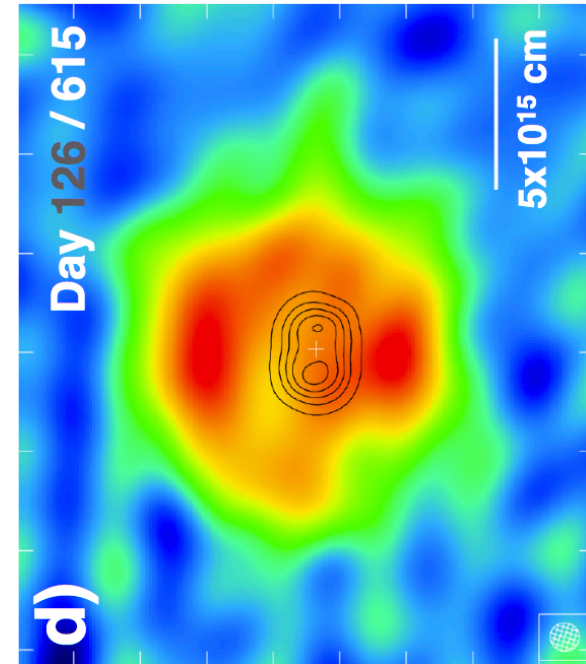
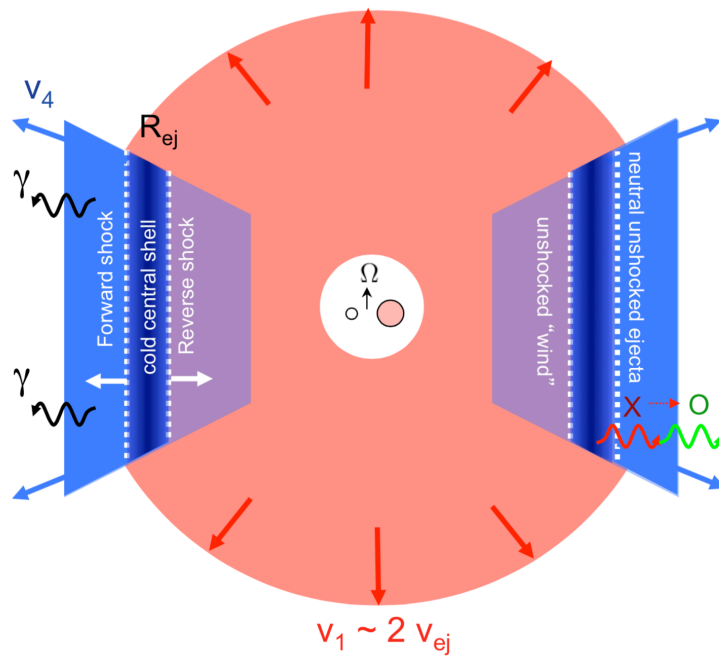


Shocks and Relativistic Particle Acceleration in Novae



Chomiuk et al. 2014

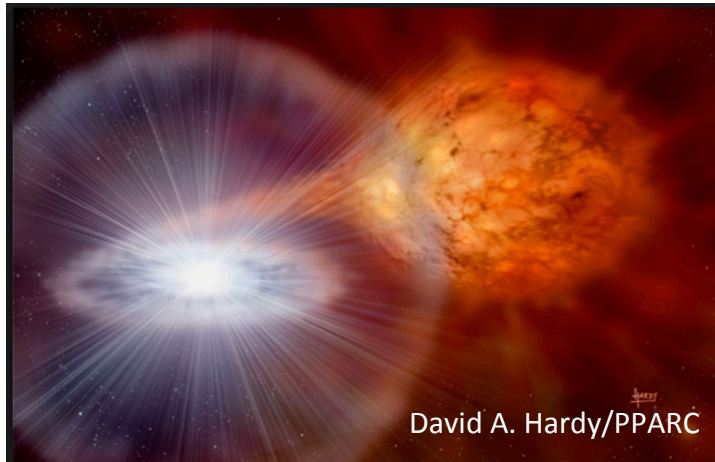
Brian Metzger (Columbia University)

Primary Collaborators

Andrei Beloborodov, Jeno Sokoloski, Jennifer Weston, **Andrey Vlasov**, Indrek Vurm (Columbia)
Laura Chomiuk, Tom Finzell (Michigan State), Damiano Caprioli (Princeton)

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

Classical & Symbiotic Novae

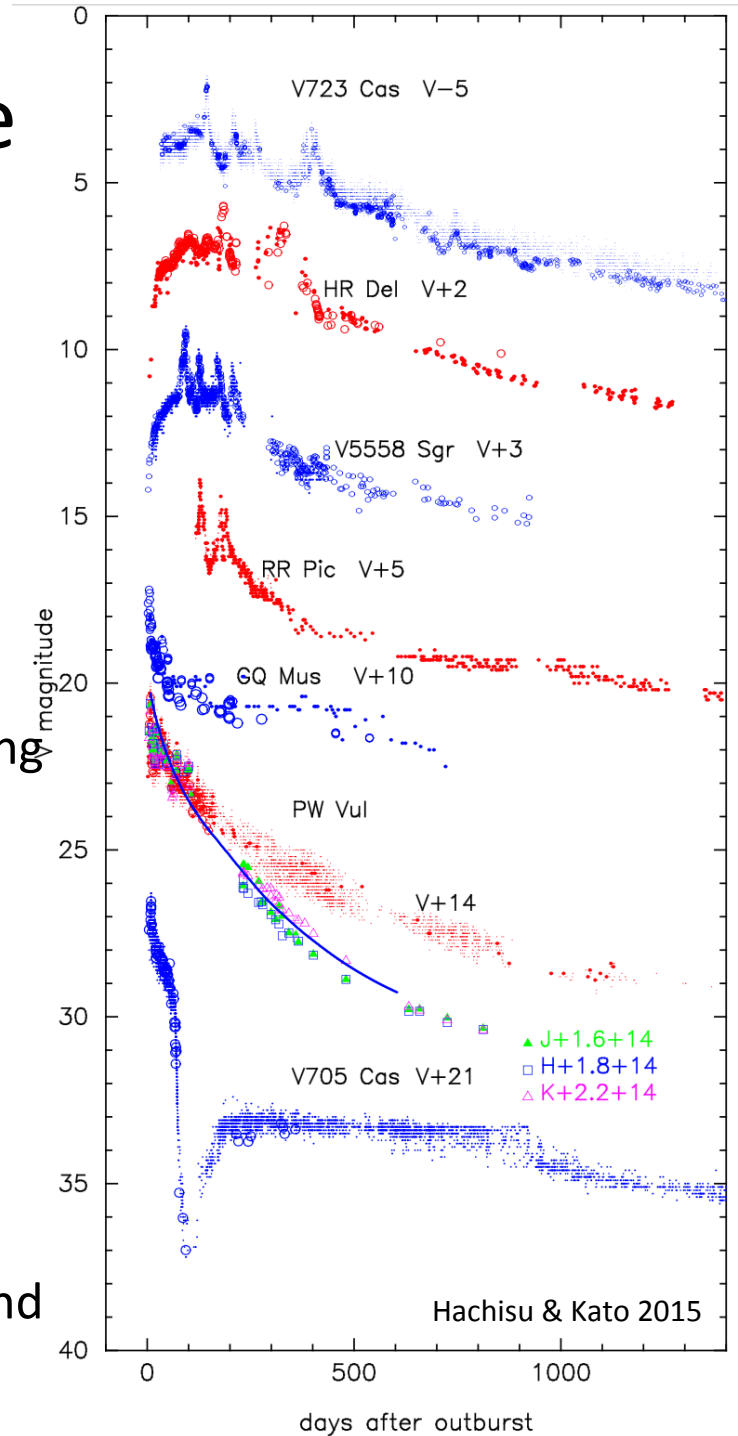


Runaway hydrogen burning on white dwarf accreting from a *main sequence* or *red giant* companion.

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

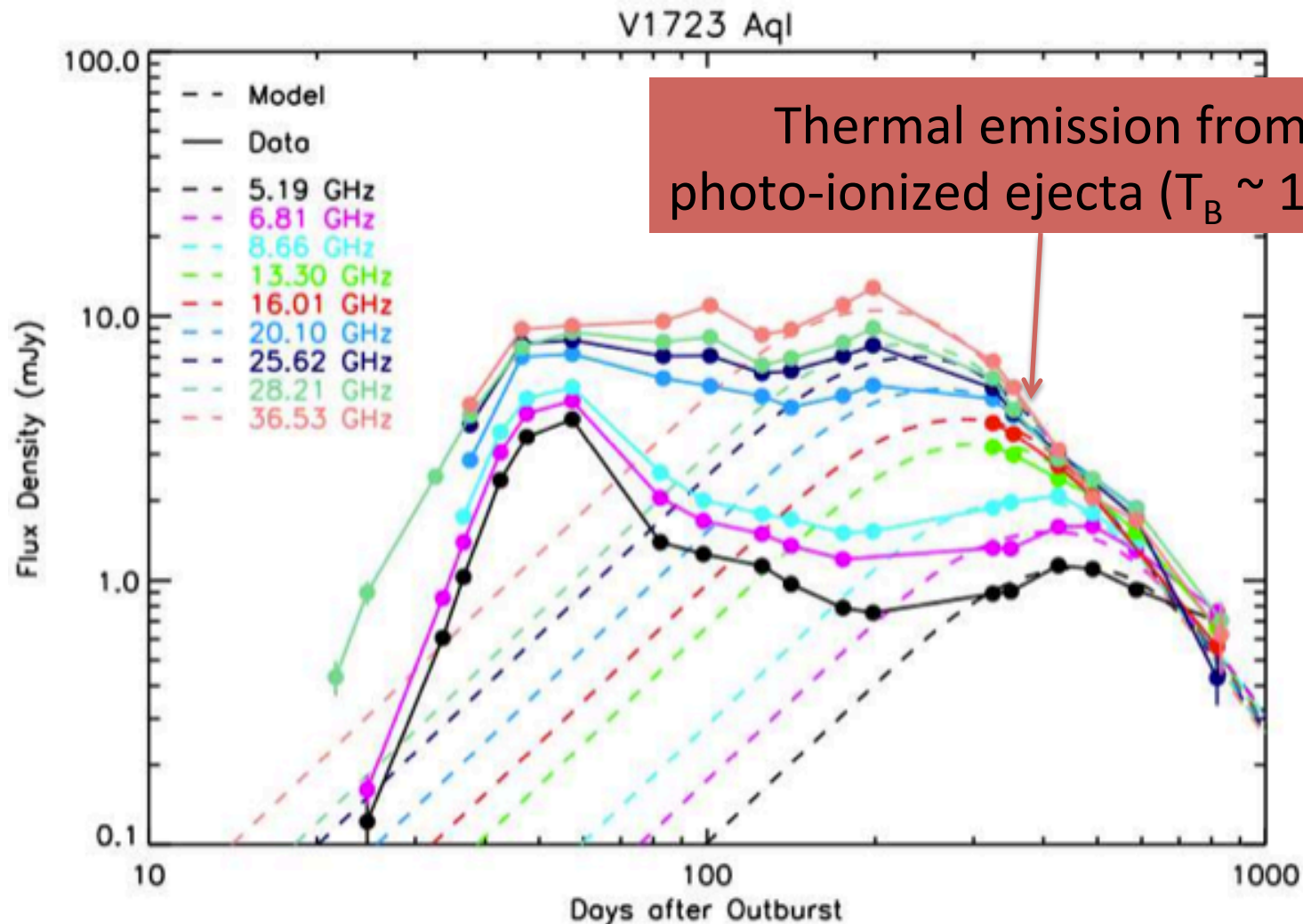
Ejecta velocities of $\sim 300 - 3,000 \text{ km s}^{-1}$ and total mass of $\sim 10^{-5} - 10^{-4} M_{\odot}$.

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



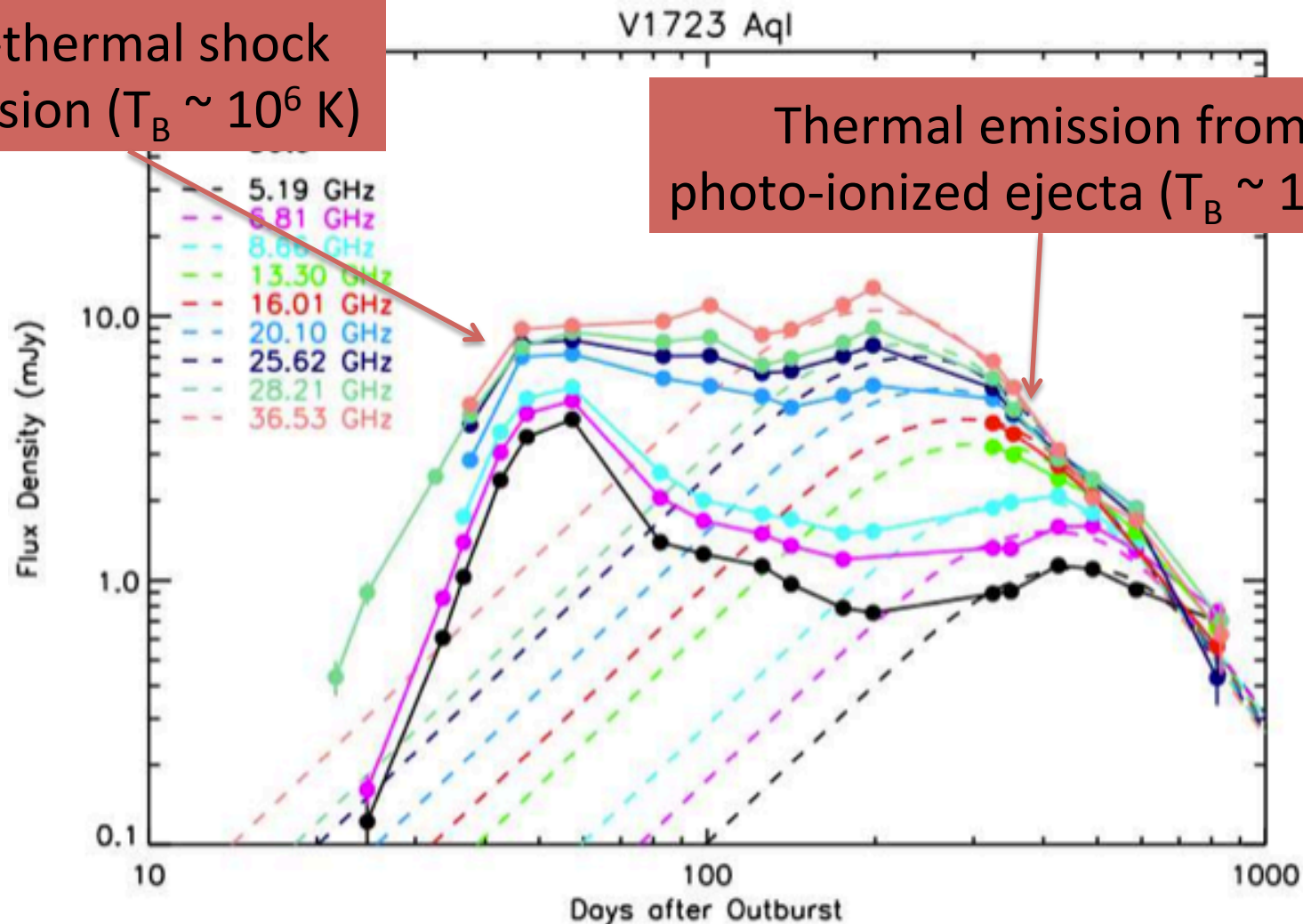
Weston et al. 2013 (see also Taylor et al. 1987, Krauss et al. 2011; Weston et al. 2015)

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)



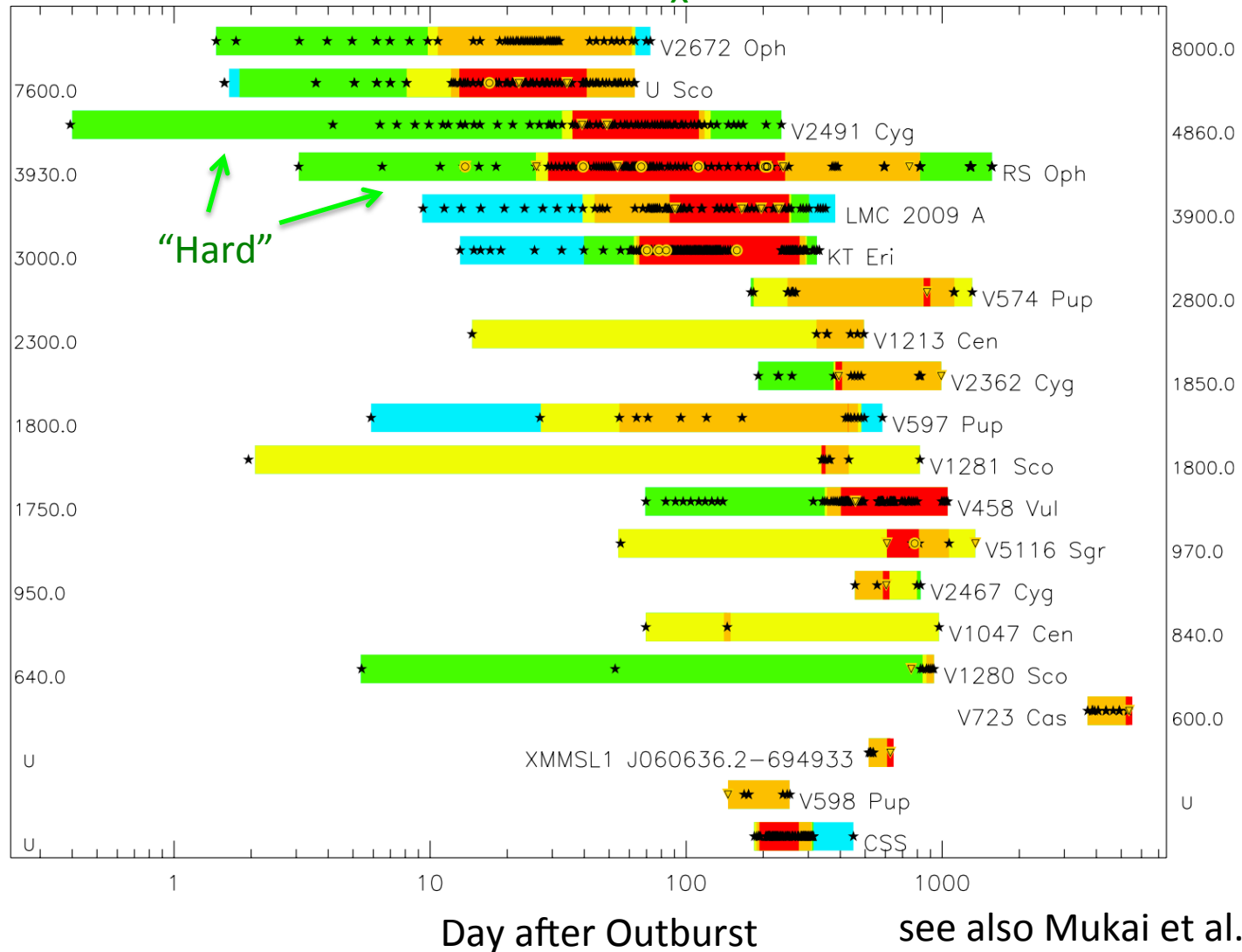
Weston et al. 2013 (see also Taylor et al. 1987, Krauss et al. 2011; Weston et al. 2015)

Evidence for Shocks in Novae:

2. Hard (> keV) Thermal X-rays

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

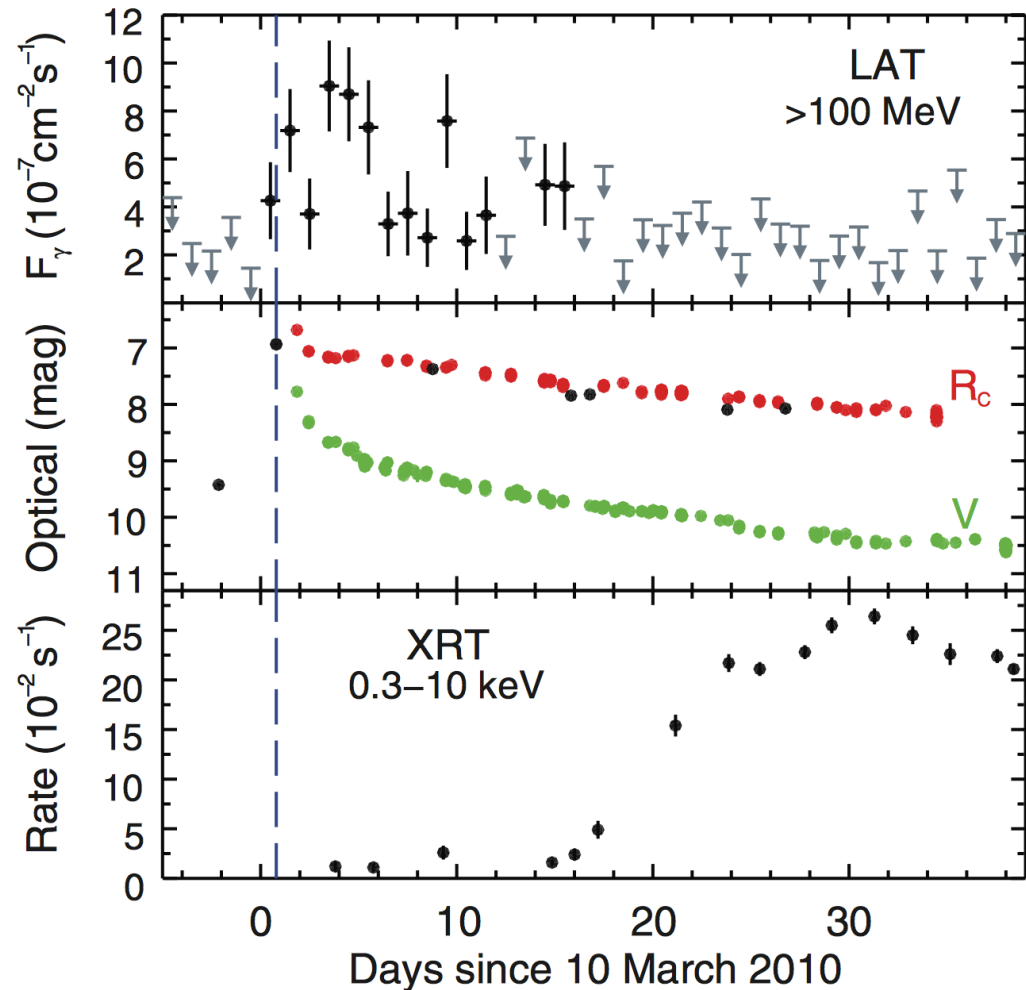
Schwarz et al. 2011



LAT Detects Symbiotic Nova V407 Cyg

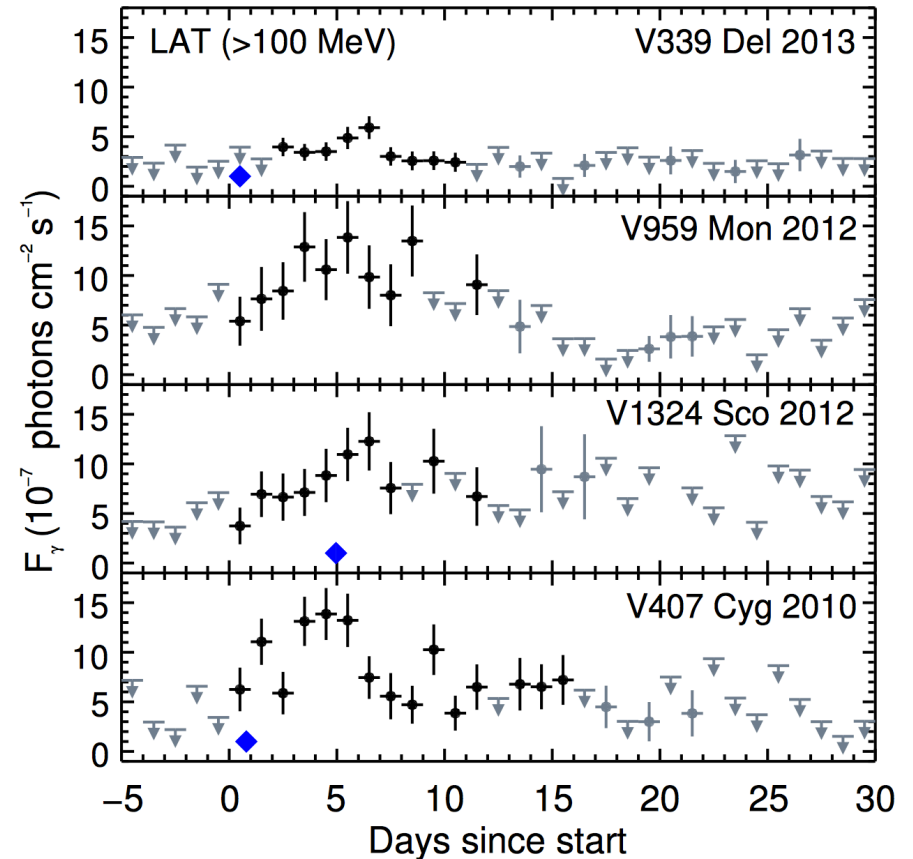
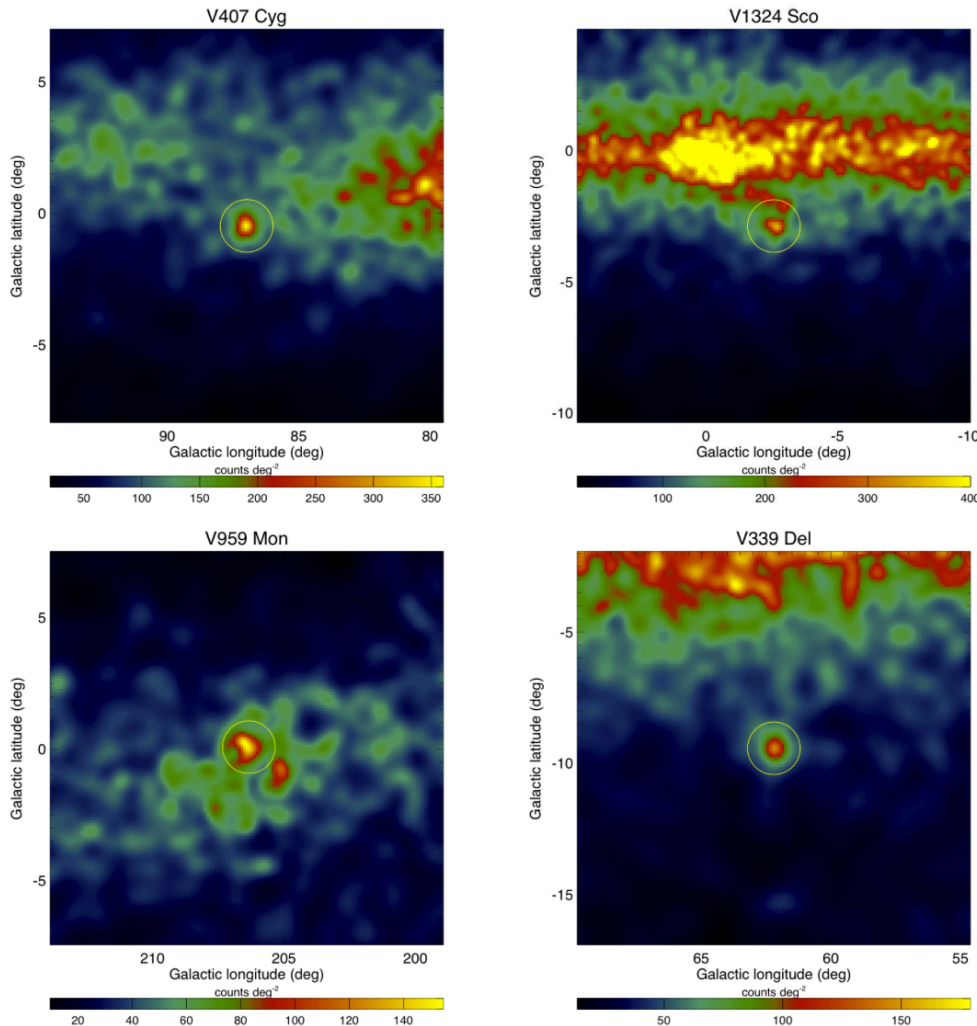
Abdo et al. 2010

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!

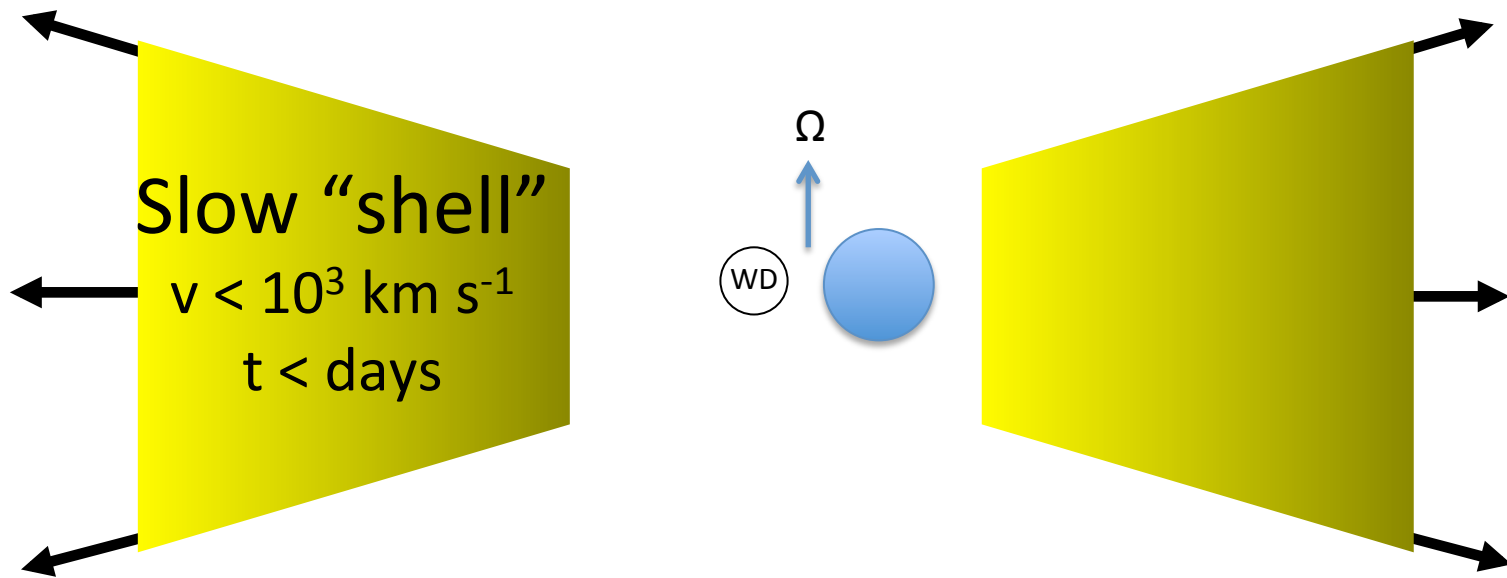


Ackermann et al. 2014

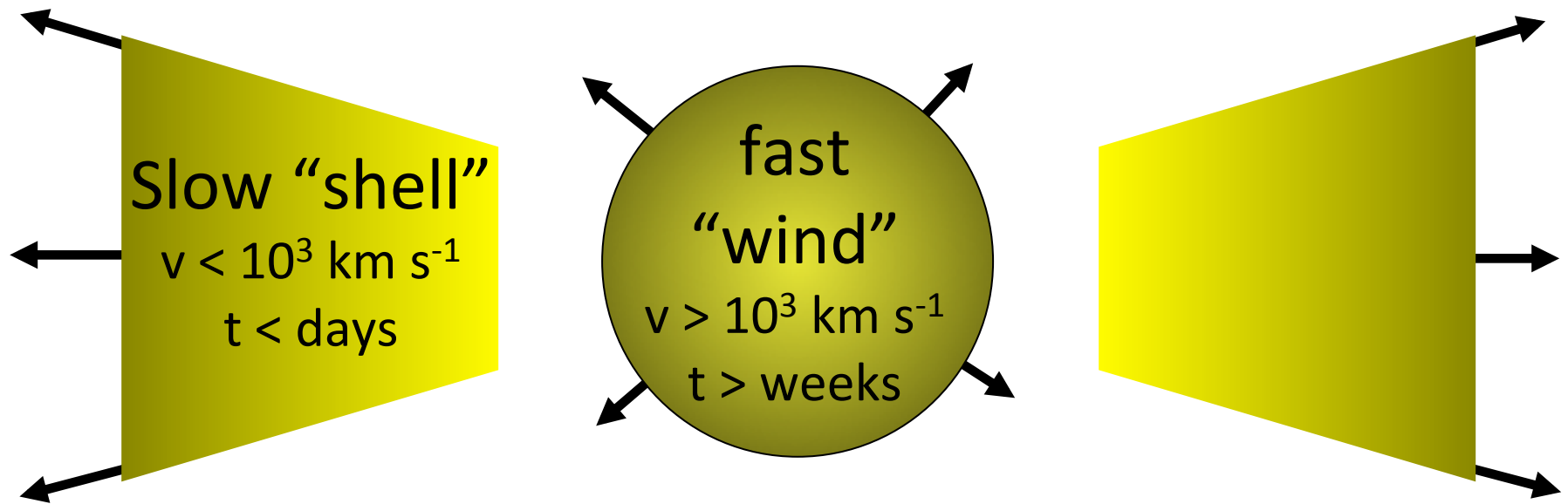
L_γ (0.1-10 GeV) $\sim 10^{35-36}$ erg s^{-1}
Duration \sim weeks (similar to optical)

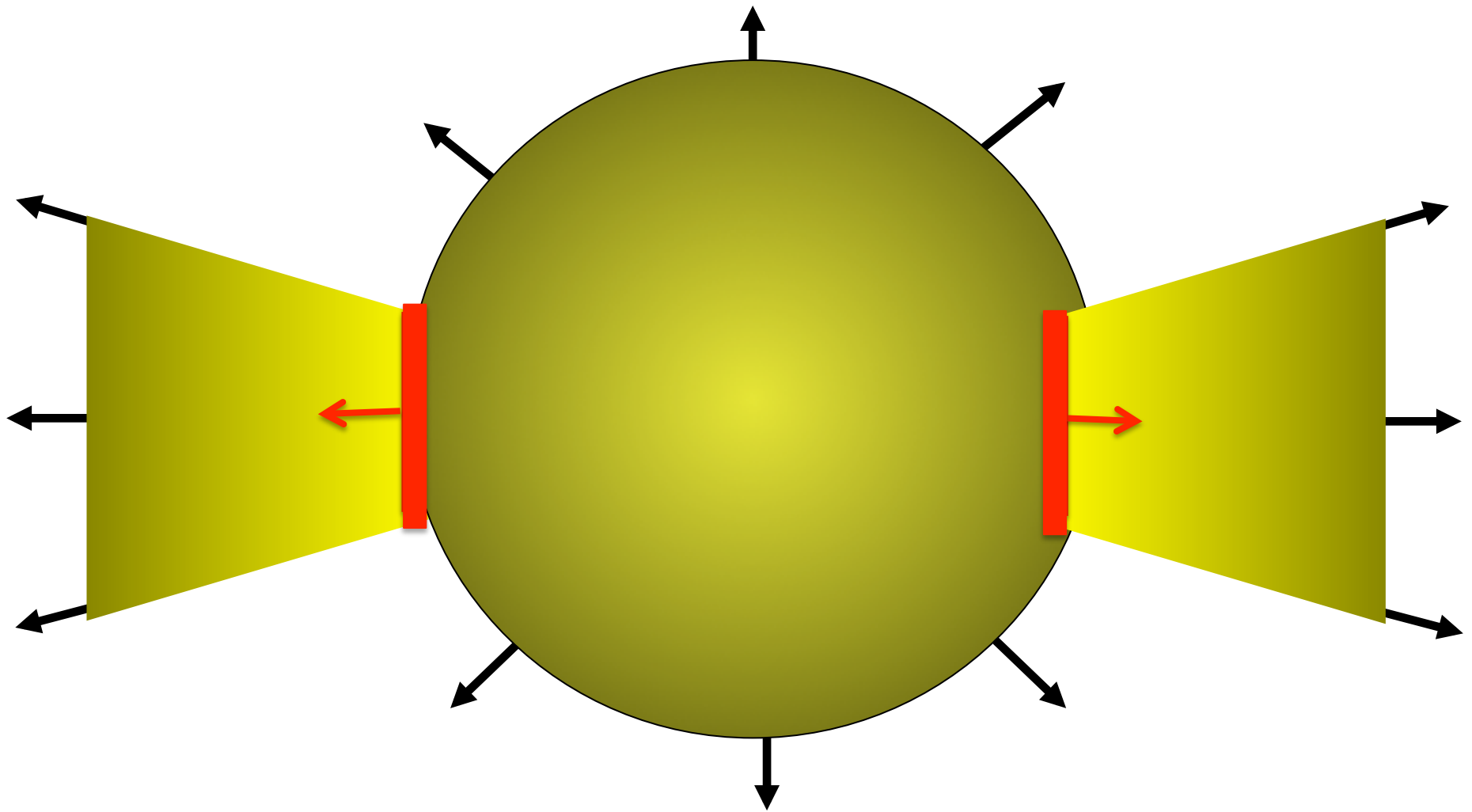
+2-3 more events (unpublished)

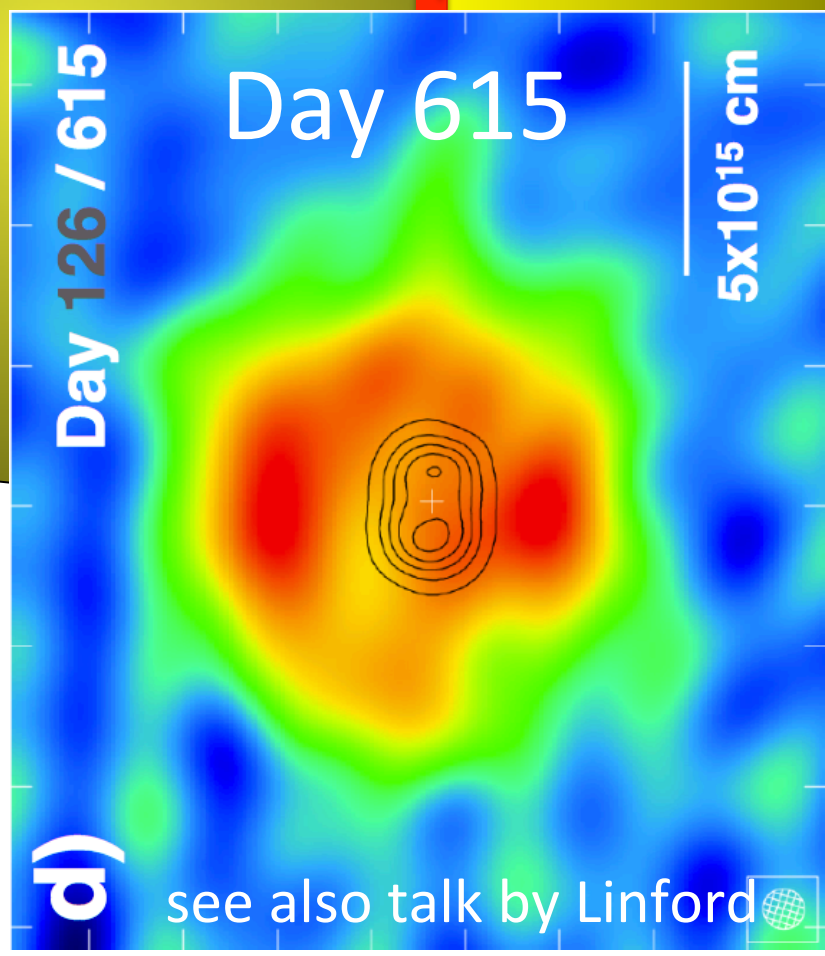
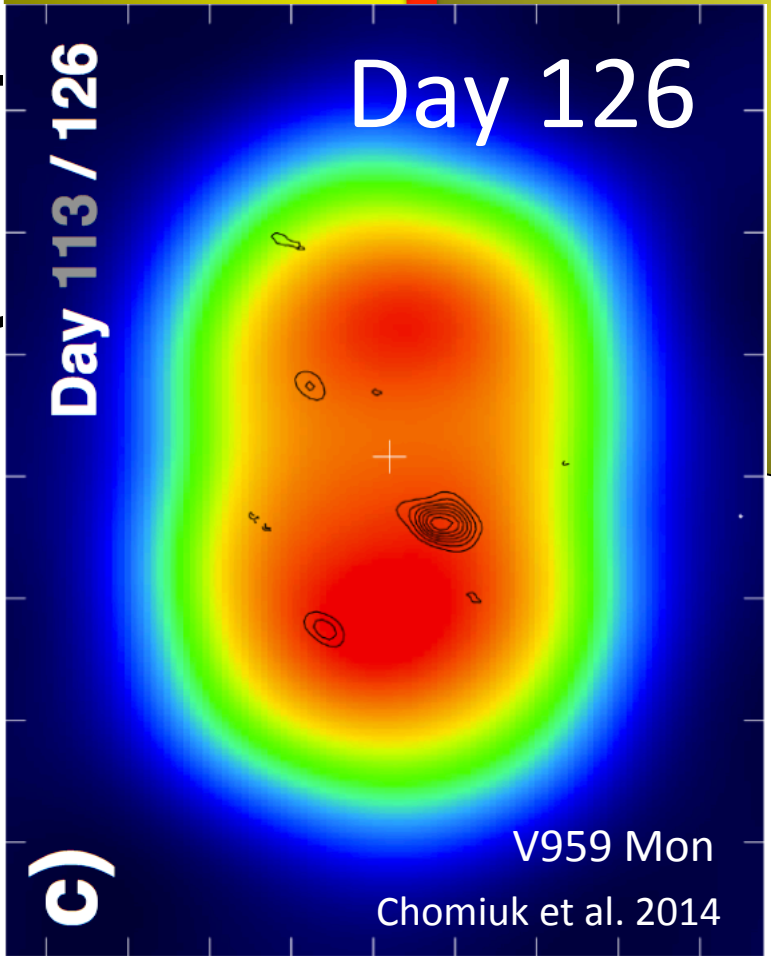
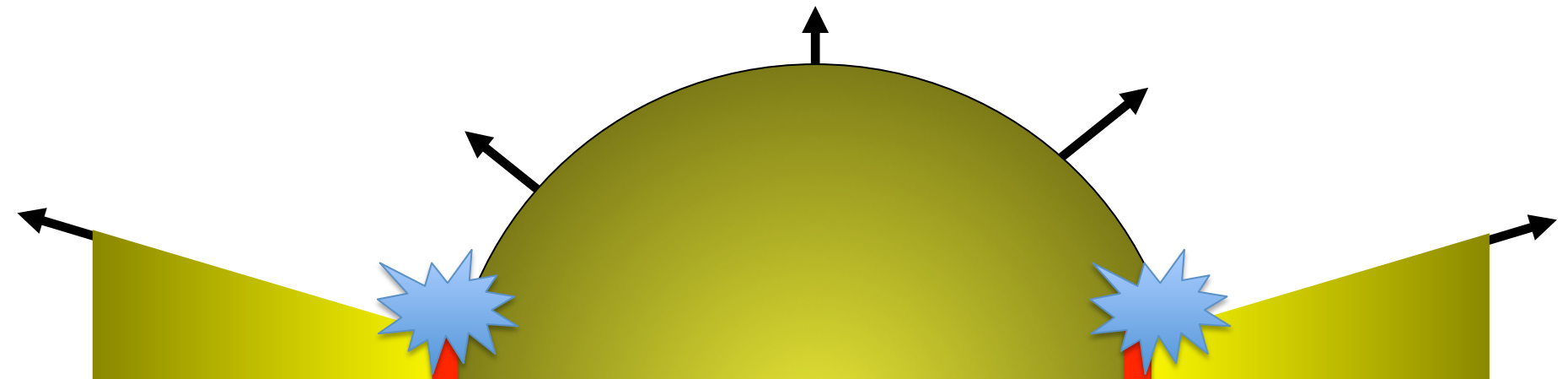
Geometry of Classical Nova Shocks



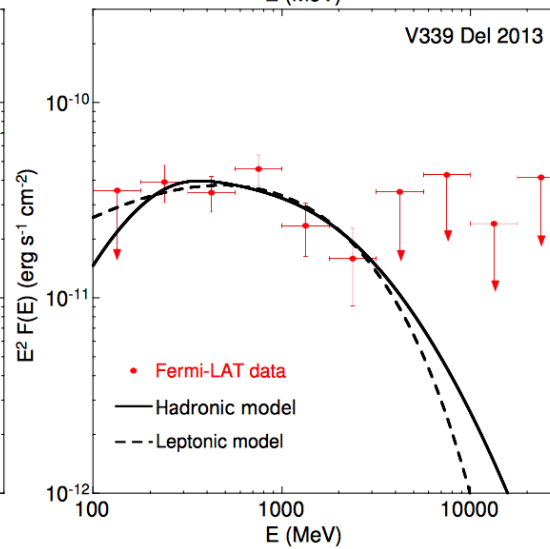
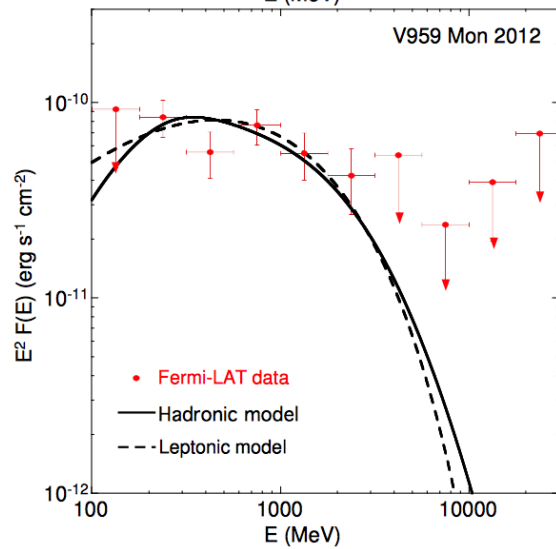
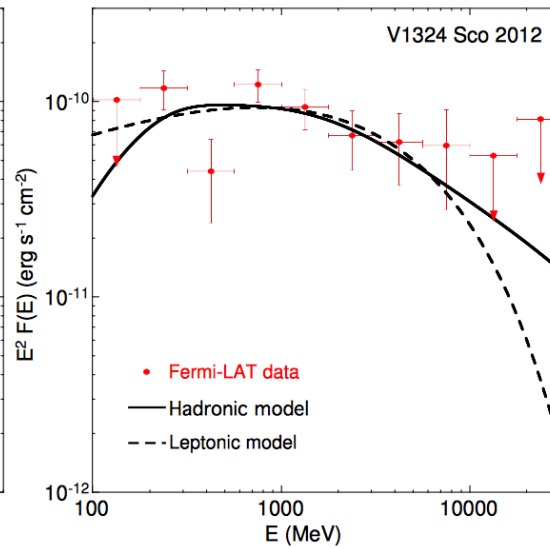
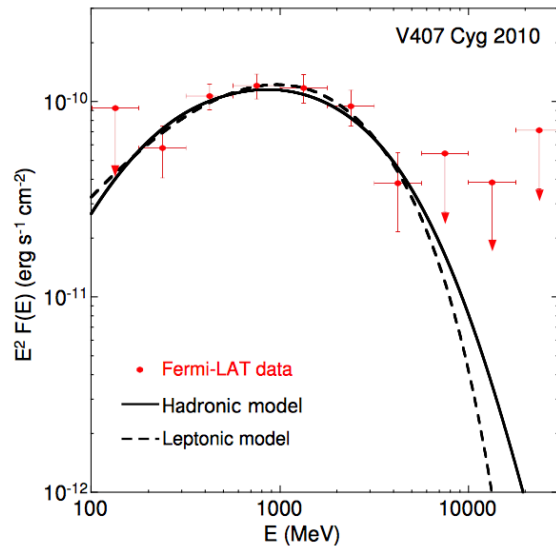
Geometry of Classical Nova Shocks







LAT Spectrum: Hadronic or Leptonic?



Leptonic

$$e^- + \gamma_{opt} \Rightarrow e^- + \gamma'$$

$\gamma_e \sim 10^4$

$$e^- + p \Rightarrow e^- + \gamma'$$

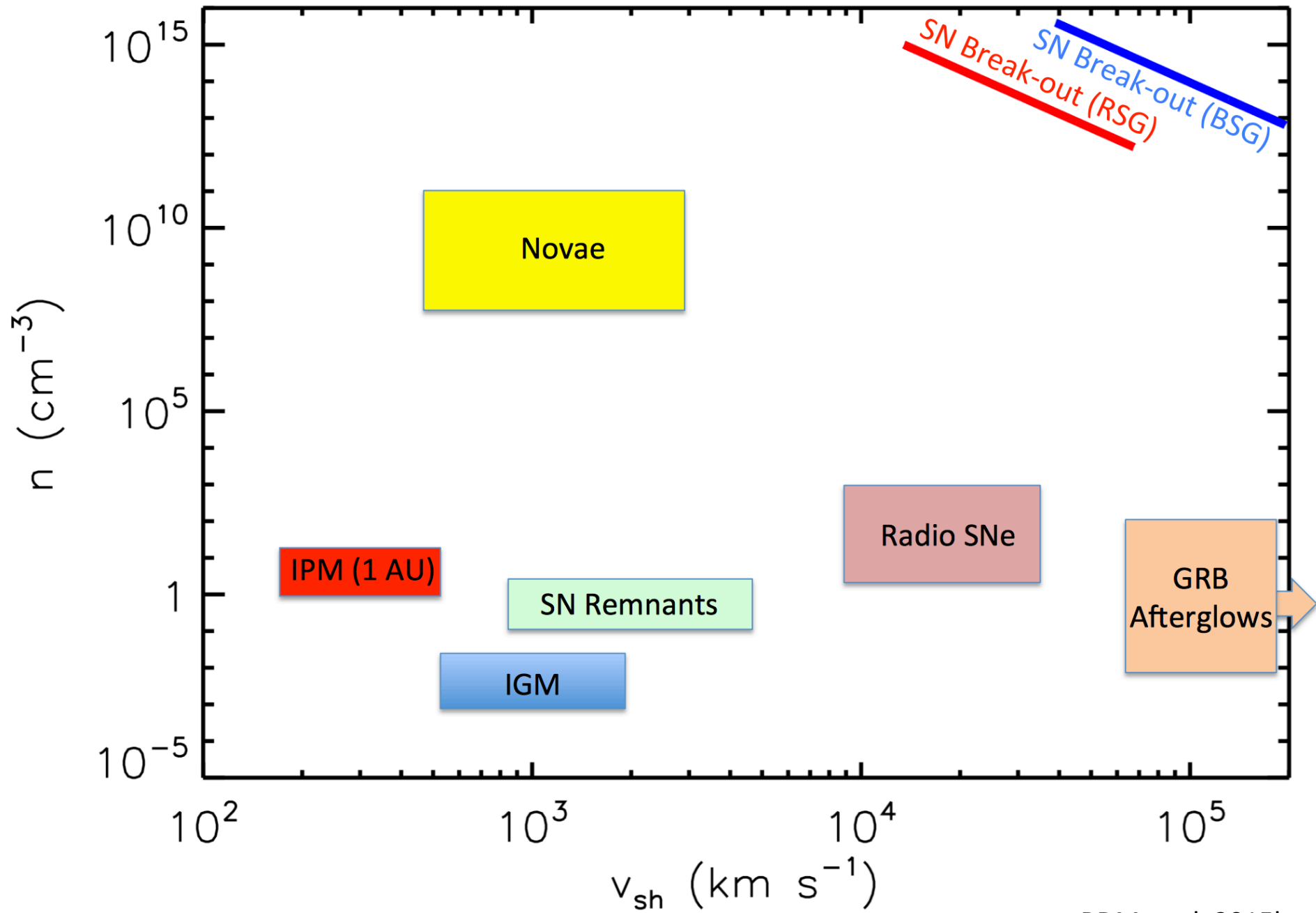
$\gamma_e \sim 10^3$

Hadronic

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

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

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



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

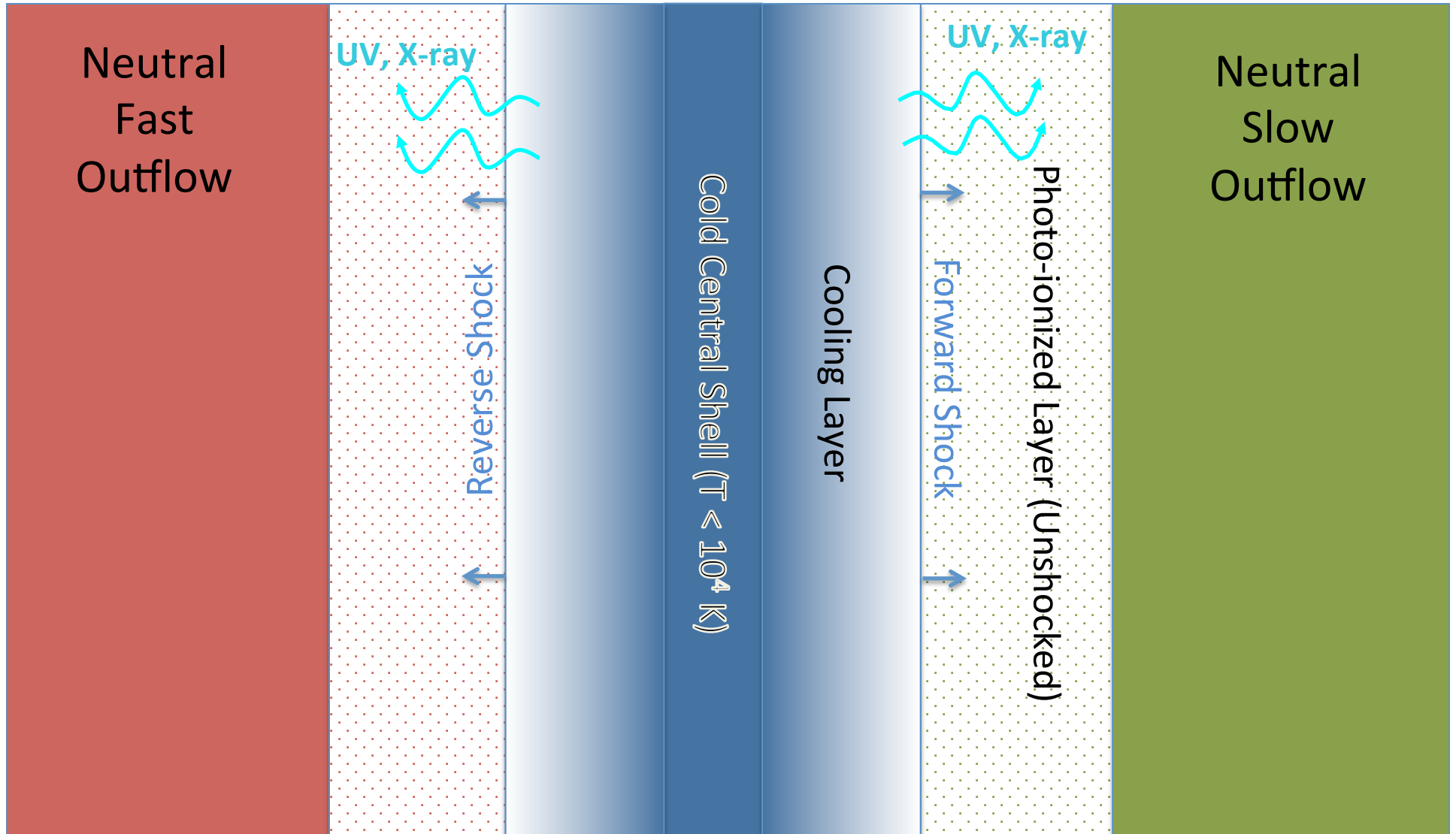
$$\frac{t_{\text{cool}}}{t} \approx \begin{cases} 2.7 \times 10^{-3} \eta v_8^4 M_{-4}^{-1} t_{\text{wk}}^2 & \text{FS} \\ 0.13 v_8^4 \dot{M}_{-5}^{-1} t_{\text{wk}} & \text{RS} \end{cases} \ll 1$$

→ most kinetic power dissipated by shock emerges as radiation

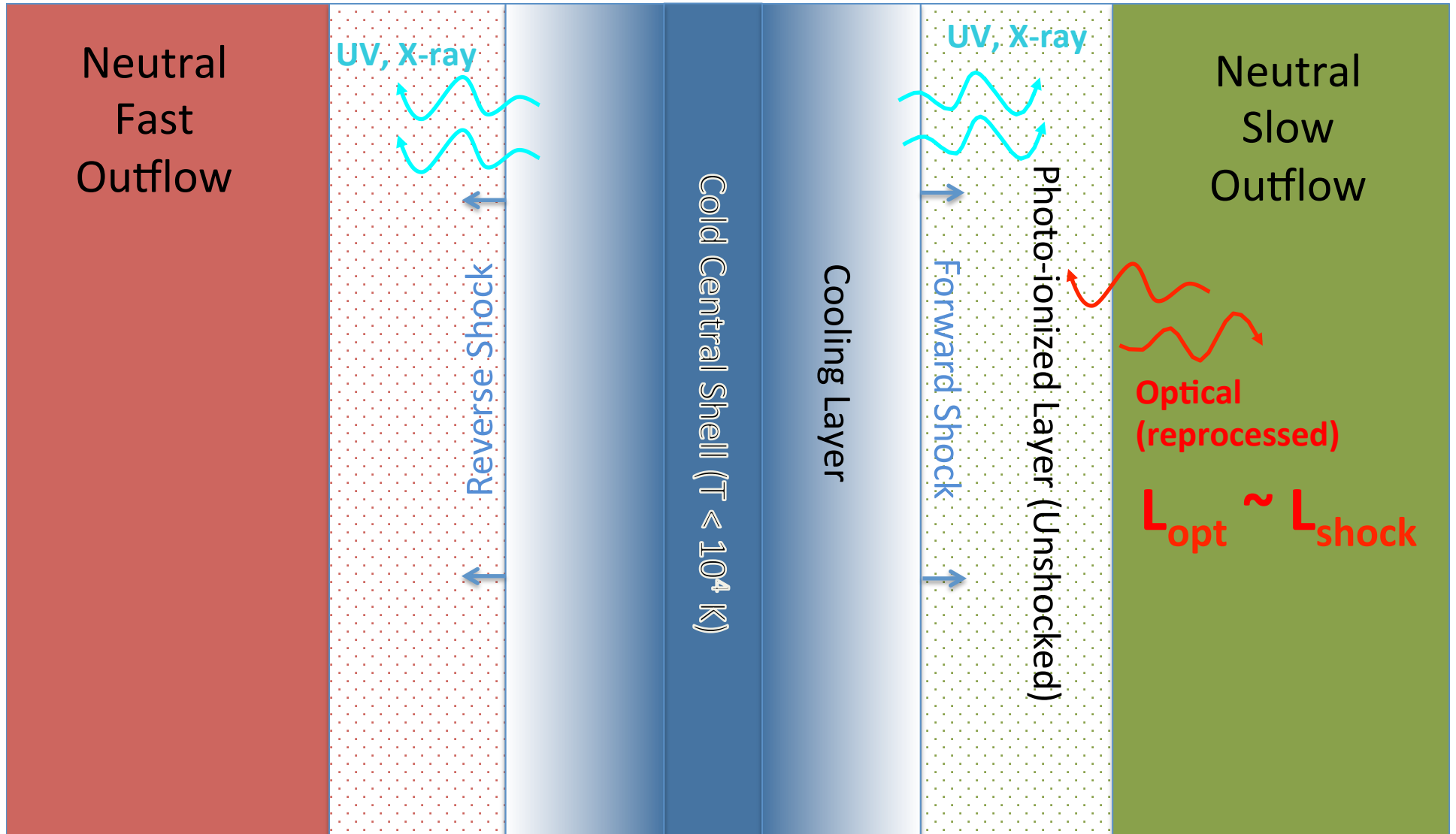
3. opaque to soft X-rays (bound-free) & radio (free-free)

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

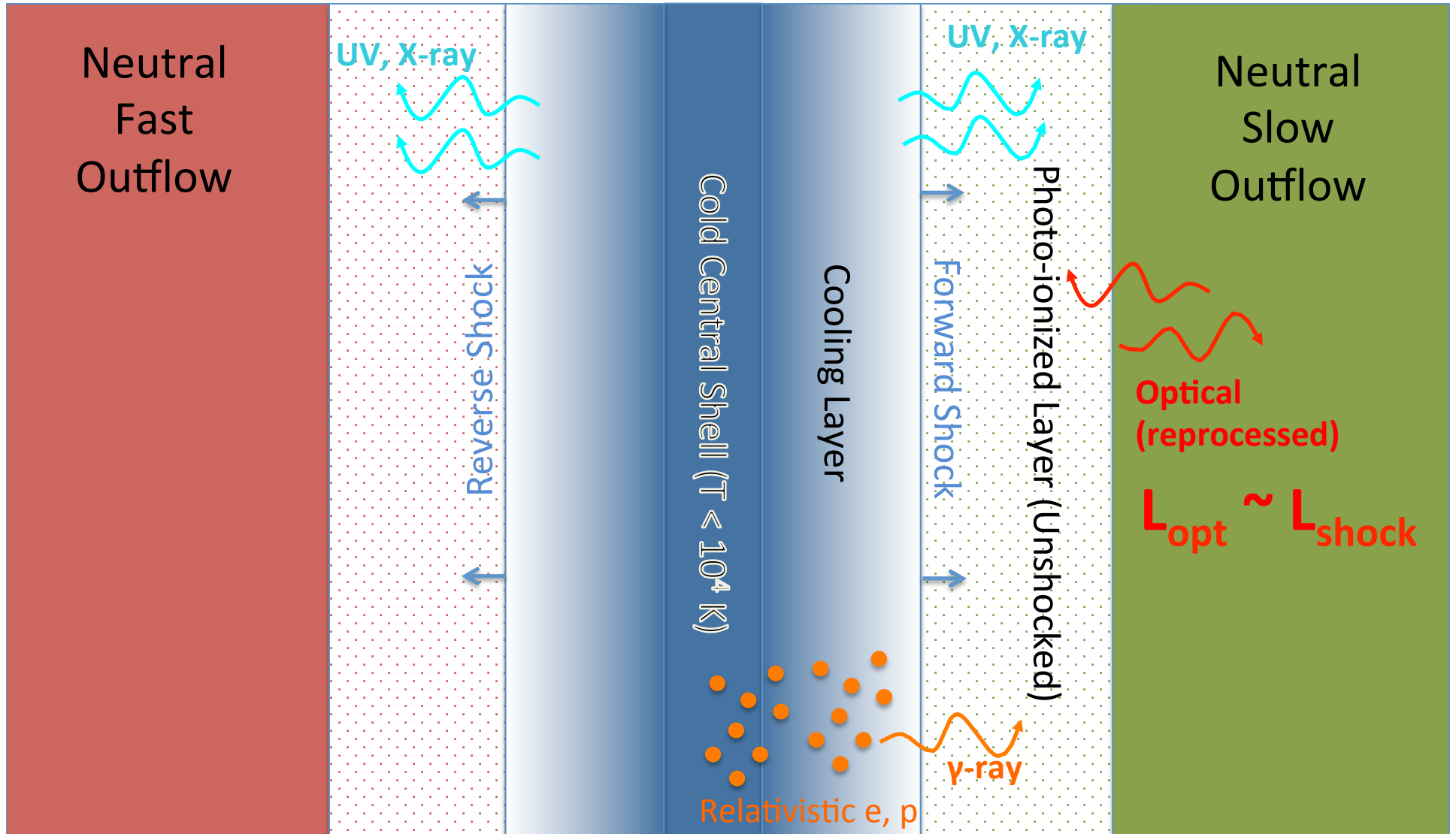
Anatomy of a Nova Shock



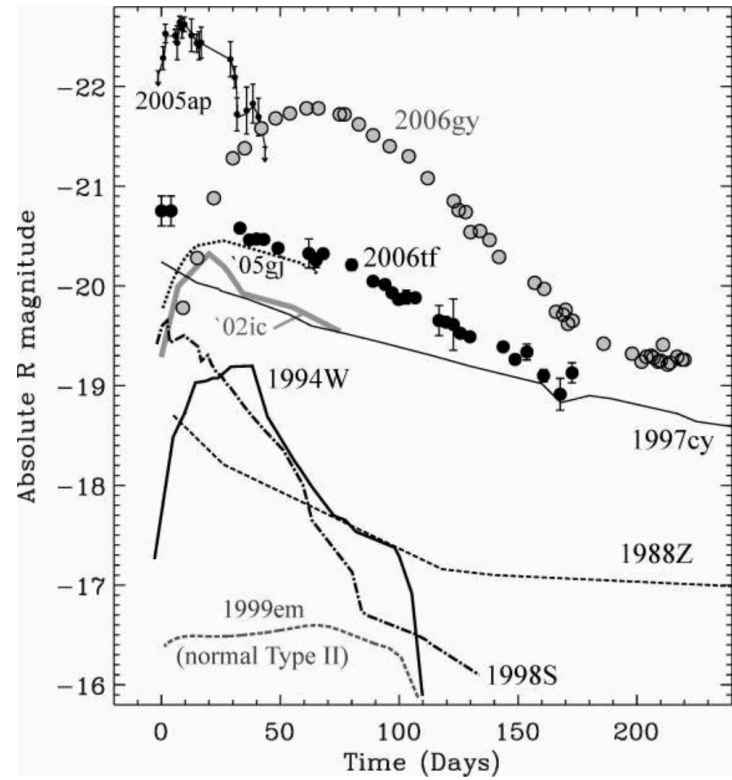
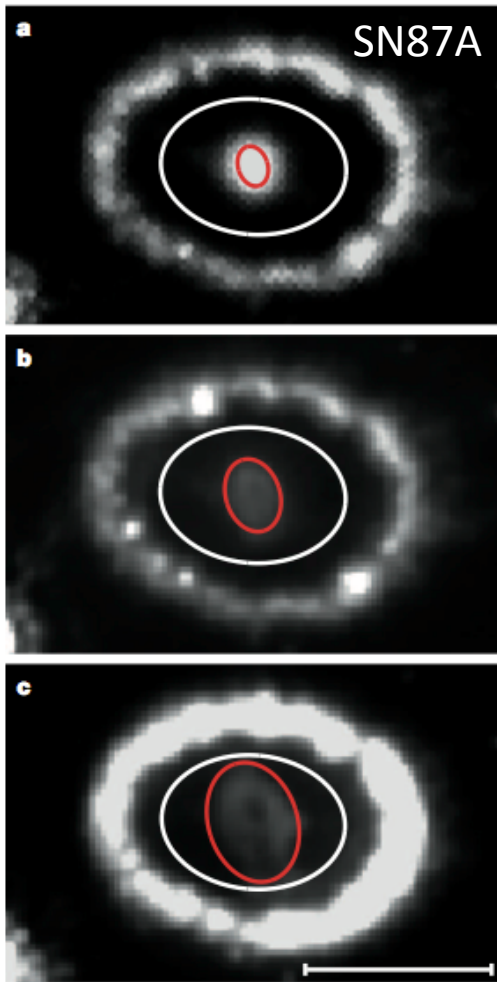
Anatomy of a Nova Shock



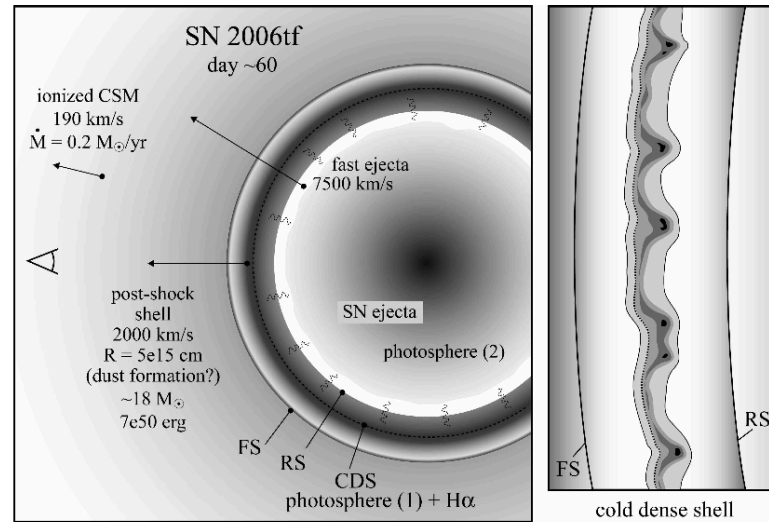
Anatomy of a Nova Shock



Interaction Powered Type II_n Supernovae



SN 2006tf Gets the Bronze



Smith et al. 2008

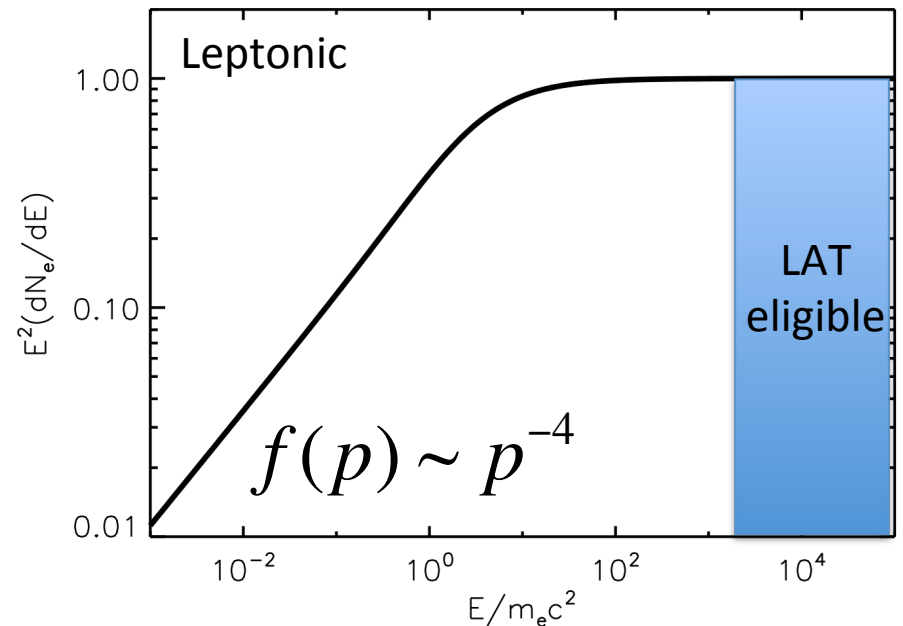
As Probes of Particle Acceleration

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

Leptons & hadrons are fast cooling

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

$$\epsilon_\gamma < 0.1-0.3$$

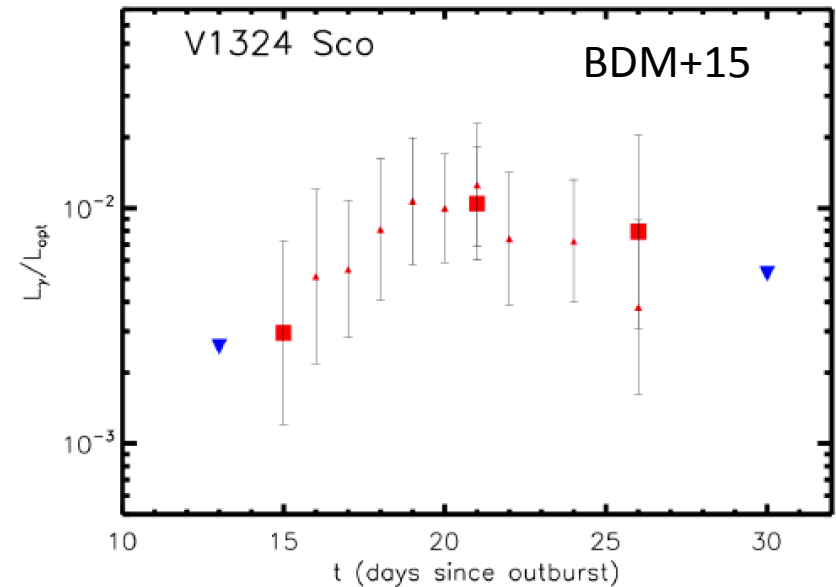
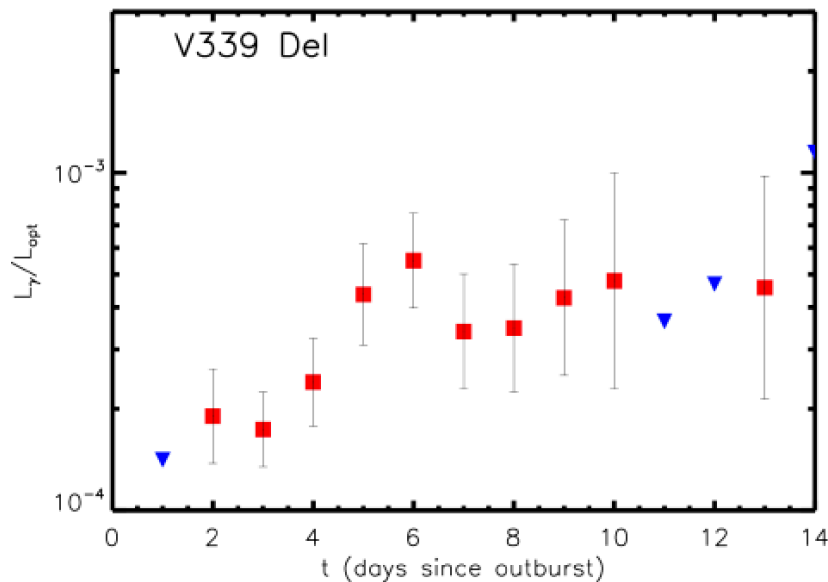


Don't overproduce optical emission:

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

measured

Non-Thermal Acceleration Efficiency



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

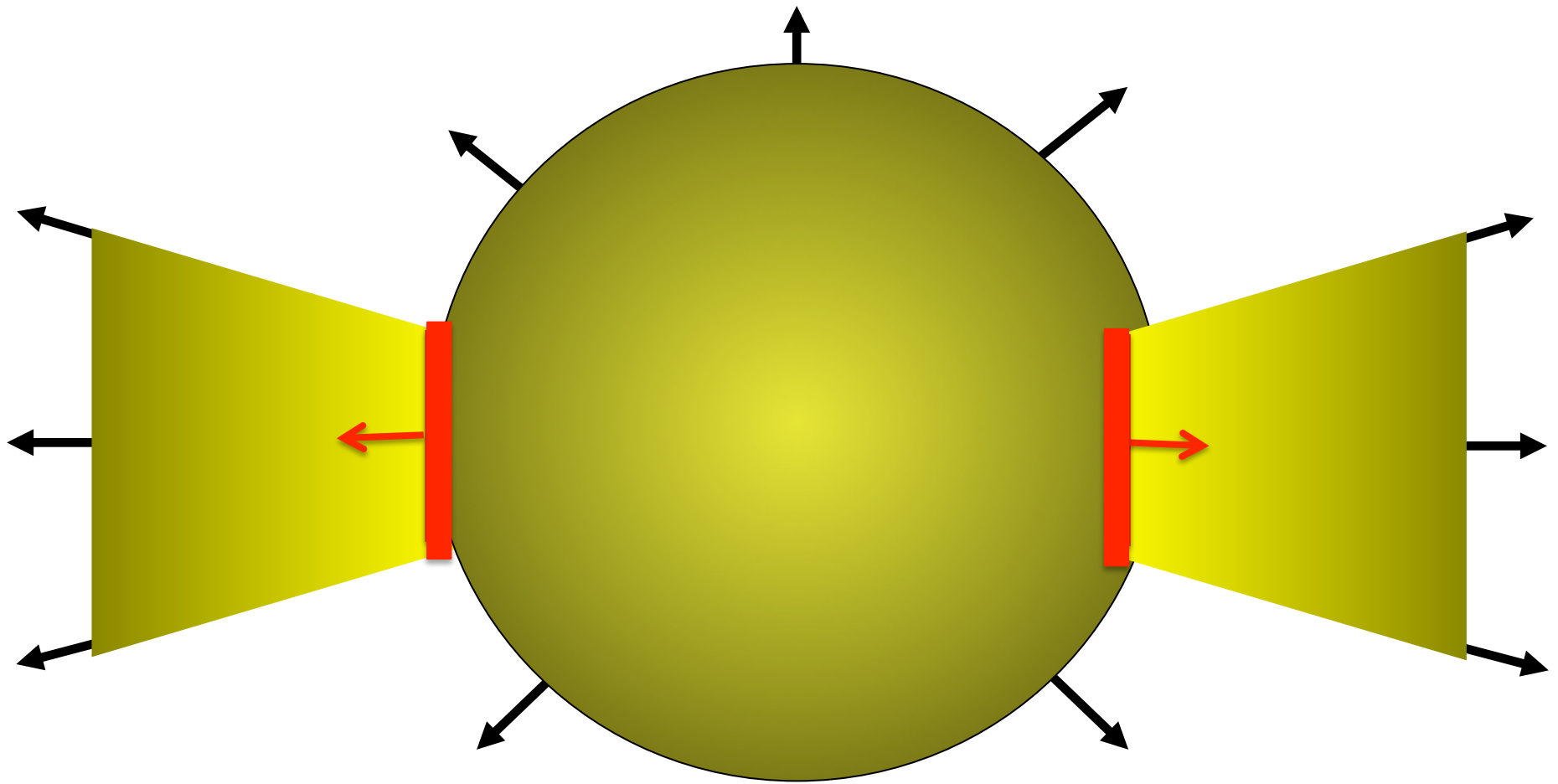
$$\epsilon_{\text{nth}} > 10^{-3} - 10^{-2}$$

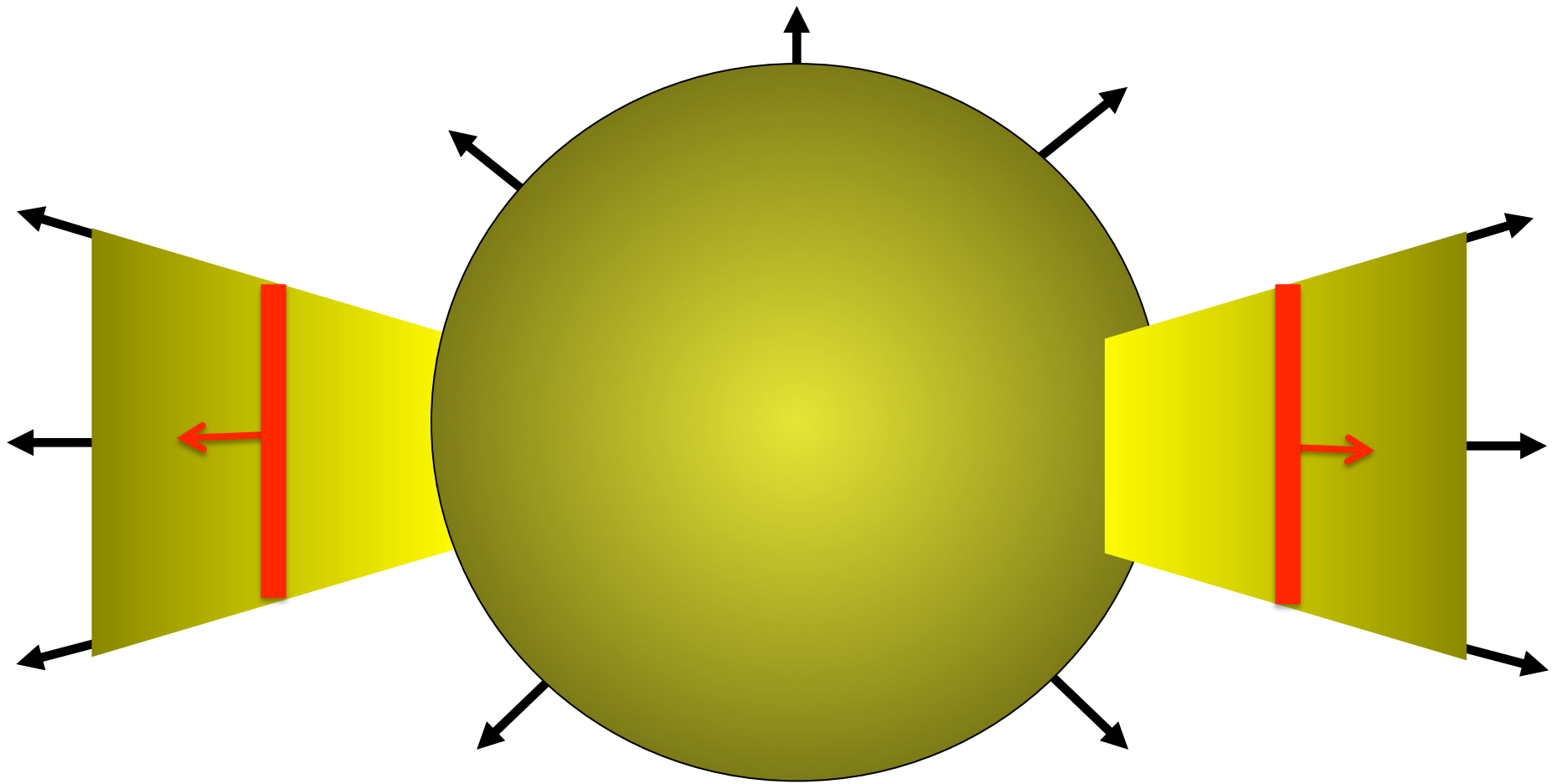
Hadronic Scenario:

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

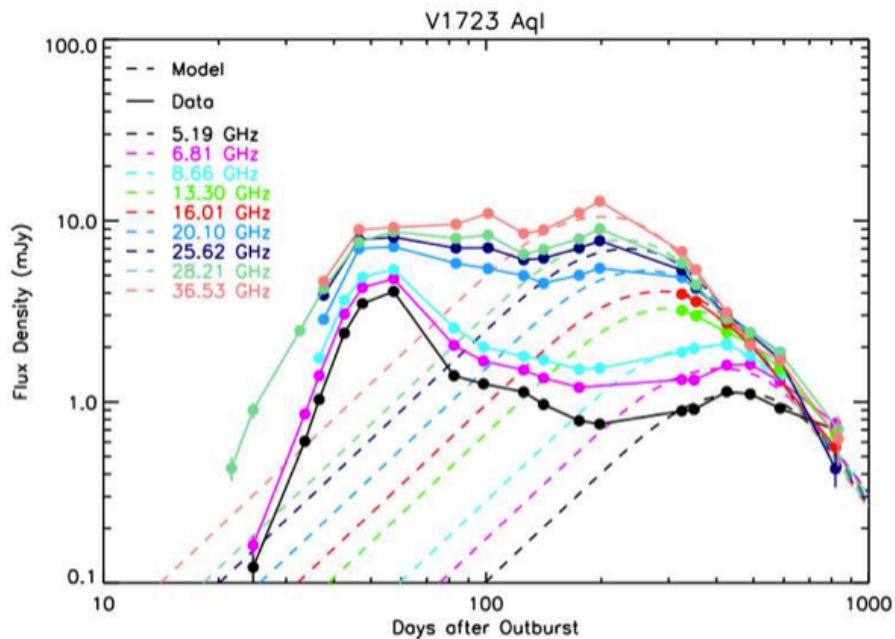
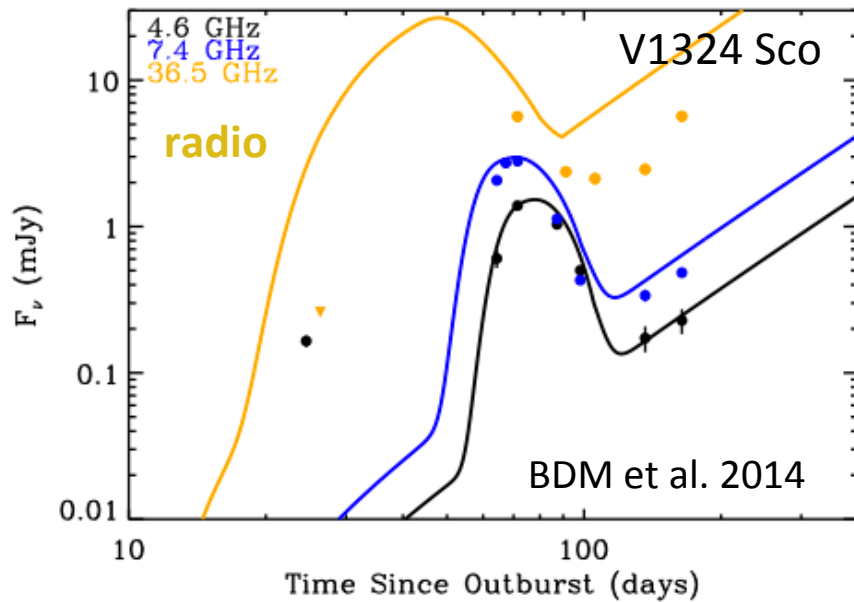
Leptonic Scenario:

$\epsilon_{\text{nth}} < 10^{-3}$ from observations & hybrid PIC (e.g. Kato 14, Park et al. 2014)

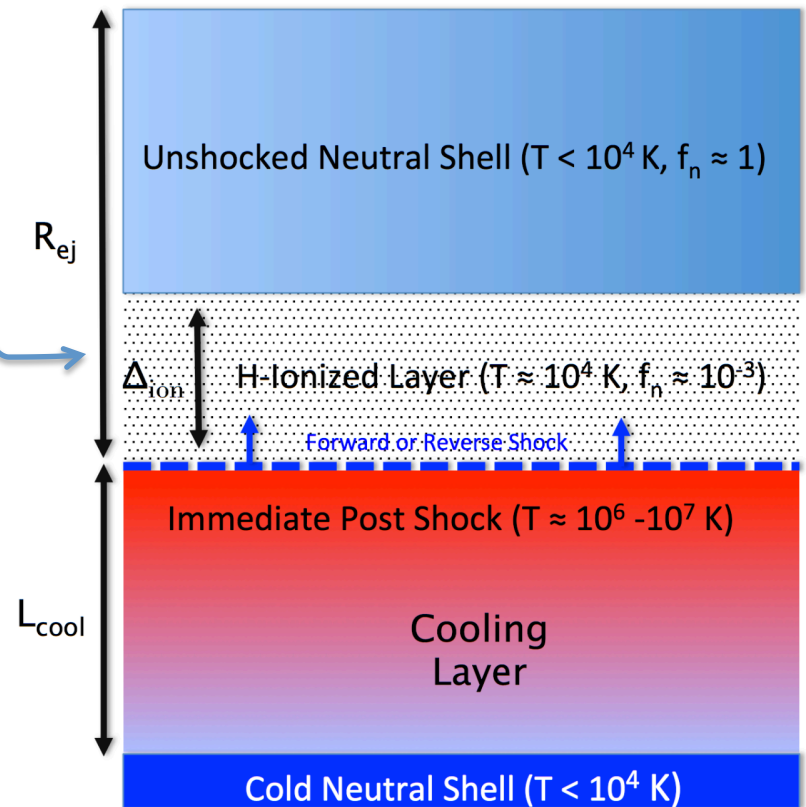




Non-Thermal Radio Emission



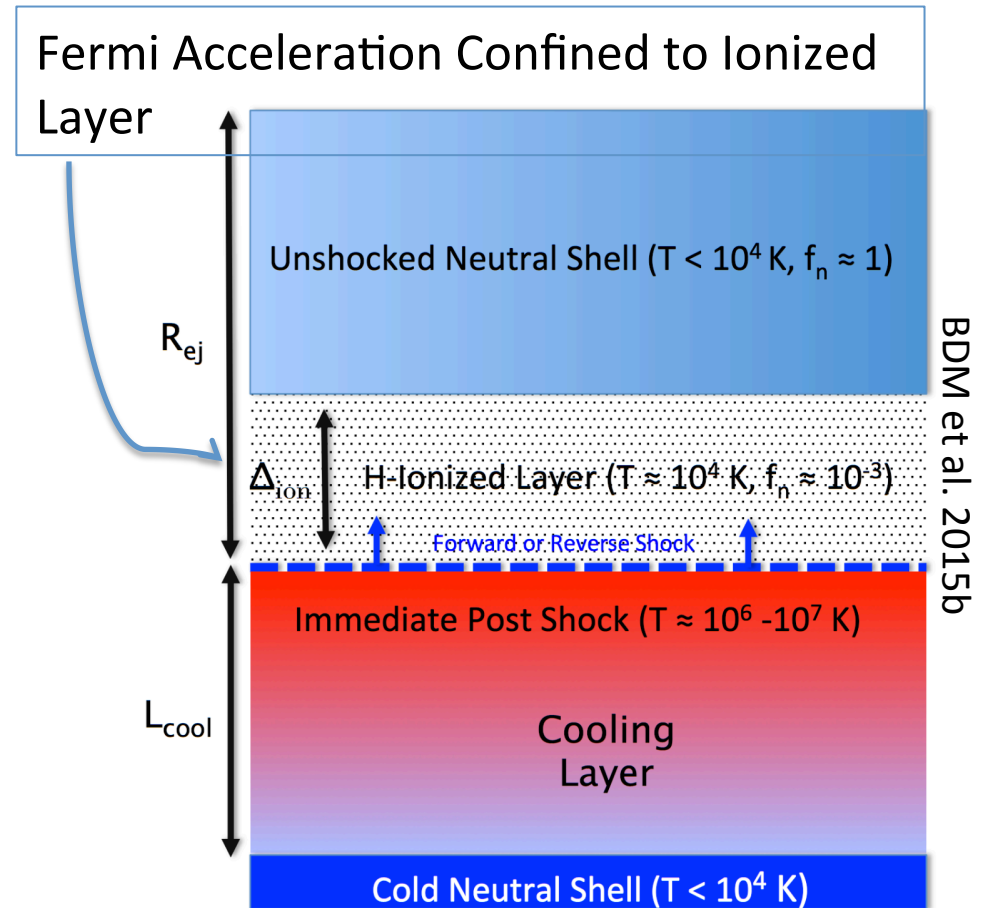
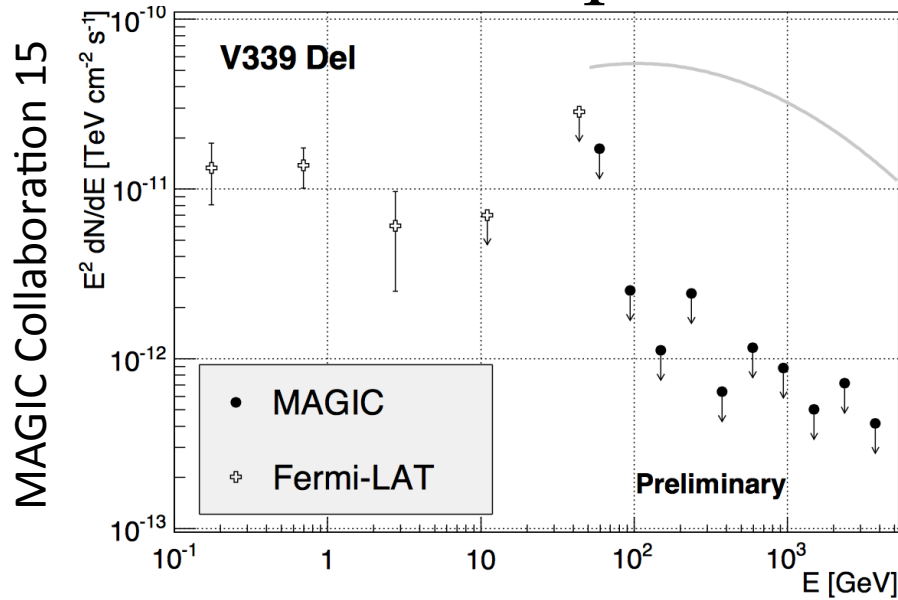
Rise delayed by free-free absorption



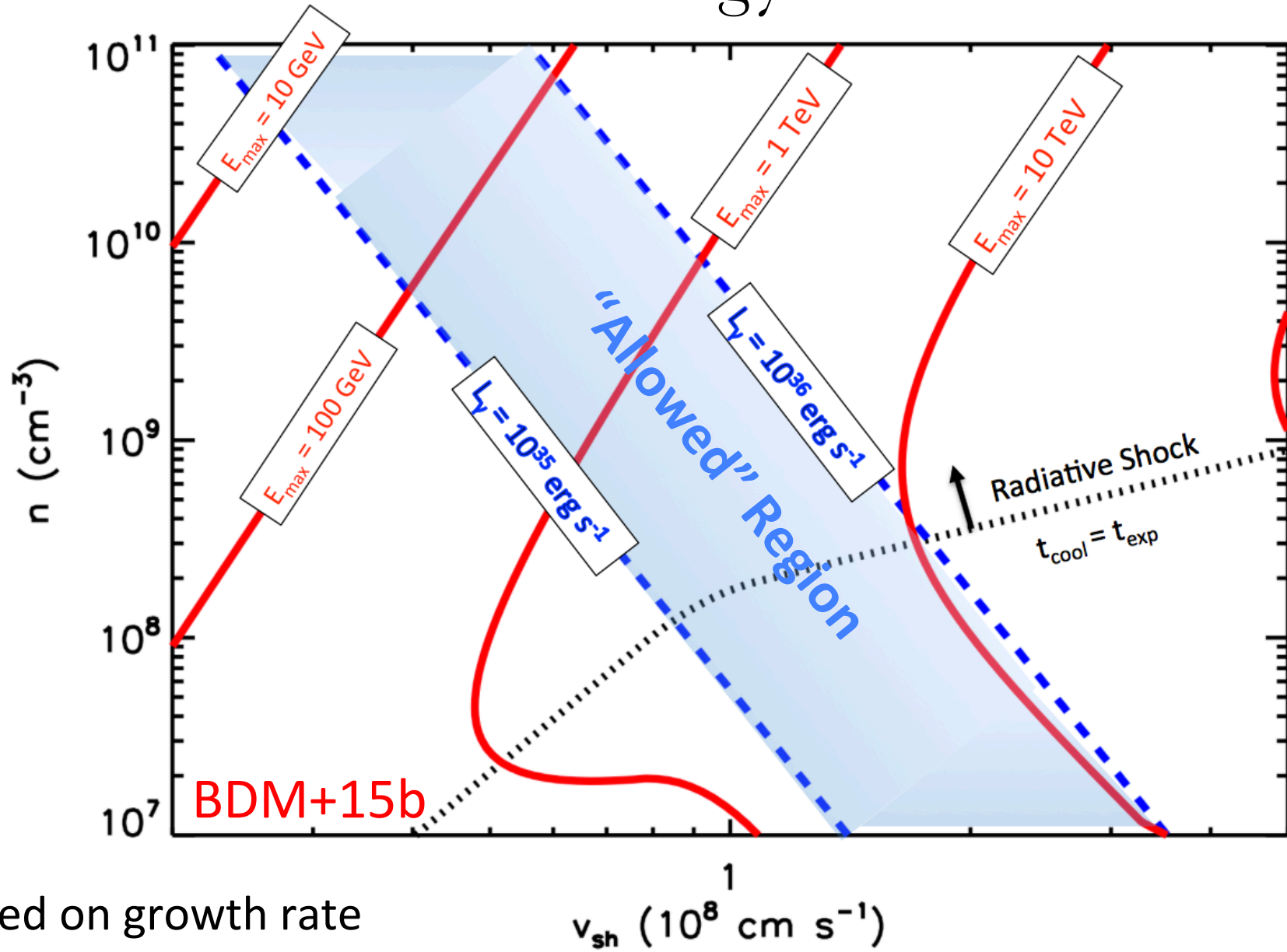
BDM et al. 2015b

Peak brightness temperature constrains ϵ_{nth} of relativistic electrons (see Vlasov Poster).

Prospects for TeV Emission



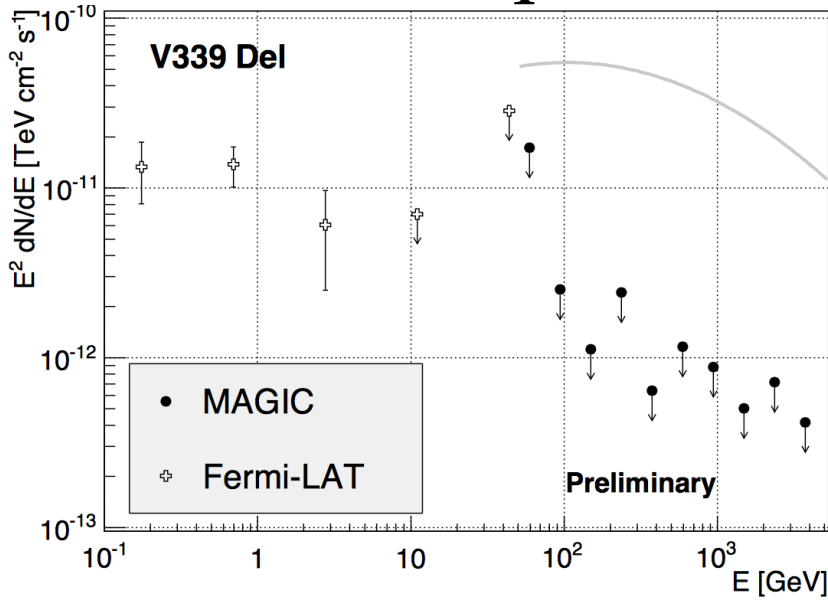
Maximum Particle Energy in Nova Shocks



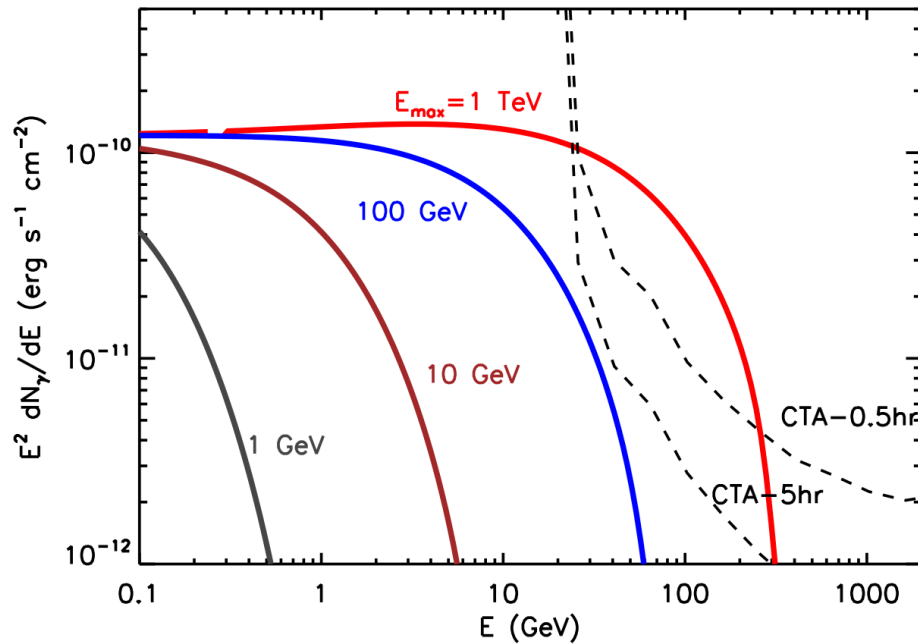
Based on growth rate analysis of Bell (2004) instability

Prospects for TeV Emission

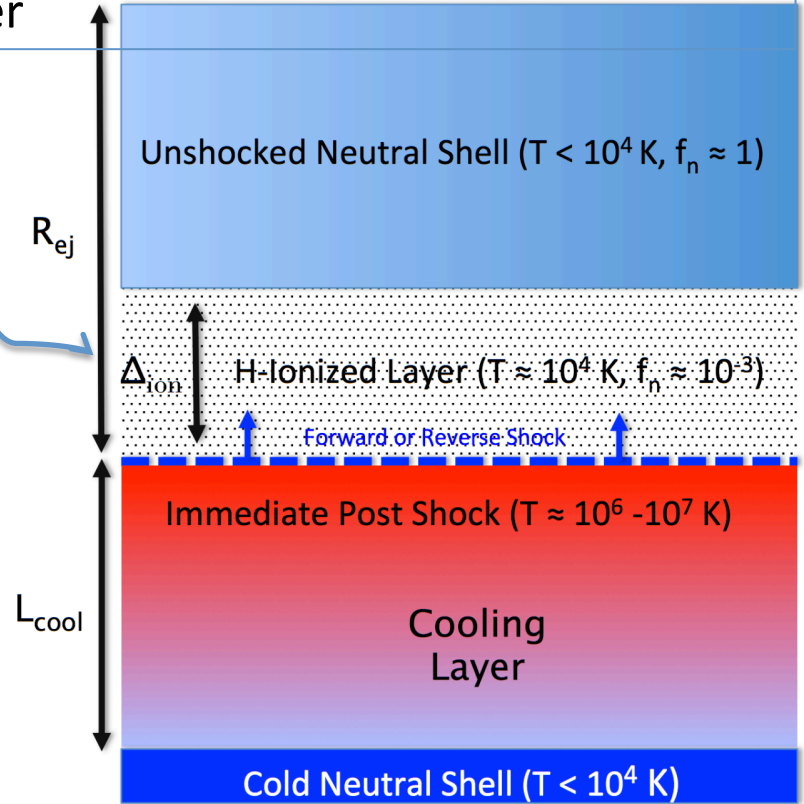
MAGIC Collaboration 15



Metzger+15b



Fermi Acceleration Confined to Ionized Layer



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 II In SNe.
- Measured ratio of γ -ray to optical luminosities places lower limit on acceleration efficiency of non-thermal particles, ϵ_{nth} . High measured values $\epsilon_{\text{nth}} > 10^{-2}$ - 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.