Multiwavelength observations of mass ejection in novae

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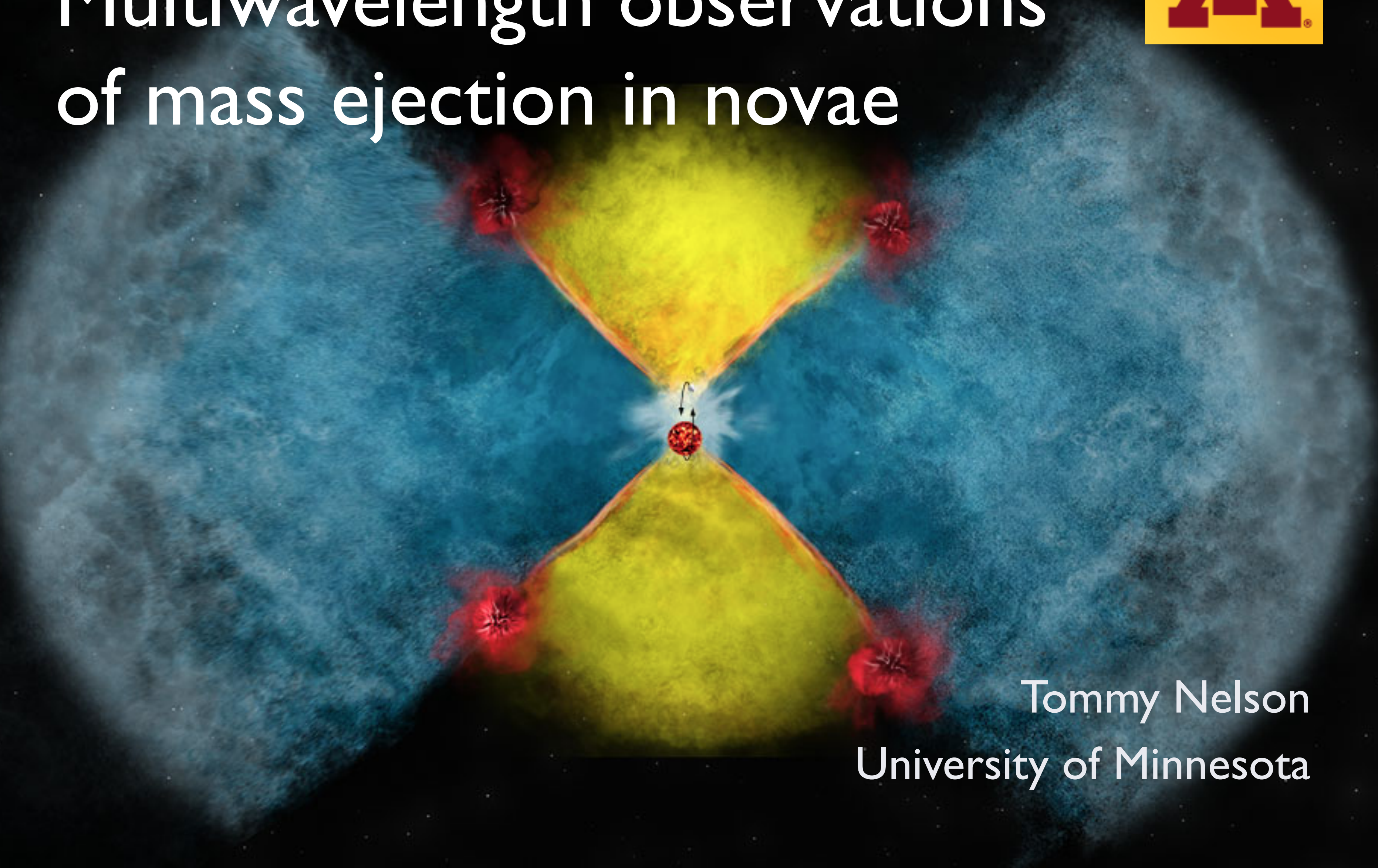
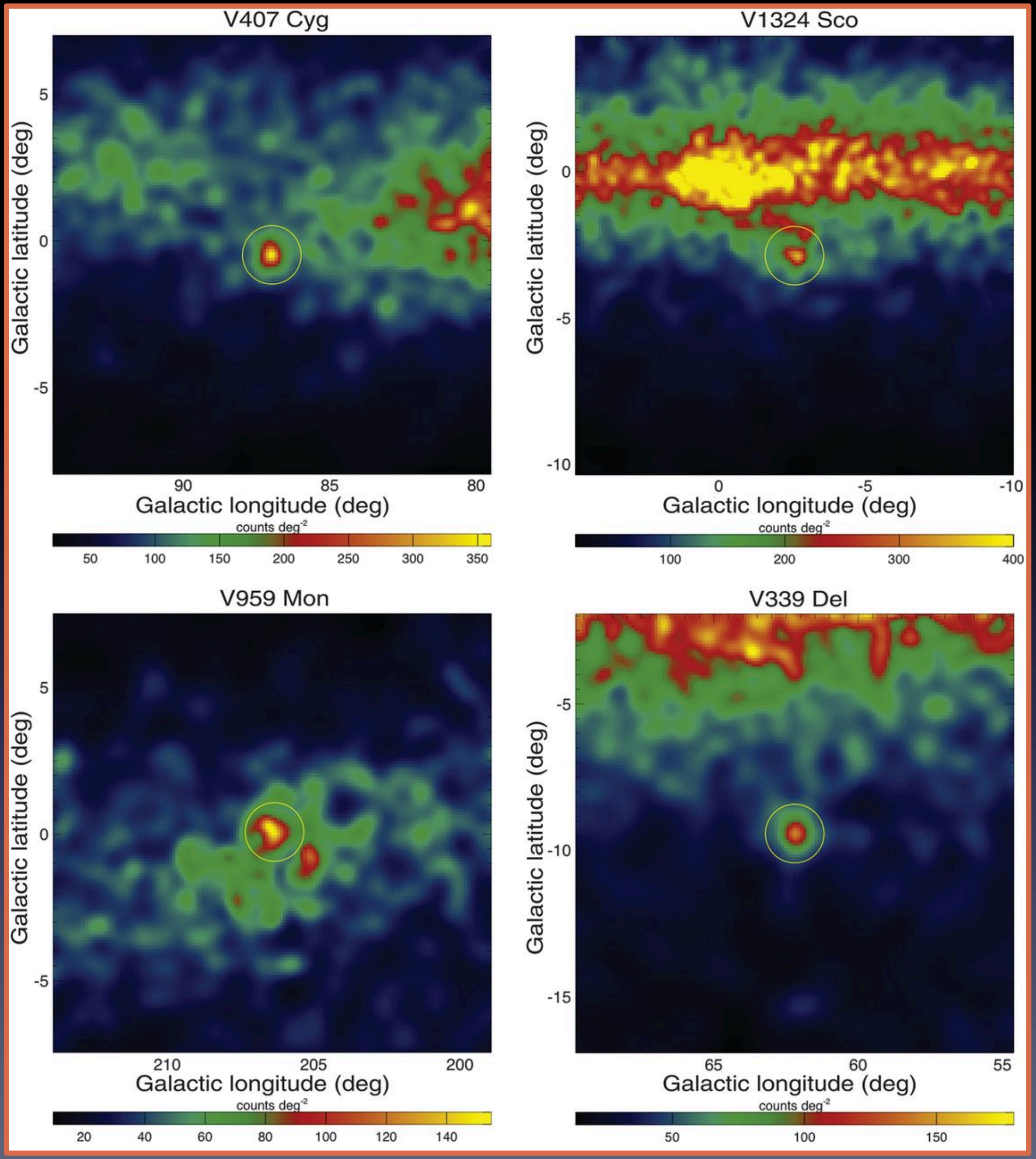


Cartoon of radio emitting ejecta in V959 Mon

What is a nova?

Typical nova characteristics

- Ejected mass: 10^{-6} to 10^{-4} $M_\odot$
- Maximum ejecta speed: 1000-3000 km s^{-1}
- Kinetic energy budget: a few 10^{44} ergs
- Total energy budget (inc. nuclear burning): 10^{46} ergs
- Typical binary separation only 10^{11} cm: ejecta engulf the binary within a few hours: *common envelope physics may be important for mass ejection*



Fermi has firmly established novae as a new class of gamma-ray transient

Nova Cen 2013 and V745 Sco also detected with Fermi, but not shown here

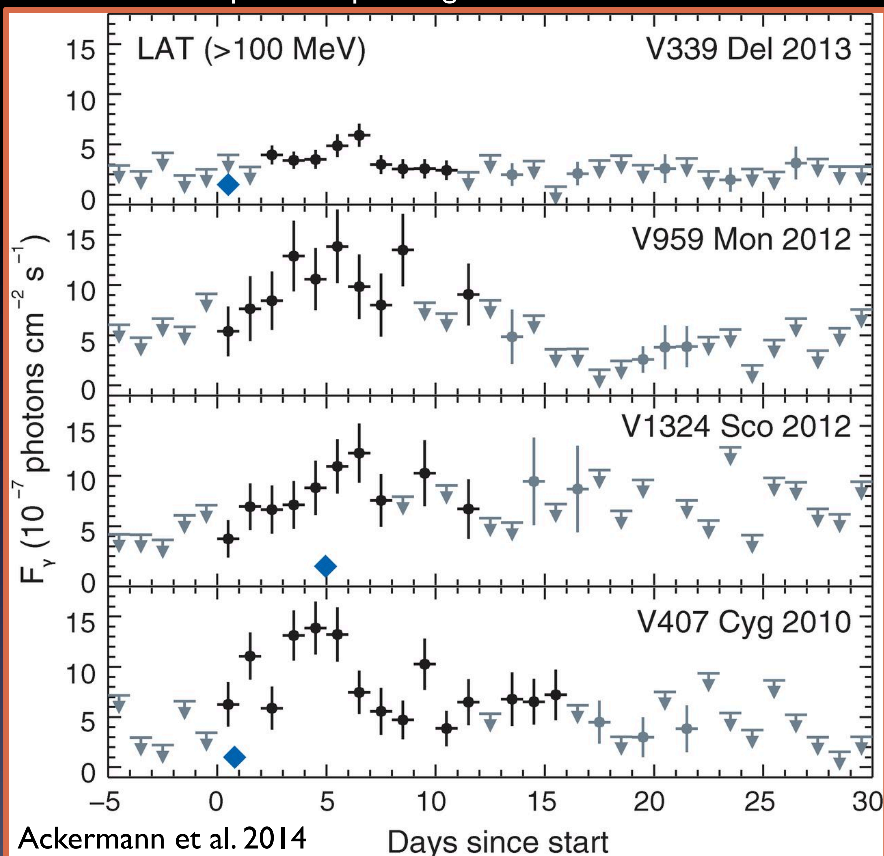
Ackermann et al. 2014

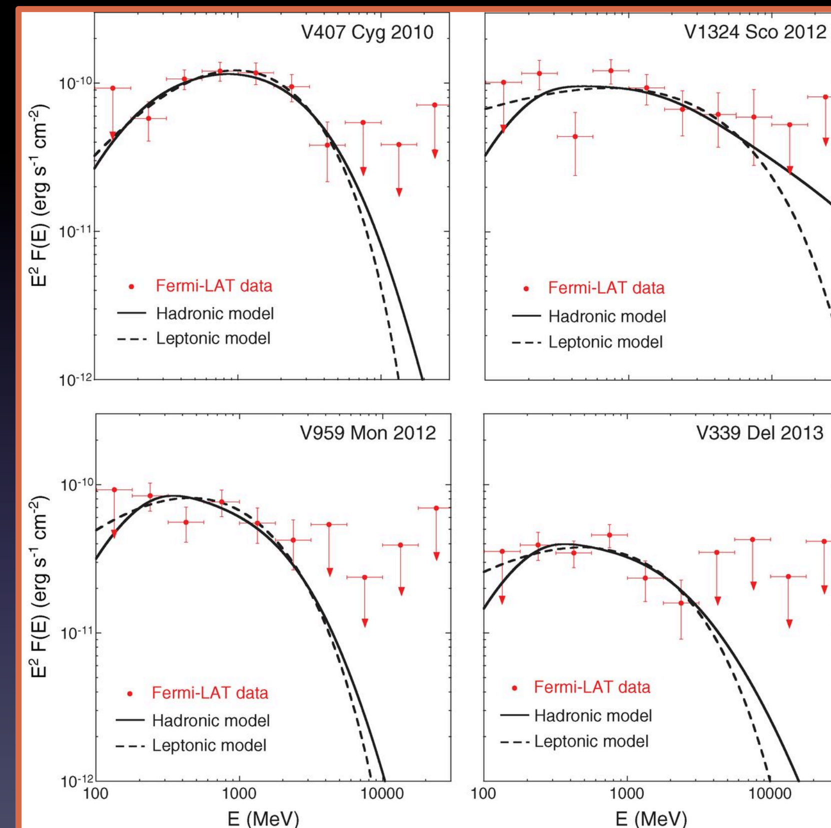
Why is gamma-ray emission surprising in novae?

- Most novae appear to explode into a "clean" environment with very little gas or dust nearby (Harrison et al. 2013, Hoard et al. 2014)
- Not enough mechanical power in forward shock to account for observed gamma-ray emission
- Although "internal" shocks are seen in many novae, they are poorly characterized and their ability to accelerate the particles required for gamma-ray emission has not been explored
- Big questions remain about how mass is ejected in novae…

Gamma ray characteristics of novae

Blue diamonds: peak of optical light curve





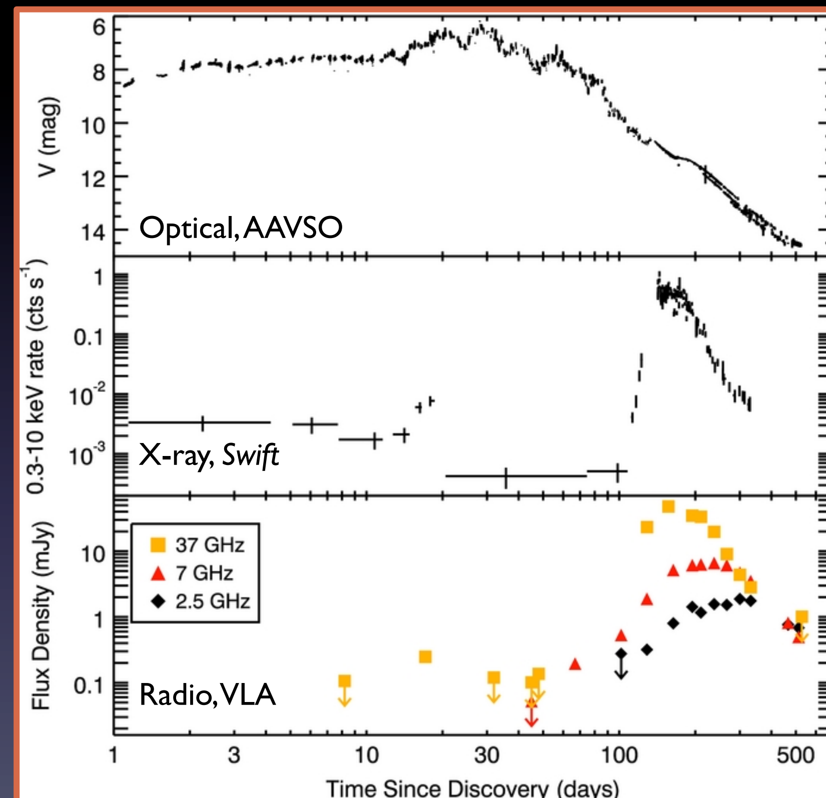
Novae show similar gamma-ray brightness and to date are detected within the first 2 weeks of the outburst

Gamma-ray spectra show diversity in both observed properties and in terms of best-fit physical models

Mass ejection in novae

- TNR ejects shell of accreted material into the environment
- Recent observations of novae (e.g. T Pyx) have revealed surprising aspects of the mass ejection process
- **Any effort to understand gamma-ray production in novae must start with the more fundamental question of how, and when, mass is ejected during nova outbursts**
- MWL datasets, especially radio and X-ray data, provide a powerful probe of mass ejection

Nelson et al. 2014,
Chomiuk et al. 2014



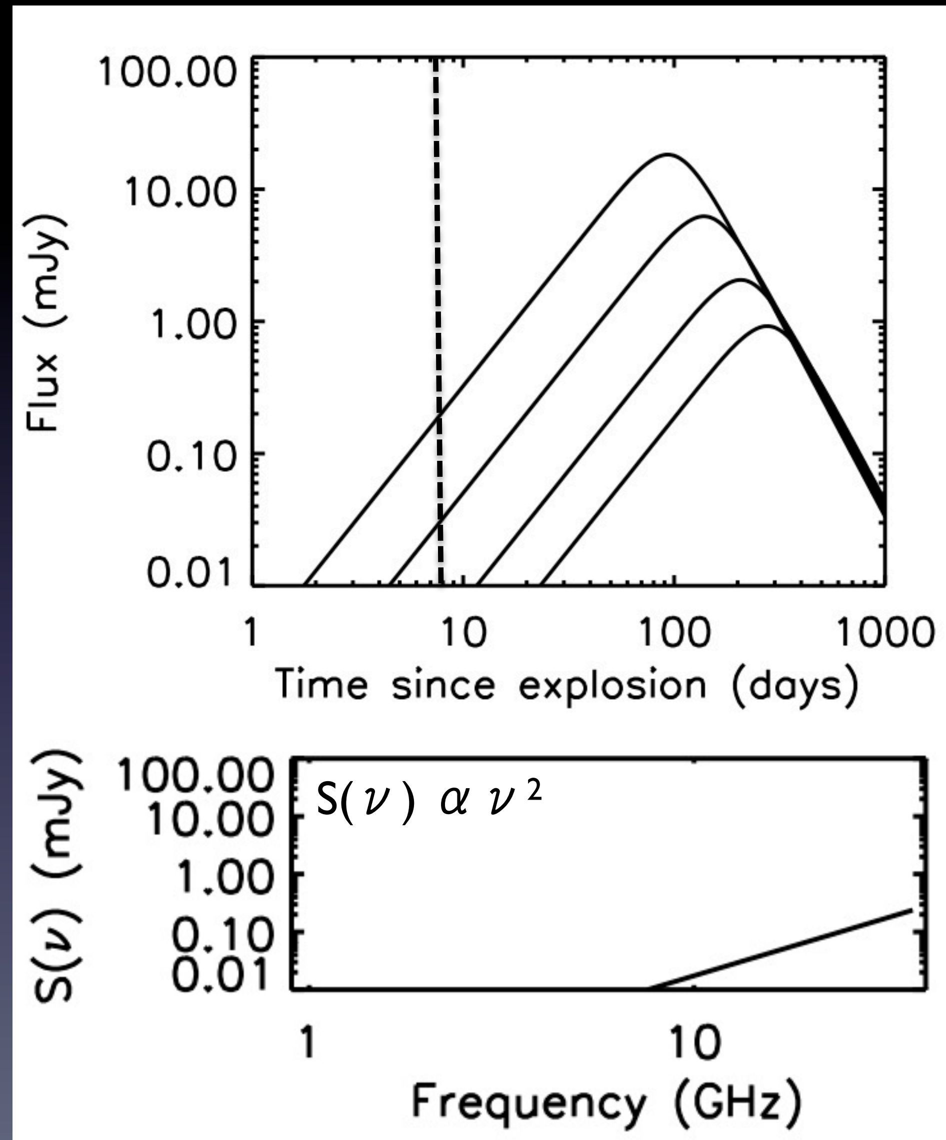
Radio and X-ray light curves of T Pyx revealed surprisingly massive ejecta that was not expelled until 50 days after outburst

Radio observations probe fundamental properties of the nova

- VLA upgrade has resulted in huge increase in bandwidth, and hence sensitivity (10,000 x compared to old VLA)
- Renewed effort to obtain radio light curves of novae (google E-Nova Project!)

- Radio light curves can in principle yield
  - The ejected mass (light curve modeling)
  - The temperature of the ejecta (imaging)
  - The mass loss history (light curve features)
  - Distance (expansion parallax in conjunction with spectroscopy)

Radio emission traces the expanding ejecta



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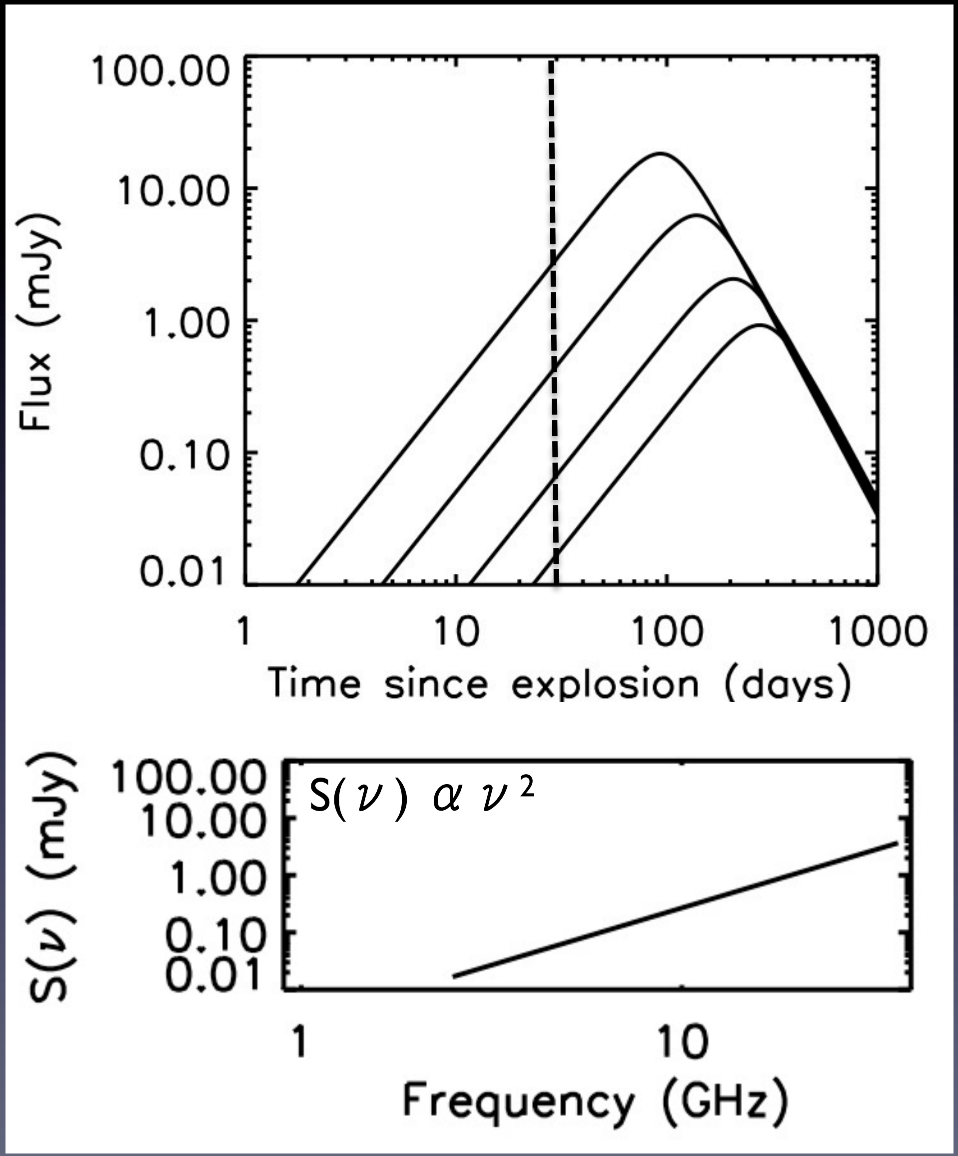

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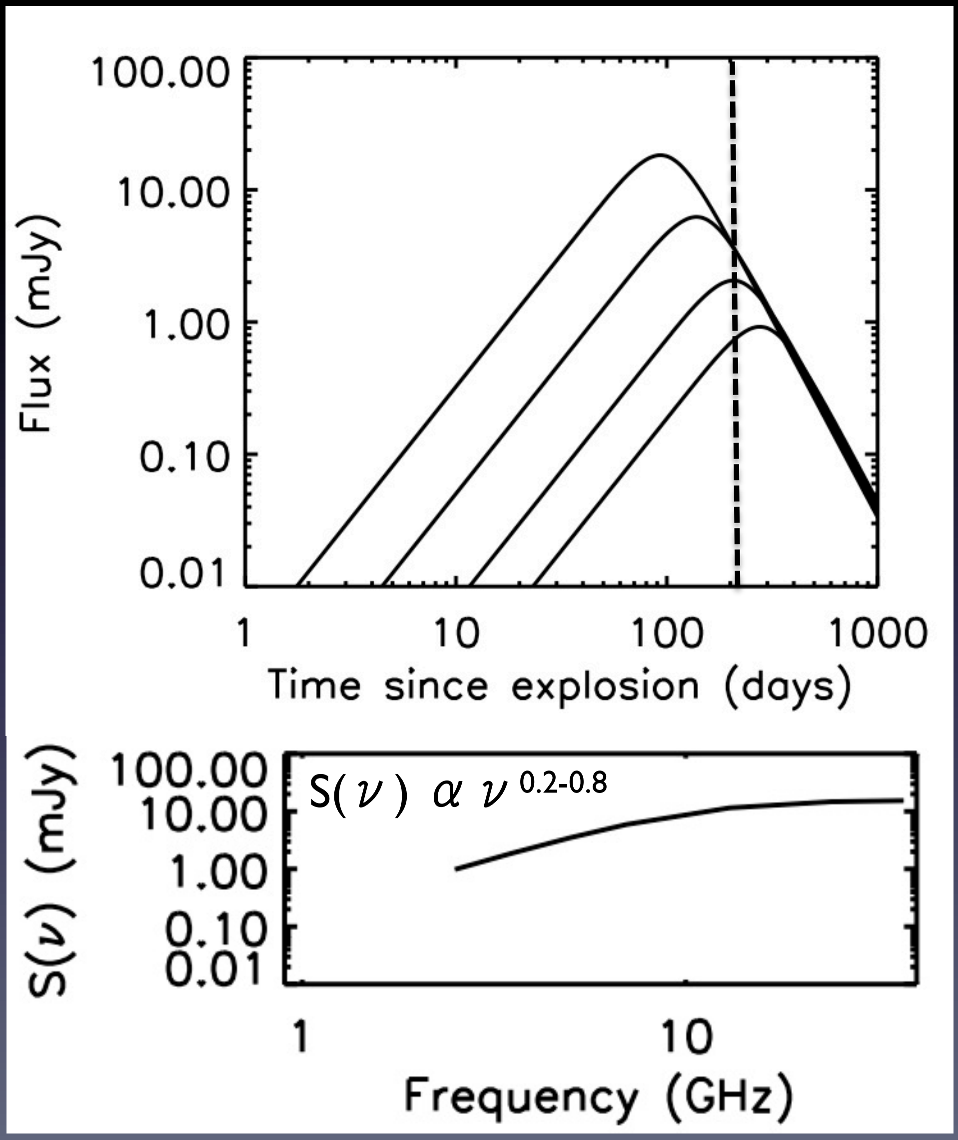

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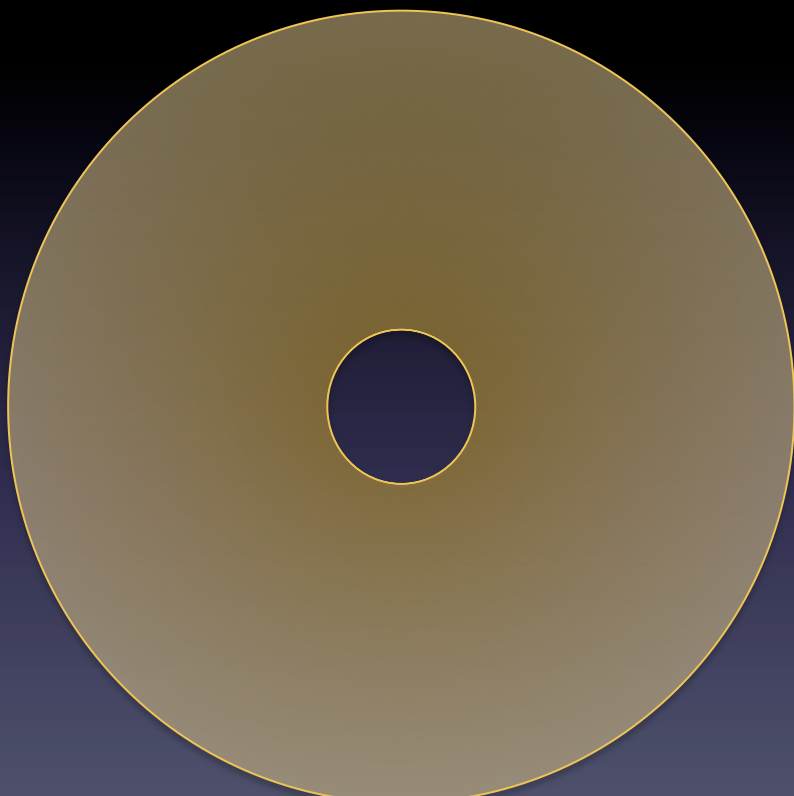
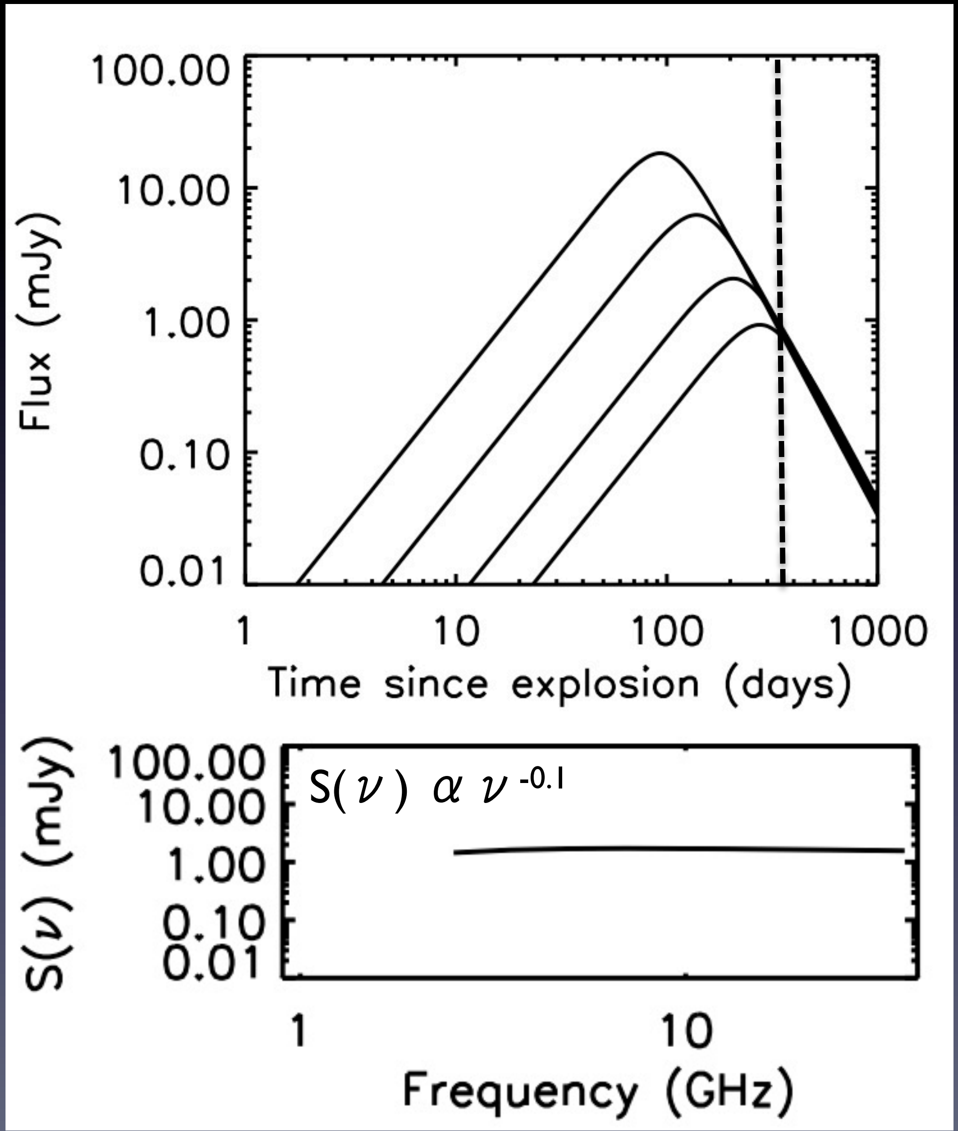
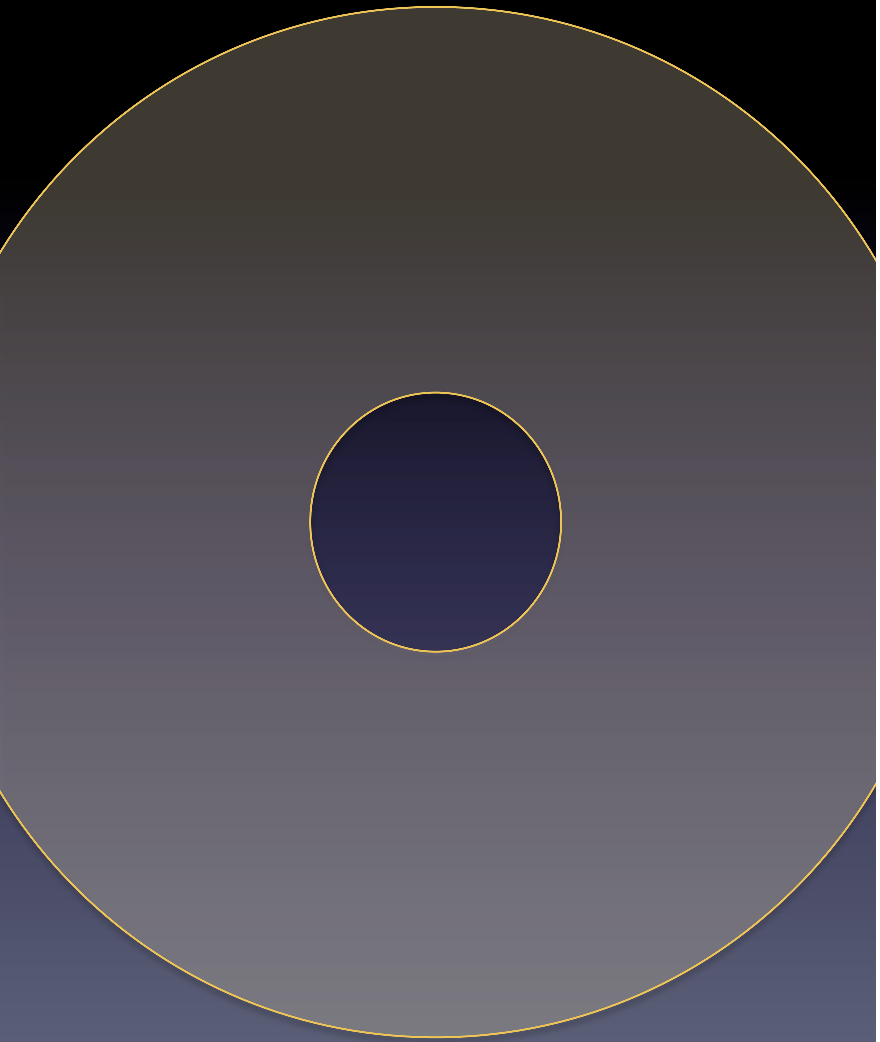
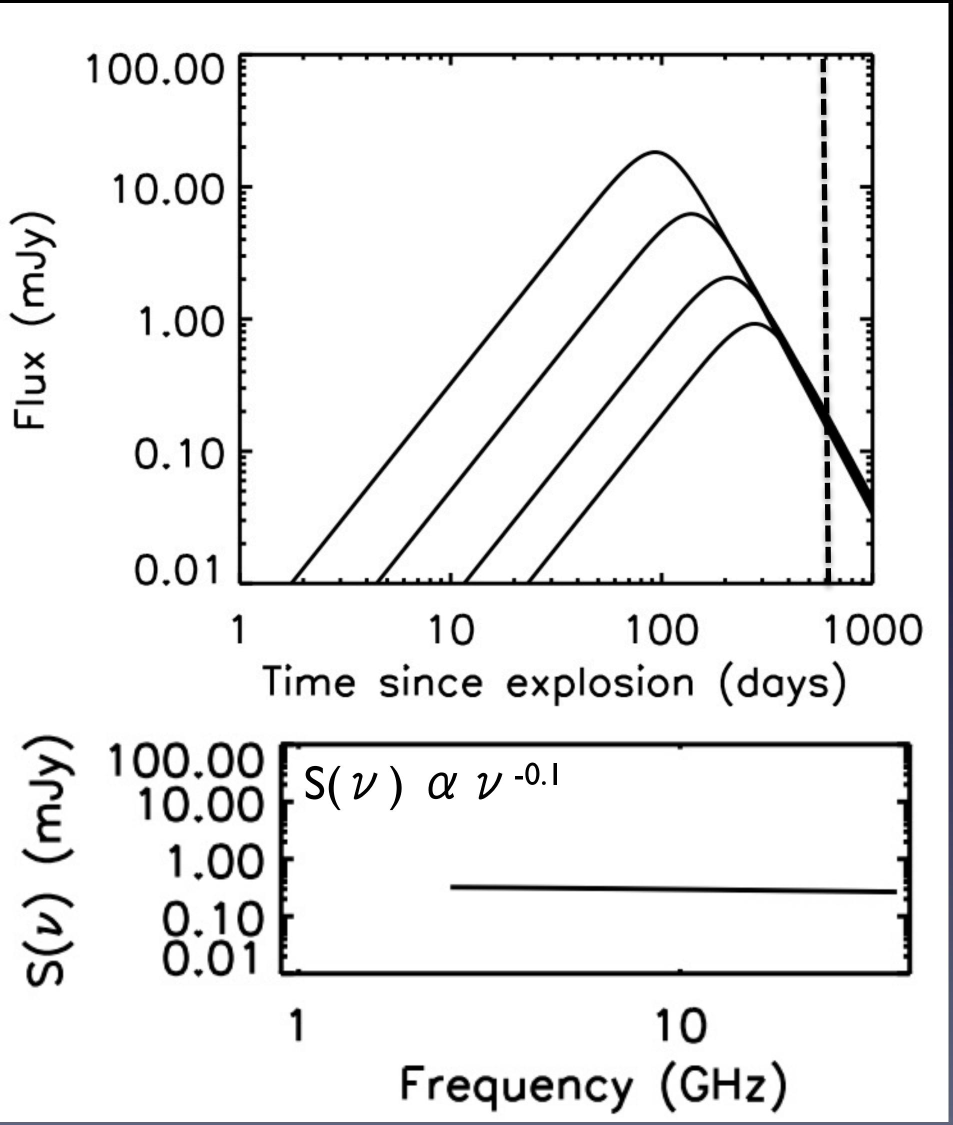


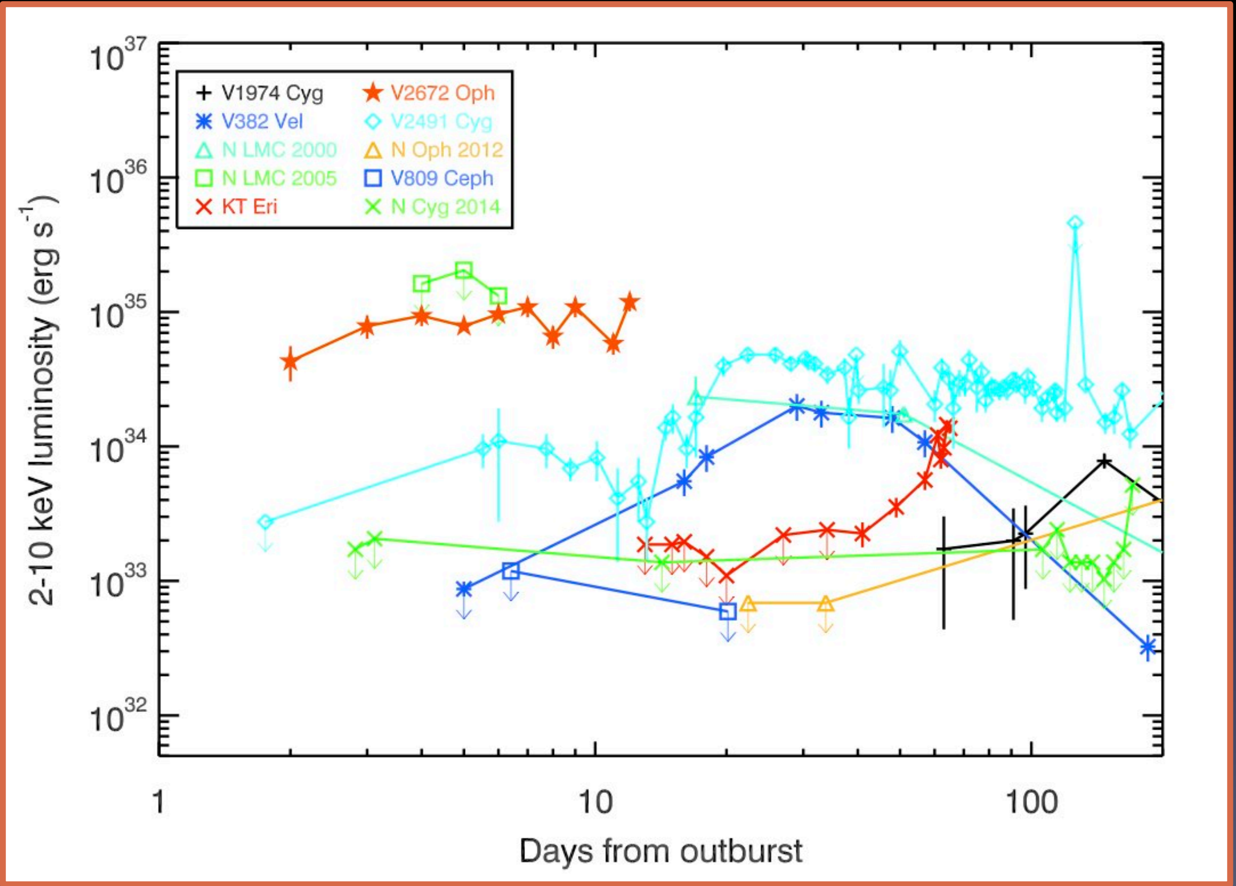


Radio emission traces the expanding ejecta



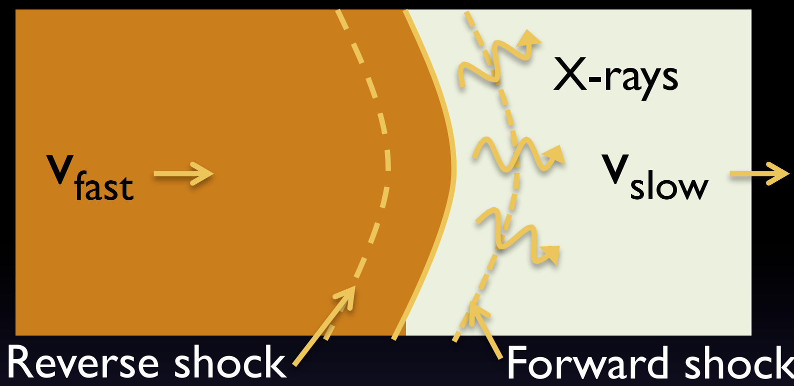


Hard X-ray emission in novae

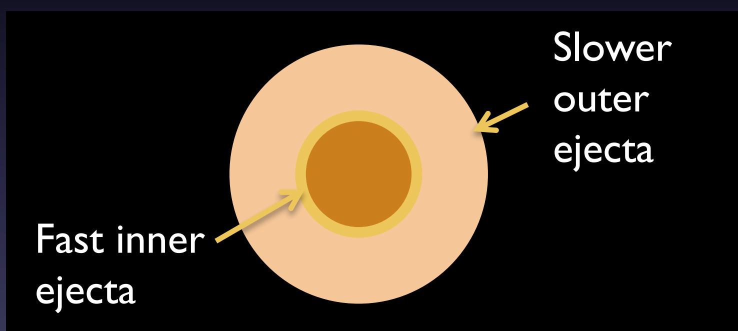


- Hard X-ray emission observed in many novae at some point during the outburst
- Where spectra are available, it is clear that X-rays are thermal: attributed to shocks
- X-ray light curves and spectroscopy can play a key role in characterizing the emitting region…

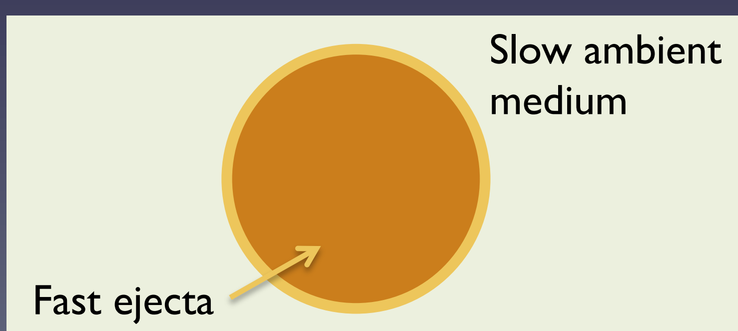
Hard X-rays trace shocks



X-ray temperature tells us about the *kinematics* of the shock

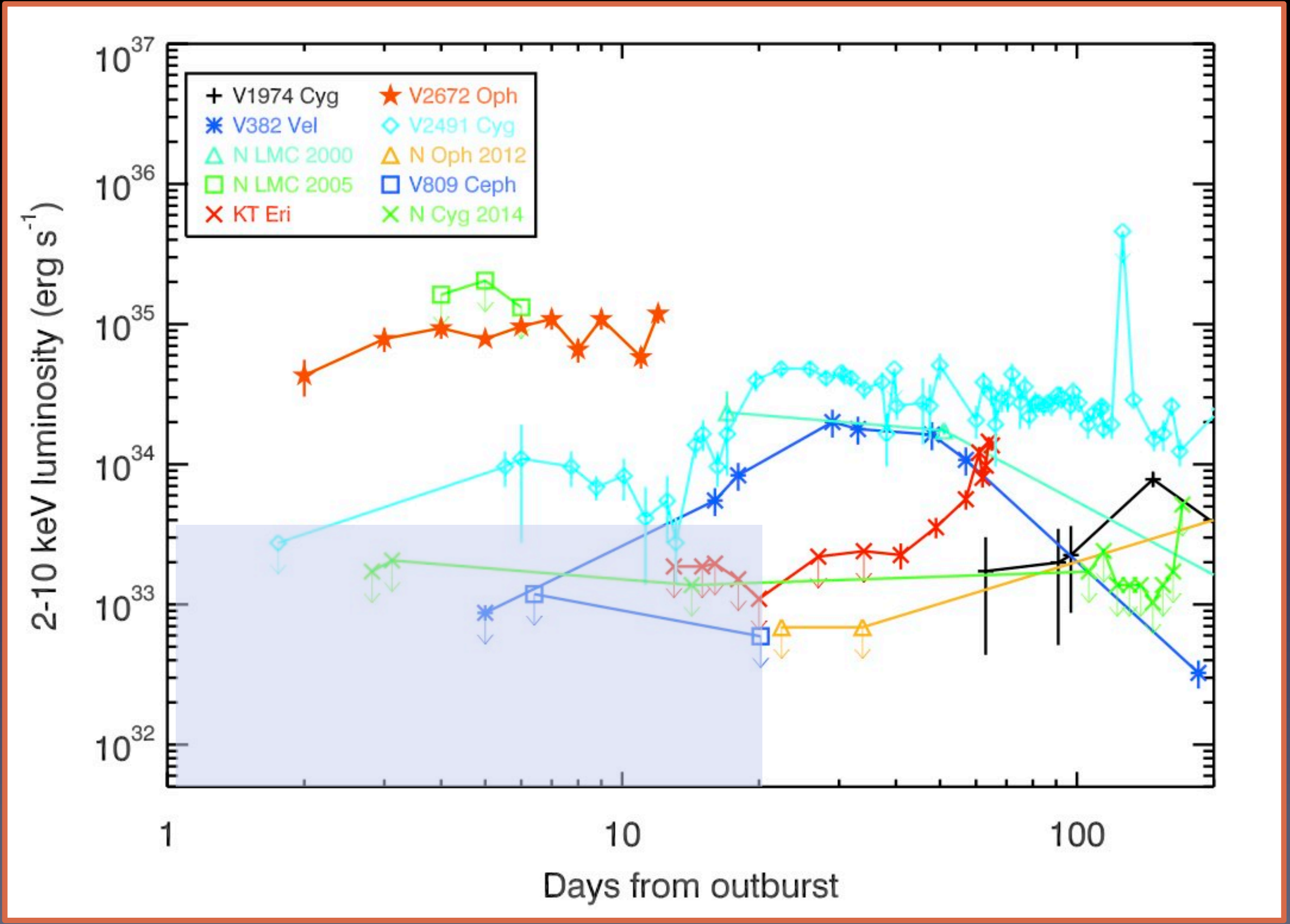


Absorption tells us about the *location* of the shock. High N(H) and late appearance of X-rays likely indicates **internal** shock in the ejecta…



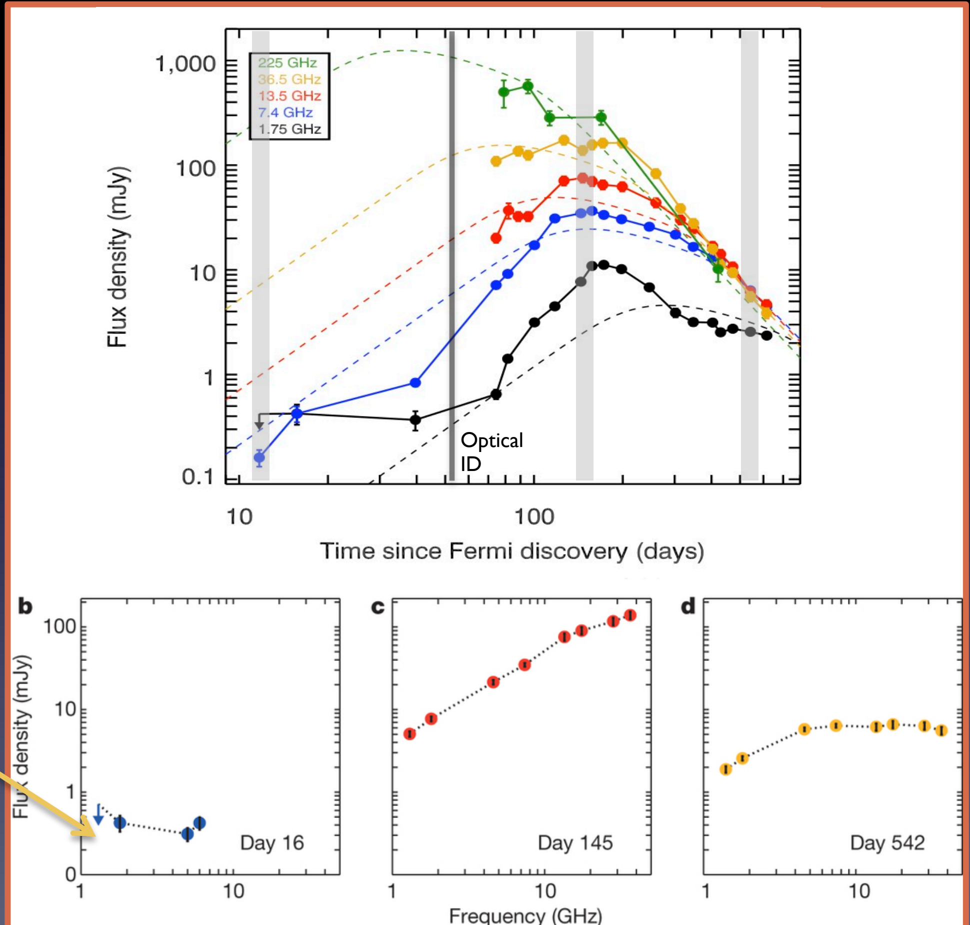
…while low N(H) and early X-ray emisison would indicate interaction with **external** medium.

Limits at early times rule out external media with red-giant densities in most novae



V959 Mon – a (somewhat) typical nova in the radio

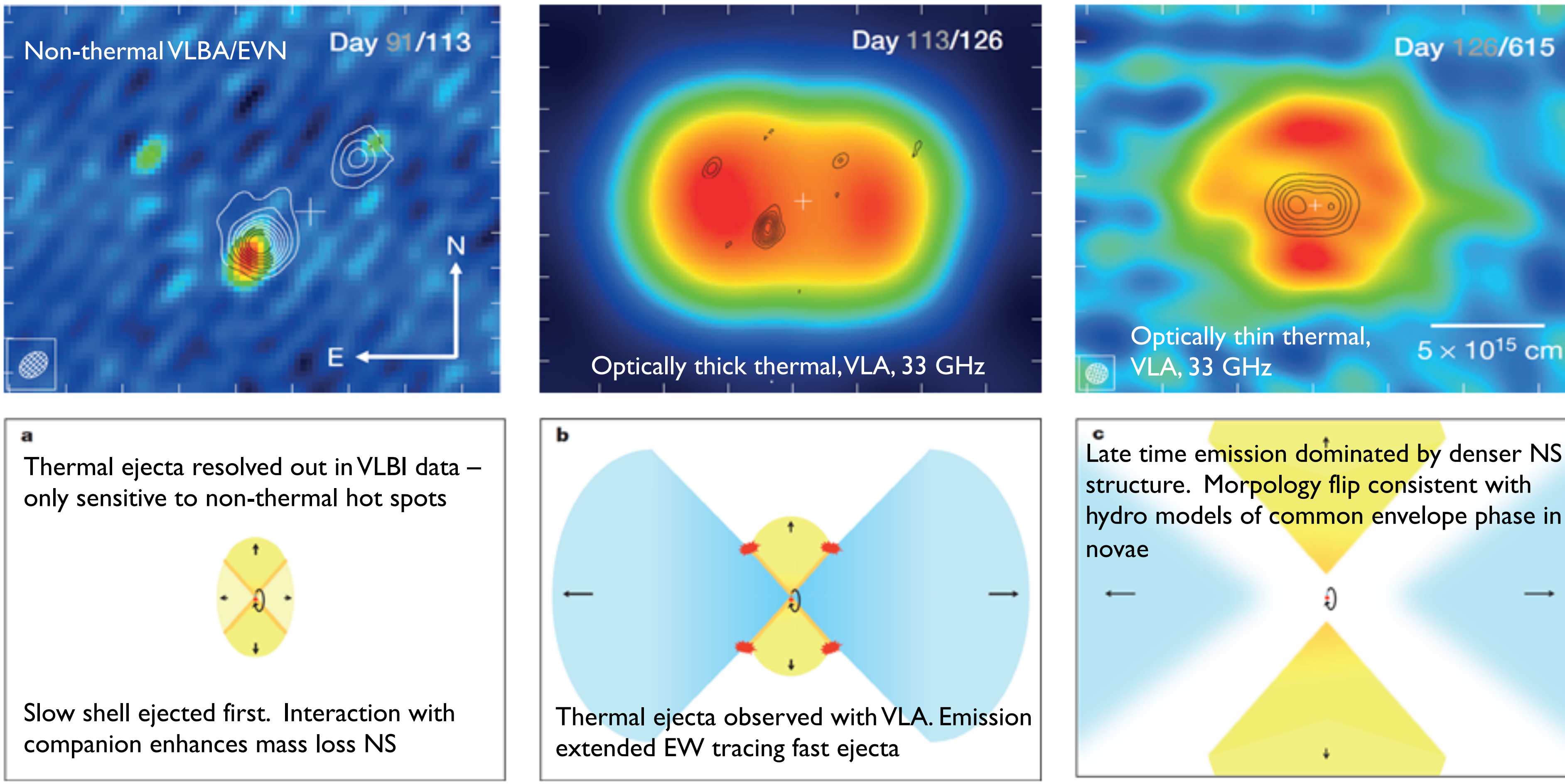
- Overall radio light curve shows expected transition from optically thick to thin over time
- Simple shell model suggests mass around 4.5 x 10^{-5} $M_{\odot}$ – not unusual
- Interesting detection of inverted spectrum after discovery with Fermi – **non-thermal** emission
- Imaging reveals that more is going on here…



From Chomiuk et al., 2014

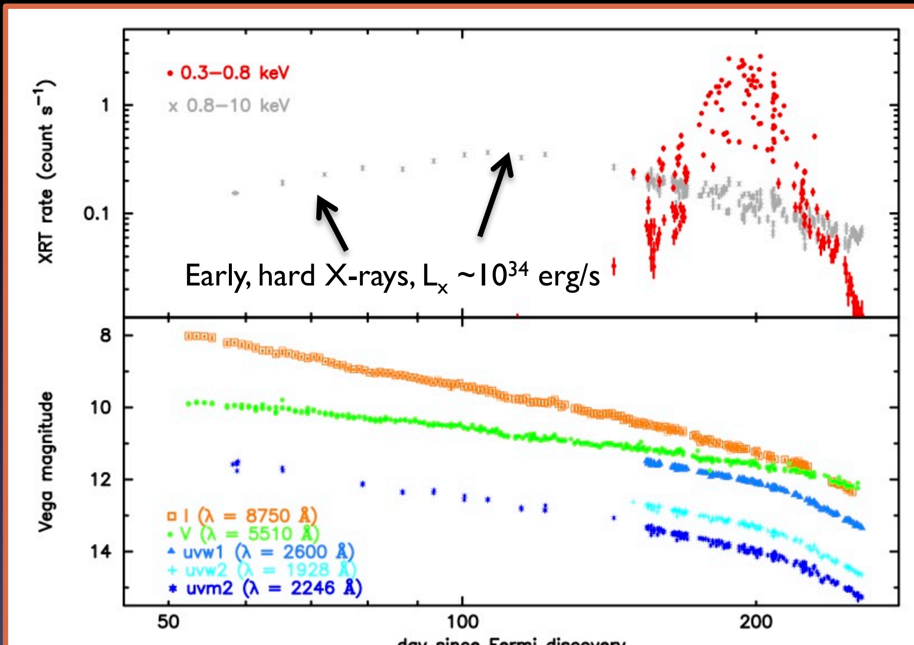
Radio observations V959 Mon reveal sites of particle acceleration and a role for the binary in shaping the ejecta

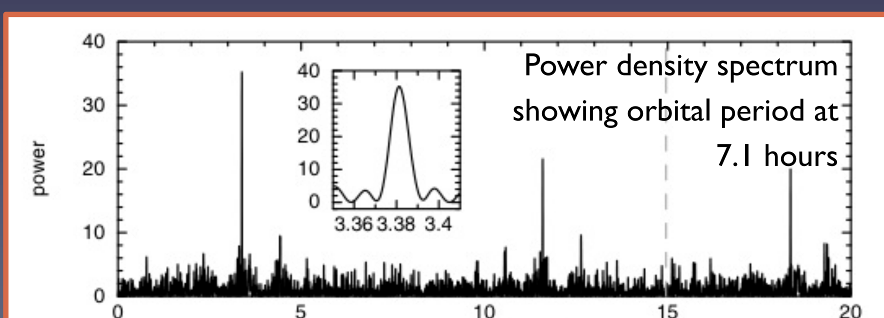
Chomiuk et al. 2014



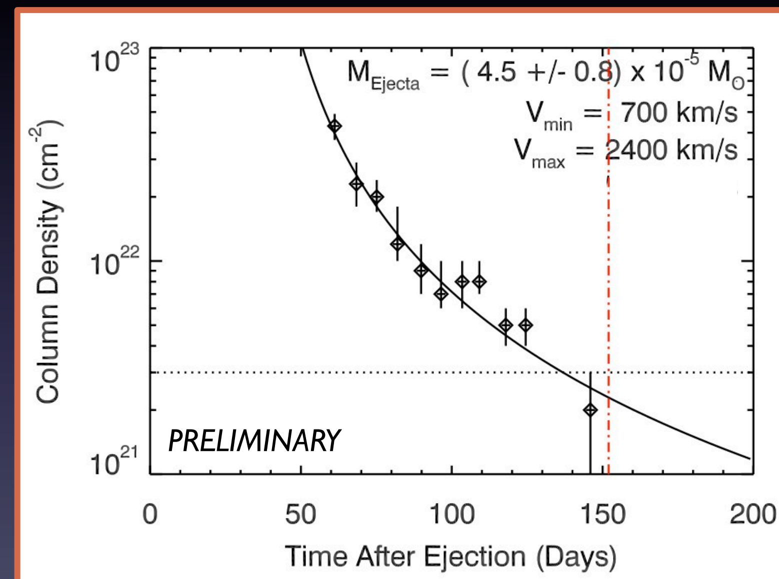
X-ray observations provide additional evidence for internal shock in the ejecta

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



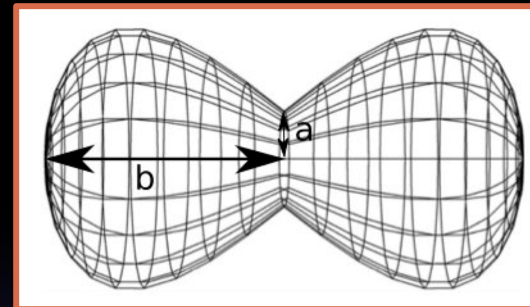


X-ray flux rules out thermal origin for VLBA knots

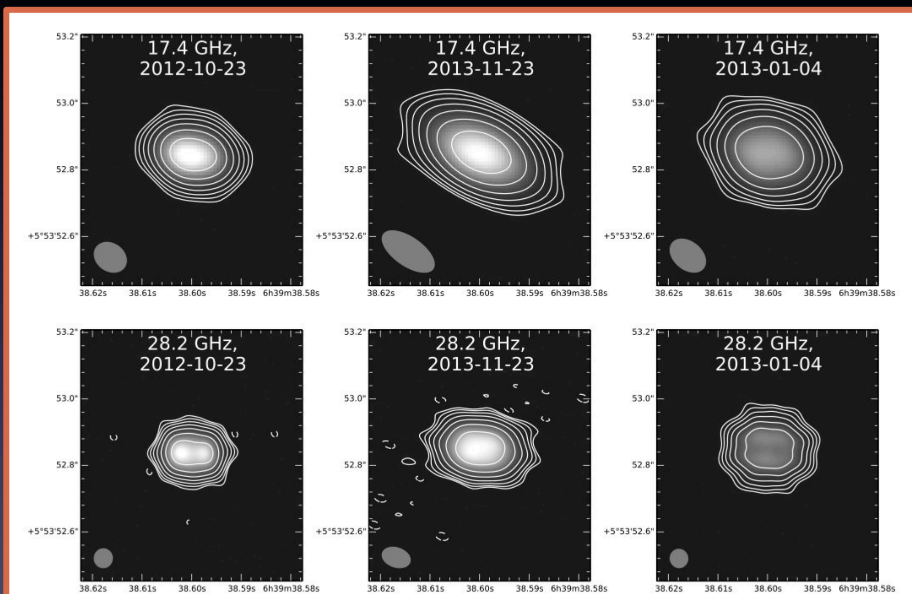


N(H) evolution consistent with internal shock and an ejected mass of at least a few 10^{-5} $M_{\odot}$ (Nelson et al., in prep)

Radio imaging constrains distance to V959 Mon



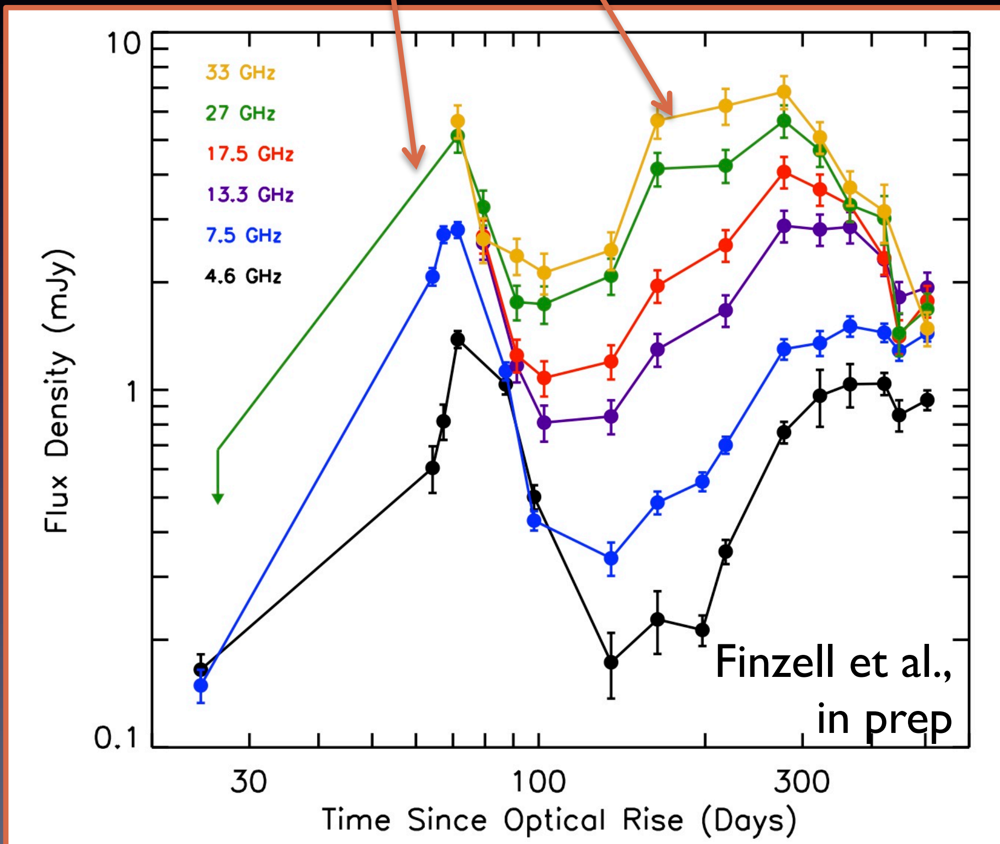
Expansion observed in radio images



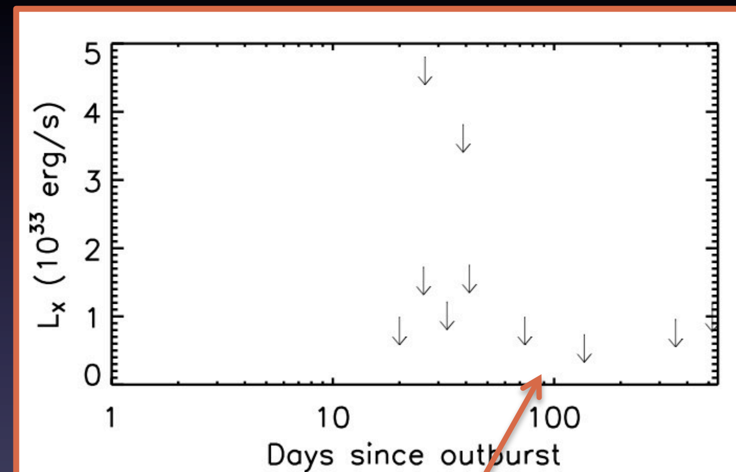
- Ribeiro et al. (2013) created morpho-kinematic model of ejecta in V949 Mon that explains emission line structure and hence *velocities* of the ejecta
- We are using the same model to interpret the radio images
- Comparing observed images to simulations, we constrain the distance to V949 Mon to be 1.4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

Very different radio/X-ray evolution in V1324 Sco

Double-peaked radio light curve



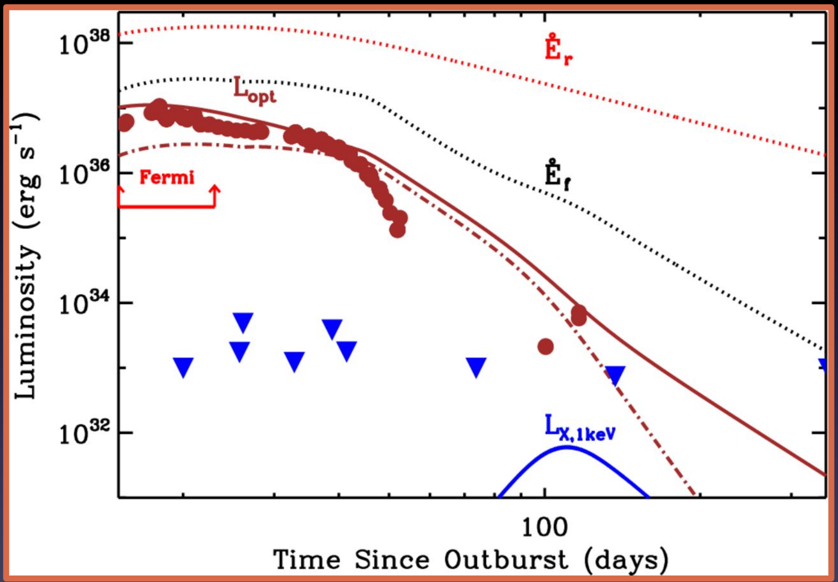
Lack of X-ray emission

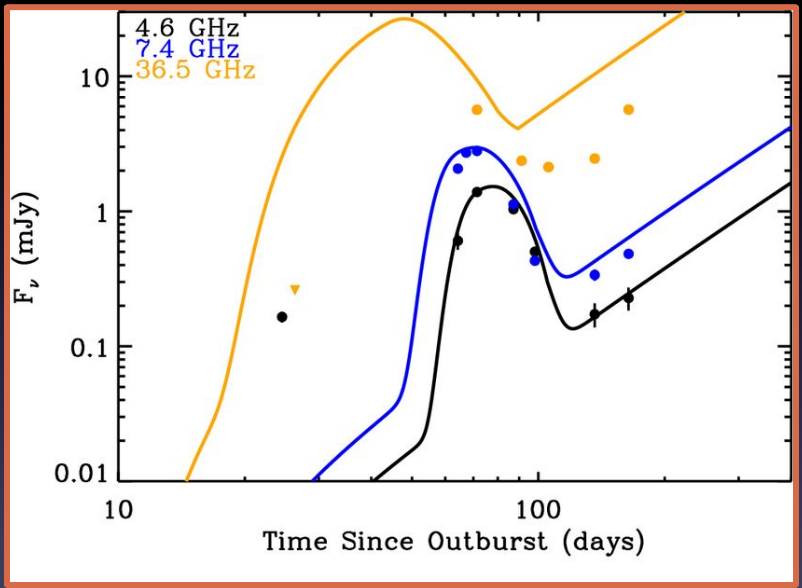


X-ray luminosity $<10^{33}$ erg/s around day 100

Multiwavelength light curve *can* be explained with an internal shock model

From Metzger et al. 2014



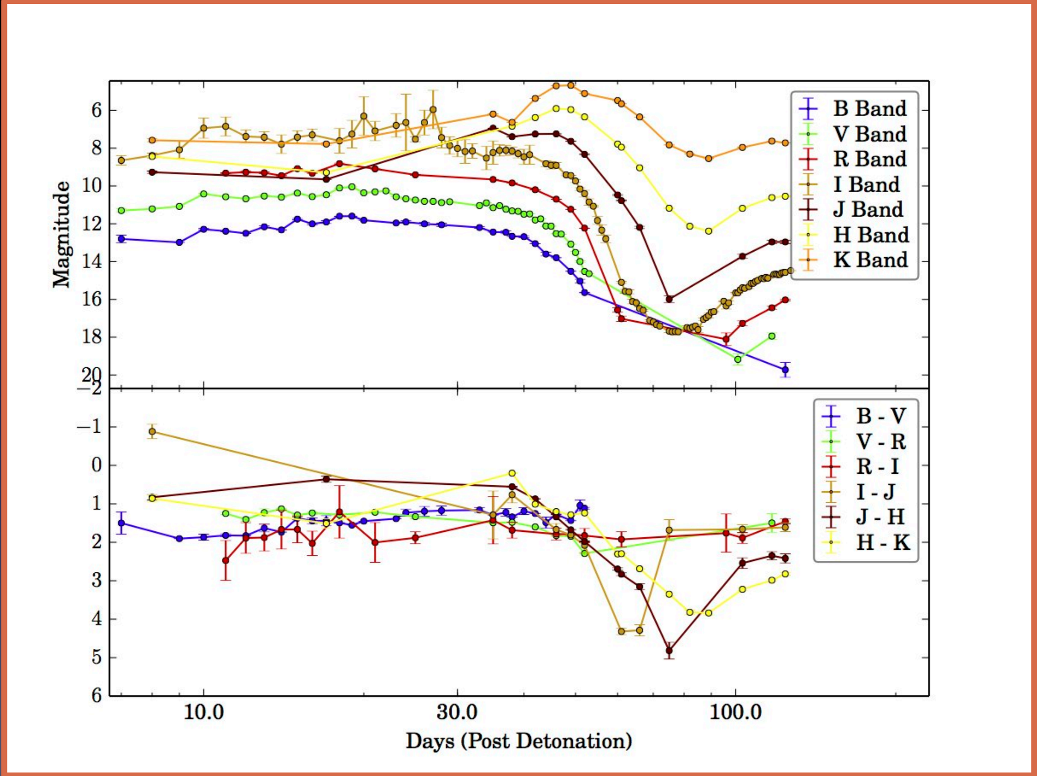


Internal shock with v_{fast} = 3000 km/s and v_{slow} = 1000 km/s can reproduce optical evolution and X-ray non-detections. **Much of the forward shock power is reprocessed into optical**

Early radio bump originates in dense, cool shell that appears at the discontinuity surface. However, early low frequency detection may still point to non-thermal contribution

Optical data constrains distance to V1324 Sco

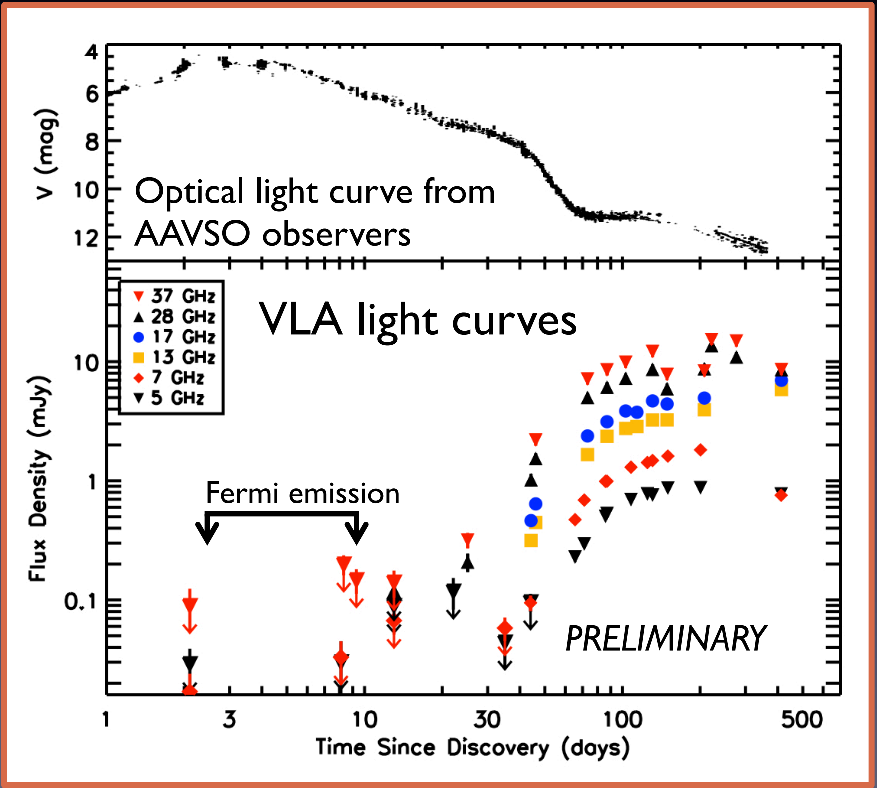
- Diffuse interstellar bands in spectrum constrain reddening to be E(B-V) = 1.02 +/- 0.17
- Applying this knowledge to the optical and near IR photometry for V1324 Sco and other nearby stars, best distance estimate is 6.7 +/- 1.2 kpc (Finzell et al., in prep)
- **This revises L_{gamma} up to 2×10^{36} erg/s**



Data from Microlensing Observations in Astronomy (see Wagner et al., 2013)

V339 Del – insights so far

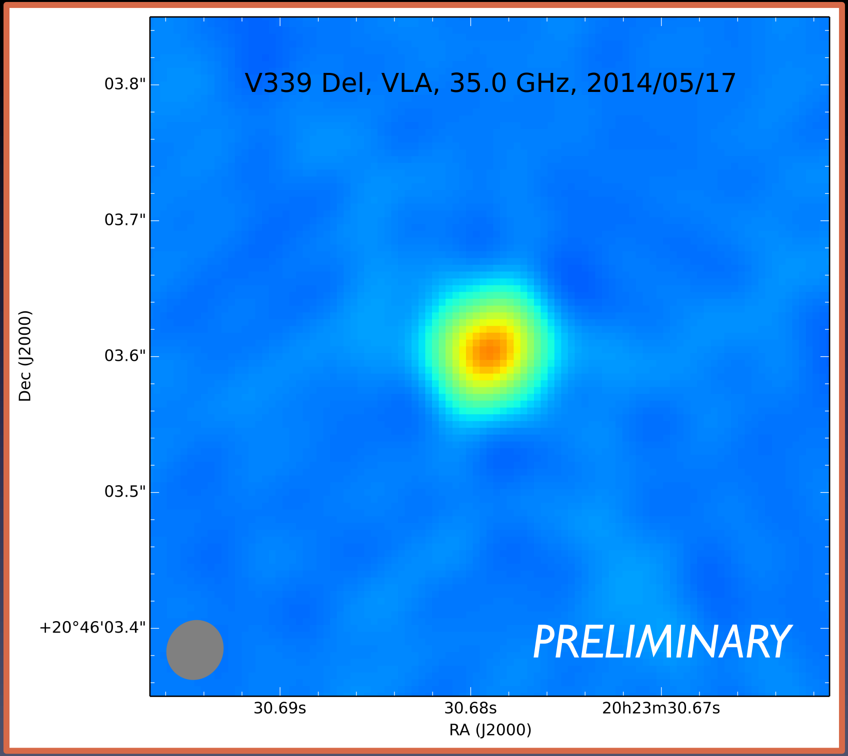
- Multiwavelength studies are ongoing. Radio light curves are evolving very slowly!



- V339 is first *Fermi* nova with good radio coverage at early times.
- VLA Non-detections before, during and after *Fermi* detection
- At 7 GHz, upper limit to flux density of 15 μ Jy: almost order of magnitude lower than V959 Mon

V339 Del – insights so far

- The ejecta were marginally resolved in May 2014 and appeared symmetric.
- Expansion observed at rate ≤ 0.07 mas/day: **very slow!**
- Could we be viewing this system pole-on?
- We will revisit the morphology during next A-configuration of the VLA…



Summary

- Radio, X-ray and optical observations of novae are telling us about the mass and distribution of the ejecta, and characterizing any shocks present during the outburst
- Evidence for internal shocks in all three *Fermi*-detected classical novae, but characteristics appear to be quite different in terms of location and temperature
- Radio images of V949 Mon have revealed a role for the binary in shaping the ejecta and identified sites of particle acceleration where fast and slow ejecta interact
- Better distances to these novae reveal more diversity in gamma-ray emission: **factor of 30 range in L_{gamma}**
- Gamma-ray detection of novae has renewed interest in these challenging sources. We are finally obtaining the MWL datasets we need to characterize mass ejection in these sources
- *Better low energy sensitivity of PASS-8 analysis may result in more nova detections: we are ready to follow-up these sources!*