Type IIn SNe from PTF Mass-loss and precursors

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and the PTF and NuSTAR collaborations

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

Outline

- SN exploding in high optical depth CSM
  - Shock breakout (e.g., PTF09uj)
  - Radiative shock   collisionless shock
  - Interaction power (e.g., PTF10aaxf)

- Additional evidence:
  - peak lum. Vs. rise time
  - Balmer lines
  - Precursors

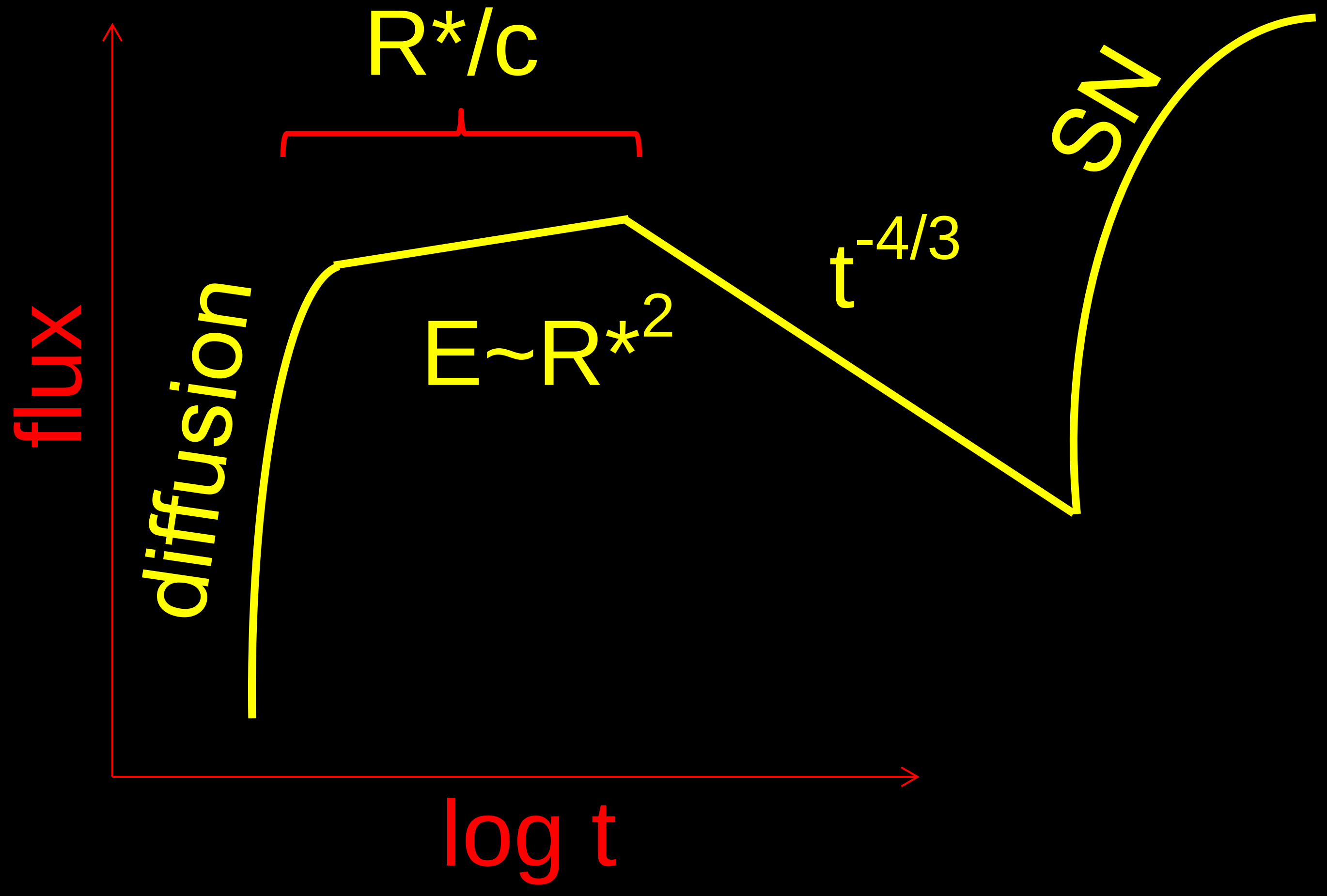
Shock breakout

- First photons emerge from the SNe when the photon diffusion time scale become shorter than the hydrodynamical time scale (i.e., photons are moving faster than the ejecta). [happens when $\tau \sim c/v$]
- Time scale and luminosity sensitive probes of progenitor radius

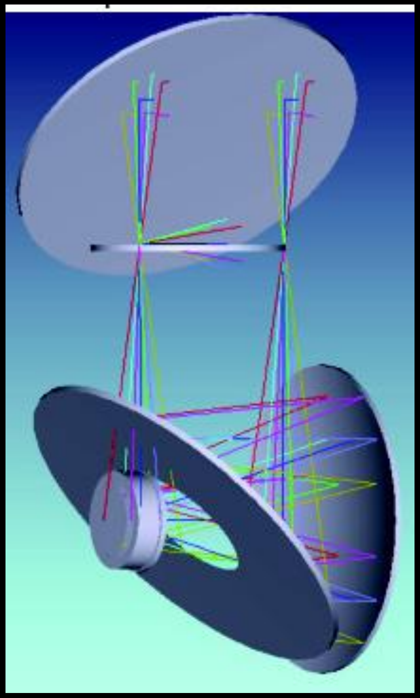
e.g., Colgate 1974; Matzner & McKee 1999
Nakar & Sari 2010; Rabinak & Waxman 2011

Obs: Soderberg+2008,...

Shock breakout / Intro

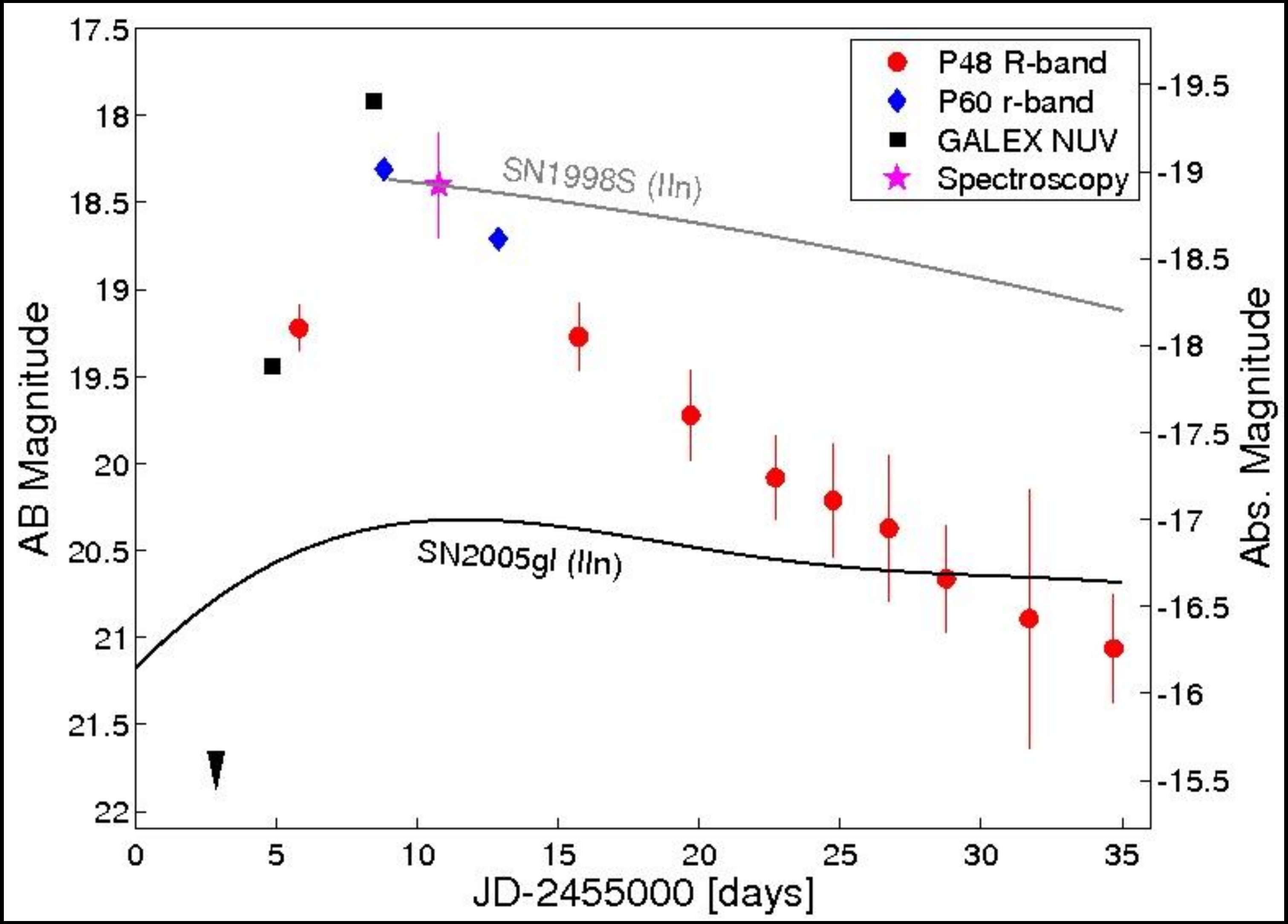


ULTRASAT



Shock breakout in CSM

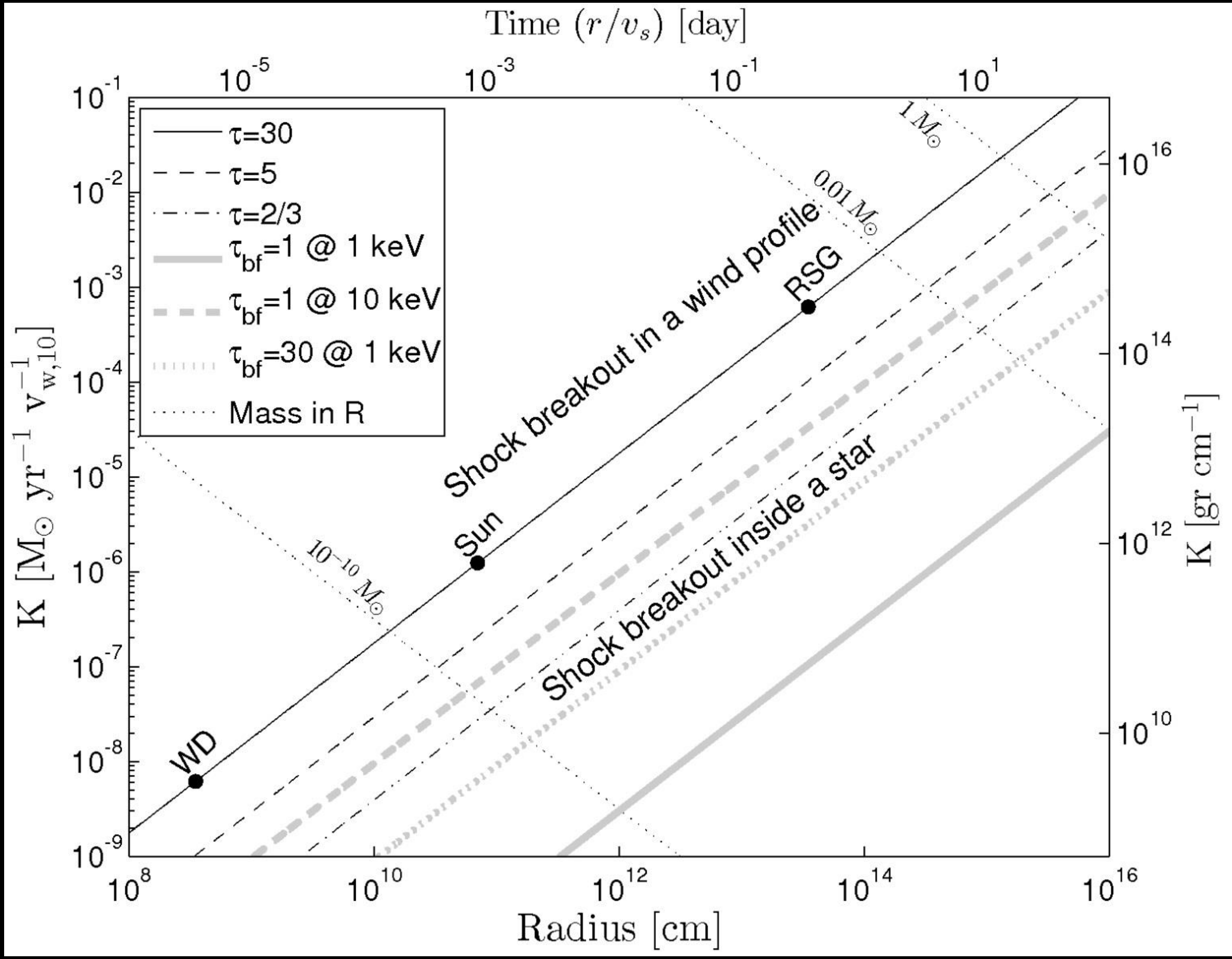
PTF 09uj



Ofek+2010 see also Chevalier & Irwin 2011

Optical depth

$\rho = Kr^{-2}$



Ofek+2013a

CSM interaction power

After shock breaks out, photon can't support
Shock and the shock become collisionless (e.g. Katz+11)

$$\left.\begin{aligned}
\rho_{ej} &\propto t^{-3}\left(r/t\right)^{-m} \\
\rho_{csm} &\propto r^{-w} \\
r_s &\propto t^{(m-3)/(m-w)} \\
v_s &\propto t^{(w-3)/(m-w)}
\end{aligned}\right\}\ \text{Chevalier (1982)}$$

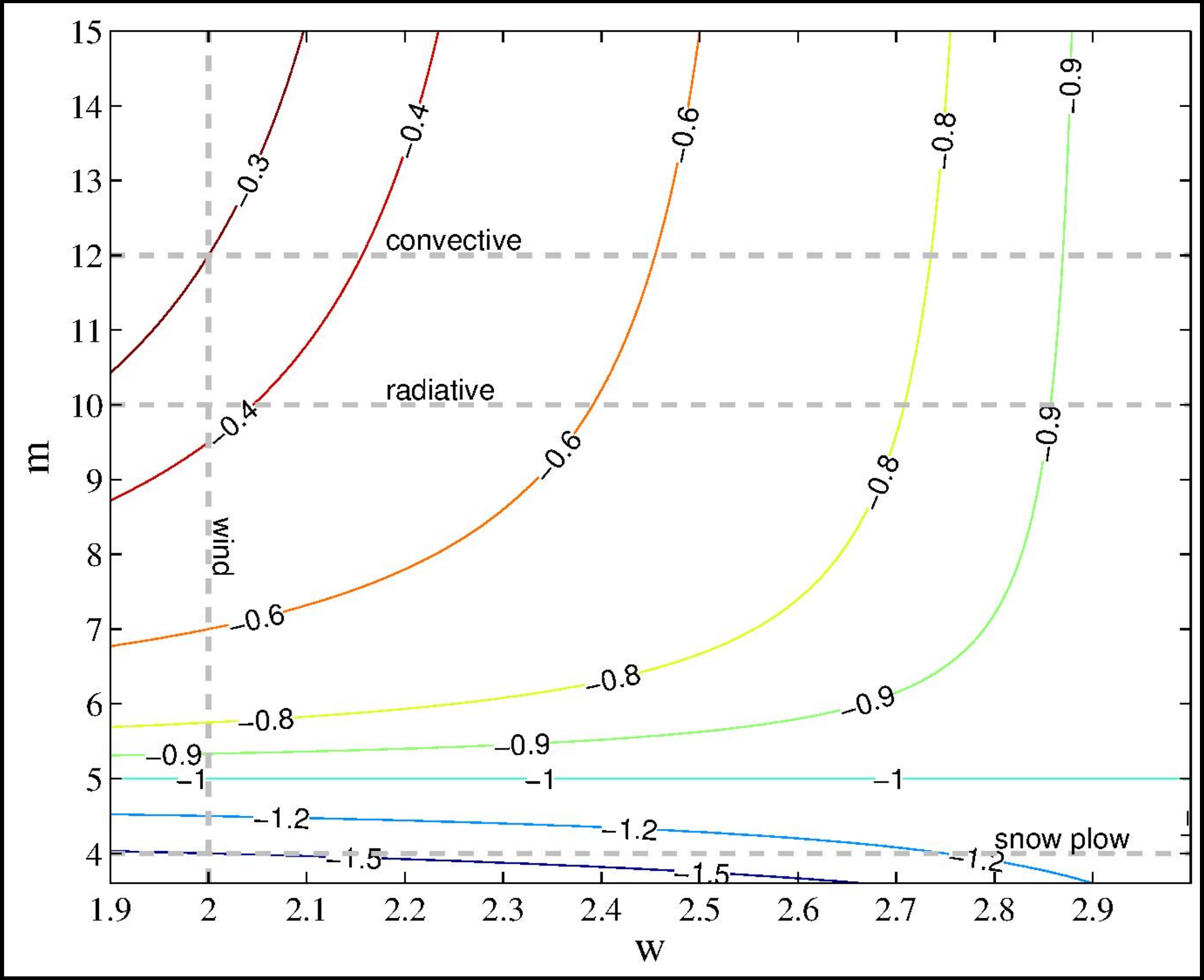
$$L = \varepsilon(\rho v_s^2/2)(4\pi r_s^2 v_s) \propto t^{\alpha}$$

Chevalier & Irwin 2012; Svirski+2012
Ofek+2014a

However, after ejecta accumulate mass
Equivalent to its own: α=-3/2

CSM interaction power

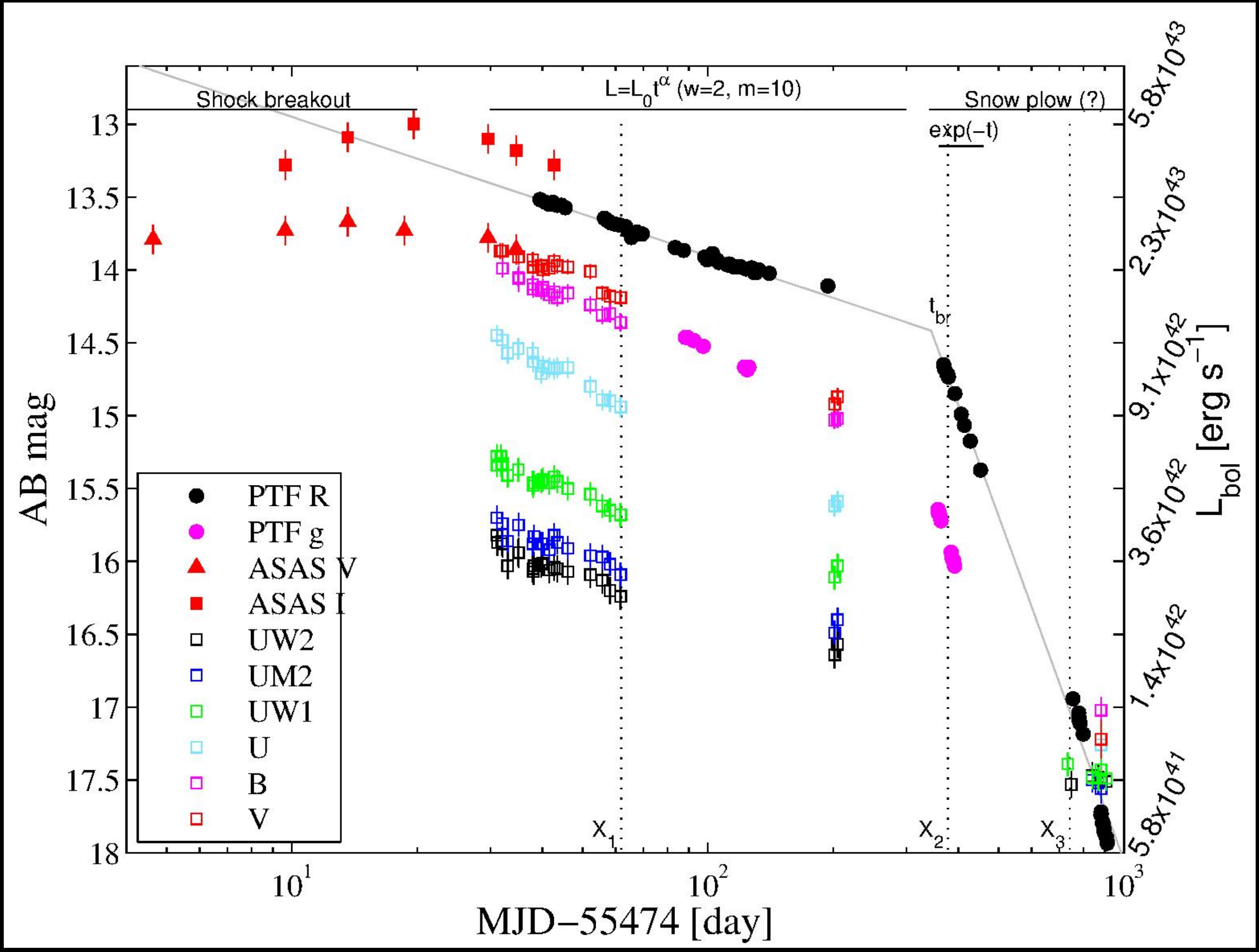
SN 2010jl (PTF10aaxf)



Ofek+2013d

CSM interaction power

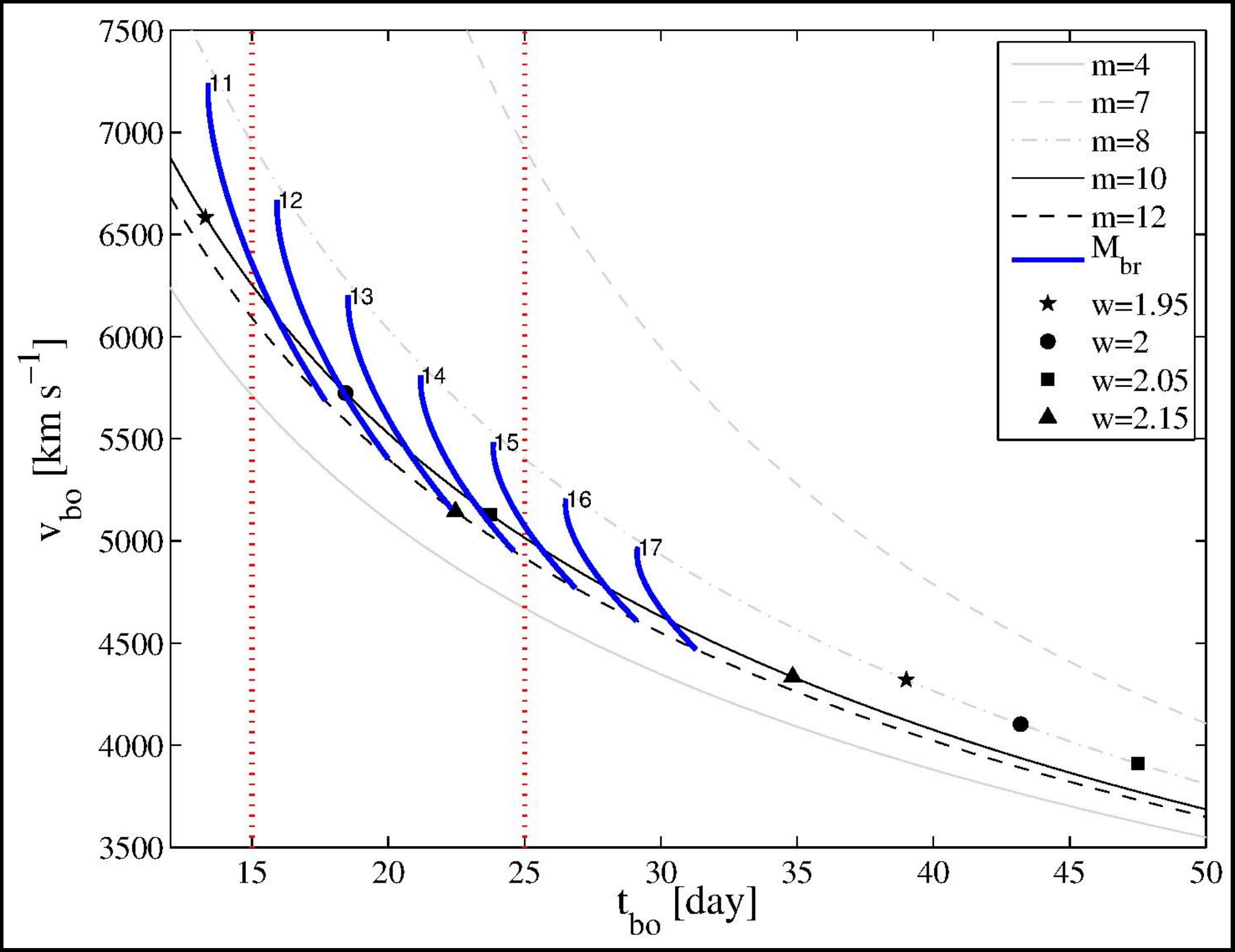
SN 2010jl (PTF10aaxf)



Zhang et al. 2012, Ofek et al. 2014a, Fransson et al. 2014

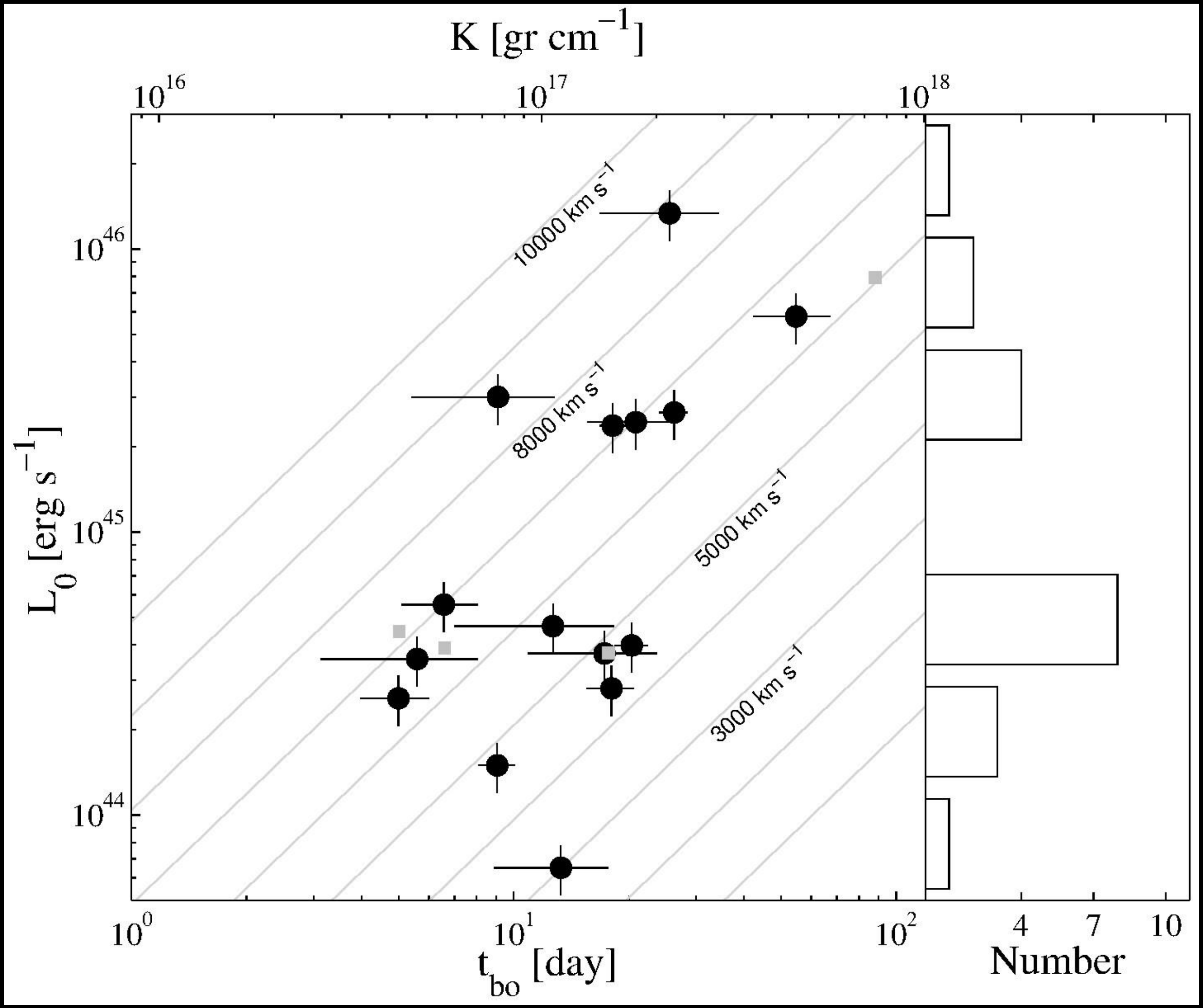
CSM interaction power

SN 2010jl (PTF10aaxf)



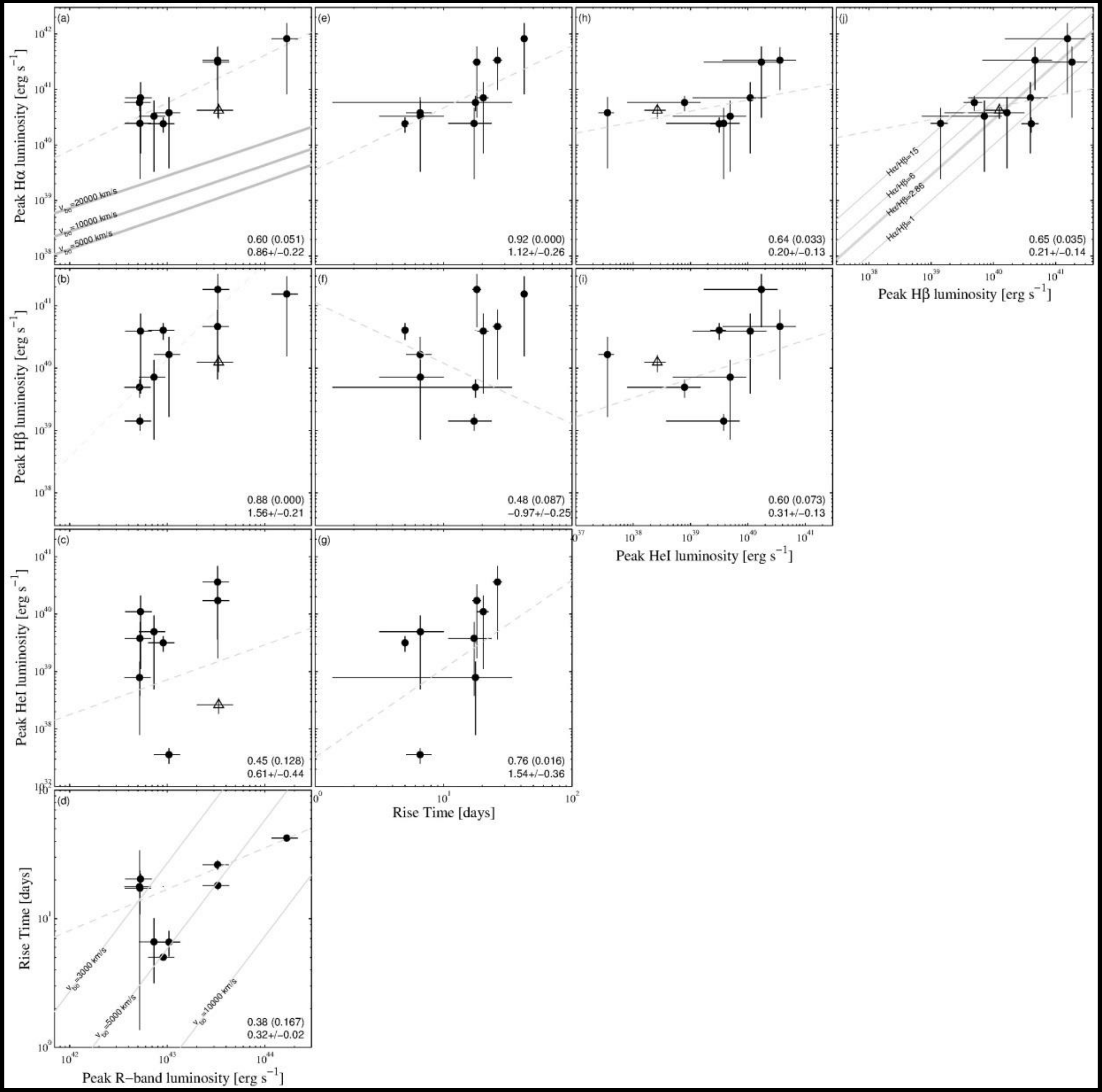
Ofek+2013d

Peak lum. Vs. rise time



Ofek+2014c

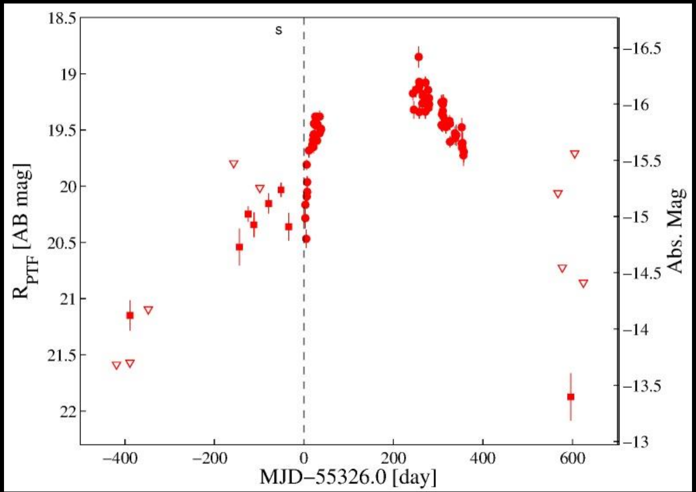
Emission lines

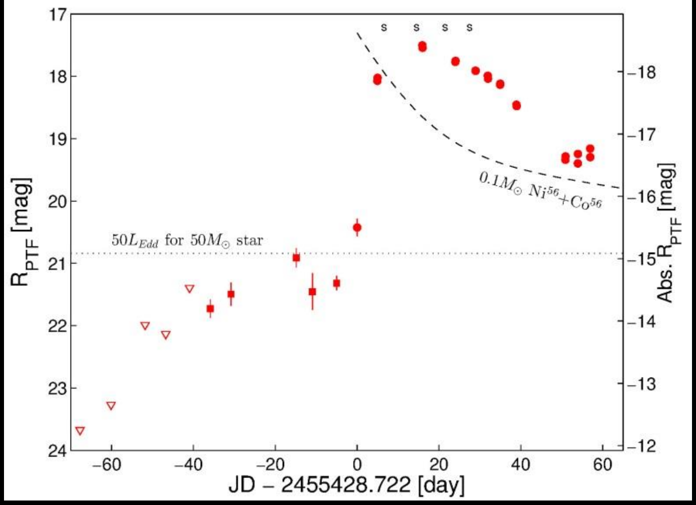


Ofek+ in prep.

Precursors

- PTF search among 16 IIn
- Precursors in 5 SN
- "Weak IIn" – less frequent
- >50% (99%CL) of IIn have precursors
- Rate >1/yr (abs mag>-14)
- Fainter precursors are more common

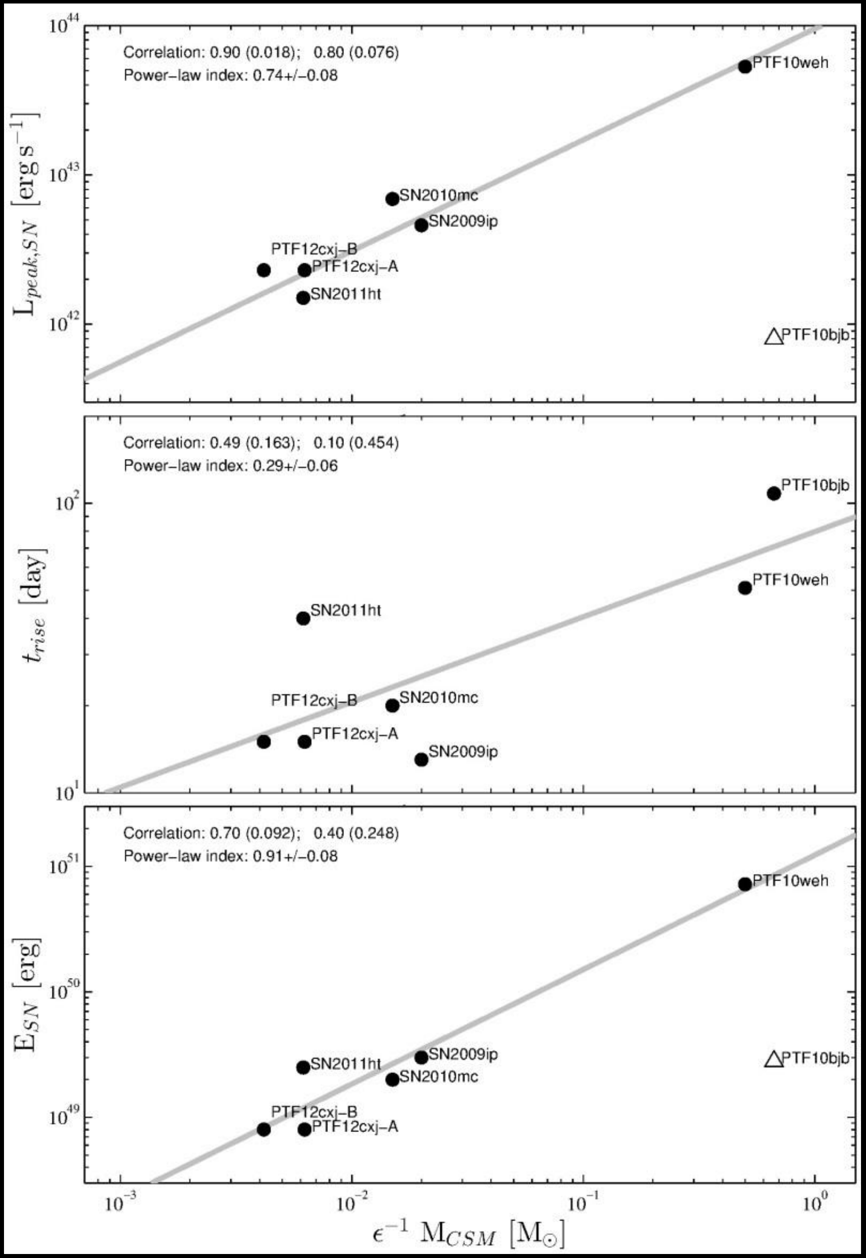




Ofek+2013b, 2014b

Precursors

- ★ Correlations(?)
- ★ Small sample…

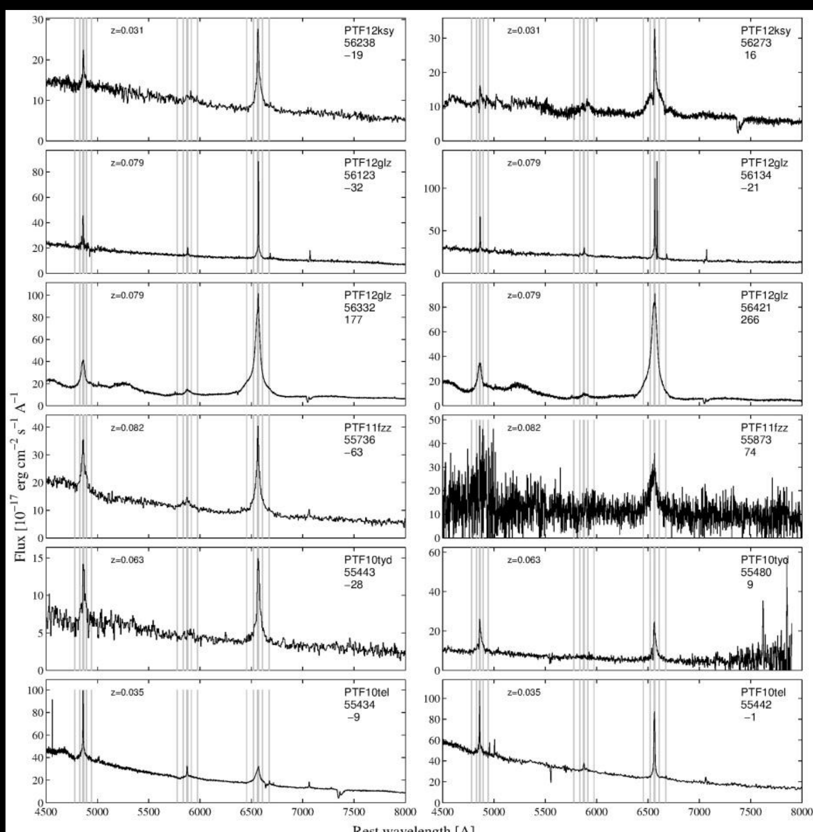


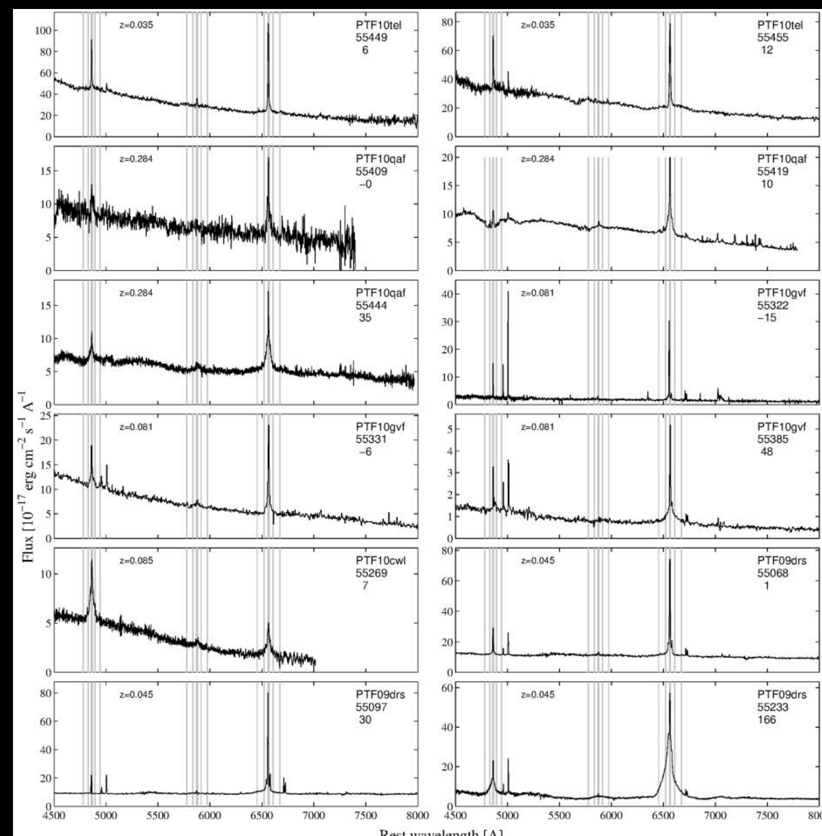
Ofek+2013b, 2014b

End

Thank you!

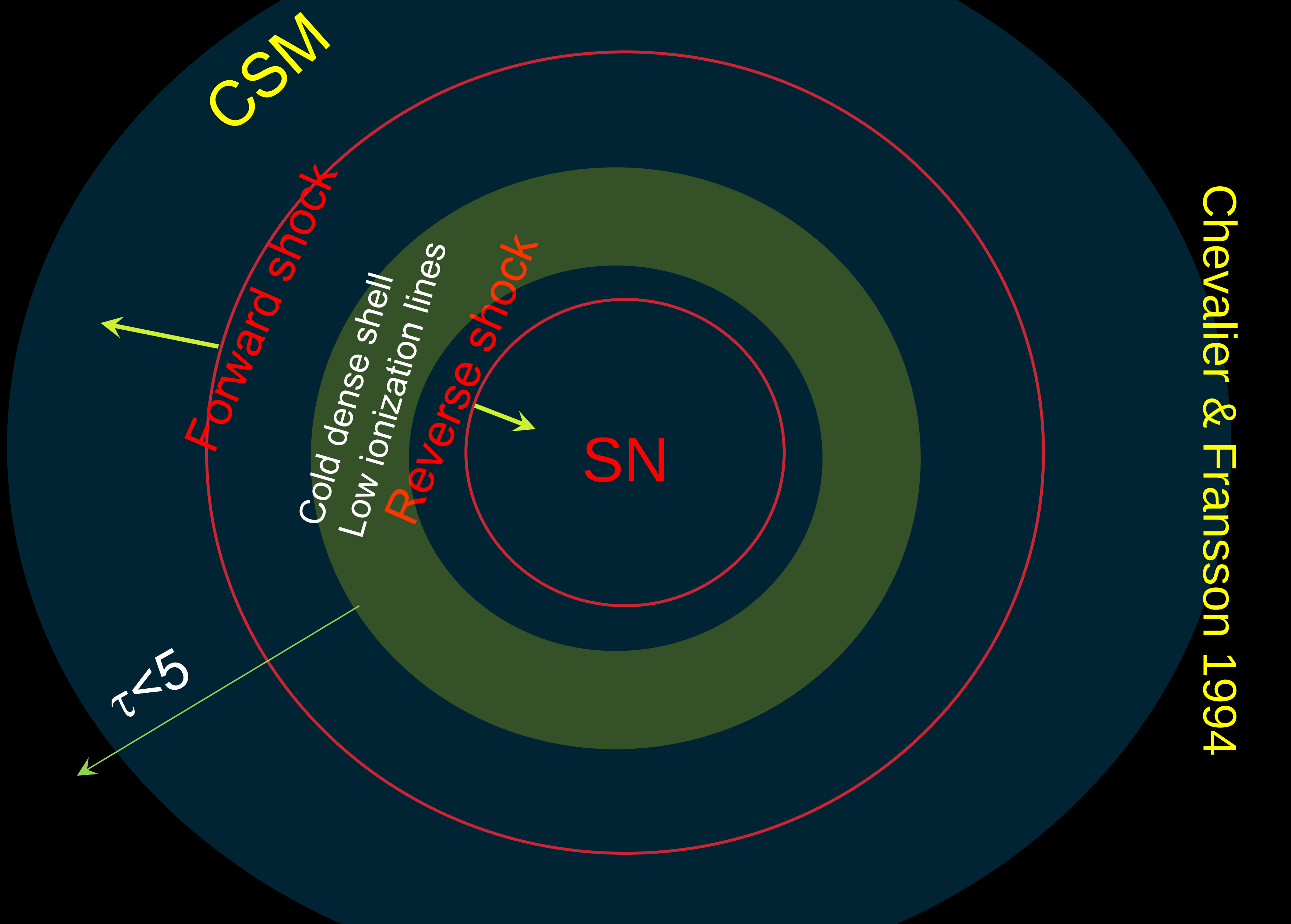
Evolution of the Balmer lines





Ofek+ in prep.

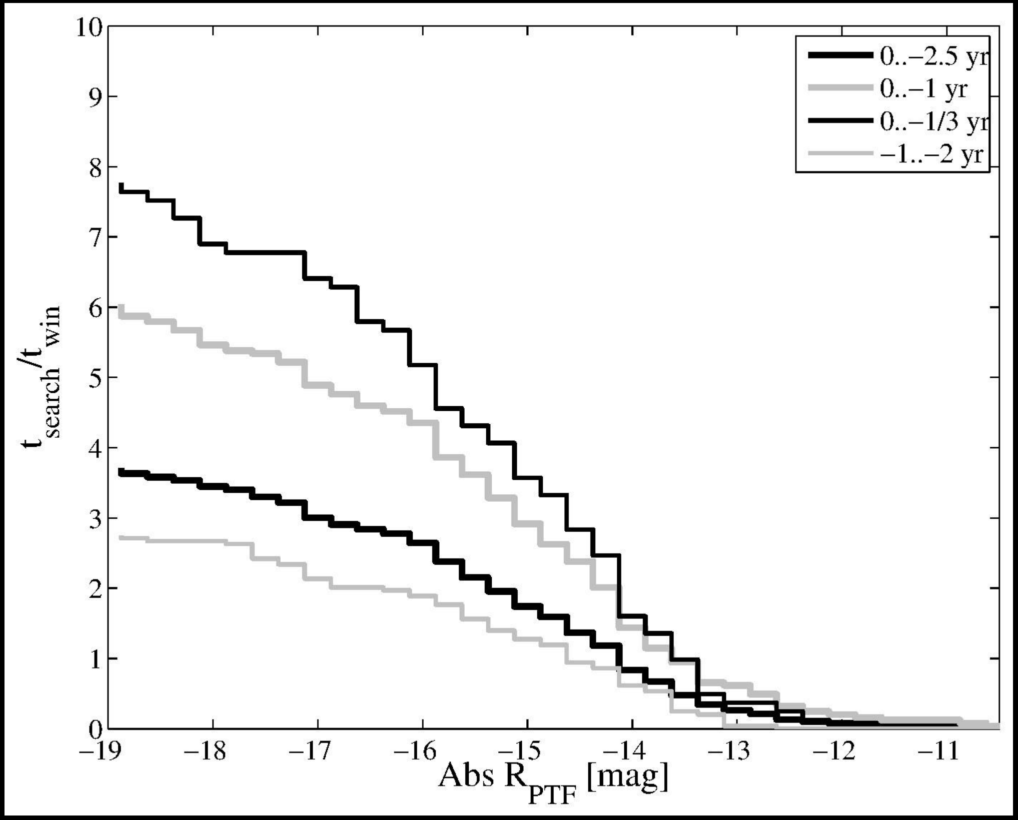
The picture


CSM
Forward shock
Cold dense shell
Low ionization lines
Reverse shock
SN
τ<5
Chevalier & Fransson 1994

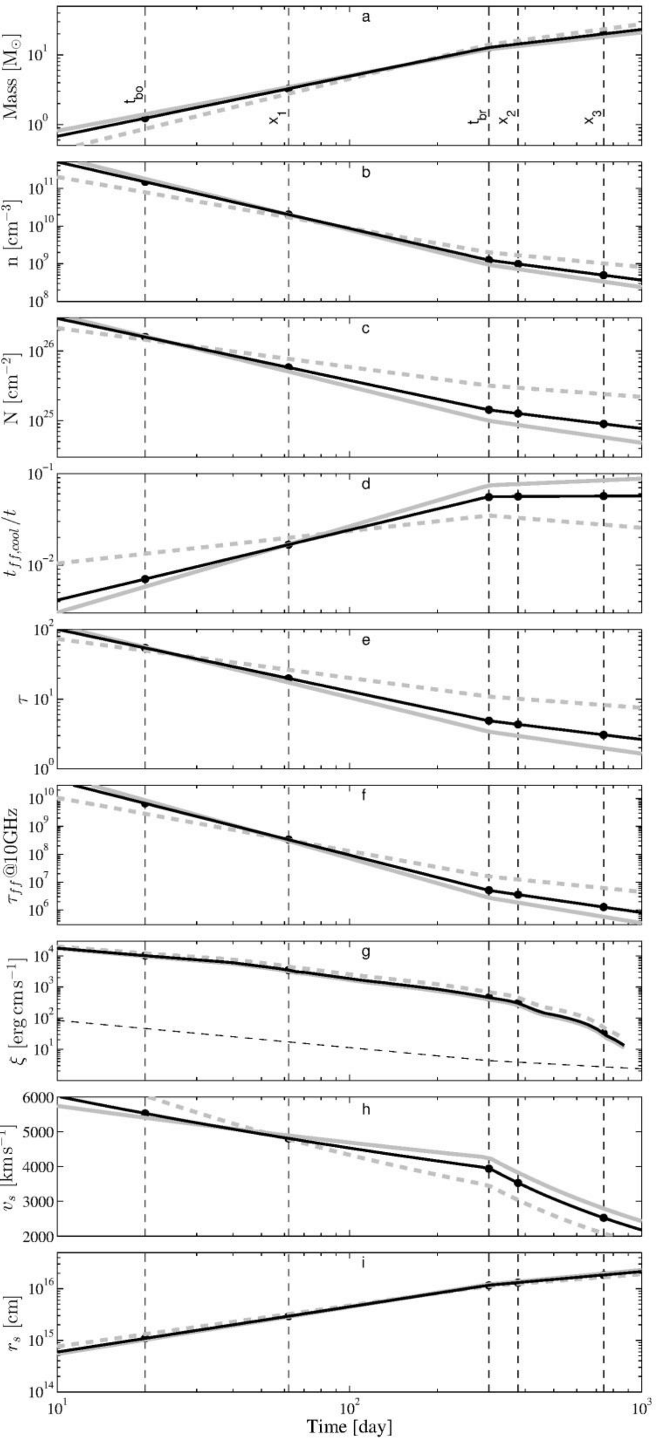
Precursors

Control time

- >50% (99%CL) of IIn have precursors
- Rate >1/yr (abs mag>-14)
- Fainter precursors are even more common



Ofek+2013b, 2014b



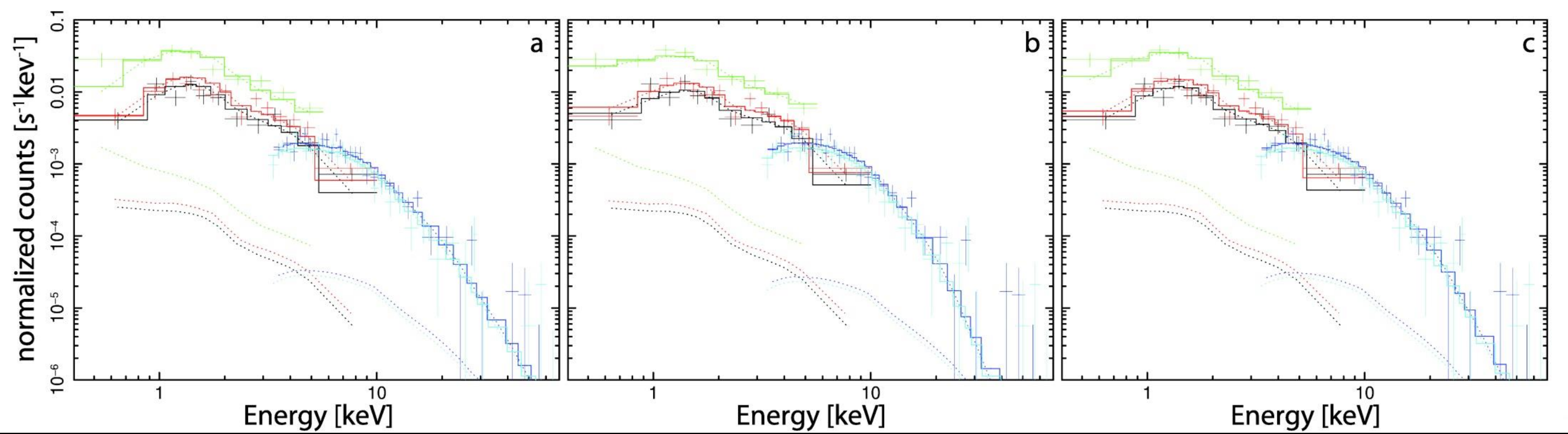
CSM interaction power

SN 2010jl (PTF10aaxf)

Ofek+2013d

CSM interaction power

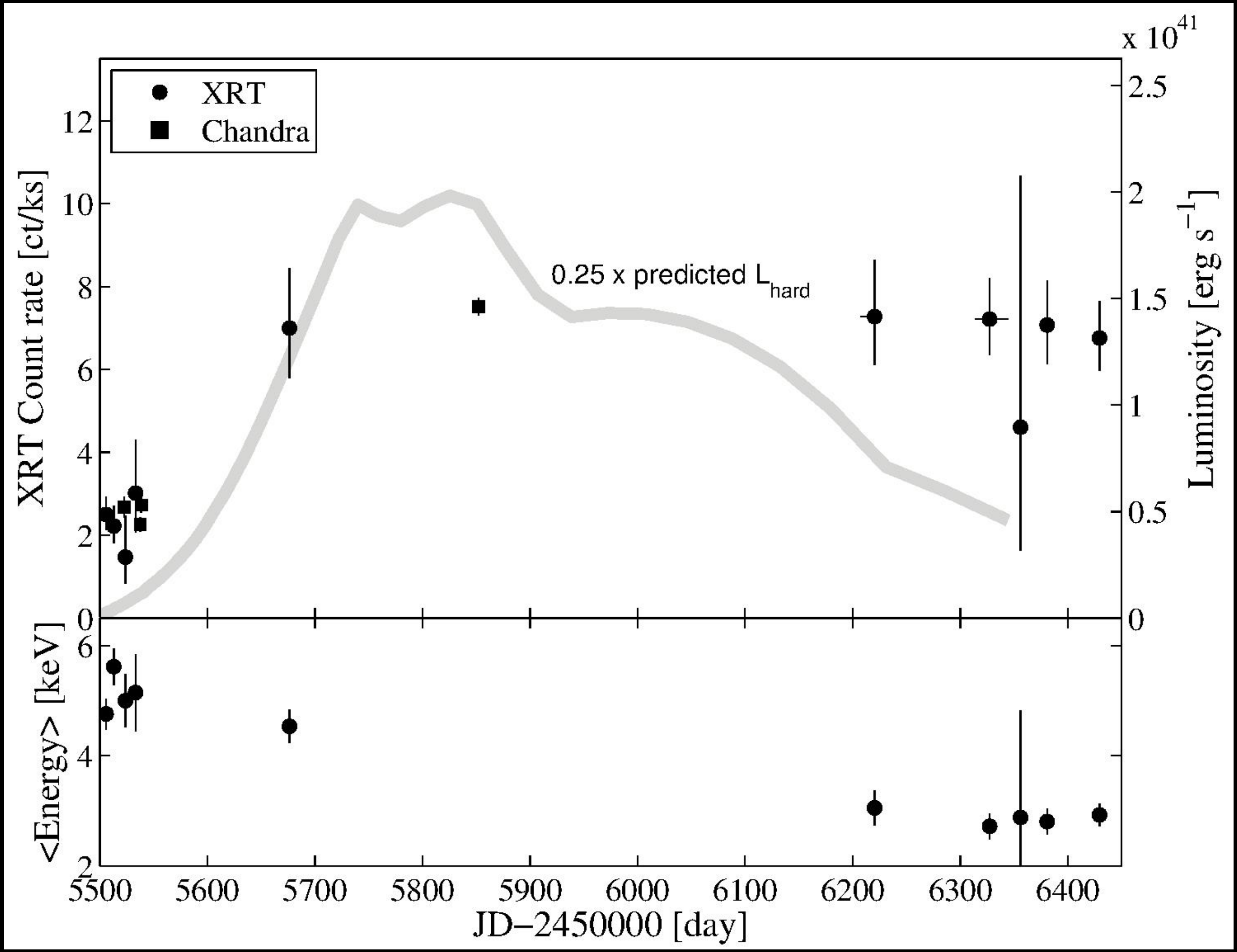
SN 2010jl (PTF10aaxf)



Ofek+2013d

CSM interaction power

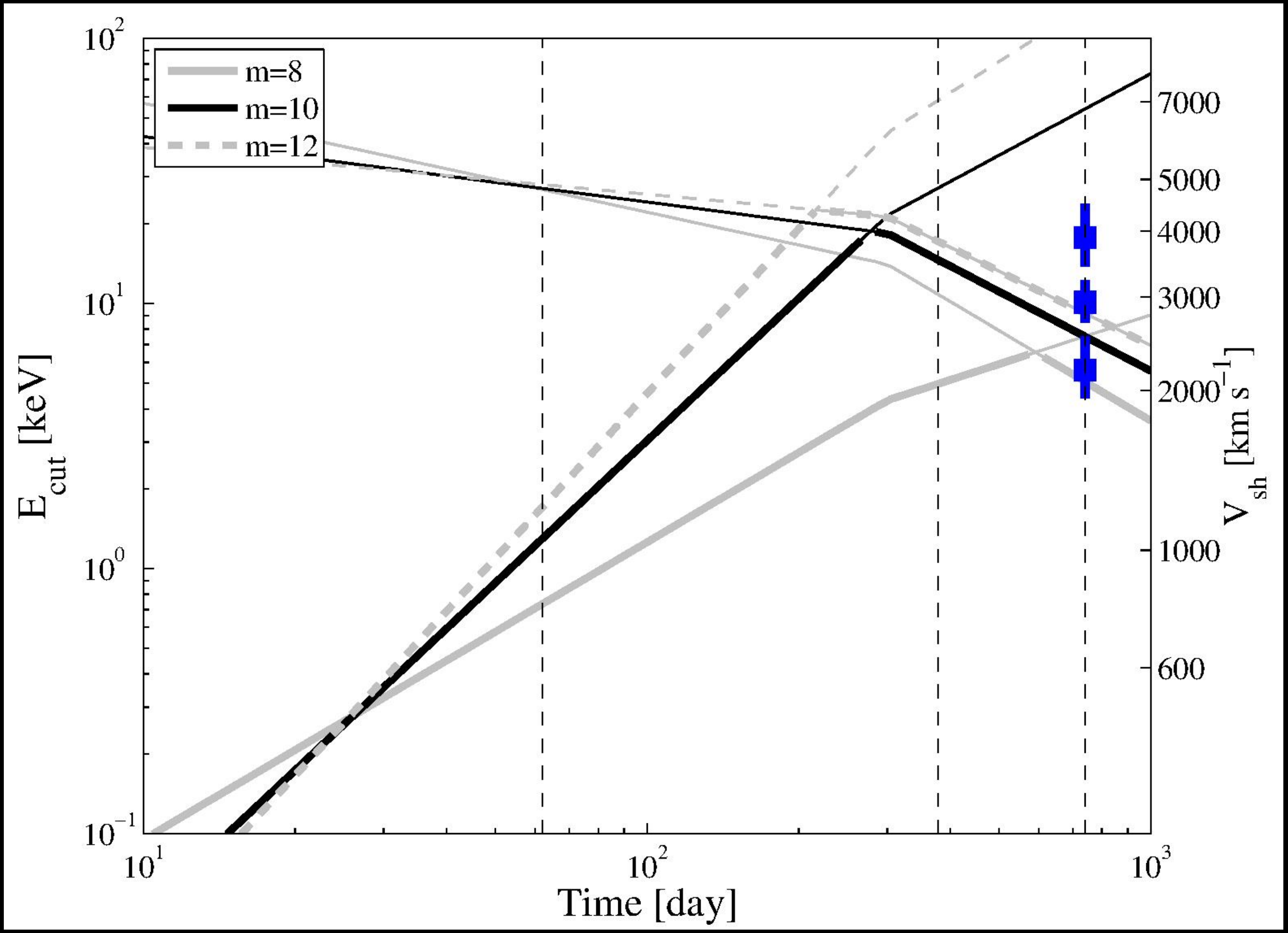
SN 2010jl (PTF10aaxf)



Ofek+2013d

CSM interaction power

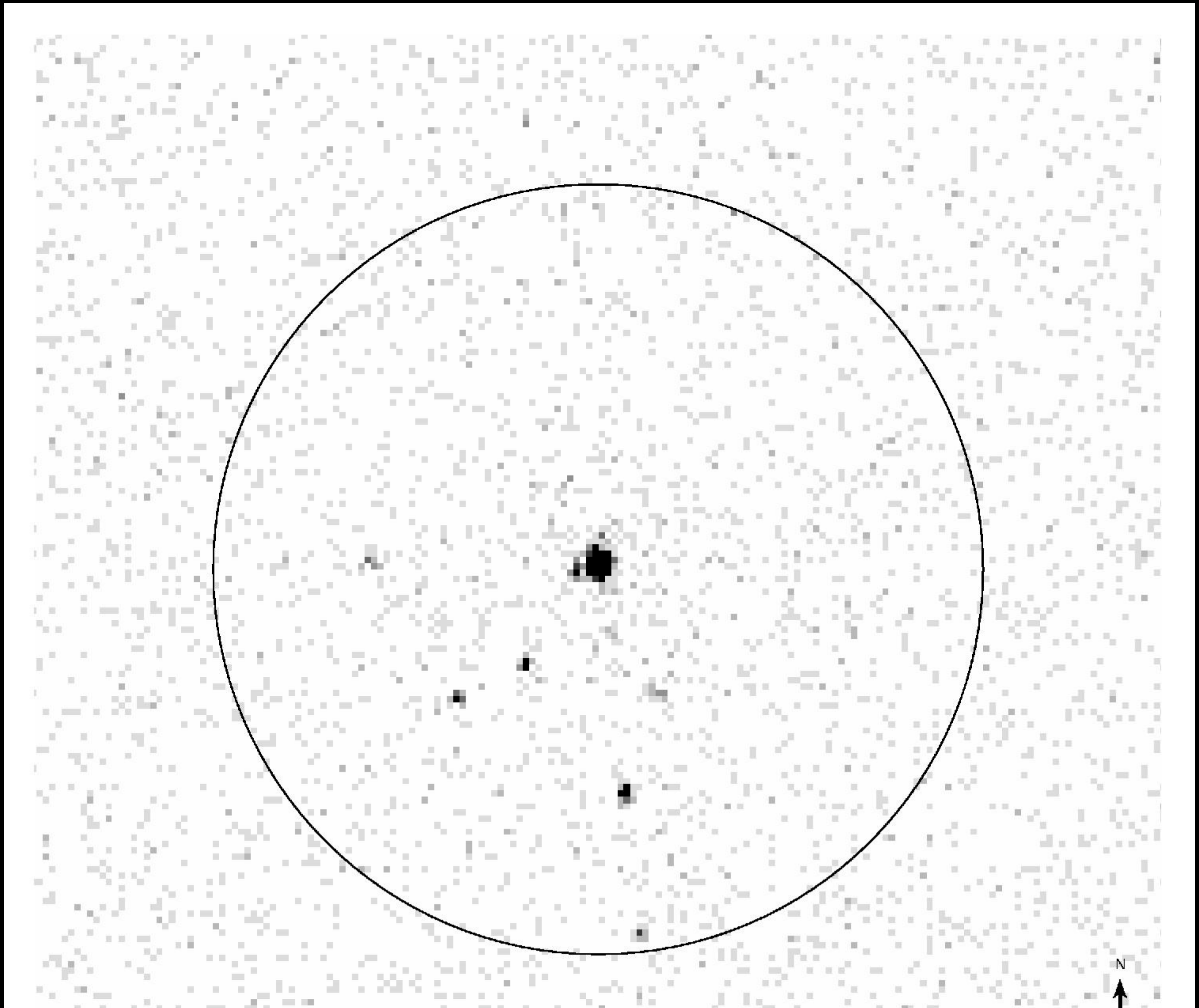
SN 2010jl (PTF10aaxf)



Ofek+2013d

CSM interaction power

SN 2010jl (PTF10aaxf)

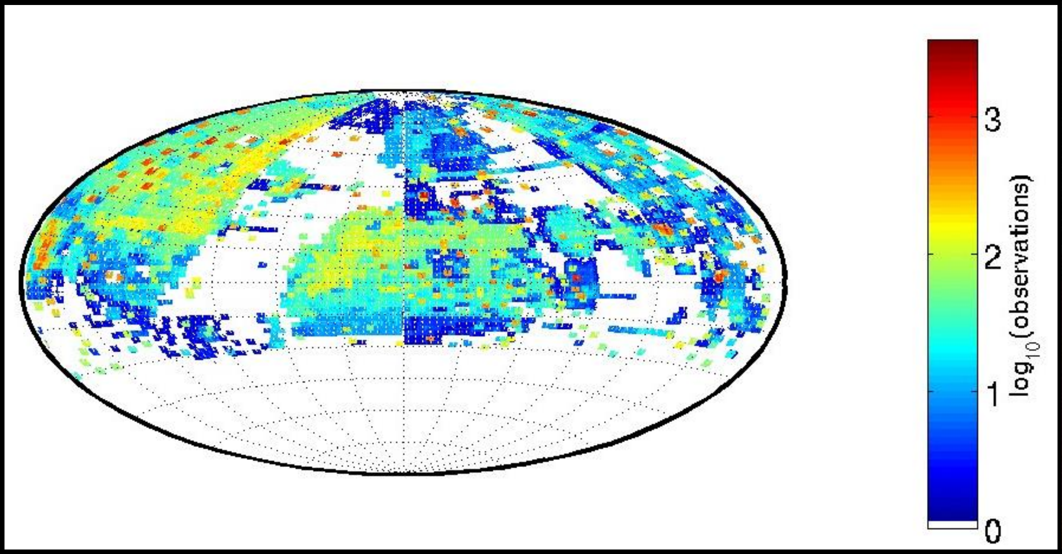


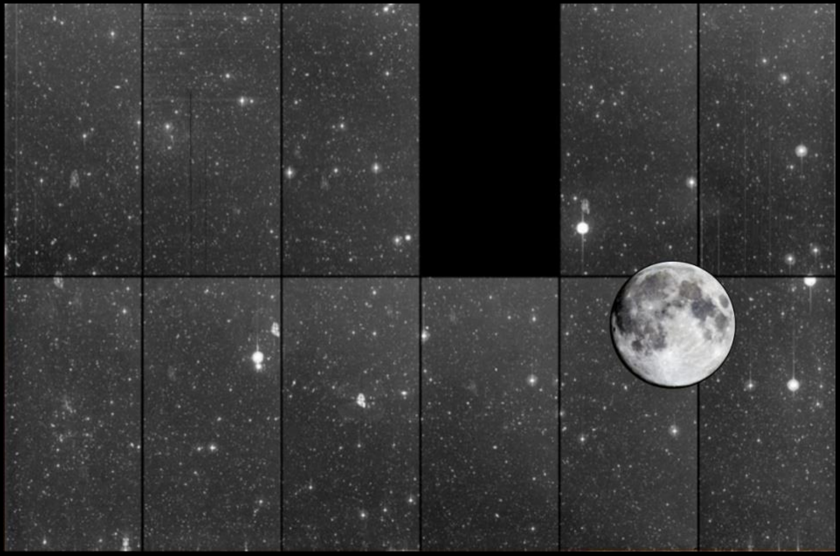
Chandra +2012; Ofek+2013d

The Palomar Transient Factory

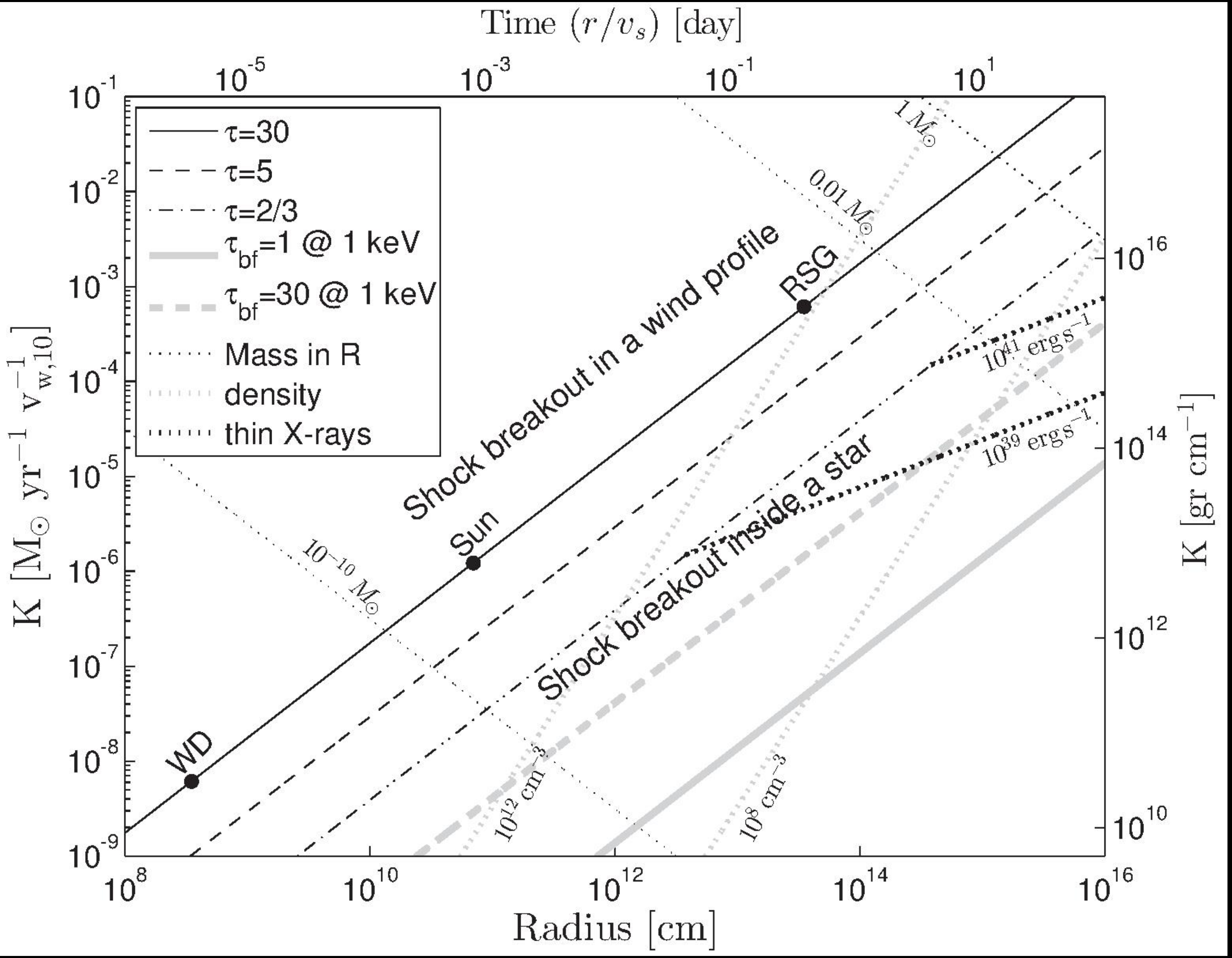
Law et al. 2009, Rau et al. 2009

- 48" Oschin Schmidt camera (Palomar obs.)
- 7.26 deg^2 FOV (92 Mpix)
- Scale: 1"/pix, lim. mag ~21
- Robotic telescope & scheduler





CSM breakout/Collisionless shocks

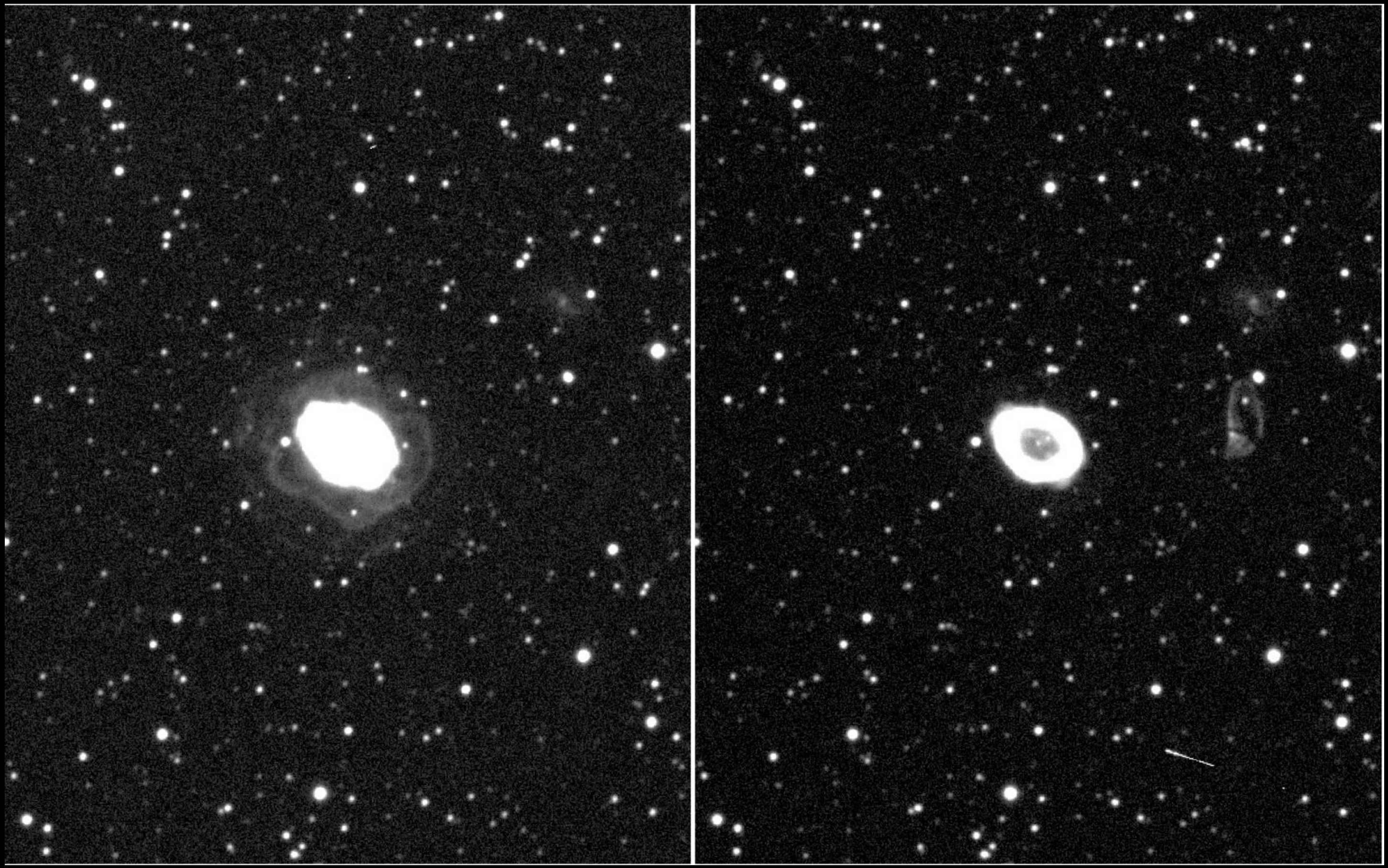


Ofek+2013a

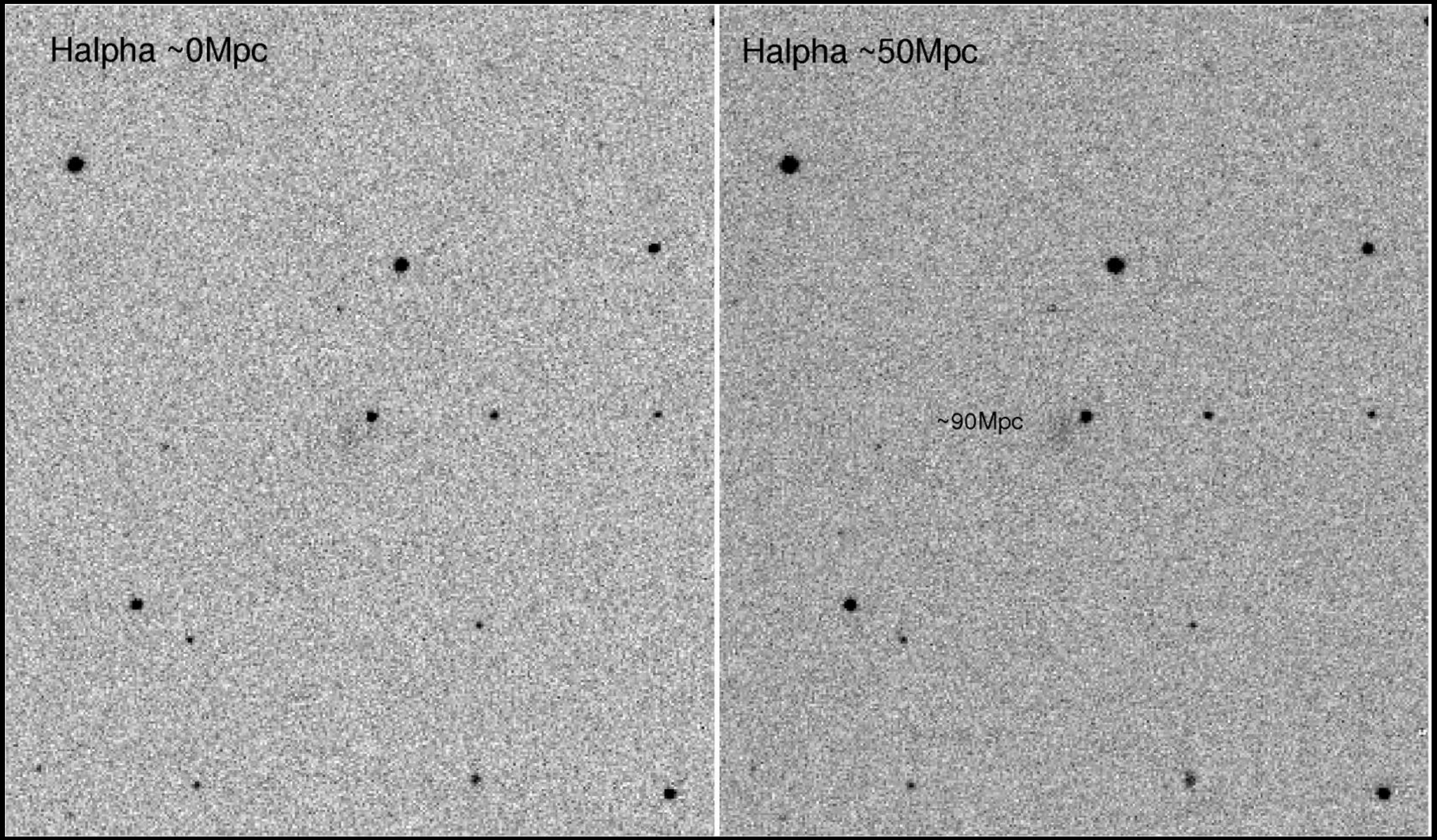
Shock breakout / Intro

- Photons first emerge from SN (breakout) when they diffuse ahead of the shock faster than the shock propogates
- Happens at optical depth: $\tau = c/v$
- duration: $\sim r/c$
- Decay time: $\sim r/v$

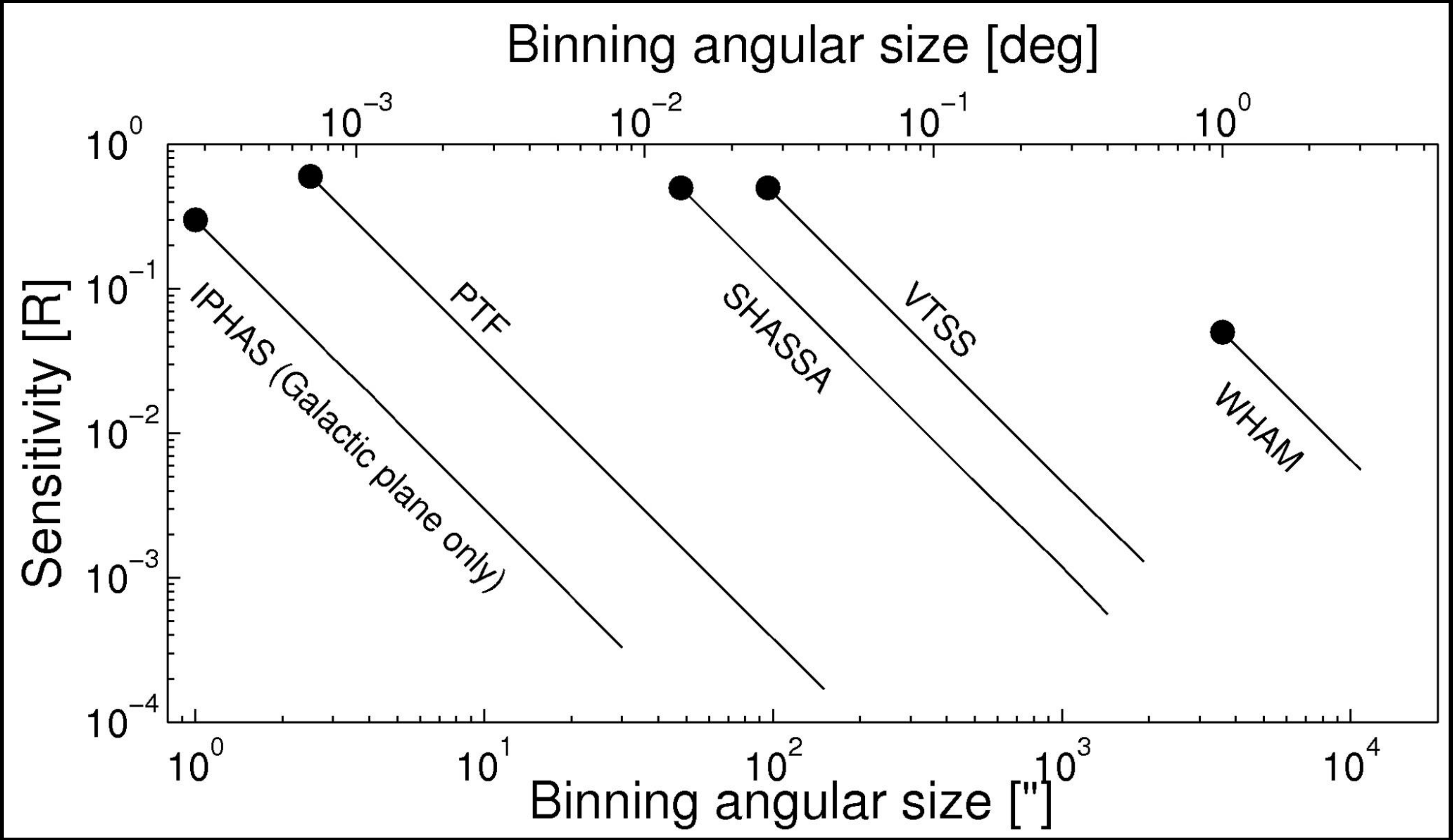
H alpha survey



H alpha survey



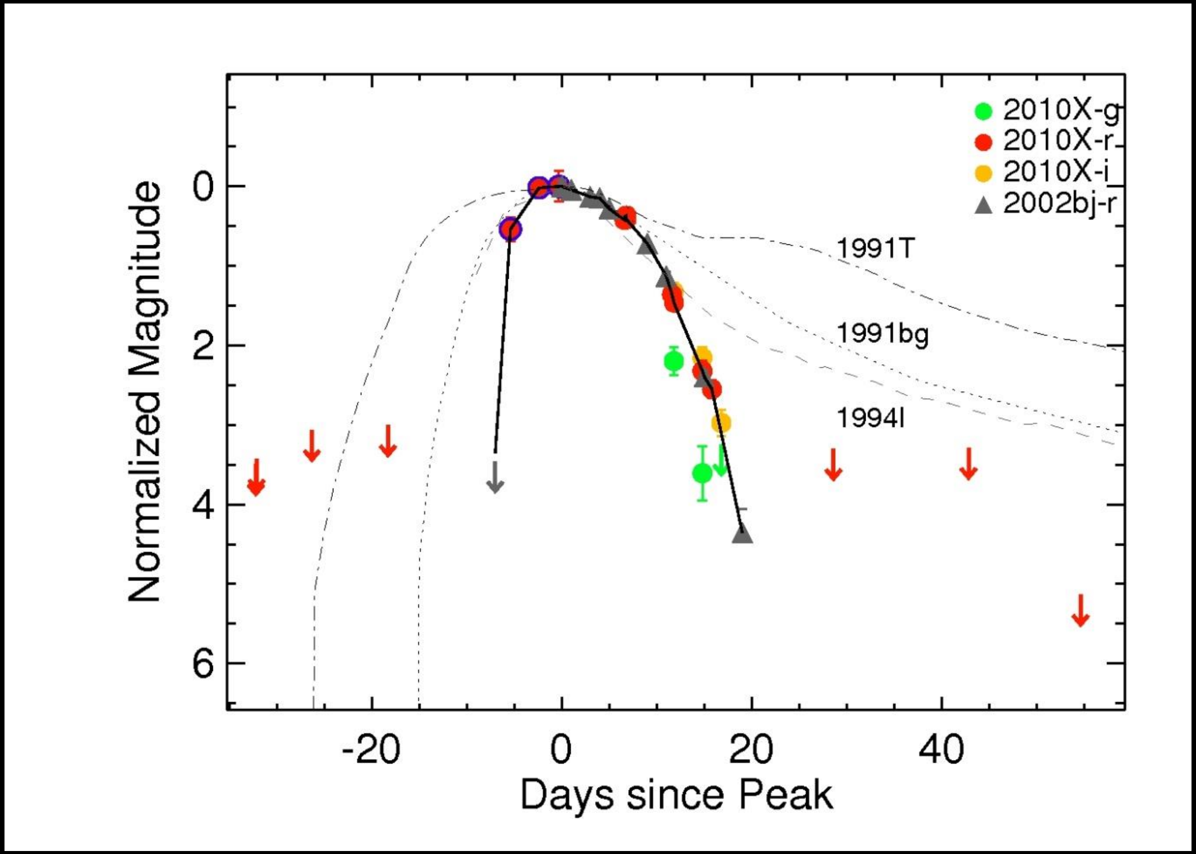
H alpha survey



Fast supernovae: 10bhp

Kasliwal et al., ApJ 723, 98

★ Very fast: decay ~5 days, M_R~-17 (e.g., similar to SN200bj, [Poznanski+10])

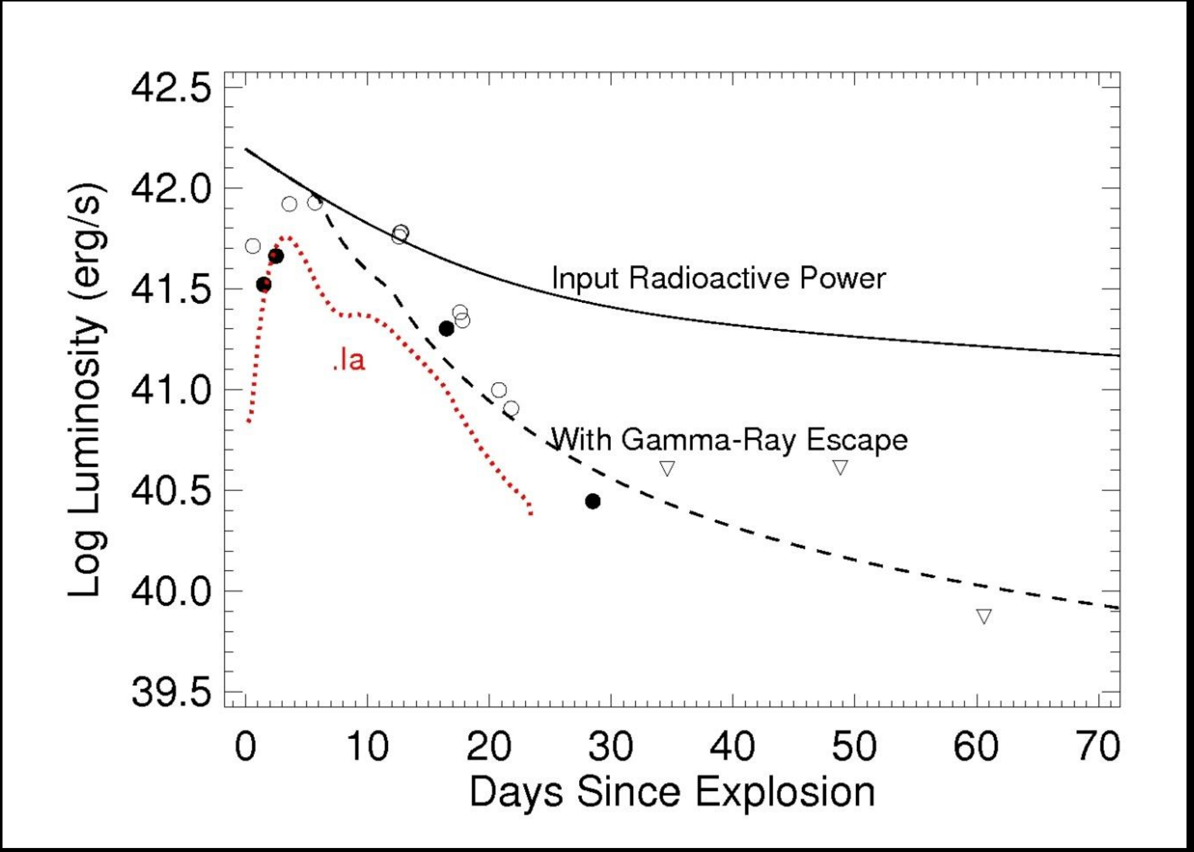


Fast supernovae: 10bhp

Kasliwal et al., ApJ 723, 98

- If powered by ^{56}Ni then Ni mass ~0.02 M_{sun} and SN quickly becomes optically thin to γ-rays.

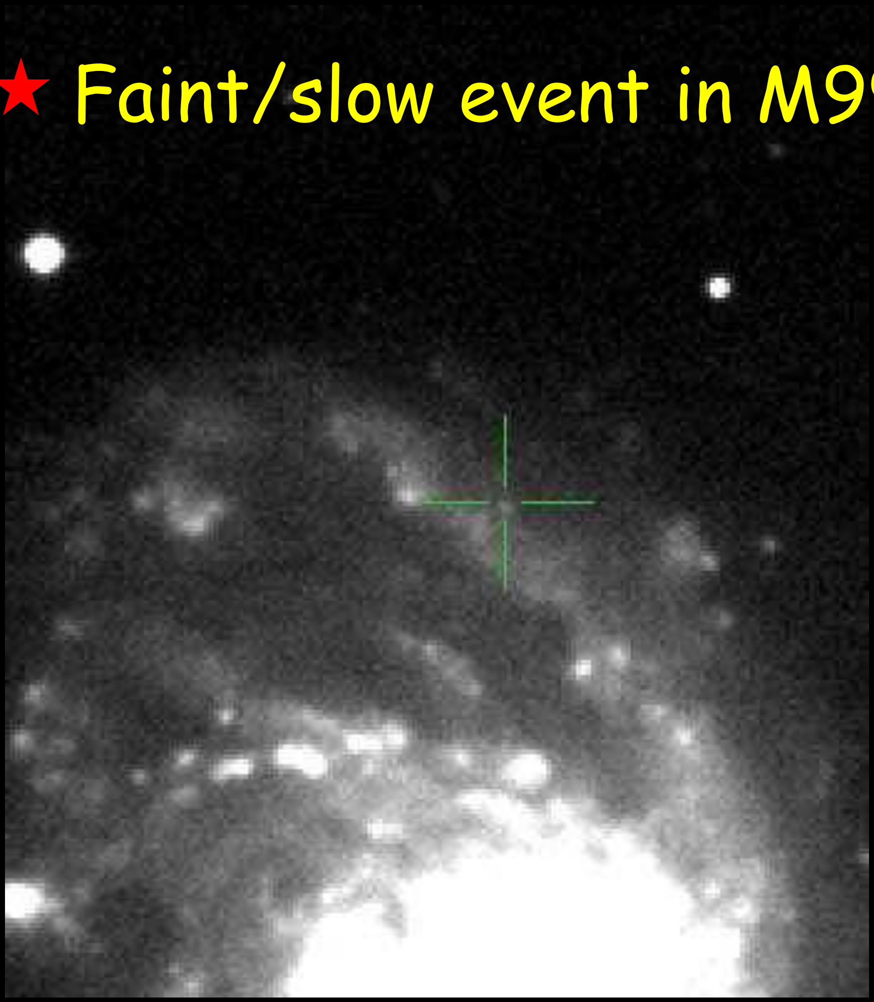
- AIC (?)
  .Ia (?)

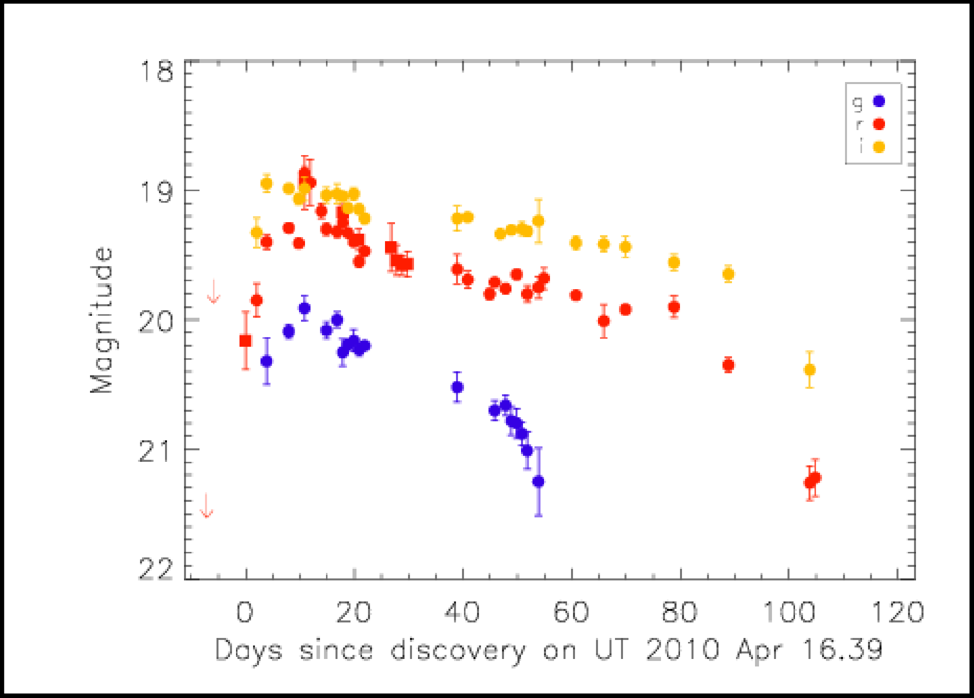


Luminous red nova
PTF 10fqs in M99

Kasliwal et al., 1005.1455

- Faint/slow event in M99: M_R~-11

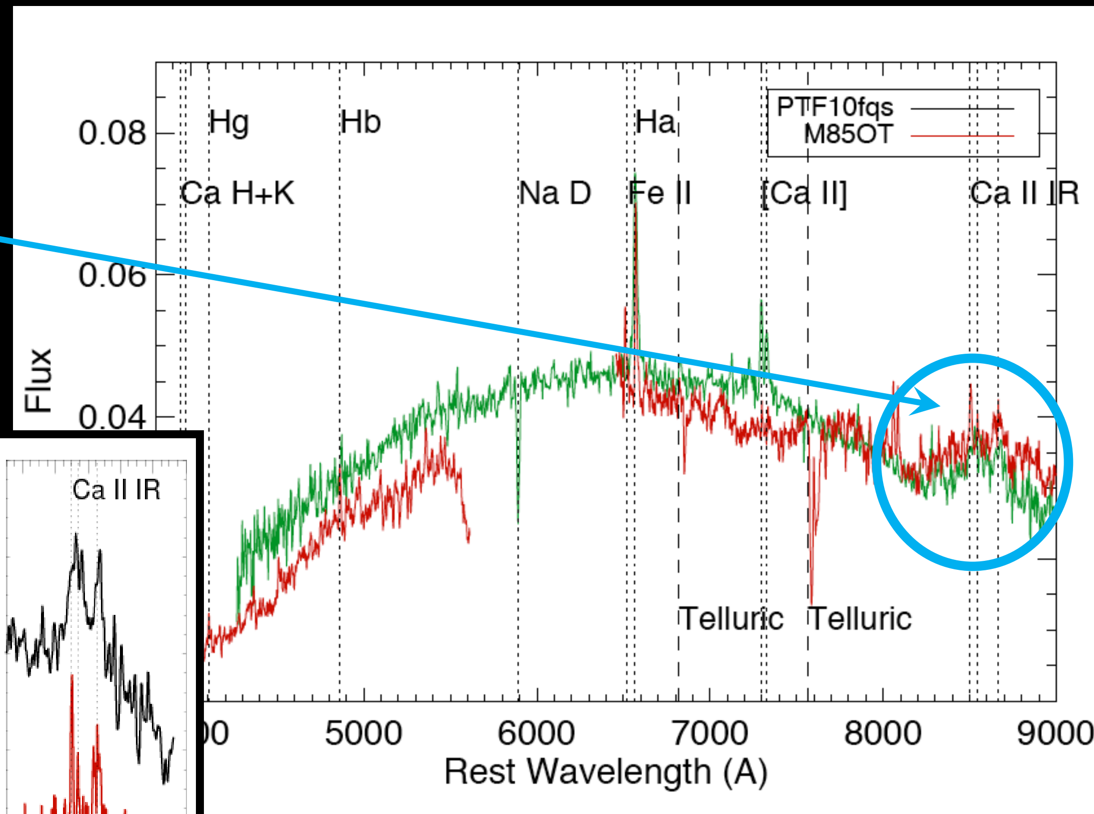


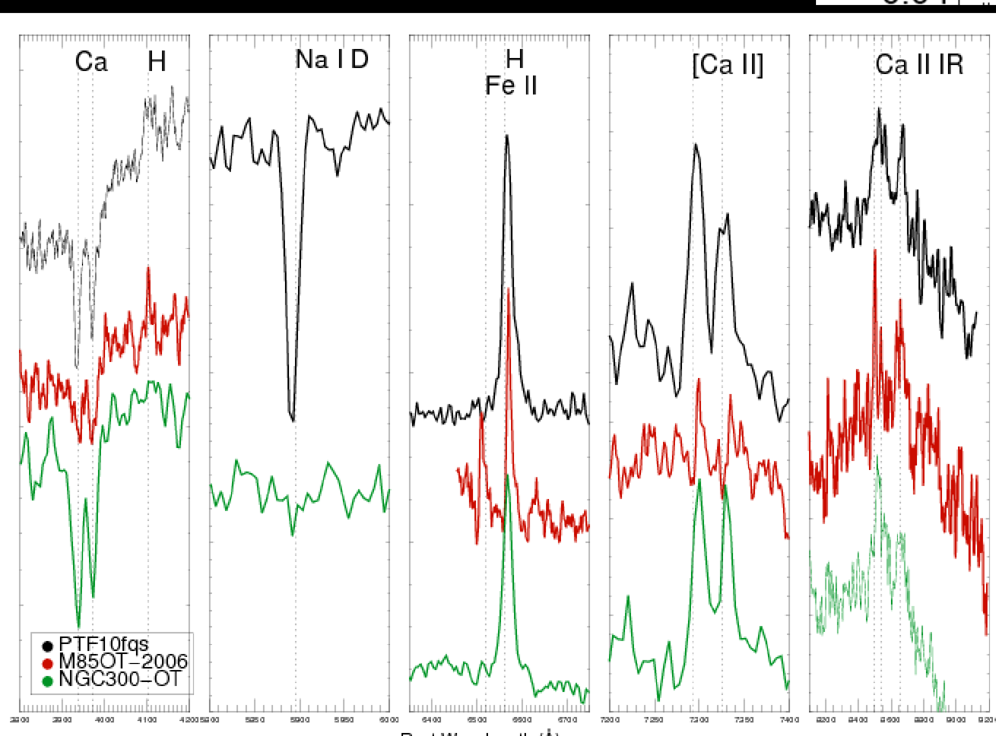


PTF 10fqs

Kasliwal et al., 1005.1455

~10,000 km/s (?)





Search for SB in Chandra archive

with Mike Muno

- Downloaded the entire Chandra archive
- Search for transients and highly variable Objects (on short time scale)

First pass completed:
complete for events brighter than 40 counts

No SN 2008D-like events (Soderberg et al. 2008)

Next: calc. efficiency and extend to faint sources

Relative photometry

Solution using linear least squares

Solving per field (overlap between fields not guaranteed)

i-star (1..p), j-image (1..q)

m_{ij} – instrumental mag

σ_{ij} – instrumental mag err

$$m_{ij} = \overline{m}_j + z_i$$

Relative photometry

Using linear least squares

$$m_{ij} = \overline{m}_j + z_i$$

$$\underbrace{\begin{vmatrix} 1 & 0 & 0 & \cdots & 1 & 0 & 0 & \cdots \\ 1 & 0 & 0 & \cdots & 0 & 1 & 0 & \cdots \\ 1 & 0 & 0 & \cdots & 0 & 0 & 1 & \vdots \\ \vdots & \vdots & \vdots & \ddots & & \vdots & \cdots & \ddots \\ 0 & 1 & 0 & \cdots & 1 & 0 & 0 & \cdots \\ 0 & 1 & 0 & \cdots & 0 & 1 & 0 & \cdots \\ 0 & 1 & 0 & \cdots & 0 & 0 & 1 & \vdots \\ \vdots & \vdots & \vdots & \ddots & & \vdots & \cdots & \ddots \\ \vdots & & & & & & & \end{vmatrix}}_{\text{H (“design matrix”)}} \vec{P} \cong \begin{vmatrix} m_{11} \\ m_{12} \\ m_{13} \\ \vdots \\ m_{21} \\ m_{22} \\ m_{23} \\ \vdots \end{vmatrix}$$

Observations

$$\vec{P} = \begin{vmatrix} \vdots \\ z_j \\ \vdots \\ \vdots \\ \overline{m}_i \\ \vdots \\ ? \\ ? \\ ? \end{vmatrix}$$

Free parameters

Relative photometry

Solution using linear least squares

$$m_{ij} = \overline{m}_j + z_i$$

We need to solve (in the presence of errors):

$$\chi^2 = (\vec{m}_{ij} - HP)^T \left|\sigma_{ij}^2\right|^{-1} (\vec{m}_{ij} - HP)$$

Relative photometry

Simultaneous absolute calibration

$$
\begin{vmatrix}
1 & 0 & 0 & \cdots & 1 & 0 & 0 & \cdots \\
1 & 0 & 0 & \cdots & 0 & 1 & 0 & \cdots \\
1 & 0 & 0 & \cdots & 0 & 0 & 1 & \vdots \\
\vdots & \vdots & \vdots & \ddots & & \vdots & \cdots & \ddots
\end{vmatrix}
\vec{P} \cong
\begin{vmatrix}
m_{11} \\ m_{12} \\ m_{13} \\ \vdots
\end{vmatrix}
$$

$$
\begin{vmatrix}
0 & 1 & 0 & \cdots & 1 & 0 & 0 & \cdots \\
0 & 1 & 0 & \cdots & 0 & 1 & 0 & \cdots \\
0 & 1 & 0 & \cdots & 0 & 0 & 1 & \vdots \\
\vdots & \vdots & \vdots & \ddots & & \vdots & \cdots & \ddots
\end{vmatrix}
\qquad
\begin{vmatrix}
m_{21} \\ m_{22} \\ m_{23} \\ \vdots
\end{vmatrix}
$$

$$\vdots$$

H is (pq)x(p+q) matrix
However, rank is p+q-1

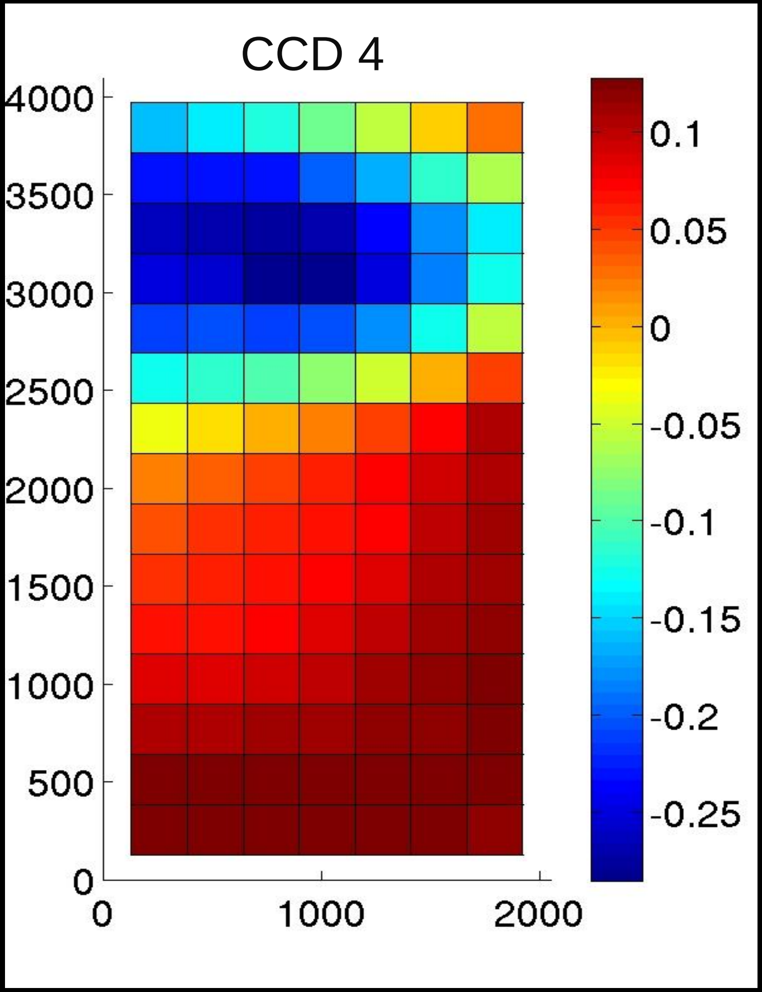
$$
\begin{vmatrix}
0 & 0 & 0 & \cdots & 1 & 0 & 0 & \cdots \\
0 & 0 & 0 & \cdots & 0 & 1 & 0 & \cdots \\
0 & 0 & 0 & \cdots & 0 & 0 & 1 & \vdots \\
\vdots & \vdots & \vdots & \ddots & & \vdots & \cdots & \ddots
\end{vmatrix}
\qquad
\begin{vmatrix}
M_1 \\ \vdots \\ M_j \\ \vdots
\end{vmatrix}
$$

Adding calibration block

Calibrated photometry

Ofek et al. 2011 submitted

- Photometry calibration good to 2-3%
- Using SDSS stars as standard stars to calibrate fields outside SDSS footprint (photometric nights)



Relative photometry
Additional de-trending

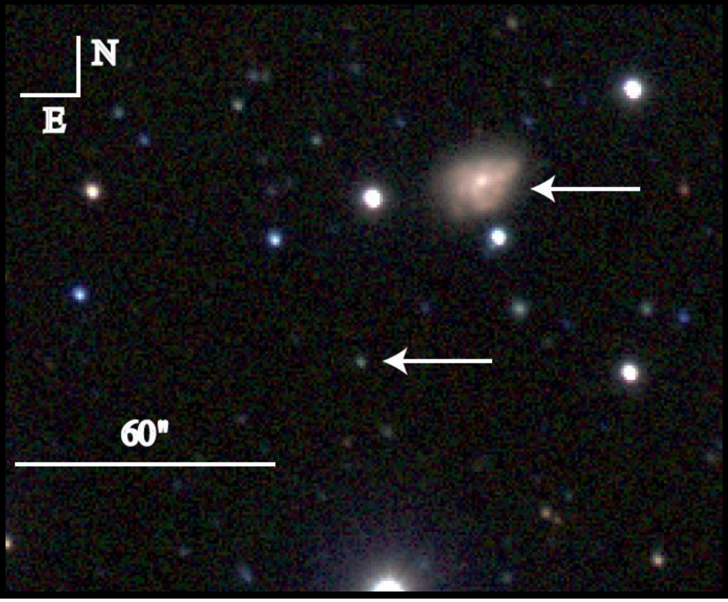
We can add more columns to H and P.
For example:

- Airmass x color term ← Δm_b^{obs}

- Positional terms

- Multiple CCDs (i.e, overlap)

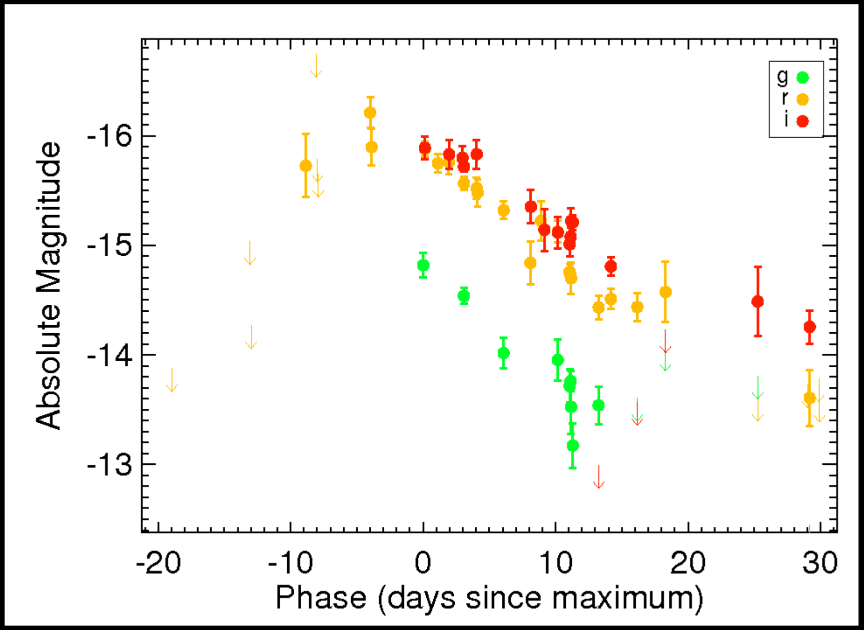
The SN2005E family: 09dav

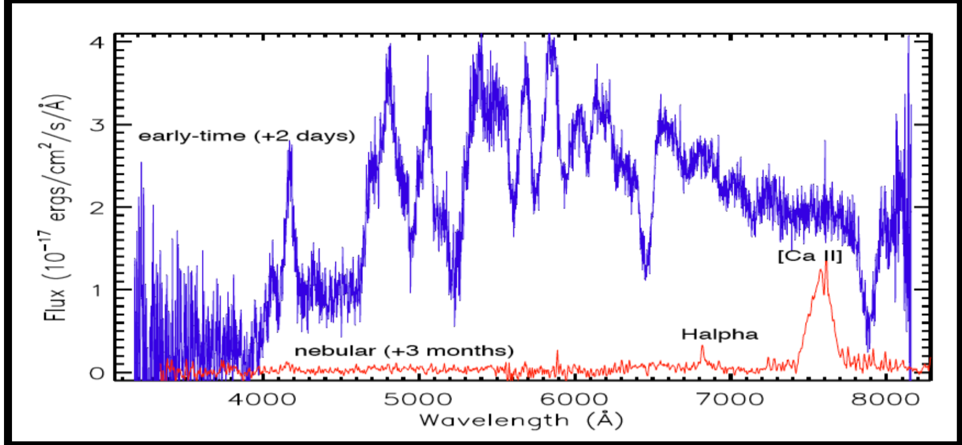


40kpc from putative spiral host
Abs R mag ~-15
Fast: 1 mag in 10 day
Very red, g-r = 1.2

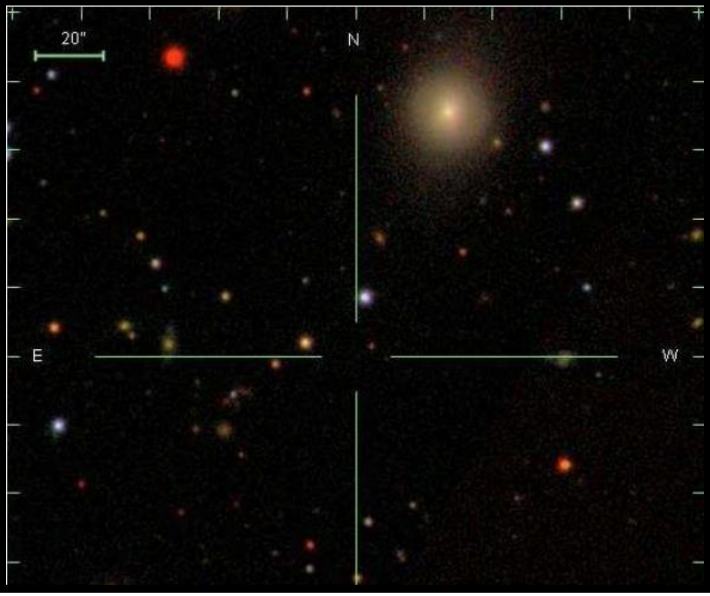
Similar to SN1991bg but with He
Hydrogen in nebular phase

Kasliwal et al., in prep.
Sullivan et al., in prep.





The SN2005E family: 10iuv



37 kpc from putative host
Abs R. mag ~ -15.
Fast: 1 mag in 10 days
Intriguing Nebular Spectra

Kasliwal et al., in prep.