超新星爆発 shock breakout と遠方超新星爆発探査

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「超新星爆発と数値シミュレーション」

C: A. de Ugarte Postigo (ESO) et al.

Contents

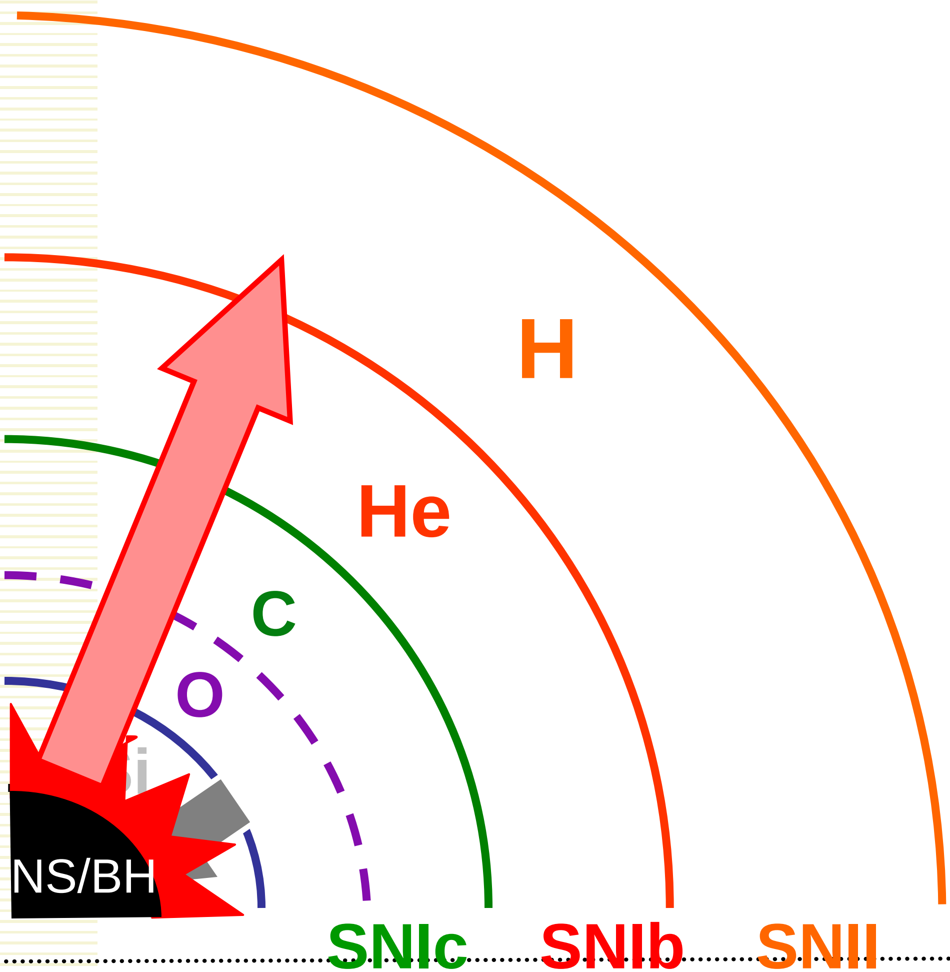
- What is shock breakout?
- Multigroup radiation hydrodynamics
- Application for shock breakout
- Proposal of future SN survey

What is shock breakout?

Core-collapse supernovae

Massive Star (>10$M_\odot$)

e^--capture SNe (8-10$M_\odot$)



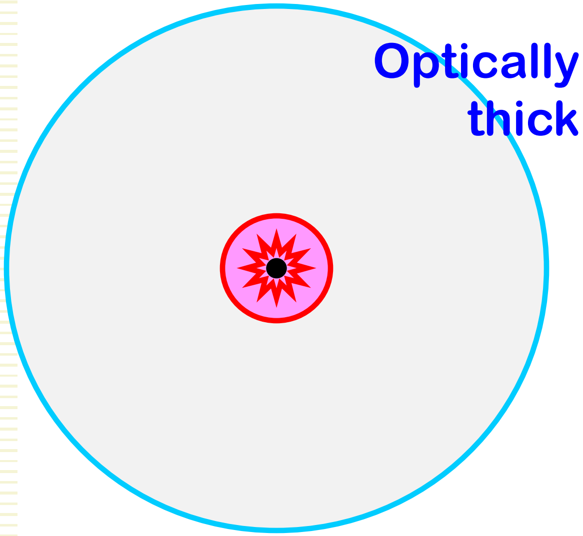
Temp [10^8K]	Burning Stage	Products
0.2	H	He
1.5	He	C,O
7	C	Ne,Mg
15	Ne	O,Mg
30	O	Si
40	Si	Cr,Mn
50	NSE	^{56}Ni

Core collapse driven by Fe photodisociation

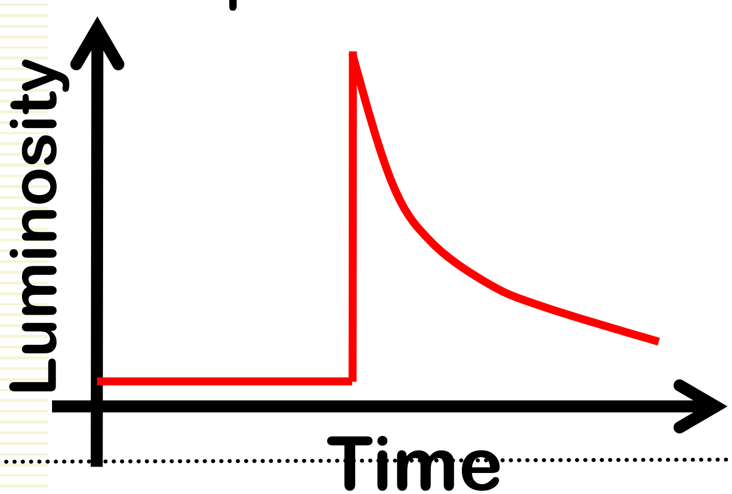
NS/BH formation

Energy deposition

Shock breakout



Core collapse



Massive Star ($>10M_\odot$)

e^-–capture SNe (8–$10M_\odot$)

At the shock emergence, a stored energy is released as radiation.

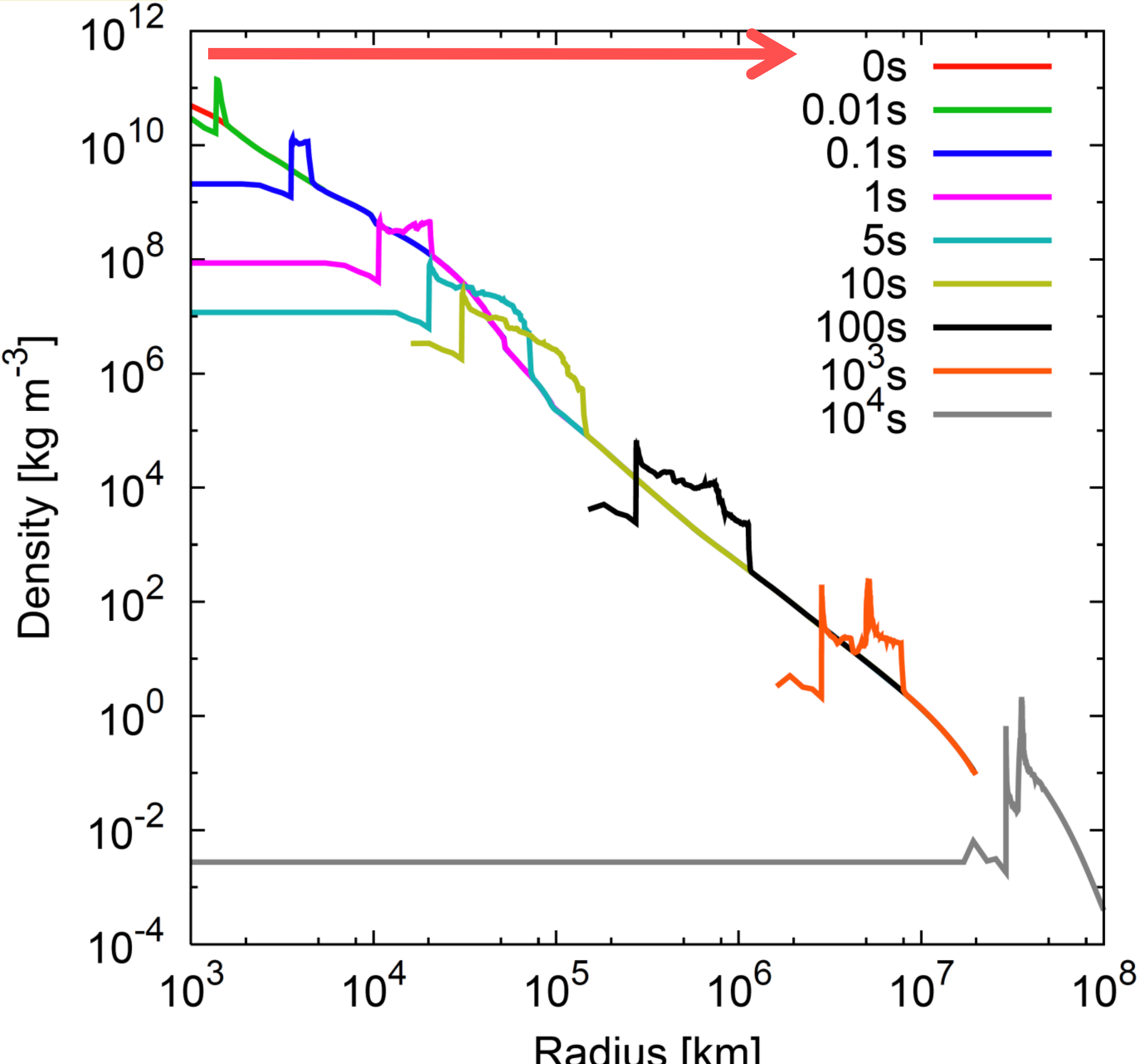
Spectra are quasi-blackbody

$$T \sim R^{-3/4}E^{1/4}$$

Spectra peaked at X-ray-UV.
It lasts a few sec- a few day.

It is theoretically predicted in 1970s but observationally first reported in 2008.

Shockwave in stellar interior

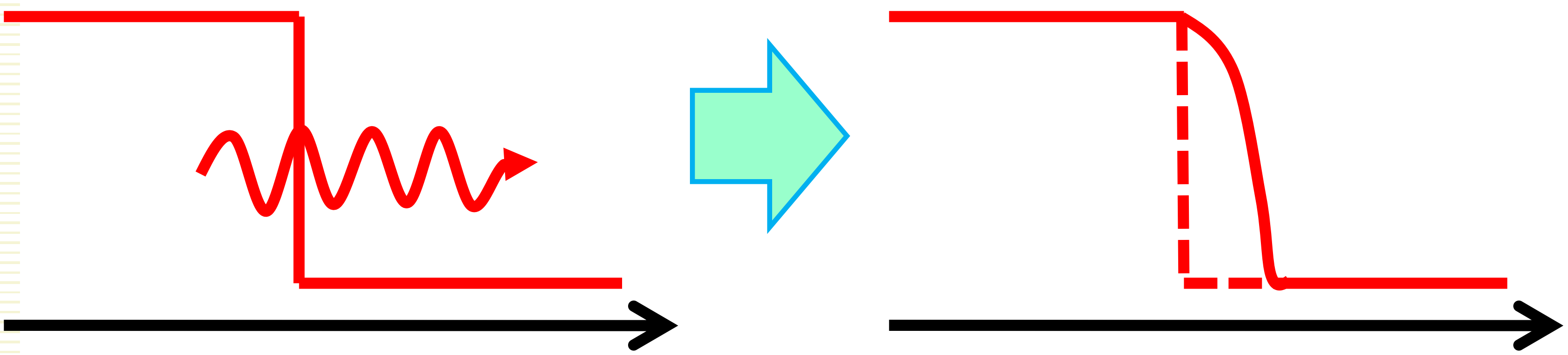


衝撃波後方は輻射優勢

光学的厚さが厚いため
物質の衝撃波と輻射の衝撃波
が同じ位置に存在

Shock breakout の起こる条件

- 衝撃波の速度＜光子のdiffusion速度
- $v_s \lesssim c/\tau$



- 衝撃波からの光子で衝撃波の上流の加熱
- 衝撃波の鈍り

Many analytic studies (note: incomplete)

- Matzner & McKee 1999
  - The Expulsion of Stellar Envelopes in Core-Collapse Supernovae
- Waxman + 2007
  - GRB 060218: A Relativistic Supernova Shock Breakout
- Li 2007
  - Shock breakout in Type Ibc supernovae and application to GRB 060218/SN 2006aj
- Chevalier & Fransson 2008
  - Shock Breakout Emission from a Type Ib/c Supernova: XRT 080109/SN 2008D
- Nakar & Sari 2010
  - Early Supernovae Light Curves Following the Shock Breakout
- Sapir + 2011
  - Non-relativistic Radiation-mediated Shock Breakouts. I. Exact Bolometric Planar Breakout Solutions

Shock Breakoutの物理

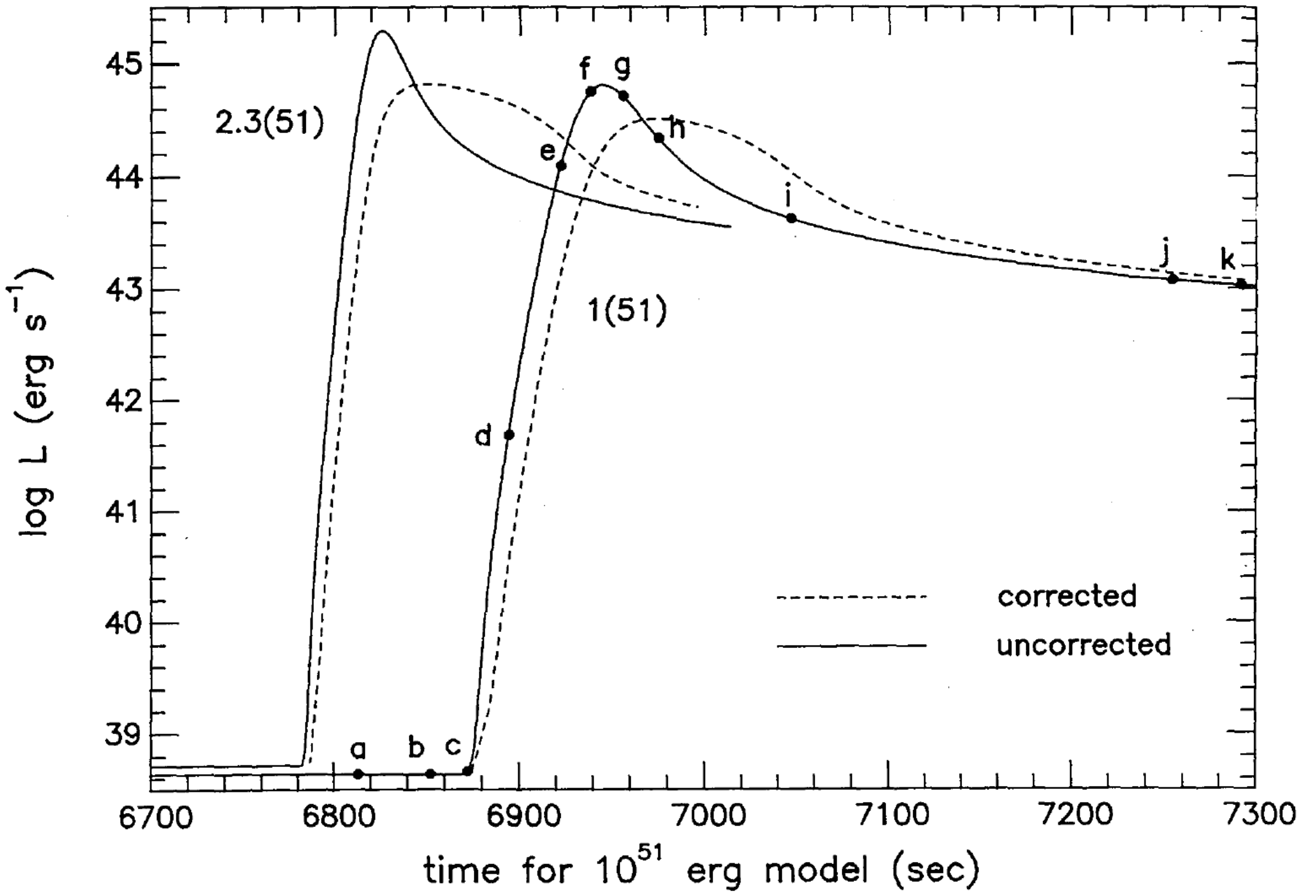
1978年 Klein & Chevalier によって提案された

- 1-2日以下の物理現象
- Radiation hydrodynamics
  - 流体と輻射輸送が相互作用
  - ⇔超新星光度曲線:流体は大体homologous ($r \propto v$)
- Radiative precursor
  - 異なる輻射の温度とガスの温度
  - (最低でも2温度の) Radiation hydrodynamics

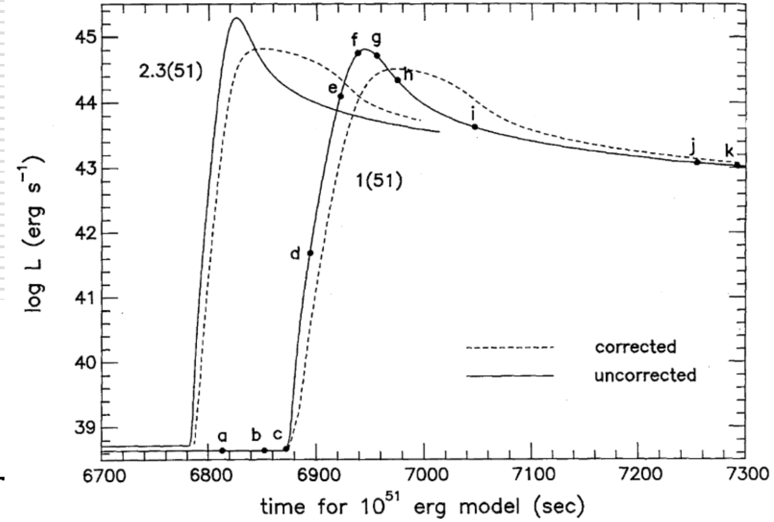
→方程式は Mihalas & Mihalas (1984)
概念は Zel'dovich & Raizer (1966)

Shock Breakout とは?
(Ensman & Burrows 92)

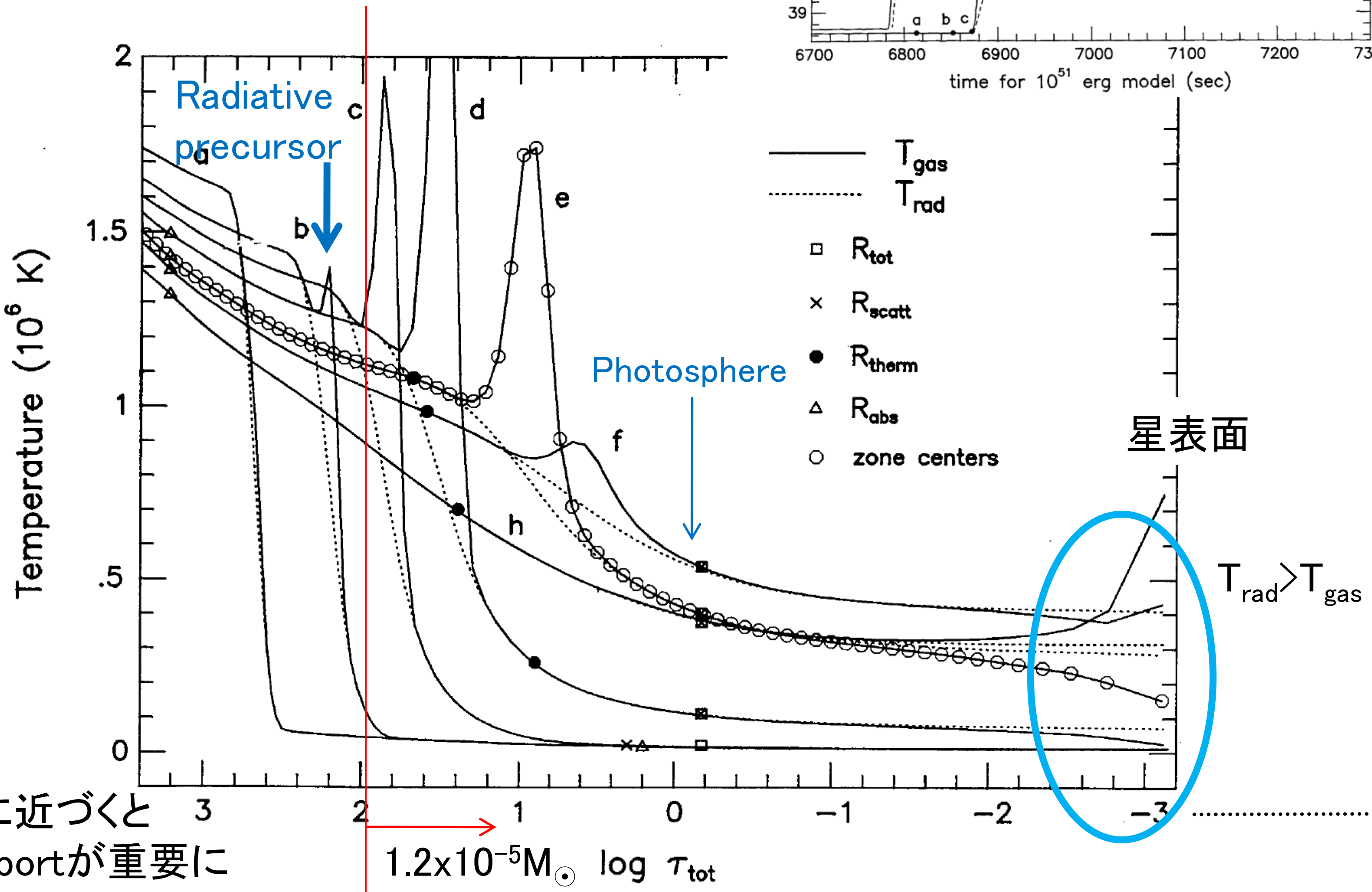
- Light curve (SN1987A[青色巨星]の場合)



Shock Breakout とは?
(Ensman & Burrows 92)



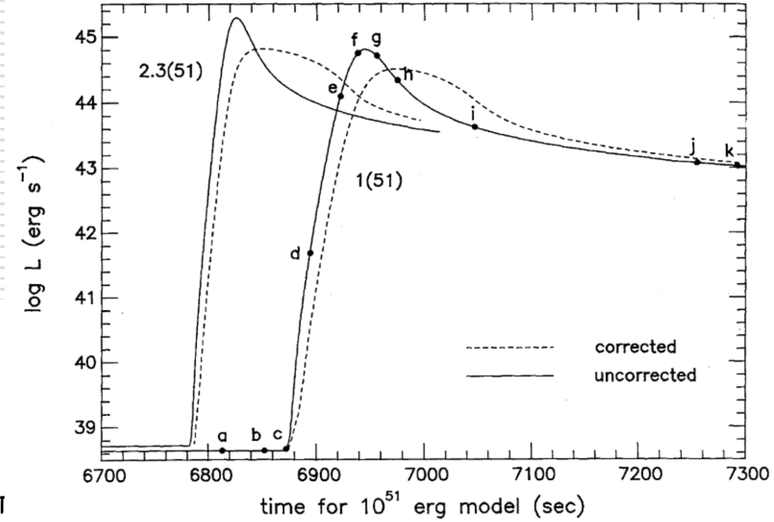
- Temperature structure

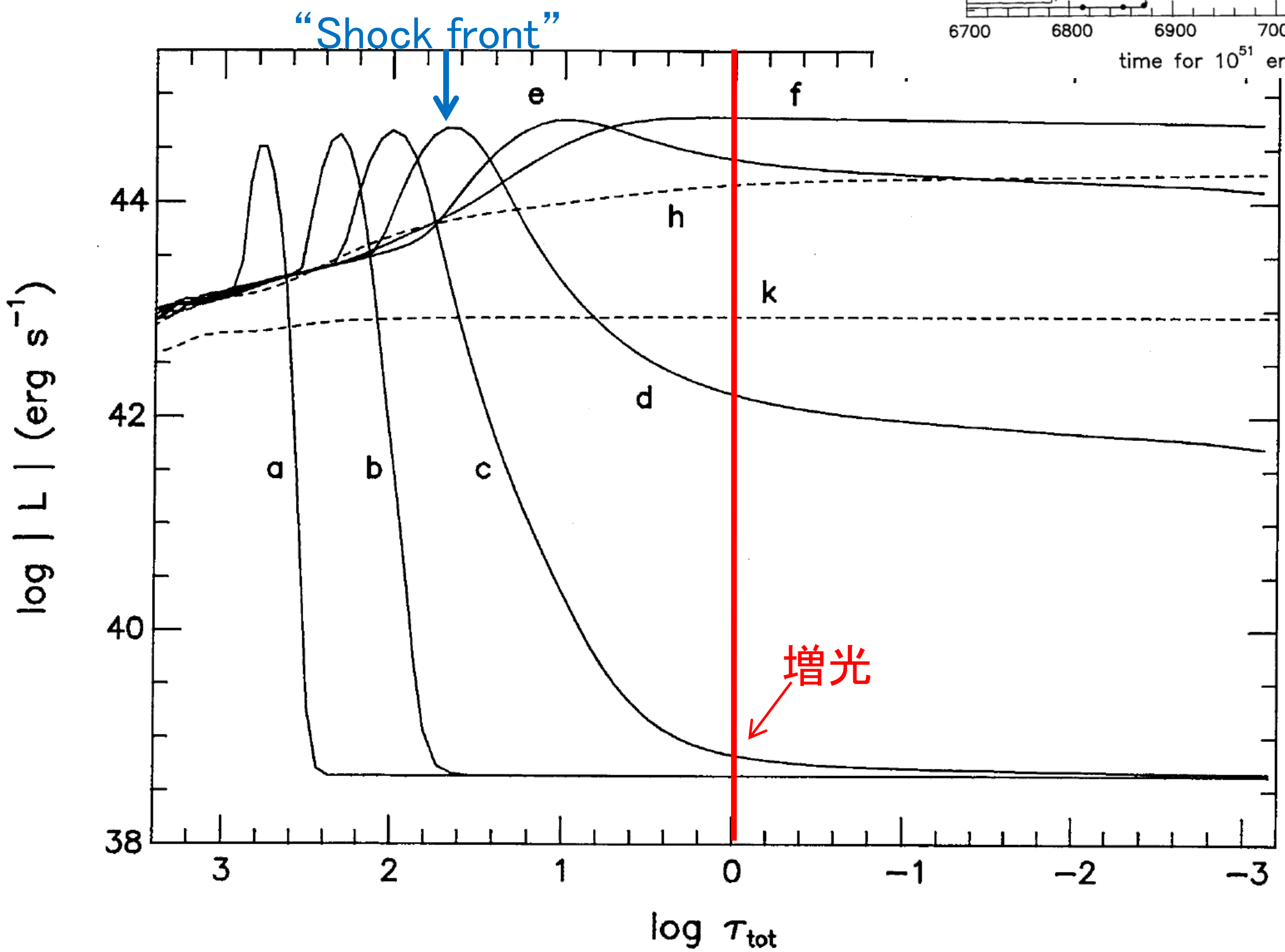


Optically thinに近づくと radiative transportが重要に

Shock Breakout とは?
(Ensman & Burrows 92)

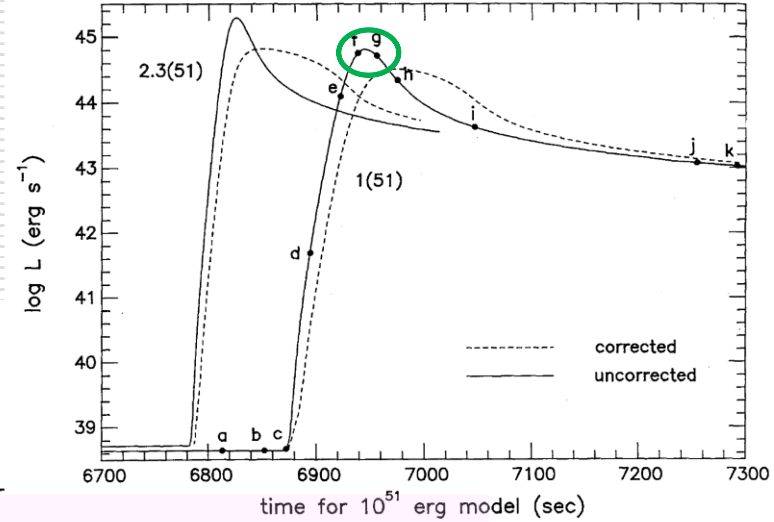
- Luminosity structure



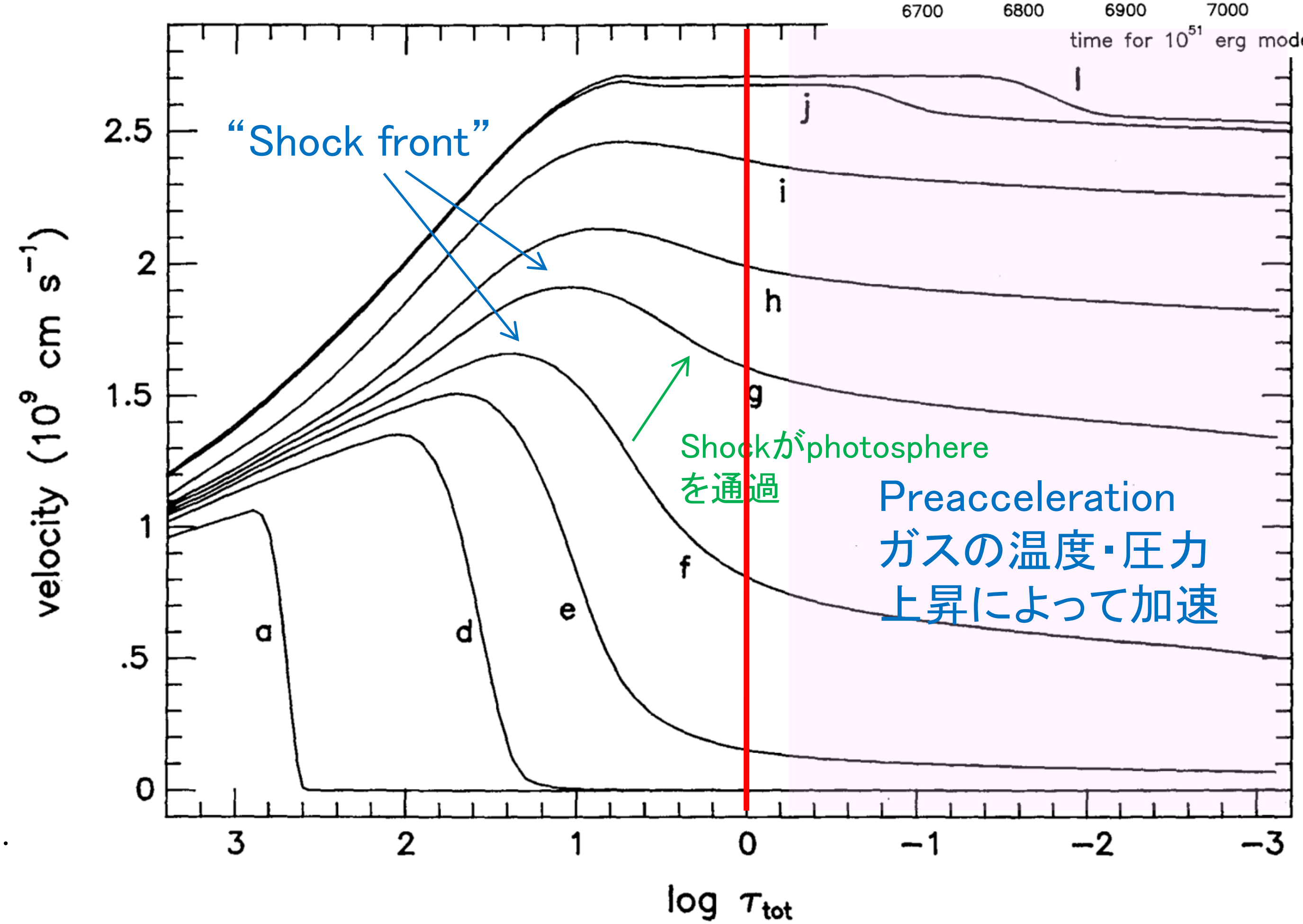


Shock Breakout とは?

(Ensman & Burrows 92)



- Velocity structure



Multigroup radiation hydrodynamical code **STELLA** (Blinnikov+98;00;06)

STELLA (Blinnikov+98)

- Multigroup radiation hydrodynamics code
- Spherical symmetry with Lagrangean coordinate
- Implicit methods on rad. transfer & hydrodynamics
- Non-equlibrium radiation transfer
  - Moment equations
  - Closure relation: Variable Eddington factor
- LTE level population (Saha-Boltzmann eq.)
  - 15 most abundant elements (H-Ni)
- Opacity
  - f-f, b-f, 1.5×10^5 spectral lines, electron scattering
- Energy deposition from radioactive decay
  - 1-group grey radiative transfer

輻射輸送の式

$$\left(\frac{1}{c}\frac{\partial}{\partial t}+\frac{\partial}{\partial s}\right)I_\nu = \eta - \chi I_\nu,$$

球対称、comoving flame、O(v/c) とすると、

$$\begin{aligned}
&\frac{1}{c}\frac{DI_\nu}{Dt}+\frac{\mu}{r^2}\frac{\partial(r^2 I_\nu)}{\partial r}\\
+&\quad \frac{\partial}{\partial\mu}\left\{(1-\mu^2)\left[\frac{1}{r}+\frac{\mu}{c}\left(\frac{v}{r}-\frac{\partial v}{\partial r}-\frac{a}{c^2}\right)\right]I_\nu\right\}\\
-&\quad \frac{\partial}{\partial\nu}\left\{\nu\left[(1-\mu^2)\frac{v}{cr}+\frac{\mu^2}{c}\frac{\partial v}{\partial r}+\frac{\mu a}{c^2}\right]I_\nu\right\}\\
+&\quad \left[(3-\mu^2)\frac{v}{cr}+\frac{1+\mu^2}{c}\frac{\partial v}{\partial r}+\frac{2\mu a}{c^2}\right]I_\nu\\
=&\quad \eta-\chi I_\nu.
\end{aligned}$$

Mihalas & Mihalas (1984)

STELLA (Blinnikov+98)

- Invariant photon distribution function

$$I_\nu = \frac{2h\nu^3}{c^2} f_\nu(r, \mu)$$

- Angler moments of f_ν

$$\mathscr{J}_\nu = \tfrac{1}{2} \int_{-1}^{1} d\mu f_\nu ,$$

$$\mathscr{H}_\nu = \tfrac{1}{2} \int_{-1}^{1} d\mu \mu f_\nu ,$$

$$\mathscr{K}_\nu = \tfrac{1}{2} \int_{-1}^{1} d\mu \mu^2 f_\nu ,$$

STELLA (Blinnikov+98)

- Monochromatic rad. energy eq.

$$\frac{\partial \mathcal{J}_\nu}{\partial t} = -\frac{c}{r^2}\left(\frac{\partial}{\partial r}\right)(r^2\mathcal{H}_\nu) + c(\bar{\eta}_\nu - \chi_a \mathcal{J}_\nu)$$

$$+\frac{u}{r}(3\mathcal{K}_\nu - \mathcal{J}_\nu) - \frac{1}{r^2}\left(\frac{\partial}{\partial r}\right)(r^2 u)(\mathcal{J}_\nu + \mathcal{K}_\nu)$$

$$-\frac{1}{\nu^3}\left(\frac{\partial}{\partial \nu}\right)\nu^4\left[\frac{u}{r}(3\mathcal{K}_\nu - \mathcal{J}_\nu) - \frac{1}{r^2}\left(\frac{\partial}{\partial r}\right)(r^2 u)\mathcal{K}_\nu\right]$$

- Monochromatic rad. momentum eq.

$$\frac{\partial \mathcal{H}_\nu}{\partial t} = -c\frac{\partial \mathcal{K}_\nu}{\partial r} - \frac{c}{r}(3\mathcal{K}_\nu - \mathcal{J}_\nu)$$

$$-2\left(\frac{u}{r} + \frac{\partial u}{\partial r}\right)\mathcal{H}_\nu - c(\chi_a + \chi_s)\mathcal{H}_\nu + \dot{\mathcal{H}}_{\nu\,\mathrm{diff}}$$

STELLA (Blinnikov+98)

- Hydrodynamical eqs.

$$\frac{\partial r}{\partial t} = u \ ,$$

$$\frac{\partial u}{\partial t} = -4\pi r^2 \frac{\partial (p+q)}{\partial m} - \frac{Gm}{r^2} + a_r + a_{\mathbf{mix}} \ ,$$

$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \rho} \ .$$

- Radiative acceleration

$$a_r = \frac{4\pi}{c} \int_0^\infty (\chi_a + \chi_s) \frac{H_\nu}{\rho} \, d\nu$$

STELLA (Blinnikov+98)

- EOS for material temperature

$$\left(\frac{\partial e}{\partial T}\right)_\rho \frac{\partial T}{\partial t} = \varepsilon + 4\pi \int_0^\infty (\alpha_\nu J_\nu - \eta_\nu)\mathrm{d}\nu - 4\pi \frac{\partial (r^2 u)}{\partial m} T \left(\frac{\partial p}{\partial T}\right)_\rho$$

$$\left(\mathrm{d}e + p\mathrm{d}V = \mathrm{d}e - \frac{p}{\rho^2}\mathrm{d}\rho = \left(\frac{\partial e}{\partial T}\right)_\rho \mathrm{d}T - \frac{T}{\rho^2}\left(\frac{\partial p}{\partial T}\right)_\rho \mathrm{d}\rho,\right)$$

- Closure relation
  - Variable Eddington factor $\mathscr{K} = f_{\mathbf{E}} \mathscr{J}$
- Boundary condition
  - Outer boundary: p=0 & $\mathscr{H} = h_{\mathbf{E}} \mathscr{J}$
  - Inner boundary: diffusion approximation

Variable Eddington factor

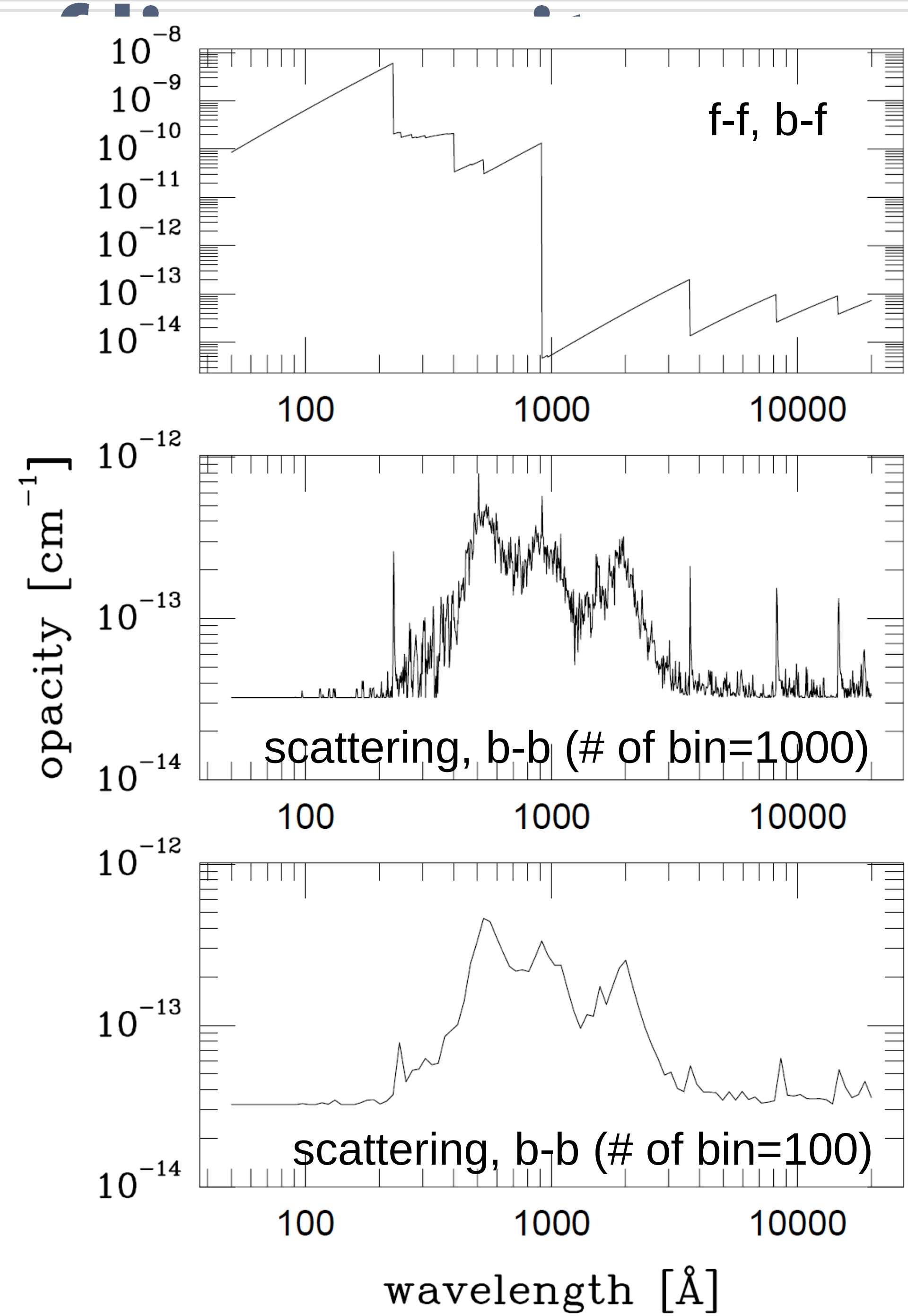
In 1 time step, the following procedures are iterated to convergence.

- $j_{\mu\nu}$ derived by a formal solution with S_ν
  - Feautrier method
- f_E, h_E calculated with $j_{\mu\nu}$
- Radiation hydrodynamics eq. solved with f_E, h_E
  - J_ν, H_ν, ρ, T, v
- S_ν estimated with new J_ν

Treatment
-Expansi

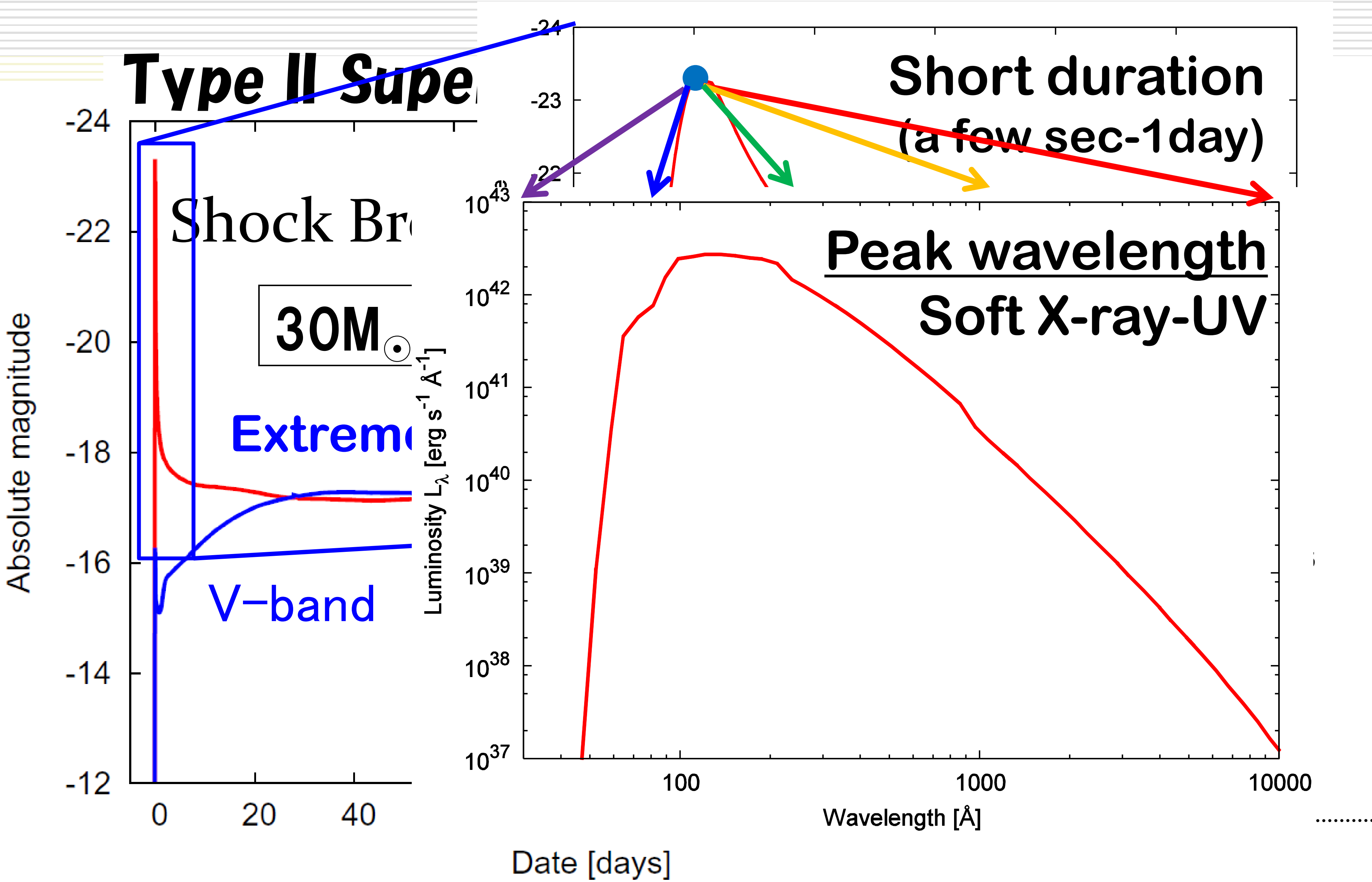
- A supernova is a
- Doppler shift shou
- Effective opacity a
- Effective line opa
  - = ave. num. of intera
  - – single scattering a

$$\chi_{\mathrm{exp}} = \frac{\nu}{\Delta\nu}\left(\frac{v}{rc}\right)\sum_j \int_0^1 ($$



Application for shock breakout

LCs of Type IIP SNe



Semianalytical solution of shock breakout

(Matzner & McKee 99)

$$E_{se} = 1.7 \times 10^{48} \left(\frac{\kappa}{0.34\ \mathrm{cm^2\ g^{-1}}}\right)^{-0.87} \left(\frac{\rho_1}{\rho_*}\right)^{-0.086} \times \left(\frac{E_{in}}{10^{51}\ \mathrm{ergs}}\right)^{0.56} \left(\frac{M_{ej}}{10\ M_\odot}\right)^{-0.44} \times \left(\frac{R_*}{500\ R_\odot}\right)^{1.74} \mathrm{ergs}$$

$$T_{se} = 5.55 \times 10^{5} \left(\frac{\kappa}{0.34\ \mathrm{cm^2\ g^{-1}}}\right)^{-0.10} \left(\frac{\rho_1}{\rho_*}\right)^{0.070} \times \left(\frac{E_{in}}{10^{51}\ \mathrm{ergs}}\right)^{0.20} \left(\frac{M_{ej}}{10\ M_\odot}\right)^{-0.052} \times \left(\frac{R_*}{500\ R_\odot}\right)^{-0.54} \mathrm{K}$$

$$t_{se} = 790 \left(\frac{\kappa}{0.34\ \mathrm{cm^2\ g^{-1}}}\right)^{-0.58} \left(\frac{\rho_1}{\rho_*}\right)^{-0.28} \times \left(\frac{E_{in}}{10^{51}\ \mathrm{ergs}}\right)^{-0.79} \left(\frac{M_{ej}}{10\ M_\odot}\right)^{0.21} \times \left(\frac{R_*}{500\ R_\odot}\right)^{2.16} \mathrm{s}$$

For larger radius,

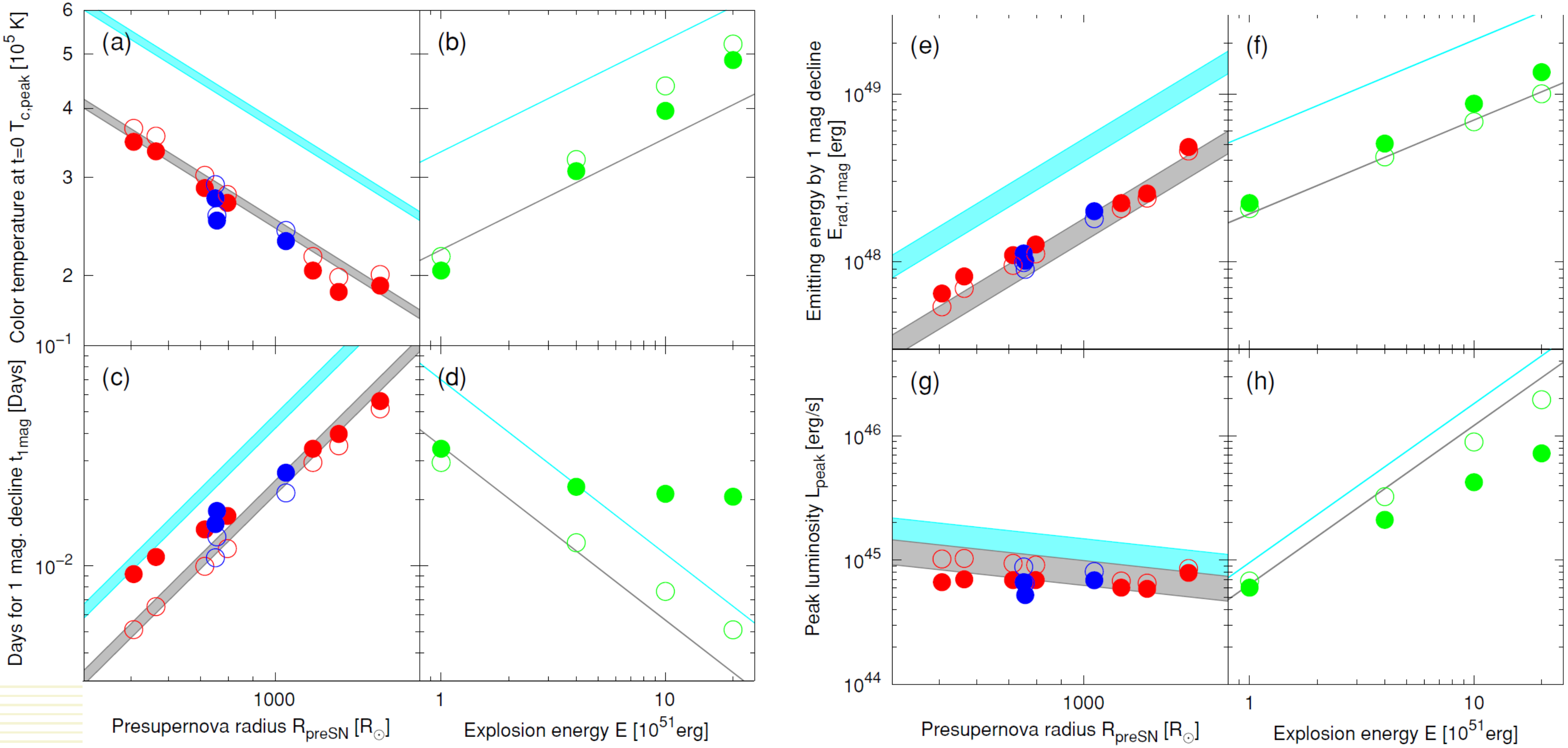
longer duration,

higher total energy, and

lower temperature

(i.e., redder color).

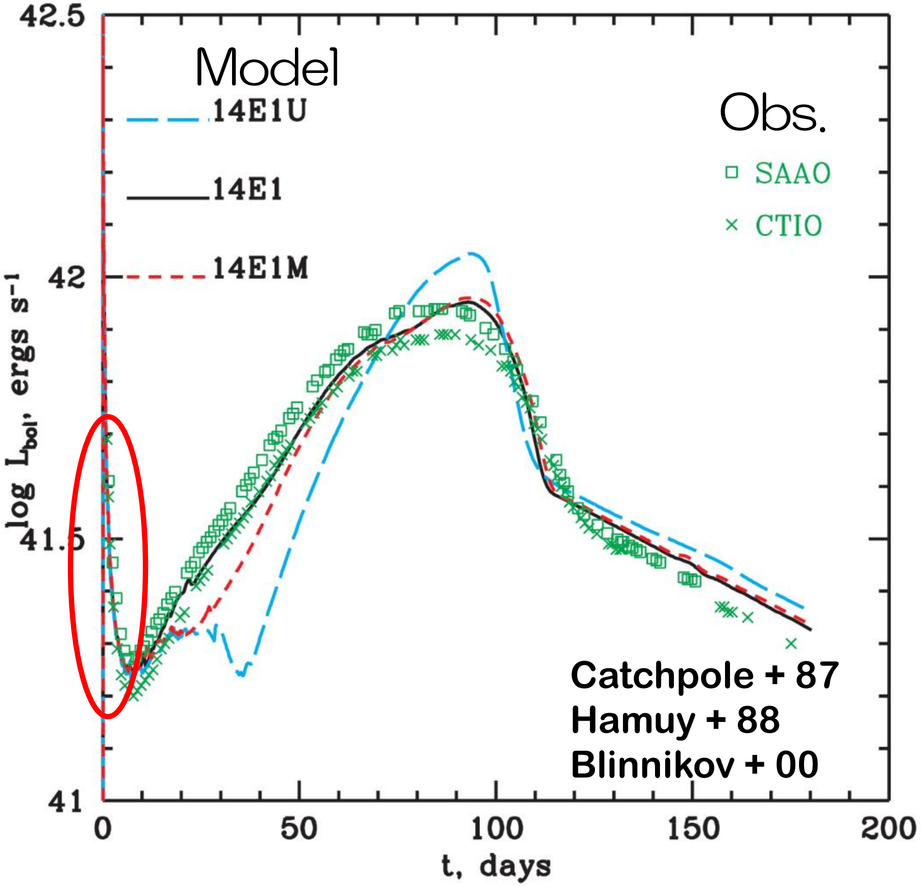
Comparisons with semianalytical solutions

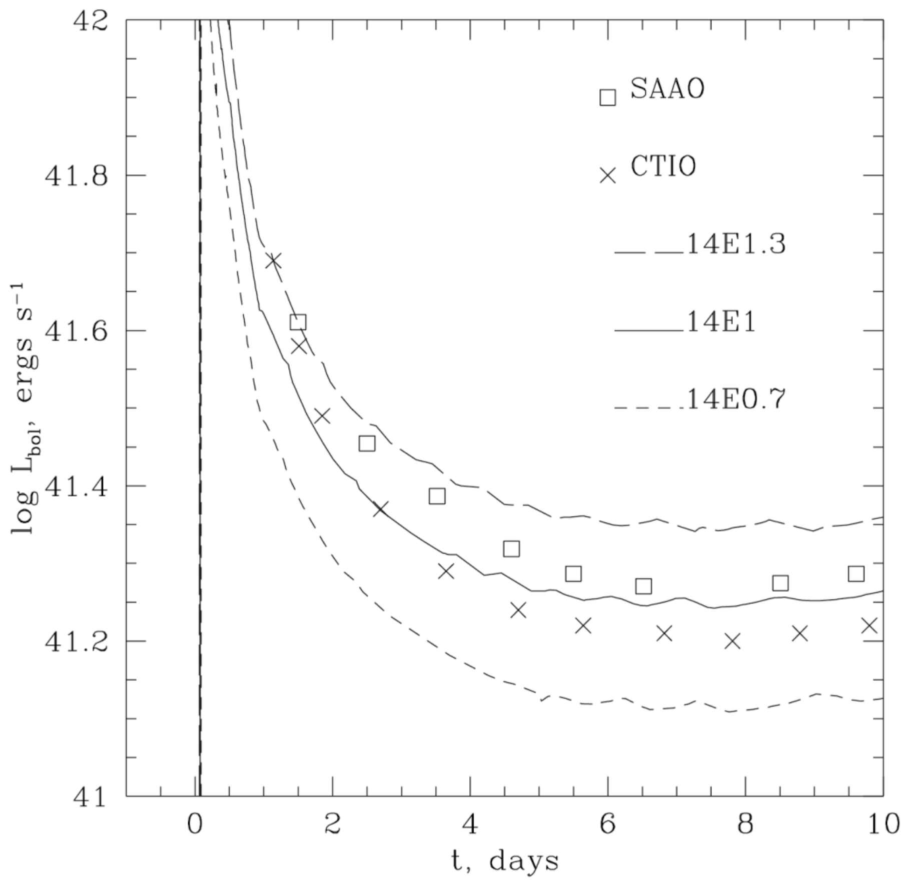


Adopting $T_{ana}/1.5$, $t_{ana}/2$, $E_{ana}/3$, $L_{ana}/1.5$,
analytical and numerical solutions are consistent (NT+11).

Comparison with observed shock breakout tail (Blinnikov+00)

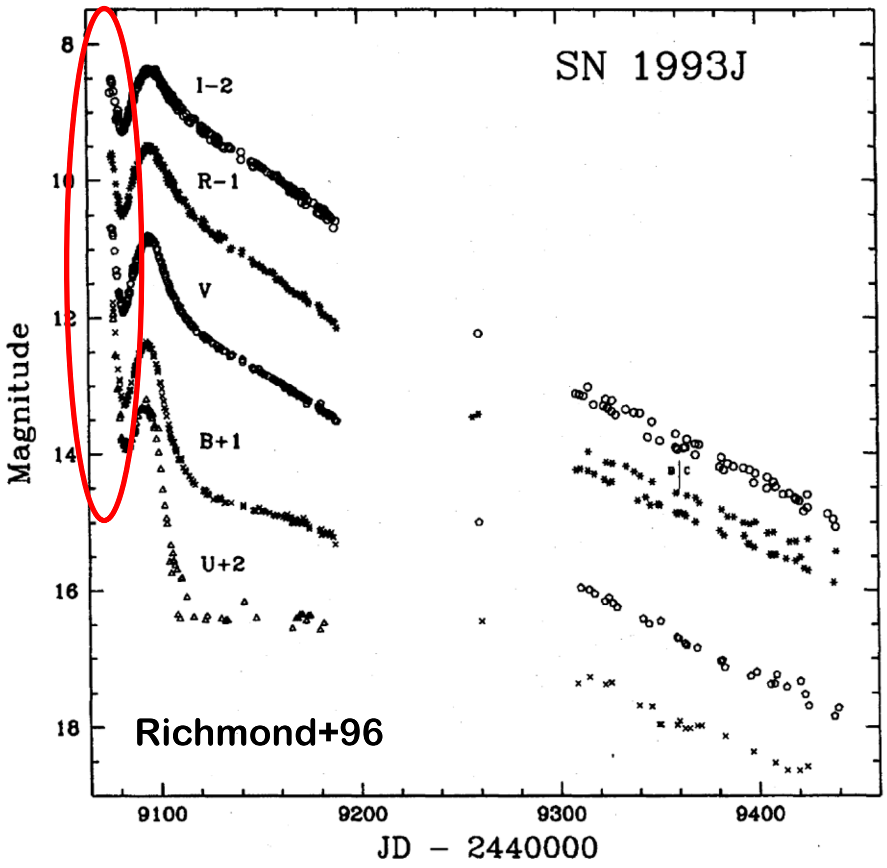
Type II-peculiar SN1987A



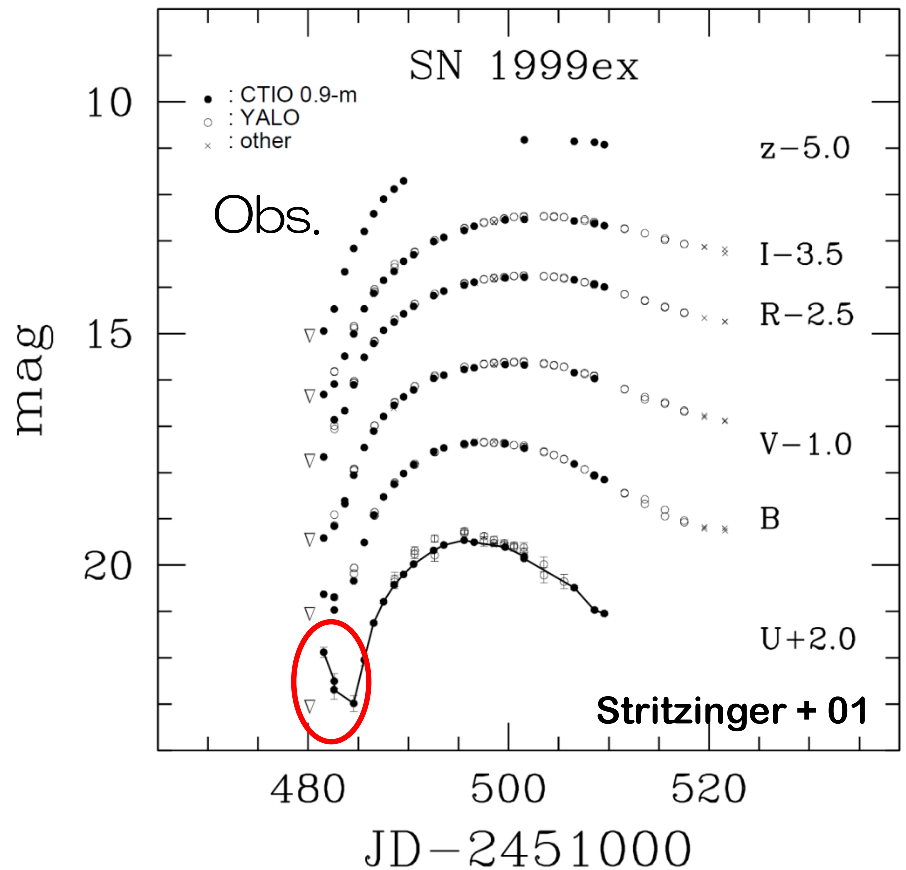


Shock breakout tails
—Observations before 2008—

Type IIb SN1993J



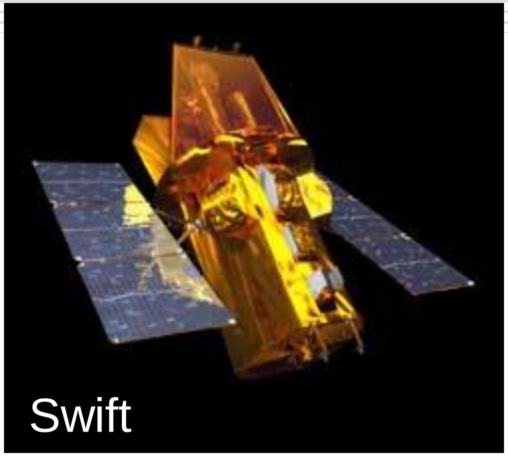
Type Ib SN1999ex

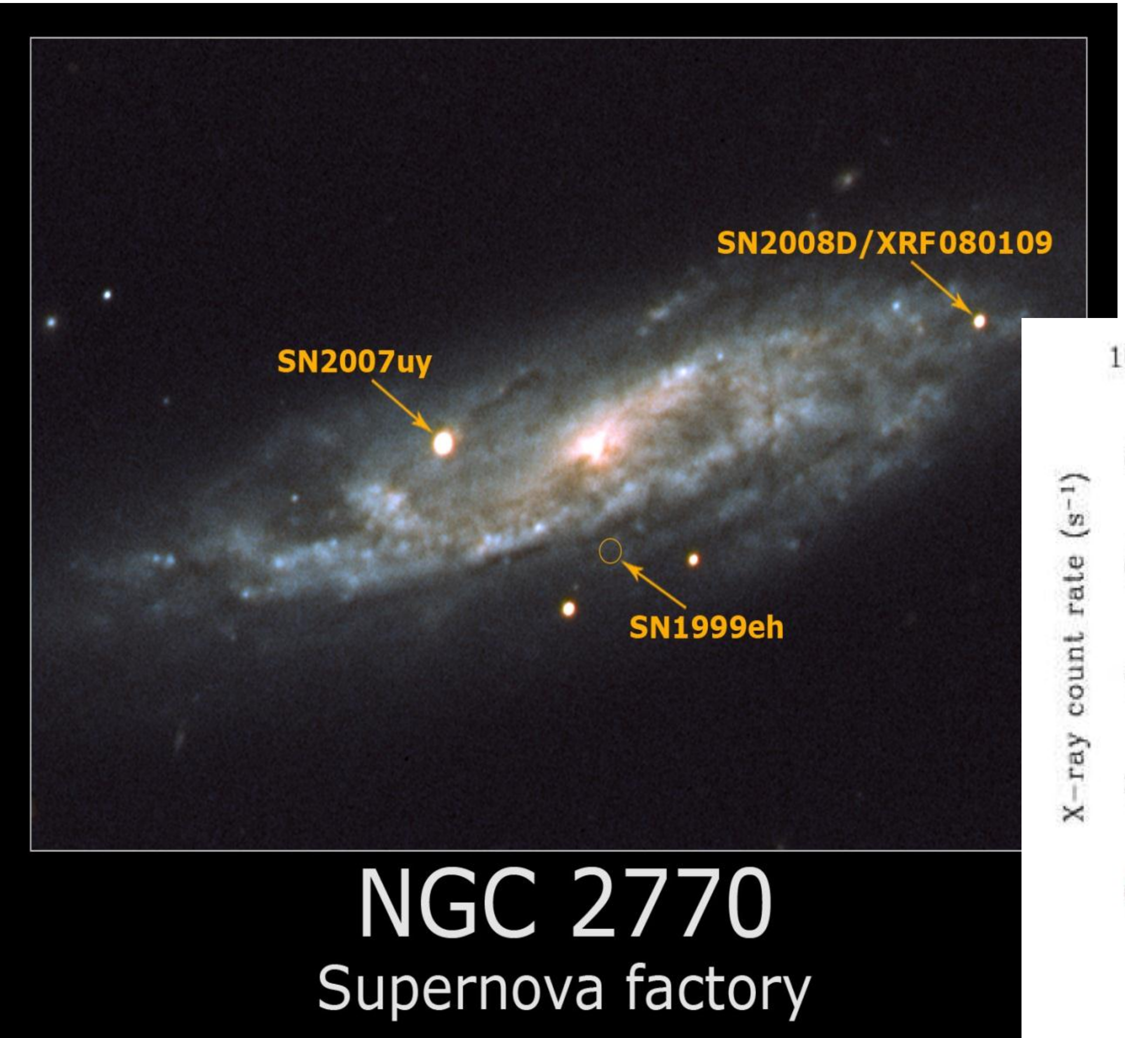


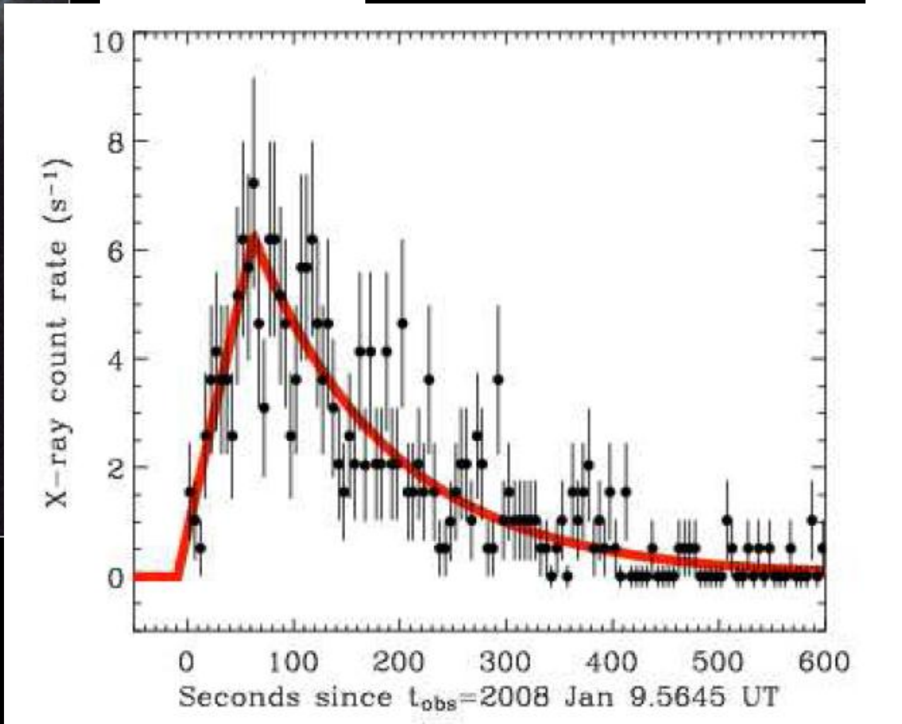
近傍の超新星でのみ、偶然見つかることがある。

3 events were reported in 2008

- Type Ib SN2008D/XRO080109
  - Soderberg + 08; Modjaz + 09





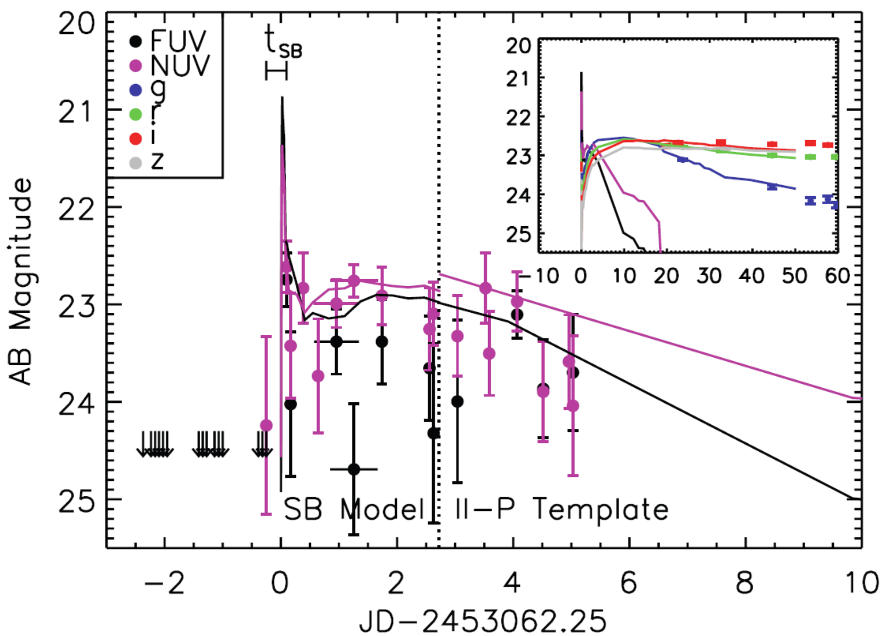


Only 3 events from a rising part

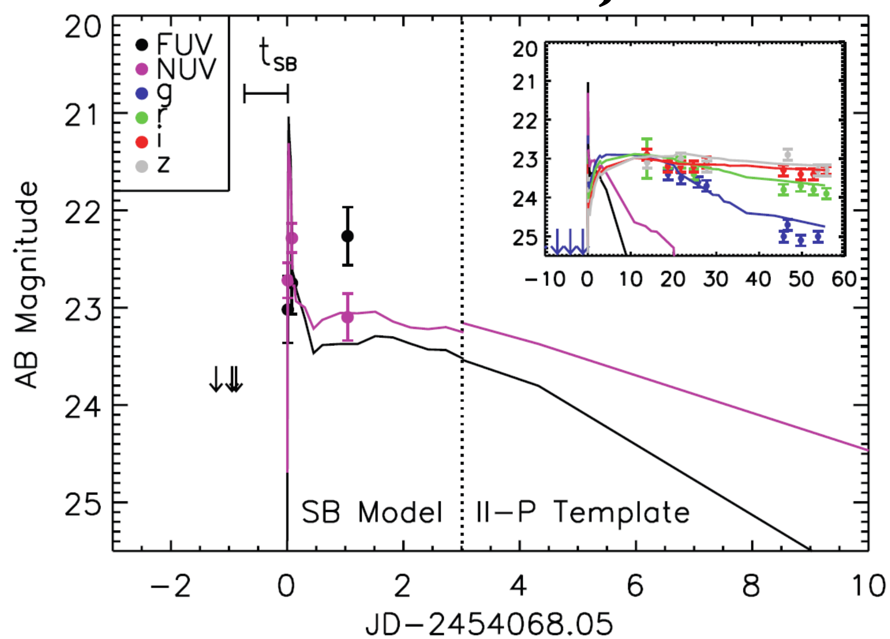
SNLS SuperNova Legacy Survey

- Type II-P SN SNLS-04D2dc (z=0.1854)
  - Schawinski et al. 08; Gezari et al. 08
- Type II-P SN SNLS-06D1jd (z=0.324)
  - Gezari et al. 08

SNLS-04D2dc



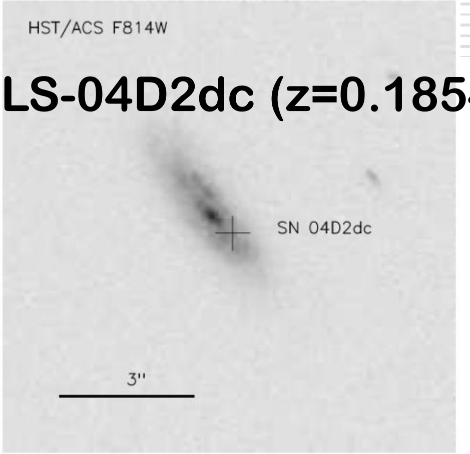
SNLS-06D1jd



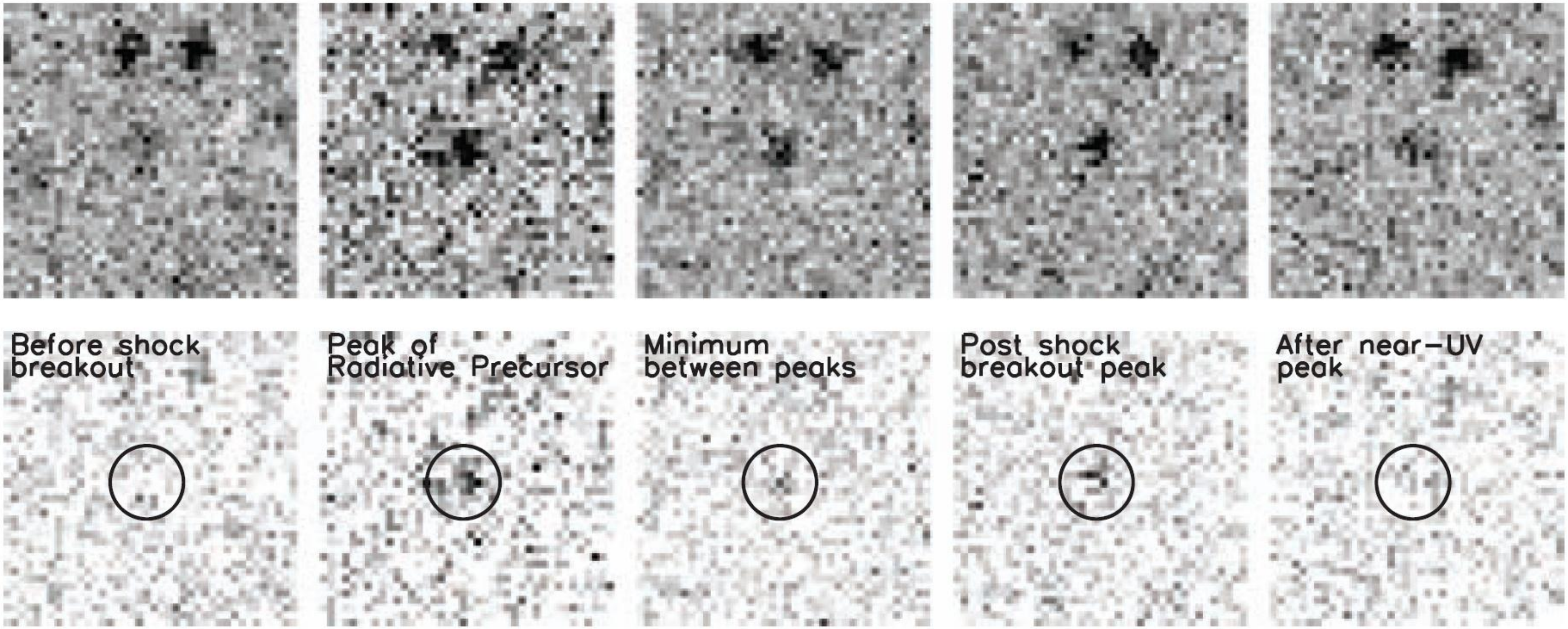
Shock breakout of Type II-P SN
-SNLS-04D2dc-

SNLS SuperNova Legacy Survey

SNLS-04D2dc (z=0.1854)

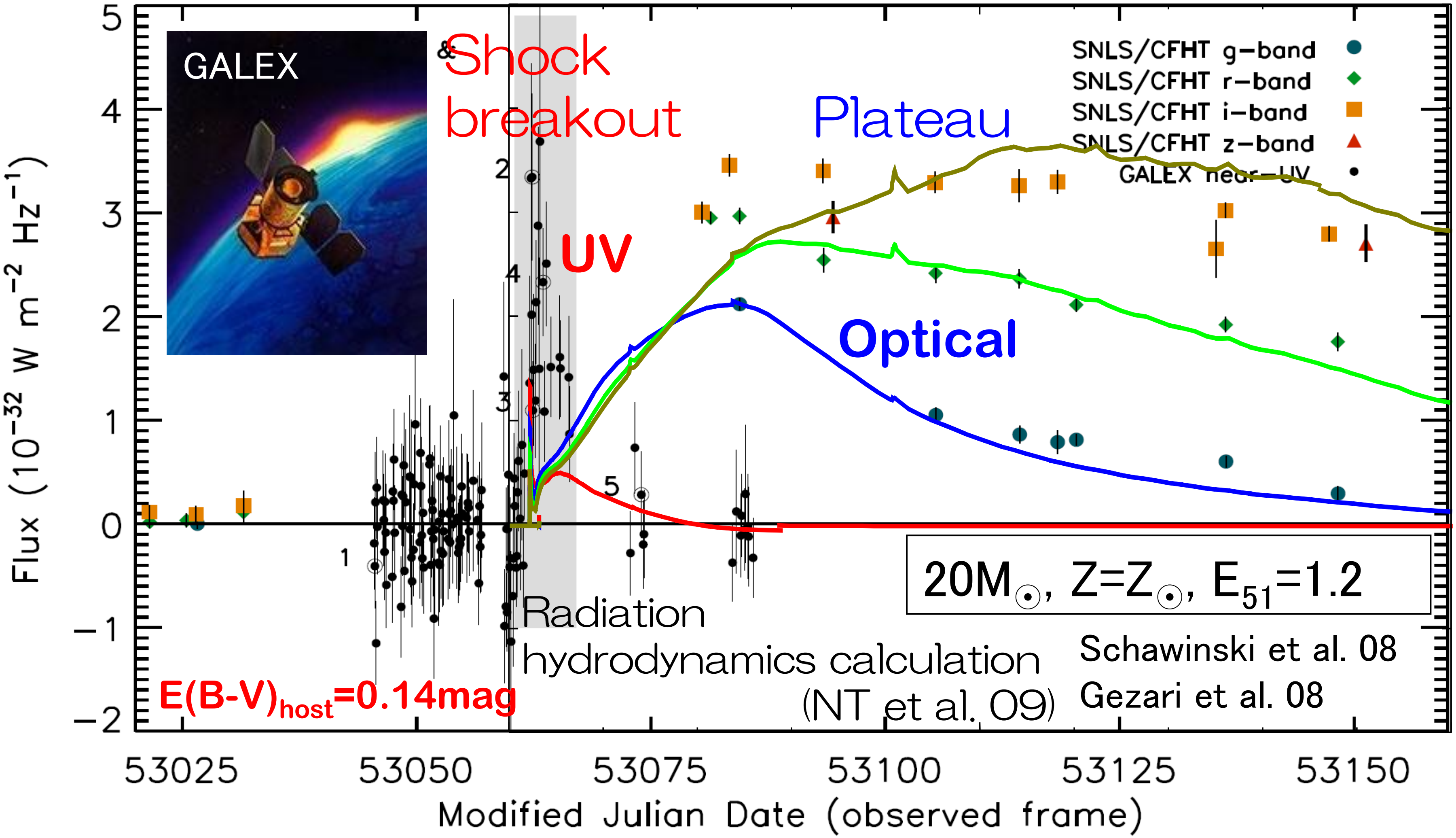


Schawinski et al. 08
Gezari et al. 08

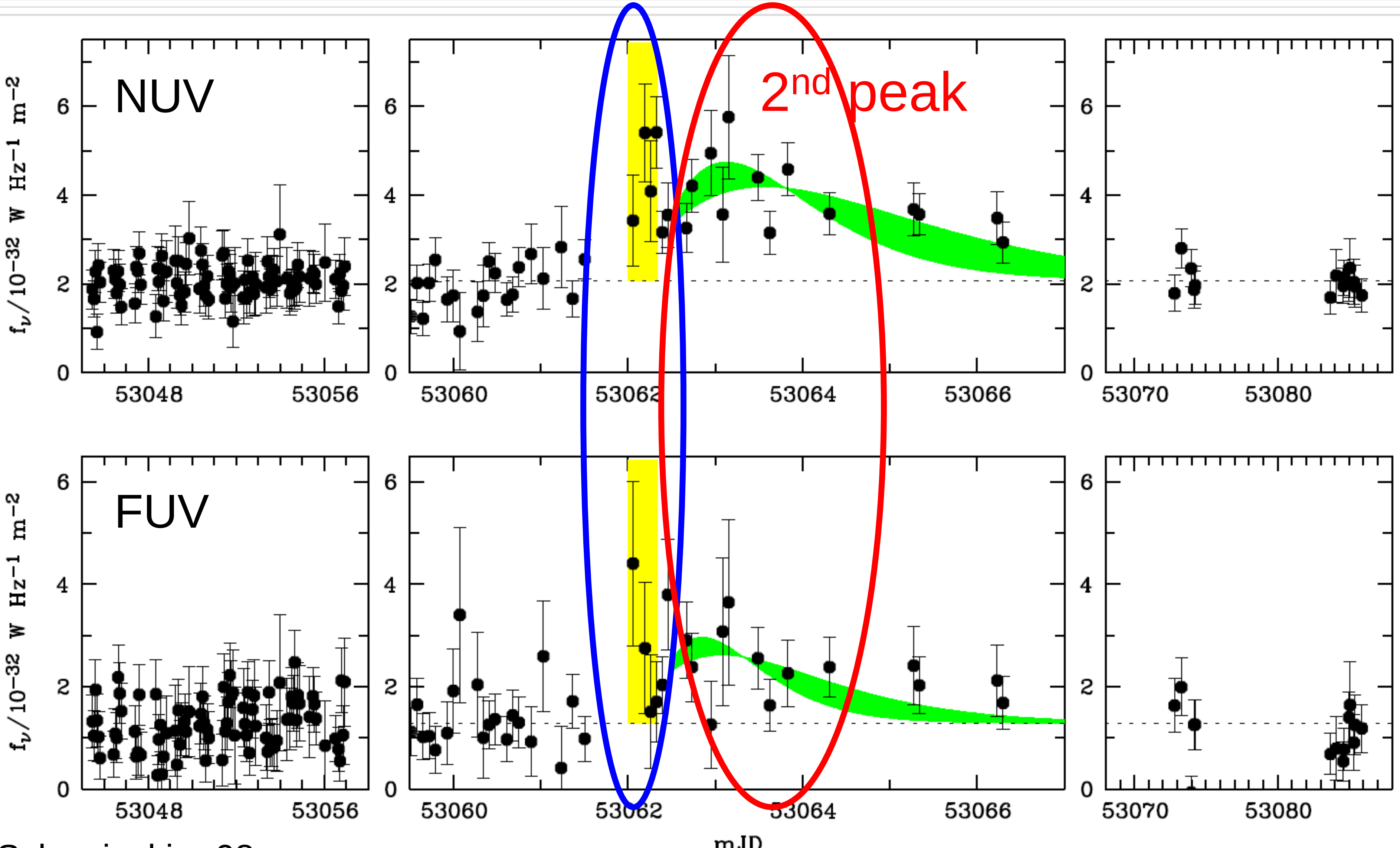


Shock breakout of Type IIP SN
-Multicolor light curves-

SNLS-04D2dc

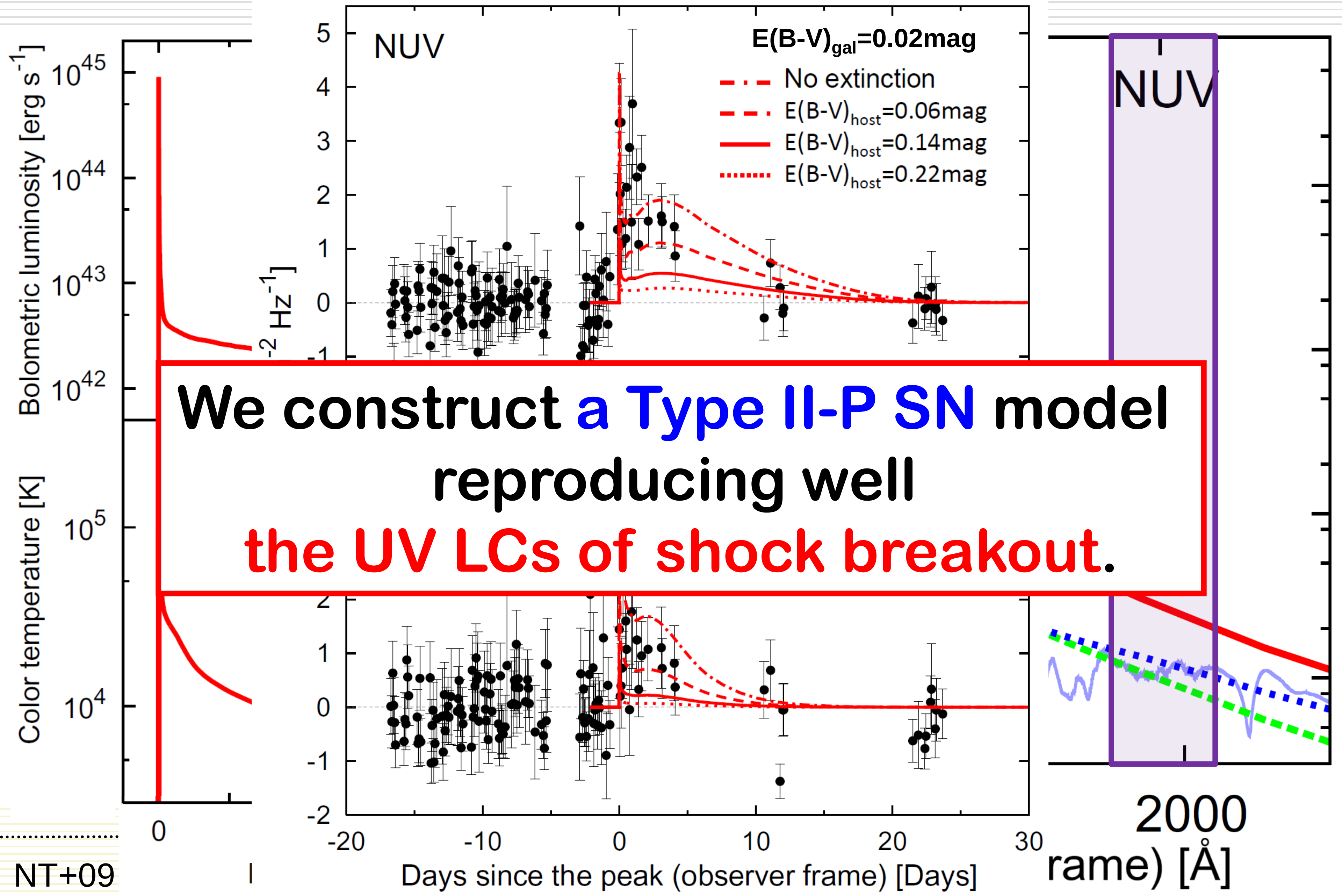


UV LCs of Shock breakout



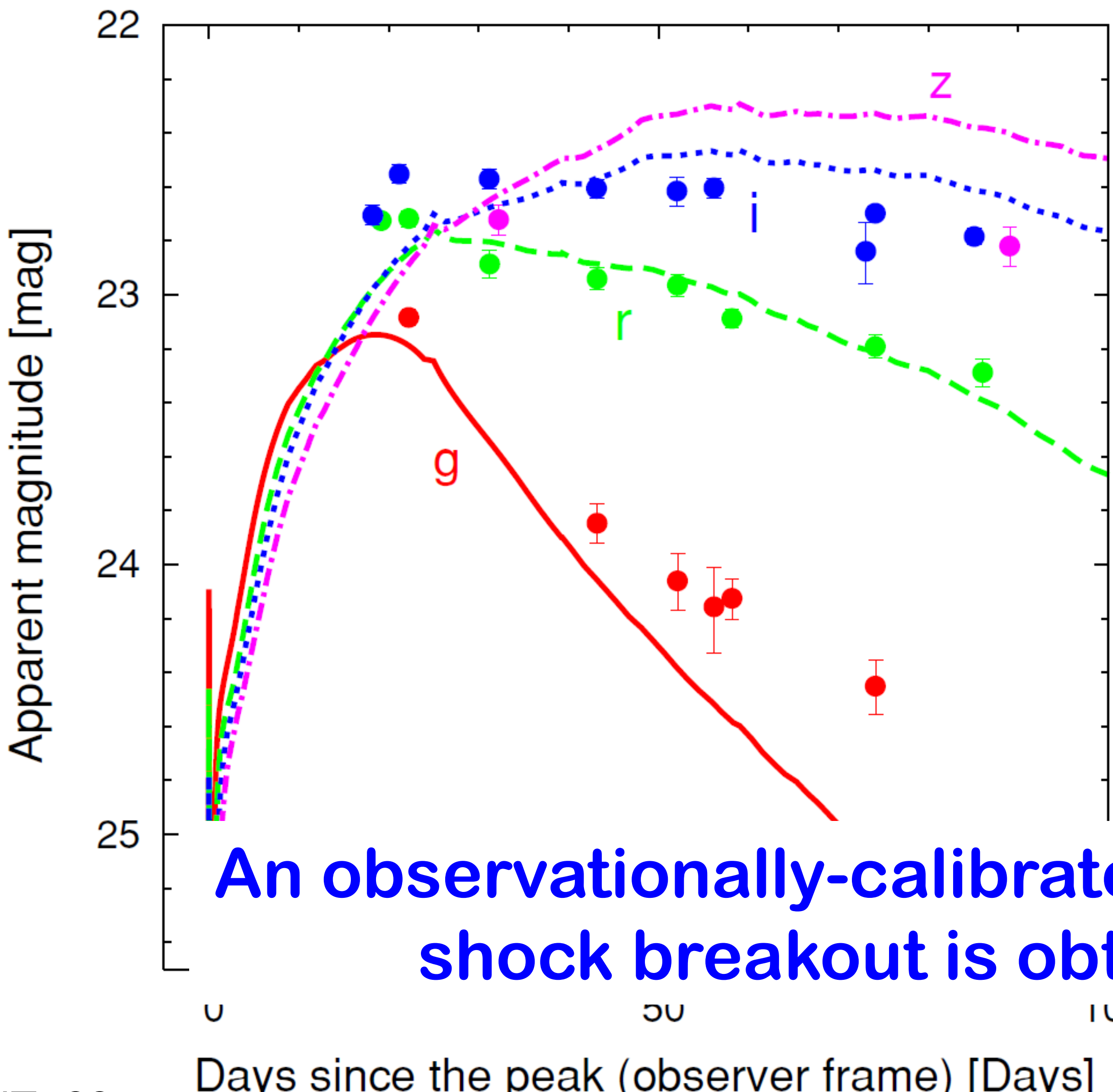
Schawinski + 08

Model: light curve & color evolution



We construct a Type II-P SN model reproducing well the UV LCs of shock breakout.

Optical LCs are also well reproduced.



SNLS-04D2dc

$M_{ms}=20M_{\odot}$

$M_{preSN}=18.4M_{\odot}$

$R_{preSN}=800R_{\odot}$

$E=1.2\times10^{51}$erg

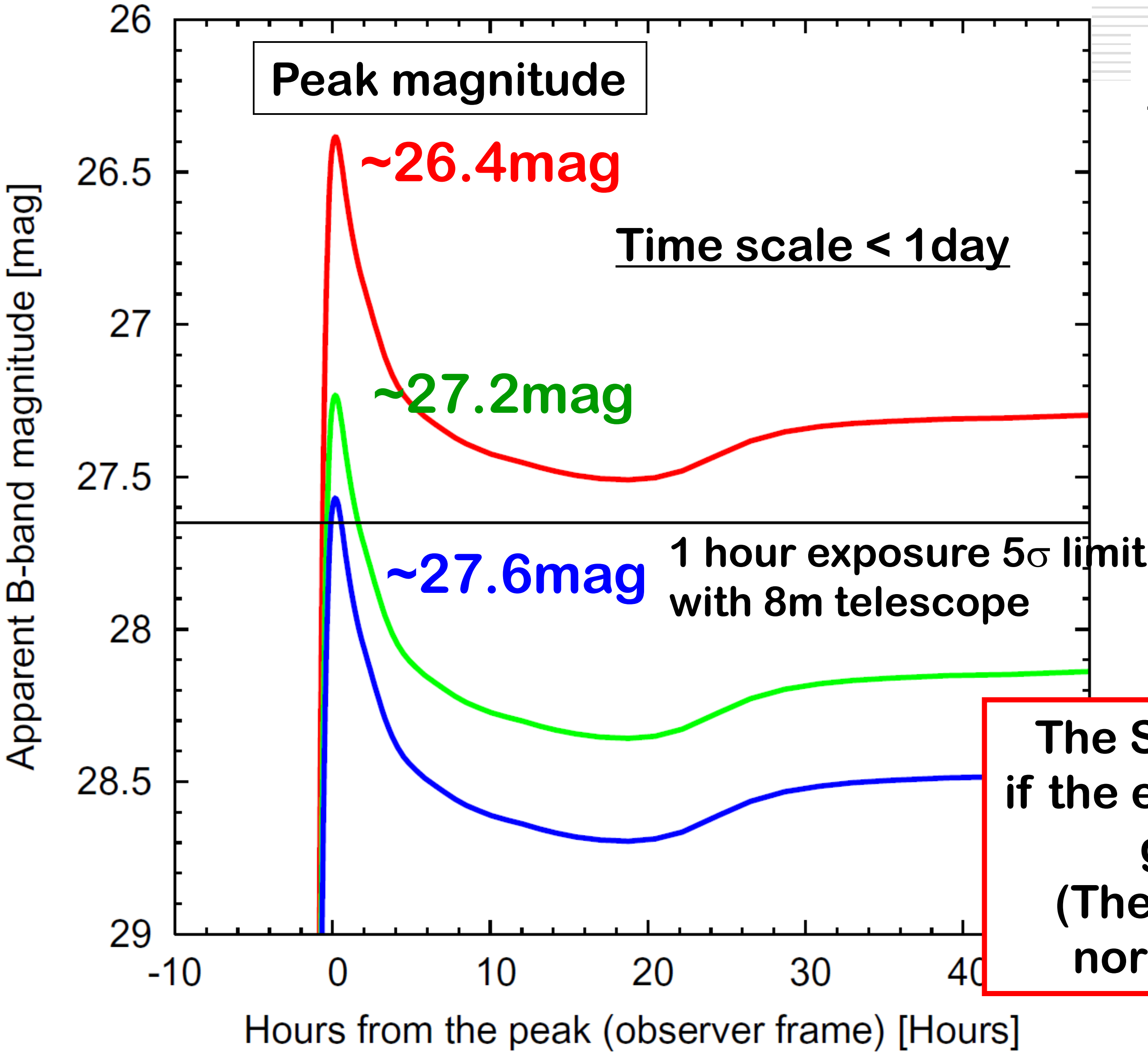
(= E of SN1987A)

Typical Type II-P SN

An observationally-calibrated model for shock breakout is obtained.

NT+09

When the same SN takes place at high z,



SNLS-04D2dc

Redshift z=1

$E(B-V)_{Gal}$=0.02mag.

$E(B-V)_{host}$=0

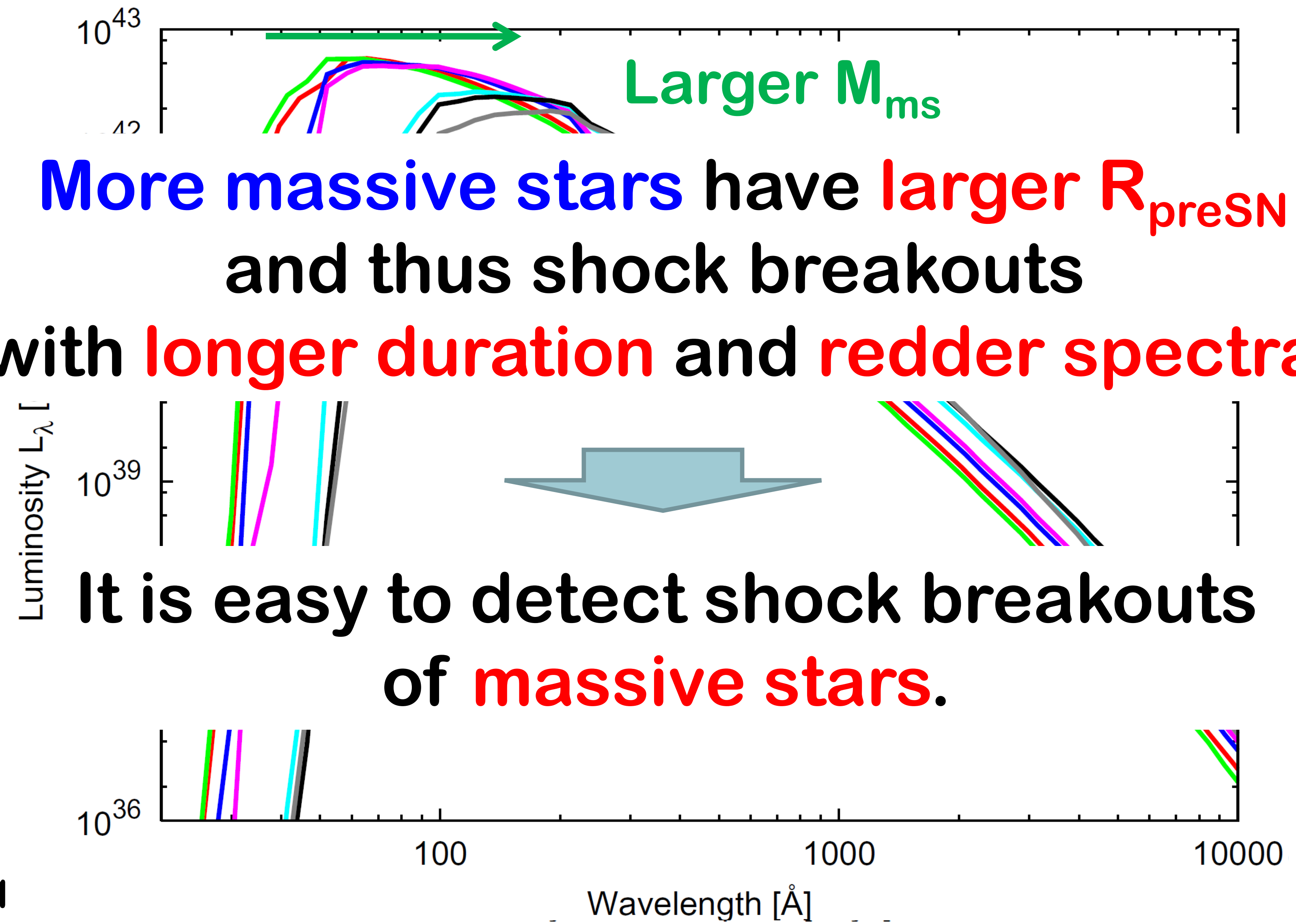
$E(B-V)_{host}$=0.1mag.

$E(B-V)_{host}$=0.14mag.

The SN can be detected, if the extinction of the host galaxy is small. (The current record of normal SNe is z<0.9.)

Proposal for future SN survey

SN shock breakout of stars with different M_{ms}

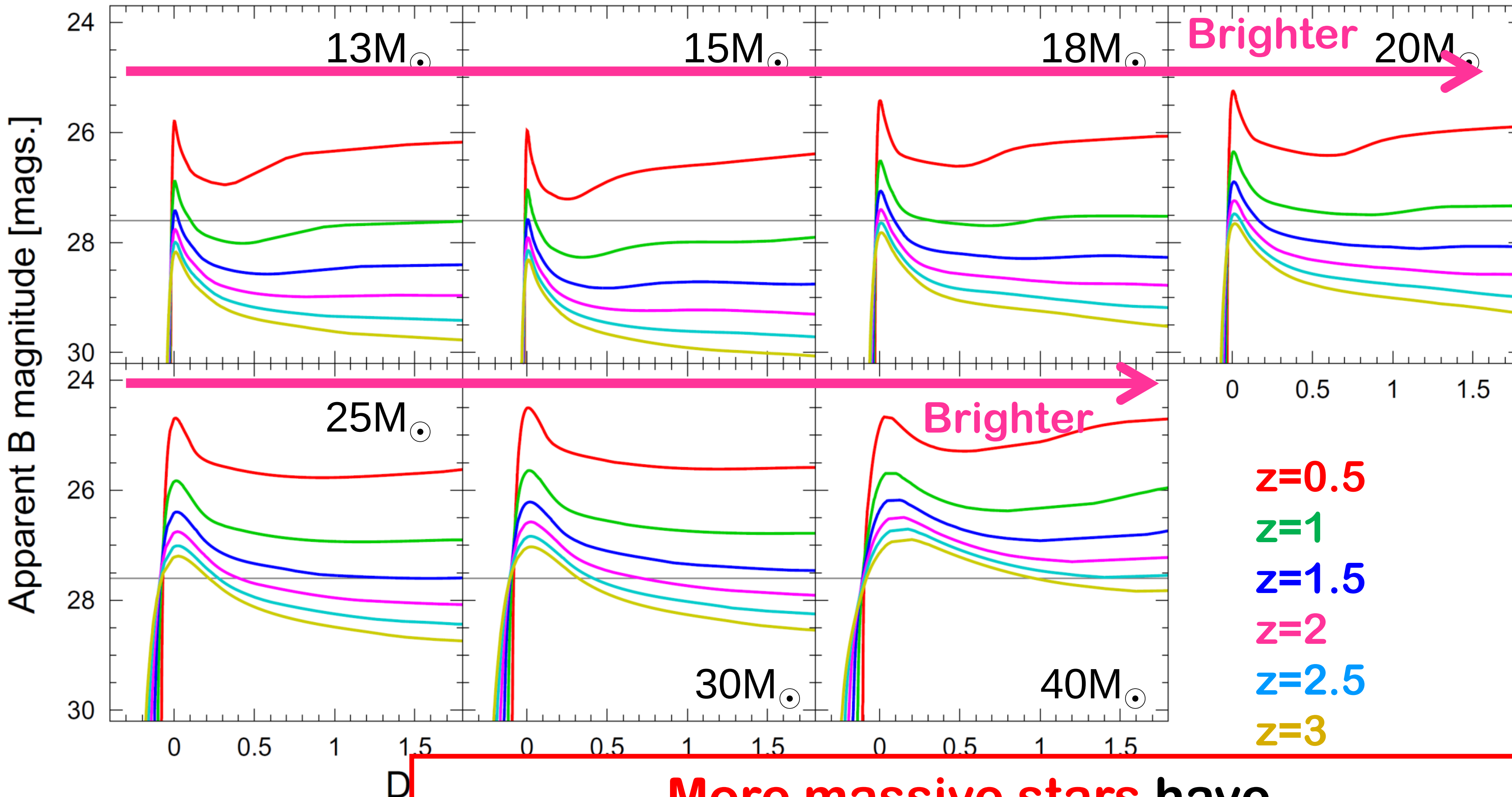


More massive stars have **larger R_{preSN}** and thus shock breakouts with **longer duration** and **redder spectra**.

It is easy to detect shock breakouts of massive stars.

NT +11

Theoretical predictions
-B-band light curves-

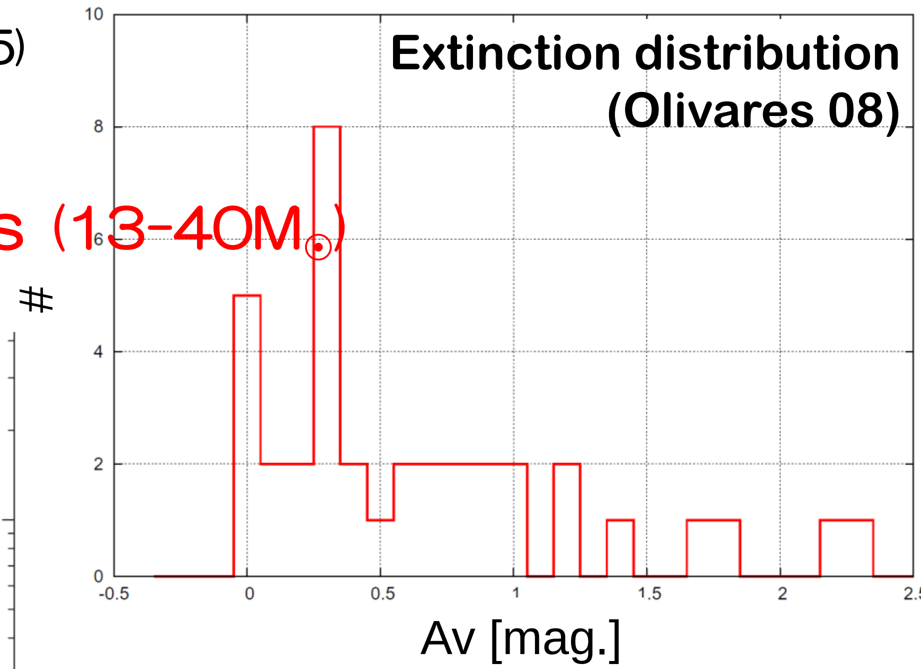


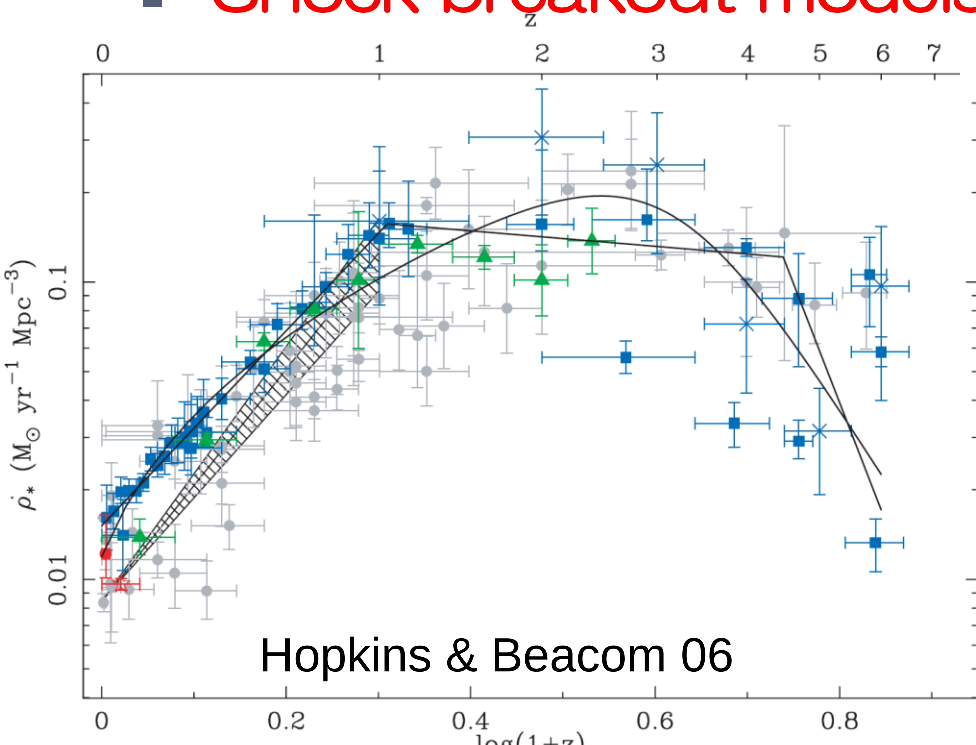
More massive stars have apparently more luminous shock breakout.

NT + 11

Expected number of detection

- Cosmic star formation history (Hopkins & Beacom 2006)
- Distribution of host galaxy extinction (Olivares 08)
- IGM absorption (Madau 95)
- Salpeter's IMF
- Shock breakout models (13-40$M_\odot$)





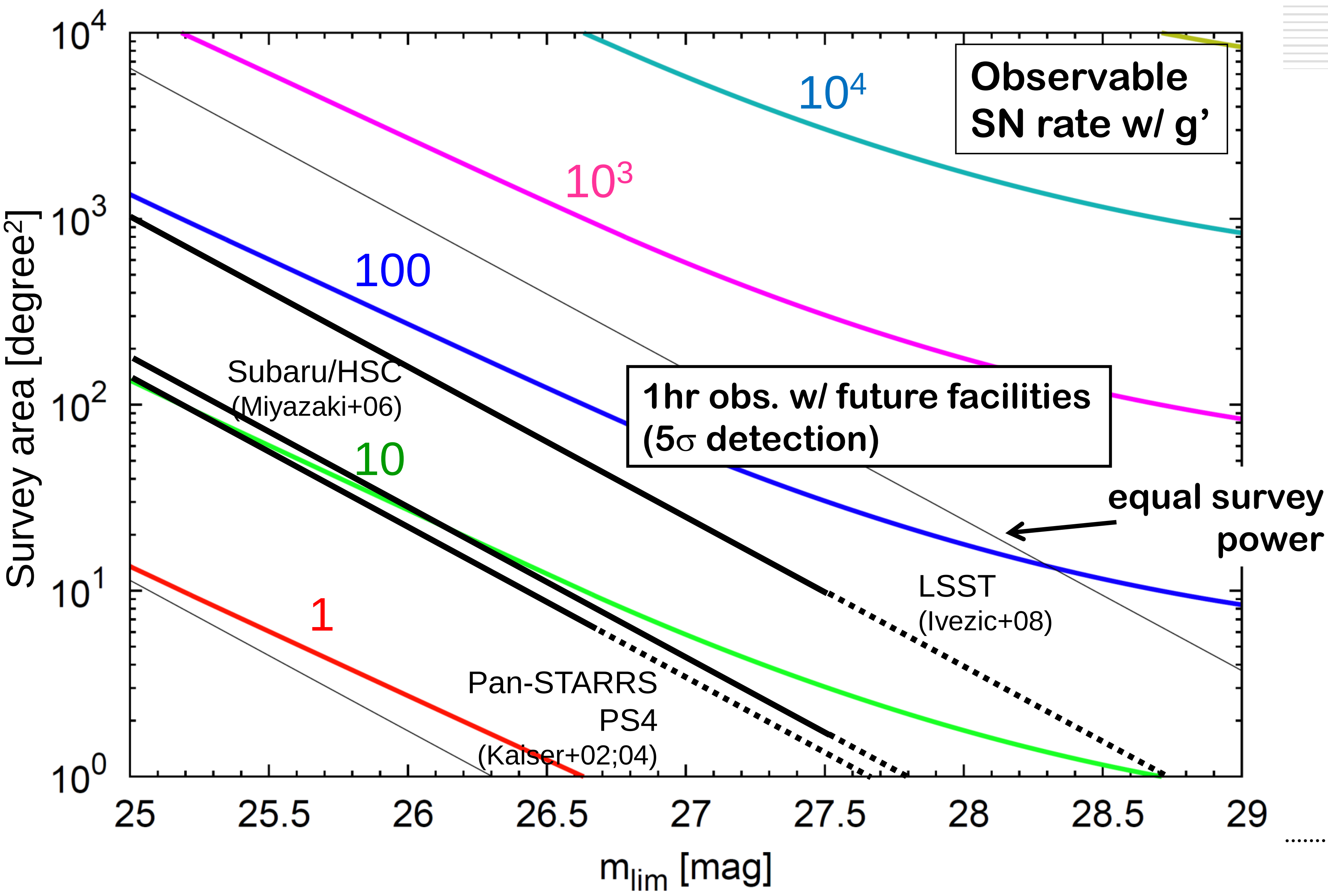
gray: Hopkins (2004)

Hatched region & green: FIR (24 mm)

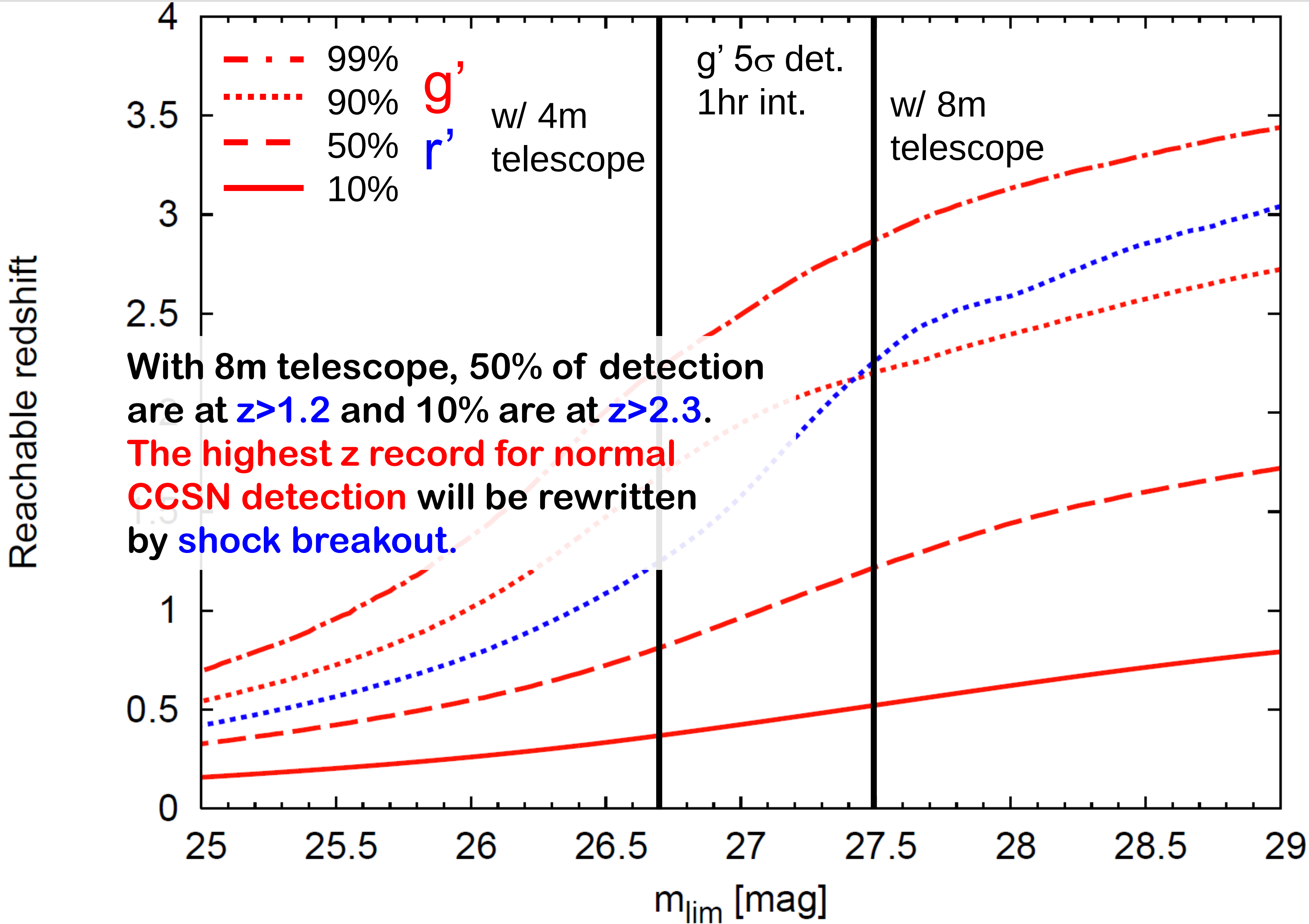
red: radio (1.4 GHz) & H estimate

blue: UV & UDF

$n(m_{peak}<m_{lim})$: m_{lim} vs. Survey area

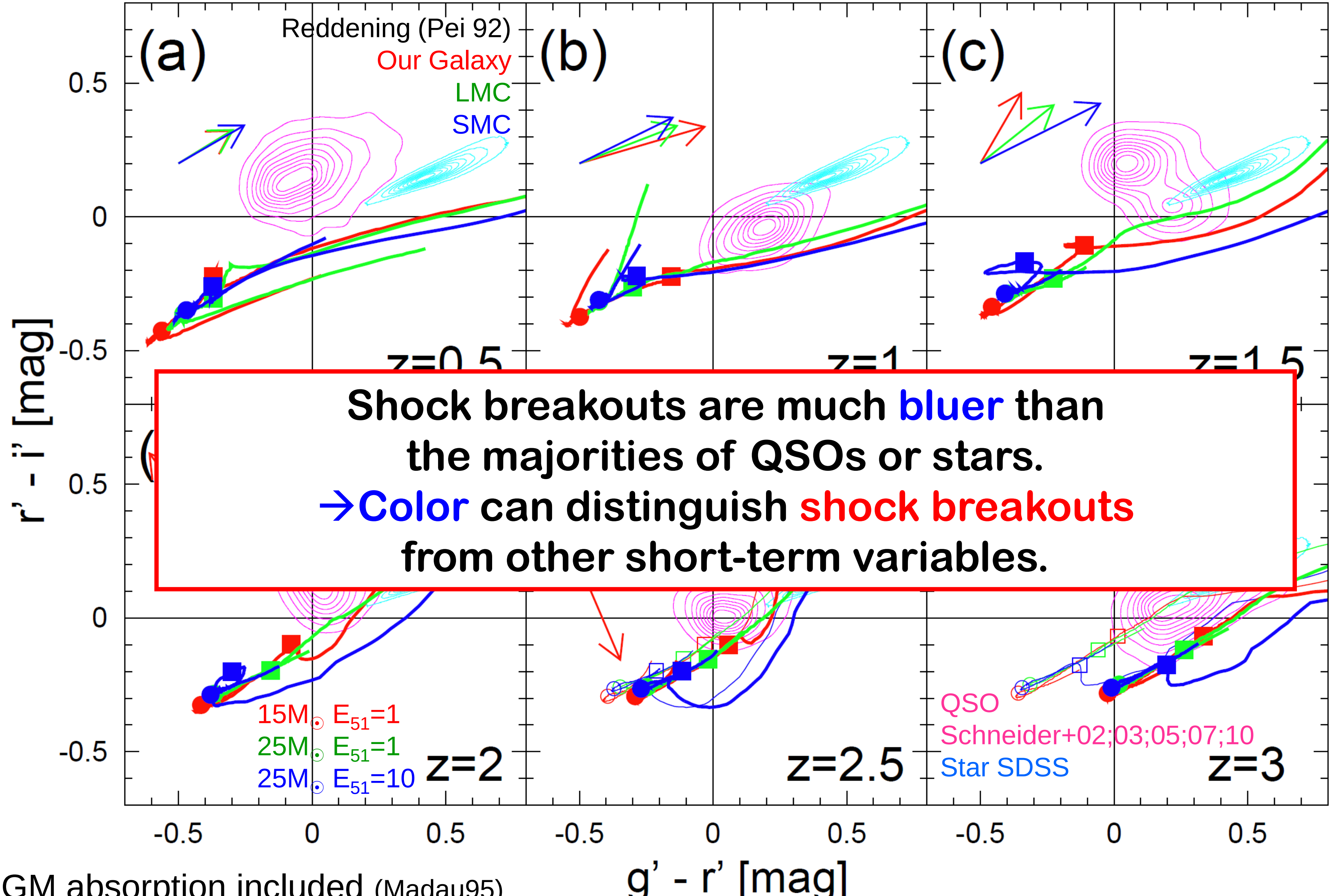


z_{max} vs. m_{lim}



With 8m telescope, 50% of detection are at z>1.2 and 10% are at z>2.3.
The highest z record for normal CCSN detection will be rewritten by shock breakout.

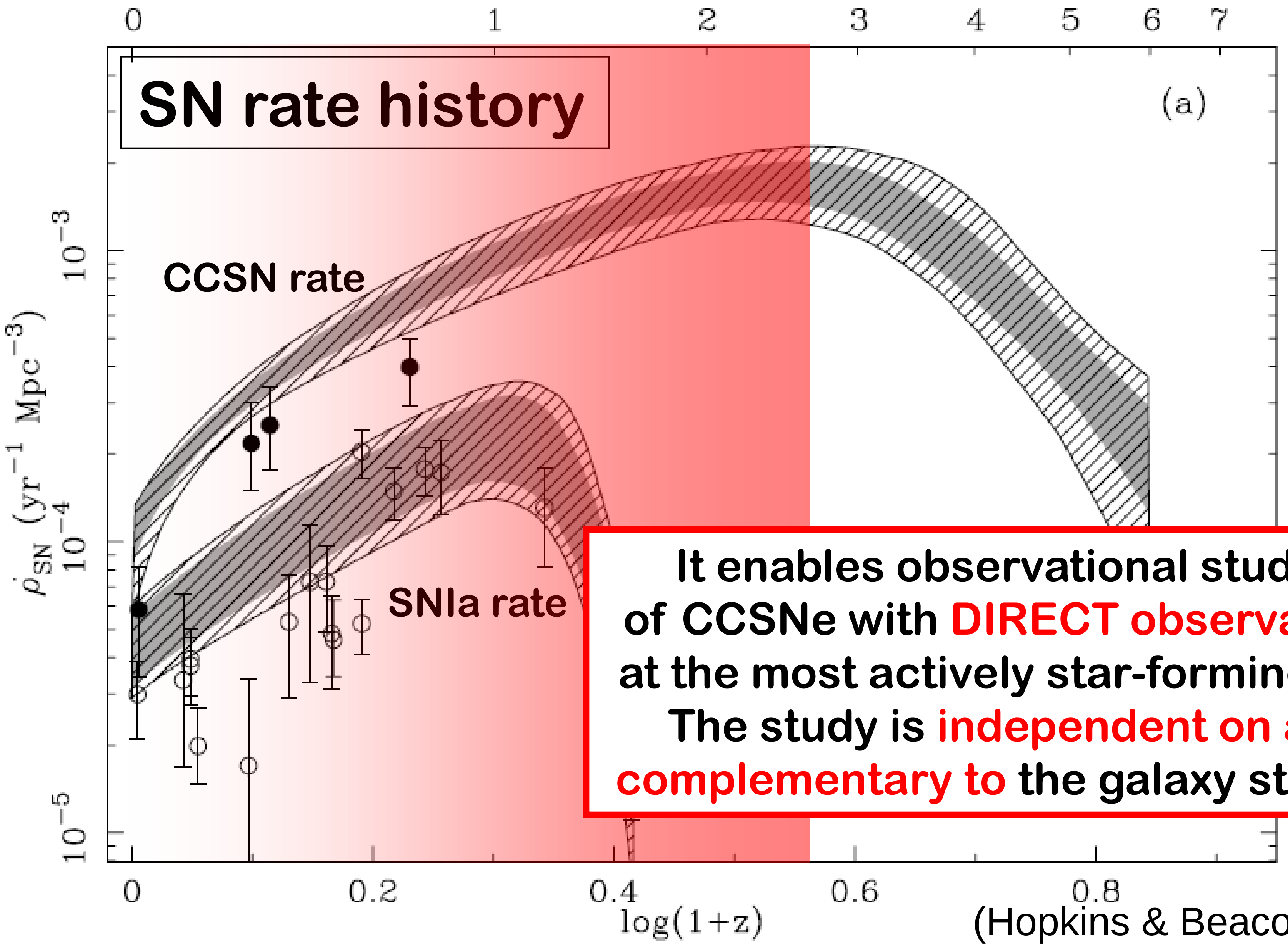
Shock breakout identified by colors



Shock breakouts are much bluer than the majorities of QSOs or stars.
→Color can distinguish shock breakouts from other short-term variables.

IGM absorption included (Madau95)

We can use shock breakout for CCSN study up to z~3!!



It enables observational studies of CCSNe with DIRECT observations at the most actively star-forming age. The study is independent on and complementary to the galaxy studies.

(Hopkins & Beacom 2006)

まとめ

- Shock breakout を取り扱うには、輻射流体計算が必要である。
- 多波長輻射流体計算コードSTELLAを用いた shock breakout の輻射流体計算を行った。
- 観測された shock breakout の多色光度曲線を再現し、さらに遠方宇宙で起こる shock breakout の予想される光度曲線を提出した。
- 通常の超新星爆発でも遠方宇宙でも観測でき、遠方宇宙における超新星研究に非常に有用な天体である。
- 多数の観測によって shock breakout の物理が確立することも期待される。