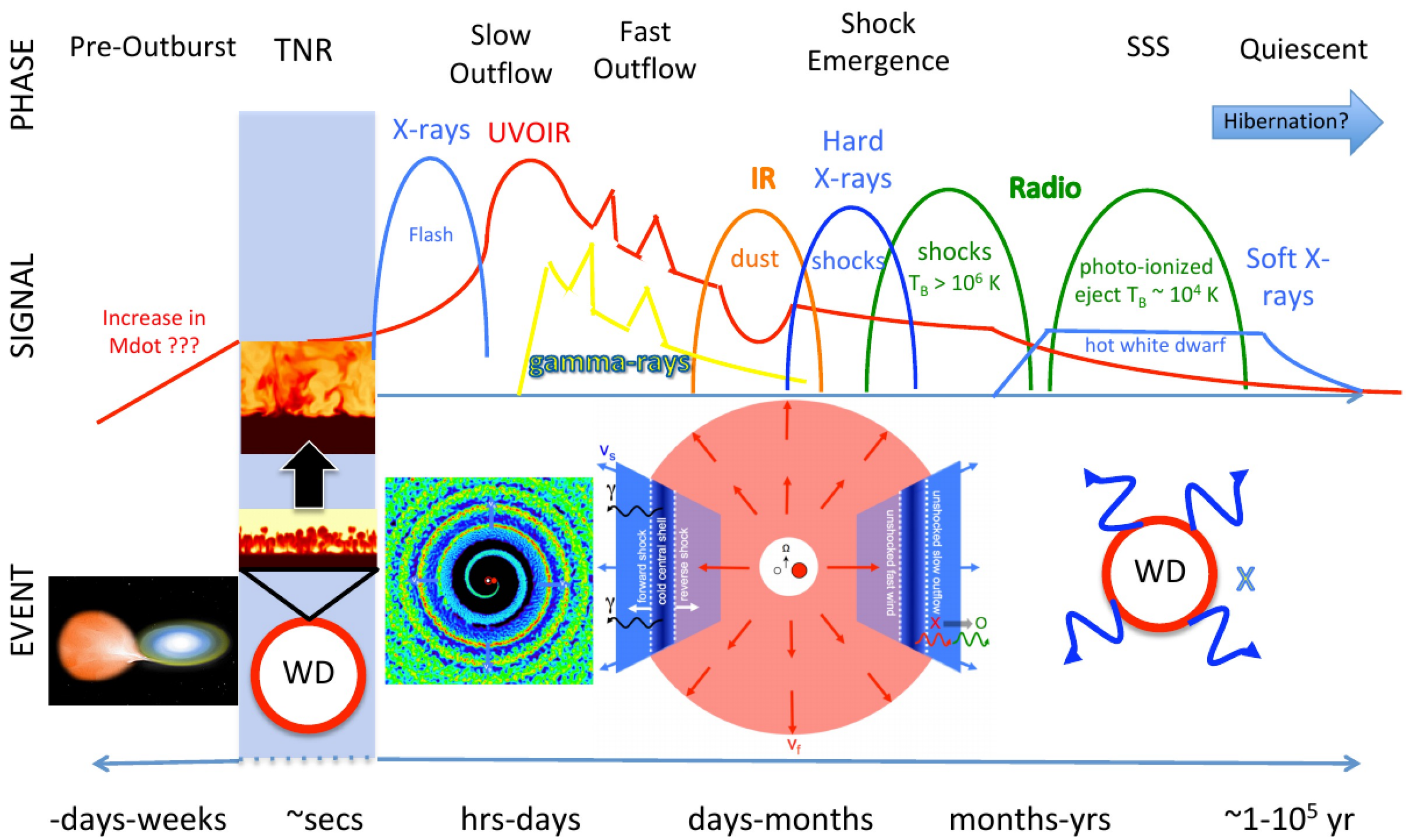
Shocking New Insights into Classical Novae



Brian Metzger - **Flatiron Institute CCA & Columbia University**

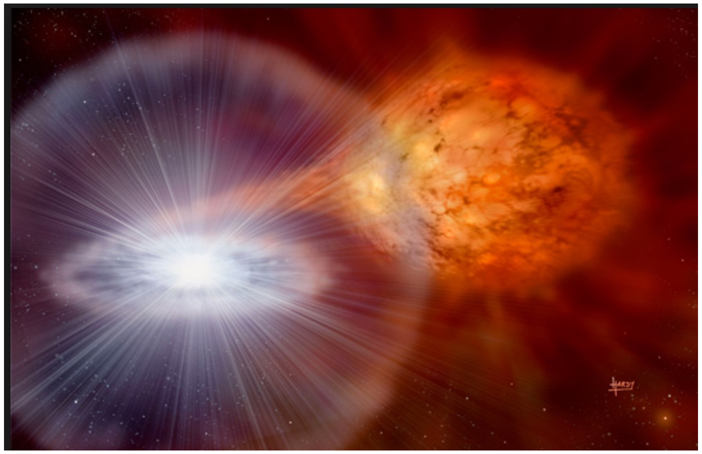
Primary Collaborators

Elad Steinberg (Hebrew), Andrei Beloborodov, Jeno Sokoloski (Columbia), Andrea Derdzinski (Zurich), Laura Chomiuk, Elias Aydi (MSU), Ray Li (Tsing Hua), Damiano Caprioli (Chicago), Ondrej Pejcha (Charles) Indrek Vurm (Tartu), Ken Shen (Berkeley), Tommy Nelson (City of Asylum), Jennifer Weston (US Naval Obs.)

Chomiuk, Metzger & Shen (ARAA in press, arXiv:2011.08751)

Classical & Embedded Novae

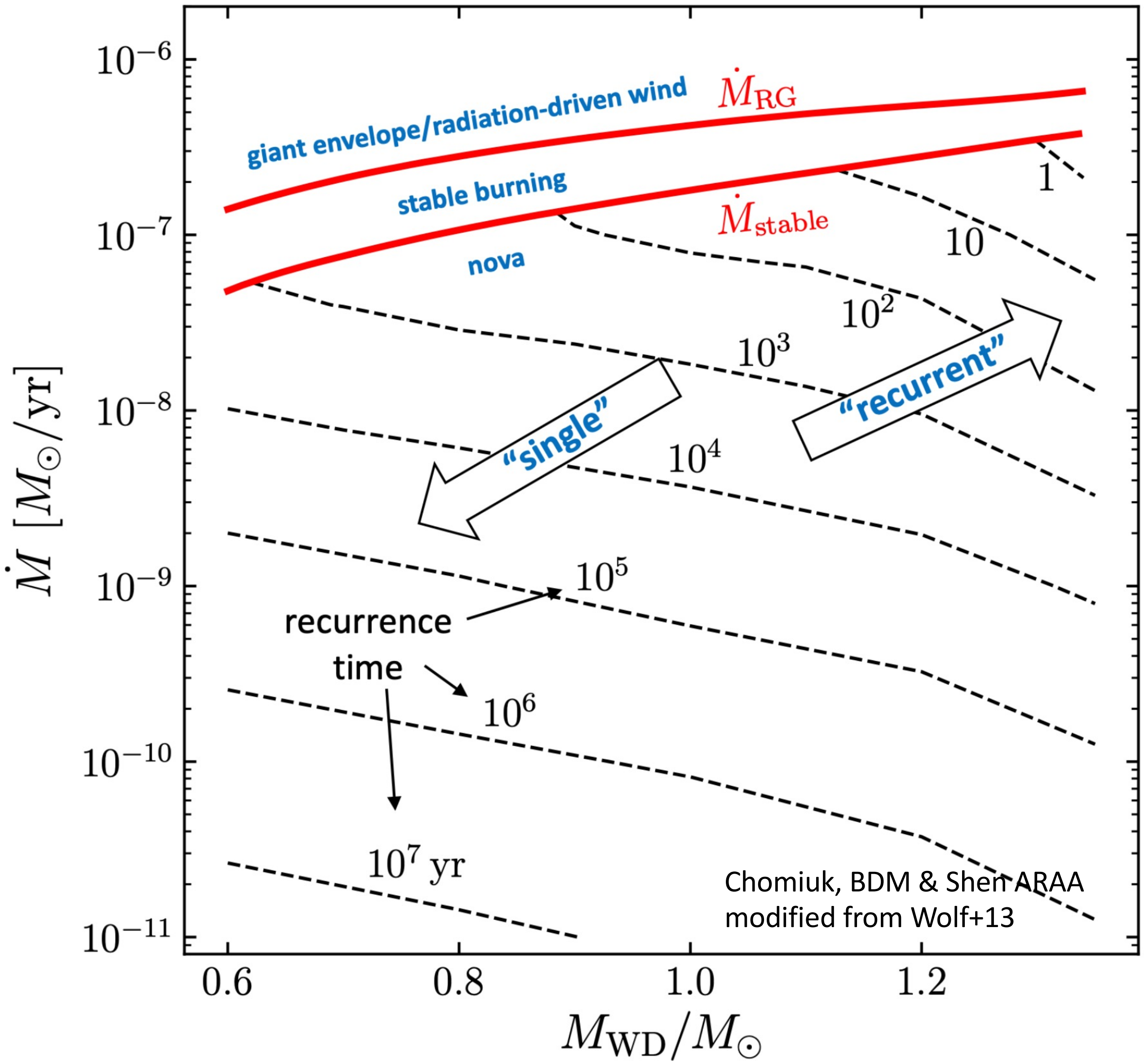
Runaway hydrogen burning on WD accreting from *main sequence* or *giant* companion



Thermonuclear runaway
=> envelope expansion
=> mass-loss + light

Recurrence times
~1 year to ~10^7 year

Critical to CV evolution & single degenerate SN-Ia



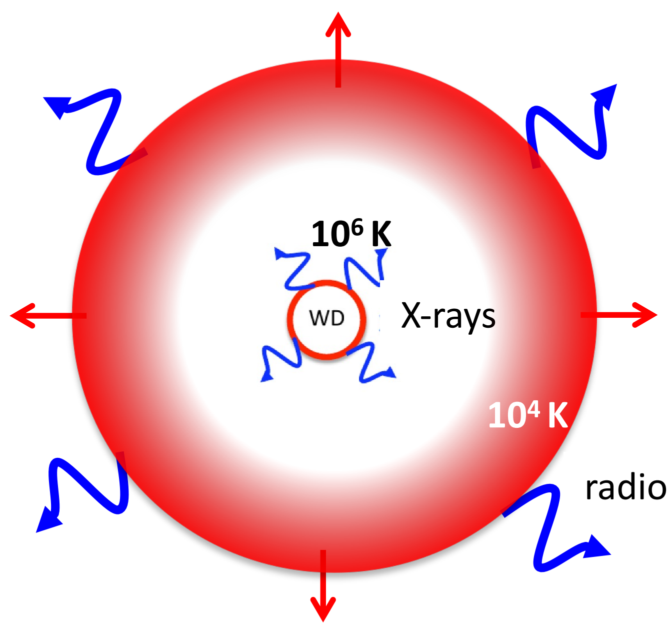
Thermal Paradigm

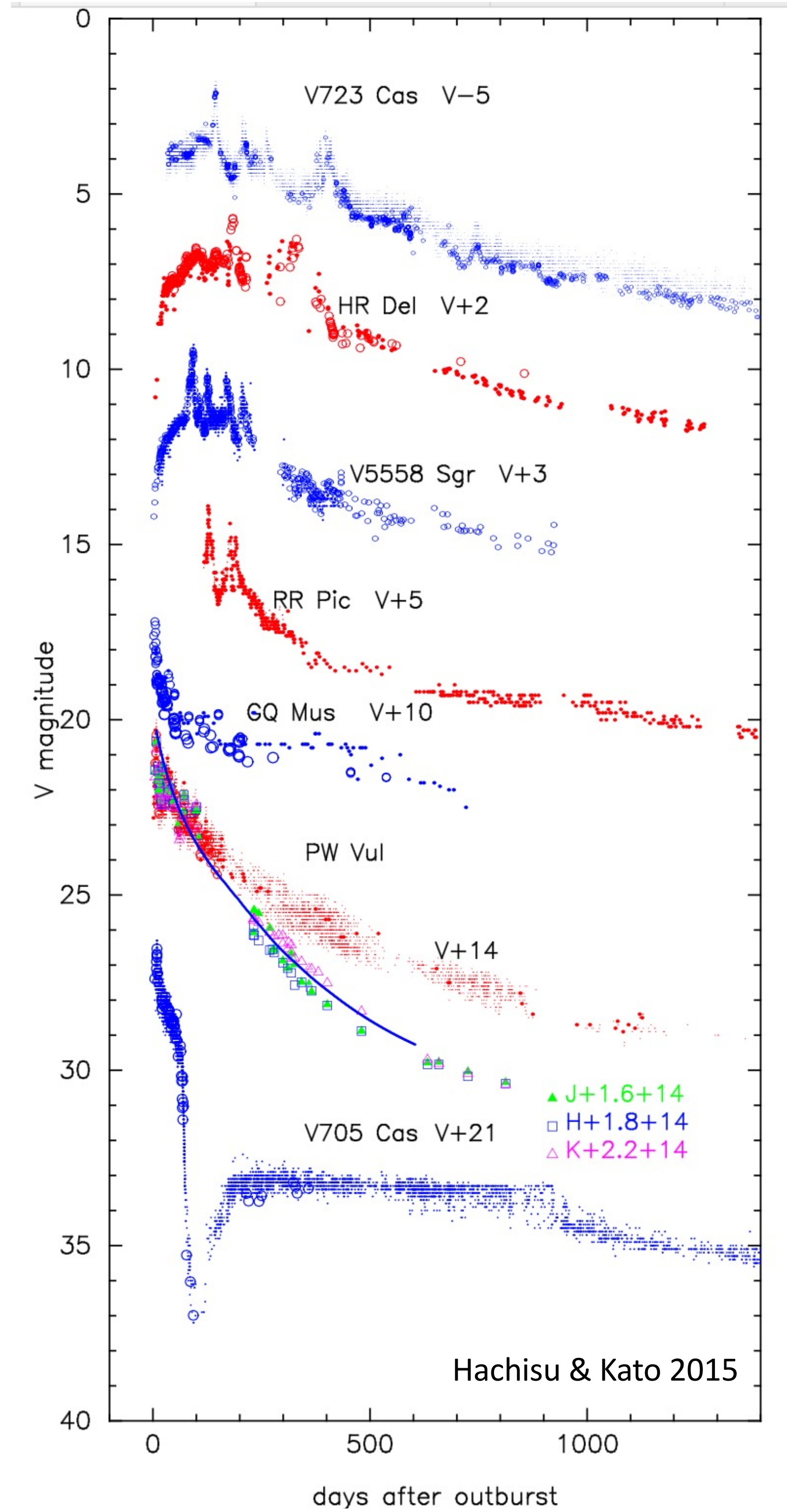
optical peaks in days & lasts weeks - months
(timescale for envelope removal)

L_{peak} ~ 1-10 L_{edd} ~ 10^{38-39} erg s^{-1}

v_{ej} ~ 300 - 5,000 km s^{-1}
M_{ej} ~10^{-6} – 10^{-4} $M_{\odot}$

soft X-rays (white dwarf surface)
and **radio free-free** (photo-ionized ejecta shell)





Thermal Paradigm

optical peaks in days & lasts weeks - months

(timesc

L_{peak} ~

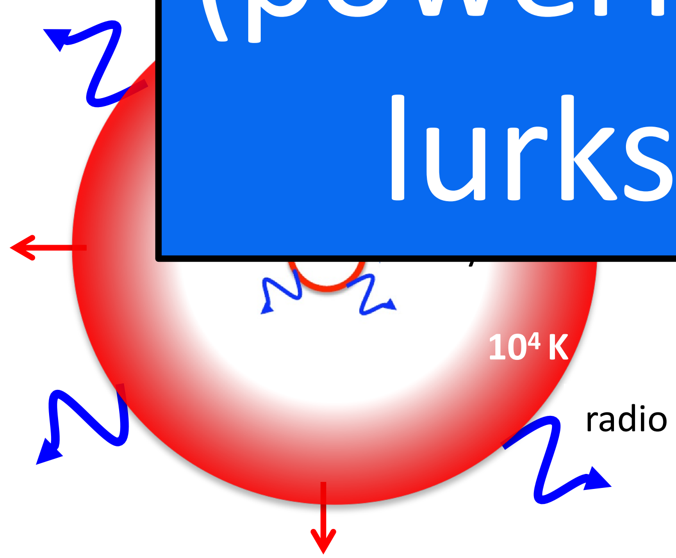
v_{ej}

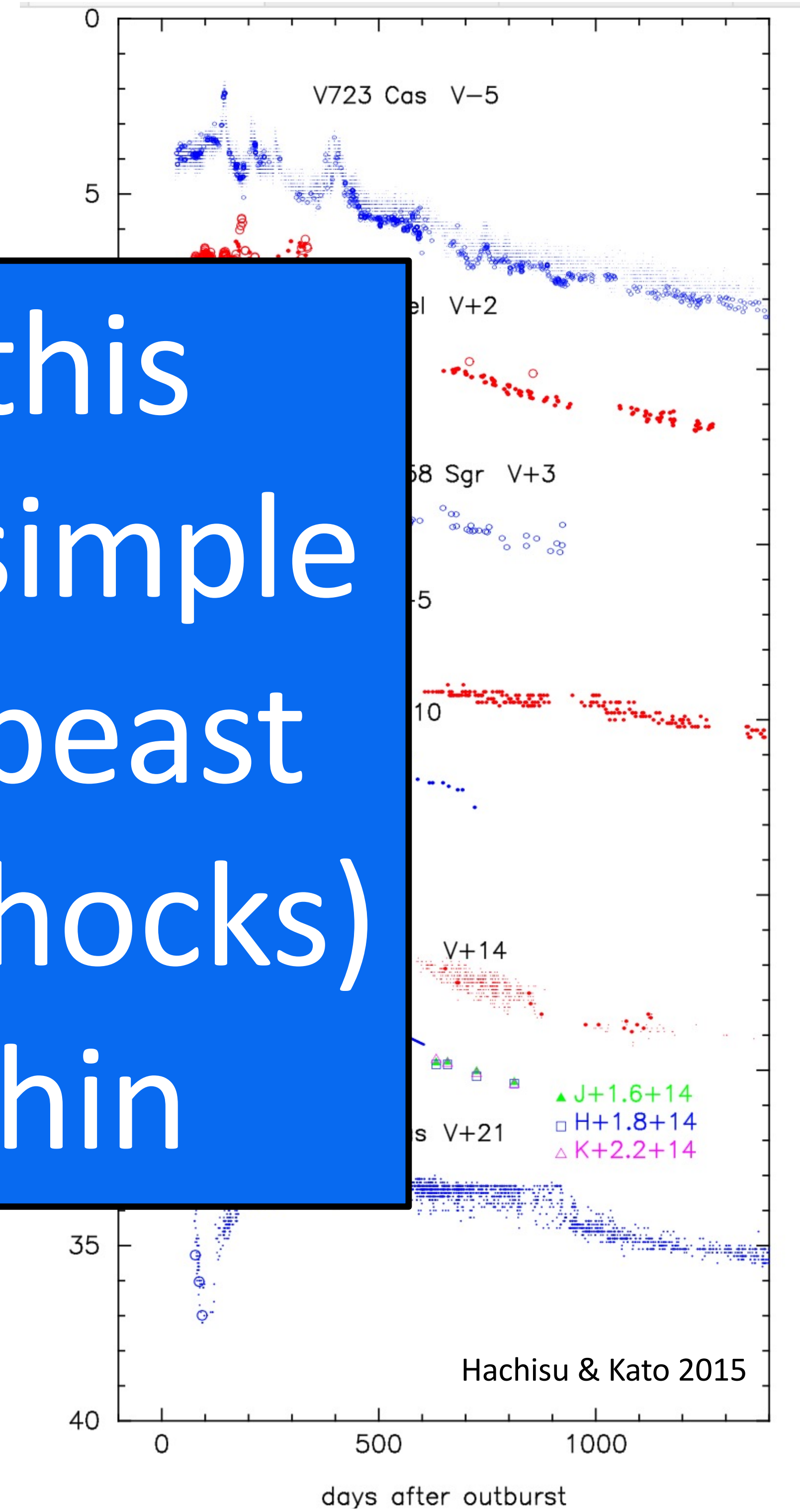
N

soft X-r

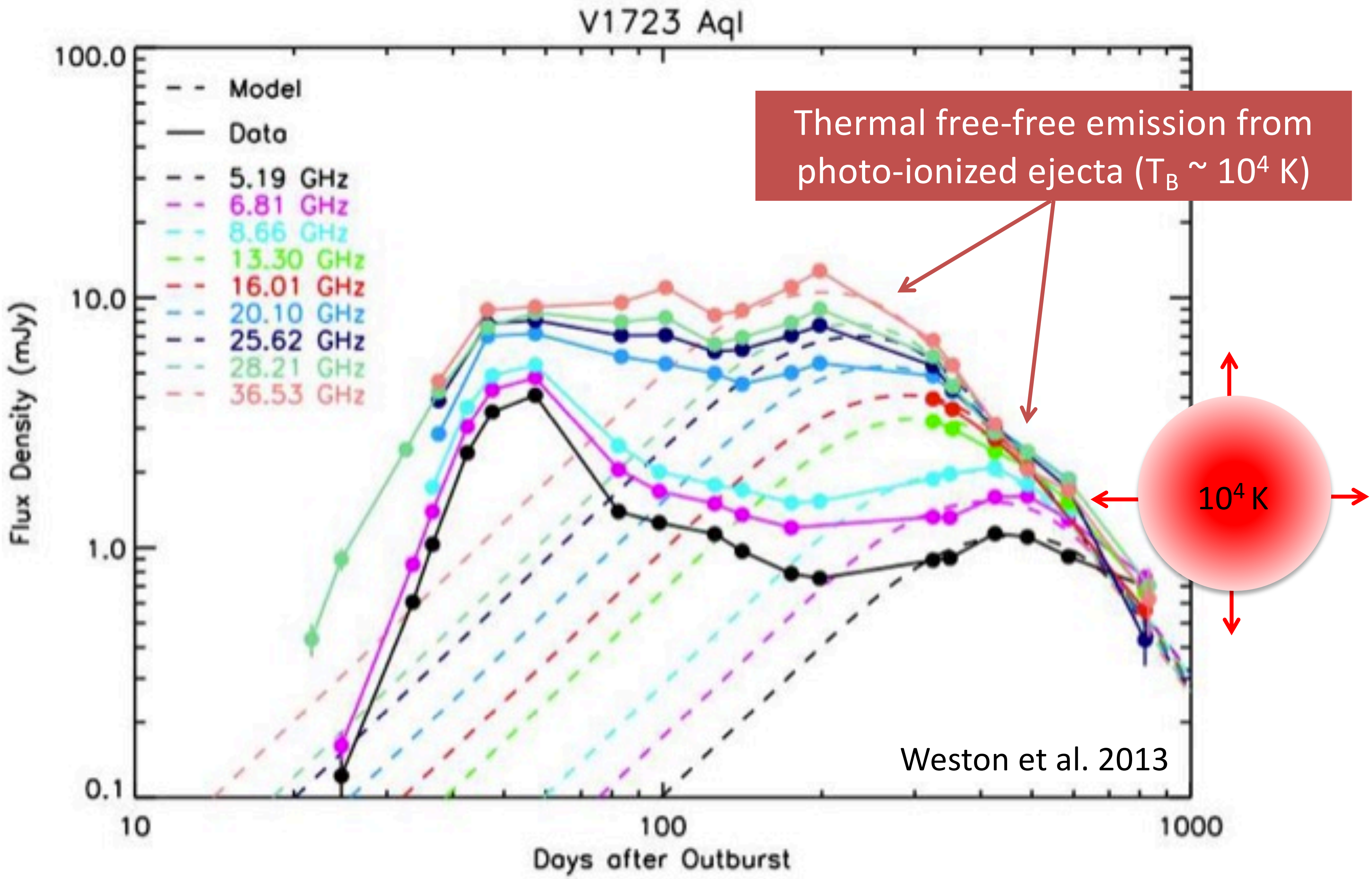
and **radio free-**

Despite this seemingly simple picture, a beast (powerful shocks) lurks within





Early Non-Thermal Radio Emission



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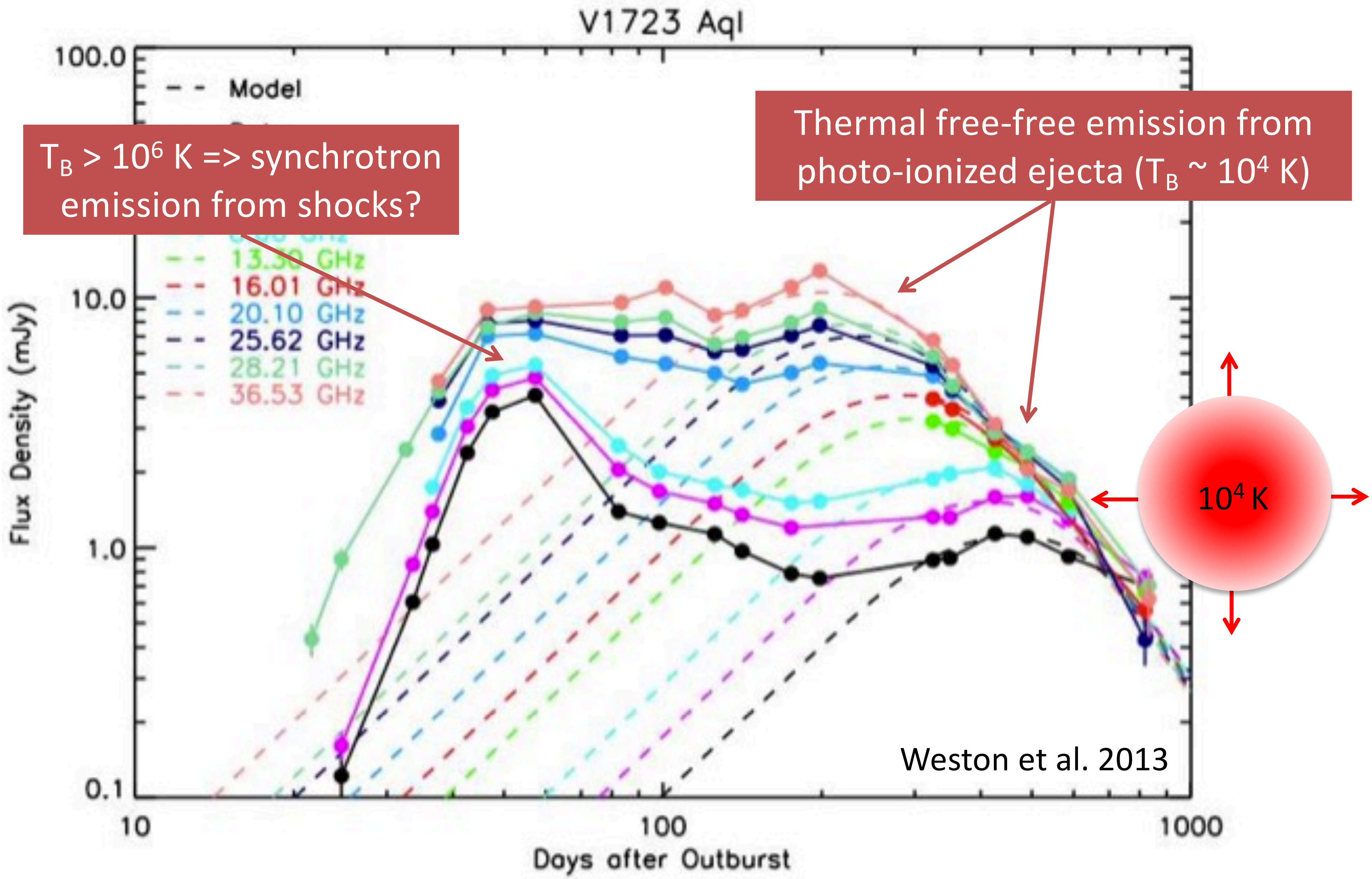
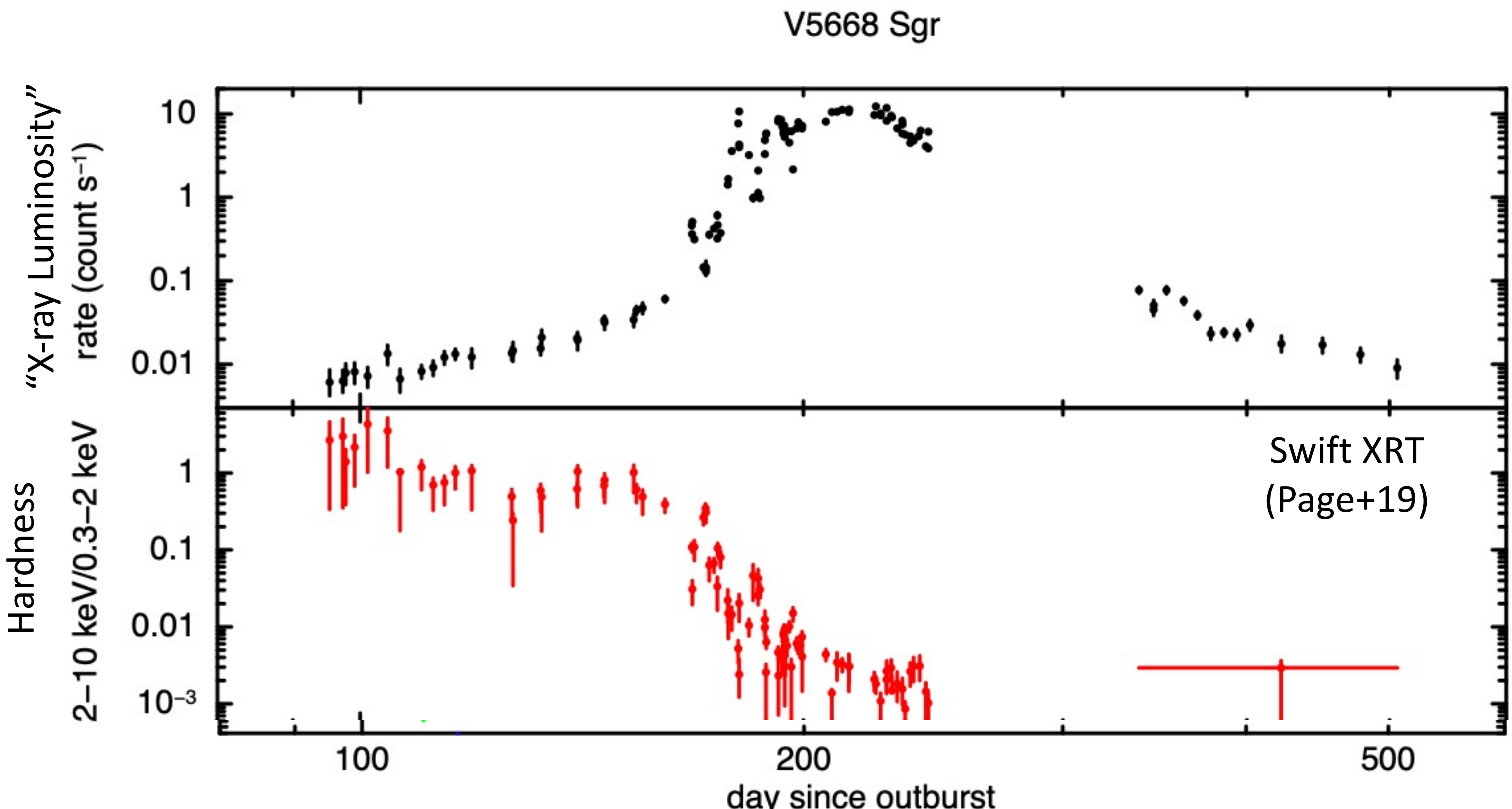


Hard Thermal X-rays from Shocked Gas

temporally and spectrally distinct from soft X-rays from WD surface

(e.g., Mukai & Ishida 01; Gordon+20)



T ~ 10^7 K => ~10^3 km/s shocks

$L_x \sim 10^{32}$-10^{34} erg $s^{-1} << L_{bol}$

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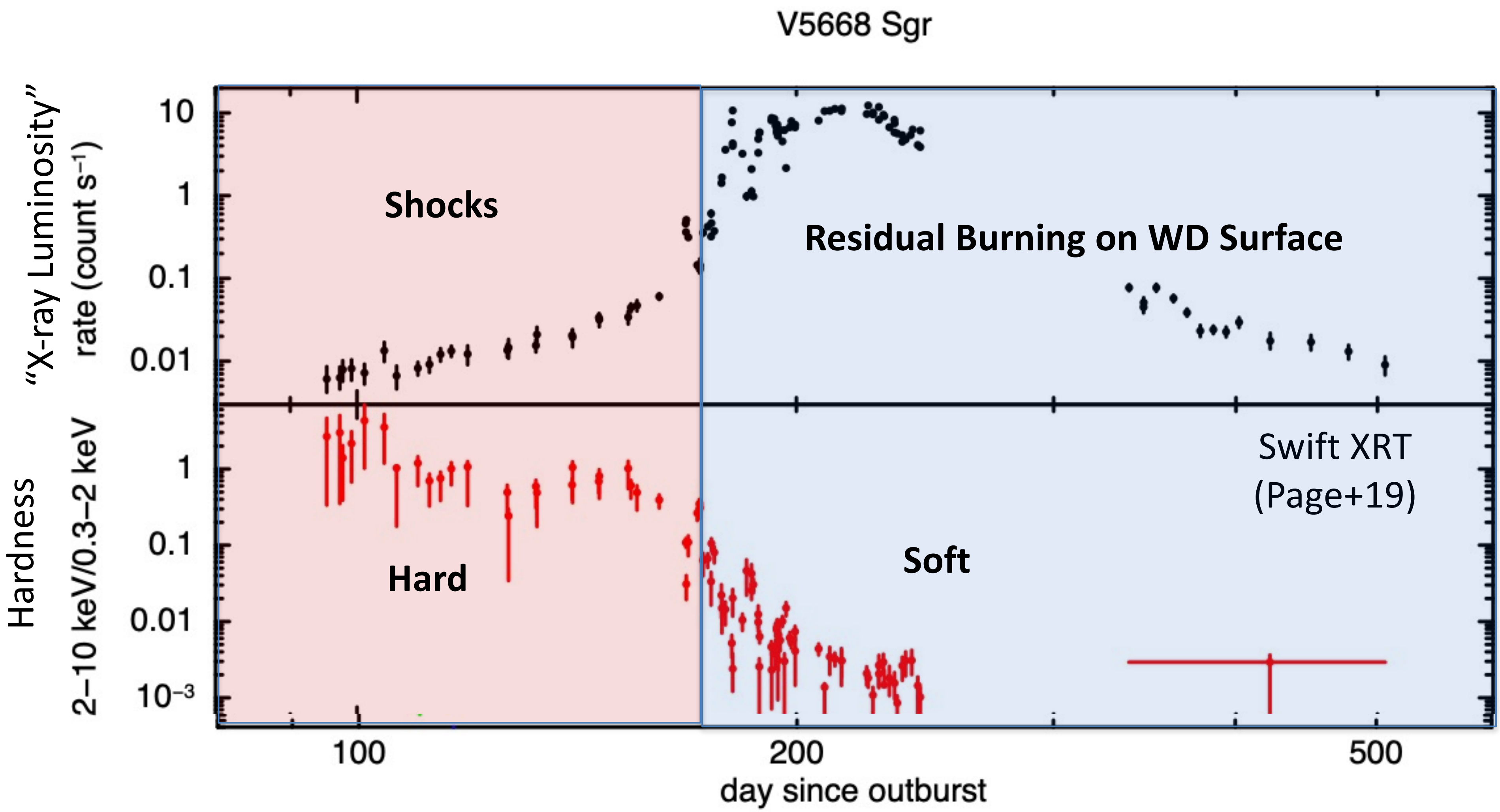
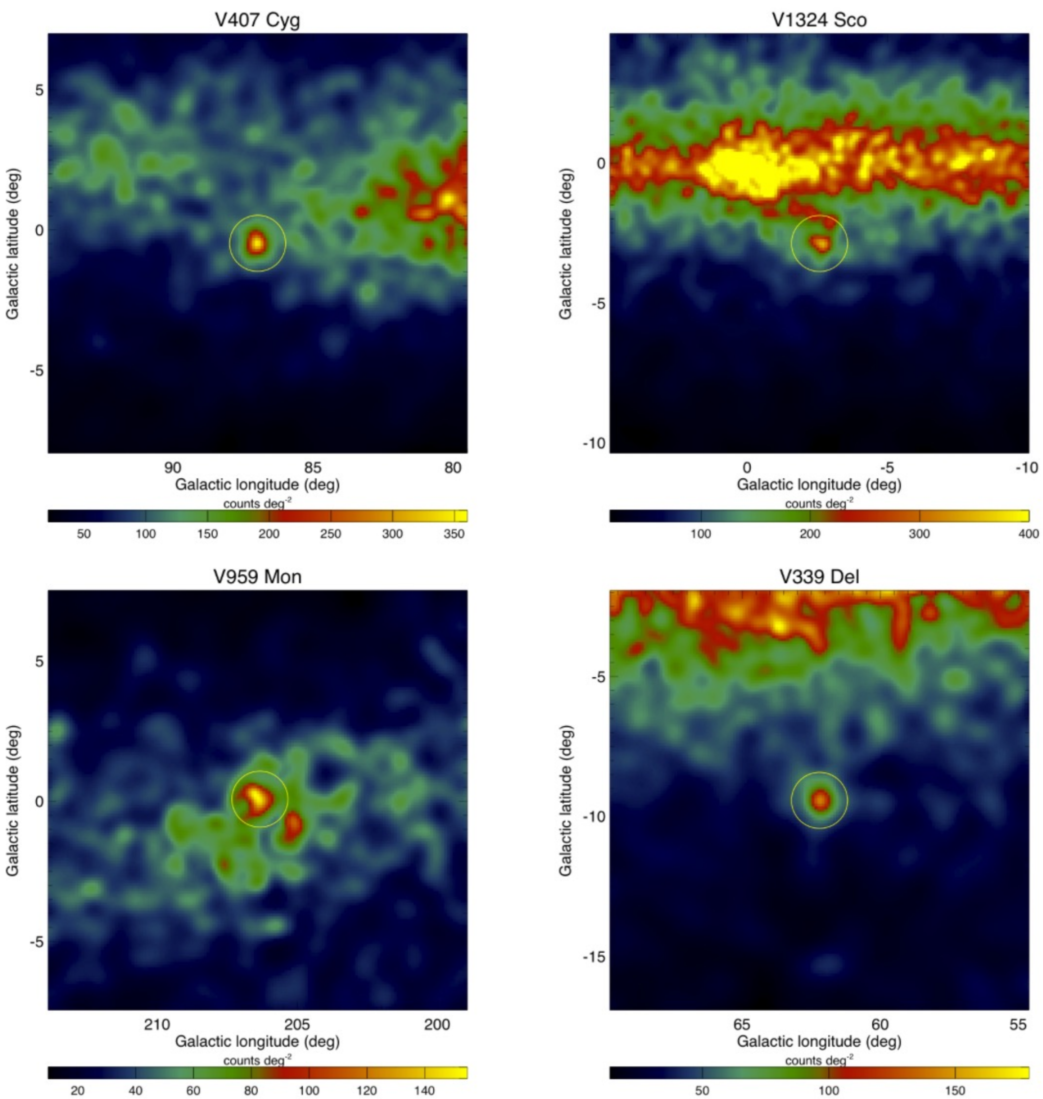
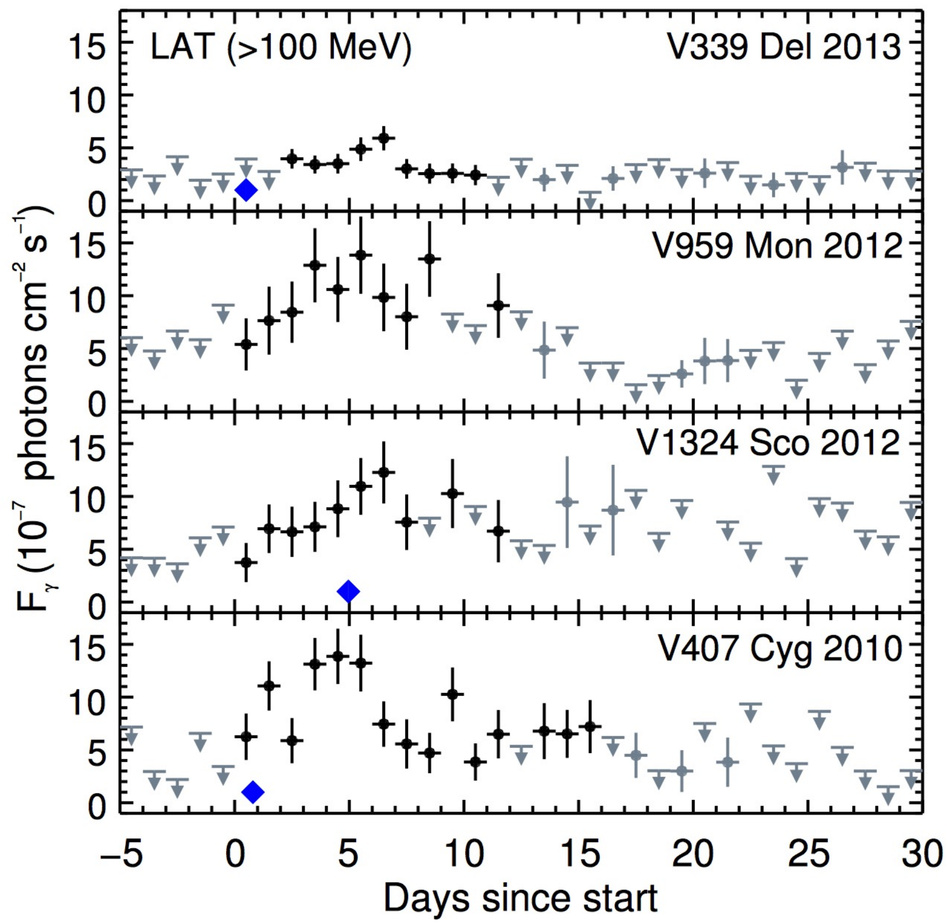


T ~ 10^7 K => ~1000 km/s shocks

$L_x \sim 10^{32}$-10^{34} erg $s^{-1} \ll L_{bol}$

Fermi LAT detects classical novae





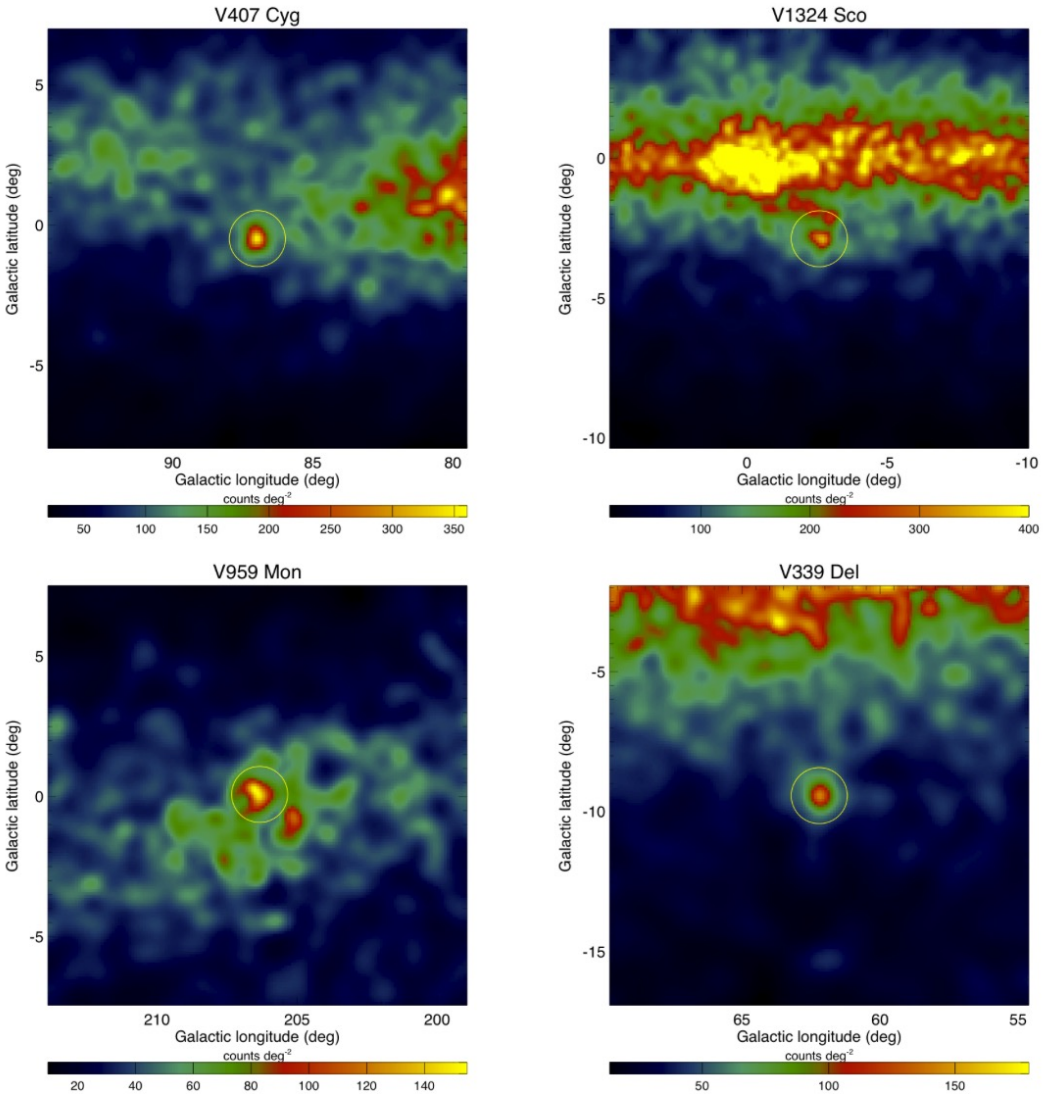
Ackermann et al. 2014

$L_\gamma \sim 10^{35\text{-}36}$ erg s^{-1}

=> $L_{shock} \sim 10^{37\text{-}38}$ erg s^{-1} $\sim L_{bol}$

now ~15+ gamma-ray detections (flux-limited), **consistent with accompanying most novae**

Fermi LAT detects classical novae



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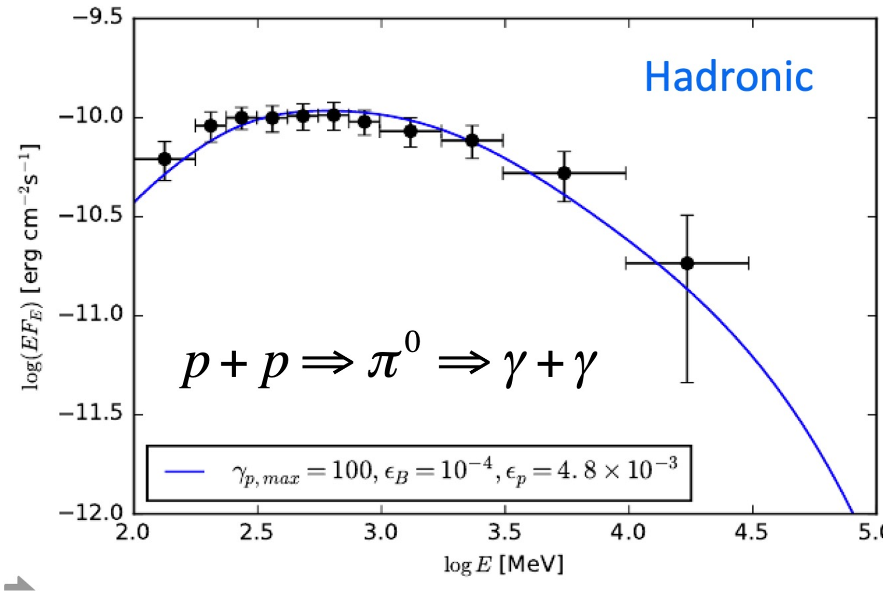

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=> **$L_{shock} \sim 10^{37\text{-}38}$ erg s^{-1} ~ L_{bol}**

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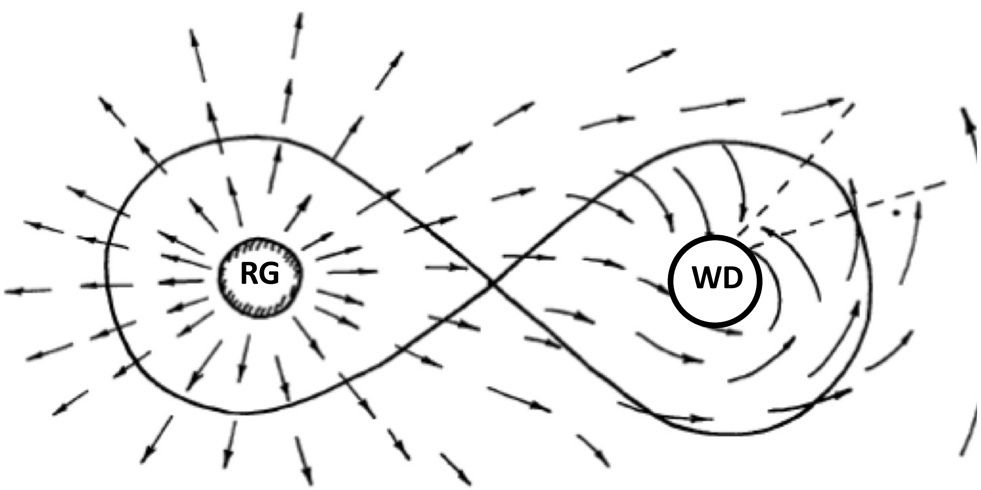
What’s the Nova Ejecta Colliding With?

Embedded Novae

(V407 Cyg – 1st gamma-ray detection)

Red Giant Companion



Dense Giant Wind

$\dot{M} \sim 10^{-6}\ M_{\odot} yr^{-1}$

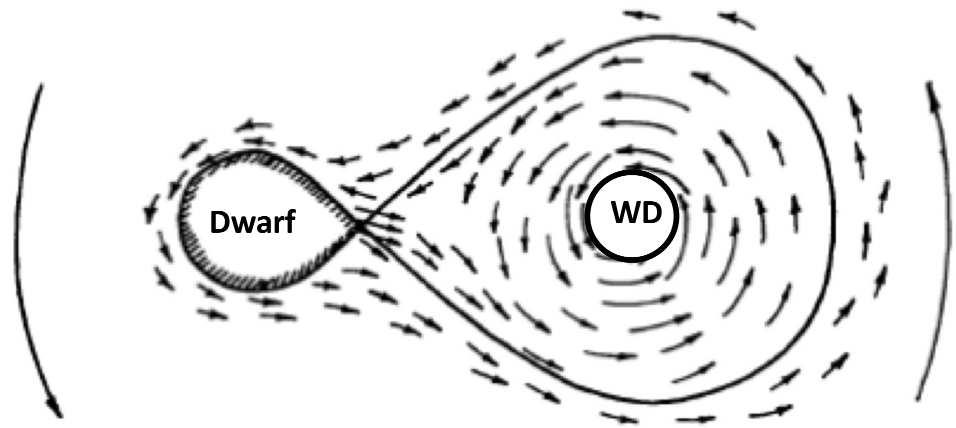
=> external shocks?

Classical Novae

(13+ gamma-ray detections)

CV - Main Sequence Companion

? ? ? ? ?



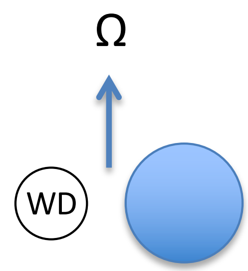
? ? ? ? ?

Mass Transfer Rate

$\dot{M} < 10^{-8}\ M_{\odot} yr^{-1}$

=> **internal shocks**

Geometry of Internal Shock Interaction



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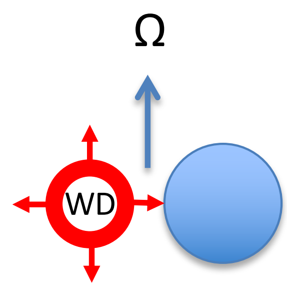

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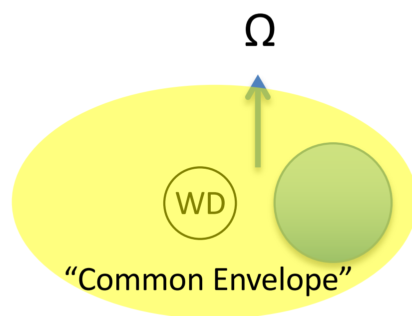

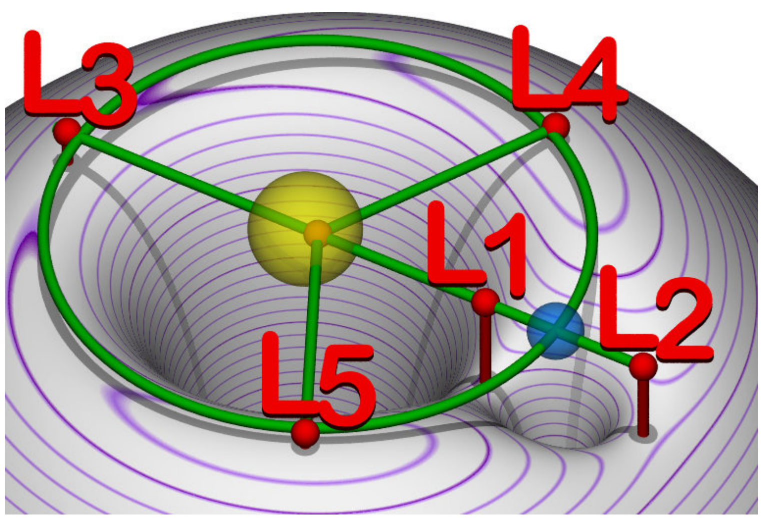

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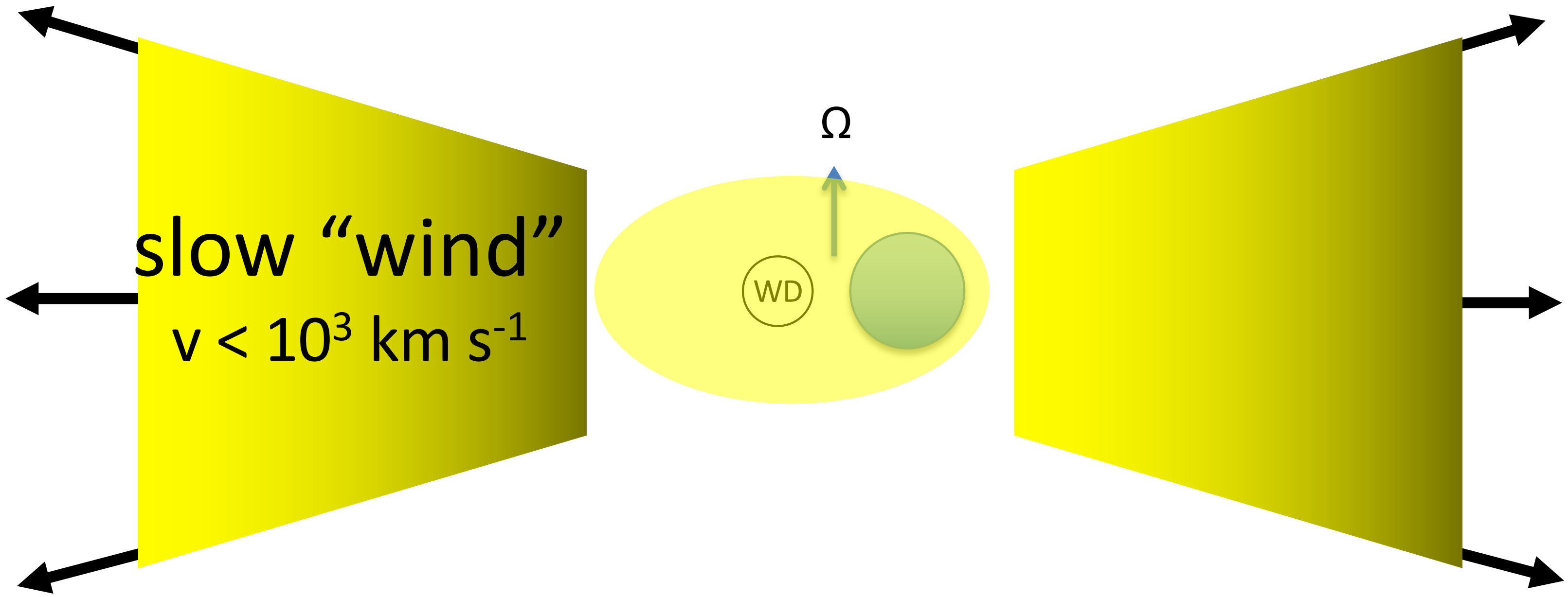
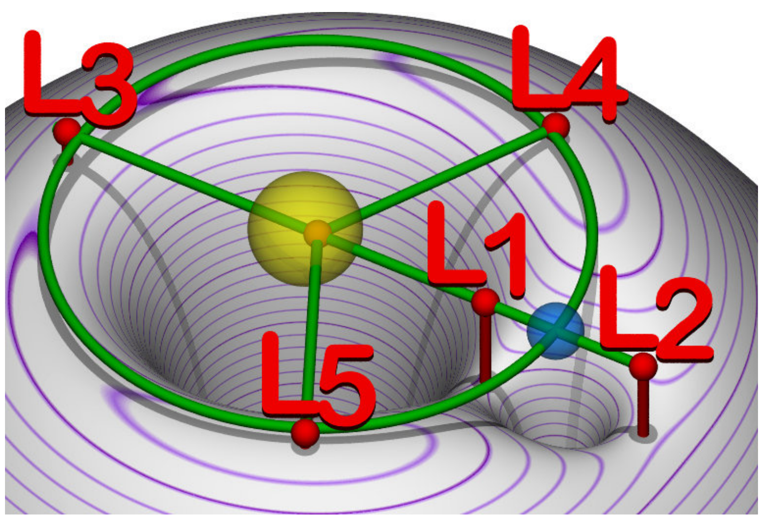
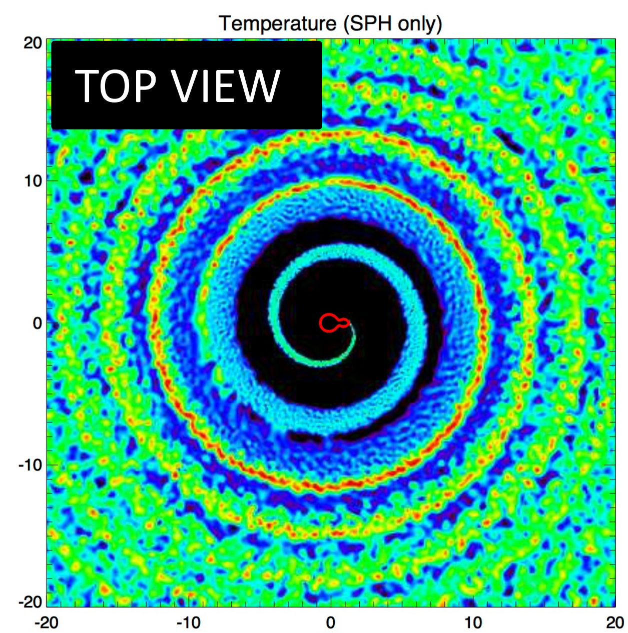


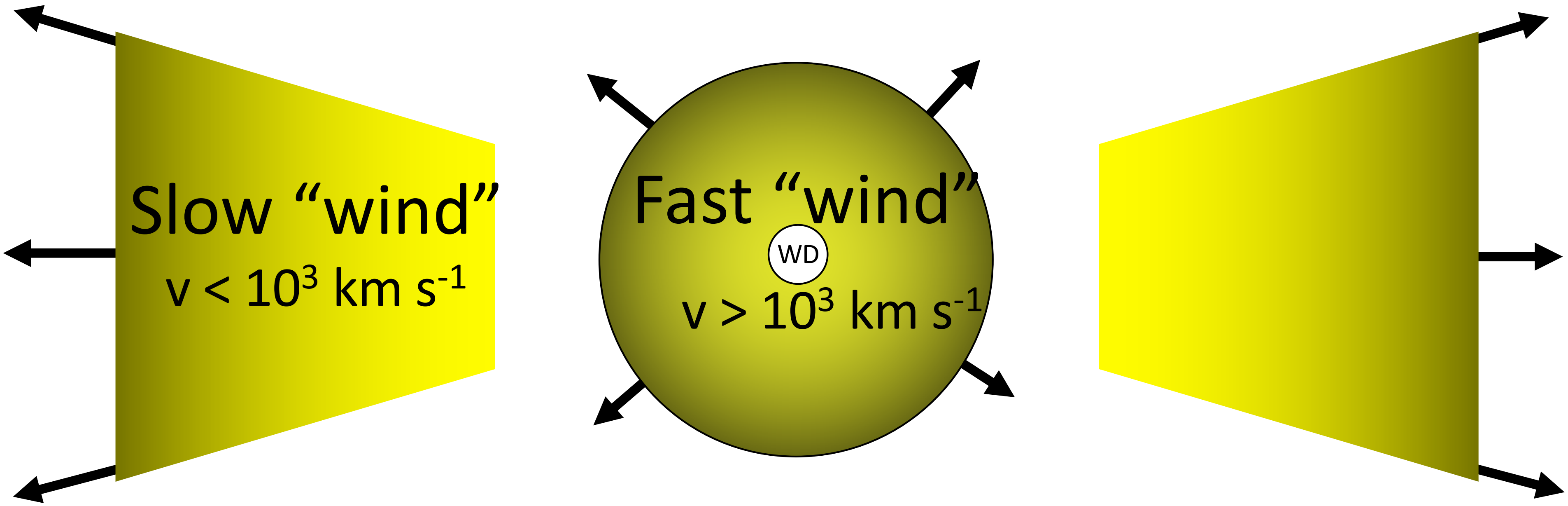
“Common Envelope” (e.g. L_2) Mass Loss



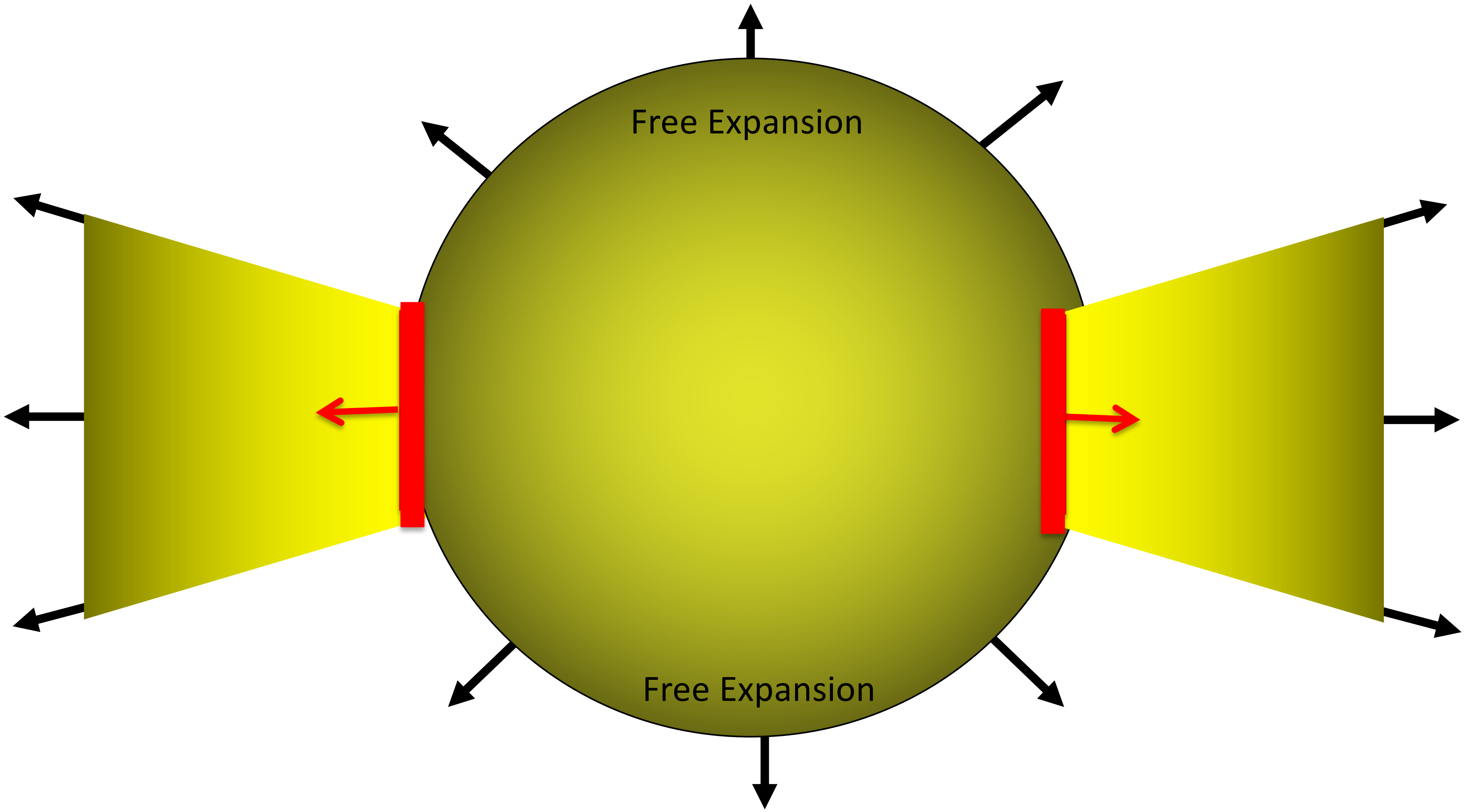


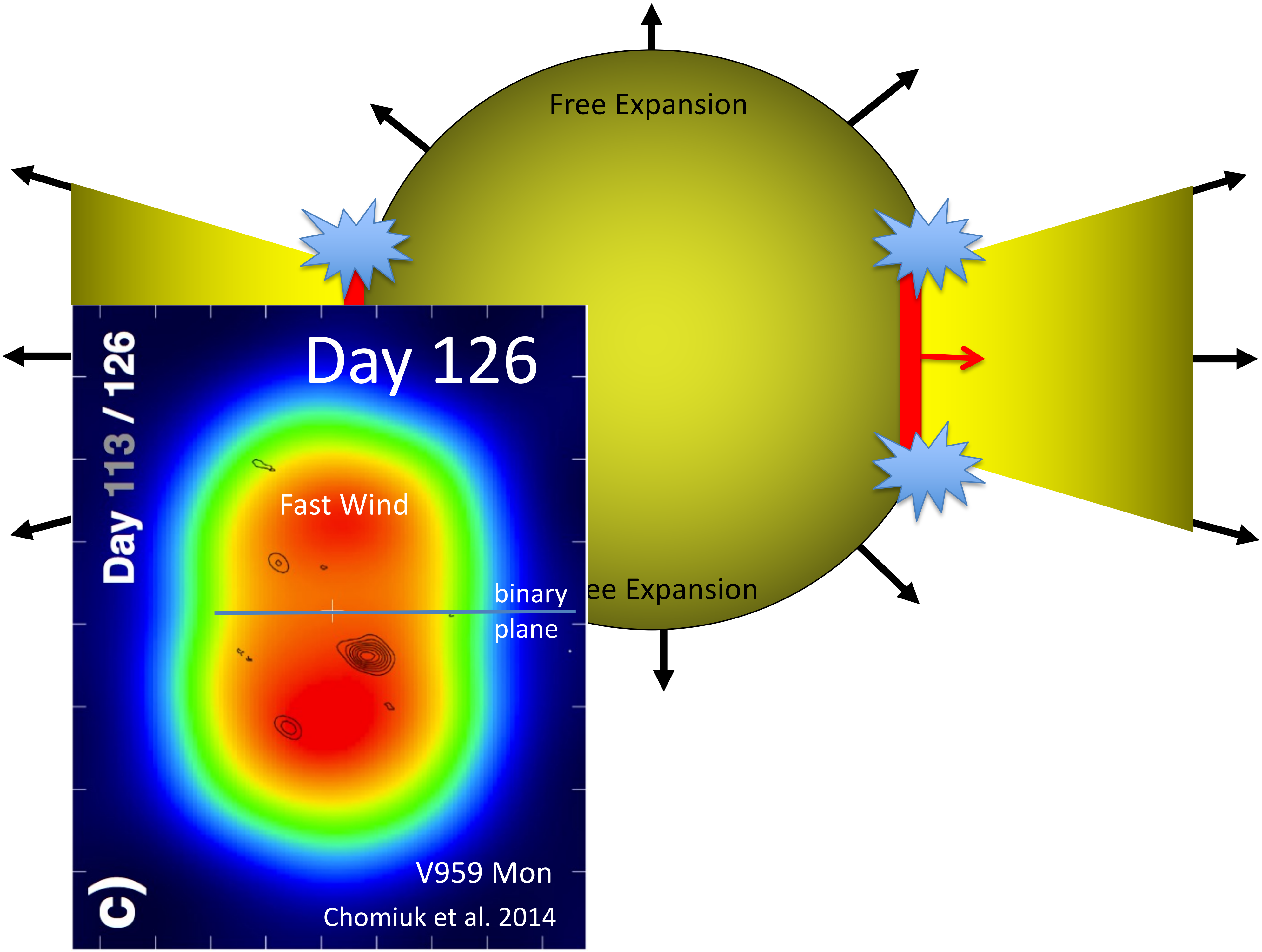
Pejcha, BDM, Tomida 16

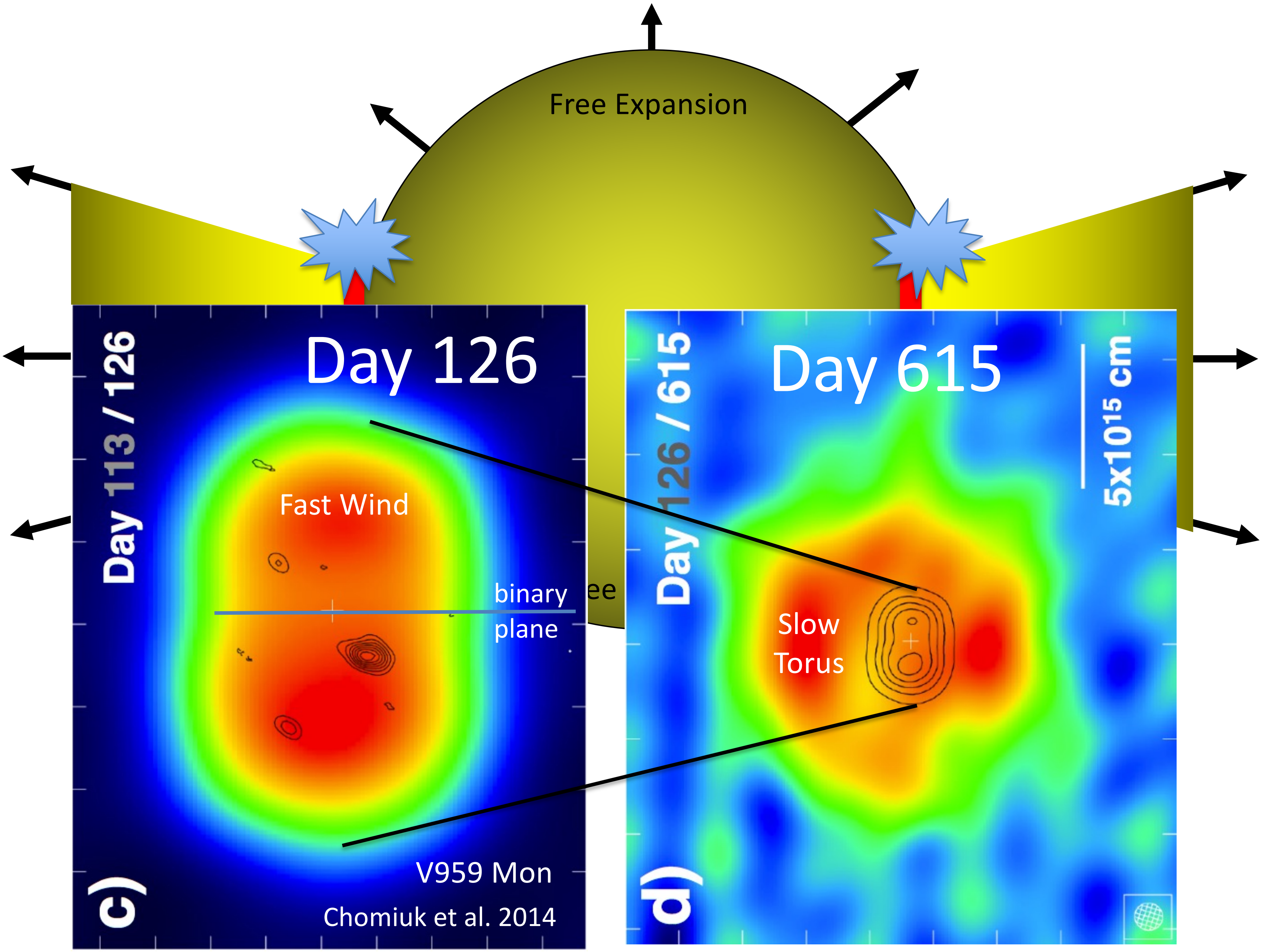
Geometry of Internal Shock Interaction



Supported by optical spectroscopy (e.g. Aydi+20)

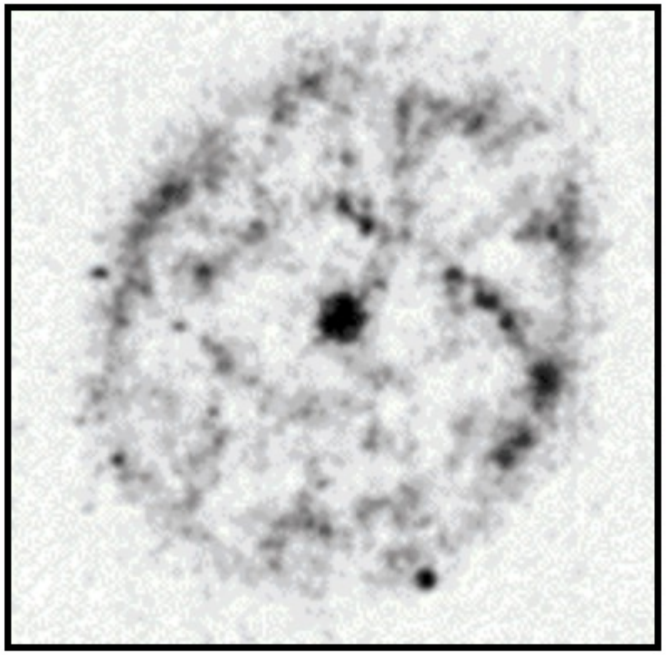

Free Expansion
Free Expansion


Free Expansion
ee Expansion
Day 126
Day 113 / 126
Fast Wind
binary
plane
V959 Mon
Chomiuk et al. 2014
c)


Free Expansion
Day 126
Day 113 / 126
Fast Wind
binary
plane
V959 Mon
Chomiuk et al. 2014
c)
Day 615
Day 126 / 615
Slow
Torus
5x10^{15} cm
d)

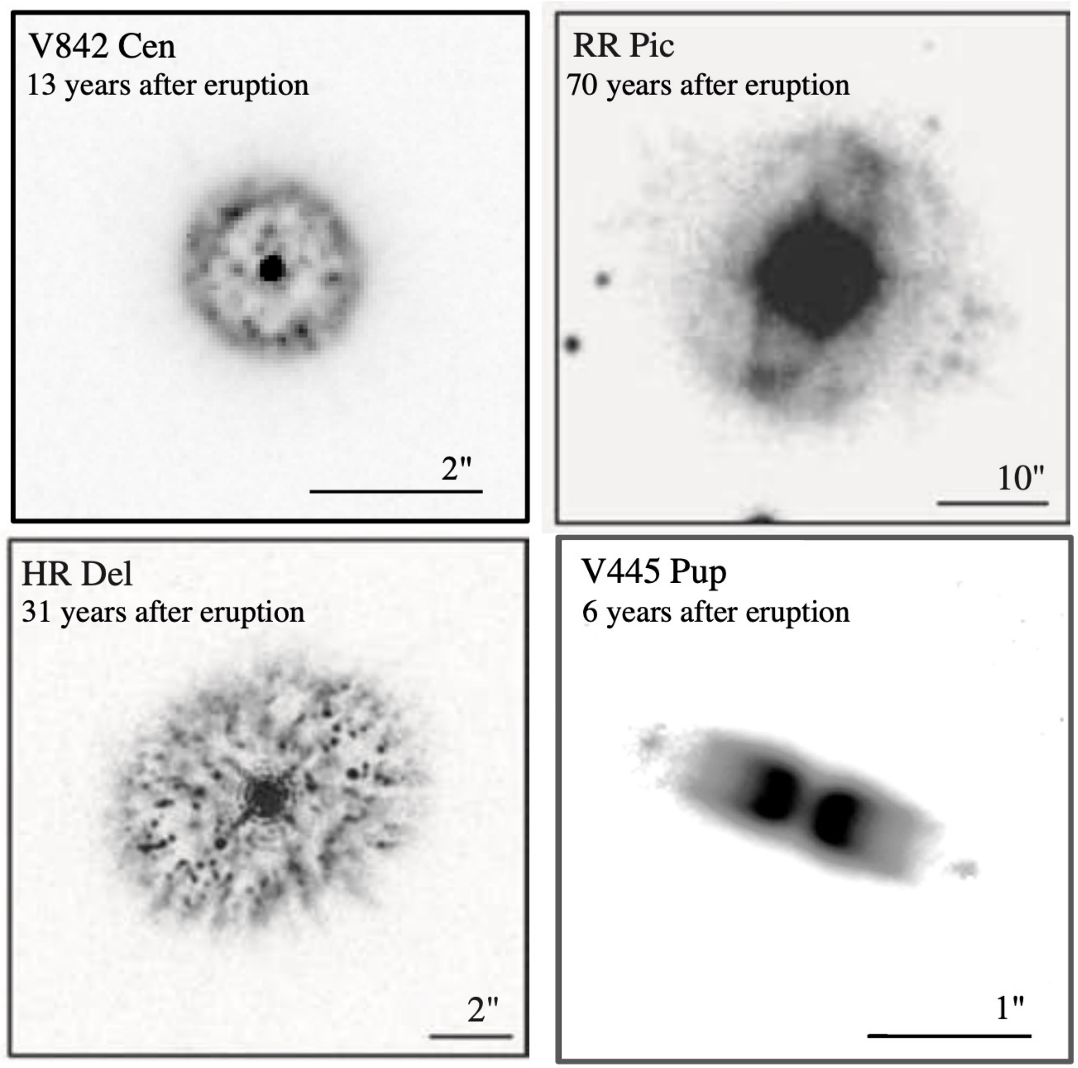
Old Nova Shells

"….the ejecta are **clumpy** but often display coherent structures, notably **equatorial rings** of enhanced emission encircling **prolate ellipsoidal shells**" (O'Brien et al. 2001)



The shell of the nova FH Ser ejected in 1970 and imaged in 1997 with the Hubble Space Telescope

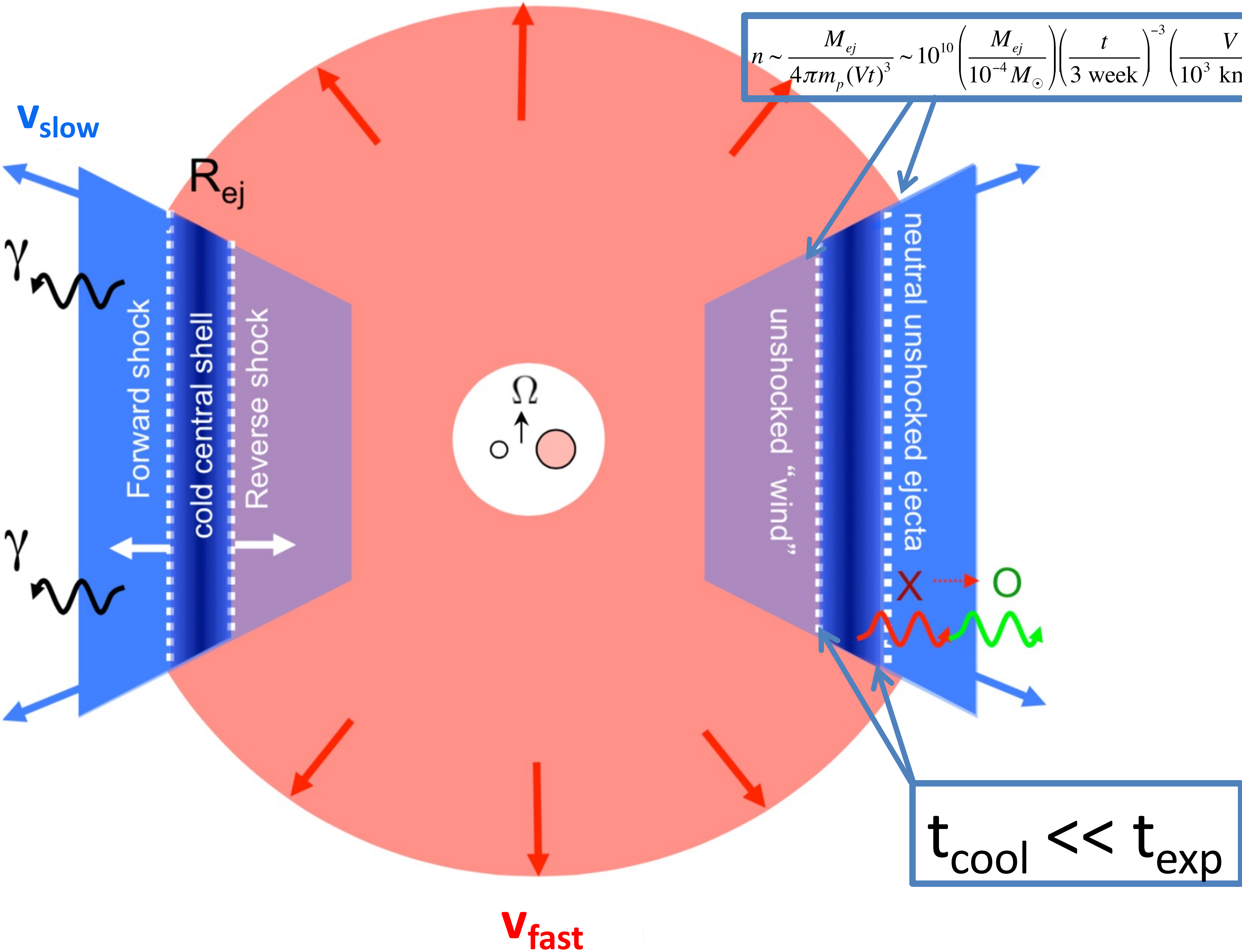
O'Brien & Gill 2000



Chomiuk, BDM, Shen ARAA

Gamma-ray shocks are *radiative*

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



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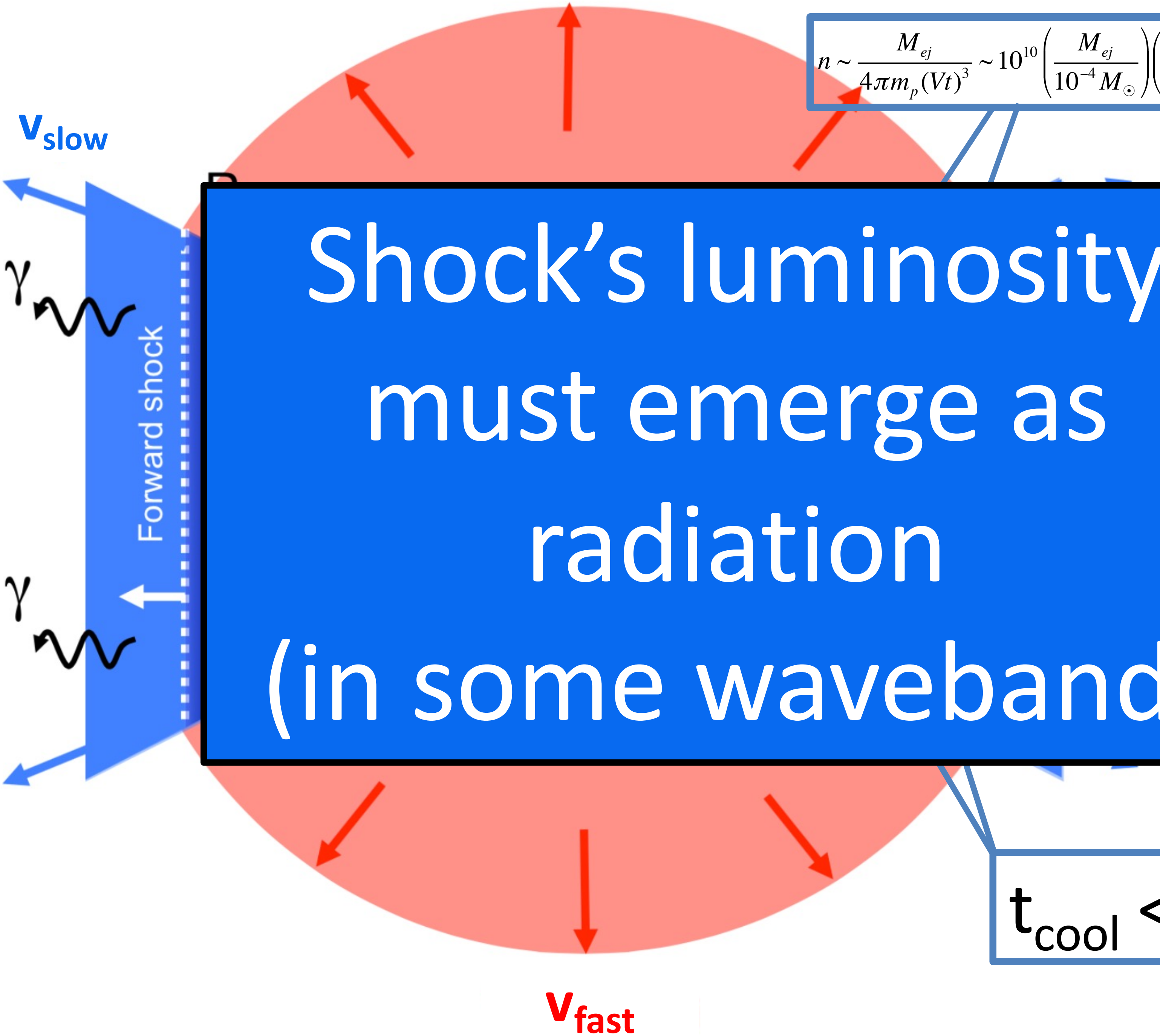

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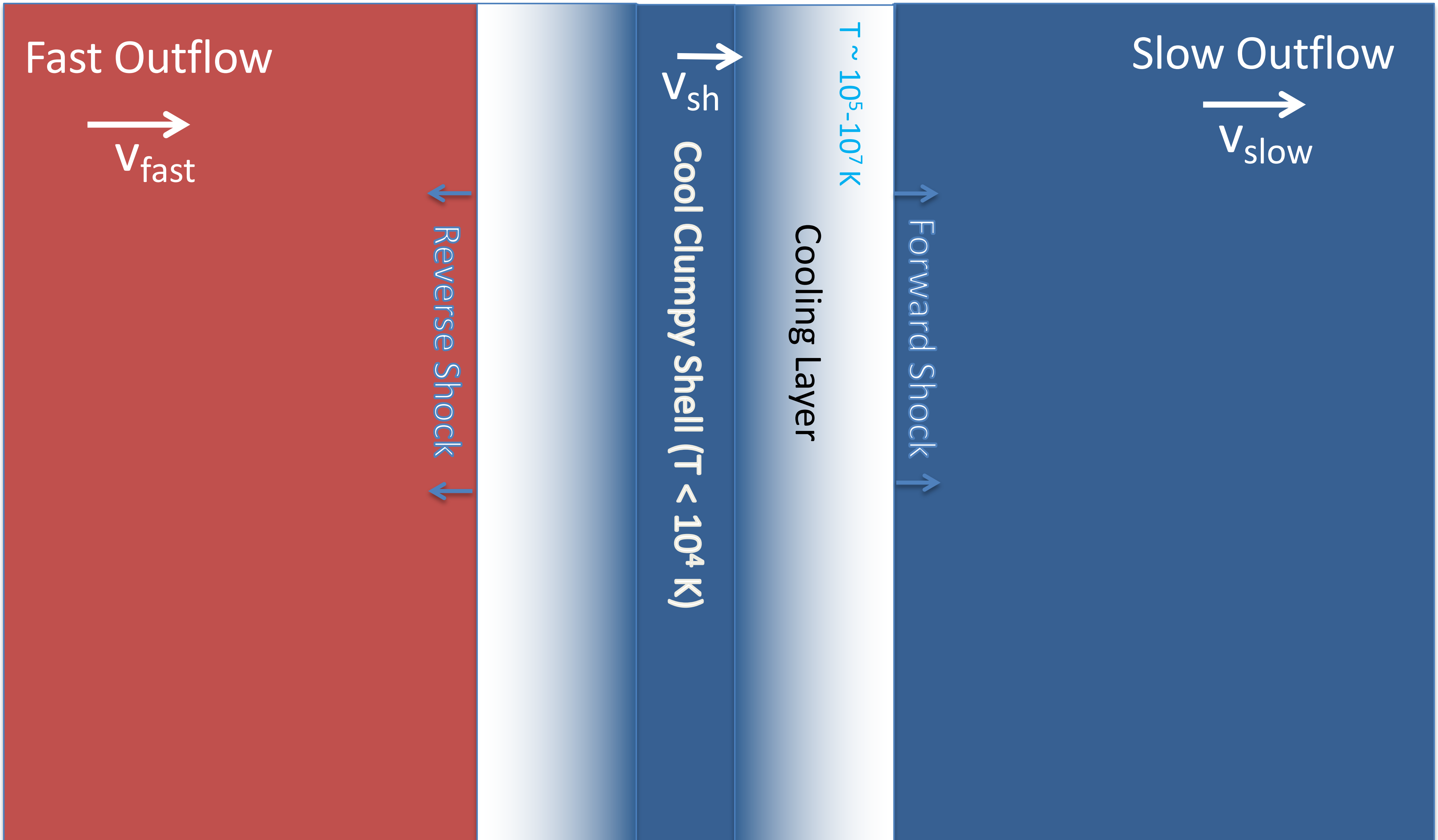
Shock's luminosity must emerge as radiation (in some waveband)

$t_{cool} << t_{exp}$

Internal Radiative Shocks

e.g. BDM+14



Internal Radiative Shocks

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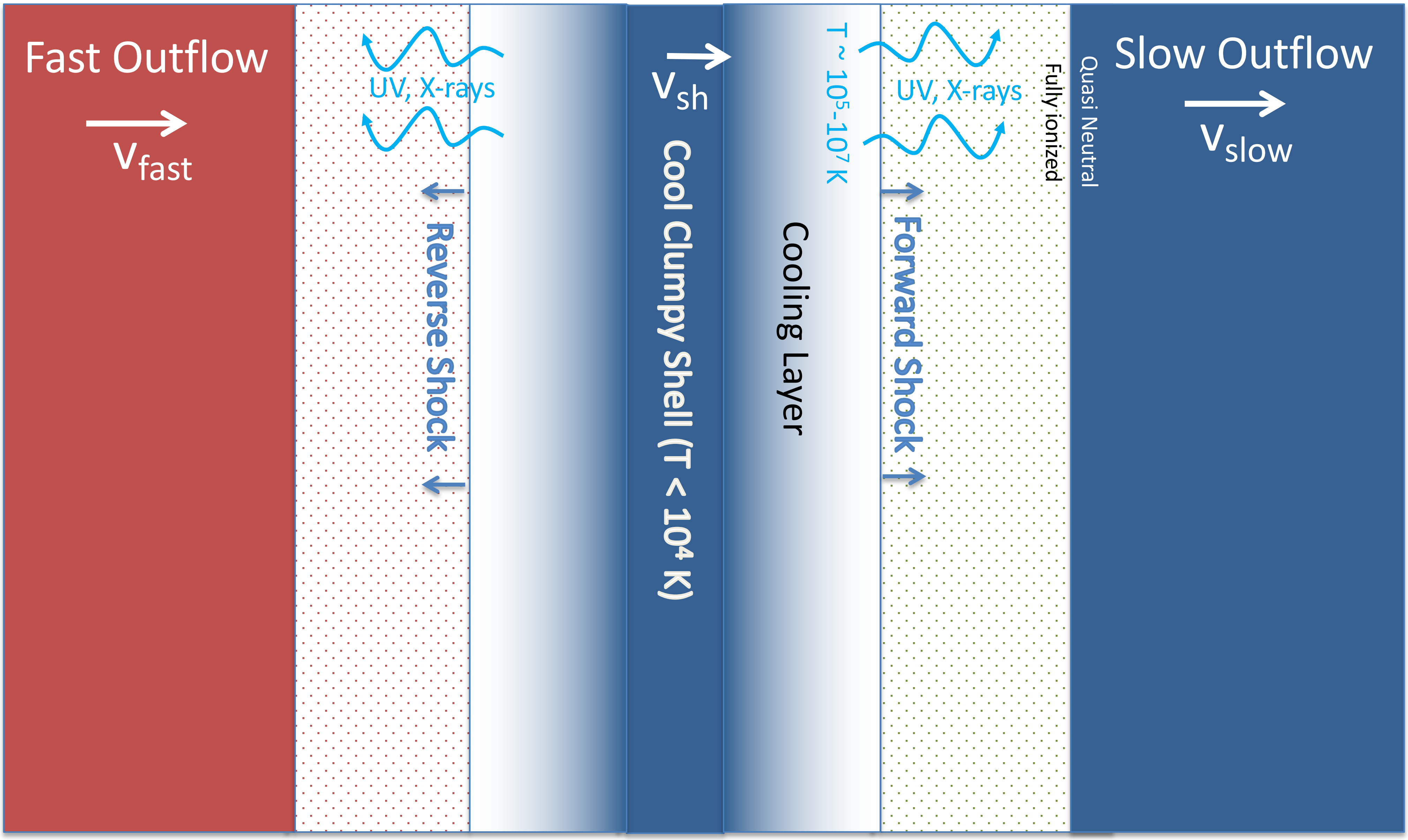

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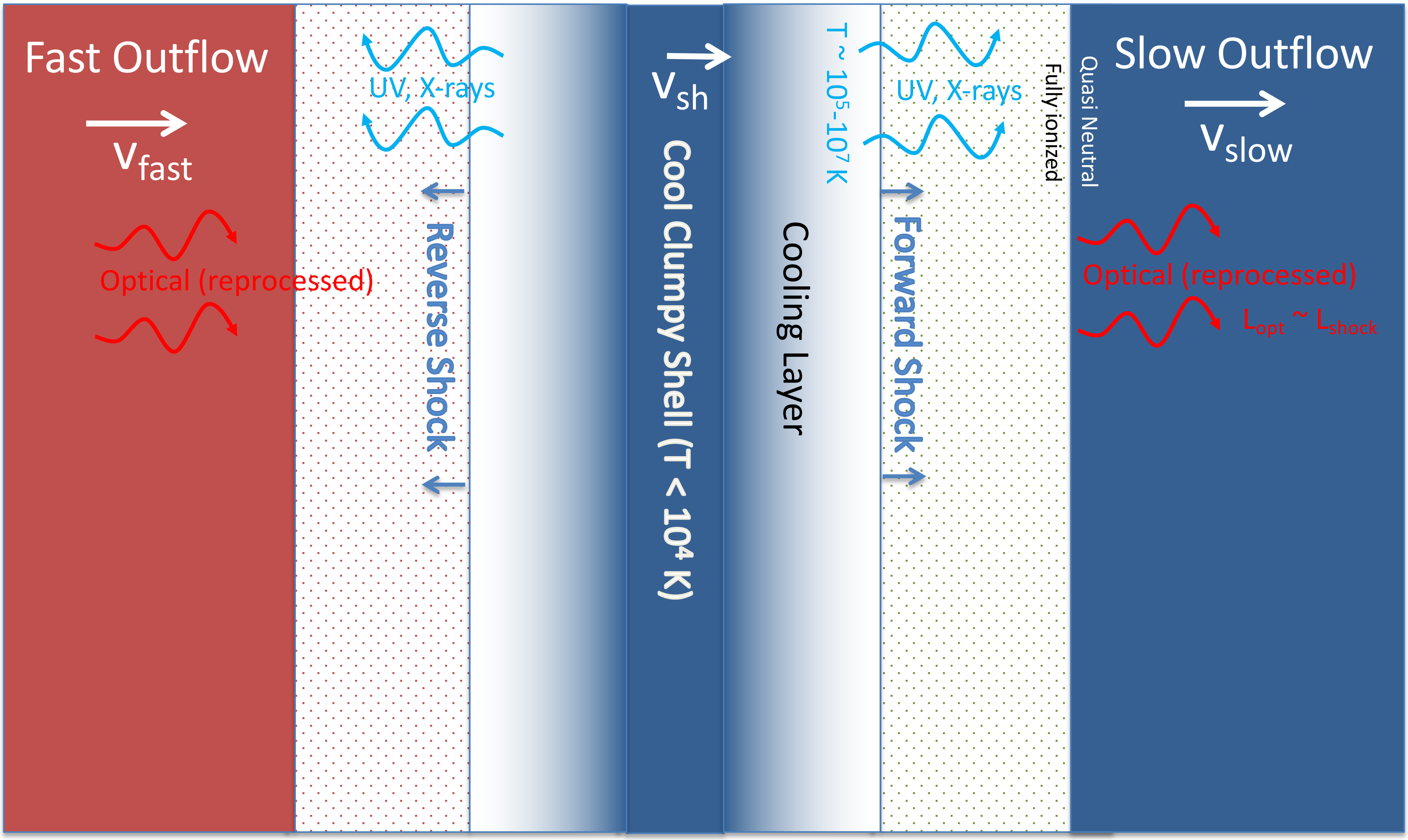

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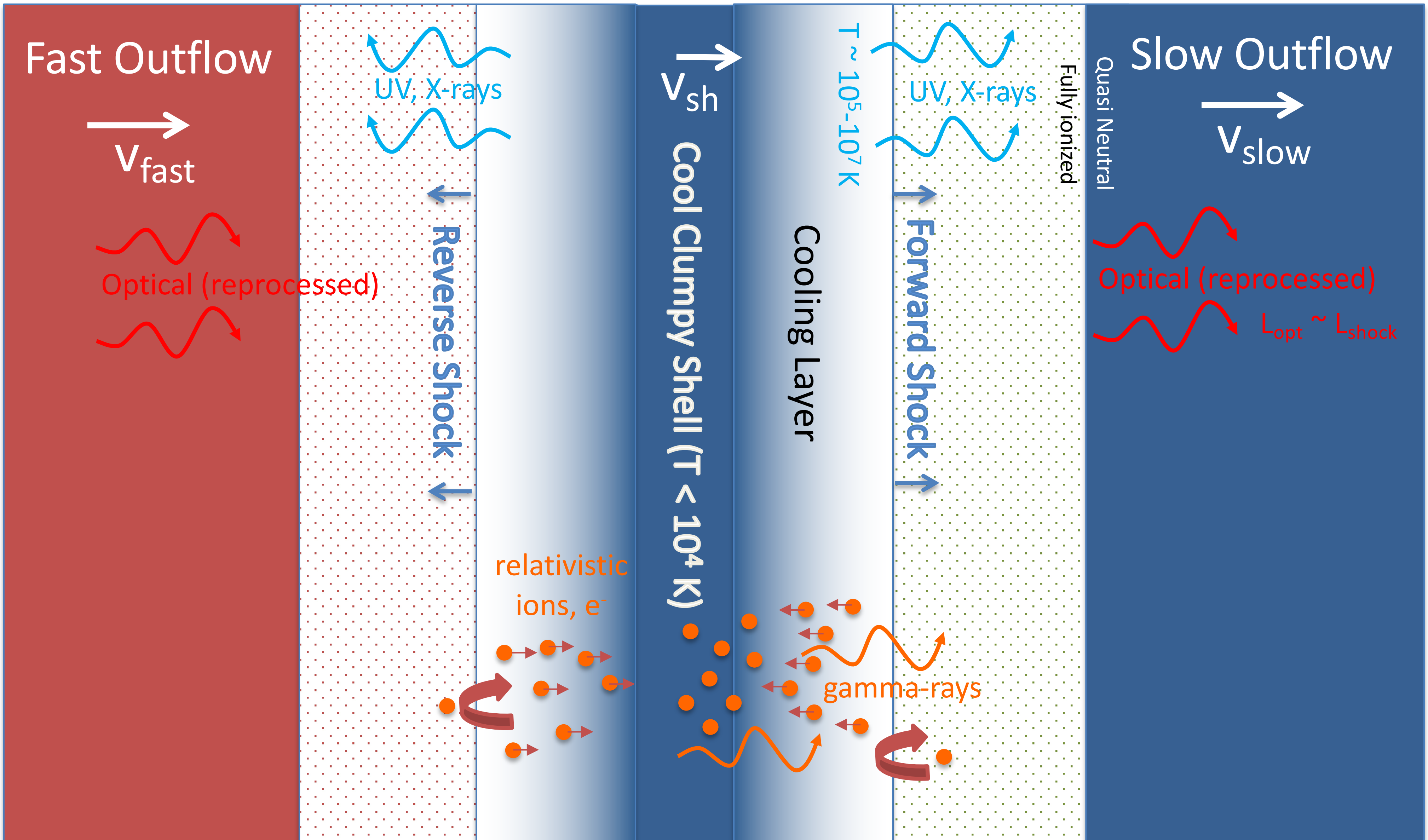

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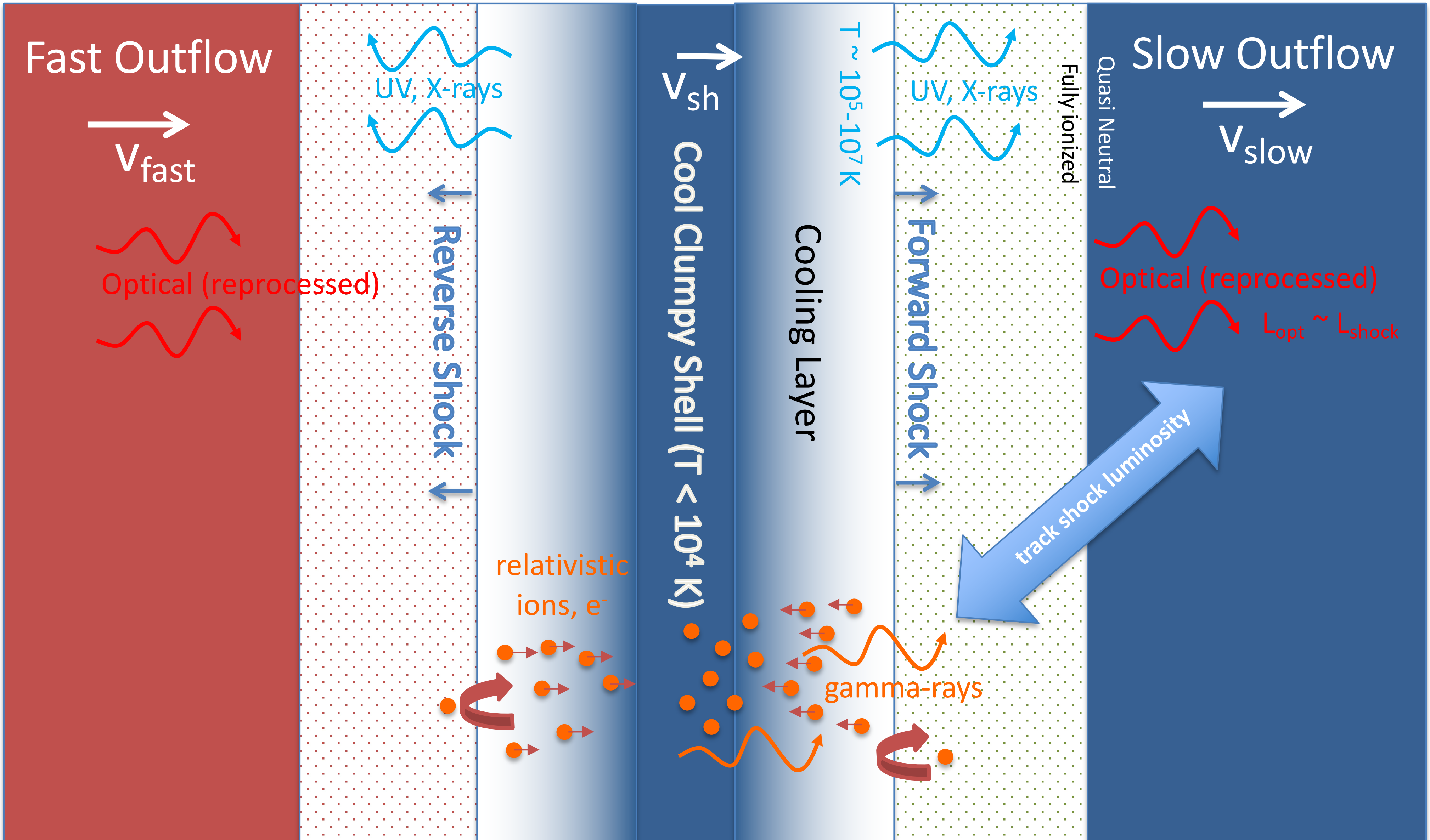
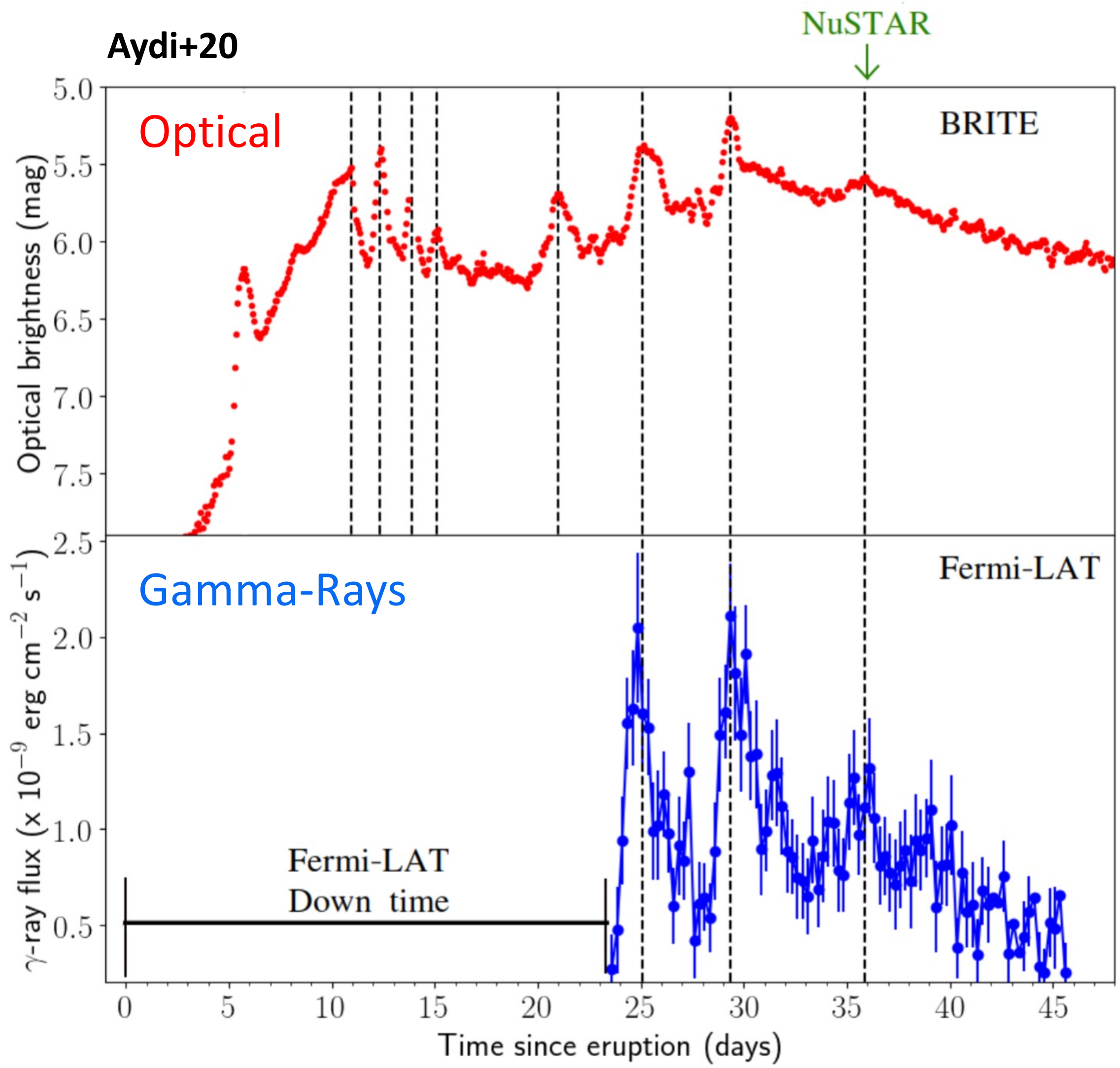


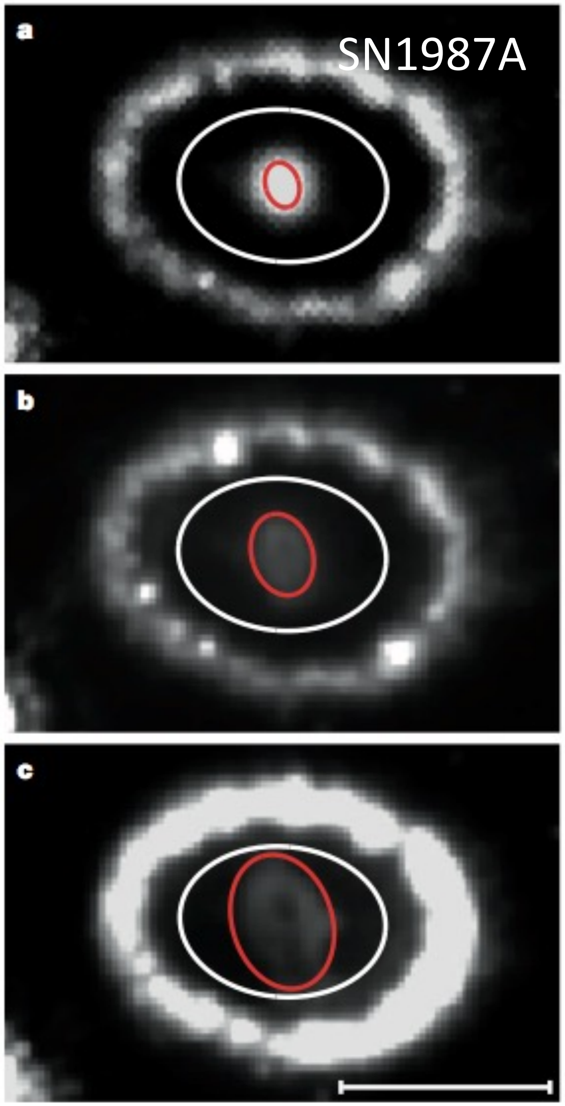
Optical/Gamma-ray Correlation

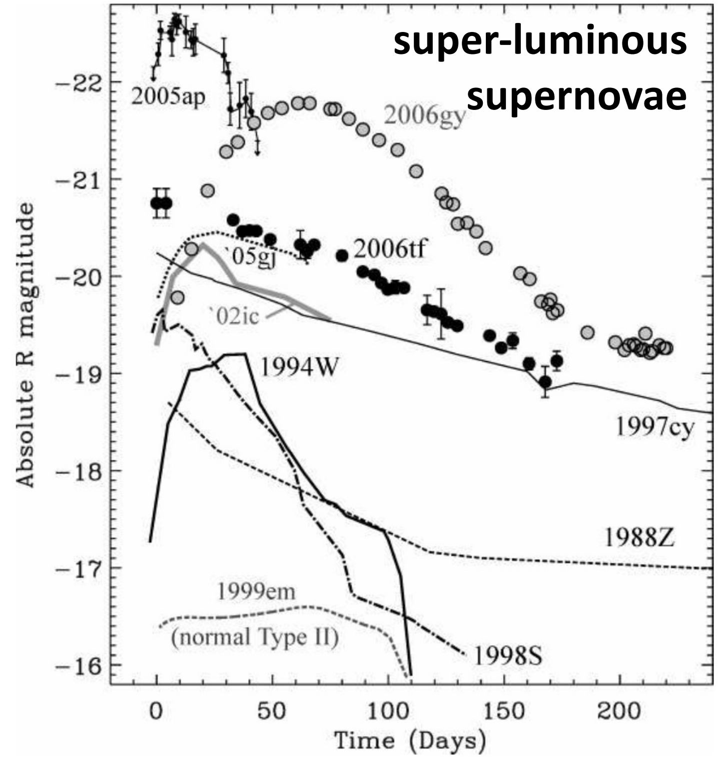


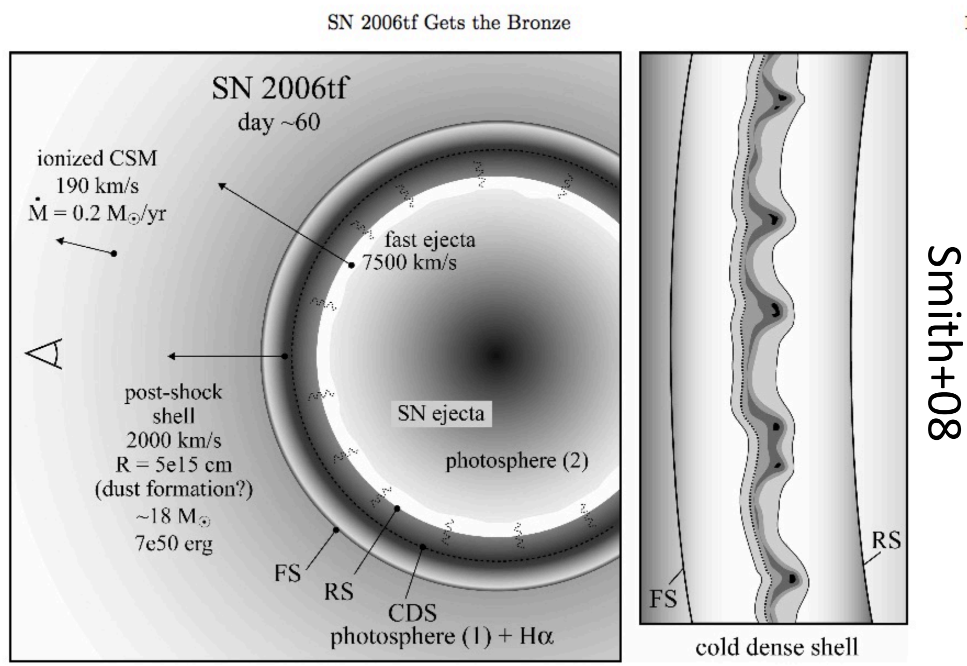
Implications

- **Large fraction of optical luminosity is shock-powered (not directly white dwarf)**
- **Super-Eddington luminosities without violating Eddington limit**
- **Ratio of optical to gamma-ray luminosity probes particle acceleration efficiency**

Interaction-Powered Supernovae







Smith+08

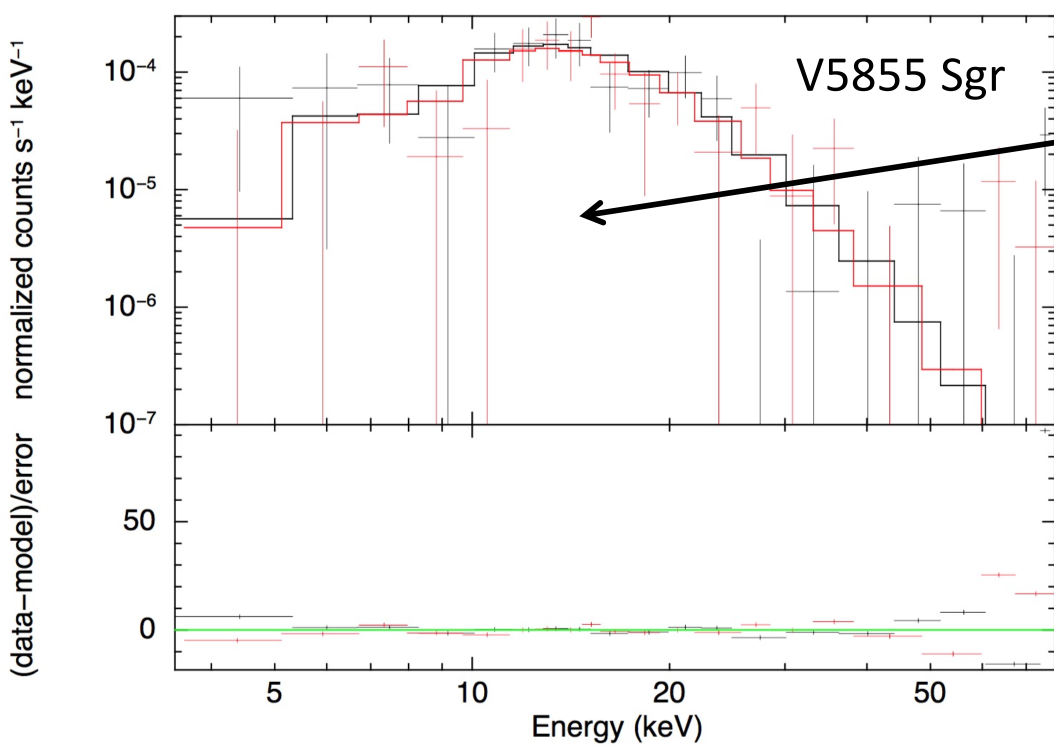
NuSTAR detections

contemporaneous with LAT detections

Nelson+19; Sokolovsky+20

Naïve expectation:

$L_X \sim L_{opt} \sim 100 L_\gamma = 10^{37} - 10^{38}$ erg s^{-1}

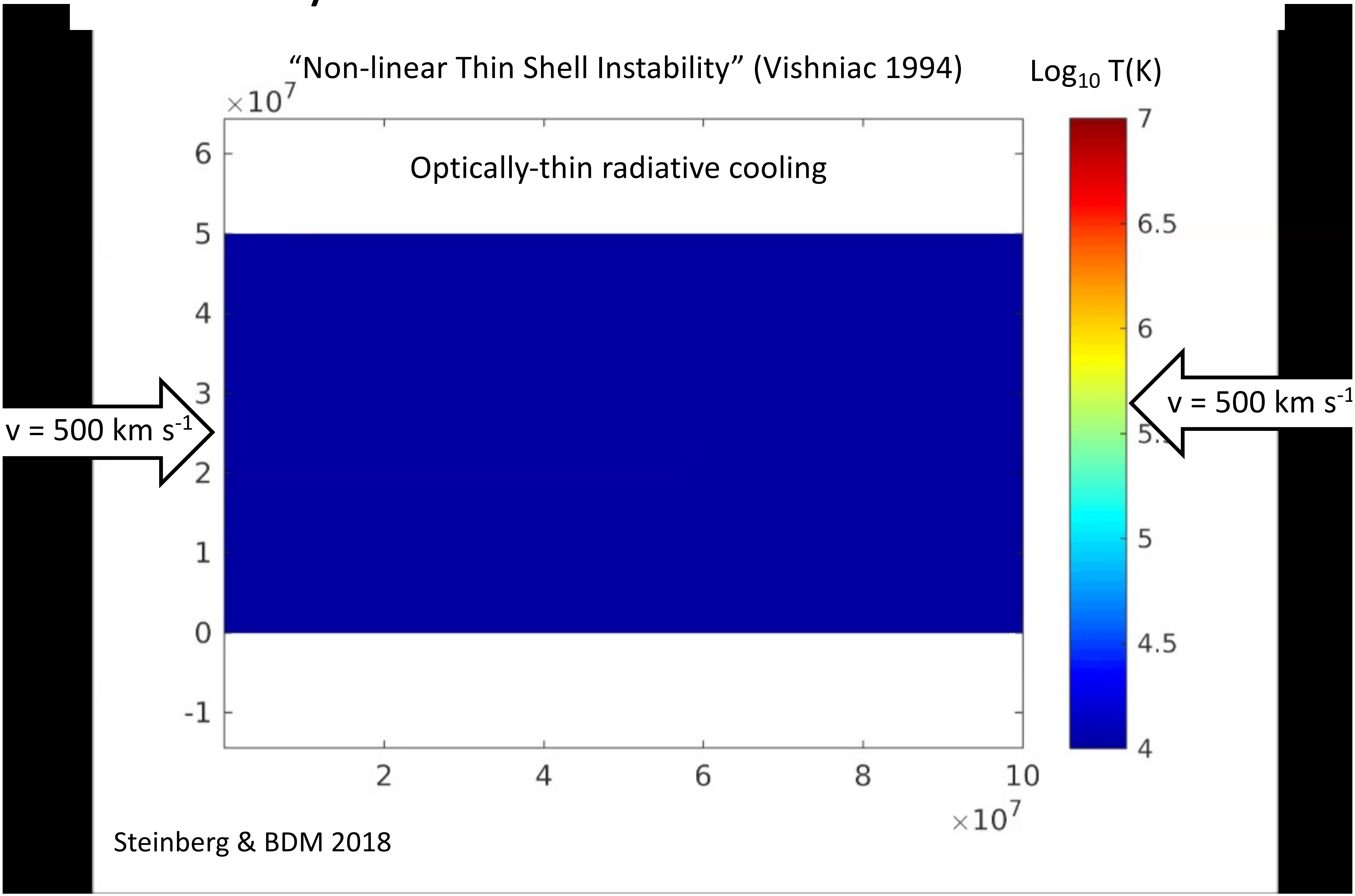


Unabsorbed luminosity

$L_X \sim$ few 10^{34} erg s^{-1}

Why are the X-rays so dim?

2D Hydro Simulation of Radiative Shocks



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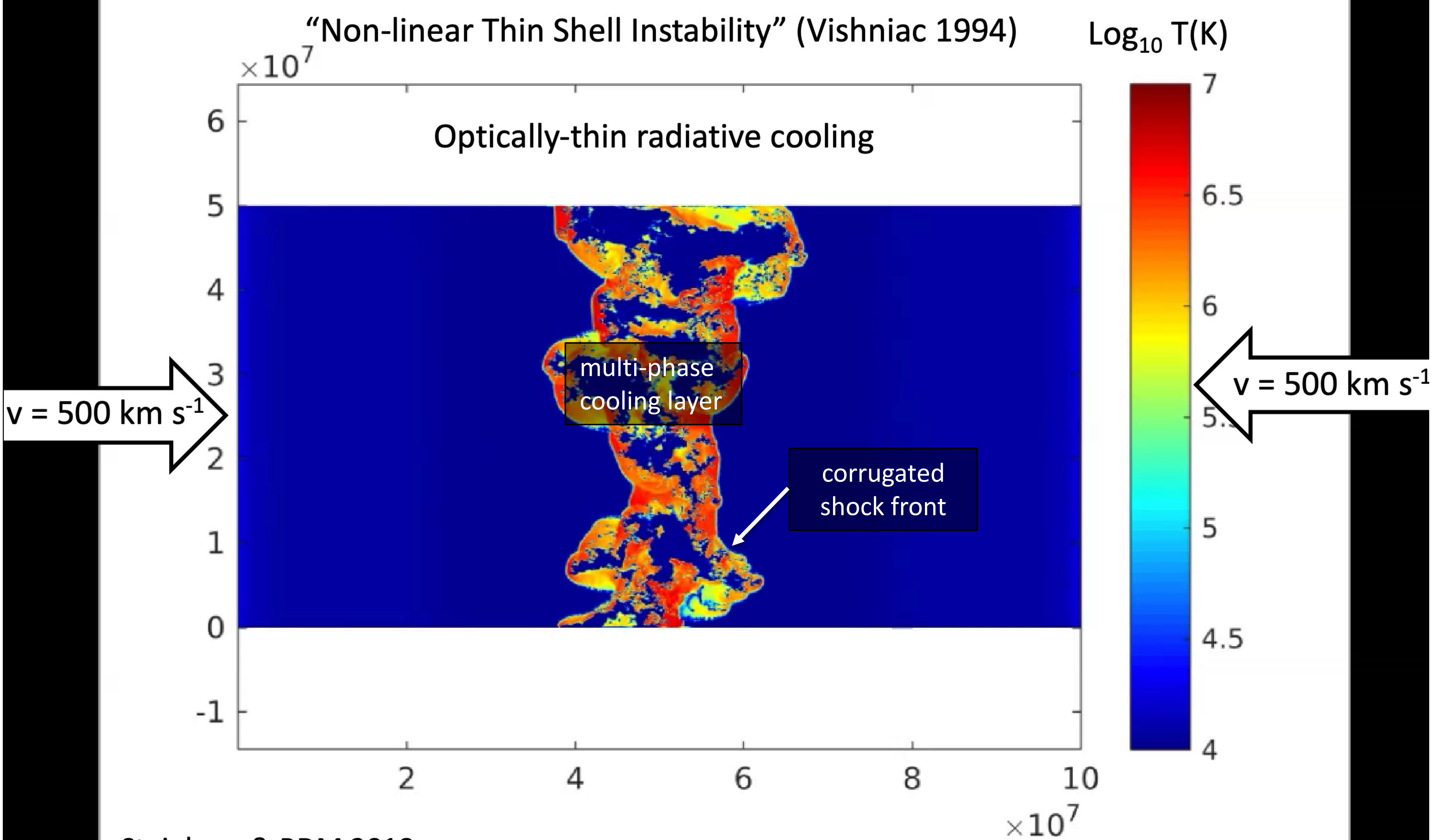
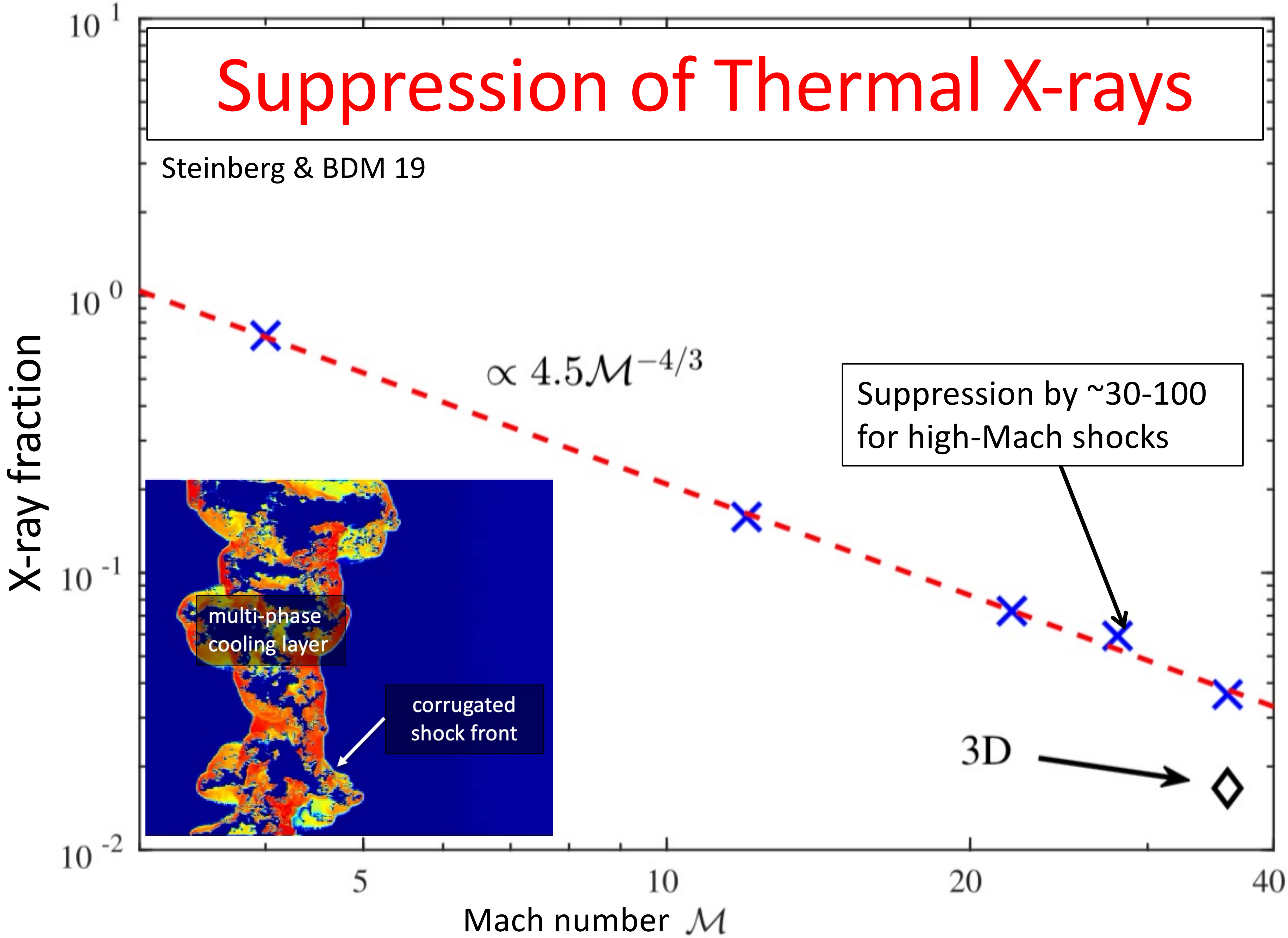


Steinberg & BDM 2018



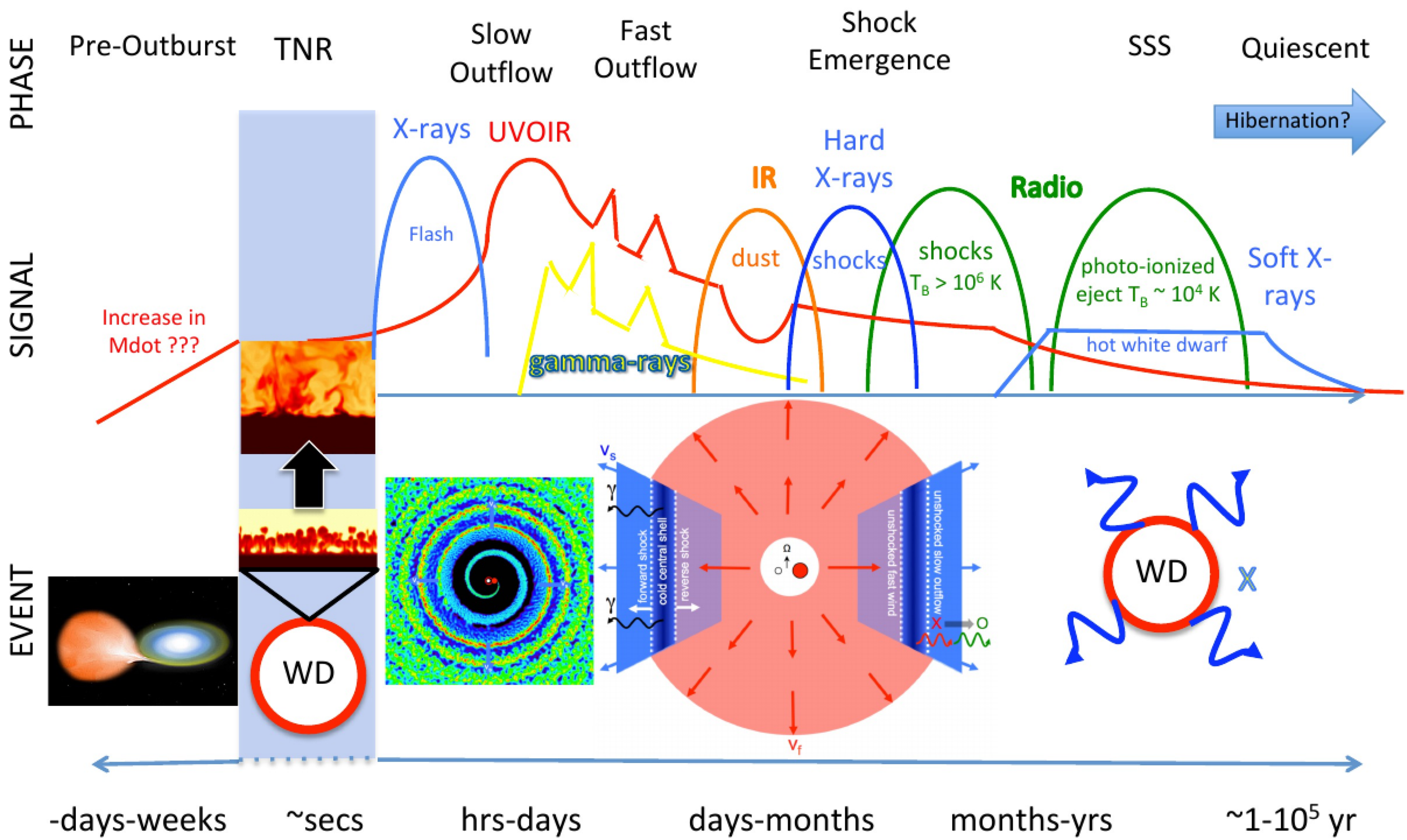
Suppression of Thermal X-rays
Steinberg & BDM 19
$\propto 4.5\mathcal{M}^{-4/3}$
Suppression by ~30-100
for high-Mach shocks
3D
multi-phase
cooling layer
corrugated
shock front
X-ray fraction
10^{1}
10^{0}
10^{-1}
10^{-2}
5
10
20
40
Mach number $\mathcal{M}$

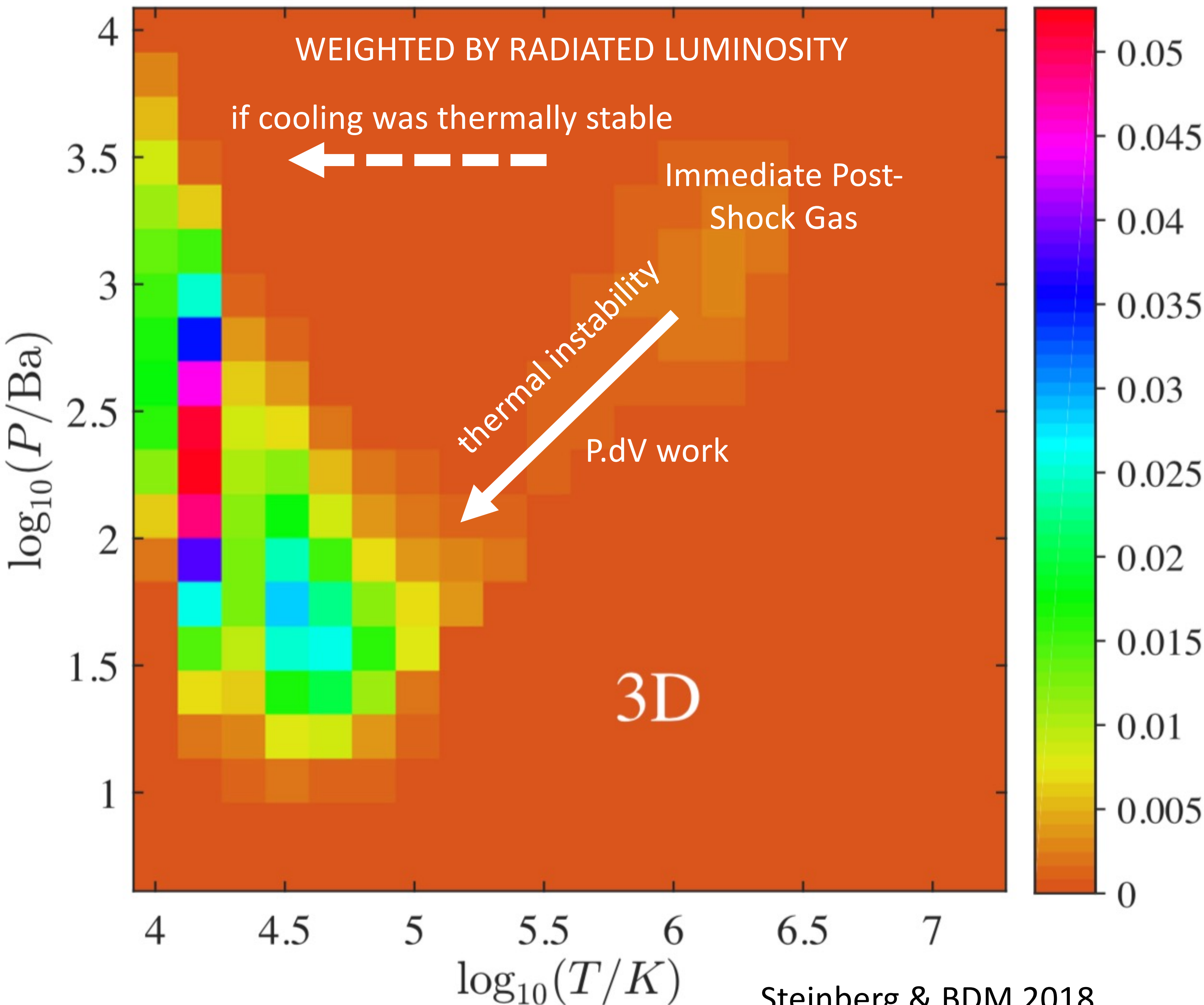
A Shocking New Paradigm for Nova Emission

- The discovery of luminous GeV gamma-rays from novae establishes shocks & relativistic particle acceleration as key features of these events.
- Shocks arise from internal collisions between different phases of outburst, as evidenced from optical spectroscopy (Elias talk) and late radio/optical imaging
- Hadronic emission mechanism favored over leptonic one => ion acceleration
- High ejecta densities => shocks **radiative** for both thermal and relativistic particles
  - Significant fraction of optical luminosity/variability can arise from shocks instead of WD envelope
  - New explanation for super-Eddington luminosities?
  - Can directly measure relativistic particle acceleration efficiency via calorimetry
  - Huge compression and instabilities provide natural source of clumpiness & dust formation
- Open Questions for Nova Theory:
  - At least two “modes” of mass-loss (“common-envelope”-like and “wind”-like) with abrupt transitions (“mode-switching”) between them
  - Ejecta geometry implies key role of binary interaction how to capture in 1D models? extend to multi-dimensions while capturing nuclear physics?
  - Impact on binary angular momentum? Implications for CV evolution?
  - Contributions of shock emission must be considered in light curve modeling. Implications for optical/NUV spectra?
  - Why are the shock X-rays so weak?

A Shocking New Paradigm for Novae

(Chomiuk, Metzger & Shen, ARAA *in press*)





Steinberg & BDM 2018