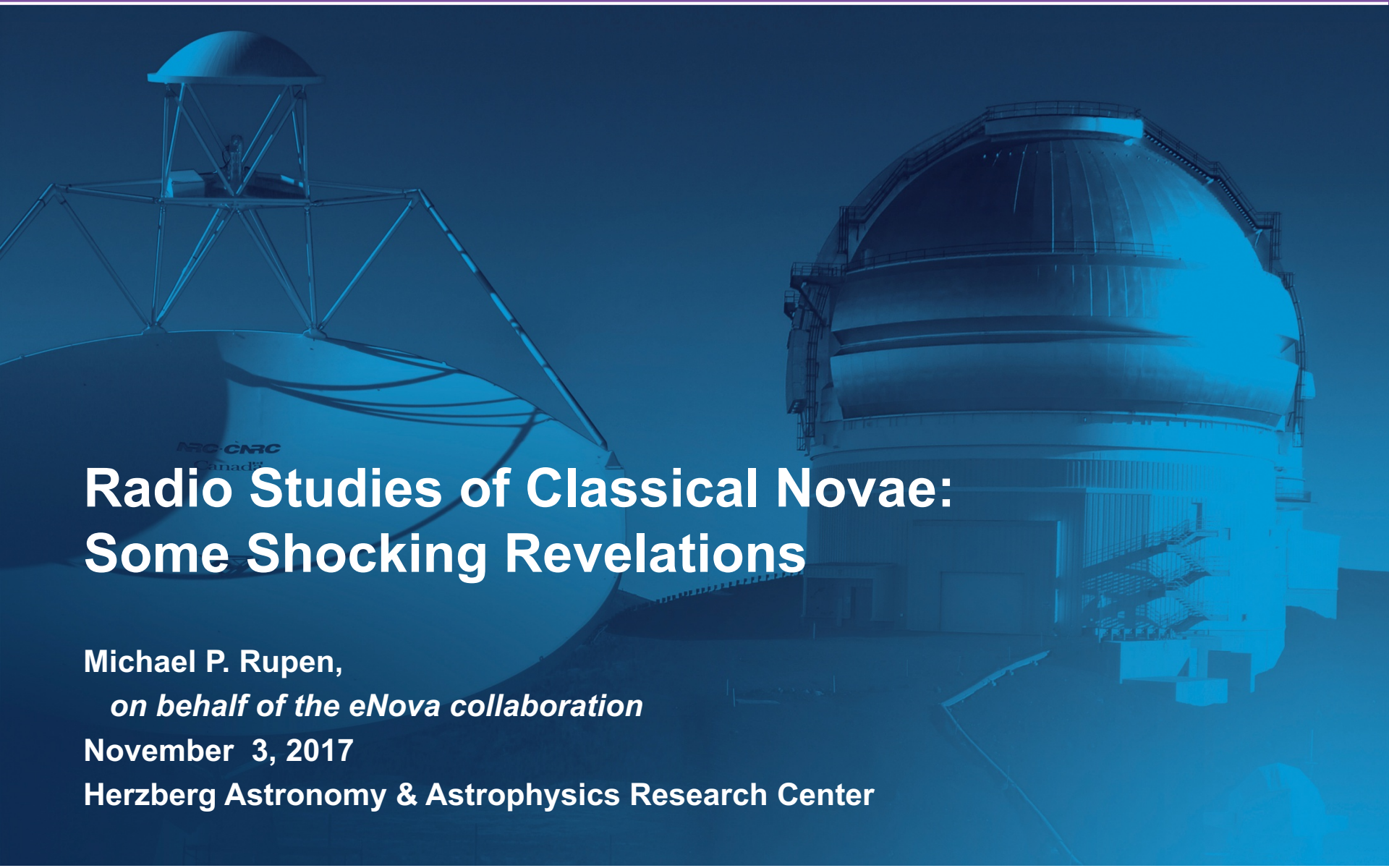

Radio Studies of Classical Novae: Some Shocking Revelations

Michael P. Rupen,
on behalf of the eNova collaboration

November 3, 2017

Herzberg Astronomy & Astrophysics Research Center

National Research Council Canada | Conseil national de recherches Canada

Canada

The eNova team

- Laura Chomiuk (MSU)
- Adam Kawash (MSU)
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- Justin Linford (GWU)
- Koji Mukai (NASA/U-Maryland)
- Amy Mioduszewski (NRAO)
- Tommy Nelson (Pitt)
- Michael Rupen (NRC Canada)
- Jeno Sokoloski (Columbia)

…and friends

- Jennifer Weston (AAAS)
- Tom Finzell (Michigan)
- Brian Metzger (Columbia)
- Indrek Vurm (Columbia)
- Tim O'Brien (Jodrell Bank)
- Valerio Ribeiro (Botswana)
- Alexander van der Horst (GWU)
- Fred Walter (Stony Brook)
- Ulisse Munari (Padua)
- and more!

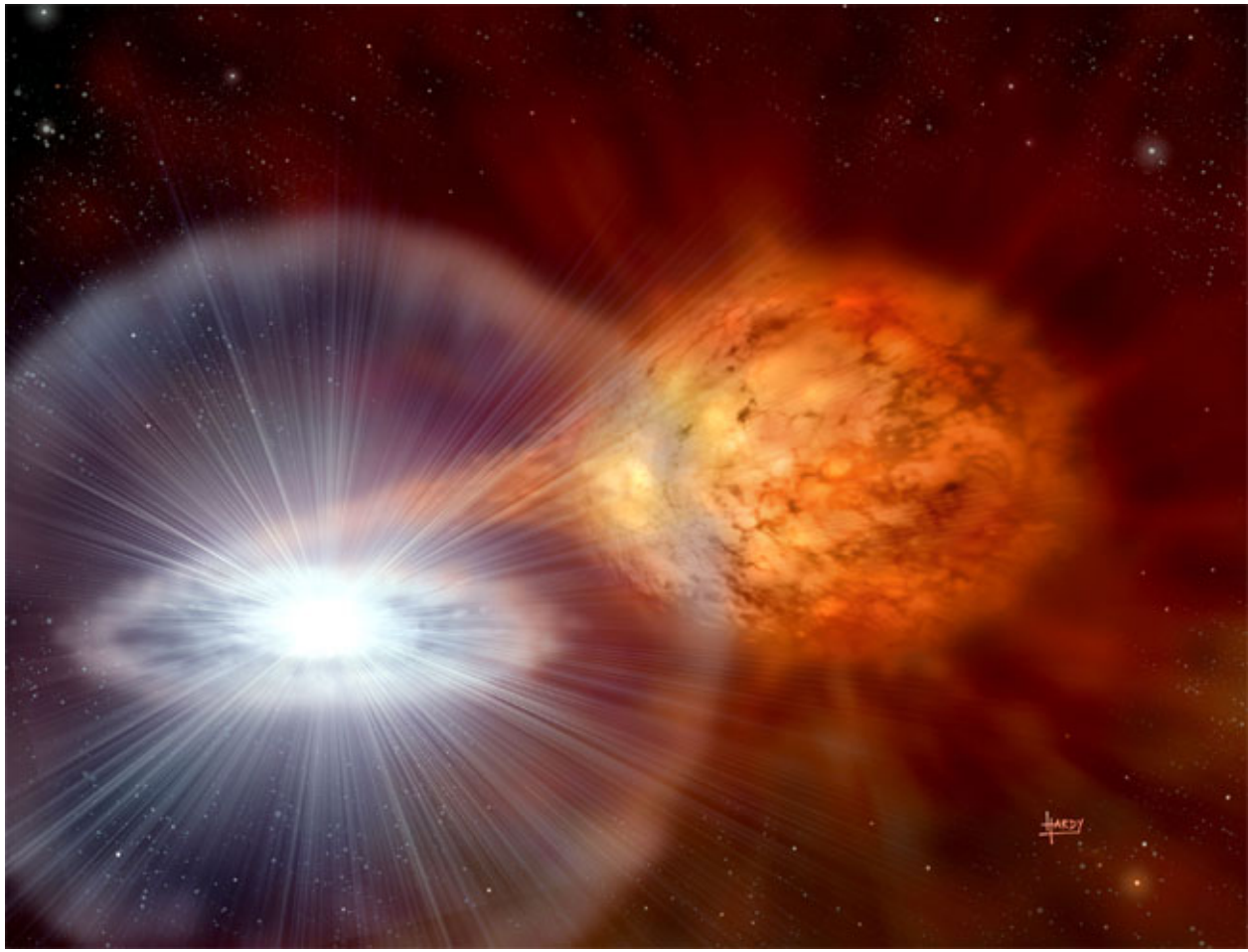
Introduction to classical novae

Thermonuclear runaway (TNR) on the surface of a white dwarf, that ejects a large amount of accreted matter. *(K. Mukai)*

- Accretion → TNR – interacting binary
- Could be in CV or symbiotic binary

10^{-7} to 10^{-3} M_{sun} ejected at 500-5000 km/s
→KE~ 10^{44}-10^{46} ergs

~8 observed (of ~35) per year in Milky Way

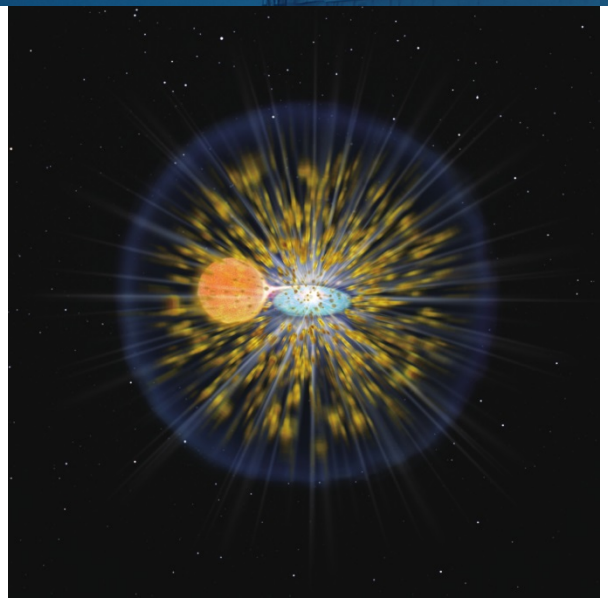


This talk *avoids* **recurrent novae** (RS Oph, T Pyx, …)

Introduction to classical novae

Basic paradigm:
expanding HII region powered by hot white dwarf

- Mass ejected by WD explosion (TNR)
- Homologous (Hubble flow) expansion



Introduction to classical novae

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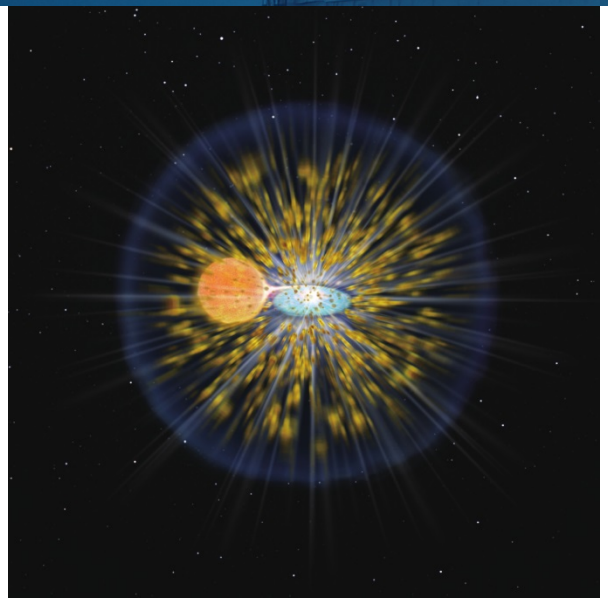

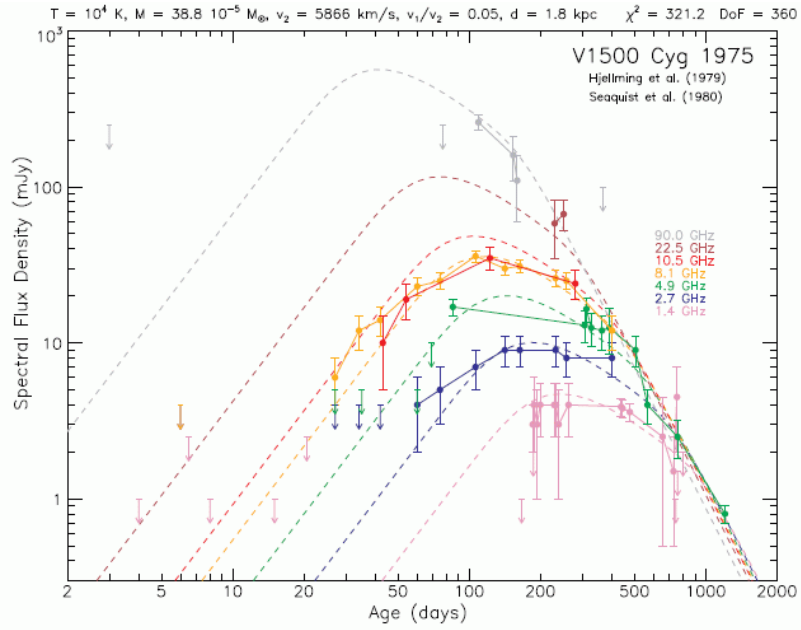

Radio:

- $T_{b,max} \sim 10^4$ K
- Rise: t^2 ν^2
- Decay: t^{-3} $\nu^{-0.1}$

Roy et al. 2012

Introduction to classical novae

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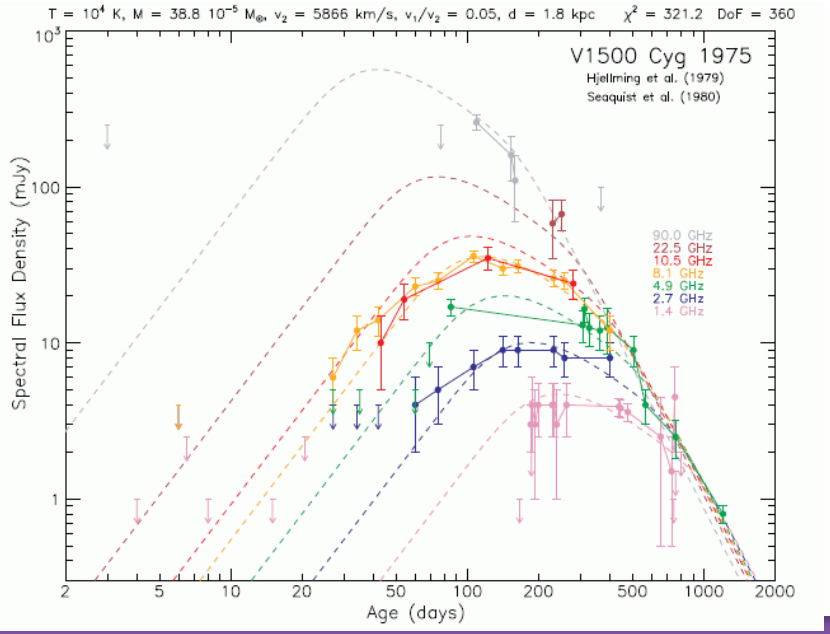
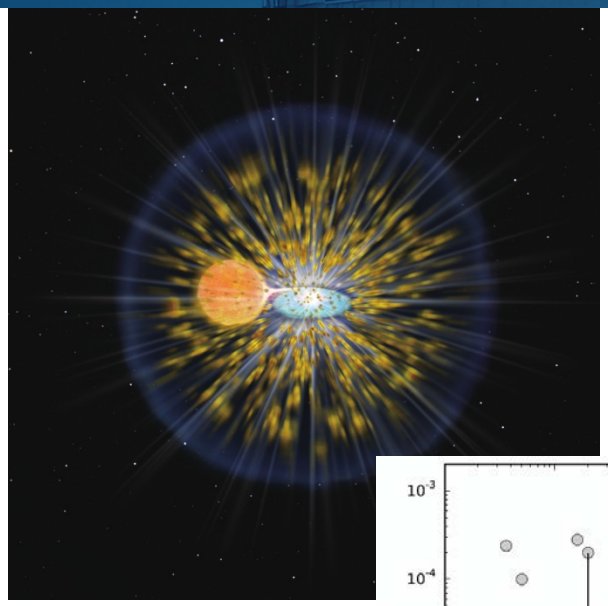


Roy et al. 2012



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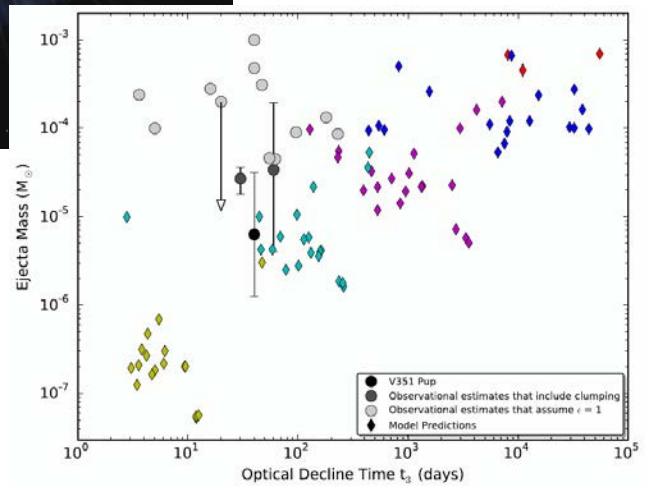
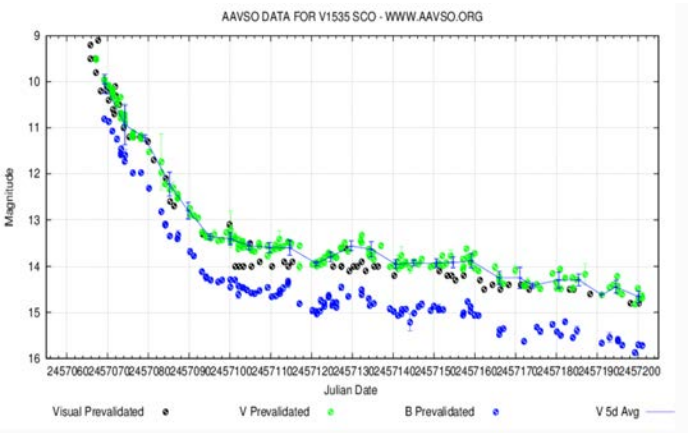
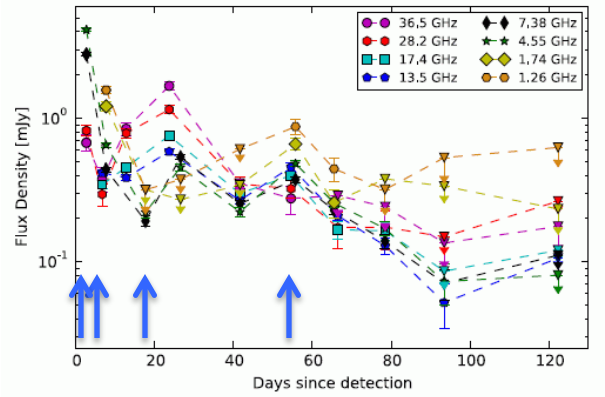


Wendeln et al. 2017

Mass estimates – match theory *if* highly clumped

Cracks in the paradigm: not just free-free emission…and not just one peak

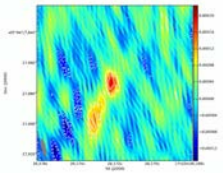




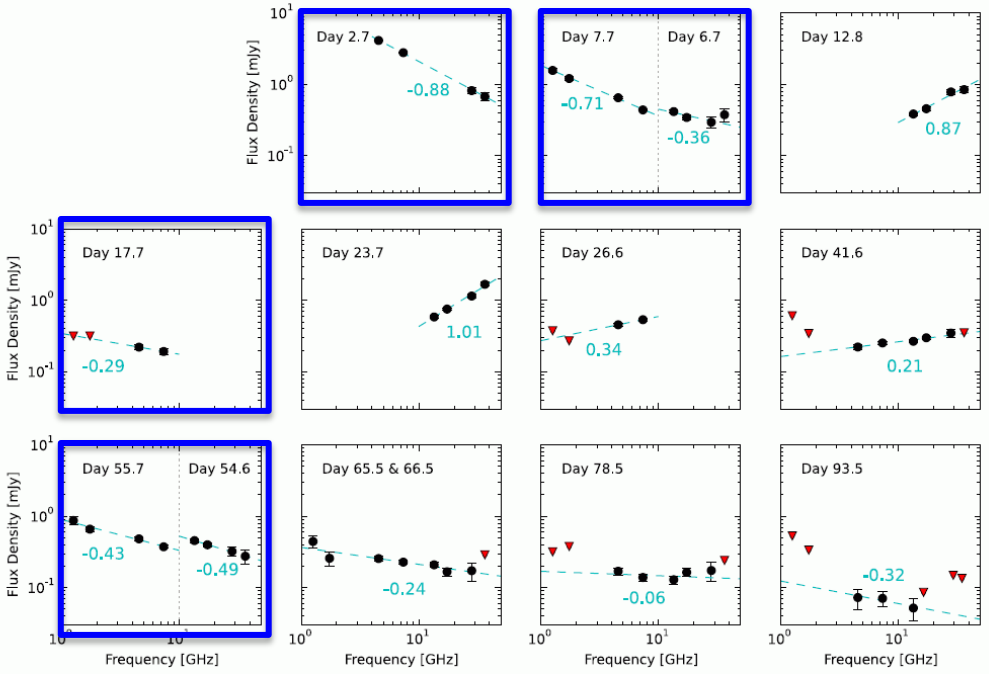
V1535 Sco 2015

…**Embedded**: K giant

…hard X-rays



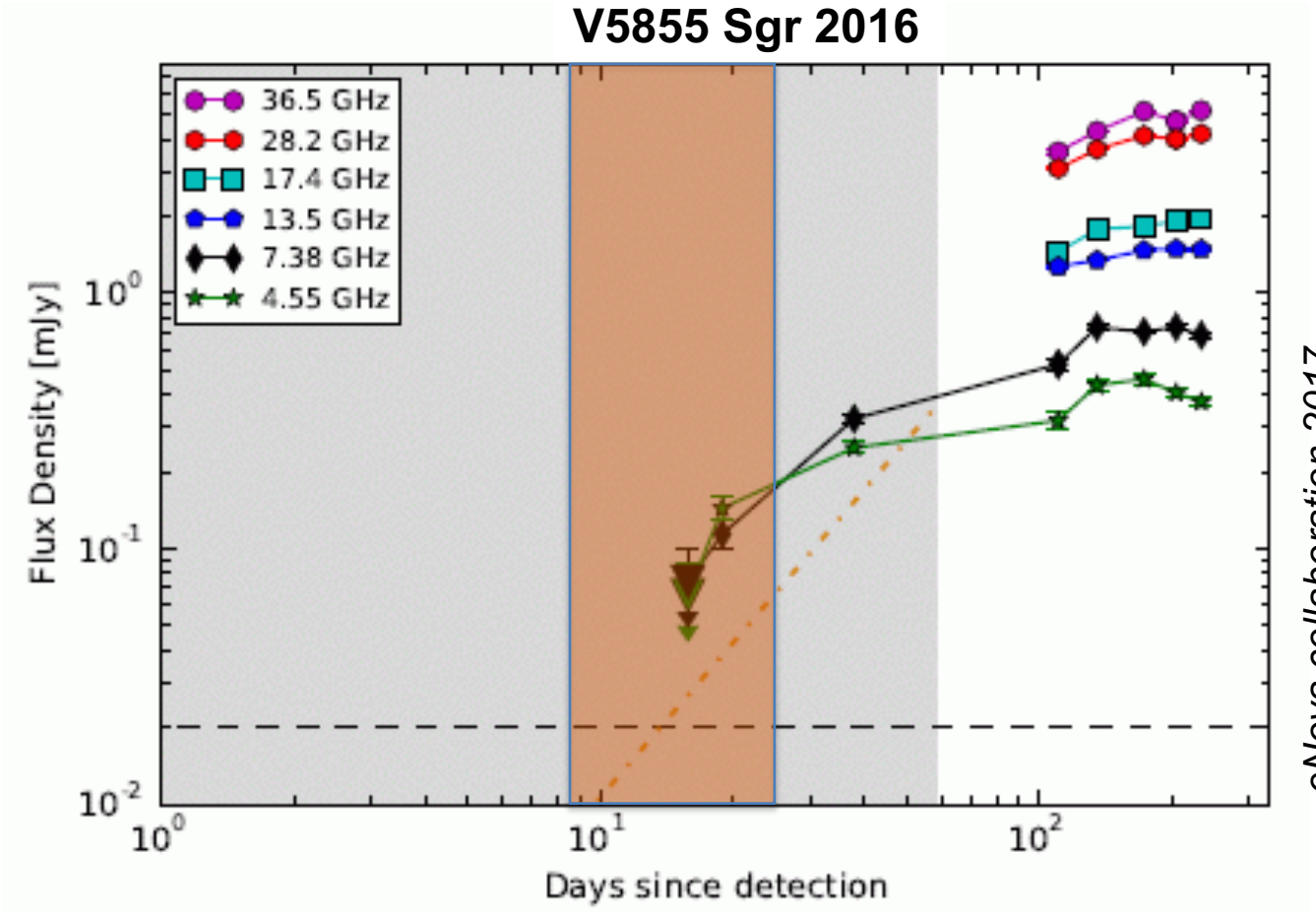
T_b>6x10^5 K



Linford et al. 2017

NRC·CNRC

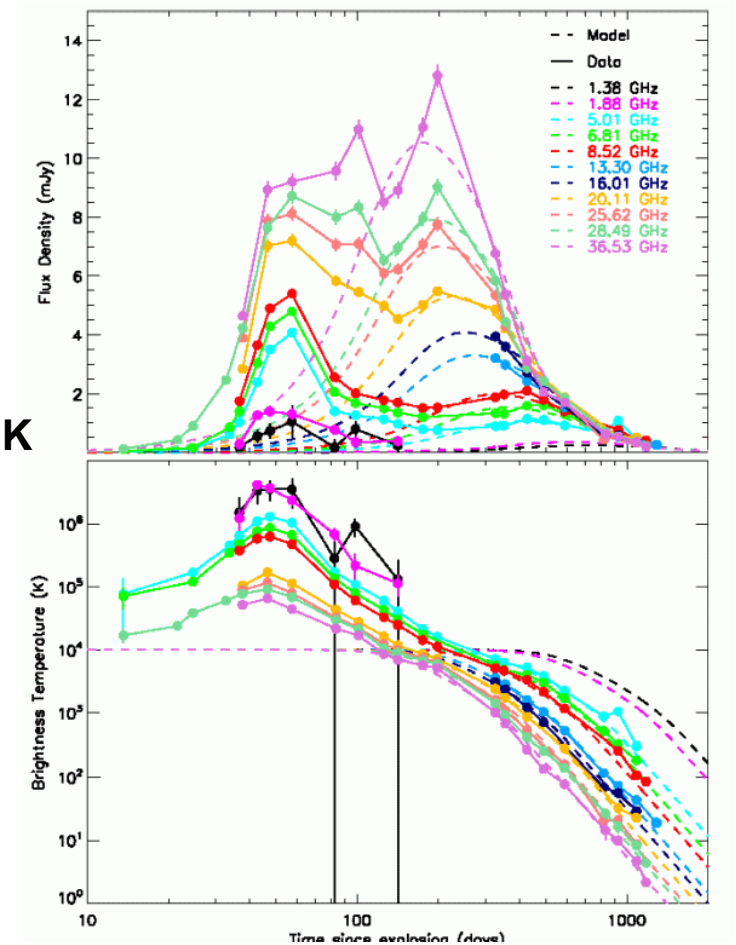
Cracks in the paradigm: synchrotron spectra



Cracks in the paradigm: double peaks

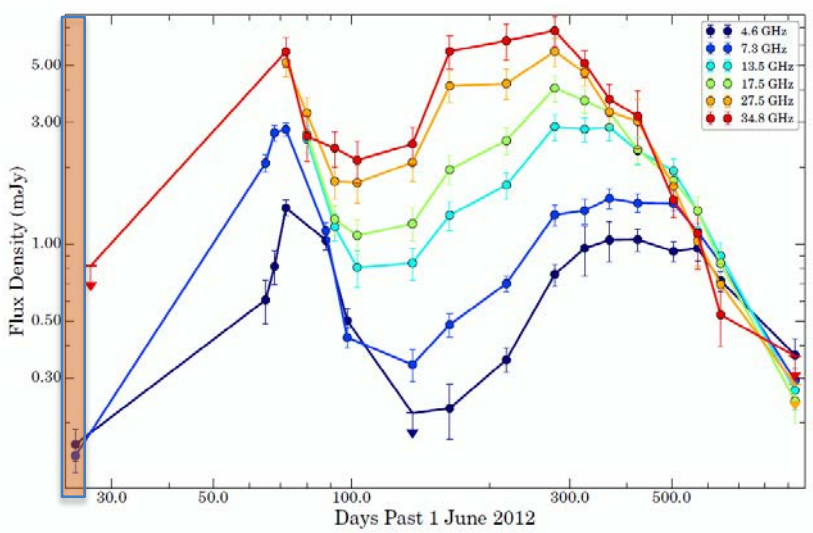
V1723 Aql 2010

- 6kpc ?
- **NOT embedded**
- v_{max}~ 1500 km/s
- **Initial peak:**
  - **$t^{3.3}$, $\nu^{1.3}$**
  - **T_b up to few million K**
- **2nd peak reasonably thermal** (albeit $\nu^{1.5}$)



Weston et al. 2016

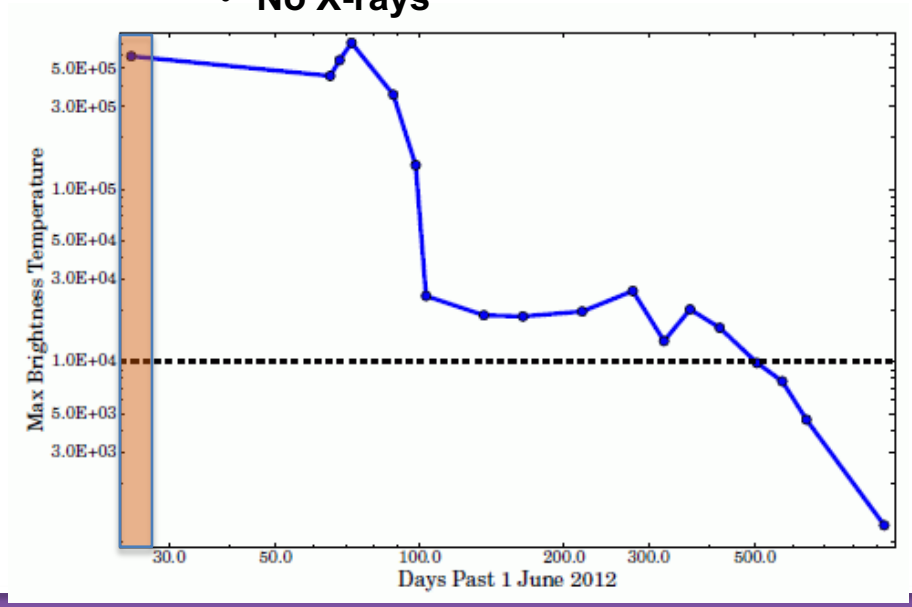
Cracks in the paradigm: double peaks



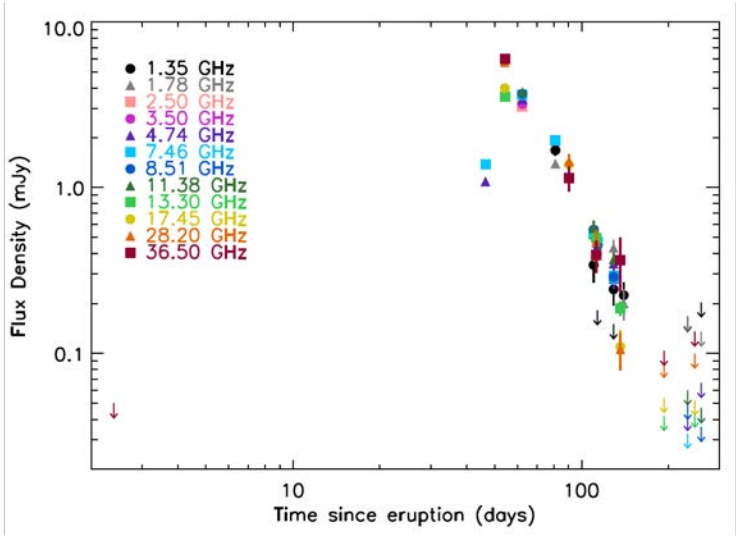
Finzell et al. 2017

V1324 Sco 2012

- >6.5 kpc
- **MS companion**
- Highly reddened + dust formation
- Vej 1150 km/s
- **T_b up to 600,000 K**
- Actually ν^2 day 60-80! But $\nu^{1.3}$ for slow rise
- **Very lum. γ-rays**
- **No X-rays**

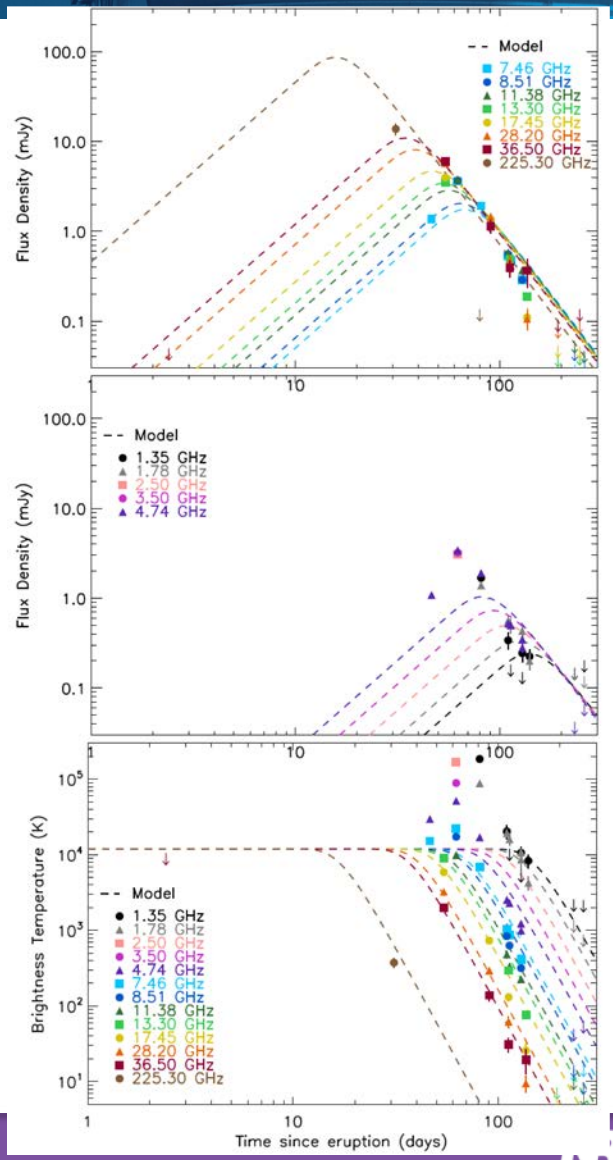


Cracks in the paradigm: even single-peaked issues



V5589 Sgr 2012

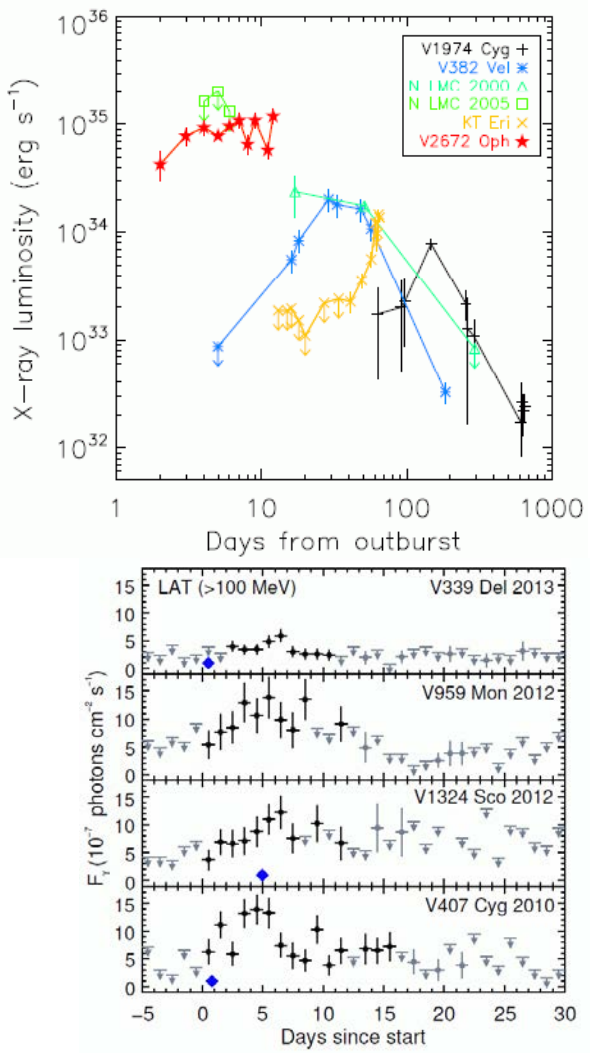
- 4 kpc
- **NOT embedded**
- **Radio: $t^{3.9}$ at 5 GHz ; $\nu^{0.9}$**, then flatter as rose
- **T_b>100,000 K**
- No γ-rays – less luminous
- **Very hard X-rays –** 33keV, softening to 1.3 by time radio appears
- Opt slow+fast
- No extra N_H



Weston et al. 2016

Evidence for shocks & complex mass loss

- **Radio**: synchrotron spectra, high T_b, complex radio light curves
- **Optical**: multiple spectral components, complex optical light curves
- **Hard X-rays (>1 keV) & γ-rays**
  - not always same ones, and not at same time…
- **This seems to be *normal***
  - Many sources
  - MS companions, wide orbits as well as “embedded” novae



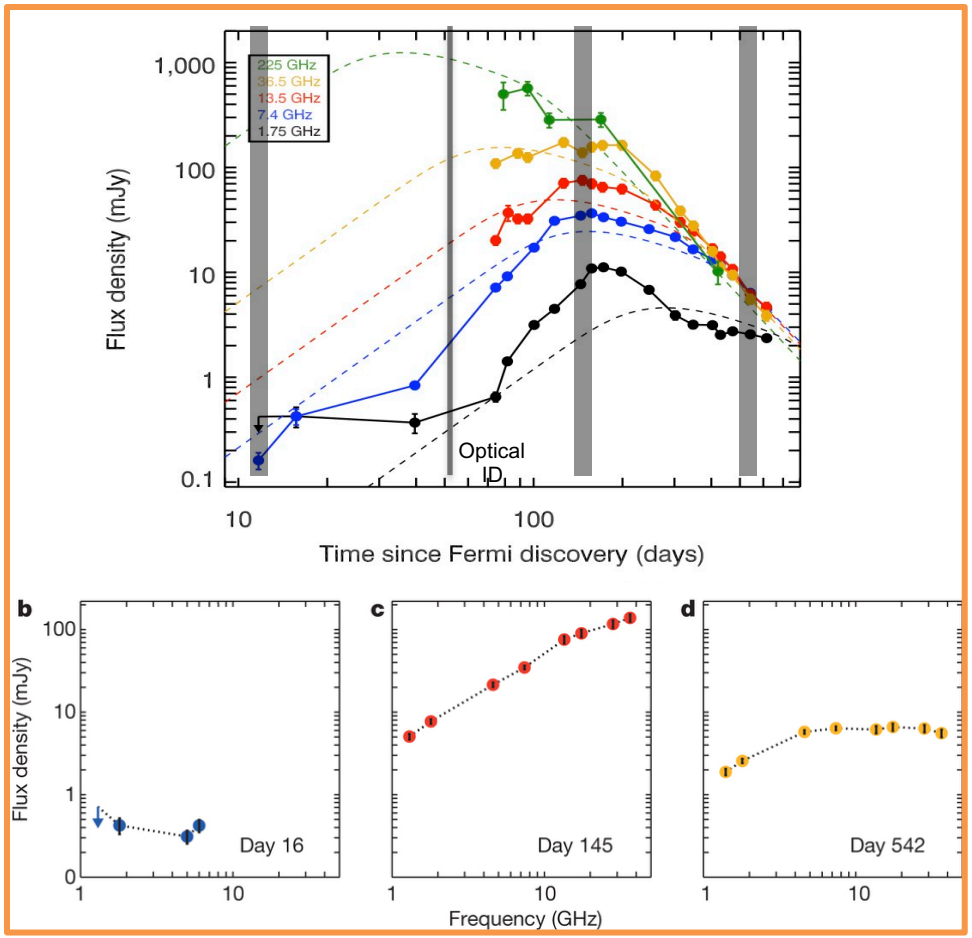
Mukai. 2016

Ackermann et al. 2014

Ackermann et al. 2014

V959 Mon: a test case

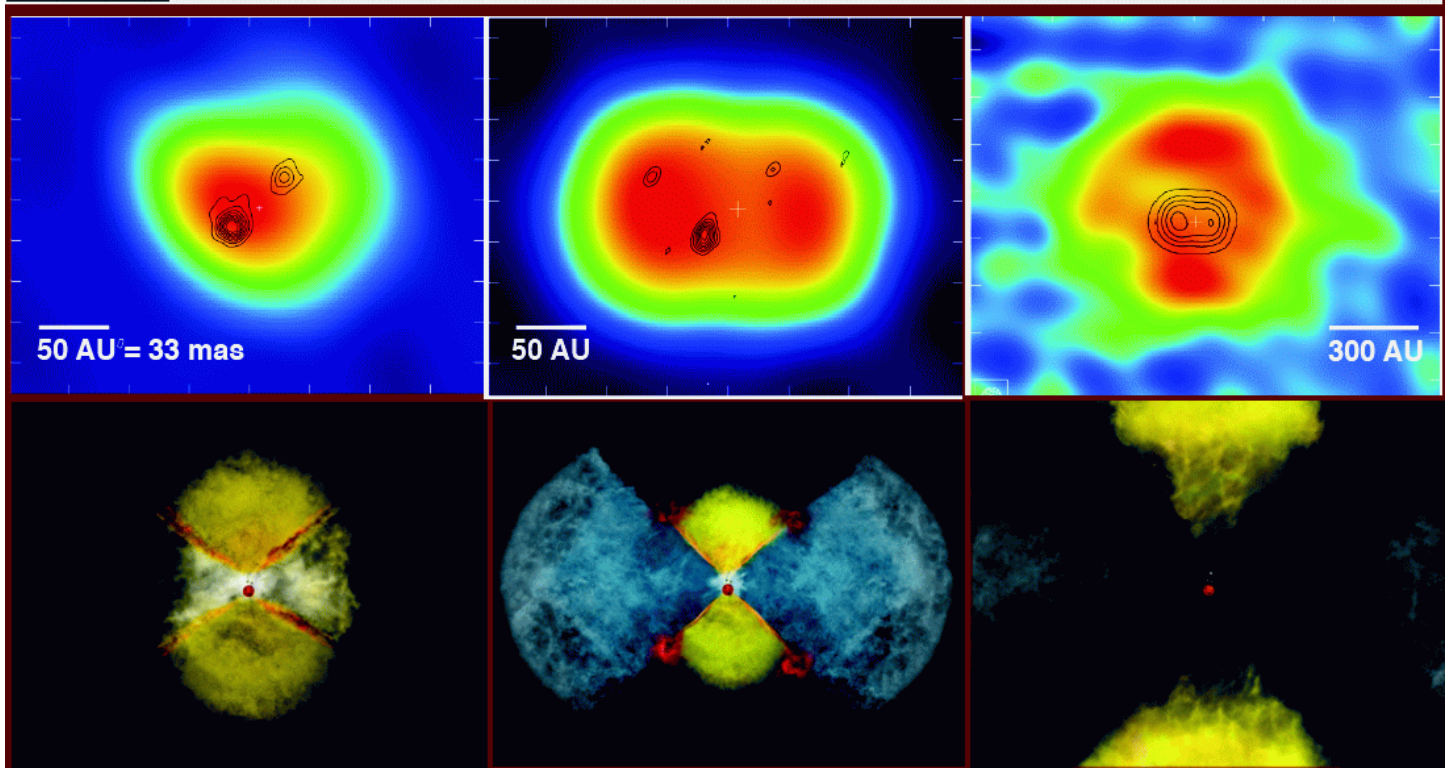
- First “classical” γ-ray nova
  - Note late ID
- Radio behavior fairly typical
  - Note early synchrotron excess



Chomiuk et al. 2014

V959 Mon: two orthogonal flows, with shocks

Color-scale	e-MERLIN Day 87 (54 mas resolution)	VLA Day 126 (43 mas resolution)	VLA Day 615 (106 mas resolution)
Black Contour	EVN Day 91 (7 mas resolution)	EVN Day 113 (7 mas resolution)	VLA Day 126 (43 mas resolution)



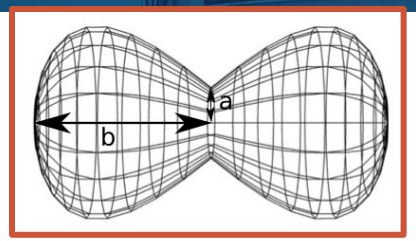
Slow shell ejected first. Interaction with companion enhances mass loss N/S

Thermal ejecta observed with VLA. Emission extended E/W tracing fast ejecta

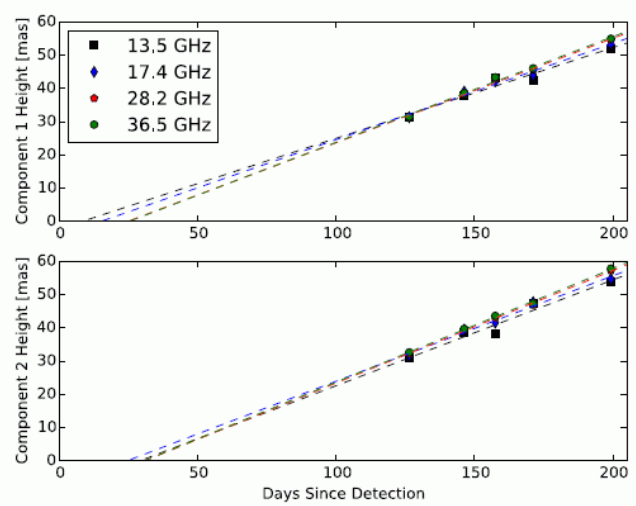
Chomiuk et al. 2014

V959 Mon: a consistent picture

- Optical lines suggest bipolar expansion
- Comparison to radio images gives parallax
- Same model agrees with basics of X-ray emission/absorption (*Nelson et al.*)

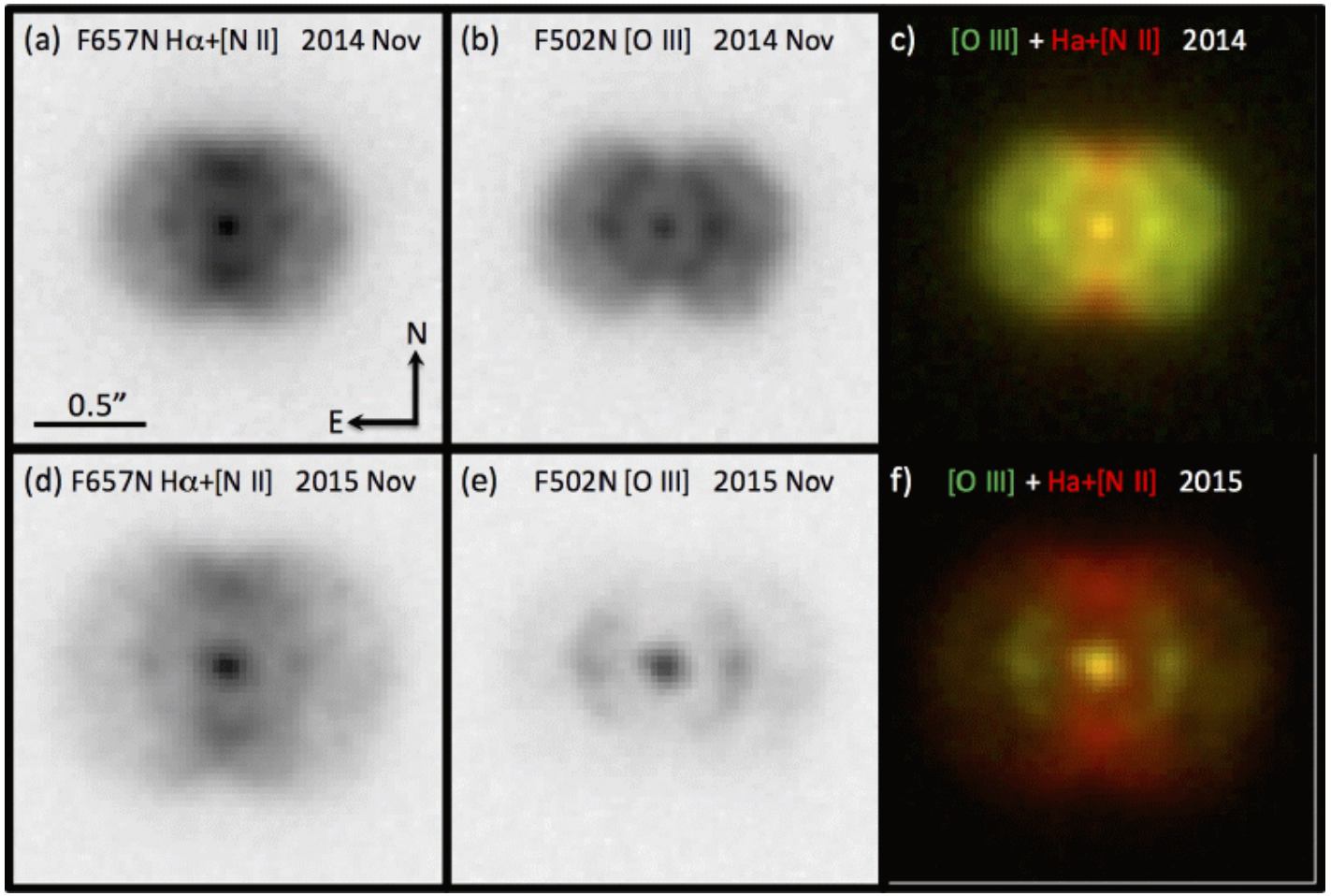


Ribeiro et al. 2013



Linford et al. 2015

V959 Mon: HST & growth of symmetry



Sokoloski et al. 2017

Nova challenges

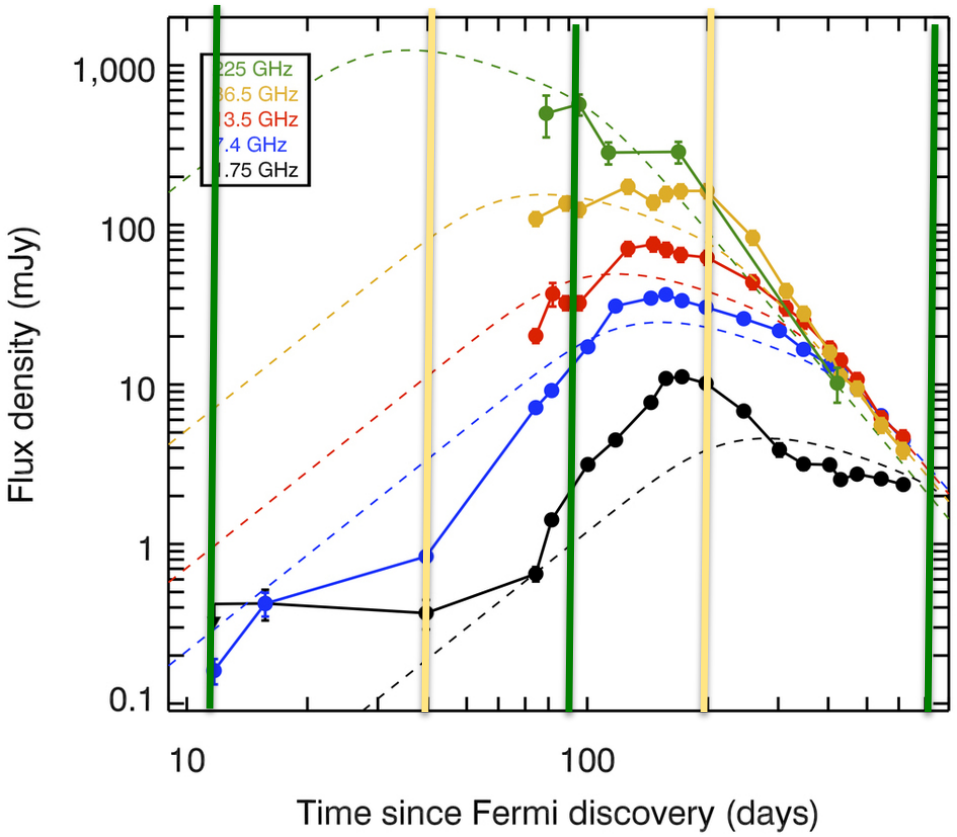
- Confirm or refute the “two-wind” paradigm
  - *Geometry & viewing angle*
  - *Origin of flows*
  - *Common envelope & delayed ejections*
- Importance (and measurement!) of clumping (mass estimates)
- Observational
  - *Why not ν^2 t^2?*
  - *What sets fast rise rate & timing?*
  - *Do we ever see $\nu^{0.1}$?*
- Source of γ-ray emission
  - *Hadronic or leptonic? What explains the range of L_γ?*
- Importance of shocks
  - *Where does the shock energy go?*
  - *Making γ-rays, dust, relativistic particles*
  - *Powering optical*

The next steps in the radio

- The next few years
  - *More sources*
  - *More consistent (esp. earlier) coverage*
  - *More consistent modeling*
  - *Imaging, imaging, imaging*
  - *Correlations across wavelengths (γ-rays, X-rays [0.1-100 keV], optical, IR, …)*
  - *Radio recombination lines*
  - *ALMA: thermal emission, dust, molecules*
  - *A nearby northern nova!*

- The next decade(s)
  - *Sensitivity -- samples & sources*
  - *Imaging, imaging, imaging – spatial dynamic range, full sampling, wide frequency range*
  - *Radio light echoes (continuum & line)*

ngVLA: the ideal instrument



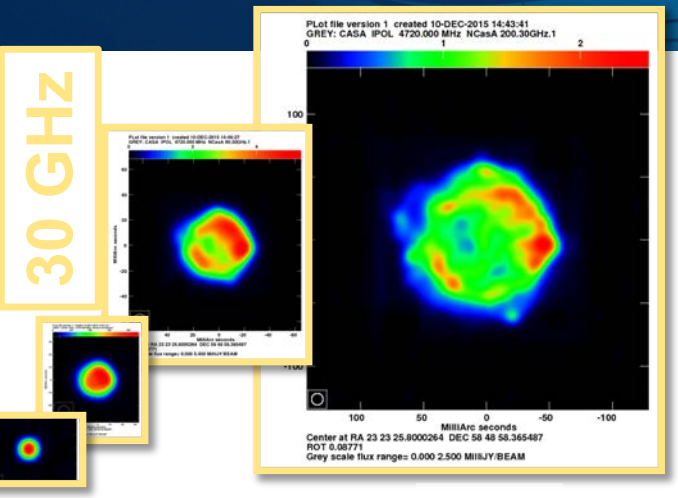
ngVLA, 1 hr/epoch

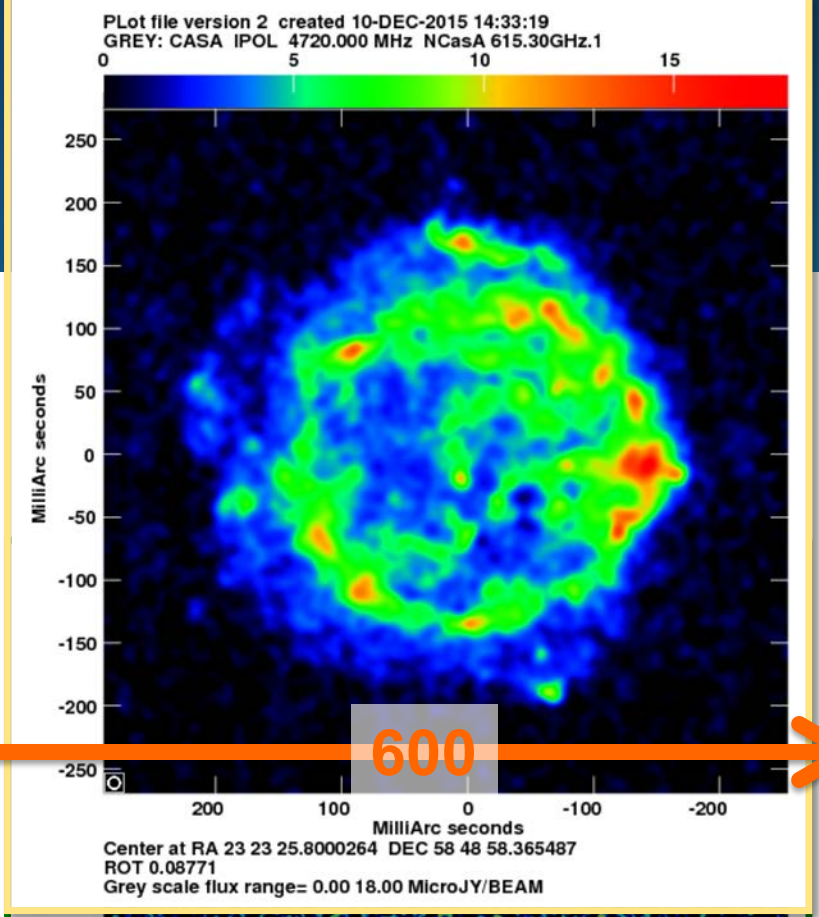
30 GHz

100 GHz

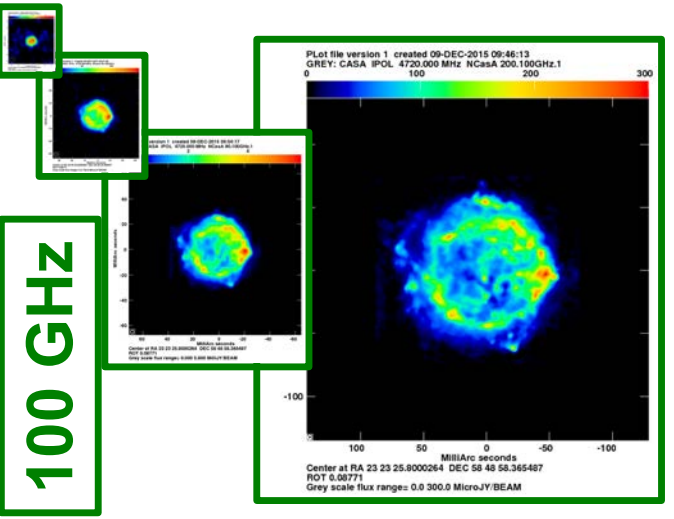
- VLA flux densities (worst-case spectra)
- 0.6 mas/day (1000km/s@1kpc)

Nova ngCas A

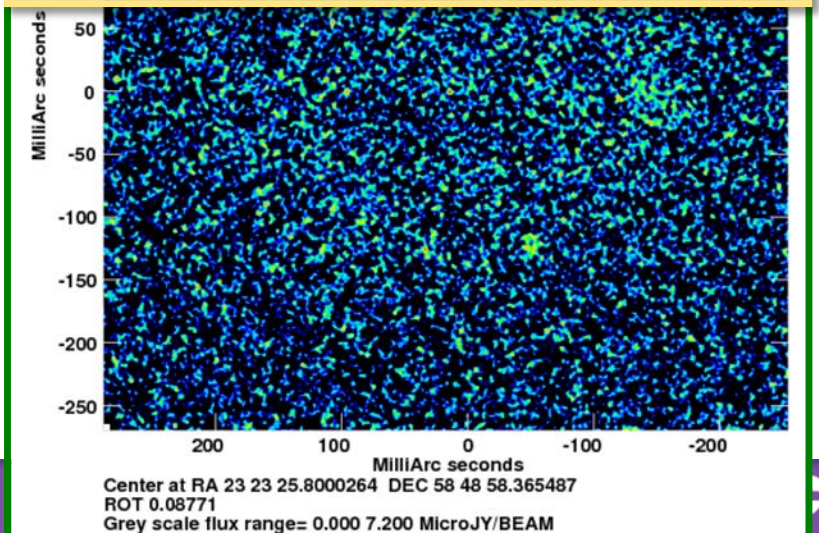




10 200 600



Age



Questions?

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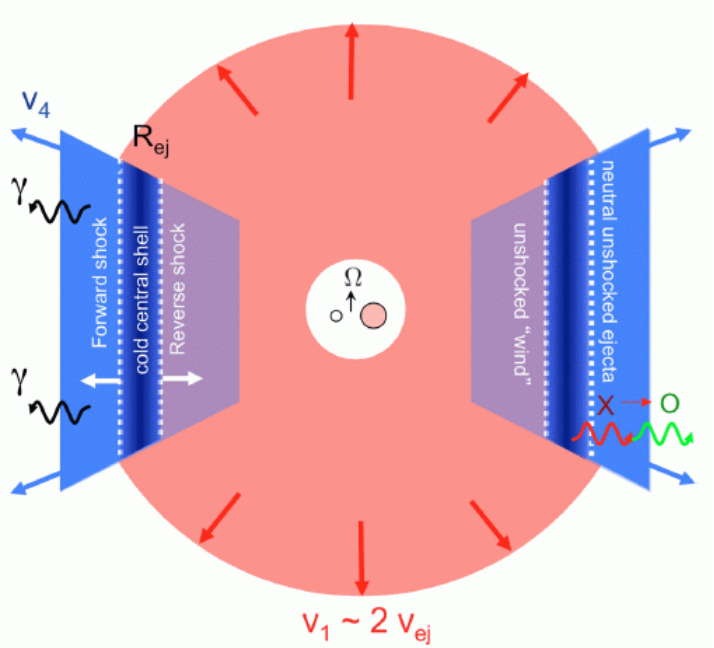
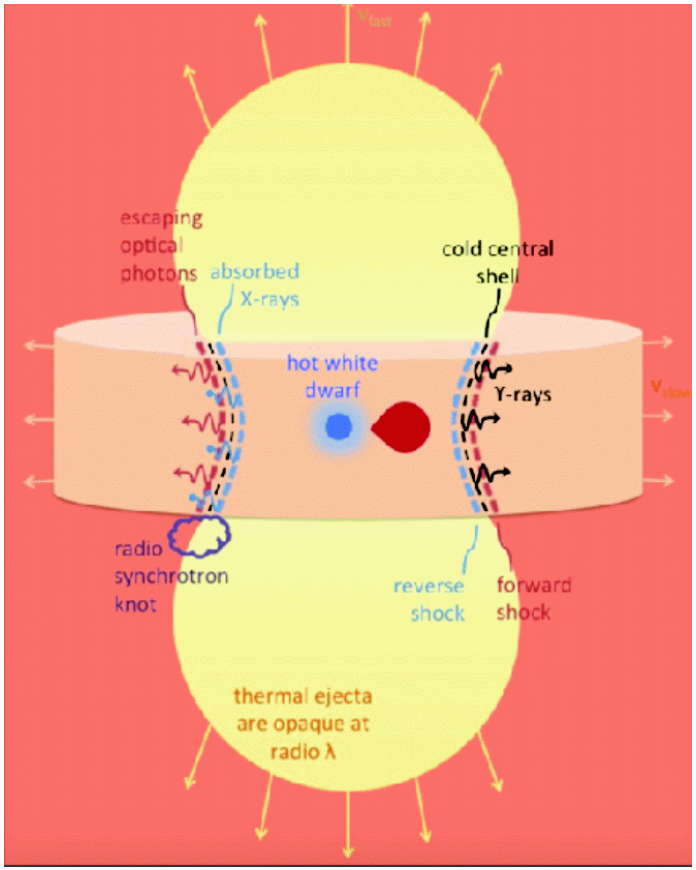
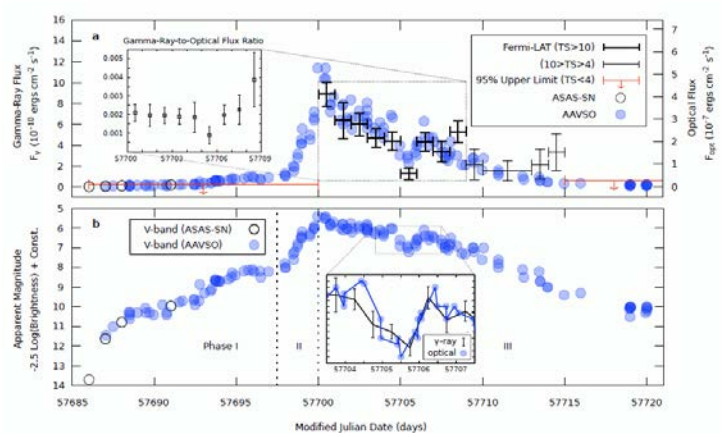
Metzger cartoons



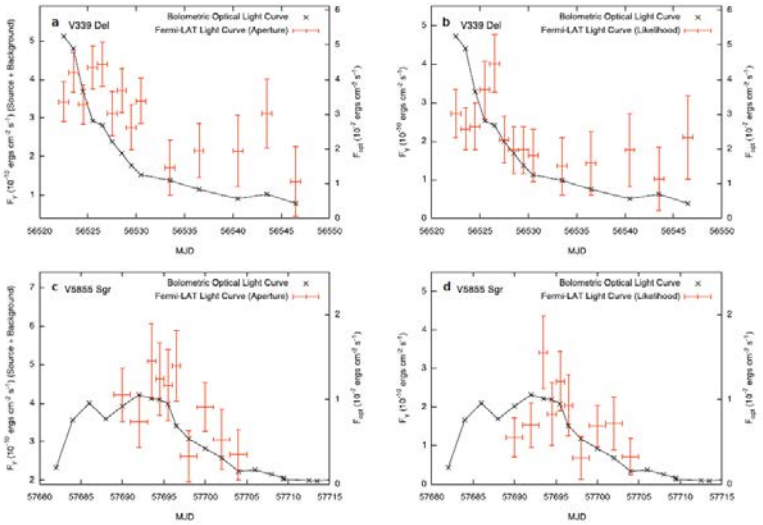
Metzger et al. 2015

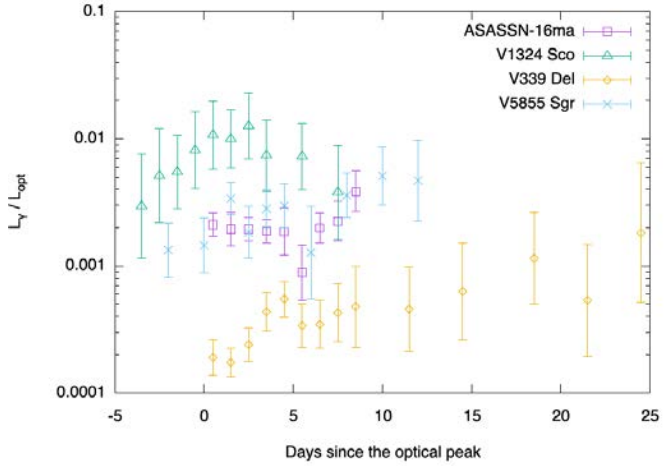


V5856 Sgr 2016: Gamma-rays track optical

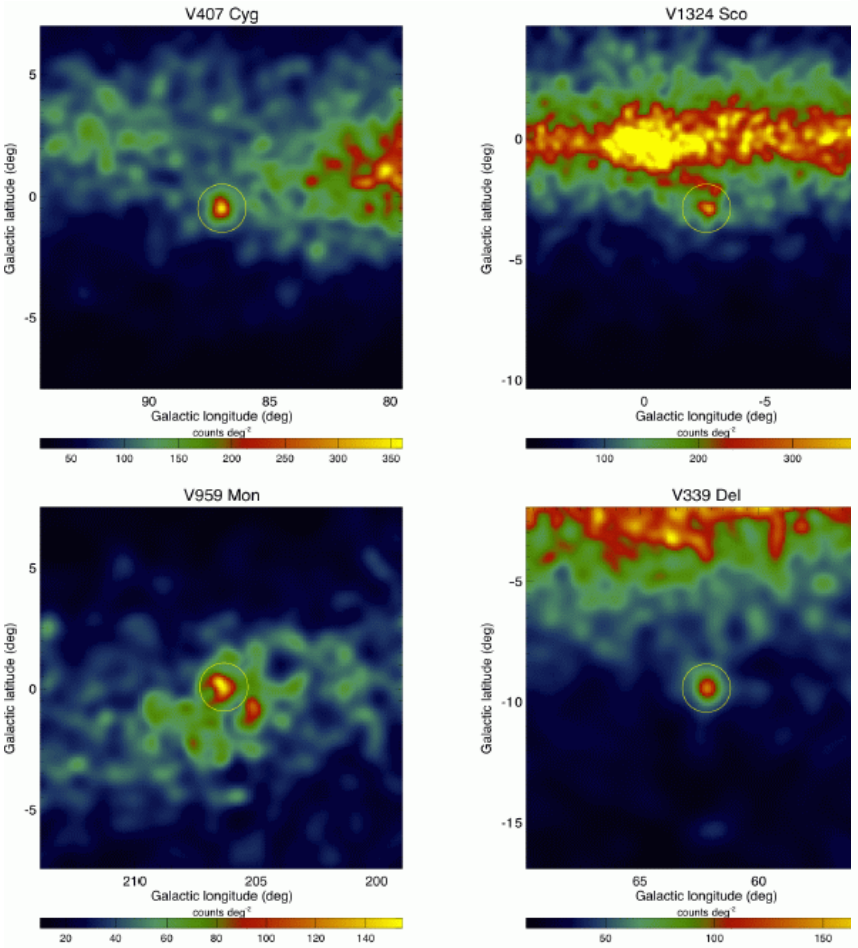


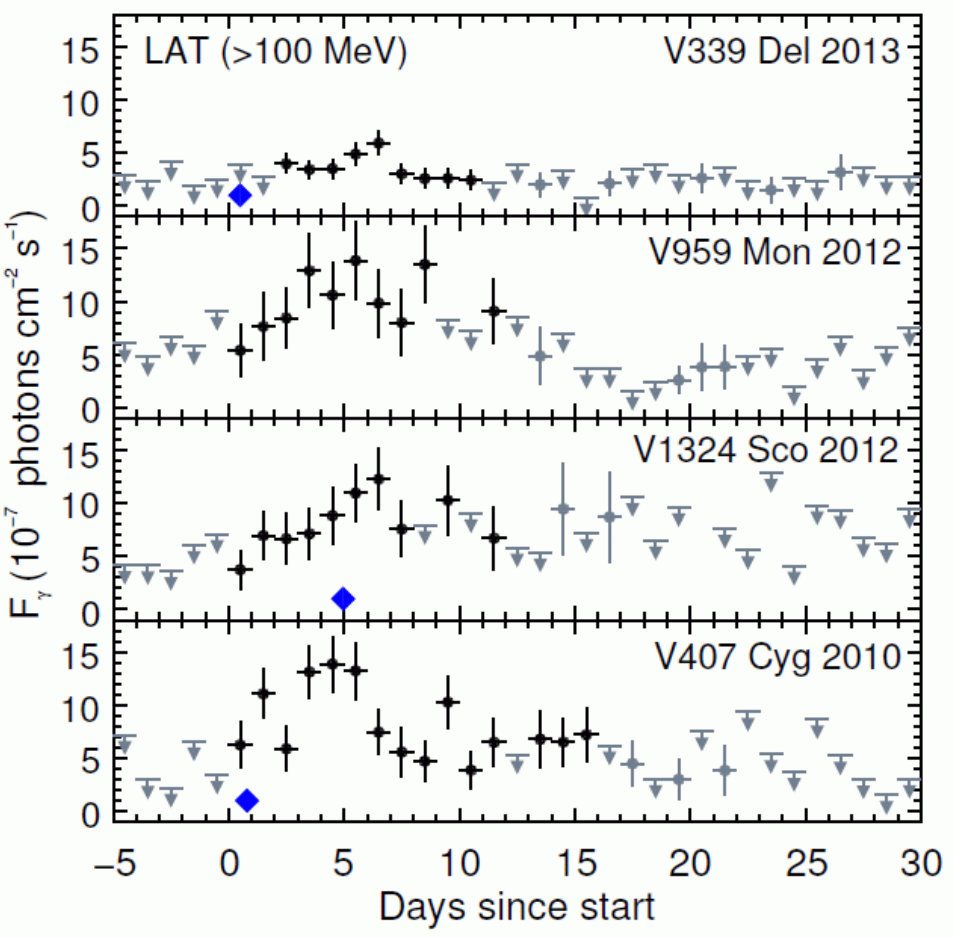
Li et al. 2017





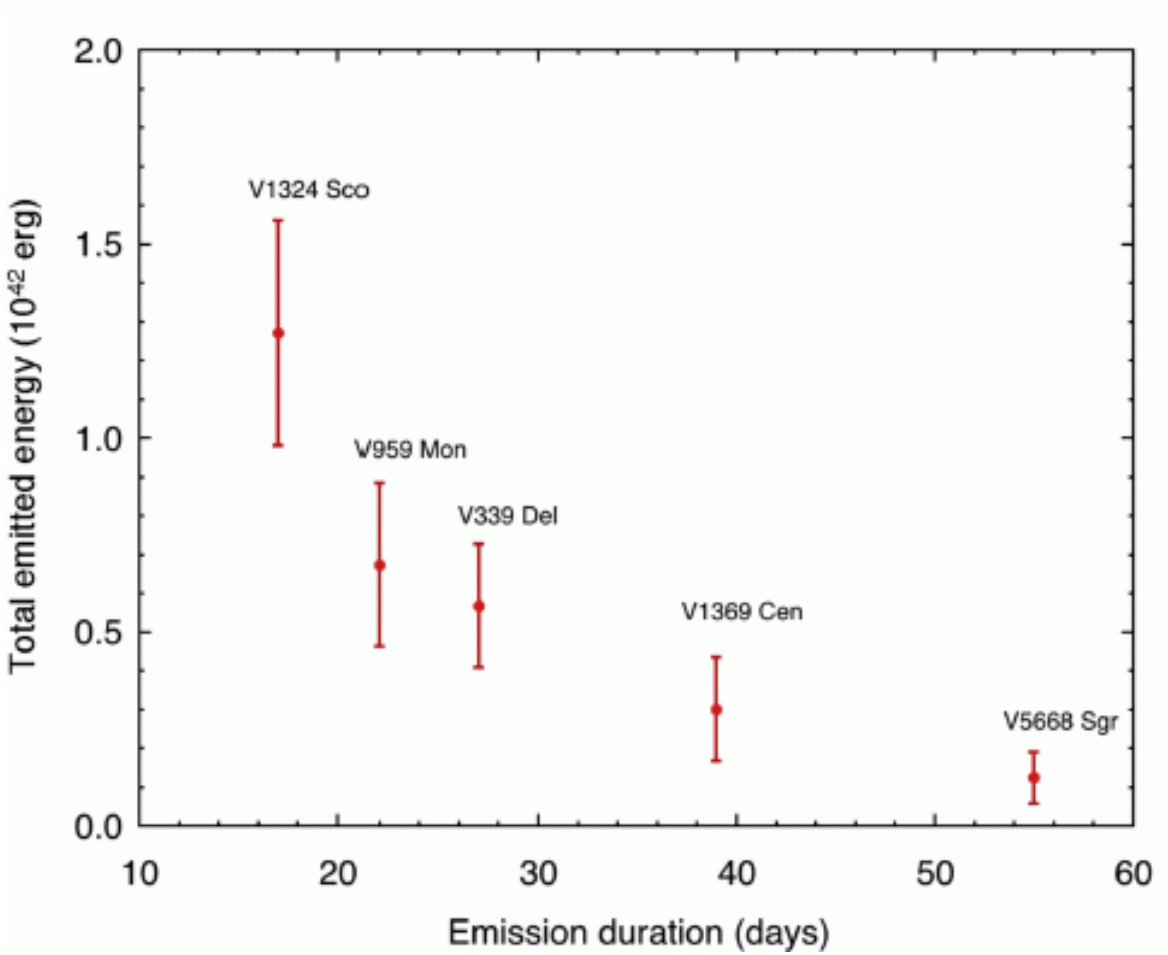
Gamma-rays from novae





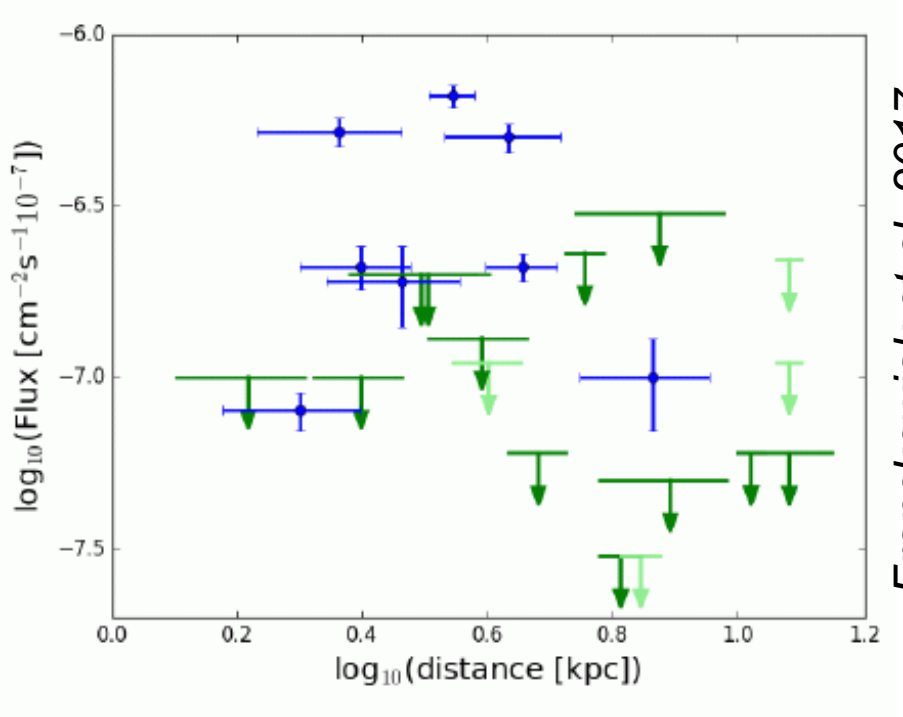
Ackermann et al. 2014

Gamma-rays from novae: not standard candles

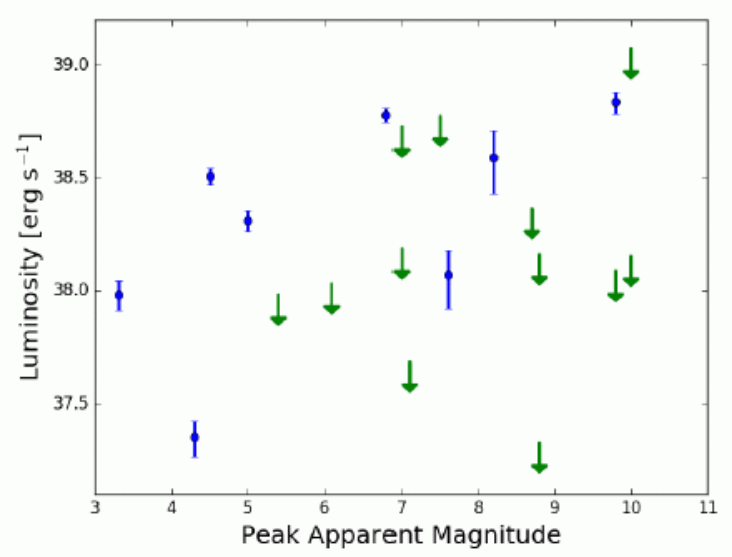


Cheung et al. 2016

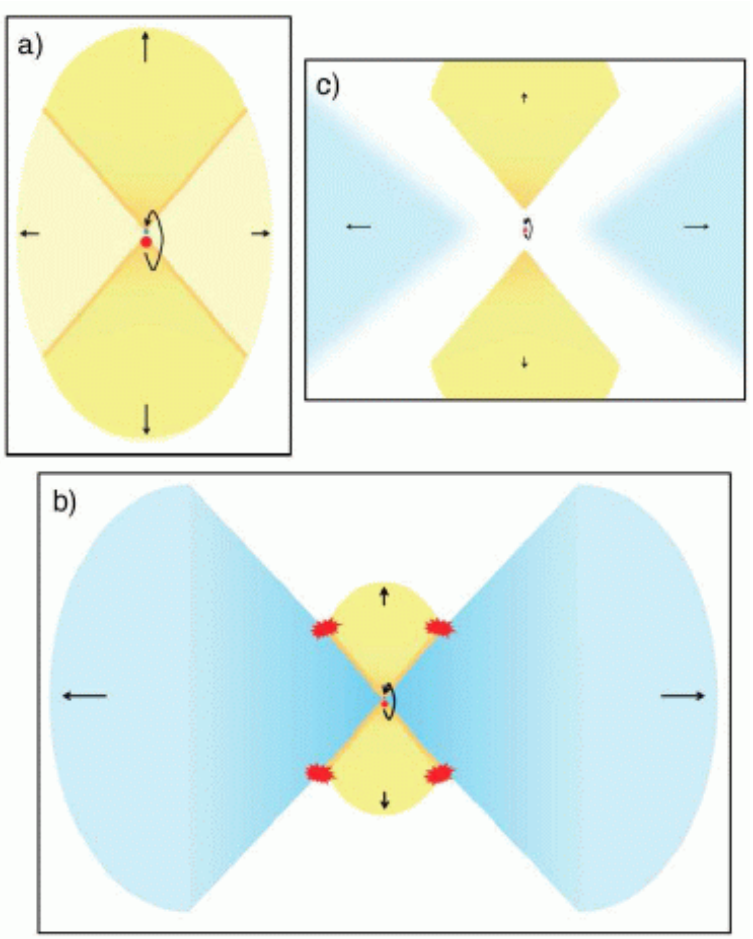
Gamma-ray novae: not standard candles



Franckowiak et al. 2017



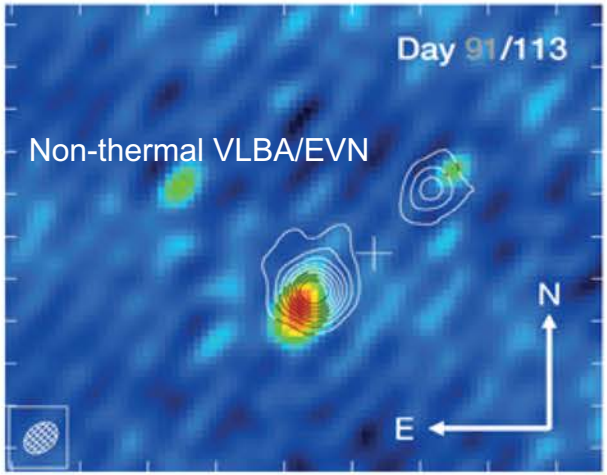
V959 Mon cartoon

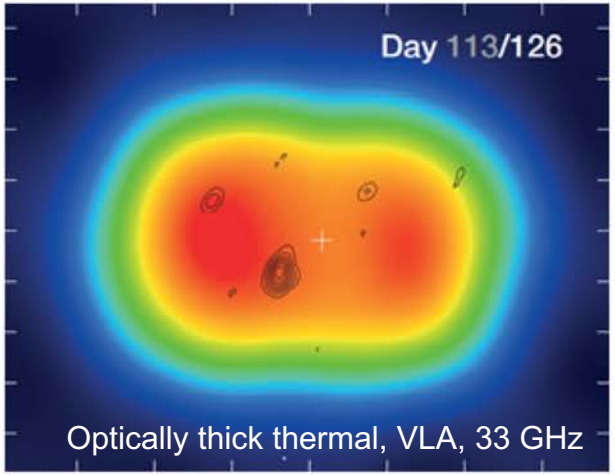


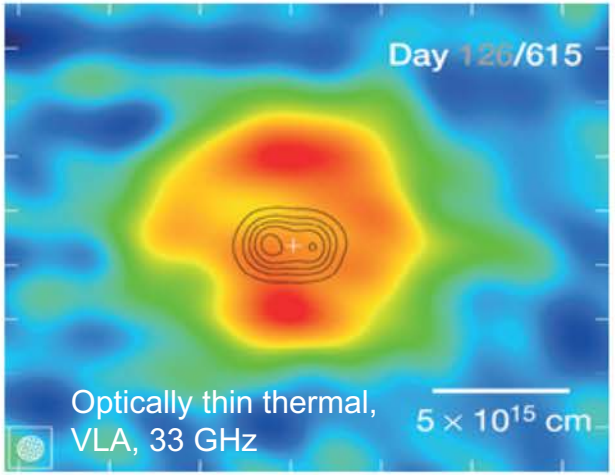
Chomiuk et al. 2012

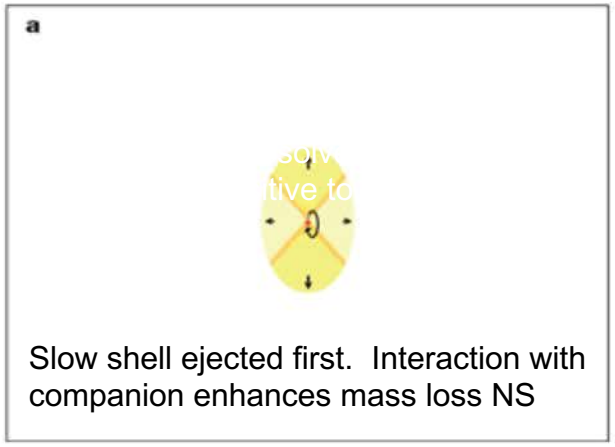
V959 Mon

Chomiuk et al. 2014

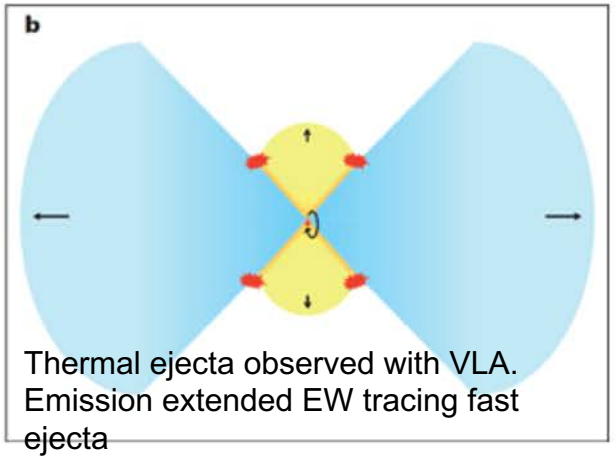




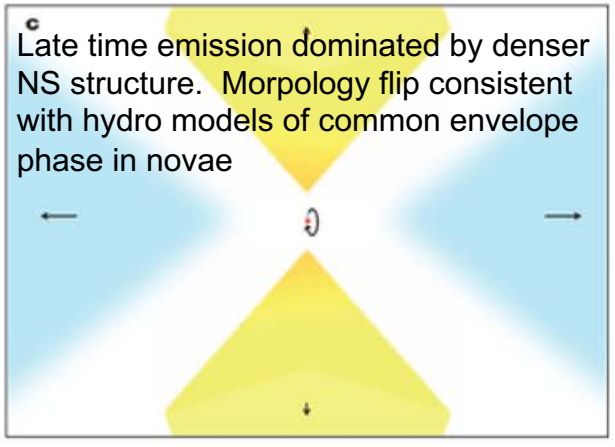




Slow shell ejected first. Interaction with companion enhances mass loss NS



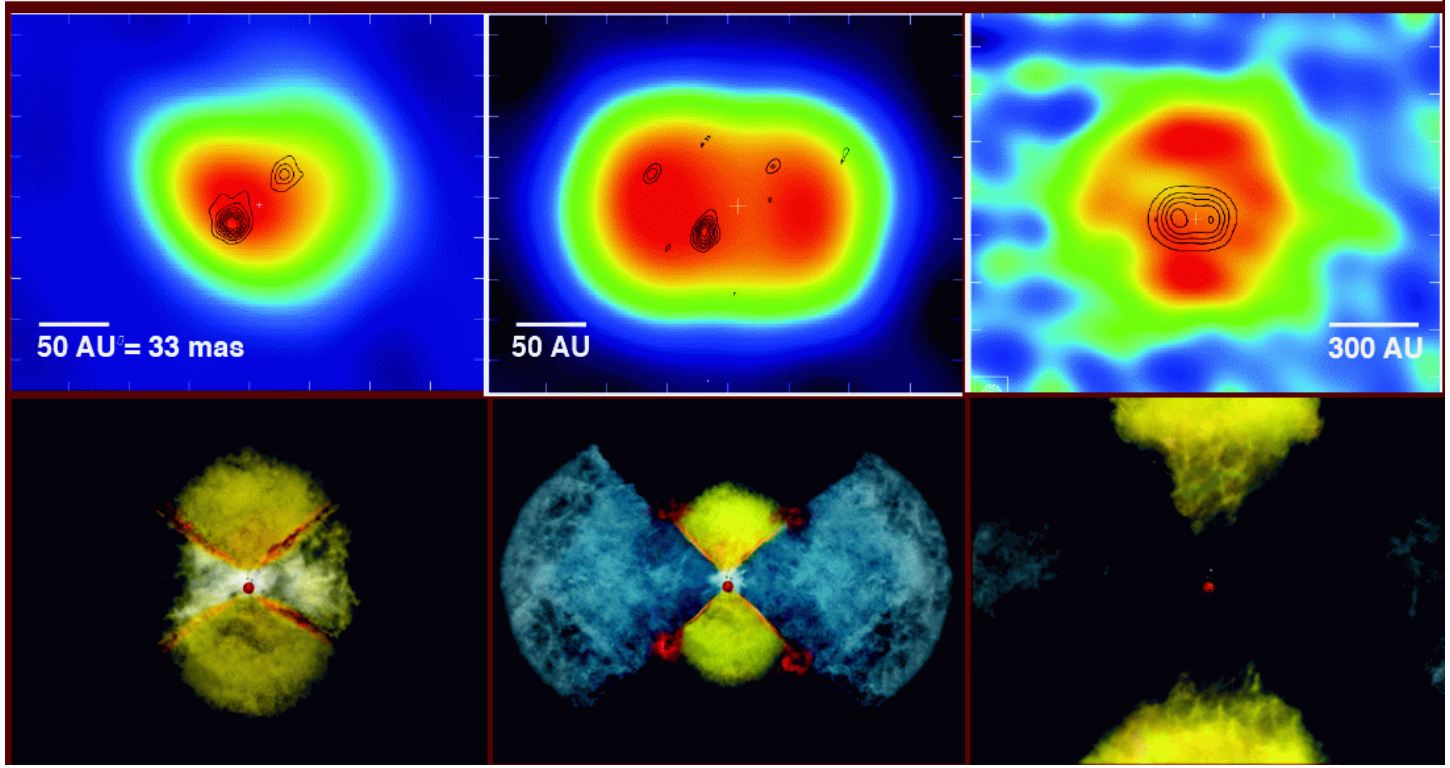
Thermal ejecta observed with VLA. Emission extended EW tracing fast ejecta



Late time emission dominated by denser NS structure. Morpology flip consistent with hydro models of common envelope phase in novae

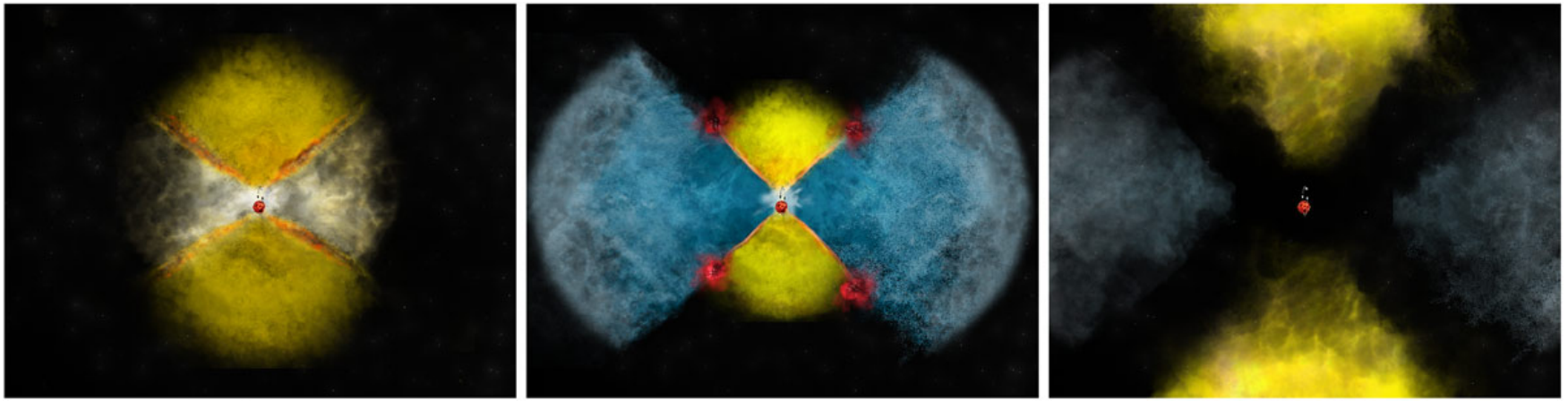
V959 Mon

Color-scale	e-MERLIN Day 87 (54 mas resolution)	VLA Day 126 (43 mas resolution)	VLA Day 615 (106 mas resolution)
Black Contour	EVN Day 91 (7 mas resolution)	EVN Day 113 (7 mas resolution)	VLA Day 126 (43 mas resolution)



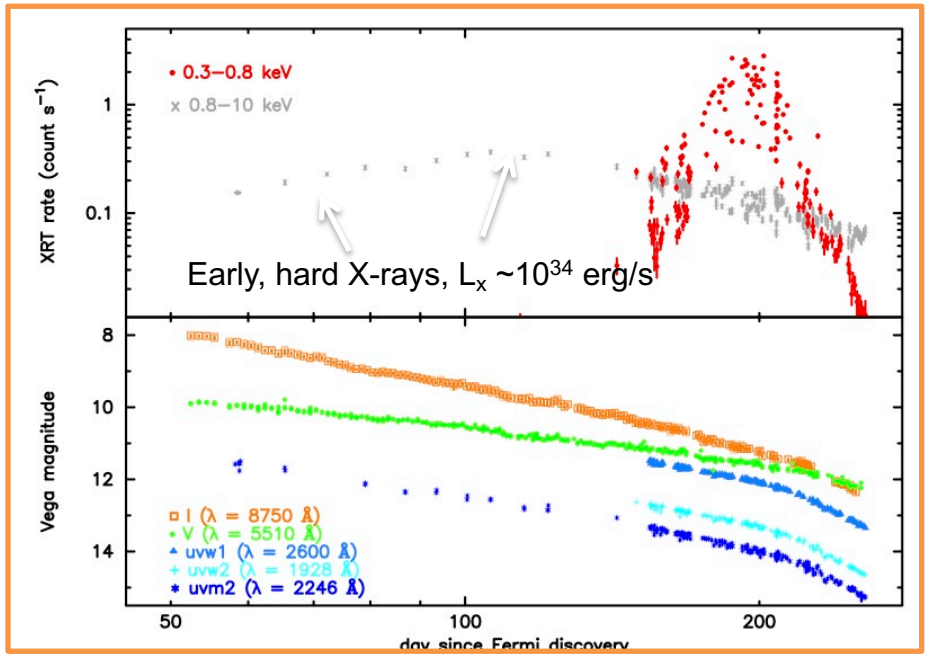
Chomiuk et al. 2014

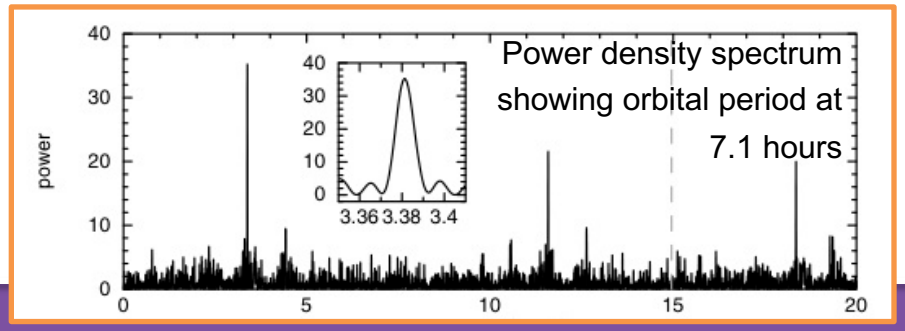
V959 Mon: NRAO cartoon



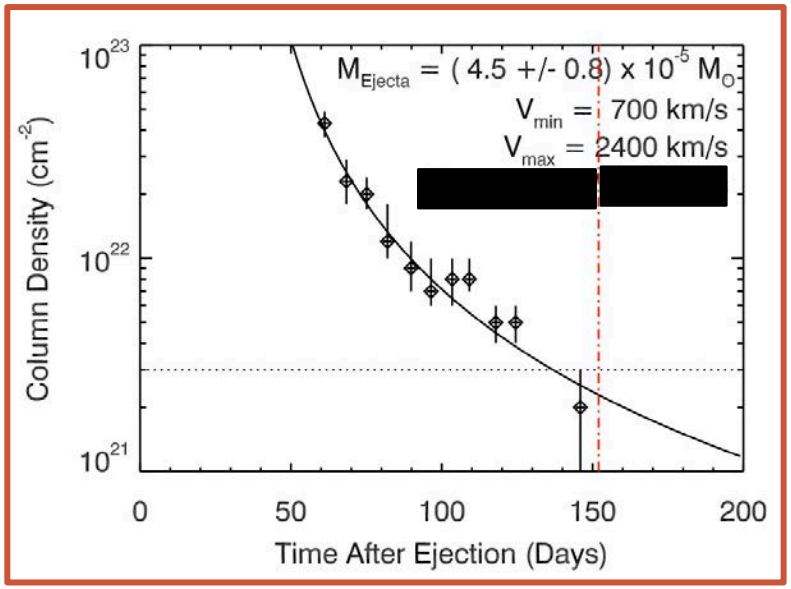
V959 Mon: X-ray observations

Page et al. 2013: V959 Mon XRT, UVOT and ground-based optical light curves



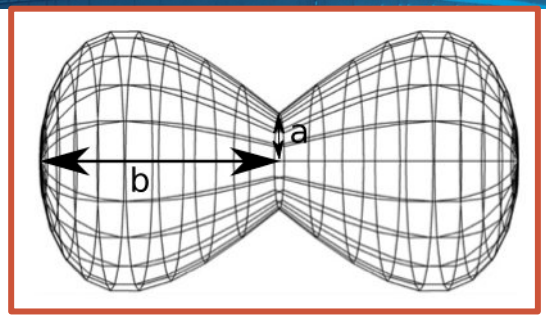


X-ray flux rules out thermal origin for VLBA knots

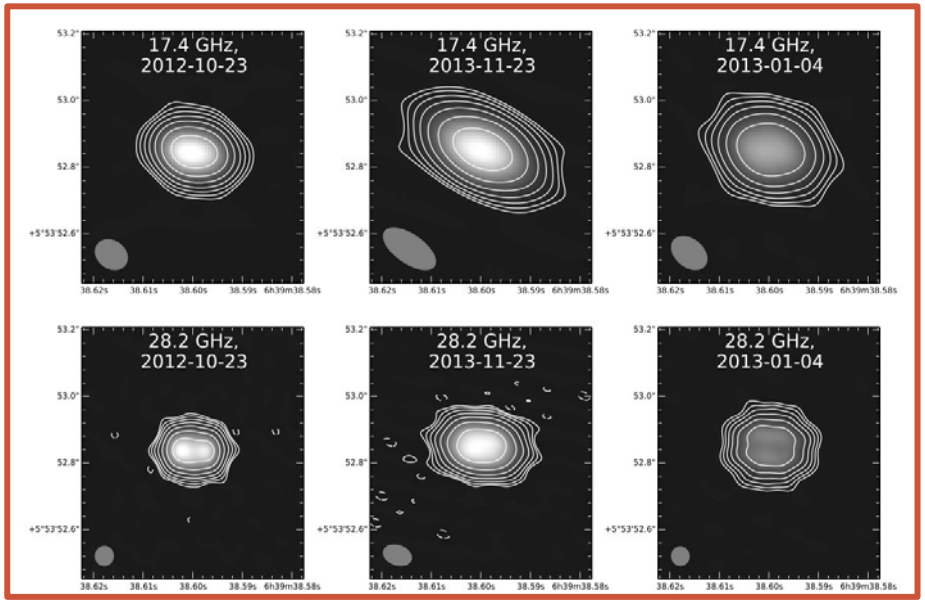


N(H) evolution consistent with internal shock and an ejected mass of at least a few 10^{-5} $M_\odot$ (Nelson et al., in prep)

V959 Mon expansion parallax

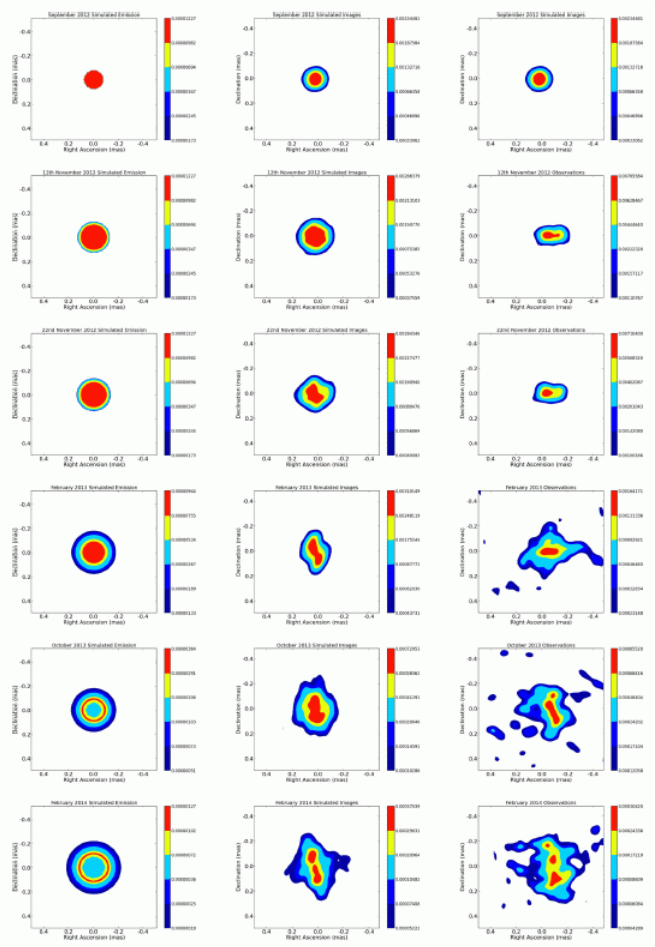


Expansion observed in radio images



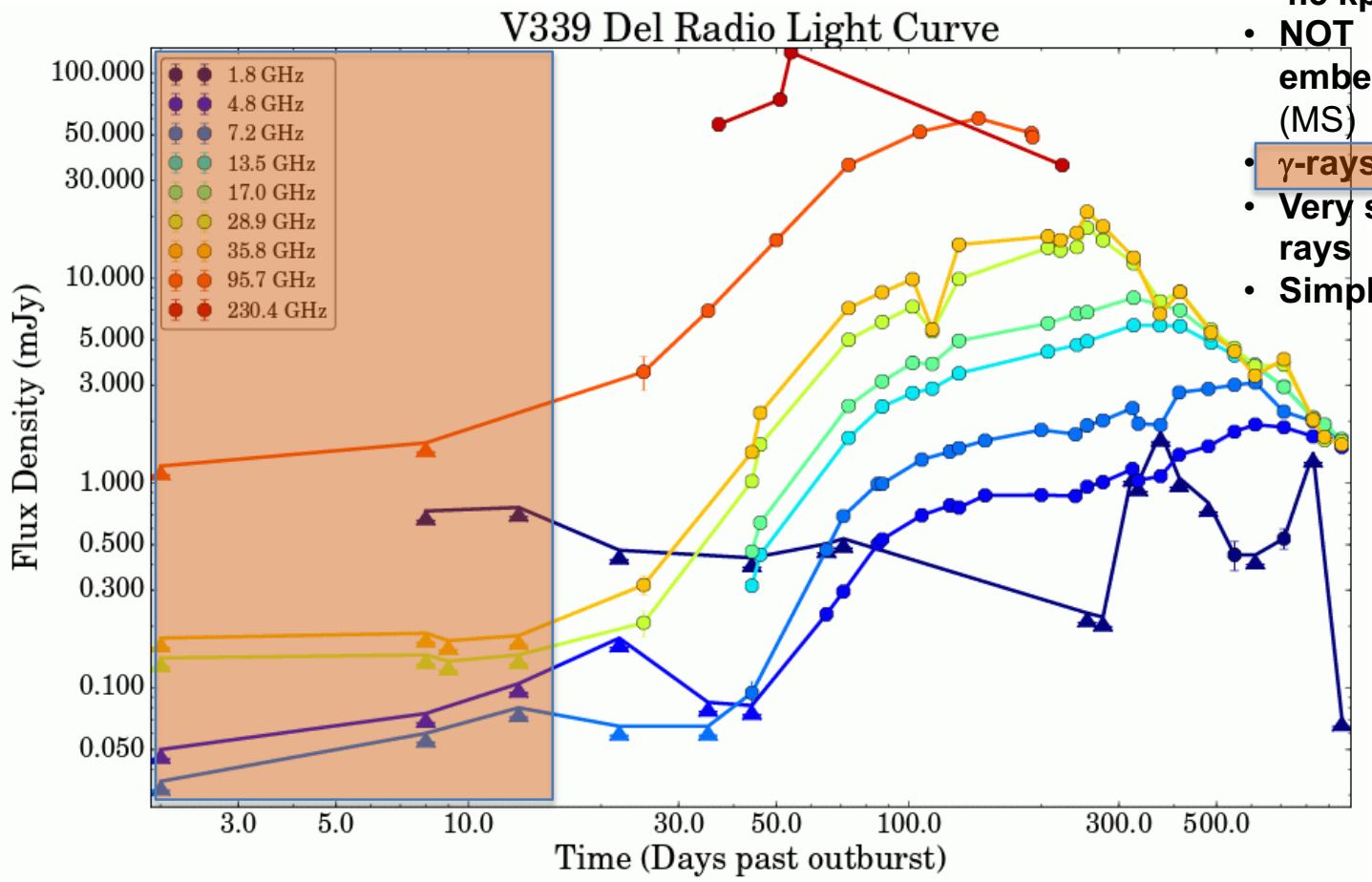
- Ribeiro et al. (2013) created morpho-kinematic model of ejecta in V949 Mon that explains emission line structure and hence *velocities* of the ejecta
- We are using the same model to interpret the radio images
- Comparing observed images to simulations, we constrain the distance to V949 Mon to be 1.4 (+0.9,-0.5) kpc (Linford et al., in prep)
- **Revises gamma-ray luminosity down to 6 x 10^{34} erg/s**

V959 Mon: perils of eMERLIN



Healy et al. 2016

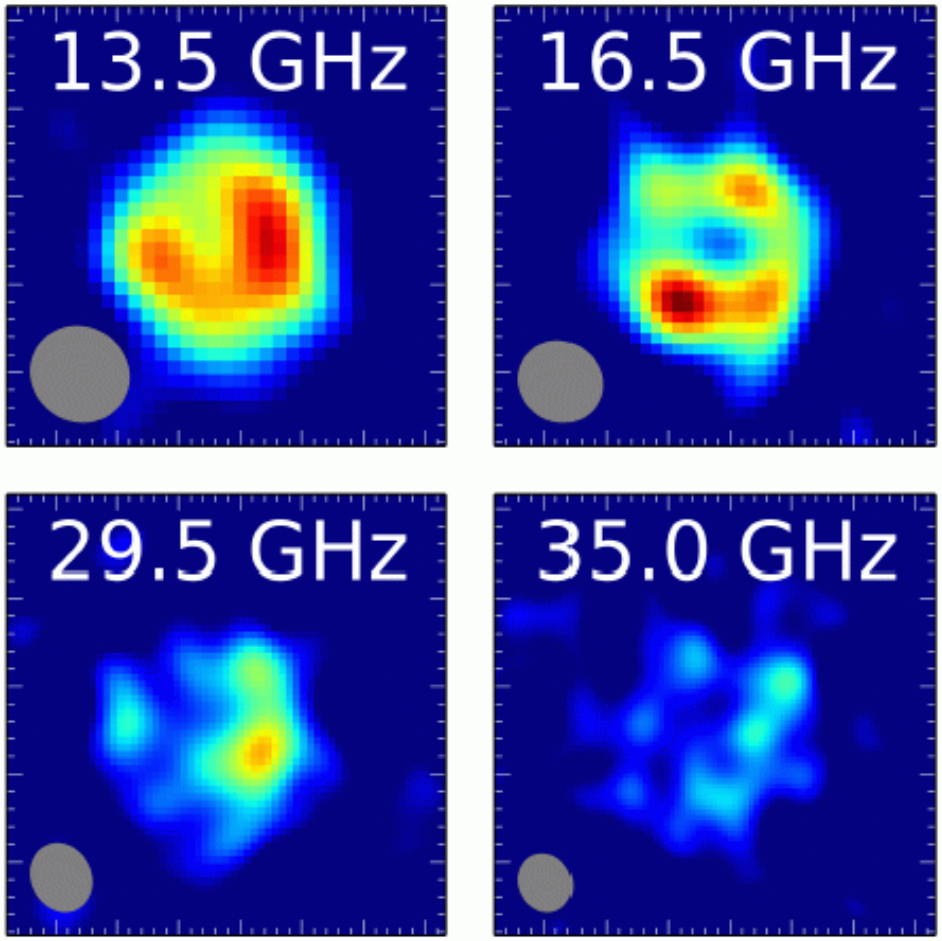
V339 Del 2013



- **4.5 kpc??**
- **NOT embedded** (MS)
- **γ-rays**
- **Very soft X-rays**
- **Simple radio**

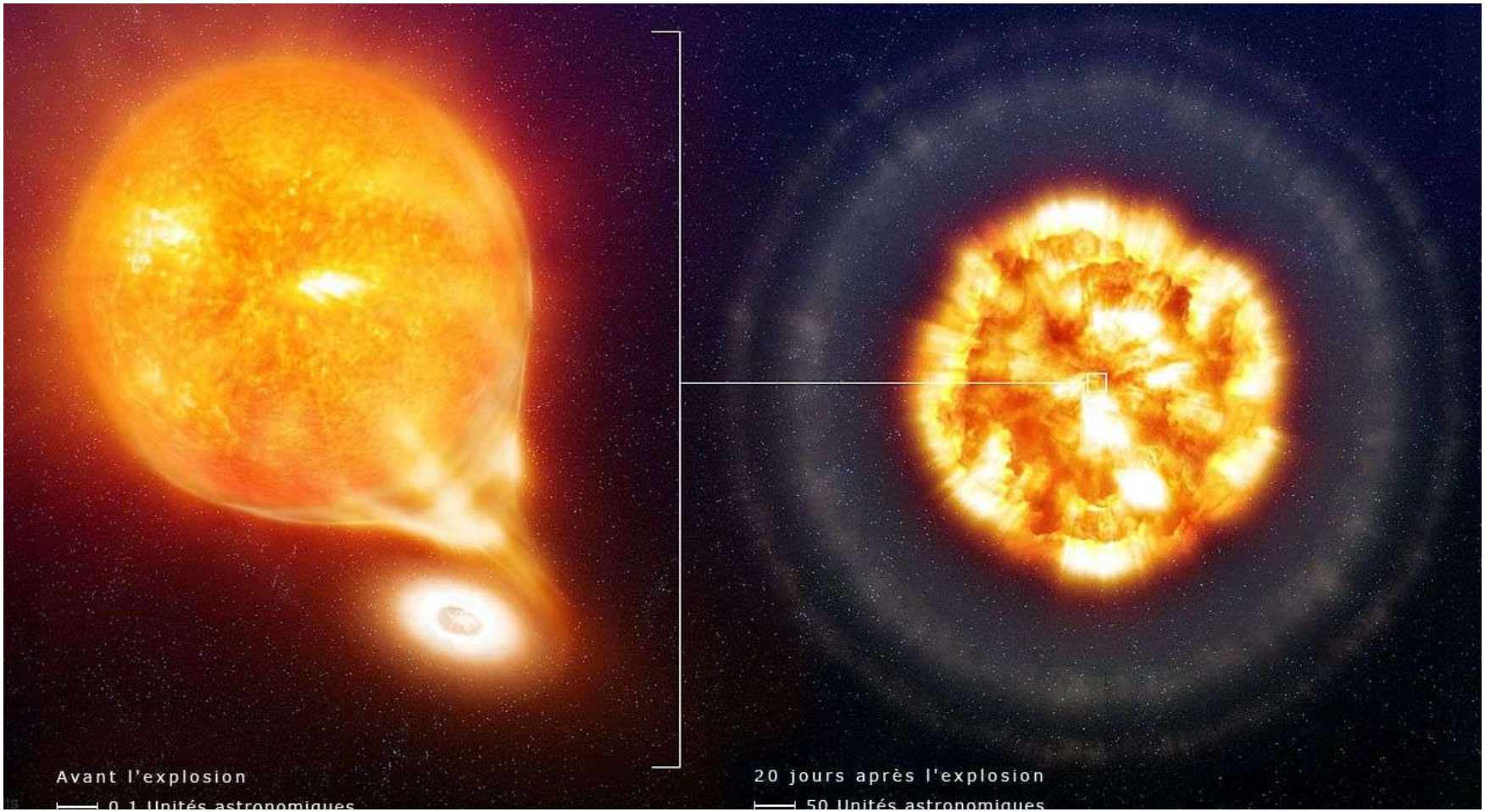
eNova collaboration 22apr2016

V339 Del 2013

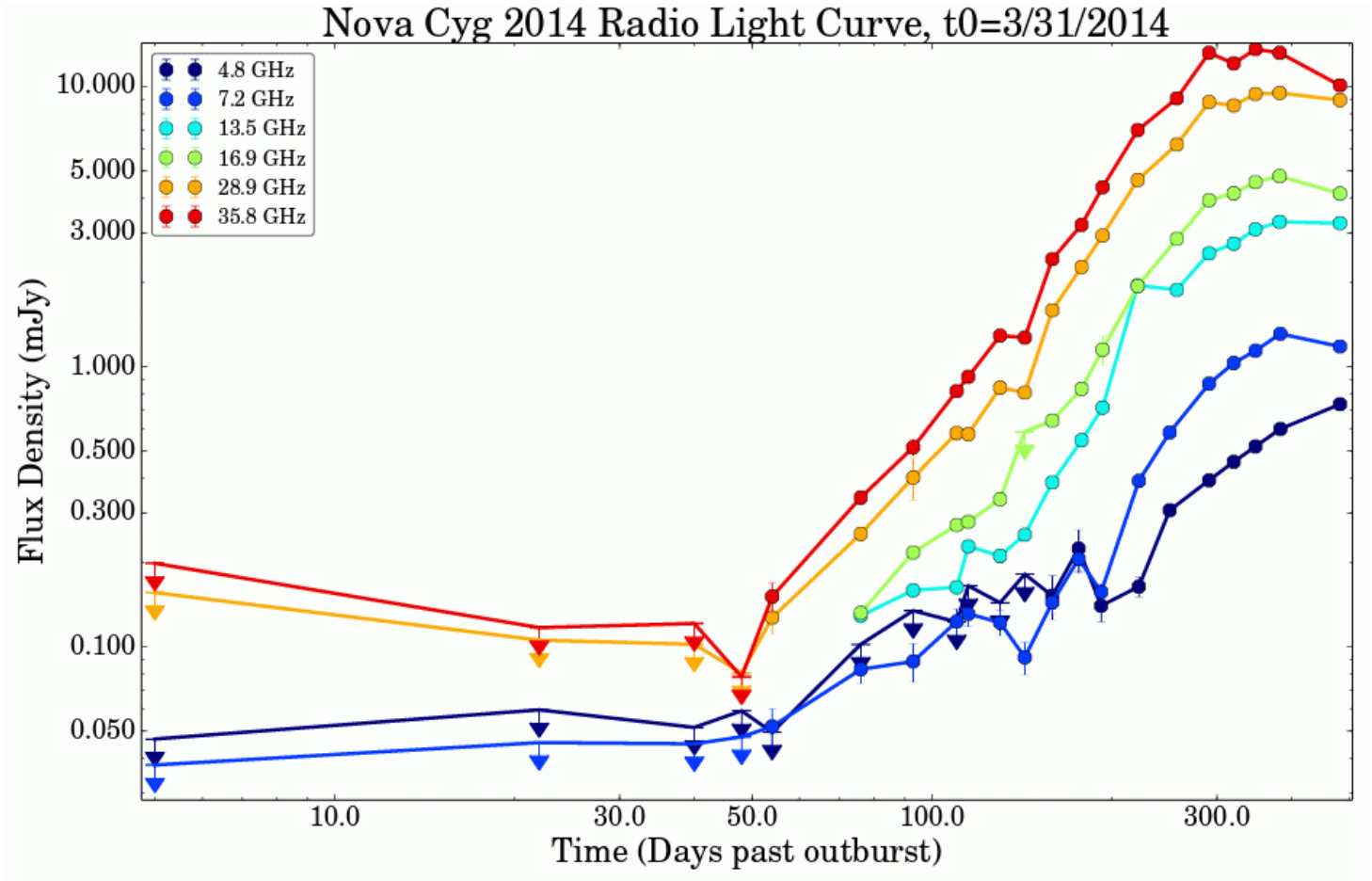


eNova collaboration 2017

V339 Del: ESO art

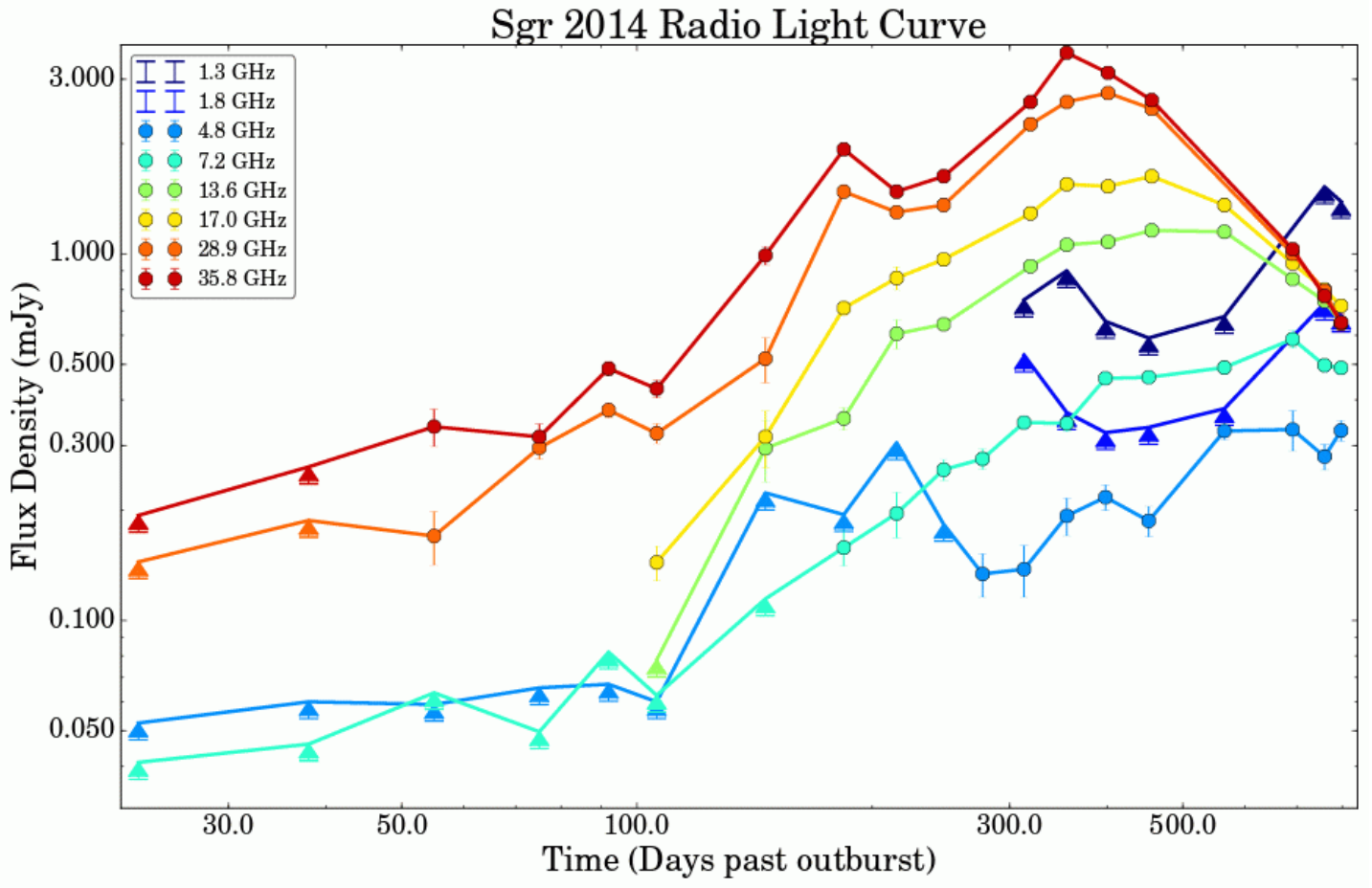


V2659 Cyg 2014



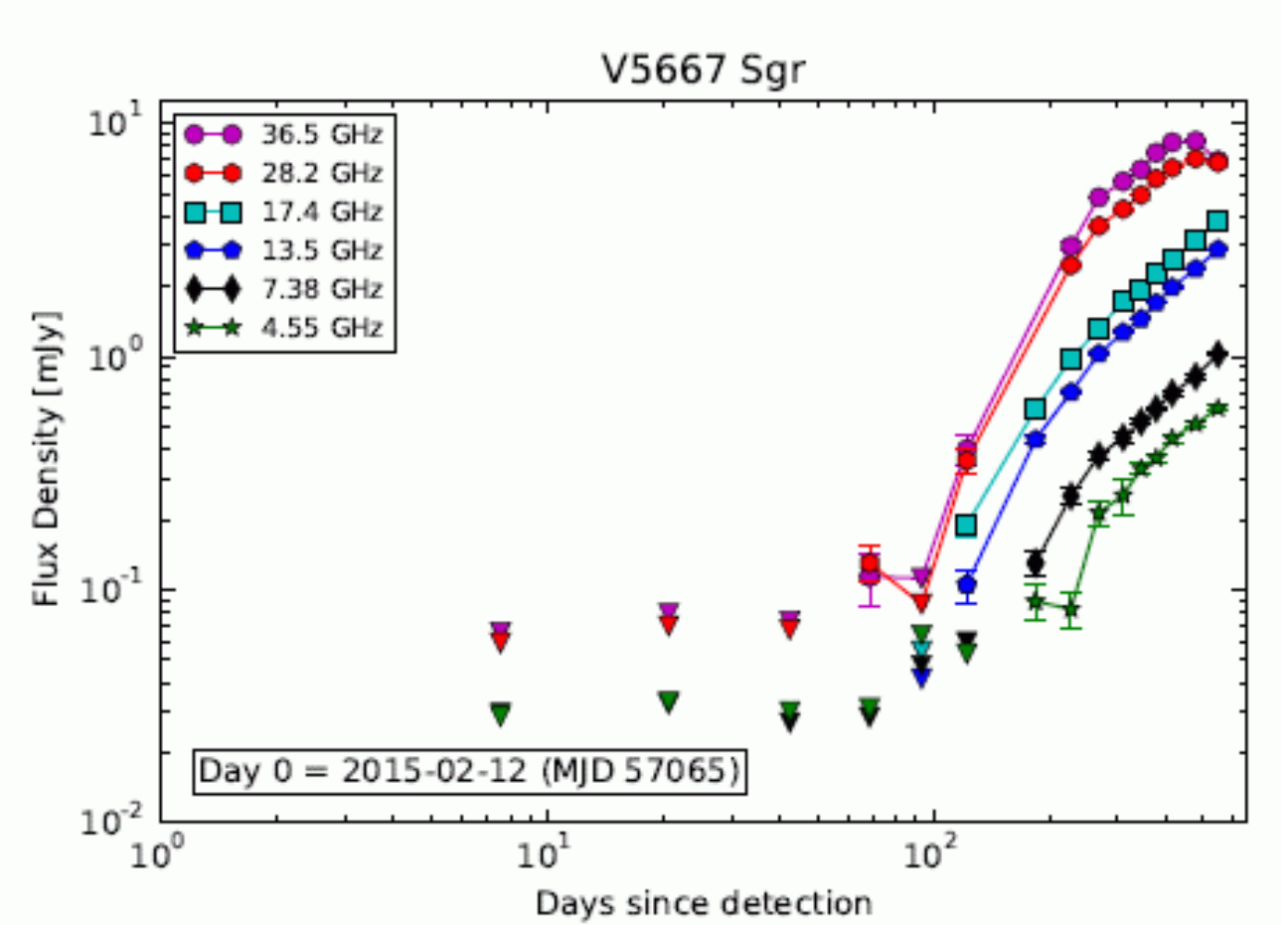
eNova collaboration
17nov2015

V5666 Sgr 2014



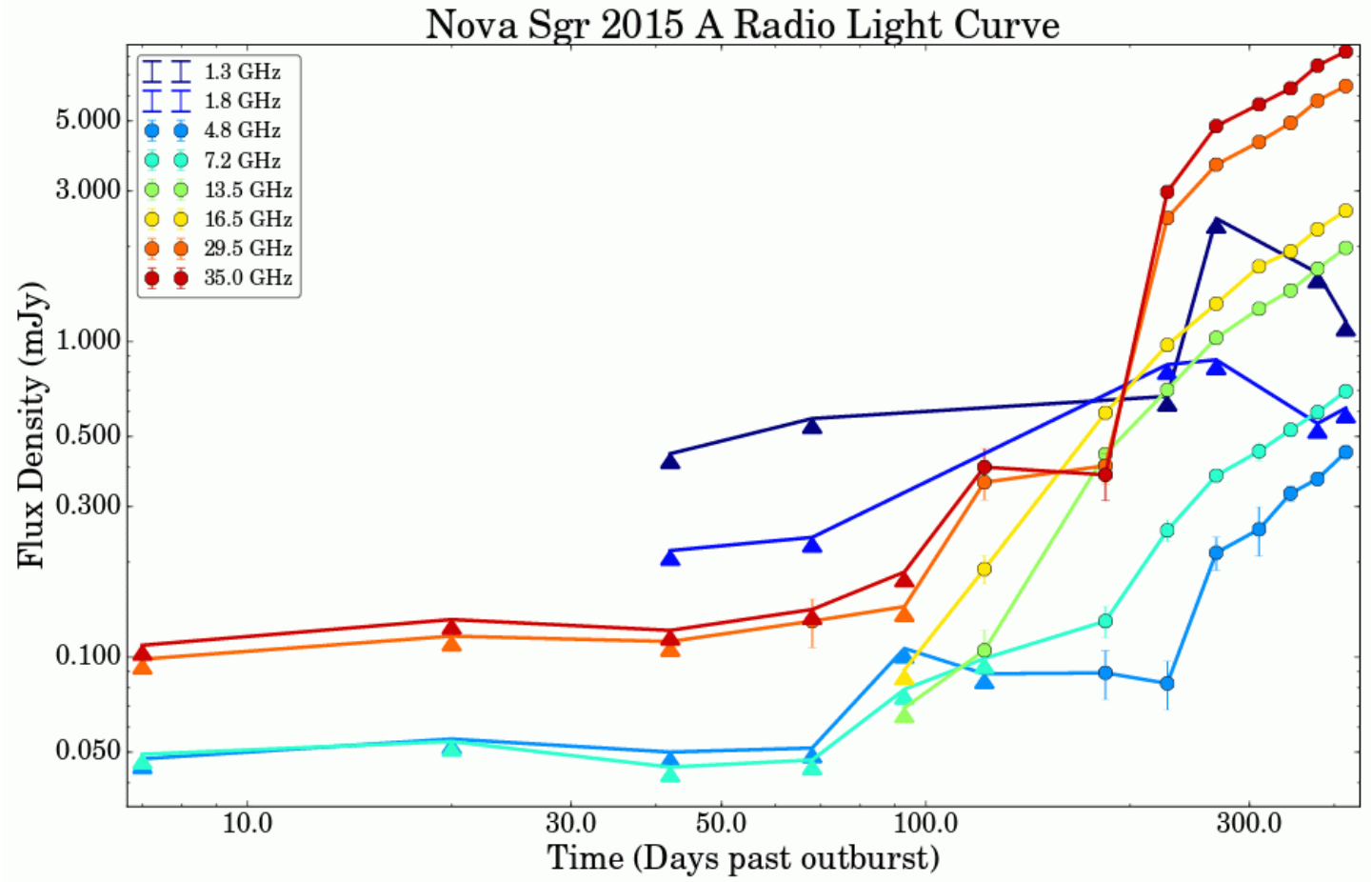
eNova collaboration 22apr2016

V5667 Sgr 2015



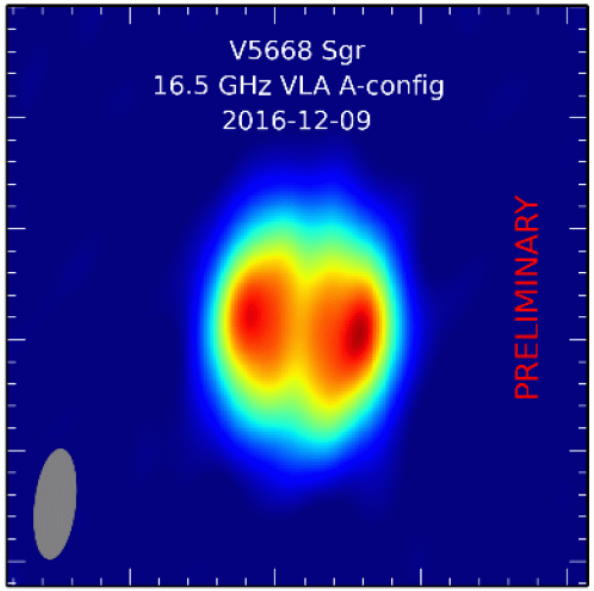
eNova collaboration 2017

V5667 Sgr 2015

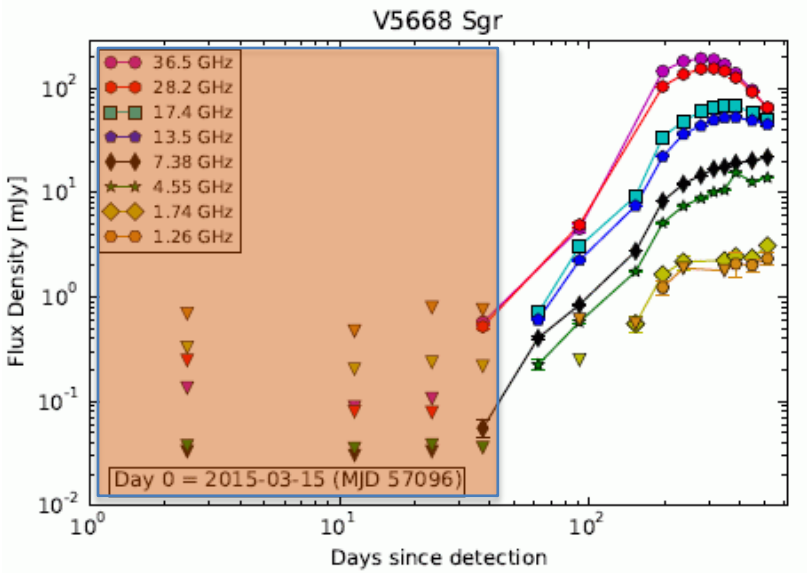


eNova collaboration 22apr2016

V5668 Sgr 2015

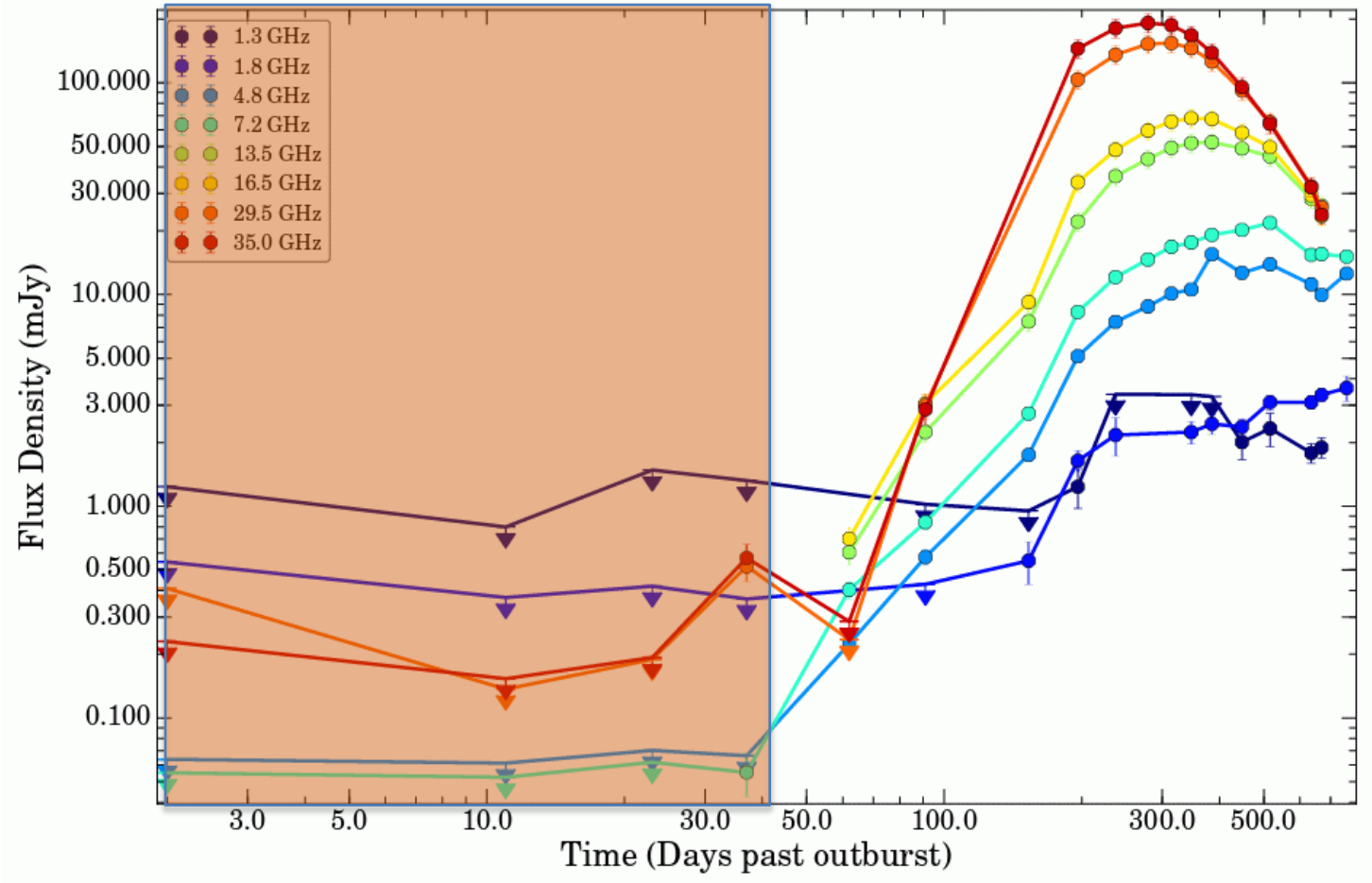


Linford et al. in prep.

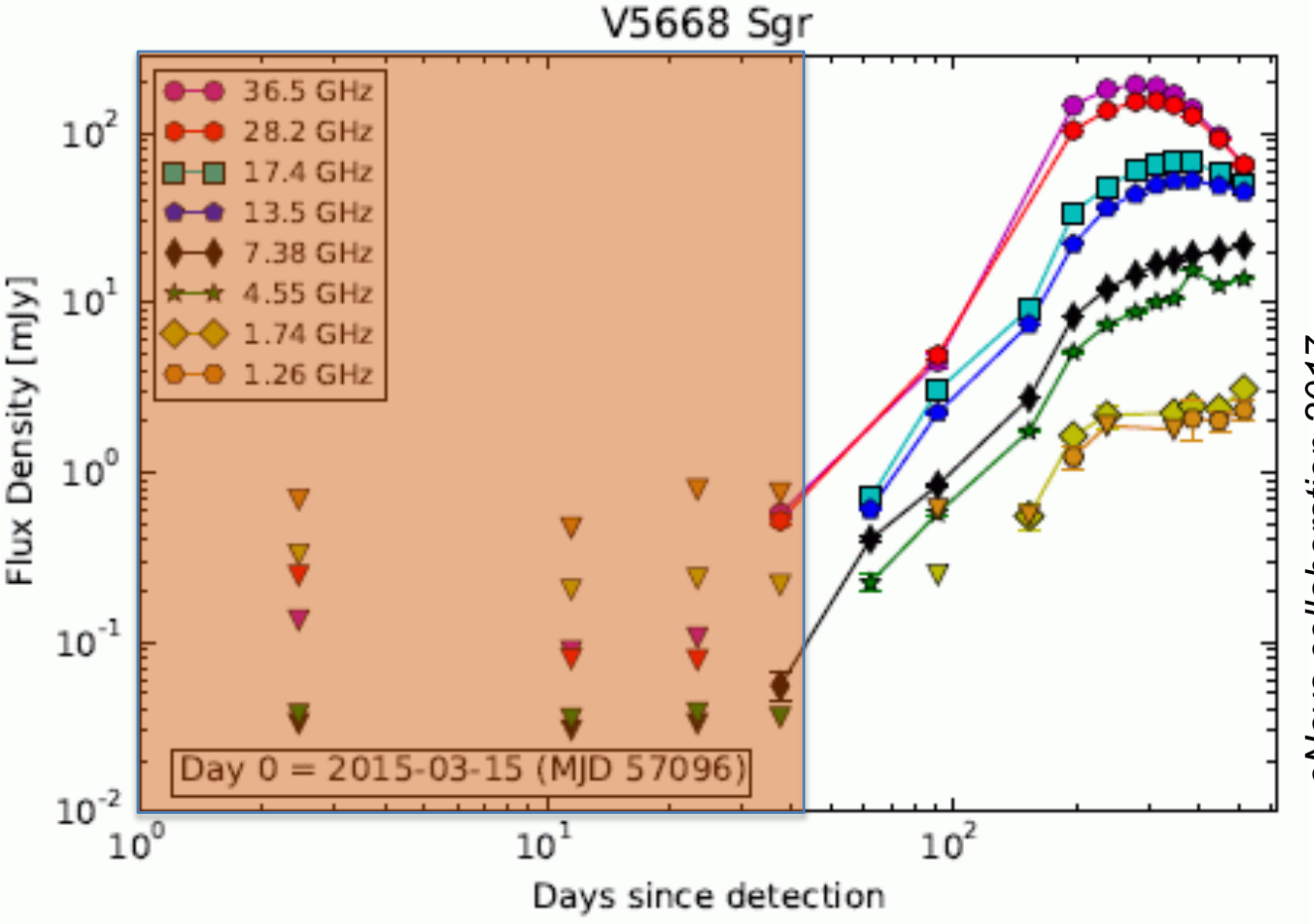


- **8.5 kpc??**
- **Embedded** (K giant)
- **γ-rays**
- Opt bounces – cf. AAVSO

V5668 Sgr 2015

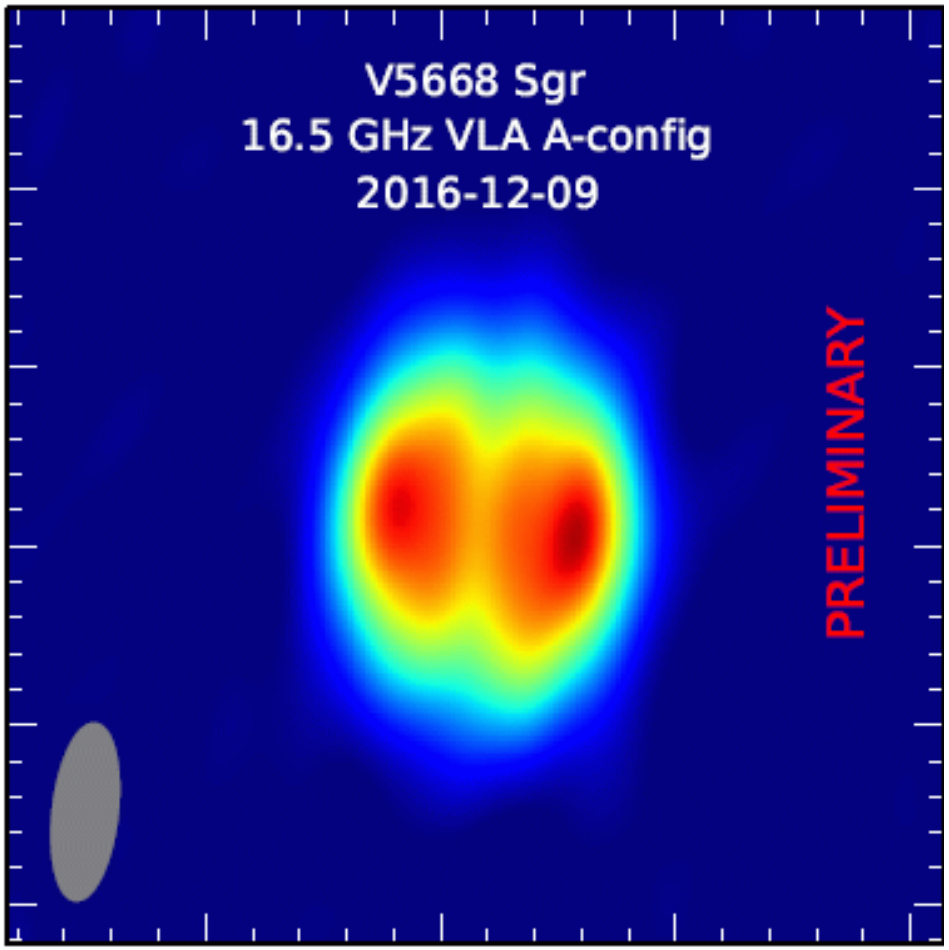


V5668 Sgr 2015



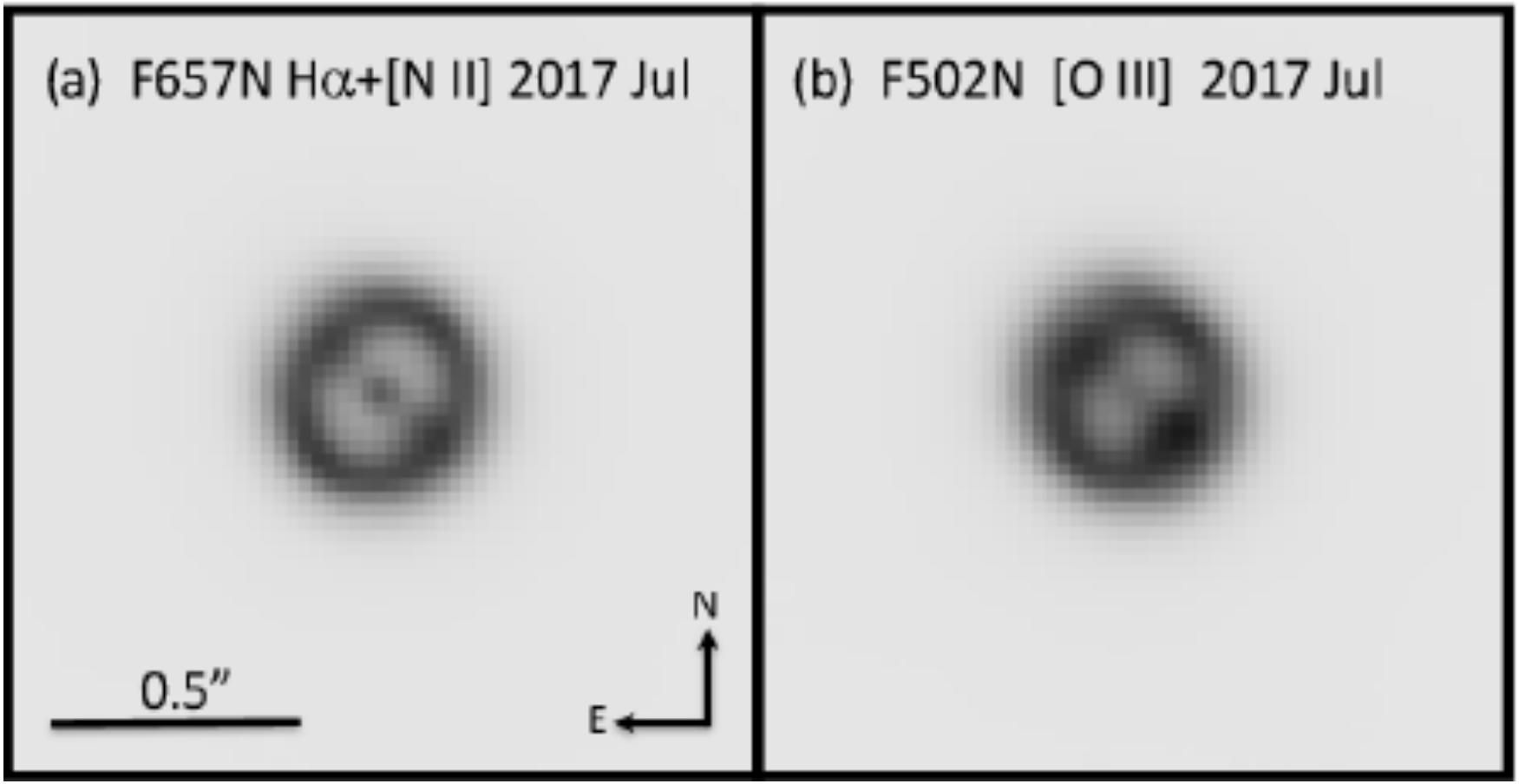
eNova collaboration 2017

V5668 Sgr 2015



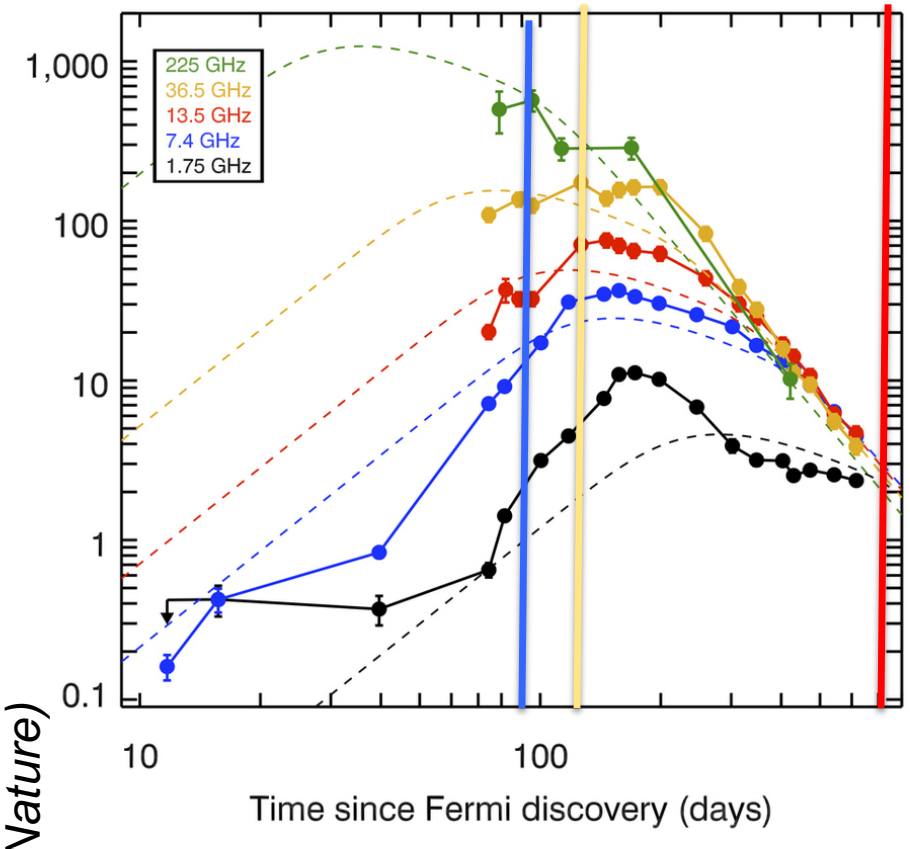
Linford et al. in prep.

V5668 Sgr 2015 HST

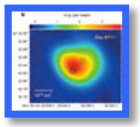


Sokoloski et al. in prep.

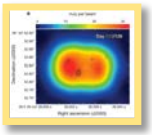
Importance of imaging – gamma-ray nova V959 Mon



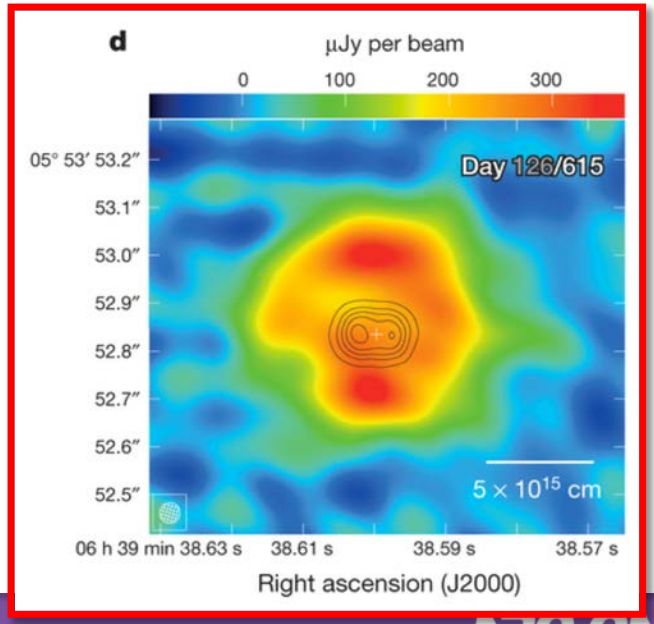
Chomiuk et al. 2014 (Nature)



eMERLIN day 87
5 GHz



VLA day 126
36.5 GHz



VLA day 615
17.5 GHz

Insights from imaging

- Multiple (orthogonal) outflows
- Shocks leading to gamma-rays