Gamma-rays from radio supernovae

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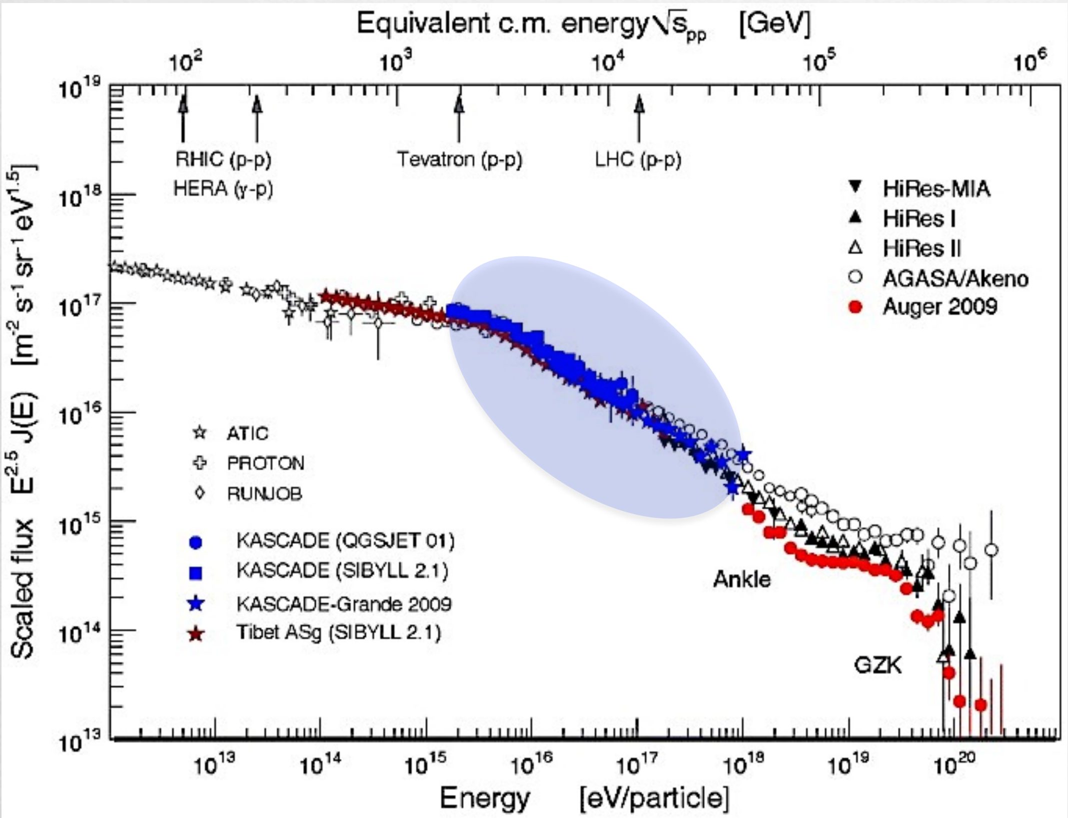
Introduction: scientific context



G.Matthiae '10

origin of multi-PeV to 0.1-1 EeV CR component ? (Budnik+08)

- Produce gamma-rays above 10-100 TeV.
  => high sensitivity at high energy.
- Produce neutrinos beyond a few tens of TeV.

When a CR source is a Pevatron ?

Based on supernova remnants:

- Need to wait for sufficiently long time because $E_{max}(t)$ is maximal: at the start of the Sedov-Taylor phase.
- Need to look for more extreme (and short lived) conditions: fast shocks as $t_{acc} \sim V_{sh}^{-2}$
  - Free expansion phase => softer spectra (Zirakashvili & Ptuskin'05, Ptuskin+10, Schure & Bell'13, Cardillo+15)

Other objects may contribute to this component: massive stellar clusters & superbubbles, fast rotating pulsars … discussed in this meeting.

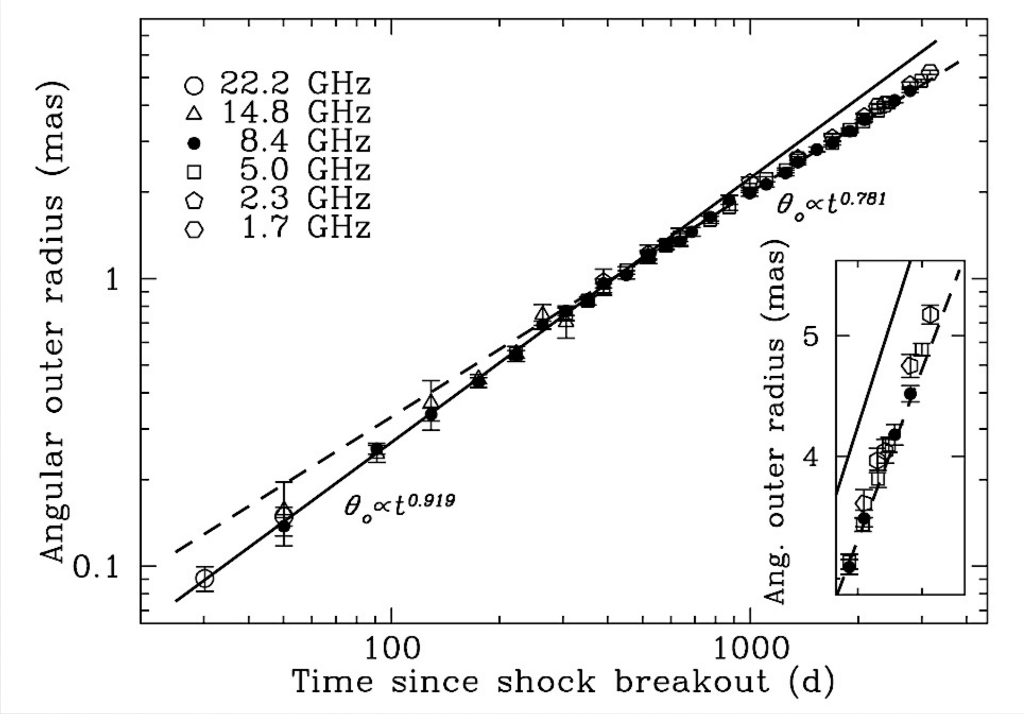
This study

- Considers the second case.
- Fastest "common objects" velocities: early stages of SNe evolution, after the forward shock breakout.
  - common objects ⇔ observational test because Pevatron phase should not last for long.
- Adapt more recent theoretical advances on SNR to SNe (see also: Bell'04, Tatischeff'09 (T09 hereafter), Schure & Bell'13, Marcowith+14, Cardillo+15, Giacinti & Bell'15, Zirakashvili & Ptuskin'16…).
- A large part of this study is based on T09.

Supernovae: SN1993J

- Nearby SN d~3.5 Mpc in M81.
- Core collapse SN of type II b.
- Progenitor: red supergiant star M~15 solar masses, likely in a binary system (Aldering+94)
- Best multi-wavelength-monitored object with SN 1987A (Marcaide+97, Bietenholz+03)
- Well monitored also in X-rays (van Dyk'08)

Radio observations: shock dynamics and magnetic field strength



Barthel+02 $\theta \sim t^m$

m = 0.919 +/− 0.019 (30 d < t < 306 d)

m = 0.867 +/− 0.026 (306 d < t < 582 d)

m = 0.781 +/− 0.009 (586 d < t < 1893 d)

T09 argued that a self-similar solution (Chevalier'82) can fit all data with

θ= 0.292+/− 0.04 (t/100 d)^m

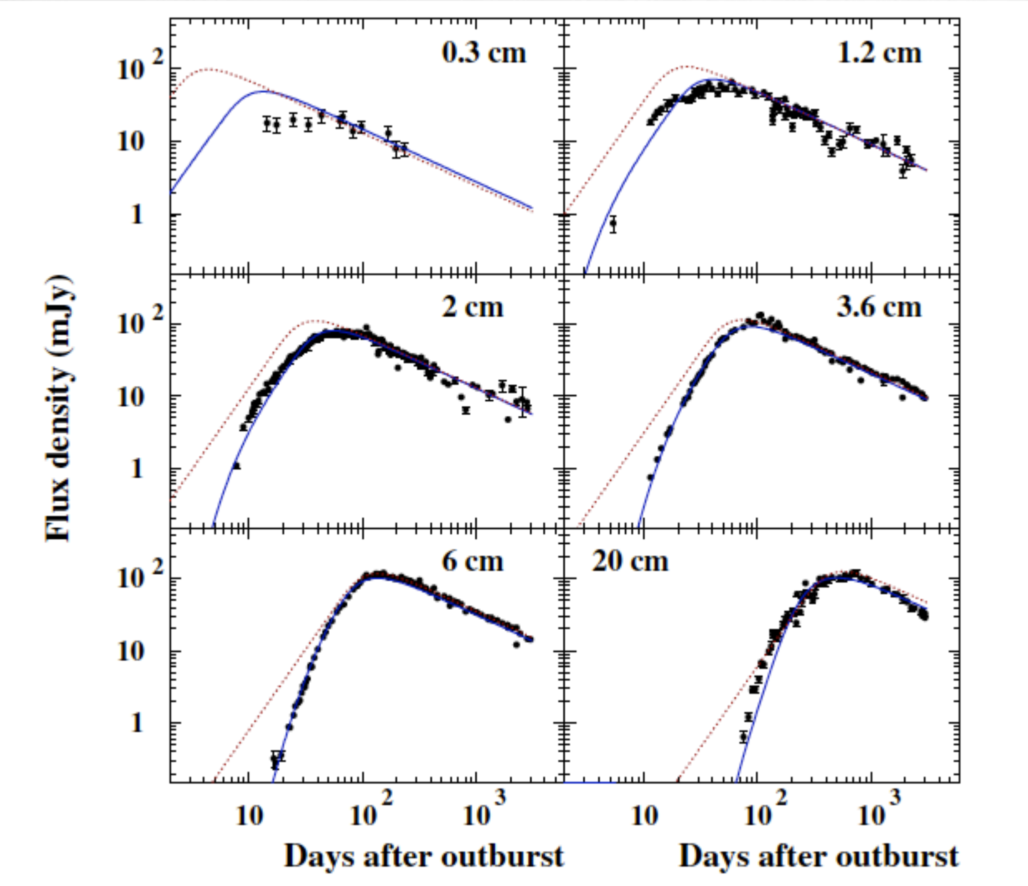
m=0.829+/- 0.05

extrapolated to 1d after the outburst

$R_{sh}=R_0\,(t/1d)^{0.83}$, $R_0=3.5\ 10^{14}$ cm

$V_{sh}=V_0\,(t/1d)^{-0.17}$, $V_0=3.35\ 10^9$ cm/s

Radio observations: shock dynamics and magnetic field strength



T09: best fit model including SSA, free-free absorption

B=(2.4+/-1.0)G (t/100d)^{b}

b=-1.16+/-0.2

extrapolated to 1d gives

B~500 Gauss.

Fransson & Bjornsson'98 found :
B~340 G (t/1d)$^{-1}$

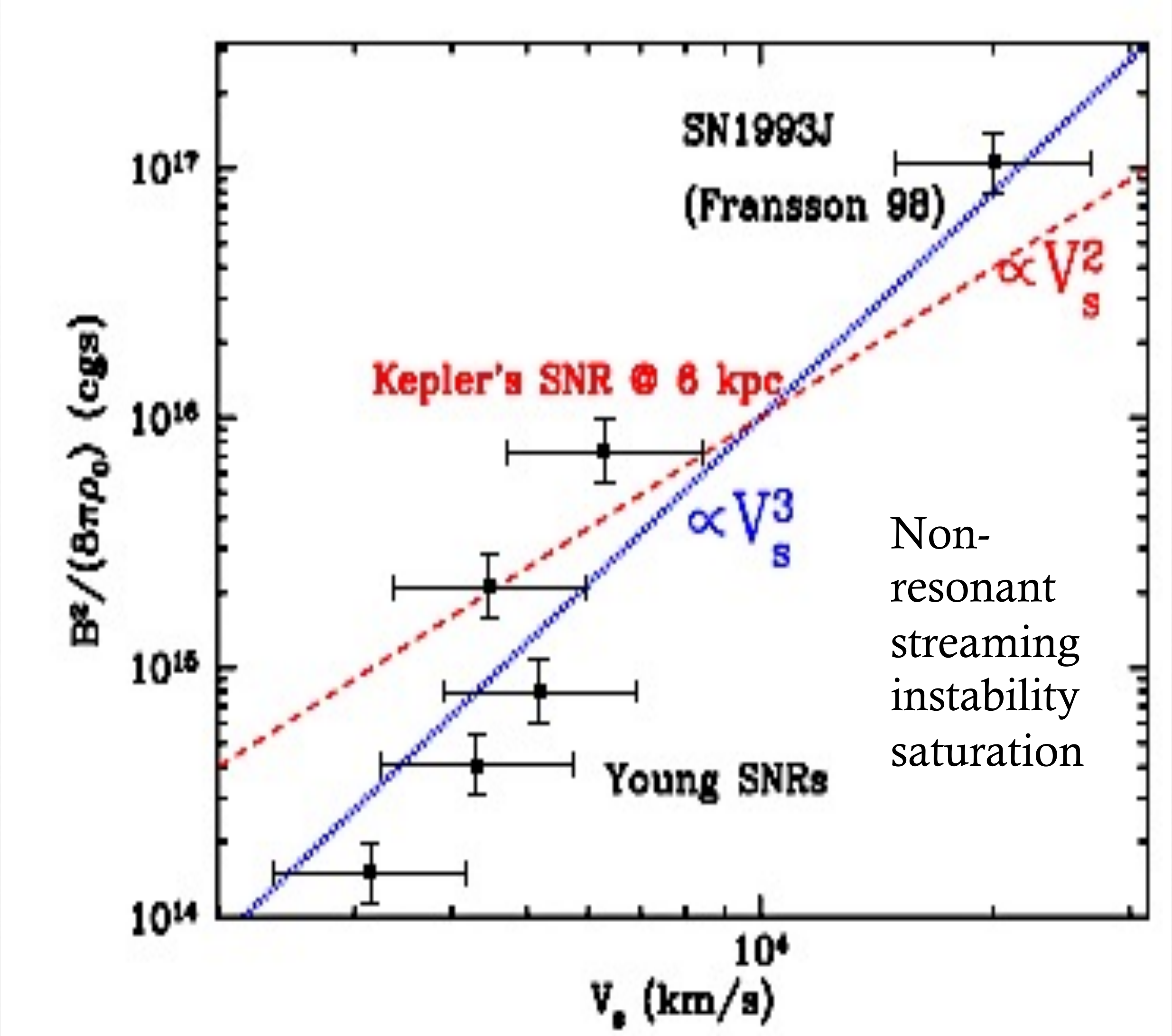
data, best fit (solid): Weiler+07, Synchrotron self-absorption model (dotted) (see T09)

Wind model

- We adopt a model with a constant mass loss rate so a wind density $\rho \sim r^{-2}$
  - Propagation index in self-similar solution m=(n-3)/(n-s) hence m=0.83 and s=2 gives for ejecta velocity profile index n=7.88
- Best fit radio gives a mass loss rate ~ $3.8\ 10^{-5}$ solar masses/year.
- RSG wind u_w=10 km/s
- Wind magnetic field strength unknown: equipartition field ~ 0.1 gauss. (<< 500 G!)
- Topology unknown (to be discussed later).

Model assumptions

- Magnetic field amplified by the means of CR induced instabilities.
  - This is likely the origin of X-ray filaments in young SNRs.



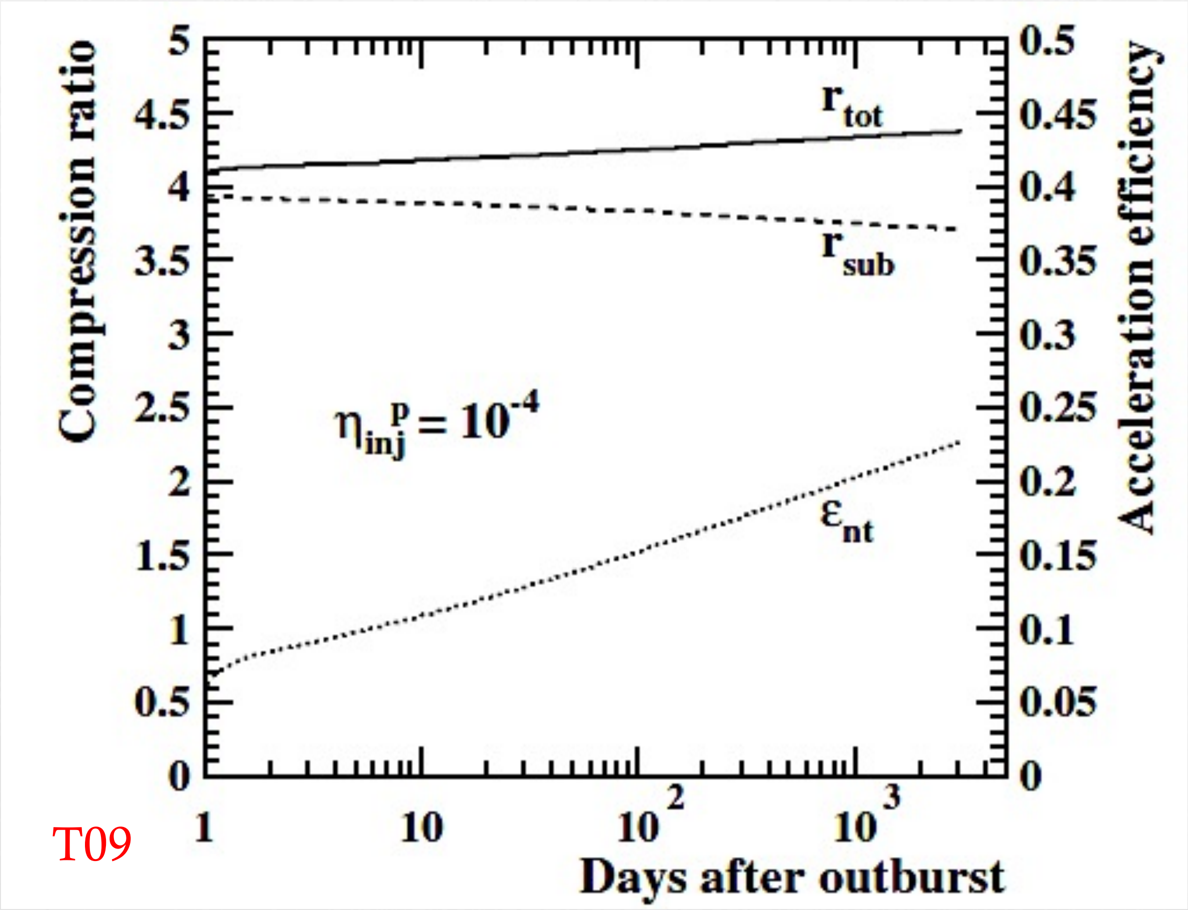
Non-resonant streaming instability saturation

Vink'09

Model assumptions

- Magnetic field amplified by the means of CR induced instabilities.
  - This is likely the origin of X-ray filaments in young SNRs.
  - caveat: no observational support yet of ultra-relativistic particle acceleration.
    - Synchrotron radiation by relativistic electrons with energy distribution E^{-m}; m~3.
    - No gamma-ray detected yet.

Cosmic Ray acceleration efficiency



weakly modified shock at T < a few hundred days

Cosmic Ray induced instabilities in fast SN shocks

- Streaming instabilities : non-resonant and resonant.
- Filamentation instability.
- Oblique mode generation.
- Fluid instability produced by a CR gradient.

Streaming instabilities: non-resonant and resonant

- Non-resonant instability (NRI) minimum growth time (Bell'04)

$$T_{\min} = \frac{2\phi}{\xi}\frac{R_L c}{V_{sh}^3} V_{A,CSM} \sim (0.09d)\frac{\phi_{16}}{\xi_{0.05}} E_{PeV} t_d^{1.17}$$

with $\phi = \ln(E_{max}/E_{inj})$; $\xi = P_{CR}/\rho V_{sh}^2$

- Resonant instability (RI) (Amato & Blasi'09)

$$T_{\min} = R_L\sqrt{\frac{8}{\pi\sigma}} \sim (0.4d)\frac{E_{PeV}}{\omega\xi_{0.05}^{1/2}} t_d; \sigma = 3\xi V_{sh}^3 / c; \omega = B_{CSM} / B_{eq}$$

Intraday growth times

Condition for instability growth

- R= Ratio instability growth time/advection time in the precursor < 1.
- Advection time ?
  - Case of parallel shock
  - Diffusion at a rate $\eta\ \kappa_{Bohm}$

$$\boxed{T_{adv} = \frac{\eta R_L c}{3V_{sh}^3}}$$

- $R_{NRI,93J} < 1$ (~0.5)
- $R_{RI,93J} > 1$ (~$2.5\ t_d^{-0.17}$, 1 at 219 days)

Magnetic field saturation

- Magnetic tension=Lorentz force (Bell'04, Pelletier+06)

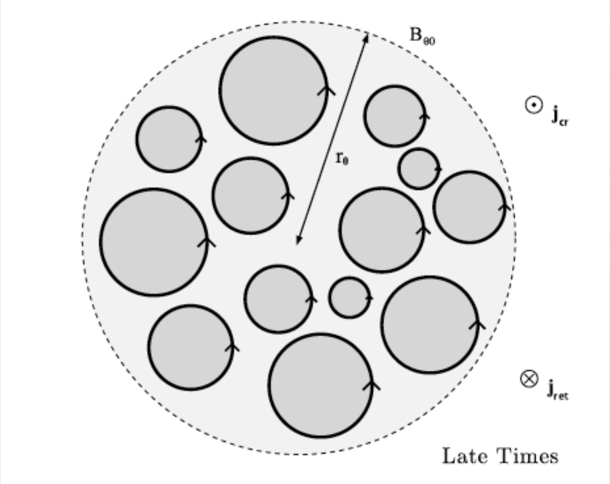
$$B_{sat}^2 = 12\pi \frac{\xi}{\phi} \rho \frac{V_{sh}^3}{c} \Rightarrow B_{sat} \sim 15G \sqrt{\frac{\xi_{0.05}}{\phi_{16}} t_d^{-1}}$$

- Amplification factor A= B_{sat}/B_{CSM}

$$A \sim \frac{111}{\omega} \sqrt{\frac{\xi_{0.05}}{\phi_{16}} t_d^{-0.17}}$$

Filamentation instability

- Long-wavelength generation: high-energy CR acceleration.
- Filamentation ⇔ -J_{CR}xB force : n_{CR} increase in the filament, n_g outside



Reville & Bell'12, Caprioli & Spitkovsky'13

Fast grow but increases rapidly with time

$$T_{\min} = \sqrt{\frac{\phi}{\xi}\frac{R_L^* c}{V_{sh}^2}} \sim (10^{-3} d)\frac{\omega}{\phi_5^*}\left(\frac{\phi_{16}}{\xi_{0.05}}\right)^{3/2} E_{PeV} t_d^{1.425}$$

$$R_L^* = \frac{R_L}{A}$$

$$\phi^* = \ln\left(\frac{E_{\max}}{E_{th}}\right)$$

E_{th} is the threshold energy to trigger the Filamentation instability ~ 5 TeV $E_{max,PeV}$ for SN 93J

Long oblique modes generation

- CR current driven small scale instability => ponderomotive force
- CR current response on turbulence ⇔ mean field dynamo (Bykov+11)
- Fastest growing modes are oblique wrt to background MF
  - Case $k=1/\eta R_L$

$$T_{\min} = \sqrt{\frac{4}{\pi A}}\sqrt{\frac{\eta R_L}{k_{\max} V_{A,CSM}}} \sim (0.5d)\sqrt{\frac{\eta}{\omega}}\left(\frac{\phi_{16}}{\xi_{0.05}}\right)^{3/4} E_{PeV} t_d^{1.085},$$

$$k_{\max}^{-1} \sim (10^{10}\,cm) E_{PeV} \frac{\phi_{16}\omega}{\xi_{0.05}} t_d^{1.17}$$

CR gradient driven/ hydrodynamic instability

- CR gradient in the CR precursor => density fluctuations are destabilized and grow => small-scale dynamo (Beresnyak+09, Drury+12)

$$\boxed{T_{\min} = \frac{1}{2A_K}\frac{V_{A,CSM}^2 L_{coh}}{V_{sh}^3} \sim (10^{-2}\, d) L_{coh,pc} t_d^{0.51}}$$

L_{coh}: coherence length of the upstream turbulence (so in the wind), unknown, we can have a guess: a fraction of the termination shock radius so 0.1-3 pc for R_{TS}~1-10pc.

Long-wavelength modes generation

- All $T_{min,Fil}$, $T_{min,ob}$, or $T_{min,hyd} < T_{adv,u}$
- So if NRS instability can be triggered both Filamentation and oblique modes generation should work.
- In case NRS does not operate, one may rely on hydrodynamic instability to generate long wavelengths.

Caveats

- CSM magnetic field obliquity and strength.
  - In case of a perpendicular shock, the advection time is reduced.

$$T_{adv} = \frac{R_L c}{3\eta V_{sh}^2}; \eta > 1$$

$$R_{NR} \propto \eta\omega$$

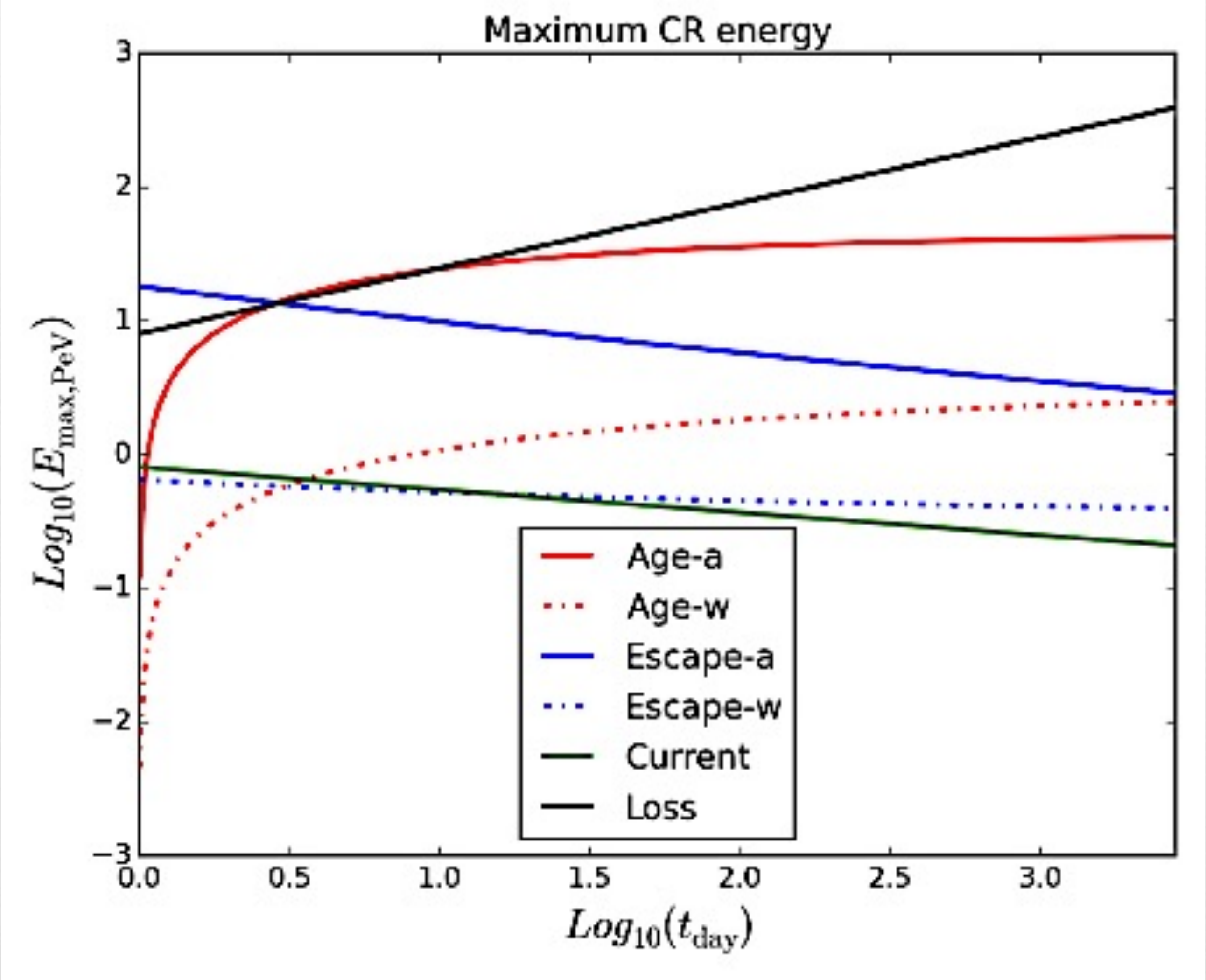
If the product $\eta\omega < 1$ the NRI instability can still grow, but if $\eta\omega > 1$ the NRI instability is quenched.

➢ Highly dependent on the CSM MF strength and topology !

Particle distribution

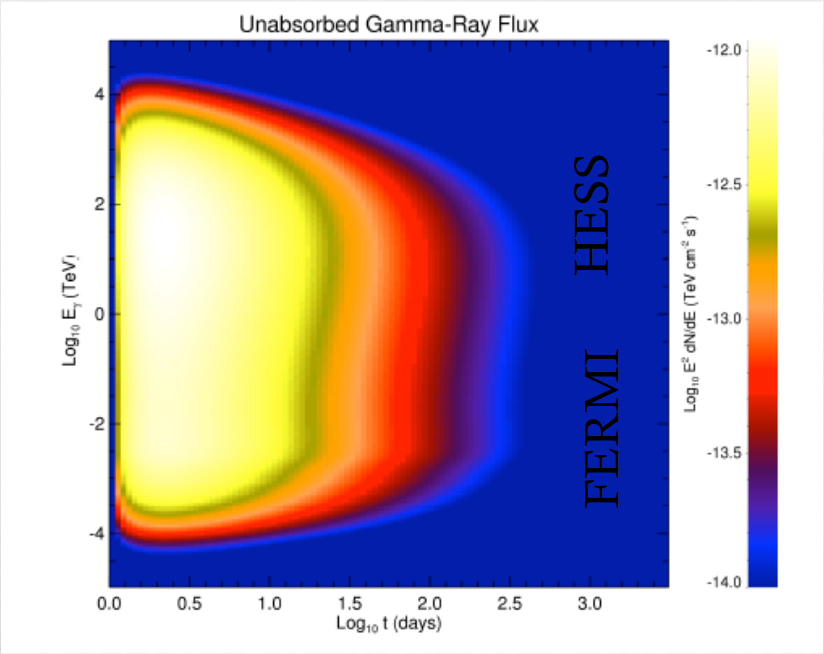
- Two-zones model:
  - Non-linear acceleration including CR backreaction (Berezhko & Ellison'99) => F_{shock}, $E_{max}(t)$
  - Downstream: Losses = radiative (synchrotron/Inverse Compton, Bremsstrahlung), collisions (neutral pion), adiabatic losses.
  - Secondaries from charged pions
  - Gamma-ray radiation including *anisotropic* gamma-gamma absorption over SN photosphere photons.

Maximum (proton) energy



Results: gamma-rays

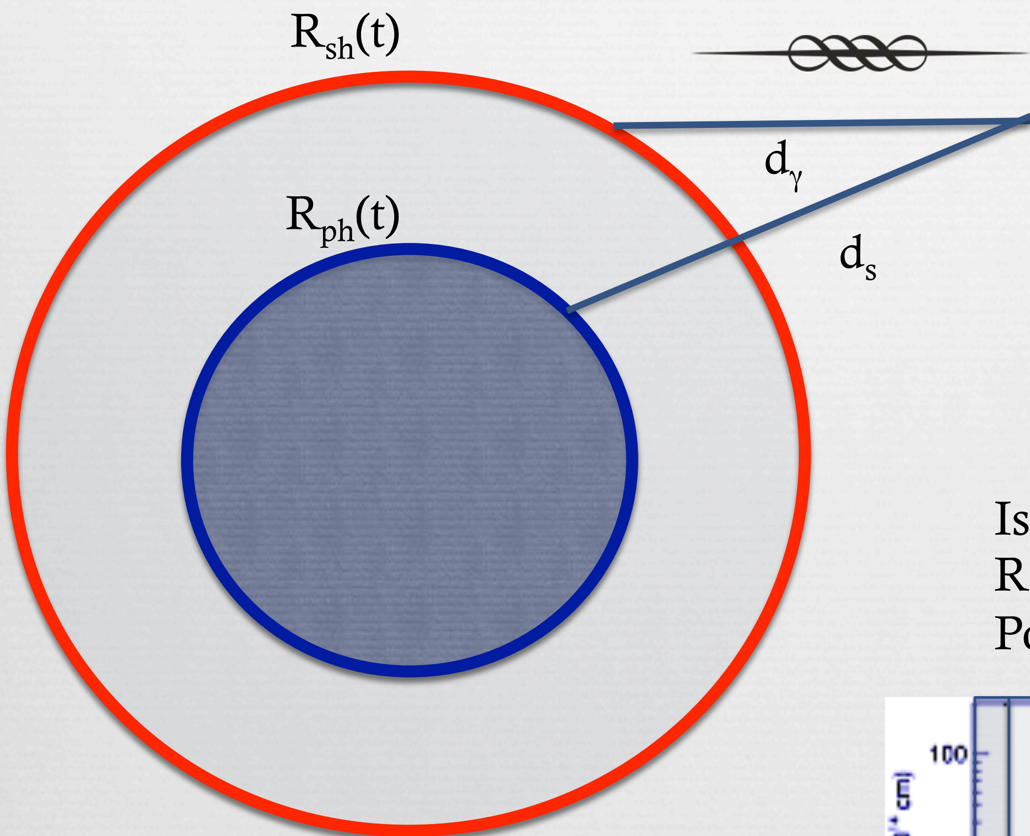
- Gamma-rays are produced by pp neutral pion decay (IC negligible because of high MF strengths).
  - Kirk+95 $F_{93J}(>1\mathrm{TeV}) \sim 2\ 10^{-12}$ ph/cm^{2}s



gamma-gamma absorption

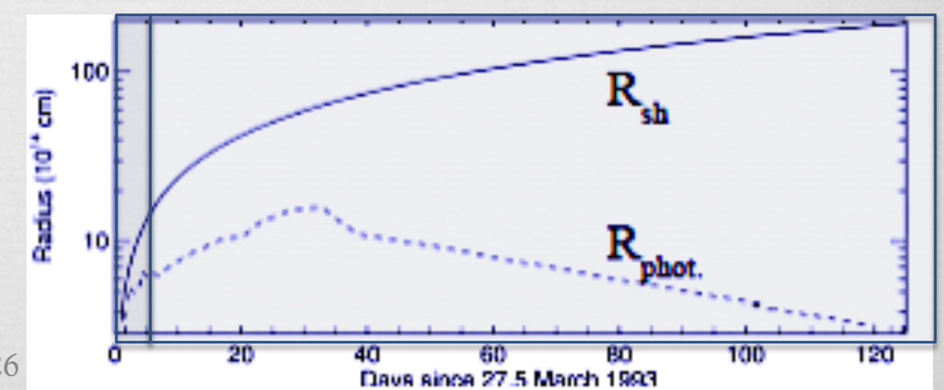
- But the source is compact: gamma-gamma absorption on SN photosphere photons.
  - Tatischeff'09 $F_{93J}(>1\mathrm{TeV})\sim 4\ 10^{-15}\mathrm{ph/cm^2s}$ but after 270 days.
  - But gamma-gamma interaction is:
    1. anisotropic
    2. time-dependent

Gamma-gamma opacity calculation

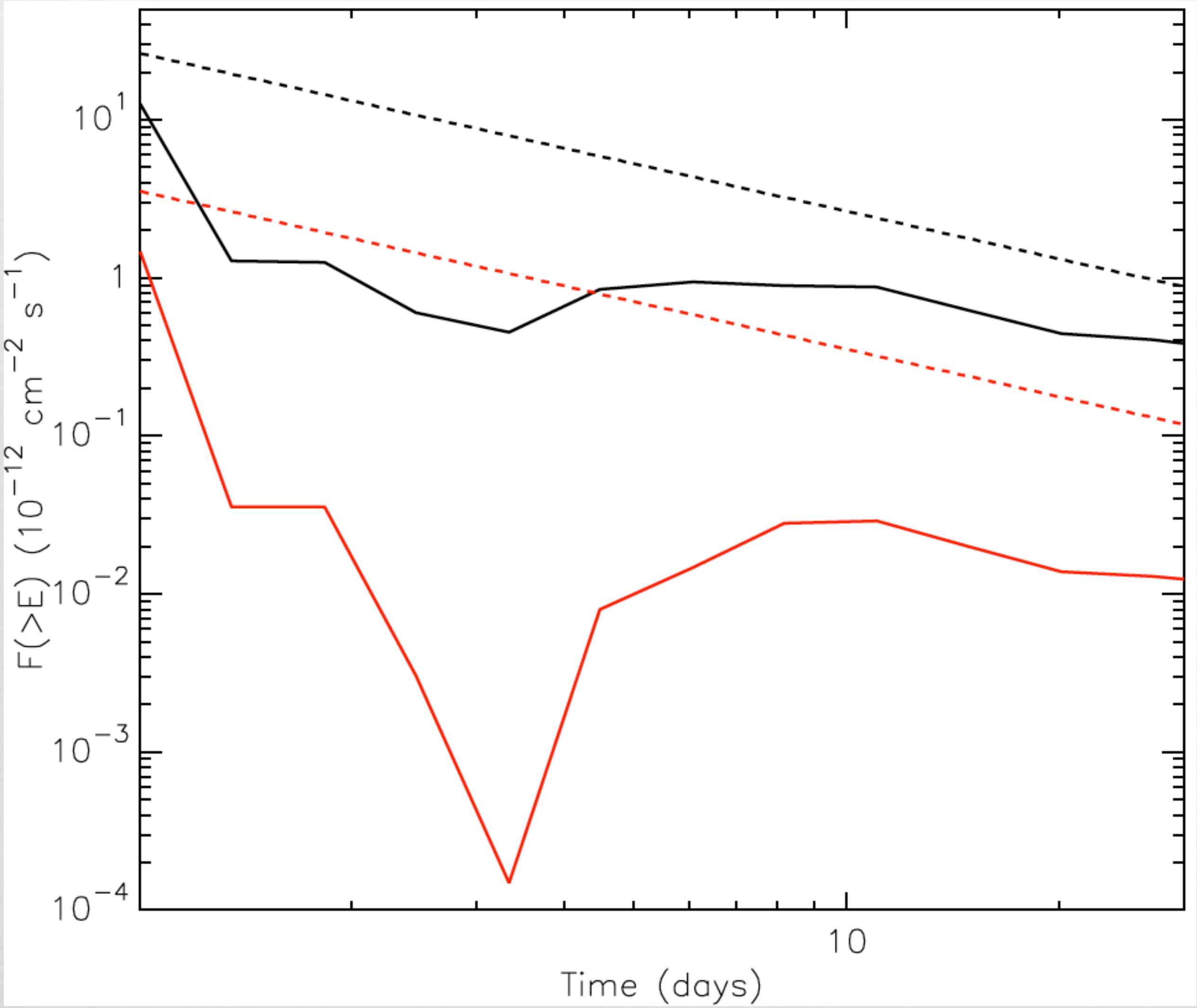


Interaction at time t
gamma photon emitted at t-d_γ/c
soft photon emitted at t-d_s/c
+ doppler shift

Isotropy good approximation up to
R_{sh}/R_{ph}~3 (< 15 days)
Point source approximation beyond



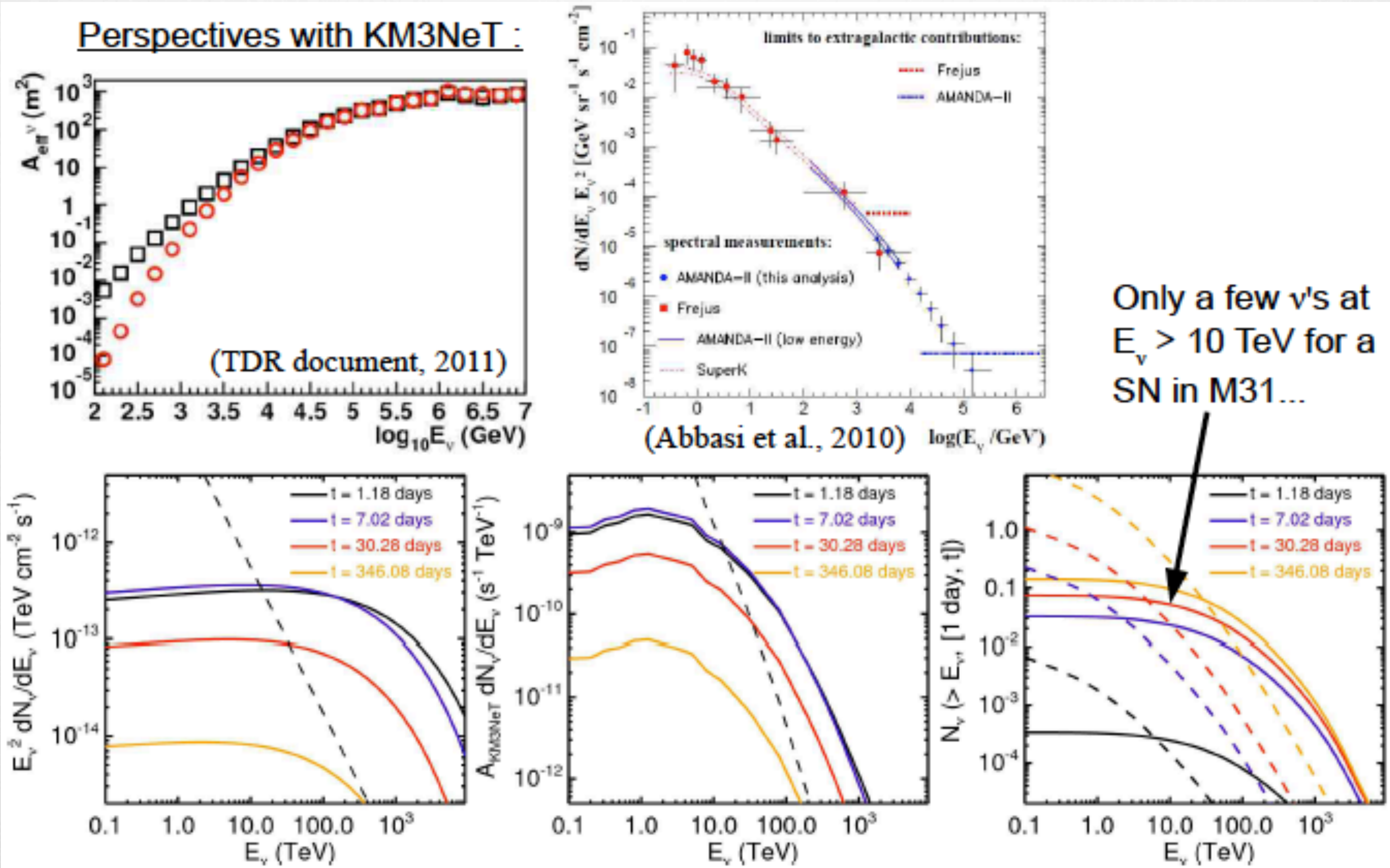
Integrated gamma-ray signal



b: E> 100 GeV
r: E> 1TeV

best windows:
1-2 after the explosion
one week after 8-15 days

Neutrino signal



Secondaries

Time-dependent transport equation :

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

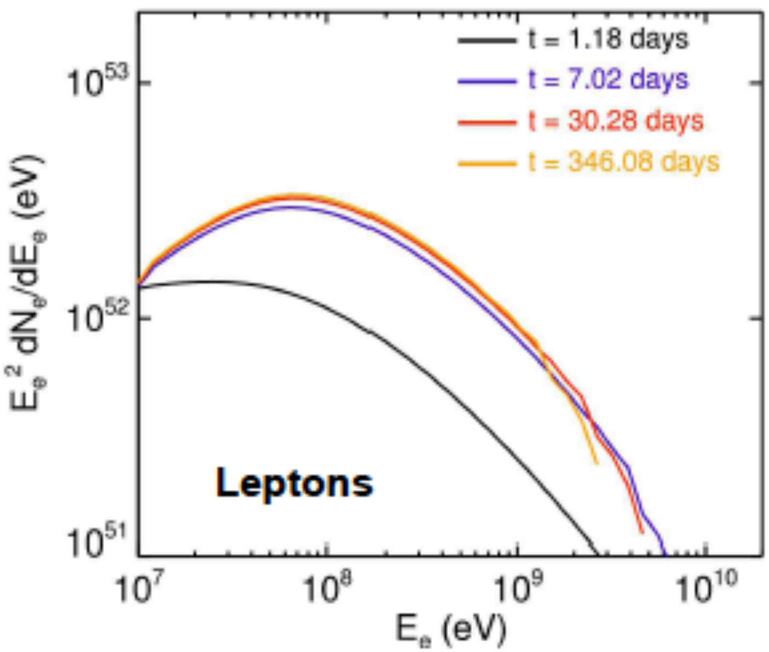
$$\boxed{N(E,t) = \int_{t_0}^{t} Q(E,t') \times \exp\left(-\int_{t'}^{t} C(E,t")dt"\right) dt'}$$

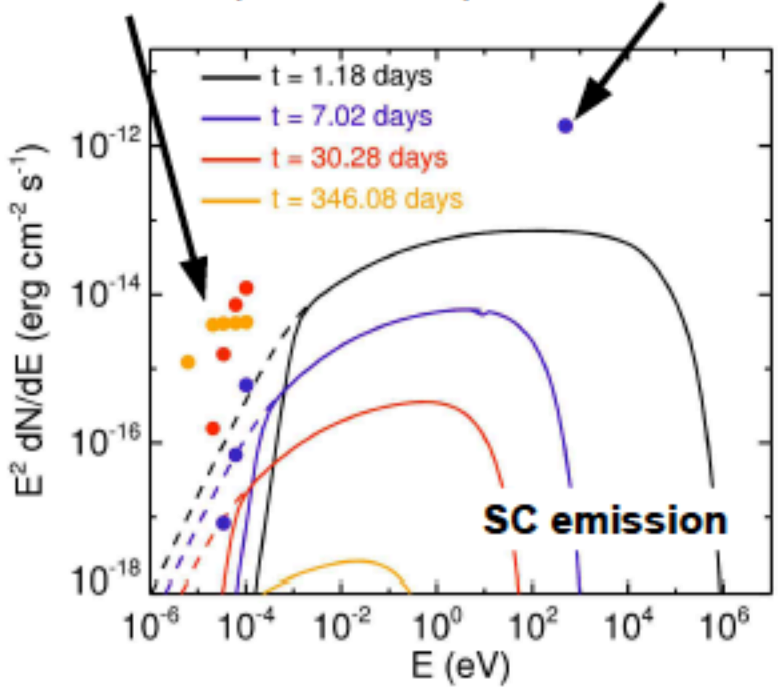
$\alpha(t) = (4/3)\sigma_T c\, B^2(t)/8\pi m_e^2 c^4$

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

Radio measurements (Weiler et al. 2007)

X-ray measurements (Zimmermann et al. 1994)





Relevant parameters

Key parameters	Effects
F= Mass loss rate/wind velocity	Instability growth, gamma-ray luminosity
Shock velocity	Acceleration efficiency
Local magnetic field	Shock obliquity, instability growth
SN luminosity	gamma-gamma absorption
Distance	gamma-ray flux

Core collapse SNe

- SN IIb about 5-6% of cc SNe. Most relevant are the "extended" IIb (see Chevalier & Soderbergh'10): extended radii and higher mass loss rates.
- SN IIP about 50% of CCSNe but with lower F ratios, dimmer X-rays (ambient medium especially heavy elements possibly partially ionized at times t > 10 days, Dwarkadas'14)
- SN IIn: (wrt to IIb) higher F ratios but more rare (1-4% of CCSNe), but develop different hydro profiles (dense shells) (no self-similar solutions).
- SN Ib/Ic: likely connected with Wolf-Rayet phase (lower ratio R), are also rare. Bordered by a dense shell.
- Need a relatively nearby source (D ≤ 10-20 Mpc). Probed at other wavelength cm: VLA, mm: ALMA over month timescales (Murase+09) or by the emission of multi TeV neutrinos (Katz+12).

Conclusion

- CR may be efficiently accelerated in early SNe phases, after the outburst.
- CR driven instabilities can grow fast and compensate short CR advection time.
  - They may explain high MF deduced from SSA analysis in radio SNe.
  - But this depends on the wind MF topology.
- Gamma-ray emission: sensitive to gamma-gamma absorption.
  - Best observation window 1-2 days or 8-15 days after the outburst (SN 93 J case)
  - Potential targets for CTA: observation strategy to set-up.
- Still difficult task because: targets should have high F and should be close enough: so rare (very rare) events.
- Potential detection rate remains to be determine for CTA.

Announcement

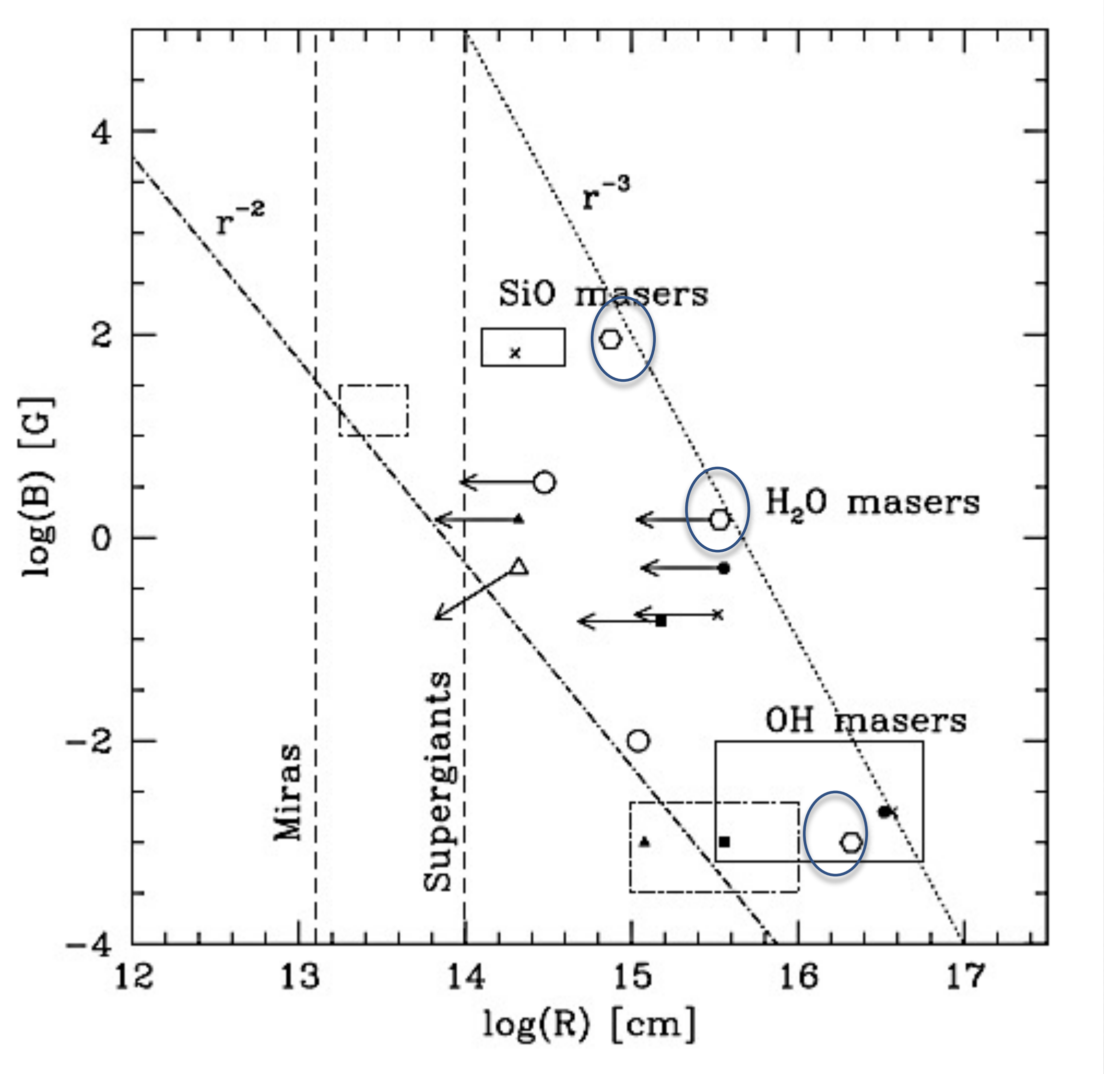
https://iaus331.lupm.in2p3.fr/

February 20-24th 2017

Saint Gilles de la Réunion.

cc-SNe as stellar explosive outcomes
cc-SN explosion mechanisms
cc-SN remnants and impacts
Particle acceleration & Origin of cosmic rays
SN 1987A, 30 years later
Non-thermal multi-wavelength/multi-messenger data on SNe and SNRs

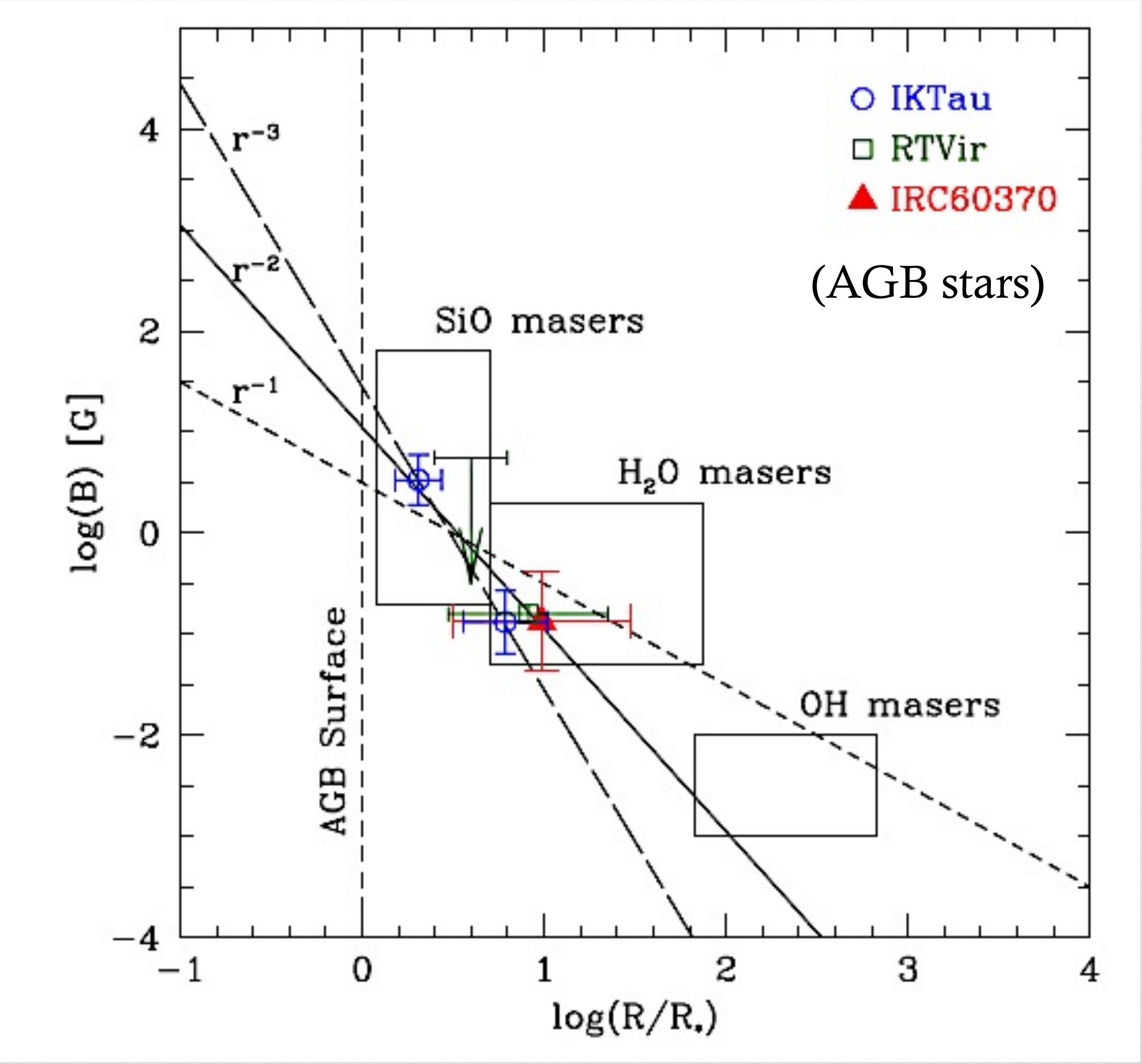
CSM Magnetic field



VX Sgr:
(RSG)

Vlemmings +05

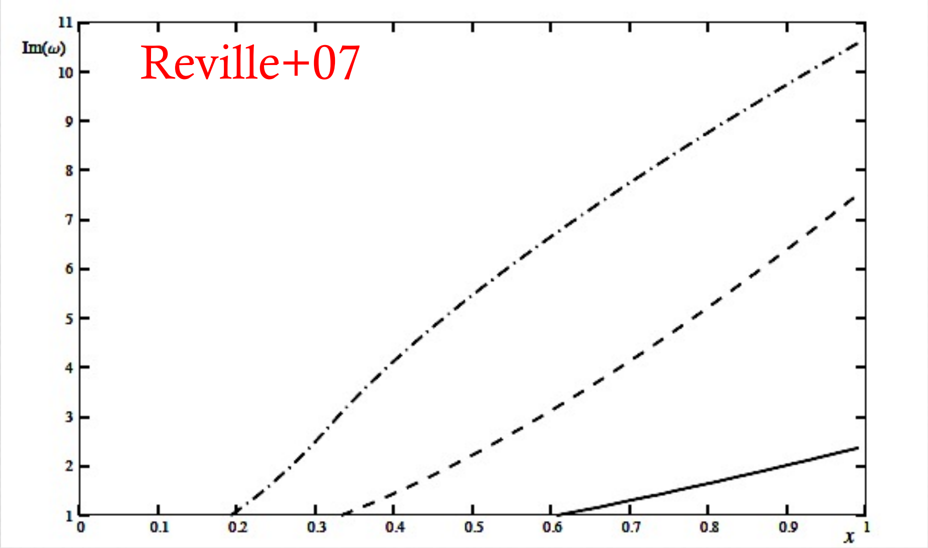
CSM magnetic fields



Leal-Ferreira+13

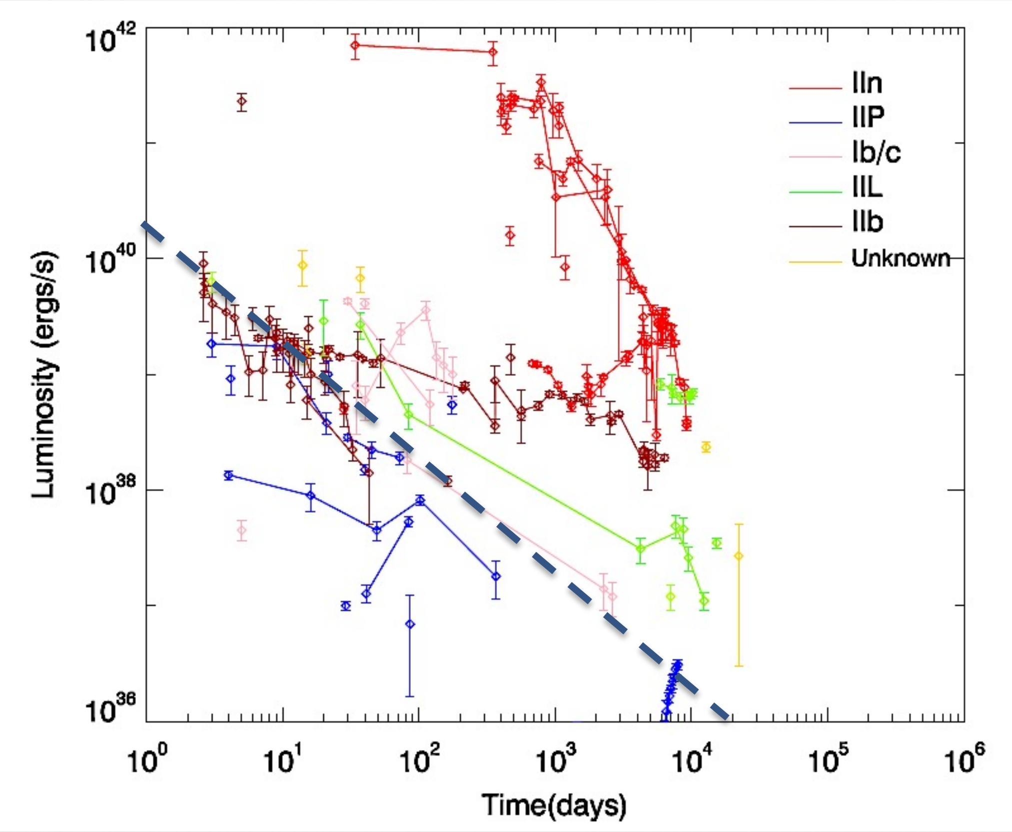
Ionization degree

- Ionization fraction: effects of neutrals => NR modes damping.



SNR conditions
solid n=0.1 cc T=10^4K
dashed n=1cc T=10^3K
dot-dashed n=10 cc T=100 K

X-rays



Dwarkadas'14

X-rays from Bremsstrahlung (e-i equilibration)

$$L_X \sim (310^{40}\, erg/s) g_{ff} C_n \left(\frac{M_{lr,-5}}{V_{w,10}} \right)^2 t_d^{-1}$$