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What Can We Learn from the Early Optical Light Curve of Type I SNe?

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Reference: Piro & Nakar, 2013, ApJ

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Energy Sources of SN Light Curves

- A typical supernova (SN) light curve is powered by a combination of two sources:

  1. **The radioactive decay of Ni56** that was synthesized during the explosion.

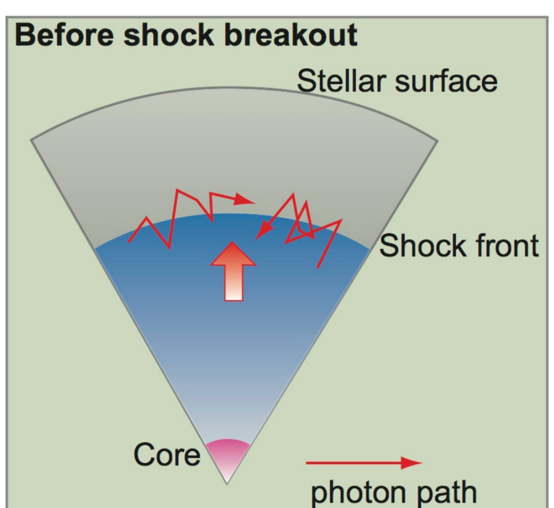
  2. The energy deposited by **the SN shock.**

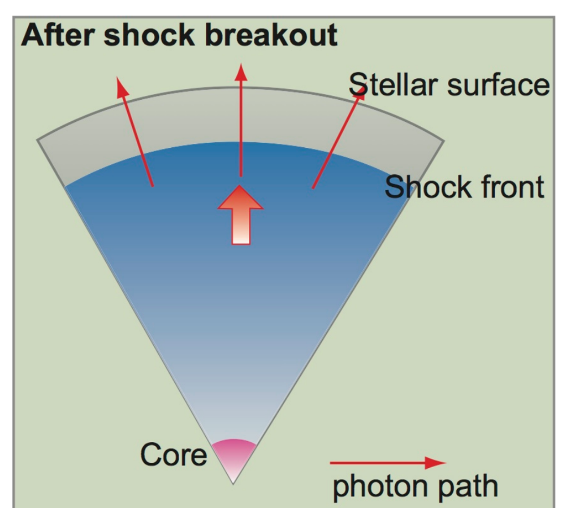
     - The first light from shock breakout and the following early emission (for the first minutes to days) are dominated by the shock-deposited energy

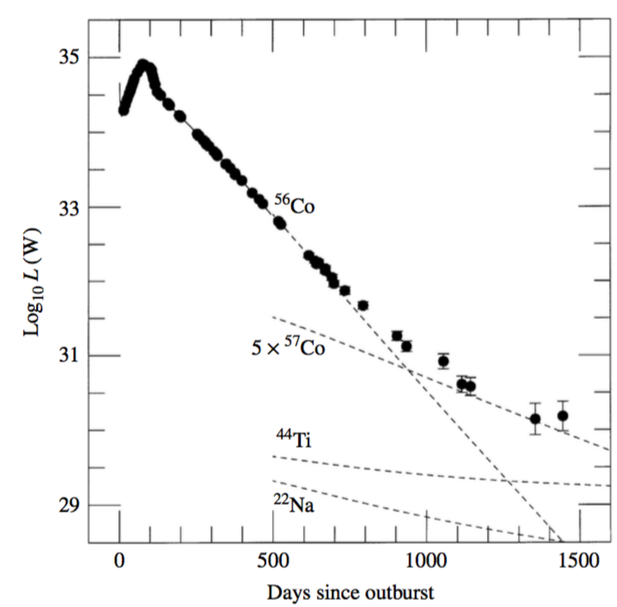
- The relative influence of these power sources depends on two main factors: (1) **the progenitor radius R_*** and (2) **the amount of Ni56**

  - **The bolometric luminosity** from shock heating increases linearly with **the progenitor radius**

  - **The peak of the radioactively powered luminosity** is roughly linear with the **total mass of Ni56**

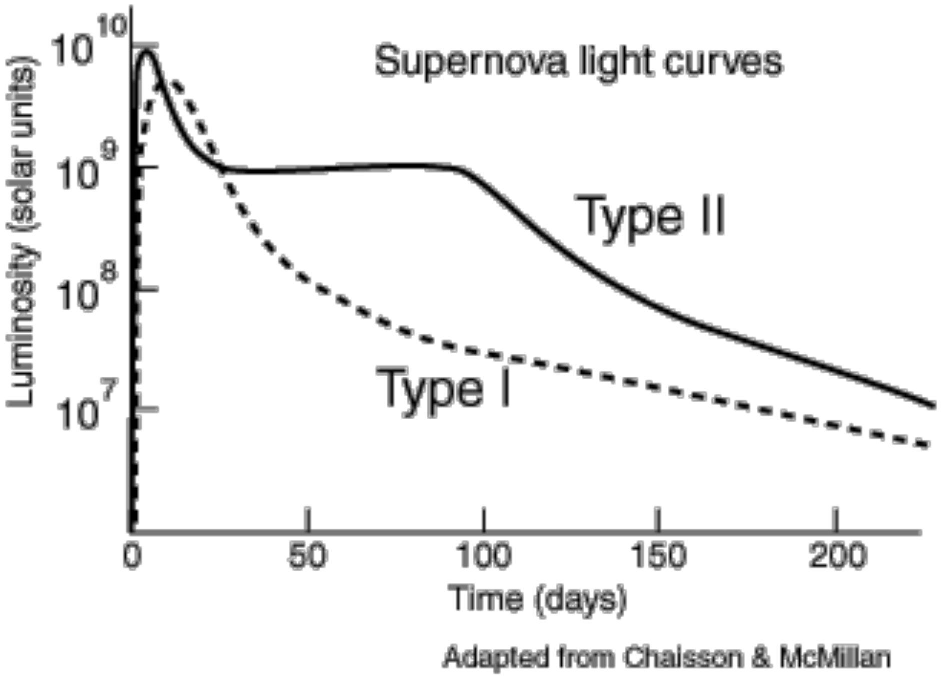


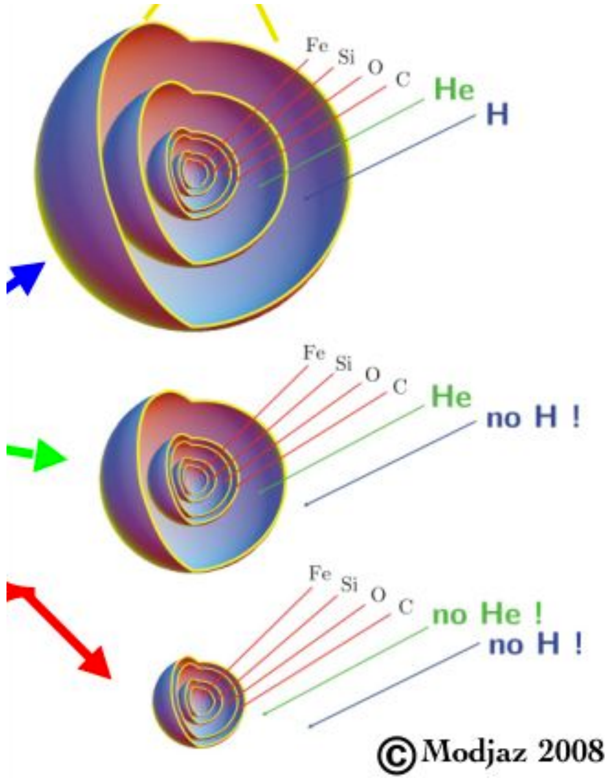


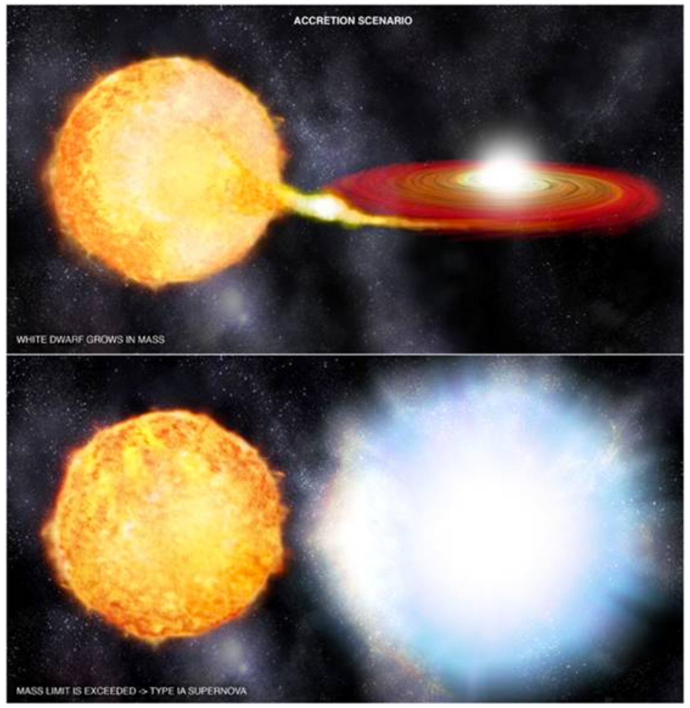


Light Curve of SNe

- The light curve of the explosion of a star with a radius 10–100 R⊙ is **powered mostly by radioactive decay**.
- Observationally, such events are dominated by **hydrogen-deficient progenitors**, i.e.,
  - Type I supernovae (SNe I), i.e., white dwarf thermonuclear explosions (**Type Ia**),
  - Core collapses of hydrogen-stripped massive stars (**Type Ib/c**).
- Current transient surveys are finding SNe in increasing numbers and at earlier times, allowing their early emission to be studied in unprecedented detail.

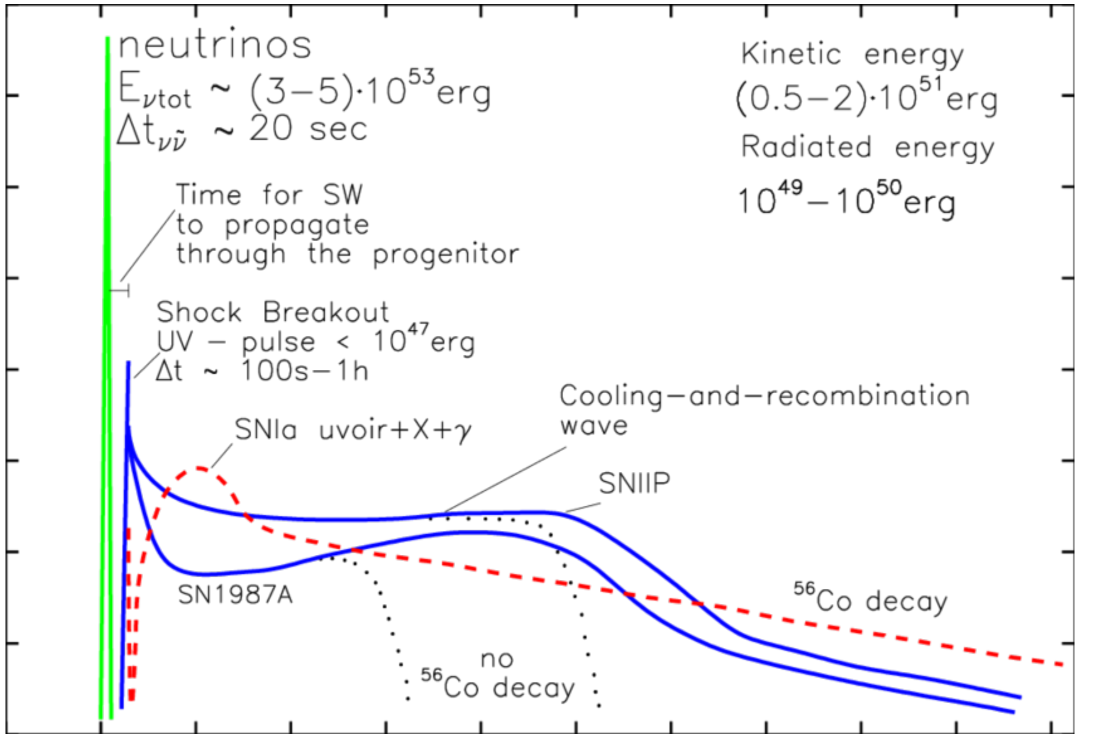


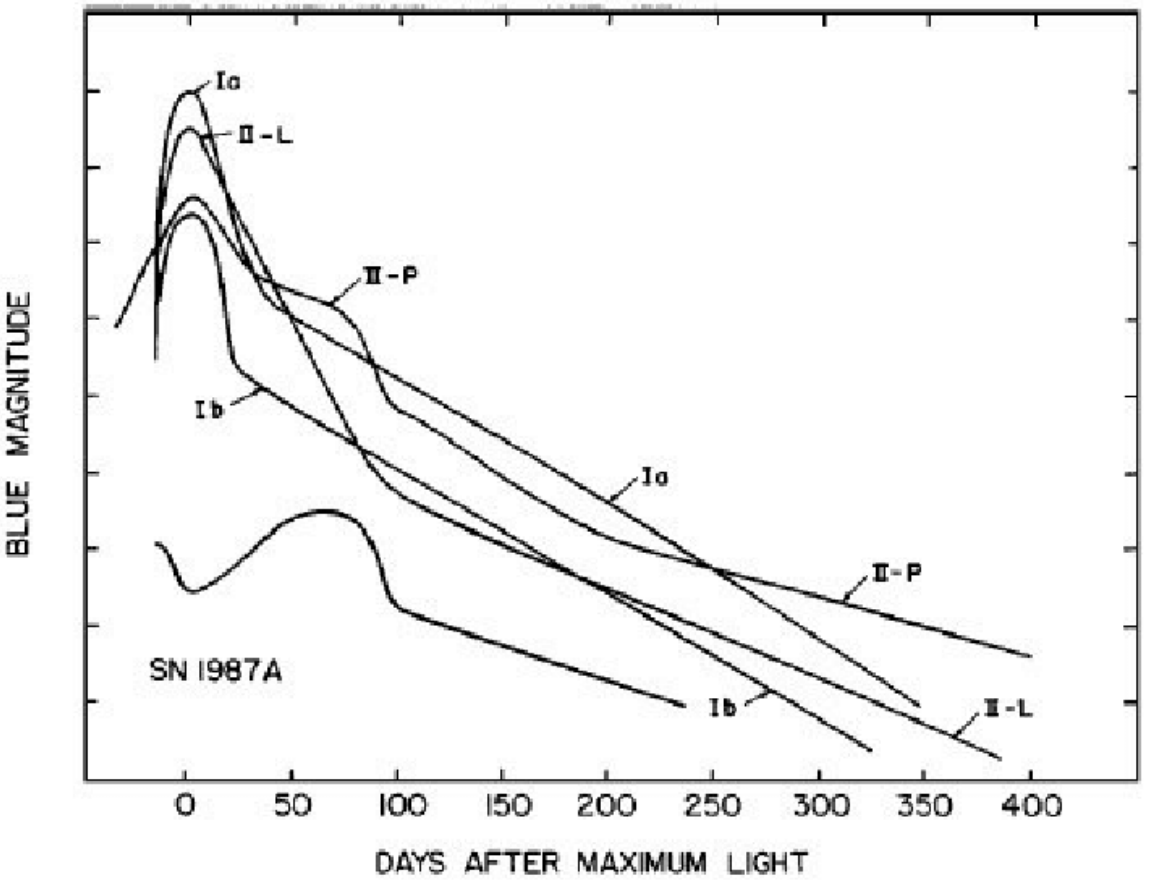




Shock Heating vs ^{56}Ni

- For compact progenitors the main SN event is dominated by radioactive power, while for more extended progenitors, it is dominated by shock heating:
  - SNe II-P ($R_* \sim 500\ R_\odot$): powered by the cooling of shock-heated material.
  - SNe IIb ($R_* < 10\ R_\odot$): both shock-heated material and a separate radioactive peak.
  - SNe Ib/c ($R_* < 10\ R_\odot$): dominated by radioactive power
  - SNe Ia ($R_* < 0.01\ R_\odot$): the synthesis of $\sim 0.5\ M_\odot$ of Ni56.



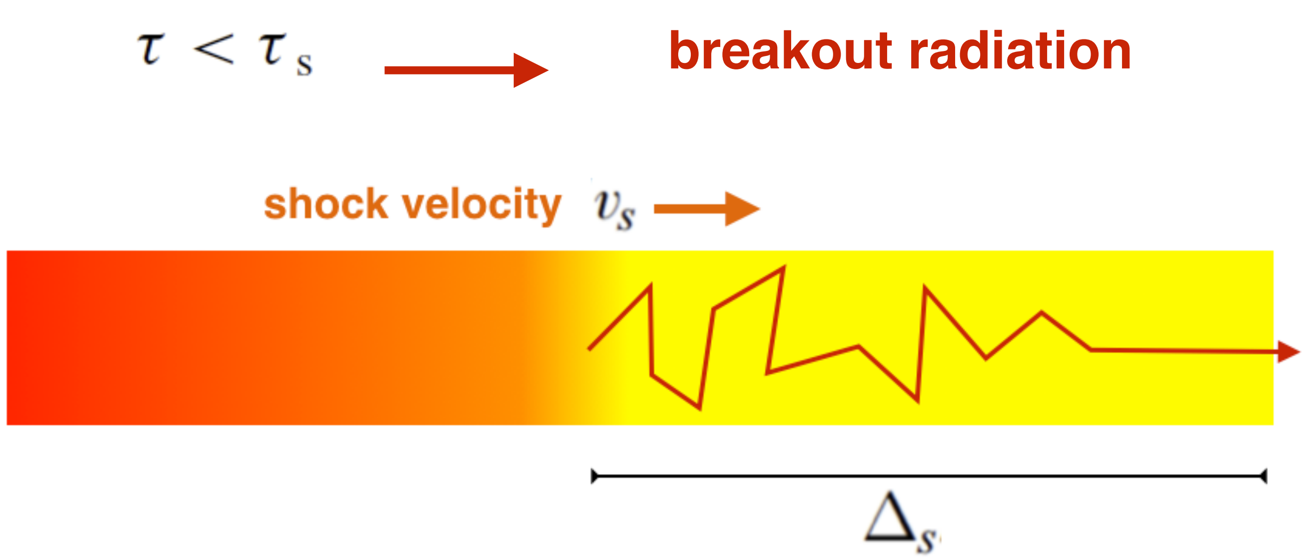


Shock Breakout

- Just prior to emission, **a shock is traveling through the envelope**. This heats and accelerates the material, unbinding it from the star.

- The shock continues to shallower regions until **the optical depth falls to $\tau \approx c/v_s$**. At this point, the photons are no longer trapped; they stream away and the shock dies.

- UV/X-ray flash by a shock breakout has **a strong dependence on the radius**, allowing the progenitor star to be studied from its detection.



R_{RSG}=500-1000 R_{sun}

R_{BSG}=25-50 R_{sun}

R_{WR}=5-10 R_{sun}

Shock-heated Cooling

- Immediately after shock breakout, the observed radiation is **out of thermal equilibrium** until roughly the time when the gas doubles the progenitor radius at t ≈ R_*/v_f

- The observed photons then gain thermal equilibrium and the expansion enters its spherical homologous phase

- **As the material that has been heated by the shock expands, a thermal diffusion wave begins backing its way through the ejecta.**

- Above the depth of the diffusion wave, material cools via photon diffusion. Below this depth, material evolves adiabatically.

- The bolometric luminosity and the color temperature are

$$L \approx 2 \times 10^{41} \frac{E_{51}^{0.91} R_1}{\kappa_{0.2}^{0.82} M_1^{0.73}} \left(\frac{t}{1\ \mathrm{hr}}\right)^{-0.35} \mathrm{erg\ s}^{-1} \quad T_c \approx 4 \frac{E_{51}^{0.11} R_1^{0.38}}{\kappa_{0.2}^{0.23} M_1^{0.11}} \left(\frac{t}{1\ \mathrm{hr}}\right)^{-0.61} \mathrm{eV}$$

- In the optical/UV, the luminosity is rising as long it is in the Rayleigh–Jeans tail

$$L_{\mathrm{opt/UV}} \propto t^{1.5}. \quad \longleftarrow \quad L_{\mathrm{opt/UV}} \propto \frac{r_c^2 T_c}{\tau_c}$$

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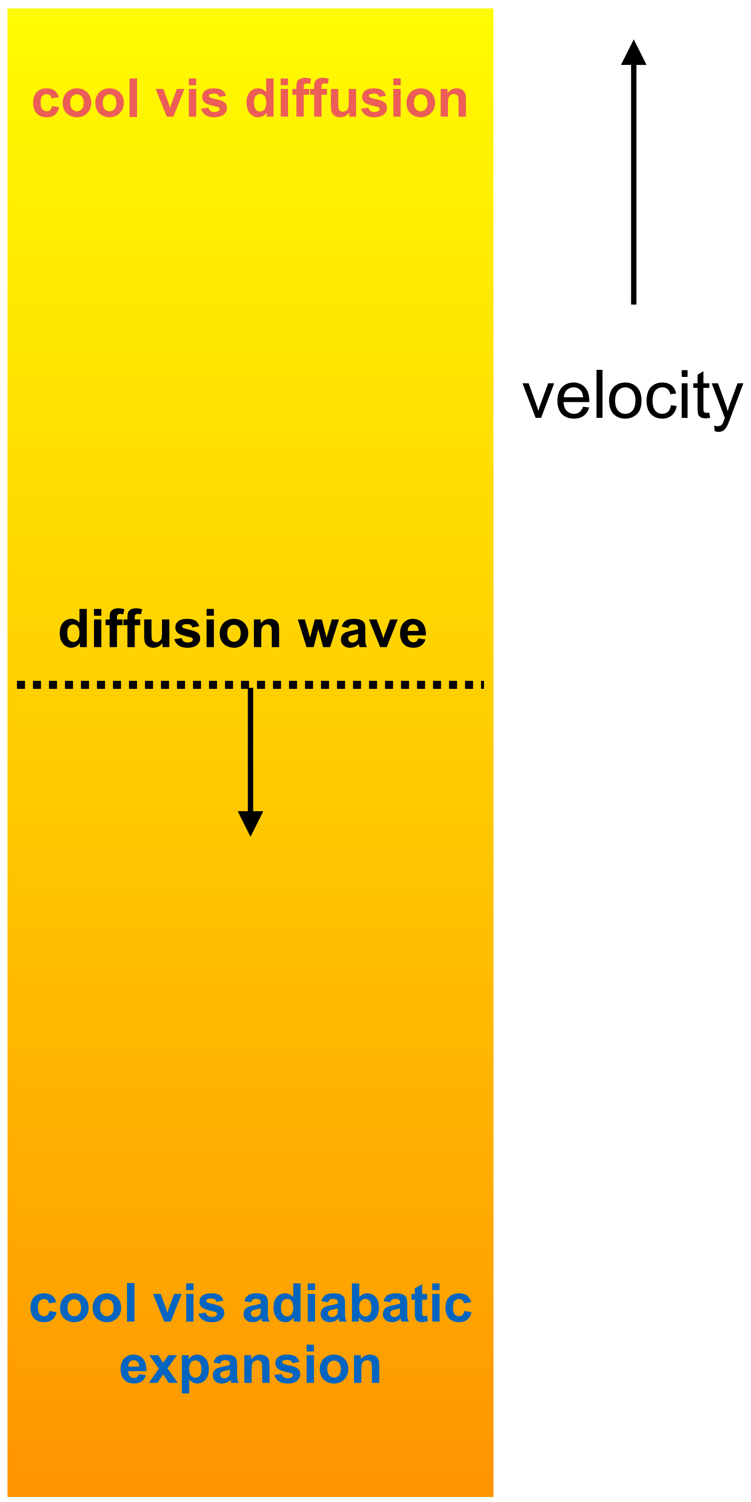


^{56}Ni Shallower than Diffusion Depth

- When the thermal diffusion wave reaches the shallowest deposits of Ni56, the energy generation from Ni56 roughly goes directly into the observed bolometric luminosity

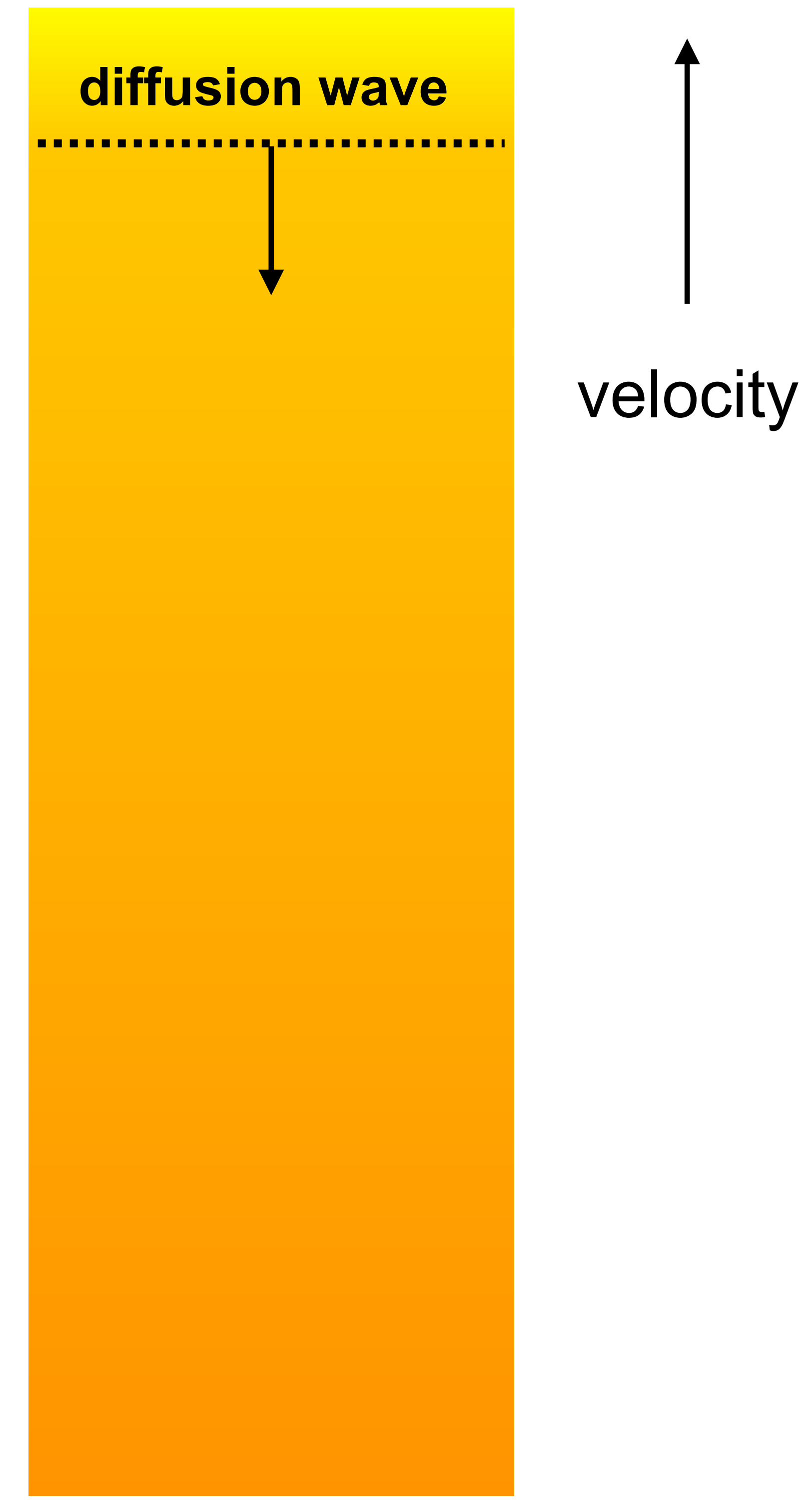
$$L_{56} \approx M_{56}\epsilon, \quad \epsilon(t) = \epsilon_{\mathrm{Ni}} e^{-t/t_{\mathrm{Ni}}} + \epsilon_{\mathrm{Co}}(e^{-t/t_{\mathrm{Co}}} - e^{-t/t_{\mathrm{Ni}}}),$$

- The depth of the diffusion wave tells us which part of the exploding star is being probed by the observations, and it is related to the time after explosion by

$$\Delta M_{\mathrm{diff}} \approx 8 \times 10^{-2} \frac{E_{51}^{0.44}}{\kappa_{0.1}^{0.88} M_1^{0.32}} \left(\frac{t}{1\ \mathrm{day}}\right)^{1.76} M_\odot$$

- If the explosion time is known, the above equation provides ΔM_{diff} into which this Ni56 is mixed. **From this, the mass fraction $X_{56} \approx M_{56}/\Delta M_{diff}$ can be inferred as a function of the depth ΔM_{diff}.**

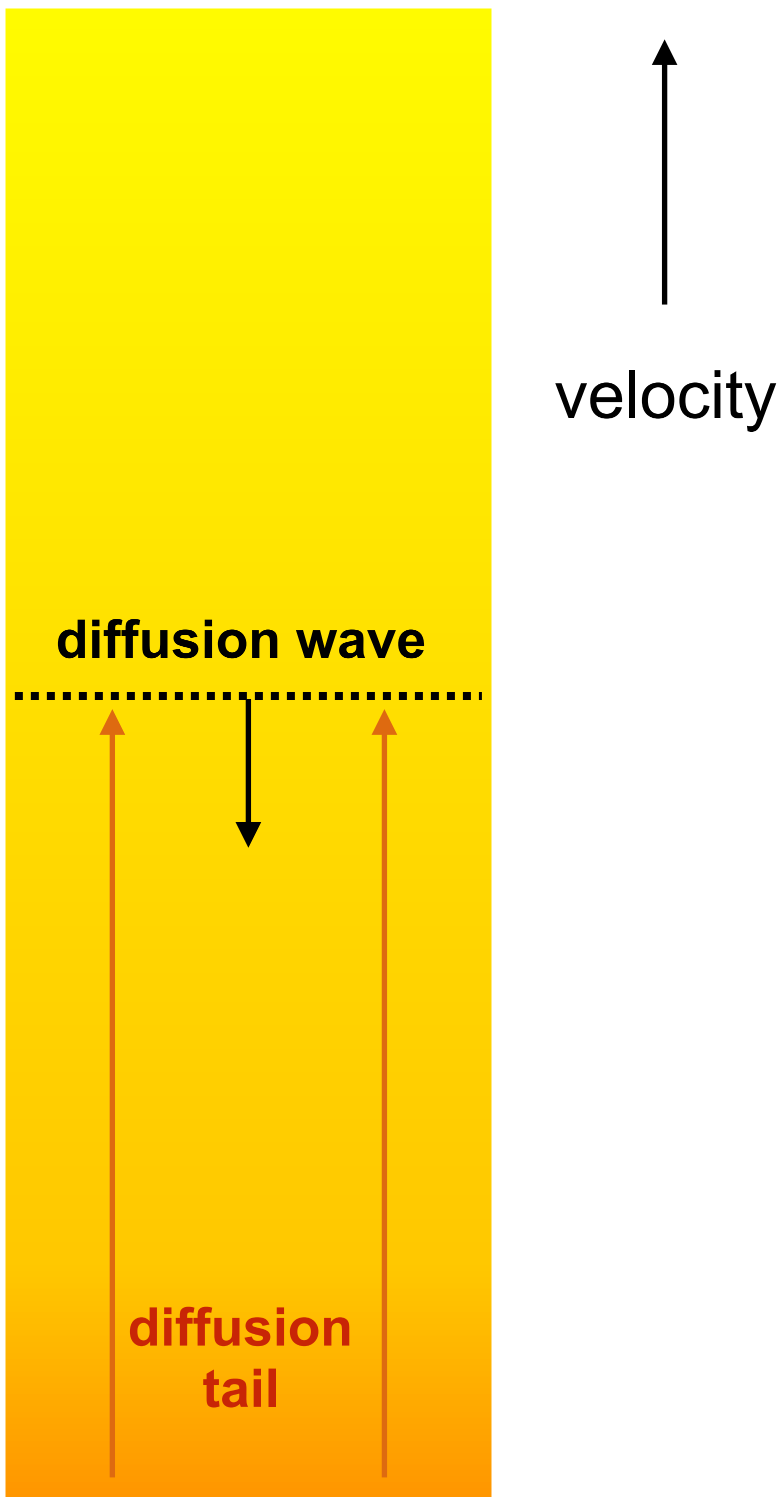
- **Thus, in principle, detection of the rise of the Ni light curve should provide an estimate of the distribution of Ni56**



^{56}Ni Deeper than Diffusion Depth

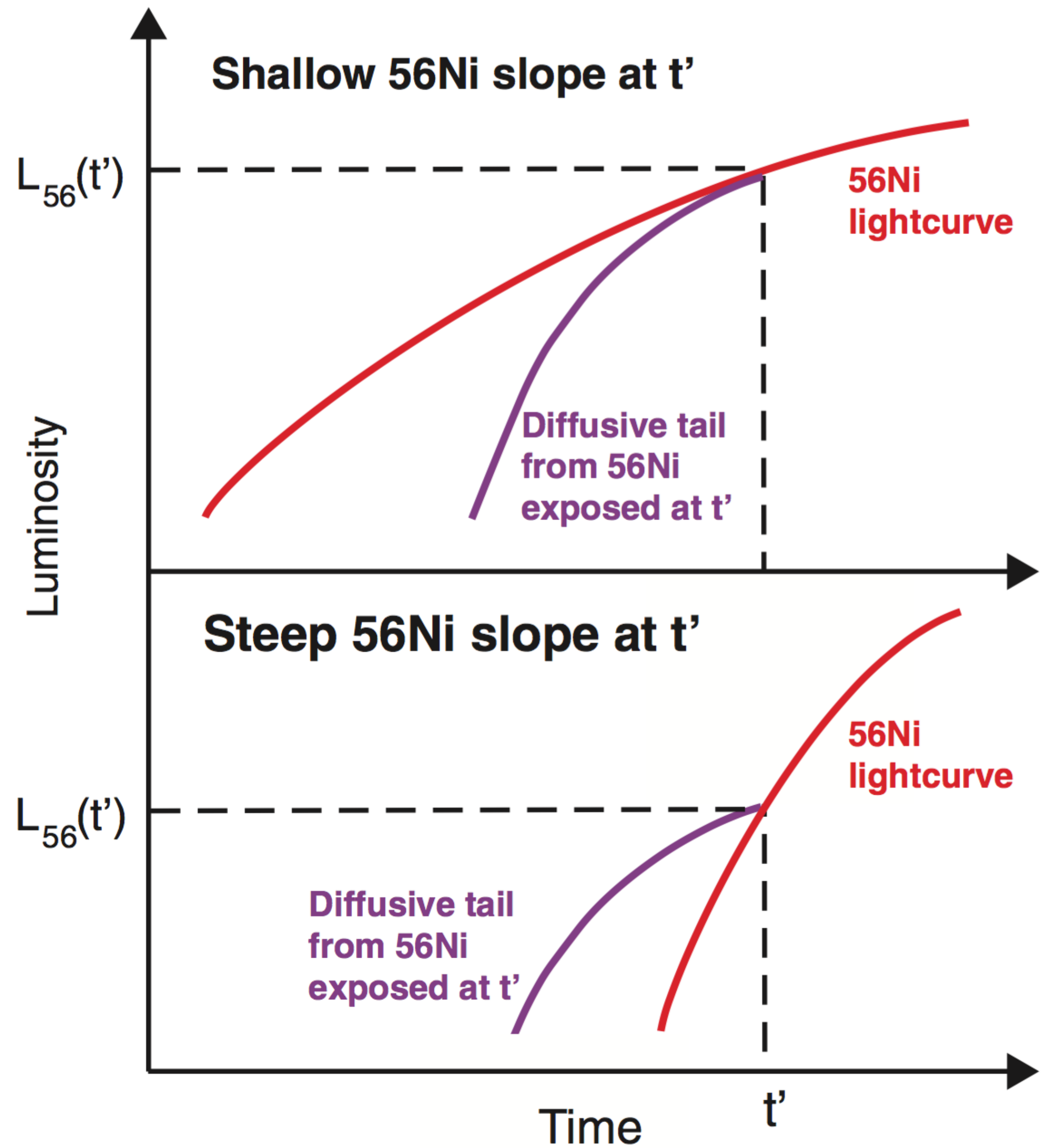
- If there is **a steep increase** in the Ni56 abundance, then the assumption that the observed emission is generated only by the composition **at the location of the diffusion wave may not be valid.**

- A “diffusive tail” of the energy released in Ni-rich layers deeper than the diffusion depth may actually **dominate over** the energy released in Ni-poor layers shallower than the diffusion depth.



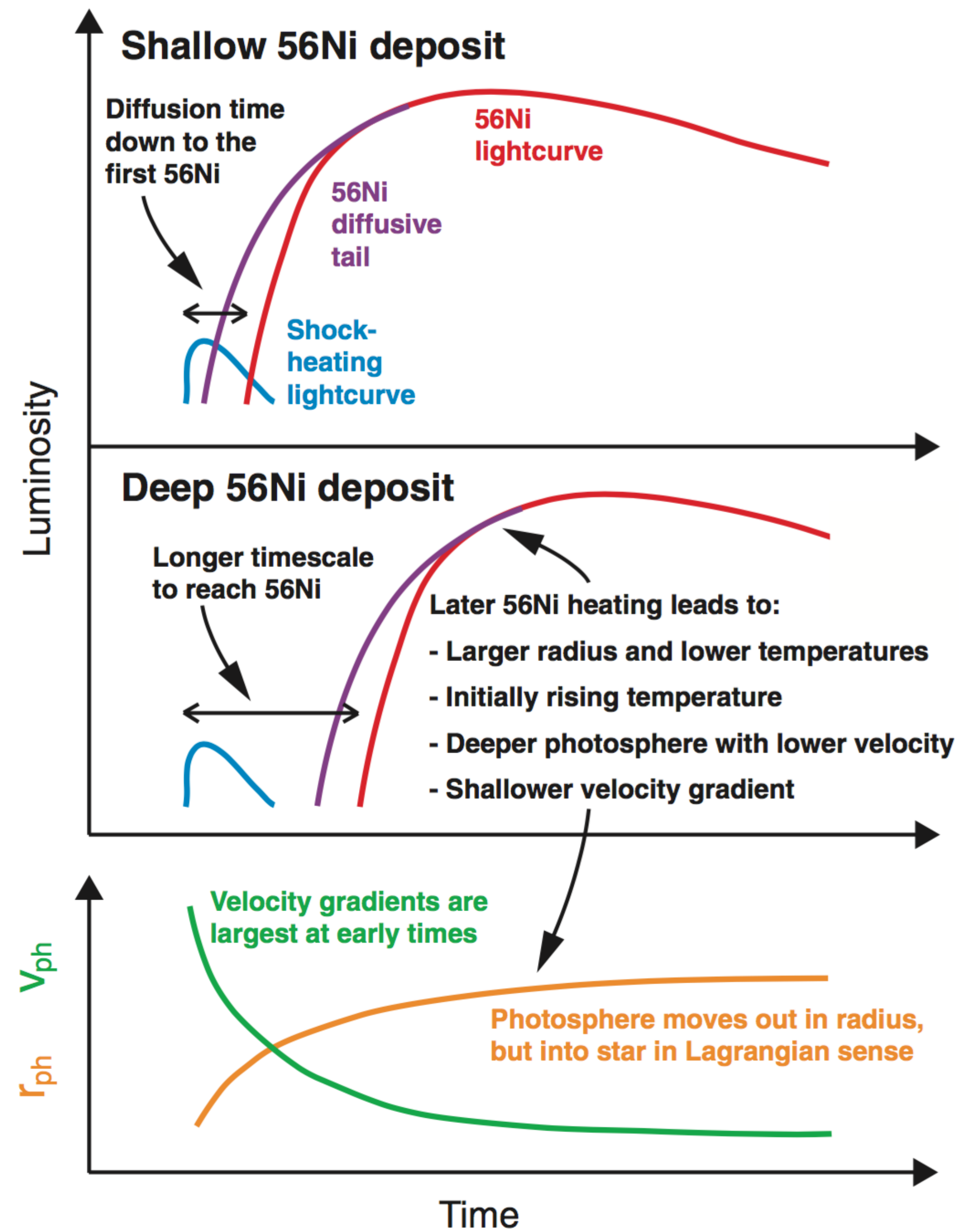
Light Curve for Different ^{56}Ni Distribution

- In the top panel, the Ni56 has a rather shallow distribution which produces the L_{56} (t), in which case, **the diffusive tail always falls below the L_{56} light curve**.
    - This is a case where the shallow Ni56 prevents the diffusive tail from having a noticeable impact, and M_{56} can be approximated from the observations. Furthermore, $X_{56} \approx M_{56}/\Delta M_{diff}$ can be inferred as a function of time if the explosion time is well constrained
- In the bottom panel, the Ni56 has a steeper distribution. When the diffusive tail is drawn back from a point at time t′, **it exceeds the L_{56} light curve.**
    - In this case, the diffusive tail will dominate the observed rise, and this must be accounted for before attempting to infer M_{56}



Importance of Time of Explosion

- If the Ni56 is deposited into rather shallow layers, the timescale between the beginning of the explosion and the rise of the light curve is fairly short.
    - In this case, the time of explosion could be reasonably well approximated by extrapolating the ^{56}Ni light curve back in time.
- If the Ni56 is deposited in deeper layers, and correspondingly the delay between the shock heating and rising light curve is longer.
    - In this case, extrapolating the Ni56 light curve back in time would provide a poor estimate for the time of explosion
- **One cannot simply estimate the time of explosion by extrapolating the rising light curve back in time because its position relative to the moment of explosion depends on the depth of radioactive heating**



Clues about Depth of ^{56}Ni

- When the shock breakout and shock heating are not detected (as is often the case), **additional information from color or, even better, spectroscopic observations can be used to break the degeneracy between the depth of 56Ni and the time of explosion**.

- The time-dependent radius of the photosphere (orange curve) during an SN is

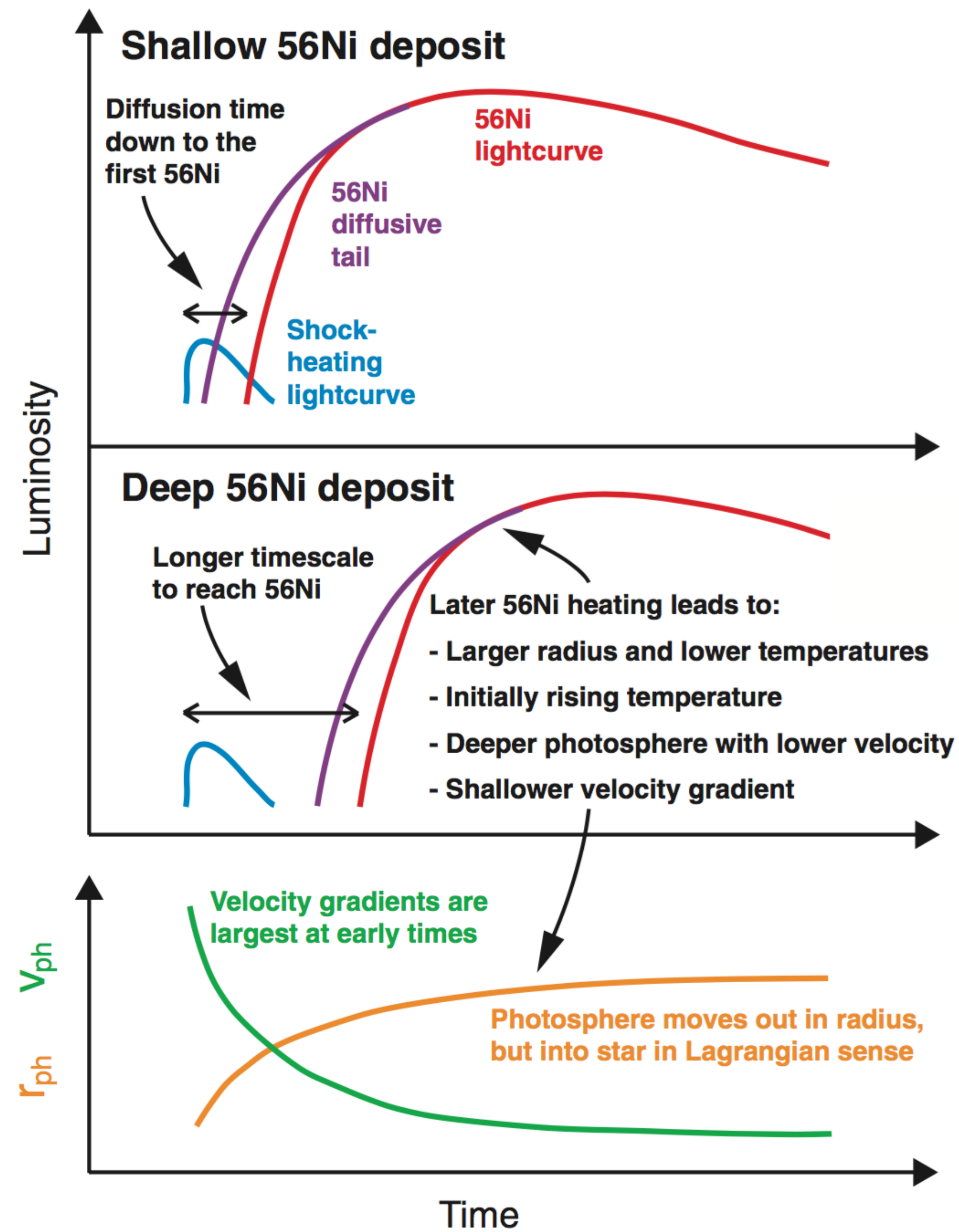
$$r_{\rm ph}(t) \approx 3 \times 10^{14} \frac{\kappa_{0.1}^{0.11} E_{51}^{0.39}}{M_1^{0.28}} \left(\frac{t}{1 \text{ day}}\right)^{0.78} \text{ cm},$$

- The observed color temperature is

$$T_c \approx \left(\frac{L\tau_c}{4\pi r_c^2 \sigma_{\rm SB}}\right)^{1/4} \gtrsim \left(\frac{L}{4\pi r_{\rm ph}^2 \sigma_{\rm SB}}\right)^{1/4}$$

- The photospheric velocity is

- $$v_{\rm ph}(t) \approx 35{,}000 \frac{\kappa_{0.1}^{0.11} E_{51}^{0.39}}{M_1^{0.28}} \left(\frac{t}{1 \text{ day}}\right)^{-0.22} \text{ km s}^{-1}$$



Minimum Explosion Time

- **A single measurement of the photosphere velocity and color temperature during the rise can provide a strict, model-independent, upper limit to the time of explosion before that measurement.**

- The bolometric luminosity is $L \approx 4\pi r_c^2 \sigma_{SB} T_c^4 / \tau_c$. $r_c \approx v_c t_{exp}$

- One can estimate the explosion time as $t_{exp} \approx \left(\frac{L\tau_c}{4\pi v_c^2 \sigma_{SB} T_c^4} \right)^{1/2}$.

- It is therefore useful to have a quantity that can simply be estimated directly in terms of observable quantities.

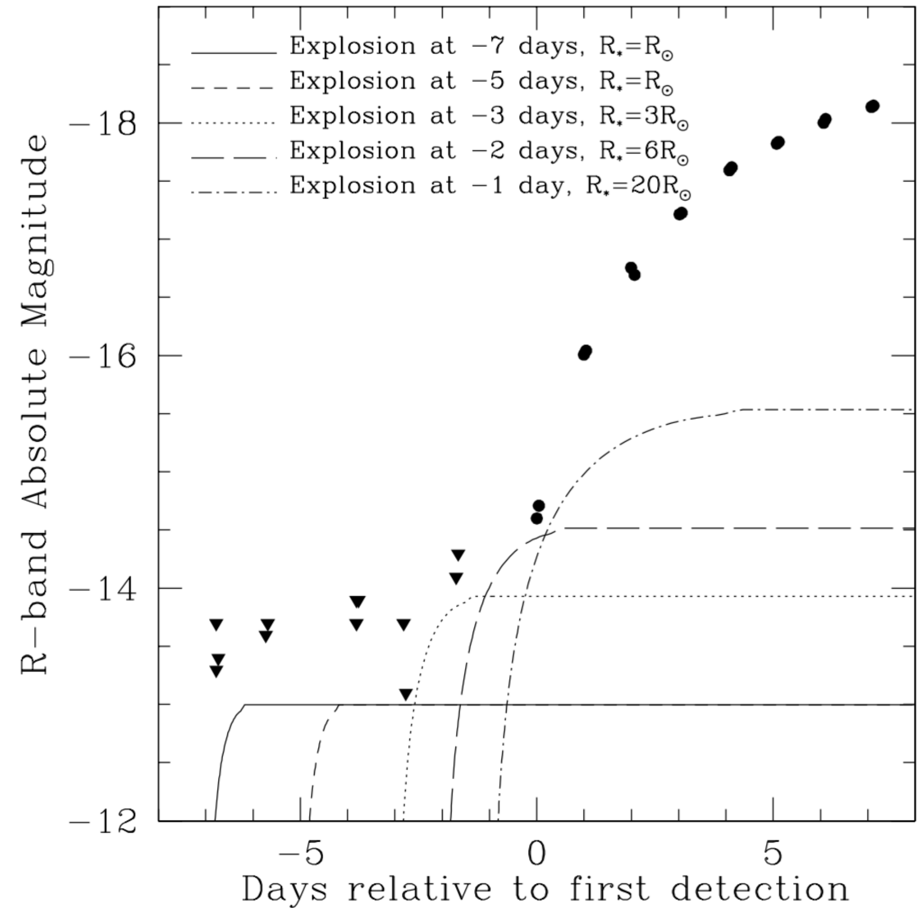
$$t_{min} \equiv \left(\frac{L}{4\pi v_{ph}^2 \sigma_{SB} T_c^4} \right)^{1/2} = \frac{t_{exp}}{\tau_c^{1/2}} \left(\frac{v_c}{v_{ph}} \right) \lesssim t_{exp}.$$

$$t_{min} = 4.3 \left(\frac{L}{10^{42}\ \mathrm{erg\ s^{-1}}} \right)^{1/2} \left(\frac{T_c}{10^4\ \mathrm{K}} \right)^{-2} \left(\frac{v_{ph}}{10^4\ \mathrm{km\ s^{-1}}} \right)^{-1} \mathrm{days}.$$

- **Therefore, t_{min} is an observable quantity that provides a model-independent lower limit to the time of explosion. it only requires that the velocity and temperature of the SN be obtained at a single time.**

PTF 10vgv

- PTF 10vgv is an SN Ic that was discovered on 2010 September 14 with the Palomar Oschin Schmidt 48 inch telescope (P48) by the PTF survey
- In a previous image taken on 2010 September 12.4830, it was not seen down to a limiting magnitude of **R > 20.2**.
- Following detection, the R-band luminosity rises quickly to a peak ≈10 days later. A single **spectrum was taken ≈2 days** after detection.
- PTF 10vgv did have an early detection of the rising light curve and upper limits in the time before this.
- Without knowing the time of explosion, the radius can only be constrained to be **$R_* = 1$–$20R_\odot$**



$$L \approx 2\times 10^{41}\,\frac{E_{51}^{0.91}R_1}{\kappa_{0.2}^{0.82}M_1^{0.73}}\left(\frac{t}{1\ \mathrm{hr}}\right)^{-0.35}\ \mathrm{erg\ s^{-1}}$$

$T_c \approx 0.6$ eV as found for the plateau

$$L_p \approx 7\times 10^{40}\,\frac{E_{51}^{0.85}R_1^{0.78}}{\kappa_{0.2}^{0.69}M_1^{0.67}}\ \mathrm{erg\,s^{-1}},$$

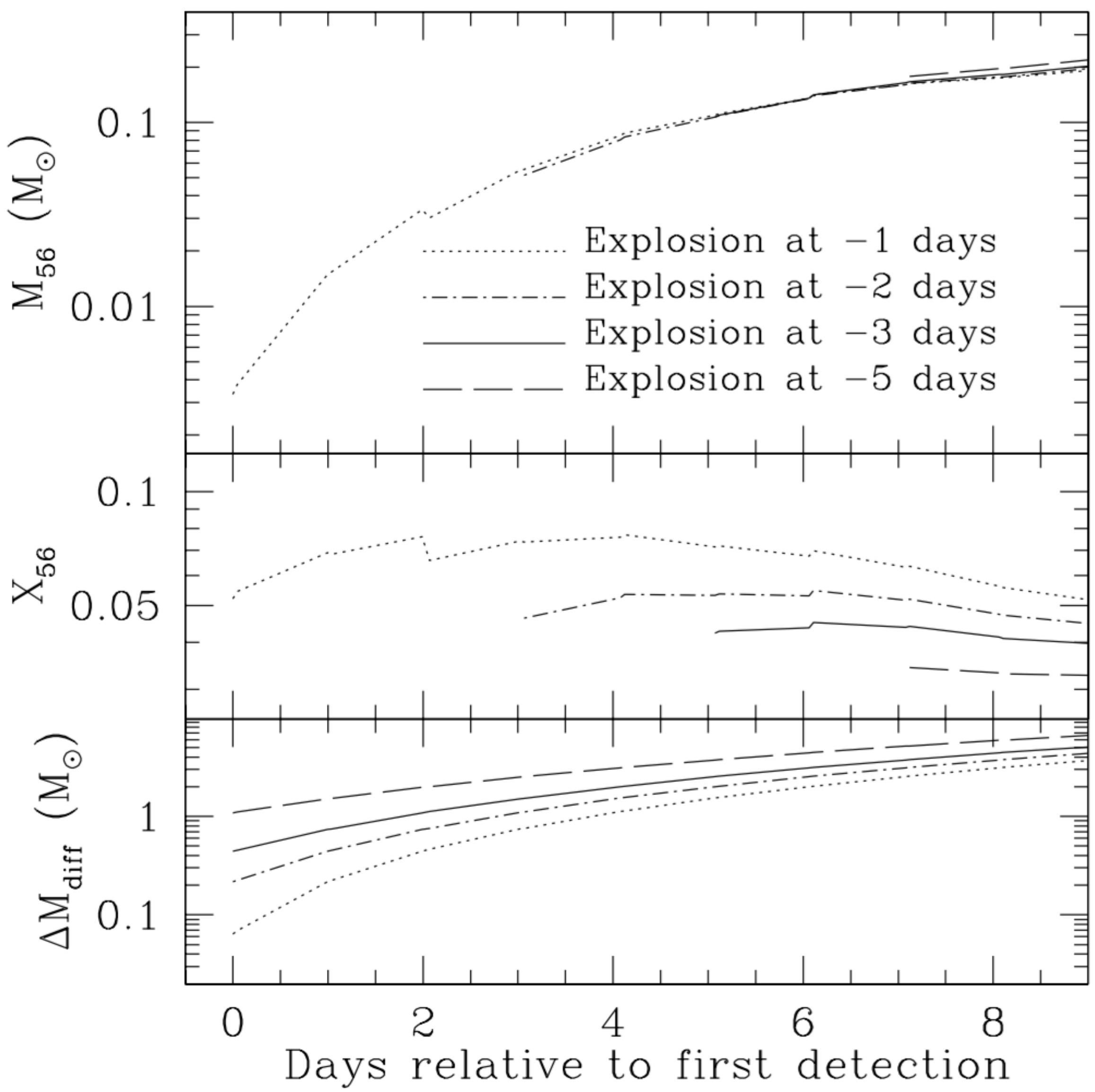
Bolometric Light Curve of PTF 10vgv

- In order to obtain the bolometric light curve with the Ni distribution, one must consider **the impact of a diffusive tail.**

- There is **a degeneracy between the explosion time and Ni distribution** unless more information is available.

- It is difficult to determine which of these three explosion times are more accurate from just this information.

- Nevertheless, one can still try to constrain **the mass and distribution of Ni56** as a function of the explosion time



Temperature and Velocity Constraints of PTF 10vgv

- If the correct temperature were known, then tight constraints could be placed on the time of explosion

- Using Equation

$$t_{\rm min} = 4.3 \left(\frac{L}{10^{42}\ {\rm erg\ s^{-1}}} \right)^{1/2} \left(\frac{T_c}{10^4\ {\rm K}} \right)^{-2} \times \left(\frac{v_{\rm ph}}{10^4\ {\rm km\ s^{-1}}} \right)^{-1} {\rm days.}$$

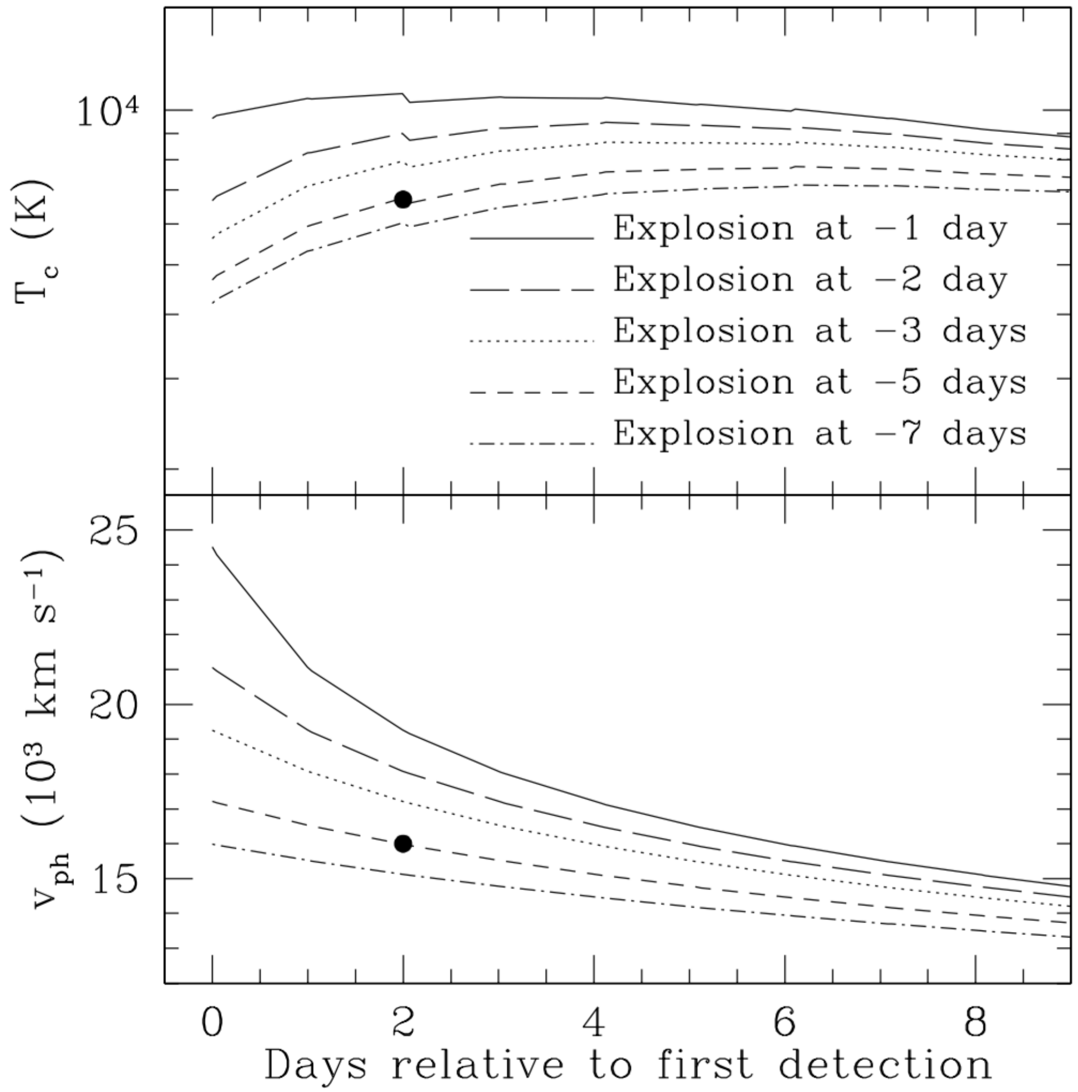
- One can estimate the minimum time of the explosion

$$t_{\rm min} \sim 7\ {\rm days.}$$

- It is powerful that **even a single velocity and temperature measurement provides such stringent constraints**

- If the temperature at 2 days past first detection is ~6700 K, then the explosion **occurred ~5 days or more** before first detection.

- The radius is constrained to be 1 R⊙ and the Ni56 must be located much deeper in the ejecta.



For $T_c = 6700$ K, $v_{\rm ph} = 16{,}000$ km s^{-1} and $L \approx 1.5 \times 10^{42}$ erg s^{-1}

Summary

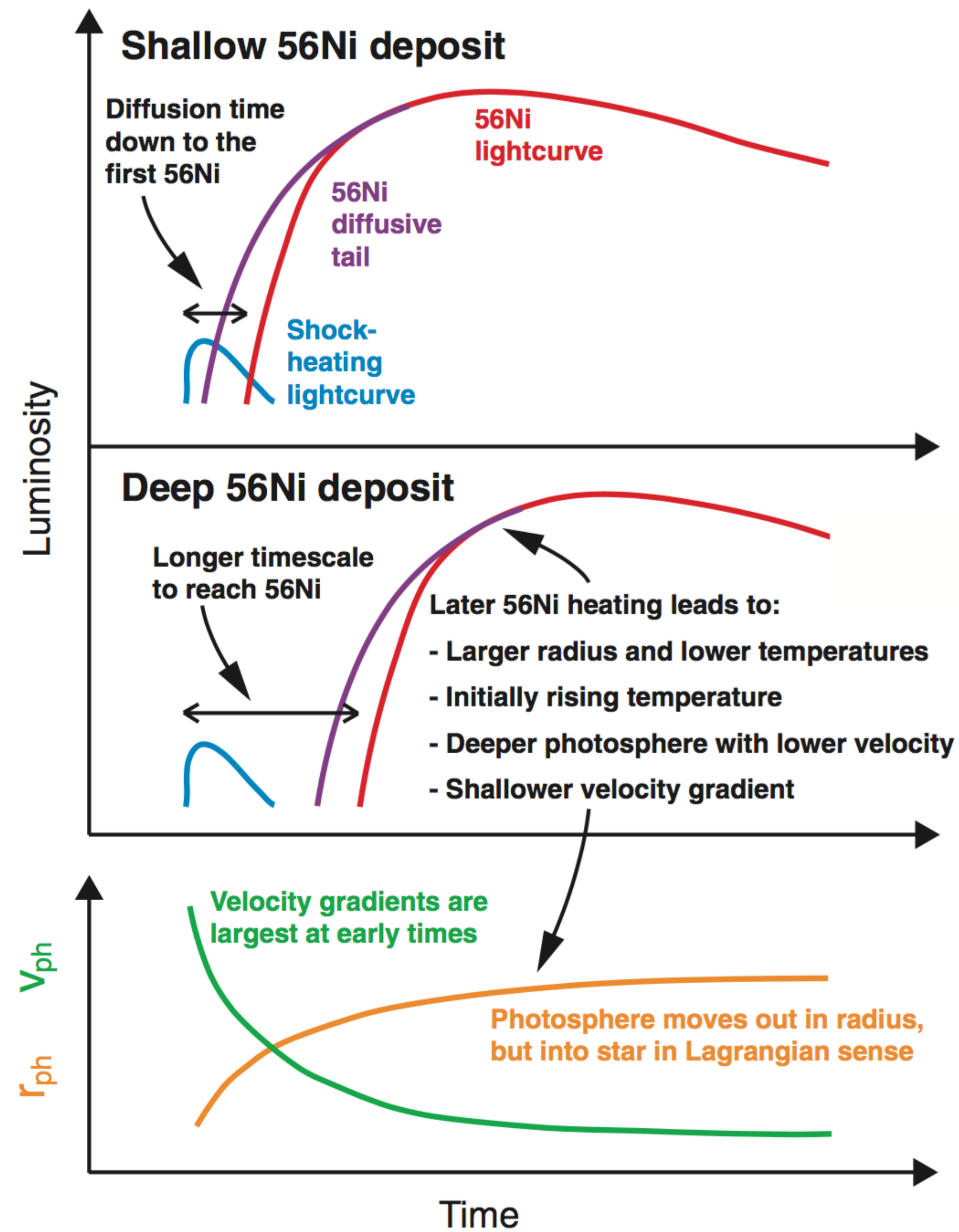
- An SN may exhibit a dark phase between the moment of explosion and the rise of the 56Ni light curve (likely first reflecting the impact of the diffusive tail).

- This means that extrapolating the Ni56 light curve back in time is not a reliable method for estimating the time of explosion, and that without a known explosion time, constraints on R_* are less stringent.

  - If caught when rising, shock-heated cooling can also identify the time of explosion.

  - Conversely, if the UV/optical rise is steeper than ~t^1.5, then this argues that the shock-heated cooling is not being observed, and the explosion time is not well constrained.

    - If the time of explosion is unknown, having even a single temperature and velocity measurement during the rise can go a long way toward supplementing the photometric data and provide strong constraints on the time of explosion

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