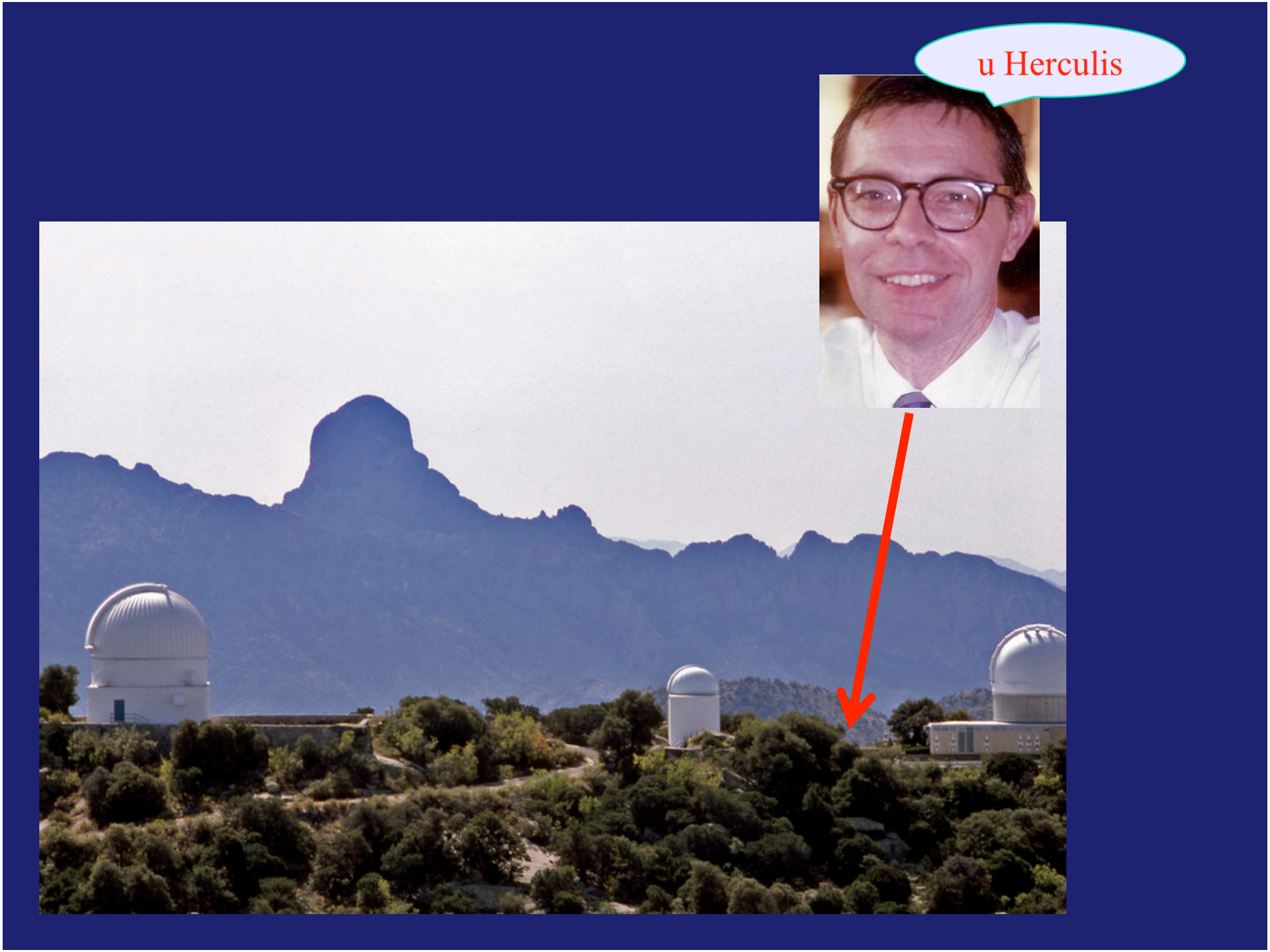
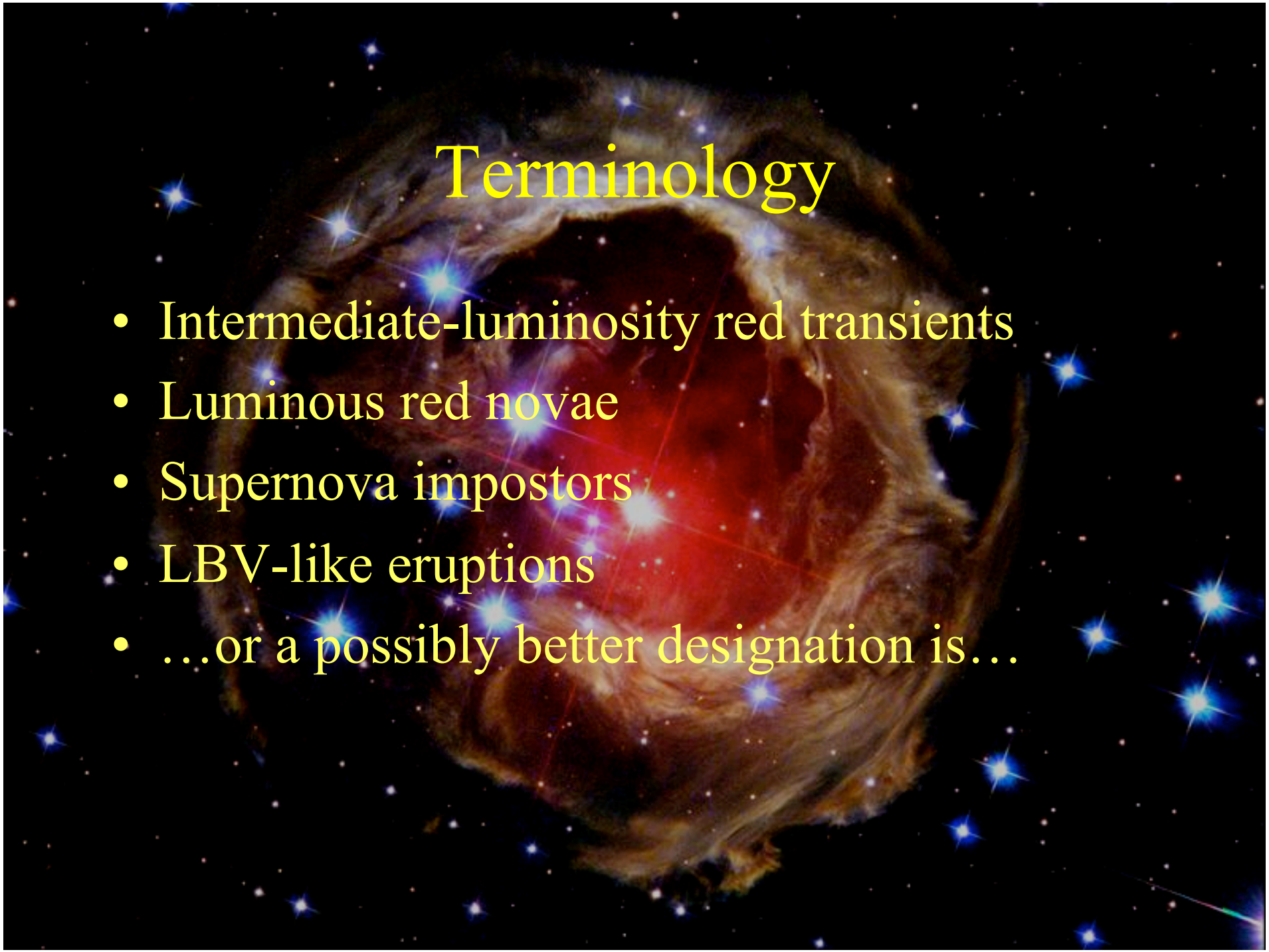

u Herculis


Intermediate-Luminosity
Red Transients:
Catastrophic Stellar Mergers?
Howard E. Bond
Space Telescope Science Institute
2011 August 11
Villanova University Memorial Workshop for Robert H Koch



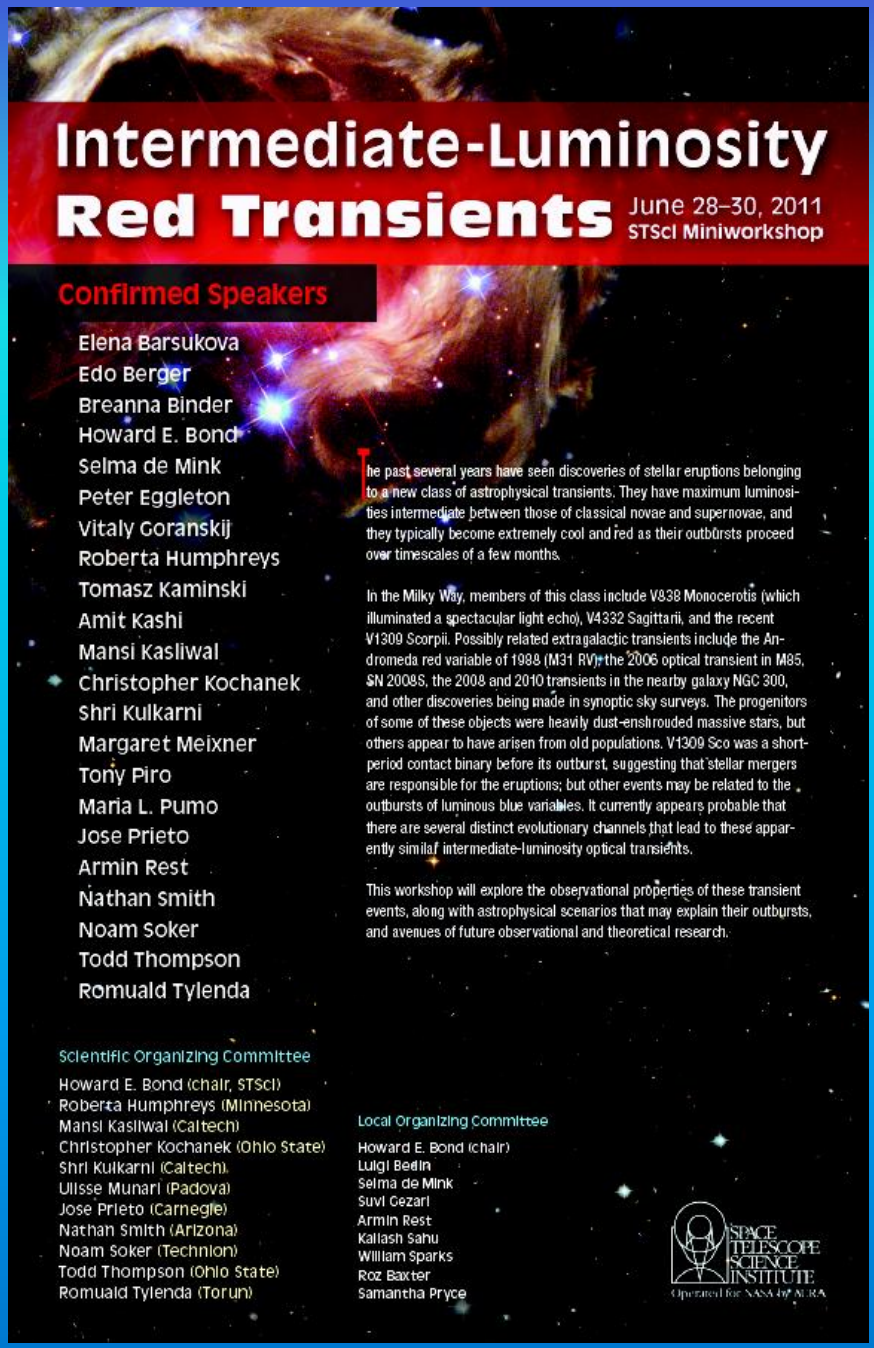
Terminology

- Intermediate-luminosity red transients
- Luminous red novae
- Supernova impostors
- LBV-like eruptions
- …or a possibly better designation is…

“Pretty Good Novae”

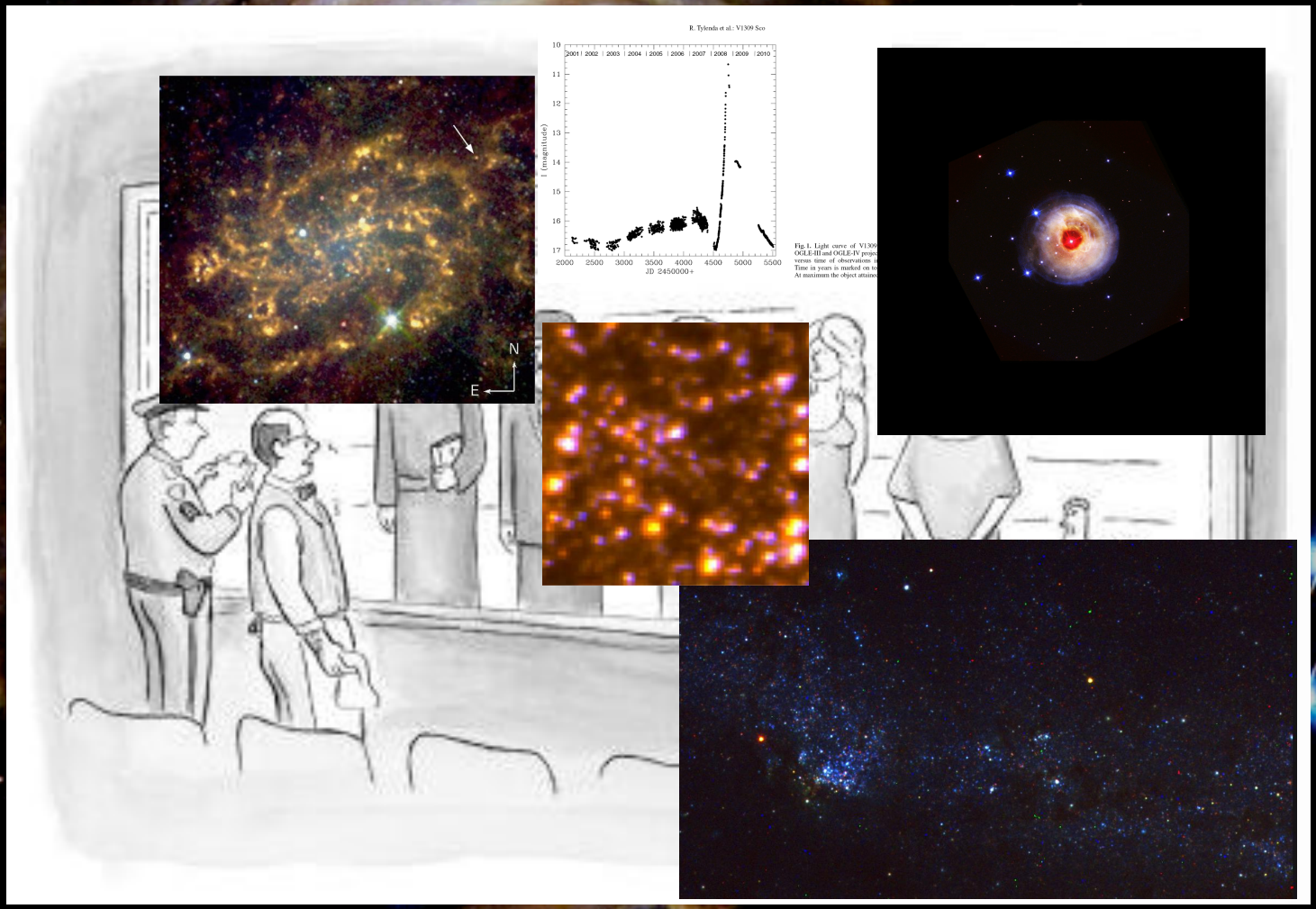
STScI Workshop on ILRTs was held June 28-30, 2011

program:
www.stsci.edu/~bond/program.txt



Let's Line Up the Suspects

Let's Line Up the Suspects



M31 RV

- Erupted 1988 in bulge of Andromeda (3′ from nucleus)
- Reached $M_{bol} \sim -10$
- Remained bright ~3 months
- Cool & red throughout; evolved from M0 to late M spectral type
- Deep *HST* images, 1999-2010, show only normal bulge old red giants at outburst site

V4332 Sagittarii

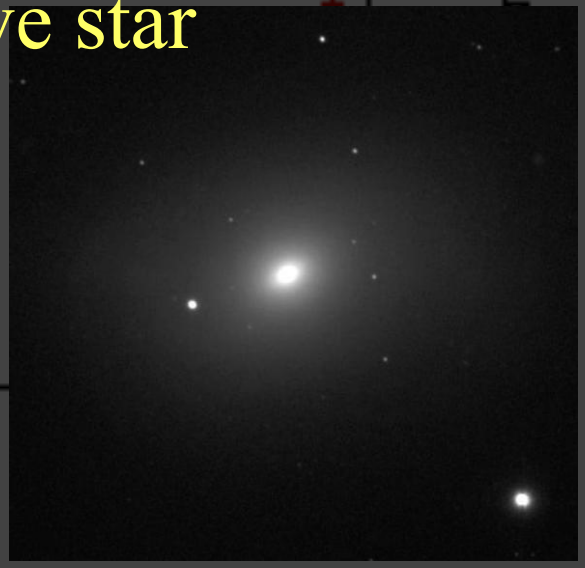
- 1994 event in direction of Milky Way bulge
- Rose ~10 mag to peak at 8.5 vis mag, with K-type spectrum.
- Declined 10 mag in ~3 months, with T_{eff} dropping from 4400 to 2300 K. Spectrum evolved from K to late M
- Similarities to M31 RV were noted (Martini et al. 1999)

V838 Monocerotis

- Outburst in 2002.
- Evolved from K to M to L spectral type
- Illuminating spectacular light echo
- Absolute mag at max similar to M31 RV
- Member of young cluster, unlike the old populations of M31 RV & V4332 Sgr
- Has recently ingested a distant B3 V companion

M85 OT 2006-1

- 2006 eruption in Virgo galaxy M85
- Reached $M_V \sim -13$
- Cool throughout its ~100-day outburst
- M85 is S0 galaxy without active star formation



NGC 300 OT 2008-1

- Discovered by amateur (B. Monard) at 14th mag (abs *V* mag ~ −12.9)
- In spiral arm of NGC 300
- Became very red as outburst proceeded
- Deep pre-eruption *HST* images showed no optical progenitor to ~28.5 mag
- *Spitzer* pre-outburst frames showed luminous mid-IR progenitor

"SN" 2008S

- In spiral galaxy NGC 6946 (supernova factory, $d \sim 5.6$ Mpc)
- Reached $M_V \sim -13.6$
- Near-twin of NGC 300 OT 2008
  - no optical progenitor
  - luminous *Spitzer* mid-IR progenitor

"SN" 2010dn

- In spiral galaxy NGC 3184 ($d \sim 12$ Mpc)
- Reached $M_V \sim -13$
- Spectroscopic near-twin of NGC 300 OT 2008, SN 2008S

The Floodgates Open

- Most of the ILRTs known until ~2010 were discovered by amateurs (V4332 Sgr, V838 Mon, NGC 300 OT-2008, SN 2008S, SN 2010dn, V1309 Sco; M31 RV [found independently by amateurs])
- Professional synoptic surveys (PTF, Pan-STARRS, …) are now going to be finding them in large numbers

PTF 10fqs

- In spiral arm of Virgo galaxy M99
- Peak $M_r \sim -12.3$, red color, slow decay (1 mag in 68 days)

PTF 10fqs

- In spiral arm of Virgo galaxy M99
- Peak $M_r \sim -12.3$, red color, slow decay (1 mag in 68 days)

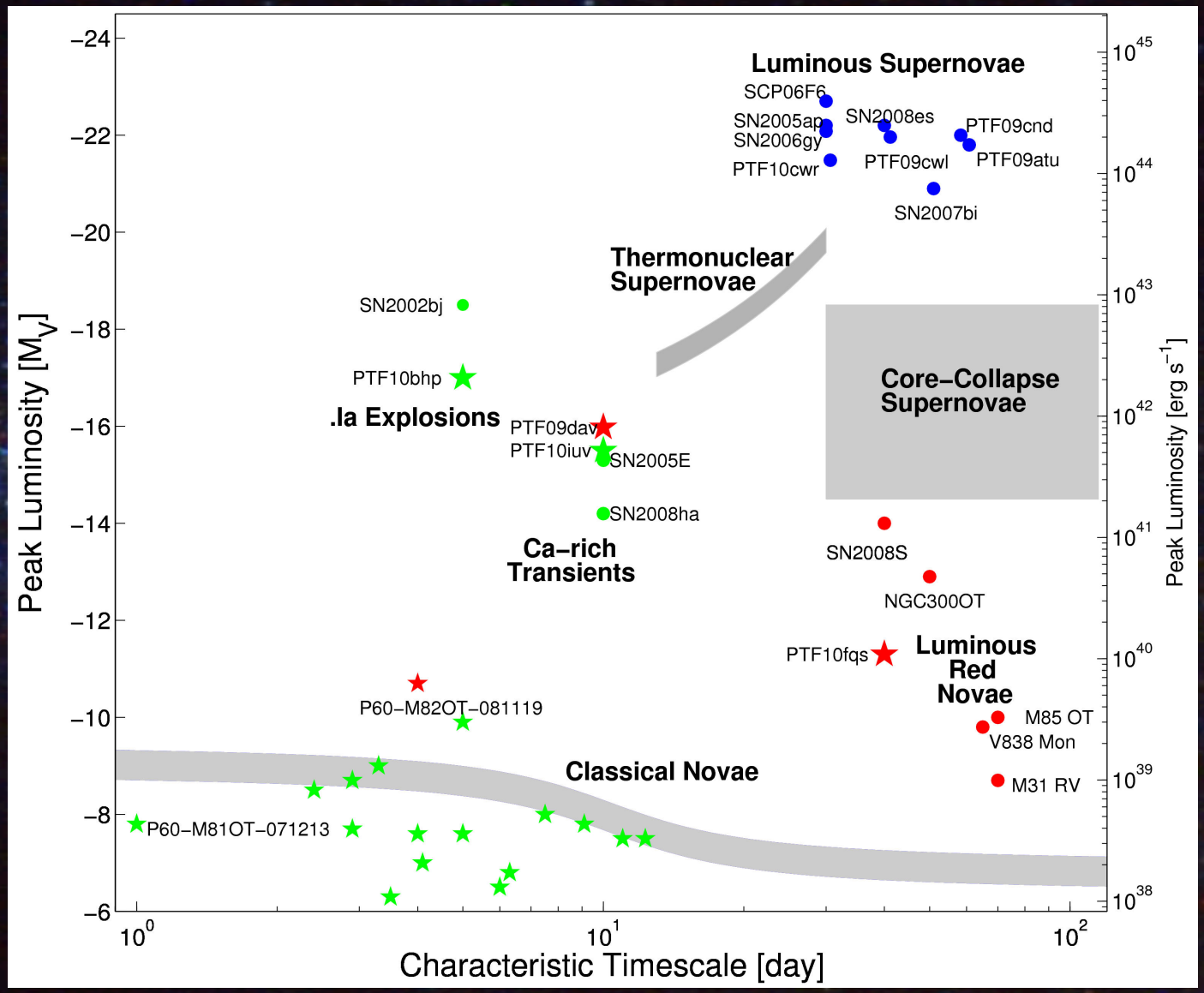
PTF 10fqs

- In spiral arm of Virgo galaxy M99
- Peak $M_r \sim -12.3$, red color, slow decay (1 mag in 68 days)

PTF 10acbp

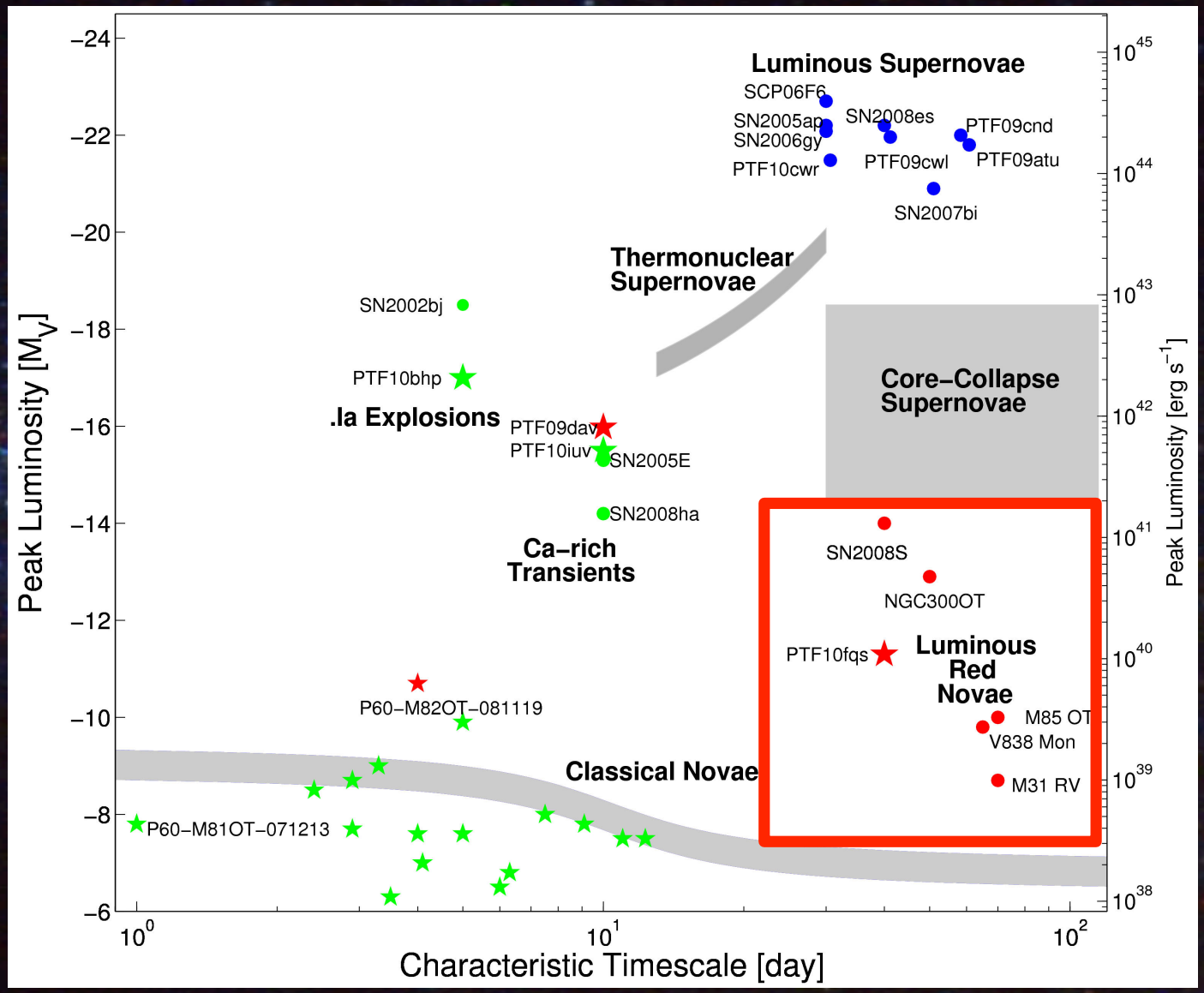
- In spiral UGC 11976
- Peak $M_r \sim -14$

Phase Space of ILRTs



courtesy
Mansi Kasliwal

Phase Space of ILRTs



courtesy
Mansi Kasliwal

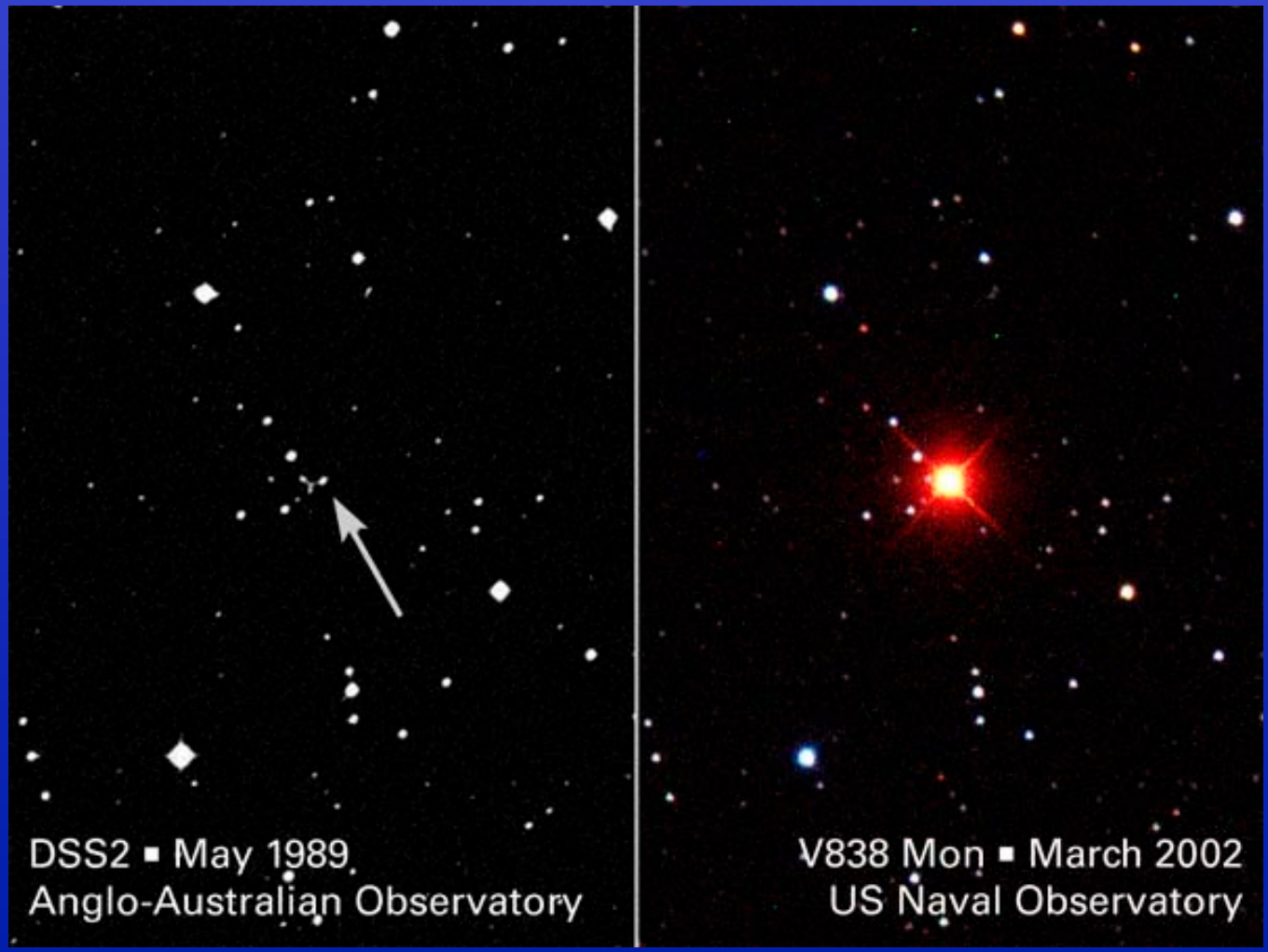
V1309 Scorpii

- Rose to 6.8 *I* mag in 2008
- In Galactic bulge, 3º from center
- Spectrum evolved from F to late M over several months
- In an OGLE field with extensive monitoring for several years *before* the outburst

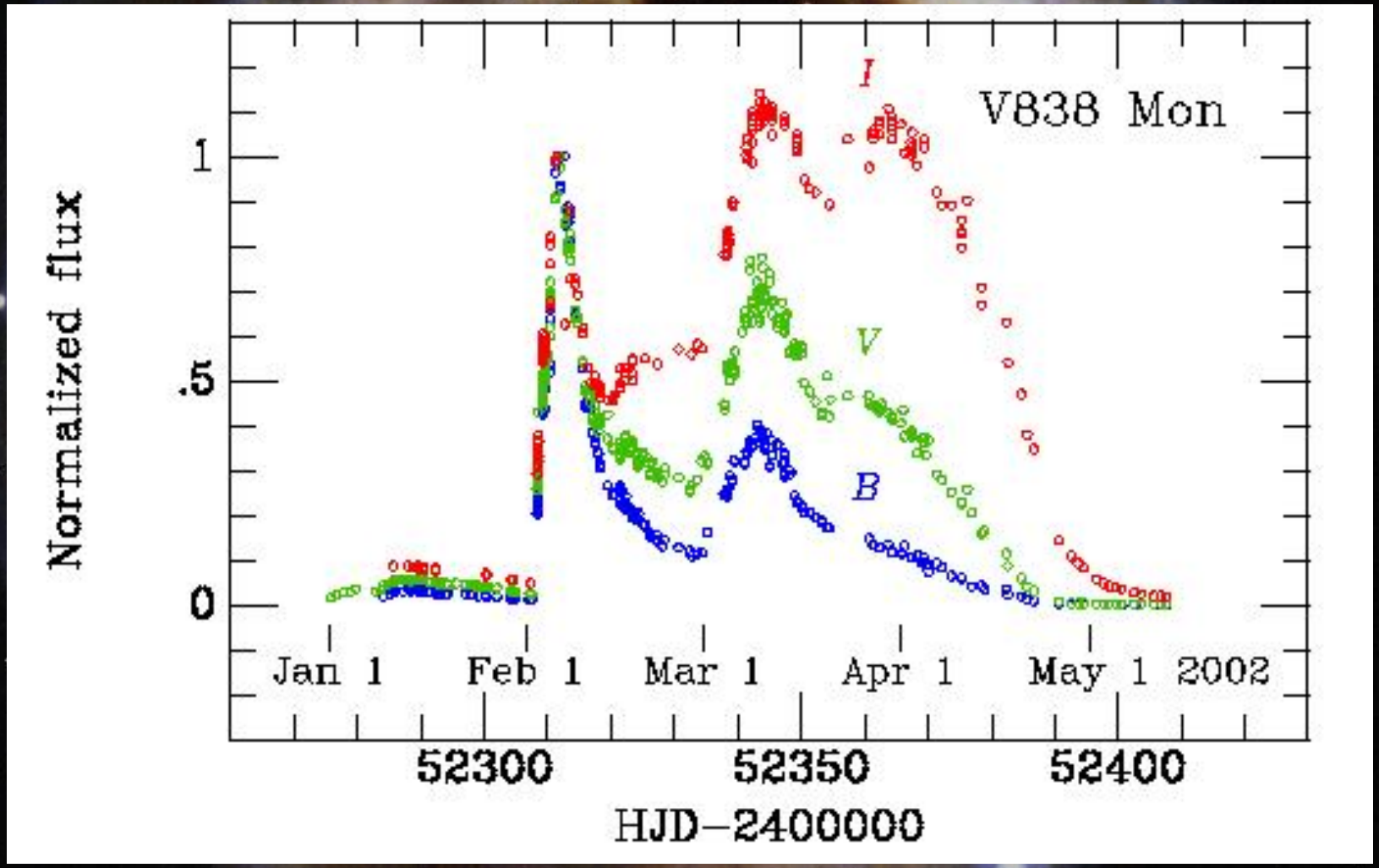
V838 Monocerotis Light Echo

Hubble Heritage

V838 Monocerotis
Before & During 2002 Outburst



Outburst light curve
(normalized brightness vs. time)



Discovery of Light Echo

Arne Henden, USNO Flagstaff 1m

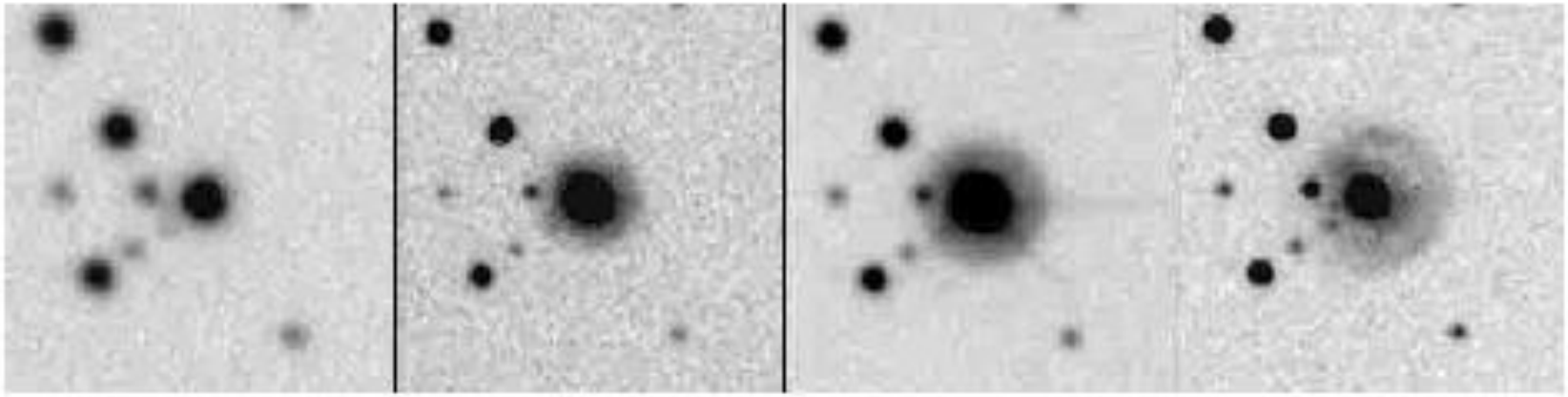
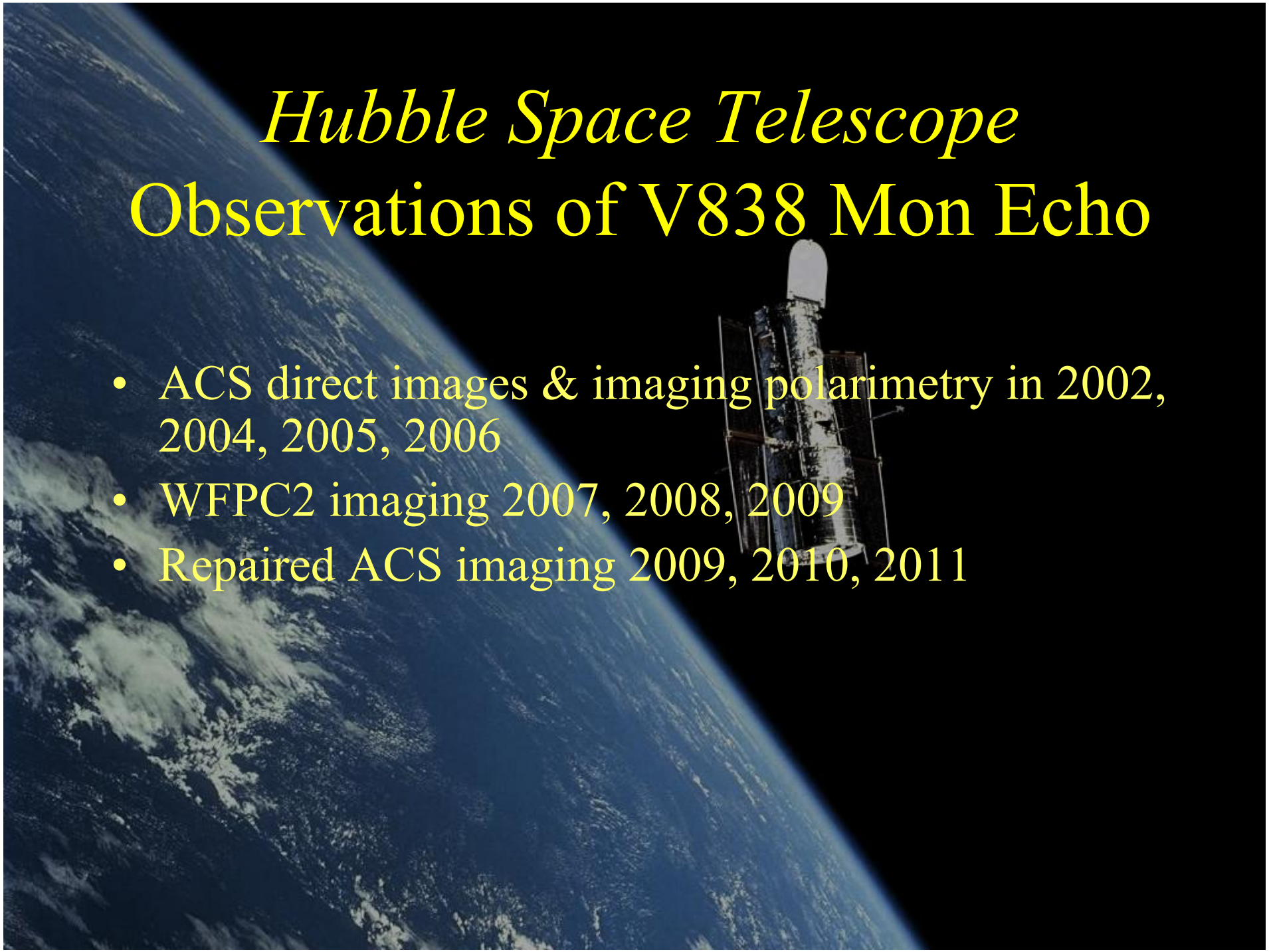


Fig. 1. Expansion of the light-echo around V838 Mon, revealing a previously invisible ring of circumstellar material. U band 67×67 arcsec images obtained with the USNO 1 m telescope (North to top, East to the left). Dates (seeing in arcsec, U mag of central V838 Mon) from left to right: Jan. 13 ($3.2''$, $U = 13.33$), Feb. 27 ($2.3''$, $U = 12.05$), March 10 ($2.5''$, $U = 10.62$) and March 27 ($2.2''$, $U = 12.28$).



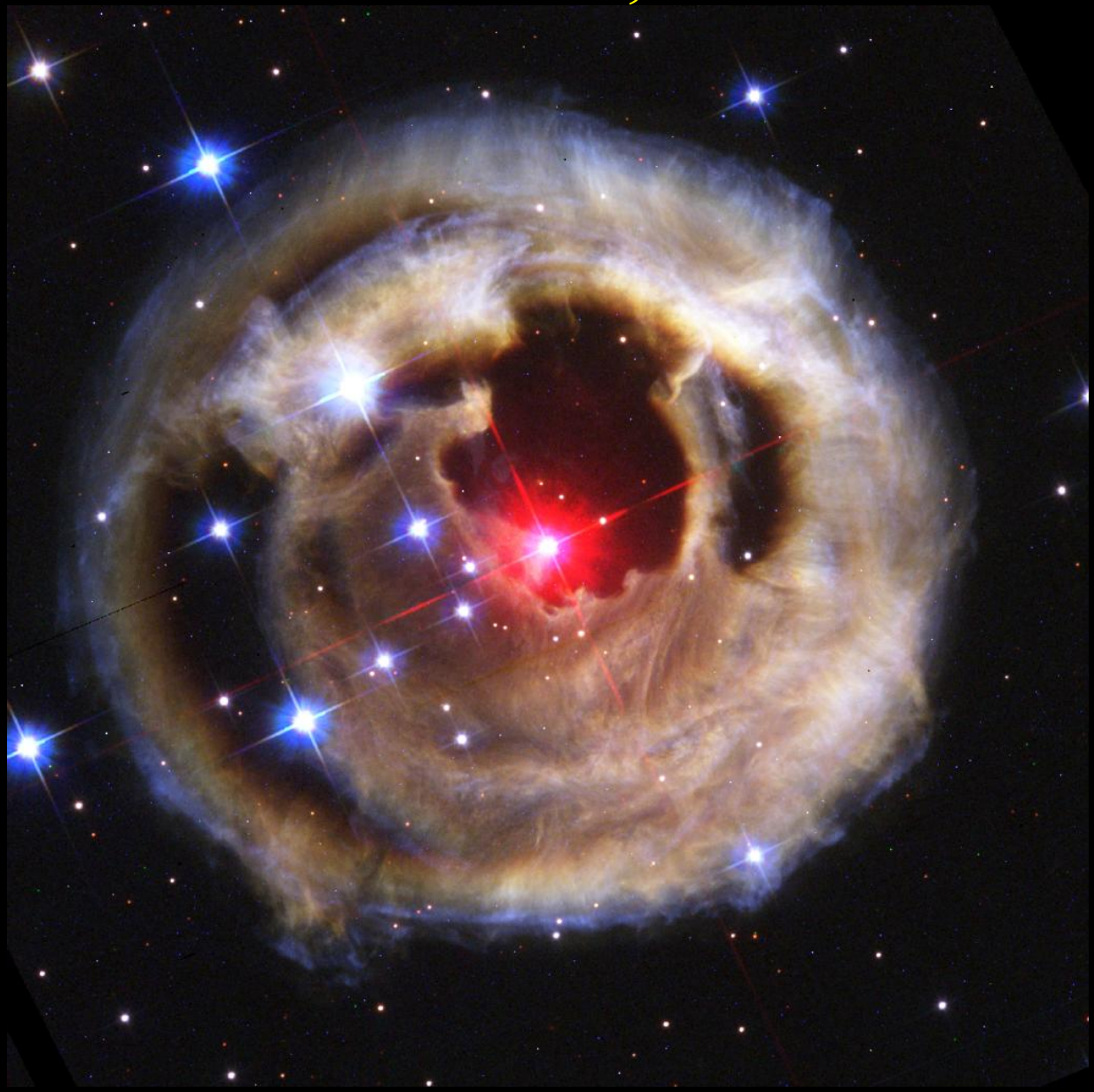
Hubble Space Telescope Observations of V838 Mon Echo

- ACS direct images & imaging polarimetry in 2002, 2004, 2005, 2006
- WFPC2 imaging 2007, 2008, 2009
- Repaired ACS imaging 2009, 2010, 2011

May 20, 2002

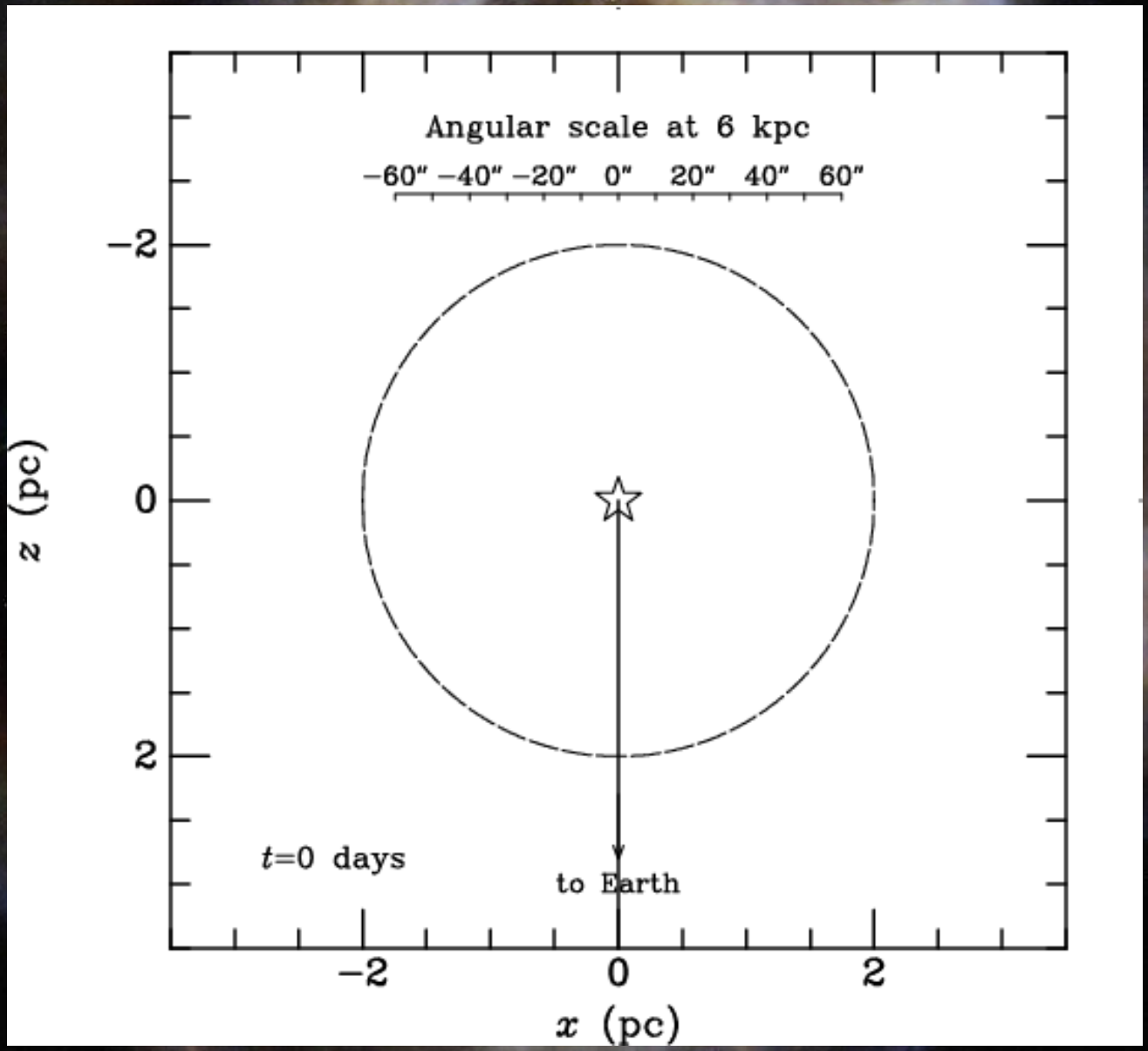
September 2, 2002

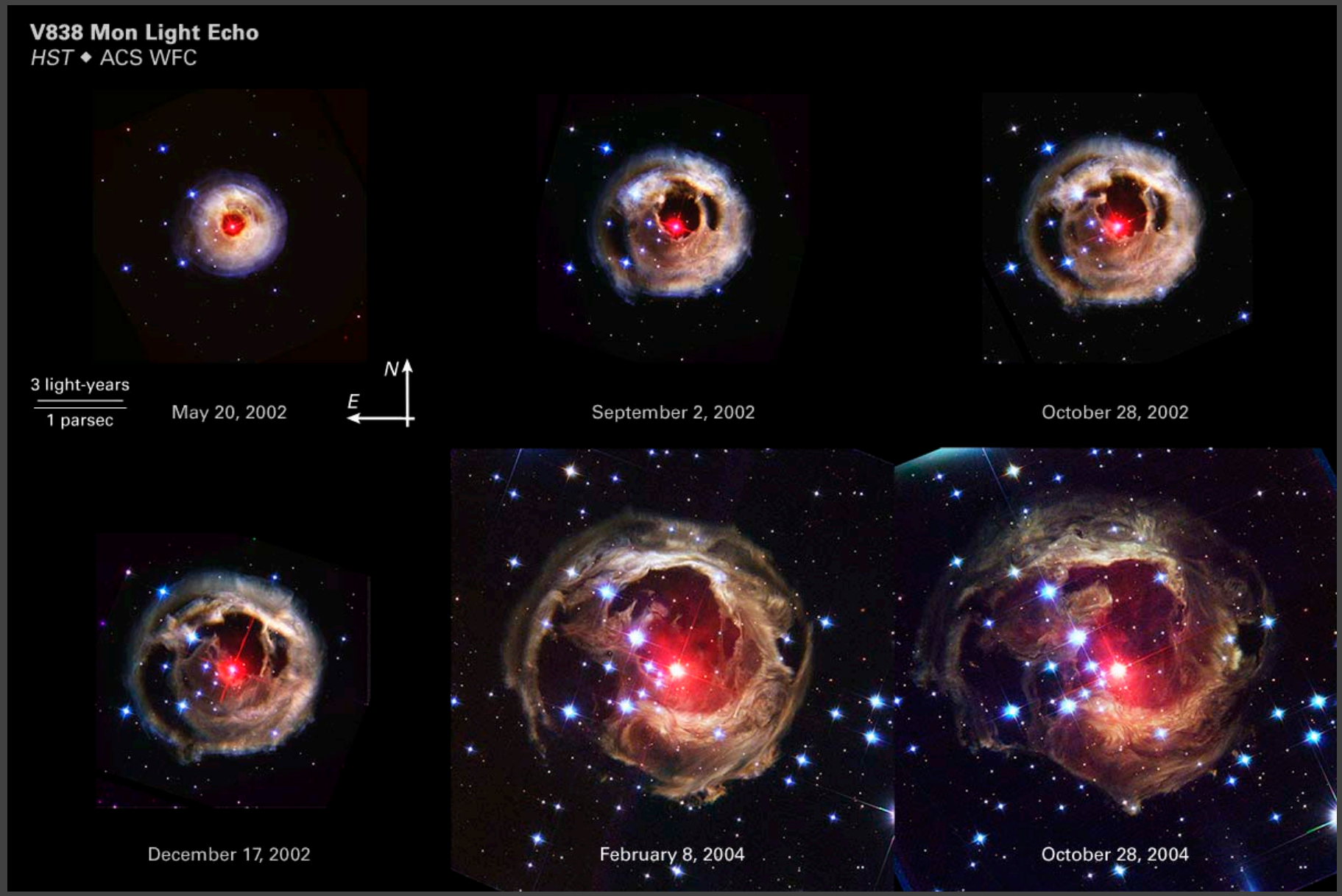
October 28, 2002



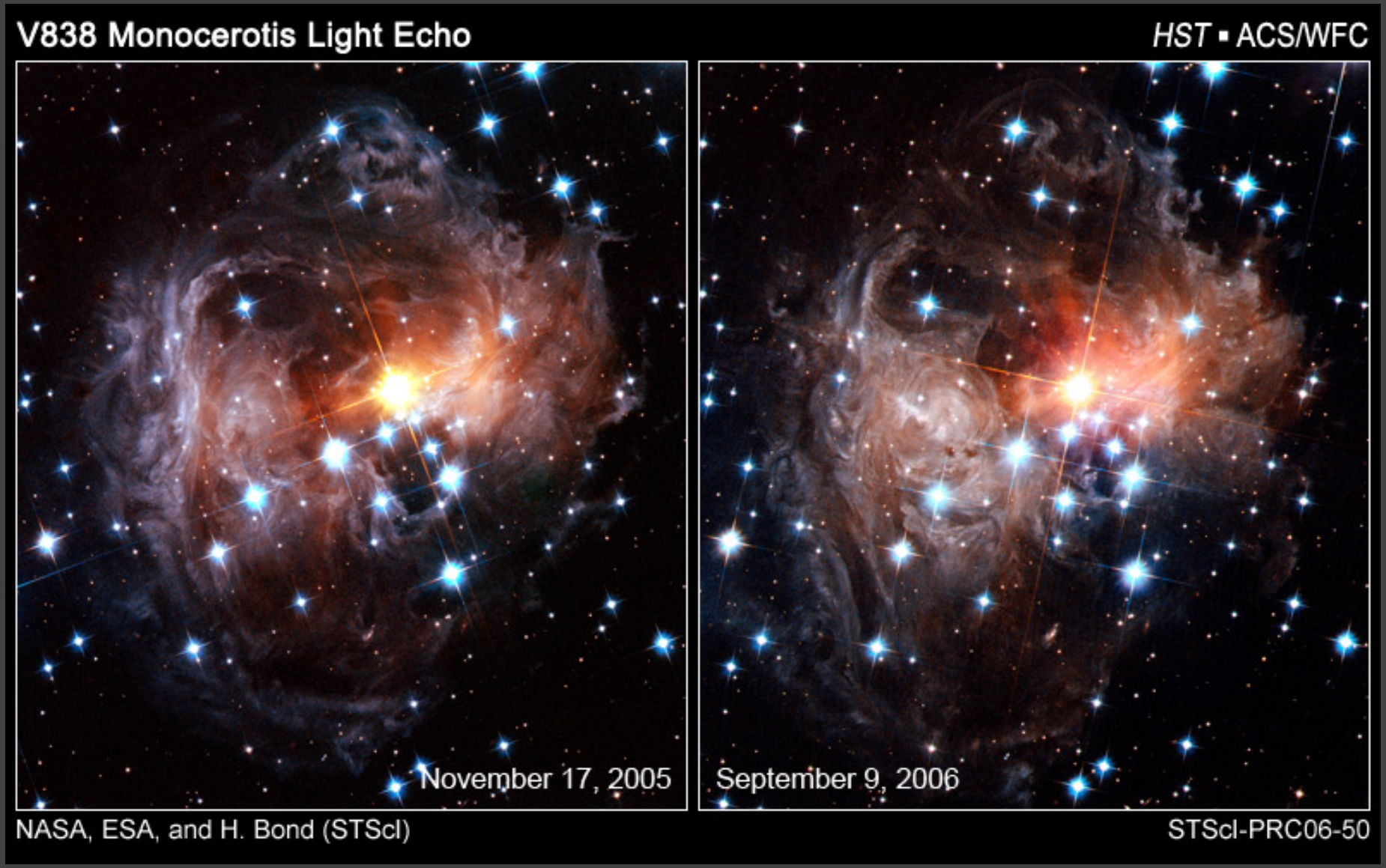
December 17, 2002

Animation (200-day time steps)

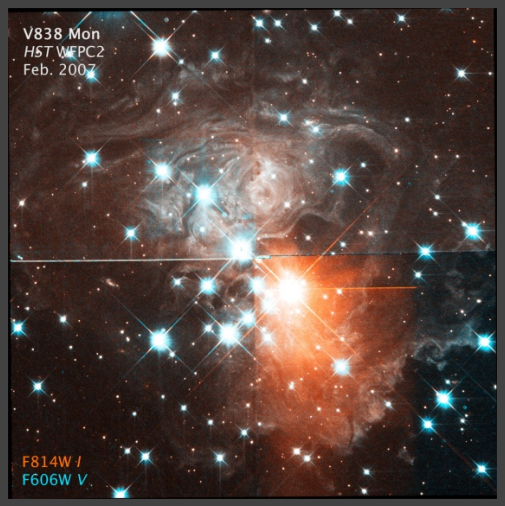



V838 Mon Light Echo
HST ◆ ACS WFC
3 light-years
1 parsec
N
E
May 20, 2002
September 2, 2002
October 28, 2002
December 17, 2002
February 8, 2004
October 28, 2004

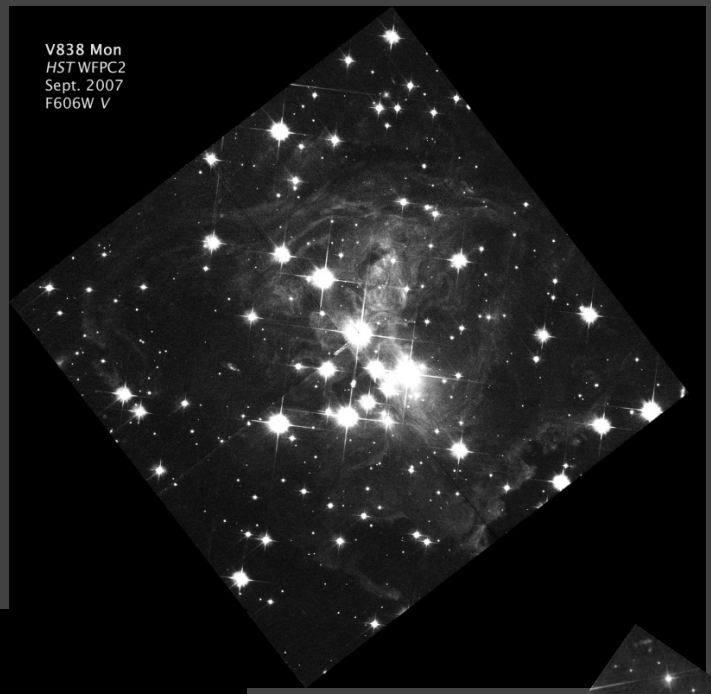
November 2005 & September 2006



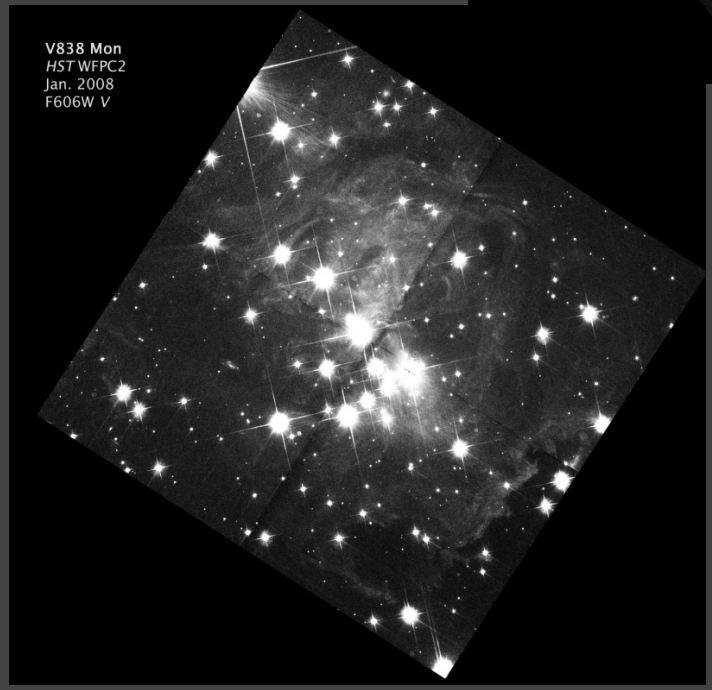
Feb 2007

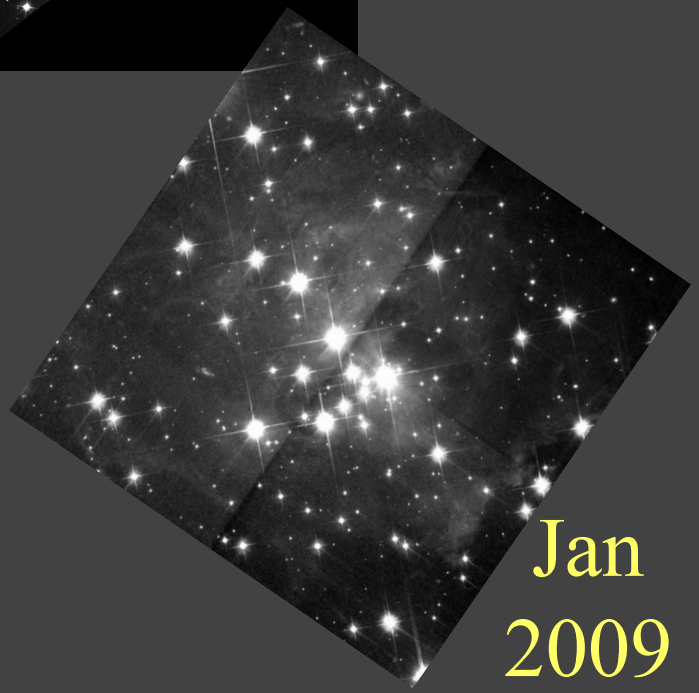


Sep 2007



Jan 2008

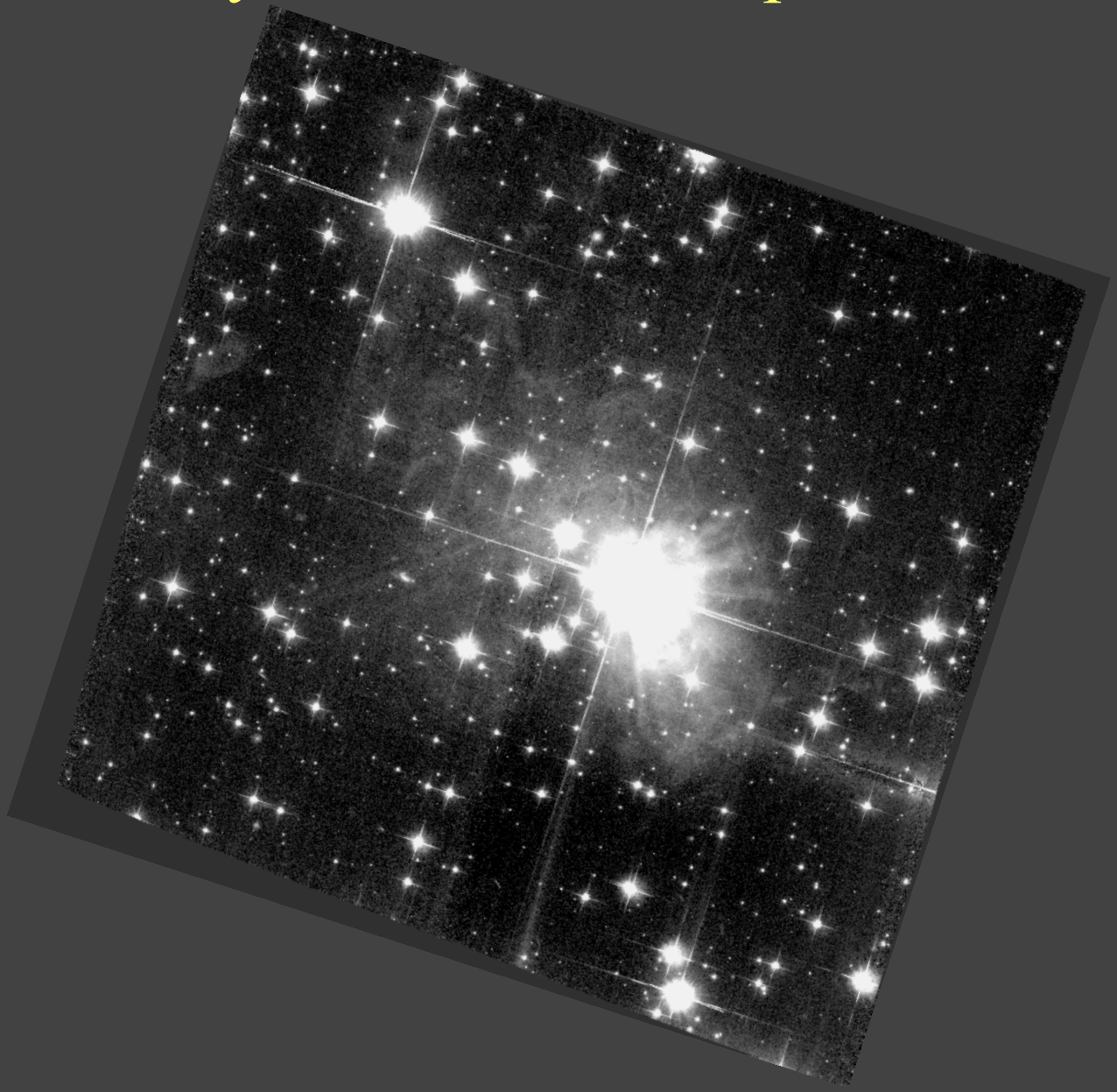




Jan 2009

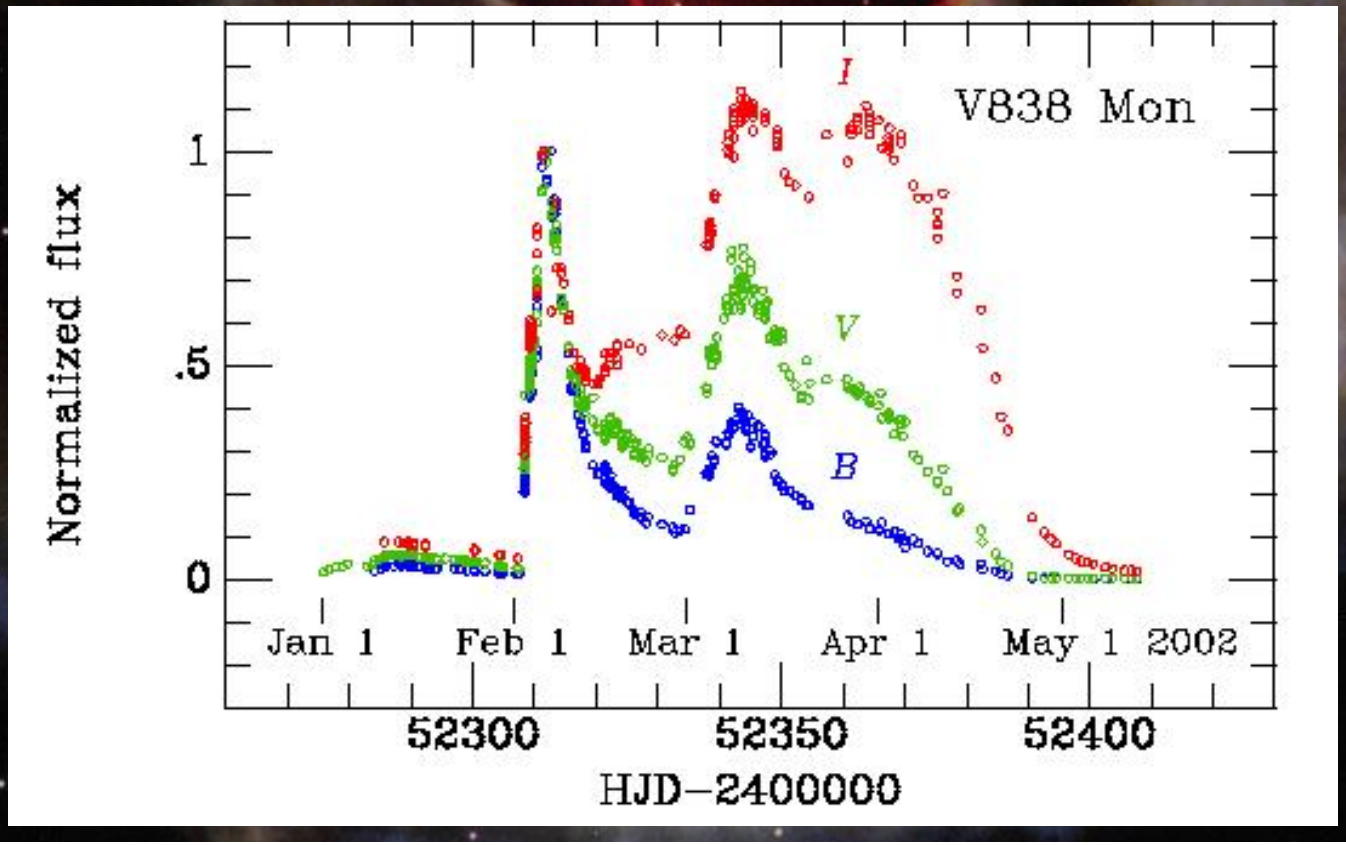
September 28, 2009 with repaired ACS

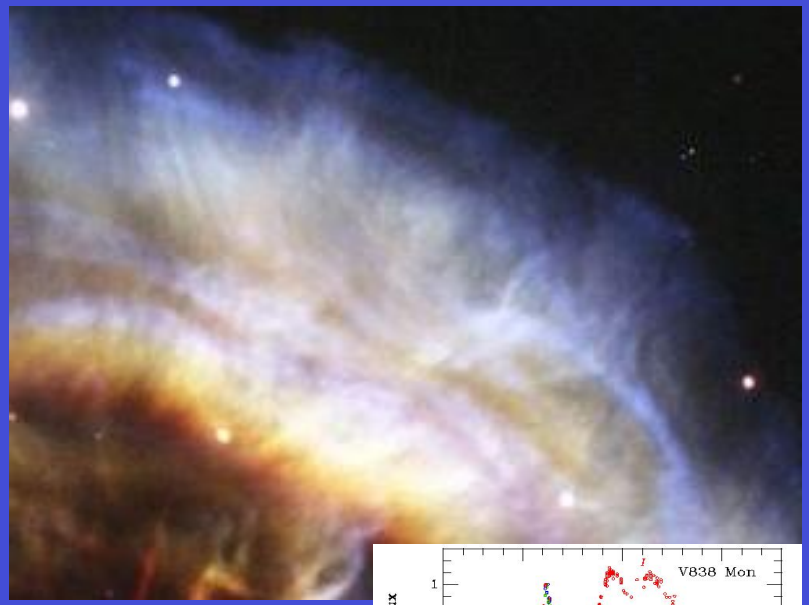
February 20, 2011 with repaired ACS

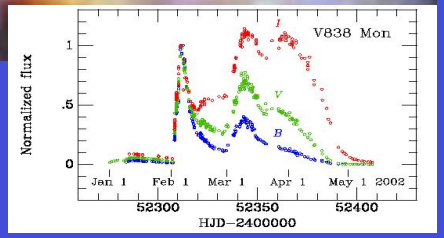


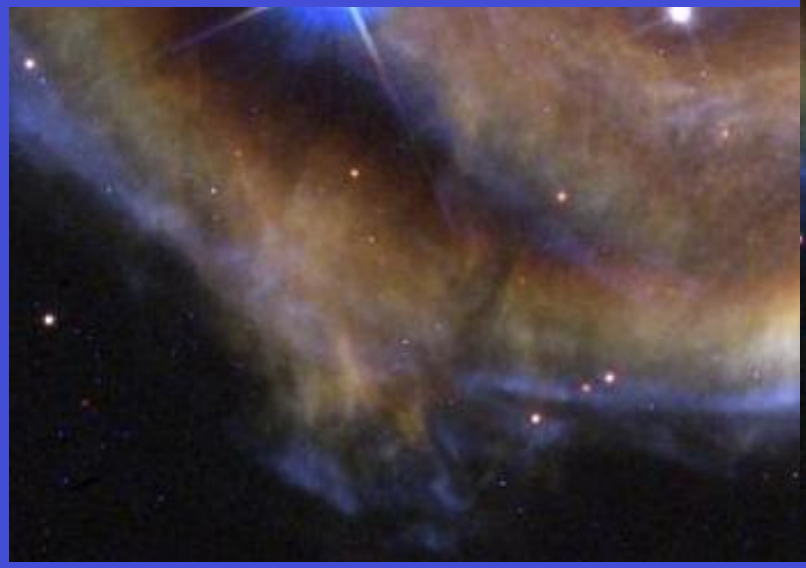
Detailed examination of the images shows numerous replicas of the outburst light curve

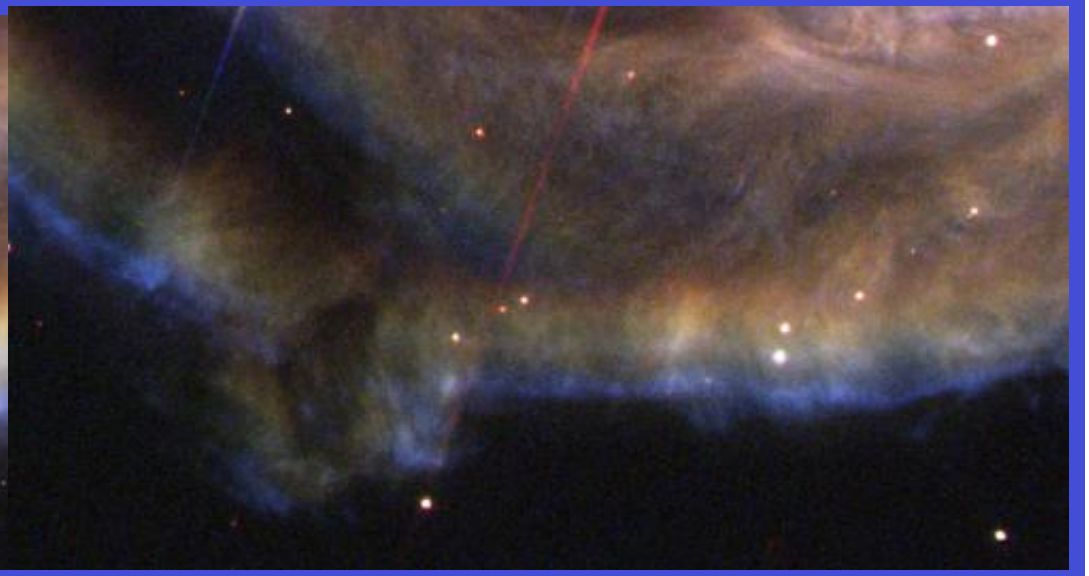
Remember the light curve? Sharp blue peak, dip, broad red plateau:

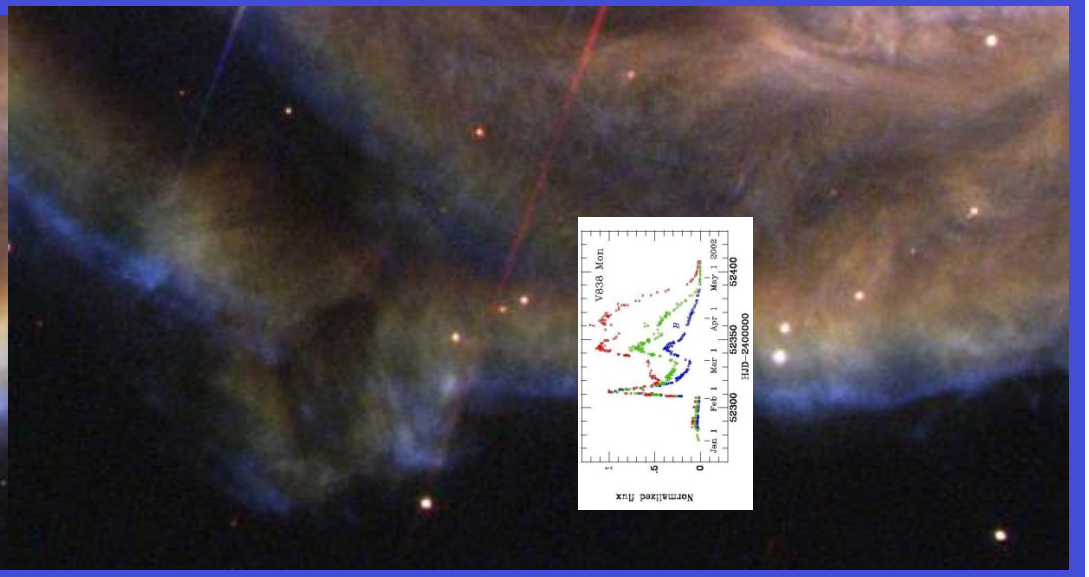




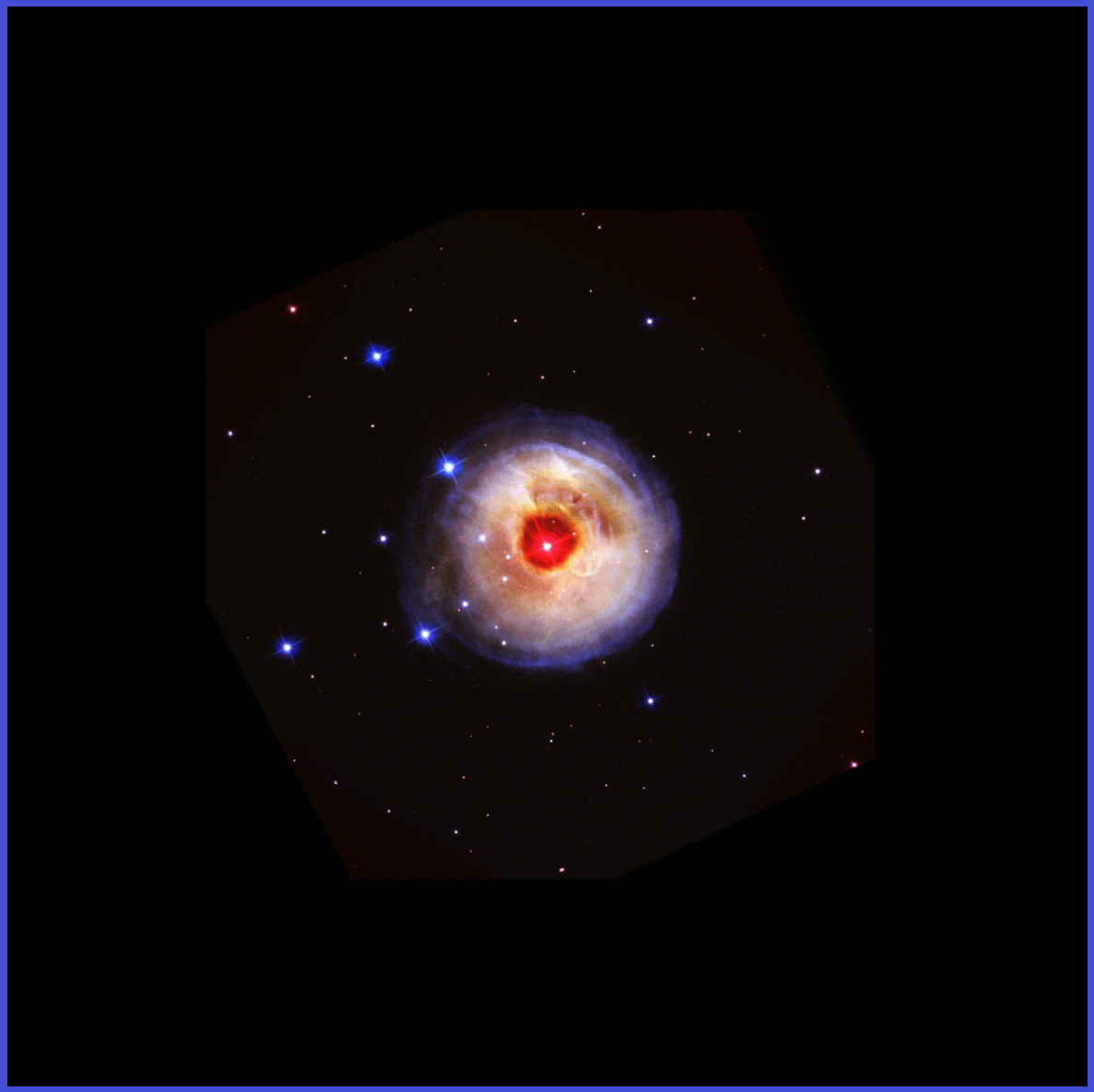

V838 Mon
I
V
B
Normalized flux
1
.5
0
Jan 1
Feb 1
Mar 1
Apr 1
May 1 2002
52300
52350
52400
HJD−2400000



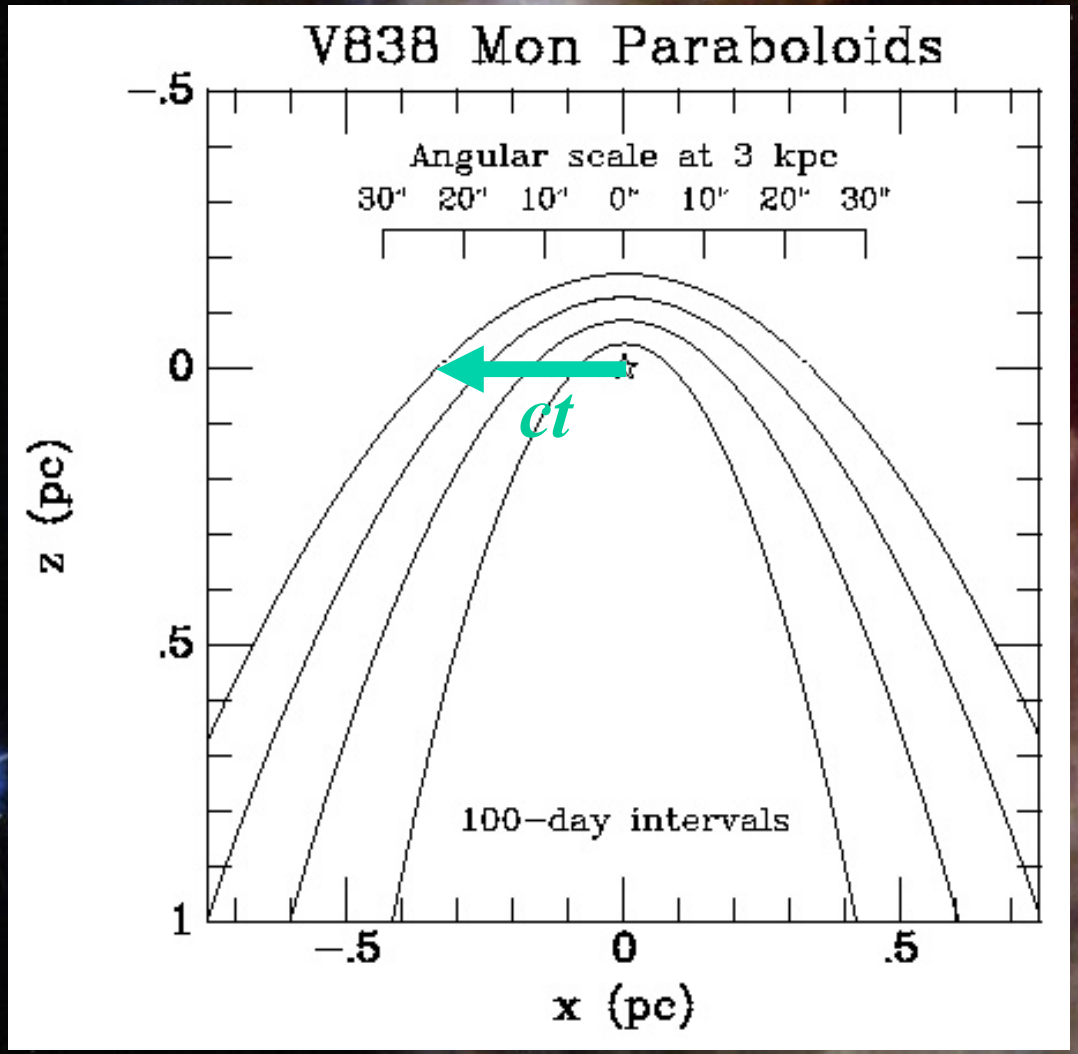



V838 Mon
B
V
I
Normalized Flux
1
.5
0
Jan 1
Feb 1
Mar 1
Apr 1
May 1 2002
52300
52350
52400
HJD-2400000

V838 Mon: the Movie (2002-6)



Distance from Polarimetry



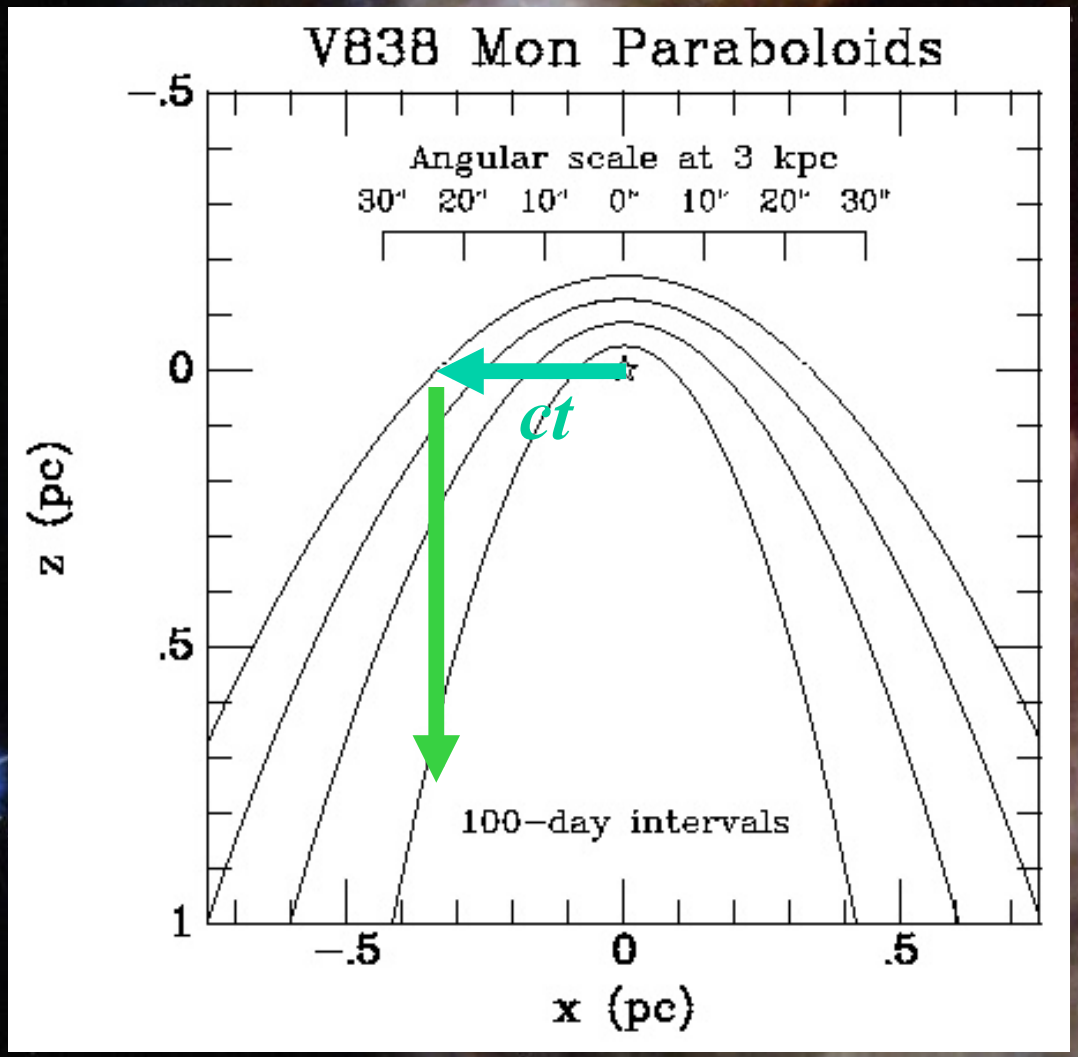
Maximum linear polarization occurs for 90° scattering.

This dust lies at $x = ct$.

The corresponding angular separation from the star gives d.

(Sparks 1994)

Distance from Polarin



M
p
90º scattering.

This dust lies at $x = ct$.

The corresponding angular separation from the star gives d.

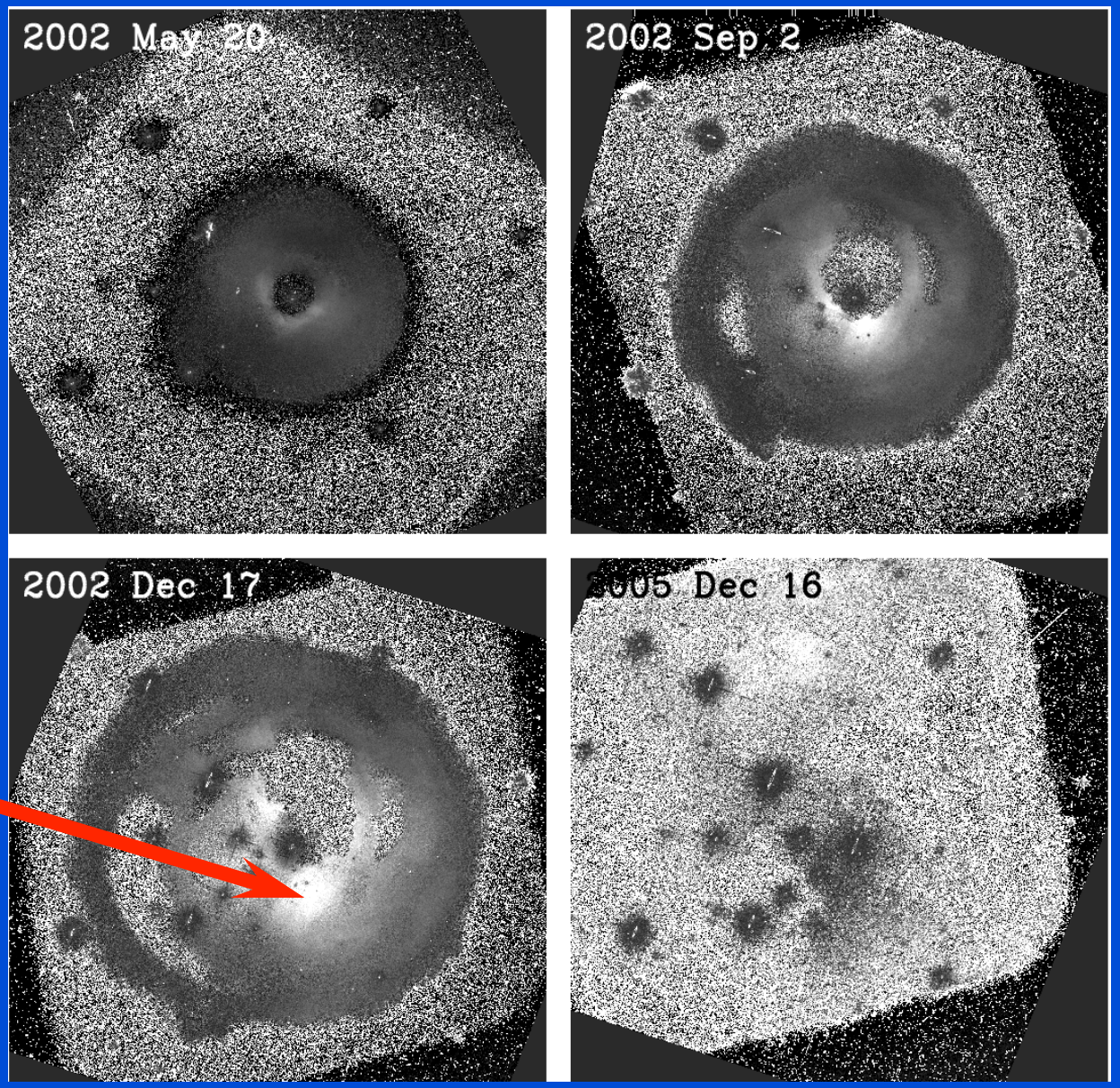
(Sparks 1994)

Polarimetric Distance

Percent-linear-polarization images

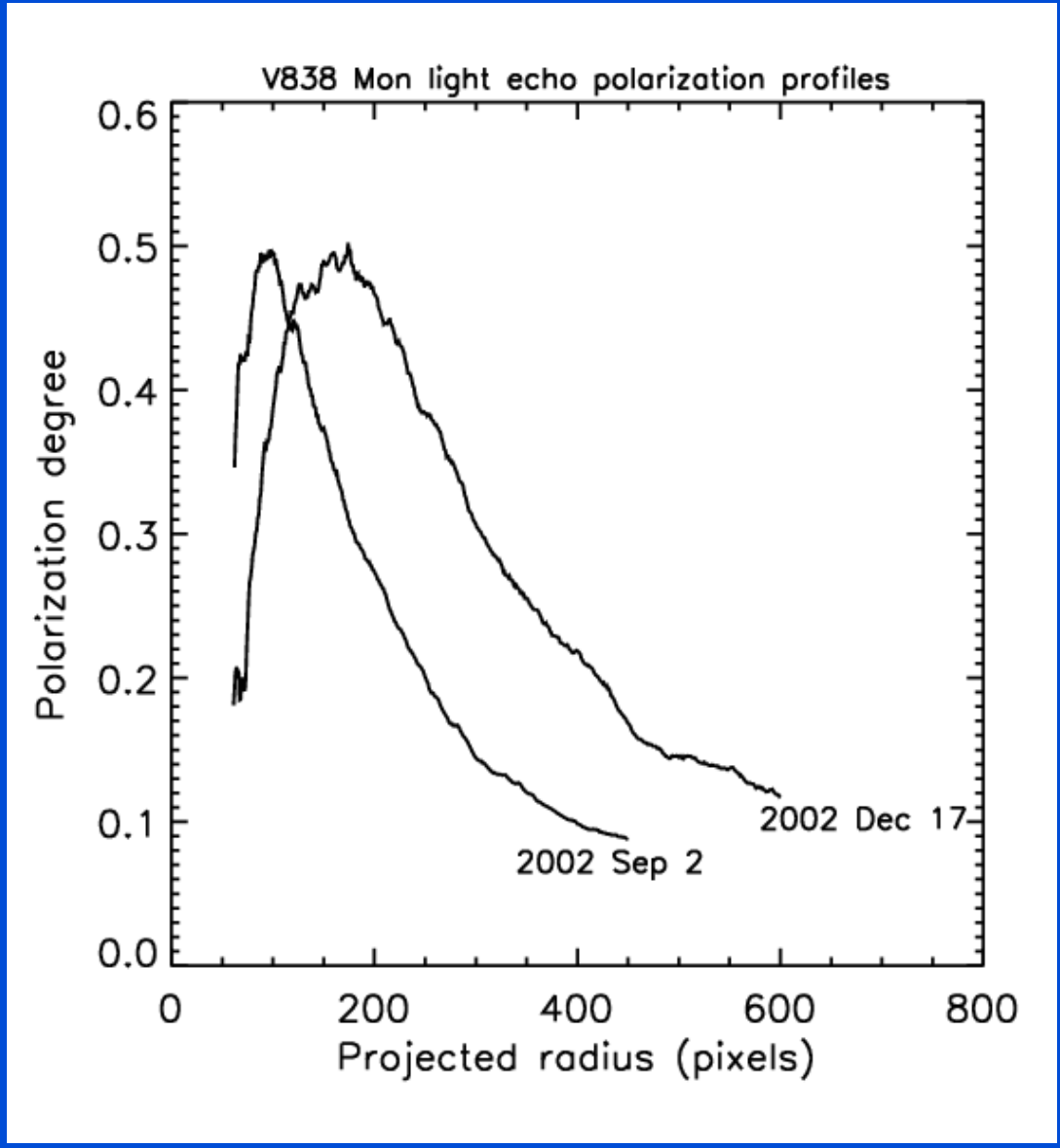
$(Q^2+U^2)^{1/2}/I$

50% linear polarization!



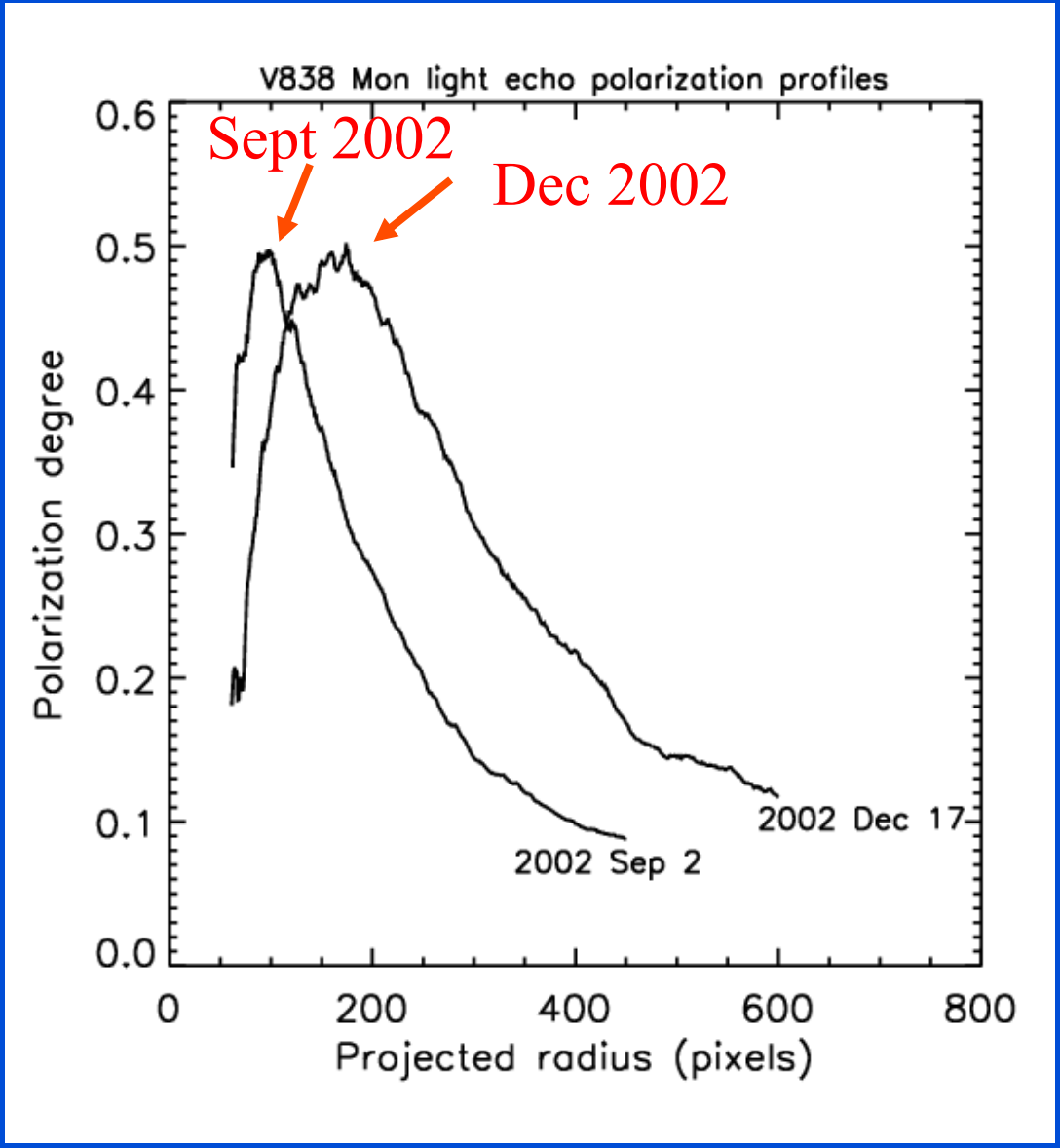
Polarimetric Distance

Azimuthally averaged linear polarization



Polarimetric Distance

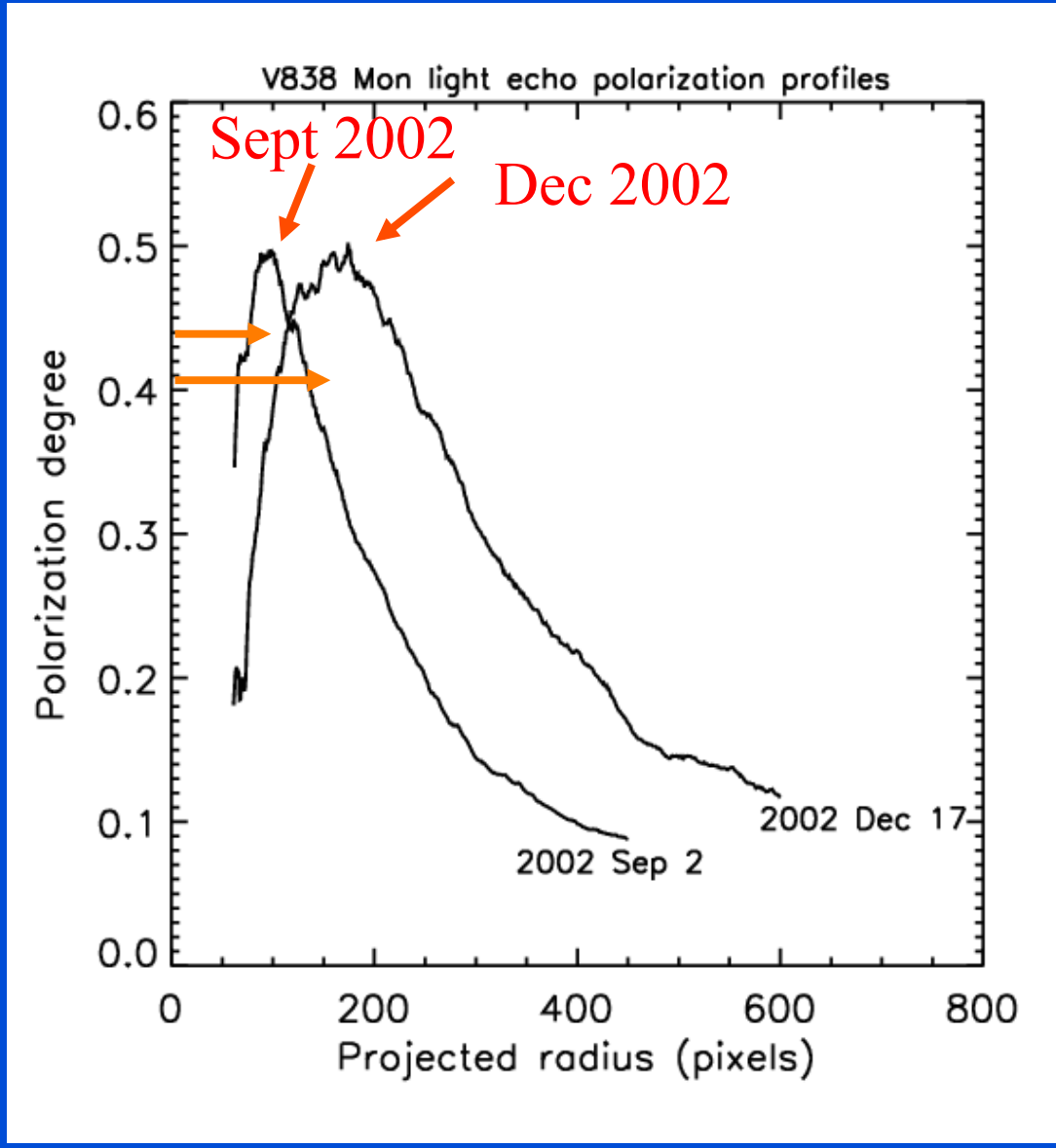
Azimuthally averaged linear polarization



Polarimetric Distance

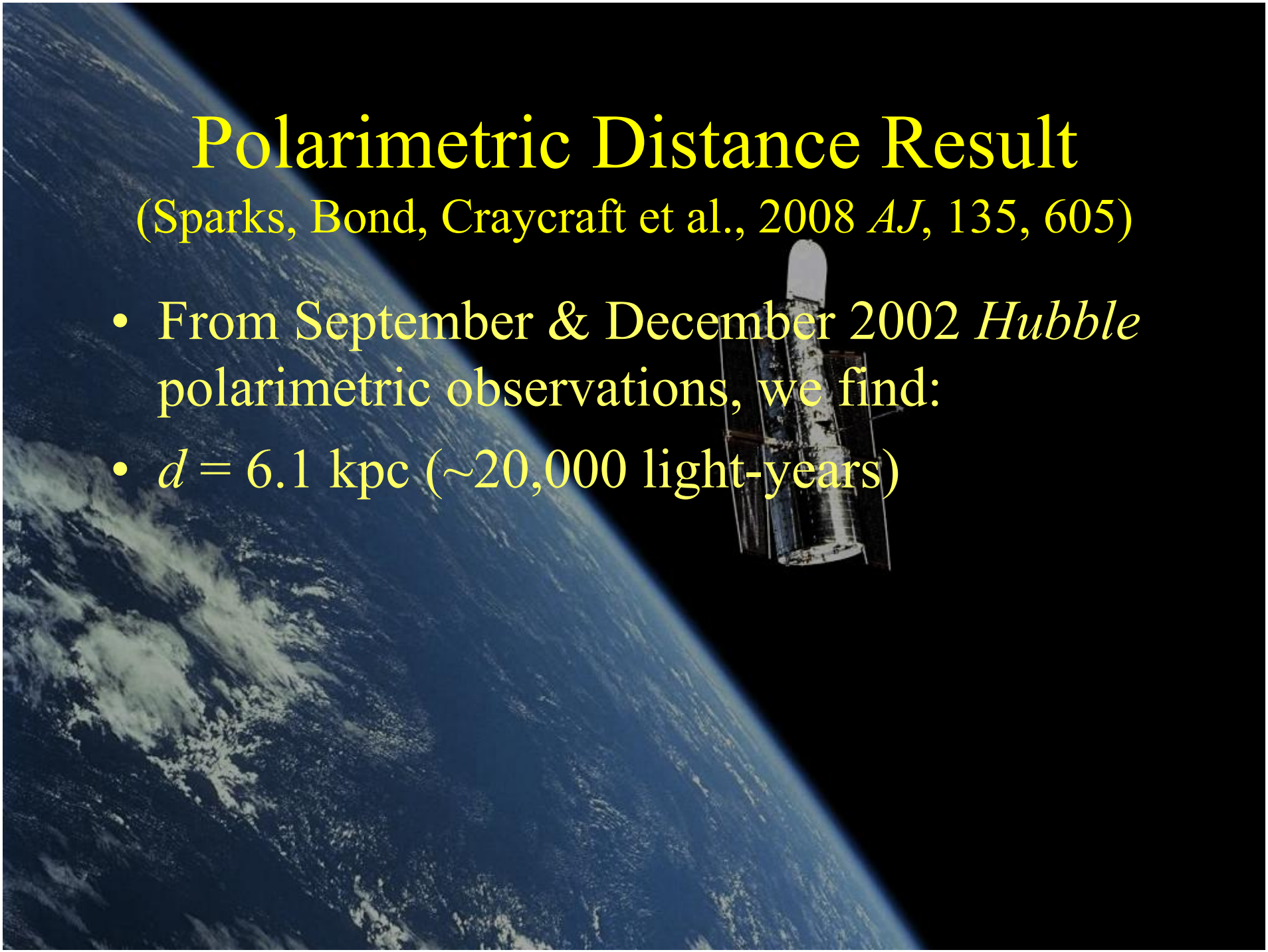
Arrow lengths proportional to time since explosion

Setting angular ring radii to *ct* yields *d*



Polarimetric Distance Result

(Sparks, Bond, Craycraft et al., 2008 *AJ*, 135, 605)

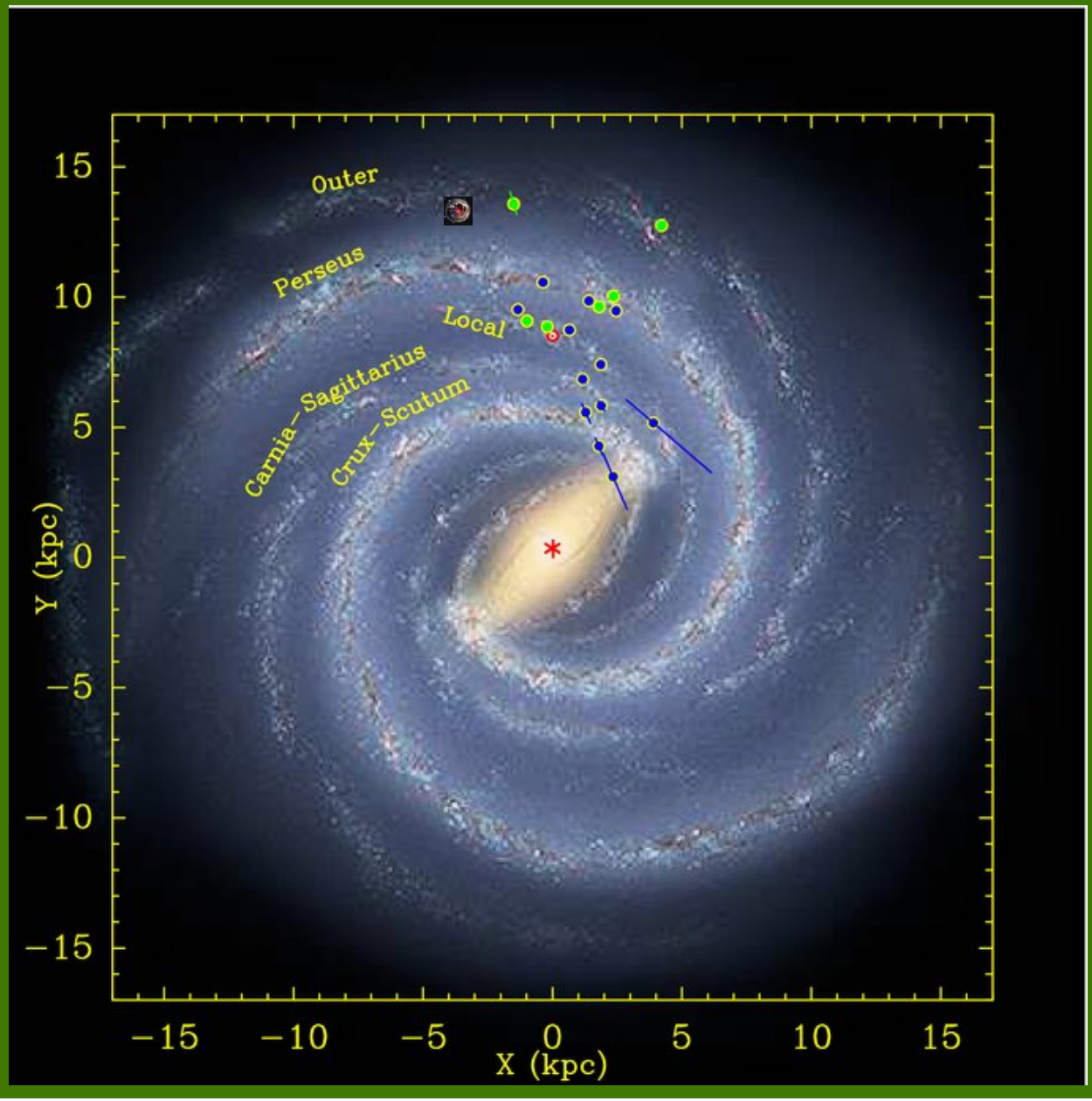


- From September & December 2002 *Hubble* polarimetric observations, we find:
- d = 6.1 kpc (~20,000 light-years)

Implications

- At a distance of 6.1 kpc—
- —V838 Mon is located on ***outer fringes*** of Milky Way
- —V838 Mon was ***extremely luminous*** during its outburst

Location in Milky Way



Red dot: Sun.
Red star: Galactic center
Filled circles: distances from trig parallaxes of methanol (blue) & H_2O or SiO masers (green) from Reid et al. *ApJ* 2009.
Background: artist's conception of modern Galactic structure, based on *Spitzer* observations (R. Hurt, SSC)

The High Luminosity

- For $d \sim 6.1$ kpc, absolute visual magnitude of V838 Mon was $M_V \sim -9.8$
  - 600,000 times brighter than the Sun!
- One of the brightest stars in the entire Milky Way (temporarily)
  - brighter than all but the very brightest classical novae
  - but fainter than SN Ia or normal SN II

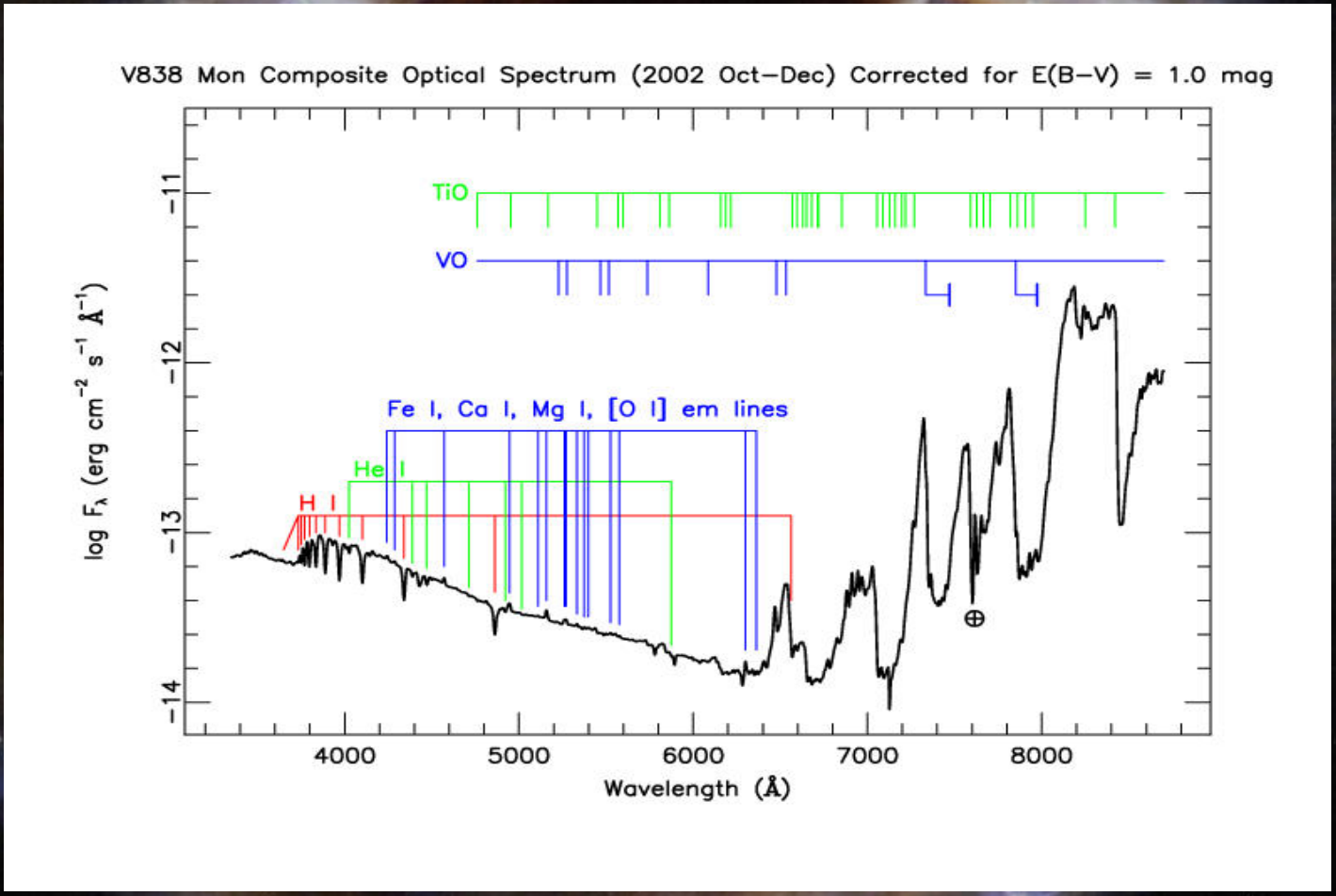
Unprecedented Nature of the V838 Mon Outburst

- Spectroscopy shows it was large and cool—a red supergiant—throughout outburst.
- Very unlike classical nova, which ejects outer layers and rapidly becomes blue.
- V838 Mon is *still* very luminous in the IR, and one of the coolest known stars (type L).

The next amazing fact…

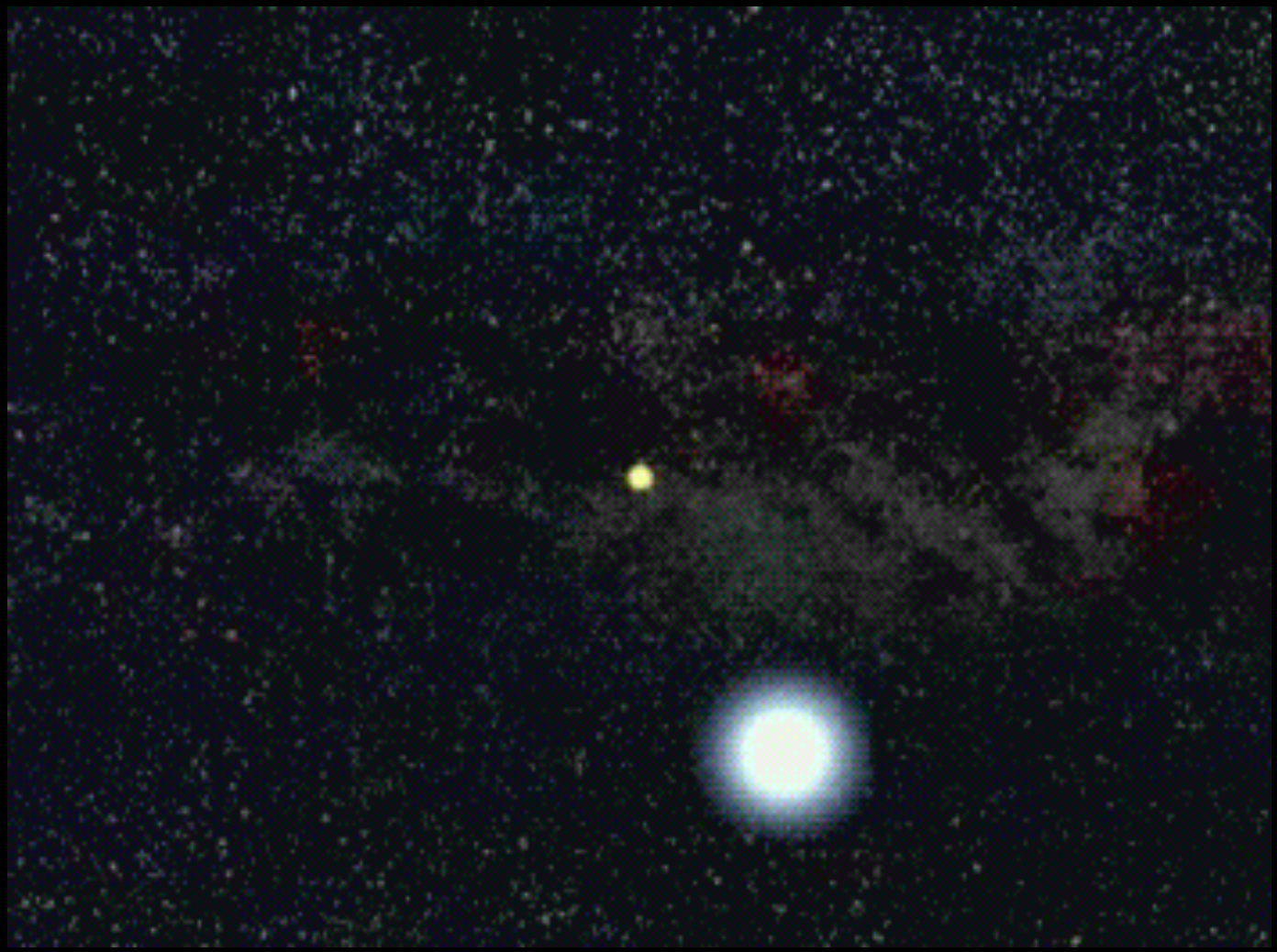
V838 Mon is a binary!

Hot (B3 V) star + the cool outbursting star



MMT spectra, Wagner & Starrfield, fall 2002

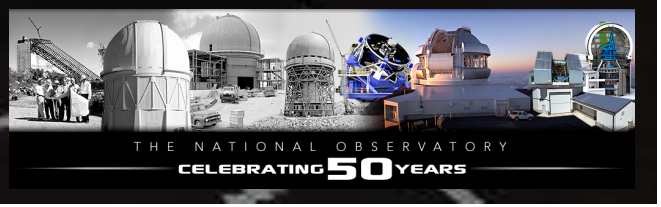
Outburst Cartoon



Greg Bacon, STScI

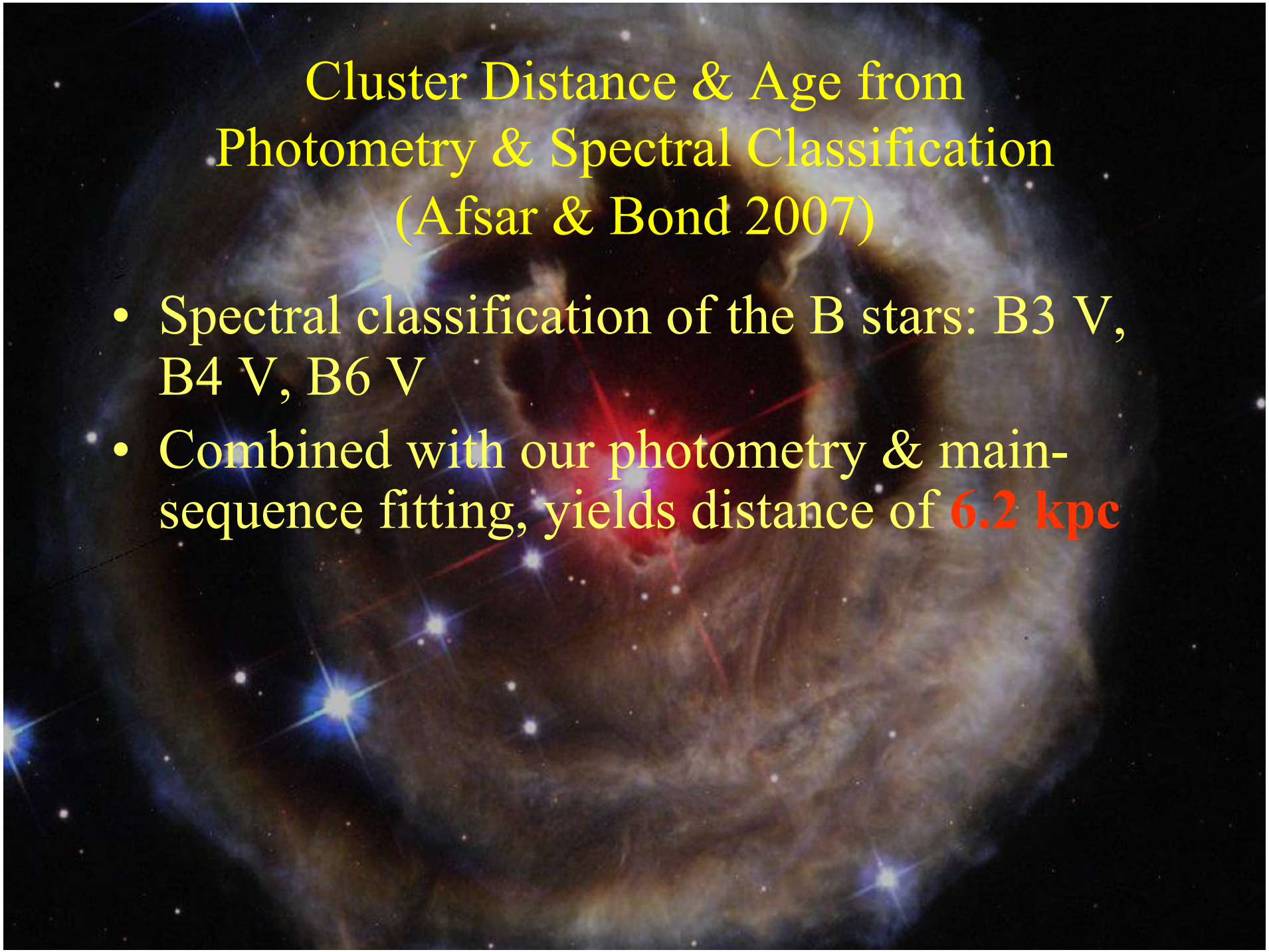
Serendipity

- We monitor the spectrum of V838 Mon with SMARTS 1.5m, Cerro Tololo/NOAO
- By chance, neighboring star happened to lie on the slit, and proved to be B-type!
- Subsequent spectra disclosed 2 further B stars in the vicinity (Afsar & Bond 2007)
- ⇒V838 Mon is in a *young* stellar cluster!



B Stars near V838 Mon

B Stars near V838 Mon



Cluster Distance & Age from Photometry & Spectral Classification (Afsar & Bond 2007)

- Spectral classification of the B stars: B3 V, B4 V, B6 V
- Combined with our photometry & main-sequence fitting, yields distance of **6.2 kpc**

Cluster Distance & Age from Photometry & Spectral Classification (Afsar & Bond 2007)

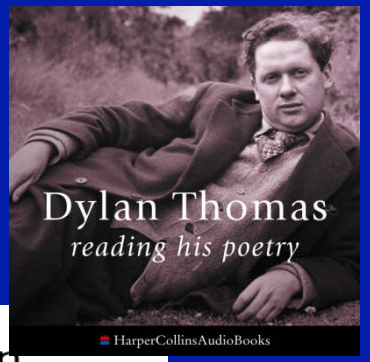
- Spectral classification of the B stars: B3 V, B4 V, B6 V
- Combined with our photometry & main-sequence fitting, yields distance of **6.2 kpc**
- Superb agreement with the *HST*-based polarimetric result of **6.1 kpc !**
- Cluster age < 25 Myr
- Confirms that V838 Mon lies in Outer Arm

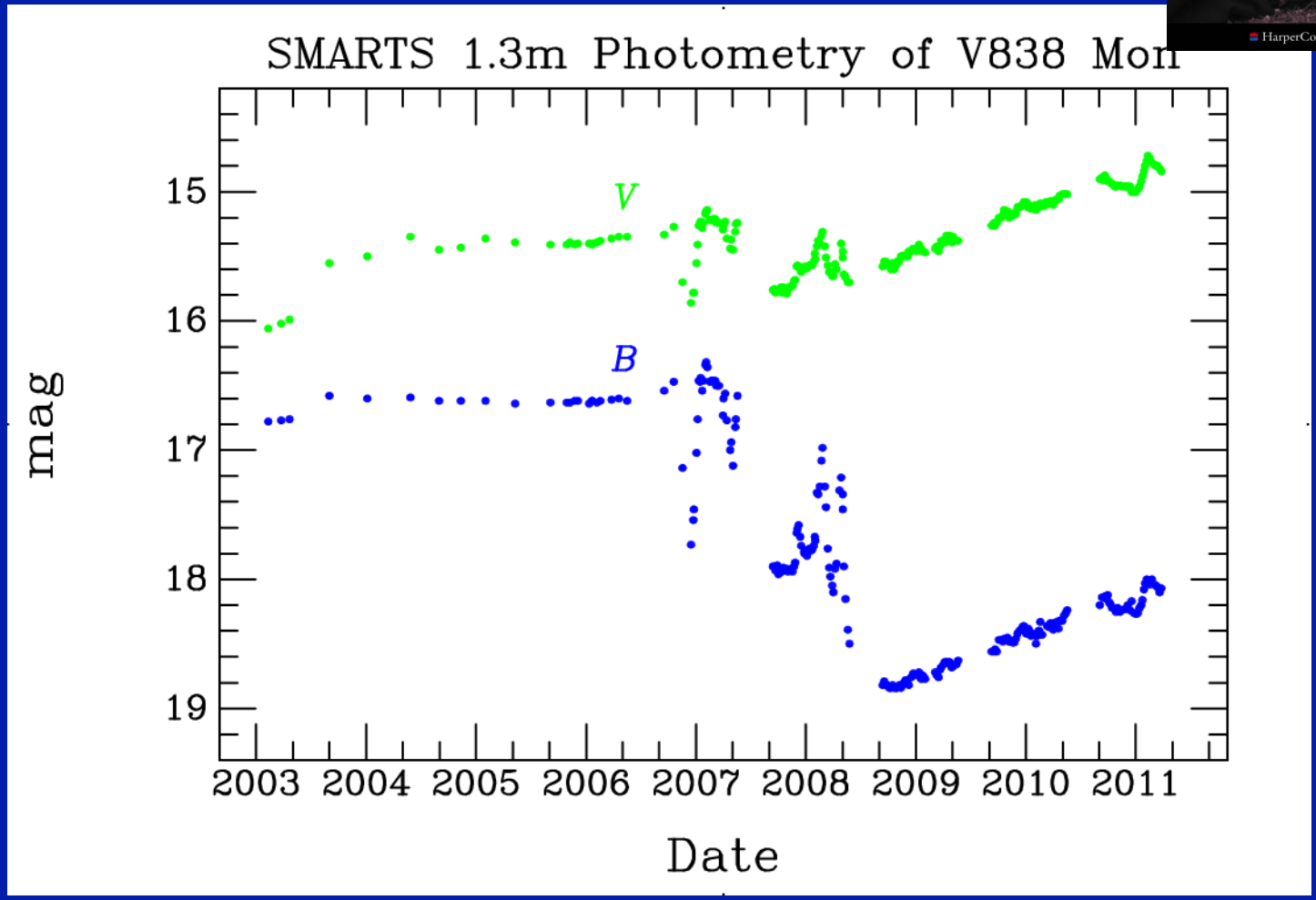
V838 Mon cluster compared with Pleiades

Pleiades cluster moved to 6100 pc

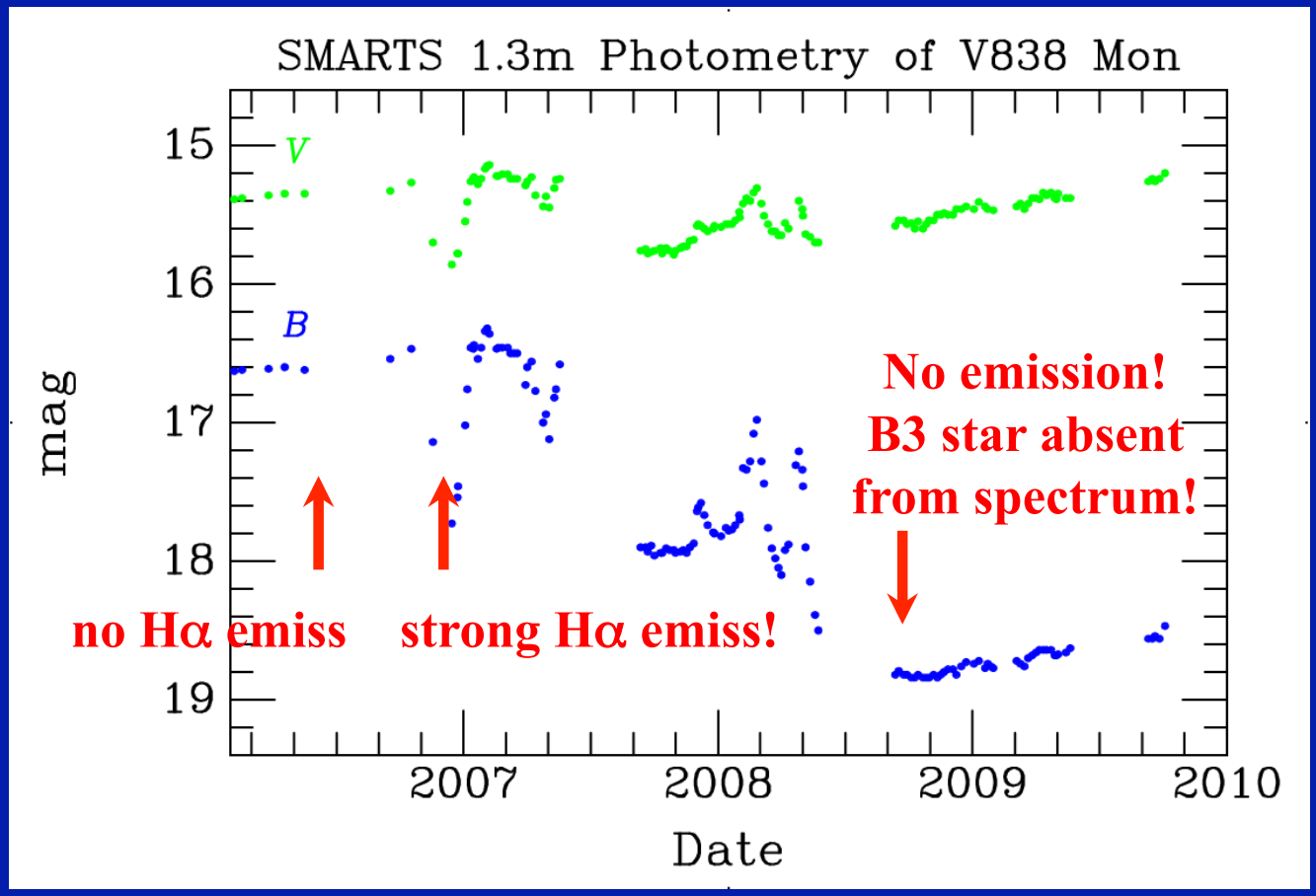
V838 Mon if in Pleiades: ~ –3.5 mag

The Dying of the Light

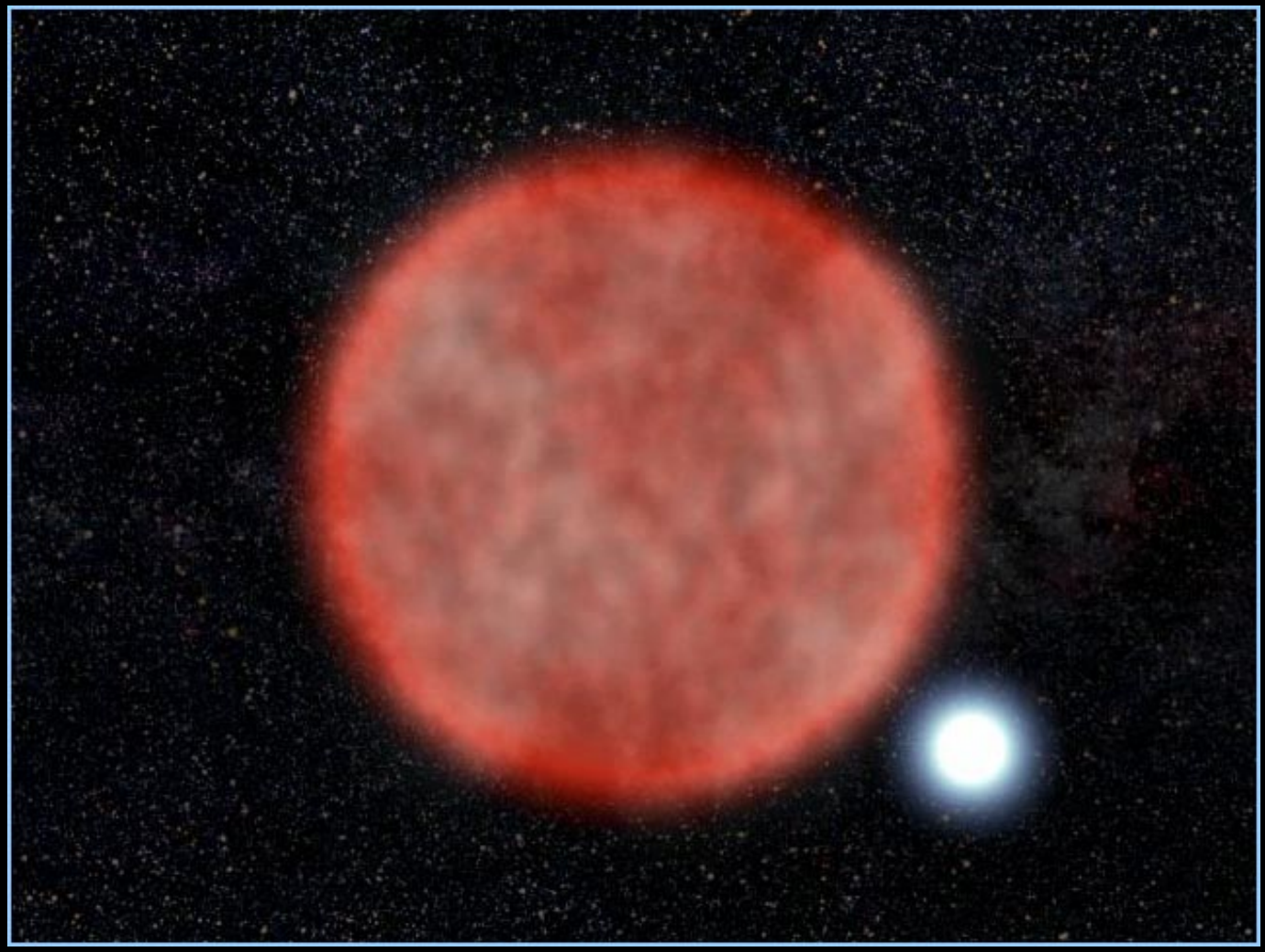




V838 Mon Engulfs Companion

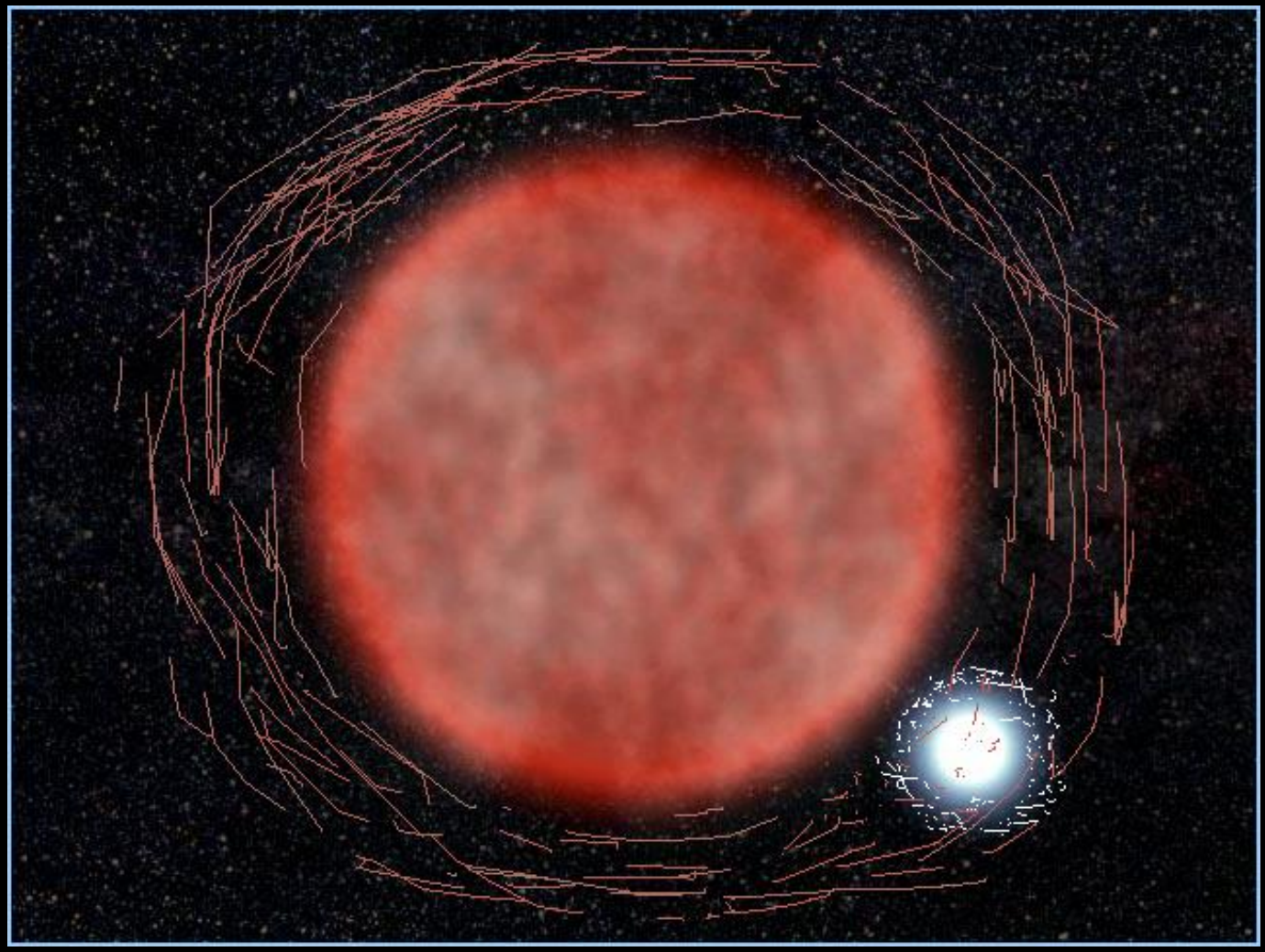


Stellar Cannibalism



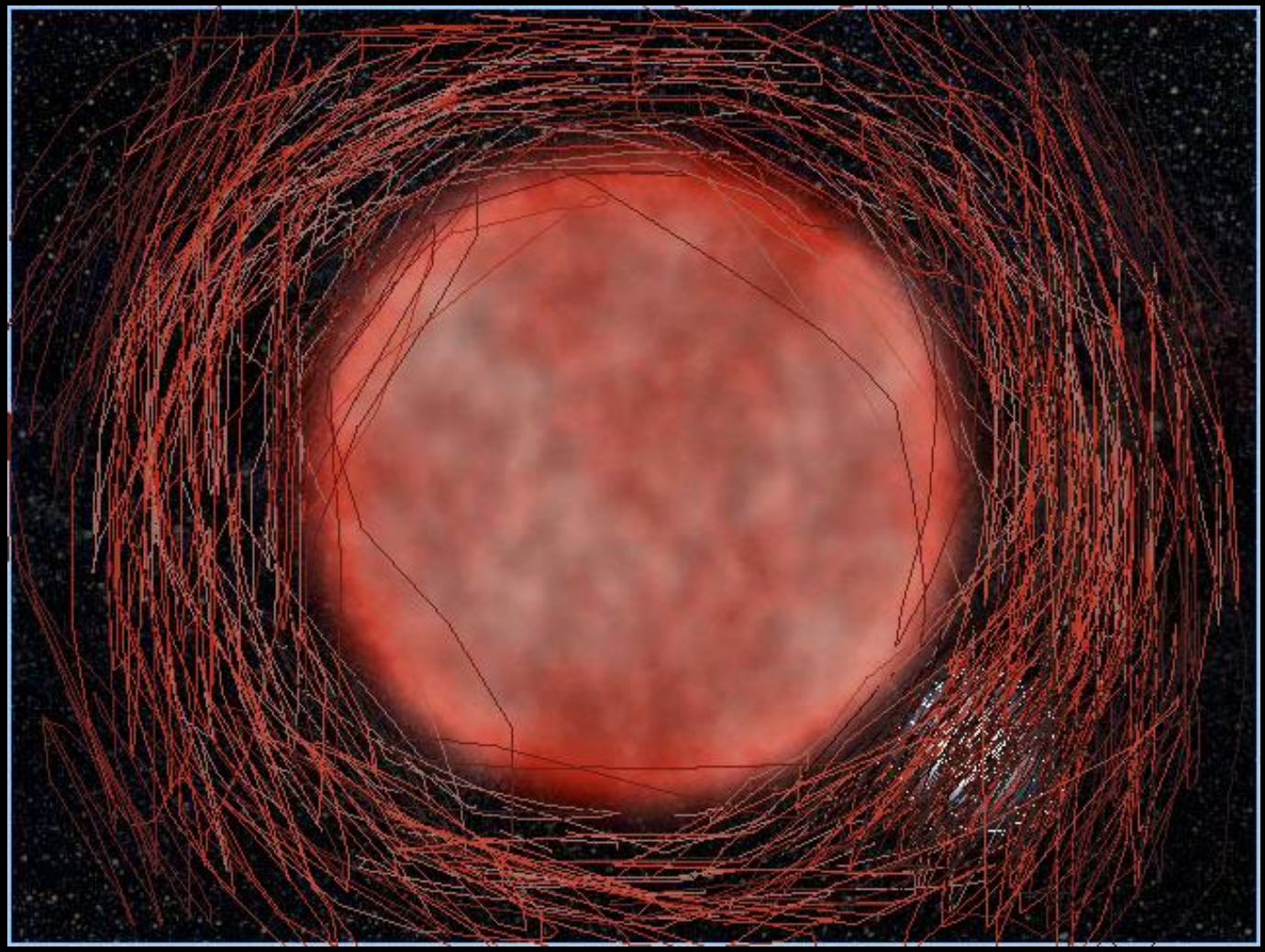
Greg Bacon, STScI

Stellar Cannibalism



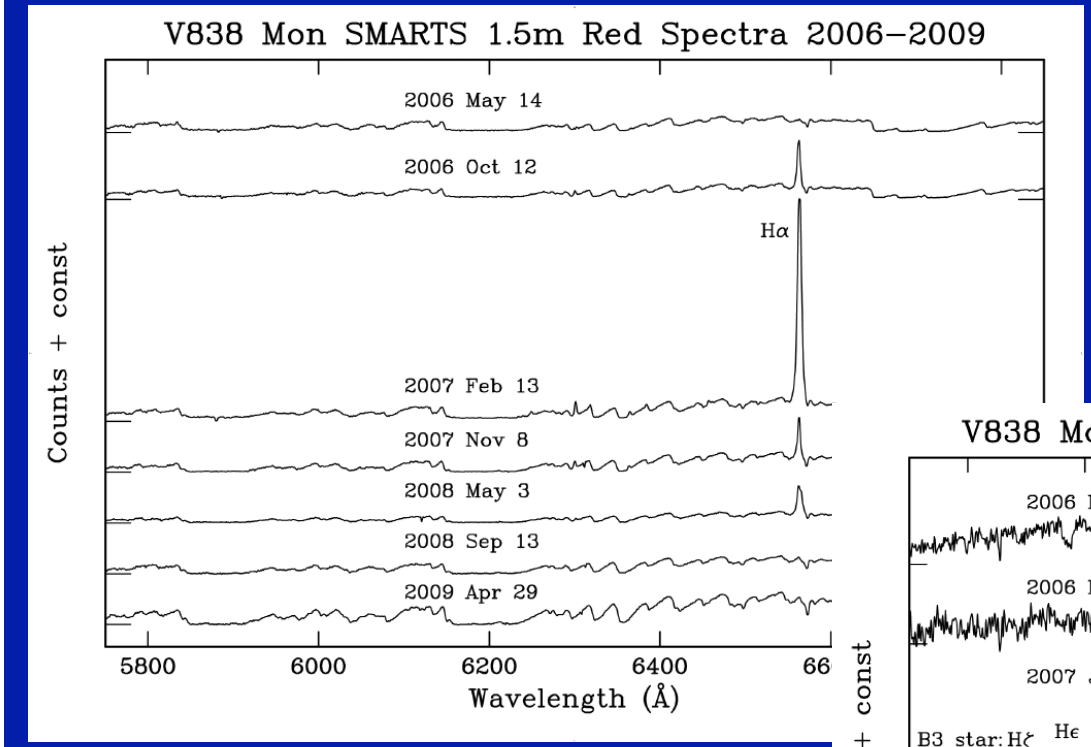
Greg Bacon, STScI; defaced by HEB

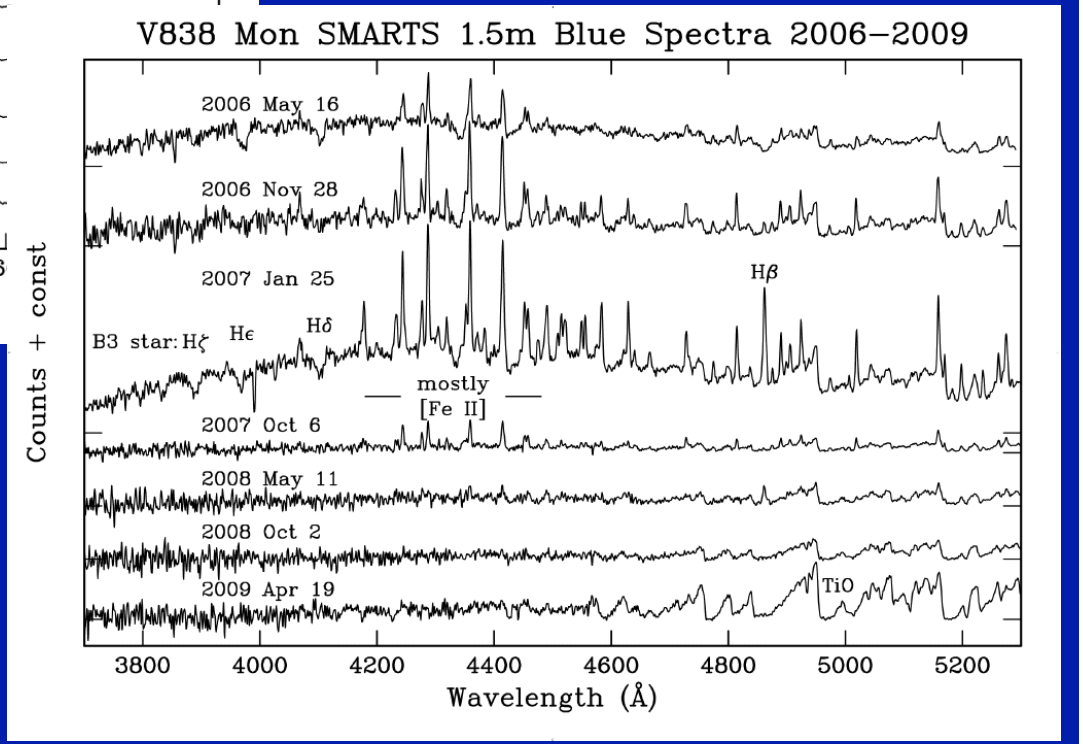
Stellar Cannibalism



Greg Bacon, STScI; defaced by HEB

Spectroscopic Changes





Phase Space of Optical Transients

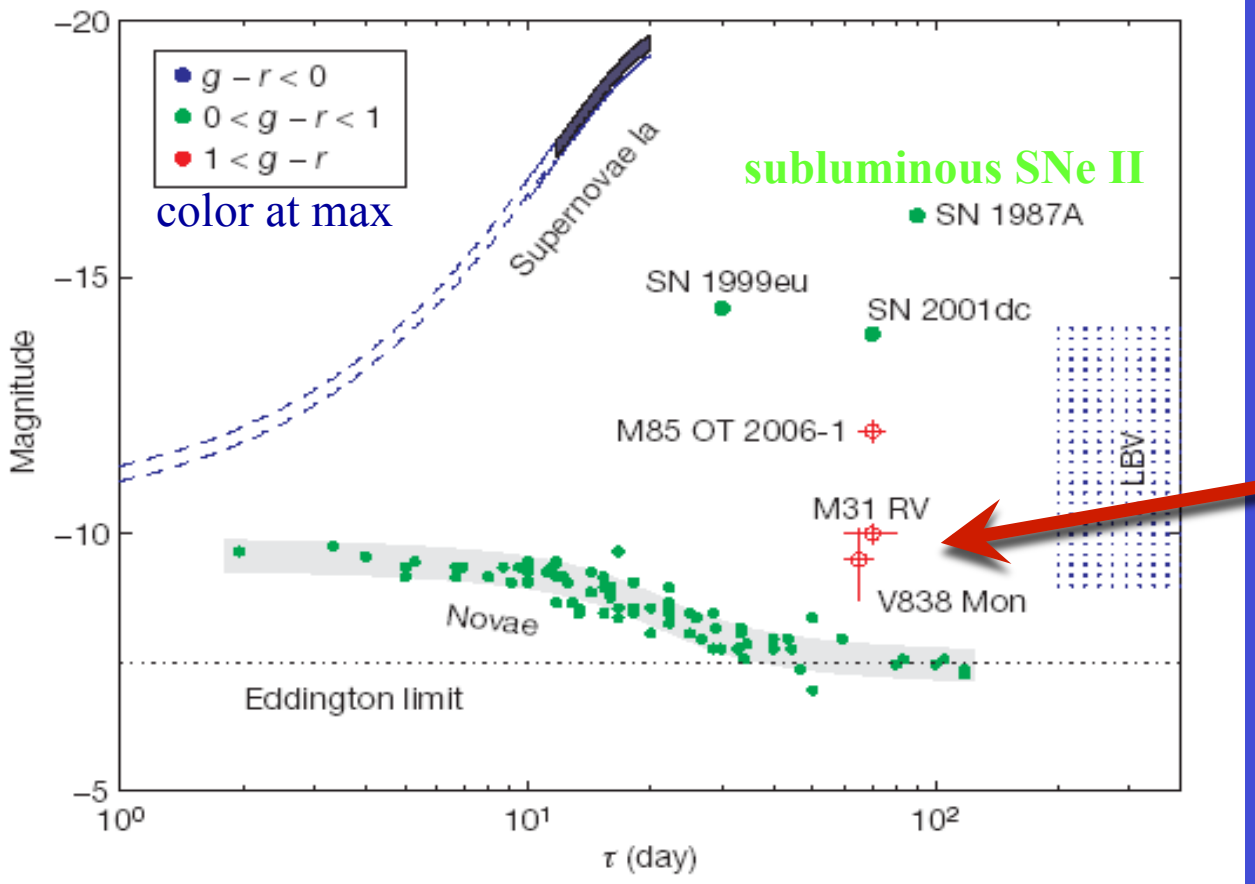
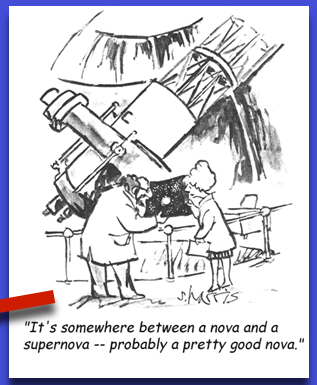


Figure 4 | Phase space of cosmic explosive (supernovae) and eruptive (novae and LBVs) transients. The vertical axis is the peak brightness in the *R* band and the horizontal axis is the duration of the event (τ). Events are



Kulkarni et al.
Nature 2007

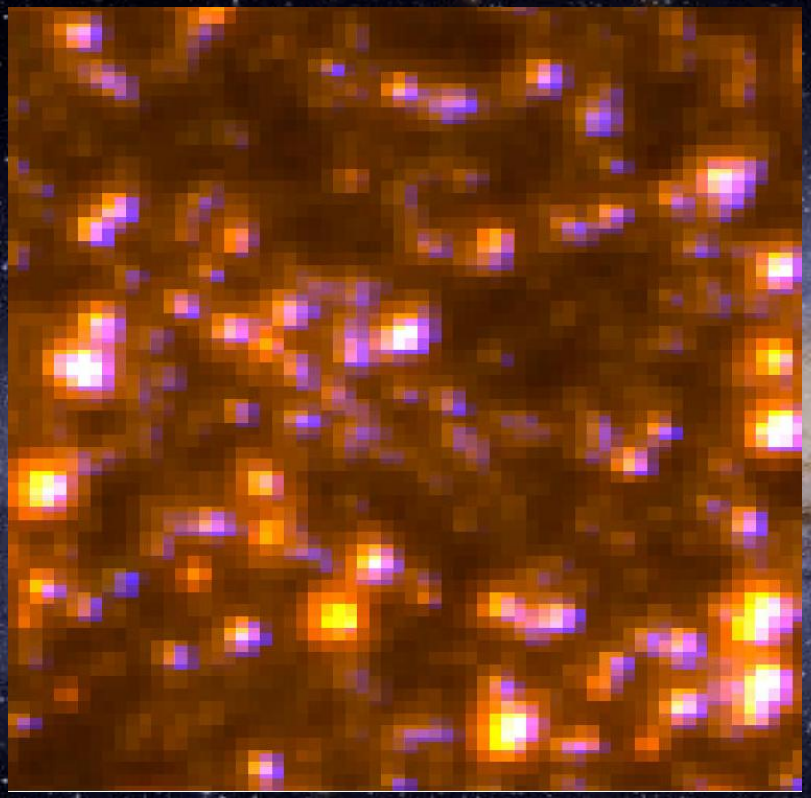
A Few Words about M31 RV

- Erupted 1988 in bulge of Andromeda (3′ from nucleus)
- Reached $M_{bol} \sim -10$
- Remained bright ~3 months
- Cool & red throughout; evolved from M0 to late M spectral type

HST Observations of M31 RV Site

- Deep *HST* images of site were obtained serendipitously in 1999
  - in parallel WFPC2 imaging mode during spectroscopy of M31 nucleus
- Analyzed by Bond & Siegel (AJ, 2006)
- Site located precisely (<1″) using frames (on 9-track tapes) obtained in 1988 by R. Ciardullo showing M31 RV in outburst

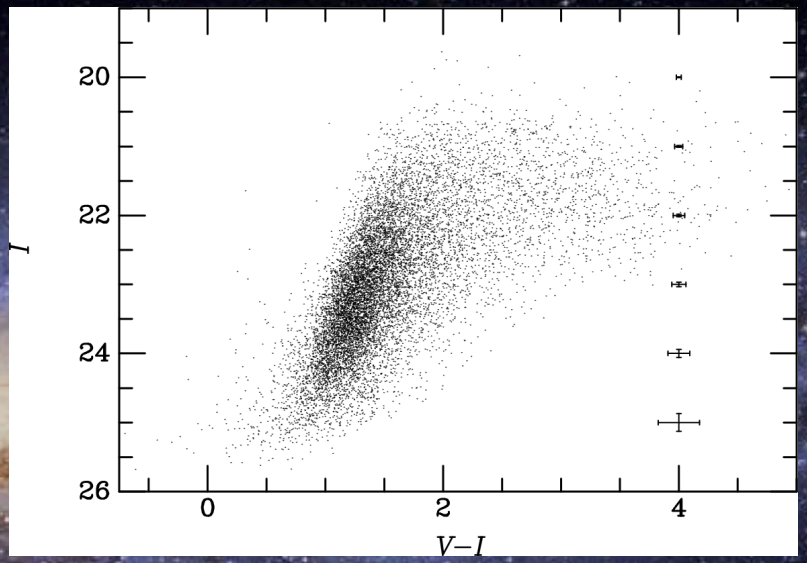
Only normal red giants at M31 RV Site

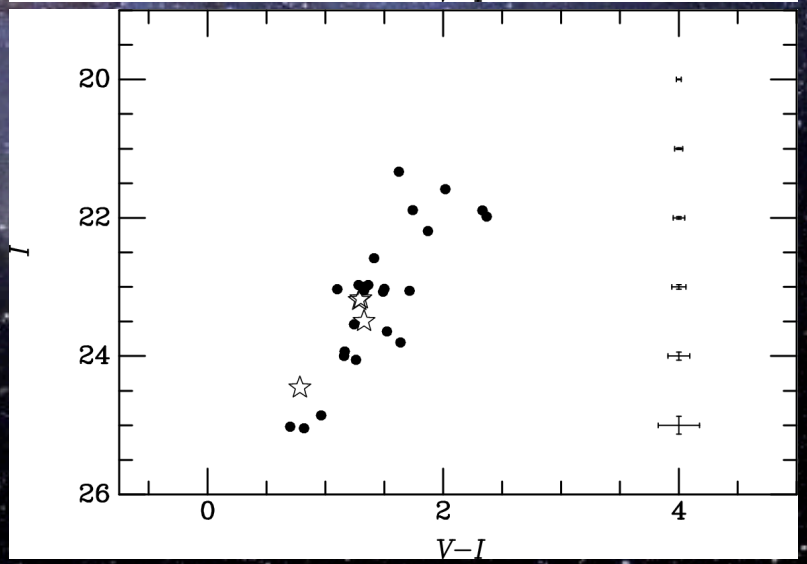


3″ × 3″ *V, I* images

Bond & Siegel 2006

whole chip



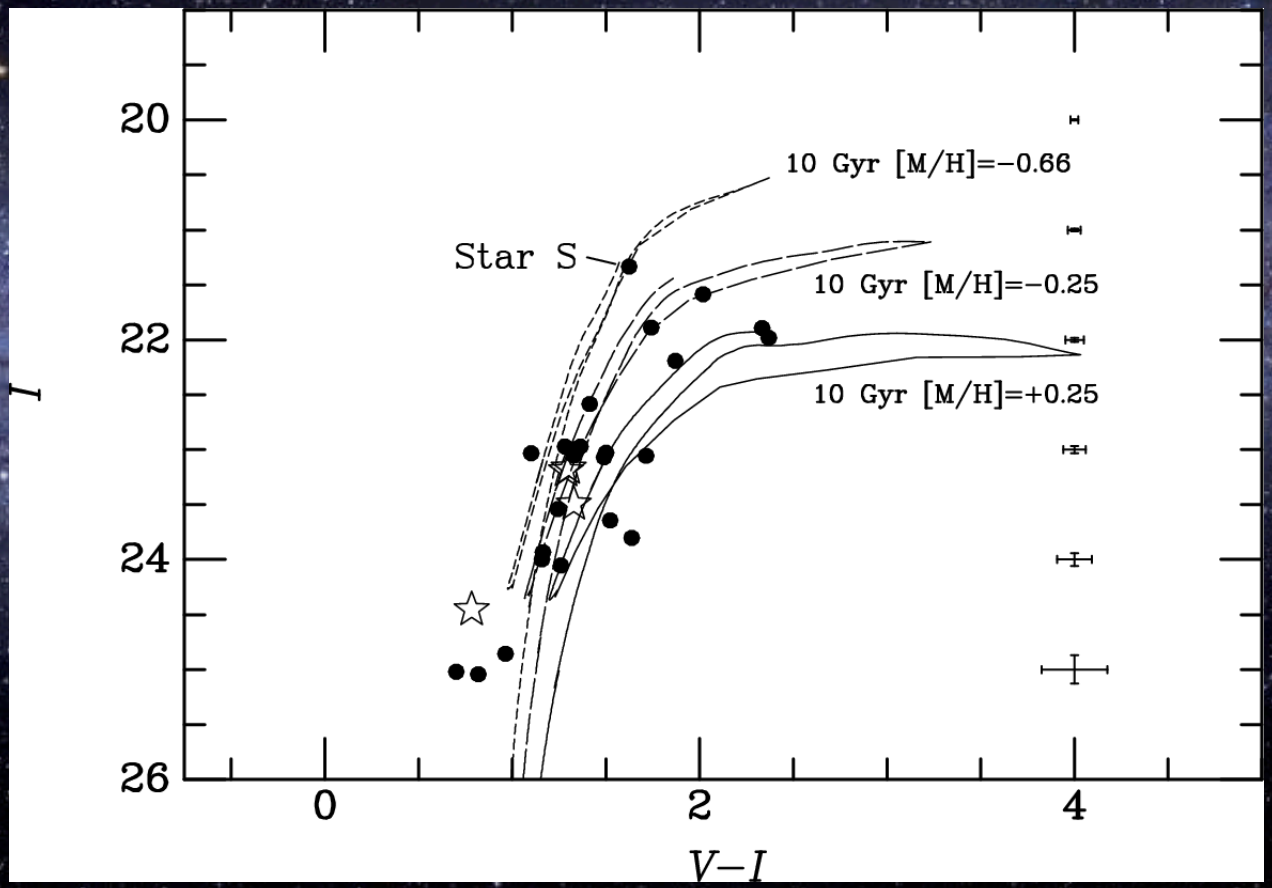


error box

HST Observations of M31 RV Site

- Only normal red giants of ~10 Gyr bulge population at outburst site
  - Shara et al. (ApJ 2010) claimed, from same *HST* frames, a hot UV source in the error box
  - …due to unfortunate case of cosmic rays hitting same pixel in two exposures, plus misapplication of STmagnitude system
  - see Bond, ApJ 2011

HST Observations of M31 RV Site



Pietrinferni et al. BaSTI isochrones figure from Bond 2011

HST Observations of M31 RV Site

- Only normal red giants of ~10 Gyr bulge population at outburst site
- So the remnant had, within 11 years, faded below *HST* optical detectability, or is blended with one of the red giants, or *is* one of the red giants

Outburst Mechanism Constraints and Puzzles

- V838 Mon & M31 RV became luminous red supergiants in weeks.
- Progenitors inconspicuous
- Occurred in young & old populations
- V838 Mon is in cluster too young to contain white dwarfs

Thermonuclear Energy Ruled Out?

- Nova explosion of unusual type?
  - Behaved unlike any known nova
  - Can't make a WD in < 25 Myr!
- Core collapse? Exotic SN (electron-capture)?
  - M31 RV occurred in old population with no obvious massive stars

LBV-like Eruption?

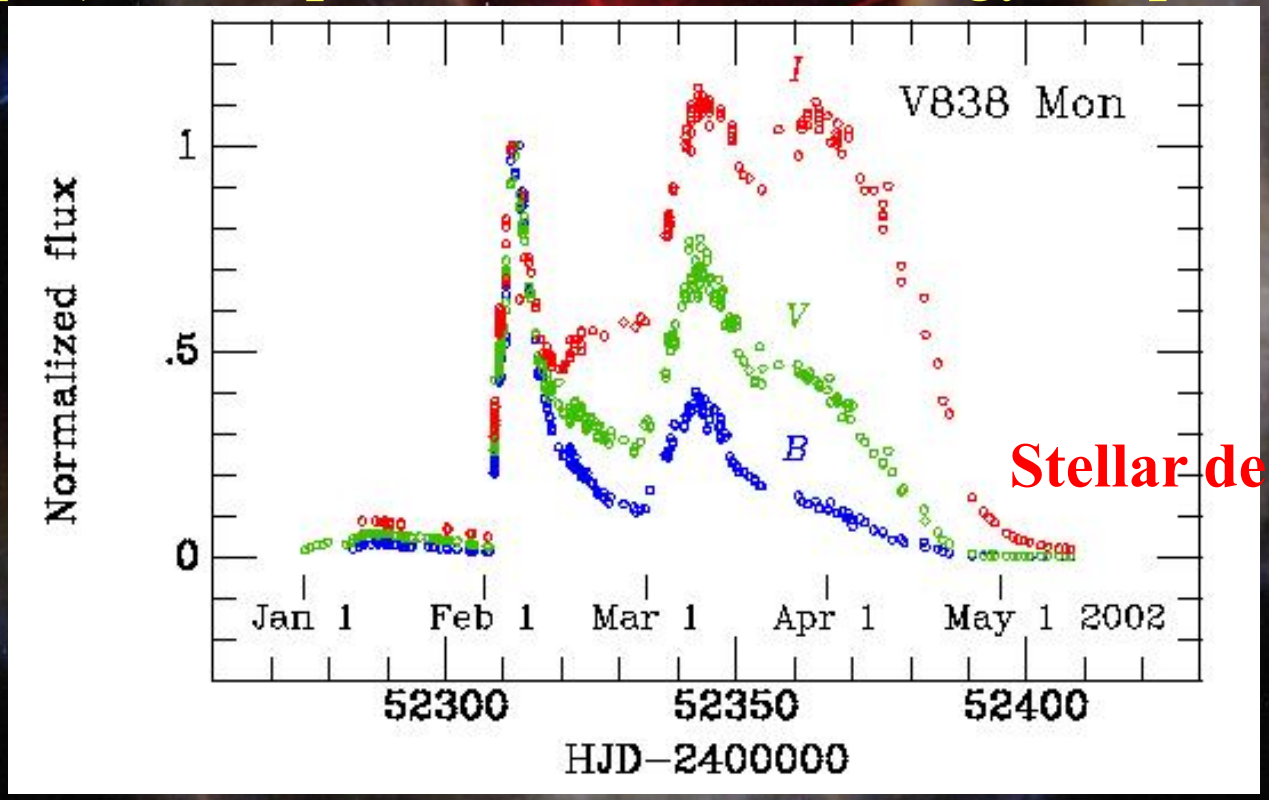
- No luminous optical stars present before outbursts of V838 Mon & M31 RV

Gravitational Energy

- Stellar collision or merger (e.g. in an unstable triple) could provide observed energy output

Gravitational Energy

- Stellar collision or merger (e.g. in an unstable triple) could provide observed energy output

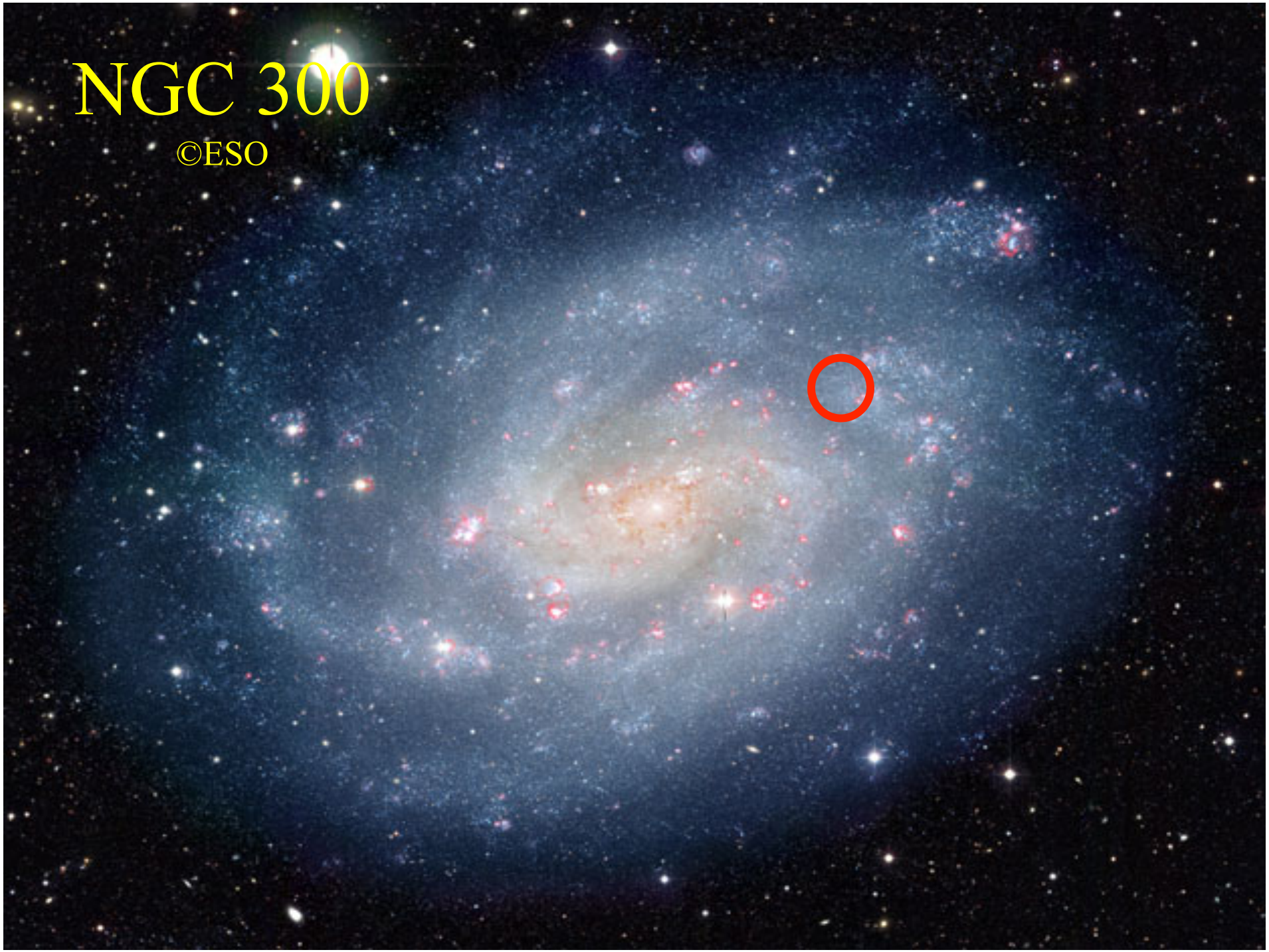


Stellar death spiral?

HST V838 Mon Team

- Sumner Starrfield (Arizona State U)
- Zolt Levay, Nino Panagia, Bill Sparks, Misty Cracraft, Ben Sugerman, Rick White (STScI)
- Arne Henden (AAVSO)
- Mark Wagner (U Arizona)
- Romano Corradi (ING, La Palma, Canarias)
- Ulisse Munari (Padova)
- Lisa Crause (SAAO)
- Mike Dopita (ANU)
- H. E. Bond (STScI), PI

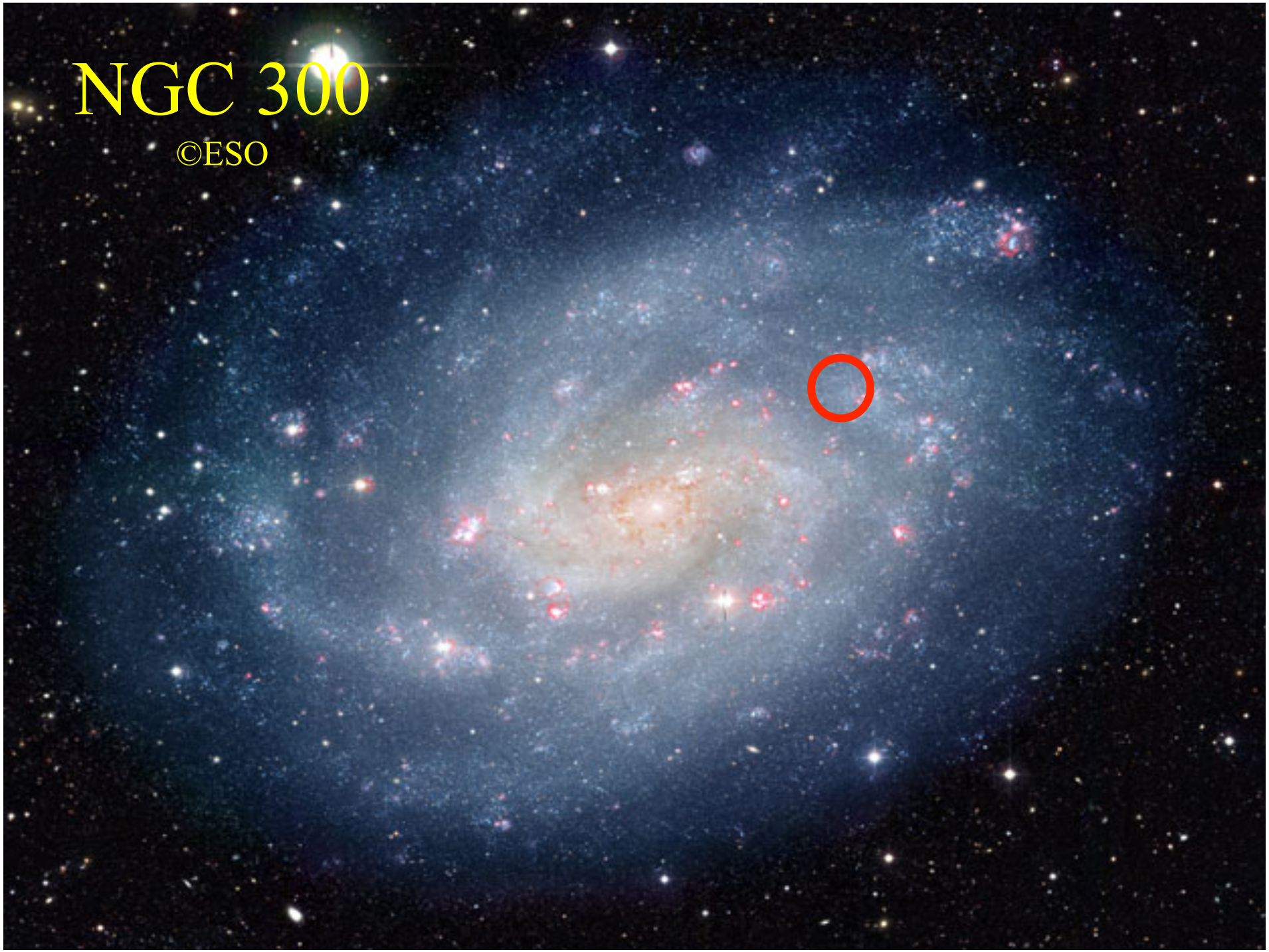
The 2008 Optical Transient in NGC 300


NGC 300
©ESO

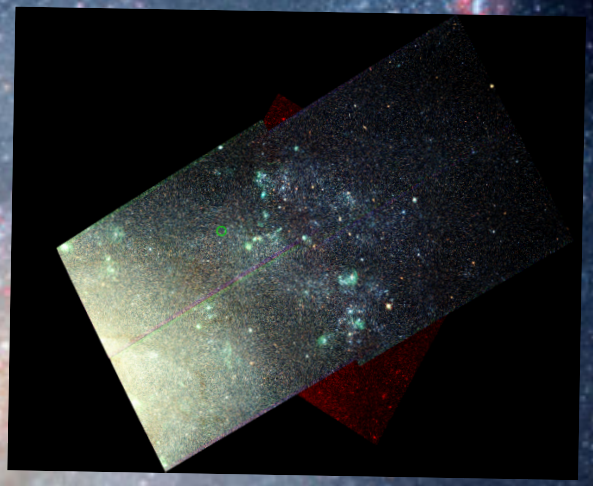
NGC 300 OT 2008-1

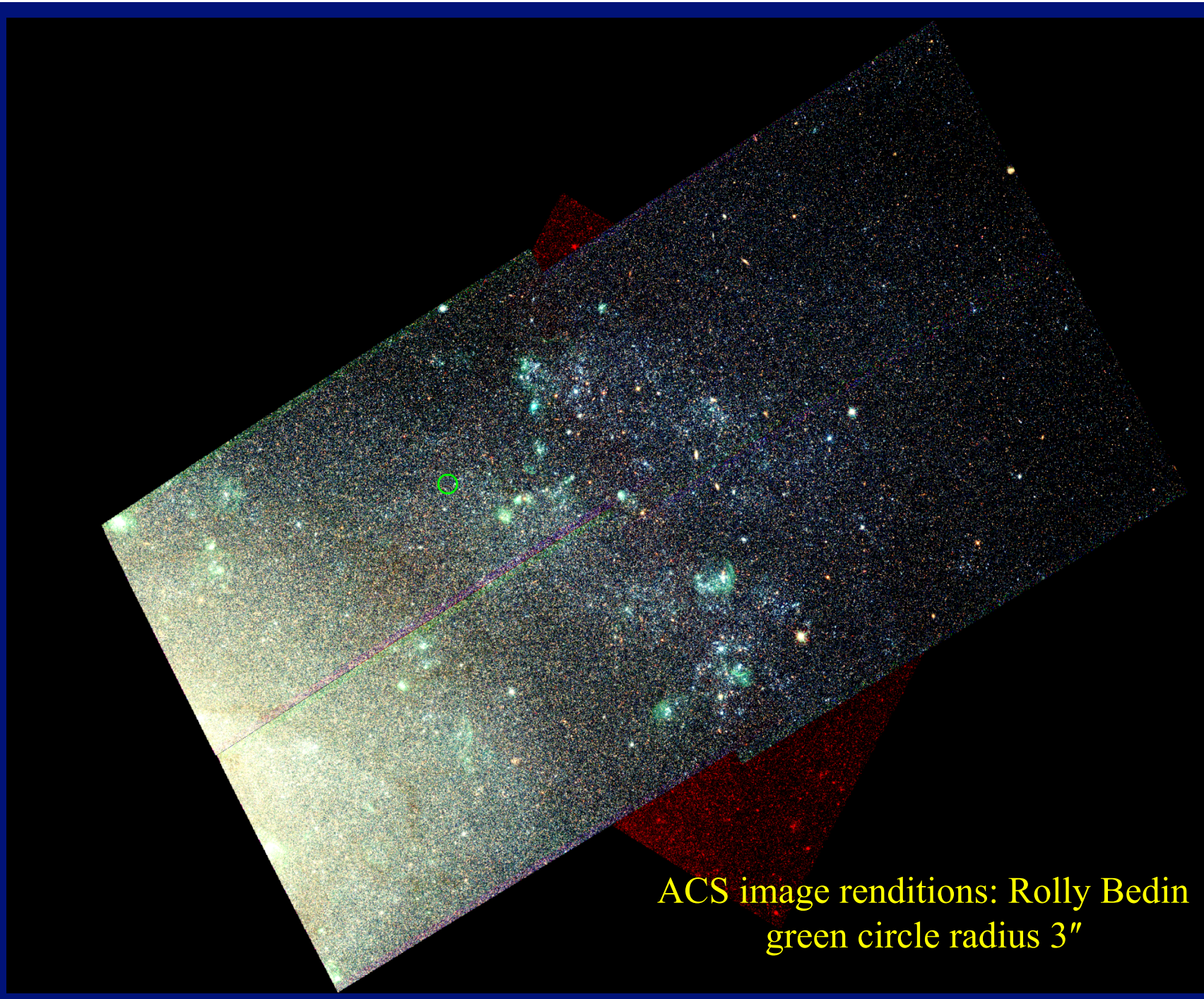
- Discovered by amateur (B. Monard) at 14th mag (abs *V* mag ~ −12.9)
- In spiral arm of NGC 300
- Became very red as outburst proceeded
- Deep pre-eruption *HST* images showed no optical progenitor to ~28.5 mag
- *Spitzer* pre-outburst frames showed luminous mid-IR progenitor

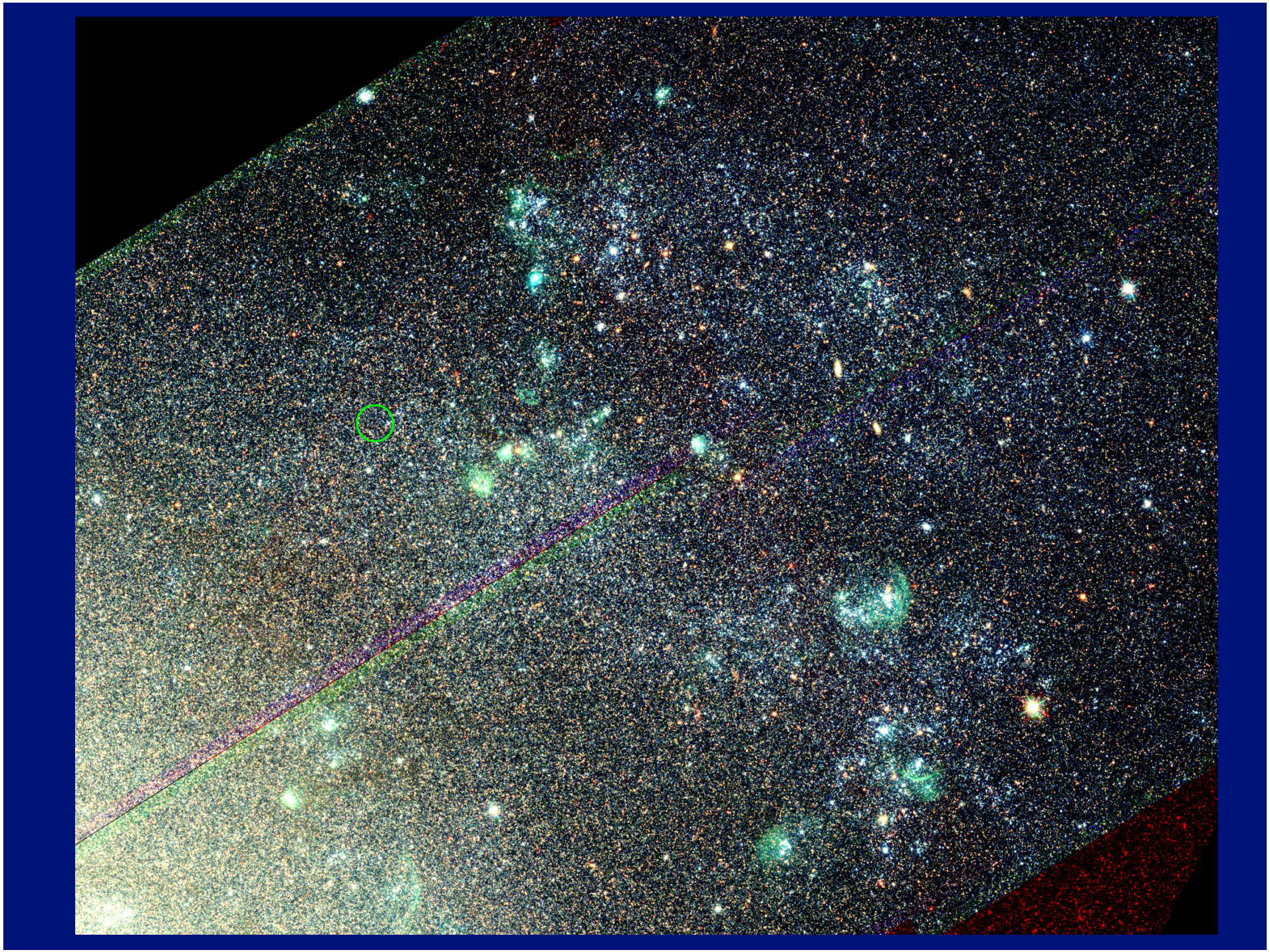

Searching for the Progenitor:

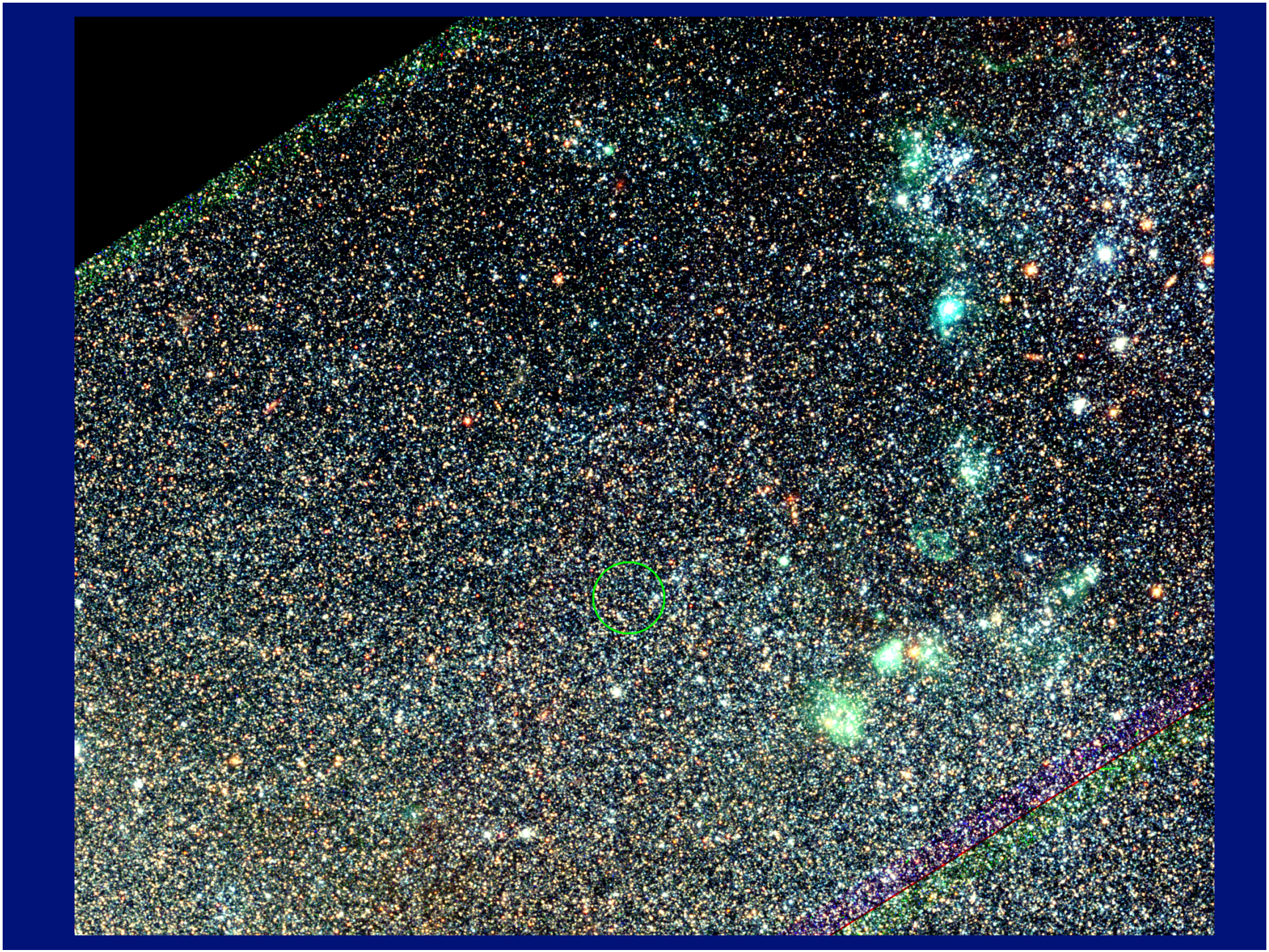

NGC 300
©ESO

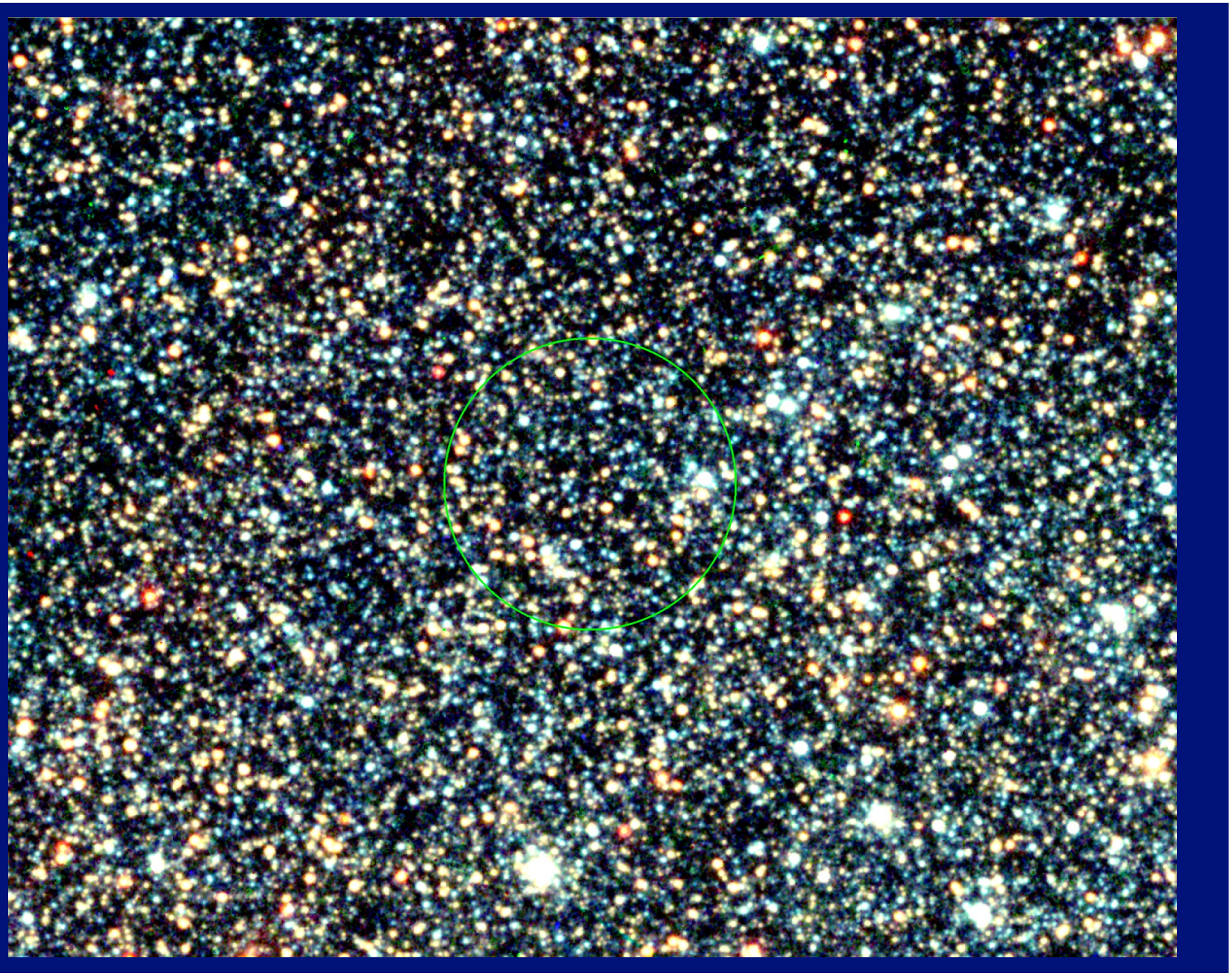
Searching for the Progenitor: Archival *HST*/ACS images, 2002 & 2006

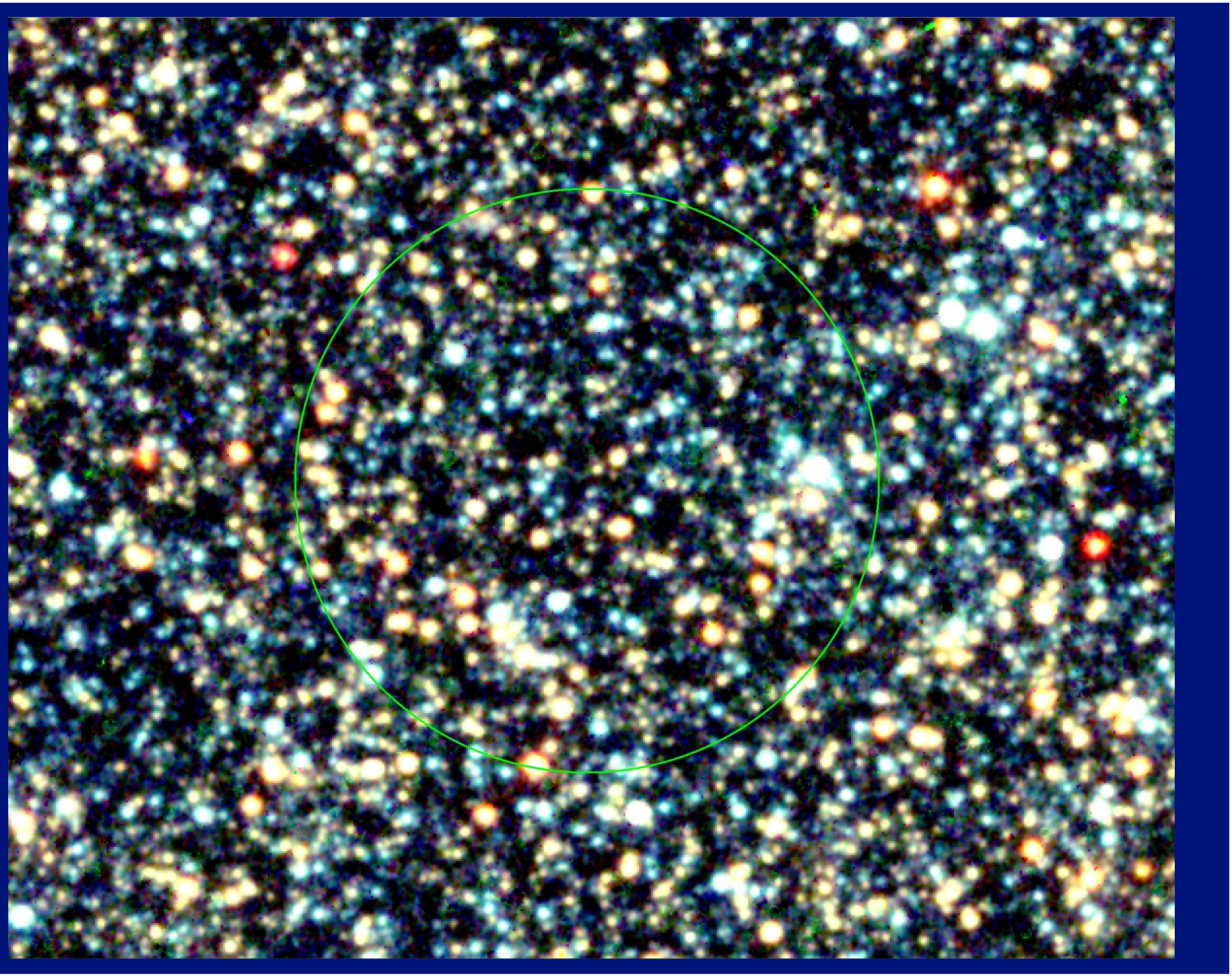



ACS image renditions: Rolly Bedin
green circle radius 3″



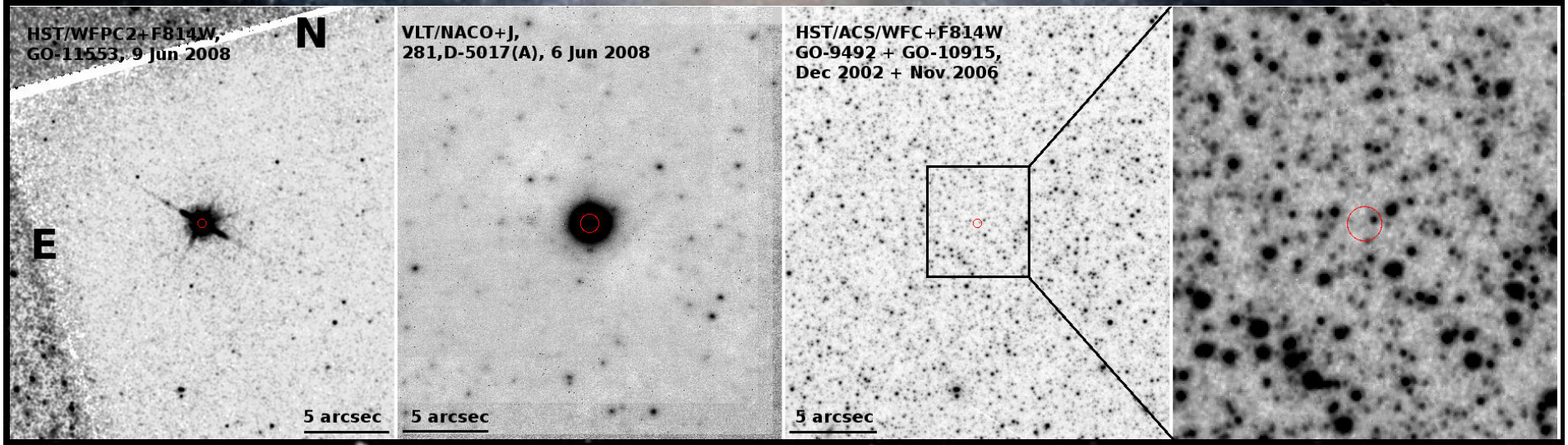




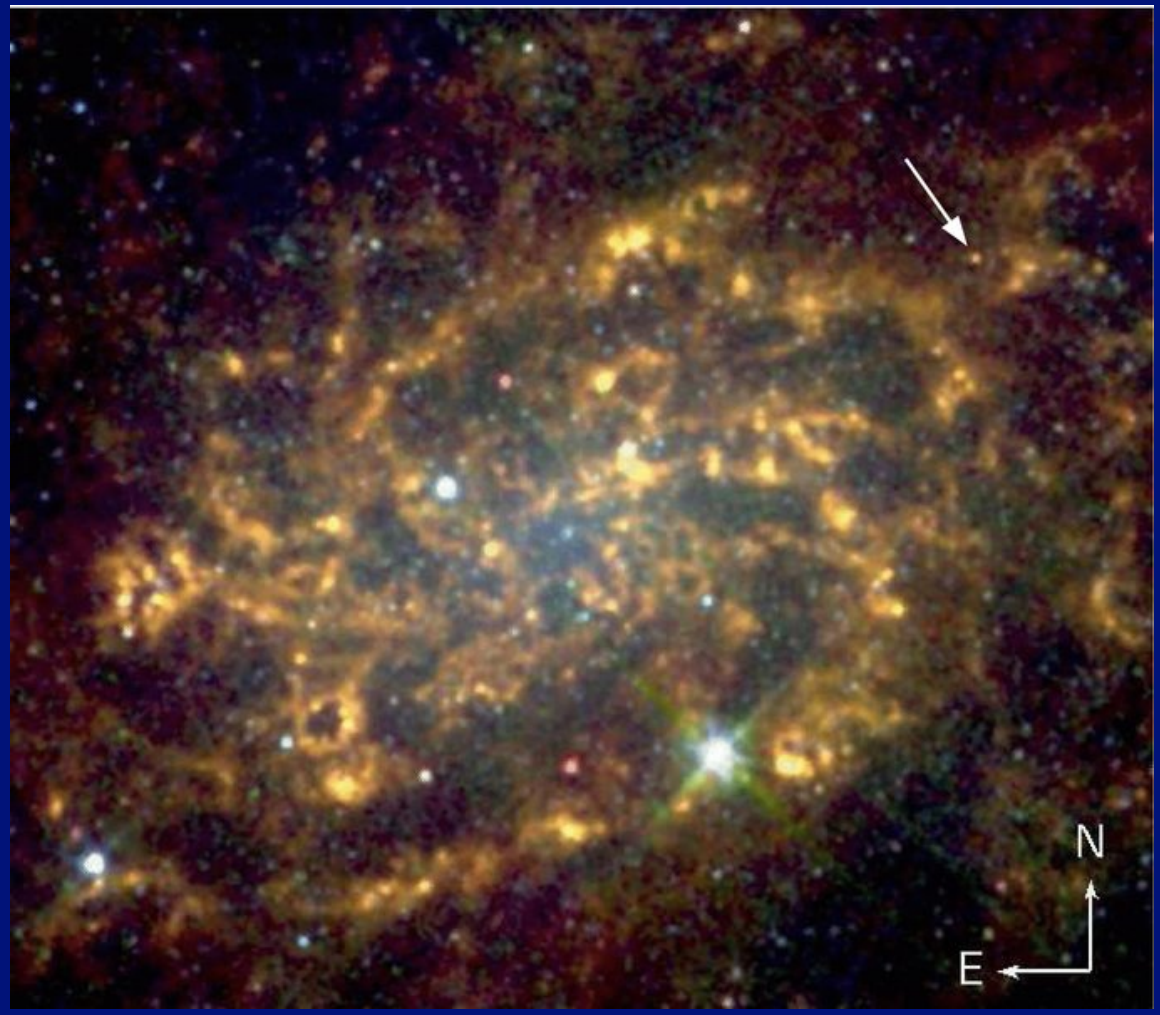


The 2008 Optical Transient in NGC 300

- Pre-outburst *HST* images (Bedin & HEB) show no star at site brighter than ~28.5.
  - confirmed by our DD *HST* imaging on 6/9/08, showing precise location of transient

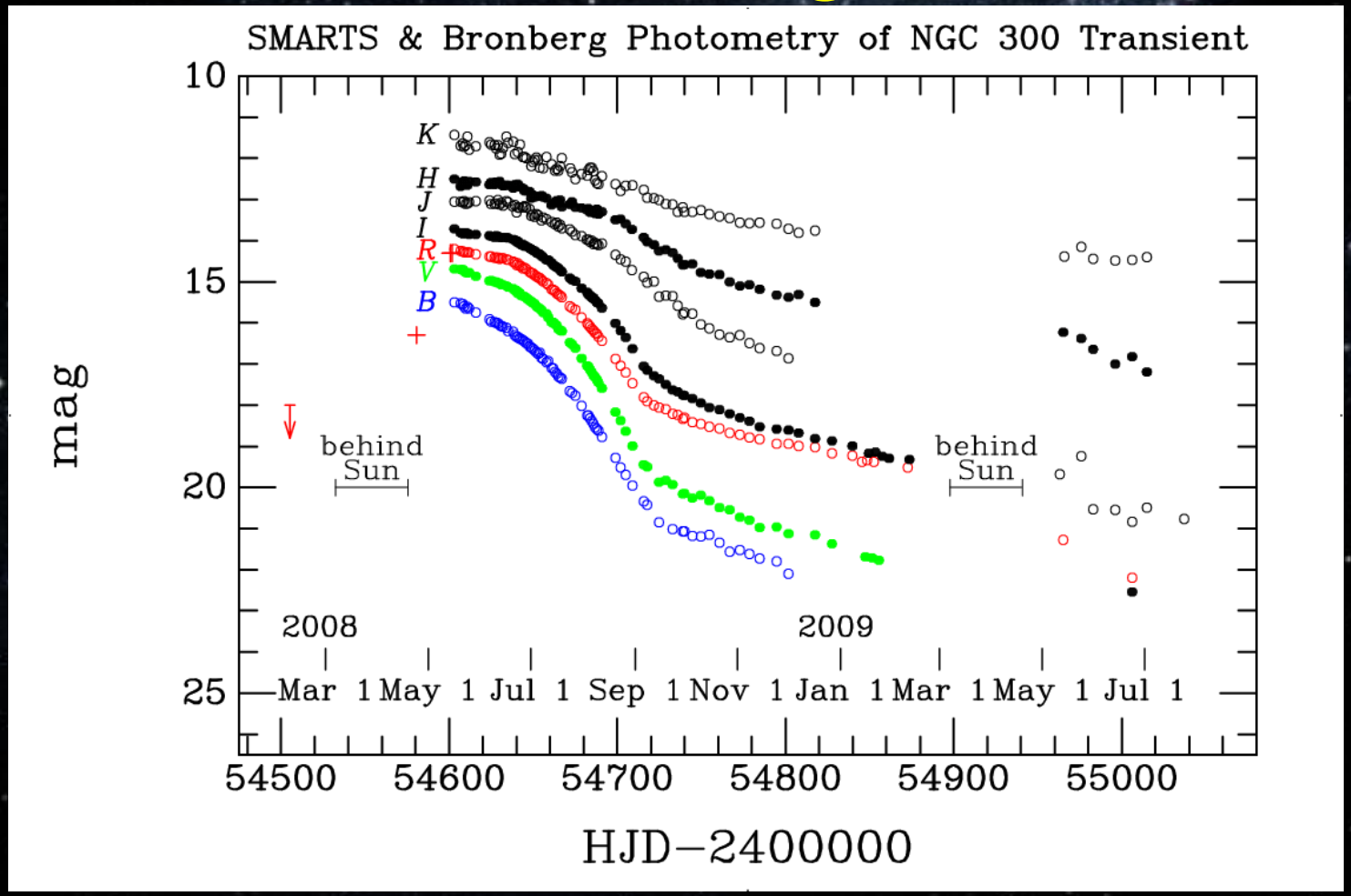


Pre-outburst *Spitzer* Image



Berger et al. 2009; IRAC RGB=8.0,5.8,4.5 μm

NGC 300 OT Light Curve



SMARTS 1.3m, CTIO, NOAO

NGC 300 OT's Environment

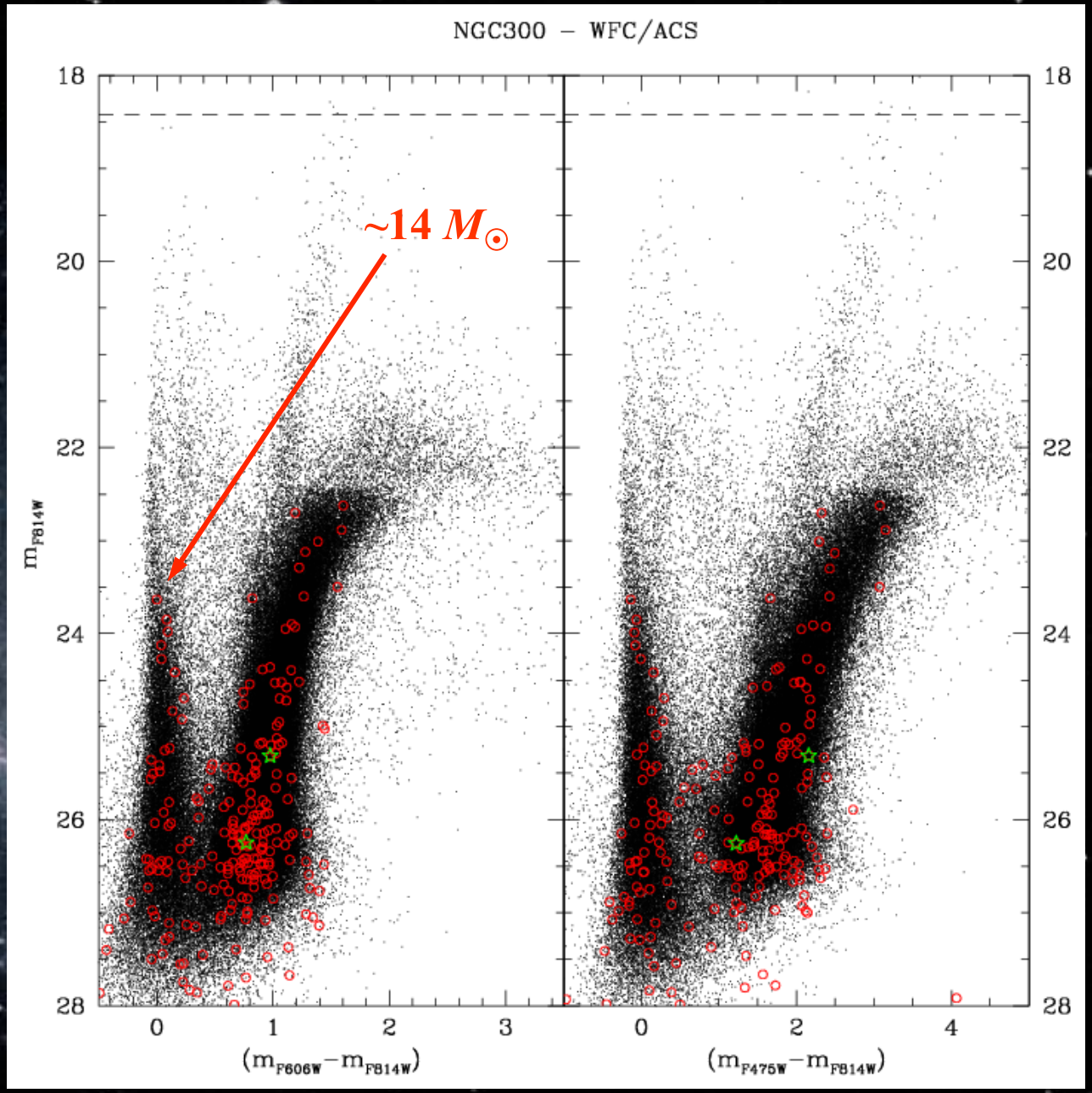
- Surrounding population contains stars formed in burst ~8–13 Myr ago, with MSTO at ~12–25 $M_{\odot}$ (Gogarten et al. 2009).

HST/ACS CMD

courtesy L. Bedin

black dots: entire ACS field
red circles: within 2.5″ of transient
green stars: within 0.25″

2.5″ = 23 pc

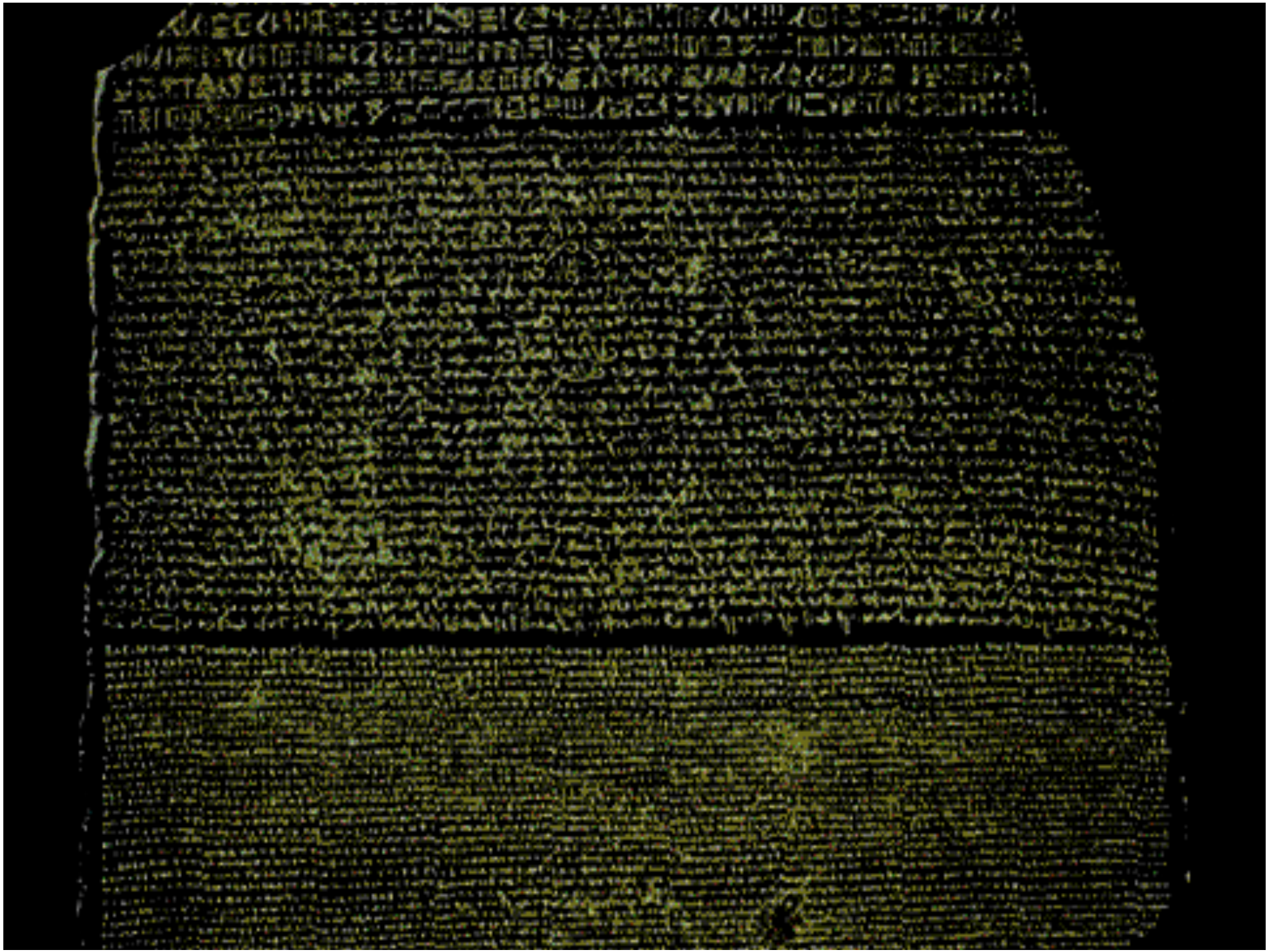


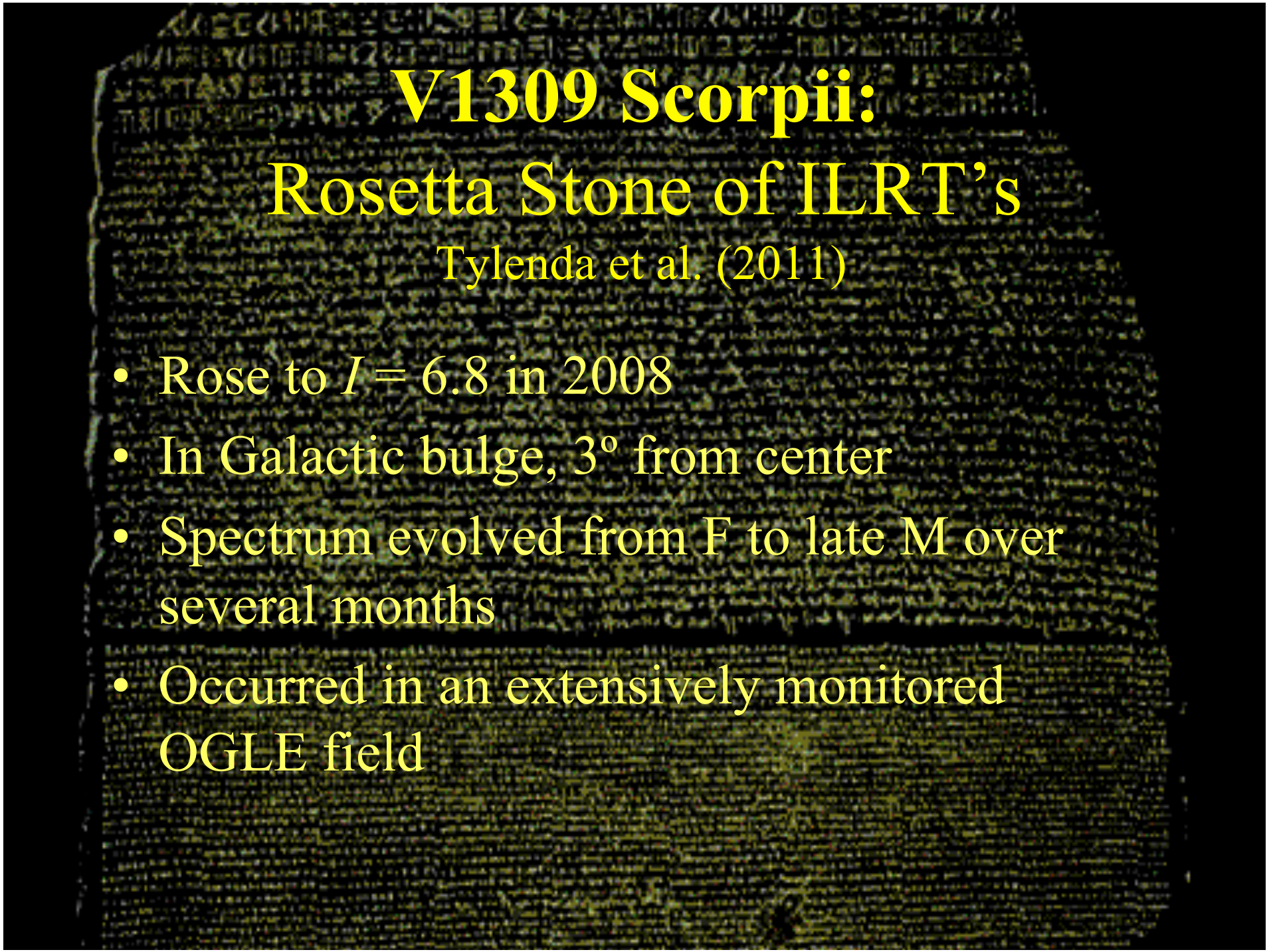
Outburst Mechanism
Explosion or Eruption?

- Proposals include—
  - Electron-capture SN from super-AGB star
  - LBV giant eruption
  - Extreme mass-transfer episode or merger in a massive binary

NGC 300 Team

- Rolly Bedin (STScI)
- Alceste Bonanos (STScI, now Nat'l Obs Greece)
- Roberta Humphreys (Minnesota)
- Berto Monard (Bronberg Obs, South Africa)
- José Prieto (Ohio State; now Hubble Fellow @ Carnegie Obs)
- Fred Walter (Stony Brook)
- H. E. Bond (STScI), PI




V1309 Scorpii:
Rosetta Stone of ILRT's
Tylenda et al. (2011)
• Rose to $I = 6.8$ in 2008
• In Galactic bulge, 3° from center
• Spectrum evolved from F to late M over several months
• Occurred in an extensively monitored OGLE field

V1309 Sco OGLE Light Curve

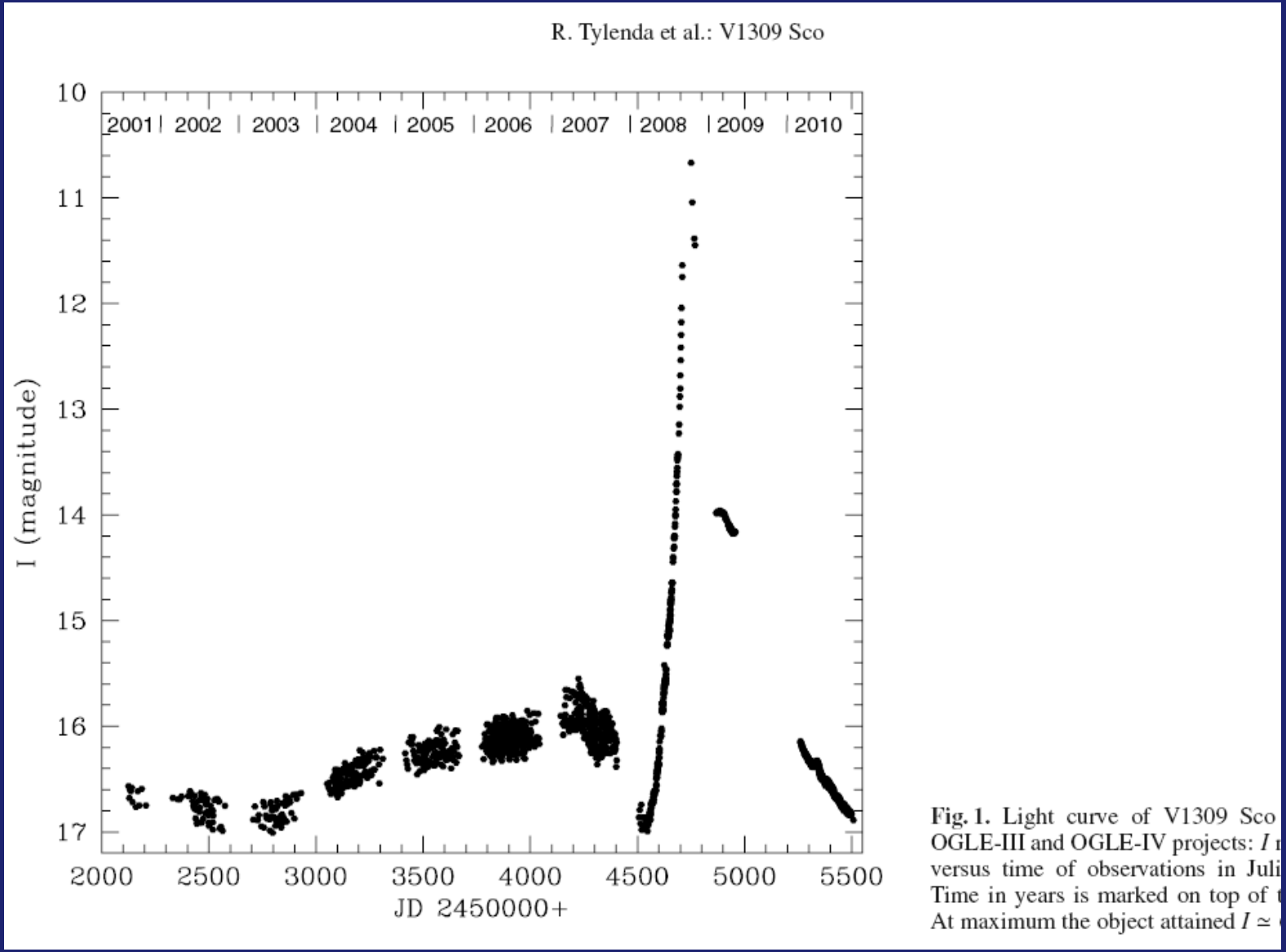
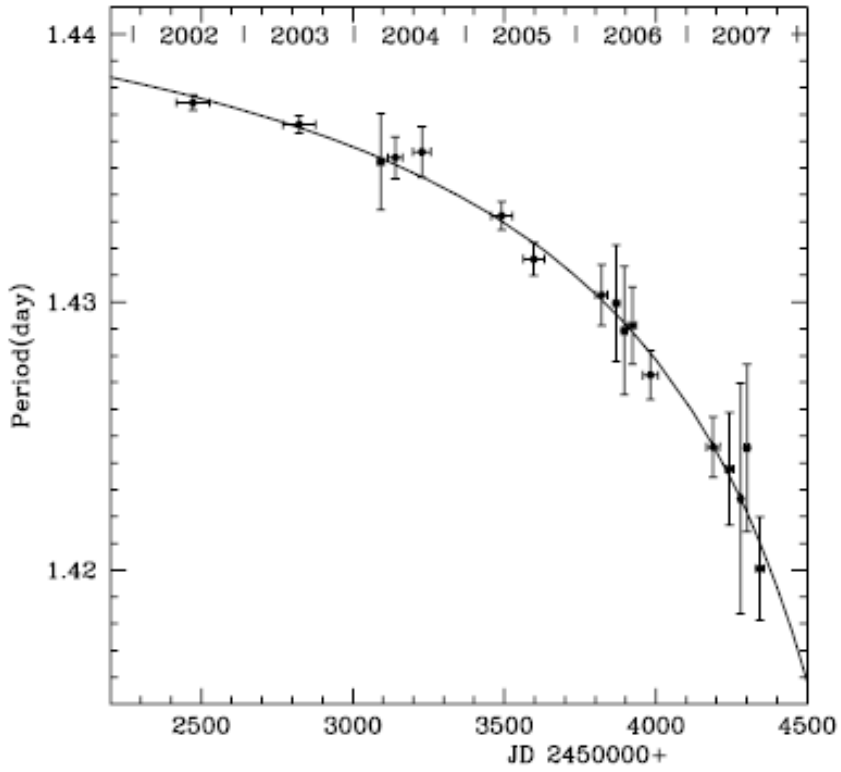
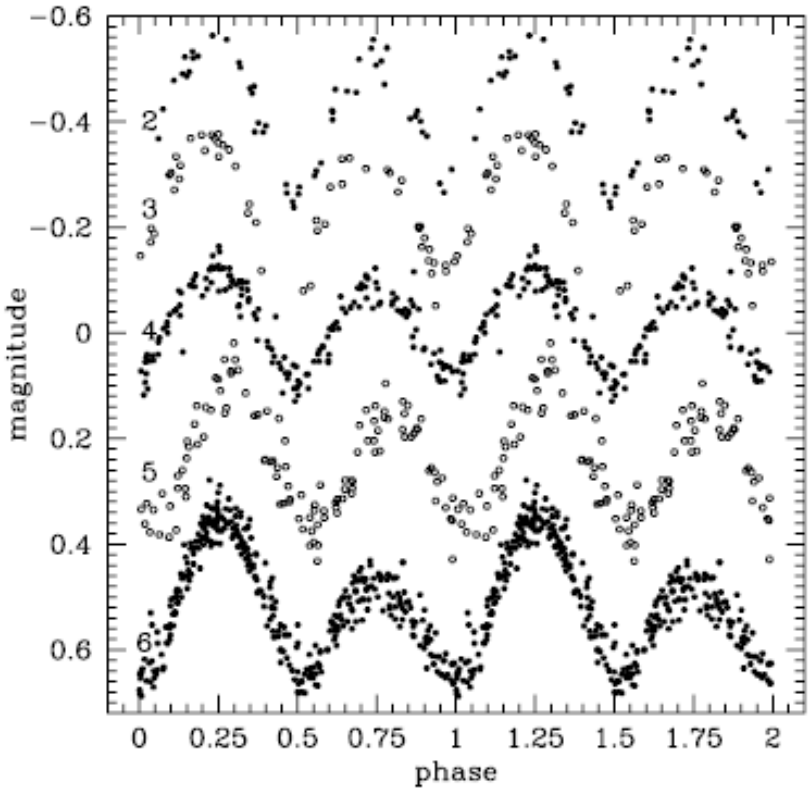


Fig. 1. Light curve of V1309 Sco
OGLE-III and OGLE-IV projects: *I*
versus time of observations in Juli
Time in years is marked on top of
At maximum the object attained *I* ≃

1.4-day contact binary, period shortening rapidly, leading to violent merger

V1309 Sco





Tylenda et al. 2011

Summary

- V838 Mon, M31 RV, NGC 300 OT-2008: prototypes of new classes of stars that rapidly expand to cool supergiants
- **Intermediate-luminosity red transients**
- V838's multi-peaked light curve & X-ray flaring may support merger scenario
- V1309 Sco was demonstrably a merging binary

Summary, contd.

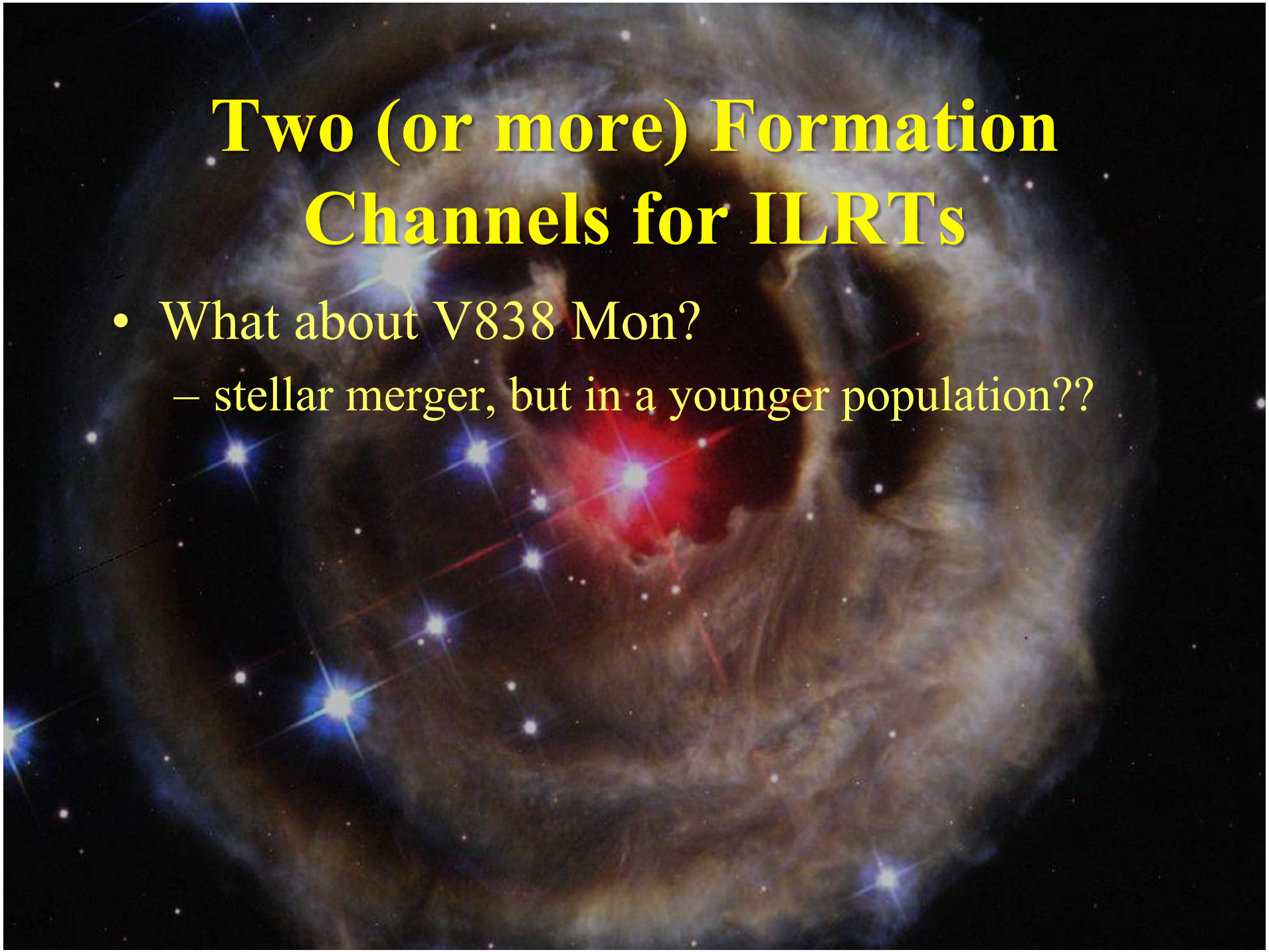
- V838 Mon, M31 RV, V4332 Sgr, V1309 Sco probably have a different origin than the more luminous ILRTs that arise from massive stars (SN 2008S, NGC 300 OT, etc.)

Summary cont'd

- NGC 300 OTs 2008 & 2010, & SN 2008S occurred in dust-obscured massive stars
  - Origin of their outbursts uncertain
  - Related to LBVs? e-capture SN? Binaries??
- These classes of intermediate-luminosity events ***are not rare!***
- They are examples of the **zoo of unanticipated new transients** that synoptic surveys will find in enormous numbers!

Two (or more) Formation Channels for ILRTs

- From old, low-mass populations—
  - M31 RV, V4332 Sgr, M85 OT, V1309 Sco
  - stellar mergers?
- From young, massive, dust-enshrouded stars (~9-15 $M_{\odot}$)—
  - NGC 300 2008, SN 2008S, PTF 10fqs
  - related to LBVs but in cooler stars??
  - physical mechanism uncertain



Two (or more) Formation Channels for ILRTs

- What about V838 Mon?
  - stellar merger, but in a younger population??


"As the astronomical community embarks upon an era of more intensive transient studies, more examples [of ILRTs] will … illuminate and quantify … this diverse range of properties."
—N. Smith et al. 2011

V mag at max at various distances

Located in …	V838 Mon	NGC 300 OT
M31	15.0	11.7
M81	18.0	14.7
Virgo cluster	21.9	18.6
Coma cluster	25.4	22.1
$z = 0.05$	27.0	23.7