Particle acceleration and non-thermal emission in a nova

The 2010 outburst of V407 Cygni

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(soon at 

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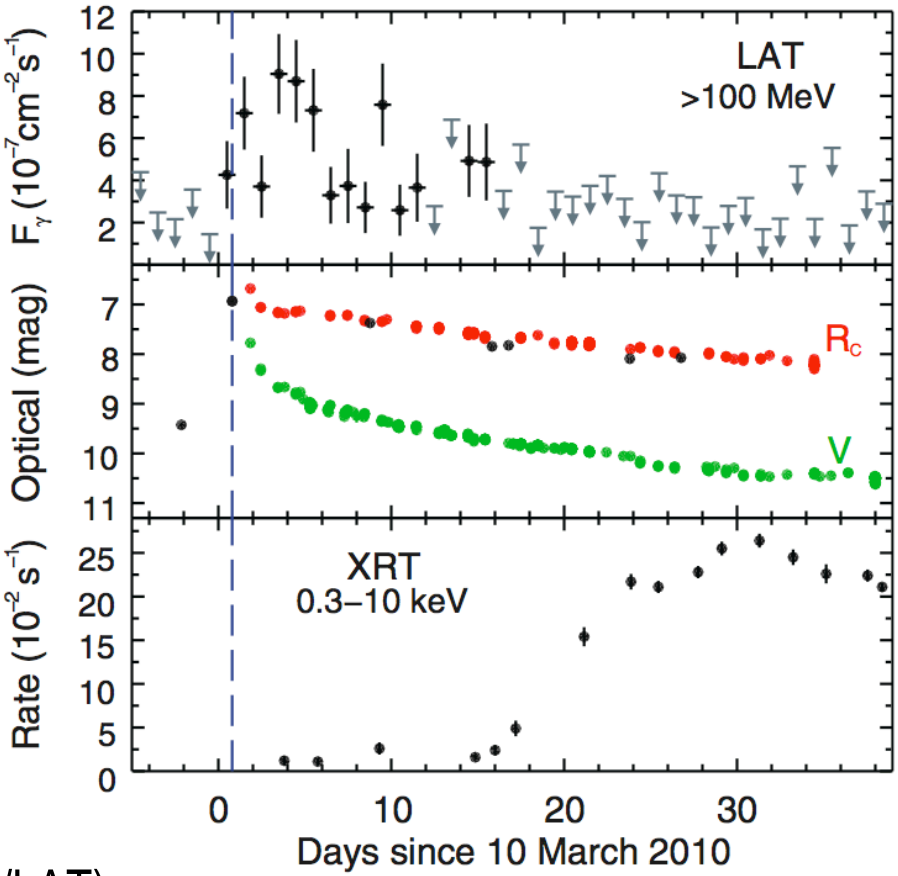
V407 Cygni: Main facts

The binary system (1936)

- White dwarf (WD) + red giant (RG)
- Period ~50yr, separation ~10AU
- Distance 2.7kpc
- Accretion via wind



The March 2010 outburst

- V magnitude jump by 5 on March 10th
- He/N nova expanding in RG wind
- M_{ej} ~10^{-6} $M_\odot$ and V_{ej} ~3000 km.s^{-1}
- First observed in GeV gamma-rays (by Fermi/LAT)
- Follow-up over weeks/months in radio / X-rays / optical / IR

Transient high-energy emission attesting to short-lived episode of particle acceleration ?

Scaled-down / fast-forward version of supernova ?

Novel test bed for theory on Galactic cosmic rays (GCRs) ?

The model

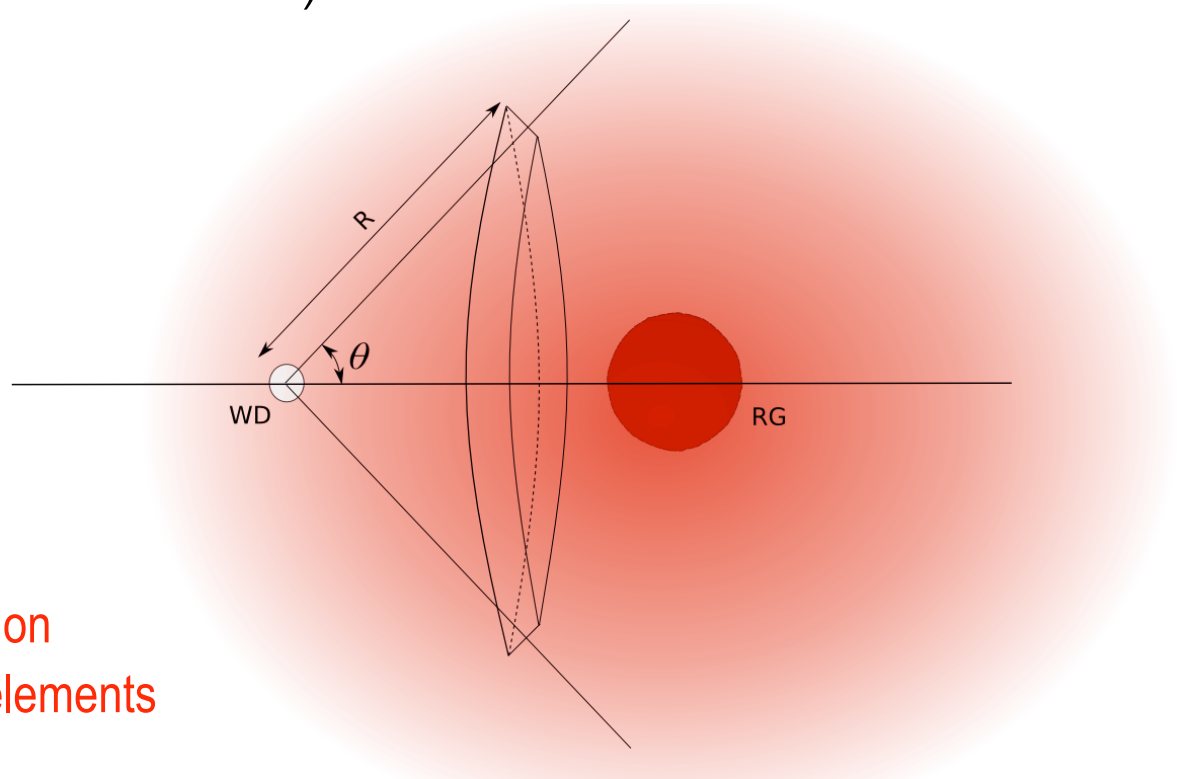
- *Geometry and dynamics*
- *Circumstellar/binary environment*
- *Acceleration*

V407 Cygni: Geometry and dynamics

V_{ej}: ejecta velocity
E_{ej}: ejecta energy
M_{su}: swept-up mass

Blast wave dynamics

- Ejecta-dominated stage (ED): V_{ej}=constant
- Sedov-Taylor stage (ST): $V_{ej}=(2E_{ej}/M_{su})^{1/2}$
- (*Stops if crash into RG and dead zone behind RG)*



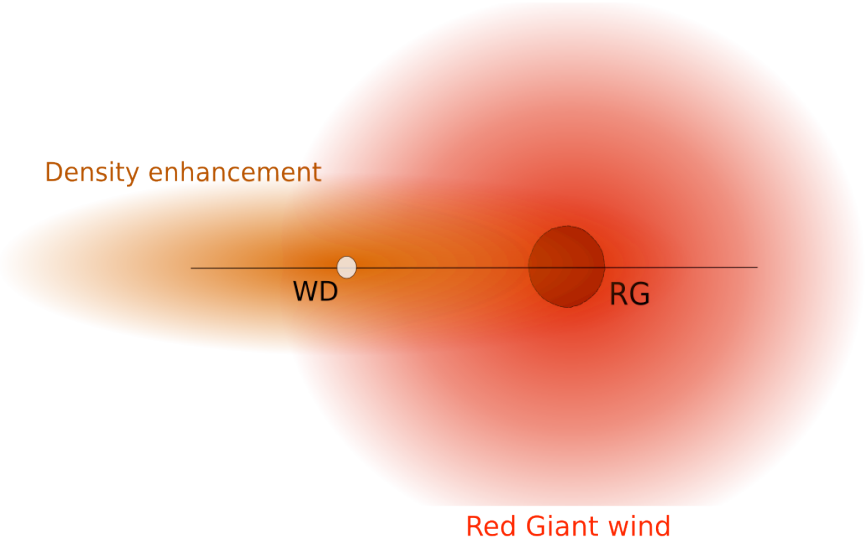
Aspherical shock expansion
Azimuthally-symmetric shock elements

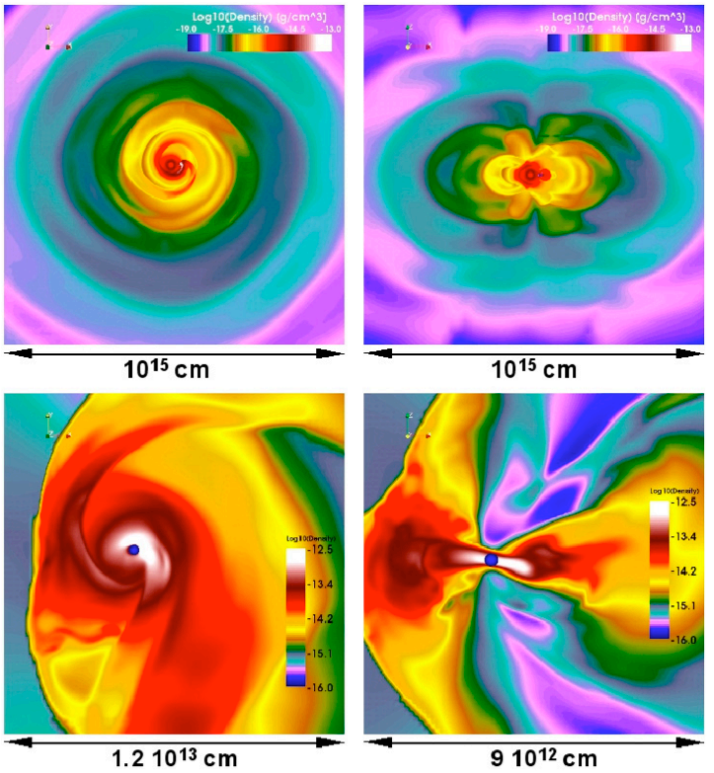
2D cylindrical geometry

V407 Cygni: Circumbinary/circumstellar medium

Circumstellar density enhancement (CDE) ?

- Accretion from RG wind and orbital motion of WD
- Accumulation of gas in orbital plane and around WD





Suggested by hydrodynamical simulation of RS Oph (Walder-2008)

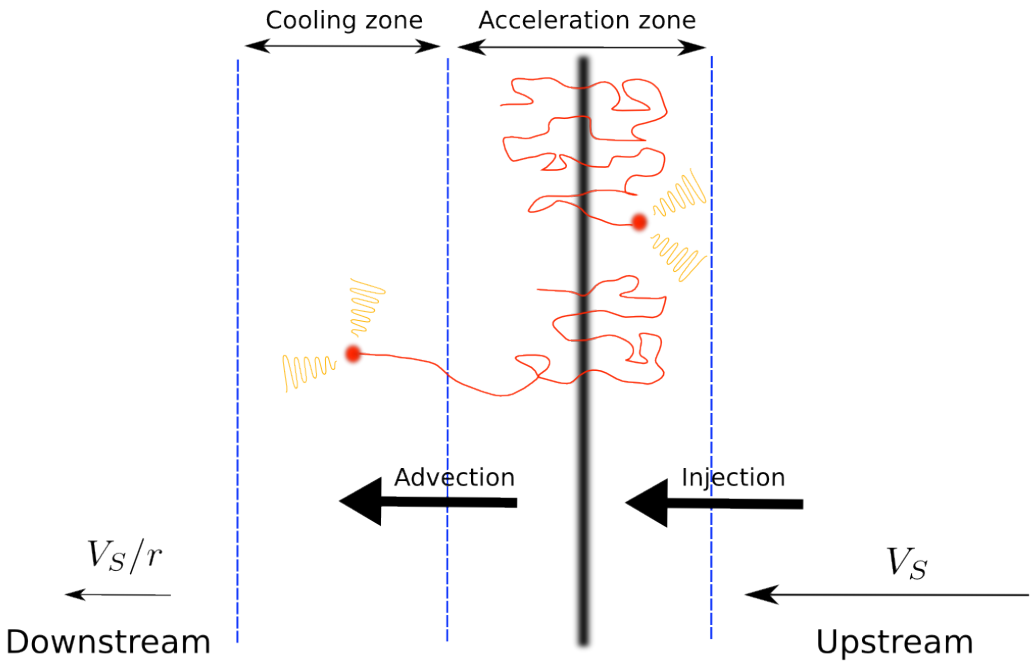
Required in modelling of X-ray light curve of V407 Cyg (Orlando-2012)

V407 Cygni: The accelerator

Thin-shell approximation

- Acceleration zone and cooling zone
- Neglect shock radial structure
- Neglect cosmic ray spread downstream

$$\frac{dN_{A,B}}{dt} = \frac{d}{dp}\left(\dot{p}_{A,B} N_{A,B}\right) - \frac{N_{A,B}}{\tau_{A,B}} + Q_{A,B}$$



Acceleration

- Test particle approximation
- Uniform diffusion coefficient over accelerator
- Scalable diffusion efficiency w.r.t. Bohm
- Equipartition magnetic field upstream

$$\left(\frac{dp}{dt}\right)_{DSA} = \left(\frac{r-1}{3r}\right)\frac{V_s^2}{D(1+r)}\,p$$

$$D(p) = \zeta\frac{p\beta c}{3eB_s} = \zeta D_{Bohm}$$

Injection

- Scalable fraction of inflowing particles
- Fixed injection momentum p_{inj} =1 MeV/c (degeneracy, $E_{NT} \propto \eta_{inj}\, p_{inj}$)
- Both uniform over shock front (simplification, Volk-2003 for SN1006)

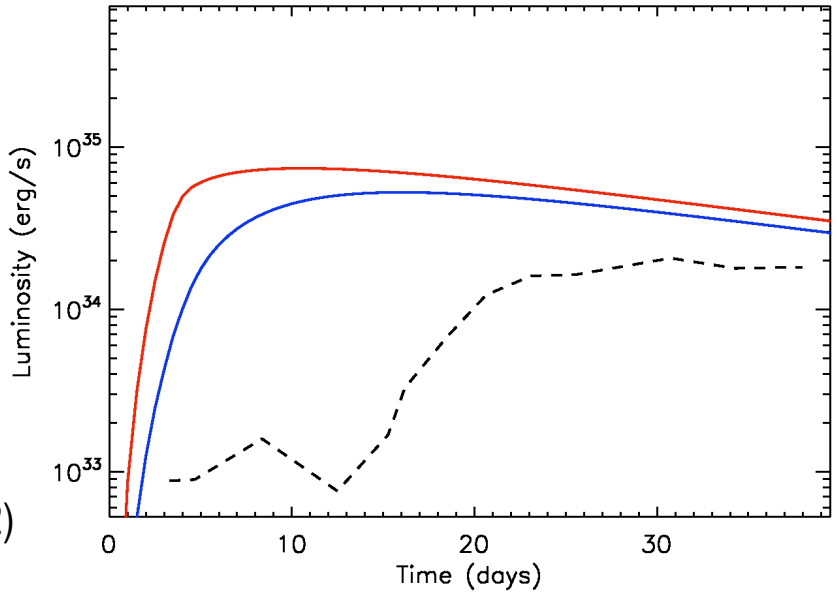
V407 Cygni: The thermal model

Assumptions

- Swept-up material in a shell of width 10% of shock radius
- Post-shock temperature from adiabatic approximation

Shortcomings (identified by comparison with published hydro simulations)

- Overestimates luminosities at early times 0-20 days
- Cannot handle flow convergence on rear side of RG
- But allows estimates at late times >20 days



Red: total thermal luminosity

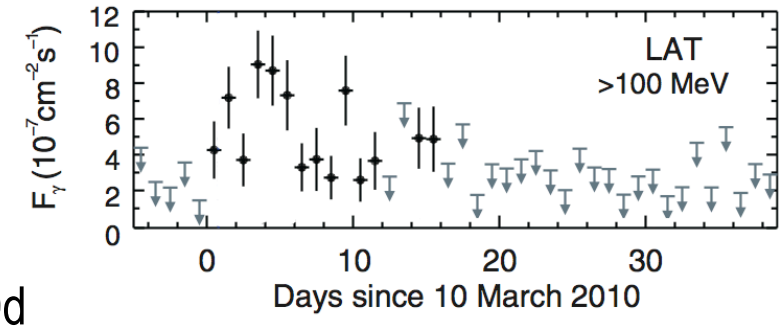
Blue: thermal luminosity in Swift/WRT band

Dashed: from hydrodynamical simulations (Orlando-2012)

V407 Cygni: The problem summarized

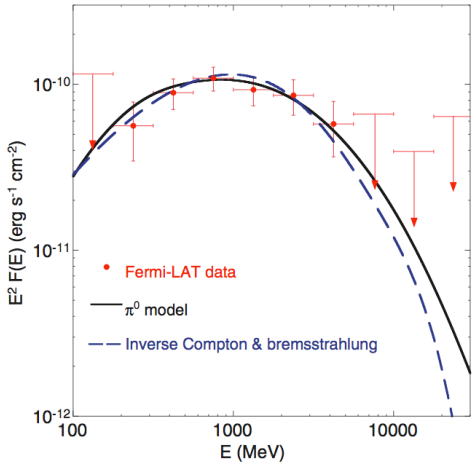
What do we want to get ?

- γ-ray emission maximum within 4d
- γ-ray emission drop by >10 after 20d
- γ-ray spectrum as observed over 0-15d
- Thermal X-rays in 0.3-10keV ~10^{34} erg/s over 20-40d
- (Shock slowing down from 3000 to 400 km/s at 50d ?)



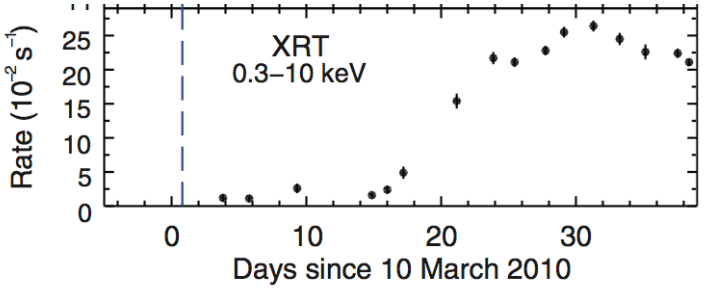
Under what constraints ?

- Non-thermal efficiency 10-15%
- e-to-p ratio at injection $K_{ep}= \eta_e/\eta_p$ <1 (=0.01 ?)



How can we help ? Free/tunable parameters

- Orbital separation R_{orb}~10-15 AU
- Mass-loss rate M_{dot}~10^{-7} $M_\odot$/yr
- Density enhancement
- Ejecta mass M_{ej} ~10^{-6} $M_\odot$
- Injection fractions η_p/η_e, diffusion efficiency ξ



About non-thermal particles

- *Maximum energies*
- *Effect of anisotropies*
- *(Shock propagation in wind only, for illustration)*

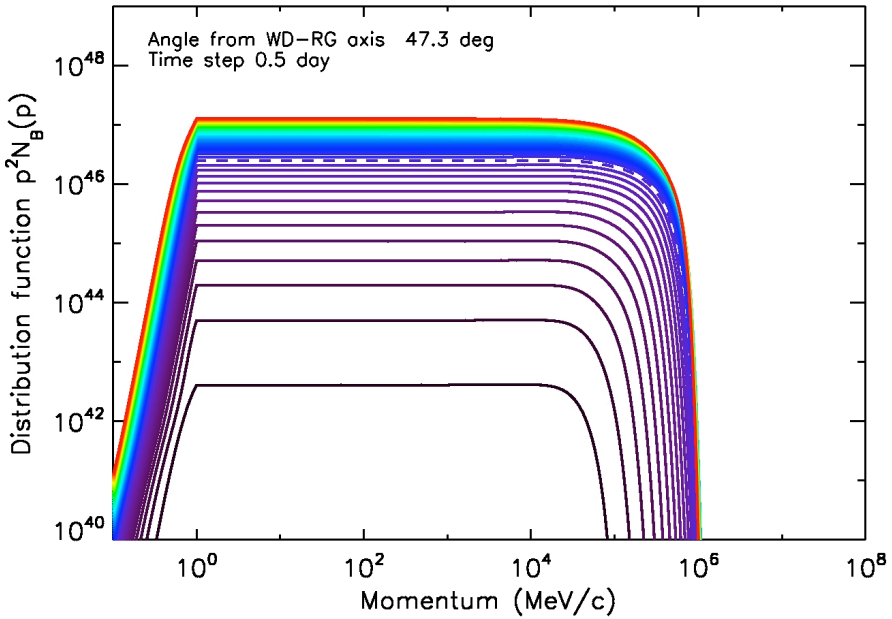
V407 Cygni: non-thermal particles

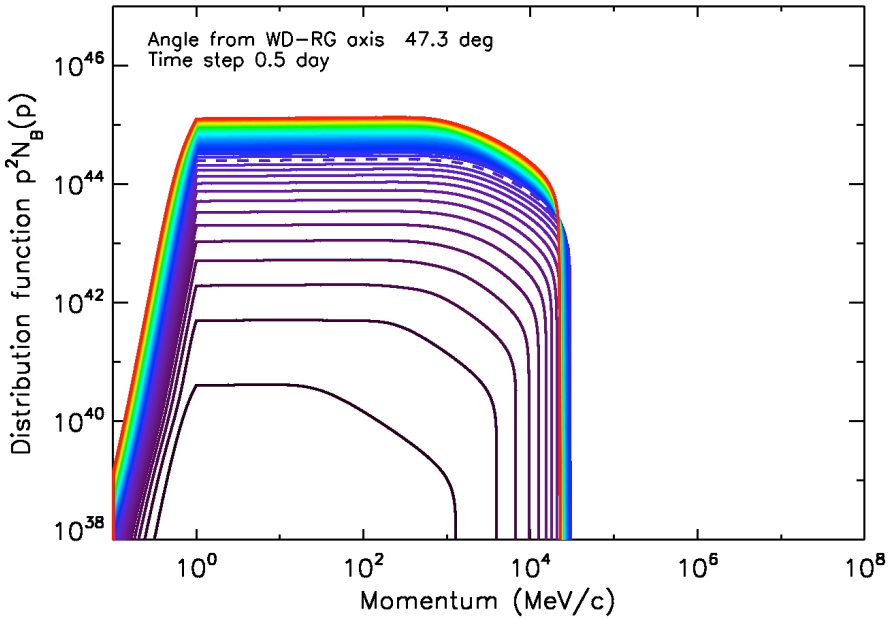
Parameters

- R_{orb}=10 AU
- Mdot=5.10^{-7} $M_\odot$/yr
- M_{ej}=10^{-6} $M_\odot$
- V_{ej}=3000 km/s
- η_p= 10^{-3}, η_e= 10^{-5}
- ξ=1

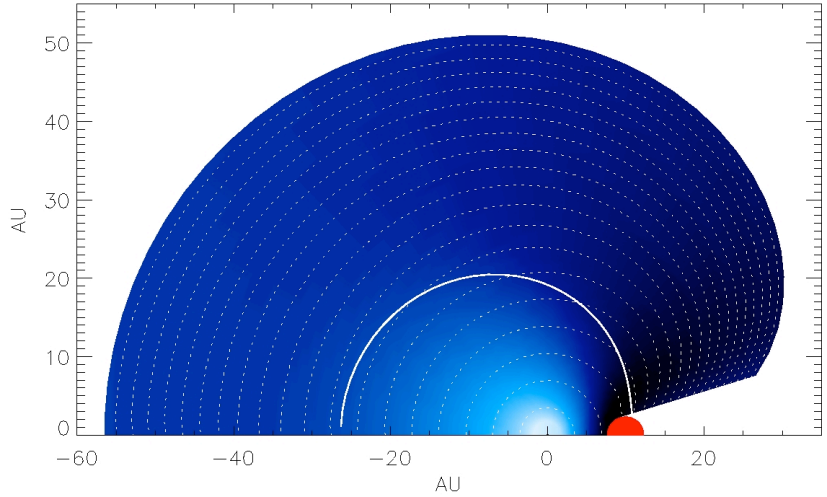
Particle momentum distribution

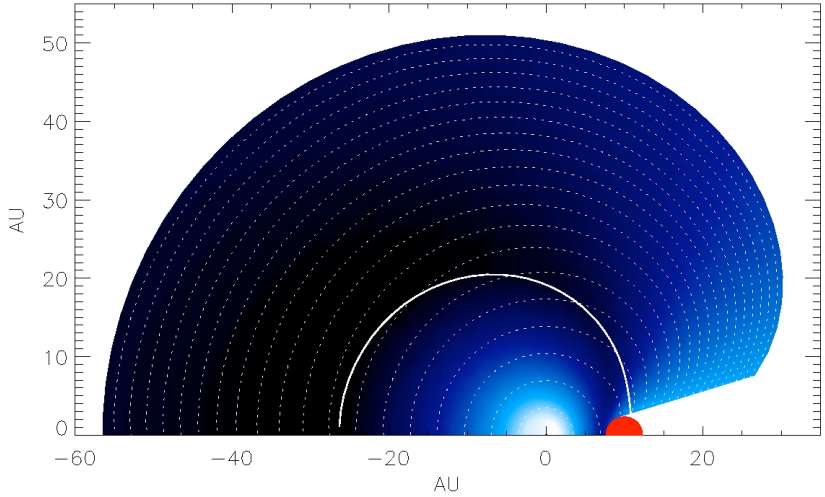
- Protons are age-limited: >10GeV within a day, ~1TeV at transition
- Electrons are IC-limited:~1GeV within a day, >10GeV at transition
- Electron distribution steepened by losses (IC dominant)





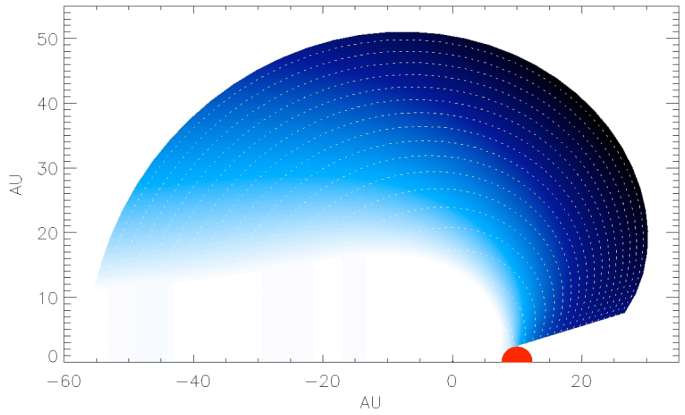
V407 Cygni: non-thermal particles





Particle spatial distributions

- Proton/electron do not reach maxima over same domain
- Electron maximum energy less uniform over shock front
- Non-thermal energy set by amount of swept-up mass



About gamma-ray emission I

- *Shock propagation in wind only*
- *Can we match the Fermi/LAT data ?*
- *Do we need a density enhancement ?*

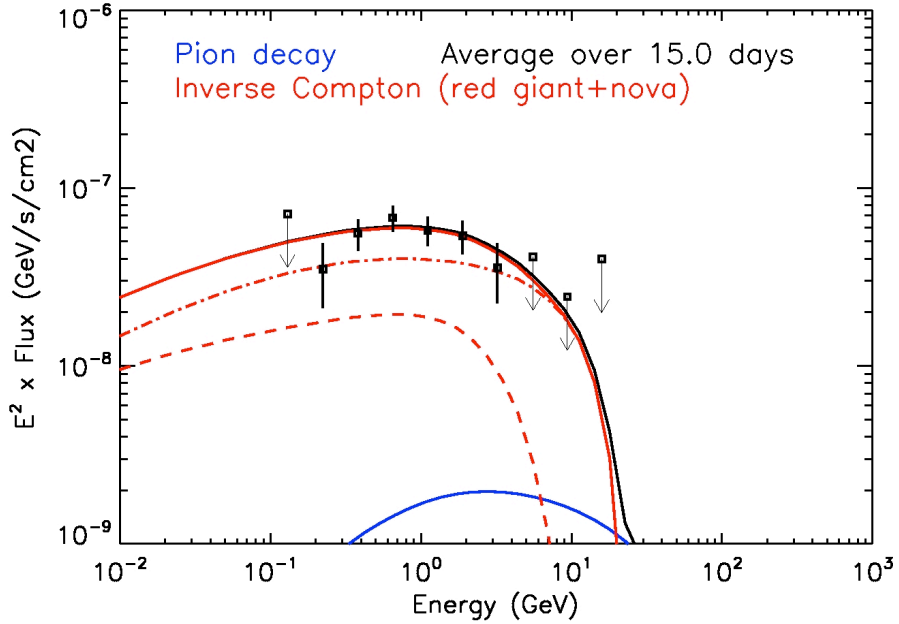
V407 Cygni: Gamma-ray emission

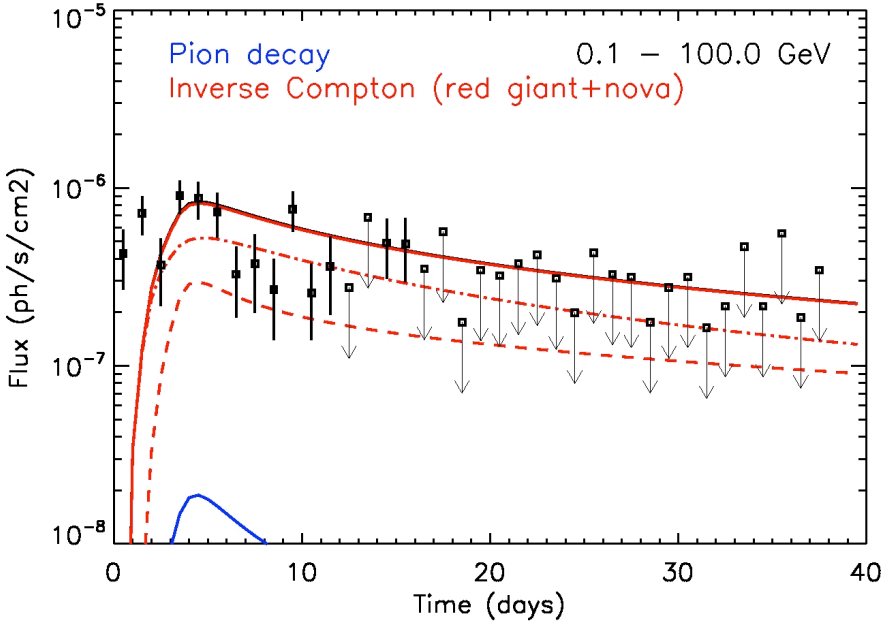
Spectrum and light curve

- Dominantly leptonic emission scenario
- IC on nova light dominates
- Bohm diffusion in upstream magnetic field

Parameters

- R_{orb}=6 AU
- Mdot=10^{-7} $M_\odot$/yr
- M_{ej}=2.10^{-6} $M_\odot$
- V_{ej}=3000 km/s
- η_p= 6.10^{-3}, η_e= 6.10^{-4}
- ξ=1





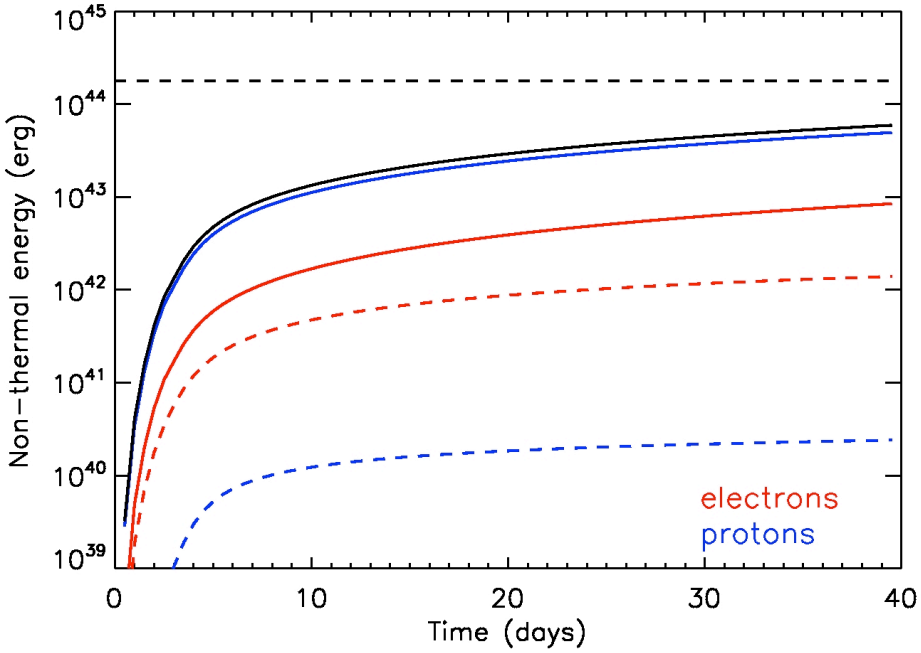
About thermal emission constraints

- Impose low circumbinary density → reduced proton radiation efficiency
  → higher injection fractions to compensate

V407 Cygni: Global energetics

Non-thermal energy in particles and radiation (solid and dashed)

- Nova kinetic reservoir ~2.10^{44} erg
- Non-thermal efficiency ~30% at day 40
  ~50% at day 80
- Electron radiation efficiency ~20%



Conclusions on scenario of shock propagation in wind only

- Robust trends: slow decline and close to Bohm diffusion in upstream field
- Early rise needs small orbital separation (cannot be fully excluded)
- Excessive non-thermal efficiency
- High e-to-p ratio at injection K_{ep}=10%

About gamma-ray emission II

- *Shock propagation in more realistic environment*
- *Effect of a circumstellar density enhancement*
- *Hadronic and/or leptonic emission scenario*

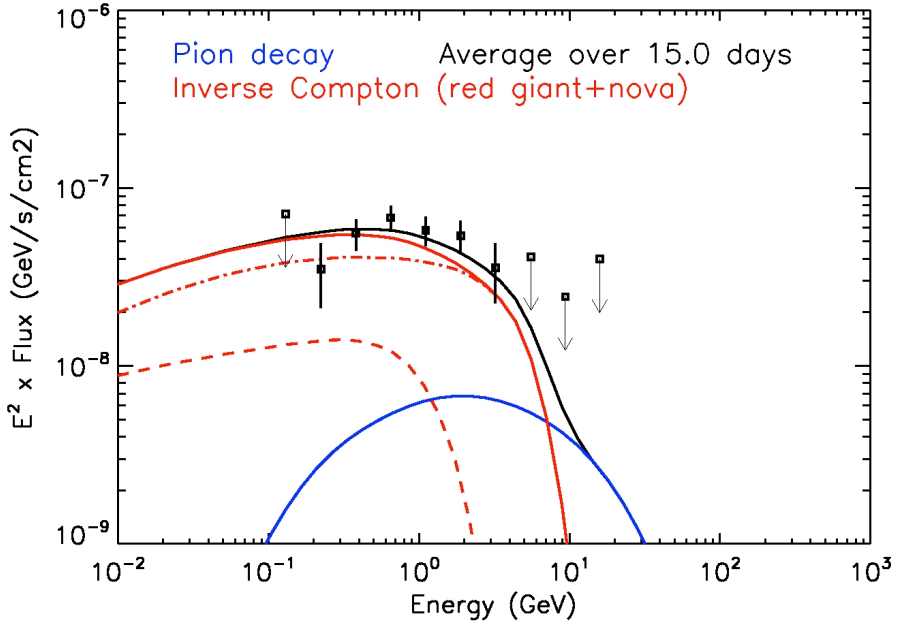
V407 Cygni: Gamma-ray emission

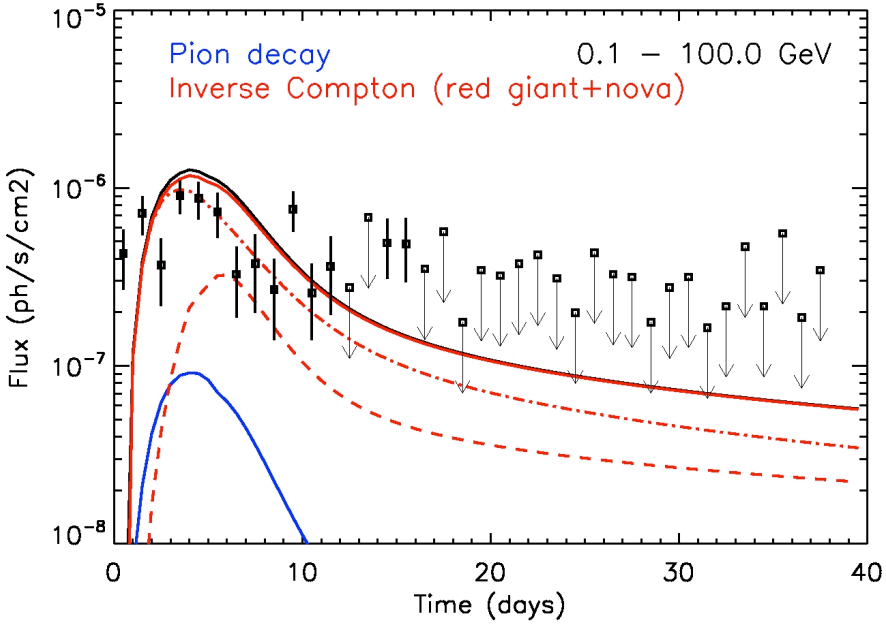
Spectrum and light curve

- Dominantly leptonic emission scenario
- IC on nova light dominates
- Close to Bohm diffusion in upstream magnetic field

Parameters

- R_{orb}=10 AU
- Mdot=5.10^{-8} $M_\odot$/yr
- M_{ej}=2.10^{-6} $M_\odot$
- V_{ej}=3000 km/s
- η_p= 5.10^{-3}, η_e= 3.10^{-4}
- ξ=3





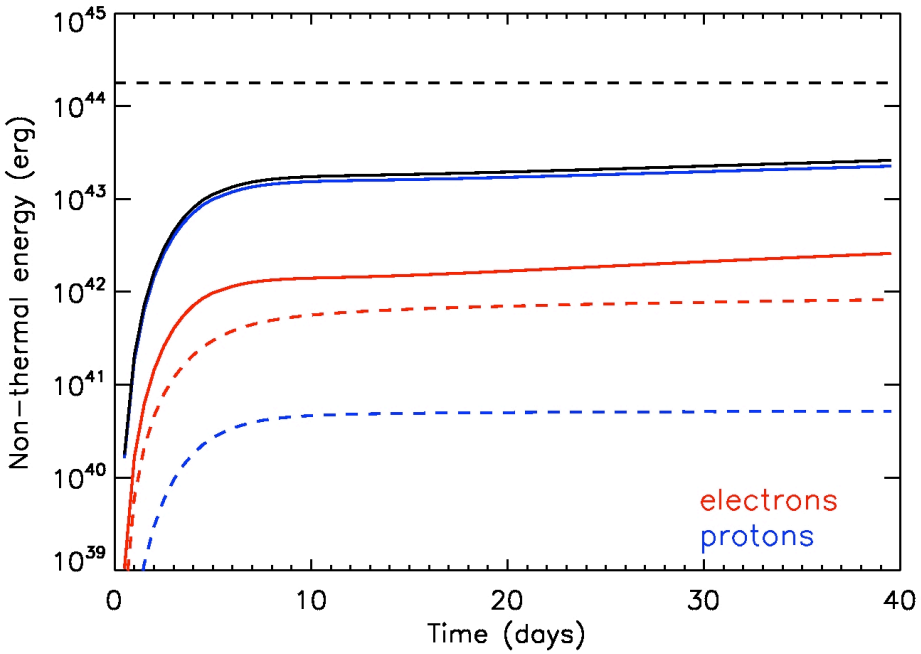
About circumstellar density enhancement

- Peak density 10^8 cm^{-3} and typical size 10 AU (not optimized from formal multivariate fit)
- Provides sufficient electrons early enough

V407 Cygni: Global energetics

Non-thermal energy in particles and radiation (solid and dashed)

- Nova kinetic reservoir ~2.10^{44} erg
- Non-thermal efficiency ~10% at day 15
  ~13% at day 40



Conclusions on scenario with density enhancement

- Improves fit to gamma-ray constraints
- Density enhancement profile compatible with thermal X-rays ?
- Problem with shock velocities >2000km/s at day 40 ?
- Cannot exclude hadronic/mixed emission scenario and cosmic-ray-dominated shock

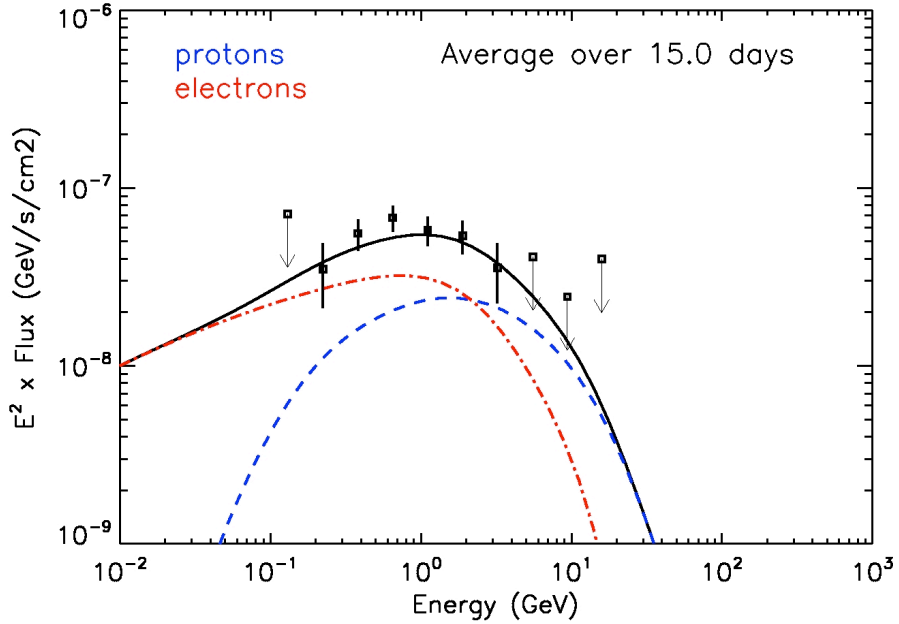
V407 Cygni: Gamma-ray emission

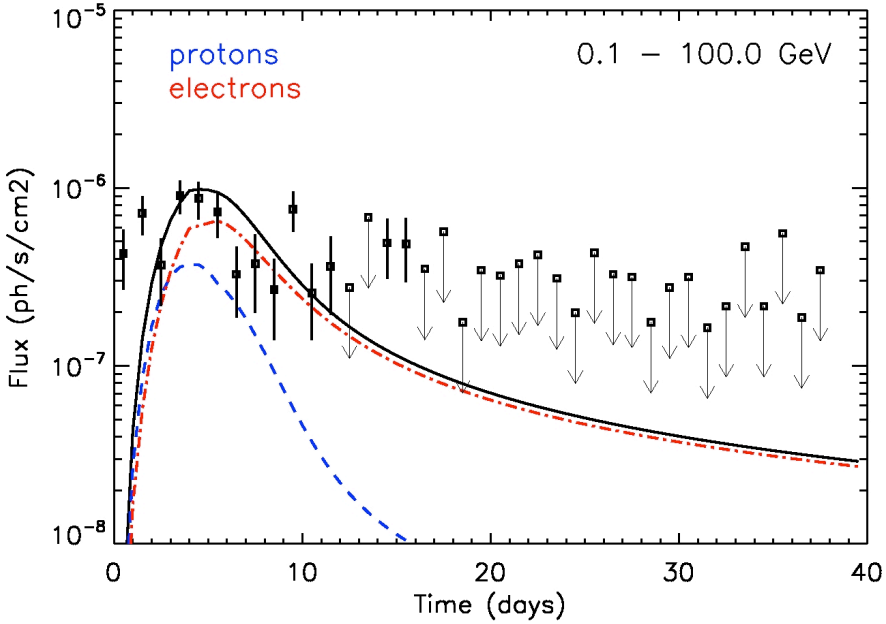
Spectrum and light curve

- Mixed hadro-leptonic emission scenario
- Close to Bohm diffusion in upstream magnetic field

Parameters

- R_{orb}=10 AU
- Mdot=5.10^{-8} $M_\odot$/yr
- M_{ej}=2.10^{-6} $M_\odot$
- V_{ej}=3000 km/s
- η_p= 2.10^{-2}, η_e= 2.10^{-4}
- ξ=5





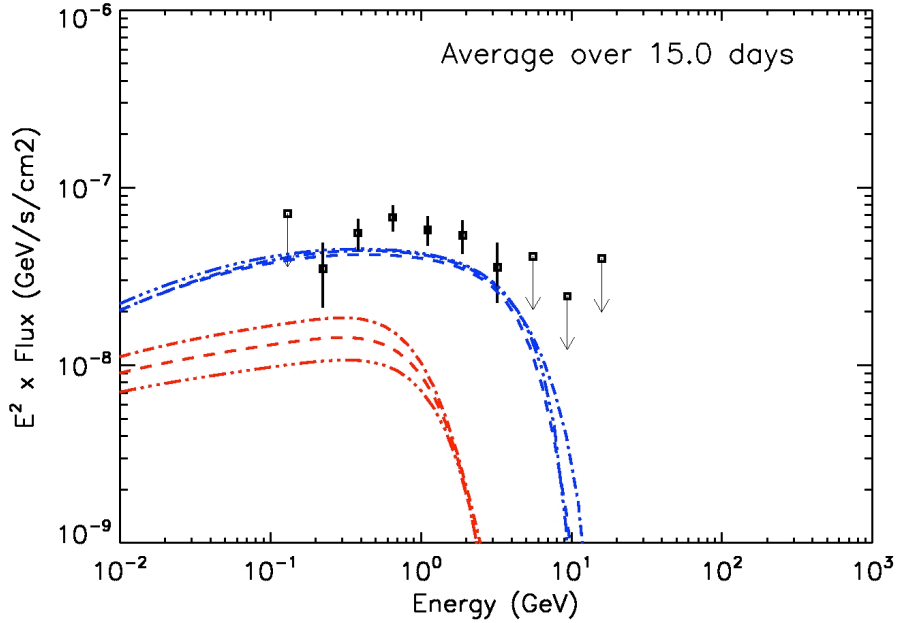
About energetics

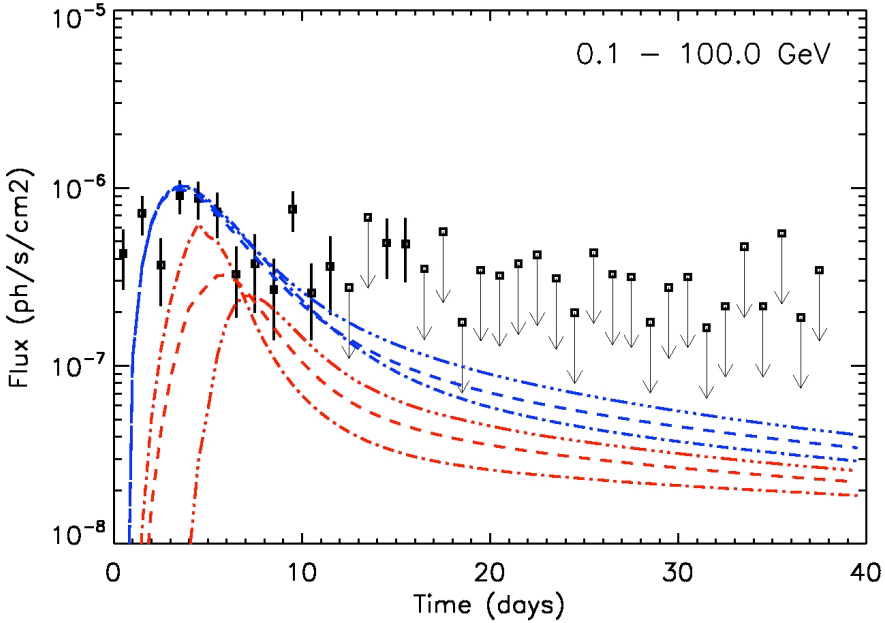
- Non-thermal efficiency >50% at day 40 for parts of the shock

V407 Cygni: Anisotropic inverse-Compton

Effect on spectrum and light curve

- Extreme cases of superior and inferior conjunction, edge-on binary
- Isotropic case for comparison





Conclusions

- Nova IC: not much effect (as expected)
- Red giant IC: superior conjunction favours quicker emission rise and decline
- From emission line analysis, we may be close to superior conjunction (WD behind RG)

Summary for V407 Cyg and the like

- *Production of non-thermal particles*
- *High-energy emission scenario*
- *Perspectives for future detections*

Conclusions/Perspectives

Non-thermal particles

- Protons up to 300GeV, electrons up to 20GeV, 10^{43} erg of particles
- Novae in symbiotics are no significant contributor to GCRs
- Bohm diffusion in non-amplified equipartition field

Gamma-ray emission

- Leptonic scenario favoured, IC in nova light
- Novae in symbiotics are no class of TeV emitters
- A few events like V407 Cyg to be detected by Fermi/LAT

The system

- Density enhancement helps, to be checked against X-rays
- Issue of shock/ejecta slowing-down

About radio constraints

- Observations (>d14): 3-30GHz fluxes of order 10mJy, rising up to d50, with $F(\nu) \propto \nu^{0.7}$
- Our model: synchrotron fluxes of order 100mJy, falling after d5, with $F(\nu) \propto \nu^{-0.5}$
- Very likely significant free-free absorption and emission in UV-ionized wind

Conclusions/Perspectives

Things are getting even more interesting…

- Two γ-ray transients associated with novae: Nova Mon 2012 and Nova Sco 2012
- Classical novae, accretion from main-sequence star via Roche lobe
- Nova envelope ejected at 2000-2500km/s
- γ-ray maximum contemporaneous with optical maximum
- What is the mass reservoir for acceleration ? Magnetic field ?

- Also, tightening of constraints at <100MeV for V407 Cyg (Pass 7 Fermi/LAT data)
- Excluding IC, favouring pion decay ?