Supernova shocks in circumstellar medium: from puzzles to cosmological tools

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IPMU, 8 Feb 2012

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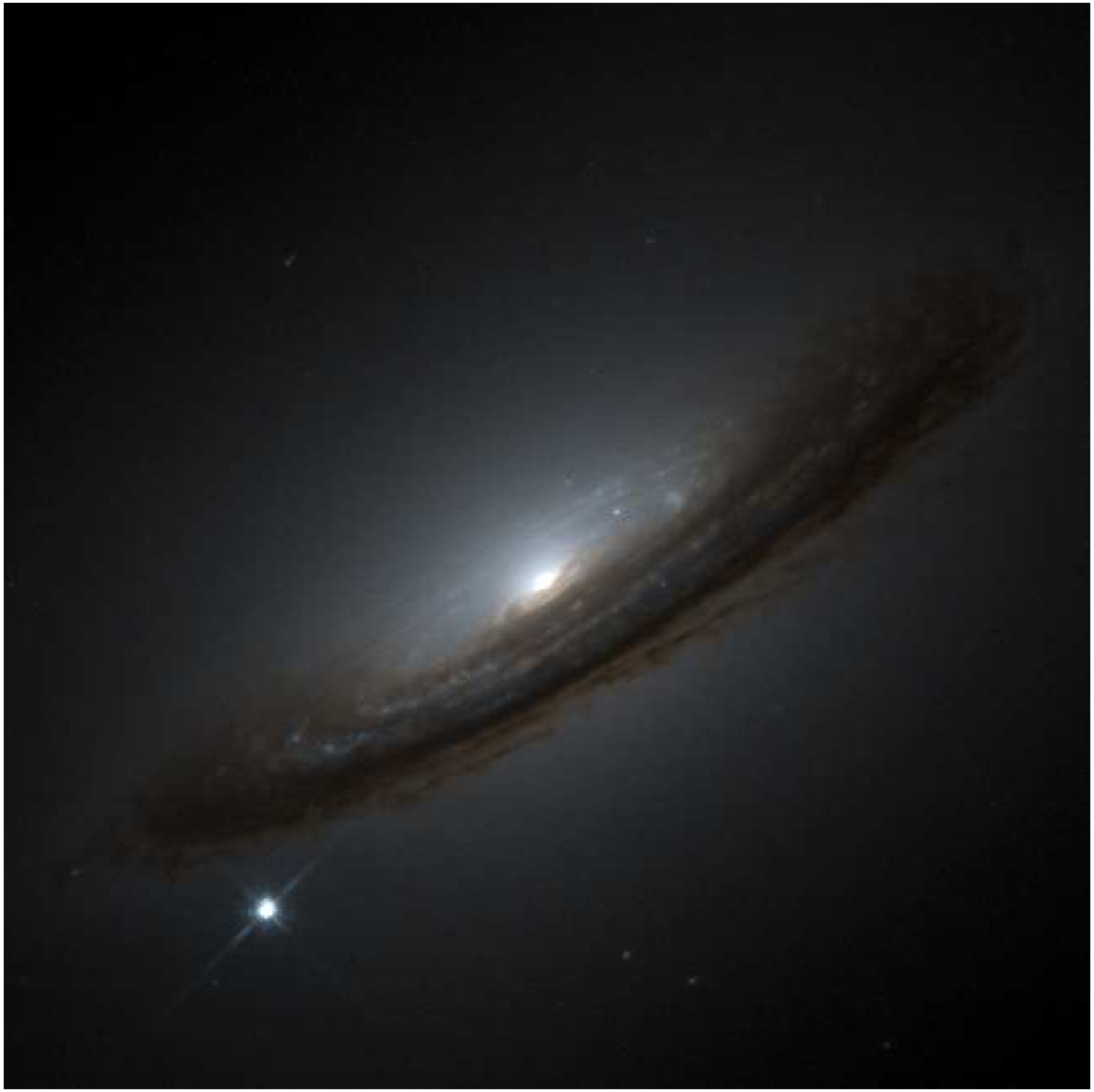
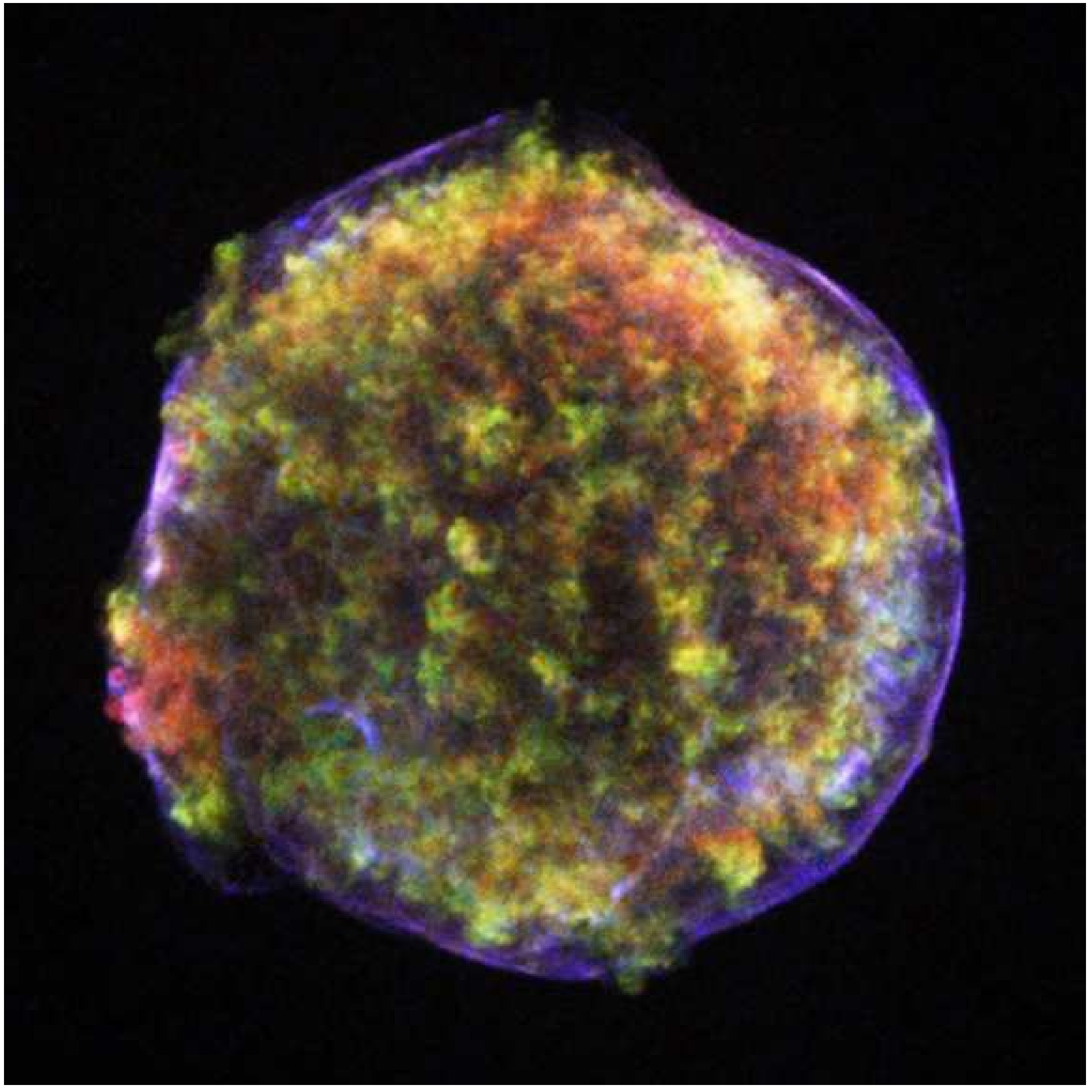
Supernova SN1994D in NGC4526

Shocks are not important for light in “Nobel prize” SNe Ia



SNR Tycho in X-rays (Chandra)



Supernova: order of events

- Core collapse (CC) or explosion

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Supernova: order of events

- Core collapse (CC) or explosion
- Neutrino/GW signal, accompanying signals
- Shock creation if any, propagation and entropy production inside a star
- Shock breakout (!)
- Diffusion of photons and cooling of ejecta

Core-Collapse-SN (CCSN)

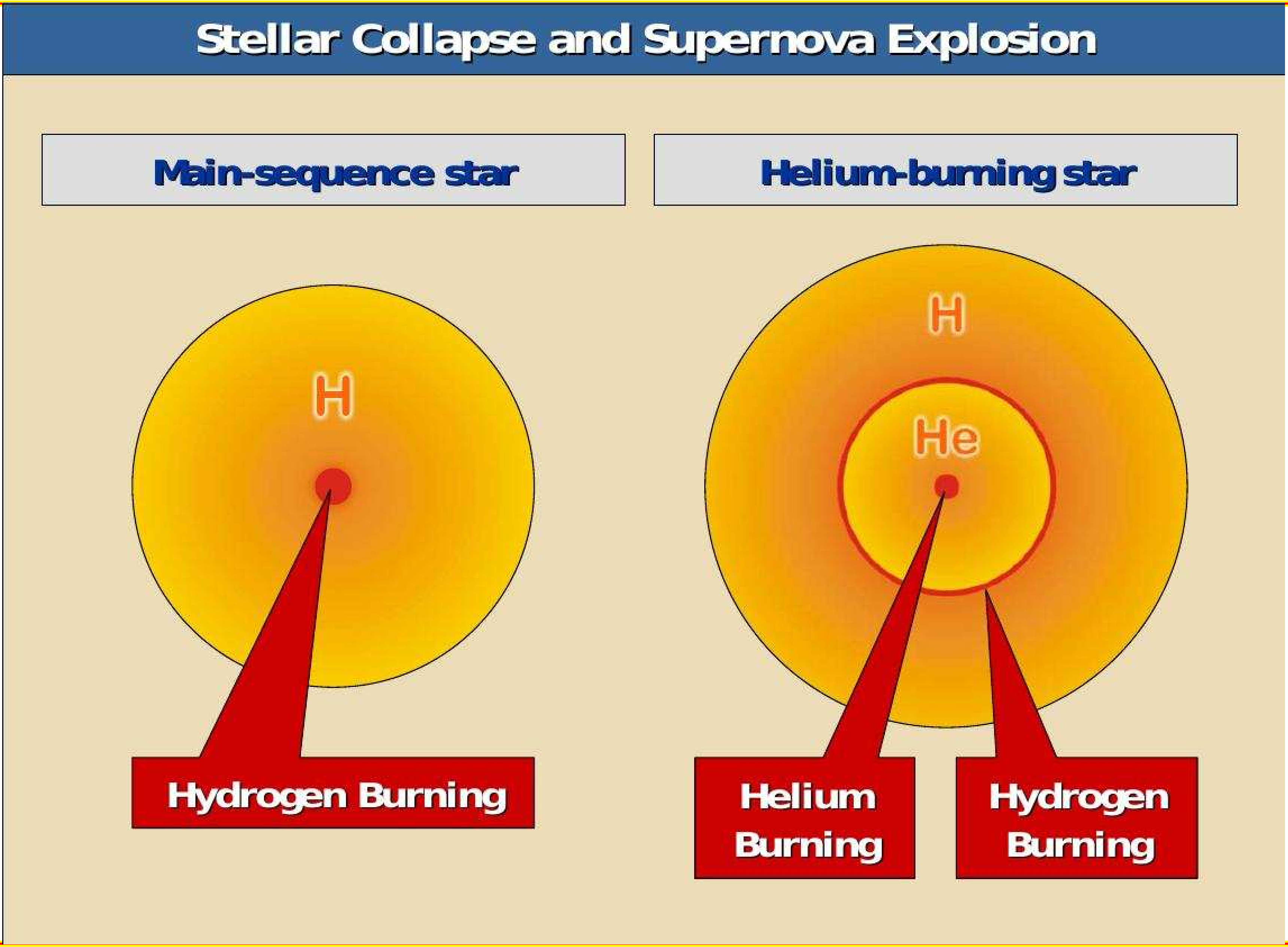
Standard description of Chronology

- 1 sec: Core collapse, bounce, or SASI$^{\star)}$, or rotMHD, shock revival
- 1 min to 1 day: shock propagates and breaks out (1st EM signature). Fallback? NS vs. BH formation?
- Mins to days: Final ejecta acceleration to homology (velocity $u \propto r$)

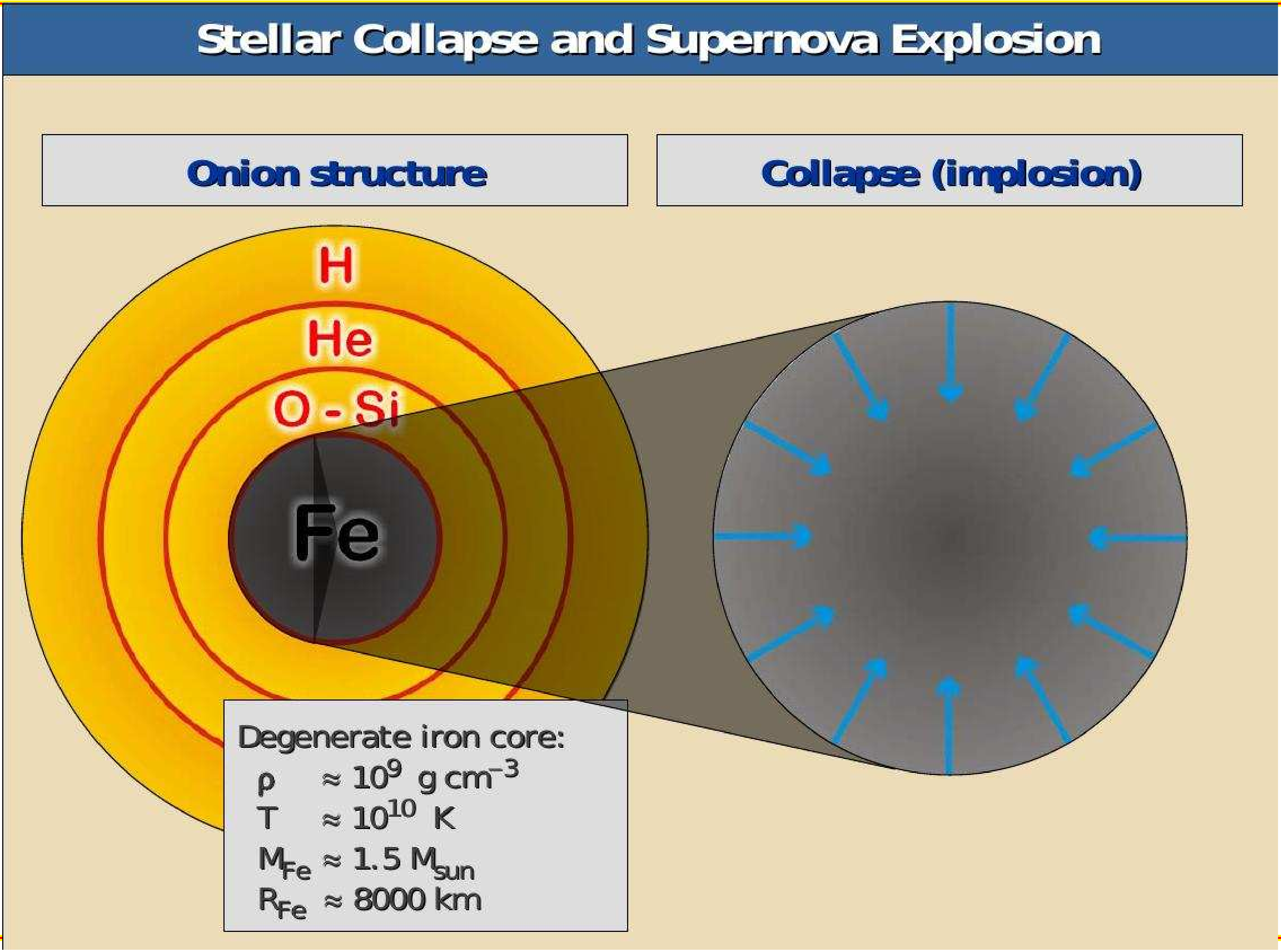
$^{\star)}$ Standing accretion shock instability

Actually some weak EM signals are inevitably produced **before** shock breakout

Burning in center and in shells



Many shells next few slides from Raffelt (2010) and other sources



Stellar Collapse and Supernova Explosion

Onion structure

Collapse (implosion)

Degenerate iron core:

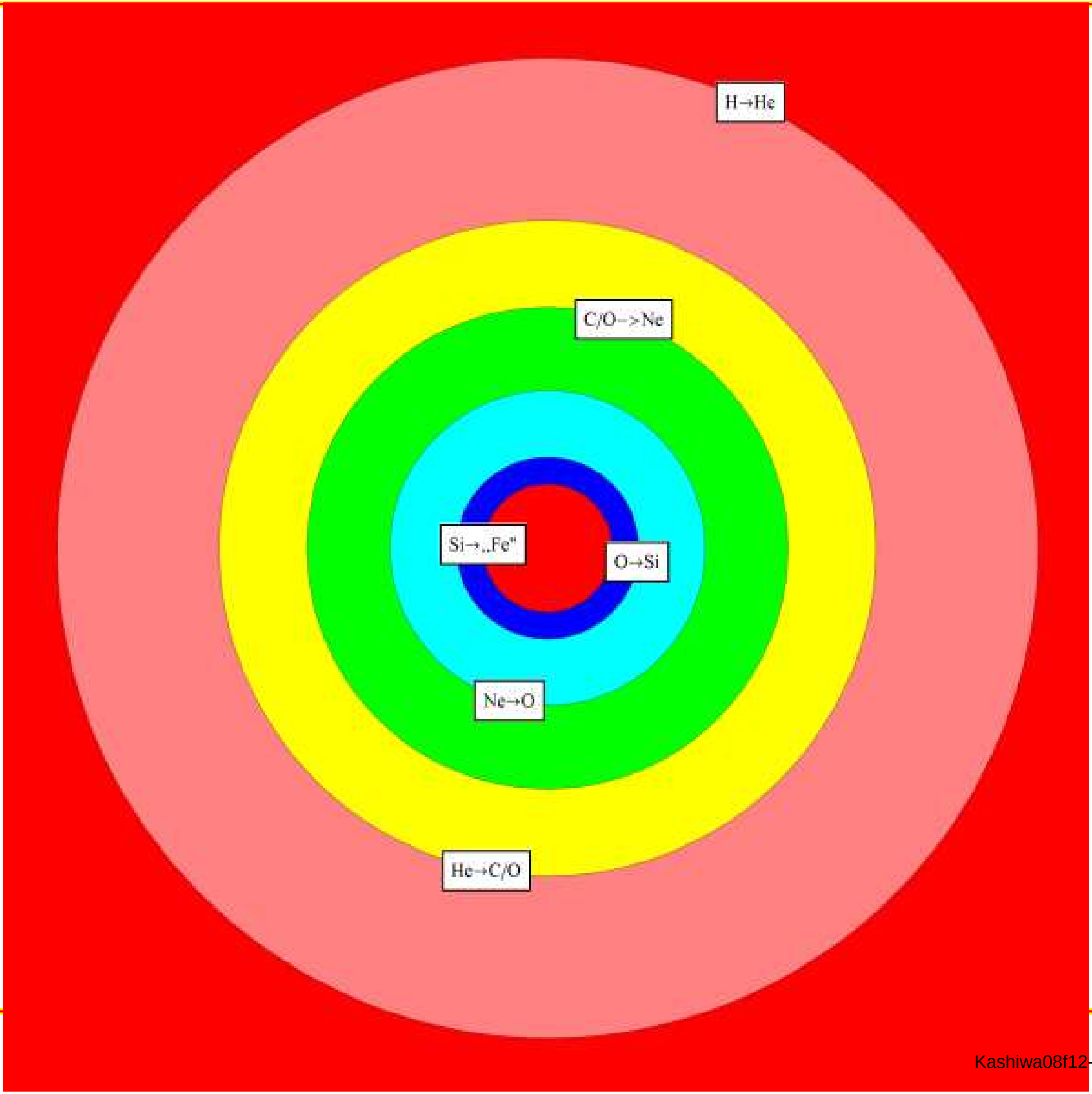
$\rho \approx 10^9$ g cm^{-3}

$T \approx 10^{10}$ K

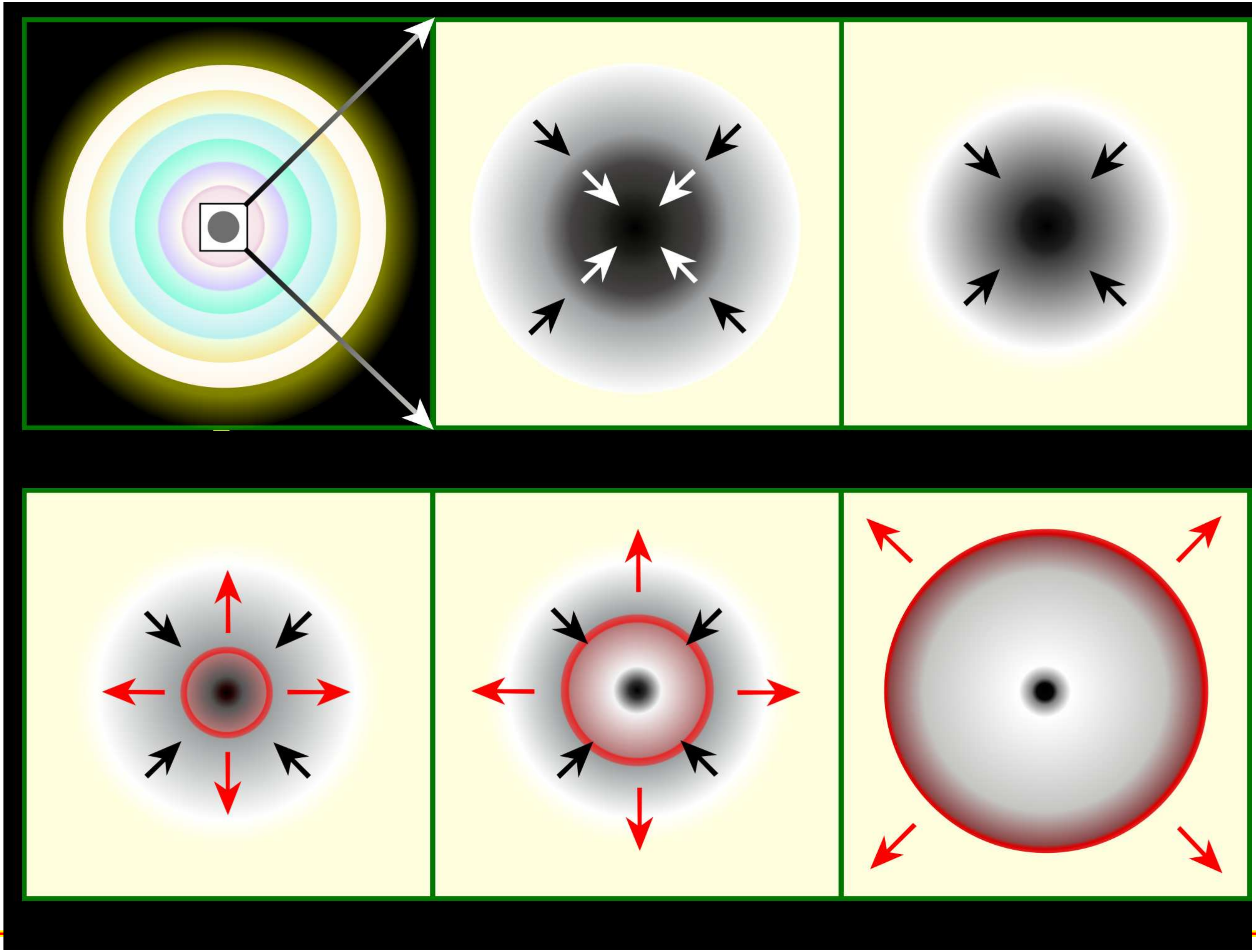
$M_{Fe} \approx 1.5\ M_{sun}$

$R_{Fe} \approx 8000$ km

Shells in a preSN



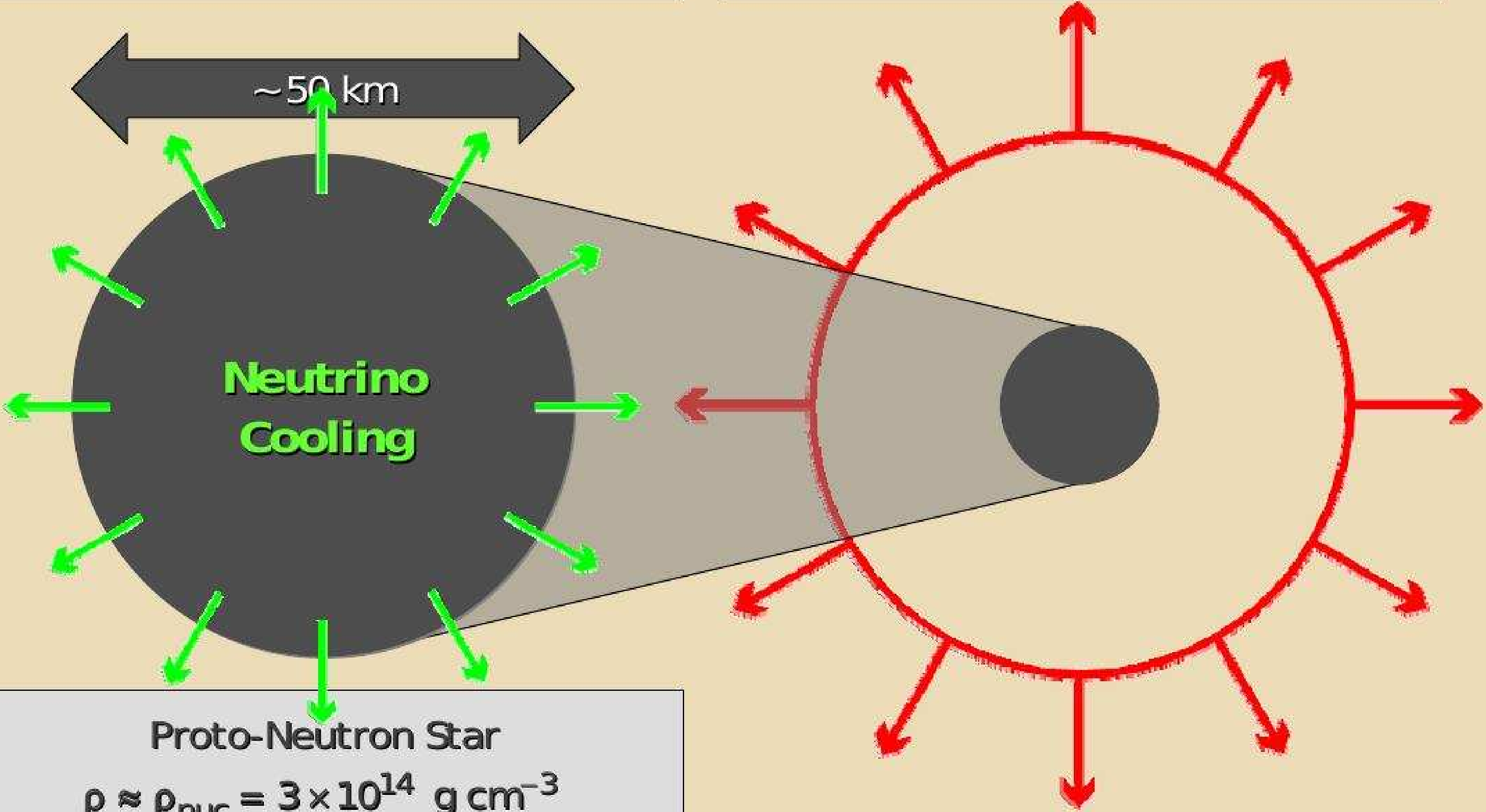
Collapse scenario



Stellar Collapse and Supernova Explosion

Newborn Neutron Star

Explosion



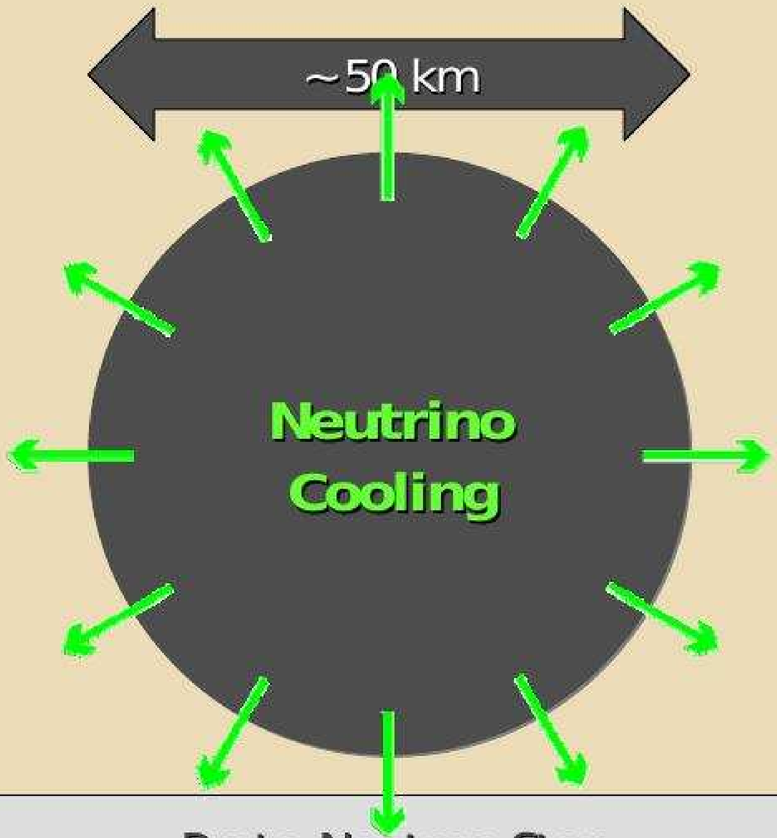
Proto-Neutron Star

$\rho \approx \rho_{\mathrm{nuc}} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \approx 30$ MeV

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

$\rho \approx \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \approx 30\ \mathrm{MeV}$

Gravitational binding energy

$E_b \approx 3 \times 10^{53}\ \mathrm{erg} \approx 17\% M_{SUN}\, c^2$

This shows up as

99% Neutrinos

1% Kinetic energy of explosion (1%of this into cosmic rays)

0.01% Photons, outshine host galaxy

Neutrino luminosity

$L_\nu \approx 3 \times 10^{53}\ \mathrm{erg} /\ 3\ \mathrm{sec}$
$\approx 3 \times 10^{19}\ L_{SUN}$

While it lasts, outshines the entire visible universe

First messengers of explosions

Neutrino?

First messengers of explosions

$\boxed{\text{Neutrino?}} \rightarrow \boxed{\text{Gravitational waves?}}$

First messengers of explosions

Neutrino? → Gravitational waves? →

Radio waves? At least in atmospheric explosions

First messengers of explosions

Neutrino? → Gravitational waves? →

Radio waves? At least in atmospheric explosions →

Shock breakout

To discuss 3 topics

Shock breakouts and constraints for fundamental physics

To discuss 3 topics

Shock breakouts and constraints for fundamental physics $\longrightarrow$

Shock breakouts and star formation rate

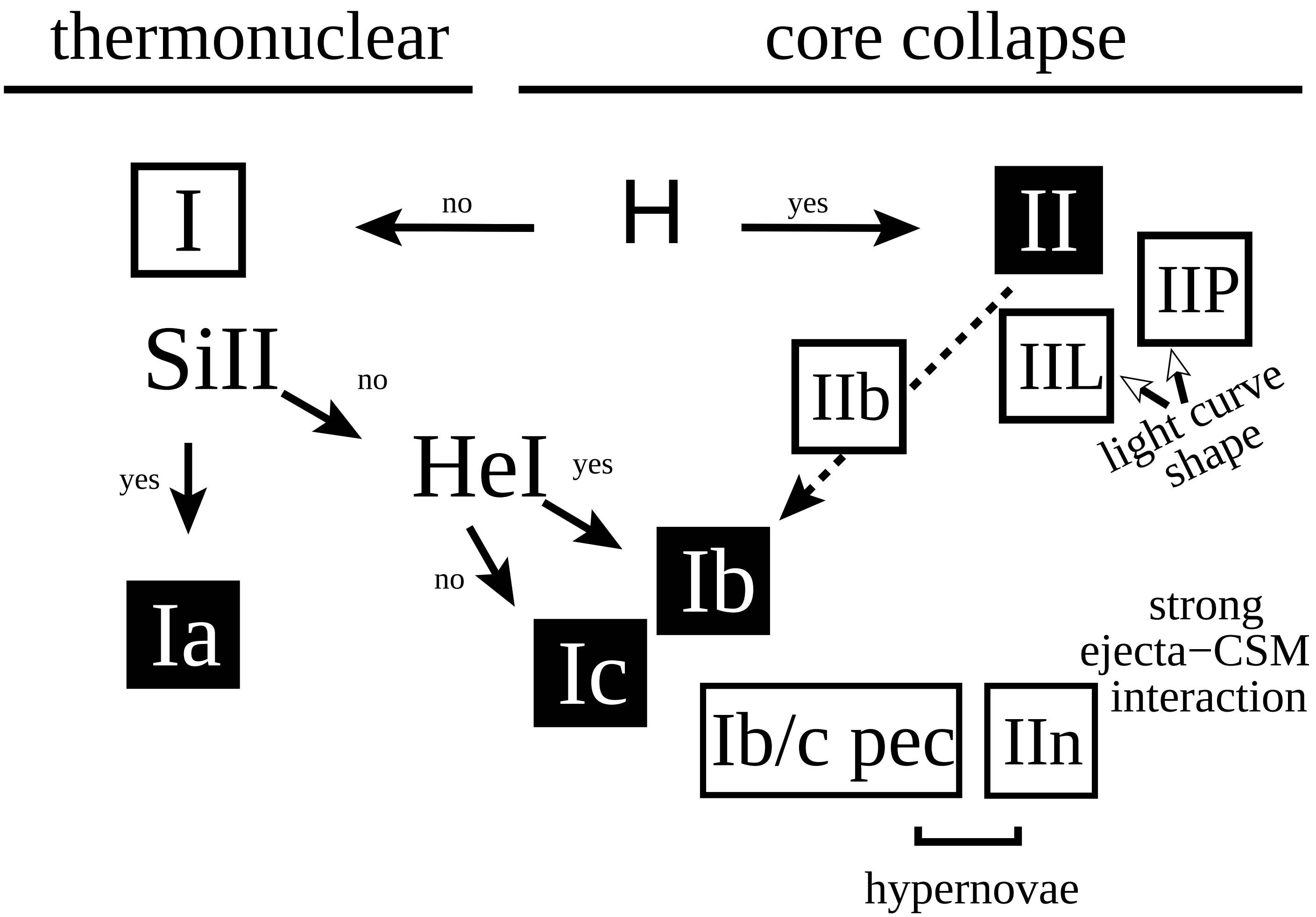
To discuss 3 topics

Shock breakouts and constraints for fundamental physics →

Shock breakouts and star formation rate →

SN shocks and cosmology

SN classification



thermonuclear

core collapse

I

no

H

yes

II

IIP

IIL

light curve shape

IIb

SiII

no

yes

HeI

yes

no

Ia

Ib

Ic

strong ejecta−CSM interaction

Ib/c pec

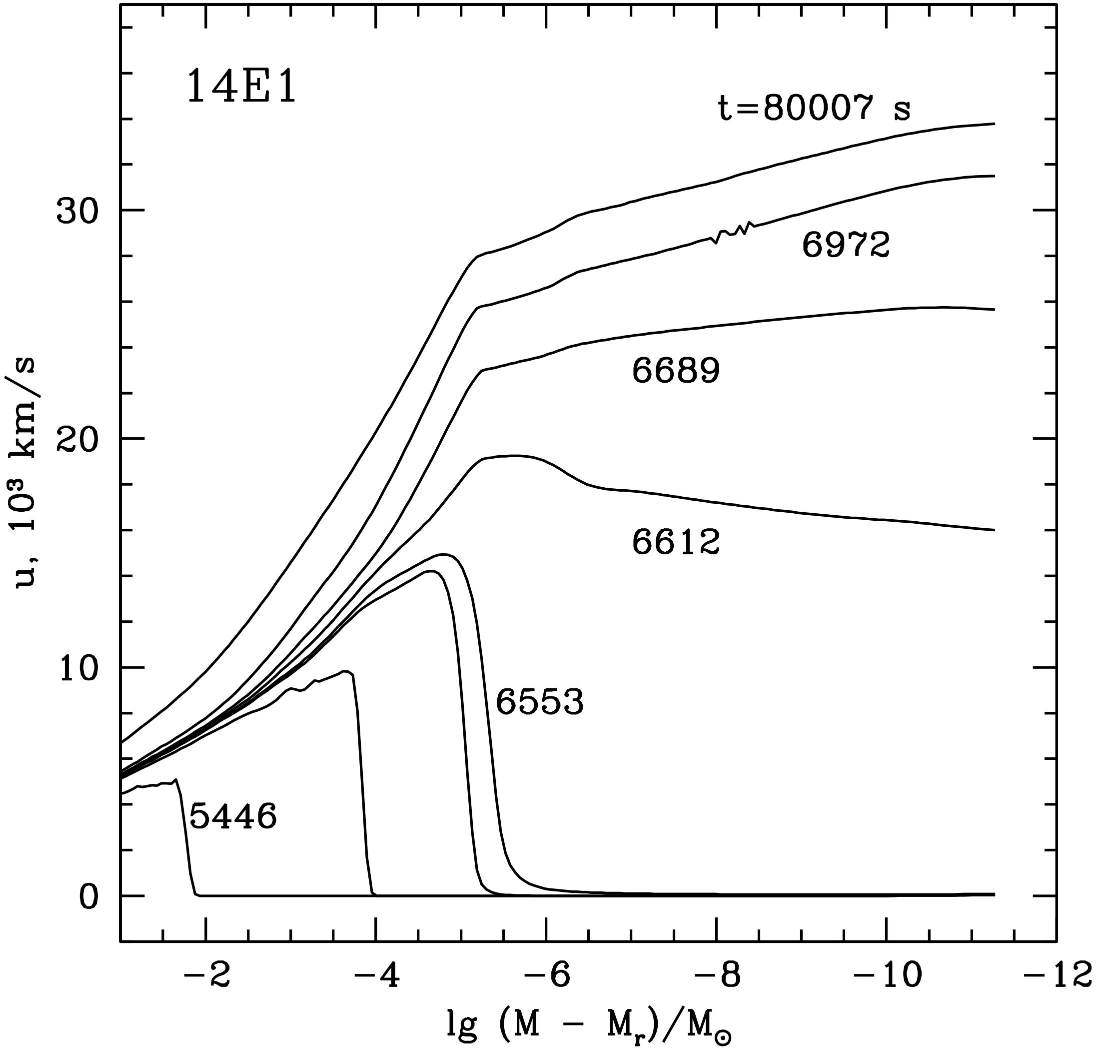
IIn

hypernovae

Turrato 2003

Shocks inside SNe, e.g., SN 1987A

velocity *vs* mass from surface, time in seconds is given



Shocks: entropy source for SN II

A shock inside the star remains in adiabatic phase while optical depth,

$$\tau \equiv \frac{\delta R}{l} > \frac{c}{D},$$

where l is photon mean free path and δR is the distance from the shock to the photosphere (Ohyama N. 1963, also Imshennik V.S., Morozov Yu.I. 1964)

When

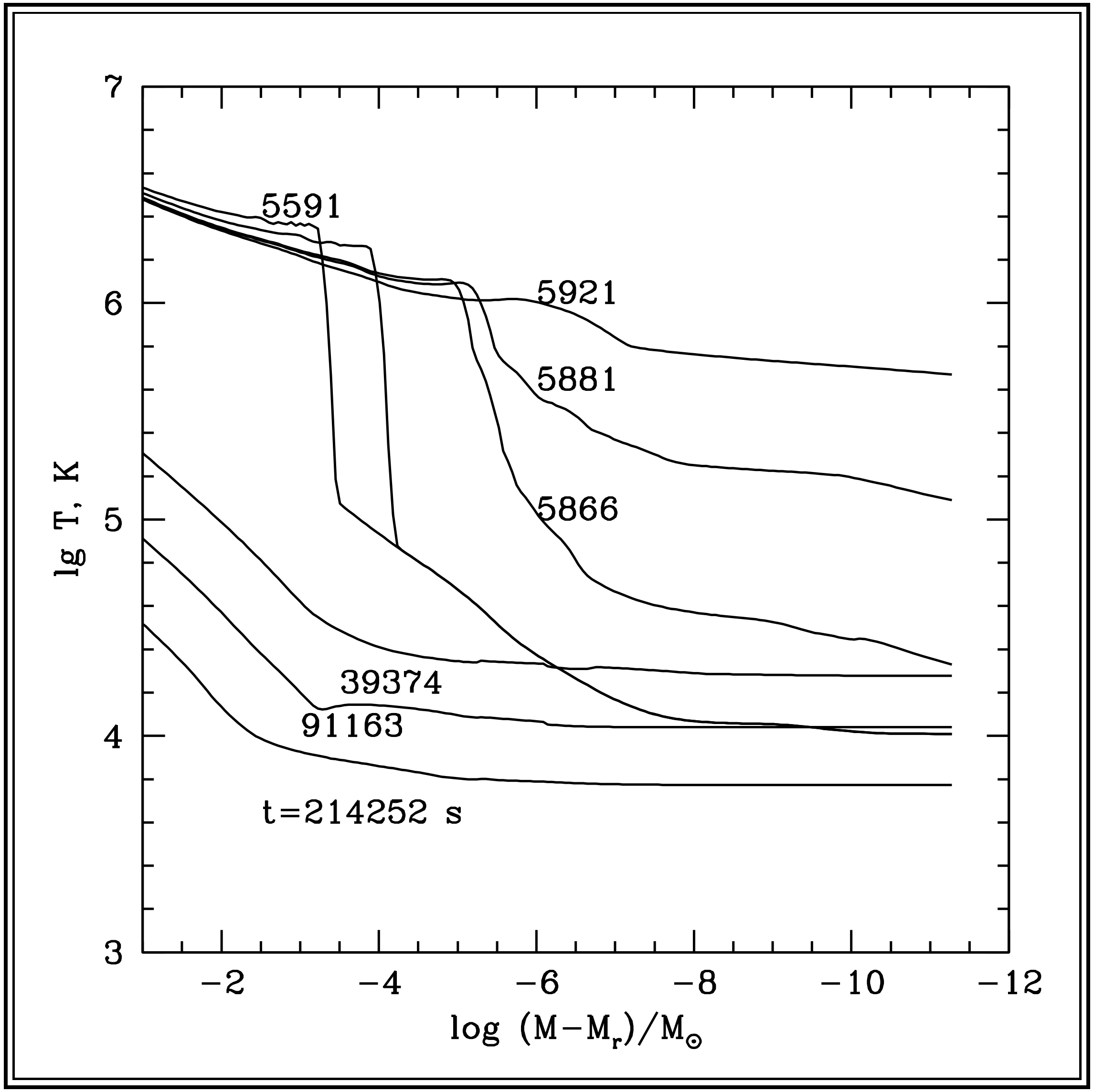
$$\tau = \frac{\delta R}{l} \lesssim \frac{c}{D},$$

the burst of photon luminosity begins:

shock break-out .

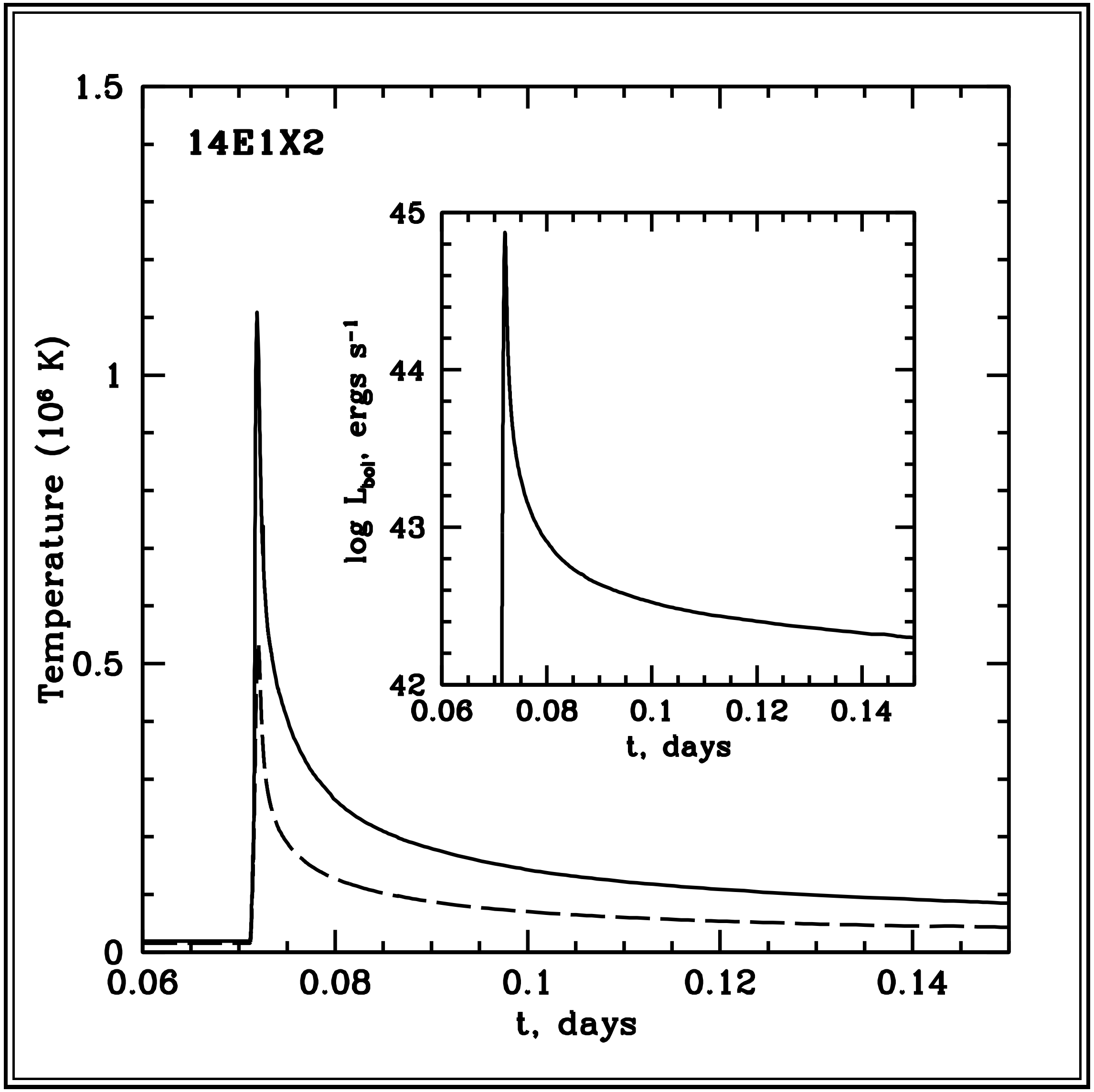
Shock $T(m)$ in SN 1987A

Normal opacity



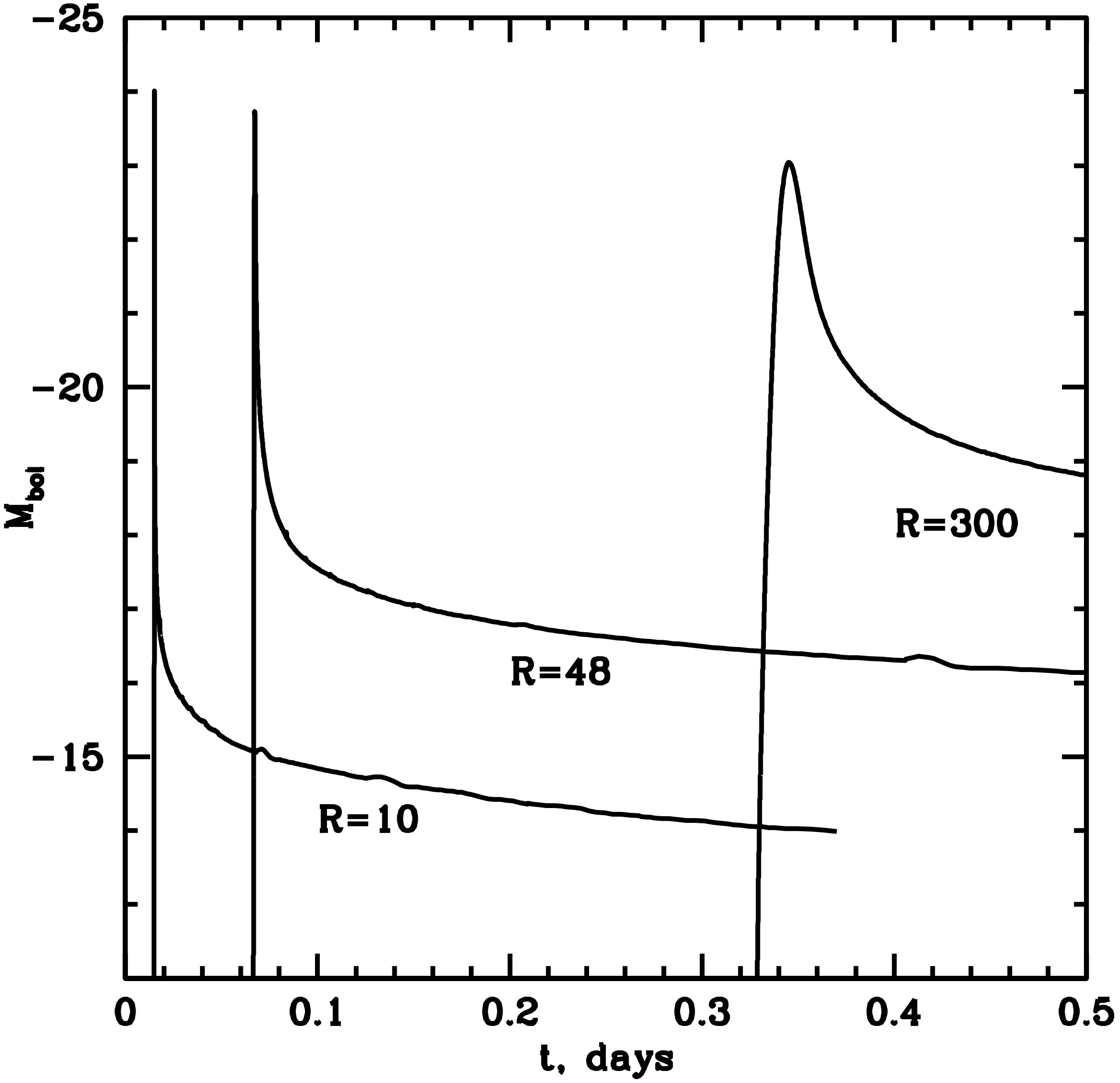
SN87A Luminosity and $T_{\rm obs}$

$$N_f = 200, \lambda_{\min} = 0.01$$

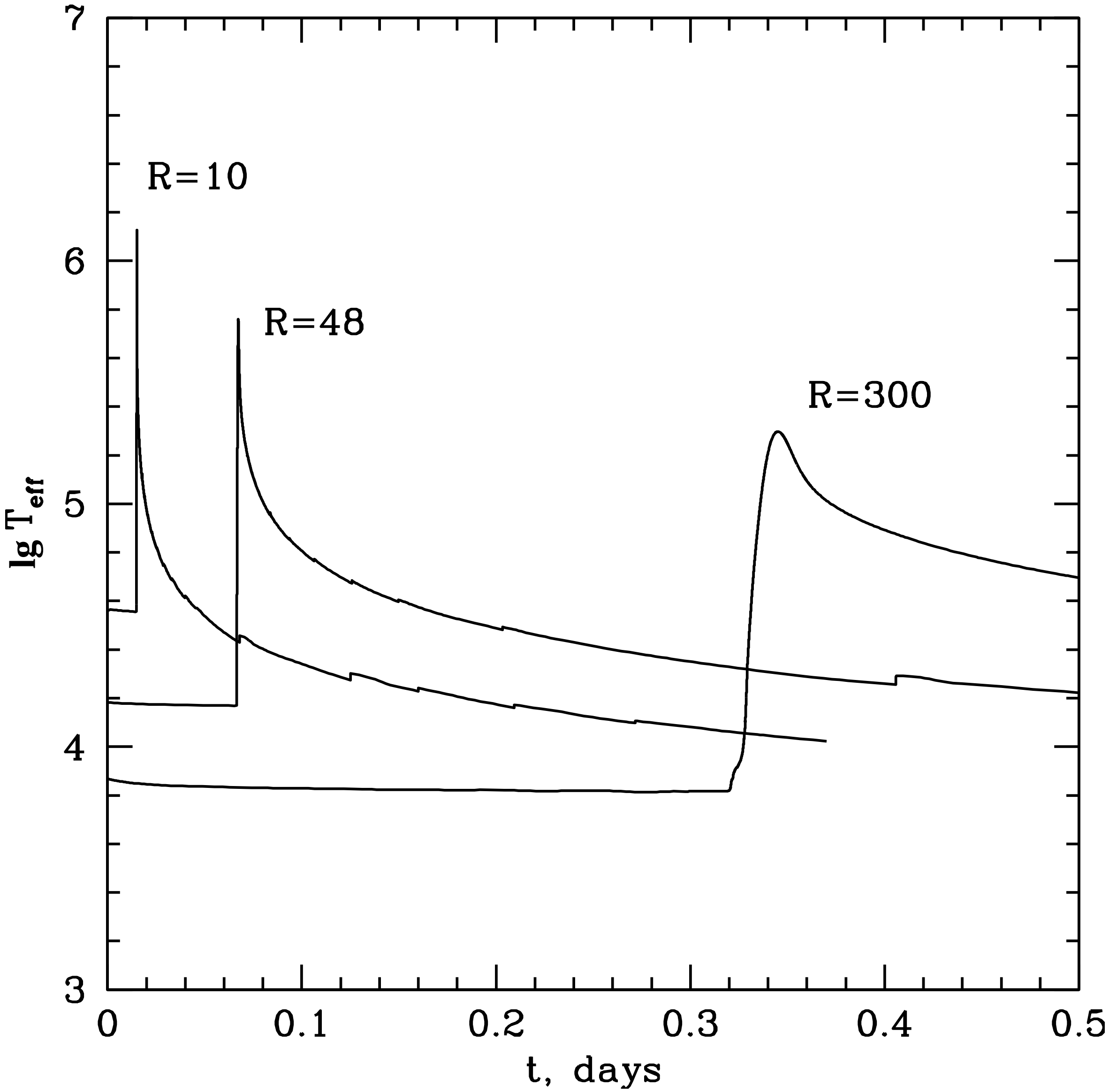


Shock Luminosity in SNe II

Shocks:
Different radii at shock-breakout epoch



Effective Temperature in SN II



Computing shock-breakout

When the shock approaches surface, where the density of matter ρ falls as $\rho \propto (\delta R)^n$, velocity grows in agreement with the self-similar solution by Gandel'man and Frank-Kamenetskii (1956), Sakurai (1960).

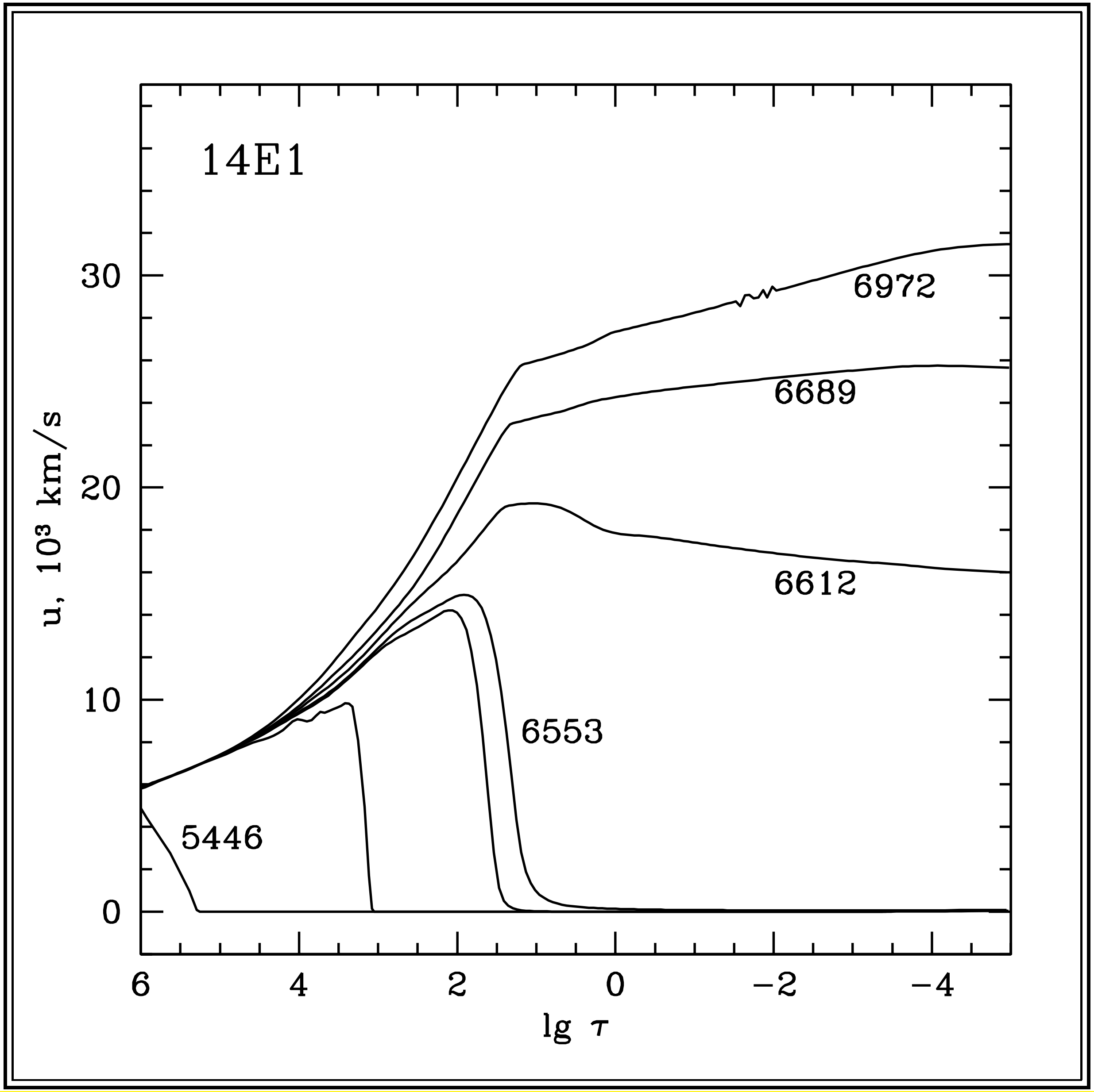
In the outermost layers (with Thompson optical depth $\tau \sim c/D \approx 10$ and less, where D is the shock velocity) the radiative losses become significant and shock acceleration ends.

End of shock acceleration

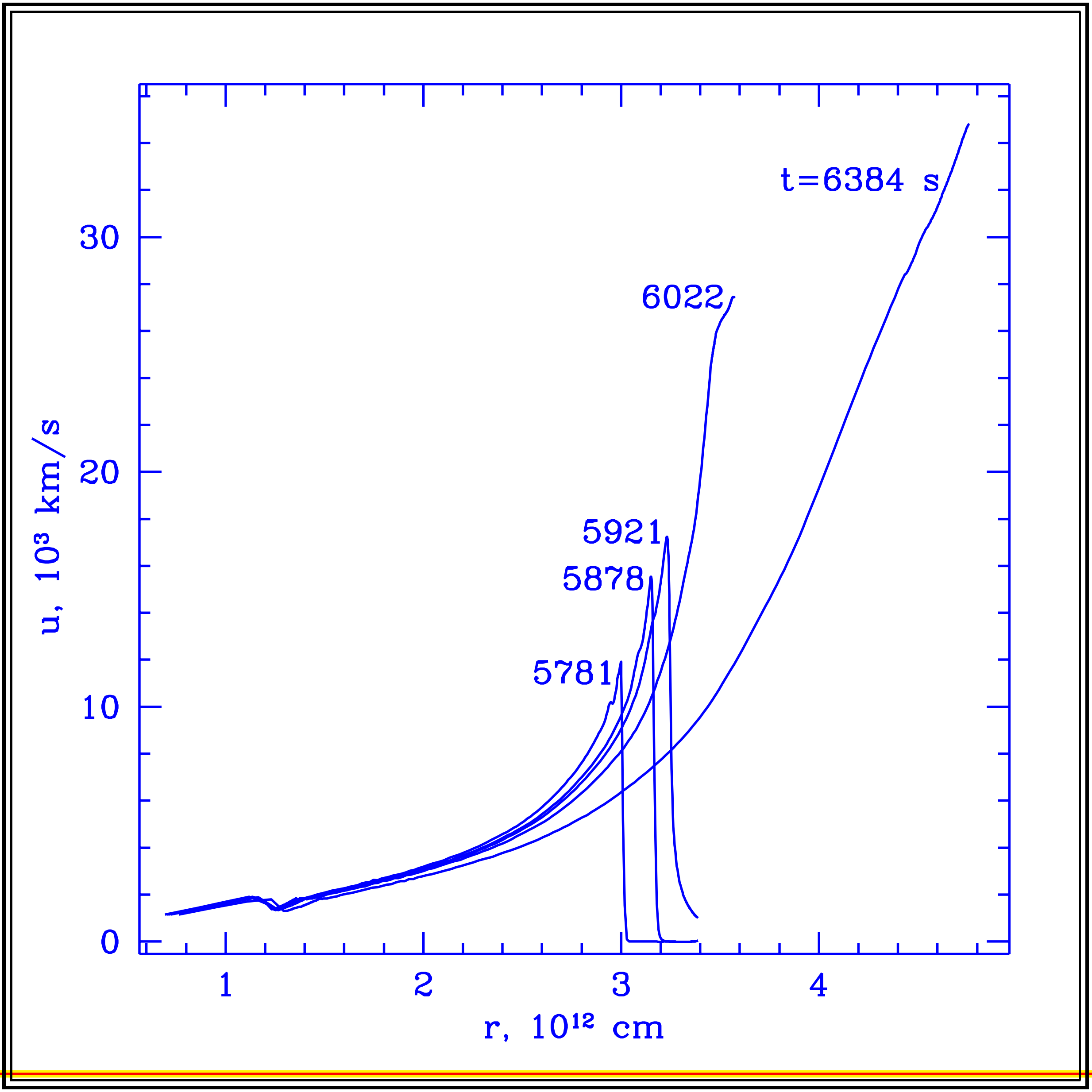
The termination of the shock acceleration process is clearly observed in computations.

Next figure shows the profiles of velocity as a function of optical depth τ (Blinnikov 1999). Just at $\tau \sim c/D \sim 10$, as predicted, the photons start ‘running-out’ from behind the shock front. These photons slightly accelerate the outer layers, however, the cumulation of energy on the small mass is already not efficient due to strong radiative losses.

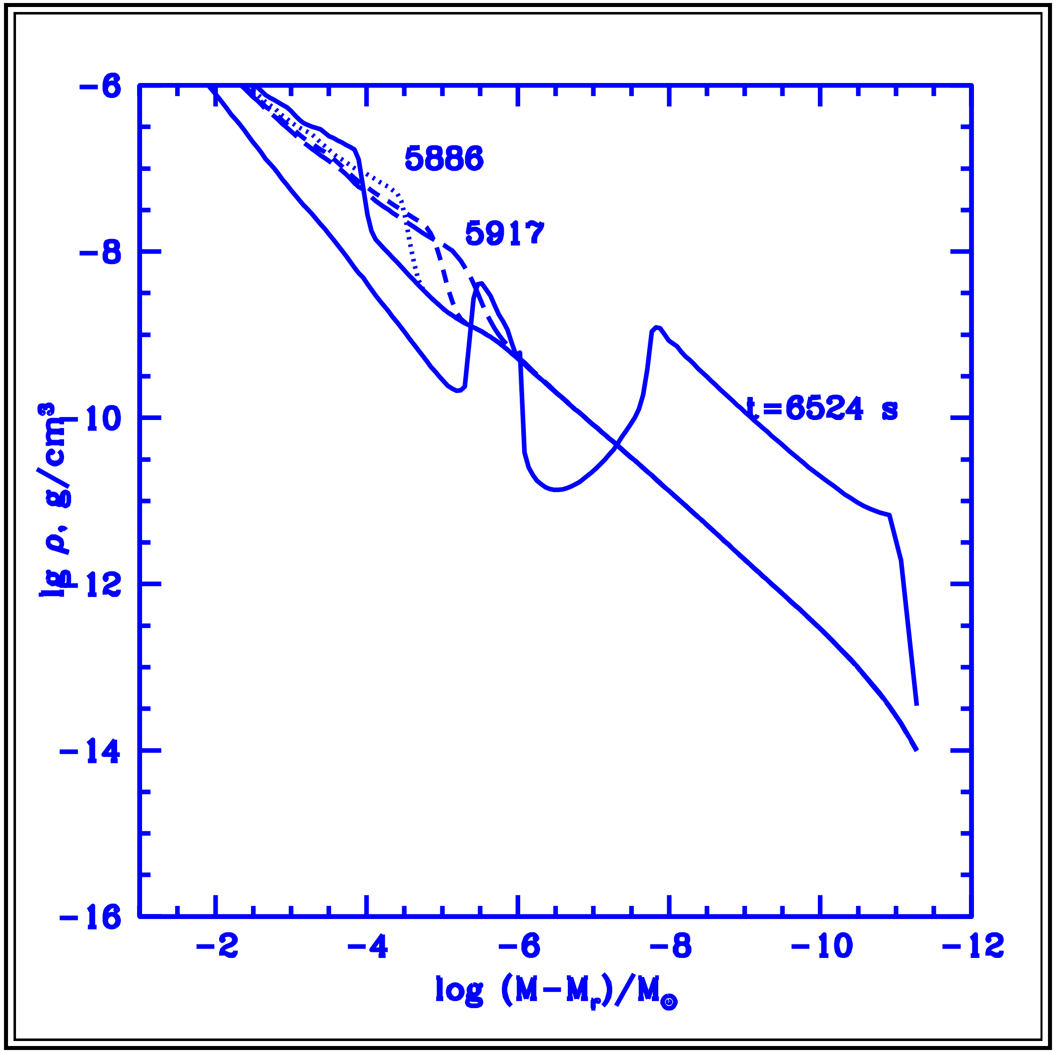
Velocity – optical depth



Velocity, Eulerian



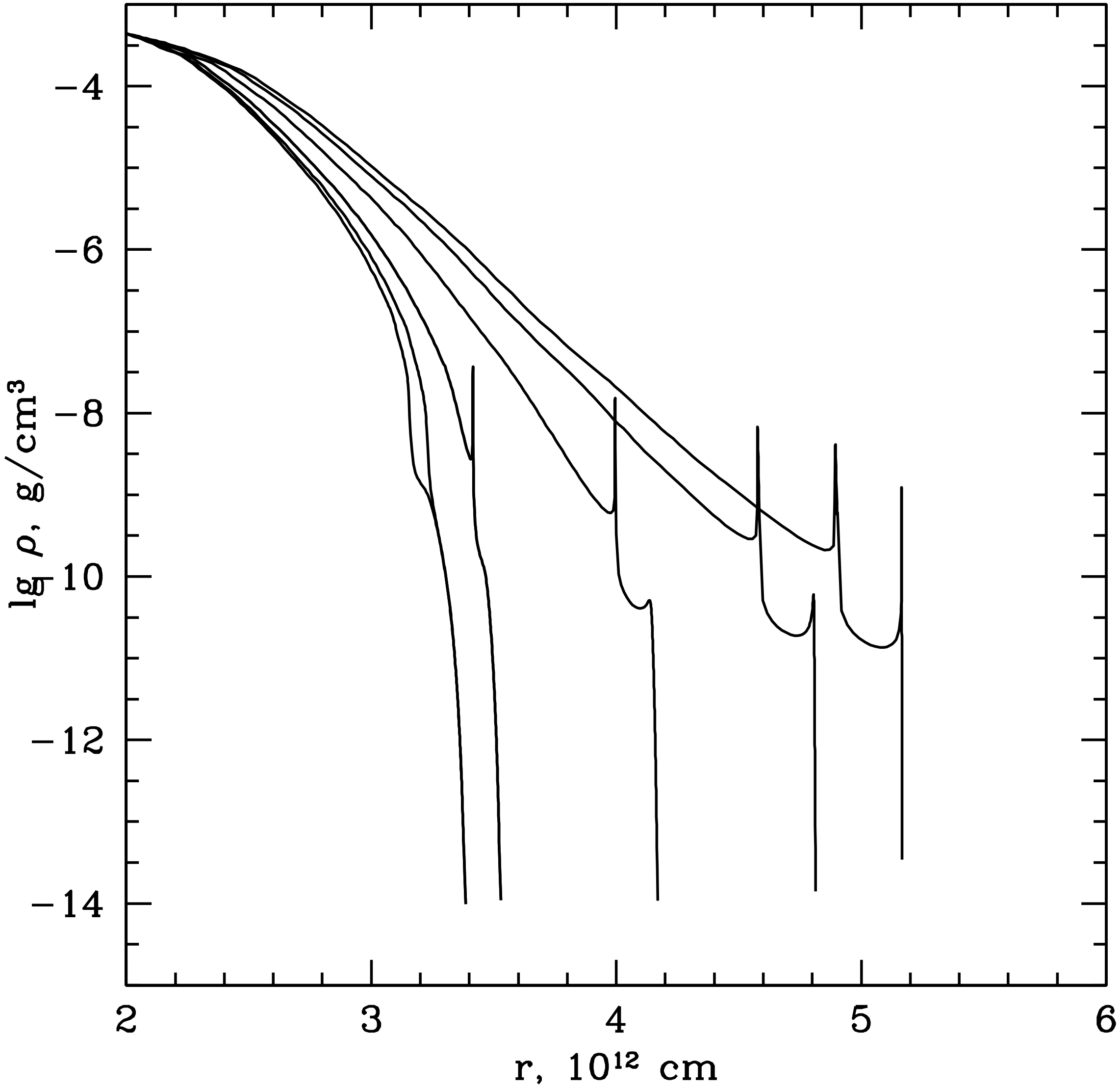
Density as a function of mass



Due to inefficient acceleration a density peak is formed in outer layers. Next plot shows that this is a very thin layer of matter

Density as a function of radius

Due to inefficient acceleration a density peak is formed in outer layers.



Radiative shocks

First, consider shock waves where the accompanying radiation (photons, and/or neutrinos) is trapped in the matter, contrary to SNRs.

see Zeldovich and Raizer (1966) “Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena”

Important papers/books:

R.G.Sachs 1946

Ya.B.Zeldovich 1957, Yu.P.Raizer 1957

R.E.Marshak 1958

F.A.Baum, S.A.Kaplan,K.P.Stanjukovich 1958

H.K.Sen, A.W.Guess 1958

T.Kogure, T.Osaki 1961, N.Ohyama 1963

V.S.Imshennik, Yu.Morozov 1962 – 1975, also a book 1981

I.A.Klimishin+ 1959 – ... also book 1984

S.Narita 1973, T.A.Weaver 1976

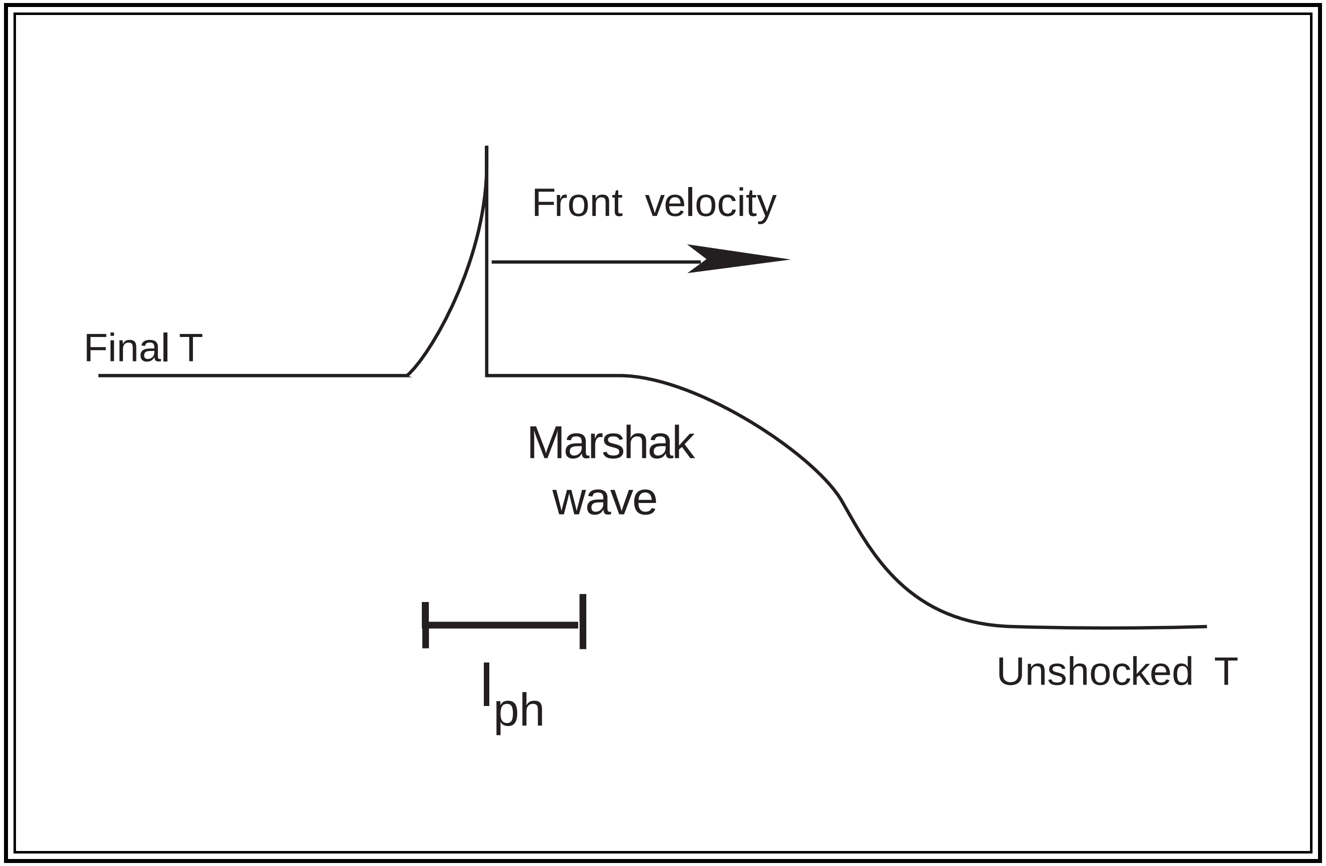
Zeldovich shock classification

Radiative shock waves are divided into four classes in order of increasing strength:

1) Subcritical Shocks
2) Critical Shocks
3) Supercritical Shocks
4) Radiation Dominated Shocks

Supercritical Shock Waves

The principal transport of energy is carried out by radiation through the leading Marshak wave. Almost all of the compression occurs as matter crosses the shock front.



Radiation Dominated Shocks

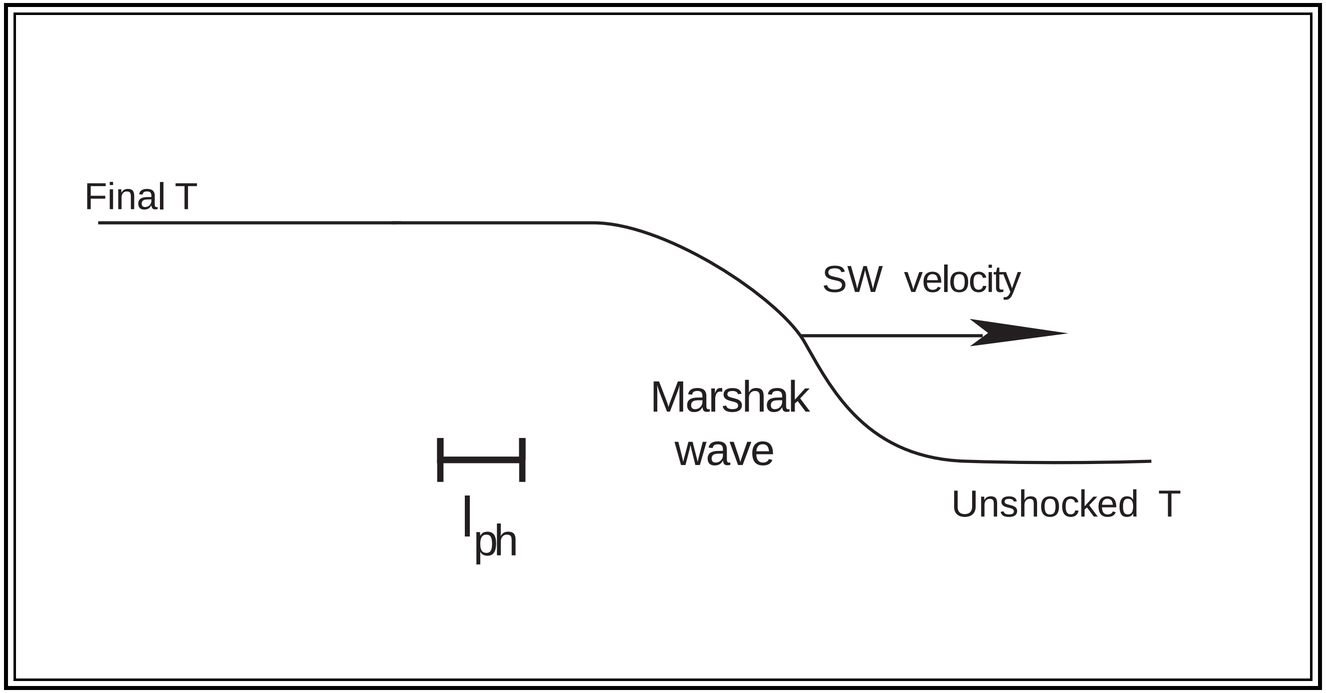
In extremely strong shocks the radiation pressure and energy density exceeds the kinetic pressure and energy of the gas. At this point we basically have a shock in a photon gas. Accordingly, it is the properties of a photon gas ($\gamma = 4/3$) that dominates the situation.
The maximum shock compression is thus:

$$(4/3 + 1)/(4/3 - 1) = 7 \, .$$

But this is true only for adiabatic shock. For radiative (almost isothermal) shocks the compression may be orders of magnitude higher.

Viscous jump disappears

In radiation dominated shocks the preheating effect becomes so large that one of the most typical features of classical shock waves, namely, the viscous jump in pressure and density at the hydrodynamic shock front – diminishes and completely disappears in a sufficiently strong shock.



No jump for large P_r/P_g

In the equilibrium diffusion approximation the jump dissappears when the ratio between radiation pressure and gas pressure is $P_r/P_g \simeq 4.4$ - (S.Z.Belen'kii – unpublished report, V.A.Belokon' 1959) . Agrees with Weaver and Chapline.

In radiation dominated shocks not only the preheating effect is important. The *momentum transfer* from photons to electrons (and hence to ions, via the electric field) is very large. This also destroys the viscous jump in pressure and density at the hydrodynamic shock front.

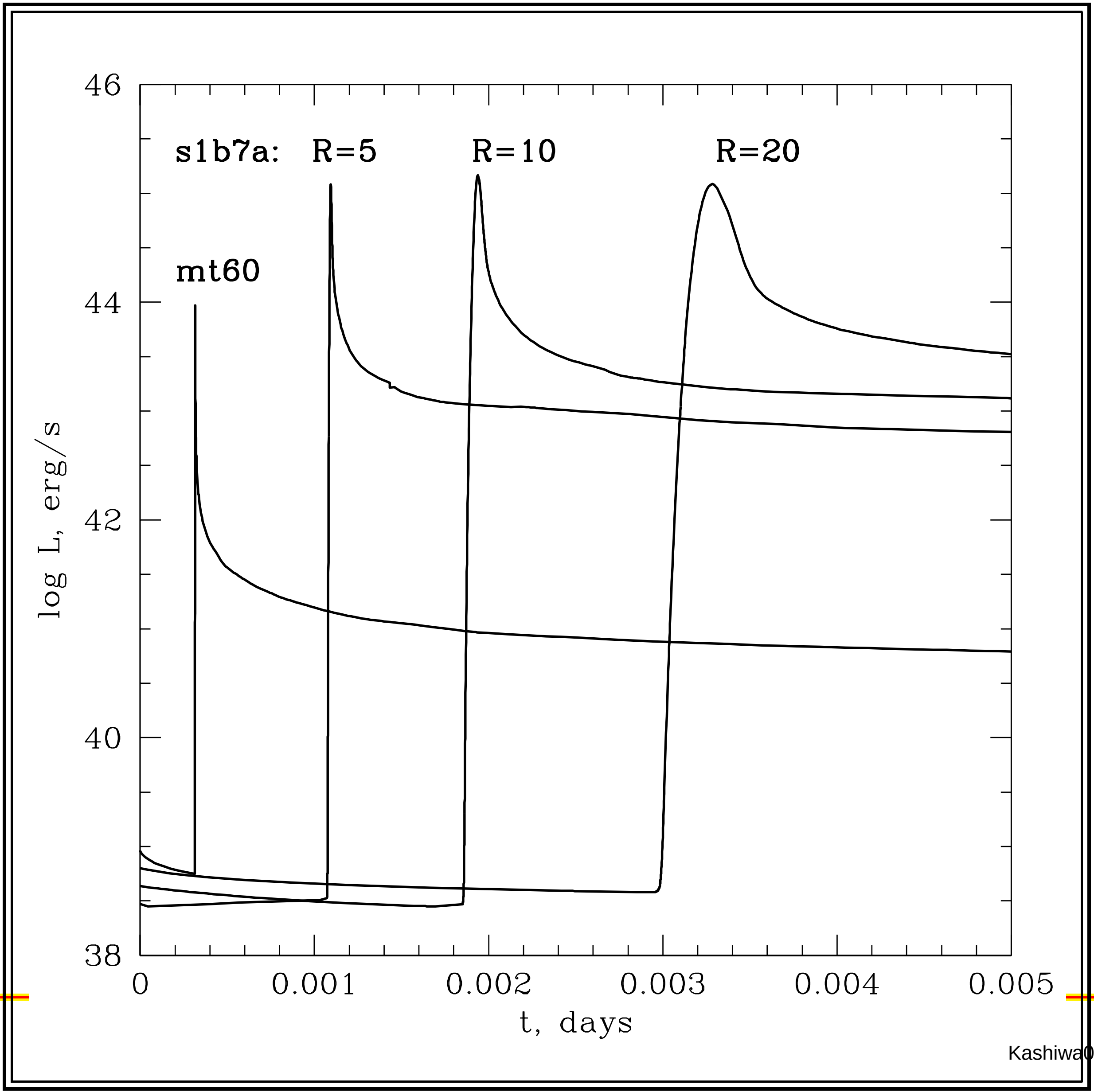
Imshennik, Morozov (1964) have found with accurate account of photon transfer that this happens when $P_r/P_g \simeq 8.5$

Similarity to CR domination

In the shocks with non-thermal relativistic particles, trapped by magnetic field (cosmic rays) a similar transition is possible - the viscous jump can disappear and the shock is mediated then by cosmic rays (see, e.g. Malkov & Drury; Bulanov & Sokolov; etc.).

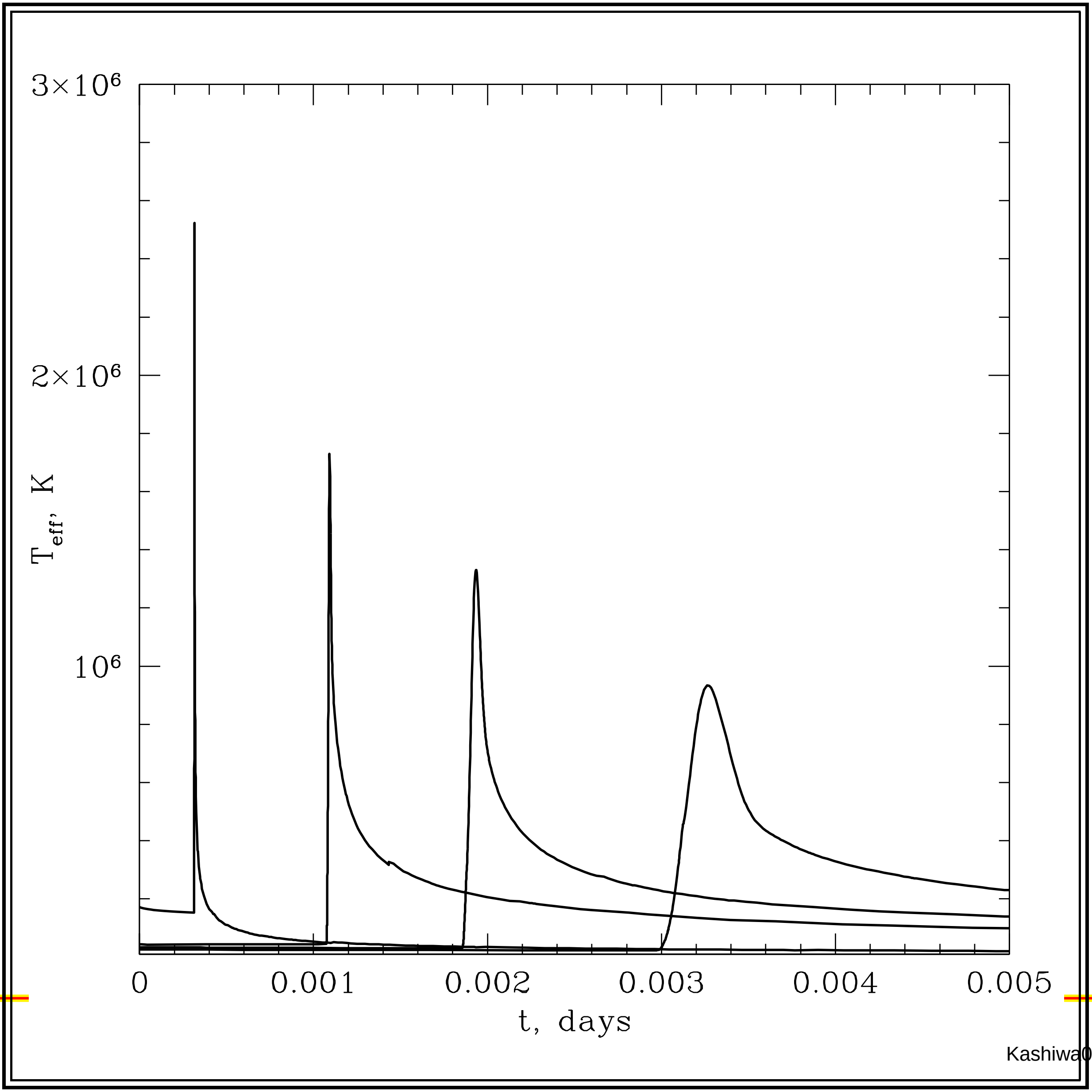
Shock Luminosity SNIb/c

Luminosity for 4 models



Shock radiation T SNIb/c

T_{eff} for 4 models



Comoving frame transfer

For arbitrary Lorentz-factor γ (with $\beta = u/c$) Eq. (95.9) in (Mihalas & Mihalas 1984):

$$\begin{aligned}
&\frac{\gamma}{c}(1+\beta\mu)\frac{\partial I(\mu,\nu)}{\partial t} + \gamma(\mu+\beta)\frac{\partial I(\mu,\nu)}{\partial r} + \\
&+\gamma(1-\mu^2)\Big[\frac{(1+\beta\mu)}{r} - \frac{\gamma^2}{c}(1+\beta\mu)\frac{\partial\beta}{\partial t} - \gamma^2(\mu+\beta)\frac{\partial\beta}{\partial r}\Big]\frac{\partial I(\mu,\nu)}{\partial\mu} - \\
&-\gamma\Big[\frac{\beta(1-\mu^2)}{r} + \frac{\gamma^2}{c}(1+\beta\mu)\frac{\partial\beta}{\partial t} + \gamma^2\mu(\mu+\beta)\frac{\partial\beta}{\partial r}\Big]\nu\frac{\partial I(\mu,\nu)}{\partial\nu} + \\
&+3\gamma\Big[\frac{\beta(1-\mu^2)}{r} + \frac{\gamma^2\mu}{c}(1+\beta\mu)\frac{\partial\beta}{\partial t} + \gamma^2\mu(\mu+\beta)\frac{\partial\beta}{\partial r}\Big]I(\mu,\nu) = \\
&= \eta(\nu) - \chi(\nu)I(\mu,\nu)\ .
\end{aligned}$$

Here η - emission coefficient, χ - exctinction coefficient

STELLA vs RADA for SNIb/c

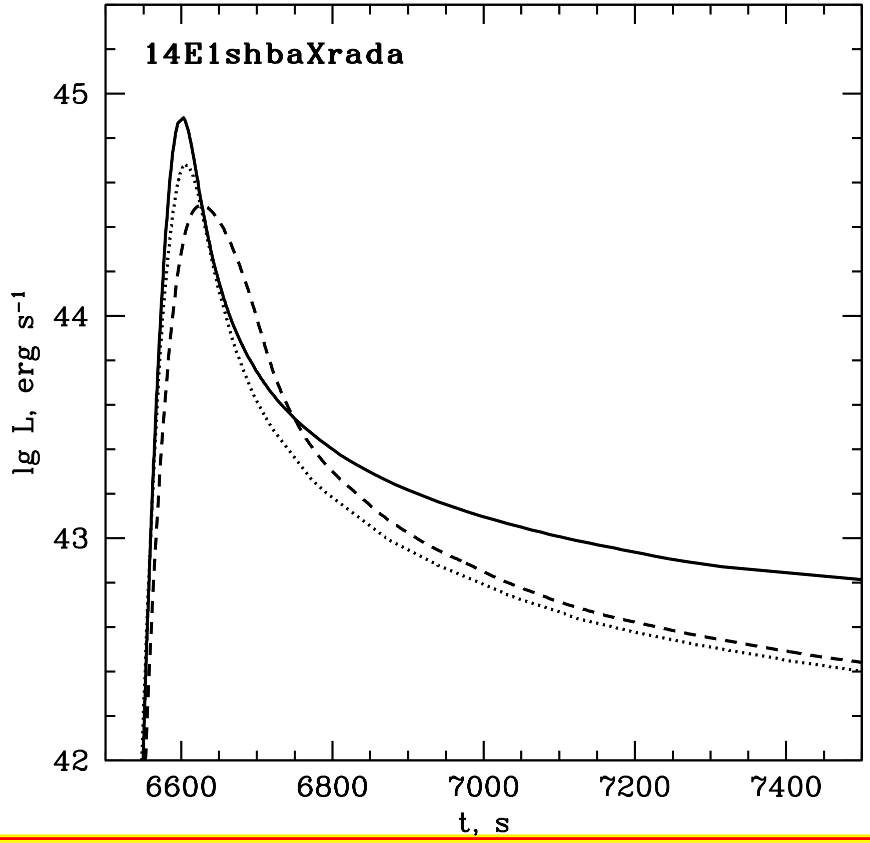
We used two algorithms: STELLA and RADA

Two radiation hydro codes

STatic Eddington-factor Low-velocity Limit Approximation

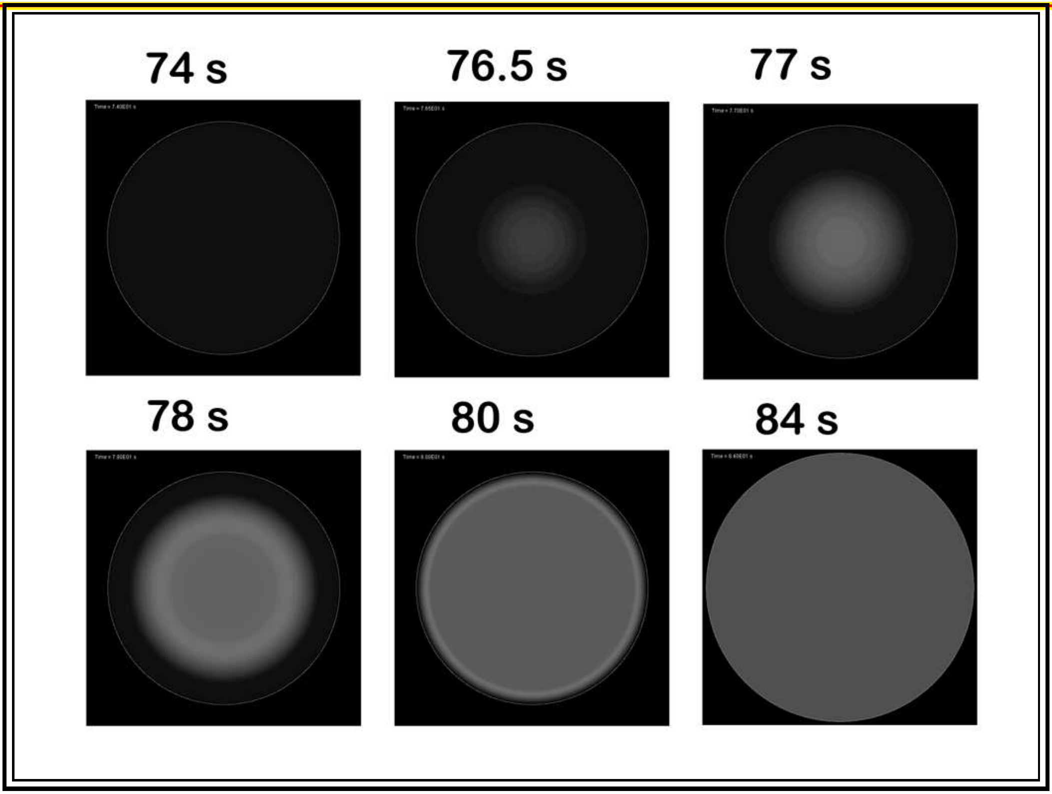
STELLA (solid) vs RADA (dotted)

A.Tolstov: RADA – fully Relativistic rADiation transfer Approximation



Dashed line represents RADA calculations in observer’s frame with light-travel-time correction.

Flash at shock breakout



Notice rings due to light-travel time delay:

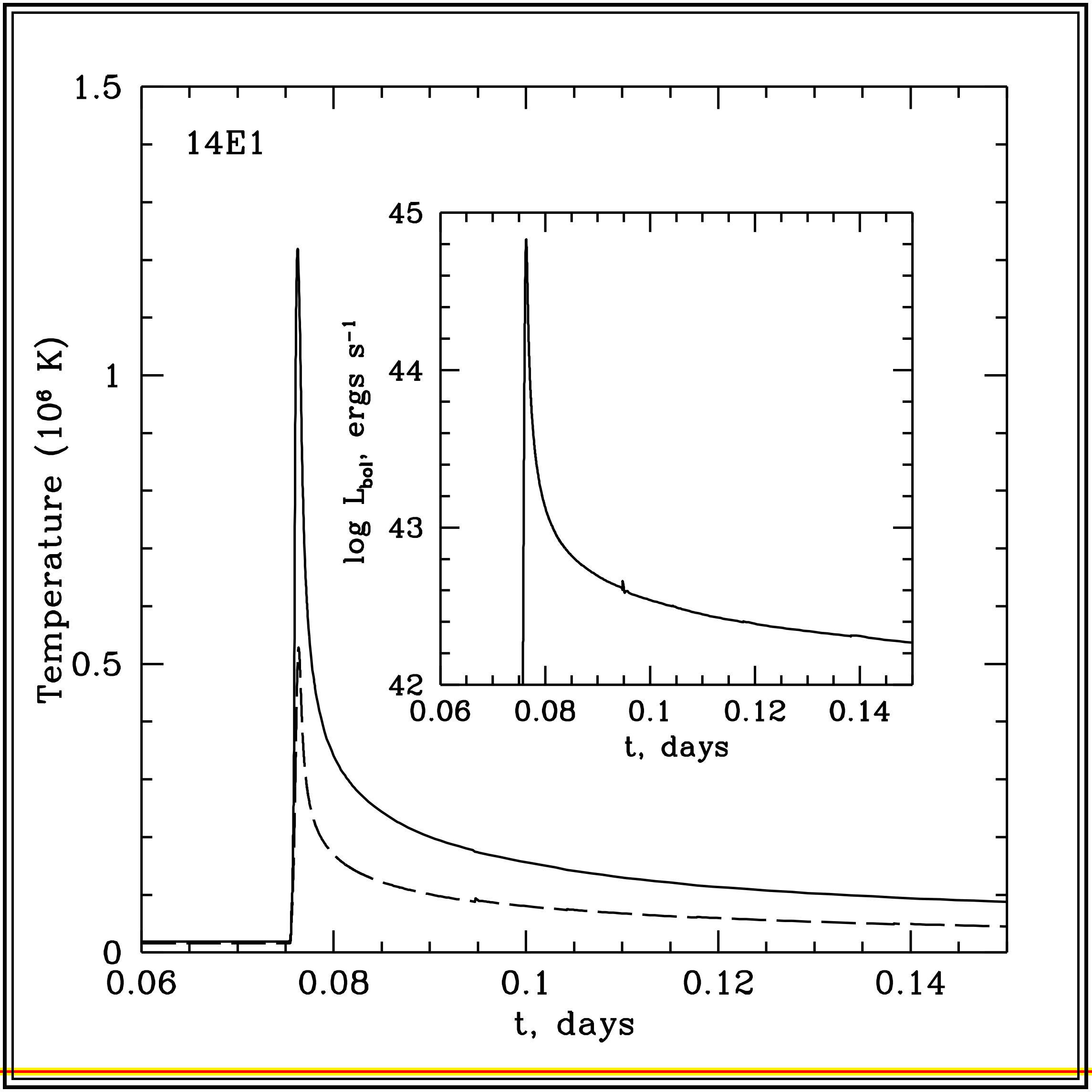
– click here

Very Important: T radiation

Old simulations predicted for large stars like Red Supergiants and SN 1987A a very hard X-ray spectrum. We predict (with STELLA and RADA) rather soft spectra. Numerically this was already studied by Weaver (1976) but for higher density. He never gets those high T shocks. His work is virtually ignored by the SN community. He was crticized for assuming equilibrium diffusion, but he had reasons.

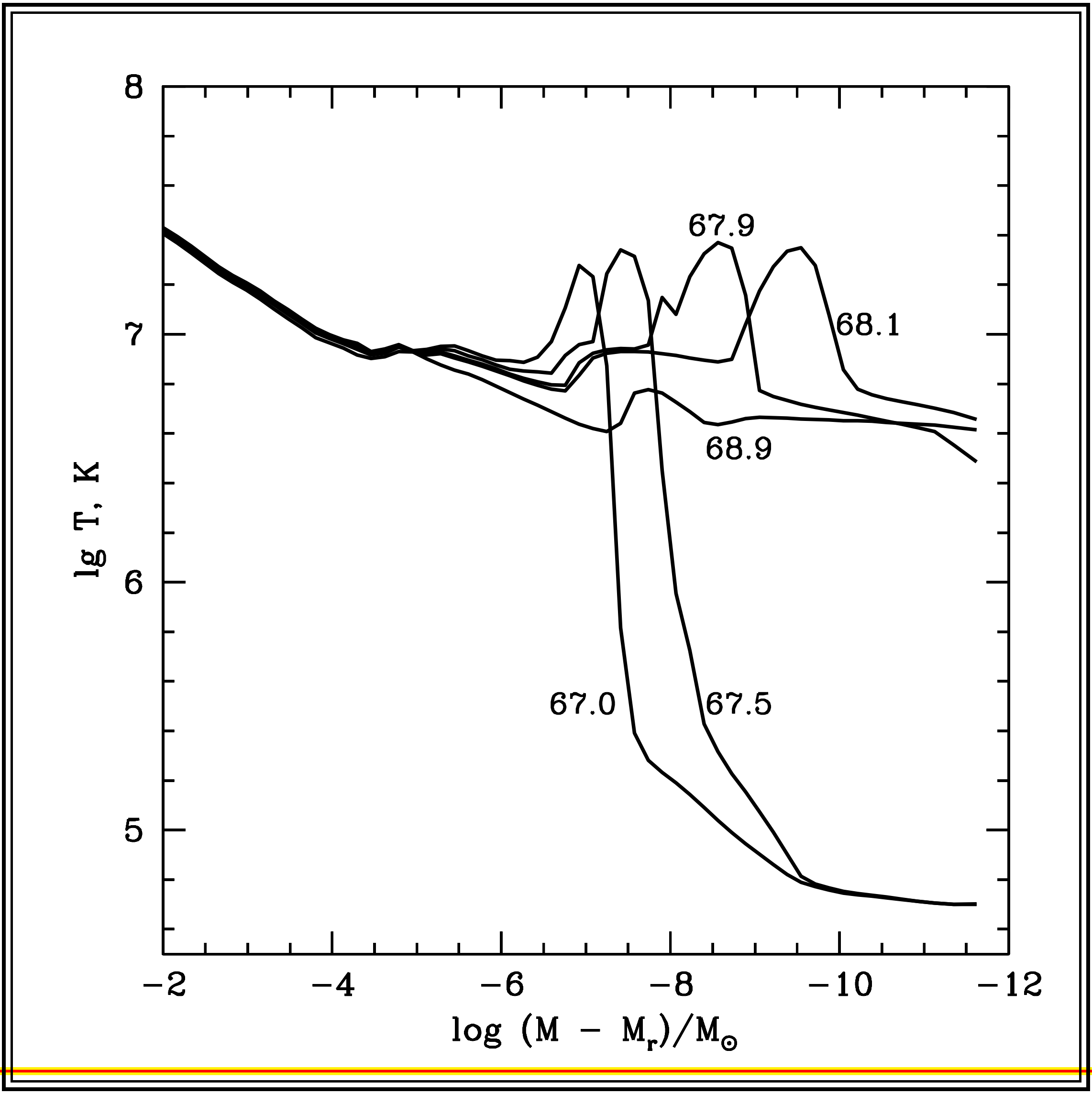
Luminosity and T, soft

$$N_f = 100, \lambda_{\min} = 1$$



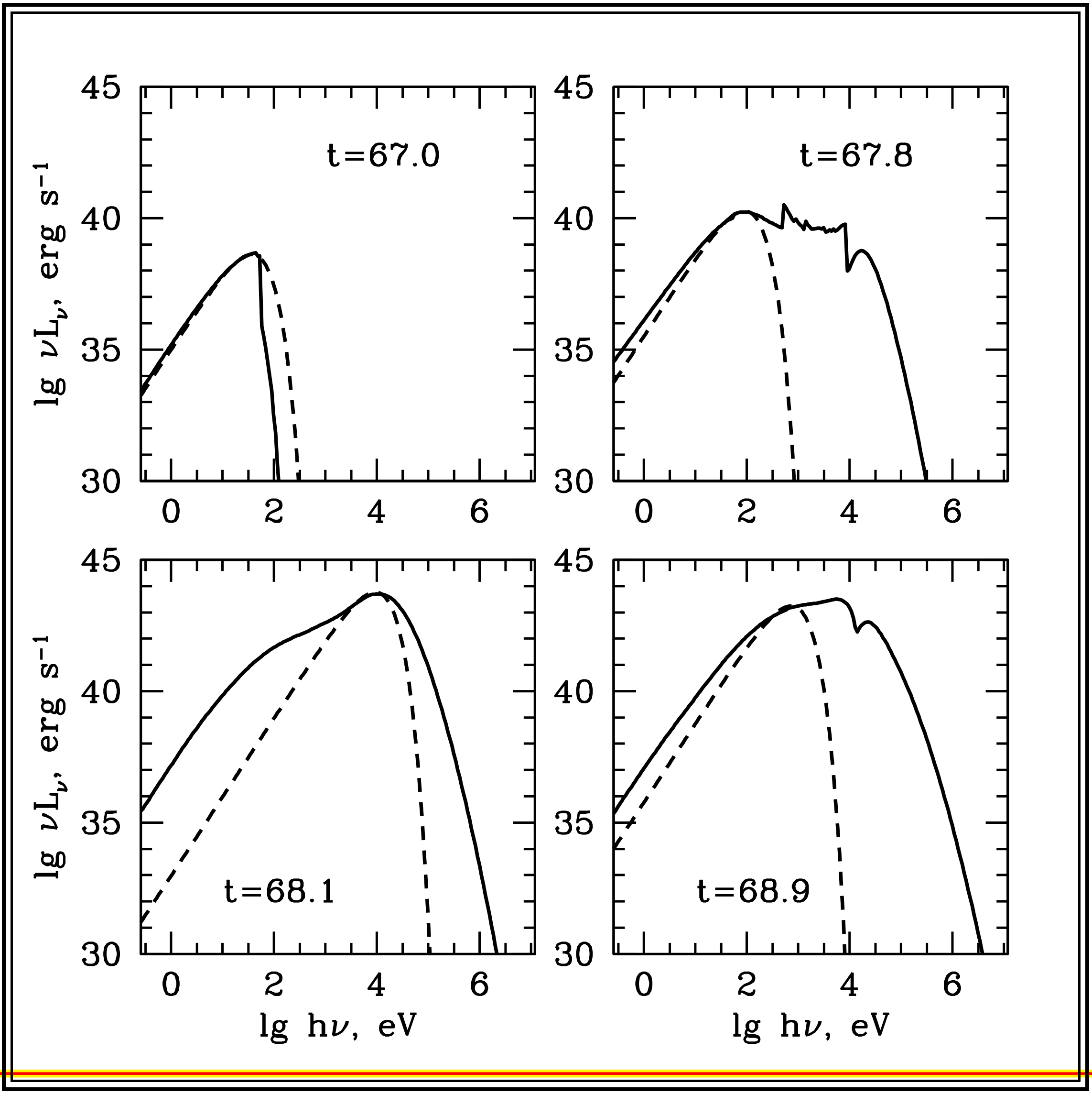
SN Ib s1b7a run: $T(m)$

$N_f = 200, \lambda_{\min} = 0.001$; Peak T at $\tau \sim 200,\ 50,\ 4,\ 0.5$

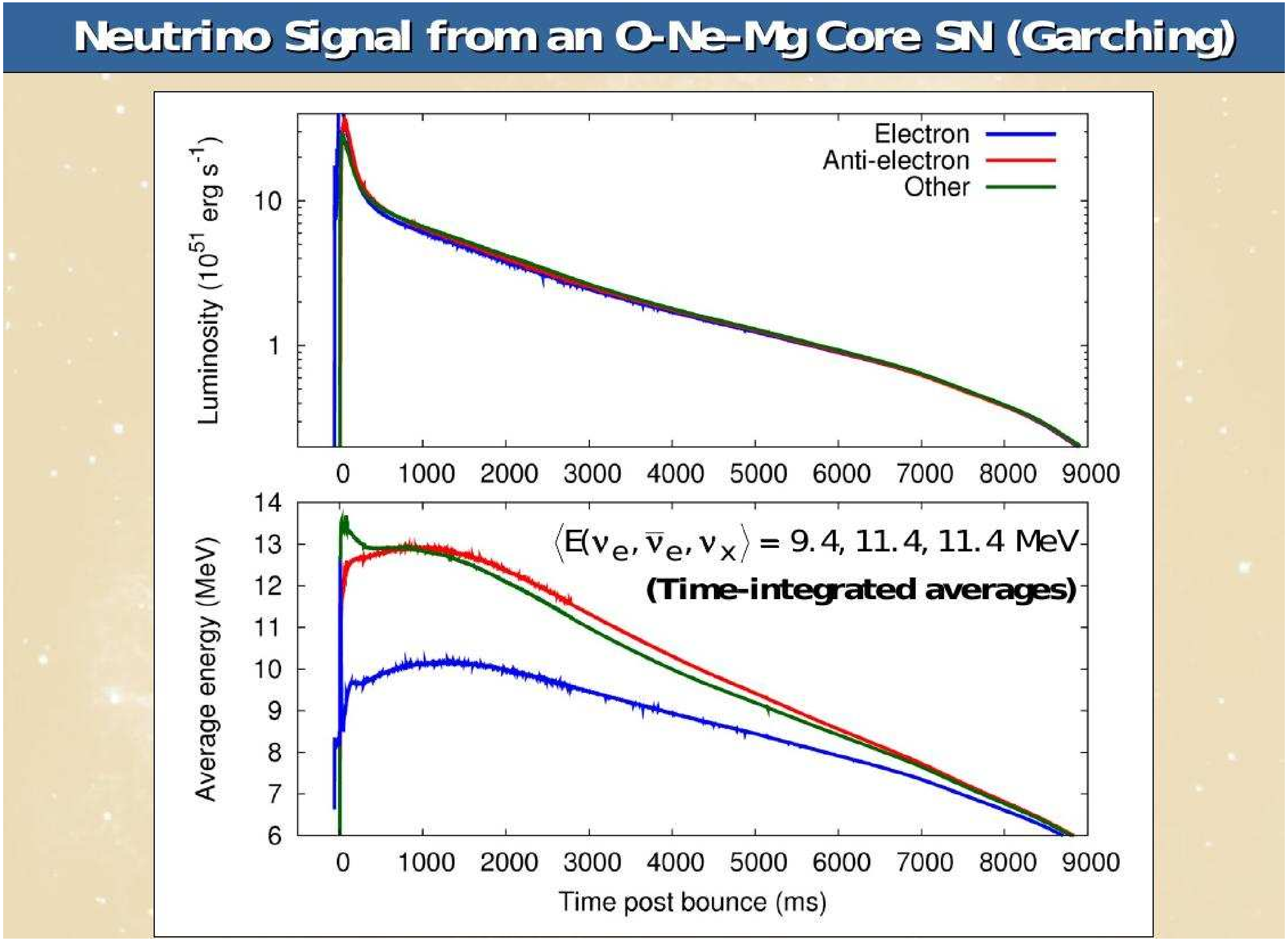


Spectra νF_ν, s1b7a $\alpha = 10^{-6}\sigma$ run

$N_f = 200, \lambda_{\min} = 0.001$



ONeMg-core Nu signal

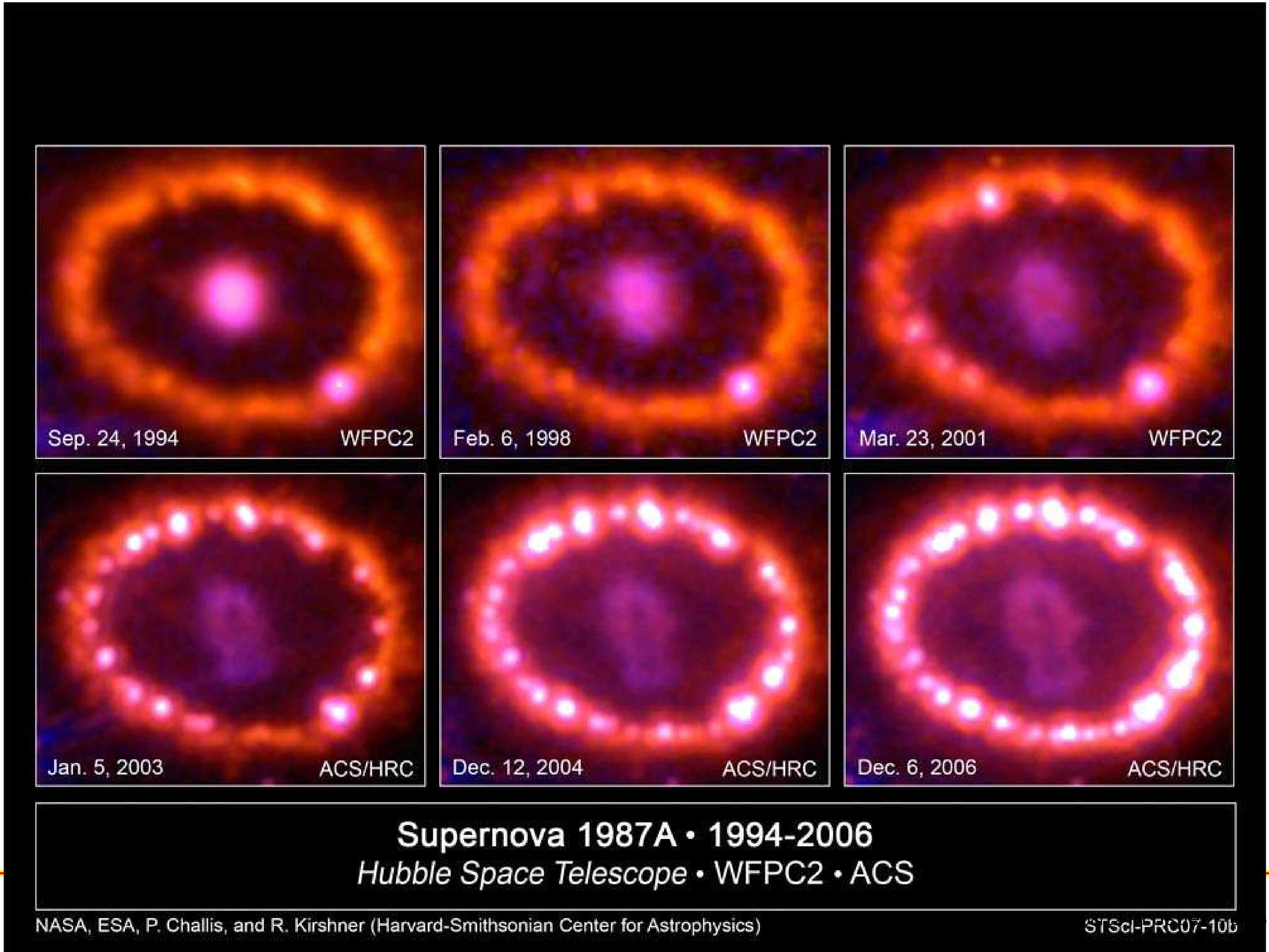


Neutrino Signal from an O-Ne-Mg Core SN (Garching)

$\langle E(\nu_e, \bar{\nu}_e, \nu_x) \rangle = 9.4, 11.4, 11.4$ MeV

(Time-integrated averages)

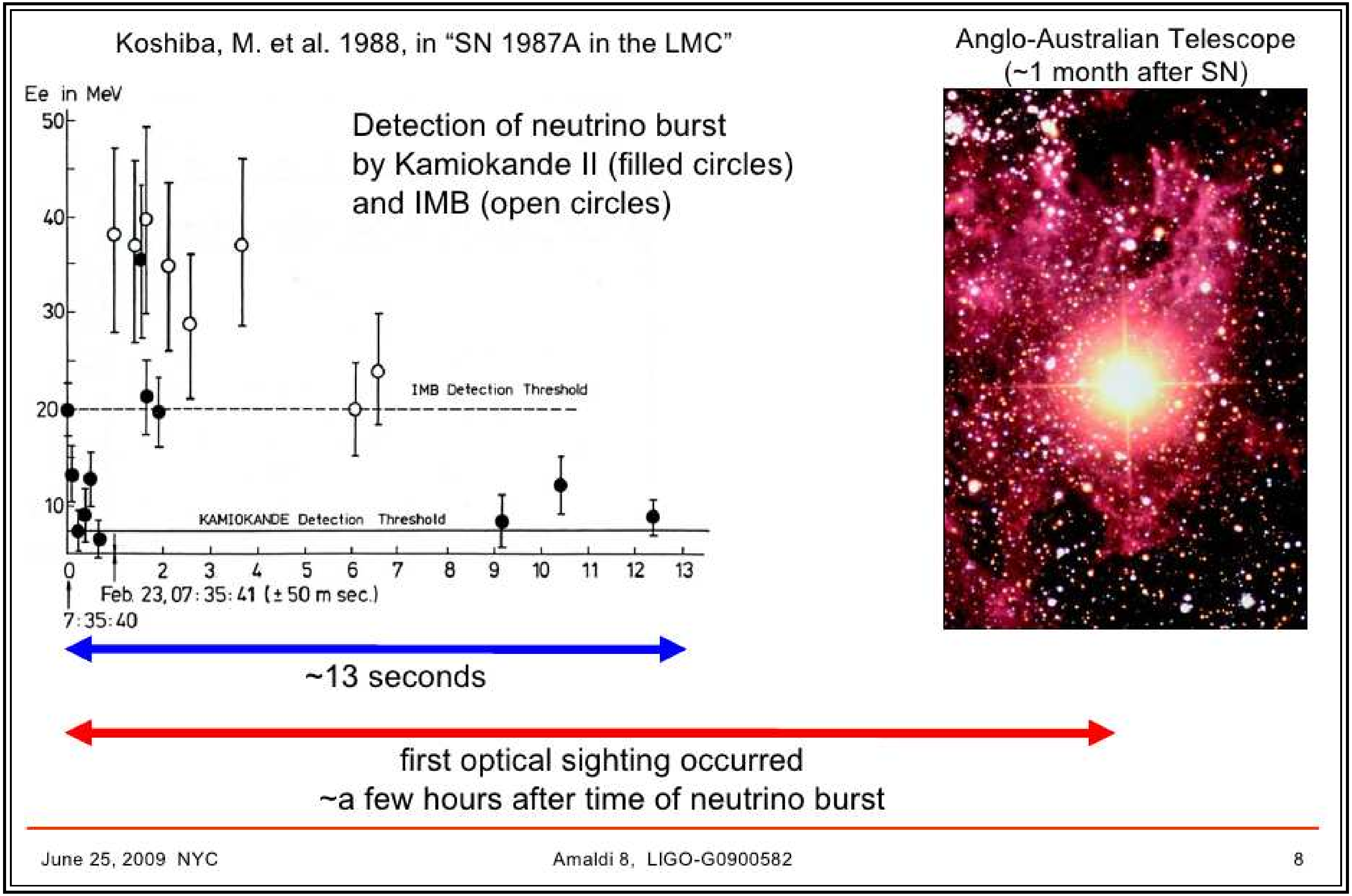
SN 1987a – 25 years soon!



Supernova 1987A • 1994-2006
Hubble Space Telescope • WFPC2 • ACS

NASA, ESA, P. Challis, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics) STScI-PRC07-10b

Supernova 1987A Neutrinos



Koshiba, M. et al. 1988, in "SN 1987A in the LMC"

Detection of neutrino burst by Kamiokande II (filled circles) and IMB (open circles)

Anglo-Australian Telescope
(~1 month after SN)

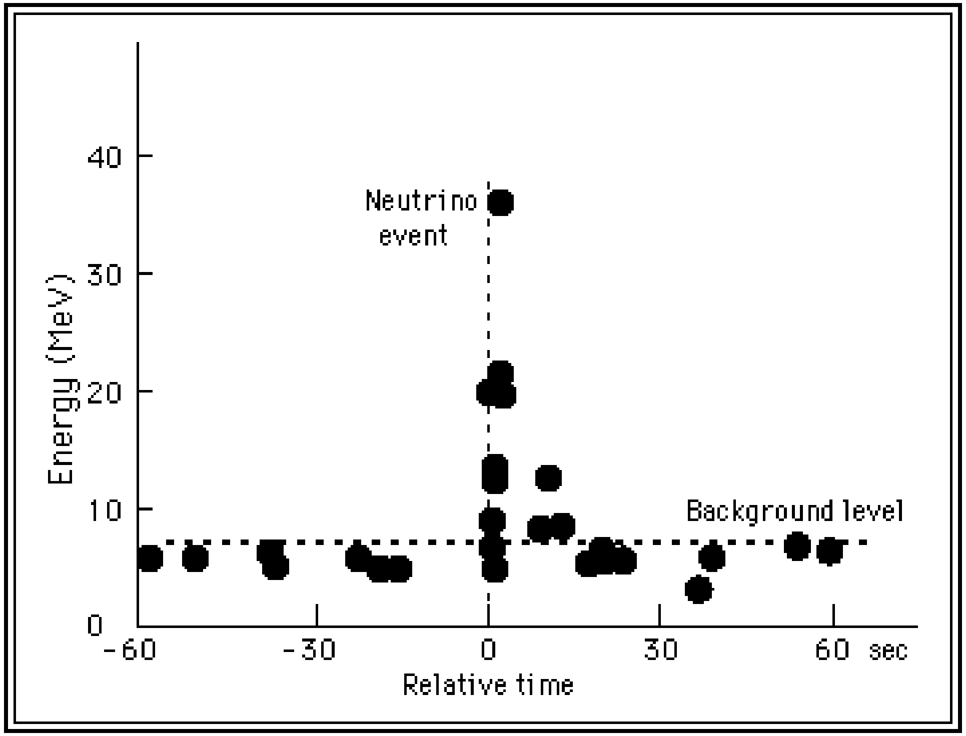
~13 seconds

first optical sighting occurred
~a few hours after time of neutrino burst

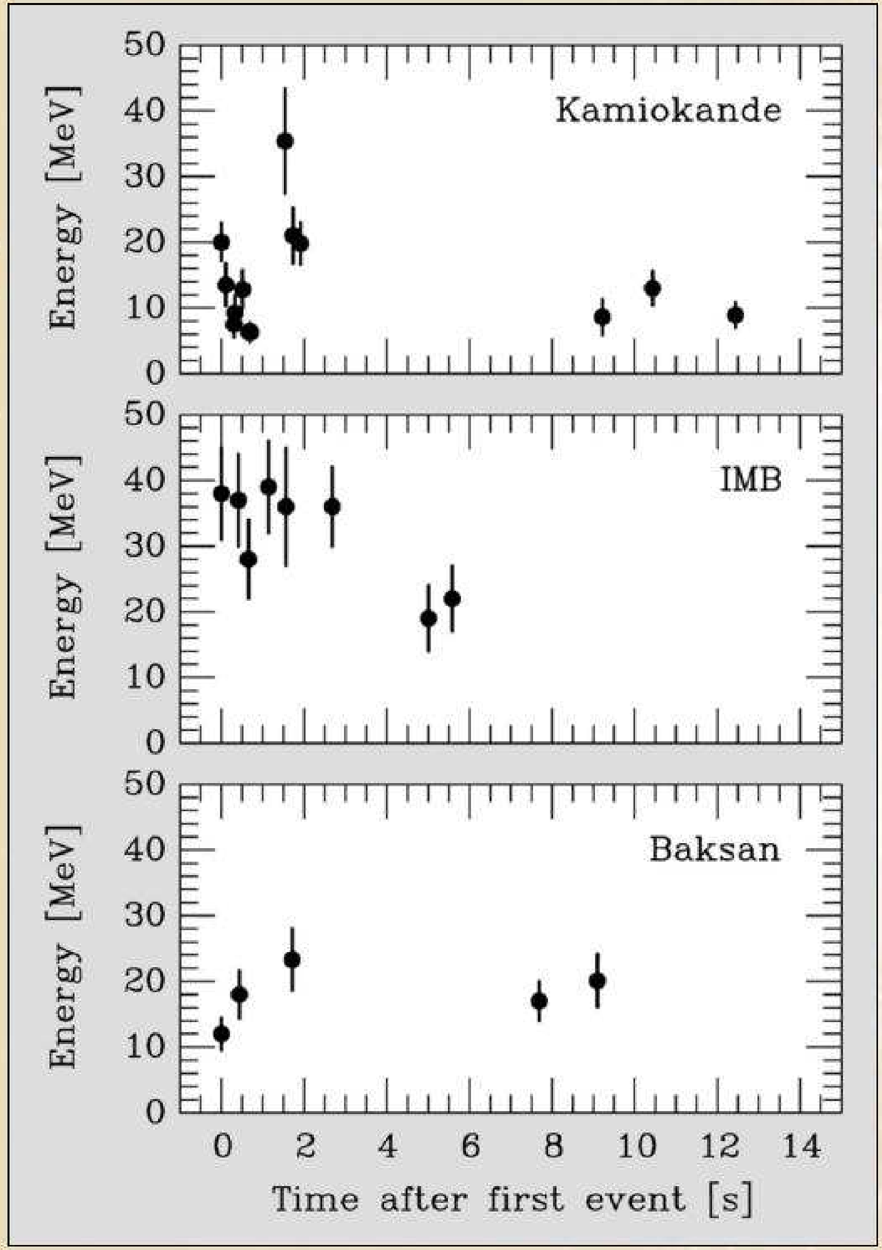
June 25, 2009 NYC Amaldi 8, LIGO-G0900582 8

SN 1987A Neutrinos

Ten neutrino events were detected in a deep mine neutrino detection facility in Japan which coincided with the observation of Supernova 1987A. They were detected within a time interval of about 15 seconds against a background of lower energy neutrino events. A similar facility, IMB in Ohio detected 8 neutrino events in 6 seconds. These observations were made 18 hours before the first optical sighting of the supernova.



Neutrino Signal of Supernova 1987A



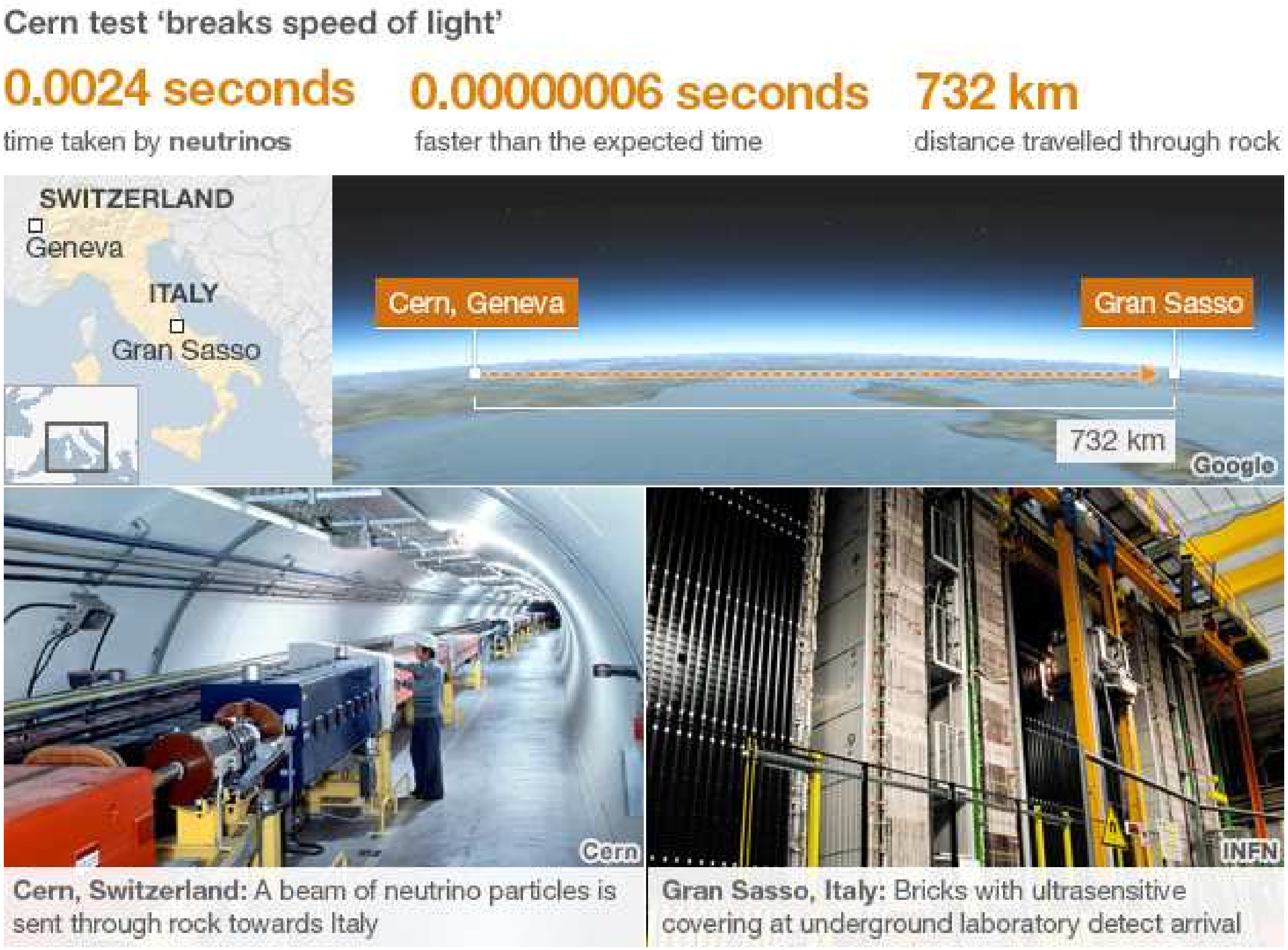
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~0.7/day
Clock uncertainty +2/-54 s

Within clock uncertainties,
signals are contemporaneous

Hottest: speed of light broken!



Cern test ‘breaks speed of light’

0.0024 seconds
time taken by **neutrinos**

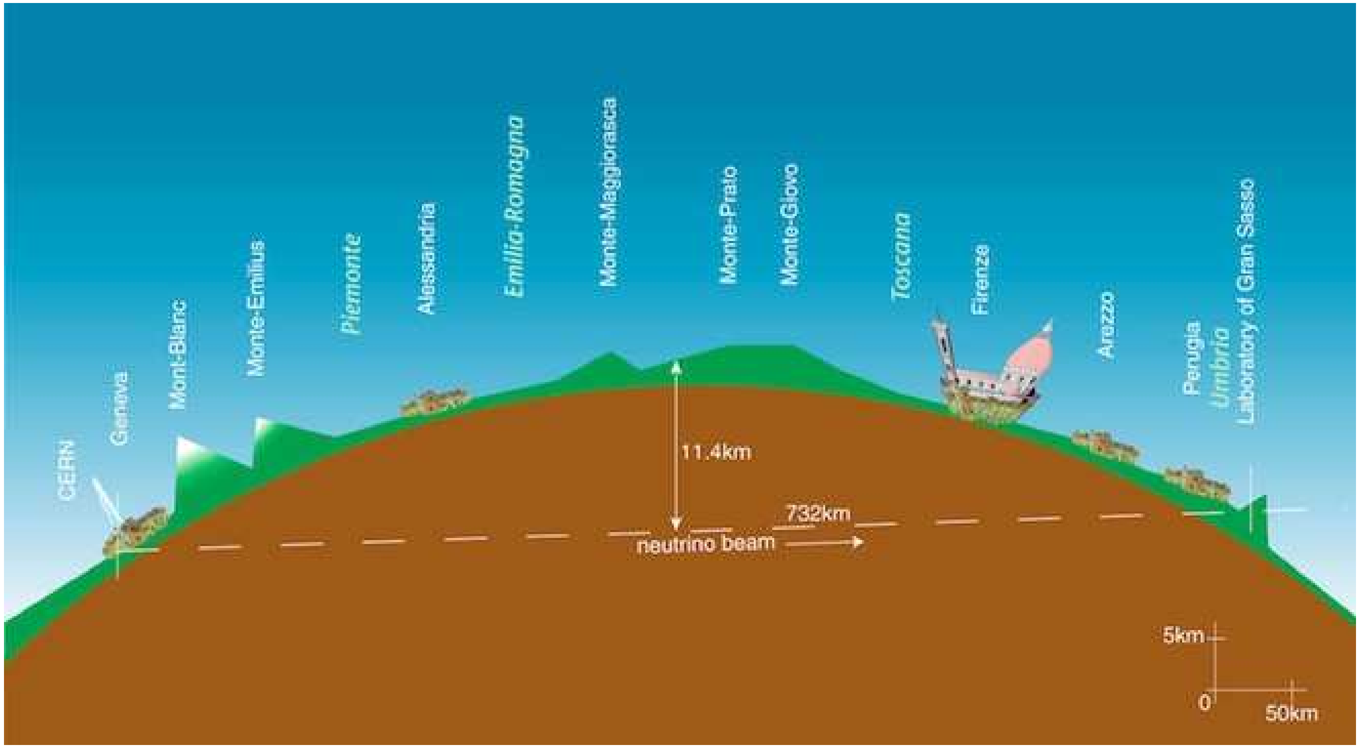
0.00000006 seconds
faster than the expected time

732 km
distance travelled through rock

Cern, Switzerland: A beam of neutrino particles is sent through rock towards Italy

Gran Sasso, Italy: Bricks with ultrasensitive covering at underground laboratory detect arrival

Neutrino beam CERN - GrSasso



No theory is discussed here

Many papers are written on Lorentz-violation.

(Ask Alexander Dolgov on a high-level expert evalution of these works.)

Speed of gravity is also measured by some workers.

Constraints on GW speed may be found from SN shocks as well.

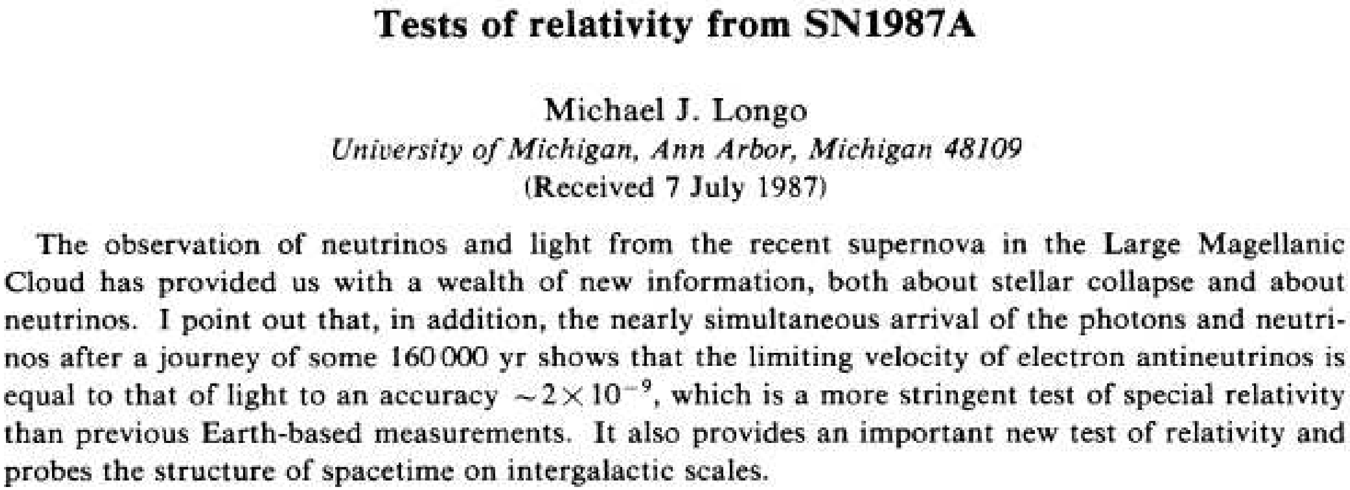
Superlumnal neutrino cartoons...

... and songs!

© Corrigan Brothers And Pete Creighton
“The Neutrino Song”

– click here

Longo PRD 36(1987)3276



Tests of relativity from SN1987A

Michael J. Longo
University of Michigan, Ann Arbor, Michigan 48109

(Received 7 July 1987)

The observation of neutrinos and light from the recent supernova in the Large Magellanic Cloud has provided us with a wealth of new information, both about stellar collapse and about neutrinos. I point out that, in addition, the nearly simultaneous arrival of the photons and neutrinos after a journey of some 160 000 yr shows that the limiting velocity of electron antineutrinos is equal to that of light to an accuracy $\sim 2\times 10^{-9}$, which is a more stringent test of special relativity than previous Earth-based measurements. It also provides an important new test of relativity and probes the structure of spacetime on intergalactic scales.

Distance $= 1.6 \times 10^5$ ly, $\Delta t \approx 3^{\mathrm{h}}$, hence

$$|(c - c_\nu)/c| \lesssim 3^{\mathrm{h}}/(1.6 \times 10^5 \times 365 \times 24) = 2 \times 10^{-9}$$

Where does $\Delta t \approx 3^{\mathrm{h}}$ come from?
Could the constraint be improved?

Importance of Shocks breakouts

The first powerful burst of photon radiation in a supernova appears when the shock front is a few photon mean-free paths below the star photosphere.

This is called the shock breakout and is the first observable event after the neutrino and gravitational wave (GW) bursts in core-collapsing supernovae.

Any early information about collapse is vitally important for understanding the physics of explosion, for understanding presupernovae, etc.

Moreover, shock breakout observations correlated with neutrino or GW signals from core collapsing stars may give most stringent constraints on superluminal neutrino or GW propagation, which is currently a hot topic in particle physics.

SN1987A discovery

Timing (times in Universal Time)

7:36, 23 February, neutrinos observed

9:30, 23 February

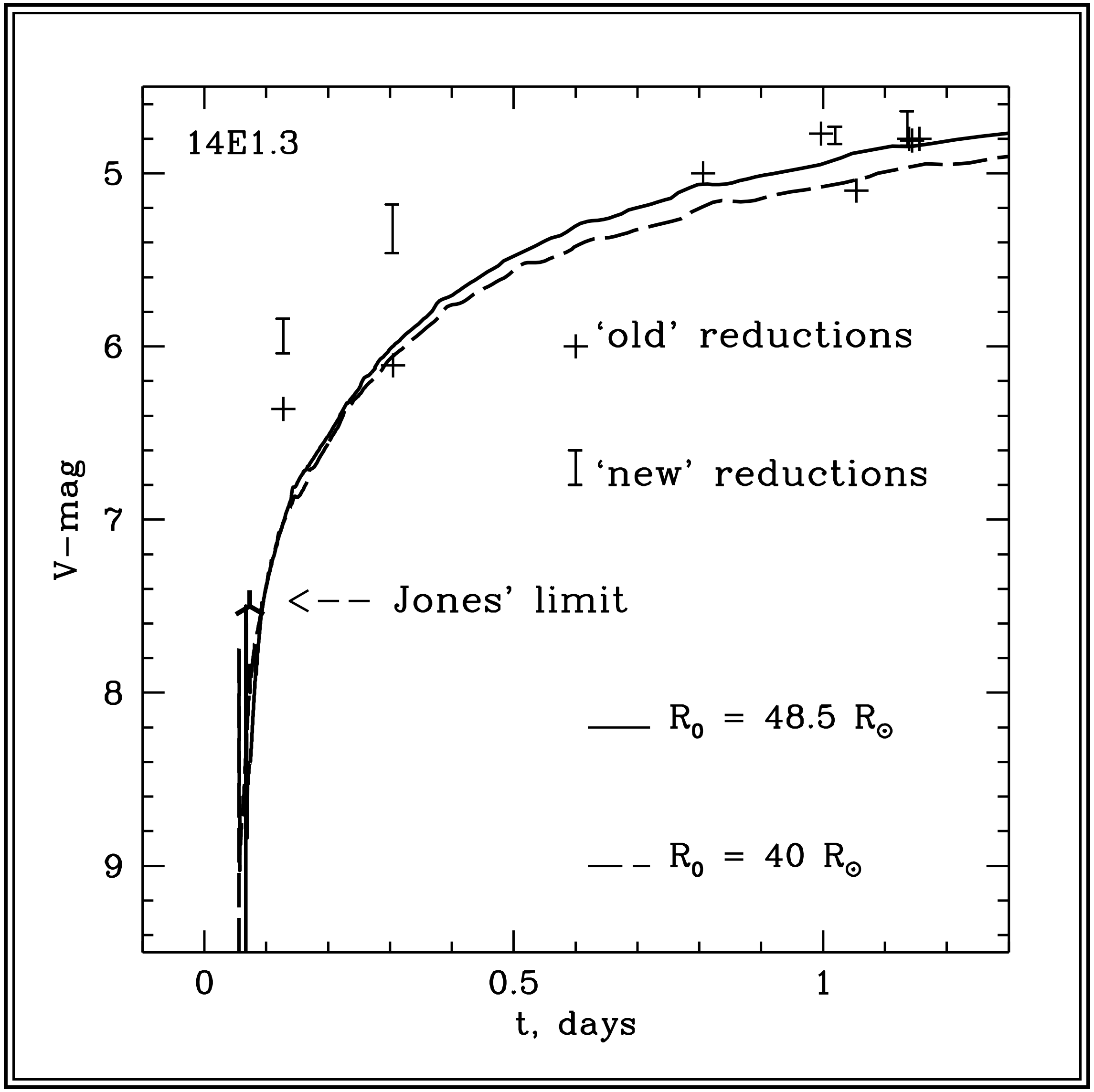
- Albert Jones, amateur astronomer, observes Tarantula Nebula in LMC
- He sees nothing unusual

10:30, 23 February

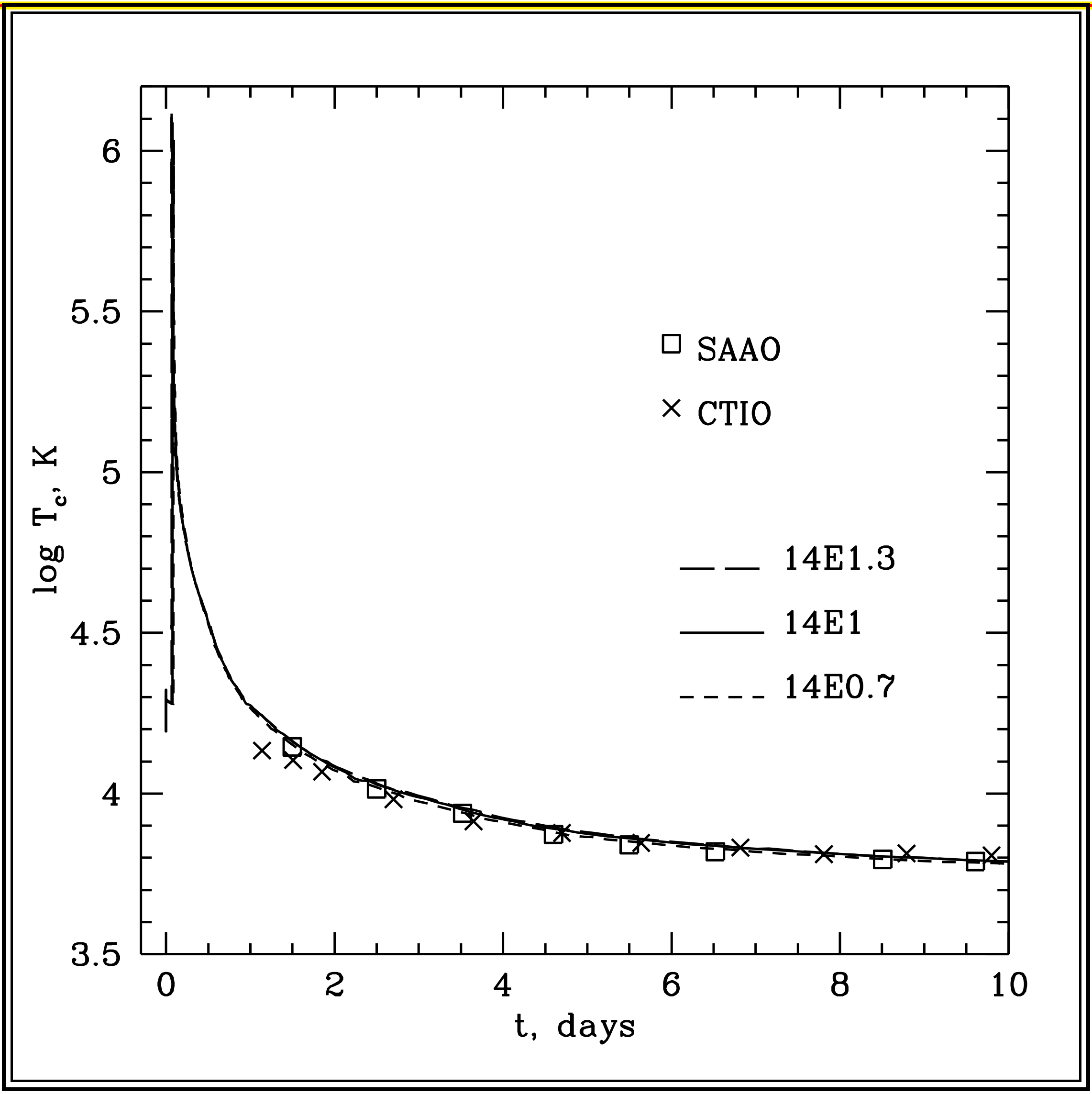
- Robert McNaught photographs LMC
- When plate is developed, SN1987A is there.
- Some 20 hours later, Ian Shelton’s discovery.

SN87A early observations

Blinnikov with K.Nomoto ea



SN87A early observations



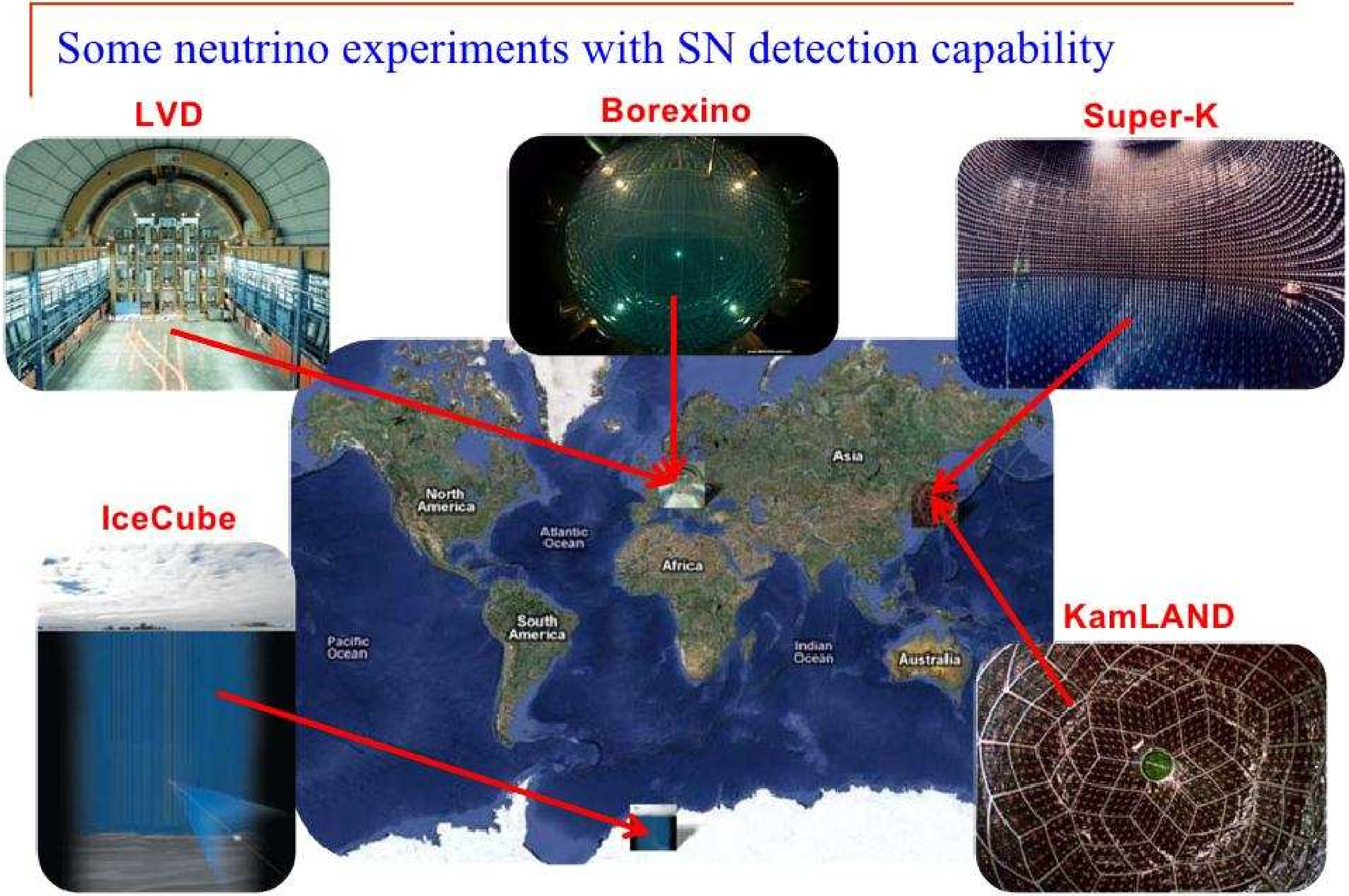
Improvement of c_ν constraint

If the flash at shock breakout were observed we would get

$$|(c - c_\nu)/c| \lesssim 2 \times 10^{-10}$$

Much better improvement is possible in principle!
If a precollapse suspect is monitored and its prompt quake is registered e.g. in radio simultaneously with ν and/or GW signal.

ν detectors

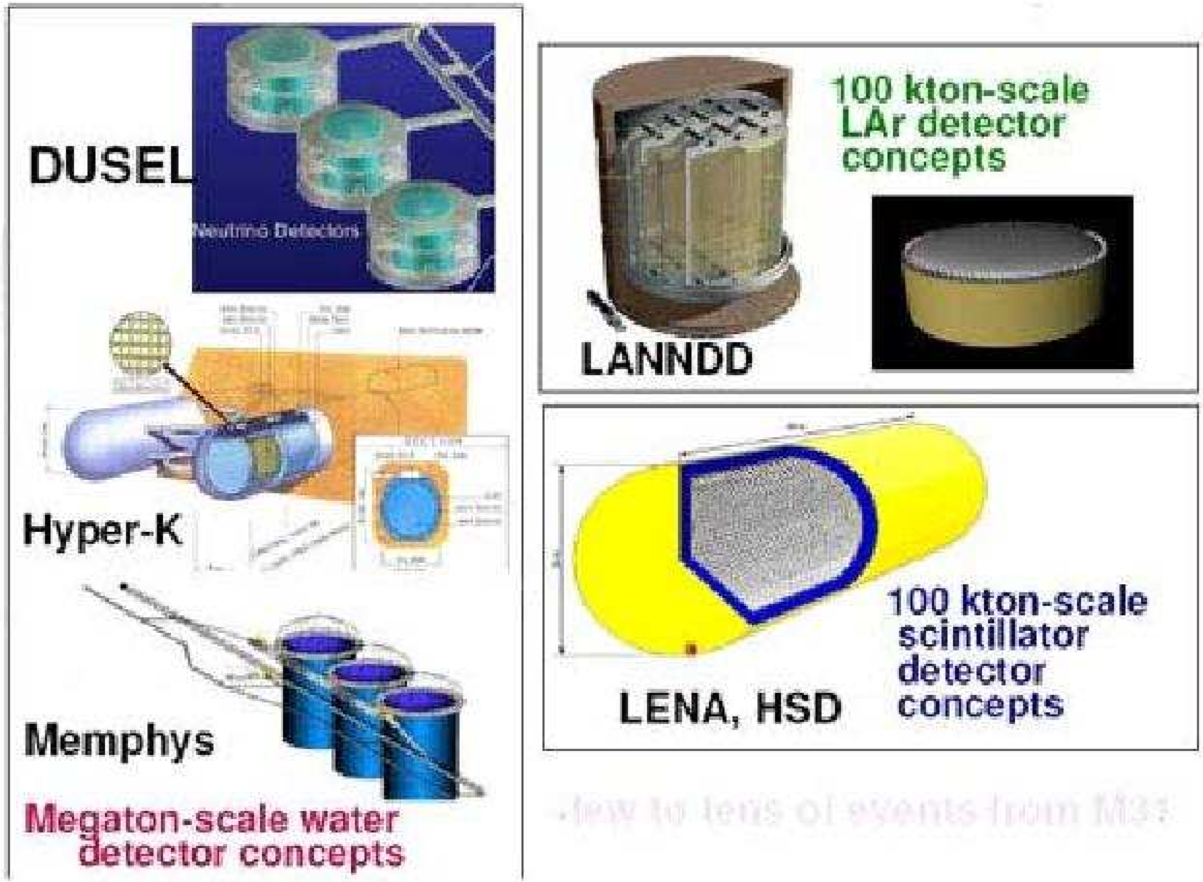


Some neutrino experiments with SN detection capability

Next generation ν detectors

Next generation neutrino mega-detectors (10-20 years)

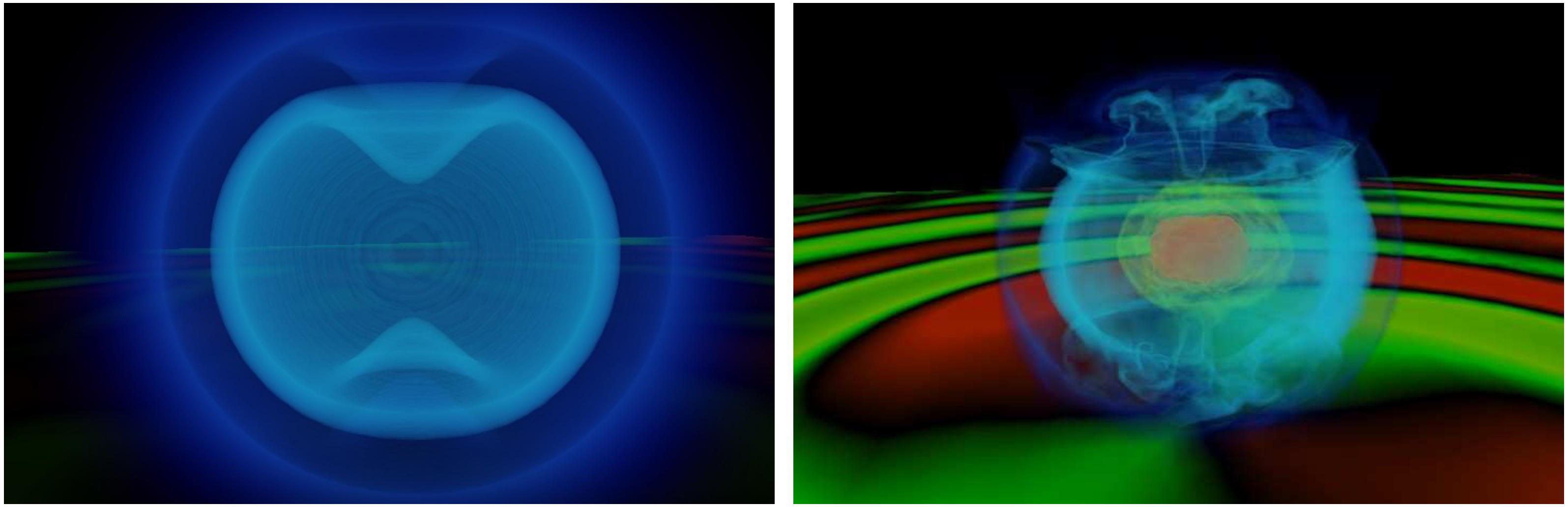
~few to tens of events from M31



~few to tens of events from M31

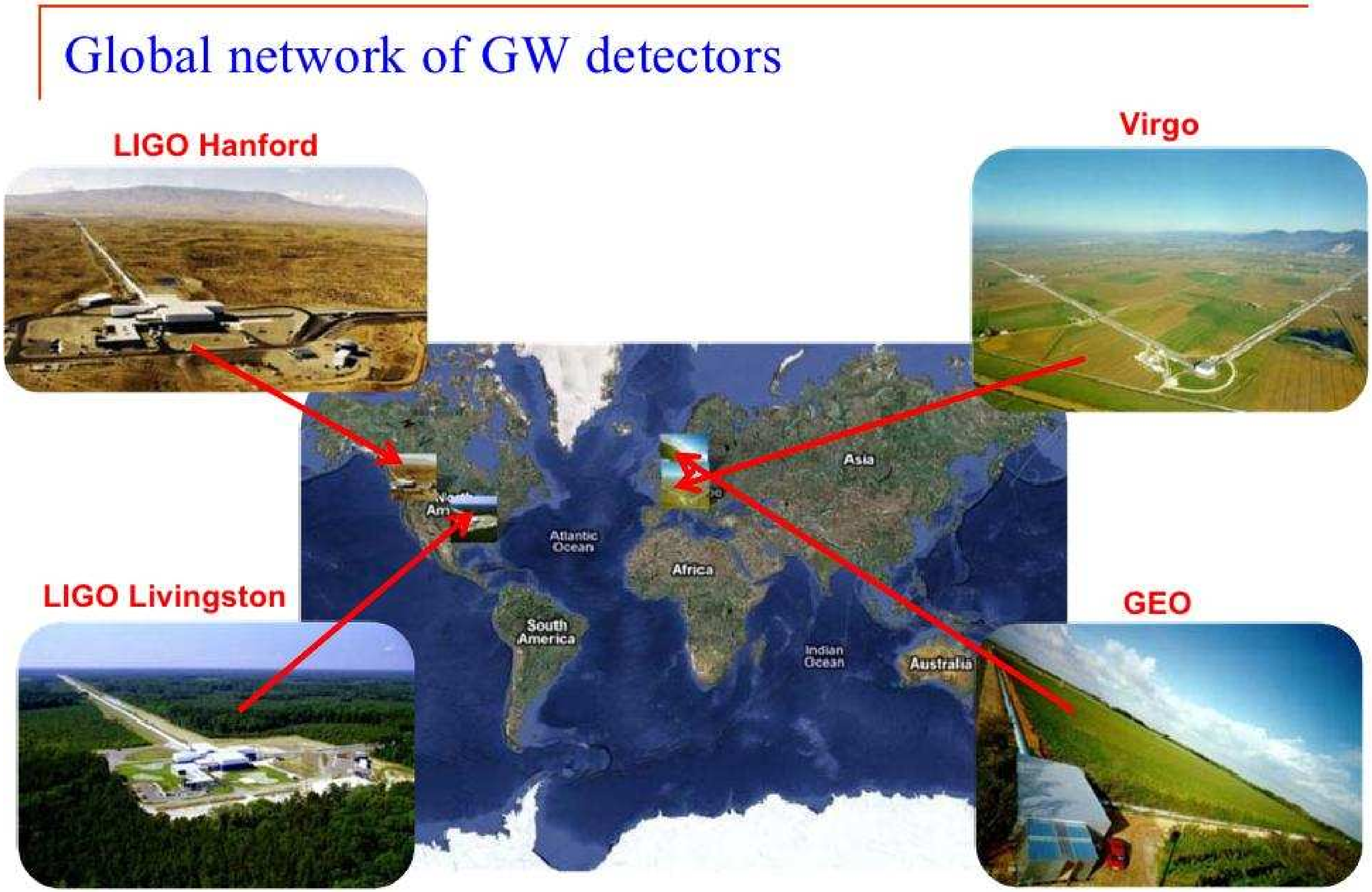
Gravitational Waves from CCSNe

http://numrel.aei.mpg.de/images



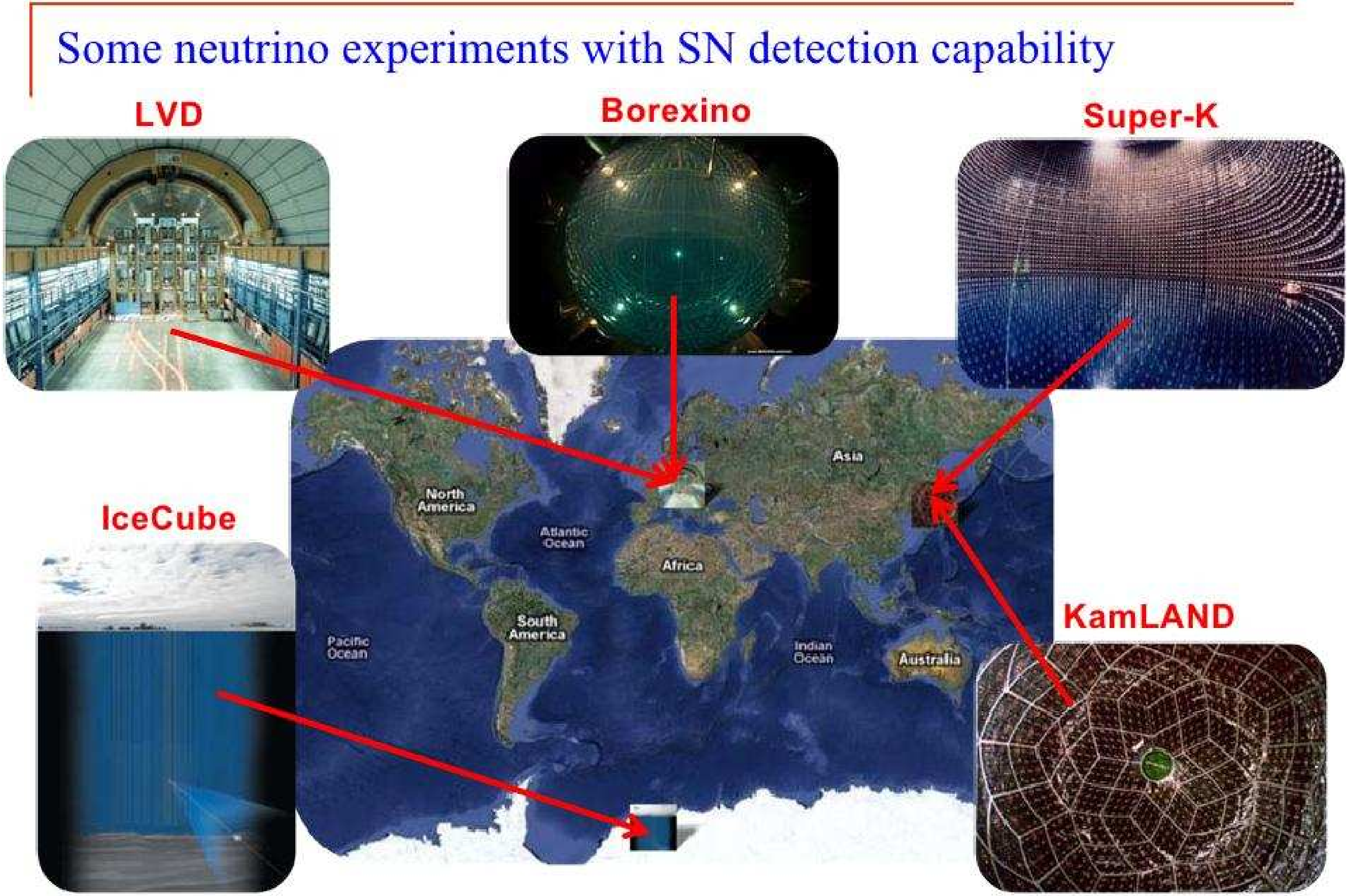
These images are copyright of AEI, ZIB, LSU and SISSA

GW detectors



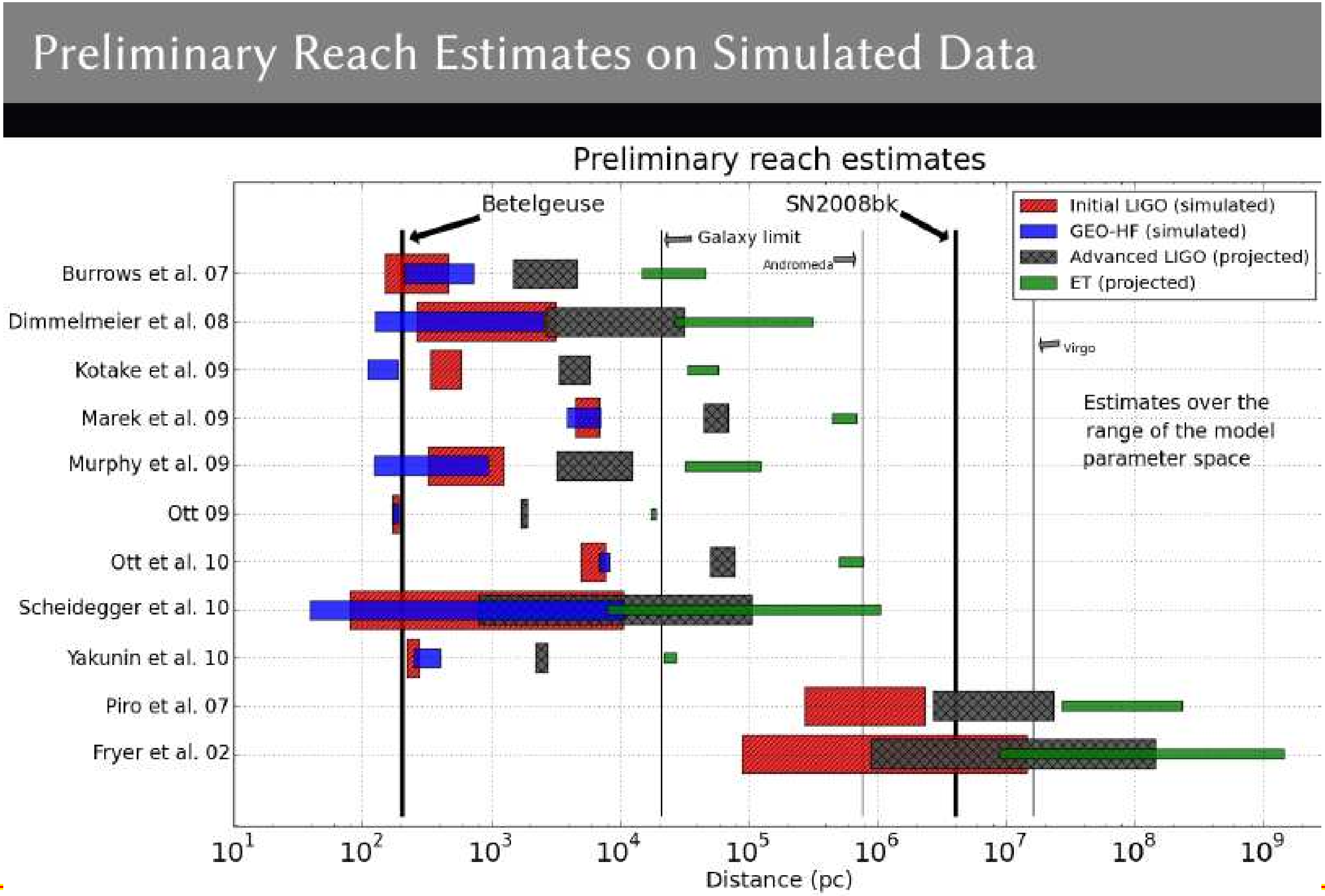
Global network of GW detectors

ν detectors



Some neutrino experiments with SN detection capability

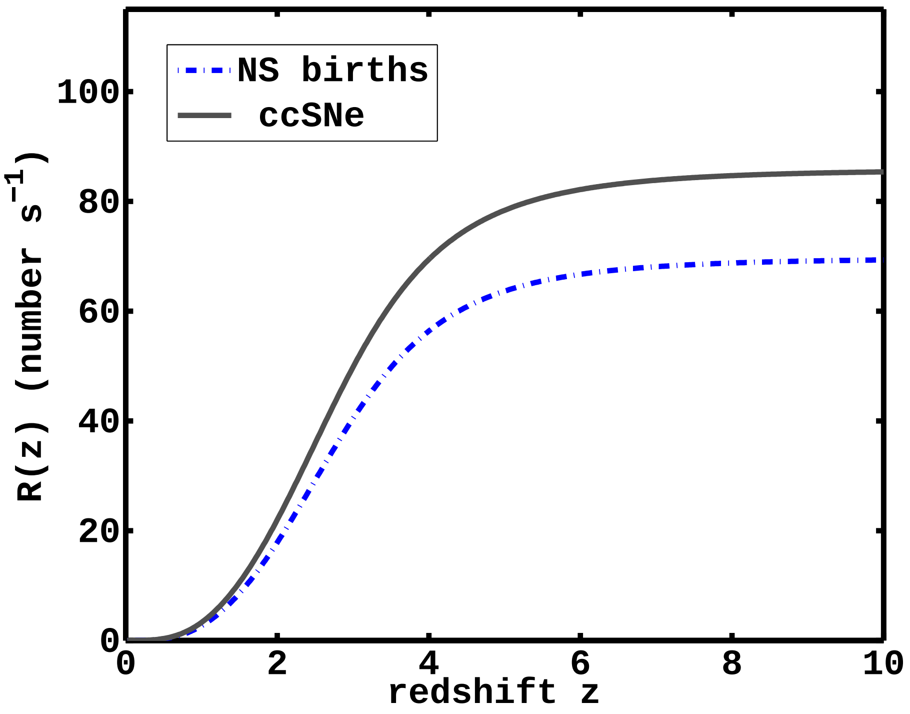
GW LIGO estimates



Preliminary Reach Estimates on Simulated Data

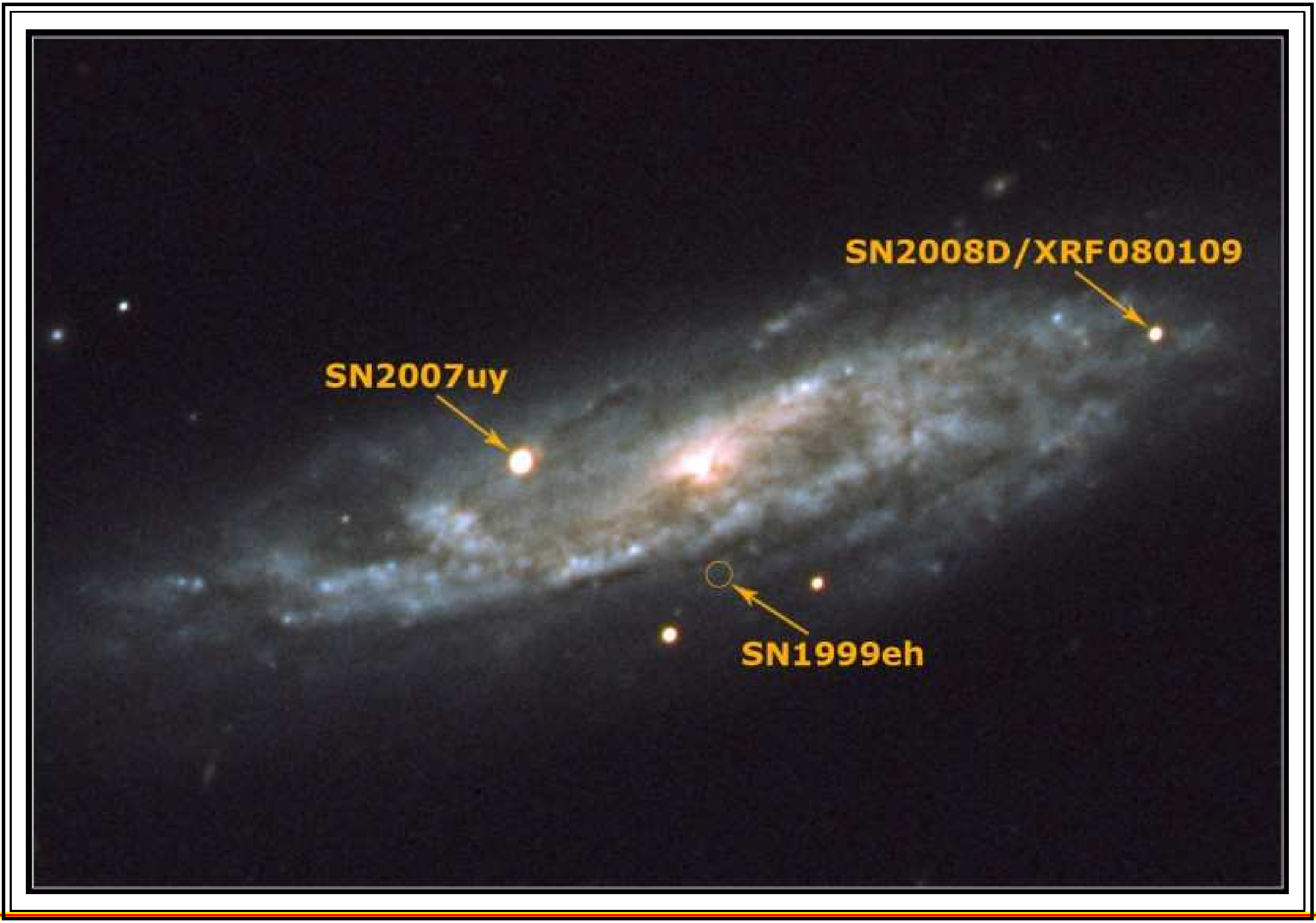
Star formation rate = SFR

Smartt S. J., 2009, ARAA, 47, 63

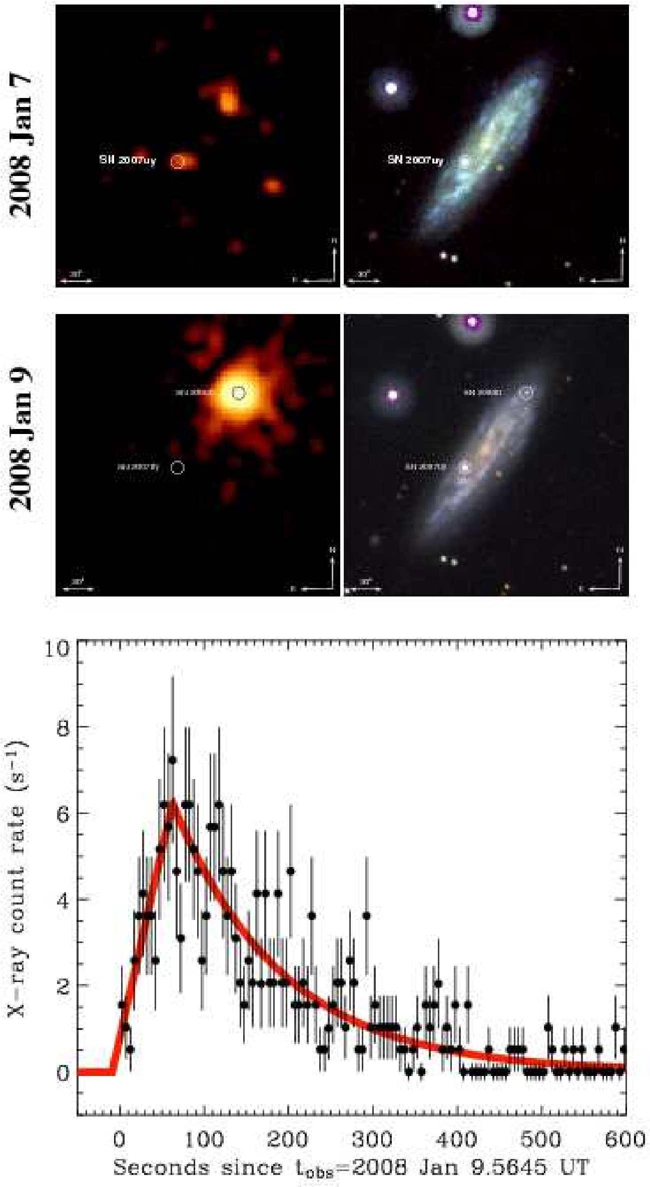


SN factory NGC2770

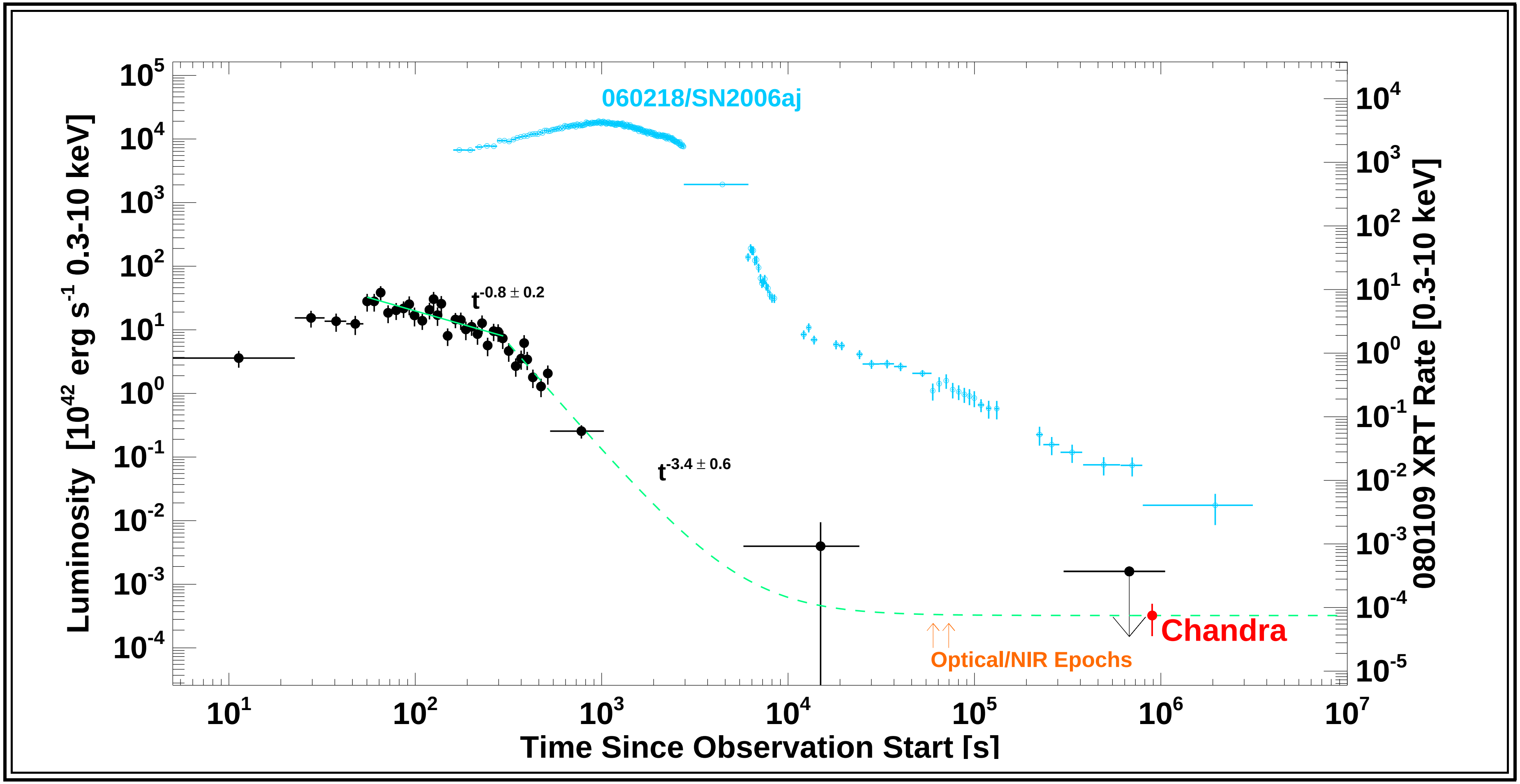
SN2008D shock-breakout caught by A.Soderberg et al.; LC Modjaz et al. (2008); image 12 Jan 2008



XRT 080109/SN 2008D

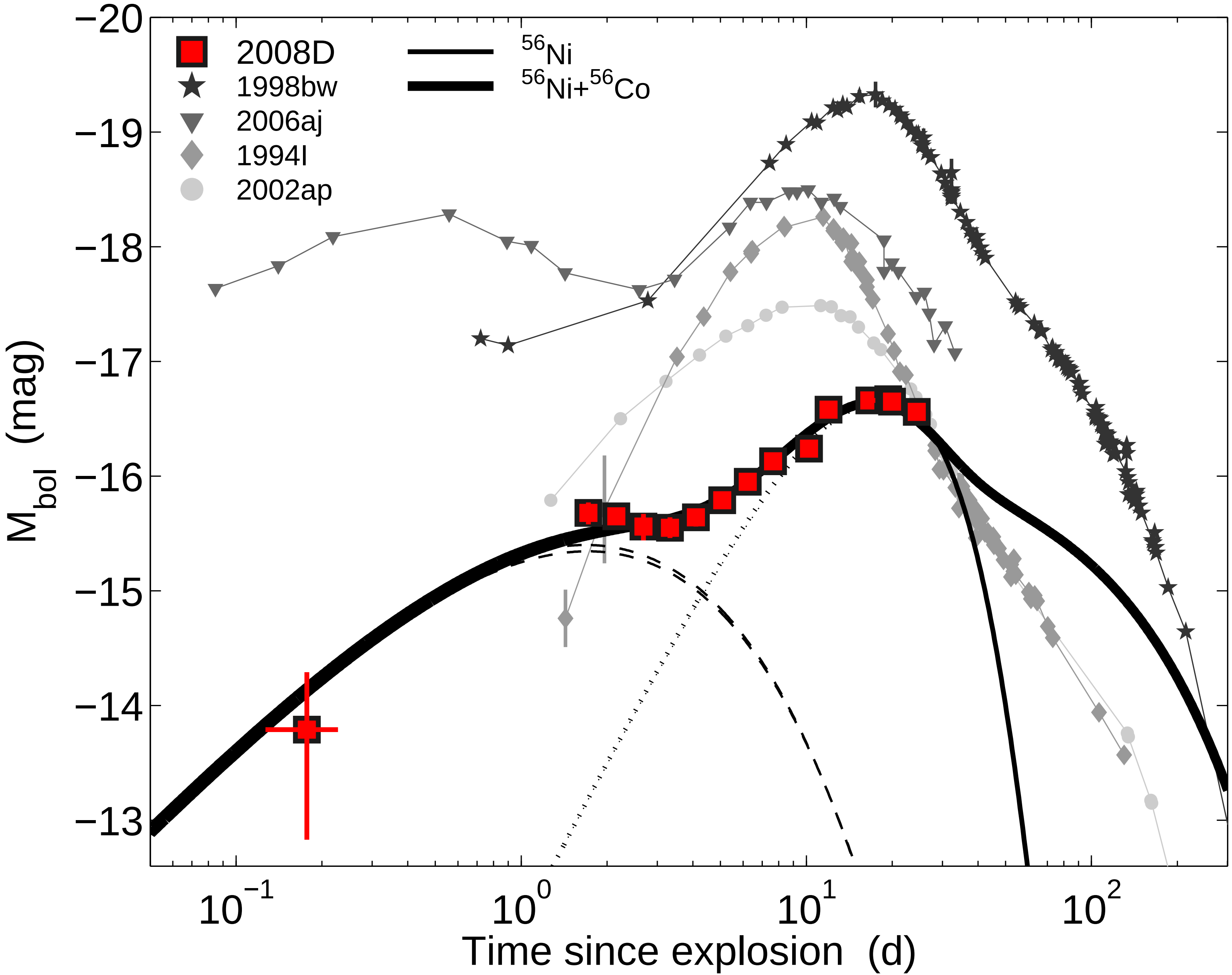


XRT 080109



060218/SN2006aj
$t^{-0.8 \pm 0.2}$
$t^{-3.4 \pm 0.6}$
Chandra
Optical/NIR Epochs
Luminosity [10^{42} erg s^{-1} 0.3-10 keV]
080109 XRT Rate [0.3-10 keV]
Time Since Observation Start [s]
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{7}
10^{6}

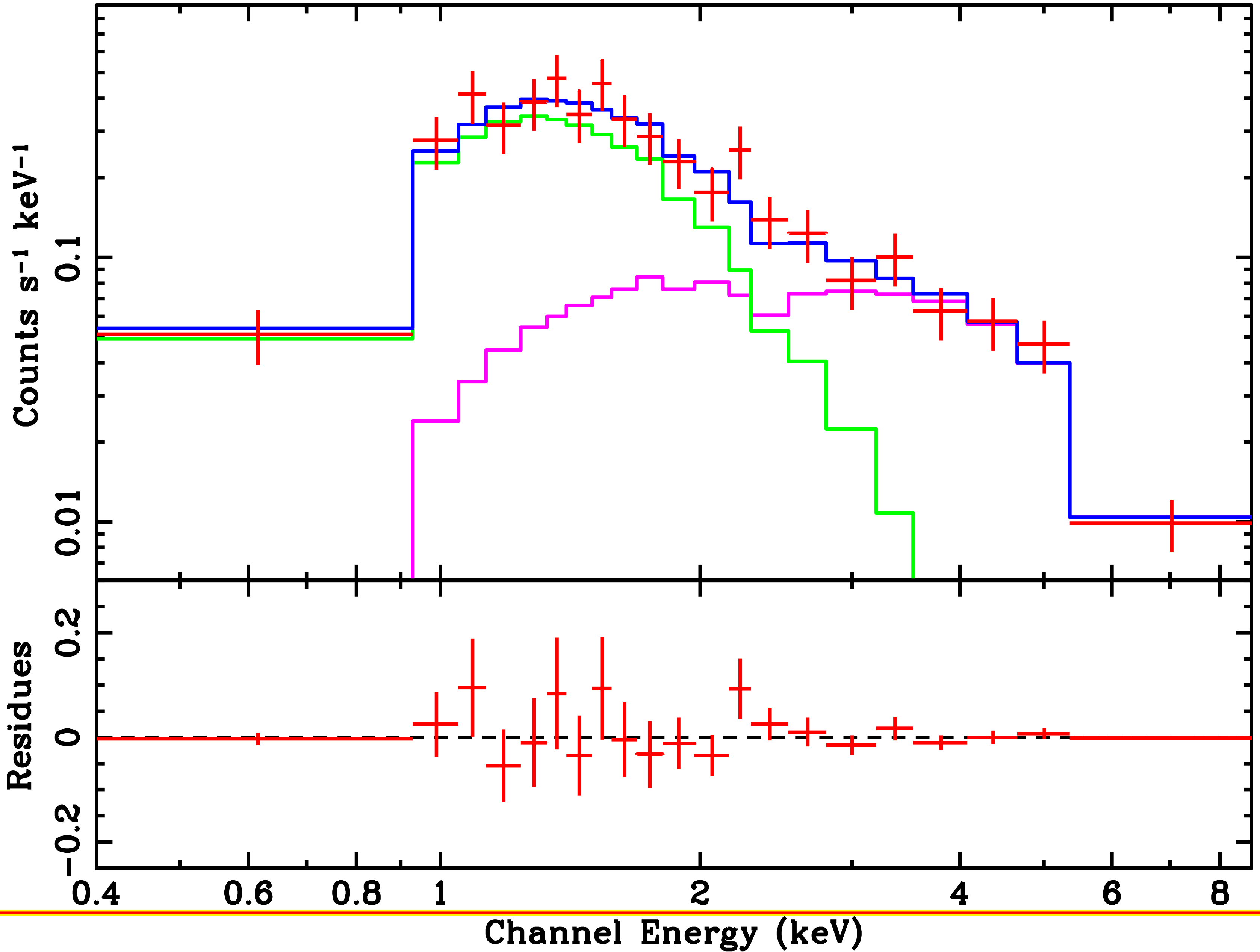
SN 2008D and other SNIb/c



XRF080109, no shock breakout?

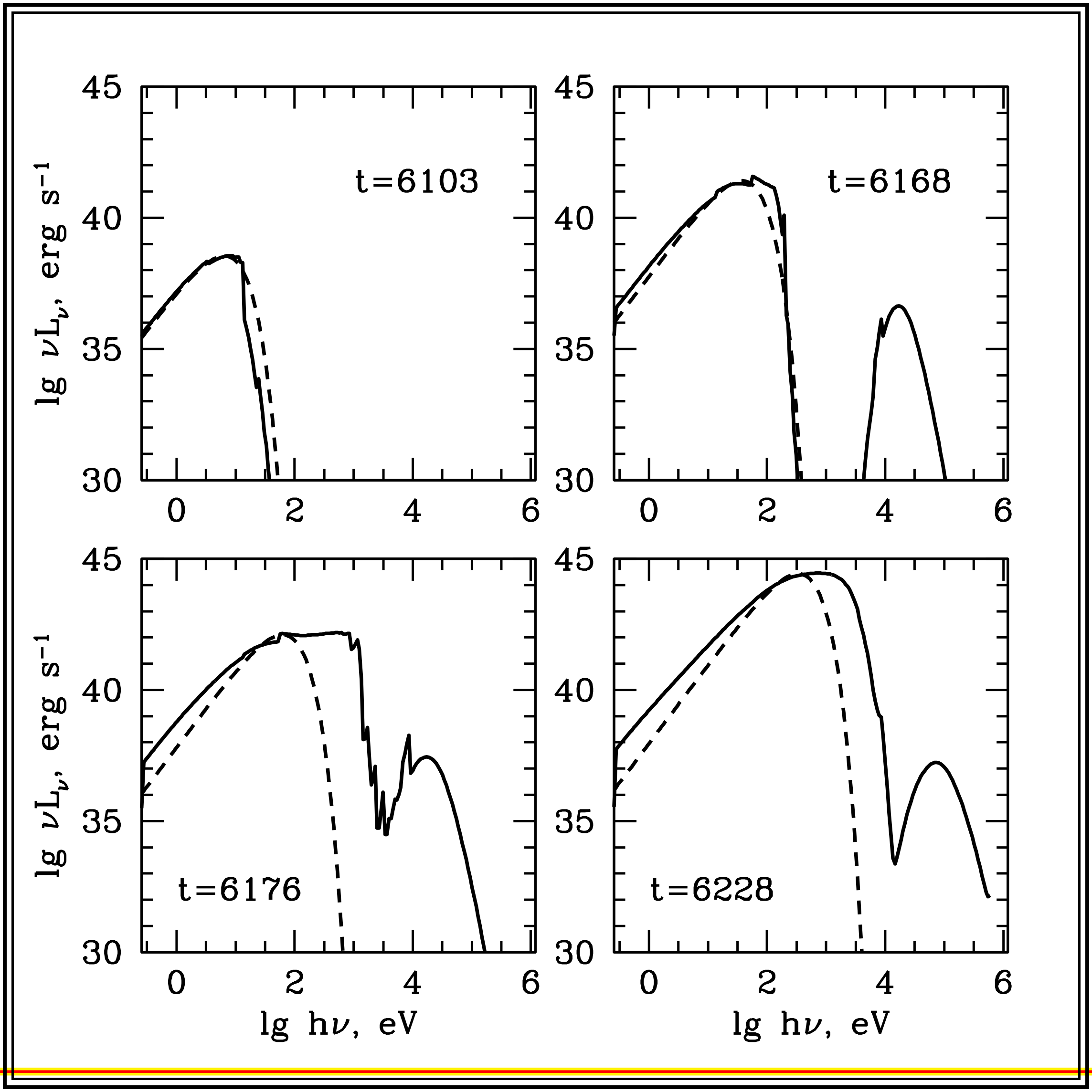
Li-Xin Li MNRAS 388(2008)603
2 T bb spectrum
Claims $R_{\rm ph}$ too small.
No problem!

Two-temperature spectrum



Now our spectra νF_ν

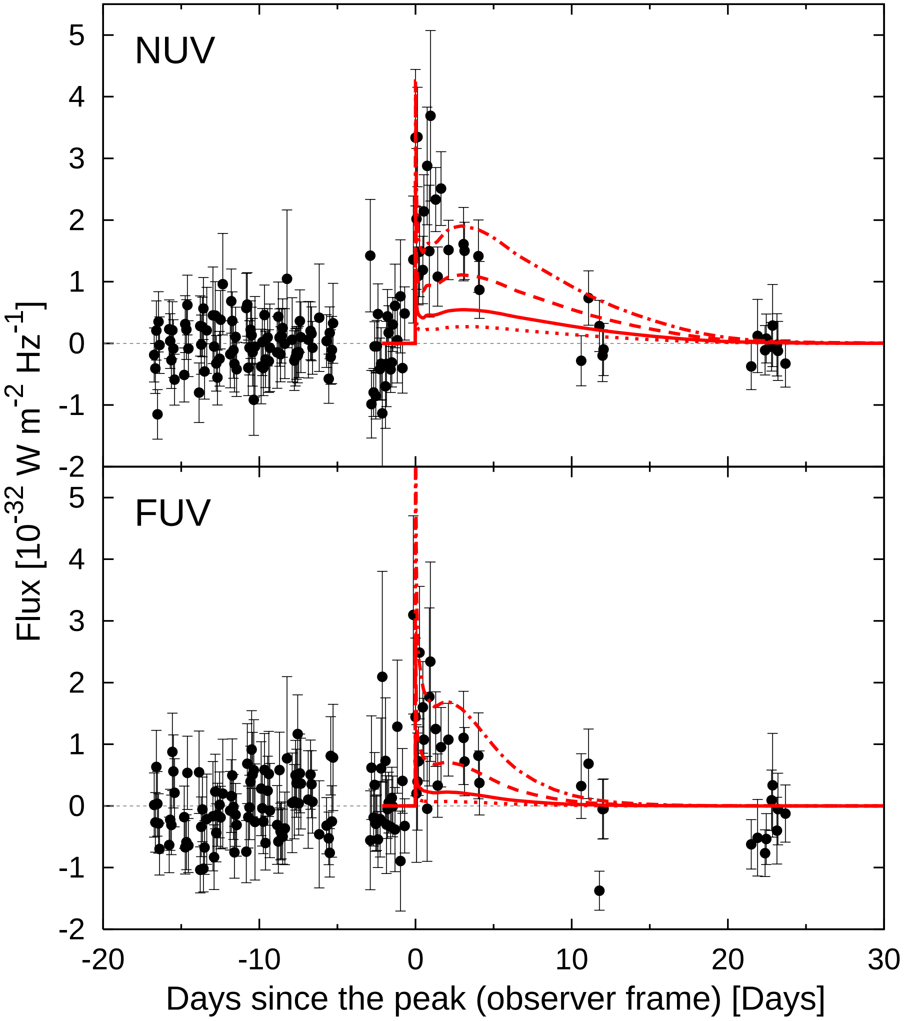
$N_f = 200, \lambda_{\min} = 0.01$



SN II shocks observed

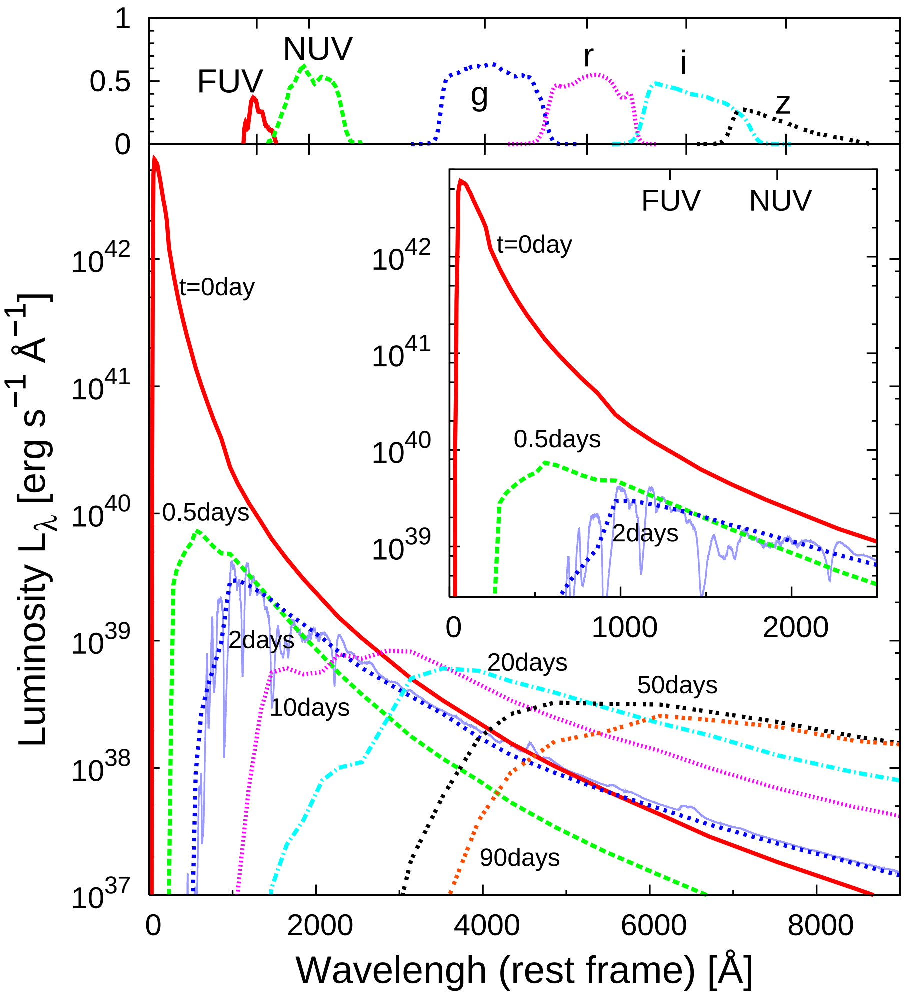
Observations Gezari ea’08, Schawinski ea’08, simulations Tominaga ea’09

Observed flash and STELLA



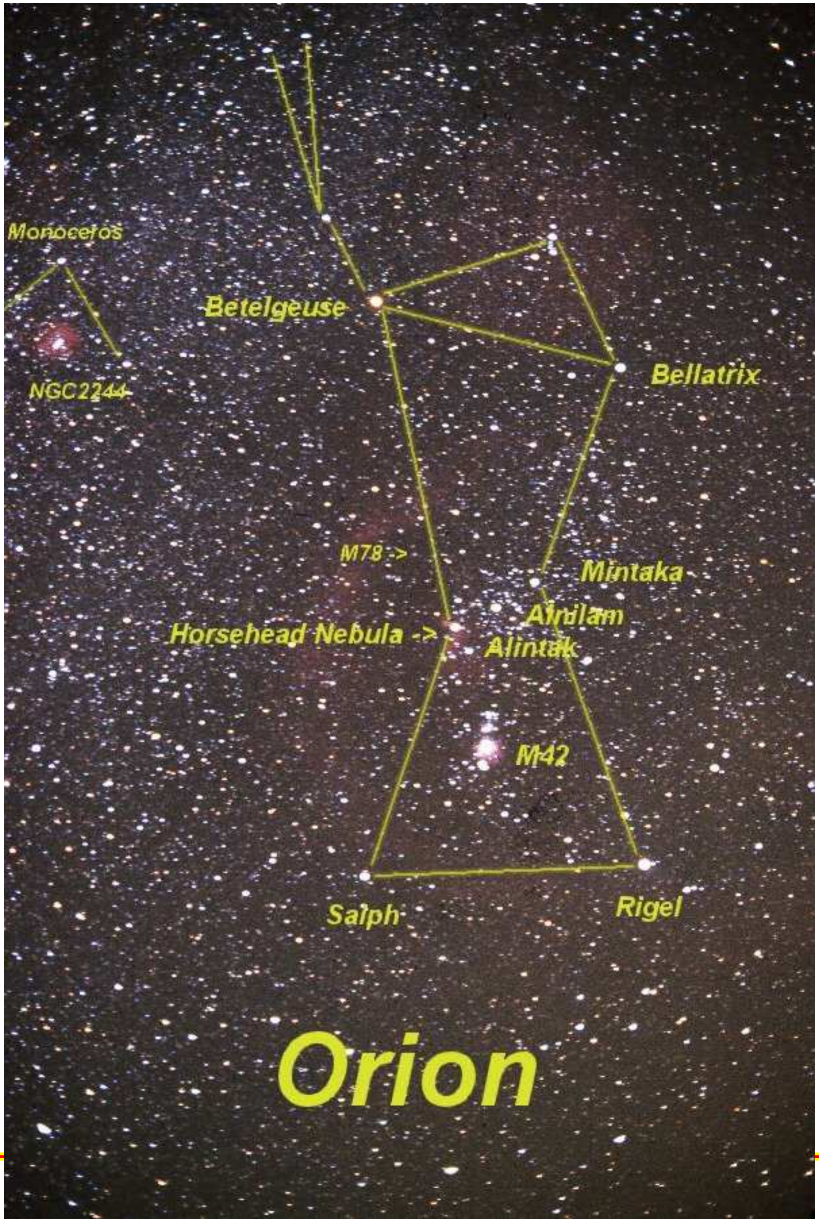
SN II shock spectrum

Observed spectrum and STELLA

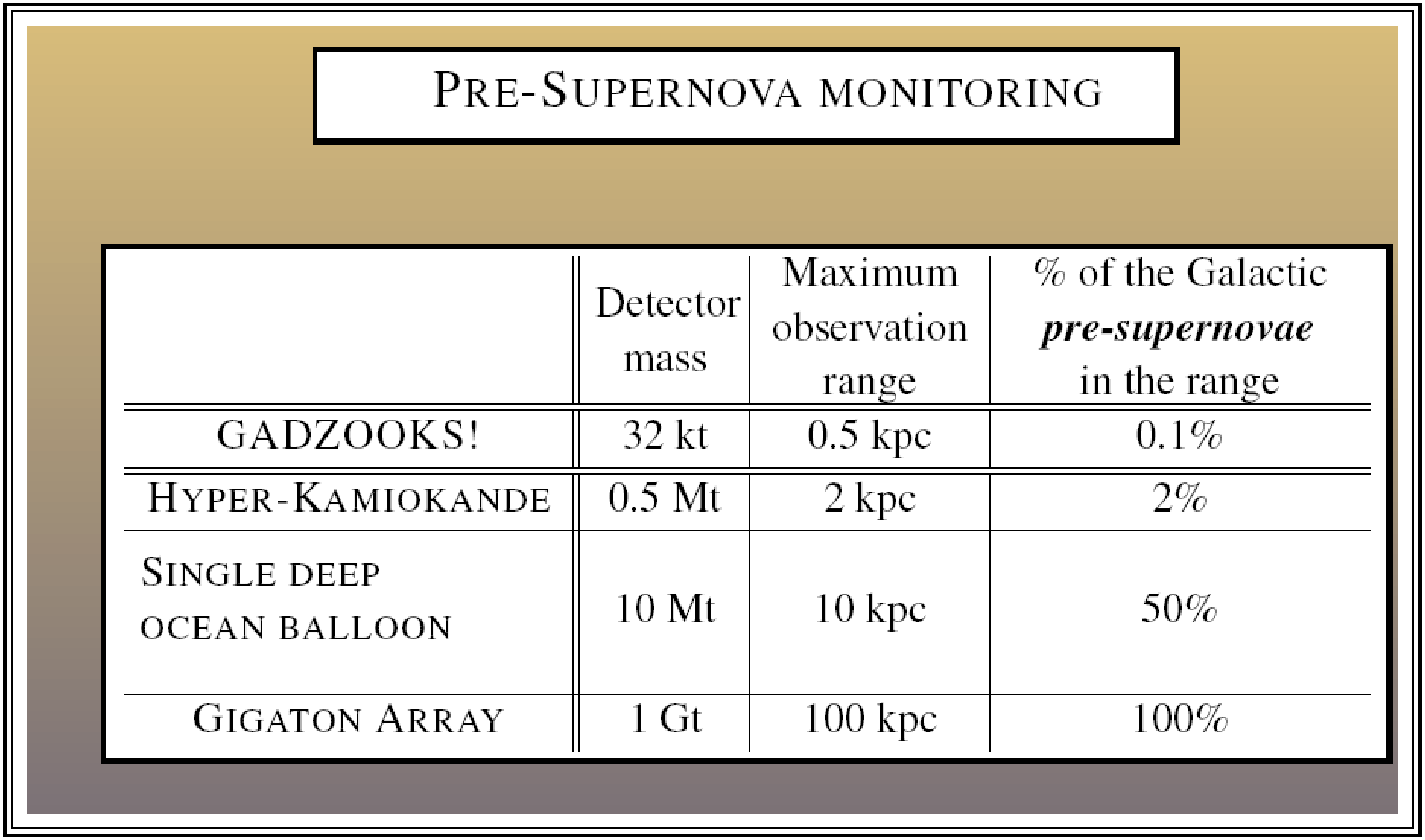


Nearby candidate:

Betelgeuse in ORION – distance 130 pc



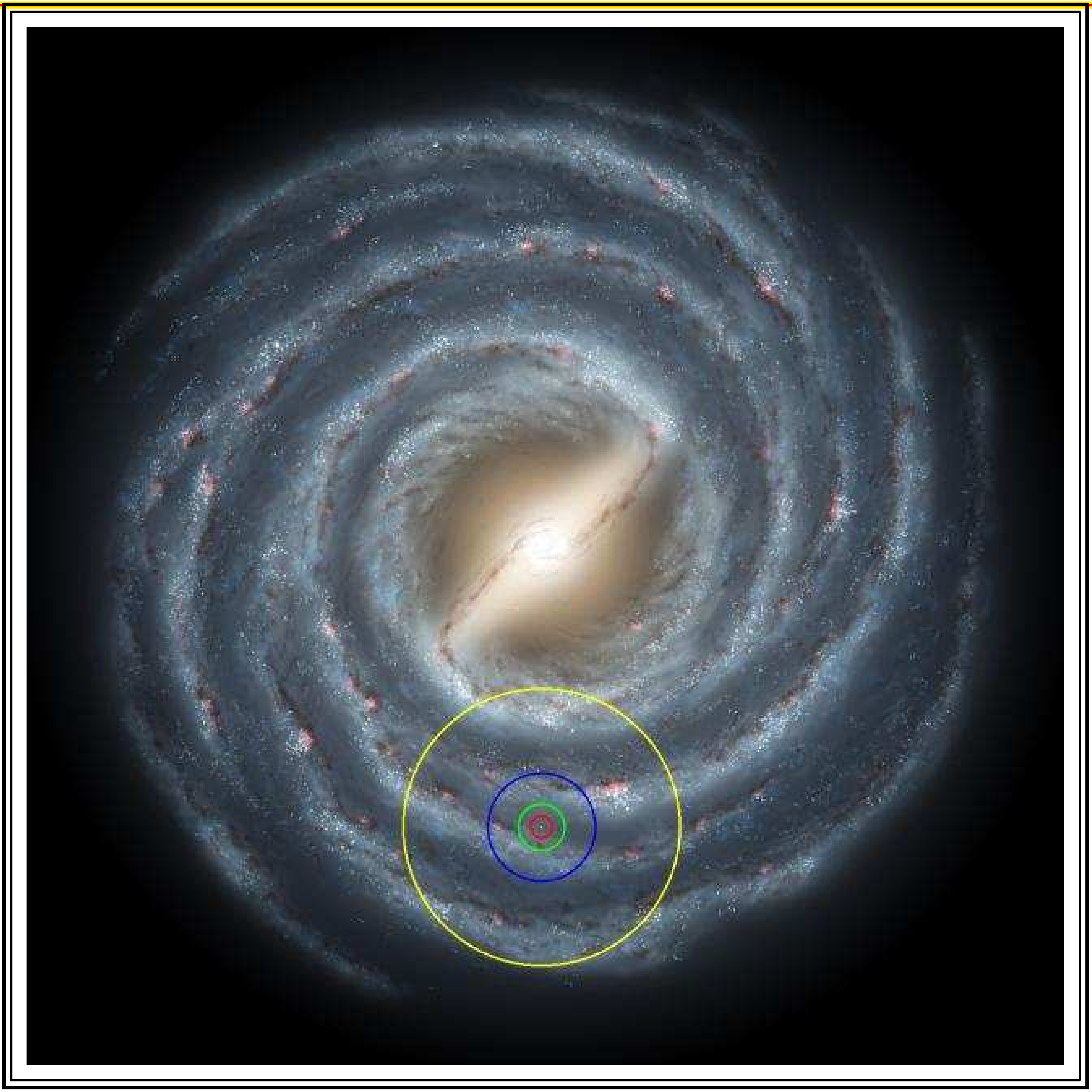
From Ordzywolek et al.



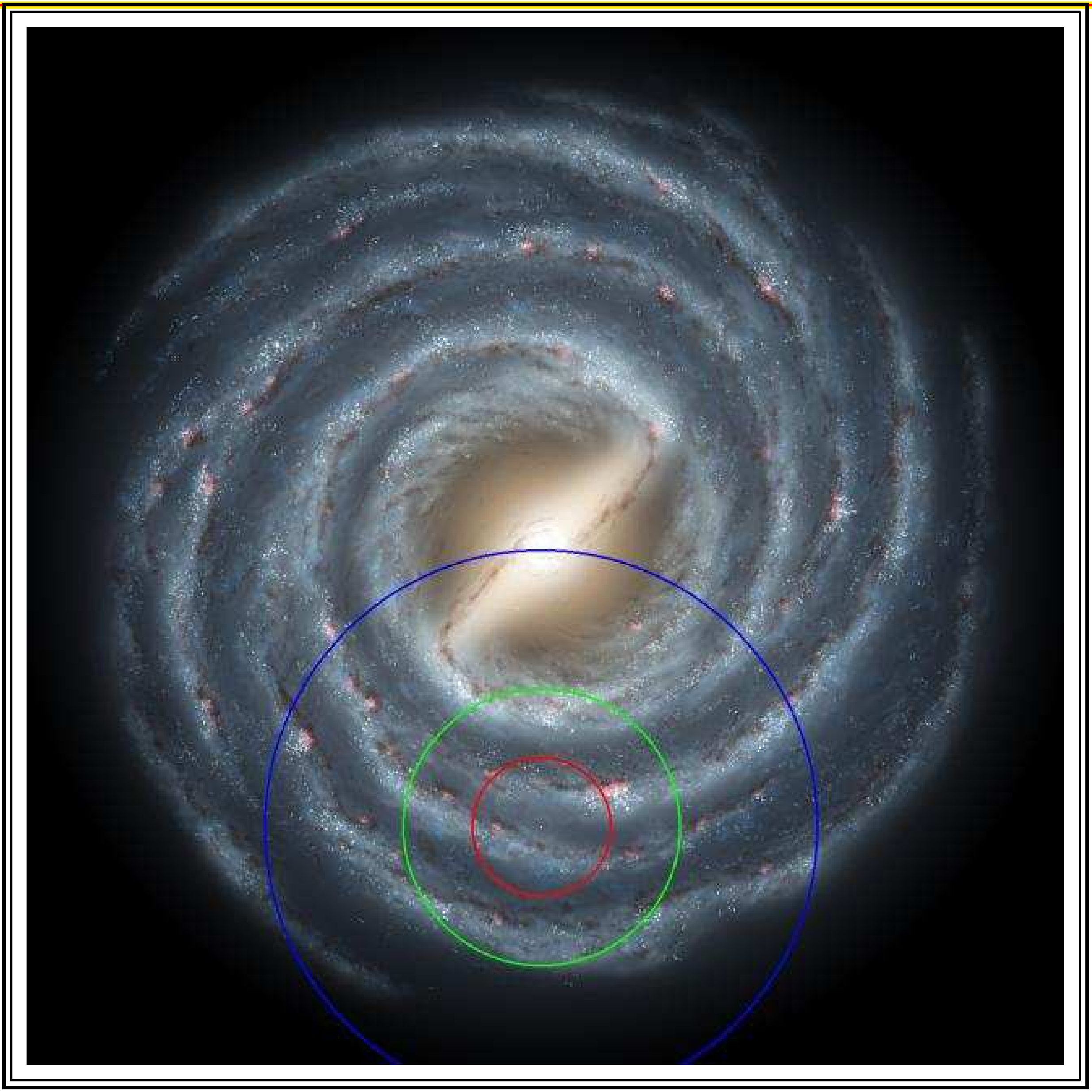
PRE-SUPERNOVA MONITORING

	Detector mass	Maximum observation range	% of the Galactic *pre-supernovae* in the range
GADZOOKS!	32 kt	0.5 kpc	0.1%
HYPER-KAMIOKANDE	0.5 Mt	2 kpc	2%
SINGLE DEEP OCEAN BALLOON	10 Mt	10 kpc	50%
GIGATON ARRAY	1 Gt	100 kpc	100%

Neutrinos: 1 day MW warning



3 hours MW warning



SN Shocks for SFR and cosmology

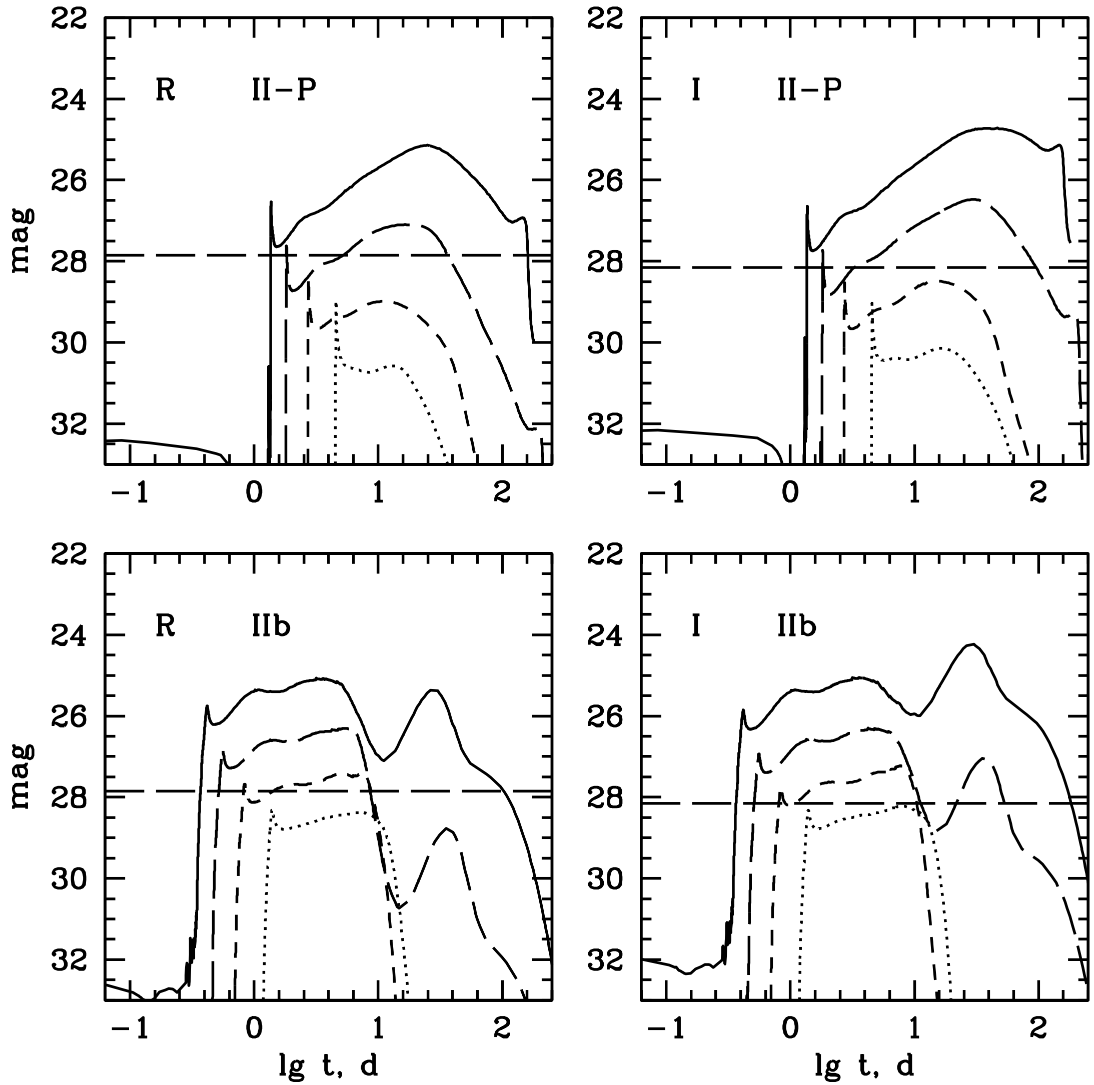
Two ways of SN shock breakout applications –

1) Discovering and counting for SFR

2) Using methods a la Baade for distance determination

SN II at $z = 0.5,\ 1,\ 2,\ 4$

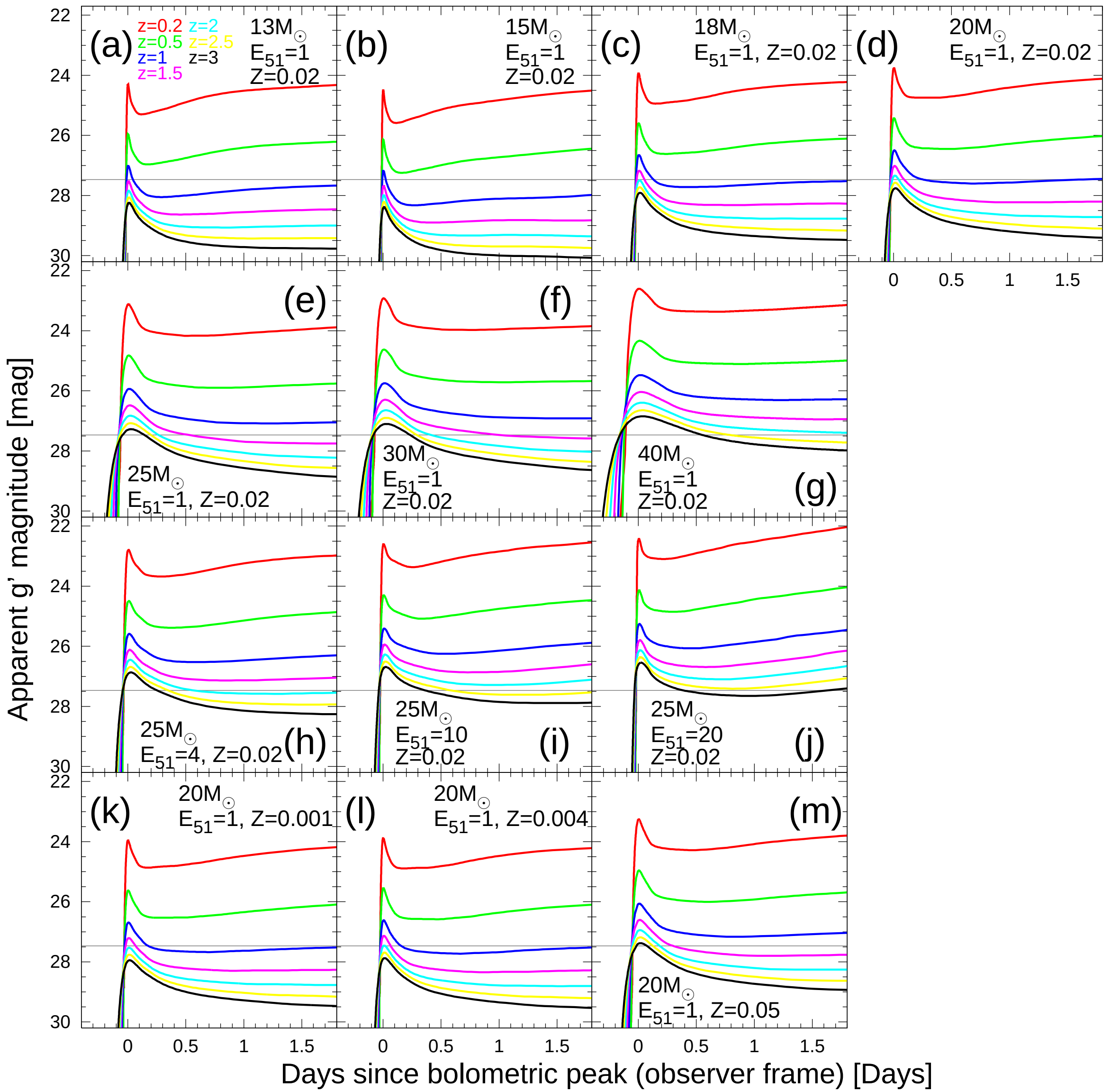
Our paper with N.Chugai, P.Lundqvist, 2000



Tominaga et al. 2011 ApJS 193:20

Next slide shows Apparent g'-band LCs of the models at $z = 0.2$ (*red*), $z = 0.5$ (*green*), $z = 1$ (*blue*), $z = 1.5$ (*magenta*), $z = 2$ (*cyan*), $z = 2.5$ (*yellow*), and $z = 3$ (*black*). No extinction and no IGM absorption are assumed. The horizontal line shows a 5σ detection limit in g' band for Subaru/Suprime-Cam 1 hour integration, assuming $0\overset{\prime\prime}{.}7$ seeing, $1\overset{\prime\prime}{.}5$ aperture, and 3 days from New Moon

Tominaga et al. 2011, fig.7

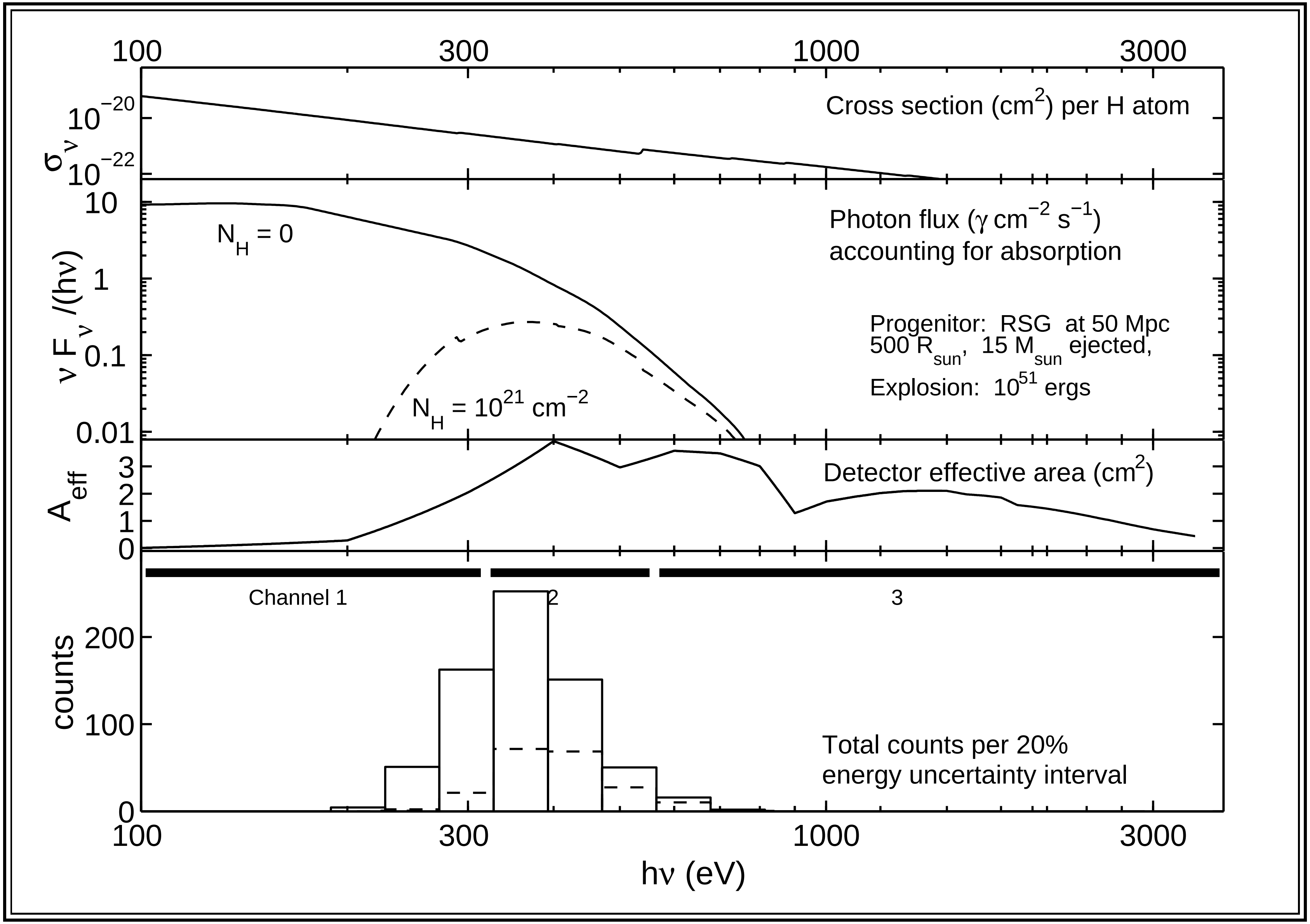


CM04 LOBSTER predictions

There is a possibility of obtaining new data if the LOBSTER space observatory (or any X-ray station of a similar type) could be launched (ROSITA?) (Calzavara, Matzner 2004). E.g., the experiment MAXI (Monitor of All-sky X-ray Image) on board the module Kibo at ISS (Matsuoka 1997) is already started FOV = 160°(L) $\times 1.5^\circ$ (FWHM), 2% of all-sky (instant); scans 90 to 98% of all-sky every 96 min (one orbit/rotation period of the ISS), and the satellite EXIST (Energetic X-ray Imaging Survey Telescope) (Grindlay 2003, Band 2008), is under consideration.

Next slide is for a red supergiant model. The breakout flash was calculated by Blinnikov et al. (1998) for SN 1993J.

CM04 LOBSTER predictions a



LOBSTER instrument response

SN detection distance and rate versus model type. The factor $f_{\rm obs}$ represents the unknown population of each sub-class. In each model, $M_{\rm ej} = 15 M_\odot$, $E_0 = 10^{51}$ erg, and $\kappa = 0.34$ cm^2 g^{-1}.

Progenitor Type	N_H (10^{21} cm^{-2})	R_0 ($R_\odot$)	$D_{\rm max}$ (Mpc)	Detections per year
BSG	5	50	86	$\sim 12 f_{\rm obs}$
RSG	5	500	66	$\sim 6 f_{\rm obs}$
WR core	1	5	58	$\sim 1 f_{\rm obs}$

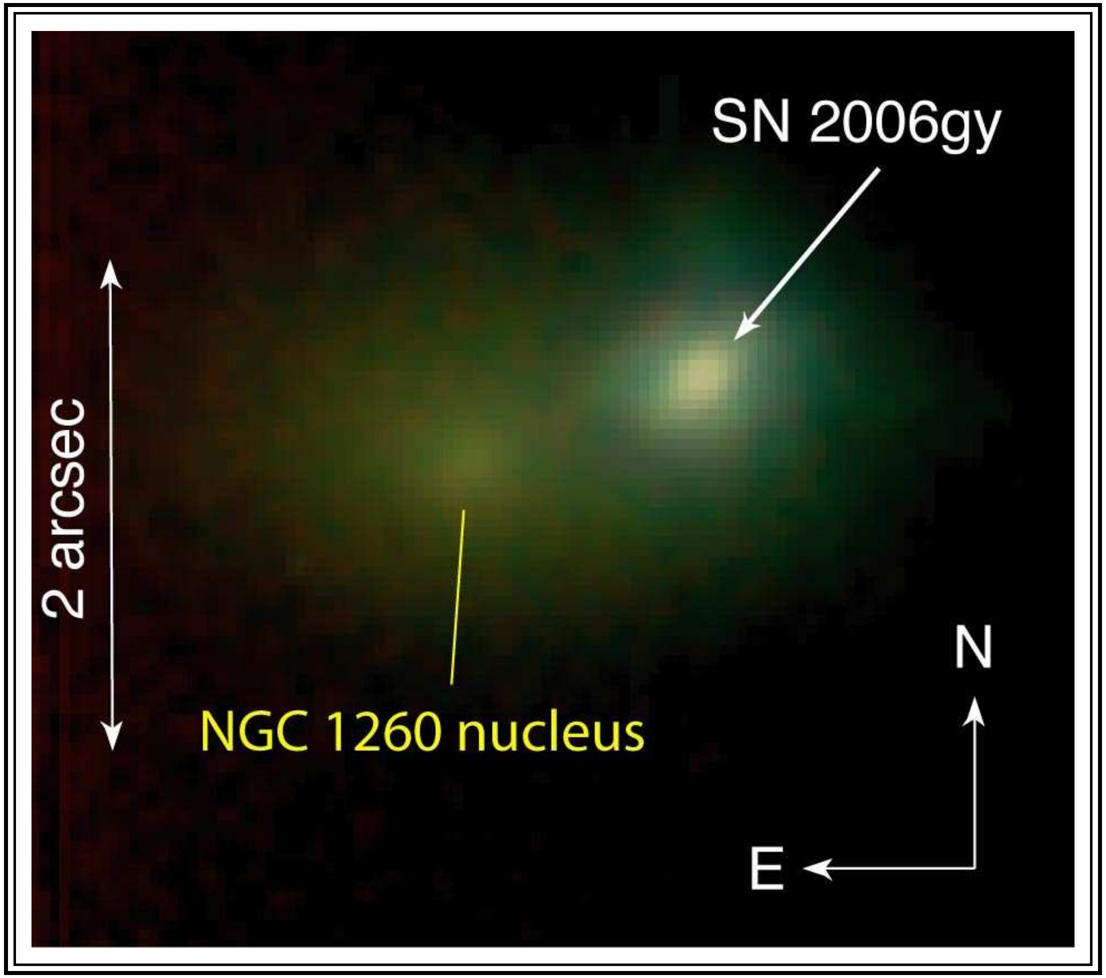
Circumstellar matter

The main puzzle for XRF080109-SN2008D is its long duration (for a compact preSN Ib/c.
Explained by a rather dense wind, a circumstellar cloud.
This may be a general feature for some of the **Most Luminous Supernovae** on much larger scale.

SN 2006gy

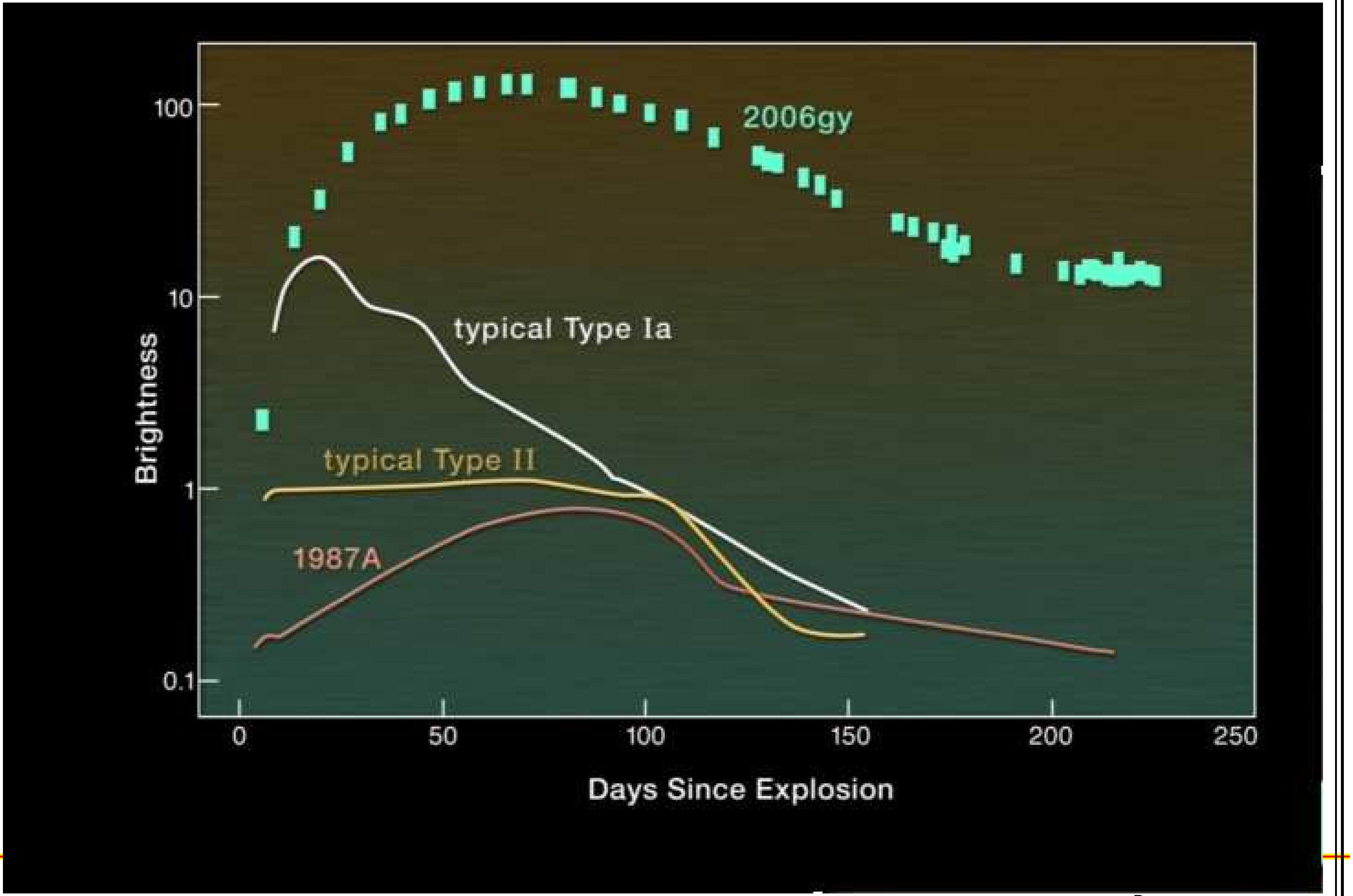
Ofek et al. 2007, ApJL, astro-ph/0612408)

Smith et al. 2007, Sep. 10 ApJ, astro-ph/0612617)

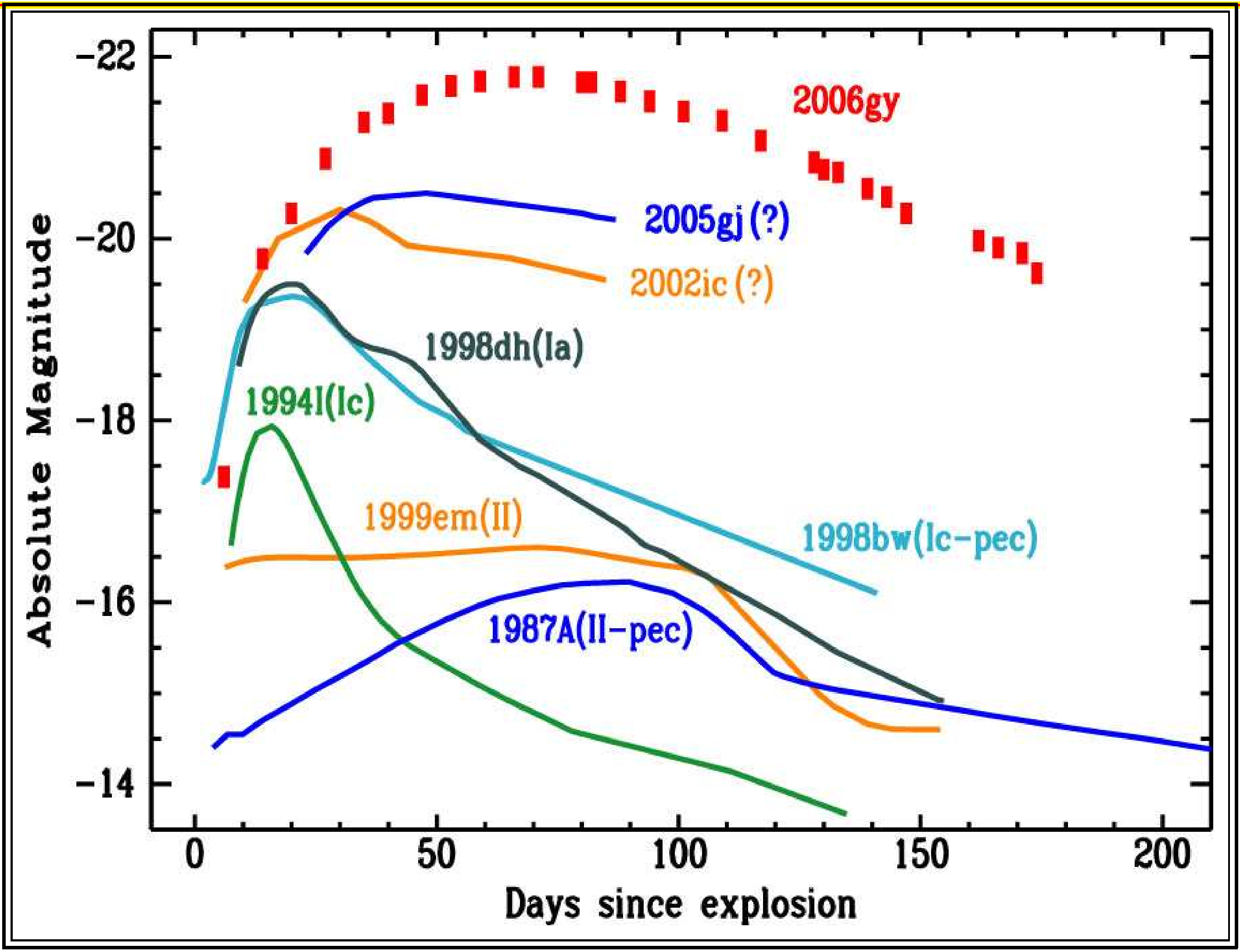


Brightest. Supernova. Ever

by N.Smith



It was Most Luminous SN ever



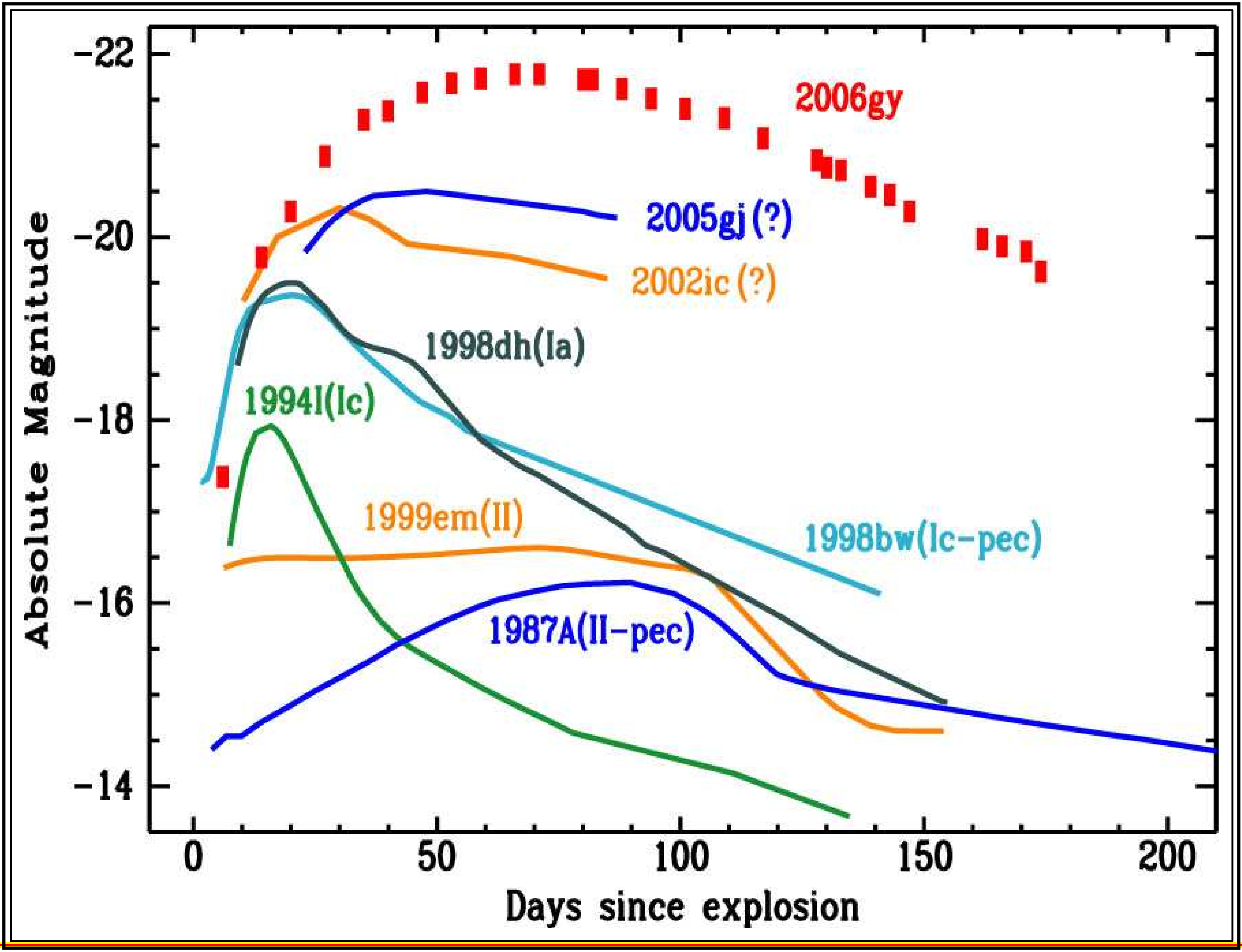
Luminous SN: too many photons?

Now we know a few other SNe with peak luminosity even higher than SN 2006gy.

Total light 10^{51} ergs: 2 orders of mag higher than normal core collapsing SN and 1 order more than brightest thermonuclear SN

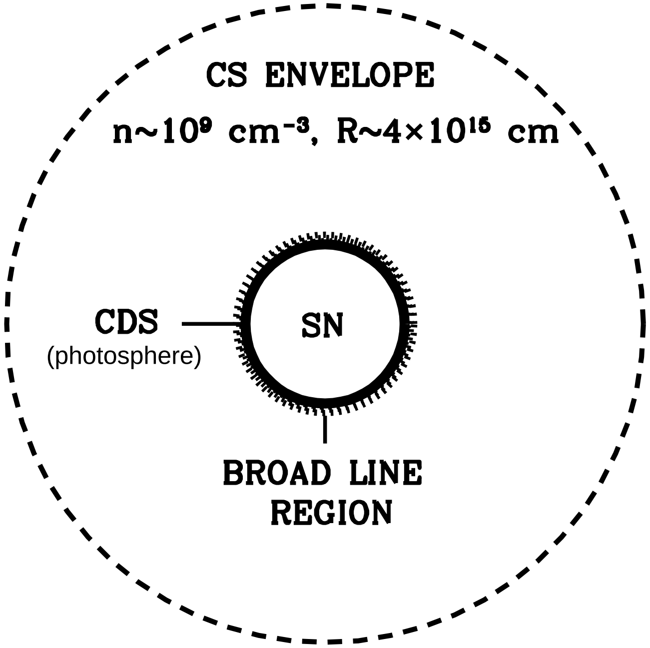
To explain this light we inevitably involve long-living radiative shocks.

Models for powerful light



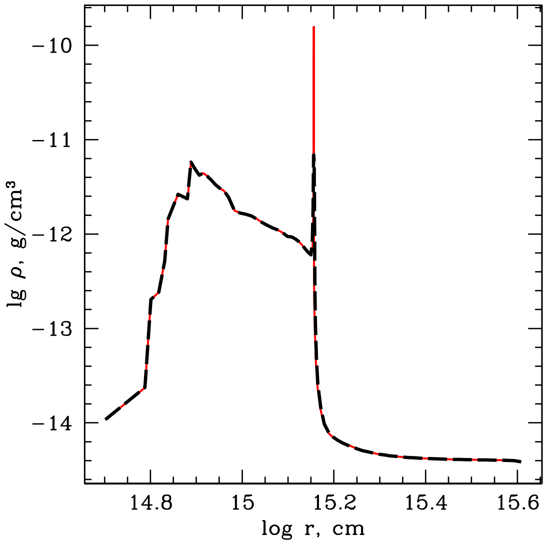
Models for powerful light

Radiative shock, Chugai, Blinnikov ea’04, Woosley ea’07 ...



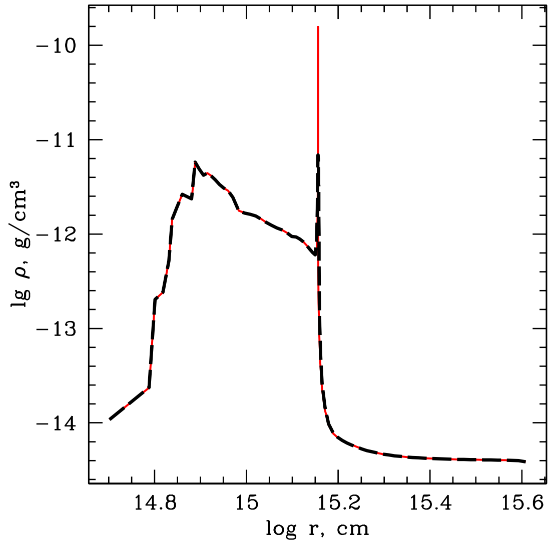
Models for powerful light

Dense shell Chugai, Blinnikov ea'04

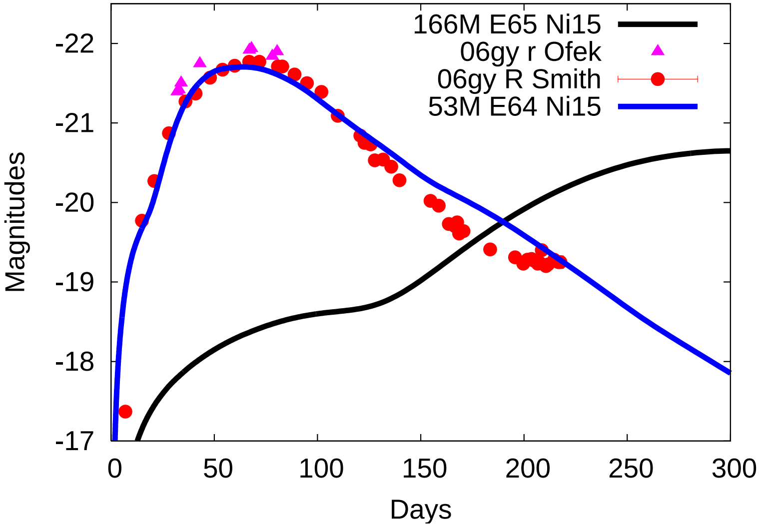


Models for powerful light

Dense shell Chugai, Blinnikov ea’04

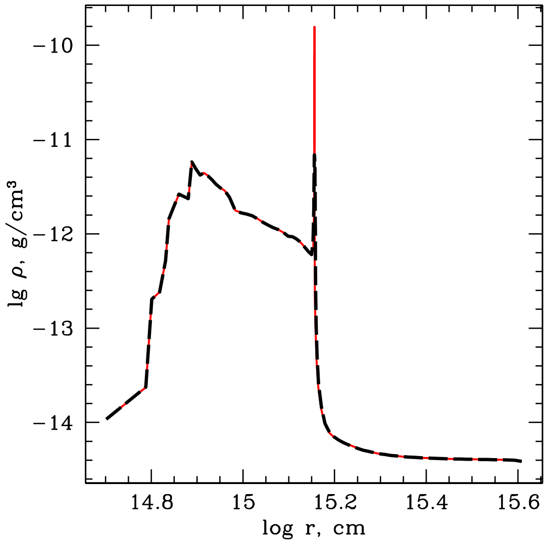


Radioactive, Nomoto, Tominaga ea’07

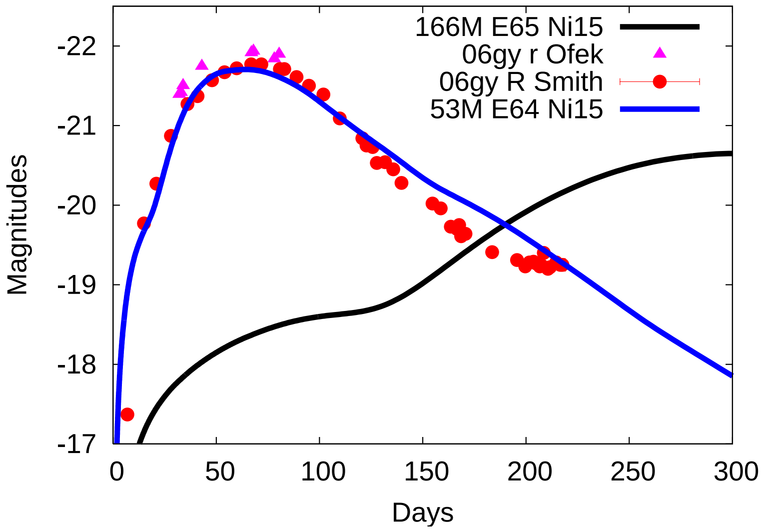


Models for powerful light

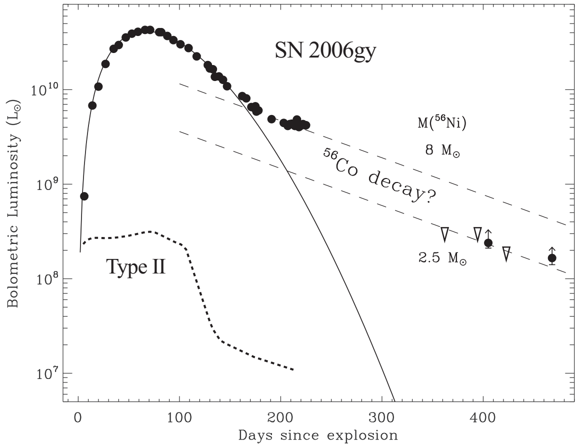
Dense shell Chugai, Blinnikov ea’04



Radioactive, Nomoto, Tominaga ea’07

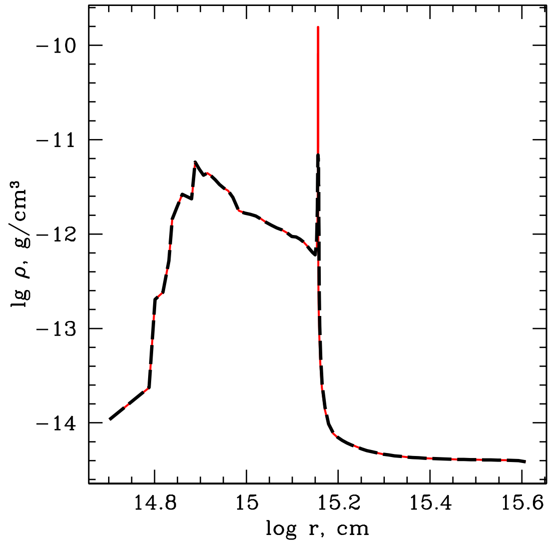


Diffusion, McCray, Smith’07

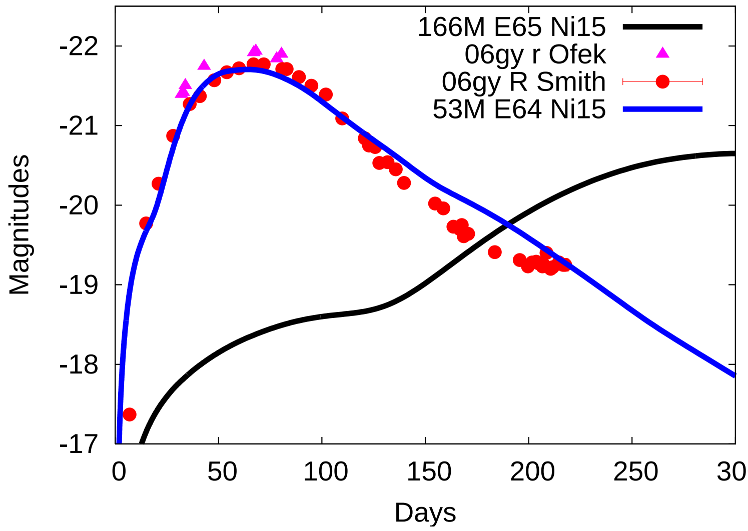


Models for powerful light

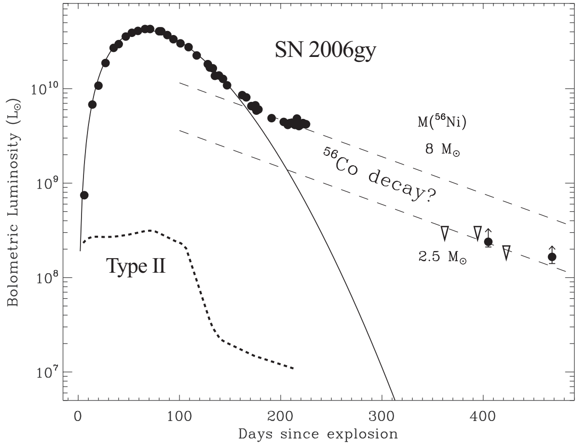
Dense shell Chugai, Blinnikov ea’04



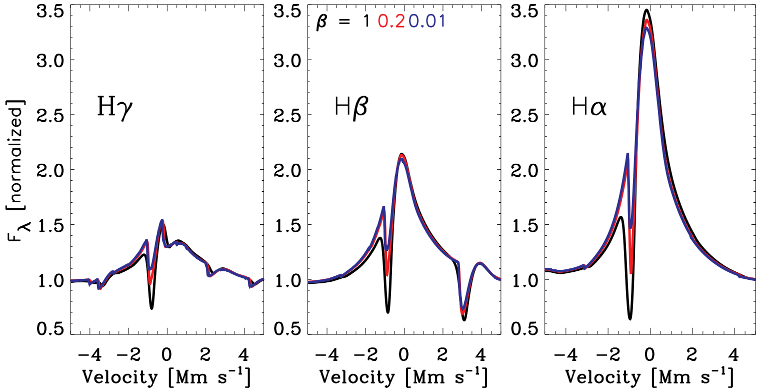
Radioactive, Nomoto, Tominaga ea’07



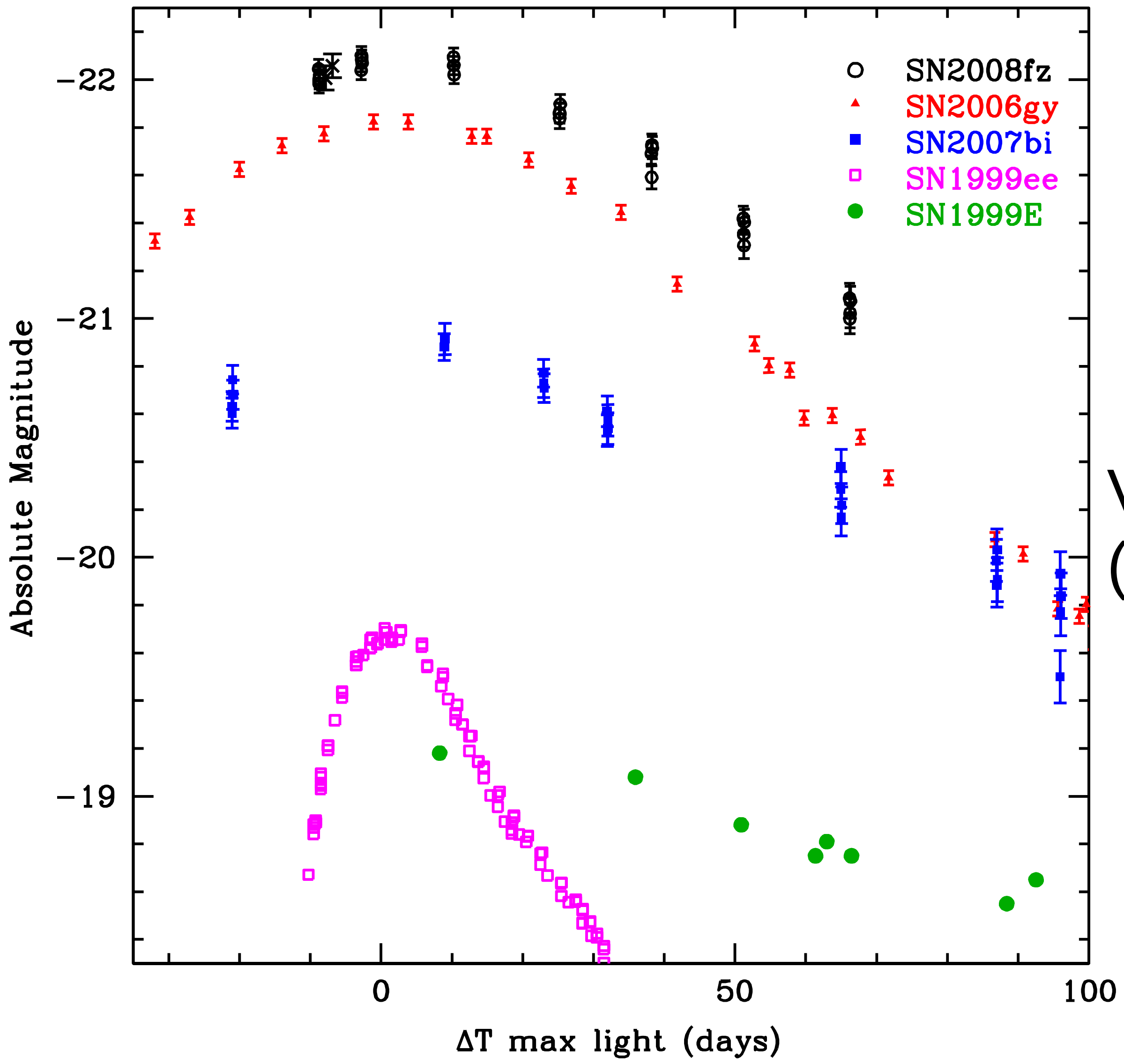
Diffusion, McCray, Smith’07



Atmospheric, Dessart ea’08

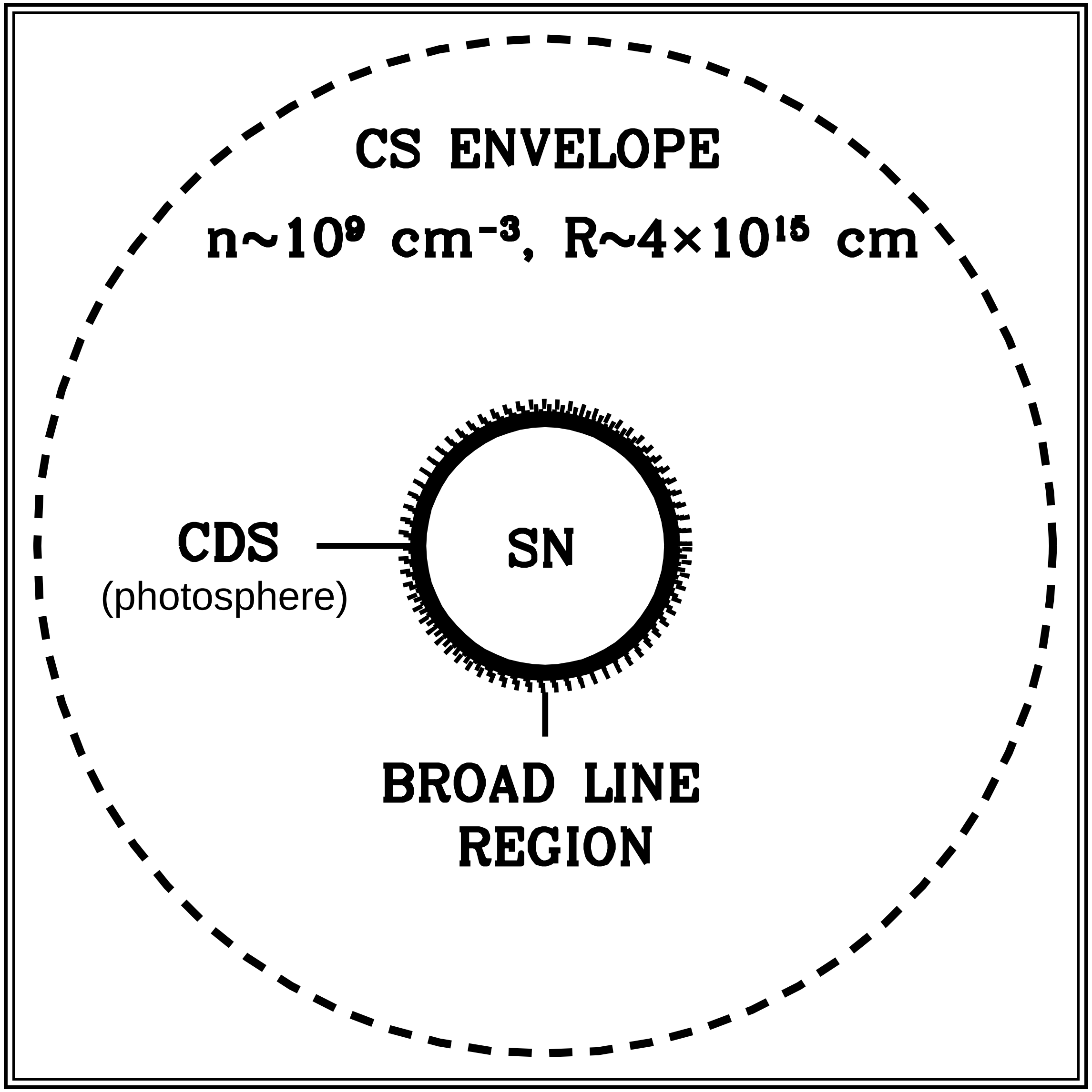


Extremely bright Type IIn SNe

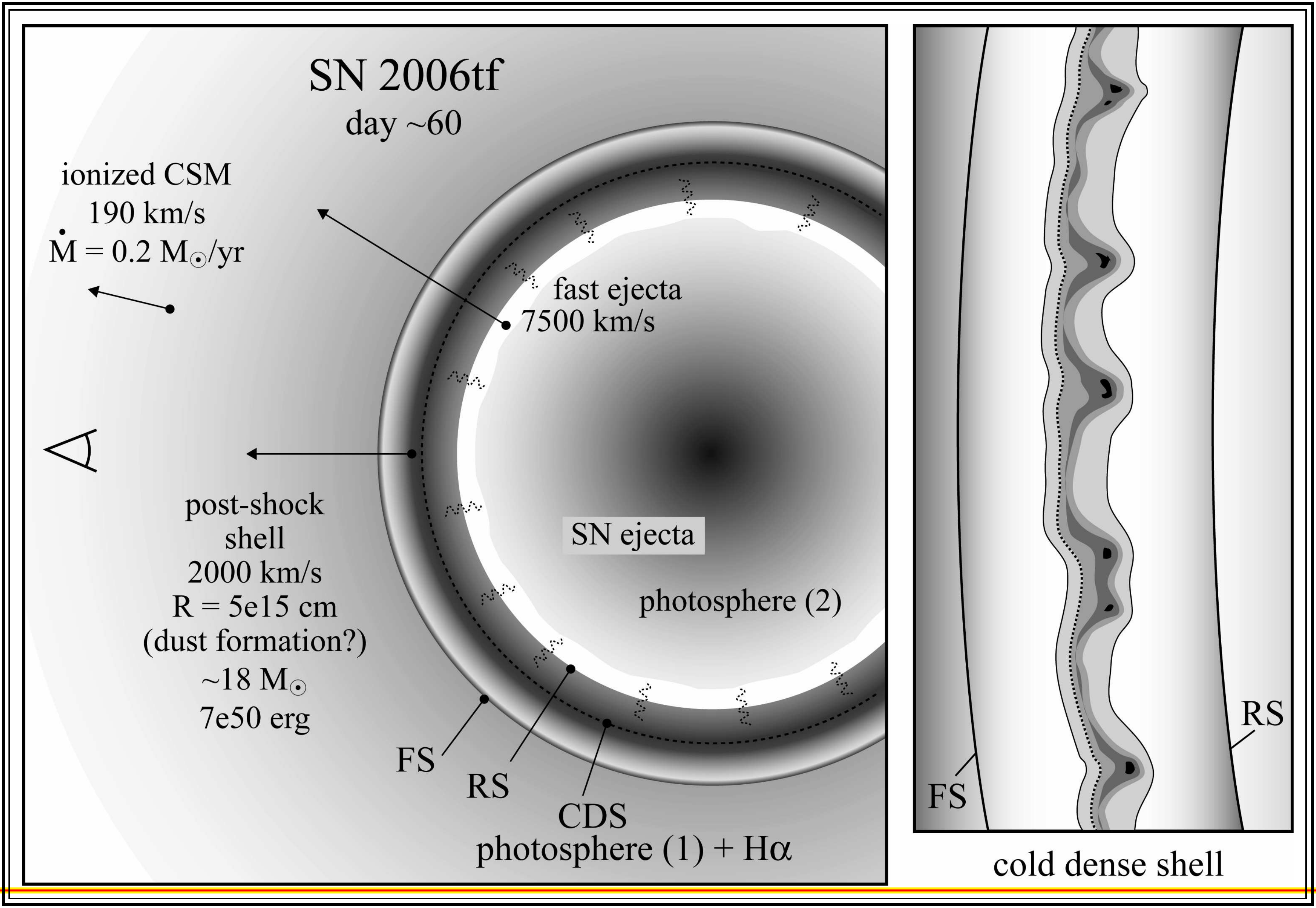


V-band
(Drake et al. 2010)

SN IIn structure, Chugai, SB ea’04

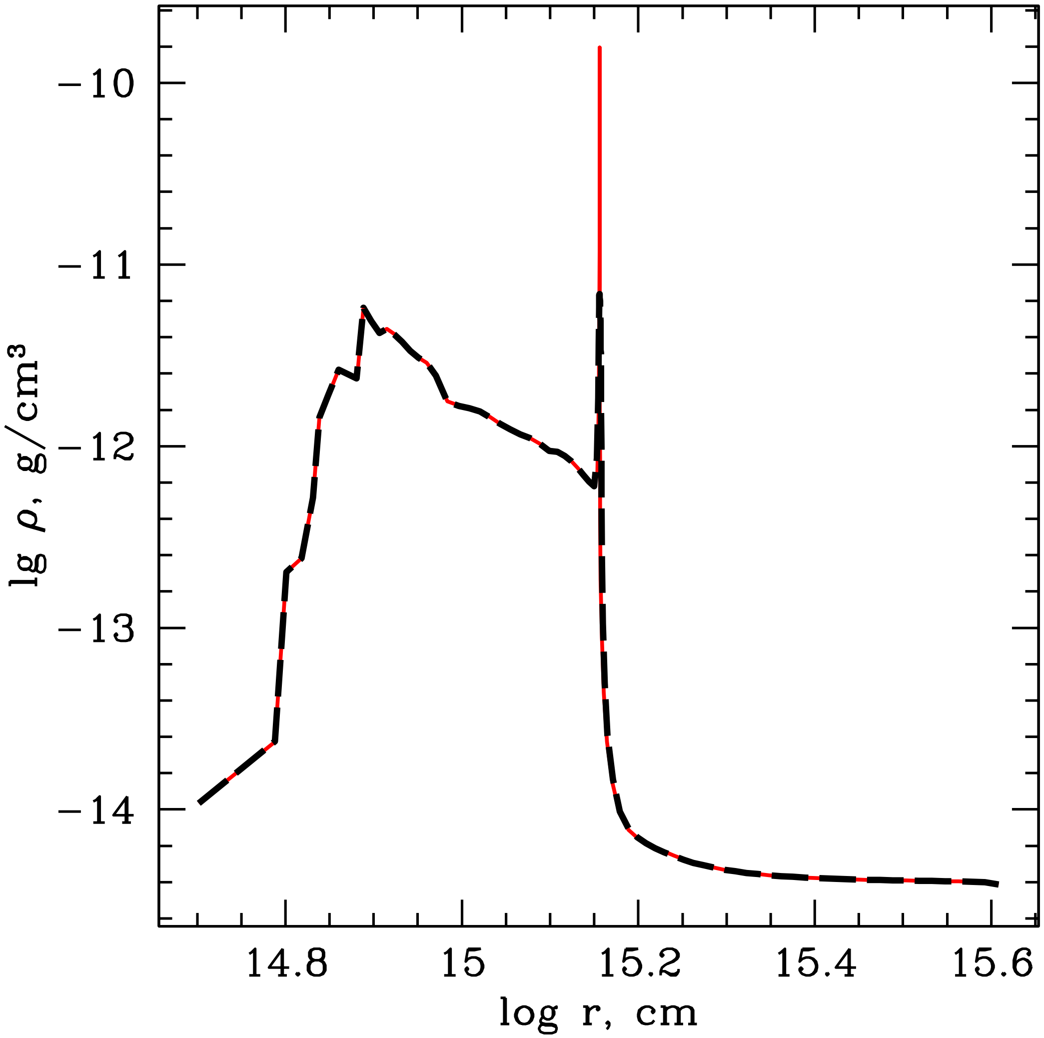


Smith,Chornock ea cartoon, 06tf



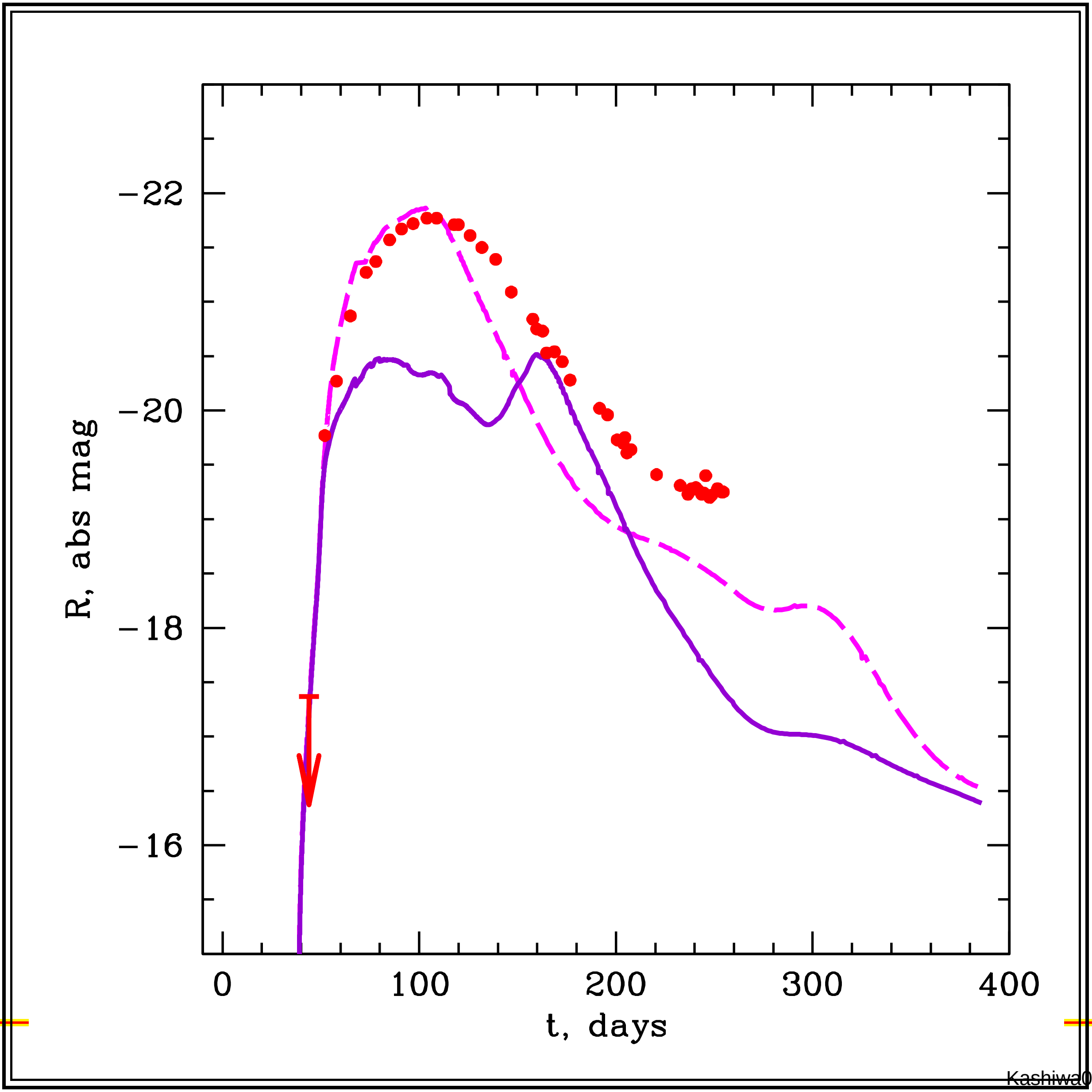
Shocks in SNe IIn

A long living shock: an example for SN1994w of type IIn. Density as a function of the radius r in two models at day 30. The structure tends to an isothermal shock wave.



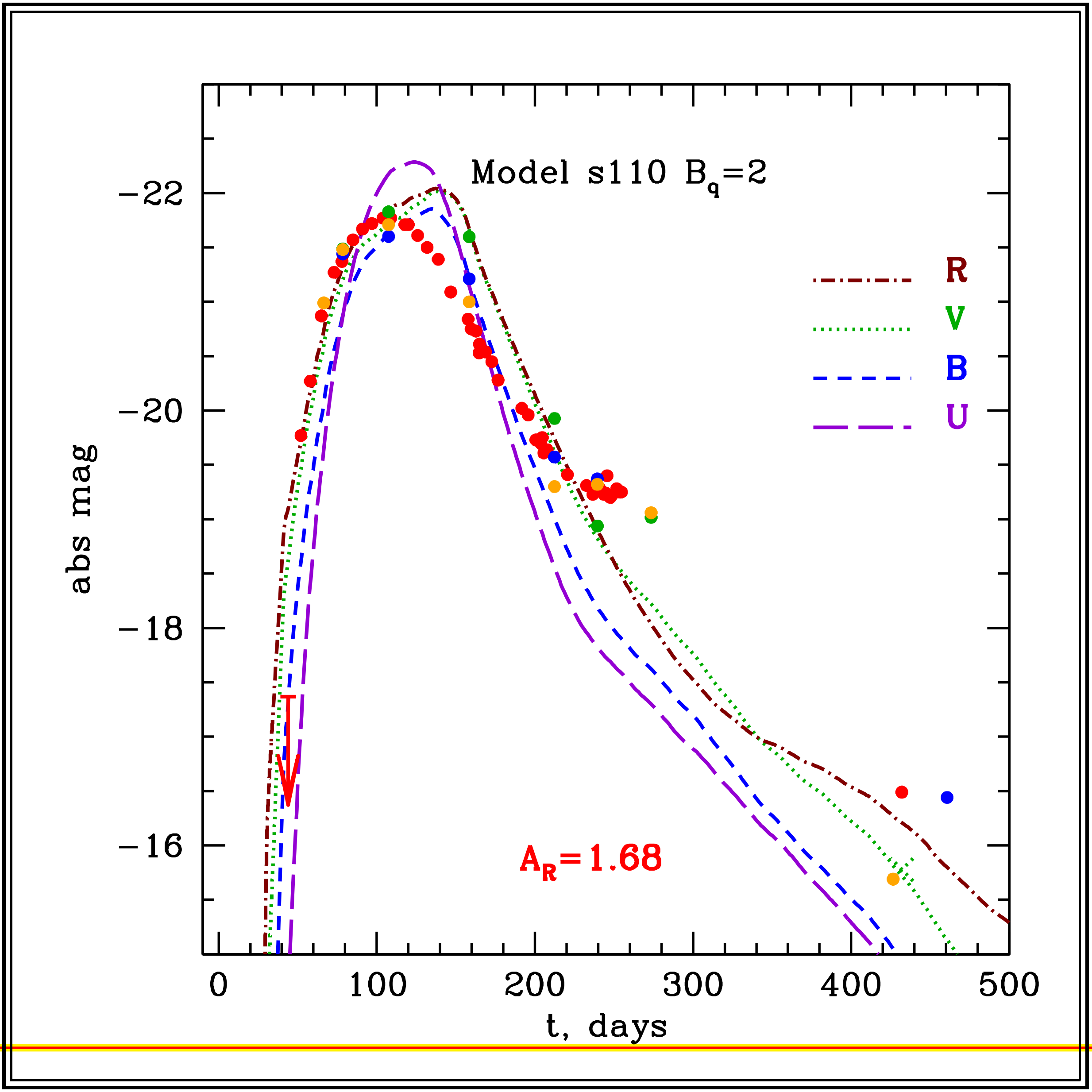
Light curve for SN2006gy

from Woosley, SB, Heger (2007)



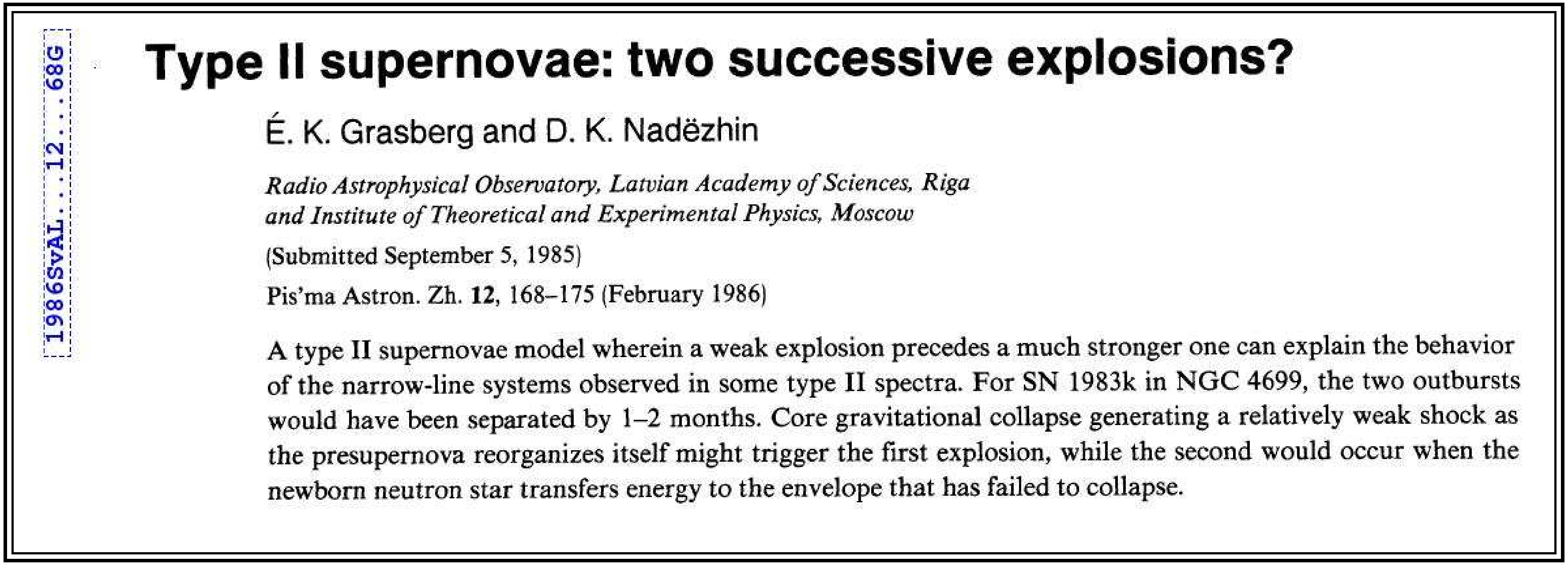
Stella: LCs for SN2006gy

new runs



Double explosion: old idea

Grasberg & Nadyozhin (1986)



1986SvAL...12...68G

Type II supernovae: two successive explosions?

É. K. Grasberg and D. K. Nadëzhin

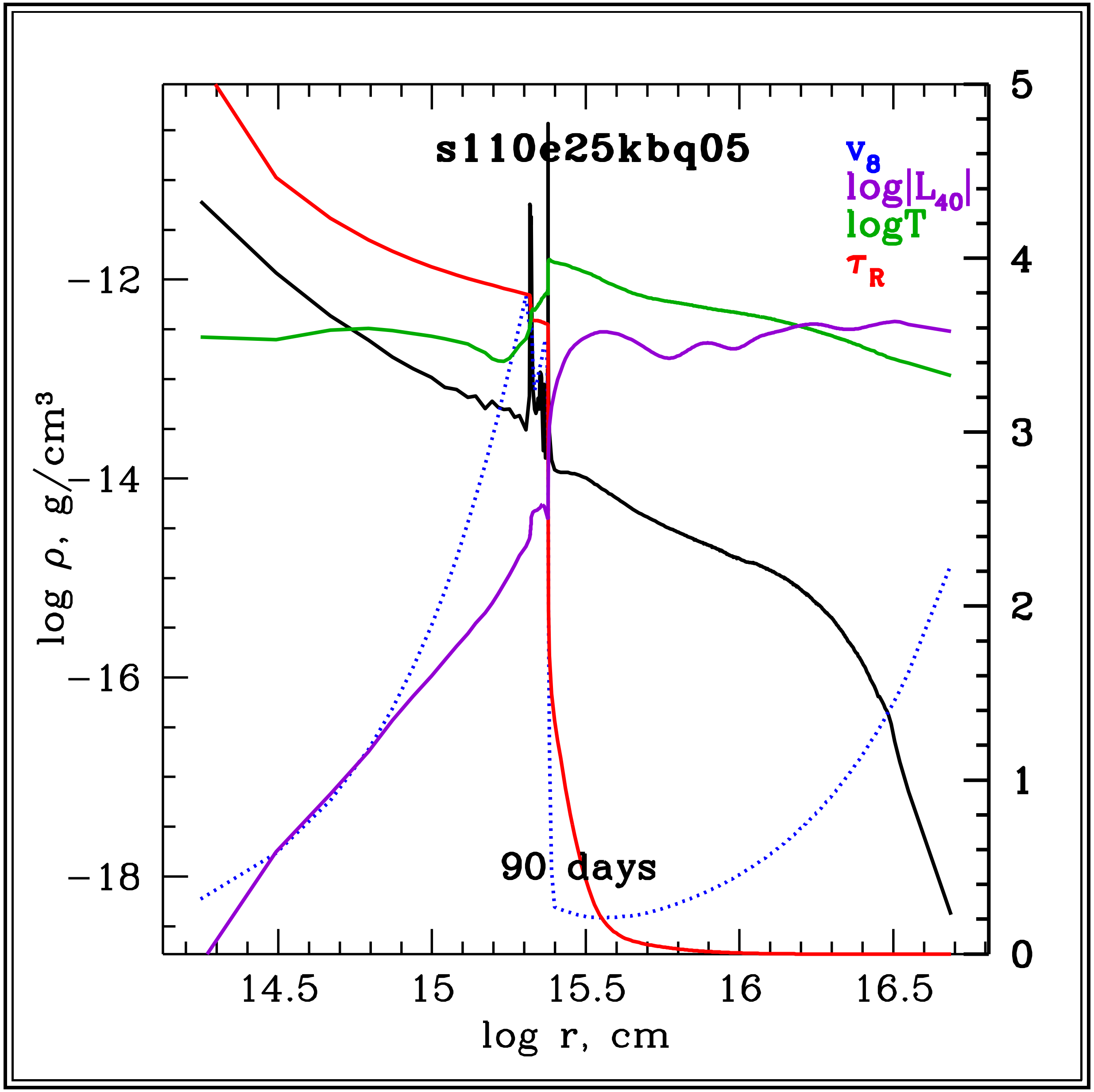
Radio Astrophysical Observatory, Latvian Academy of Sciences, Riga
and Institute of Theoretical and Experimental Physics, Moscow

(Submitted September 5, 1985)

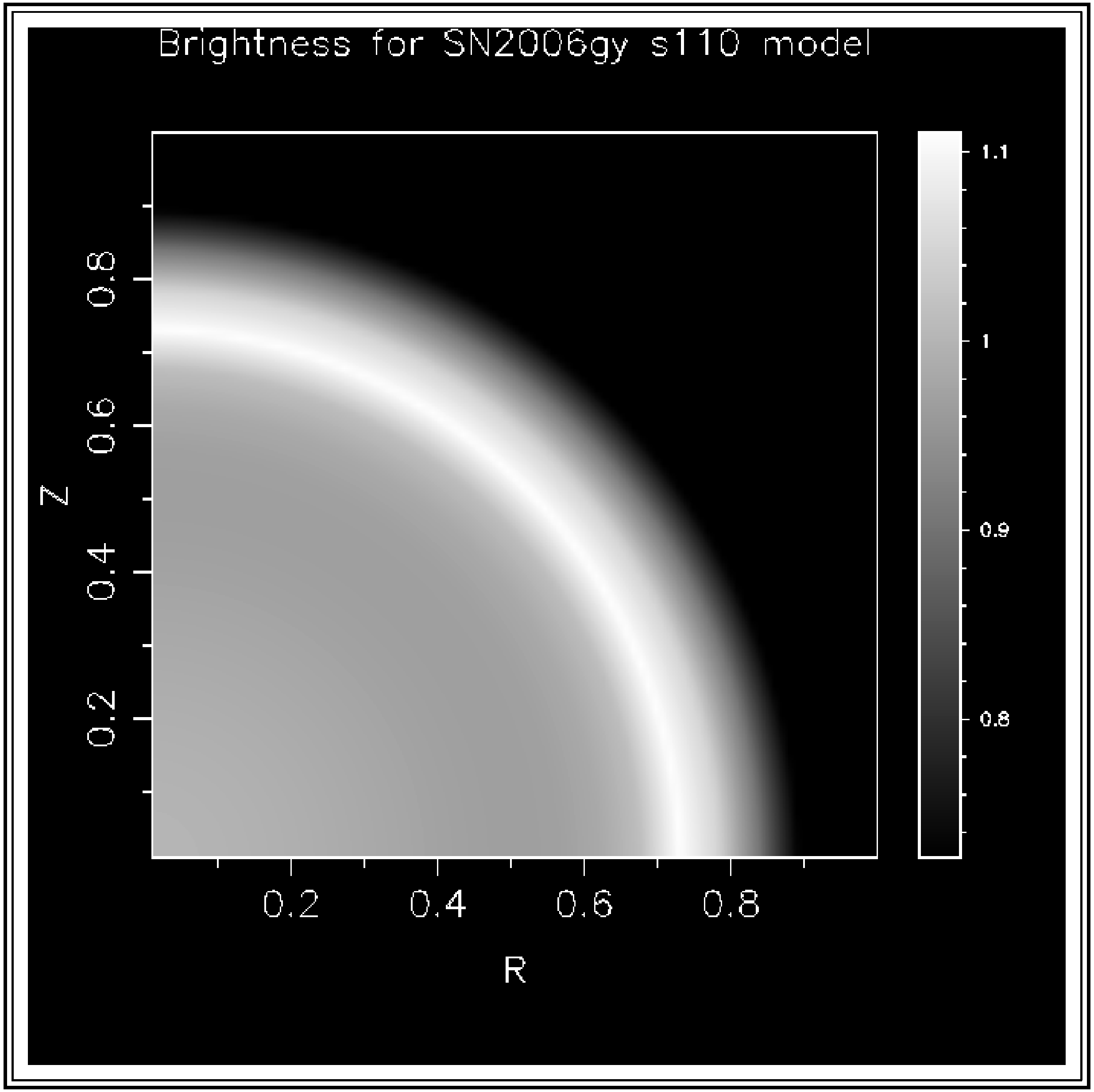
Pis'ma Astron. Zh. **12**, 168–175 (February 1986)

A type II supernovae model wherein a weak explosion precedes a much stronger one can explain the behavior of the narrow-line systems observed in some type II spectra. For SN 1983k in NGC 4699, the two outbursts would have been separated by 1–2 months. Core gravitational collapse generating a relatively weak shock as the presupernova reorganizes itself might trigger the first explosion, while the second would occur when the newborn neutron star transfers energy to the envelope that has failed to collapse.

Hydro structure 90 d



‘Visible’ disk of SN 2006gy

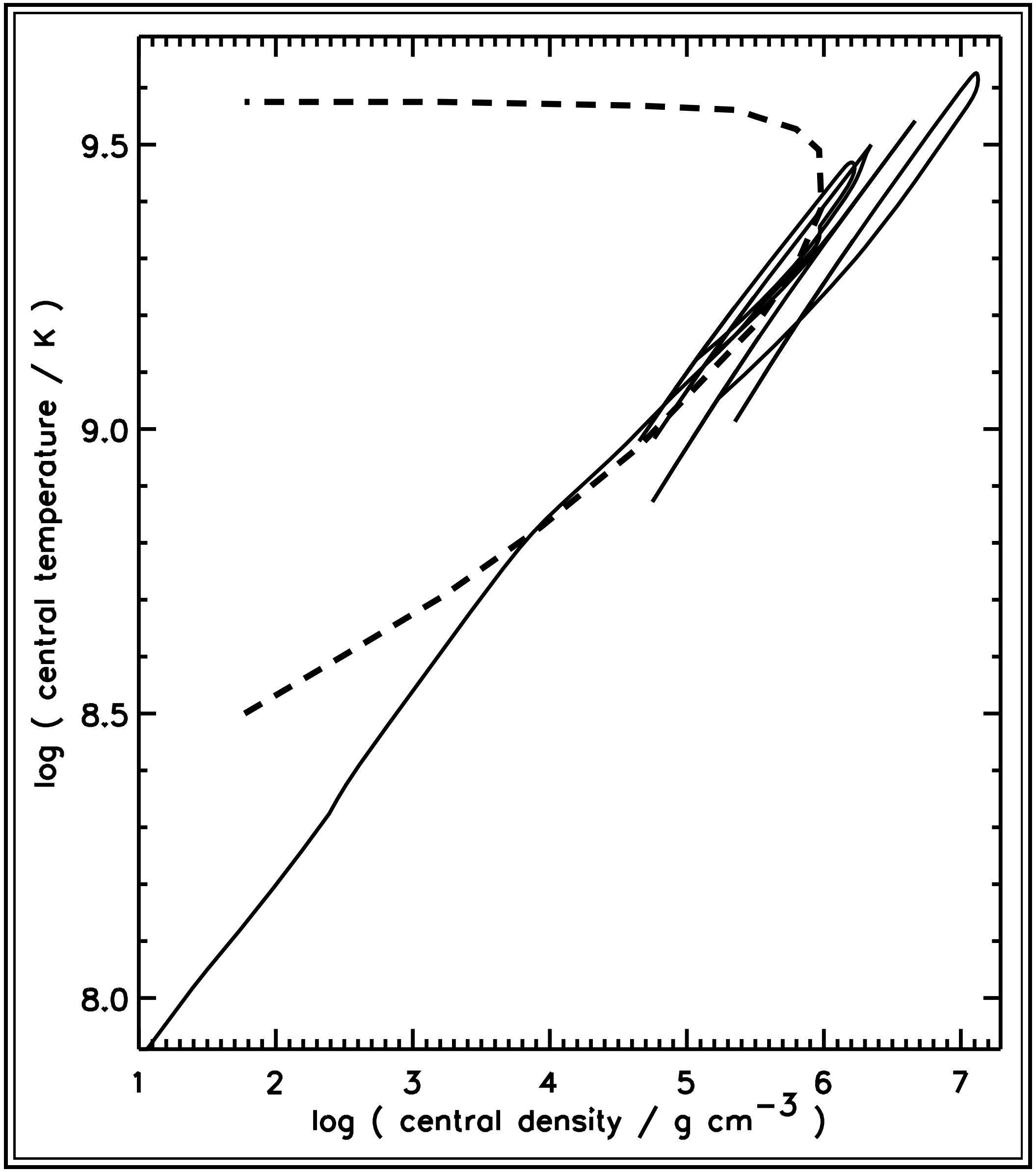


Four kinds of deaths

With some uncertainty about exact demarcations, one can delineate four kinds of deaths for non-rotating helium stars. (For rotation decrease main sequence mass 10 - 20%)

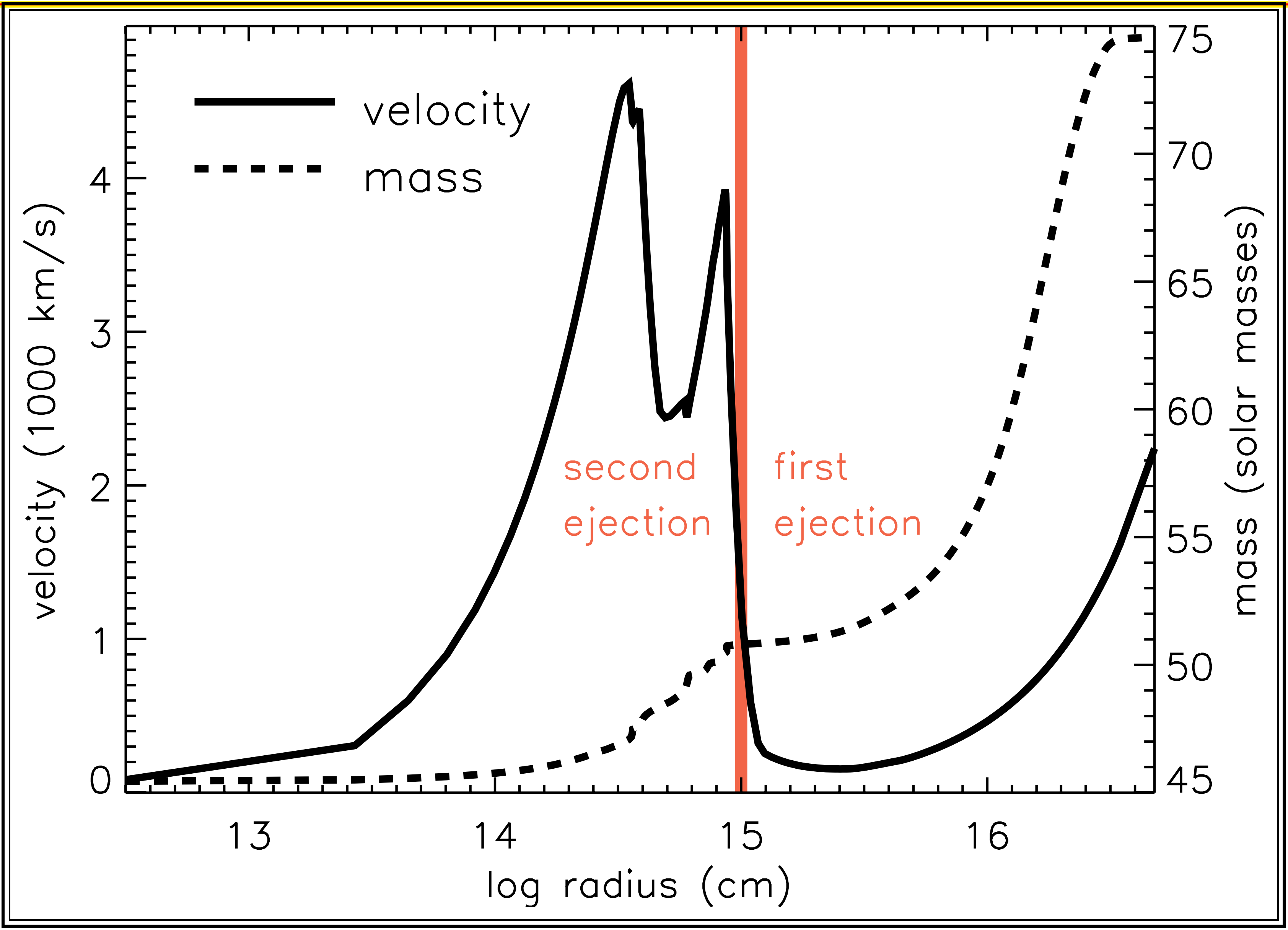
He Core	Main Seq. Mass	Supernova Mechanism
$2 \leq M \leq 40$	$10 \leq M \leq 95$	Fe core collapse to neutron star or a black hole
$40 \leq M \leq 60$	$95 \leq M \leq 130$	Pulsational pair instability followed by Fe core collapse
$60 \leq M \leq 137$	$130 \leq M \leq 260$	Pair instability supernova
$M \geq 137$	$M \geq 260$	Black hole. Possible GRB

Woosley, Blinnikov, Heger, s103



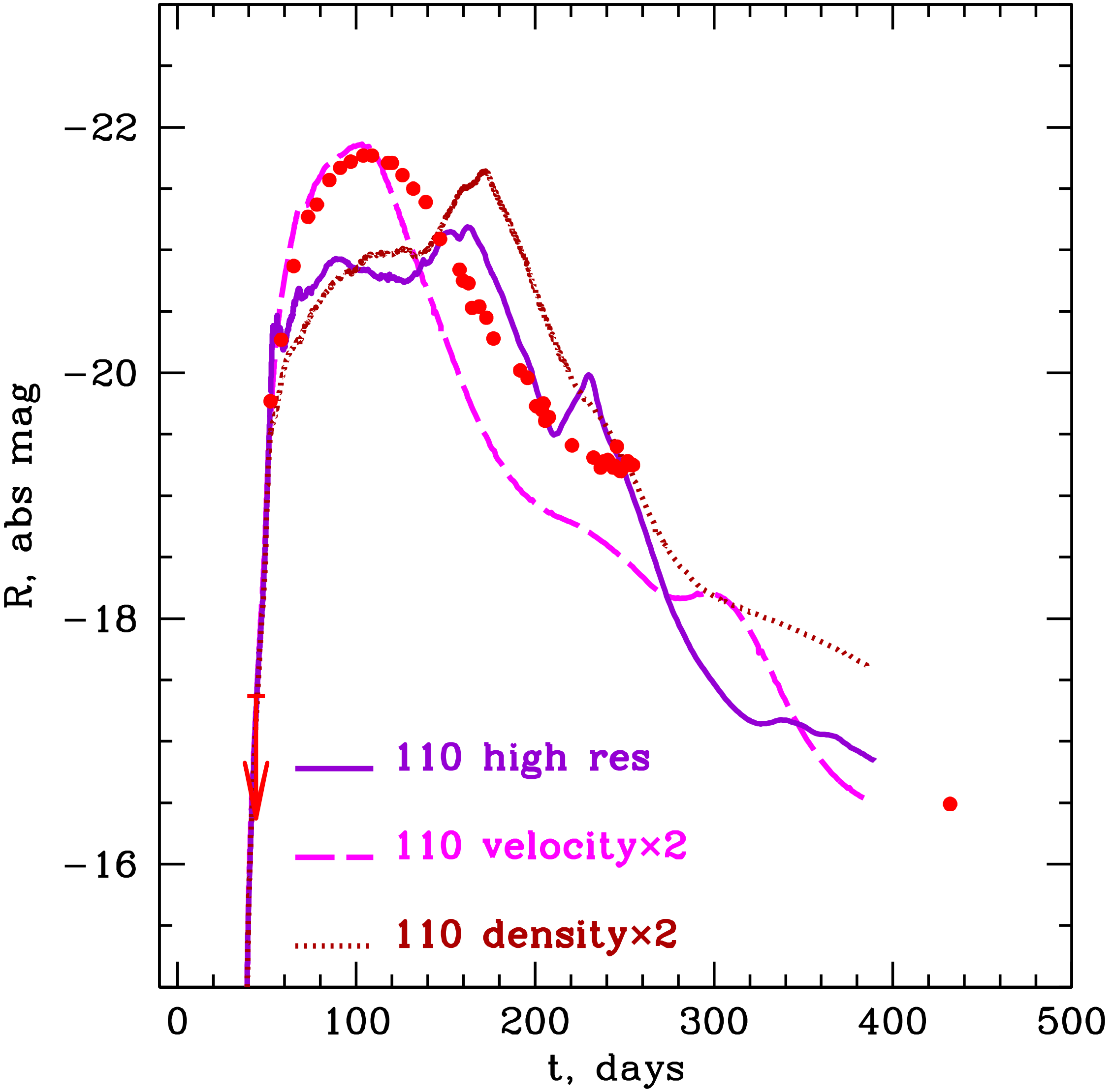
This gives the Most Luminous Supernovae!

Two mass ejections

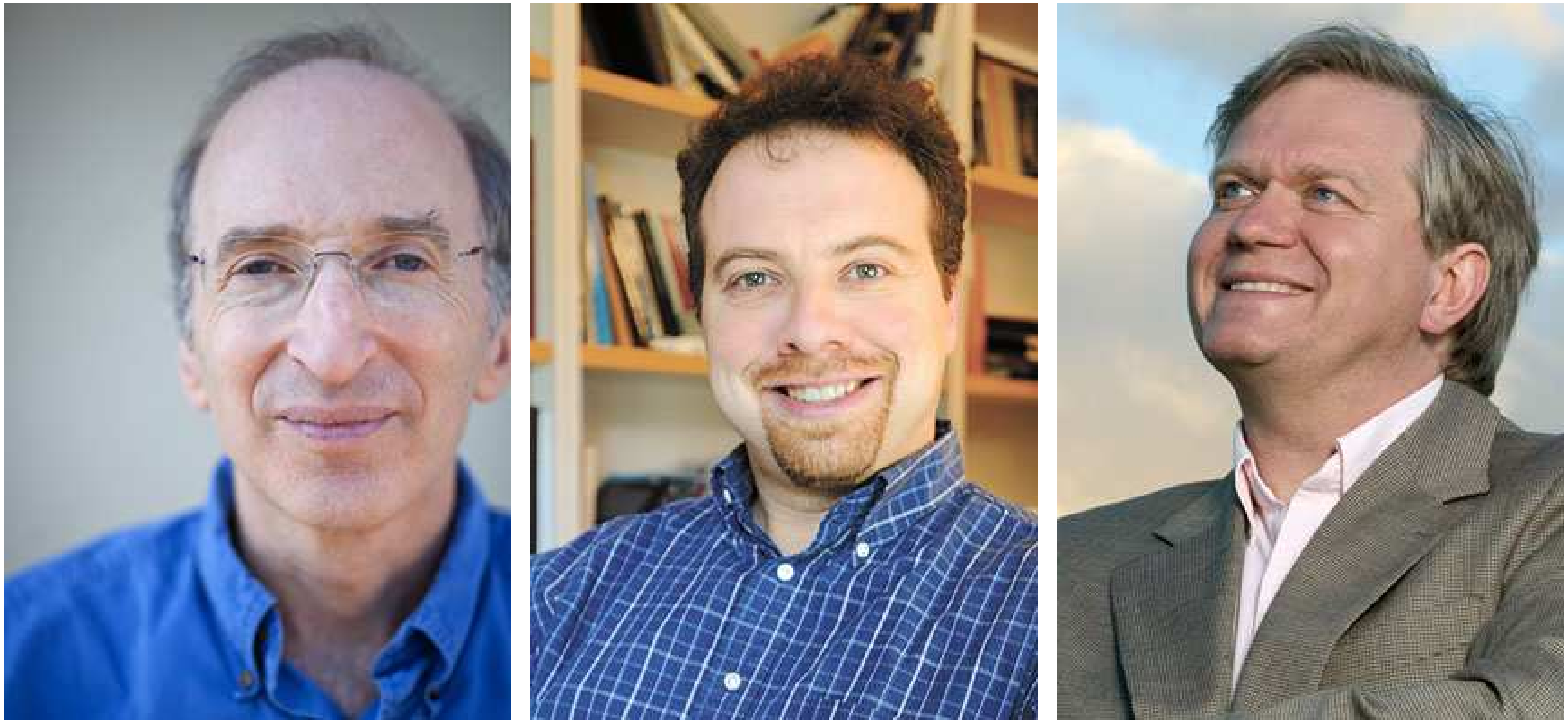


Higher res., tail observed

K. Kawabata,
et al. ApJ
697(2009)747;
Courtesy
M.Tanaka



S.Perlmutter A.Riess B.Schmidt

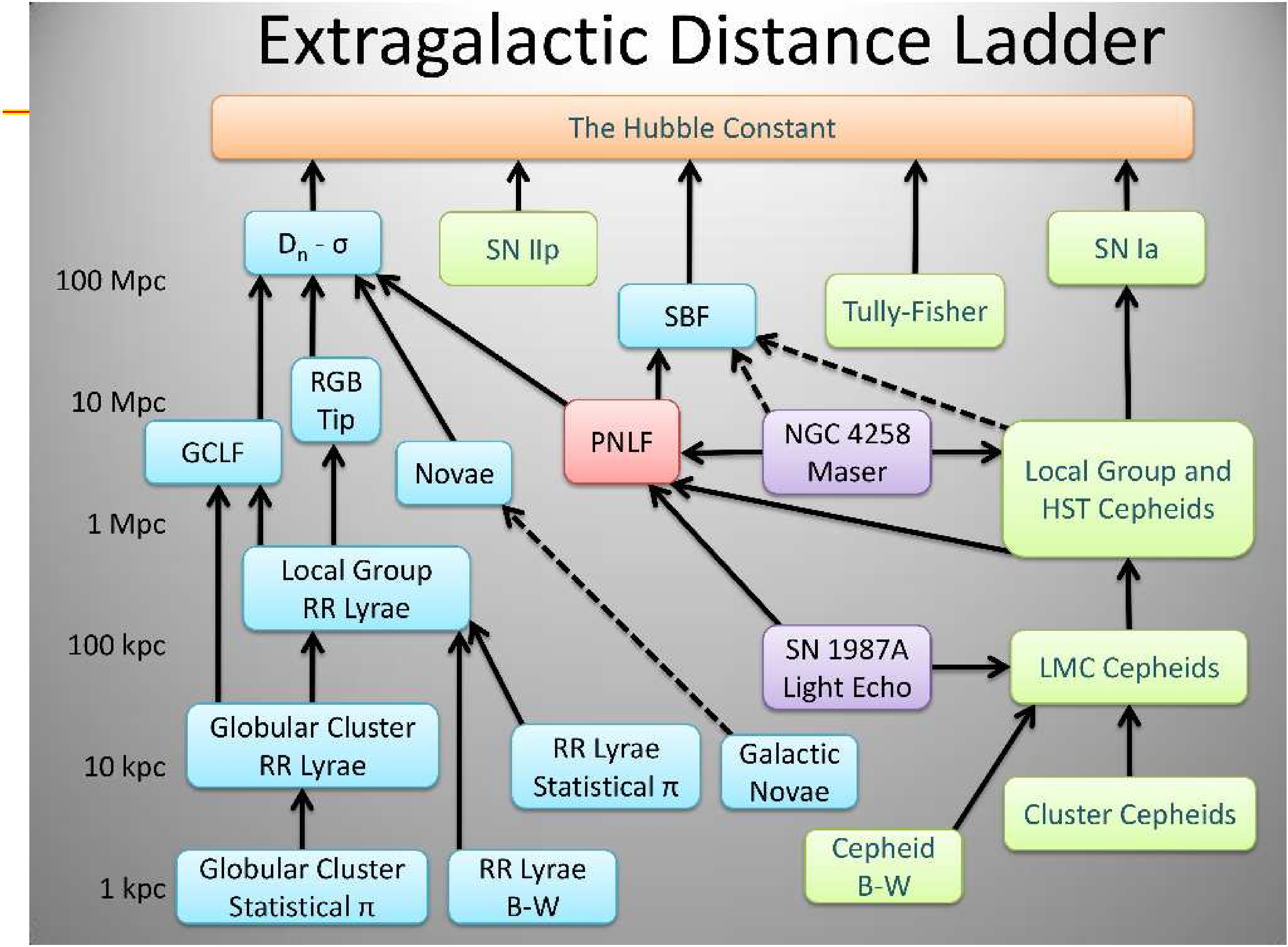


Nobel prize in physics 2011

Prize motivation: "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

Neither acceleration, nor the expansion itself of the Universe are directly observable!

This is hard because decades of accurate observations are about 10^{-9} of the age of the Universe. Accuracy of observations of distances and angles in large scale is orders of magnitude worse.



Extragalactic Distance Ladder

The Hubble Constant

$D_n - \sigma$

SN IIp

SBF

Tully-Fisher

SN Ia

100 Mpc

10 Mpc

1 Mpc

100 kpc

10 kpc

1 kpc

GCLF

RGB Tip

Novae

PNLF

NGC 4258 Maser

Local Group and HST Cepheids

Local Group RR Lyrae

SN 1987A Light Echo

LMC Cepheids

Globular Cluster RR Lyrae

RR Lyrae Statistical π

Galactic Novae

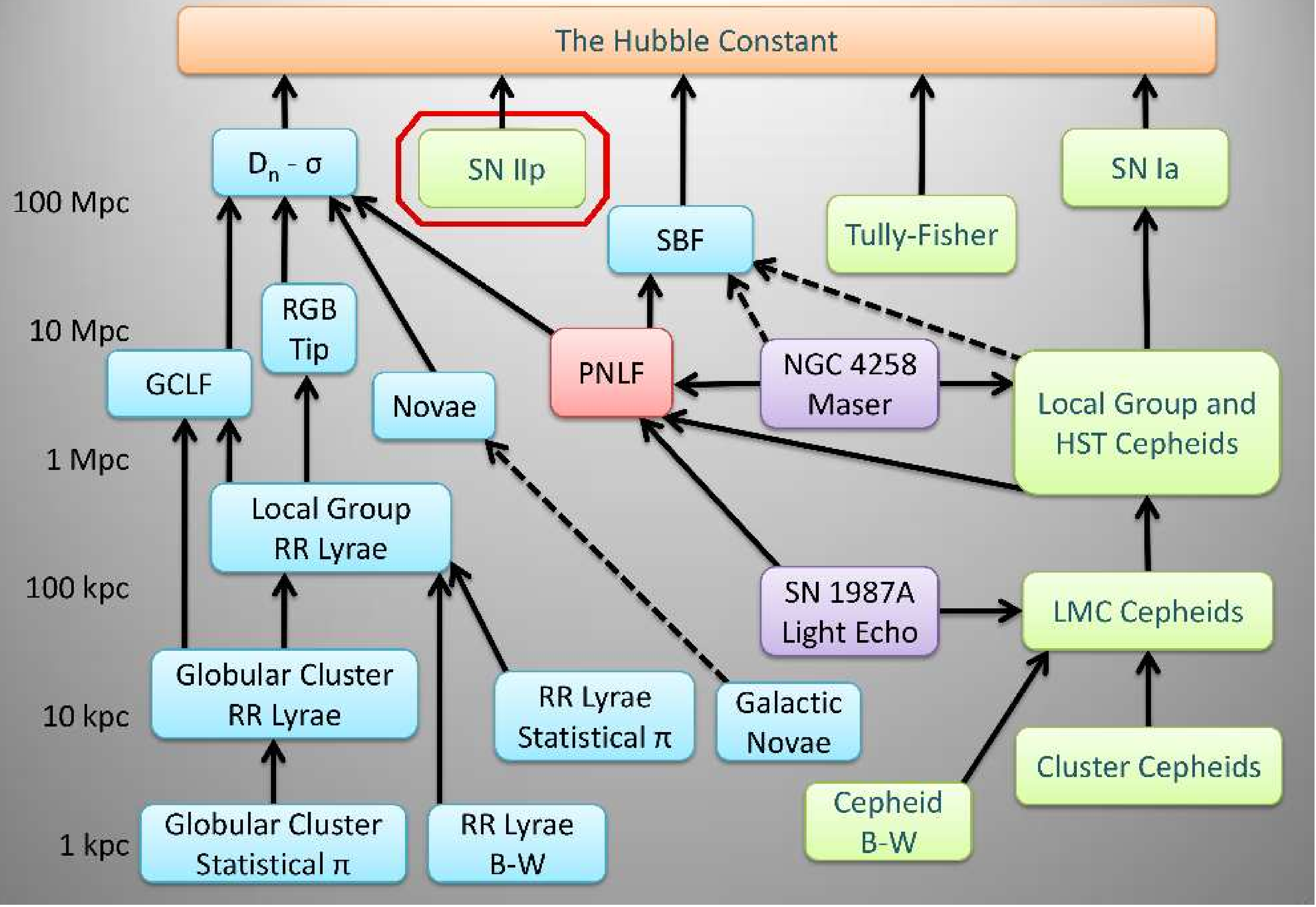
Cluster Cepheids

Cepheid B-W

Globular Cluster Statistical π

RR Lyrae B-W

Extragalactic Distance Ladder



Basics for Cosmography

Photometric distance:

$$d_{\mathrm{ph}}^2 = \frac{L(\text{emitted, ergs/s})}{4\pi F(\text{observed, ergs/s/cm}^2)}$$

Dependence on redshift z

$$d_{\mathrm{ph}}(z)(\Omega_m, \Omega_{DE}, w(z))|_{\text{theory}}$$

is determined by cosmology. Comparison with the

$$d_{\mathrm{ph}}(z)(\text{observed})$$

allows one to find $\Omega_m, \Omega_{DE}, w(z)$, etc.

Expanding Photosphere Method (EPM)

Cf. Baade(1926)-Wesselink(1946) method for Cepheids . Measuring color and flux at two different times, t_1 and t_2, one finds the ratio of the star's radii, R_2/R_1 (or from interferometry).

Using weak lines which are believed to be formed near the photosphere one can measure the photospheric speed v_{ph}.

Then $\int_{t_1}^{t_2} v_{\mathrm{ph}} dt$ would give $\Delta R_{\mathrm{ph}} = R_2 - R_1$.

Knowing R_2/R_1 and $R_2 - R_1$, it is easy to solve for the radii.

The ratio of fluxes gives

$$\frac{d^2}{R^2} = \frac{F_\nu(\mathrm{emitted})}{F_\nu(\mathrm{observed})} ,$$

hence the distance d.

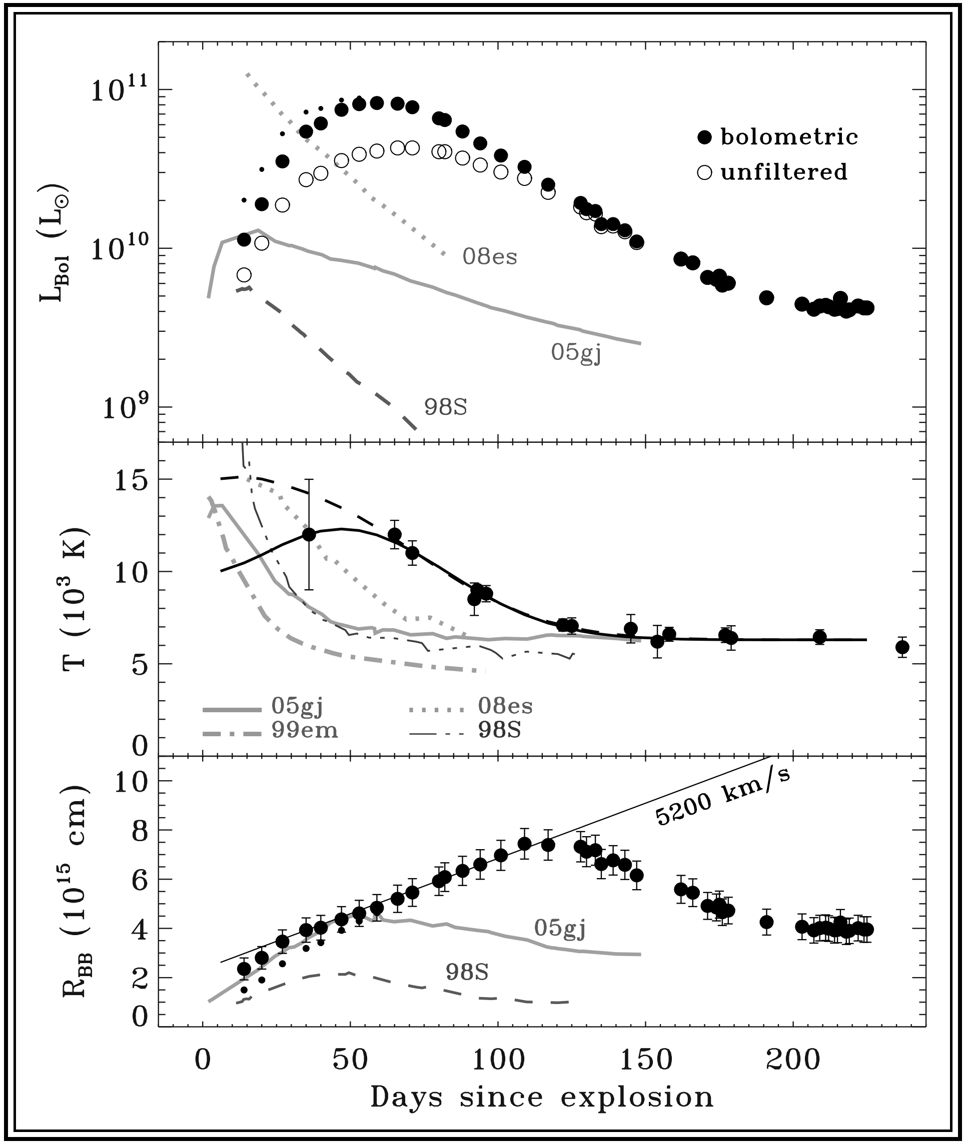
Distance from EPM

Now the distance d to the supernova is

$$d = R_{\mathrm{ph}} \sqrt{\frac{F_\nu(\mathrm{model})}{F_\nu(\mathrm{observed})}}$$

if a reliable model flux $F_\nu(\mathrm{model})$ at the SN photosphere is compared with the detected flux $F_\nu(\mathrm{observed})$.

Observed $R(t)$ of SN2006gy



New DSM for SNe IIn

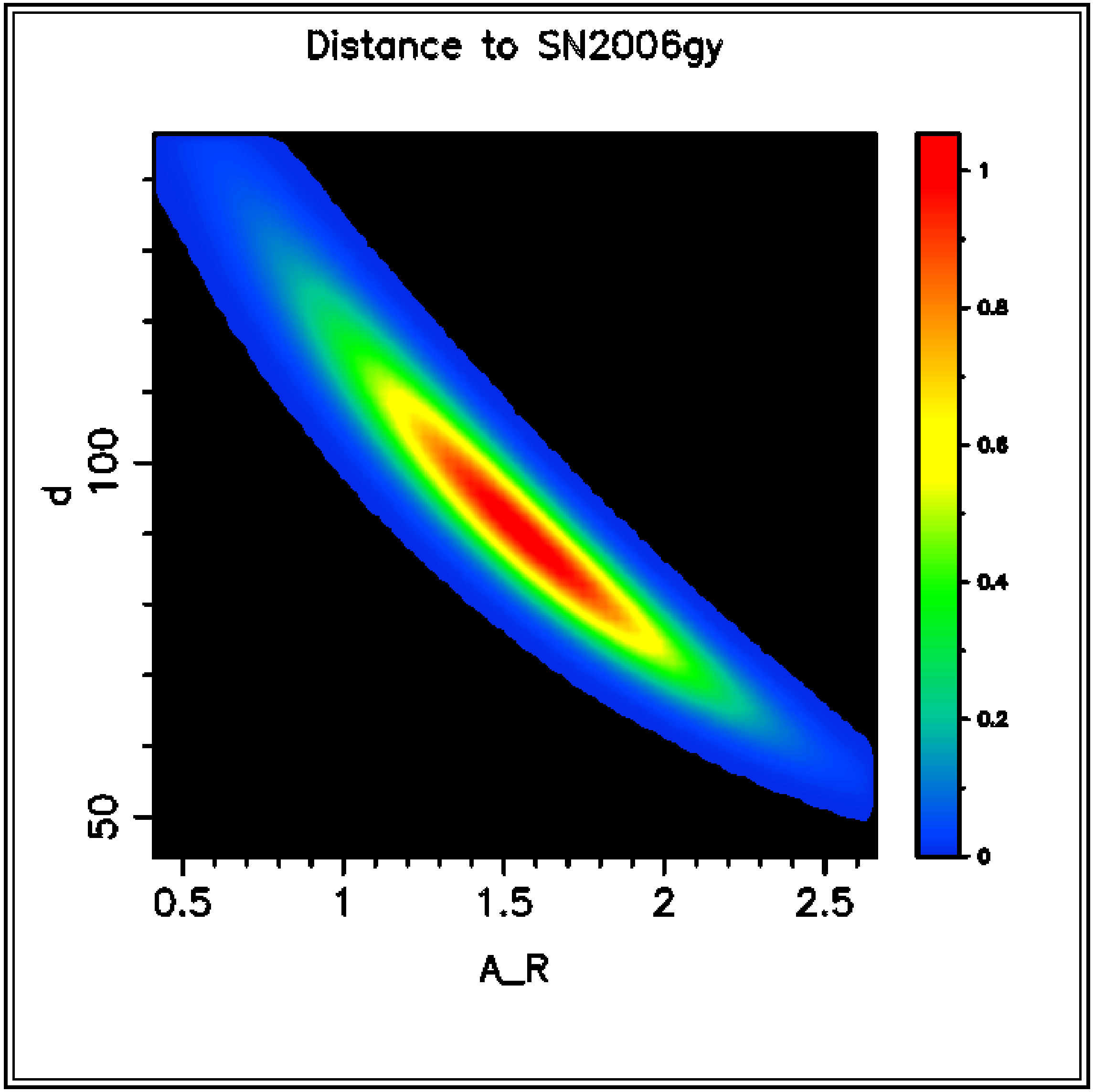
- Measure narrow line components to estimate the properties of CS envelope (may be done crudely).
- Measure wide line components to find the photospheric speed $v_{\rm ph}$ (as accurately as possible).
- Build a best fitting model for broad band photometry and the speed $v_{\rm ph}$.

New DSM for SNe IIn

- Although the "Hubble"-law $v = r/t$ is not applicable, v_{ph} now measures true velocity of the photospheric radius (not only the matter flow speed, as in type II-P).
- Now the original Baade's idea works for measuring the radius by integrating v_{ph} (of course, with due account of scattering, limb darkening etc in a time-dependent SEAM). This must be used when iterating the best fitting model.
- The observed flux then gives the distance.

MC probable d to SN 2006gy

for $T = 9 \times 10^3$ K at day 80



$H_0 \approx 60 \pm 20$ km/s/Mpc

Summary on SN IIn in cosmology

- Radiating shocks are most probable sources of light in most luminous supernovae of type IIn like SN2006gy
- Most luminous SN IIn events may be observed at high z [for years due to $(1+z)$] and may be useful as direct, primary, distance indicators in cosmology
- The new DSM is based on original Baade idea which really works now

B.Schmidt S.Perlmutter A.Riess

Congratulations!

Conclusions vs Plan

We witness direct observations of shock breakouts in extremely interesting events like XRF080109-SN2008D. I will discuss some puzzles related to this object. The theory must be developed here and this may lead eventually to better understanding of presupernova environments and physics of strong shocks like diffusive particle acceleration. I will discuss also prospects of discoveries of shock breakouts in the most numerous supernovae of type II at cosmological distances which can be a powerful means to measure the rate of core collapses and hence the star formation rate.

Applications

Finally, I describe our current understanding of the most luminous subtype II supernovae (SNIIn with narrow lines in spectra) which manifest pulsational pair-instability of massive stars. The potential use of their long living radiative shocks as a tool for measuring distances and cosmological parameters without invoking the cosmological distance ladder will be discussed.

Importance

1) Planned all sky soft Xray monitors will be able to see the shock breakouts several times a year within tens of megaparsecs and this will be very important for correlation and identification of future GW signals of core collapses in the noisy background.

2) The shock breakouts should not produce cosmic rays in large amounts, but I will explain a similarity of the physics of radiation dominated shocks in supernova envelopes and CR-dominated shocks in SNRs (like the disappearance of the viscous jump in the shock). The first real observations of shock breakouts like XRF080109-SN2008D have shown that our theory of those shocks is in infant stage, and the development of the theory will surely lead eventually to better understanding of CR generation, enrichment of the ISM with heavy elements, etc.

3) The core collapsing stars in the range of initial masses slightly above 10 Msun and up to about 20 Msun produce most abundant class of all supernovae and understanding their rates for redshifts like z=1 will help us to understand the stellar formation rate evolution, and the rate of formations of their remnants - main contributors to cosmic ray generation.