Hα Line Profile emerging from Wind Driven model

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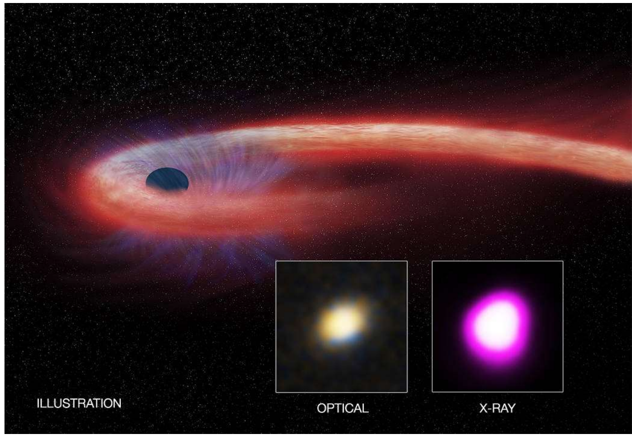
Introduction: Tidal Disruption Event

- Tidal Disruption Event (TDE) is an event which **stellar mass star is disrupted** by Super Massive Black Holes (**SMBH**) due to their strong tidal force.

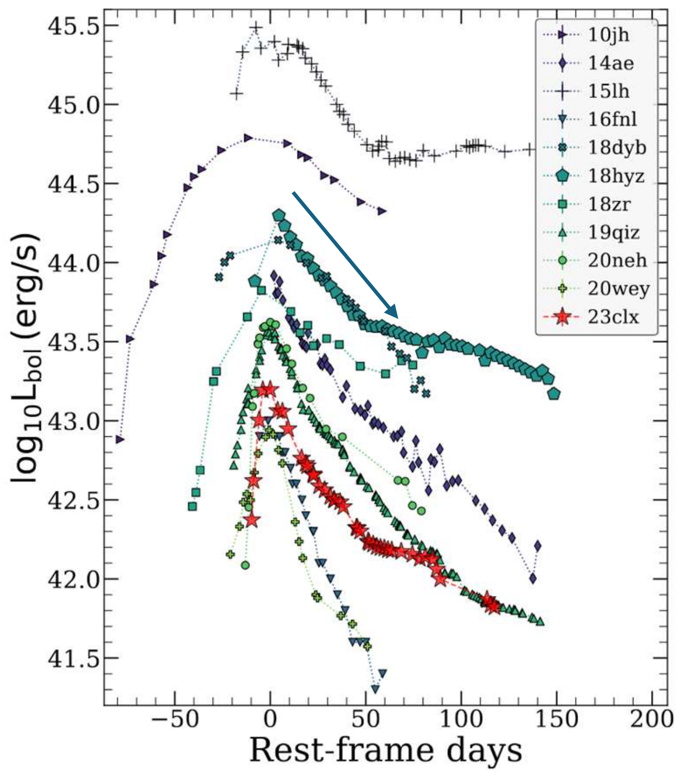


NASA

Typical Luminosity and Timescale

- TDEs have peak luminosity $> \mathbf{10^{43} erg/s}$
- Then they decay as $L \propto t^{-\frac{5}{3}}$
- TDE flares show modest effective T $T_{eff} \sim 10^{4.2} - 10^{4.7}$K.
- TDE has large photosphere radii $\sim \mathbf{10^{14} - 10^{15} cm}$

Sarin+24

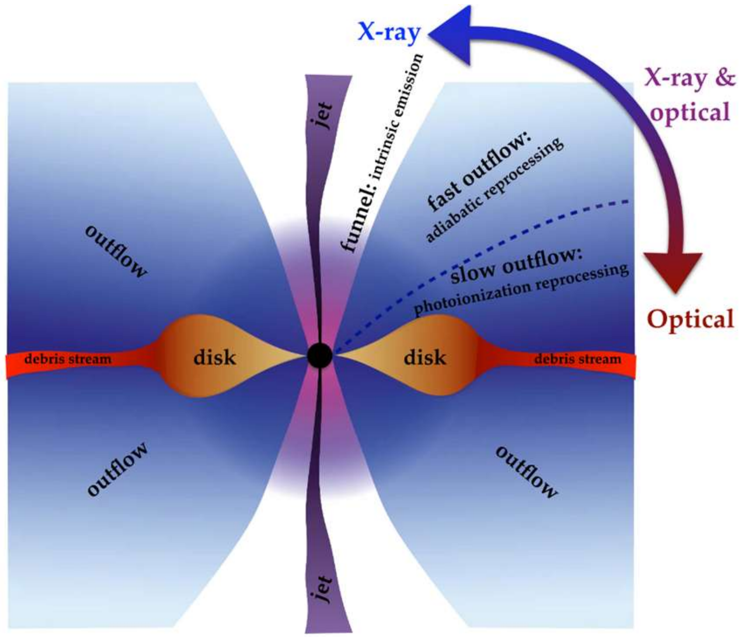


Charalampopoulos+24

The proposed model for TDE

- The disrupted star will be circularized and create an **accretion disk**.
- Then its accretion rate reaches **super-Eddington** to make outflow.

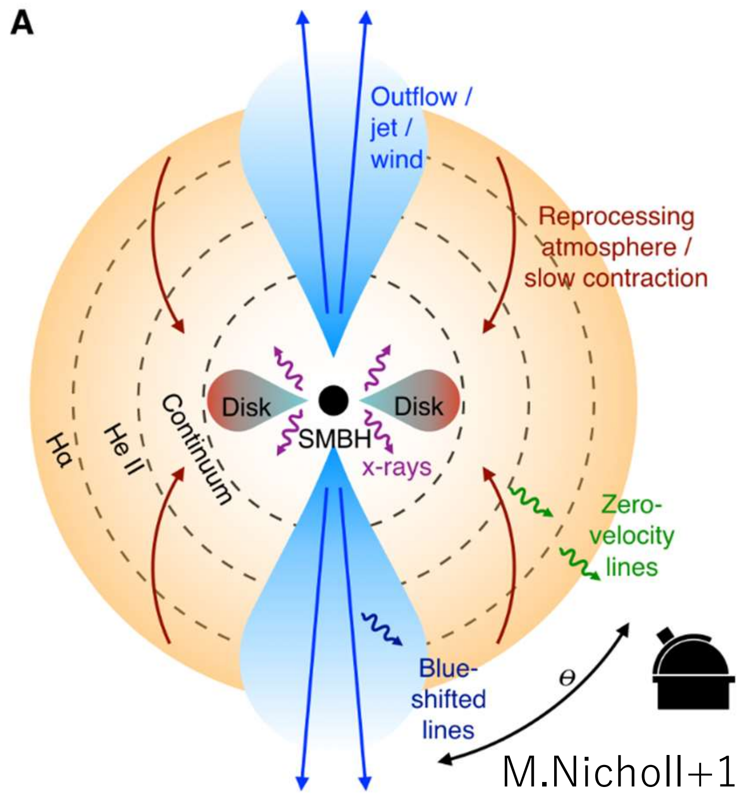
- 3D GRRMHD simulations revealed **optically thick wide-angle outflows** are launched from the accretion disk.



Dai+18

The origin of emission in TDE

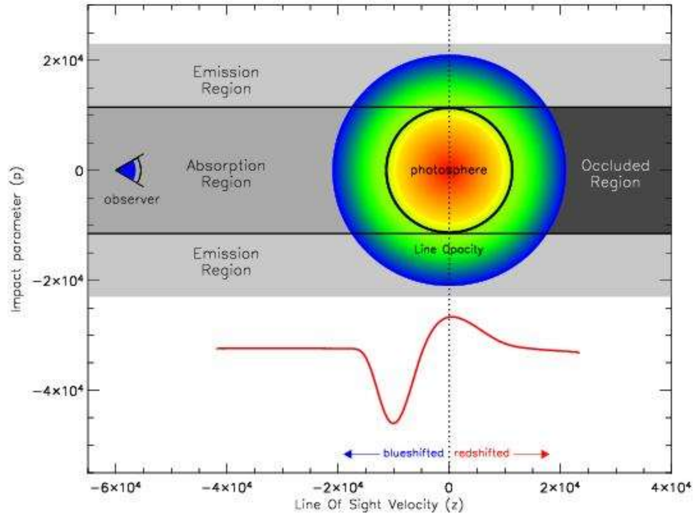
- TDEs show **broad** spectral features from hard X-ray to radio.
- X-rays are emitted from inner accretion disk around the SMBH.
- Then the high energy emission is absorbed and re-emitted (**reprocessed**) through the **optically thick outflow**.



M.Nicholl+19

Motivation: the line emergence in outflow

- In the classical theory of line emission in supernova, line emission will emerge **above its photosphere**.
- The region along the observer will **absorb** continuum emission from photosphere surface.
  ⇒**P-Cygni profile** can be seen in line profile of SNe.



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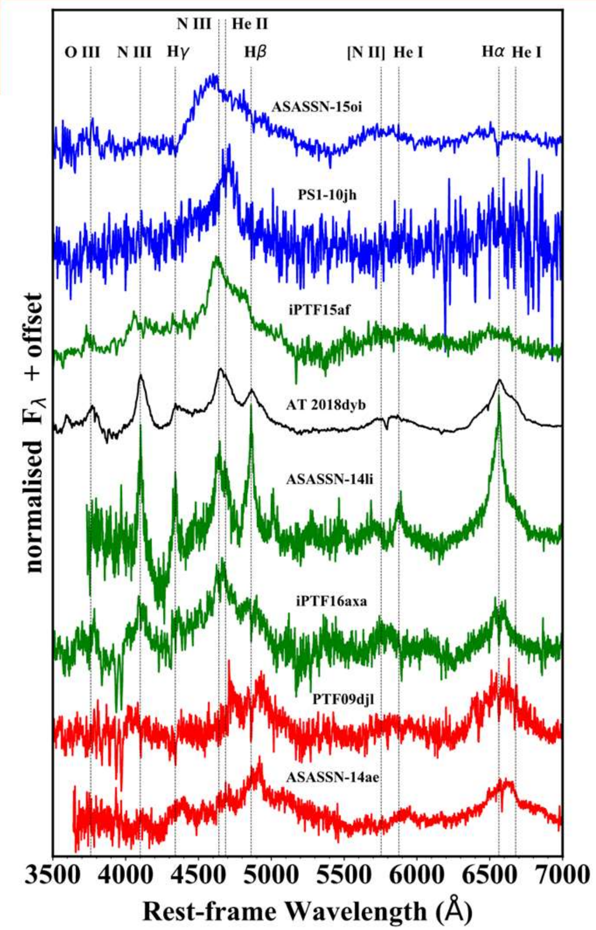
The present understanding in TDE's line

- For TDE, they **rarely** show P-Cygni profile due to highly irradiated outflows from its central BH.
- Usually, TDE's Hα shows **broad** feature of emission.
- There are some methods to make line features of TDE (e.g. Roth&Kasen18), but there are no unified explanation about **TDE's line forming**.

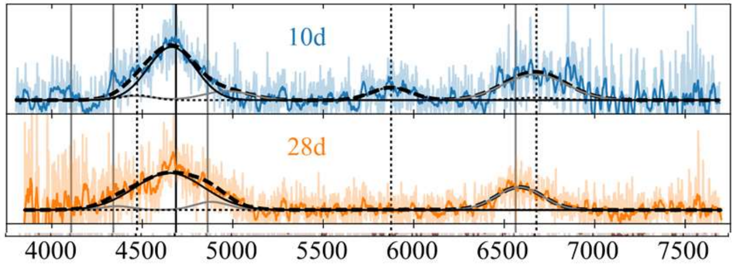


Leloudas+19

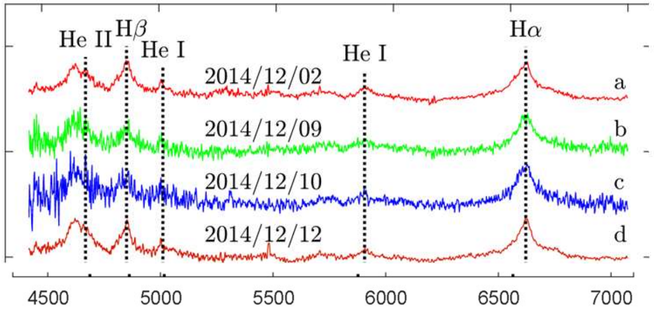
Various types of TDE line profile

- TDE’s are roughly spectroscopically classified as **H** (with H line), **He** (not with H, but with He line), and **featureless** (no strong line).
- However, some TDEs show simultaneously **both H and He** line.
- Also, there are **various shapes of line profile** in the same class of TDEs.

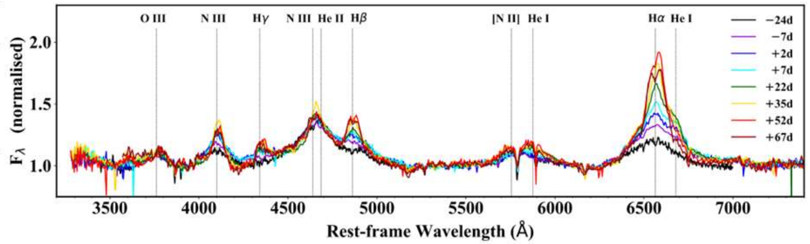
Various shape of Balmer lines in TDE-H



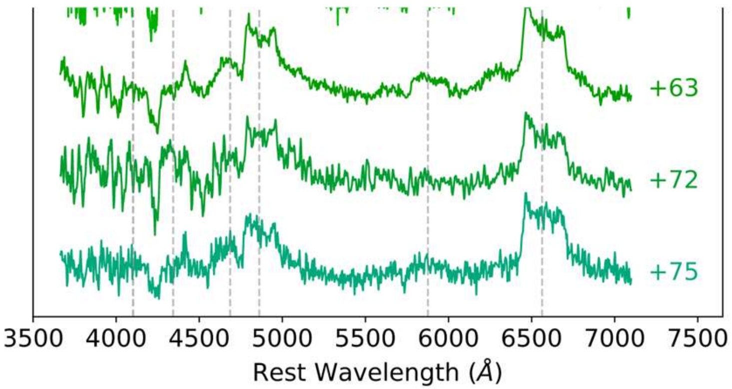
Broad Hα in 17eqx, Nicholl+19



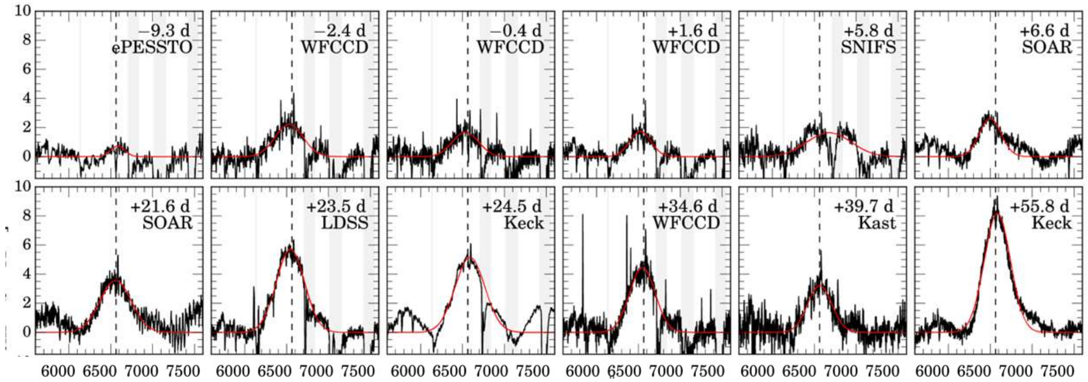
Sharp Hα in 14li, Cao+18 disk?



Broad(~10000km/s) Hα in 18dyb, Leloudas+19 disk?



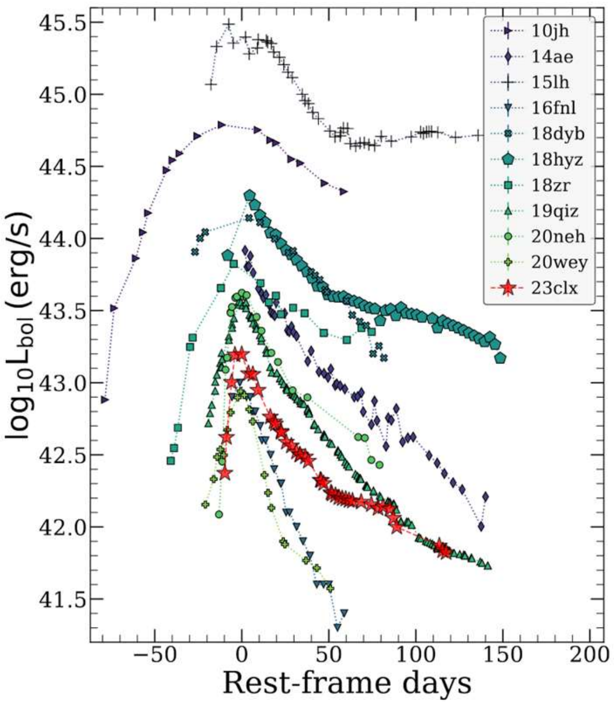
Double horned Hα in 18hyz, Short+20



Sharp, broad Hα in 19azh, Hinkle+21. not from reprocessing?

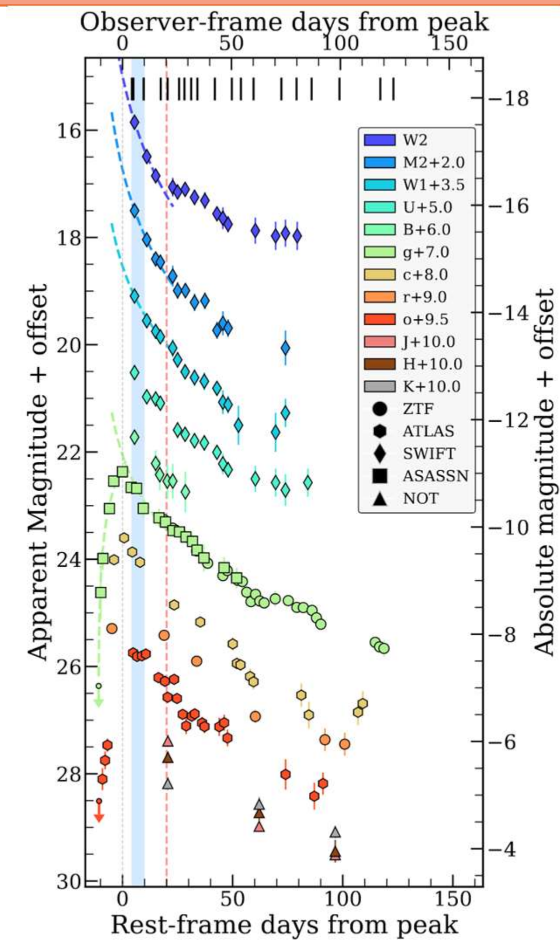
Target: AT 2023clx

- AT 2023clx is one of the **nearest and faintest** TDEs.(Charalampopoulos+24)



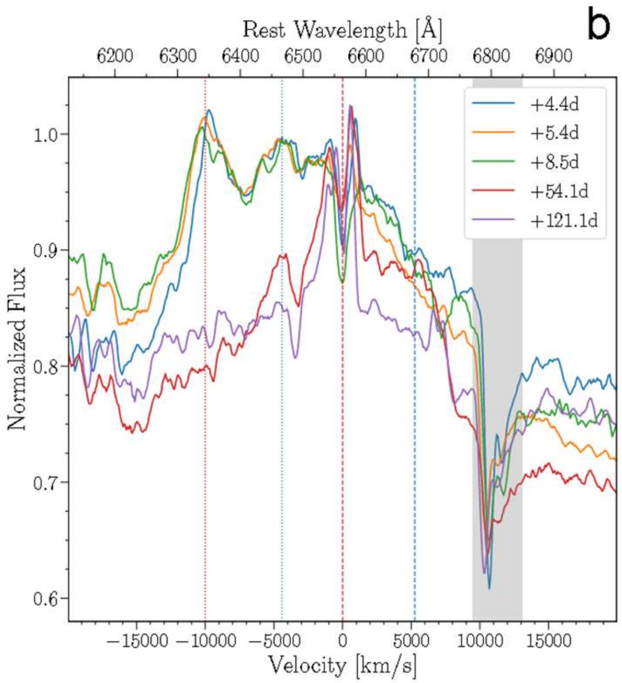
Comparison of LC with Other TDEs

LC of clx



Unique line profile of clx

- Hα profile in clx shows **broad in blueshifted** region,
  and **sharply fading in redshifted** region.
- In later times, blueshifted broad component **vanished**.
- This broad (~-10000km/s) component is not explained completely (Jiazheng Zhu+23 attributed to [OI], Charalampopoulos+24 suspected clumped matter preceding the outflows.)



Line evolution of Hα, K. Uno+25

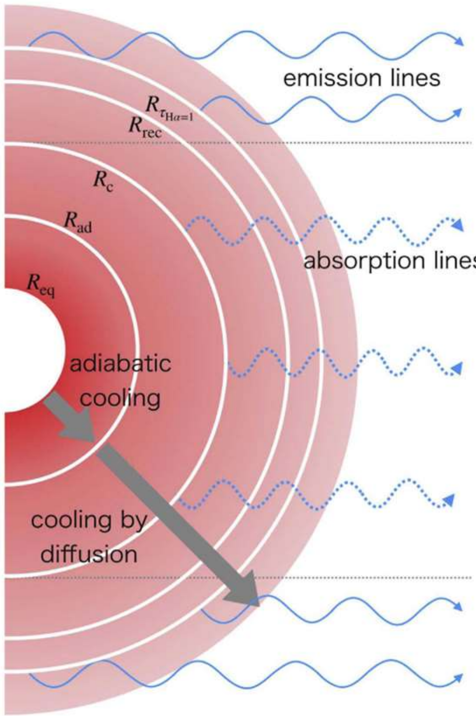
Model: Wind-Driven model

- Wind Driven model is independently proposed model by Uno & Maeda 2020, and Piro & Liu 2020,
  which can explain the light curve behavior of AT2018cow(**FBOT**).
- Because AT2018cow is believed to be powered by **mass accretion** onto a central compact object,
  this model can reproduce **TDE-like -5/3 light curve decline** (Uno&Maeda23).

Wind Driven model

- In Wind-Driven (WD) model, we can get **radial structure of density and temperature** which assumes pure hydrogen outflow.

- In WD model, wind velocity of outflow is assumed to be **constant** in radial direction.



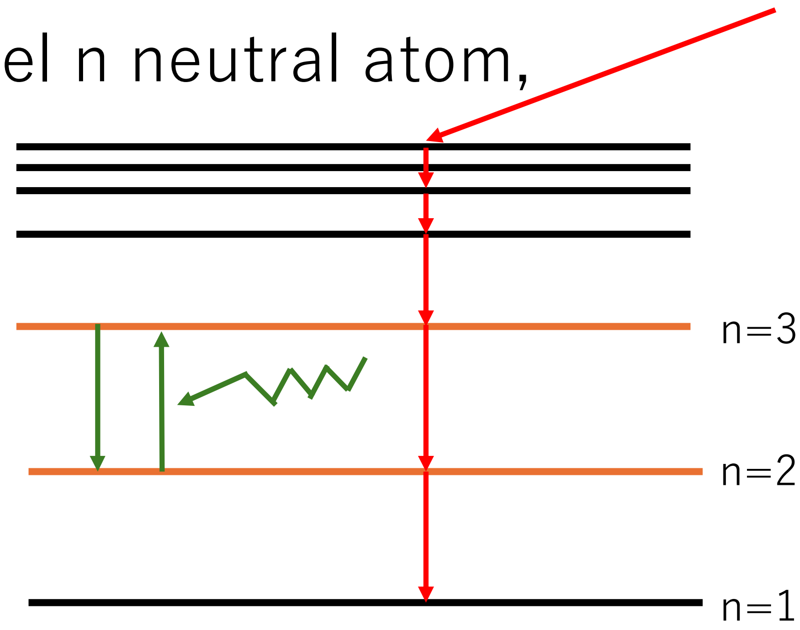
Wind-Driven outflow
Uno&Maeda2020

Motivation of this research

- There is no reports which calculate line profile of **Hα emission from WD model**,
  and how line profile from **constant velocity wind** will be.
- ⇒In this research, the goal is
  comparison the line profile shape and broadening, strength
  between **WD model and observed TDEs**
  such as 23clx, 18hyz and so on.

Line Source of Hα in WD model

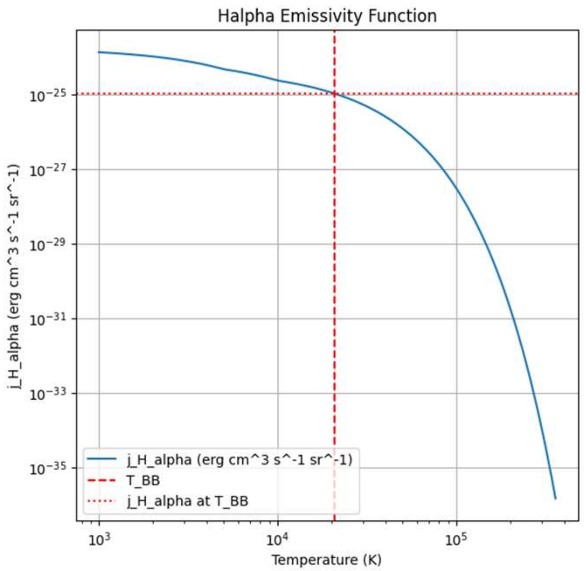
- Two main sources of Hα are considered in this research.
- **Recombination**
  - Ionized H captures electrons -> level n neutral atom, then **cascading onto n=1**, and emit Hα line.
- **Resonance Scattering**
  - neutral n=2 H absorbed radiation to n=3, then **de-excited onto n=2** and emit Hα line.



Line Calculation - Recombination

- The emissivity of Recombination is obtained from Osterbrock & Ferland 2005.
  emissivity $\frac{4\pi j}{n_e n_p}$ (erg cm^3/s) in Case A is tabled for four Temperature points.
- We extra-interpolate these points to use.

  (Case A is an assumption that the system is optically thin for all emission even for Lyα emission)



Emissivity in Osterbrock

Line Calculation – Resonance Scattering

- We calculate emissivity of resonance scattering by thermalization assumption.

$$j_{resonance} = \alpha B_\nu(T)$$

- We used Sobolev approximation to evaluate the opacity of this line;

$$\tau_{sob} = \frac{\pi e^2}{m_e c} f_{32}\lambda_0 n_{n=2}(r)\left(\left|\frac{dv}{dl}\right|\right)^{-1}$$

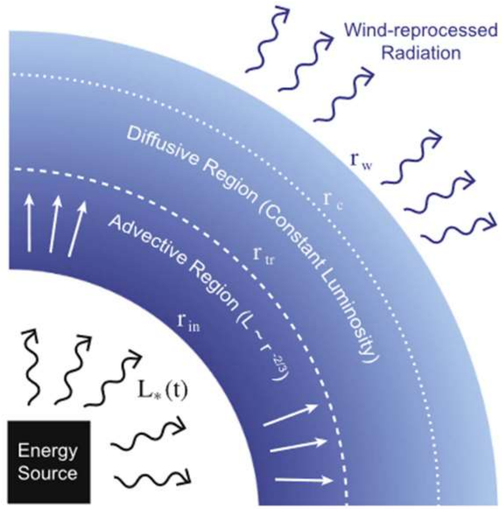
$$\boldsymbol{\alpha = \frac{\nu N_{line}}{c\Delta\nu}\left(\frac{\partial v}{\partial l}\right)(1 - \exp(-\tau_{sob}))}$$

Method①: Temperature calc in WD model

- Temperature structure is decided by **diffusion approximation** in original WD model.
- In diffusion, T is determined by

$$T(r,t) = \left[\frac{\kappa_s K(t) L_{obs}(t)}{4\pi r^3 ac}\right]^{\frac{1}{4}},$$

  and opacity κ is assumed to be constant.
- So this assumption would be valid in dense environment,
  not for line forming region.



Piro & Lu 2020

Temperature Calc by Kramers Opacity

- Then we evaluate outward Temperature structure by equilibrate the radiation;

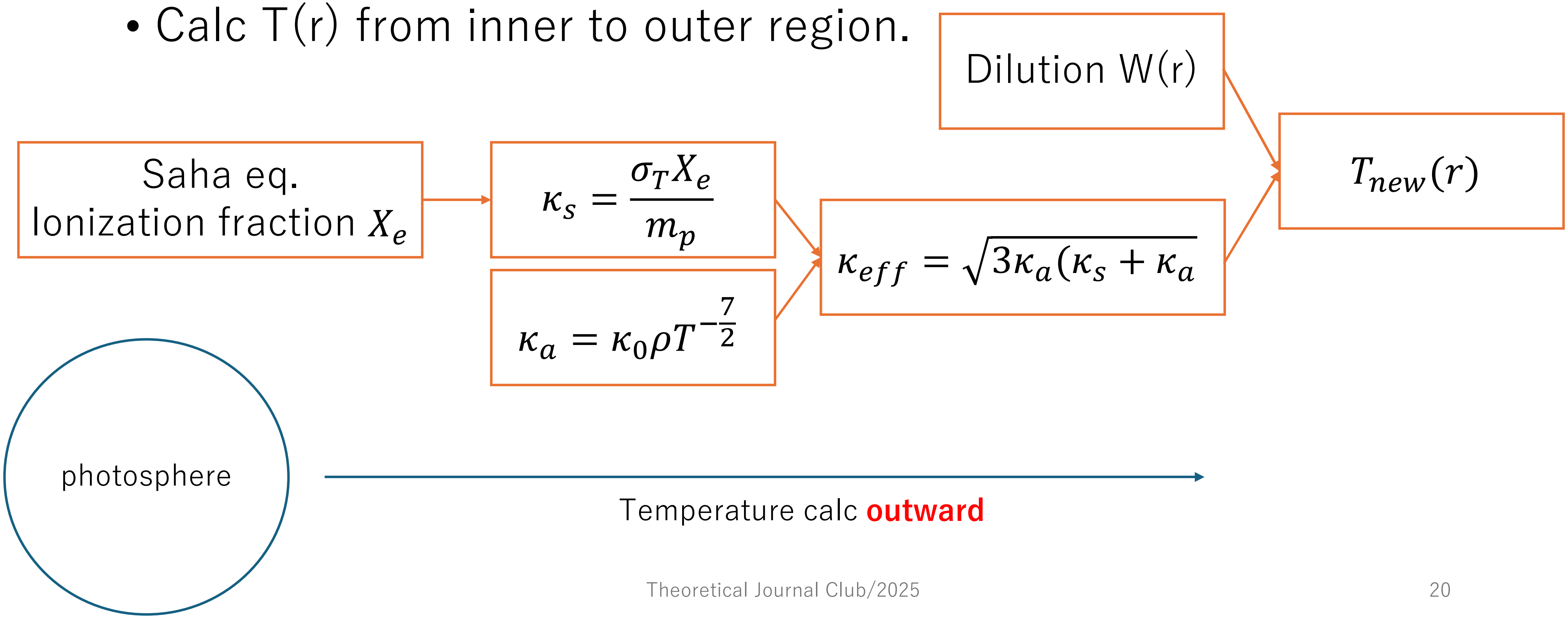
$$\kappa\rho W e^{-\tau} T_{ph}^4 = \kappa\rho T(r)^4,$$

$$\boldsymbol{T(r) = (We^{-\tau})^{\frac{1}{4}} T_{ph}}$$

- (LHS): absorbed radiation at r, which is **diluted** by $W = \frac{1}{2}\left(1 - \sqrt{1 - \left(\frac{R_{ph}}{r}\right)^2}\right)$, and **extincted** by $\tau_{eff} = \sqrt{3\kappa_a(\kappa_a + \kappa_s)}$
- (RHS): black body emission at r

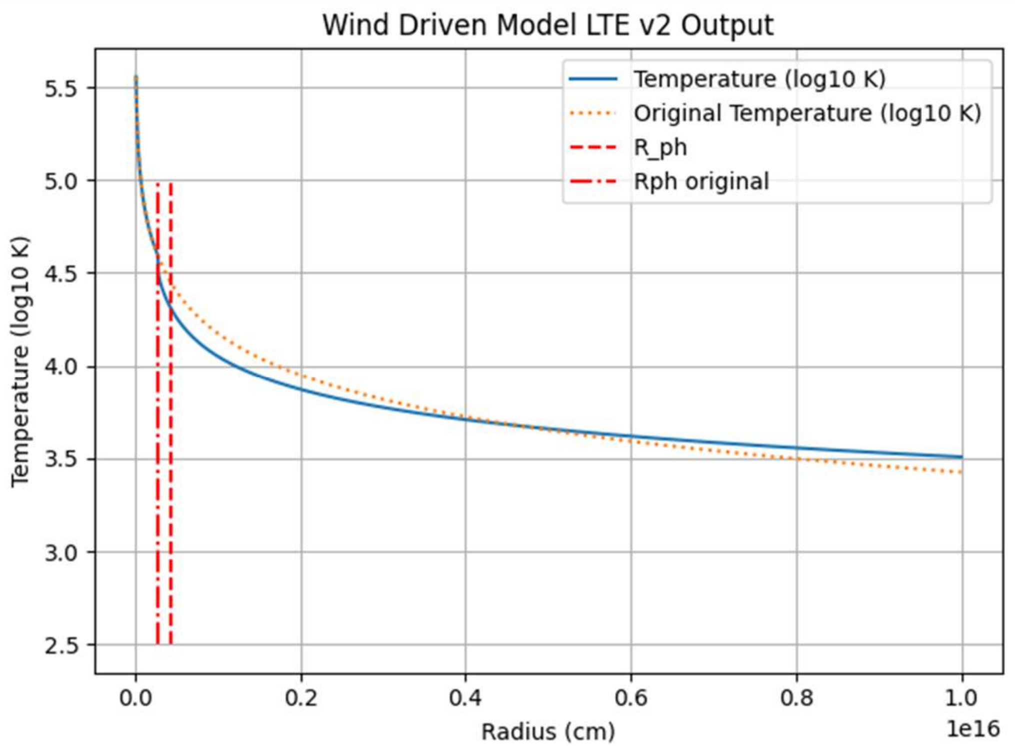
Method①: Temperature determination

- Calc T(r) from inner to outer region.



Result①: Revised radial structure

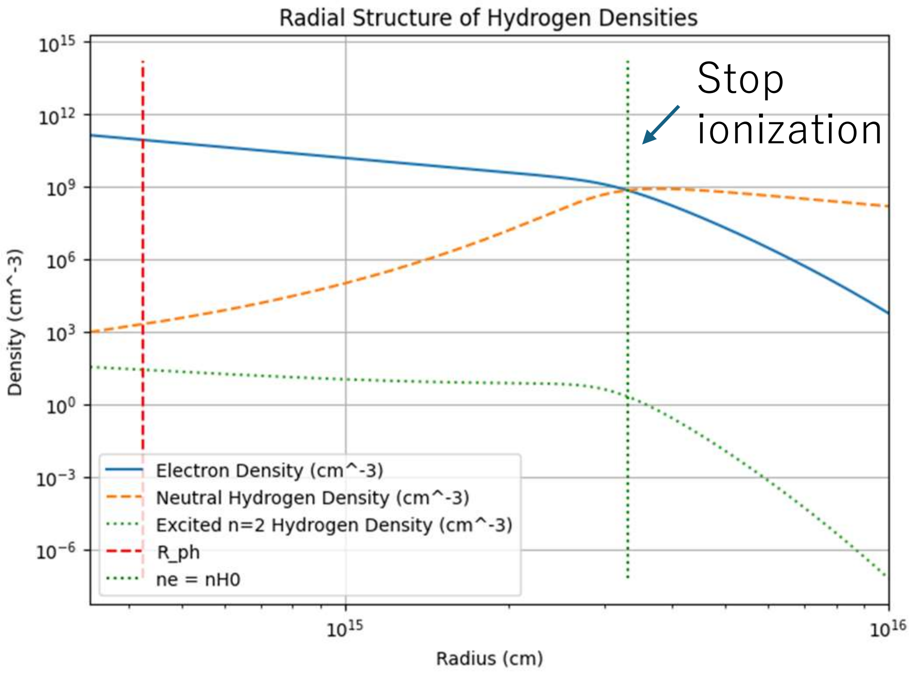
- Revised T **decreases** around photosphere.
- T drops originally $\propto r^{-\frac{3}{4}}$, $\propto \boldsymbol{r^{-\frac{1}{2}}}$ in revised (by dilution $W \sim r^{-\frac{1}{2}}$).
- Photospheric radius rises due to T↘, κ↗, τ↗.



Temperature structure comparison

Radial Composition Structure

- **Number densities** of electrons anc neutral H atoms are obtained from **Saha equation** with ionization occurs from only n=1 H atoms.
- Also, number density of **n=2 H atoms** is obtained from **Boltzmann equation** under the assumption; main level is n=1.



Number densities (loglog)

Radial Structure of emissivity

- Compare two emission source in unit **erg/cm^3/s/str**.
- Recombination emissivity is calculated from tabulated data in Osterbrock by

$$\boldsymbol{\epsilon_{rec}(r) = n_e(r)^2 j_{tabulated} \frac{1}{4\pi}}$$

- Resonance scattering is obtained for constant velocity field;

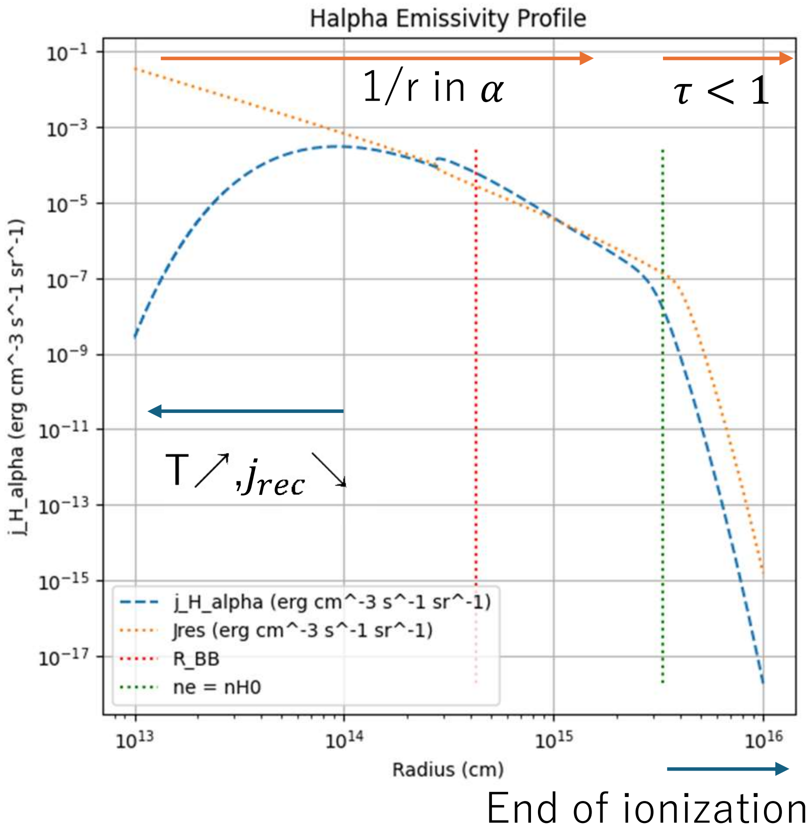
$$\tau = (constant) n_{n=2}(r) \frac{r}{v \sin^2 \theta}$$

$$\alpha = \frac{\nu}{\Delta\nu} \frac{v}{cr} \sin^2 \theta \, (1 - e^{-\tau})$$

$$\boldsymbol{\epsilon_{res}(r) = \alpha B_\nu(\nu_0, T) \Delta\nu}$$

Calculated emissivity

- Two emission are of **comparable** order above photosphere.
- Both emission drastically drop around 4e15cm(~0.4R).
- Expected line profile from this outflow have the **same order of contribution** from both emission sources.

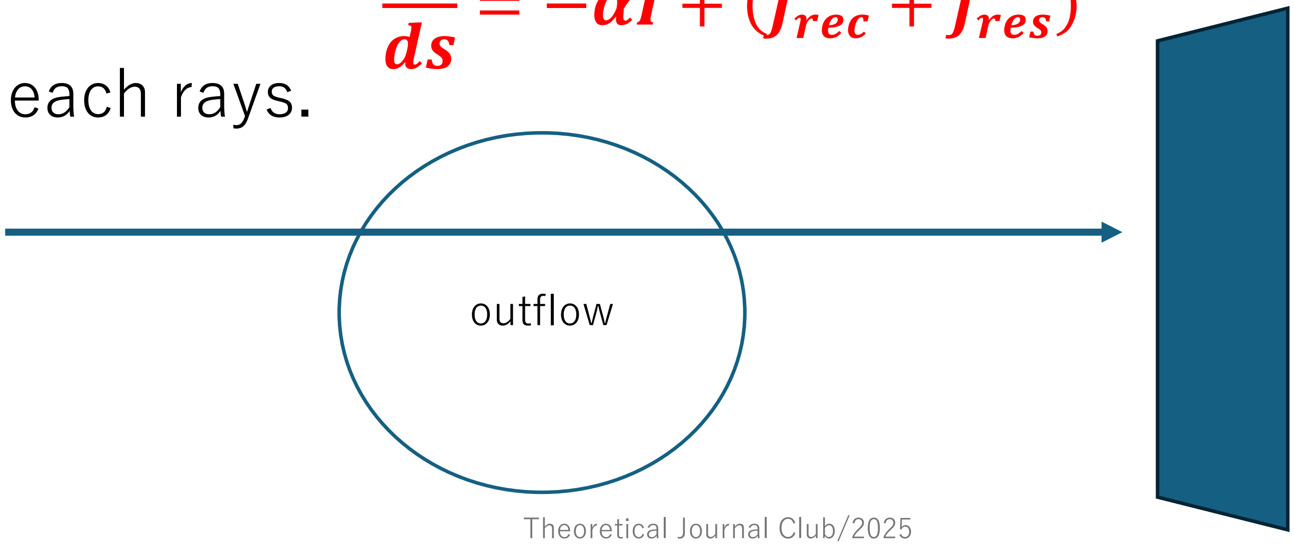


Method②: Radiative Transfer

- We have done one dimensional radiative transfer by casting rays into the system.
- In radiative transfer, we conducted calculating

$$\frac{dI}{ds} = -\alpha I + (j_{rec} + j_{res})$$

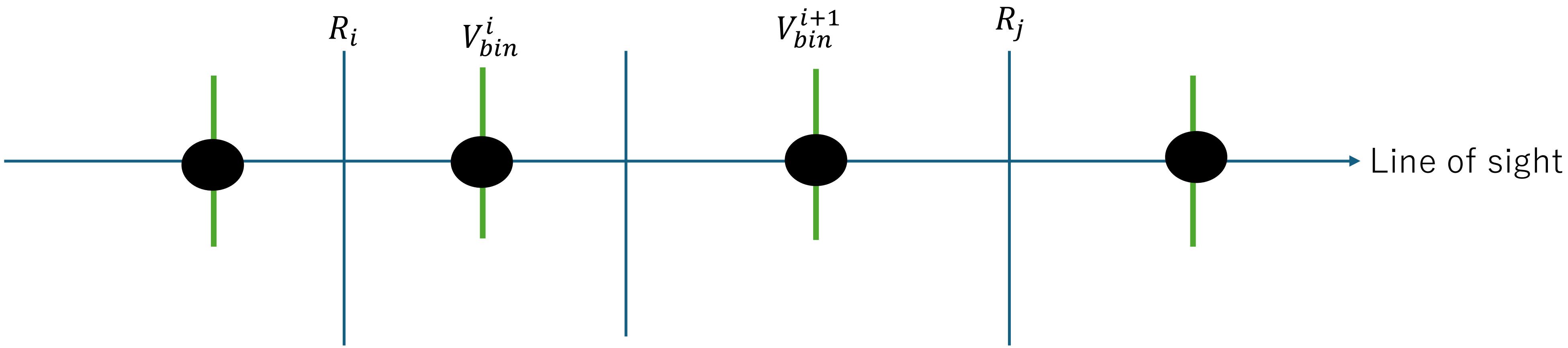
along each rays.



Calculate radiative transfer equation and gather rays.

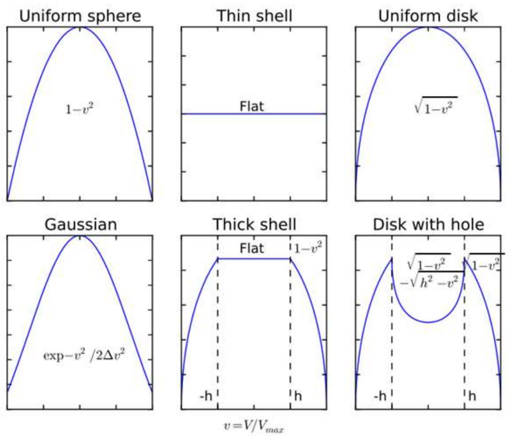
How to calculate the RT equation

- For each ray, we first calculate the **crossing points** between the trajectory of ray and velocity bin.



Test Case: Jerkstrand 2017

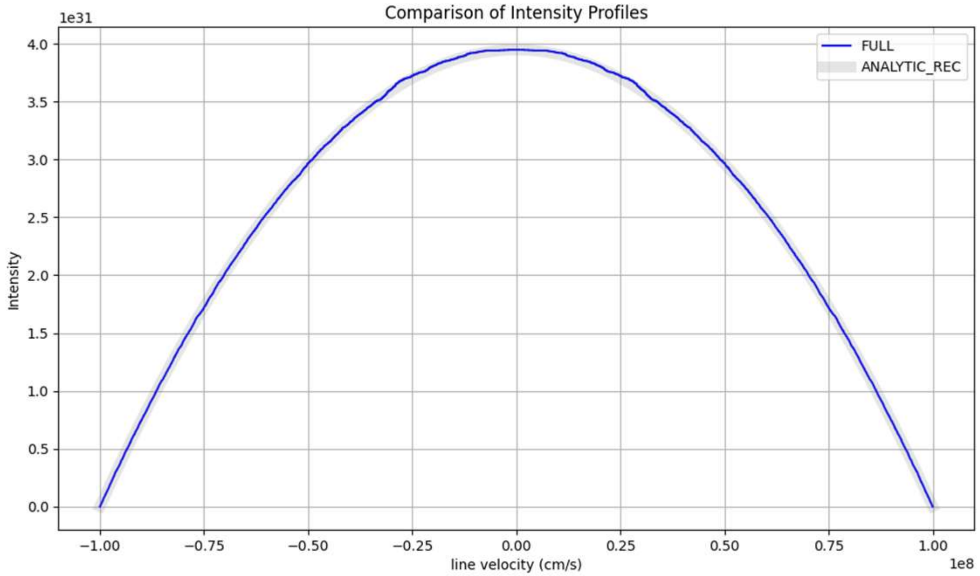
- We **test** the validation of this method with analytic cases proposed by Jerkstrand 2017.
- In Jerkstrand 2017, analytic solution of line profile in **homologously expanding ejecta** for 6 cases.

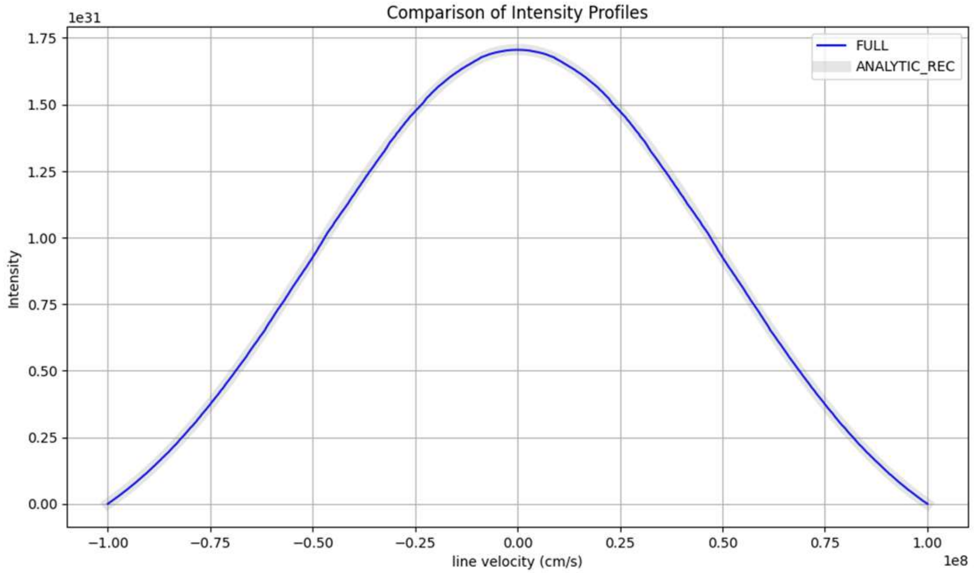


Test cases in Jerkstrand 2017

Test Result: Uniform and gaussian sphere

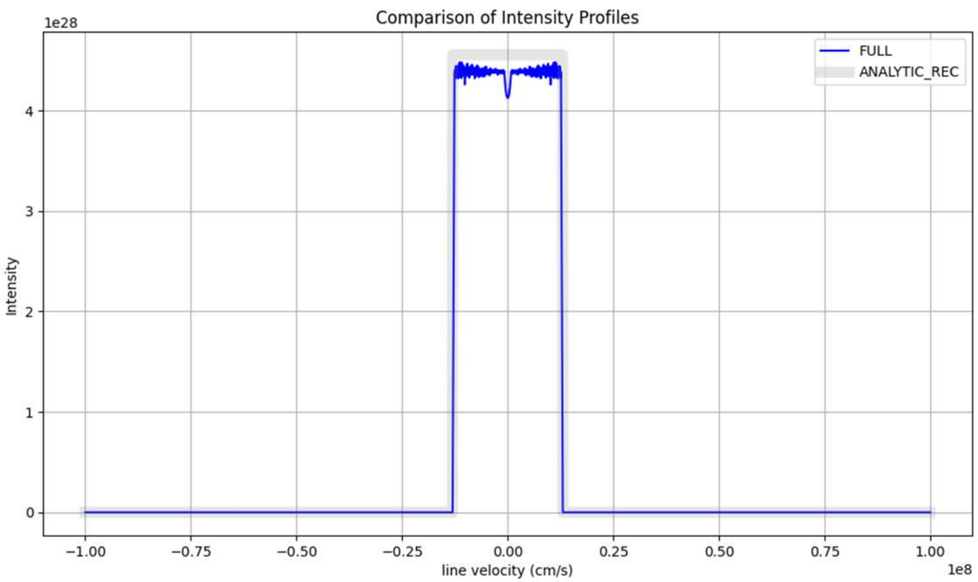
- In uniform($j_{rec} = const$) and gaussian($j_{rec} = j_0 \exp\left(-\frac{V}{V_0}\right)^2$) case, gray line is analytic and blue one is simulated.

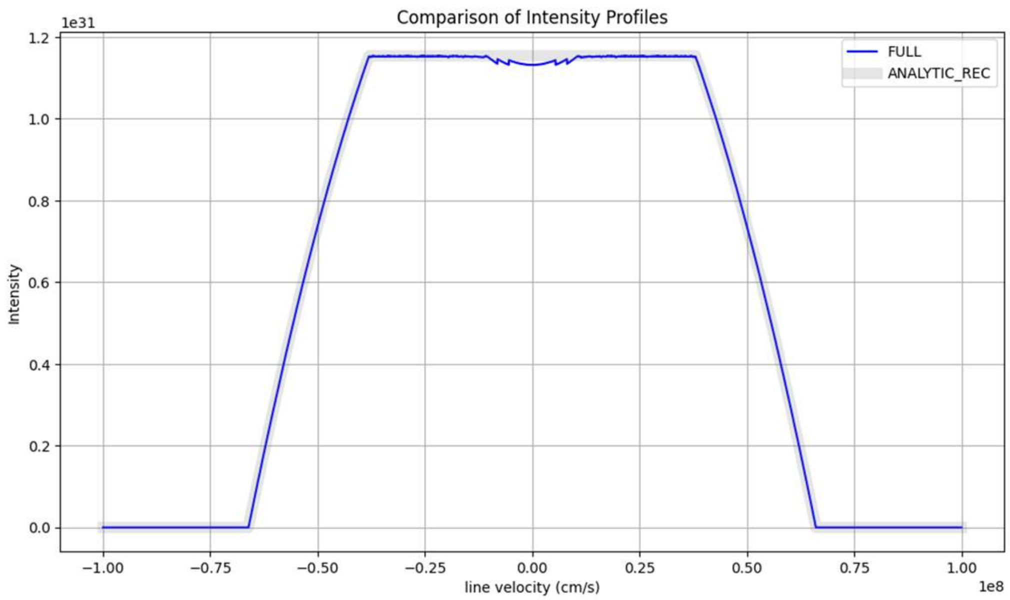




Test result: thin and thick shell

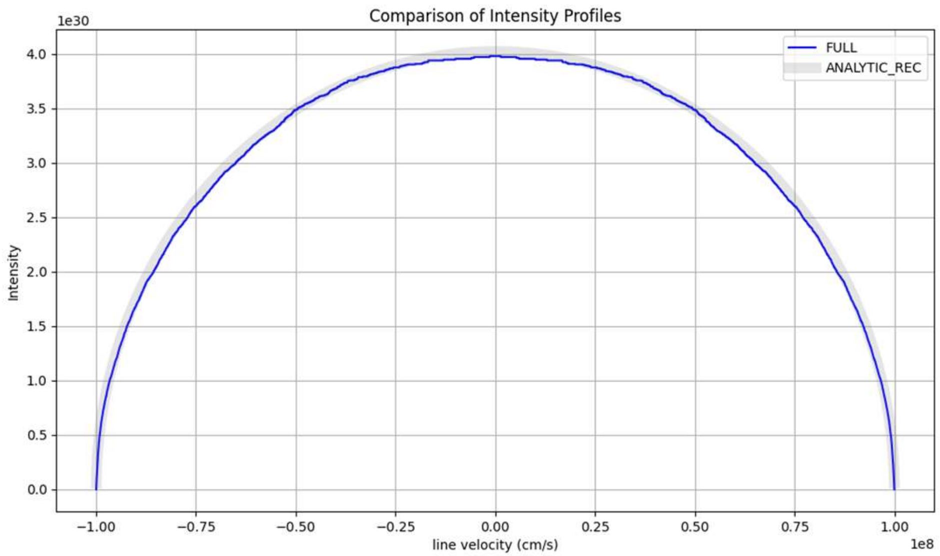
- In thin shell (Δr is small) and thick shell case,

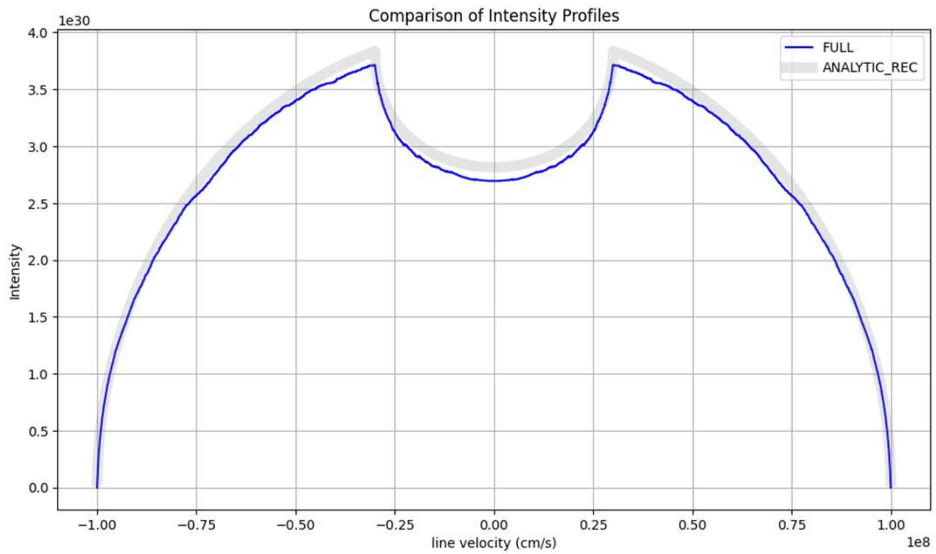




Test result: uniform disk and disk+hole

- In uniform disk and disk with hole case.
  Disk is defined with radius R and width Δx, and observer is seeing this disk from **edge-on** sight.

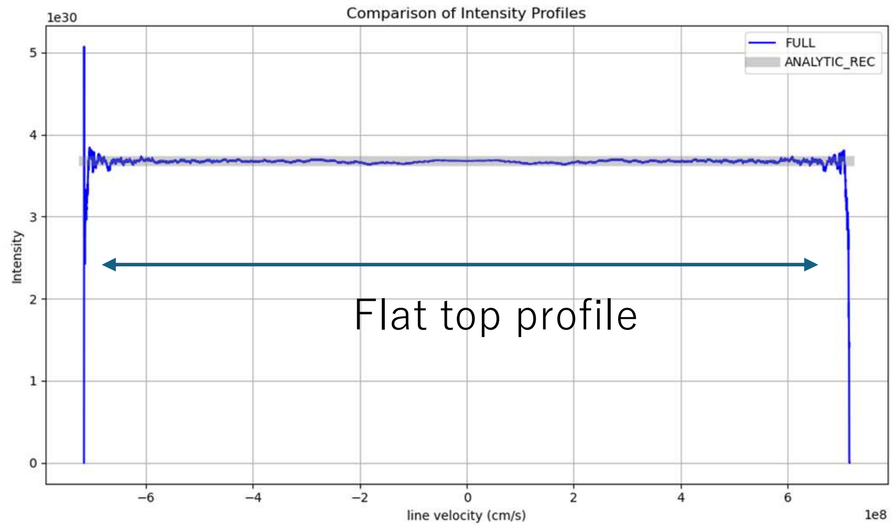




Test Case: constant-V field

- We can know the analytic solution of LP when the ejecta is expanding in **constant velocity field**.
- Through some calculation, obtained LP shape is **flat top** one.

- This profile is reproduced by the method.

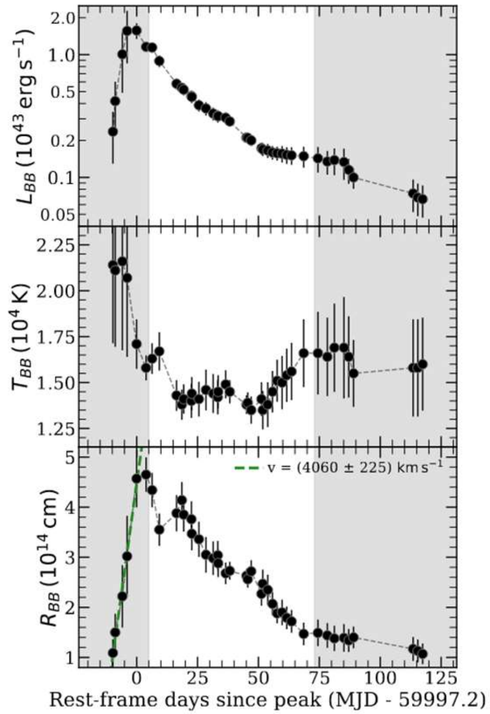


Setting: WD model for TDE AT2023clx

- Charalampopoulos + 24 provides the photosphere properties of AT2023clx.

- We can get proper setting for a snapshot of clx.

  Search for input to WD model $(\dot{M}, v, R_{eq})$ which has near value about T_{BB}, R_{BB}.

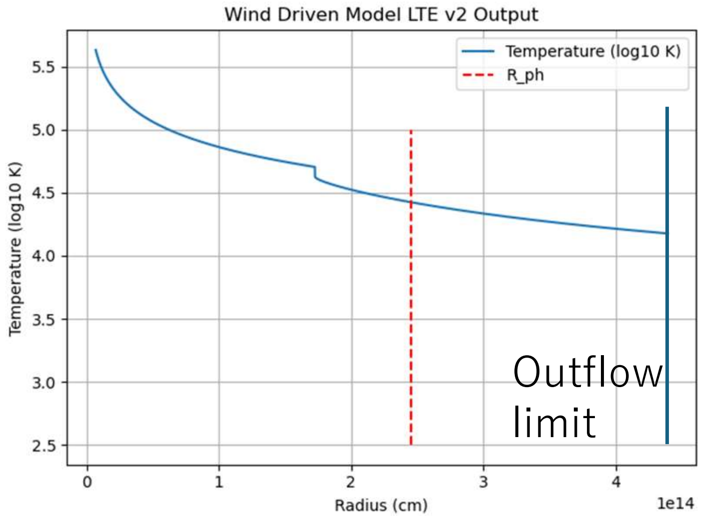


WD model at 5days

- Obtained parameters for WD model are

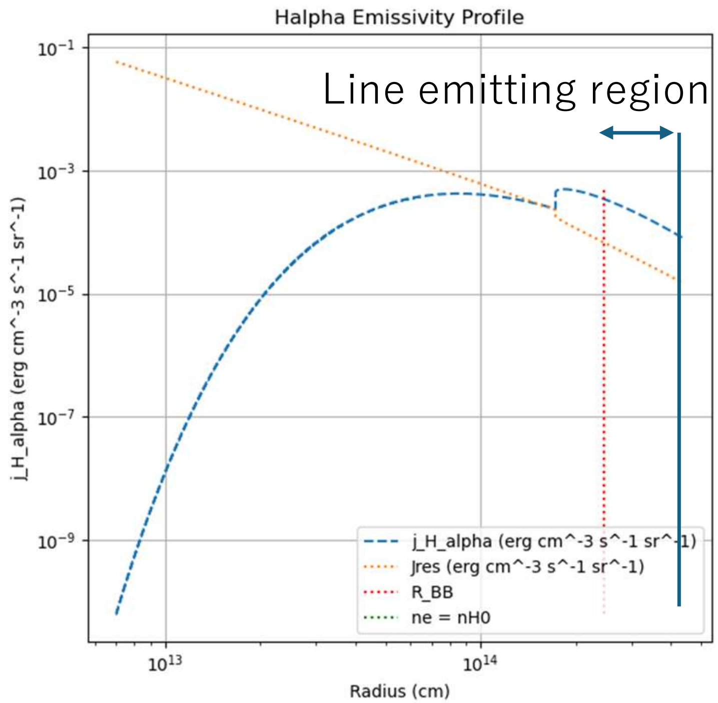
  Mdot: 5.0$M_{\odot}$/yr
  Req : 7.0e12cm
  v : 1.0e9cm/s

- Because v=1.0e9cm/s, the outflow can reach $v \times 5day$~**5.0e14cm**.



Emission structure at 5days

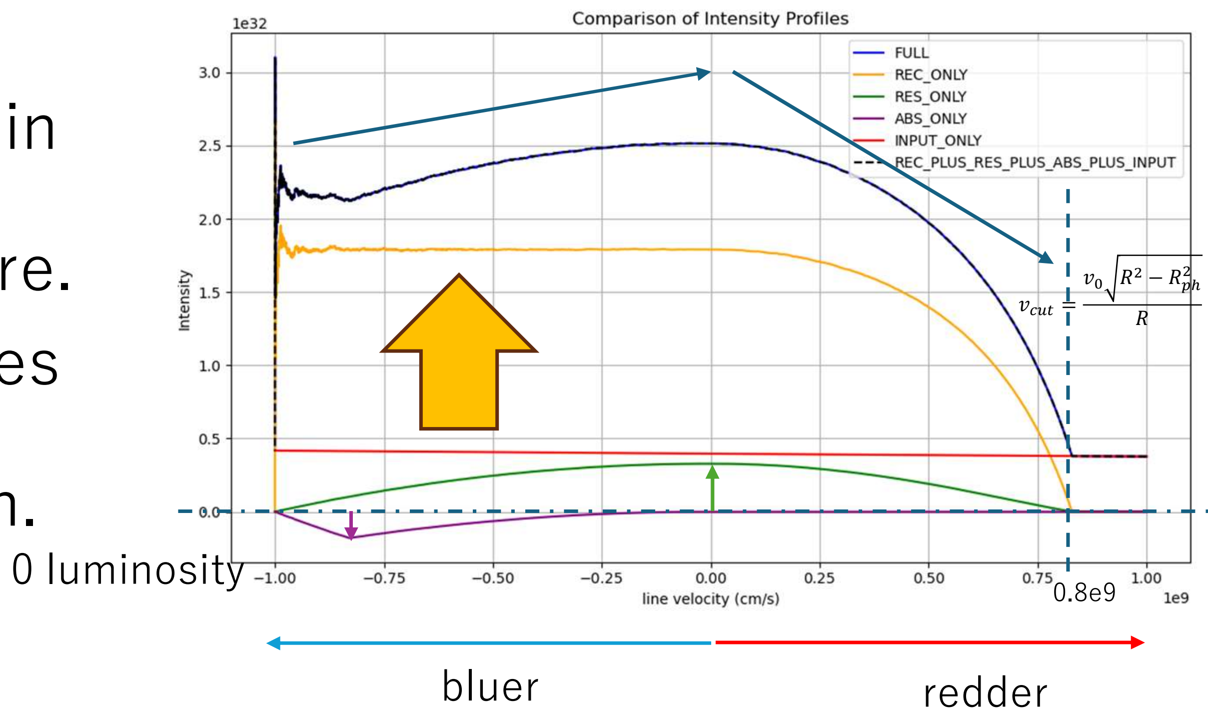
- The outflow extends to about **twice** the radius of photosphere.
- In this case, the line emission originates from a limited region above the photosphere.



Result②: Line Profile from WD model

- Calculated line profile is as follows.

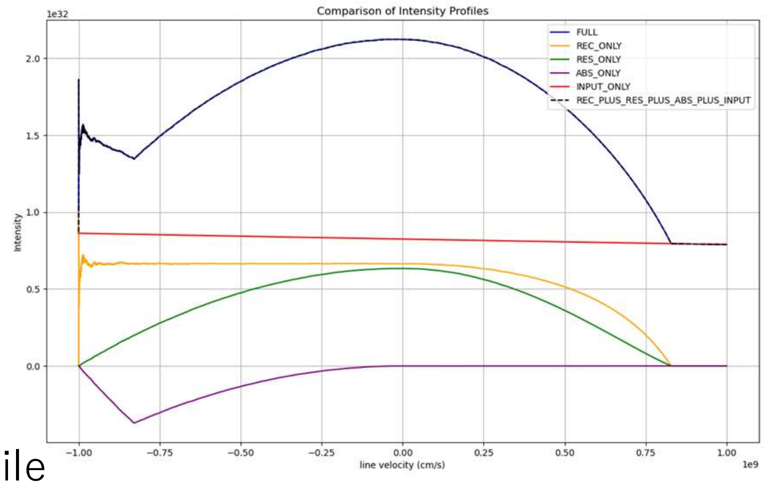
- Recombination makes **flat** in **bluer region**, while redder region is **cut** by photosphere.
- Resonance scattering makes **less, symmetric** profile compared to recombination.



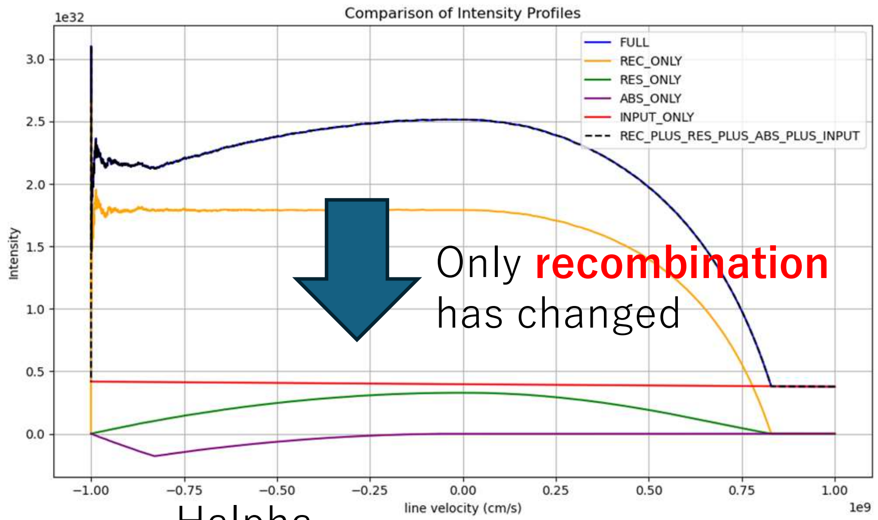
Line Profile for Hβ

- Line profile of Hβ can be computed as well as Hα.
  The difference between Hβ and Hα derives from the change of constant $\boldsymbol{j_{tabulated}} \Rightarrow \boldsymbol{\frac{j_\beta}{j_\alpha} \sim \frac{1}{3}}$. $\Rightarrow$line ratio is $\boldsymbol{\frac{L^{\alpha}_{top}}{L^{\beta}_{top}} \sim 1.17}$.

On the other hand, **observed Balmer decrement** shows ~**1.58**.
Non-LTE effect??



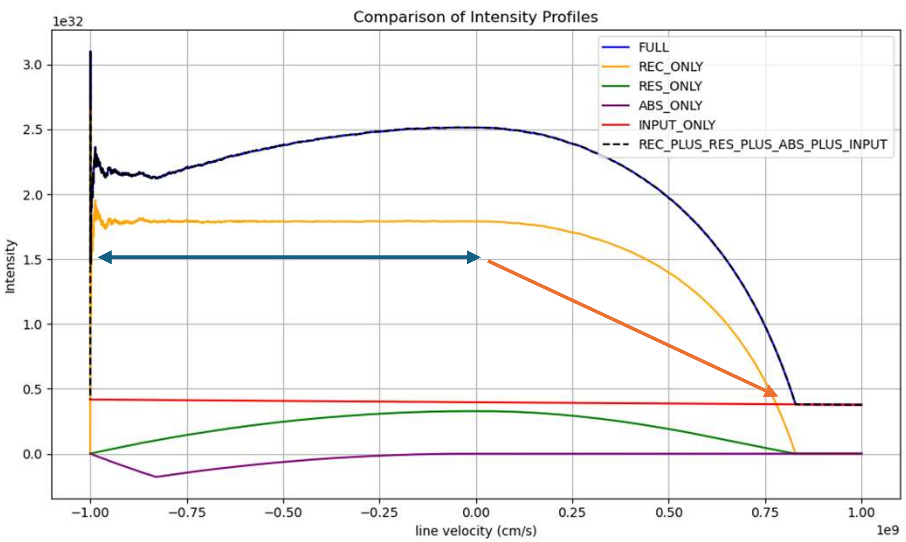
Hbeta line plofile

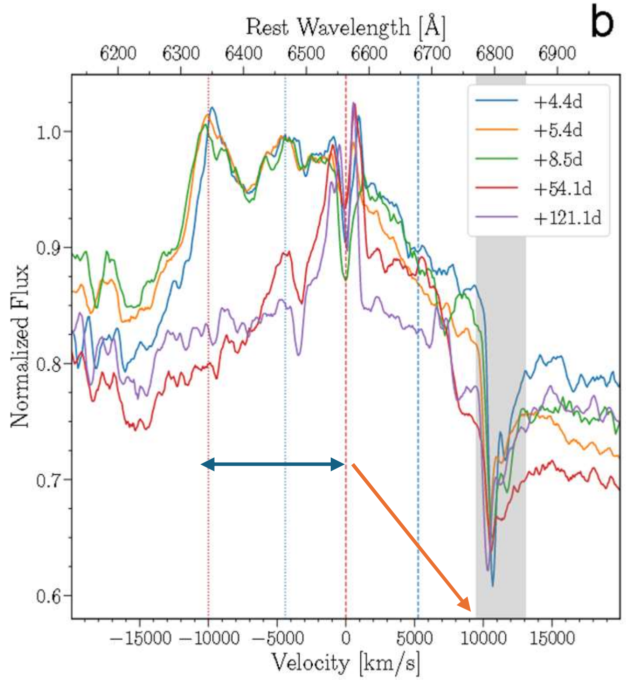


Halpha

Discussion②: The shape comparison

- The simulated profile is similarly blue-dominated profile as 23clx in +5.4d.

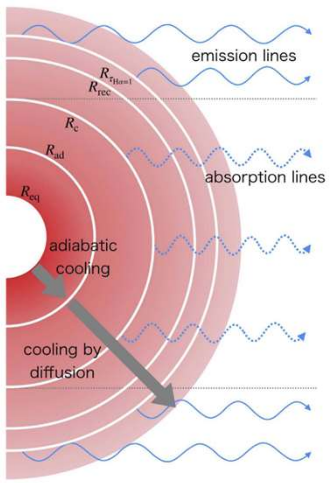




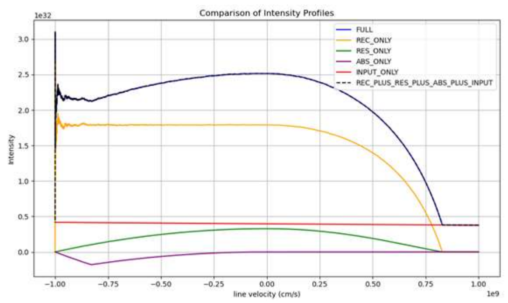
LP of clx, Uno+25

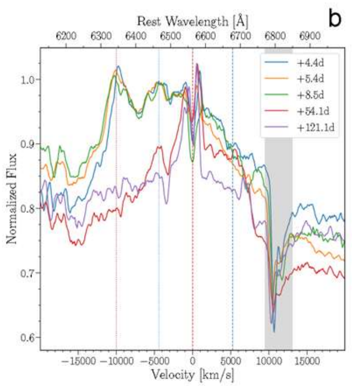
Summary

- Line profile calculation by radiative transfer in Wind-Driven model
- The calculated profile shows Wind-Driven model can make TDE-like, **non P-Cygni profile,** and have TDE-like **broad, bluer profile**.



Uno&Maeda20





Uno+25

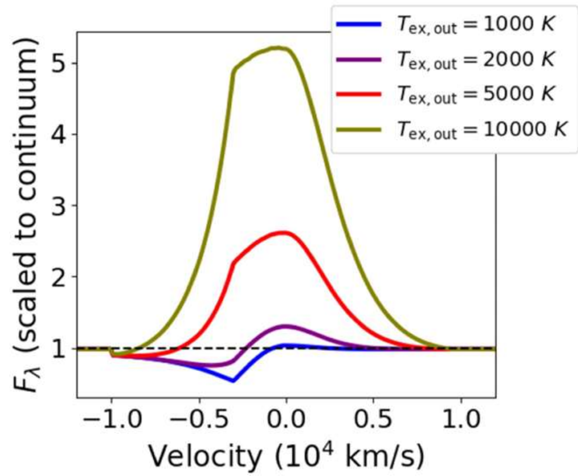
Future Work

- The procedure of **estimation of input parameters** can be more systematically as Uno & Maeda20.
- We would like to calculate line profile at other times to see time evolution.
- Also would like to find **other parameters** which can show other profiles including not TDE-like ones.

Appendix

Why P-Cygni cannot be seen TDE?

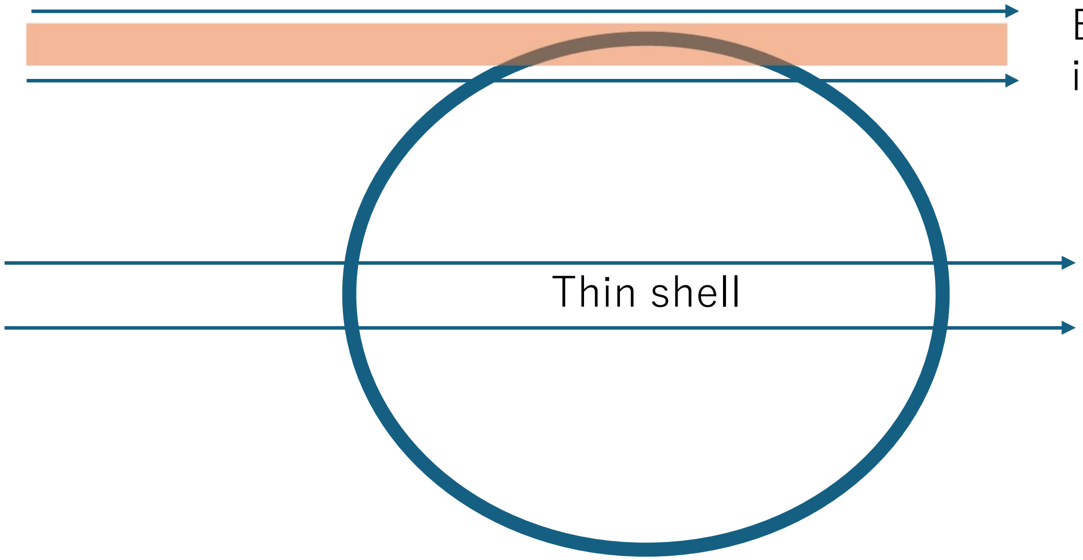
- When P-Cygni occurs, there is a condition that **line excitation temperature T_{ex} is less than T_{bb}** (so absorption overcomes emission).
- Tex corresponds to the population ratio: $\frac{n_2}{n_1}$
- As for the case of TDE, which outflow is highly irradiated, population is not effectively small so that **Tex will be as large as Tbb**.
  ⇒absorbing region in SNe can emit as strong as absorb.



Roth & Kasen 2018

Thin and thick shell case

- In a case of shell, it is difficult to accurately estimate the emission components from the direction **perpendicular to the line of sight**.

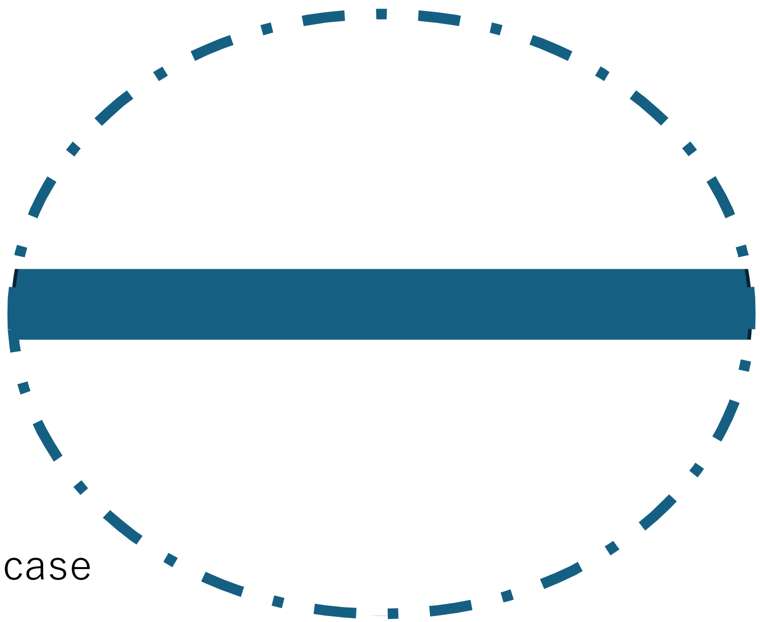


But for perpendicular, it is difficult in the same ray displacement.

Parallel to observer, it is easy to cross the shell

Disk case

- In the case of disk test, we treated the emitter as a part of sphere with width Δx. So there are some underestimates of L.



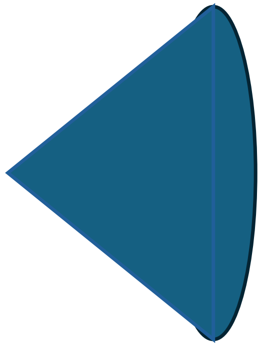
Test case

Intended configuration

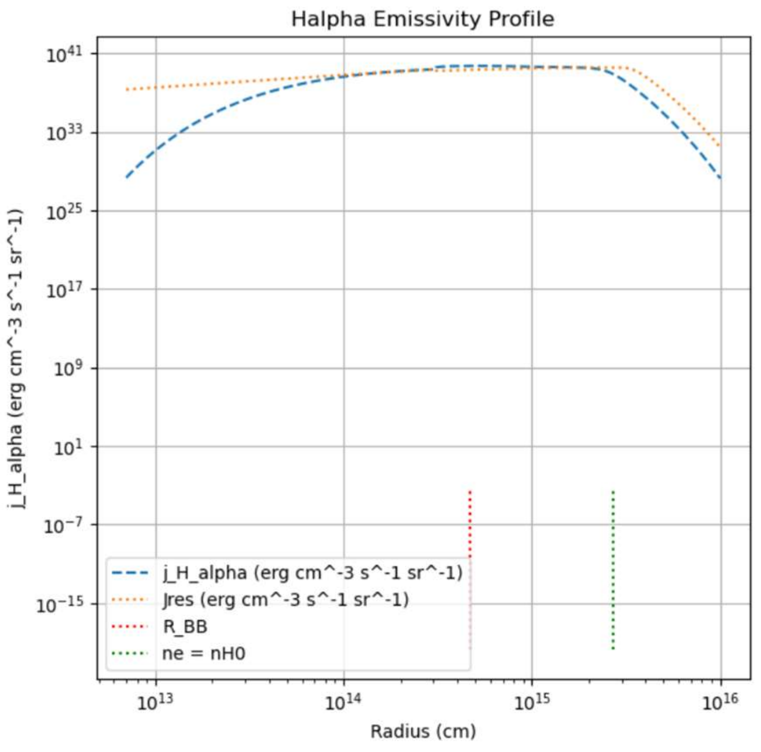
The calculation in constant-V field

- For constant velocity field, co-line velocity plane will be cone with open angle θ.
- This area will be $\frac{1}{2}R^2 2\pi\sin\theta = \pi R^2 \sin\theta$.
- Thus, $L(\theta) = j_0\pi R^2 \sin\theta\, d\theta$,

$\boldsymbol{L(v) = j_0\pi R^2 \frac{dv}{v_0}}$ is the Luminosity per velocity.



j timed by r^3



Halpha Emissivity Profile
10^{41}
10^{33}
10^{25}
10^{17}
10^{9}
10^{1}
10^{-7}
10^{-15}
j_H_alpha (erg cm^-3 s^-1 sr^-1)
j_H_alpha (erg cm^-3 s^-1 sr^-1)
Jres (erg cm^-3 s^-1 sr^-1)
R_BB
ne = nH0
10^{13}
10^{14}
10^{15}
10^{16}
Radius (cm)

Estimated value in clx

- Mdot was estimated as $5.0 M_\odot/\mathrm{yr}$, this value lies common in Uno&Maeda20, which apply WD model to sample TDEs.

However, it has **large Mdot** for its faint luminosity.

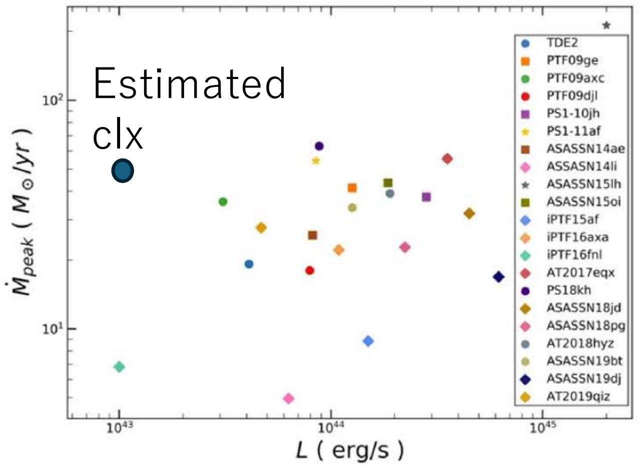


Figure 3. $\dot{M}_{\rm peak}$ estimated by the wind-driven model.

$$\dot{M}_{\rm fb} \approx 3.45\, M_\odot\ \mathrm{yr}^{-1} \left(\frac{M_{\rm BH}}{10^6 M_\odot}\right)^{-\frac{1}{2}} \left(\frac{M_*}{M_\odot}\right)^{\frac{4}{5}}.$$

Mdot_peak and fallback rate in Uno&Maeda20

Estimated R_eq

- However, Req obtained was 7.0e12cm.
  This value is somewhat less than typical value for TDEs.
- If we assume launched radius as disk wind like;

$$R_{launch} \sim 2\, R_{tidal} = 2R_* \left(\frac{M_{BH}}{M_*}\right)^{\frac{1}{3}}$$

  and if disrupted star is sun,
  this value would be **1.3e13** cm.
- The estimated Req value is $< \boldsymbol{R_{launch}}$,
  ⇒have to take the same procedure as Uno&Maeda20??;
  treat Req as input parameter, and **calculate Mdot and v** from Req and L_ph, T_ph.

Appendix