UNIVERSITÀ DEGLI STUDI DI TRIESTE

Early-time constraints on CR acceleration in the core-collapse SN 2023ixf with Fermi-LAT

G. Martí-Devesa, C.C. Cheung, N. Di Lalla, M. Renaud, G. Principe, N. Omodei, F. Acero, on behalf of the Fermi-LAT Collaboration

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Fermi Gamma-ray Space Telescope

①

Which source populations can substantially contribute to the knee of the cosmic-ray spectrum?

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Which source populations can substantially contribute to the knee of the cosmic-ray spectrum?

②

How can *Fermi*-LAT uniquely test those ideas?

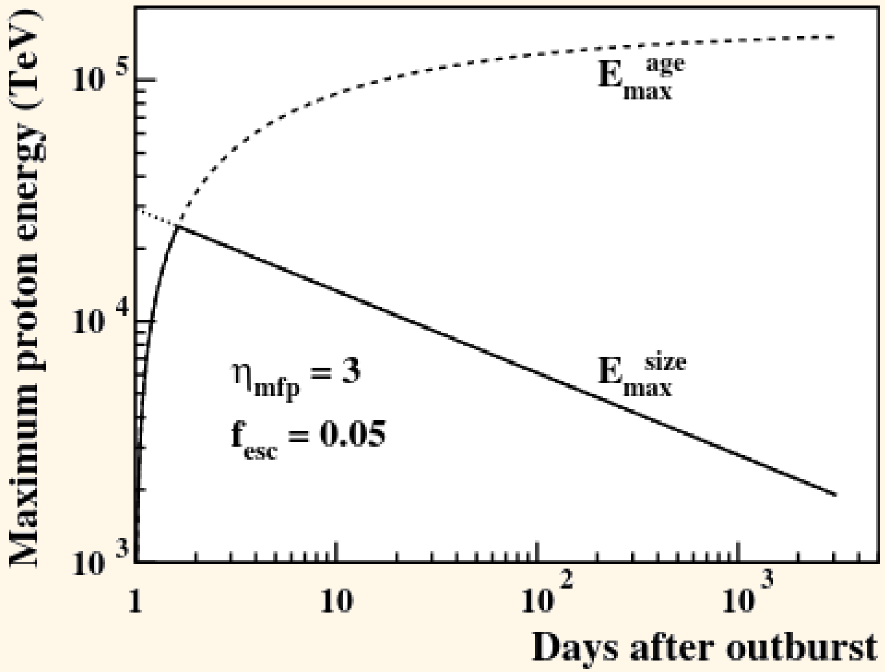
Focus: Early-time acceleration up to 1 PeV in SNe?

Theory

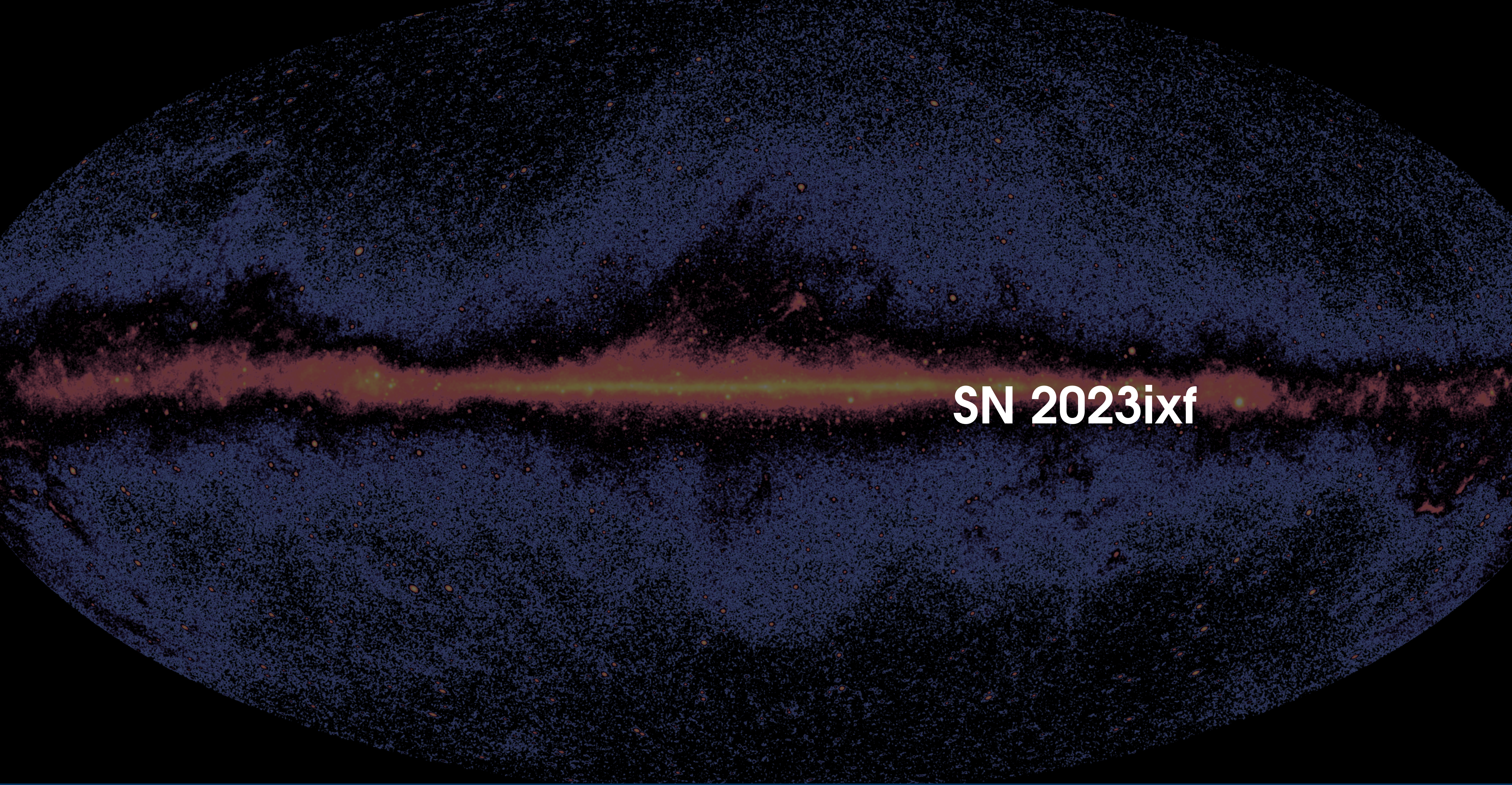
Very-early free expansion of the shock might lead to efficient acceleration

Experimental tests

GeV: Min. exposure 1 month
TeV: Strong γ–γ absorption



Credit: Tatischeff 2009

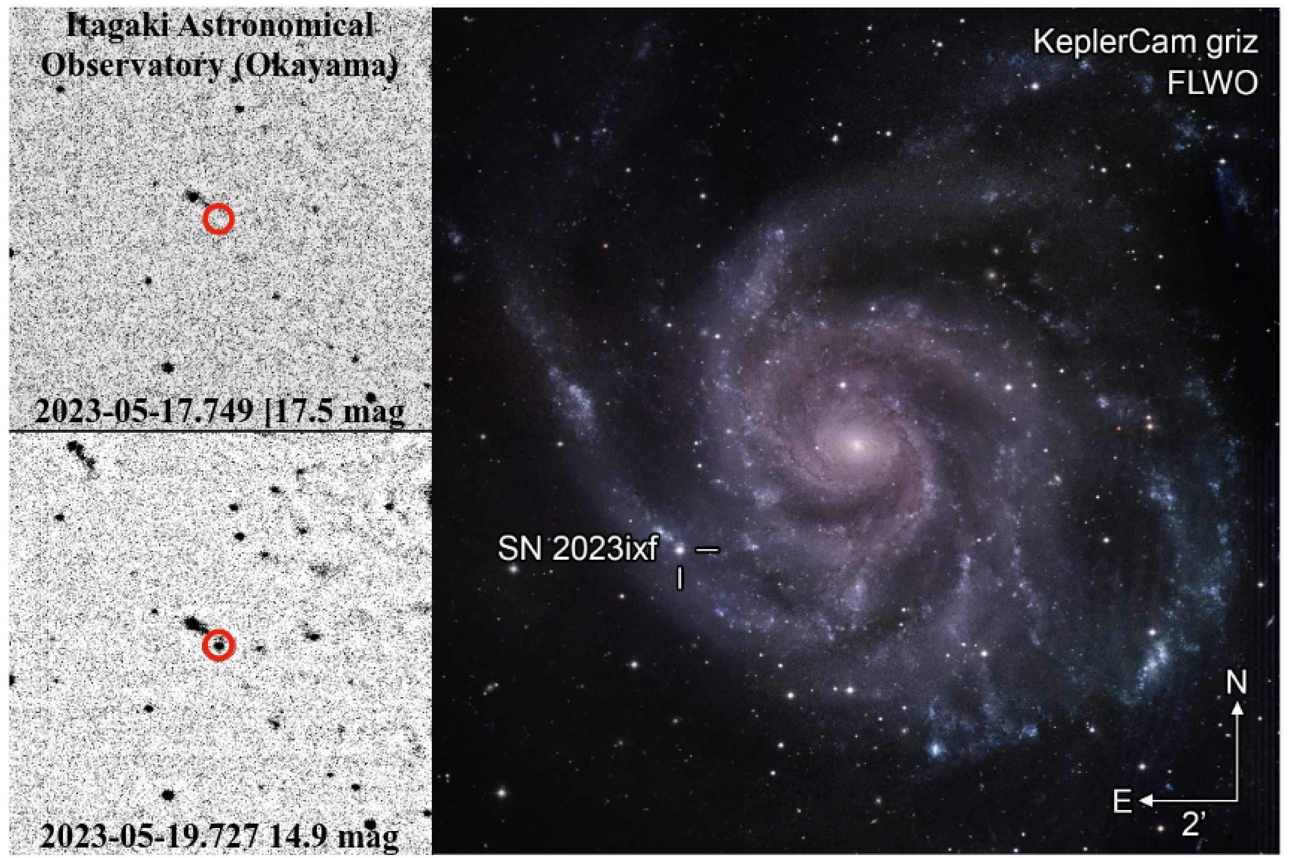

SN 2023ixf

SN 2023ixf: A SN Type II in M101

$D = 6.85$ Mpc

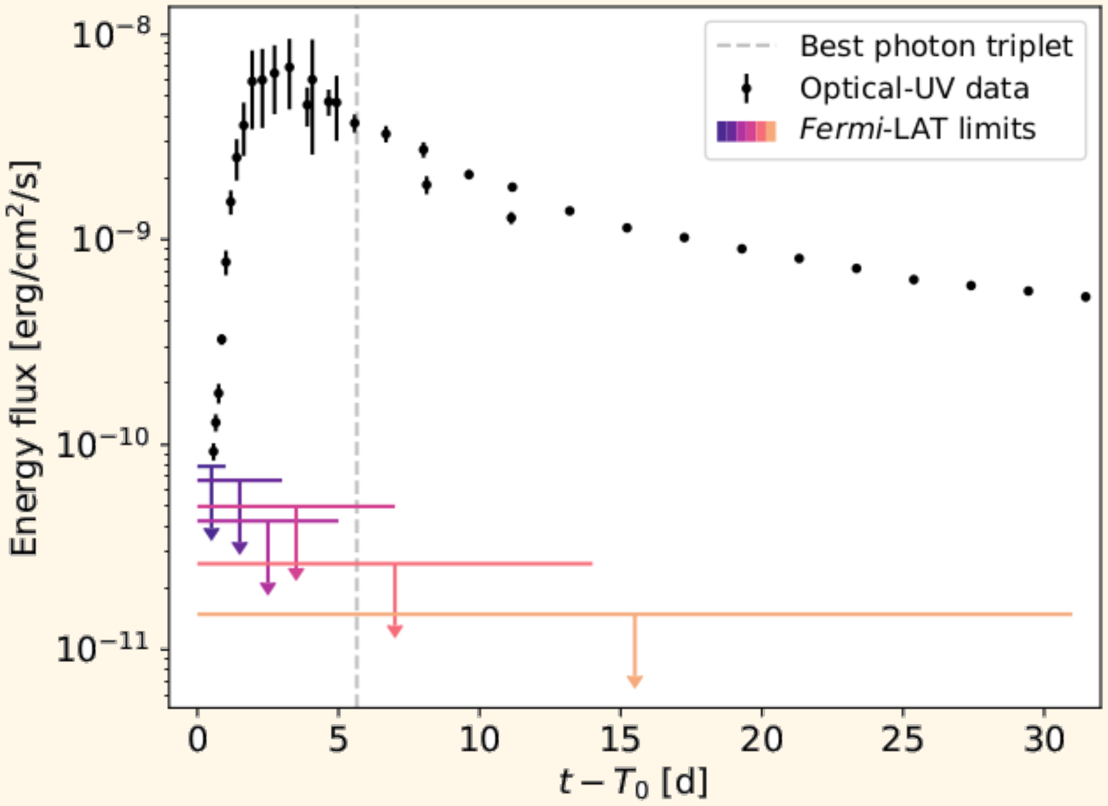
$L_{opt} \sim 10^{43}$ erg/s

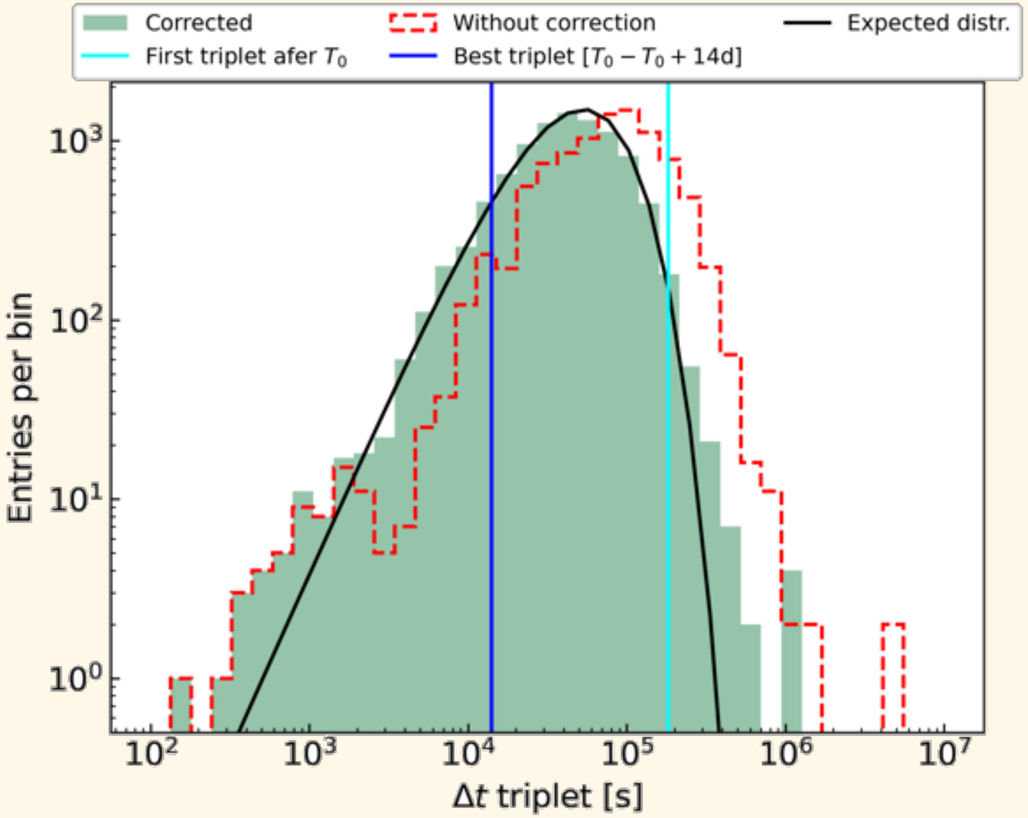
From scaling, 1 month
$L_{\gamma,UL} \sim 10^{41}$ erg/s



Credit: Hiramatsu et al. 2023

Energy flux limits and photon triplets





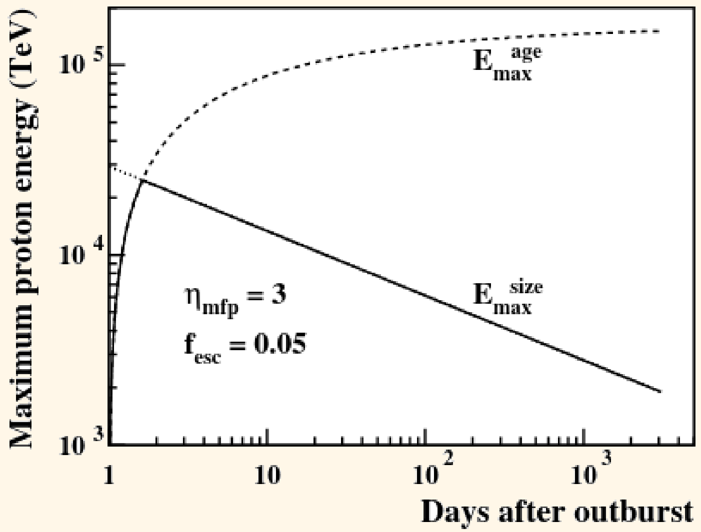
Constraints on a SN 1993J's model

$$\frac{dN_\gamma}{dE} = 3.5\times10^{-11}\left[\frac{D}{6.85\ \mathrm{Mpc}}\right]^{-2}\left[\frac{\dot{M}_{\mathrm{RSG}}}{10^{-2}\ \mathrm{M}_\odot/\mathrm{yr}}\right]^{2}\left[\frac{t}{1\ \mathrm{d}}\right]^{-1}$$

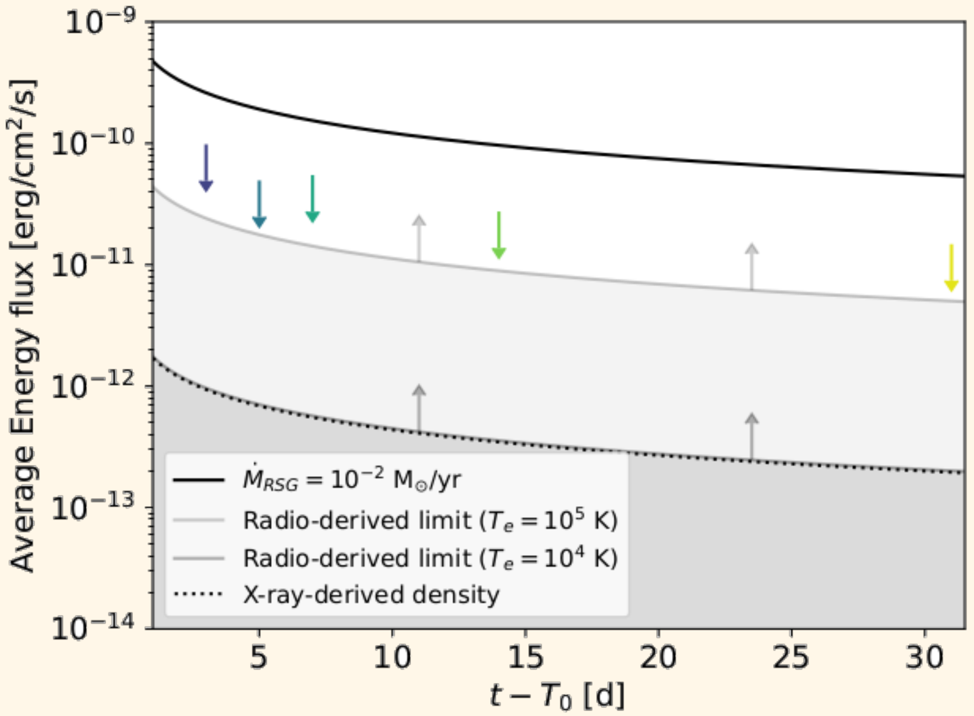
$$\times\left[\frac{V_{\mathrm{S}}}{10^4\ \mathrm{km/s}}\right]^{2}\left[\frac{u_{\mathrm{w}}}{100\ \mathrm{km/s}}\right]^{-2}\left[\frac{E}{1\ \mathrm{TeV}}\right]^{-2}\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Theory

Very-early free expansion of the shock might lead to efficient acceleration



Credit: Tatischeff 2009



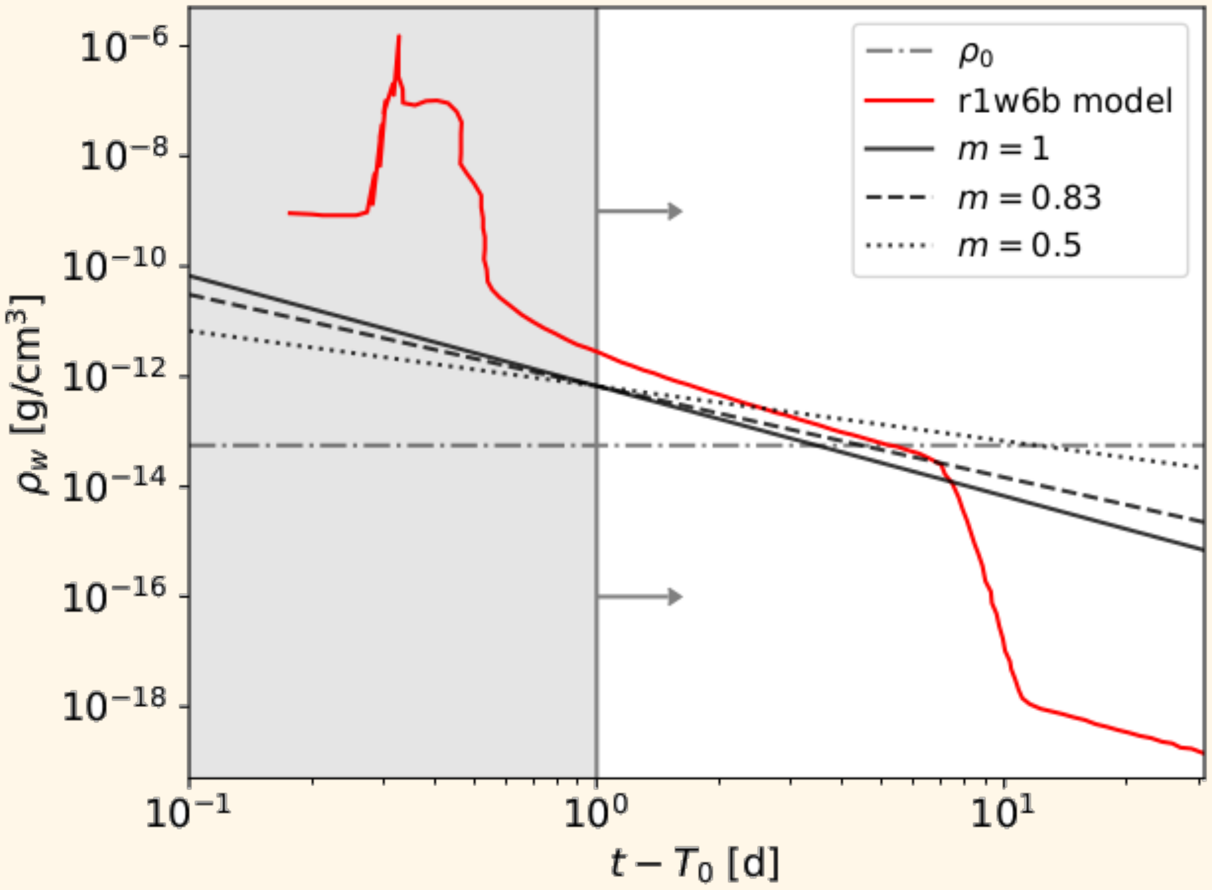
SN shock through a RSG wind

$$R_s(t) = V_{s,0}\left[\frac{t}{1\mathrm{day}}\right]^m$$

for a free expansion, $m = 1$

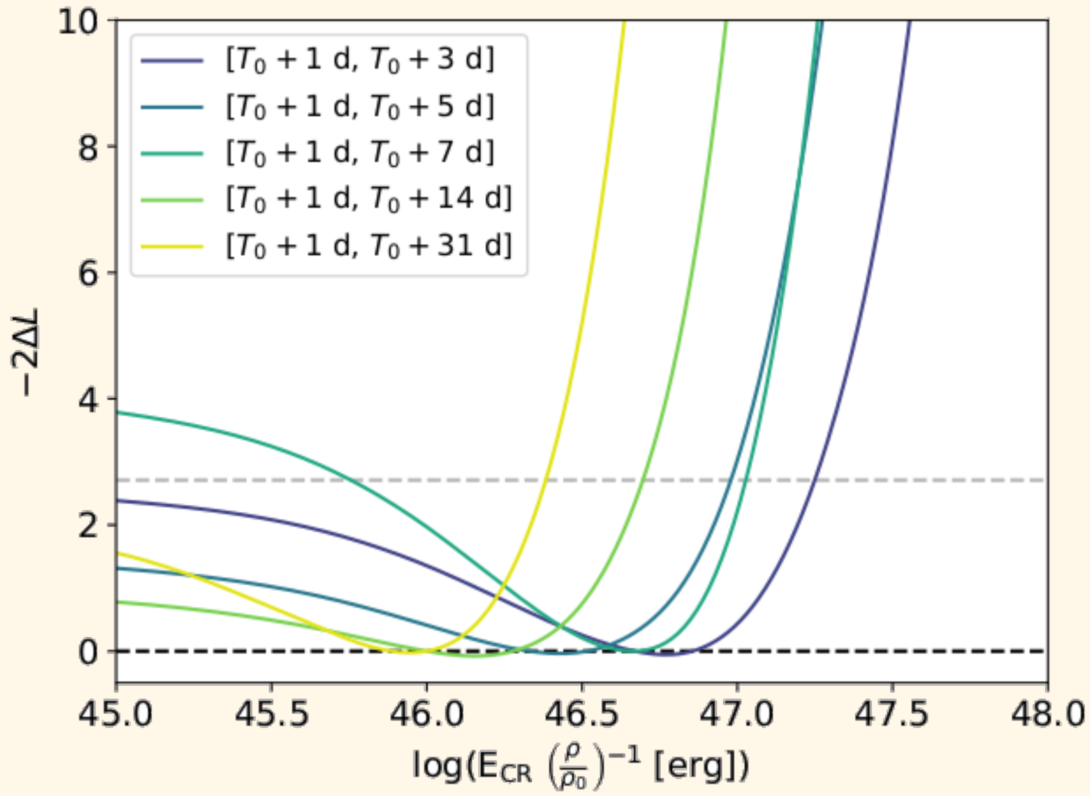
$$\rho_w(r) = \frac{\dot{M}_{\mathrm{RSG}}}{4\pi r^2 u_w}$$

$$\frac{dN_{\mathrm{CR}}}{dE} = \beta N_0 \left(\frac{E}{E_0}\right)^{-p} \exp\left\{-\left(\frac{E}{E_{\mathrm{cutoff}}}\right)\right\}$$

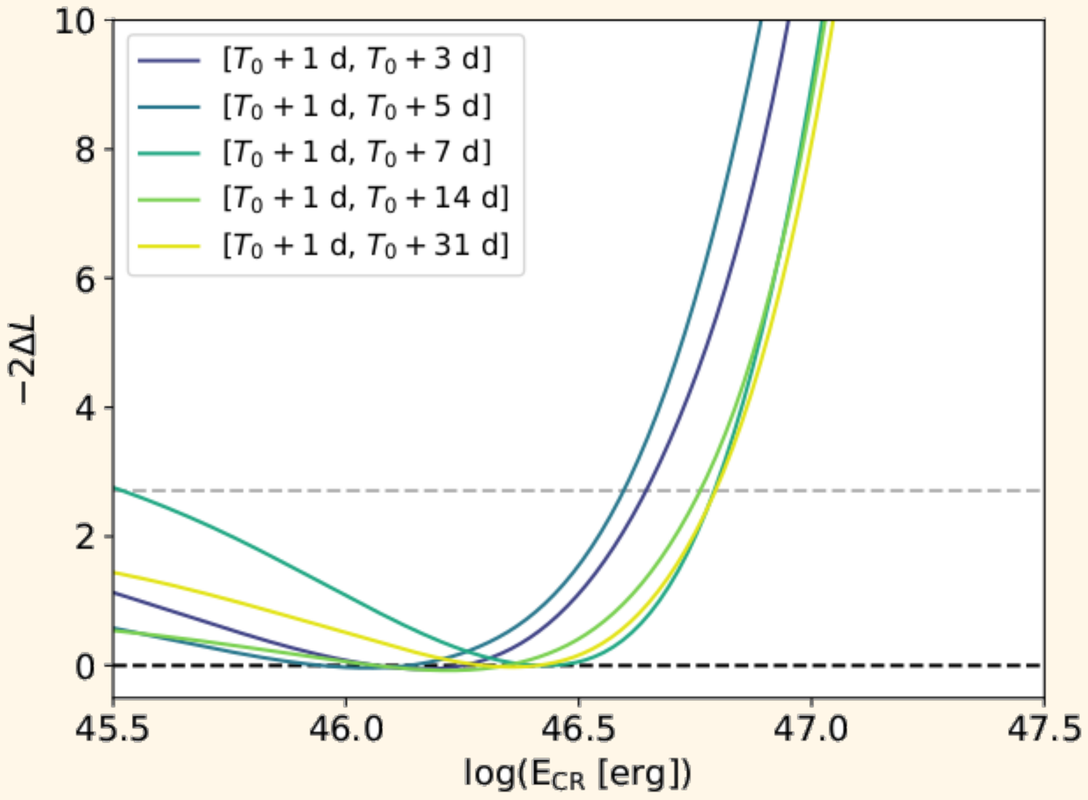


Likelihood profile on E_{CR}

Flat profile



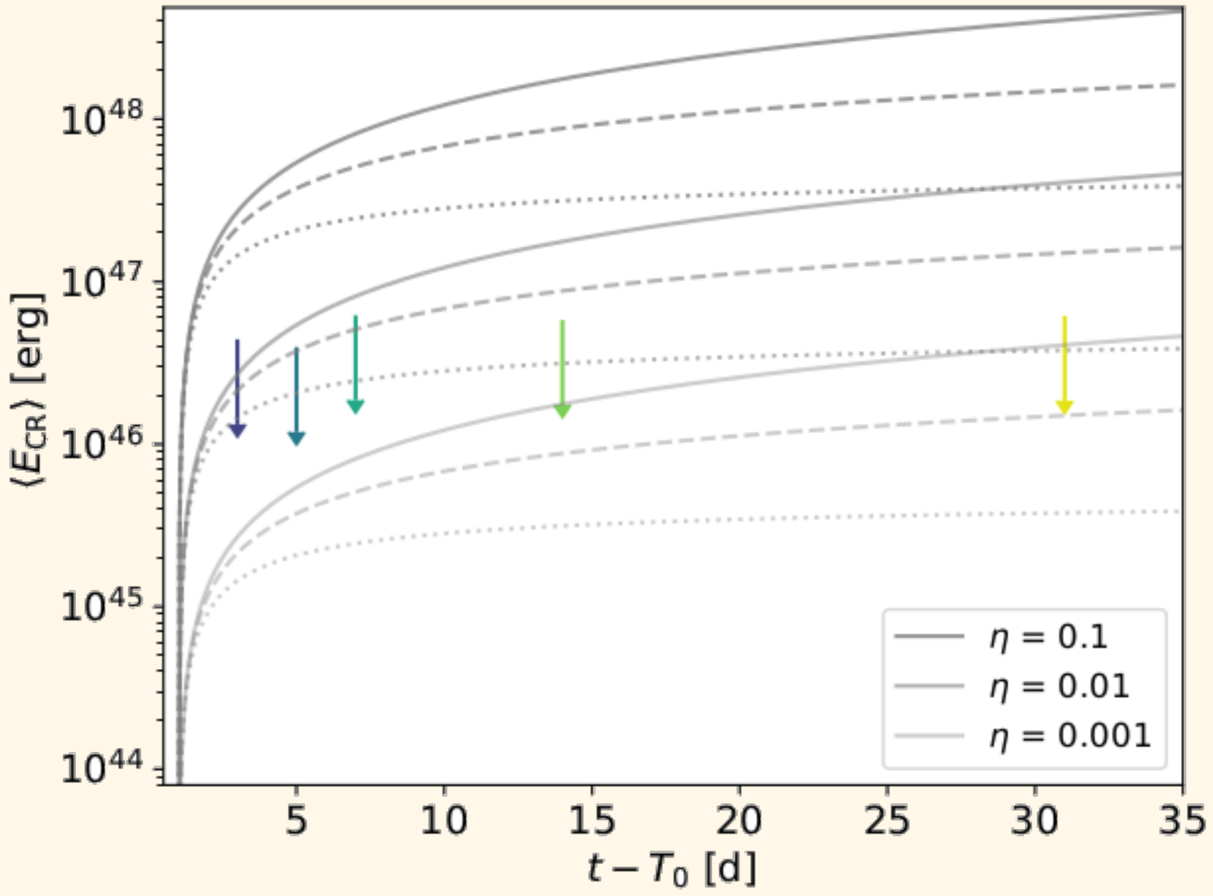
Wind profile



Limits on the efficiency

$$E_{\mathrm{CR}} = \eta \int_{t_0}^{t_f} \frac{1}{2}\rho_w V_s^3 4\pi R_s^2 dt$$

$\eta < 1\%$?
We expected 10% ...



First approach: possible biases explored

(1) The density profile $\rho_W(r)$ is too simple

(2) γ-rays are heavily absorbed

(3) CR escape or particle losses are substantial

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First approach: possible biases explored

(1) The density profile $\rho_W(r)$ is too simple

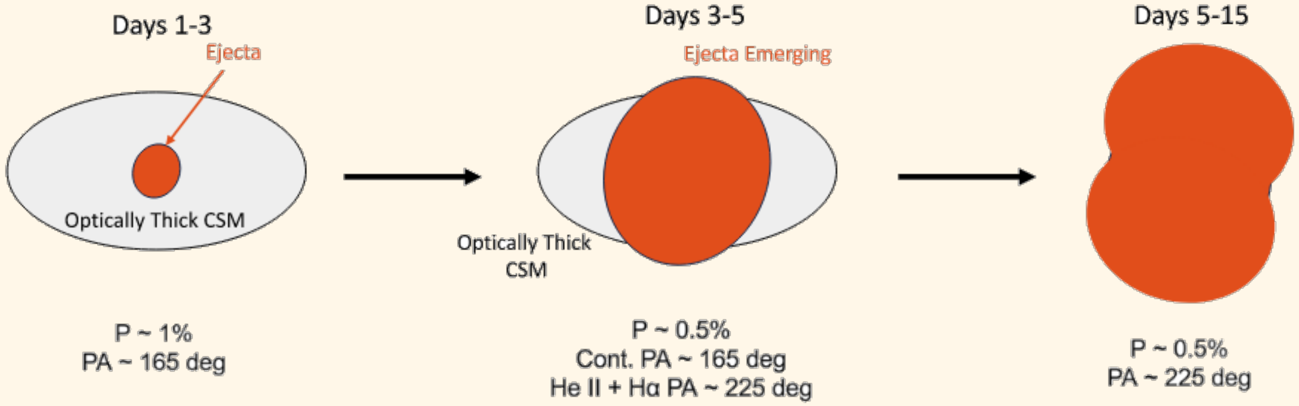
~~(2) γ-rays are heavily absorbed~~
Not relevant below 10/100 GeV (Fang et al. 2020)

~~(3) CR escape or particle losses are substantial~~
Factor 2 only (Cut-off $\sim$ TeV)

Geometry and the volume filling factor

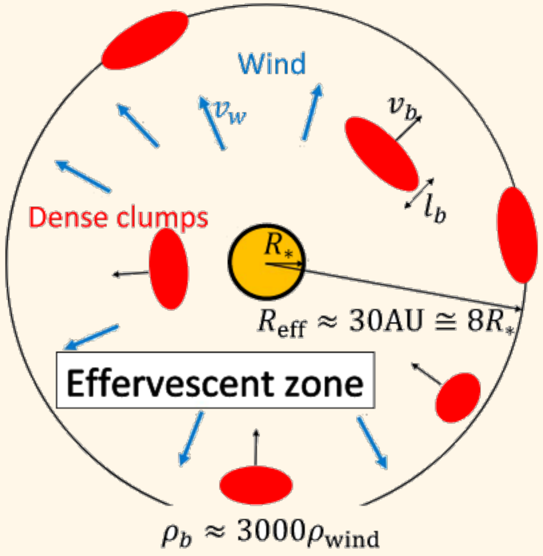
We assumed a spherically symmetric, 1D density profile. But ...

Pre-SN binary



Credit: Smith et al. / Vasylyev et al. 2023

RSG wind clumps



Credit: Soker 2023

If $f_V \sim 0.1$, limit relaxed


... and summary

Summary

Take-home message: For the first time we can test shock models at high energies within one week after a SN explosion

- No detection: no shock emission & no GeV flash. Luminosity ratio not larger than in novae ($L_\gamma/L_{\rm opt} < 0.01$)
- Results point to $<$ 1% efficiency, far from 10%. In principle, limit relaxed getting rid of spherically symmetric CSM. Other possible biases (e.g. absorption, losses) seem negligible on first estimates
- We provide a set of limits up to 1 yr for future, more sophisticated modelling (see Martí-Devesa et al. 2024, A&A, 686, A254)