Gamma-rays from young SNRs in dense circumstellar environments

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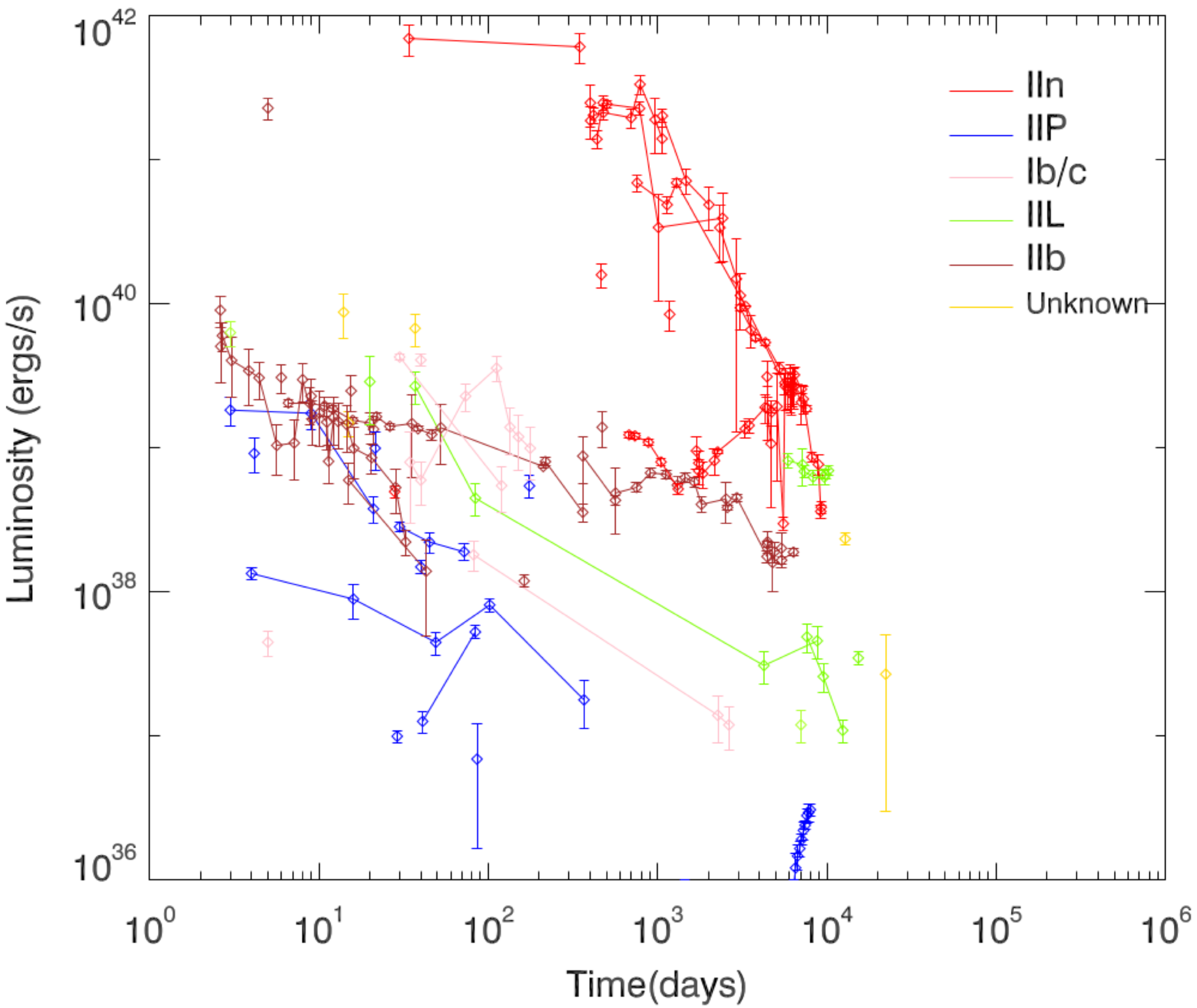
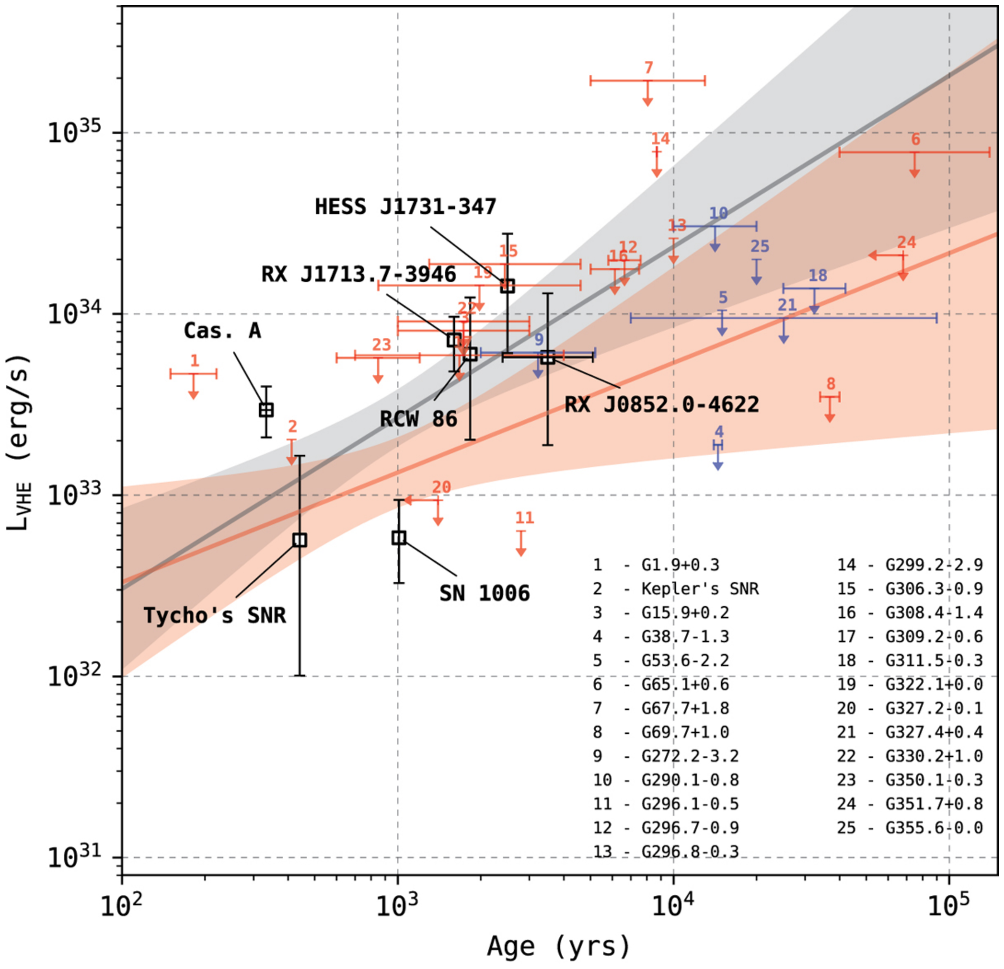
Types of Supernovae

- 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)
- Nature of X-ray emission is usually unclear, thermal vs. non-thermal (Chevalier & Fransson, 2017)
- 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)



X-ray luminosity of selected supernovae vs. time (Chevalier & Fransson 2017)

Supernovae as sources of Galactic CRs

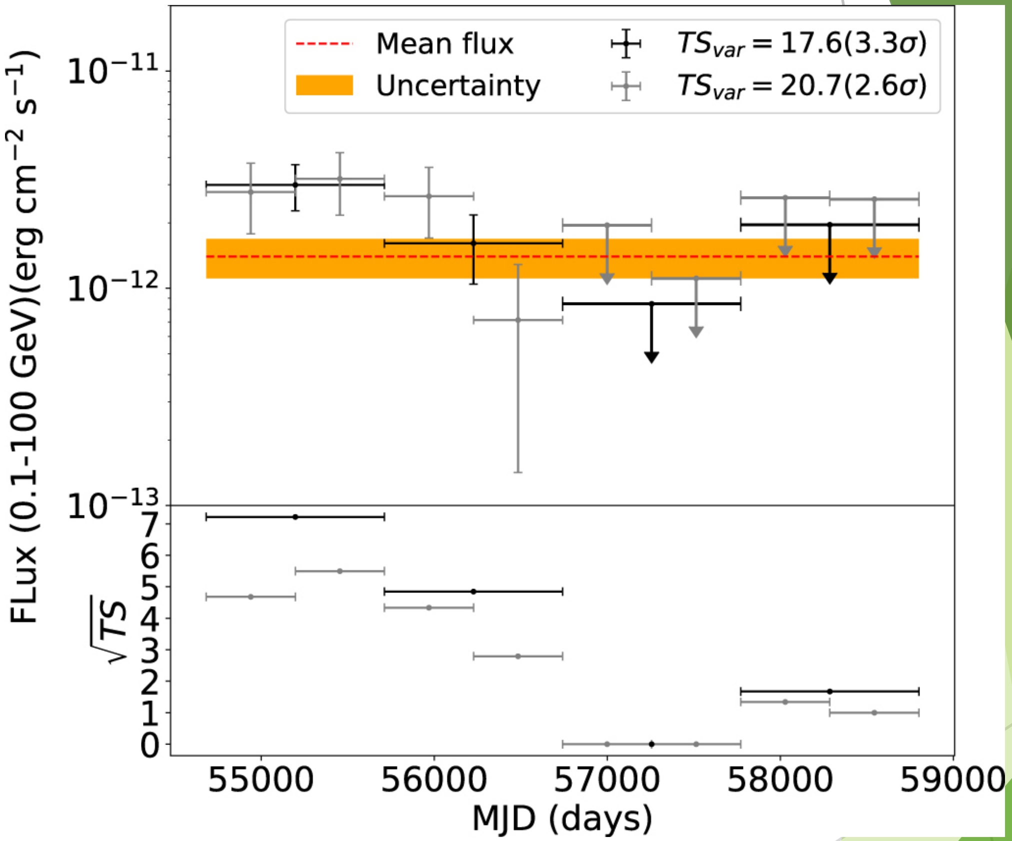


VHE Luminosity of Galactic SNRs vs. age from H.E.S.S. Collaboration (2018)

- SNRs are observed with FERMI and IACTs such as HESS, up to few thousand years old.
- Analysis and modelling shows that SNRs can accelerate particles up to 100 TeV, but difficult to get to the Knee of the CR spectrum at 3 PeV (Parizot+2006)
- Suggestions that very young SNRs (<10-100 years) could be PeVatrons (Bell+2013, Marcowith+2018)
- Calculations of detectability at TeV energies, including $\gamma\gamma$ absorption (Cristofari+2020)

Attempts to detect γ-rays from SNe

- H.E.S.S. Collaboration (2019) obtained upper limits on TeV emission from nearby CCSNe (see HESS AT2019krl contribution, N. Komin [436]).
- 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)



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

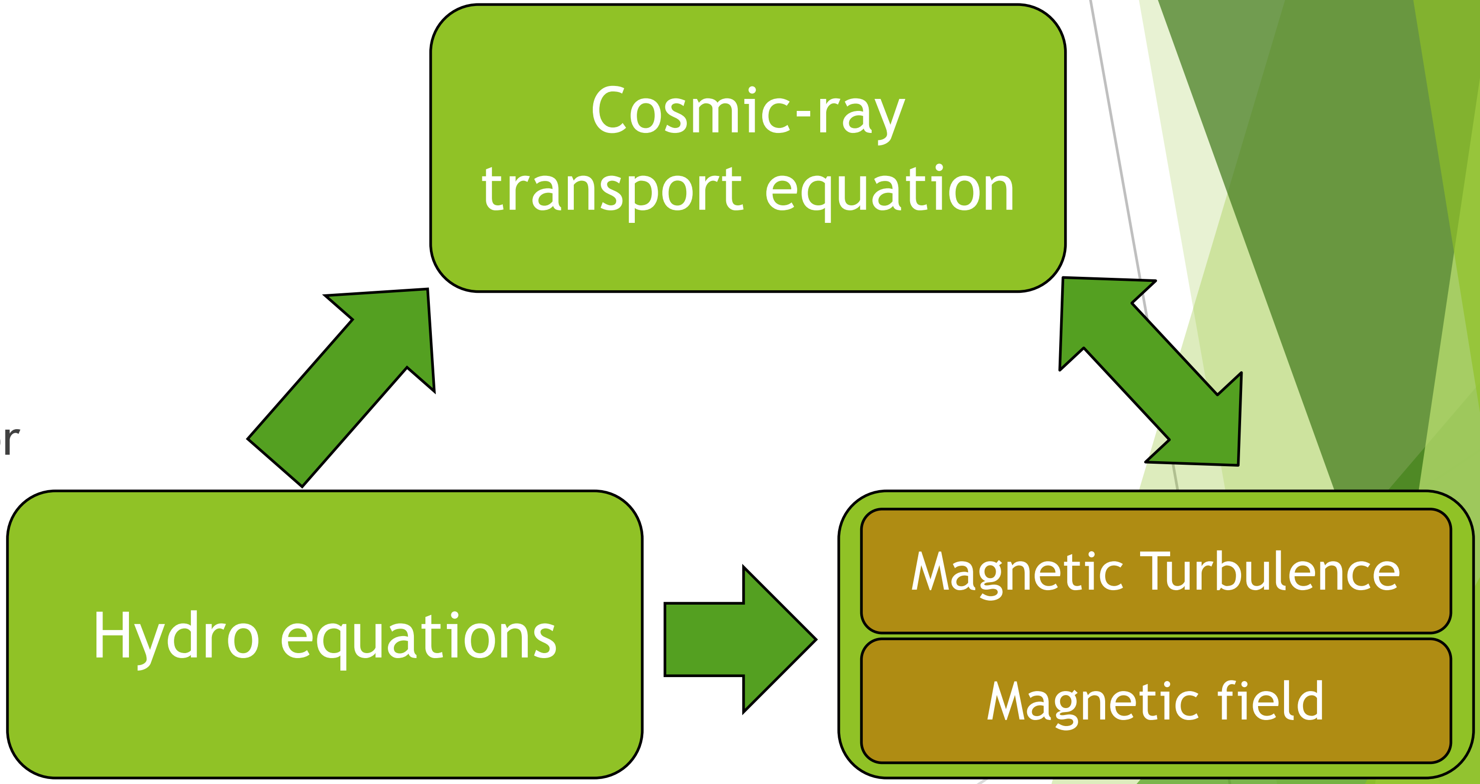
Powered by

RATPaC particle acceleration and radiation code

$$\frac{\partial N}{\partial t} = \nabla D_r \nabla N - \nabla v N - \frac{\partial}{\partial p}\left(N\dot{p} - \frac{v}{3} N p\right) + Q$$

The equations that are solved:

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



See other RATPaC ICRC contributions:
[55] SNRs in wind blown cavities
[697] SNRs in dense CSM
[432] Modelling SN87A
[291] G39.2-0.3 a hadronic SR accelerator
[429] TeV halos of SNRs

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

$$\frac{\partial E_W}{\partial t} = -\left(v\nabla_r E_W + c\nabla_r v E_W\right) + k^3\nabla_k D_k \nabla_k \frac{E_W}{k^3} + 2\left(\Gamma_g-\Gamma_d\right)E_W$$

SNe expanding into steady wind medium

"Luminous Blue Variable (LBV)" model

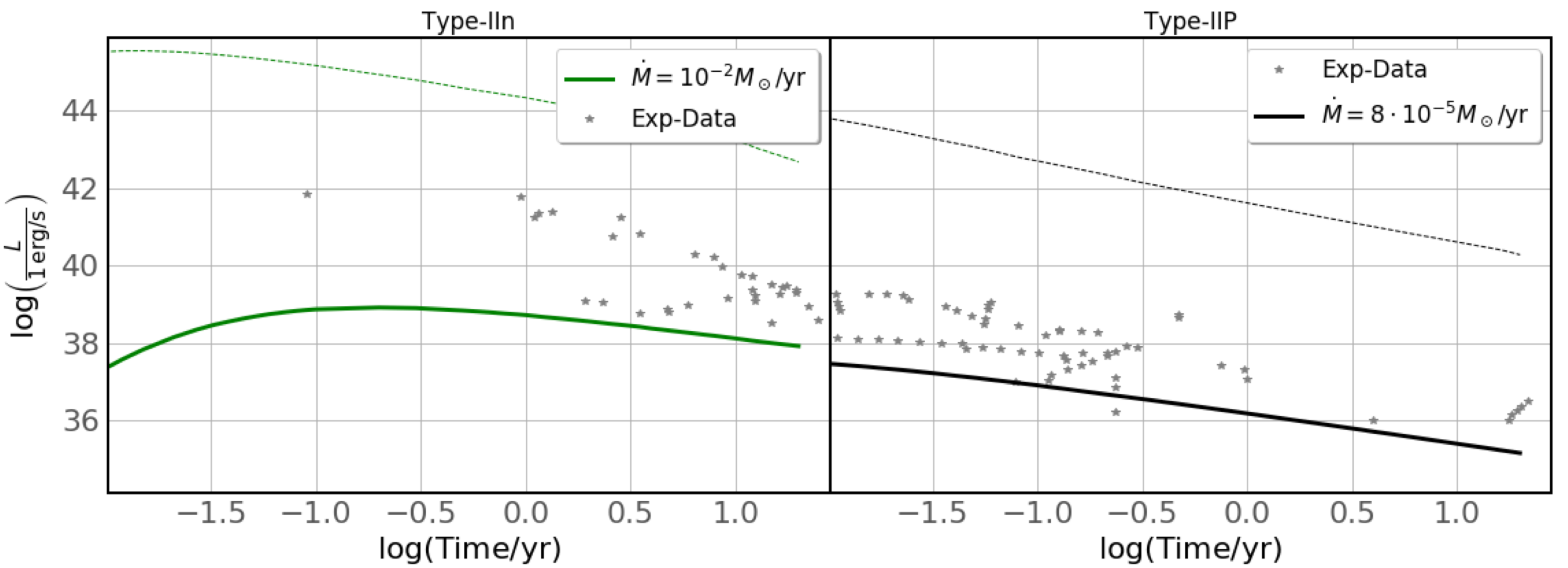
- Dense and powerful wind from a massive star
- $\dot{M} = 10^{-2} M_{\odot}/yr$
- $v_{\infty} = 100\ km/s$

Red Supergiant (RSG) Model

- Slow dense wind from RSG progenitor, at upper end of mass range
- $\dot{M} = 8\times10^{-5} M_{\odot}/yr$
- $v_{\infty} = 15\ km/s$

- Model 1: a fixed 5μG magnetic field in the wind at all r upstream, 16μG downstream
- Model 2: 1G stellar field at $1000R_{\odot}$ swept into Parker Spiral with $B \propto r^{-1}$
- Both cases: SN modelled following Chevalier (1982) with parameters:
  $E = 10^{51} erg,\ M_{ej} = 10M_{\odot}$, density power-law index $n = 10$ (LBV)
  $E = 10^{51} erg,\ M_{ej} = 3M_{\odot}$, density power-law index $n = 9$ (RSG)
- Initial conditions: inject SN at radius $10^{14}\ cm$, follow hydrodynamic evolution.

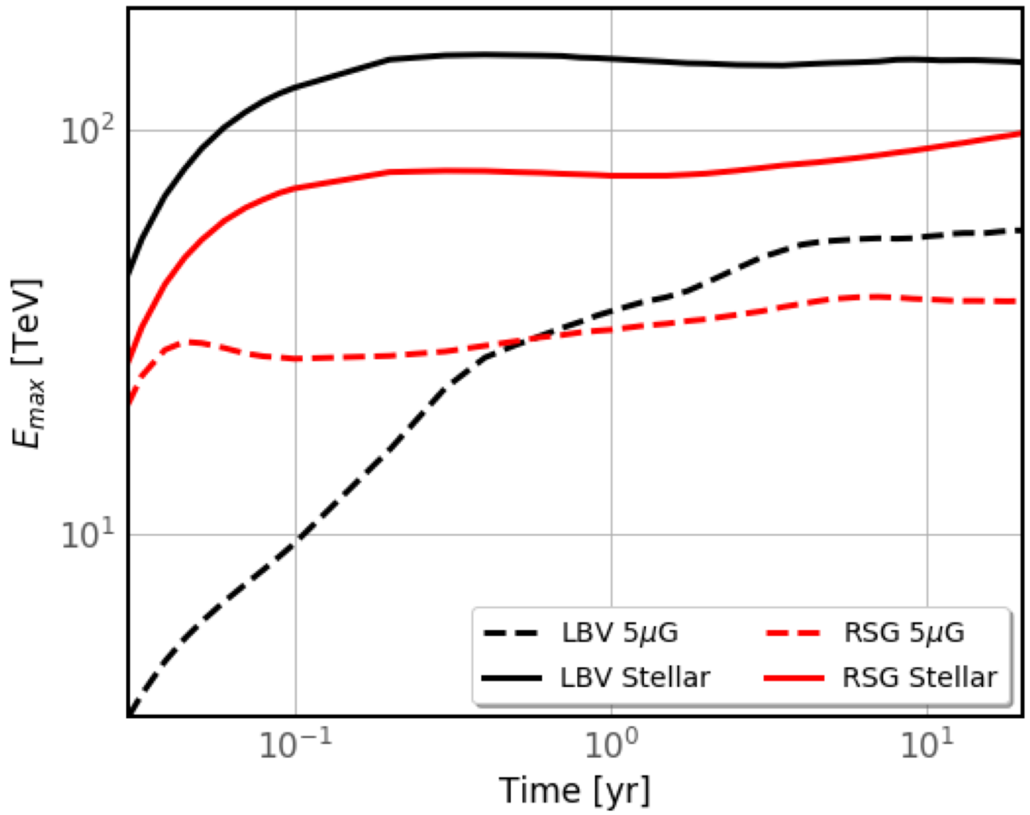
Thermal X-ray emission from model



X-ray data from Dwarkadas (2014)

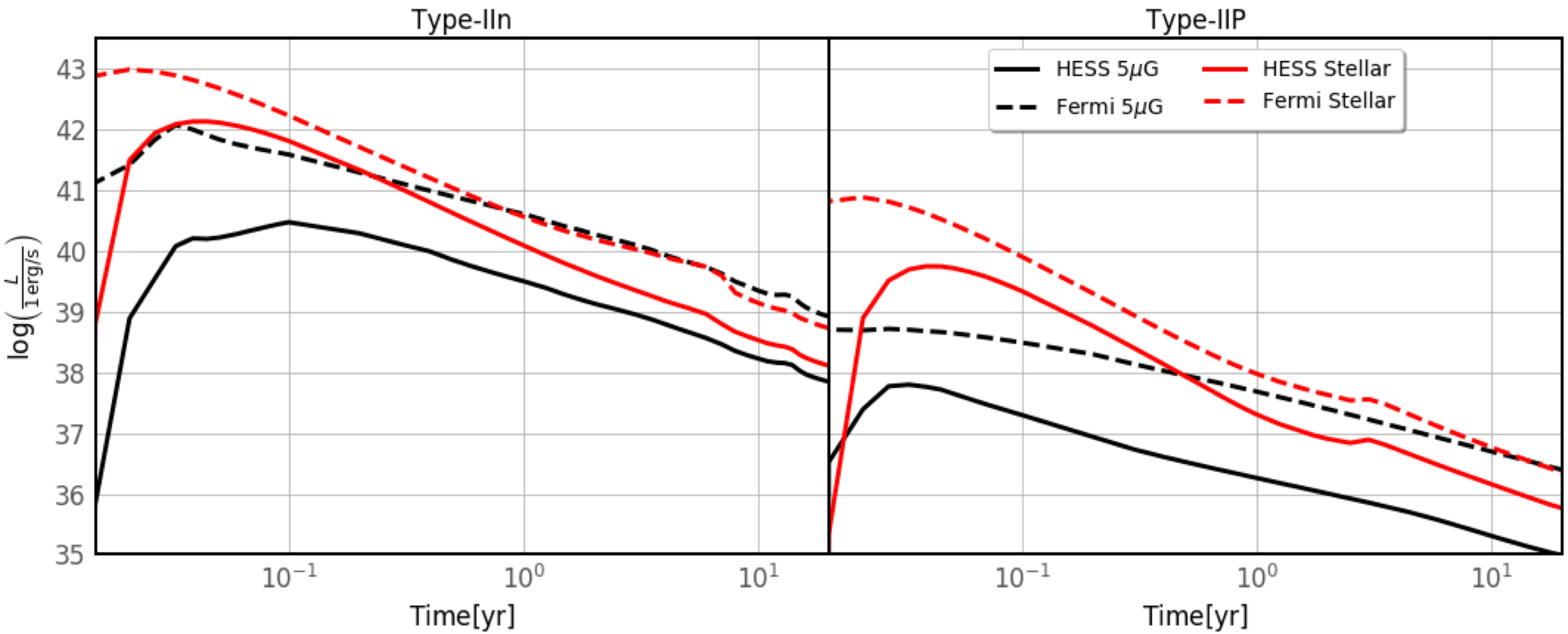
- Relatively simple calculation of X-ray emissivity in post-shock medium.
- Unabsorbed X-ray luminosity far above observations
- Considering local absorption in stellar wind and shocked shell, obtain better agreement with observations
- Peak of lightcurve later in denser wind because of absorption
- L decreases approximately as $1/t$ (cf. Dwarkadas 2014)

Time evolution of particle spectrum



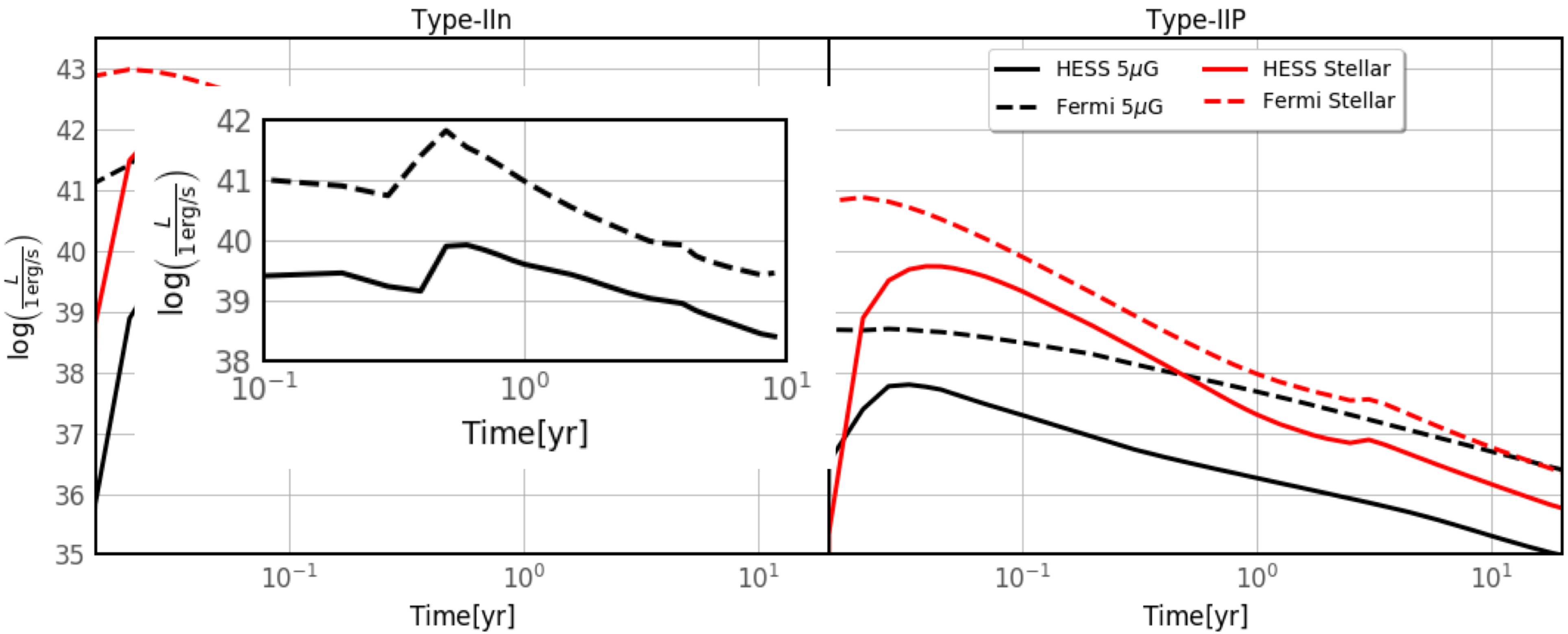
- Resulting momentum spectrum fit with power-law plus exponential cutoff.
- Acceleration time is ~1month to get to quasi-steady state.
- Maximum energy for simulations with a constant (and weak) upstream B-field is 30-50 TeV.
- Simulations with $B \propto r^{-1}$ have higher maximum energy, around 100-200 TeV
- No model assumptions give $E_{max} \geq 1PeV$
- “stellar” field already quite strong

Gamma-ray emission



- Gamma-ray luminosity in FERMI-LAT energy range peaks early (days to 2 weeks) after explosion, and decreases approx. $L \propto t^{-1}$
- Type IIn approx. 100x more luminous then IIP
- TeV emission peaks later than GeV emission, few weeks to month post-SN
- TeV emission also decreases approx. as $L \propto t^{-1}$ or slightly faster
- $\gamma\gamma$ absorption not yet included → early luminosity overestimated

Gamma-ray emission



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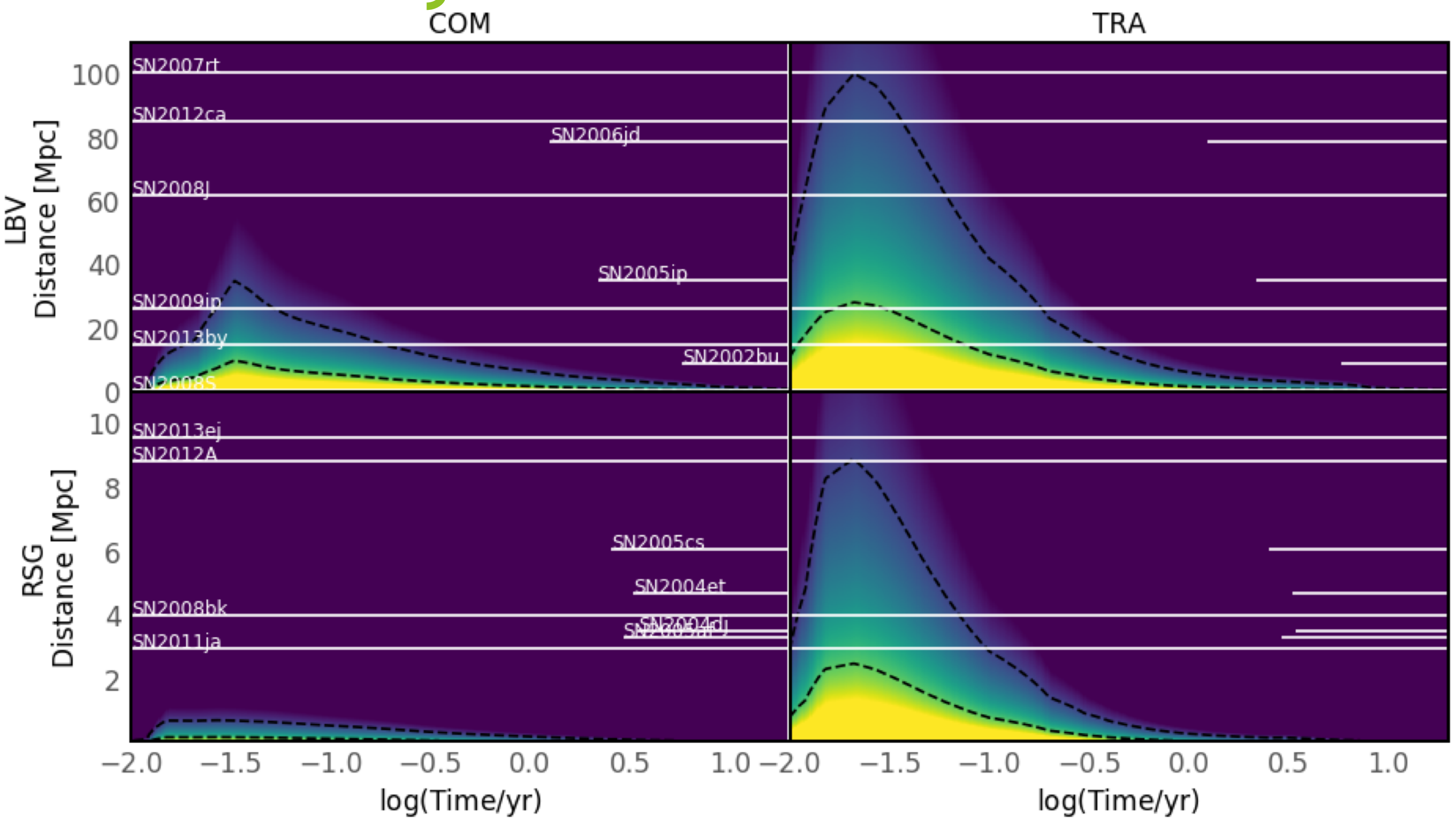
Detectability with FERMI



Lines:
- 5-sigma in 1month
- 5 sigma in 1 year

Colour scale is flux as function of distance and time.

- Optimal detection timescale is approx. 1 week post explosion for most assumptions.
- Type IIn detectable out to 10 Mpc at 5-σ (depending on assumptions)
  Type IIP about 100x fainter → must be 10x closer for detection.
- All cases have GeV emission fading strongly after <1 month.

Conclusions and Future Work

- Supernovae of type IIP and IIn suggested as transient gamma-ray sources
- Theoretical modelling suggests SN could be PeV accelerators in first months and years.
- 1D time-dependent modelling of hydrodynamics, particle acceleration and high-energy radiation, from SN expanding into LBV and RSG winds.
- Verify that thermal X-ray emission consistent with observations of IIn/IIP SN
- Depending on assumptions about magnetic field, obtain ~100 TeV maximum particle energy from 0.1-10 year timescales.
- GeV emission peaks on days to week timescales, TeV on week to month timescale (without $\gamma\gamma$ absorption).
- 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.
- Predict that some SN should be detectable with FERMI over its mission lifetime