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Gamma-ray morphology of SNRs and their halos

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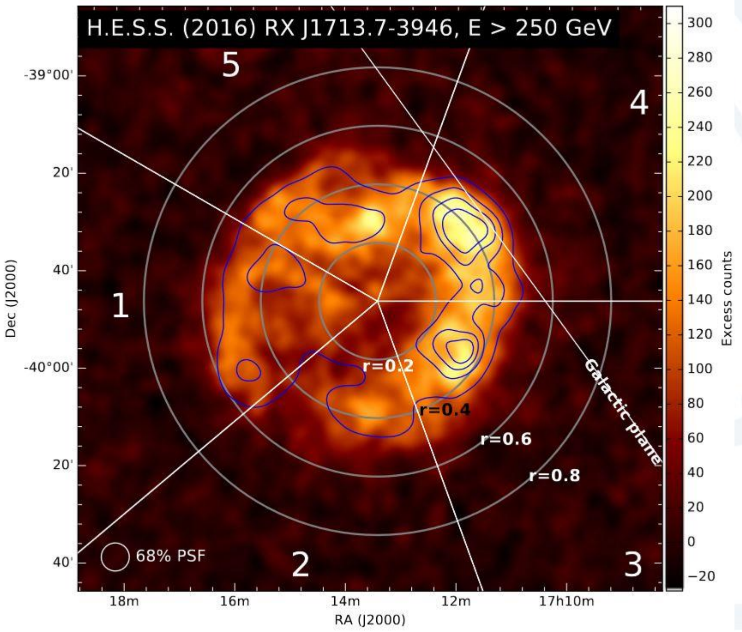
37th ICRC, 12-23 July 2021

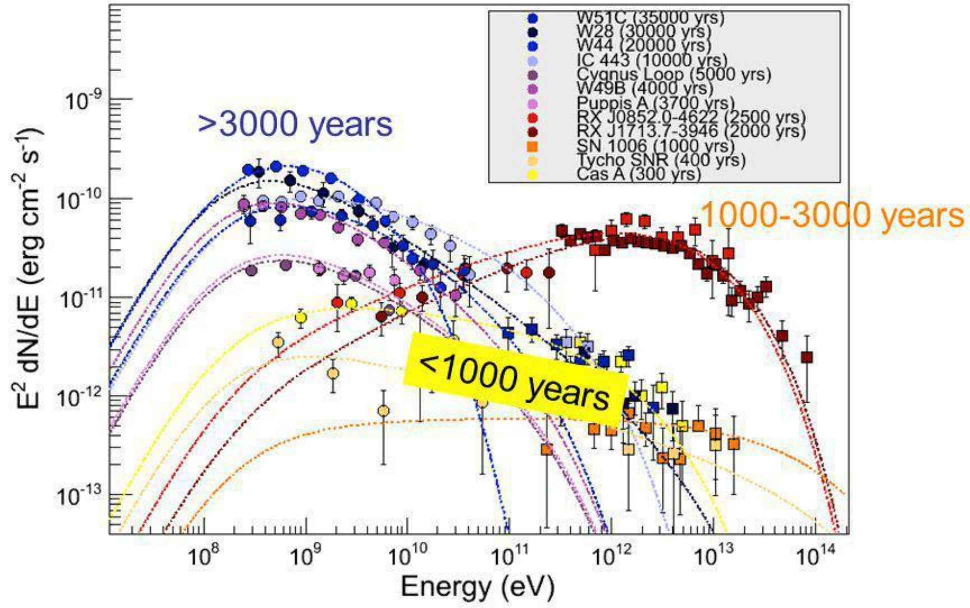
The cosmic-ray spectrum
Experimental evidence



More and more observational constrains:

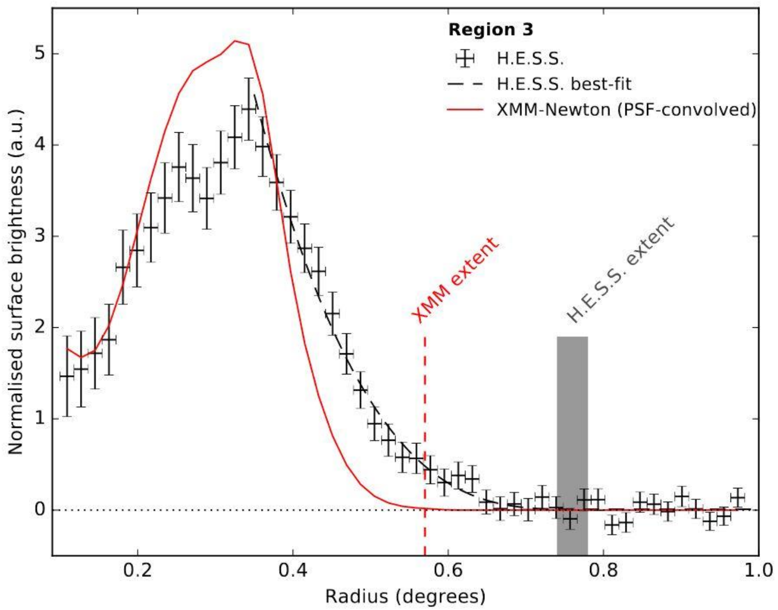
Models need to account for spectral evolution and morphology

Evolution of particle acceleration in the shell-type SNRs



Stefan Funk, August 5th 2011, TeVPA

Figure: Gamma-ray flux from various SNRs (Funk, TeVPa 2011)



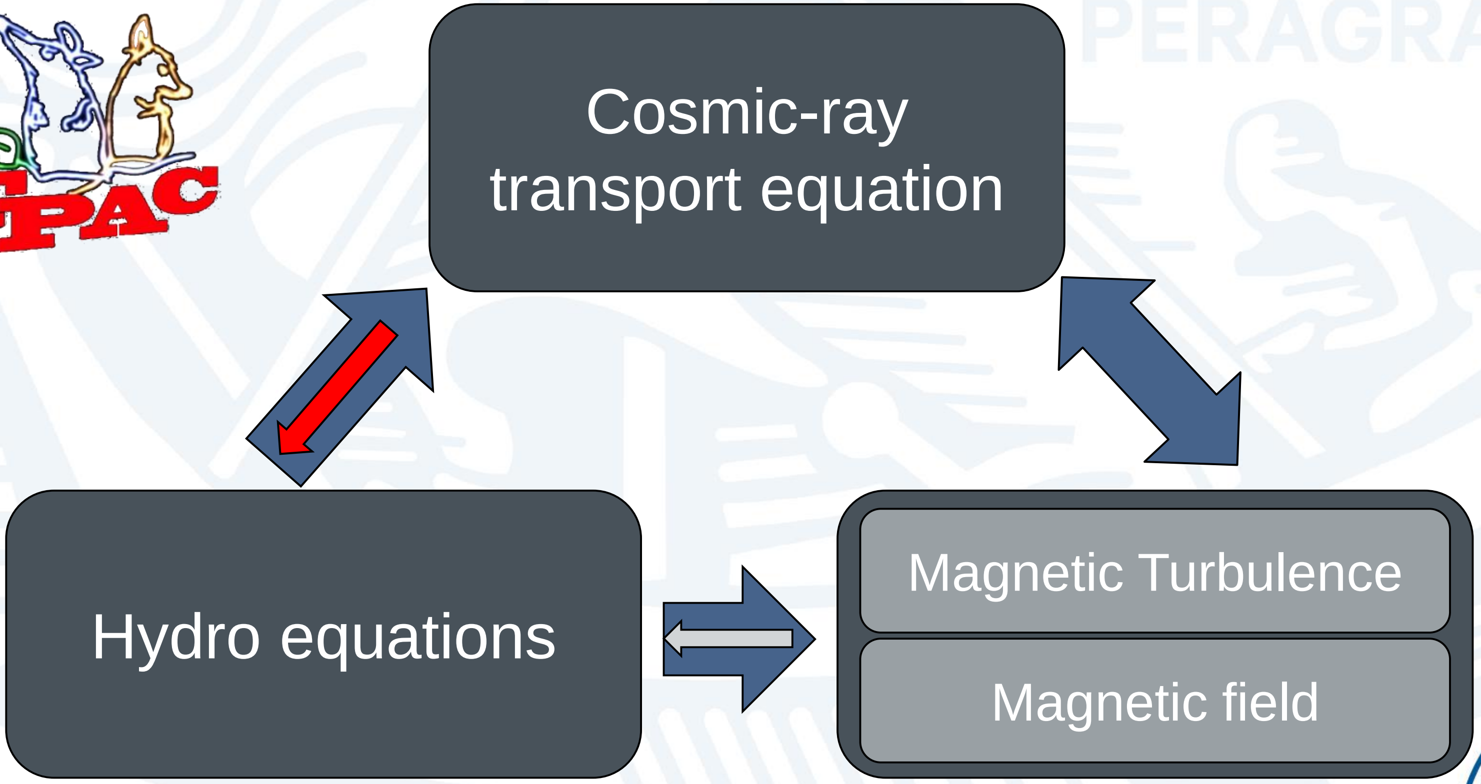
Figures:
(Top) Excess-count map of RX J1713.7-3946

(Left) Gamma-ray and X-ray profiles of RX J1713.7-3946 (H.E.S.S. 2018)

Fermi acceleration

Coupled equations

Powered by RATPAC



Standard DSA | Non-linear DSA | NDSA + high MF

Other contributions using RATPaC:

- [55] SNRs in wind blown cavities
- [697] SNRs in dense CSM
- [432] Modelling SN87A
- [291] G39.2-0.3 a hadronic SR accelerator

Fermi acceleration

The equations

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

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

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

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

The equations are solved:

- One dimensional
- Assuming spherical symmetry
- Including Synchrotron cooling for electrons
- On a comoving, expanding grid for turbulence and CRs → no free escape boundary
- Type-Ia, $B_0 = 5\mu G$

Fermi acceleration

Turbulence setup

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Initial turbulence derived from 1/10th of the Galactic diffusion coefficient ➡ $D_r(t=0) = 10^{28}\left(\frac{pc}{10GeV}\right)^{1/3}\left(\frac{B_0}{3\mu G}\right)^{-1/3} cm^2/s$

Growth rate based on pressure gradient of CRs (resonant CR-instability *x*10) ➡ $\Gamma_r = \mathbf{10}\,\frac{v_A p^2 v}{3E_W}\left|\frac{\partial N}{\partial r}\right|$

Damping as diffusion in wavenumber space ➡ $D_k = k^3 v_A \sqrt{\frac{E_W}{2B_0^2}}$

Results

Gamma-ray spectra

Spectral evolution: very young SNRs

Observation:

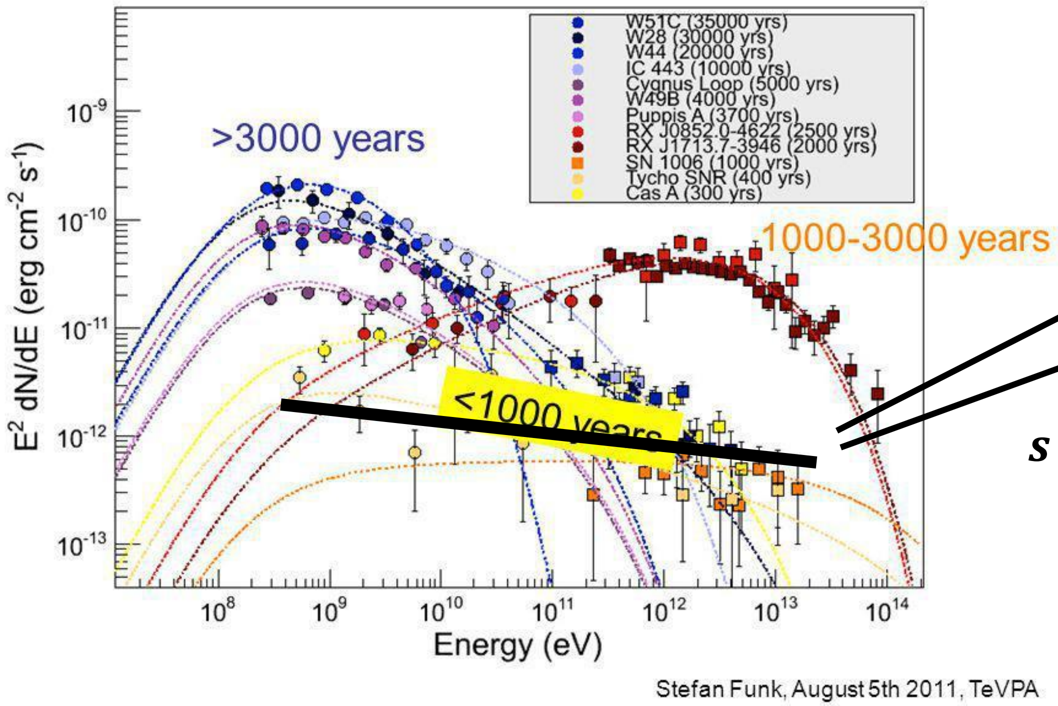
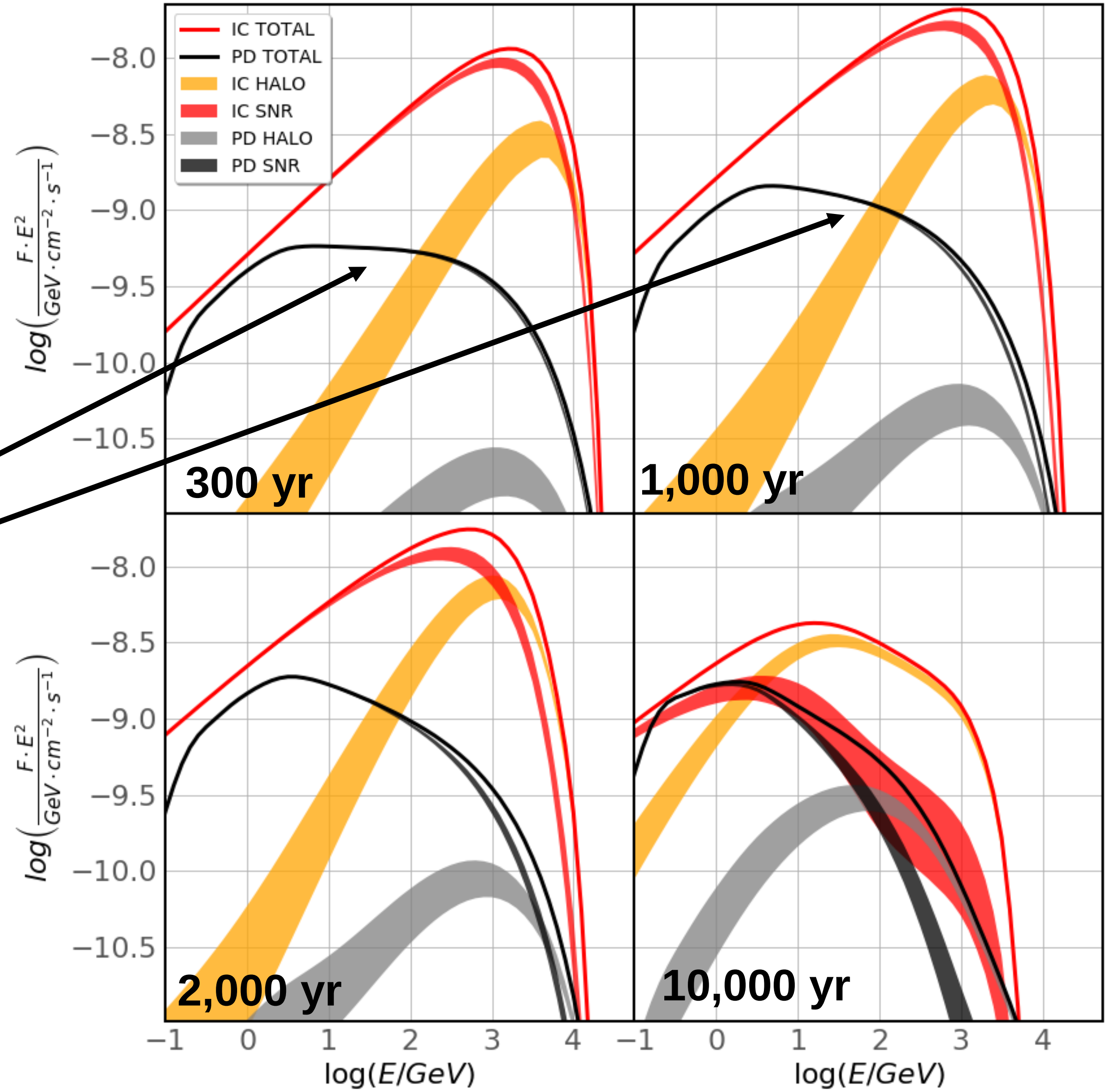


Figure: Gamma-ray flux from various SNRs (Funk, TeVPa 2011)

$s \approx 2$

Model prediction:



Gamma-ray spectra

Spectral evolution: young SNRs

Observation:

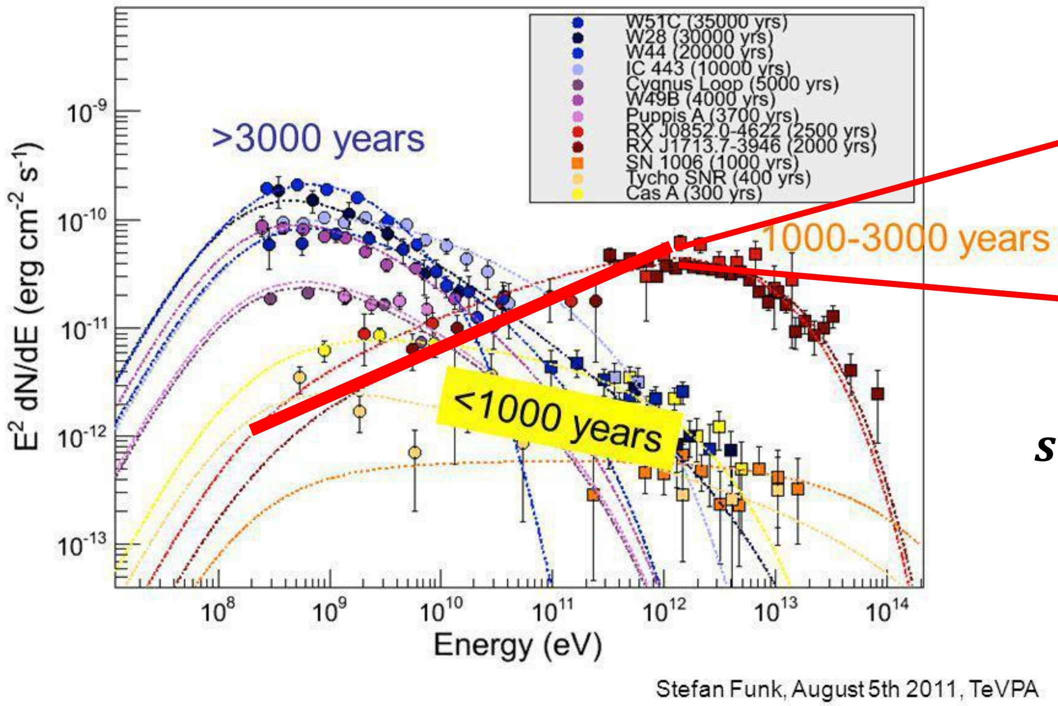
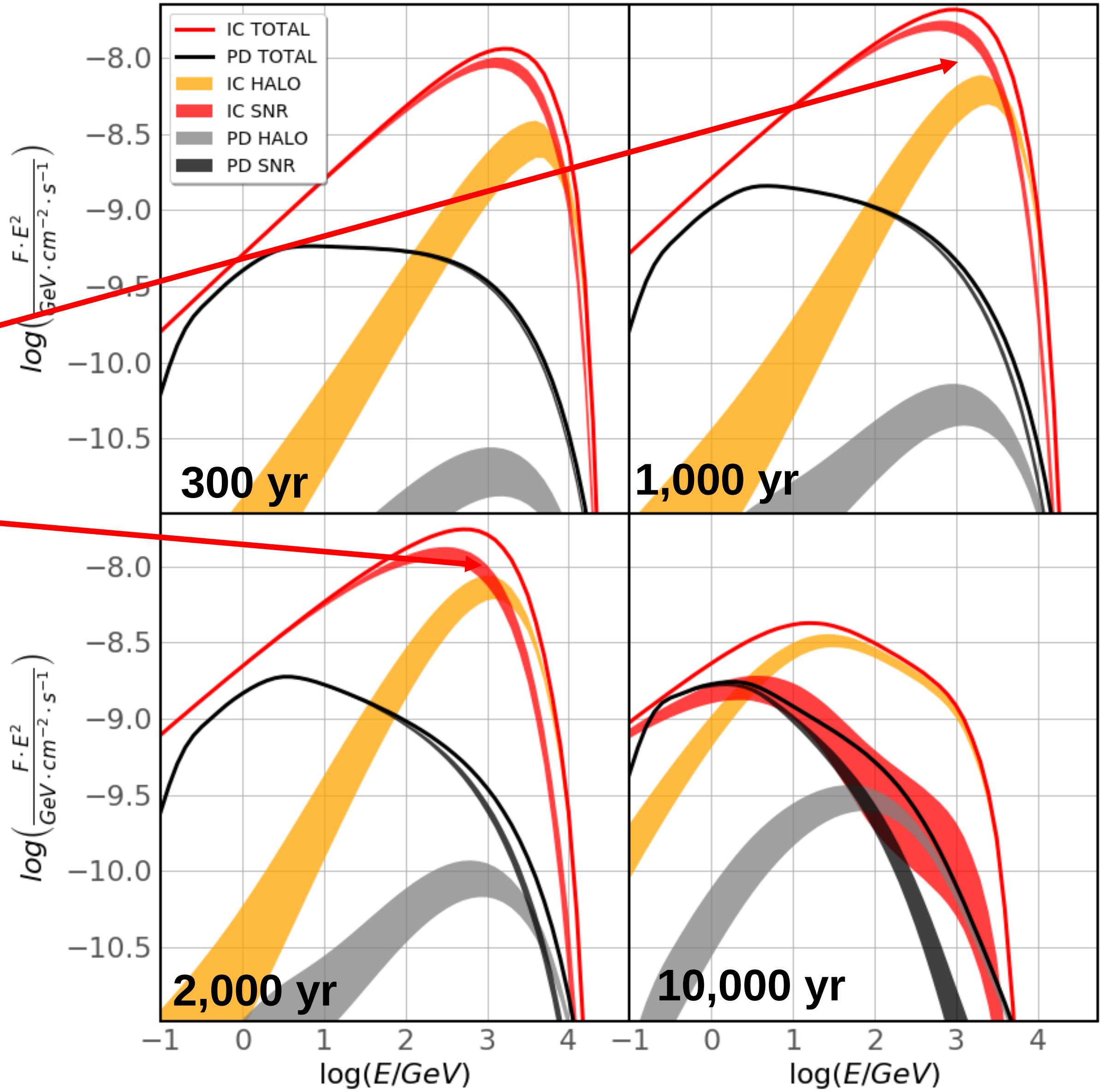


Figure: Gamma-ray flux from various SNRs (Funk, TeVPa 2011)

$s \approx 1.5$

Model prediction:



Gamma-ray spectra

Spectral evolution: evolved SNRs

Observation:

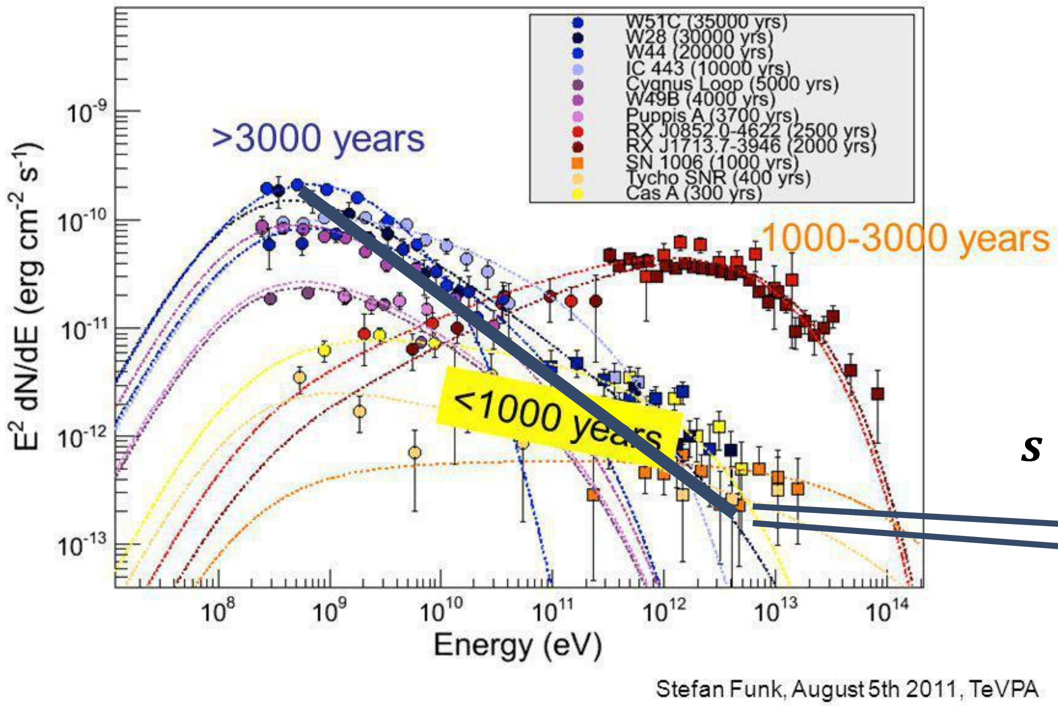
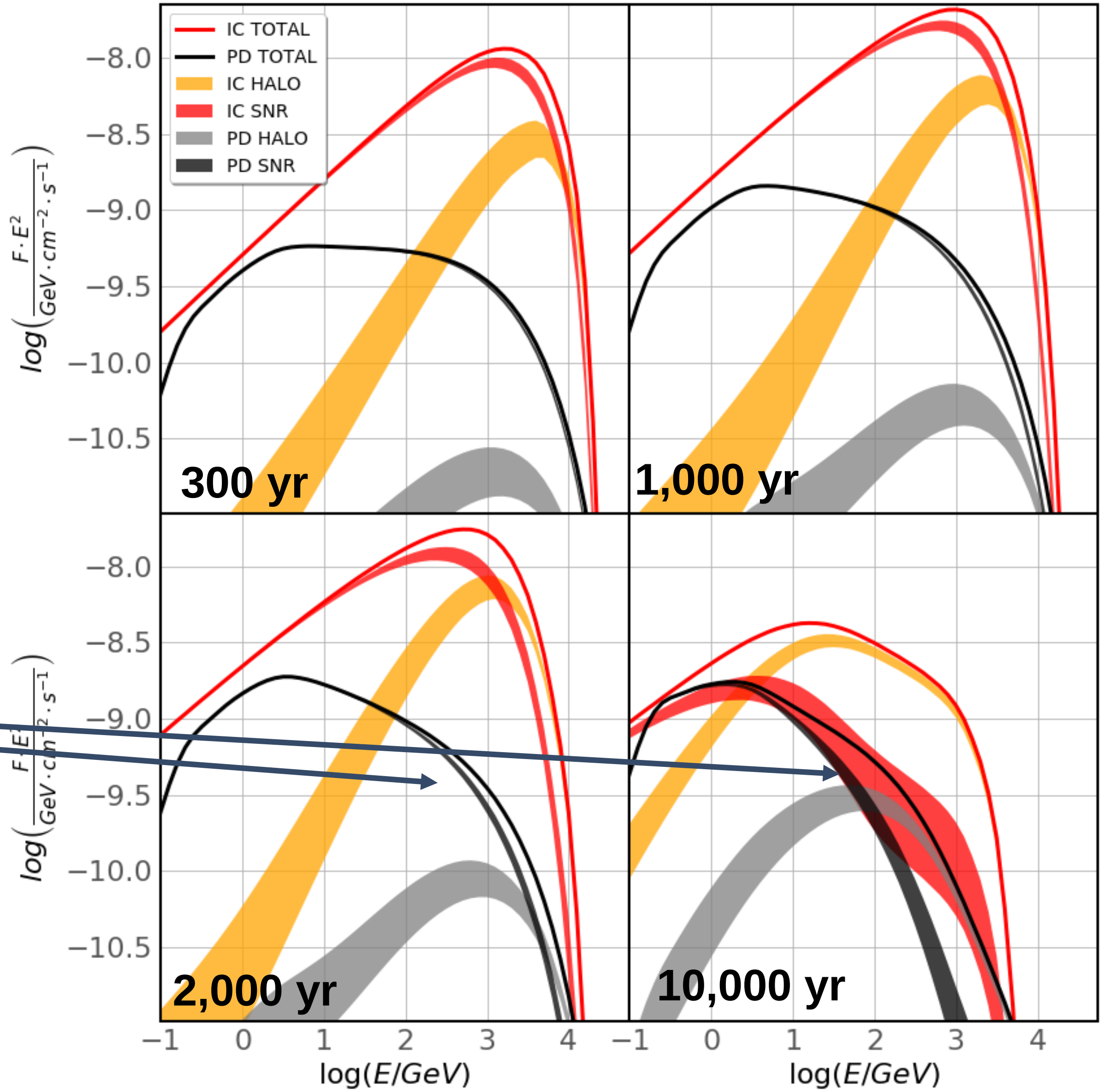


Figure: Gamma-ray flux from various SNRs (Funk, TeVPa 2011)

$s \geq 2.7$

Model prediction:



Gamma-ray morphology

Emission and spectral index maps

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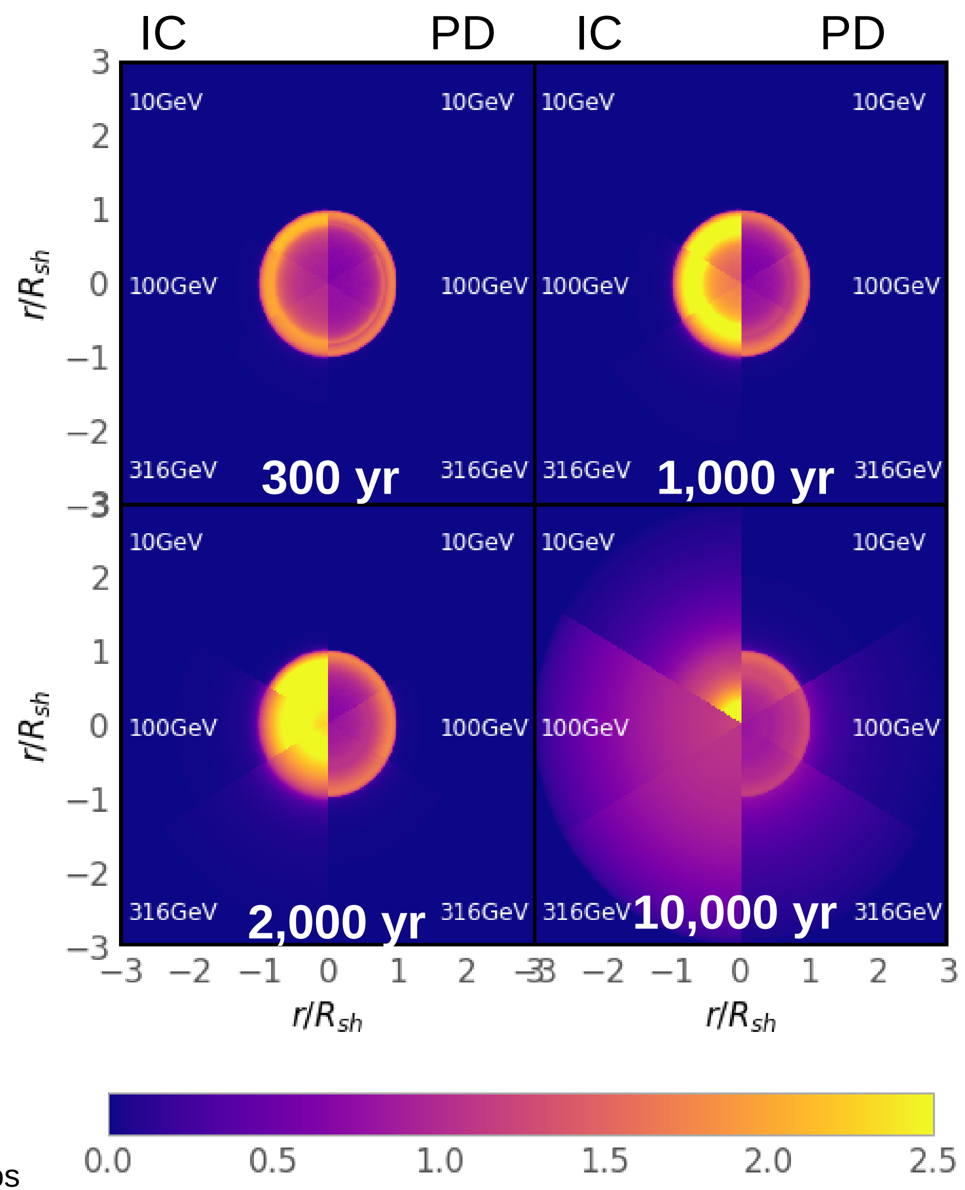
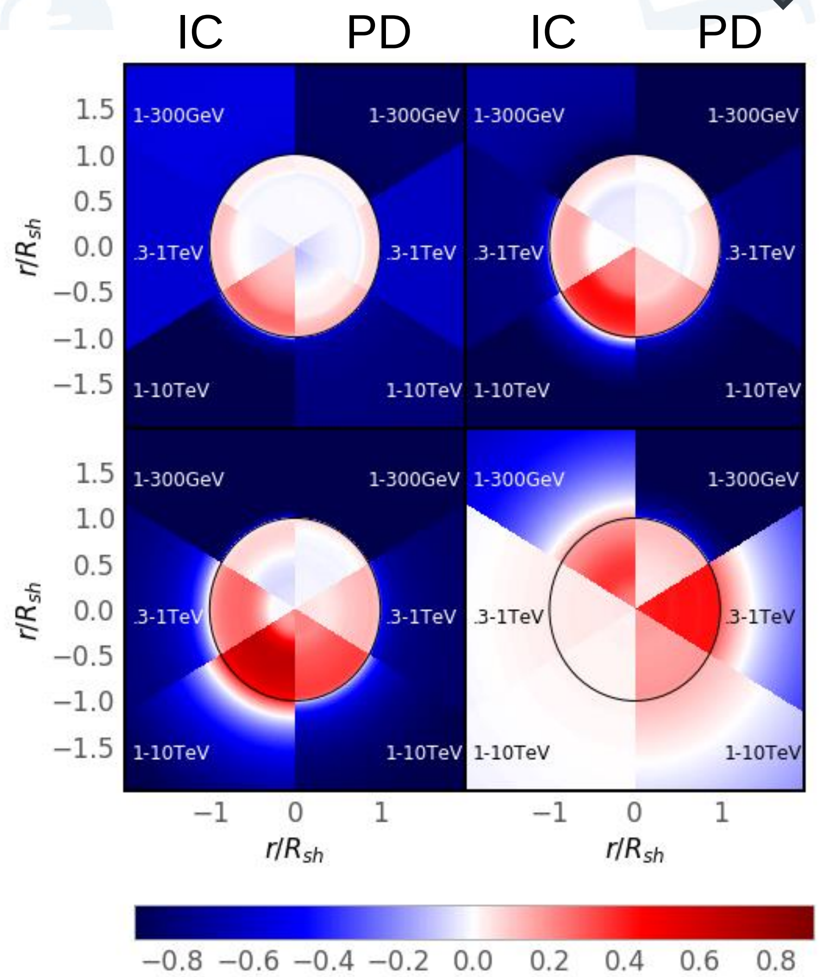
PD-emission:
- Shell-like morphology throughout all phases and energies
- Faint halo emission

IC-emission:
- Initially shell like morphology
- Transition to center-filled
- Halo emission already after 2kyr

Spectral index distribution:
- No significant deviation from regions of brightest emission



Emission maps
Spectral index deviation maps



Halo diffusion coefficient

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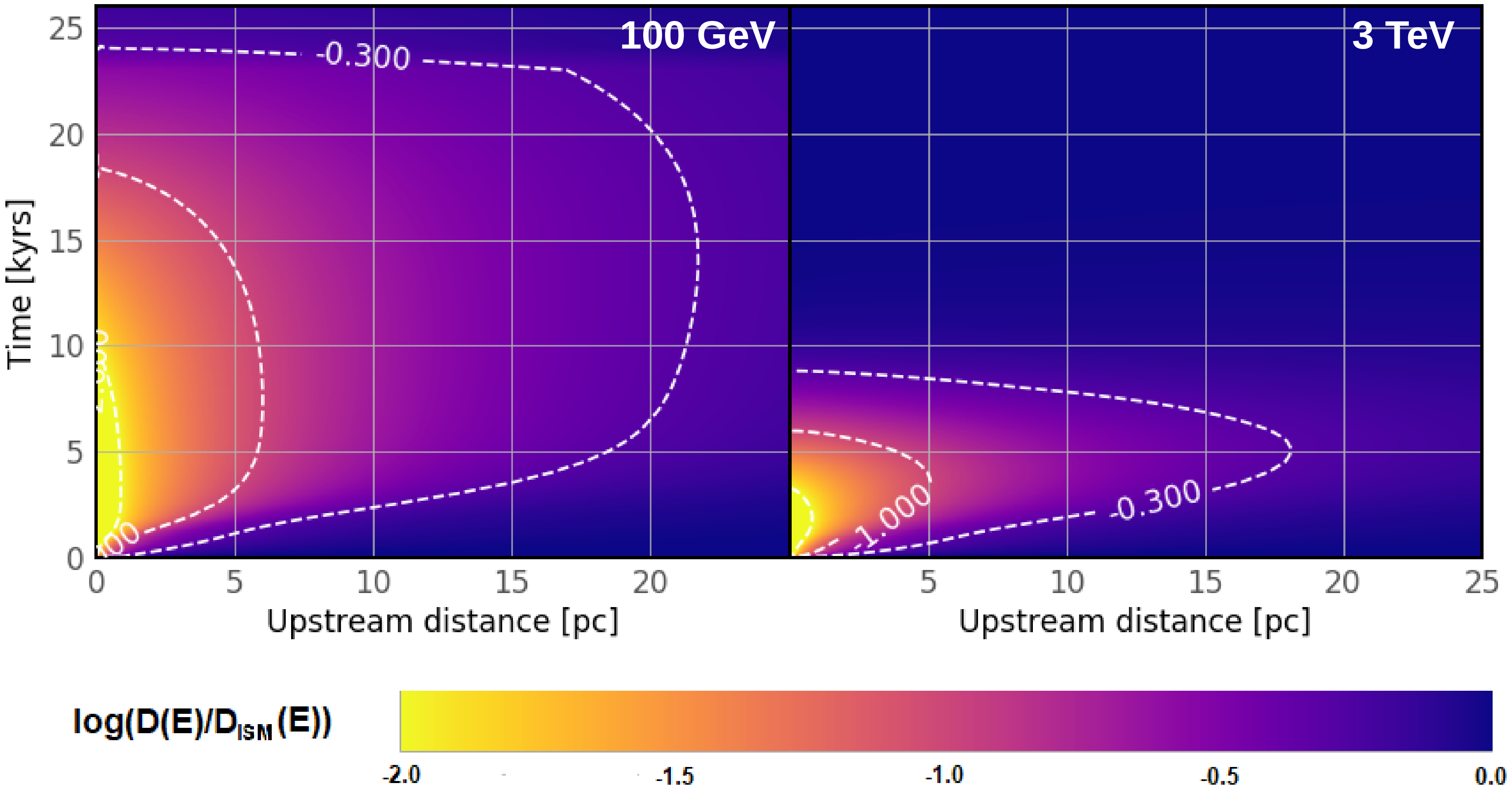
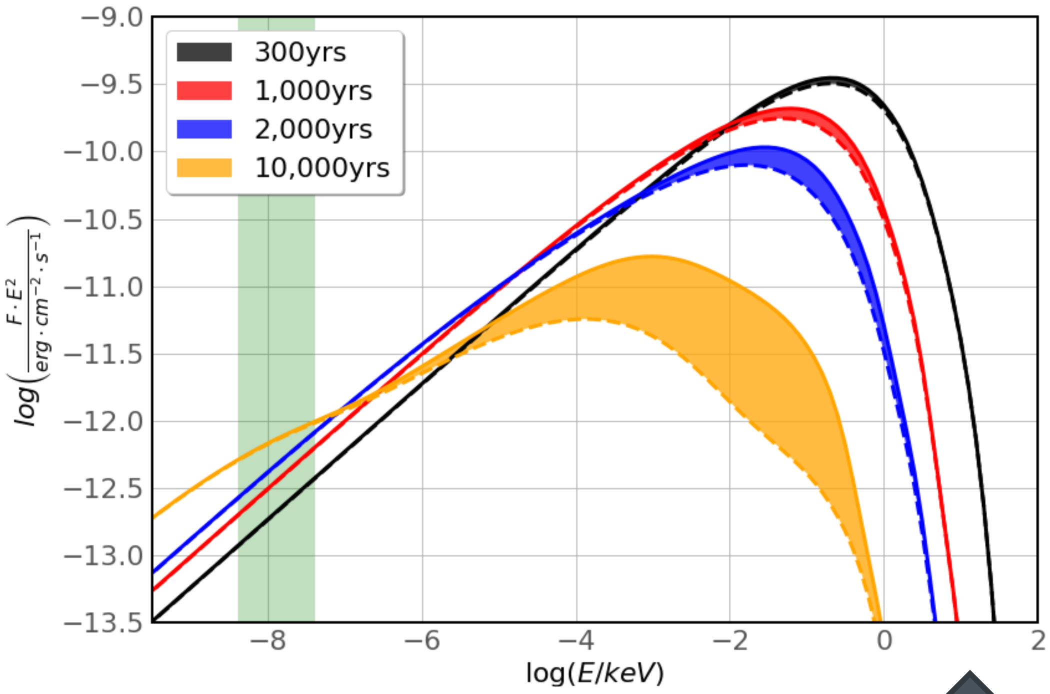
- Diffusion coefficient gets reduced up to ~20pc into the upstream
- Rise time similar across energies → down cascading
- Escaping CRs govern diffusion for low-energetic CRs



Synchrotron emission
Radio and X-ray emission

X-ray emission:
- No non-thermal X-rays after ~2kyrs
- Shell-like morphology

Radio-emission:
- Shell-like → center-filled
- Steadily increasing flux
- Spectral softening at ~10kyrs



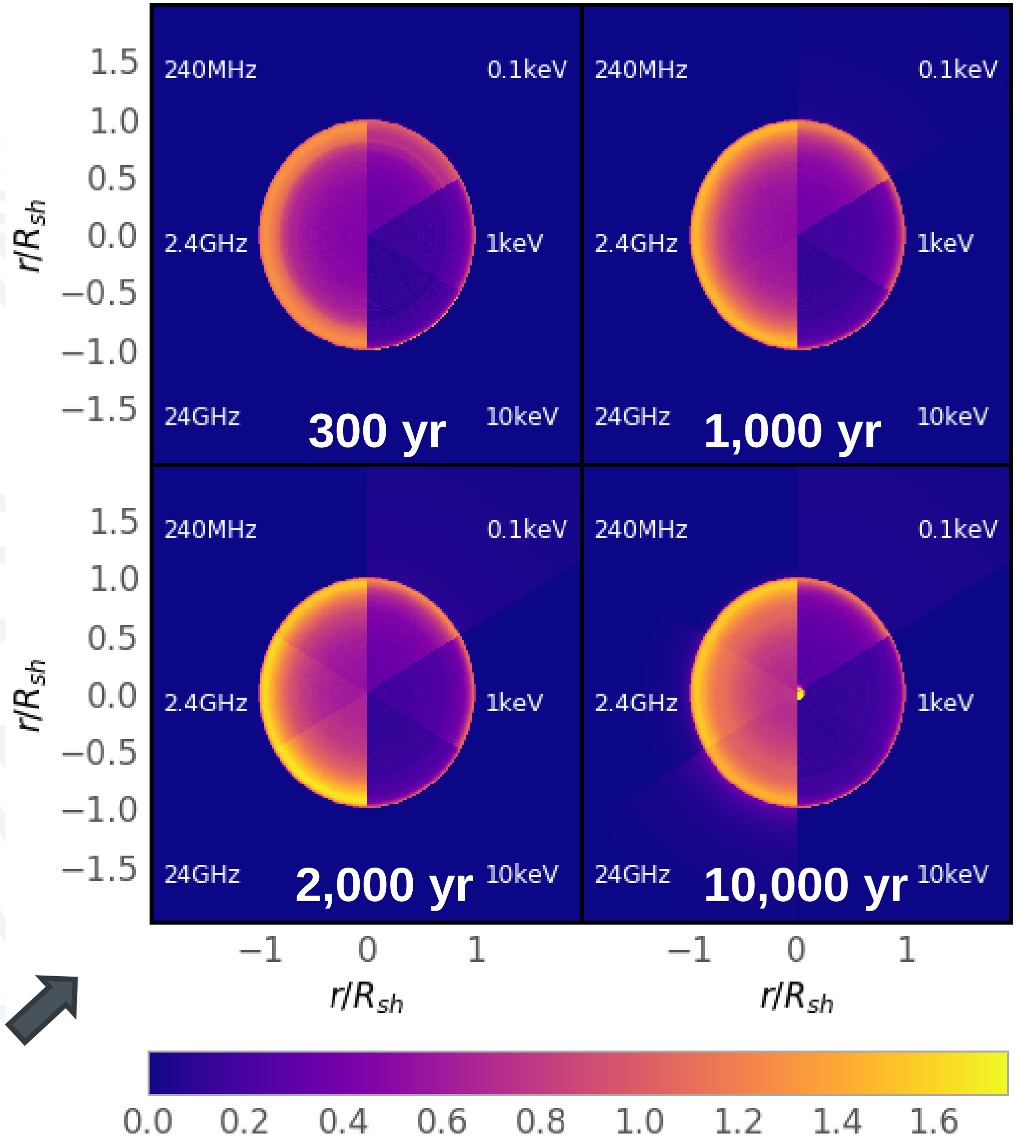


Figure: Predicted synchrotron emission SED ; Emission maps

Conclusions

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- Strong spectral evolution powered by early self-confinement and later CR-escape
- The gamma-ray morphology depends strongly on the emission mechanism:
    - Persistent shell-like structure for hadronic emission
    - Shell-like to center filled evolution for leptonic emission
- Stronger halo-emission for the leptonic channel → potentially detectable by current-generation IACTs
- No significant spectral-index deviation expected due to projection effects
- No non-thermal X-rays after a few kyrs
- Radio morphology shifts from shell-like to (more) center filled
- Reduction of the diffusion coefficient in the upstream; strong spatial and temporal evolution

Thank you for your attention!