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Core-collapse supernovae in dense environments

Particle acceleration and non-thermal emission

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TeVPa, 8-12 August 2022



Galactic cosmic-rays

Possible sources

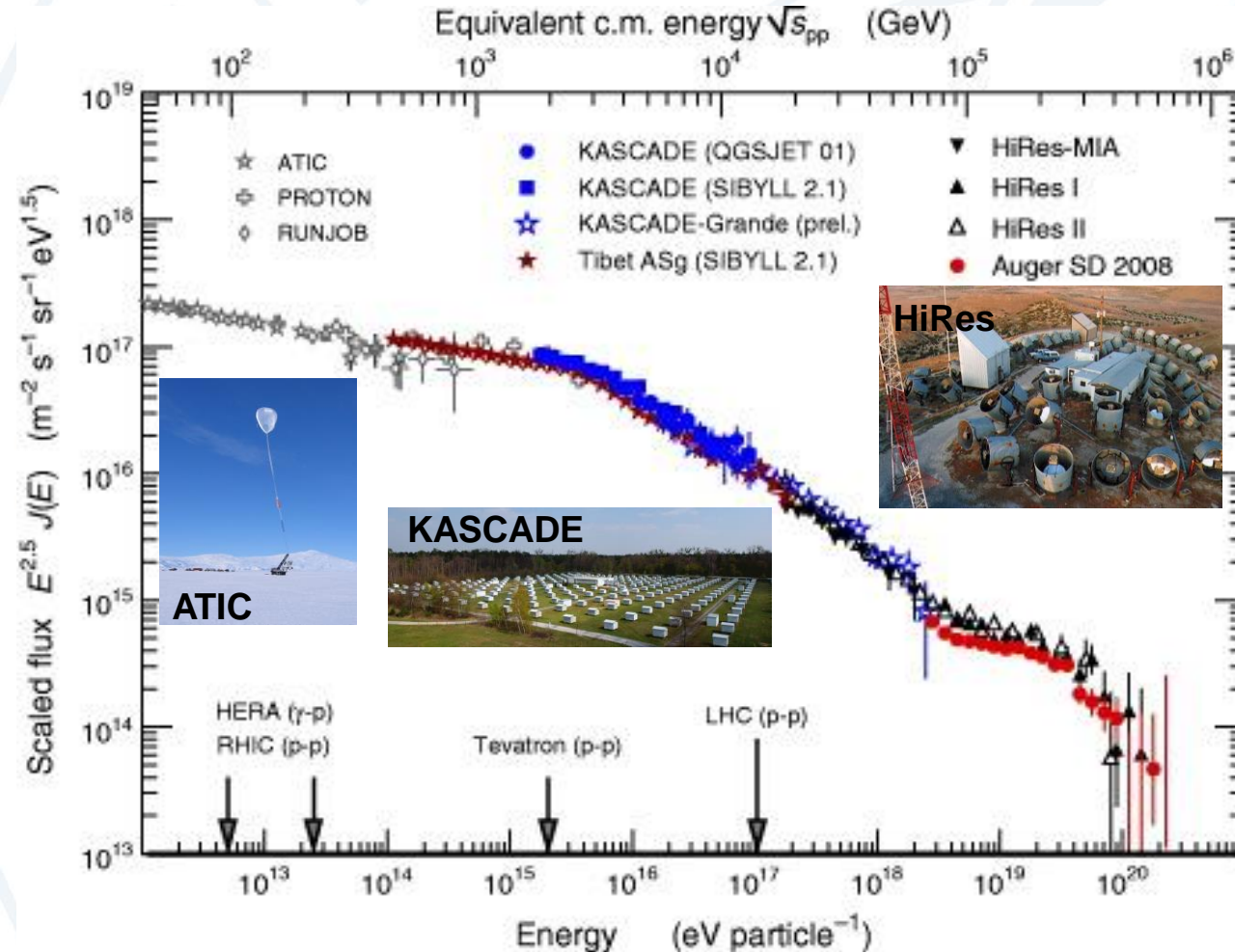


Figure: The cosmic ray spectrum (Blümer et al. 2019)

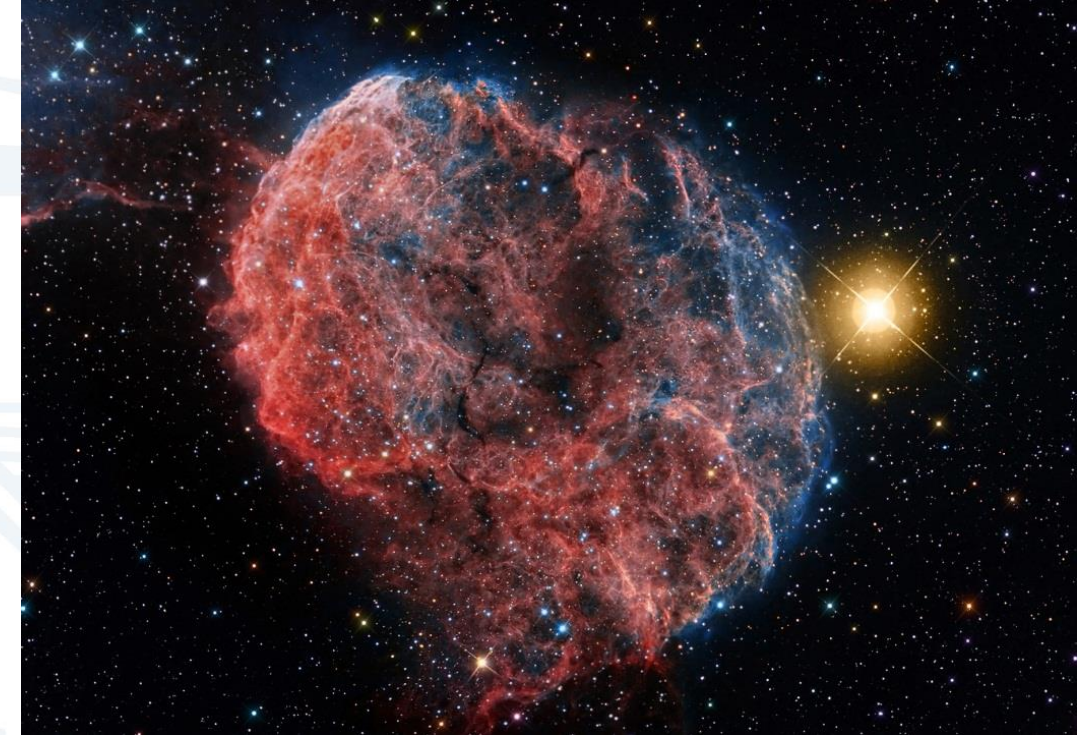


Figure: IC443 – multi wavelength image (credit: Dieter Willasch)

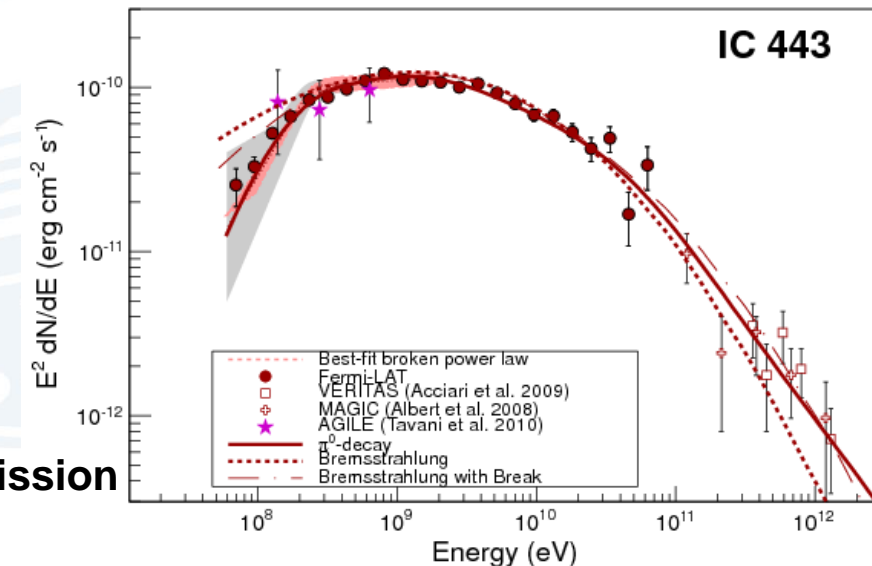


Figure: IC443 – gamma ray emission (Funk et al. 2013)

Galactic cosmic-rays

Possible sources

Figure: Cas A, (credit: Chandra, NASA/CXC/SAO)

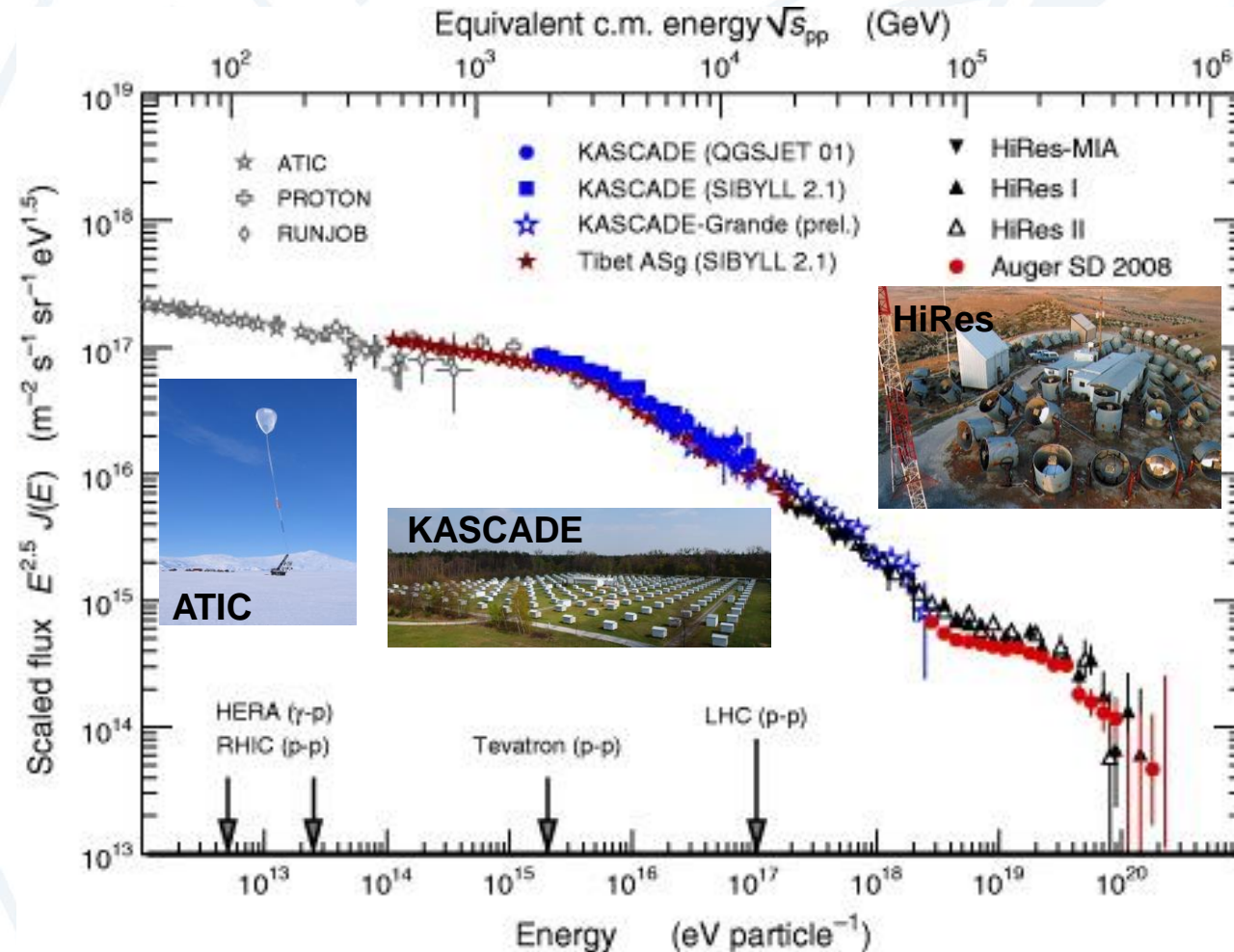


Figure: The cosmic ray spectrum (Blümer et al. 2019)



Figure: SN1994D (credit: Hubble, NASA/ESA)

SNRs as cosmic-ray sources

Experimental evidence

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

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Radio Lightcurves for All SNe with Known Types

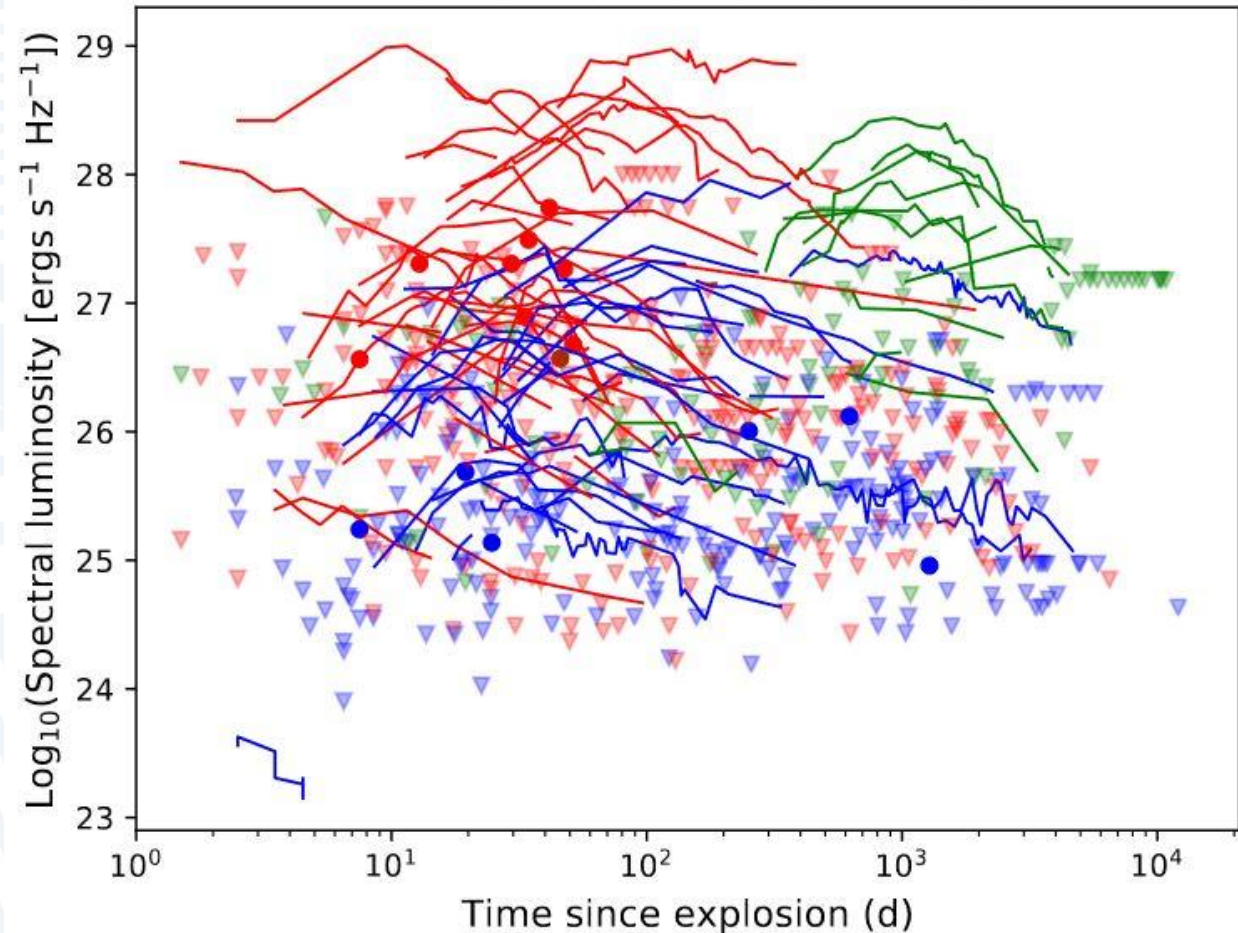


Figure: Early-time Radio emission from SNs of various types (Bietenholz et al.2021)

SNRs as cosmic-ray sources

Experimental evidence

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- 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)

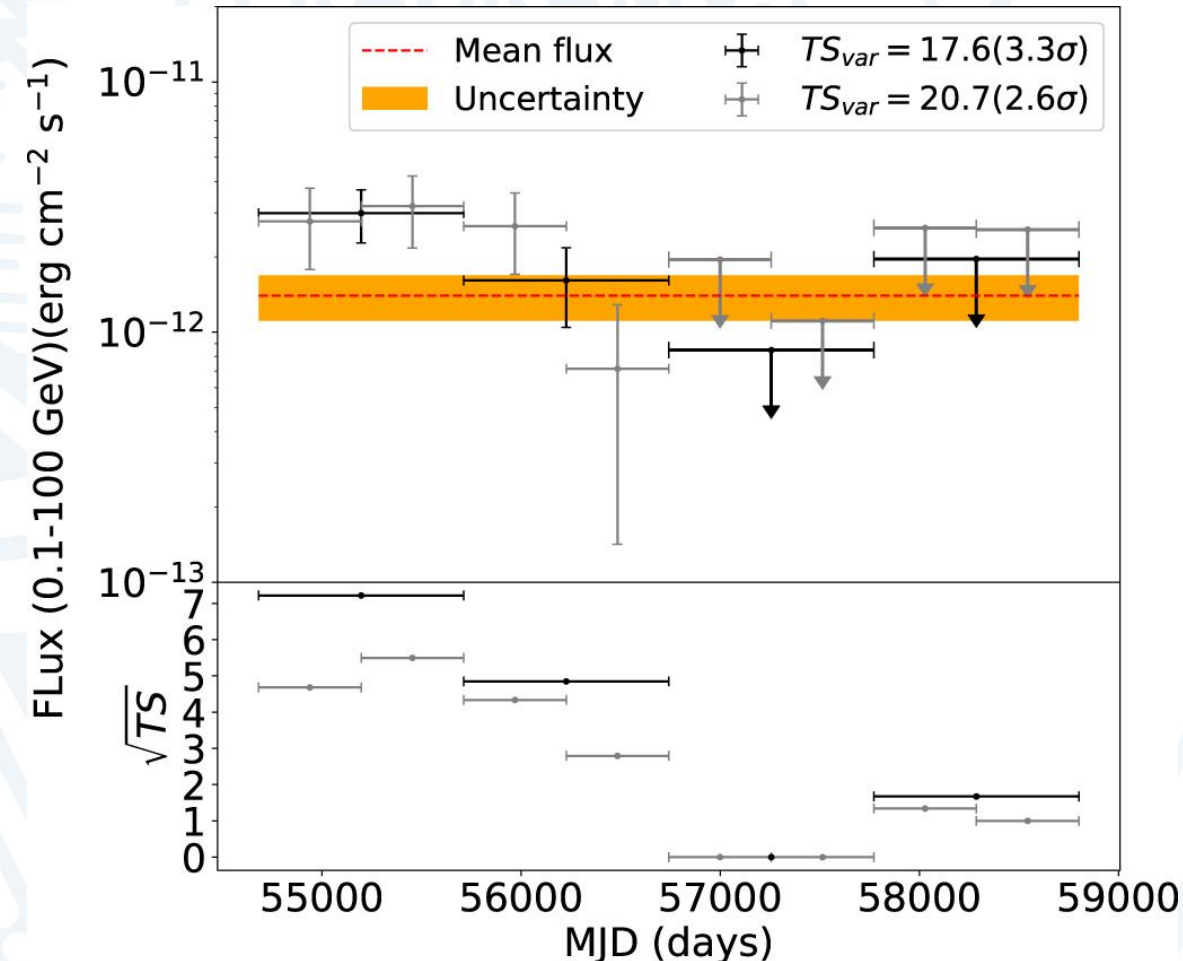


Figure: Light curve of the gamma-ray flux from SN 2004dj (Xi et al. 2020)

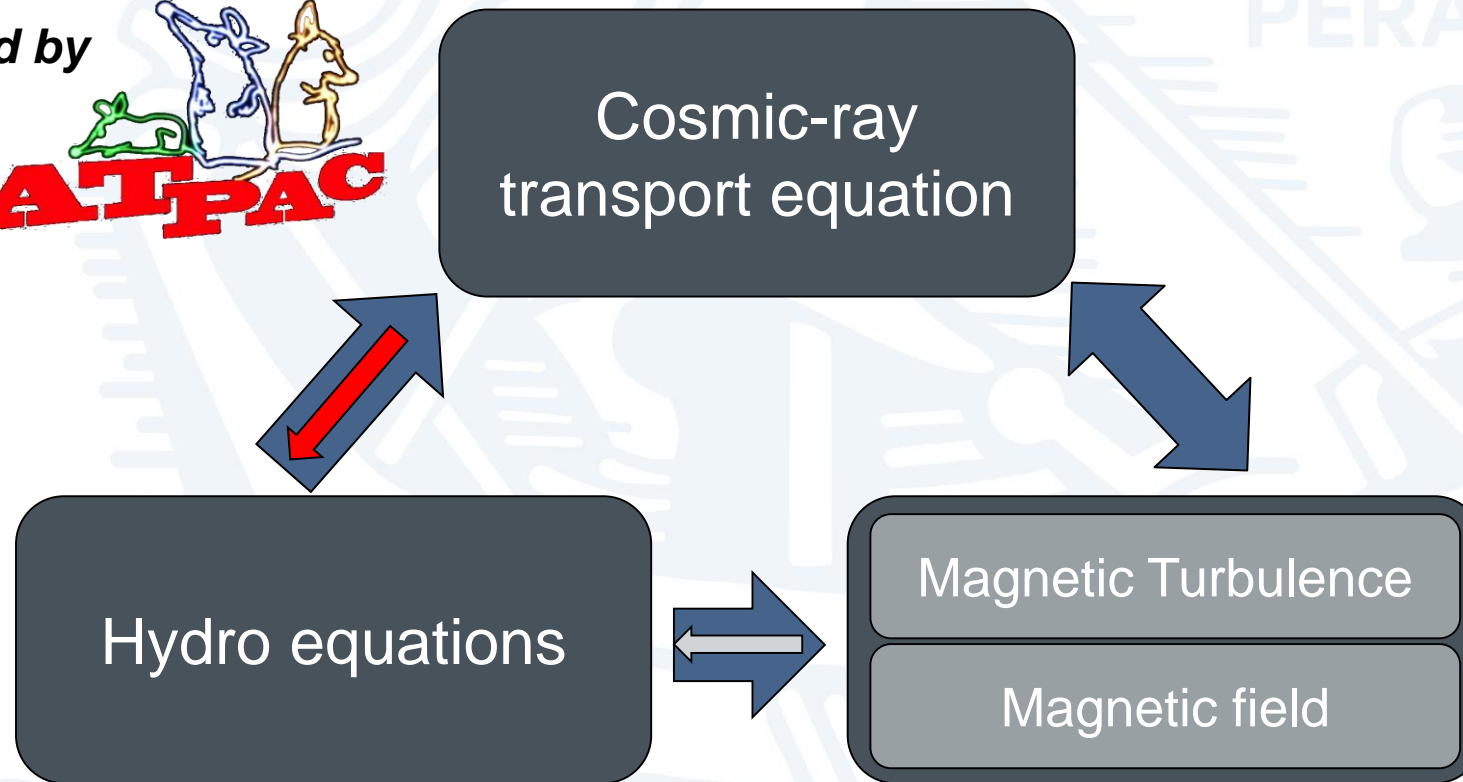
Fermi acceleration

Coupled equations

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Well-tested code in development since 2012

- 10+ papers
- 140+ citations

Standard DSA

Non-linear DSA

NDSA + high MF



Fermi acceleration

The equations

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

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

$$\frac{\partial}{\partial t} \begin{pmatrix} \rho \\ \mathbf{m} \\ E \end{pmatrix} + \nabla \begin{pmatrix} \rho \mathbf{v} \\ \mathbf{m} \mathbf{v} + (P) \mathbf{I} \\ (E + P) \mathbf{v} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ L \end{pmatrix} \quad \frac{\rho v^2}{2} + \frac{P}{\gamma-1} = E$$

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

Fermi acceleration

Turbulence setup

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Initial turbulence derived from 1/10th
of the Galactic diffusion coefficient

$$\rightarrow D_r(t = 0) = 10^{28} \left(\frac{pc}{10 GeV} \right)^{1/3} \left(\frac{B_0}{3 \mu G} \right)^{-1/3} cm^2/s$$

Growth rate based on pressure
gradient of CRs (resonant CR-
instability x10)

$$\rightarrow \Gamma_r = 10 \frac{v_A p^2 v}{3 E_W} \left| \frac{\partial N}{\partial r} \right|$$

Damping as diffusion in
wavenumber space

$$\rightarrow D_k = k^3 v_A \sqrt{\frac{E_W}{2 B_0^2}}$$



Hydrodynamic Setup

SNe expanding into a steady wind medium

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“Luminous Blue Variable (LBV)” model

- Dense and powerful wind from a massive star
- $\dot{M} = 10^{-2} M_{\odot}/yr$
- $v_{\infty} = 100 \text{ km/s}$
- Model 1: fixed **5 μ G** magnetic field in the wind at all radii
- Model 2: **1 G at 1000 R_{sun}** stellar field with $B \propto r^{-1}$ at large r
- Both cases: Ejecta-distribution following Chevalier (1982) with:
LBV: $E = 10^{51} \text{ erg}$, $M_{ej} = 10 M_{\odot}$, density power-law index $n = 10$
RSG: $E = 10^{51} \text{ erg}$, $M_{ej} = 3 M_{\odot}$, density power-law index $n = 9$
- Initial ejecta-radius: 10^{14} cm .

Red Supergiant (RSG) Model

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

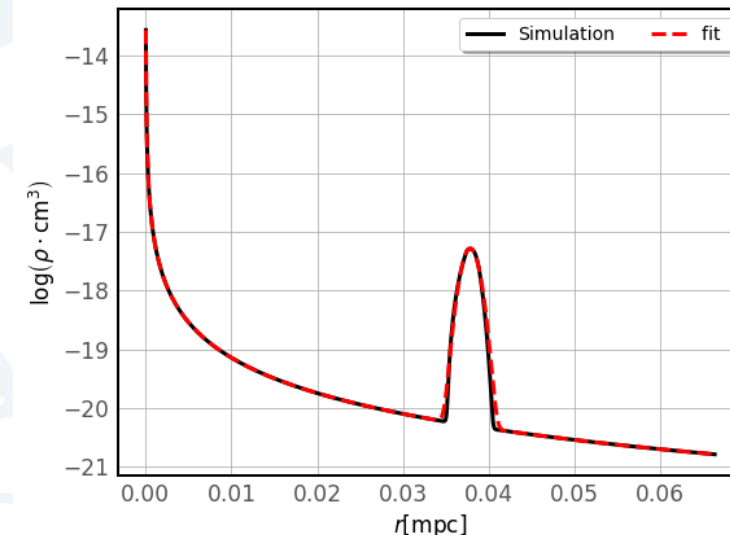


Figure: CSM-structure for a LBV (example plot)

Results

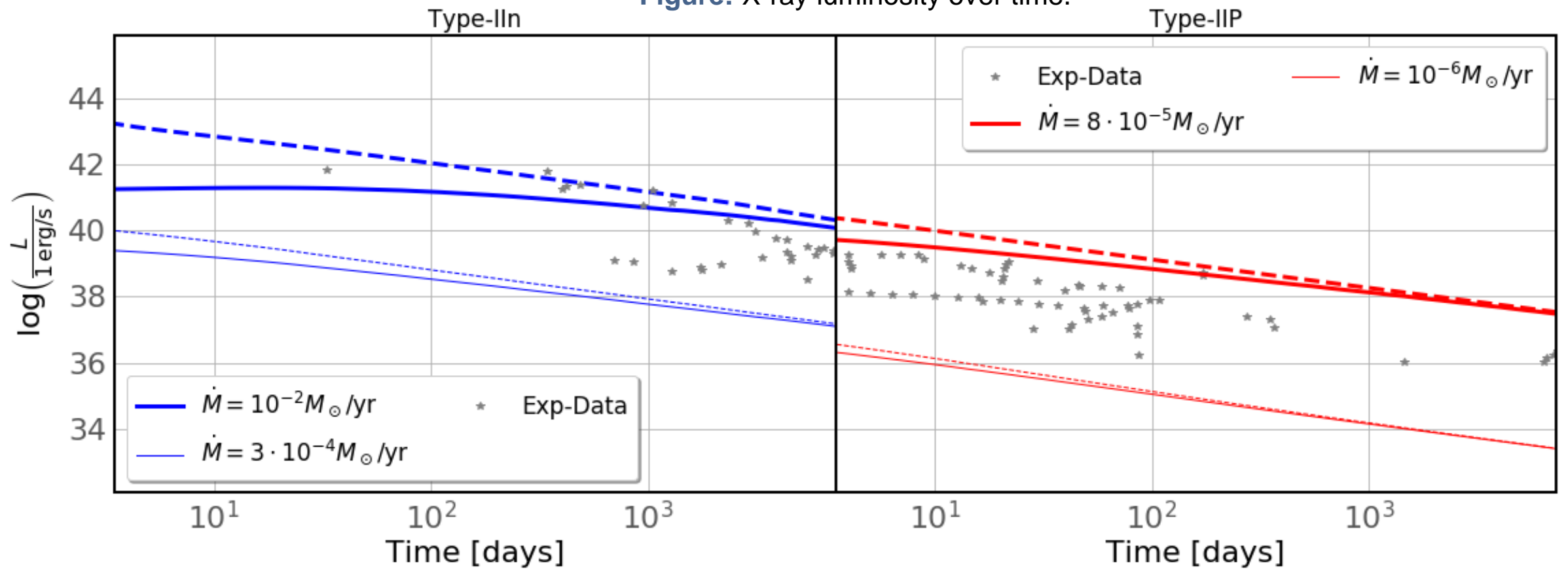
Smooth media

Thermal X-ray emission

Model vs. measurement

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Figure: X-ray luminosity over time.



- Continuum X-ray emission from post-shock medium
- X-ray absorption by traces of heavy elements → only relevant for very-high mass-loss rates



Non-thermal particle distribution

Time evolution of the maximum energy

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- Fit spectrum with power-law plus exponential cutoff $\rightarrow E_{\max}$
- **Acceleration time** is **~ 1 month** to get to quasi-steady state
- $E_{\max} \approx 600$ TeV for LBV (high \dot{M} , $B \propto r^{-1}$)
- $E_{\max} \approx 250$ TeV ($B=\text{constant}$)
- $E_{\max} \approx 70$ TeV for RSG (low \dot{M} , $B \propto r^{-1}$)

No model assumption gives

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

(stellar field is already quite strong)

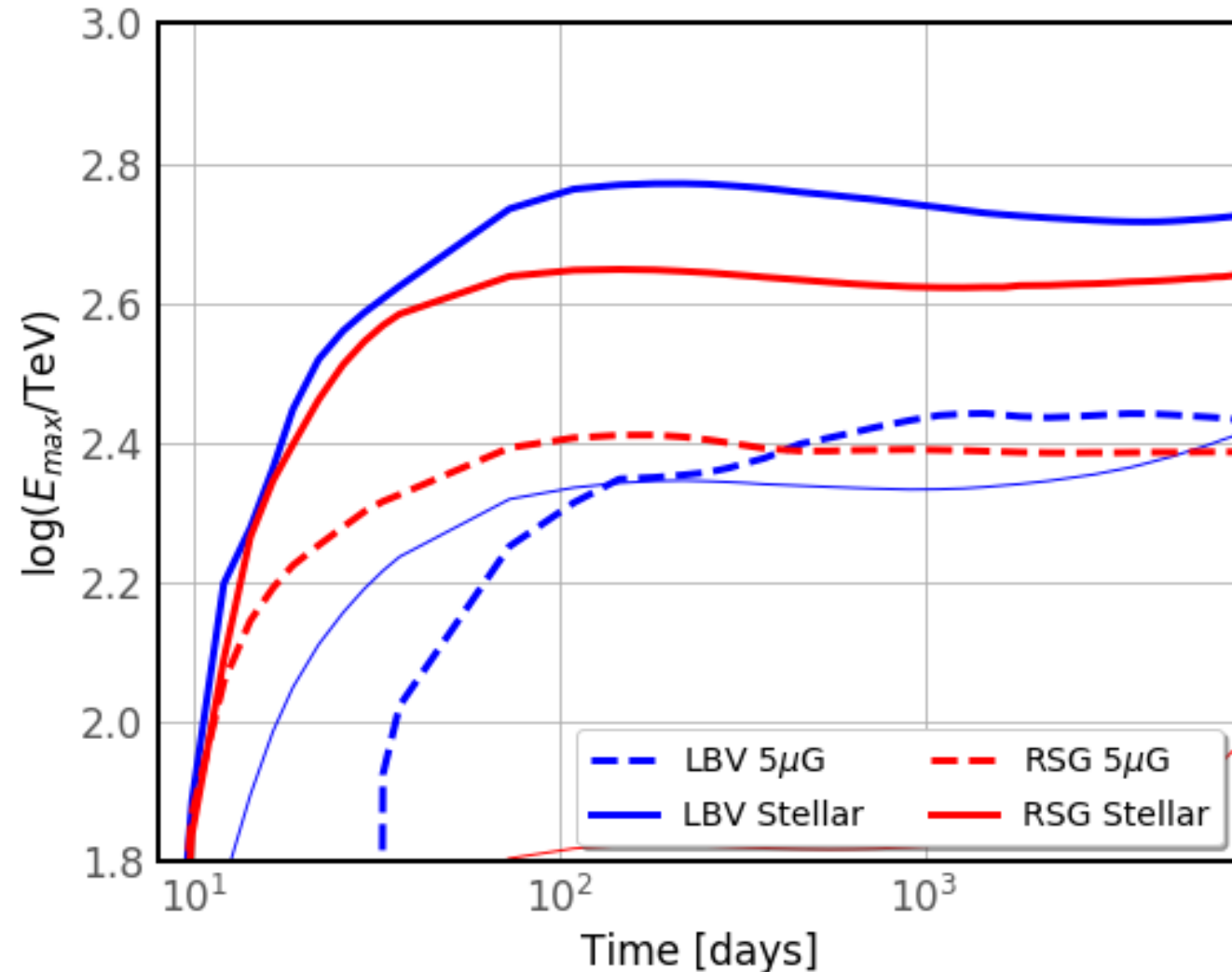


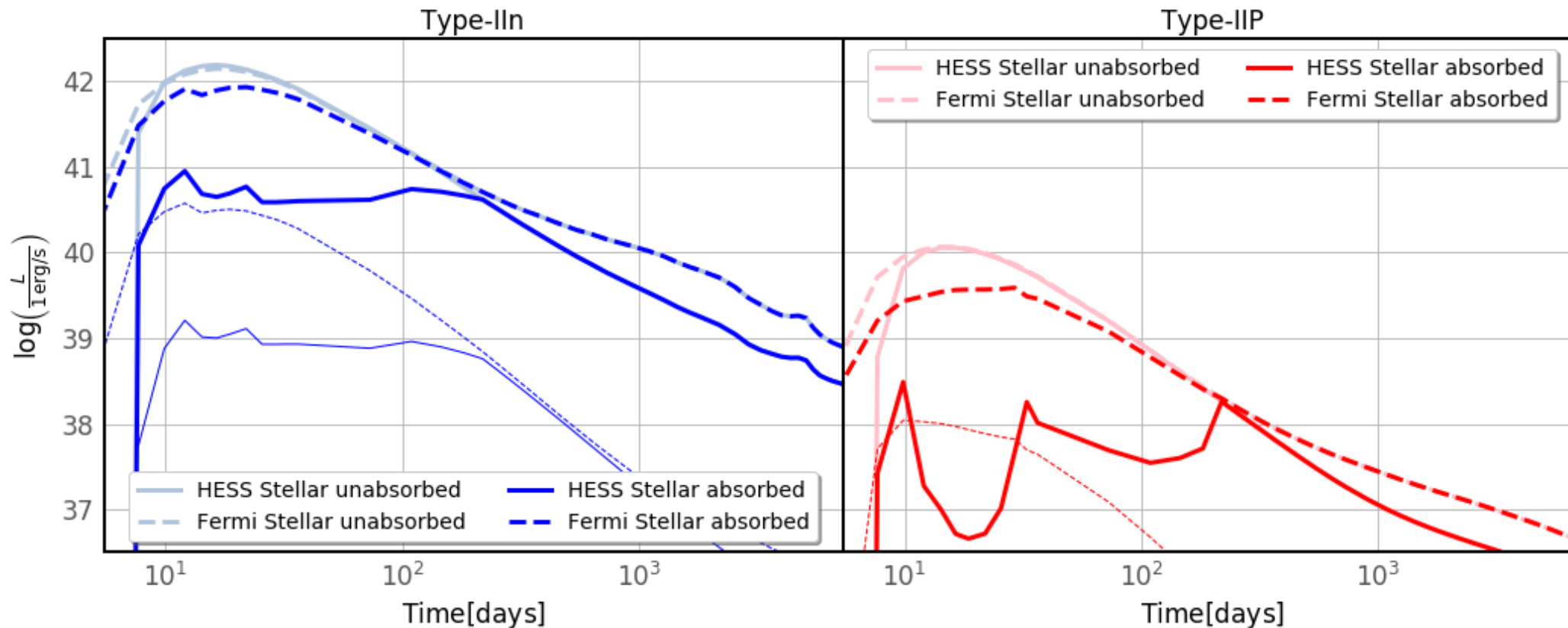
Figure: Maximum energy over time.

Gamma-ray emission

Time evolution of gamma-ray emission

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Figure: Gamma-ray luminosity over time.



- Type IIa approx. 100x more luminous than IIP
- Strong attenuation in the TeV-range
- **Fluxes well below experimental upper-limits**



Gamma-ray emission

Detectability: Survey-mode

Fermi-LAT:

- best prospects in first 100days
- RSG: up to ~50kpc
- LBV: up to ~600kpc

VHE-range:

- Best prospects after photosphere starts to retract
- RSG: up to ~40kpc
- LBV: up to ~1.5Mpc

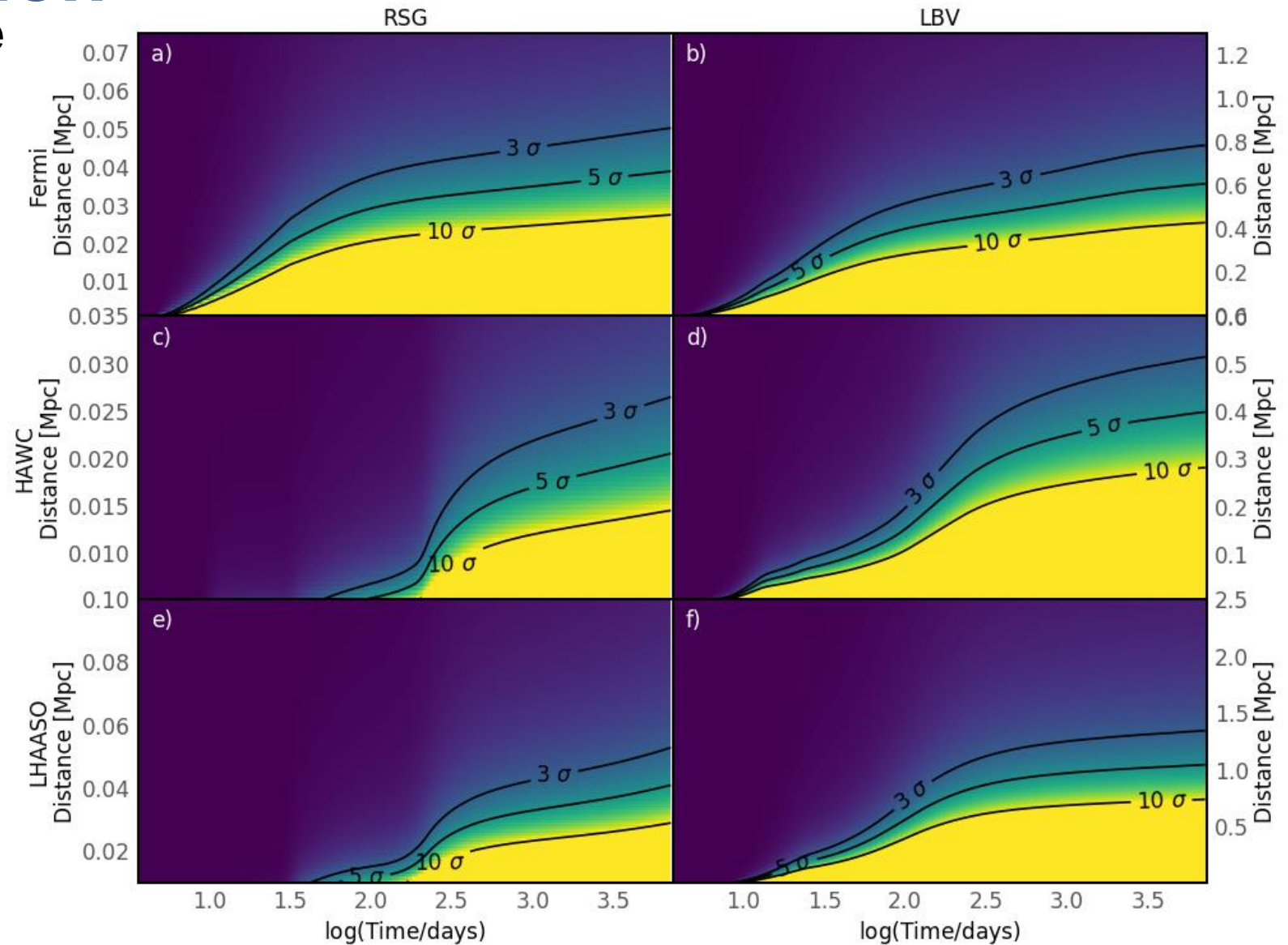


Figure: Culminated significance for survey-like instruments

Non-thermal particle distribution

Detectability of gamma-ray emission

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LBV:

- Flat VHE light curve for ~300 days
- detectable up to ~3Mpc

RSG:

- Multiple-peaked light-curve
- detectable up to ~200kpc

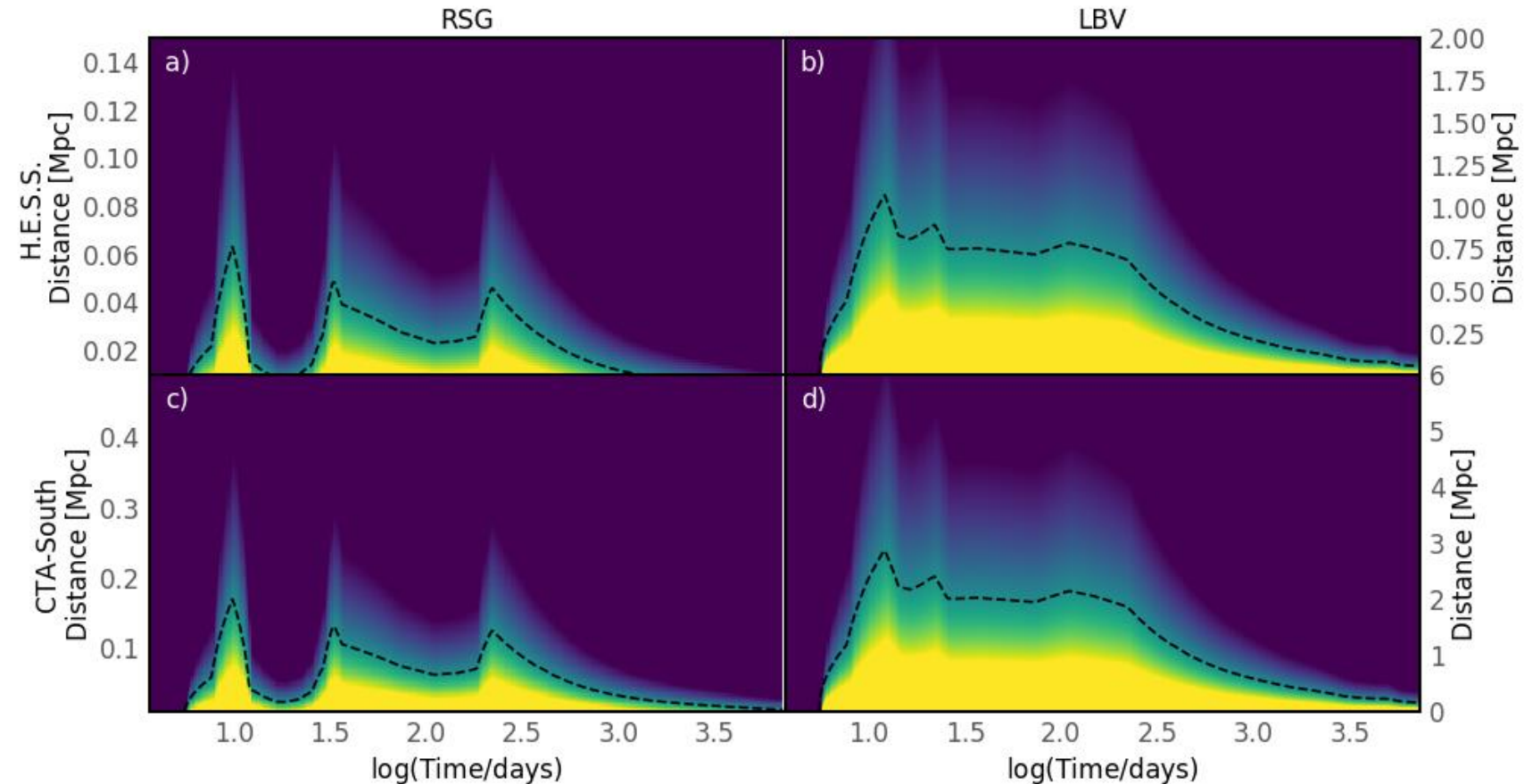


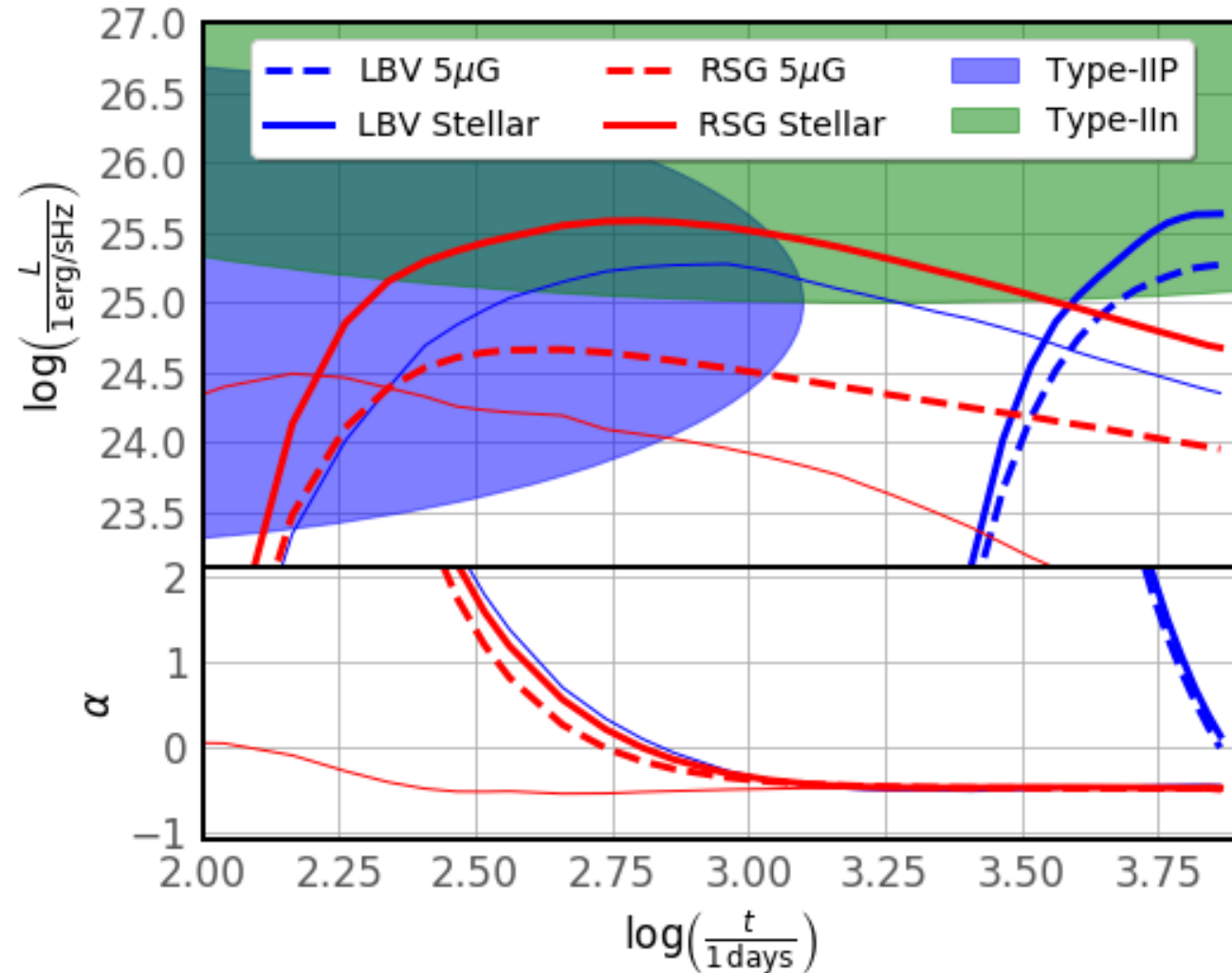
Figure: Gamma-ray flux of Sne relative to instrument-specific detection-threshold for 50hrs of observation

Non-thermal particle distribution

Radio emission

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- 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
- Strong spectral-index evolution due to free-free absorption



Figure(top):

Figure(right):

Radio luminosity at 8GHz.

Radio spectral-index 8GHz.

Results

Smooth media + CSM-shell

Non-thermal particle distribution

Interaction with inhomogeneous media: LBV

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- Adding a (gaussian) CSM-shell with:

$$M_{\text{shell}} = 2M_{\odot}$$

$$R_{\text{shell}} \approx 30\text{mpc}$$

$$D_{\text{shell}} \approx 1\text{mpc}$$

- Modest steady mass-loss with:

$$\dot{M} = 10^{-4}M_{\odot}/\text{yr}$$

- Shock-shell interaction after $\approx 100\text{days}$
- Interaction triggers reflected shocks – shock-shock interactions after:
 $\approx 124\text{days} + \approx 2.8\text{yrs}$

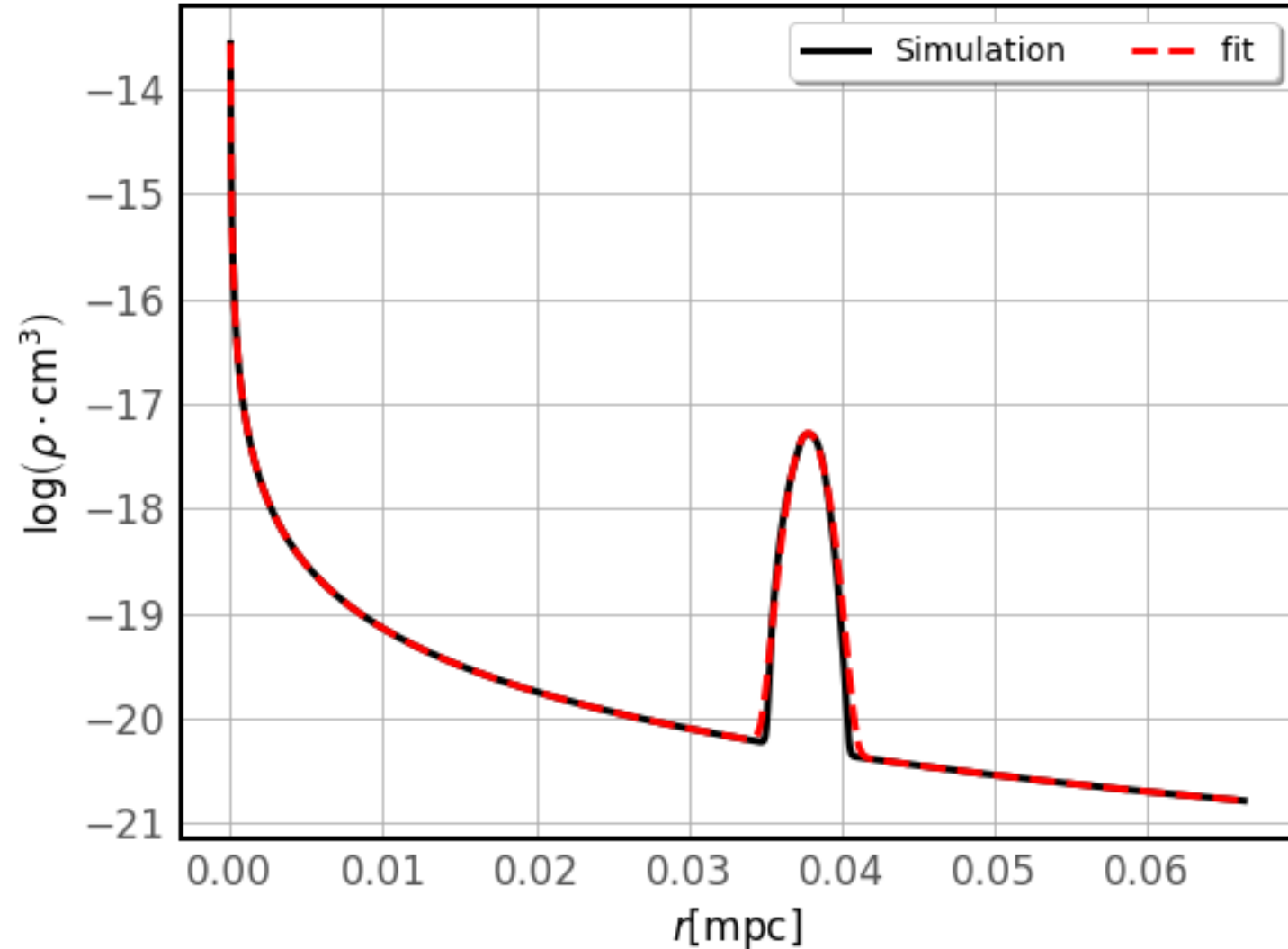


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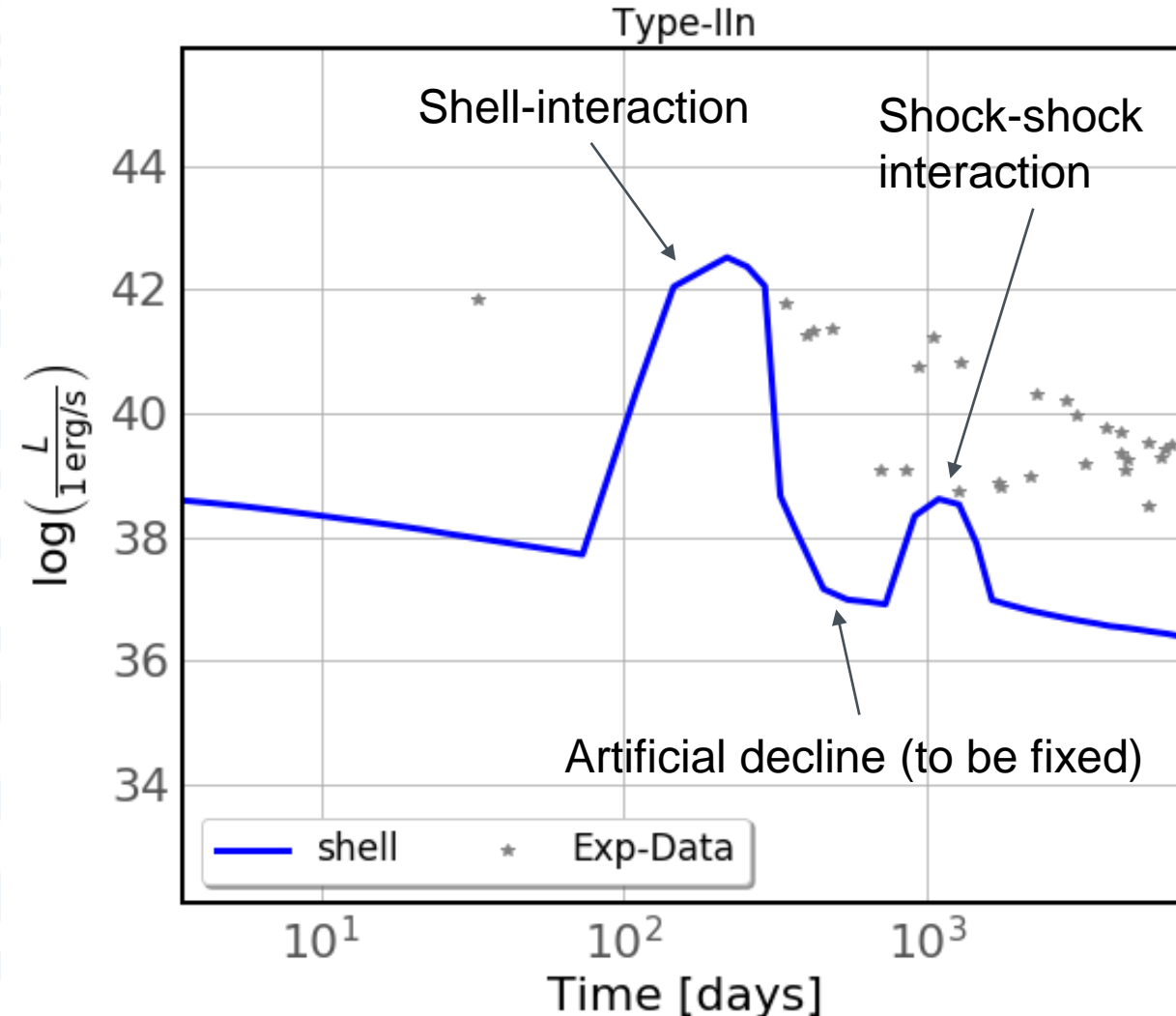
Thermal X-ray emission

Model vs. measurement

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Figure: X-ray luminosity over time.

- Same procedure as for free-wind-only case: Complicated situation during shock-shell interaction \rightarrow recipe needs to be revised
- Peak-luminosity consistent with observational values
- Shock-shock interaction might cause additional rebrightening-features (see also [Sushch et al. 2022](#))



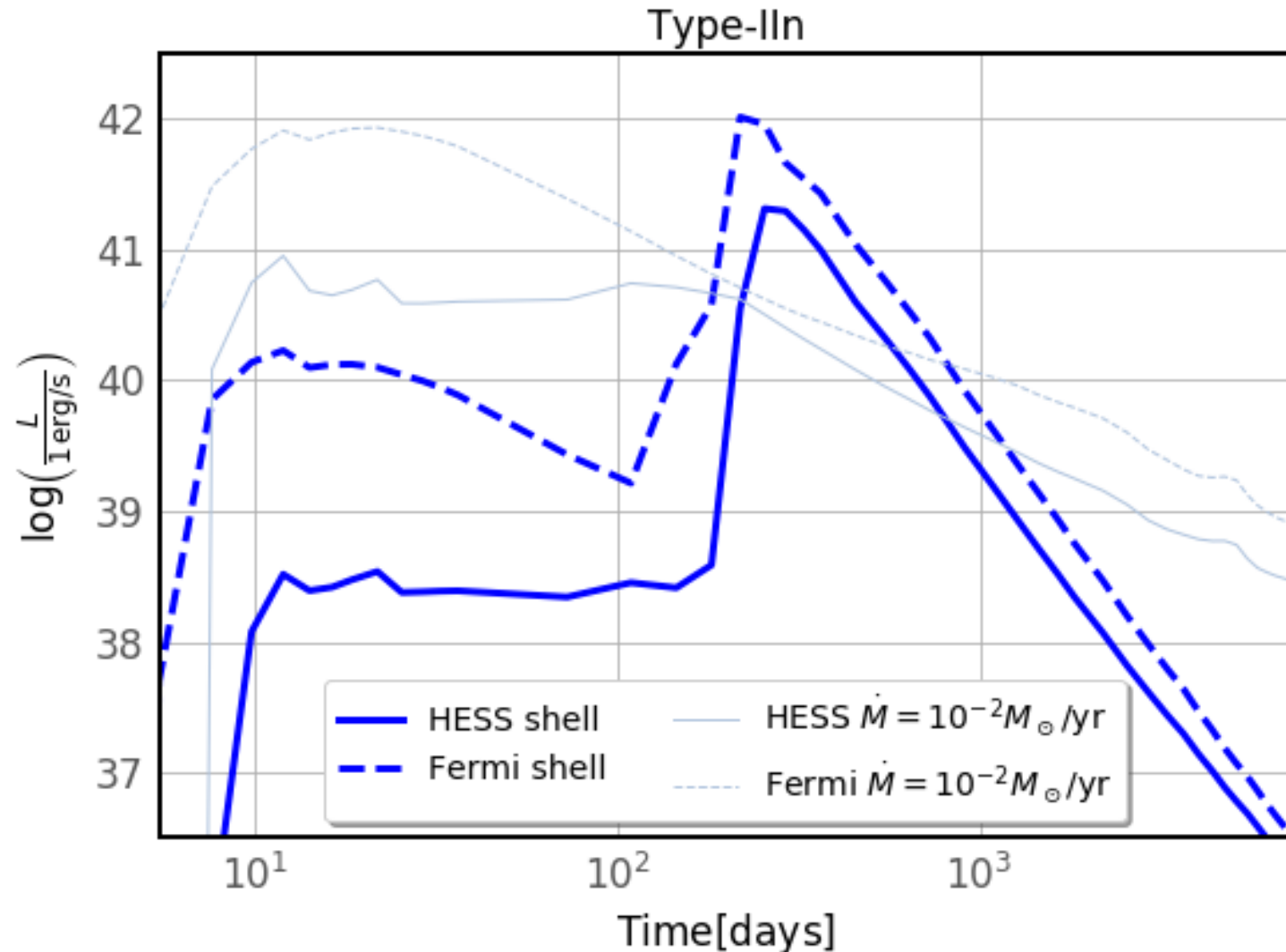
Non-thermal particle distribution

Time evolution of gamma-ray emission

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- Peak-luminosity in HE gamma-rays similar to steady-mass-loss case; reached after ~ 220 days
- Peak-luminosity in VHE gamma-rays 5-10x above steady-mass-loss case \rightarrow **Lack of absorption;** reached after ~ 260 days
- Fast-rising luminosities but ~ 40 days shift between HE and VHE peaks
- Very-fast ($\propto t^{-4}$) decline after shock-shell interaction

Figure: Gamma-ray luminosity over time.

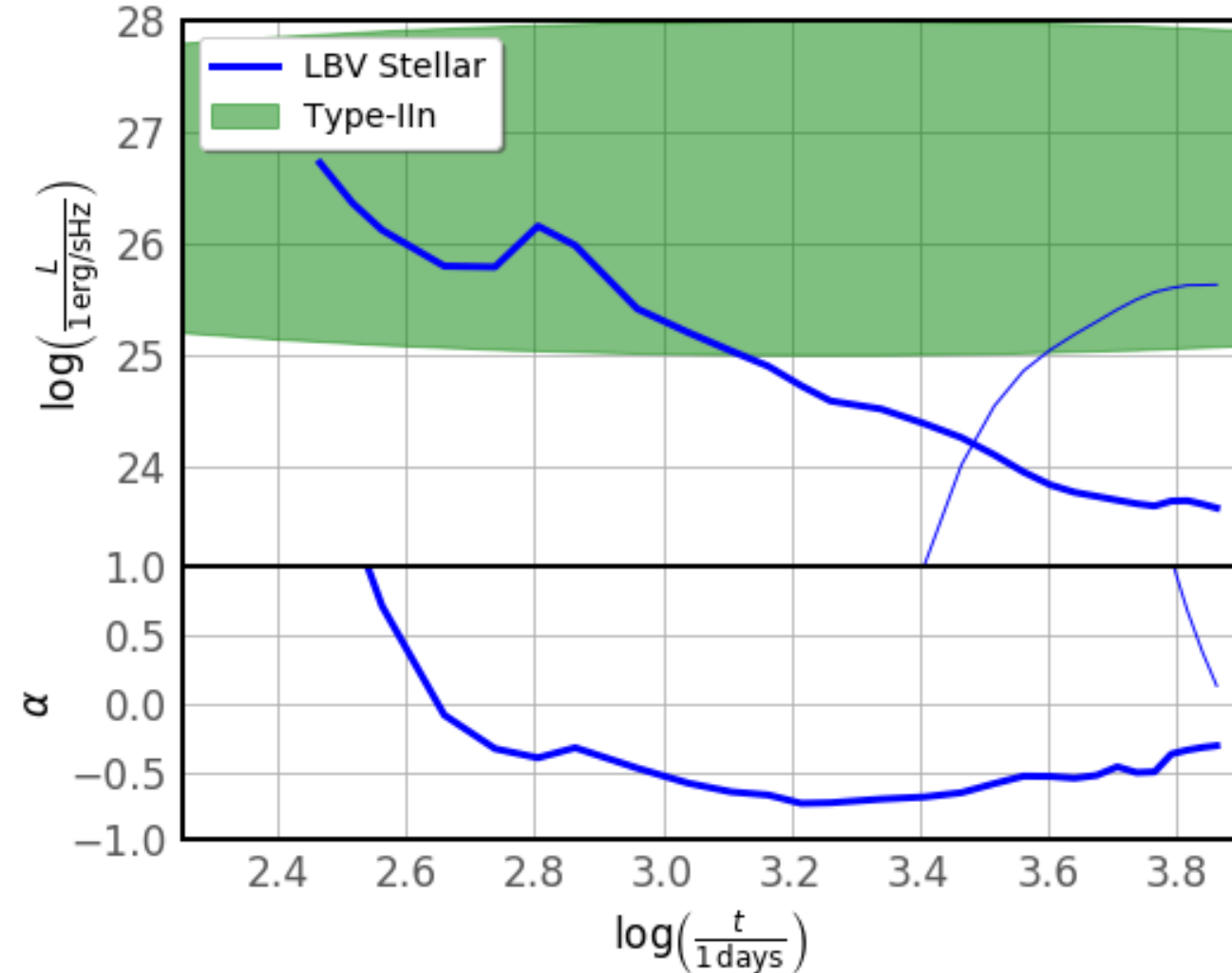


Non-thermal particle distribution

Radio emission

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- Basically complete absorption as long as $R_{shock} < R_{shell}$
- Very-fast rise of Radio-luminosity
- First peak reached after ~ 300 days
→ **peaks after gamma-ray emission**
- Complicated downstream flow-structure
→ affects Radio-emission by local B-field changes
- Strong spectral-index evolution
 - Initially due to absorption
 - Later due to shock-shell and shock-shock interaction
- **Luminosity close to population average**



Figure(top):

Radio luminosity at 8GHz.

Figure(right):

Radio spectral-index 8GHz.

Conclusions and future work

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- 1D time-dependent modelling of hydrodynamics, particle acceleration, magnetic-turbulence and high-energy radiation, from SN expanding into LBV and RSG winds
- Maximum particle energy of $E_{max} \leq 600$ TeV during the first 20 years of evolution
→ **Unlikely to be PeVatrons**
- Detection horizon of ~ 50 kpc for RSGs and ~ 3 Mpc for LBVs
- Good agreement between observed and predicted Radio-emission
- **Circumstellar shells can produce late-time re-brightening** at GeV, TeV gamma-rays, Radio and thermal X-rays
- Better detection-prospects due to reduced absorption in the VHE-domain → 5-10x brighter
- Strong spectral index-evolution in the Radio due-to shell-interaction: hardening after shell-interaction (as observed in SN1987A)

Thank you for your attention!

Photosphere

