Gamma-rays from young SNRs in dense circumstellar environments

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Galactic cosmic-rays

Possible sources

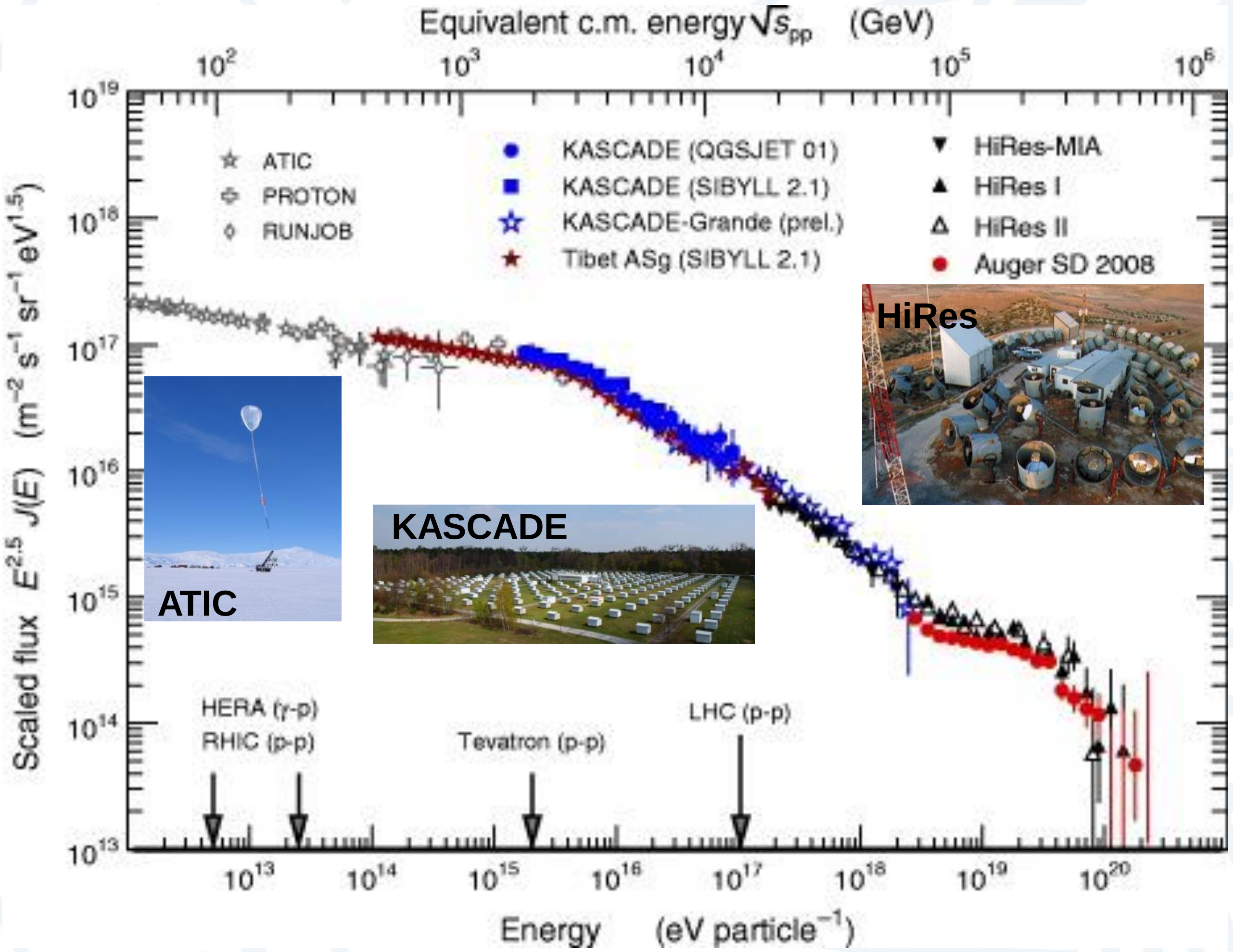


Figure: The cosmic ray spectrum (Blümer et al. 2019)

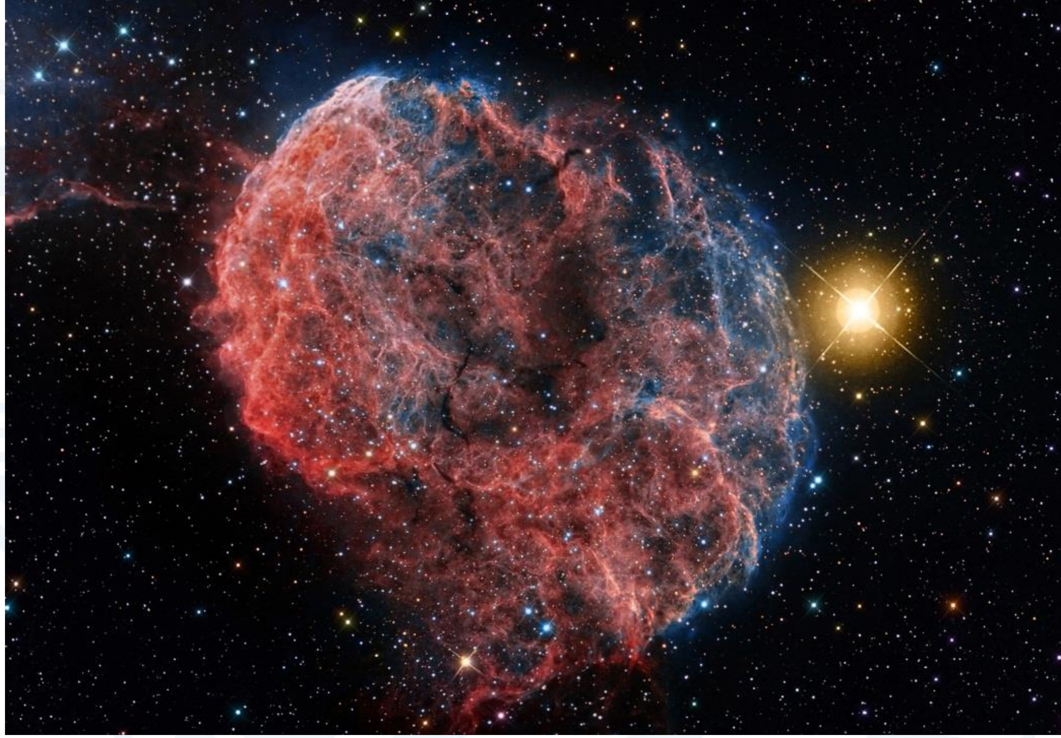


Figure: IC443 – multi wavelength image (credit: Dieter Willasch)

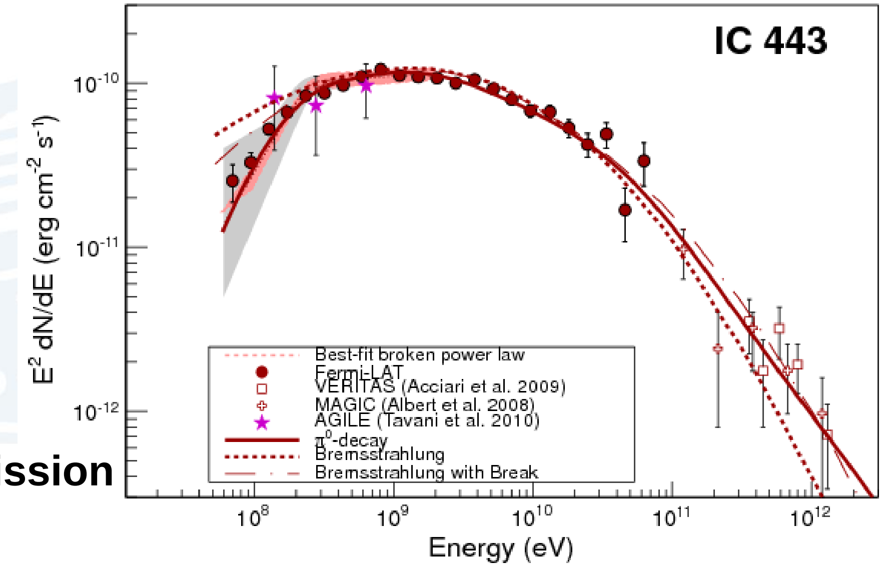


Figure: IC443 – gamma ray emission (Funk et al. 2013)

SNRs as cosmic-ray sources

Experimental evidence

- Some CC supernovae are bright in radio, optical and X-rays (Type-IIn)
- Bright Radio and X-ray SNe often show signs of circumstellar interaction (Chevalier 1982)
- Radio emission is synchrotron → also expect gamma-ray emission
- Theoretical models predict high-energy radiation if particle acceleration is efficient (e.g., Murase+2011, Marcowith+2018)

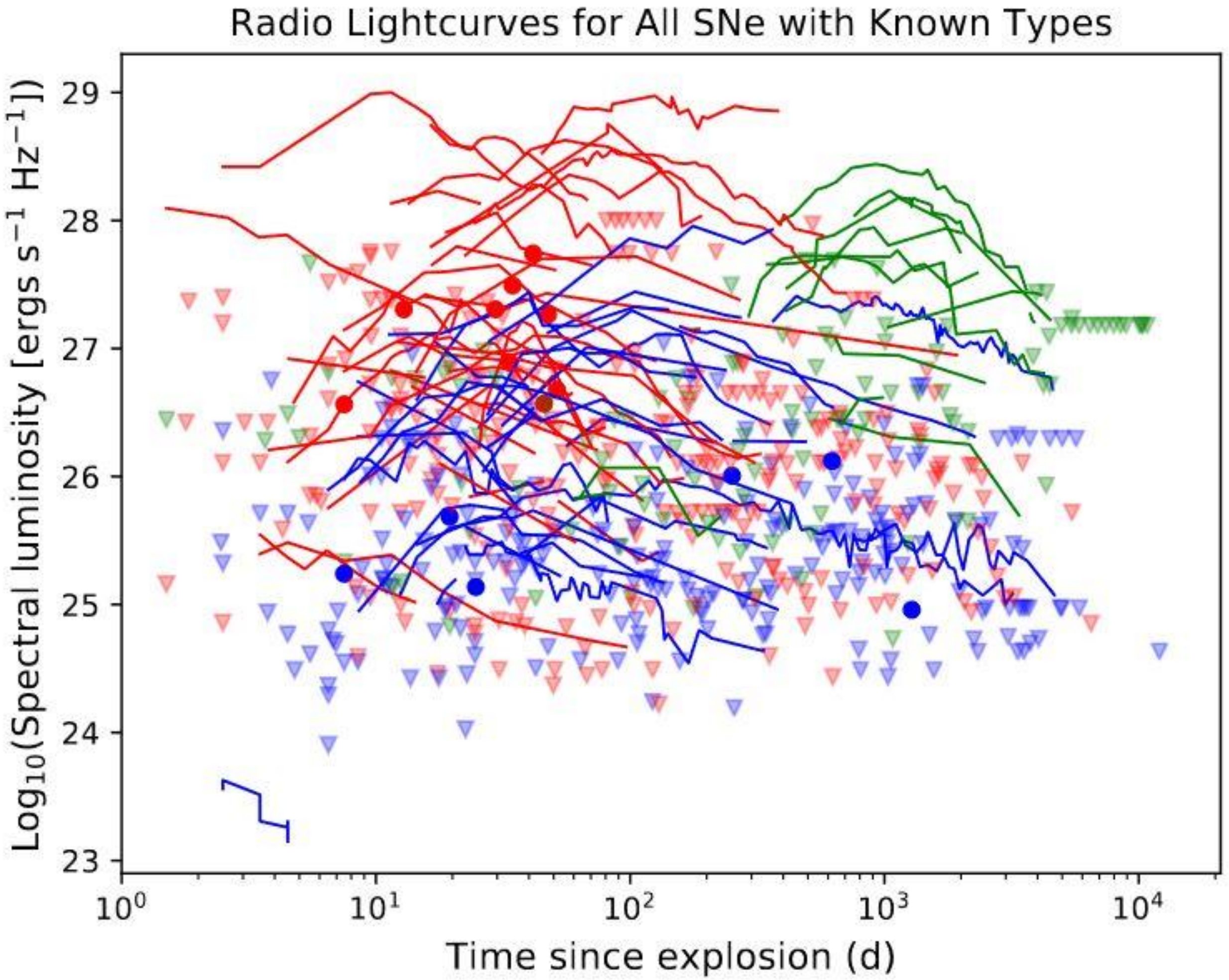


Figure: Early-time Radio emission from SNs of various types (Bietenholz et al.2021)

SNRs as cosmic-ray sources

Experimental evidence

- H.E.S.S. Collaboration (2019) obtained upper limits on TeV emission from nearby CCSNe
- Ongoing HESS ToO programme so far has no detections

- Xi+(2020) detected γ-rays from the location of SN 2004dj, a bright and nearby SN IIP, with FERMI-LAT
- A recent variability analysis of FERMI-LAT data found evidence in support of 2 further detections (Prokhorov+2021).
- Also suggestion of increasing flux from SN1987A with FERMI-LAT (Malyshev+2019)

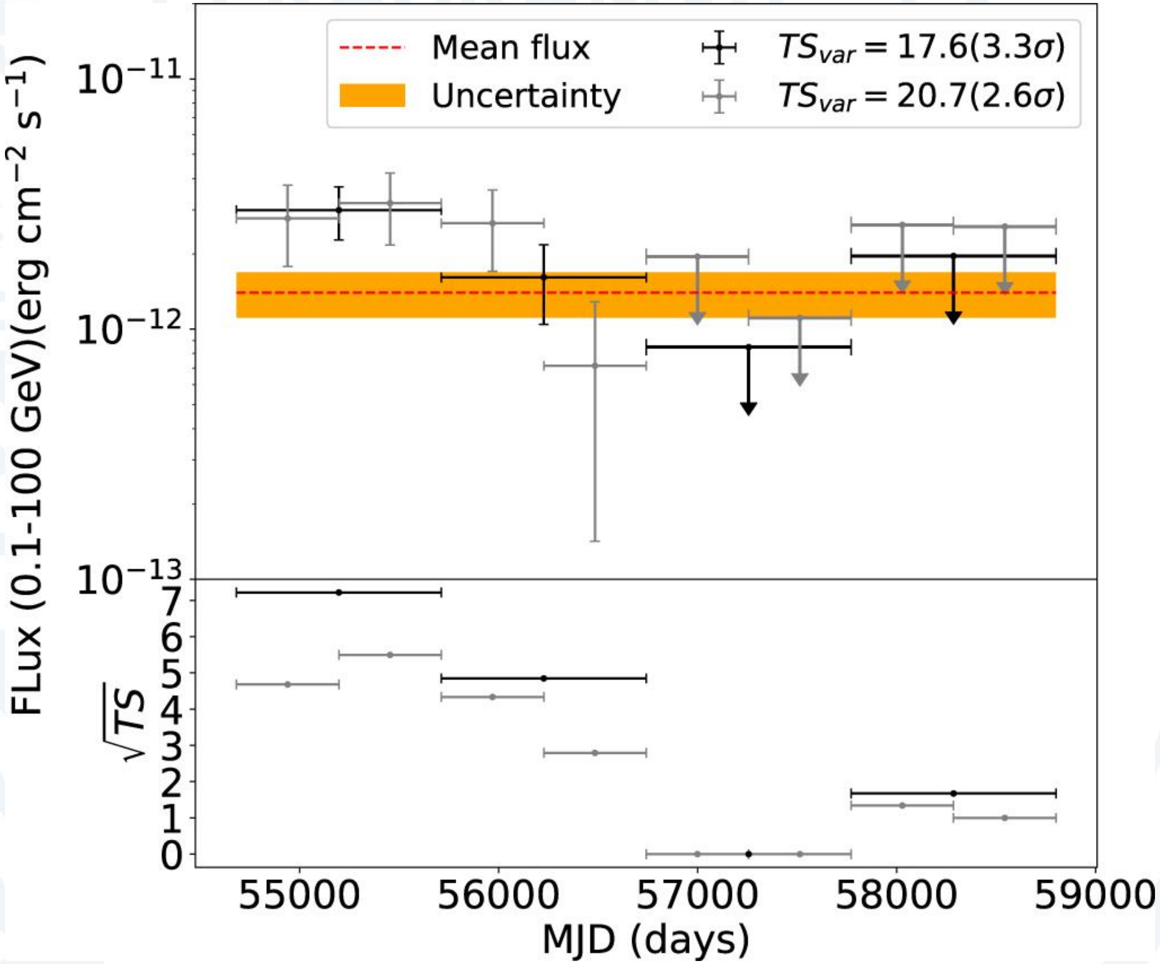


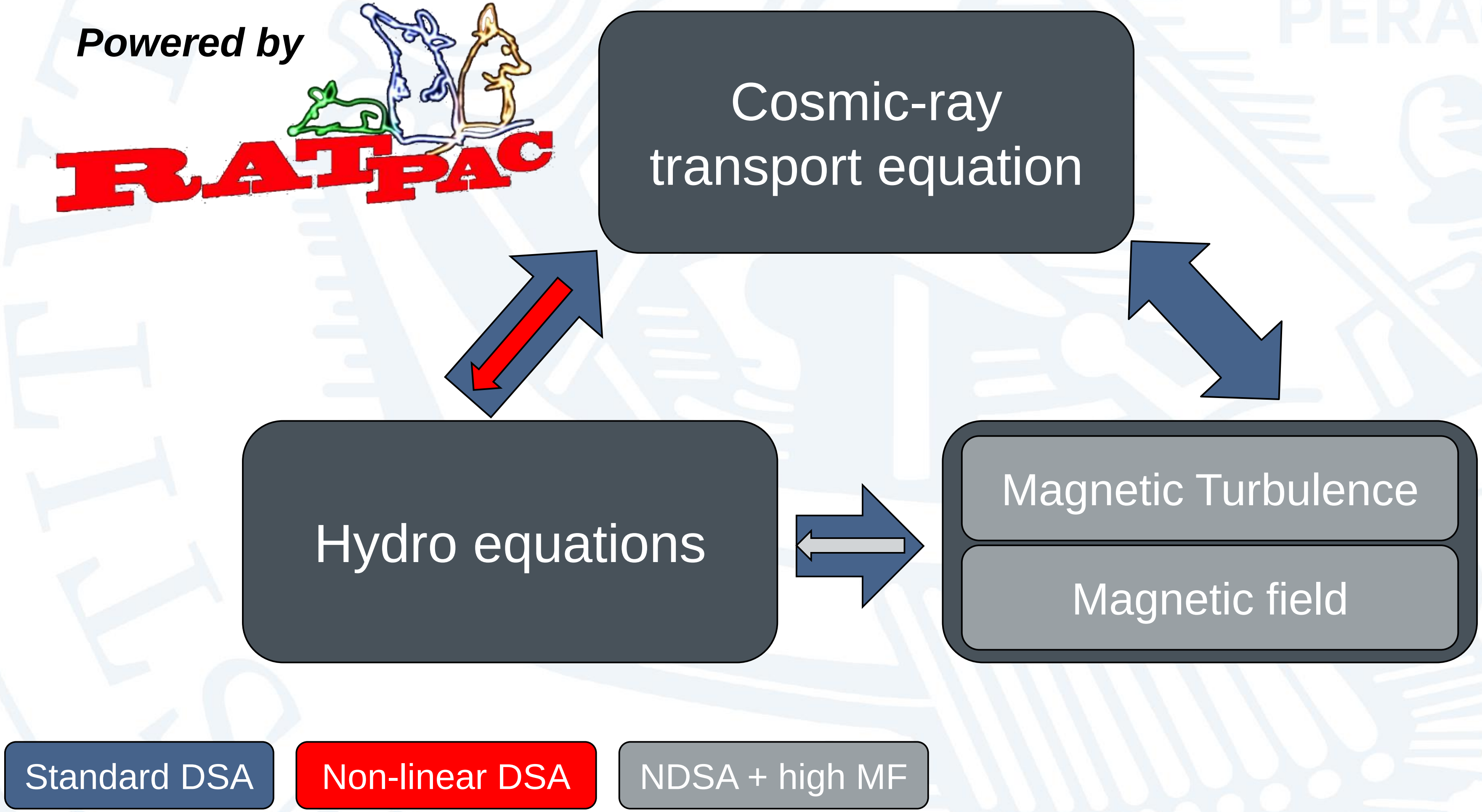
Figure: Light curve of the gamma-ray flux from SN 2004dj (Xi+2020)

Fermi acceleration

Coupled equations

Powered by

RATPaC



DIAS

Institiúid Ard-Léinn Bhaile Átha Cliath | Dublin Institute for Advanced Studies

Well-tested code in development since 2012

- 10+ papers
- 140+ citations

Other contributions using RATPaC:

[18] SNRs: CR escape and gamma-ray halo formation

[88] Spectral softening in CC-SNRs

Fermi acceleration

The equations

$$\frac{\partial N}{\partial t} = \underbrace{\nabla D_r \nabla N}_{\text{Diffusion}} - \underbrace{\nabla v N}_{\text{Advection}} - \frac{\partial}{\partial p}\left(\underbrace{N\dot{p}}_{\text{Cooling}} - \underbrace{\frac{v}{3}Np}_{\text{Acceleration}}\right) + \underbrace{Q}_{\text{Injection}}$$

$$\frac{\partial E_W}{\partial t} = -\underbrace{(v\nabla_r E_W + c\nabla_r v E_W)}_{\text{Advection + Compression}} + \underbrace{k^3\nabla_k D_k \nabla_k \frac{E_W}{k^3}}_{\text{Cascading}} + \underbrace{2(\Gamma_g - \Gamma_d)E_W}_{\text{Growth + Damping}}$$

$$\frac{\partial}{\partial t}\begin{pmatrix}\varrho\\ \boldsymbol{m}\\ E\end{pmatrix} + \nabla\begin{pmatrix}\varrho\boldsymbol{v}\\ \boldsymbol{mv}+(P)\boldsymbol{I}\\ (E+P)\boldsymbol{v}\end{pmatrix} = \begin{pmatrix}0\\ 0\\ L\end{pmatrix}$$

$$\frac{\rho v^2}{2} + \frac{P}{\gamma-1} = E$$

The equations are solved:

- One dimensional
- Assuming spherical symmetry
- Including Synchrotron and inverse-Compton cooling for electrons
- On a comoving, expanding grid for turbulence and CRs → no free escape boundary

Hydrodynamic Setup

SNe expanding into a steady wind medium

“Luminous Blue Variable (LBV)” model

- Dense and powerful wind from a massive star
- $\dot{M} = 10^{-2} M_{\odot}/yr$
- $v_{\infty} = 100\ km/s$

Red Supergiant (RSG) Model

- Slow dense wind from RSG progenitor, at upper end of mass range
- $\dot{M} = 8 \times 10^{-5} M_{\odot}/yr$
- $v_{\infty} = 15\ km/s$

- Model 1: fixed **5µG** magnetic field in the wind at all radii
- Model 2: ***1 G* at 1000 Rsun** stellar field with $B \propto r^{-1}$ at large r
- Both cases: Ejecta-distribution following Chevalier (1982) with:
  LBV: $E = 10^{51} erg,\ M_{ej} = 10 M_{\odot}$, density power-law index $n = 10$
  RSG: $E = 10^{51} erg,\ M_{ej} = 3 M_{\odot}$, density power-law index $n = 9$
- Initial ejecta-radius: $10^{14}\ cm$.

Results

Thermal X-ray emission

Model vs. measurement

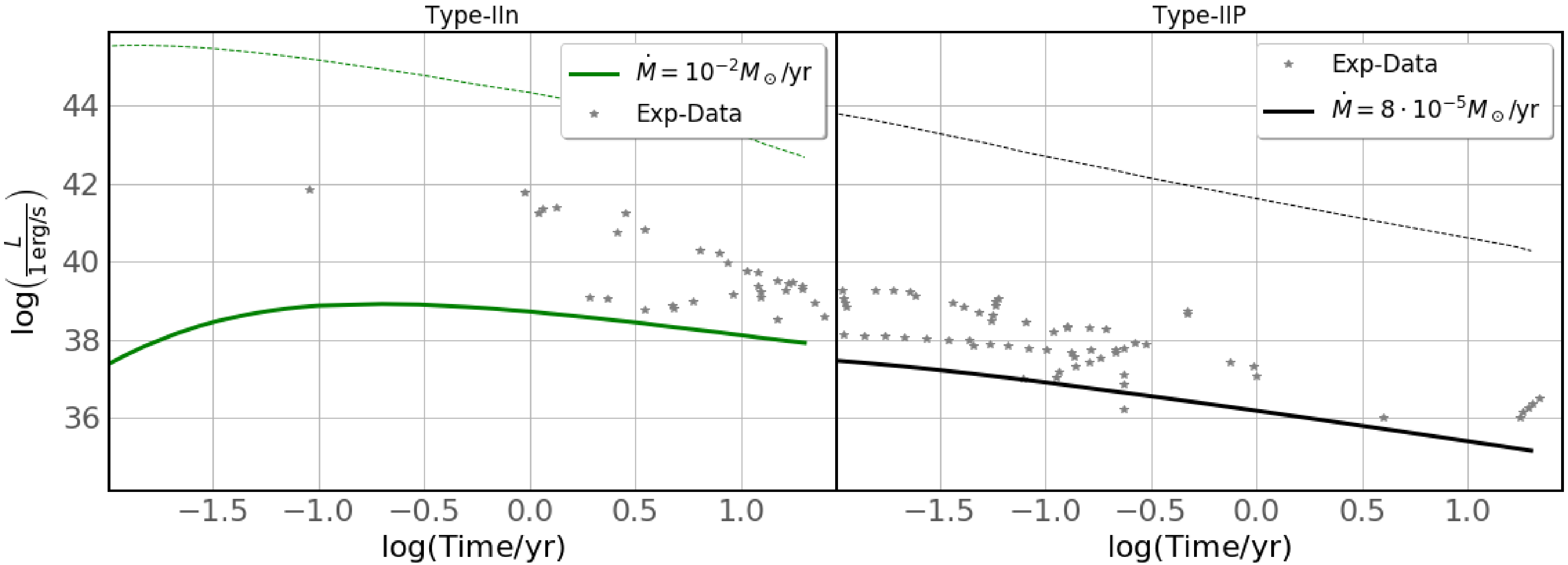


Figure: X-ray luminosity over time.

- Continuum X-ray emissivity in post-shock medium
- Unabsorbed X-ray luminosity far above observations
- Considering local absorption in stellar wind and shocked shell, obtain better agreement with observations (Dwarkadas 2014)
- Peak of lightcurve later in denser wind because of absorption

Non-thermal particle distribution

Time evolution of particle spectrum

- Fit momentum spectrum with power-law plus exponential cutoff → E_{max}
- **Acceleration time** is **~1 month** to get to quasi-steady state
- $E_{max} \approx 250$ TeV constant (and weak) upstream B-field
- $E_{max} \approx 700$ TeV for $B \propto r^{-1}$ ambient-field

No model assumption gives

$$\boldsymbol{E_{max} \geq 1PeV}$$

(stellar field is already quite strong)

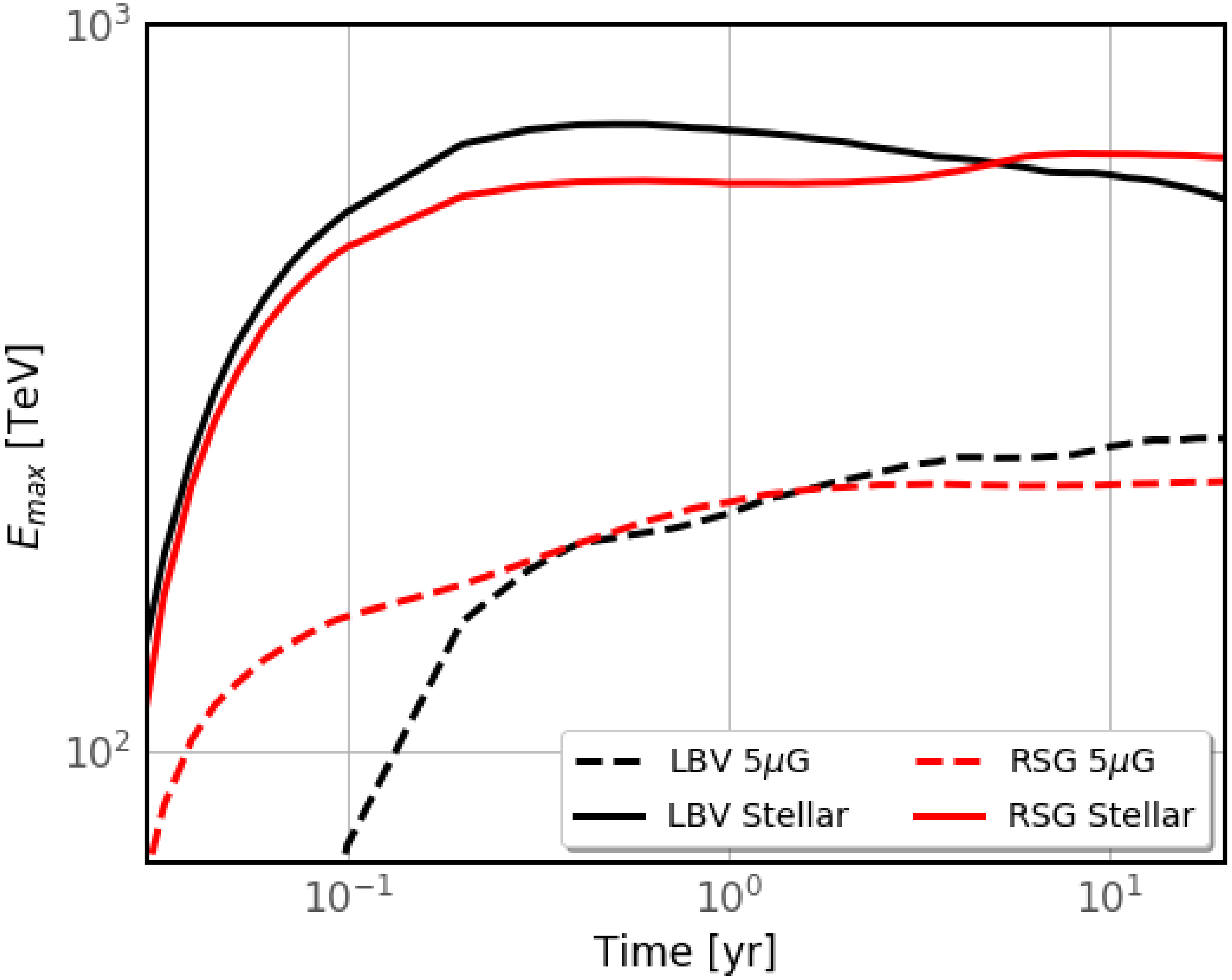


Figure: Maximum energy over time.

Non-thermal particle distribution

Time evolution of gamma-ray emission

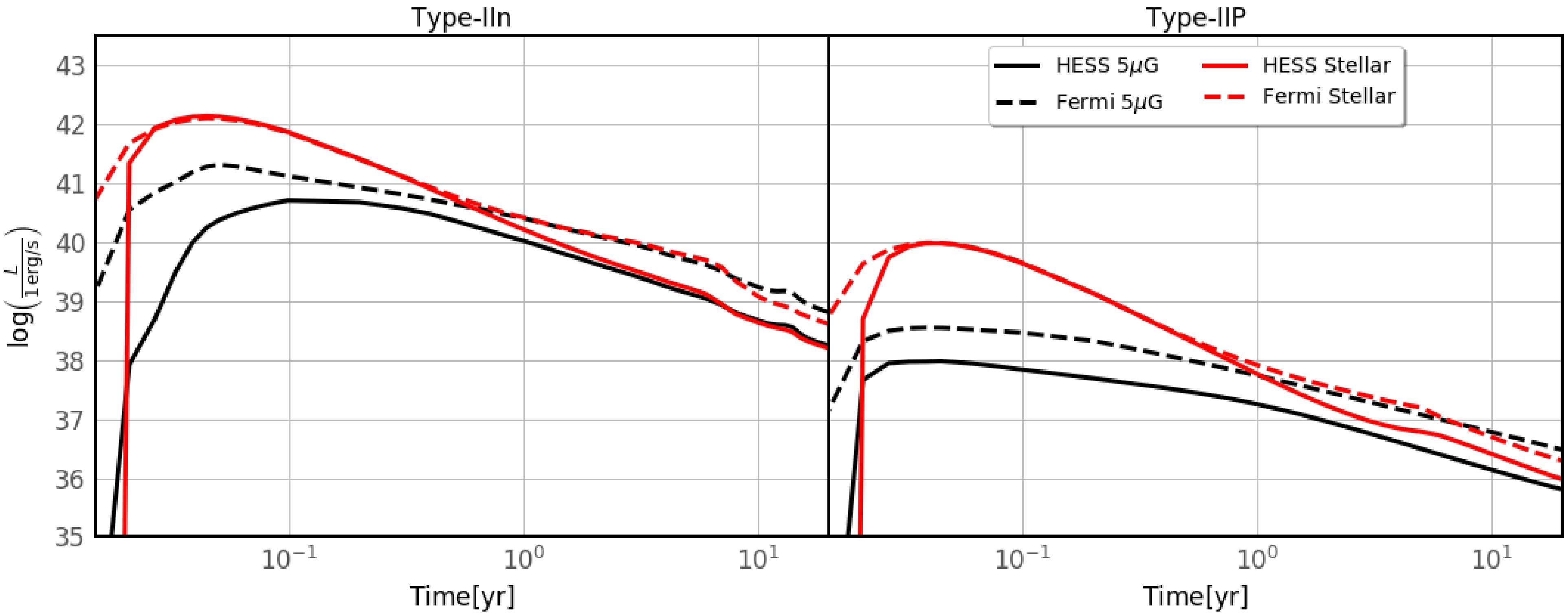


Figure: Gamma-ray luminosity over time.

- Gamma-ray luminosity in FERMI-LAT energy range rises fastest after explosion
- Type IIn approx. 100x more luminous then IIP.
- TeV emission peaks later than GeV emission, for a weak field
- **Gamma-gamma absorption not yet included!**

Non-thermal particle distribution

Detectability of gamma-ray emission

- Optimal detection prospects ≈ 1.5 weeks post explosion
- Type IIn detectable out to 10-30 Mpc
- Type IIP about 100x fainter → must be 10x closer for detection.
- **All cases have GeV emission fading strongly after a few months.**

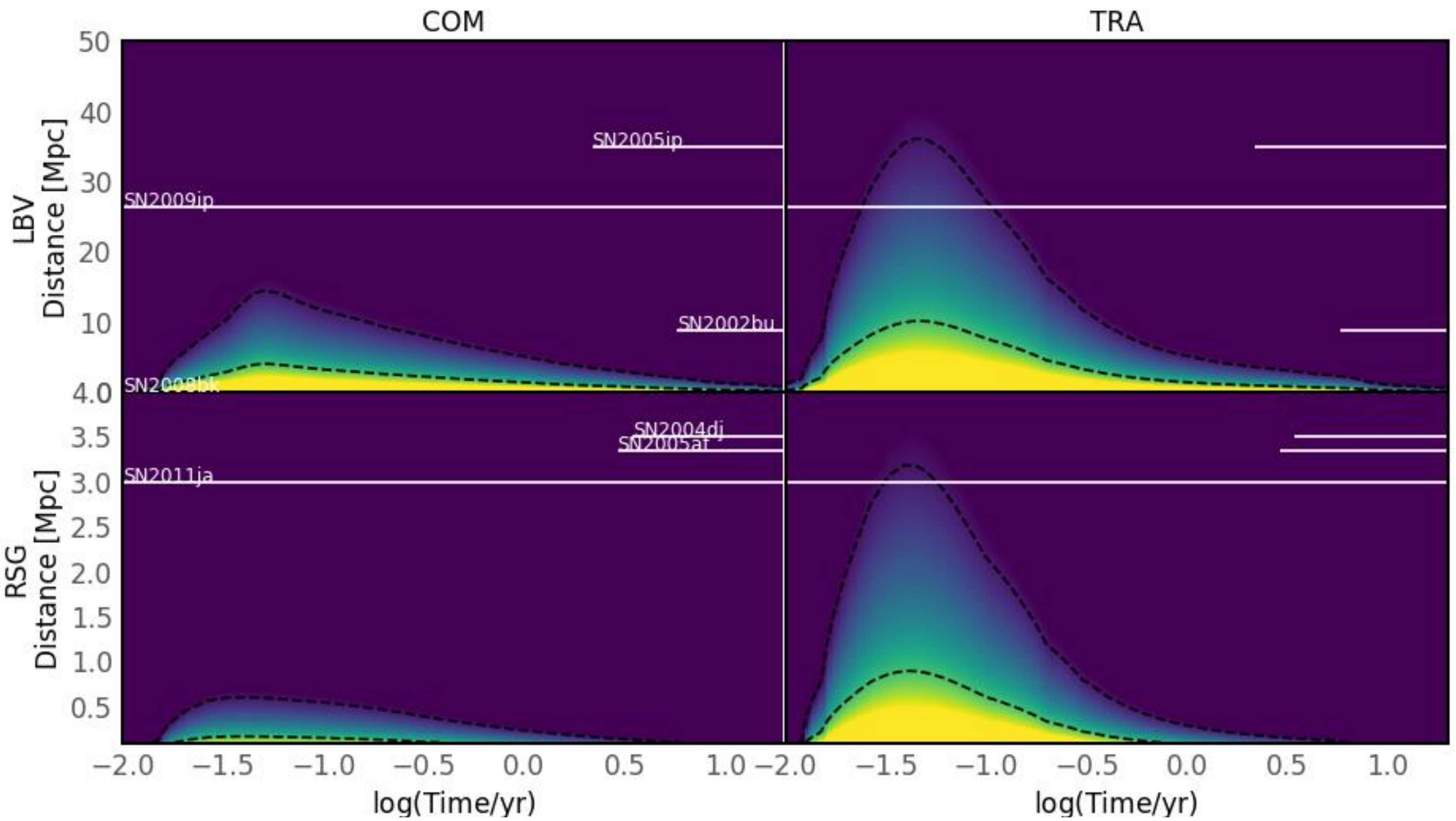
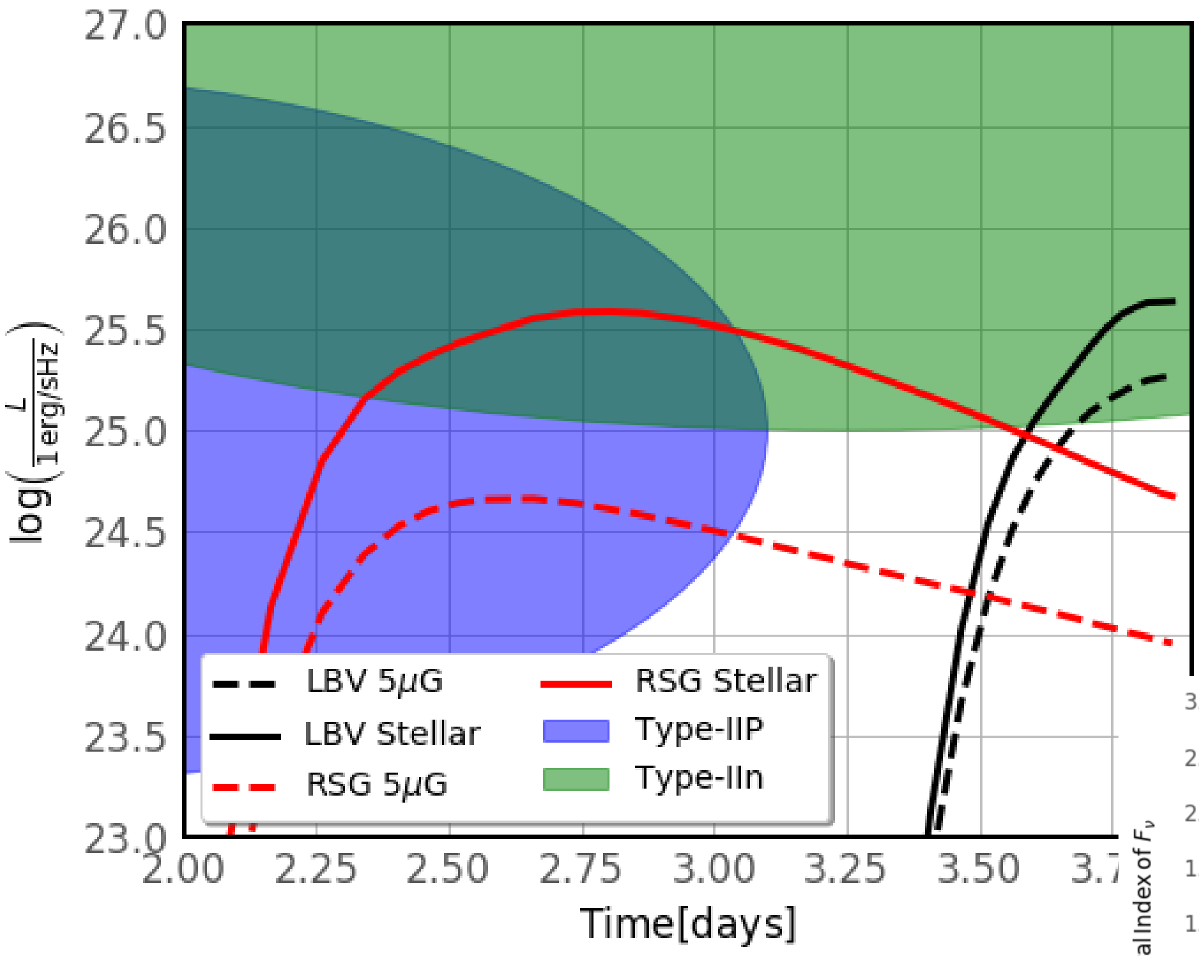


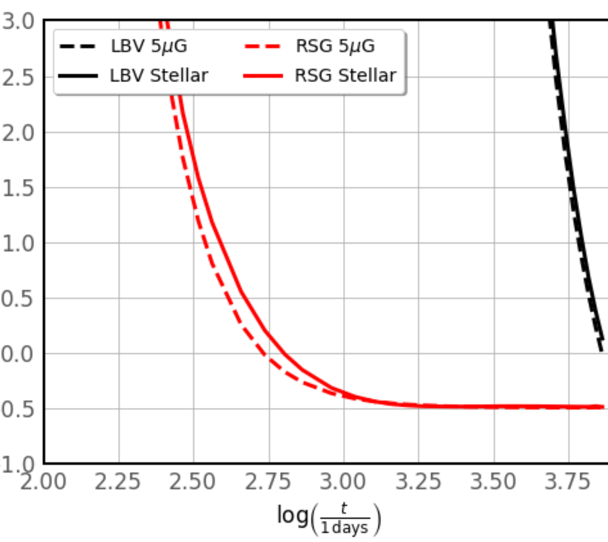
Figure: Lines: 8 sigma in 1 day and 1 month respectively. Color scale is flux depending on distance and time.

Non-thermal particle distribution

Radio emission

- Radio emission rise-times and peak-luminosities consistent with observations
- Injection-fraction based on historical remnants (e.g. SN1006) and magnetic field-amplification automatically produce the right radio-flux
- **No additional downstream-field generation needed.**





Figure(top): Radio luminosity at 8GHz.
Figure(right): Radio spectral-index 8GHz.

Non-thermal particle distribution

Interaction with inhomogeneous media: LBV

- Adding a **$1M_\odot$ shell** to the background wind of the LBV **at 6×10^{15}cm / 0.002pc**

- Gamma-ray luminosity increases by about 10x after the shell collision (for shell with 10x higher density ratio)

- TeV luminosity peaks shortly after GeV and then declines.

- Accompanying signatures in X-ray, Radio and other wavebands? **Trigger criteria for IACTs are needed!**

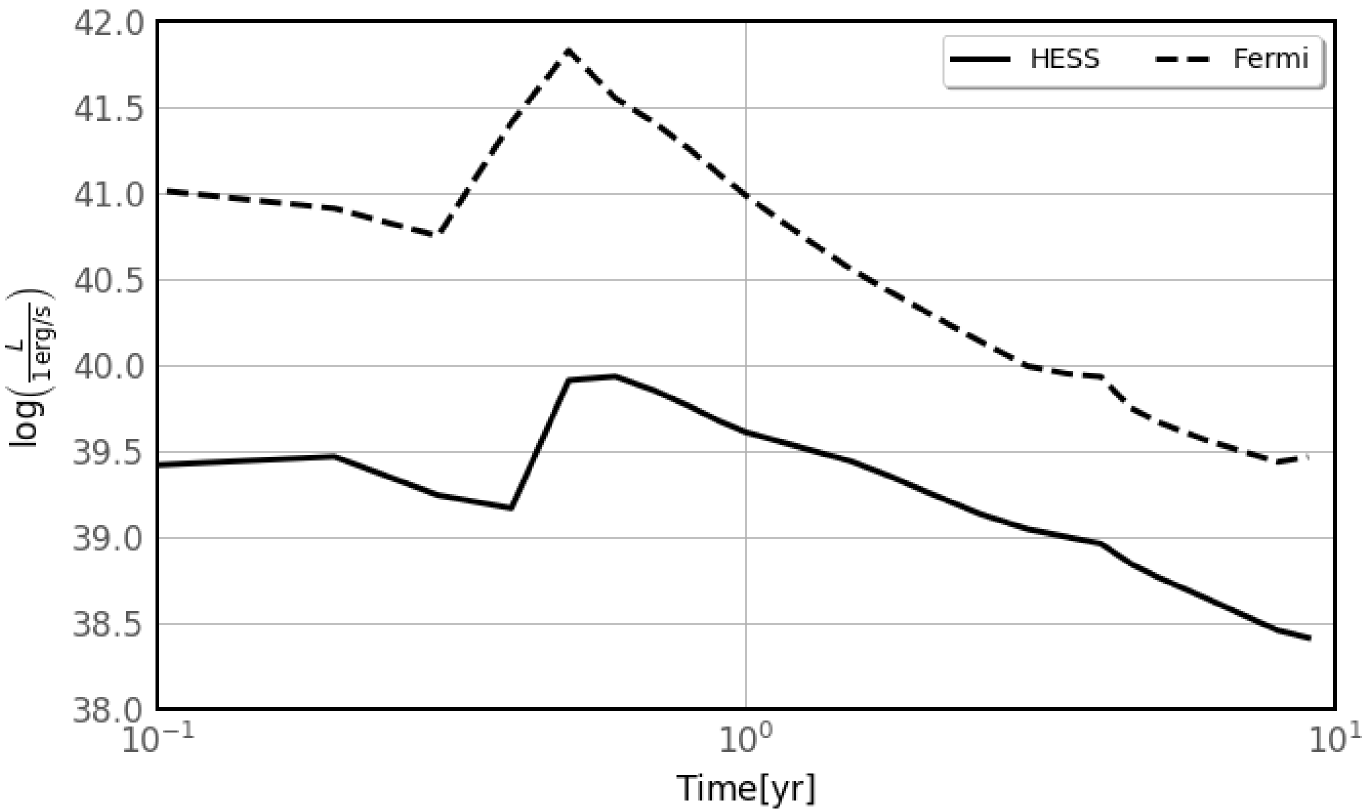


Figure: Gamma-ray luminosity over time for a LBV interacting with a $1M_{sol}$ shell.

Conclusions and future work

- 1D time-dependent modelling of hydrodynamics, particle acceleration, magnetic-turbulence and high-energy radiation, from SN expanding into LBV and RSG winds

- Verify that thermal X-ray emission consistent with observations of Type-IIn/IIP SN
- Maximum particle energy of $E_{max} \leq 700$ TeV from 0.1-10 year timescales
  → **Unlikely to be PeVatrons**
- GeV emission peaks on days to week timescales
- TeV on week to month timescale
- LBV progenitors about 100x more luminous in thermal X-rays and GeV/TeV gamma-rays.

- **Circumstellar shells can produce late-time re-brightening** at GeV and TeV.
- A few SN could be detectable with FERMI-LAT over its mission lifetime

Thank you for your attention!