Novae as particle accelerators

Emergence of a somewhat unexpected γ-ray source class

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FROM COOLING TO EXPLOSION: THE PHYSICS OF WHITE DWARFS
An International Workshop dedicated to Margarita Hernanz on the occasion of her 60th birthday
Tossa de Mar (Girona), Catalonia, June 14-16, 2017

The 2010 outburst of V407 Cygni

Binary system:

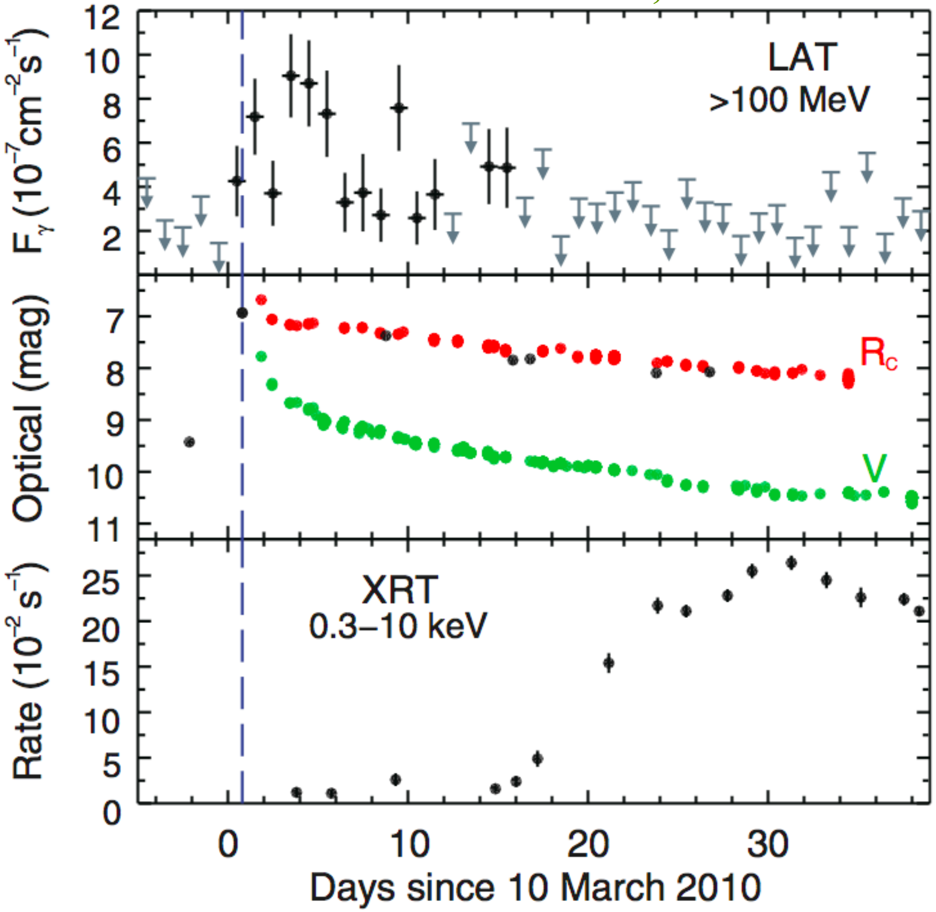
- Symbiotic (Mira) binary: white dwarf + red giant (Mira type)
- Orbital period ~ 43 years, separation ~ 15 AU
- Distance 2.7 kpc

Nova outburst of March 10, 2010:

- *Fermi*/LAT detection of high-energy (>100 MeV) γ-ray emission starting near the time of optical maximum and lasting about 2 – 3 weeks
- Particle acceleration in the strong shock between the nova ejecta and the dense wind from the RG primary
- Hadronic: π^0 decay γ-rays from p+p interactions? **or**
- Leptonic: inverse Compton scattering of the nova light?

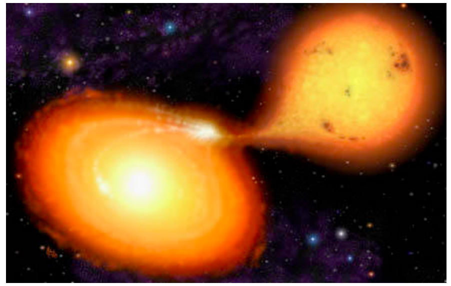
(see Martin & Dubus 2013)

Fermi-LAT Coll. 2010, *Science*



High-energy γ-ray emission from classical novae

Binary systems:

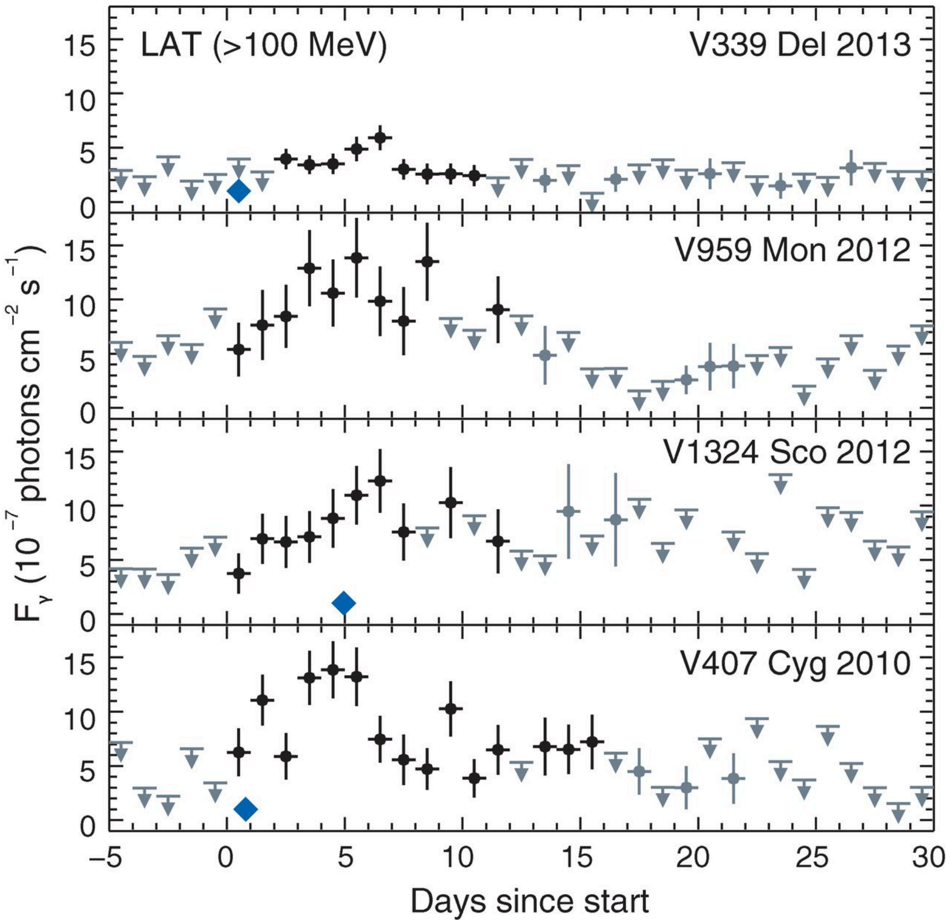


- Cataclysmic variables: white dwarf (CO or ONe) + main sequence star
- Matter accretion via Roche lobe overflow - no dense wind from the secondary

Gamma-ray emission:

- *Fermi*/LAT detection of high-energy (>100 MeV) γ-ray emission from 8 classical novae (till today)
- Wide diversity in γ-ray properties (onset, duration, luminosity..., see Cheung et al. 2016)
- How, when and where the putative shocks are generated?
- Hadronic vs. leptonic origin of the γ-ray radiation?

Fermi-LAT Coll. 2014, *Science*



Summary of detected (predicted) γ-ray novae

System	RS Oph	V407 Cyg	V1324 Sco	V959 Mon	V339 Del	V1369 Cen	V745 Sco	V5668 Sgr	V407 Lup	V5855 Sgr	V5856 Sgr
Year	(2006)	2010	2012	2012	2013	2013	2014	2015	2016	2016	2016
Distance (kpc)	1.6	2.7	6.5	1.4	4.5	2.5	8.0	2.0	?	?	?
Nova class	RN	RN	CN	CN	CN	CN	RN	CN	CN	CN	CN
***Fermi*/LAT detection**	NA	✓	✓	✓	✓	✓	3σ	✓	✓	✓	✓
γ-ray onset (days after optical maximum)	NA	0	-4	?	0	1.5	1	1.5	1	0	1
γ-ray duration (days)	NA	22	17	22	27	40	1	60	3	4	9
γ-ray flux (10^{-7} ph cm^{-2} s^{-1})	predicted	14	13	14	4	5.7	3	1.4	1.8	2.6	9.7

Adapted from Laura Delgado PhD and Martin et al. (2017)

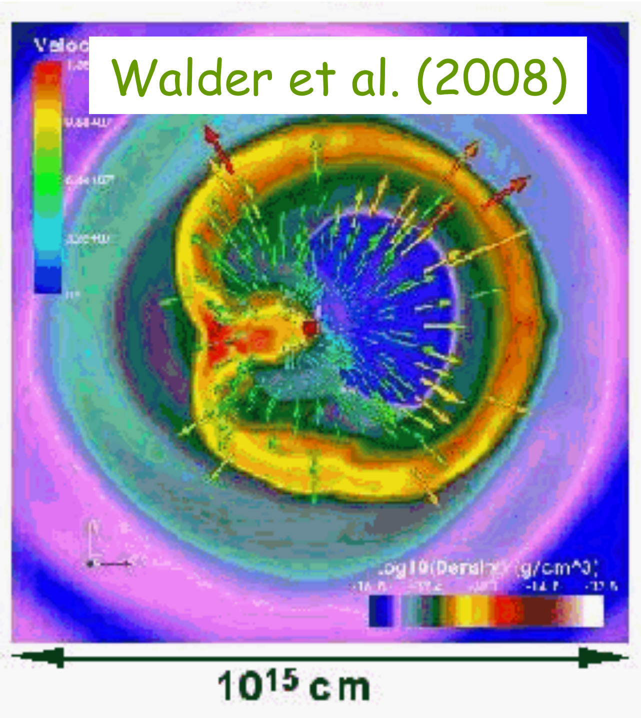
RN: Symbiotic recurrent nova

CN: Classical nova

- Detection rate since the launch of *Fermi* (June 2008): ~ 1 per year

The symbiotic recurrent nova RS Ophiuchi

- Massive white dwarf (M~1.35 $M_{\odot}$) with a red giant companion
- Outbursts: 1898, 1907, 1933, 1945, 1958, 1967, 1985, and 2006



⇒ Outburst recurrence period: ~20 years (as compared to 10^4-10^5 yrs for classical novae)

- Might be a type Ia SN in ~10^5-10^7 yrs (see Hernanz & José 2008)

Symbiotic novae as fast "miniature supernovae"

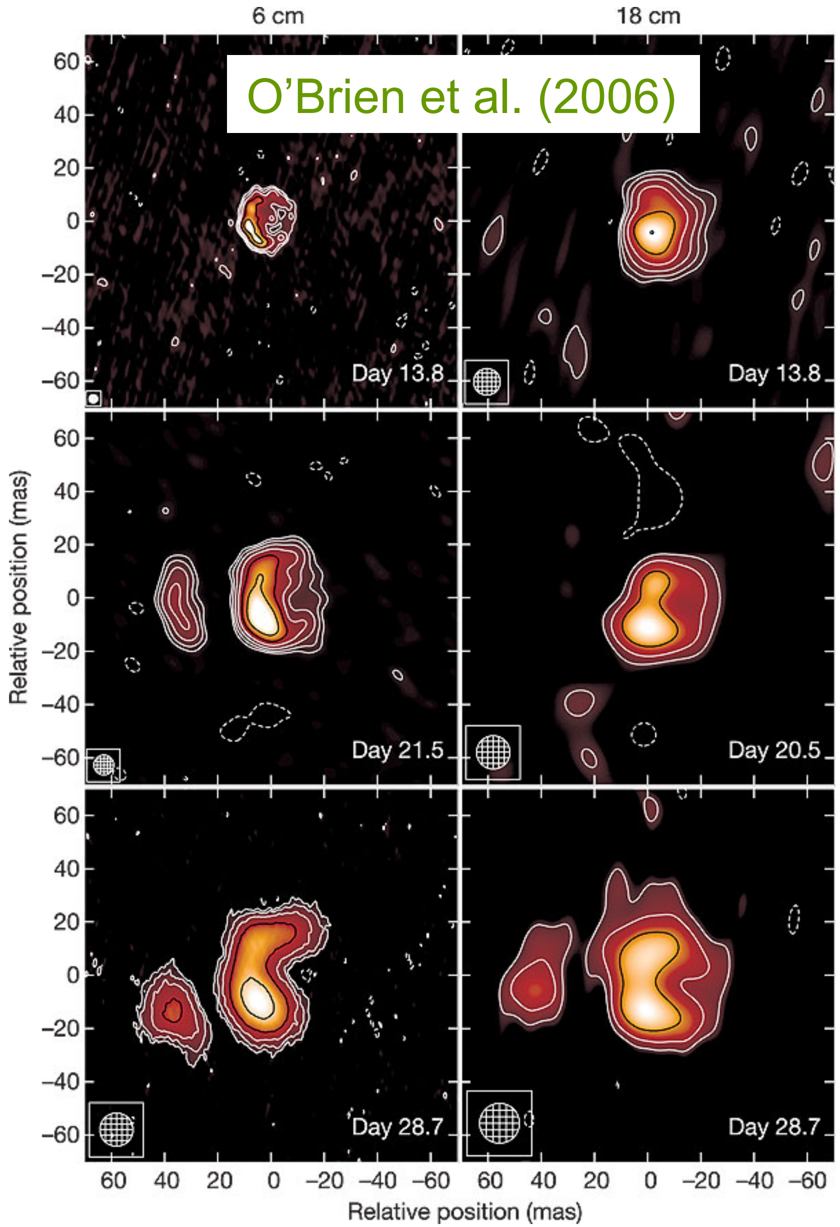
Charact. time of evolution of the shock system: $t_c \propto \frac{M_{ej}^{3/2} v_w}{E_{out}^{1/2} \dot{M}_w}$

RS Oph	SN II
$M_{ej} \sim 3\times10^{-6}\, M_\odot$	$M_{ej} \sim 10\, M_\odot$
$E_{out} \sim 10^{44}$ erg	$E_{out} \sim 10^{51}$ erg
$\dot{M}_{RG} \sim 10^{-6} M_\odot\ yr^{-1}$	$\dot{M}_{RSG} \sim 10^{-5} M_\odot\ yr^{-1}$

⇒ t_c(RS Oph) ~ 10^{-5} t_c(SN II)

- free expansion phase: days
- adiabatic phase: ~ 2 months
- then radiative cooling phase

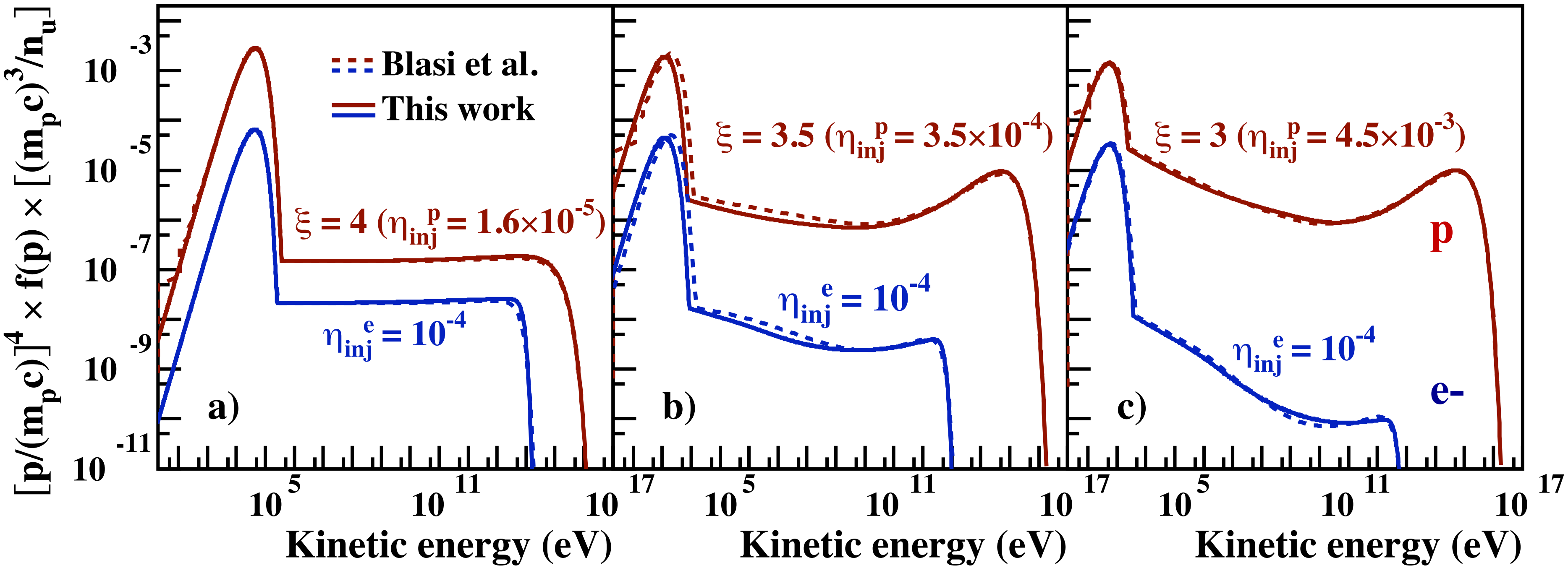
⇒ Time dependence of CR acceleration



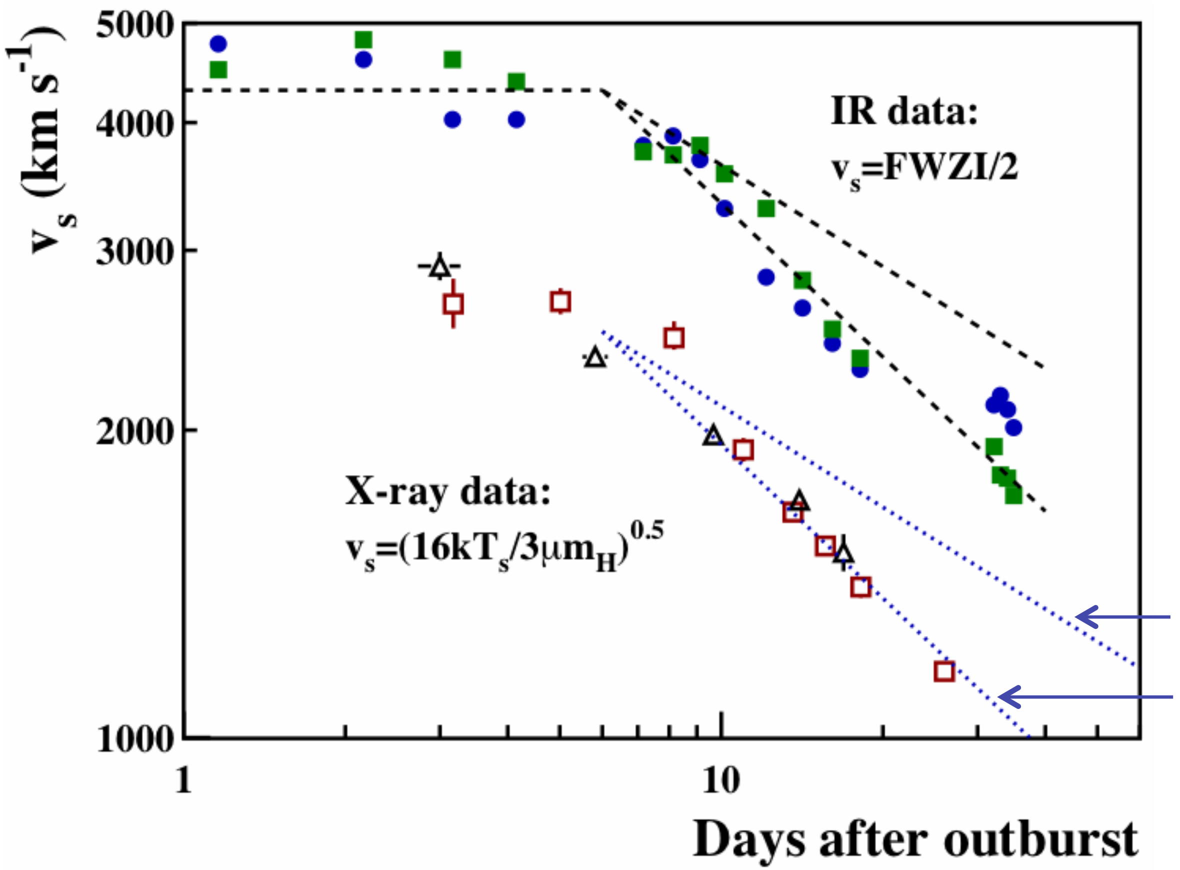
Shock modification in SNR due to CR acceleration

- Shock precursor ahead of the ordinary gas subshock
- Lower postshock temperature T_S, because of (1) the softer equation of state and (2) particle (= energy) escape (e.g. Decourchelle et al. 2000)
- Higher magnetic field B_{turb} due to resonant (Bell and Lucek 2001) and nonresonant (Bell 2004) streaming instabilities in the upstream plasma
- Higher energy particles feel a higher compression ratio ⇒ concave particle spectrum (e.g. Berezhko & Ellison 1999)

CSNSM/IEEC Non linear diffusive shock acceleration model:



Blast wave evolution in RS Oph (2006)



The $v_s - T_s$ relation:

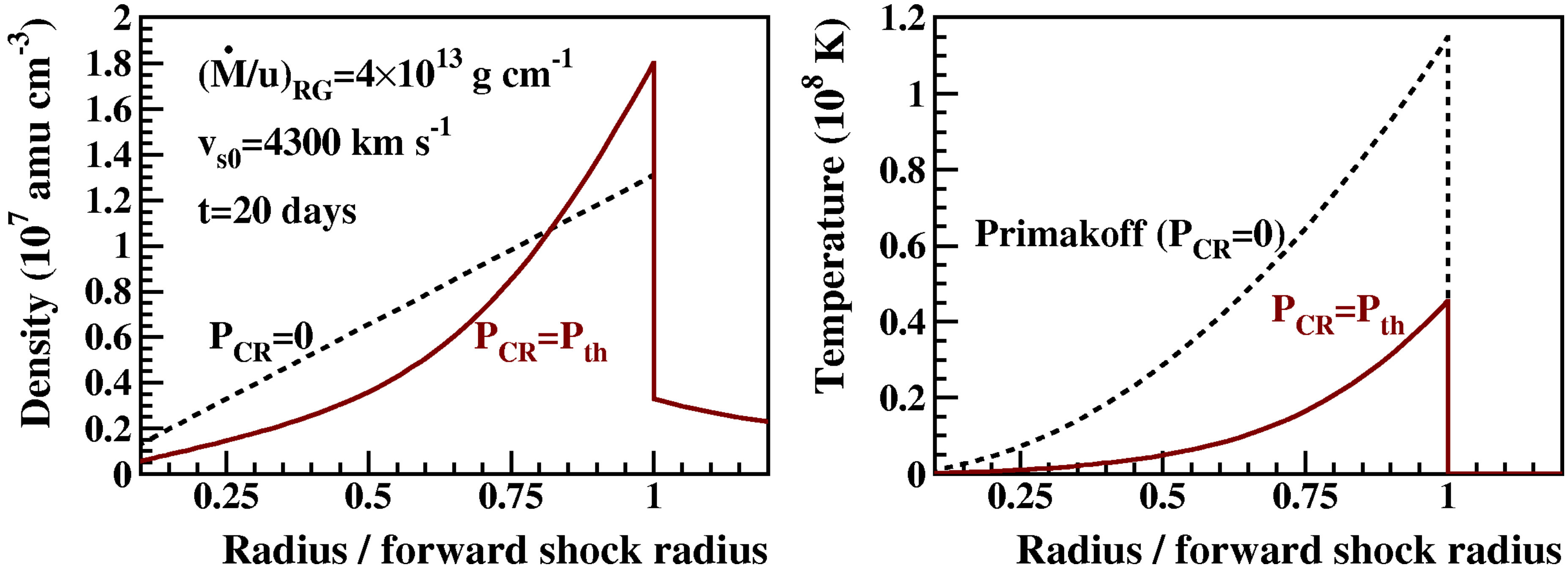
$$P_{g,s} = \rho_u v_s^2 \left(1 - \frac{1}{r}\right)$$

$$P_{g,s} = \frac{r \rho_u k T_s}{\mu m_{\mathrm{H}}}$$

with $r = 4$

- What cooled the shock after ~6 days (T_s ~ 10^8 K at day 6 and radiative cooling was not important)? ⇒ Cosmic rays?
- What makes the X-ray measurements of V_s lower than the IR data? ⇒ CRs?

Effects of cosmic-rays on the v_s-T_s relation



From the two-fluid, self-similar solutions (Chevalier 1983)

The well-known relation for a test-particle strong shock, $v_s = \sqrt{\frac{16}{3}\frac{kT_s}{\mu m_H}}$

underestimates v_s when particle acceleration is efficient,

because T_s is lower (softer equation of state + particle escape)

Cosmic-ray acceleration in RS Oph (2006)

- Good agreement with the *RXTE*/PCA and *Swift*/XRT measurements of T_s for $\eta_{inj} \gtrsim 10^{-4}$ and Alfvén wave heating of the precursor

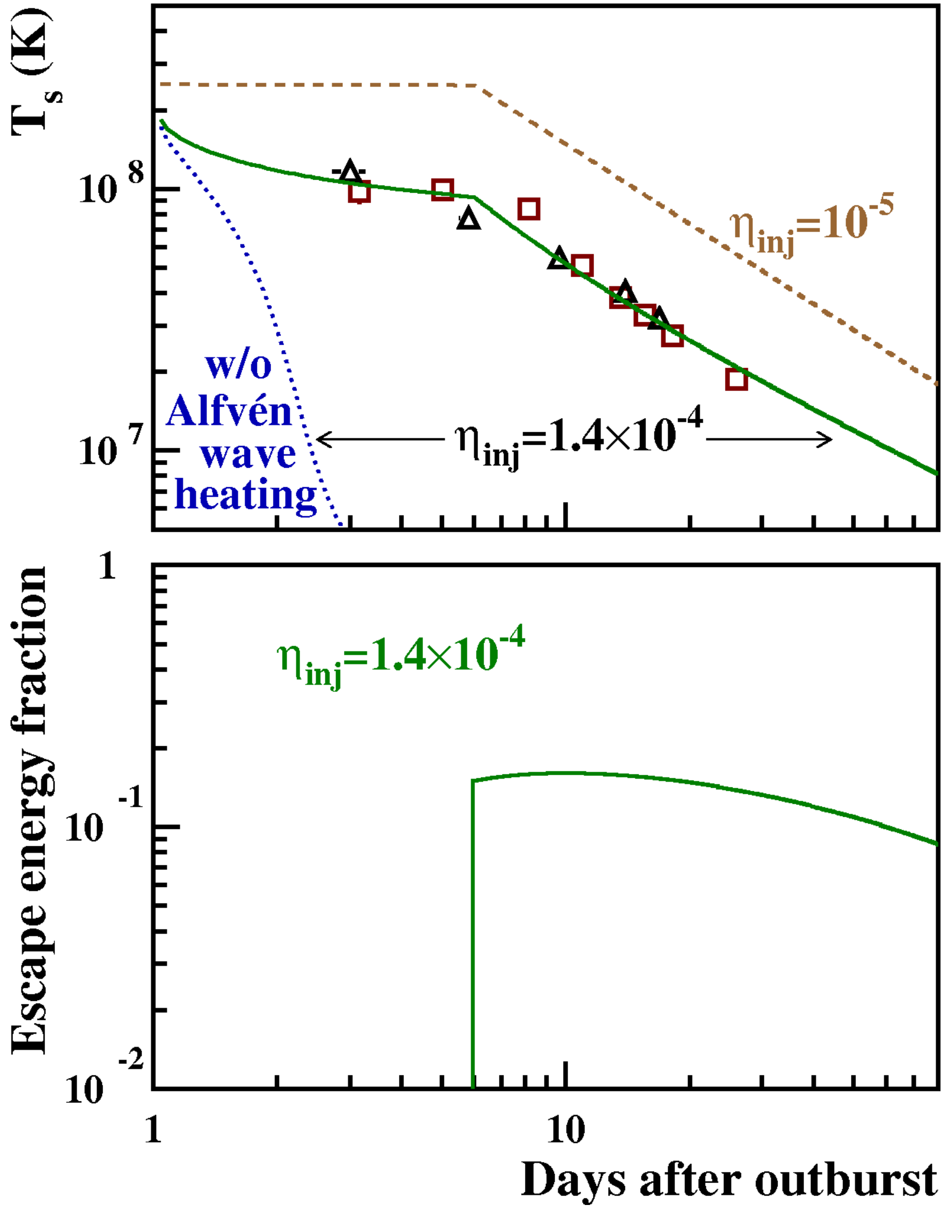
⇒ Energy loss rate due to particle escape:

$$2\times10^{38}\left(\frac{\varepsilon_{esc}}{0.15}\right)\left(\frac{t}{6\text{ days}}\right)^{-1.5}\text{ erg s}^{-1}$$

~ 100 times the bolometric luminosity of the postshock plasma at $t = 6$ days

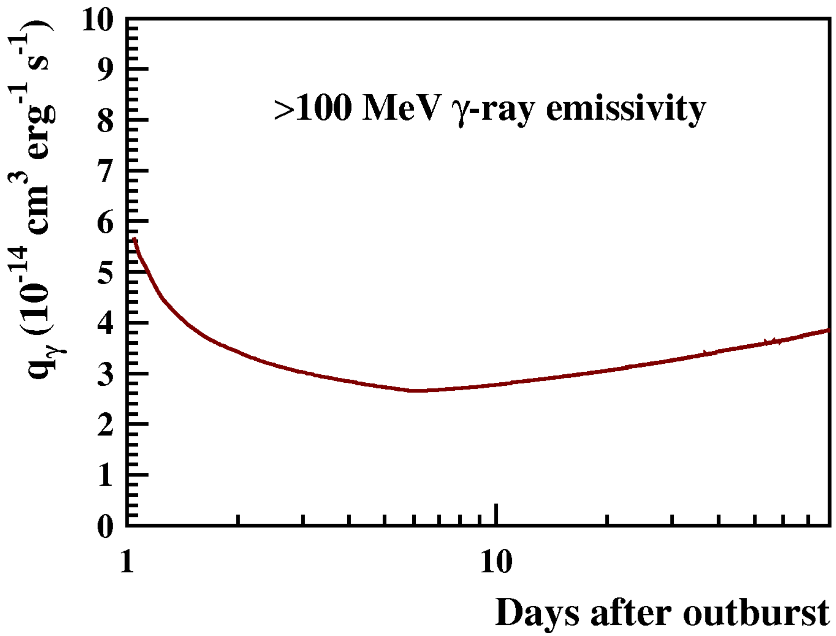
⇒ Efficient cosmic-ray cooling

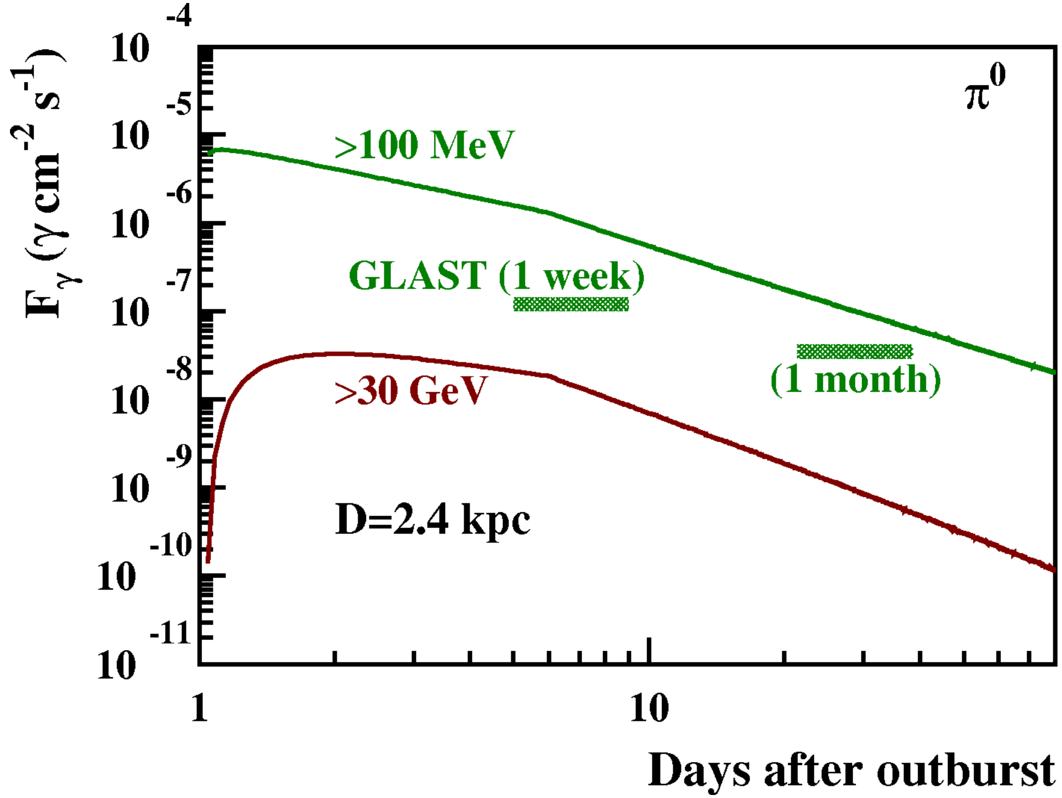
- First evidence for particle acceleration to TeV energies in a nova (VT & M. Hernanz 2007)



Gamma-ray emission from π^0 production

- Cosmic ray interaction with the shocked gas from the dense red giant wind
- $f(p,t) \Rightarrow$ γ-ray emissivity $q_\gamma(t)$ (Dermer 1986)
- $F_\gamma = \frac{q_\gamma}{4\pi D^2} \int_0^{r_s} n_H(r)\varepsilon_{rel}(r) 4\pi r^2 dr$





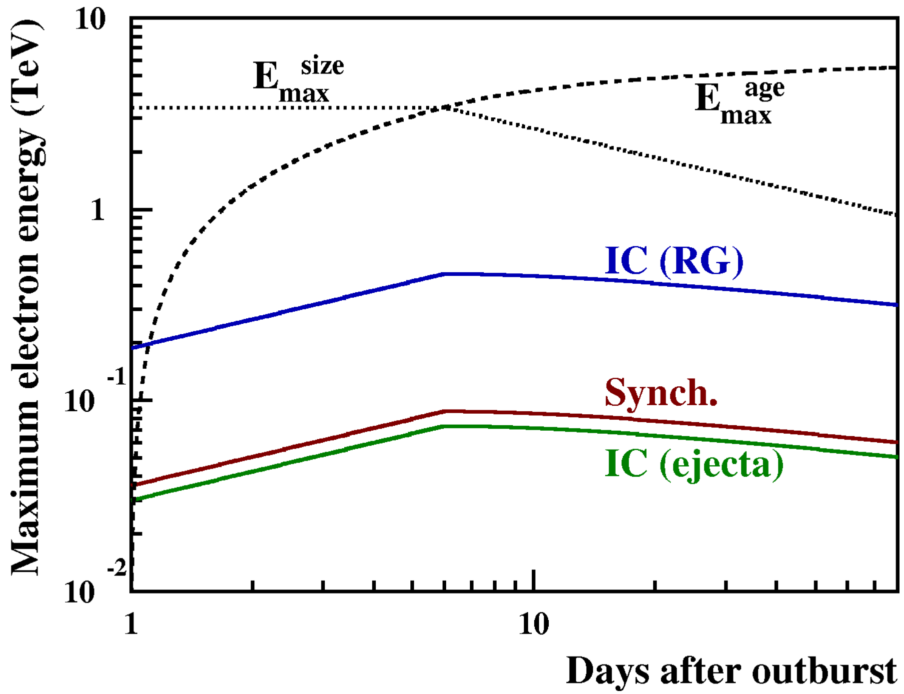
* GLAST LAT sensitivity for a 5σ detection in all-sky survey operation

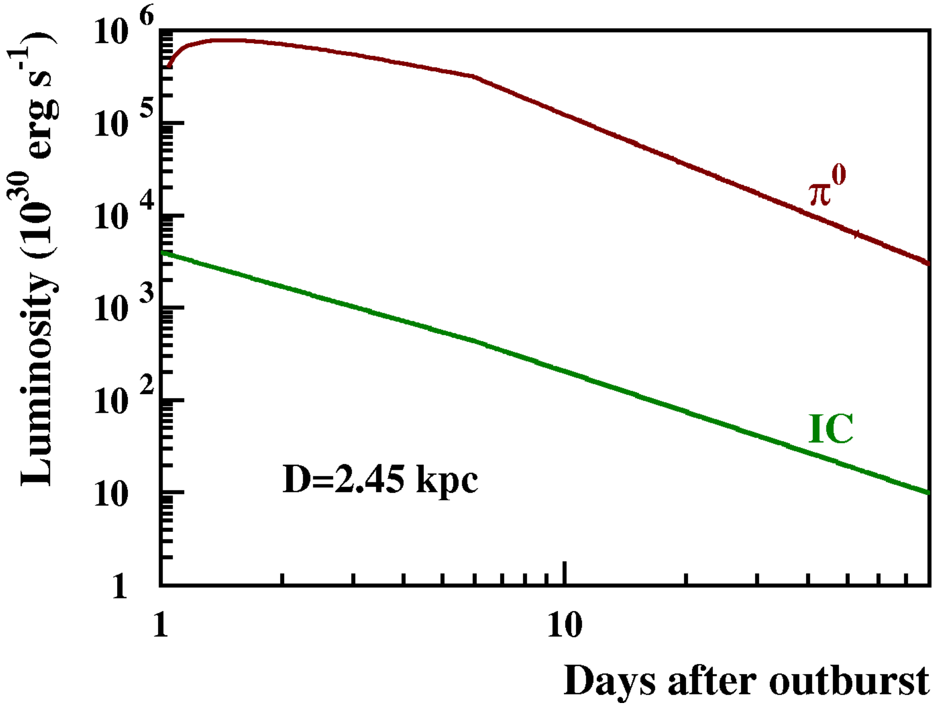
- **RS Ophiuchi (2006) would have been detected by GLAST** (VT & M. Hernanz, COSPAR 2008; Hernanz & VT 2012)

Inverse Compton contribution

- **Radiation fields**:
  Red giant: L_{RG} = 5.1×10^{36} erg s^{-1}
  (Skopal et al. 2007)
  Ejecta: L_{ej} ~ L_{Edd} = 2×10^{38} erg s^{-1}
  (residual H burning on the WD)

- $E_{e,\,max}$ limited by radiative losses





- **Nonthermal synchrotron**:
  Main component at ν < 1.4 GHz
  ⇒ L_{syn} ~ 5×10^{33} $t_d^{-1.3}$ erg s^{-1}
  (Kantharia et al. 2007)

- $L_{IC} = L_{syn} \times U_{rad}/(B^2/8\pi) \sim L_{syn}$

- **γ-rays mainly from π^0 production**

Known or suspected symbiotic recurrent novae

	m_{max}	m_{min}	Dist (kpc)	Sec. type	Outburst (years)
T CrB	2.0p	10.2v	1.3	M3III	1866, 1946
RS Oph	5.0v	11.5v	2.4	M0/2III	1898, 1907, 1933, 1945, 1958, 1967, 1985, 2006
V3890 Sgr	8.2v	17.0:	5.2	M5III	1962, 1990
V745 Sco	9.6v	19.0:	8	M6III	1937, 1989, **2014**
V407 Cyg	**6.9v**	**13-16v**	**2.7**	**M6III (Mira)**	**1936, 2010**
V723 Sco	9.8p	19.0j		NIR ph. [1]	1952
EU Sct	8.4p	18p		– [2]	1949
V3645 Sgr	12.6p	18.0p		– [2]	1970
V1172 Sgr	9.0p	18.0j		– [2,3]	1951

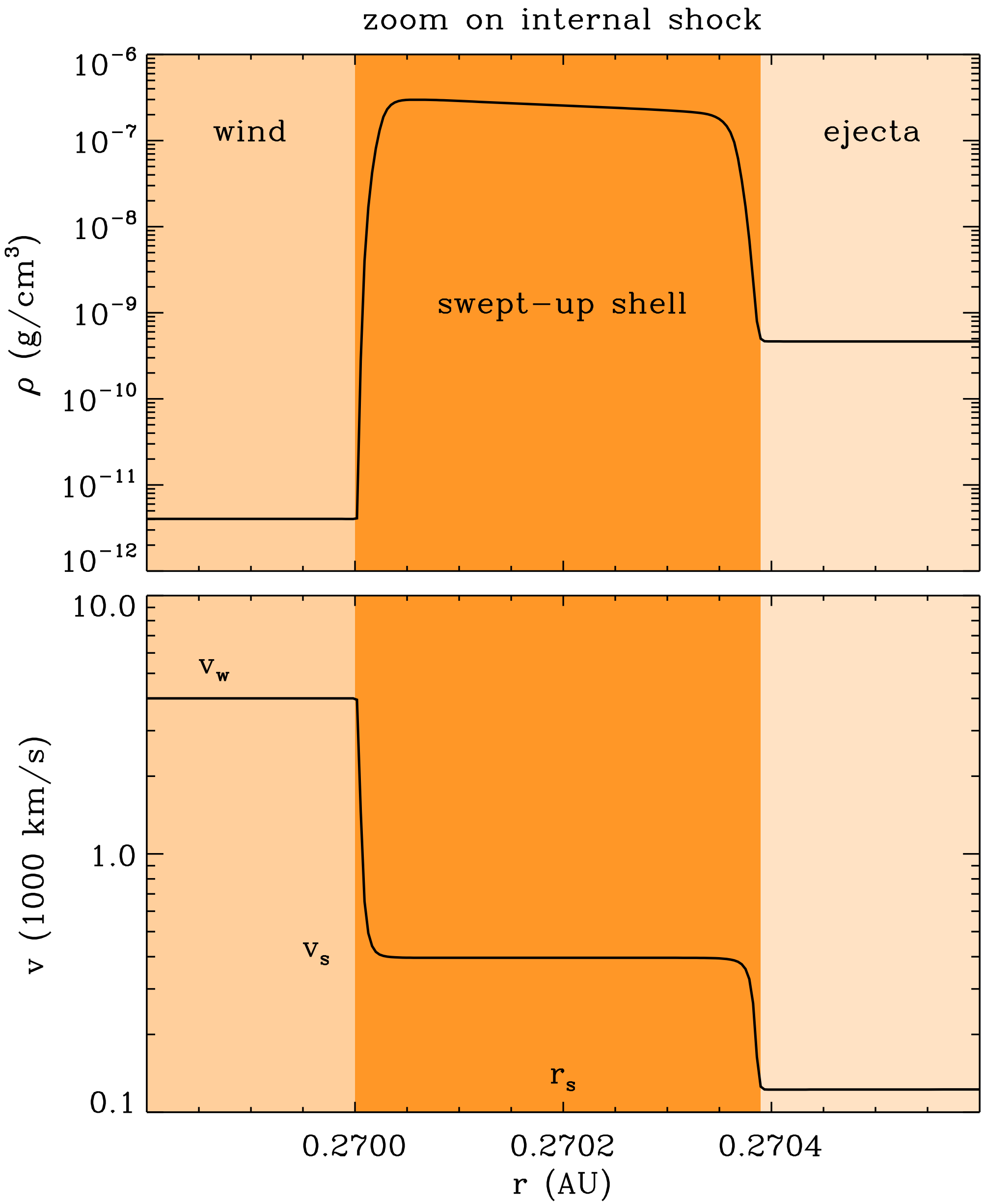
[1] Harrison et al. (1992); [2] Weight et al. (1994); [3] Hoard et al. (2002)

- ~ 340 CN outbursts detected since 1850 ⇒ ~5% in red giant sec.
- Galactic nova rate: 20-40 yr^{-1} (~10% detected) ⇒ ~1-2 yr^{-1} with RG
- GLAST would detect a burst like RS Oph (2006) at D_{max} = 10.5 kpc

⇒ GLAST should detect ~1 RS Oph-like nova per year **(prediction 2008)**

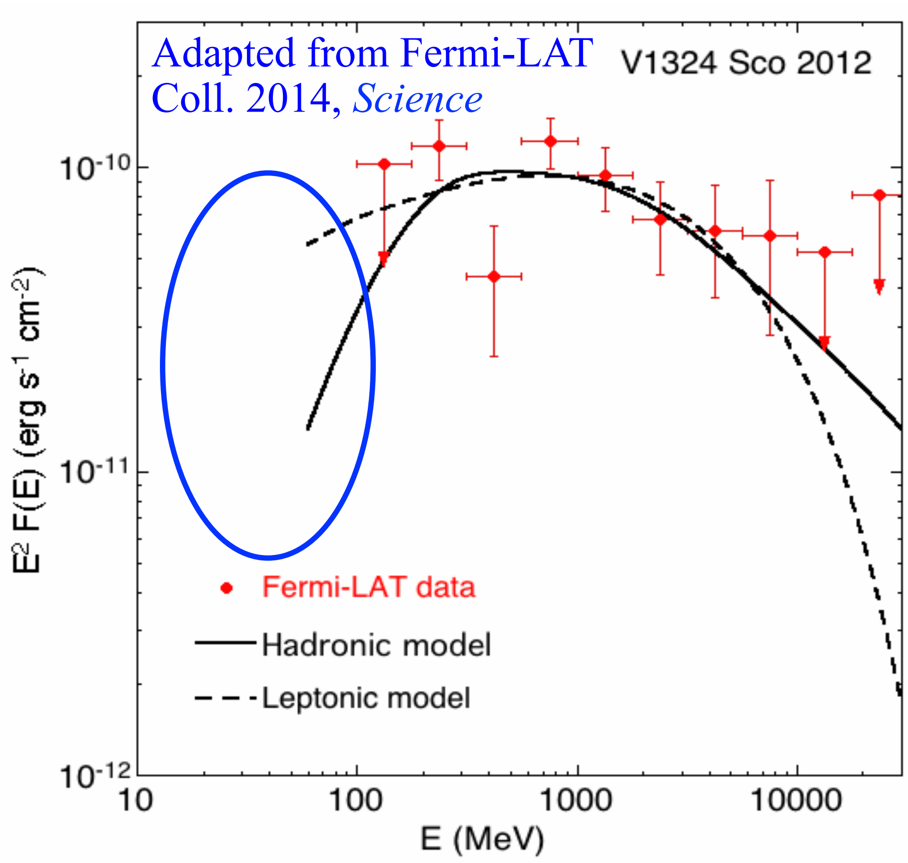
Gamma-ray emission in classical novae

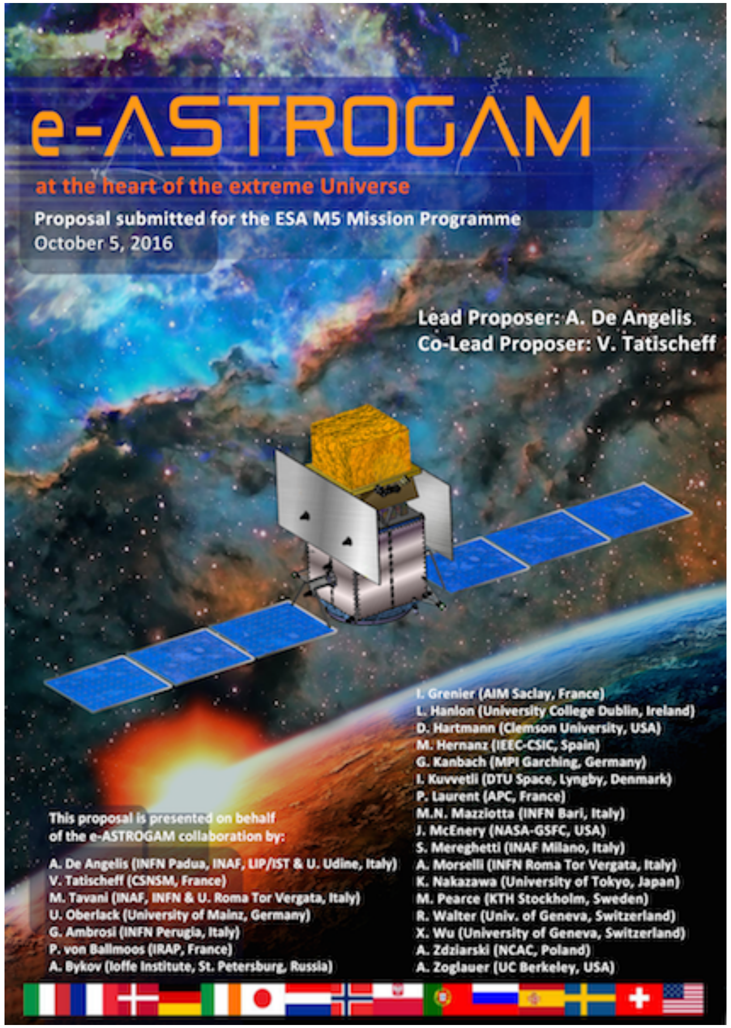
- Internal shocks from the collision of a fast, radiation-driven wind and slower nova ejecta (see Metzger et al. 2014, 2015 and references therein)
- γ-rays from particles accelerated at the reverse shock and undergoing hadronic interactions in the dense layer downstream (Martin et al. 2017, in prep.)
- Model fitted to Fermi-LAT data of six novae (V407 Cyg, V1324 Sco, V959 Mon, V339 Del, V5668 Sgr)
- Diversity in γ-ray properties can be explained by that of the nova wind properties



e-ASTROGAM Gamma-ray novae

- With a sensitivity of ~ 10^{-11} erg cm^{-2} s^{-1} at 30 MeV in 10 days, **e-ASTROGAM** will detect several γ-ray novae in the inner Galaxy and clearly distinguish the hadronic and leptonic components





See Exp. Astron. (June 2017) & https://arxiv.org/abs/1611.02232