Pair-instability сверхновые и предвестники коллапса звезд

С.И.Блинников

sergei.blinnikov@itep.ru

ITEP, SAI, also partly IPMU

SINP MSU, 15th May 2012

S.I.Blinnikov[1,2,3]

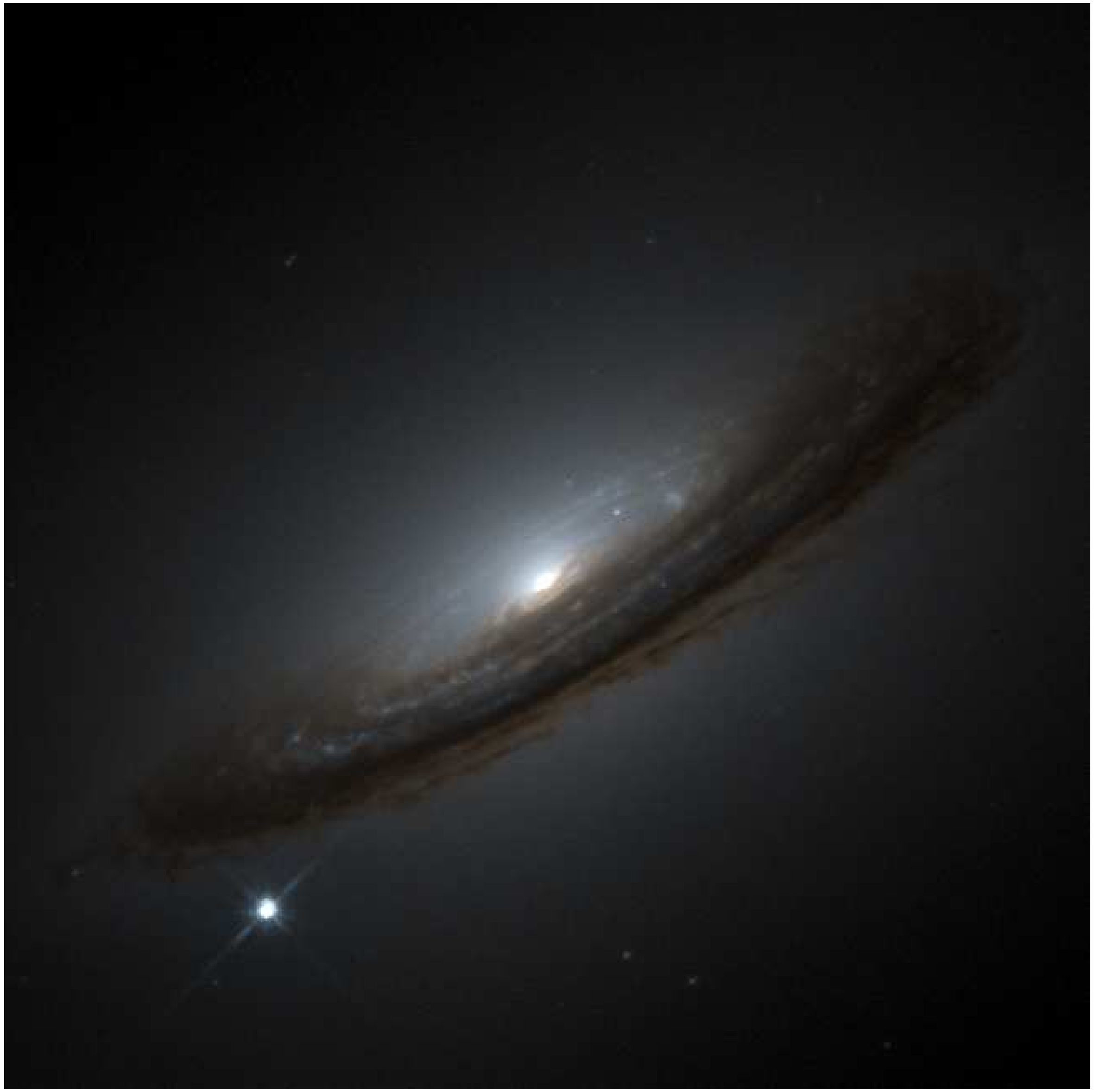
[1] *Institute for Theoretical and Experimental Physics (ITEP), Moscow*

[2] *Sternberg Astronomical Institute (SAI), MSU, Moscow*

[3] *work partly done at IPMU, Tokyo University, Kashiwa*

Supernova SN1994D in NGC4526

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

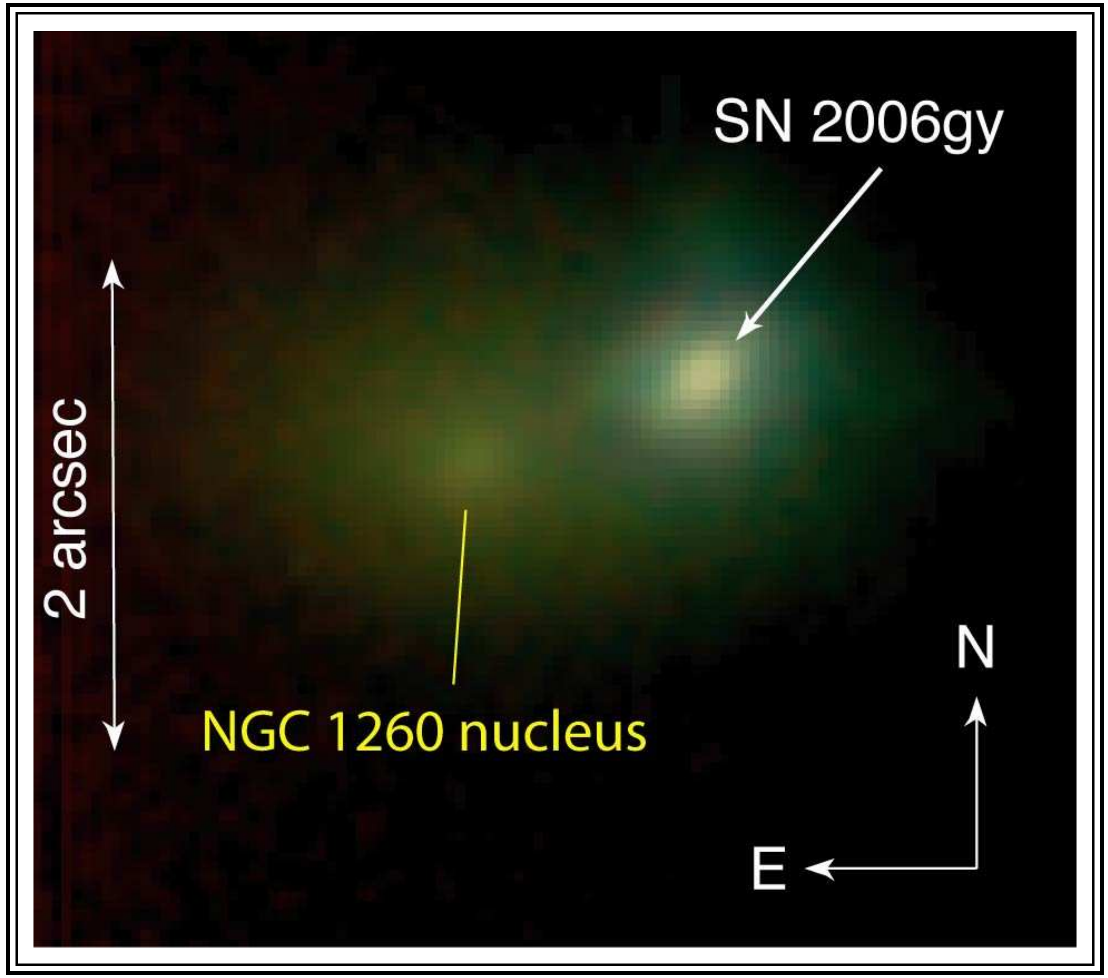


SN 2006gy

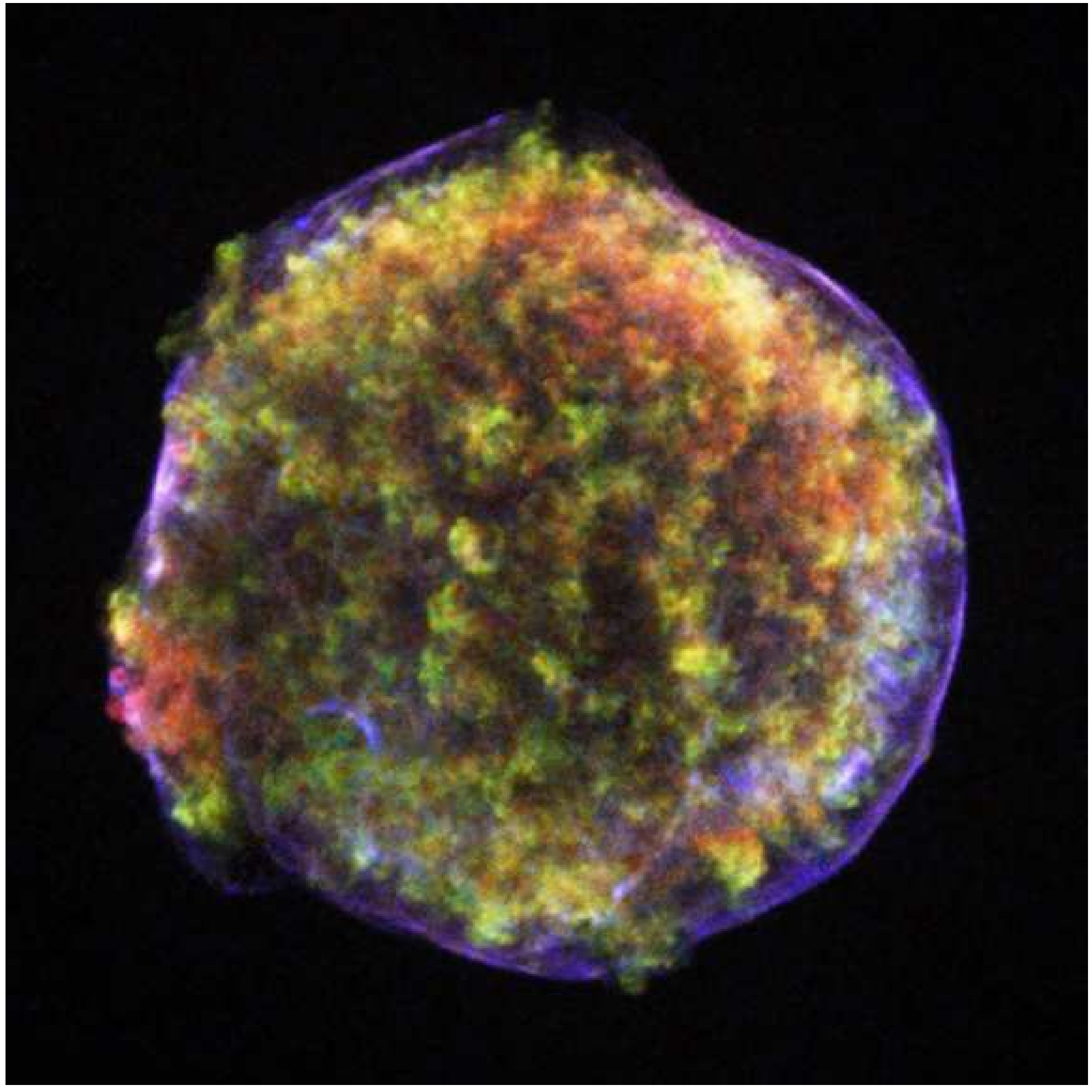
Ofek et al. 2007, ApJL

Smith et al. 2007, ApJ

Shocks are vital for explaining light of those superluminous events for many months...



SNR Tycho in X-rays (Chandra)



...and thousands of years in SNRs

Supernova: order of events

- Core collapse (CC) or explosion

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- Neutrino/GW signal, accompanying signals

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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)

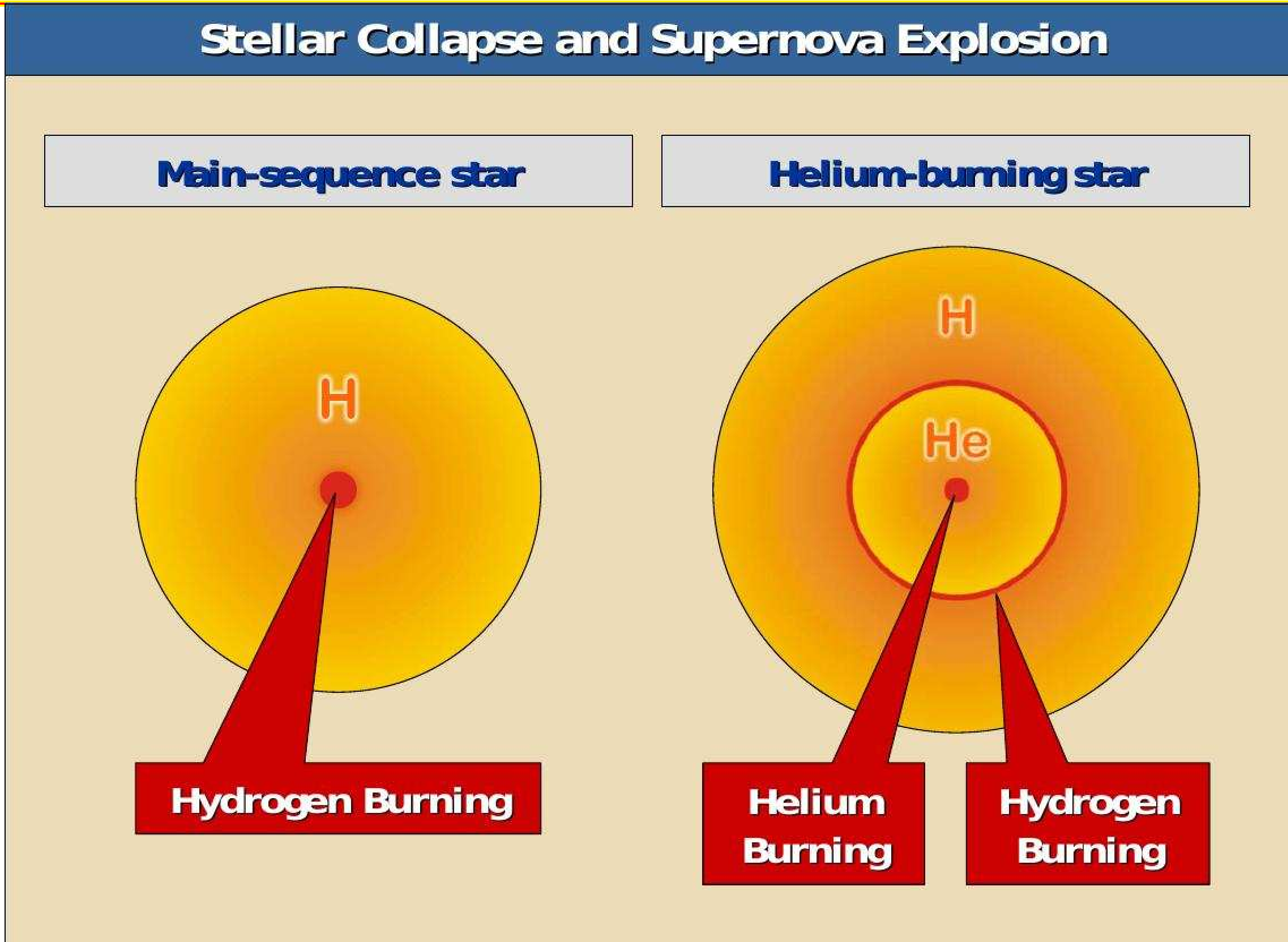
Standard description of Chronology

- 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 $u \propto r$)

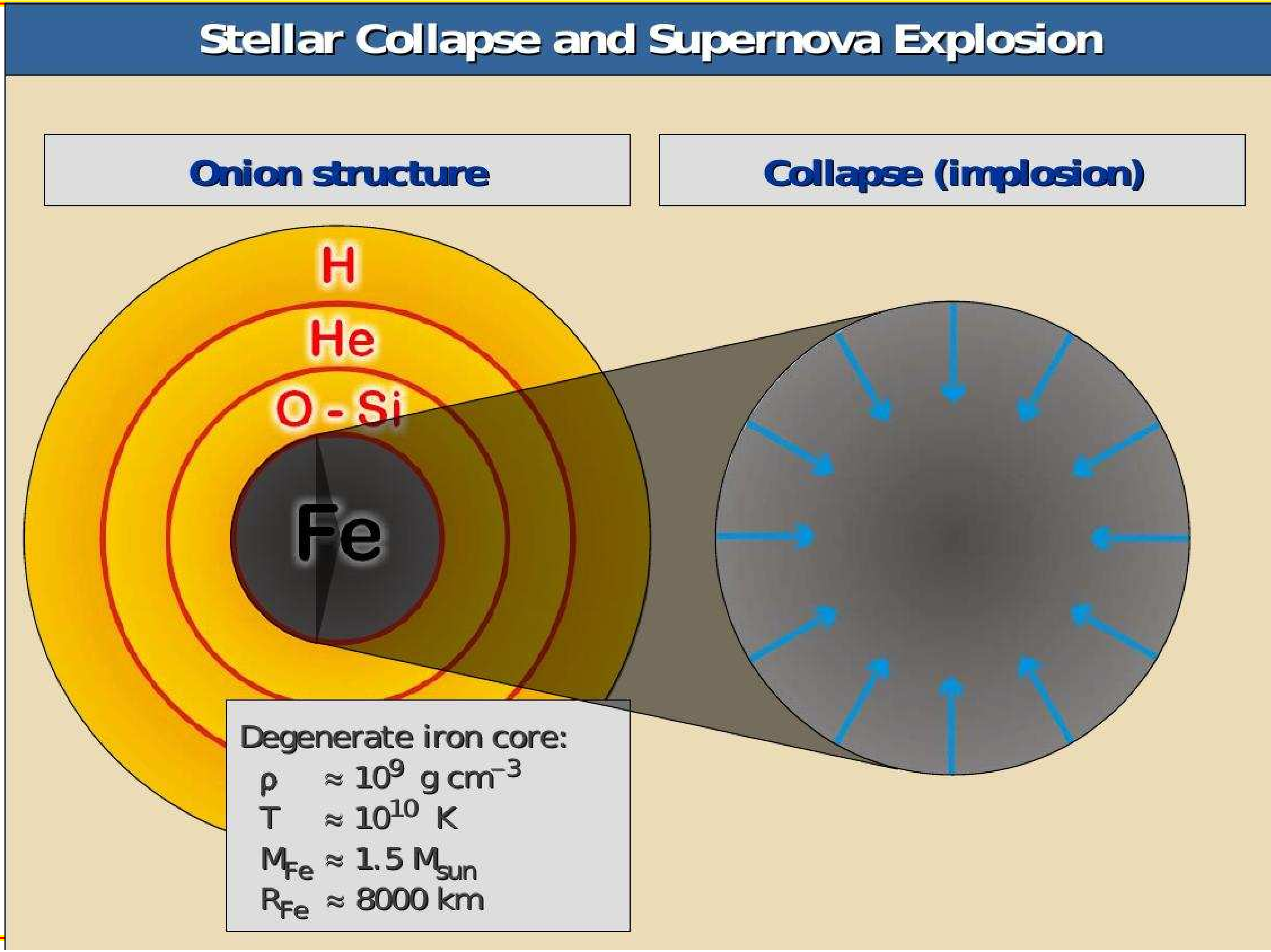
$^{\star)}$ Standing accretion shock instability

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

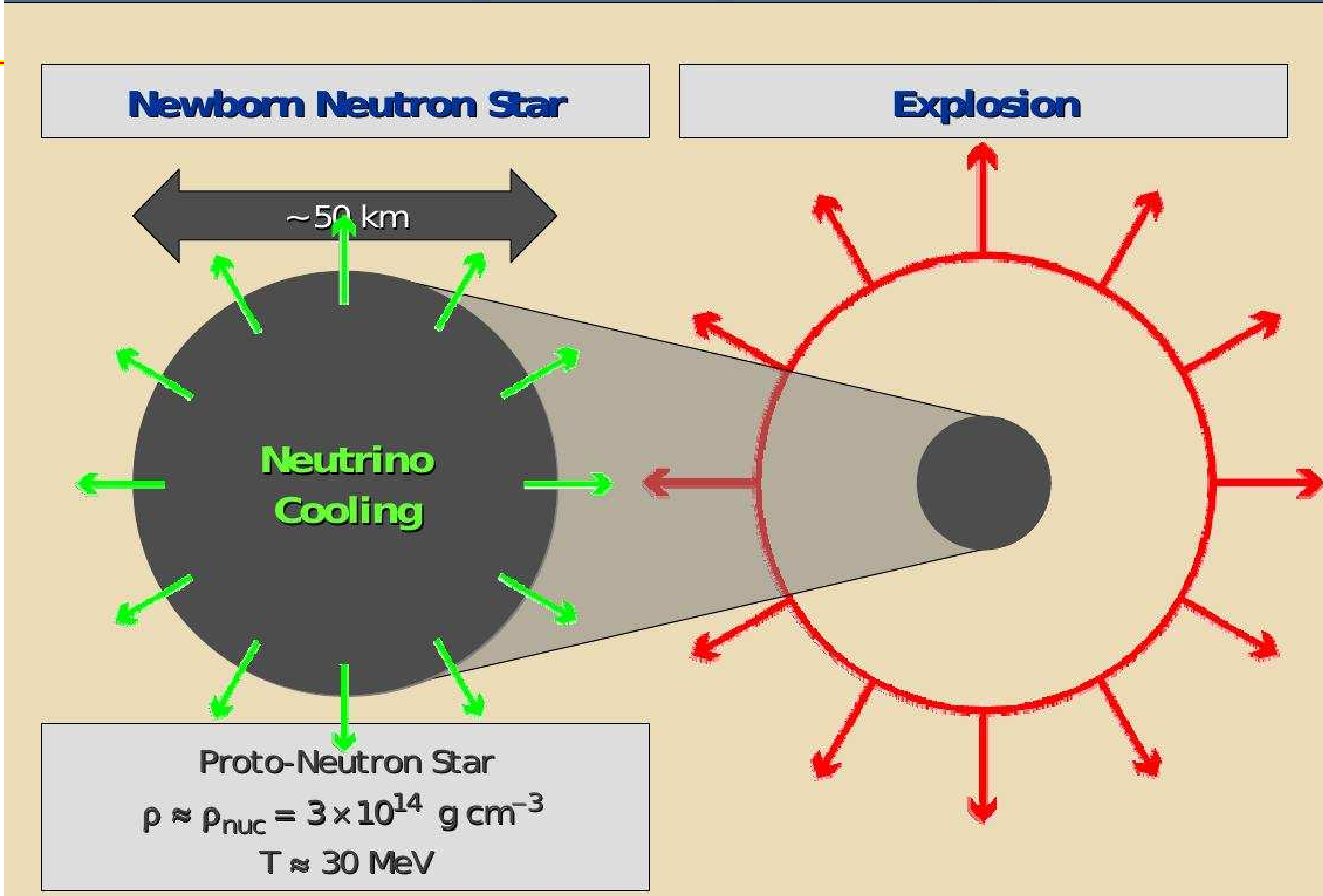
Burning in center and in shells



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

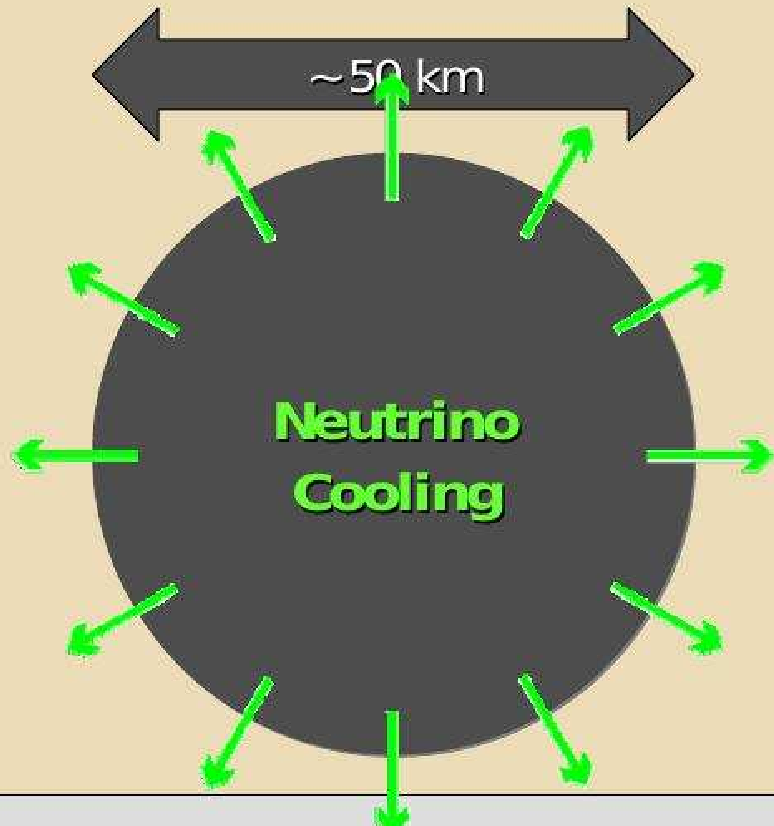


Stellar Collapse and Supernova Explosion



Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

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

$T \approx 30$ MeV

Gravitational binding energy

$E_b \approx 3 \times 10^{53}$ 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

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

While it lasts, outshines the entire visible universe

First messengers of explosions

$\boxed{\text{Neutrino?}}$

First messengers of explosions

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

First messengers of explosions

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

$\boxed{\text{Radio waves? At least in atmospheric explosions}}$

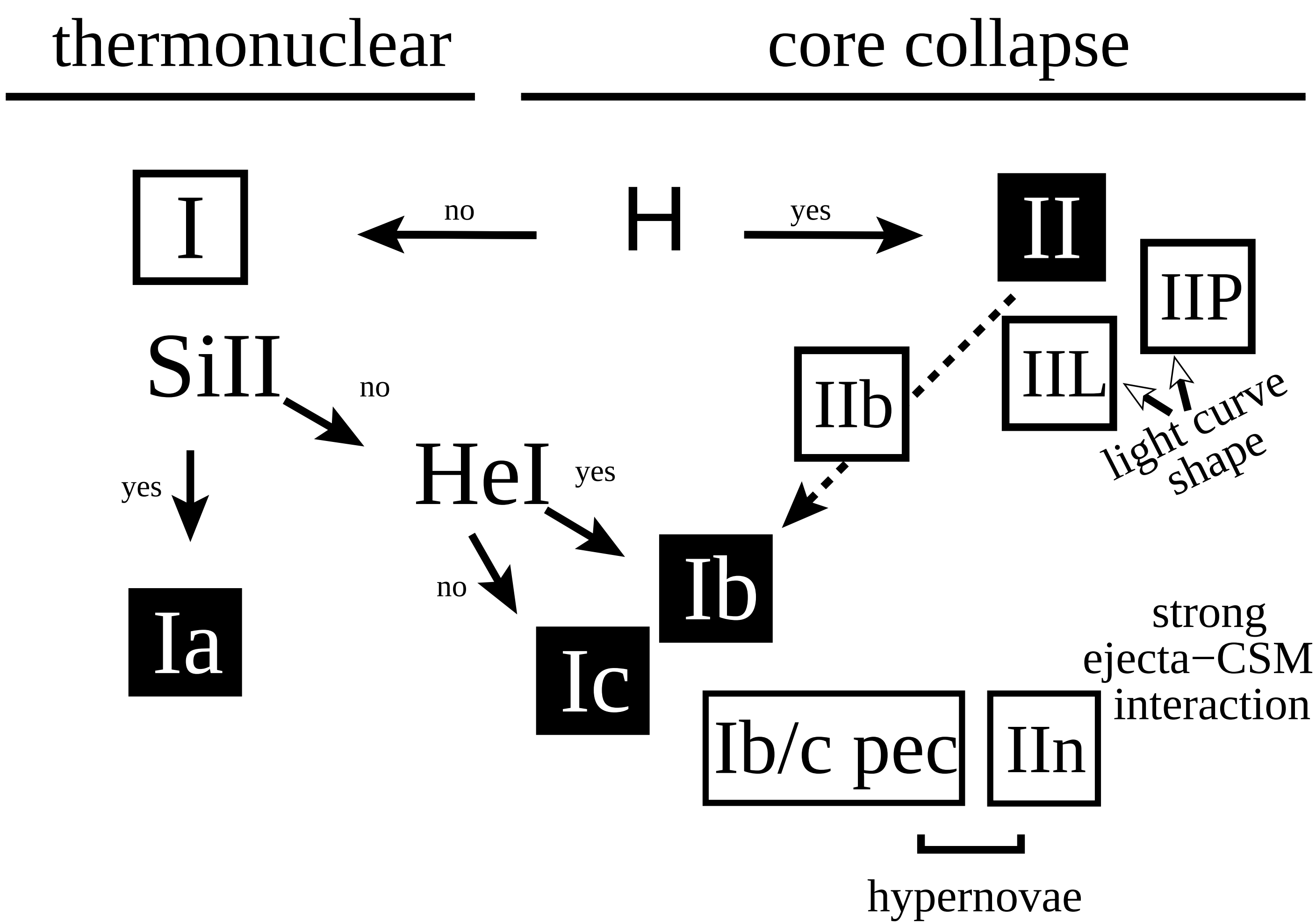
First messengers of explosions

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

$\boxed{\text{Radio waves? At least in atmospheric explosions}} \rightarrow$

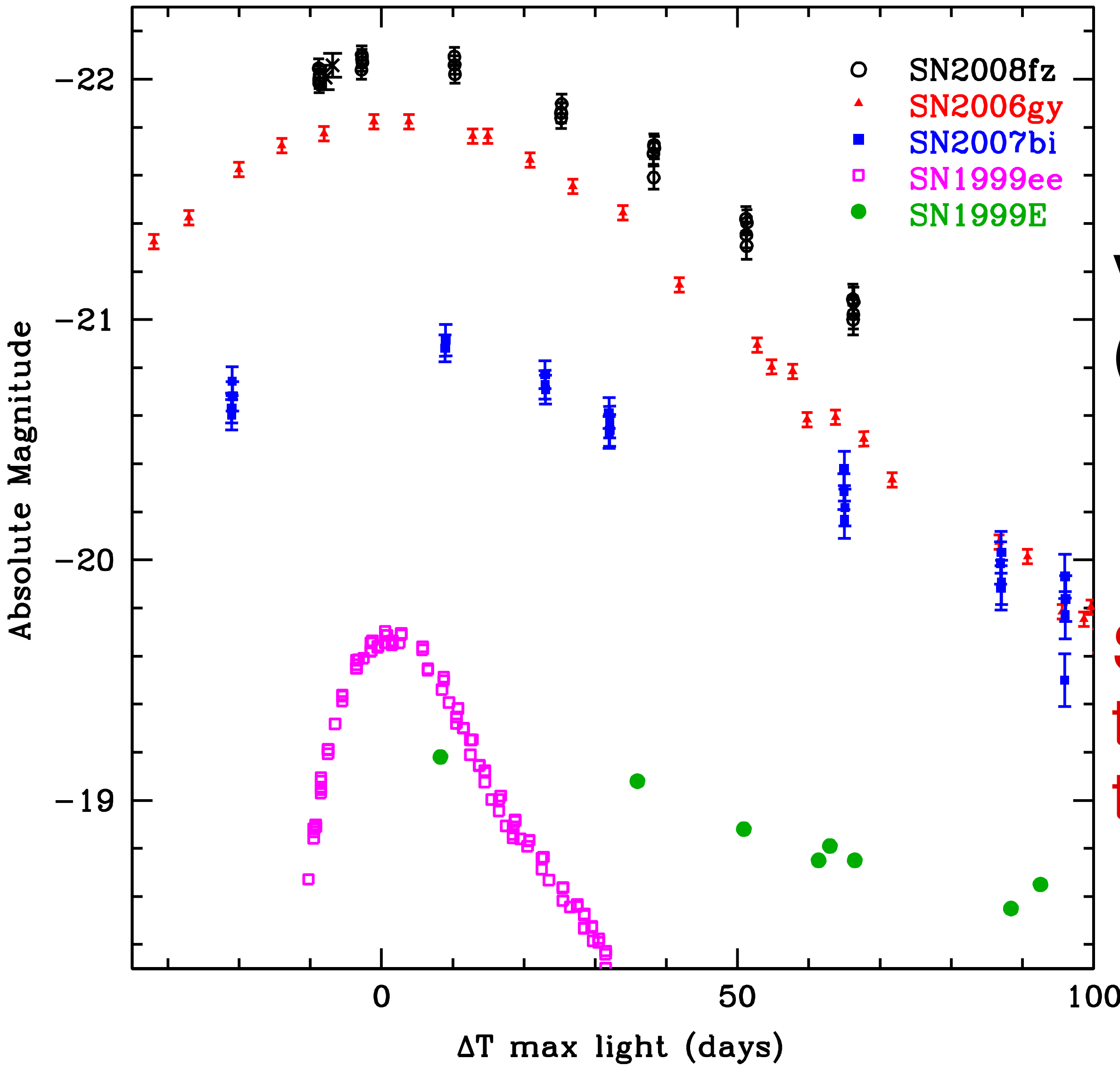
$\boxed{\text{Shock breakout}}$

SN classification



Turrato 2003

Extremely bright Type IIn SNe

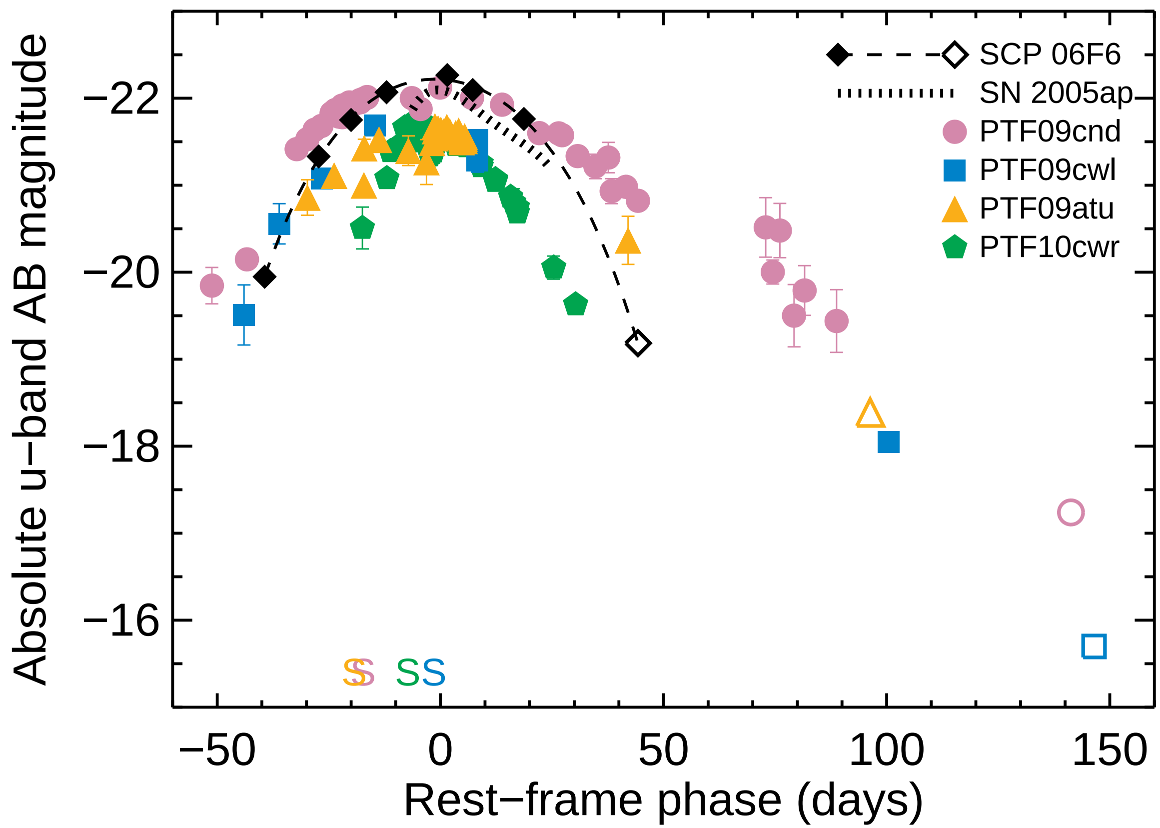


V-band
(Drake et al. 2010)

SN1987A and a typical SNII below the frame!

H-poor superluminous SNe

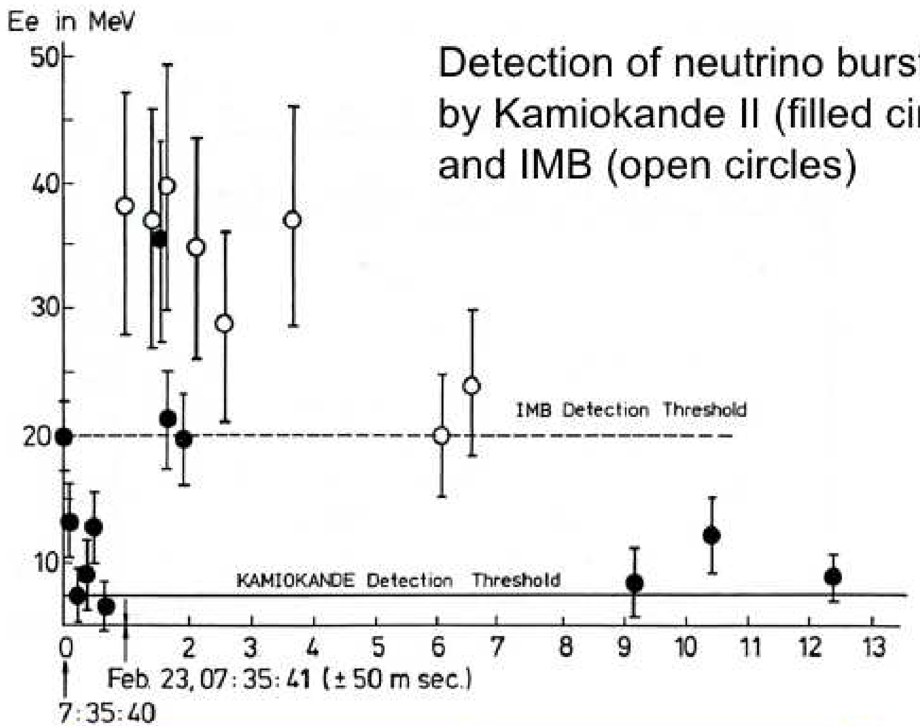
Quimby et al. 2011



Still enigmatic. Most probably explained by a long living radiative shock. No better model is suggested

Supernova 1987A Neutrinos

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



Anglo-Australian Telescope
(~1 month after SN)

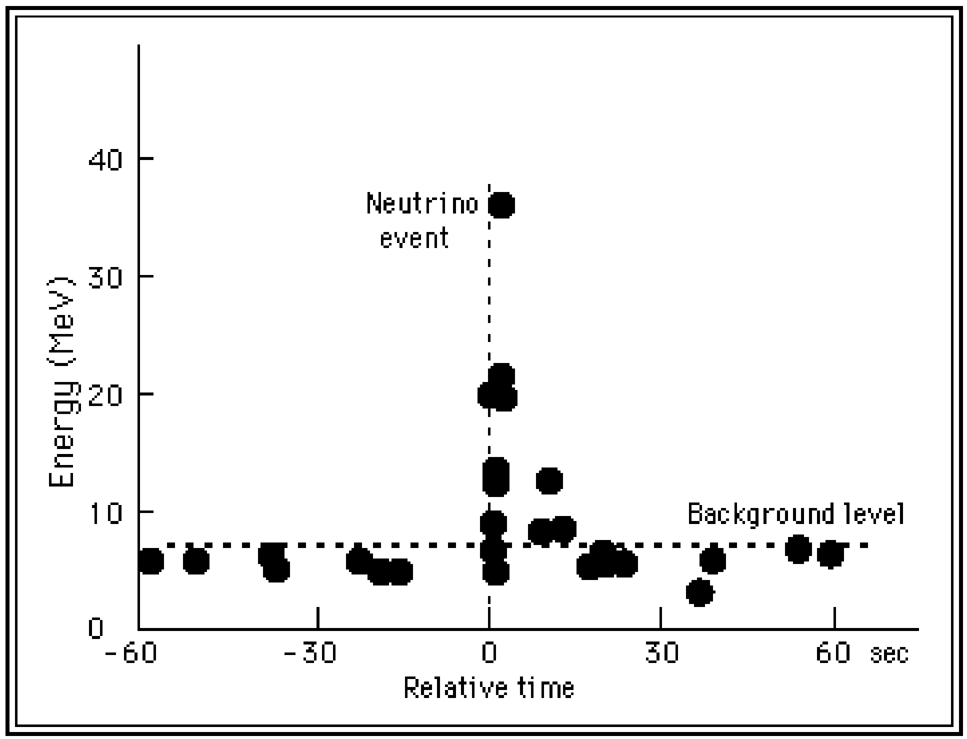
~13 seconds

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.



Superlumnal neutrino cartoons...

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 $\sim 2\times10^{-9}$, 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, $\Delta t \approx 3^{\rm h}$, hence

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

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

SN1987A discovery

Timing (times in Universal Time)
7:36, 23 February, neutrinos observed
9:30, 23 February

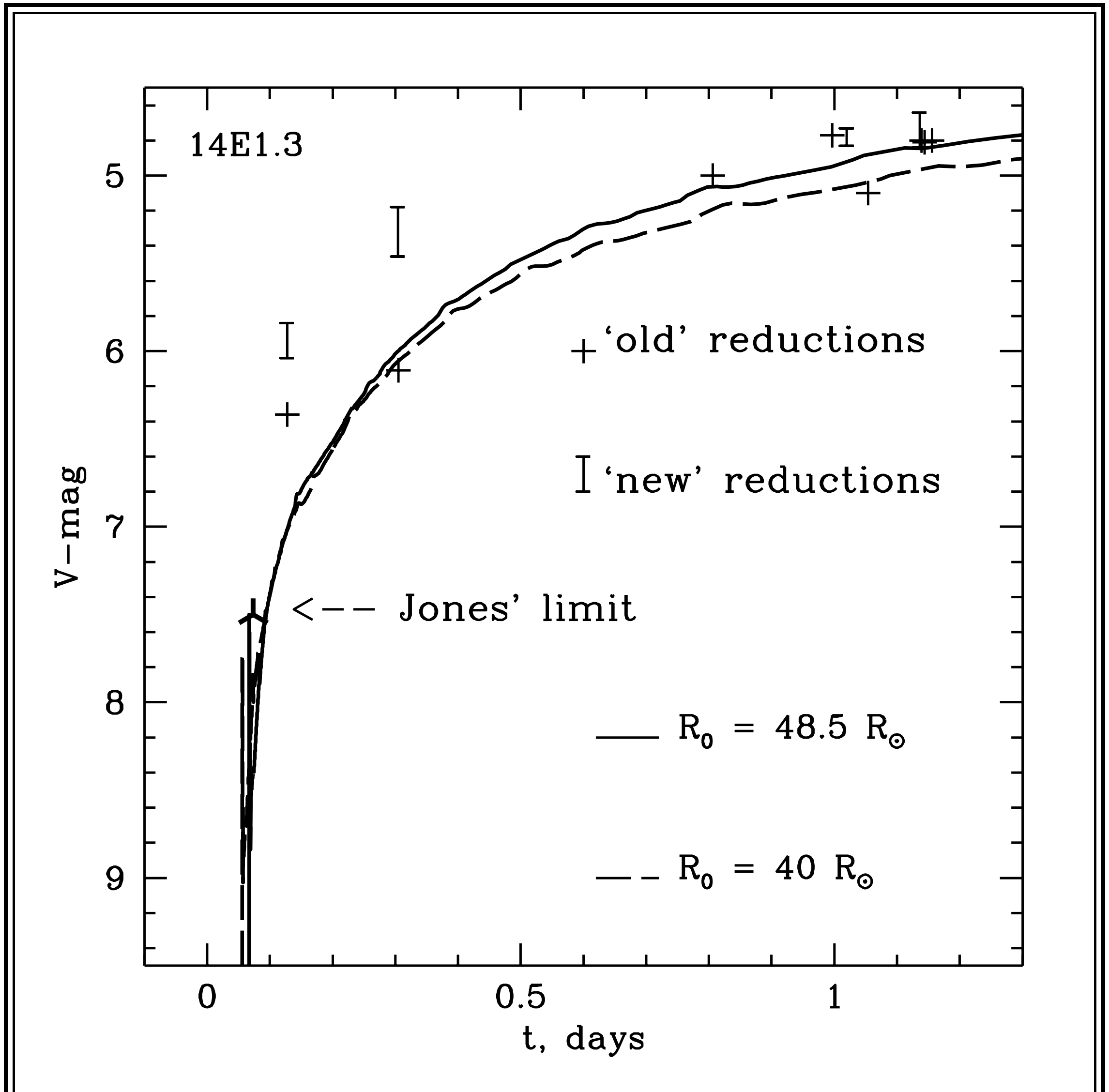
> Albert Jones, amateur astronomer, observes
> Tarantula Nebula in LMC
> He sees nothing unusual

10:30, 23 February

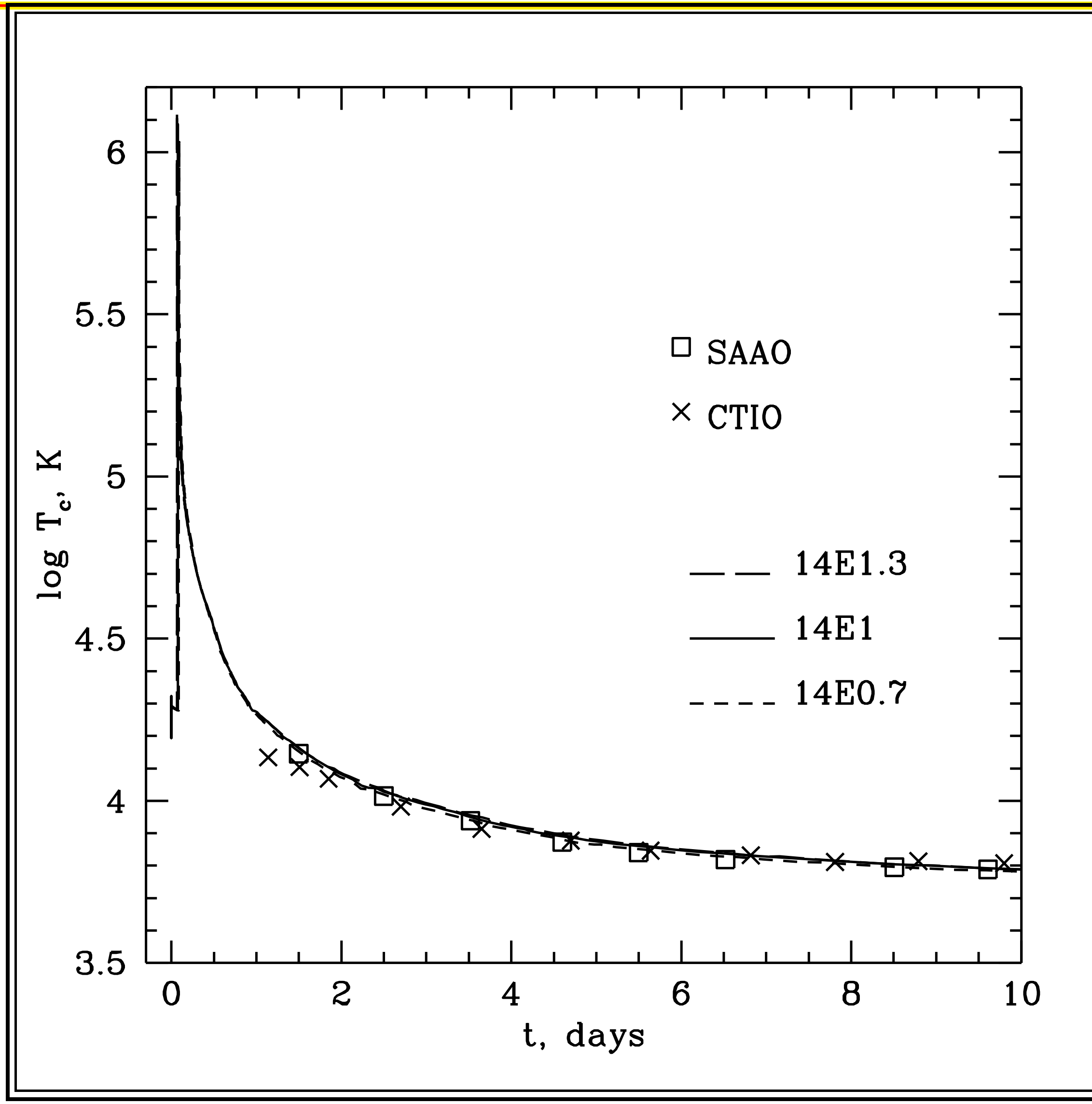
> Robert McNaught photographs LMC
> When plate is developed, SN1987A is there.
> Some 20 hours later, Ian Shelton's discovery.

SN87A early observations

Blinnikov with K.Nomoto ea



SN87A early observations



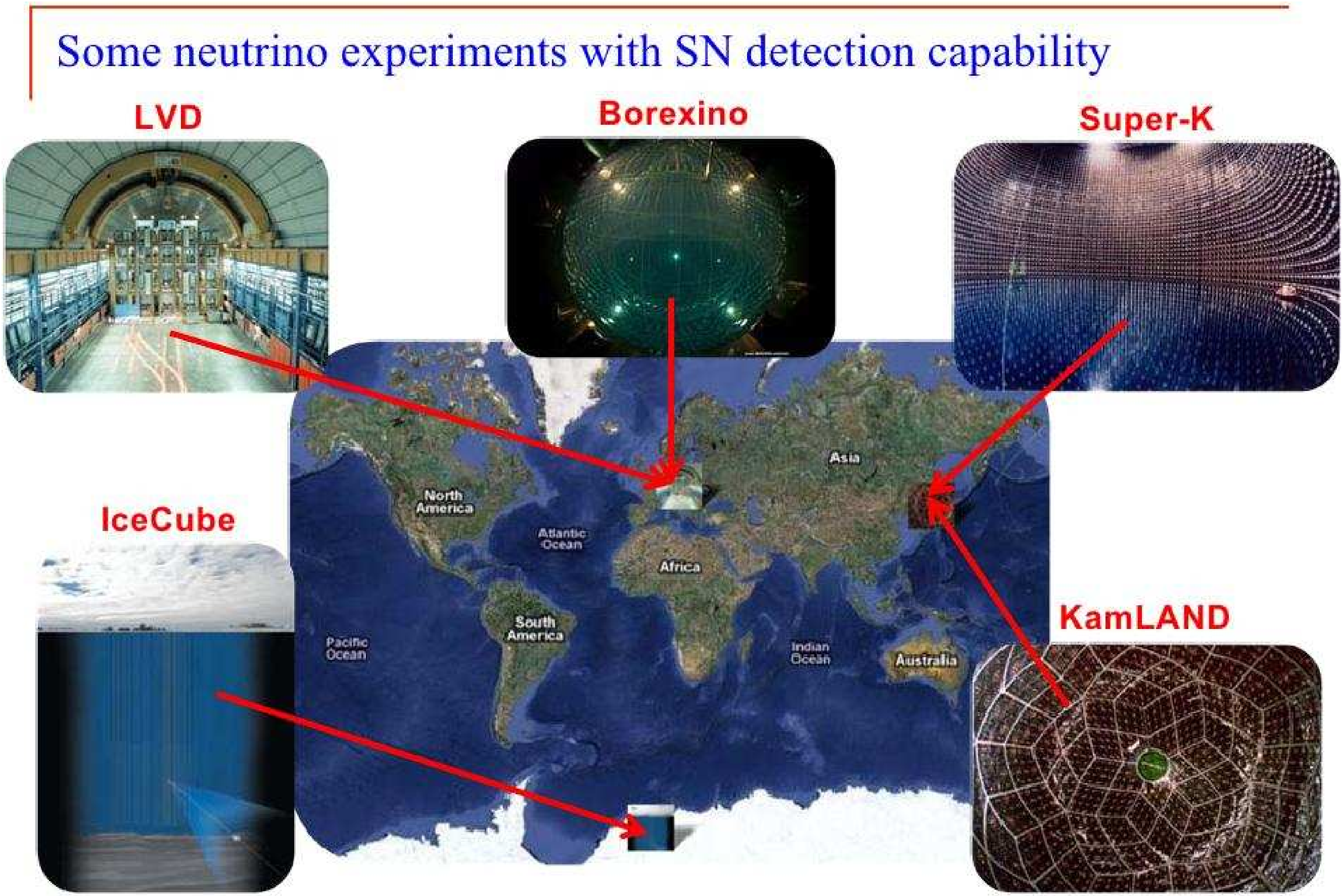
Improvement of c_ν constraint

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.

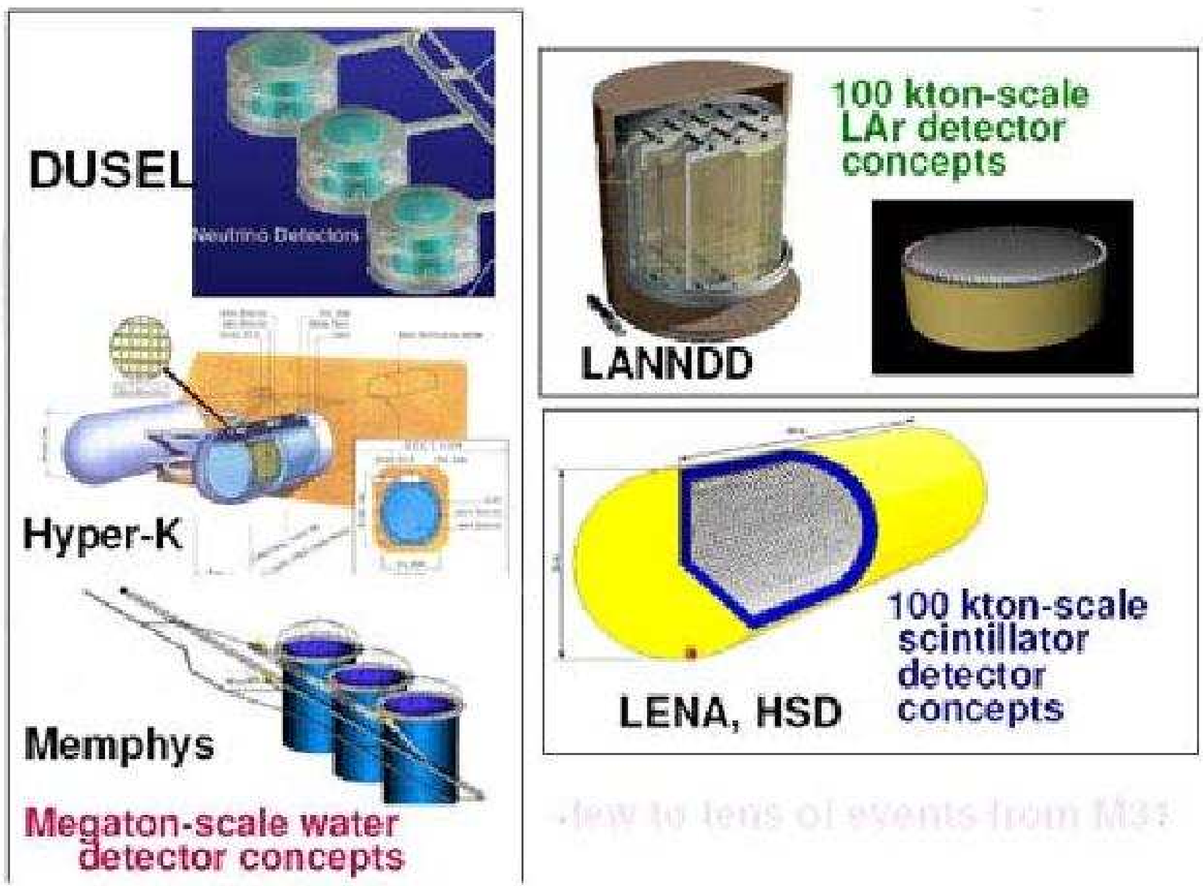
ν detectors



Next generation ν detectors

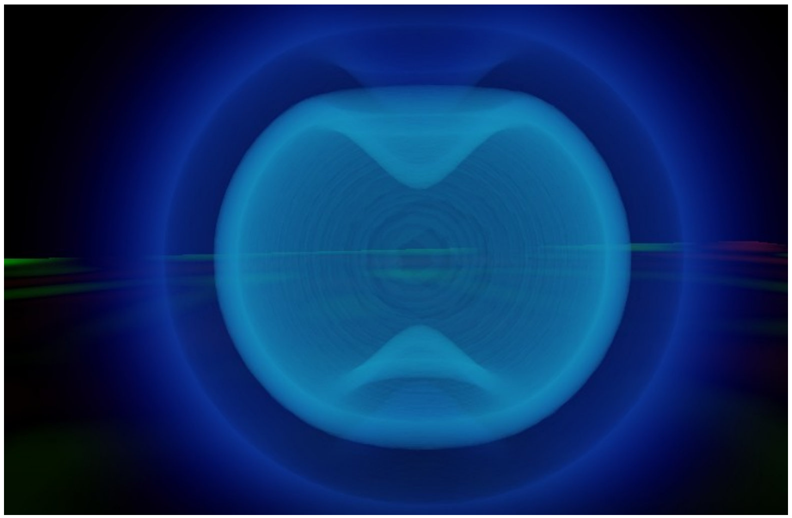
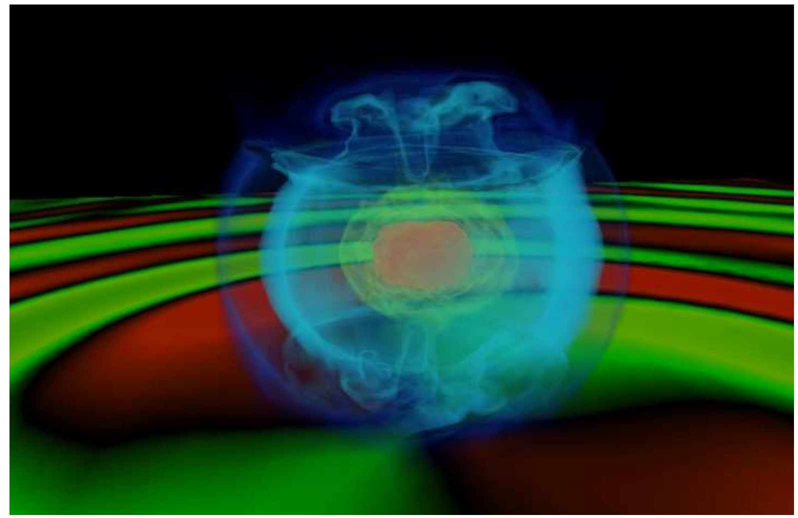
Next generation neutrino mega-detectors (10-20 years)

~few to tens of events from M31



Gravitational Waves from CCSNe

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

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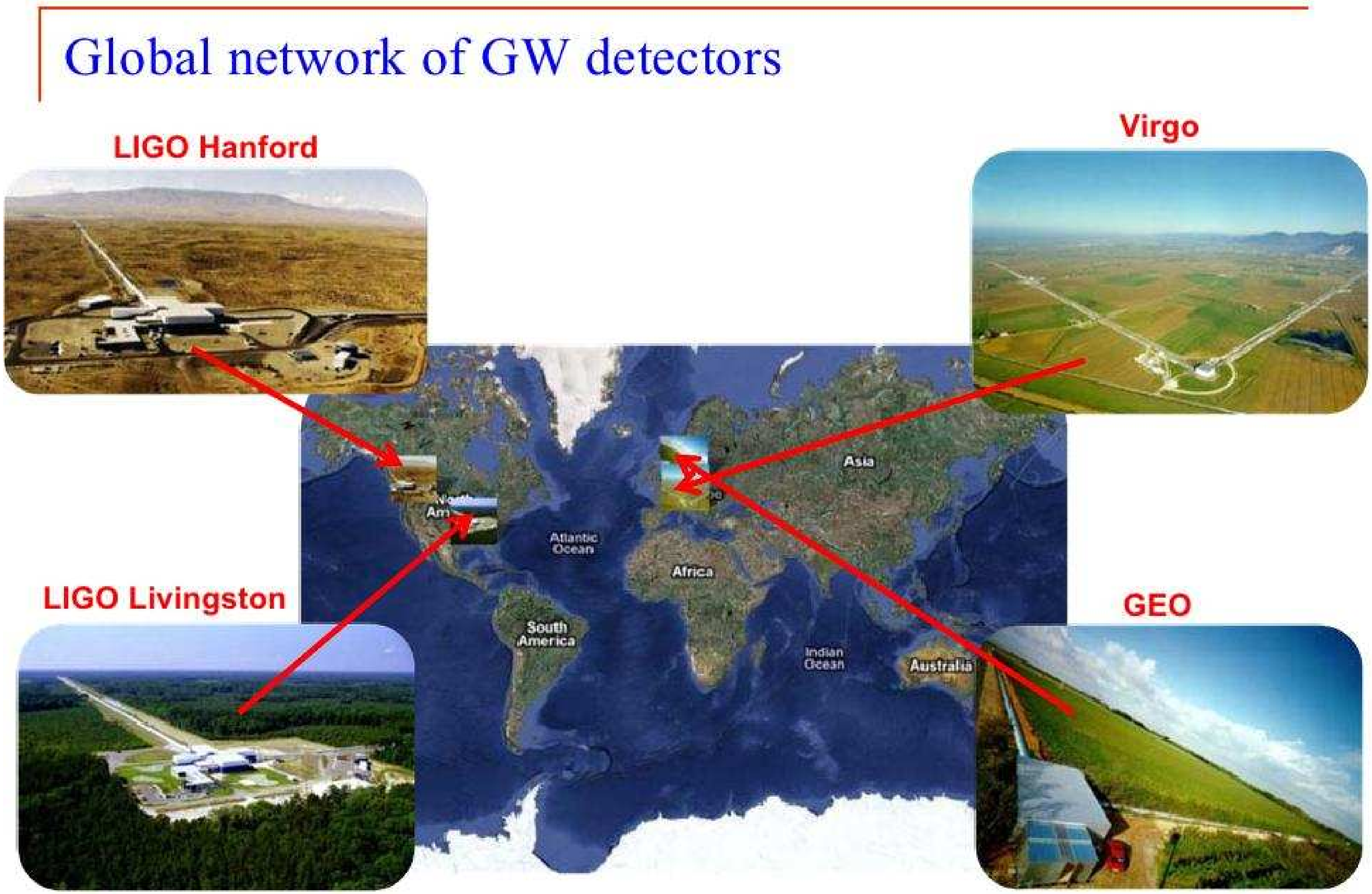
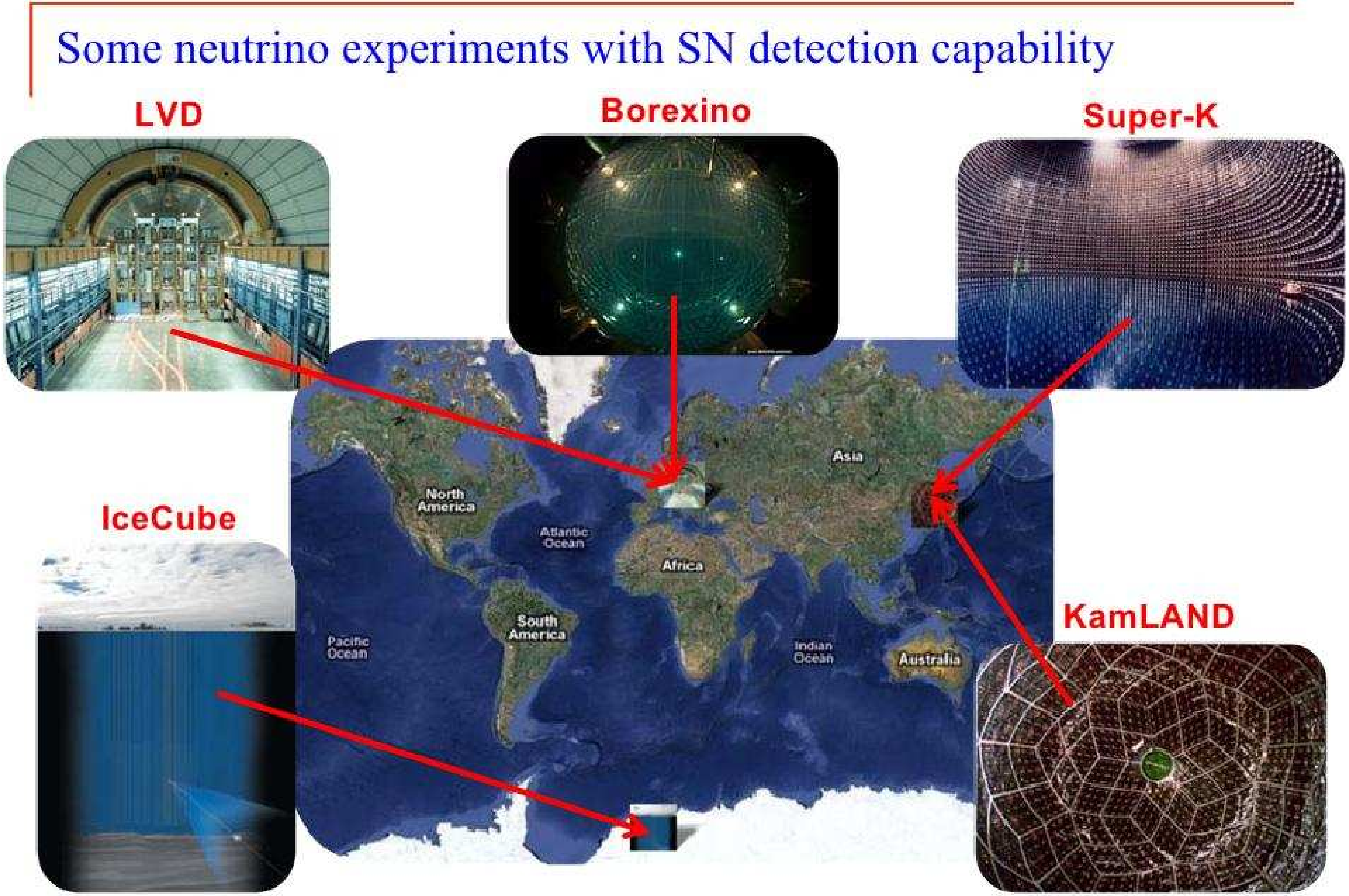
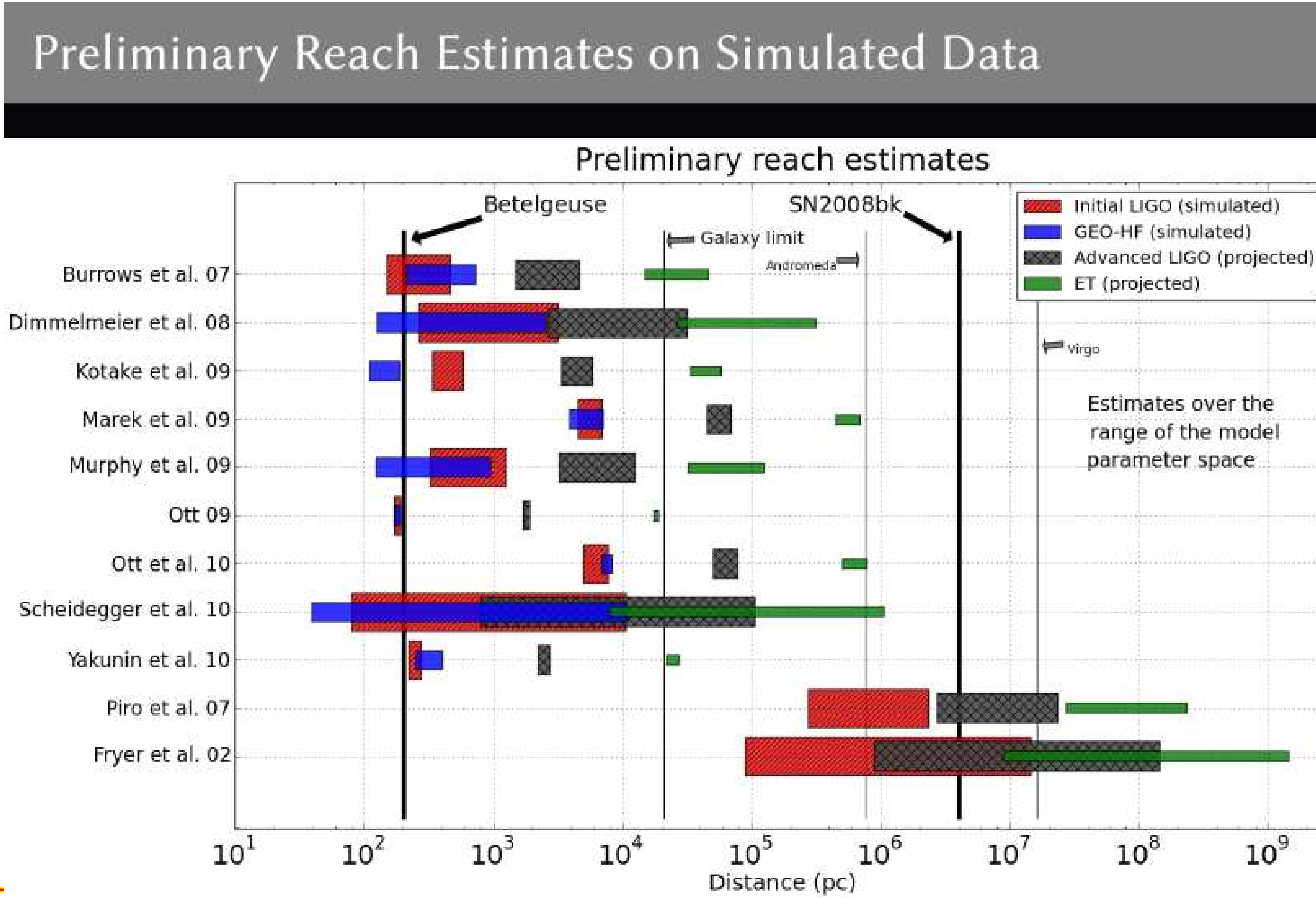
GW detectors



ν detectors



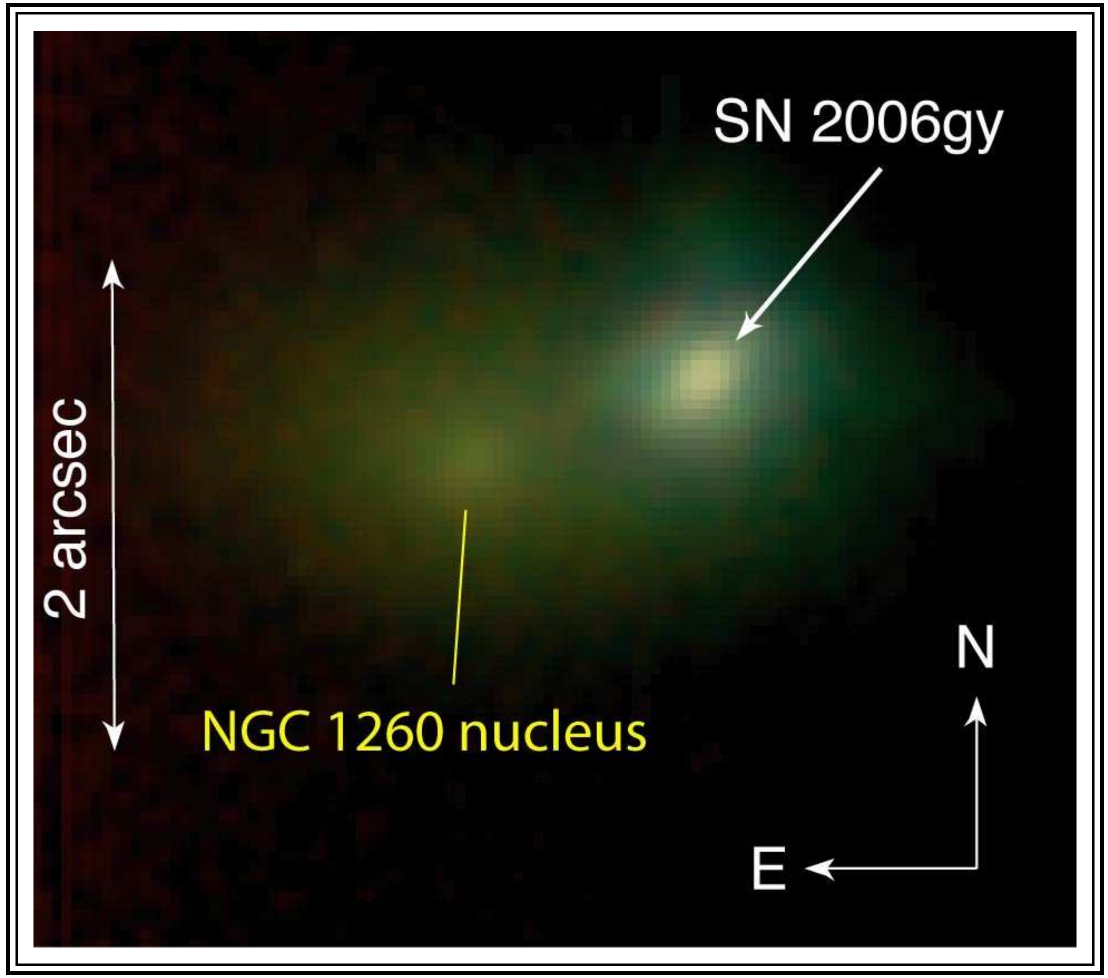
GW LIGO estimates



SN 2006gy

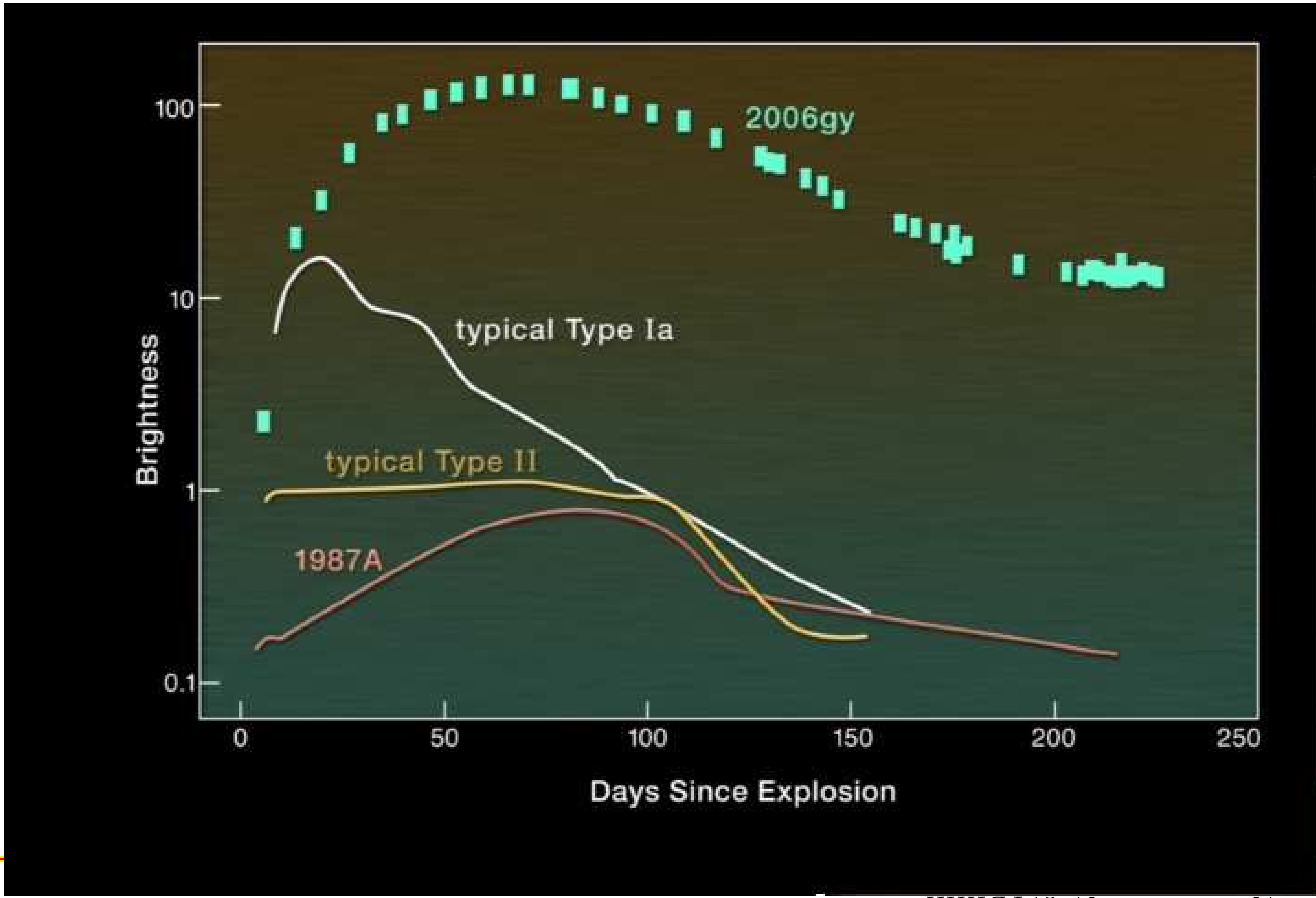
Ofek et al. 2007, ApJL, astro-ph/0612408)

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

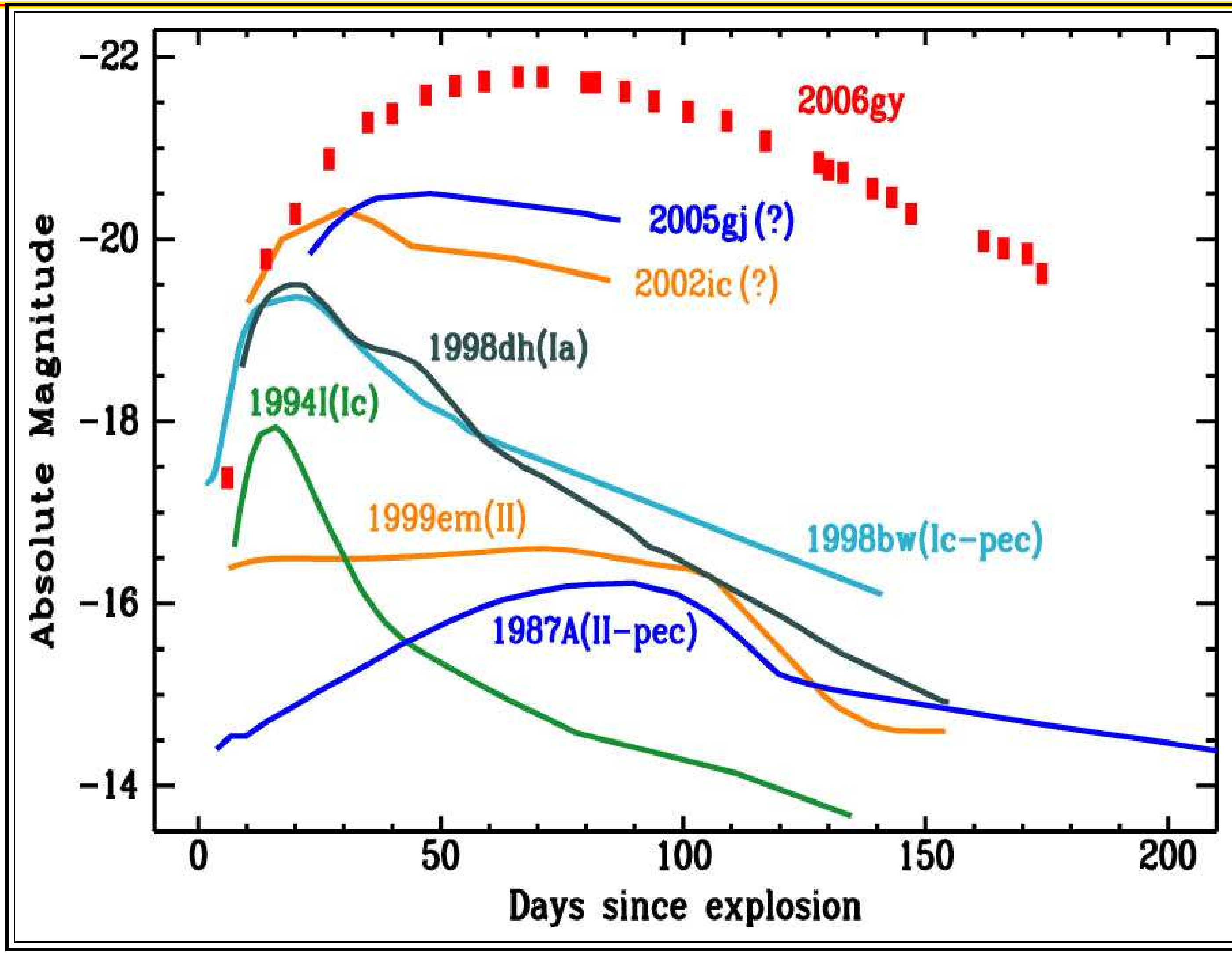


Brightest. Supernova. Ever

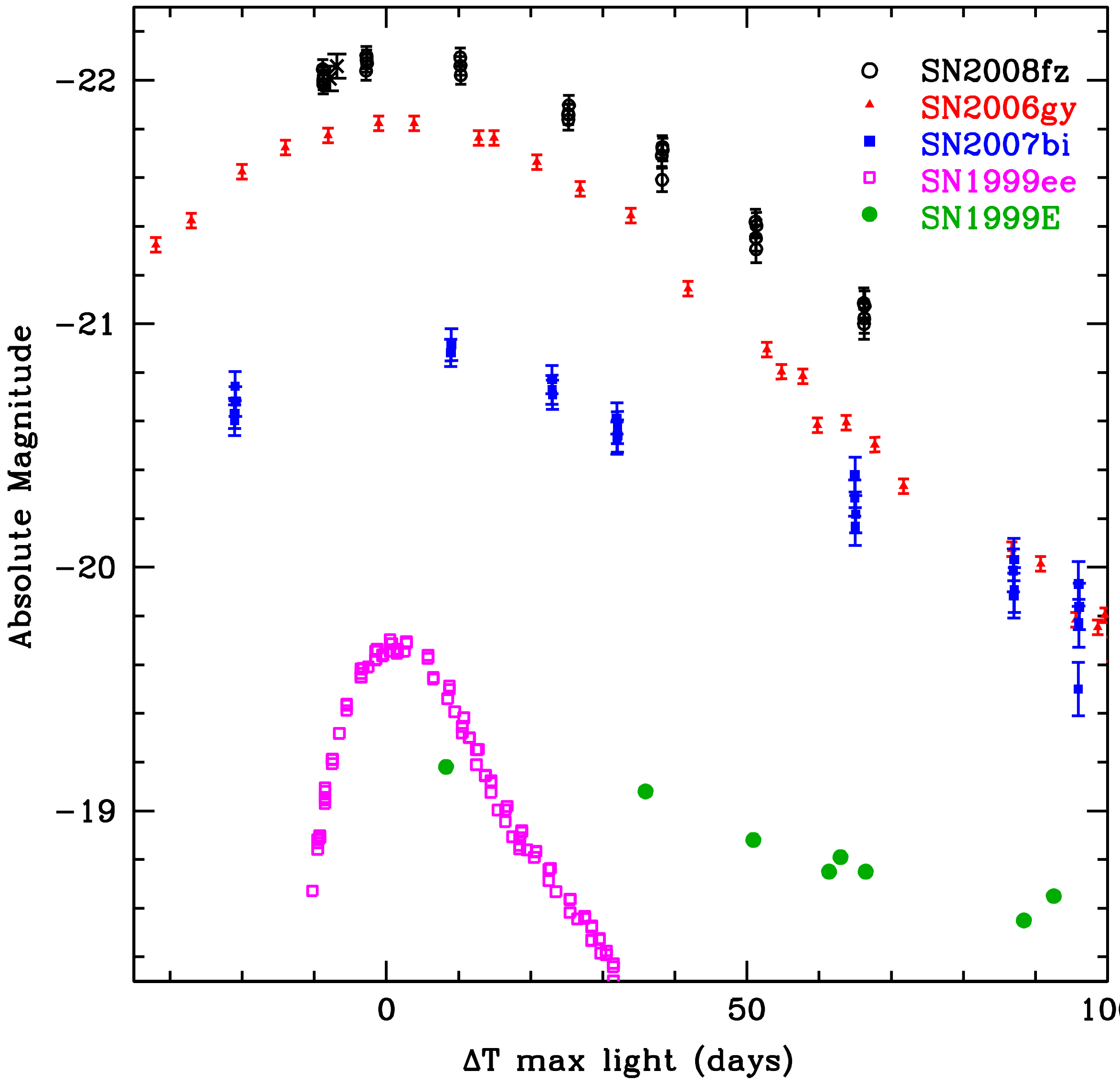
by N.Smith



It was Most Luminous SN ever



Extremely bright Type IIn SNe



V-band
(Drake et al. 2010)

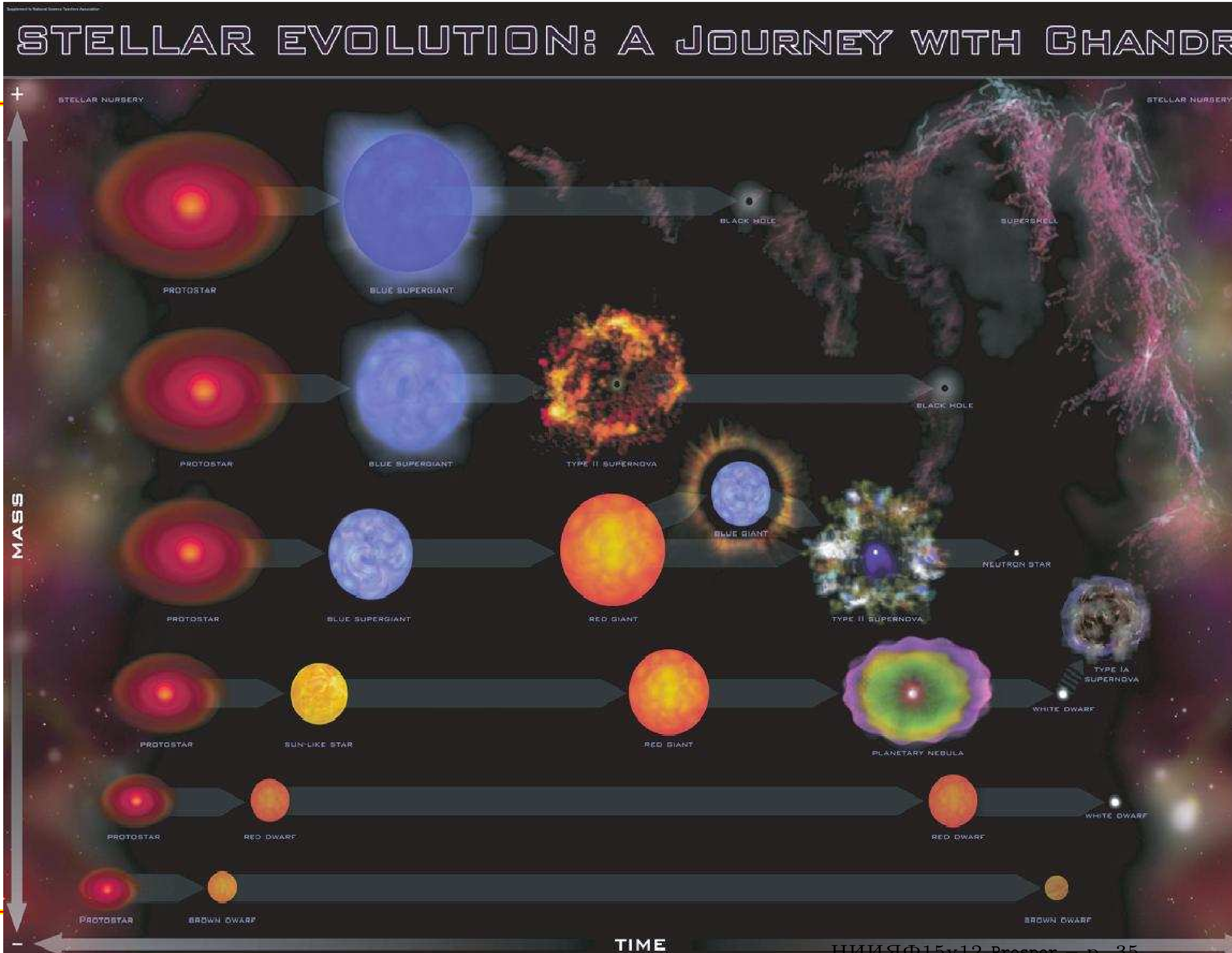
Luminous SN: too many photons?

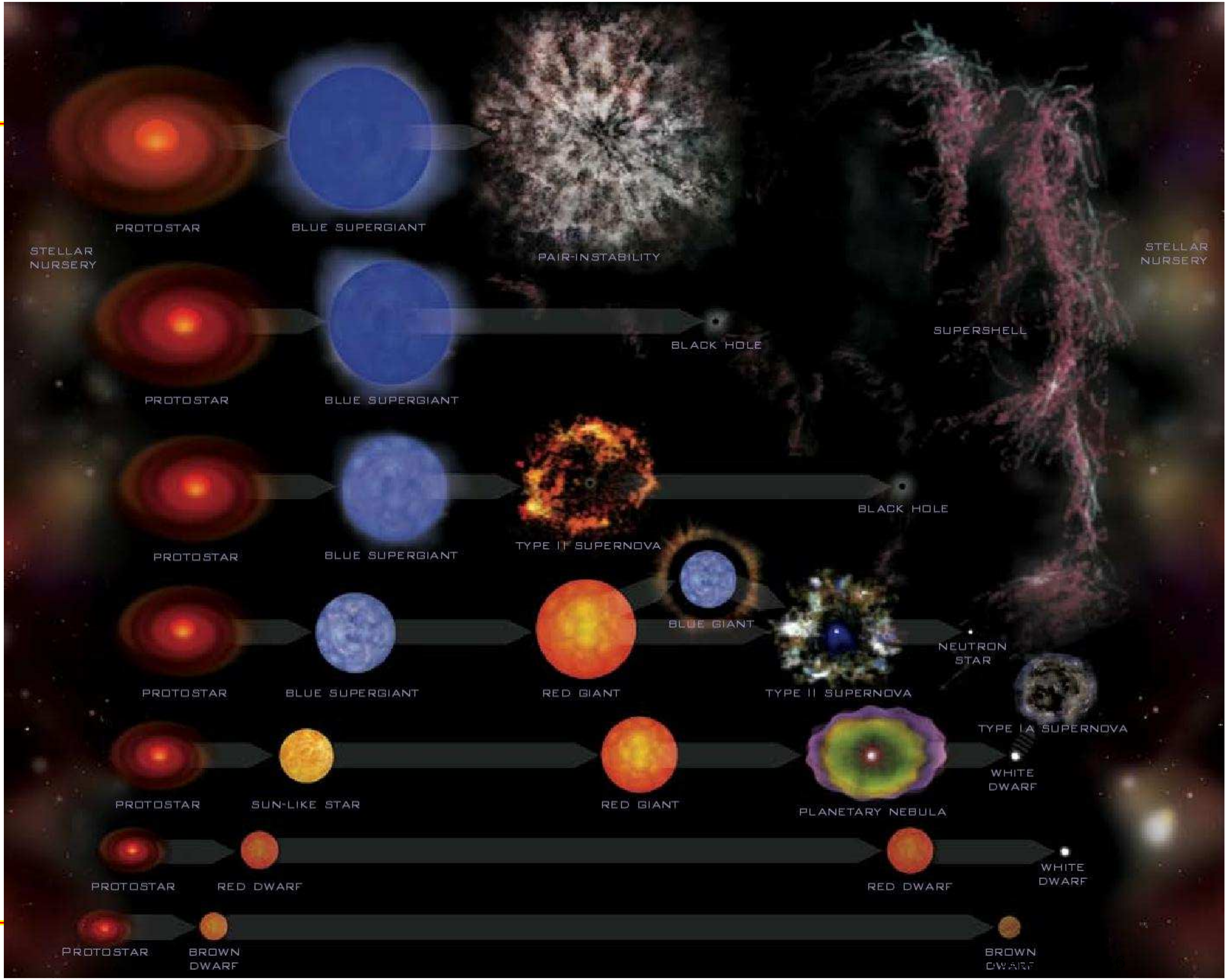
Now we know a few other SNe with peak luminosity even higher than SN 2006gy.

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 large stellar masses.

I will try to explain why the evolution of stars with $M > 10M_\odot$ is quite different from low mass stars, and what happens at $M \sim 100M_\odot$


STELLAR EVOLUTION: A JOURNEY WITH CHANDR
STELLAR NURSERY
STELLAR NURSERY
MASS
+
-
TIME
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
TYPE IA SUPERNOVA
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF


STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
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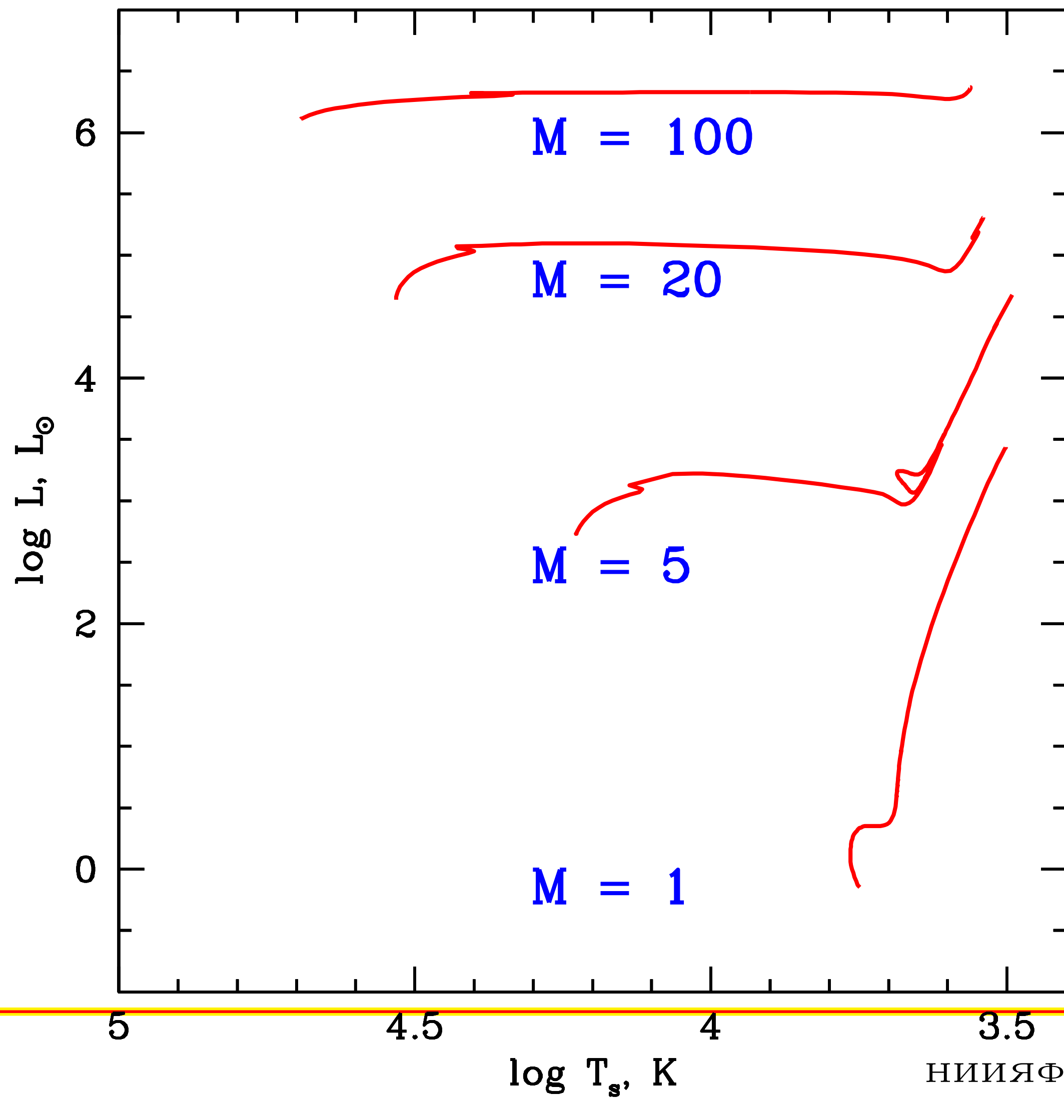
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF

Stellar evolution

HR ($L - T_{\rm eff}$) diagram needed for comparison with observations



Compression in center
even if $R_{\rm out}$ grows

massive than about $2.25M_\odot$ approach a common path, as is shown in Figure 4 (from Iben 1973a). This is a consequence of the fact that the density and pressure distributions in the inner parts of the hydrogen-exhausted core and the rate of energy

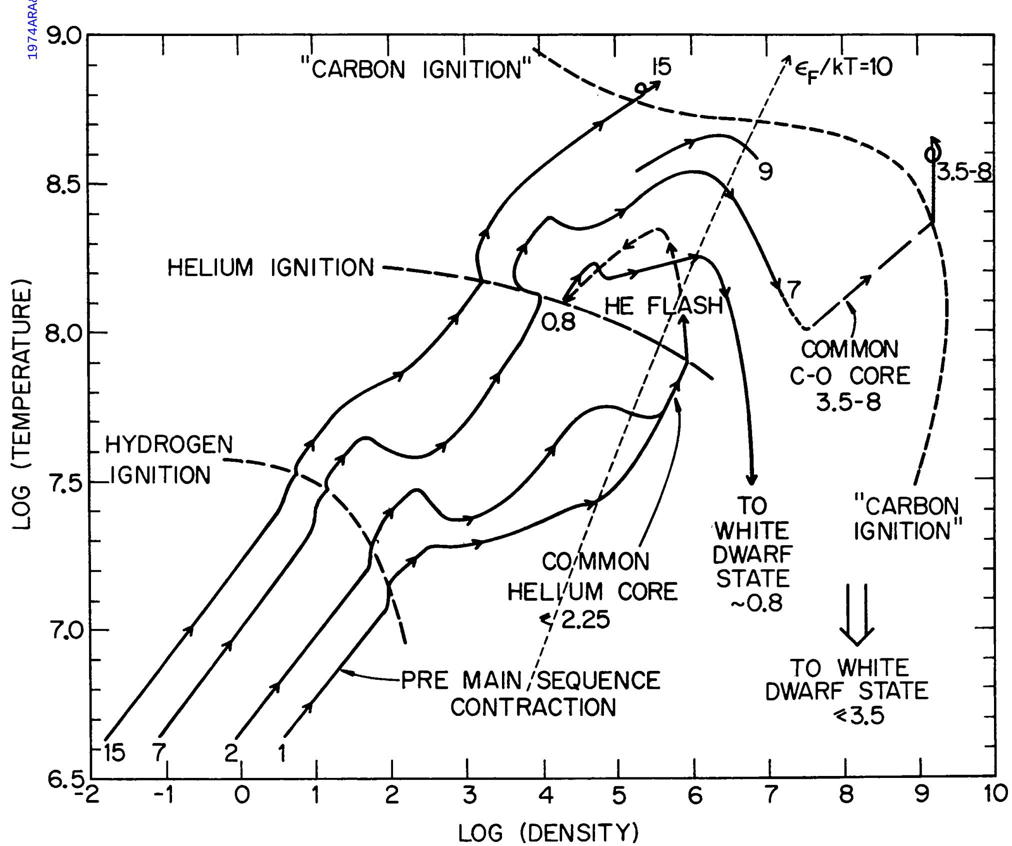


Figure 4 Tracks in the ρ-T plane traced out by the centers of stars of various masses (Iben 1973a).

Central Pressure

Omitting all coefficients of order unity, pressure and density in the center are:

$$P_c \simeq \frac{G_\mathrm{N} M^2}{R^4}, \; \rho_c \simeq \frac{M}{R^3}.$$

and we find

$$P_c \simeq G_\mathrm{N} M^{\frac{2}{3}} \rho_c^{4/3}.$$

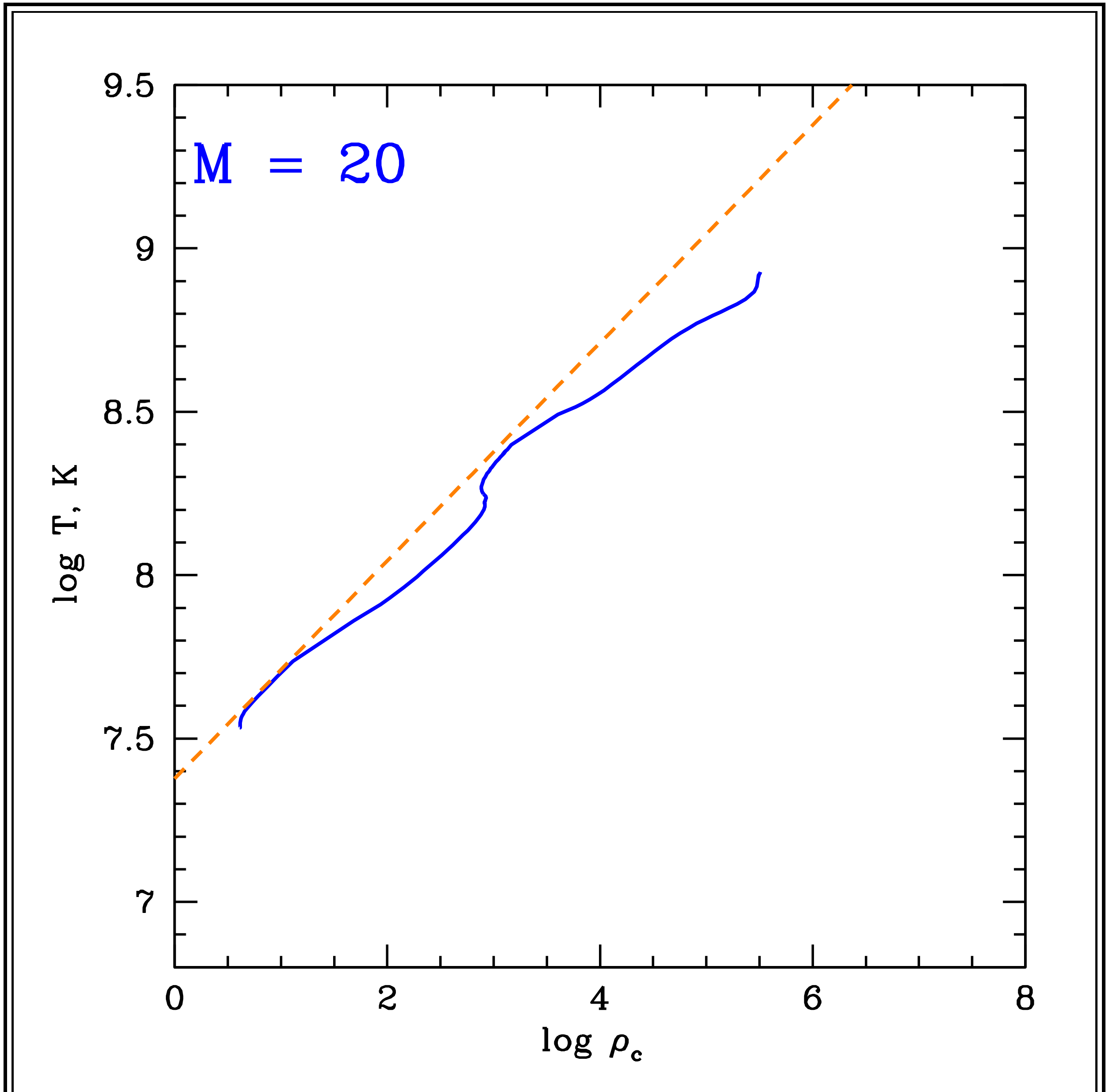
$T_c \propto M^{2/3}\rho_c^{1/3}$ in ND stars

So if we have a classical ideal plasma with $P = \mathcal{R}\rho T/\mu$, where $\mathcal{R}$ is the universal gas constant, and μ – mean molecular mass,

$$T_c \simeq \frac{G_{\mathrm{N}} M^{2/3} \rho_c^{1/3} \mu}{\mathcal{R}}.$$

With $\mu \simeq 1$ for H-He fully ionized plasma we get for the Sun $T_c \simeq 10^7$ K $\simeq 1$ keV.

Now check: $T_c \propto M^{2/3} \rho_c^{1/3}$



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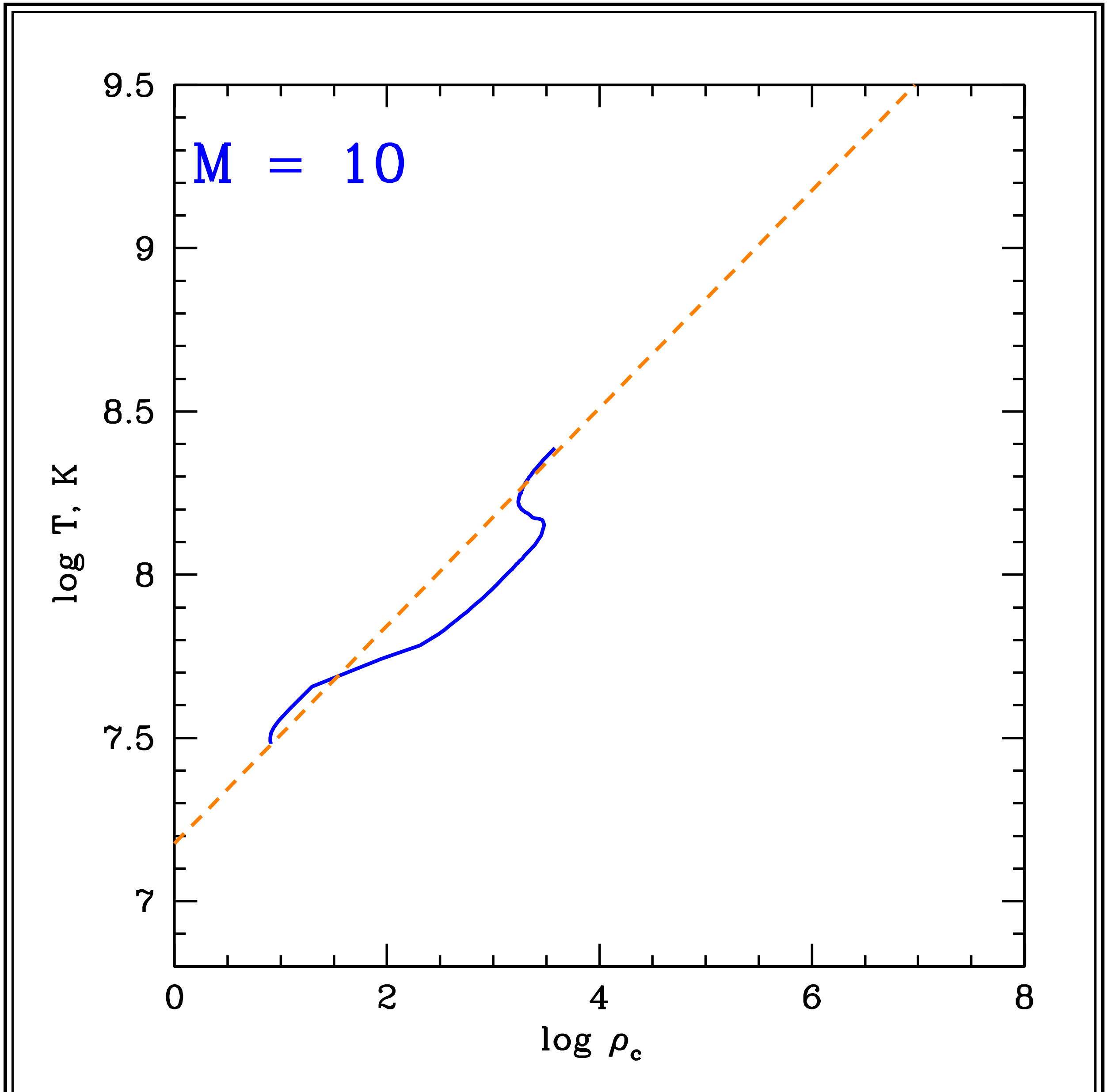
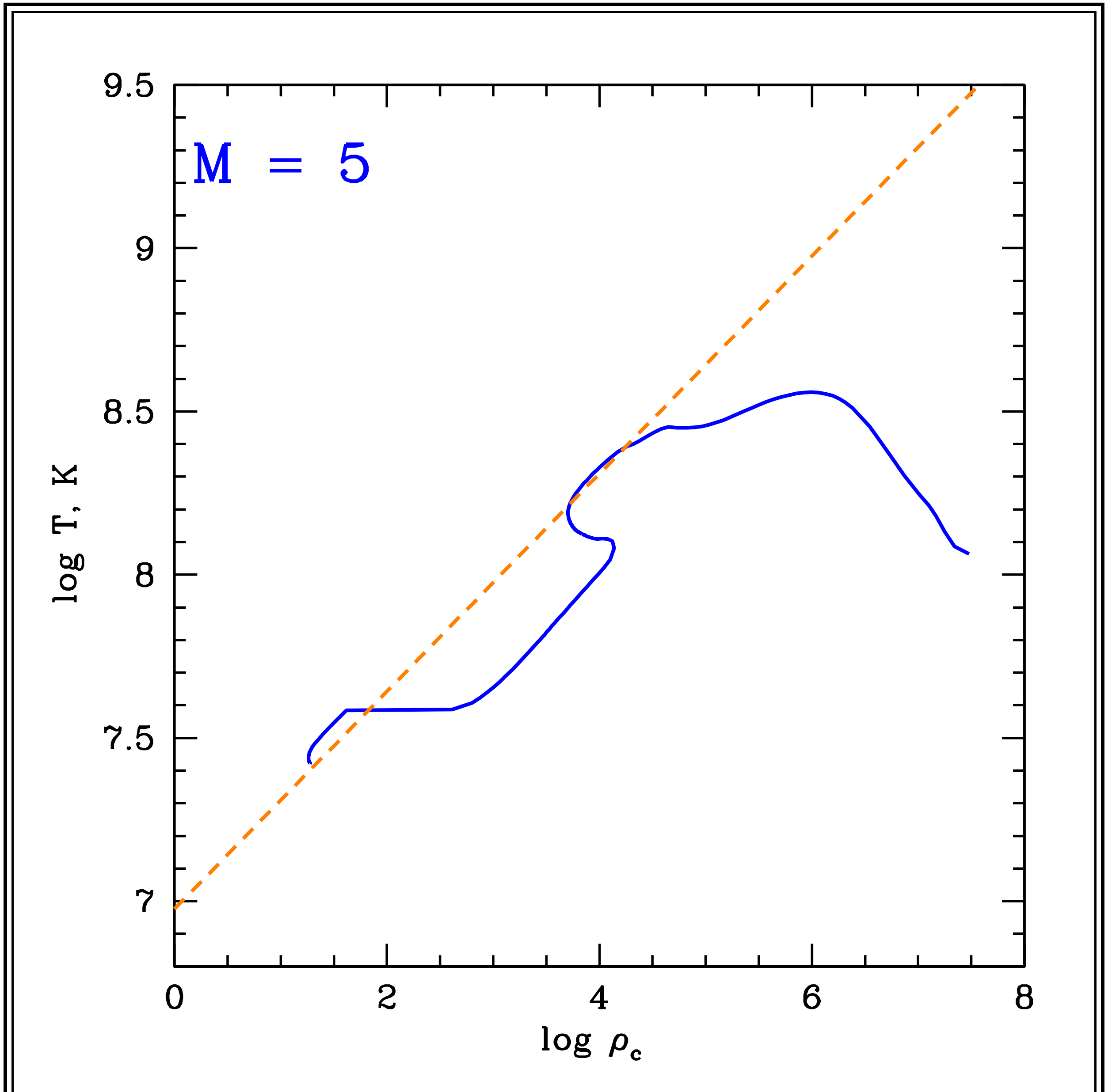
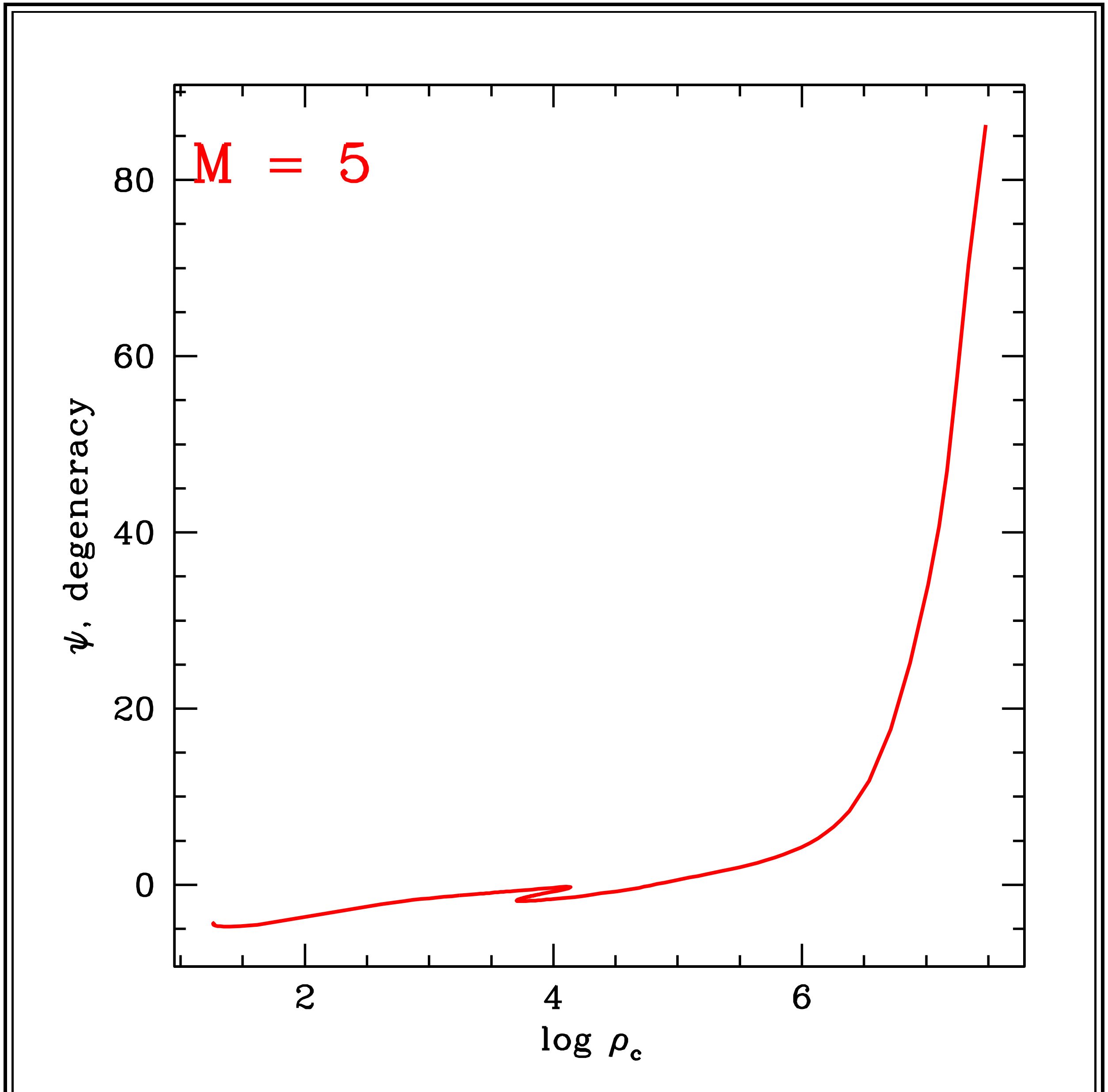


Not so for lower masses



Degeneracy of electrons



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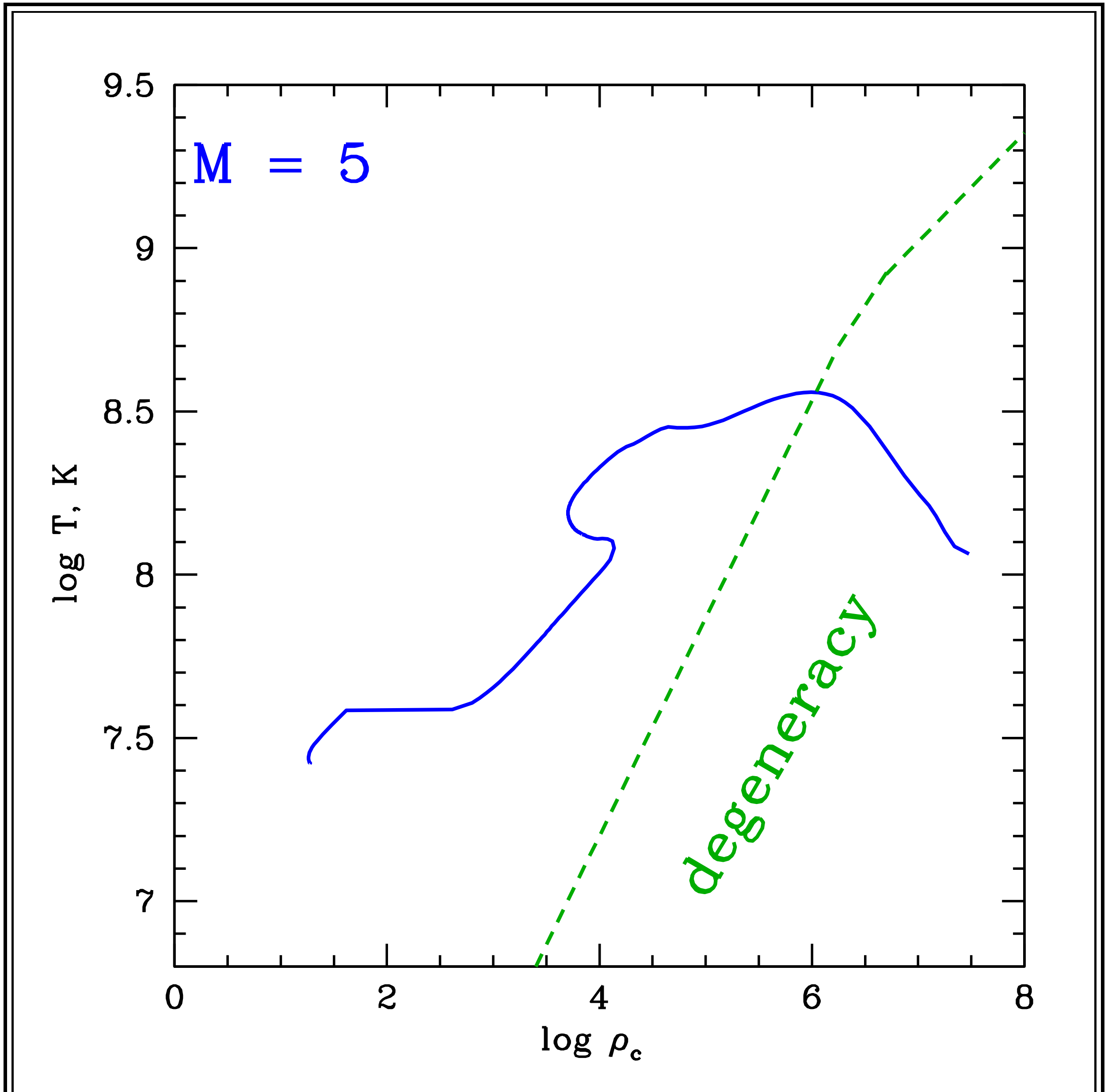
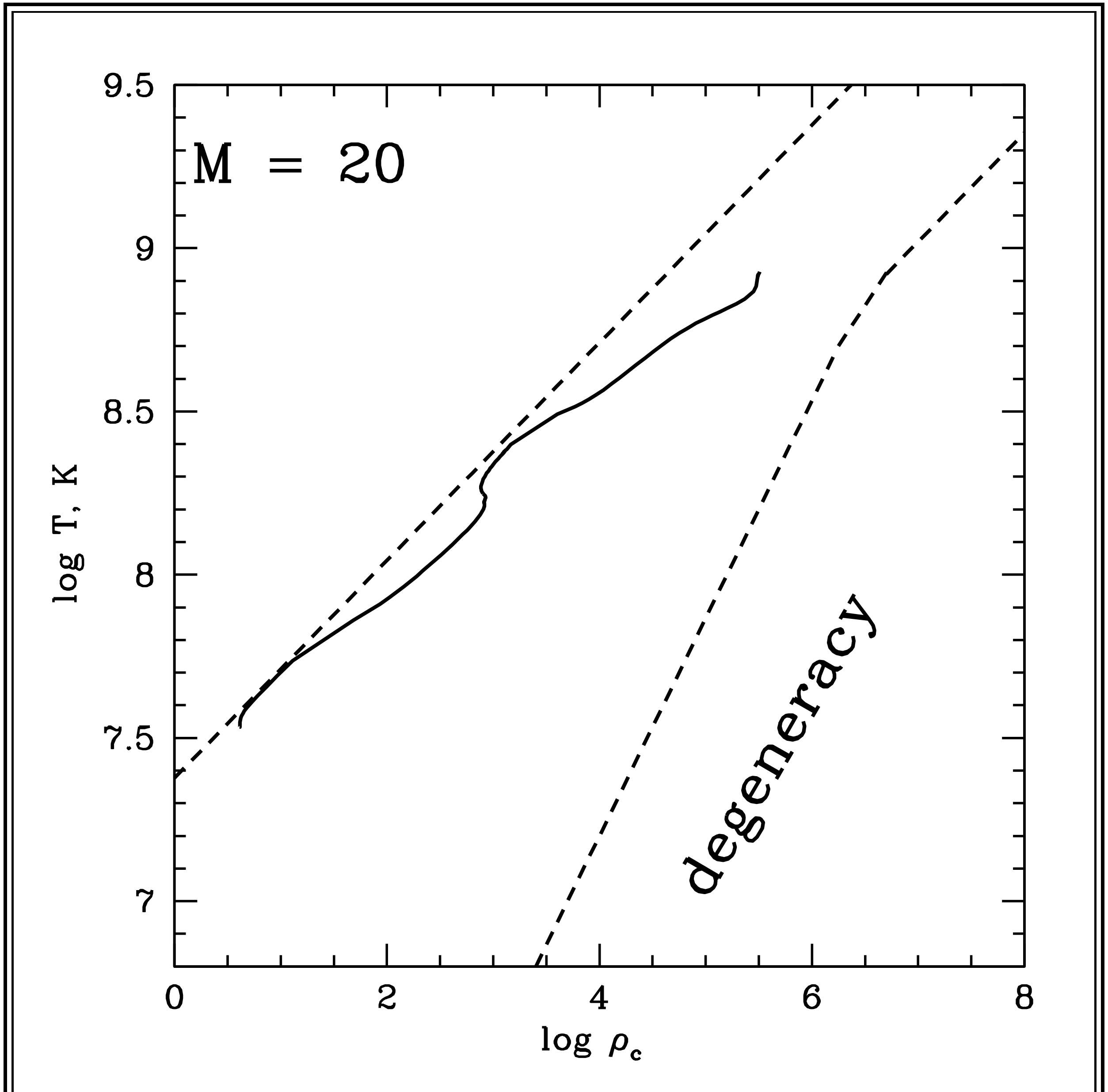
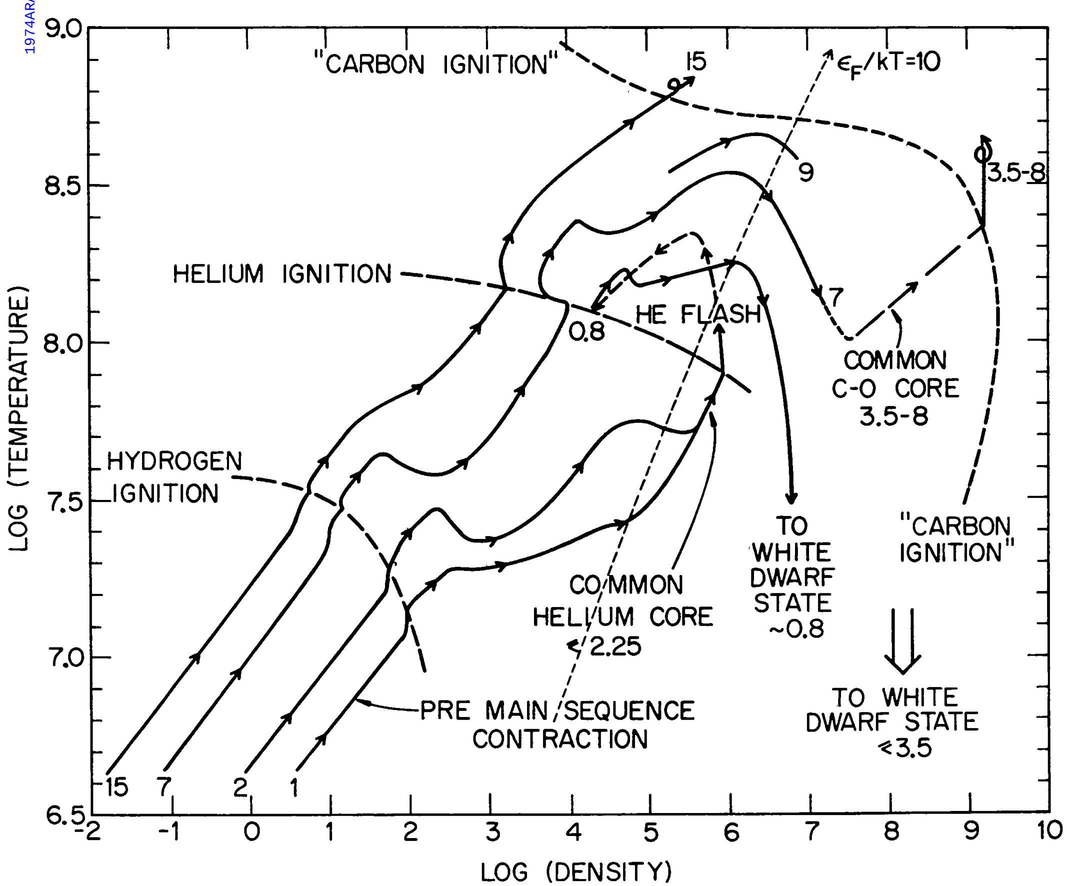


$M > 10 M_\odot$ never degenerate



Compare with old Iben's results

massive than about $2.25 M_{\odot}$ approach a common path, as is shown in Figure 4 (from Iben 1973a). This is a consequence of the fact that the density and pressure distributions in the inner parts of the hydrogen-exhausted core and the rate of energy



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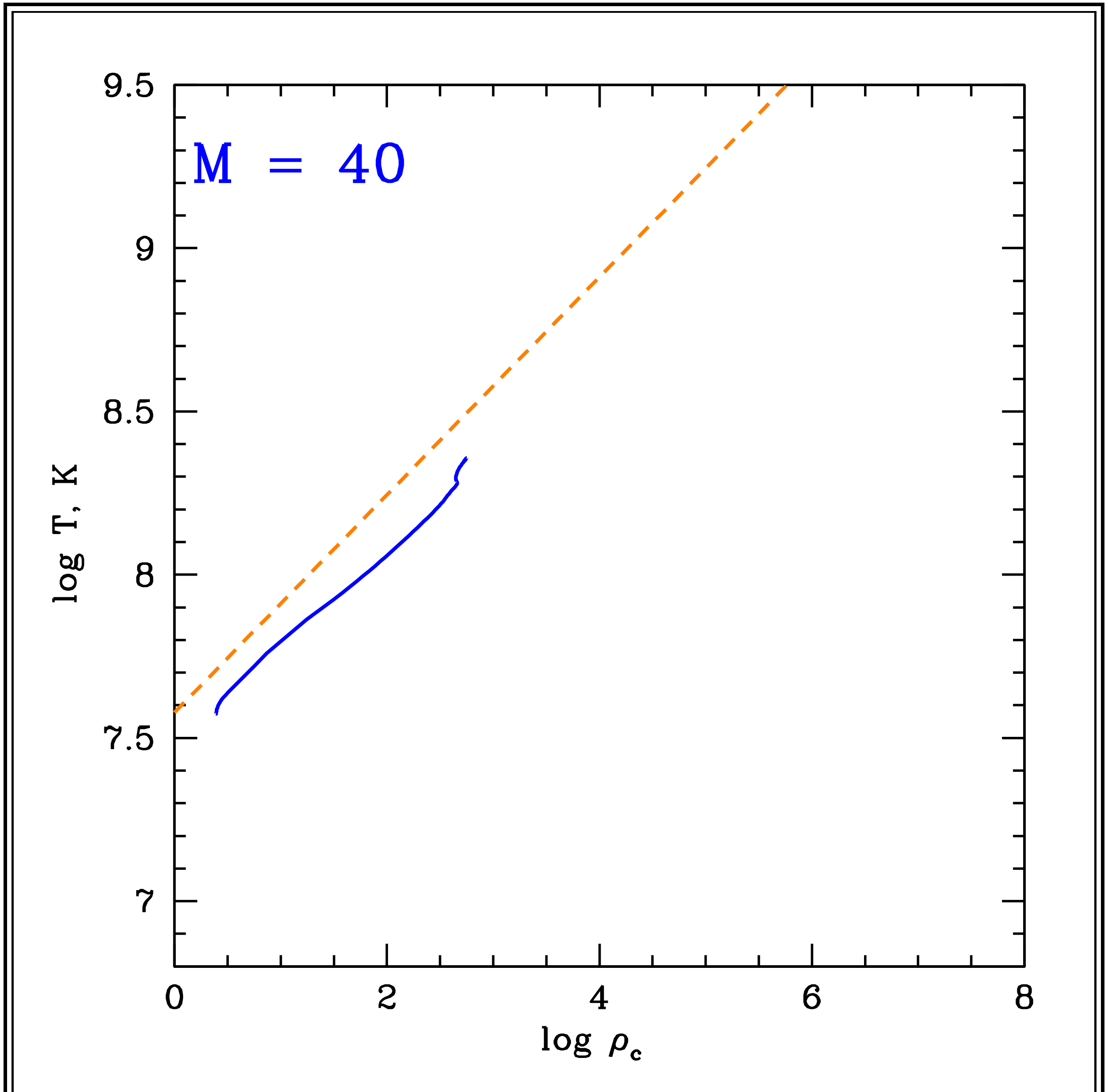

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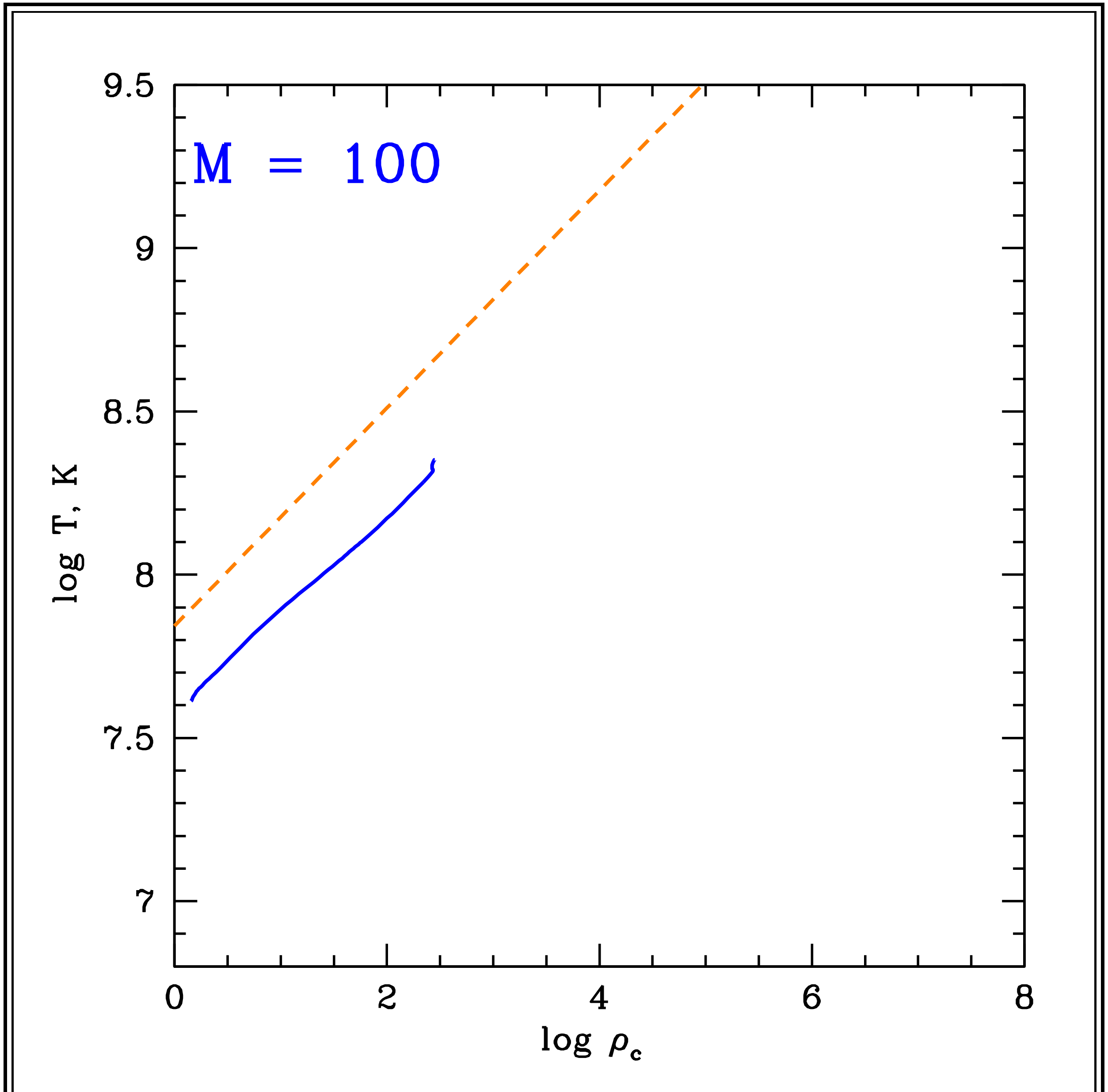
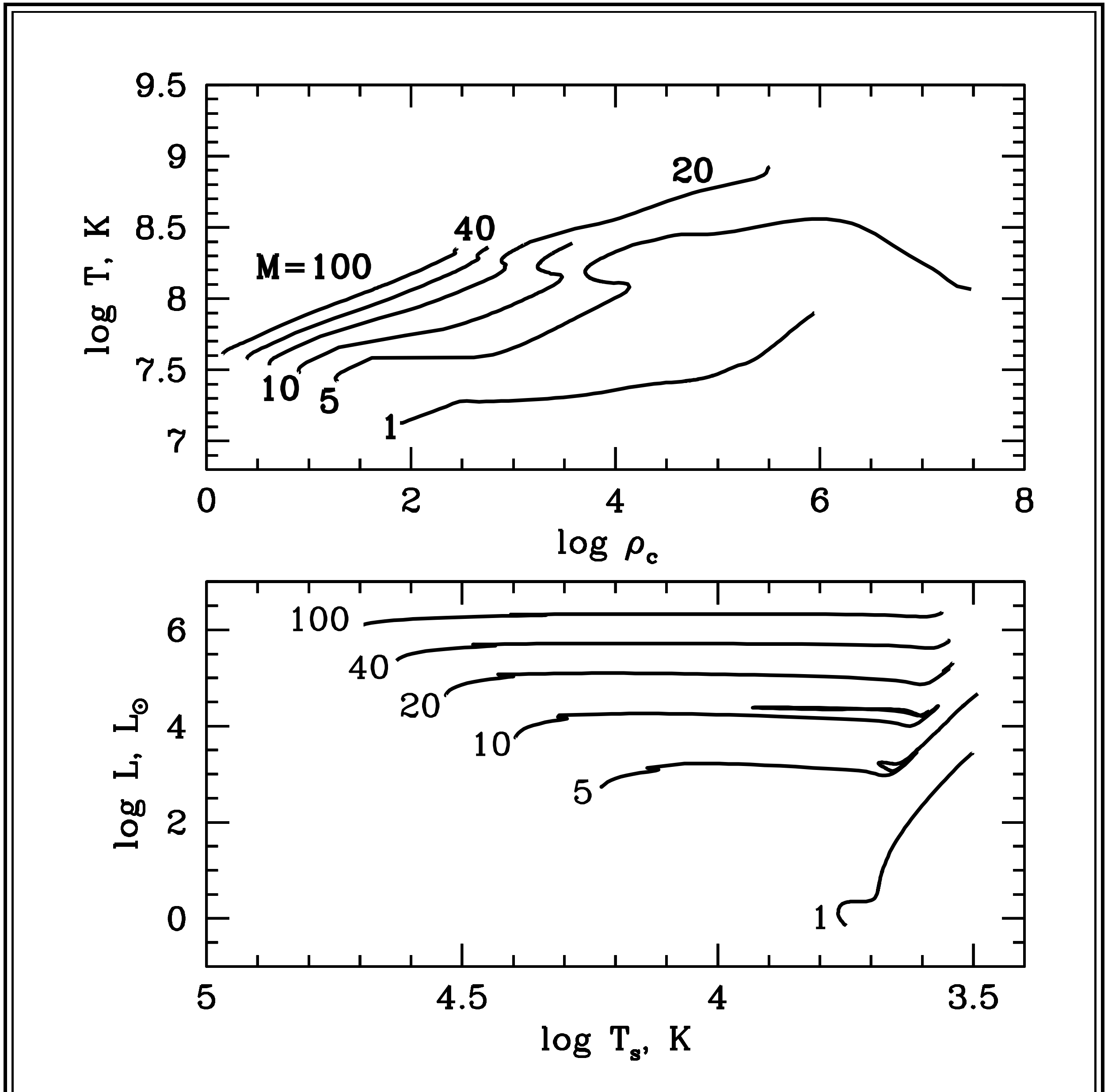


If radiation dominates in P

When plasma is radiation-dominated (for massive stars), then, $P \propto T^4$, and

$$T_c \propto M^{1/6} \rho_c^{1/3}.$$

HR and $T_c - \rho_c$ evolution



Compute stars yourself

Computational Astrophysics:

http://rainman.astro.uiuc.edu/ddr/

The Digital Demo Room

10000 stars evolve together – find on this site – click here

7 stars of masses $20M_{\odot} < M < 80$ evolve in a combined run and explode as SNe – find on this site – click here

The carbon-oxygen cores of low mass stars turn out to be degenerate at the moment when the carbon burning begins. The temperature of their interiors is also strongly affected by the neutrino energy losses. Should the carbon burning only begin in degenerate conditions, it acquires a violent, explosive nature giving rise to the explosion of Type Ia supernovae.

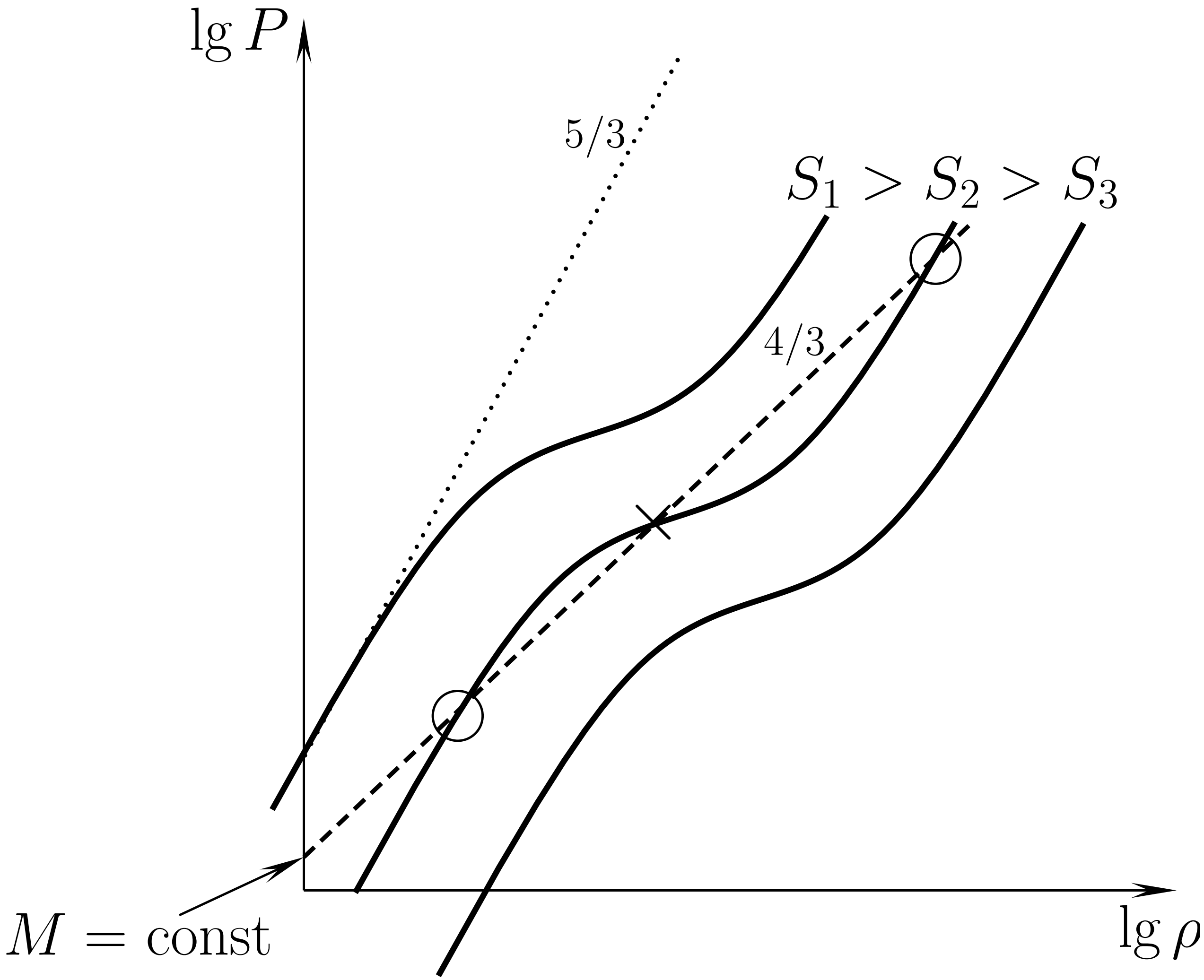
On hydrodynamical instability

Equilibrium requires (in Newtonian gravity):

$$P_c \simeq G_{\mathrm{N}} M^{2/3} \rho_c^{4/3}.$$

This implies that adiabatic exponent $\gamma < 4/3$ may lead to a hydrodynamic instability.

Mechanical stability



Relativistic particles

lead to $\gamma \to 4/3$

We have $\gamma \sim 4/3$ due to high entropy S (photons and e^+e^- pairs).
At low $S \to 0$ we have $\gamma \to 4/3$ due to high Fermi energy of degenerate electrons at high density ρ.

Causes for a collapse: pairs

For very massive stars the radiation pressure $aT^4/3$ must be much larger than $\mathcal{R}\rho T$.
Here per gram

$$E_{\rm th} = aT^4/\rho$$

and from

$$TS = E_{\rm th} + P/\rho \quad \text{for} \quad \mu = 0,$$

we find per unit mass

$$S = \frac{4}{3}\frac{aT^3}{\rho}.$$

Photons and ...

$$T = \left(\frac{3}{4}\frac{S\rho}{a}\right)^{1/3}, \quad P = \frac{1}{3}aT^4 = \frac{a}{3}\left(\frac{3}{4}\frac{S\rho}{a}\right)^{4/3},$$

i.e. $P \propto \rho^{4/3}$ for constant S, and $\gamma = 4/3$. When $T \gtrsim 0.1 m_e c^2$ for small μ in non-degenerate gas the pairs (e^+e^-) are born intensively, so for $T \gg m_e c^2$ the total thermal energy

$$E_{\rm th}\rho = aT^4 + \frac{7}{4}aT^4 = \frac{11}{4}aT^4,$$

$(7a/8)$ is added per each polarization of fermions.
Exact formulae see, e.g., SB,Dunina-Barkovskaya,DKN, 1996, ApJS.

. . . and e^+e^- pairs

pressure

$$P = \frac{11}{12} a T^4,$$

and entropy per gram

$$S = \frac{11}{3} \frac{aT^3}{\rho}.$$

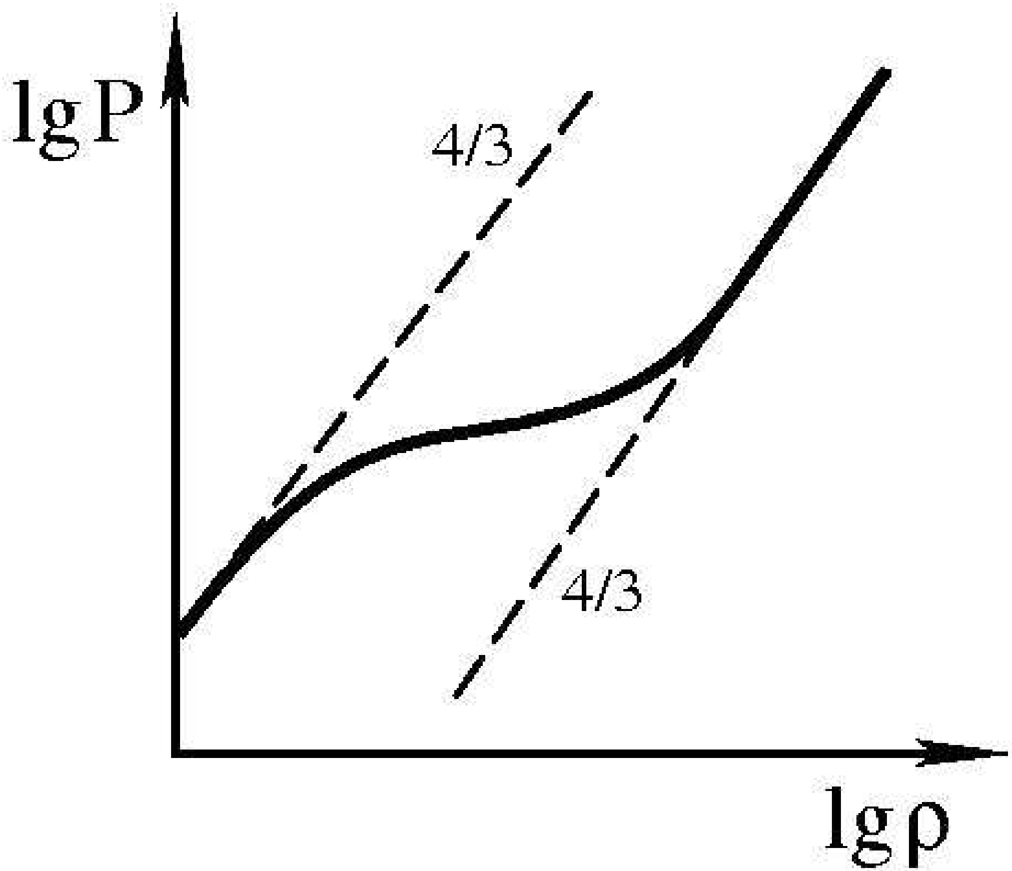
Thus for $T \gg m_e c^2$ again $P \sim \rho^{4/3}$, but the coefficient is smaller

$$P = \frac{11}{12} a T^4 = \frac{11a}{12} \left(\frac{3}{11} \frac{S\rho}{a} \right)^{4/3},$$

so in between the slope $\log P - \log \rho$ must be less than $4/3$.

Pair instability

A radiation dominated star was already at the verge of the loss of the stability ($P \propto \rho^{4/3}$), and now it is unstable if ($\gamma < 4/3$).



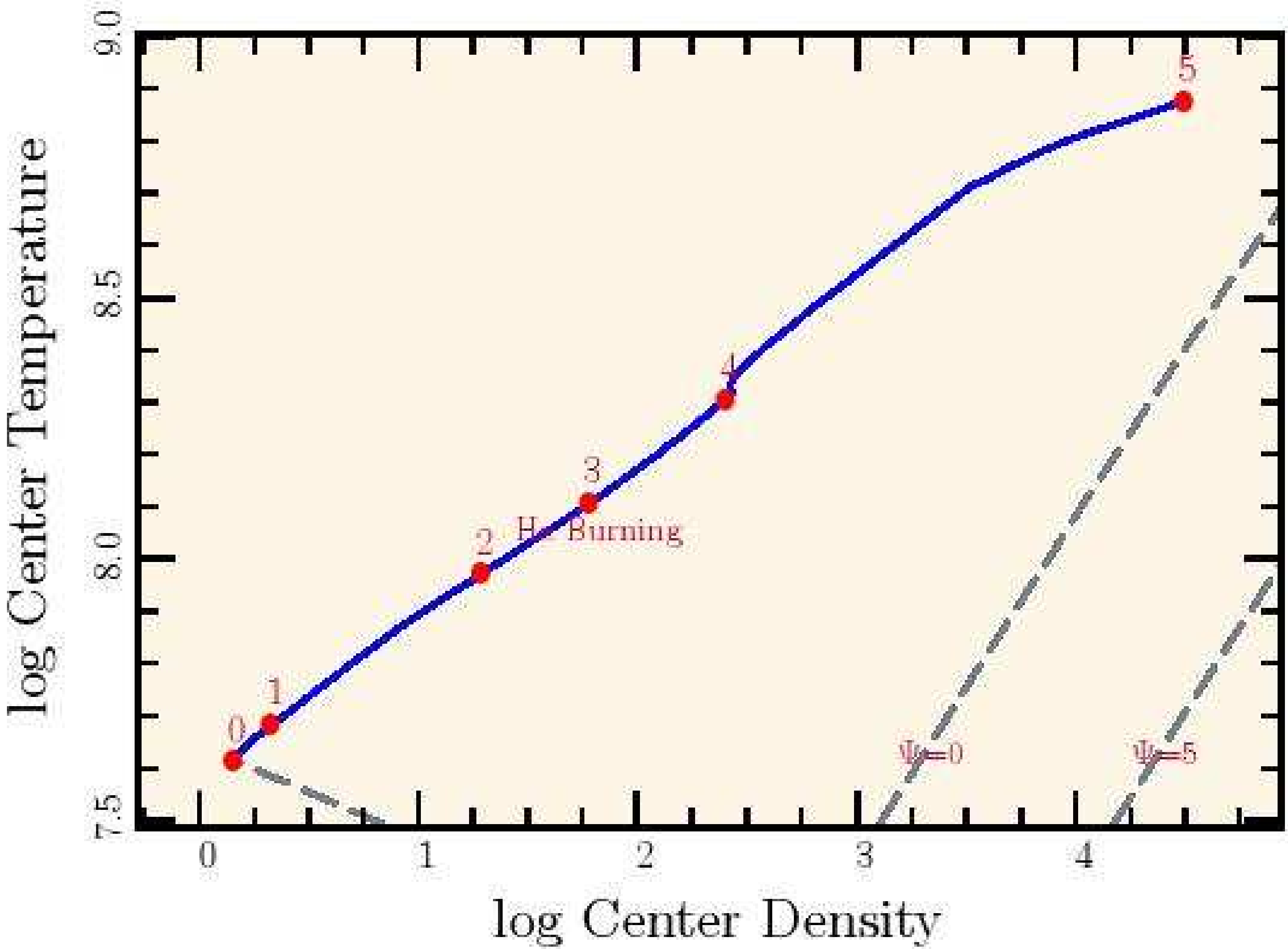
Open evolution code

Hertzsprung-Russell and Center Temperature-Density Tracks for Metallicity Z = 0.02. The “He” symbols show where the net of power from nuclear reactions beyond hydrogen burning minus neutrino losses from all sources reaches the break-even point.

Paxton: P.Eggleton evolution code

Higher mass means higher T_c

for the same ρ, hence pair creation



Open evolution code

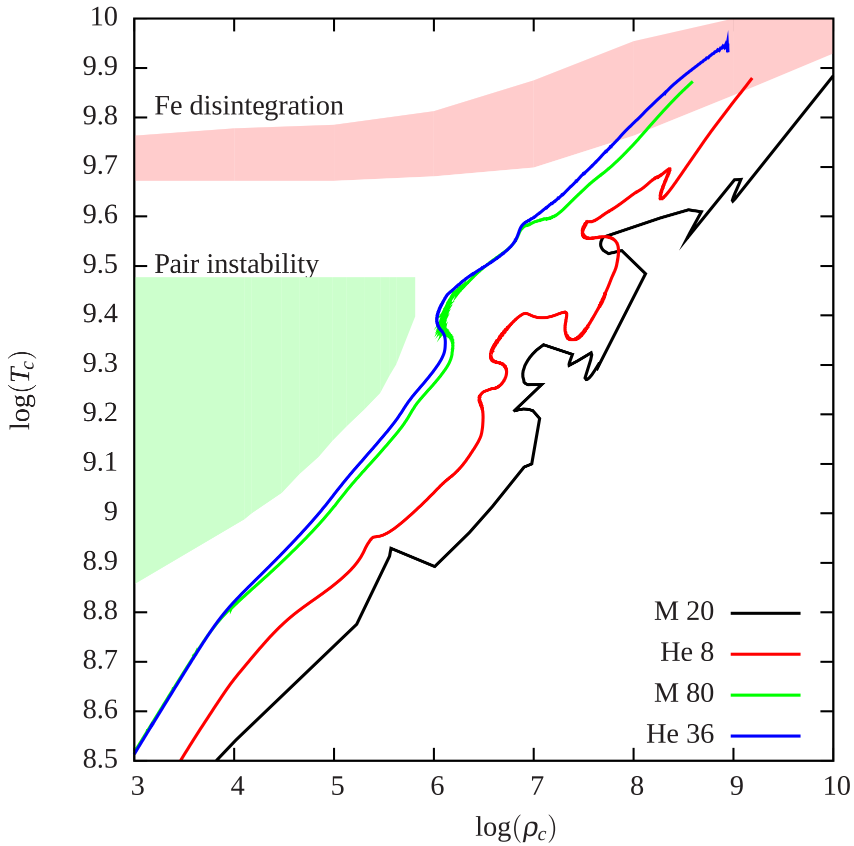
Previous plot is taken from here

$\boxed{\text{Paxton: P.Eggleton evolution code}}$

Centre Temperature-Density Tracks for Metallicity $Z = 0.02$.
The “He” symbols show where the net of power from nuclear reactions beyond hydrogen burning minus neutrino losses from all sources reaches the break-even point.

Более наглядные графики ниже — Roni Waldman `arXiv:0806.3544`.
Better looking plots below are from Roni Waldman’s eprint `arXiv:0806.3544`.

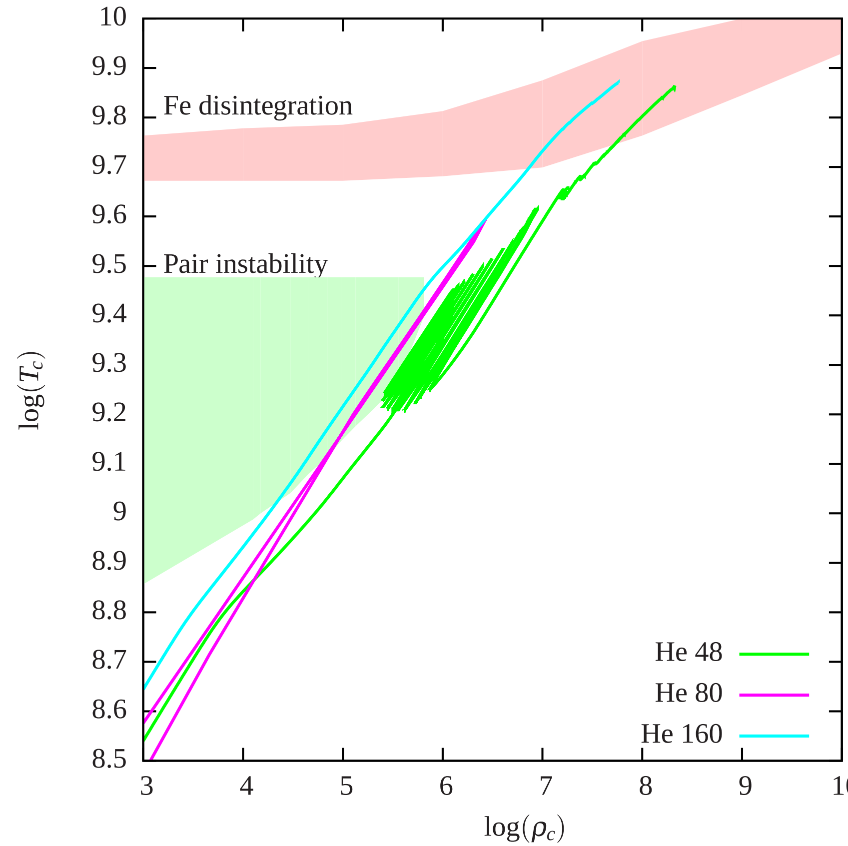
Massive stars and their He-cores



Each line is labeled "M" for stellar models and "He" for He-core models, followed by the mass of the model or of the core. Here are stars that reach core collapse avoiding pair instability.

3 outcomes of pair-instability

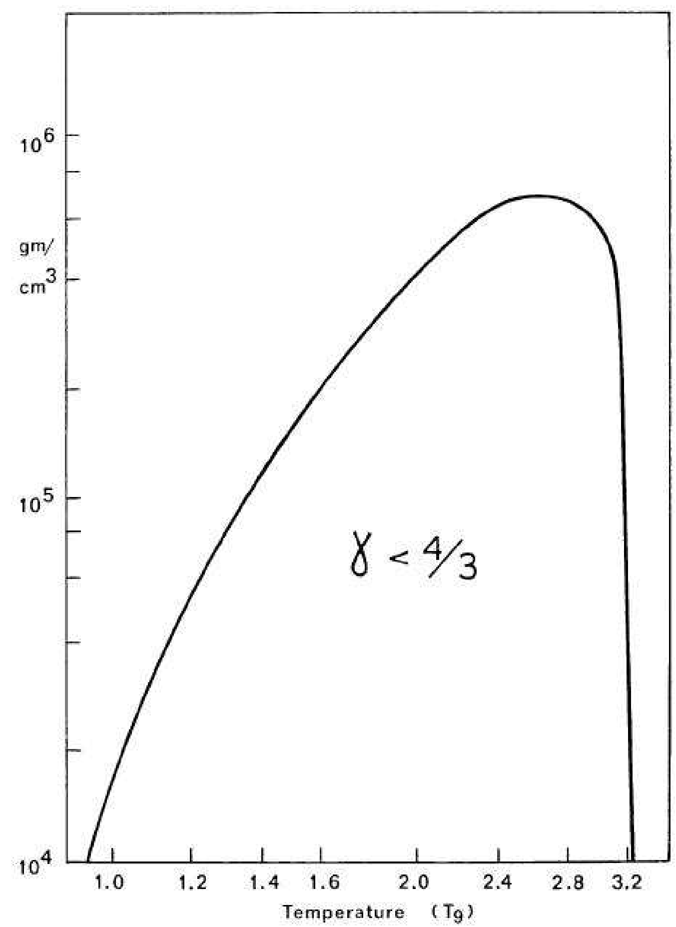
Here are only He-core models, labeled by “He” and the mass of the core. They all reach pair instability, subsequently experiencing 1) pulsations (He48), 2) complete disruption (He80), or 3) direct collapse (He160).



$\gamma < 4/3$ domain in $T - \rho$ plane

Gary S. Fraley 1968. Pair-instability SNe

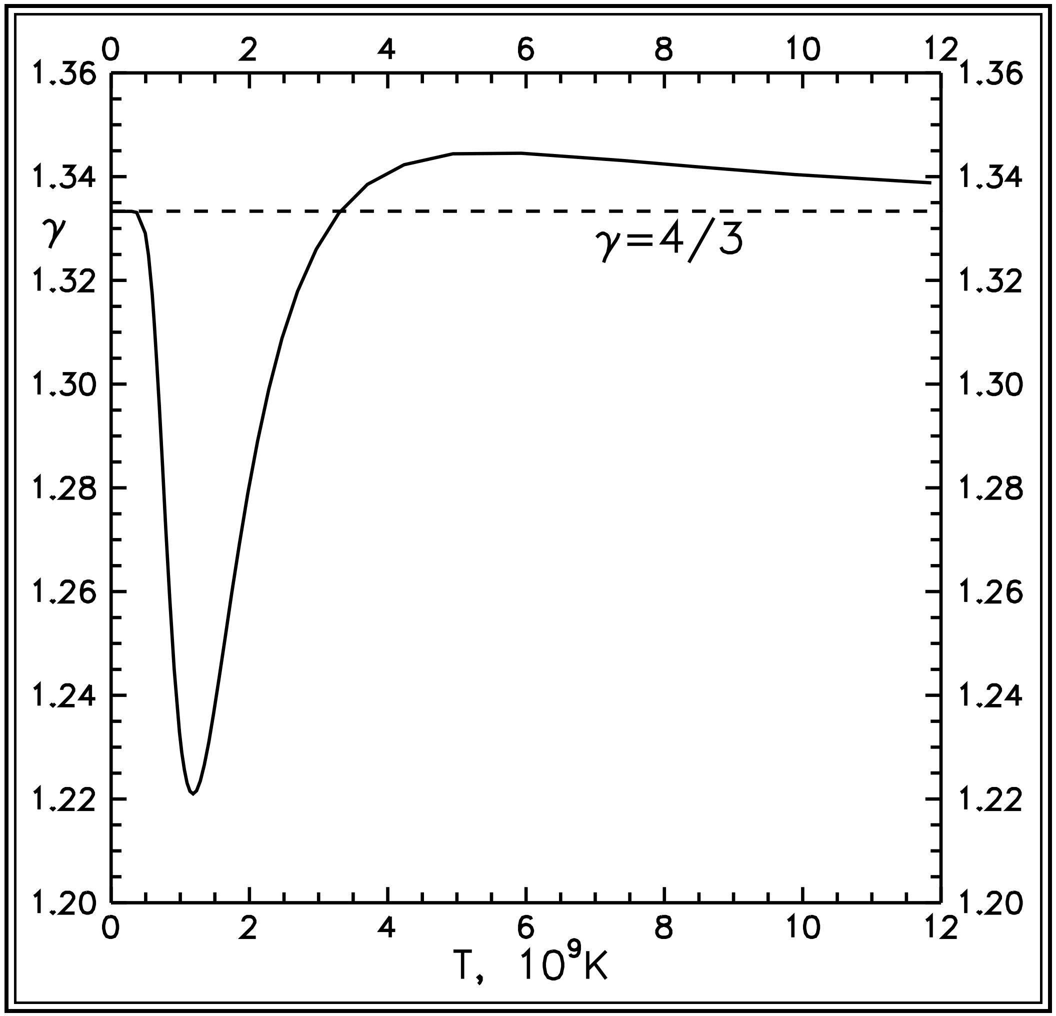
SUPERNOVAE EXPLOSIONS INDUCED BY PAIR-PRODUCTION INSTABILITY



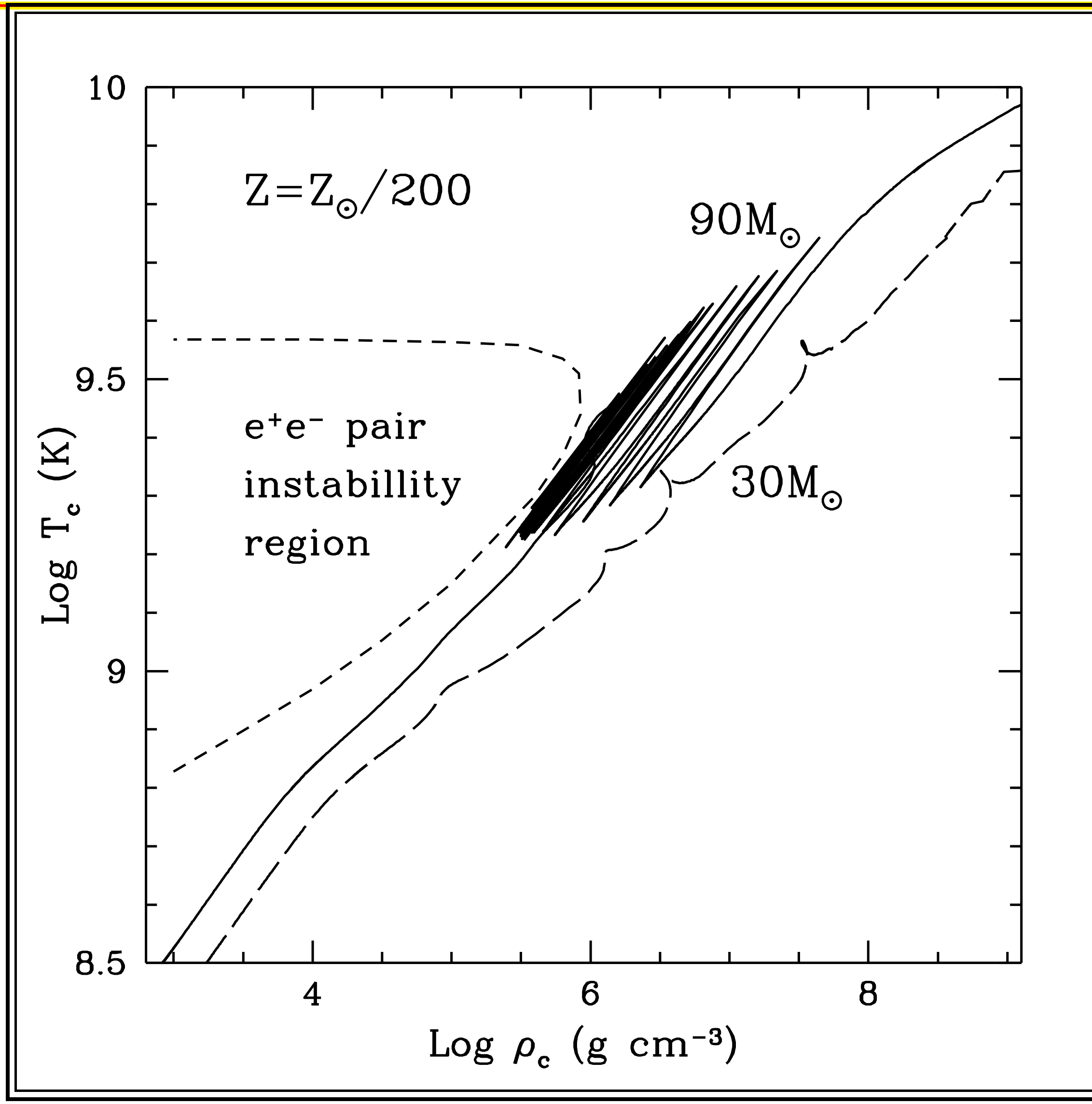
The area in which γ becomes less than $\frac{4}{3}$ due to electron-positron pair production

Adiabatic γ for pairs at very low density

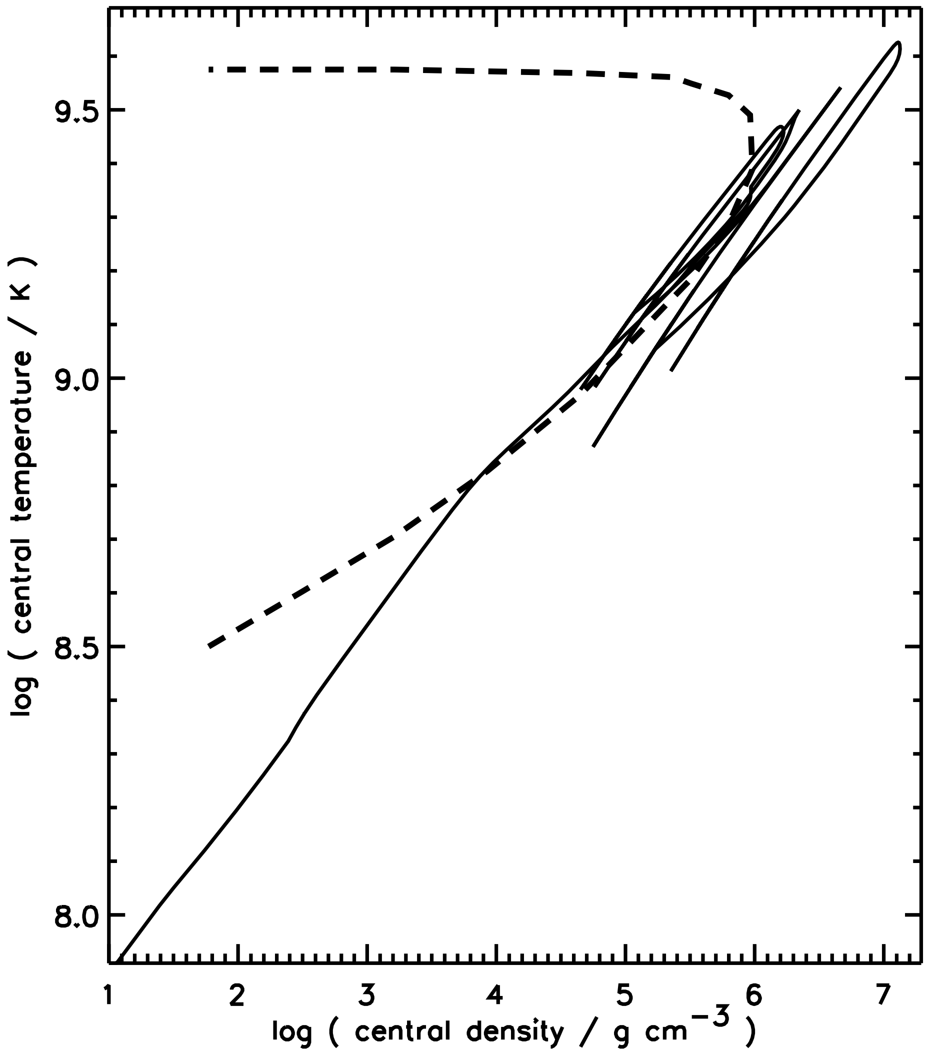
D.K.Nadyozhin 1974, see SB,Dunina-Barkovskaya,DKN, 1996, ApJS



Umeda and Nomoto 2007

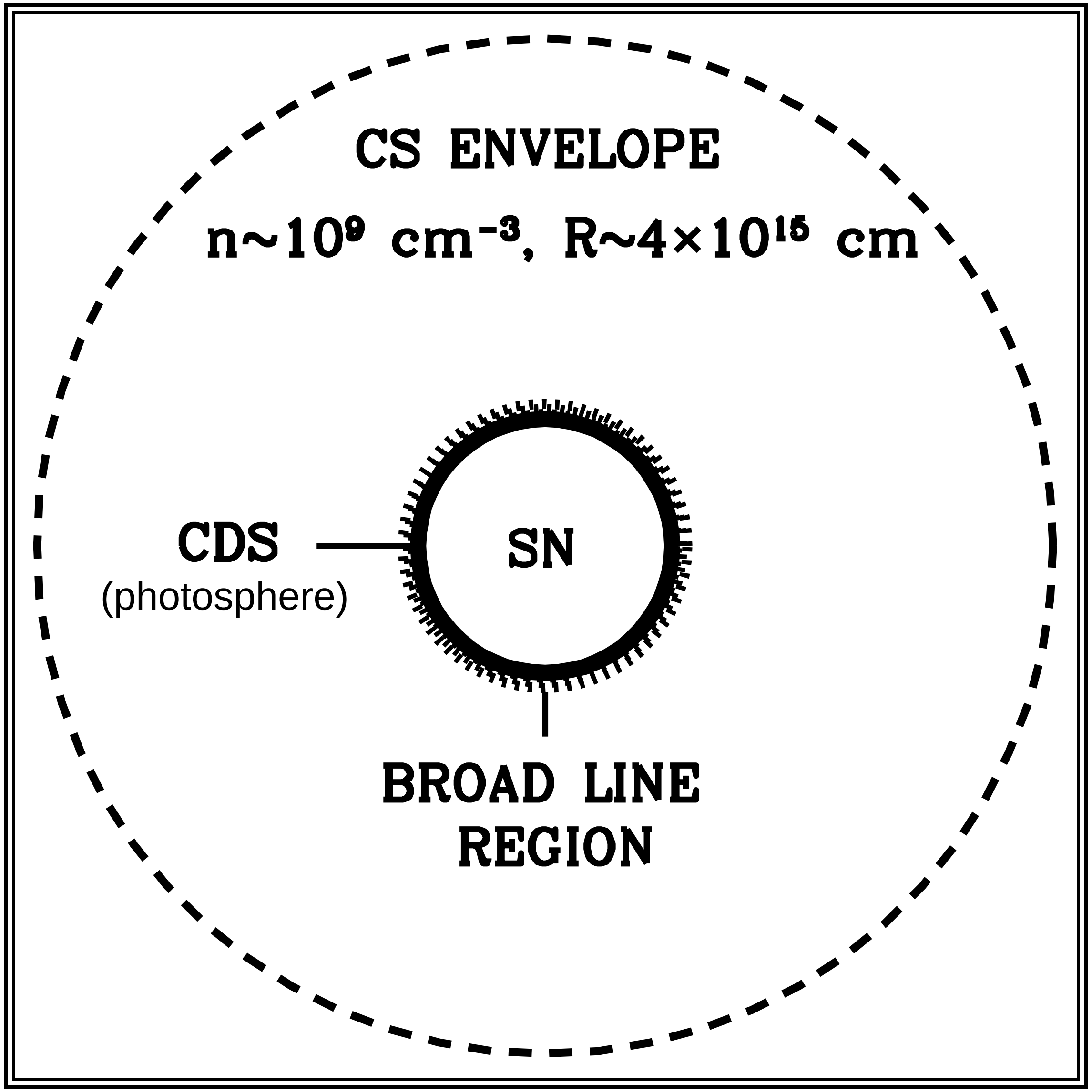


Woosley et al. 2007, 103 $M_\odot$ star



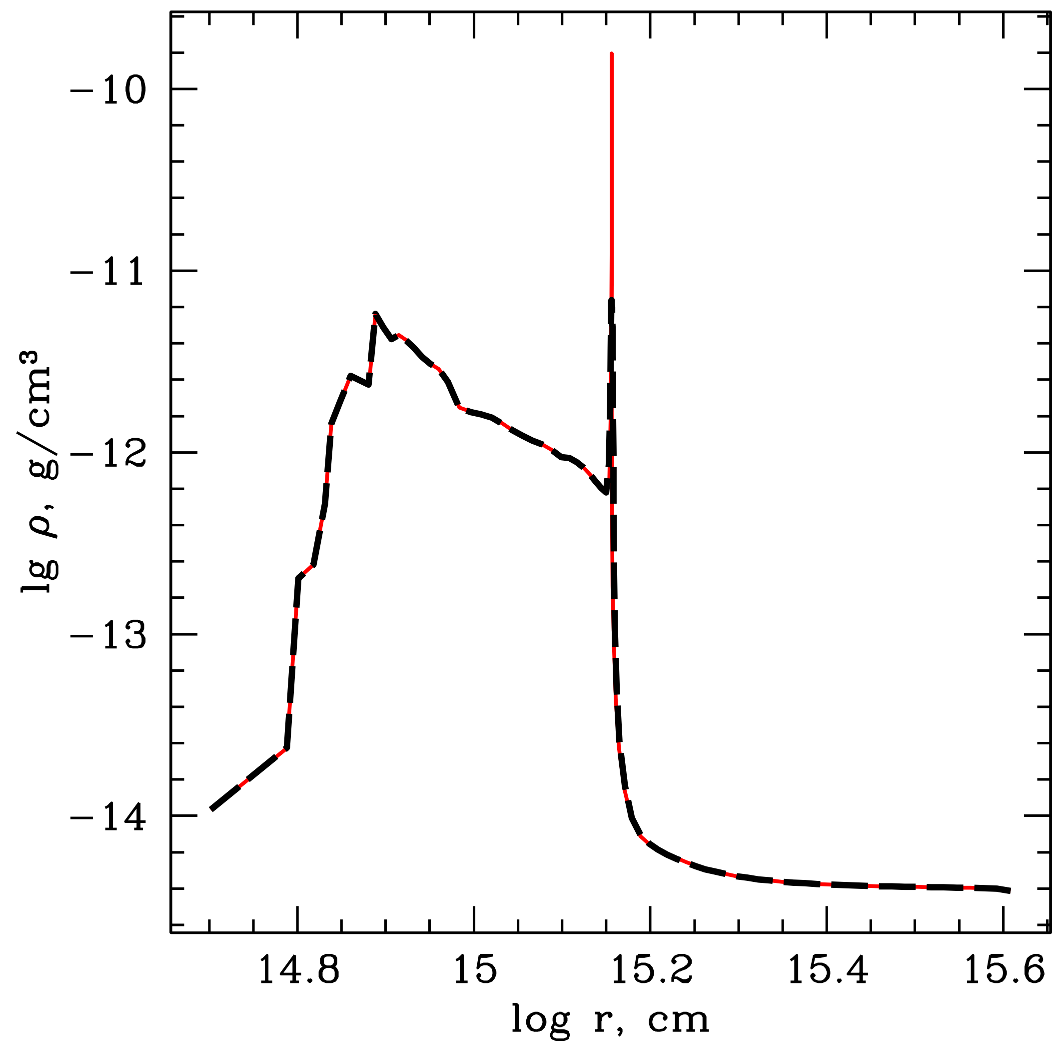
This gives the Most Luminous Supernovae (!), because, instead of one SN explosion, we have several mass ejections and collisions of mass shells which produce bright radiating shocks.

SN IIn structure, Chugai, SB ea'04

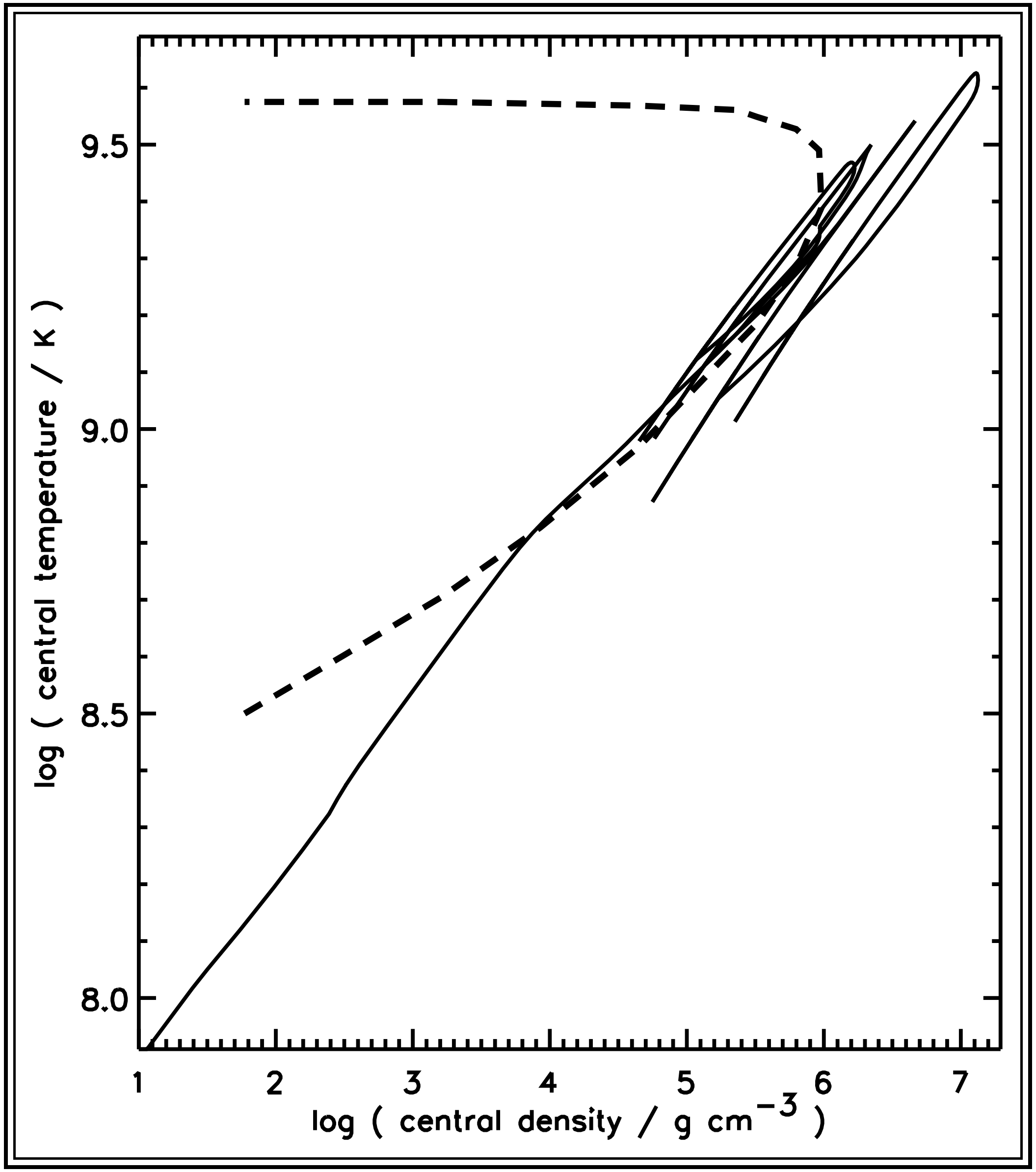


Shocks in SNe IIn

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.

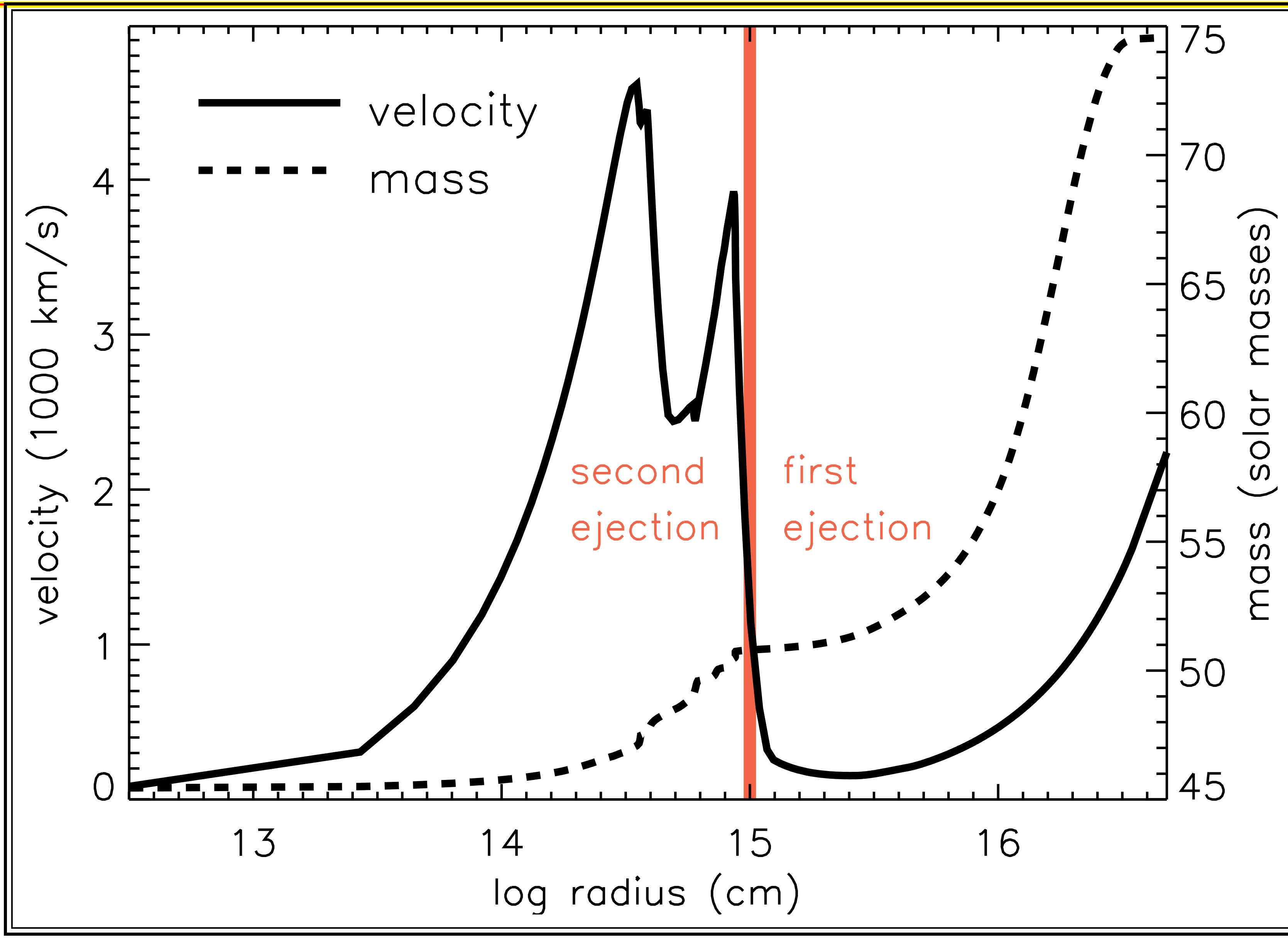


Woosley, Blinnikov, Heger, s103



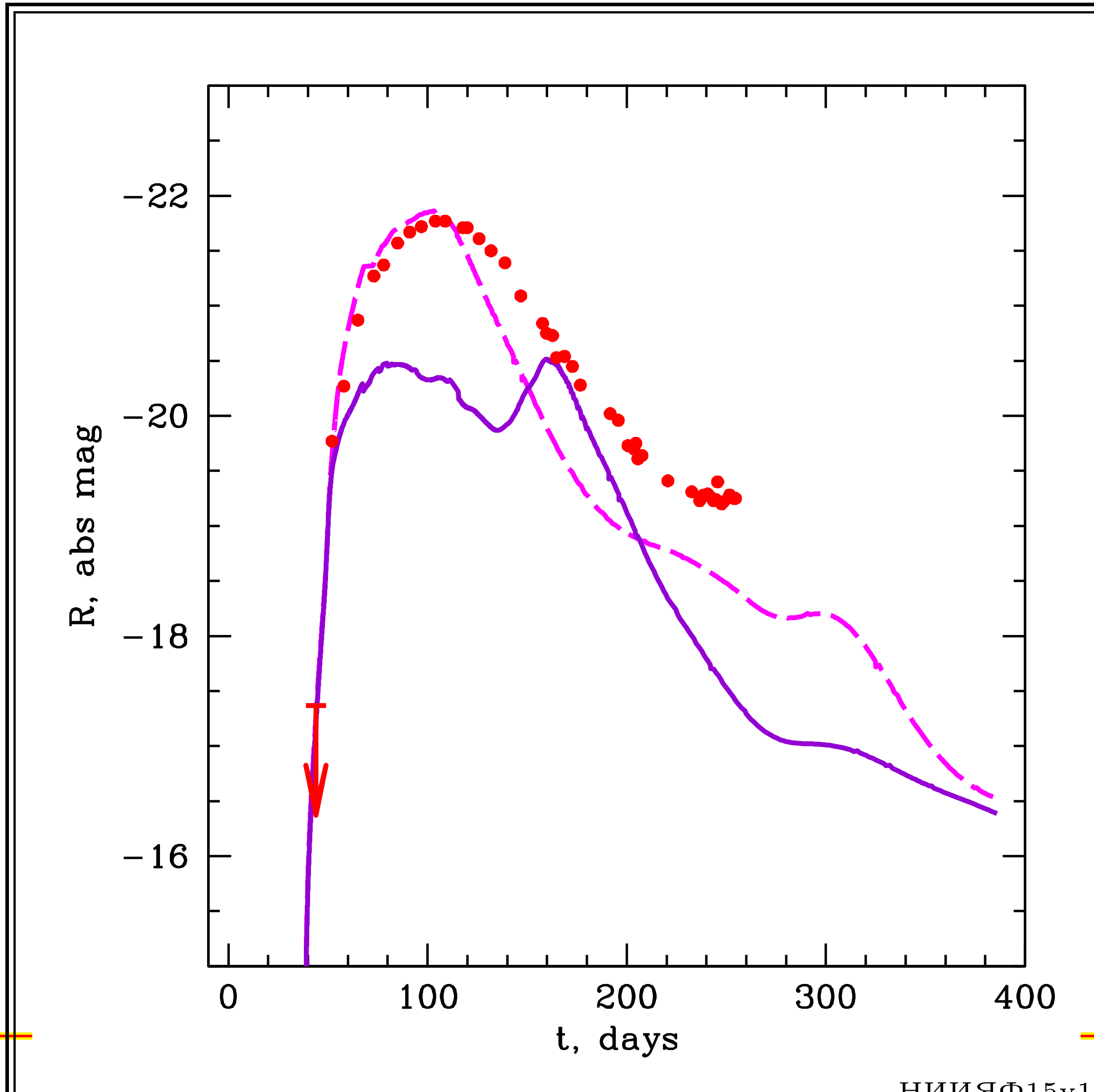
Pulsational pair instability may give the Most Luminous Supernovae!

Two mass ejections



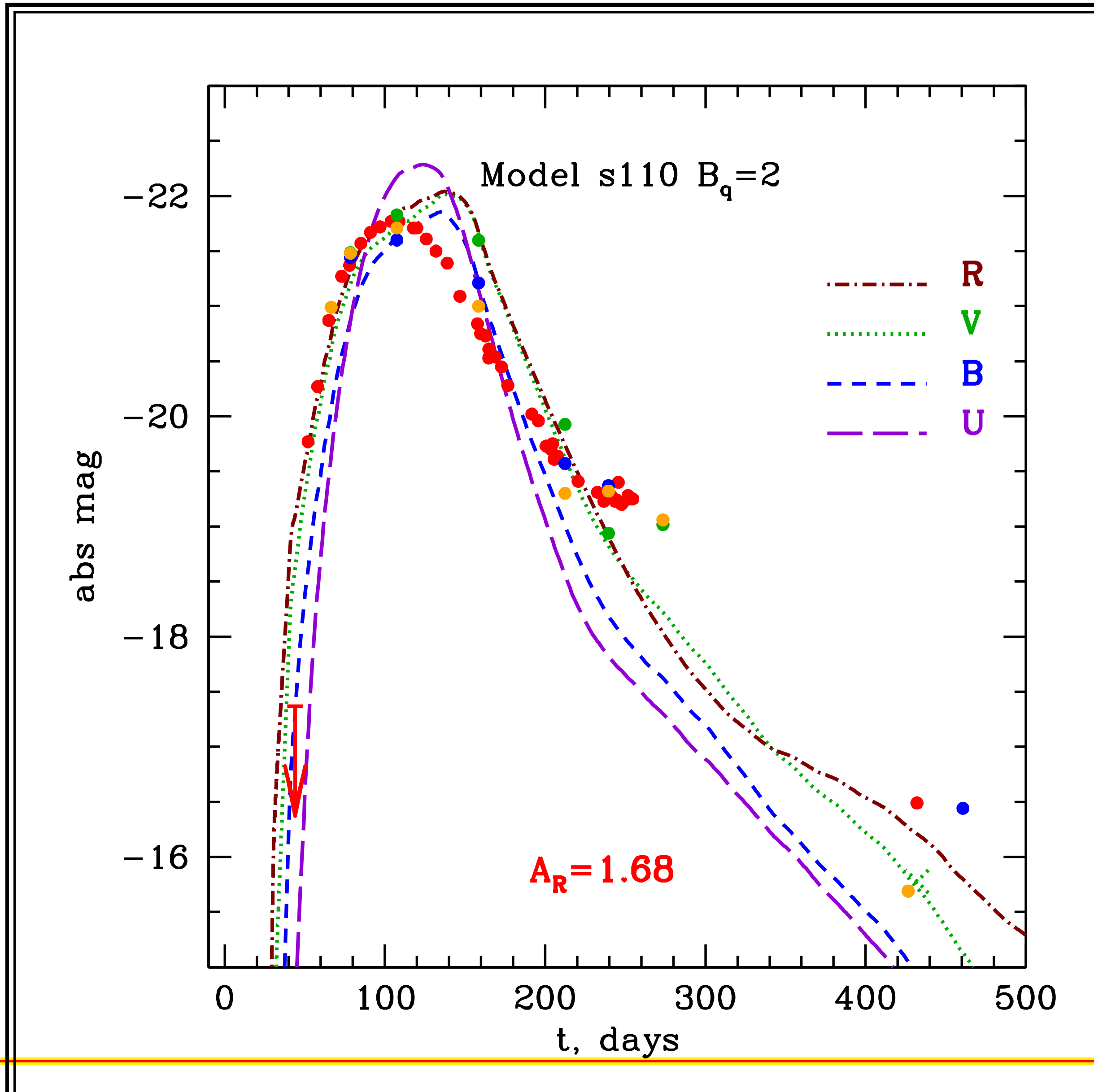
Light curve for SN2006gy

from Woosley, SB, Heger (2007)



Stella: LCs for SN2006gy

new runs



Double explosion: old idea

Grasberg & Nadyozhin (1986)

Type II supernovae: two successive explosions?

É. K. Grasberg and D. K. Nadëzhin

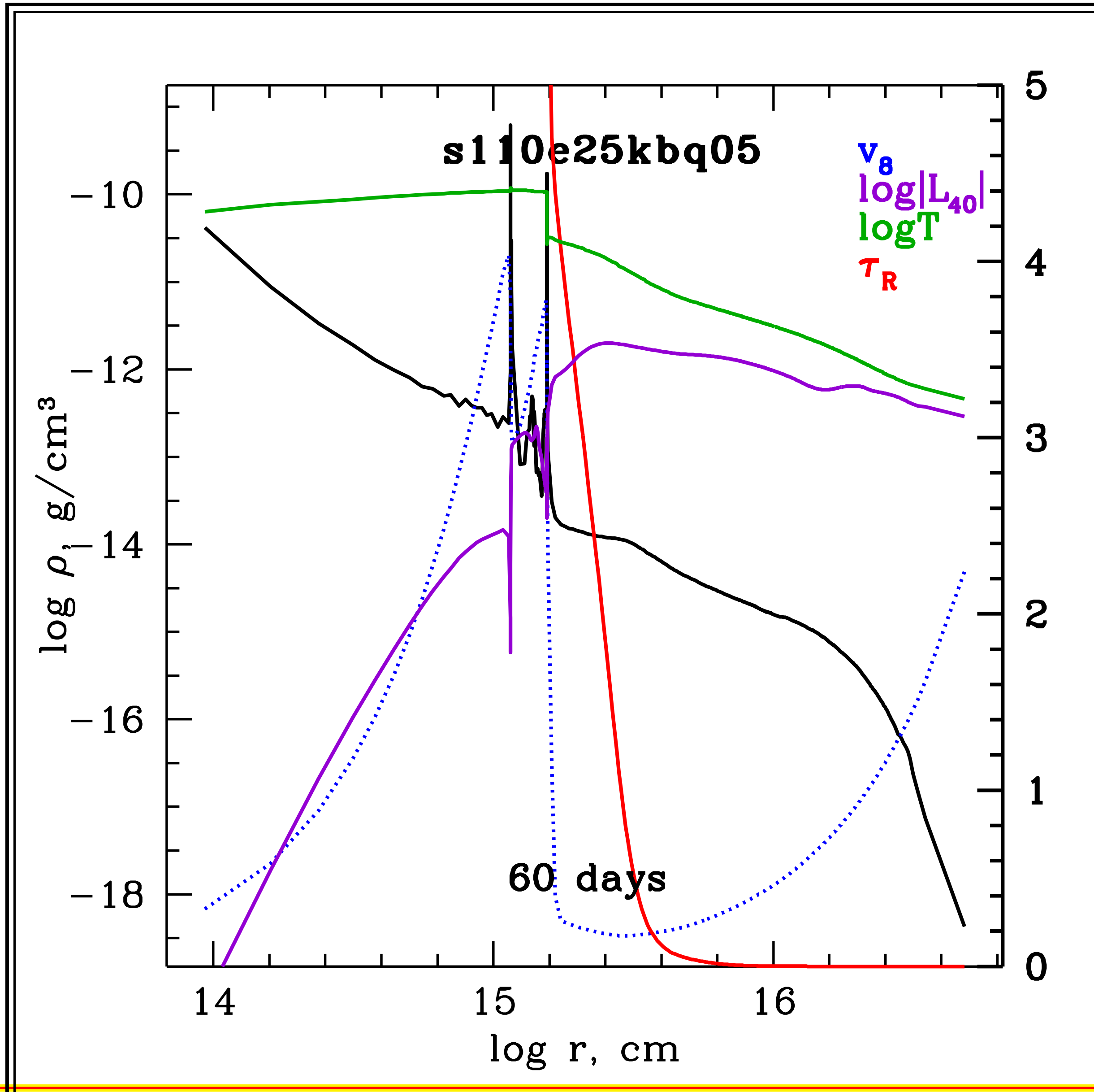
Radio Astrophysical Observatory, Latvian Academy of Sciences, Riga
and Institute of Theoretical and Experimental Physics, Moscow

(Submitted September 5, 1985)

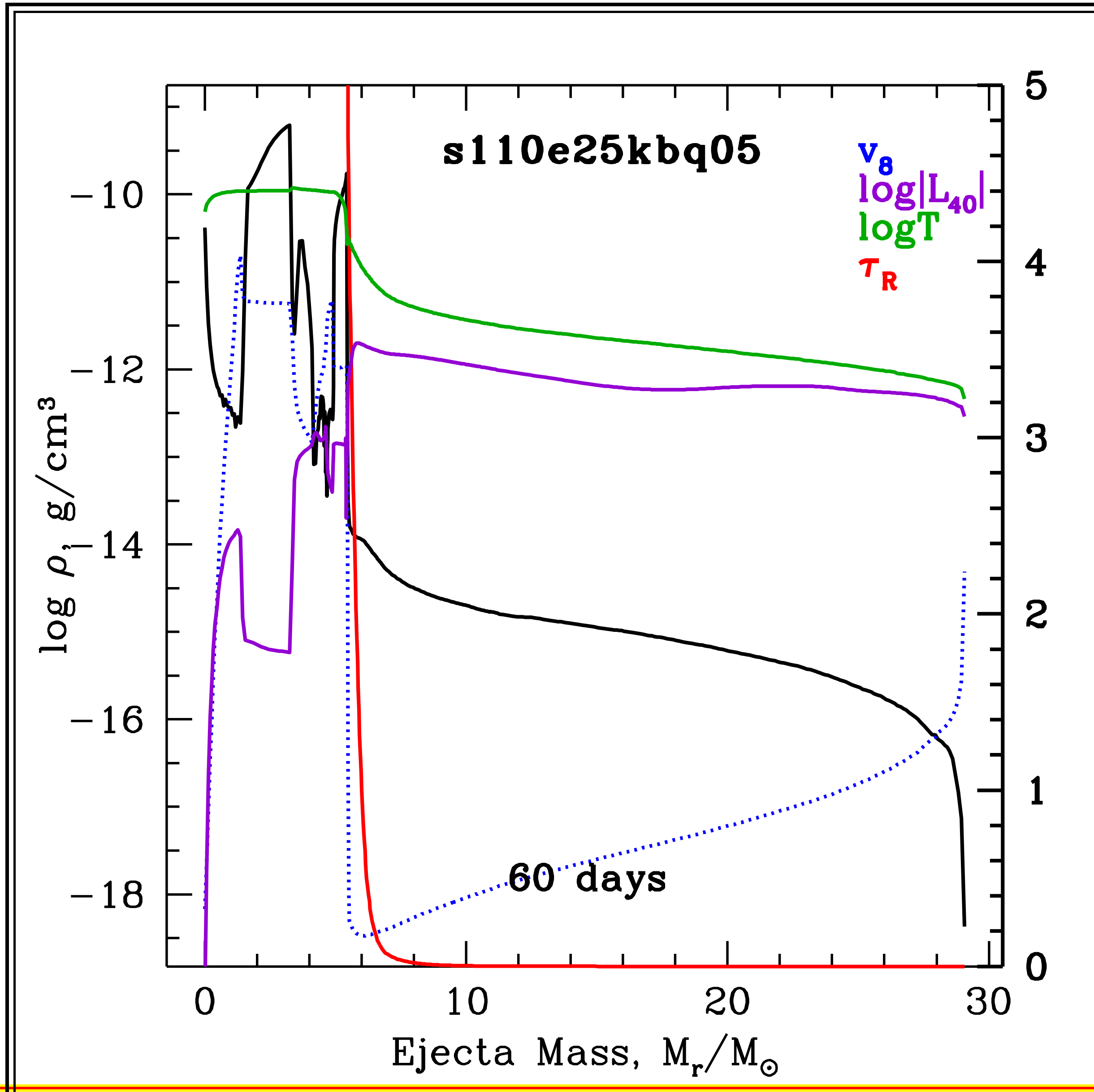
Pis'ma Astron. Zh. **12**, 168–175 (February 1986)

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.

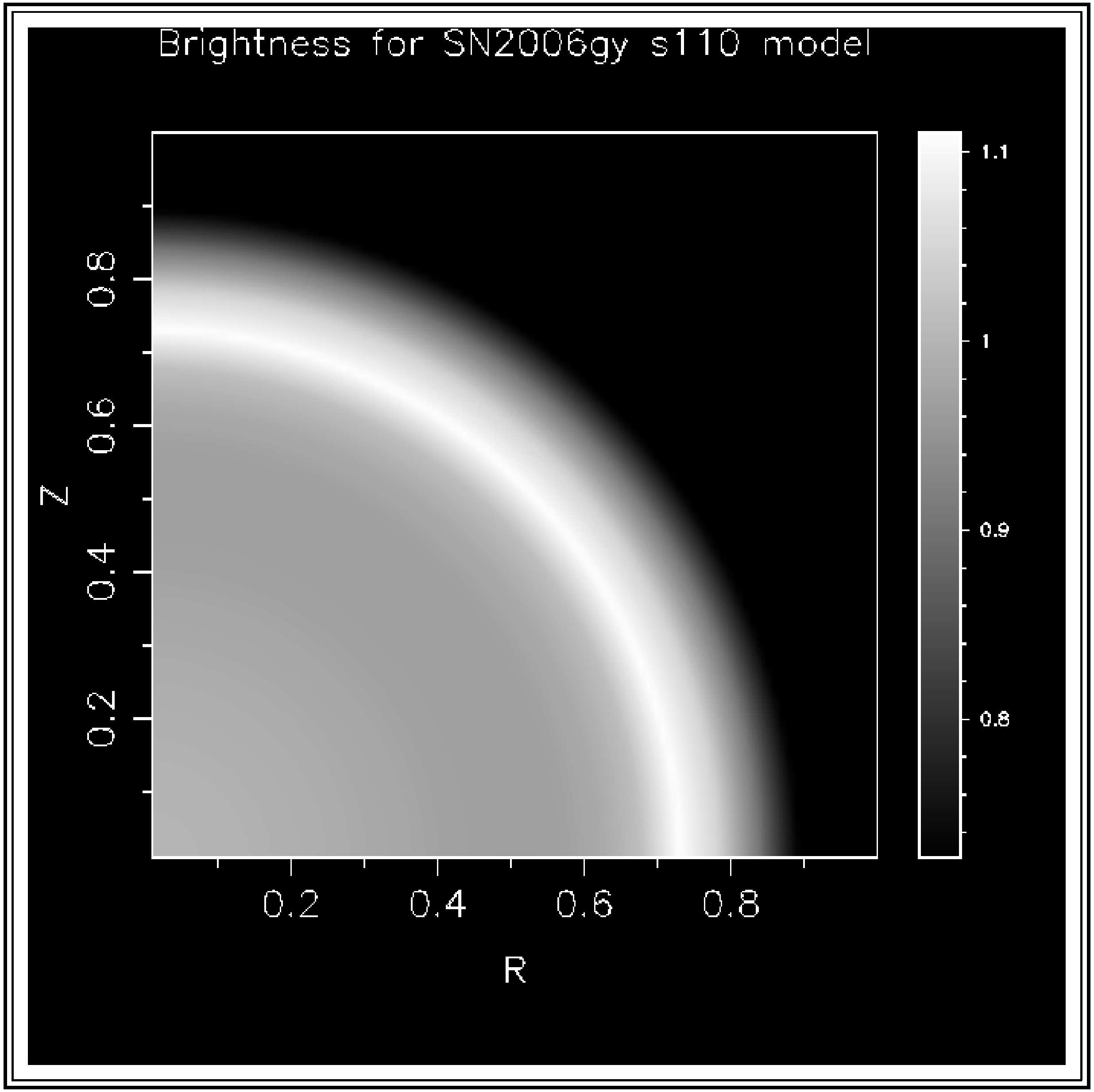
Hydro structure 60 d



60 d, mass coordinate

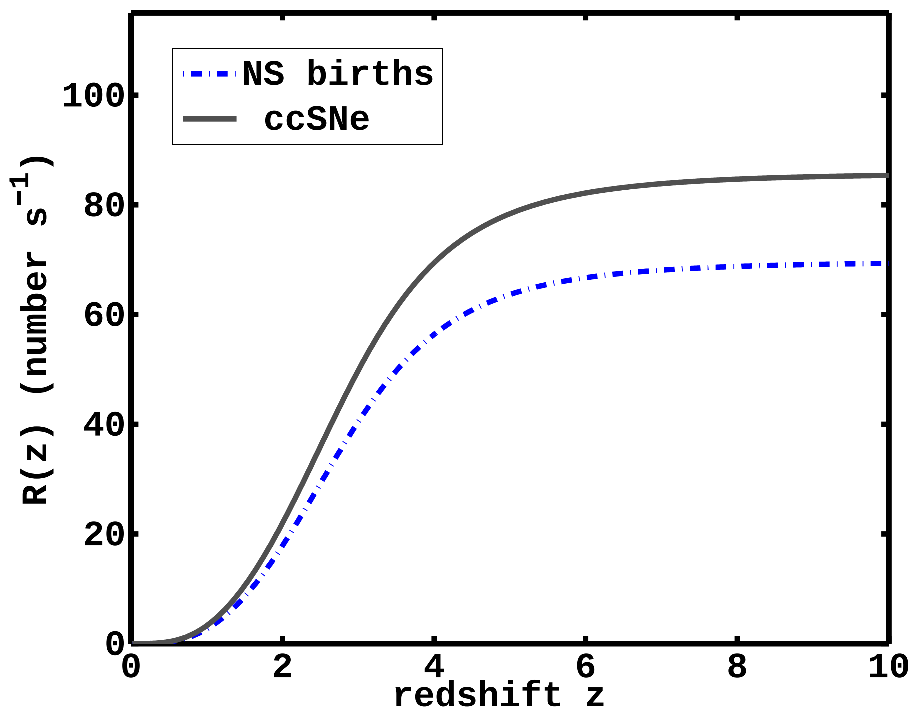


‘Visible’ disk of SN 2006gy



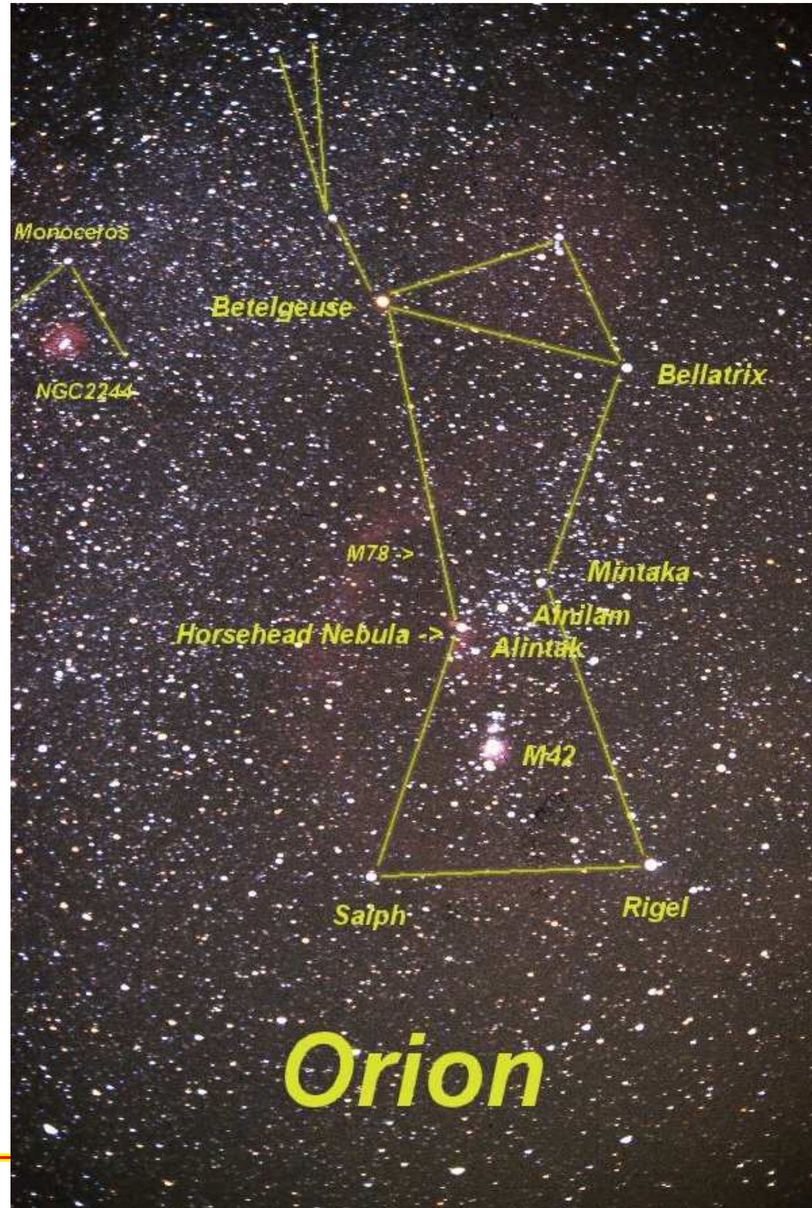
Star formation rate = SFR

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

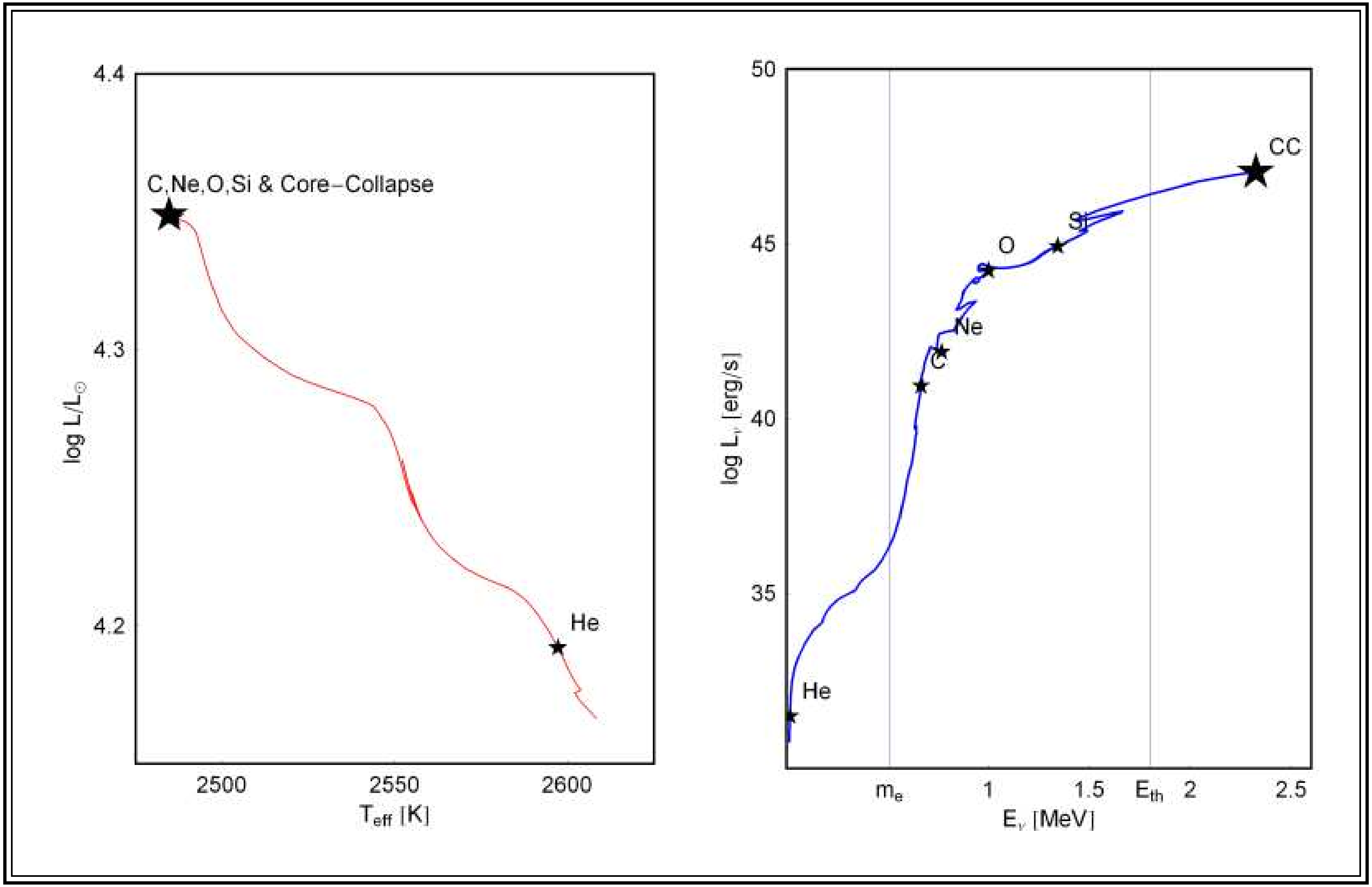


Nearby candidate:

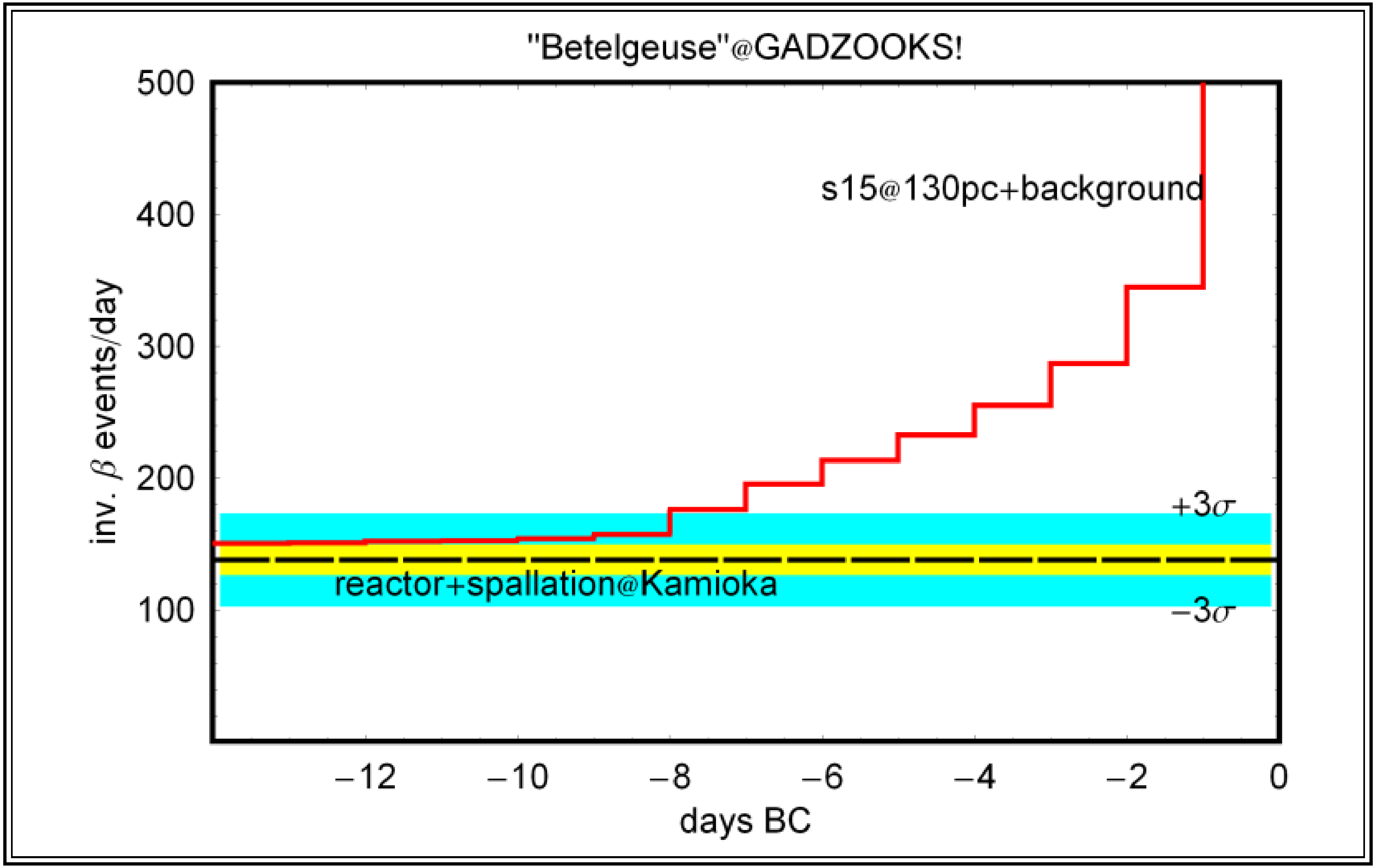
Betelgeuse in ORION – distance 130 pc



Neutrino warning



Neutrino emission



From Odrzywolek 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: Milky Way warning

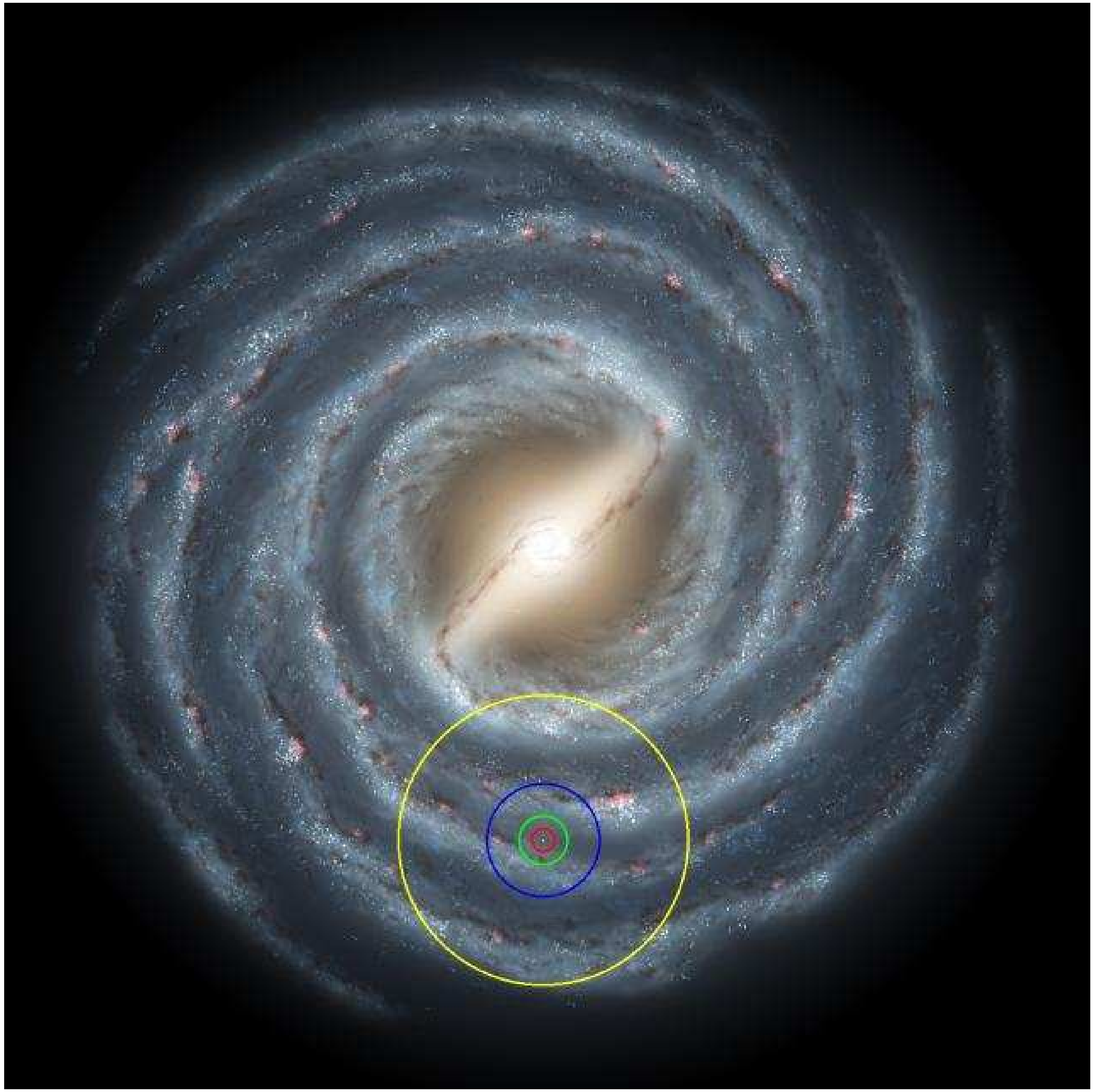
Red circle is expected range for GADZOOKS!/Super-Kamiokande detector

Green circle is expected range for Gd-loaded 0.5 Mt water detector (UNO, Hyper-Kamiokande, LAGUNA)

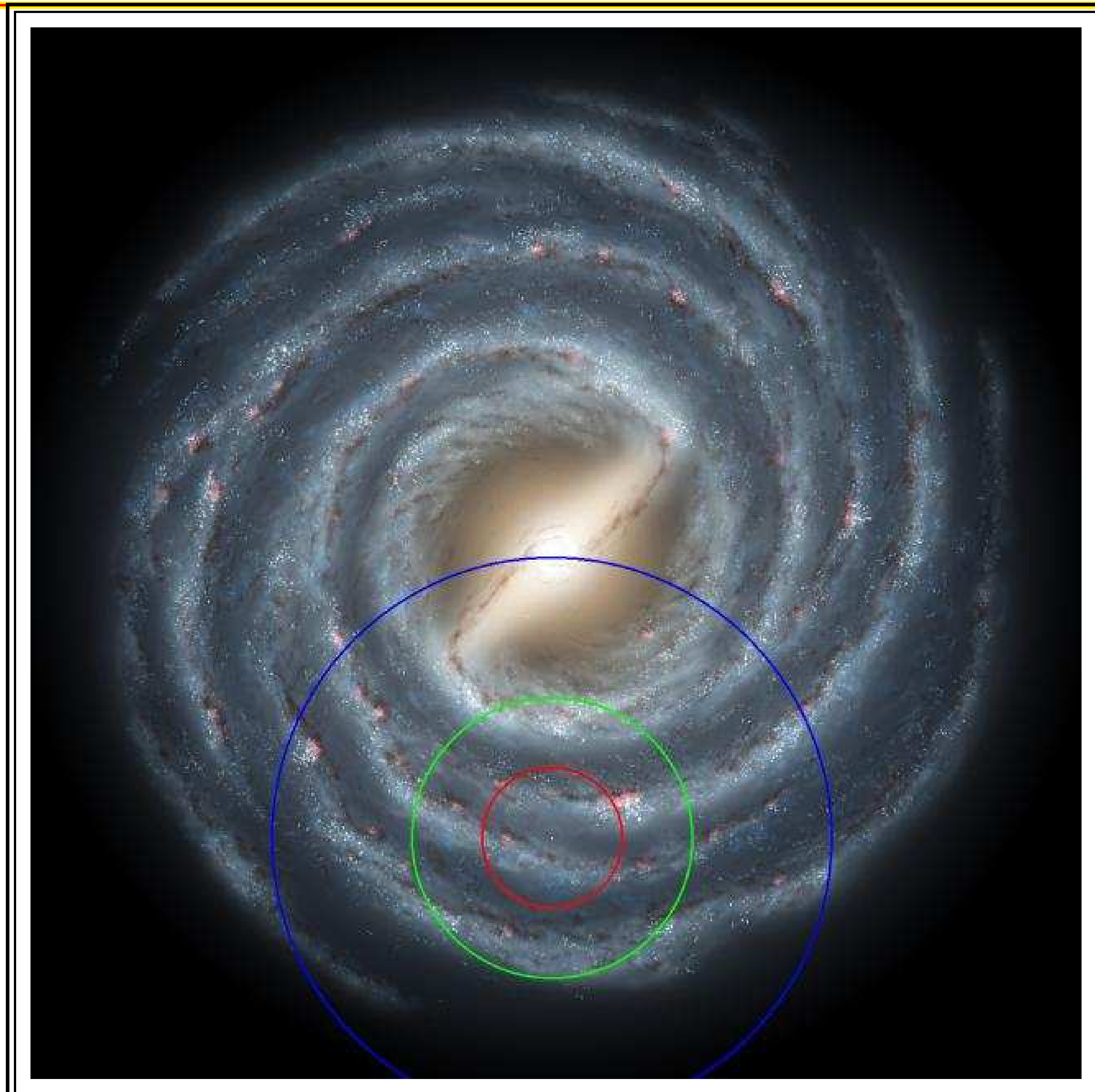
Blue circle is expected range for hypothetical 10 Mt underwater detector (TITAN-D, underwater balloon)

Yellow circle is expected range for futuristic “Gigaton Array” detector — for three hour warning range is much larger than Galaxy radius

Neutrinos: 1 day MW warning



3 hours MW warning



Summary

- 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

Conclusions-1

- The shock wave which runs through rather dense matter surrounding an exploding star can produce enough light to explain very luminous SN events. No ^{56}Ni is needed in this case to explain the light curve near maximum light (some amount may be needed to explain light curve tails).
  We need the explosion energy of only 2-4 Bethe for the shell with $M = 3 - 6 M_\odot$ and $R \lesssim 10^{16}$cm. NARROW LINES MAY NOT BE PRODUCED!

Conclusions-2

- Questions on the latest phases of star evolution arise:
  - Is it possible to form so big and dense envelopes? And how?
  - Time scale for such a formation
  - How far can the envelope extend?
  - Density and temperature profiles inside the envelope right before the explosion
- Question to observations: try to find traces of such shells for bright explosions.
  (There are spectral evidence of circumstellar shells for type IIn and Ibn SNe. Is it possible to find C–O envelopes as well?)

Conclusions-3

- Many technical problems in light curve calculations:
  - line opacities;
  - dimensionality: 3D is preferable, since the envelope can most probably be clumpy;
  - NLTE spectra

Acknowledgements

Our work is supported by Grants of the Government of the Russian Federation 11.G34.31.0047, RFBR 10-02-00249, 10-02-01398, RF Sci. School 3458.2010.2, 3899.2010.2, by a grant IZ73Z0-128180/1 of the Swiss National Science Foundation (SCOPES), and in Germany by MPA guest program. This research has been partly done at IPMU, Tokyo University, and supported in part by World Premier International Research Center Initiative, MEXT, Japan