Early cooling emission

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With

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16 March 2012

Ofek, Rabinak et al. 2010, ApJ, 724,1396
Rabinak & Waxman 2011, ApJ, 728, 63
Rabinak, Livne & Waxman 2011, arXiv:1108.5548

SB and early emission obs.

- High cadence wide field ground based surveys, wide field hard X-ray space monitoring, and some luck (SN2008D).
- Source: SB and cooling env. emission of the outer $10^{-3} M_{\odot}$.
- Infer $\boldsymbol{R_*}$, **surface composition**, $\boldsymbol{A_\lambda}$ and $\boldsymbol{E/M}$ from the early emission.

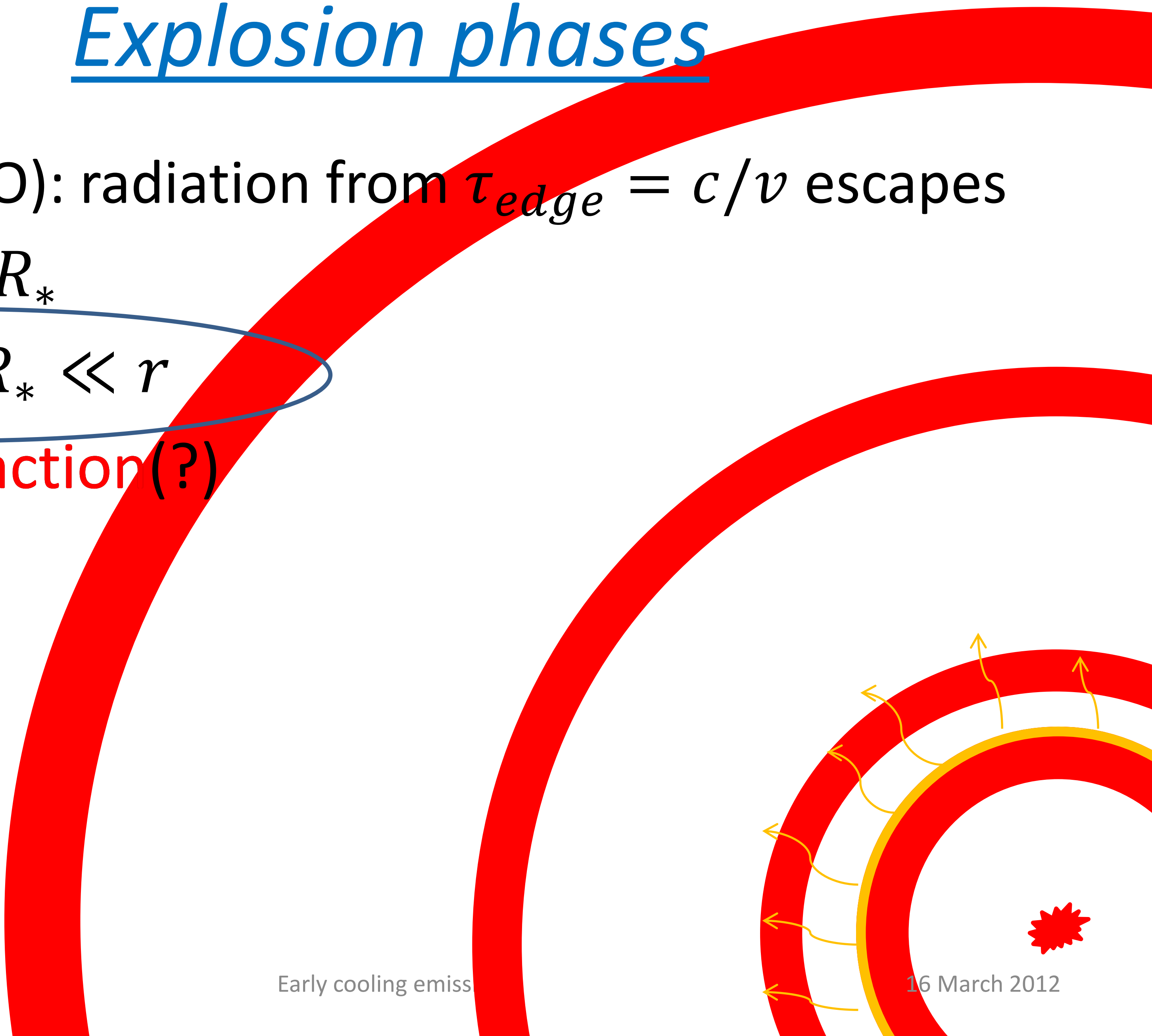
Explosion phases

Breakout (BO): radiation from $\tau_{edge} = c/v$ escapes

Planar: $r \sim R_*$

Spherical: $R_* \ll r$

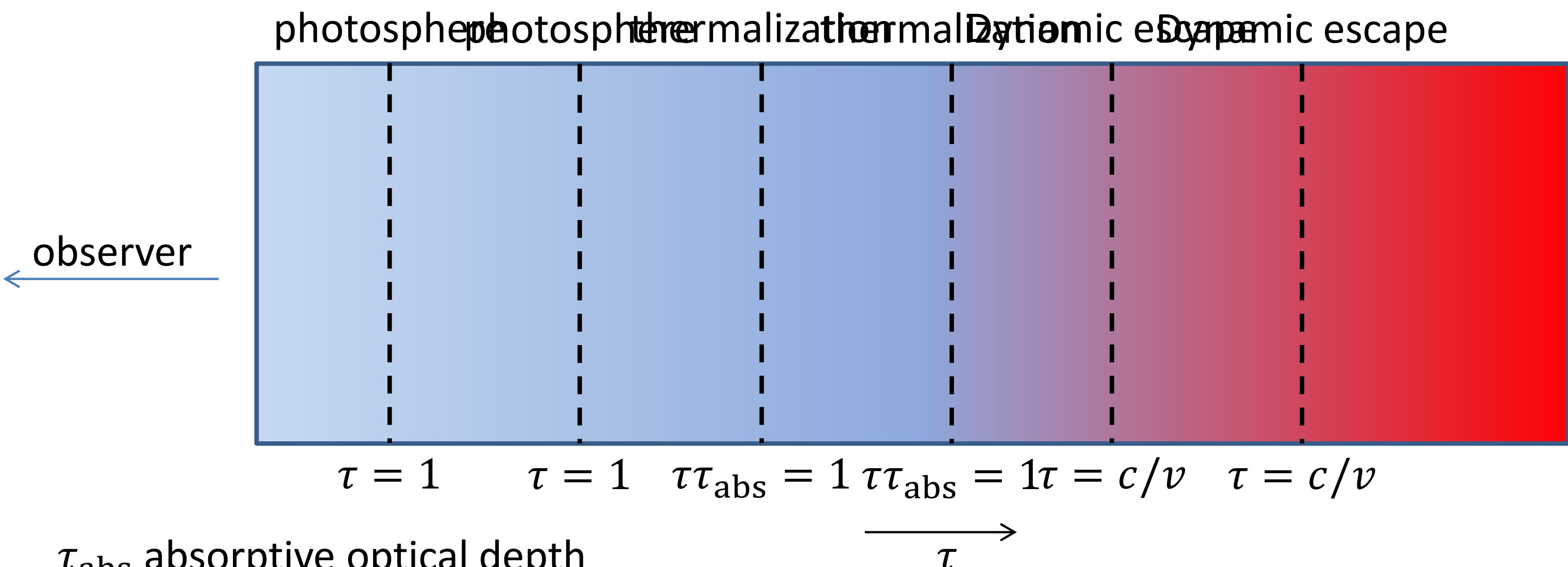
Wind interaction(?)



The emission

The energy of the emission is set by hydrodynamics

Typical photon energy is set by diffusion/thermalization



τ_{abs} absorptive optical depth

Results: early emission (const. κ)

- For $r \gg R_*$, for all $\rho_0(r)$[1]:

$$\delta M_{\text{photo.}}/M \approx 10^{-2.5}\frac{(\sigma_T/m_p\kappa)^{0.8}E_{51}^{0.8}}{(M/M_{sun})^{1.6}}t_{\text{day}}^{1.6};$$

$$E = E_{51}10^{51}\text{erg}$$

$$\text{R} = \text{R}_{12}10^{12}\text{cm}$$

$$T_{\text{eff.}} \approx 1(\sigma_T/m_p\kappa)^{-0.27}R_{12}^{1/4}t_{\text{day}}^{-1/2}\text{eV};$$

$$L_{\text{bol}} \approx 10^{42}(\sigma_T/m_p\kappa)^{-0.8}\frac{E_{51}^{0.9}R_{12}t_{\text{day}}^{-1/3}}{(M/M_{sun})^{0.7}}\text{erg s}^{-1};$$

$$f_T = T_{therm.-depth}/T_{\text{eff.}} \approx 1.2(\kappa_{\text{abs.}}/\kappa_{\text{abs. OP}})^{-1/8};$$

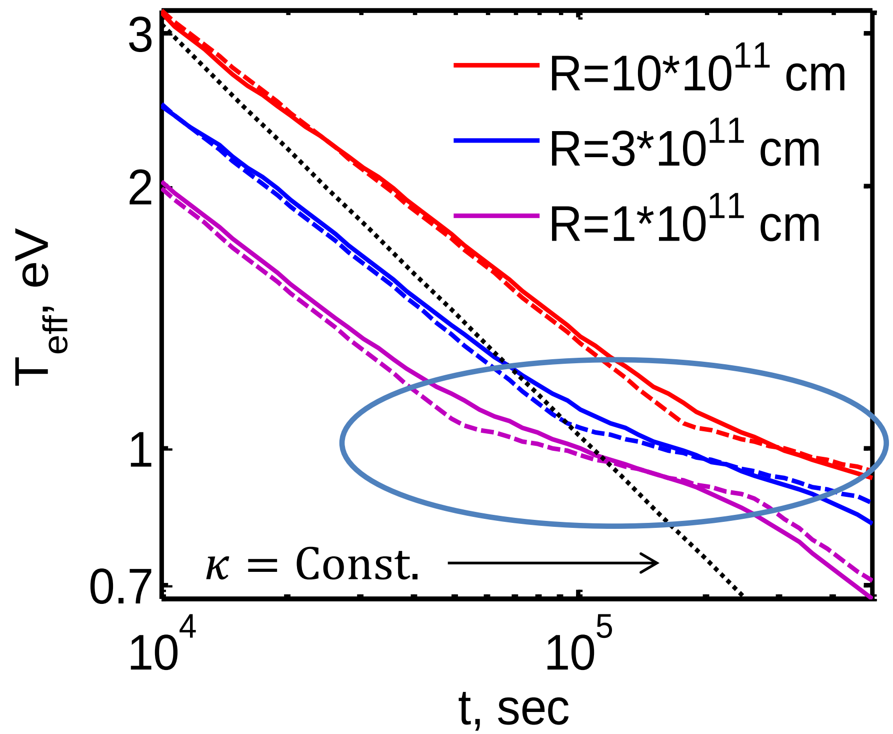
Measure R (from T), $/M(@\ \delta M = 0.003\ M_\odot)$

[1] [Rabinak & Waxman 2011]

Analytic approx

- κ declines with recombination
  - Small progenitors:
    Lower T < 1eV @ 1 day
    Absence of H

Solid: OP Table
Dashed: Approx



$X_{\mathrm{He}} = 0.7, X_{\mathrm{CO}} = 0.3$

- Consider 3 compositions
  - H: const. κ until $T \approx 0.5$ eV
  - He: moderate κ decline 3eV> T >1eV
  - C/O (& heavier): steeper κ decline 3eV> T >0.5eV

Inferring the extinction

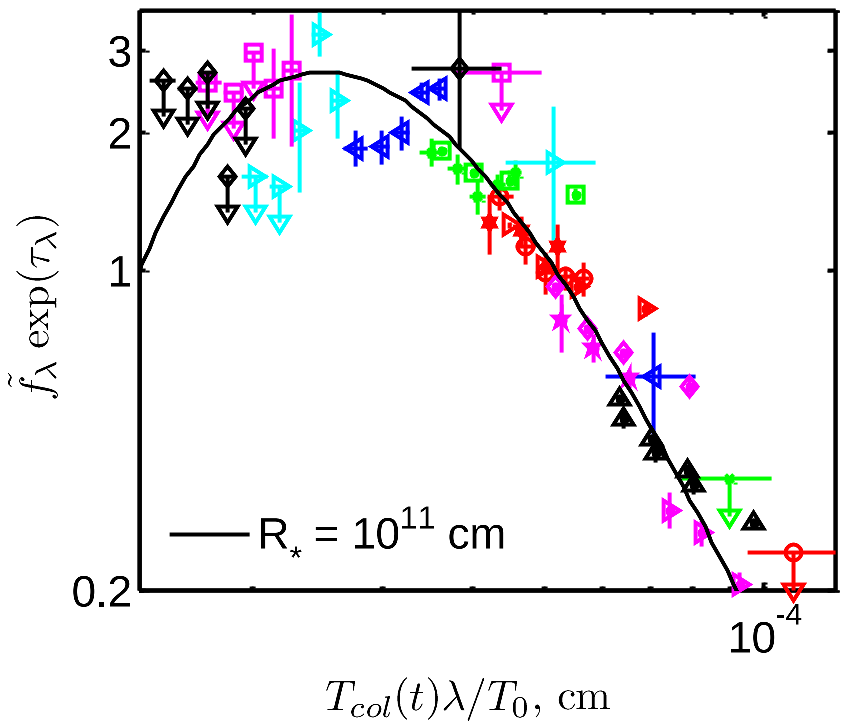
- Extinction distorts T_{col}. Note: $R_* \propto T_{\rm col}^4 \kappa^{-1}$
- Model predicted Obs.

$$f(\lambda; t) = \text{Const.} \times r^2(t) g_{\rm BB}\left[\frac{hc}{\lambda T(t)}\right] e^{-\tau_\lambda}$$

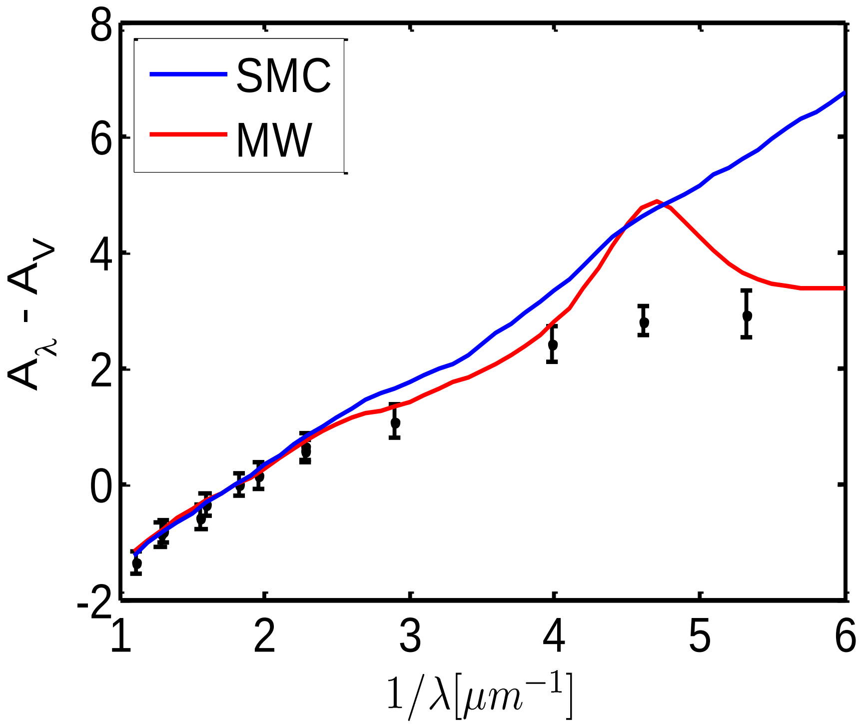
- Rescale Obs. $x = \lambda T(t)/T_0$ BB curve
- All obs. in λ, t fall on single BB up to extinction
- Recall: $T(R, \text{Comp.}; t), r\left(\frac{E}{M}; t\right)$

Example SN2008D

For the correct R & comp., scaling brings all $f_\lambda(t)$ to a universal form



Norm → relative extinction



R & comp. → relative extinction → extinction curve → E/M

SN2008D results

- SN2008D: R=10^{11} cm

  He with C/O

  Relative extinction curve, E(B-V) = 0.6

  $E_{51}/(M/M_{sun}) \approx 0.8$ (Assuming A_λ)

- Compare late spectroscopy[1,3]:

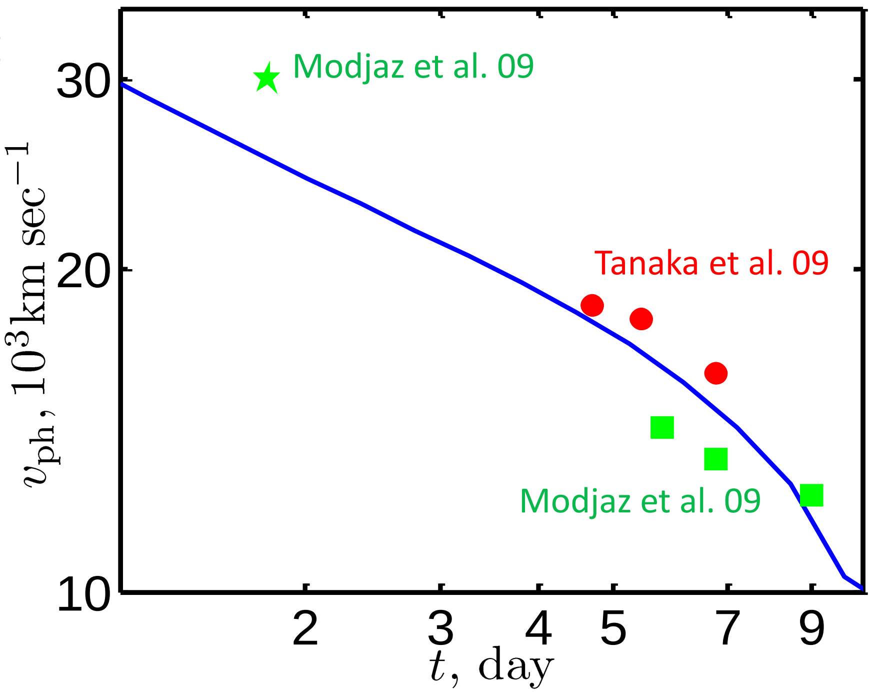
  $0.8 < E_{51}/(M/M_{sun}) < 1.3$

  30% C at 20,000 km/s

  $0.4 < E(B-V) < 0.8$

- Progenitor models[2]:

  $0.9 < R/10^{11}\mathrm{cm} < 1.9$



[1] [Soderberg et al. (2008)]
[2] [Tanaka et al. (2009)]
[3] [Mazzali et al. (2008)]

Early emission from Ia's: Compact progenitors

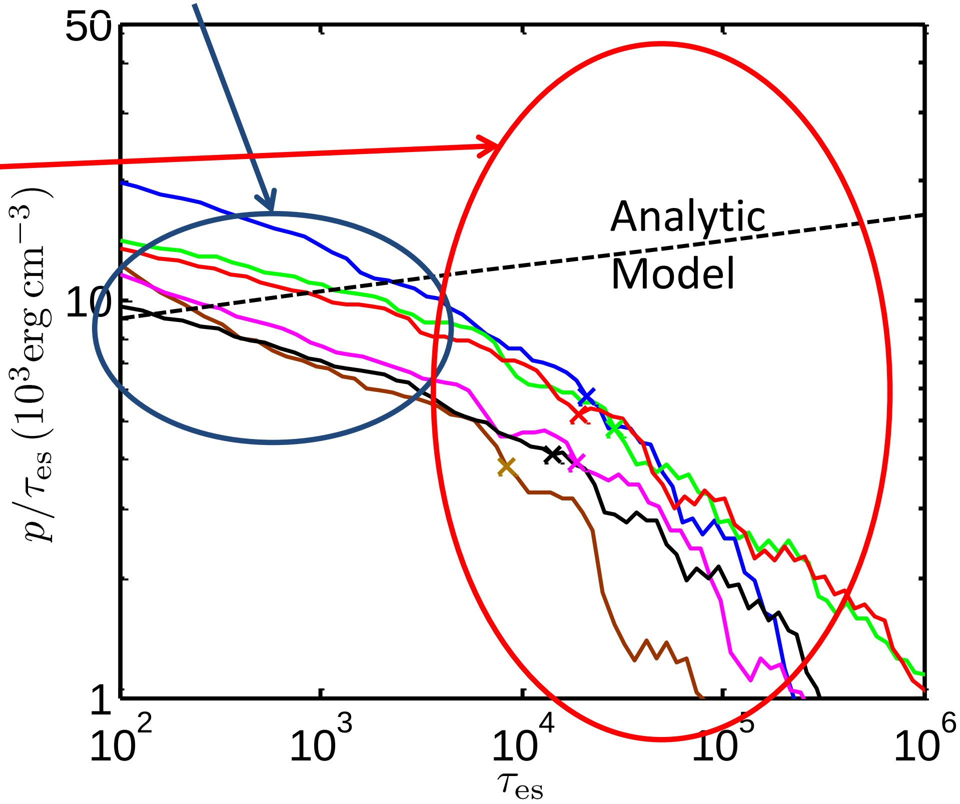
- Small progenitors $R_* < 3\times10^9 E_{51}^{-1} (M/1.4M_{\rm sun})^{4/3}$ cm
- Radiation do not dominate pressure throughout ejecta.
- Strong drop in emission starts when diffusion sphere reaches layers where $p_{\rm gas} = p_{\rm rad}$[1]

$$t_{\rm drop} = 1 \frac{E_{51}^{0.8} R_{8.5} (\sigma_T / m_p \kappa)^{0.5}}{(M/1.4M_{\rm sun})^{0.6}} \text{ hr.}$$

[1] [Rabinak, Livne & Waxman 2011]

SN Ia DDT Simulations: profiles for $r \gg R_*$

- Modification of pre-deton. $\rho(r)$ has small effect on final profile
- Deviation from radiation domination has large effect on $p(\tau)$



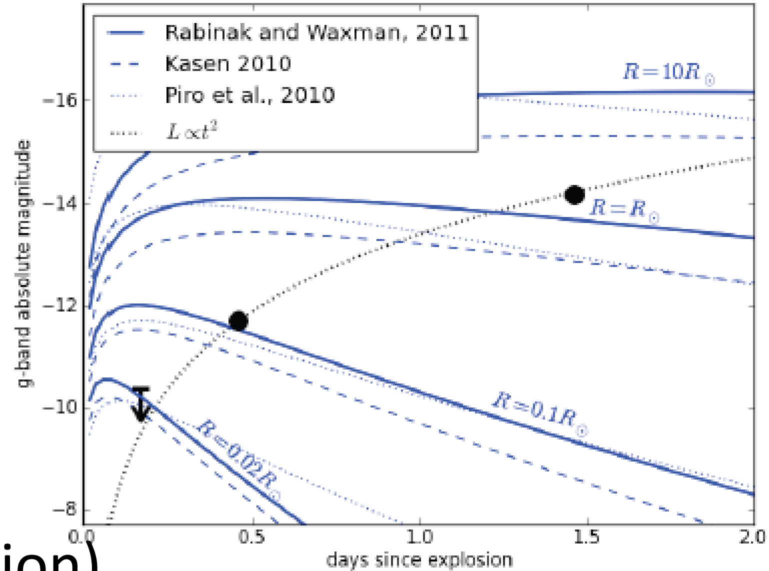
$$L_{bol} \approx 4\times10^{39} \frac{E_{51}^{0.8} R_{8.5}^{0.8} t_{hr}^{0.01}}{(M/1.4M_{sun})^{0.7}} \mathrm{erg\ s^{-1}};$$

$$T_{eff.} \approx 1.5 R_{8.5}^{0.2} t_{hr}^{-1/3} \mathrm{eV};$$

- Lower deflagration velocity higher luminosity $L \propto v^{-1}$

Direct upper limit for Ia progenitor R_*

- Upper limits on early emission set an upper limit to R_*
- Example Ia SN2011fe
  - $R_* < 10^{10}$cm[1]
    (detection $L_g \approx 10^{40}\,\mathrm{erg\,s^{-1}}$)
  - $R_* < 10^{9}$cm[2] →Degenerate
    (non detection 7hr before detection)
  - difficult to constrain radius below 3×10^{9}cm.



- Example Ic PTF2010vgv[3]: $R_* < 10^{11}$cm

[1] [Nugent+ 2011]
[2] [Bloom+ 2011]
[3] [Corsi+ 2012]

Summary

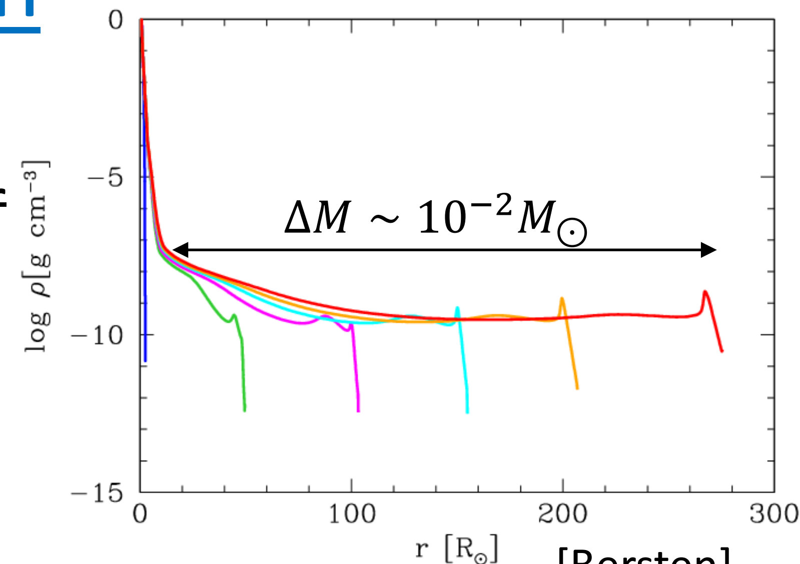
- Analytic model was derived for early cooling emission: including κ(recomb.+lines) & EOS.
- CC SN : given obs. on a day time scale
  - Obtain R and outer comp. of progenitor (A_λ indep.)
  - Obtain relative extinction & E/M
  - SN2008D: $R_* \approx 10^{11}$cm, He+C/O composition, $E_{B-V} = 0.6$.
- SN Ia : given obs. on an hour time scale
  - Constrain R_*
  - $R_* < 3 \times 10^9$cm for SN2011fe
  - Indicating to DDT explosion.

SN2011dh

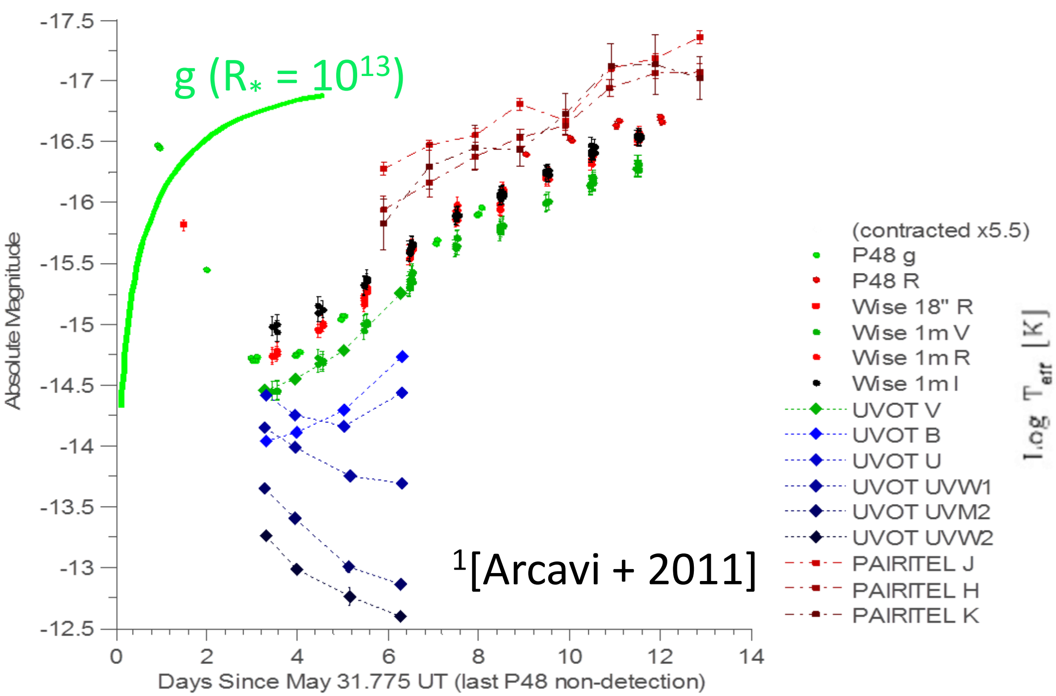
Pre-explosion image shows $R_* = 10^{13}$cm.

Problem[1]: LC rising @2 days→ ~~progenitor~~

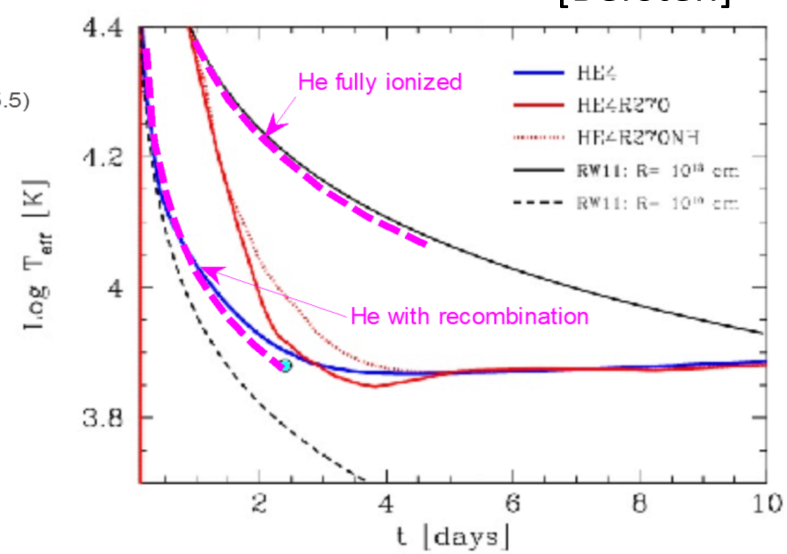
Solution (Bersten) : low mass extended envelope



[Bersten]



[1][Arcavi + 2011]



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The End