Modelling Light Curves: Luminous Red Novae

KITP Massive Stars Program

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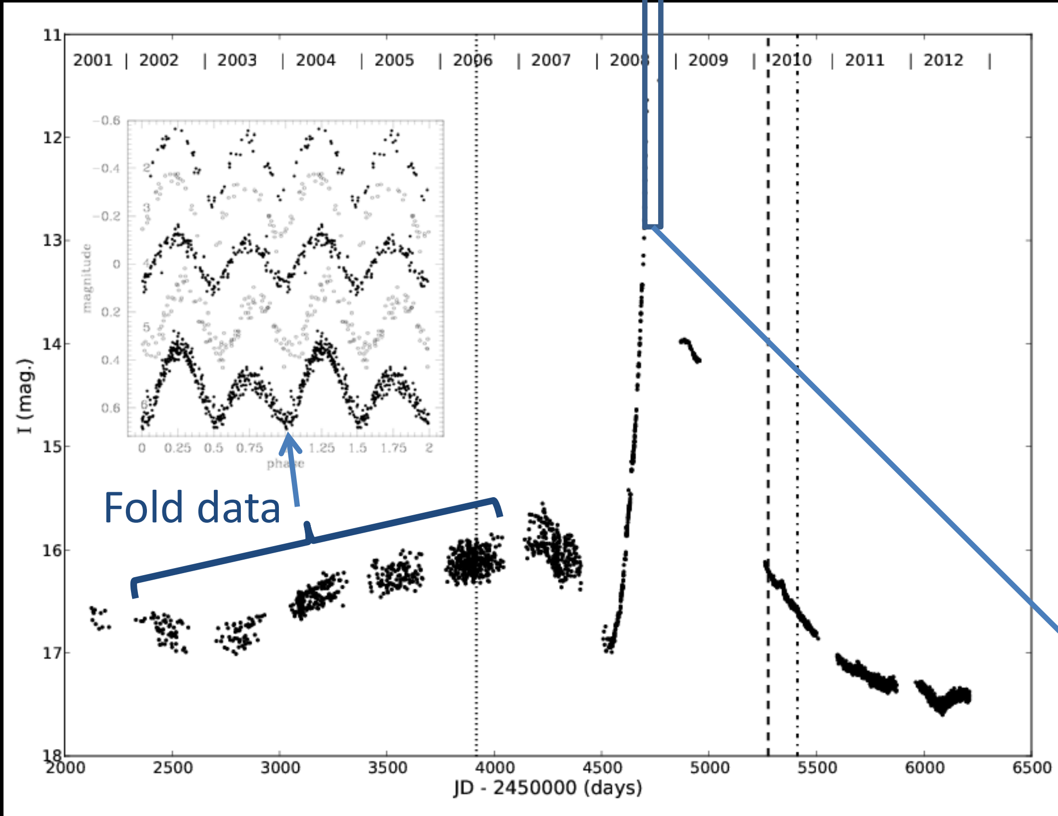
May 4, 2017

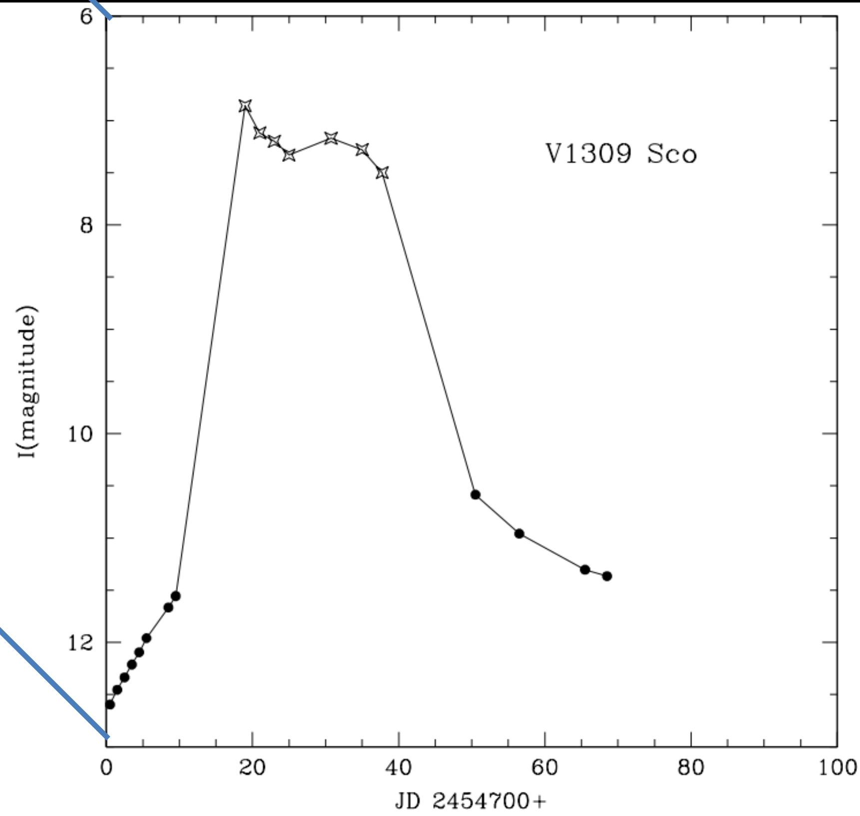
Acknowledgments (Before I run out of time)

- John Wenskovitch for *FluxE* (and sharing slides!)
- Jason Ferguson for creating custom Rosseland and Planck opacity tables
- Evghenii Gaburov for creating our gravity library
- Fabio Antonini, Josh Faber, and Marcelo Ponce for work on V838 Mon
- Allegheny students who've worked on…
  - V838 Mon, including Travis Court '18, Kayla Sweet '16, Brianne Zins '14
  - V1309 Sco, including Jordan Caldwell '17, Roger Hatfull '16, Mack Price '17, Zach Silberman '13
- NSF grant AST-13130901

V1309 Sco



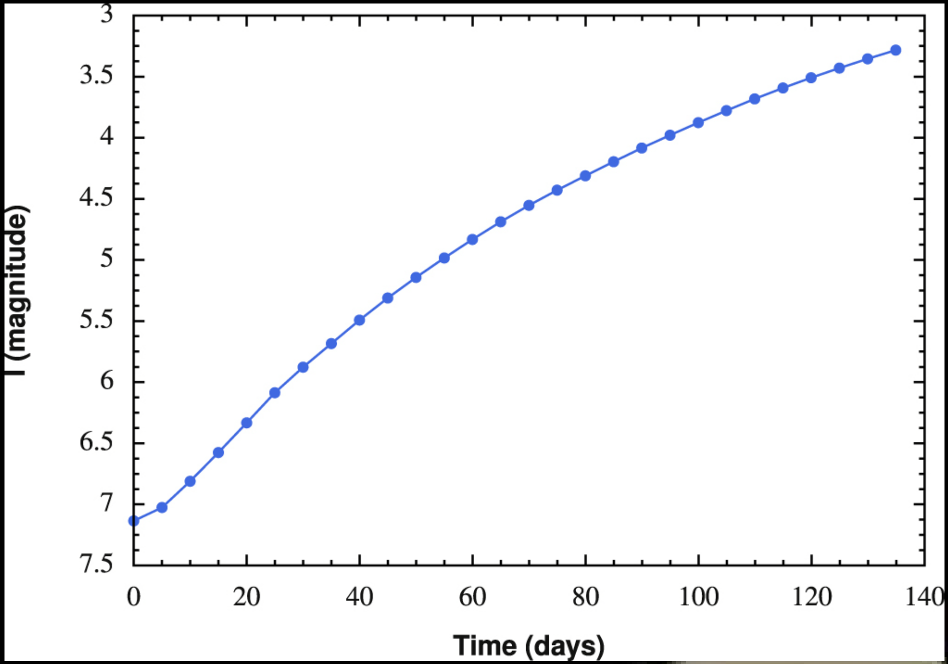
As shown in Tylenda et al. (2011) & Nicholls et al. (2013)



As shown in Ivanova et al. (2013)

Publications on light curve modelling

- Ivanova et al. (2013)
  - By analogy with Type IIP SNe, established LRNe (a.k.a. ILOT, ILRT, …) light curves can be explained by Common Envelope Events
  - V1309 Sco's light curve was fit with two outbursts each treated with the analytic Popov model
- Wenskovitch, Lombardi, & Hatfull (2016)
  - *FluxE* = Flux Explorer, software for effective temperature and spectral flux density from simulations
  - FluxE is publically available at http://starsmasher.allegheny.edu/fluxe/
- Galaviz et al. (2017)
  - Post-process grid based calculations to generate light curves
  - Considers example case of 0.88 $M_\odot$ giant + 0.6 $M_\odot$ point mass companion
  - Highlights obstacles to realistic light curves, which include
    - hot vacuum used in grid-based codes
    - the need to account for radiative cooling at late times



From Galaviz et al. (2017)

Modelling radiative energy losses

- The rate of change of the specific internal energy u_i of particle *i* is due to pressure force exchanges, artificial viscosity used to treat shocks, and radiative energy losses:

$$\left.\frac{\mathrm{d}u_i}{\mathrm{d}t}\right|_{\mathrm{HYDRO}} = \left.\frac{\mathrm{d}u_i}{\mathrm{d}t}\right|_{\mathrm{Press}} + \left.\frac{\mathrm{d}u_i}{\mathrm{d}t}\right|_{\mathrm{AV}} + \left.\frac{\mathrm{d}u_i}{\mathrm{d}t}\right|_{\mathrm{RAD}}$$

- Although $\mathrm{d}u_i/\mathrm{d}t|_{\mathrm{RAD}}$ is small and has little effect on the bulk dynamics, it does affect temperatures near and outside the photosphere and therefore affects the light curve.
- Simple approximation used/tested in Stamatellos et al. (2007), Forgan et al. (2009), Wilkins & Clarke (2012), Lombardi et al. (2015), Pejcha et al. (2016a,b):

$$\left.\frac{\mathrm{d}u_i}{\mathrm{d}t}\right|_{\mathrm{RAD}} = \frac{4\sigma_{\mathrm{SB}}\left(T_0^4(\boldsymbol{r}_i) - T_i^4\right)}{\bar{\Sigma}_i^2\bar{\kappa}_{\mathrm{R}}(\rho_i, T_i) + \kappa_{\mathrm{P}}^{-1}(\rho_i, T_i)},$$

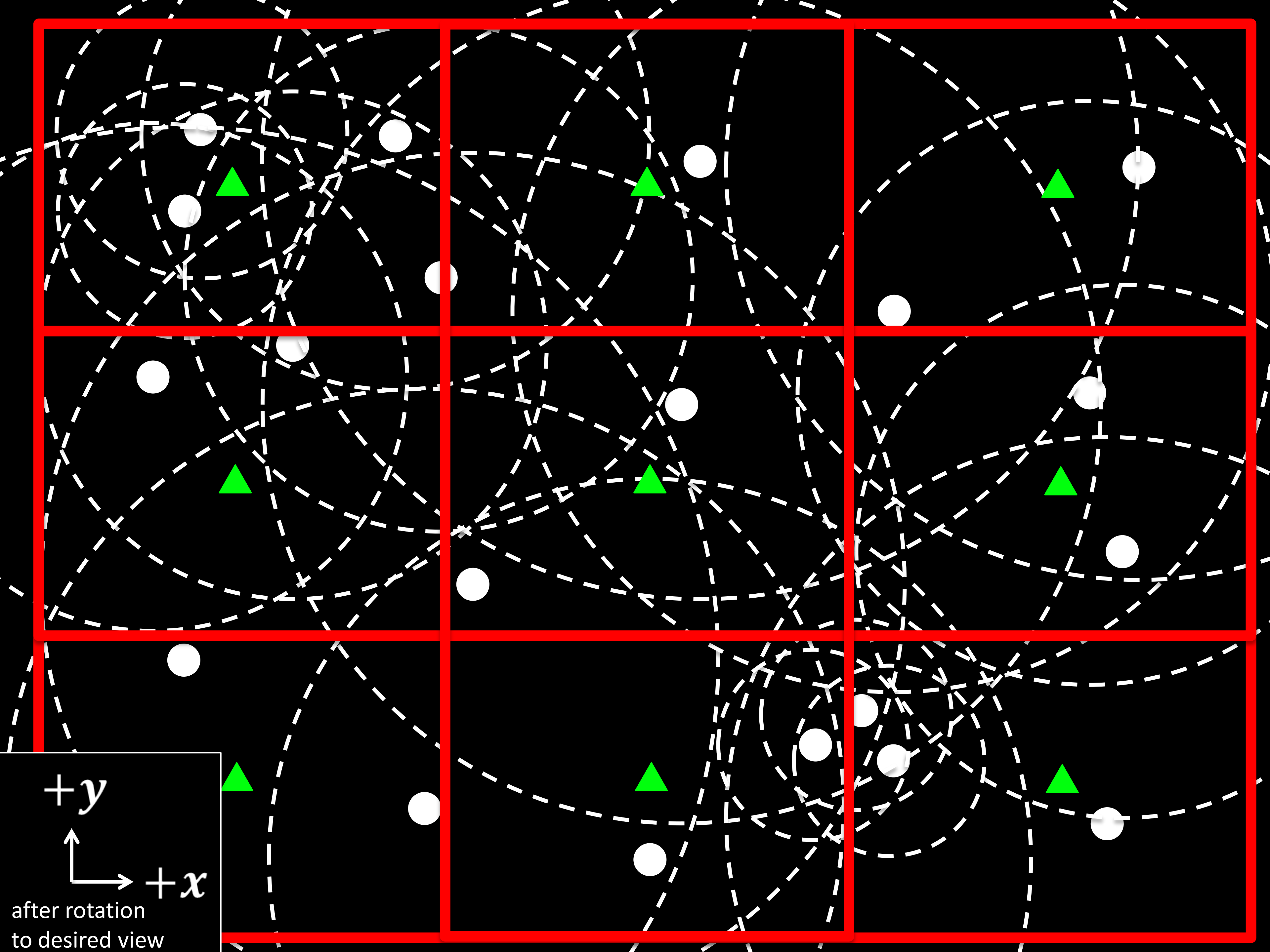
e.g. $1.06\rho_i H_{\mathrm{P},i}$

where particle *i* has position $\boldsymbol{r}_i$, temperature T_i, density ρ_i, estimated column density $\bar{\Sigma}_i$ (to the surface), and local background temperature T_0. The $\bar{\kappa}_{\mathrm{R}}$ is an estimated average Rosseland mean opacity to the surface, and κ_{P} is the Planck opacity.

- At estimated optical depth $\bar{\tau}_i = \bar{\Sigma}_i\,\bar{\kappa}_{\mathrm{R}} >> 1$, the first term in the denominator dominates, and we have and approximation for radiative diffusion.
- At estimated optical depth $\bar{\tau}_i = \bar{\Sigma}_i\,\bar{\kappa}_{\mathrm{R}} << 1$, the second term in the denominator dominates, and the cooling rate is that of the optically thin limit.

From Particles to Flux Densities

- Wenskovitch, Lombardi, & Hatfull (2016)
- Choose viewing angle and rotate coordinate system so that the *xy* plane is the plane of the sky.
- Partition the sky onto a 2D rectangular grid.
- In the center of each grid cell, integrate for optical depth τ, flux F, and spectral flux density S_ν for each desired frequency ν.


+y
+x
after rotation
to desired view

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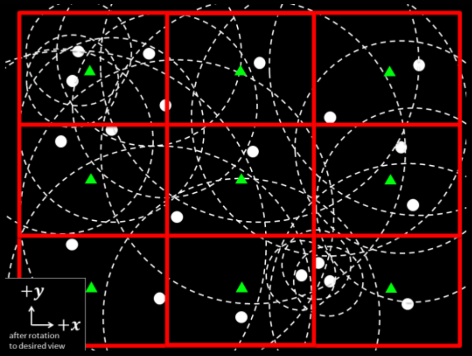
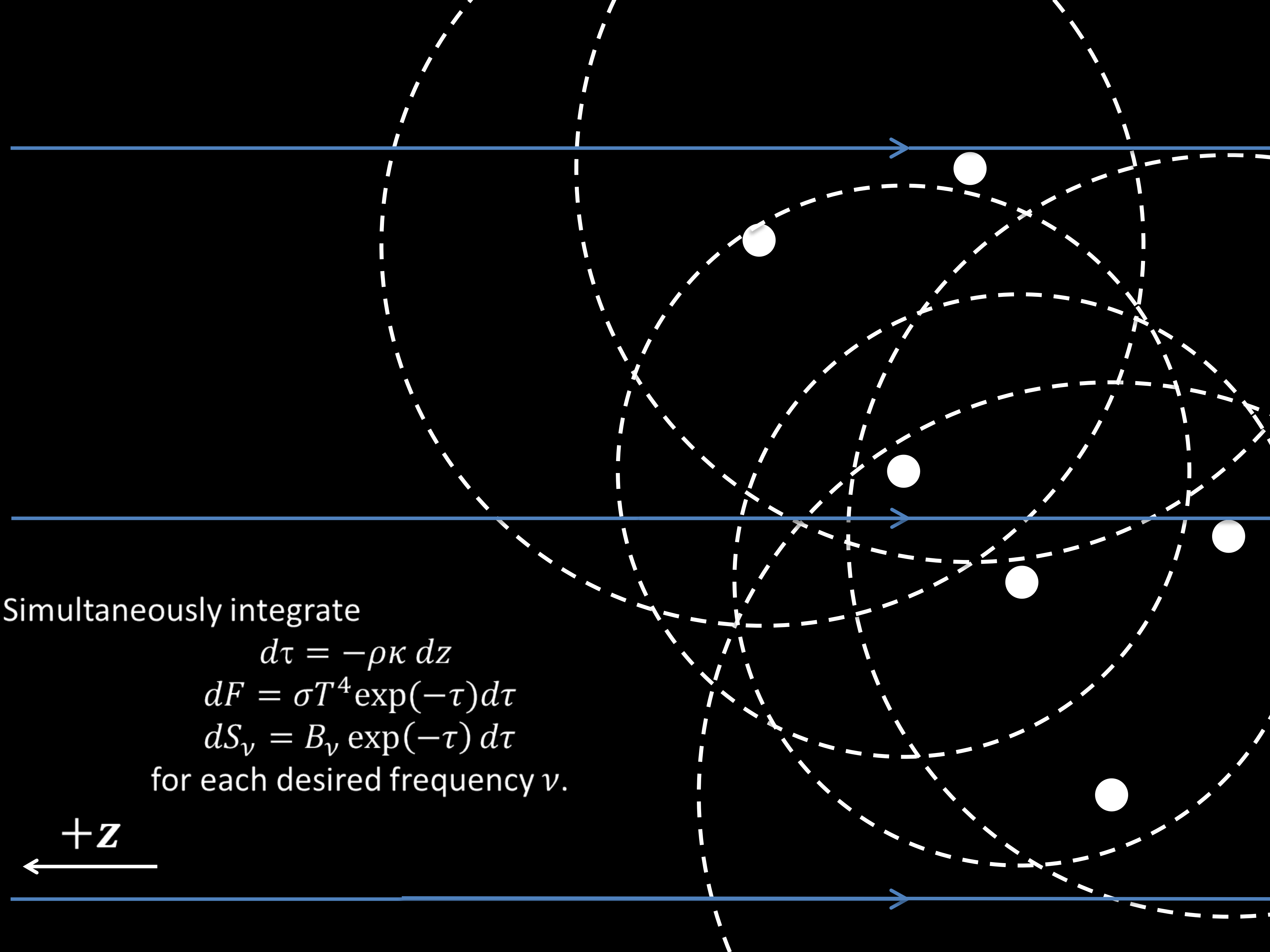


$$d\tau = -\rho\kappa\, dz$$

$$dF = \sigma T^4 \exp(-\tau) d\tau$$

$$dS_\nu = B_\nu \exp(-\tau)\, d\tau$$



Simultaneously integrate

$$d\tau = -\rho\kappa\, dz$$

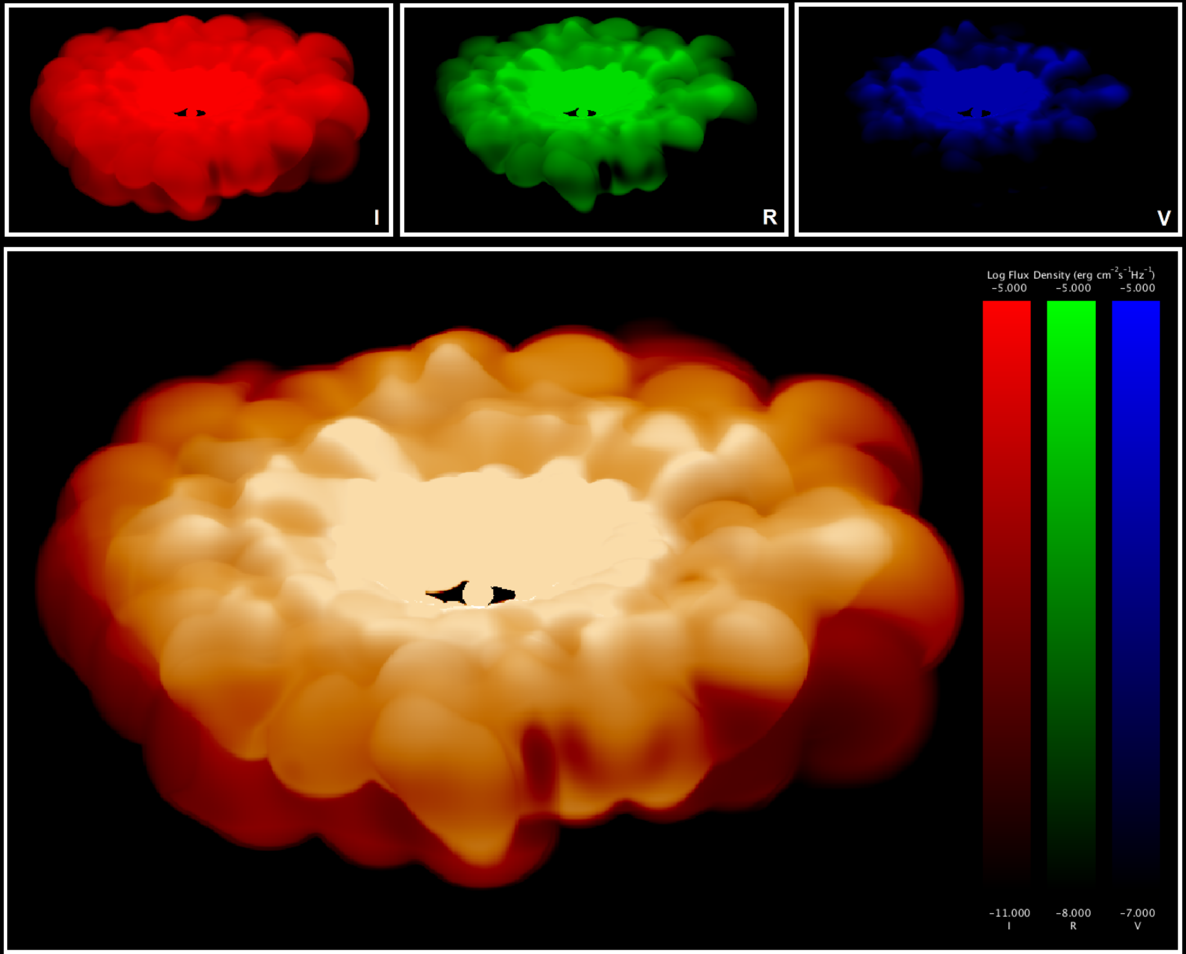
$$dF = \sigma T^4 \exp(-\tau) d\tau$$

$$dS_\nu = B_\nu \exp(-\tau)\, d\tau$$

for each desired frequency ν.

Visualize with *FluxE*

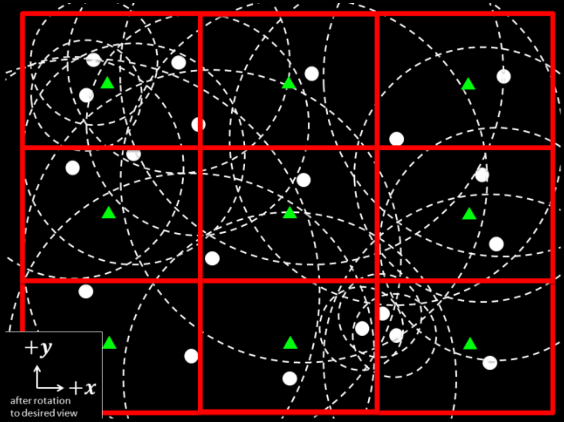
- *FluxE* is designed for exploring the resulting data
  - Specral flux densities S_ν
  - Effective temperatures $T_{\mathrm{eff}}=(F/\sigma_{\mathrm{SB}})^{1/4}$
  - light curves (next slide)



What about the light curve?

The total flux density at the observer is calculated as

$$F_\nu = \sum_{\text{all cells}} \frac{A S_\nu}{{R_0}^2}$$



where A is the cell area and R_0 is the distance to the observer (or 10 pc if want absolute magnitude). Magnitudes are then calculated as

$$m_\nu = m_{\mathrm{ext},\nu} - 2.5 \log_{10} \frac{F_\nu}{F_{0,\nu}},$$

where $F_{0,\nu}$ can be looked up in tables and $m_{\mathrm{ext},\nu}$ accounts for interstellar extinction.

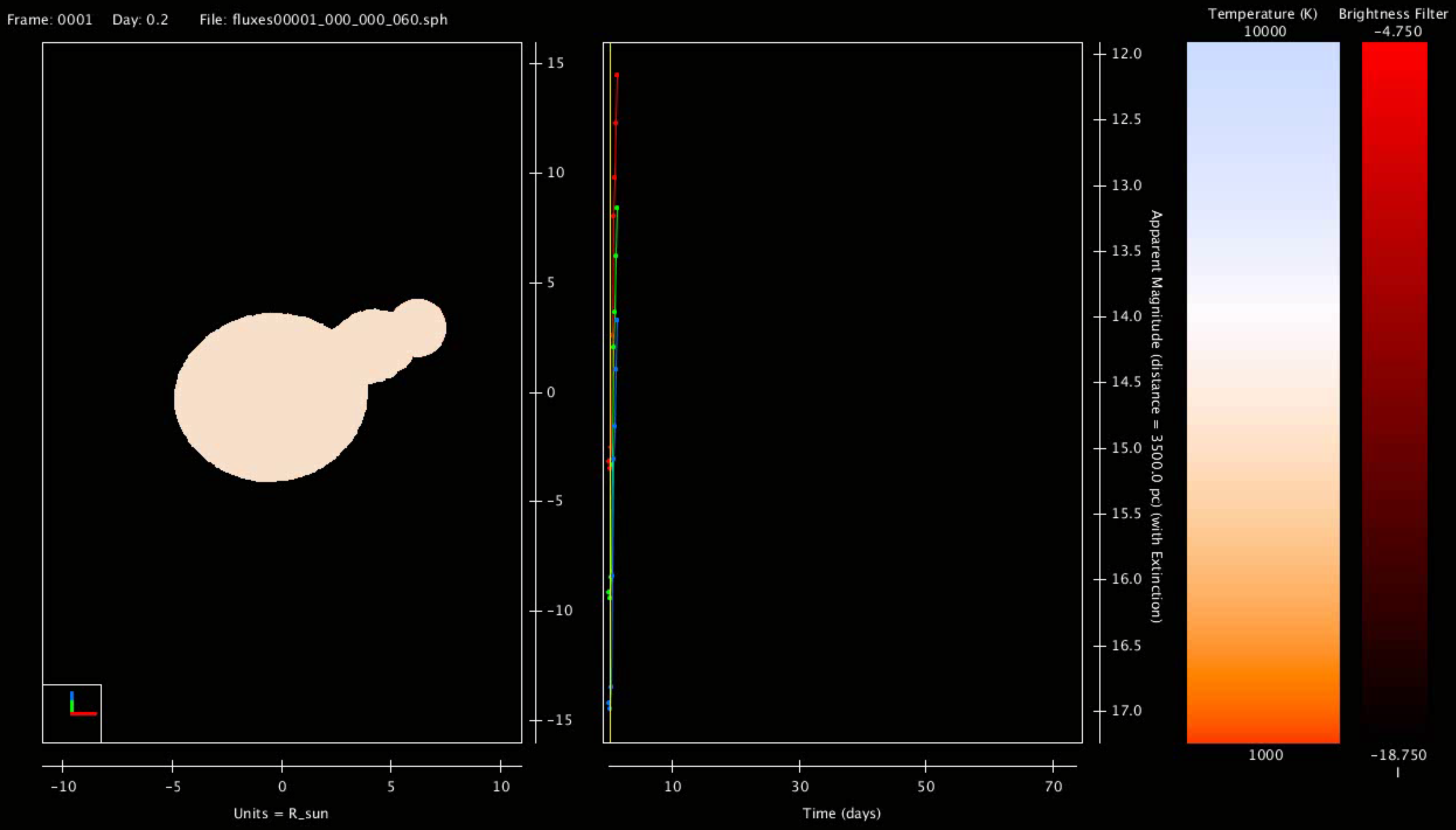
Example merger

- $1.52M_{\odot} + 0.16\ M_{\odot}$
- N = 320k particles
- EOS tabulated from MESA
- Rosseland and Planck opacities allow for molecules but not dust grains
- $T_0 = 500$ K
- View such that orbital inclination $i = 70^{o}$ (Important! See Kashi and Soker 2017)

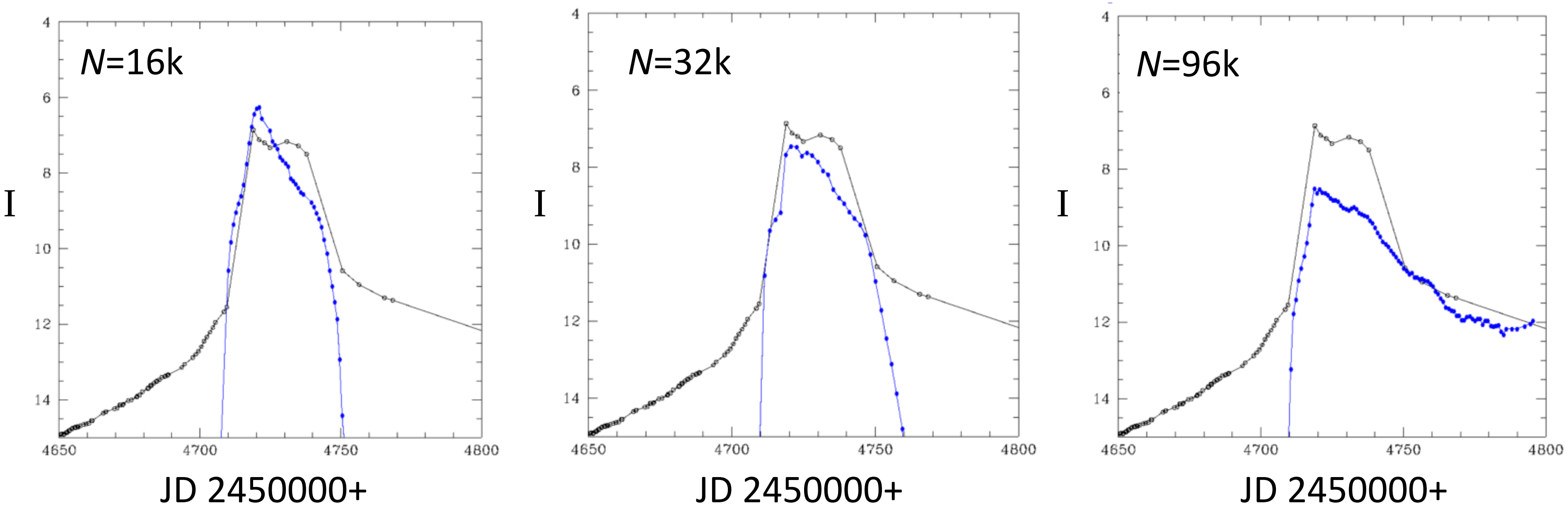
Column density visualization

Inspect with FluxE

Pre-cooked Visualization



Resolution is important



Here: 1.52 $M_\odot$ + 0.12 $M_\odot$

Rise from simulations is always too fast

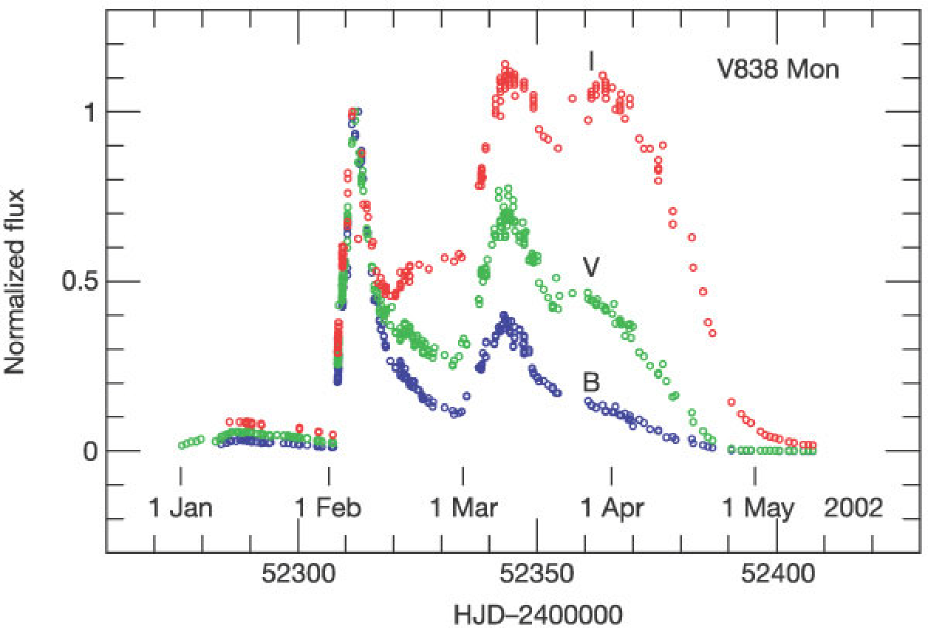
Here no grains and no molecules in opacity

Clearly *N* is important: early time light curve converges by N ~ 100k

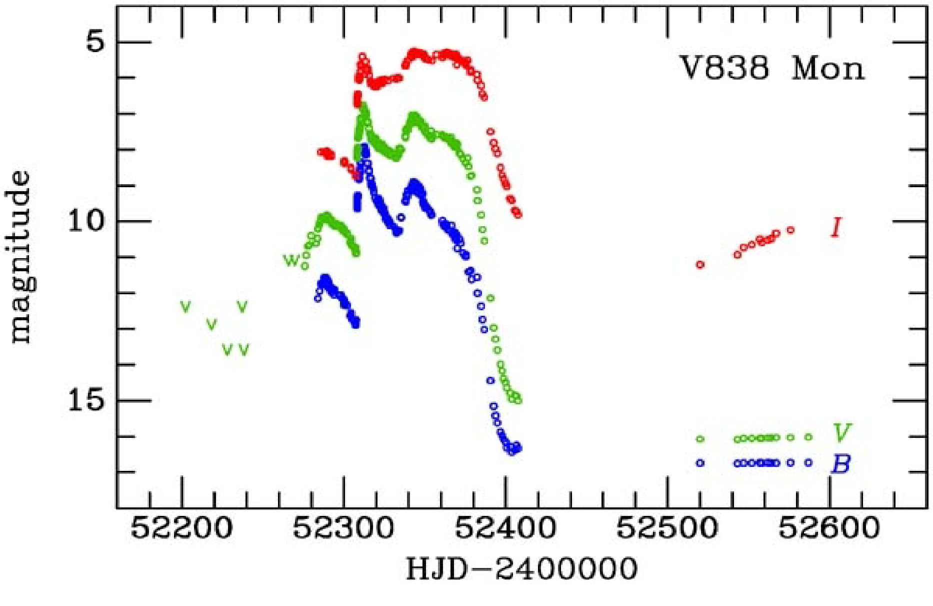
late time light curve converges for N > ~300 k

Mackinzie Price ‘17 senior project

V838 Mon



Bond et al. (2003)



Sparks et al. (2008)

HST 2002-2006
Light echo gives
distance 6.1kpc

Toy model of dust (& molecule) formation

- Parameterized by a dust formation radius R_f, inside of which radiation prevents dust from forming

$$\kappa = \begin{cases} \kappa_{\mathrm{NN}} & \text{if } r \leq R_f \\ (1-f)\kappa_{\mathrm{NN}} + f\,\kappa_{\mathrm{YY}} & \text{if } r > R_f \end{cases}$$

where NN=no grains, no molecules; YY=yes grains, yes molecules.

- The dimensionless parameter

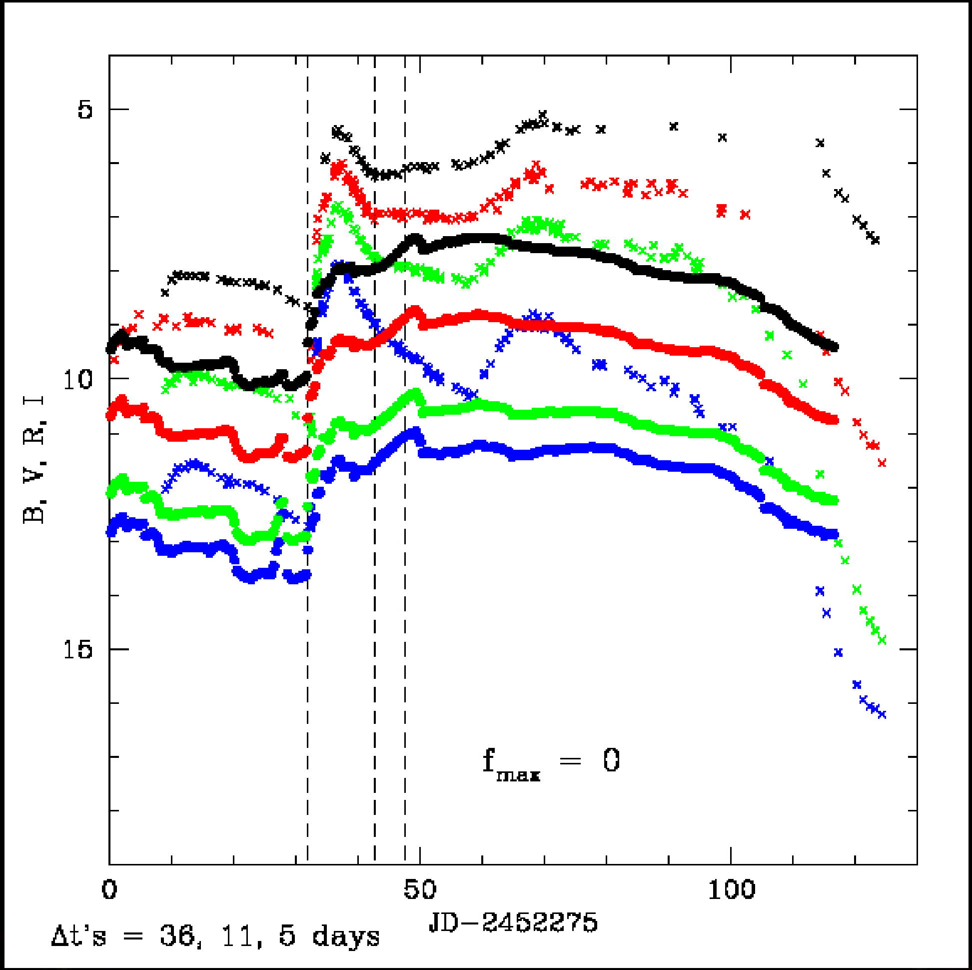
$$f = f_{\mathrm{max}}\left[1-\left(\frac{R_{\mathrm{f}}}{r}\right)^3\right]^3.$$ [typo has been fixed]

Functional form is motivated by Kochanek (2014) & Nanni et al. (2013).

- Note:
  - setting f_{max} = 0 means dust cannot form
  - setting f_{max} = 1 lets dust grow to its equilibrium size as r → ∞
  - turning the f_{max} dial lets us to probe effects of dust on the light curve

Vary dust (& molecule) formation

- Simulation of a 6$M_\odot$ + 0.24 $M_\odot$ direct collision by Travis Court '18
- Four passages before merger: dashed vertical lines mark periastron passages
- N = 40k particles
- EOS tabulated from MESA
- Rosseland and Planck opacities allow for no molecules and no dust grains <u>during the hydro</u>
- Vary opacity via f_{max} in the post-processing
- T_0 = 100 K
- View such that orbital inclination i = 70°



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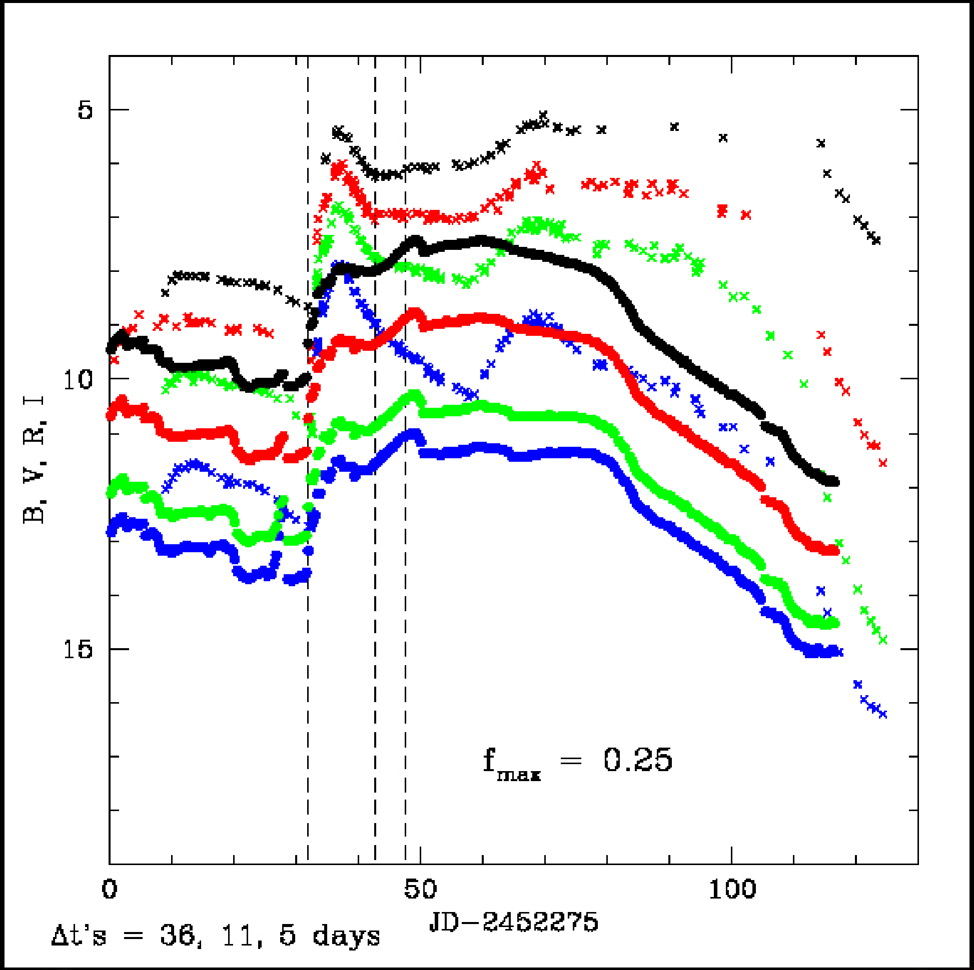

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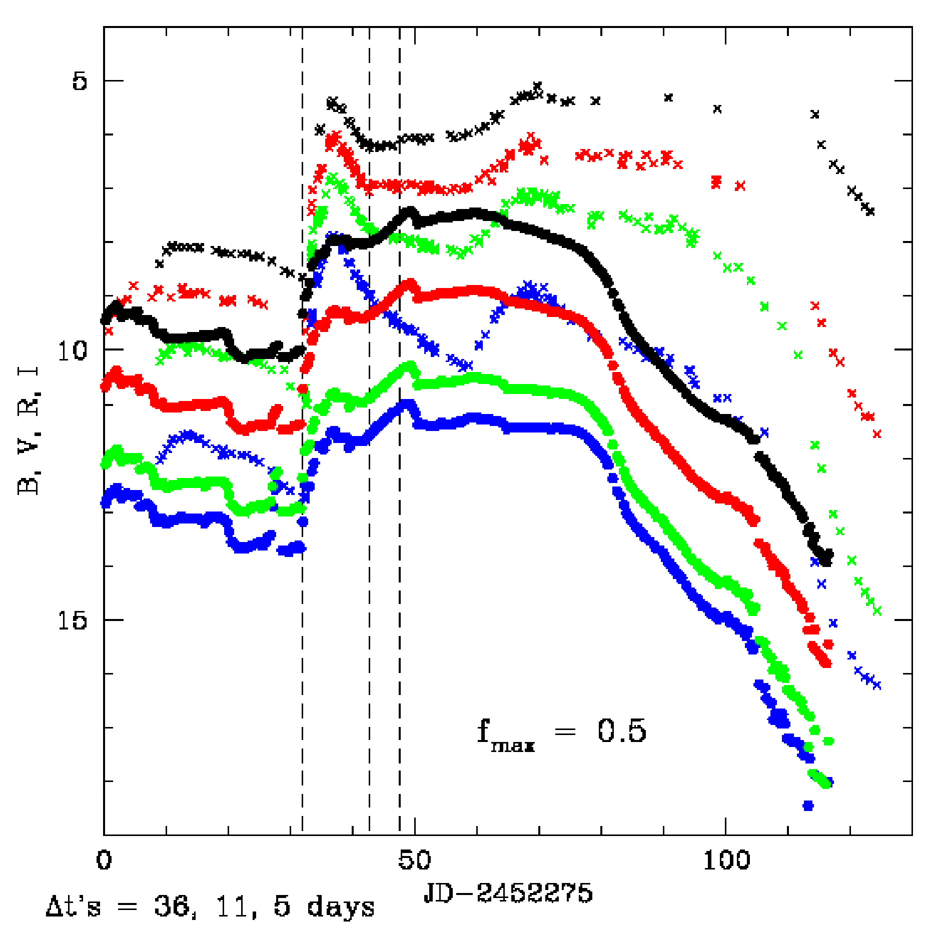

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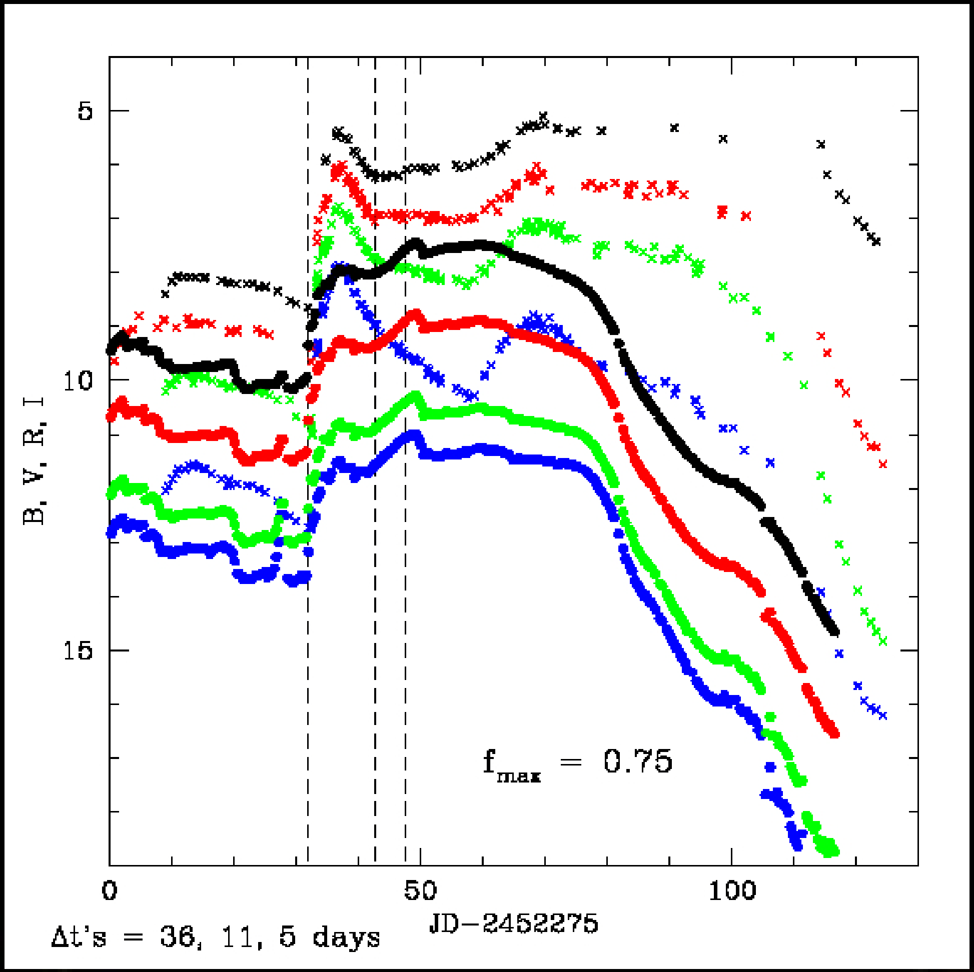

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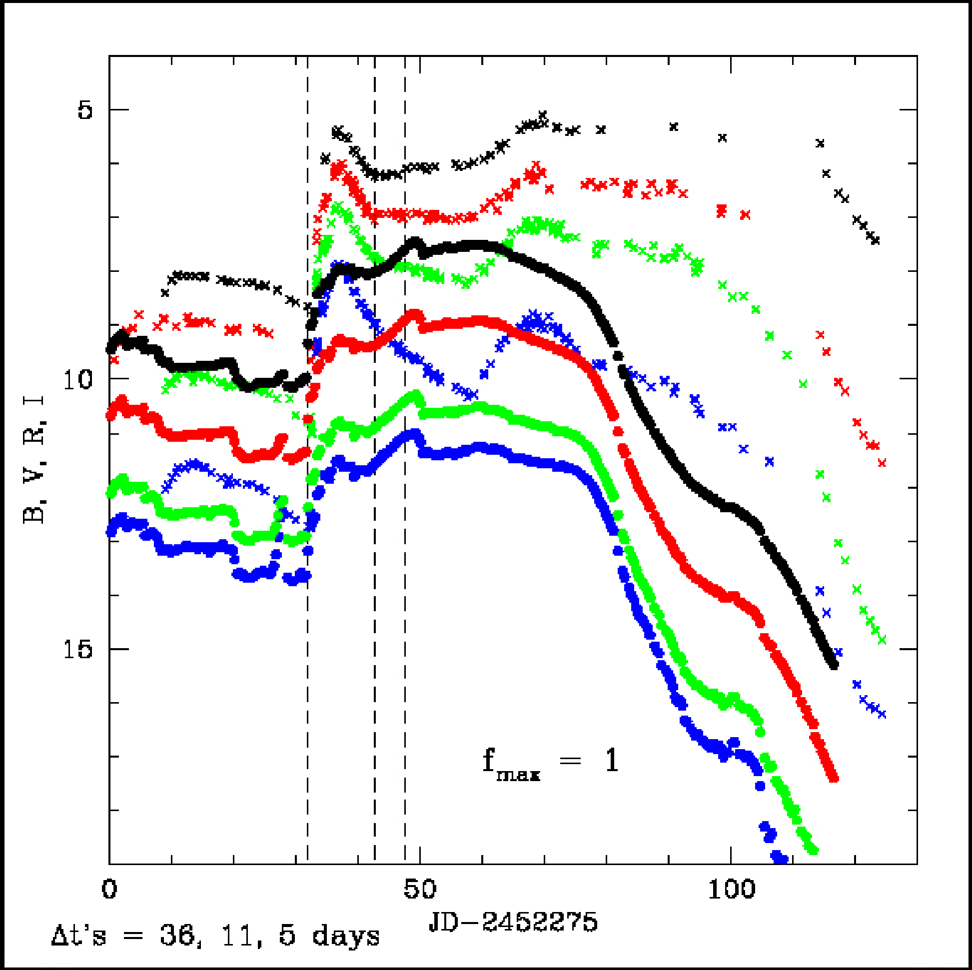
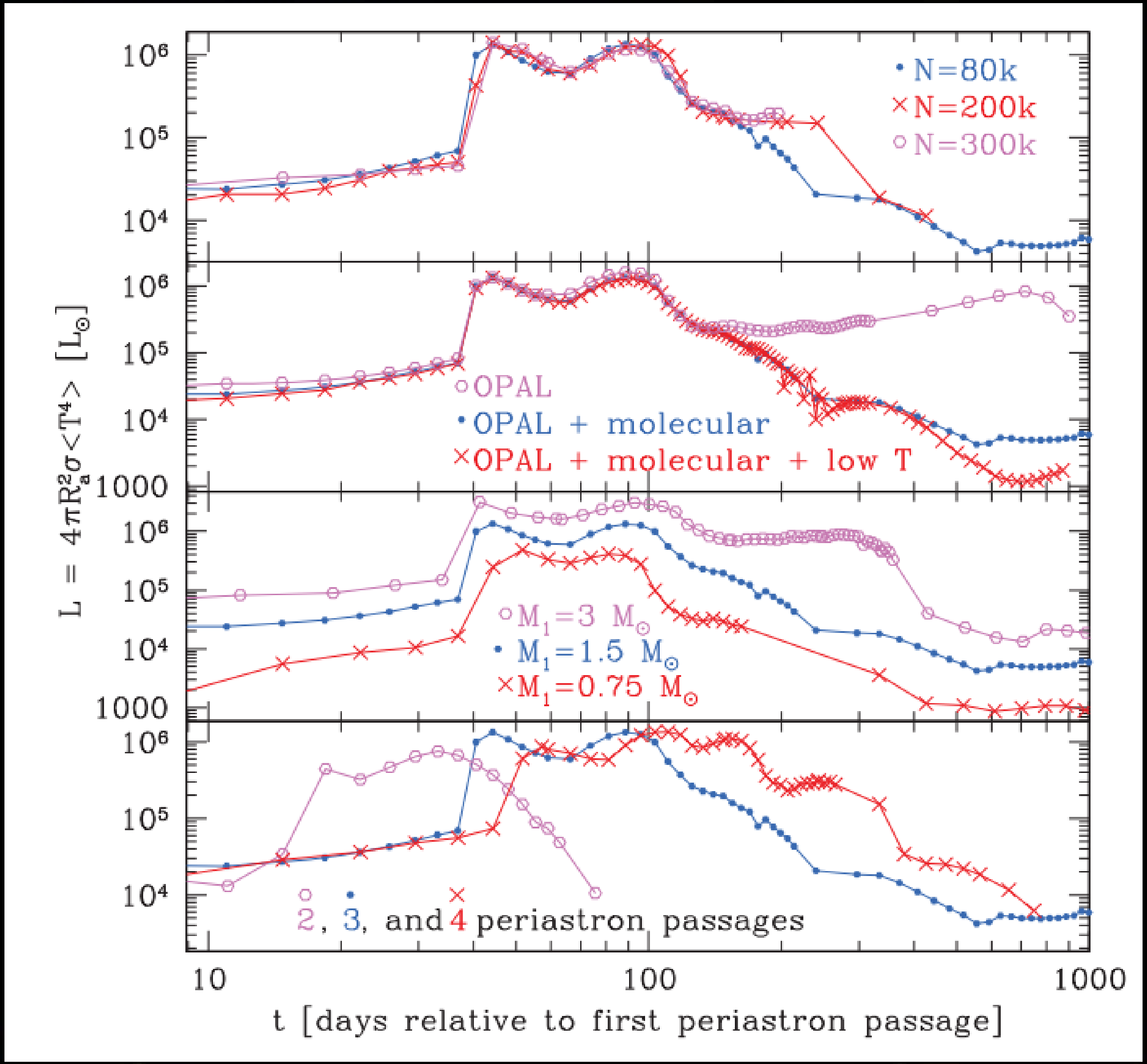
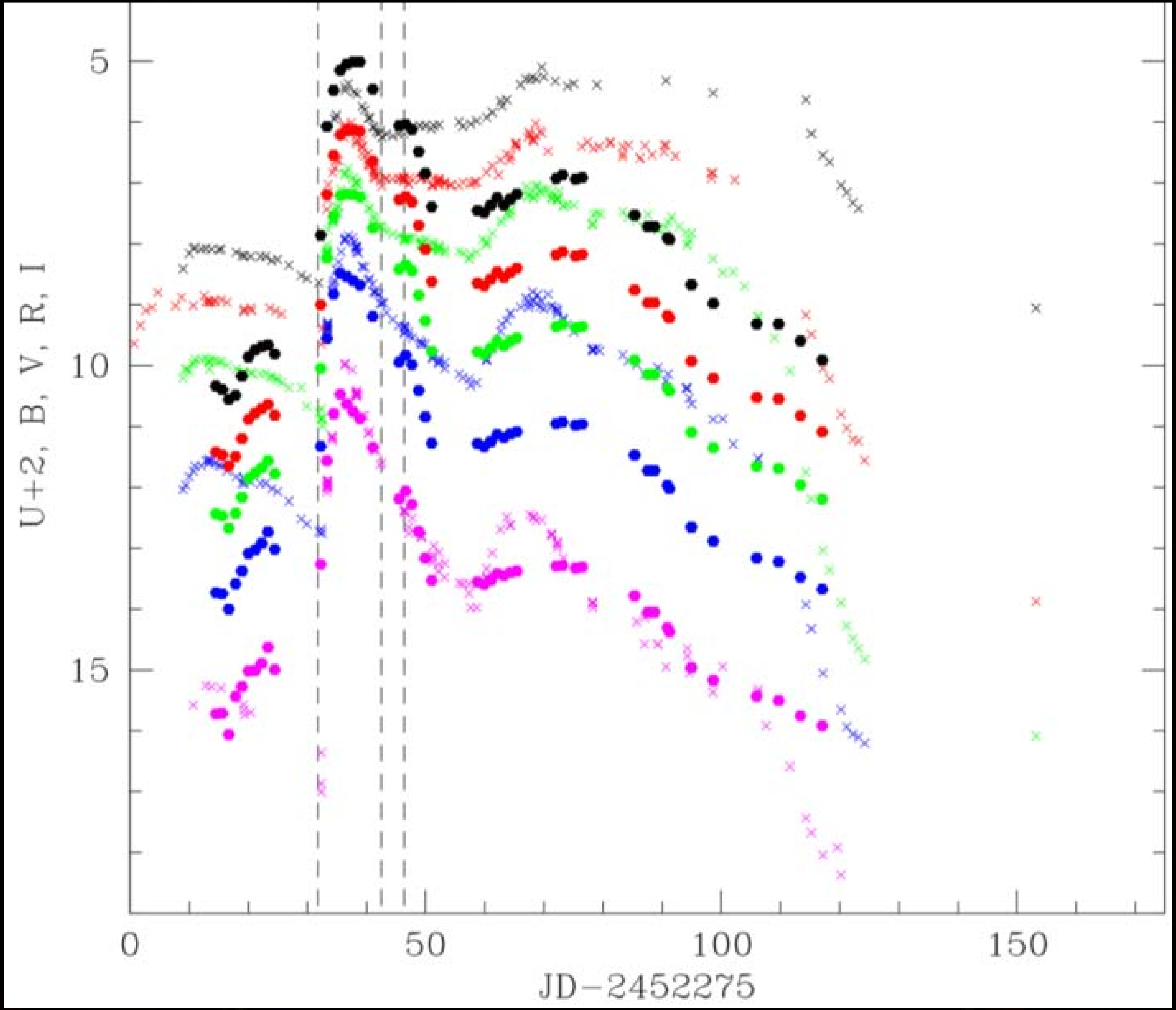


- There are lots of dials to turn →
- It would be great to know the timescales of molecule and dust formation, so there are fewer dials to turn
- Ultimately should treat molecule formation and dust formation on a particle by particle basis during the hydro simulation



- One of our nicer looking V838 Mon results so far…



Time for lunch…