Novae: a new class of high energy emitters

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GK Per
Nova Per 1901

Outline

Introduction:

- *Novae Classification & System Properties*
- *Importance in Chemical enrichment & Distance Indicators*

Panchromatic View:

- *Optical/nIR light curves & spectra*
- *X-ray emission*
- *Radio emission*

Novae as sources of particle acceleration:

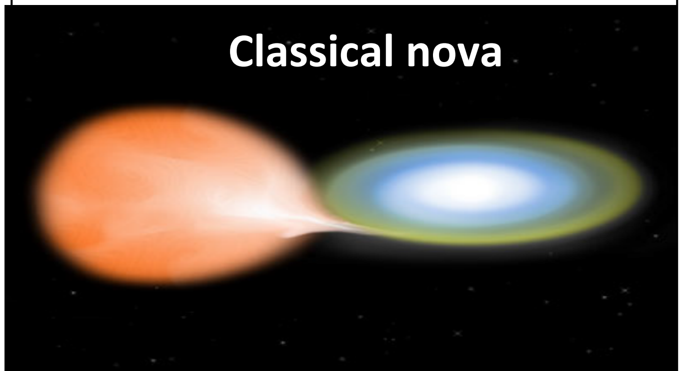
- *FERMI – LAT Discoveries*
- *Gamma-ray light curves*
- *Gamma-ray spectra*
- *Future developments*

Novae

Cataclysmic Variable

WD + Late type (V,IV)

Mass transfer via RLO



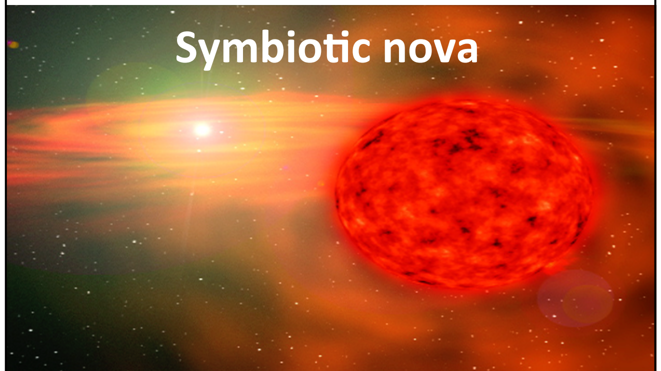
P_{orb} ~ 1.3hr – 5d

Known: 400 CNe in MW

Symbiotic binary

WD + Red Giant or Mira

Mass transfer via wind



P_{orb}> yrs –decades

Known: 14 SyNe in MW

Recurrent Novae

6 RNe & 5 SyRNe

Classical & Recurrent Novae

Classical Novae (CNe):

- **One observed outburst**
- **Recurrence timescales: $10^3 - 10^5$ yr**
- Donors: late-type MS or Giant
  $P_{orb} \sim 1.1h - 5d$
- CO WDs: enhanced CNO ejecta -H/He solar
  ONe WDs: enhanced O,Ne – C depletion
- **Range of WD Mass: $0.5 - 1.3\ M_\odot$**
- Accretion rate quie.: $\dot{M} \sim 10^{-11}\text{-}10^{-9}\ M_\odot/yr$
- **$L_{peak} \sim$ few $10^4\ L_\odot$**
- Speed classes: Very fast-to-slow
  $V_{eject} \sim$ few 10^2 – few 10^3 km/s
  FeII &He/N spectra associated to speed
- **$M_{eject} \sim 10^{-5} - 10^{-4}\ M_\odot$**

Recurrent Novae (RNe):

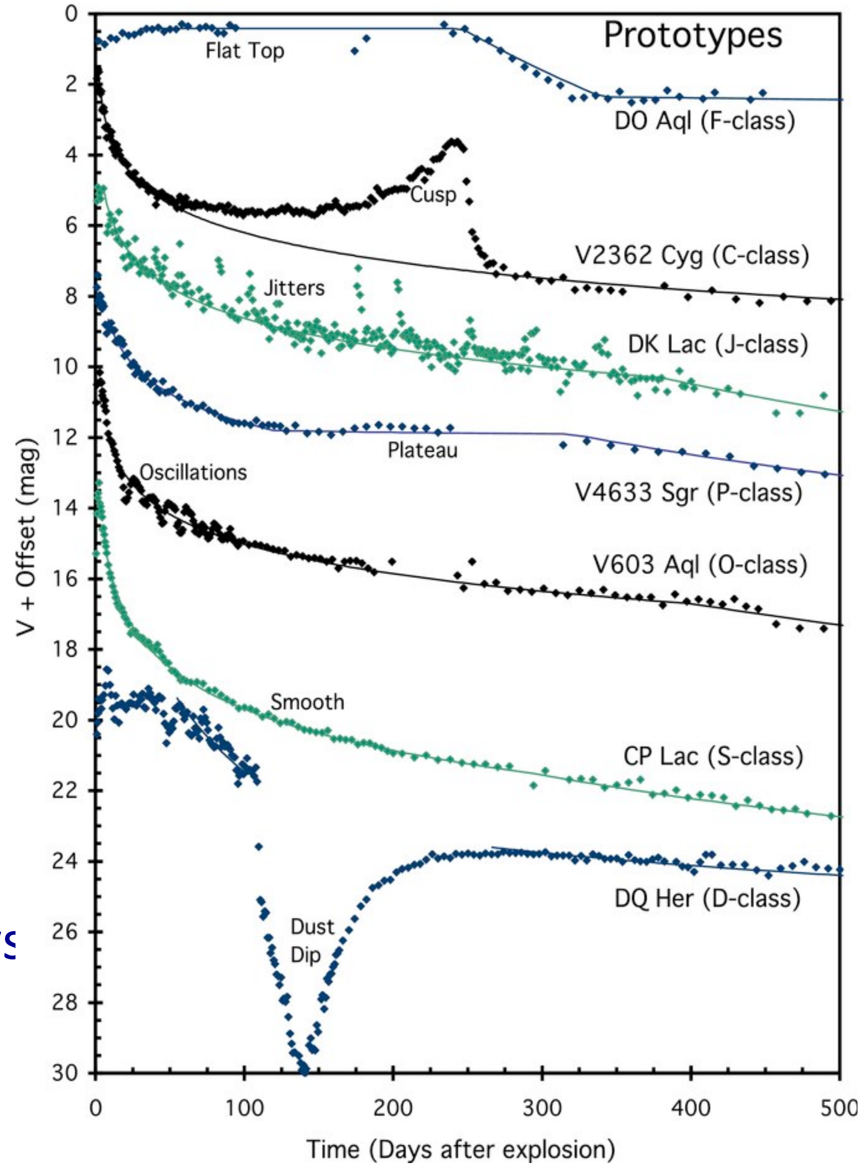
- **> 1 recorded outburst**
- **Recurrence timescale : 20- 80yr**
- Donors: K-M V (T Pyx) $P_{orb} < 1d$ (3)
  K IV (U Sco) $P_{orb} \sim 1.5d$ (3)
  M III (RS Oph) $P_{orb} \sim 200\text{-}500d$ (4)
  Mira (V407 Cyg) $P_{orb} \sim 43yrs$ (1)
- **High mass WDs: $1.0 - 1.2\ M_\odot$**
- Accretion rate quie.: $\dot{M} \sim 10^{-8} - 10^{-7} M_\odot/yr$
- **$L_{peak} \sim$ up to $10^5\ L_\odot$**
- Speed Classes: Very fast-to-slow
  SyRNe: fast $V_{eject} > 10^3$km/s
  U Sco: very fast $V_{eject} \sim 10^4$ km/s
  T Pyx: slow $V_{eject} \sim$ few $10^2 - 3\times10^3$ km/s
- **$M_{eject} \sim 10^{-6}\text{-}10^{-5} M_\odot$**

Nova Light curve diversity:

Morphology:

- Large amplitude (ΔV≈11-15mag)
- Variable length (rise and decay)
- **t_2 defines Speed Class: Fast & Slow**
- Diversity starting 3-4mag below V_{max}.:

- Smooth decline: Fast Novae ≥0.1mag/d
- Oscillations (1-1.5mag) Quasi-period days
- Dips (7-10mag): onset of **dust** (nIR increases)

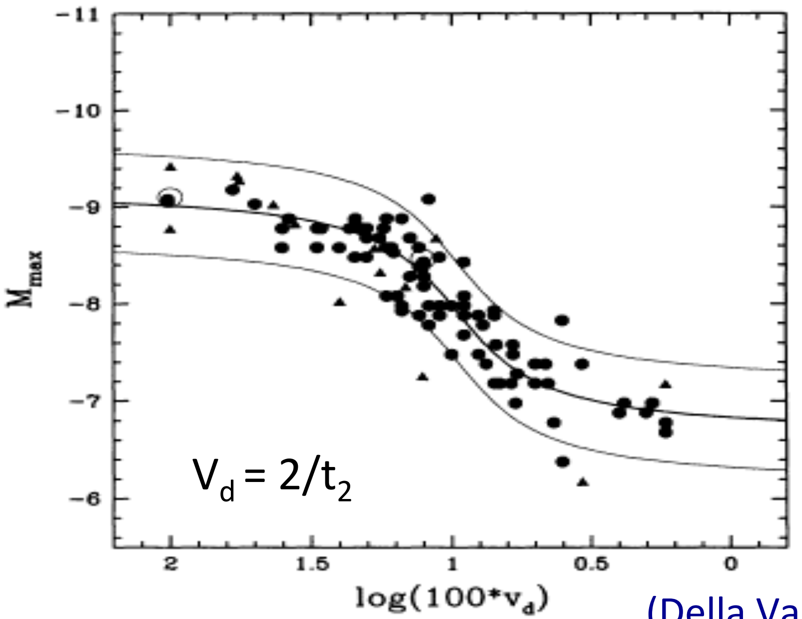


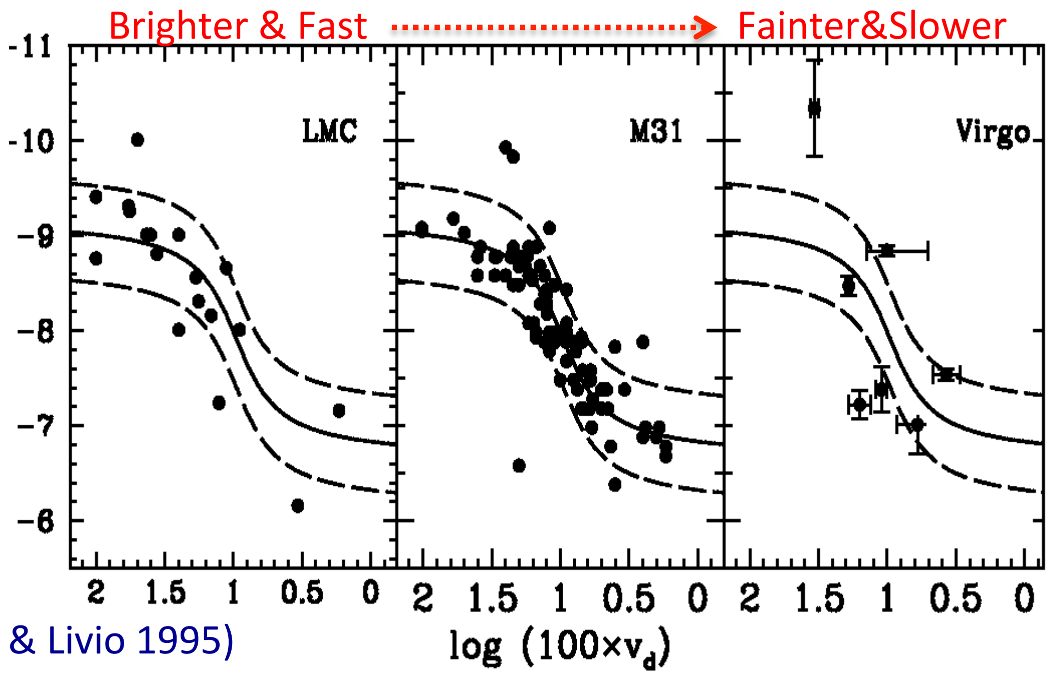
Strope et al. 2010

Nova as distance indicators

- Magnitude Max vs Rate of Decline (MMRD) in Galaxy, M31, LMC & Virgo (della Valle & Livio 1995) :

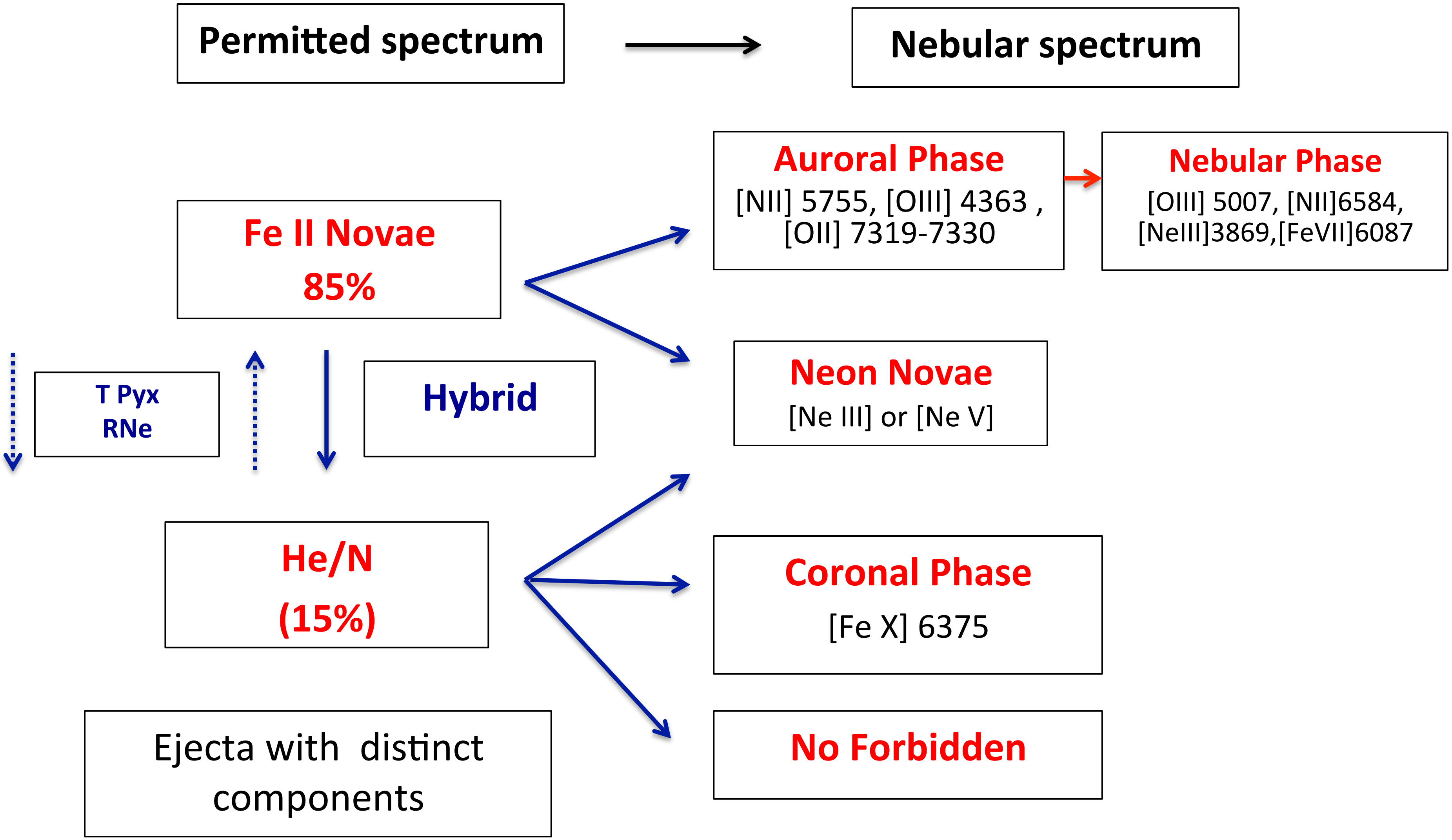
$$M_{V,max} = -7.92 \; -0.81 \times \tan^{-1} [(1.32-\log_{10} t_2)/0.23]$$





(Della Valle & Livio 1995)

Optical/nIR Spectral evolution



(Williams 2012, Shafter et al. 2011; Shore et al. 2011, Anupama 2011, 2012)

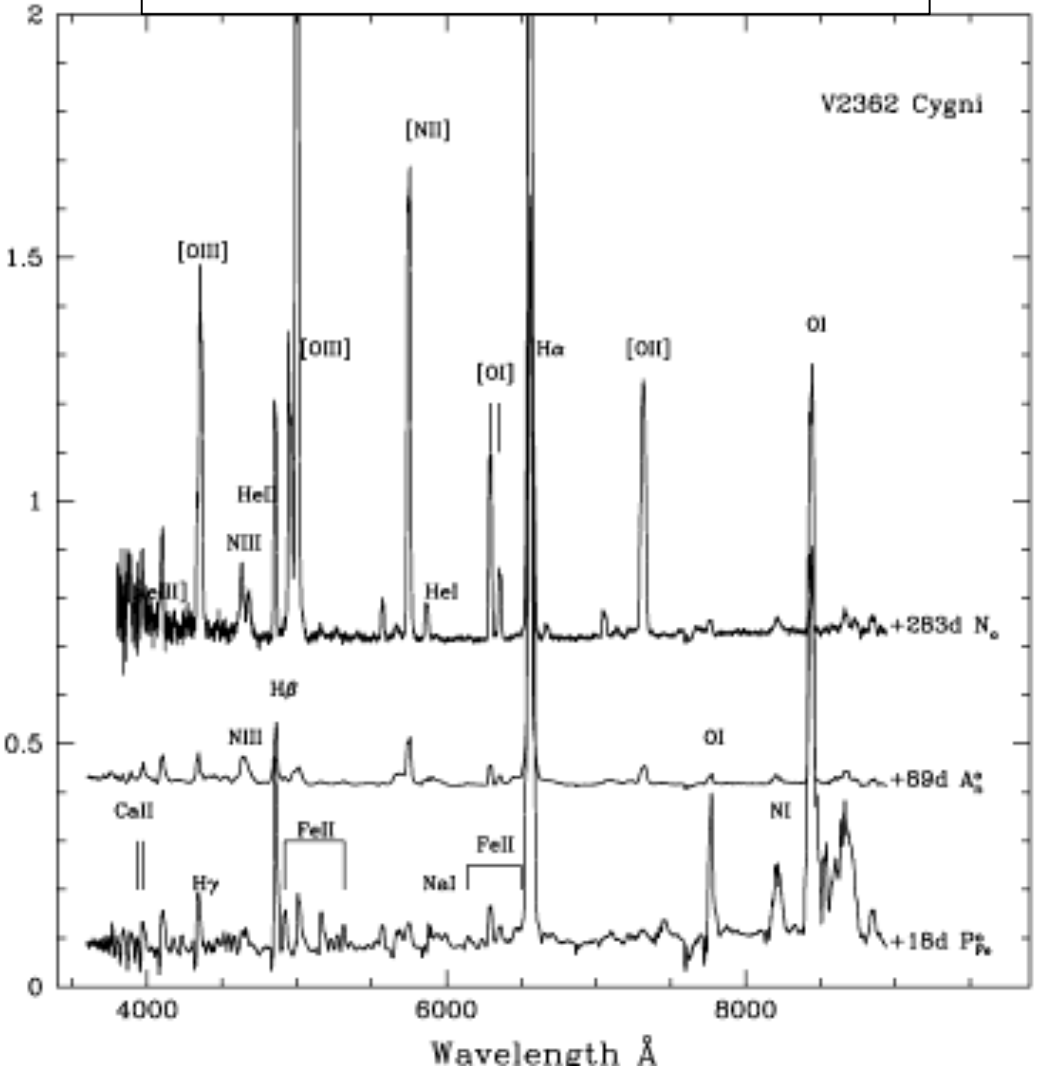
Spectral evolution

few examples

FeII Nova   V2362 Cyg

Anupama 2011,2012

t_3 = 21 d



+283d

+89d

+18d

Nebular spectrum

Auroral spectrum

Permitted spectrum

Time

Spectral evolution

Complexities in ejecta

t_3 = 21 d

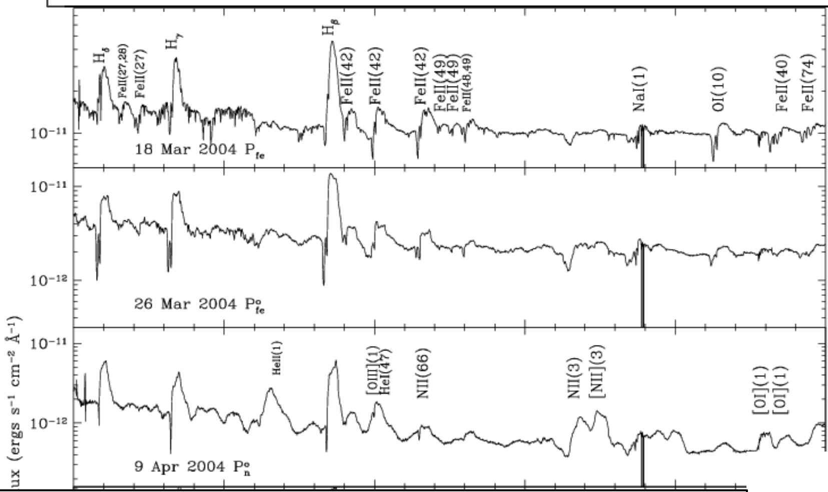
Hybrid (FeII->He/N) Nova V5114Sgr

Ederoclite et al. 2006

+1d

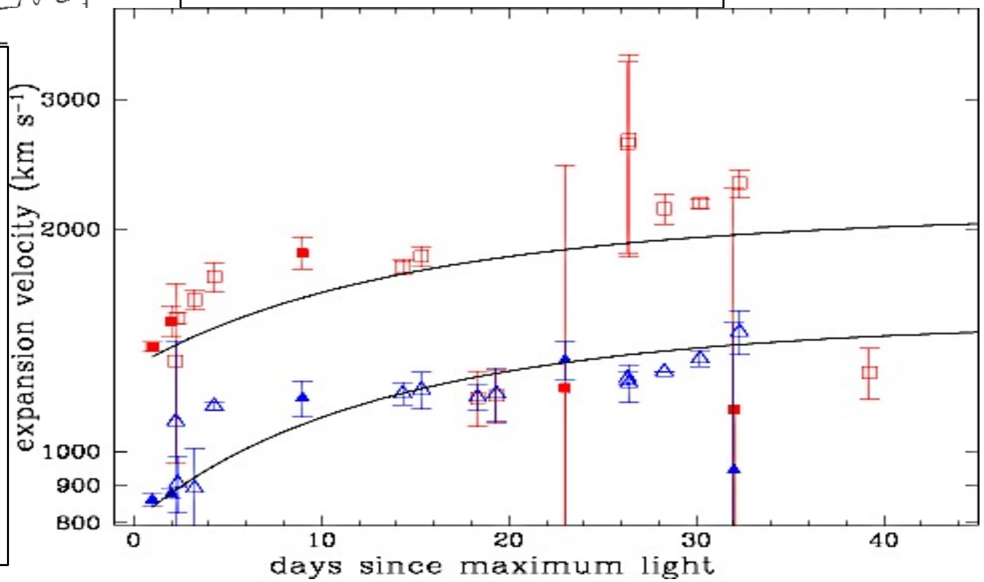
+8d

+23d



Permitted FeII spectrum

Permitted He/N spectrum



Absorption components evolution

Double P-Cyg profiles of Balmer lines

High and low velocity modelled as :

$$V(t) = V_0 - (V_0 - V_\infty)\, e^{-t/\tau}$$

V_0= 1300 km/s V_∞= 2100km/s

V_0= 800 km/s V_∞= 1500km/s

Novae Explosion

- Novae Energetics:

  $L \approx 2\text{-}4\times10^{4} - 5\times10^{5}\, L_{\odot} \geq L_{Edd}$ $[\, L_{Edd} \approx 1.2\times10^{38}\, (M/M_{\odot})$ erg/s]

  $M_{eject} \approx 10^{-6} - 10^{-4}\, M_{\odot}$ → radiation pressure as driving force

  Energy ≈ 10^{45} erg over $t \leq 10^{8}$ s

  Veject ≈ few 100 – 3000 km/s

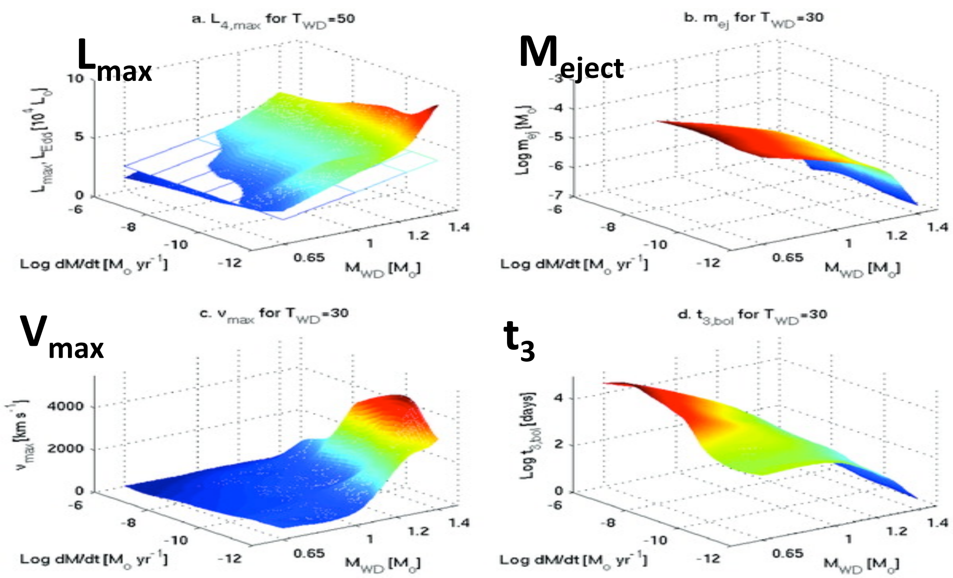
  Produced by thermonuclear Runaway on WD surface

(Kraft 1963, Giannone & Wigert 1967; Starrfield 1971, 1976; Gallagher&Starrfield 1978)

- 3D MHD simulation to test parameter space with observables :

  M_{acc}, T_{WD}, M_{WD}

(Yaron et al. 2005)



Novae Explosions

- Importance of nucleosynthesis:

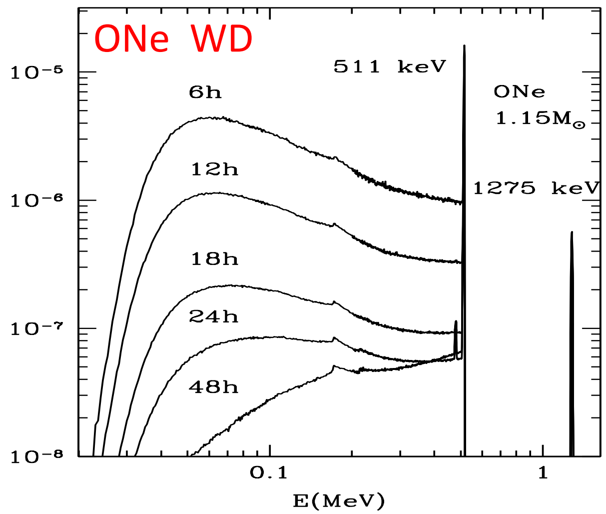
- Novae not major contributors to ISM abundances but **important contributors of isotopes**:

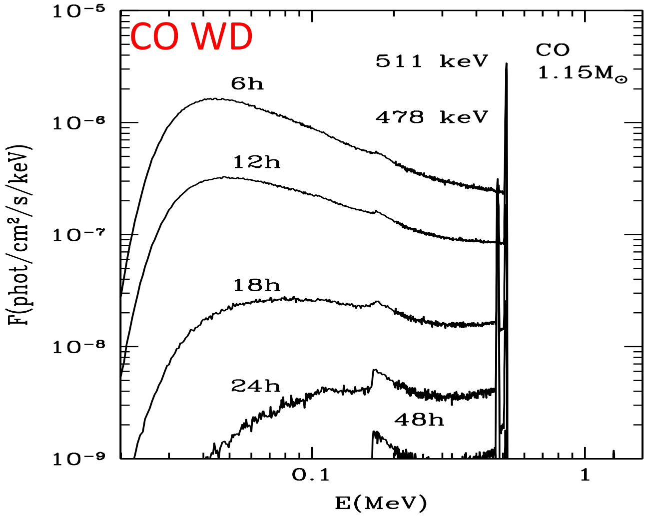
- CO and ONe WDs: overabundances of : ^{7}Li, ^{22}Na, ^{26}Al

Hernanz 2014

Table 1. Main radioactive nuclei synthesized in nova explosions.

Isotope	Lifetime	Main disintegration process	Type of emission	Nova type
^{13}N	862 s	β^+-decay	511 keV line and continuum	CO and ONe
^{18}F	158 min	β^+-decay	511 keV line and continuum	CO and ONe
^{7}Be ^{7}Li	77 days	e^--capture	478 keV line	CO
^{22}Na ^{22}Ne	3.75 years	β^+-decay	1275 and 511 keV lines	ONe
^{26}Al ^{26}Mg	10^6 years	β^+-decay	1809 and 511 keV lines	ONe





Test with observations:

No γ-ray detection

but ^{7}Be optical lines (Izzo et al. 2015, 2018)

Need high sensitivity

High energy emission from Novae

- X-ray emission:

Since EXOSAT and ROSAT novae detected as strong soft X-ray sources

Soft X-rays appear several days after optical maximum:

(Super-Soft X-ray Source – SSS)

$L_{soft} \approx 10^{37\text{-}38}$ erg/s $\approx L_{EDD}$ $\quad$ $kT \approx 30\text{-}80$eV

(Orio et al. 2001, 2004; Krautter 2008)

High energy emission from Novae

- X-ray emission:

  3 separate X-ray phases

- Early hard X-ray phase (few to tens days)::

  Ejected material absorbes X-rays & UV

  Expansion at L_{bol}≈const

  X-rays are hard

- Later SSS phase:

  Ejected material becomes optically thin

  Photosphere expands until nuclear burning decreases envelope mass

  X-rays are soft

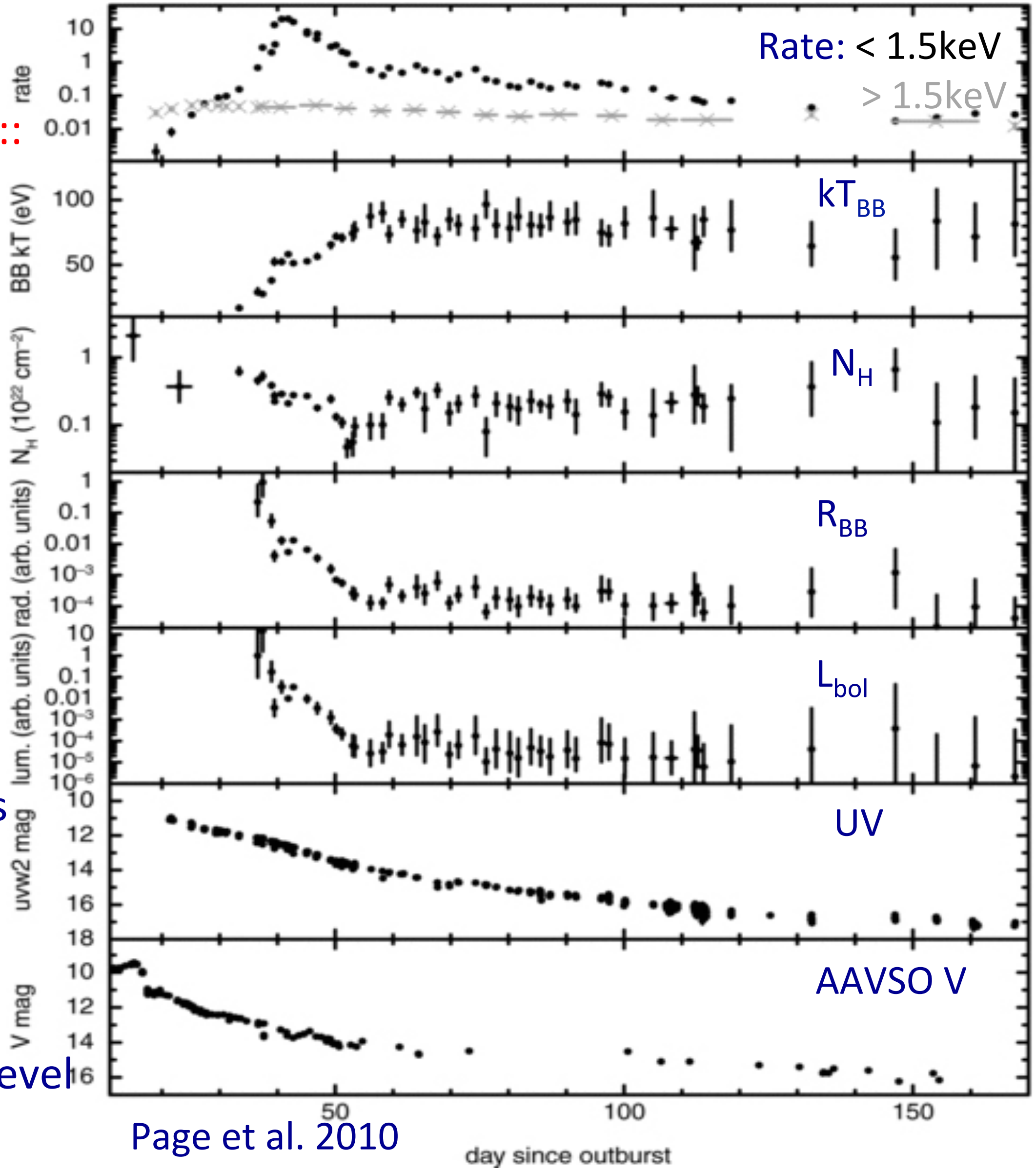
  Photosphere shrinks & Temperature rises

- SSS decline:

  Fast Soft X-ray decline $t^{-\alpha}$ α=3.1

  Slow Hard decline $t^{-\alpha}$ α=0.8 at pre-nova level

V2491 Cyg – Nova Cyg 2008 Swift/XRT



Page et al. 2010

High energy emission from Novae

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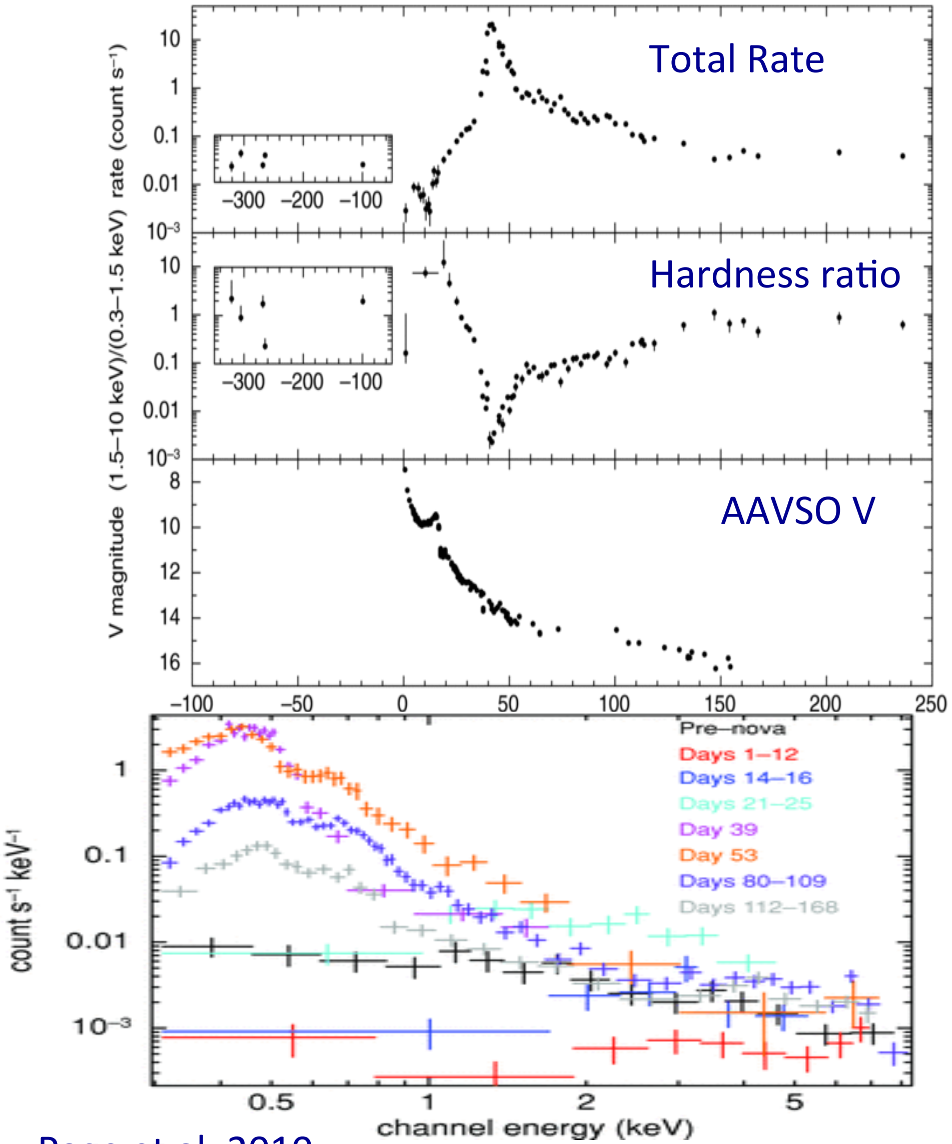


Page et al. 2010

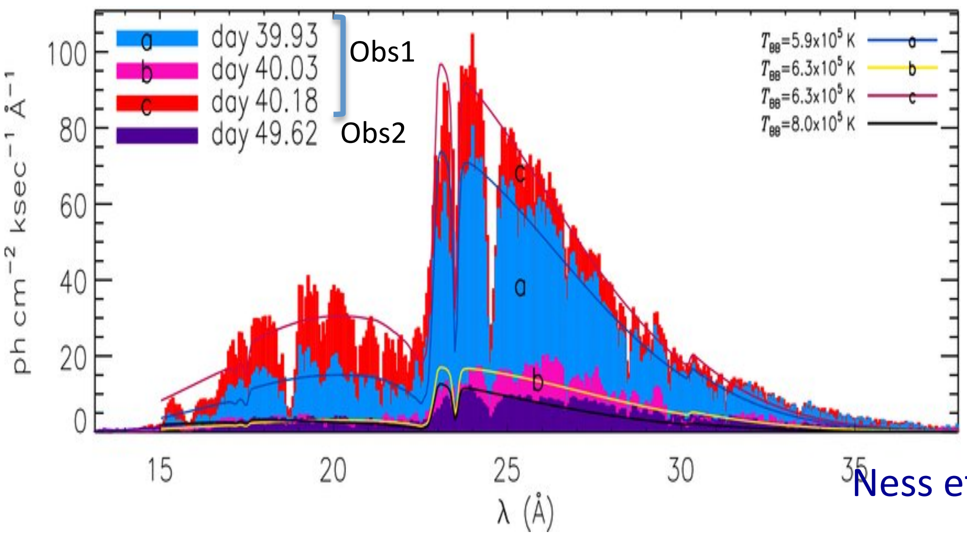
High energy emission from Novae

- Requirement for 2 components:
  Opt. Thick + Opt. Thin

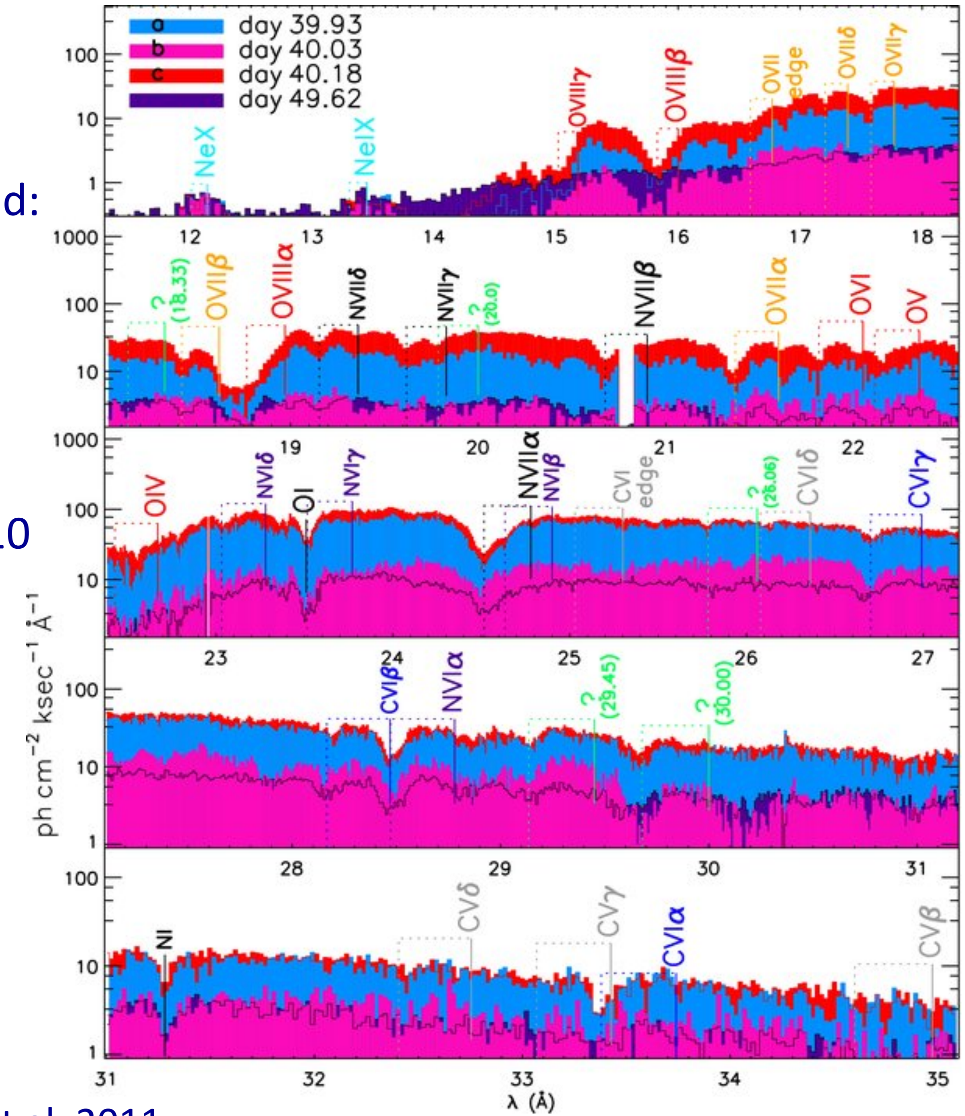
1) Soft Opt.thick component:

The SSS allows to determine Teff, log g, abund:

- Strong absorption edges and broad lines of elements with different abundances
- velocity blue-shifts up to -3200km/s
- BB overestimates Luminosity by a factor >10



V2491 Cyg – Nova Cyg 2008 XMM-Newton/RGS



Ness et al. 2011

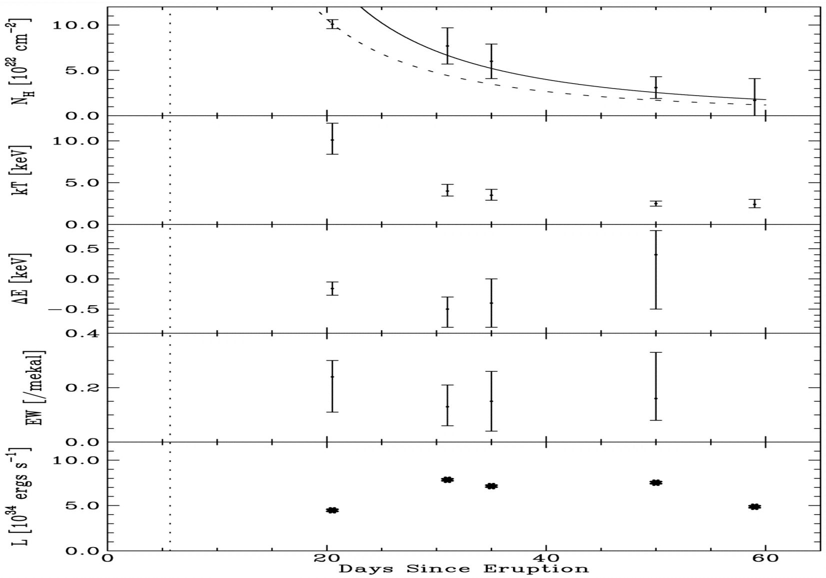
High energy emission from Novae

2) Hard Opt.thin component:

- Optically thin thermal emission: Lx ≈ 10^{32}-10^{-36} erg/s in many novae
- Hard X-rays slowly decrease:
- Temperatures decrease from 10-20keV to ≈ 1keV (Mukai et al. 2008)
- Absorbing column decreases as the ejecta expands in most cases

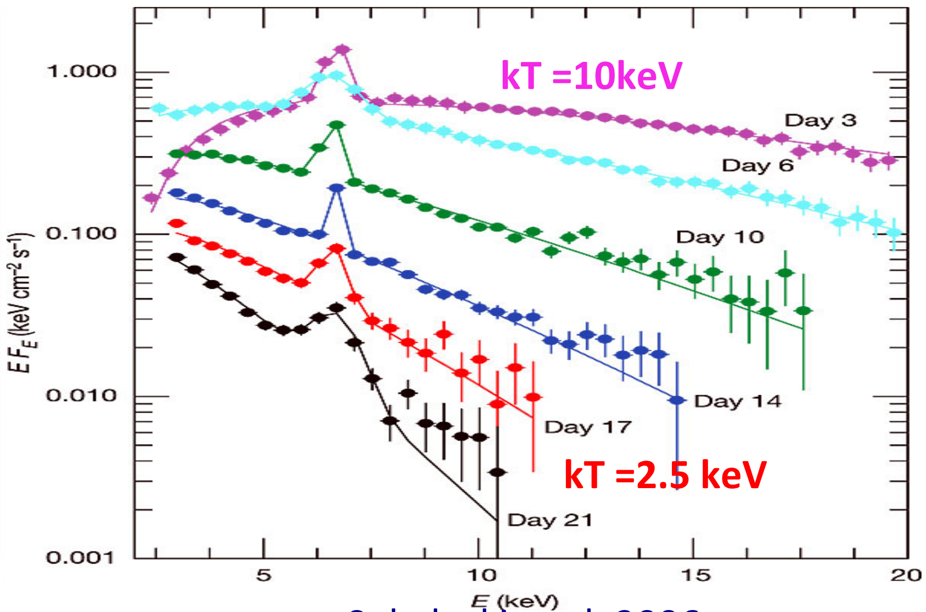
→ **Shocks** within ejecta in CNe or with the Giant/Mira wind in SyNe

V382 Vel (Nova Vel 1999)



Mukai & Ishida 2001

RS Oph 2006 Outburst

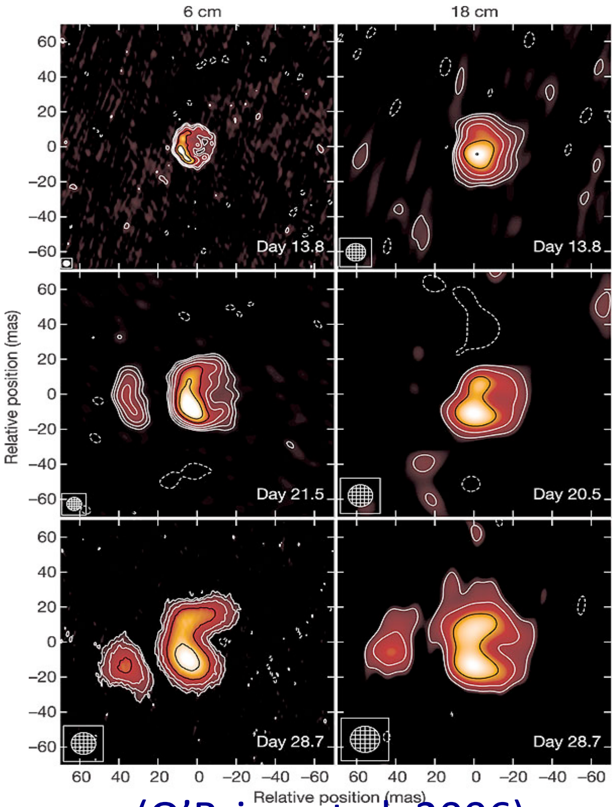


Sokoloski et al. 2006

Asymmetric ejecta

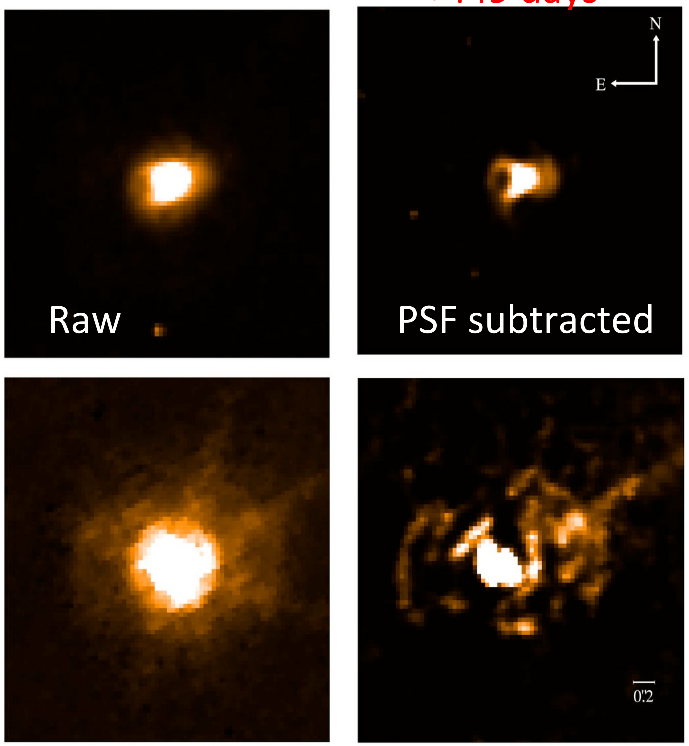
- Ejecta are complex and asymmetric: bipolar outflow
- Asymmetric ejection of   SyRN RS Oph 2006 outburst: a dumbbell structure
- Thermal radio emission at centre – non-thermal at lobes

VLBI   RS Oph   +14 days

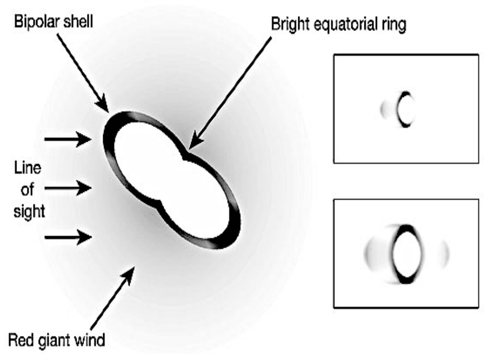


(O'Brien et al. 2006)

HST ACS/HRC [OIII]   +155 days
+449 days



(Ribeiro et al. 2009)



High energy emission from Novae

The surprising Y-ray detection (> 100 MeV) from Fermi-LAT:

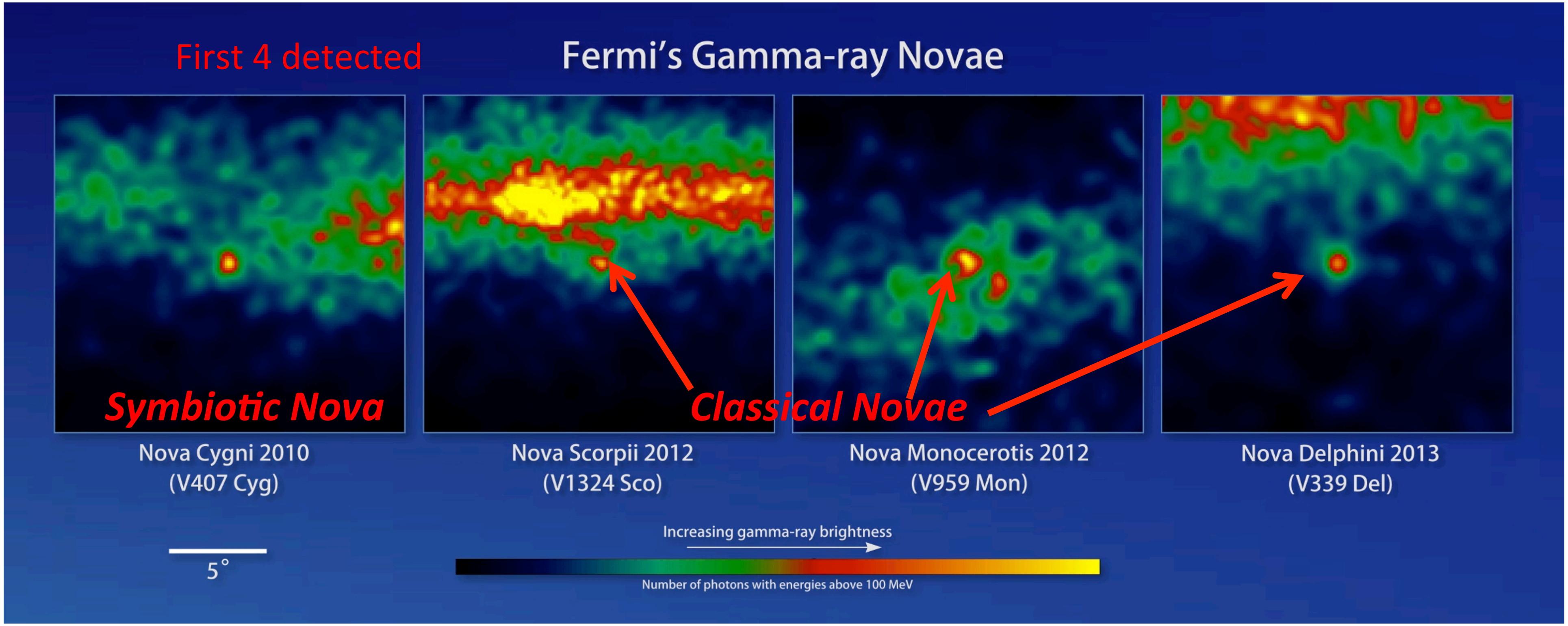
Ackermann et al. 2014
Cheung et al. 2016
Finzell et al. 2018
Franckowiak et al. 2018
+ ATels 2016-2018

Novae as new class of Y-ray sources

- 2008-2018: FERMI-LAT decteced 14 Novae + 2 Candidates (3 σ):

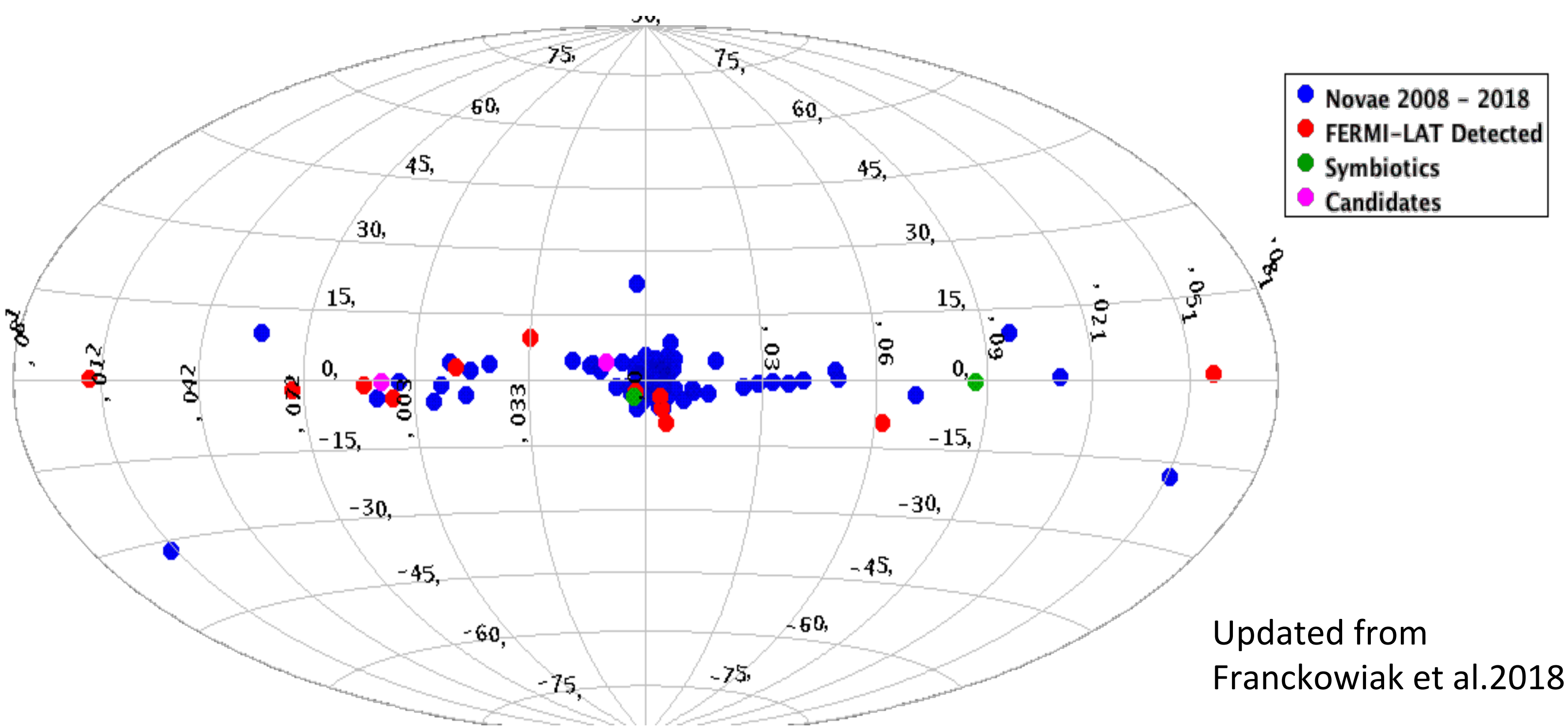
  13 Classical Novae, 2 SyRNe, 1 Symbiotic Nova

- Archival Compton/OSSE searches: CN V382 Vel (Nova Vel 1999) @ 0.1MeV



Novae a new class of Y-ray sources

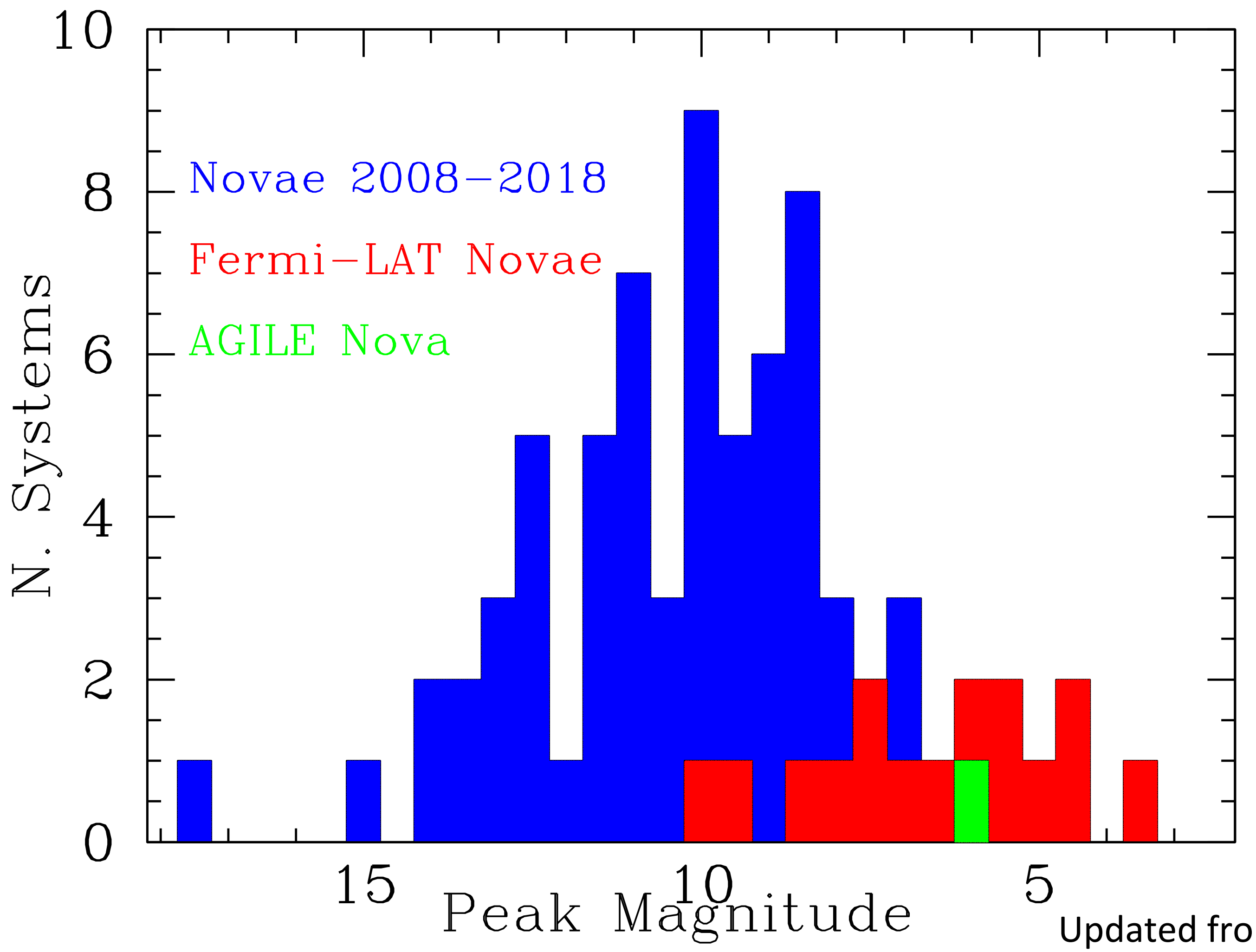
- Aug. 2008-Apr. 2018: 103 "well" sampled Galactic Novae (AAVSO !!)
- Most concentrated in the Galactic Plane and Bulge
- Fermi-LAT Galactic Novae: detected **14** + **2** candidates



Updated from
Franckowiak et al.2018

Novae a new class of Y-ray sources

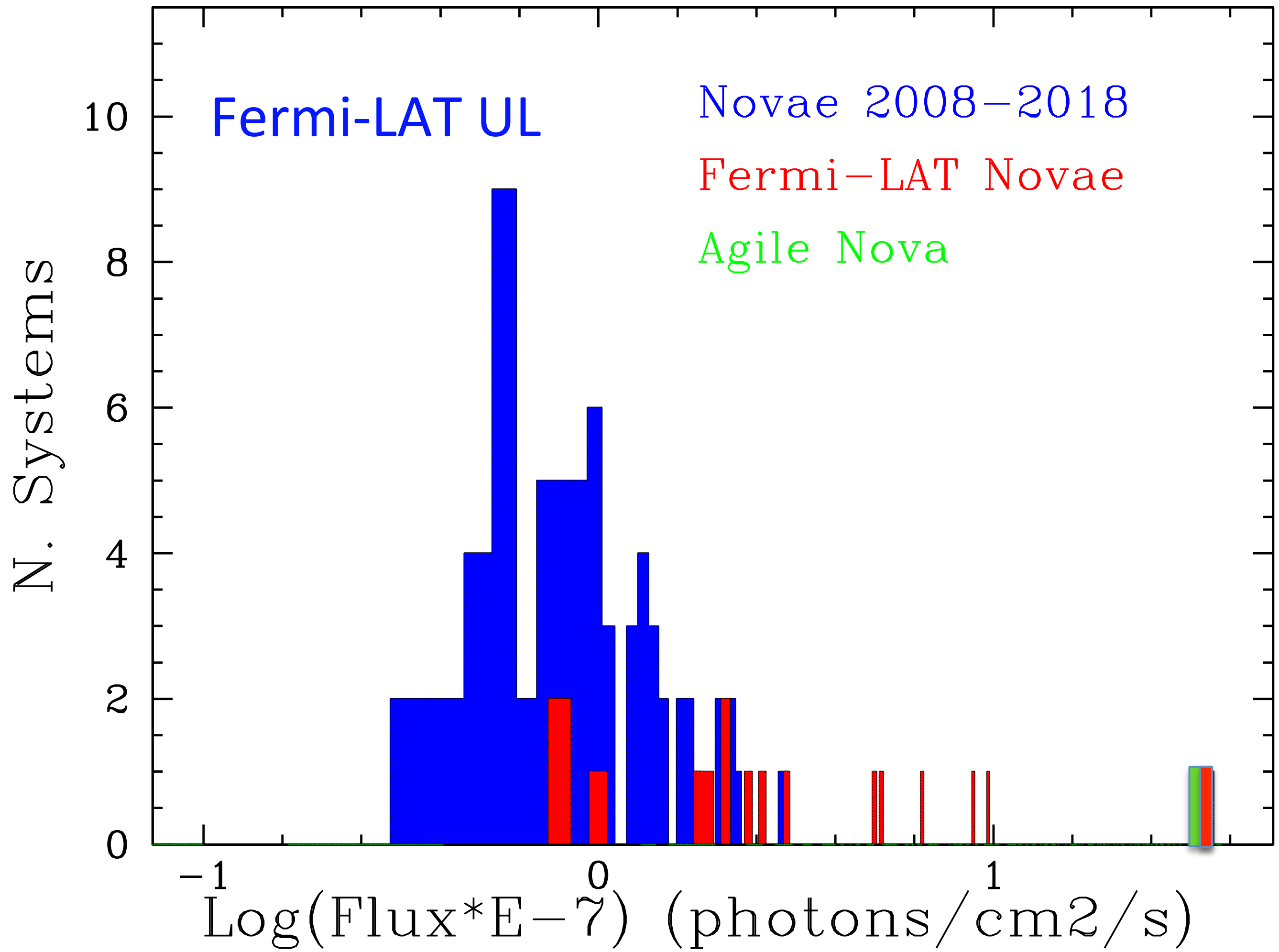
- Fermi-LAT novae are optically bright



Updated from
Franckowiak et al. 2018

Novae a new class of Υ-ray sources

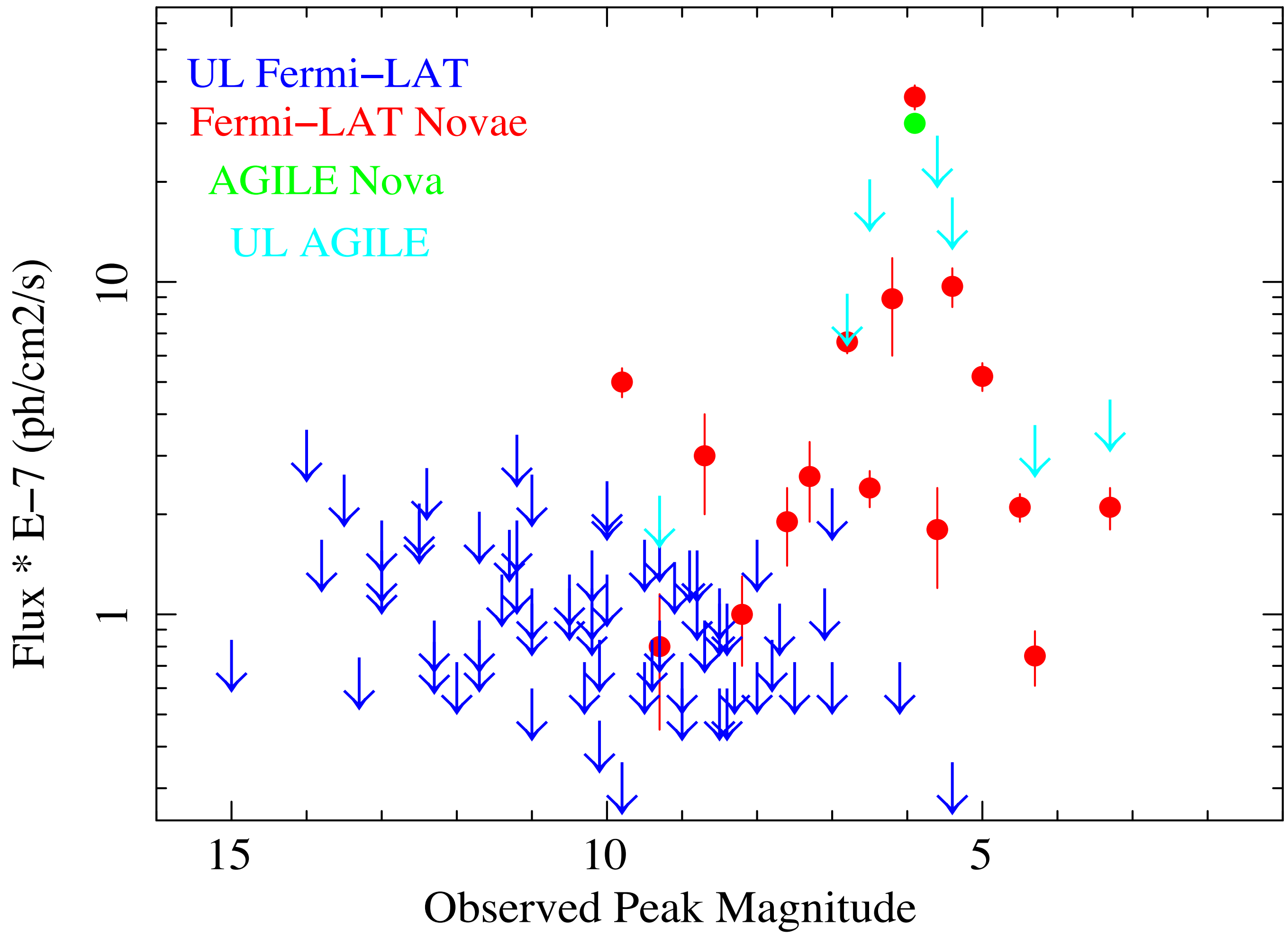
- High γ-ray flux : > 0.8 x 10^{-7} ph/cm2/s



Updated from Franckowiak et al. 2018

Novae a new class of ϒ-ray sources

- No correlation between optical and ϒ-ray brightness

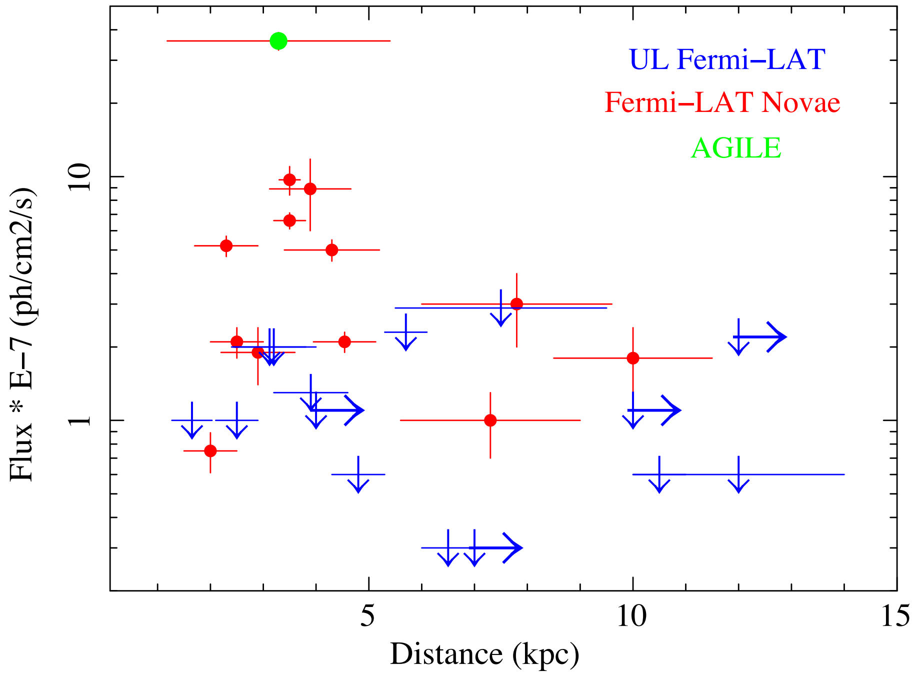


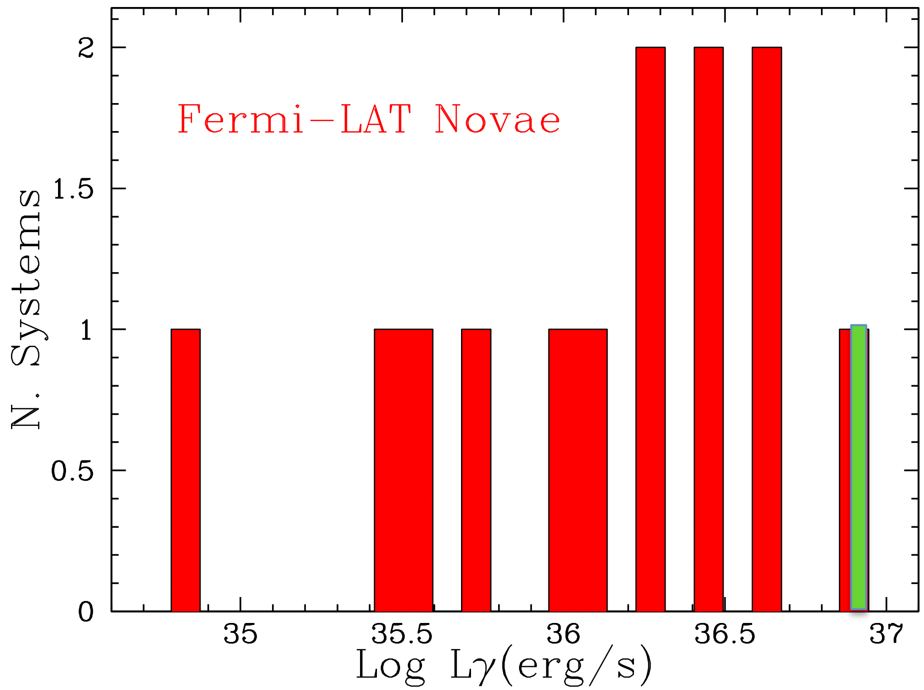
AGILE UL courtesy from G.Piano

Updated from Franckowiak et al. 2018

Novae a new class of ϒ-ray sources

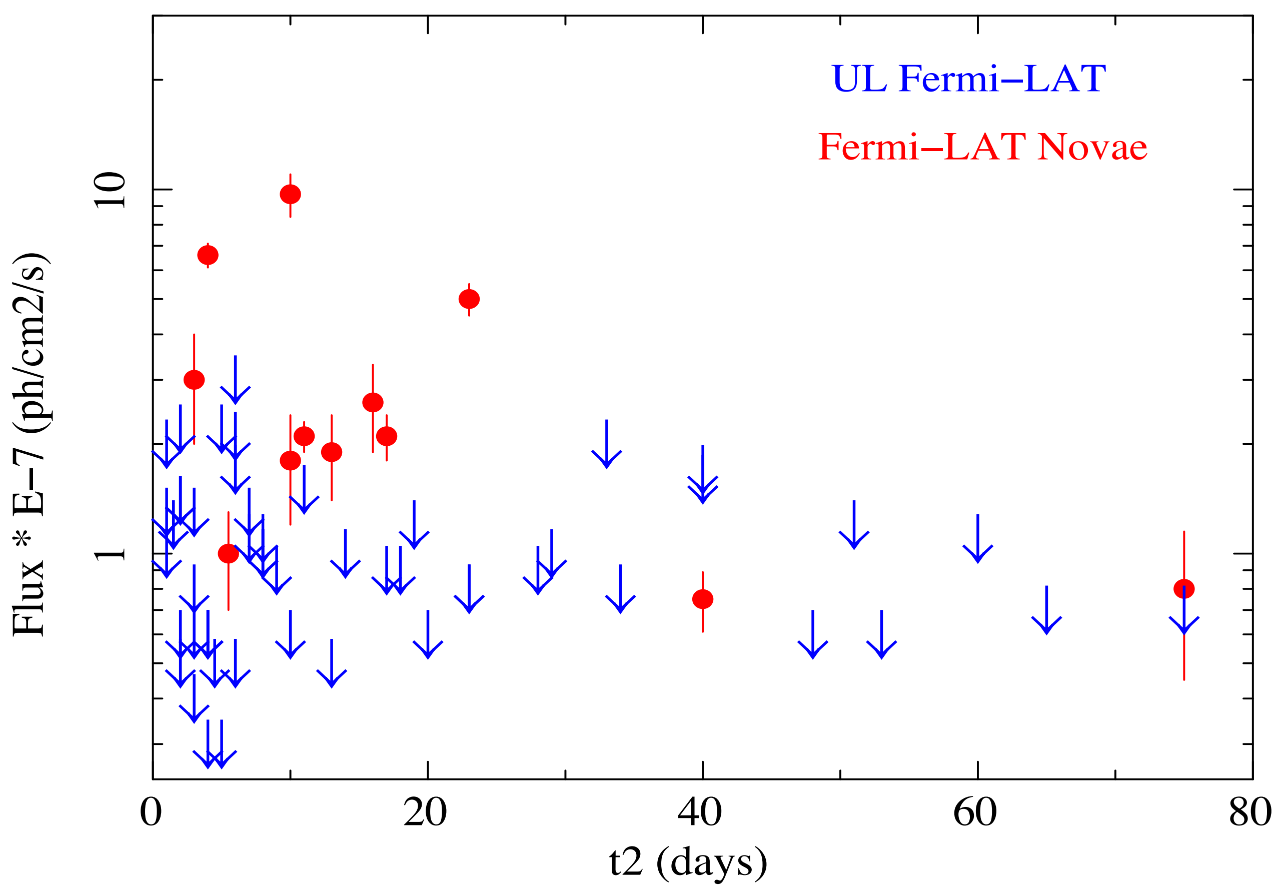
- Distance plays a role: most within 5kpc but not all detected
- Low ϒ-ray Luminosities: <10^{37} erg/s





Novae a new class of Y-ray sources

- 5 Novae out of 16 are fast (t2 ≤ 13days)

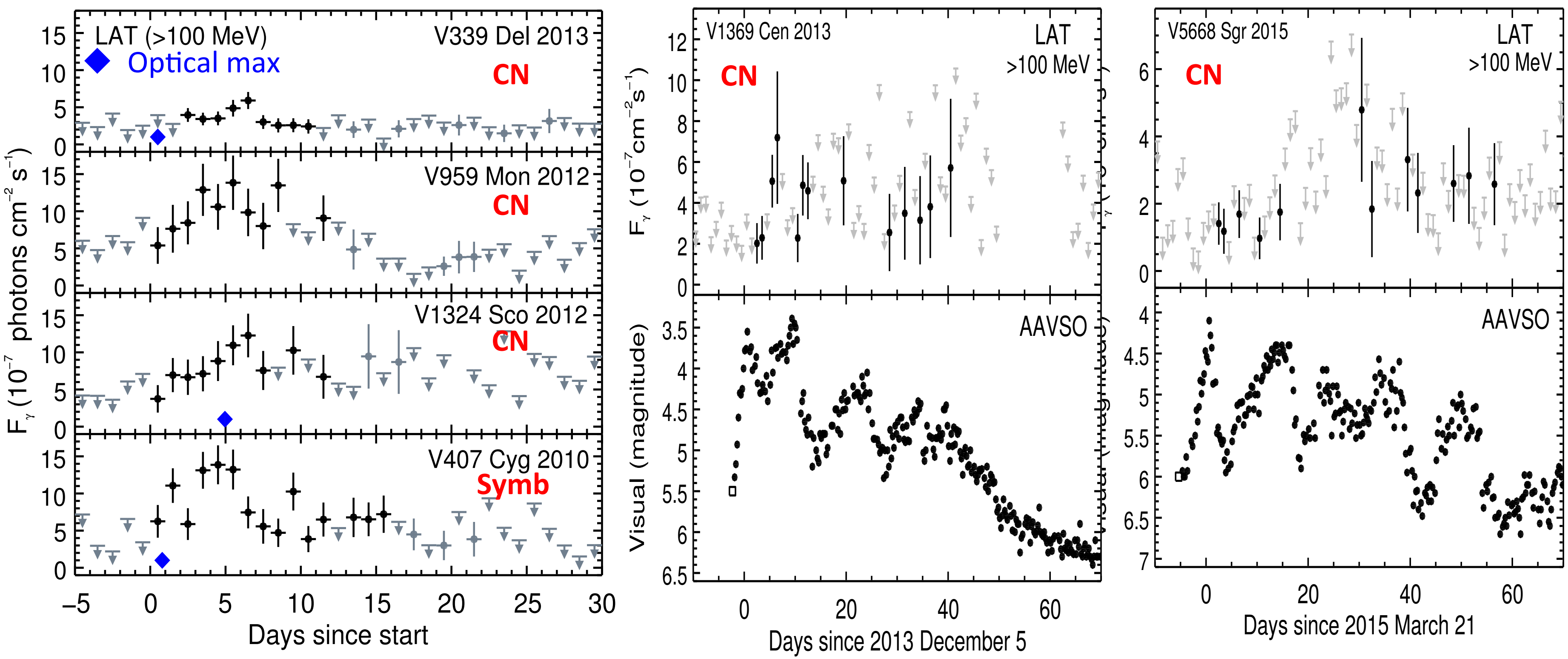


High energy emission from Novae

Similarities in ϒ-ray light curves despite being CN or Symbiotic:

- Rise and Fall times similar : ~ 2-7 days
- Duration: 17-30 days
- Broad peak reaching 1-2 x 10^{-6} ph/cm2/s in a few novae
- Total energy: 6-13 x 10^{41} erg

Ackermann et al. 2014
Cheung et al. 2016



High energy emission from Novae

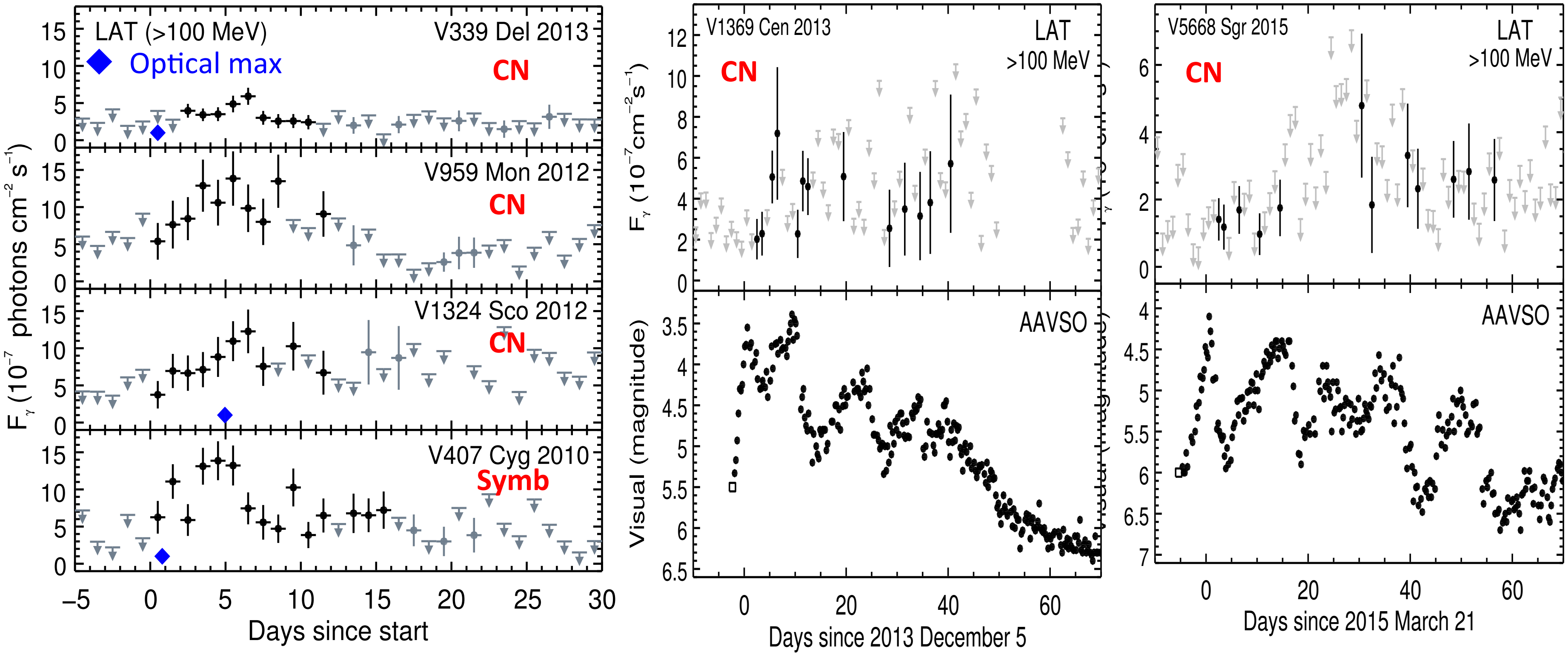
Optical & γ-ray light curves:

- Y-ray &. Optical maxima:

  sometimes coincident but often lag (few days up to 30days)
- Delay: travel time in CNe ~ 1hr -> later shocks within ejecta

  in Symb > 5 days -> shocks in Mira's wind

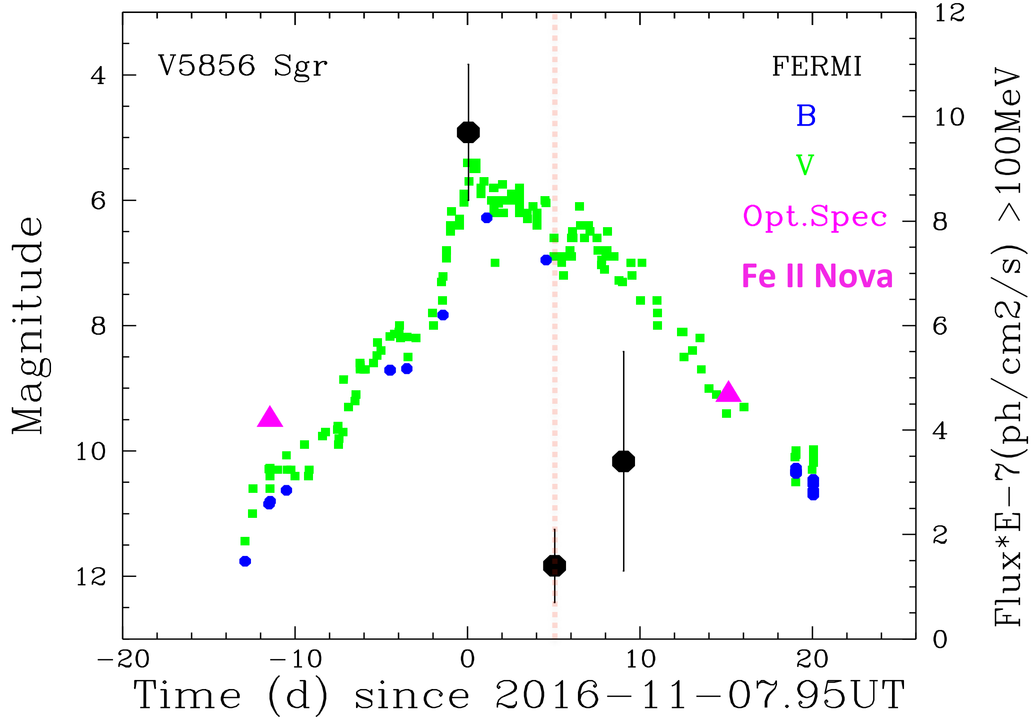
Ackermann et al. 2014
Cheung et al. 2016



Clues from Recent Classical Novae

V5856 Sgr – Nova Sgr. 2016 N.4 :

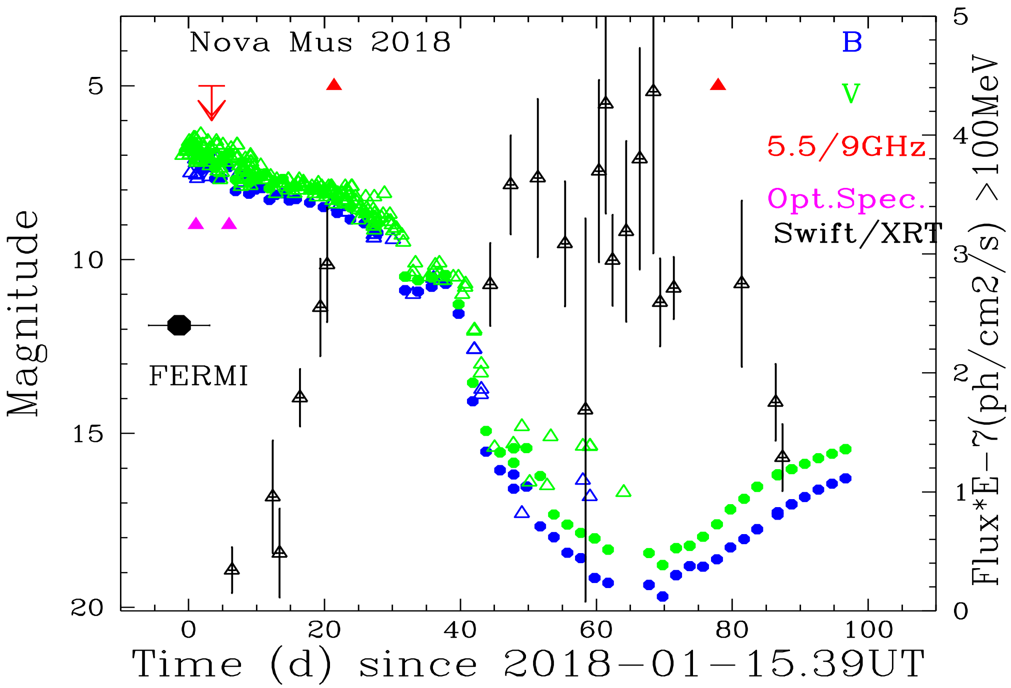
- ϒ-ray peak at optical maximum
- ϒ-ray and optical dips almost coincident
- No X-ray detection by Swift/XRT @ opt. Max
- Fast nova : t2 ≈ 10days but still bright (≈ 12.5mag) in 2018
- Pre-Nova counterpart from GAIA DR2 : quiescence (≈ 20mag) - no parallax

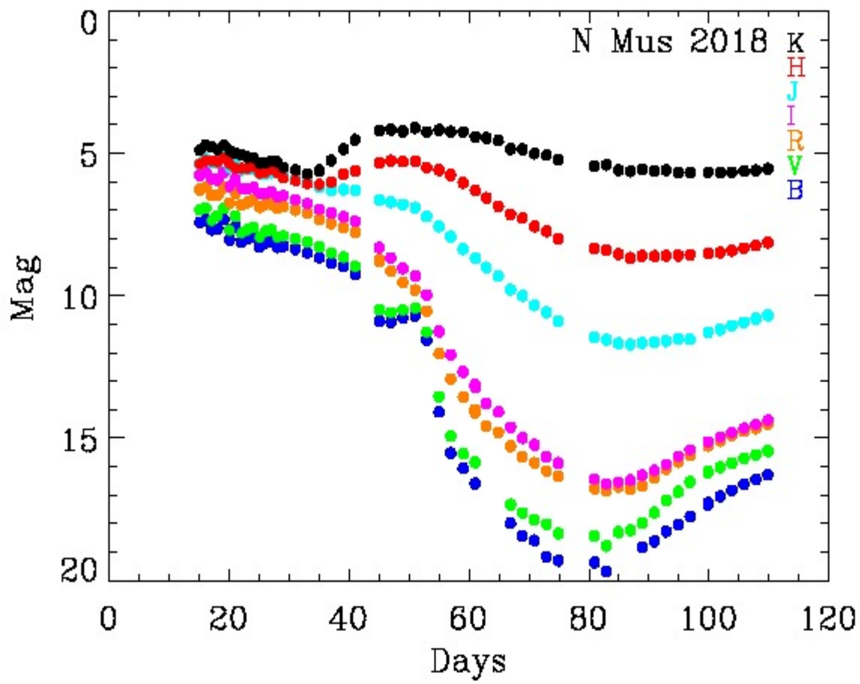


Clues from Recent Classical Novae

Nova Mus 2018 :

- ϒ-ray peak at optical maximum
- No X-ray detection by Swift/XRT in the first week
- X-rays increase after 20days up $F_{(0.3\text{-}10keV)} \approx 6\times10^{-12}$ erg/cm2/s
- Radio detection at t > 20days – slowly fading
- nIR coverage : dust develops at later times – coincident with X-ray maximum

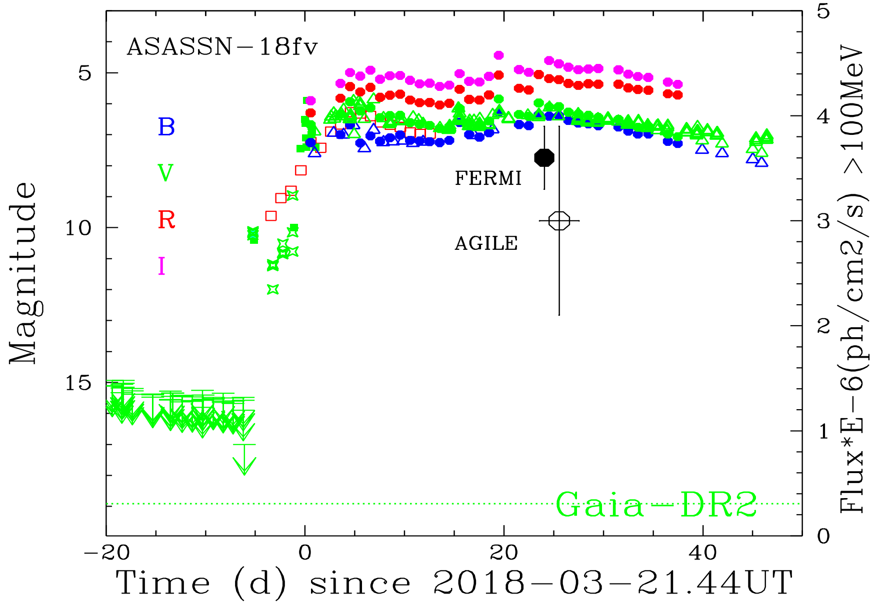




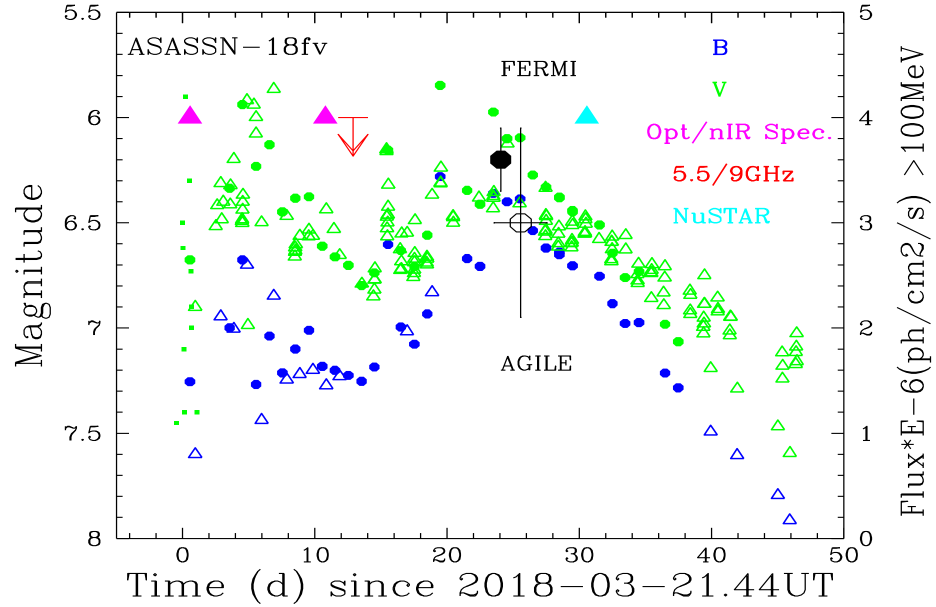
Clues from Recent Classical Novae

Nova Car 2018 – aka ASASSN-18fv:

- ϒ-ray peak at late stage of optical maximum detected by **Fermi** and **AGILE**
- NuSTAR: heavily absorbed opt. thin (kT ~ 8keV) at $F_{(3\text{-}78keV)} \sim 3\times10^{-12}$ cgs
- No radio detection @9 or 5.5GHz on Day 3 from maximum
- Pre-Nova from GAIA DR2 : V~18.9 - uncertain parallax d ~ 3.3 kpc
- Slow-Nova: t2 > 48days



Fe II → FeII + He/N Nova



High energy emission from Novae

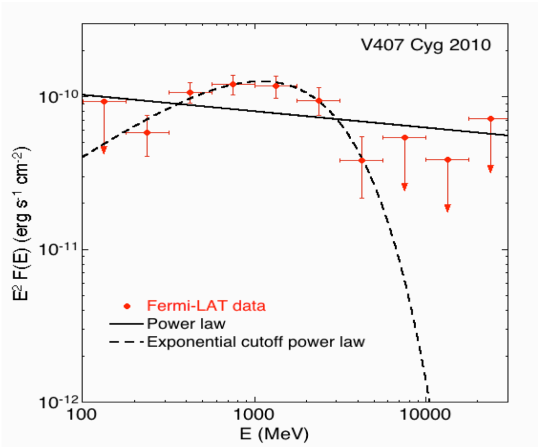
Similarities of Y-ray spectra:

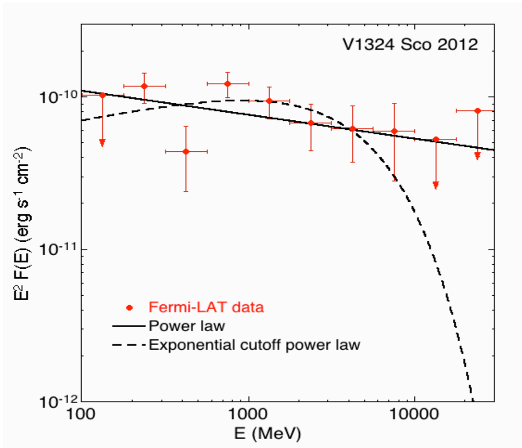
Ackermann et al. 2014
Cheung et al. 2016
Franckwoiak et al. 2018

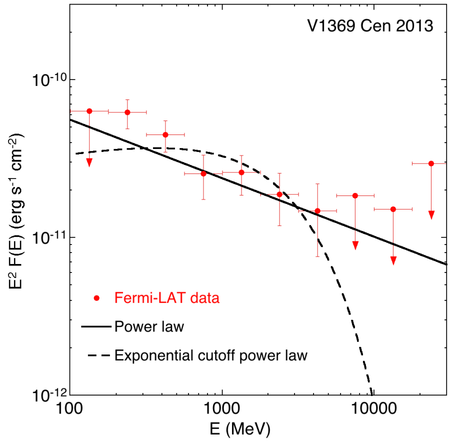
--- Power Law: $N(E) \approx E^{-\Gamma}$ $\Gamma \approx 2.0 - 2.3$

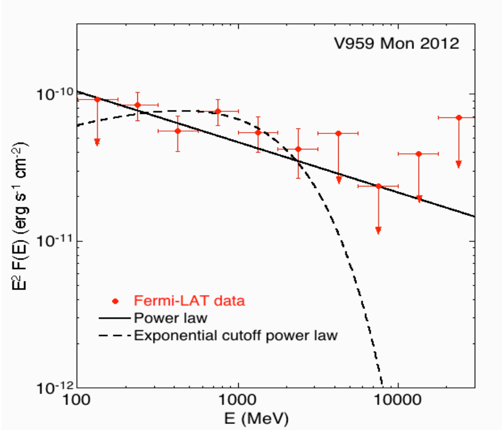
or

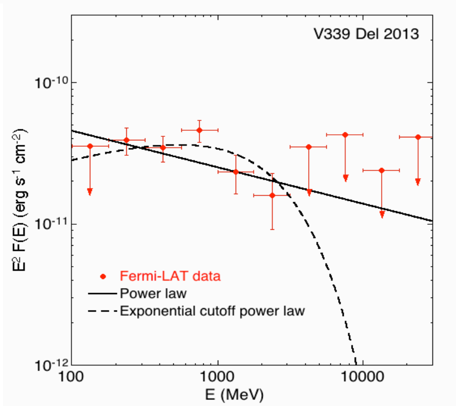
--- Exp. Cutoff Power Law: $N(E) \approx E^{-s}\, e^{-E/Ec}$ $s = 1.7 - 1.8$; $E_c \approx 1\text{-}4$ GeV

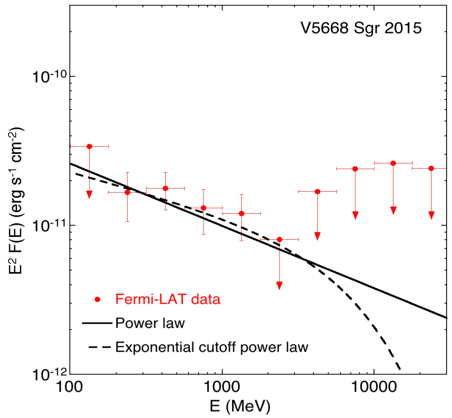








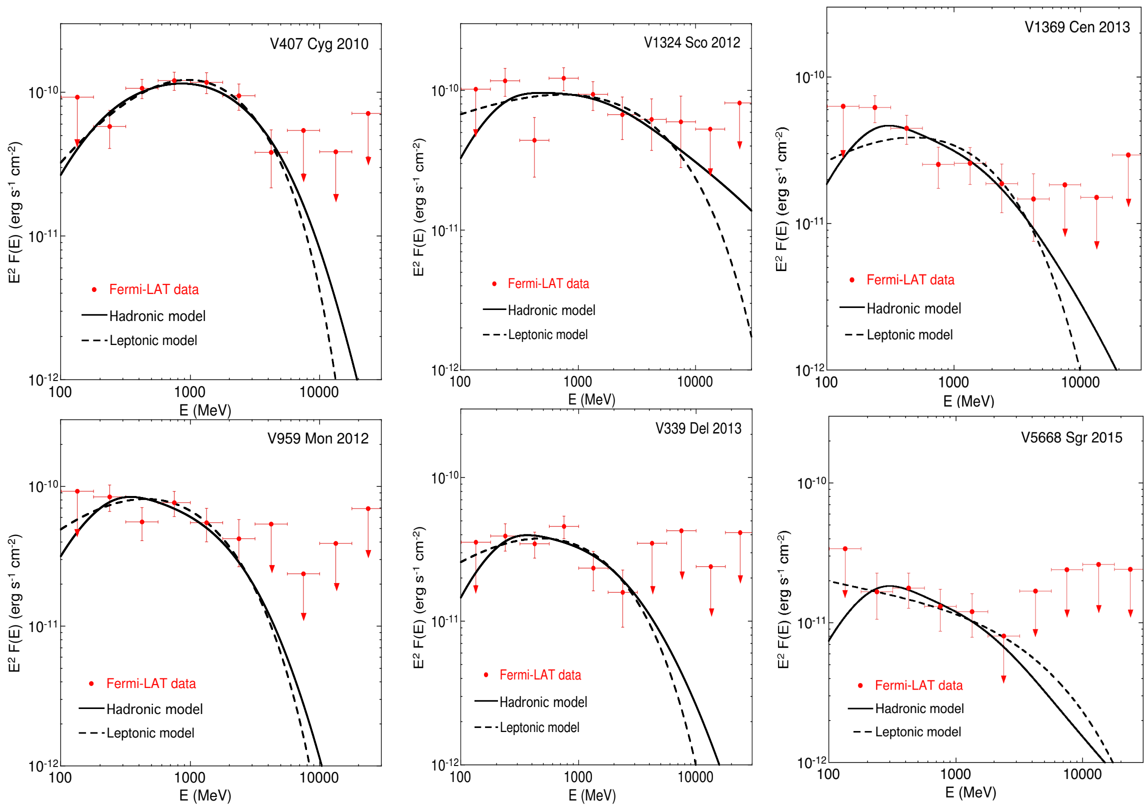




High energy emission from Novae

Similarities in Y-ray spectra:

- Interaction of accelerated protons or electrons within ejecta
  but origin and production site is still an open problem



Hadronic scenario:
pp collisions → π^o → 2Y
B> 10^{-3} G to accelerate protons

indistinguishable

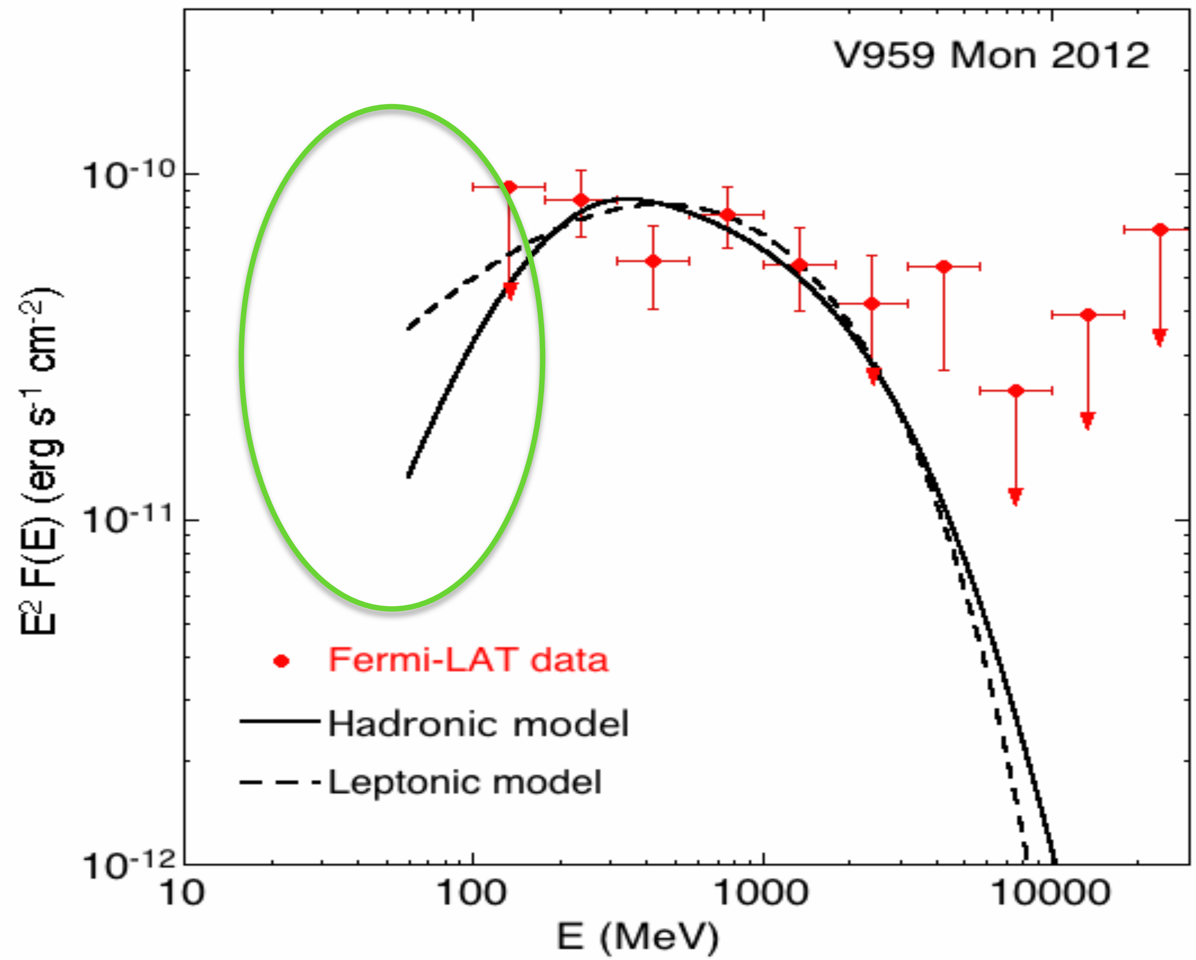
Leptonic scenario:
IC scattering of electrons with low-energy photons from the nova

Cheung et al. 2016

High energy emission from Novae

Similarities in Υ-ray spectra:

- Interaction of accelerated protons or electrons within ejecta
  but origin and production site is still an open problem



Hadronic scenario:
pp collisions → π^o → 2Υ
B> 10^{-3} G to accelerate protons

indistinguishable

Leptonic scenario:
IC scattering of electrons with low-energy photons from the nova

Soft Υ-ray coverage important !!

Cheung et al. 2016

Summary

- Although discovered more than 3500yrs ago Novae still give surprises !
- Novae emit at all energies: from radio to γ-rays → Panchromatic studies
- 16 detected Novae by Fermi → a new class of γ-ray emitters
- Particle acceleration origin and production site still an open problem :
  Shocks in ejecta/companion wind - hadronic or leptonic scenarios
- Hard X-ray and soft γ-ray coverage with sensitive instruments !