Light curves and spectra for astrophysical explosions

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Overview:

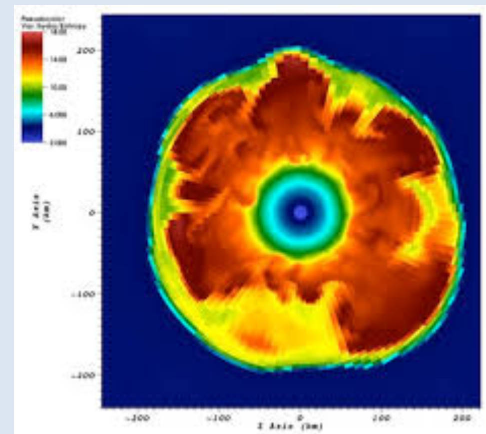
- Brief introduction to supernovae
  - Observations to study
- Considerations for modelling radiation transport for supernovae
  - Suitability of MCRT techniques
- Light curve calculations (Lecture 1)
  - Simple 1D example
- Spectrum calculations (Lecture 2; Wed afternoon)
  - Macro Atom methods for radiative equilibrium

Variety of bright astronomical transients that are associated with explosions…

Supernovae and related transients

Variety of bright astronomical transients that may be associated with explosions:

- Stellar core collapse
- Thermonuclear runaway (accretion, mergers, collisions)
- Tidal disruption events
- Neutron star mergers
- …



Radiation could be powered in many ways:

- Heat deposited in explosion
- Radioactivity (decay of products of explosive nucleosynthesis)
- Central engine (accreting compact object? magnetar?)
- Interaction with environment (rad. hydro)
- …

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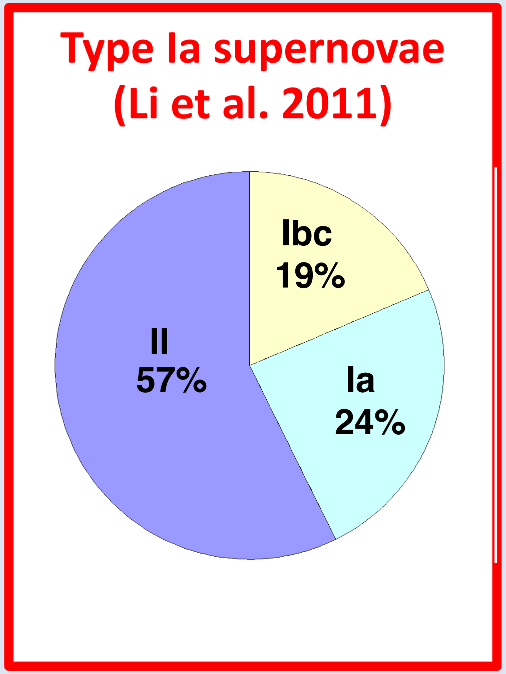

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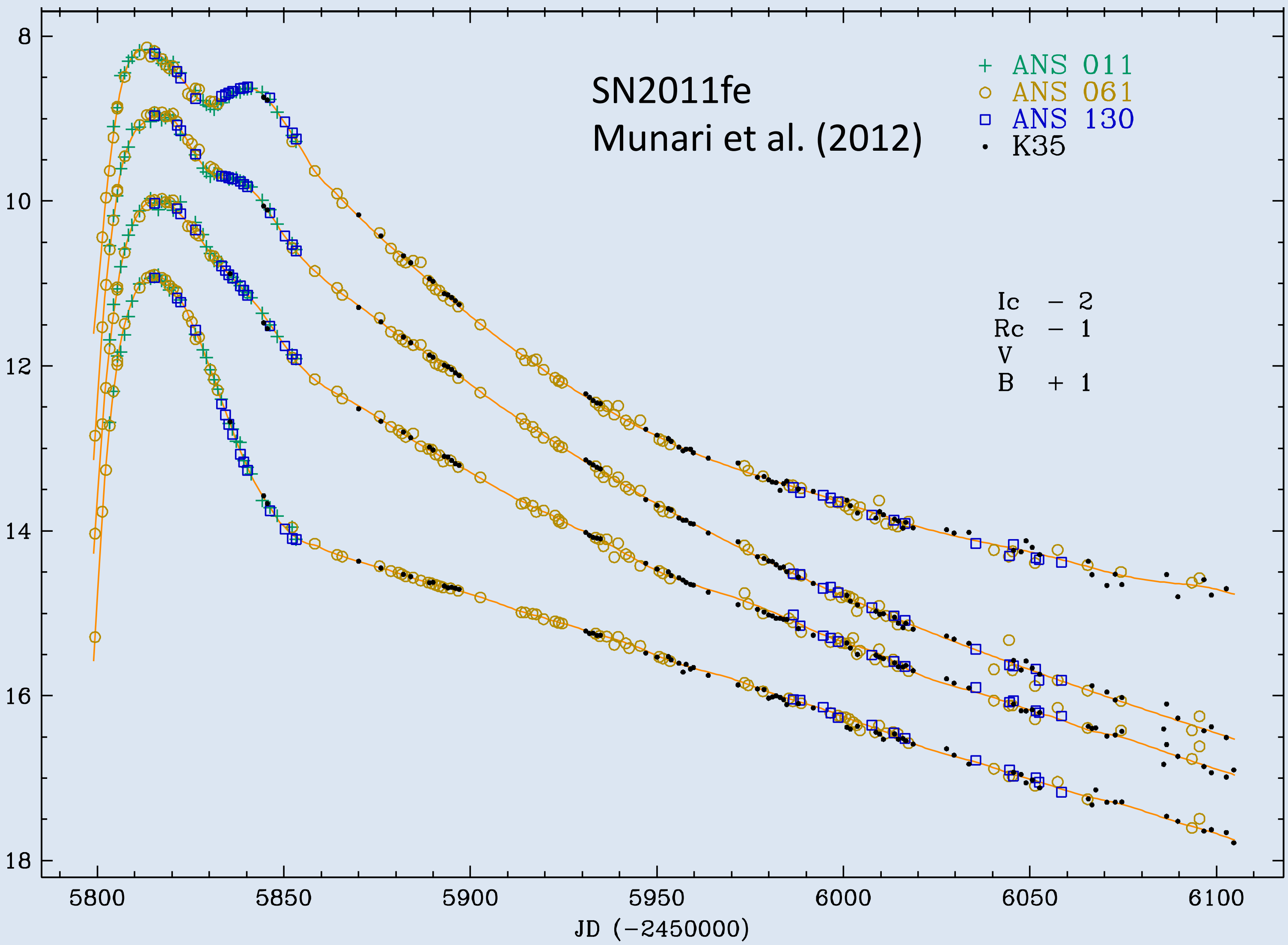
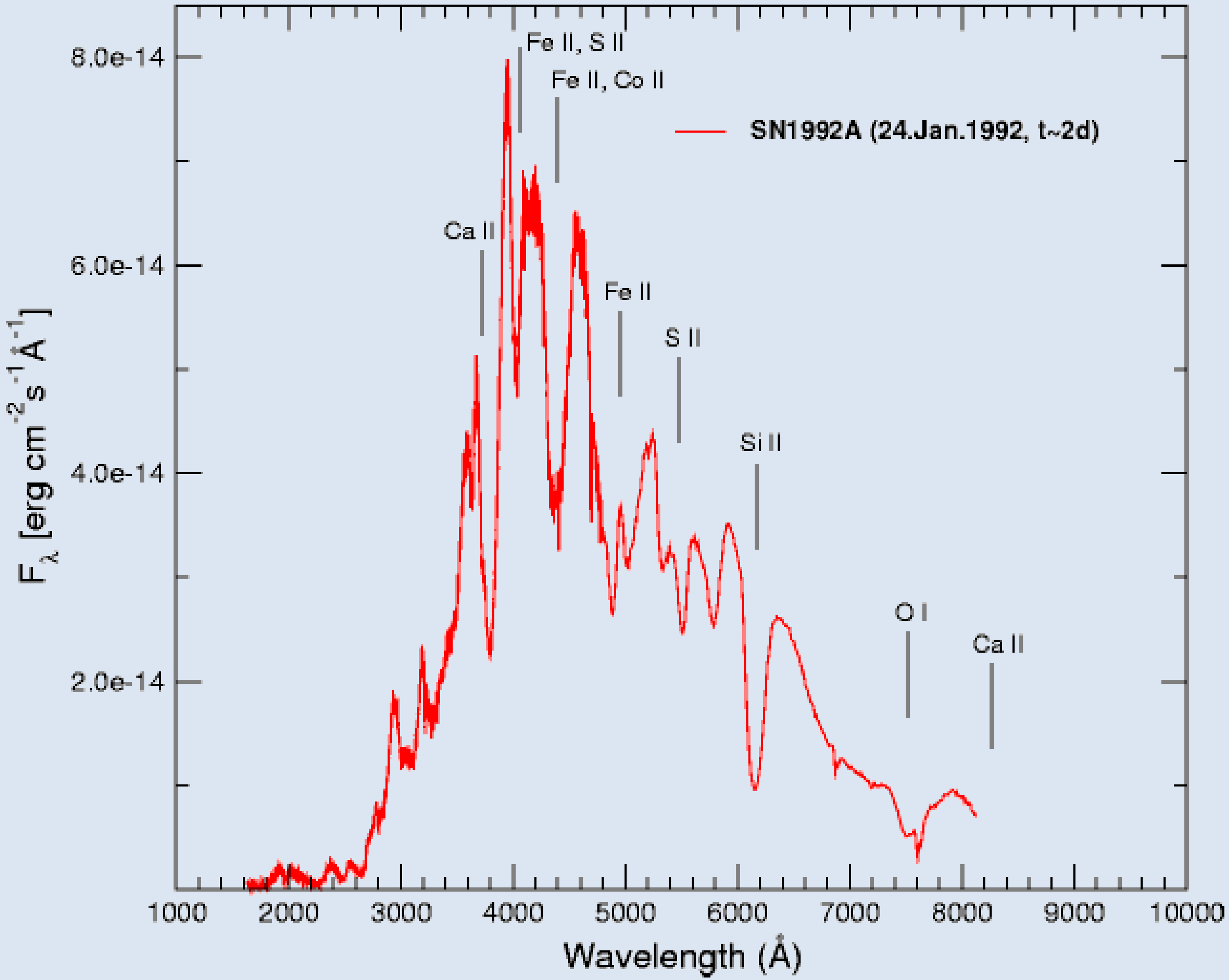
Observing Supernovae

SN1994D in NGC 4526
NASA/HST

Supernova (Type Ia) lightcurves



Supernova (Type Ia) spectrum



Supernova modelling

Considerations:

- Time-dependence
- Large velocities
- Homologous flow (i.e. not coupled dynamics)

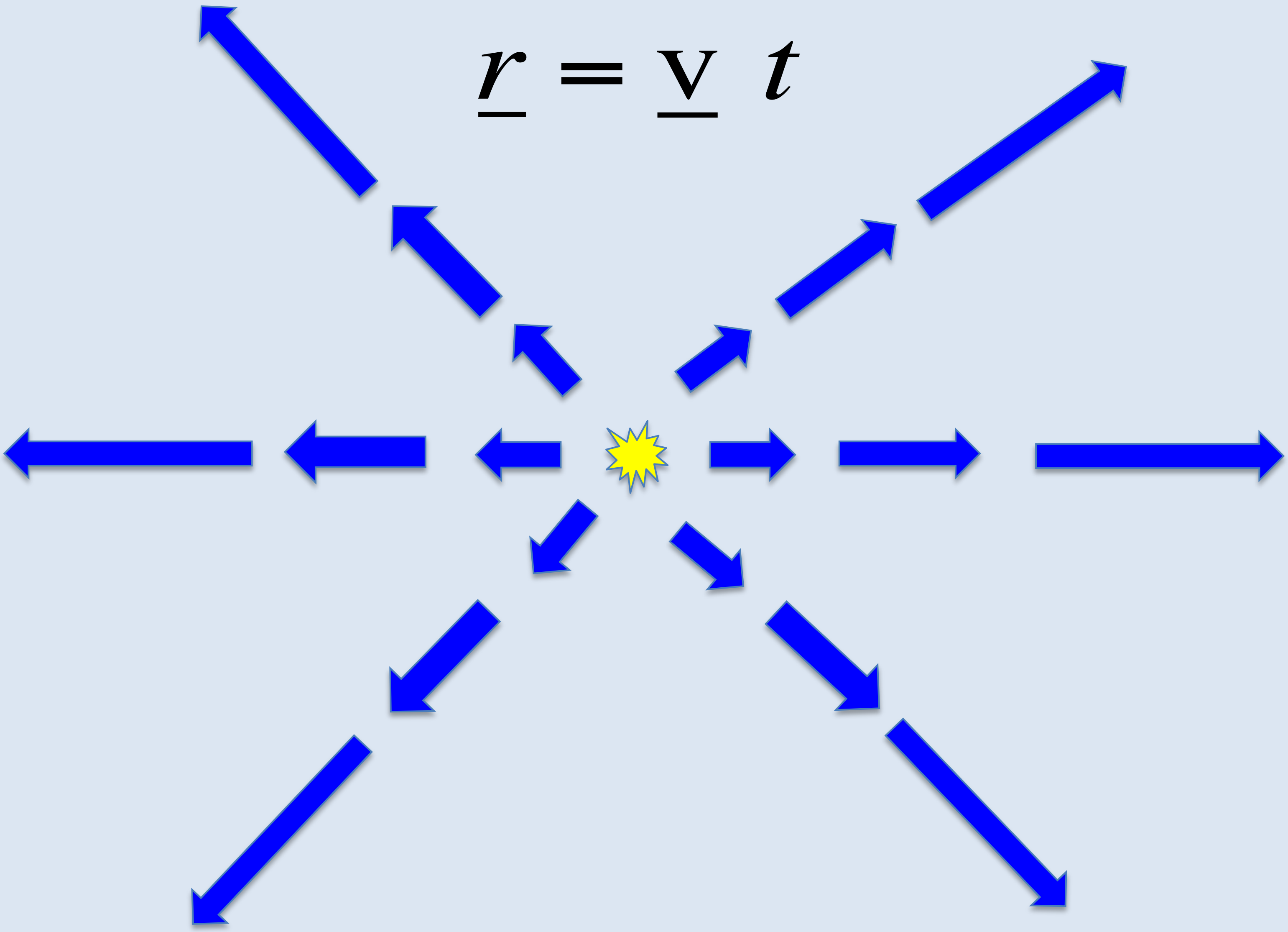
Monte Carlo RT:

- Easy to track time on trajectories
- Mixed frame approach makes easy; line blending
- Pure radiation (radiative equilibrium)

Homologous flow

normally established within seconds to hours

$$\underline{r} = \underline{\mathrm{v}}\ t$$



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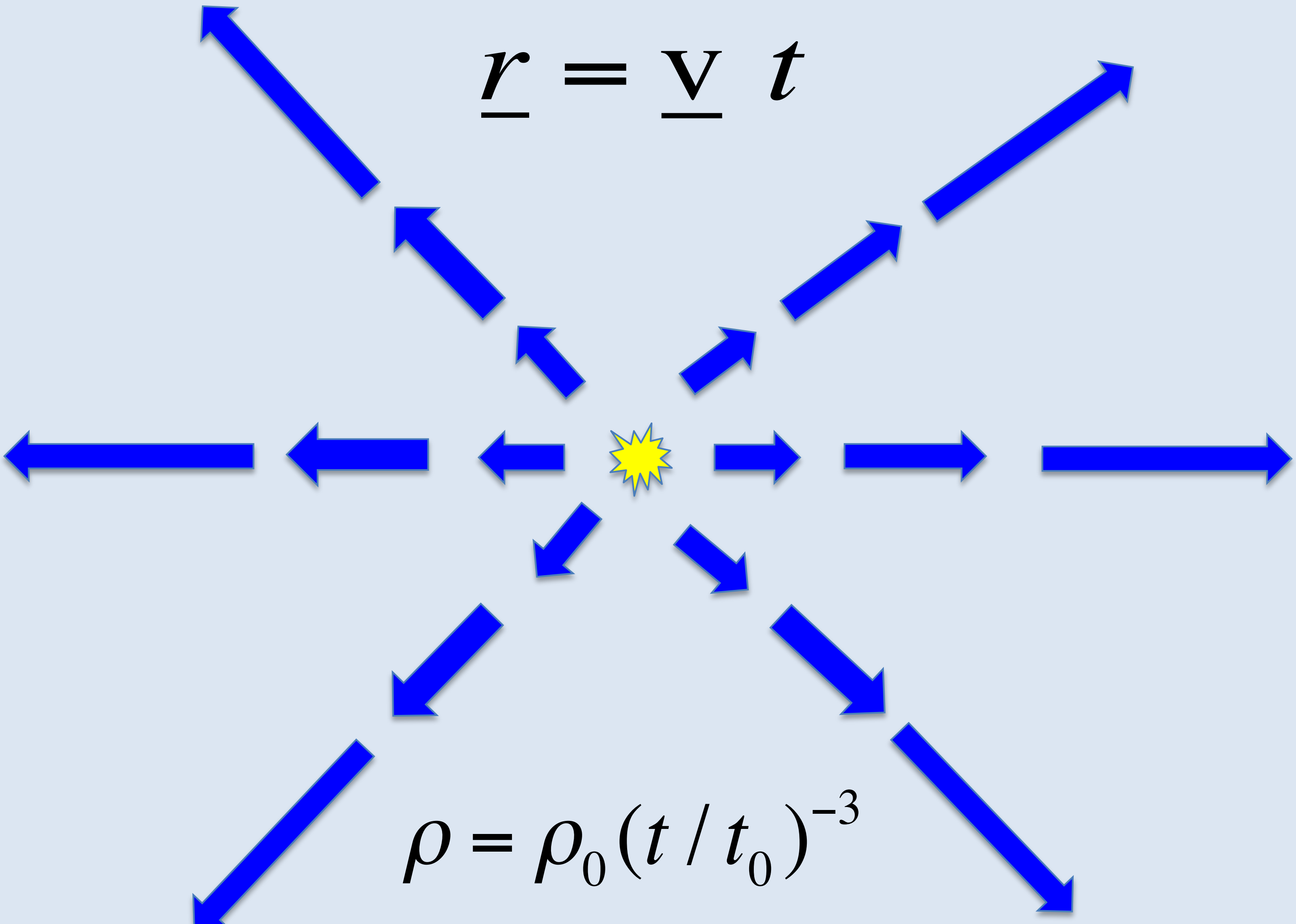

$$\rho = \rho_0 (t / t_0)^{-3}$$

Supernova modelling

Considerations:

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- Multi-dimensional

Monte Carlo RT:

- Easy to track time on trajectories
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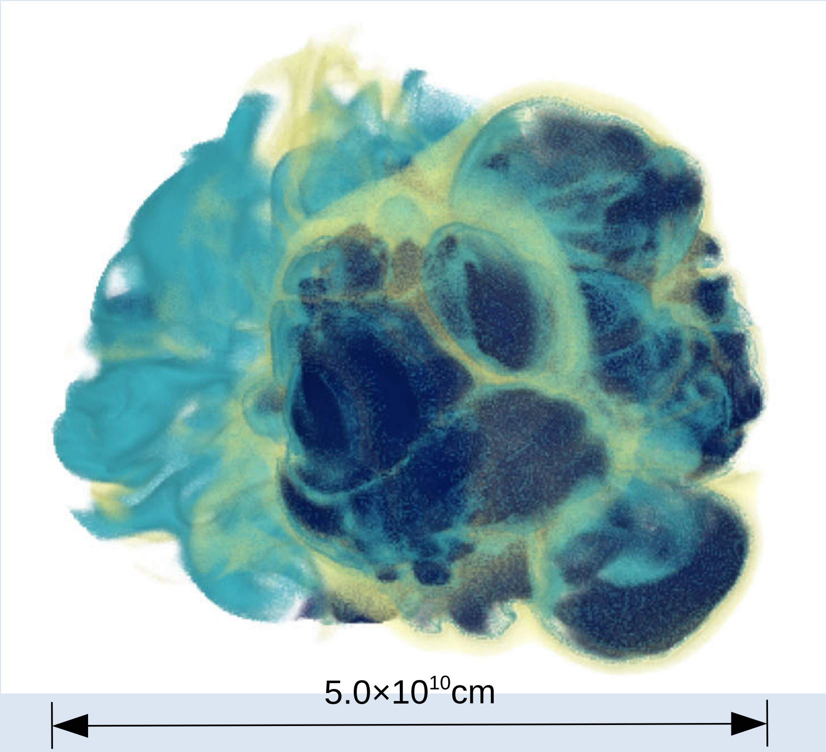
- 3D grid easy

Multi-dimensional

departures from sphericity large in some models

Flash Centre simulation (early phase)

Kromer et al. 2015
(composition rendering at 10s)



Supernova modelling

Considerations:

- Time-dependence
- Large velocities
- Homologous flow (i.e. not coupled dynamics)
- Multi-dimensional
- NLTE
- Metal-rich

Monte Carlo RT:

- Easy to track time on trajectories
- Mixed frame approach makes easy; line blending
- Pure radiation (radiative equilibrium)
- 3D grid easy
- Most serious challenge (estimators for rates)

Light curve modelling

Lucy (2005), SEDONA/ARTIS codes

Procedure:

- Define homologous model, including energy source (e.g. based on hydro simulation), grid zones and time steps

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- Define homologous model, including energy source (e.g. based on hydro simulation), grid zones and time steps
- Inject energy packets to make a ensemble that represents the injection process.
- Use radiative equilibrium MC algorithm to simulate the propagation of an ensemble of energy packets (“photon bundles”)
    - Indivisible energy packet algorithm (e.g. Abbott & Lucy 1985 …Lucy 2005)

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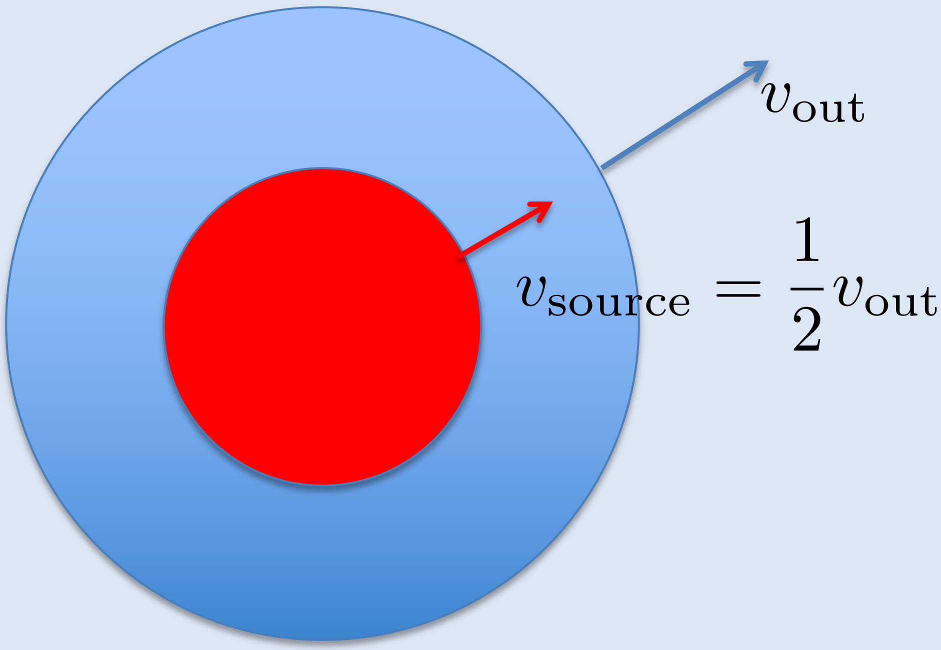
Light curve modelling

Simple example; suppose:

- Spherical, uniform density ejecta with constant opacity coefficient
- Energy source from (single isotope) radioactive decay (inner half of ejecta)
- Compute light curve for 2 – 100 days after explosion



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Light curve modelling

Injecting packets - use random numbers to select

- time of injection
- Location of injection
- Initial direction

Light curve modelling

Time of injection:

- **E.g. for radioactive decays**

$$\frac{\mathrm{d}N(t)}{\mathrm{dt}} = -\frac{N_0}{t_0}\exp\left(-t/t_0\right)$$

- **Which is easy to sample a time using a random number**

$$t = -t_0 \ln z$$

- **Convenient to restrict decay times to duration of simulation**

Light curve modelling

Location of injection:

- **For homologous expansion the outer boundary is located at:**

$$R_{\rm out} = v_{\rm out} t$$

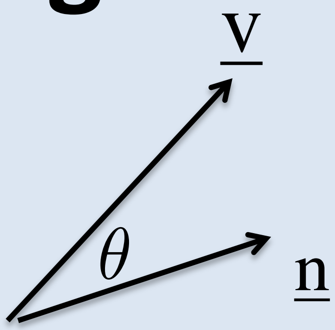
- **Similarly,**

$$R_{\rm source} = v_{\rm source} t$$

- **So select random starting radius for packet inside source region by sampling volume at the time of injection:**

$$r = z^{1/3} \, v_{\rm source} \, t$$

Light curve modelling



Direction of injection:

- **For our simple problem, sufficient to specify direction cosine:**

$$\mu = \cos\theta$$

- **Assuming that emission is isotropic in fluid frame, can randomly select**

$$\mu_{\rm ff} = -1 + 2z$$

- **Then in observer frame, angle aberration gives**

$$\mu_{\rm obs} = \frac{\mu_{\rm ff} + \beta}{1 + \mu_{\rm ff}\beta} \qquad \beta = \frac{v}{c} = \frac{r}{ct}$$

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Light curve modelling

Propagation:

- Once a packet in injected into the simulation box its subsequent propagation can be followed using a standard MCRT "random walk" algorithm:

  1. **Compute three time intervals**:
     - To reach grid zone boundary
     - To reach end of current time step
     - To reach (randomly selected) interaction point

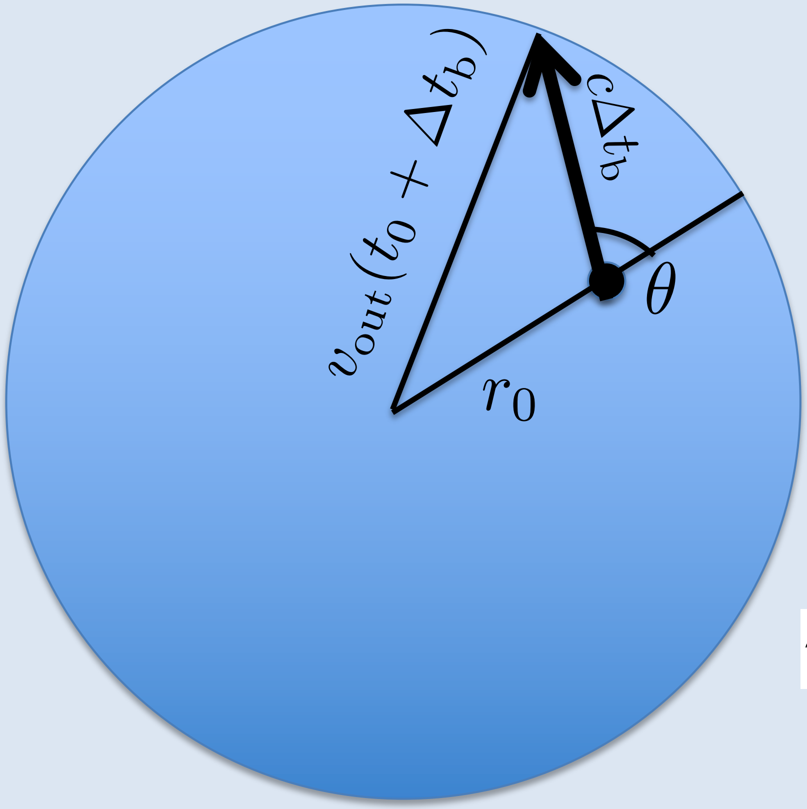
  2. **Select shortest of these three distances and accordingly**:
     - Move into next grid zone
     - Move on to next time step [or store and come back]
     - Simulate the interaction

  3. **Rinse and repeat…until packet leaves simulation** (or reach final time step)

Light curve modelling

Time intervals for our simple example:

- **To reach (the only!) grid zone boundary, starting from** r_0 , t_0



$$v_{\rm out}^2 (t_0 + \Delta t_{\rm b})^2 = r_0^2 + c^2 \Delta t_{\rm b}^2 + 2 r_0 c \mu \Delta t_{\rm b}$$

…solve for the time interval needed to reach boundary, $\Delta t_{\rm b}$

Light curve modelling

Time intervals for our simple example:

- **To reach end of time step is even simpler:**

$$\Delta t_{\mathrm{t}} = T_{\mathrm{next}} - t_0$$

Light curve modelling

Time intervals until interaction:

- Use random number to draw optical depth to interaction point:

$$\tau = -\ln z$$

- Convert this to a photon travel time to interaction point:

$$\Delta t_{\mathrm{i}} = \frac{\tau}{c\rho\kappa}$$

Light curve modelling

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In observer frame
(Doppler factor)

Light curve modelling

Decision:

- **Knowing:**

$$\Delta t_{\rm b} \ , \ \Delta t_{\rm t} \ , \ \Delta t_{\rm i}$$

…select the shortest:

$\Delta t_{\rm b}$ → Move packet to boundary and cross into new zone (or flag it as having escaped)

$\Delta t_{\rm t}$ → Move packet to position for end of time step and then proceed to next time step: fluid properties (e.g. density $\rho \propto t^{-3}$) will change;

Light curve modelling

$$\Delta t_{\mathrm{i}}$$ → Move packet to interaction point and undergo fluid interaction

Complex part, where codes differ in detail, but same general idea:

Radiative equilibrium → **"effective" scattering (Lucy 1999, 2005); conserve radiative energy in fluid frame**

$$\epsilon_{ff}^{\mathrm{after}} = \epsilon_{ff}^{\mathrm{before}}$$

E.g. for grey opacity with isotropic emission, just need Lorentz transformations of packet energy:

$$\epsilon_{ff} = \gamma \epsilon_{obs} (1 - \mu_{obs} \beta)$$

So that in interaction:

$$\epsilon^{\mathrm{after}} = \epsilon^{\mathrm{before}} \frac{(1 - \mu_{obs}^{\mathrm{before}} \beta)}{(1 - \mu_{obs}^{\mathrm{after}} \beta)}$$

Aberration of angles

Δt_{i} → Move packet to interaction point and undergo fluid interaction

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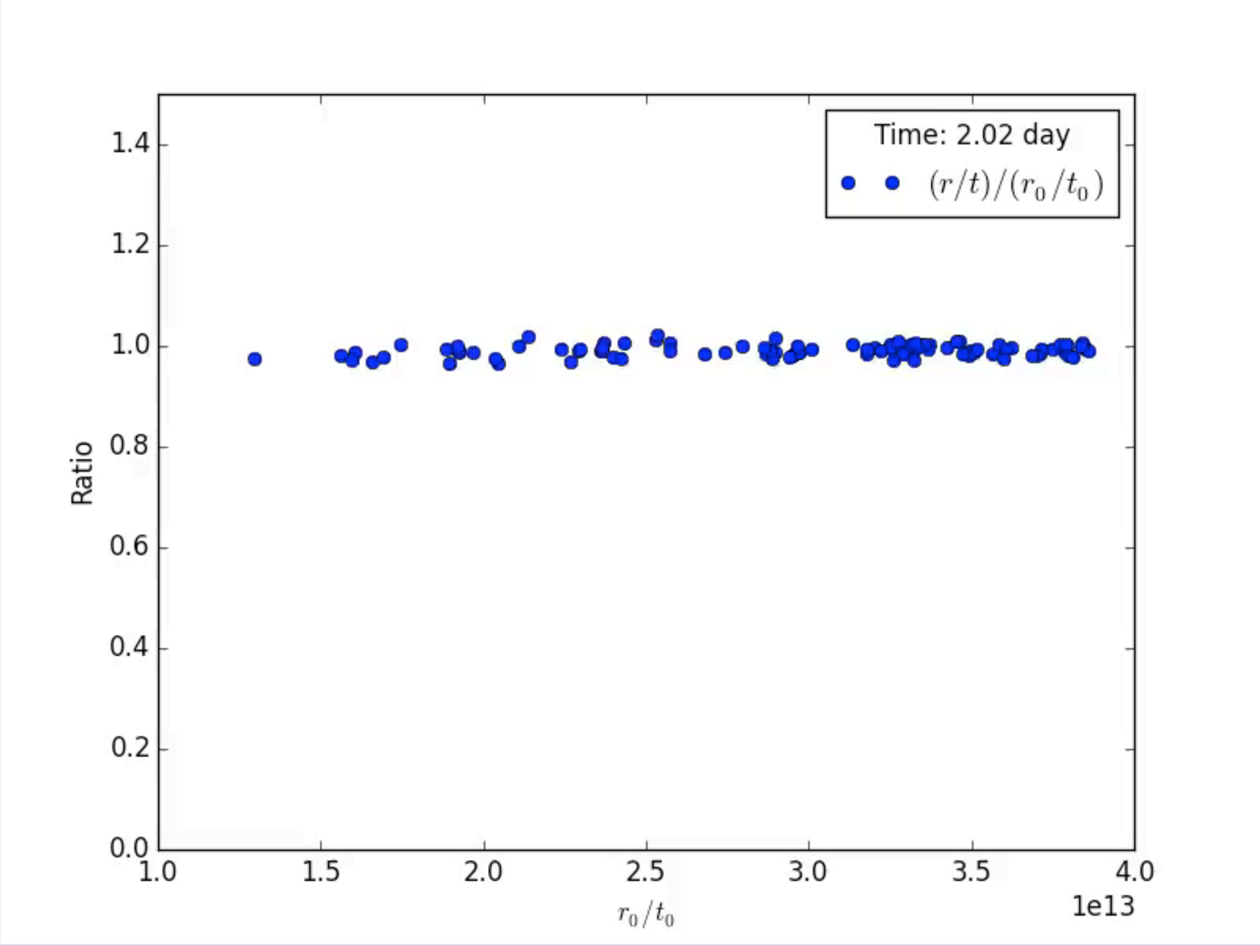
Isotropic (in fluid frame) → μ_{obs}^{after}

Light curve modelling

Note: correct application of frame transformations is needed for:

- **Advection in optically-thick regime**
- **Work done on ejecta by radiation**



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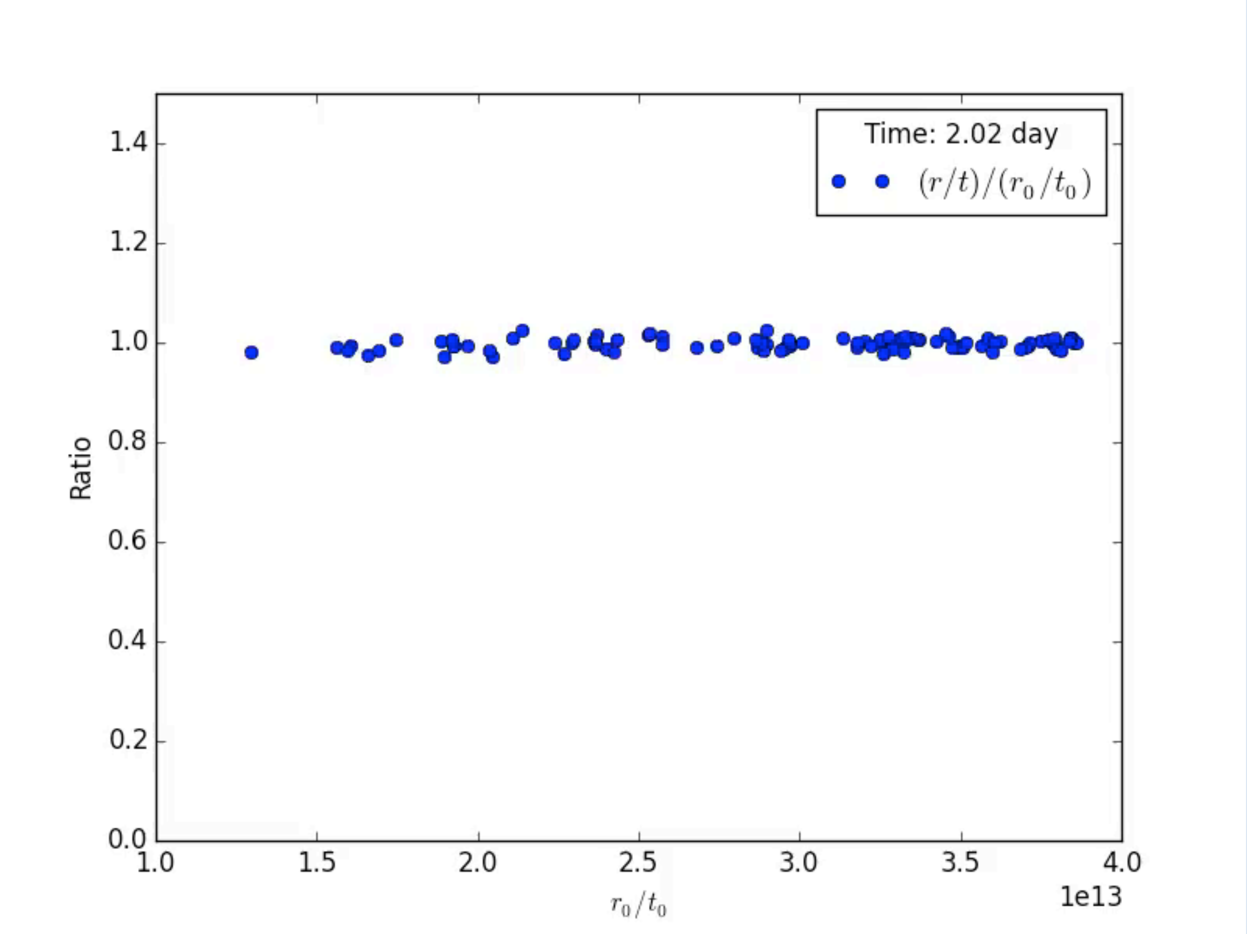

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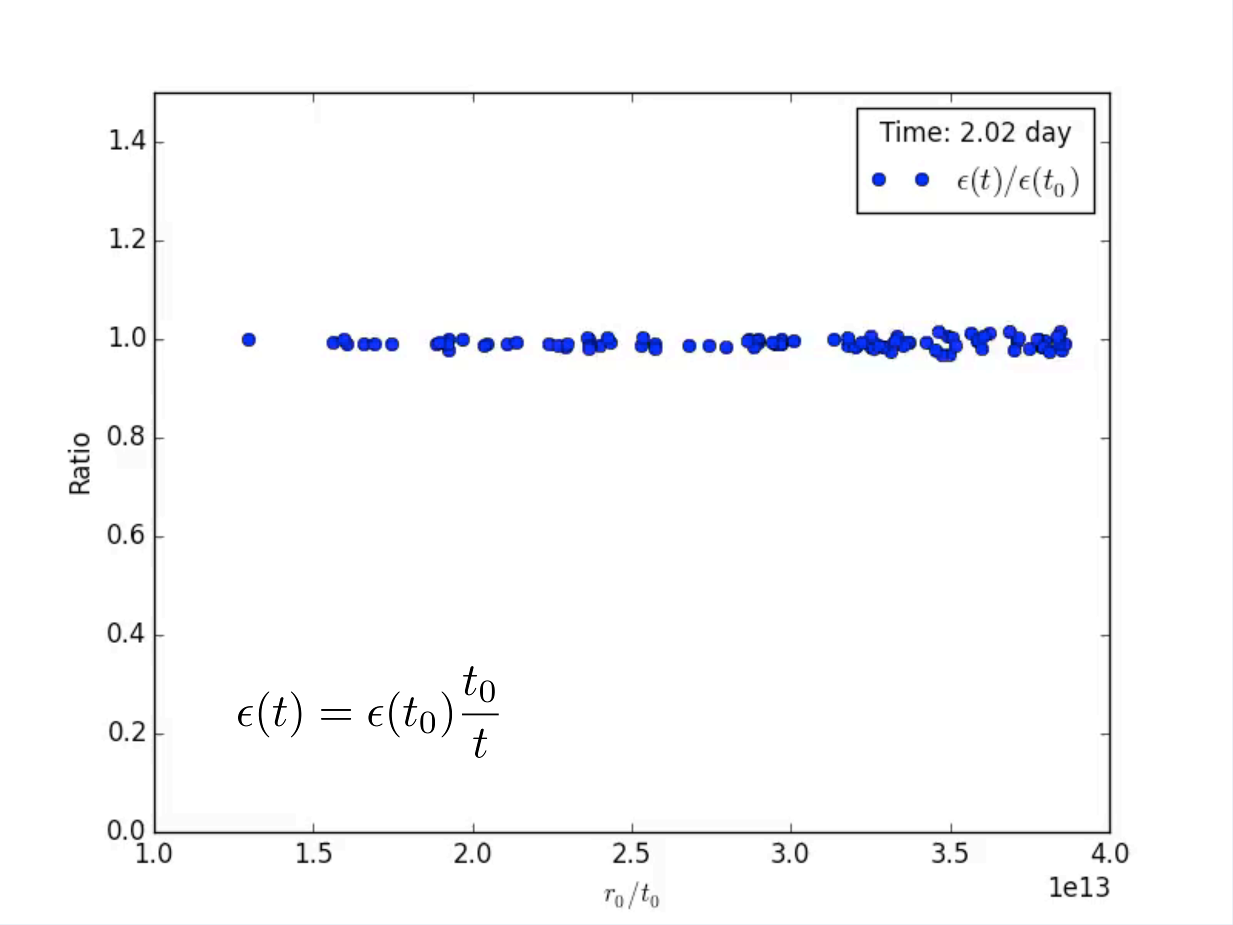

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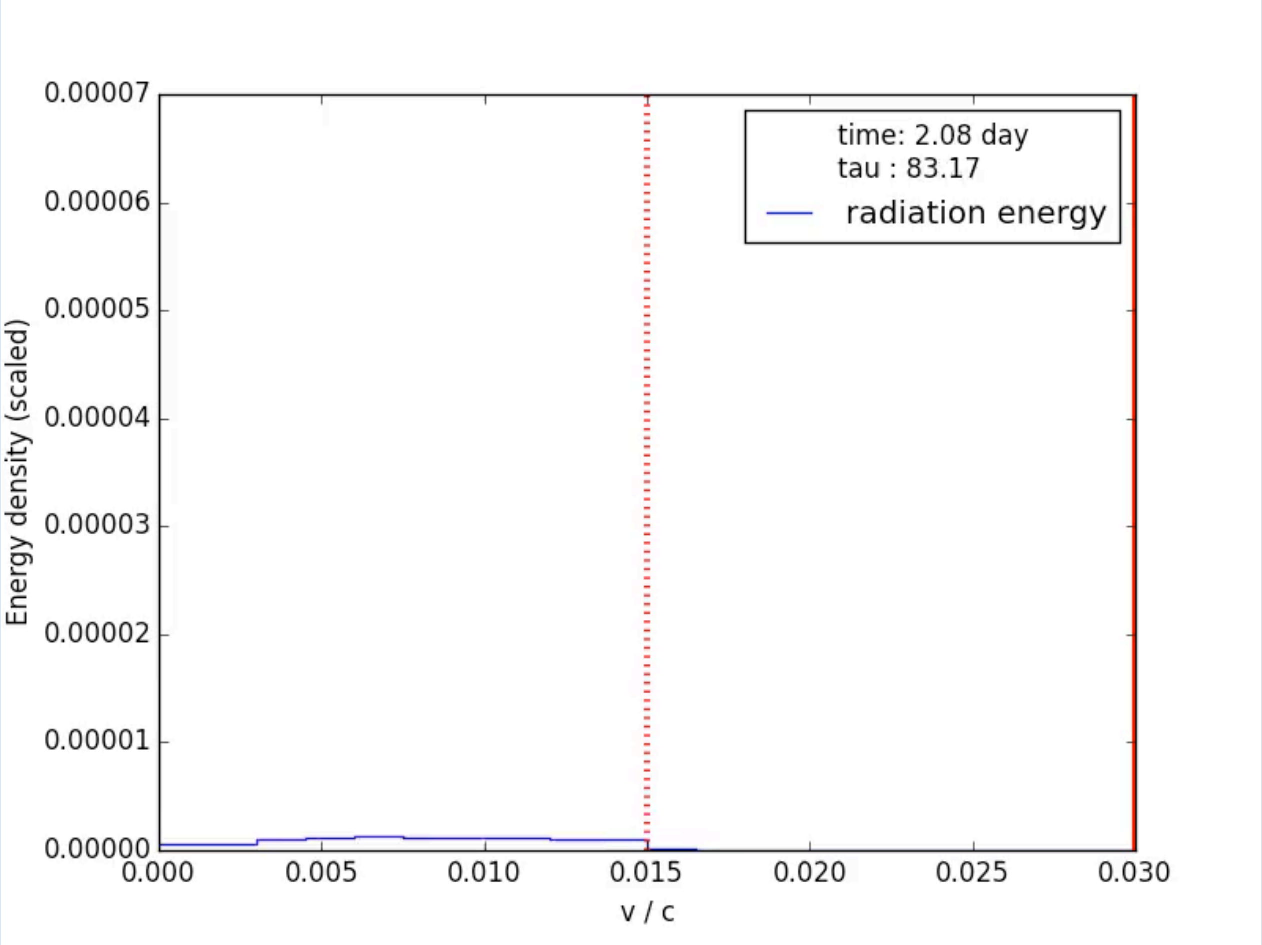
3. **Rinse and repeat…until packet leaves simulation** (or reach final time step)
    - Record properties of escaping packets: bin to make light curve
    - Can also use more sophisticated estimators to make light curve…

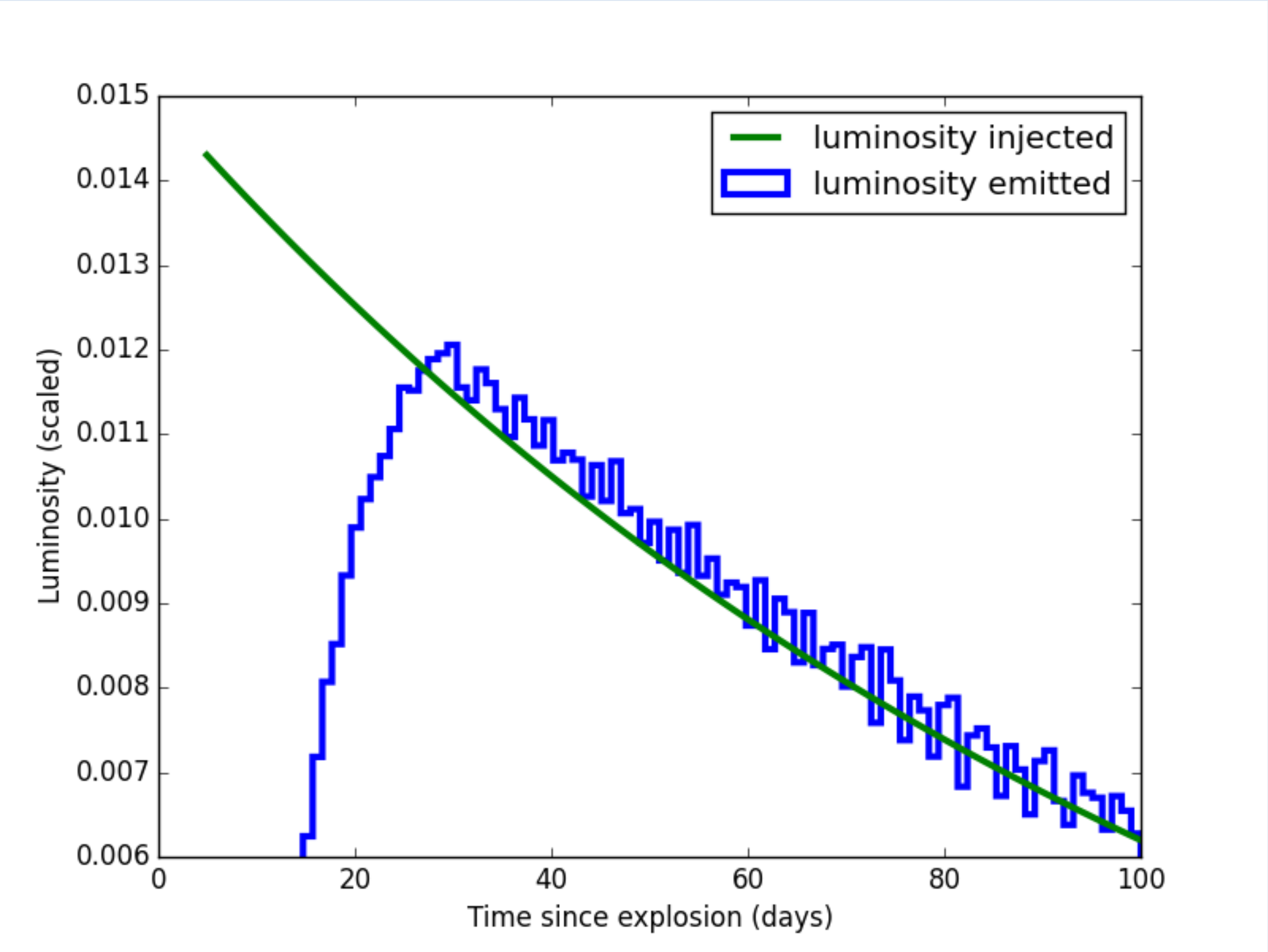
Light curve modelling

Example toy code: result of code



Light curve modelling

Example toy code: **result of code**



Light curve modelling

Simplifications made today:

- (Minor) Energy source: can be easily generalized for other internal energy sources
- (Minor) Uniform density / spherical: just need to identify boundaries
- (Minor) Need to consider radiation energy already present at start of simulation (initial conditions)
- (Major) Realistic calculations need non-grey opacities: commonly will involve use of Sobolev line-opacities and continuum; ideally non-LTE
- (Major) Need detailed interaction microphysics: frequency redistribution, thermalisation etc.