CNRS IN2P3
Institut national de physique nucléaire
et de physique des particules

LUPM
LABORATOIRE UNIVERS & PARTICULES MONTPELLIER

Particle acceleration in radio supernovae & the associated hadronic signatures

Matthieu Renaud, Alexandre Marcowith
LUPM, CNRS-IN2P3, Univ. Montpellier II, France

Vincent Tatischeff
CSNSM, CNRS-IN2P3, Univ. Paris-Sud, France

& Vikram Dwarkadas
Department of Astronomy and Astrophysics, Univ. of Chicago, USA

SNe as cosmic-ray sources

COSMIC RAYS FROM SUPER-NOVAE

By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

B. Intensity of Cosmic Rays.—The considerations of the preceding paper (these Proceedings, **20**, 254 (1934)) suggest that in order to produce the stupendous radiation of a super-nova each particle of mass m must on the average contribute energy of the order

$$\overline{U} = 0.1\, mc^2, \qquad (1)$$

which per proton corresponds to an energy of approximately 10^8 volts. Individual photons or material particles ejected from the super-nova may of course possess energies much greater than $\overline{U}$. We therefore feel justified in advancing tentatively the hypothesis that *cosmic rays are produced in the super-nova process.* It also seems reasonable to assume that a con-

SNe as cosmic-ray sources

Particle acceleration in SNRs :

Many *indirect* observational & theoretical lines of evidence for efficient acceleration. However, no *direct* evidence for efficient hadron acceleration nor E_{max} ~ E_{knee} in the SNRs observed in the HE/VHE gamma-ray domains...

Particle acceleration in SNe :

Galactic CRs above E ~ PeV could be produced immediately after the SN explosion
→ SN shock propagating into the stellar wind of the progenitor
(Völk & Biermann 1988, Biermann 1993, Berezhko & Völk 2000, Bell & Lucek 2001, Ptuskin et al. 2010)

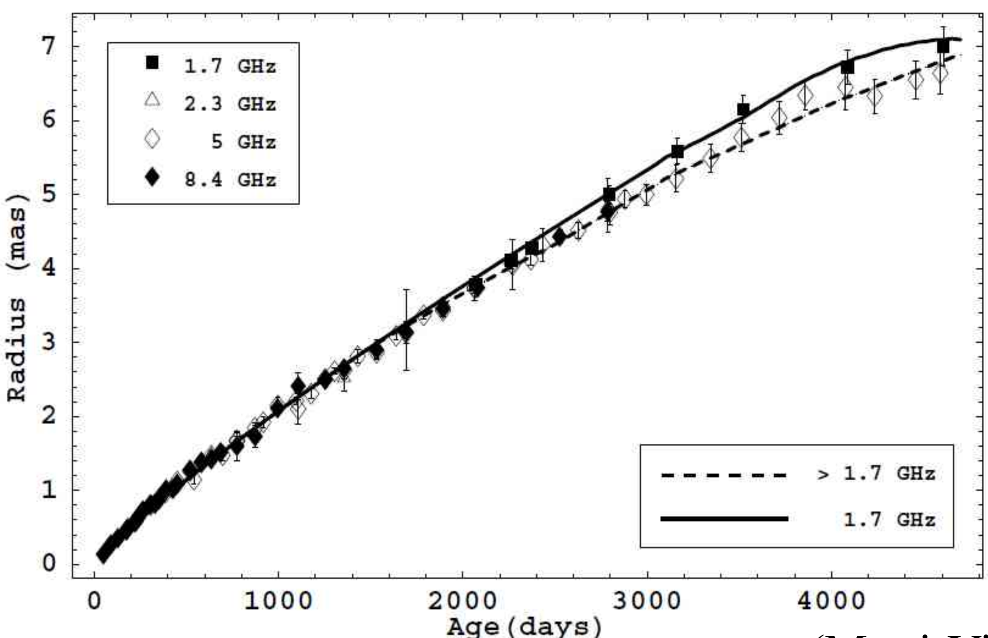
$$E_{max} \sim 3.5 \times 10^{17}\,\mathrm{eV} \left(\frac{u_{\rm sh}}{2 \times 10^4\,\mathrm{km.s^{-1}}}\right)^2 \left(\frac{\dot{M}}{5 \times 10^{-5}\,M_\odot\,\mathrm{yr^{-1}}}\right)^{1/2} \left(\frac{P_{CR}}{0.1 \rho u_{\rm sh}^2}\right) \left(\frac{u_{\rm w}}{10\,\mathrm{km.s^{-1}}}\right)^{-1/2}$$

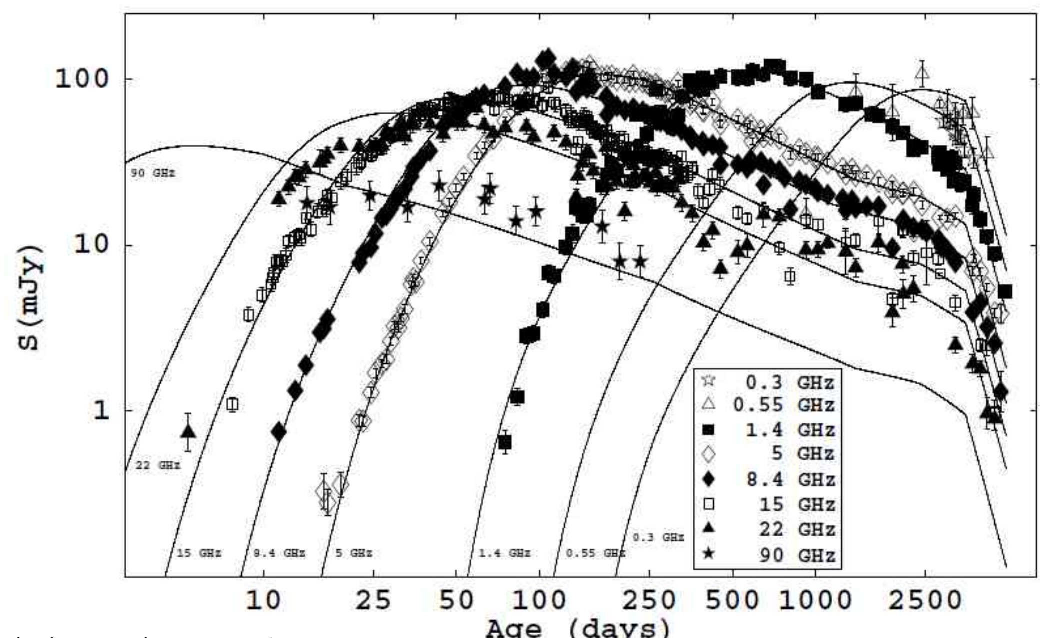
{Fast shocks, high $\dot{M}$ and slow winds} favorable for E_{max} and p-p interactions
→ subsequent γ-ray emission (Berezinskii & Ptuskin 1988, Kirk et al. 1995, Tatischeff 2009)

Interesting cases of Type IIb SNe (Smartt 2009, Claeys et al. 2011, Meynet et al. 2011)

SN 1993J : Particle acceleration

Type IIb SN (Filippenko et al. 1993) discovered by F. Garcia on 1993/03/28 in M81
$d_{Cepheids}$ = 3.63 ± 0.34 Mpc (Freedman et al. 1994) d_{ESM} = 3.96 ± 0.29 Mpc (Bartel et al. 2007)
13-20 $M_{\odot}$ RSG with most of its H envelope lost to a binary companion (Maund et al. 2004)



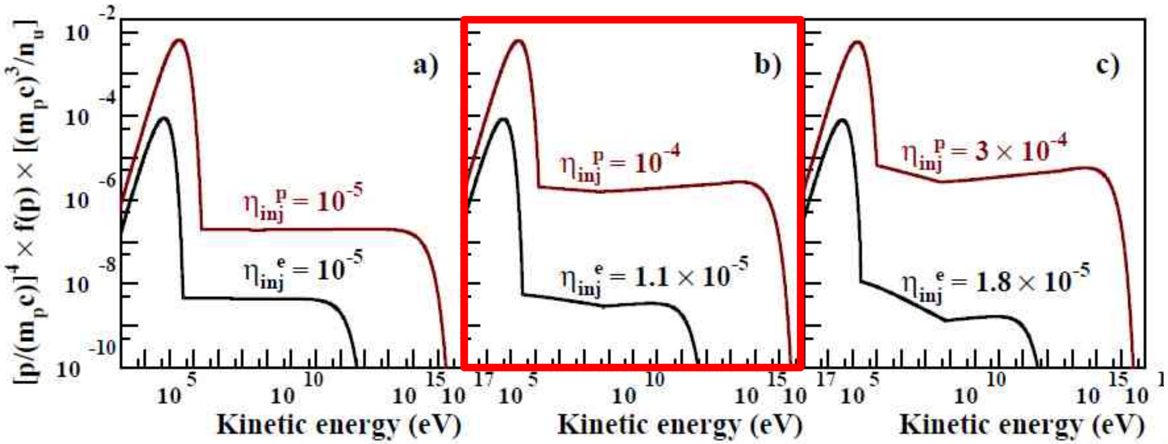


(Marti-Vidal et al. 2011)

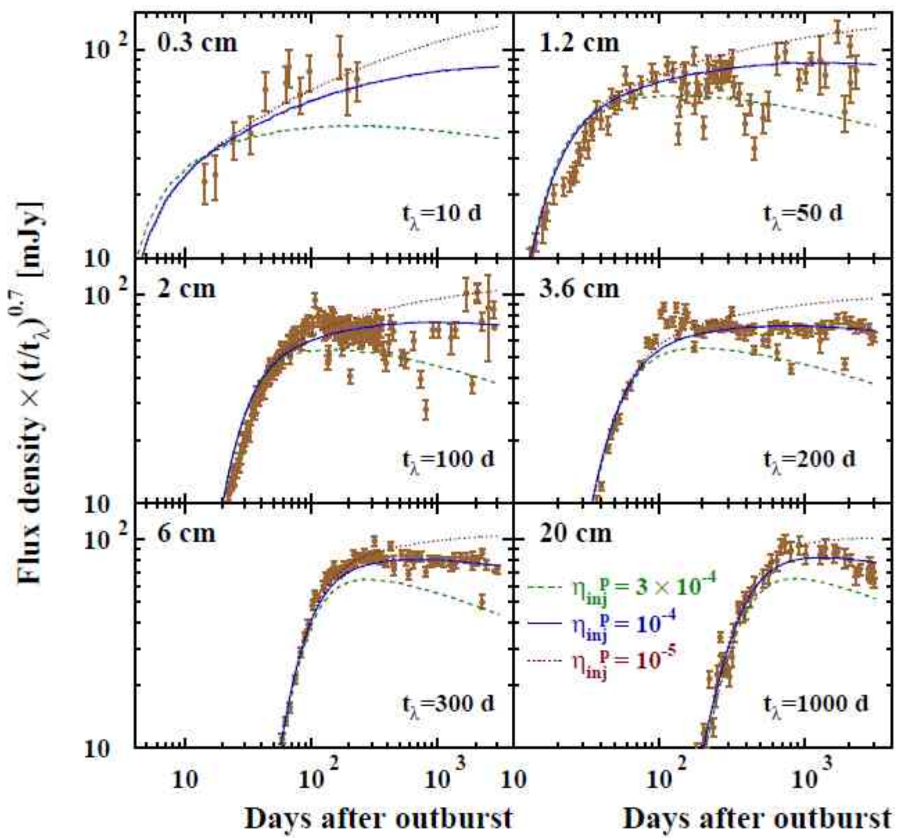
Long-term radio monitoring of shock radius R_{sh} & flux density F_{ν}
Standard r^{-2} CSM, $\mathbf{B_d \approx 64\ (R_{sh}/10^{15}cm)^{-1}\ G}$, $dn_e/d\gamma_e \propto \gamma_e^{-2.1}$ (Fransson & Björnsson 1998)

SN 1993J : Particle acceleration

Type IIb SN (Filippenko et al. 1993) discovered by F. Garcia on 1993/03/28 in M81
$d_{Cepheids}$ = 3.63 ± 0.34 Mpc (Freedman et al. 1994) d_{ESM} = 3.96 ± 0.29 Mpc (Bartel et al. 2007)
13-20 $M_\odot$ RSG with most of its H envelope lost to a binary companion (Maund et al. 2004)



(Tatischeff 2009)



Long-term radio monitoring of shock radius R_{sh} & flux density F_ν
Standard r^{-2} CSM, **$B_u \approx 50\ (t/1day)^{-1}$ G**, NLDSA with **$<\varepsilon_{CR}>_{8.5yr} \sim 0.19$** (Tatischeff 2009)

SN 1993J : hadronic signatures

Parametrization of the Tatischeff's modeling to estimate the hadronic signatures
→ γ-rays, neutrinos and SC from secondary e^-/e^+ (Huang et al. 2007,2008)

d = 3.63 Mpc , $\dot{M} = 3.8\times10^{-5}\ M_\odot\ yr^{-1}$, u_w = 10 km s^{-1}

$R_{sh}(t) = 3.49 \times 10^{14}$ cm $\times\ t_{day}^{\ m}$ [m = 0.83]

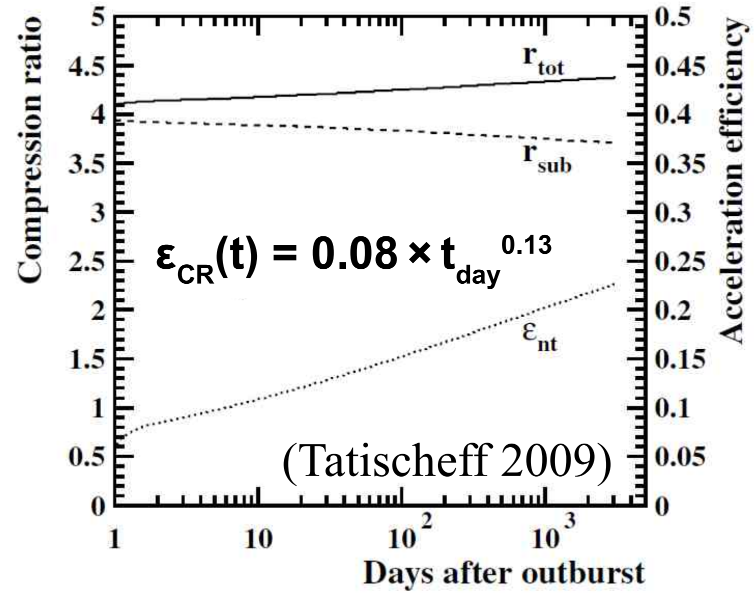
$u_{sh}(t) = 3.35 \times 10^{4}$ km $s^{-1} \times t_{day}^{\ m-1}$

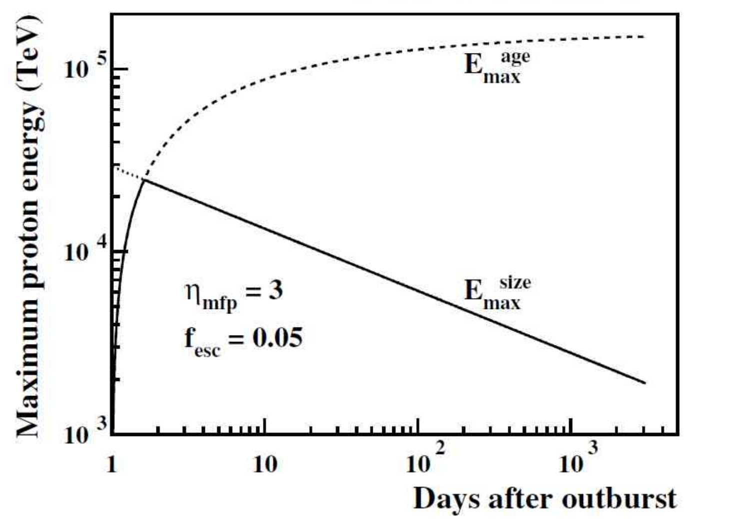
$$E_{\rm max}^{\rm size} = 1.75 \times 10^{18} \left(\frac{f_{\rm esc}}{\eta_{\rm mfp}}\right)\left(\frac{m}{0.83}\right)^{-1}\left(\frac{B_{u0}}{50\ {\rm G}}\right) \times \left(\frac{V_0}{3.35\times10^4\ {\rm km\ s^{-1}}}\right)^2\left(\frac{t}{1\ {\rm day}}\right)^{2(m-1)}\ {\rm eV}.$$

$$E_{\rm CR} \cong \int_{t_0}^{t_f} \epsilon_{\rm nt} \times \frac{1}{2}\rho_u V_s^3 \times 4\pi R_s^2 dt = 7.4 \times 10^{49}\ {\rm erg}$$

$<n_p> = n_d^e/(1+2X)$, with: $n_d^e = \dfrac{\dot{M}_{\rm RSG} r_{\rm tot}}{4\pi R_s^2 u_w m_{\rm H}}\left(\dfrac{1+2X}{1+4X}\right)$

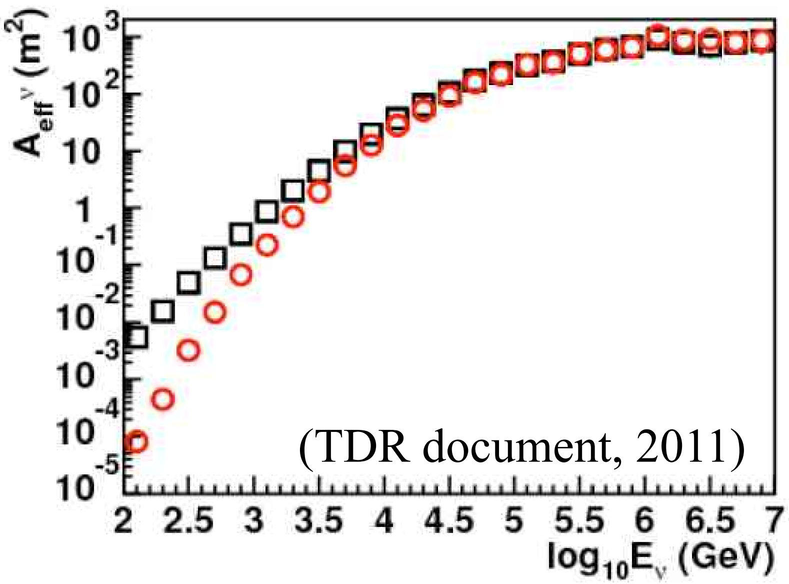
$dN_{CR}/dE_{CR} = A_{CR}(t)\ E_{CR}^{\ -2} \exp(-E_{CR}/E_{max}(t))$



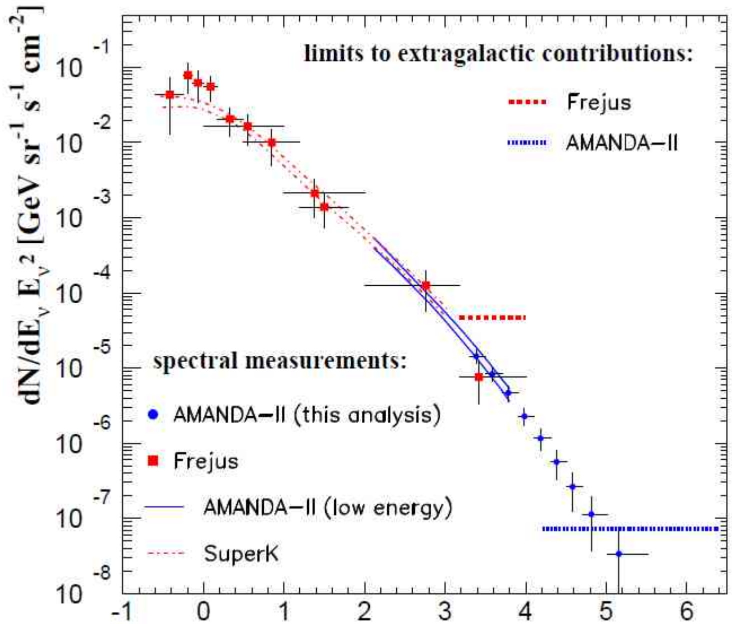


SN 1993J : neutrinos

Perspectives with KM3NeT :

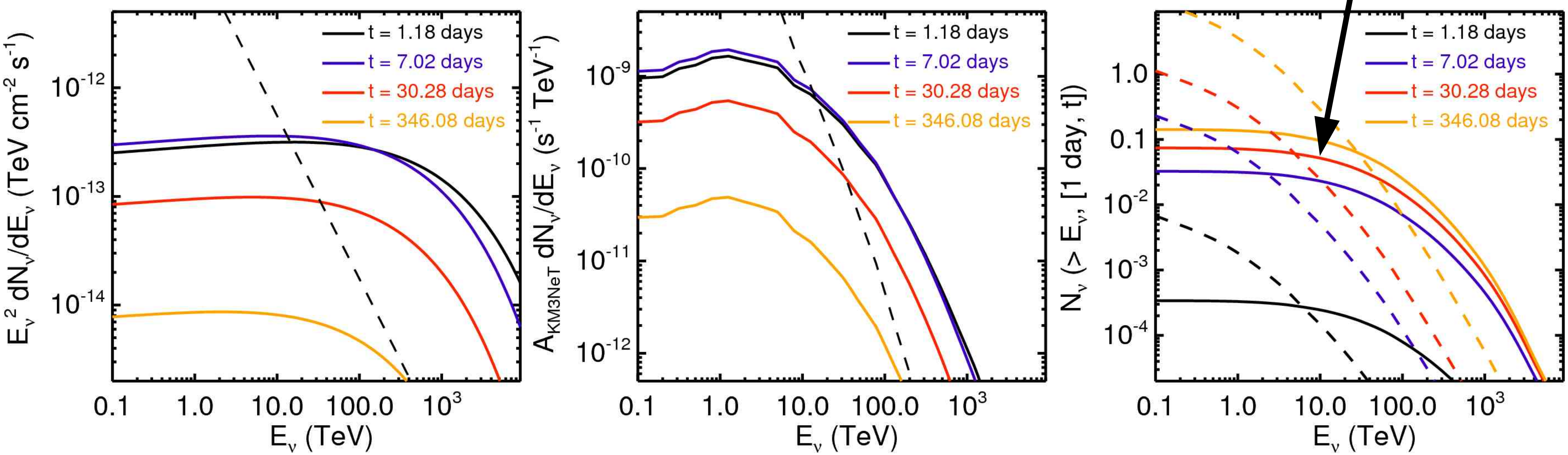


(TDR document, 2011)



(Abbasi et al., 2010)

Only a few ν's at E_ν > 10 TeV for a SN in M31...



SN 1993J : secondary e^-/e^+

Time-dependent transport equation :

$$\frac{dN}{dt} = Q(E(t),t) - C(E(t),t)N(t) \quad C(E,t) = \partial \dot{E}/\partial E \quad \dot{E} = -\alpha(t)E^2$$

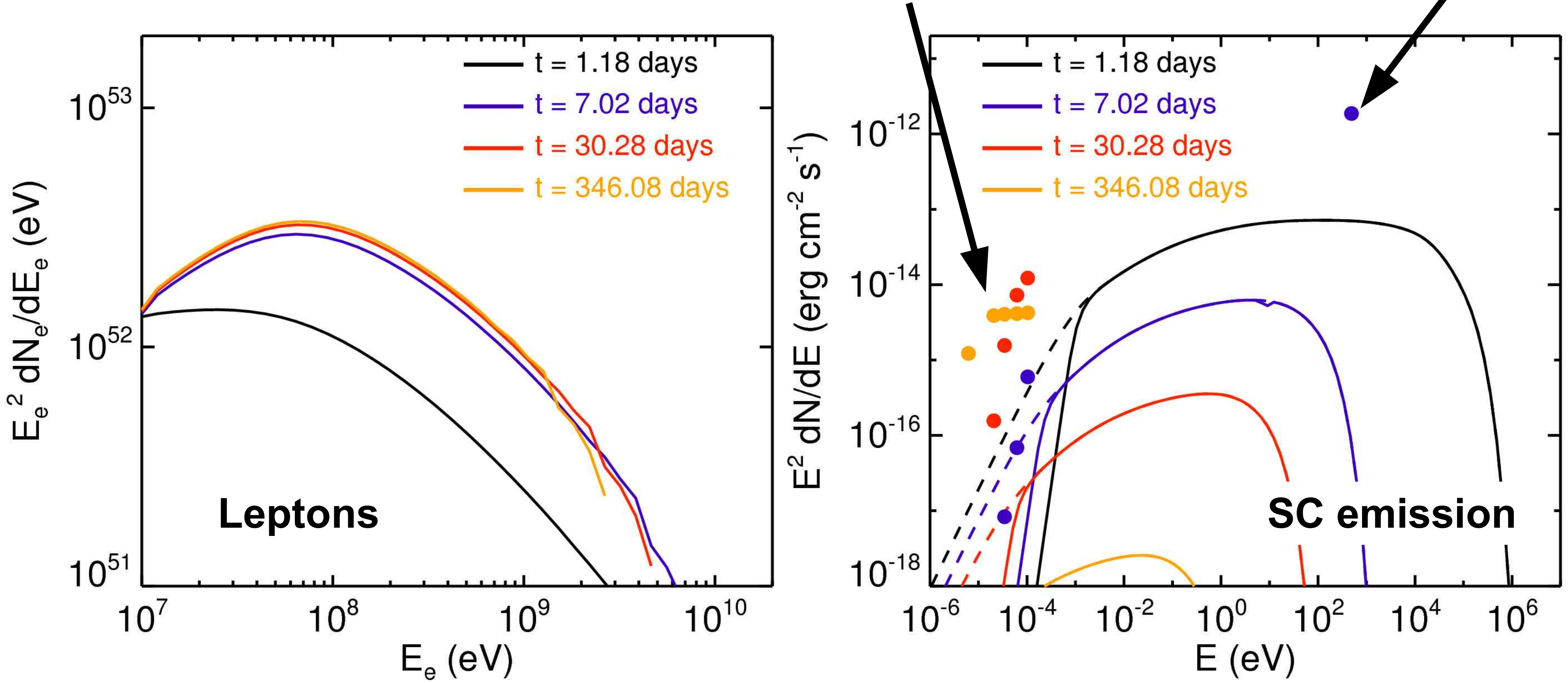
$$N(E,t) = \int_{t_0}^{t} Q(E,t') \times \exp\left(-\int_{t'}^{t} C(E,t")dt"\right) dt'$$

$\alpha(t) = (4/3)\sigma_T c\, B^2(t)/8\pi m_e^2 c^4$

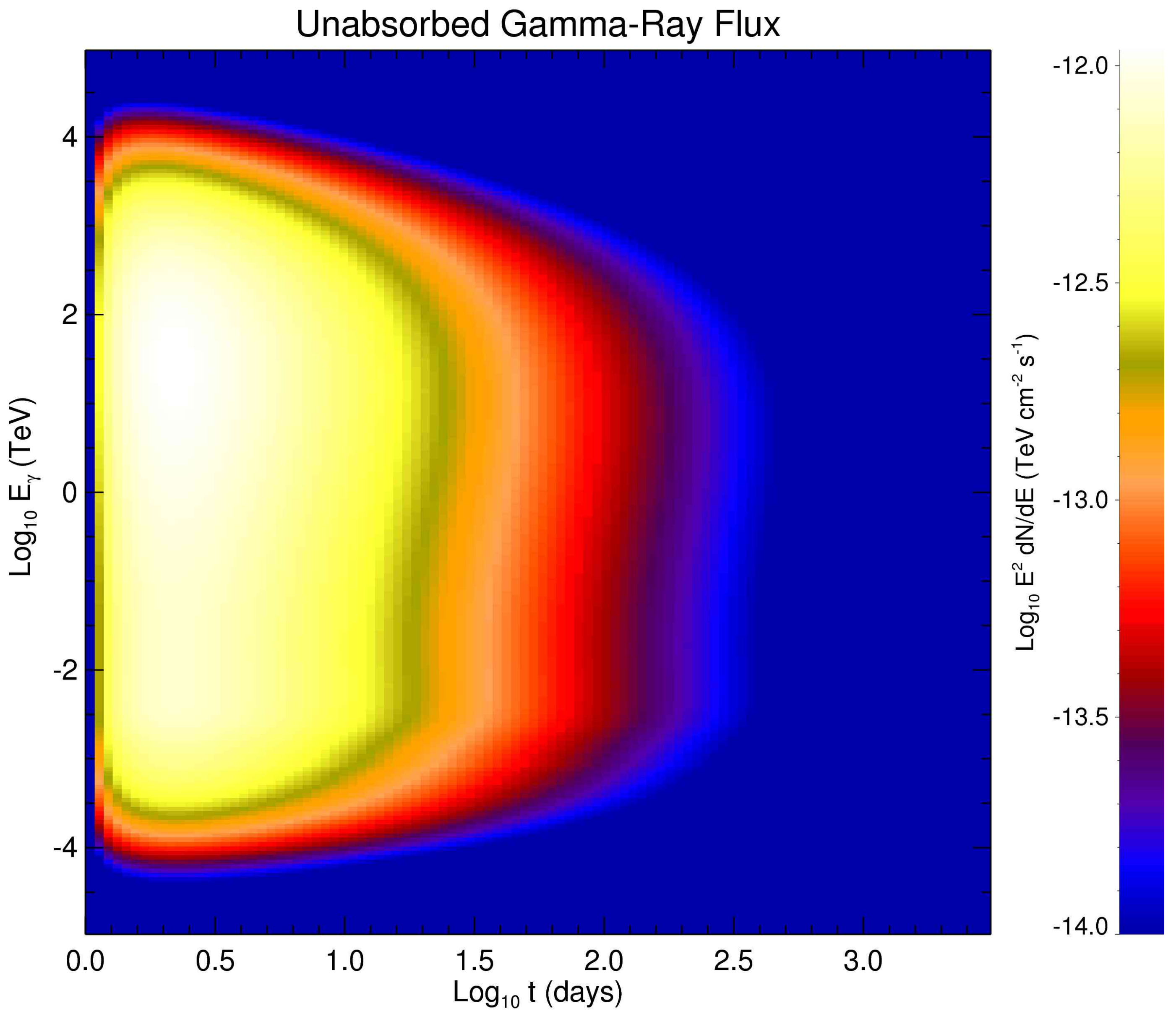
$Q(E,t)$ from p-p $\rightarrow \pi^{+/-} \rightarrow e^{+/-}$

Radio measurements (Weiler et al. 2007)

X-ray measurements (Zimmermann et al. 1994)



SN 1993J : gamma-ray emission



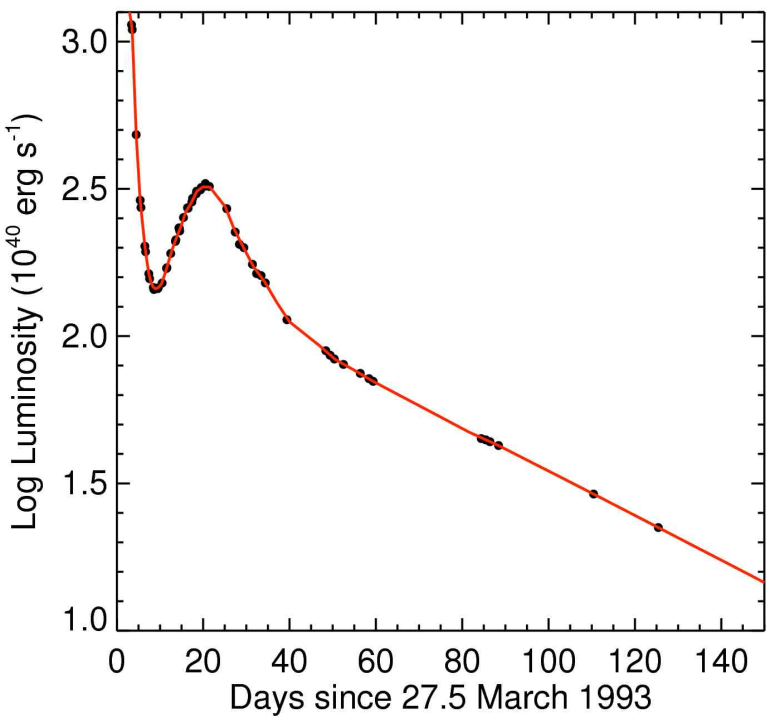
SN 1993J : gamma-ray emission

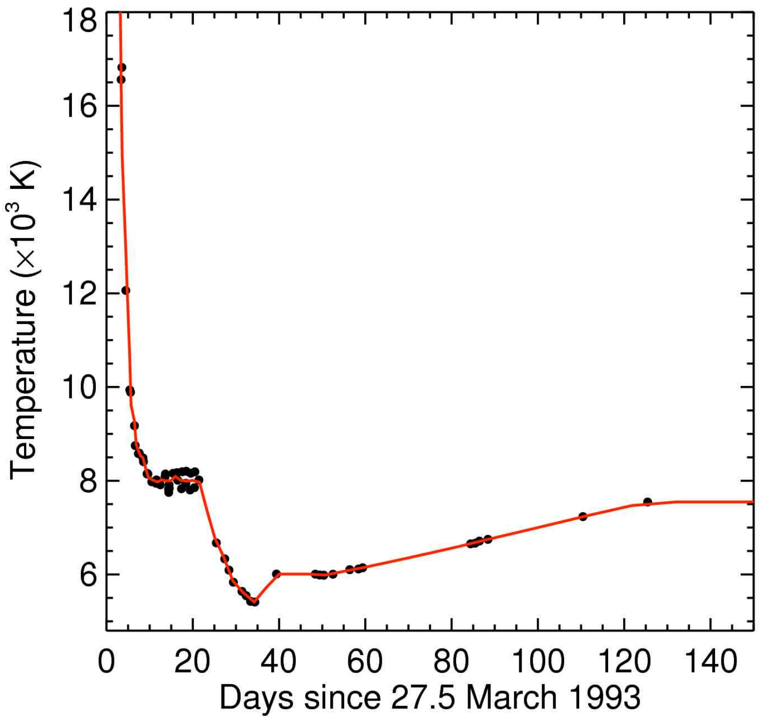
Pair-production process : $\gamma + \gamma \rightarrow e^- + e^+$

$$\tau_{\gamma\gamma}(E_\gamma) \approx R_s \kappa_{\gamma\gamma}(E_\gamma)$$

$$\kappa_{\gamma\gamma}(E_\gamma) = \frac{45\sigma_T U_{rad}}{8\pi^4 k T_{bb}} f_{\gamma\gamma}(E_\gamma, T_{bb})$$

$$U_{rad} \approx L_{bol}/(4\pi c R_s^2)$$

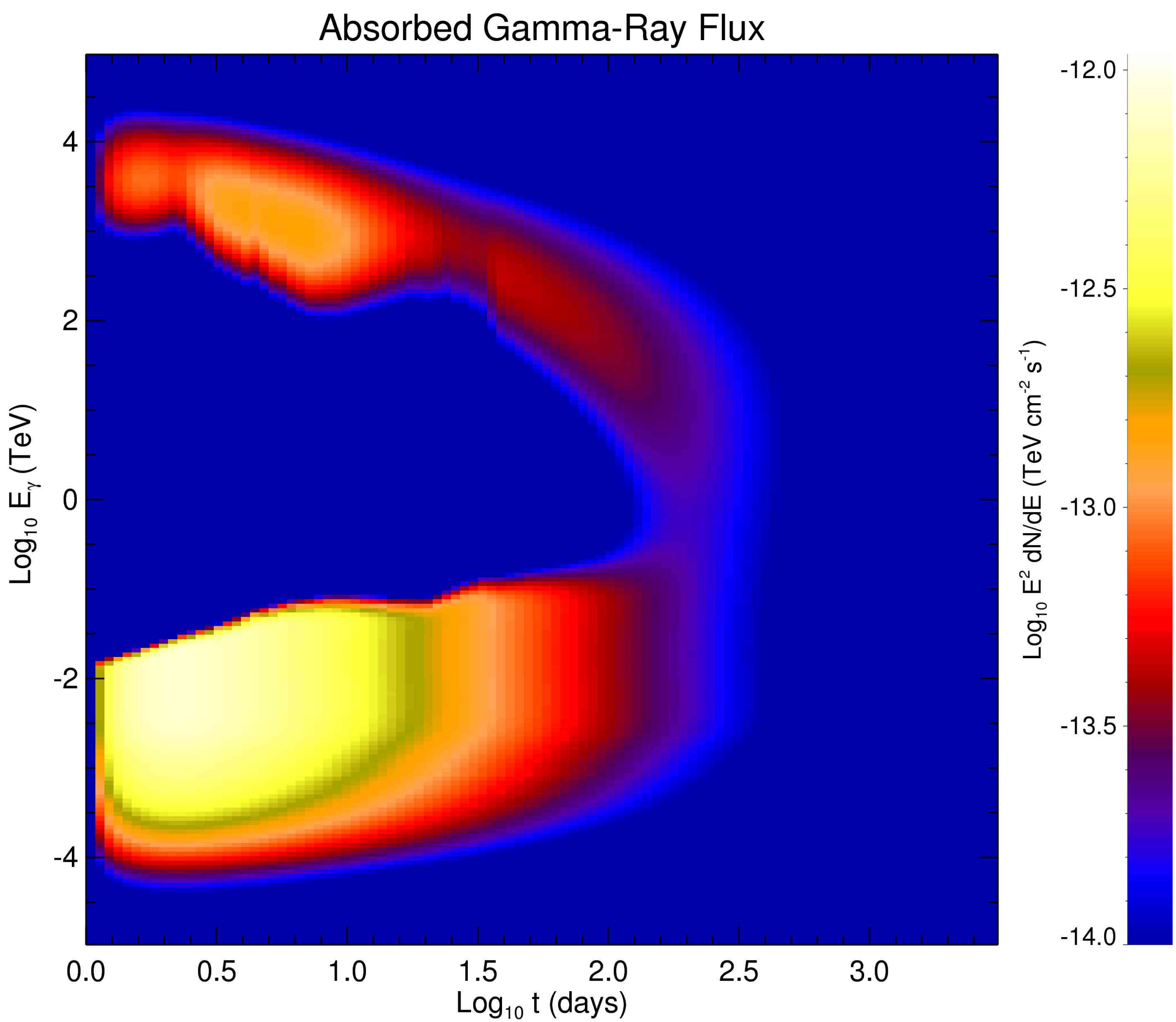




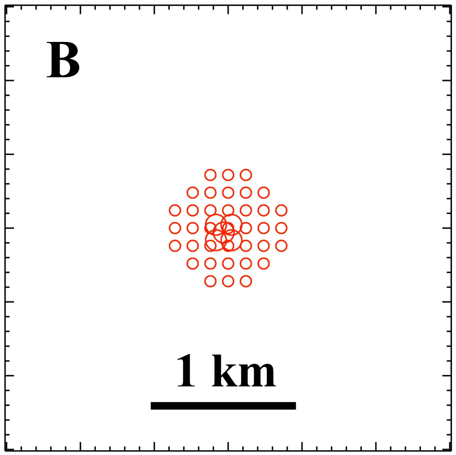
Time evolution of L_{bol} & T_{bb} of the photosphere at days 2-125 (Lewis et al. 1994)

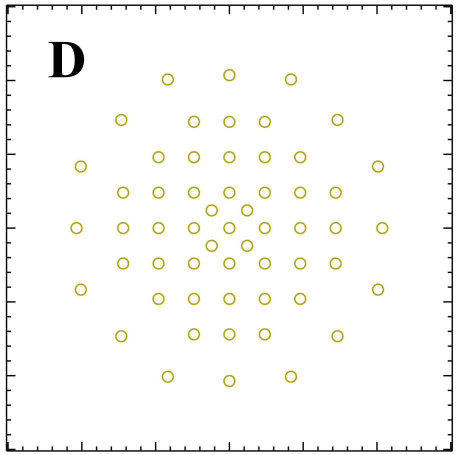
Calculation of the $\gamma\gamma$ opacity in the isotropic case (Aharonian et al. 2008)

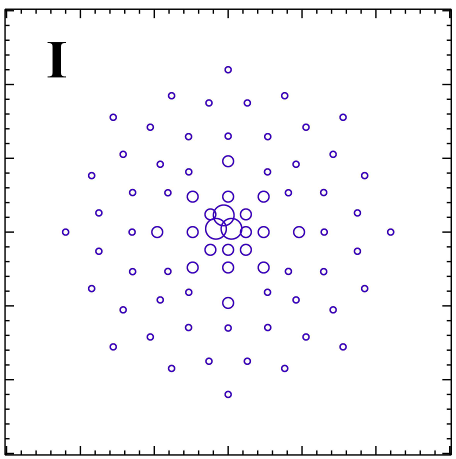
SN 1993J : gamma-ray emission



Cherenkov Telescope Array



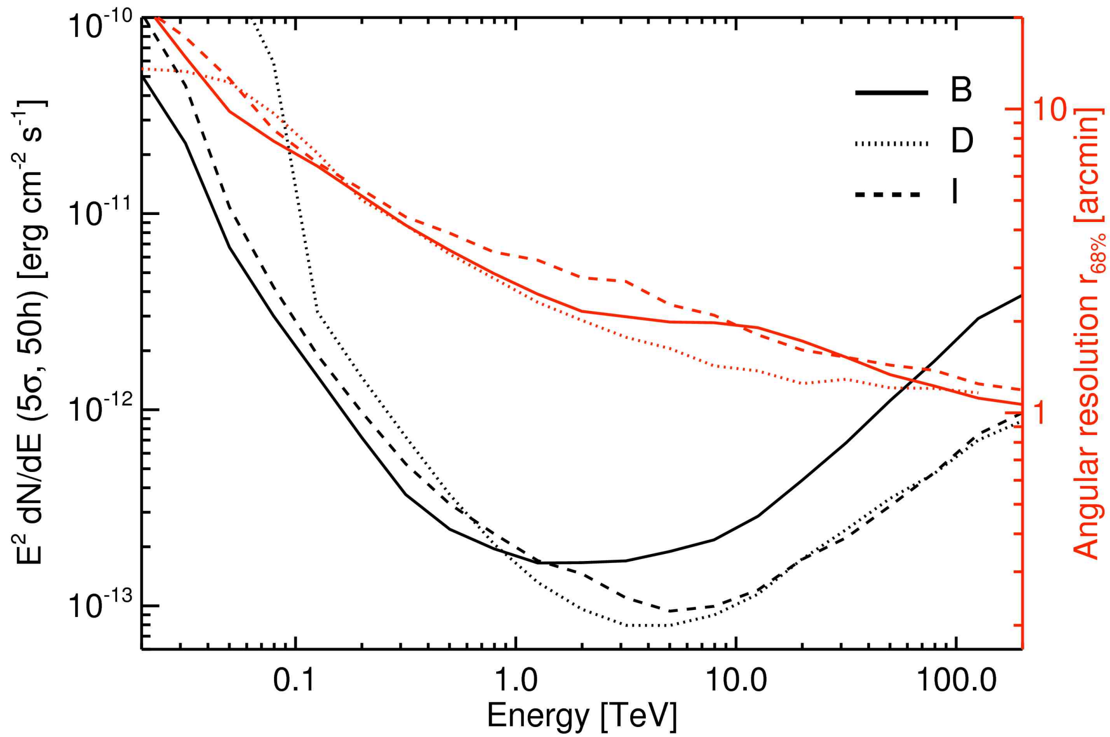




B: better performance at low energies

D: better performance at high energies

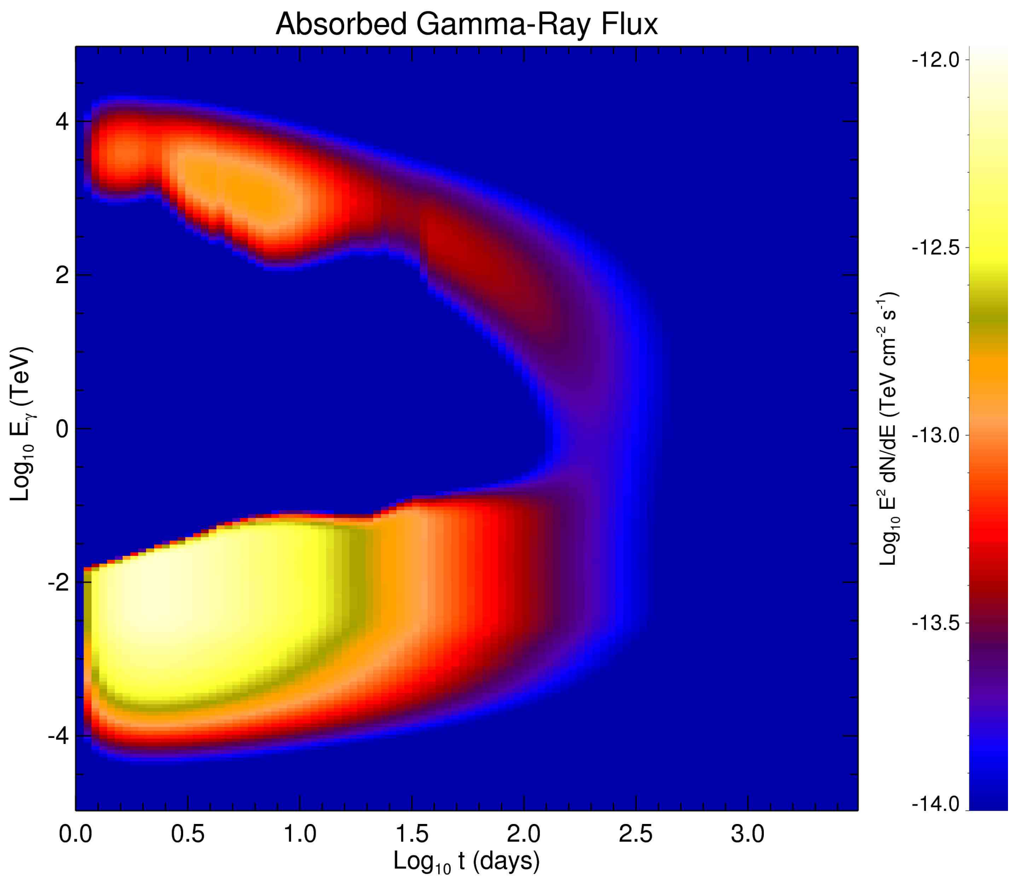
I: better performance over the whole range

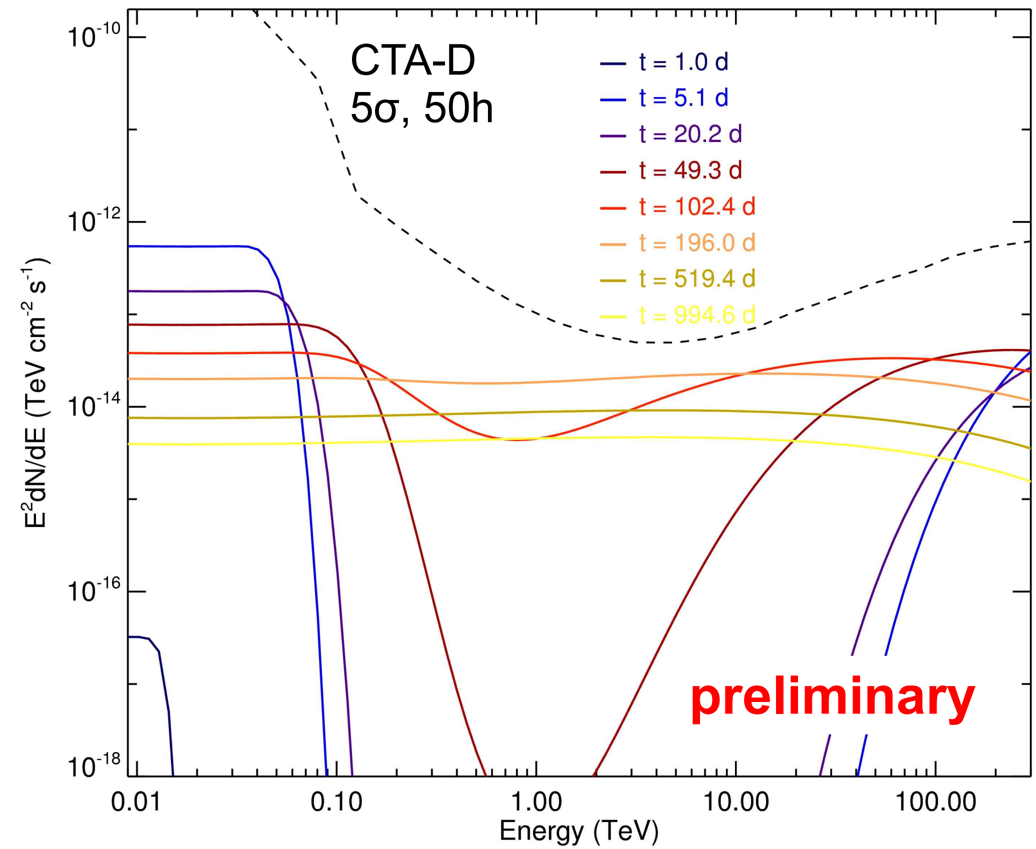


(Renaud et al. 2011)

The CTA consortium
« Design Concepts for the Cherenkov Telescope Array » (Actis et al. 2011)

SN 1993J : gamma-ray emission





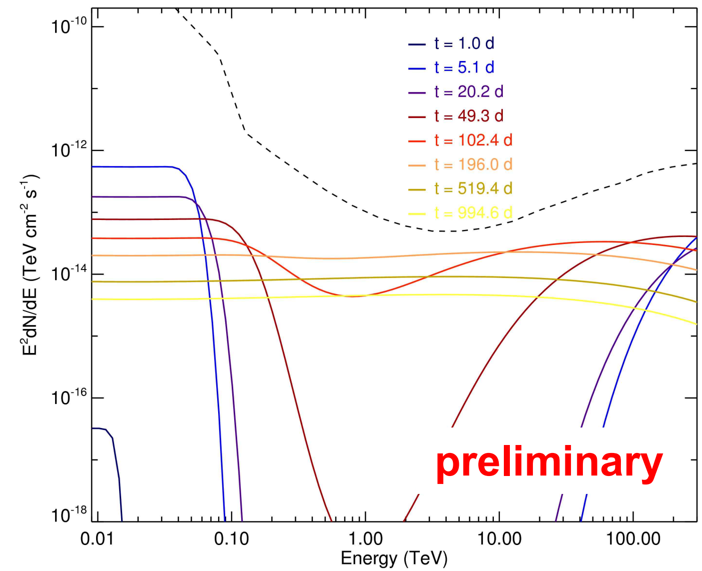
Search for the optimal S/N ratio (Li & Ma 1983) in $\{E_{min}, E_{max}, t_{min}, t_{max}\}$ assuming :
CTA Configurations I-D & 3 hrs of observation time per night

→ S/N ~ 5 – 6 in 50 hrs starting at day 130 in the 3 – 300 TeV energy range

Conclusion & perspectives

Hadronic signatures arising from efficient CR acceleration in radio SNe

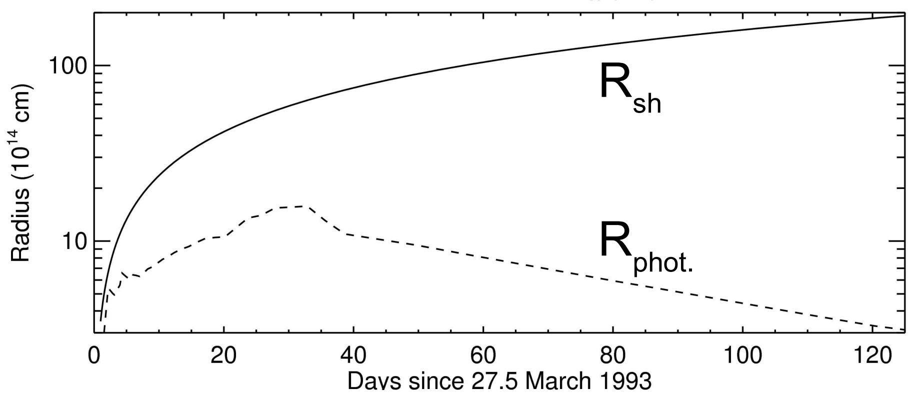
- High-energy neutrinos detectable with KM3NeT if SN in M31
- SC emission from secondaries does not violate radio measurements
- VHE emission from SN 1993J detectable with CTA



<u>Perspectives :</u>

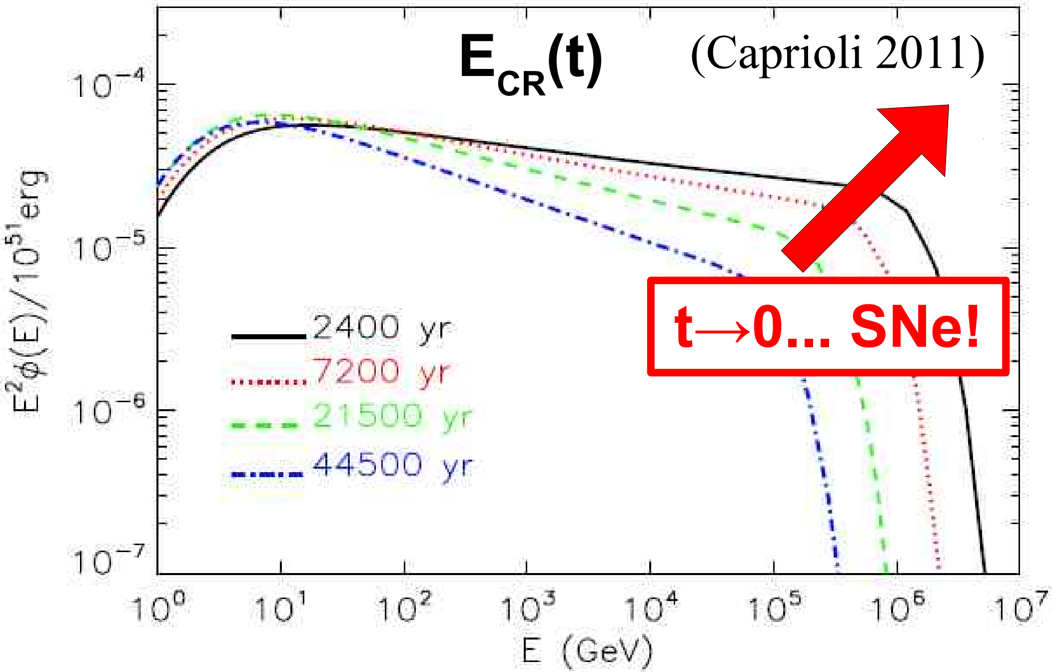
Geometry of the $\gamma + \gamma \rightarrow e^- + e^+$ process
$\rightarrow$ smaller $\gamma\gamma$ opacity, higher significance...

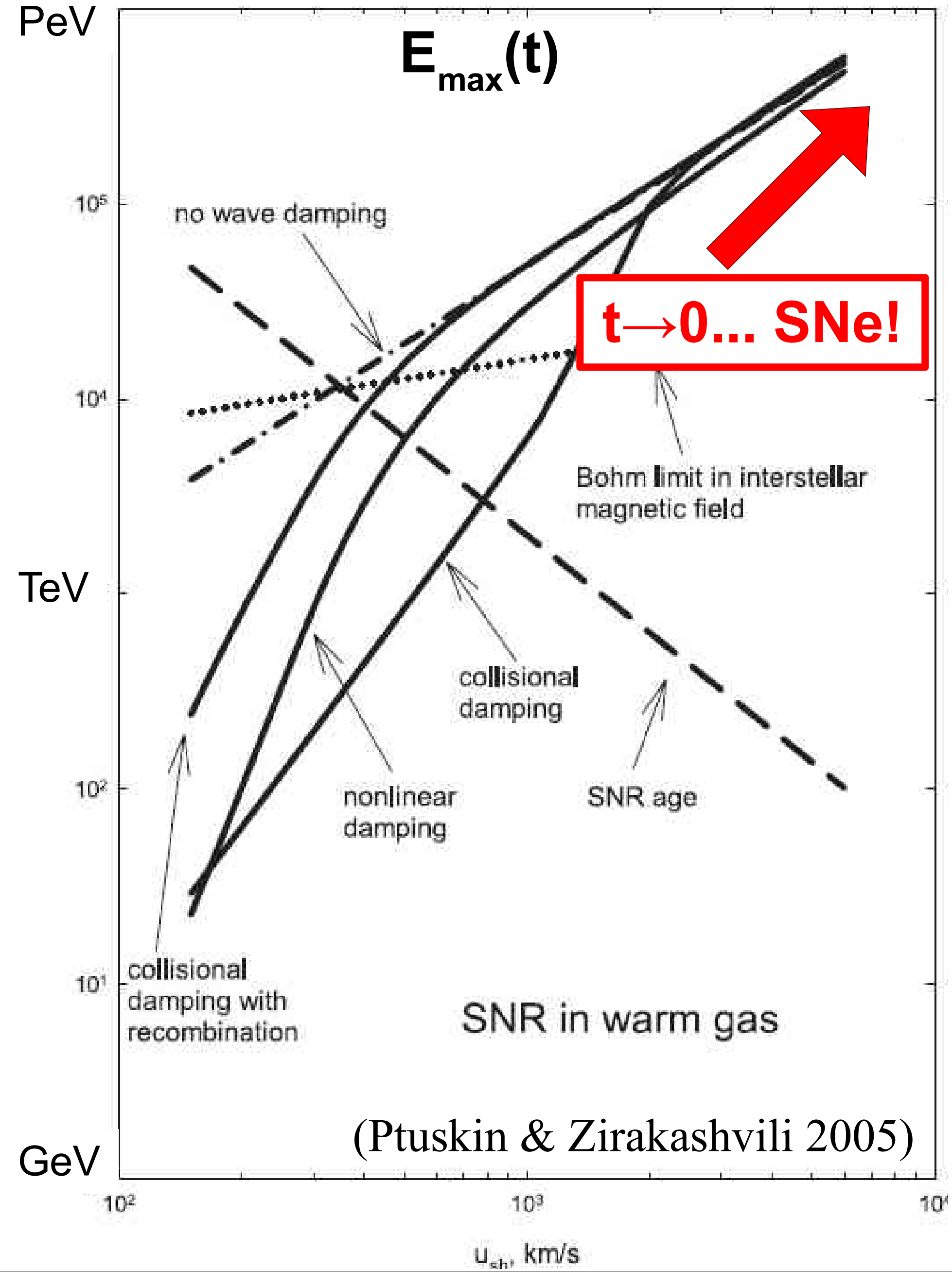
Perform similar calculations for other SN types (II-P, II-L, IIn, Ib/c) based on their $\{u_w, \dot{M}\}$ properties (e.g. Chevalier & Soderberg 2010)

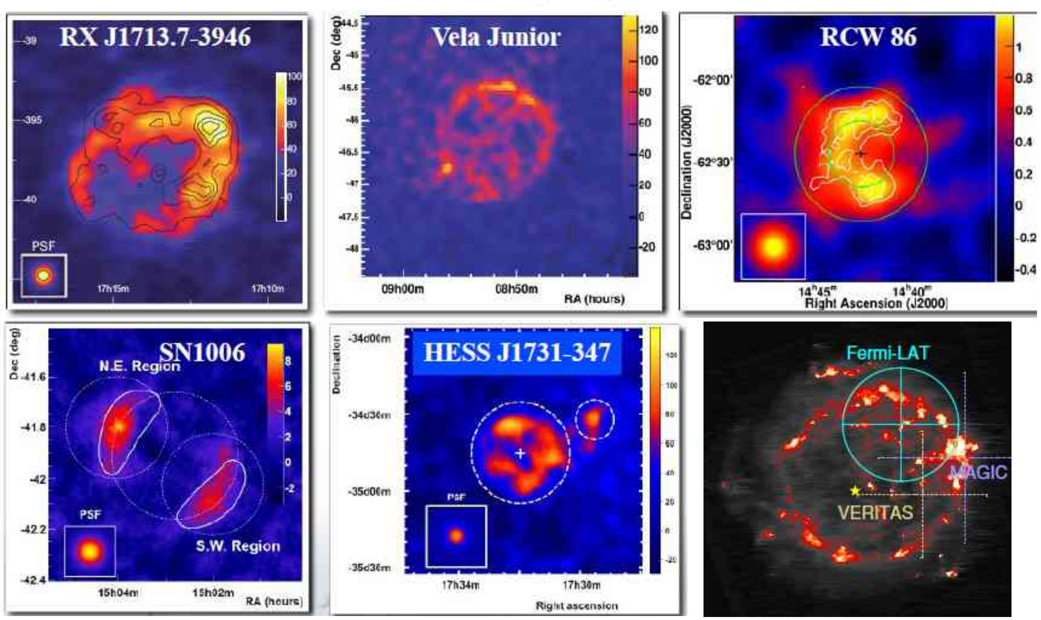


$\rightarrow$ How many detectable SNe with CTA...?

SNe as cosmic-ray sources

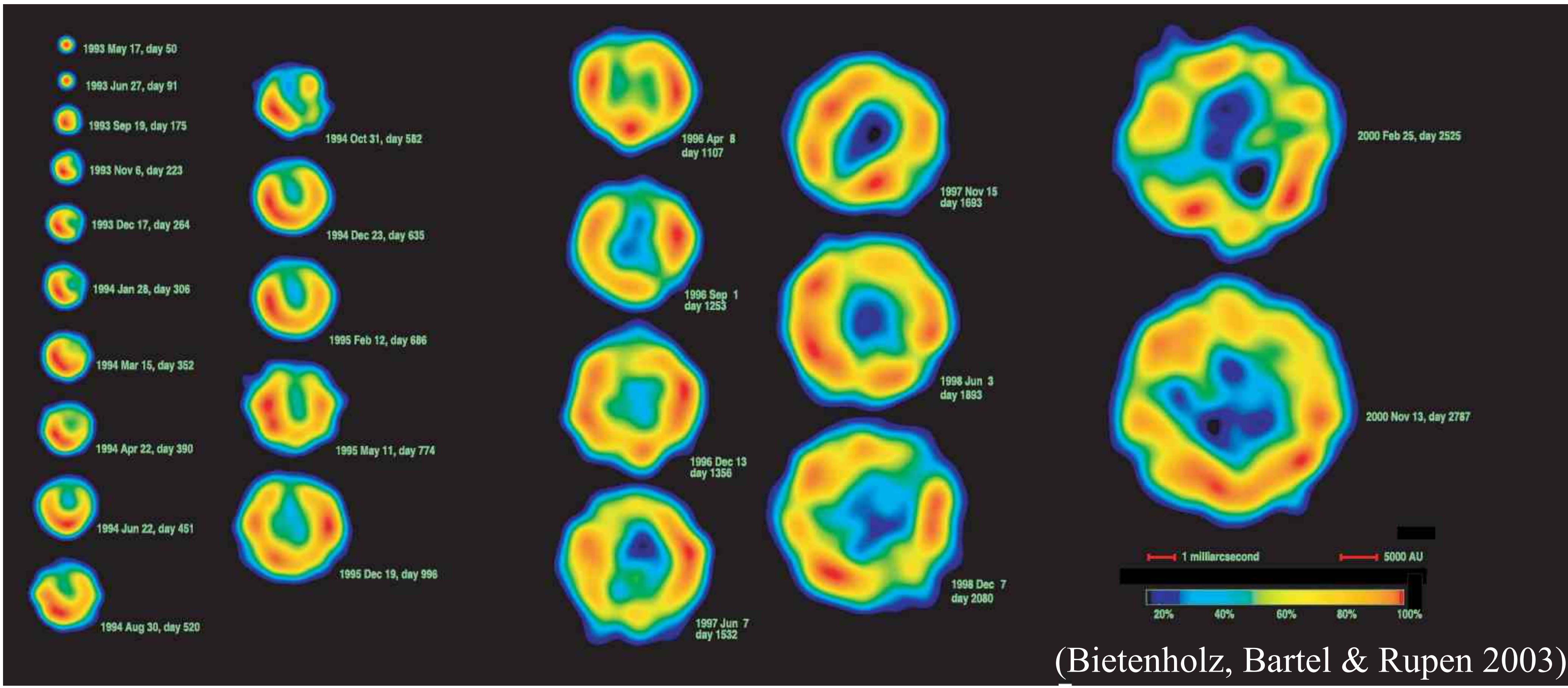






SN 1993J : Generalities

Type IIb SN (Filippenko et al. 1993) discovered by F. Garcia on 1993/03/28 in M81
$d_{Cepheids}$ = 3.63 ± 0.34 Mpc (Freedman et al. 1994) d_{ESM} = 3.96 ± 0.29 Mpc (Bartel et al. 2007)
13-20 $M_{\odot}$ RSG with most of its H envelope lost to a binary companion (Maund et al. 2004)



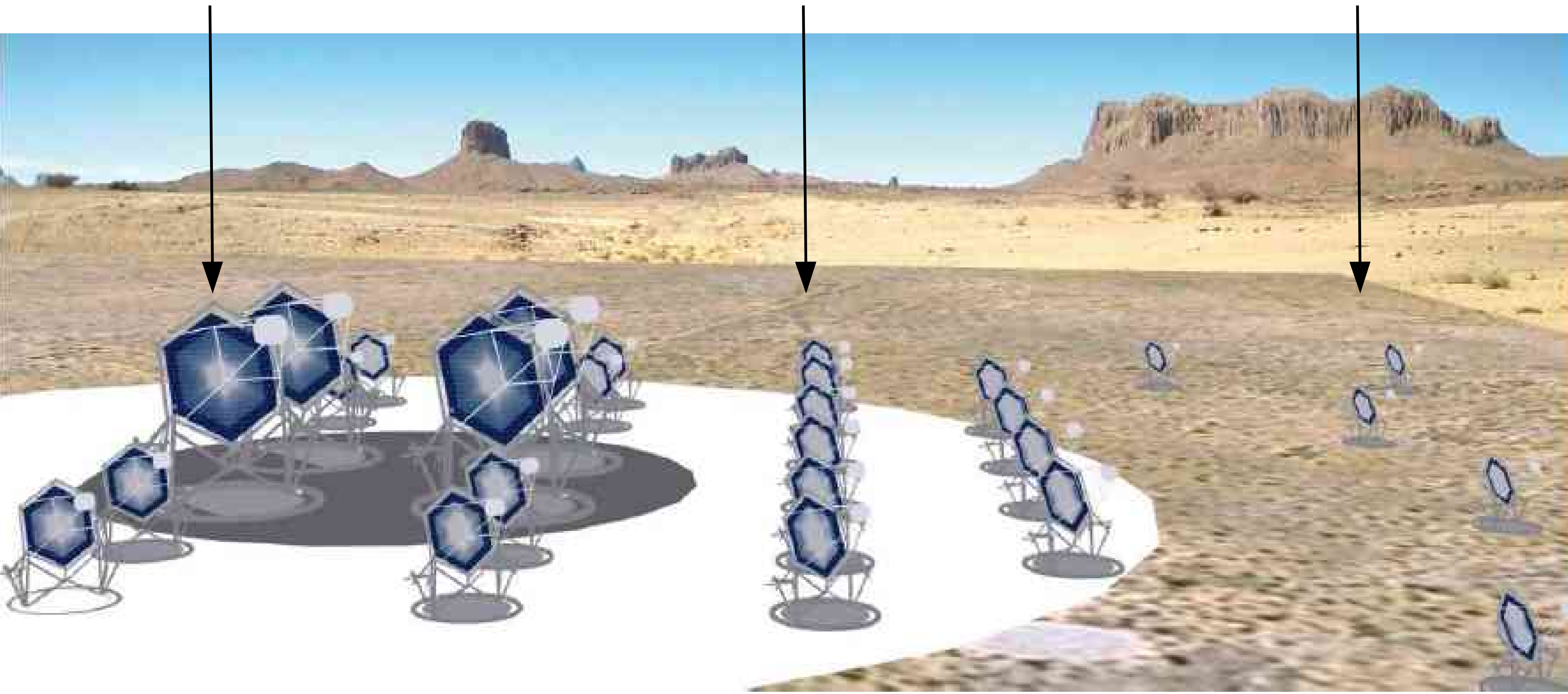
(Bietenholz, Bartel & Rupen 2003)

Cherenkov Telescope Array

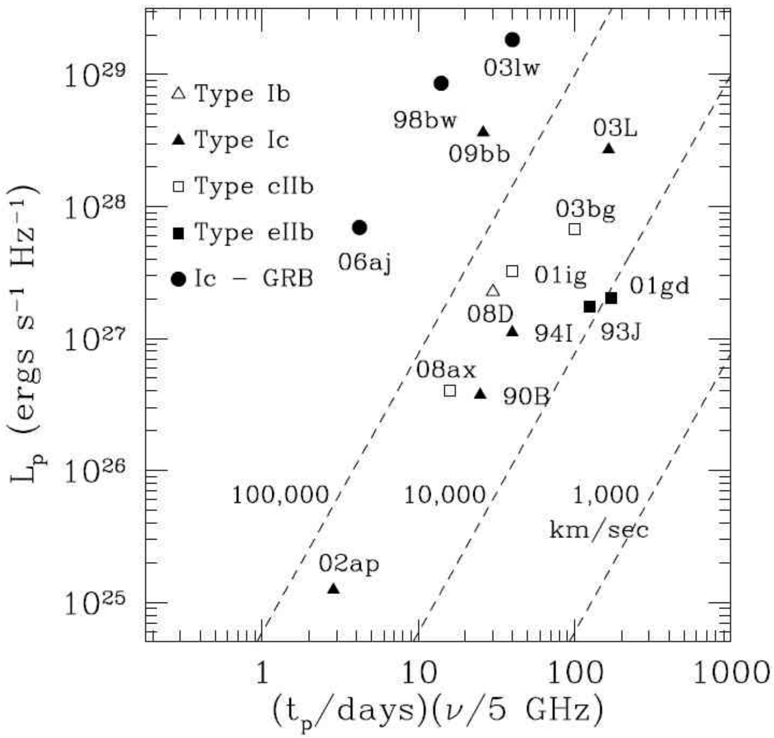
Low-energy section
energy threshold
of ~ 20–30 GeV
23–24 m telescopes

Medium energies
mcrab sensitivity
~100 GeV–10 TeV
10–12 m telescopes

High-energy section
10 km^2 area at
multi-TeV energies
5–8 m telescopes



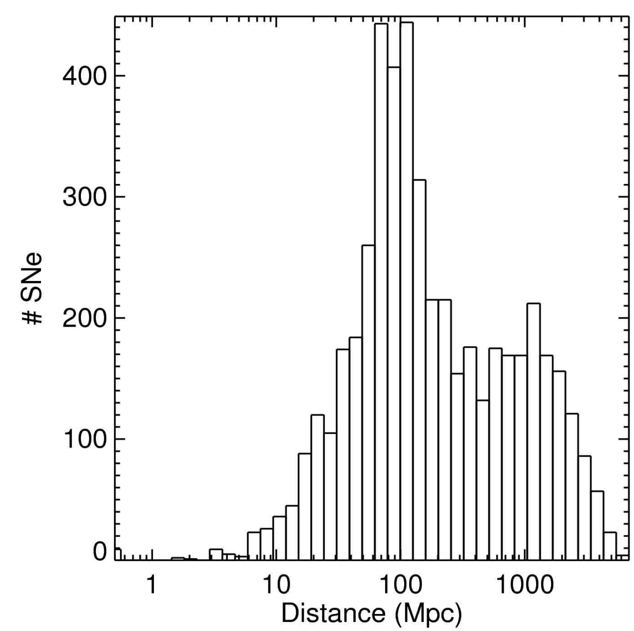
Radio SNe & rates

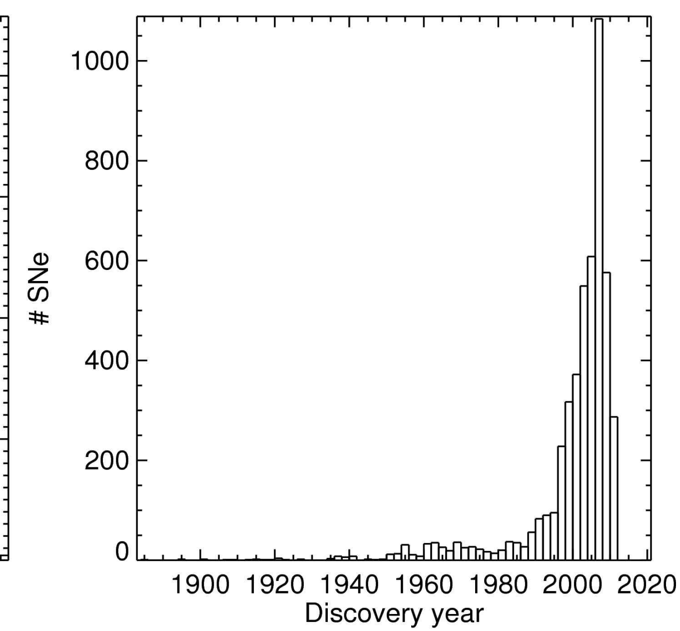


(Chevalier & Soderberg 2010)

(Smartt 2009)

	Sample				
Type	SECM08	LWVetal07	VLF05	PSB08	CET99
II-P	58.7±8.0%	67.6±10%	62.9±4.7%	75.5±9.8%	77.7±10.8%
II-L	2.7±1.7%				
IIn	3.8±2.0%	4.4±2.5%	9.2±1.8%		
IIb	5.4±2.7%	1.5±1.5%	3.2±1.0%		
Ib	9.8±3.3%				
Ic	19.6±4.5%	26.5±6.2%	24.7±3.0%	24.6±5.6%	22.3±5.8%
Sample size	92	68	277	77	67





SAI SN Catalog *(http://www.sai.msu.su/sn/sncat/)*

Degree of ionization & growth rate of long-λ mode instabilities

(Fransson, Lundqvist & Chevalier 1996)

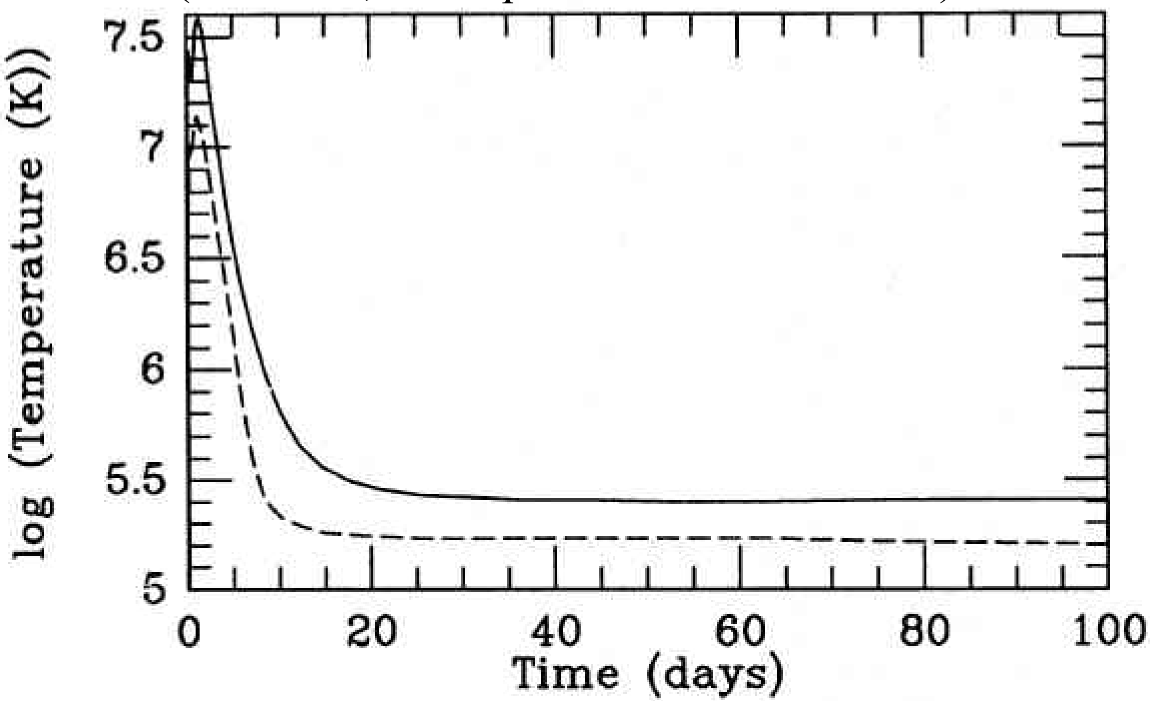
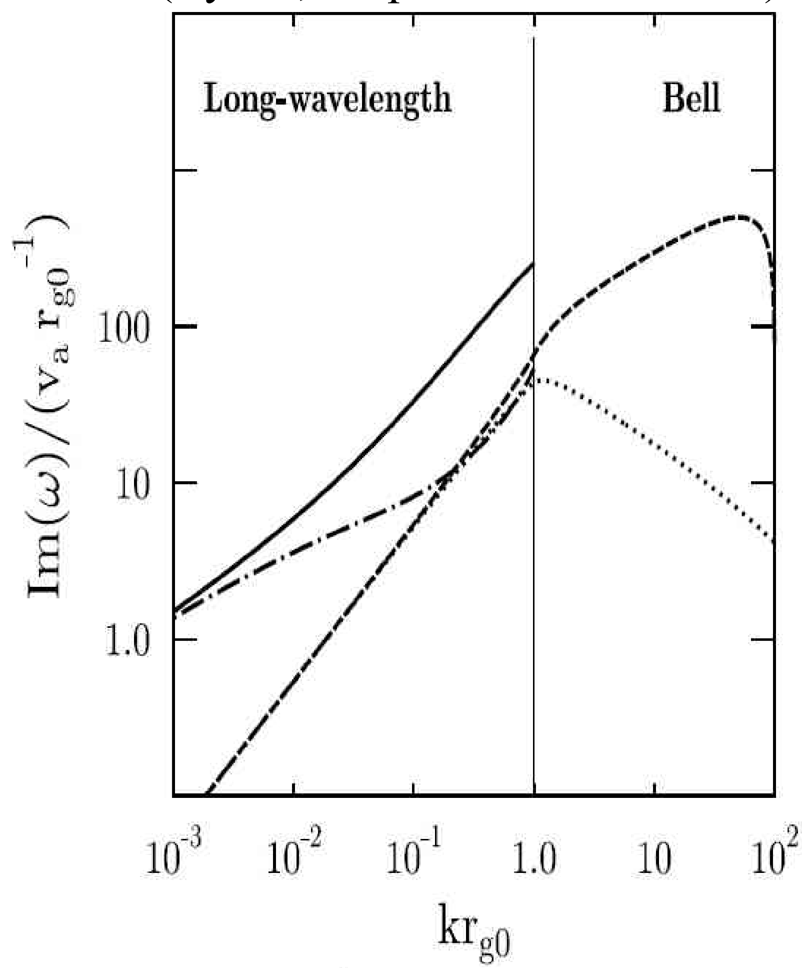


FIG. 11.—Temperature of the circumstellar gas at $R = 1.5 \times R_s$ for $s = 1.7$ and $\dot{M}_{-5}/v_{w1} = 4.0$ (*dashed line*), and $s = 2.0$ and $\dot{M}_{-5}/v_{w1} = 5.0$ (*solid line*).

Upstream medium at R = 1.5×R_{sh} almost fully ionized

(Bykov, Osipov & Ellison 2011)



$$t_g = [1.5 \times 10^4] s \times \left(\frac{E_{10PeV}}{V_{sh,10^4}}\right)^{1/2} \times \frac{1}{A^{1/2} n_{CR}^{1/2}} (kr_g 0)^{-1/2}$$

A = amplification factor by Bell's instability ~ 10–30