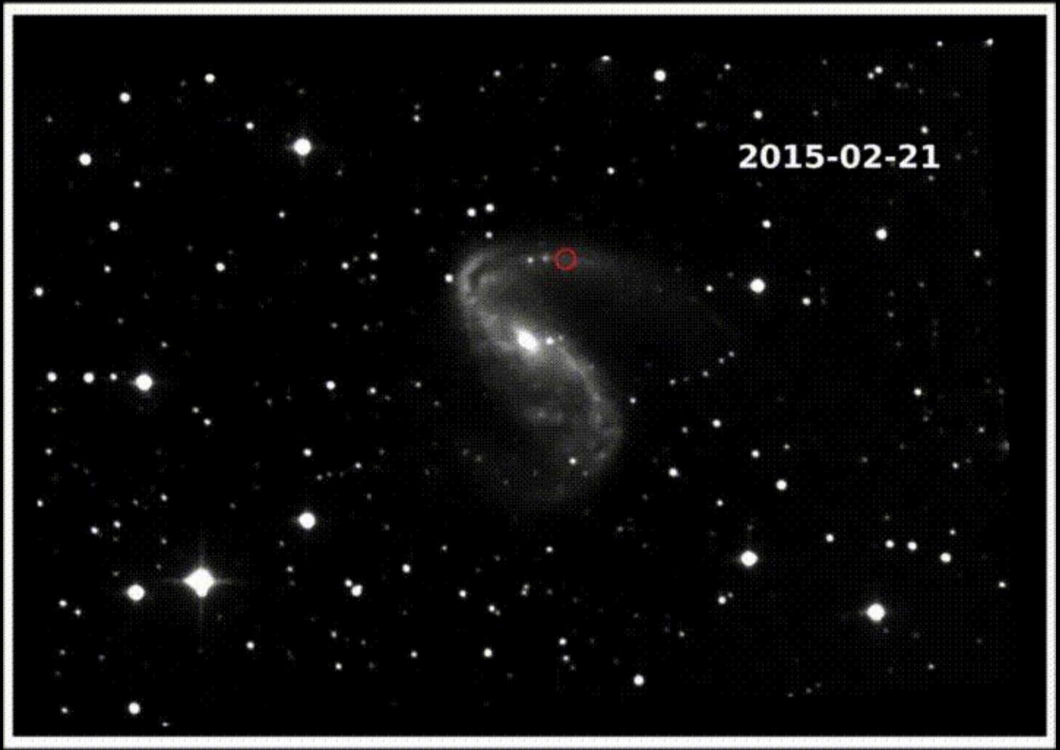


Astrophysical Transients

Optical time domain astronomy with the LSST

“The Rise and Fall of Type Ia Supernova 2015F”, astroberto54, https://imgur.com/dPl1aNM

Agenda

This slide deck covers:

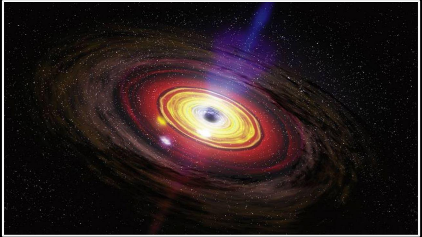
- physical phenomena that create optical transients
- the transient Zoo, nomenclature
- open questions & scientific motivation for transient studies (big picture)
- what makes a survey good for transients?
- the transient-related science goals of the LSST
- expected yields for transients from the LSST
- DIA data products from the LSST
- transient-related challenges in the LSST era
    - sidebar on photometric classification & host association
- how the science community is preparing for transient science with the LSST
- some of my plans for easy early transient science

Astrophysical Transients on *Human Timescales*

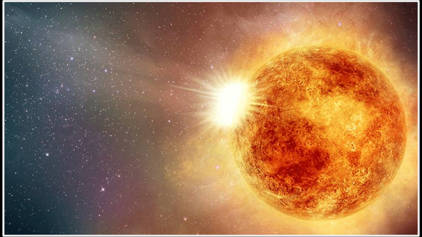
Astrophysical objects that change in brightness are transient *or* variable.
Transient behaviour lasts for a “short” time and does not repeat.

Today we’re focusing on *intrinsic* transients, and skipping *extrinsic* transients, changes in brightness with *external* causes, like microlensing events.

Some variables have *transient features*; we’re not covering these today either.



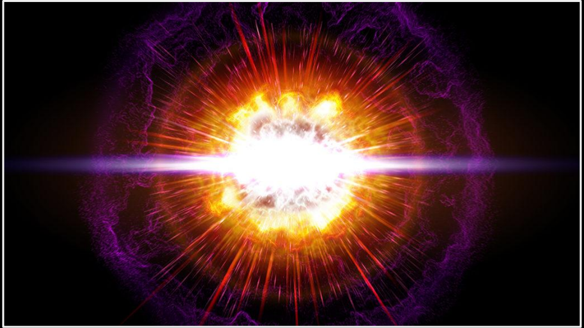
E.g., Active Galactic Nuclei (AGN)
- they turn on and off
- have “changing look” spectral features
- but are variable on human timescales



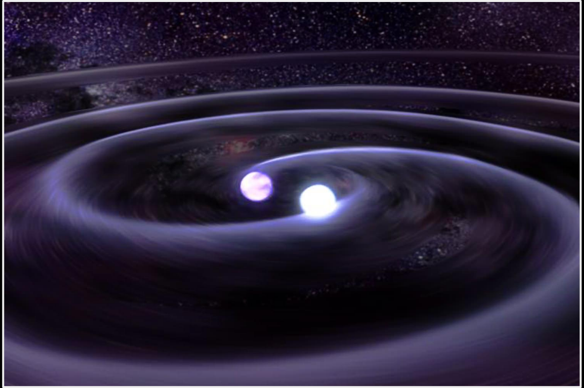
E.g., variable stars
- can flare or erupt

Betelgeuse gif credit: NASA, ESA, and E. Wheatley (STScI)

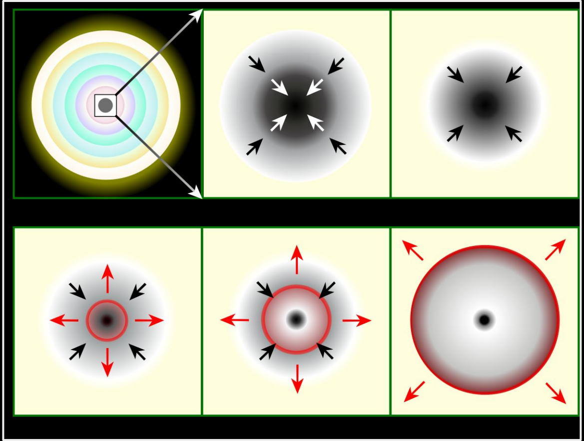
Transient Astrophysical Phenomena



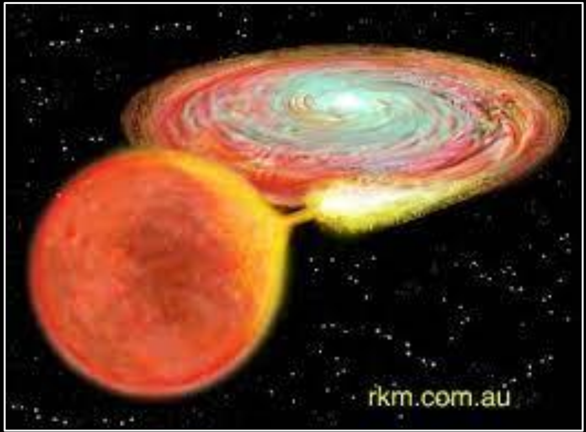
detonation & explosion



merger / collision

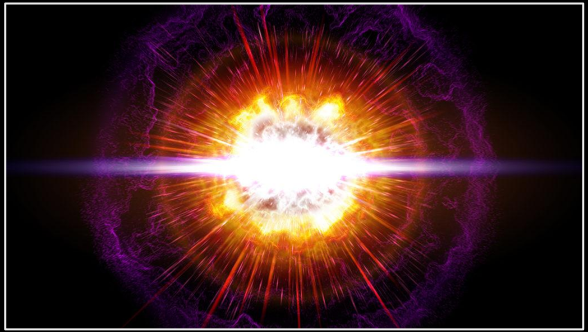


collapse:
implosion + explosion

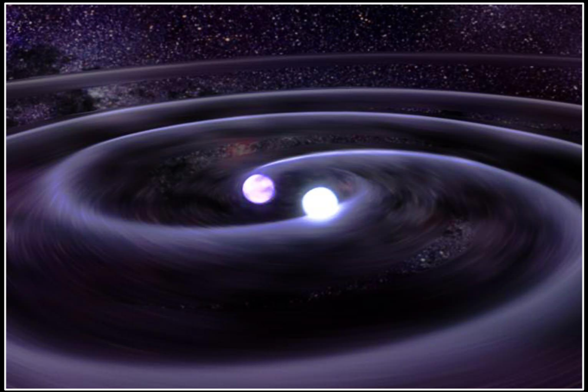


accretion / interaction
can also cause variability

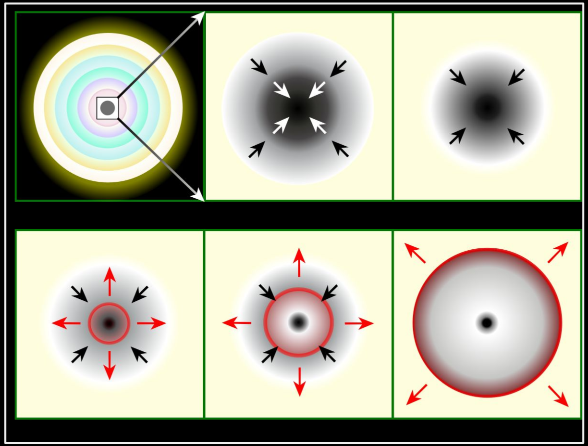
Transient Astrophysical Phenomena



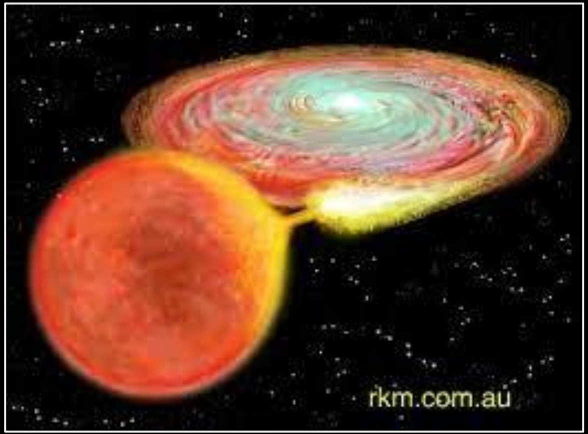
supernovae



supernovae
kilonovae



supernovae



novae
tidal disruption events

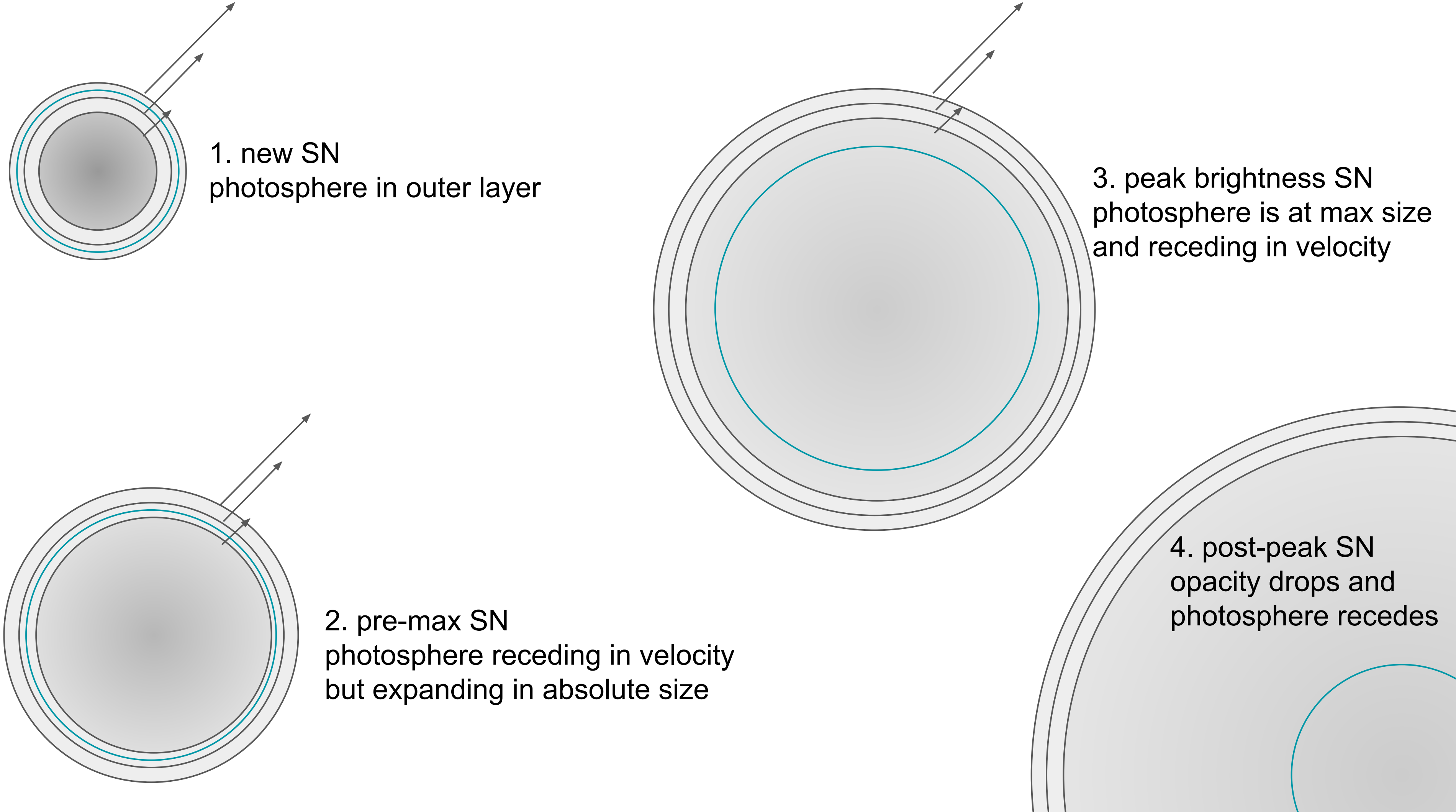
Transient Astrophysical Phenomena

Where do the optical photons come from, in supernovae, in general?

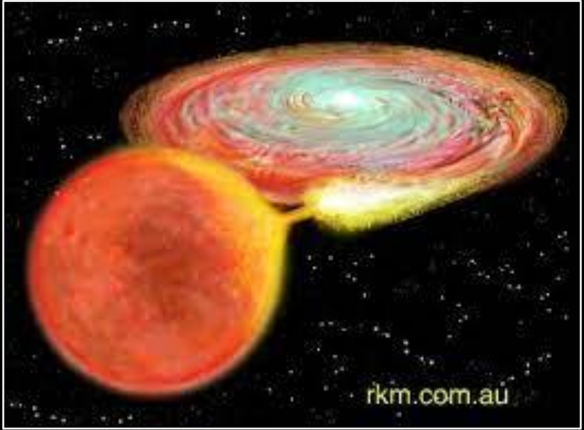
- processes that inject energy into the material
  - shock heating followed by recombination
  - burning: deflagration (subsonic) or detonation (supersonic)
  - fusion: runaway thermonuclear reaction
  - nucleosynthesis of radioactive material which then decays

Very young SNe typically look like a hot featureless blackbody, then absorption and emission features appear.

As the SN ejecta expands its density & opacity drops first in the outer layers. The photosphere (surface of last scattering) recedes “down” into the ejecta, but its radius increases because the material is expanding. After peak brightness, photosphere is in the slower-expanding layers and their opacity continues to drop, so the photosphere’s radius decreases.


1. new SN
photosphere in outer layer
2. pre-max SN
photosphere receding in velocity
but expanding in absolute size
3. peak brightness SN
photosphere is at max size
and receding in velocity
4. post-peak SN
opacity drops and
photosphere recedes

Novae



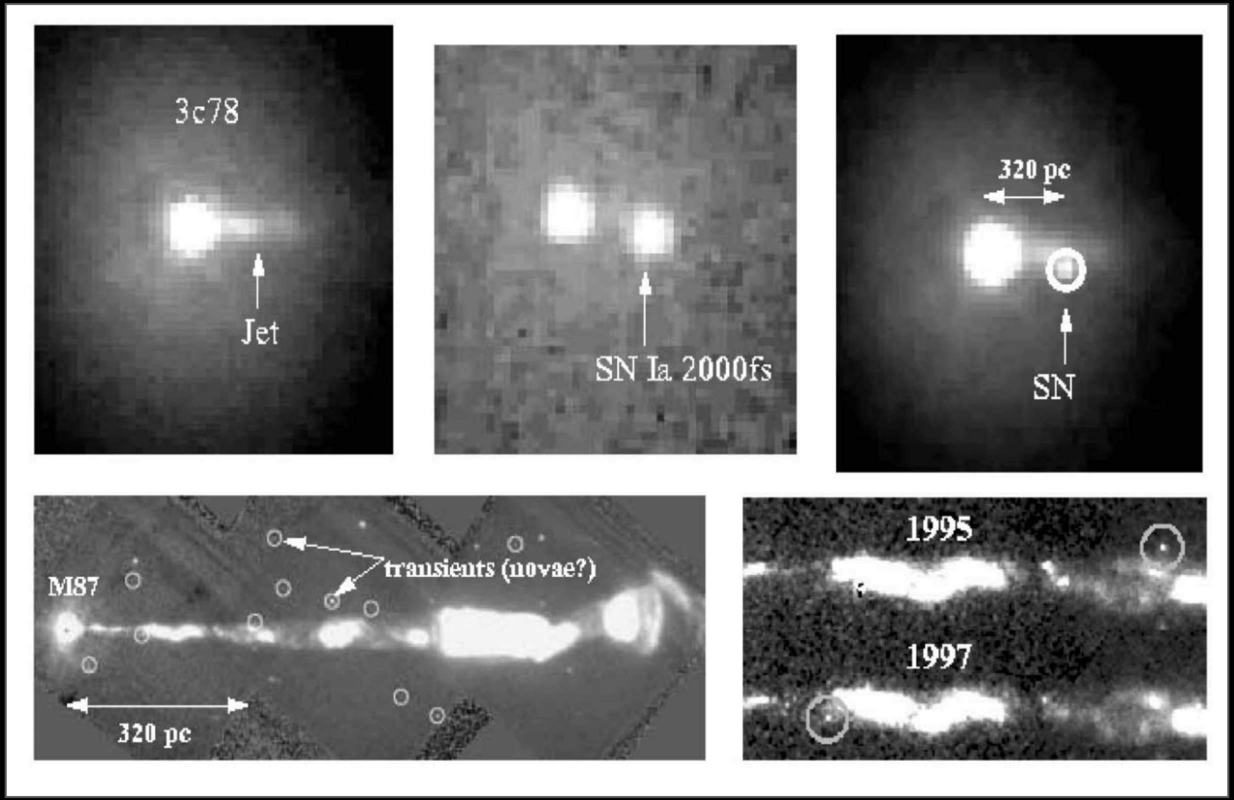
White dwarf stars in binary systems.
Also called cataclysmic variables (CVs).

Accreted material builds up, heats up, and erupts.

Three main types:

- classical novae
  - white dwarf + non-degenerate companion
- recurrent novae
  - eruptions separated by years
- dwarf novae
  - fainter and repeat more frequently

Novae

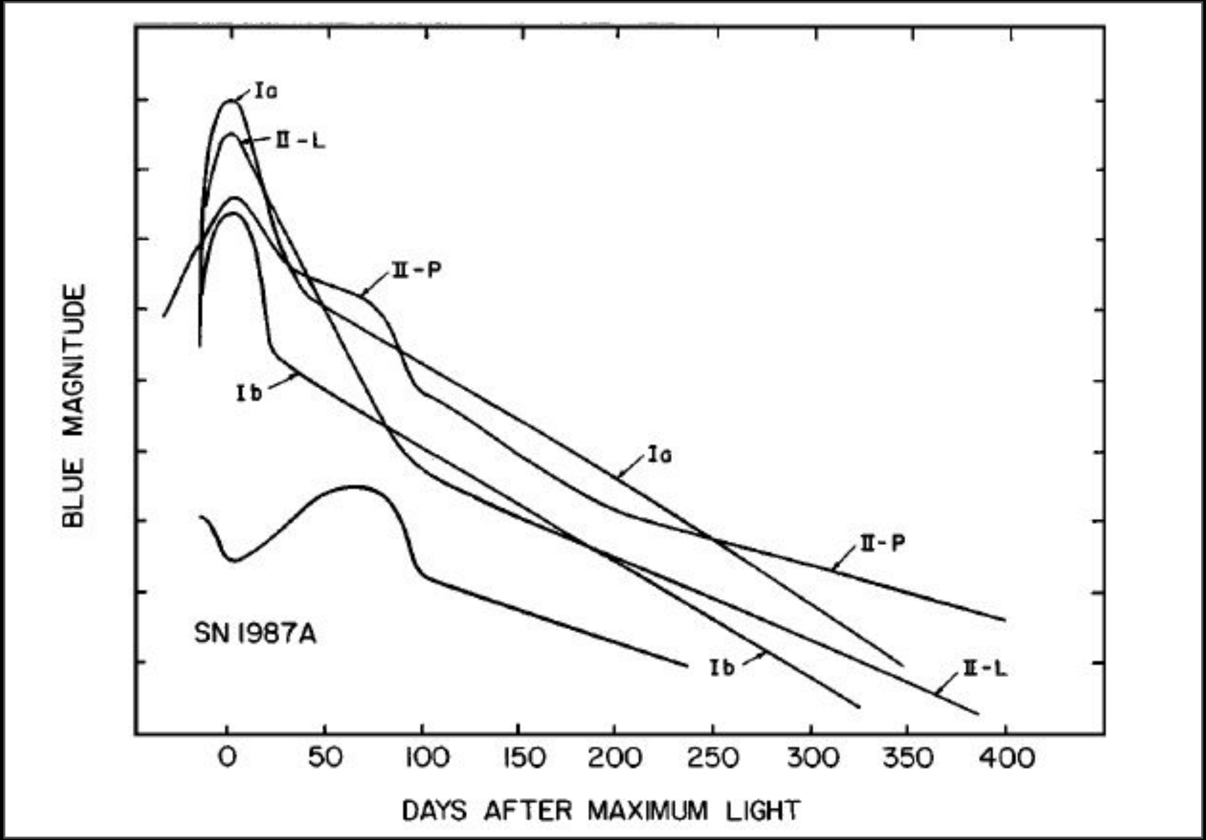


Could the rate of transients caused by accretion be enhanced by AGN jets?

In 2002, it seemed that the rate of novae along the jet in M87 was enhanced.

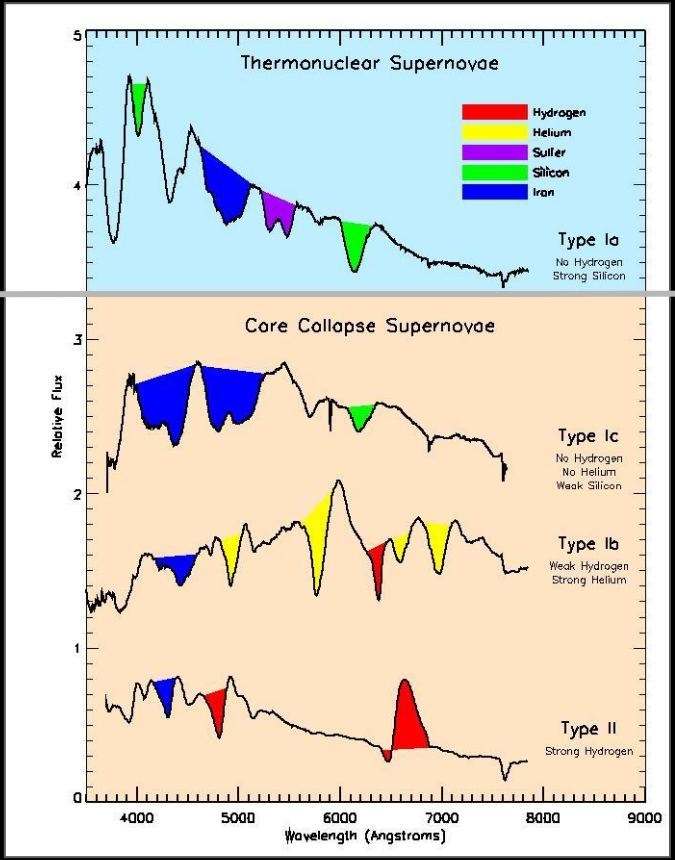
Livio et al. 2002

Supernovae



Filippenko 1997

Supernovae



Thermonuclear detonations of carbon-oxygen white dwarf stars.

Core collapse of massive stars.

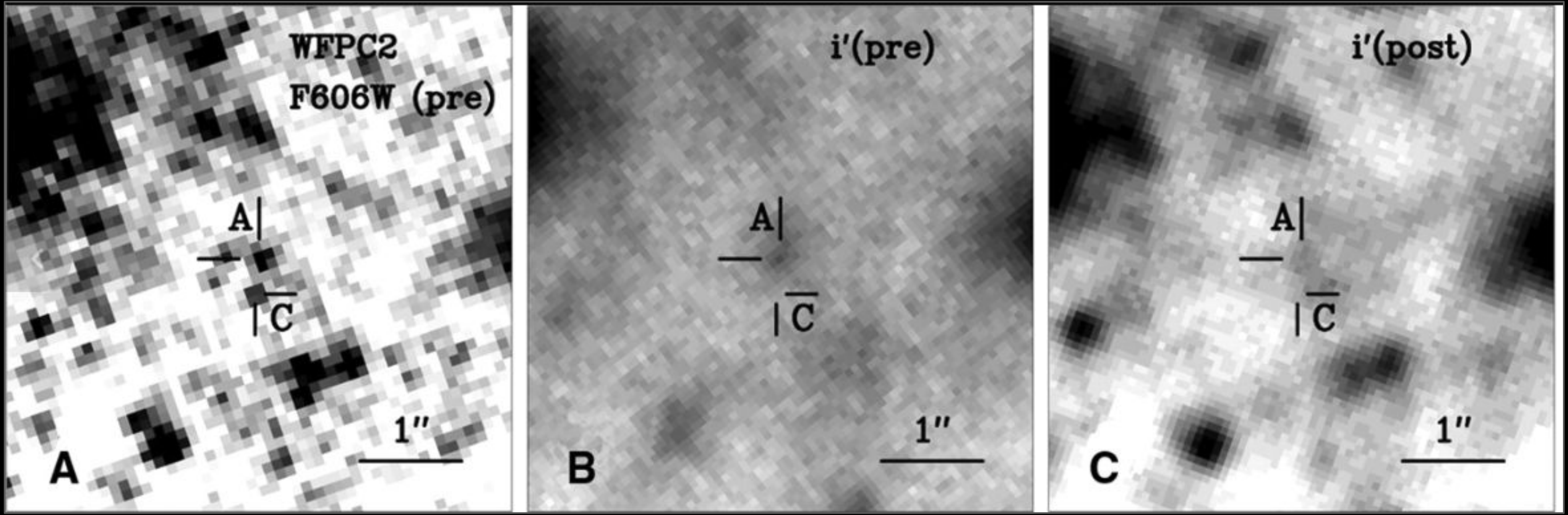
increasing mass
&
increasing amount of mass lost from the star's envelope

Dan Kasen

Supernovae: Core Collapse

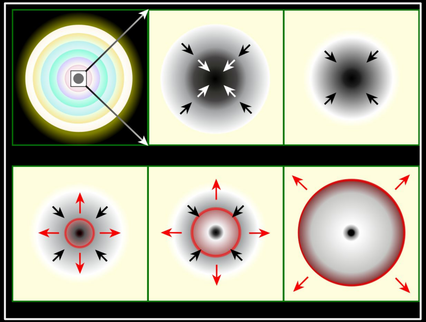
Direct evidence that Type II SNe are from massive stars.

The disappearance of a red supergiant at the location of SN-IIP 2003gd (A) in M74 with Gemini GMOS.



Maund & Smartt 2009

Supernovae: Core Collapse



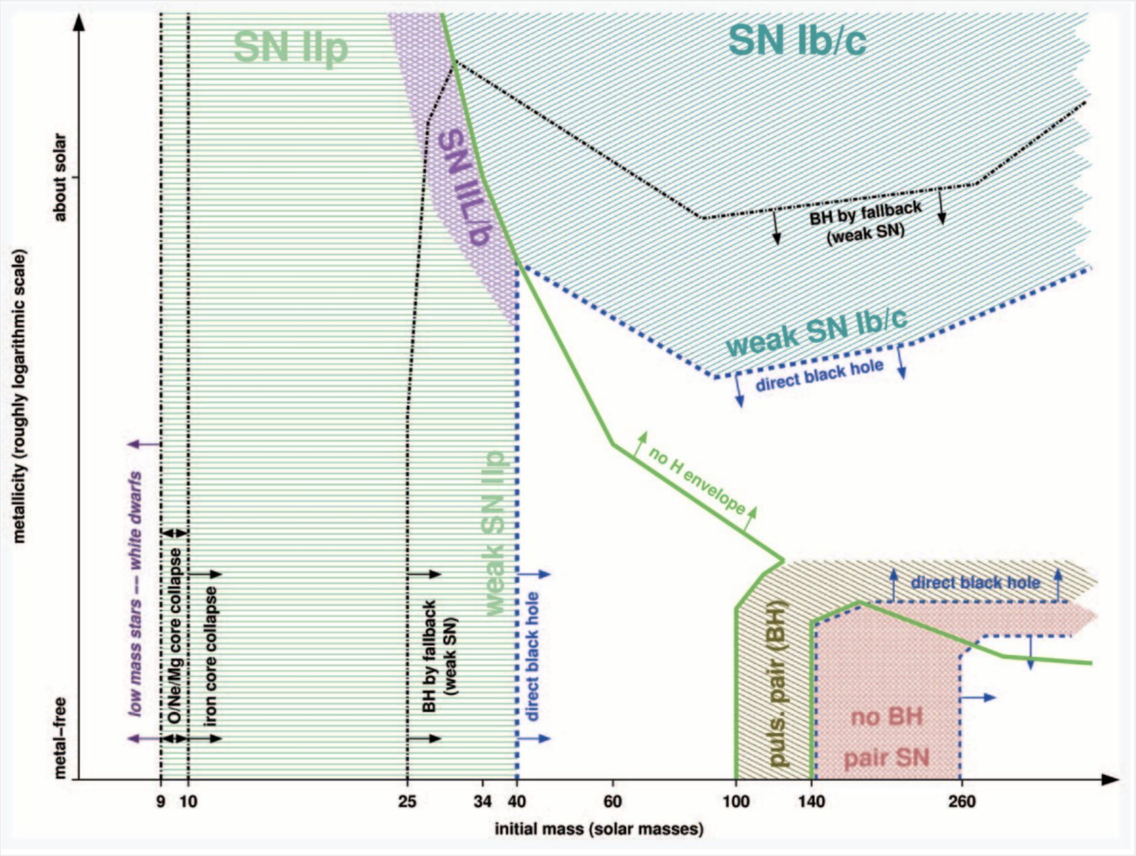
Core collapse to neutron star
- Type II and Ib/c (CC SNe)
- initial mass 8-25 M_{sun}
- "IIn" when narrow emission is seen

Core collapse to black hole
- "fallback" supernovae, initial mass 25-40 M_{sun}
  - theoretical faint and fast event
- direct collapse, NO supernova, initial mass 40-100 M_{sun}
  - look for disappearing massive stars, e.g., N6946-BH1

Pair-instability supernovae
- >100 M_{sun}, low-metallicity stars (Pop III?)
- energetic γ-rays cause e^--e^+ pair production, core pressure drop
- leads to partial collapse and a thermonuclear runaway
- theoretical: several candidates exist

Supernovae: Core Collapse

How massive single stars end their life.



Supernovae types from nonrotating massive single stars as a function of initial metallicity and initial mass.

Heger et al. (2003)

Supernovae: Core Collapse

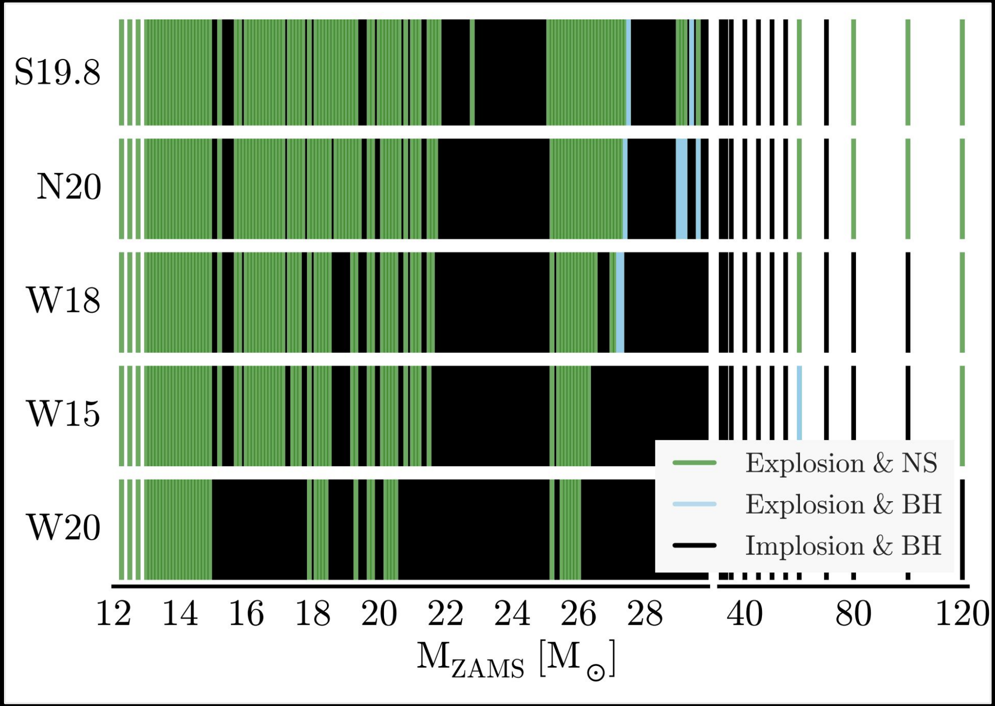


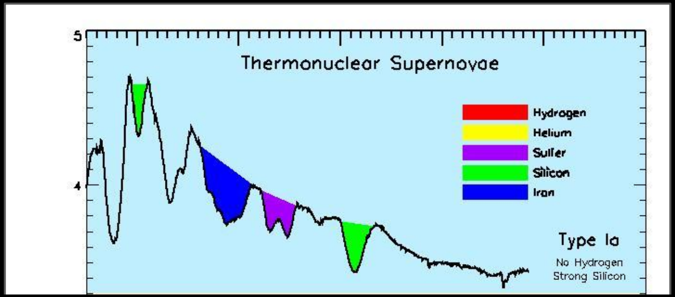
TABLE 1
SN 1987A Models

model	$M_{preSN}/M_\odot$	$M_{He}/M_\odot$	$M_{CO}/M_\odot$	$L/10^{38}$ erg s^{-1}	T_{eff}	$\zeta_{2.5}$	$Z/Z_\odot$	Rotation
W18	16.93	7.39	3.06	8.04	18000	0.10	1/3	Yes
N20	16.3	6	3.76	5.0	15500	0.12	low	No
S19.8	15.85	6.09	4.49	5.65	3520	0.13	1	No
W15	15	4.15	2.02	2.0	15300	-	1/4	No
W20	19.38	5.78	2.32	5.16	13800	0.059	1/3	No

Models reveal that factors other than initial mass, such as rotation rate, metallicity, and compactness, influence whether a star explodes or implodes, and whether the remnant is a neutron star (NS) or black hole (BH).

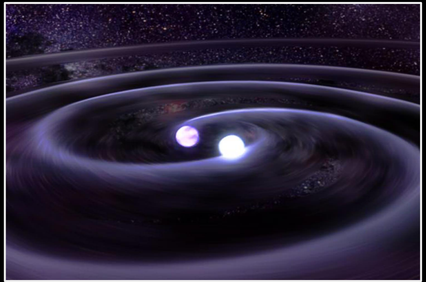
Sukhbold et al. (2015)

Supernovae: Type Ia



Thermonuclear detonations of carbon-oxygen white dwarf stars (Type Ia).

- accretion from or merger with companion
- initial mass 2-8 M_{sun}



Direct detection of progenitor stars is unlikely, so how do we know they're white dwarfs?

- found in old stellar populations
- total energy output consistent with the decay of ~half a solar masses of radioactive Ni-56
- near-peak spectrum (upper left) shows intermediate-mass elements
- nebular-phase spectrum (not shown) exhibits broad features of nickel, cobalt, and iron
- there is no remnant

Dan Kasen

Supernovae: Type Ia

Double degenerate

- two white dwarfs
- merge → explode
- old stellar populations
- no hydrogen in system

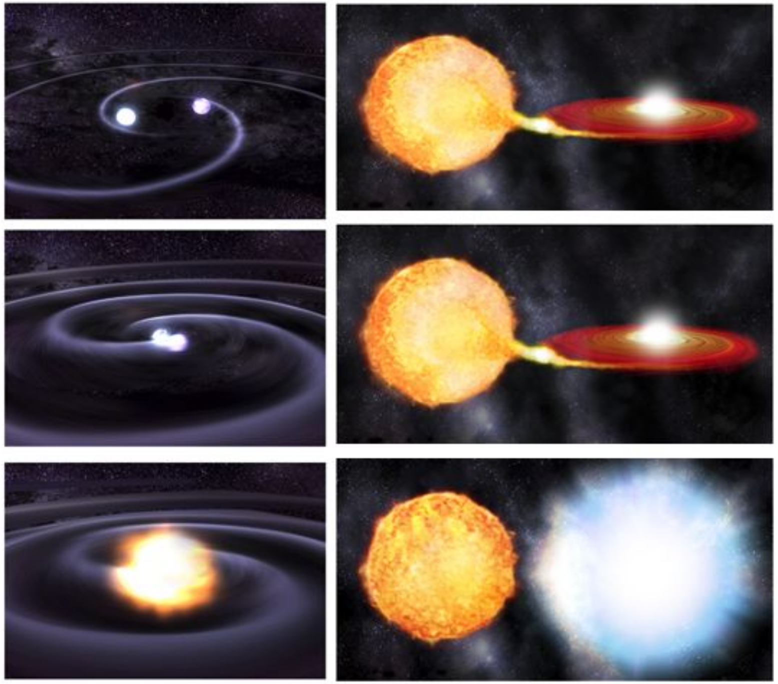
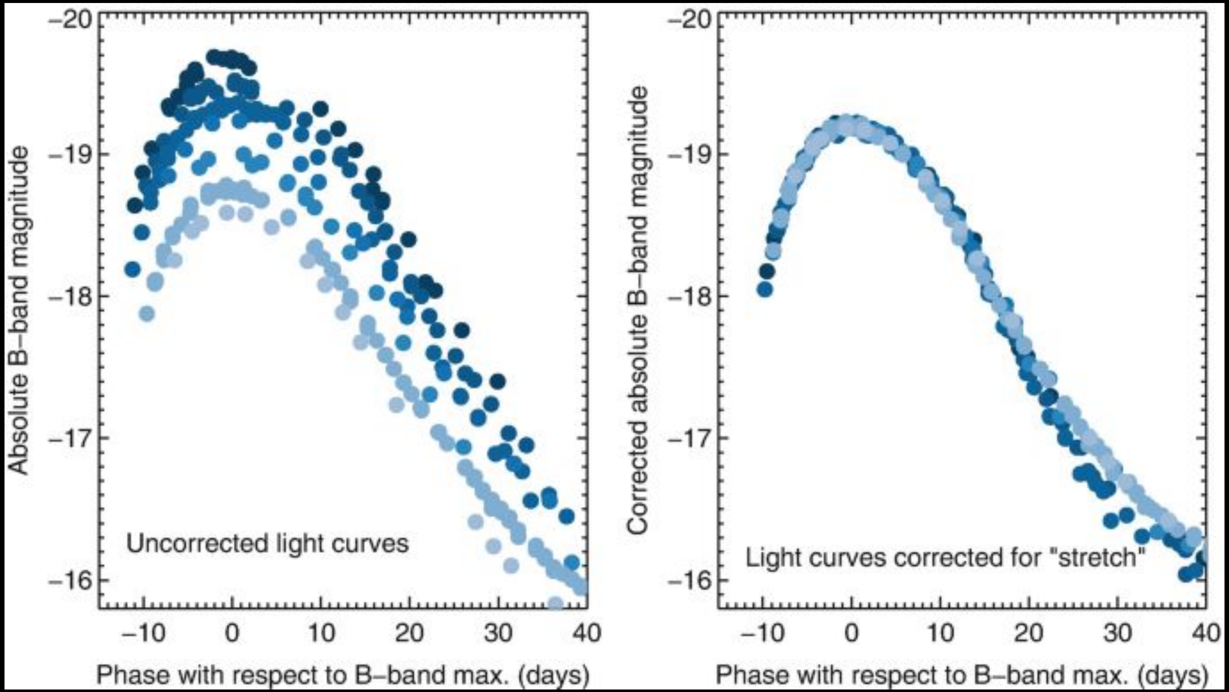


Figure 1: The double degenerate (left) and single degenerate (right) models of a type Ia supernova. Images taken from Wikipedia Commons and Discover Magazine.

Single degenerate

- one white dwarf
- one non-degenerate star
  - red giant or
  - main sequence
- younger stellar populations
- circumstellar hydrogen

Supernovae: Type Ia



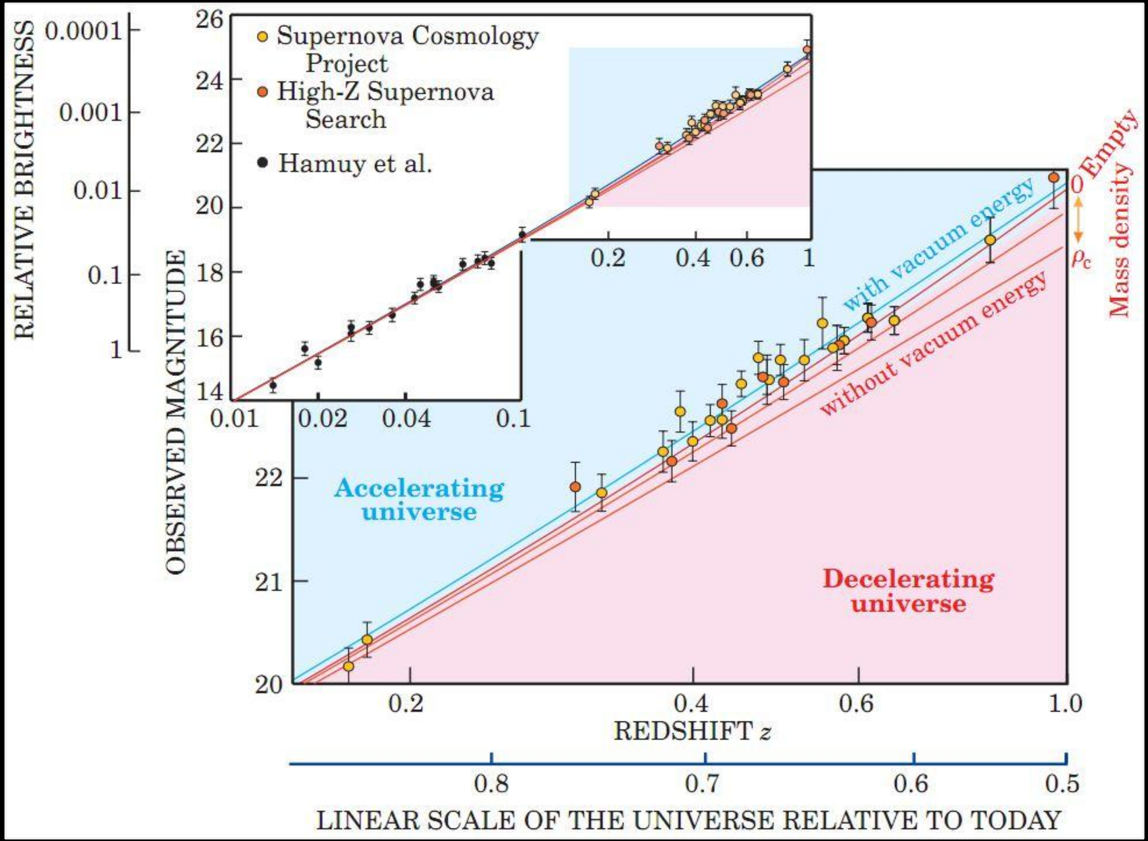
SN Ia light curves.

The width-luminosity relation for Type Ia SN allows them to be “corrected” to events of standard intrinsic brightness.

Thus their apparent peak brightness can be used as a distance indicator.

Maguire et al., Handbook of Supernovae

Supernovae: Type Ia



SN Ia Hubble diagram, the relationship between peak apparent brightness (distance) vs. recession velocity (redshift).

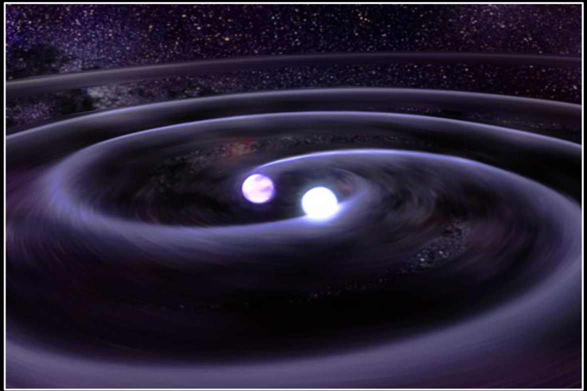
Blue area shows universes that accelerate; pink area shows universes in which the expansion decelerates.

The SN Ia measured in the late 1990's were fainter (and thus farther away) than expected for a universe that is decelerating, i.e., without dark energy.

Physics Today 56, 4, 53 (2003)

https://www.darkenergysurvey.org/the-des-project/science/

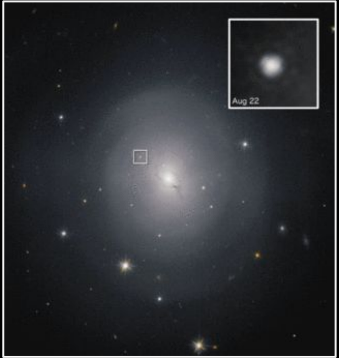
Kilonovae

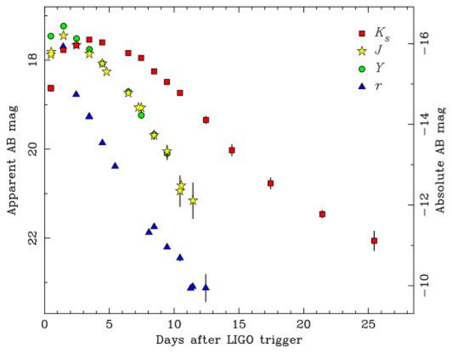


Kilonovae
- mergers
  - binary neutron stars (BNS; NSNS)
  - neutron star + black hole (NSBH)
- optical counterparts to gravitational wave events
  - (and short gamma-ray bursts)

GW170817 / AT2017gfo

→ HST observes the kilonova to fade over six days (NASA/ESA).

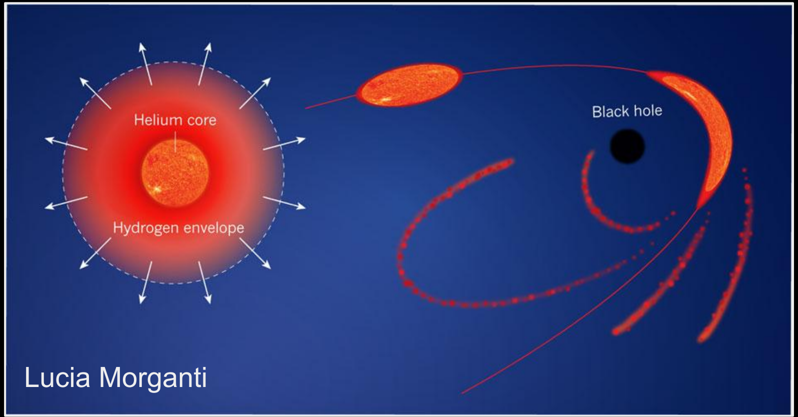




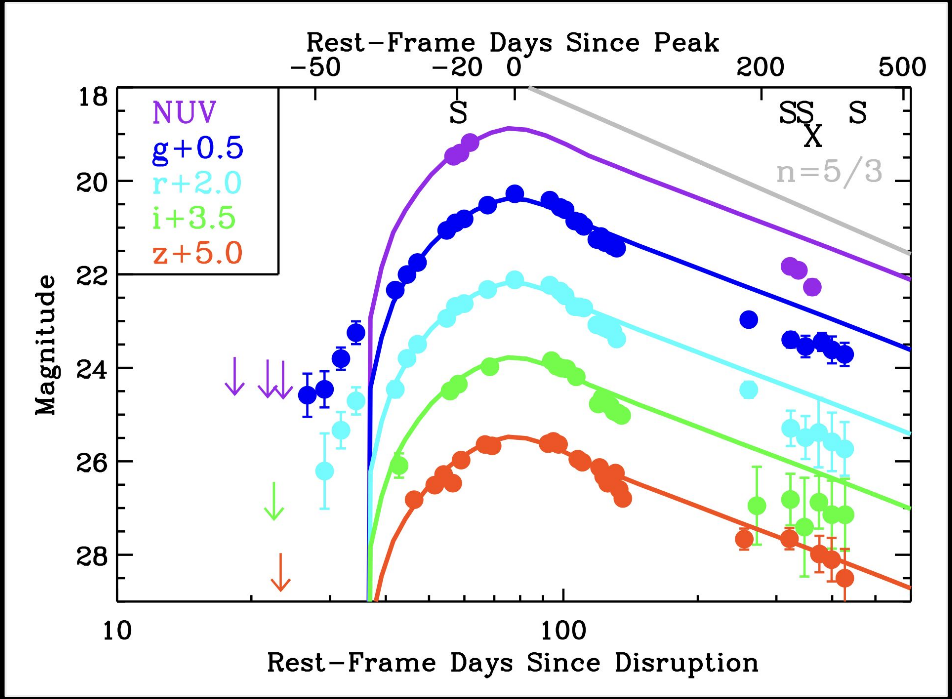
← The kilonovae fades faster in the bluer optical bands (Tanvir et al. 2017).

Tidal Disruption Events

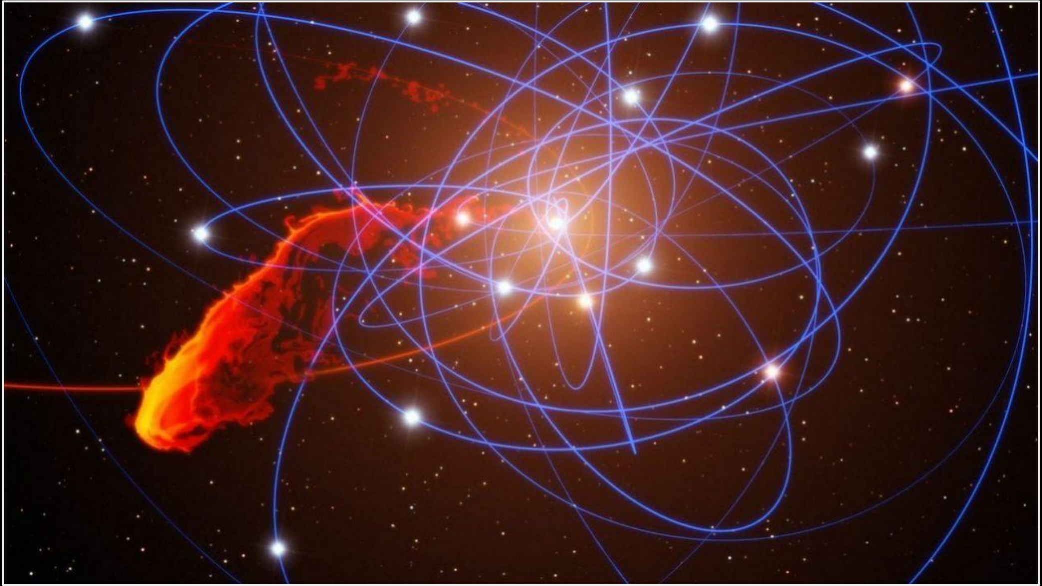
A star passes too close to a supermassive black hole (SMBH) and is tidally disrupted; it's material is accreted over hundreds of days.



An example TDE light curve from Gezari et al. (2012), the "rise-time" is far longer than a supernova.



Tidal Disruption Events

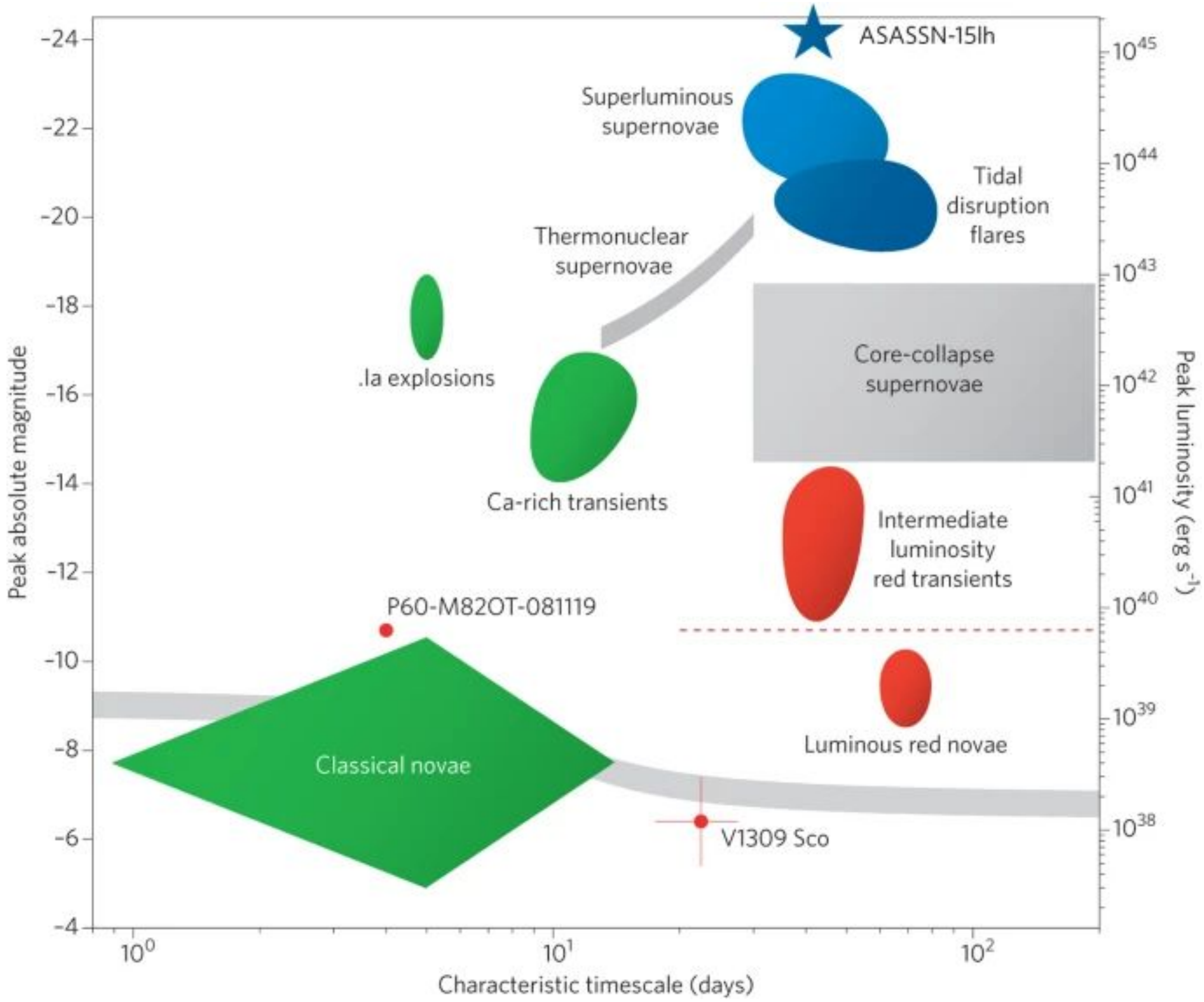


We’ve seen a similar event in our own Milky Way.

←
The disruption of the G2 gas cloud as it passes close to Sgr A*.

Artist’s impression, but star positions and orbits are accurate (for 2011).

ESO / MPE / Marc Schartmann



Transient "Zoo" Diagram

Cenko (2017); Kasliwal (2012)

Blue, green, and red indicate the optical color (hotter to cooler temperatures) of the transients at peak.

Grey regions represent the three classes of transients established before 2005.

This plot is from a paper on ASASSN-15lh, a very luminous event whose physical nature remains unclear (SLSN vs TDE).

Why study transients? What are the open questions?

cosmology

- SNe are probes of universe’s accelerated expansion
- when strongly lensed, SNe probes of dark matter profiles

stellar evolution

- SNe are the end points of single and binary star evolution
- circumstellar material (CSM; mass lost by star) is lit up by the SN
- it is not clear which stars direct-collapse to a black hole

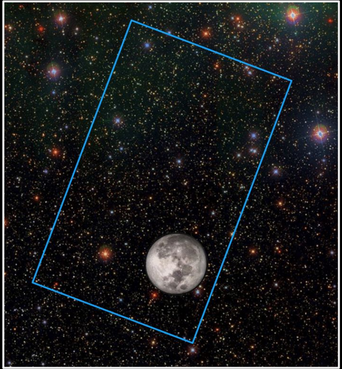
galaxy evolution

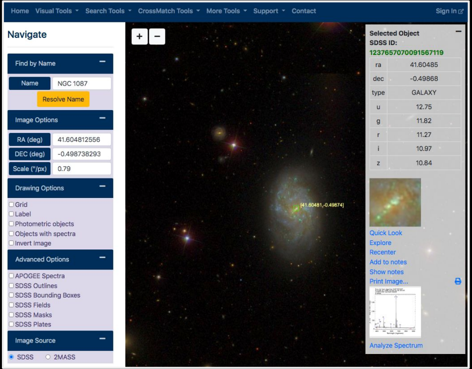
- SNe blow gas away and limit star formation
- tidal disruption events help to grow supermassive black holes

chemical enrichment / dust production

- SNe help synthesized material escape to make… everything else

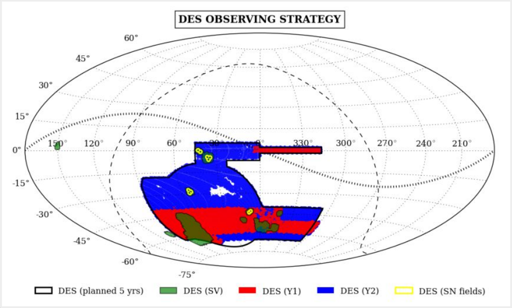
A few recent & current optical sky surveys

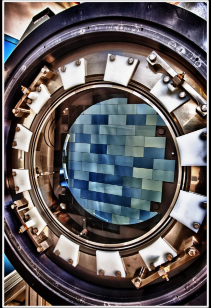




Sloan Digital Sky Survey (SDSS)

- 2.5m telescope at APO, 6 deg^2 field-of view
- 18 data releases covering the northern sky
- publicly searchable archive
- huge range of science (enhanced by spectra)

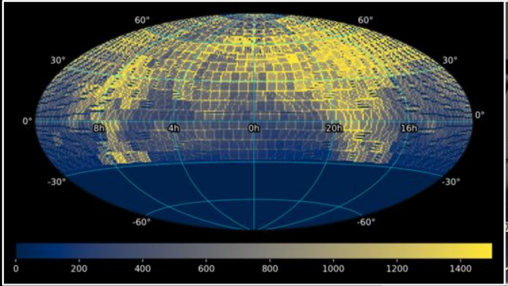


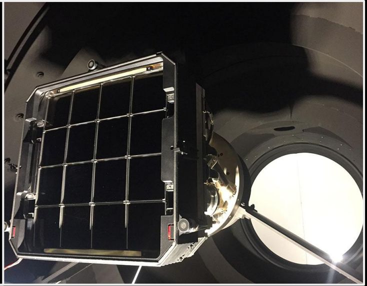


Dark Energy Survey (DES)

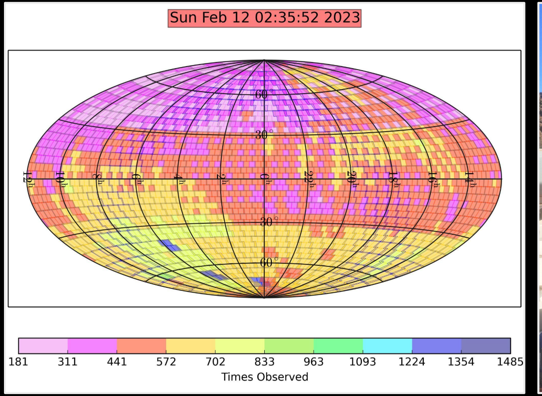
- 4m Blanco telescope, 2.2 deg^2 field-of-view
- surveyed 5000 deg^2 of the southern sky in five filters
- publications focus on SN Ia cosmology

A few recent & current optical sky surveys



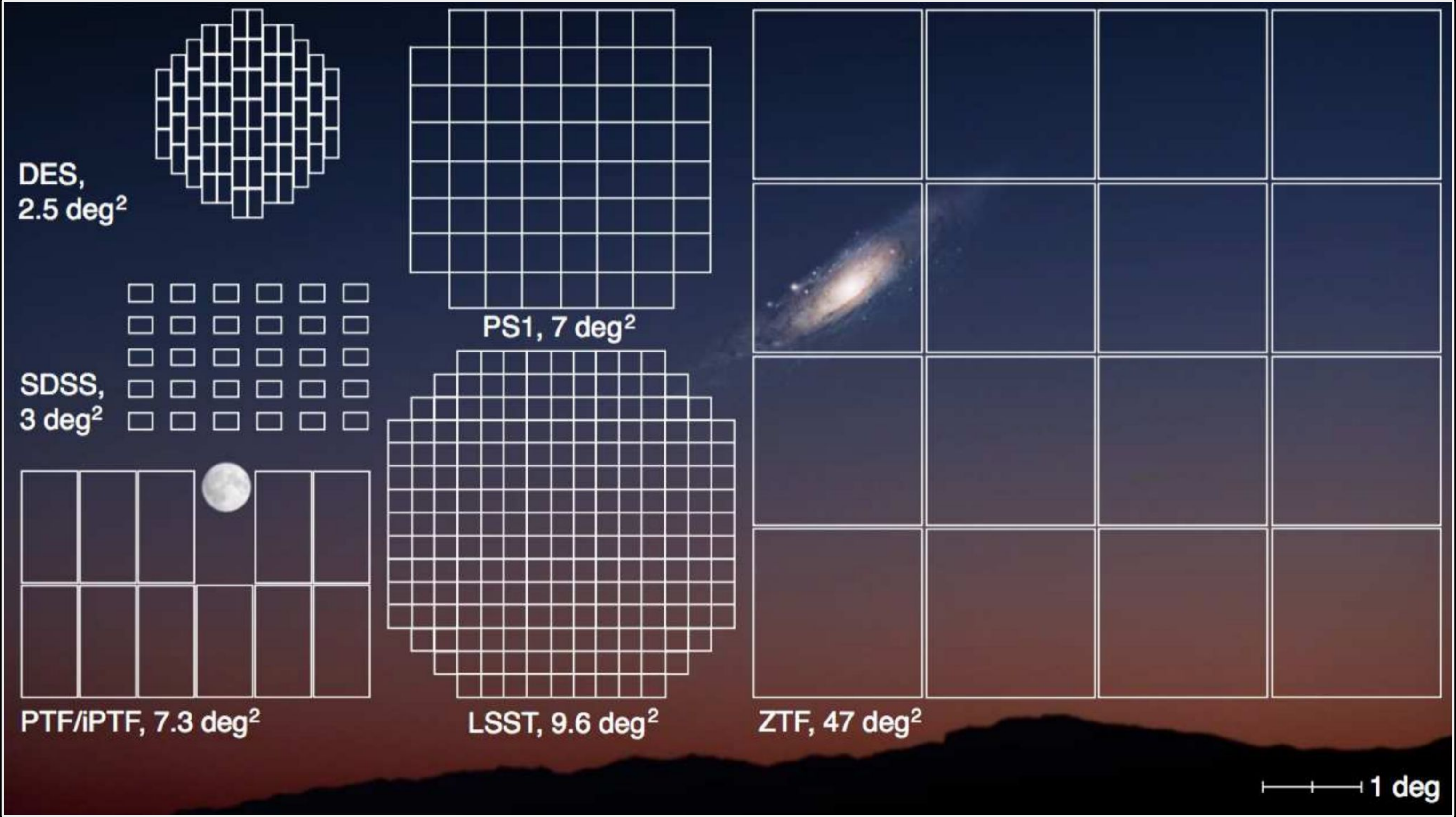


Zwicky Transient Facility (ZTF)
- 1.2 m telescope, 47 deg^2 field-of view
- northern sky in g and r, 2-day cadence
- alert distribution to brokers (built by LSST)
- wide variety of transient & variable science



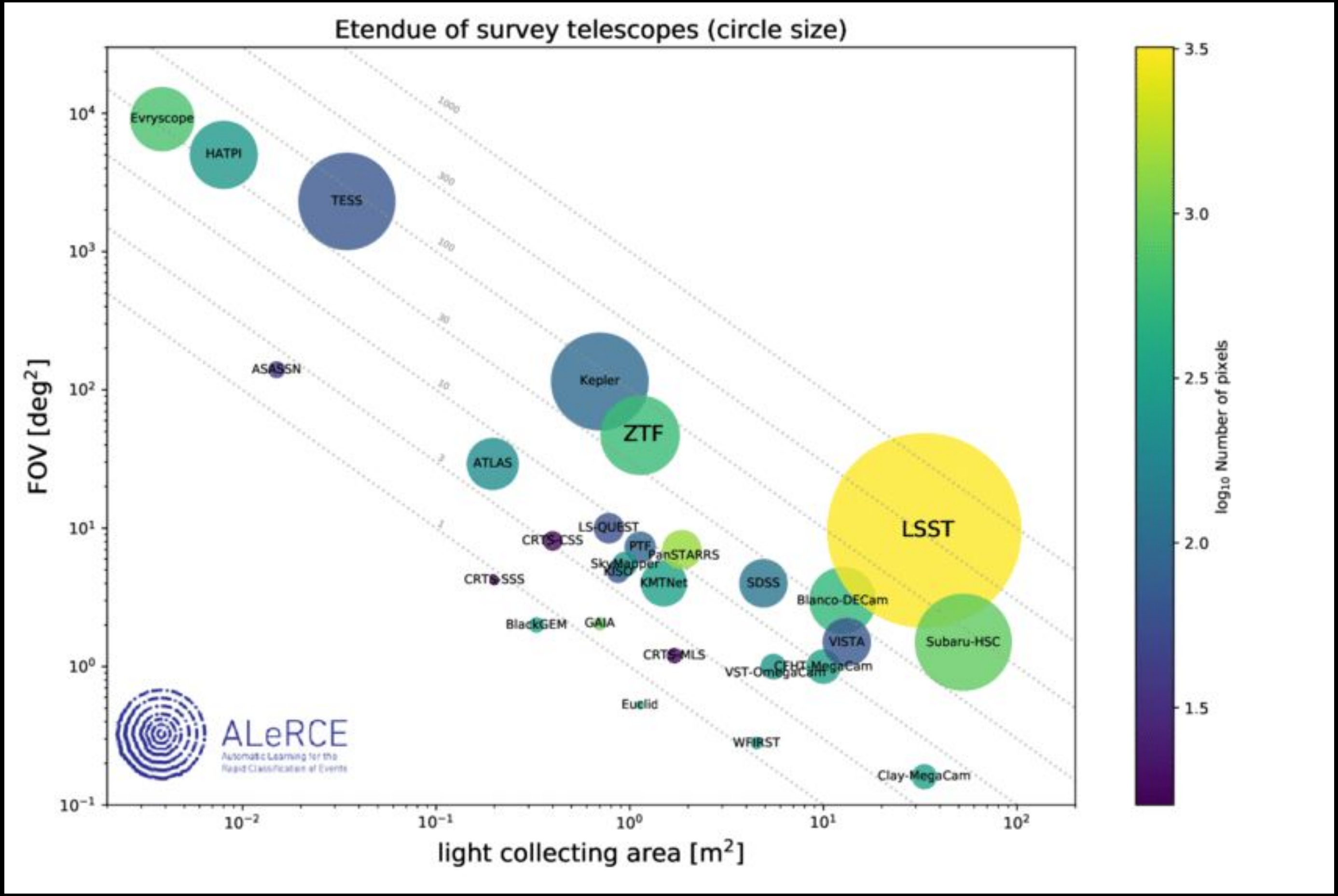
All-Sky Automated Survey for Supernovae (ASAS-SN)
- 24 14cm telescopes across 5 sites worldwide
- 4.5 deg^2 field-of view, V & g filters
- finds “everything” down to 18th mag
- many science results focus on “complete” samples

A few recent & current optical sky surveys



Laher et al. (2017); Joel Johansson

A few recent & current optical sky surveys



Field of view *vs.* light-collecting area.

The product of the two, etendue, is indicated by circle size.

Circle color indicates the number of pixels in the camera.

Förster et al. (2020)

LSST as a follow-up tool for gravitational wave optical counterparts

VERA C. RUBIN
OBSERVATORY

Vera C. Rubin Observatory
Data Management

Rubin Observatory Processing of Gravitational Wave TOO Data in the Early Operations Era

Eric C. Bellm

RTN-008

Latest Revision: 2022-08-15

The “etendue” of the LSST will make it effective at finding optical counterparts of gravitational wave detections.

See ls.st/rtn-008

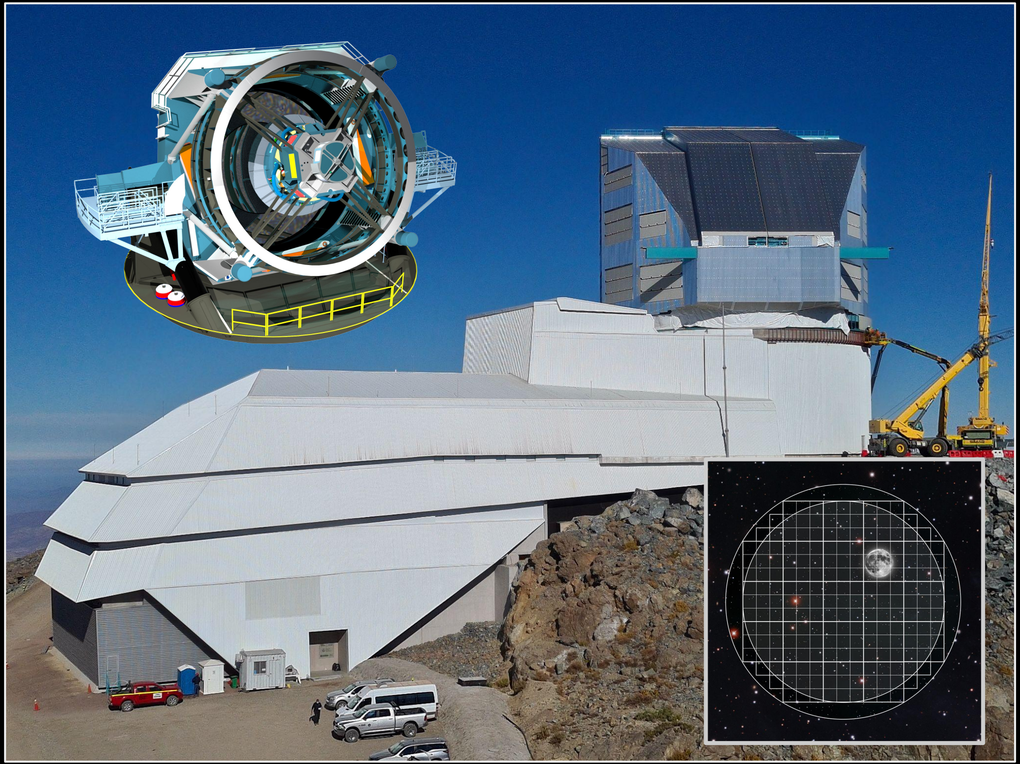
What makes a survey good for transient discovery?

- large field of view
- large light-collecting area
- fast readout time
- fast slew & settle
- multiple filters
- multiple field revisits

What makes a survey good for transient discovery?

- large field of view
- large light-collecting area
- fast readout time
- fast slew & settle
- multiple filters
- multiple field revisits

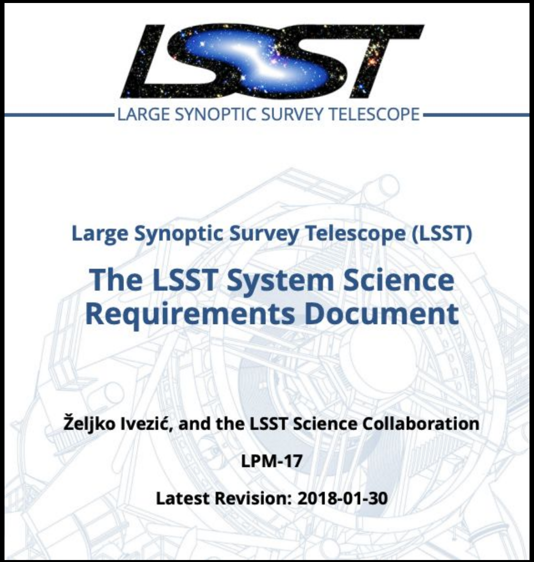
Sounds familiar!?



What are the transient-related science goals of the LSST?

LSST Science Requirements Document (ls.st/srd)

- “open a new window on the variable sky”
- novel technology for 60-second alerts
- good performance in crowded fields
- provide color information (survey in six filters)
- cover timescales from minutes to years
- discovery and analysis of known transient types
- identify new classes of transients


LSST
LARGE SYNOPTIC SURVEY TELESCOPE

Large Synoptic Survey Telescope (LSST)

The LSST System Science Requirements Document

Željko Ivezić, and the LSST Science Collaboration

LPM-17

Latest Revision: 2018-01-30

What are the transient-related science goals of the LSST?

Just a few examples!

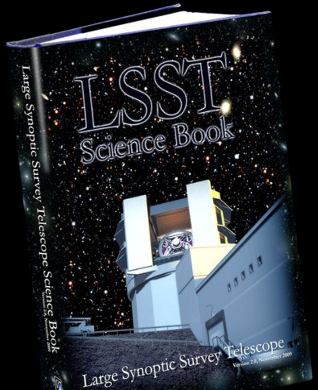
Supernovae & Cosmology
- find the earliest SNe from metal-poor stars
- evolution in SN Ia characteristics
- dark energy isotropy
  - Hubble diagram for different sightlines

Gap Transients (complete the Zoo)
- build samples of fast and faint transients
  - gamma-ray burst (GRB) afterglows
  - kilonovae (GW counterparts)
- Intermediate-Luminosity Optical Transients (ILOTs)
  - giant mass-loss eruptions in stars
  - mergers of low-mass binaries
  - dust-enshrouded supernovae
- discover new transient types (anomalies)

Tidal Disruption Events
- build sample to study population
- evolution of supermassive black hole grown
- constrain origin of optical emission

Light Echos
- reveal mass-loss histories
- offer multiple sightlines into an event

2022
arXiv/2208.04499

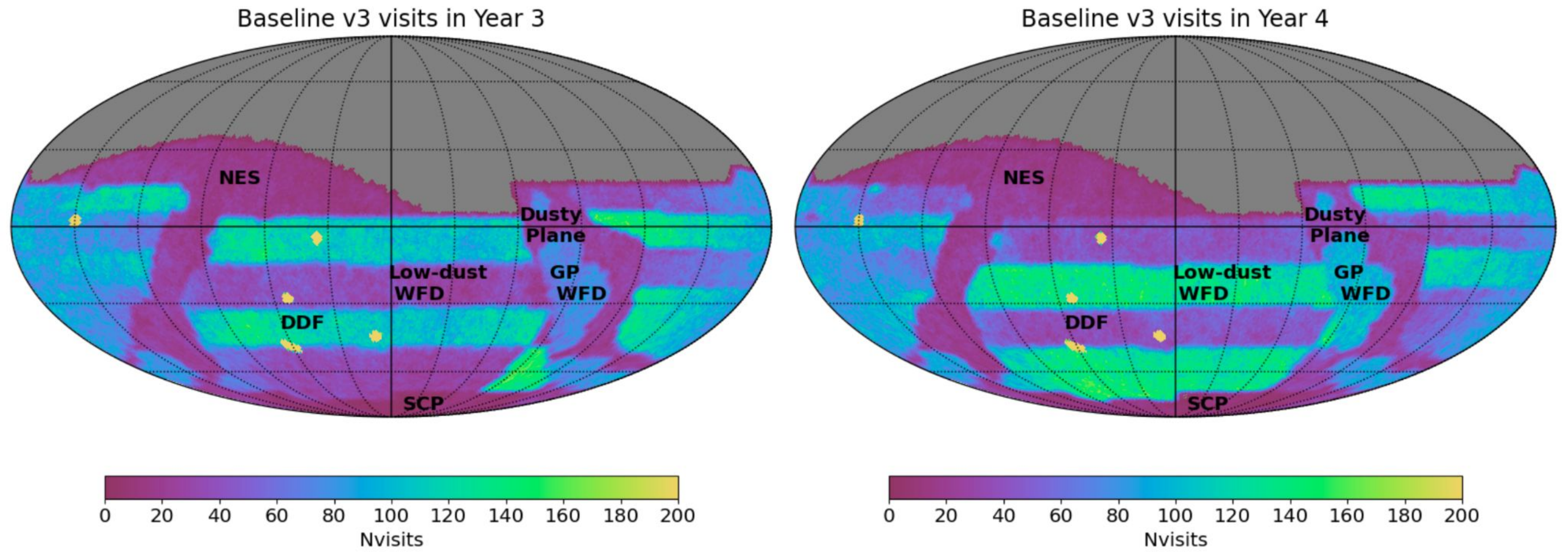


2009
lsst.org/scientists/scibook

LSST survey strategy and expected yields

Latest "baseline" survey strategy calls for "rolling" (alternating areas with more visits).

This should give a ~2 day cadence (in any filter).



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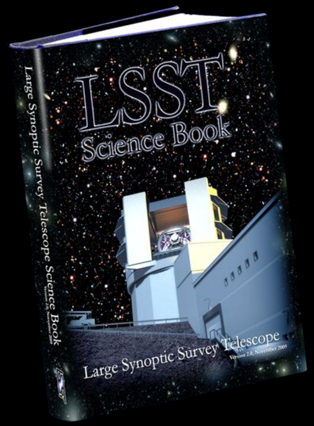


~10 million supernovae over 10 years (total detectable)
~1 million supernovae per year

Estimates for the fraction with a “good” lightcurve is ~10%.
(Where “good” means, e.g., >10 points detected in multiple filters.)

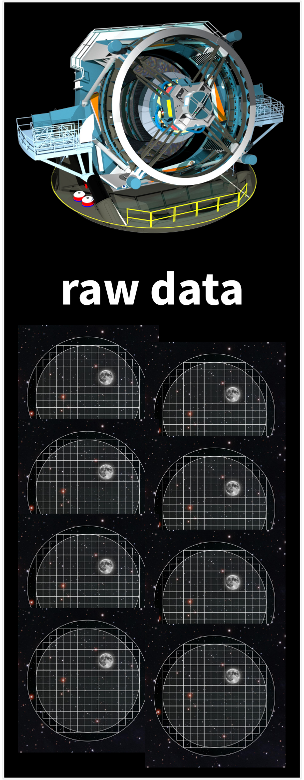
~100000 “good” SN lightcurves per year.

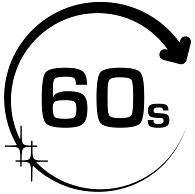
A 10x increase, just in year one, over the ~10000 detected SN to date!

The ratio of core collapse to thermonuclear is about 5 : 1 (CC : Ia).

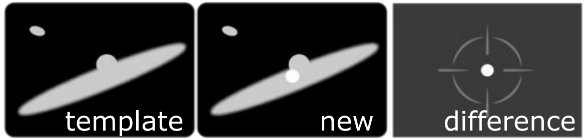
Even for rare transients, for which we now have “a few”, will have hundreds of examples.

Data Products for Transients

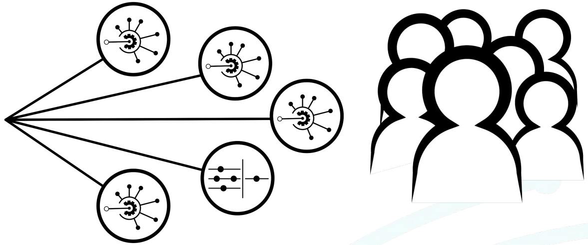




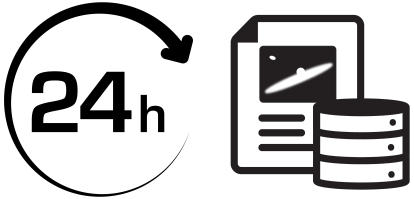
Difference Image Analysis (DIA)



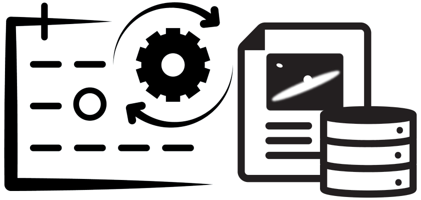
In 60s, raw images are processed, a template is subtracted, and difference-image sources are detected, associated, characterized, and…



…distributed as alerts to brokers, where they can be rapidly analyzed by users.

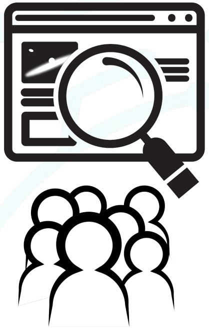


In 24h, the Prompt Products Database is updated with the DIA data products.



Yearly data releases include reprocessed DIA data products for all images.

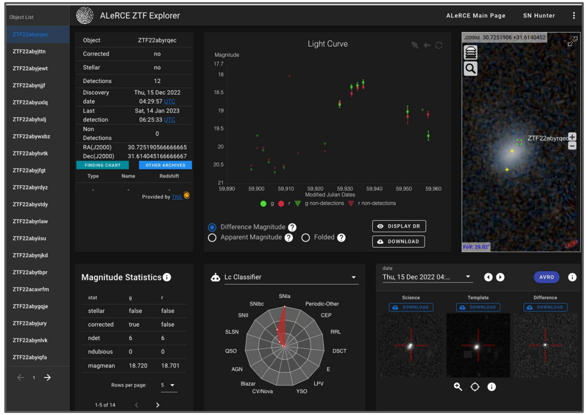
The Prompt (24h) and Data Release (annual) data products will be available for users to analyze via the Rubin Science Platform.



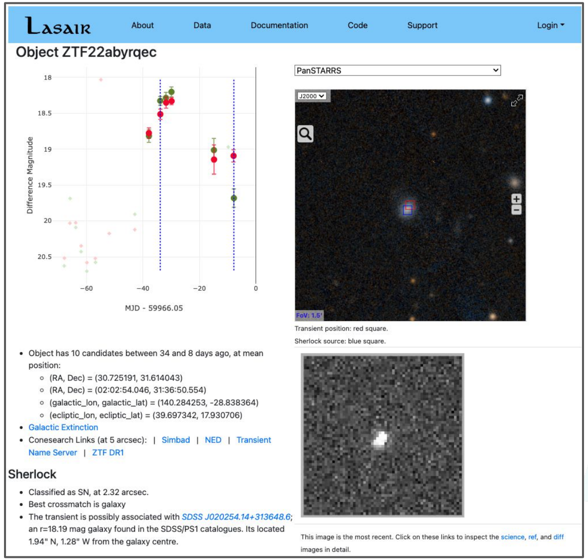
Alerts & Brokers

There are seven brokers which will receive and process the full LSST alert stream.

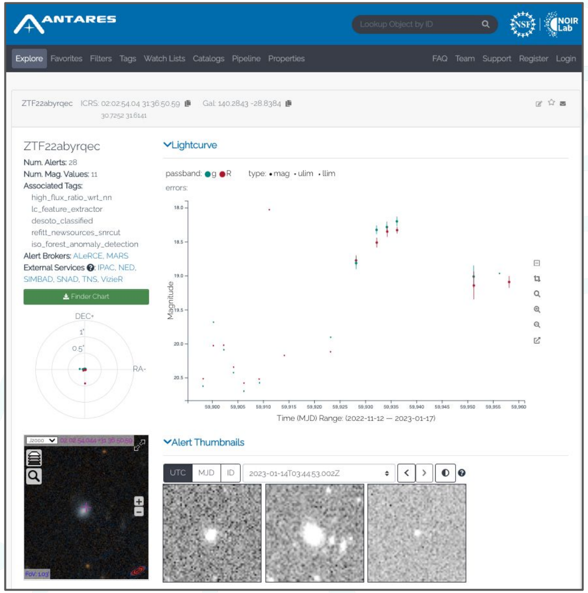
They offer users query interfaces and filtering tools for access to samples or individual objects.
Below, the single-object page for ZTF22abyrqec is shown for each of three brokers.



alerce.science



lasair.lsst.ac.uk



antares.noirlab.edu

Challenges for transient studies with LSST

Real-time alert processing by brokers

- cross-match to other surveys, archival data
- prioritization for follow-up (competition for spectroscopy)

Photometric classification (photo-id)

- identifying transient type from first few days of photometry

Host galaxy association

- correctly identifying the host helps with photo-id

Deriving occurrence rates

- requires intrinsic luminosity functions
- understanding & applying survey characteristics like detection efficiency

Theoretical predictions

- especially for new & anomalous types of transients

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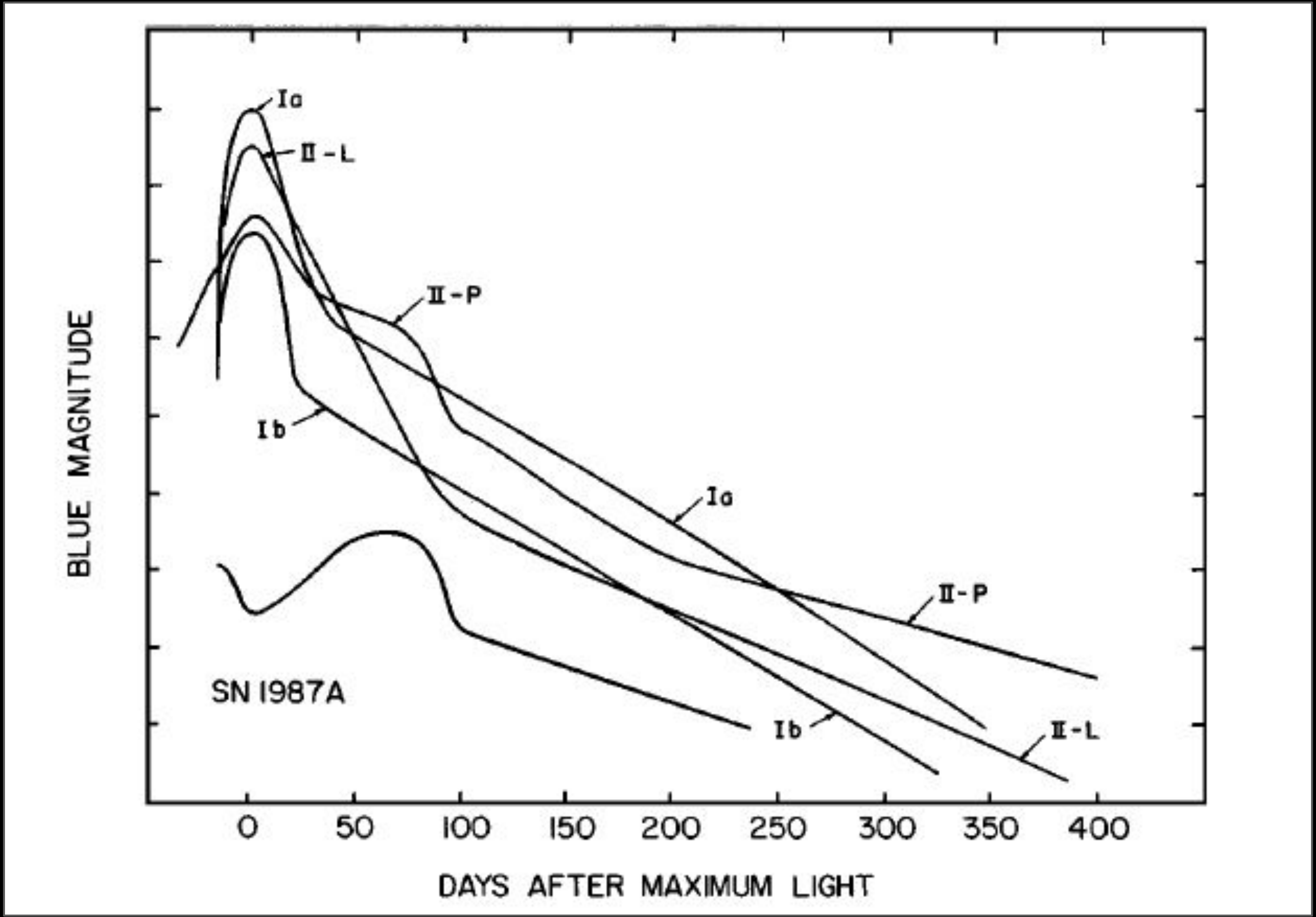
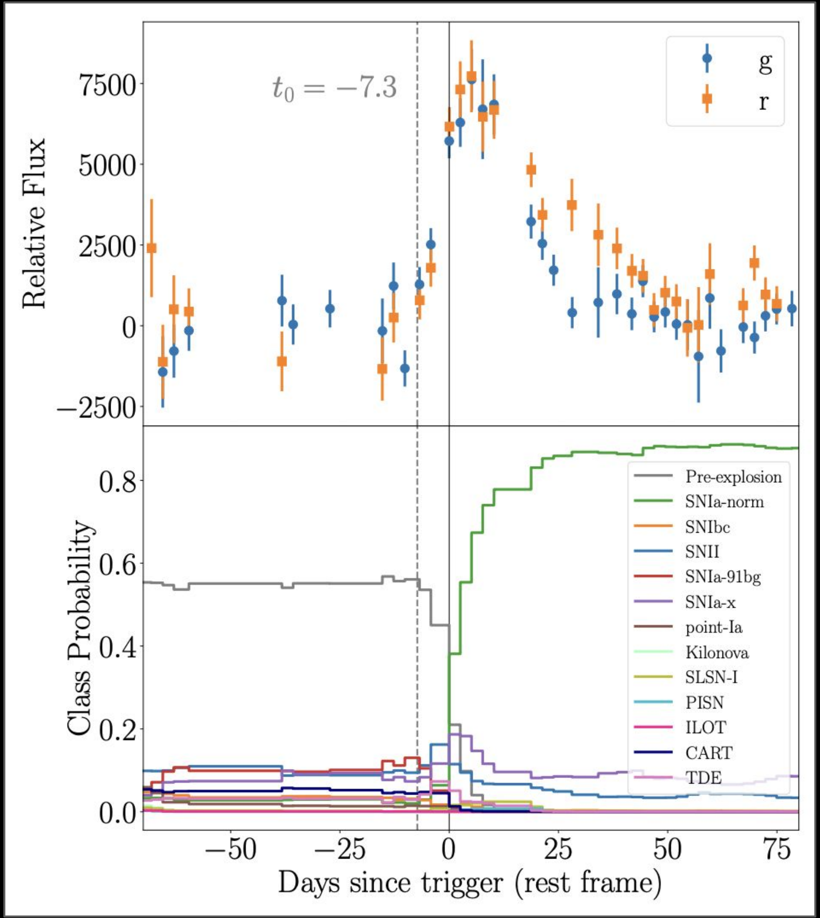
Photometric Classification



Filippenko 1997

Photometric Classification



1. Build a set of template lightcurves.
2. Fit them to your data points.
3. Derive a photometric classification.

Challenges:
- degeneracy between SN types
- early classification with few points
- template set completeness
- running algorithms at scale

← example
RAPID
Real-time Automated Photometric IDentification
Muthukrishna et al. (2019)

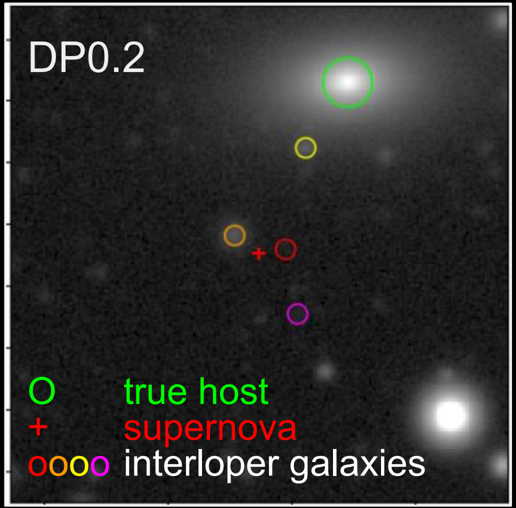
(This class will cover ML separately, later.)

Host Galaxy Association

Identifying the host galaxy helps with photometric classification.
(E.g., enables use of host redshift, type as a prior.)

The LSST Object table will have many faint high-z galaxies.

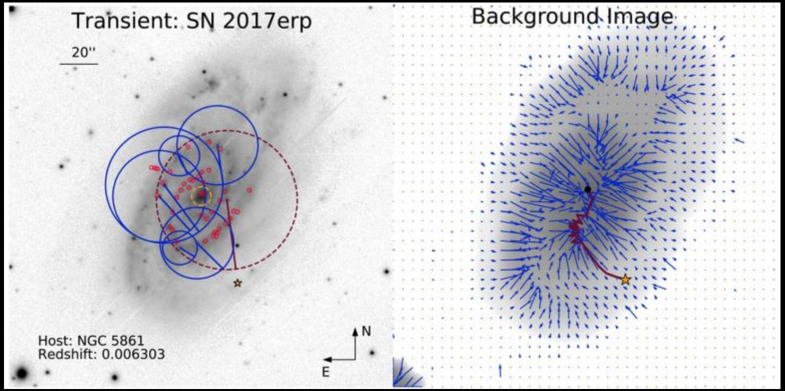
Initial studies with DP0.2 show that the true host galaxy is the "nearest" galaxy only ~70% of the time for redshifts <0.2.
(And only 90% of the time for redshifts up to 1.0.)



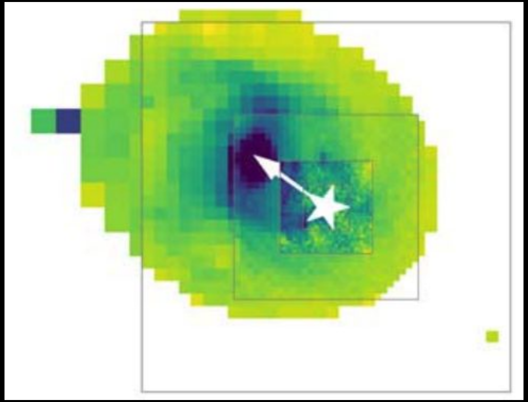
github: rubin-dp0/delegate-contributions-dp02/dia_exploration/dia_SNIa_host_association.ipynb

Host Galaxy Association

Two examples of methods to improve and expedite host galaxy association.



Galaxies HOsting Supernova Transients (GHOST) database
Gagliano et al. 2021
- uses deep postage stamps of the field around a transient
- presents the "gradient ascent method" for host id
- shows that this method provides accurate host id
- demonstrates how host id helps photometric classifications



DELIGHT: Deep Learning Identification of Galaxy Hosts of Transients using Multiresolution Images
Förster et al. 2022
- multiresolution stamps conserves file size
- shows method is accurate with less information
- proposes to use multires stamps in alert packets

What else are people doing now to prepare for transient science?

A lot of collaborative work (e.g., TVS-SC, DESC), especially on infrastructure and scalable algorithms (e.g., LINCC)

Use brokers now, with ZTF alerts

- ANTARES, Lasair, Alerce, and others
- integrate Target Observation Managers (TOMs)
- Astronomical Event Observatory Network (AEON)

Automating discovery & follow-up

- photometric classification algorithms
- how to prioritize targets follow-up
- build training sets for machine learning

Use simulated data sets

- PLAsTiCC & ELAsTiCC (classification challenges)
- DP0.2 time-domain data products