Gamma-ray radiation from type IIb supernova remnants prospect for the Cerenkov Telescope Array

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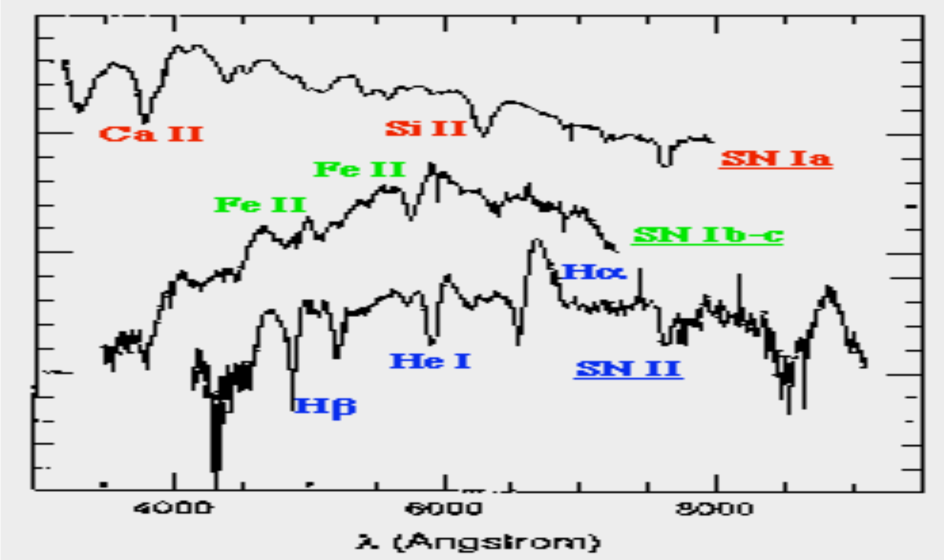
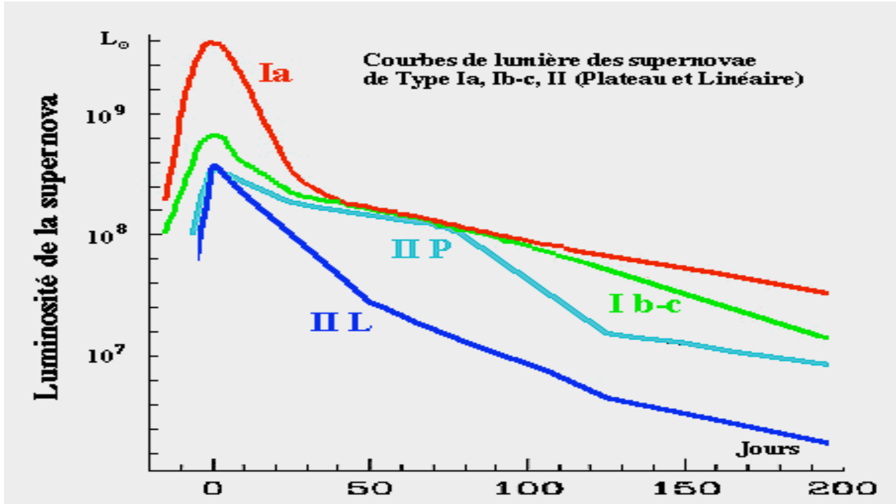
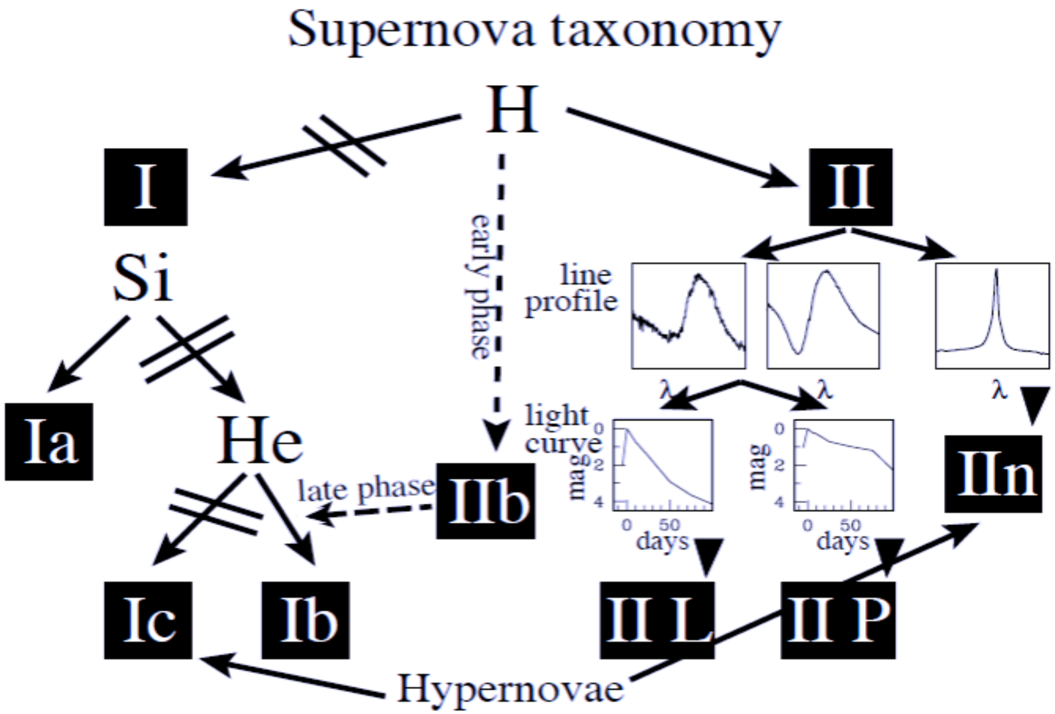
OUTLINES

- Introduction:
  - Types and frequencies of supernovae (SN)
  - Type IIb SN: properties.
- A test case: SN 1993J:
  - Radio observations
  - Particle acceleration and magnetic field
- Gamma-ray radiation from 1993J type objects:
  - Pair opacity calculation
  - Observability by CTA
  - Other objects
- Conclusions

Types of Supernovae

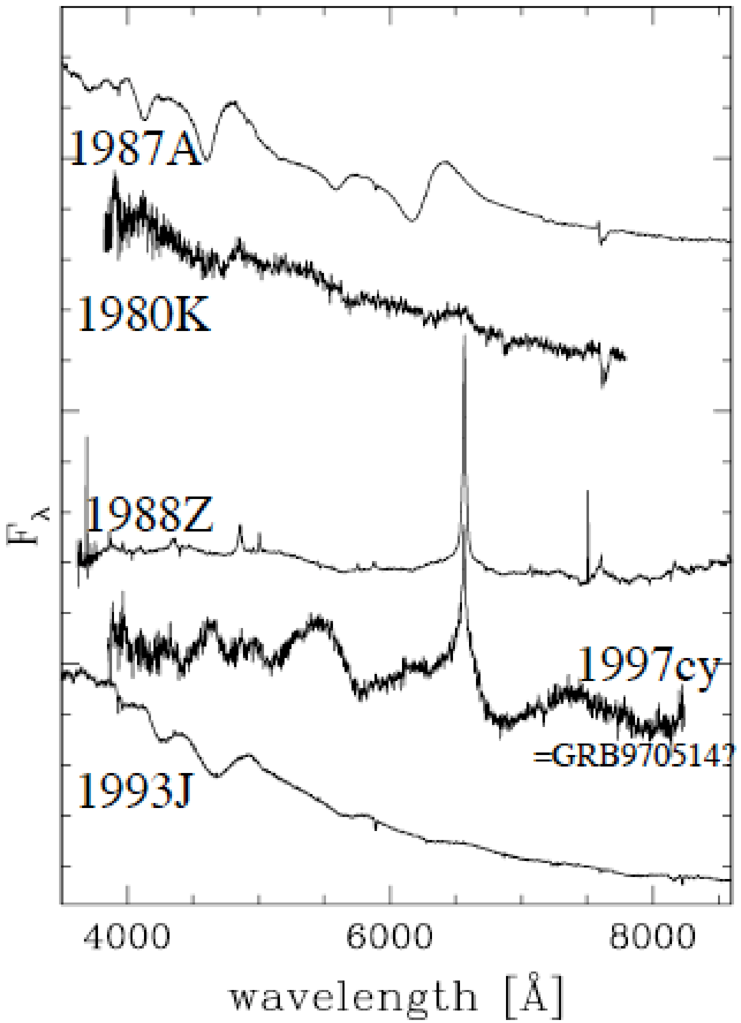






Cappellaro & Turatto'01

All inject ~10^{51} ergs !



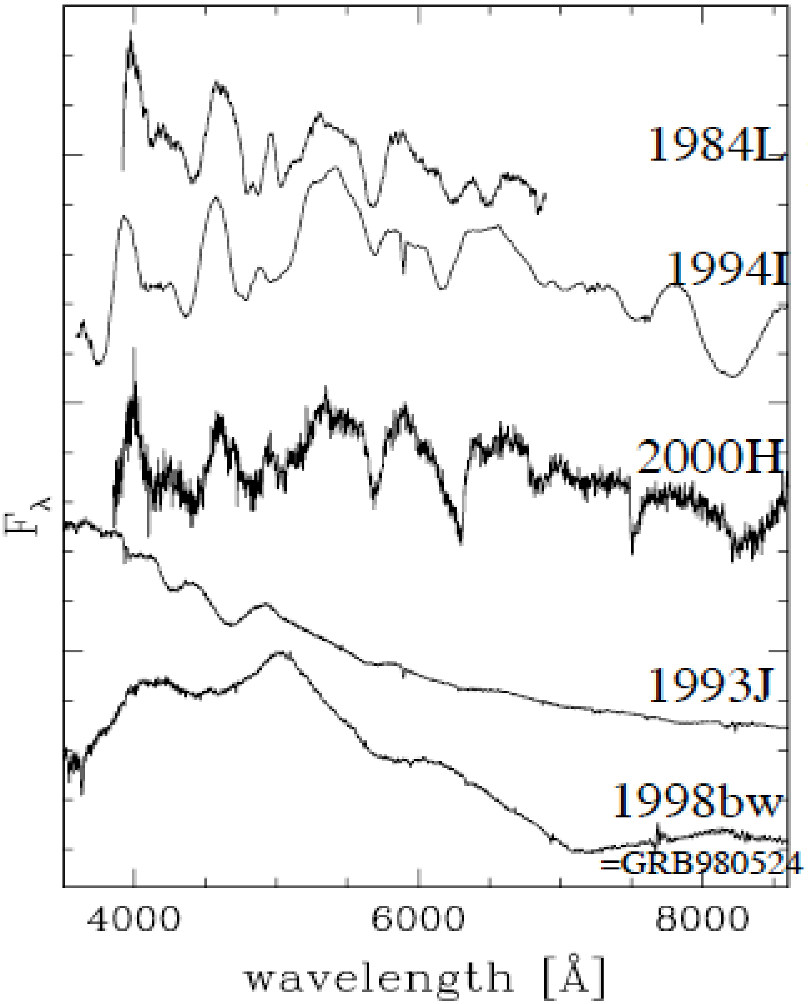
SN II

	^{56}Ni	total	ejecta	(H)
IIP	0.07$M_\odot$	20$M_\odot$	15$M_\odot$	(10)
IIL	0.07$M_\odot$	10$M_\odot$	5$M_\odot$	(1)
IIn	? $M_\odot$	8,30$M_\odot$	1,15$M_\odot$	
IIpec	?–3$M_\odot$	25$M_\odot$	5$M_\odot$	
IIb	0.08$M_\odot$	13$M_\odot$	2.5$M_\odot$	(0.2)

Cappellaro & Turatto'01

Figure 7. Representative spectra of SN II. On the right we report for each object the best estimate of the ^{56}Ni, total and ejecta masses (in parenthesis is the H mass in the ejecta).

SN Ib/c



Type	^{56}Ni mass	total mass	ejecta mass
Ib	$0.1M_\odot$ / $0.2M_\odot$	$13–18M_\odot$ / $50M_\odot$	$2–3M_\odot$ / $>10M_\odot$
Ic	$0.07M_\odot$	$15M_\odot$	$1M_\odot$
Ic/IIb			
IIb	$0.08M_\odot$	$12–15M_\odot$	$2.5M_\odot$
Ic	$0.2M_\odot$ / $0.7M_\odot$	$15M_\odot$ / $40M_\odot$	$2M_\odot$ / $15M_\odot$

Cappellaro & Turatto'01

Figure 10. Representative spectra of SNIb/c. On the right the best estimates of the ^{56}Ni, total and ejecta masses are reported . In some case different modeling produces significantly different results.

SN rates

Cappellaro'99,
vdBergh & Tamman'91
Smartt+09, Li+11

Milky way
Ia 0.4+/-0.2
II 1.5+/-1
About 2
SN/century

Table 1. The relative frequency of SNe types discovered between 1998-2008 (10.5 yrs) in galaxies with recessional velocities less than 2000 kms^{-1}, and type taken from Table A1. The relative frequency of all types and the relative frequency of only core-collapse SNe are listed separately.

		Relative	Core-Collapse only
Type	No.	/ per cent	/ per cent
II-P	54	39.1	58.7
II-L	2.5	1.8	2.7
IIn	3.5	2.5	3.8
IIb	5	3.6	5.4
Ib	9	6.5	9.8
Ic	18	13.0	19.6
Ia	37	26.8	...
LBVs	7	5.1	...
Unclassified	2	1.4	...
Total	138	100	100
Total CCSNe	92	66	100

Type IIb SN

- Intermediary between II (H rich) and Ib/Ic (H poor).
- Several well-known objects: SN1993J, Cassiopeia A
- Mass loss by wind stripping (masses ~ 25 solar masses) or interaction with a companion (rather favored, Claeys+11) (masses ~ 15 solar masses)
- Rare events:
  - vdBergh et al'05

  3%+/-1% of core collapse SNe in 140 Mpc limited distance

  1.5%+/-1.5% in 30 Mpc limited distance
  - Smartt'09

  5.4+/-2.7% in 28 Mpc limited distance

  ~ one every millenary at a rate of SN 2/century
- ! May enter in sequence MS=>RSG=>WNH=>SNIIb
  - WNH Wolf-Rayet (Nitrogen, Hydrogen) associated with high loss rate (above 10^{-5} solar masses) and fast winds (2000 km/s)
  - But for other models SNIIb are not associated with any WR phases (e.g. Meynet+11)

Maximum CR energy in type II SNR

- Galactic CRs at PeV and beyond could be produced right after the SN explosion; when the BW is propagating into the massive star wind (other models exist; e.g. Bykov'01, Parizot,A.M.+04)
- For protons (Voelk & Biermann '88, Bell & Lucek'01, Ptuskin+10)

$$E_{max} = 3.5\text{x}10^{17}\text{eV}\,(v_{sh,2E4})^2\,(M_{d,-5})^{1/2}\,(P_{CR,0.1\rho u})(v_{w,10})^{-1/2})$$

=> Hints toward slow winds, fast shocks, high loss mass rates: interesting case of IIb SNR SN1993J

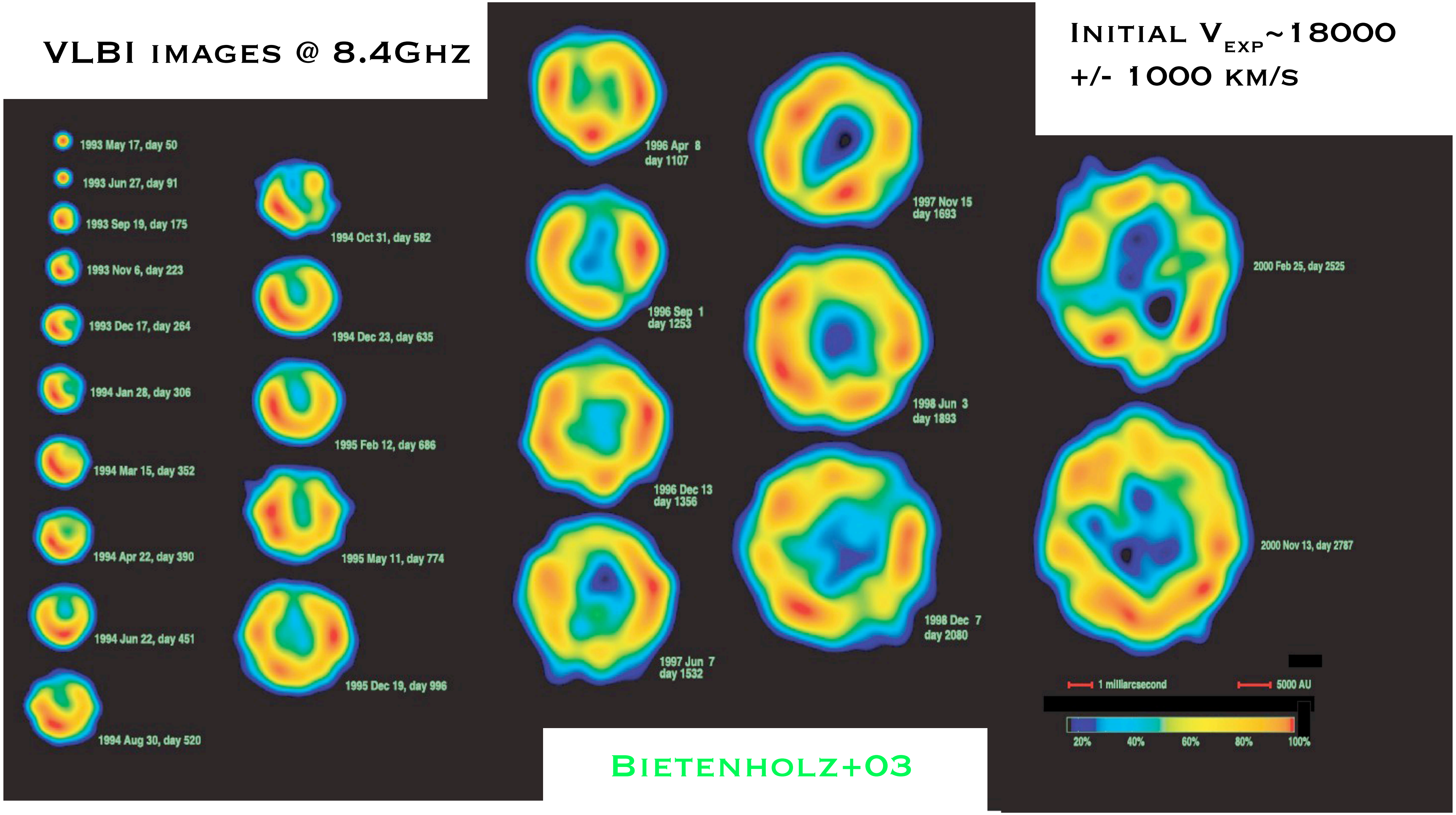
A test case: SN 1993J

- Type IIb SN (Filippenko et al. 1993) discovered by F. Garcia on 1993 March 28th 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_{sun} RedSuperGiant (RSG) which had lost most of its H envelope to a close binary companion (Maund et al. 2004)

Radio follow-up

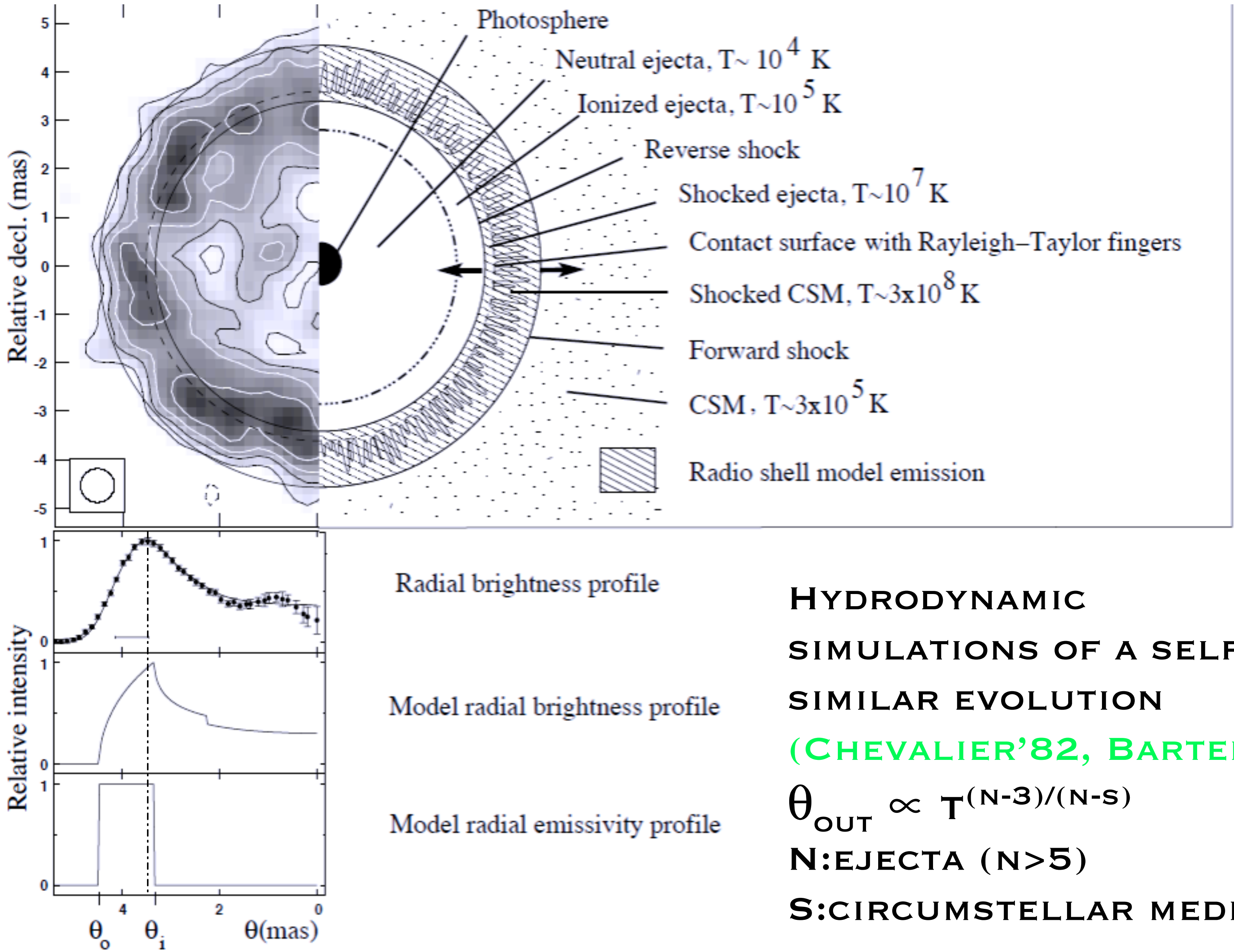
VLBI images @ 8.4GHz

Initial V_{exp}~18000 +/- 1000 km/s



Bietenholz+03

Shell @ T >175 days



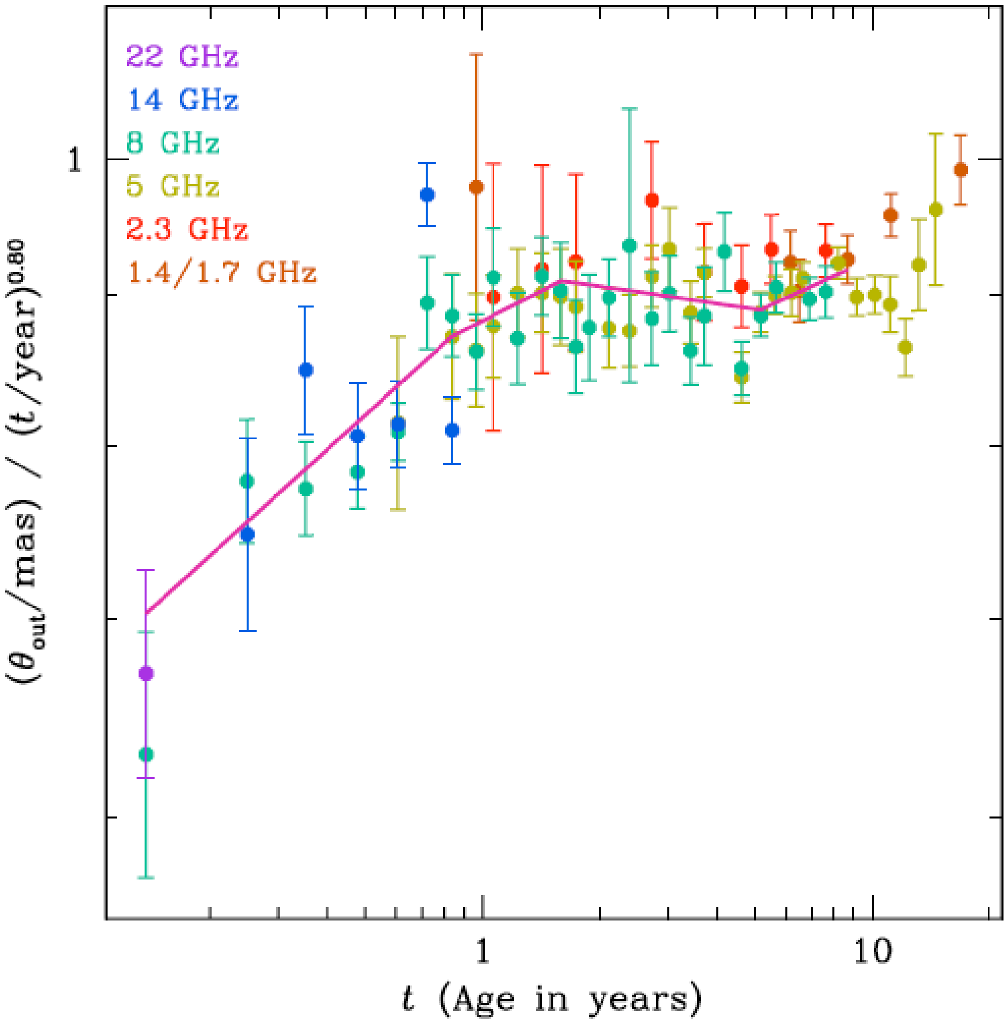
HYDRODYNAMIC SIMULATIONS OF A SELF-SIMILAR EVOLUTION (CHEVALIER'82, BARTEL+08)

$\theta_{OUT} \propto T^{(N-3)/(N-S)}$

N:EJECTA (N>5)

S:CIRCUMSTELLAR MEDIUM

Light curves & spectra



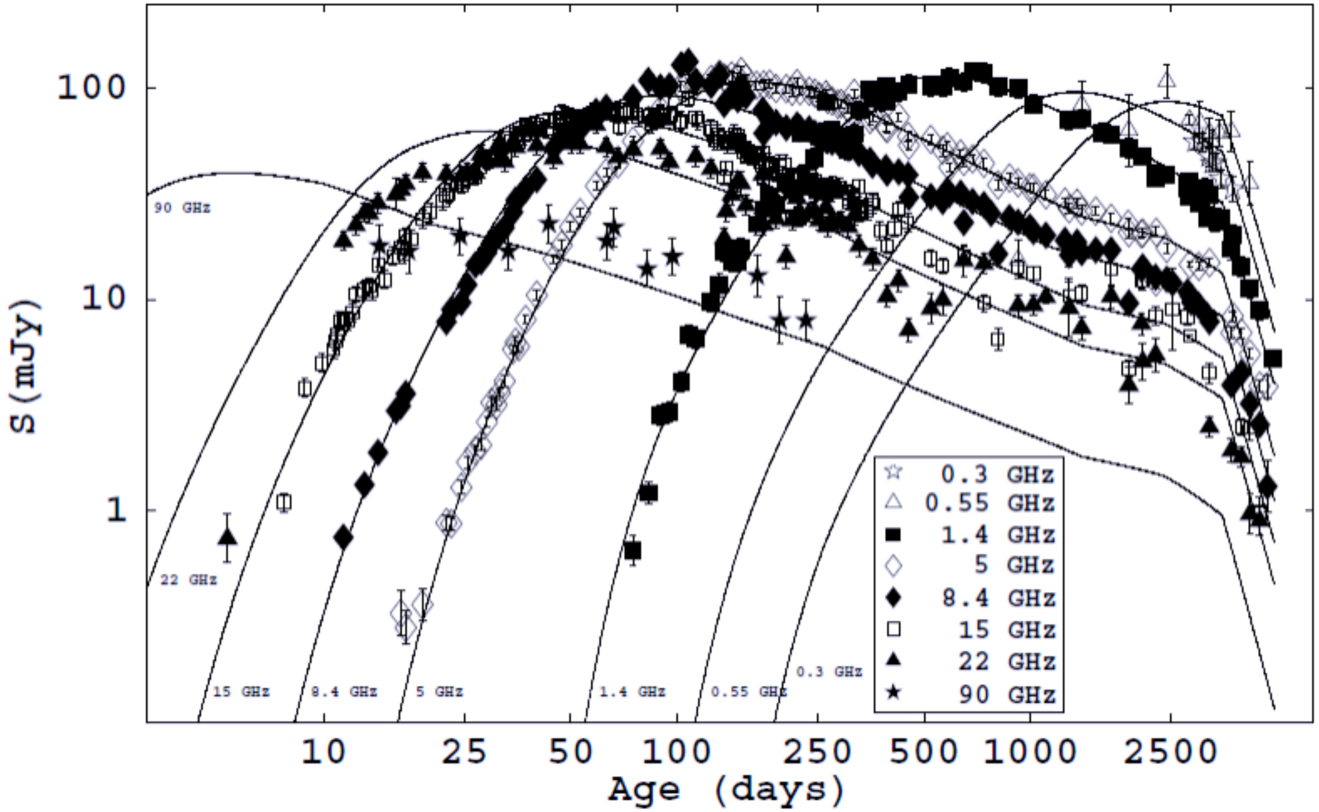
$\theta_{out} \propto t^{m}$

m ~ 0.93 t<1 yr

m ~ 0.82 t>1 yr

Bietenholz+11

Light curves & spectra



Marti-Vidal+11

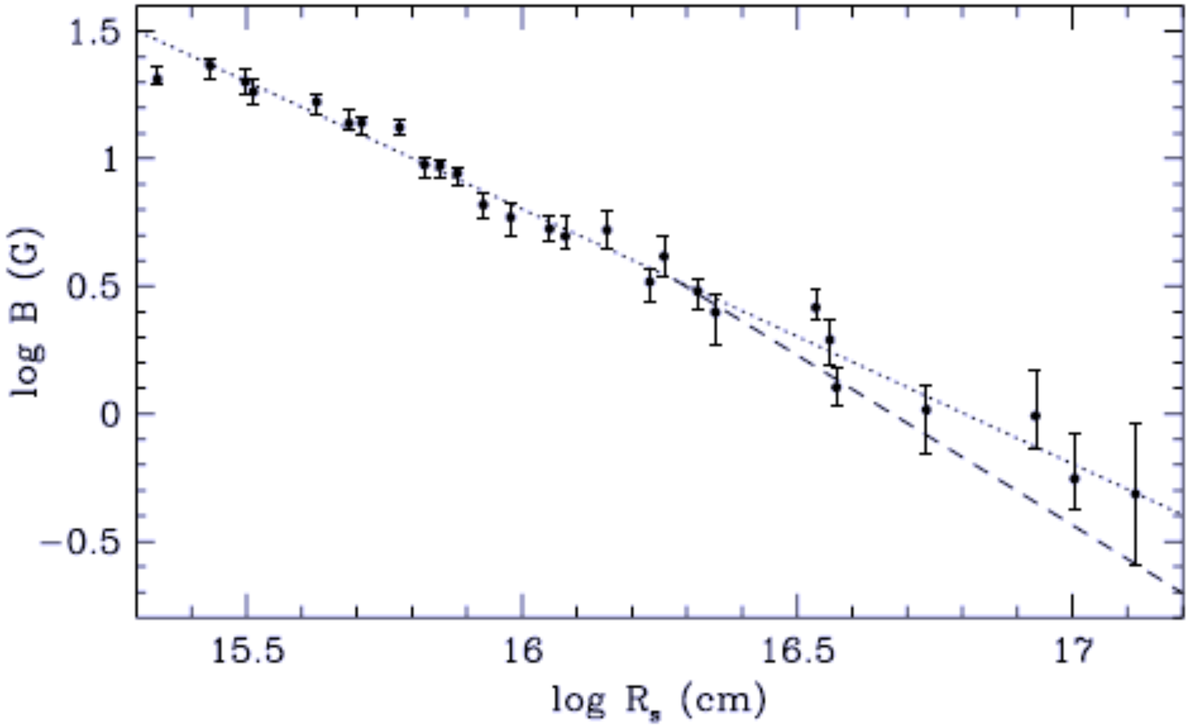
Fit synchrotron self-absorbed model

B~64G $(R/10^{15}cm)^{-1}$

$N(E) \propto E^{-2.1}$

Argue for a constant amplification wrt to an ambient toroidal magnetic field (Bjornsson & Fransson'98)

Magnetic field amplification



- MF 3 orders of magnitude above MF-wind equipartition

$$B_{eq}=(u_w M_d)^{1/2}/r=2.5\ \mathrm{mG}\ (M_{d,-5})^{1/2}(u_{w,10})^{1/2}(r_{,15})^{-1}$$

Conclusions from radio data

- Forward shock dynamics
  - No strong evidences at the outer edge of deviation from circular shape.
  - Expansion well reproduced by hydrodynamical models.
  - Most of the radio emission coming from the forward shock (?)
- Magnetic field
  - evolution in r^{-1} or t^{-1}
  - Amplification

Some assumptions

From the outburst time:

- MF is amplified through the Bell mechanism (Bell'04)
- hadrons are accelerated as well as electrons.

⇒ Gamma-ray radiation ?

  - Inverse Compton
  - Neutral pion decay (density profile of circum stellar medium)
    - The latter likely dominant in strong MF.

Circumstellar medium

- Effective density behind the forward shock:

$$n_{eff} = \frac{M_d r_{eff}}{4\pi R_{sh,out}^{2} u_w m_H (1+4X)}$$

Density scales as r^{-2} with $R(t=0)=3.5\ 10^{14}$ cm (deduced from $\theta_{out}(t)$); $U_w=10$ km/s (velocity at infinity)

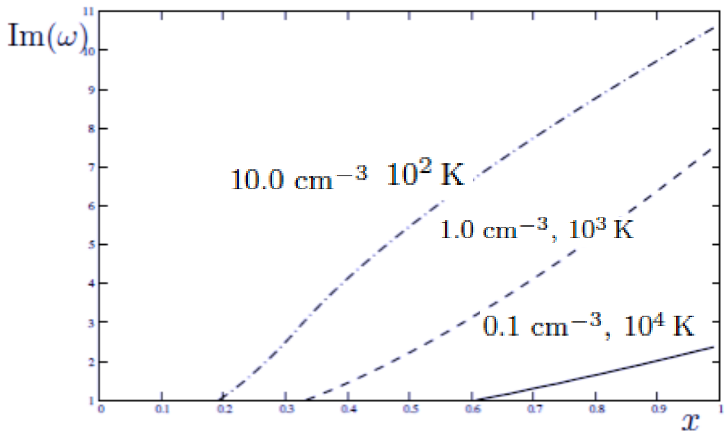
$N_{eff} \sim 3\ 10^9\ cm^{-3}$ at t=0 (outburst)

- Stromgren sphere (B2 star) $R_s \sim 13$pc $N_{e,cm-3}^{-2/3}$: likely fully ionized medium once the RSG phase starts.
- questioned after (but see Fransson+96)

NB: 10 years at 10^4 km/s is 0.1pc.

- Magnetic field (magnetization) $B \sim 1$ milli G @ 10^{16} cm => $\sigma \sim 2\ 10^{-9} << 1$.

Bell instability growth rate Vs ionization fraction



Reville+06

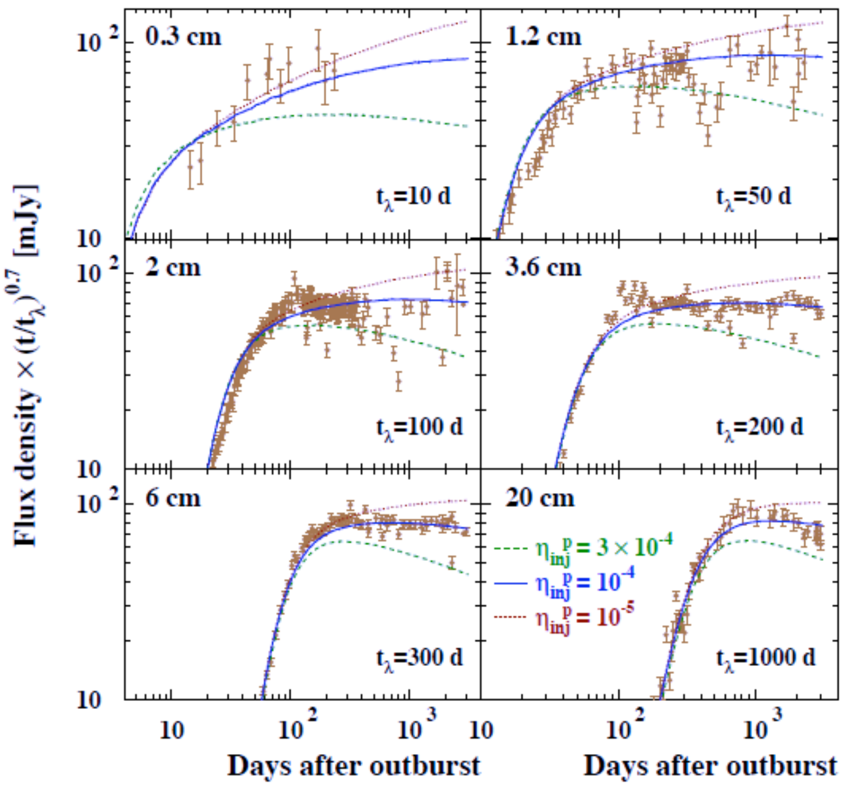
Cosmic Ray acceleration I

- Estimation by Voelk & Biermann'88
  - <u>Non amplified MF</u>:
    - $K_1=(c^2/3)*E/(ZeB_{back}(R_s))$
    - Oblique shock case: $K_2 = K_1/2$
  - Linear acceleration: $R_{tot}=R=4$
  - Stellar radius ~ 400 solar radii
- Other estimation:
  - <u>Amplified MF</u>:
    - $K_1(B_{ampl})$
    - Tangled MF at the shock front $K_2< K_1/2$
  - Non-linear effects $R_{tot}>4$
  - Stellar radius RSG > 1000 solar radii.

Cosmic Ray acceleration II

- Iterative Fit radio data with a synchrotron model
- 1D non-linear model (Berezhko & Ellison'99)
  - $V_{sh}(t)$, $B_u(t)$, T_{CSM}, $\rho_u(t)$ => solutions : F_p, F_e
- Solutions stay close to the test-particle regime (Alfvèn heating included).
- Acceleration efficiency increases with time up to 25%

$$\varepsilon_{NT}=F_{CR}/1/2\rho_u v_{sh}^3$$



Tatischeff'09

- Downstream: self-similar model by Chevalier'82

two differents solutions for B: advection/damping

Synchrotron model fitting

- <u>Fit radio emission of very young SNR:</u>

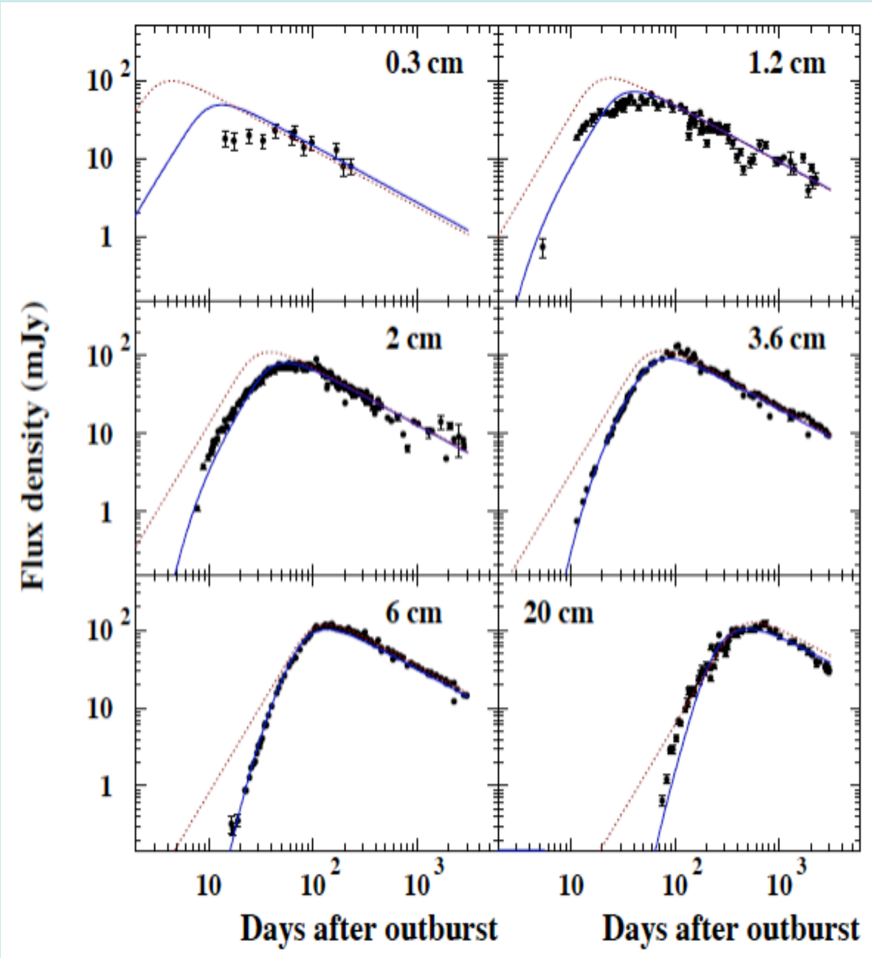
$$F(\mathrm{mJy}) = K_1 \left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{\alpha} \left(\frac{t}{1\ \mathrm{day}}\right)^{\beta} A_{\mathrm{CSM}}^{\mathrm{homog}} A_{\mathrm{CSM}}^{\mathrm{clumps}} A_{\mathrm{SSA}}$$

A factors = attenuation by
- Homogeneous circumstellar matter
- Clumps in circumstellar matter
- Internal Synchrotron-self asborption

=> 4 parameters (K_1, α, K_3(CSM), K_5(SSA)) fitted with 6 different wavebands (fig)

- <u>Synchrotron model</u> => MF

$$\langle B \rangle = (2.4 \pm 1.0)\left(\frac{t}{100\ \mathrm{days}}\right)^{b}\ \mathrm{G},\ \text{with } b = -1.16 \pm 0.20.$$



SN1993J Tatischeff'09

Consistent with b=1 (also in other young objects SN2008D Ib/c)

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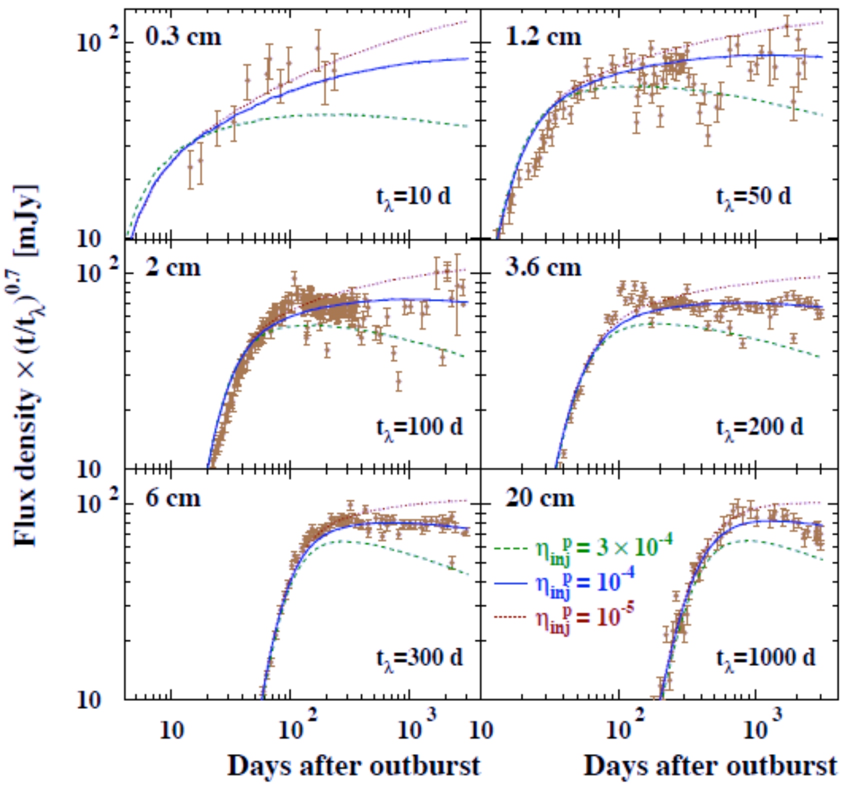

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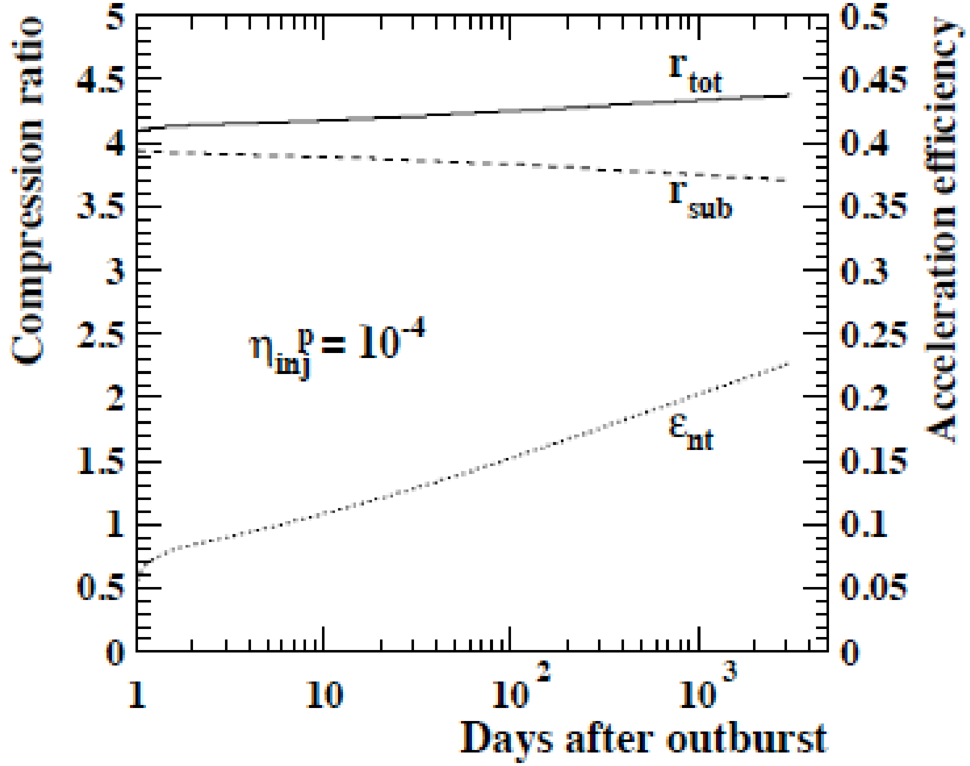

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Tatischeff'09

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Magnetic field amplification

- Observations (based on SSA model): $B(t) = 501G\ (t/1d)^{-1.16}$
- Link to microphysics through streaming instability (Bell'04)

$$B_{NR}^2=8\pi\xi_{CR}\,\rho_u v_{sh}^3/2\phi;\ \phi=\ln(p_{max}/p_{min})$$

Downstream $B_D = (1/3+2/3R_{sub}^2)^{1/2}\,B_{NR}$

$$\xi_{CR} \propto p_{inj}/v_{sh}^2; p_{inj}\ \xi_{CR}\propto v_{sh} \Rightarrow \xi_{CR}\propto v_{sh}^{-1}$$

This produces B_{NR} in t^{-1}

- Growth timescale (Bell instability)

$$\tau=3.3\times10^{-2}\ \text{days}\ (\phi/15)(\varepsilon_{NT}/0.1)^{-1}(E_{max,PeV})(t_{day})^{-1.34}$$

+Long wavelengths

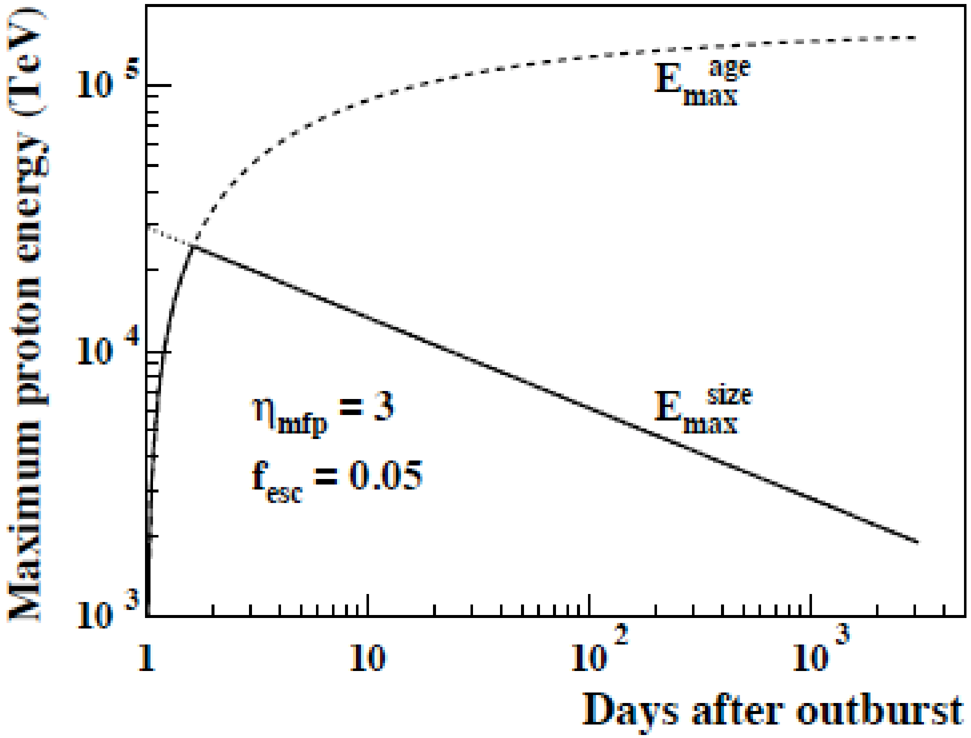
Bykov+11

$$t_g = [1.5\times10^4]s \times \left(\frac{E_{10PeV}}{V_{sh,10^4}}\right)^{1/2} \times \frac{1}{A^{1/2} n_{CR}^{1/2}} (kr_g0)^{-1/2}$$

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

Maximum particle energy

- Fixing up- and downstream magnetic fields
- Bohm diffusion regime
  - Fixes the maximum energy by escape losses and time limited effect



Tatischeff'09

Gamma-ray radiation

- Total energy put into CRs (swept-up mass is < M_{EJ}) from day 1 to 3100.

$$E_{CR} = \int dt 4\pi R_{sh}^{2} \varepsilon_{NT} F_{NT} = 7.9\times10^{49}\ \text{ergs}$$

- With a dense target gamma-rays are expected but absorbed due to electron-positron pair production.

γ (gamma)γ(UV-optical)$\rightarrow e^{+}/e^{-}$

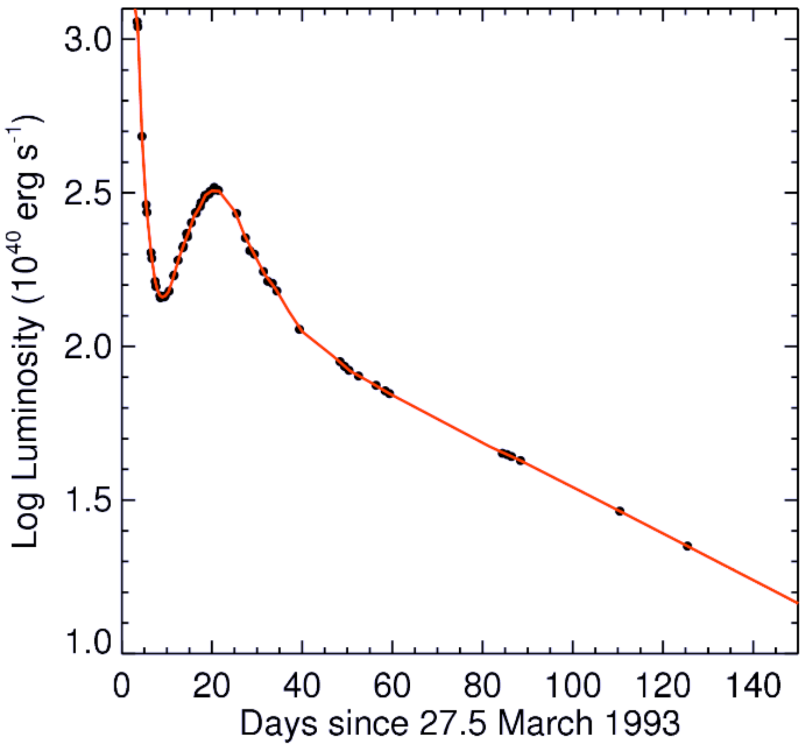
$$\tau_{\gamma\gamma}(E_\gamma) \approx R_s \kappa_{\gamma\gamma}(E_\gamma) ,$$

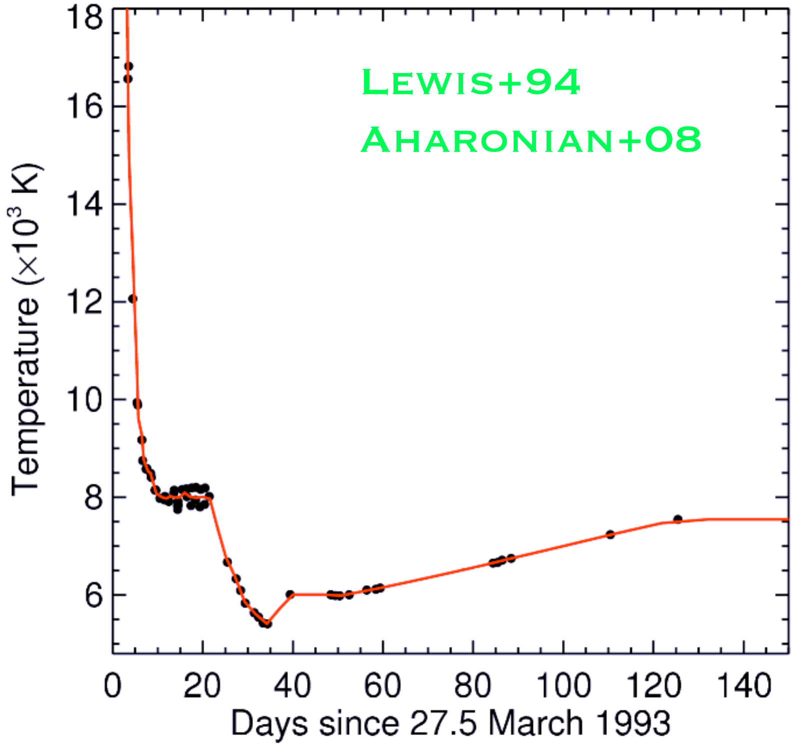
where

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

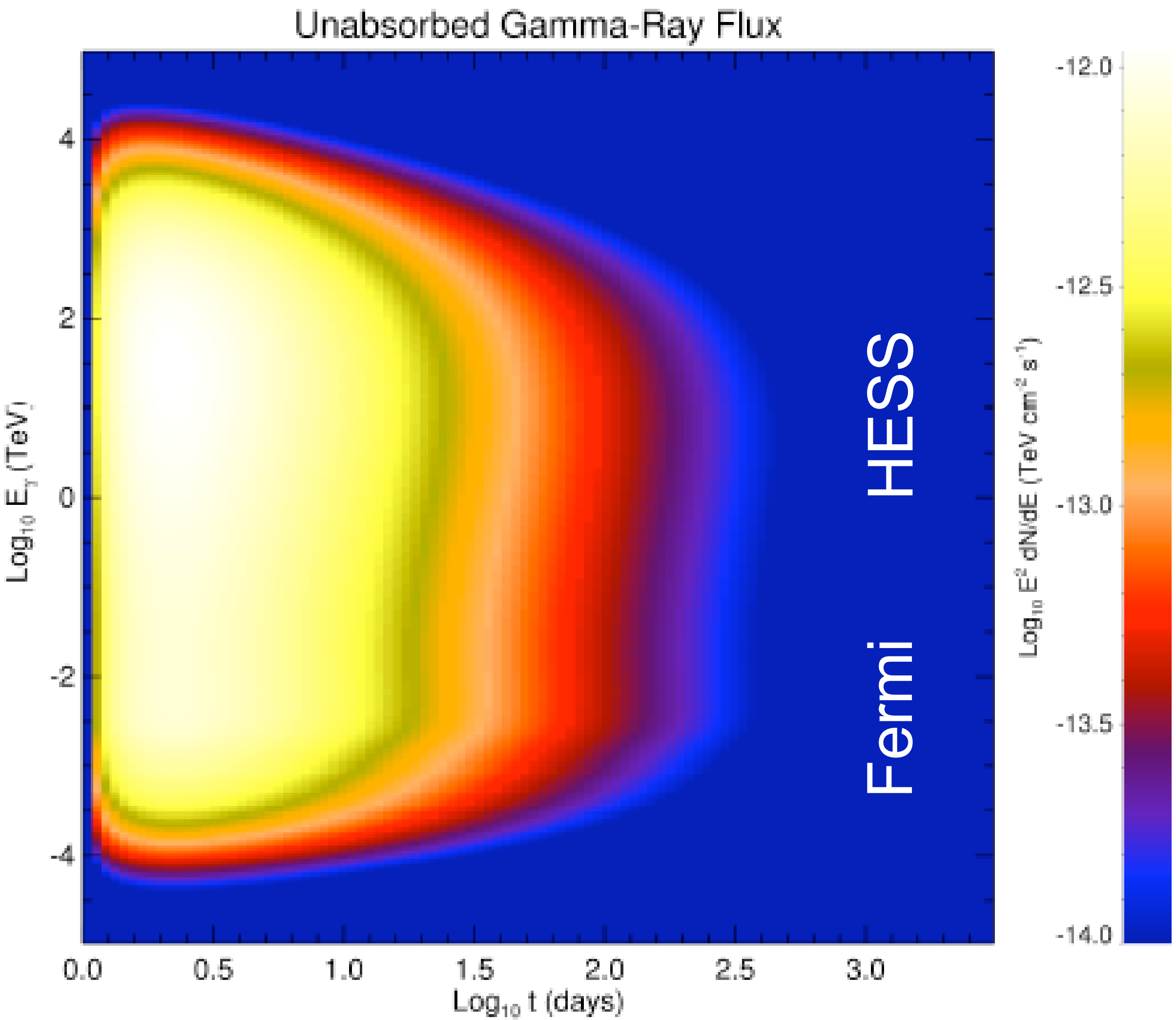
Soft photons

Bolometric luminosity

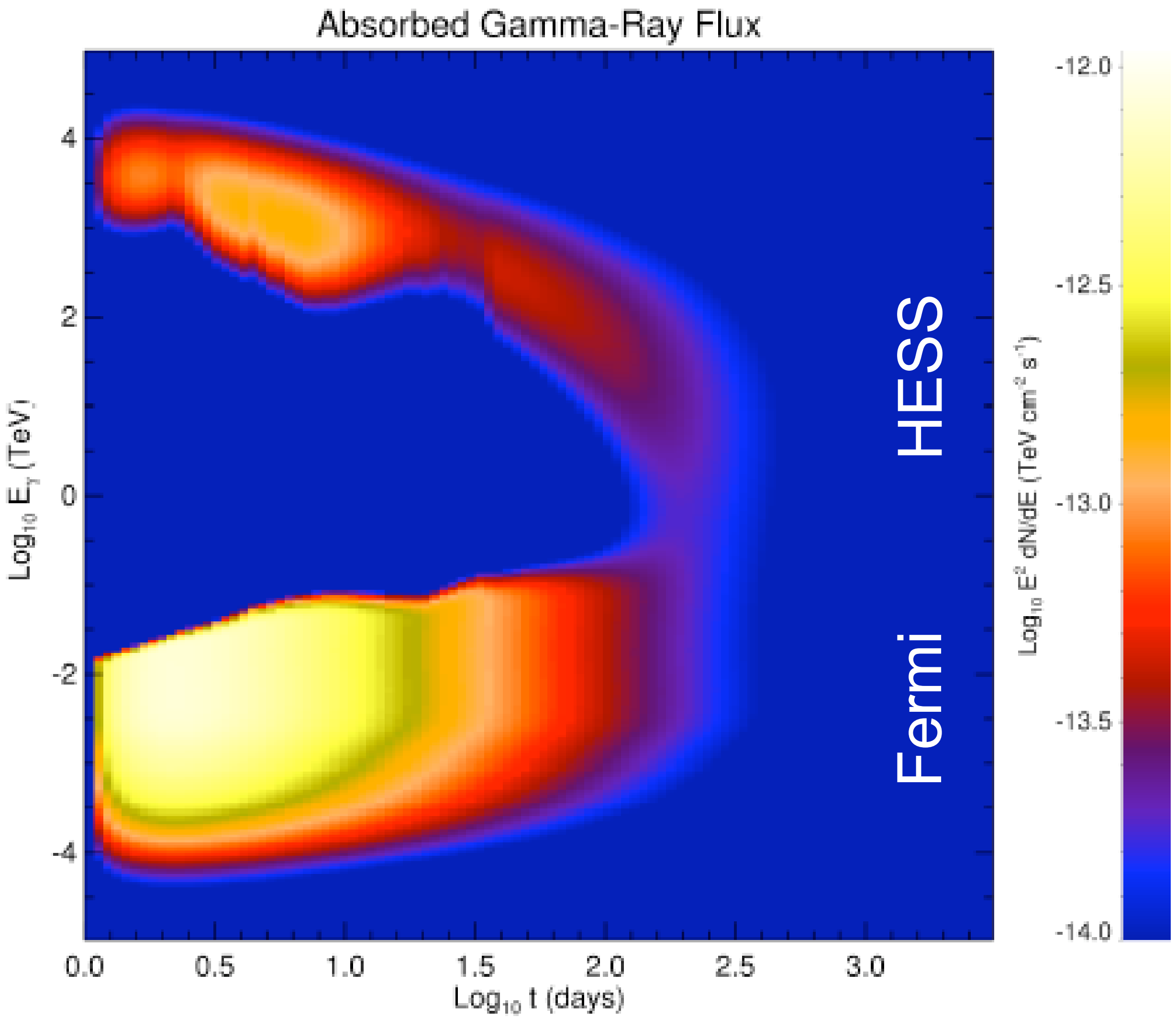




SN photosphere => Black body, UV dominates the first week and hence T~7000 K after day 120.



At the level of F(>1TeV)~2 $10^{-12} cm^{-2} s^{-1}$ (Tatischeff'09, Kirk+95)



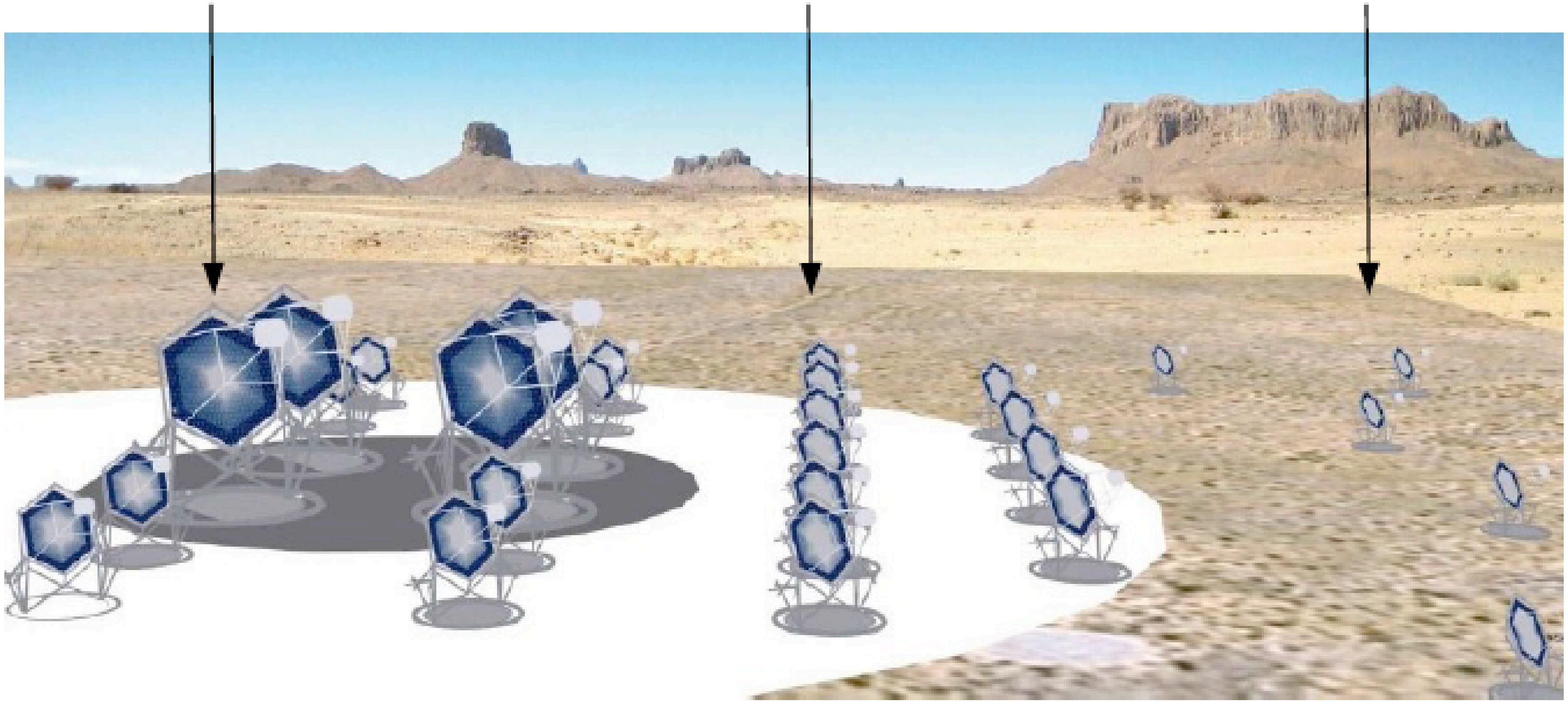
Absorbed Gamma-Ray Flux
Log10 Eγ (TeV)
Log10 t (days)
Log10 E2 dN/dE (TeV cm-2 s-1)
HESS
Fermi
4
2
0
-2
-4
0.0
0.5
1.0
1.5
2.0
2.5
3.0
-12.0
-12.5
-13.0
-13.5
-14.0

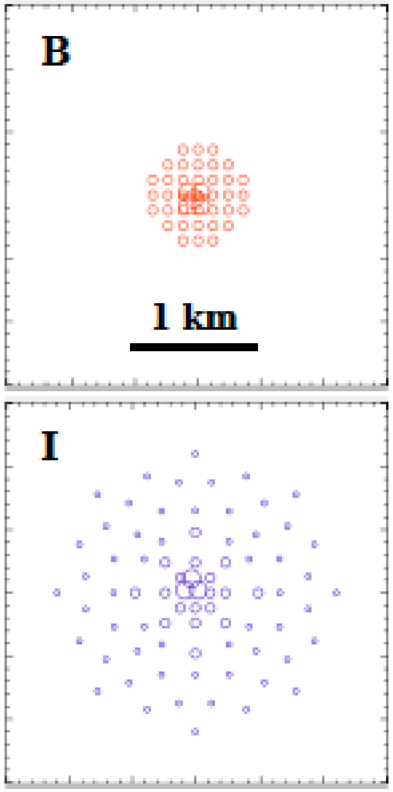
Perspectives: Cerenkov Telescope Array

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

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

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

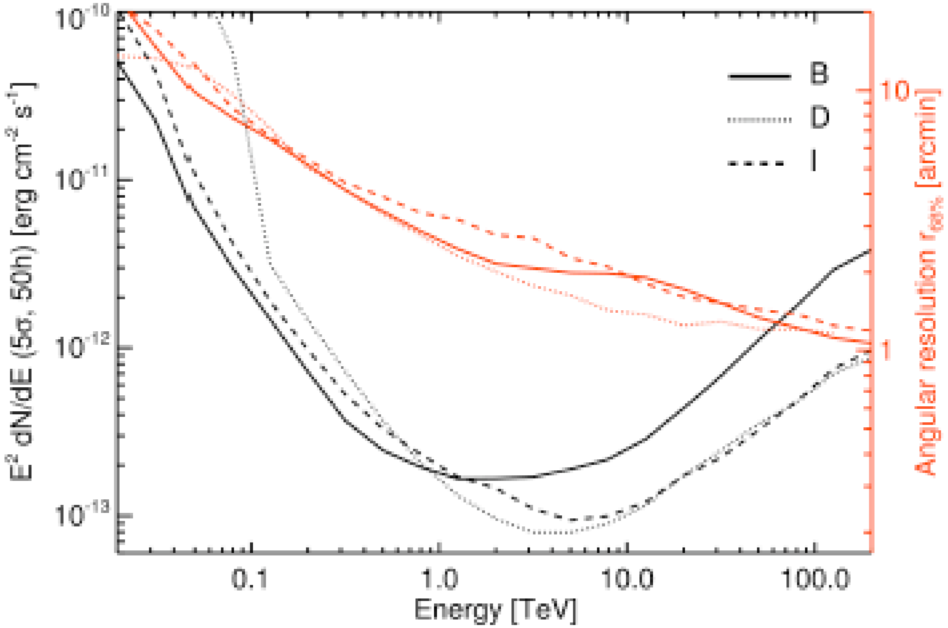




B: better performance at low energies

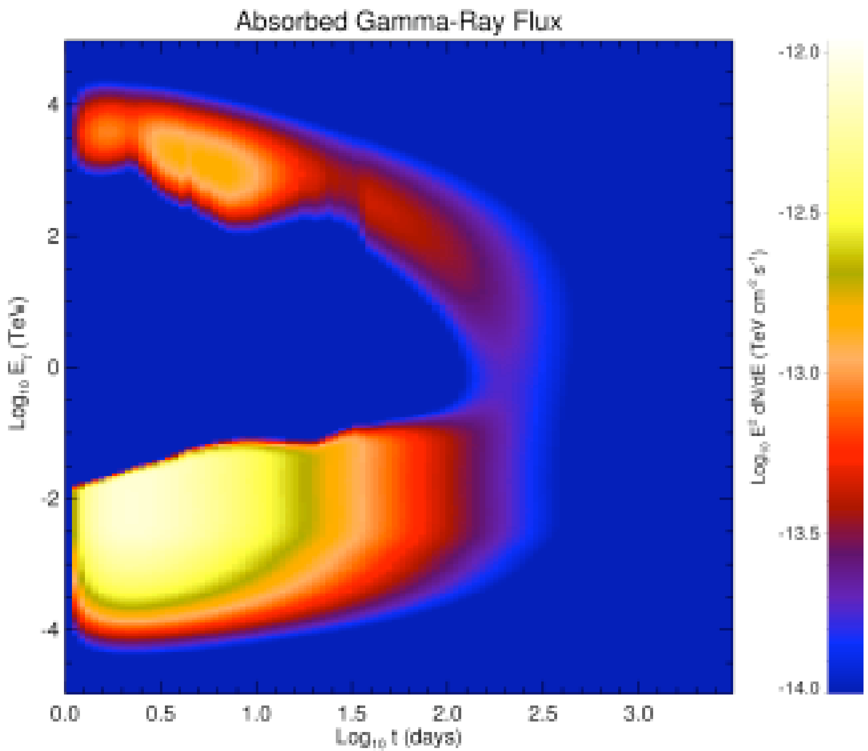
D: better performance at high energies

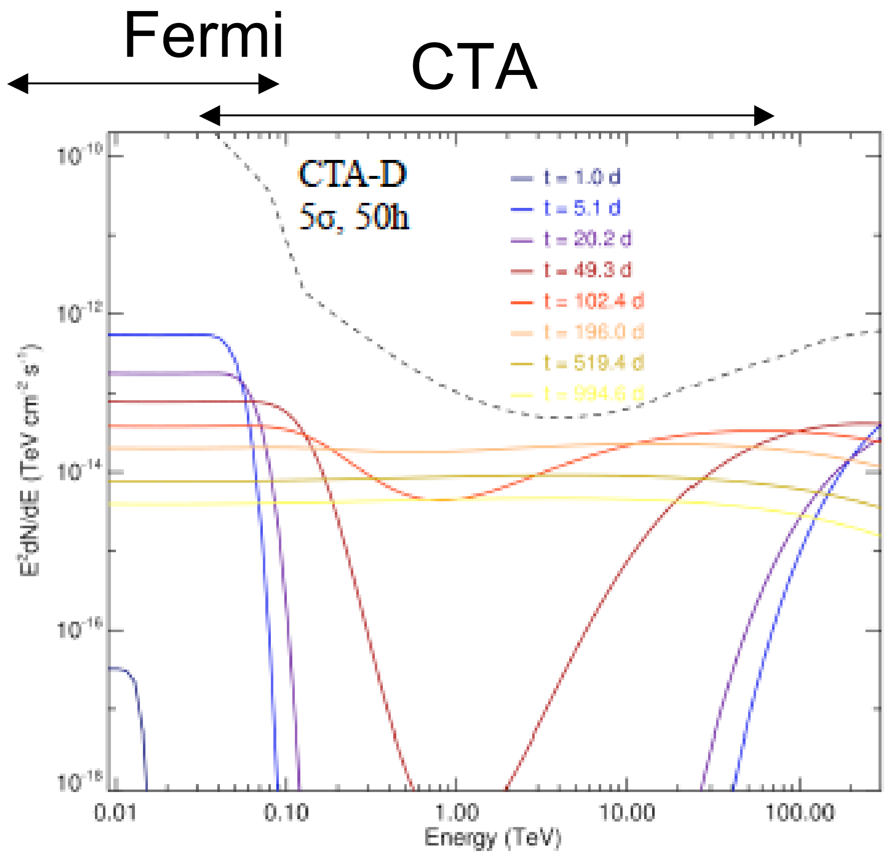
I: better performance over the whole range



(Renaud 2011, arXiv:1109.4326)

The CTA consortium
« Design Concepts for the Cherenkov Telescope Array » (arXiv:1008.3703)





Search for the optimal S/N ratio (Li & Ma 1983) in $\{E_{min}, E_{max}, t_{min}, t_{max}\}$ space assuming :

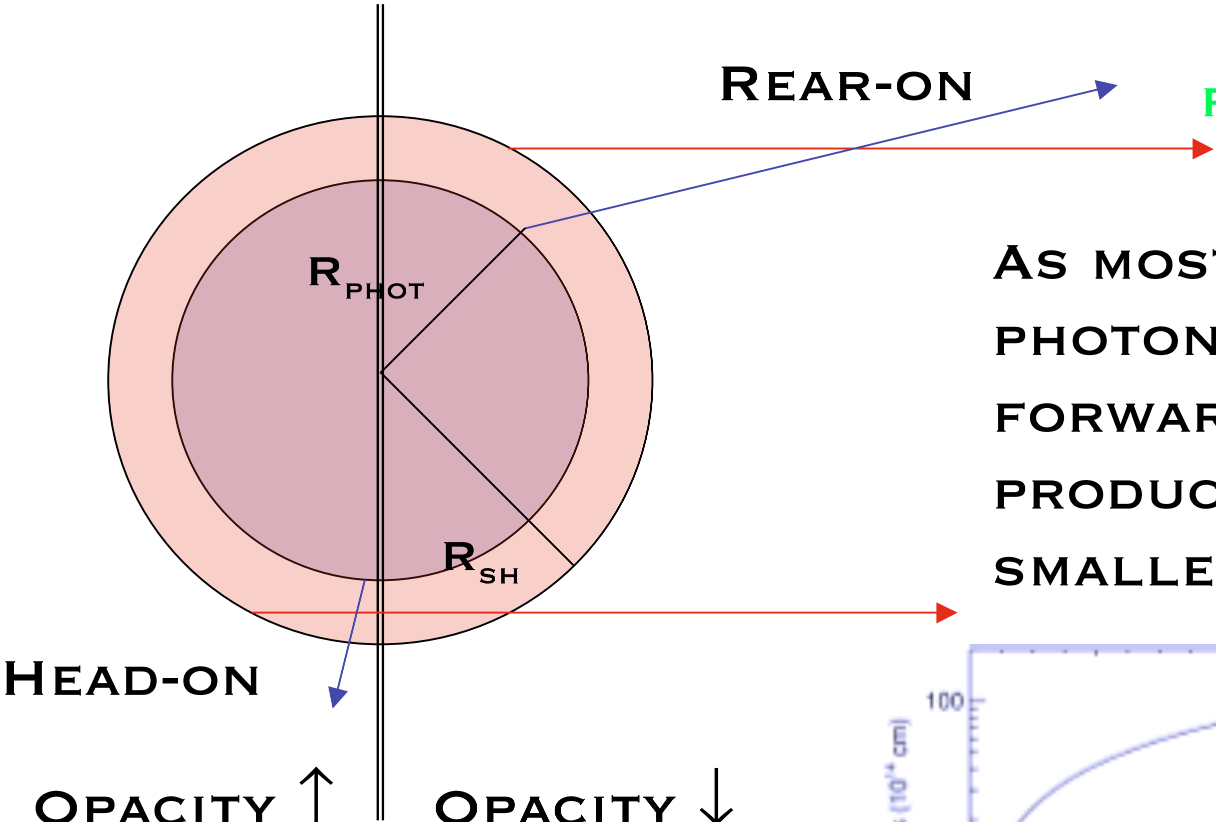
CTA Configuration D, Zenith Angle = 20°, $\alpha = Exp_{ON}/Exp_{OFF} = 0.1$

3 hrs of observation time (i.e. 6 runs) per night

→ S/N = 5.6 in 50 hrs starting at day 130 in the 3 – 300 TeV energy range

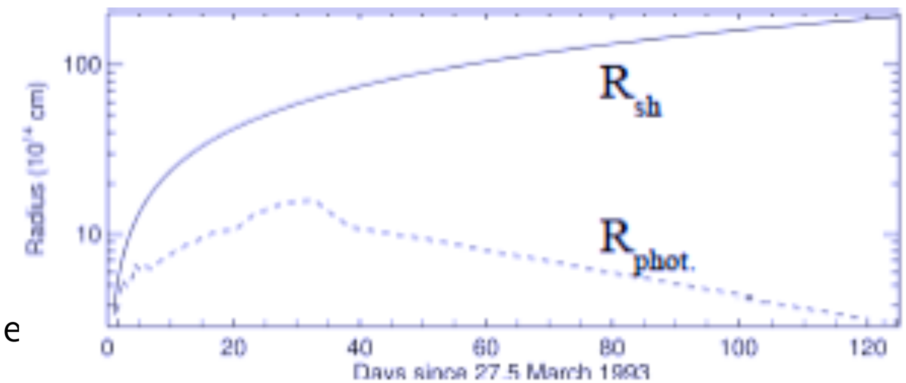
But likely an underestimation

Anisotropic pair production



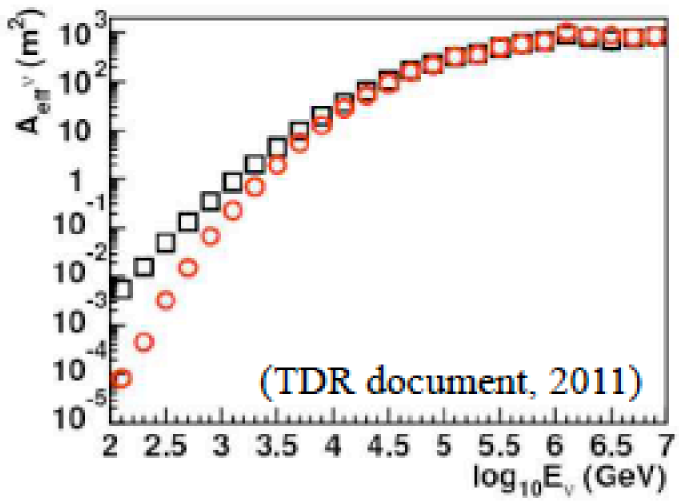
Renaud, A.M.+ in prep

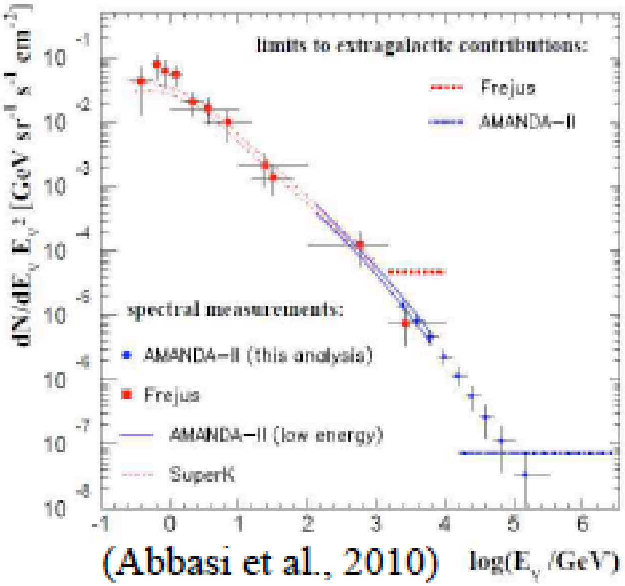
As most gamma-ray photons are produced forward anisotropic pair production gives smaller opacities.



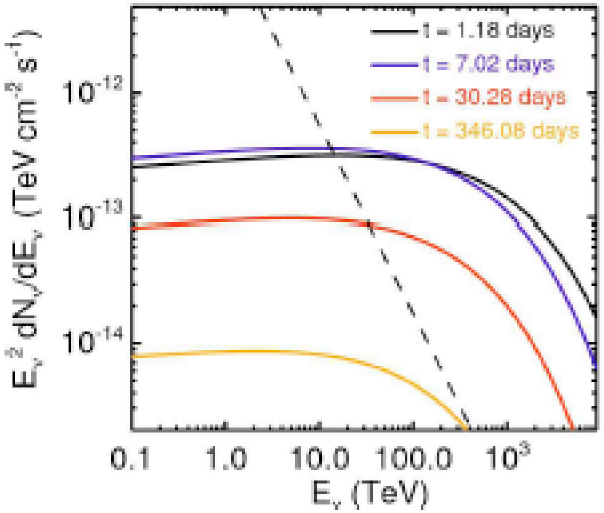
Neutrinos

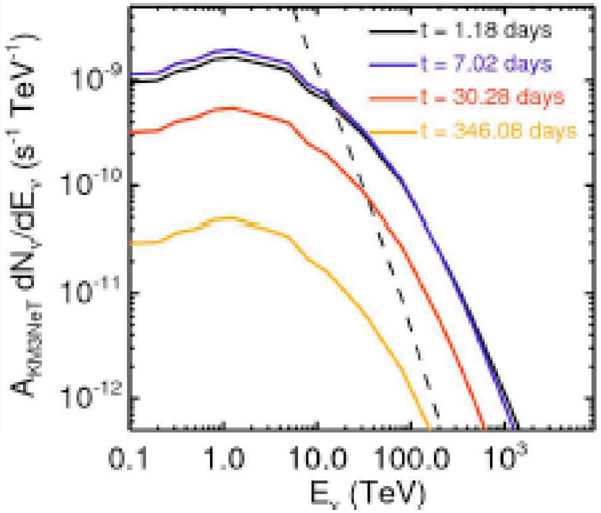
Perspectives with KM3NeT :



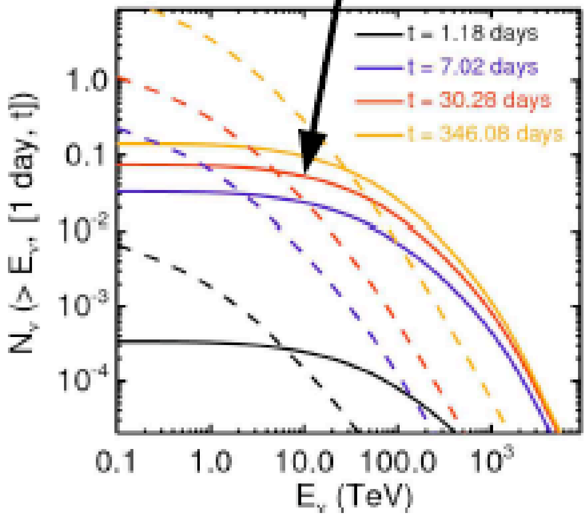


(Abbasi et al., 2010)





Only a few ν's at E_{ν} > 10 TeV for a SN in M31...



Secondary leptons

Time-dependent transport equation :

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

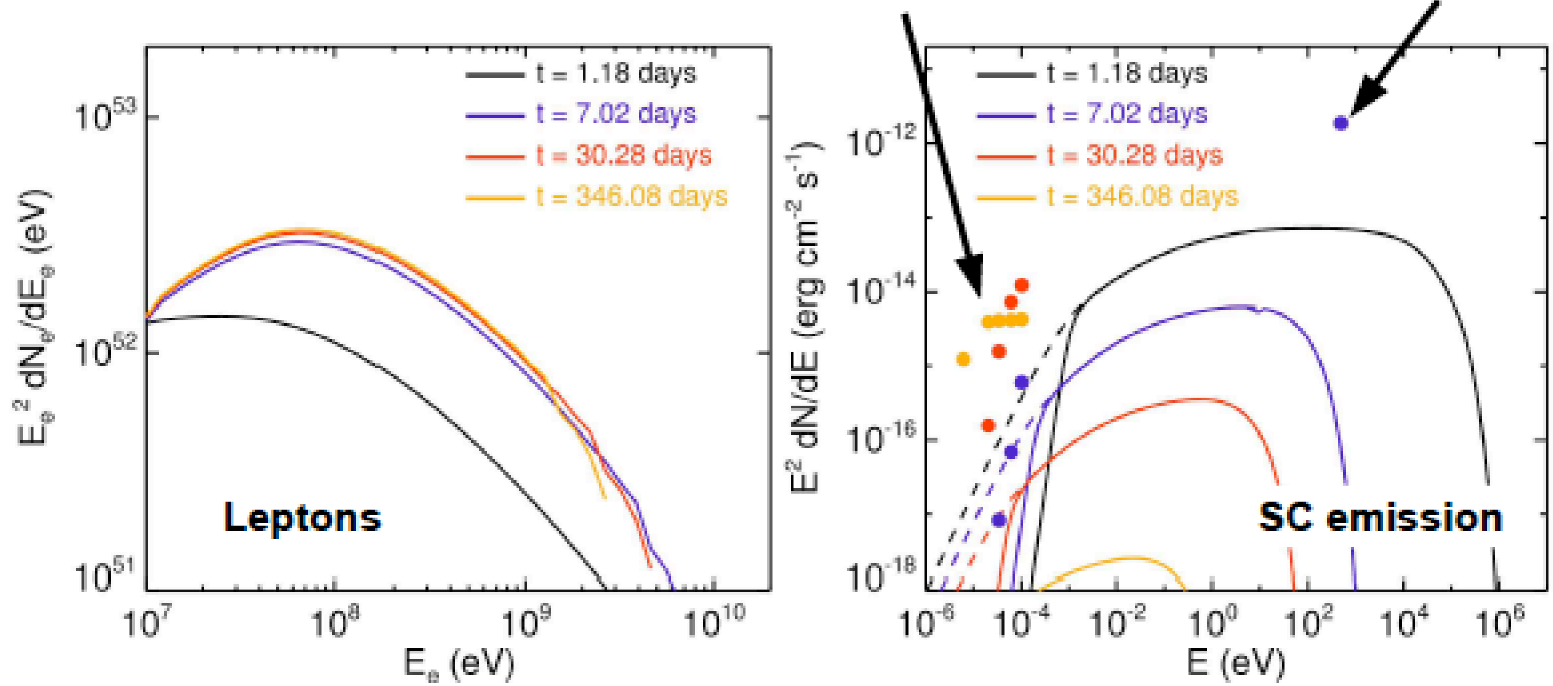
$$N(E,t) = \int_{t_0}^{t} Q(E,t') \times \exp\left(-\int_{t'}^{t} C(E,t'')dt''\right) dt'$$

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

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

Radio measurements (Weiler et al. 2007)

X-ray measurements (Zimmermann et al. 1994)



Perspectives: SN

- If a Wolf-Rayet phase occurs after RSG phase then the peak of gamma-ray emission is shifted in time.
- majority of type II SN; i.e. IIP may enter in a simple sequence

MS(8-16 solar masses)=>RSG=>SNIIP

$M > 90 M_\odot$: O - Of - WNL - (WNE) - WCL - WCE - SN(SNIbc/BH/SNIIn)? (PCSN/Hypernova low Z?)

$60 - 90\ M_\odot$: O - Of/WNL⇔LBV - WNL(H poor)- WCL-E - SN(SNIbc/BH/SNIIn)?

$40 - 60\ M_\odot$: O - BSG - LBV ⇔ WNL -(WNE) – WCL-E - SN(SNIb)
- WCL-E - WO SN (SNIc)

$30 - 40\ M_\odot$: O - BSG - RSG – WNE - WCE - SN(SNIb)
OH/IR ⇔ LBV ?

$20 - 30\ M_\odot$: O -(BSG)- RSG – BSG (blue loop) – RSG – SN(SNIIb, SNIIL)

$10 - 20\ M_\odot$: O - RSG - (Cepheid loop, $M < 15\ M_\odot$) RSG – SN (SNIIP)

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Table 1. Properties of the RSGs. The first 27 stars are from LM05, while the following 12 stars are from JB00. The colun marked V is the assumed wind speed. The column marked λ is the flux averaged wavelength. $L_{\rm Lev}$ is the luminosity giv in LM05 (from their $M_{\rm bol}$) and $L_{\rm phot}$ is the luminosity obtained by integrating the UBVIJHKL + IRAS photometry. . is derived with Jura's formula, where the used luminosity is $L_{\rm phot}$.

Name	$m-M$ (mag)	$E_{\rm B-V}$ (mag)	$f_{12}/f_{\rm K}$	V (km s^{-1})	D (kpc)	f_{60} (Jy)	λ_m (μm)	$L_{\rm Lev}$ (L$_\odot$)	$L_{\rm phot}$ (L$_\odot$)	$\dot{M}$ (M$_\odot$ yr^{-1})
V589 Cas	11.50	0.78	0.156	14	2.00	3.61	1.72	52 000	35 000	5.0×10^{-7}
BU Per	11.40	0.66	0.435	14	1.90	5.23	2.20	58 000	38 000	7.4×10^{-7}
SU Per	11.40	0.66	0.241	19	1.90	6.87	1.77	90 000	85 000	7.7×10^{-7}
RS Per	11.90	0.56	0.417	20	2.40	9.93	2.28	144 000	95 000	2.0×10^{-6}
S Per	11.39	0.66	1.226	20	1.90	40.59	3.67	81 000	86 000	6.8×10^{-6}
V441 Per	11.40	0.66	0.156	16	1.90	3.54	1.69	66 000	50 000	4.2×10^{-7}
YZ Per	11.40	0.66	0.291	16	1.90	5.28	1.86	48 000	55 000	6.5×10^{-7}
W Per	11.40	0.66	0.495	16	1.90	14.87	2.55	54 000	56 000	2.1×10^{-6}
BD+57647	11.40	0.66	0.351	14	1.90	6.47	2.24	80 000	37 000	9.3×10^{-7}
NO Aur	10.70	0.47	0.146	18	1.38	5.12	1.62	67 000	73 000	2.9×10^{-7}
α Ori	5.57	0.18	0.177	15	0.130	299.00	1.64	...	56 000	1.5×10^{-7}
TV Gem	10.70	0.66	0.294	19	1.38	6.06	1.69	100 000	84 000	3.5×10^{-7}
BU Gem	10.70	0.66	0.248	19	1.38	10.50	1.62	83 000	86 000	5.9×10^{-7}
V384 Pup	13.00	0.57	0.260	18	4.00	2.76	1.84	37 000	75 000	1.4×10^{-6}
CK Car	11.70	0.55	0.531	22	2.20	13.98	2.11	161 000	123 000	2.1×10^{-6}
V602 Car	11.60	0.48	0.596	22	2.10	12.40	2.61	105 000	124 000	1.9×10^{-6}
V396 Cen	11.60	0.75	0.201	23	2.10	4.98	1.73	164 000	140 000	6.2×10^{-7}
KW Sgr	12.40	0.92	1.218	27	3.00	18.39	2.81	363 000	228 000	5.6×10^{-6}
NR Vul	11.80	0.94	0.590	21	2.30	12.28	2.26	224 000	111 000	2.2×10^{-6}
BI Cyg	11.00	0.93	0.671	22	1.58	51.23	2.67	226 000	123 000	4.6×10^{-6}
KY Cyg	11.00	0.93	0.702	22	1.58	50.74	3.15	272 000	138 000	4.9×10^{-6}
RW Cyg	10.60	1.22	0.481	23	1.32	60.69	1.96	144 000	145 000	3.2×10^{-6}
μ Cep	9.70	0.69	0.361	20	0.87	127.00	1.69	340 000	410 000	1.4×10^{-6}
V354 Cep	12.20	0.63	0.566	18	2.75	8.01	2.89	369 000	76 000	2.4×10^{-6}
V355 Cep	12.20	0.63	0.292	14	2.75	3.27	2.38	94 000	37 000	1.0×10^{-6}
PZ Cas	11.90	0.69	1.217	30	2.40	96.48	3.57	212 000	193 000	2.6×10^{-5}
TZ Cas	11.90	0.69	0.541	19	2.40	9.47	2.38	98 000	83 000	2.0×10^{-6}
EV Car	13.13	0.51	0.745	39	4.20	25.87	2.57	...	675 000	1.3×10^{-5}
HS Cas	12.00	0.83	0.275	17	2.50	3.51	1.92	...	59 000	7.5×10^{-7}
XX Per	11.14	0.66	0.492	16	1.69	4.23	2.03	...	50 000	4.3×10^{-7}
KK Per	11.14	0.66	0.117	16	1.69	2.23	1.59	...	50 000	2.0×10^{-7}
AD Per	11.14	0.66	0.164	15	1.69	2.85	1.66	...	42 000	2.7×10^{-7}
PR Per	11.14	0.66	0.131	14	1.69	2.37	1.55	...	34 000	2.3×10^{-7}
GP Cas	11.40	0.66	0.200	15	1.90	4.45	2.01	...	43 000	5.9×10^{-7}
VY CMa	10.28	0.47	6.959	47	1.14	1453.00	7.77	...	295 000	1.6×10^{-4}
α Sco	6.34	0.10	0.165	17	0.185	115.50	1.73	...	71000	1.2×10^{-7}
VX Sgr	10.98	0.52	2.334	25	1.57	262.70	4.14	...	343 000	2.0×10^{-5}
Case 49	11.70	0.87	0.155	15	2.19	6.58	2.01	...	42 000	1.1×10^{-6}
U Lac	12.20	0.63	0.685	23	2.75	9.04	2.51	...	147 000	2.3×10^{-6}

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SN IIP

- Less luminous

  => decreases opacity to pair production

  => P=Plateau: mean luminosity higher with time wrt IIb and IIL => extend the effect of pair production.

- Remains to be tested.

Conclusions

- SNR associated with RSG phase are interesting objects:
  - If *medium fully ionized* the Bell instability may grow fastly (within days timescale)
  - Maximum CR energies may reach PeV also rapidly (within days timescale)
- SN 1993J is one of the most observed SN IIb at all wavelengths
  - Shock velocity ~ 0.2c, high magnetic field that may be interpreted as generated by CRs
  - High energy CRs may be produced within day timescales uploading a few % of SN explosion
  - Translated into gamma-rays signal modulo pair production can lead to a detection by CTA @ 5.6sigma within 50 days
- Other targets to be tested e.g. SN IIP