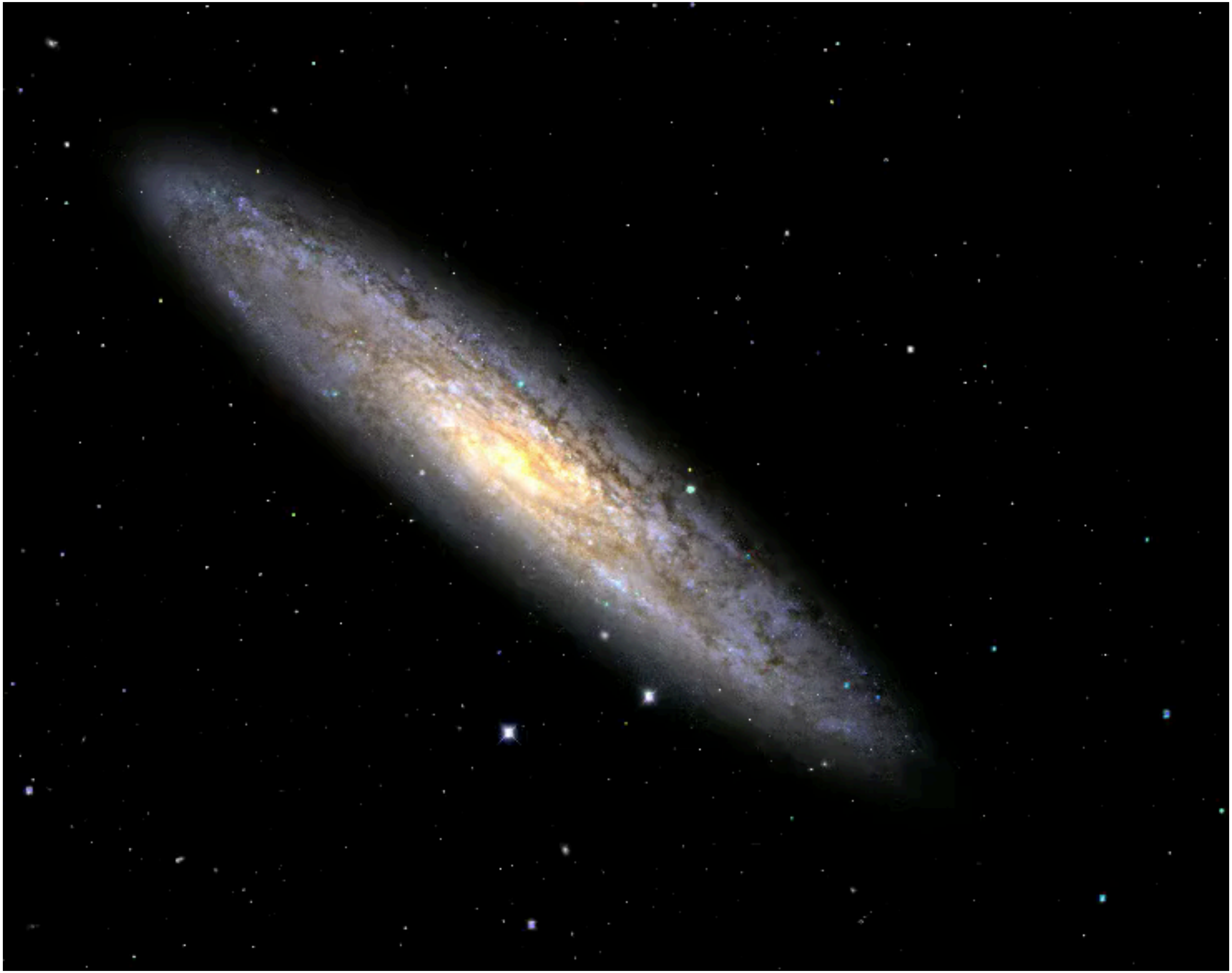


Difference Image





Surveys

Dark Energy Survey (DES)

2013-2018

Large Synoptic Survey Telescope (LSST)

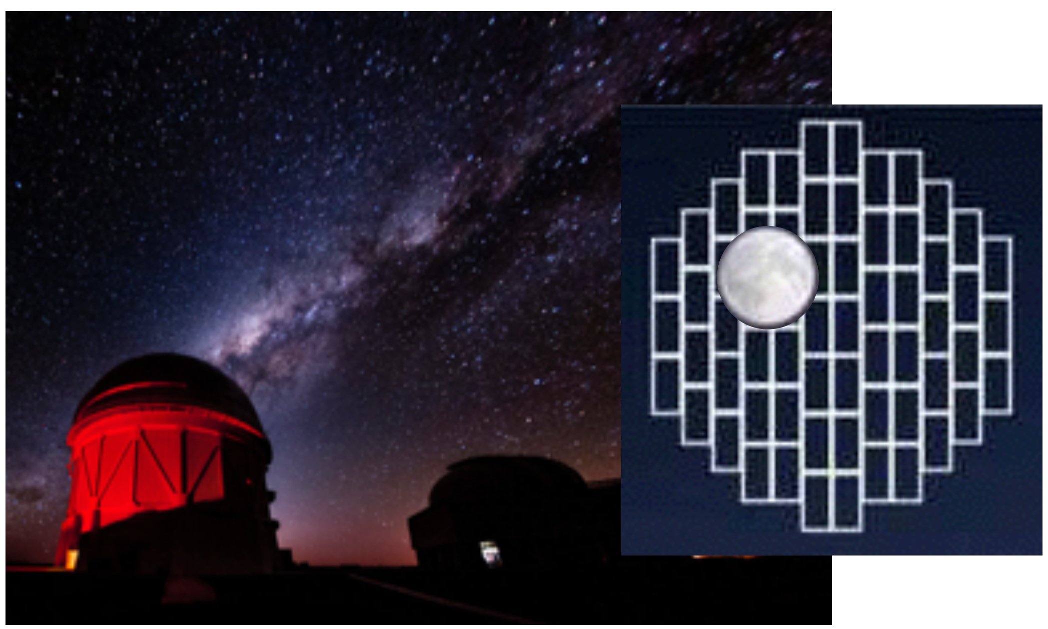
2020-2030

Surveys

Dark Energy Survey (DES)

2013-2018

➔ 27 deg^2 of the sky
➔ 4 filters



>0.1 TB of data per night

30.000 transients in 5 years

Large Synoptic Survey Telescope (LSST)

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Surveys

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2013-2018

➔ 27 deg^2 of the sky
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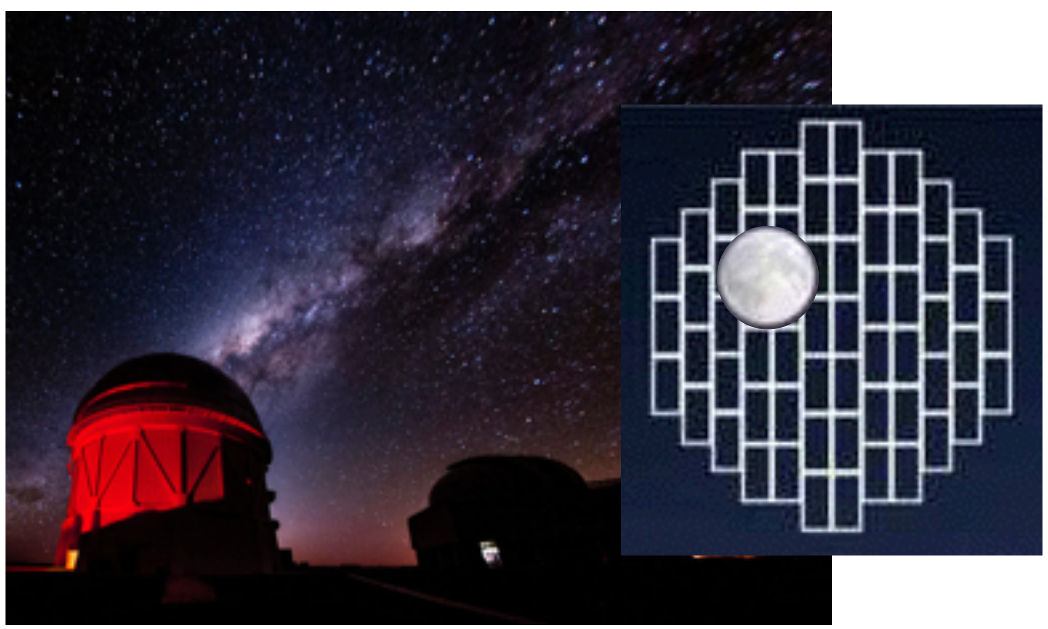


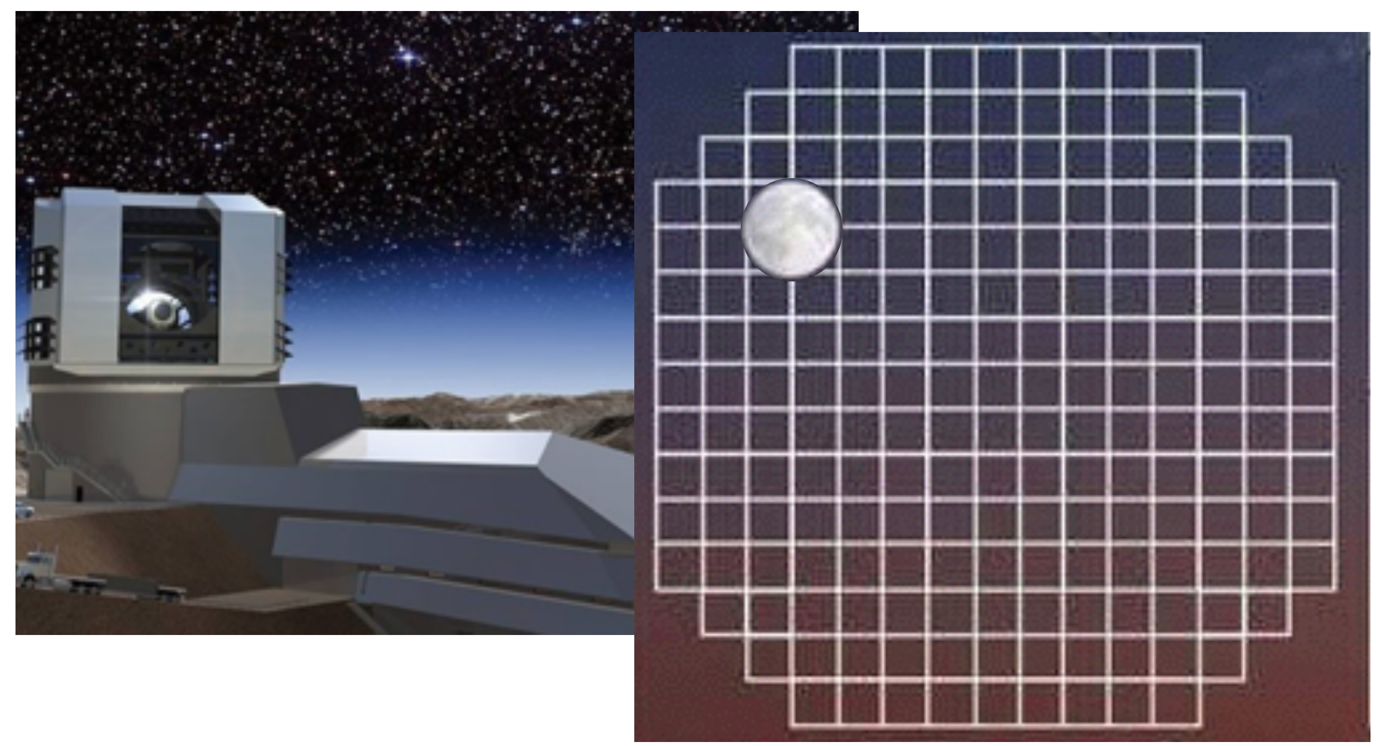
>0.1 TB of data per night

30.000 transients in 5 years

Large Synoptic Survey Telescope (LSST)

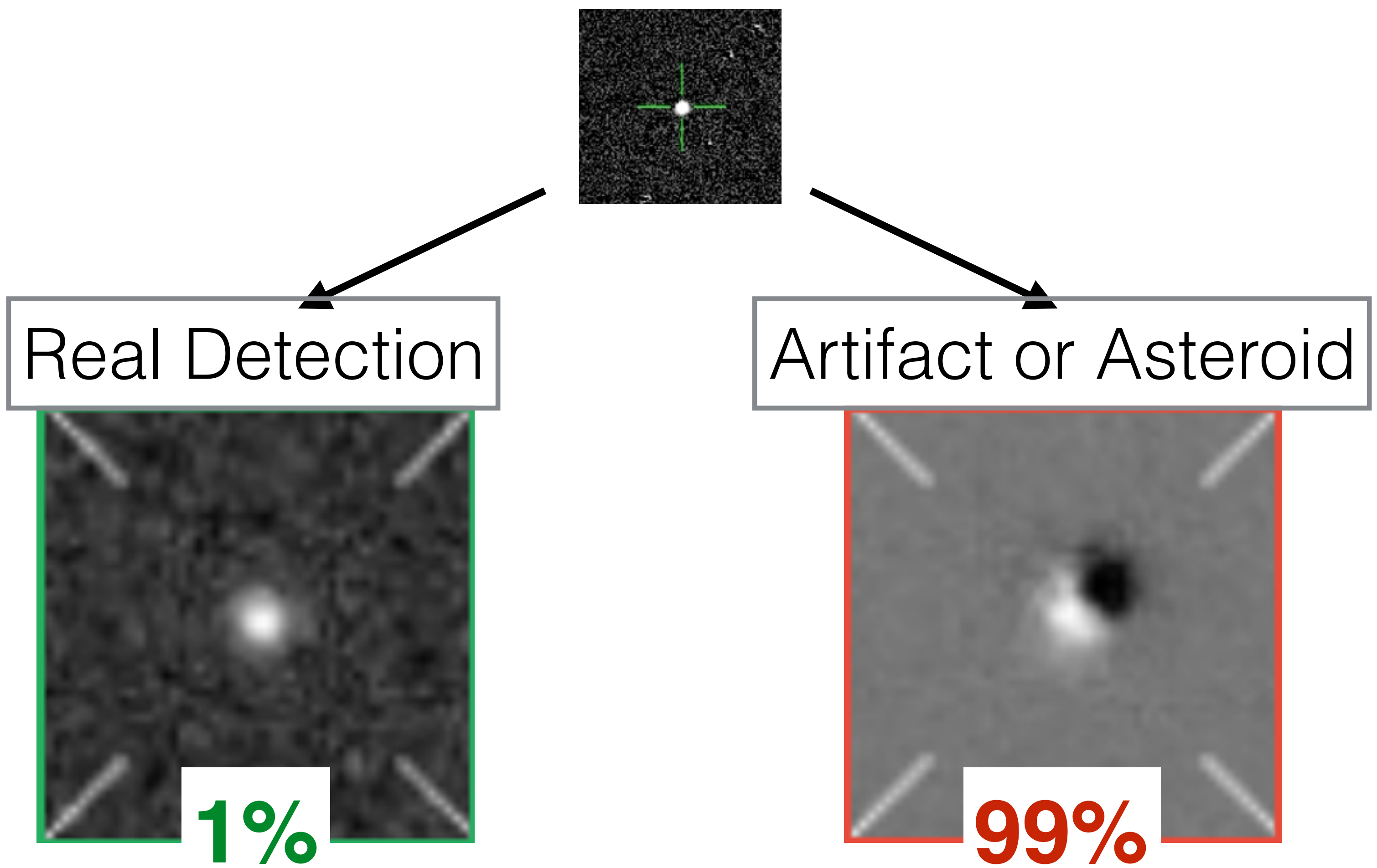
2020-2030

➔ 1500 deg^2 of the sky
➔ 6 filters



20 TB of data to process **per night**
10^6 transients alerts **per night**
Billions of transients in 10 years

How this works in practice



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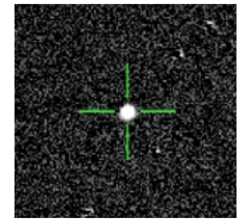
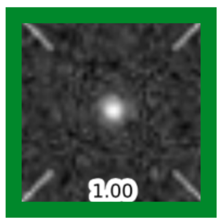
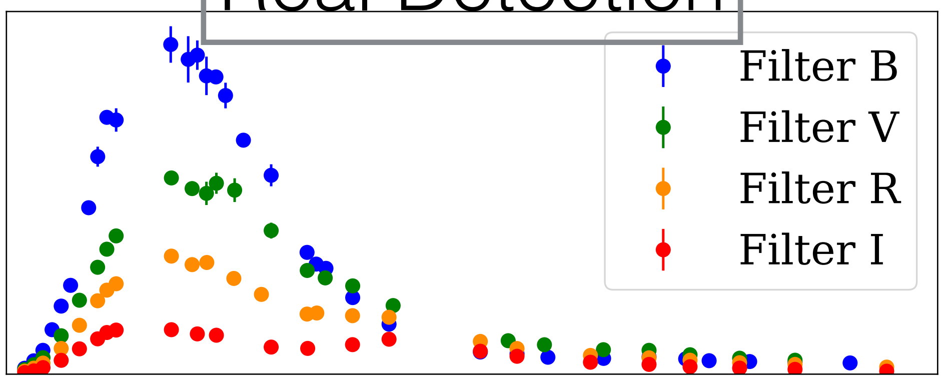
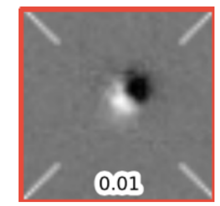


Real Detection

Artifact or Asteroid







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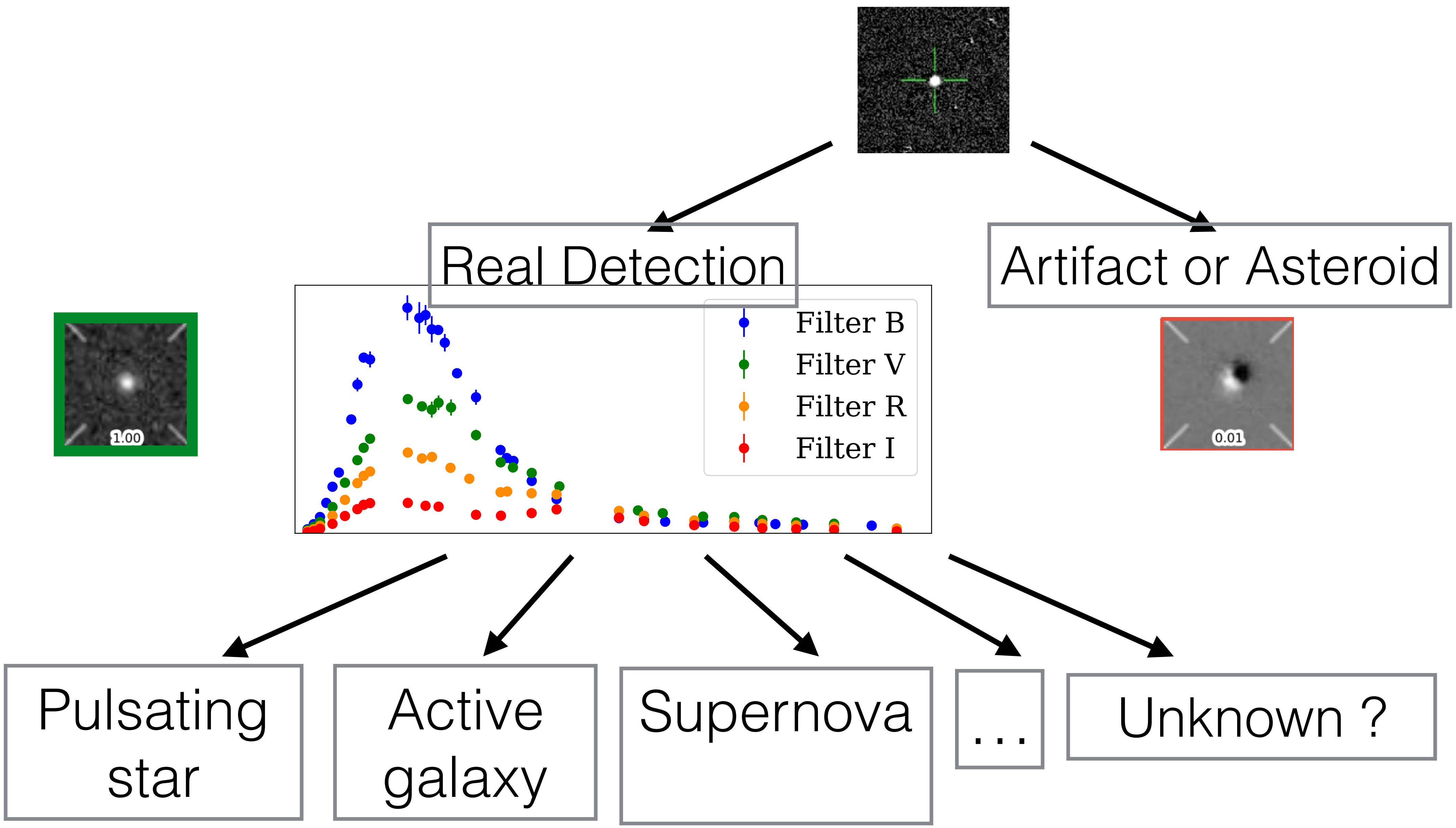

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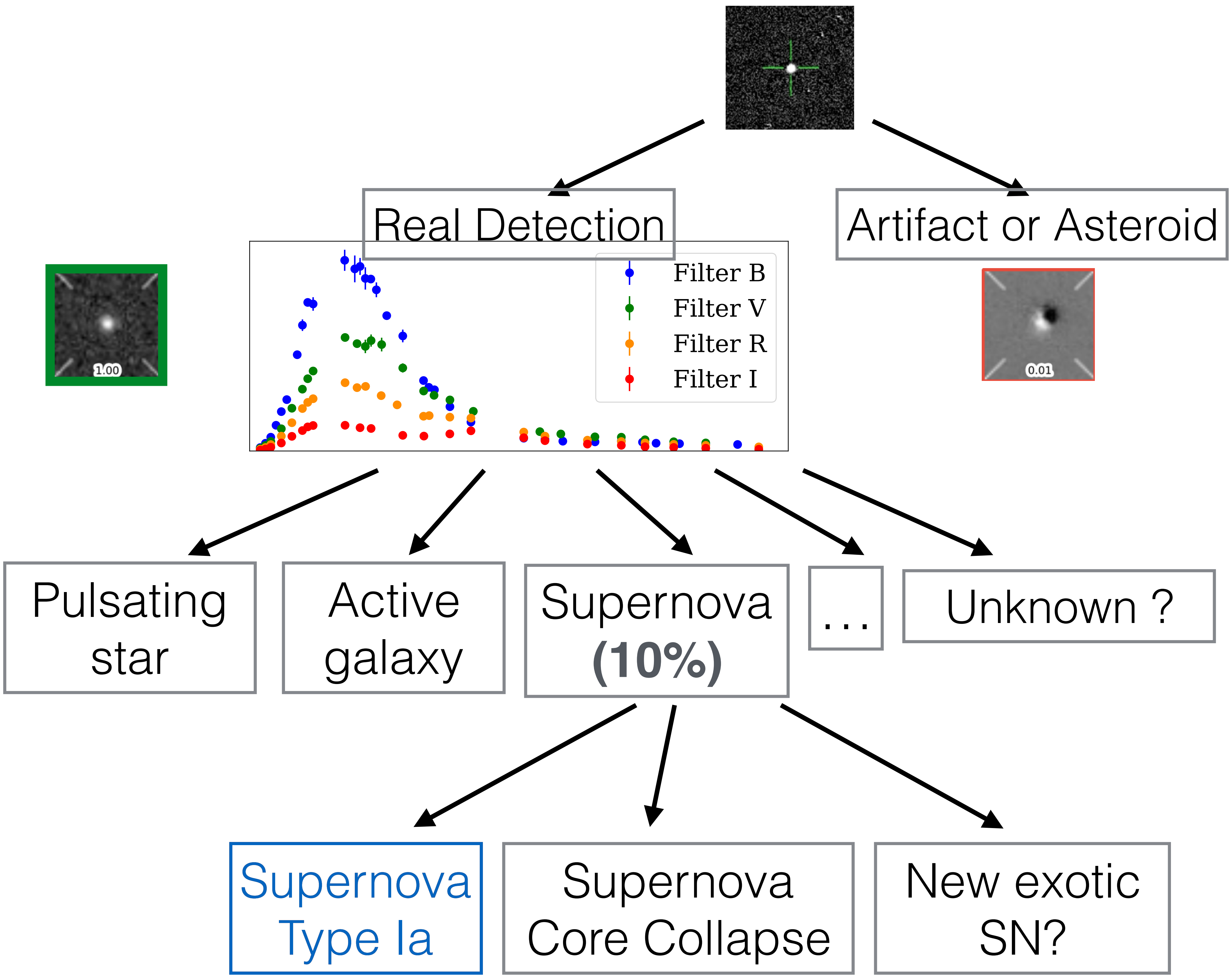

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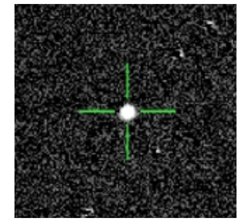

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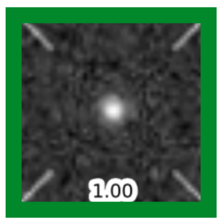
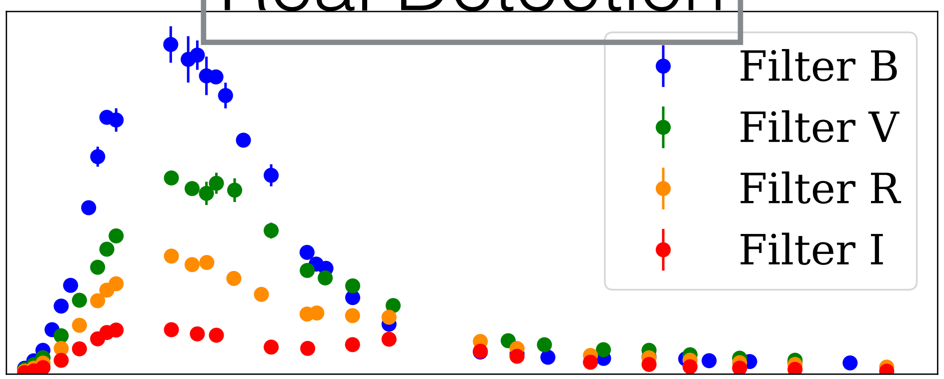
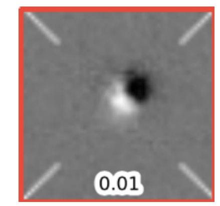






OK!

Goldstein et al. 2016

Pulsating star

Active galaxy

Supernova
(10%)

...

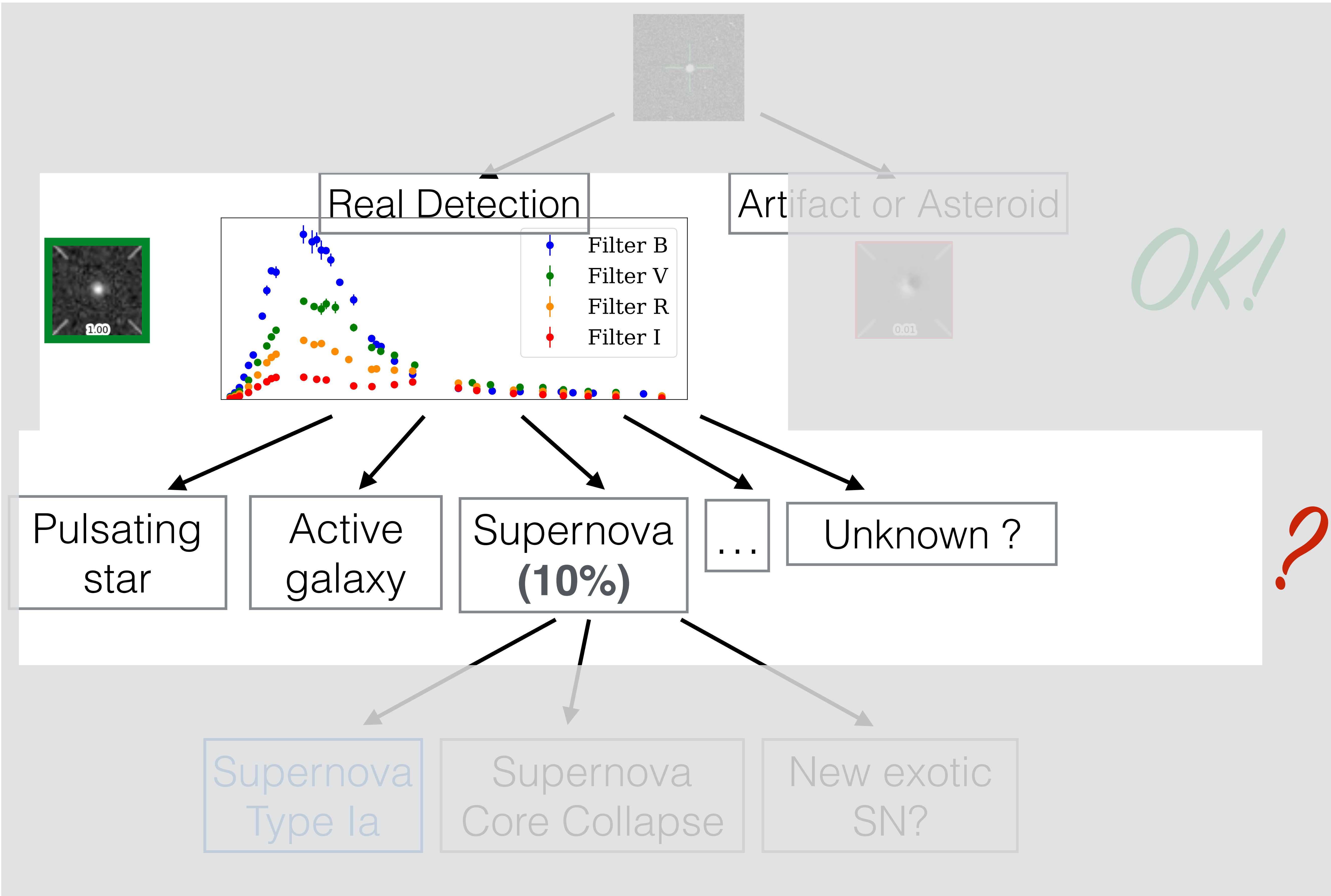
Unknown ?

Supernova Type Ia

Supernova Core Collapse

New exotic SN?

How this works in practice



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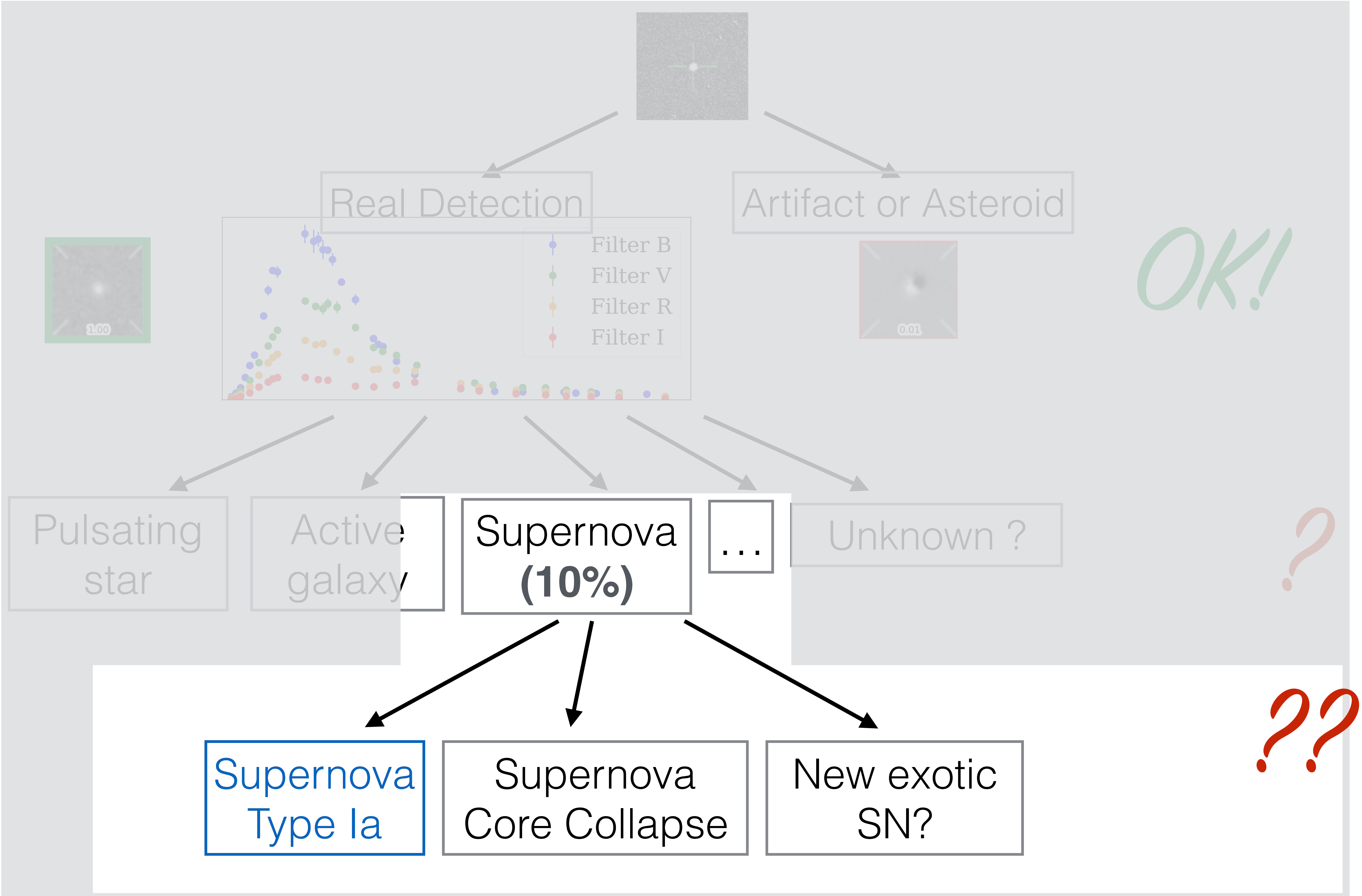
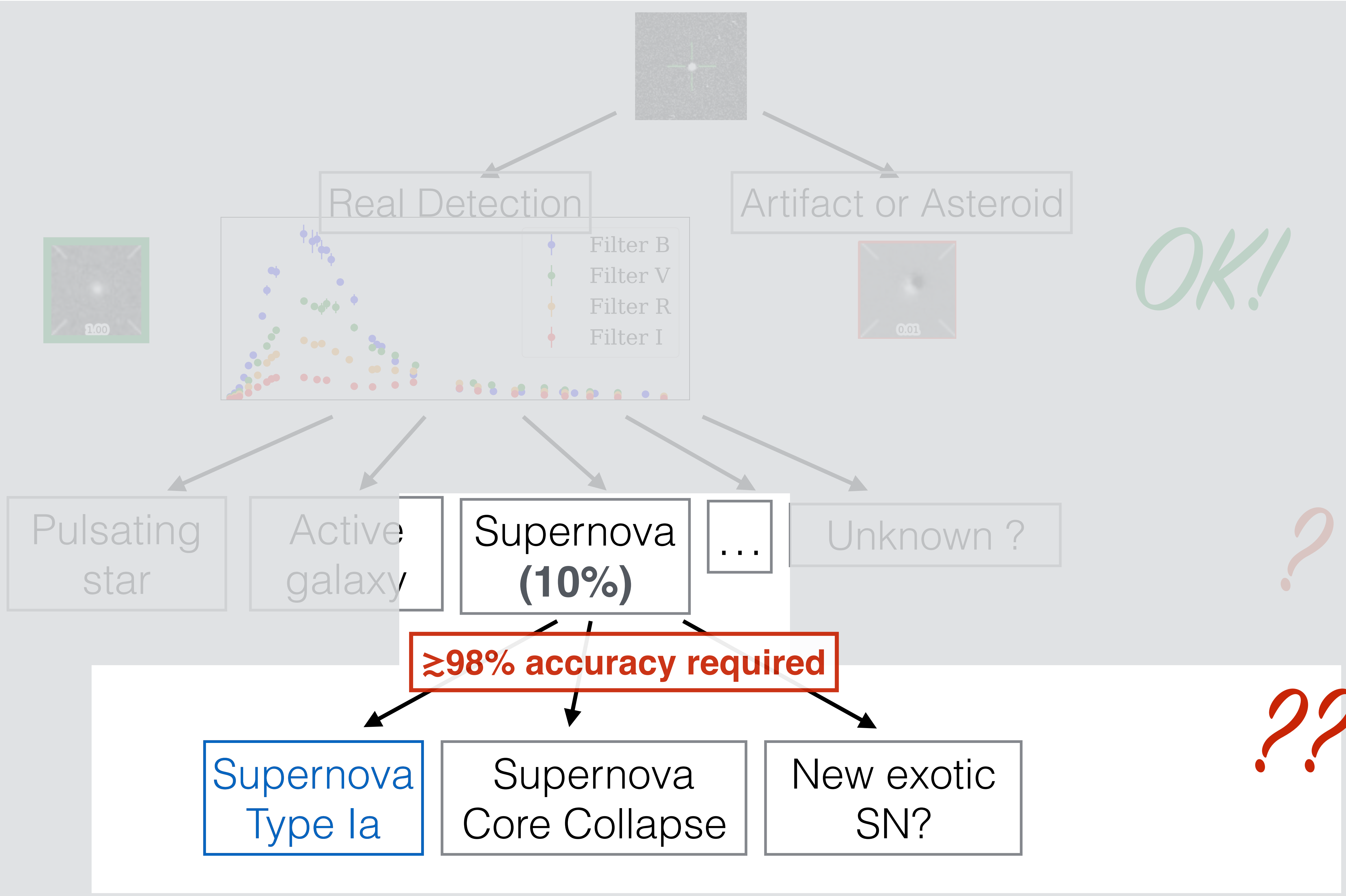


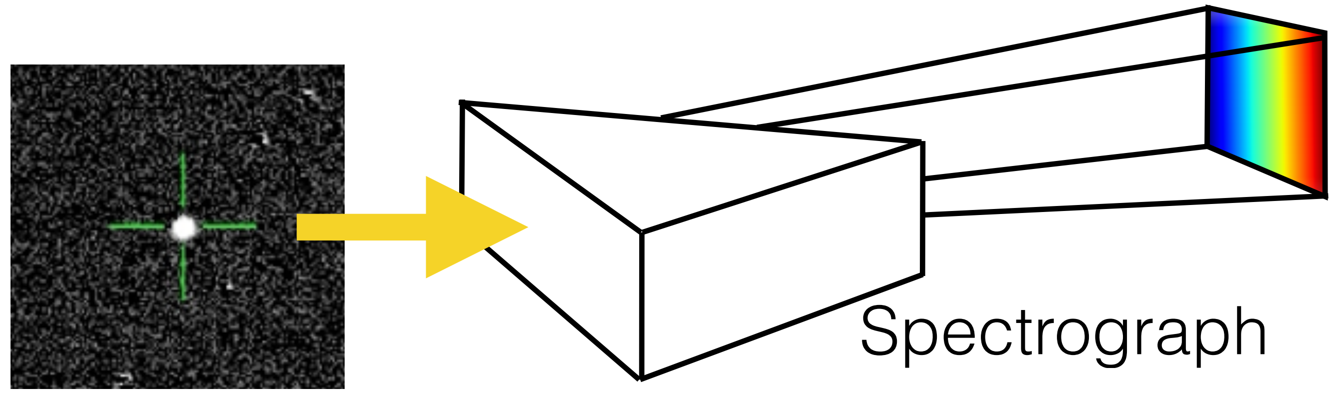
Campbell et al. 2014, Sako et al. 2014, Lochner et al. 2016

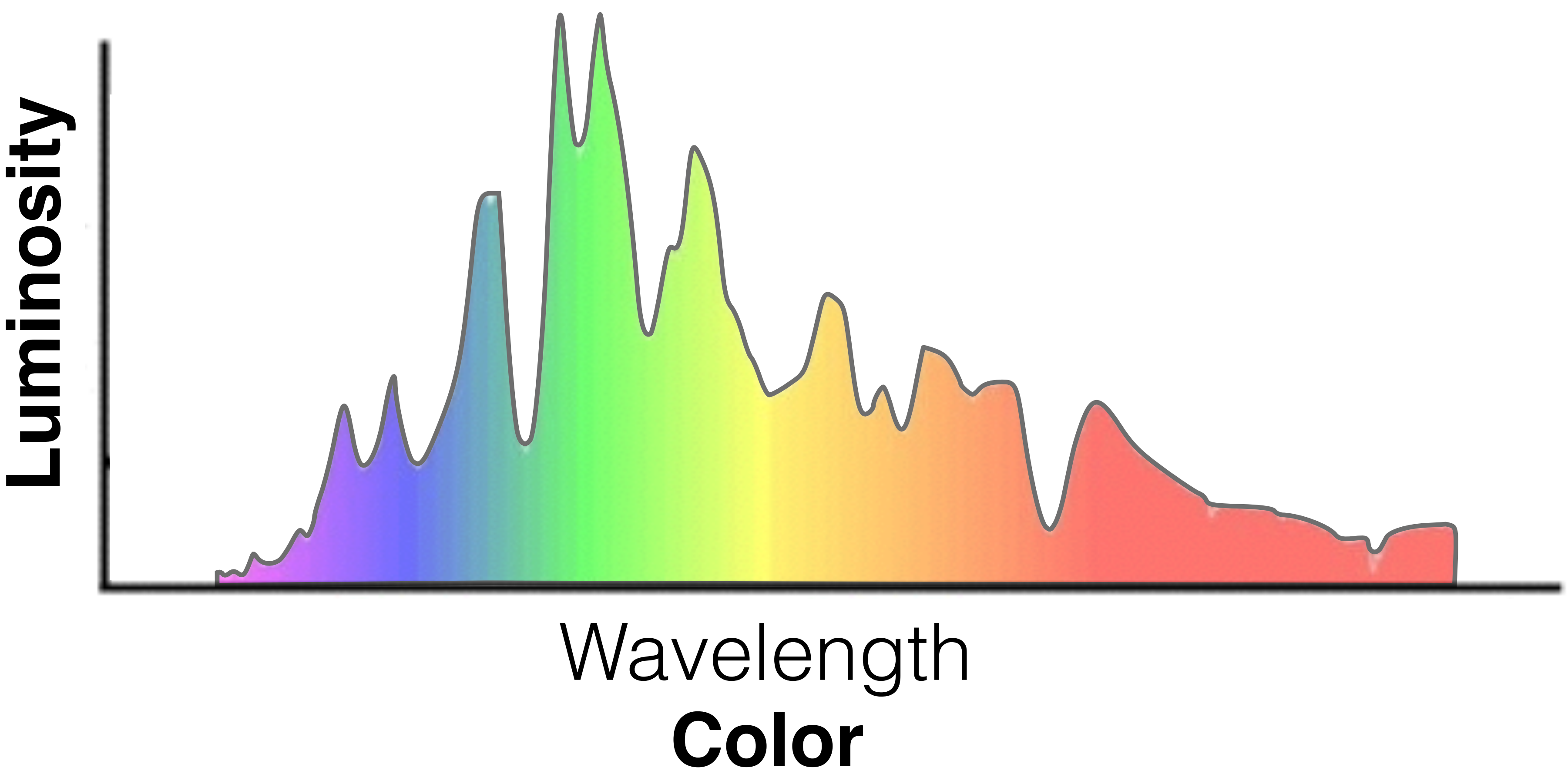
How this works in practice



Campbell et al. 2014, Sako et al. 2014, Lochner et al. 2016

Imaging —> **Spectroscopy**





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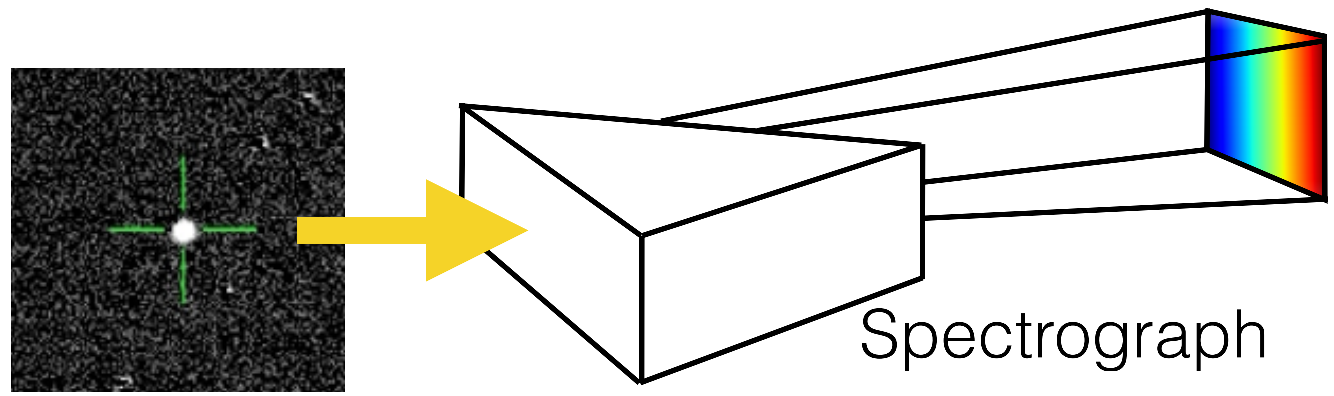
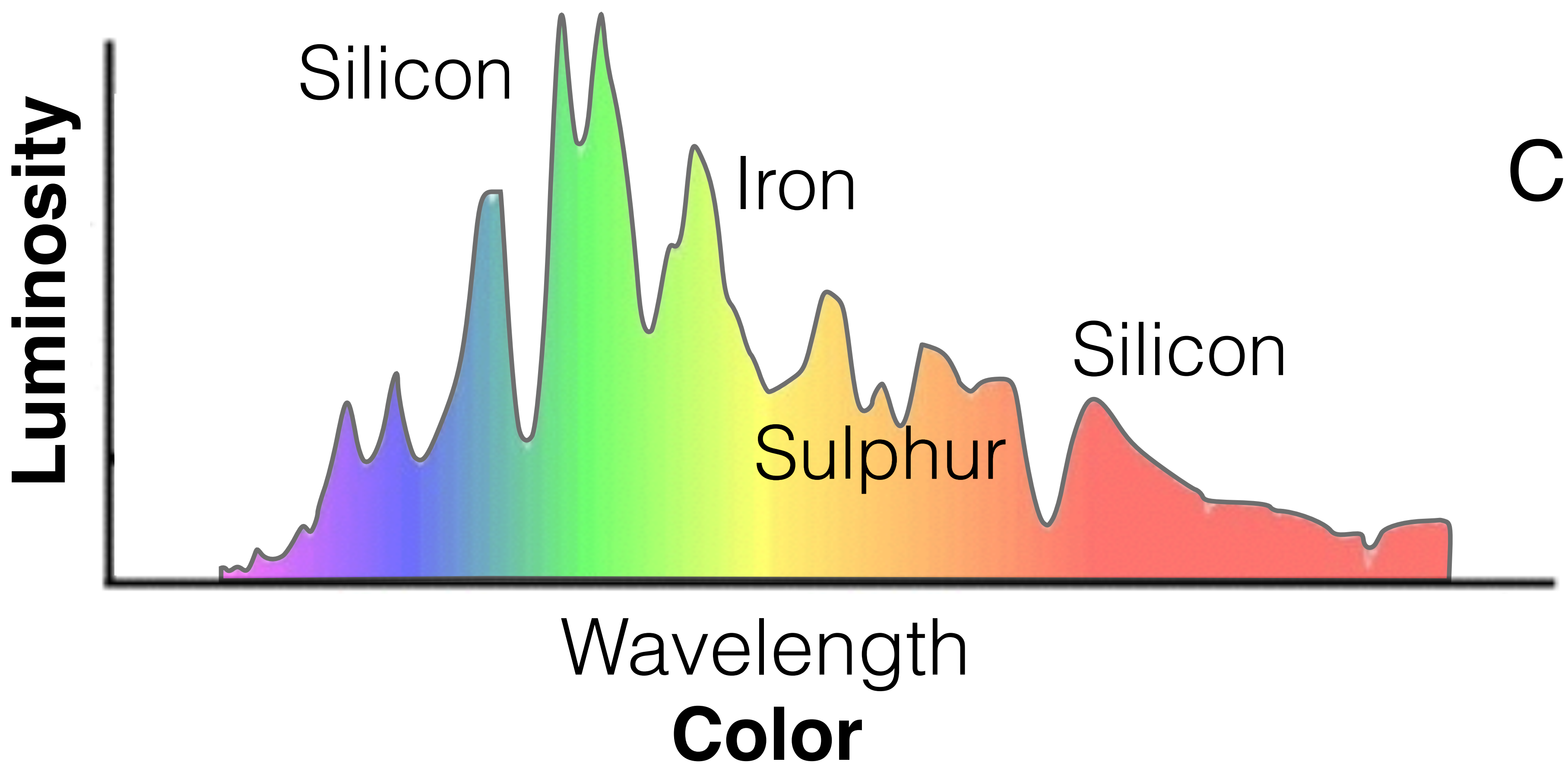


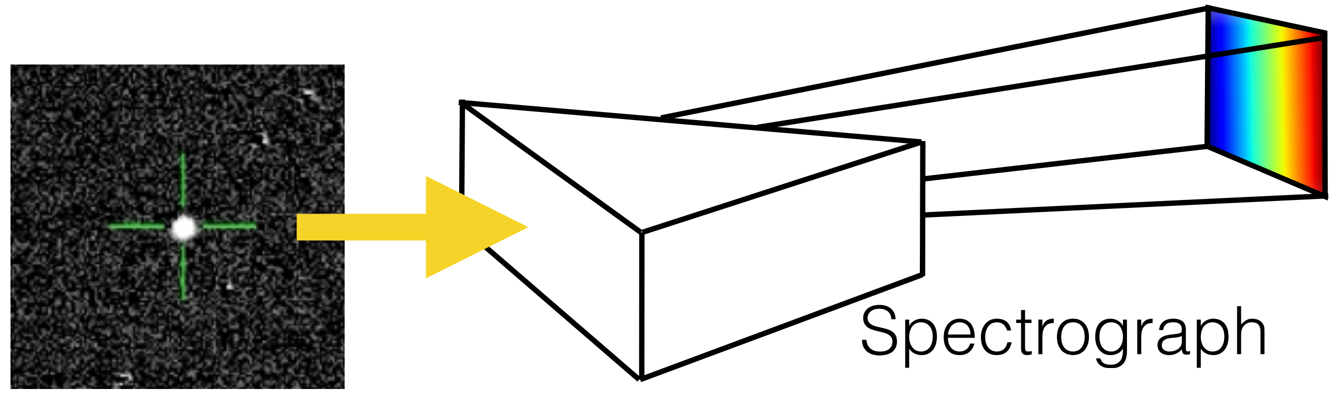


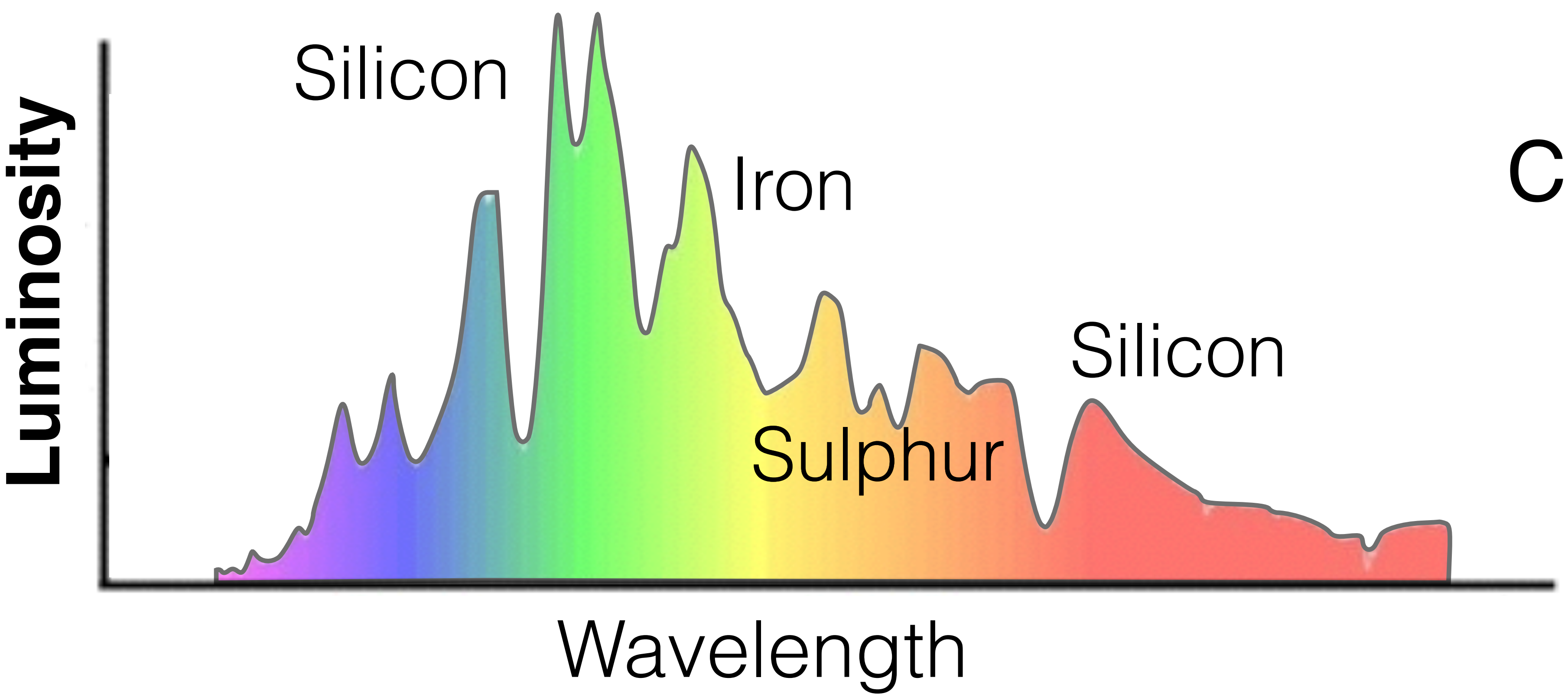
Spectrum

↓

Chemical elements

Imaging —> **Spectroscopy**





Color

Spectrum

↓

Chemical elements

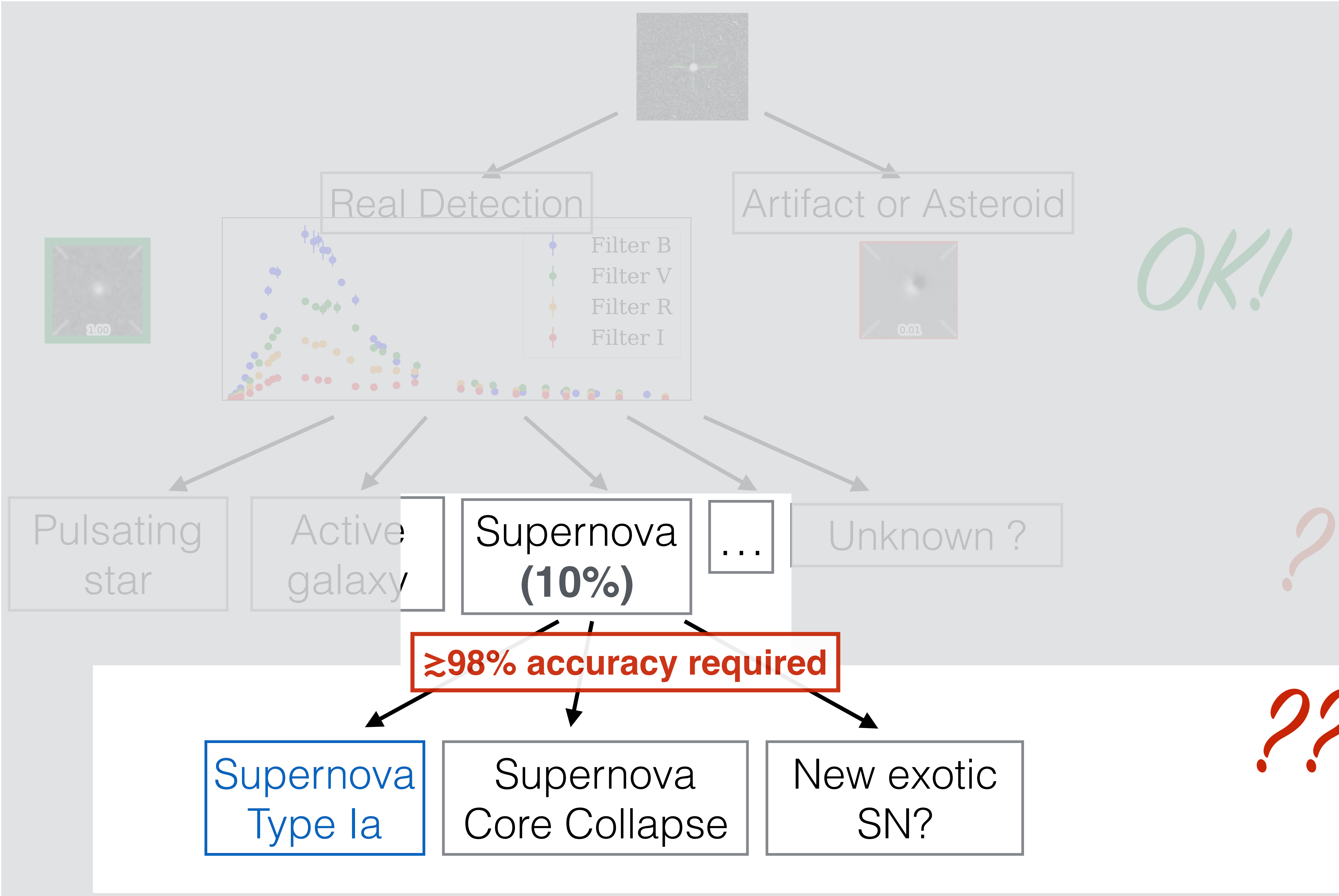
↓

Type Ia Supernovae

Problems:

- Only 10% of the sample can be scanned with spectrograph
- Training sample: bias towards brighter objects (i.e. SNe Ia)

How this works in practice



Campbell et al. 2014, Sako et al. 2014, Lochner et al. 2016

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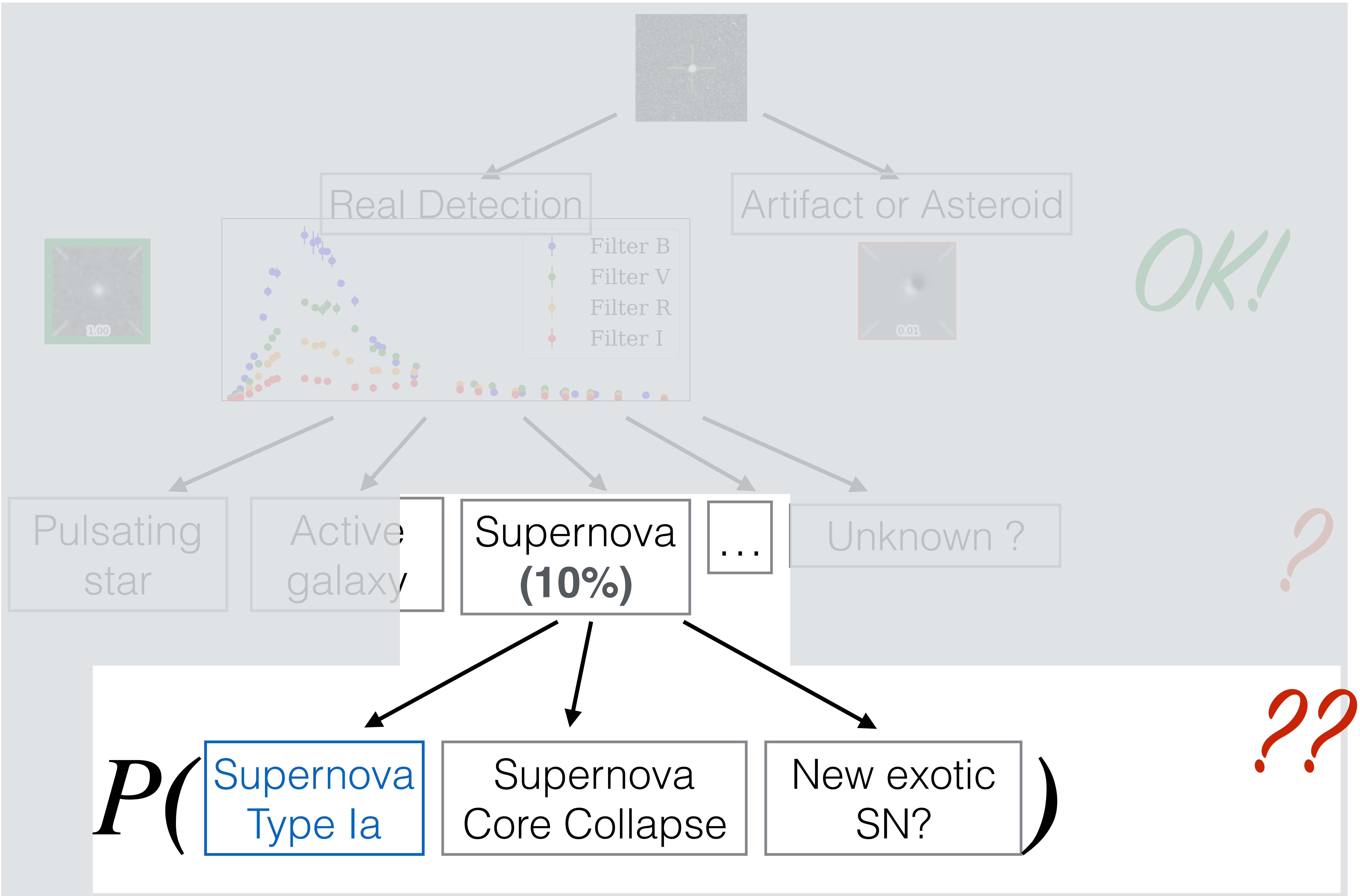

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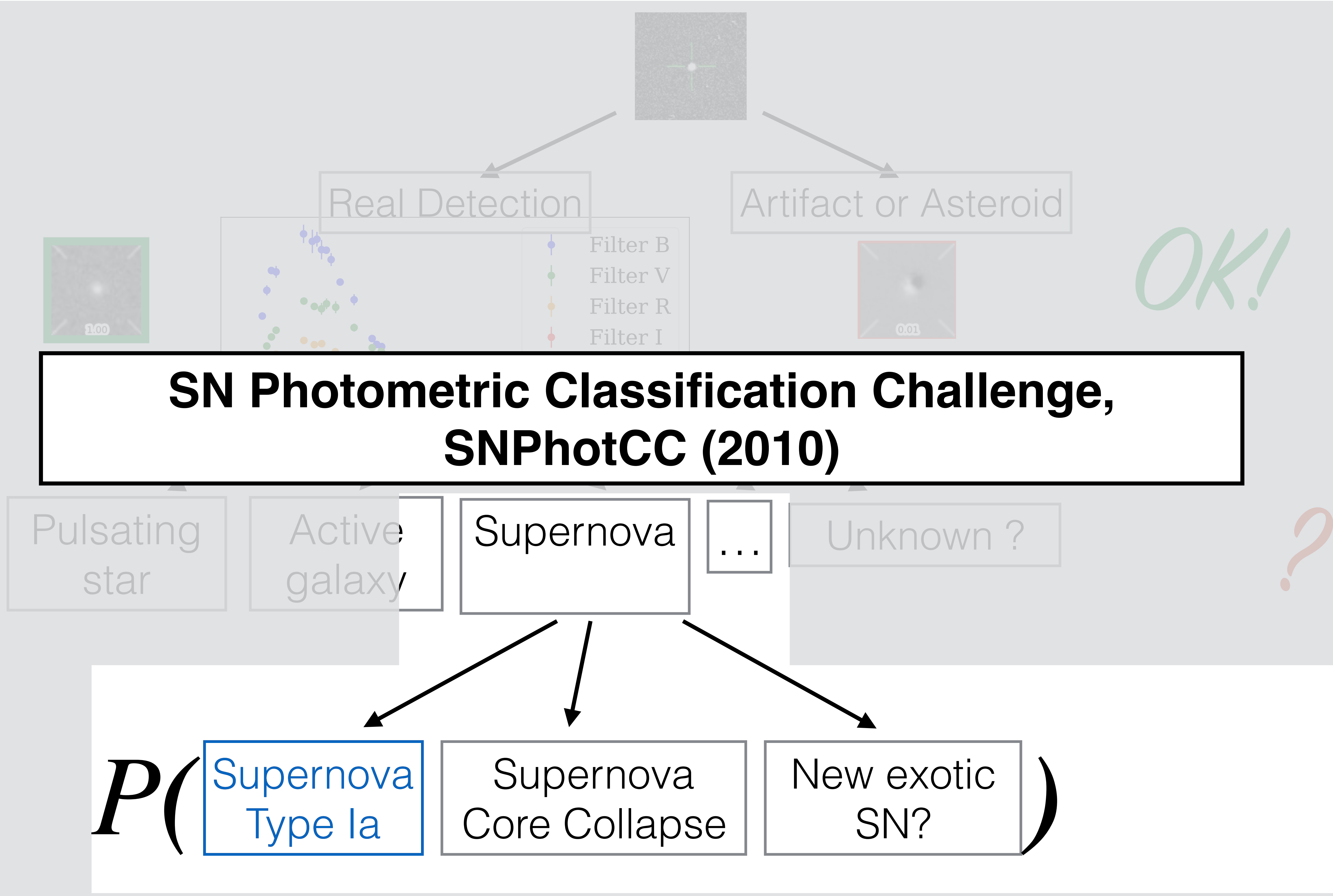
Challenges to the community of astronomers and data scientists

SN Photometric Classification Challenge, SNPhotCC (2010)

Photometric Classification Challenge for LSST, PLAsTiCC (2018)



Kessler et al. 2009, 2010

SN Photometric Classification Challenge, SNPhotCC (2010)

Simulations using 3 Classes (SN Ia, 2 types of CC SN)

Training sample: 1,103 Supernovae

Test sample: 20,216 Supernovae

SN Photometric Classification Challenge, SNPhotCC (2010)

Simulations using 3 Classes (SN Ia, 2 types of CC SN)
Training sample: 1,103 Supernovae
Test sample: 20,216 Supernovae

PSNID	**SNmachine**
Template fitting, no ML involved	Feature engineering + ML algorithms (RF, NB, SVM, BDT, ANN)
Sako et al. 2008, Sako et al. 2014	Lochner et al. 2016

SNmachine (Lochner et al. 2016)

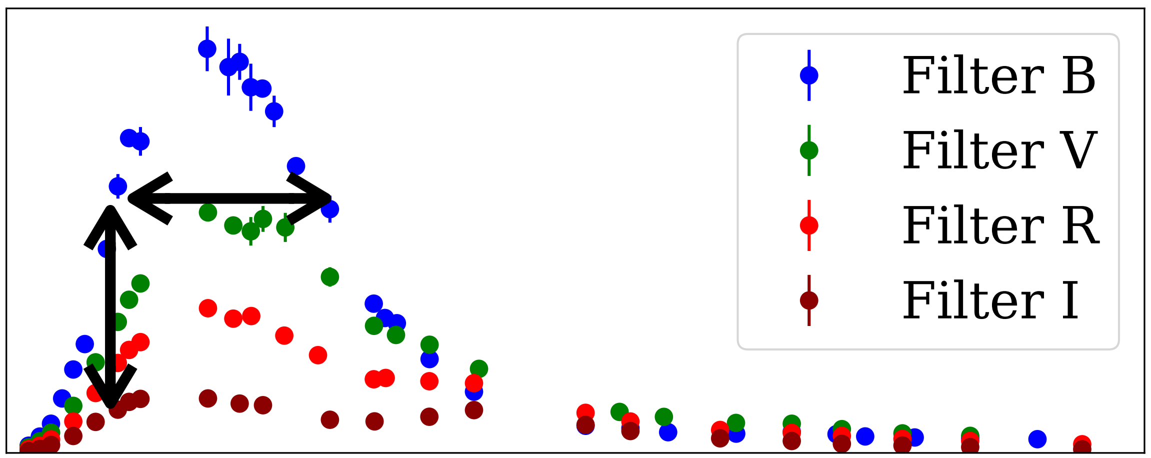
Method (1)

Method (2)

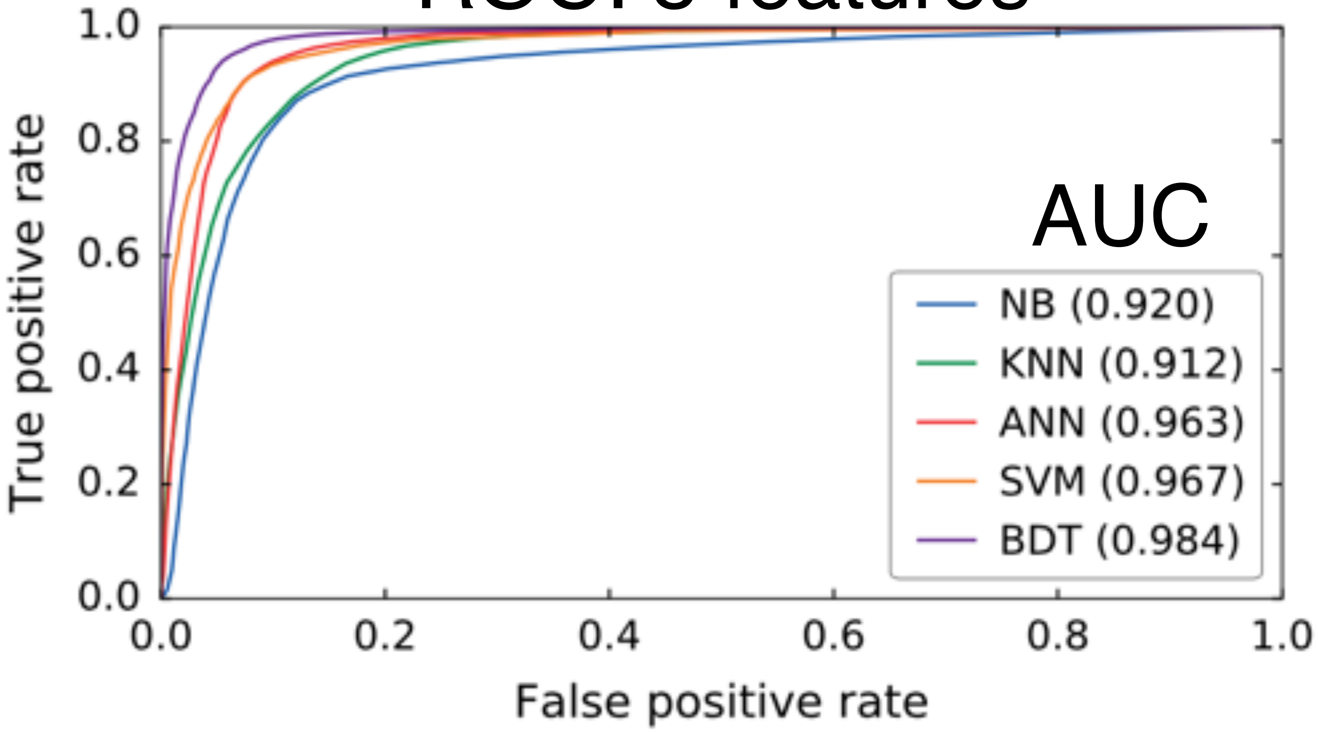
SNmachine (Lochner et al.2016)

Method (1)

➔ **5 features:** width, amplitude, color (B vs V), rise time, galaxy recession velocity



ROC: 5 features



Method (2)

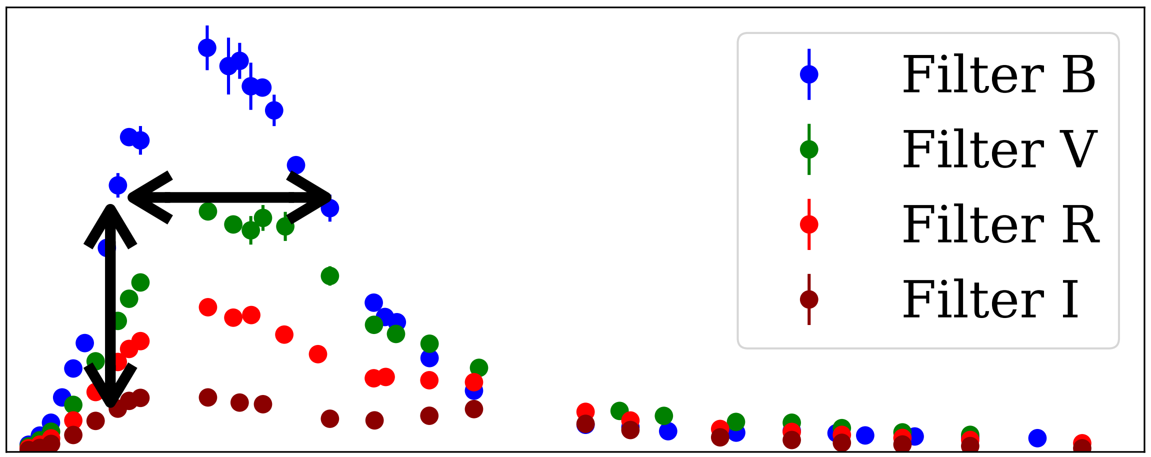
SNmachine (Lochner et al.2016)

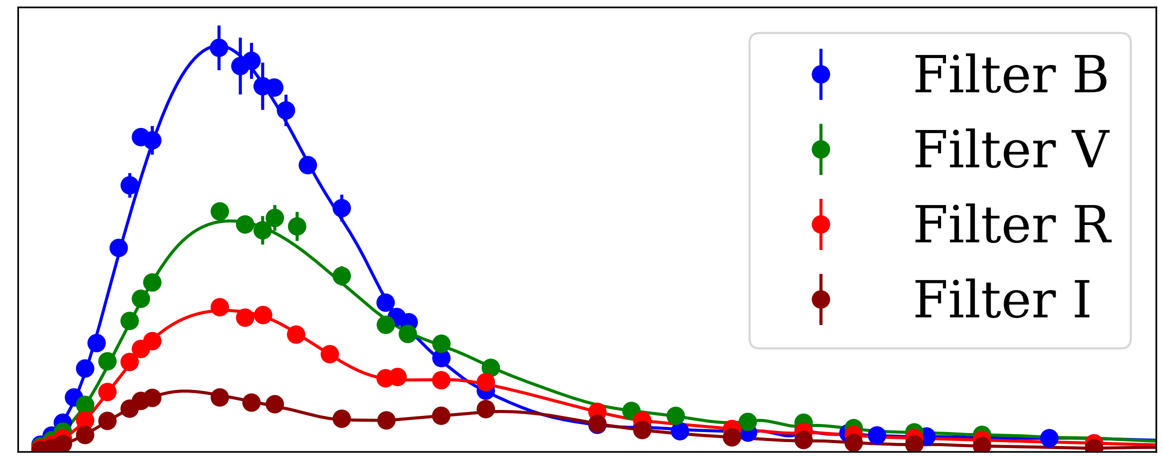
Method (1)

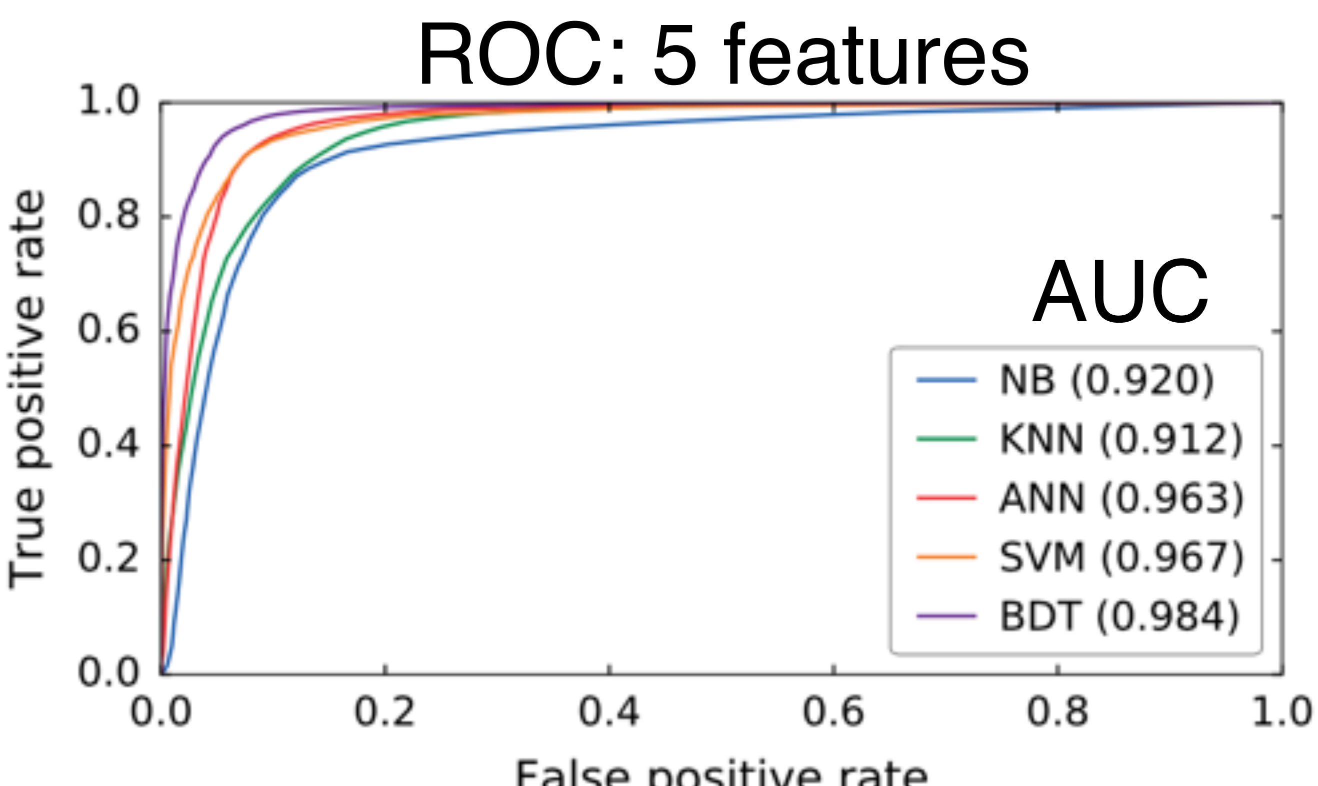
➔ **5 features:** width, amplitude, color (B vs V), rise time, galaxy recession velocity

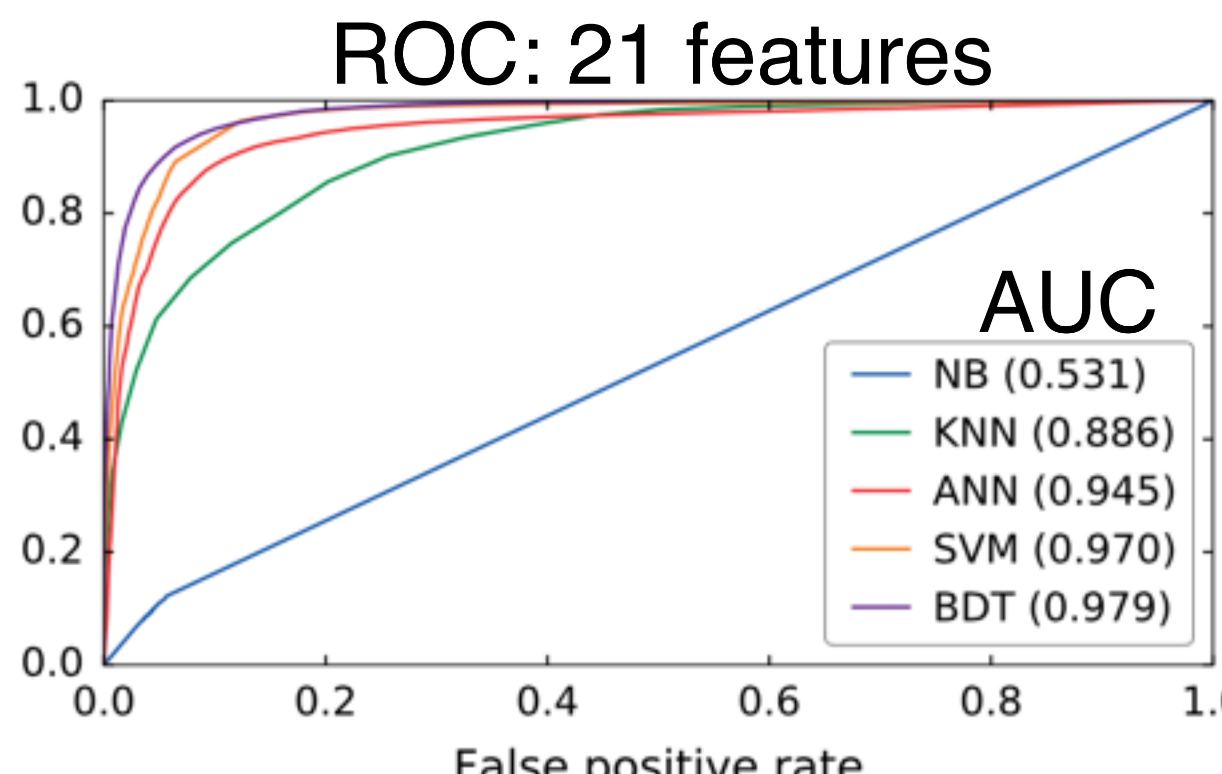
Method (2)

➔ **21 features:** Gaussian Processes +Wavelet decomposition, galaxy recession velocity









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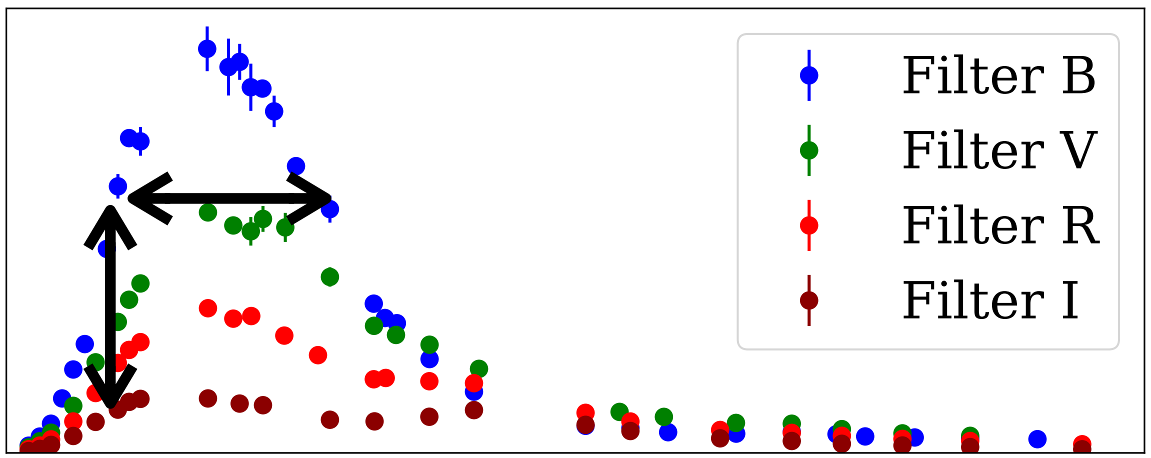
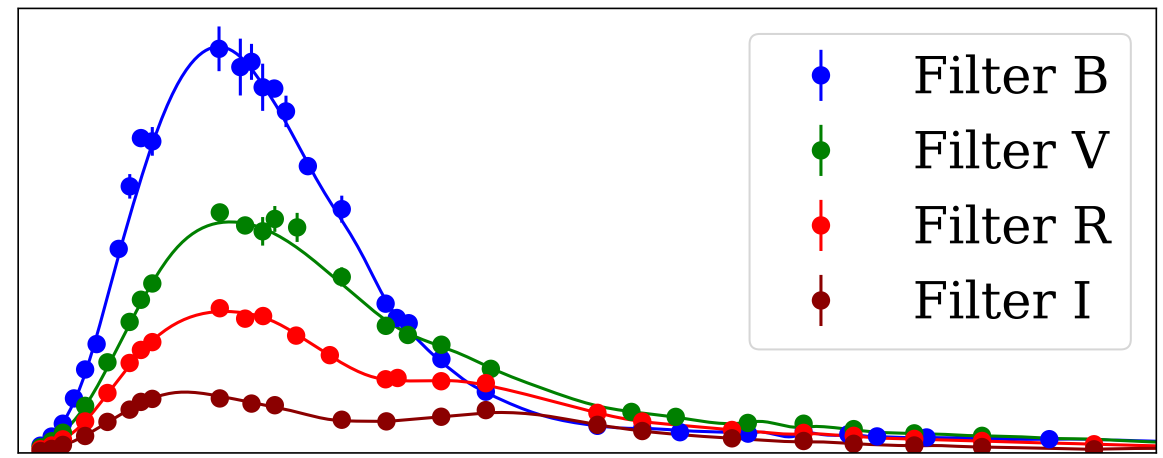


Method (2)

➔ **21 features:** Gaussian Processes +Wavelet decomposition, galaxy recession velocity



AUC < 0.85 if original training sample since this is not representative of the test sample.

SN Photometric Classification Challenge, SNPhotCC (2010)

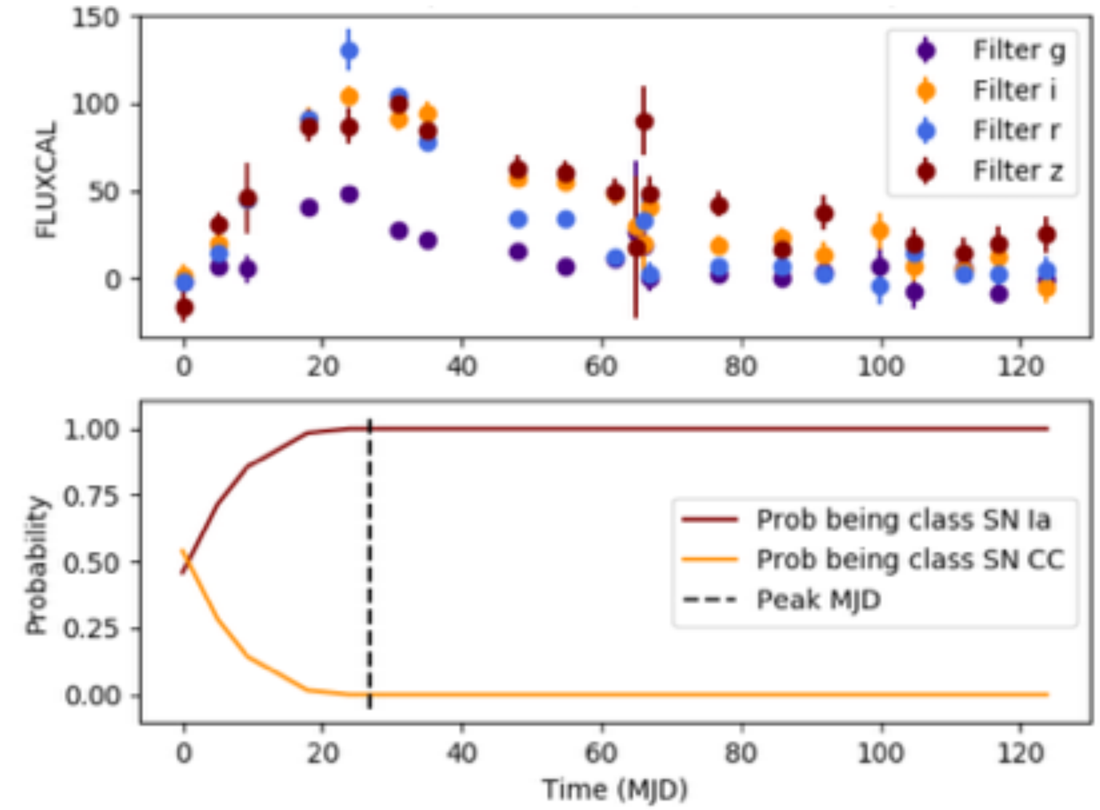
Simulations using 3 Classes (SN Ia, 2 types of CC SN)
Training sample: 1,103 Supernovae
Test sample: 20,216 Supernovae

PSNID	**SNmachine**	**RNN**
Template fitting, no ML involved	Feature engineering + ML algorithms (RF, NB, SVM, BDT, ANN)	No feature extraction, raw data and Recurrent NN
Sako et al. 2008, Sako et al. 2014	Lochner et al.2016	Charnock&Moss 2017 Moller et al. 2019

SuperNNova

open source photometric classification

Recurrent Neural Networks (Moller et al. 2019)

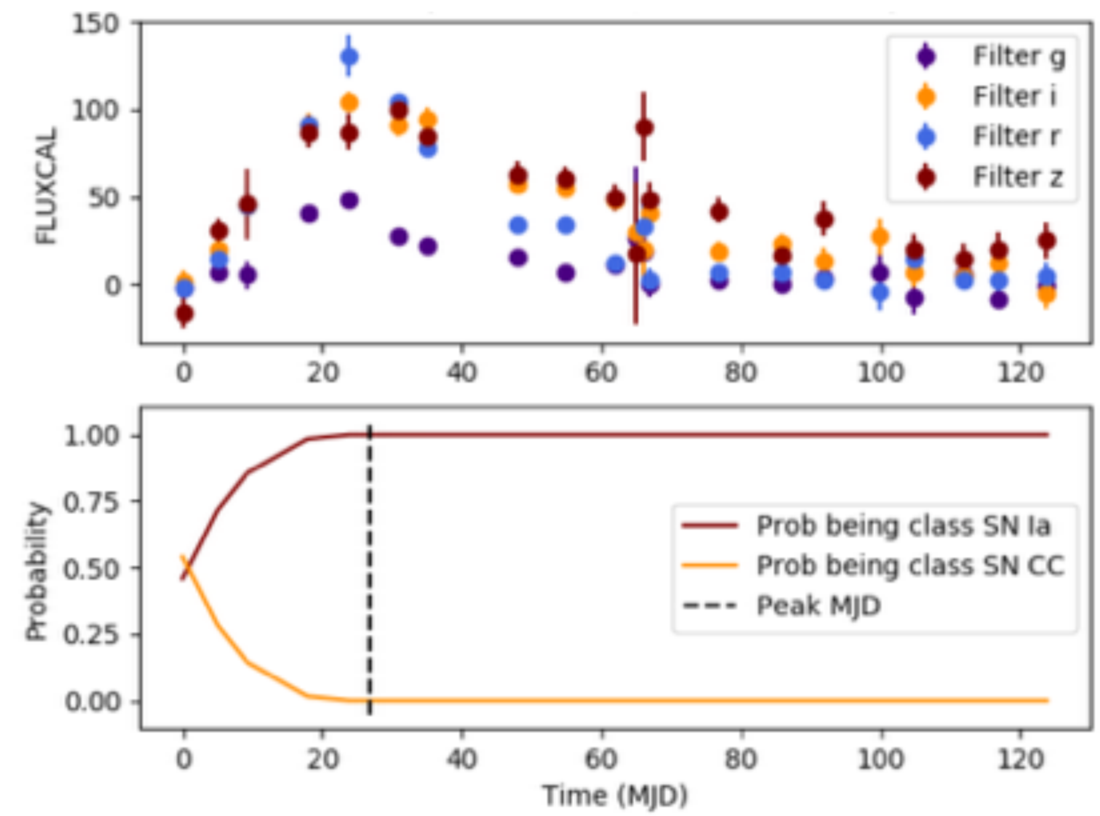


Simulations: 1,983,213 Supernovae

SuperNNova

open source photometric classification

Recurrent Neural Networks (Moller et al. 2019)



Simulations: 1,983,213 Supernovae

NON Representative Training Sample (40% Train, 60% Test)

Accuracy (Ia vs CC)

Representative Training Sample (40% Train, 60% Test)

Accuracy (Ia vs CC)

Training Sample (100%Train, 100%Test)

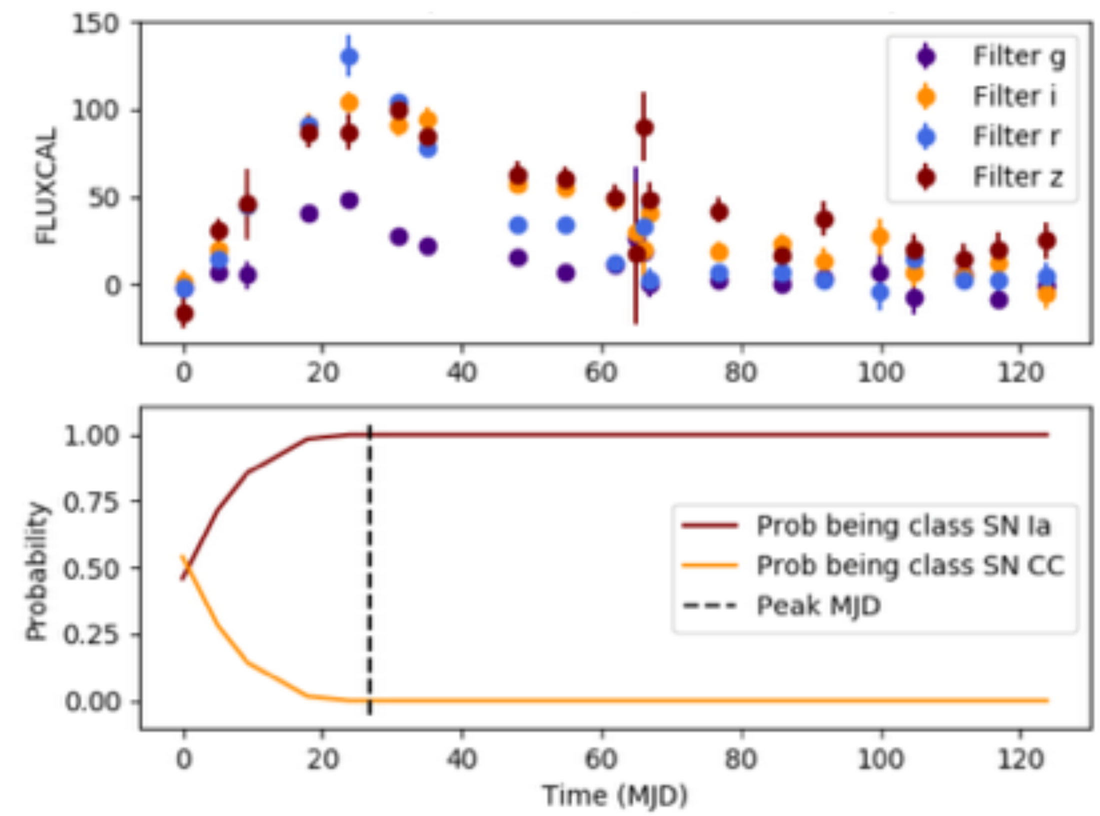
Accuracy (Ia vs CC)

SuperNNova

open source photometric classification

Recurrent Neural Networks (Moller et al. 2019)

Simulations: 1,983,213 Supernovae

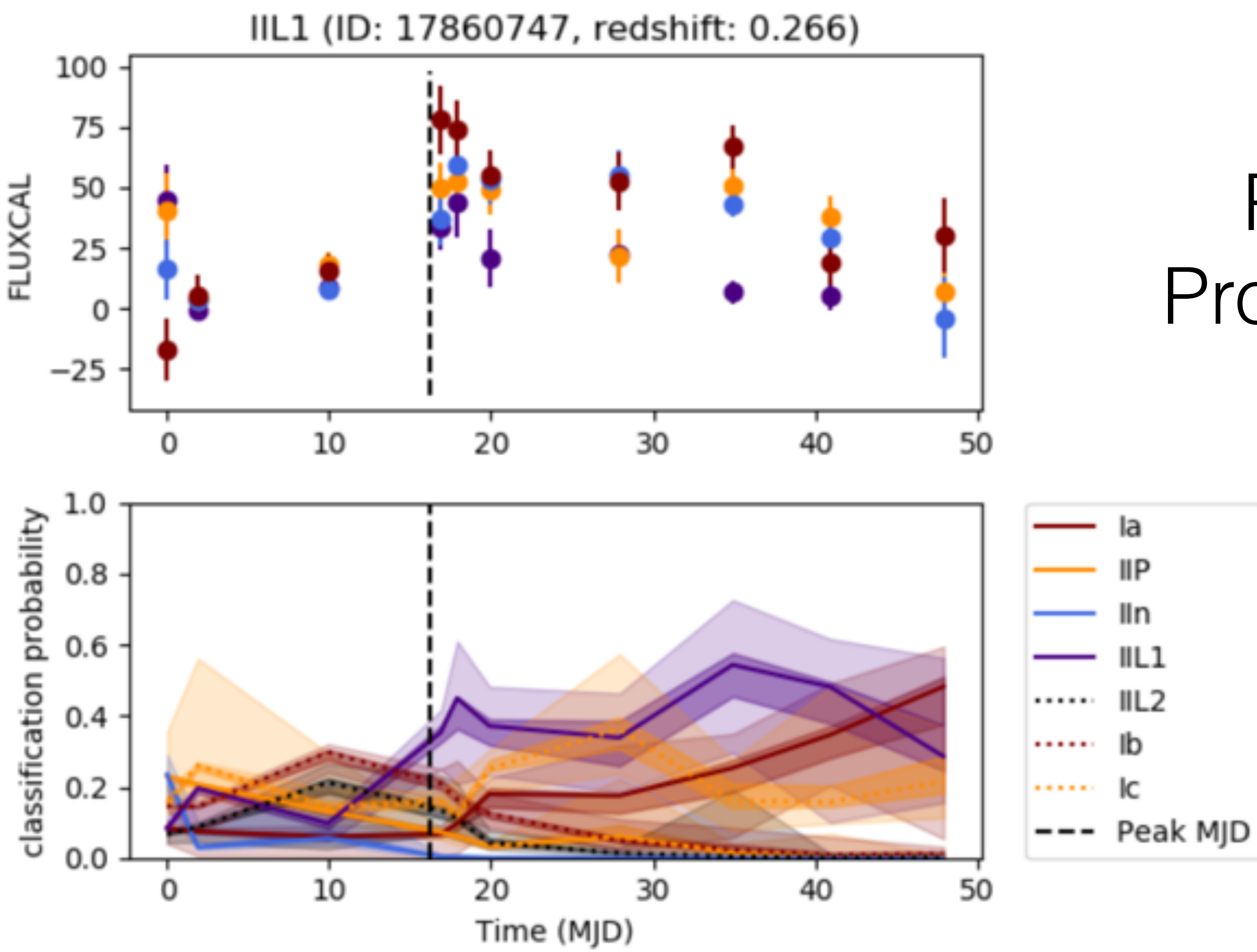


	Only first 10 days of data	All light curve
NON Representative Training Sample (40% Train, 60% Test)		
Accuracy (Ia vs CC)	97.36 ± 0.28	$\mathbf{99.51 \pm 0.08}$
Representative Training Sample (40% Train, 60% Test)		
Accuracy (Ia vs CC)	92.96 ± 0.77	$\mathbf{97.84 \pm 0.45}$
Training Sample (100%Train, 100%Test)		
Accuracy (Ia vs CC)	94.09 ± 0.14	$\mathbf{98.43 \pm 0.07}$

SuperNNova
open source photometric classification

Recurrent Neural Networks (Moller et al. 2019)

Simulations: 1,983,213 Supernovae



Probability errors?
Probability calibration?

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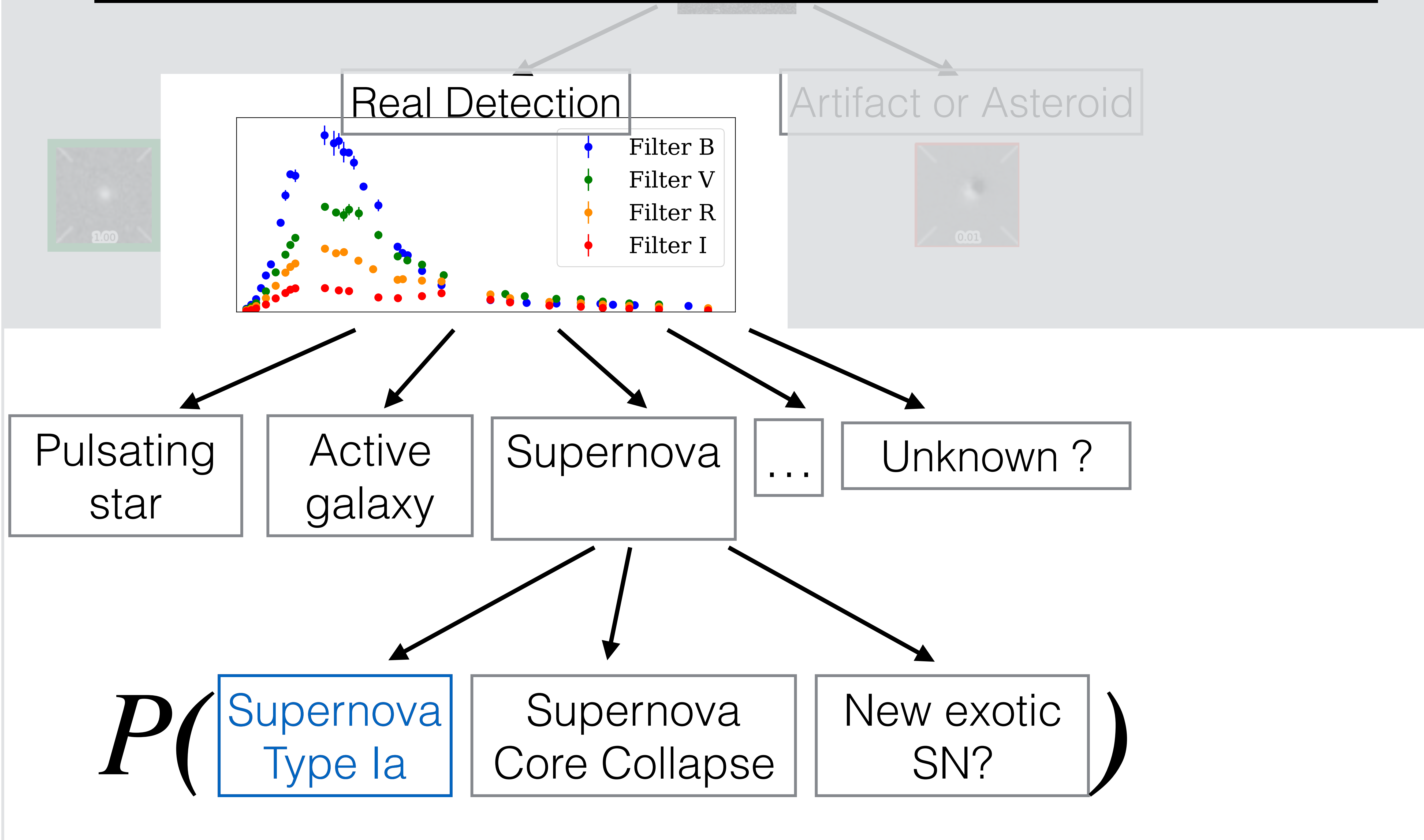
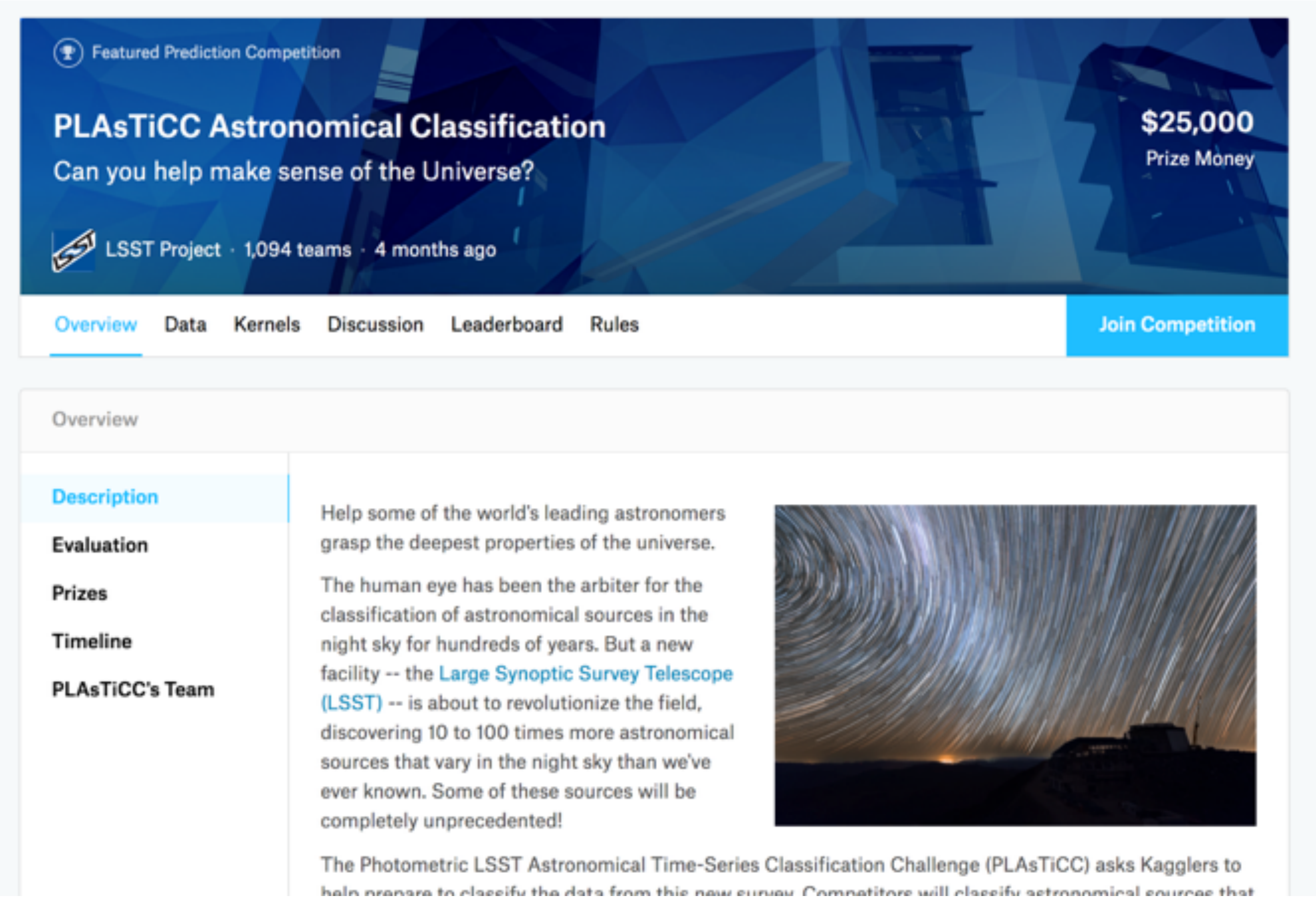
Photometric Classification Challenge for LSST, PLAsTiCC (2018)



https://plasticc.org

Photometric Classification Challenge for LSST, PLAsTiCC (2018)

Simulations using 15 classes (6 types of SNe), 14 represented in training sample.
Training: 8000 objects (NON-representative)
Testing: 3.5 million objects



Two challenges:
Early classification
Late classification

Performance metrics: log-loss

https://plasticc.org
Malz et al. 2018

What are we learning from these challenges?

1) Training samples: representative samples or biased observed samples?
2) Probabilities: calibration? statistically meaningful?
3) Training and testing is done on simulations, how **realistic** are these simulations?

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↓

My PhD: new models of Core Collapse Supernovae

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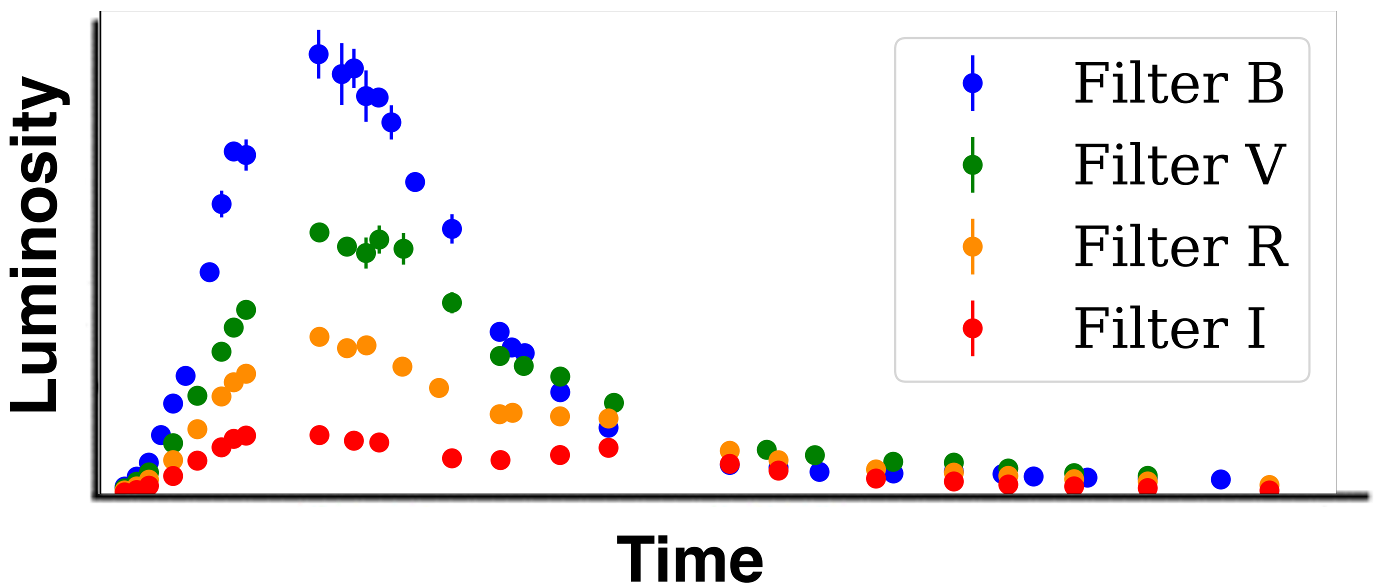
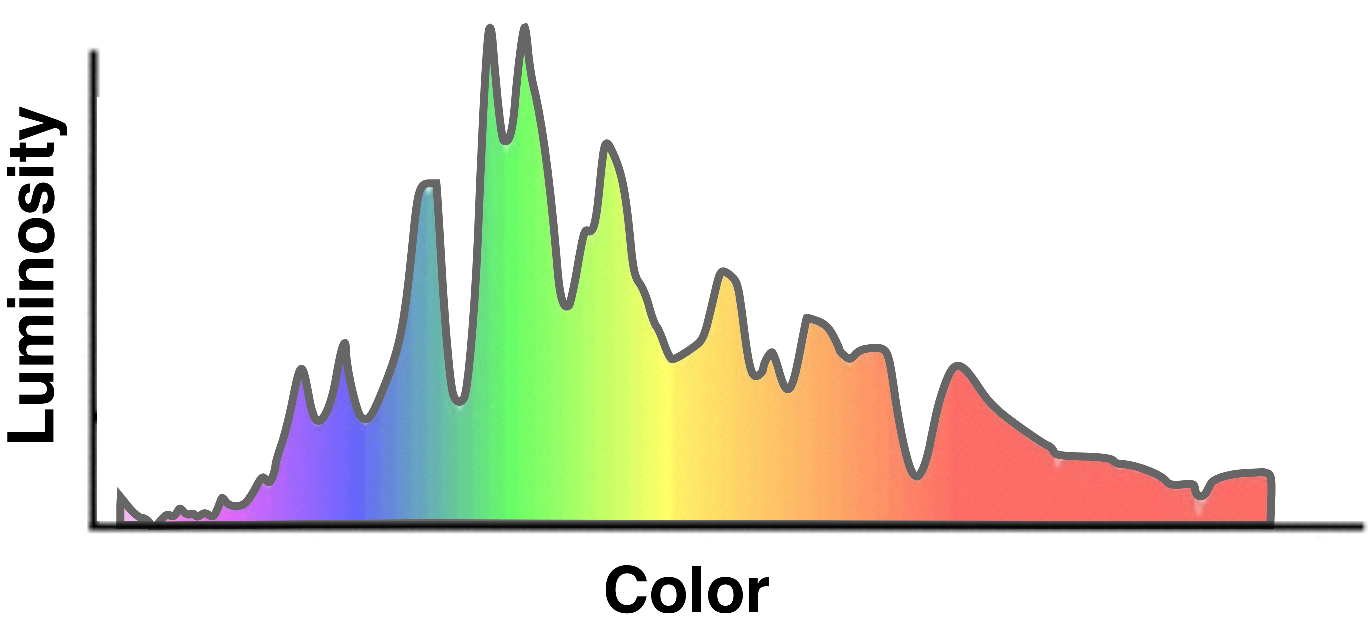
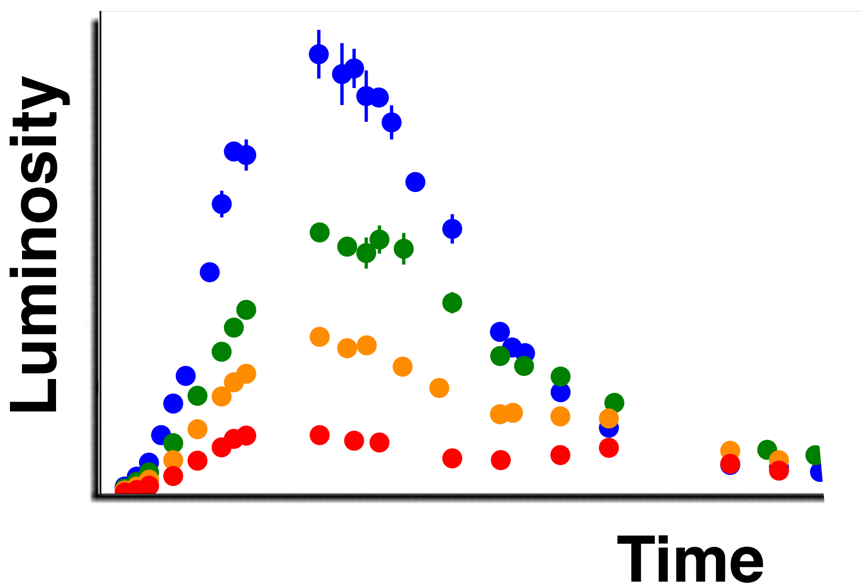
70 well observed Core Collapse Supernovae

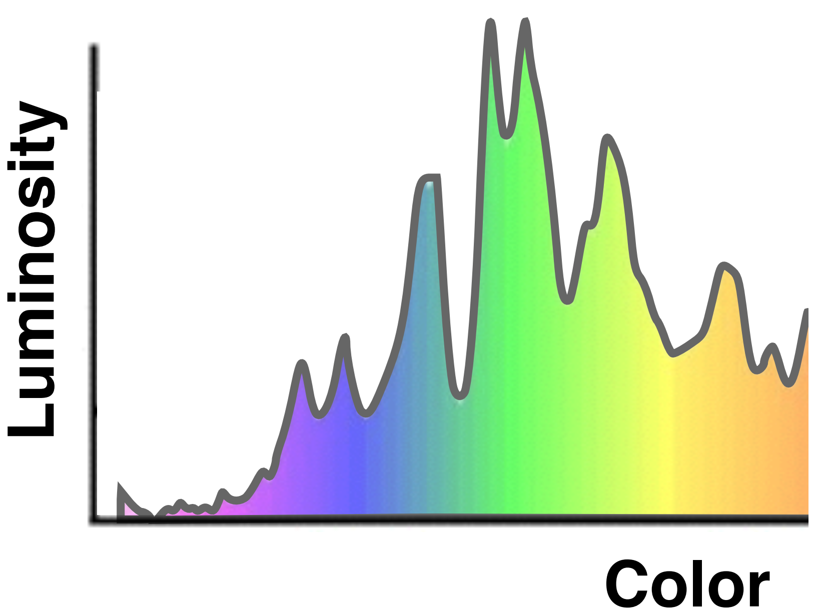




My PhD: new models of Core Collapse Supernovae

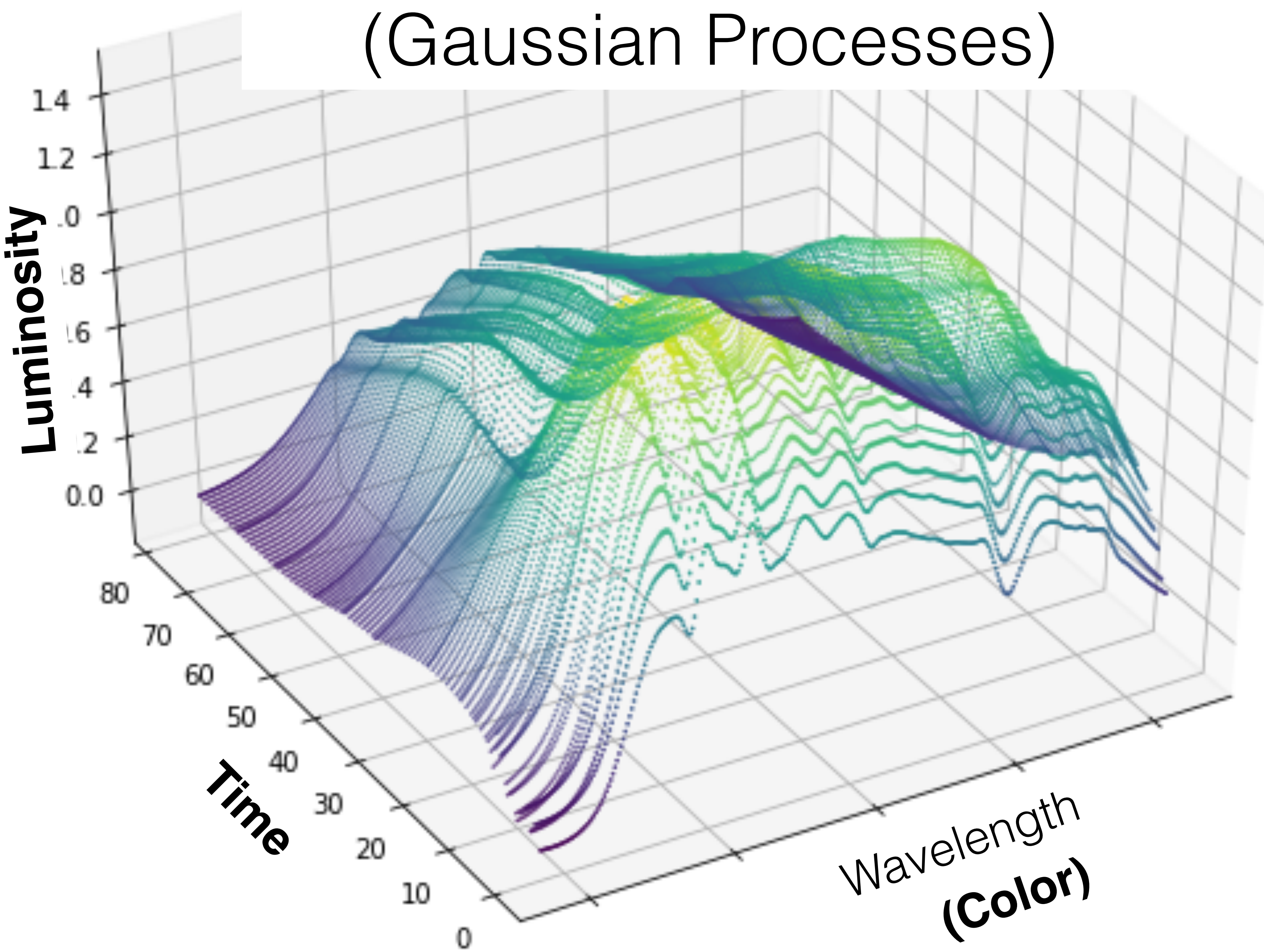
70 well observed Core Collapse Supernovae





Time - Color evolution of each Supernova

(Gaussian Processes)



My PhD: new models of Supernovae NON Ia

Previous models

→ One "average" spectral template

→ Poor "color" coverage

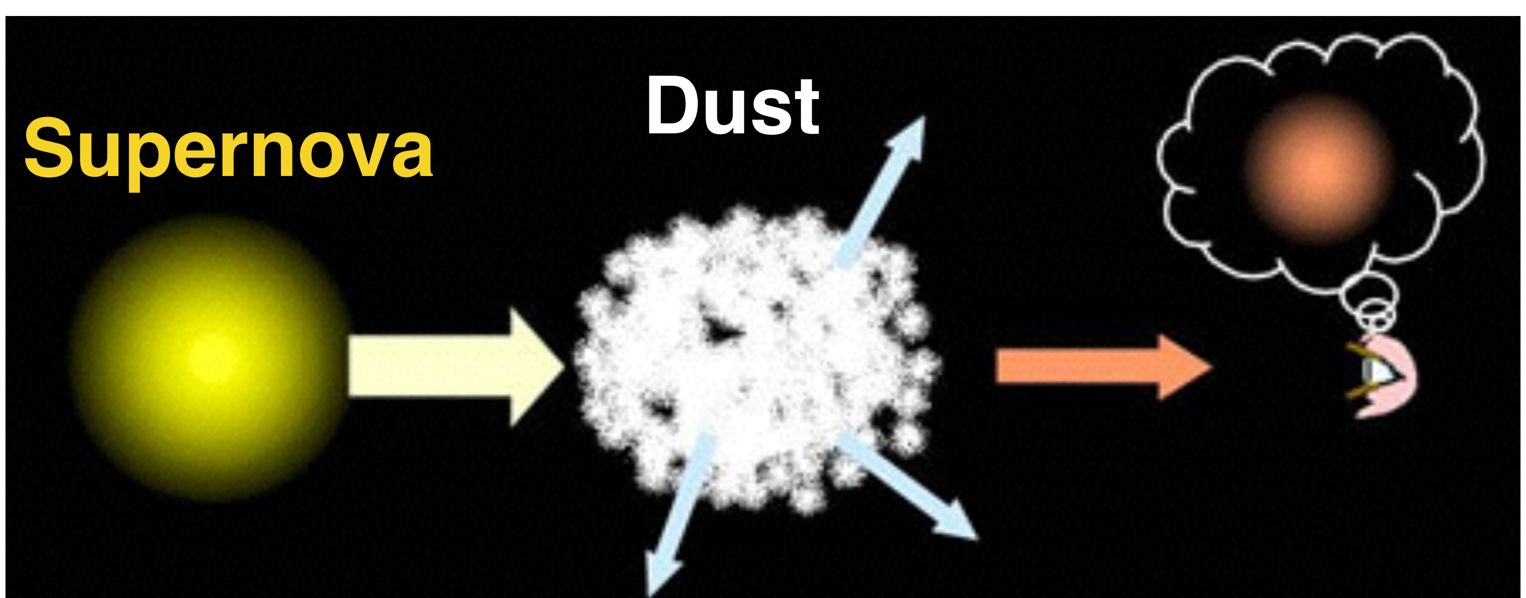
New Supernova models

→ More **diversity**

→ More "colors" information **(especially in the UV)**

My PhD: new models of Supernovae NON Ia

Previous models	New Supernova models
→ One “average” spectral template	→ More **diversity**
→ Poor “color” coverage	→ More “colors” information **(especially in the UV)**
→ No dust corrections	→ **Dust** taken out



→ Dust alter the observation
→ It’s good for data augmentation!

Conclusions & What's next?

- **Classification of Type Ia SNe (vc CC SNe)** is one of the crucial challenges for the study of the evolution of the Universe.

- The **PLAsTiCC** challenge is now the ML benchmark. However, it poses a very broad problem. Not optimal for the SNe Ia vs CC SNe problem

- New CC SNe models can help us to improve training sets for ML classifiers.

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Thank you!

Back-up slides

—> No UV extension

—> **UV extension** for simulations at high redshift