IRISH RESEARCH COUNCIL
An Chomhairle um Thaighde in Éirinn

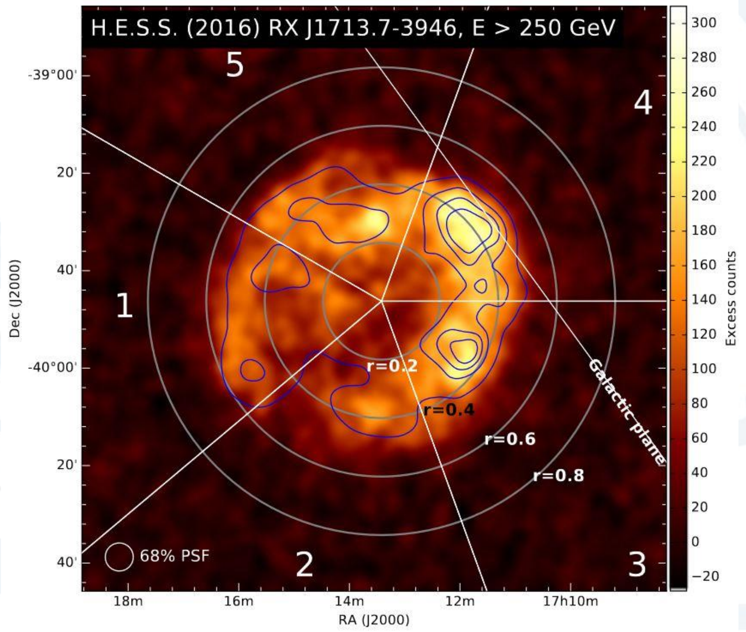
DIAS
Institiúid Ard-Léinn Bhaile Átha Cliath | Dublin Institute for Advanced Studies

SNRs – Particle escape and gamma-ray halo formation

Robert Brose, M. Pohl, I. Sushch

TeVPa, 25-29 October 2021

The cosmic-ray spectrum
Experimental evidence



More and more observational constrains:

Models need to account for spectral evolution and morphology

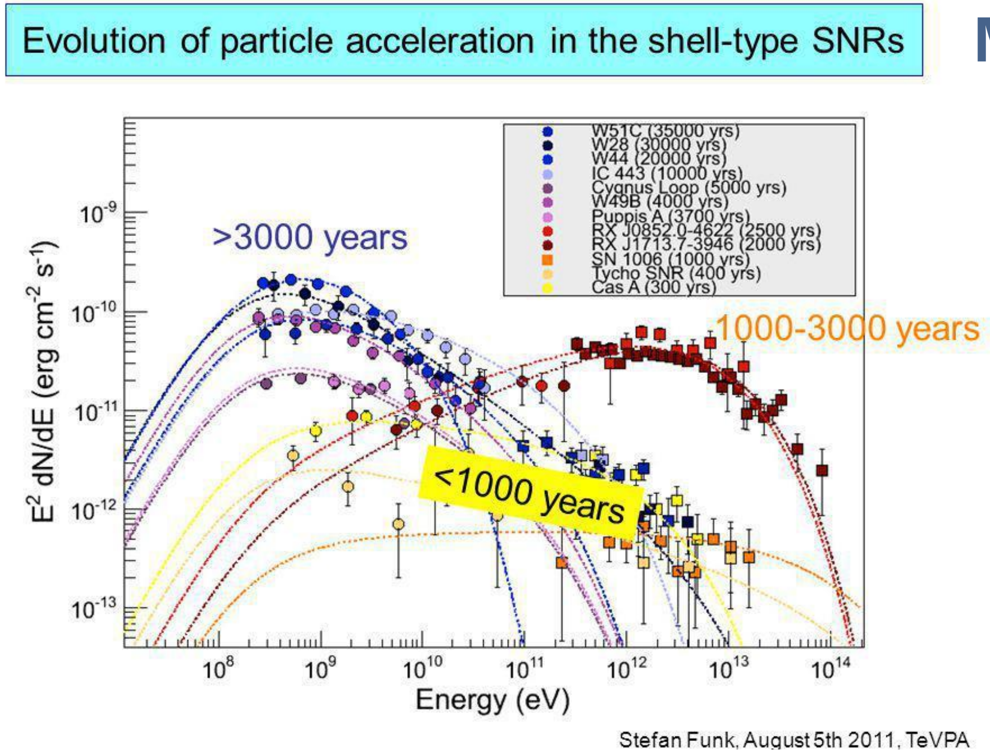
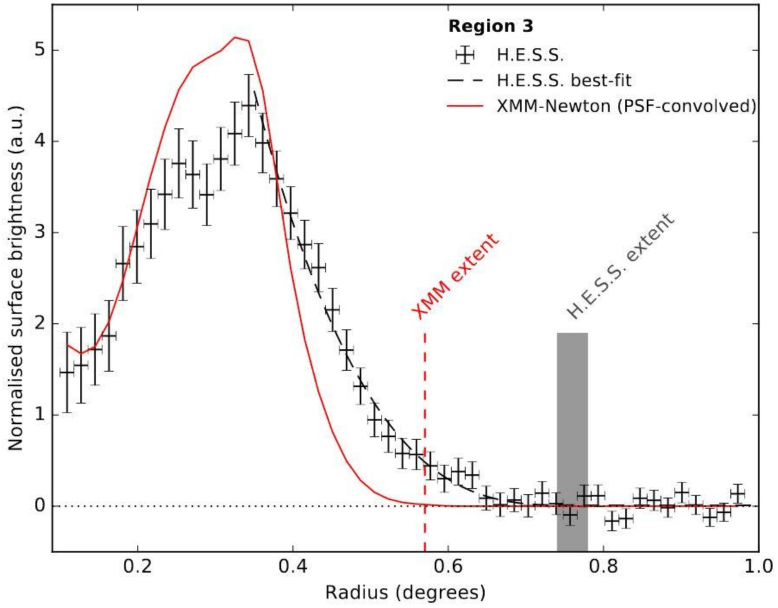


Figure: Gamma-ray flux from various SNRs (Funk, TeVPa 2011)

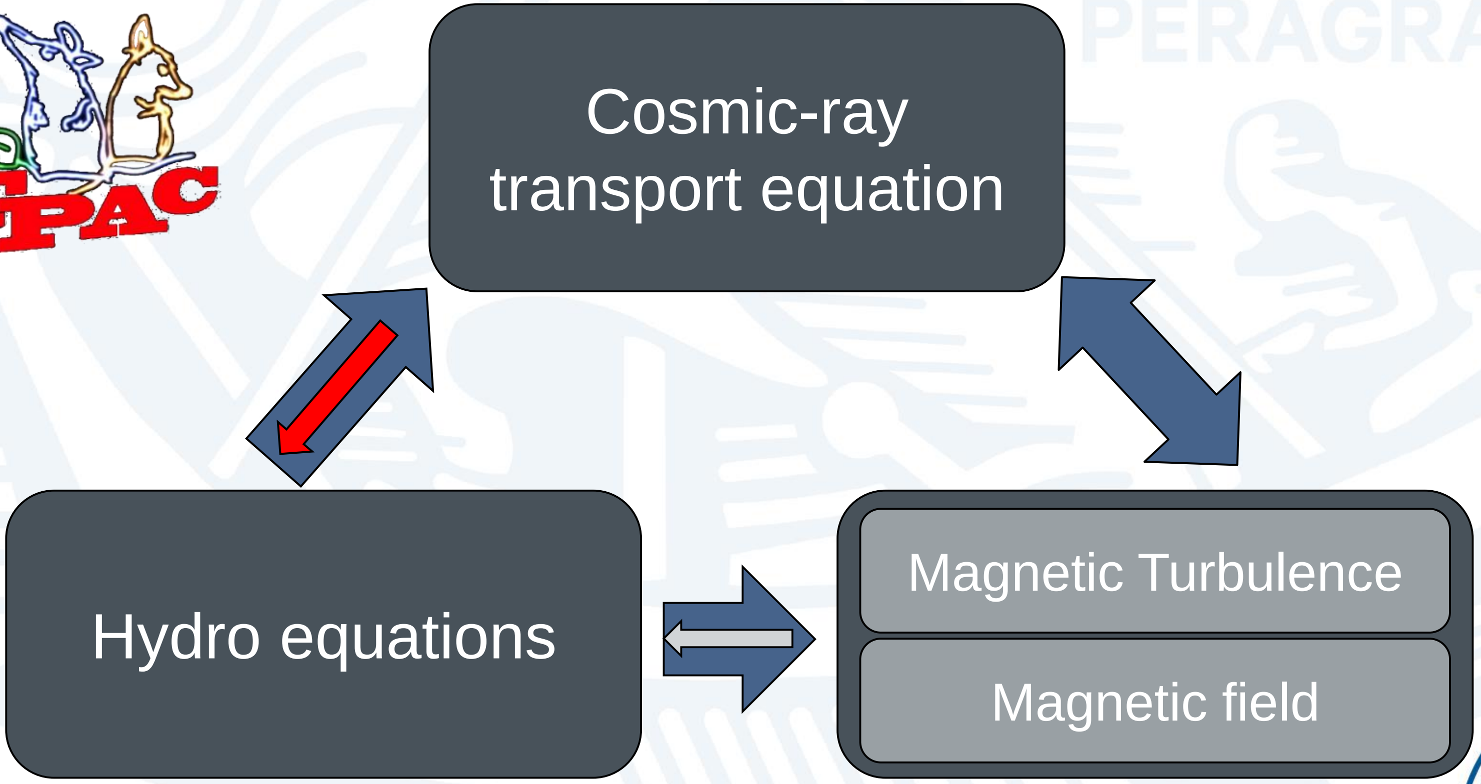


Figures:
(Top) Excess-count map of RX J1713.7-3946

(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:

[8] Young SNRs in dense environments

[88] Spectral softening in CC-SNRs

Fermi acceleration

The equations

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

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

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

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

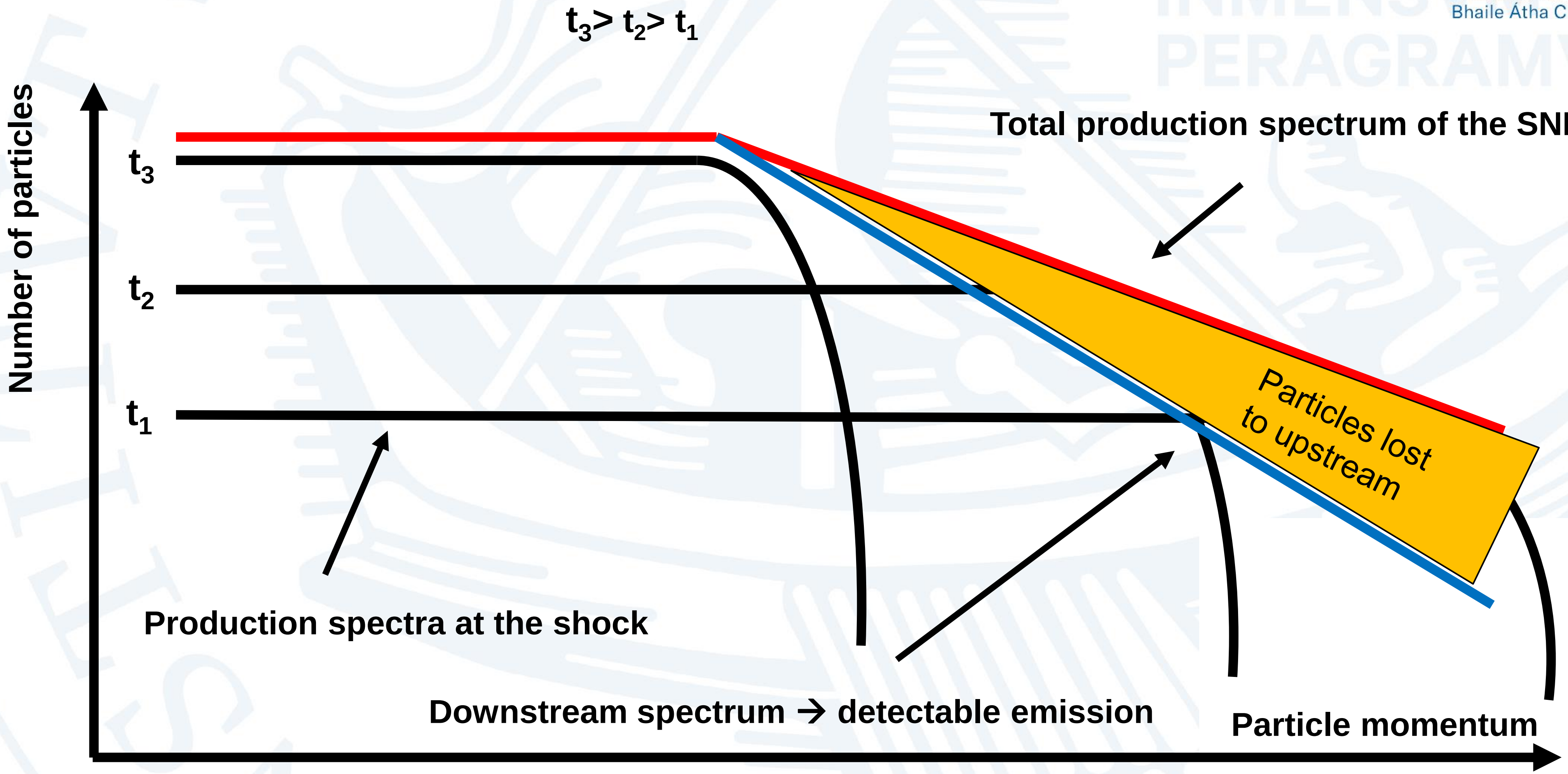
Initial turbulence derived from 1/10th of the Galactic diffusion coefficient ➡ $D_r(t=0) = 10^{28}\left(\frac{pc}{10GeV}\right)^{1/3}\left(\frac{B_0}{3\mu G}\right)^{-1/3} \quad cm^2/s$

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 ➡ $\mathrm{D}_k = k^3 v_A \sqrt{\frac{E_W}{2B_0^2}}$

Results

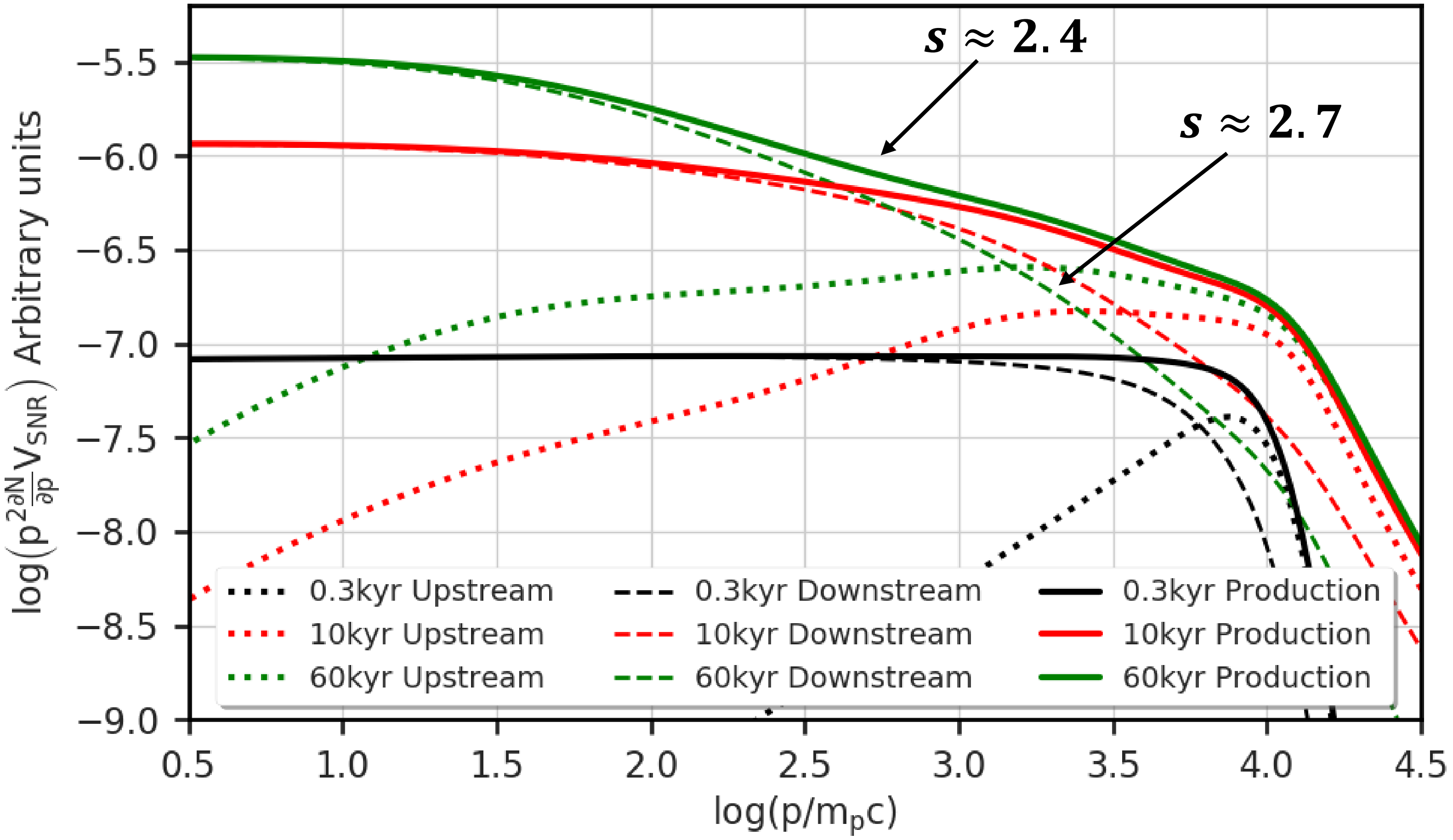
Cosmic-ray escape
The mechanism



Cosmic-ray escape

Production spectra

- The production spectrum agrees roughly with galactic propagation models
- The downstream spectra are softer than the production spectra
- Particles “escape” from deep downstream to upstream

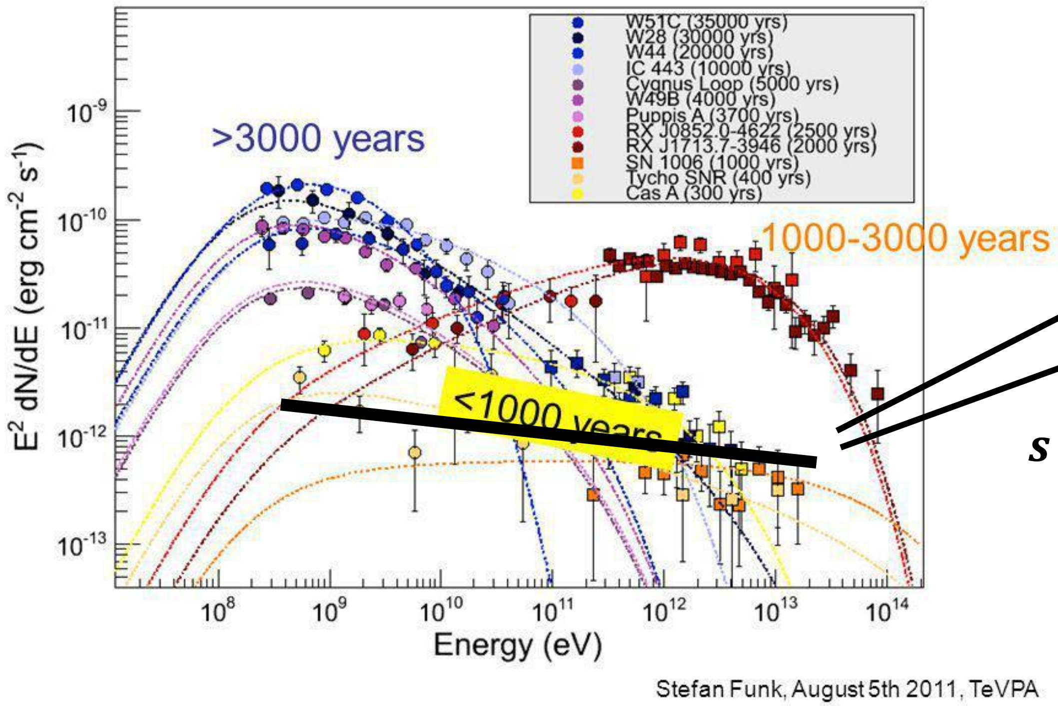


From: **A&A, 634 (2020) A59**

Gamma-ray spectra

Spectral evolution: very young SNRs

Observation:



$s \approx 2$

Model prediction:

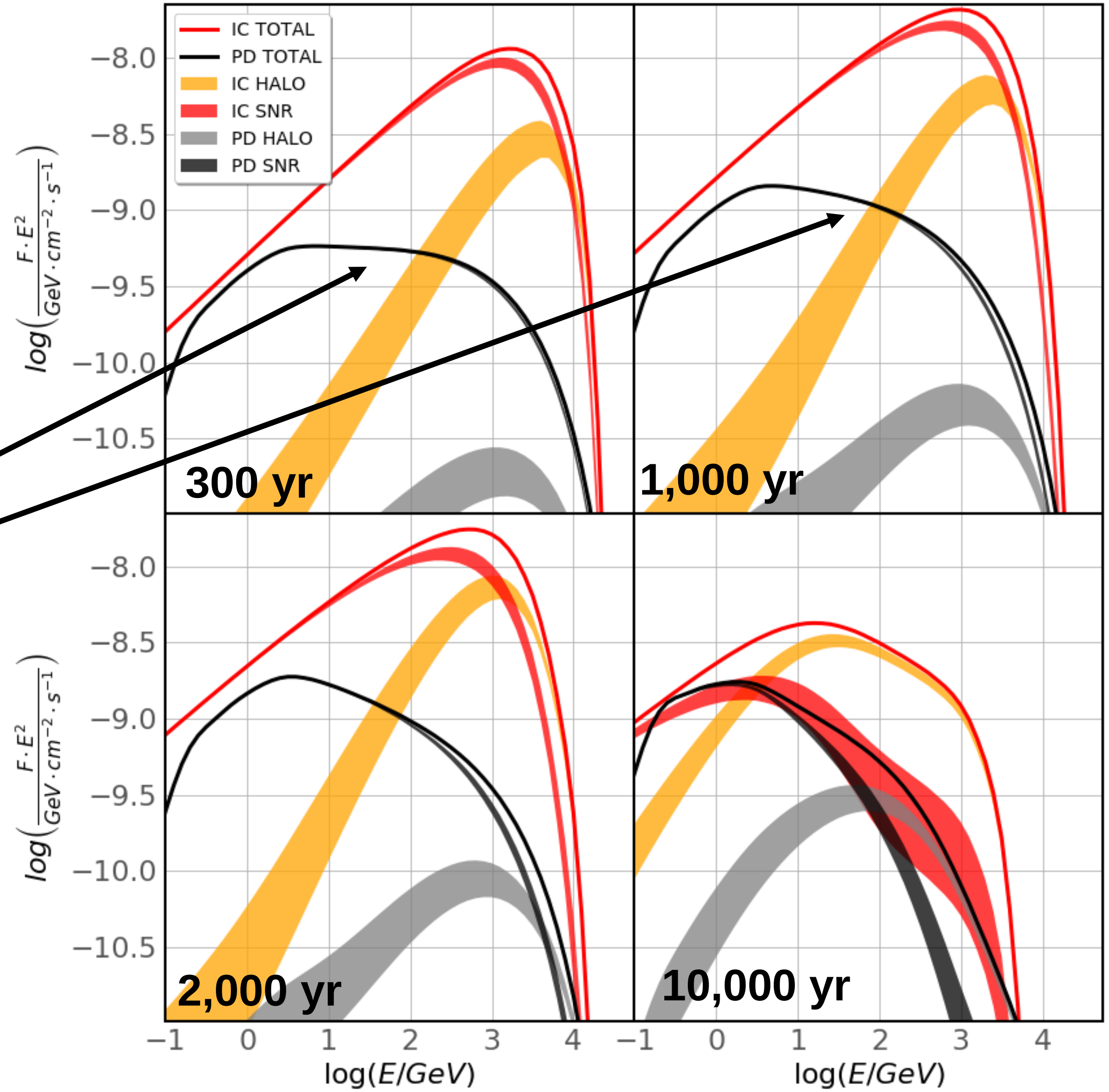
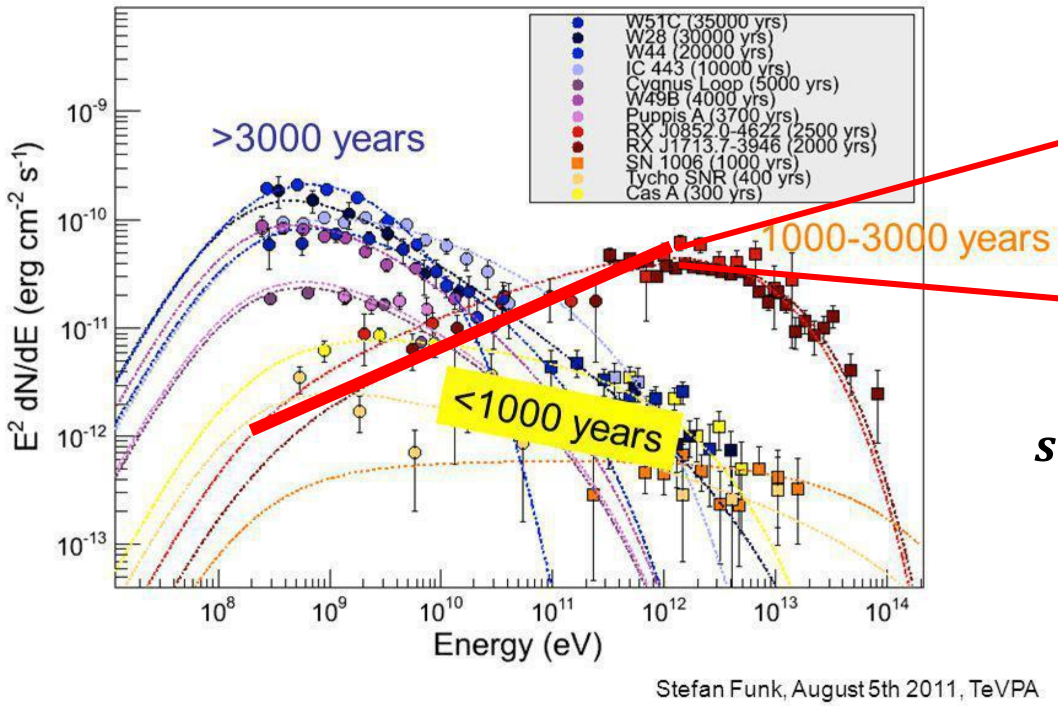


Figure: Gamma-ray flux from various SNRs (Funk, TeVPa 2011)

Gamma-ray spectra

Spectral evolution: young SNRs

Observation:



$s \approx 1.5$

Model prediction:

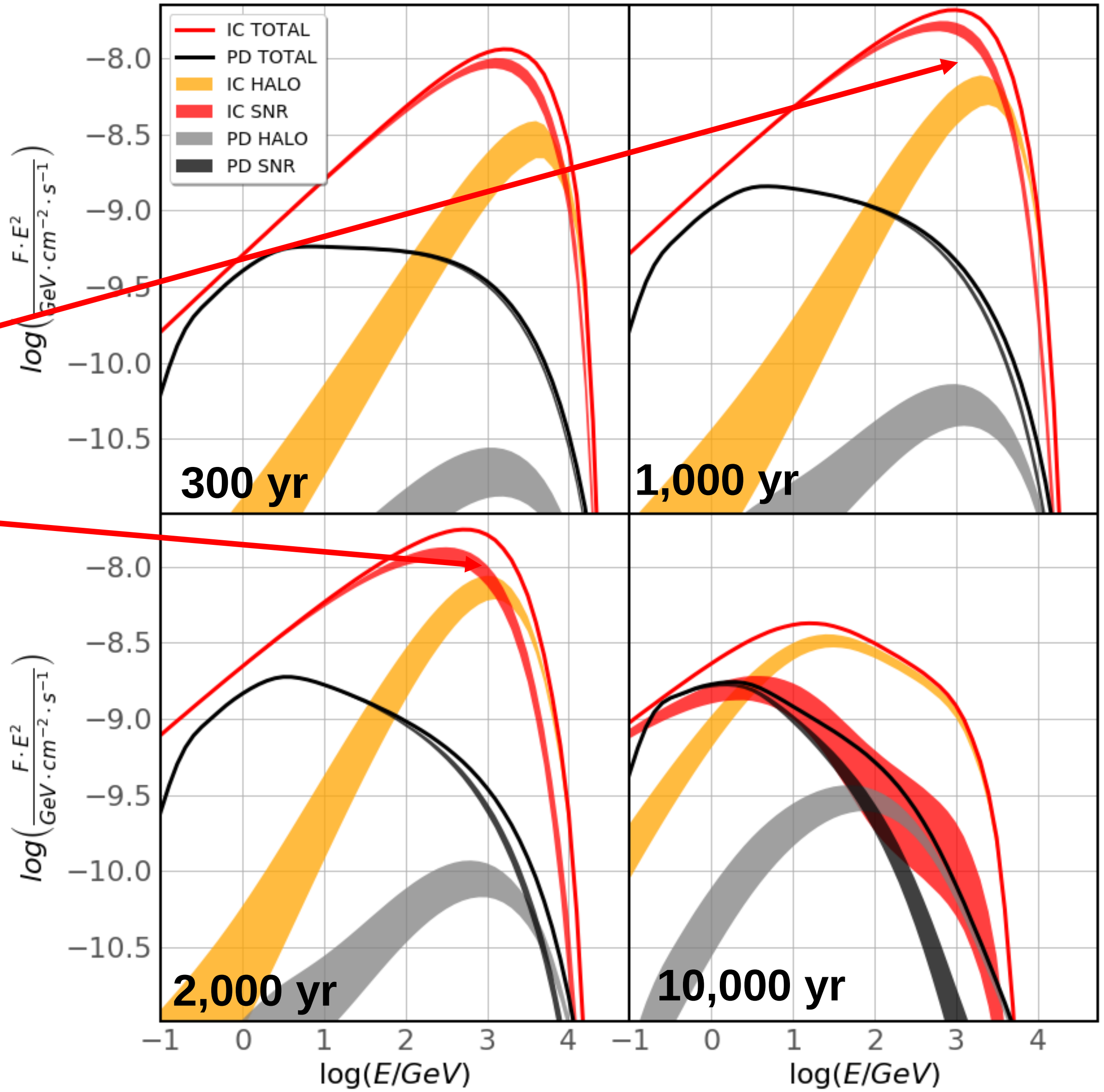


Figure: Gamma-ray flux from various SNRs (Funk, TeVPa 2011)

Gamma-ray spectra

Spectral evolution: evolved SNRs

Observation:

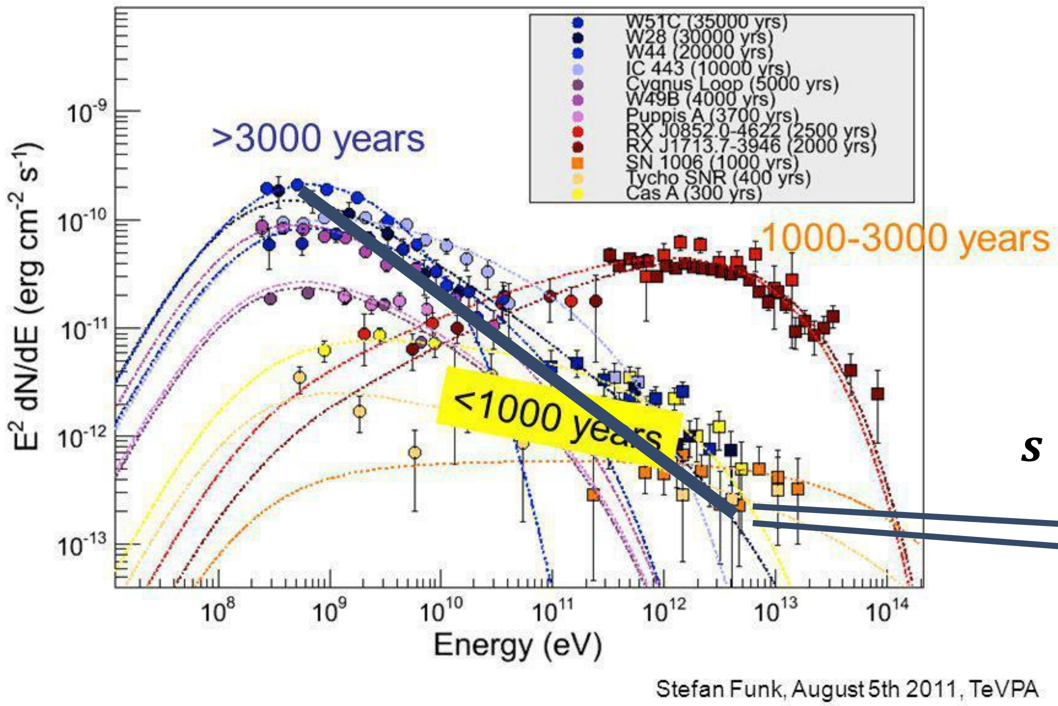
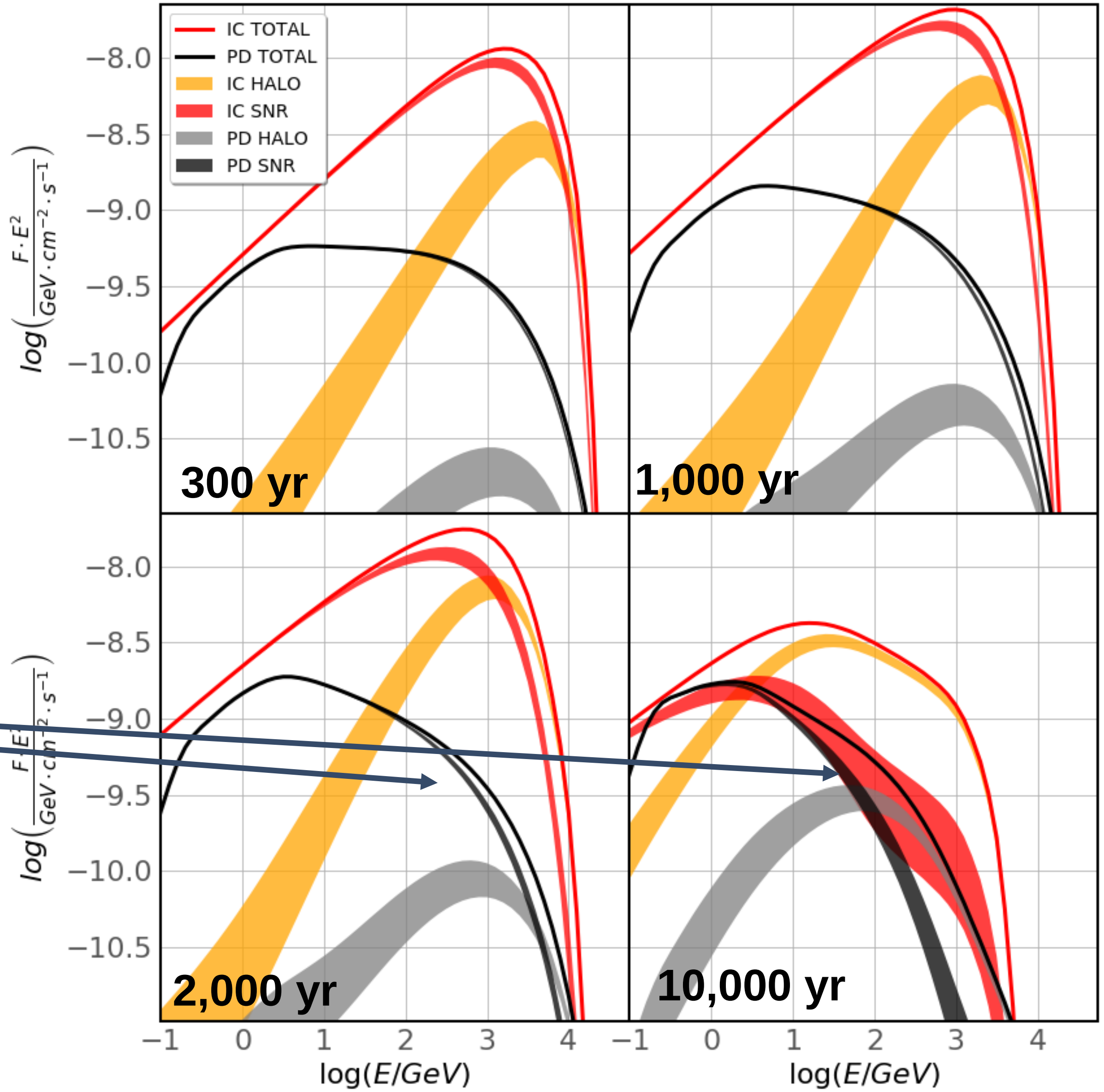


Figure: Gamma-ray flux from various SNRs (Funk, TeVPa 2011)

$s \geq 2.7$

Model prediction:



Gamma-ray morphology

Emission and spectral index maps

PD-emission:

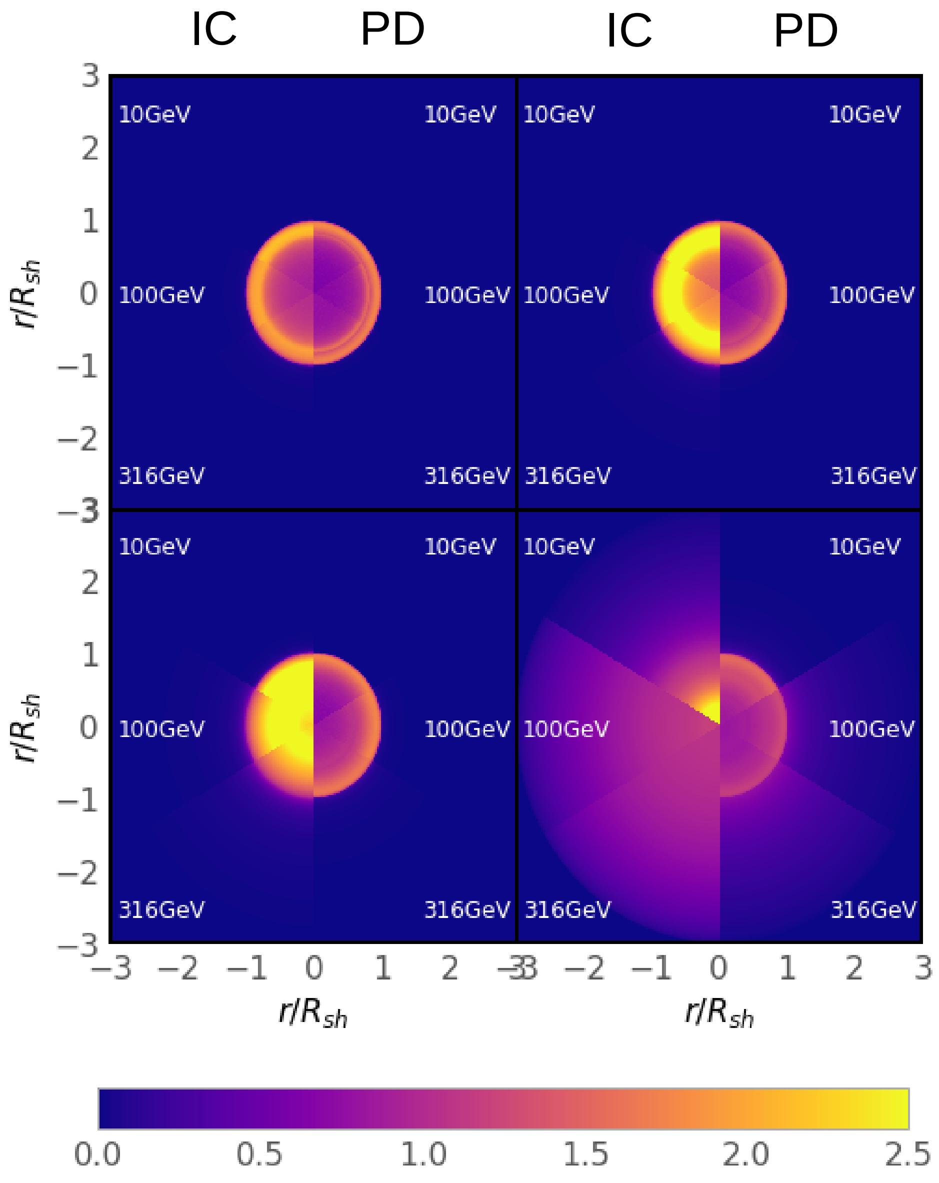
- Shell-like morphology throughout all phases and energies
- Faint halo emission

IC-emission:

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

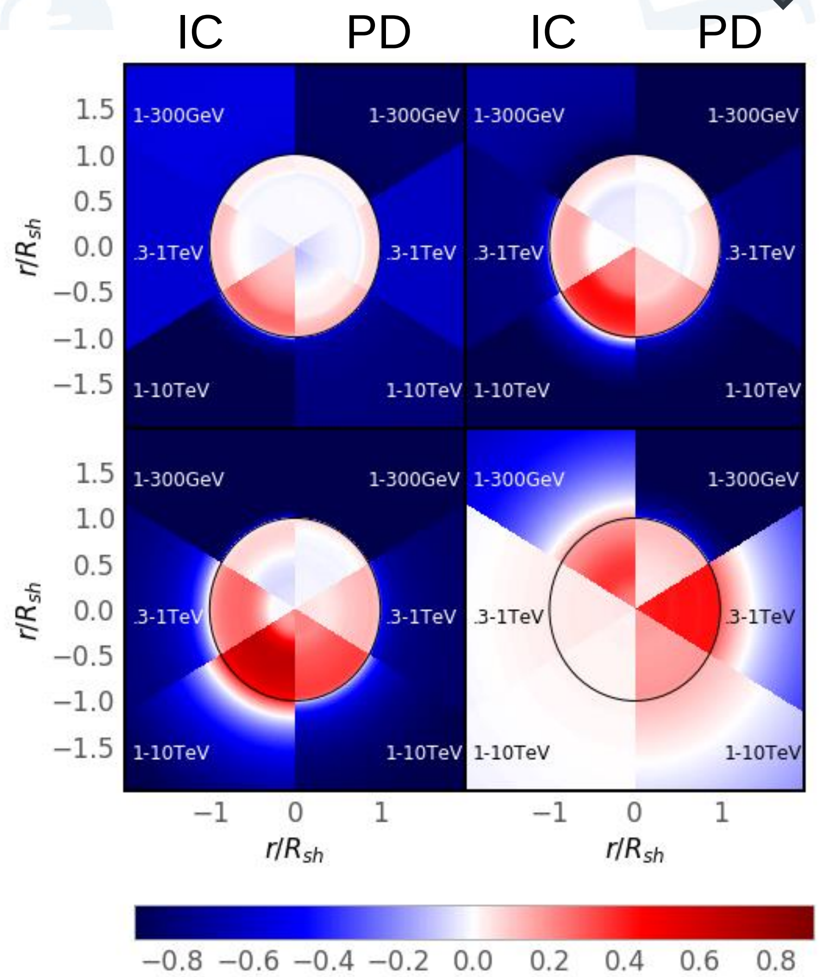
Spectral index distribution:

- No significant deviation from regions of brightest emission



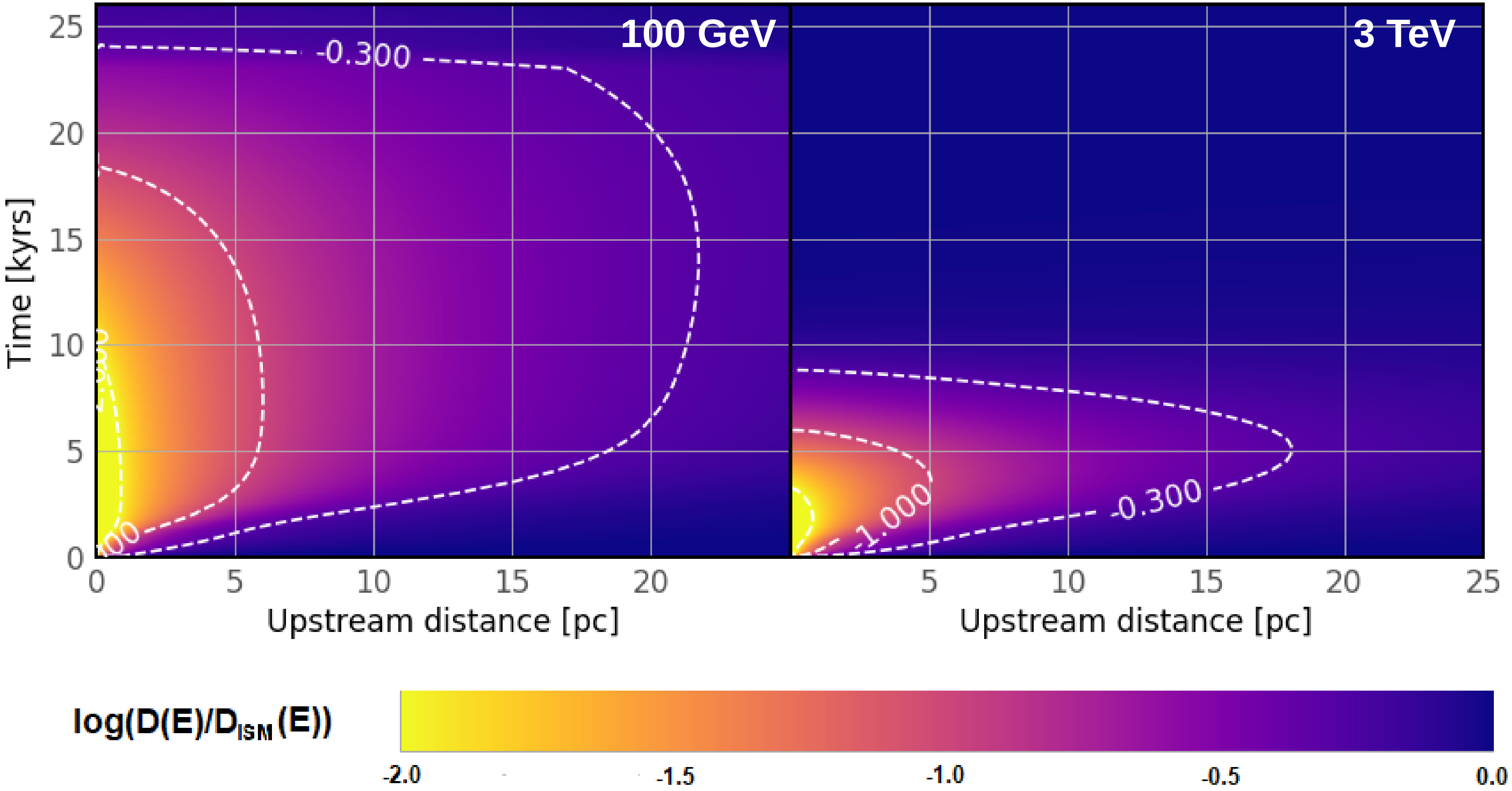
Emission maps

Spectral index deviation maps



Halo diffusion coefficient

- 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



From: **A&A, 654 (2021) A139**

The formation of gamma-ray halos around supernova remnants through particle escape
Robert Brose, TeVPa, 25-29 October 2021

Conclusions

- A strong evolution of E_{max} results in **soft production spectra** even if the acceleration mechanism is standard DSA
- The spectral index of the production spectra is $\boldsymbol{s \approx 2.4}$ **is close to the predictions by galactic propagation models** ($s = 2.2 - 2.4$)
- Particle **escape** of the highest energetic CRs **forms soft spectra at high energies** and spectral breaks between 1-10GeV
- **Reduced diffusion coefficient in the upstream**; strong spatial and temporal evolution
- 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

See also: **A&A, 634 (2020) A59; A&A, 654 (2021) A139**

Thank you for your attention!