Understanding Multimessenger Signatures with Cosmic-Ray Propagation and Interaction in Astrophysical Plasmas

Review articles:

J.K. Becker, High-energy neutrinos in the context of multimessenger astronomy, Phys.Rep. (2008)

J. Becker Tjus & L. Merten, Closing in on the origin of Galactic cosmic rays using multimessenger information, Phys. Rep. (2020)

Julia Tjus | Ruhr-Universität Bochum | 27.11.20

RAPP Center

Astroparticle Physics

- **Measurements:** photons, cosmic rays & neutrinos
- **Modeling:** Multimessenger approach → explain all signatures at the same time
- **Theory:** Microphysics (hadronic interactions/radiation), Macrophysics (cosmology, plasma physics)

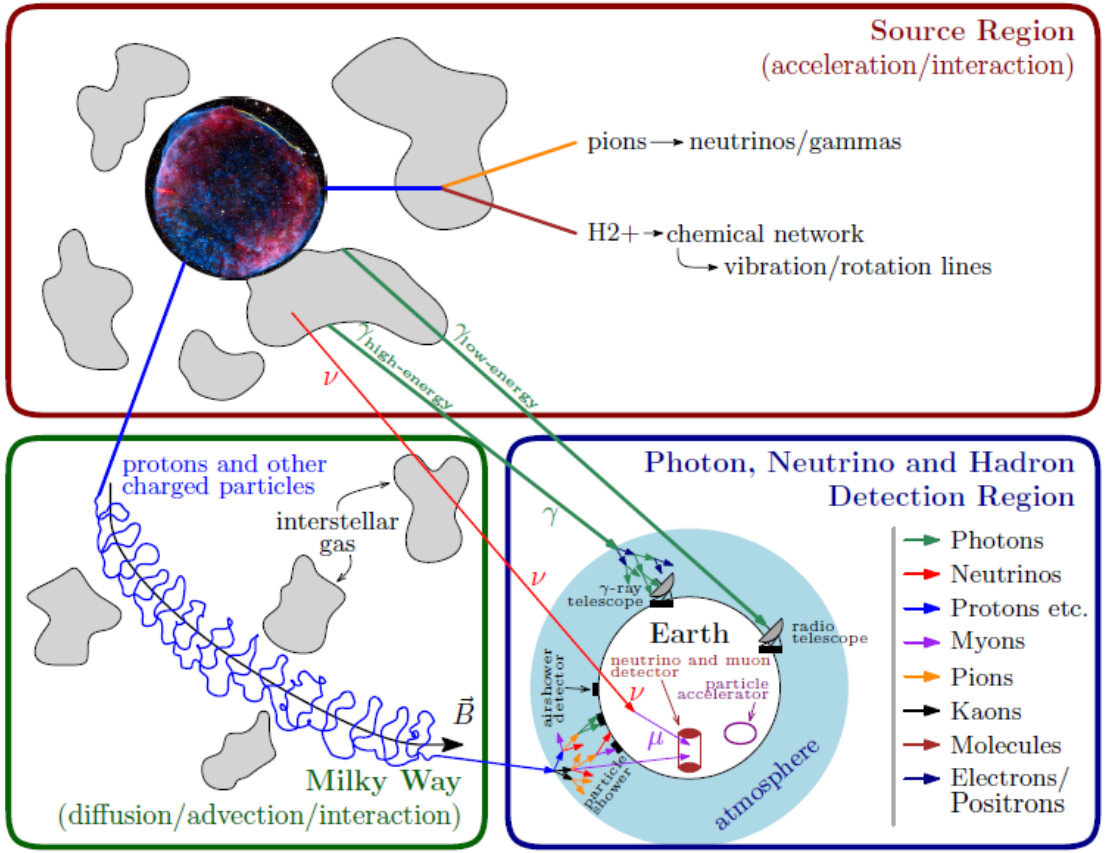

Figure: JBT & Merten, Phys.Rep. (2020)
[legacy of the Wolfgang-Wagner plot, TU Dortmund (2004)]

This talk

- **Part I: Cosmic-ray propagation –** Plasma Physics
- **Part II: Local source physics –** particle interaction & radiation
- **Part III: Multimessenger modeling**

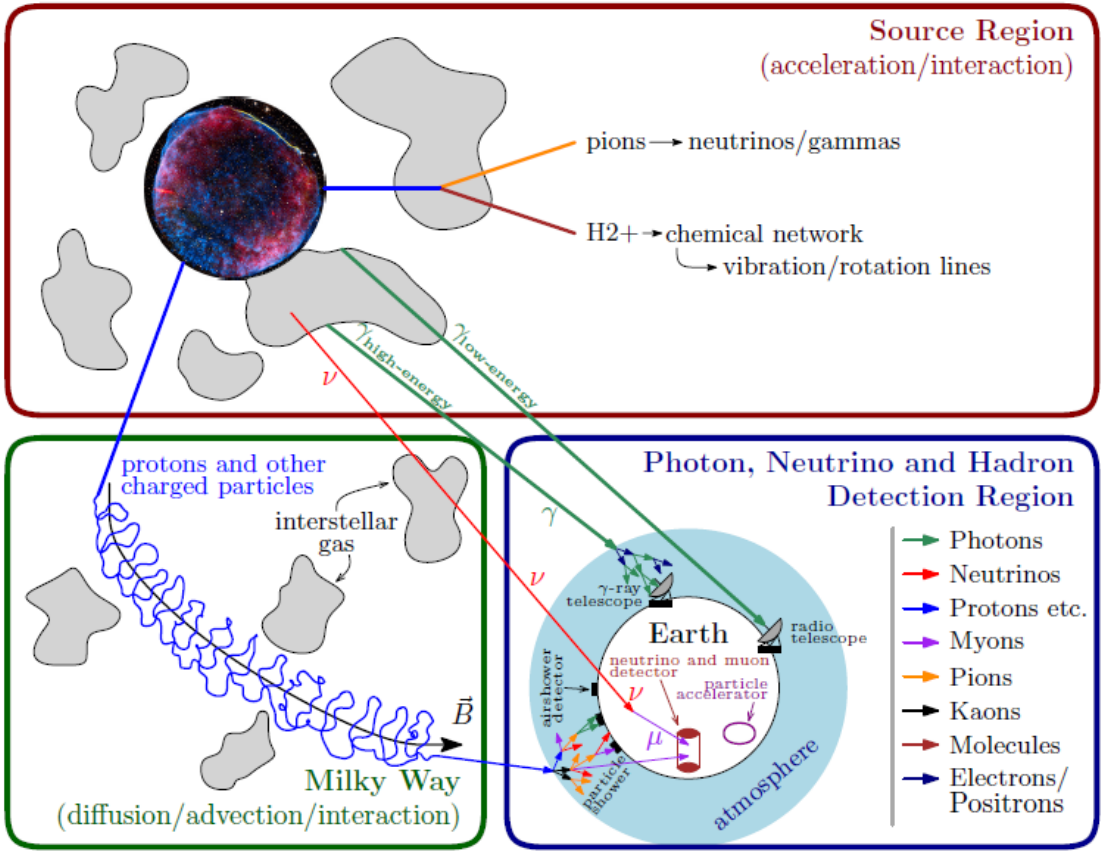

Figure: JBT & Merten, Phys.Rep. (2020)
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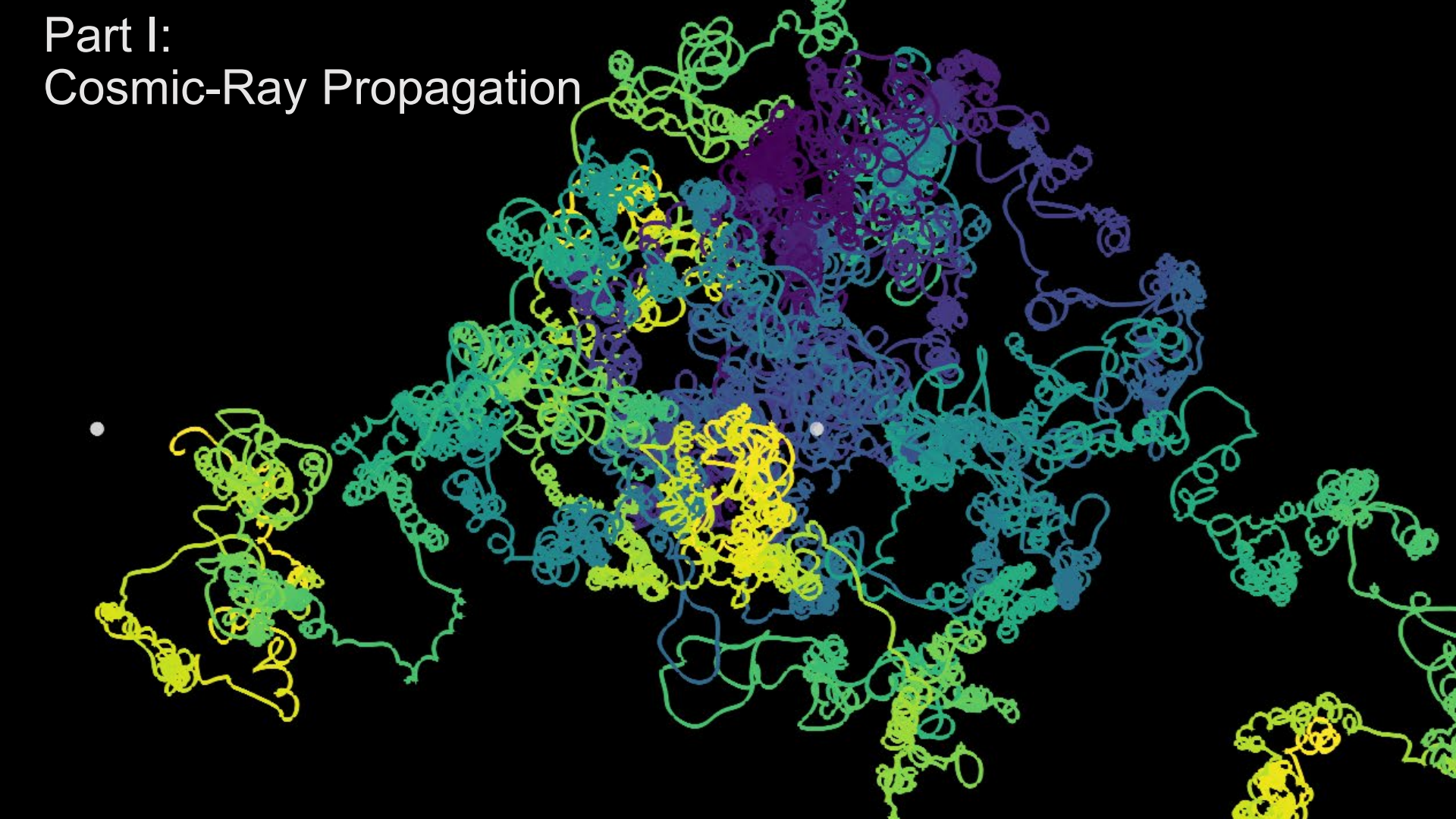
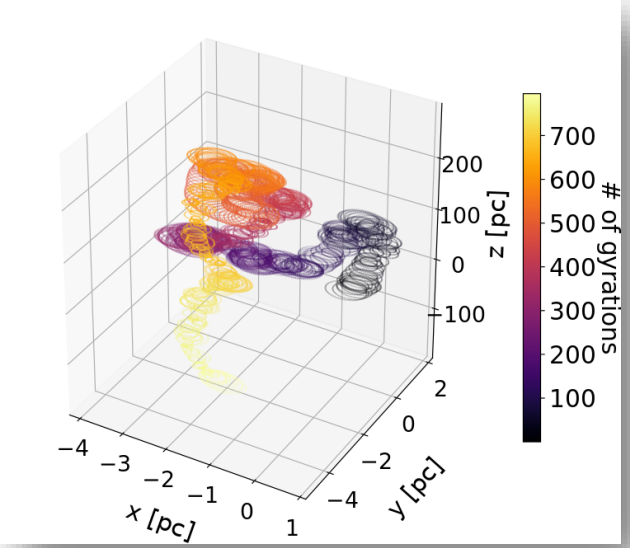
Part I:
Cosmic-Ray Propagation

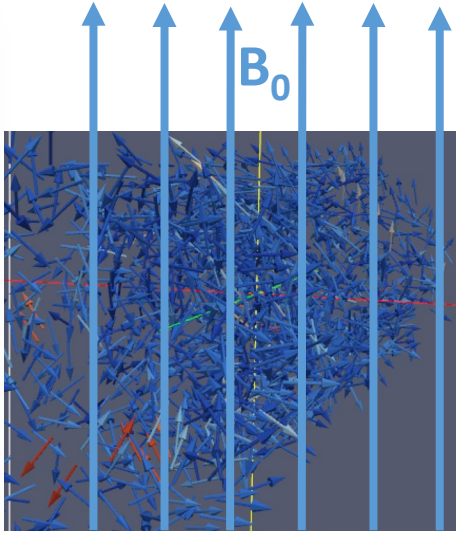


Transport: diffusive VS ballistic

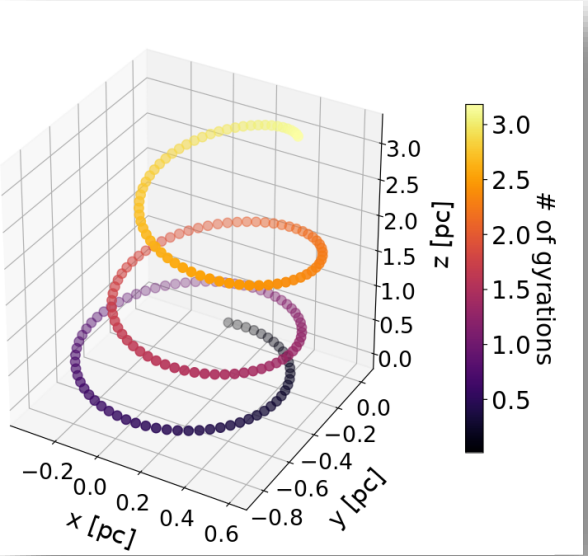
$$\frac{\delta n}{\delta t} = \nabla \cdot \left(\widehat{D} \cdot \nabla n\right) + Q$$

$$\frac{d\boldsymbol{p}}{dt} = q(\boldsymbol{v} \times \boldsymbol{B})$$





$+ \delta B$



Merten, JBT, Fichtner, Sigl, JCAP (2017)

Reichherzer, JBT, Zweibel, Püschel, Merten, MNRAS (2020)

General rule: system size >> gyro radius: diffusive propagation

The transport equation

$$\frac{dn}{dt}(\vec{r},t,E) = Q + \nabla\left(D_{xx}\nabla n - \vec{U}\cdot n\right) + \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\frac{n}{p^2}\right] - \frac{\partial}{\partial p}\left[\left(\frac{dp}{dt} - \frac{p}{3}\nabla\cdot\vec{U}\right)\cdot n\right] - \frac{n}{\tau_f}$$

Time-dependence

Source term

Spatial diffusion (3dim!)

Spatial advection

Momentum diffusion

Continuous energy change

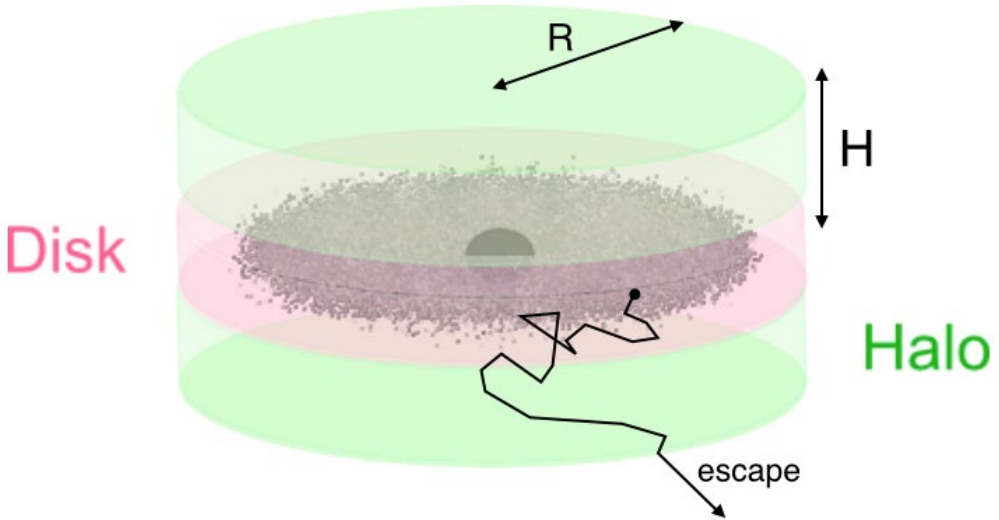
Momentum advection

Catastrophic losses

Leaky-Box Modell

1.) Assumption pure spatial diffusion: $$\frac{\partial n}{\partial t} = Q - D\Delta n \approx Q - \frac{n}{\tau_{esc}}$$

$$\tau_{esc} = \frac{D}{H^2}$$



2.) Assumption of steady-state: $$\frac{\partial n}{\partial t} \approx 0$$ ➔ $$n(E) = Q(E) * \frac{H^2}{D(E, \delta B/B)}$$

Source spectrum Q(E): stochastic acceleration

- Fermi 2nd order,
- Acceleration by surfing from one magnetized cloud to the next
- efficiency ~ $\left(\frac{v_{cloud}}{c}\right)^2 \sim 10^{-8}$

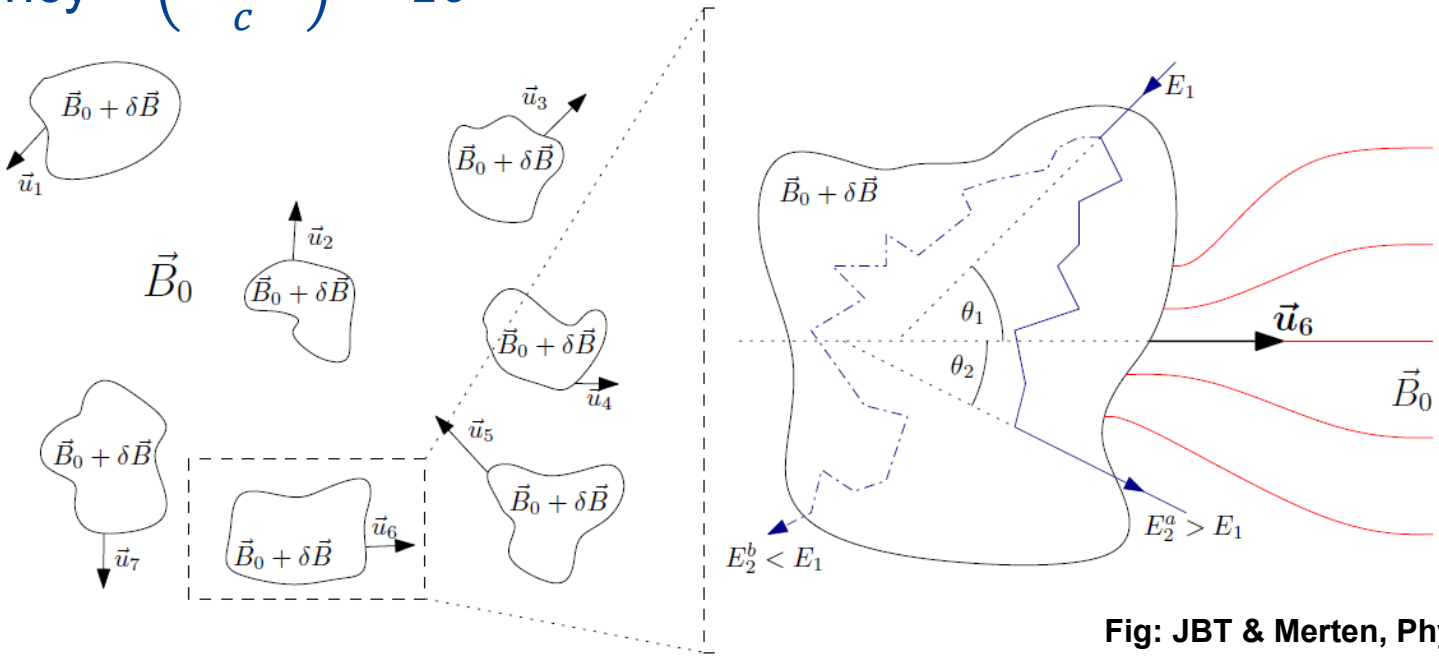


Fig: JBT & Merten, Phys.Rep. (2020)

Source spectrum Q(E): stochastic acceleration

- Fermi 1nd order
- Acceleration by playing pingpong at shock front
- Efficiency ~ $\frac{v_{shock}}{c} \sim 10^{-2}$

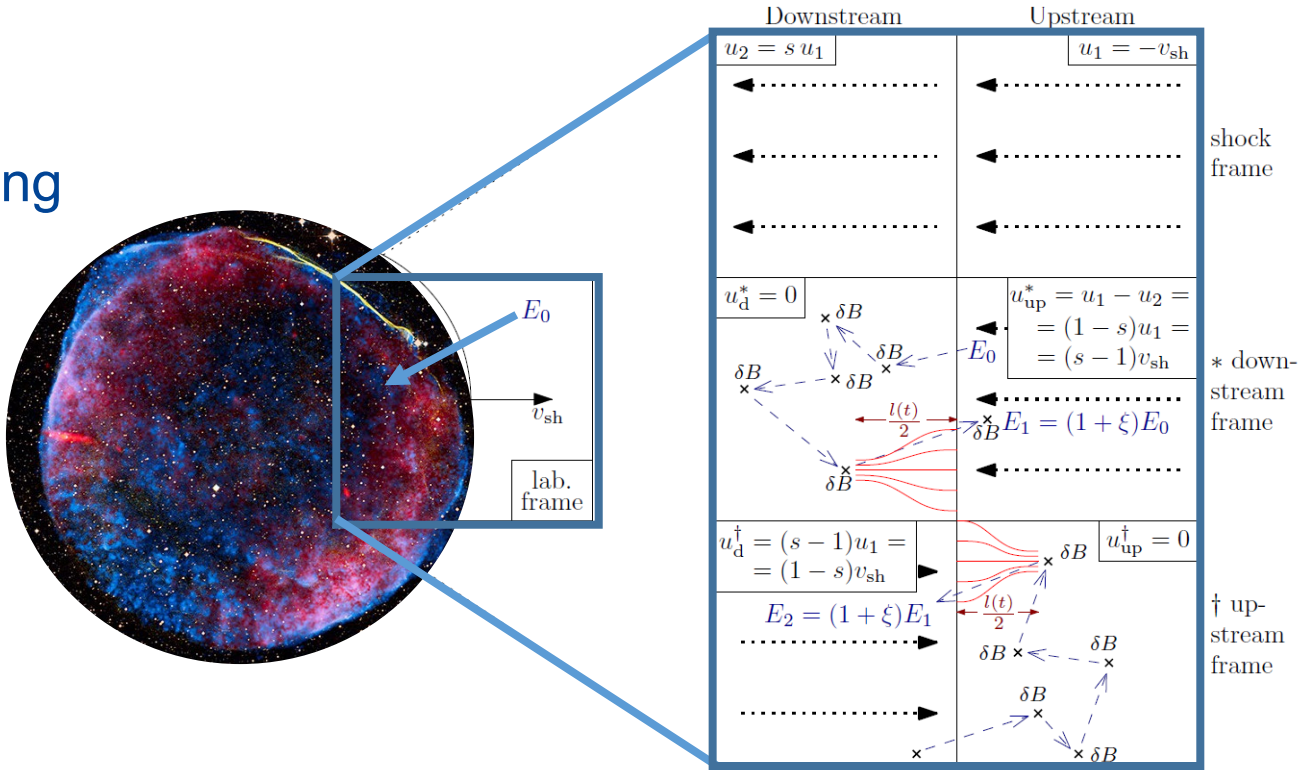
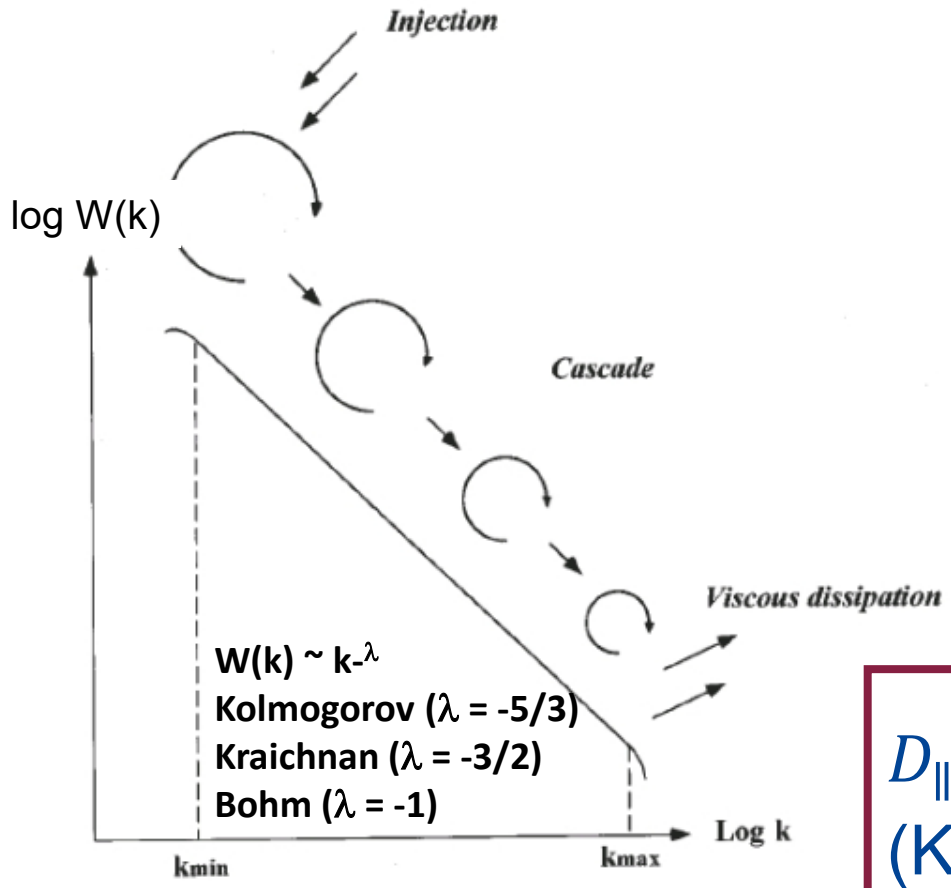


Fig: JBT & Merten, Phys.Rep. (2020)

Spectral behavior for stochastic acceleration

- Test particle, accelerated at magnetic field inhomogenities δB
- Energy gain: fraction of initial energy $$\Delta E = E - E_0 = \xi \cdot E_0$$
- n acceleration cycles $$\boxed{E_n = (\xi + 1)^n \cdot E_0}$$
- This leads to a power-law energy behavior $$\boxed{N(>E) = \sum_{i=n}^{\infty} (1 - P_{esc})^{n(E)} = \ldots \propto E^{-\gamma}}$$

Quasi-Linear Theory



- Diffusion coefficient:

$$D_{\parallel} = \frac{v^2}{2}\int_0^1 d\mu \frac{1-\mu^2}{2\,\nu_{\parallel}}$$

- Scattering rate

$$\nu_{\parallel} \approx 2\pi^2\,|\omega_B|\,\frac{k_{\rm res}\,W(k_{\rm res})}{B_0^2}$$

- $k_{res} \sim (|\mu|\, r_g)^{-1} \sim b\, E^{-1}$
- $W(k) \sim k^{-\lambda}$

$$D_{\parallel} \sim E^{2-\lambda}\left(\frac{b}{B}\right)^{-2} \sim E^{\frac{1}{3}}$$

(Kolmogorov)

Measurement of the parallel diffusion coefficient D

$$\frac{\partial n_B}{\partial t} \approx 0 =$$

$$-\frac{n_B}{\tau_{esc}} - \frac{n_B}{\tau_B} + P_{C\to B}\, n_C$$

- $\tau_{esc} \sim D^{-1}$
- $\rightarrow \frac{n_B}{n_C} \sim \frac{P_{C\to B}}{\tau_{esc}} \sim D^{-1}$

Measurements suggest a diffusion coefficient D ~ $E^{1/3}$

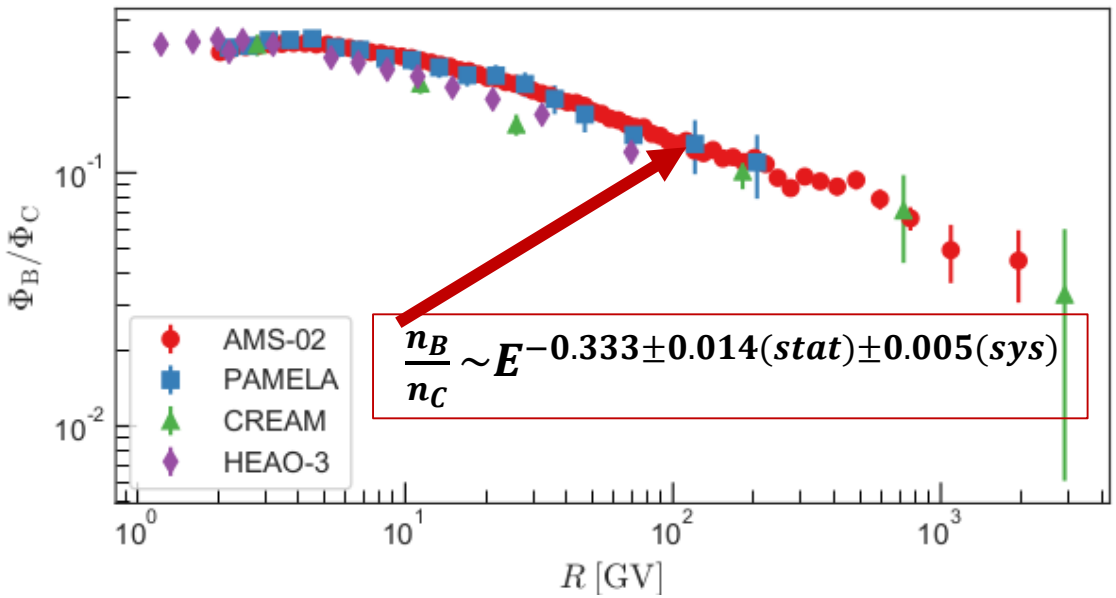
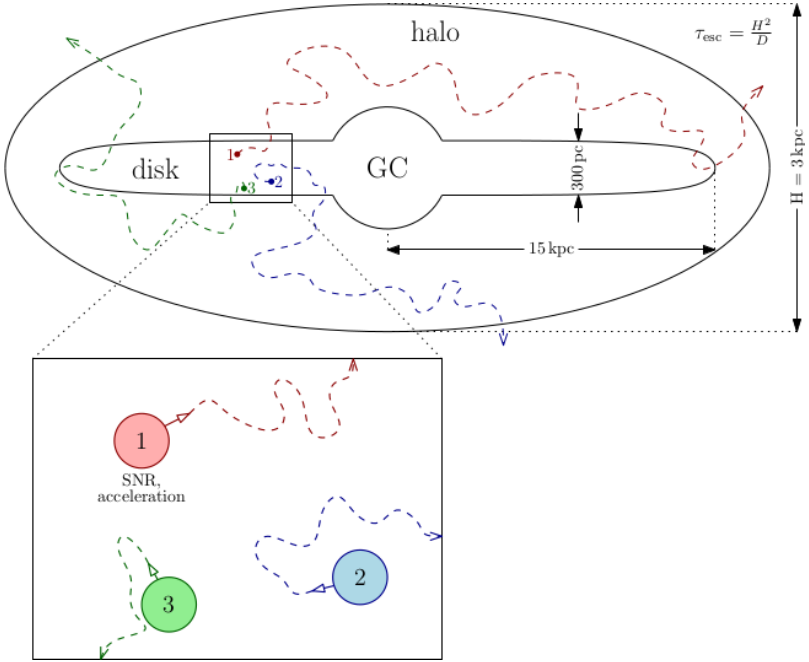


Fig: JBT & Merten, Phys.Rep (in prep)

Back to the Leaky Box Model

- $n \sim \frac{H^2}{D(E,\delta B/B)} \cdot Q(E) \sim E^{-\gamma_{tot}}$
- $Q(E) \sim E^{-\gamma_{source}}$
- $D(E) \sim E^{\gamma_{diff}}$
- $\gamma_{tot} = \gamma_{source} + \gamma_{diff} \sim 2.4 + 0.3$

- $n \sim E^{-2.7}$



Ok, that seems to work well – so can we go home now?

No! (Sorry…)

Fig: JBT & Merten, Phys.Rep. (2020)

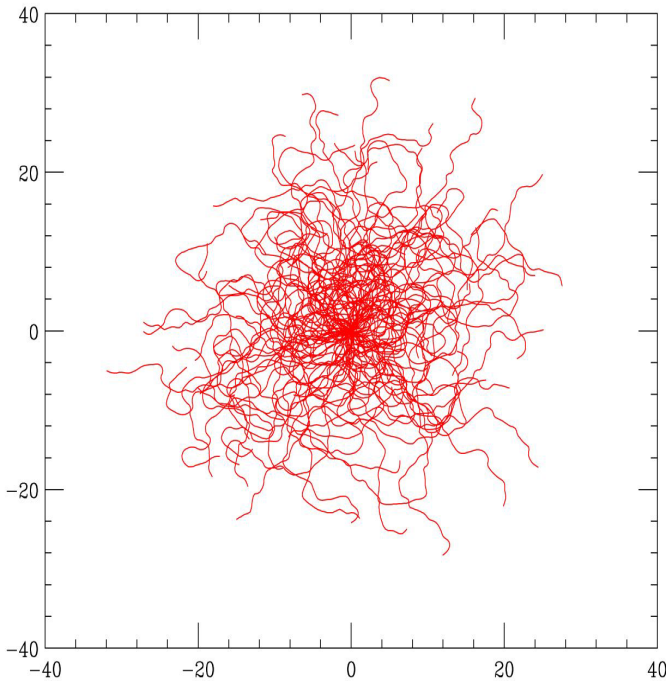
Simulations of the diffusion coefficient

Diffusion equation:

$$D(t)\Delta n(x,t) = \frac{\delta n(x,t)}{\delta t} - Q(x,t)$$

For the Green's function of the source term ($Q(x,t) = \delta(x)\delta(t)$), solution is known to be a Gaussian:

$$n(x,t) = \frac{1}{2\sqrt{\pi D_{xx} t}} \exp\left(-\frac{x^2}{4D_{xx}t}\right)$$



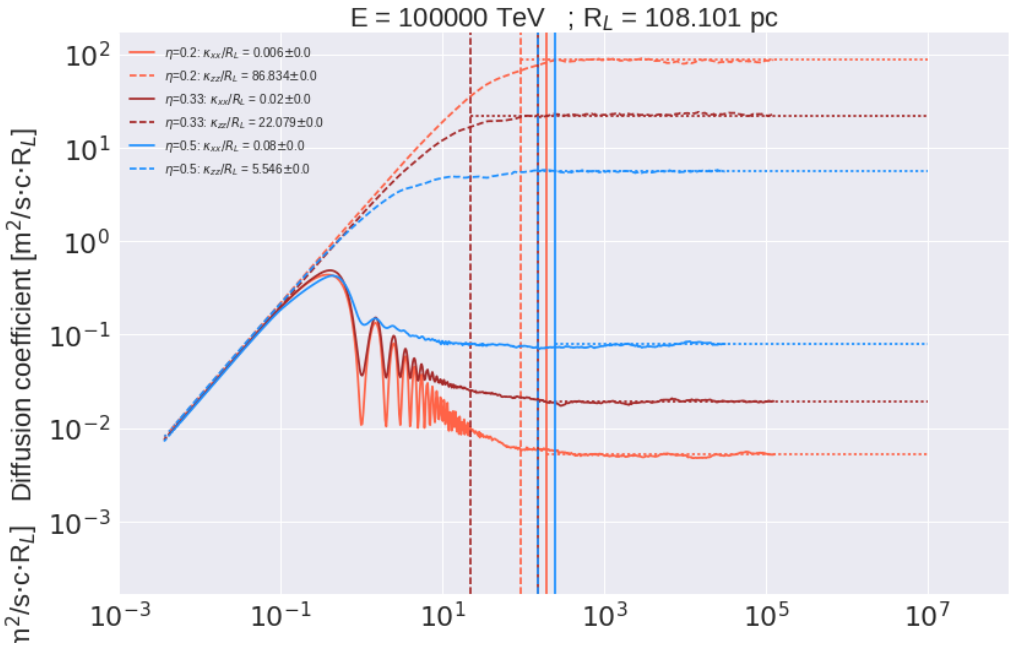
Schlegel, Frie, Eichmann, Reichherzer & JBT, ApJ (2020)
Reichherzer, JBT, Zweibel, Merten, Püschel, MNRAS (2020)
Reichherzer, Merten, Dörner, Püschel, Zweibel, JBT, Nature Appl. Sci., invited (2021)

Simulations of the steady-state diffusion coefficient

Idea (Taylor Green Kubo): calculate diffusion coefficient from numerical results:

$$\langle(\Delta x)^2\rangle = \int_{-\infty}^{+\infty} dx\, x^2 n(x,t) = 2tD_{xx}(t)$$

$$D_{xx} = \lim_{t\to\infty} \frac{\langle(\Delta x)^2\rangle}{2t}$$ =const in diffusion limit



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Reichherzer, JBT, Zweibel, Merten, Püschel, MNRAS (2020)
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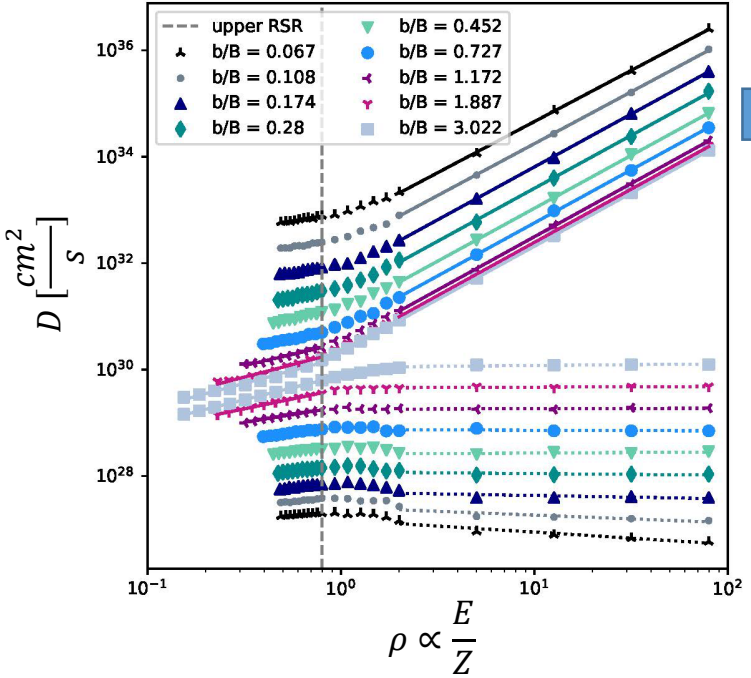
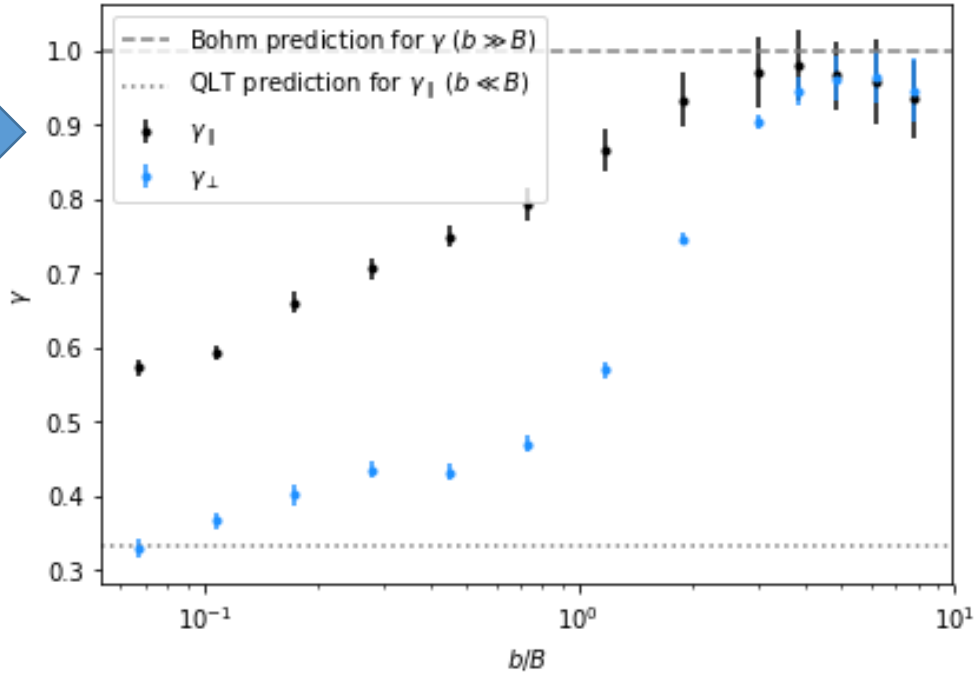
Calculation of the diffusion coefficient for different b/B





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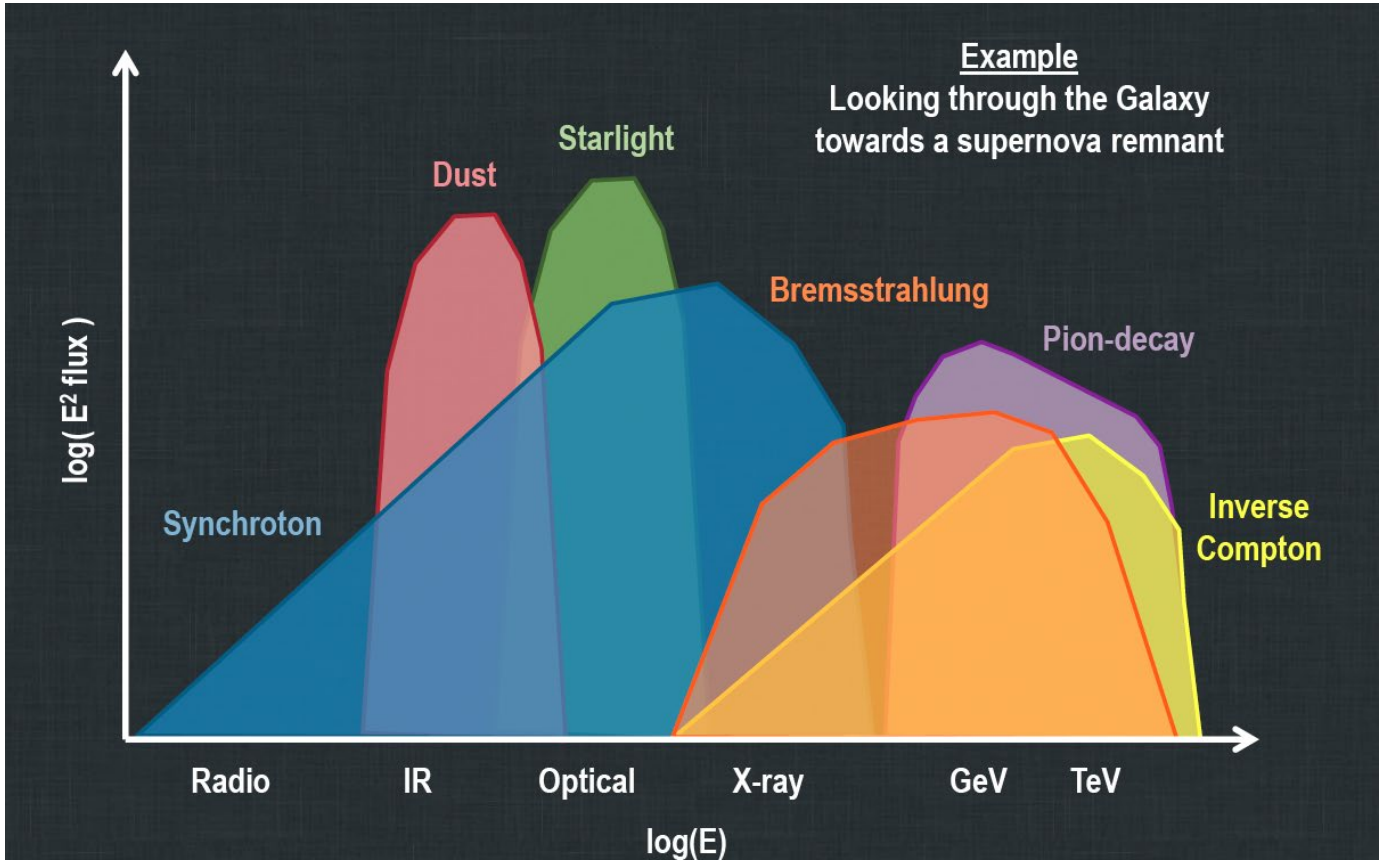
➔ Simulations show strong dependence on b/B

Part II: Local cosmic-ray sources



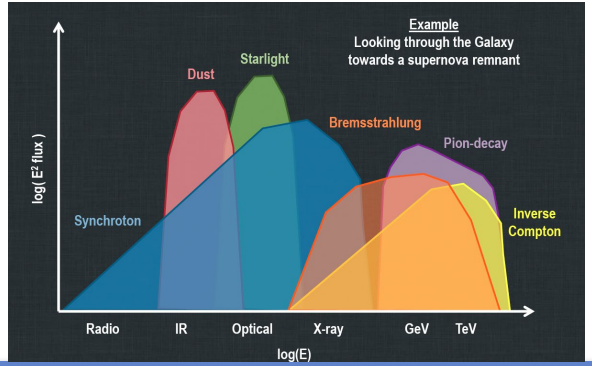
Powerlaws: How do they come about?

Electrons

- **Synchrotron radiation:** **HE e-** meet **B-field**
- **Inverse Compton scattering:** LE g (synchrotron/CMB/…) meet **HE e-**
- **Bremsstrahlung:** HE e- meet nuclei

Hadrons

- **Synchrotron radiation:** HE p meet B-field
- **Pion-decay:** HE CR meets gas target



Rule of thumb: I inject primary power-law spectra → I receive power-law radiation

Powerlaw for proton-proton

- Pion production rate for power-law injection spectrum $j_p = A_p E^{-\gamma}$

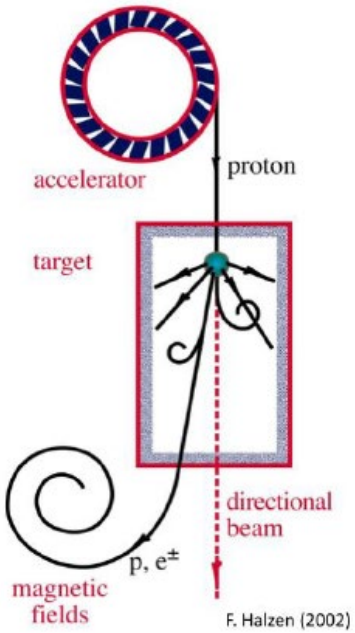
$$q_{\pi^{\pm,0}}(E_\pi) = \int_{E_{\rm th}}^{\infty} dE_p F_{\pi^{\pm,0}}(E_\pi(E_p)) \int_0^{\tau} d\tau' \, j_p \cdot \exp(-\tau)$$

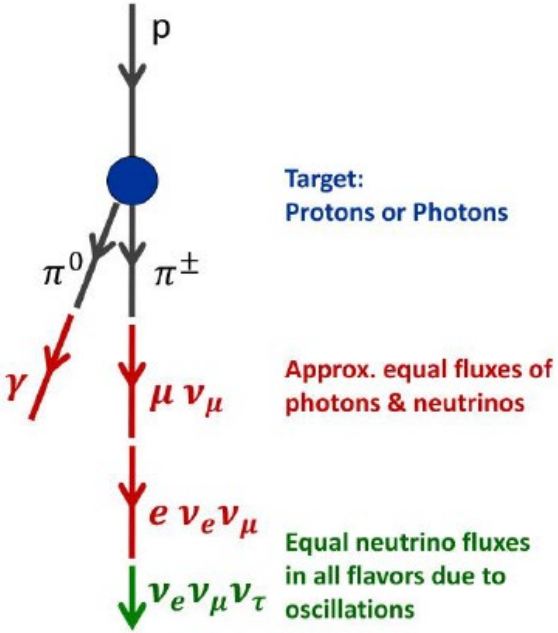
- $\tau = N_H \sigma_{pp}$ (optical depth in column N_H)
- $\sigma_{pp} \approx konst$
- Pion production rate per interaction
- Delta-Approximation: $E_\pi \sim < E_\pi > \sim E_p^{\frac{3}{4}}$

$$F_\pi = \xi_{\pi^{\pm,0}} \cdot \delta(E_\pi - \langle E_\pi \rangle)$$

- Rough (!) approximation for pion multiplicity:

$$\xi_{\pi^\pm} = 2 \cdot \left(\frac{E_p - E_{\rm th}}{\rm GeV} \right)^{1/4} \qquad \xi_{\pi^0} = \xi_{\pi^\pm}/2$$





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- ➔ $q_{\pi^\pm} \approx 20 \cdot N_H \, A_p \, \sigma_{pp} \left(\frac{6 \cdot E_\pi}{\rm GeV} \right)^{-4/3\,(\alpha - 1/2)}$
- Neutrino & γ production:

$$q_{\nu_i}(E_{\nu_i}) = q_{\pi^\pm}(E_\pi) dE_\pi / dE_{\nu_i} = 4 \cdot q_{\pi^\pm}(4E_{\nu_i})$$

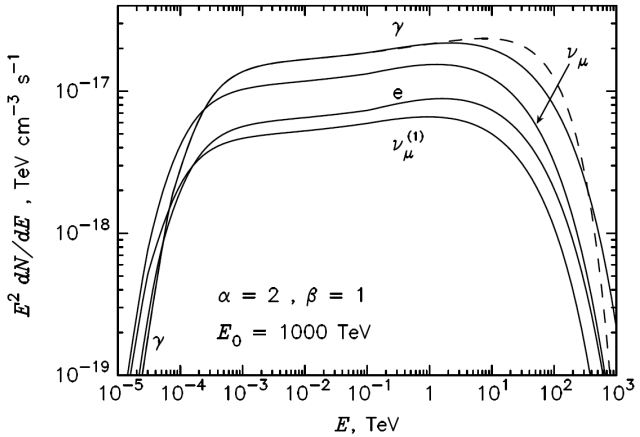
- ➔ Neutrino and γ spectra:

➔ Neutrino & γ spectra

$$q_{\nu,tot} = q^{(1)}_{\nu_\mu} + q^{(2)}_{\nu_\mu} + q_{\nu_e} \approx 300 \cdot N_H \cdot A_p \cdot \sigma_{pp} \cdot \left(\frac{24 \cdot E_\nu}{\mathrm{GeV}}\right)^{-4\alpha/3+2/3}$$

$$q_{\gamma,tot} = 2 \cdot q_\gamma \approx 50 \cdot N_H \cdot A_p \cdot \sigma_{pp} \cdot \left(\frac{12 \cdot E_\gamma}{\mathrm{GeV}}\right)^{-4\alpha/3+2/3}$$

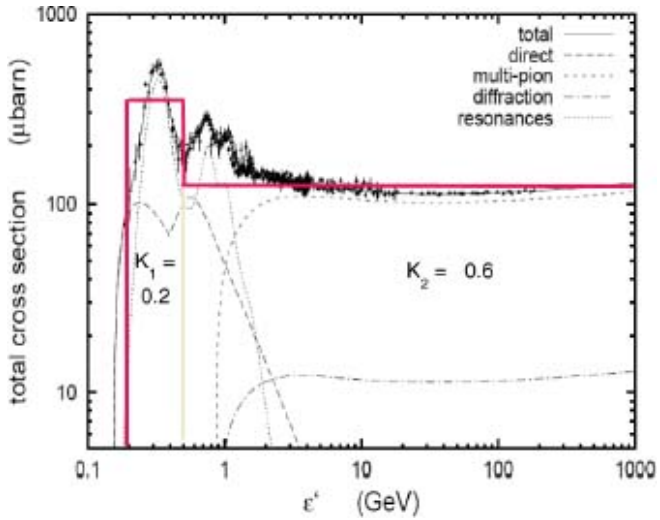
- ➔ for $\alpha \sim 2$, these spectra follow the primary distribution

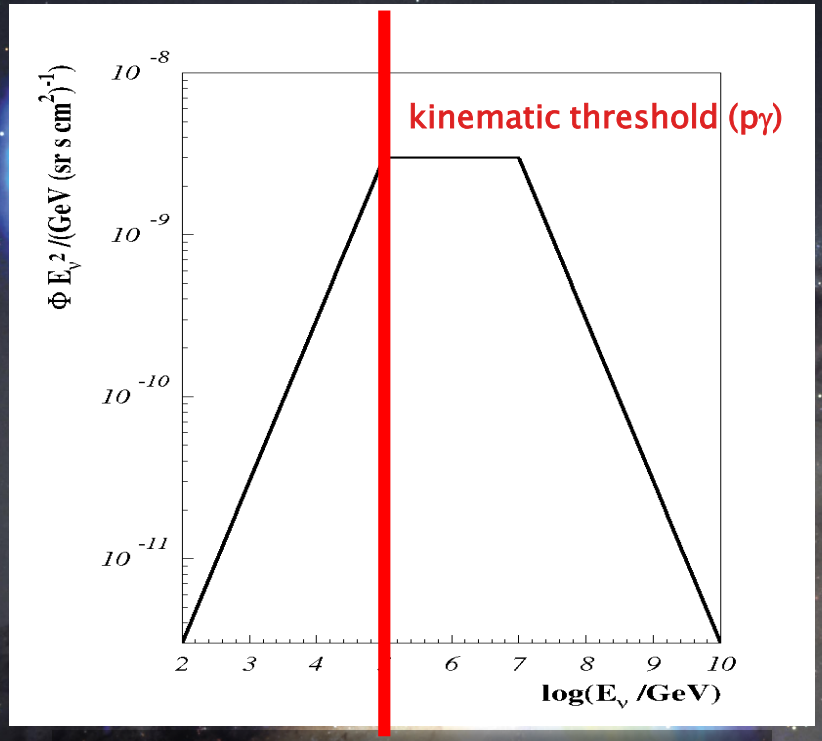


Photohadronic interactions

- $p_{CR}\ \gamma_{target} \rightarrow \Delta^+ \rightarrow \pi^{+/-}\ N$
- $\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\ \nu_e\ \bar{\nu}_\mu\ \nu_\mu$
- $\pi^- \rightarrow \mu^-\bar{\nu}_\mu \rightarrow e^-\ \bar{\nu}_e\ \nu_\mu\ \bar{\nu}_\mu$
- $\pi^0 \rightarrow \gamma\gamma$ (E~TeV)

Fig: Dermer&Atoyan, New J Phys (2006)





Kinematic threshold for pion production

$$E_p * E_\gamma > (m_\Delta^2 - m_p^2)/4$$

Above threshold: simple assumptions

→ **follows E^{-p};**

Frequenzspektrum für ein einzelnes Elektron

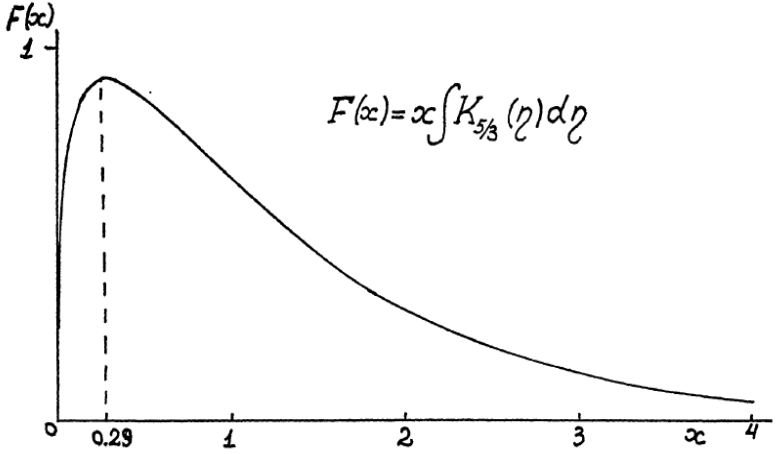
- Frequenzspektrum: Leistung pro Frequenz:

$$\frac{dW}{dt d\omega} =: P(\omega) = C \cdot F\left(\frac{\omega}{\omega_c}\right)$$

- mit der von einem Elektron gesamt abgestrahlten Leistung

$$P_{synch} = \int P(\omega) \cdot d\omega$$

- Frequenzspektrum →



Ginzburg & Syrovatskii, ARAA 3:297 (1965)

Frequenzspektrum einer Teilchenpopulation dN/dE~E^{-p}

- Elektronverteilung dN/dE = A*E^{-p} zwischen E_1 und E_2
- ➔ Von allen Elektronen abgestrahltes Synchrotorn-Frequenzspektrum:

$$P_{tot,synch}(\omega) = \int C \cdot F\left(\frac{\omega}{\omega_c}\right) \cdot \frac{dN}{dE} dE \propto \int F\left(\frac{\omega}{\omega_c}\right) \cdot E^{-p} dE$$

$$\omega_c := \frac{3}{2} \cdot \omega_B \cdot \gamma^3 \cdot \sin\alpha$$

- Gyrationsfrequenz: $\omega_B = \frac{q \cdot B}{\gamma \cdot m \cdot c} \propto \frac{1}{\gamma}$
- ➔ Kritische Frequenz: $\omega_c \propto \gamma^2$

Substitution: $E = \gamma mc^2$ ➔ $x = \omega/\omega_c = \omega/\omega_c(\gamma)$ ➔

Synchrotronstrahlung für dN/dE~E^{-p}

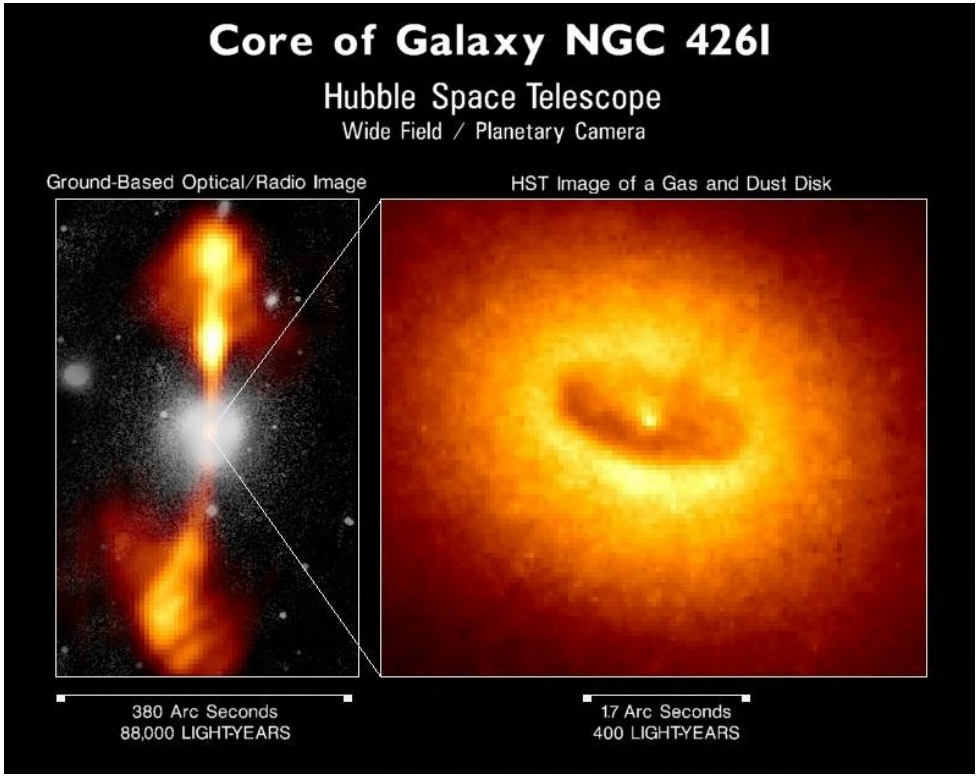
- ➔ $$P_{tot,synch}(\omega) \propto \omega^{-\left(\frac{p-1}{2}\right)} \cdot \int F(x) \cdot x^{-\left(\frac{p-3}{2}\right)} dx \propto \omega^{-\alpha}$$

$$\boxed{P_{tot,synch}(\omega) \propto \omega^{-\alpha}}$$

$$\boxed{\alpha = \frac{p-1}{2}}$$

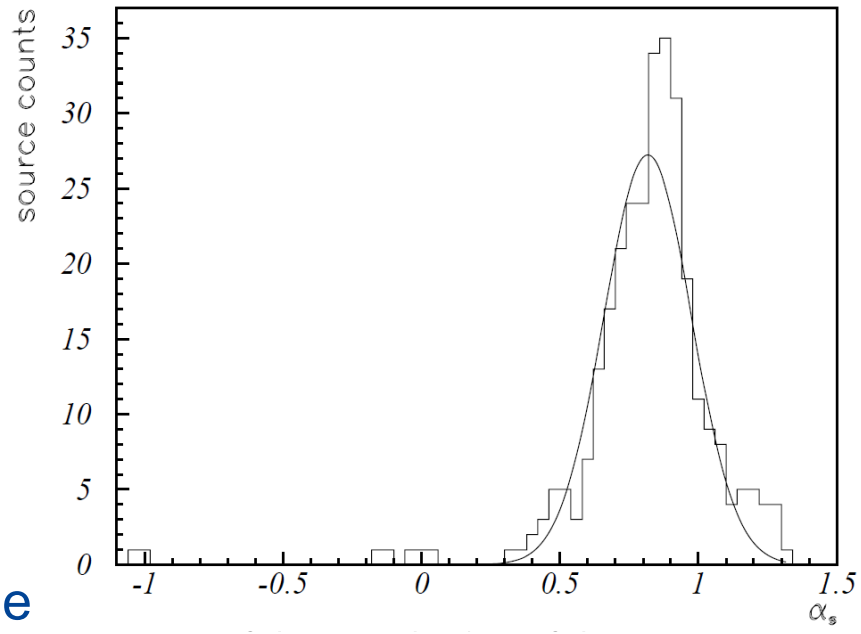
Example: active Galaxies

- Radio emission from gigantic jets
- ➔ Synchrotron emission with powerlaw behavior



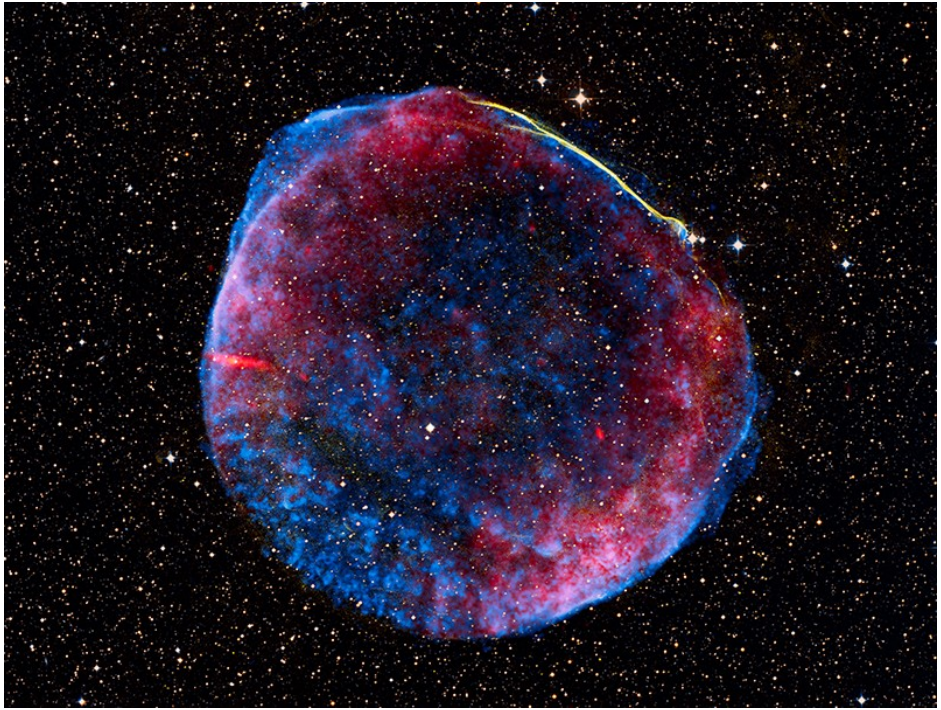
Aktive Galaxies: FR-II

- **$\langle\alpha\rangle \sim 0.8$**
- **➔ $\langle p\rangle = 2*\langle\alpha\rangle+1 \sim 2.6$**
- Steep spectra – why?
  - Intrinsically steep spectra of electrons?
  - High synchrotron losses steepen the spectrum?

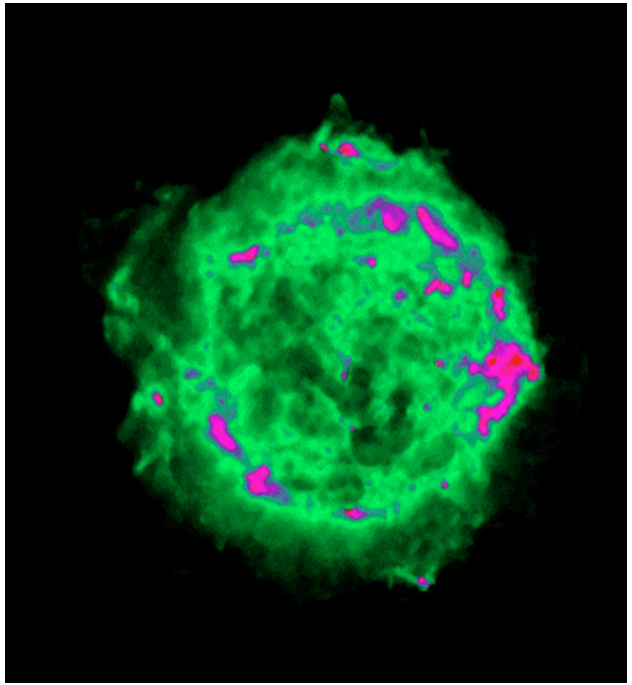


Example: Supernova remnants

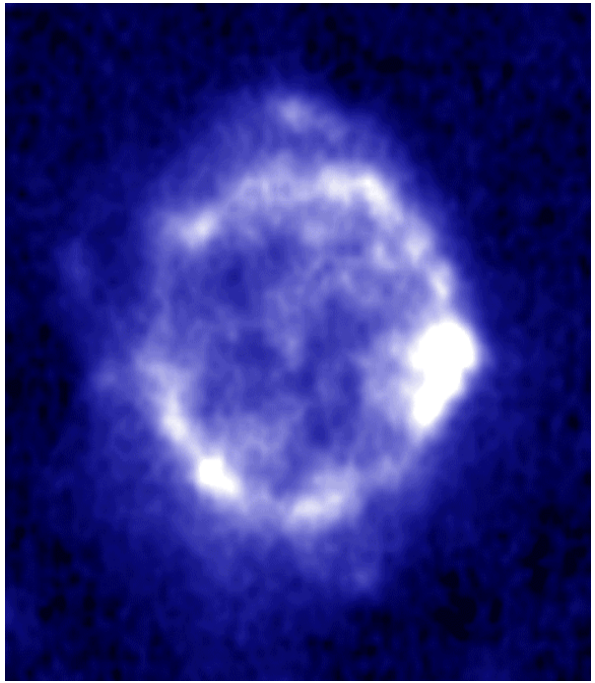
- Blue: X-ray
- Red: Radio
- Yellow (top-right): optical



Example: CasA (SNR)



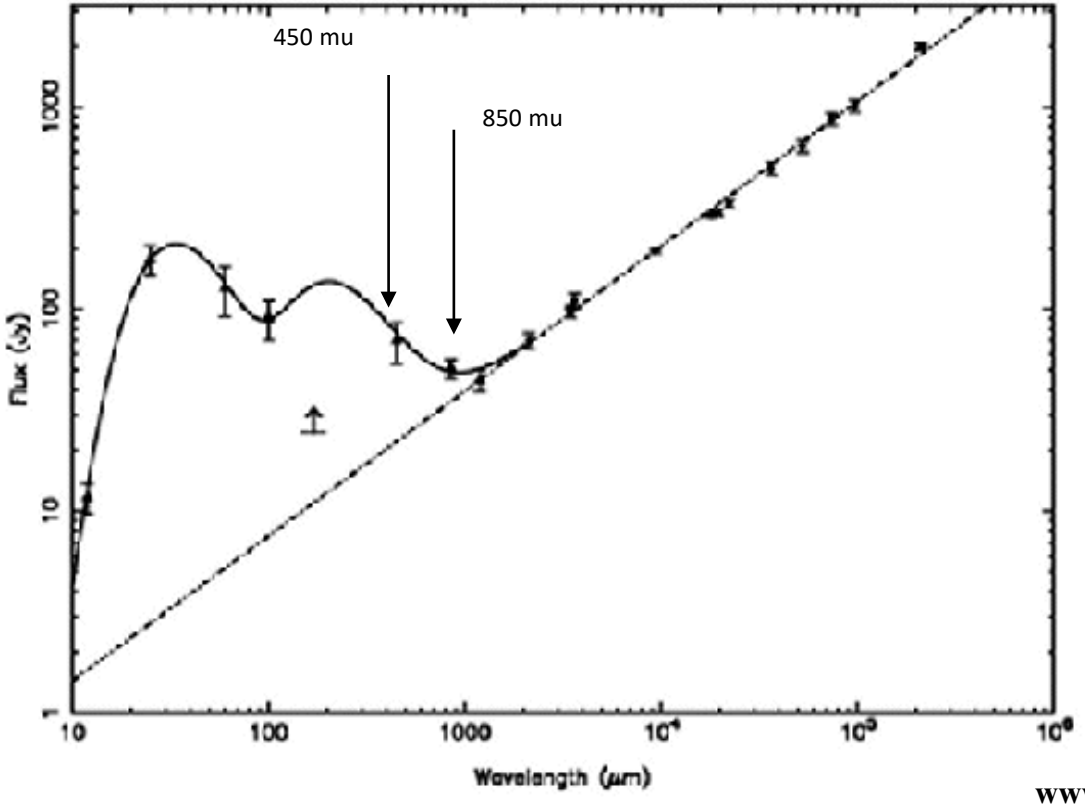
Radio



Infrared (850 micron)

www.astro.cf.ac.uk/groups/cosmo/SNe/sne.html

Observed frequency spectrum

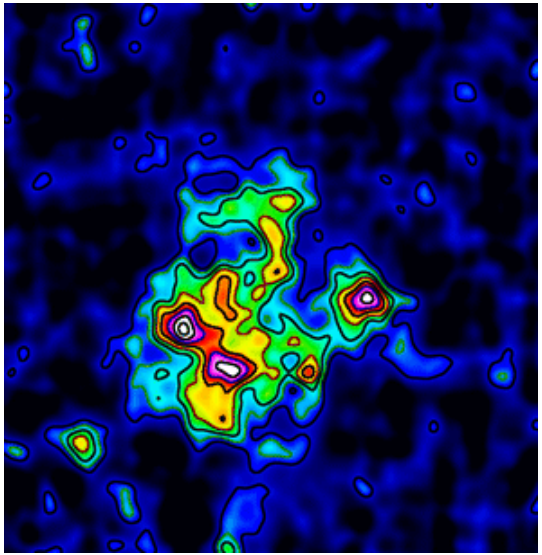


$$\lambda = \frac{c}{\nu}$$

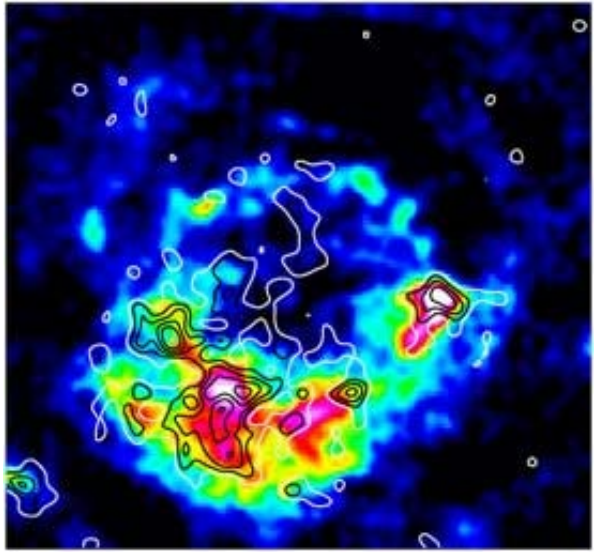
$$P(\lambda) \propto \lambda^{\alpha}$$

www.astro.cf.ac.uk/groups/cosmo/SNe/sne.html

Without Synchrotron



450 Micron without synchrotron



850 micron without synchrotron
Contours: 450 micron

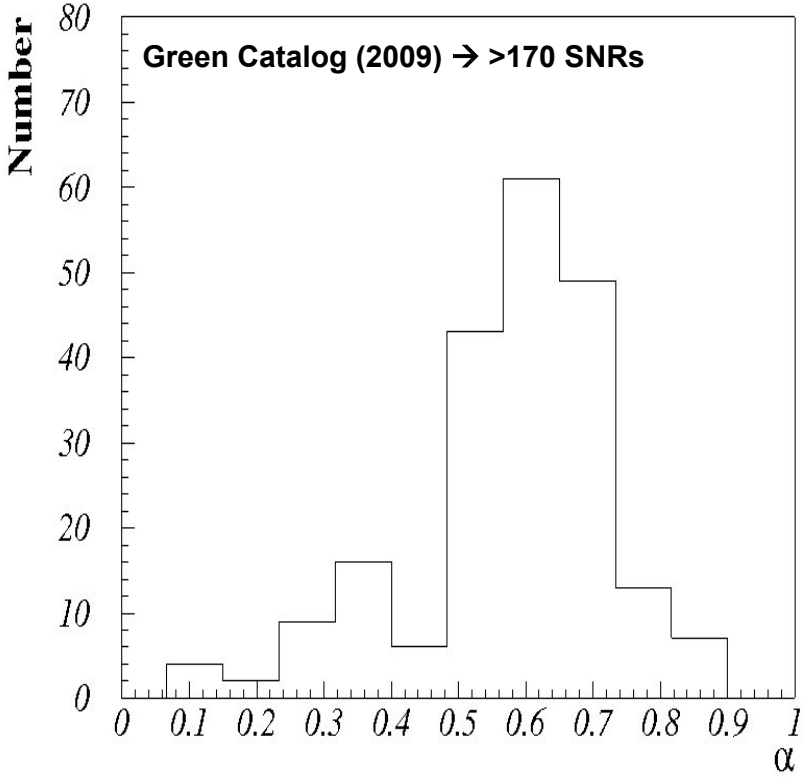
Dust regions

www.astro.cf.ac.uk/groups/cosmo/SNe/sne.html

Spectral behavior

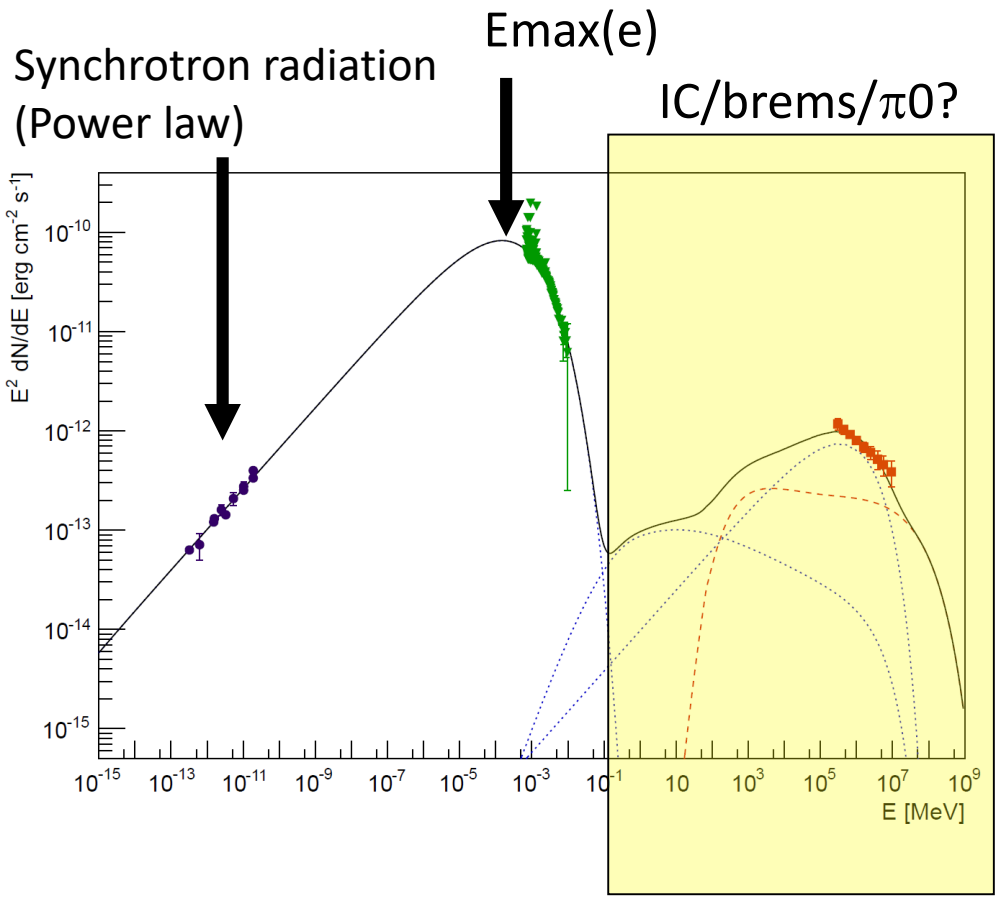
$$\alpha = \frac{p-1}{2}$$

- <α> ~ 0.6
- ➔ <p> ~ 2.2
- ➔ Kompatibel mit Schockbeschleunigungs-Szenarium



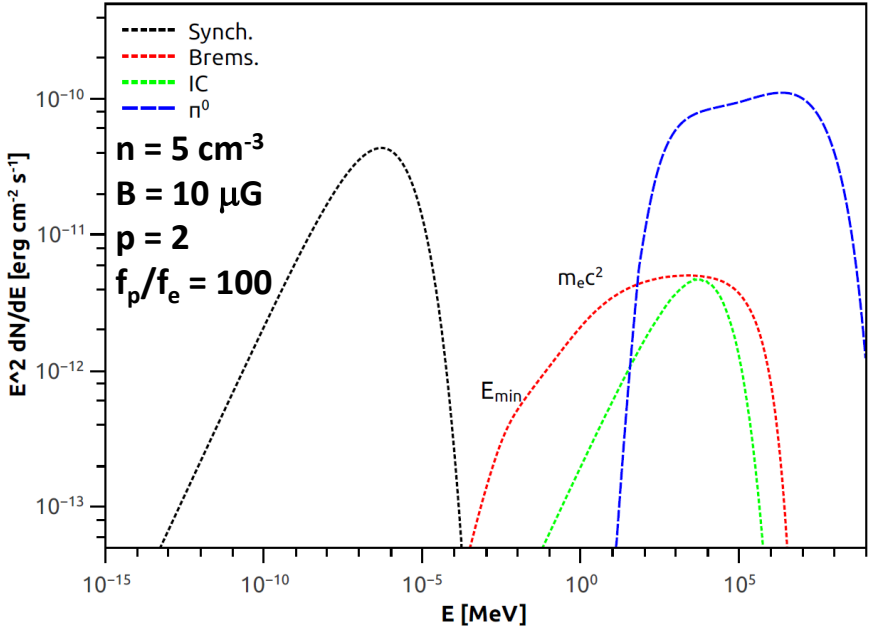
SN 1006:
Observed energy spectrum

High-energy emission:
spectral behavior?



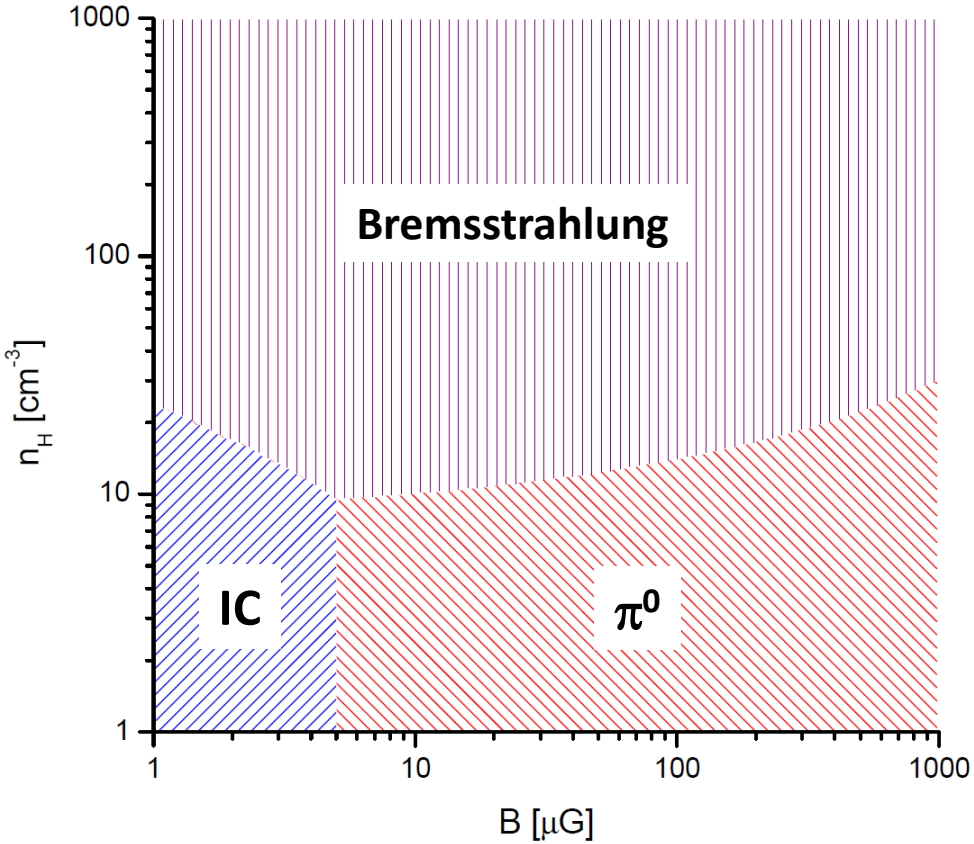
General differences in different γ-ray spectra

Prozess	dN/dE ~	Anmerkungen
Synchrotron radiation	$E^{-(p-1)/2}$	Polarisized (energy-independent)
Inverse Compton scattering	$E^{-(p-1)/2}$ E^{-p}	Thomson ($\eta << 1$) Klein-Nishina ($\eta >> 1$) Polarisized (energy-dependent)
Non-thermal bremsstrahlung	E^{-p}	
π^0-decays (pp)	E^{-p}	Emin ~ 280MeV
π^0-decays ($p\gamma$)	E^{-p+1} E^{-p}	$E < E_{break}$ $E > E_{break}$



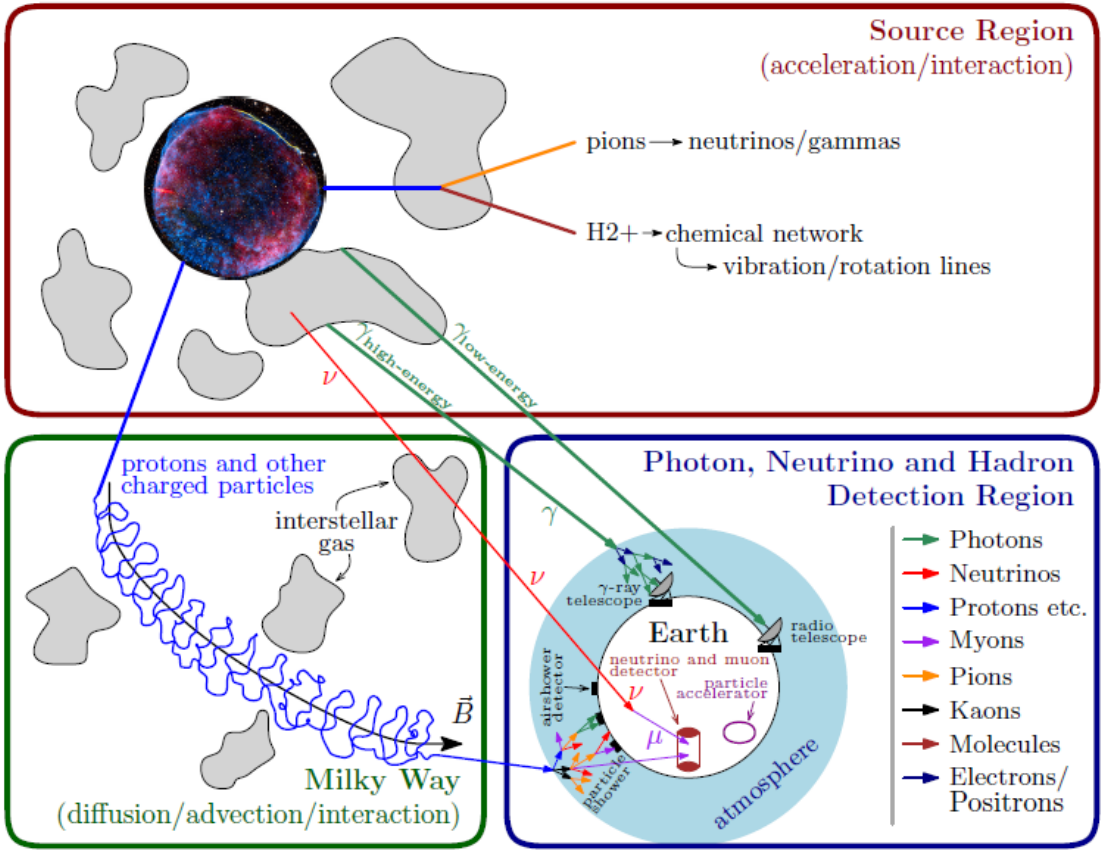
Brems – IC – π^0

- Assumption:
  - E^{-2} spectrum
  - Synchrotron spectrum fixed by observations (i.e. product $n_e B^2$)
- ➔ dominant contribution at highi energies changes depending on gas density and B-field of the system



Mandelartz & Becker Tjus, arXiv:1301.2437

Part III: Multimessenger Modeling

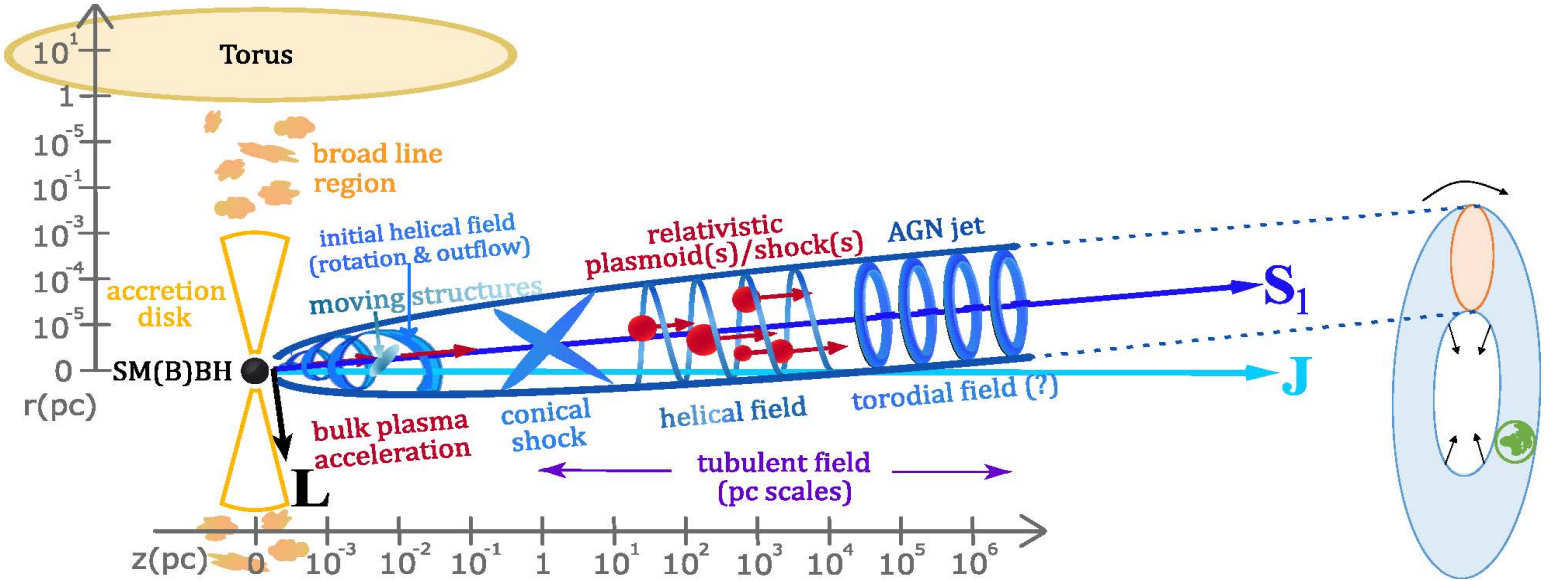


Here: focus on

- Active Galactic Nuclei as extragalactic …
- Supernova Remnants as Galactic …

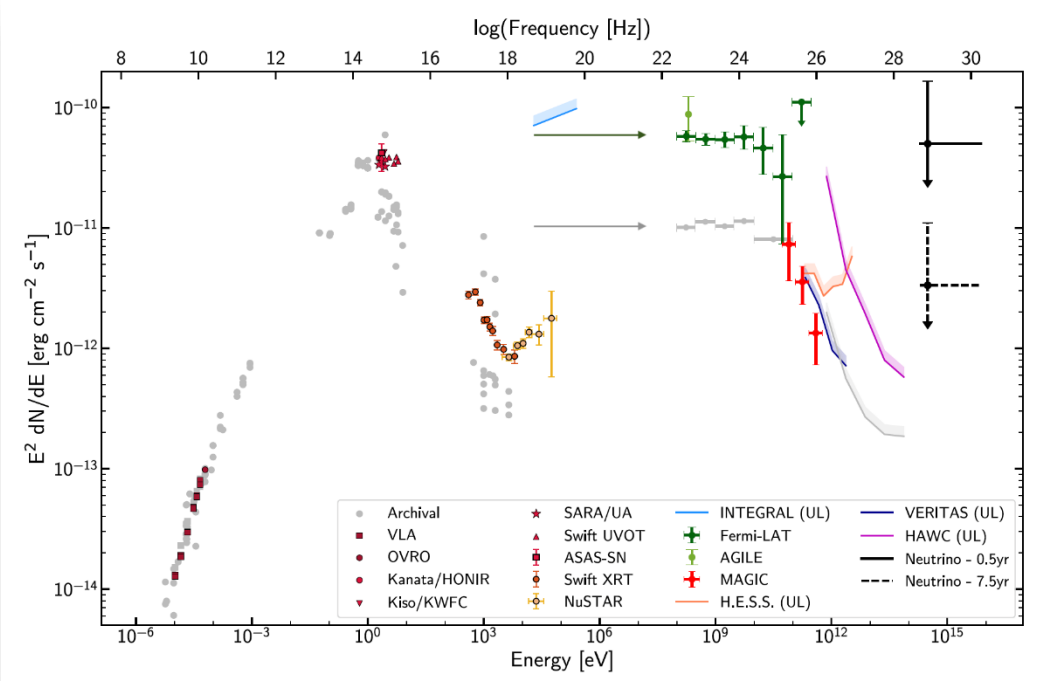
… cosmic-ray sources

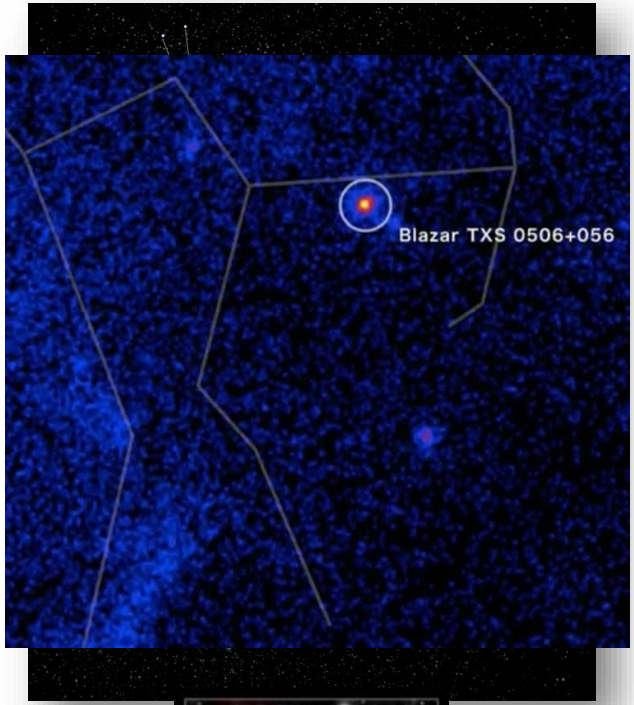
AGN with structure relevant for cosmic rays



- **B-field structure** (blue/red): acceleration (shocks/plasmoids), propagation dominantly along fieldlines, diffusion and energy dependence sensitive to $\delta B/B$
- Gas structure/Photon fields (yellow/red): interactions, relevant for γ-ray & neutrino production, gamma absorption

Multimessenger emission from TXS0506+056 – energy domain

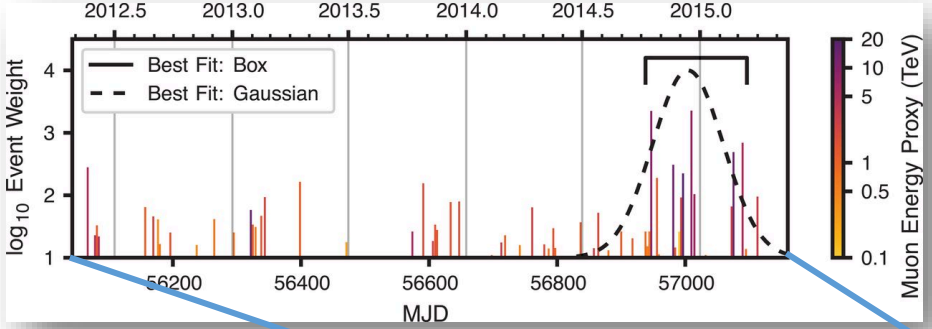




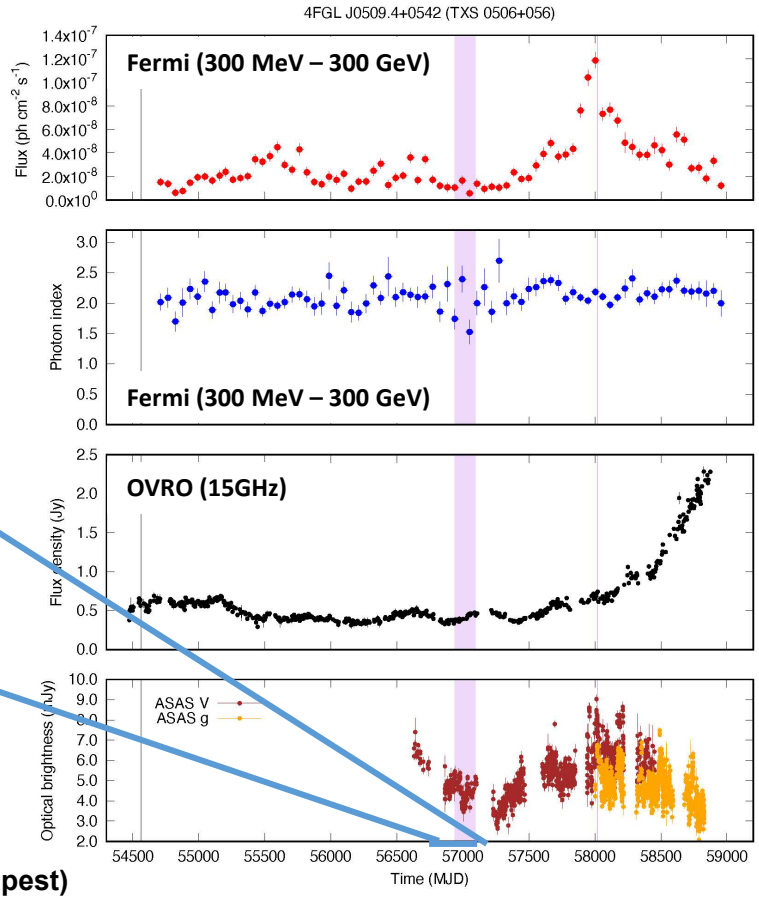
Aartsen, ..., JBT, ... et al (IceCube/Fermi/MAGIC Coll), Science (2018)

Multimessenger emission from AGN at the example of TXS0506+056 – time domain

Neutrino excess @ ~3σ in 2014/2015



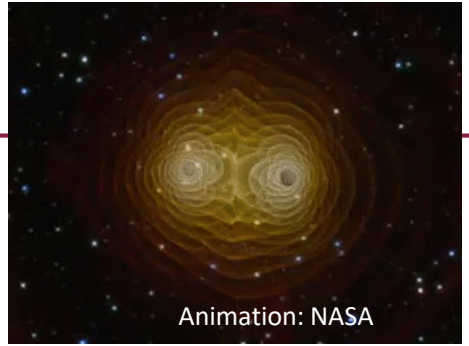
Aartsen, ..., JBT, ... et al (IceCube Coll), Science (2018)

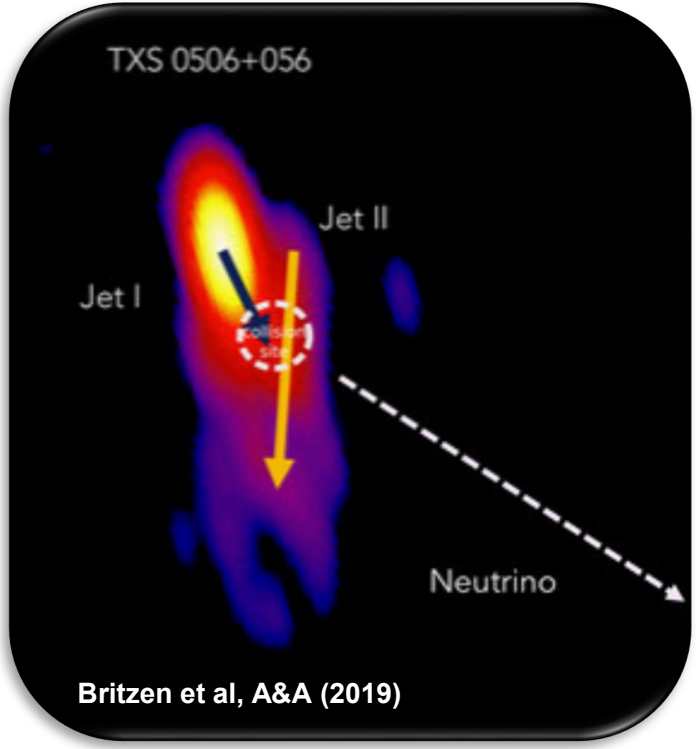


- ➔ Two potential neutrino flares of very different nature:
  - ➔ 2014/2015: ~100 days long, ~10TeV in energy, no MM activity
  - ➔ 2018: 1 neutrino with ~300TeV energy, coincident γ-ray flare

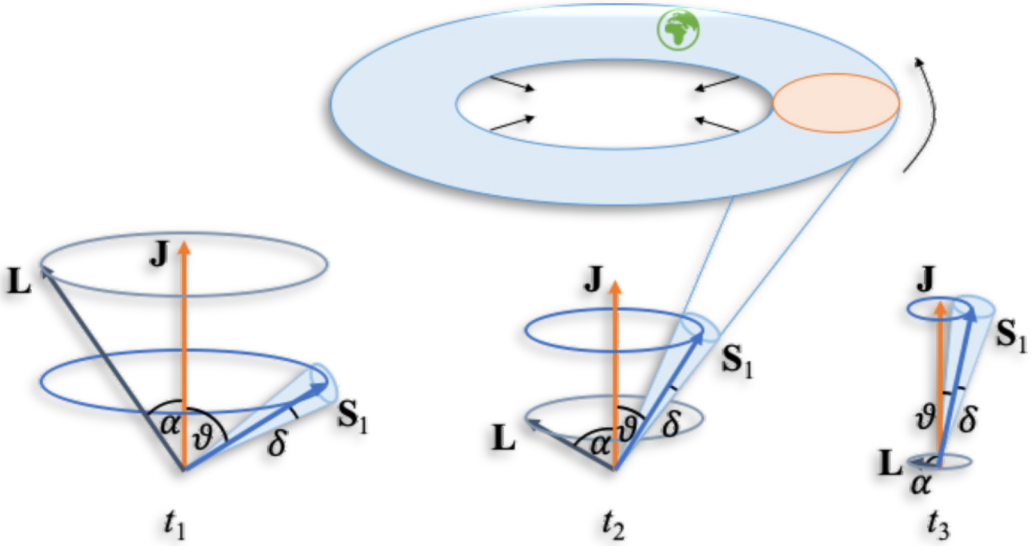
Figure: Emma Kun (Budapest)

Flares due to jet precession?





Britzen et al, A&A (2019)

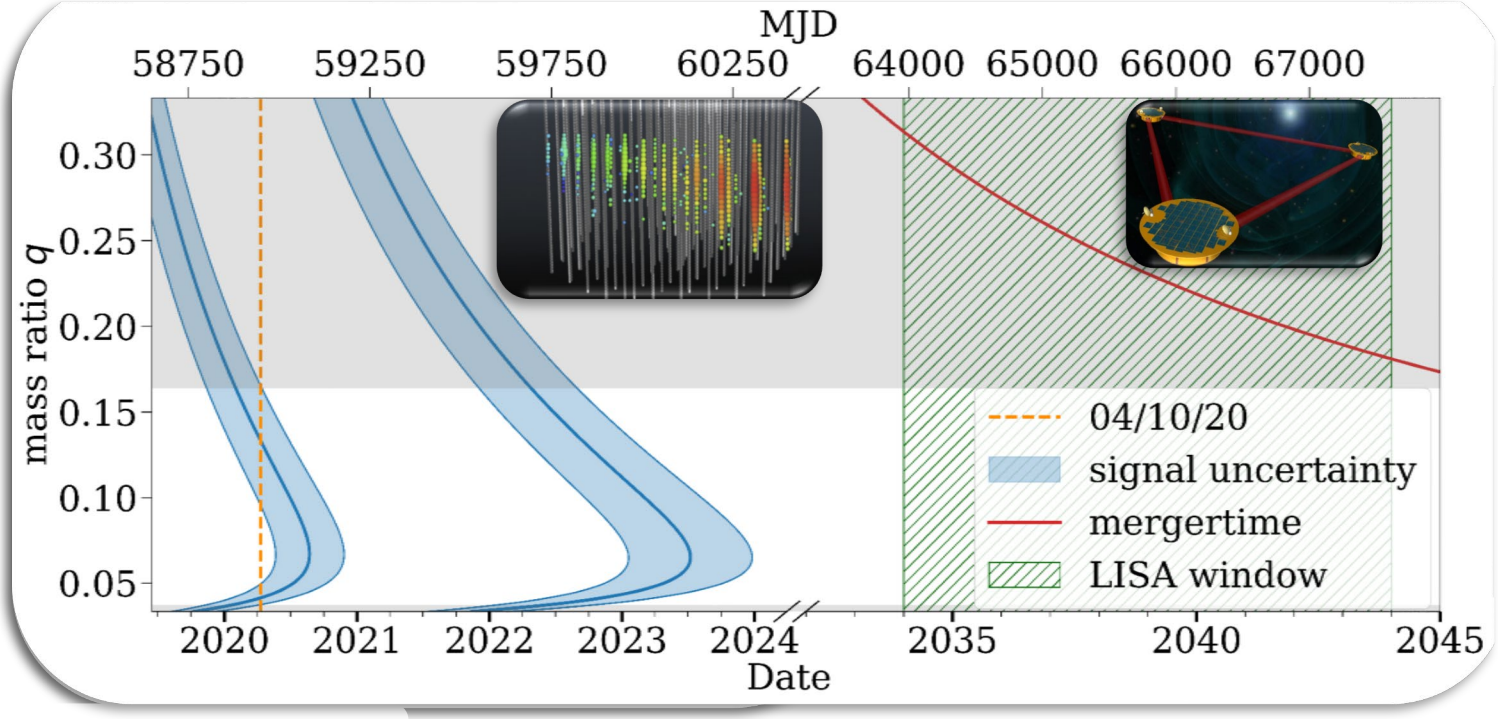


Gergely & Biermann, ApJ (2009)

Prediction of upcoming ν and GW flares

Next neutrino flare before 2021 – stay tuned for unblinding

GW-signature during LISA uptime (?!) →



de Bruijn, JBT, Bartos, ApJL accepted (2020), arXiv:2006.11288

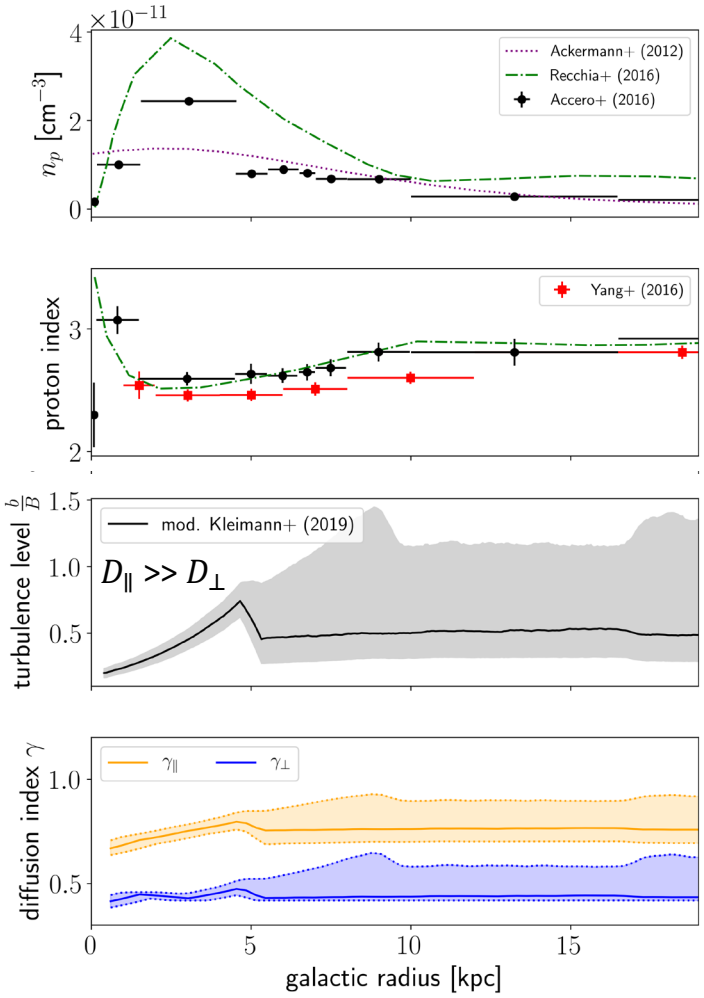
Galactic cosmic-ray gradient: local change in diffusion coefficient?

$$\frac{dN}{dE} \sim \frac{Q(E)}{D_{\parallel}(E)} \sim n_p E^{-\gamma_{tot}} \sim n_p E^{-\gamma_{source}-\gamma_{diff}\left(\frac{\delta B}{B}\right)} \sim n_p E^{-\gamma_{source}-\gamma_{diff}(r)}$$

$$B_{tot} \propto r^{-\beta}$$

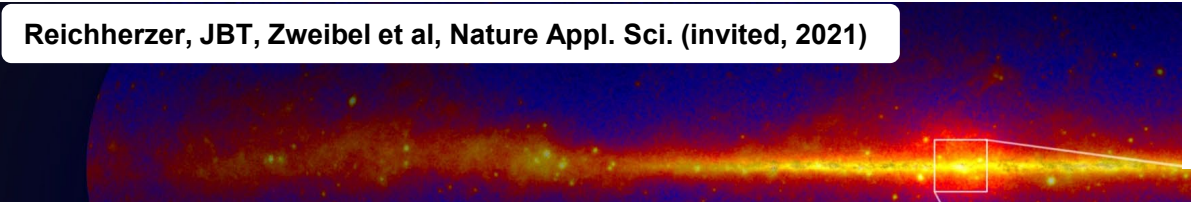
$$D \propto B_{\mathrm{tot}}^{\gamma}$$

$$\frac{D_{\parallel}}{D_{\perp}} \sim \mathrm{r}^{\beta(\gamma_{\parallel}-\gamma_{\perp})}$$

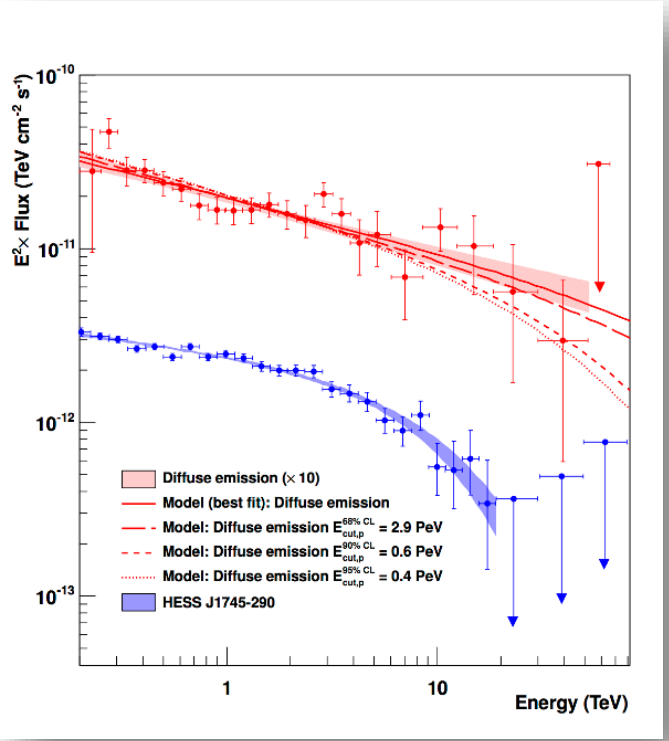


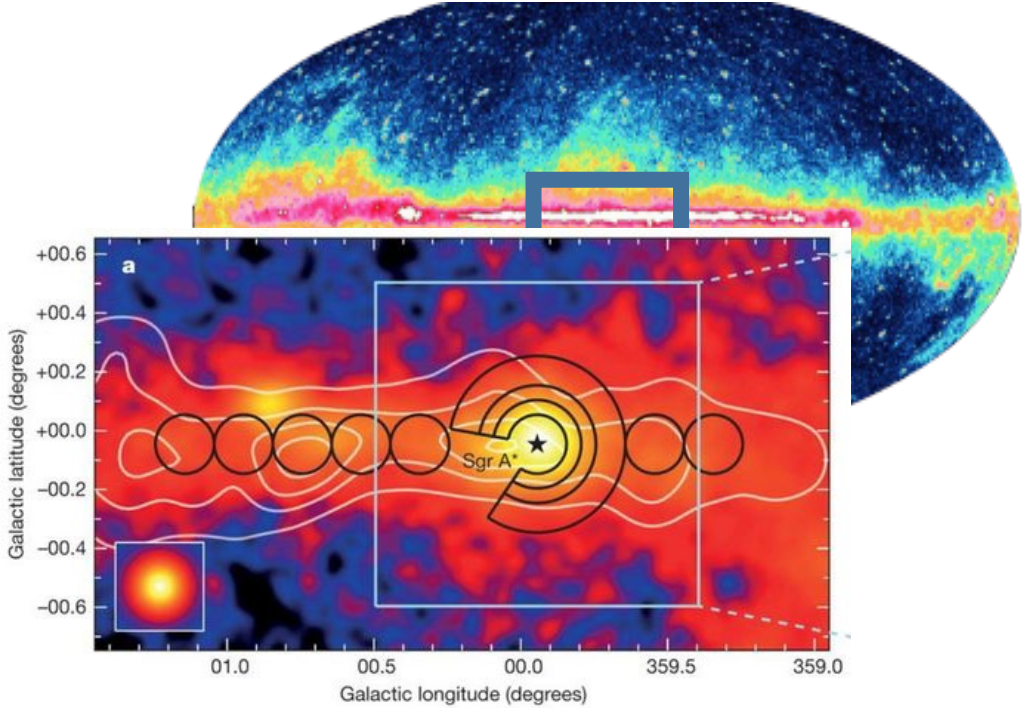
- ➔ Influence of parallel component increases with galactocentric radius
- ➔ Spectrum becomes steeper

Reichherzer, JBT, Zweibel et al, Nature Appl. Sci. (invited, 2021)



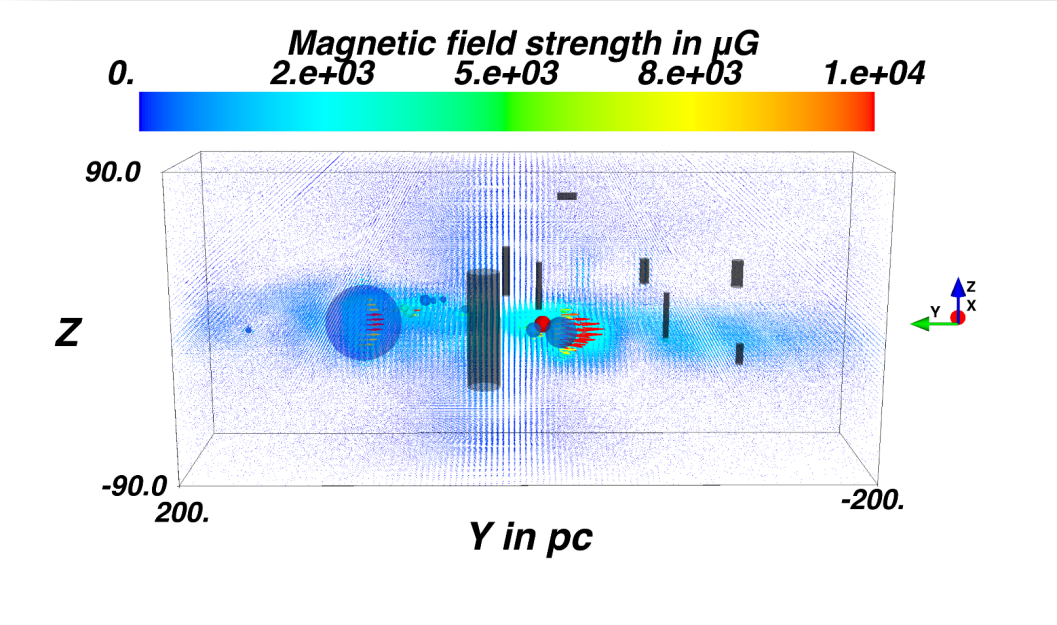
Galactic Center: first PeVatron in the Galaxy





Abramowski et al (H.E.S.S. Coll), Nature 531:476 (2016)

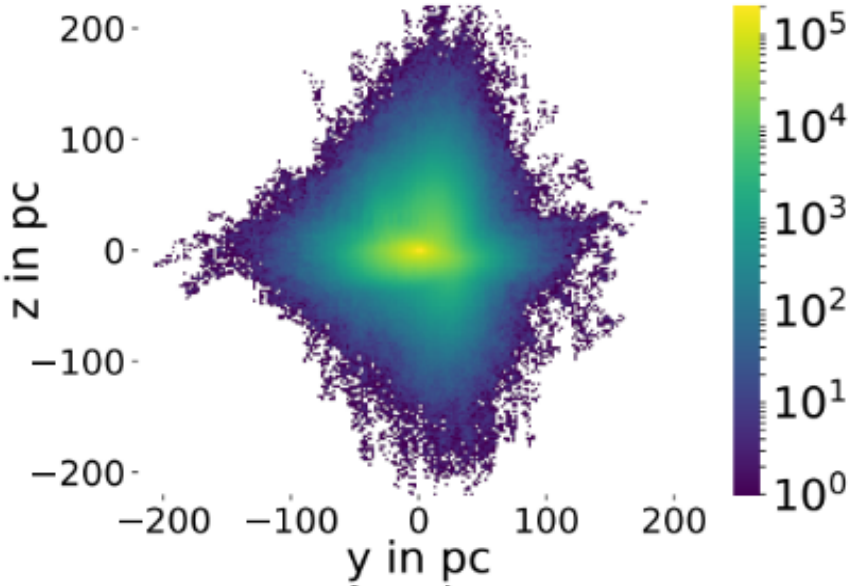
3-dimensional transport in the Galactic Center region



- CR transport sensitive to
  - gas distribution (direct measurements)
  - B-field (no direct measurements)
- ➔ build B-field model from gas distribution & theoretical arguments:
  - poloidal diffuse & NTF **[Ferrière (2009), Ferrière & Terral (2013)]**
  - horizontal MC **[Euler Ansatz]**

Gündüz, JBT, Dettmar, Ferrière, A&A sub (2020)

Cosmic-ray transport: influence of B-field structure



Jansson-Farrar Field (halo component, no disk component)

GBDF2020 Field

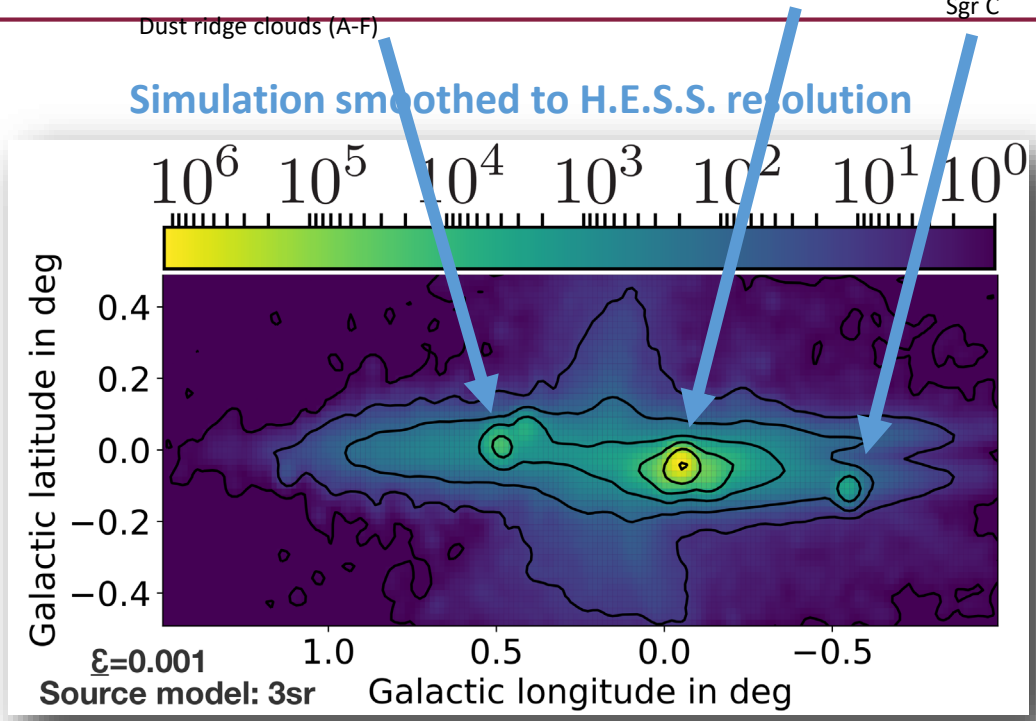
➔ distribution becomes significantly broader in realistic field configuration

Gündüz, JBT, Dettmar, Ferrière, A&A, accepted (2020)

Galactic Center – model & measurement

- H.E.S.S. data (color-contours) can be explained well
- Somewhat too steep decay toward outer edges – possible contribution from diffuse cosmic-ray flux?

- CTA: will be able to resolve illuminated MCs to high degree ➔ understanding **PeVatron, diffuse component** and this way being able to detect **dark matter?**



Simulation smoothed to CTA resolution

Gündüz, JBT, Hörbe, A&A in prep (2020)

We are on our way of solving the puzzle of the non-thermal Universe…
stay tuned!