強い重力レンズを用いた

超新星予報

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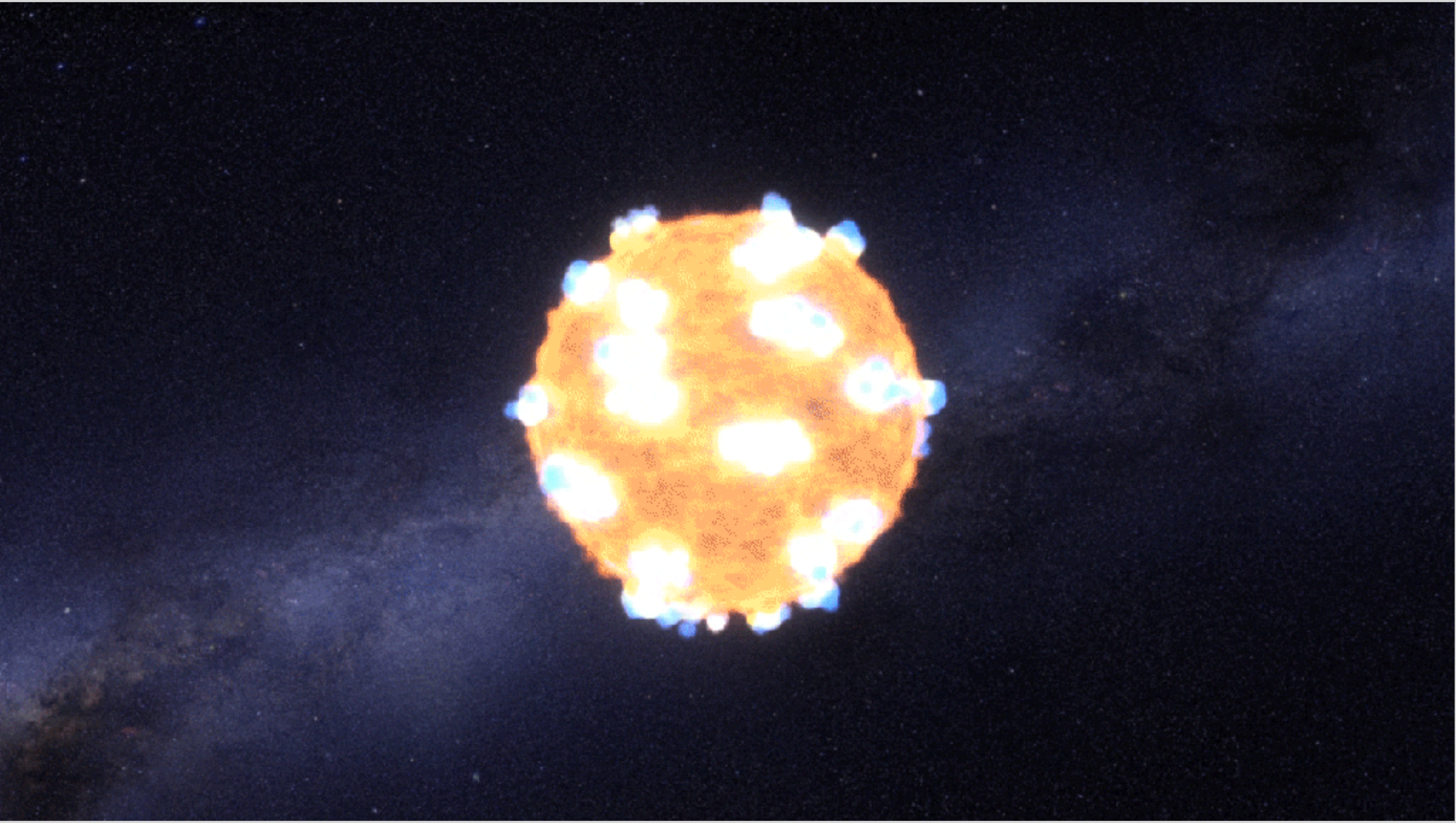
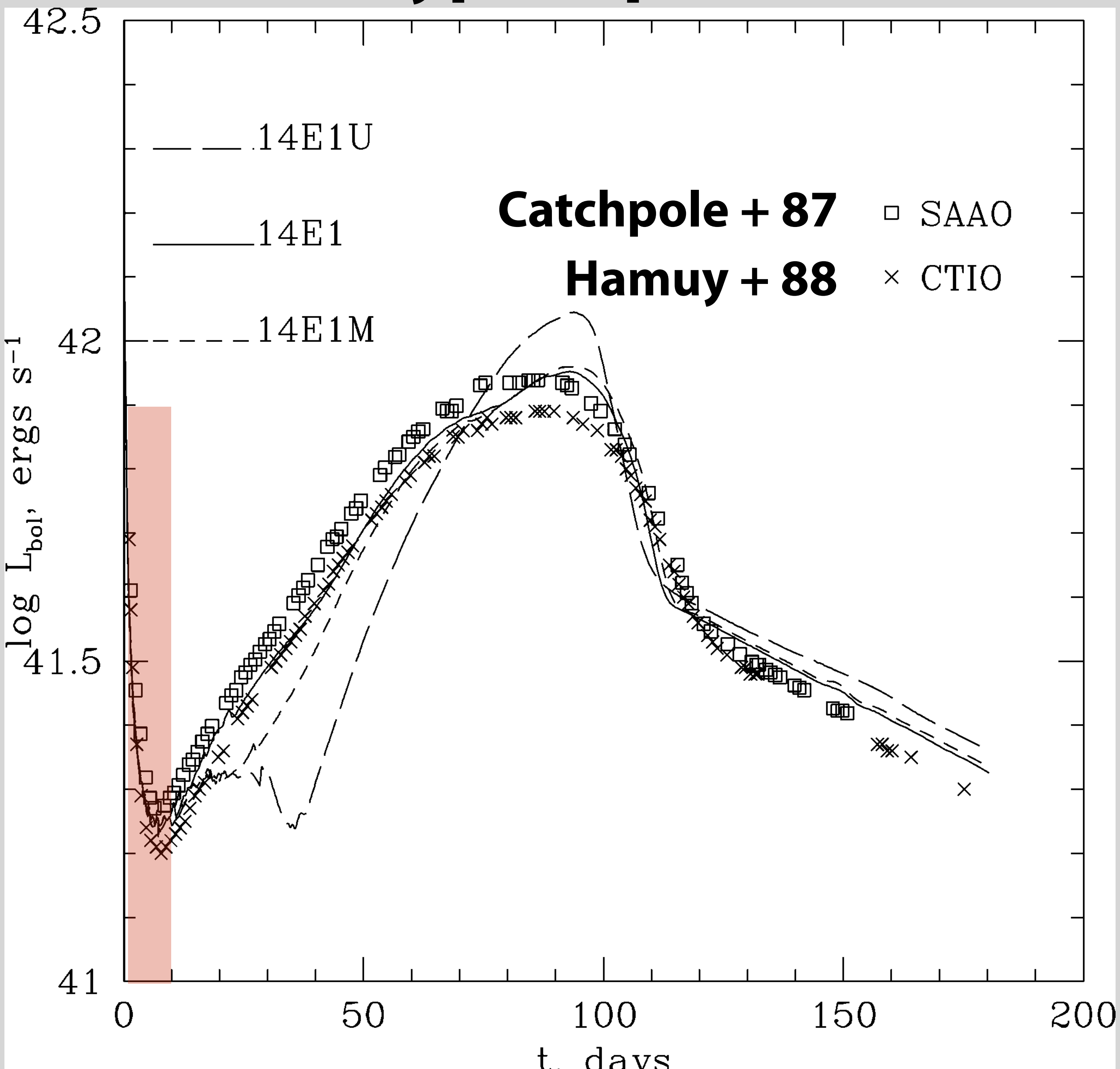
SN shock breakout



© NASA

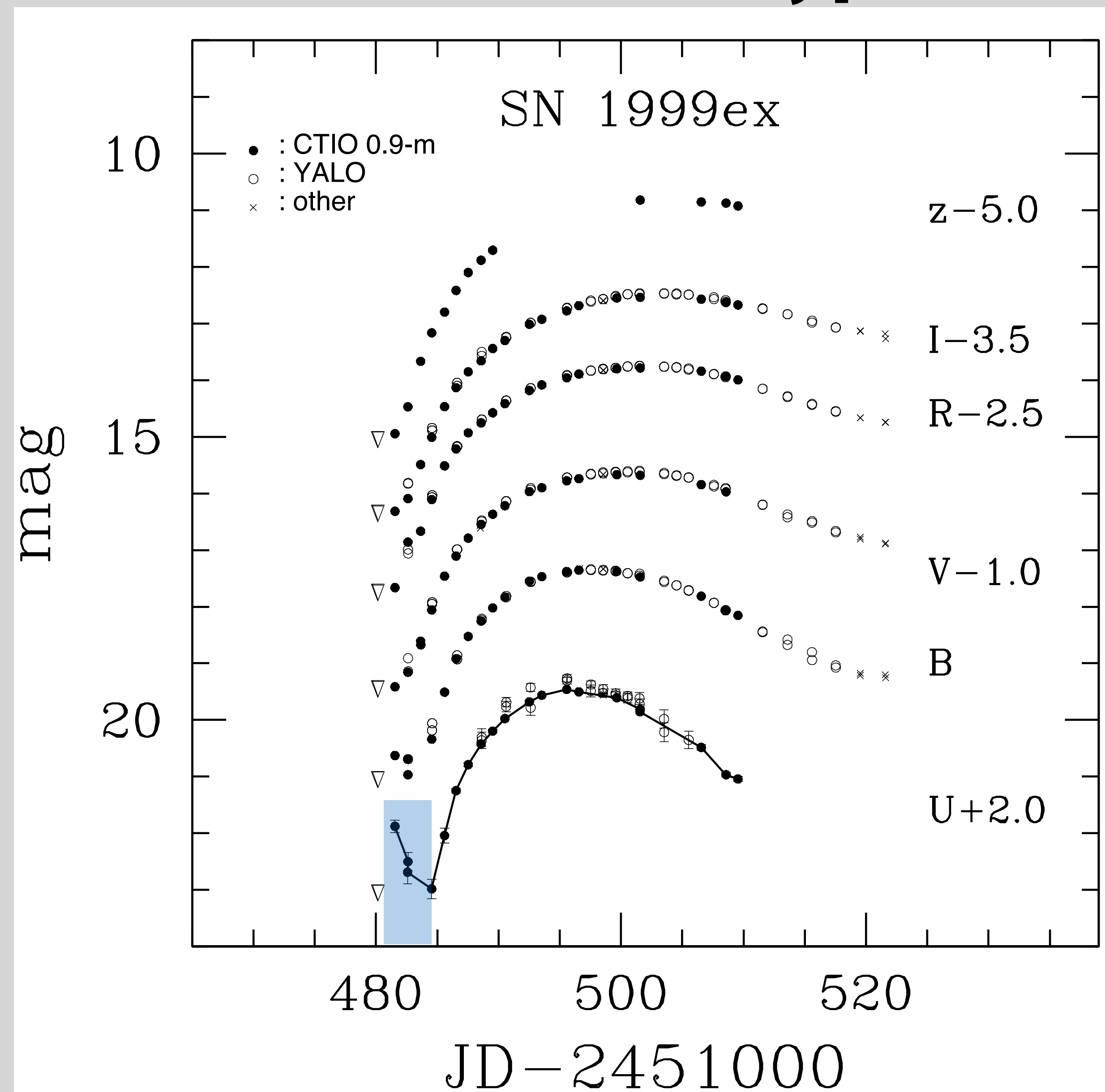
Observations before 2008

SN 1987A (type-II peculiar)



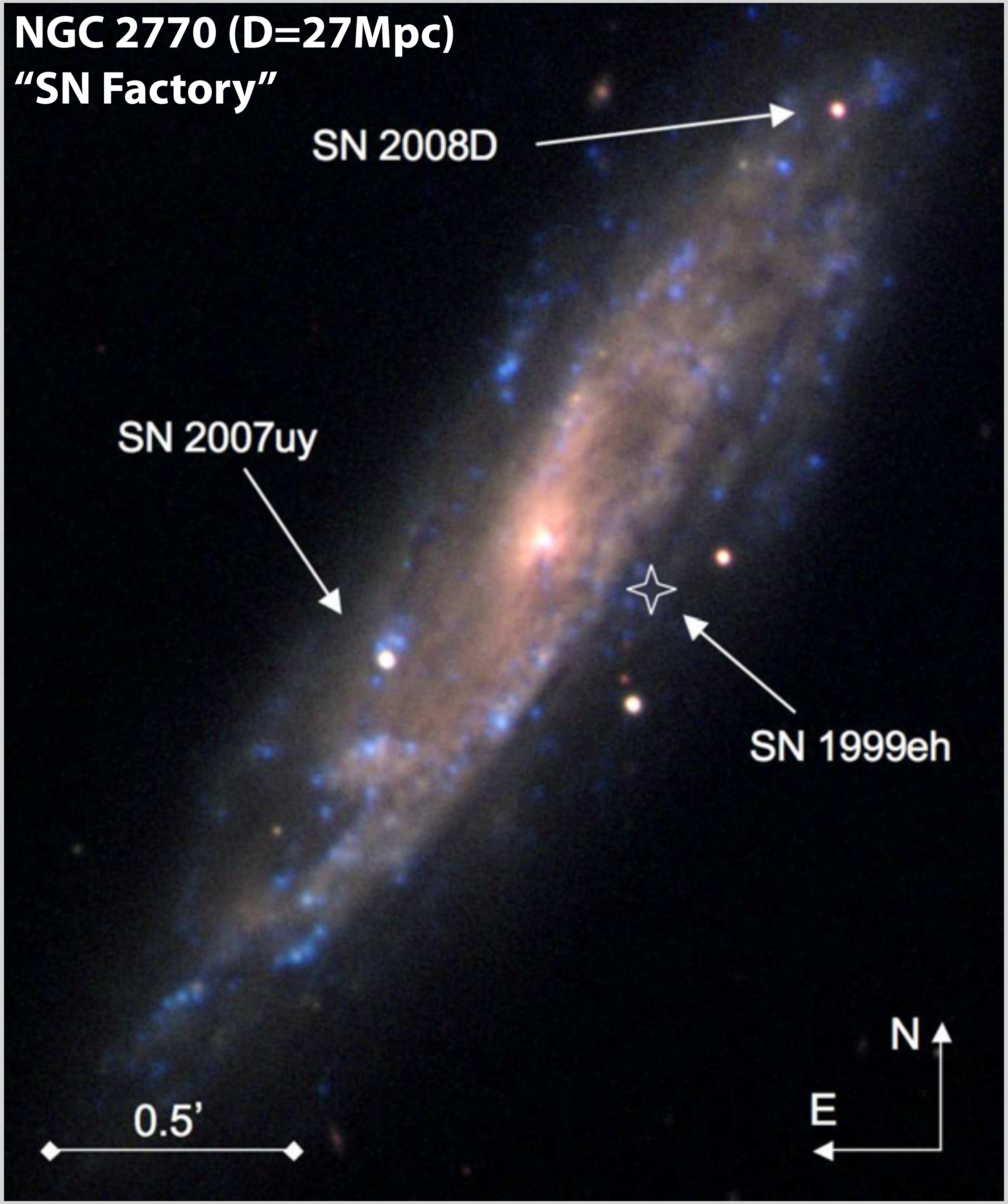
Blinnikov+ 00

SN 1999ex (type Ib/c)

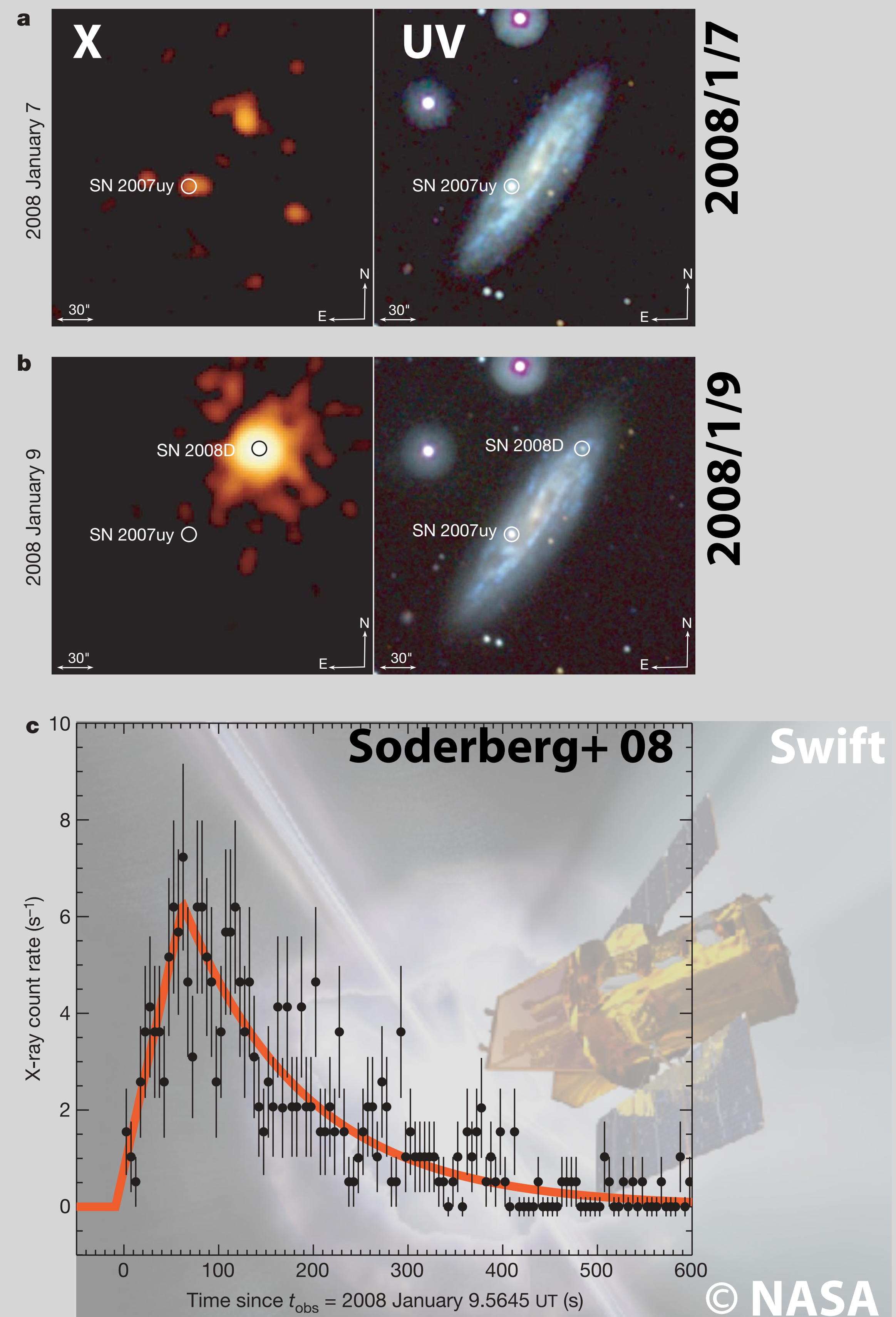


Stritzinger+ 02

SN 2008D/XRF080109 *-serendipitous detection-*



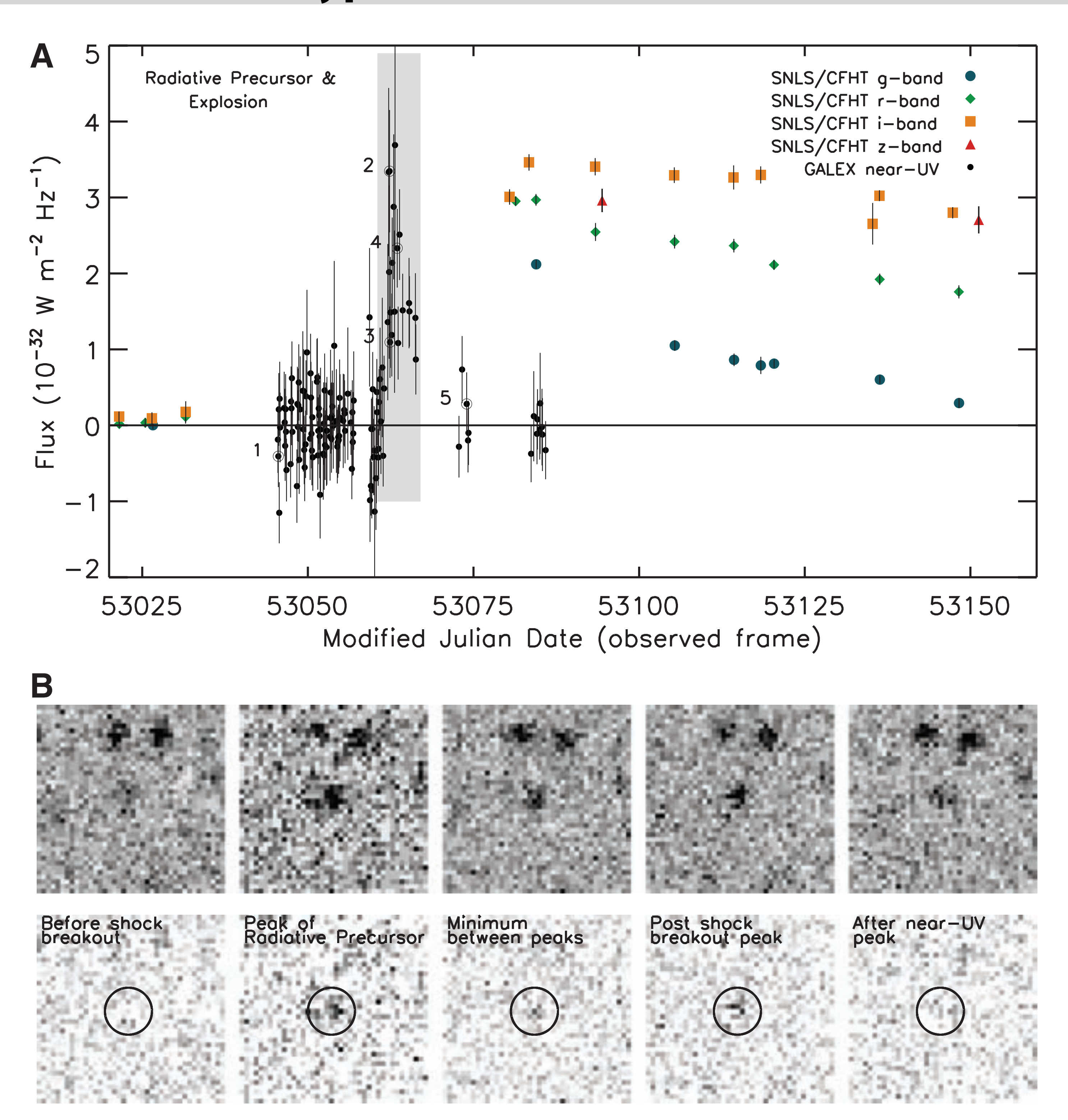
Thöne+ 09

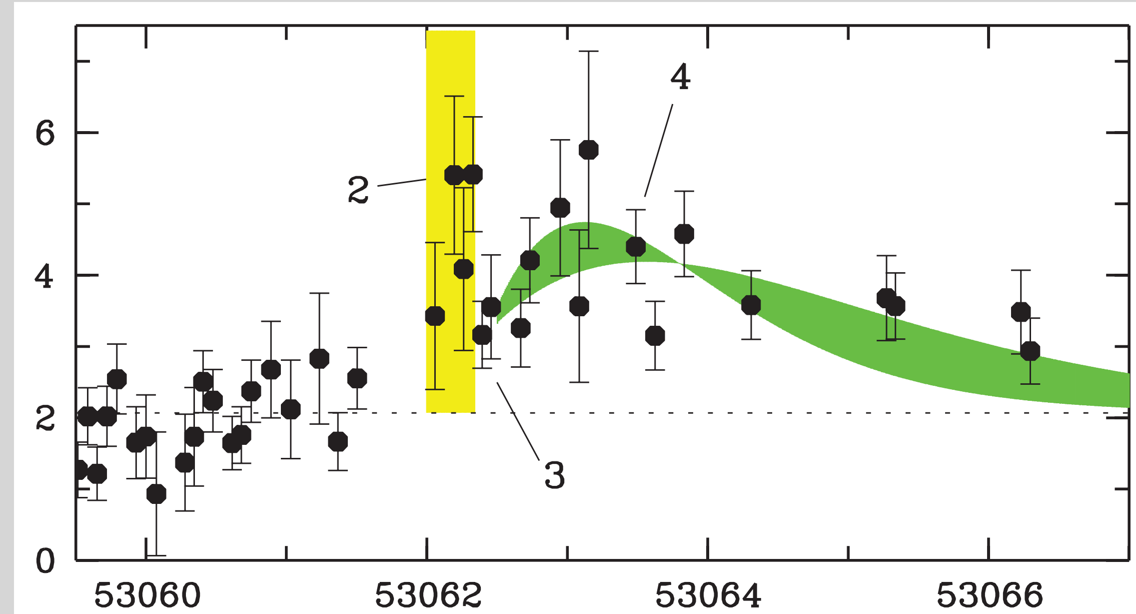


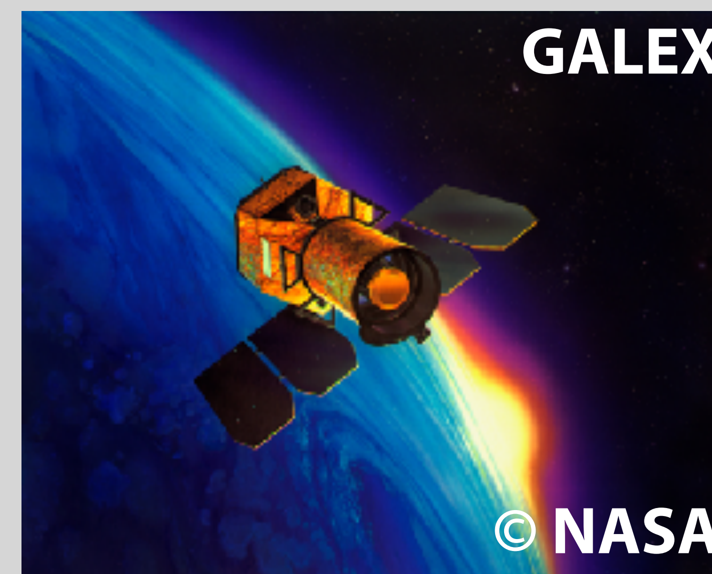
SNLS-04D2dc

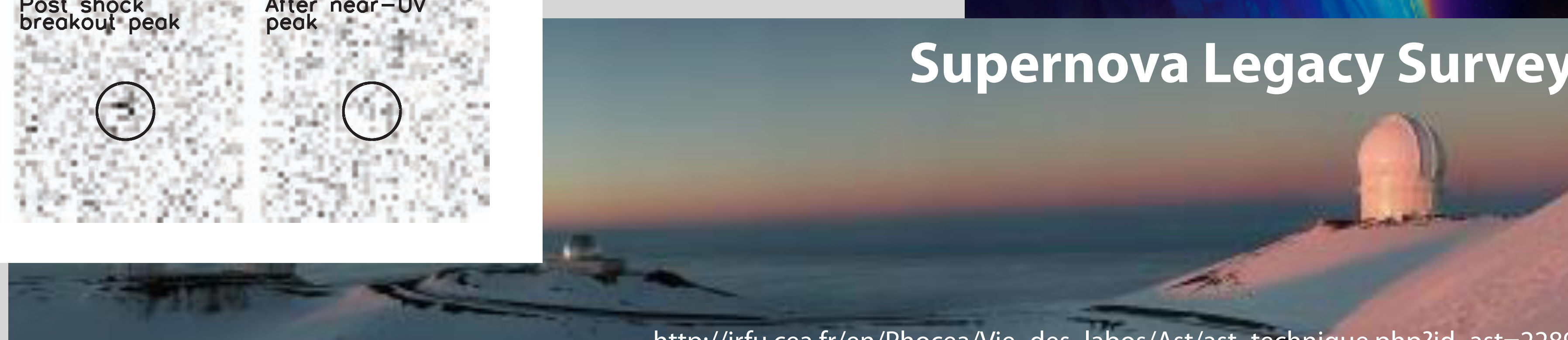
SNLS-04D2d (type II, z=0.1854)

Schawinski+ 08





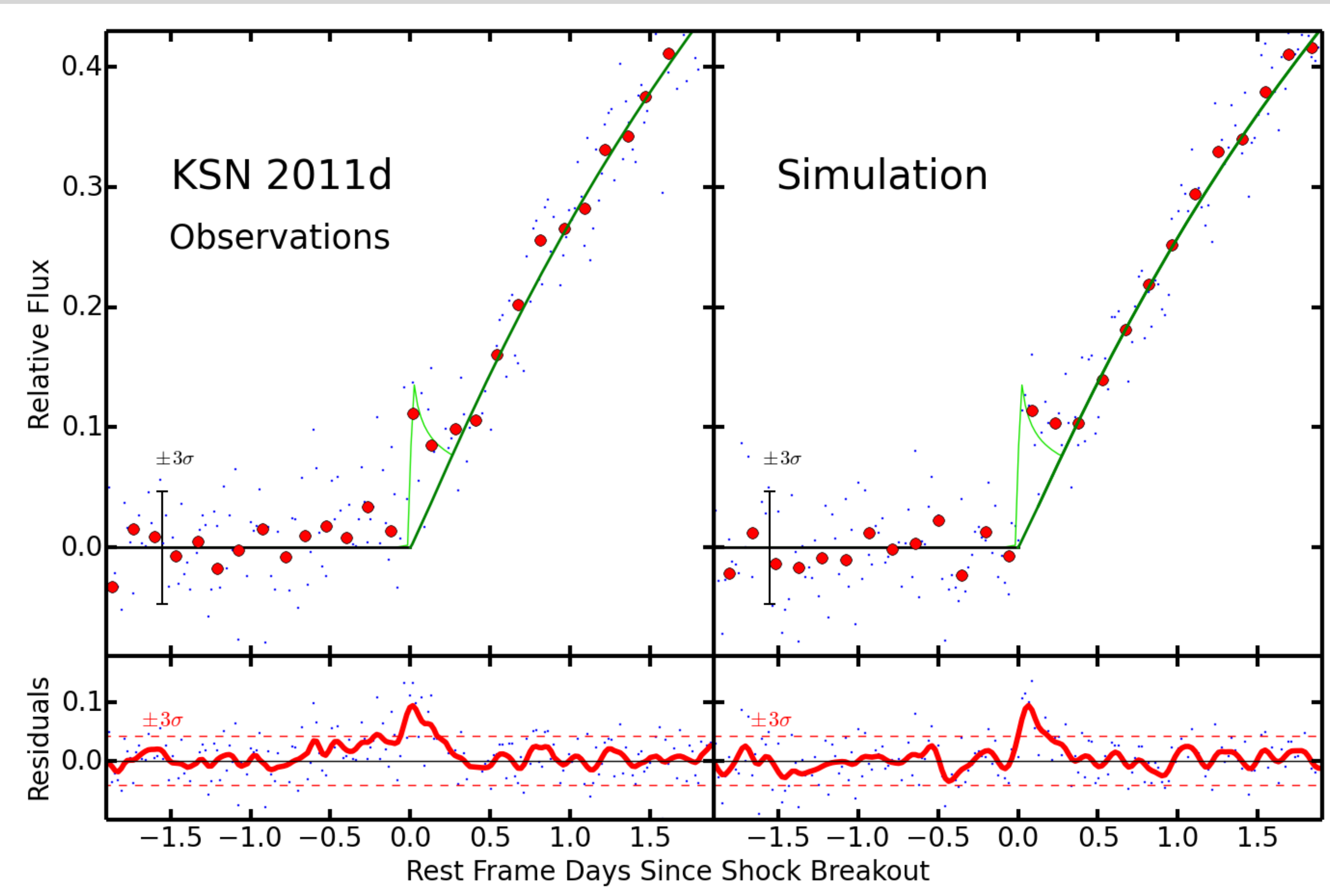


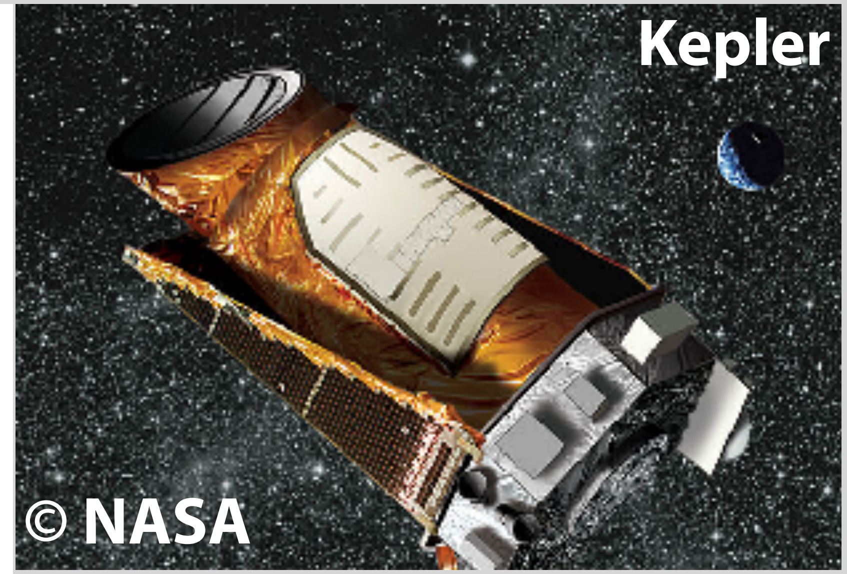


http://irfu.cea.fr/en/Phocea/Vie_des_labos/Ast/ast_technique.php?id_ast=2289 optical

KSN 2011d

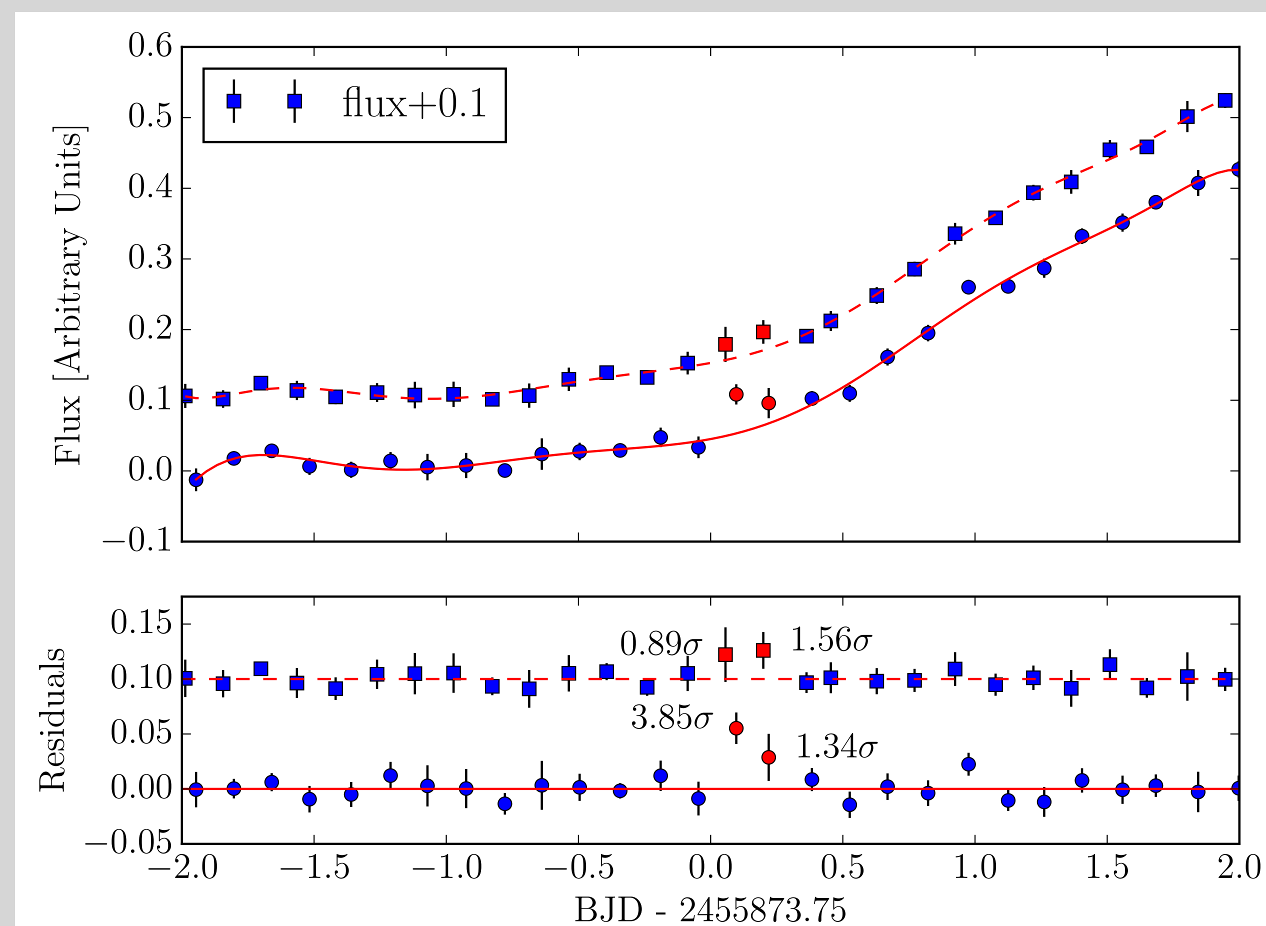
KSN 2011d (type II, z=0.087)





Garnavich + 16

Rubin & Gal-Yam 16



Survey programs for optical transient objects

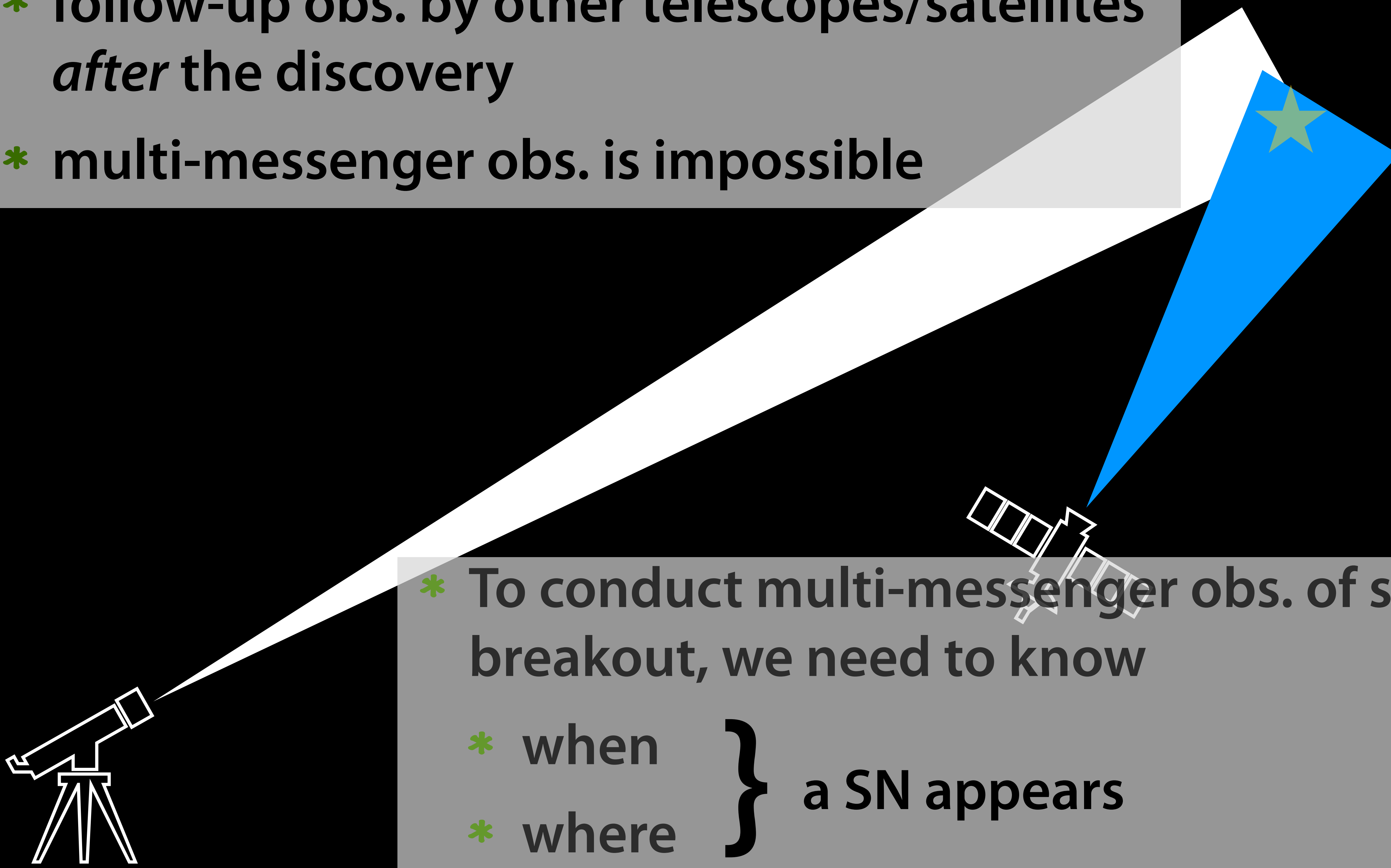
Untargeted optical transient surveys with wide-field cameras

Survey	Diameter [m]	FoV [deg^2]	Etendue ($A\Omega$, roughly) [m^2deg^2]
ASAS-SN	0.14	20	22 (8 cameras)
ROTSE-III	0.45	3.42	0.54
CRTS	0.7	8	3.1
KISS	1.05	4	3.5
PTF	1.26	7.8	9.7
Skymapper	1.33	5.7	7.9
Pan-STARRS	1.8	7	17.8
SDSS	2.5	1.5	7.4
SNLS	3.6	1	10.2
HST/GOODS	2.5	0.003	0.015
DECam	4	3.0	38
Subaru/HSC	8.2	1.75	92
LSST	8.4 (6.4)	9.62	319

from YITP lecture slide by Nozomu Tominaga

A limitation of survey programs

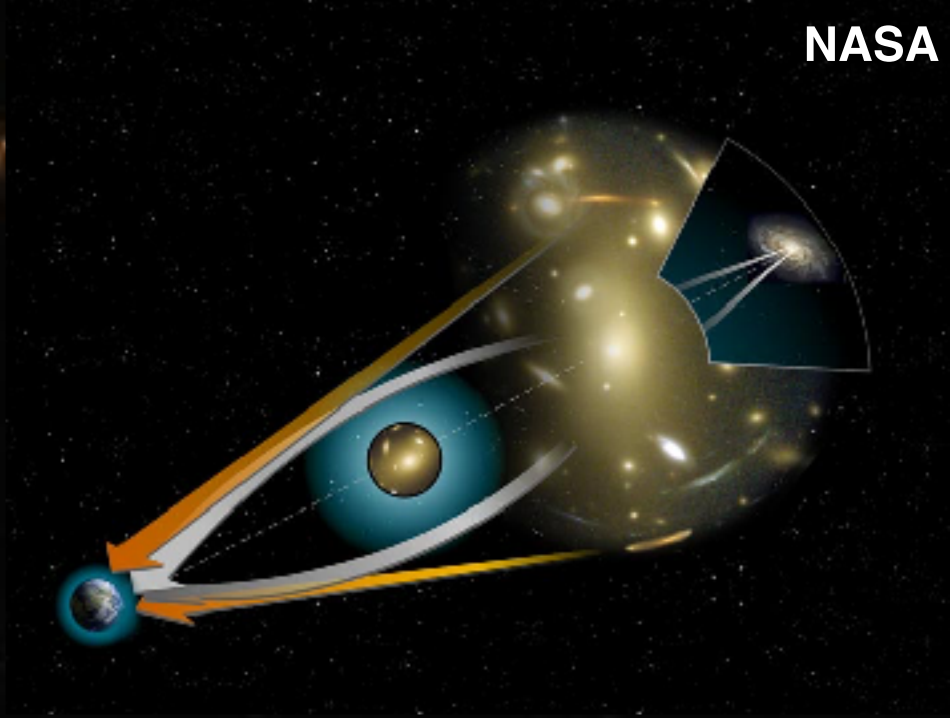
- discovery by optical telescope first
- follow-up obs. by other telescopes/satellites *after* the discovery
- multi-messenger obs. is impossible



- To conduct multi-messenger obs. of shock breakout, we need to know
  - when
  - where

  } a SN appears

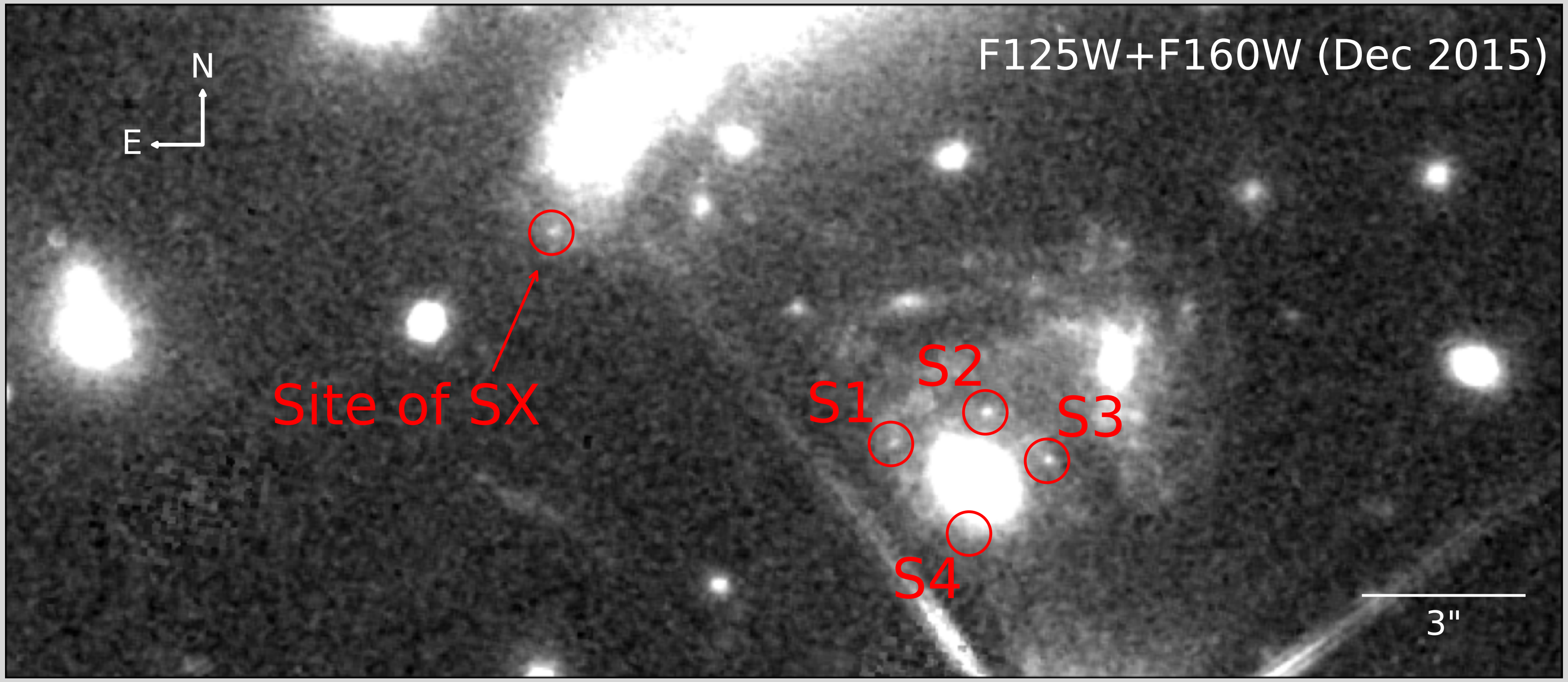
Gravitational lensing


NASA


Cosmic smiley
NASA & ESA

Strongly lensed SNe

- **There have been *three* lensed SN observations so far**
  - PS1-10afx (Ia; Quimby+ 2013), SN Refsdal (CC; Kelly+ 2015), iPTF16geu (Ia; Goobar+ 2017)
- **SN Refsdal**
  - four images were found at the same time
  - one more event had been predicted one year *after* the images
  - another image indeed appeared! (Kelly+ 2016)



Time delay

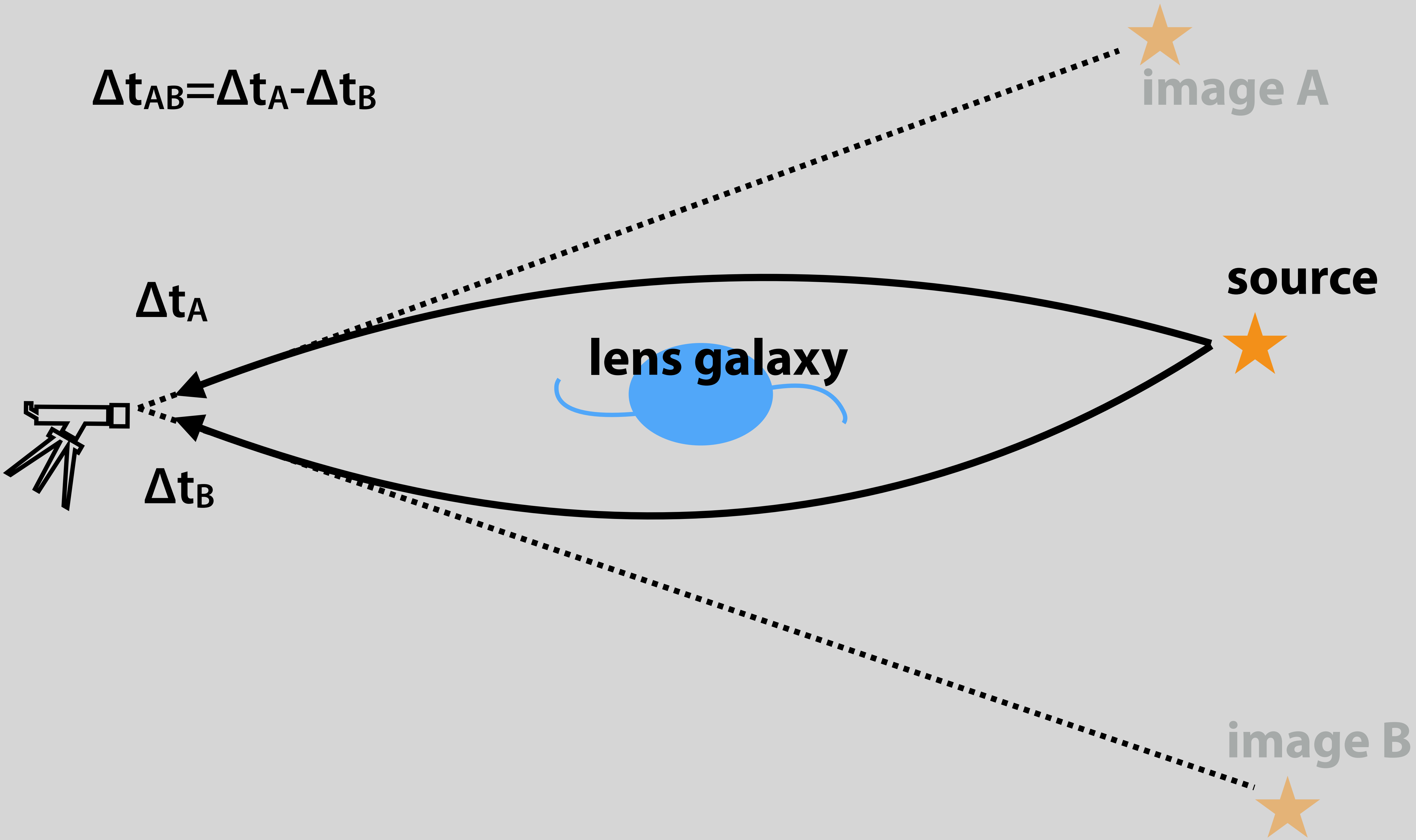
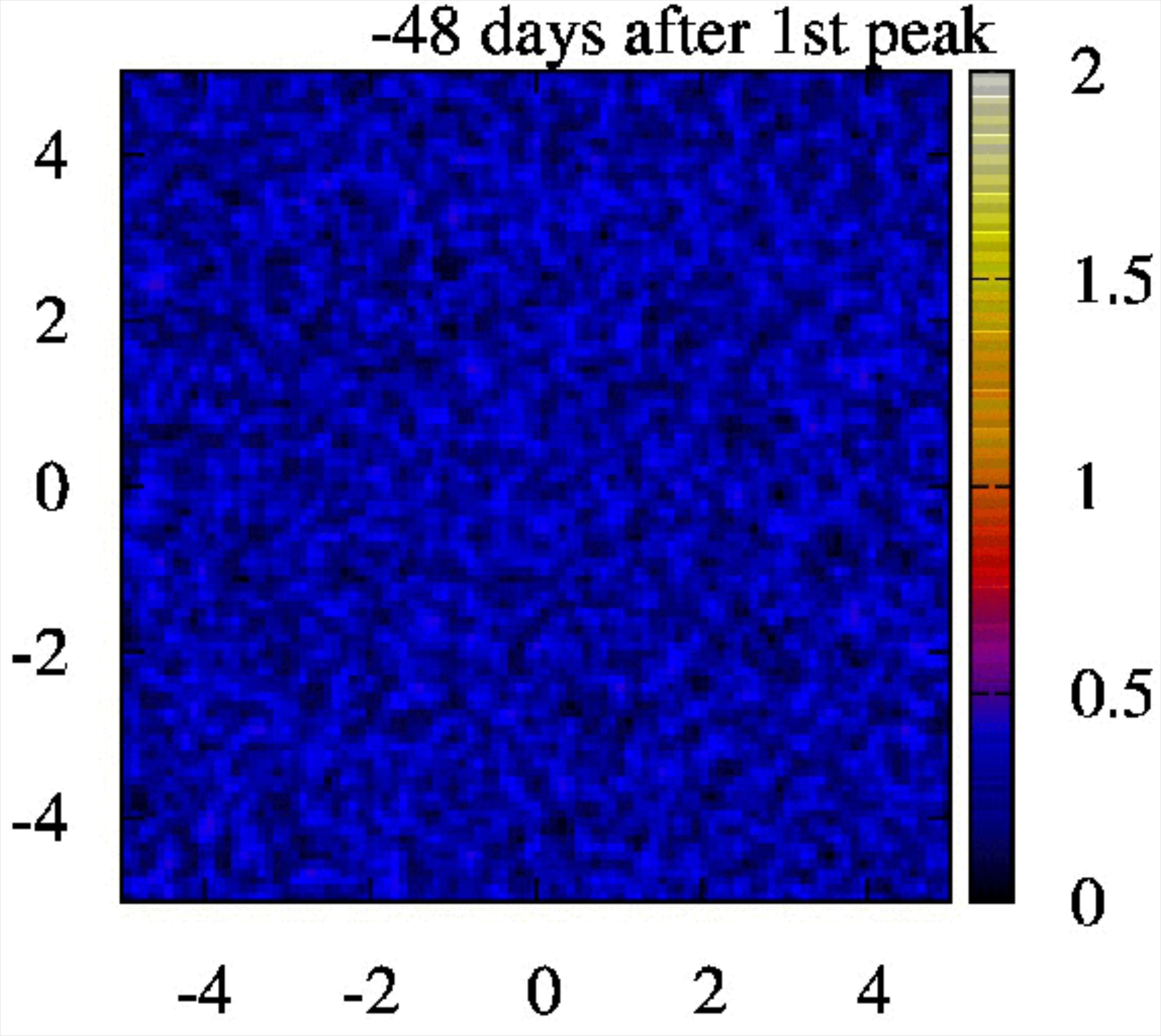
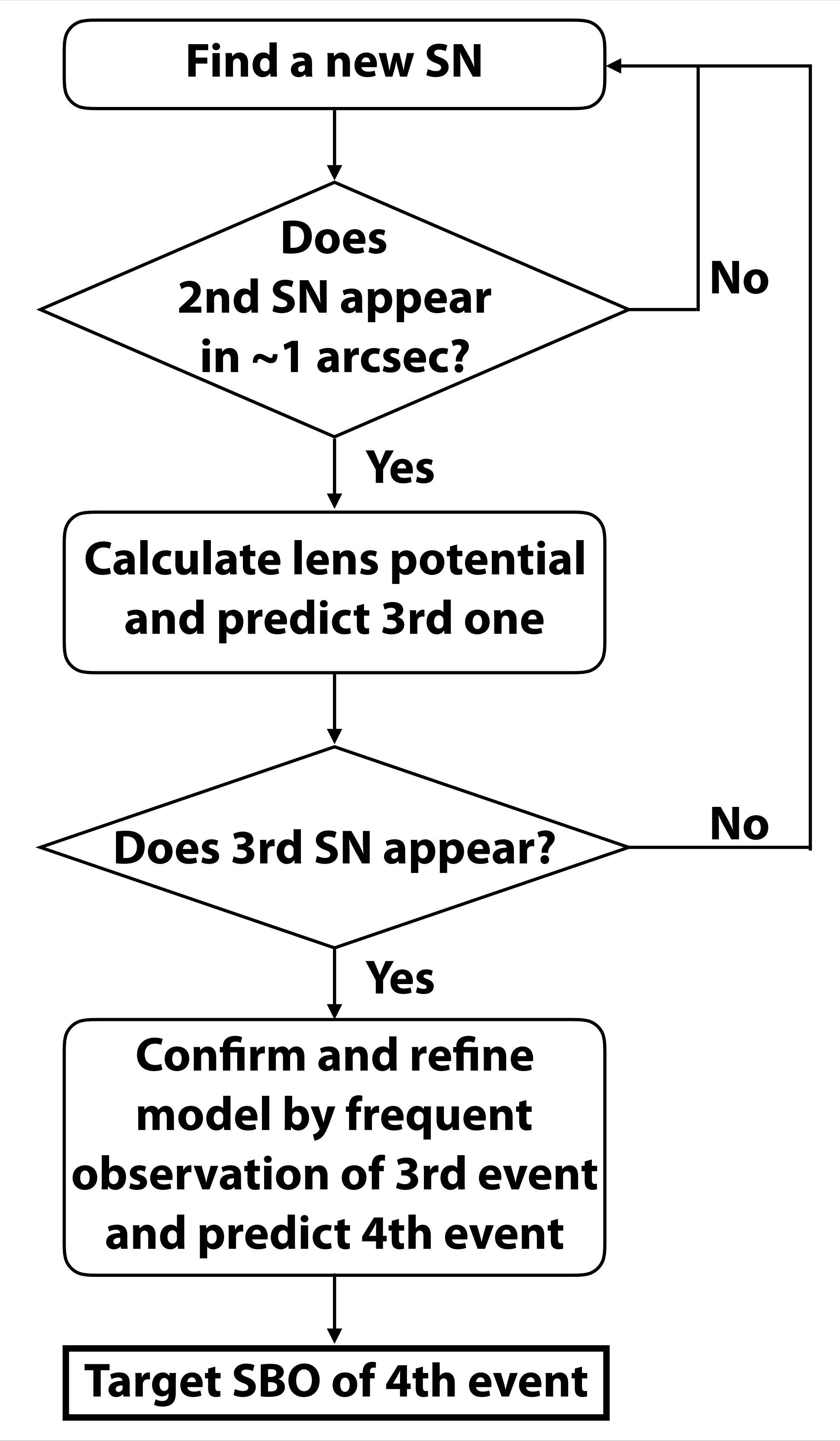


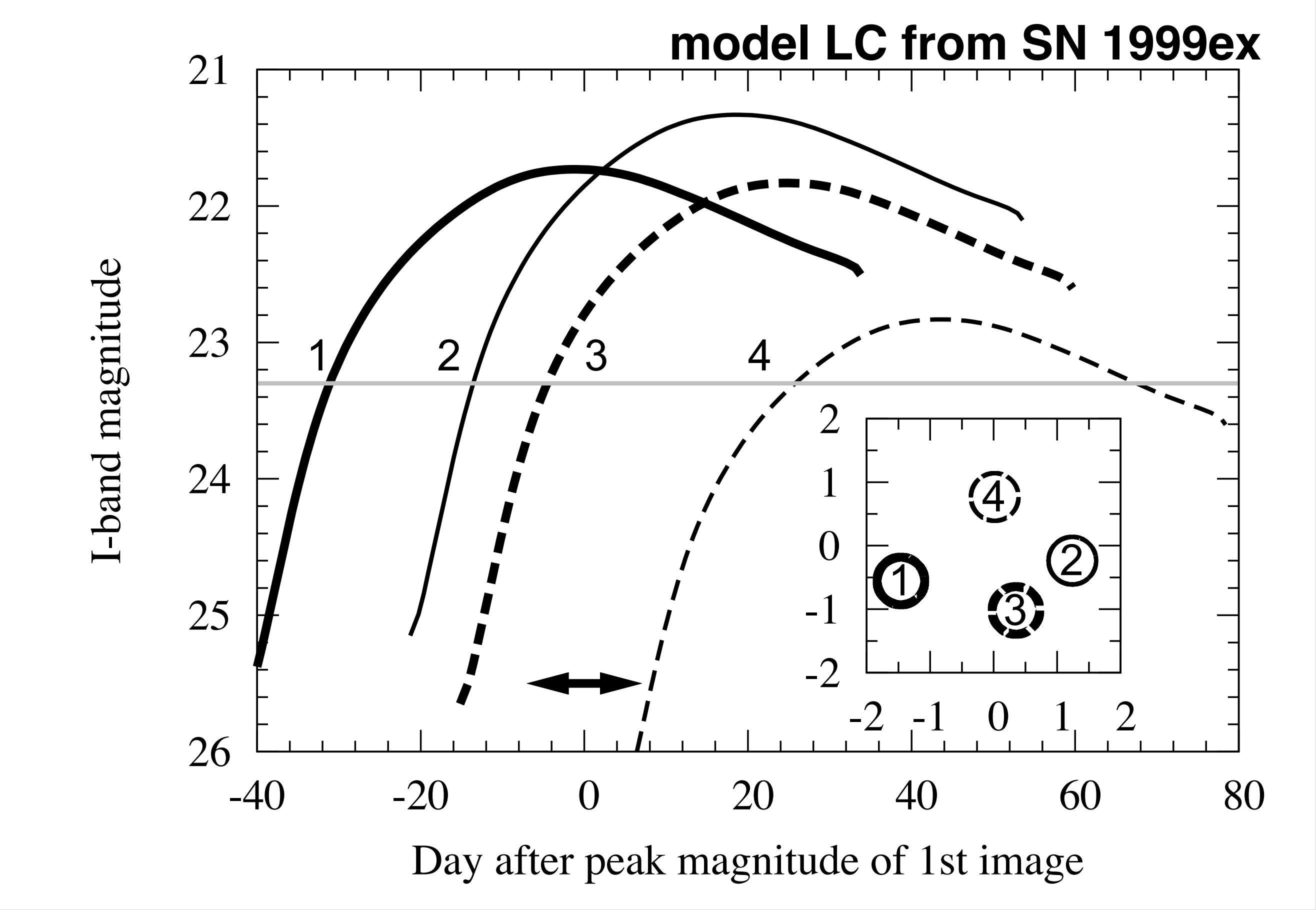
Image evolution: an example



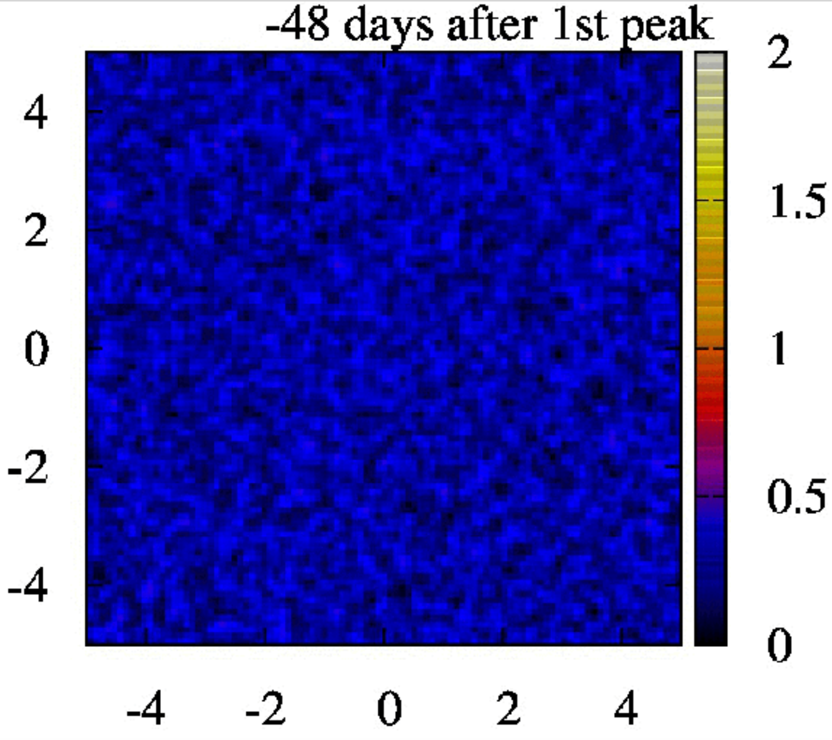
A strategy



Find a new SN
Does 2nd SN appear in ~1 arcsec?
No
Yes
Calculate lens potential and predict 3rd one
Does 3rd SN appear?
No
Yes
Confirm and refine model by frequent observation of 3rd event and predict 4th event
Target SBO of 4th event



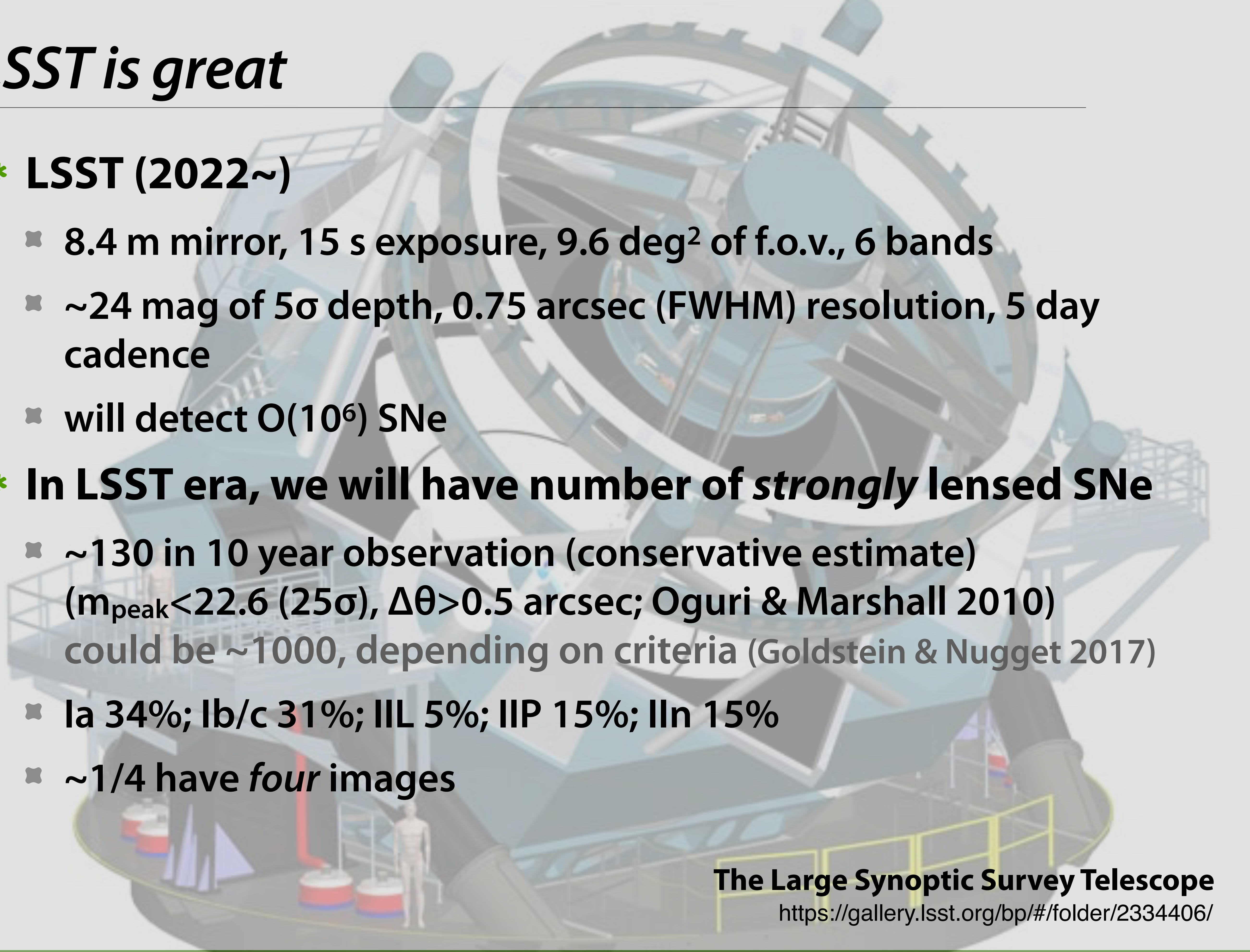
model LC from SN 1999ex
I-band magnitude
Day after peak magnitude of 1st image
1
2
3
4



-48 days after 1st peak

LSST is great

- **LSST (2022~)**
  - 8.4 m mirror, 15 s exposure, 9.6 deg^2 of f.o.v., 6 bands
  - ~24 mag of 5σ depth, 0.75 arcsec (FWHM) resolution, 5 day cadence
  - will detect O(10^6) SNe
- **In LSST era, we will have number of *strongly* lensed SNe**
  - ~130 in 10 year observation (conservative estimate) (m_{peak}<22.6 (25σ), Δθ>0.5 arcsec; Oguri & Marshall 2010) could be ~1000, depending on criteria (Goldstein & Nugget 2017)
  - Ia 34%; Ib/c 31%; IIL 5%; IIP 15%; IIn 15%
  - ~1/4 have *four* images



The Large Synoptic Survey Telescope
https://gallery.lsst.org/bp/#/folder/2334406/

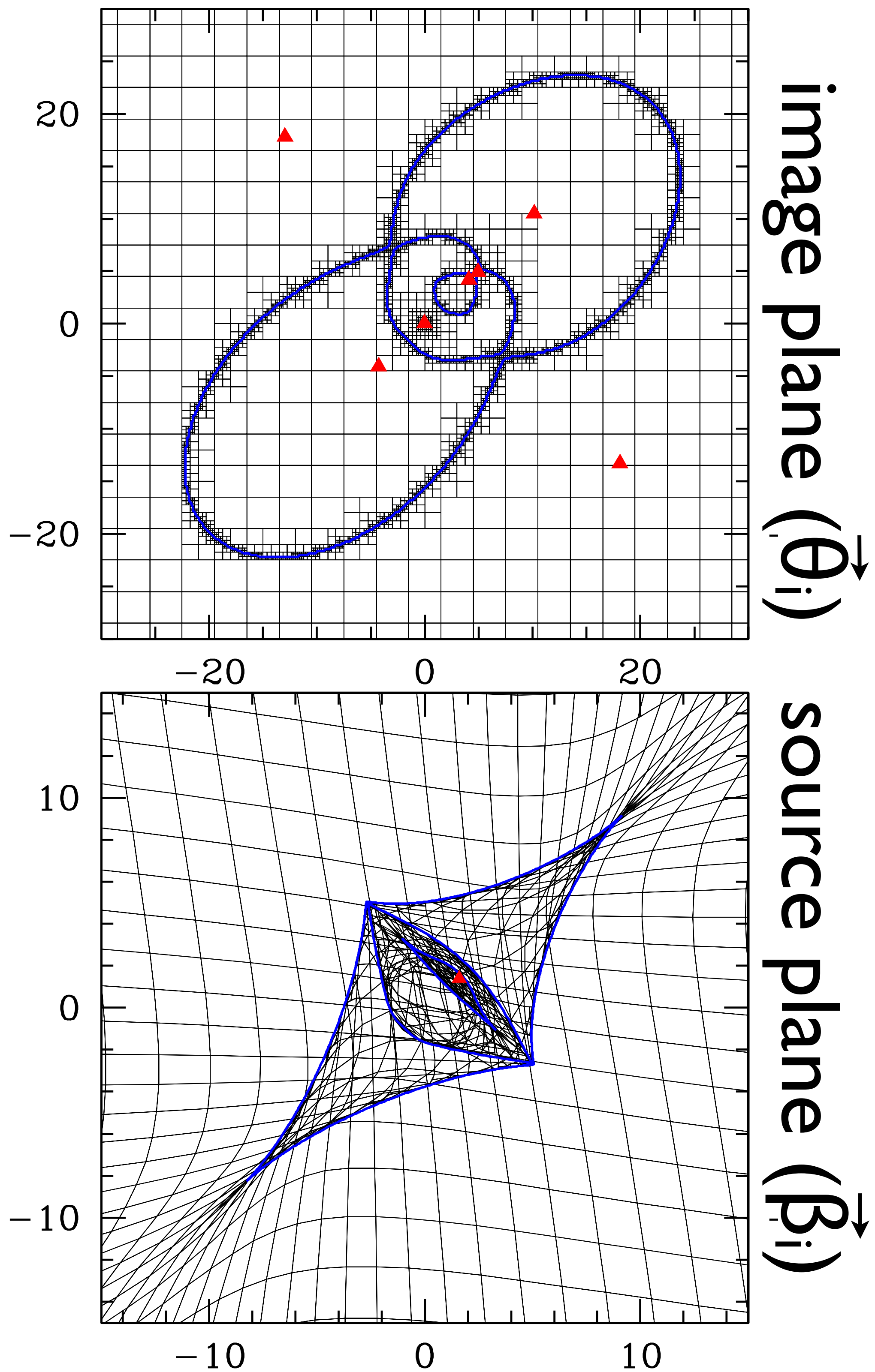
Key for SN forecast

* **Target-of-Opportunity (ToO) observation is necessary for transient observation**

* **After the discovery of 1st/2nd/3rd images, we have to trigger ToO obs. to catch 4th image**

* **A typical duration of ToO obs. is <~ 1 night for an 8m-size telescope**

* **Question:** ***how precisely can we predict when and where the 4th image appears w/ 1st-2nd-3rd image information?***



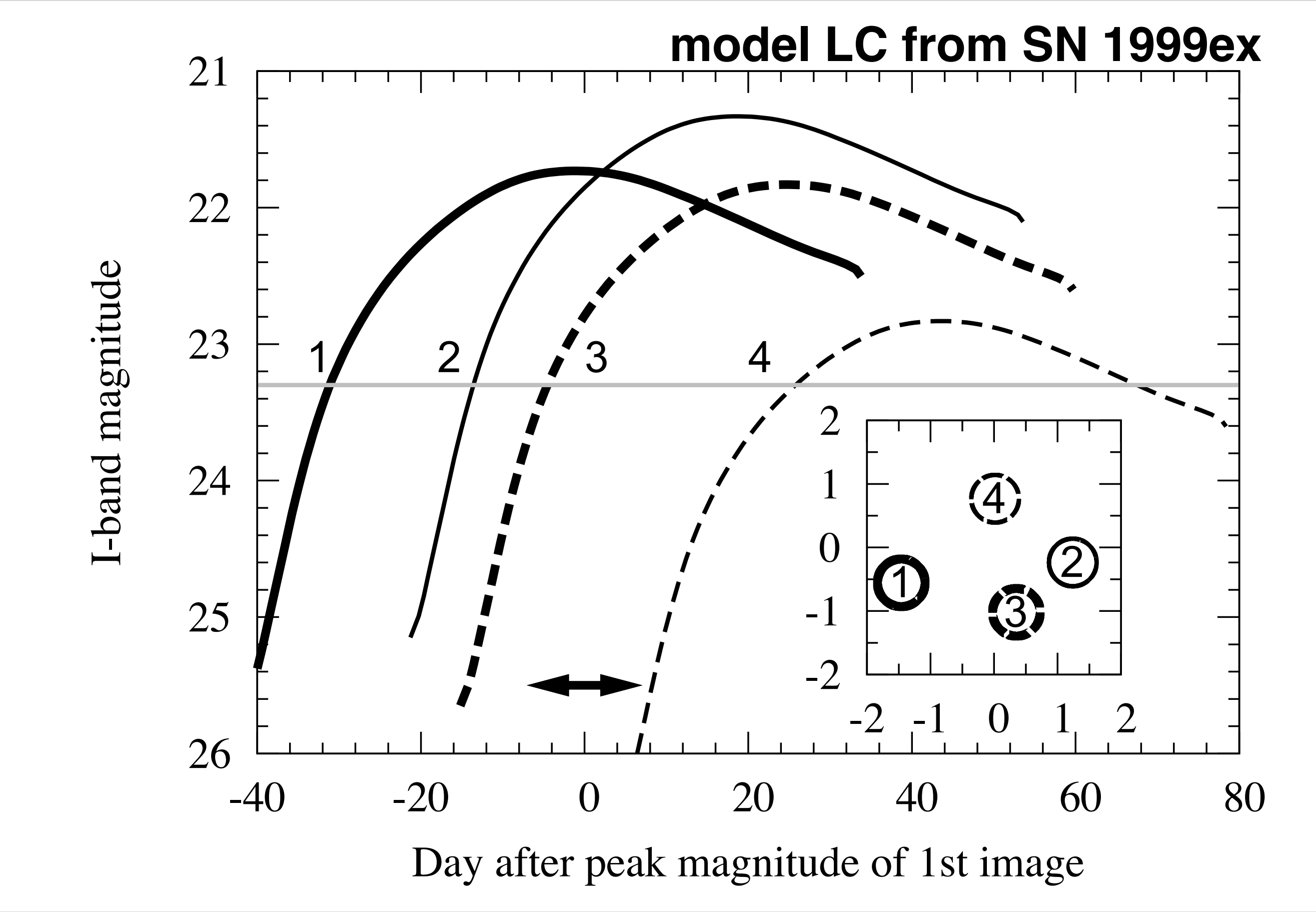
http://www.slac.stanford.edu/~oguri/glafic/

glafic

- public software for strong lensing analysis ("parametric" mass modeling)
- adaptive grid to solve lens equation efficiently
- support many lens potentials
- please use!

from YITP seminar slide by Masamune Oguri

Precision of 'prediction'



Data is taken from mock sample by Oguri & Marshall (2010)

- **Lens model parameters**
  - Singular Isothermal Ellipsoid (SIE) model
  - velocity dispersion, ellipticity, orientation of lens gal., source position
- **Observables**
  - position x3, z_{SN}, flux ratio x3, time delays x3, with some error (0.75 arcsec, 0.5, 50%, 5 days now)
- **Result** (w/ *glafic*)
  - best fit: $\Delta t_{1st\text{-}4th}$=44.741 d
  - 'answer': $\Delta t_{1st\text{-}4th}$=44.576 d
  - Error estimation needs MCMC, which will be done next

Summary

- **Shock breakout is the first flush of supernova**
  - Number of survey programs are running
  - multi-messenger obs. is required
- **Strongly lensed SNe are potential probes**
  - O(100) lensed SNe will be detected by LSST (~5 years from now)
  - SN with 4 images is an ideal target
  - With conservative error, prediction is feasible (within 1 day)