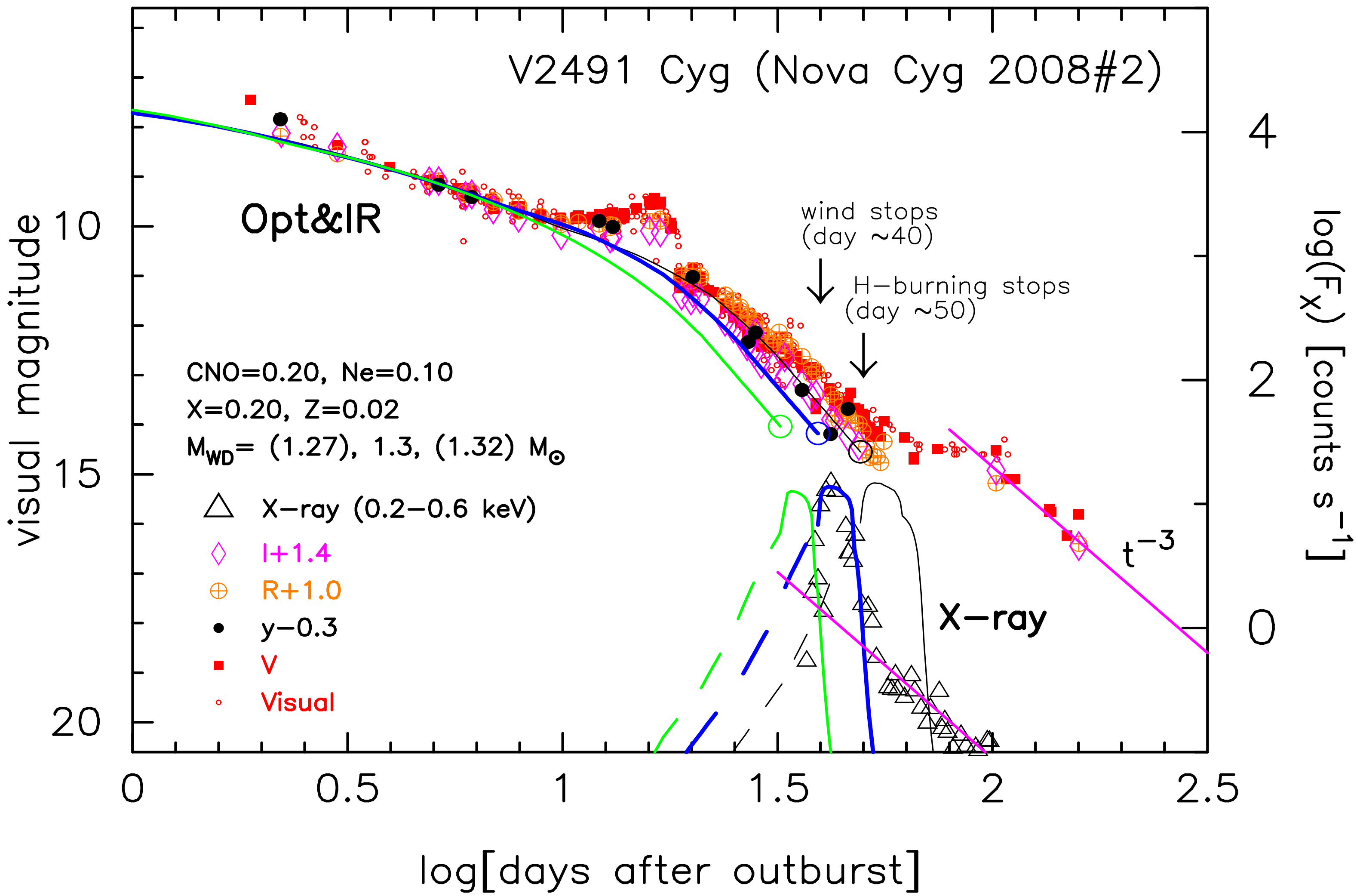
A Light Curve Model of the Shortest Superso
X-ray Phase of V2491 Cyg

Izumi Hachisu (University of Tokyo)

collaborated with Mariko Kato (Keio University)

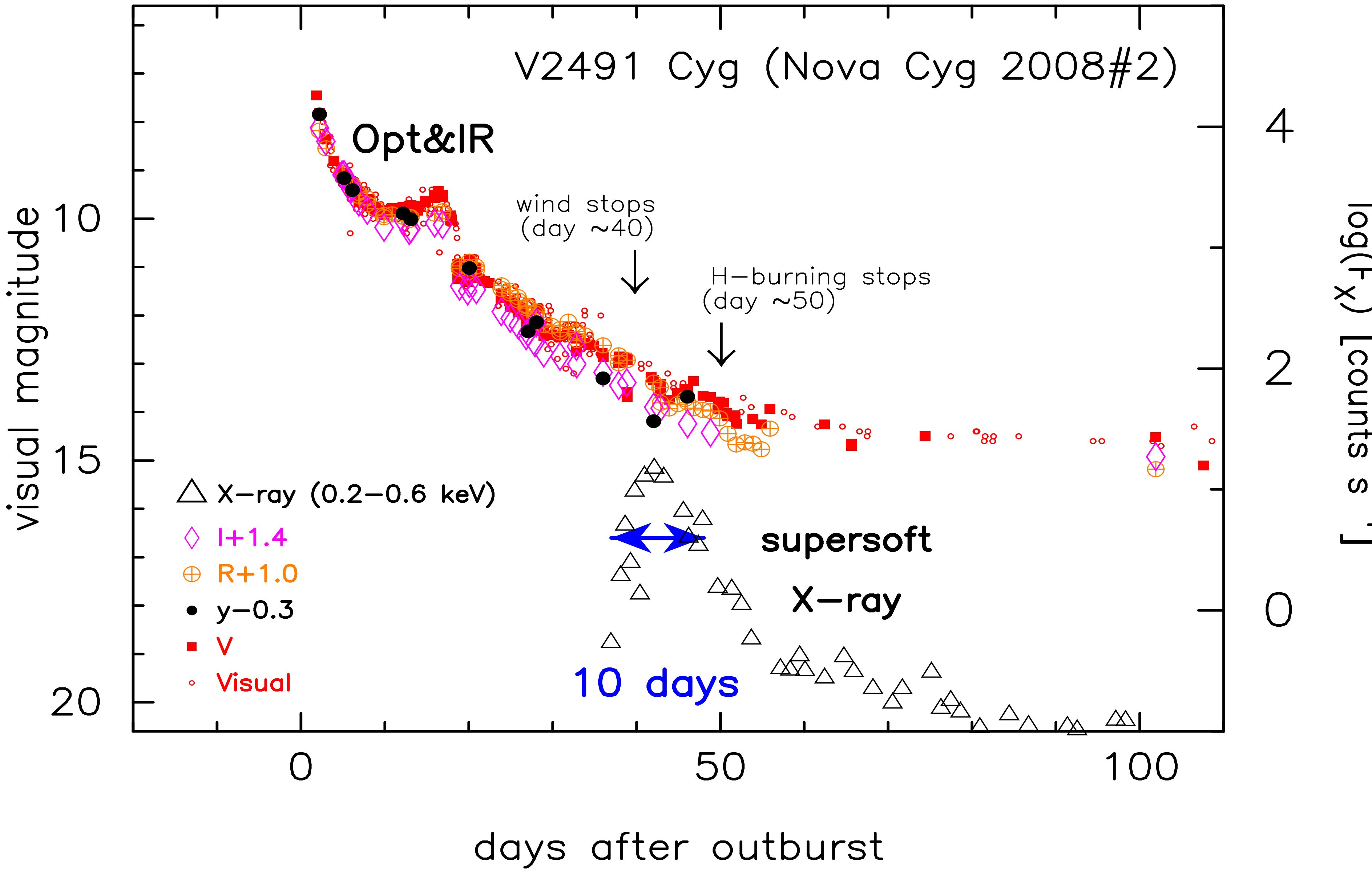


Unique Characteristics of V2491 Cyg

- ● Rapid optical decline with a secondary peak
  → Massive White Dwarf (1.3 Mo ?)
- ○ Very short supersoft X-ray duration (∽10 days)
  cf. ∽60 days in RS Oph (1.35 Mo WD)
- ○ Superhard X-ray (15-70 keV) was detected
  with Suzaku (HXD) on Day 10 (Takei et al. 2009)
  → power-law → non-thermal origin
  → strong magnetic field ?
- ○ X-ray detection from pre-nova (Ibarra et al. 2009)
  → Magnetic Cataclysmic Variable (?)
  → Polar System ? (∽10^7 G)

Rapid optical decline/secondary peak

- **t2=4.6 days** (Tomov et al. 2008), **t3=7-8 days**



AAVSO, VSOLJ, Hachisu & Kato (2009)

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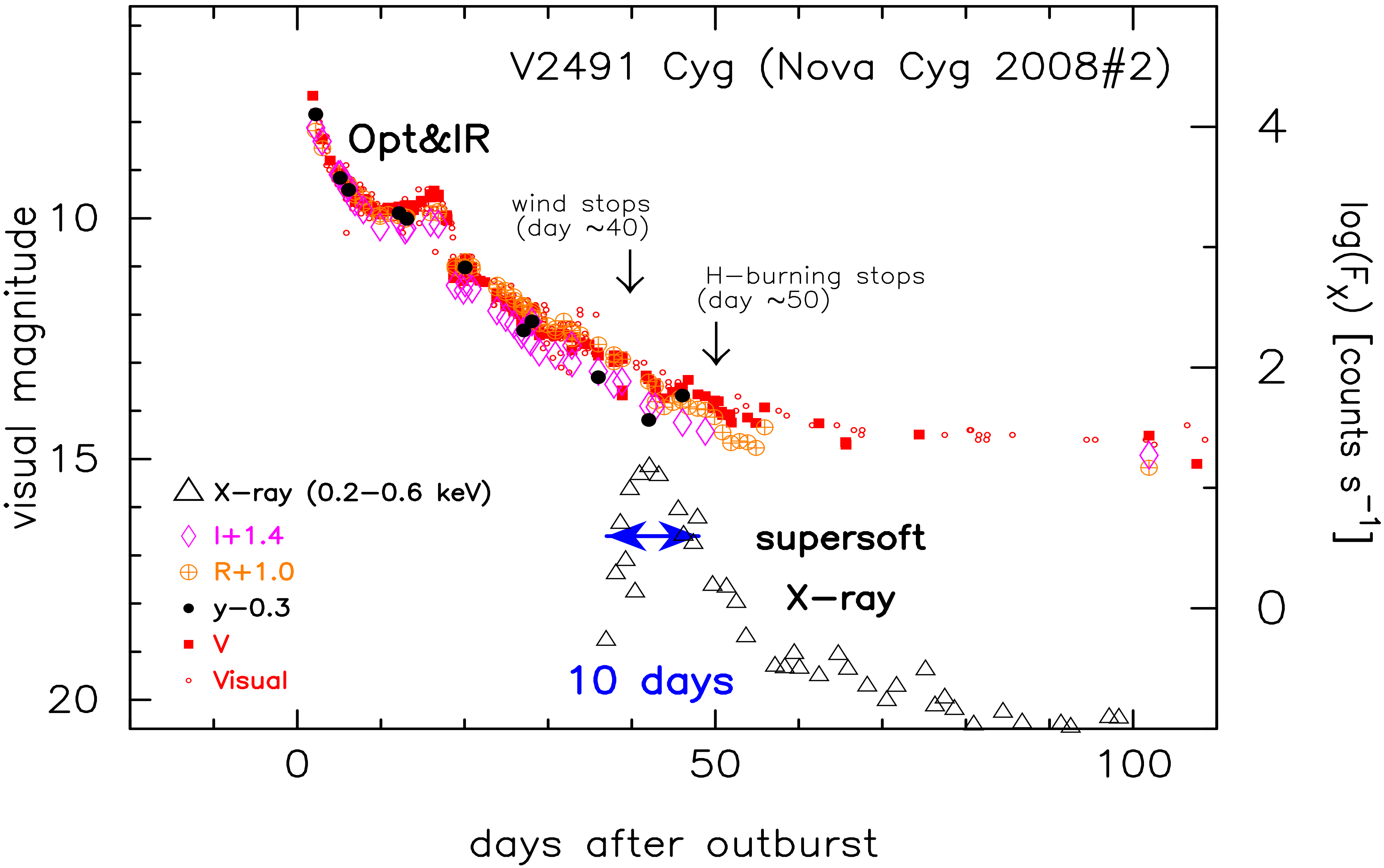
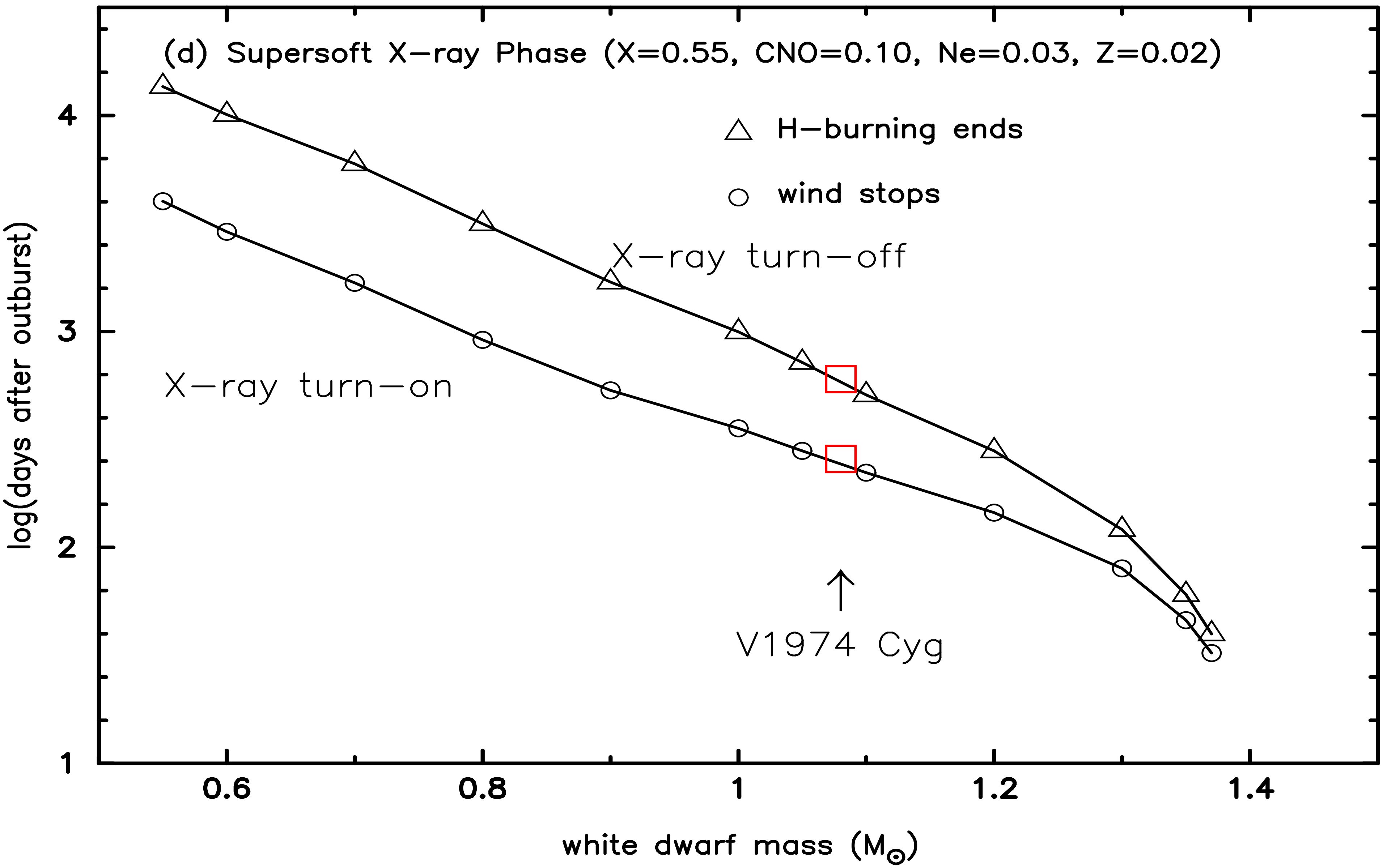


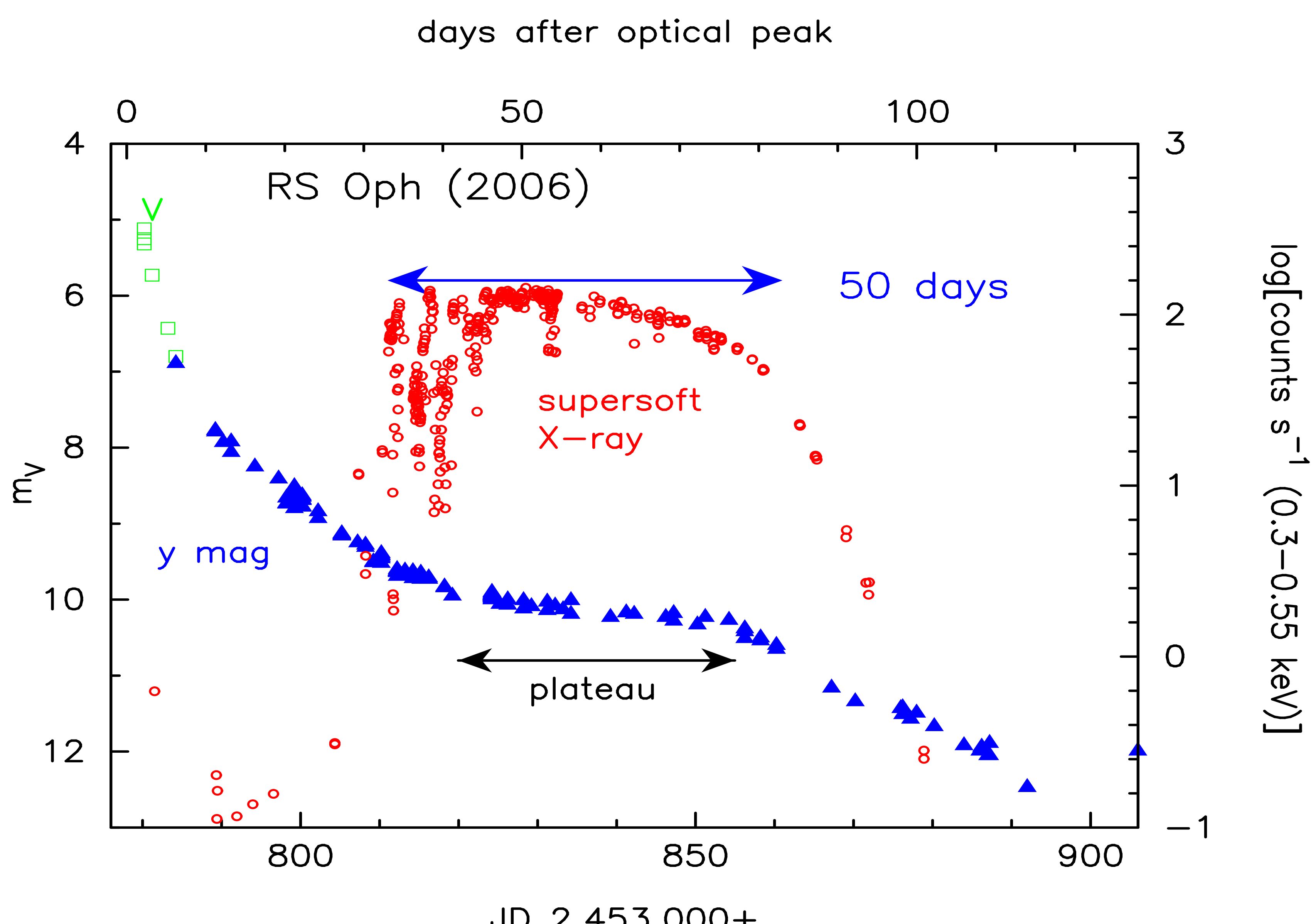
Hachisu & Kato (2009), Page et al. (2009), Osborn (today's talk)

Very short supersoft X-ray duration



Hachisu & Kato (2006)

Long SSS duration of RS Oph (2006)



Hachisu et al. (2006)

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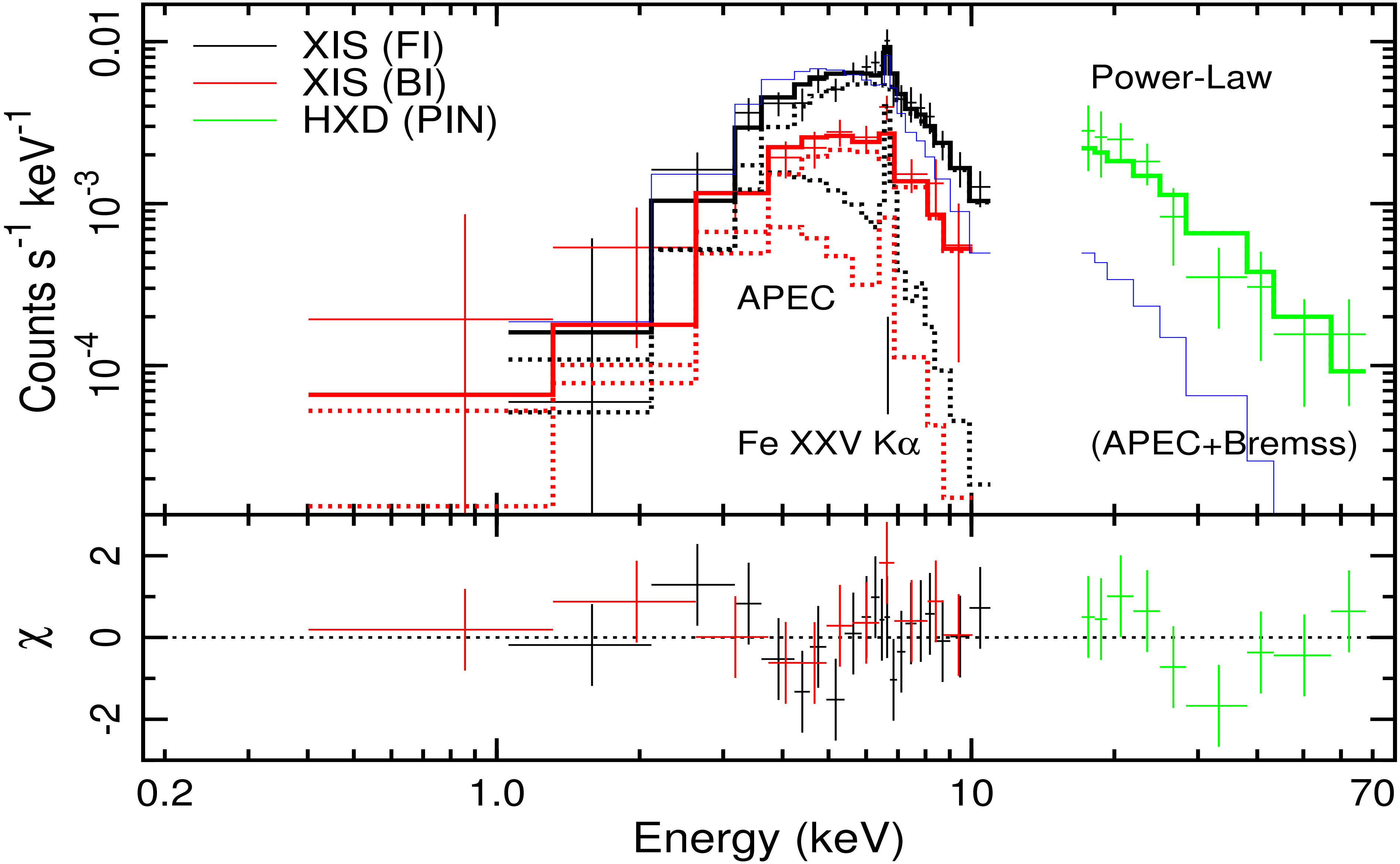
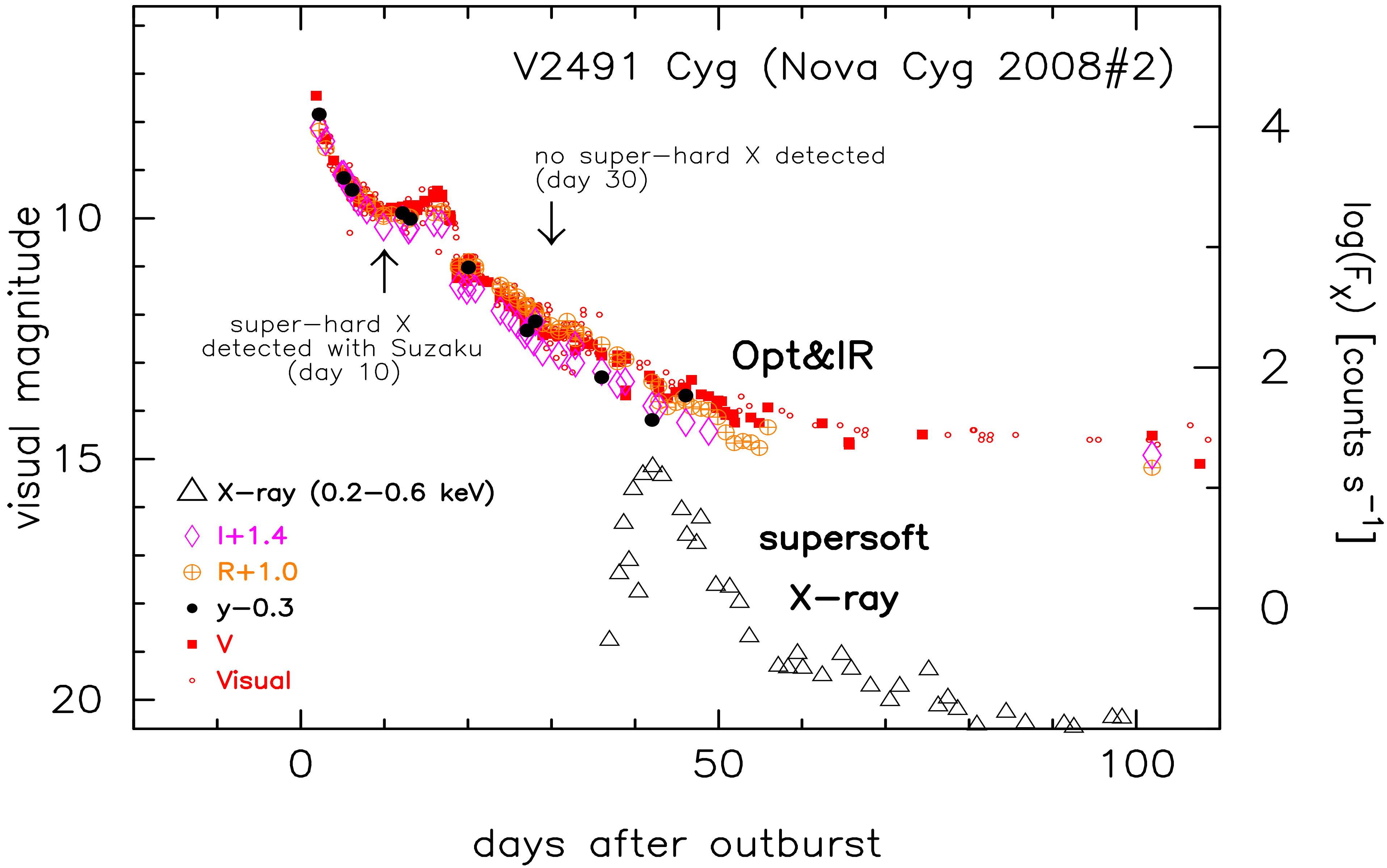
Superhard X-ray detected on Day 10



Takei et al. (2009), Takei (today's talk)

Just before the secondary peak



AAVSO, VSOLJ, Hachisu & Kato (2009)

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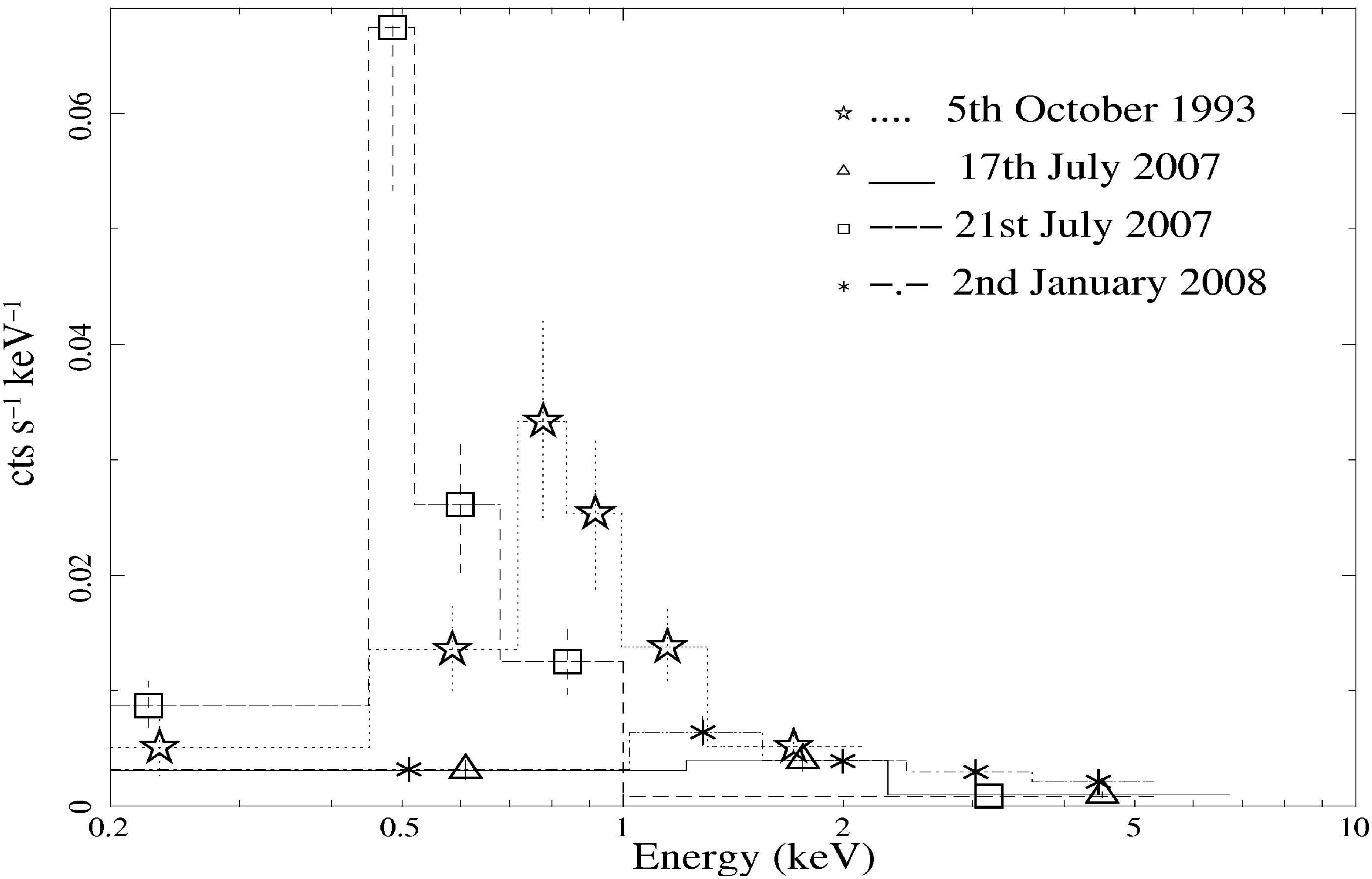
X-ray detection from pre-nova



Ibarra et al. (2009)

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Two Main Objections of V2491 Cygn

- ○ **How do we understand such a short supersoft X-ray source phase ?**

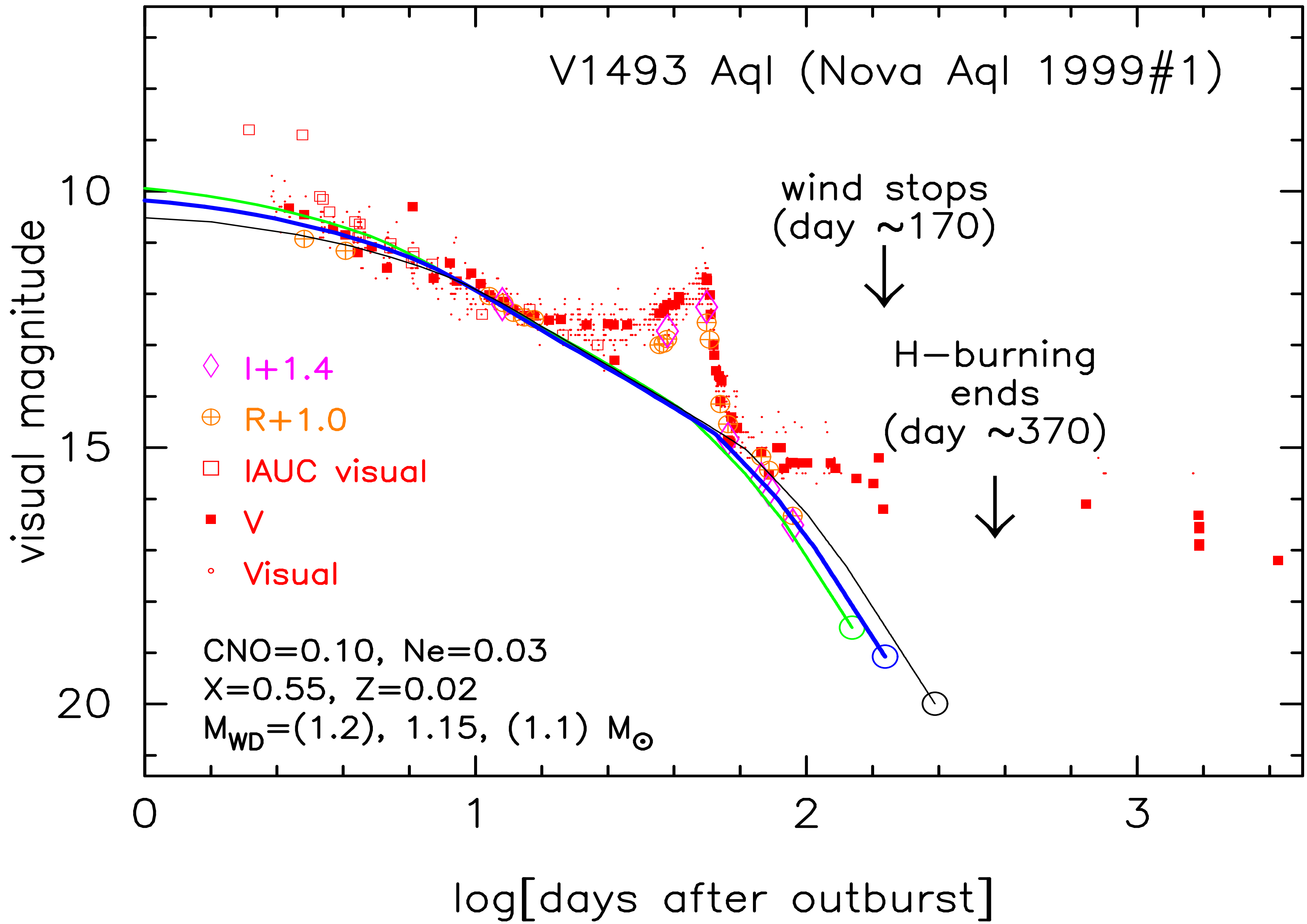
  → no thick He-layer beneath the H-burning zone
  ← thick He-layer of RS Oph (2006)

  → **white dwarf mass is so heavy but decreasing ?**

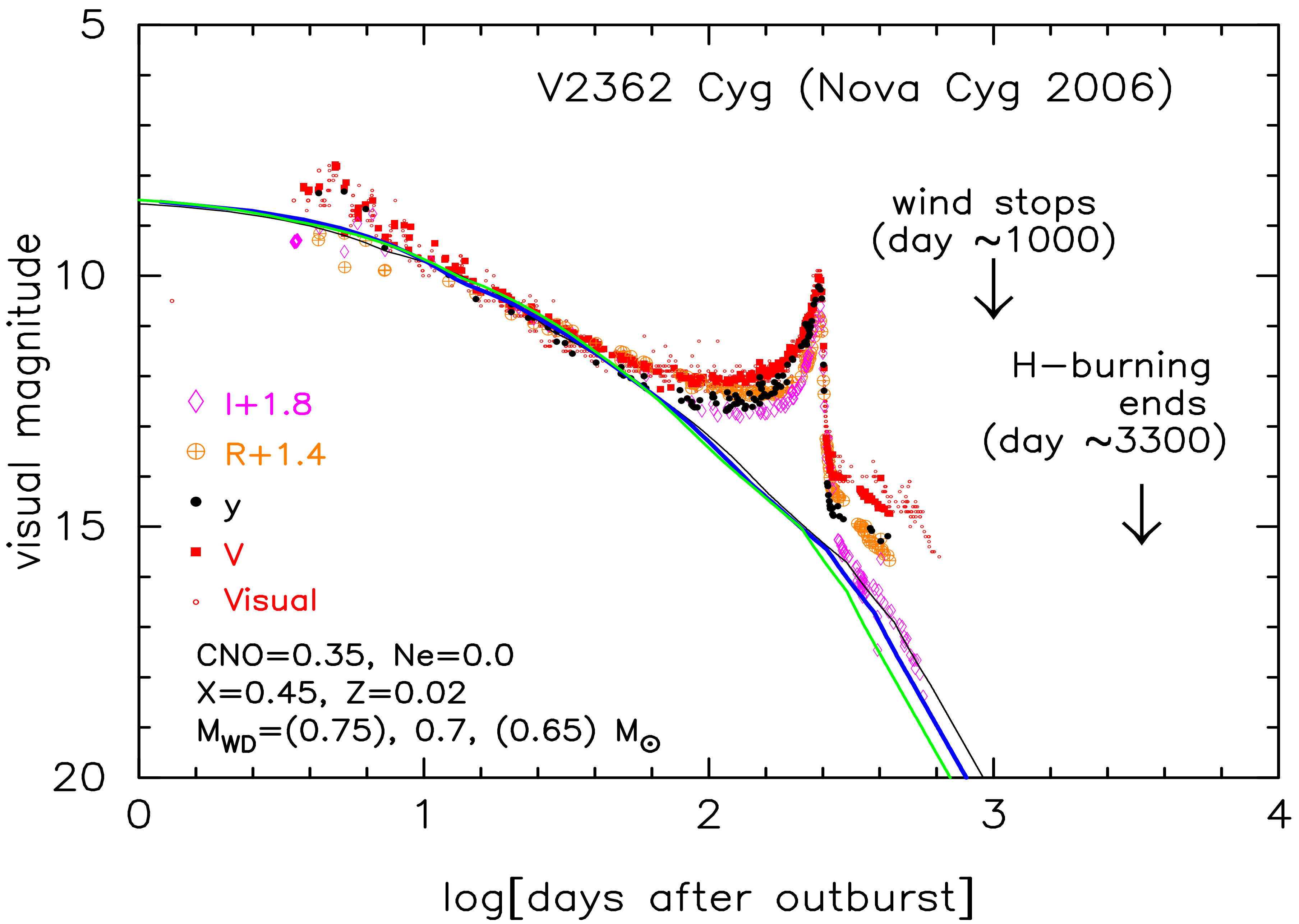
- ○ **What is the mechanism of the secondary peak ?**

  → magnetic reconnection as the energy source
  → superhard X-ray photon before the 2nd peak
  Two other twins, V1493 Aql and V2362 Cyg, show the same 2nd peak

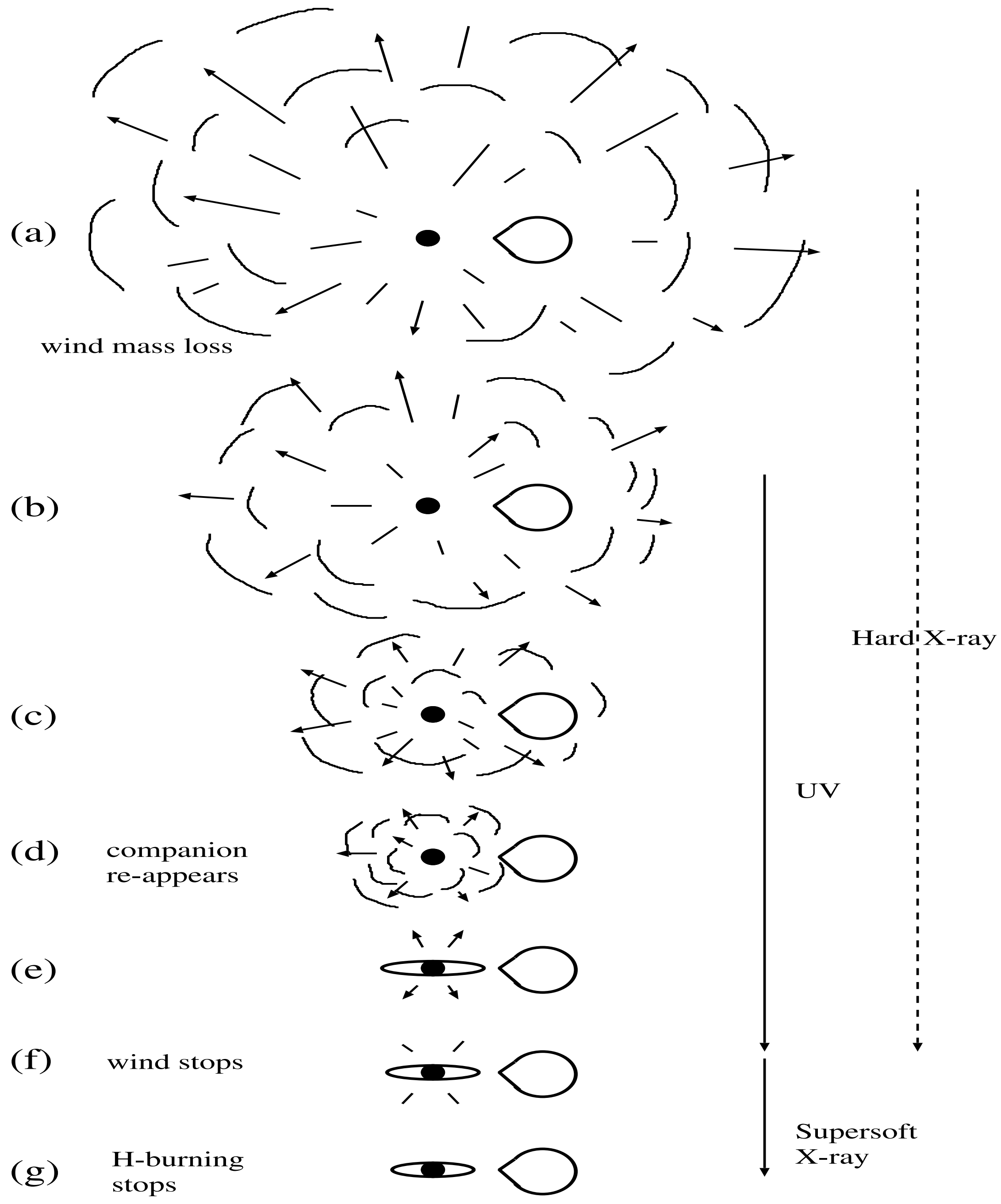
Optical Light Curve of V1493 Aql



Optical Light Curve of V2362 Cyg

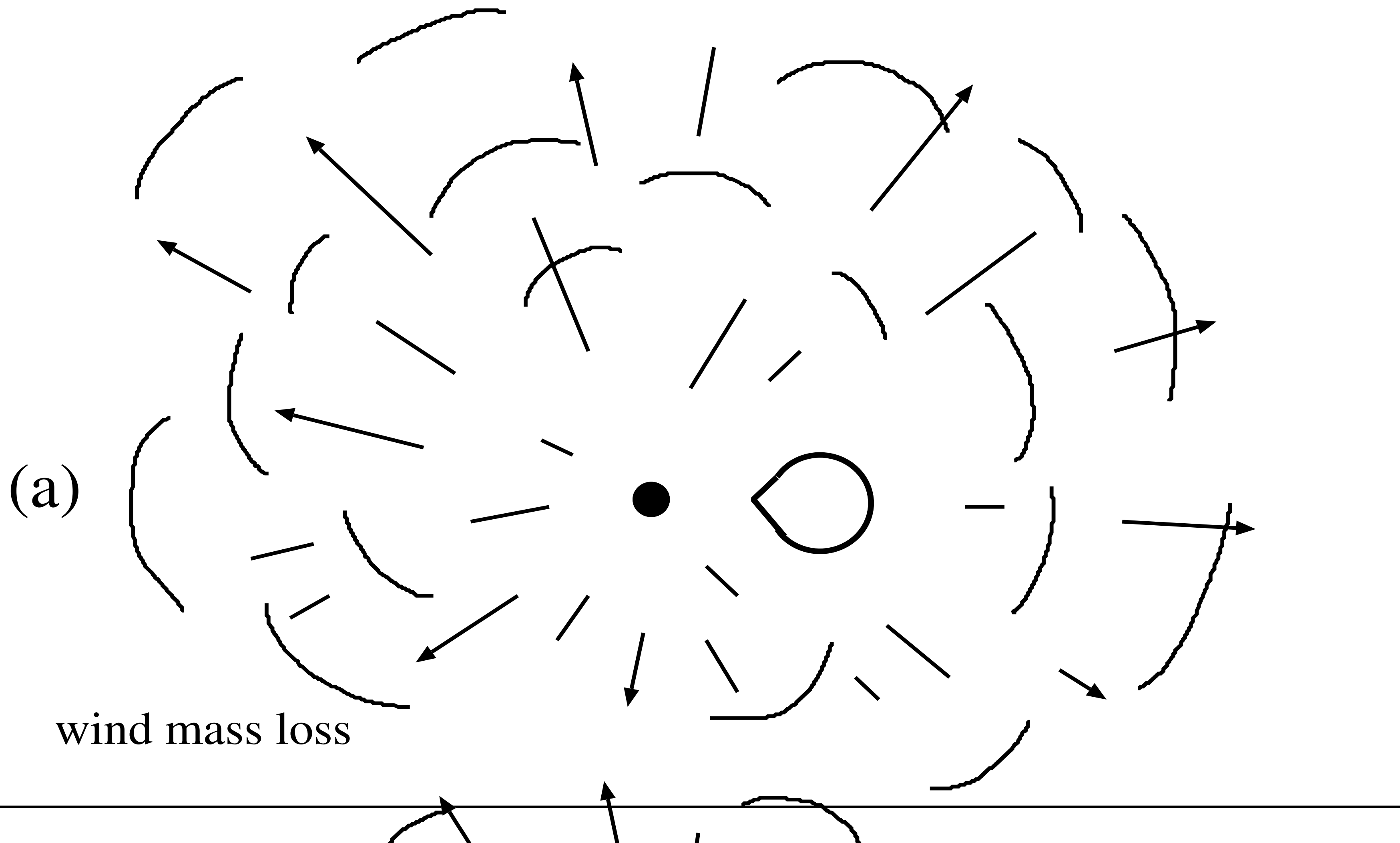


Evolution of Classical Novae



WD envelope model

- Spherical symmetry
- Steady-state



Basic equations of WD winds

$$\dot{M} = 4\pi r^2 \rho v = \mathrm{const.}$$, continuity

$$v\frac{dv}{dr} + \frac{1}{\rho}\frac{dP}{dr} + \frac{GM}{r^2} = 0$$, equation of motion

$$P = \frac{\rho k T}{\mu m_a} + \frac{1}{3}aT^4$$, equation of state

$$\frac{dT}{dr} = -\frac{3\kappa\rho L_r}{16\pi a c T^3 r^2}$$, diffusion equation

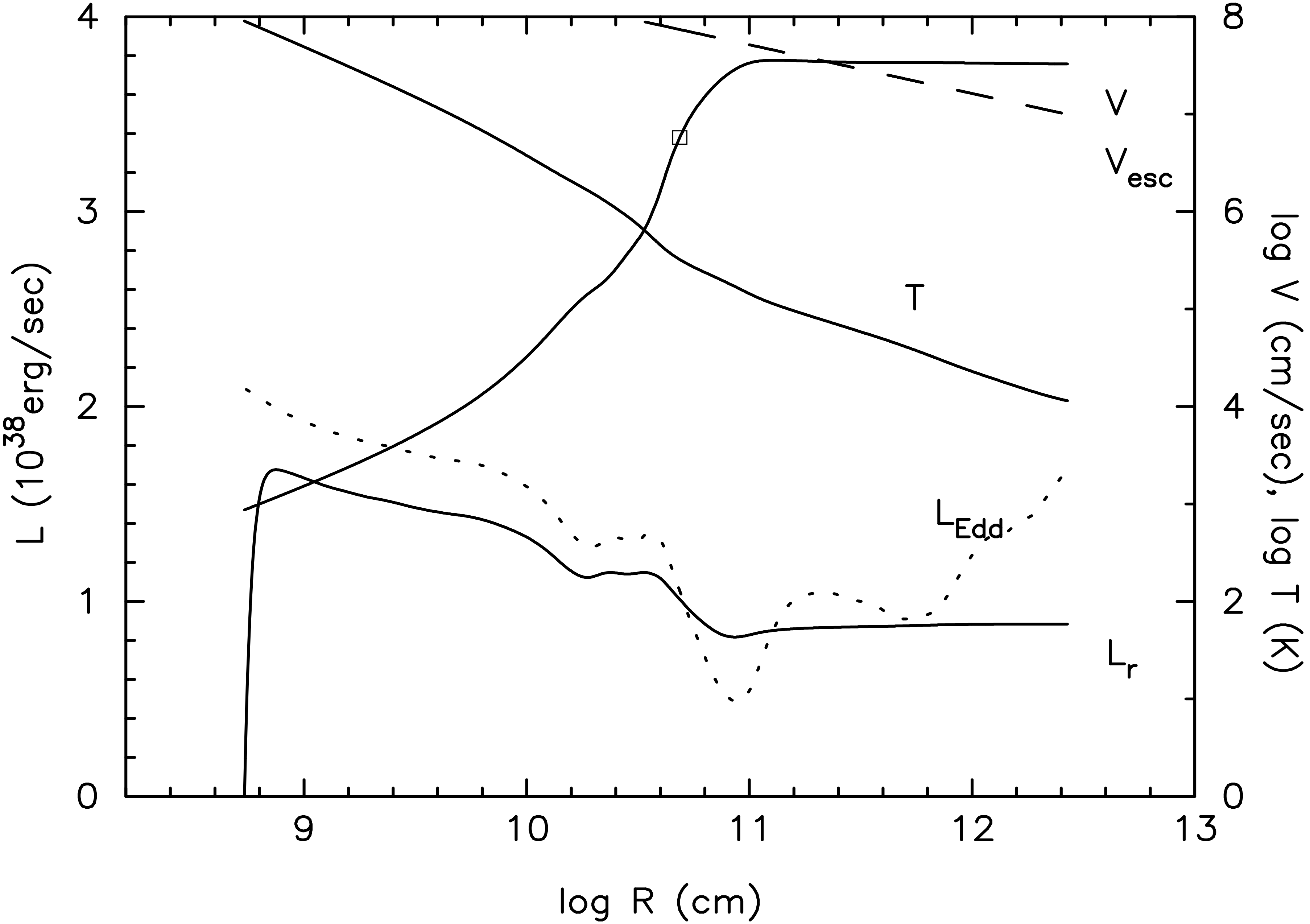
$$\Lambda = L_r + \dot{M}\left(\frac{v^2}{2} + w - \frac{GM}{r}\right) = \mathrm{const.}$$, energy

$$w = \frac{5}{2}\frac{kT}{\mu m_a} + \frac{4aT^4}{3\rho}$$, enthalpy

$$L_{\mathrm{total}} = L_r + L_{\mathrm{advection}}$$, total luminosity

$$L_{\mathrm{advection}} = \frac{4aT^4}{3\rho}\dot{M}$$, advection luminosity

Wind solution



Time evolution of WD envelope

For a given set of $(M_{\rm WD},\ R_{\rm WD},\ X,\ Y,\ Z)$

1. a series of wind solutions with decreasing ΔM

$$R_{\rm ph}(\Delta M),\quad T_{\rm ph}(\Delta M),\quad v_{\rm ph}(\Delta M)$$

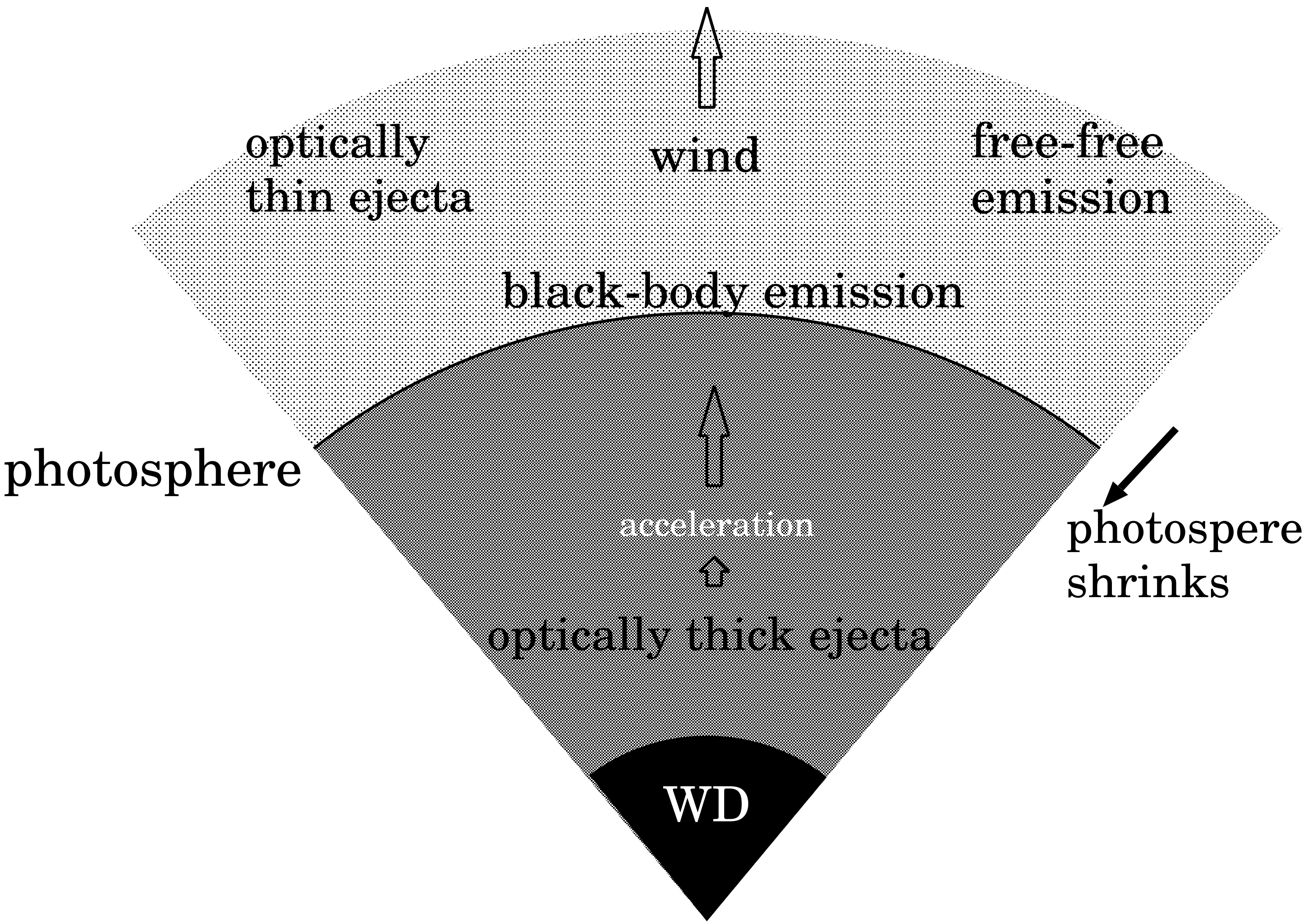
$$\dot{M}_{\rm wind}(\Delta M),\quad \dot{M}_{\rm nuc}(\Delta M)$$

2. time-sequence is mimicked by a decreasing ΔM-sequence due to wind mass loss and nuclear burning

$$\frac{d}{dt}\Delta M = \dot{M}_{\rm acc} - \dot{M}_{\rm wind}(\Delta M) - \dot{M}_{\rm nuc}(\Delta M$$

Optical & near-IR Light Curves

○ Free-free emission from optically thin plasma



Formula of free-free emission

$$
\begin{aligned}
j_\nu d\Omega dV dt d\nu \quad &= \quad \frac{16}{3}\left(\frac{\pi}{6}\right)^{1/2}\frac{e^6 Z^2}{c^3 m_e^2}\left(\frac{m_e}{kT_e}\right)^{1/2} \\
&\times \quad g \exp\left(-\frac{h\nu}{kT_e}\right) N_e N_i d\Omega dV dt d\nu
\end{aligned} \tag{1}
$$

ν : frequency

j_ν : emissivity

m_e : electron mass

T_e : electron temperature

g : gaunt factor

N_e : electron number density

N_i : ion number density

Light Curve Model of Novae

○ **(OPT&IR) optically thick wind phase**

$$F_\nu \propto \int N_e N_i dV \propto \int_{R_{\rm ph}}^{\infty} \rho_{\rm wind}^2 r^2 dr$$

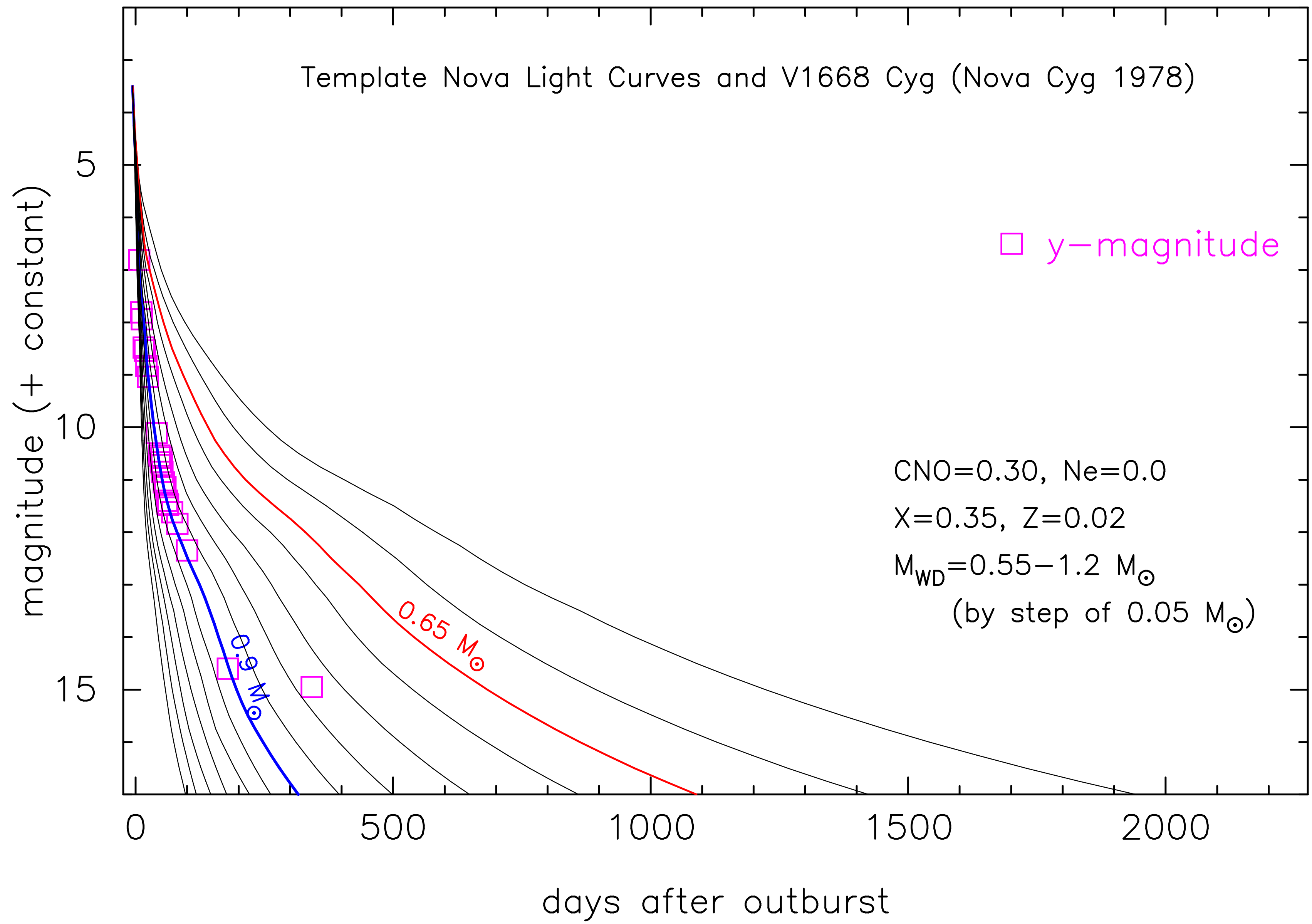
$$\propto \int_{R_{\rm ph}}^{\infty} \frac{\dot{M}_{\rm wind}^2}{v_{\rm ph}^2 \ r^4} r^2 dr = \frac{\dot{M}_{\rm wind}^2}{v_{\rm ph}^2 \ R_{\rm ph}}$$

○ **supersoft X-ray emission**

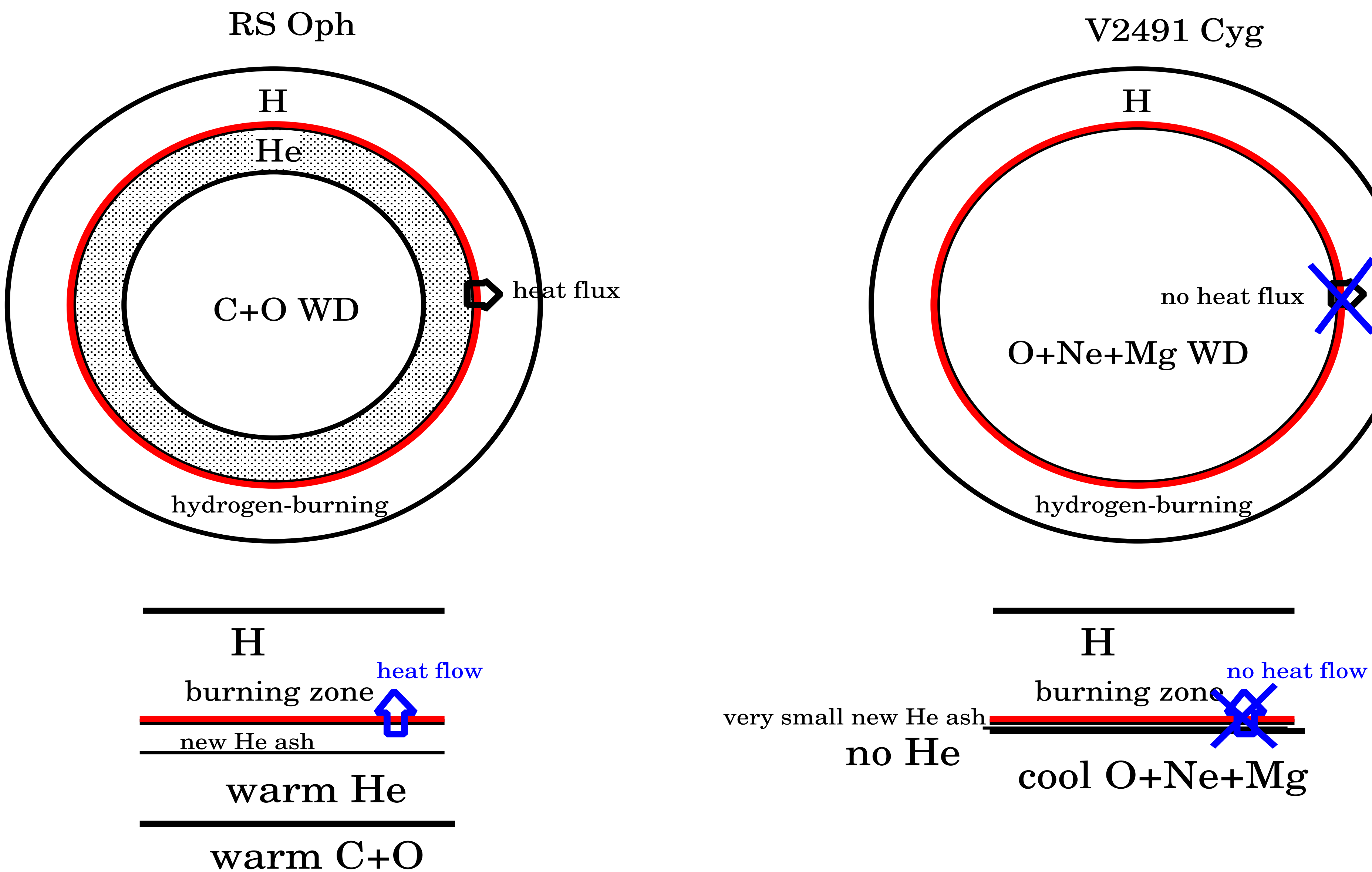
blackbody apporximation of photosphere

Model Light Curve (WD Mass)

- Timescale depends mainly on the WD mass



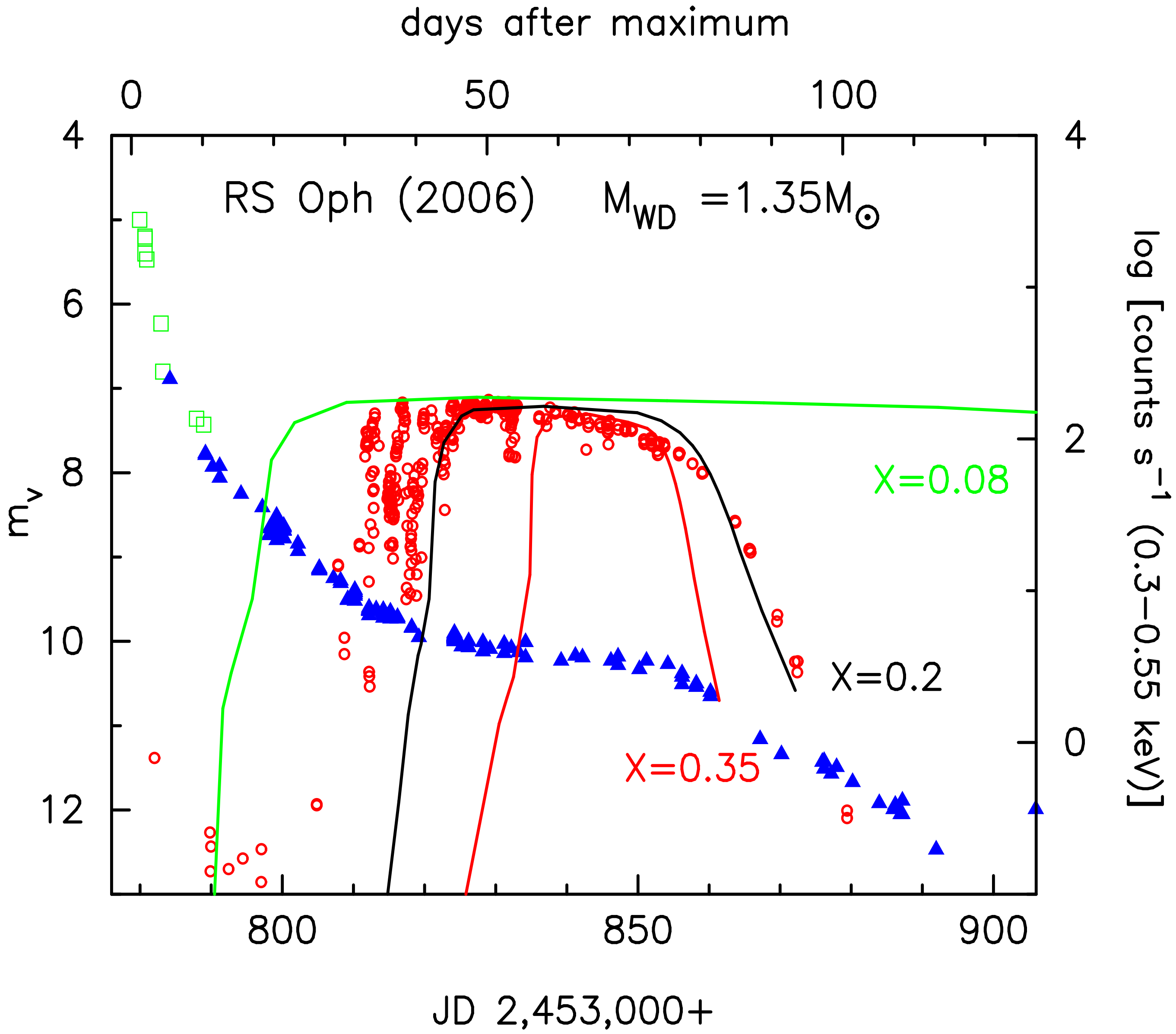
No helium layer was developed



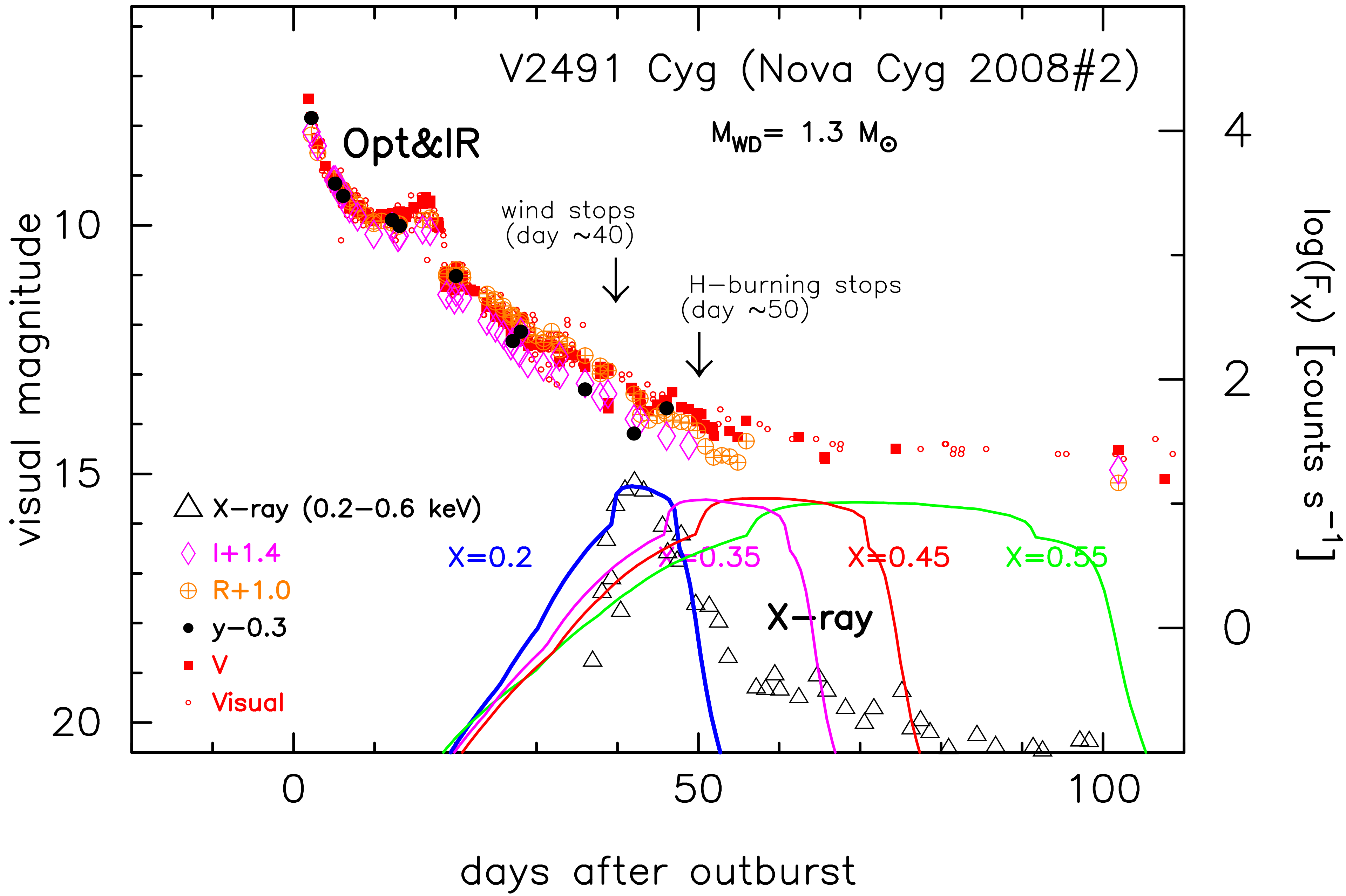
RS Oph 2006 vs. V2491 Cyg 2008

Early emergence of supersoft X-ray

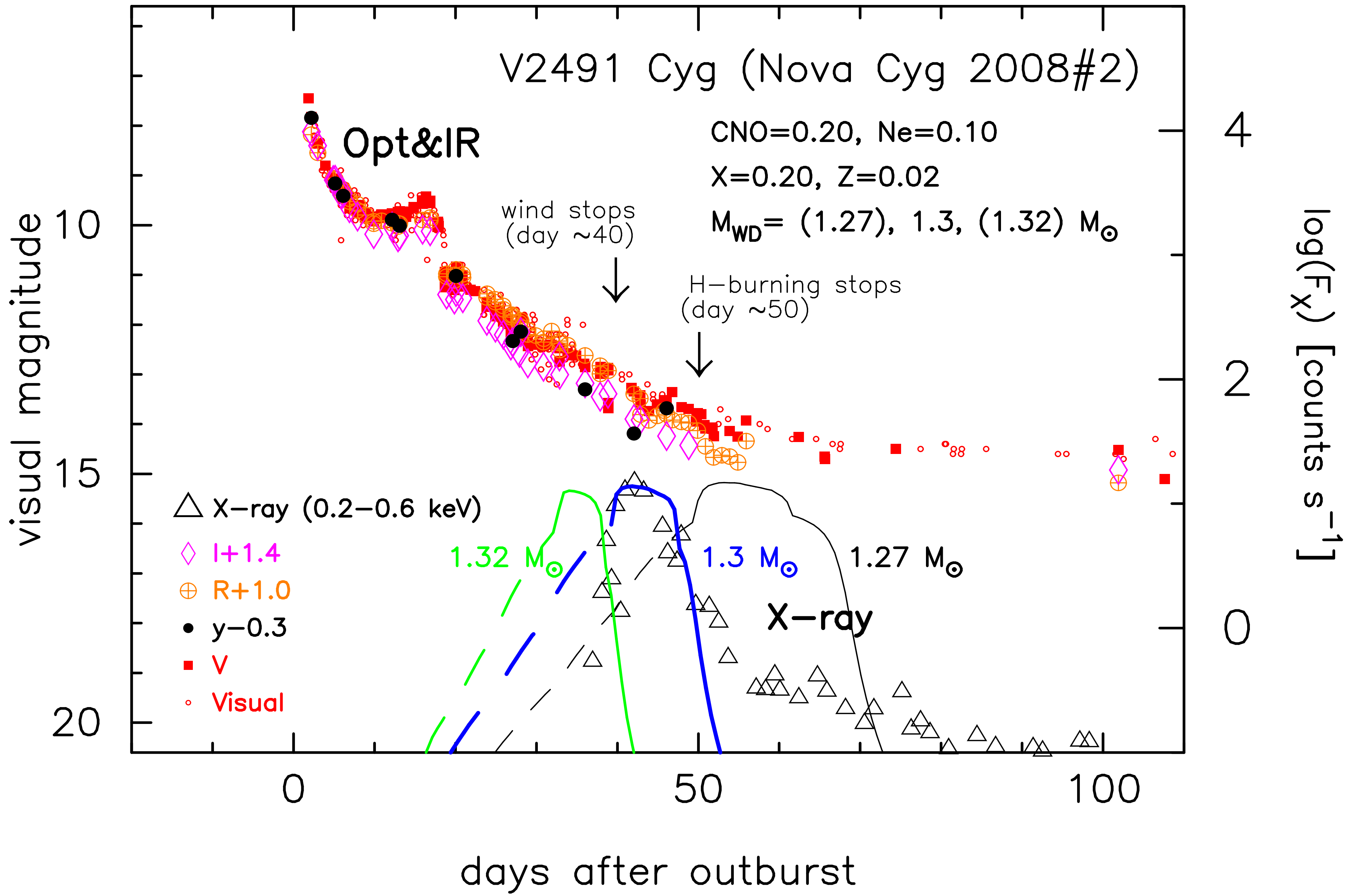
○ **depending on hydrogen content (X)**



Dependence of hydrogen content

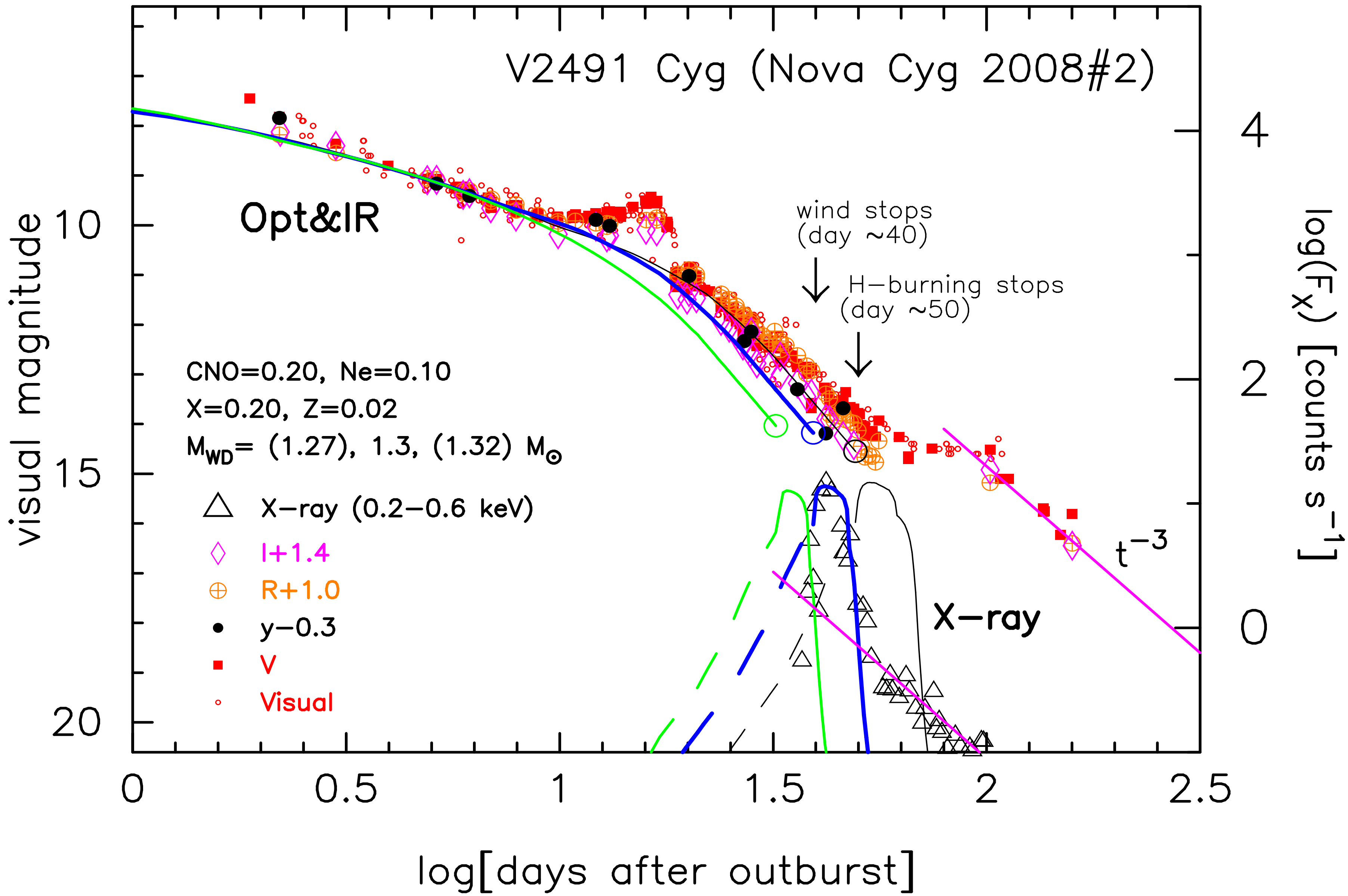


Dependence of WD mass



Opt. and supersoft X-ray light curves

(Hachisu & Kato, 2009, ApJL, 694, L103)



Summary of V2491 Cygni (1)

(Hachisu & Kato, 2009, ApJL, 694, L103)

1. **White Dwarf Mass by fitting**

$$M_{\rm WD} = 1.3 \pm 0.02 M_\odot \text{ for } X = 0.20$$

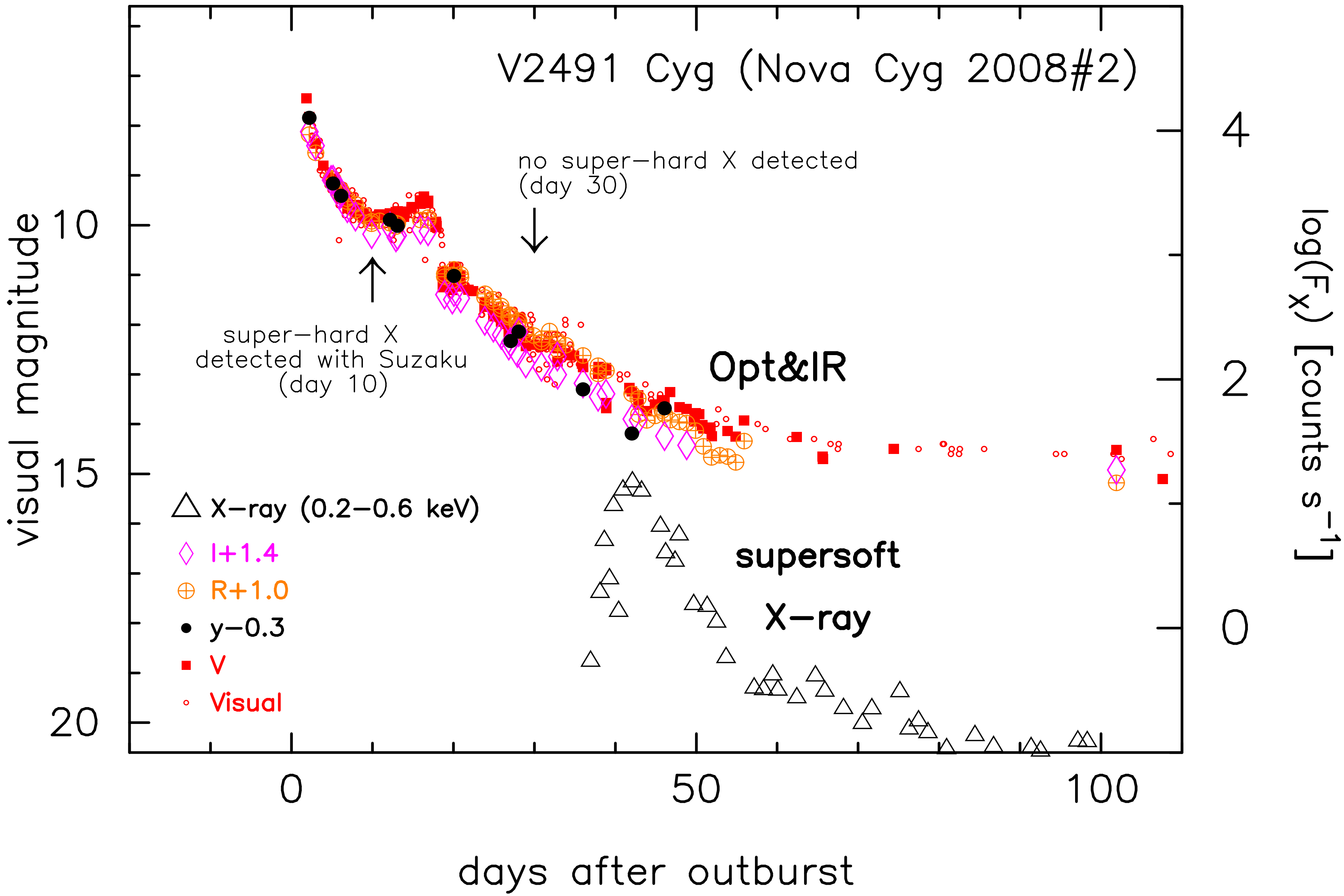
2. **No thick helium layer developed beneath the hydrogen shell-burning**

→ **WD mass does not increase but decreases**
→ **O and Ne enrichment (WD core material)**

3. **No progenitor of type Ia supernovae**

→ **WD mass does not increase but decreases**

Epoch of superhard X-ray



Magnetic Reconnection ?

○ **WD envelope** $\rightarrow$ **expand** $\rightarrow \varepsilon_{\rm rot} > \varepsilon_{\rm mag}$

$\rightarrow$ **differential rotation**

$\rightarrow$ **amplify magnetic field**

$\rightarrow$ **reconnection (additional energy)**

○ **reconnection and acceleration**

$\rightarrow$ **high energy electron** ?

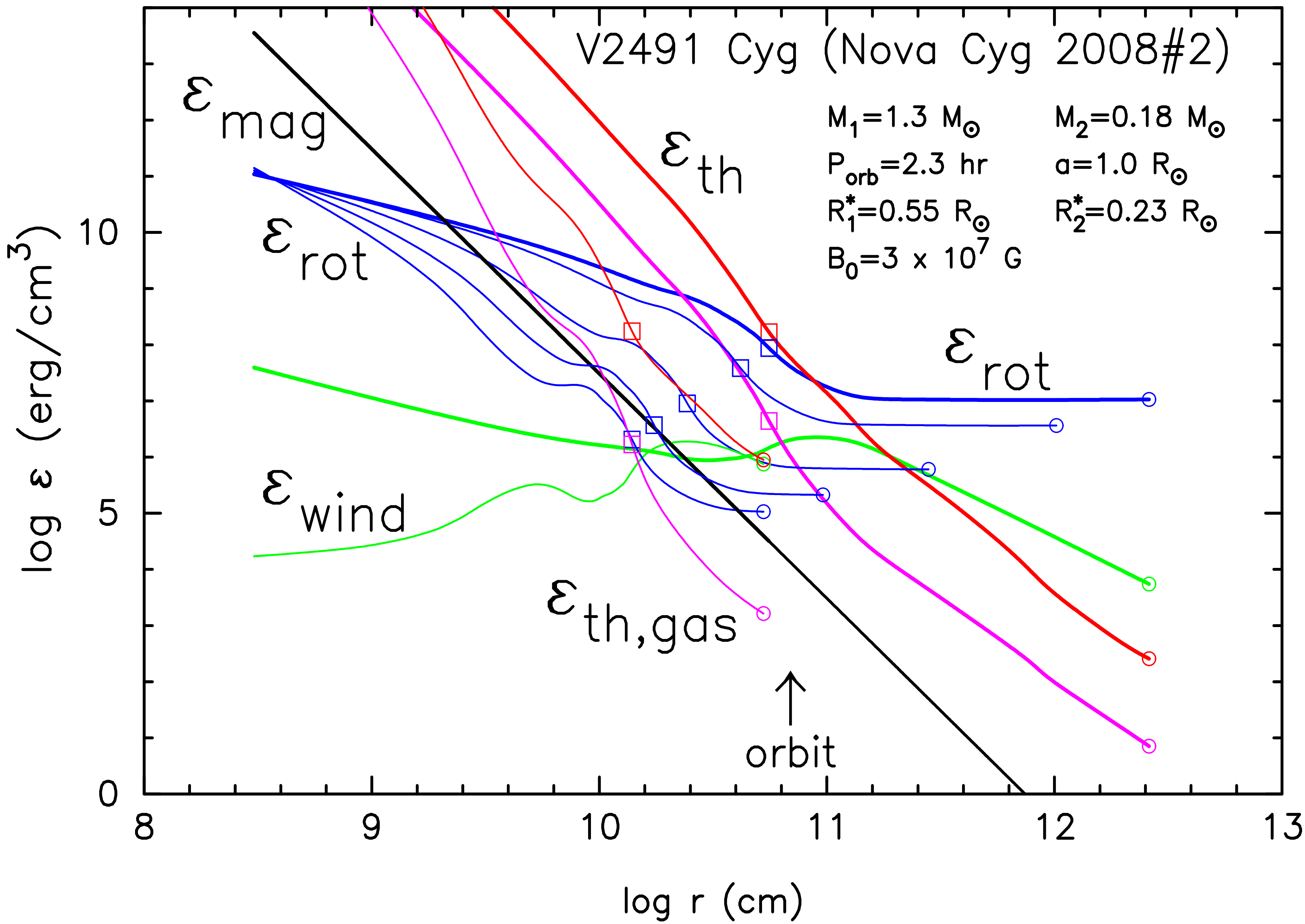
$\rightarrow$ **nonthermal superhard X-ray** ?

○ **photosphere shrinks to Roche lobe size**

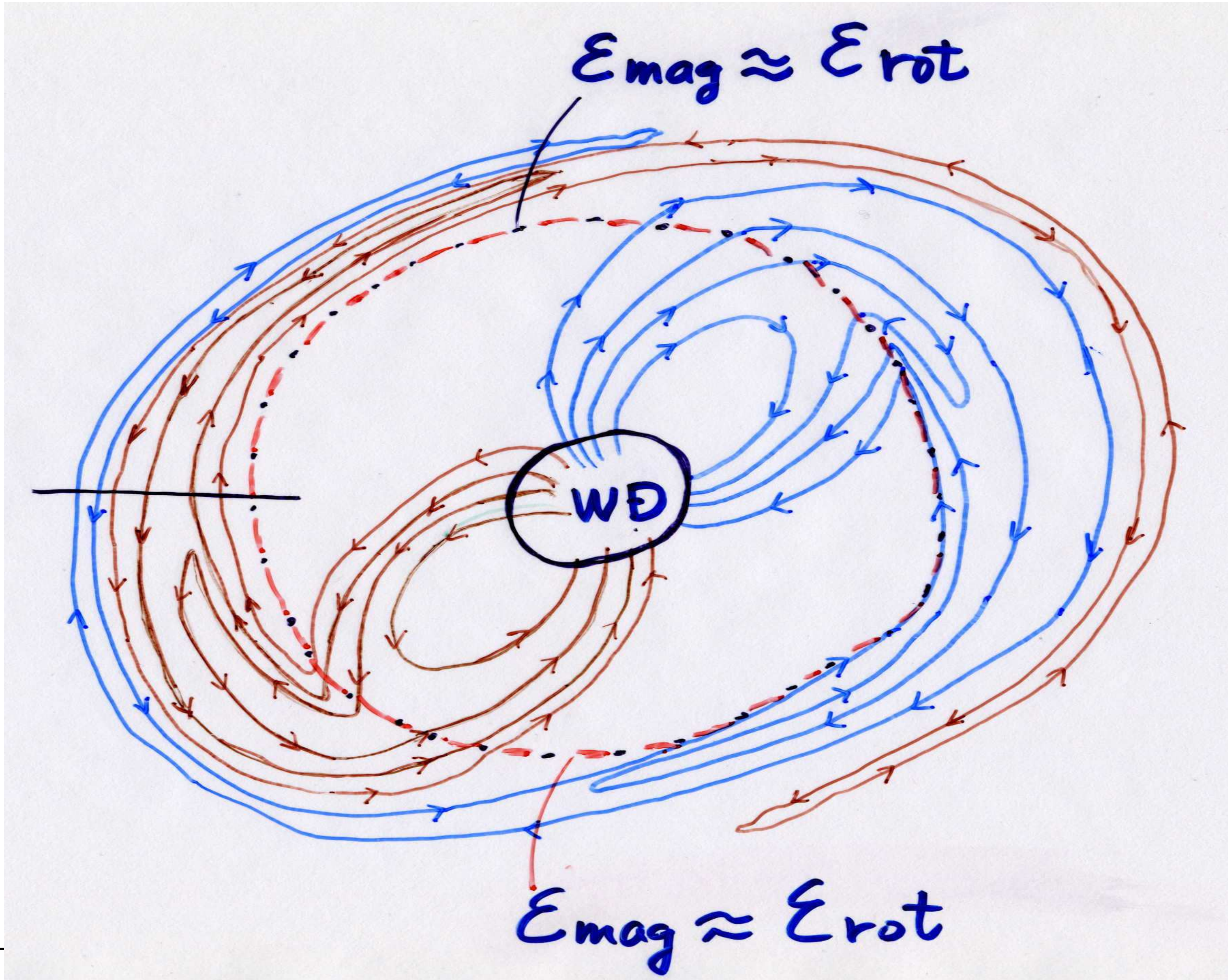
$\rightarrow$ **gas density decrease** ($\varepsilon_{\rm thermal,gas} \approx \varepsilon_{\rm mag}$)

$\rightarrow$ **mass-ejection by magnetic tension** ?

WD Envelope Model of V2491 Cyg



Magnetic activity in V2491 Cyg



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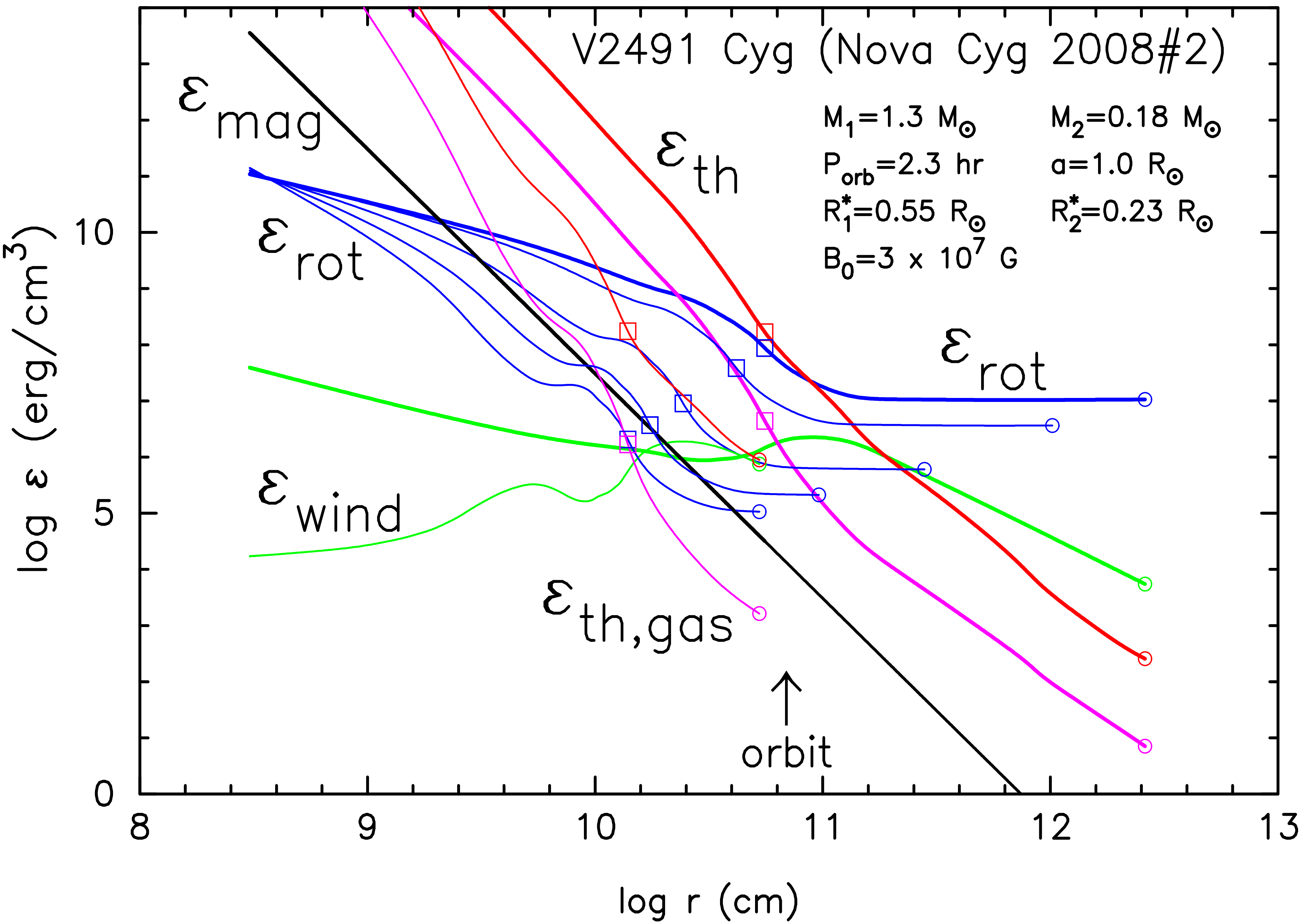

Magnetic Reconnection ?

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- **reconnection and acceleration**
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- **photosphere shrinks to Roche lobe size**
  $\rightarrow$ **gas density decrease** ($\varepsilon_{\rm thermal,gas} \approx \varepsilon_{\rm mag}$)
  $\rightarrow$ **mass-ejection by magnetic tension** ?

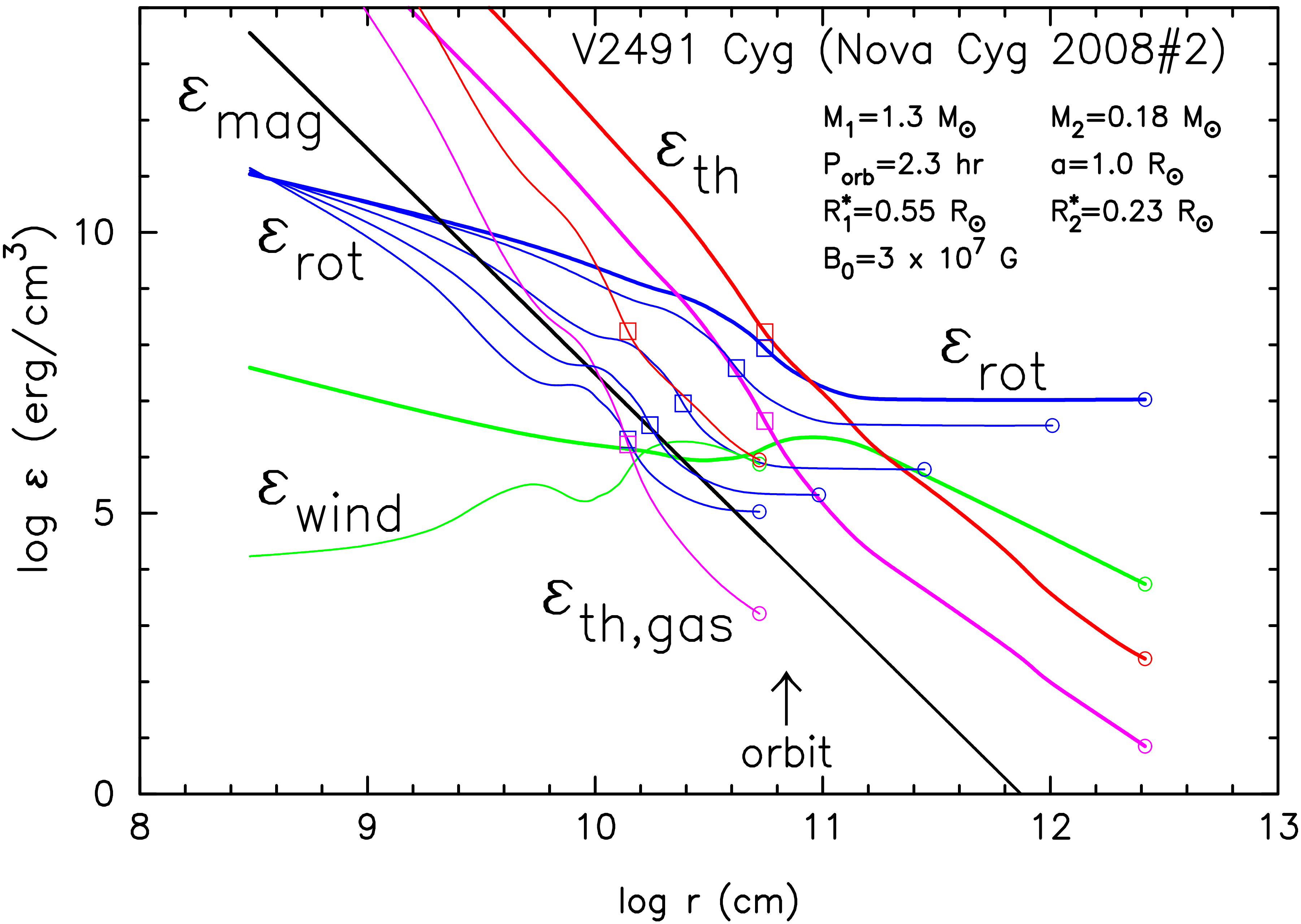
When does magnetic activity stop ?

- photosphere further shrinks
  → gas density further decrease
  → $\varepsilon_{\mathrm{rot}} < \varepsilon_{\mathrm{mag}}$
  → back to original position
  → magnetic activity ends
  after the 2nd peak

- 2nd peak corresponds to
  → $\varepsilon_{\mathrm{rot}} \approx \varepsilon_{\mathrm{mag}}$

- This day is 15 days after the outburst
  in V2491 Cyg (1.3 Mo WD)

WD Envelope Model of V2491 Cyg



When does magnetic activity stop ?

- **photosphere further shrinks**
  - $\rightarrow$ **gas density further decrease**
  - $\rightarrow \varepsilon_{\rm rot} < \varepsilon_{\rm mag}$
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- **2nd peak corresponds to**
  - $\rightarrow \varepsilon_{\rm rot} \approx \varepsilon_{\rm mag}$
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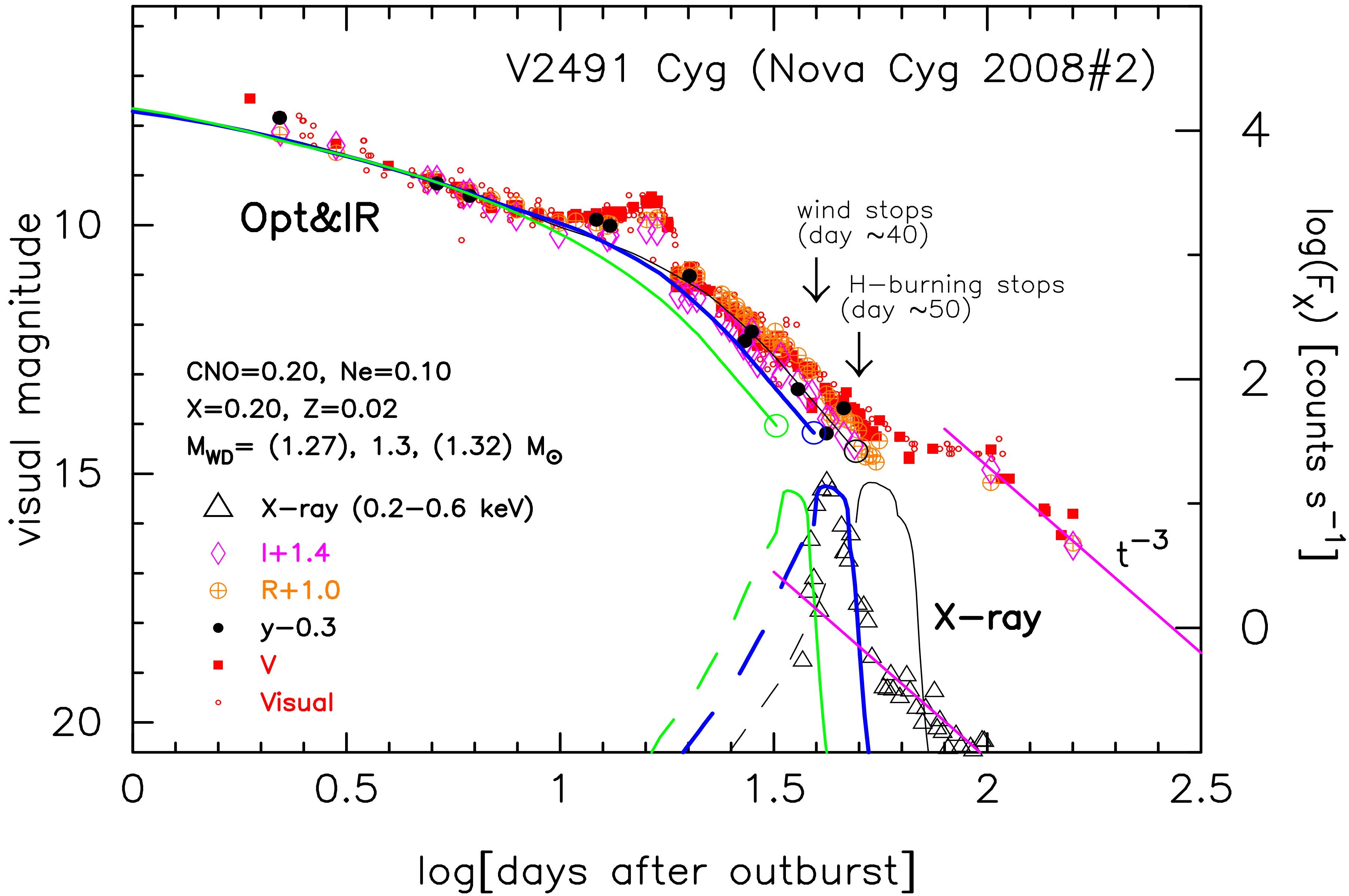
2nd peak on 15 days after outburst

(Hachisu & Kato, 2009, ApJL, 694, L103)

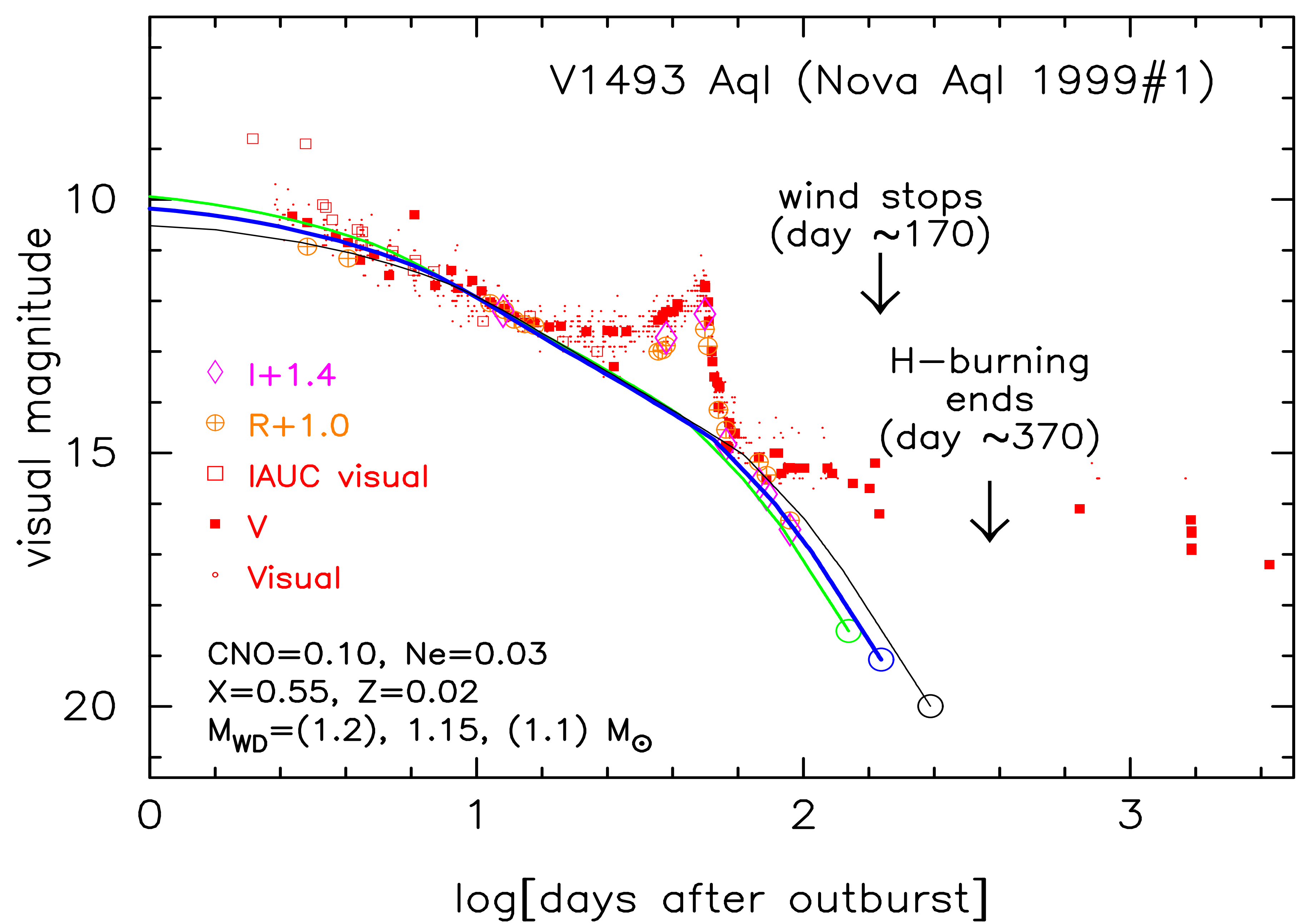


Epoch of the 2nd peak

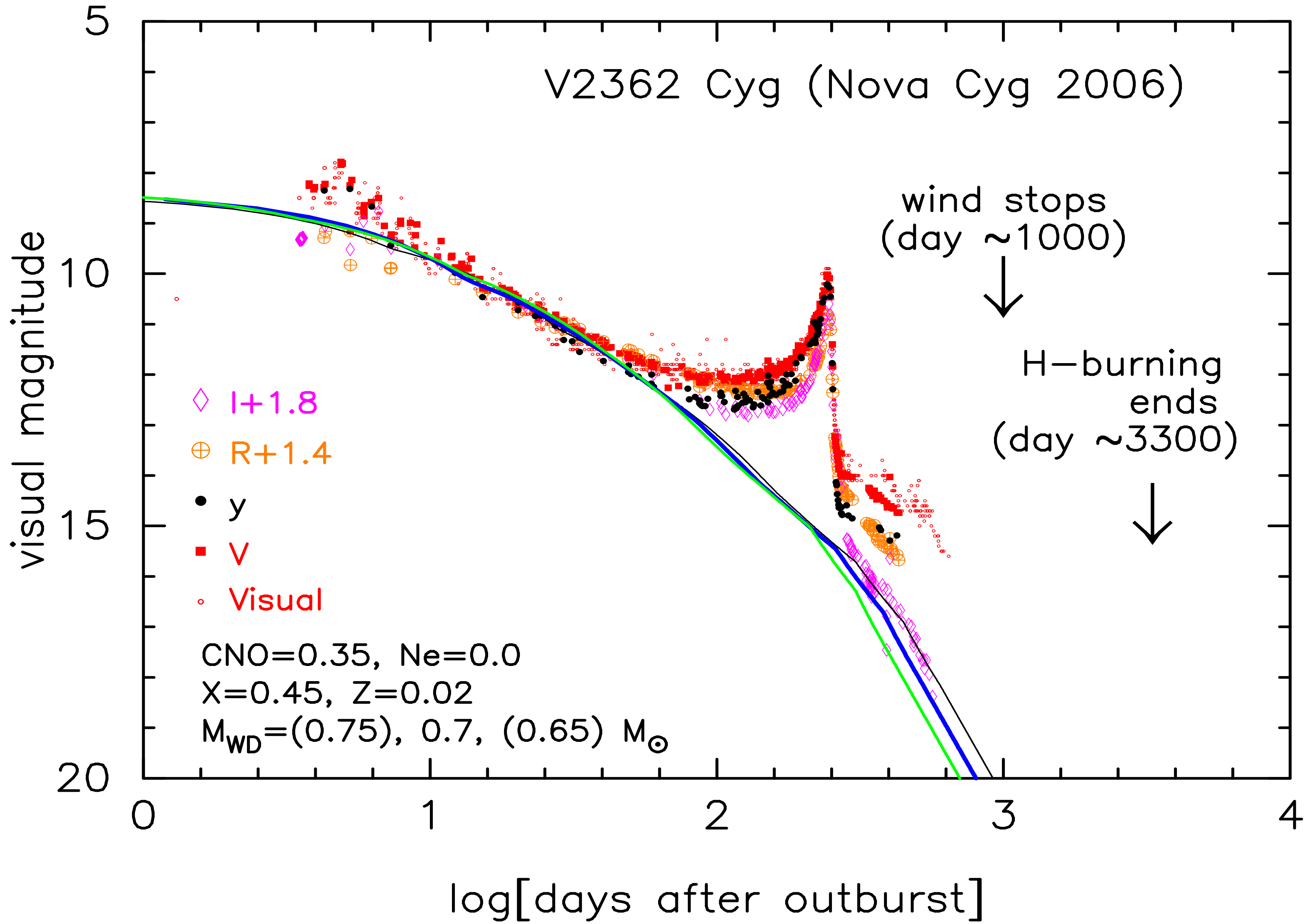
- **50 days after the outburst in V1493 Aql (1.15 Mo WD)**
- **240 days after the outburst in V2362 Cyg (0.7 Mo WD)**

object	max[a] (day)	P_{orb} (day)	M_2[b] ($M_\odot$)	a ($R_\odot$)	M_{WD} ($M_\odot$)	$\varepsilon_{\mathrm{rot}}$ (
V2491 Cyg	15	0.0958	0.18	1.0	1.32	13
					1.3	15
					1.27	18
V1493 Aql	50	0.156	0.34	1.4	1.2	40
					1.15	49
					1.1	62
V2362 Cyg	250	0.207	0.48	1.6	0.75	200
					0.7	240
					0.65	330

Optical Light Curve of V1493 Aql



Optical Light Curve of V2362 Cyg



Summary of V2491 Cygni (2)

(Hachisu & Kato, 2009, ApJL, 694, L103)

1. 2nd peak can be explained by strong magnetic activity

$$\varepsilon_{\rm mag} \approx \varepsilon_{\rm rot} \text{ for } B \sim 3 \times 10^7 {\rm G} \text{ on WD}$$

2. Timescales of the 2nd peaks can be explained by the same mechanism in V2491 Cyg, V1493 Aql, and V2362 Cyg

$$\varepsilon_{\rm rot} \approx \varepsilon_{\rm mag}$$

3. Superhard X-ray detection is probably related to the magetic activity before the 2nd peak