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On the CR spectrum released by a type II SNR expanding in the presupernova wind

Martina Cardillo, Elena Amato, Pasquale Blasi
INAF-Osservatorio Astrofisico di Arcetri

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Knee energy problem

Non-resonant instability ↔ Type II SNae

Maximum energy

Spectrum (from ED to ST phase)

KASCADE-Grande & ARGO

Magnetic field amplification

RESONANT INSTABILITY (Skilling 1975)

Excitation of Alfvén waves with $\lambda \cong r_L$
→ saturation at $\delta B/B \cong 1$
→ $E_M < 1$ PeV

NON RESONANT INSTABILITY (Bell 2004)

Purely growing waves at wavelengths $\lambda \ll r_L$, driven by the CR current j_{CR} → generation of power at larger spatial scales up to $\lambda \cong r_L$ → larger E_M

General case: Estimation of the maximum energy

$$j_{CR}(R,r) = n_{CR}(R,E_M(r))\,e\,v_{sh}(r) = e\,\frac{\xi_{CR}\,\rho(r)\,v_{sh}(r)^3}{E_0\,\Lambda(E_M)}\left(\frac{r}{R}\right)^2$$

Current at distance R

$$f_s(E) \propto E^{-(2+\beta)}$$

$\beta < 0$ *hard*

$\beta = 0$ *flat*

$\beta > 0$ *steep*

Source Spectrum

$$k_M B_0 \approx \frac{4\pi}{c} j_{CR}$$

Balance

+

$$\gamma_M = k_M V_A$$

Growth Rate

+

$$\int \gamma_M \, dt = 5$$

e-folding

$$\Lambda(E_M(R)) \approx \frac{2e}{(4-m)5cE_0}\,\xi_{CR}\,v_{sh}(R)^2\sqrt{4\pi\rho(R)R^2}$$

Maximum Energy

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General case: Estimation of the escaping sp

$$N_{esc}(E)dE = \frac{j_{CR}}{e} 4\pi R^2 dt \quad + \quad j_{CR} \quad + \quad R \propto t^{\lambda} \quad + \quad v_{sh} \propto R^{(\lambda-1)/\lambda}$$

Escape Spectrum

CR Current

Shock Radius

Shock Velocity

$$N_{CR}(E) \simeq \frac{4\pi \xi_{CR}}{E_0 S(\lambda, m)} \rho(R) v_{sh}(R)^2 R^3 \chi(E)$$

$$\chi(E) = \frac{d}{dE}\left(\frac{1}{\Phi(E)}\right) \propto \begin{cases} E^{-2} & \beta < 0 \\ E^{-2} & \beta = 0 \\ E^{-(2+\beta)} & \beta > 0 \end{cases}$$

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General case: Estimation of the escaping sp

k=[7,10]

$R \propto t^{\lambda}$ + $\rho_{ej} \propto R^{-k}$ + $\rho_{m} \propto R^{-m}$

Shock radius — Ejecta density — Medium density

$\rho_m(R) \propto R^{-m}$

$m = 2 \quad wind$

$m = 0 \quad ISM$

$$\lambda = \begin{cases} \dfrac{k-3}{k-m} & ED \\[2ex] \dfrac{2}{5-m} & ST \end{cases}$$

$$N_{CR}(E) \simeq \rho(R) v_{sh}(R)^2 R^3 E^{-(2+\varepsilon)} \propto E^{\zeta}$$

No sharp cut-off above E_M!

$\varepsilon = 0 \;\; if \;\; \beta \leq 0$

$\varepsilon = \beta \;\; if \;\; \beta > 0$

$$N_{esc}(E) = \begin{cases} E^{-(5+4\varepsilon)} & ED \\ E^{-(2+\varepsilon)} & ST \end{cases}$$

Type I
m=0, k=7

$$N_{esc}(E) = \begin{cases} E^{-(4+3\varepsilon)} & ED \\ E^{-(2+\varepsilon)} & ST \end{cases}$$

Type II
m=2, k=9

$$\zeta = \frac{(1+\varepsilon)(4\lambda - m\lambda) - (6\lambda - 4 - m\lambda)}{6\lambda - 4 - m\lambda}$$

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Our model: SNR parameters

$$R_{sh}(t) = R_0 \left[\left(\frac{t}{t_0}\right)^{\lambda_{ED}\cdot\alpha} + \left(\frac{t}{t_0}\right)^{\lambda_{ST}\cdot\alpha} \right]^{1/\alpha}$$

Shock radius

$$v_{sh}(t, E_{SN}, B) = \frac{dR}{dt}$$

Shock velocity

$$\rho(R) = \rho_{ISM}$$

ISM density

$$M_{ej} = 4\pi \int_0^{R_0} \rho(R) R^2 dR$$

Ejecta Mass

$$R_0 = \left(\frac{3M_{ej}}{4\pi\rho_{ISM}}\right)^{1/3} \approx 2\left(\frac{M_{ej}}{M_\odot}\right)^{1/3}\left(\frac{n_{ISM}}{cm^{-3}}\right) pc$$

ST radius

Wind density

$$\rho(R) = \frac{\dot{M}}{4\pi V_w R^2}$$

$$R_0 = \frac{M_{ej}V_w}{\dot{M}} \approx 1\left(\frac{M_{ej}}{M_\odot}\right)\left(\frac{V_w}{10 km/s}\right)\left(\frac{\dot{M}}{10^{-5} M_\odot / yr}\right) pc$$

$$\rho_{ej}(R,t) = A(M_{ej}, E_{SN}) R^{-k} t^{k-3}$$

Ejecta density

$$t_0 = \left[R_0 \left(\frac{B}{A}\right)^{1/(k-m)} \right]^{\frac{k-m}{k-3}} = t_0(E_{SN}, B)$$

ST time

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Our model: maximum energy

ISM

$$E_M(R) \simeq \frac{2Ze}{10}\sqrt{4\pi\rho R^2}\,\frac{\xi_{CR}}{c\Lambda}\,v_{sh}^2(R) = 130\left(\frac{\xi_{CR}}{0.1}\right)\left(\frac{M_{ej}}{M_\odot}\right)^{-2/3}\left(\frac{E_{SN}}{10^{51}\,erg}\right)\left(\frac{n_{ISM}}{cm^{-3}}\right)^{1/6} TeV$$

WIND

$$E_M(R) \simeq \frac{2Ze}{5}\sqrt{4\pi\rho R^2}\,\frac{\xi_{CR}}{c\Lambda}\,v_{sh}^2(R) = 1\left(\frac{\xi_{CR}}{0.1}\right)\left(\frac{M_{ej}}{M_\odot}\right)^{1}\left(\frac{E_{SN}}{10^{51}\,erg}\right)\left(\frac{\dot{M}}{10^{-5}\,km/yr}\right)^{1/2}\left(\frac{V_w}{10\,km/s}\right)^{1/2} PeV$$

- Type II SNR provide higher maximum energy
- Proportional to CR efficiency (ξ_{CR})
- Strong dependence on shock velocity

ED phase → **Observational problem!**

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Our model: diffusion and spallation

$$N_{diff}(E) = \frac{\Sigma}{2\pi H R_D^2}\frac{H^2}{D_0}\left(\frac{E}{Ze}\right)^{-\delta} \rightarrow N_{diff}(E) = \frac{\Sigma}{2\pi R_D^2}\frac{X(E)}{n_D \eta c m_p}$$

Diffusion

B/C ratio

$$X(E) = n_D \frac{\eta}{H} c m_p \frac{H^2}{D_0}\left(\frac{E}{Ze}\right)^{-\delta}$$

Grammage

flat

$$X(Rg) = 19\beta^3\left(\frac{Rg}{3GV}\right)^{-0.6}$$

steep

$$X(Rg) = 7.2\left(\frac{Rg}{3GV}\right)^{-0.34}$$

(Ptuskin 2009)

$$N_{spal}(E) = \left(1 + \frac{X(E)}{X_{CR}}\right) = \left(1 + \frac{X(E)}{m_p/\sigma_{sp}}\right)$$

Spallation

$$\sigma_{sp}(E)[mb] = \alpha(E)A^{\beta(E)}$$

Cross Section
(Horandel 2007)

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Our model: Observed spectrum

$$N_{obs}(E) = \underline{N_{esc}(E)} \times \underline{\frac{\Re}{2\pi R_D^2} \frac{X(E)}{n_D h c m_p}} \times \left(1 + \underline{\frac{X(E)}{m_p / \sigma_{sp}}} \right)^{-1}$$

Escape | Diffusion | Spallation

Assumptions

$M_{ej} = 1\ M_\odot$

$dM/dt = 10^{-5}\ M_\odot/yrs$

$V_w = 10$ km/s

$R_d = 10$ kpc

$X(E) = k(Rg/\ 3GV)^{-\delta}$

$\delta = 2.65 - p_{inj}$

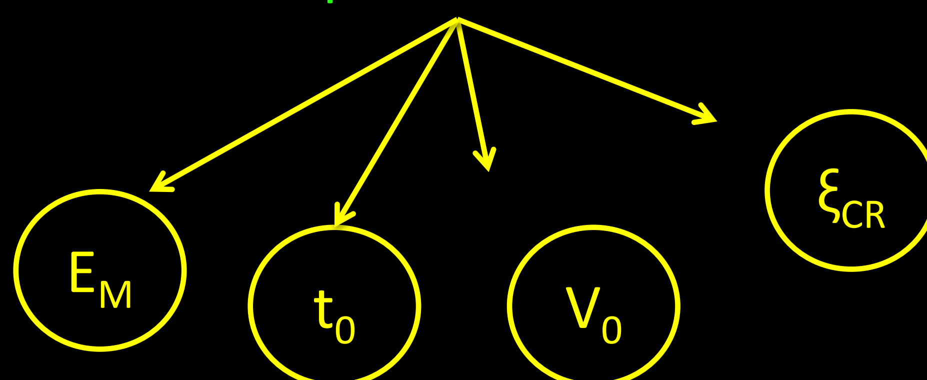
$n_d = 1\ cm^{-3}$

$\sigma_{sp} = \alpha(E)\ A^{\beta(E)}$

Variables

E_{SN} = Supernova energy

R = Explosion rate



From TRACER and CREAM

$$N_{obs} \propto E^{-2.65}$$

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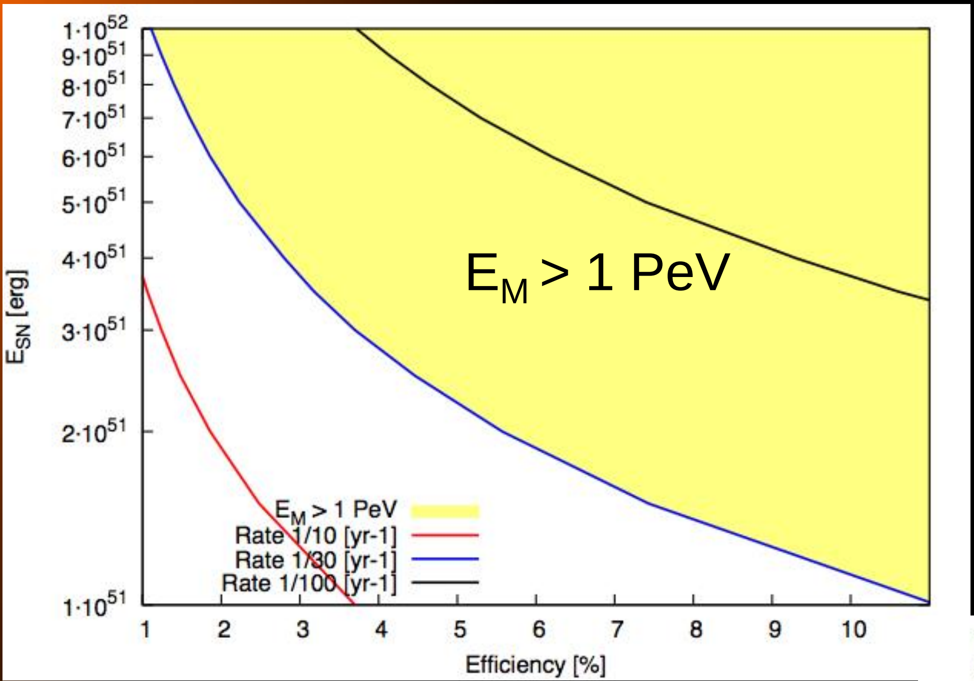
Our model: SN energy behavior



flat

E_M= 1 PeV → Ra= 1/30 yrs

ξ_{CR}= 11%

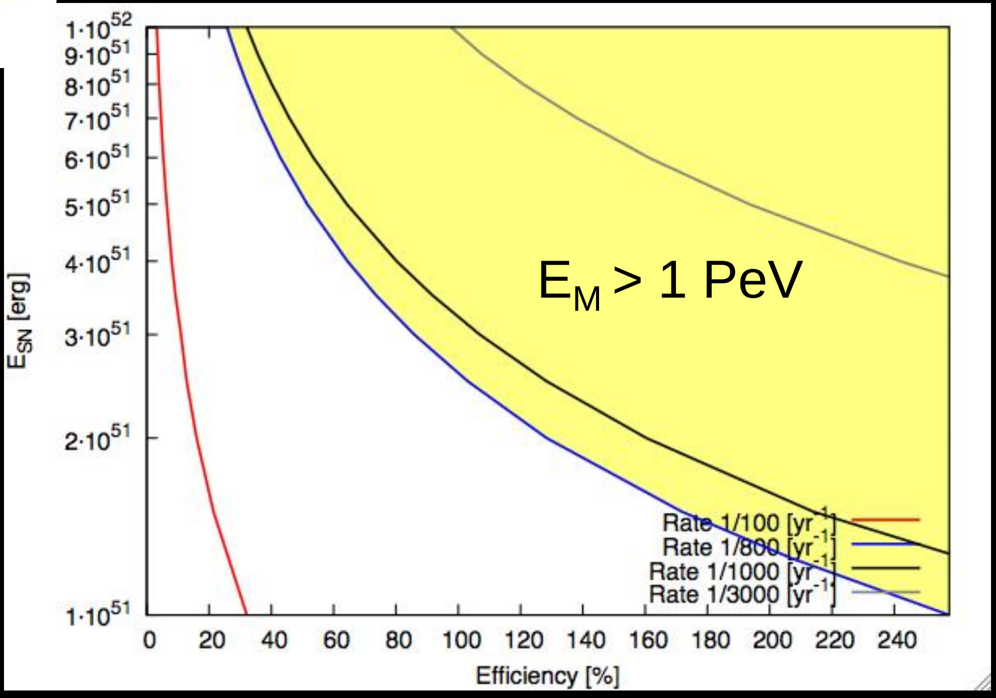
(for standard $E_{sn}=10^{51}$ erg)

steep

E_M= 1 PeV → Ra= 1/800 yrs

ξ_{CR}= 240% (!!)

(for standard $E_{sn}=10^{51}$ erg)



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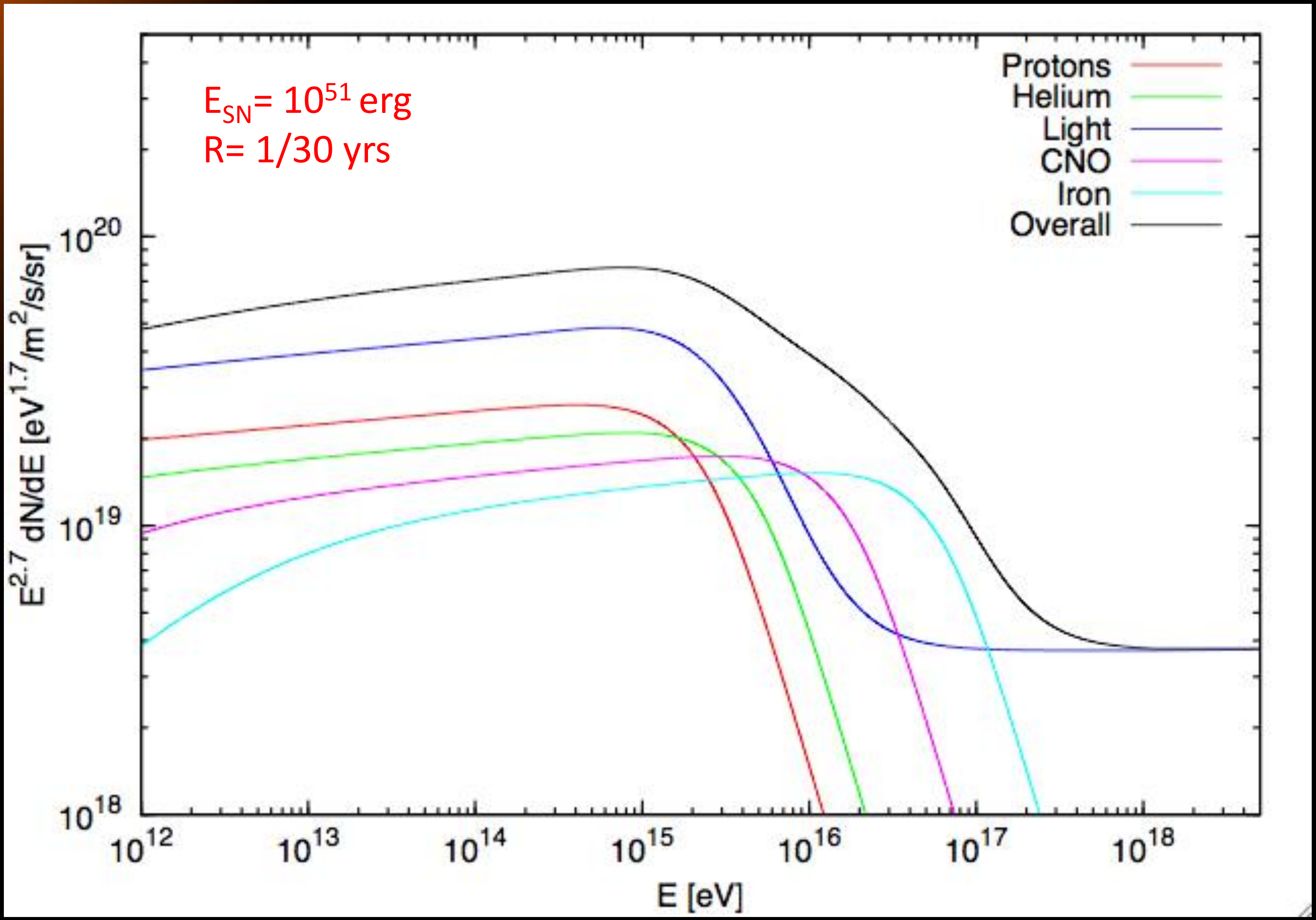
Our model: Standard energetics



E_M= 1 PeV

ξ_{CR}= 11%

t_0= 85 yrs

v_0=15.700 km/s

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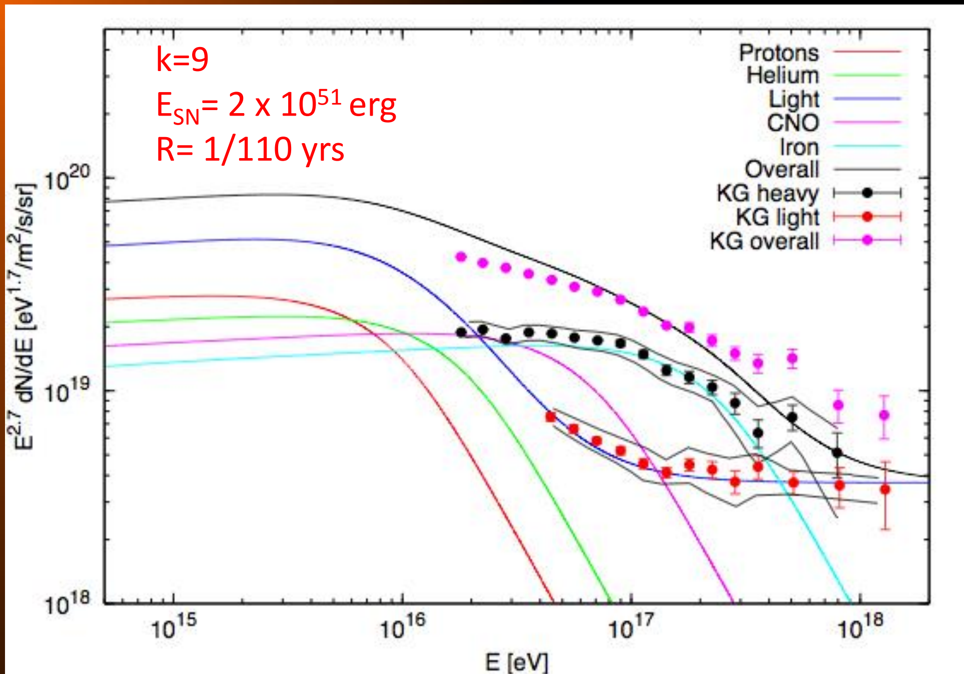
Model and data



KASCADE Grande

(Apel 2013)

$E_M \cong$ 3.7 x 10^{15} eV

$\xi_{CR} \cong$ 20 %

$t_0 \cong$ 60 yrs

$v_0 \cong$22.200 km/s

ARGO

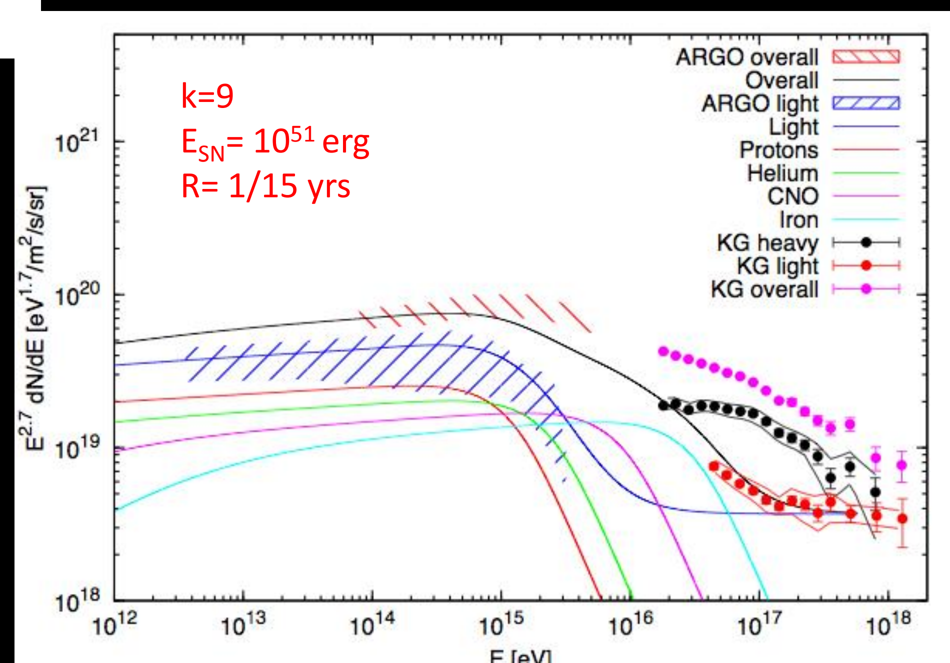
(Di Sciascio 2014)

$E_M \cong$ 507 TeV

$\xi_{CR} \cong$ 5.2 %

$t_0 \cong$ 85 yrs

$v_0 \cong$15.700 km/s



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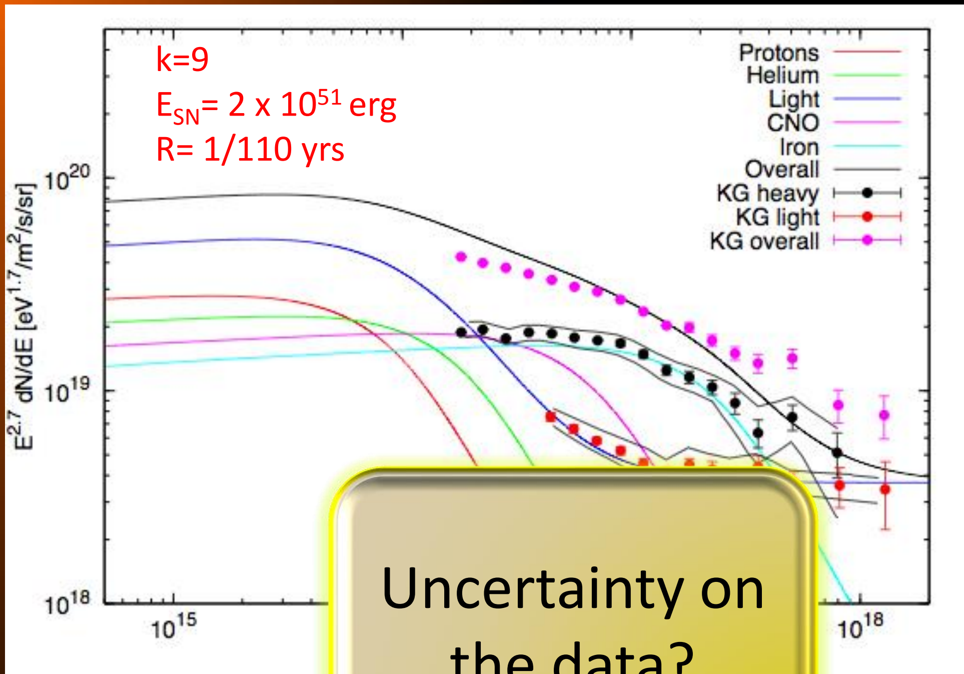
Model and data



KASCADE Grande

(Apel 2013)

$E_M \cong$ 3.7 x 10^{15} eV

$\xi_{CR} \cong$ 20 %

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Uncertainty on the data?

Additional component?

ARGO

(Di Sciascio 2014)

$E_M \cong$ 507 TeV

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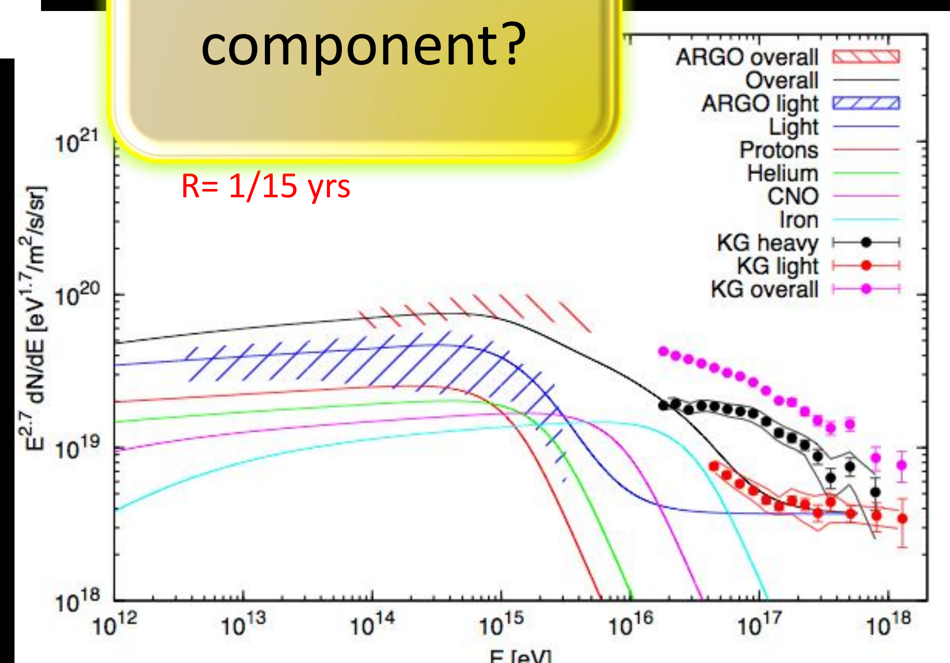
$t_0 \cong$ 85 yrs

$v_0 \cong$15.700 km/s



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Conclusions

- ✧ Bell non-resonant instability predicts that very energetic SNRs can reach PeV energies.
- ✧ NHR instability leads to the release of a steep power-law spectrum in the ejecta dominated phase → no sharp cut-off!
- ✧ Type II SNRs can accelerate particles up to the knee at very early time → detection problem.
- ✧ KASCADE Grande and ARGO data can be fitted with reasonable values of SN parameters.
- ✧ No model that can fit both ARGO and KASCADE-Grande data → need a better data understanding with a consequent theory improvement.

Thank you very much!