MCRT for astrophysical outflows:
line interactions and line driving

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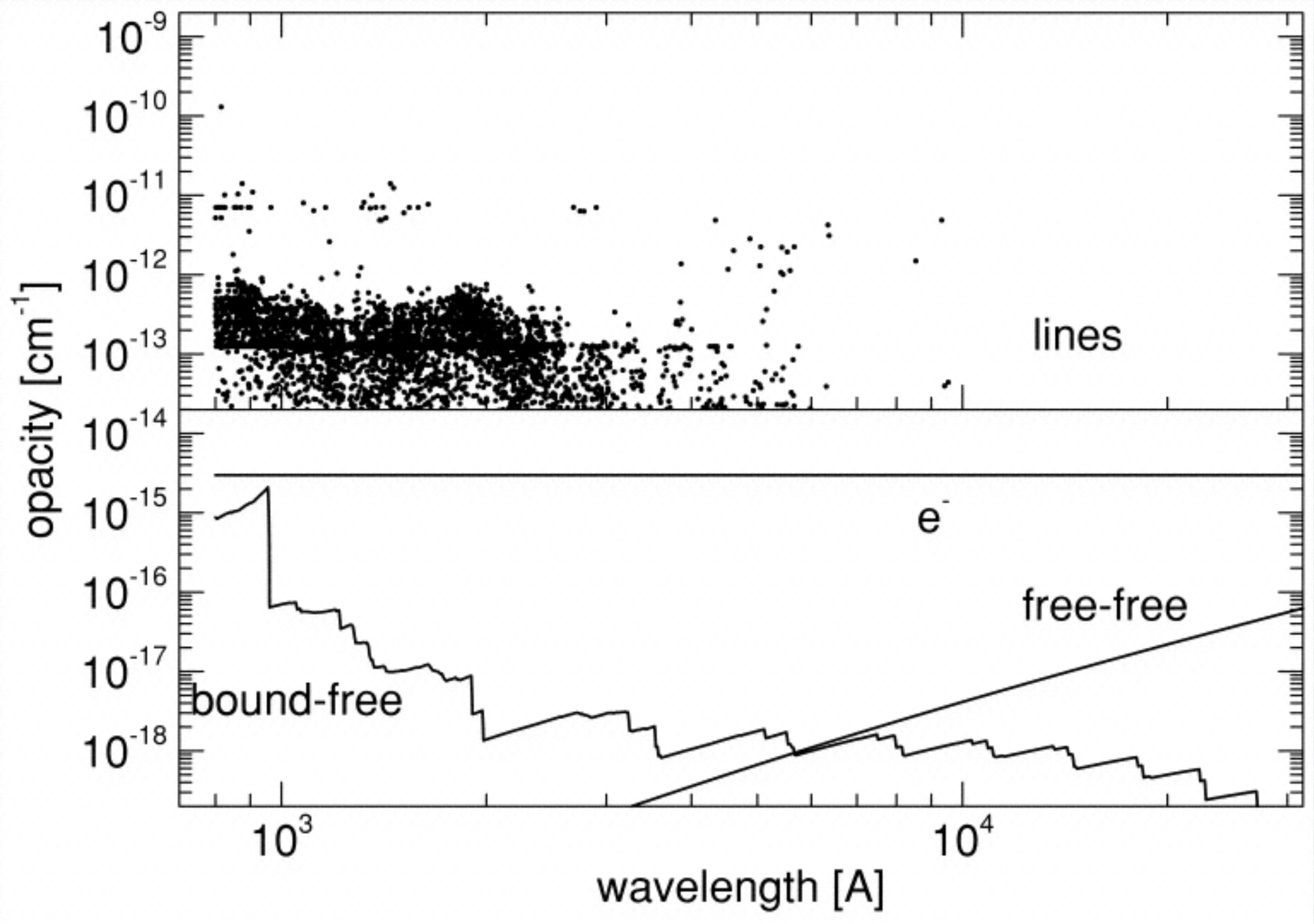
SAMCSS 2015

Overview:

- Interaction physics
    - Lucy's Macro Atom method

- Line-driven winds
    - Suitability of MCRT techniques
    - Recent stellar wind explorations

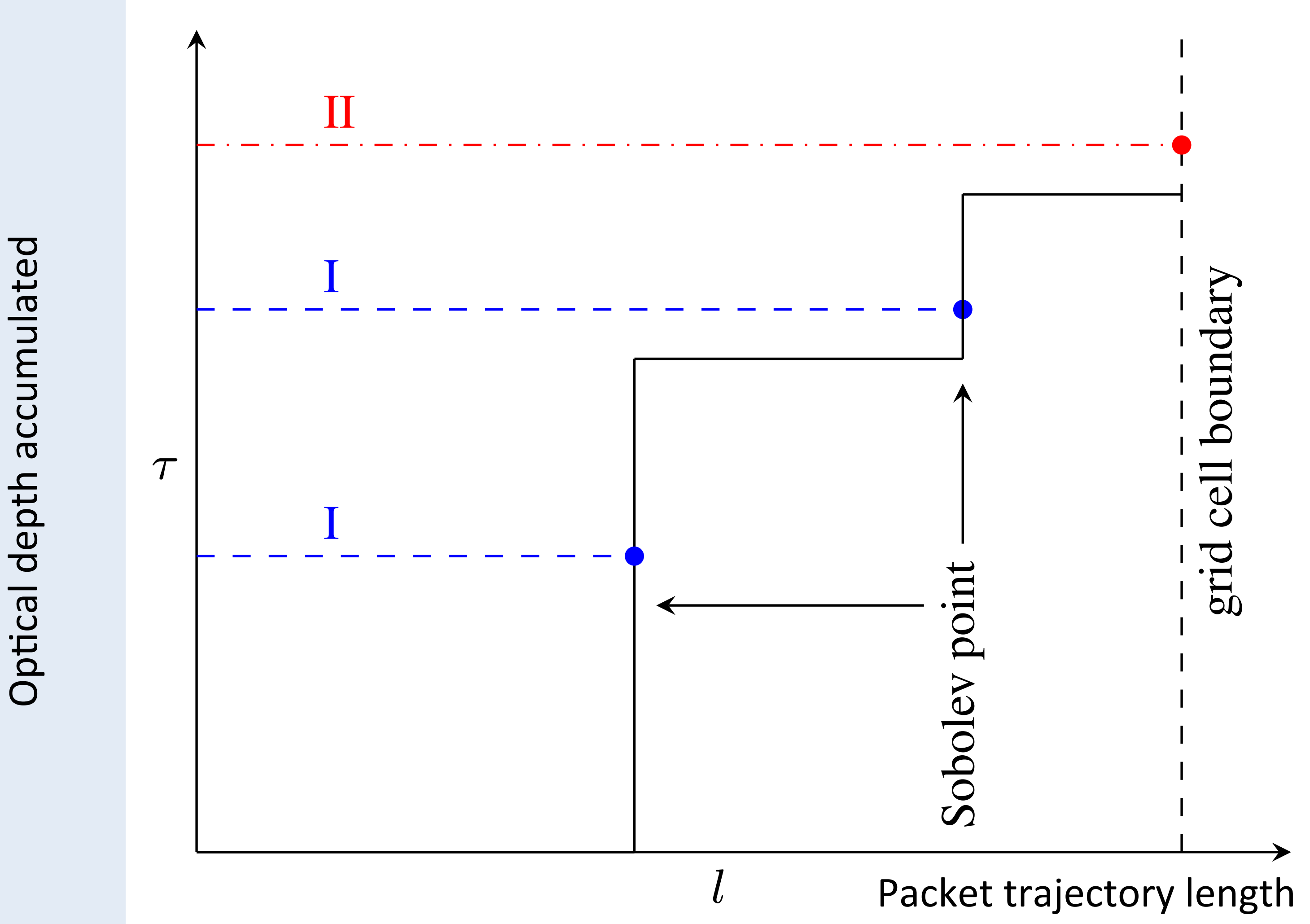
Non-grey opacity



Pinto & Eastman 2000

Sobolev approximation

Algorithm for finding interaction point (only lines):

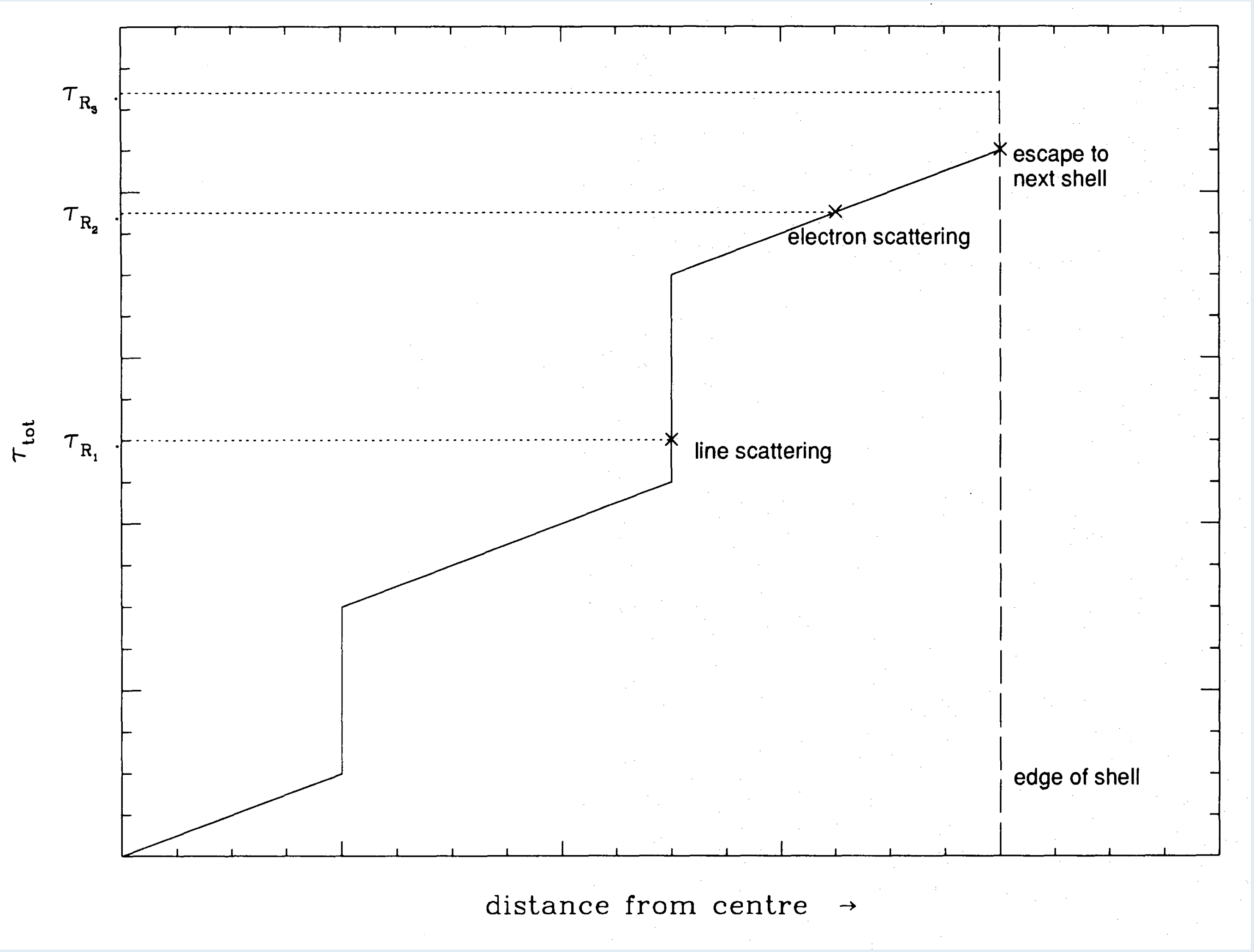


(figure from U. Noebauer)

Sobolev approximation

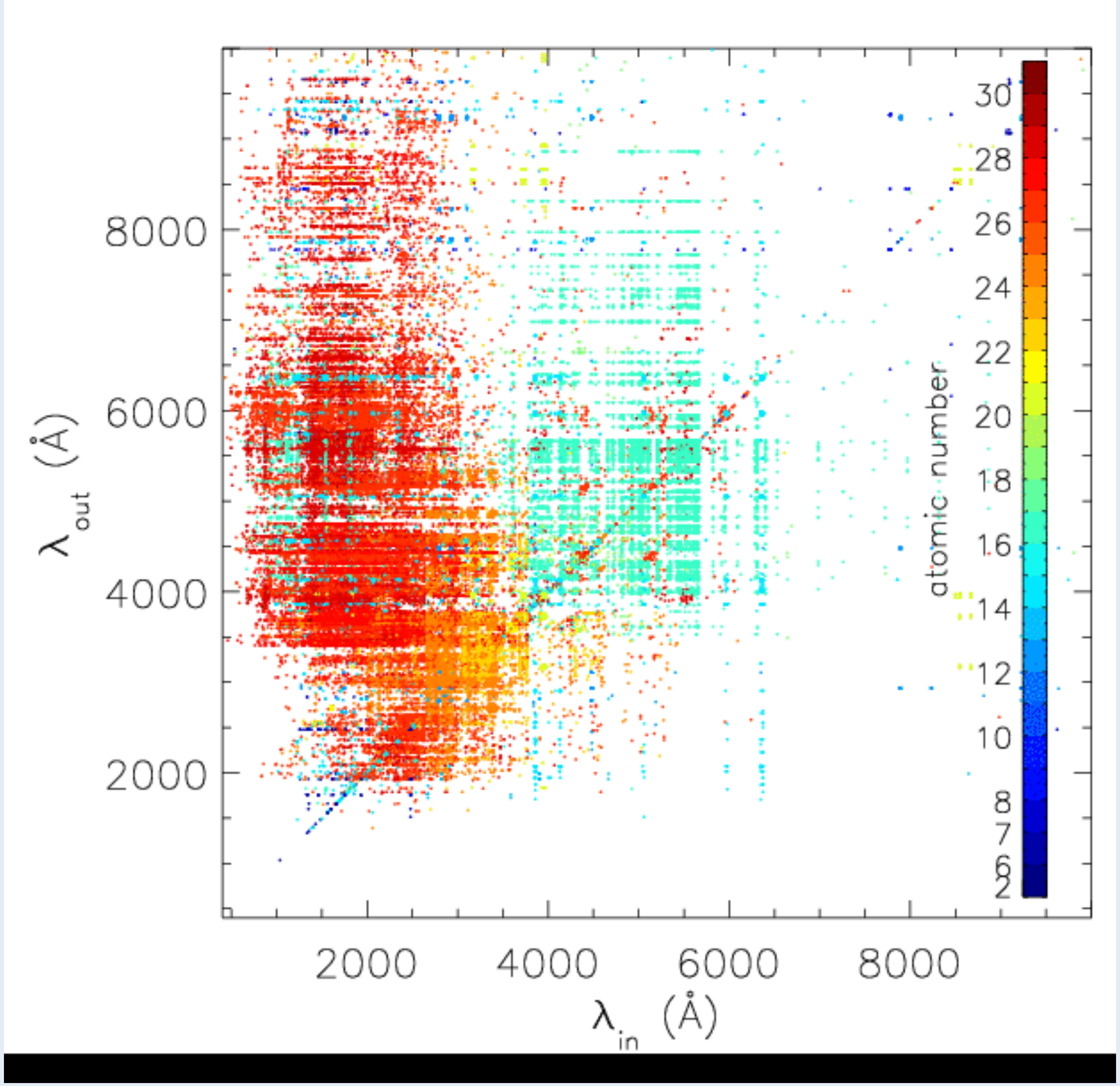
Process for finding interaction point (generalized to include continuum):

Optical depth accumulated



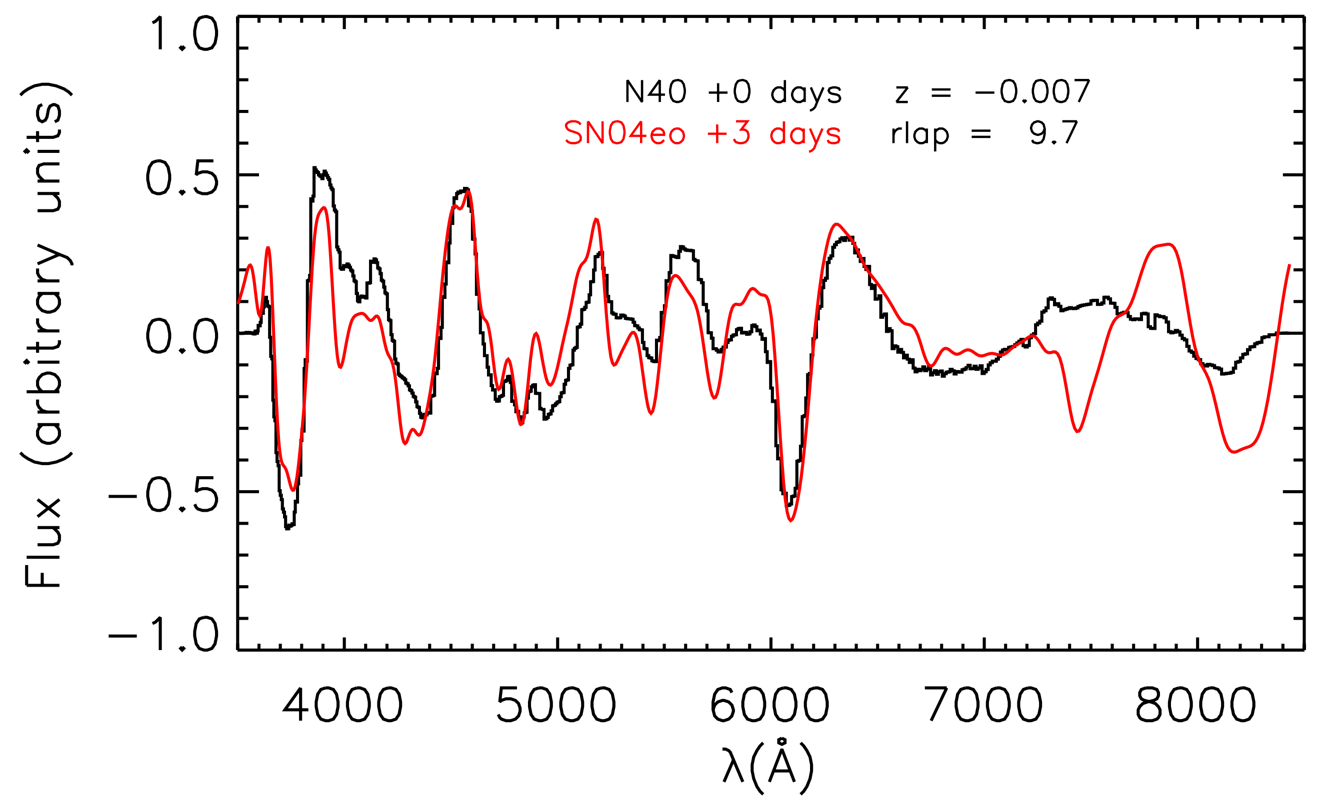
Packet trajectory length
(figure from Mazzali & Lucy 1993)

Redistribution



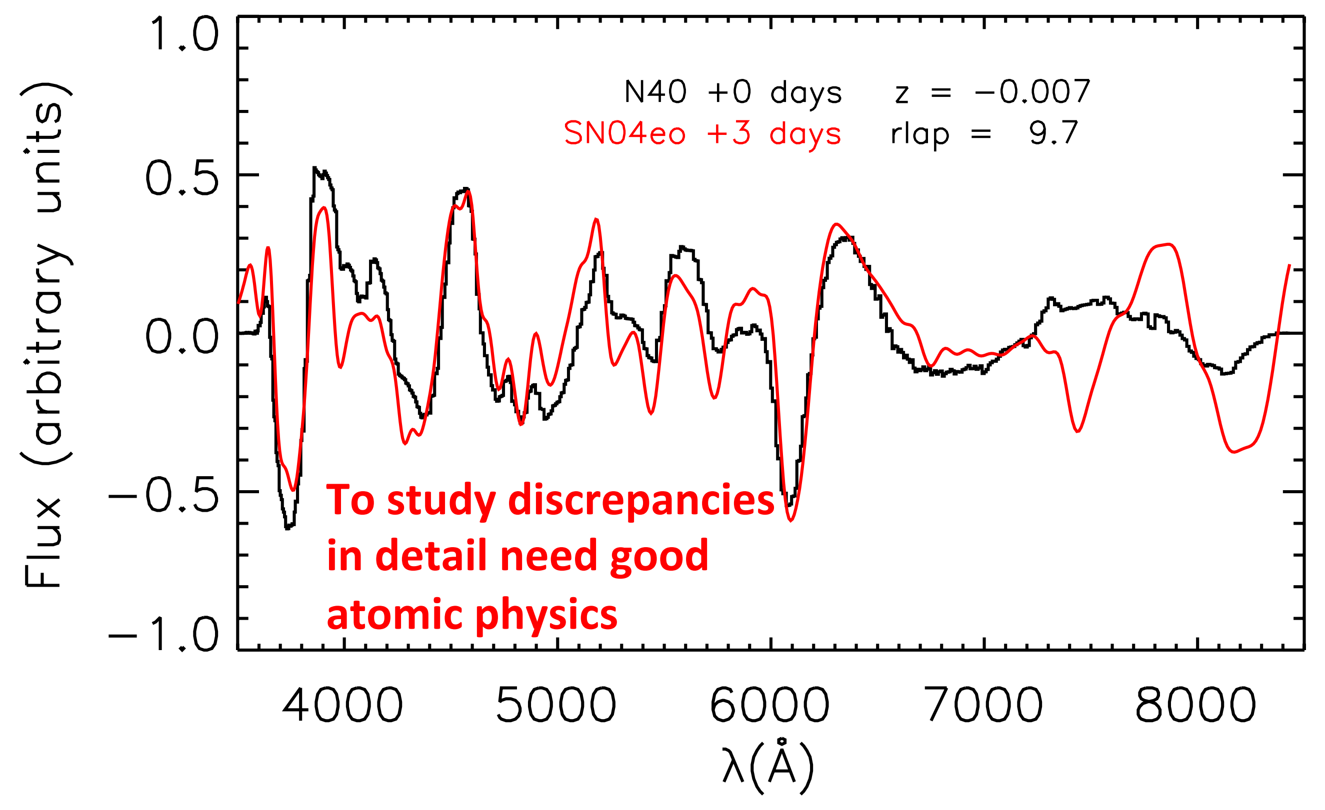
(figure from Kromer & Sim 2009)

Need for good microphysics:



Comparison of predicted spectral features for hydro model to observations (Sim et al. 2013)

Need for good microphysics:



To study discrepancies in detail need good atomic physics

Comparison of model spectral features to observations (Sim et al. 2013)

Line interaction events

Considerations:

Radiation dominated: naively calculating emission using level populations will not conserve energy unless converged

Use indivisible packets (Lucy) – imposes radiative equilibrium

- means any packet absorbed by a line transition must be re-emitted

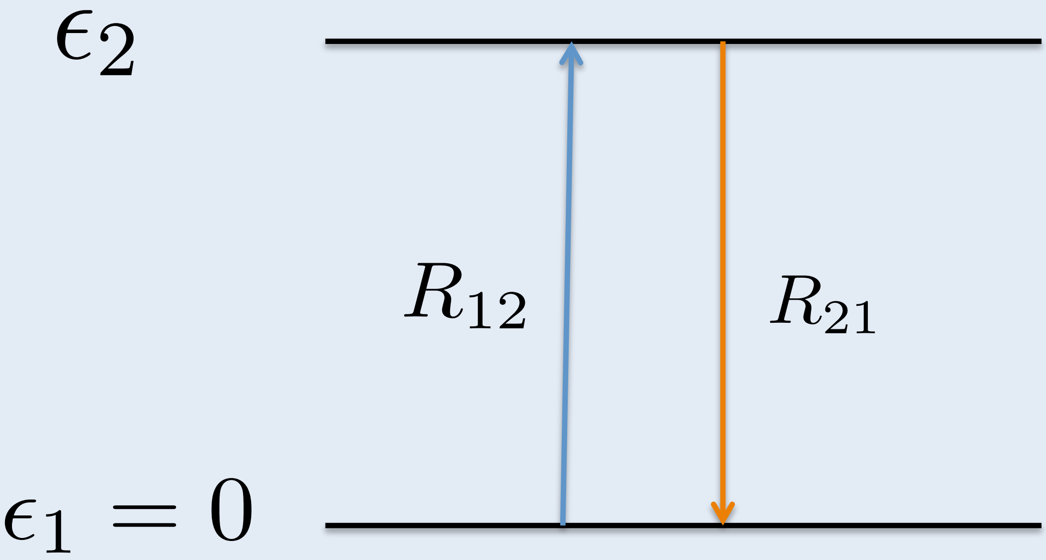
How to emit?

(1) Extremely simple to use resonance scattering approximation

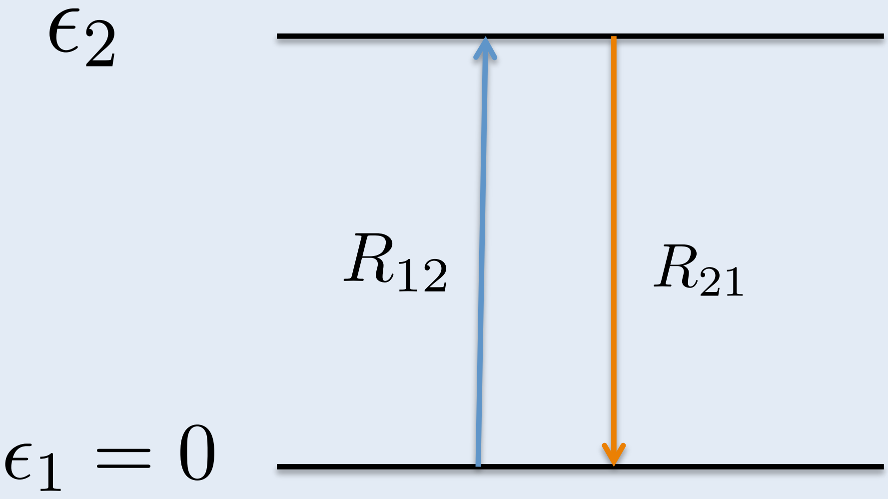
(2) Alternative schemes based on "down branching" (Mazzali & Lucy 1993) and Lucy's (2002, 2003) "macro atom" / "k-packet" methods give more physical realism (second lecture).

Two-level atom

(radiation dominated)



Two-level atom



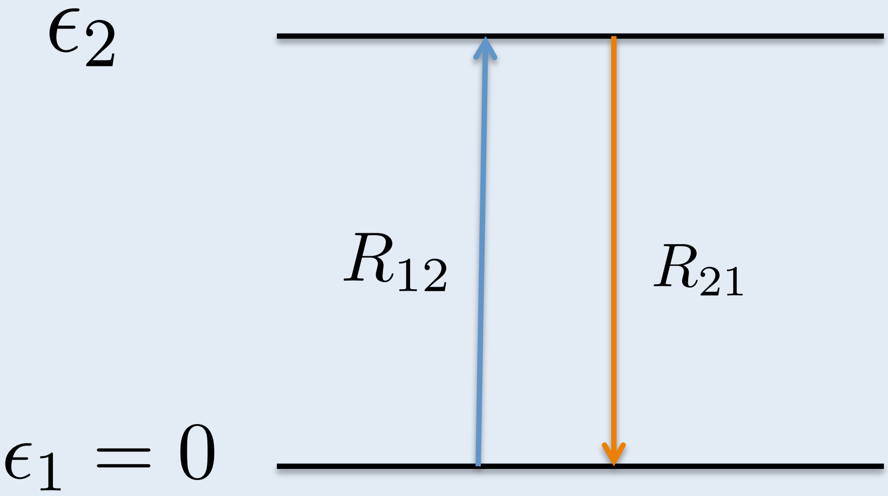
For homologous flow:

$$R_{21} = n_2 A_{21} p_{\rm sob}$$

$$p_{\rm sob} = \frac{1 - e^{\tau_s}}{\tau_s}$$

$$R_{12} = n_1 \; B_{12} \; p_{\rm sob} \; J_b \; \left(1 - \frac{n_2}{n_1}\frac{g_1}{g_2}\right)$$

Two-level atom



ϵ_2

R_{12}

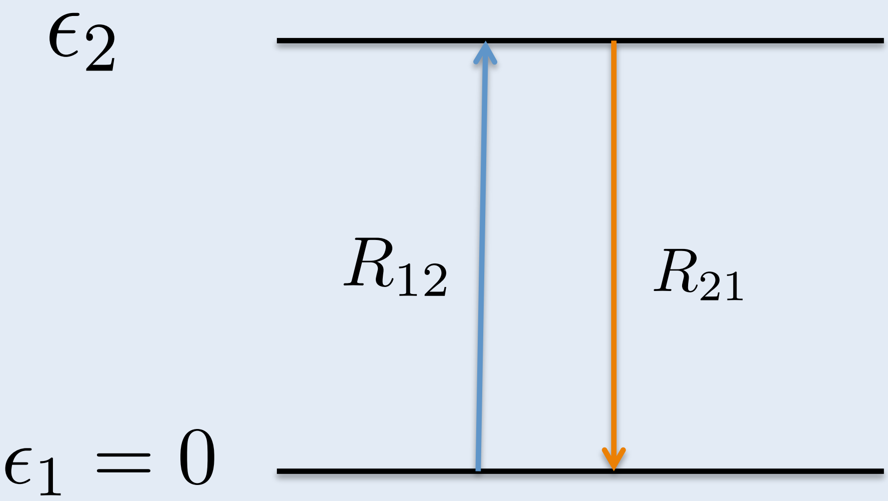
R_{21}

$\epsilon_1 = 0$

Statistical equilibrium:

$$\frac{\mathrm{d}n_2}{\mathrm{d}t} = R_{12} - R_{21} = 0 \rightarrow R_{12} = R_{21}$$

Two-level atom



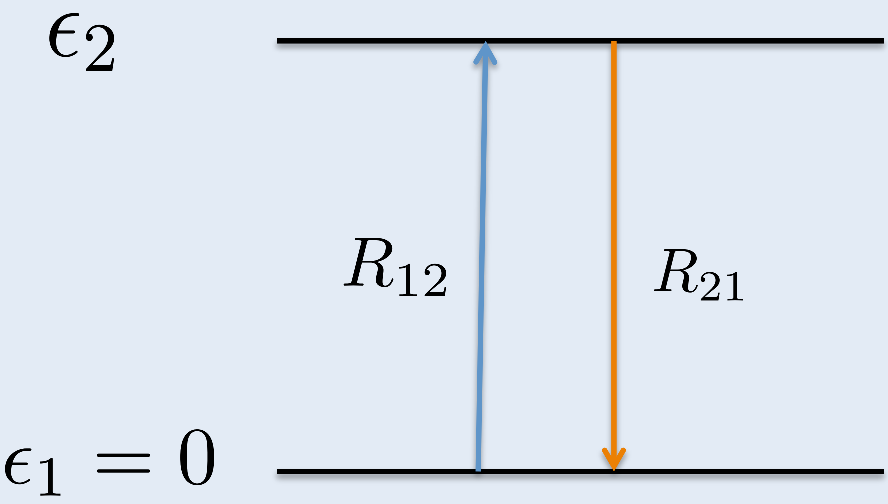
Statistical equilibrium:

Absorbing MC packets

$$\frac{\mathrm{d}n_2}{\mathrm{d}t} = R_{12} - R_{21} = 0 \rightarrow R_{12} = R_{21}$$

Re-emitted MC packets

Two-level atom

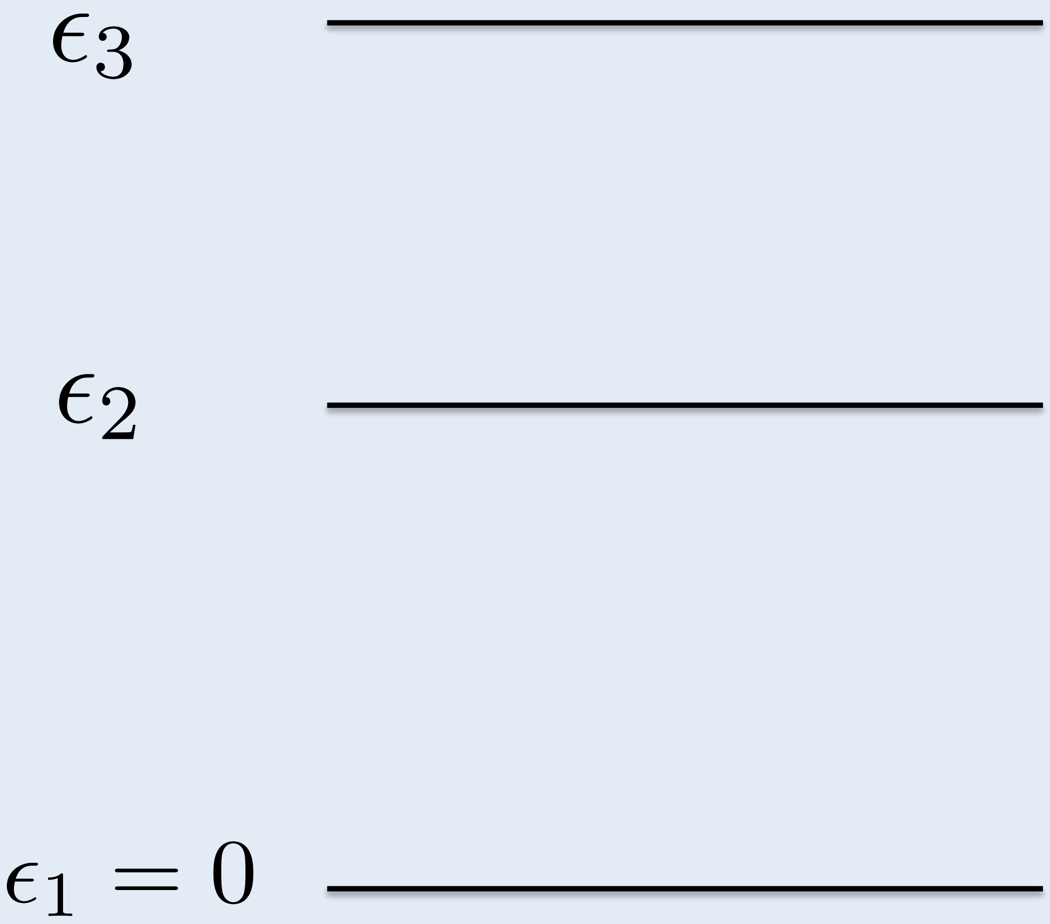


Simple algorithm (“scatter”):

Every time a line absorbs an energy packet immediately replace it with a new energy packet emitted by the same line. Effectively a scattering event – just need a new direction.

[Some codes generalize to include collisional destruction (e.g. Long & Knigge 2002)]

Radiation-dominated example

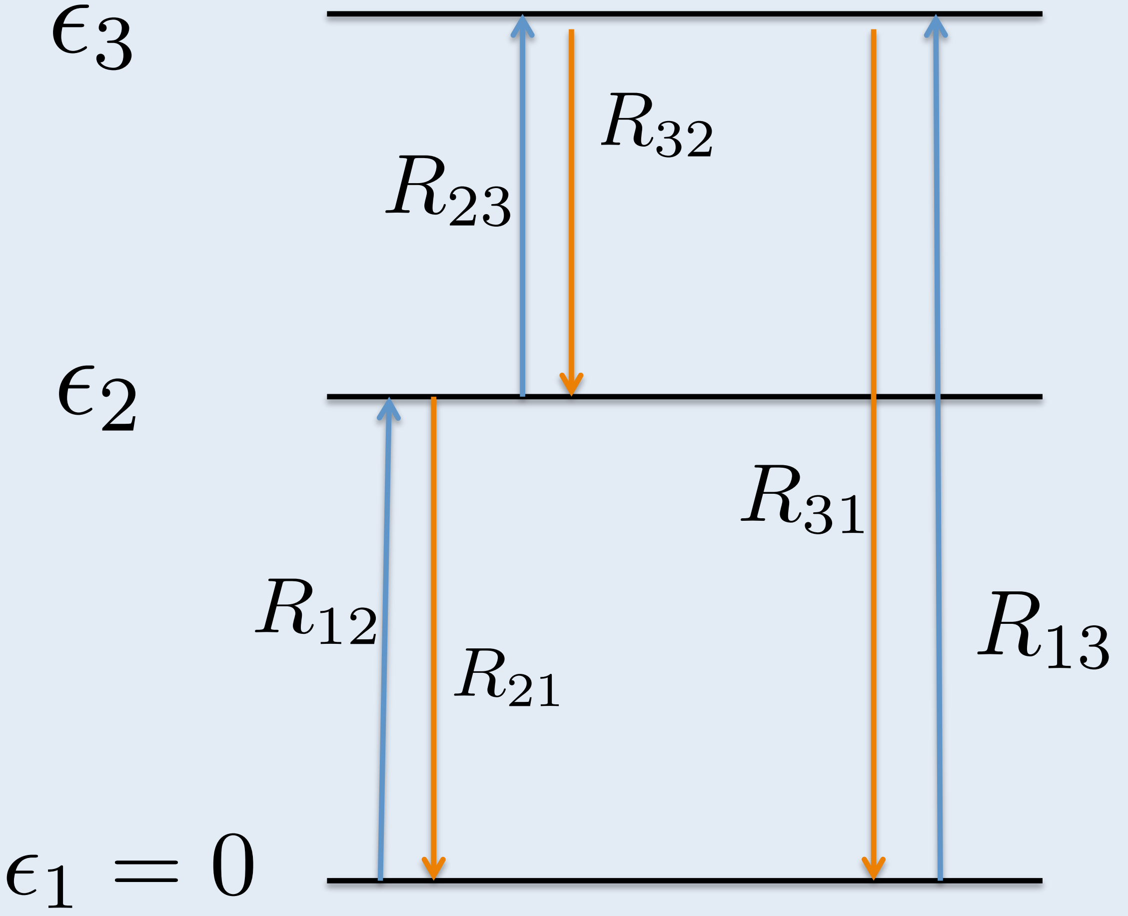


ϵ_3

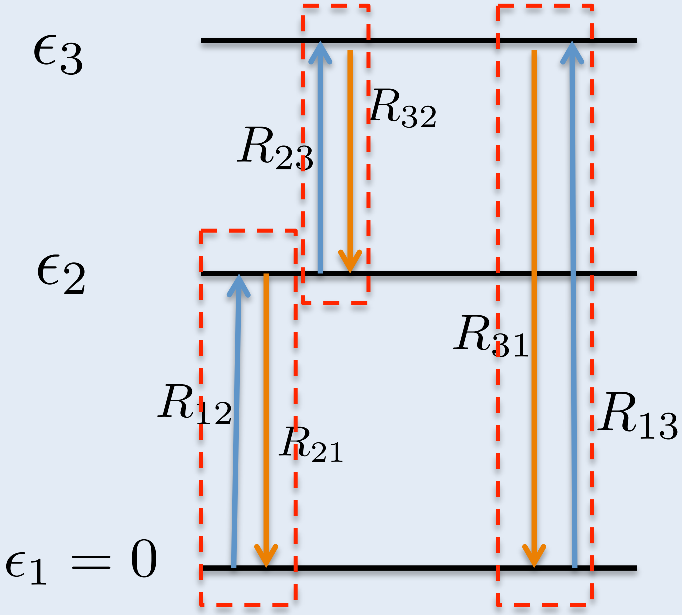
ϵ_2

$\epsilon_1 = 0$

Radiation-dominated example



Radiation-dominated example



Resonance line scattering assumption:

$$R_{12} = R_{21}$$

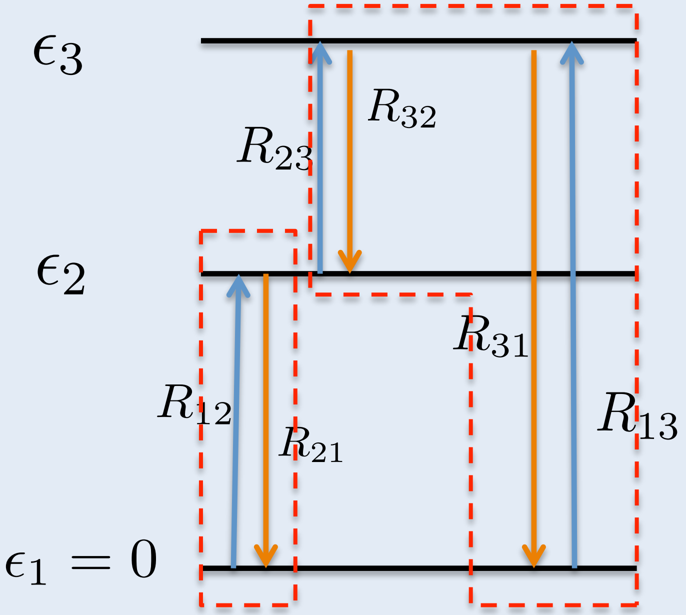
$$R_{23} = R_{32}$$

$$R_{13} = R_{31}$$

Advantages:
Very simple to implement in MCRT
Should be reasonable for many cases

Problem:
Neglects a lot of atomic physics!

Radiation-dominated example

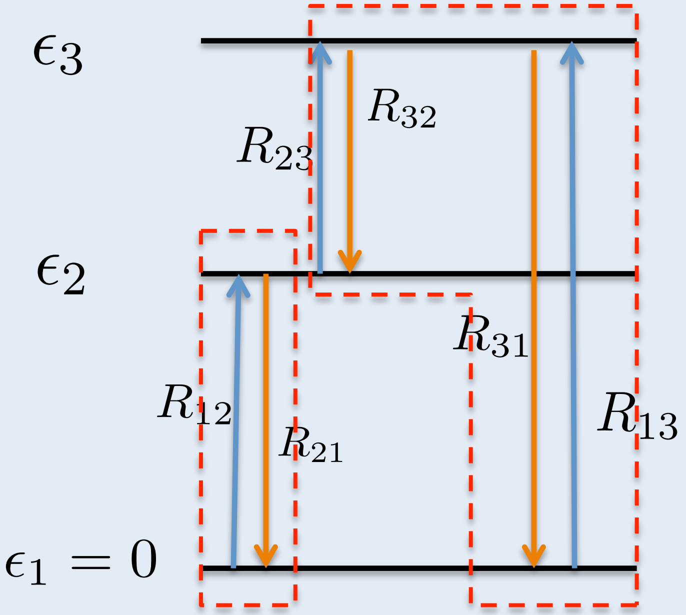


"Down-branching" approach:

Following excitation to an atomic level:

1. Randomly select a transition out of that level based on energy flow rates (Lucy 1999)
2. Emit an energy packet in that transition (energy equal to absorbed packet energy)

Radiation-dominated example



“Down-branching” approach:

E.g., following excitation to level 3, choose remission with

$$p_{31} = \frac{R_{31}\epsilon_3}{R_{31}\epsilon_3 + R_{32}(\epsilon_3 - \epsilon_2)}$$

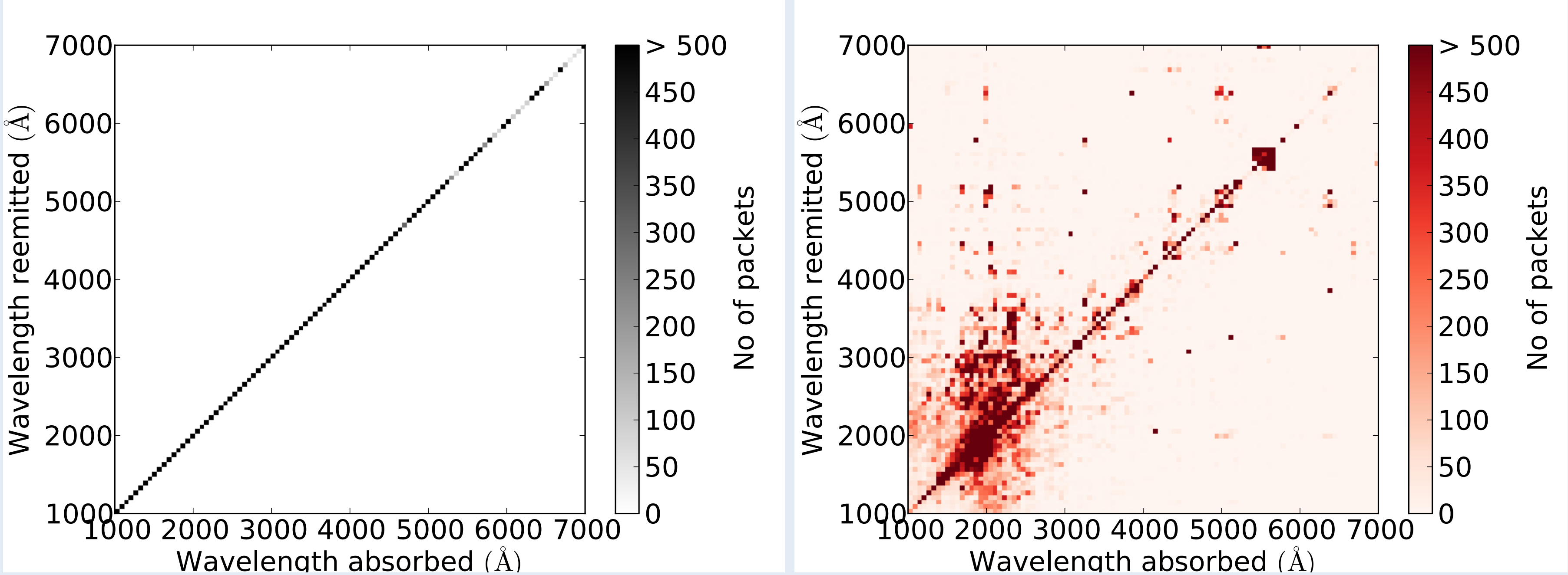
$$p_{32} = \frac{R_{32}(\epsilon_3 - \epsilon_2)}{R_{31}\epsilon_3 + R_{32}(\epsilon_3 - \epsilon_2)}$$

Advantages:
Only minor complication to MCRT
Major improvement for many cases

Problem:
Still neglects a lot of atomic physics!

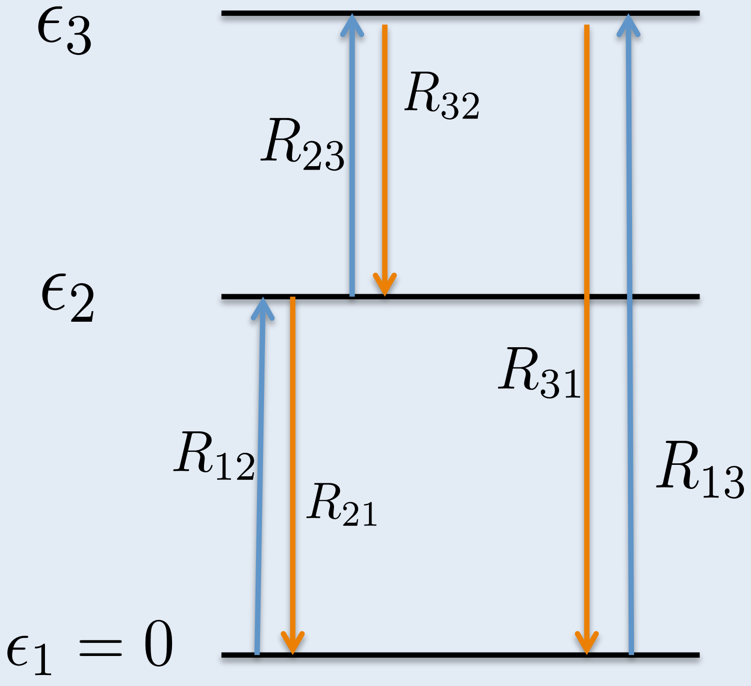
Radiation-dominated example

Kerzendorf & Sim (2014)



Resonance scattering v Downbranching

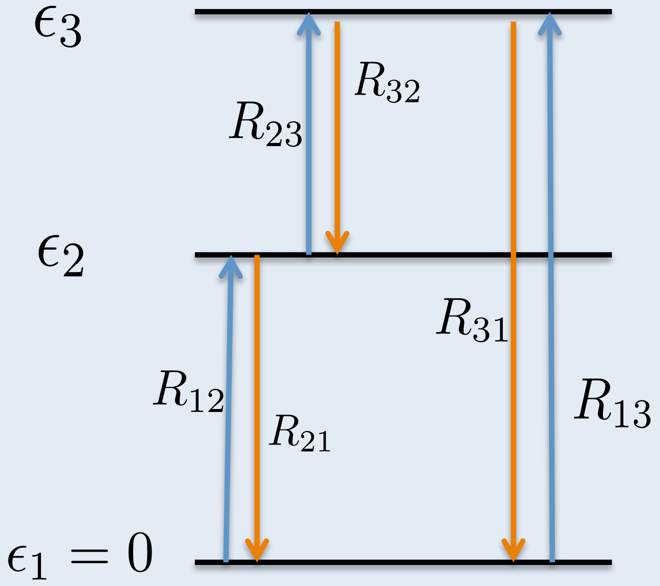
Radiation-dominated example



General solution can be found; e.g. via Lucy's "**Macro Atom**"

(see Lucy 2002)

Radiation-dominated example



Statistical equilibrium:

$$R_{13} + R_{23} - R_{31} - R_{32} = 0$$

$$R_{12} + R_{32} - R_{21} - R_{23} = 0$$

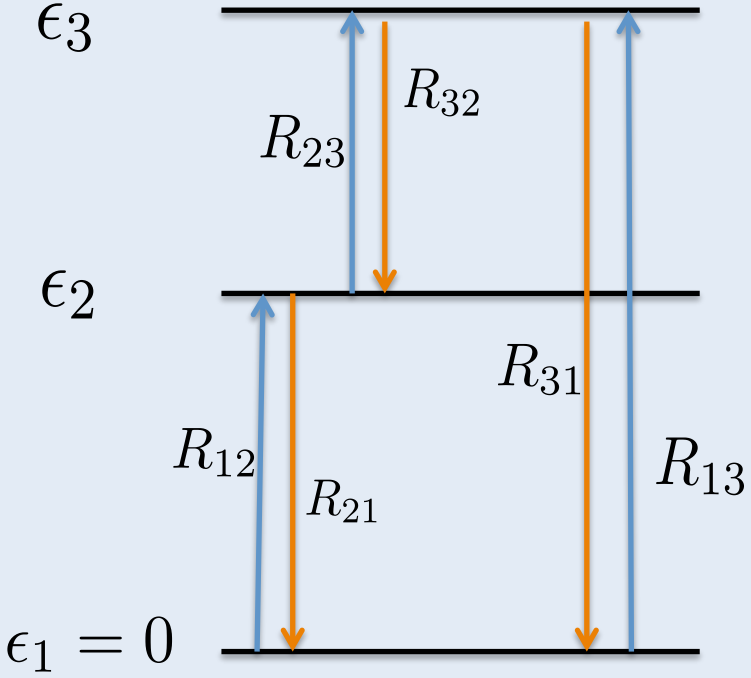
Energy “flow” rates:

$$\dot{A}_2 = R_{12}\epsilon_2 \qquad \dot{A}_3 = R_{13}\epsilon_3 + R_{23}(\epsilon_3 - \epsilon_2)$$

$$\dot{E}_2 = R_{21}\epsilon_2 \qquad \dot{E}_3 = R_{31}\epsilon_3 + R_{32}(\epsilon_3 - \epsilon_2)$$

(see Lucy 2002)

Radiation-dominated example



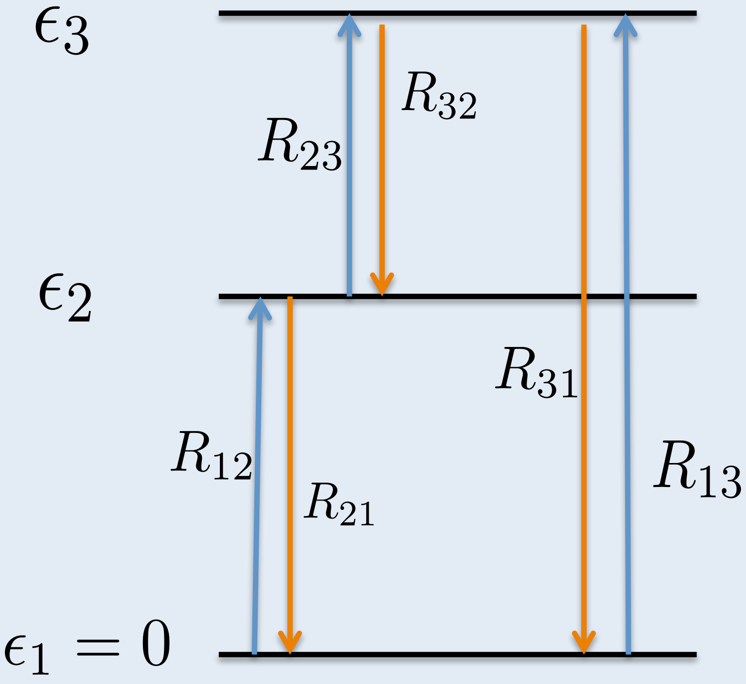
Algebra with rates and stat. eqm. from last slide:

$$\dot{A}_3 + R_{23}\epsilon_2 = \dot{E}_3 + R_{32}\epsilon_2$$

$$\dot{A}_2 + R_{32}\epsilon_2 = \dot{E}_2 + R_{23}\epsilon_2$$

Interpret as traffic flow problem: "Macro Atom" (see Lucy 2002)

Radiation-dominated example



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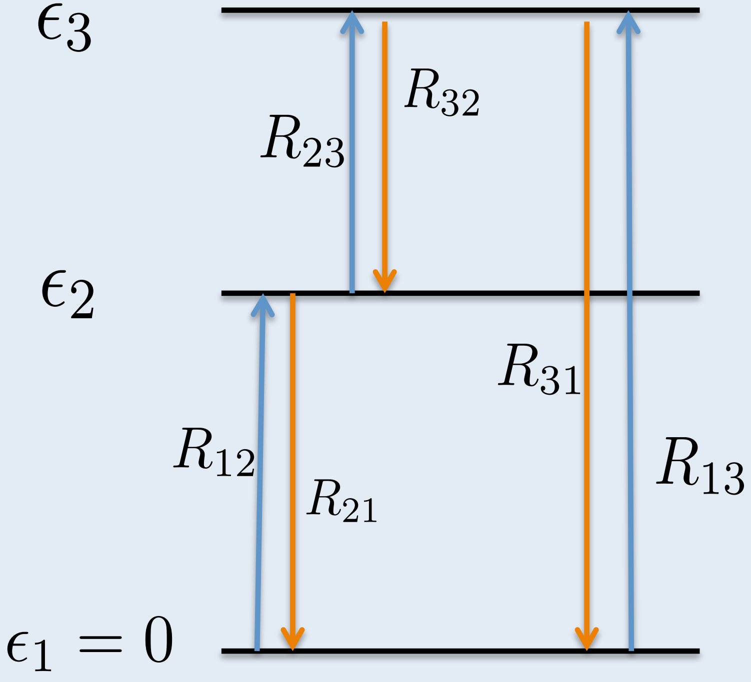
Interpret as traffic flow problem: "Macro Atom" (see Lucy 2002)

Absorption of radiation packets

Emission of packets

Radiation-dominated example



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Interpret as traffic flow problem: "Macro Atom" (see Lucy 2002)

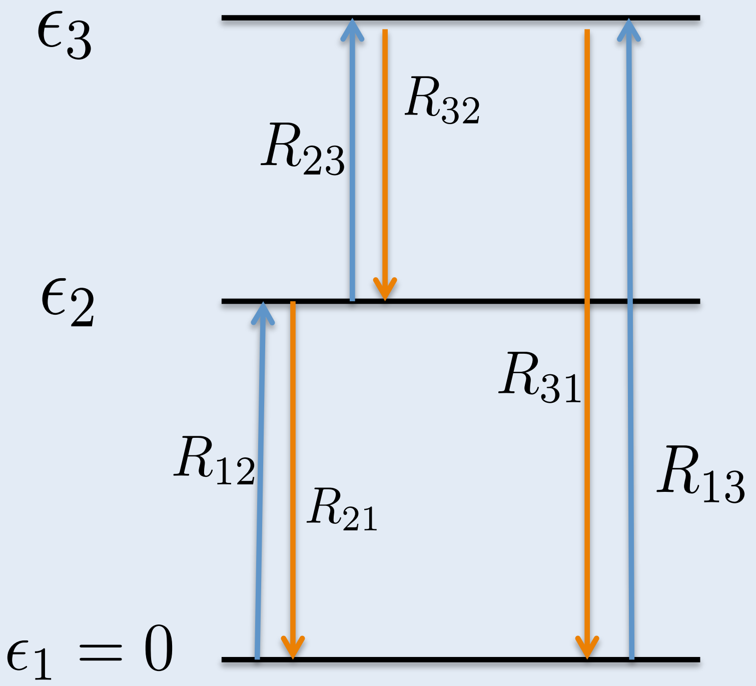
Absorption of radiation packets

Emission of packets

Internal macro atom (radiationless) transition out of level

Internal macro atom (radiationless) transition into level

Radiation-dominated example



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$$\dot{A}_3 + R_{23}\epsilon_2 = \dot{E}_3 + R_{32}\epsilon_2$$

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Interpret as traffic flow problem:
"Macro Atom" (see Lucy 2002)

Algorithm:

1. Following activation of some state, select either an emission or internal transition (probabilities proportion to terms above)

2a. If select emission emit a photon (as in "down-branch" scheme)

2b. If select an internal transition, change the macro atom state and GOTO 1

Radiation-dominated example

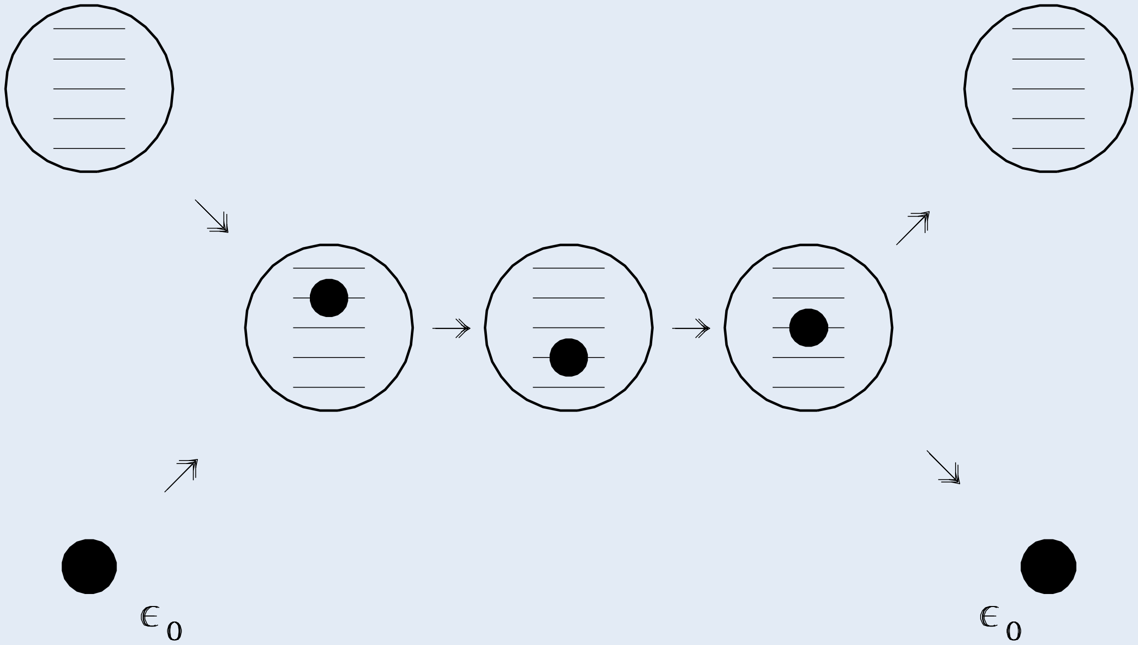
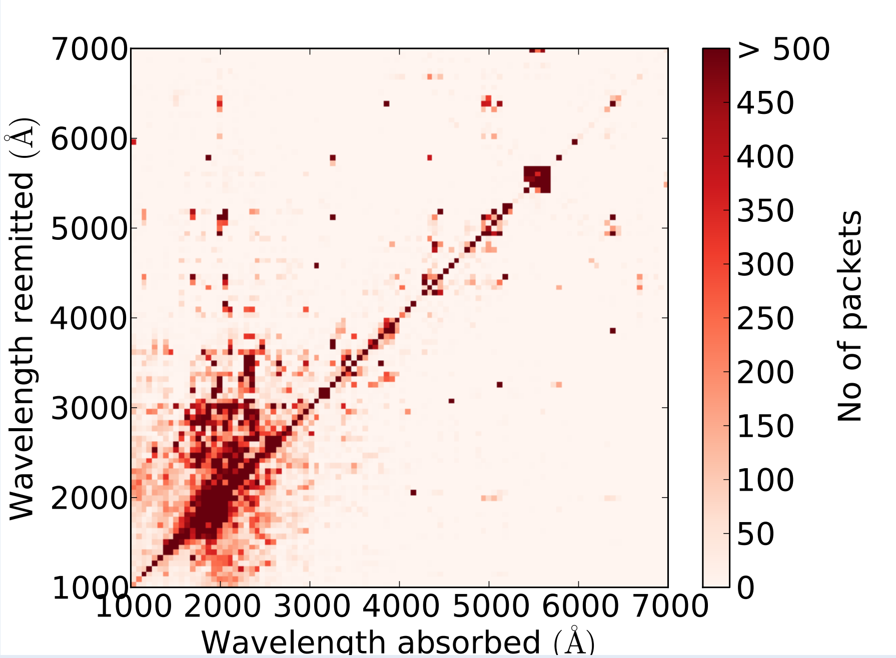


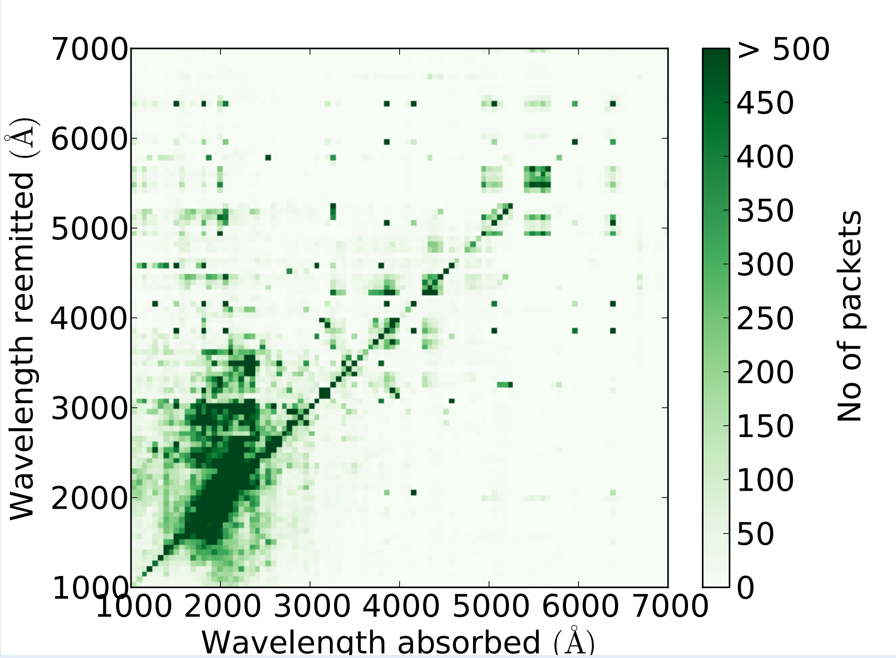
Fig. 1. Schematic representation of the interaction of a macro-atom with a packet of energy ϵ_0. The macro atom is activated by absorbing the energy packet, makes two internal transitions, and then de-activates by emitting a packet of energy ϵ_0.

Lucy 2002

Radiation-dominated example

Kerzendorf & Sim (2014)





Downbranch v Macro Atom

Radiation-dominated example

Radiation energy pool

Absorption and emission events

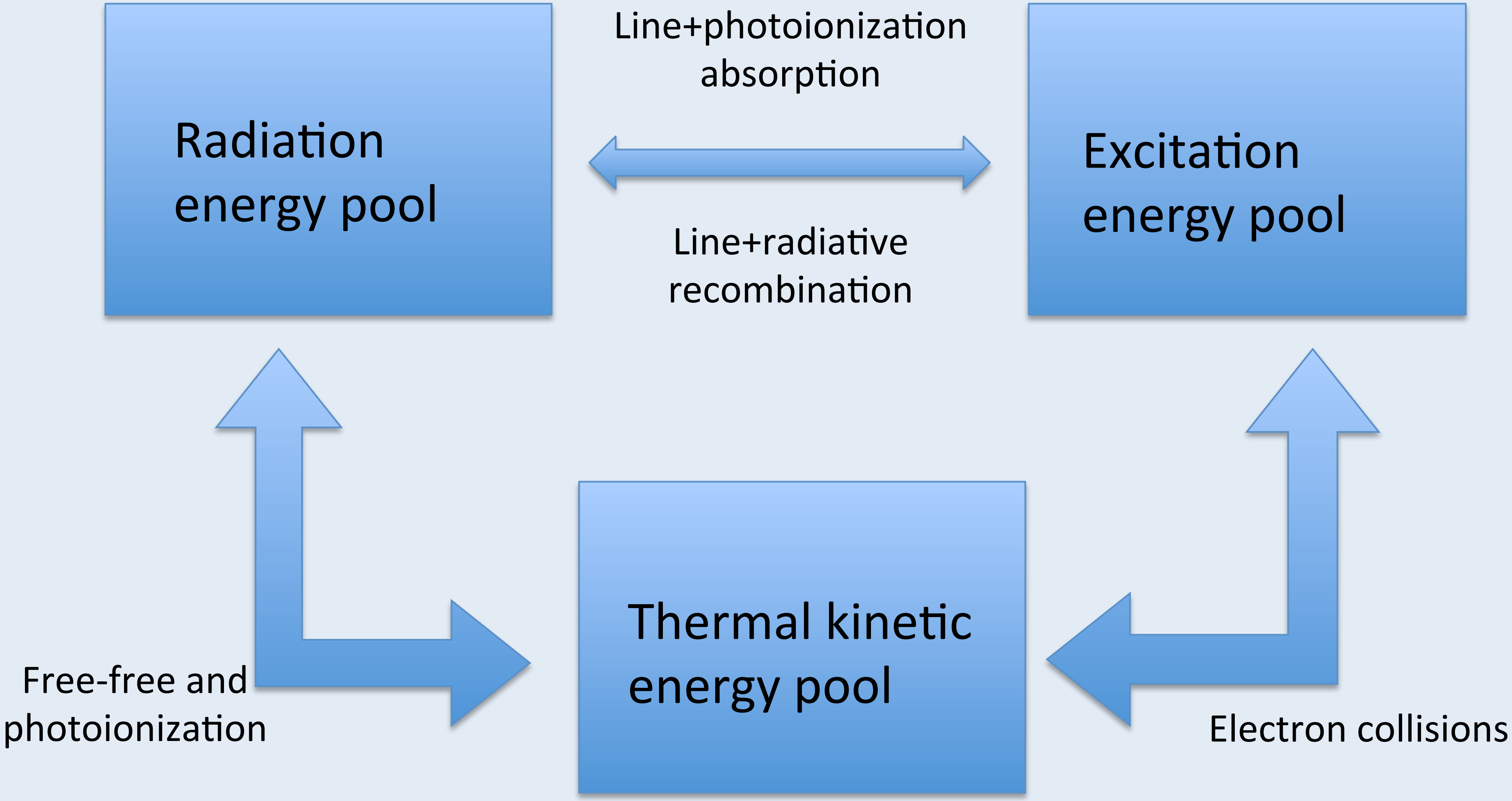
Excitation energy pool

Governed by radiative packet transport algorithm

Governed by macro atom internal transition rules

Generalization (Lucy 2003)

For full solution in radiative and thermal equilibrium can extend to include third energy pool:
(for SNe implementation e.g. Kromer & Sim 2009)



Radiation energy pool

Line+photoionization absorption

Line+radiative recombination

Excitation energy pool

Free-free and photoionization

Thermal kinetic energy pool

Electron collisions

Macro Atom implementation

- Use Macro Atom implementation in our ARTIS supernova code (Kromer & Sim 2009)
- Also implemented now in non-homologous flow codes, both Python (Long & Knigge 2002) and Sim et al. (2008,2010)
- Available as an mode in publicly available TARDIS code (extensions planned)

Lines in radiation hydrodynamics

Lines in radiation hydrodynamics

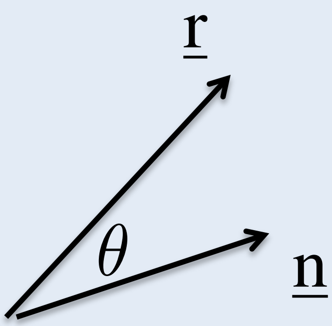
$$\rho \frac{\mathrm{D}}{\mathrm{D}t} u + \frac{\mathrm{d}}{\mathrm{d}r} P = \rho g + \enclose{circle}{G^1}$$

Momentum
transferred from
radiation field

Lines in radiation hydrodynamics

$$\rho \frac{\mathrm{D}}{\mathrm{D}t} u + \frac{\mathrm{d}}{\mathrm{d}r} P = \rho g + \boxed{G^1}$$

Momentum transferred from radiation field



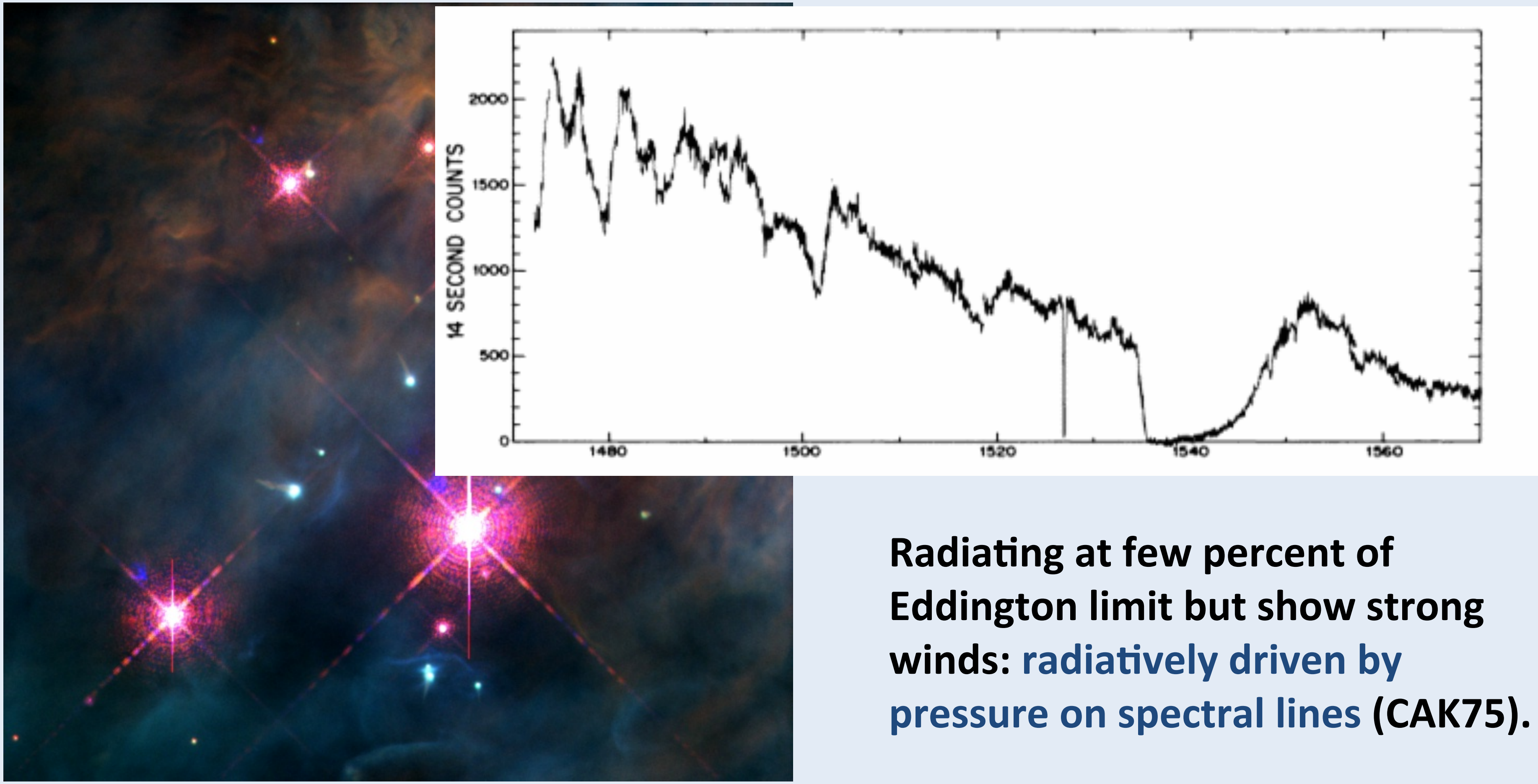
$$G^1 = \frac{2\pi}{c} \int_0^\infty \mathrm{d}\nu \int_{-1}^{1} \mathrm{d}\mu (\chi I - \eta) \mu .$$

For hot, ionized media, the radiation force can be dominated by bound-bound transitions (resonant cross-sections high)

Astrophysical line driving: OB stars

Radiating at few percent of Eddington limit but show strong winds: radiatively driven by pressure on spectral lines (CAK75).

Astrophysical line driving: OB stars



Radiating at few percent of Eddington limit but show strong winds: radiatively driven by pressure on spectral lines (CAK75).

CAK approximation

(Castor, Abbott & Klein 1975)

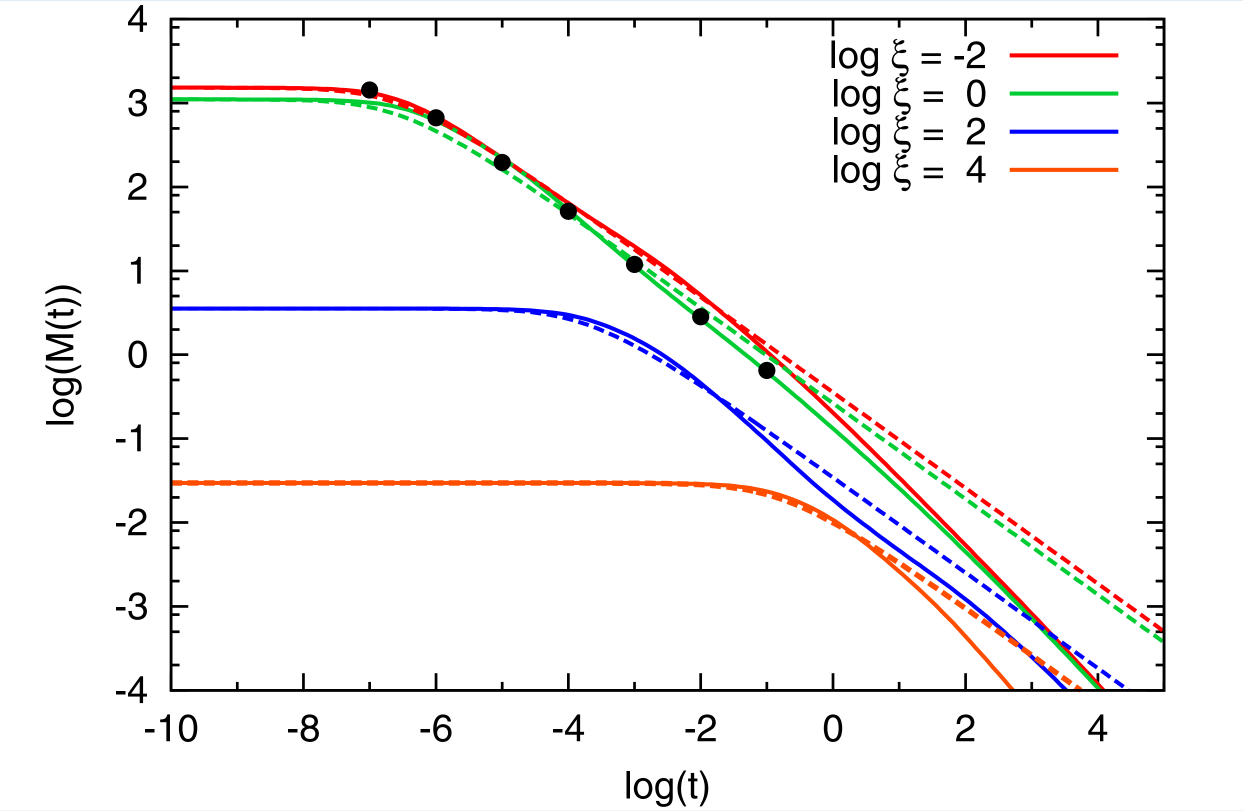
Description of the radiation force due to attenuated continuum:

$$f_{\mathrm{rad}} = \frac{\sigma_{\mathrm{e}} F}{c} M(t) \qquad t = \sigma_{\mathrm{e}} \rho v_{\mathrm{th}} \left(\frac{dv}{dr} \right)^{-1}$$

“Force multiplier”

CAK approximation

(Castor, Abbott & Klein 1975)



(from Parkin & Sim 2013)

CAK approximation

(Castor, Abbott & Klein 1975)

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"Force multiplier"

Widely used and powerful – but neglects multiple scattering, attenuation…

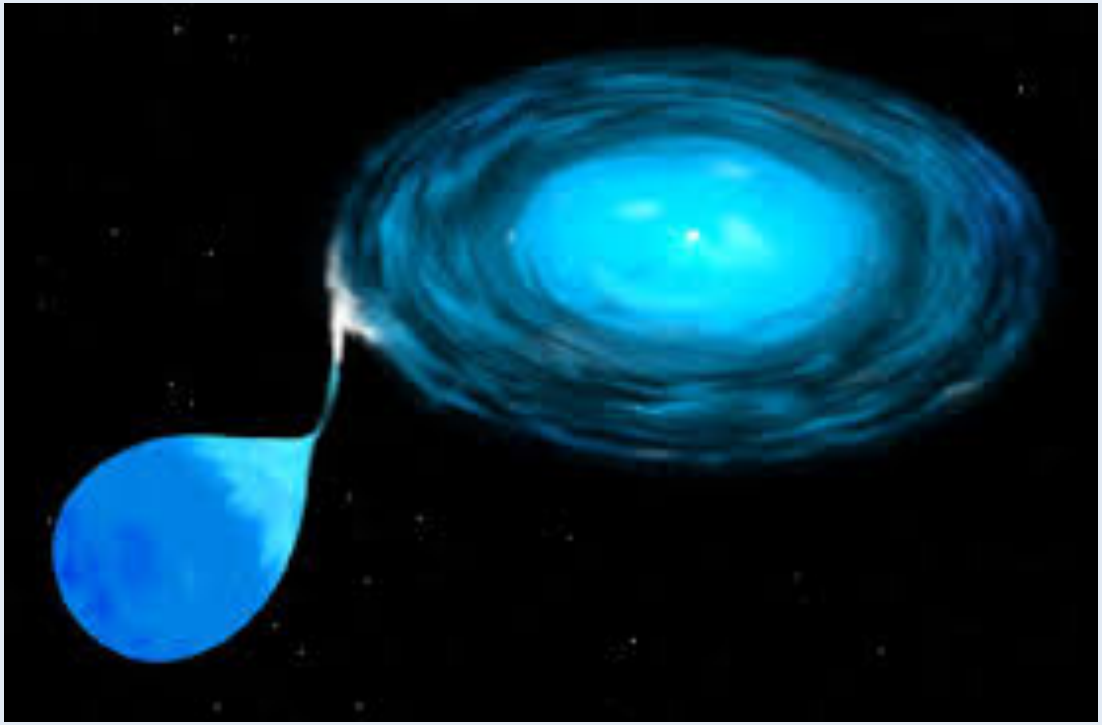
Astrophysical line driving: OB stars

Also long history of successful use of MCRT to study mass-loss from hot stars:

Abbott & Lucy (1985);
Lucy & Abbott (1993)

Vink et al. (1999, 2000, 2001) mass-loss “recipes”

Astrophysical line driving: CV disk winds



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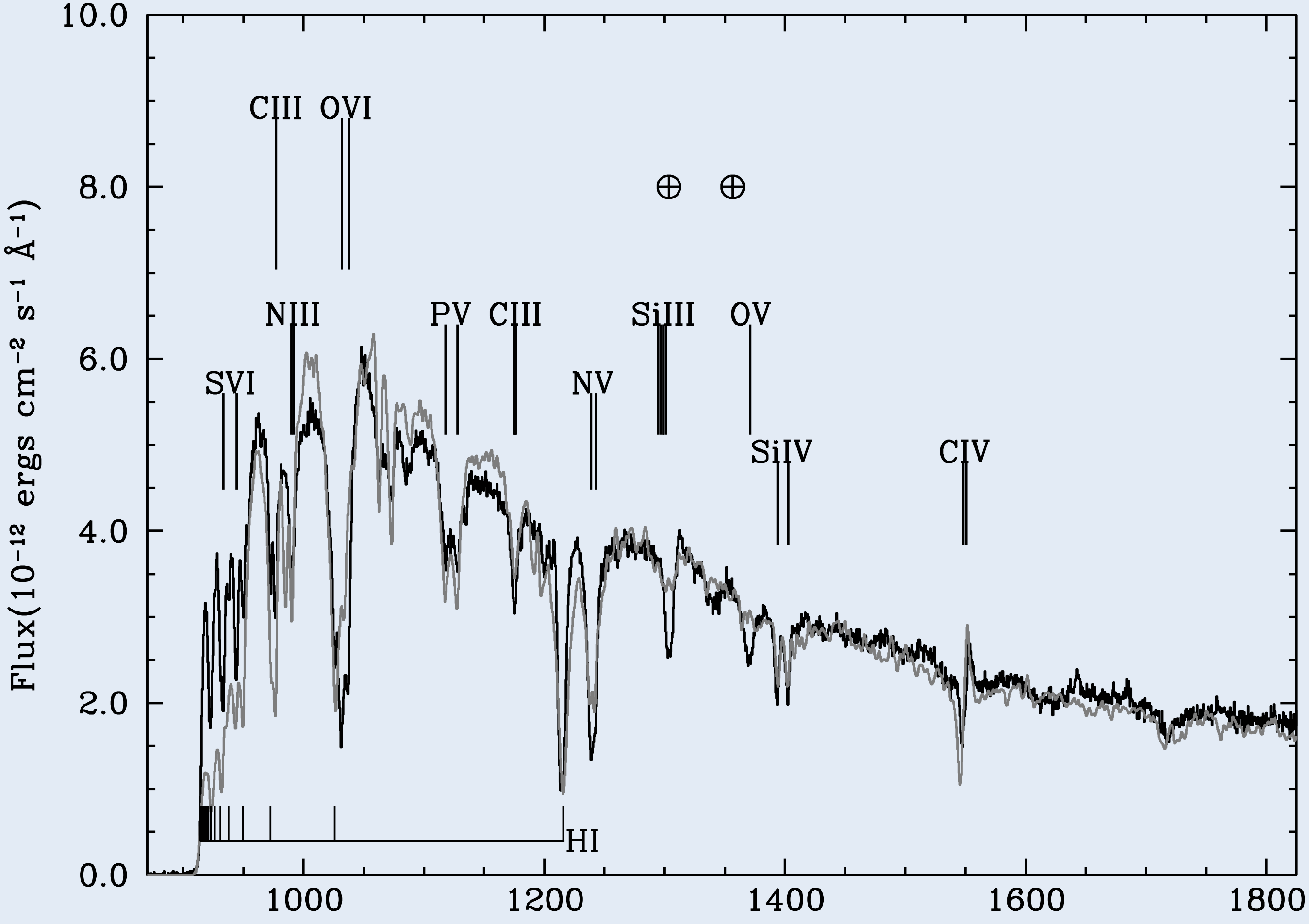
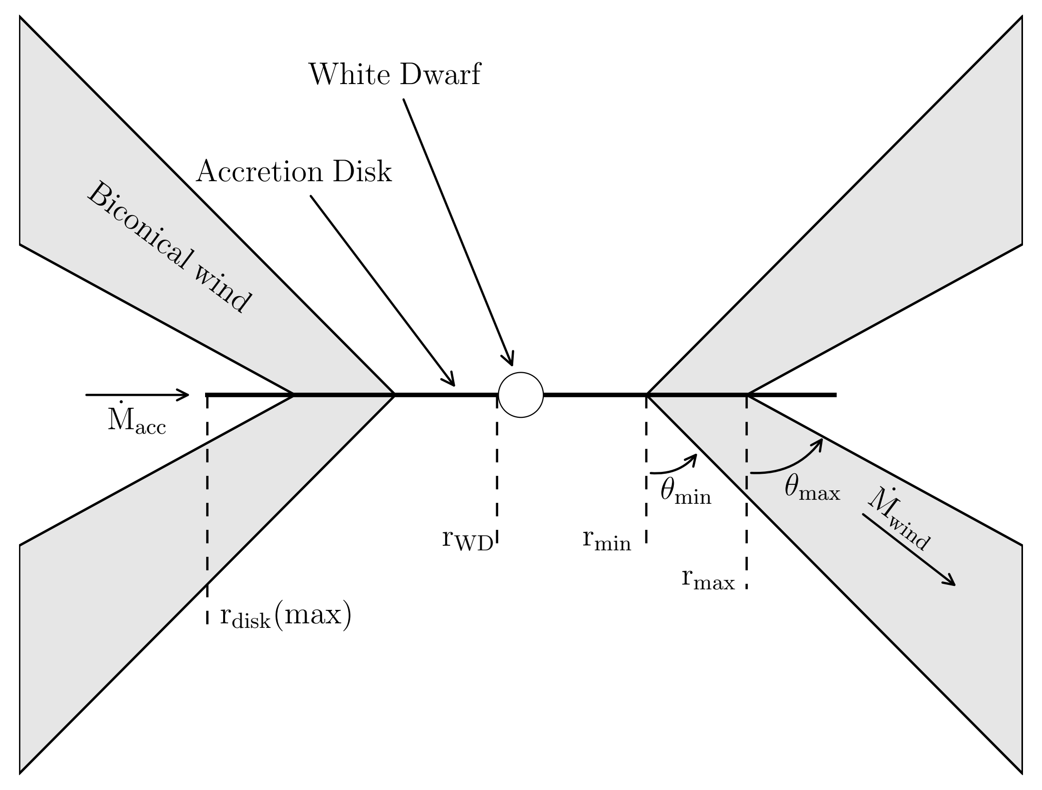


(Monte Carlo RT calculation for CV disk wind from Long & Knigge 2002)

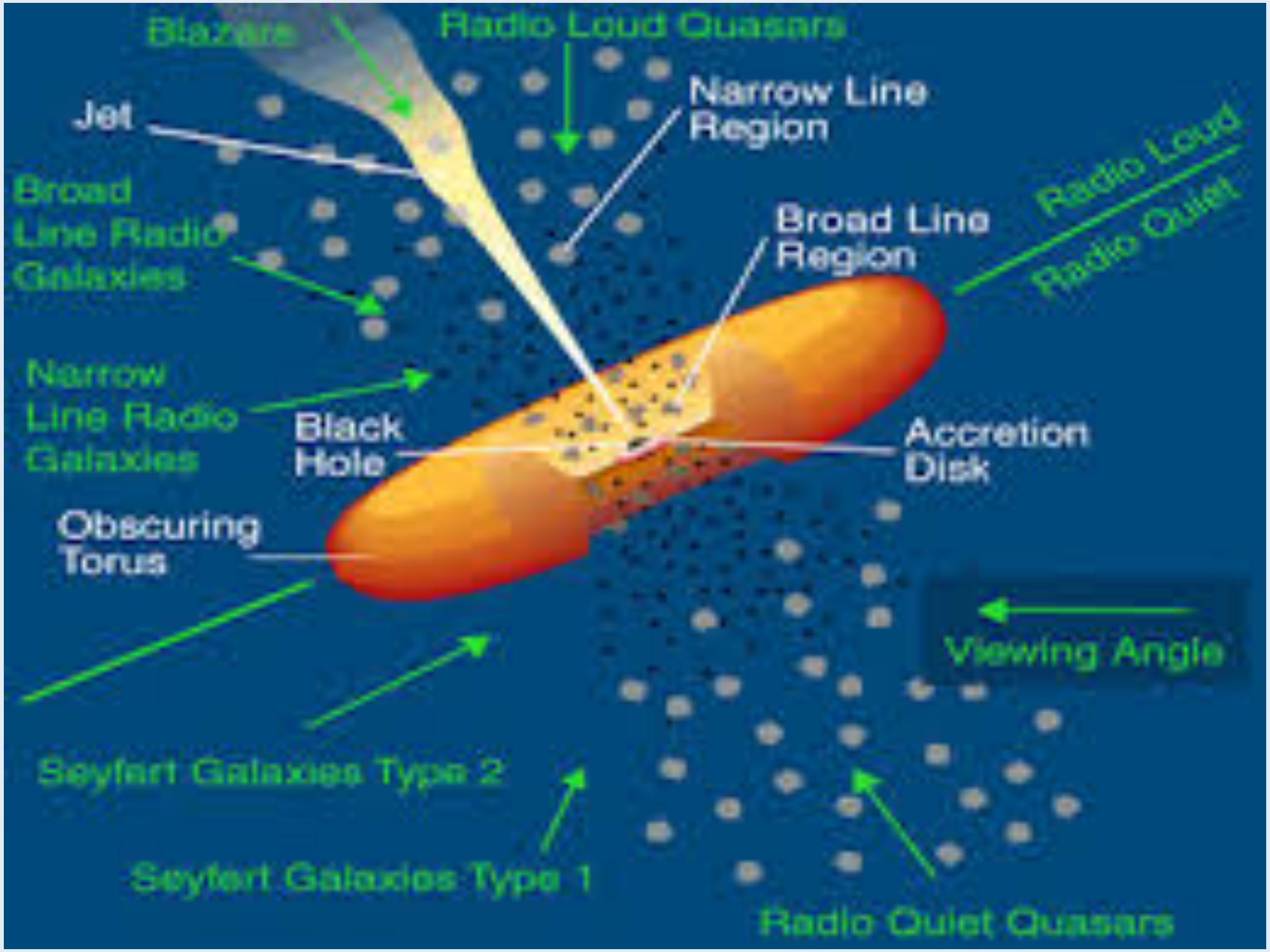
Astrophysical line driving: CV disk winds



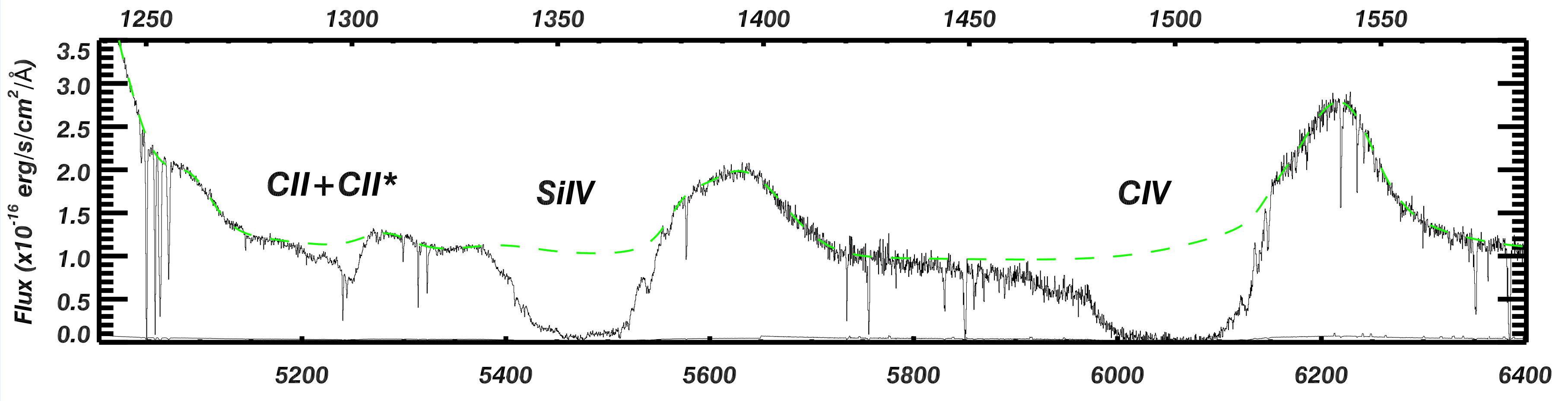
(Figure from Matthews et al. 2015)

UV bright accretion disk – similar physics to hot star?

Astrophysical line driving: AGN disk winds

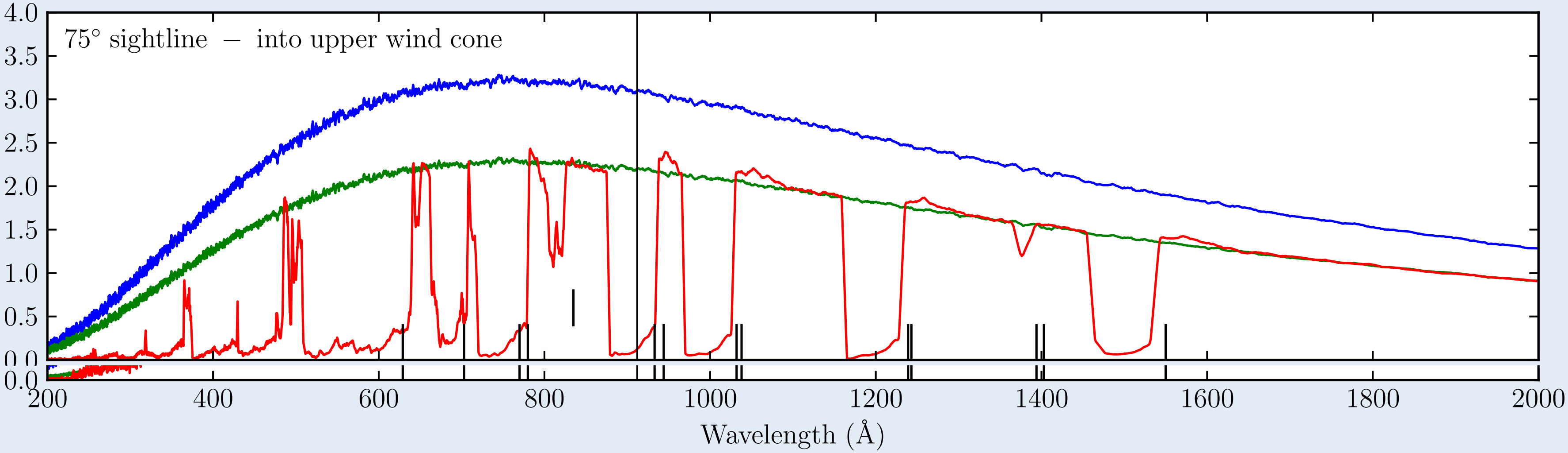


Astrophysical line driving: AGN disk winds



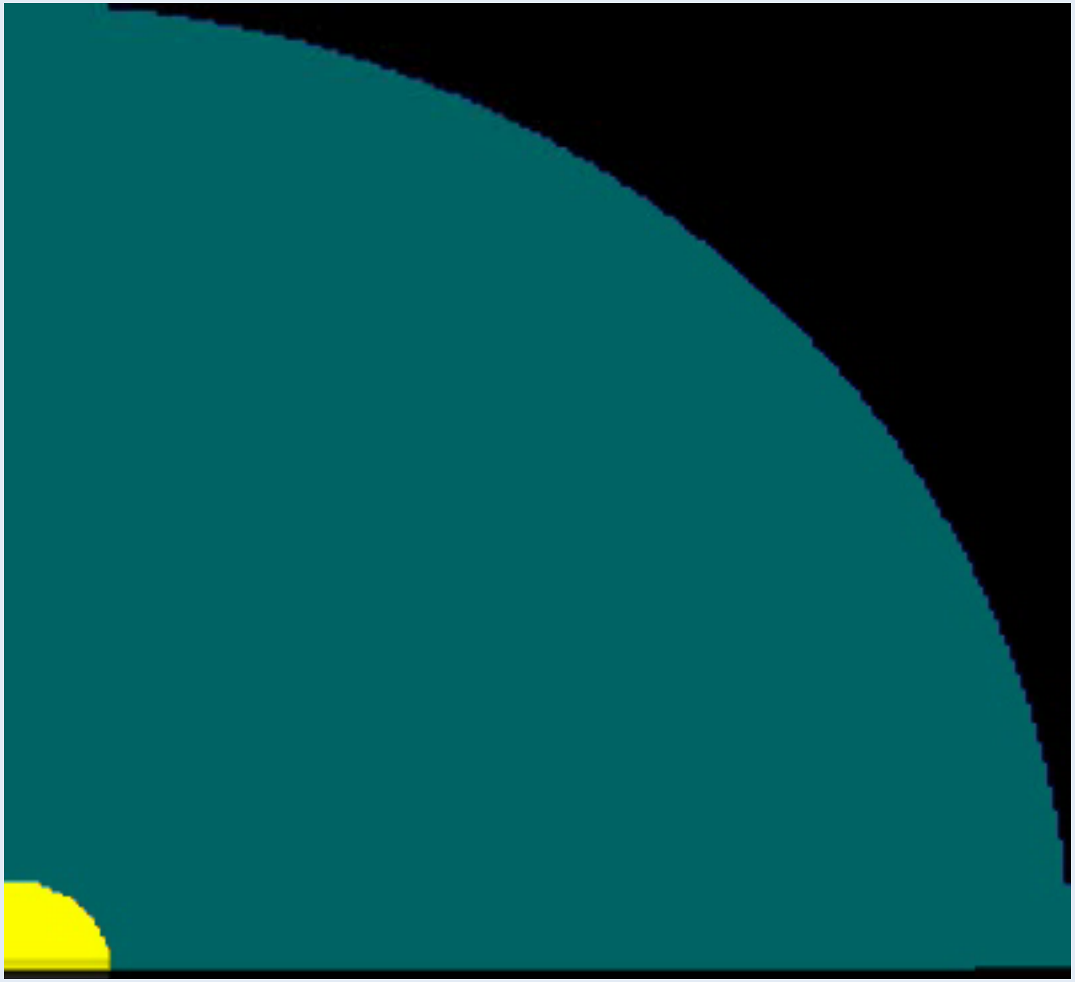
(X-shooter spectrum of BAL QSO from Borguet et al. 2012)

Astrophysical line driving: AGN disk winds



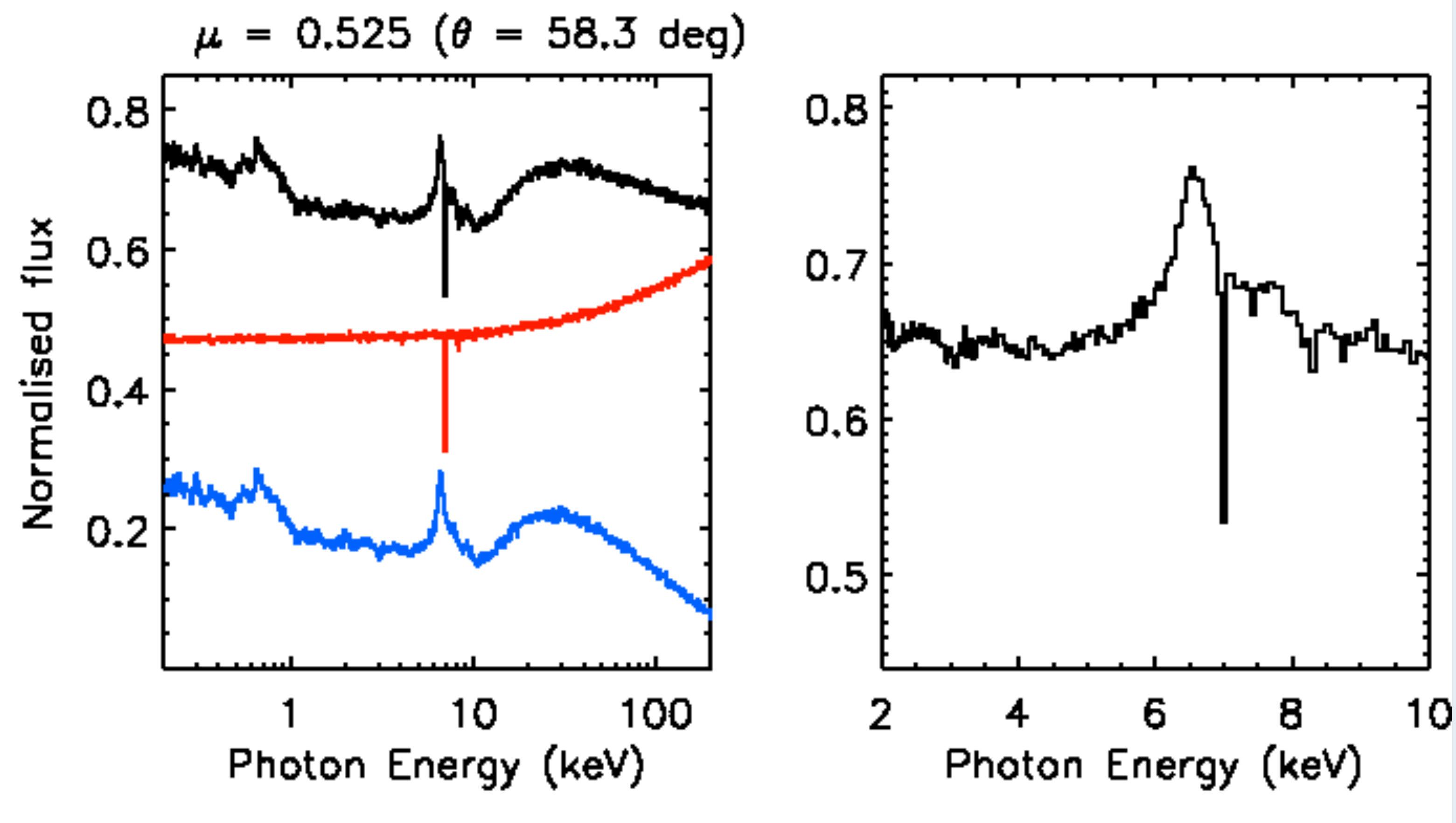
(from Higginbottom et al. 2013)

Astrophysical line driving: hydro simulation



(from Proga & Kallman 2004)

Astrophysical line driving: hydro simulation + post-processing



(from Sim et al. 2010)

Astrophysical line driving: simple MC algorithm

From a MC simulation of radiation in expanding media, want to record the momentum transfer rate on a computational grid.

Astrophysical line driving: simple MC algorithm

From a MC simulation of radiation in expanding media, want to record the momentum transfer rate on a computational grid.

Challenges to consider:

(1) Recall from last time, in expanding (1D) medium

$$\frac{\mathrm{d}\nu_{ff}}{\mathrm{d}s} = -\frac{\nu_{obs}}{c}\left(\frac{v(r)}{r}(1-\mu_{obs}^2) + \mu_{obs}^2\frac{\mathrm{d}v(r)}{\mathrm{d}r}\right)$$

… makes it hard to work directly with an estimator such as (see Tim Harries's talk):

$$\underline{\mathrm{F}}_{\mathrm{rad}} = \frac{1}{Vc\Delta T}\sum l\epsilon\kappa_{\nu}\underline{\mathrm{u}}$$

Astrophysical line driving: simple MC algorithm

From a MC simulation of radiation in expanding media, want to record the momentum transfer rate on a computational grid.

Challenges to consider:

(2) Known (previous work on winds) that many weak lines matter, thus as not good to work directly with

$$\Delta \underline{\mathrm{p}}_{\mathrm{cell}} = \sum \underline{\mathrm{p}}_{\mathrm{packet,in}} - \sum \underline{\mathrm{p}}_{\mathrm{packet,out}}$$

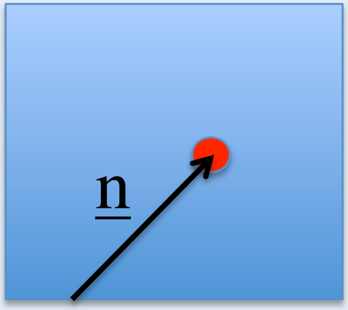
…as Tim explained, that doesn’t work well in optically thin limit

Astrophysical line driving: simple MC algorithm

From a MC simulation of radiation in expanding media, want to record the momentum transfer rate on a computational grid.

Simple alternative:

First consider momentum transferred in pure line absorption:



$$\Delta \underline{p} = \frac{\epsilon_b}{c}\underline{n}$$

● = Sobolev point

Astrophysical line driving: simple MC algorithm

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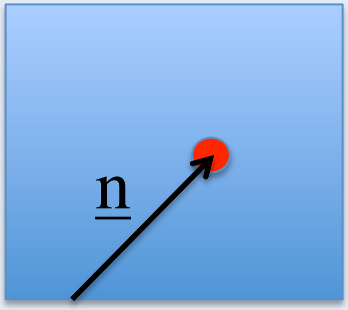

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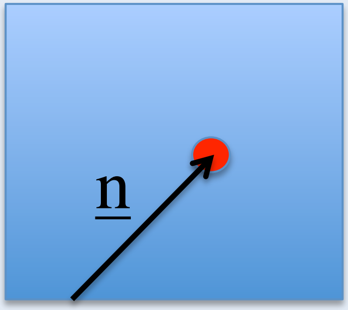

$$\Delta \underline{\mathrm{p}}_{\mathrm{cell}} = \sum_{\mathrm{events-in-cell}} \frac{\epsilon_b}{c} \underline{\mathrm{n}}$$

● = Sobolev point

Great if this is common…

Astrophysical line driving: simple MC algorithm

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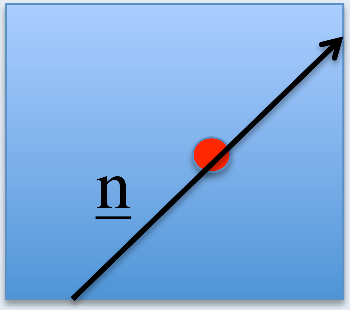


$$\Delta \underline{\mathrm{p}}_{\mathrm{cell}} = \sum_{\mathrm{events-in-cell}} \frac{\epsilon_b}{c} \underline{\mathrm{n}}$$

● = Sobolev point

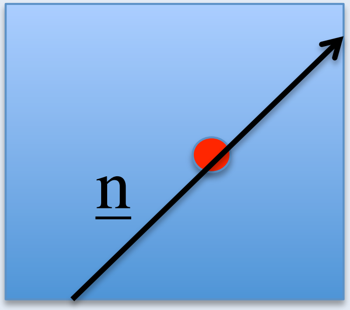
But not if this is!

Astrophysical line driving: simple MC algorithm

From a MC simulation of radiation in expanding media, want to record the momentum transfer rate on a computational grid.

<u>Simple alternative</u>:

First consider momentum transferred in pure line absorption:



$$\Delta \underline{p}_{\rm cell} = \sum_{\rm resonances-in-cell} \frac{\epsilon_b}{c}(1-e^{-\tau_s})\underline{n}$$

● = Sobolev point

Easily fixed (similar to Lucy 1999)

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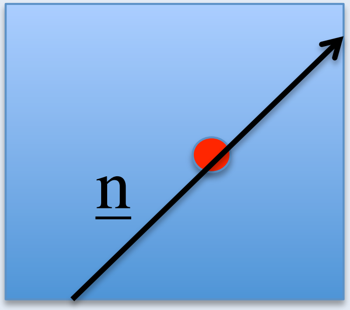

1D spherical grid:

$$\Delta p_{\mathrm{cell}} = \sum_{\mathrm{resonances-in-cell}} \frac{\epsilon_b}{c}(1 - e^{-\tau_s})\mu_b$$

● = Sobolev point

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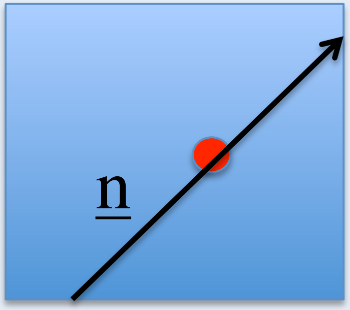
Simple alternative:

Also include re-emission:



$$\Delta p = \frac{\varepsilon^b}{c}\left[\mu^b - \gamma^2(\mu_0^a + \beta)(1 - \beta\mu^b)\right]$$

Noebauer & Sim (2015)

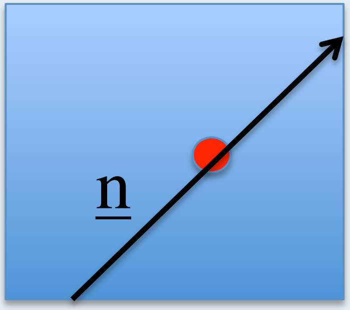
● = Sobolev point

Astrophysical line driving: simple MC algorithm

From a MC simulation of radiation in expanding media, want to record the momentum transfer rate on a computational grid.

Simple alternative:

Also include re-emission: leads to estimator for the momentum term



$$G^1_{\rm line} = \frac{1}{\Delta V c \Delta t} \sum (1 - e^{-\tau_s}) \varepsilon (\mu - \beta)$$

Noebauer & Sim (2015)

● = Sobolev point

Astrophysical line driving: simple MC algorithm

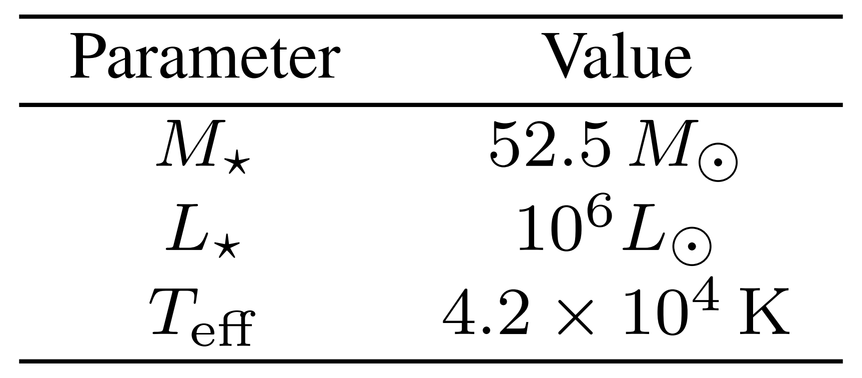
Implemented in 1D (Noebauer & Sim 2015):

- Finite-volume PPM hydro scheme
- Operator splitting
- Isothermal

Used simplified stellar winds to investigate value of this approach

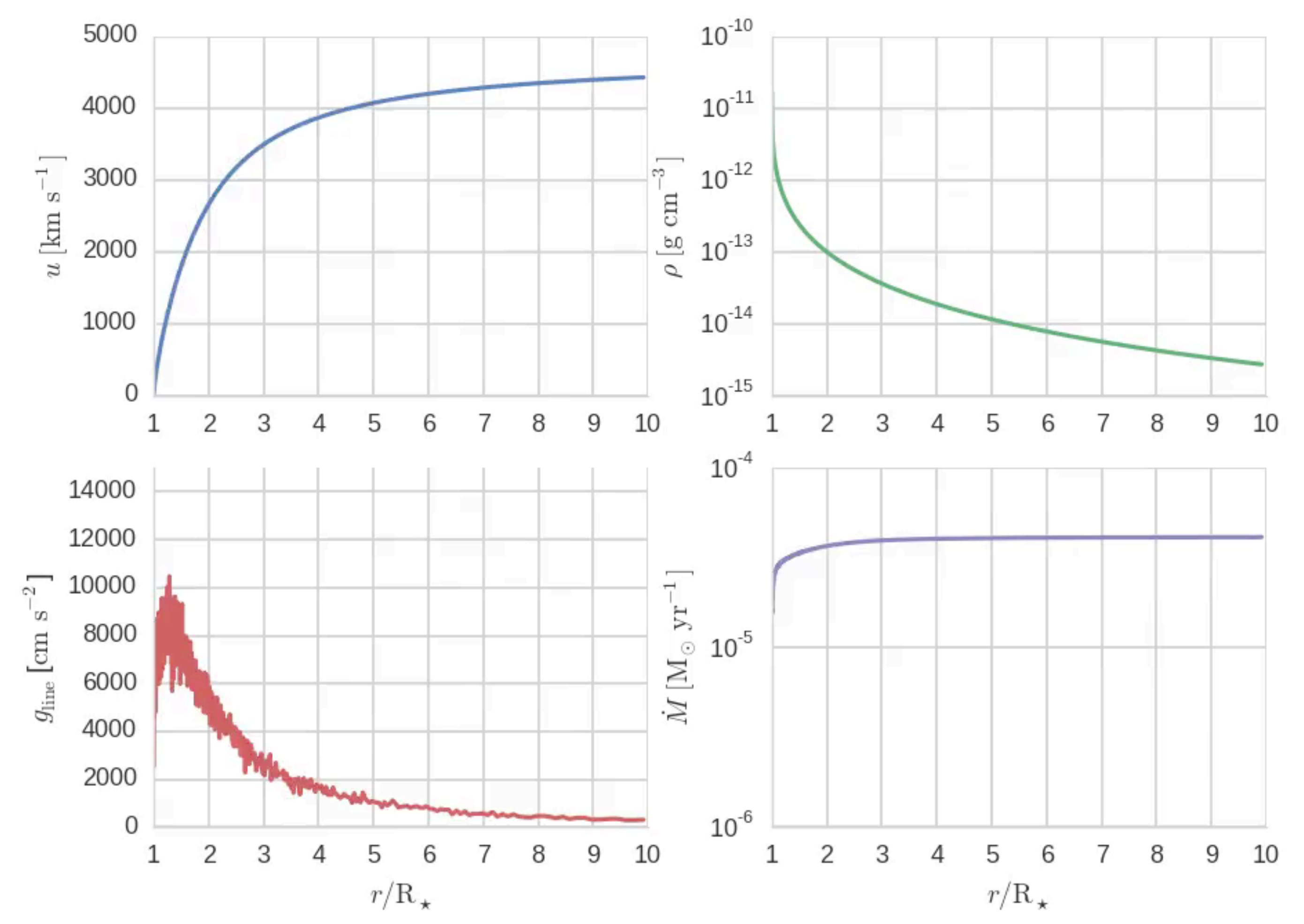
Astrophysical line driving: simple MC algorithm

Example:



Parameter	Value
$M_\star$	$52.5\,M_\odot$
$L_\star$	$10^6\,L_\odot$
$T_{\rm eff}$	4.2×10^4 K

Toy hot star wind simulation

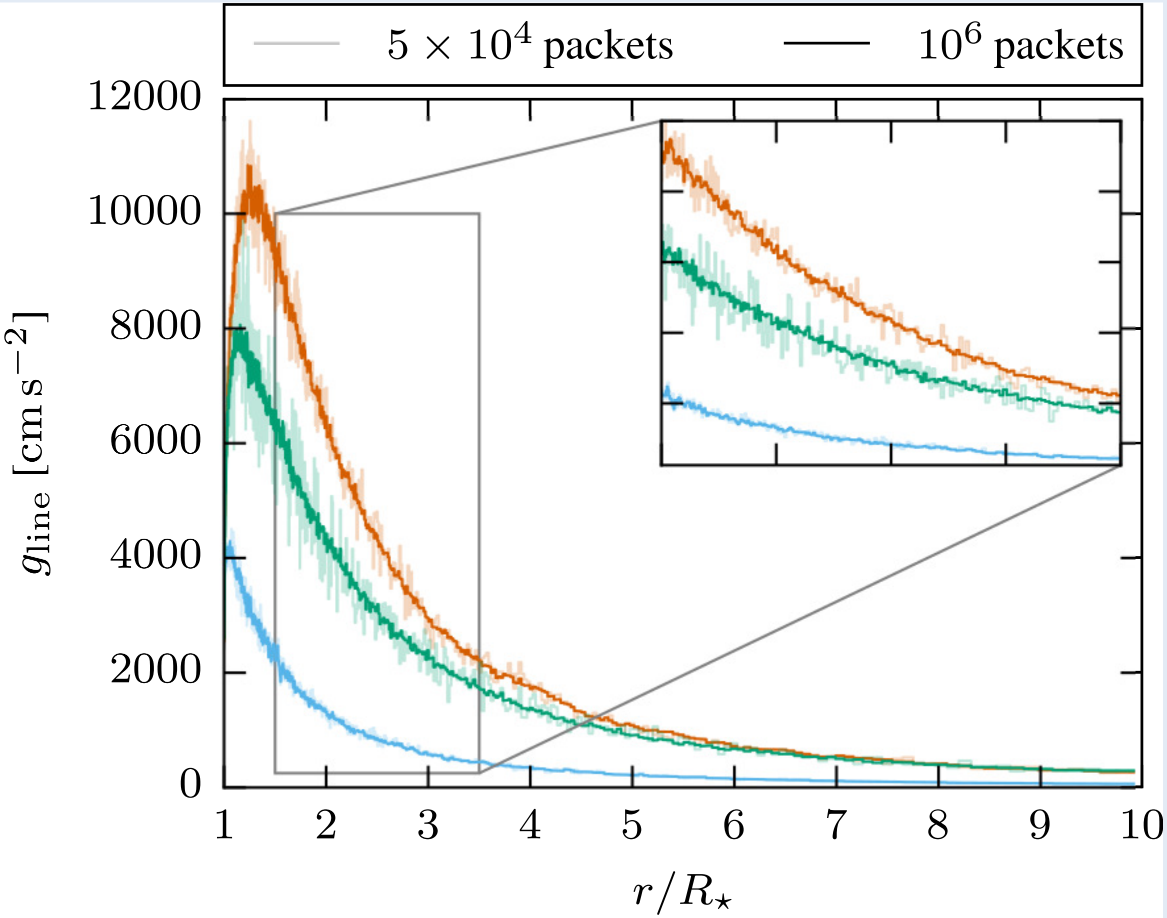


(simulation from Noebauer & Sim 2015)

Toy hot star wind simulation

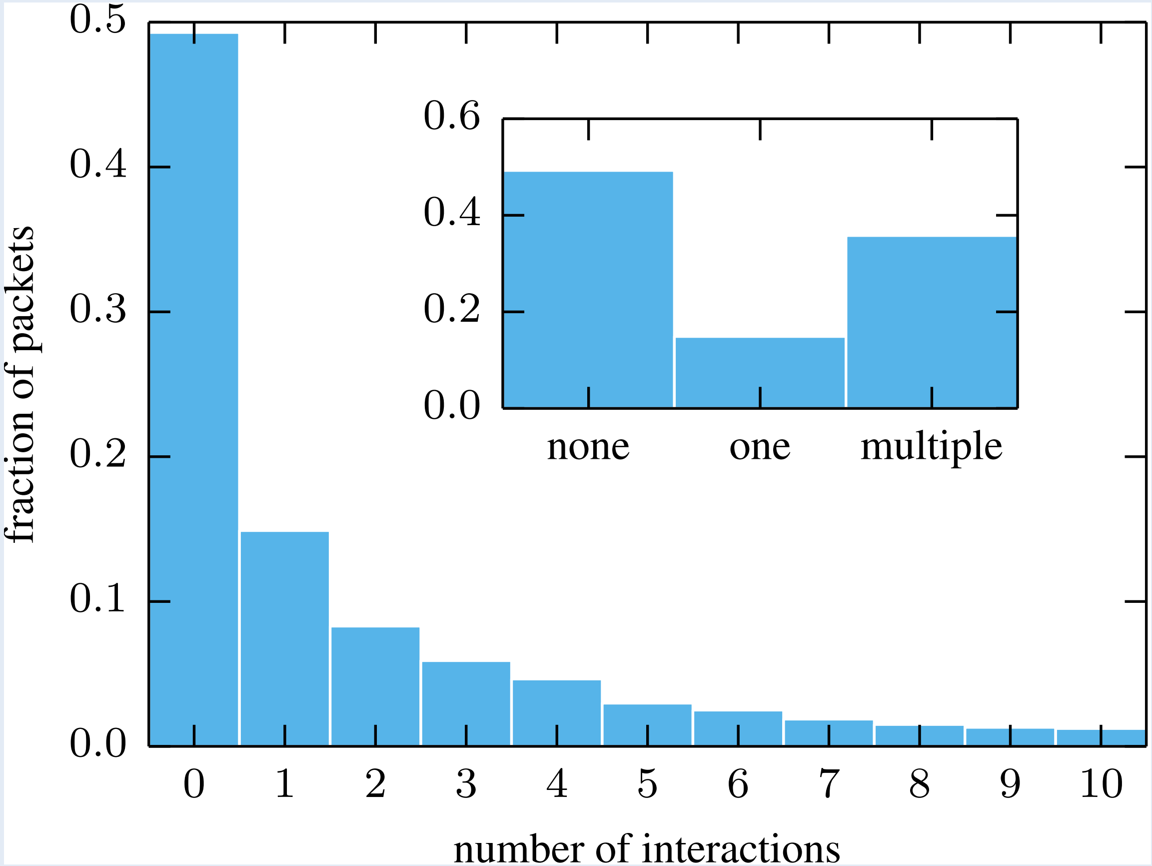
Appears to work quite well:

- noise is present (spurious fluctuations)
- but finds steady state



Toy hot star wind simulation

Lots of nice extra information from this sort of simulation:



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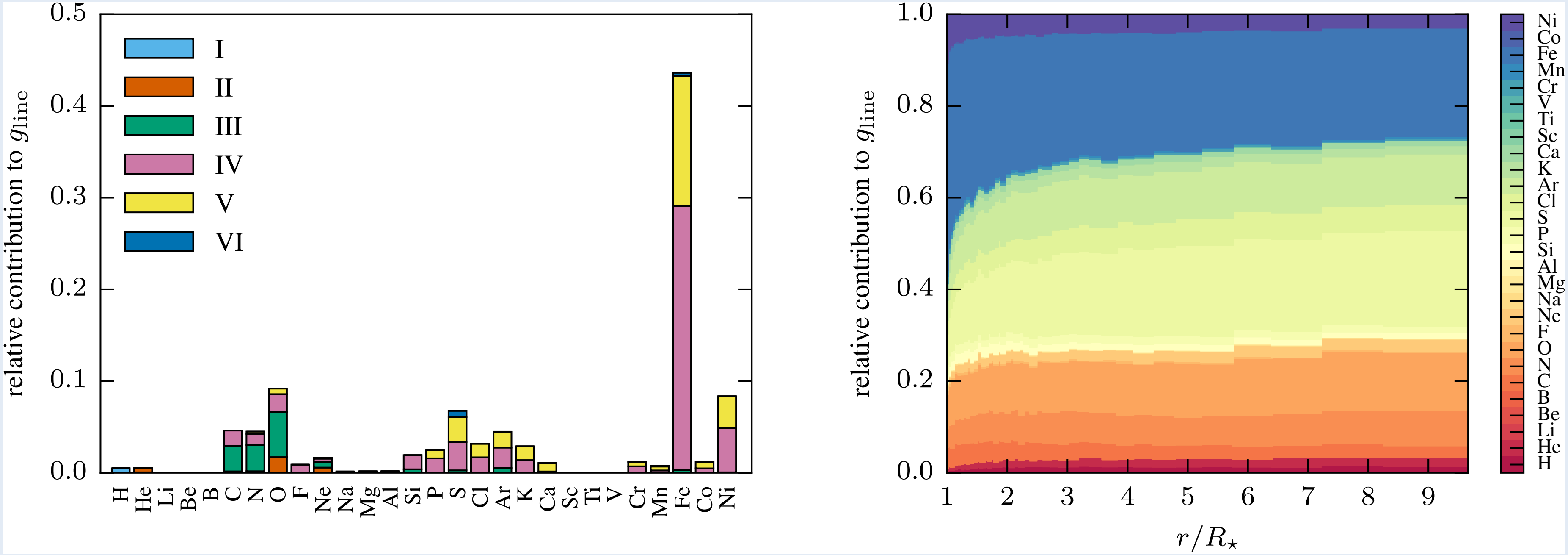
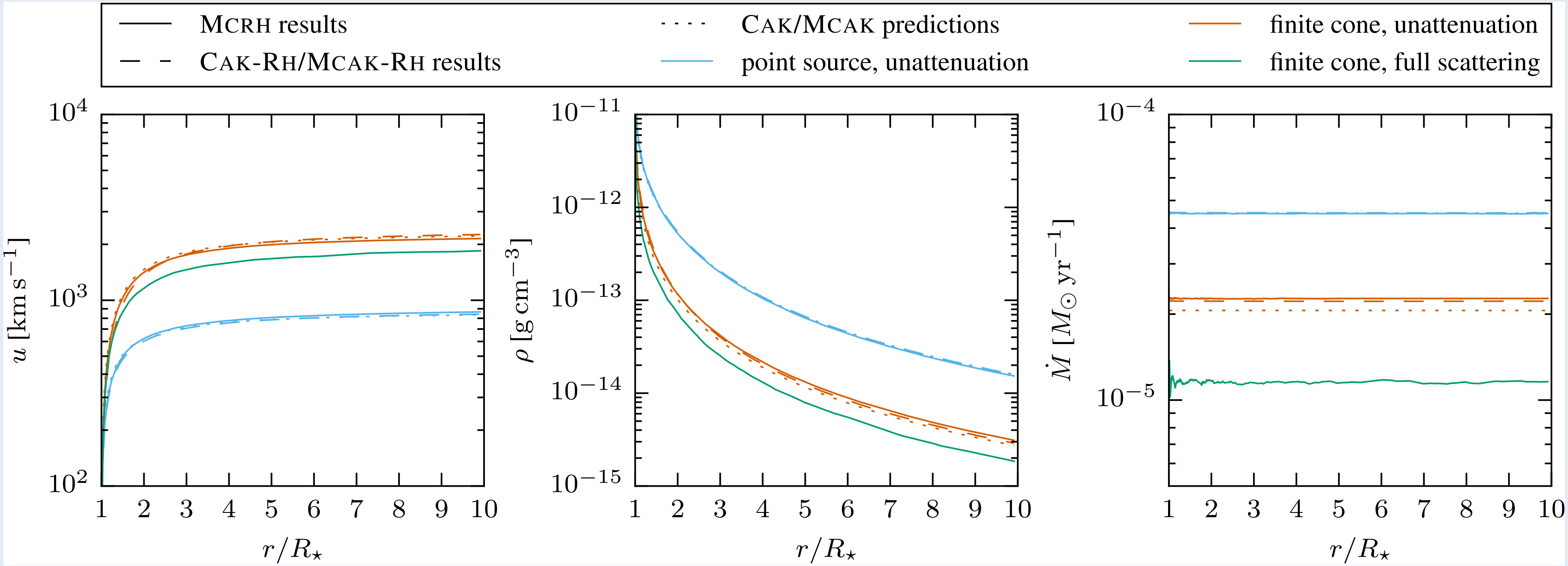


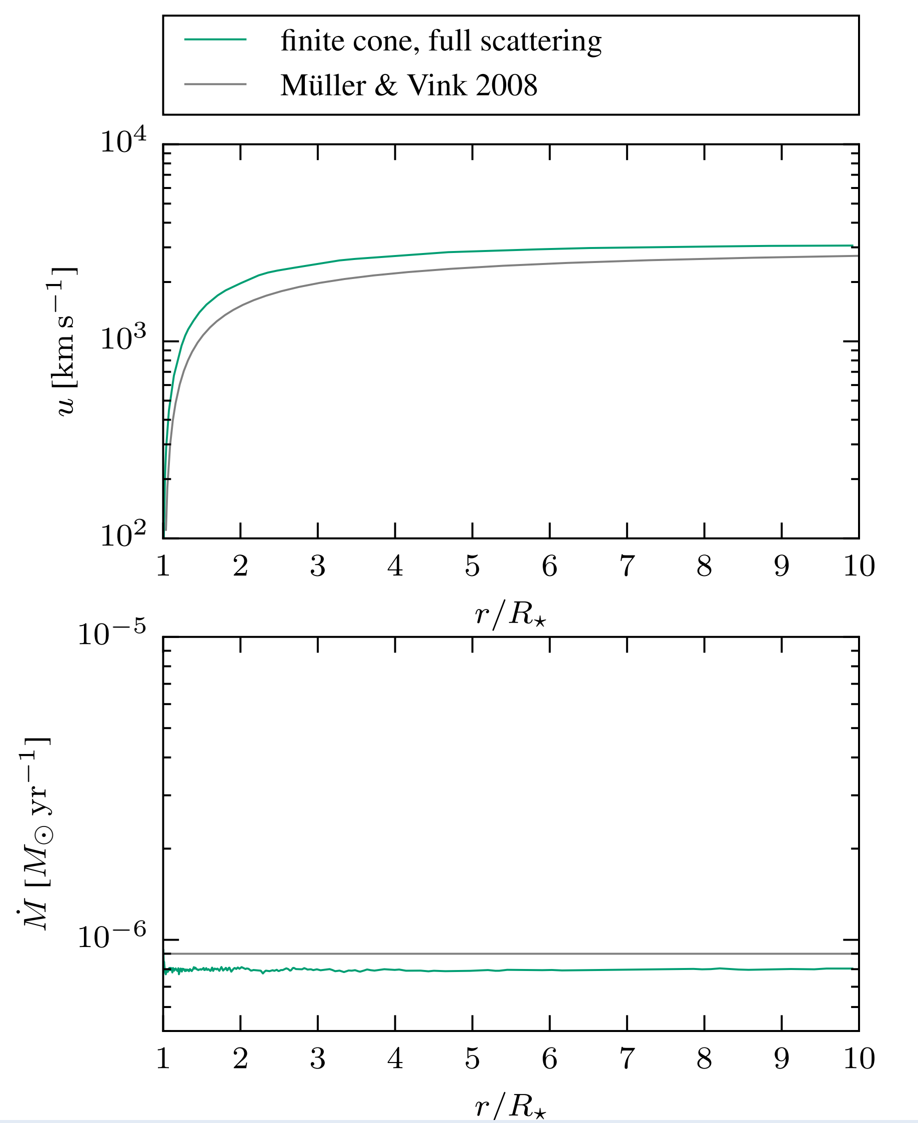
Tests/comparisons

Compare to CAK expectations:



Tests/comparisons

Compare to alternative method:



Conclusions

Using MCRH to simulate line-driven flows looks promising:

- Easy to formulate estimator for Sobolev limit that captures weak line contributions
- Noise is an issue but overall results are promising
- Comparisons to other methods suggests that results are reasonable