Radiation ~~force~~ pressure and recombination in common envelope evolution/luminous red novae

How to unbound the envelope?

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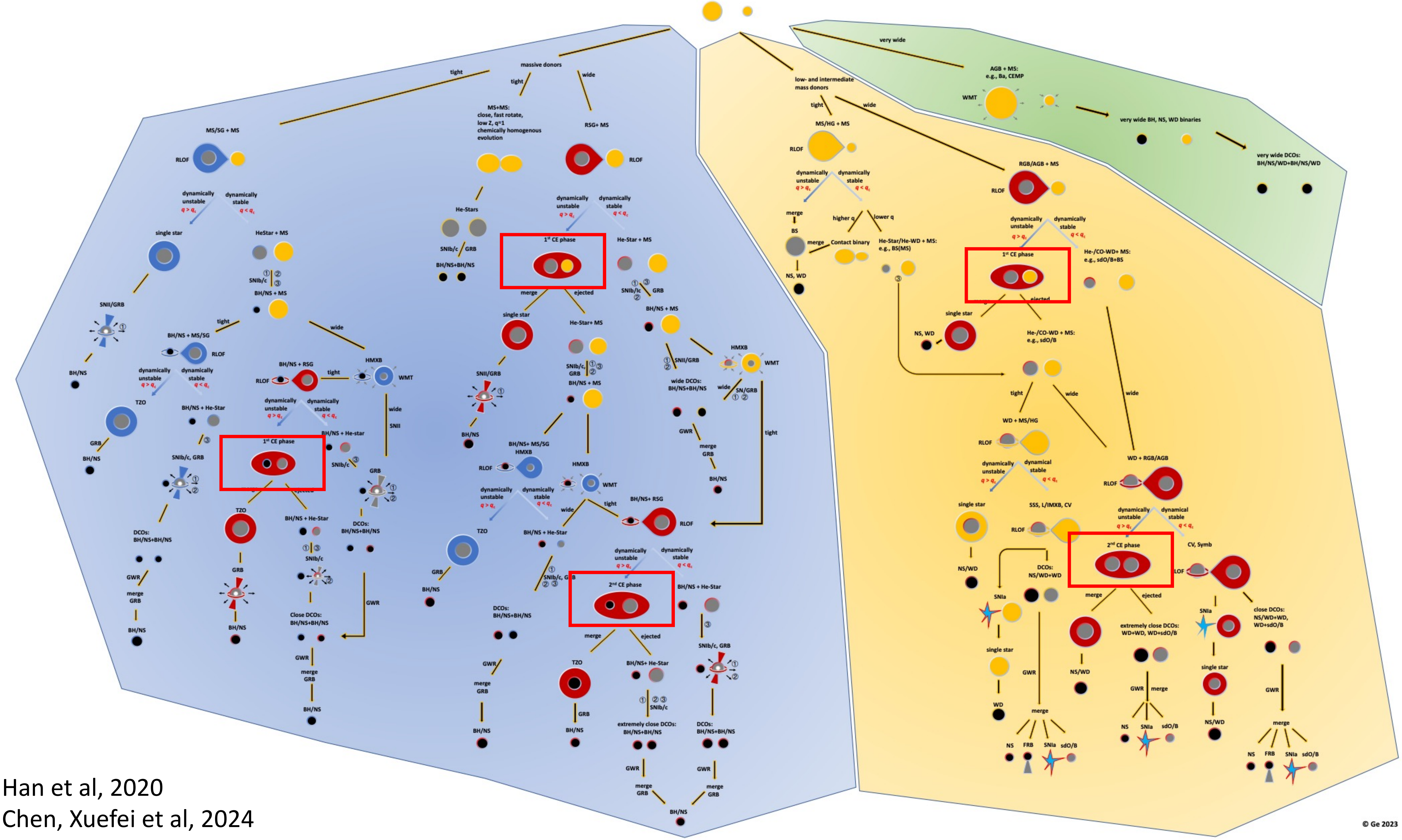
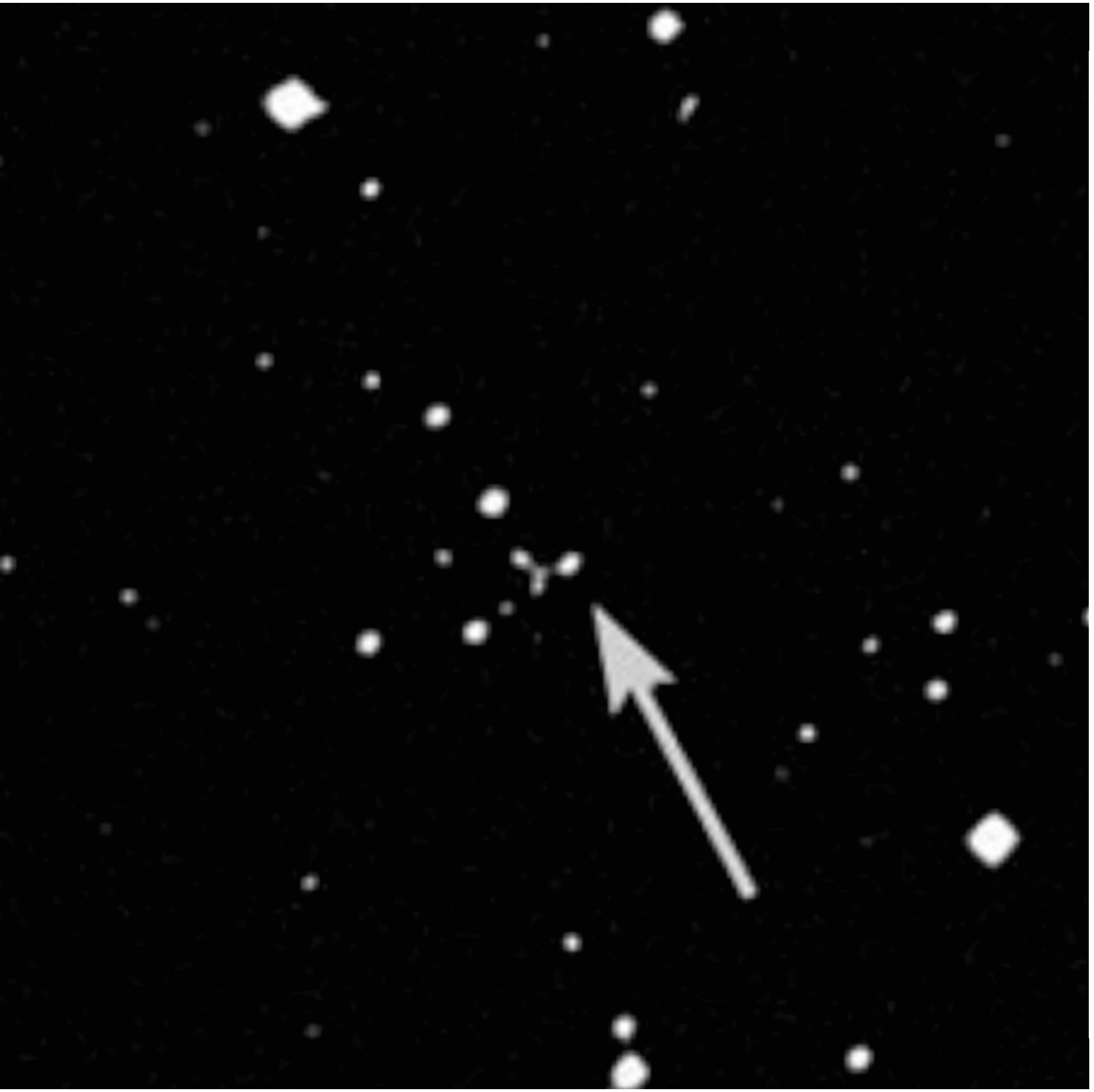
binary evolution



Han et al, 2020
Chen, Xuefei et al, 2024

Luminous red novae: the first appearance



V838 Mon image credit: NASA and ESA

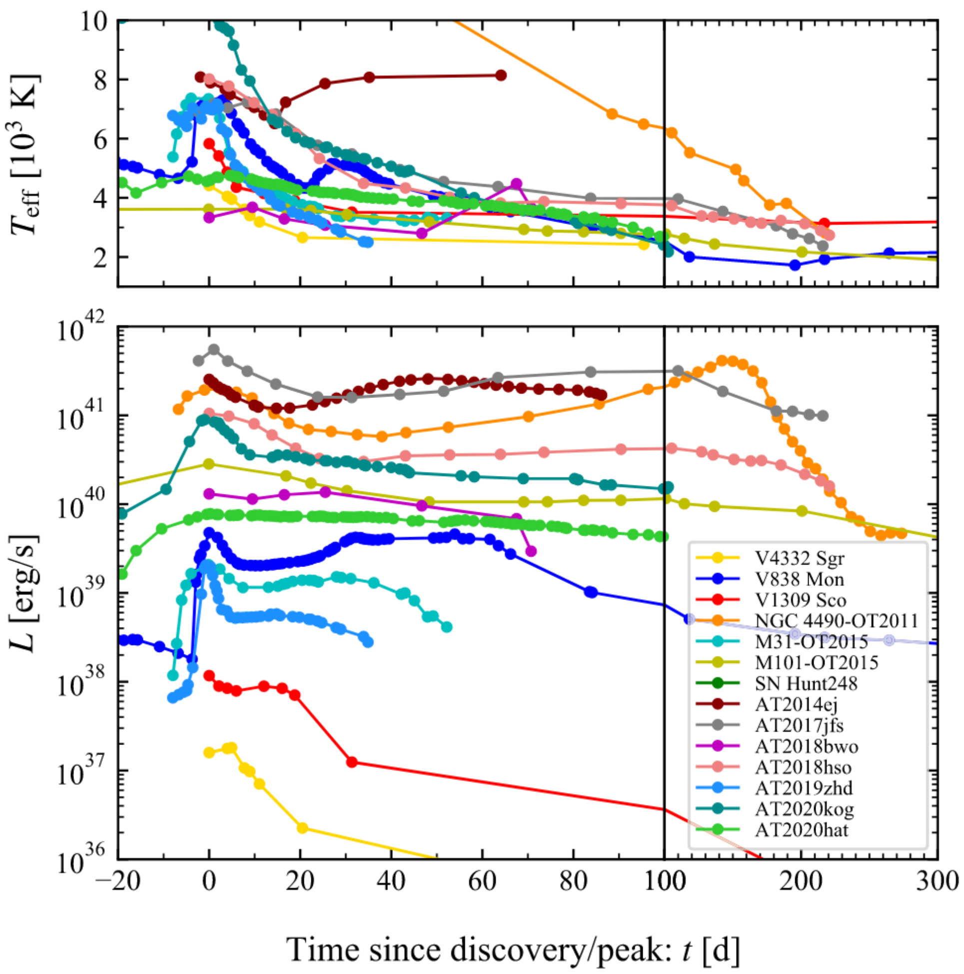
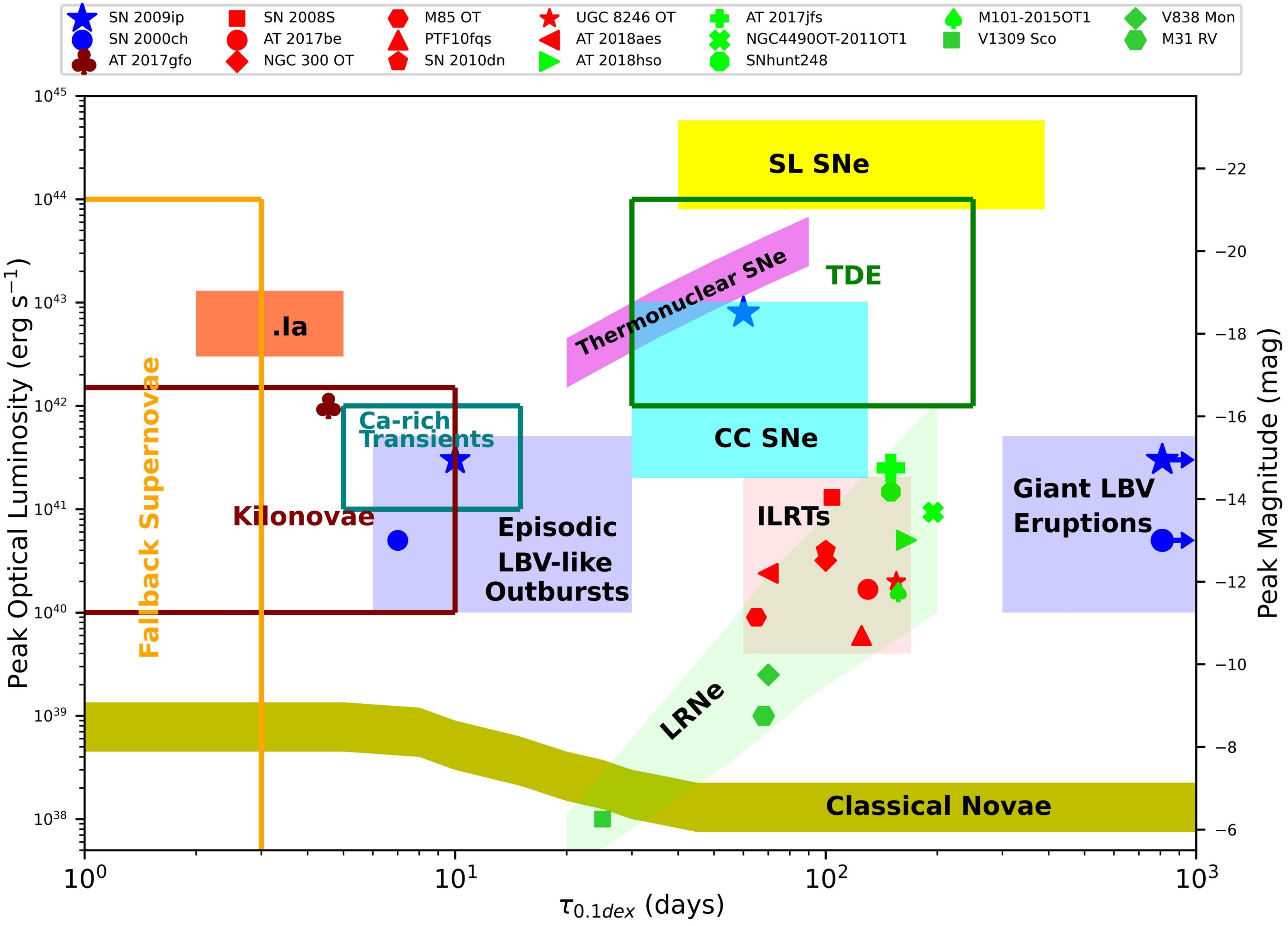
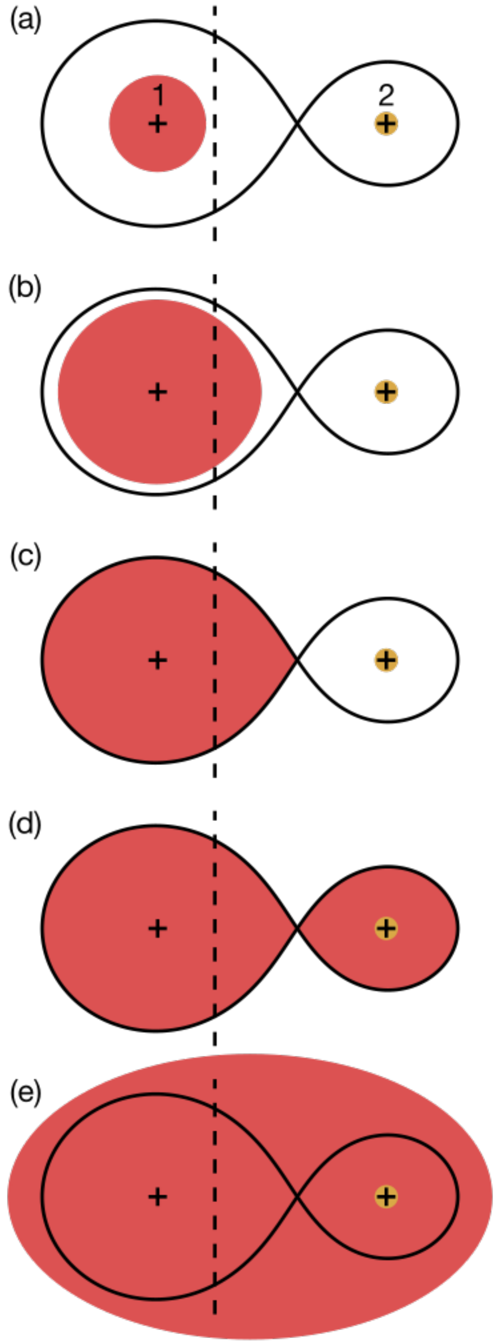


Figure 1. Bolometric light curves (bottom panel) and effective temperatures (top panel) as a function of time since peak or discovery for a sample of LRNe. See Table 1 for references to the data used to construct the figure.

Matsumoto & Metzger, 2022

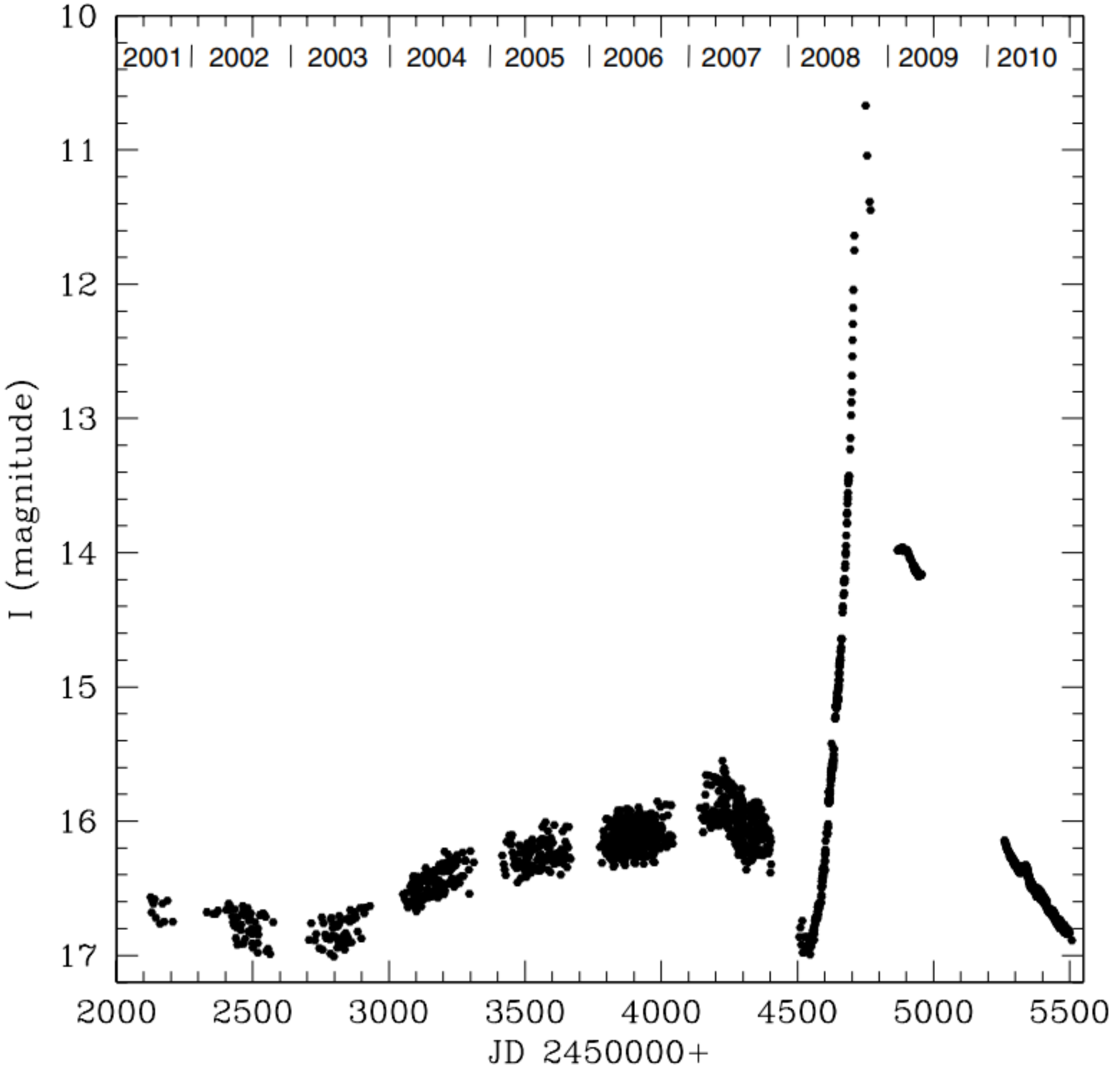
LRNe and SNe as transients





Cai et al, 2022

V1309 Sco is the first confirmed binary merger events



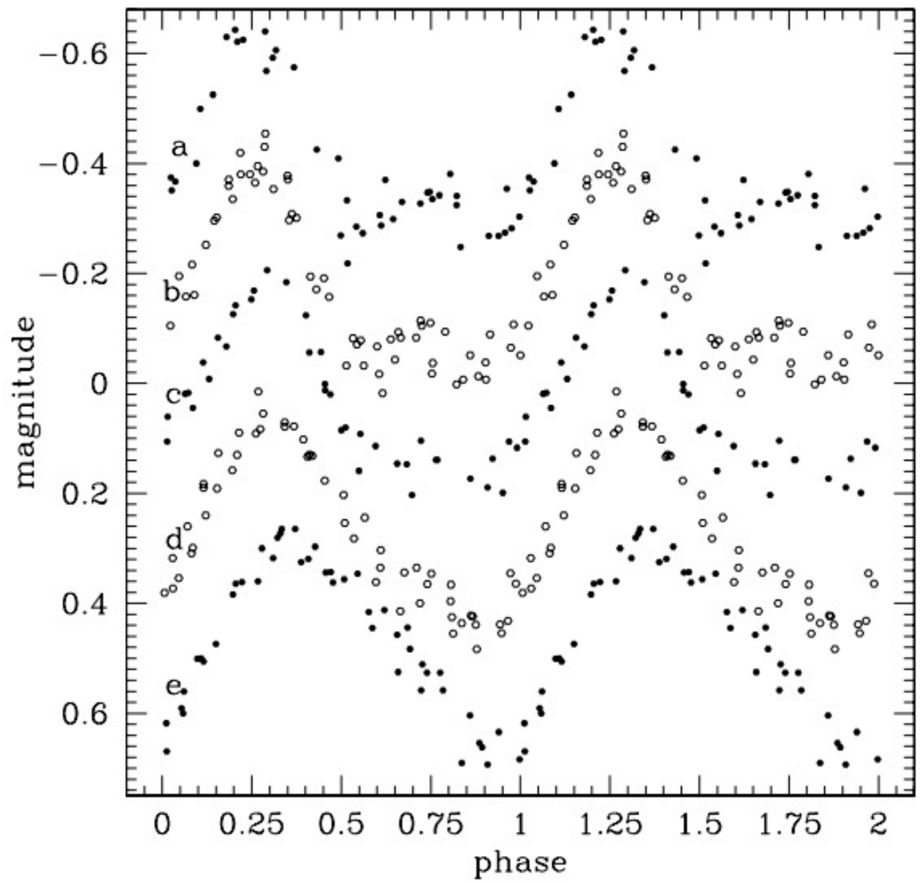
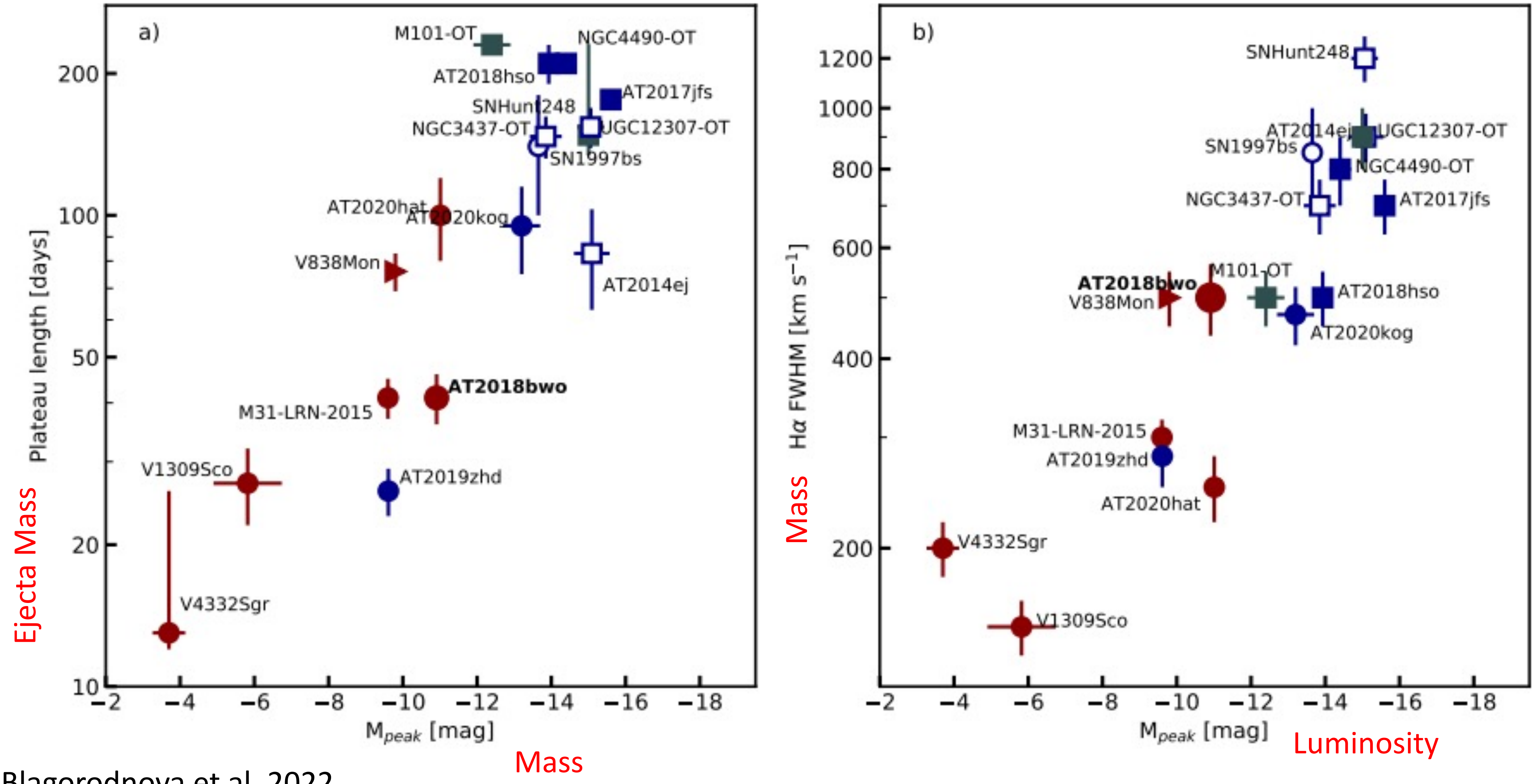


Fig. 3. Light curves obtained from folding the data with the period described by Eq. (1). *Upper part*: seasons 2002−2006. *Lower part*: season 2007 devided into five subsamples (time goes from a to e). The zero point of the magnitude (ordinate) scale is arbitrary.

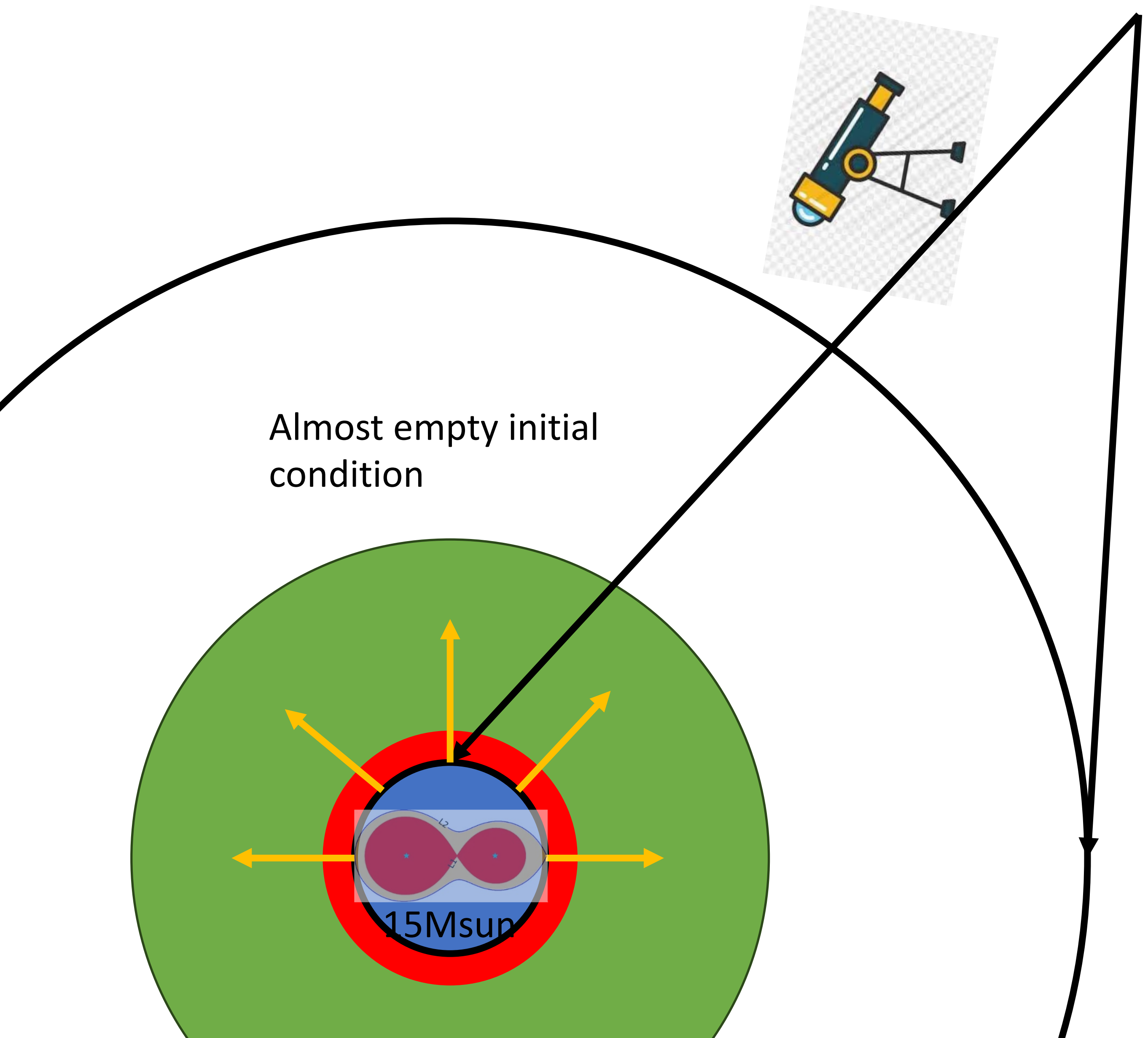
Tylenda et al, 2011

Luminous red novae:
a diverse range with correlations



Blagorodnova et al, 2022

Initial and boundary conditions in 1D



Inner and outer boundaries at 450 and 15000 $R_{\odot}$.

- The gas of the CEE emerges from the inner boundary, we call it ejecta.
- The ejecta can expand into the computational domain or fall back into the inner boundary.
- Radiation is also emerging from the inner boundary by radiation advection.
- Radiation flux is leaving the outer boundary, captured by the telescope.
- Radiation pressure and gas pressure gradients can promote mass ejection.
- Hydrogen and helium can recombine.

Governing equations and *Guangqi* (光启)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

$$\frac{\partial \rho v}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} + p\mathbb{I}) = \rho(\mathbf{a}_{\mathrm{rad}} - \nabla\phi),$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E+p)\mathbf{v}] = \rho\mathbf{v} \cdot (\mathbf{a}_{\mathrm{rad}} - \nabla\phi) + G^0,$$

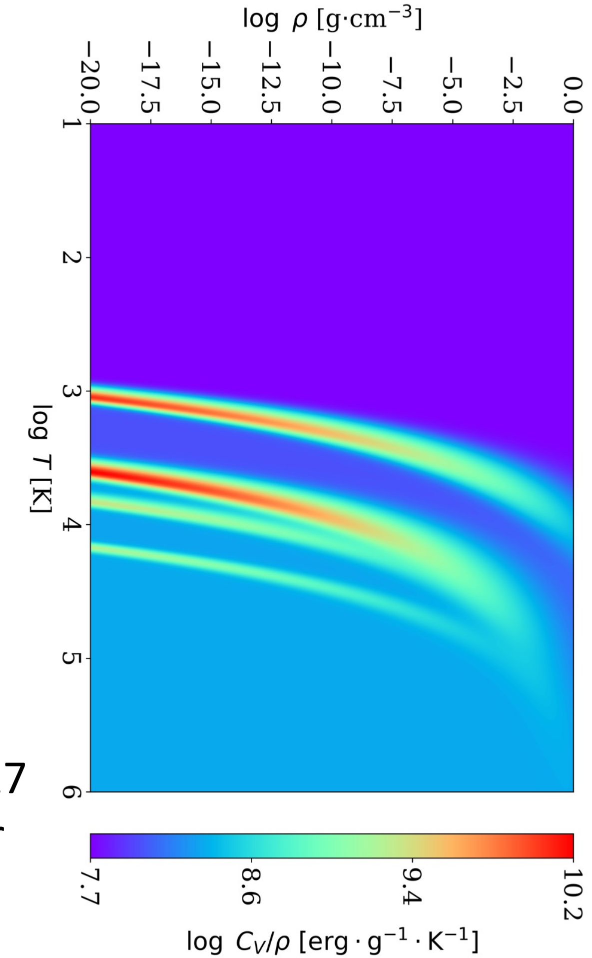
$$\frac{\partial \mathcal{E}}{\partial t} + \nabla \cdot [(\mathbf{F}_r + \mathcal{E}\mathbf{v})] = -G^0 - \mathcal{P}_r : \nabla\mathbf{v},$$

$$\frac{\partial e_g}{\partial t} = G^0$$

$$E = \rho\frac{v^2}{2} + e_g(\rho, T_g),$$

$$G^0 = \kappa_p(\mathcal{E} - a_r T^4)$$

Xu Guangqi (徐光启), a cc. 16-17 mathematician and astronomer collaborated with Matteo Ricci.



- Solve the general EoS hydrodynamic equations with general EoS Riemann solver (Chen et al 2019).
- Solve the radiation transport and gas thermodynamic equations together implicitly.

Chen & Bai, to be resubmit to the ApJS.

Governing equations and *Guangqi* (光启)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

$$\frac{\partial \rho v}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} + p\mathbb{I}) = \boxed{\rho(\mathbf{a}_{\rm rad} -} \nabla \phi),$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E+p)\mathbf{v}] = \boxed{\rho \mathbf{v} \cdot (\mathbf{a}_{\rm rad}} - \nabla \phi) + G^0,$$

$$\frac{\partial \mathcal{E}}{\partial t} + \nabla \cdot [(\mathbf{F}_r + \mathcal{E}\mathbf{v})] = -G^0 - \boxed{\mathcal{P}_r : \nabla \mathbf{v},}$$

$$\frac{\partial e_g}{\partial t} = G^0$$

$$E = \rho \frac{v^2}{2} + e_g(\rho, T_g),$$

$$\boxed{G^0 = \kappa_p(\mathcal{E} - a_r T^4)}$$

- G^0 is the radiation and gas energy exchange rate. Usually extremely fast in the CEE problem.

- When $v_{fluid} \ll c$, $\rho \boldsymbol{a}_{\rm rad} = \frac{\rho \kappa_R \mathbf{F}_r}{c} \approx -\nabla \cdot \mathcal{P}_r$, is how radiation pressure come into play.

- We adopt the flux-limited diffusion approximation, with λ and f defined the following literatures,

$$\mathbf{F}_r = -\frac{c\lambda(\mathcal{R})}{3\kappa_R \rho} \nabla \mathcal{E},$$

$$\mathcal{P}_r = \frac{\mathcal{E}}{2}[(1-f)\mathbb{I} + (3f-1)\mathbf{n}\mathbf{n}],$$

$$\mathbf{n} = \mathbf{F}_r / |\mathbf{F}_r|$$

- Optically thin, $\mathbf{F}_r = c\mathcal{E}\mathbf{n}$, $\mathcal{P}_r = \mathcal{E}\mathbf{n}\mathbf{n}$

- Optically thick, $\mathbf{F}_r = -\frac{c\nabla \mathcal{E}}{3\kappa_R \rho}$, $\mathcal{P}_r = \frac{\mathcal{E}}{3}\mathbb{I}.$

Levermore & Pomraning, 1981. Levermore, 1984

Five groups of simulations

Variable ejecta velocity.

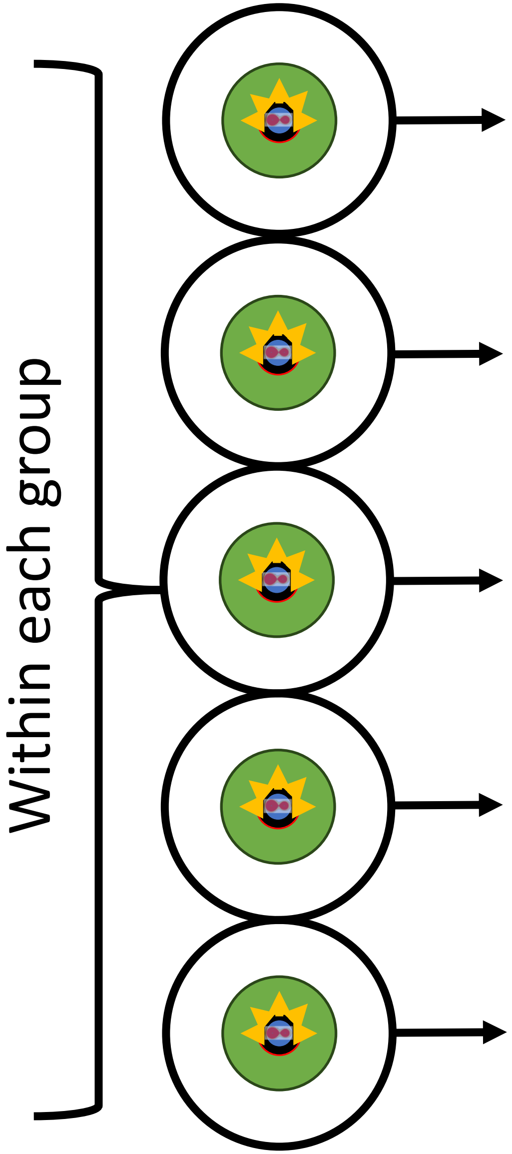
$\bar{v}_{ej} = v_{ej}/v_{esc}$

$\bar{v}_{ej} \in \{0.7, 0.75, 0.8, 0.85\}$

20 simulations in each group.

Varibable radiation to gas energy ratio
For the baseline group.

$\frac{\mathcal{E}}{e_g} \in \{0.2, 0.4, 0.8, 1.6, 3.2\}$



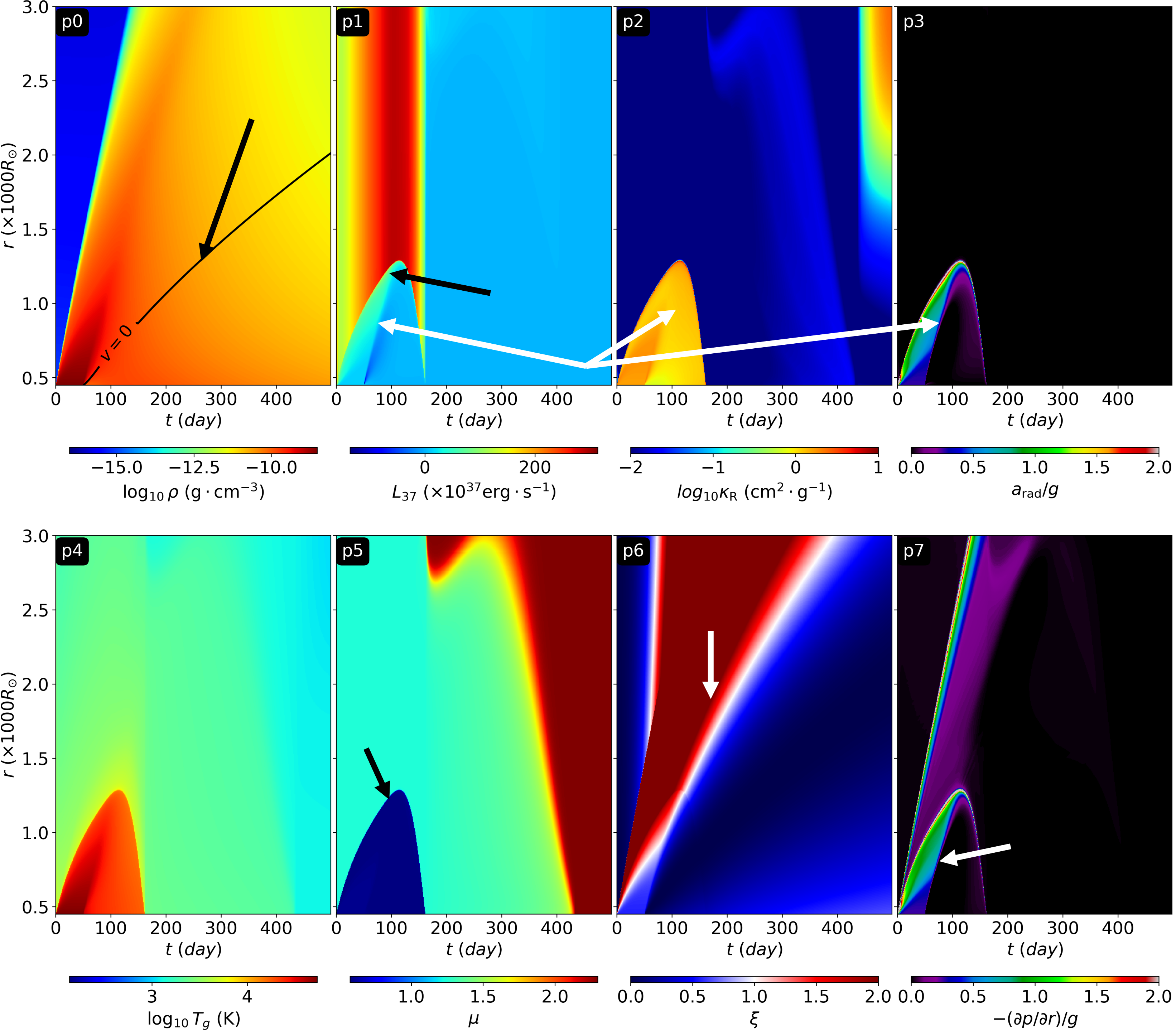
Realistic EoS, consist of hydrogen and helium. Radiation transport, radiation pressure. The baseline group.

Gamma-law gas, $\gamma = 1.4, \mu = 1$. Same outflow temperature as the baseline group.

Gamma-law gas, $\gamma = 1.1, \mu = 1$. Same outflow temperature as the baseline group.

Adiabatic real EoS. No radiation at all.

Artificially remove radiation pressure, but take radiation flux into consideration.

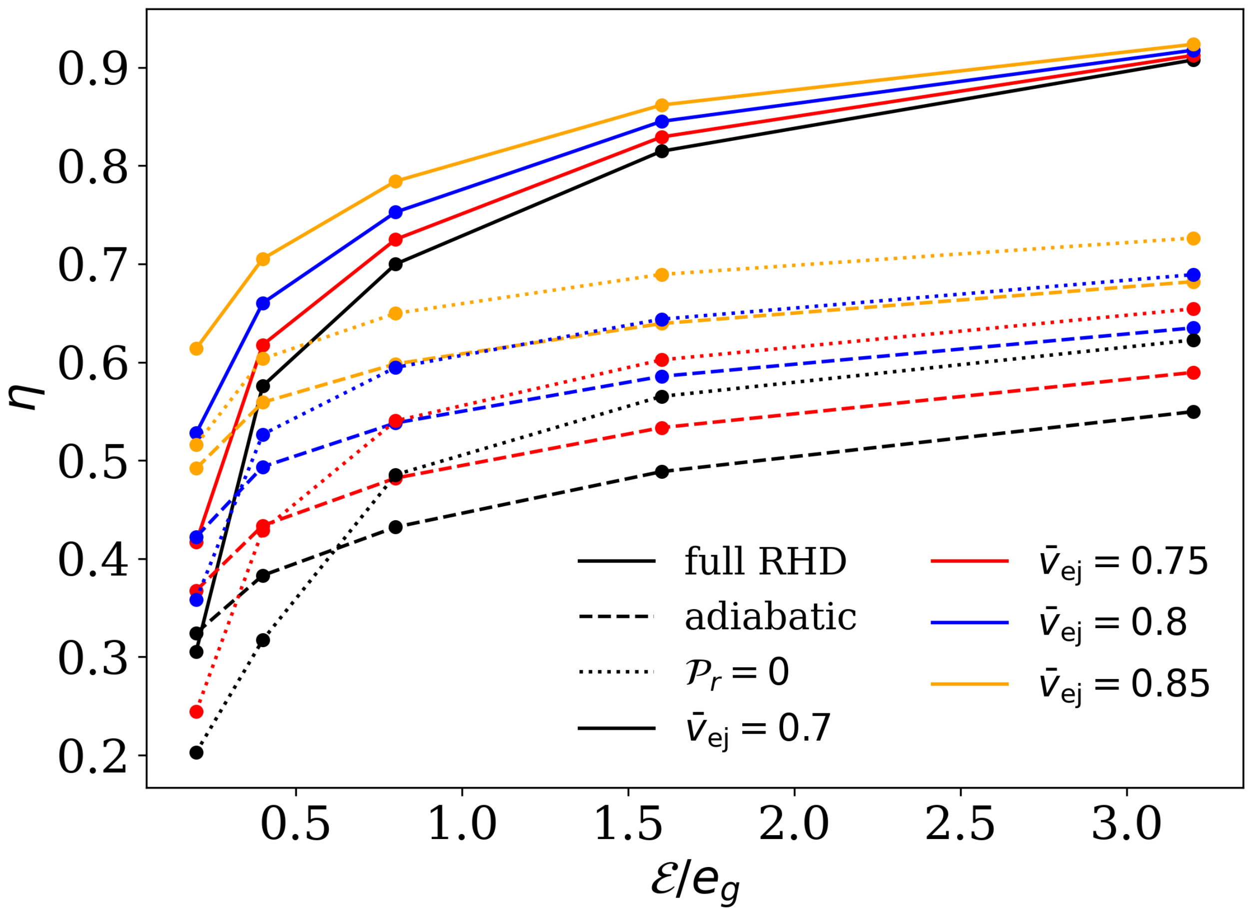


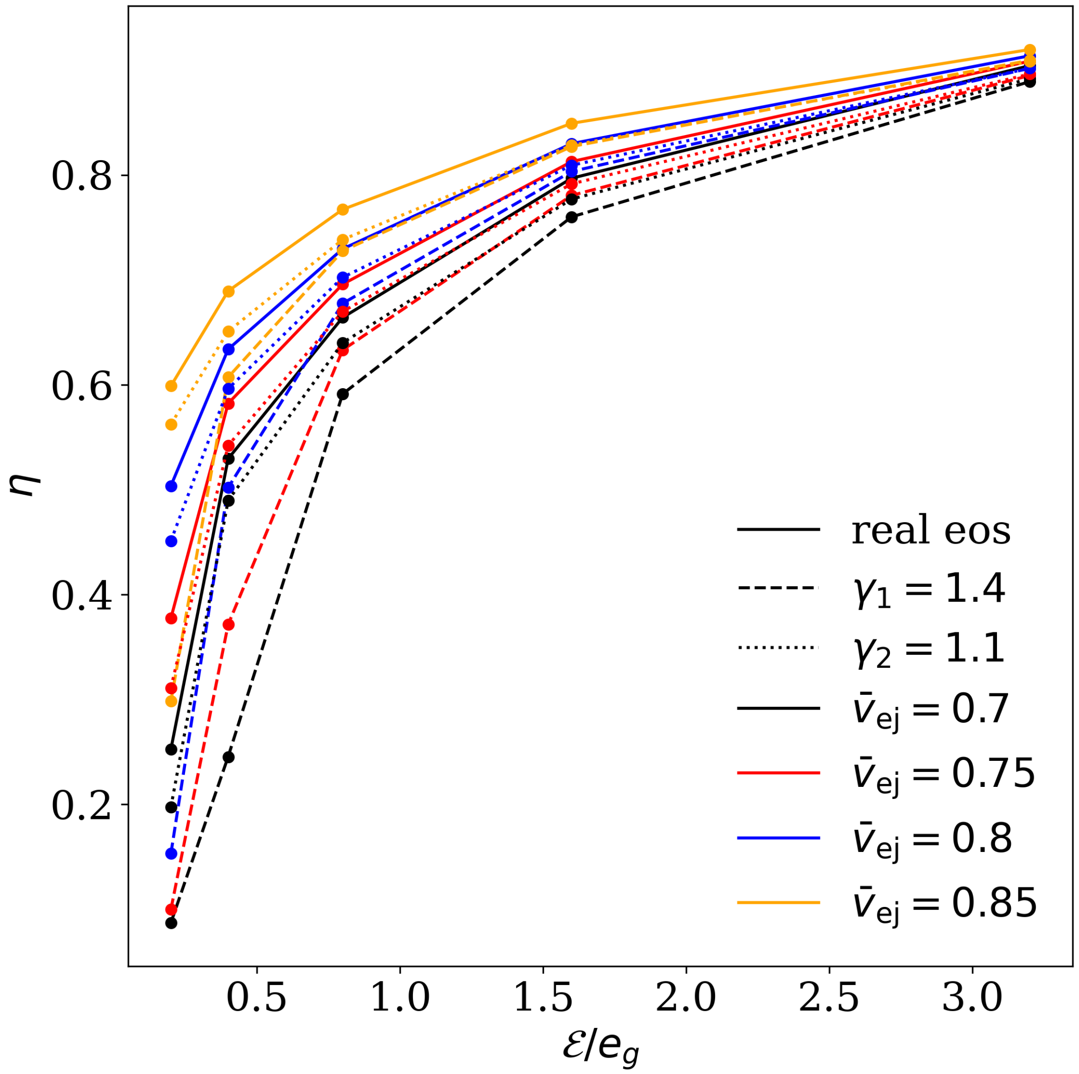
Ejecta evolution $\bar{v}_{ej} = 0.75, \frac{\mathcal{E}}{e_g} = 0.8$

- v=0 contour divides the ejecta into outflow and fallback zones.
- The mean molecular weight evolution shows the location of recombination front.
- The luminosity increases dramatically at the recombination front, and become constant.
- Below the recombination front, there is a layer with high opacity and radiation flux, pushing the envelope out.
- The pressure gradient also contribute to the acceleration of the envelope.
- Finally, some of the gas reaches the escape velocity.

Radiation pressure $\mathcal{P}_r$ is important when $\mathcal{E}/e_g$ is large. Its impact is more significant to more subescape ejecta

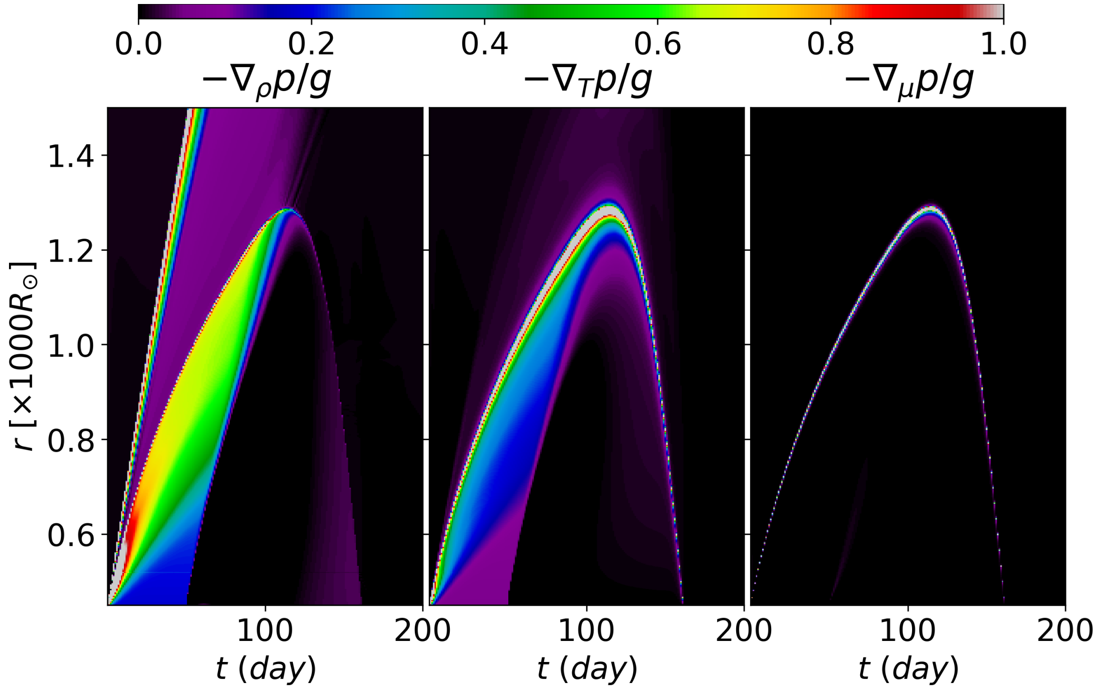
EoS affect the escape mass fraction the most when $\mathcal{E}/e_g$ is small

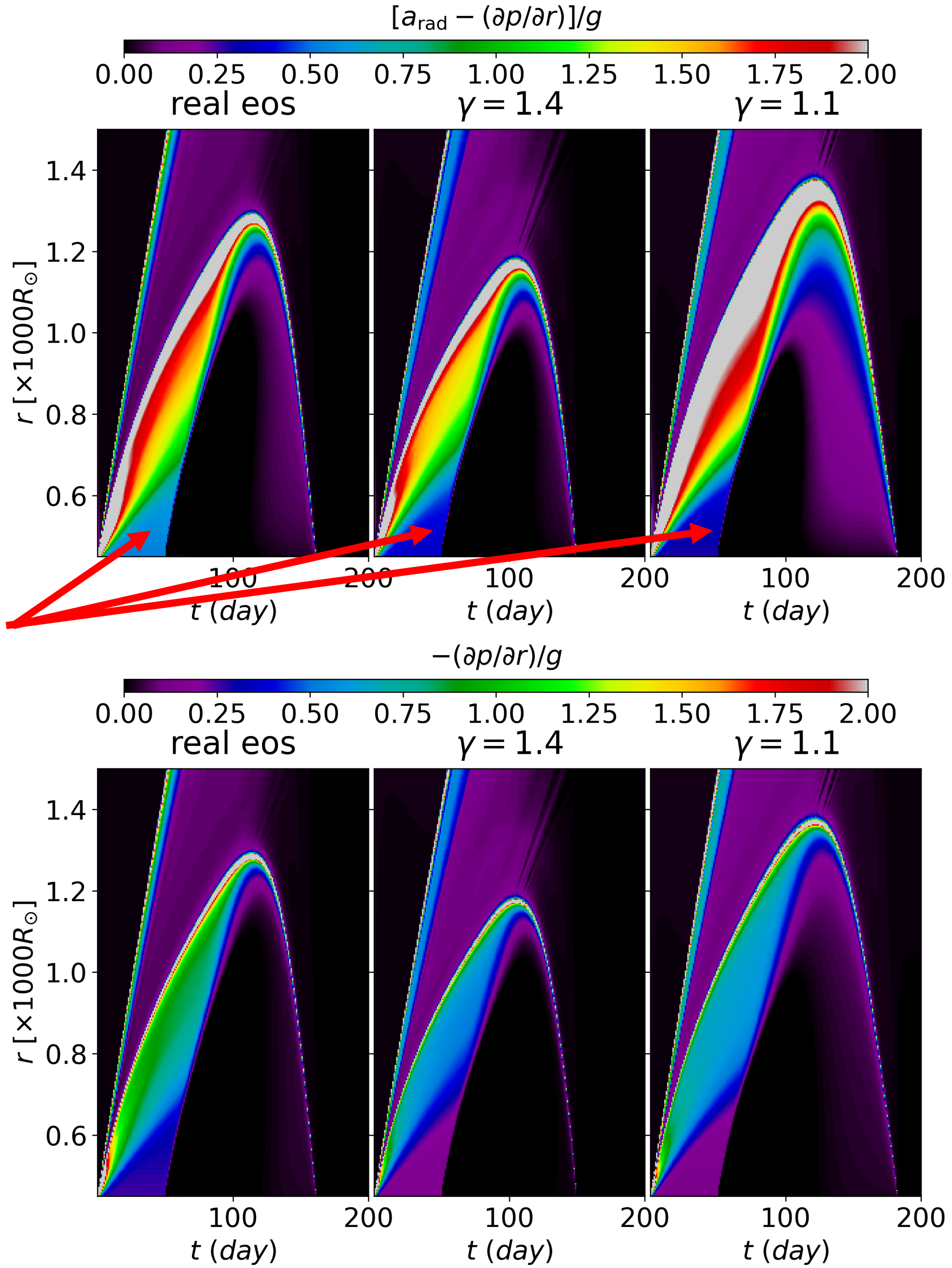




Chen, submitted to the ApJL

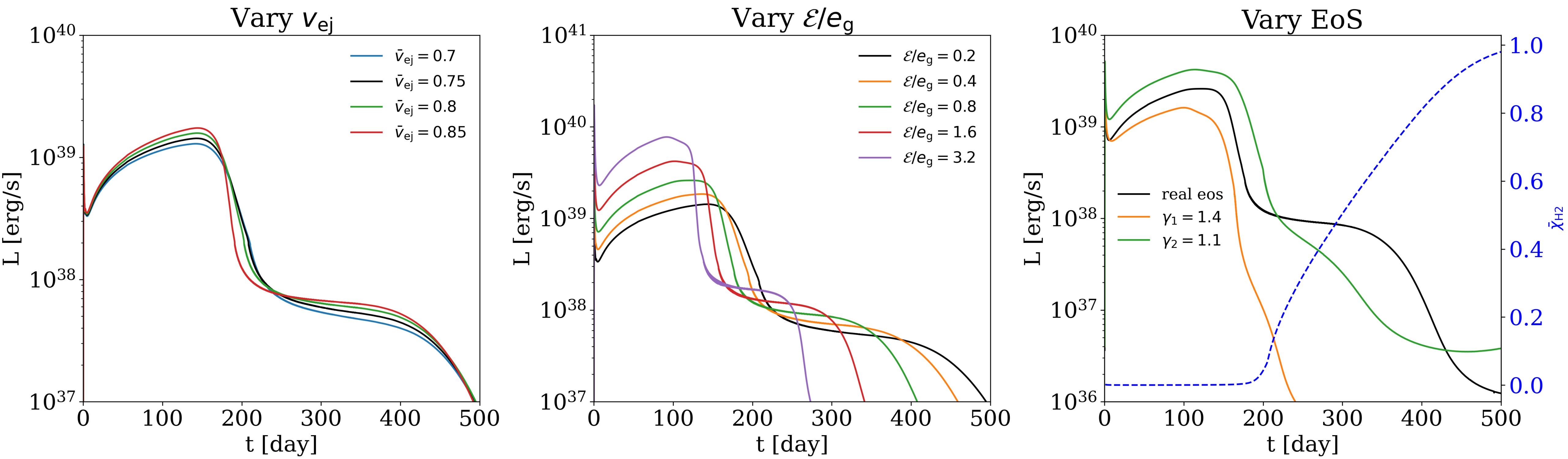
∇p v.s. EoS $\bar{v}_{ej} = 0.75, \frac{\mathcal{E}}{e_g} = 0.8$





- Radiation pressure and gas pressure gradient can promote envelope ejection.
- Realistic EoS has a steeper pressure gradient than the gamma-law gas.
- The biggest contribution to ∇p is the density pressure gradient.

Different parameters impact on the light curve



- The ejecta velocity has small impact on the light curve.
- $\mathcal{E}/e_g$ influences the shape of the light curve dramatically.
- EoS also influences the shape of the light curve.
- The recombination of $H \rightarrow H_2$ flattens the decrease of the luminosity in the realistic EoS simulation.

Chen, submitted to the ApJL

Energy conservation and convergence

- Due to source terms and the implicit solver, the numerical error is inevitable.
- When $v_{fluid} \ll c$, $\rho \boldsymbol{a}_{\rm rad} = \frac{\rho \kappa_R F_r}{c} \approx -\nabla \cdot \mathcal{P}_r$.
- Add the gas energy equation and radiation energy equations to obtain the total energy equation.

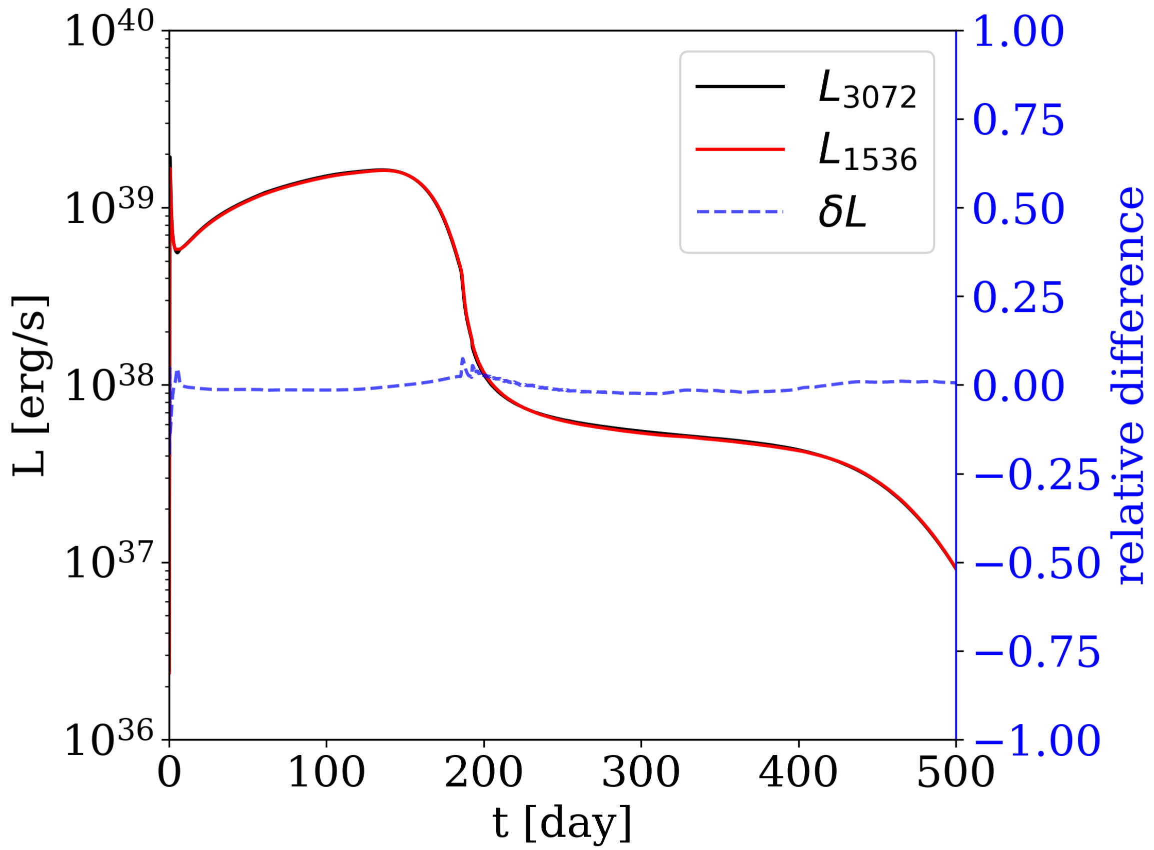
$$\frac{\partial(E+\mathcal{E}+\rho\phi)}{\partial t} + \nabla \cdot [(E+p+\mathcal{E}+\mathcal{P}_r+\rho\phi)\cdot \mathbf{v} + \mathbf{F}_r] = 0$$

- We calculate the energy error,

$$\begin{aligned} E_{\rm err} &= E_{\rm final} - E_{\rm init} + E_{\rm in} - E_{\rm out} \\ E_{\rm in} &= E_{\rm in,rhd} + E_{\rm in,\phi} \\ \delta E_{\rm err} &= E_{\rm err}/E_{\rm in,rhd} \end{aligned}$$

- **$\boldsymbol{\delta E_{err}} \leq \mathbf{1.4\%}$ for all simulations. $\boldsymbol{\delta E_{err}} \leq \mathbf{0.3\%}$ if $\frac{\mathcal{E}}{e_g} \leq 1.6$.**

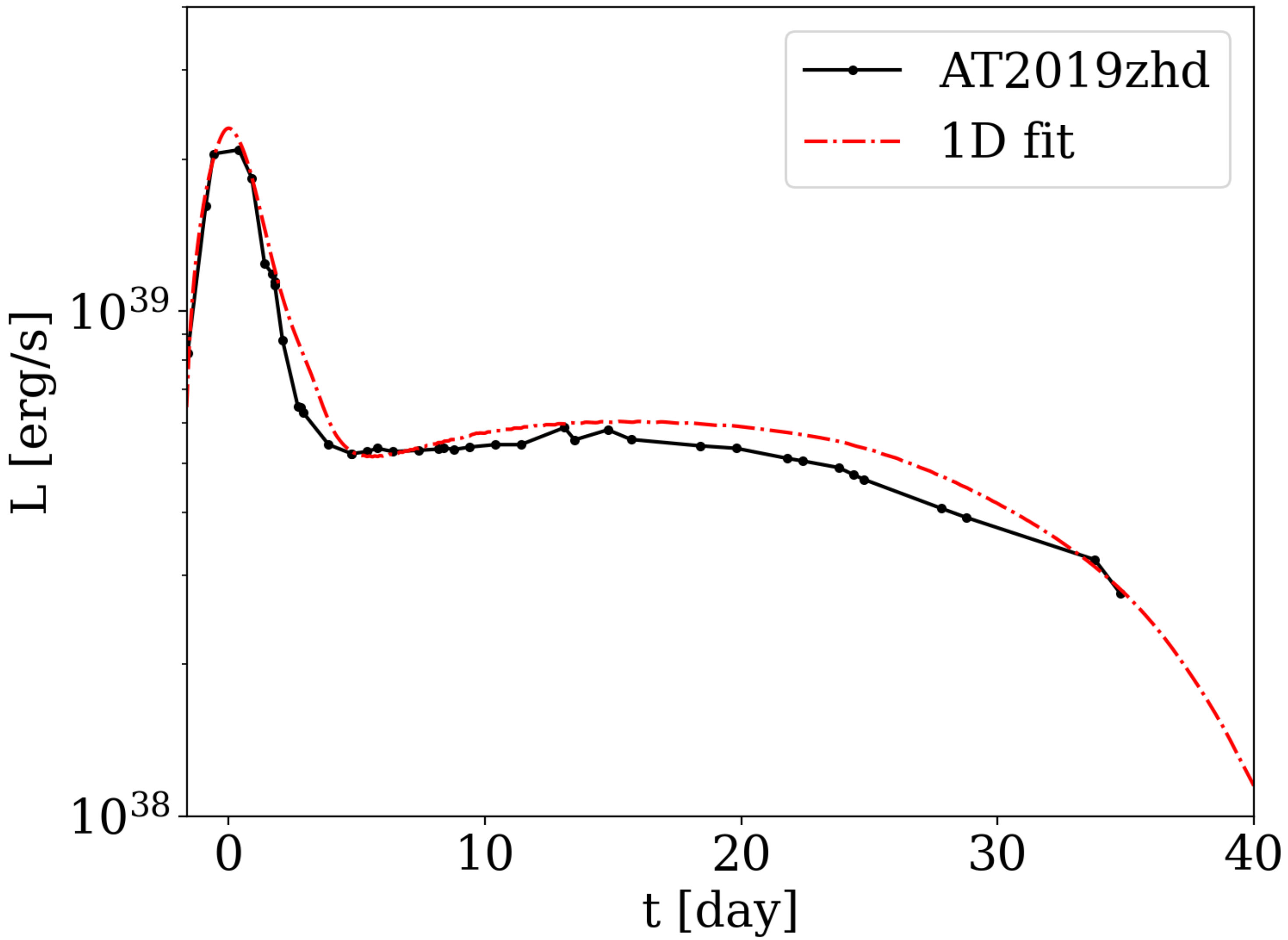
The light curves of $v_{ej} = 0.75, \frac{\mathcal{E}}{e_g} = 0.2$, with 1536 and 3072 base resolution.



The simulations are converged.

Chen, submitted to the ApJL

Fitting AT2019zhd with Guangqi



- Assume a 6Msun central object with ejecta launched at 10Rsun.
- We estimate that only 1% of the total mass is ejected during the CEE by fitting the light curve of the LRN.

Chen & Ivanova, 2024

Summary

- Both radiation pressure and gas pressure can accelerate the envelope. EoS has an impact on the gas pressure gradient.
- Radiation pressure becomes significant in a layer below the recombination front, due to the high opacity of the ionized gas and large radiation flux.
- The recombination of $H \rightarrow H_2$ may empower a late plateau in the light curve that may resemble SPRITE.
- We can use ***Guangqi*** to fit more LRNe in the era of LSST.