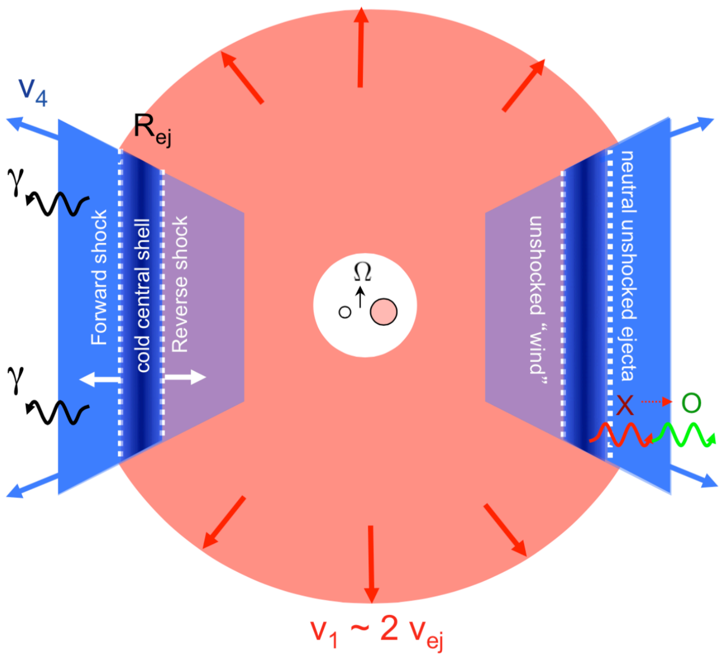
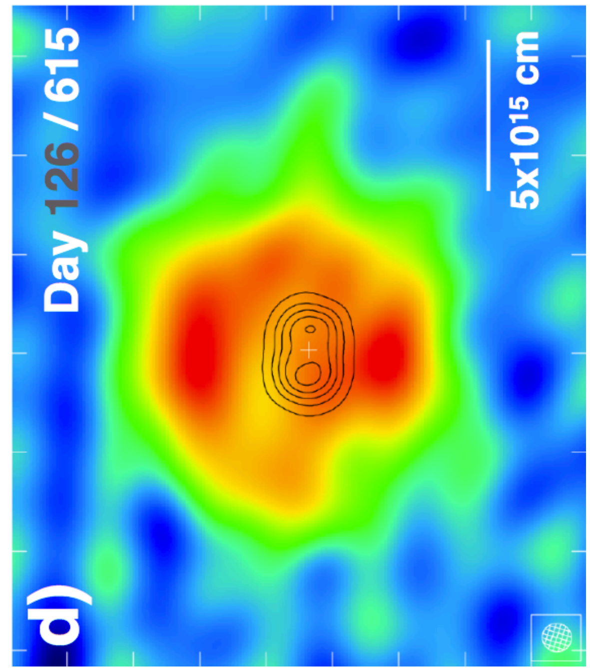
Shocks and Relativistic Particle Acceleration in Novae





Chomiuk et al. 2014

Brian Metzger (Columbia University)

Primary Collaborators

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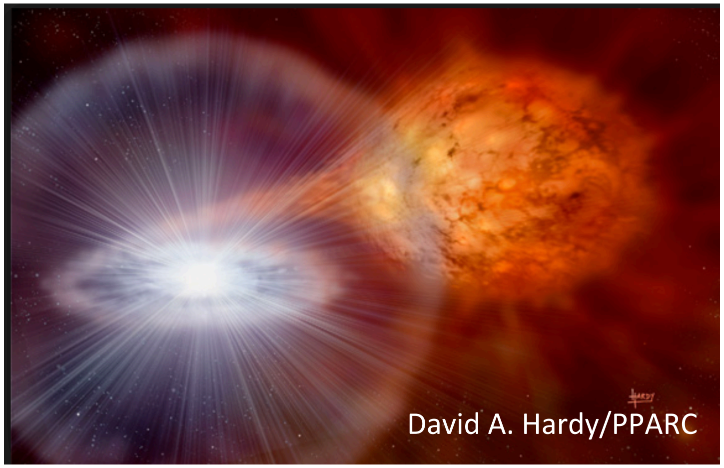
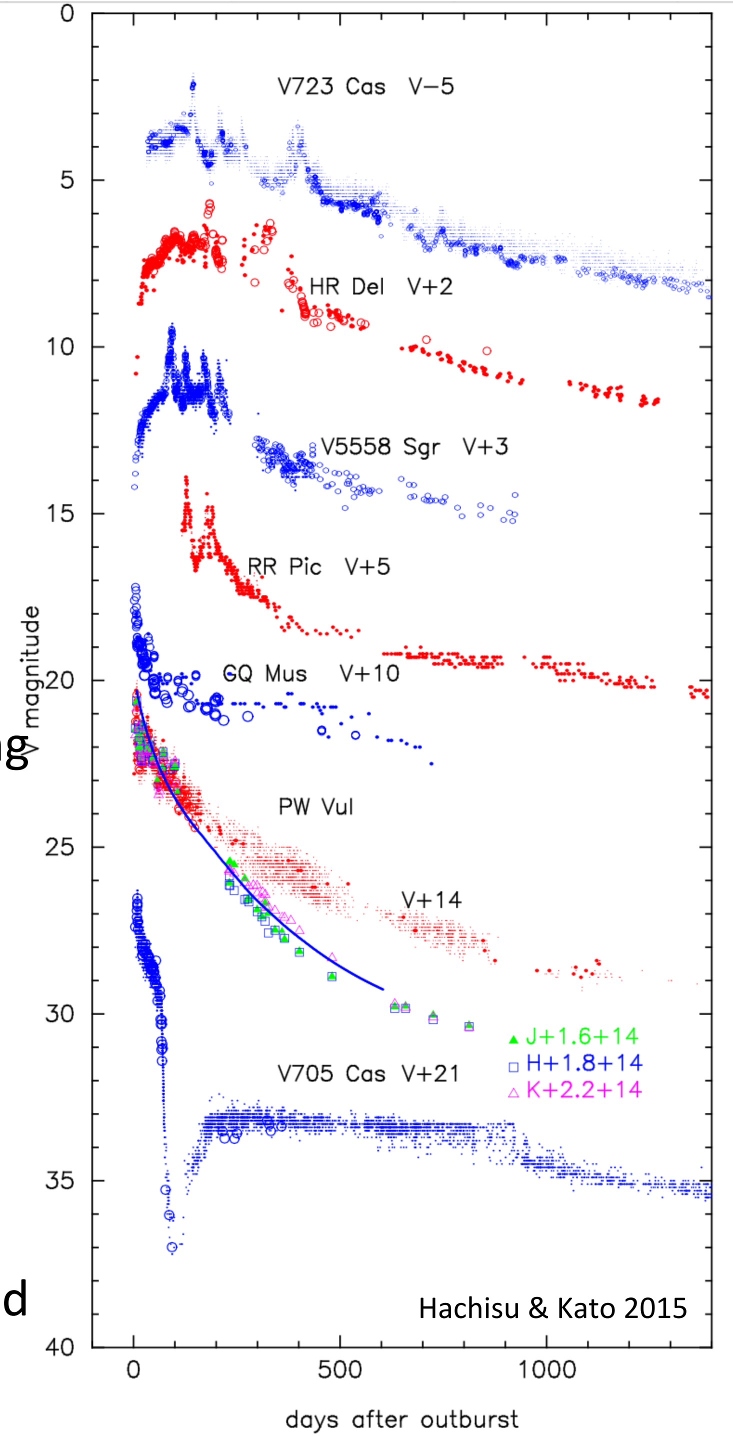
Laura Chomiuk, Tom Finzell (Michigan State), Damiano Caprioli (Princeton)

6th International Fermi Symposium – Arlington, VA - Tuesday, November 10, 2015

Classical & Symbiotic Novae





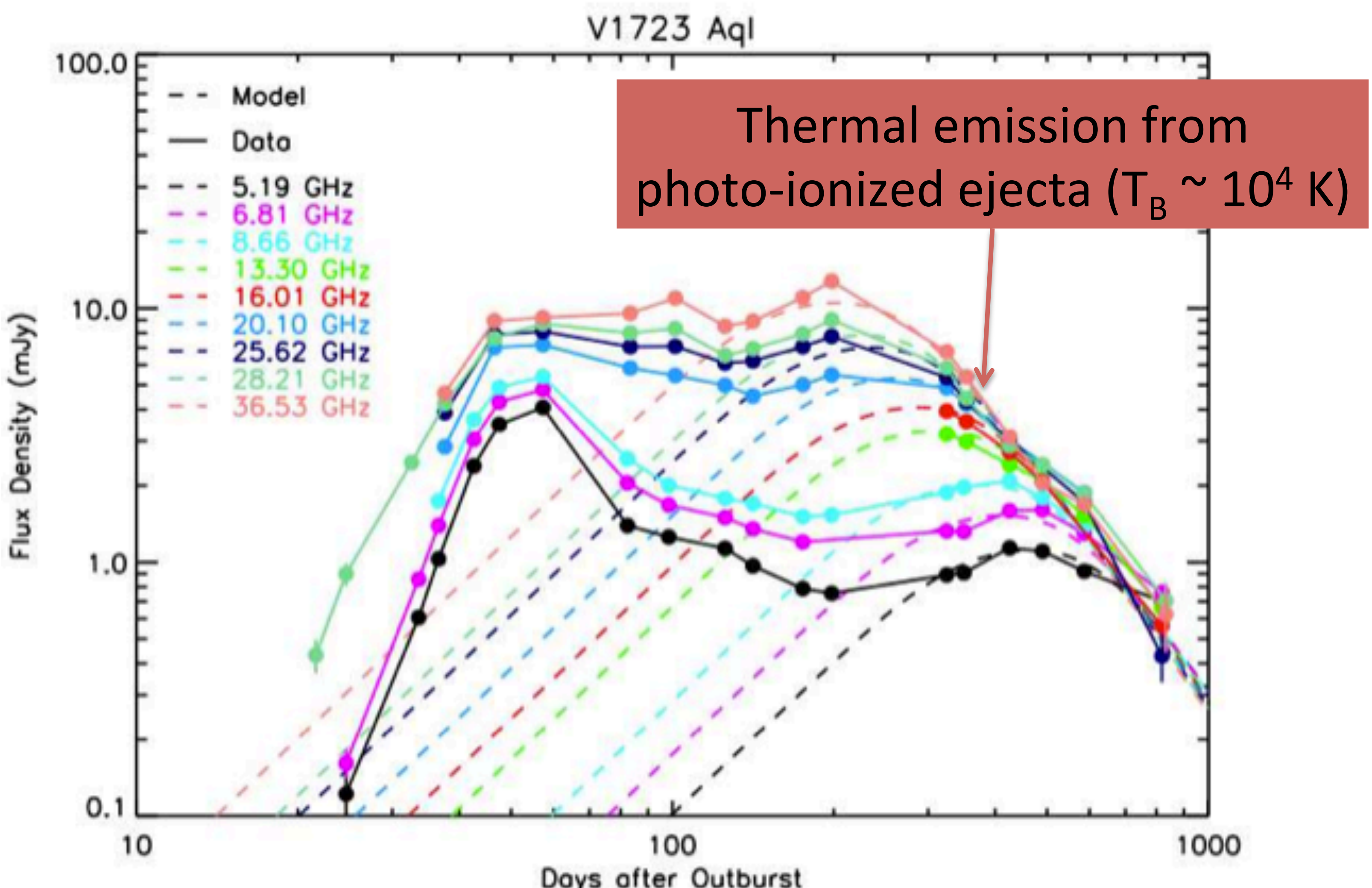
Runaway hydrogen burning on white dwarf accreting from a *main sequence* or *red giant* companion.

Optical & UV outburst lasting weeks to months with luminosity $\sim L_{edd} \sim 10^{38}$ erg s^{-1}.

Ejecta velocities of ~300 - 3,000 km s^{-1} and total mass of $\sim 10^{-5} - 10^{-4}\, M_{\odot}$.

Thermal emission: soft X-rays (10^6 K WD surface) and radio (10^4 K photo-ionized gas)

Evidence for Shocks in Novae:
1. early non-thermal radio flares



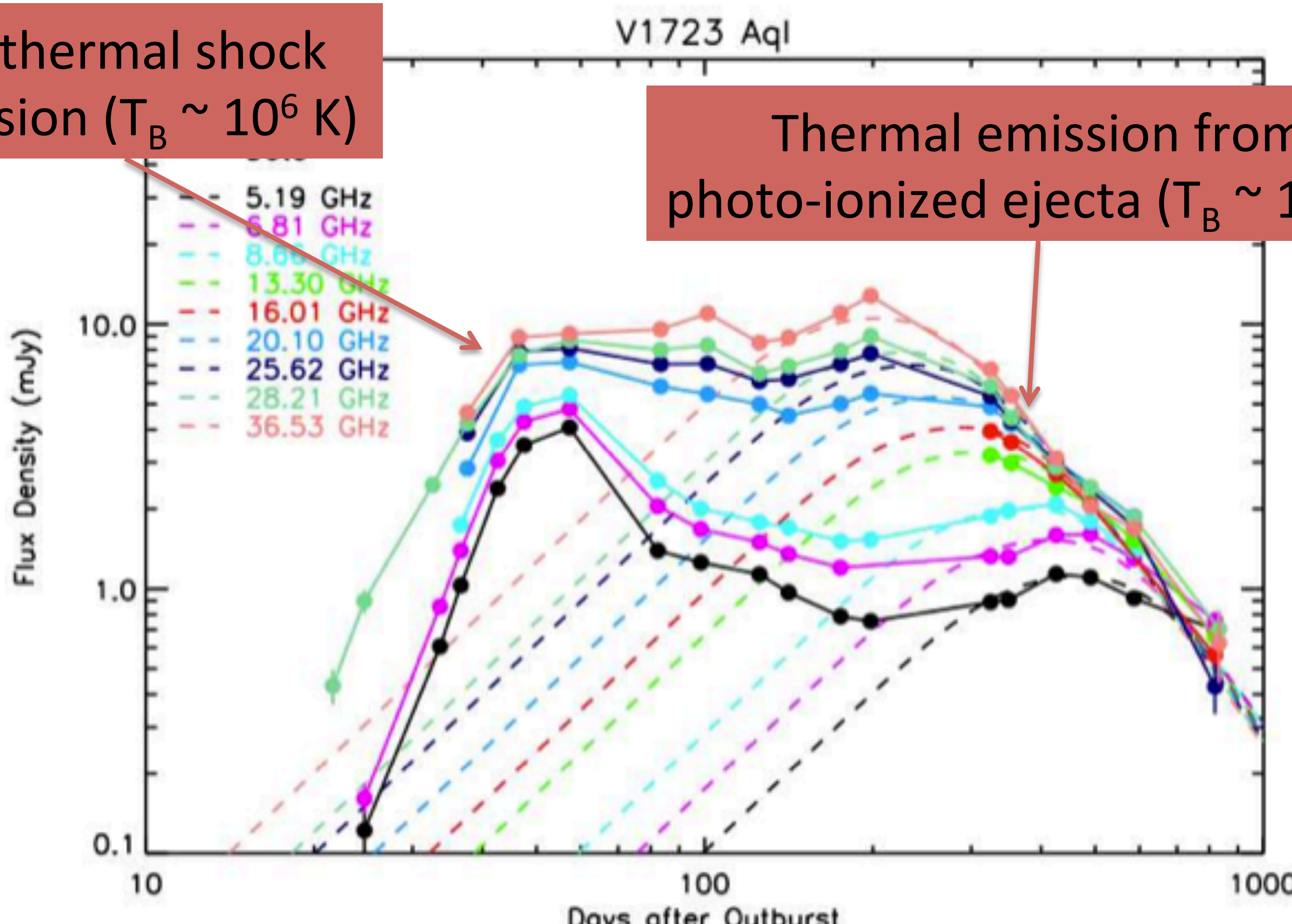
Weston et al. 2013 (see also Taylor et al. 1987, Krauss et al. 2011; Weston et al. 2015)

Evidence for Shocks in Novae:

1. early non-thermal radio flares

Non-thermal shock emission ($T_B \sim 10^6$ K)

Thermal emission from photo-ionized ejecta ($T_B \sim 10^4$ K)

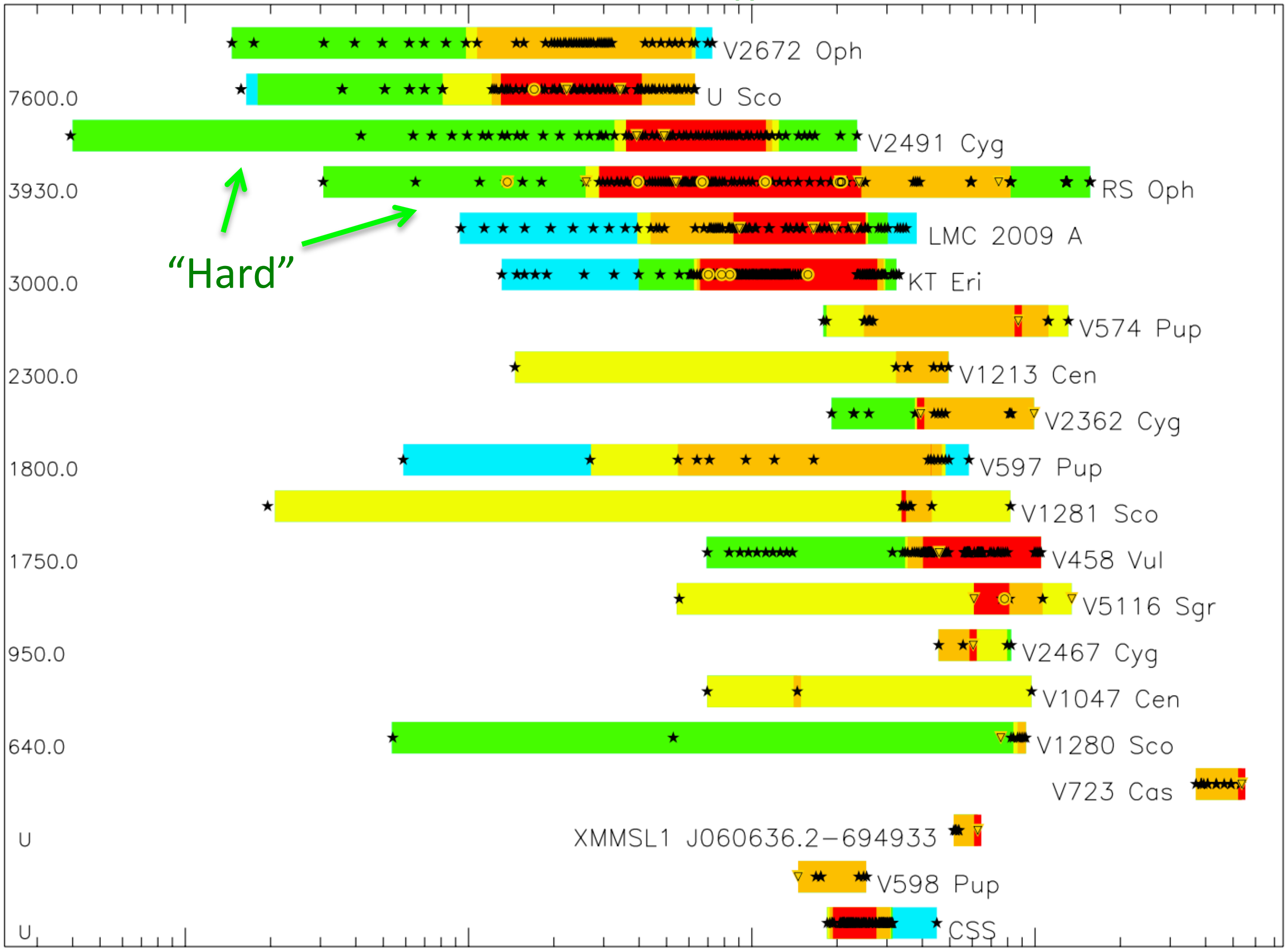


Weston et al. 2013 (see also Taylor et al. 1987, Krauss et al. 2011; Weston et al. 2015)

Evidence for Shocks in Novae:

2. Hard (> keV) Thermal X-rays

Swift Sample $L_X \sim 10^{32}$-10^{34} erg s^{-1}



Schwarz et al. 2011

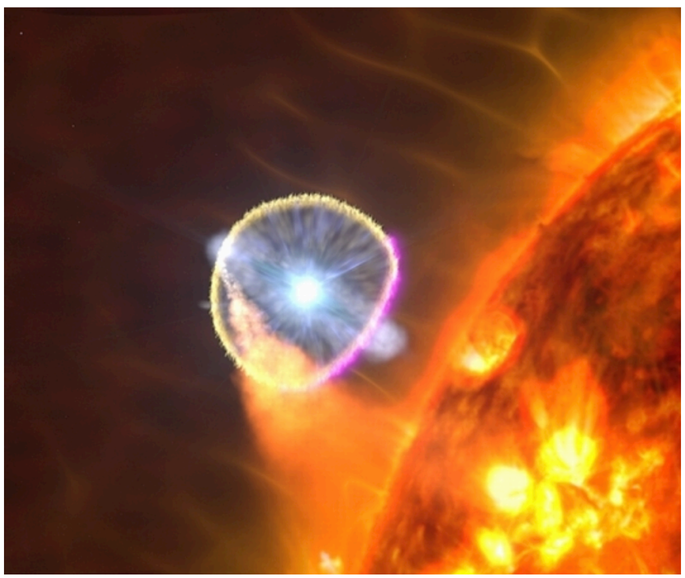
Day after Outburst

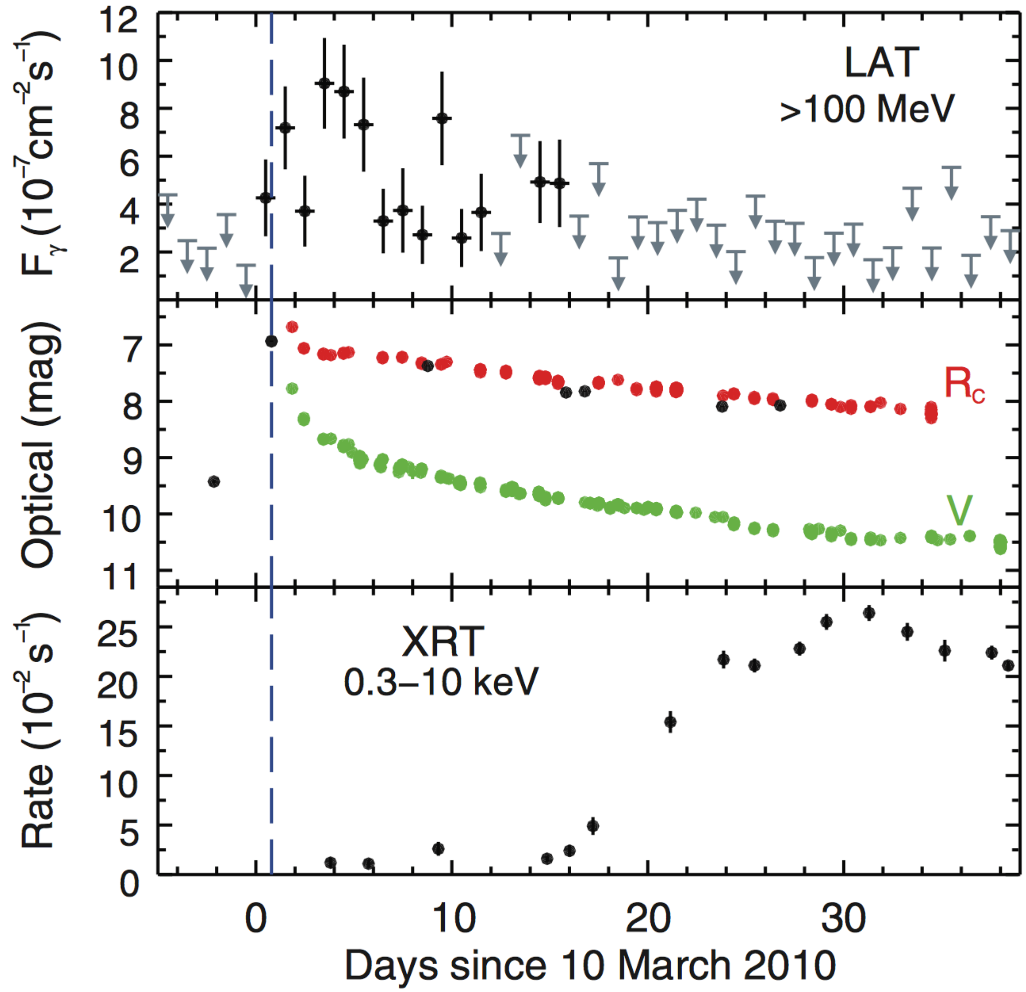
see also Mukai et al. 2008

LAT Detects Symbiotic Nova V407 Cyg

Abdo et al. 2010

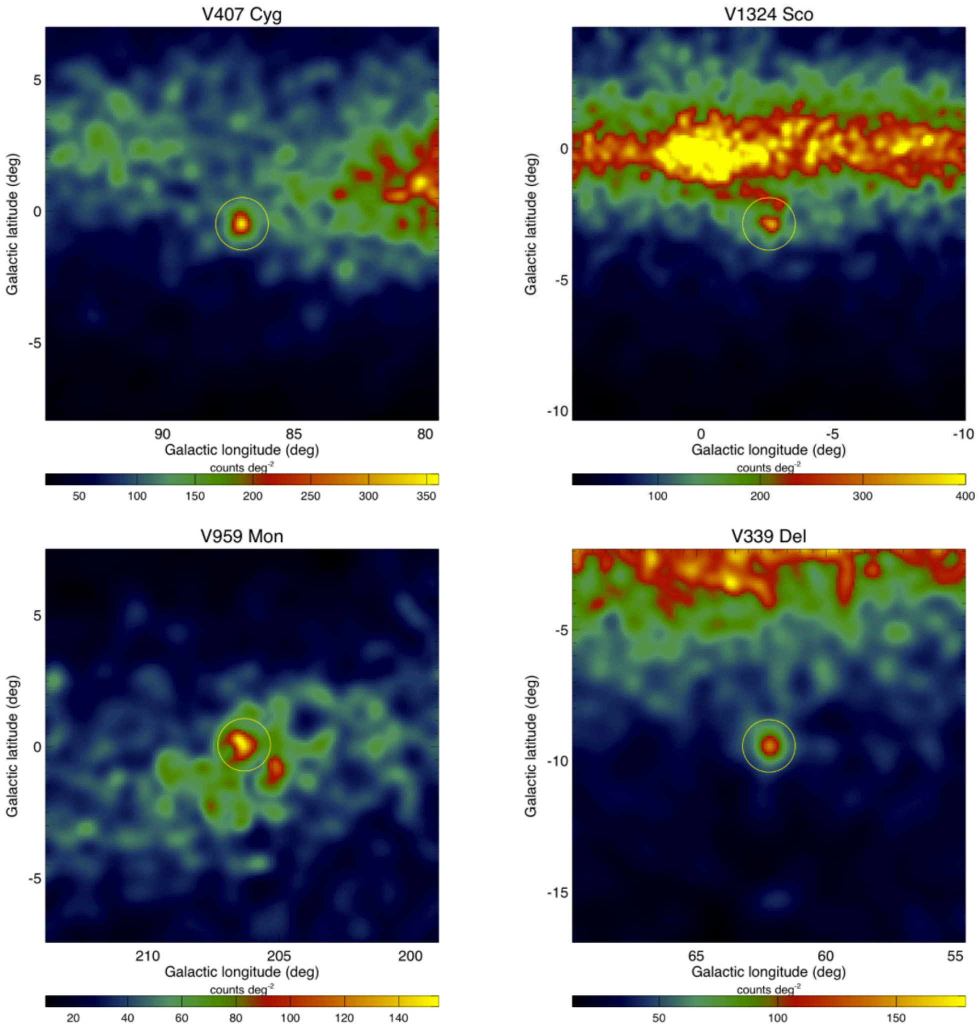
Interpretation: Shocks between ejecta and dense red giant wind
(e.g. Orlando & Drake 12, Martin & Dubus 13)



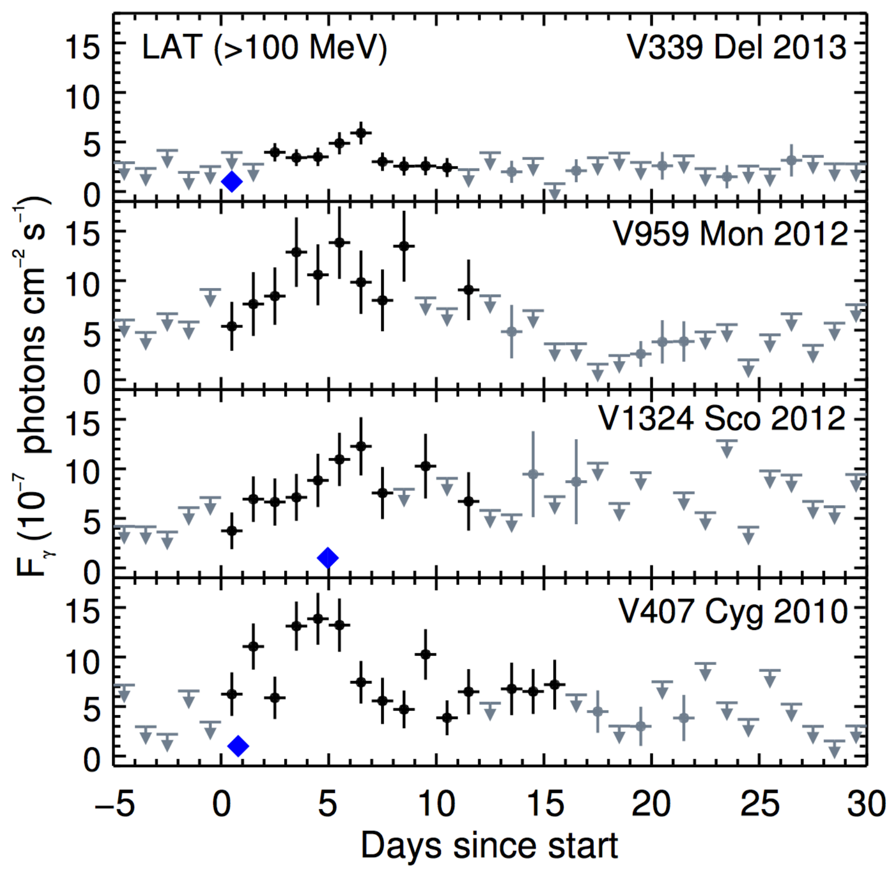


"…these sources can have dramatic influence on the local interstellar medium and Galactic cosmic rays, but few binary systems with a WD are known to have a similar environment; **hence, we expect gamma-ray novae to be rare.**"

LAT detects classical novae!



Ackermann et al. 2014

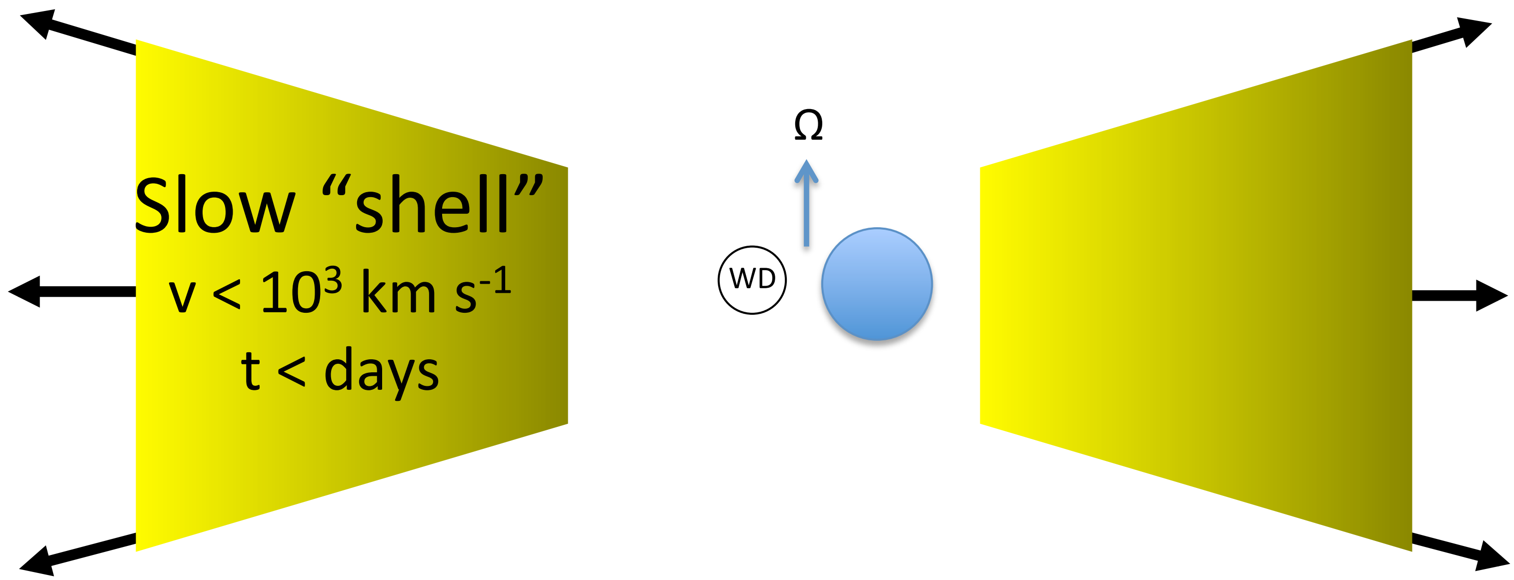


L_γ (0.1-10 GeV) ~ $\mathbf{10^{35\text{-}36}}$ **erg s^{-1}**

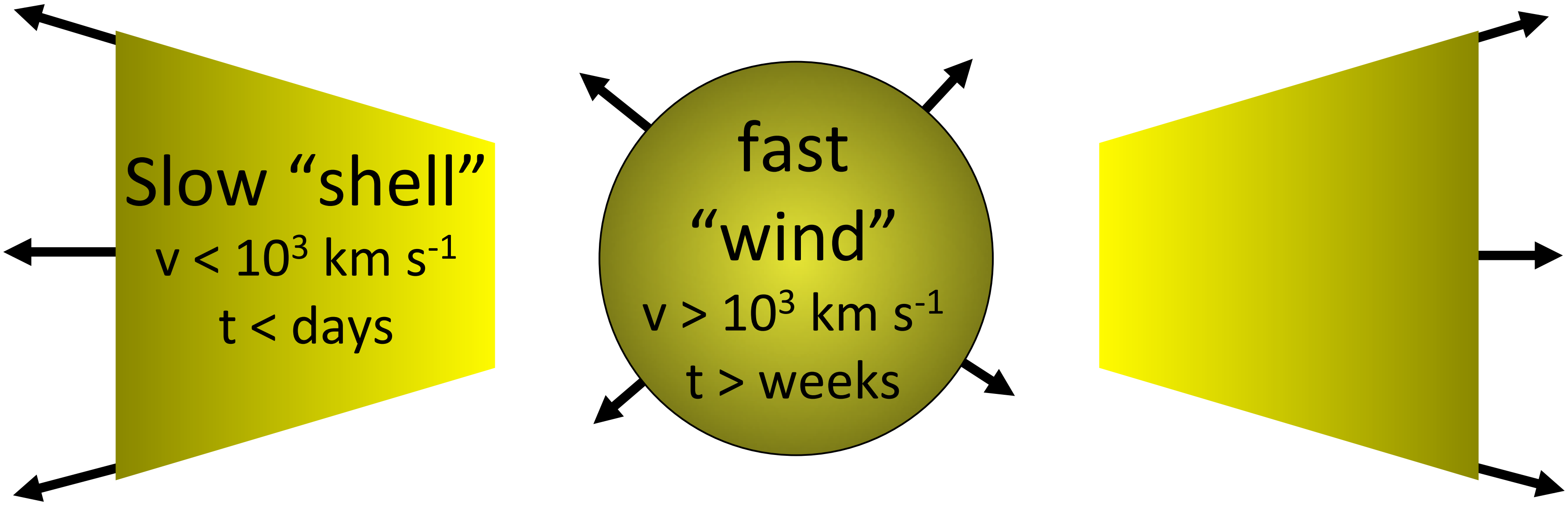
Duration ~ weeks (similar to optical)

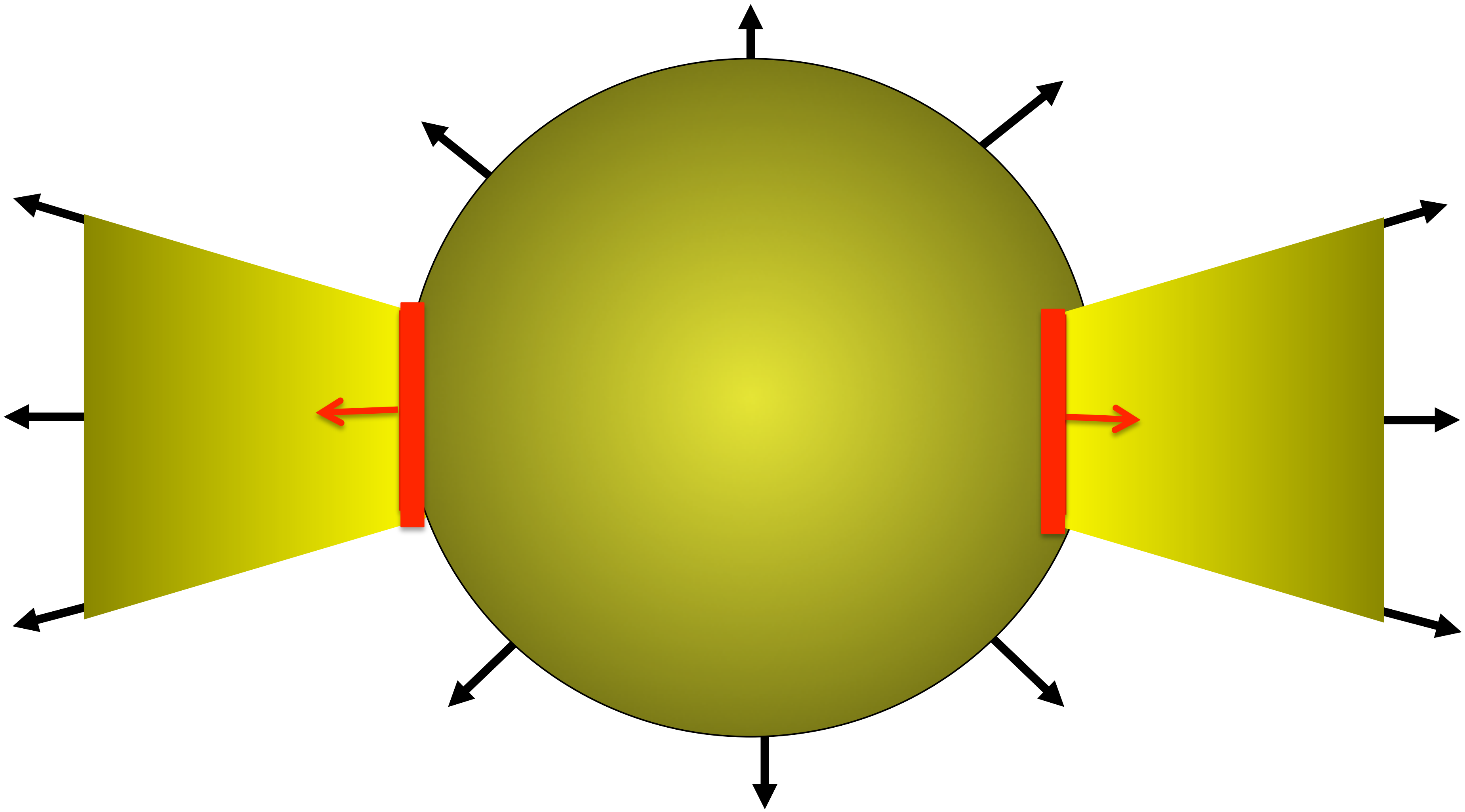
+2-3 more events (unpublished)

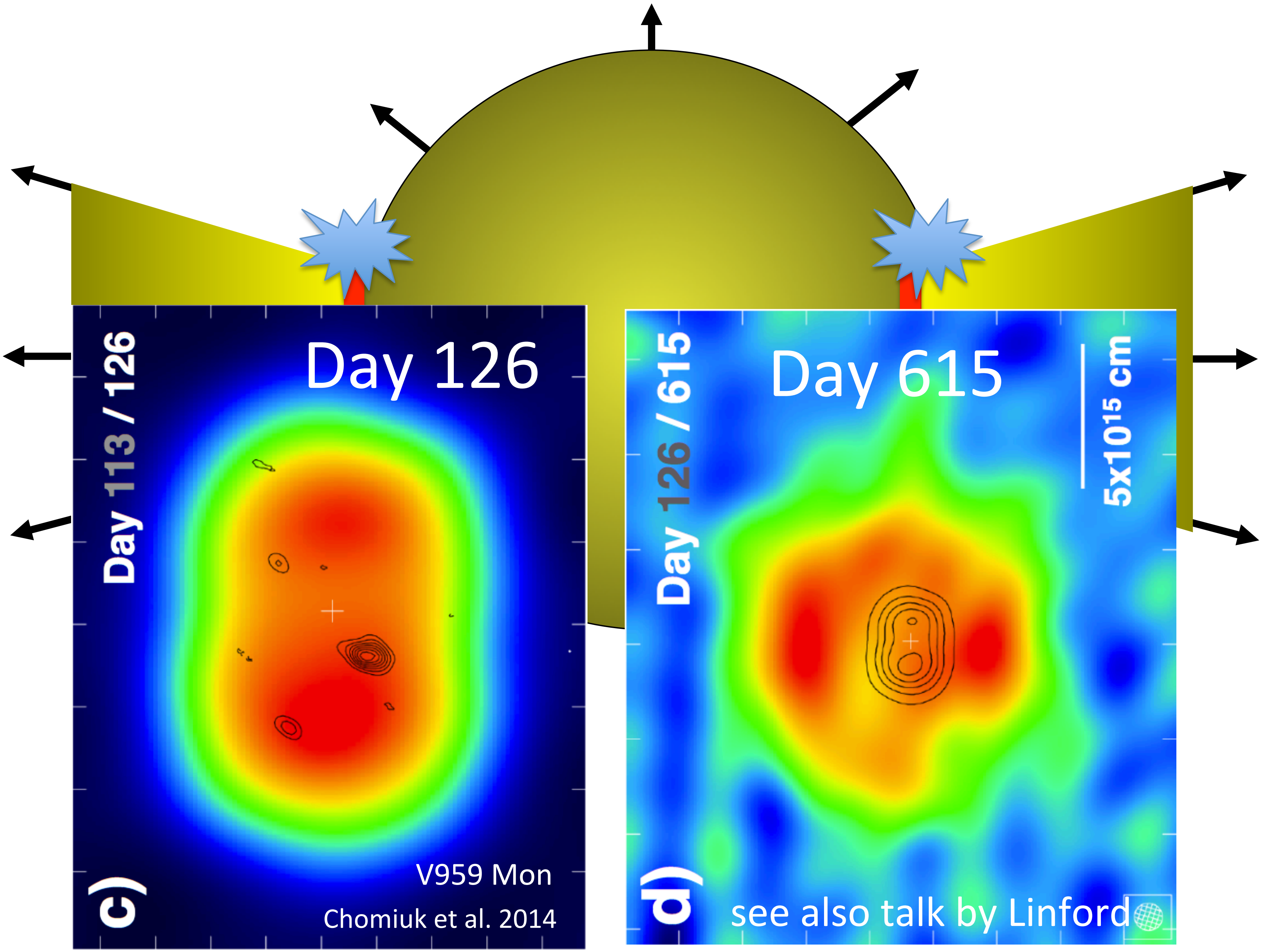
Geometry of Classical Nova Shocks



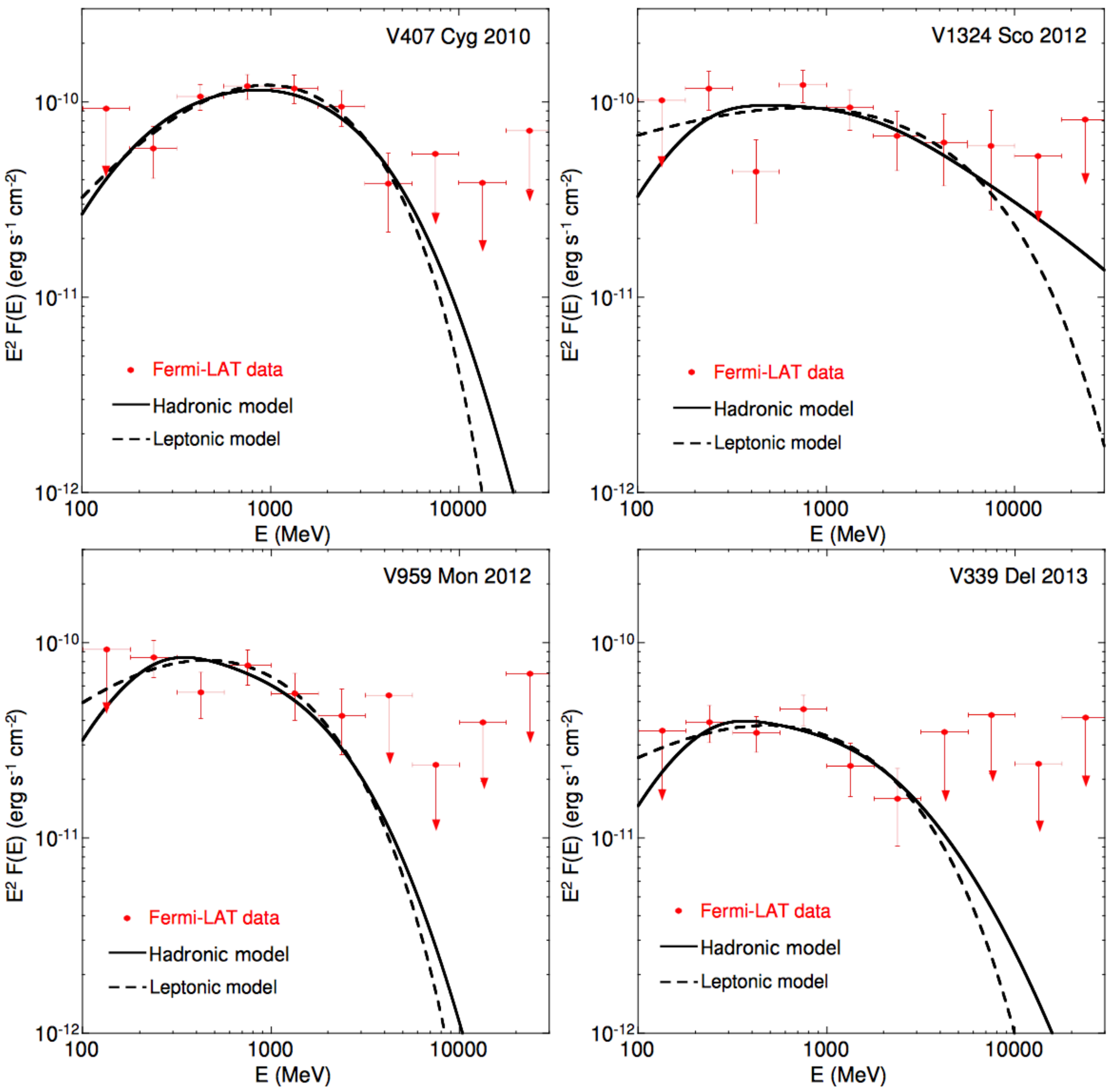
Geometry of Classical Nova Shocks






Day 126
Day 113 / 126
V959 Mon
Chomiuk et al. 2014
c)
Day 615
Day 126 / 615
5x1015 cm
d)
see also talk by Linford

LAT Spectrum: Hadronic or Leptonic?



Leptonic

$$e^- + \gamma_{opt} \underset{\gamma_e \sim 10^4}{\Rightarrow} e^- + \gamma'$$

$$e^- + p \underset{\gamma_e \sim 10^3}{\Rightarrow} e^- + \gamma'$$

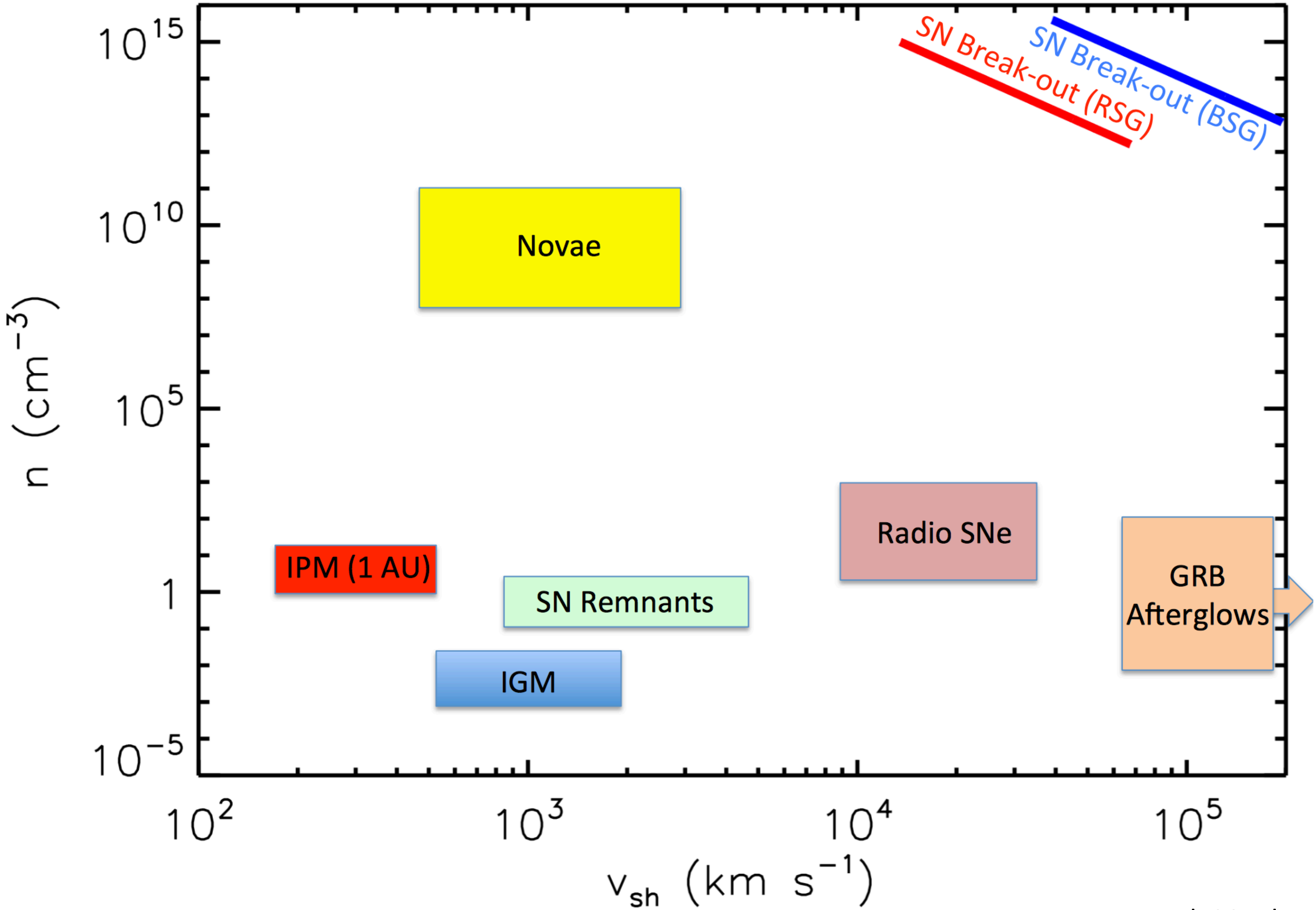
Hadronic

$$p + p \Rightarrow \pi^0 \Rightarrow \gamma + \gamma$$

$$\Rightarrow \pi^\pm \Rightarrow \nu's + e^\pm$$

$$\Rightarrow \nu's + \gamma's$$

Ackermann et al. 2014



BDM et al. 2015b

Nova shocks are **dense**

$$n \sim \frac{M_{ej}}{4\pi m_p (Vt)^3} \sim 10^{10} \left(\frac{M_{ej}}{10^{-4} M_\odot}\right) \left(\frac{t}{3 \text{ week}}\right)^{-3} \left(\frac{V}{10^3 \text{ km s}^{-1}}\right)^{-3} \text{ cm}^{-3}$$

Implications:

1. thermal electrons and ions are Coulomb coupled
2. shocks are radiative

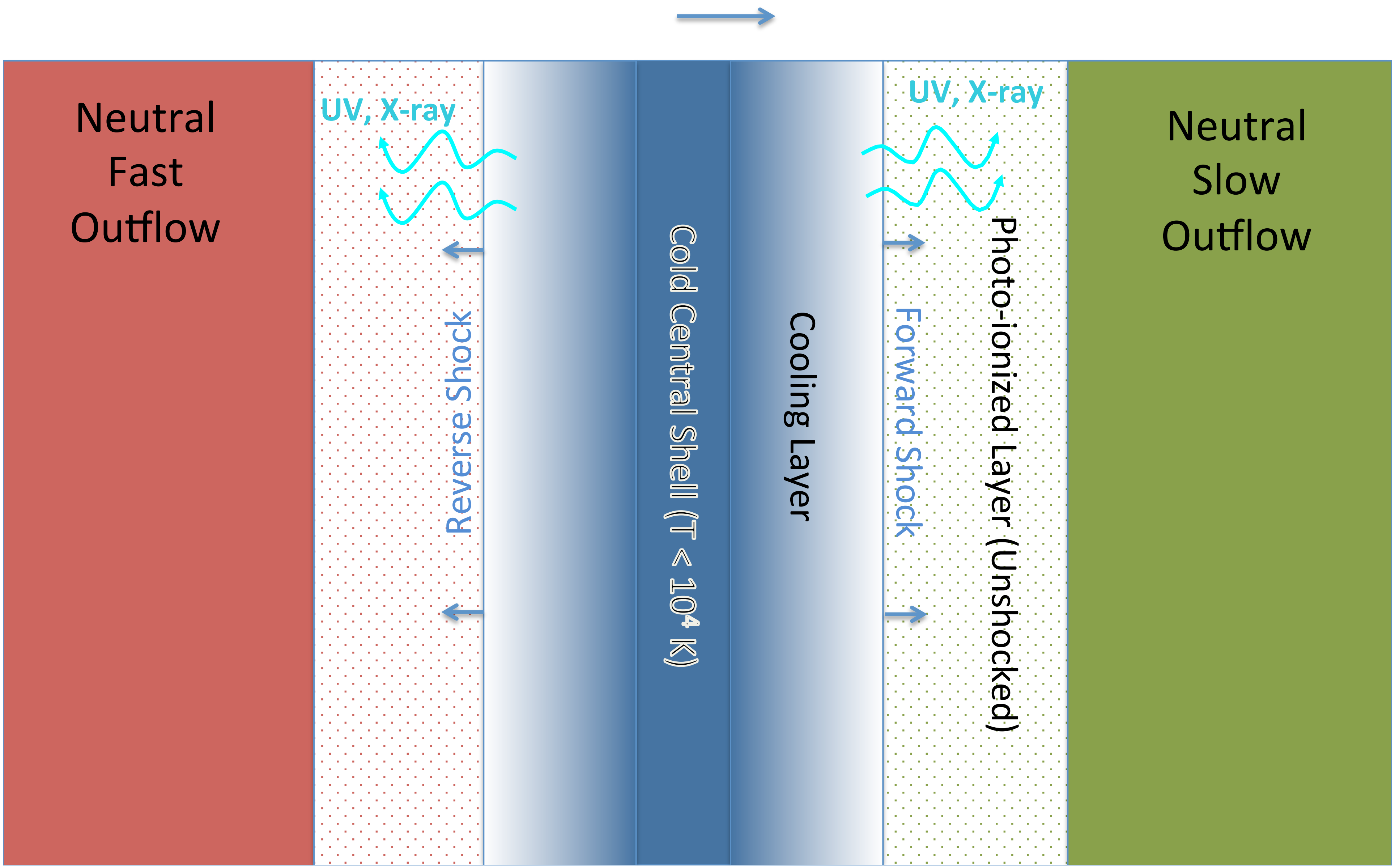
$$\frac{t_{\rm cool}}{t} \approx \begin{cases} 2.7 \times 10^{-3} \eta v_8^4 M_{-4}^{-1} t_{\rm wk}^2 & \text{FS} \\ 0.13 v_8^4 \dot{M}_{-5}^{-1} t_{\rm wk} & \text{RS} \end{cases} \ll 1$$

➔ most kinetic power dissipated by shock emerges as radiation

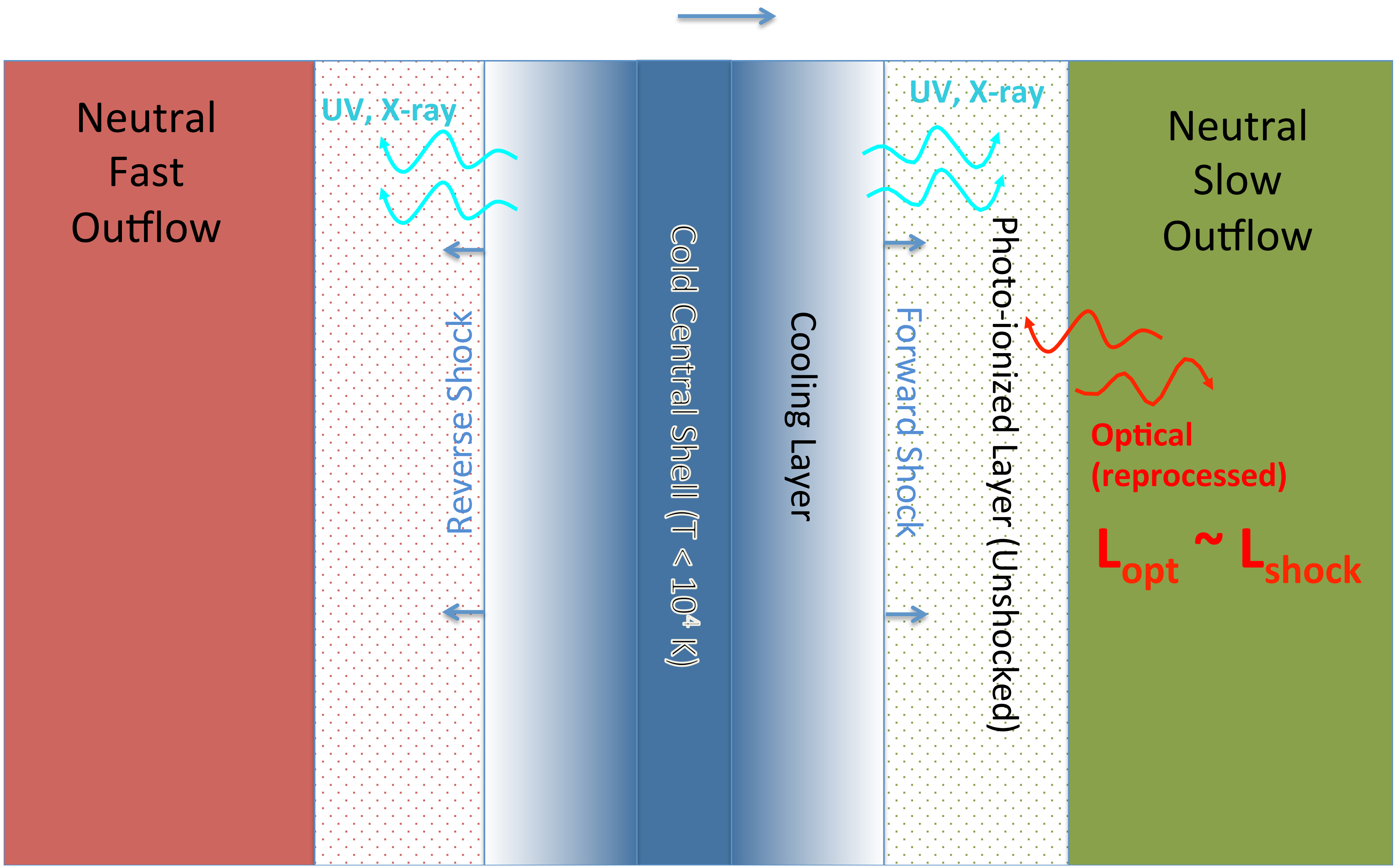
3. opaque to soft X-rays (bound-free) & radio (free-free)

➔ upstream gas is **neutral** well ahead of shock

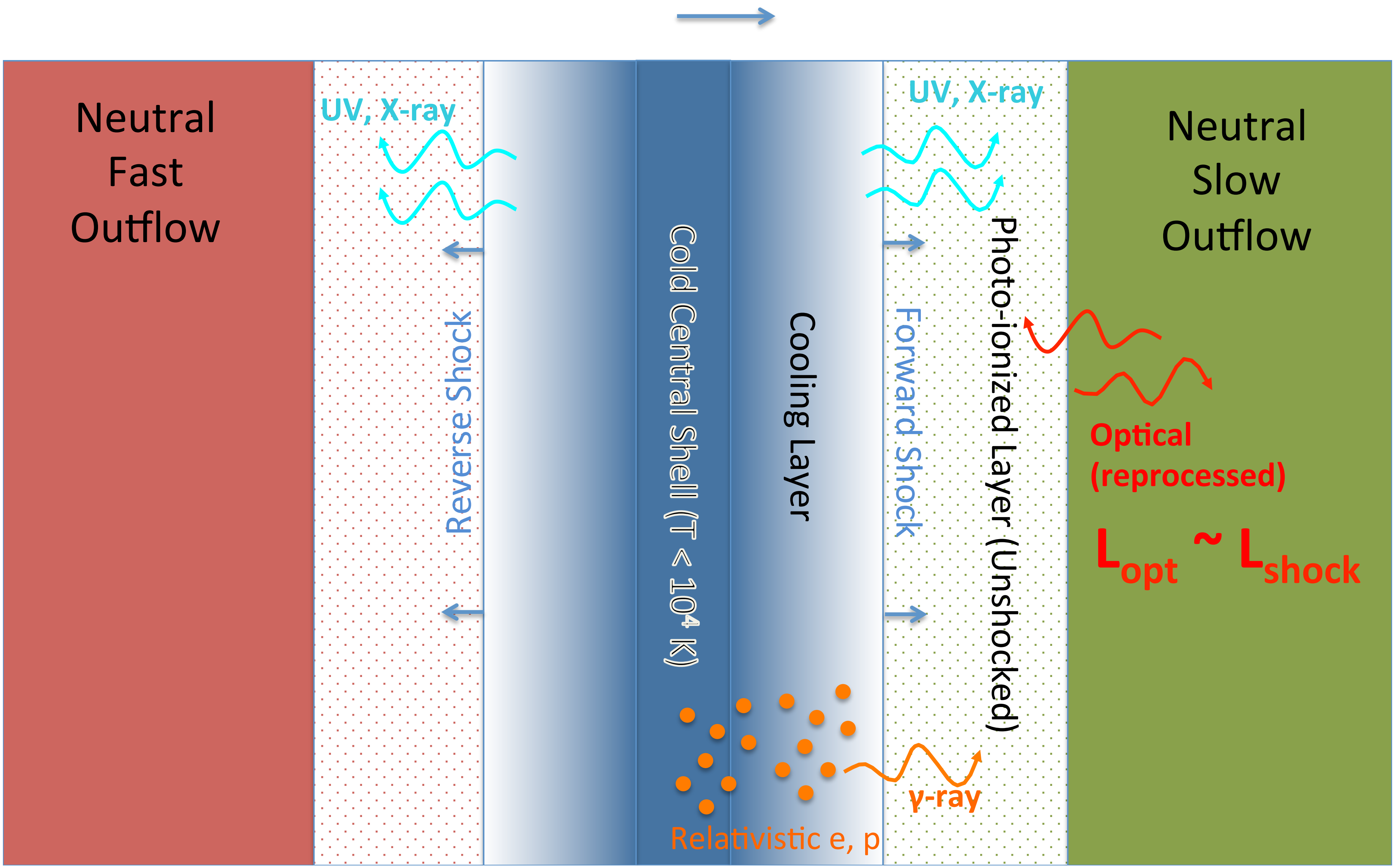
Anatomy of a Nova Shock



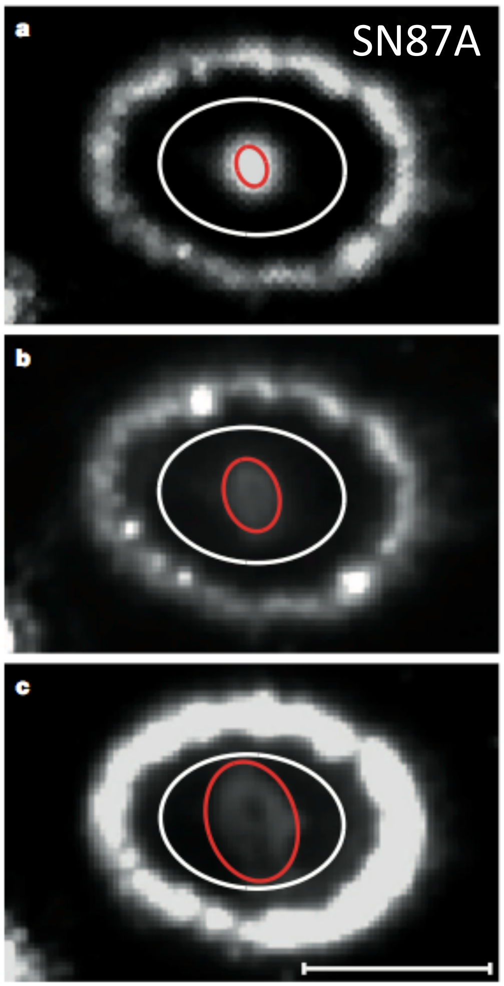
Anatomy of a Nova Shock

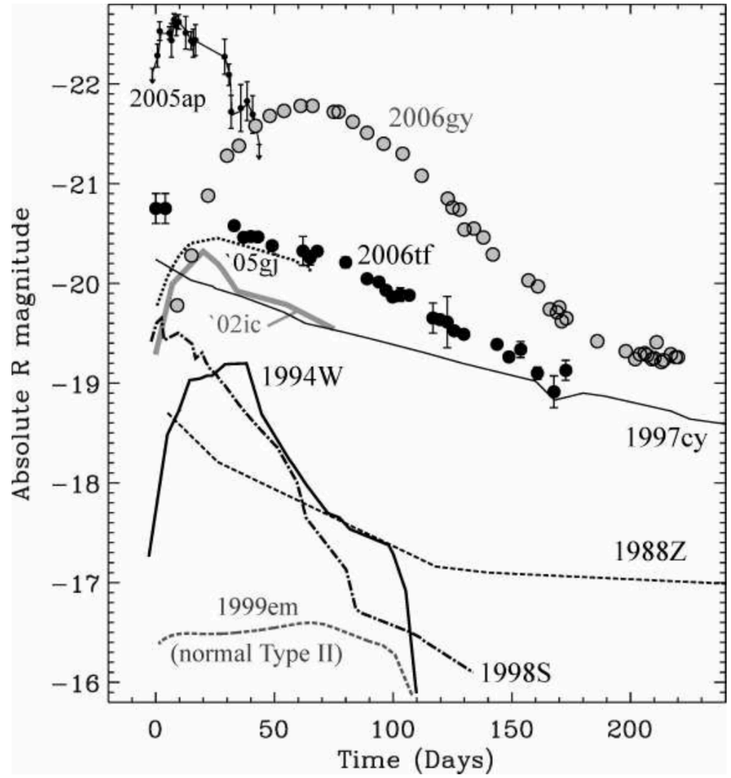


Anatomy of a Nova Shock

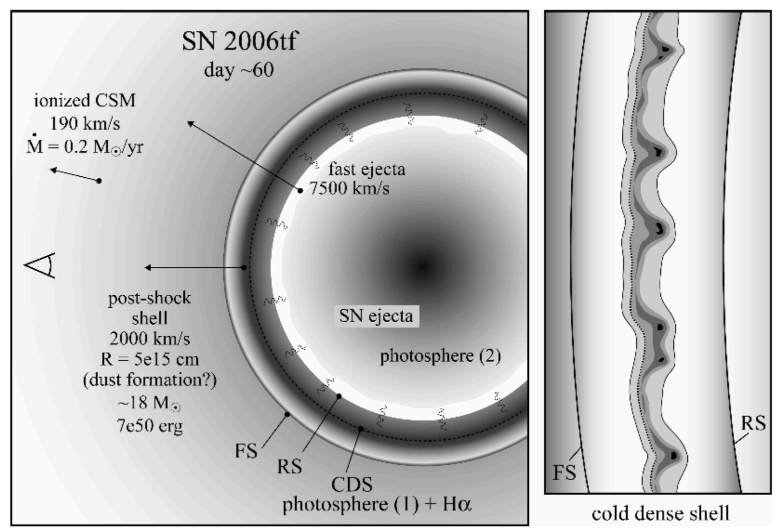


Interaction Powered Type IIn Supernovae





SN 2006tf Gets the Bronze 1



Smith et al. 2008

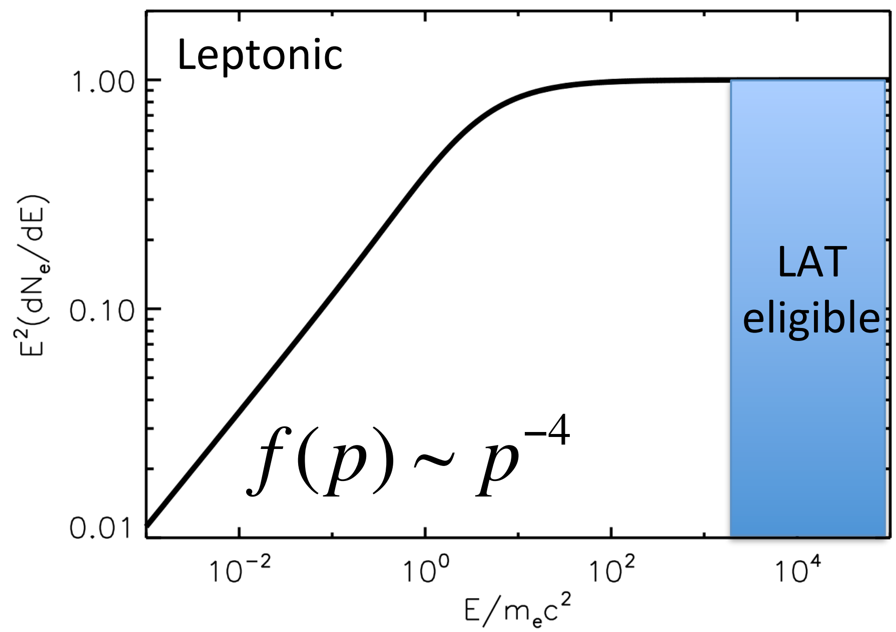
As Probes of Particle Acceleration

Measured gamma-ray luminosity: $L_\gamma = \epsilon_{\rm nth} \epsilon_\gamma L_{\rm sh}$

Leptons & hadrons are fast cooling

fraction of non-thermal particle energy radiated in LAT bandpass:

$\epsilon_\gamma <$ 0.1-0.3

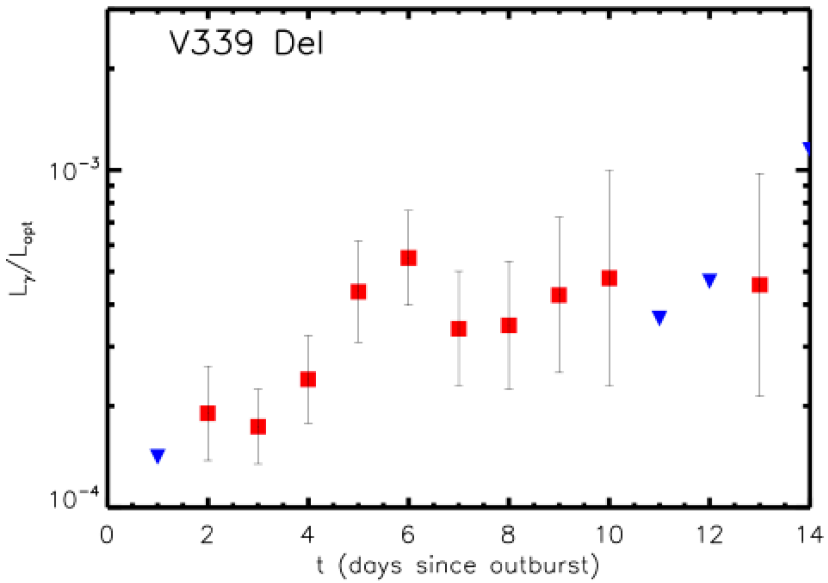


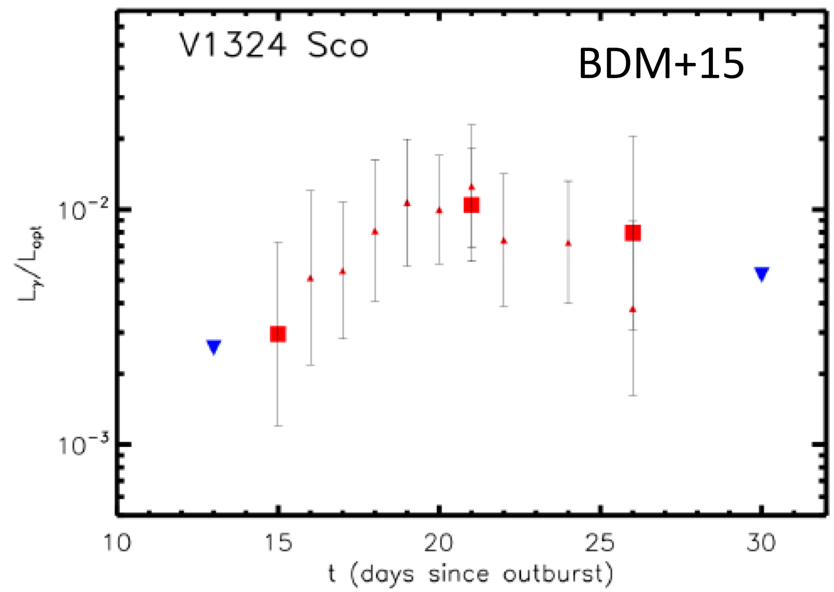
Don't overproduce optical emission:

measured

$$L_{\rm sh} < L_{\rm opt} \quad \Rightarrow \epsilon_{\rm nth} > \epsilon_{\rm nth,min} = \frac{1}{\epsilon_\gamma} \frac{L_\gamma}{L_{\rm opt}}$$

Non-Thermal Acceleration Efficiency





Nova	$\langle \log \left[\frac{L_\gamma}{L_{\rm opt}} \right] \rangle$	$\log \epsilon^{(a)}_{\rm nth,min}$
V1324 Sco	-2.2±0.4	-1.5±0.4
V339 Del	-3.5±0.2	-2.8±0.2

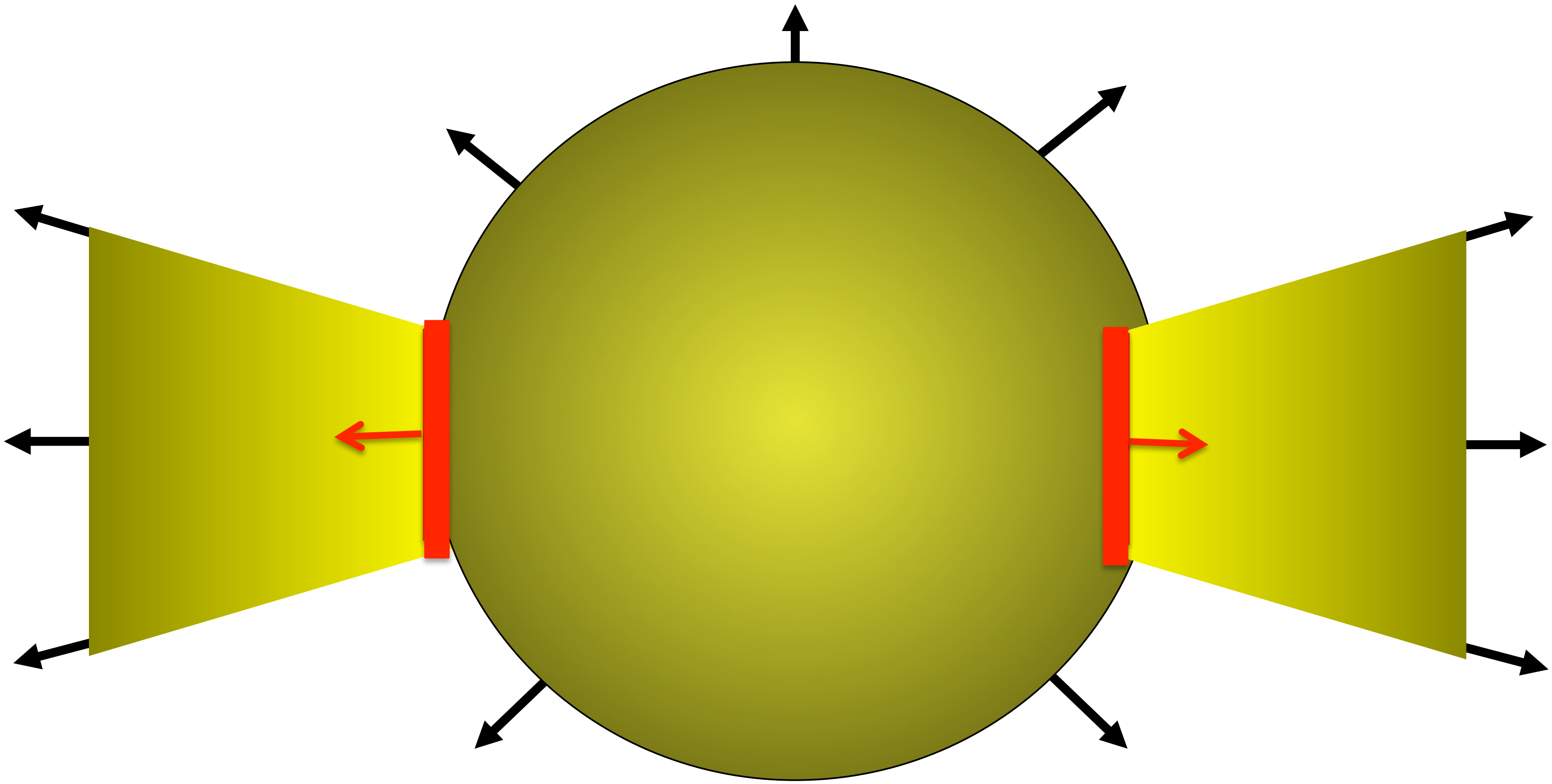
$$\varepsilon_{nth} > 10^{-3} - 10^{-2}$$

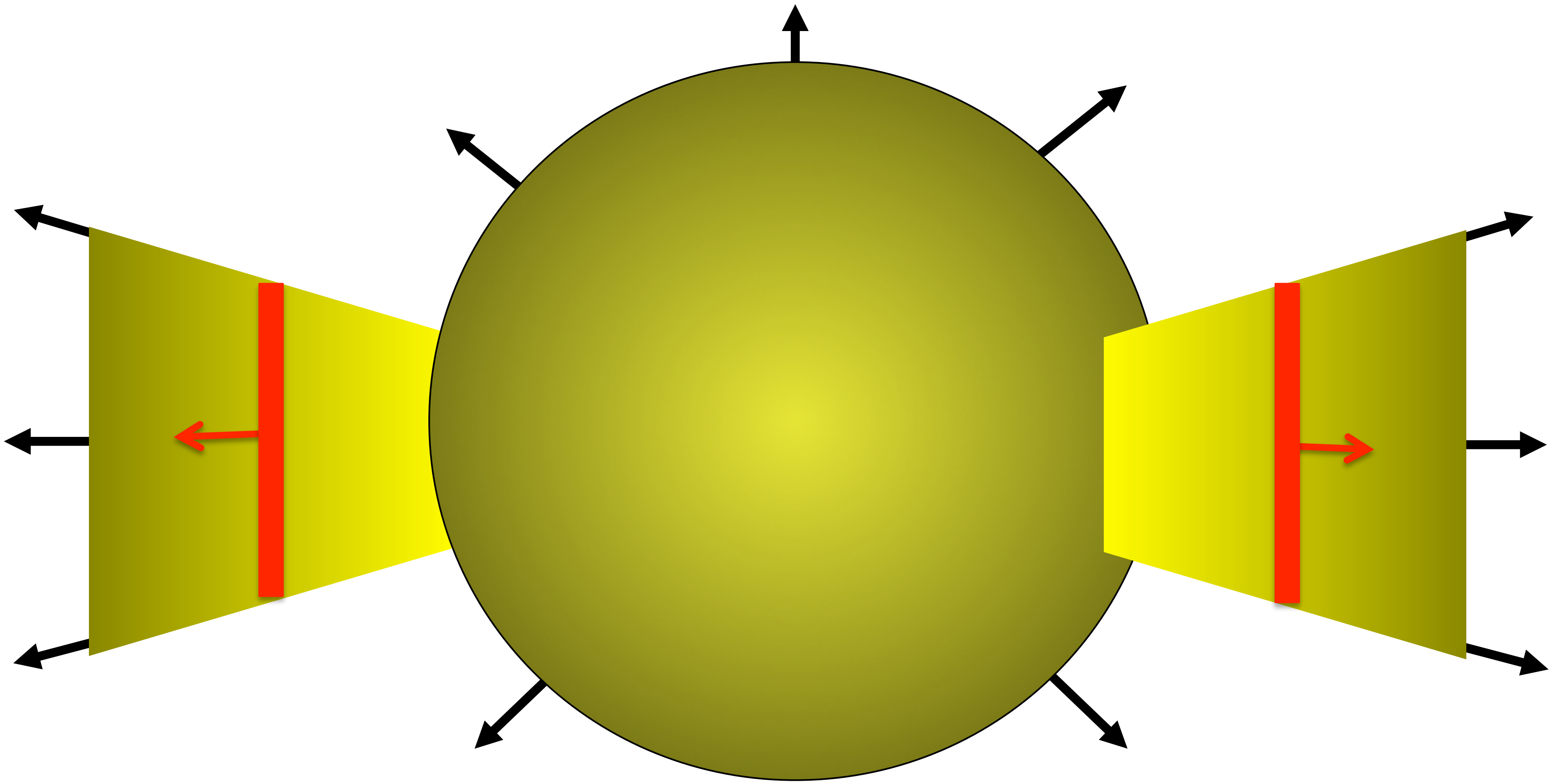
Hadronic Scenario:

ε_{nth} up to 0.1, depending on B field geometry (Caprioli & Spitkovsky 14)

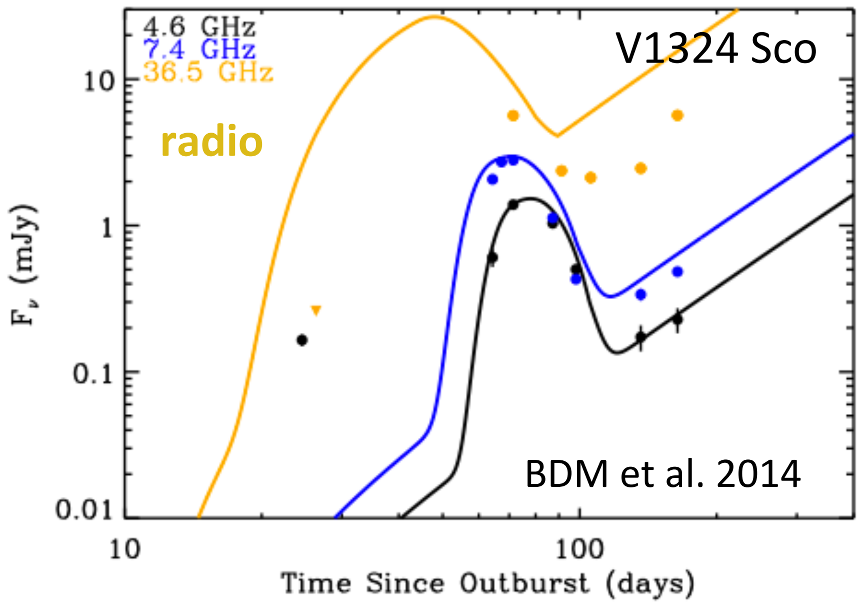
Leptonic Scenario:

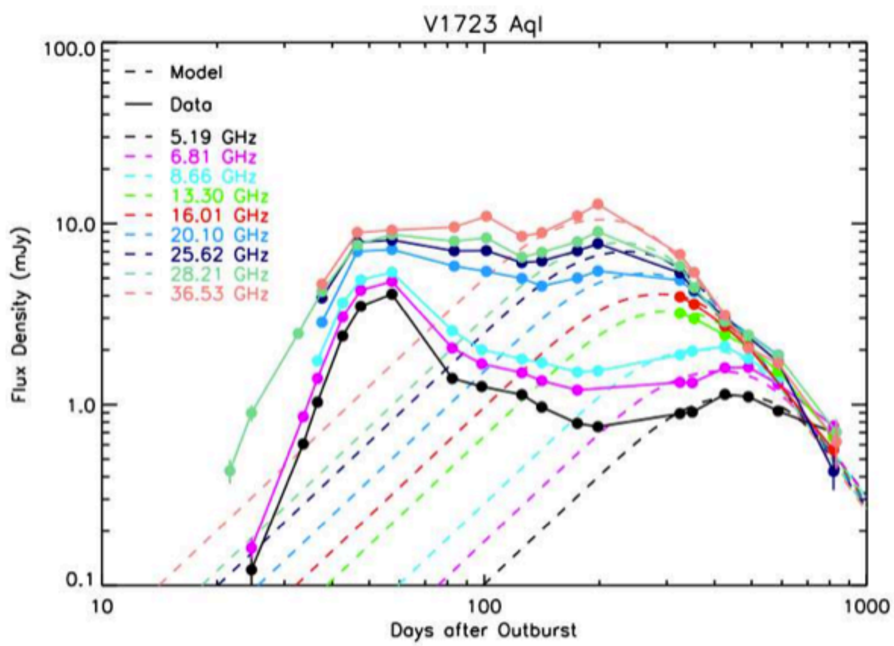
$\varepsilon_{nth} < 10^{-3}$ from observations & PIC simulations (e.g. Kato 14, Park+14)



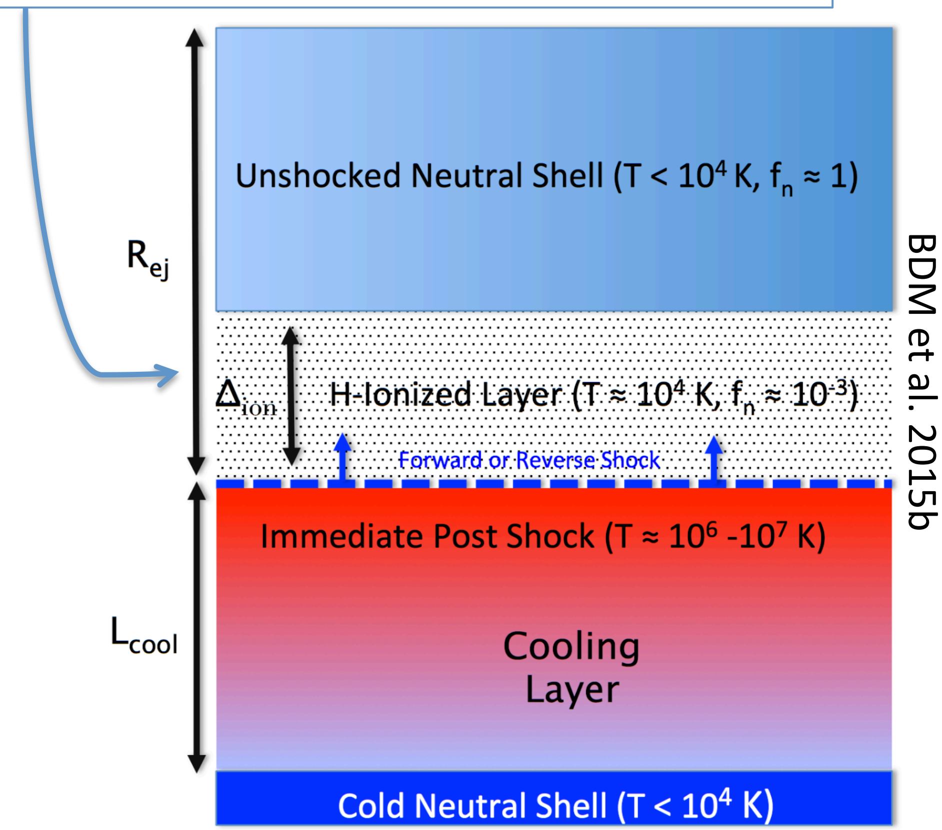


Non-Thermal Radio Emission





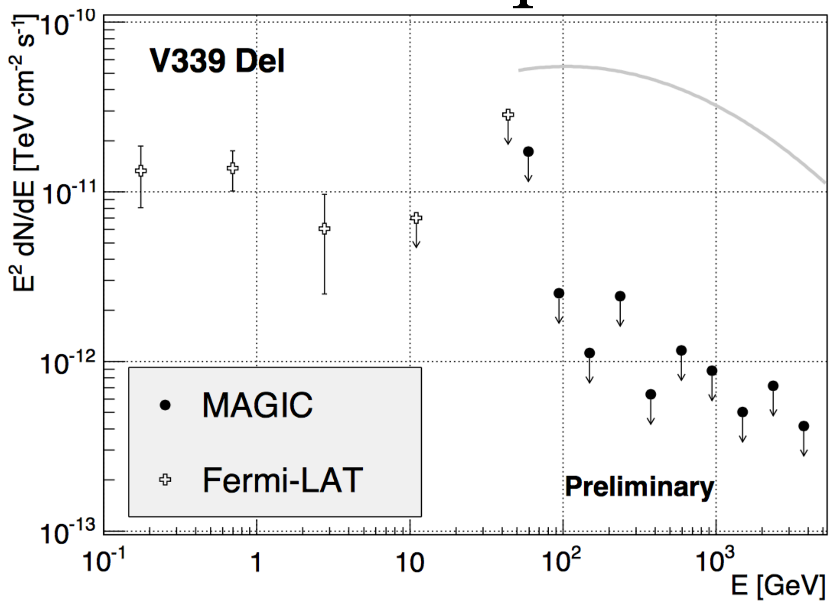
Rise delayed by free-free absorption

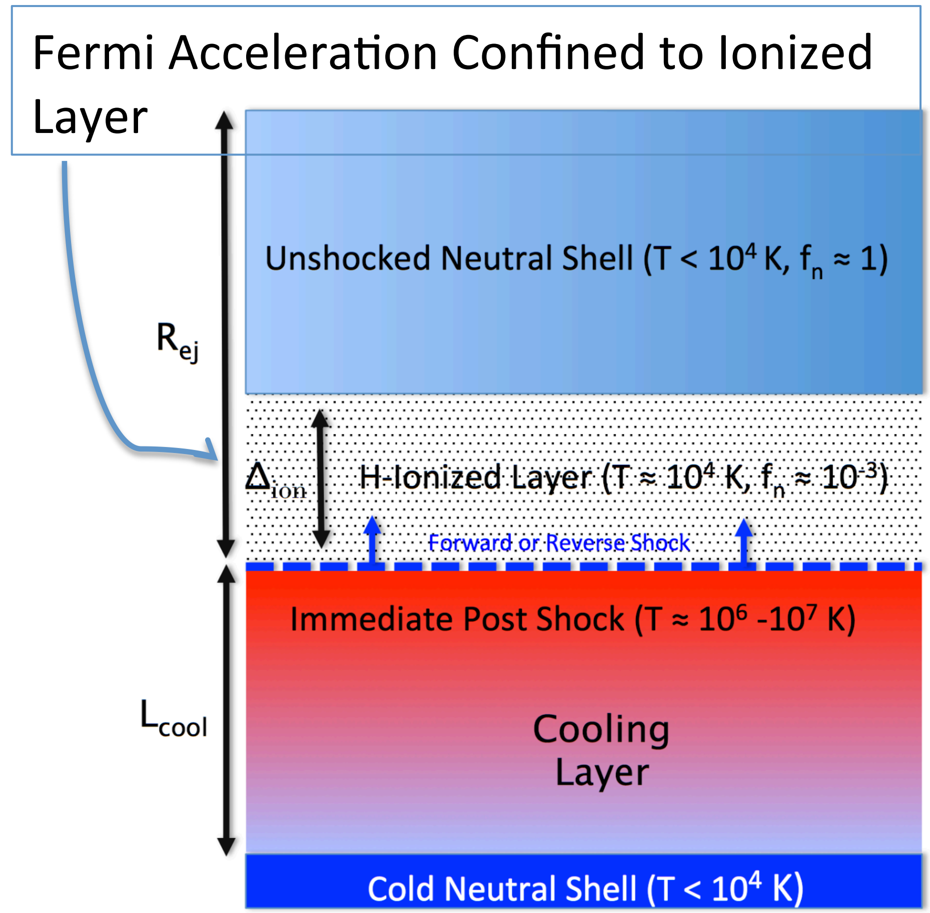


Peak brightness temperature constrains $\boldsymbol{\varepsilon}_{\mathbf{nth}}$ of relativistic electrons (see Vlasov Poster).

Prospects for TeV Emission

MAGIC Collaboration 15





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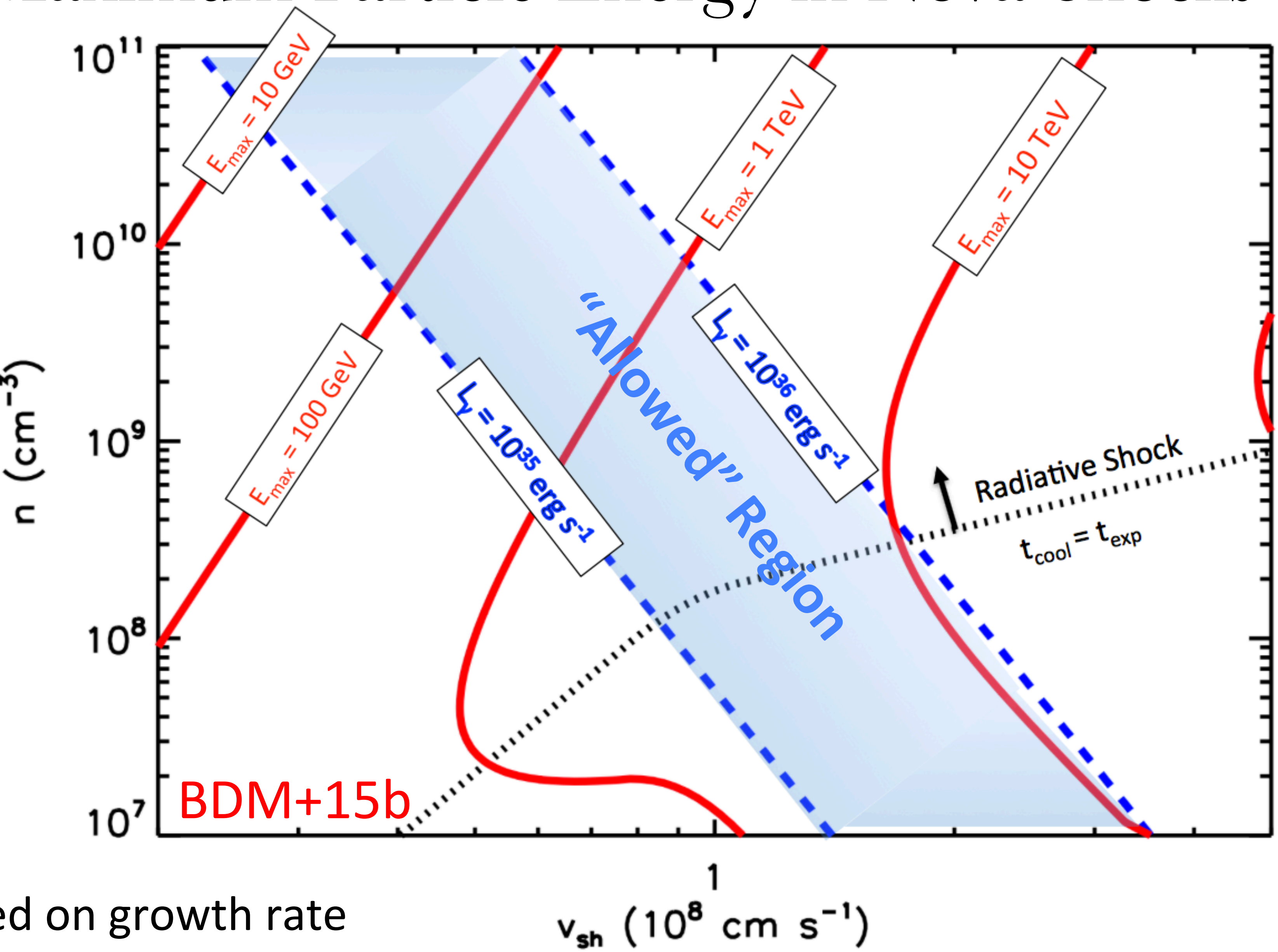
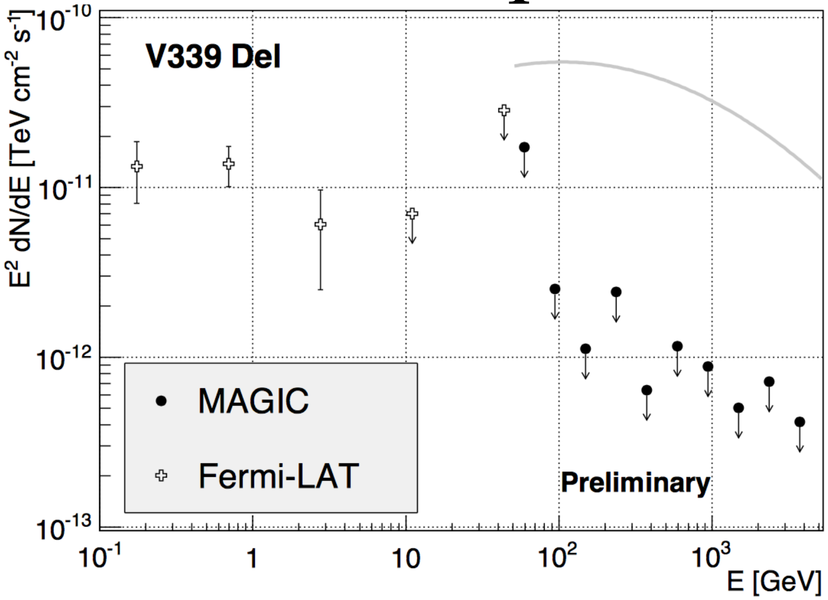
Maximum Particle Energy in Nova Shocks



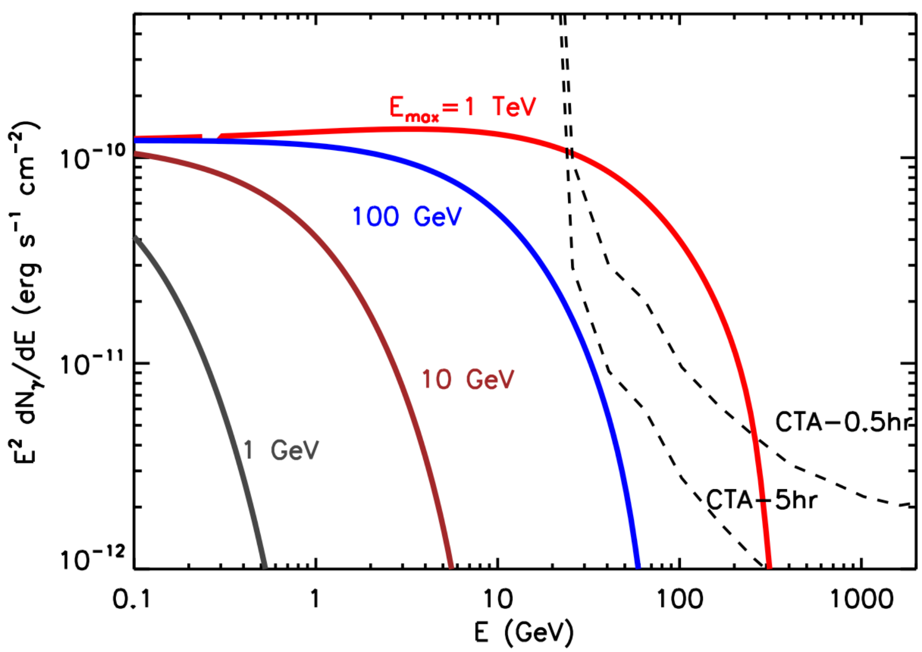
Based on growth rate
analysis of Bell (2004) instability

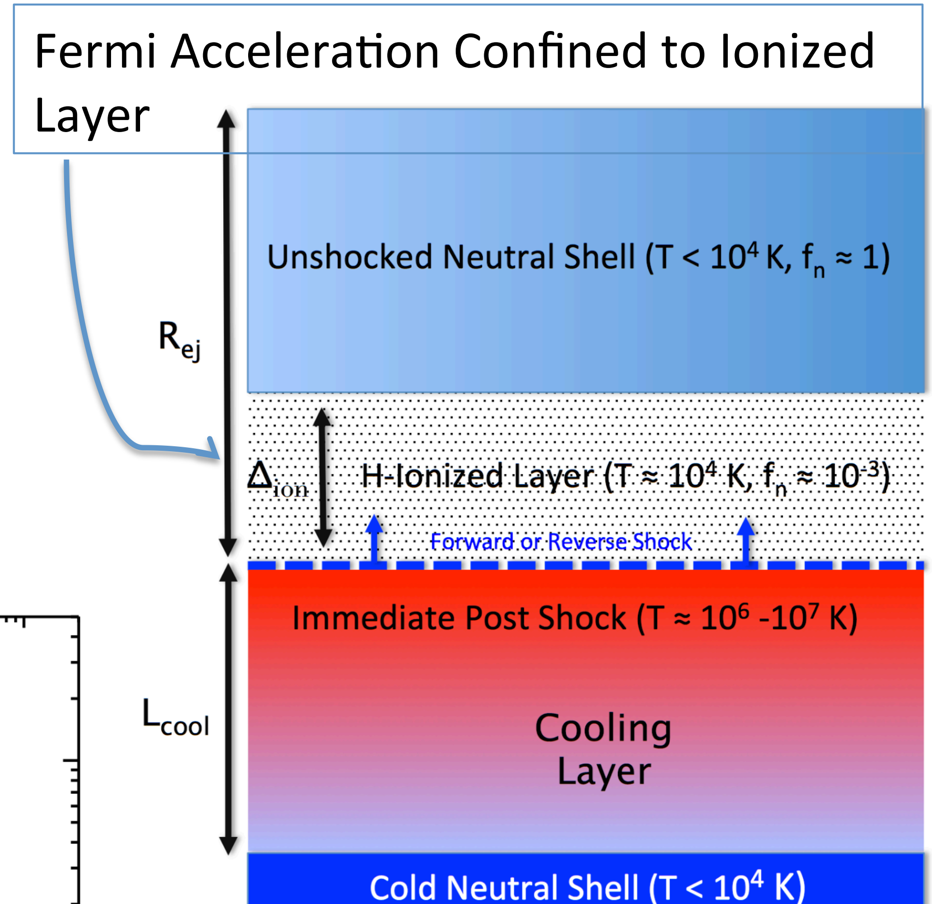
Prospects for TeV Emission

MAGIC Collaboration 15



Metzger+15b





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Potential IceCube sources (ask me)

Summary

- LAT discovery of novae as luminous GeV γ-ray sources establishes that shocks & relativistic particle acceleration are key features of these events. Leptonic/hadronic scenarios not distinguished by LAT spectrum alone.
- High densities of classical nova ejecta are novel and imply: (1) shocks are radiative; (2) gas well ahead of shock is neutral; (3) relativistic leptons/hadrons are fast cooling [calorimeter].
- Thermal X-rays from γ-ray shocks not observed at early times (absorption by neutral gas) => shock power emerges at optical/UV, as in Type IIn SNe.
- Measured ratio of γ-ray to optical luminosities places lower limit on acceleration efficiency of non-thermal particles, $\varepsilon_{nth.}$ High measured values $\varepsilon_{nth} > 10^{-2}$-$10^{-3}$ may favor hadronic scenarios.
- Non-thermal radio synchrotron emission, delayed by free-free absorption, provides a complimentary probe of electron acceleration efficiency (Linford talk).
- Nova shocks can (theoretically) accelerate particles up to TeV energies, producing emission accessible to Cherenkov telescopes and IceCube.