Interpreting the Spectra of Tidal Disruption Events with Non-LTE Radiative Transfer

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Some Milestones for *Sedona* (Monte Carlo radiative transfer code)

- 2006: Original code paper (Kasen, Thomas & Nugent), application to SN Ias
- 2010: First coupling to hydrodynamics, applied to magnetar-powered SNe (Kasen & Bildsten)
- 2012: Treatment of dust, application to AGN feedback (Roth, Kasen, Hopkins & Quataert)
- 2013: Treatment of lanthanide opacities from r-process, and application to kilonovae (Barnes & Kasen, Kasen, Badnell & Barnes)
- 2015: Coupling to hydrodynamics w/ IMC (Roth & Kasen)
- 2016: Non-LTE treatment of H and He in steady state, application to TDEs (Roth, Kasen, Guillochon & Ramirez-Ruiz)
- 2017: Non-LTE treatment of nebular phase of type Ias, including non-thermal processes (Botyanszki & Kasen)
- 2018: Non-coherent electron scattering and application to TDEs (Roth & Kasen)

Outline

- TDE background
- Results for non-LTE calculations, in 1D, with static atmosphere
- Effects of non-coherent electron scattering and outflows

TDEs: background

Tidal radius (non-spinning BH):

$$r_{\rm tide} = 7 \times 10^{12}\ {\rm cm}\ \left(\frac{M_{\rm BH}}{10^6 M_\odot}\right)^{1/3} \left(\frac{R_*}{R_\odot}\right) \left(\frac{M_*}{M_\odot}\right)^{-1/3}$$

$$\frac{r_{\rm tide}}{r_g} = 47\ \left(\frac{M_{\rm BH}}{10^6 M_\odot}\right)^{-2/3} \left(\frac{R_*}{R_\odot}\right) \left(\frac{M_*}{M_\odot}\right)^{-1/3}$$

Stars that pass within $r_{\rm tide}$ of BH are ripped apart

Mass fallback time-dependence

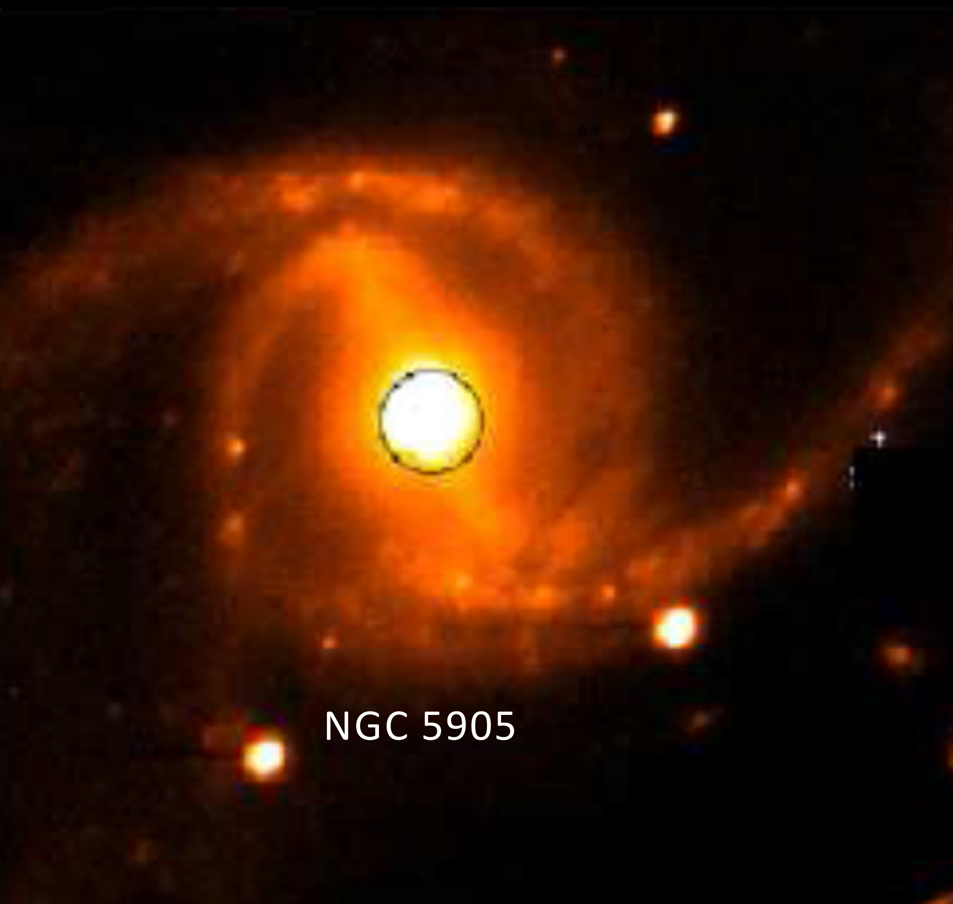
Mass fallback rate to pericenter follows $t^{-5/3}$

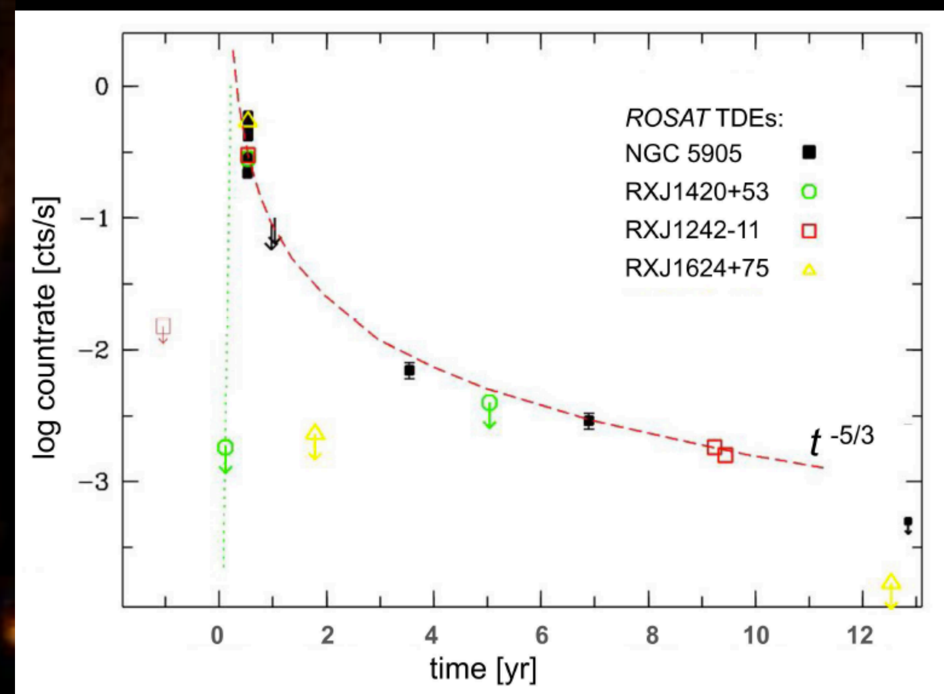
$$\frac{dM}{dT} = \frac{dM}{de}\frac{de}{dr_a}\frac{dr_a}{dT} \simeq \frac{dM}{de}(GM_p)^{2/3}T^{-5/3}\ .$$

Phinney 1989

What have we seen?

Sometimes, soft x-rays (i.e. from ROSAT)

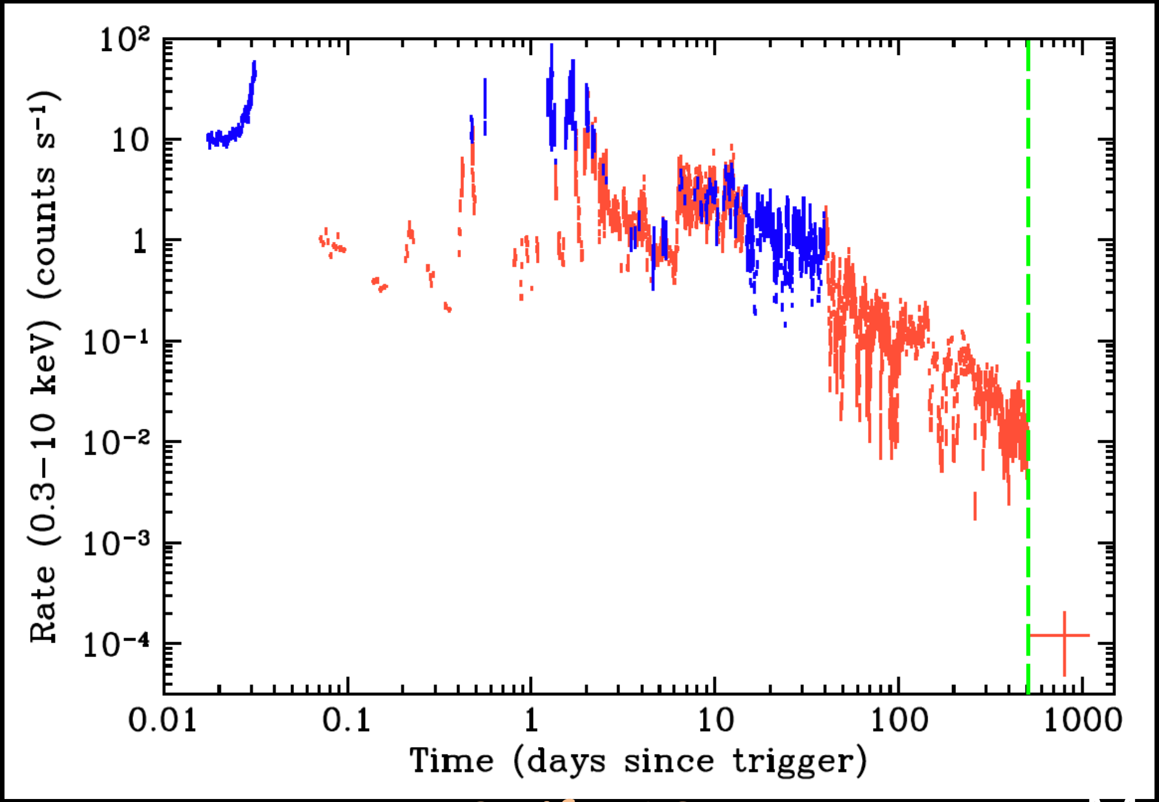




From Komossa 2015 review

What have we seen?

Sometimes, harder x-rays and radio
Indicates relativistic jet

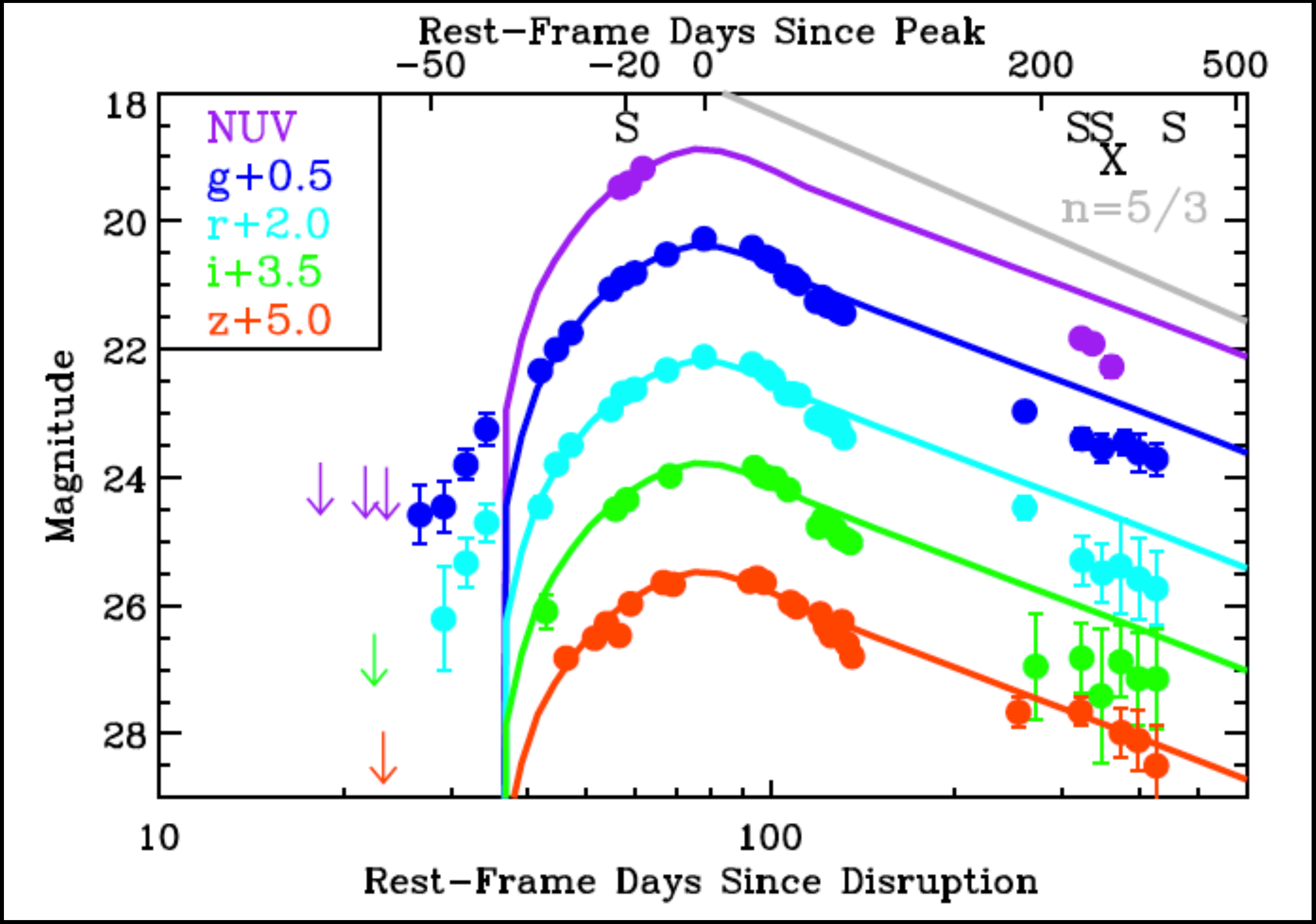


Swift J1644

Mangano+ 2016

What have we seen?

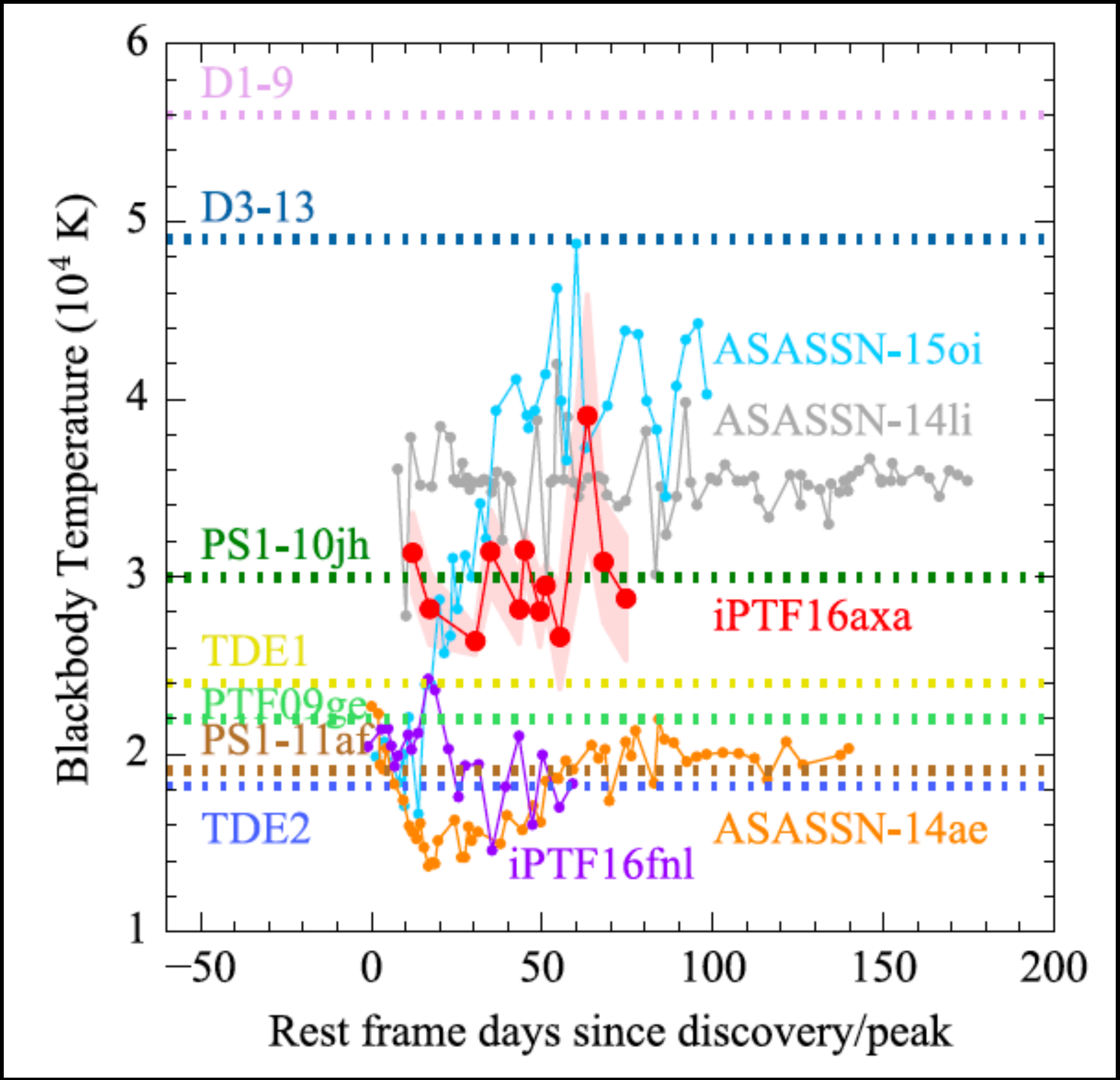
Sometimes, optical/UV



PS1-10jh

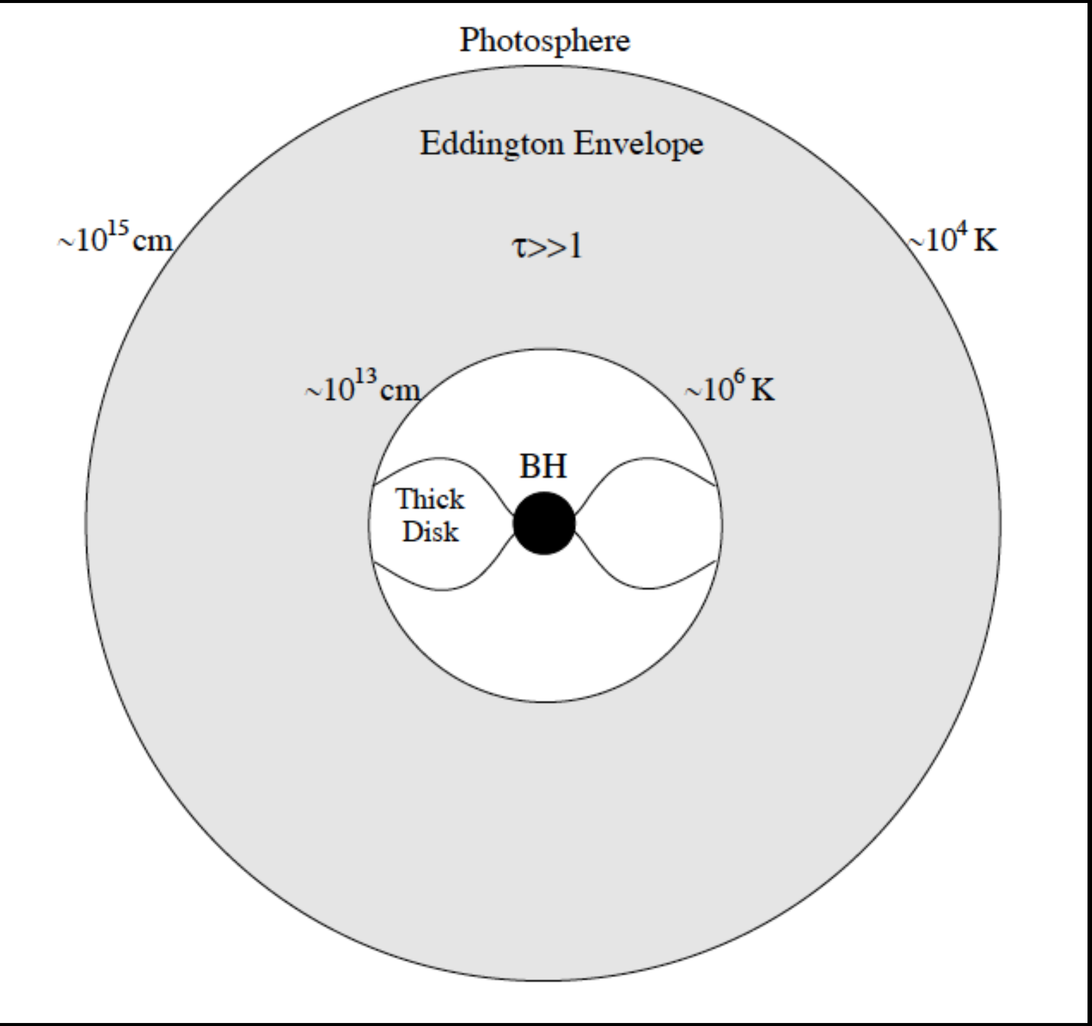
Gezari+ 2012

Lack of Color Evolution



Hung+ 2012
Including NR

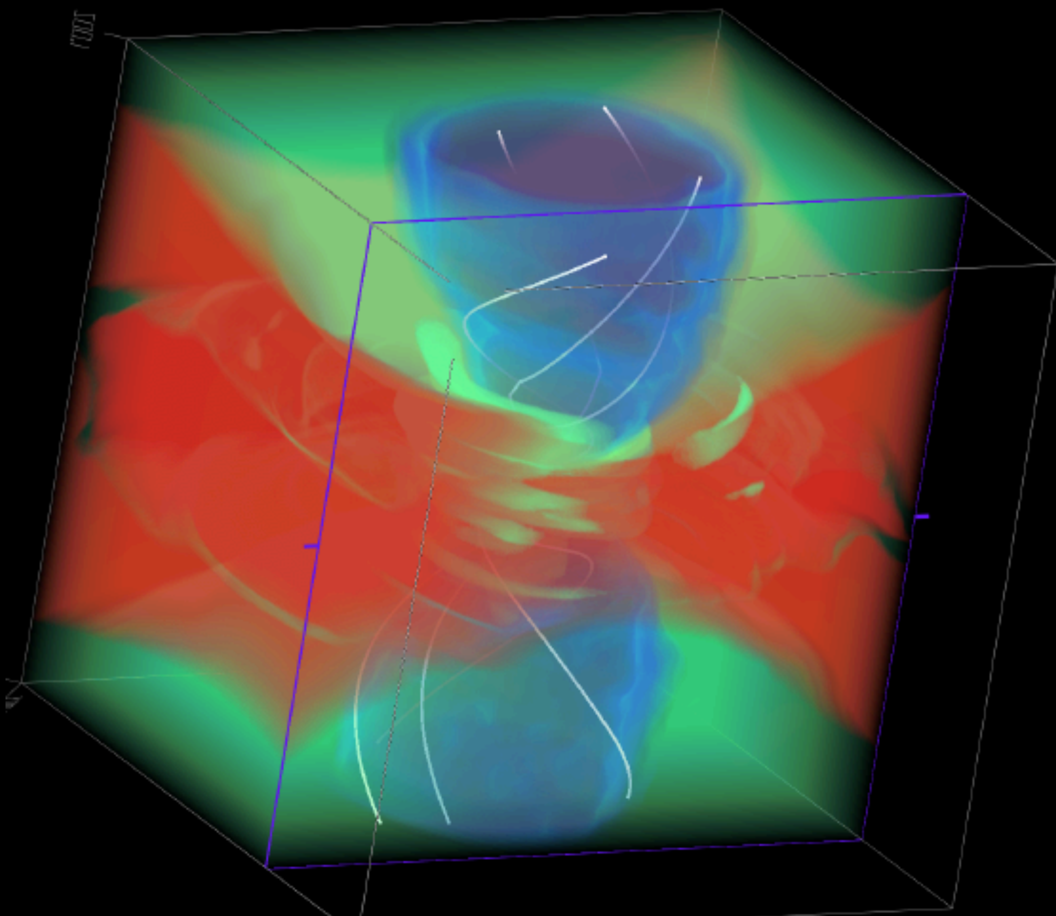
What produces the optical emission?
Reprocessing?



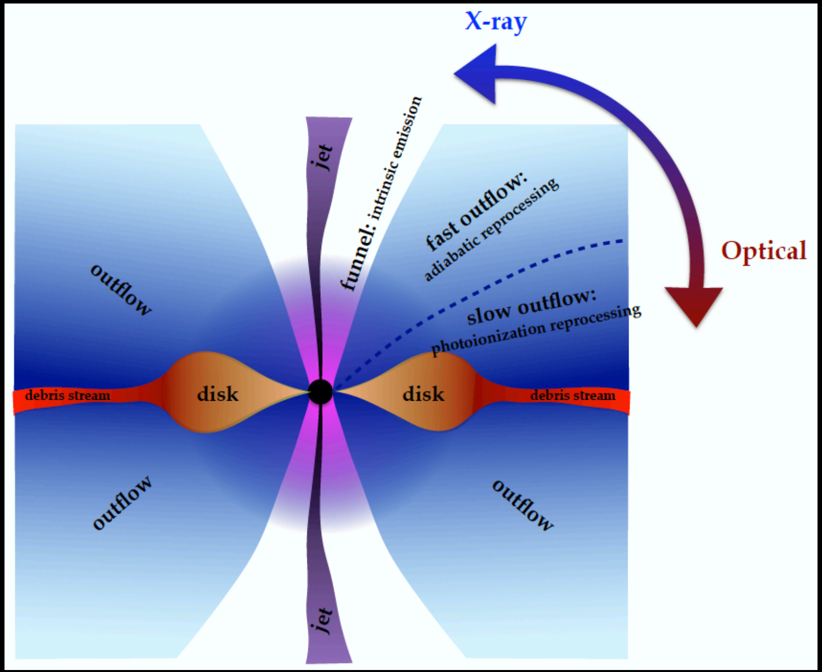
Loeb & Ulmer 1997

What produces the optical emission?

Puffy accretion disk?

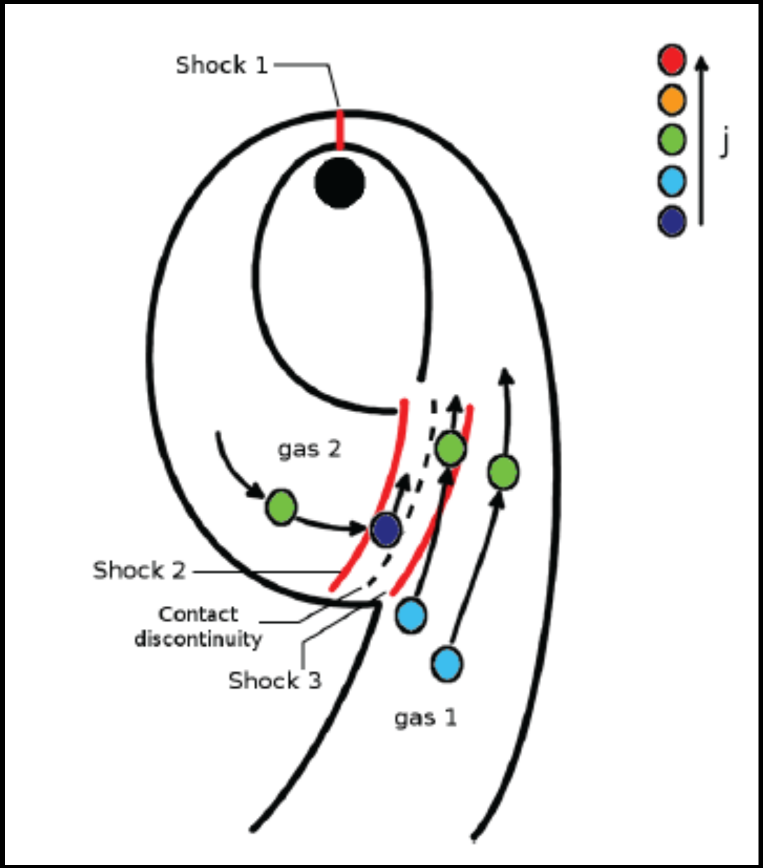


McKinney+ 2014

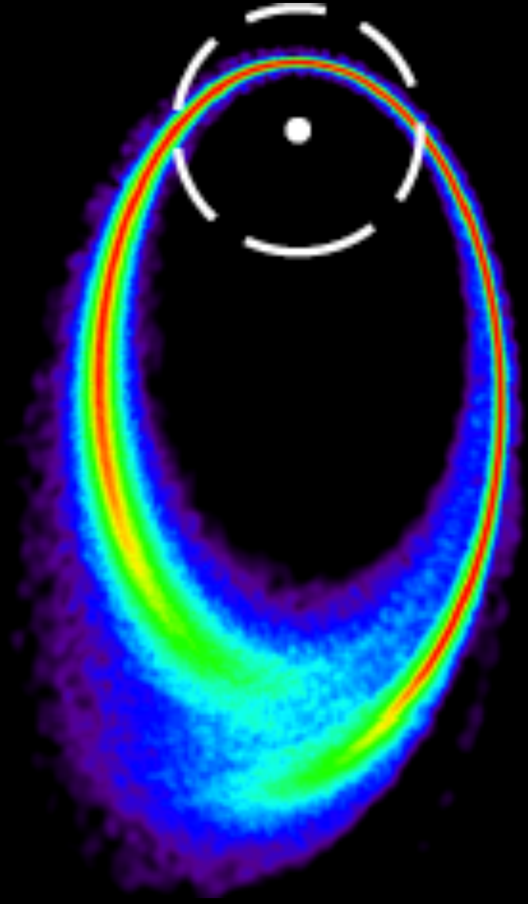


Dai+ 2018 including NR

What produces the optical emission?
Shocks from stream collisions?



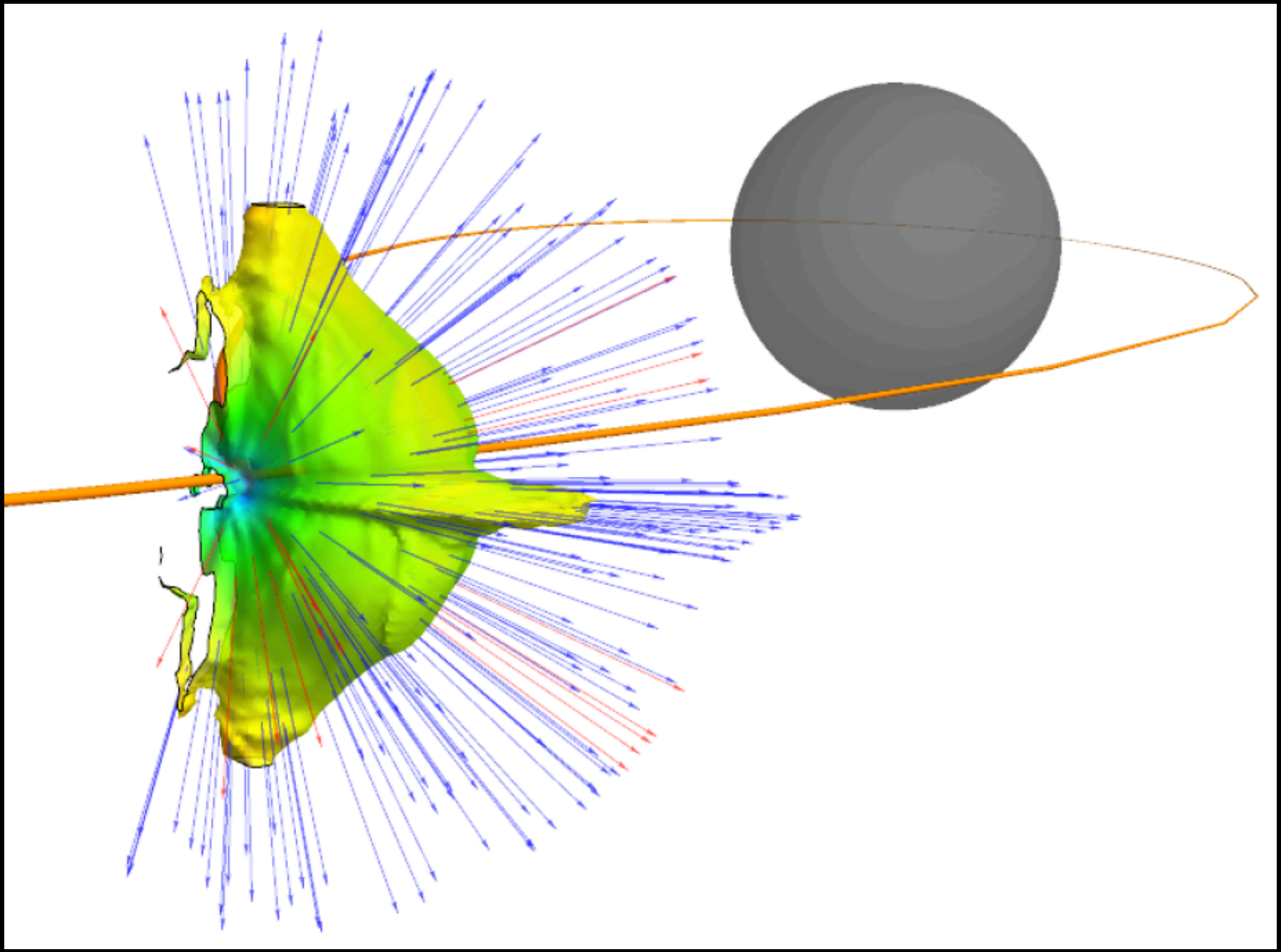
Shiokawa+ 2015



Bonnerot+ 2016

What produces the optical emission?

“Plumes” from stream collisions?



Jiang+ 2016

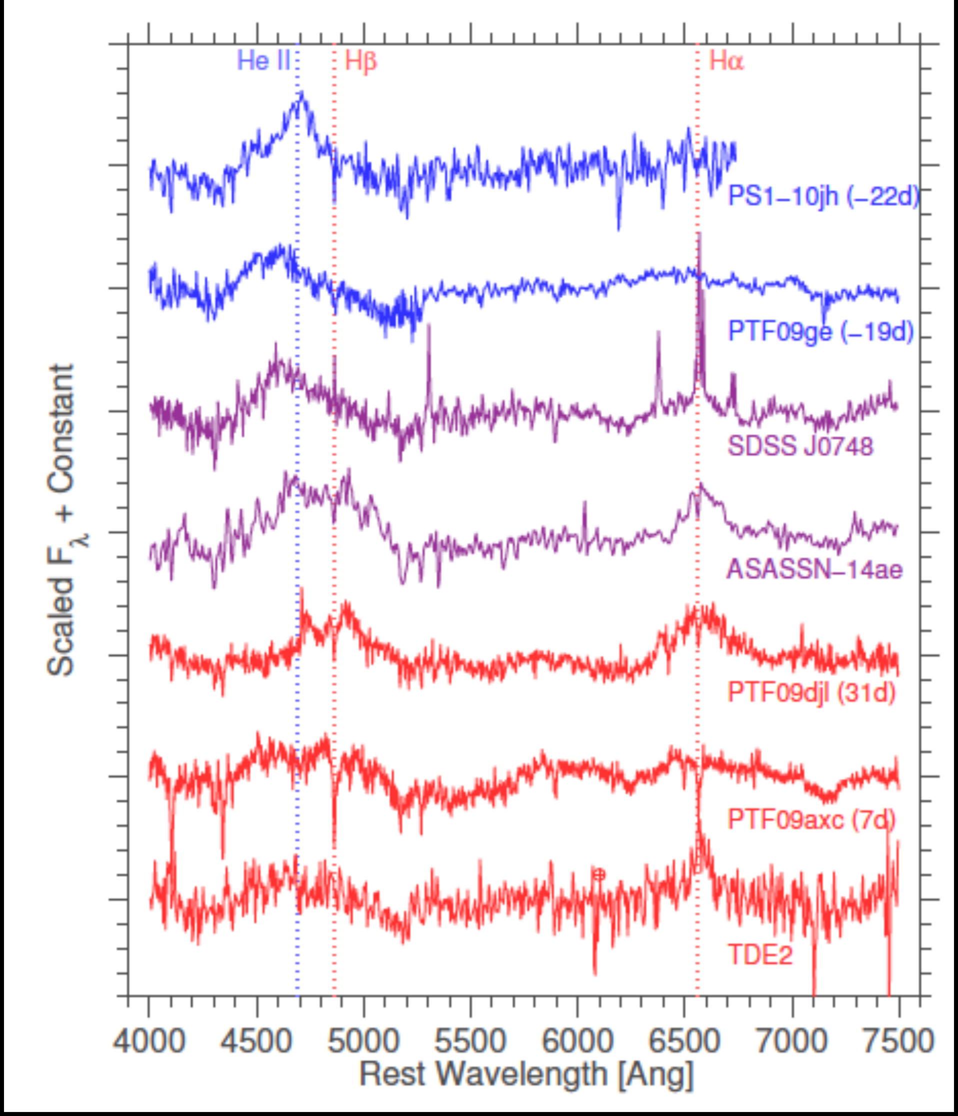
Not as simple as we hoped…

We want to learn about the black hole

- Measure its mass
- Probe super-Eddington accretion

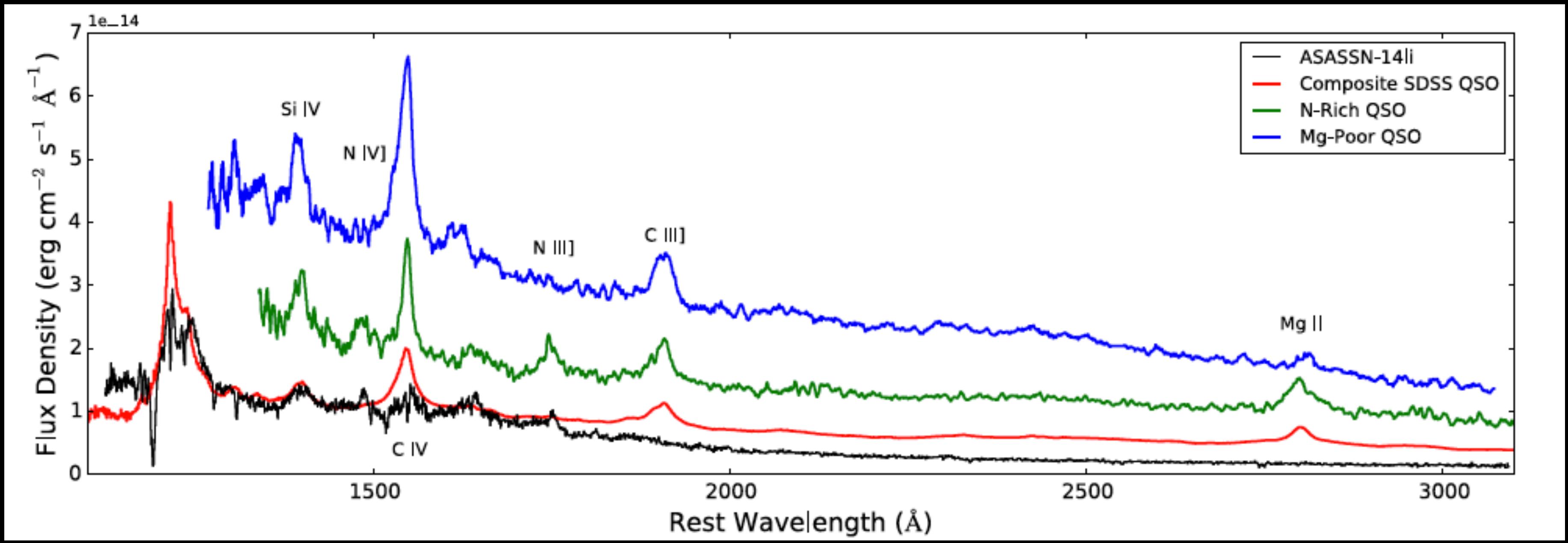
But what exactly are we seeing?

Optical spectra



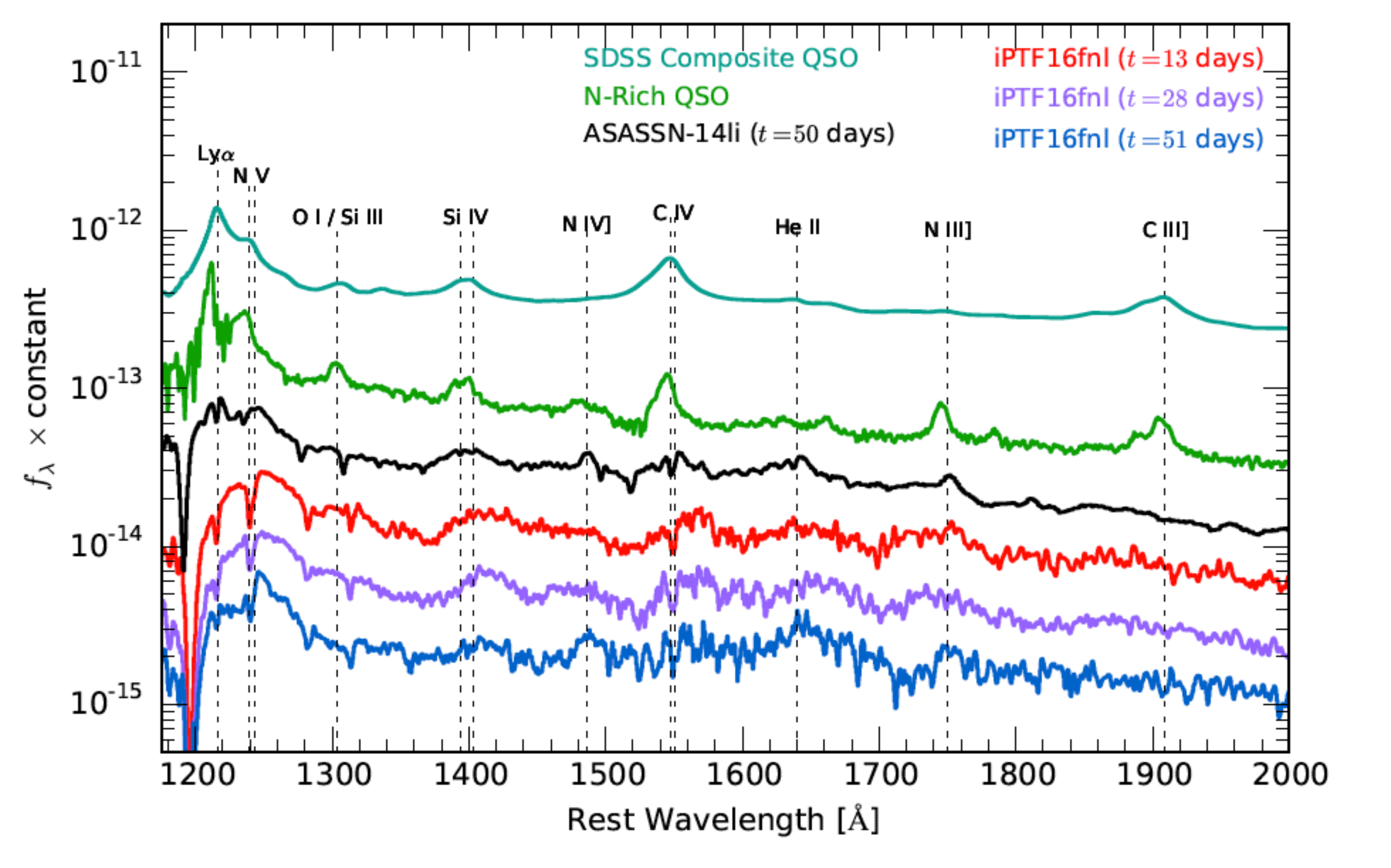
Arcavi+ 2014

Even more information in the UV



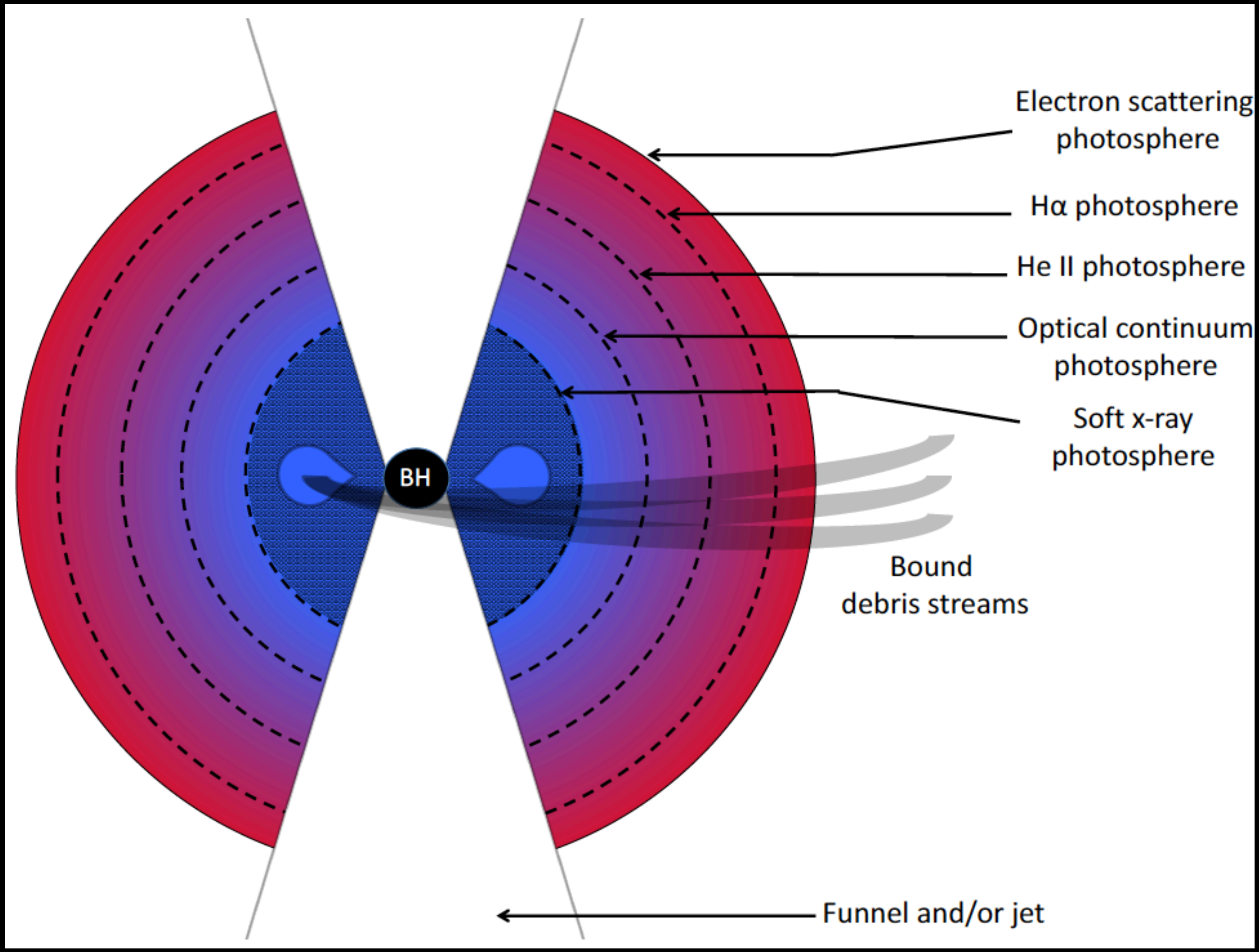
Cenko+ 2016 including NR

Even more information in the UV



Brown+ 2017

Radiative transfer calculation analogous to stellar atmosphere

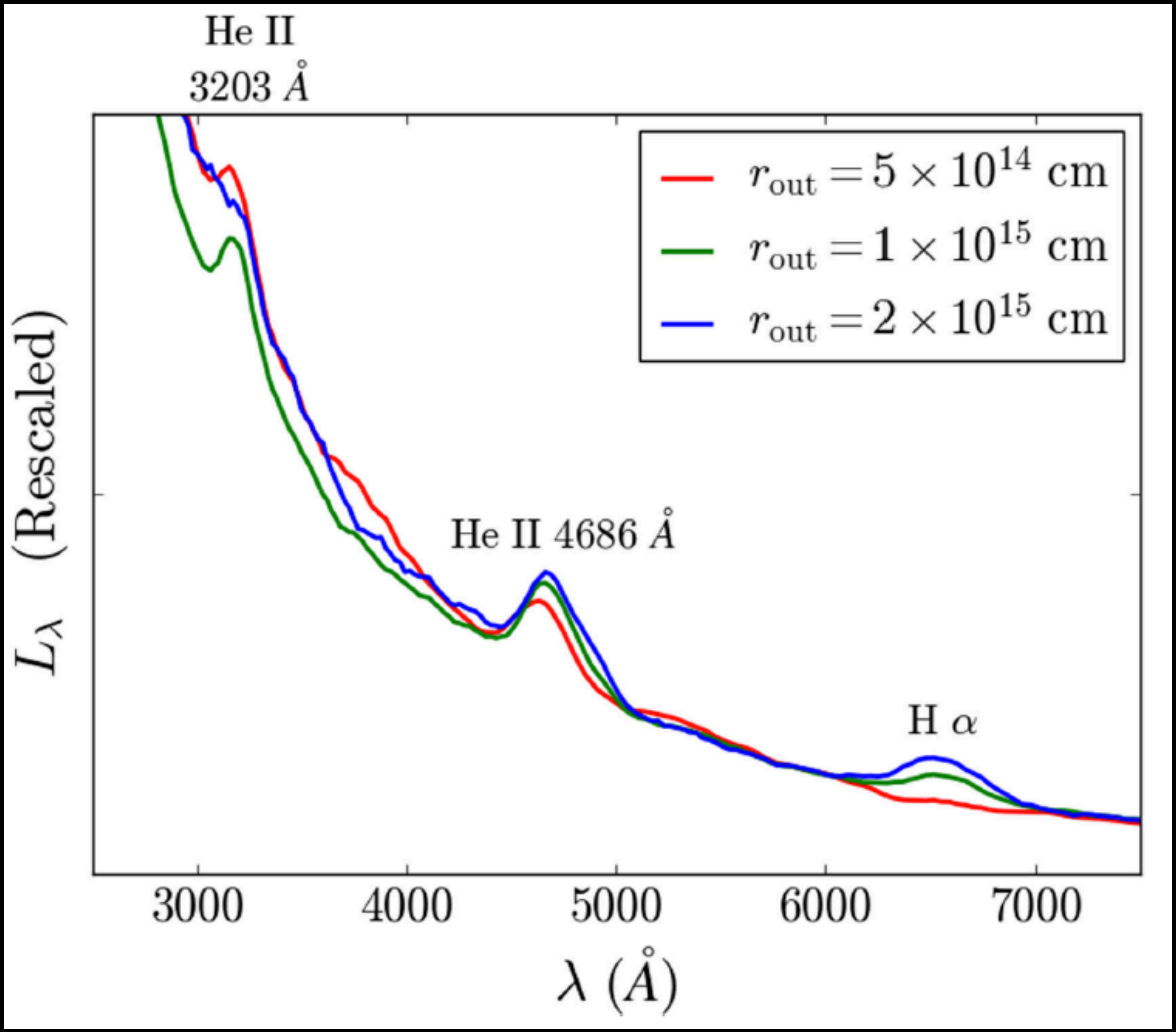


Roth+ 2016

Program flow for non-LTE calculations

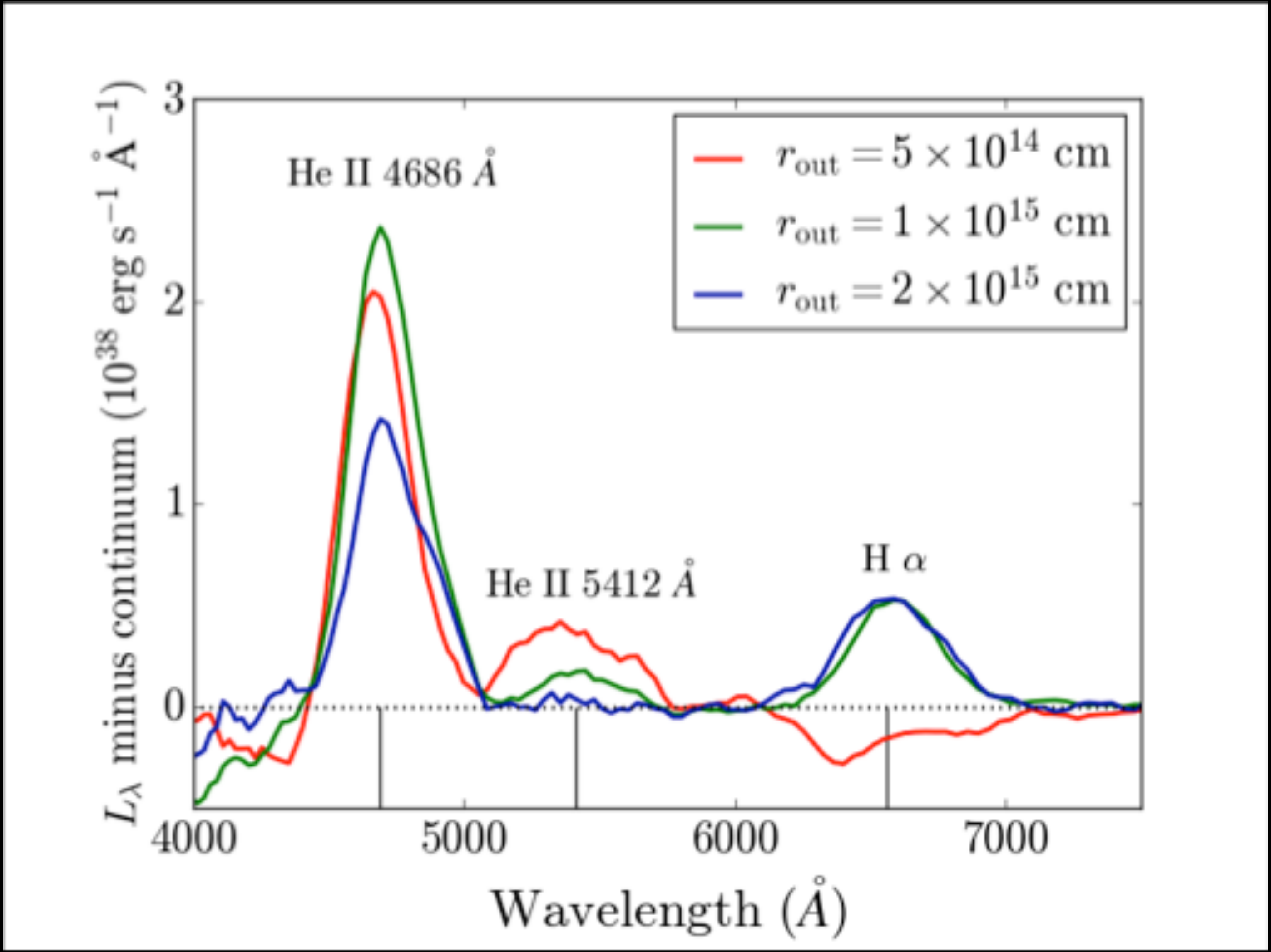
- Make initial guess for ionization state, level populations, free-electron temperature (from LTE)
- Calculate opacities/emissivities and use the Monte Carlo to solve the radiative transfer equation. Power source at inner boundary, w/ temperature there related to luminosity and tau
- Assume broad line profiles with complete redistribution
- Assumption of radiative equilibrium allows for effective scattering of absorbed photons, sampling from total emissivity distribution over wavelength
- Save radiation field J, use this to construct rates. Collisions not very important, use van Regemorter approximation.
- Solve for updated ionization states and level populations using the computed radiation field, assuming statistical equilibrium
- Solve for free electron temperature, again using radiative equilibrium.
- Compute updated emissivities/opacities, repeat…

A range of line ratios, all with solar H and He abundance ratio



Roth+ 2016

Line ratios



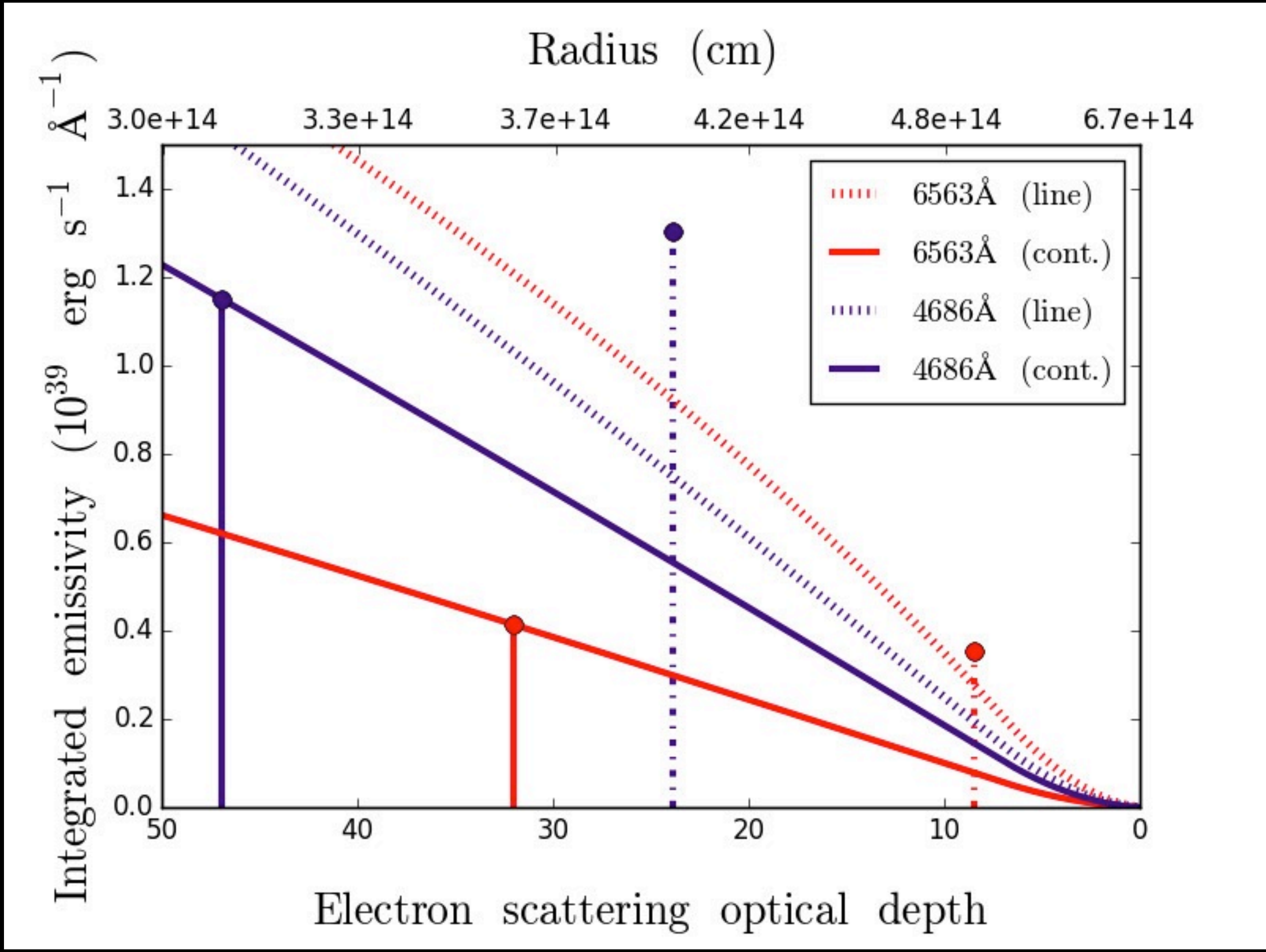
Roth+ 2016

Thermalization depth

$$\tau_{\mathrm{therm}} \approx \frac{1}{\sqrt{\epsilon}}$$

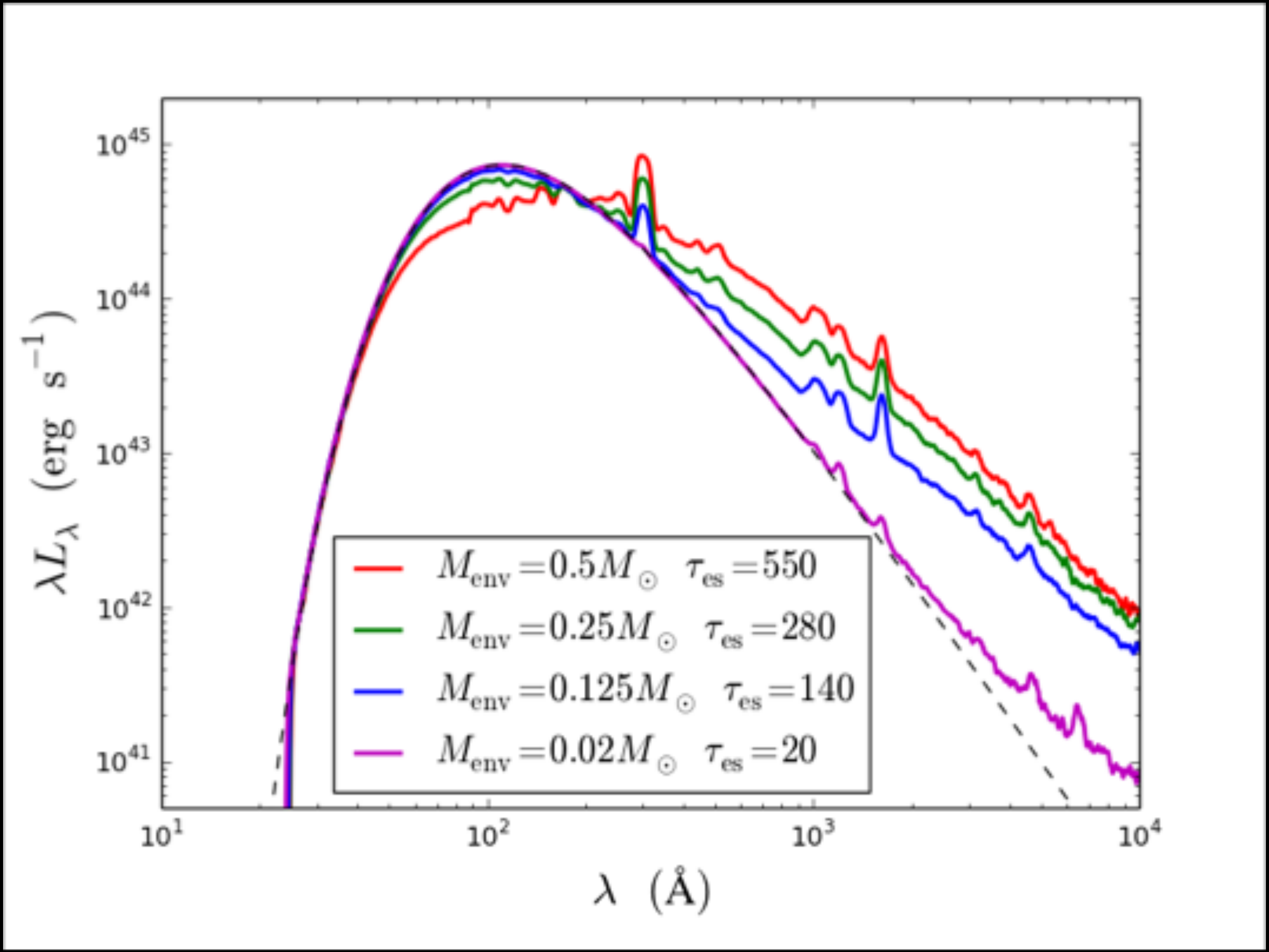
where $$\epsilon \equiv \frac{\chi^{\mathrm{abs}}}{\chi^{\mathrm{abs}} + \chi^{\mathrm{es}}}$$

Integrating emissivities



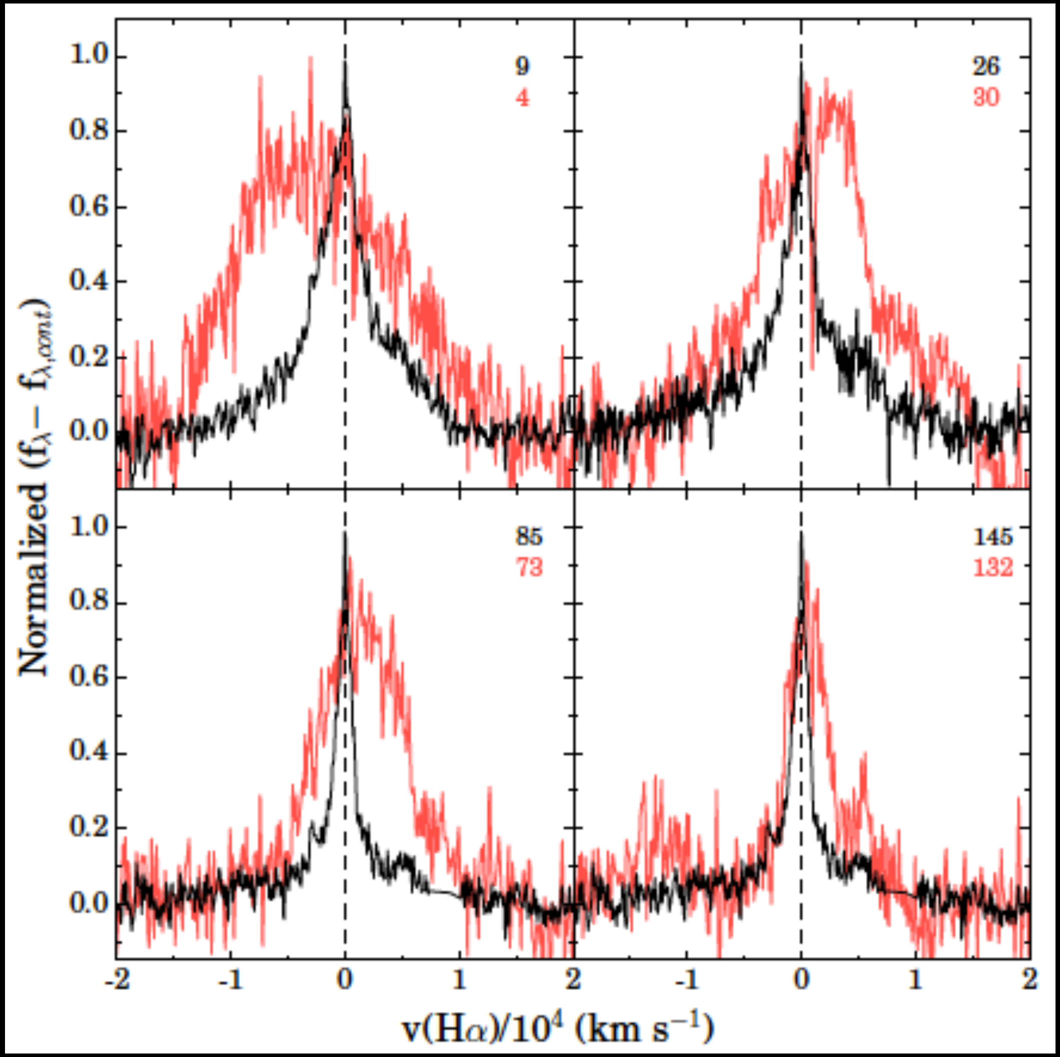
Roth+ 2016

SEDs : Varying mass in envelope



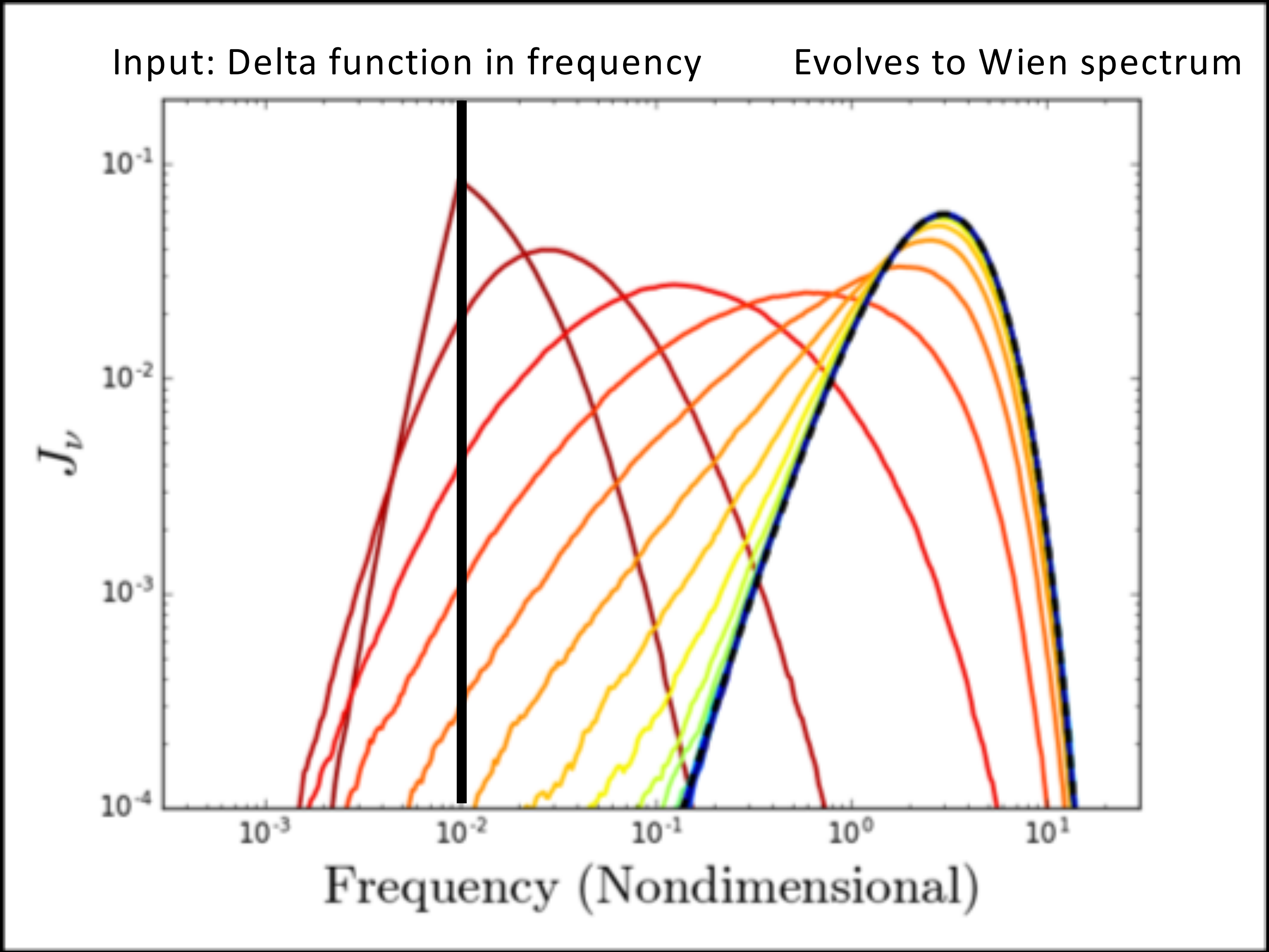
Roth+ 2016

Hα Line profiles from ASASSN-14li and ASASSN-14ae



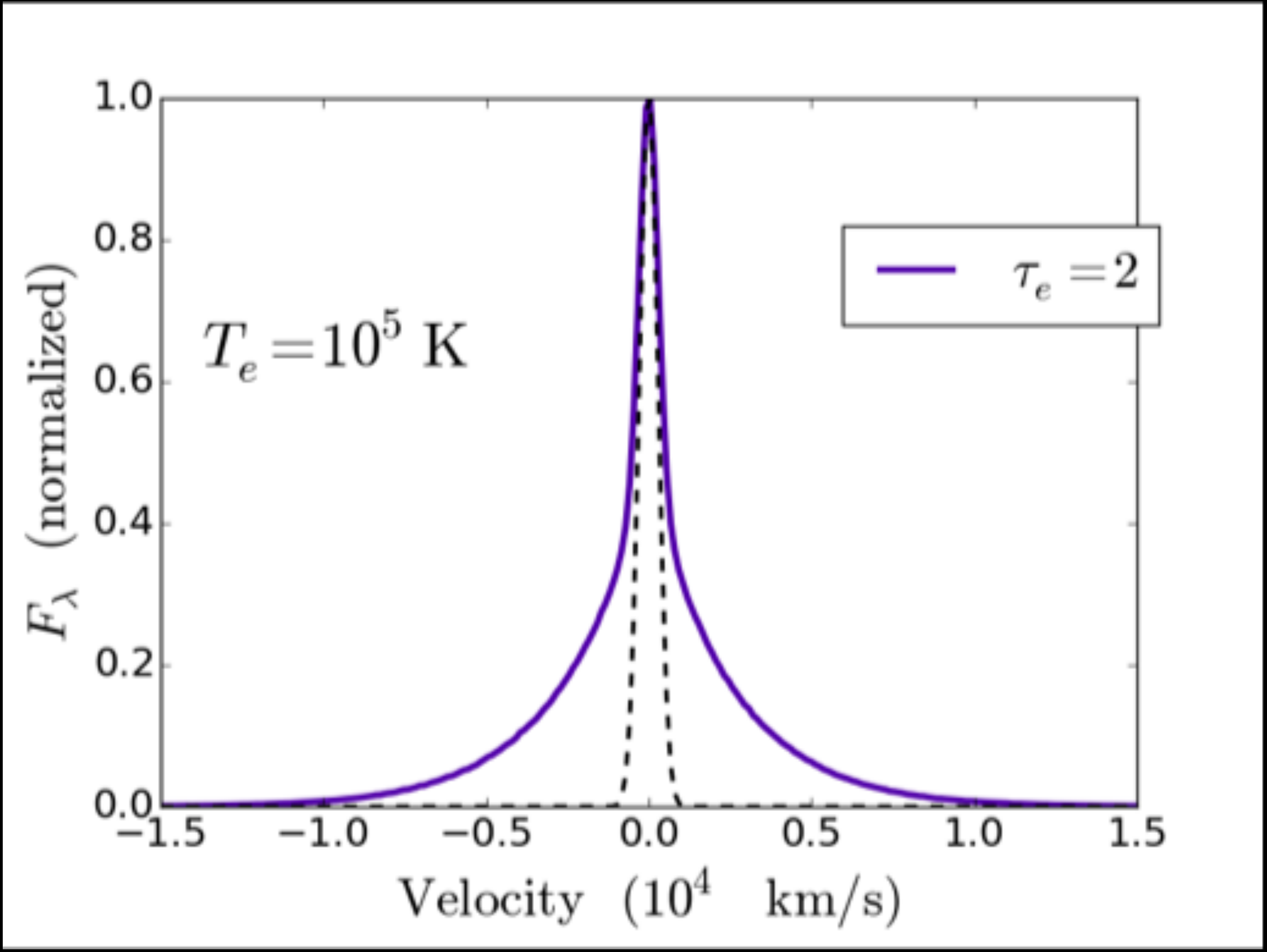
Holoien+ 2016

Comptonization



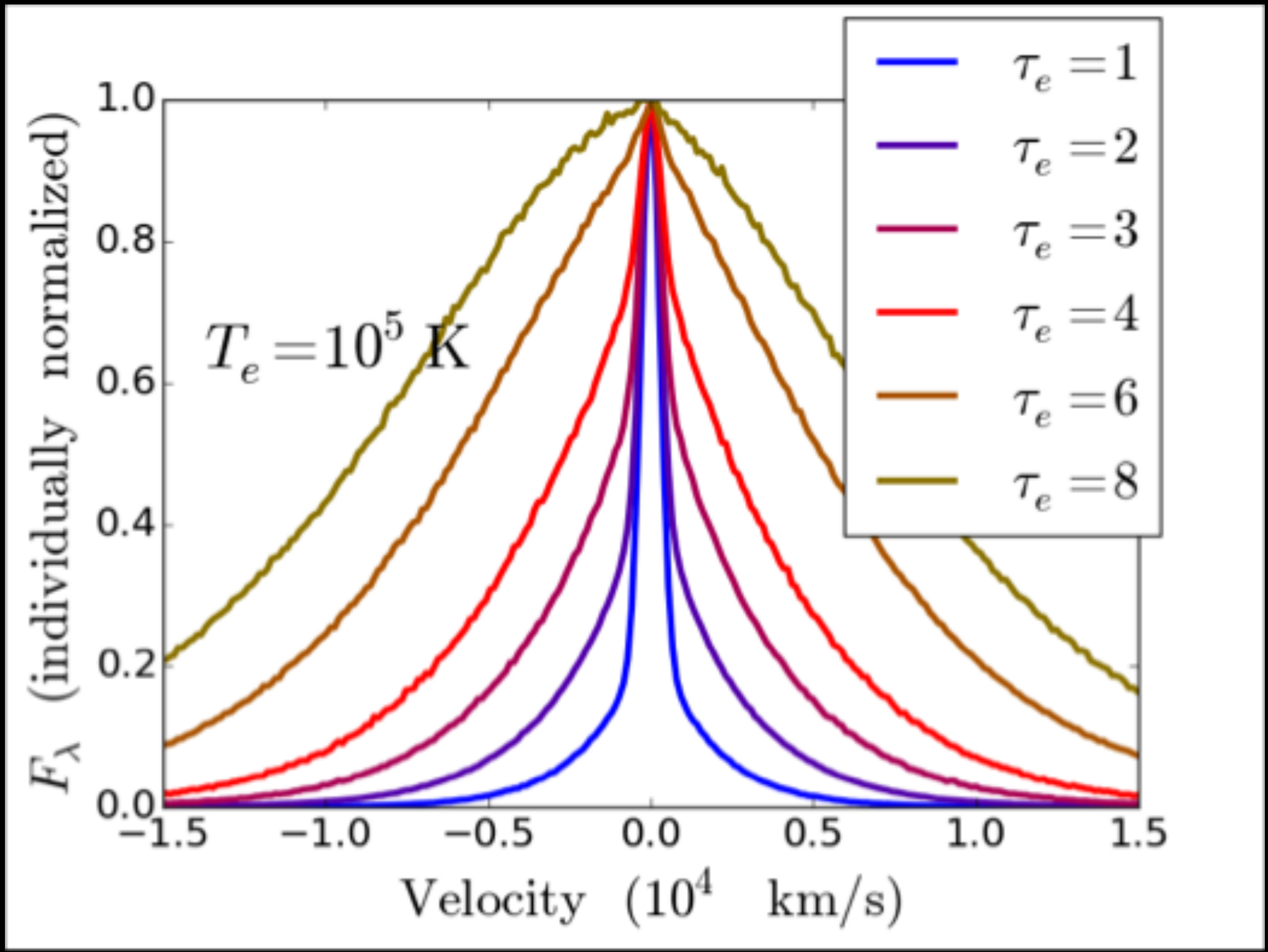
Roth & Kasen 2018

Broadening by non-coherent scattering



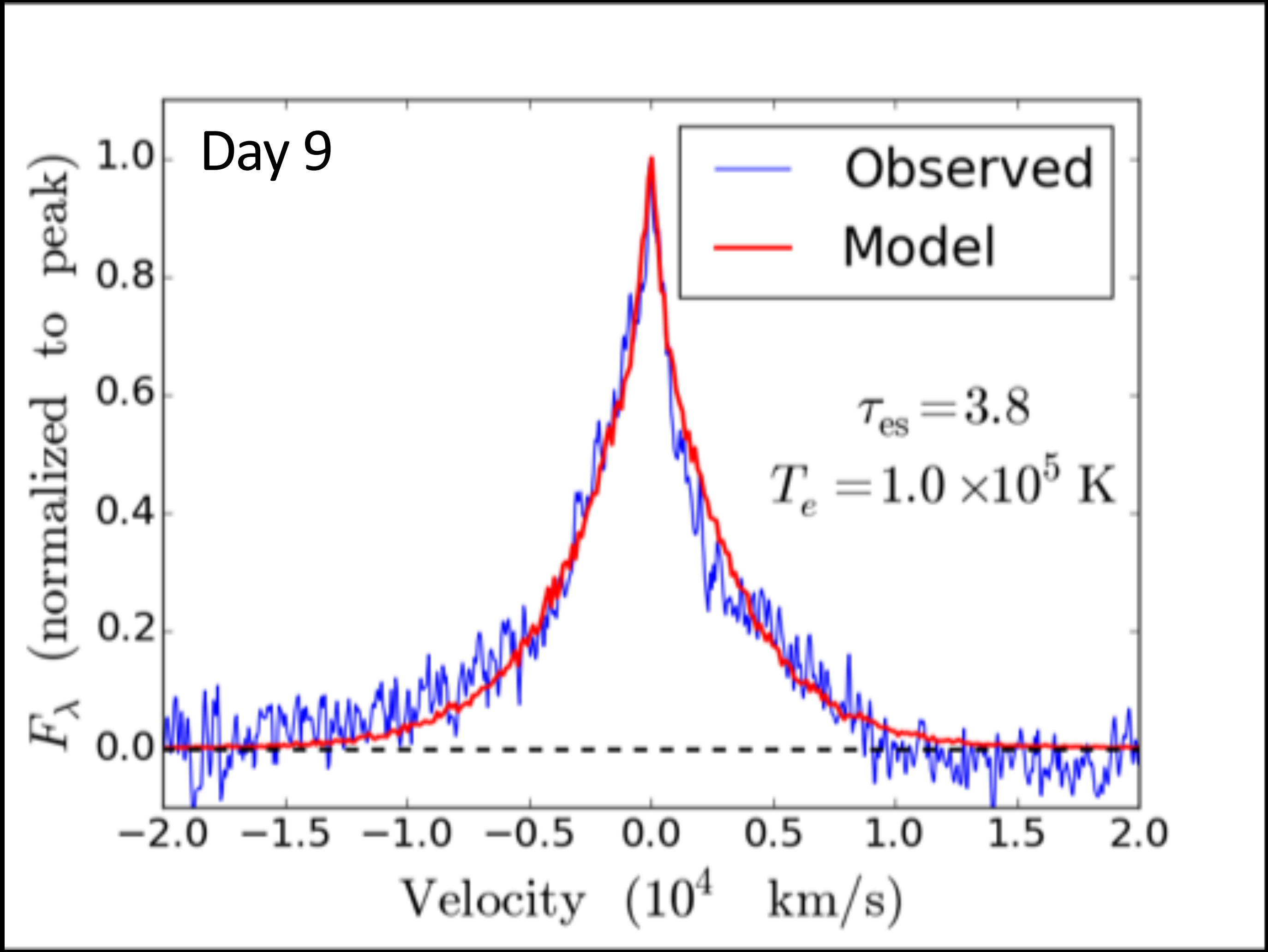
Roth & Kasen 2018

Varying optical depth



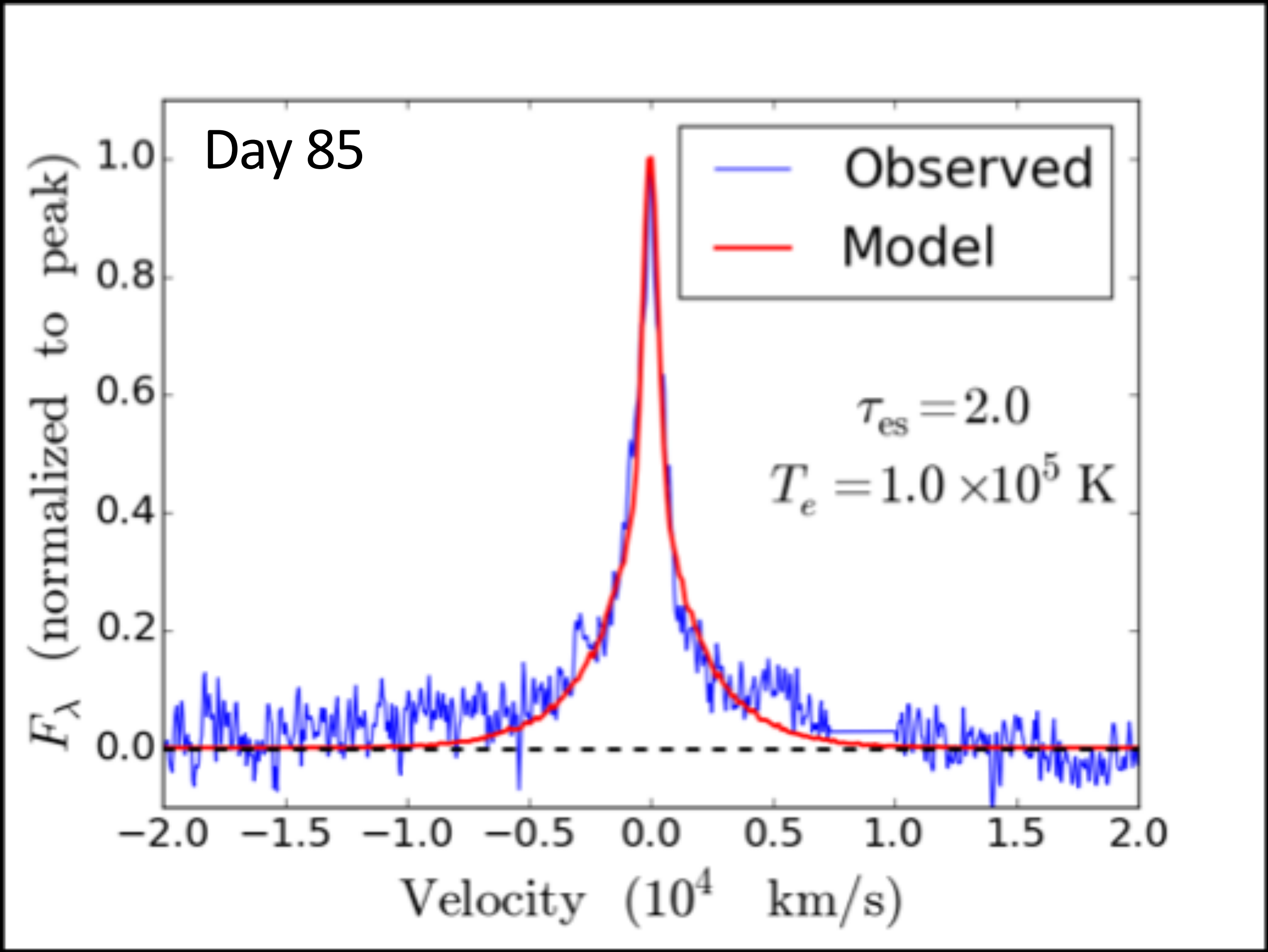
Roth & Kasen 2018

Fits to ASASSN-14li line profiles



Roth & Kasen 2018

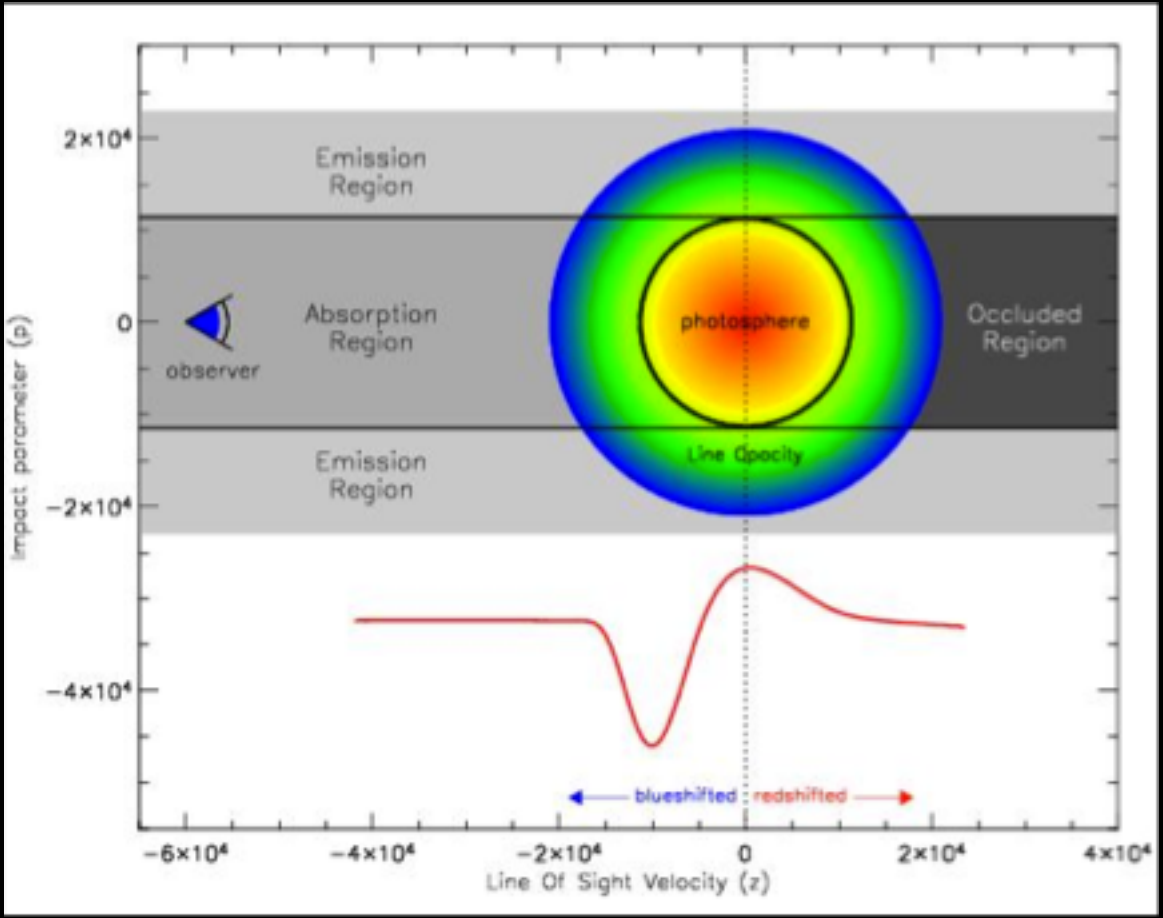
Fits to ASASSN-14li line profiles



Roth & Kasen 2018

What about an outflow/wind?

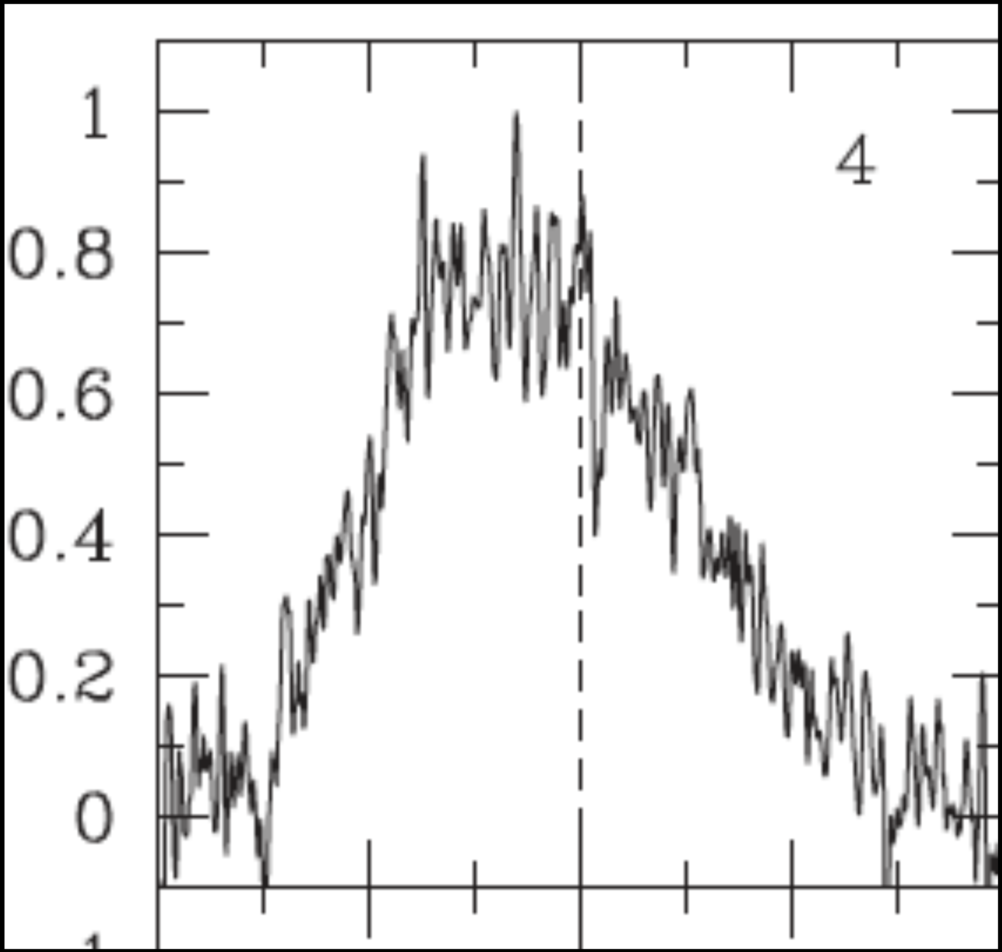
$$\tau_S = \alpha\, v_{\mathrm{D}} \left(\frac{dv}{dr}\right)^{-1}$$



Roth & Kasen 2018

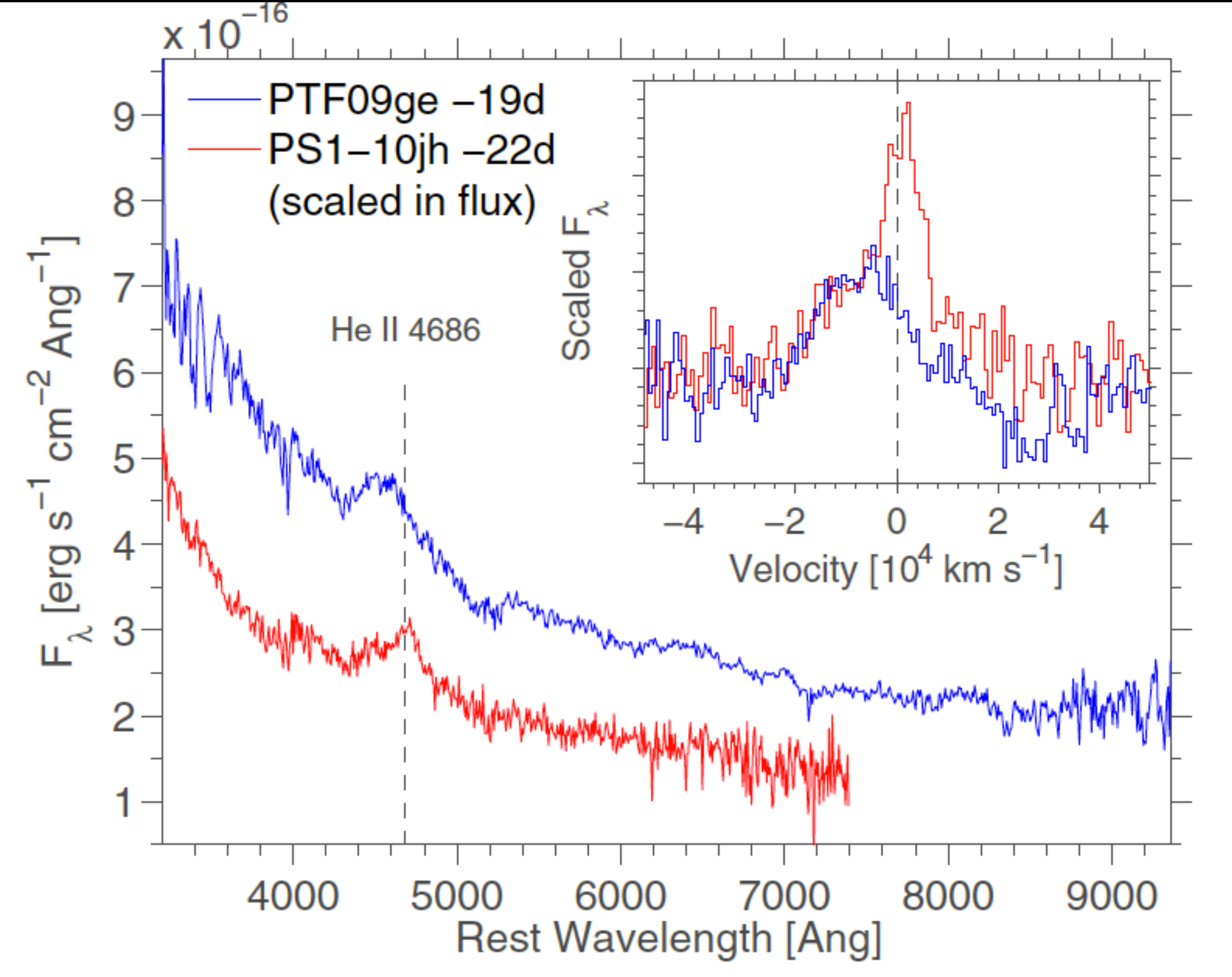
Blue-shifted peak, extended red wing

ASASSN-14ae



Holoien+ 2014

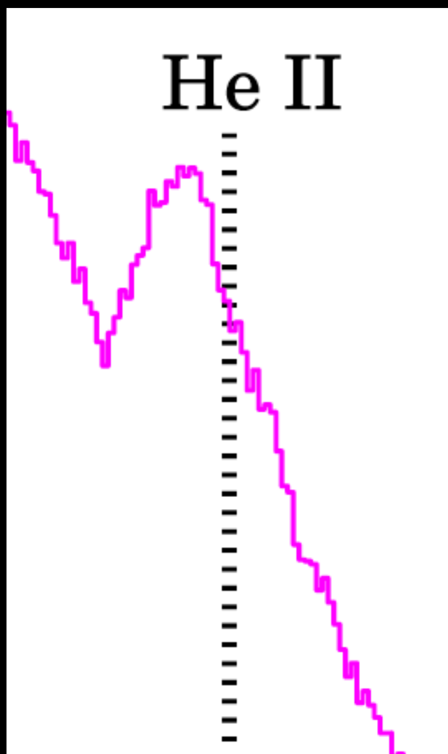
Blue-shifted peak, extended red wing

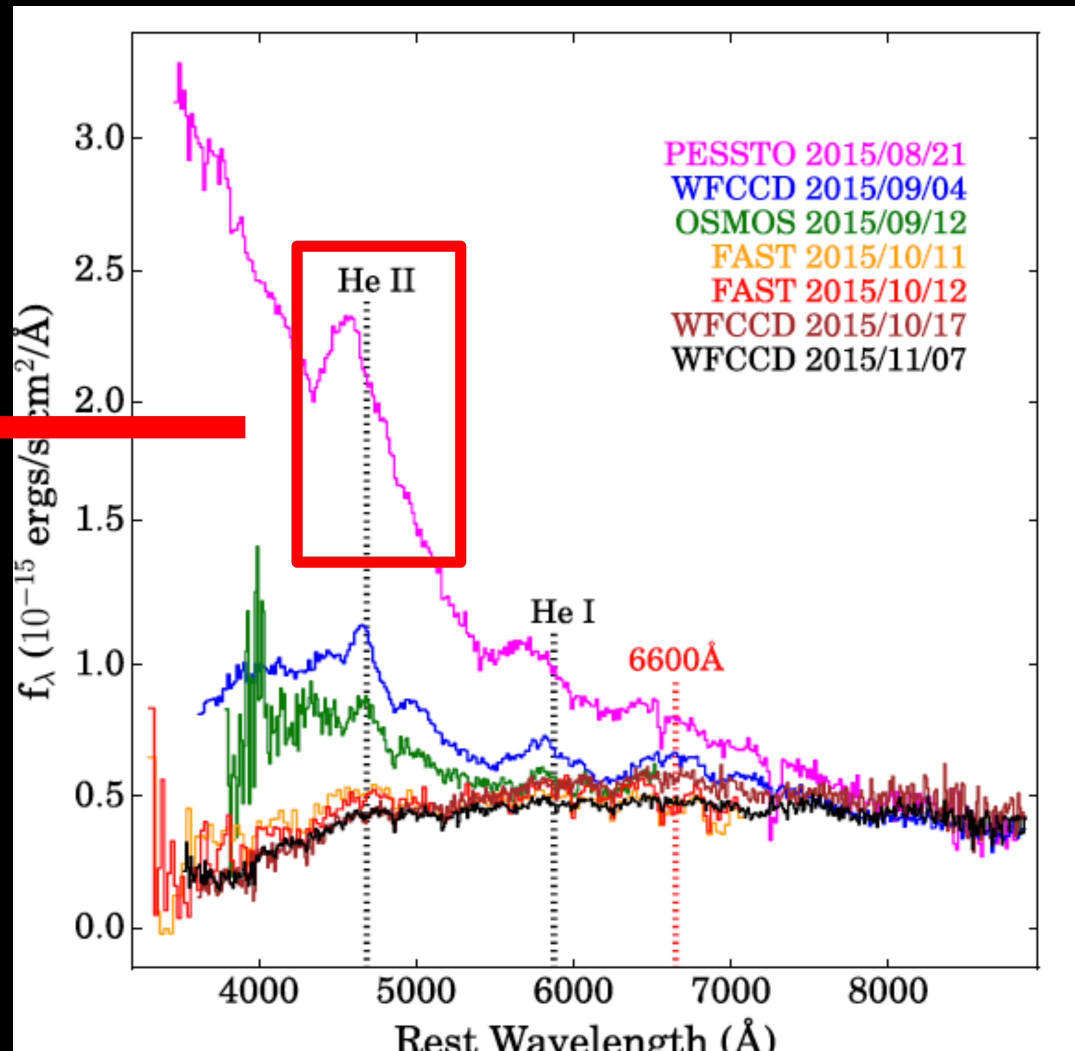


Arcavi+ 2014

Blue-shifted peak, extended red wing

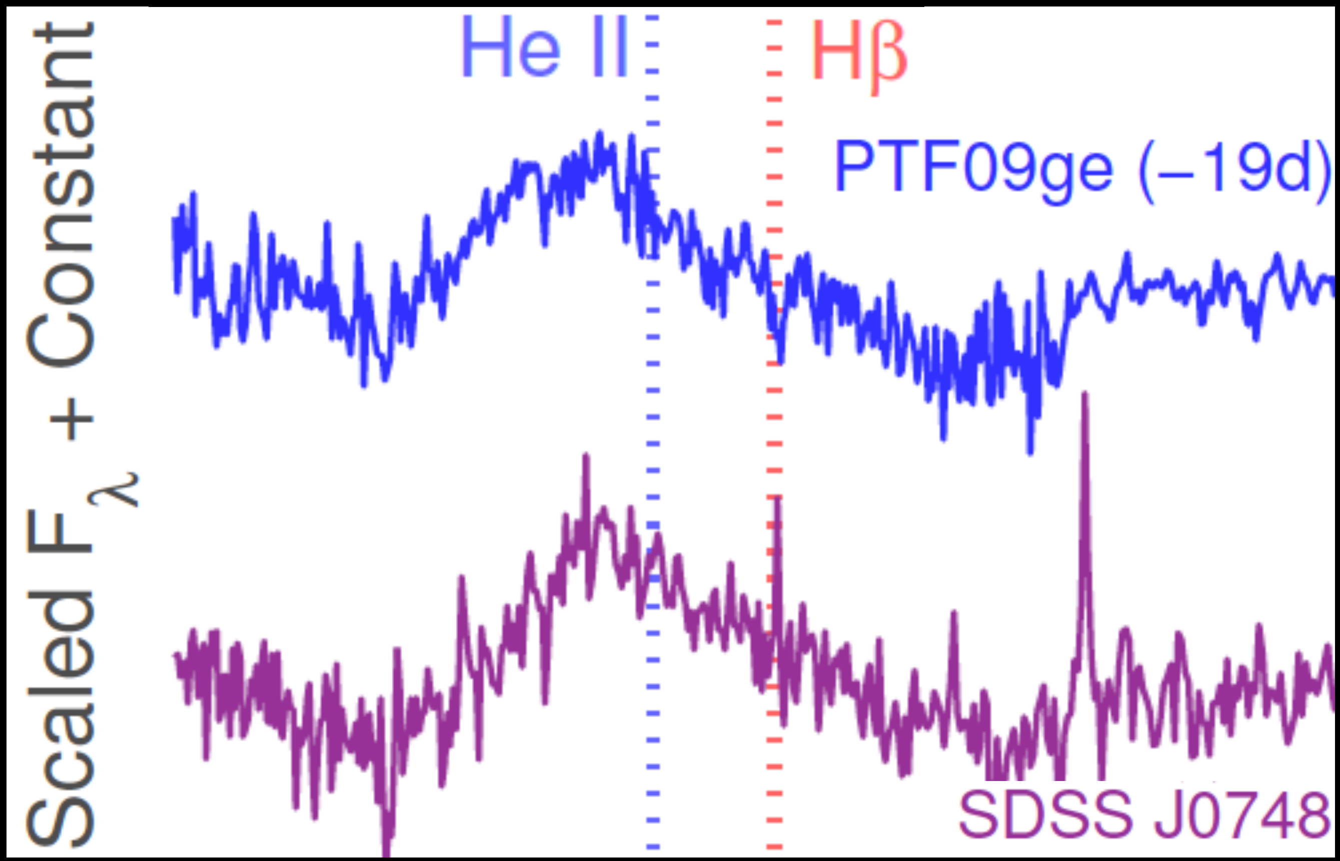
ASASSN-15oi





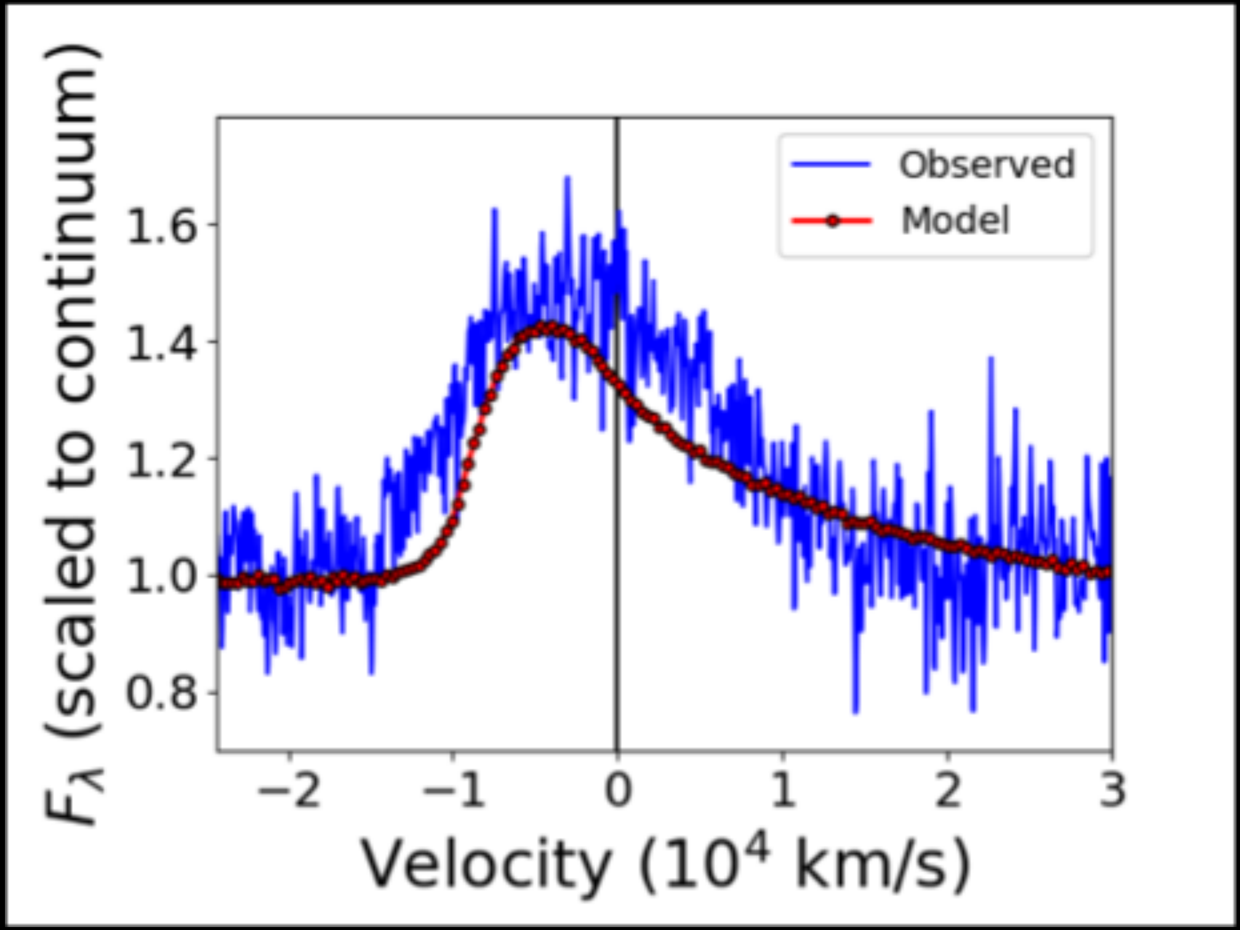
Holoien+ 2016

Blue-shifted peak, extended red wing



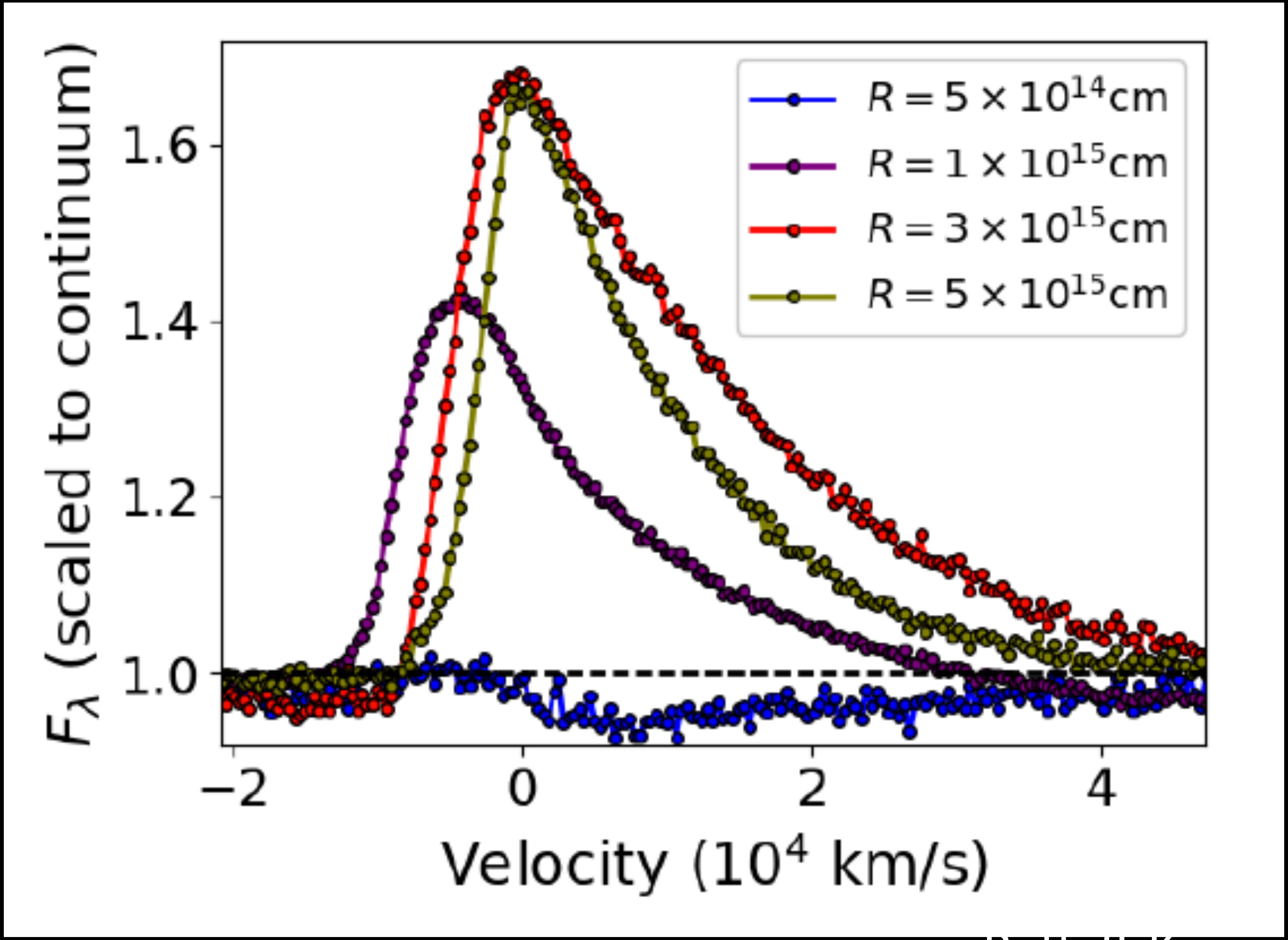
Arcavi+ 2014

Fit to ASASSN-14ae line profile



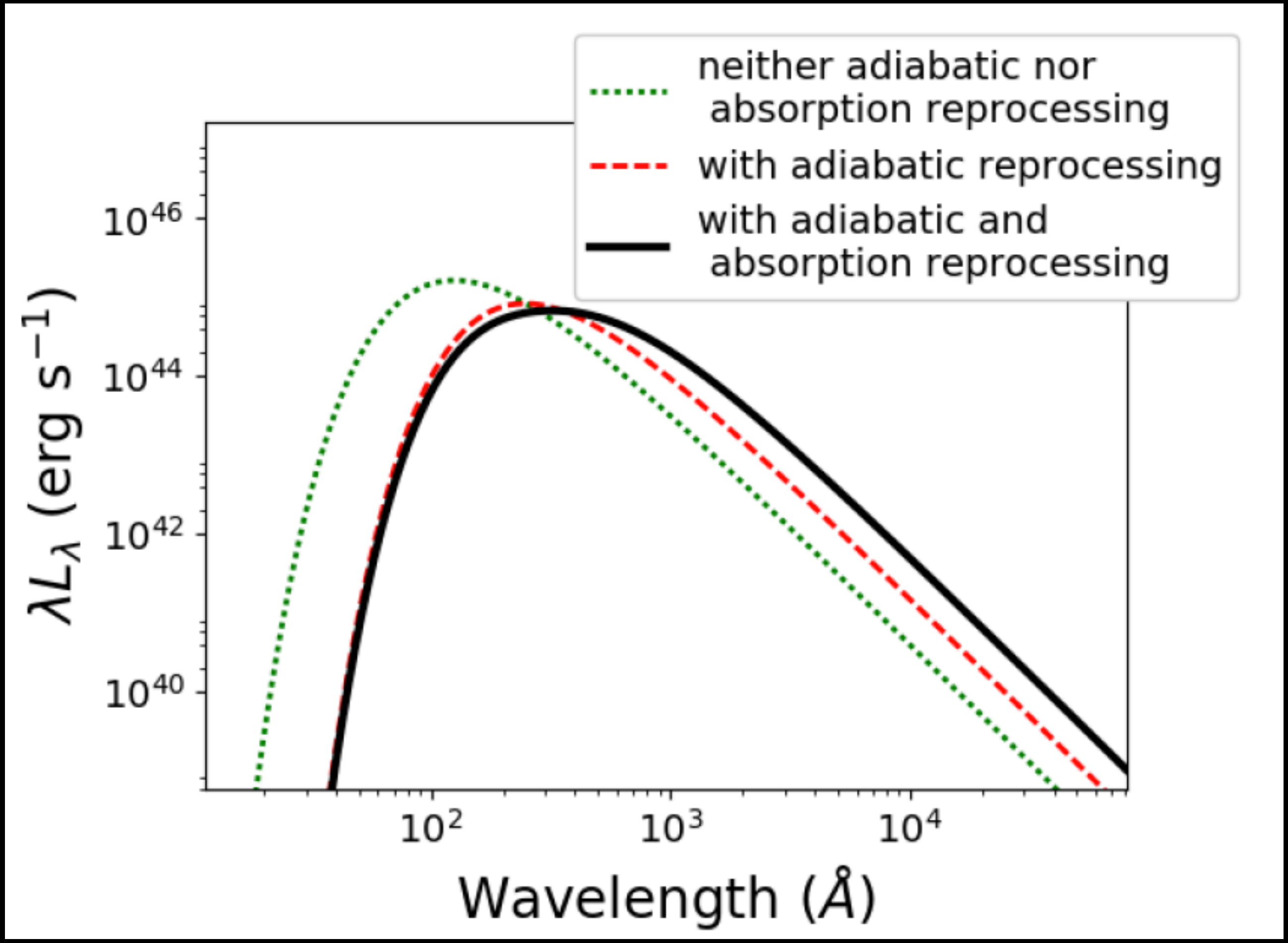
Roth & Kasen 2018

Re-centering of the line



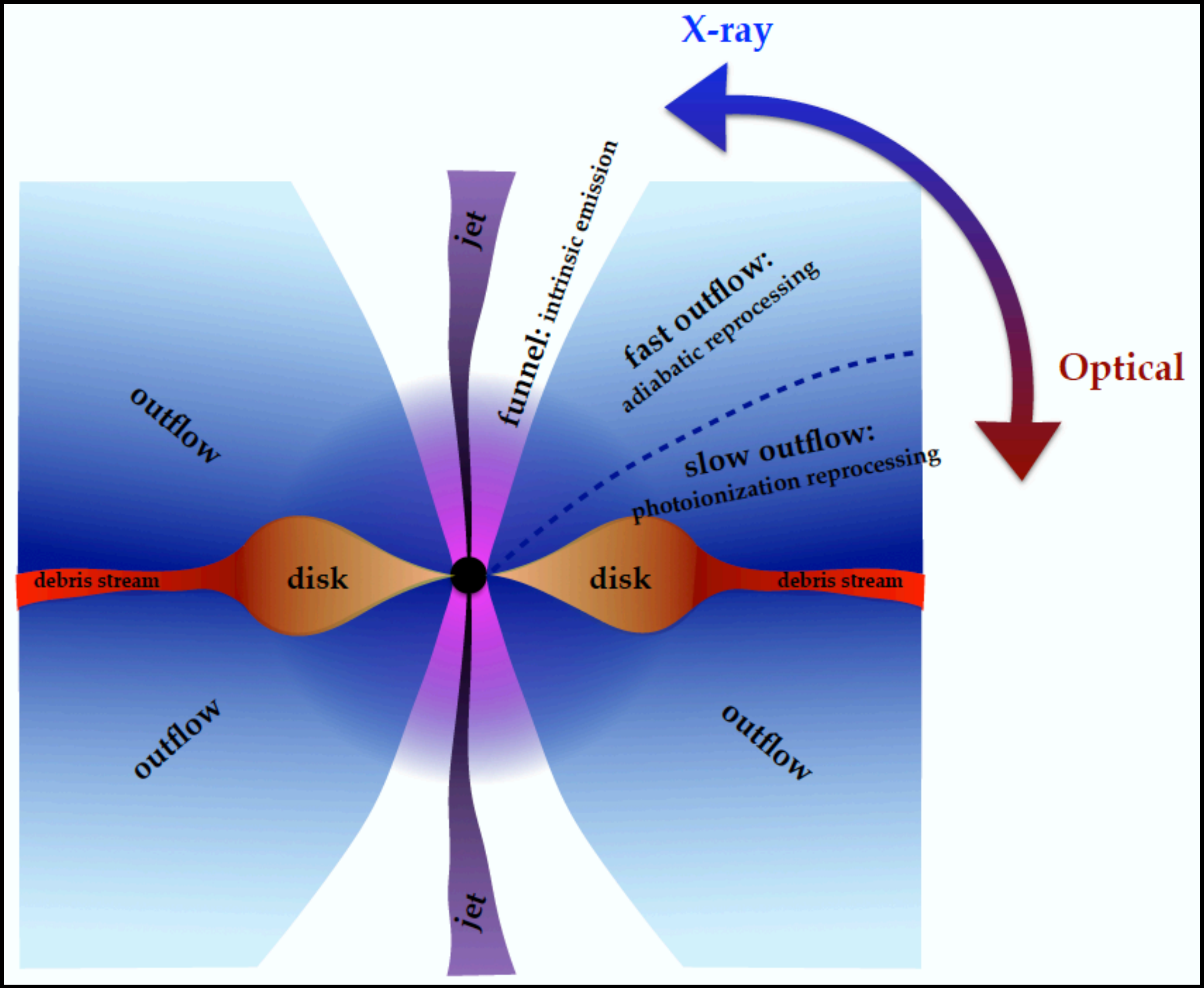
Roth & Kasen 2018

Adiabatic reprocessing in outflow



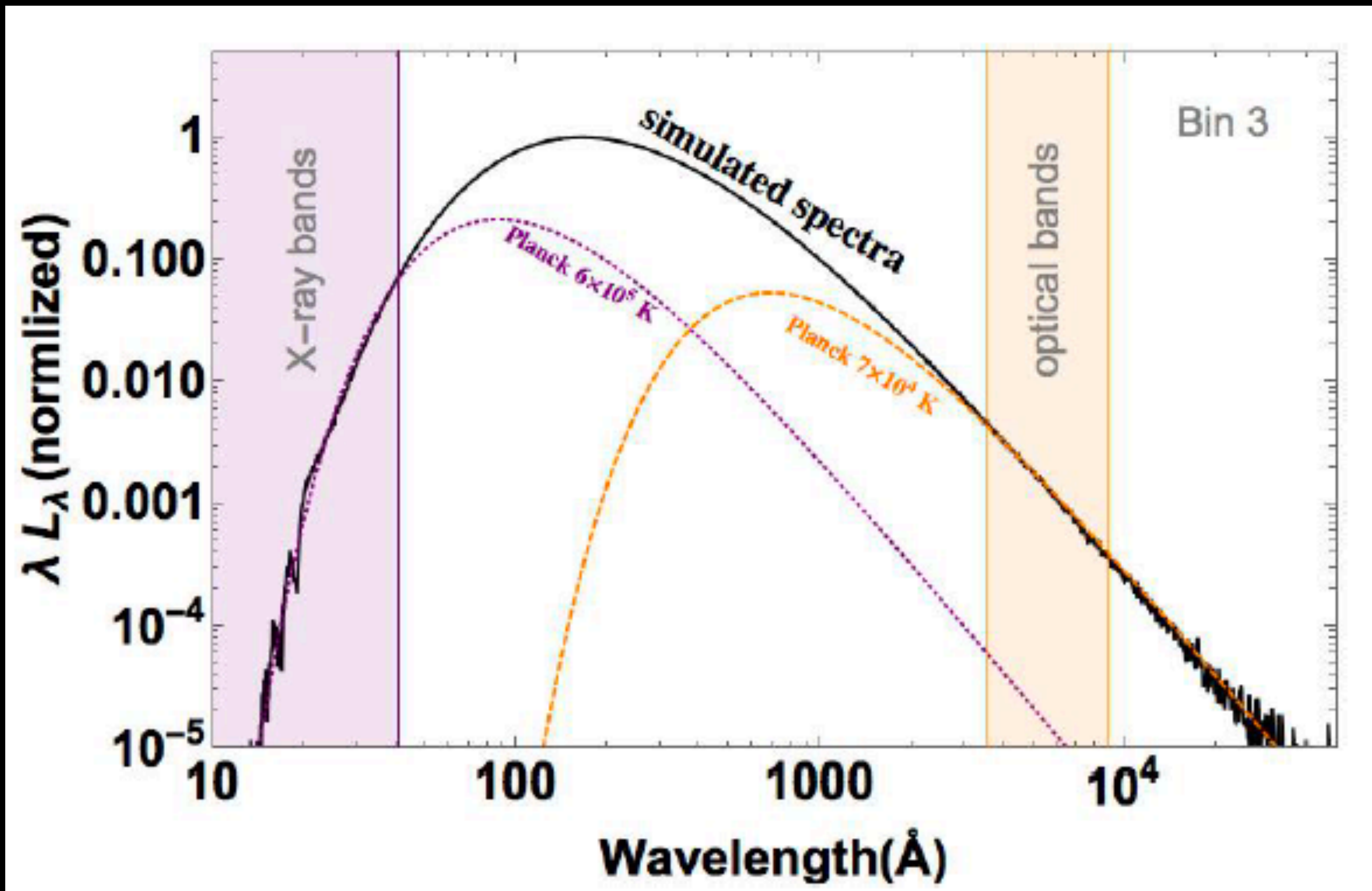
Roth & Kasen 2018

Simulations of Super-Eddington Accretion in TDEs with fast outflows



Dai+ 2018 including NR

Fast outflows lead to very broad SEDs



Dai+ 2018 including NR