IRISH RESEARCH COUNCIL
An Chomhairle um Thaighde in Éirinn

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

# The formation of γ-ray halos around SNRs through particle escape

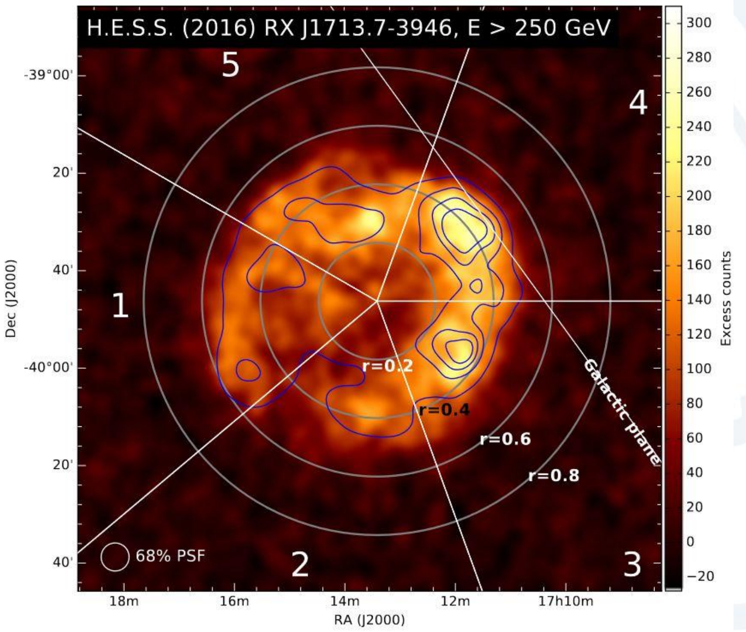
Robert Brose, M. Pohl, I. Sushch

TeVPa, 8-12 August 2022

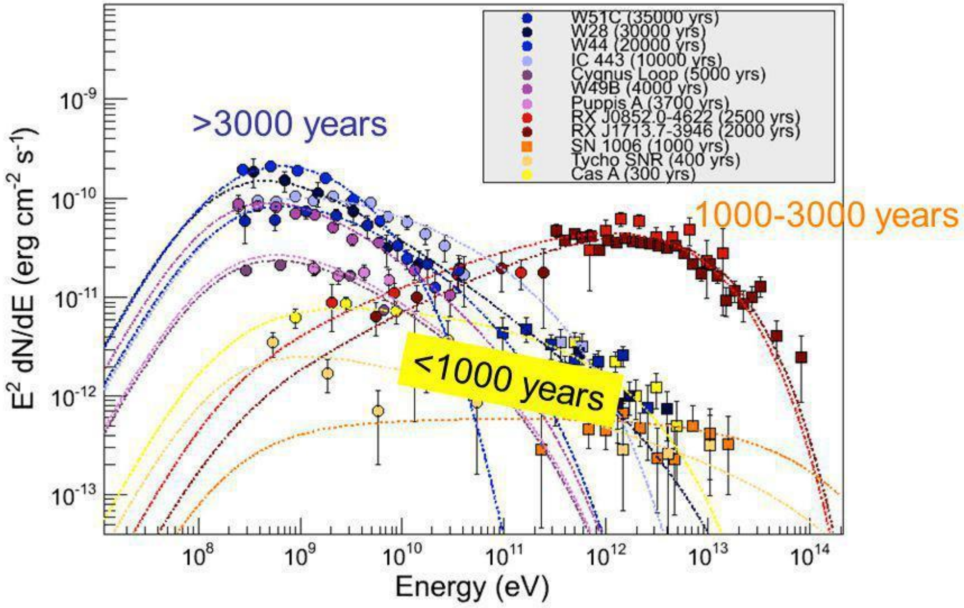
# CRs from SNRs
## Observational overview

**More and more observational constrains:**

**Models need to account for spectral evolution and morphology**

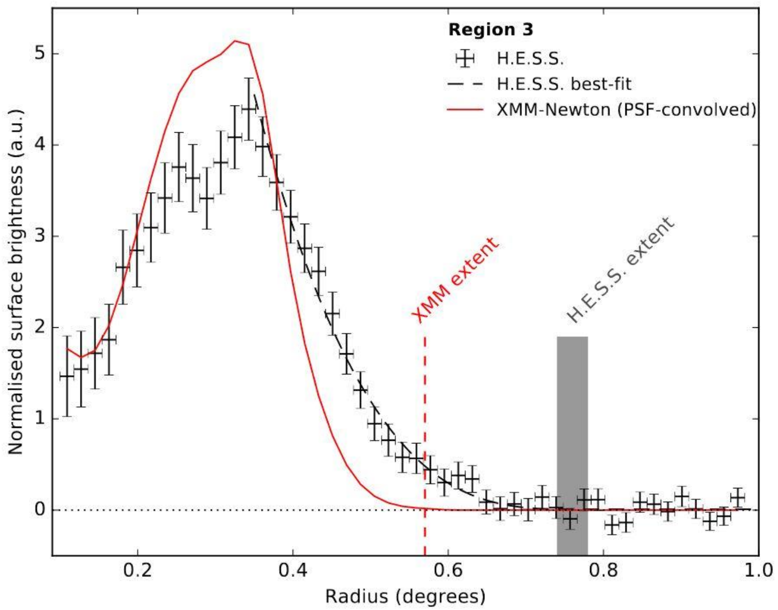



Evolution of particle acceleration in the shell-type SNRs




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)**

# CRs from SNRs
## Morphological complications

Spectral-index mismatch!

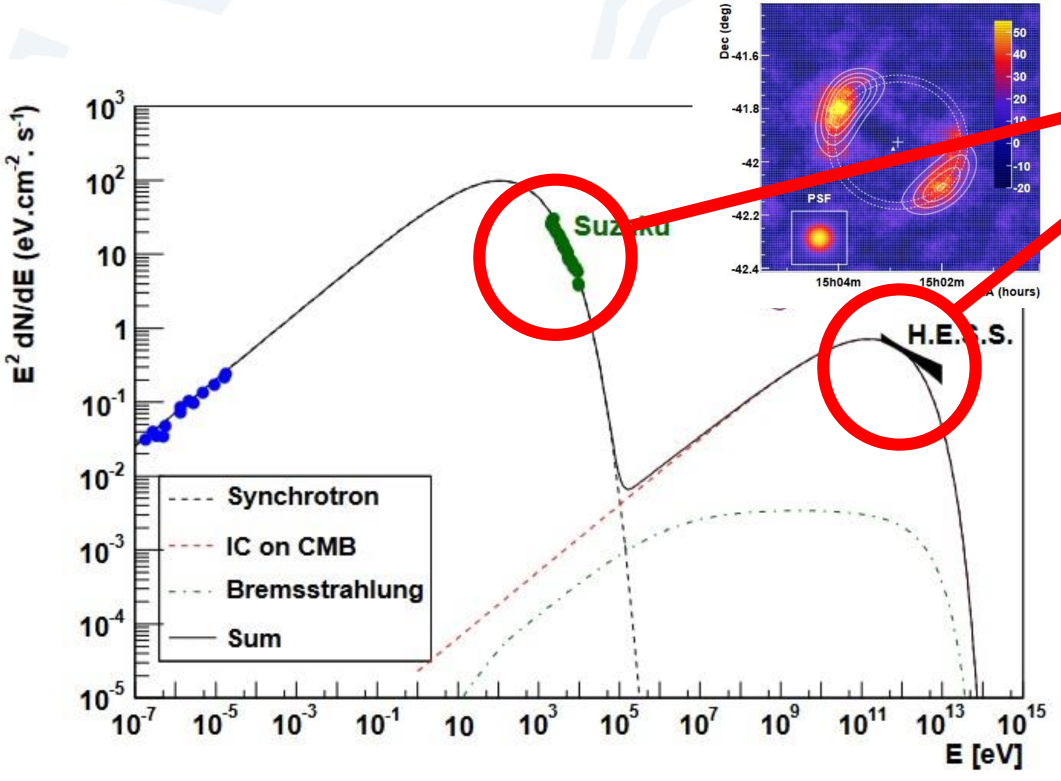



**Figure: SN1006 VHE-map and leptonic SED-model ([H.E.S.S. 2010](#))**

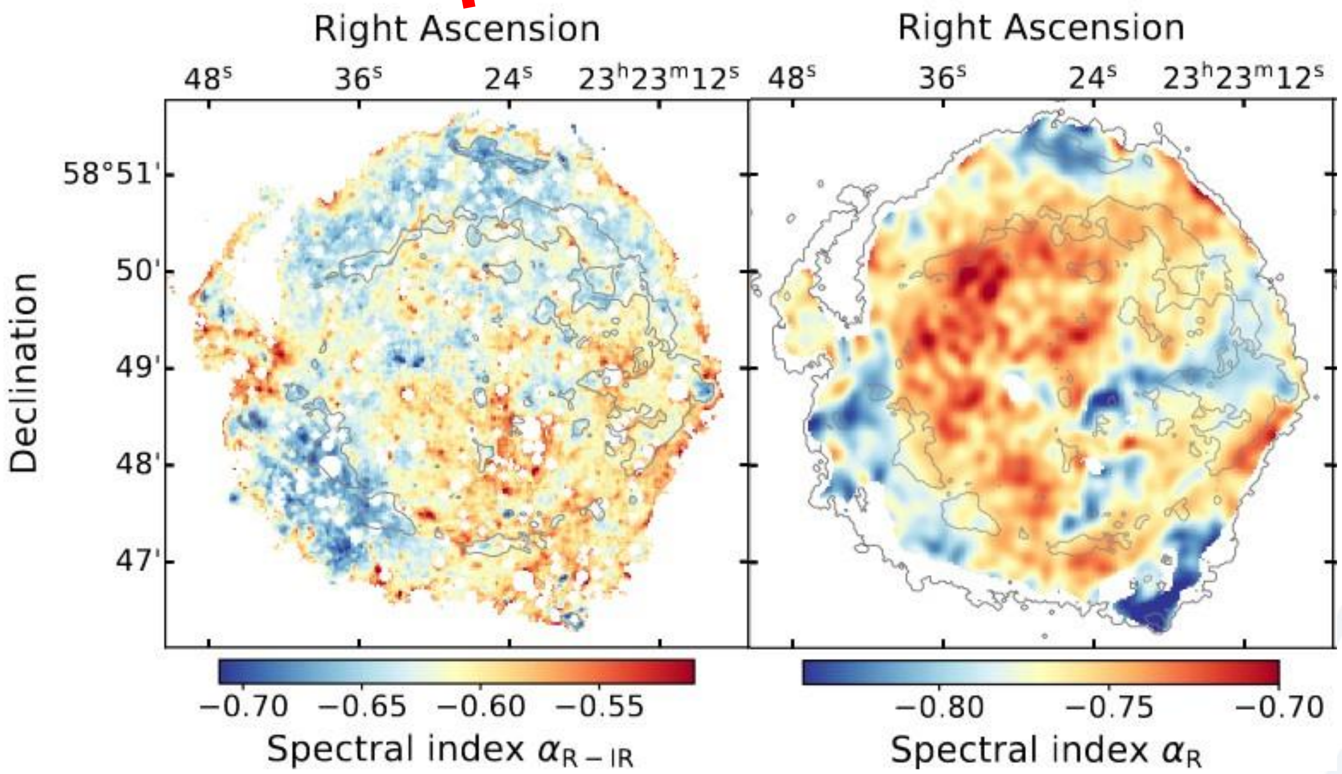



**Figure: Cas A Radio-spectral index map (right), Cas A Radio-to-IR-spectral index map (left) ([Domček et al. 2021](#))**

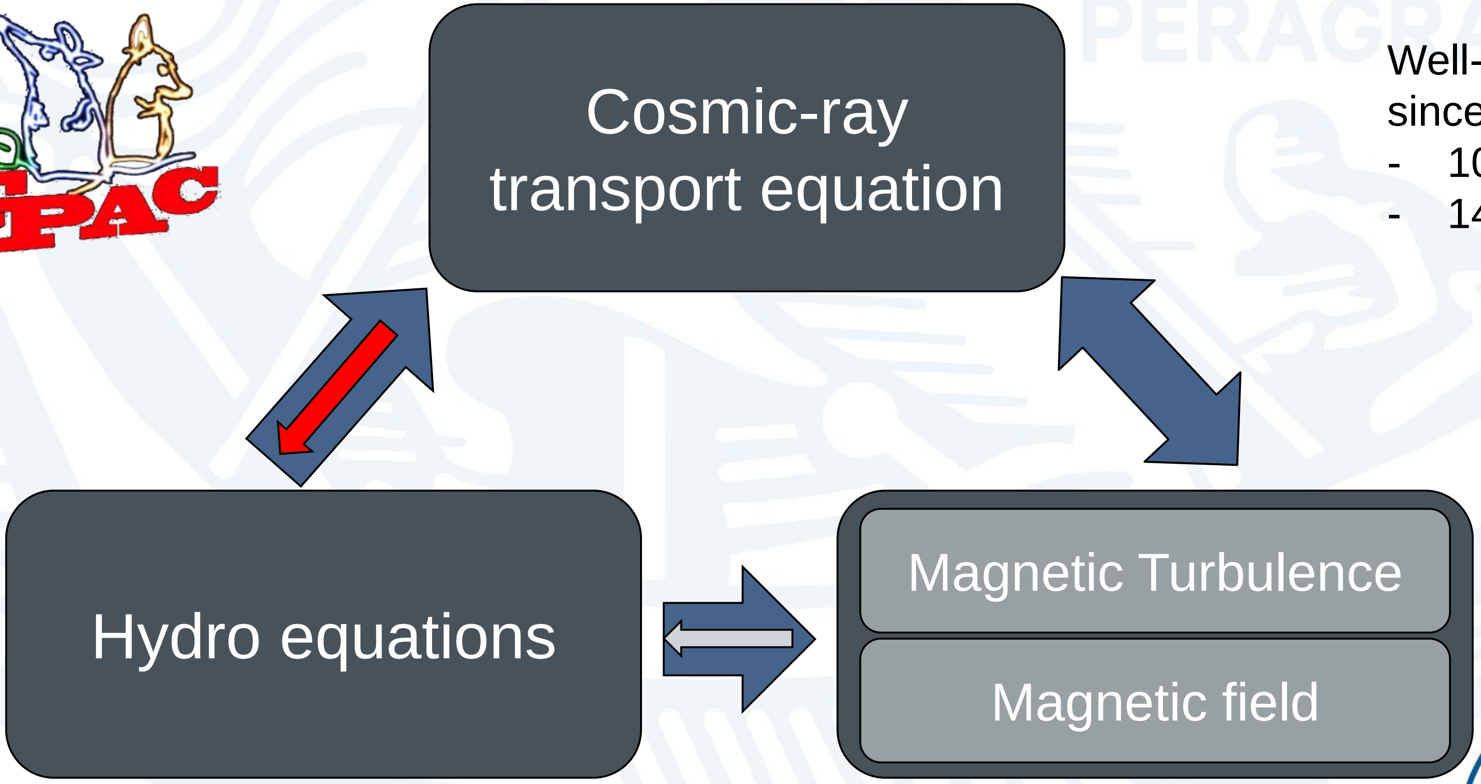
# Fermi acceleration
## Coupled equations

***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




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

# Fermi acceleration

## The equations

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

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

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

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

**The equations are solved:**

- One dimensional
- Assuming spherical symmetry
- Including Synchrotron 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

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

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

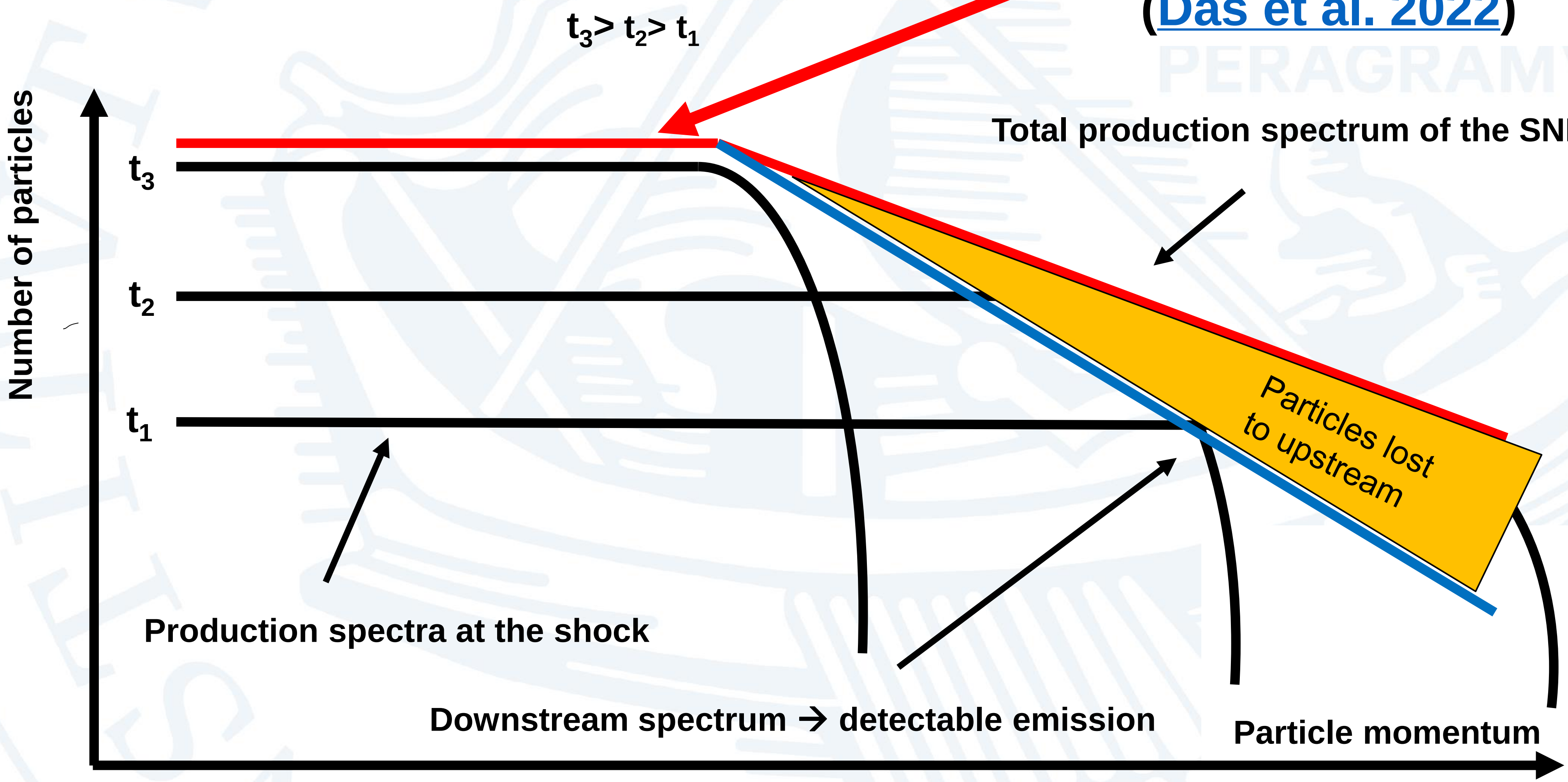
INSTITVTVM · STVD · SVP · DVBLINENSE · MCMXL · INMENSVM PERAGRAMVS

# Results

# Cosmic-ray escape

## The mechanism

**More complicated for CC-SNRs: e.g. hot CSM softens spectra ([Das et al. 2022](#))**

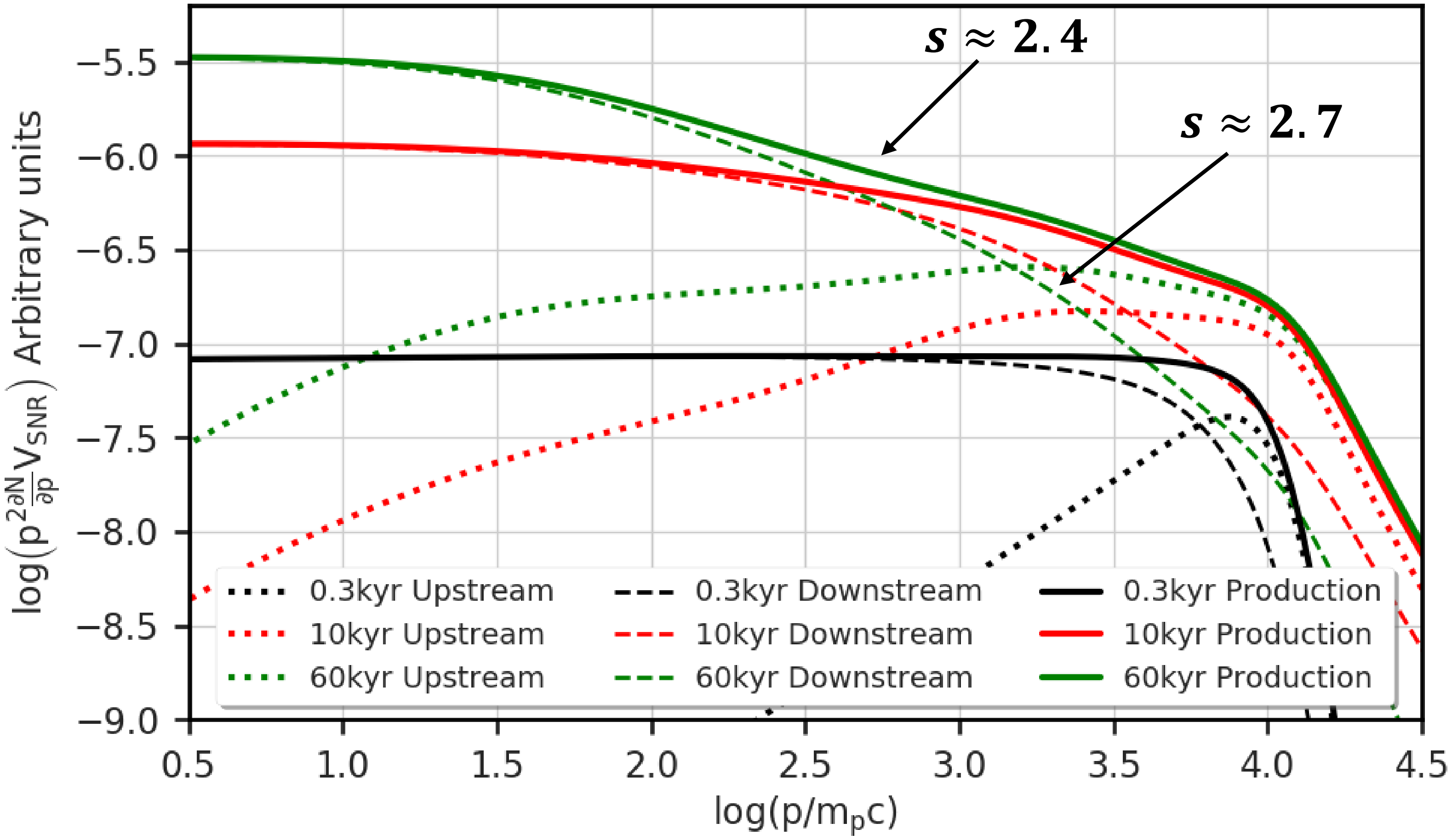


# Cosmic-ray escape

## Production spectra

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

- The production spectrum agrees with galactic propagation models (Moskalenko et al. 2002)
- The downstream spectra are softer than the production spectra
- Particles "escape" from deep downstream to upstream

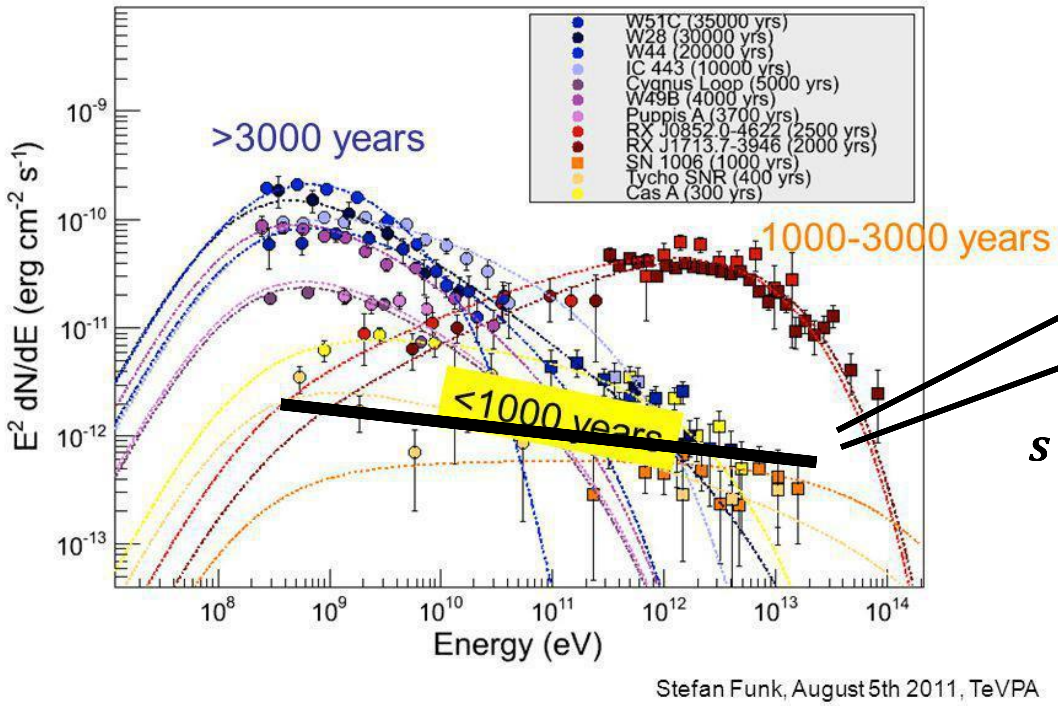



From: **A&A, 634 (2020) A59**

# Gamma-ray spectra

## Spectral evolution: very young SNRs <1000 yrs

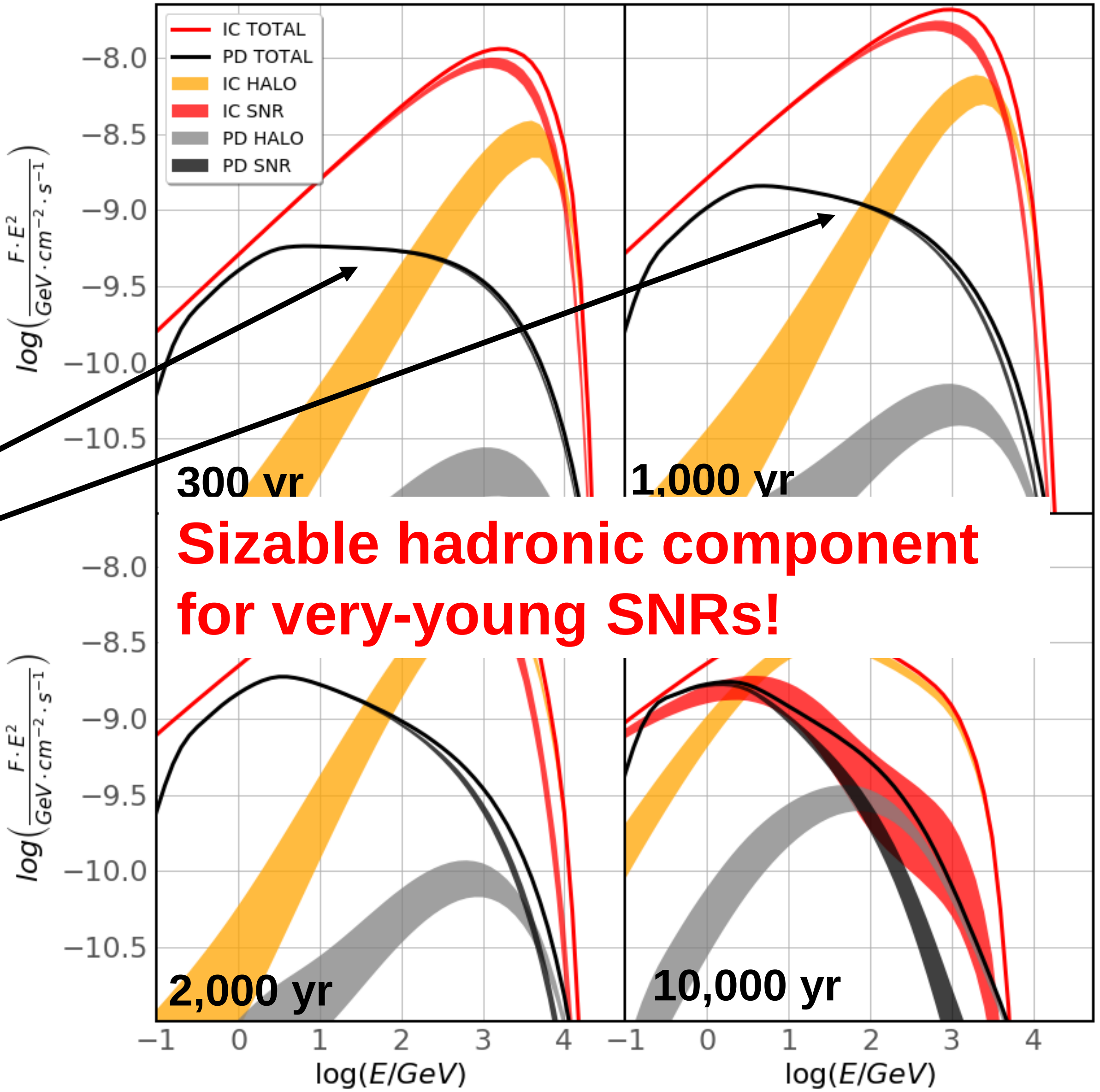
## Observation:




$s \approx 2$

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

## Model prediction:

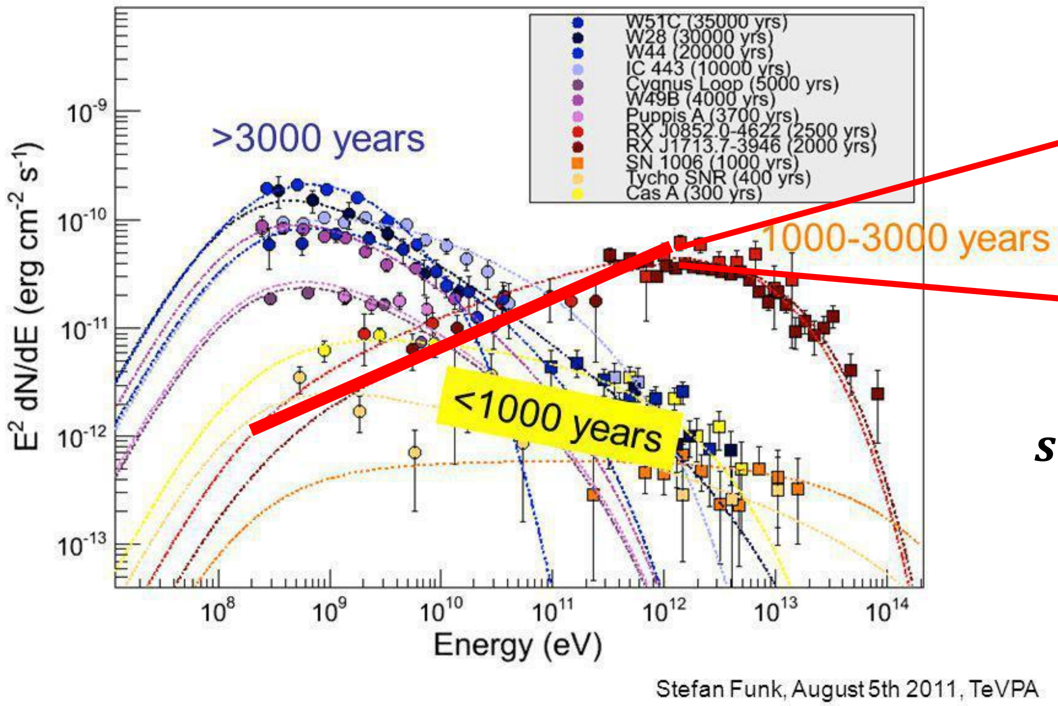



**Sizable hadronic component for very-young SNRs!**

# Gamma-ray spectra

**Spectral evolution: young SNRs 1000-3000 yrs**

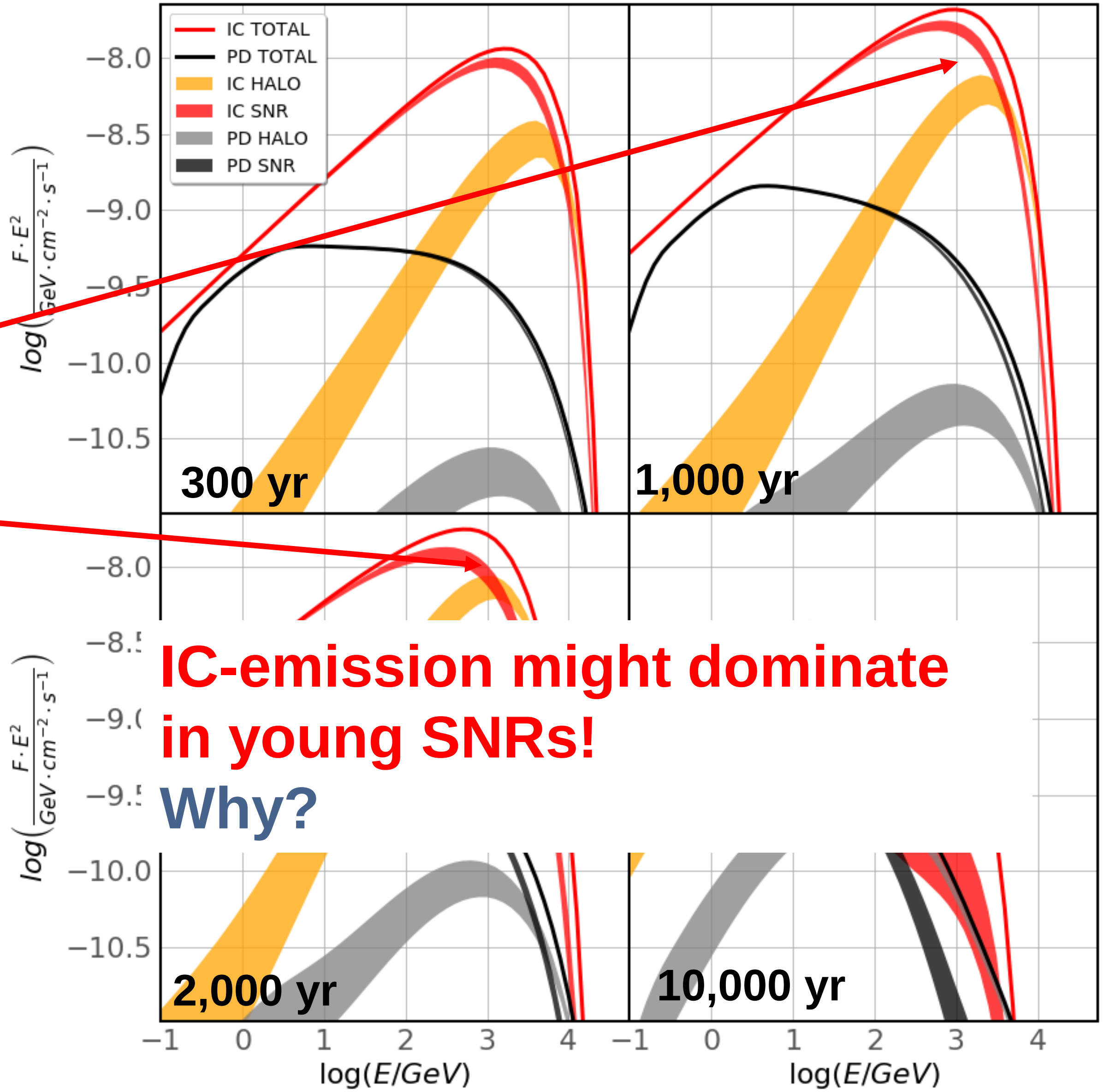
## Observation:




$s \approx 1.5$

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

## Model prediction:




**IC-emission might dominate in young SNRs!**

**Why?**

# Gamma-ray spectra

## Spectral evolution: young SNRs 1000-3000 yrs

## Observation:

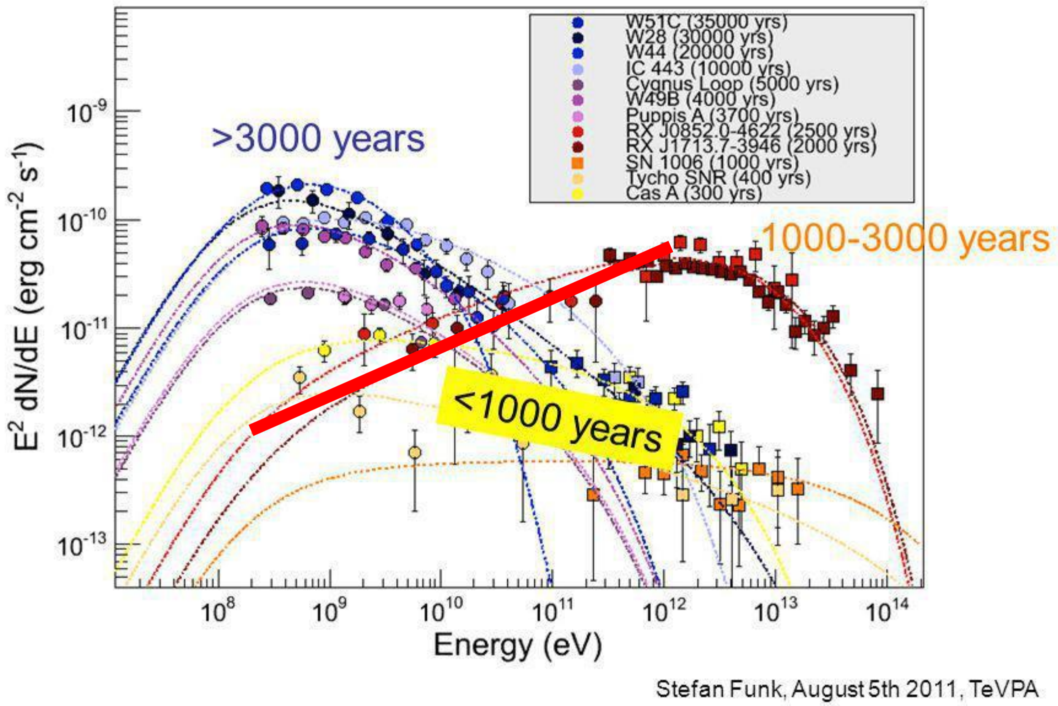



**Figure: Gamma-ray flux from various SNRs (Funk, TeVPa 2011)**

## Why are only leptonic SNRs detected in this age-range:

## Selection effects!

$$L \propto N_{CR} \cdot n_{target}$$

$$V_{SNR} \propto \rho^{-\frac{3}{5}} \cdot t^{\frac{6}{5}} \quad \text{(Sedov-solution)}$$

$$N_{CR} \propto V_{SNR} \cdot \rho = \rho^{\frac{2}{5}} \cdot t^{\frac{6}{5}} \qquad n_{target} \propto \begin{cases} 1 \; for \; IC \\ \rho \; for \; PD \end{cases}$$

$$\boldsymbol{L_{PD} \propto \rho^{\frac{7}{5}} \cdot t^{\frac{6}{5}}}$$

$$\boldsymbol{L_{IC} \propto \rho^{2/5} \cdot t^{\frac{6}{5}}}$$

**BUT**

$$V_{shock} \propto \rho^{-\frac{3}{5}} \cdot t^{-\frac{3}{5}}$$

**→ SNRs in dilute environments accelerate longer, thus reach a brighter peak IC-emission!**

# Gamma-ray spectra

## Spectral evolution: young SNRs 1000-3000 yrs

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

## Observation:

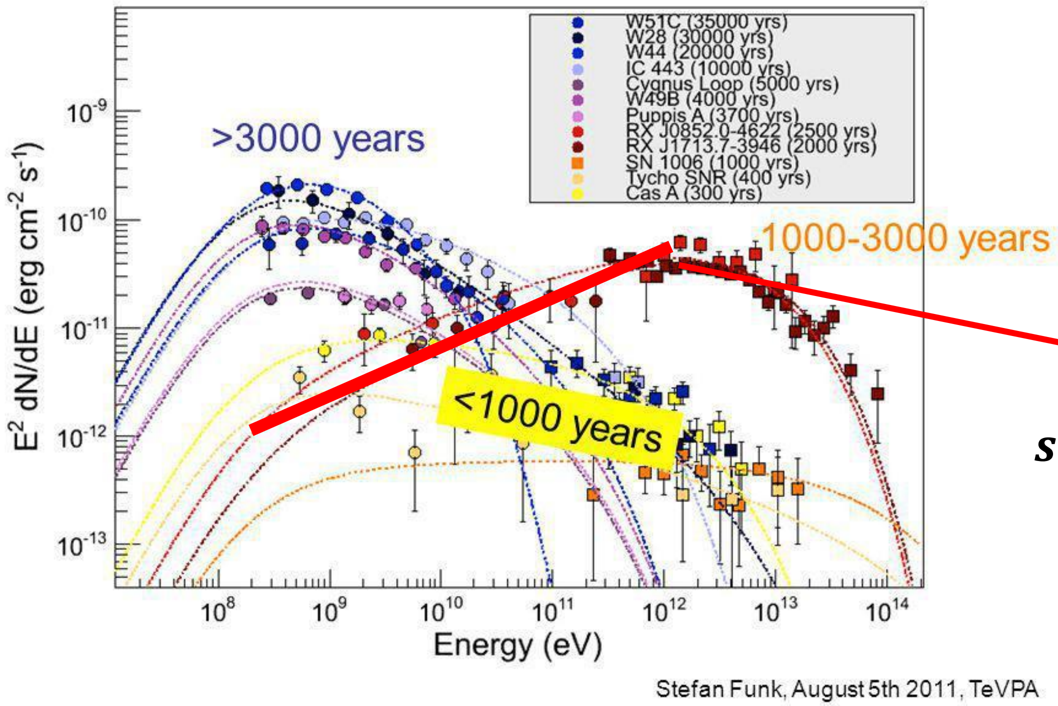
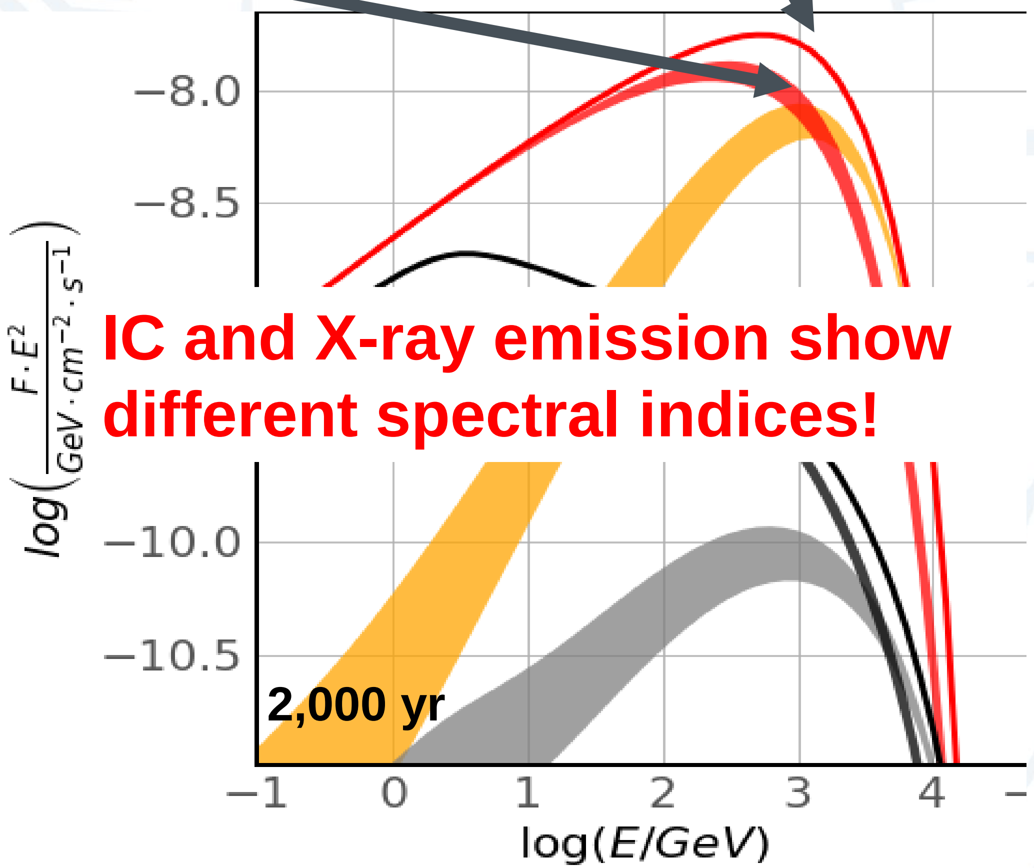



**Figure**: Gamma-ray flux from various SNRs (Funk, TeVPa 2011)

$s \approx 1.5$

**Synchrotron-emission: downstream only**

**IC-emission: all particles**




**IC and X-ray emission show different spectral indices!**

# Gamma-ray spectra

## Spectral evolution: evolved SNRs >3000 yrs

### Observation:

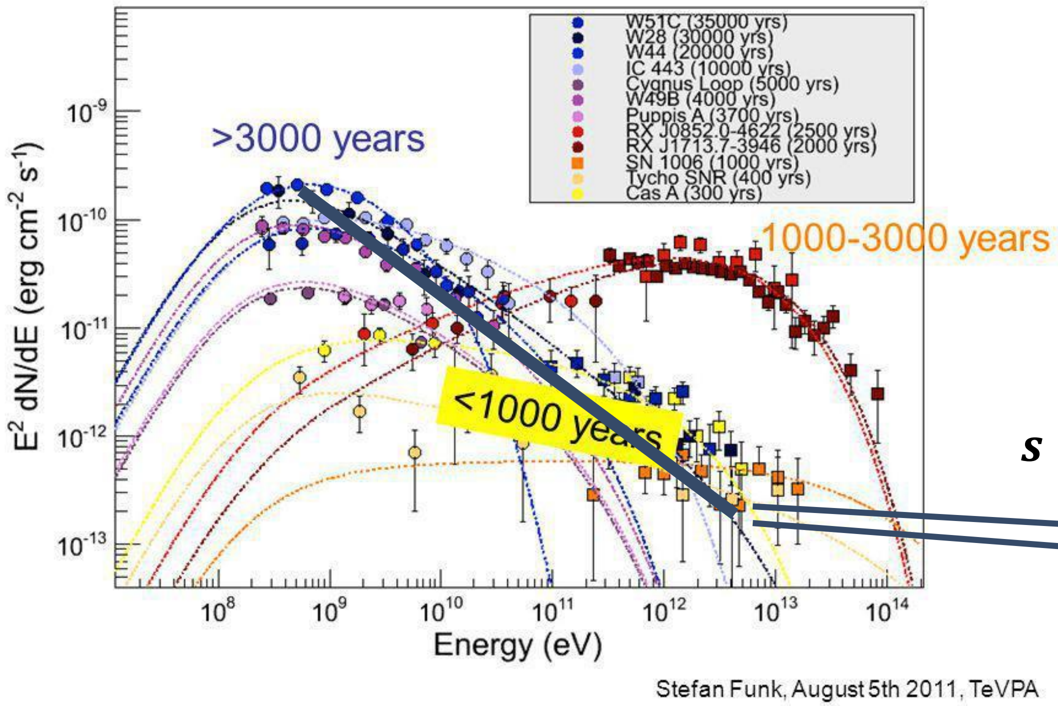
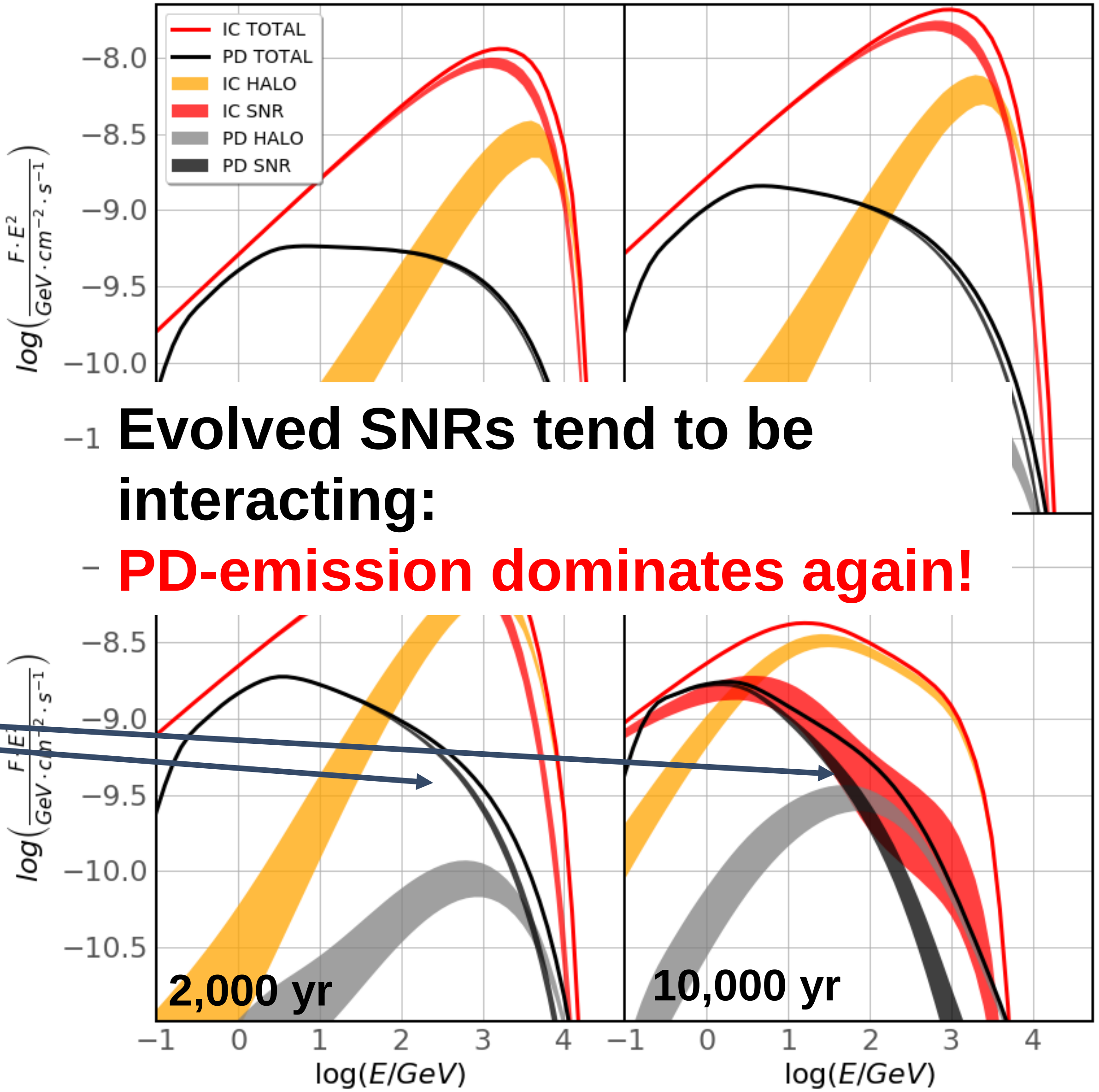



**Figure: Gamma-ray flux from various SNRs (Funk, TeVPa 2011)**

$s \geq 2.7$

### Model prediction:




**Evolved SNRs tend to be interacting:**

**PD-emission dominates again!**

# Gamma-ray morphology

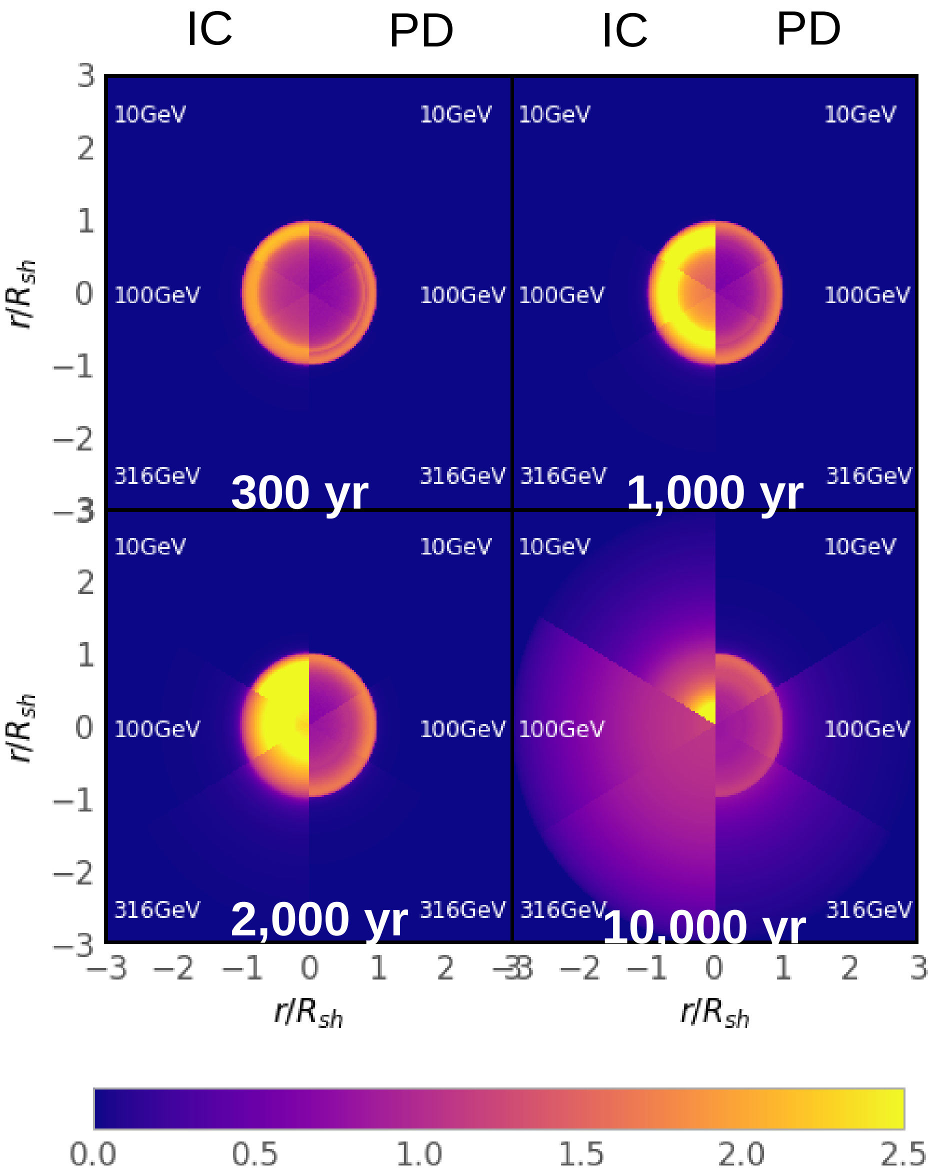
## Emission maps

**PD-emission:**

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

**IC-emission:**

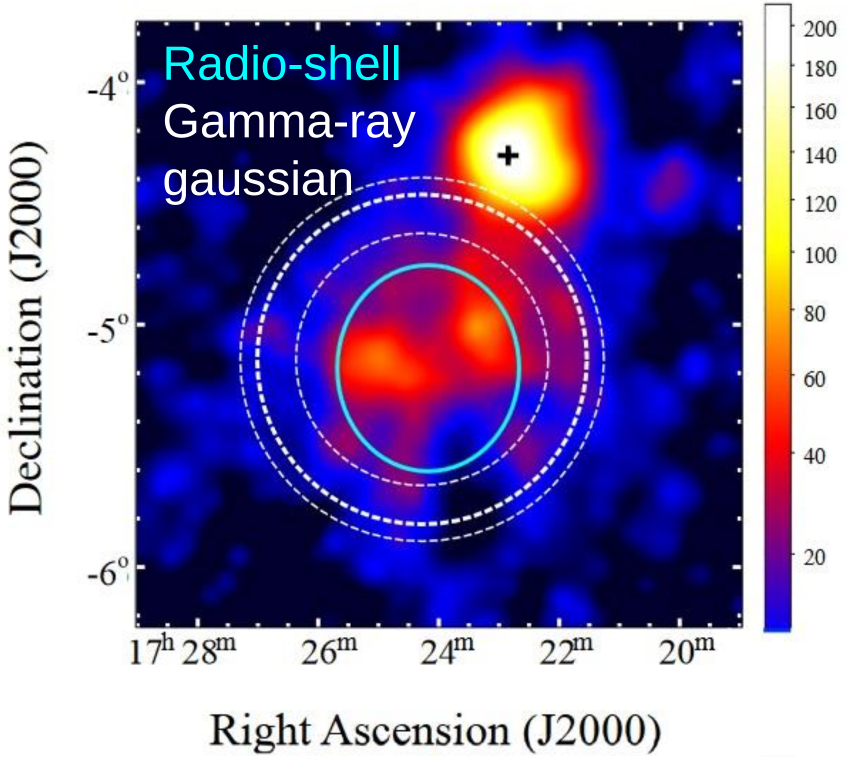
- Initially shell like morphology
- Transition to center-filled
- Halo emission already after 2kyr




Emission maps

**Extended, off-plane SNRs are excellent test-beds:**
**→ Escape is resolvable!**

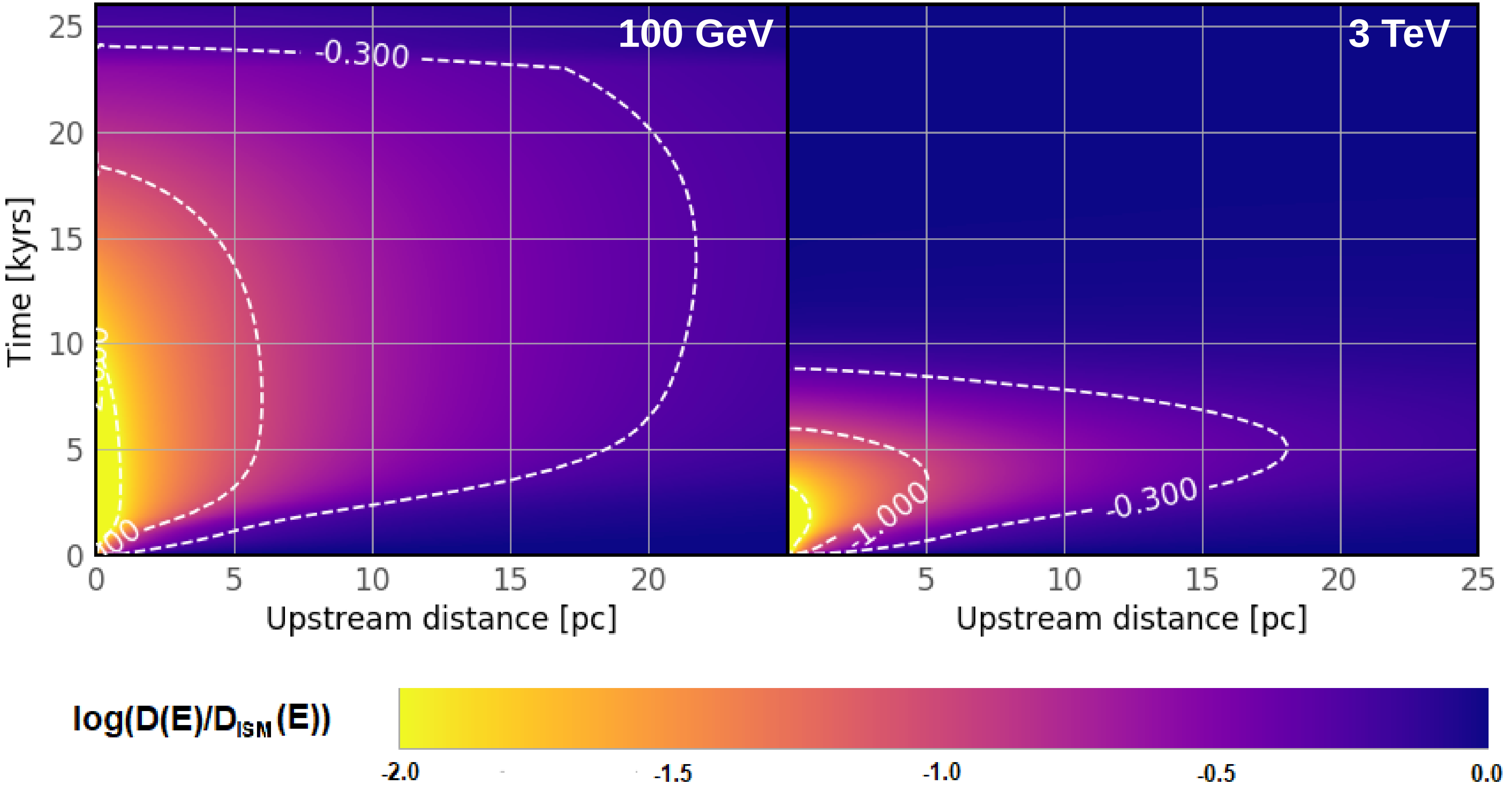
**Figure: Radio and GeV γ-rays from FHES J1723.5−0501 (G17.8+16.7) (Araya et al. 2021)**



# 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

→ **Similar behavior as in PWN-halos**




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

# Conclusions

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

- 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 1-100GeV
- **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!

# Gamma-ray morphology

## Spectral index maps and Radio emission

**Spectral index distribution:**

- No significant deviation from regions of brightest emission (gamma-rays)

**Radio-emission:**

- Continuous Radio-brightening and X-ray fading
- Escape later even affects Radio-emitting electrons
  → Spectral-index variations

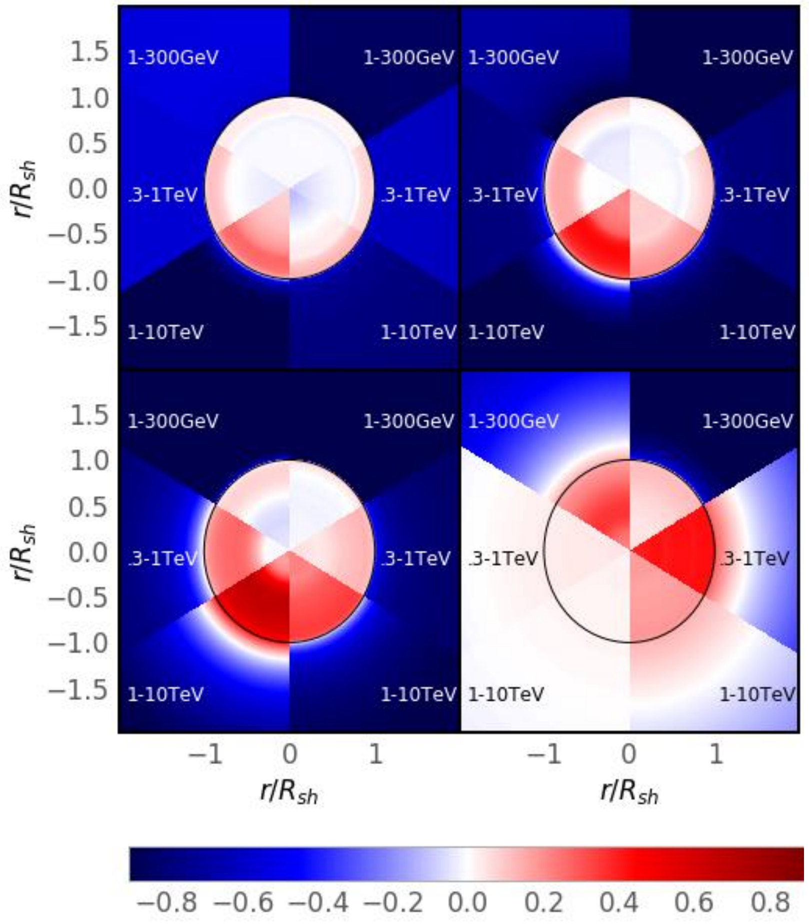



**Figure: Synchrotron-SED evolution**