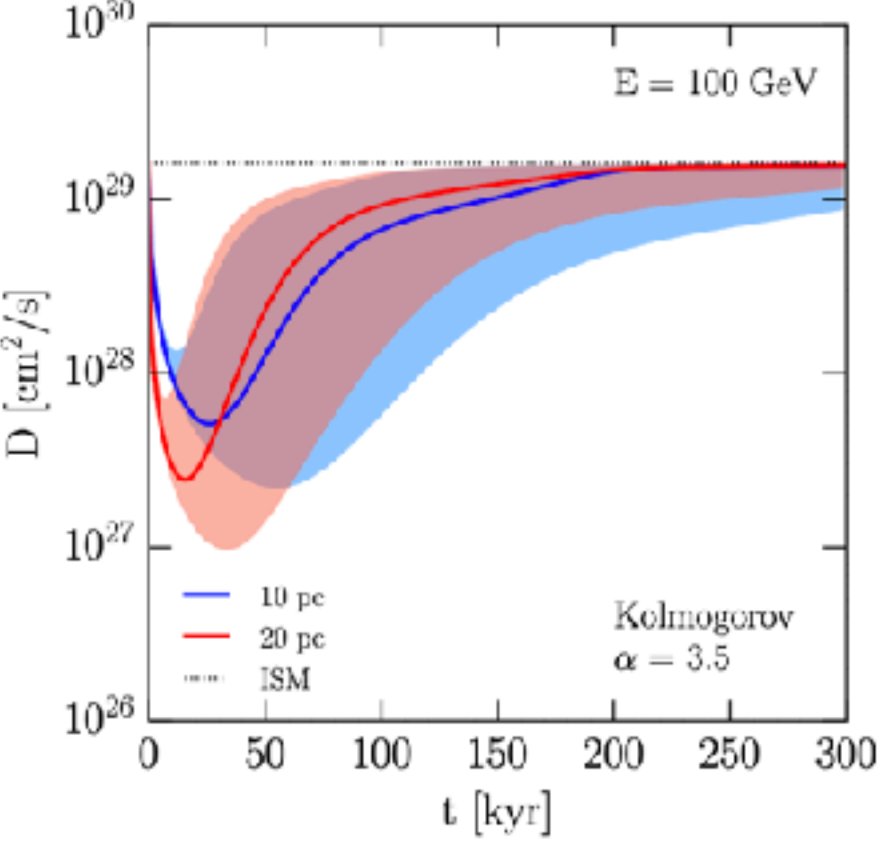
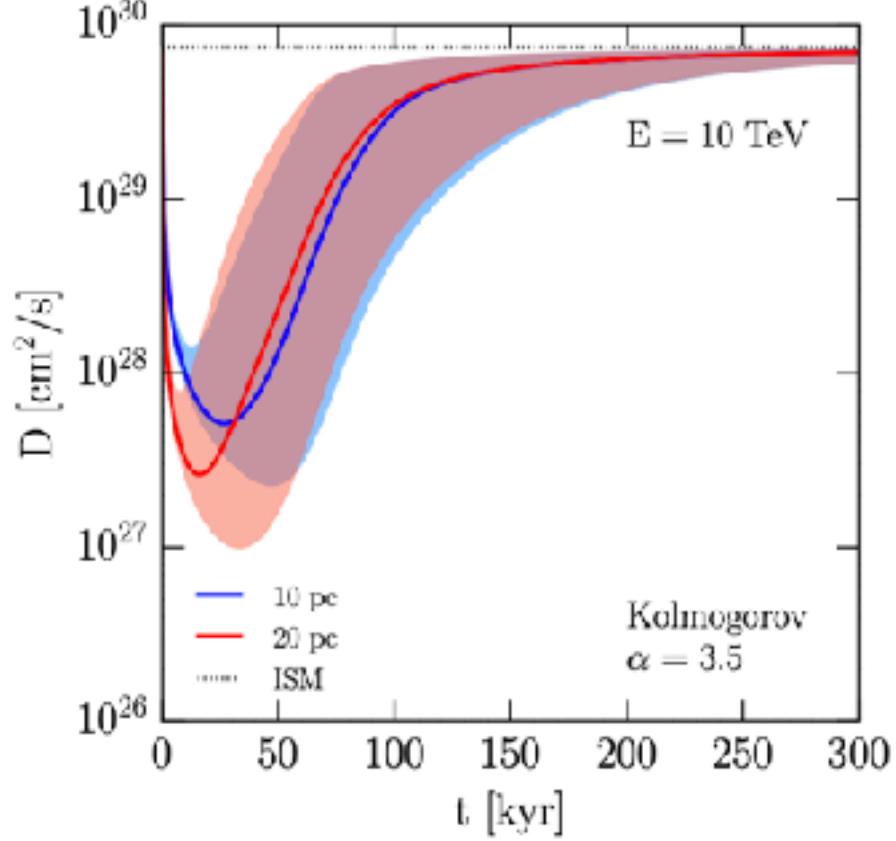
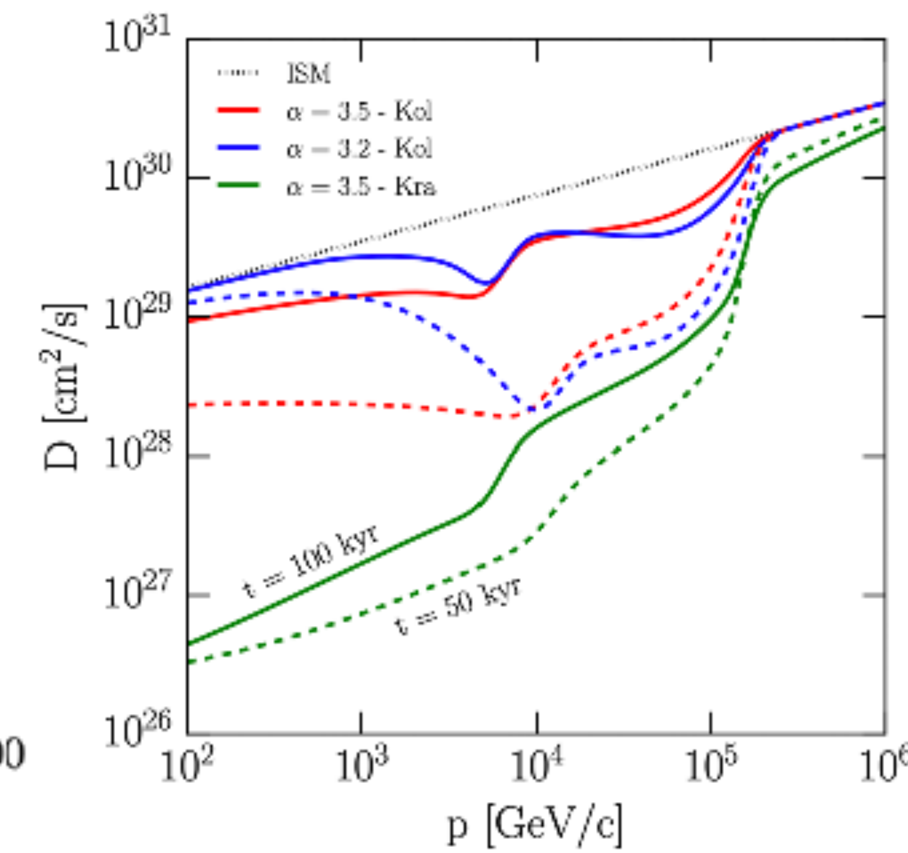






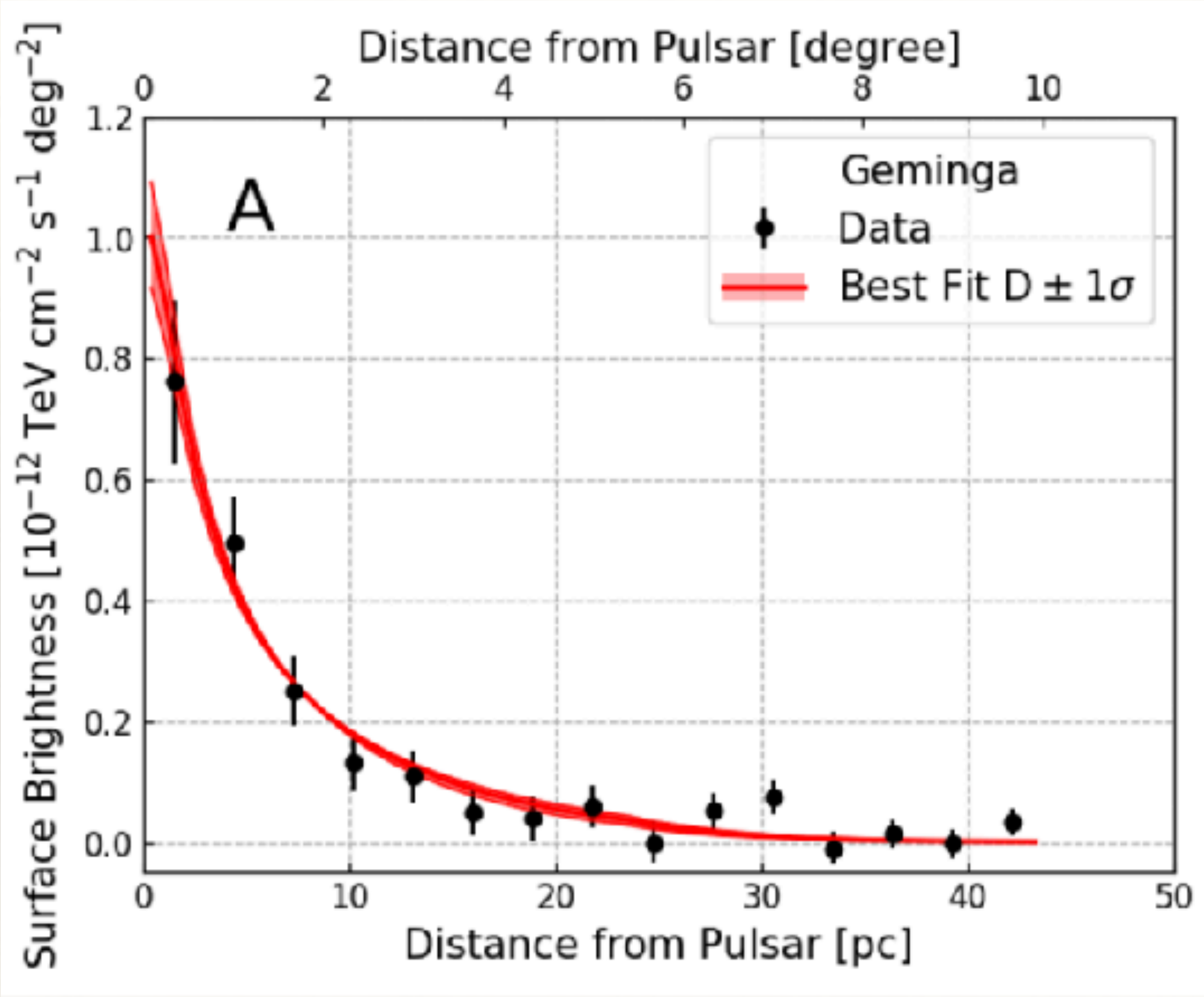
Cosmic-Ray Self-Confinement Models of TeV Halos

Tim Linden

with: Payel Mukhopadhyay and Carmelo Evoli and Giovanni Morlino

Observations indicate a Steep CR Gradient

- HAWC observations tell us that there is a steep gradient of CR electrons near Geminga.
- Such an observation is:
  - Compatible with diffusion
  - Compatible with inhibited diffusion
  - Indicates the system is not in equilibrium



CR Gradients Produce Turbulence

$$\frac{\partial W}{\partial t} + v_A \frac{\partial W}{\partial z} = (\Gamma_{CR} + \Gamma_{NLD})\, W(k, z, t)$$

- Magnetic Turbulence can be generated by cosmic-rays

$$\Gamma_{CR}(k) = \frac{2\pi}{3} \frac{c\,|v_\alpha|}{k\,W(k)} \left(\frac{B_0^2}{8\pi}\right)^{-1} \left[p^4 \frac{\partial f}{\partial z}\right]_{p_{\rm res}}$$

$$\Gamma_{NLD}(k) = c_k\, v_\alpha \begin{cases} k^{3/2} W^{1/2} & \text{Kolmogorov} \\ k^2 W & \text{Kraichnan} \end{cases}$$

- Wave-generation depends on the cosmic-ray gradient
- Wave damping depends on turbulence model.

Turbulence Suppresses CR Diffusion

$$D(p,t) = \frac{4}{3\pi} \frac{c r_L(p))}{k_{\rm res} W(z, k_{\rm res}))}$$

- The efficiency of cosmic-ray diffusion is inversely proportional to the amplitude of magnetic turbulence.
- More importantly, the inhibition of turbulence at a wavenumber k is related to the CR density at the related Larmor radius, which then inhibits the propagation of the same particles - so this is resonant.
- This is the reason why pulsars may be important in the high-energy regime, even if they are subdominant sources of cosmic-rays at GeV energies.

Original Analysis

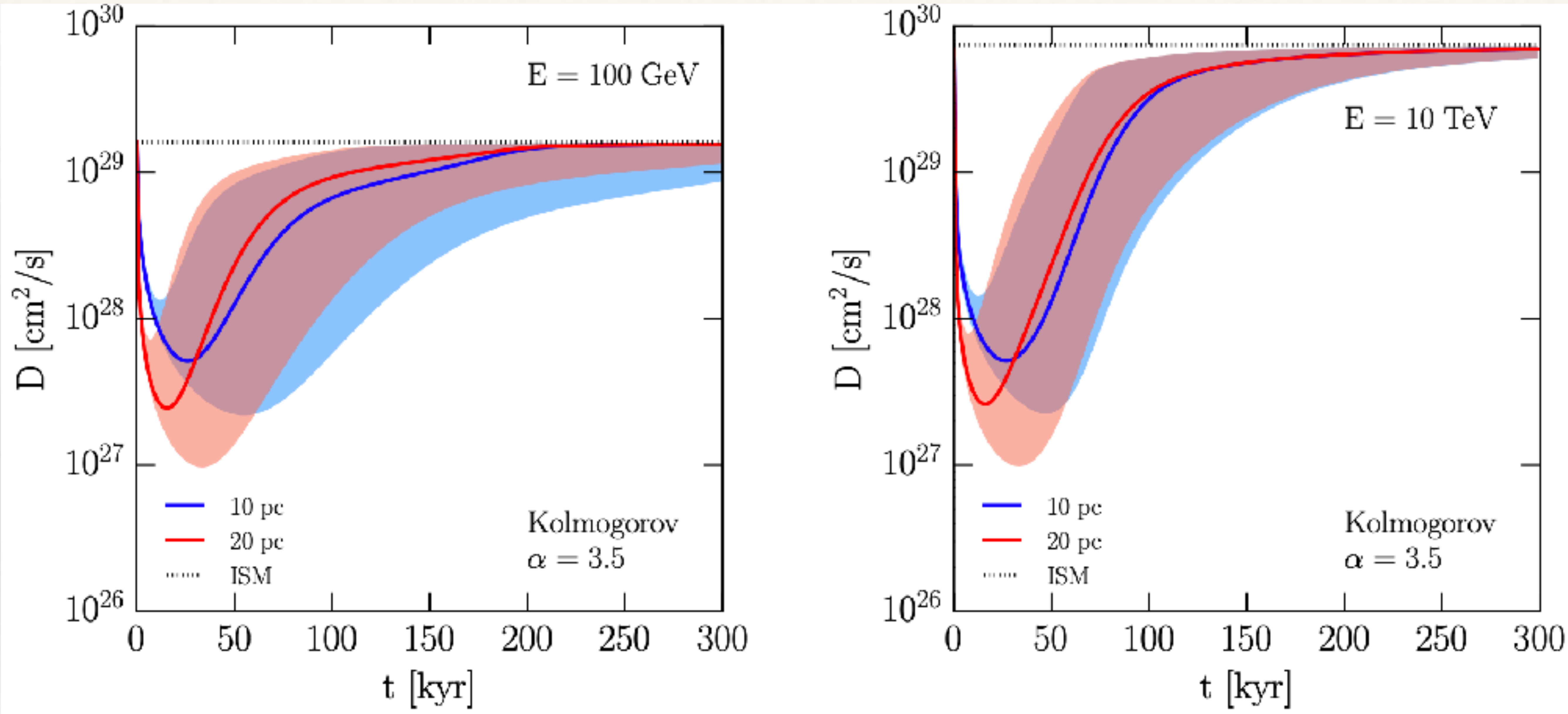
Self-generated cosmic-Ray confinement in TeV halos: Implications for TeV γ-ray emission and the positron excess

Carmelo Evoli,[1,2,*] Tim Linden,[3,†] and Giovanni Morlino[1,2,4,‡]

[1]*Gran Sasso Science Institute (GSSI), Viale Francesco Crispi 7, 67100 L'Aquila, Italy*
[2]*INFN, Laboratori Nazionali del Gran Sasso (LNGS), 67100 Assergi, L'Aquila, Italy*
[3]*Center for Cosmology and AstroParticle Physics (CCAPP), and Department of Physics, The Ohio State University Columbus, Ohio, 43210, USA*
[4]*INAF/Osservatorio Astrofico di Arcetri, Largo E. Fermi 5, Firenze, Italy*

Recent observations have detected extended TeV γ-ray emission surrounding young and middle-aged pulsars. The morphology of these "TeV halos" requires cosmic-ray diffusion to be locally suppressed by a factor of $\sim$100–1000 compared to the typical interstellar medium. No model currently explains this suppression. We show that cosmic-ray self-confinement can significantly inhibit diffusion near pulsars. The steep cosmic-ray gradient generates Alfvén waves that resonantly scatter the same cosmic-ray population, suppressing diffusion within $\sim$20 pc of young pulsars ($\lesssim$100 kyr). In this model, TeV halos evolve through two phases, a growth phase where Alfvén waves are resonantly generated and cosmic-ray diffusion becomes increasingly suppressed, and a subsequent relaxation phase where the diffusion coefficient returns to the standard interstellar value. Intriguingly, cosmic rays are not strongly confined early in the TeV halo evolution, allowing a significant fraction of injected $e^\pm$ to escape. If these $e\pm$ also escape from the surrounding supernova remnant, they would provide a natural explanation for the positron excess observed by PAMELA and AMS-02. Recently created TeV cosmic rays are confined in the TeV halo, matching observations by HAWC and H.E.S.S. While our default model relaxes too rapidly to explain the confinement of TeV cosmic rays around mature pulsars, such as Geminga, models utilizing a Kraichnan turbulence spectrum experience much slower relaxation. Thus, observations of TeV halos around mature pulsars may provide a probe into our understanding of interstellar turbulence.

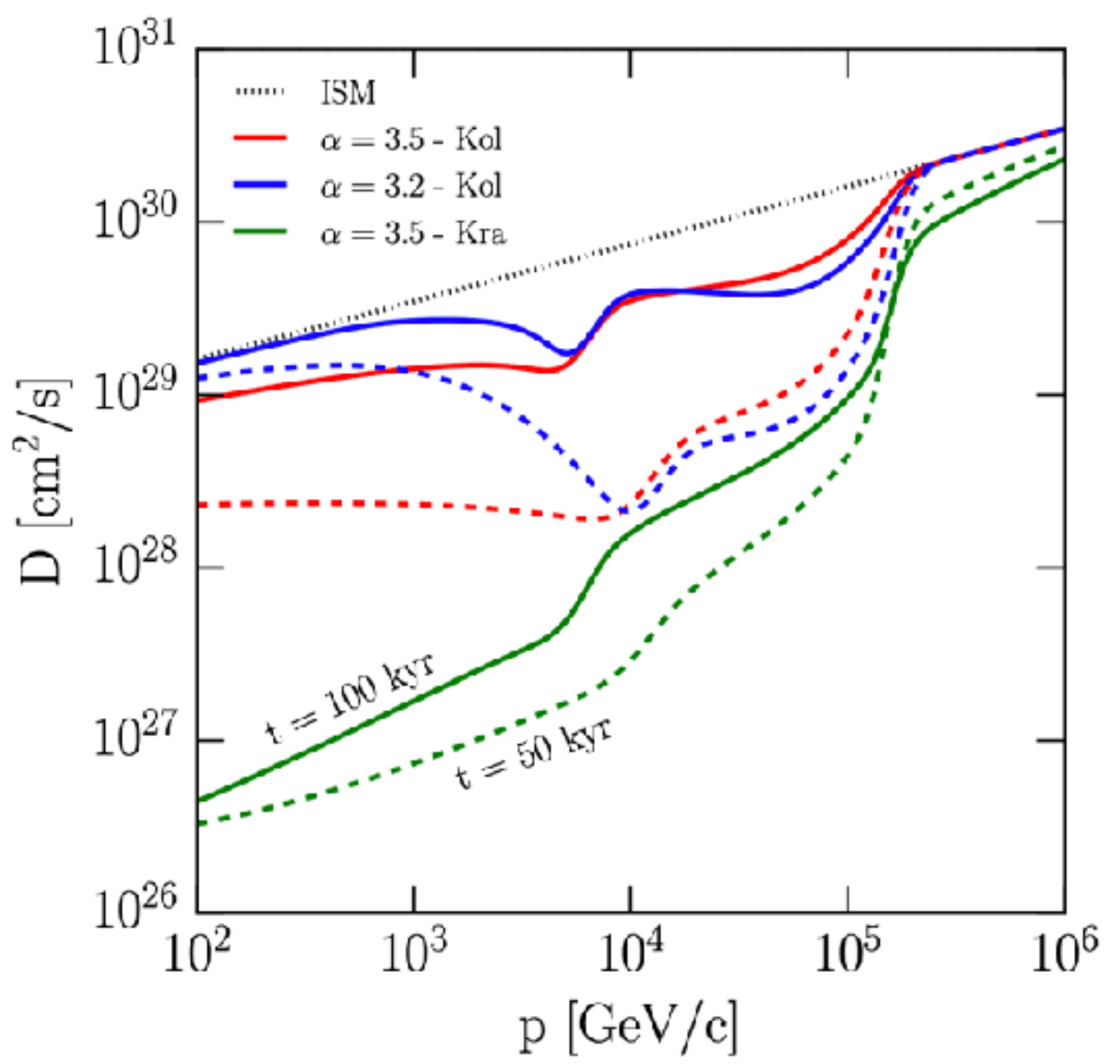
Significant Inhibition of Diffusion



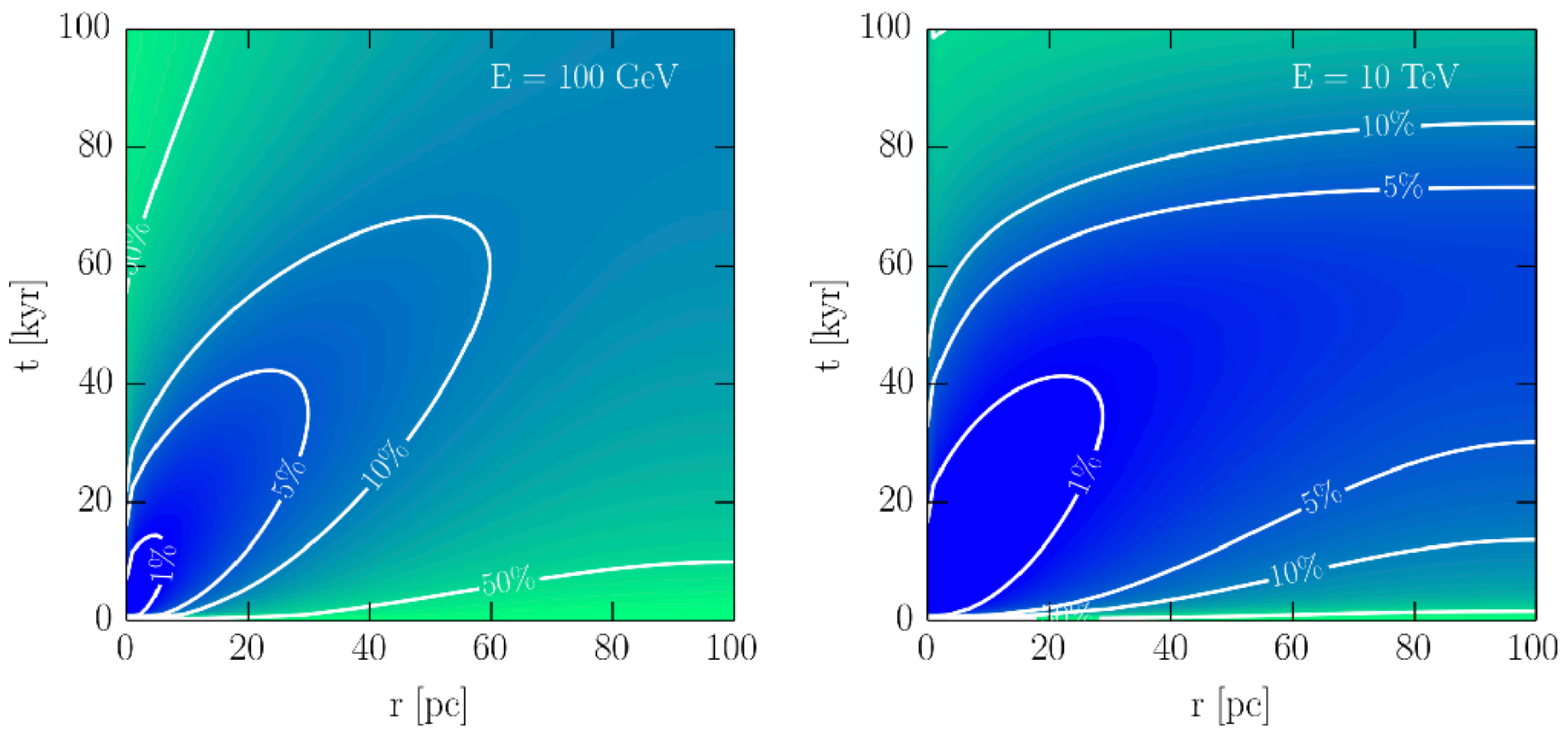
- Resonant interactions from pulsar-produced e^+e^- can significantly inhibit diffusion.

Spectral Signatures of CR Self-Confinement

- Significantly affects the spectrum of the diffusion coefficient
  - Miscast as “convection” in initial papers
- Sharp increase in diffusion when CR cooling becomes important.



Morphological Signatures of CR Self-Confinement



- Can visually see the region of inhibited diffusion spread out from the pulsar itself.

Problems with This Model

- 1.) The diffusion coefficient relaxes back to the ISM value too quickly (Geminga is 340 kyr old).
- 2.) 100% conversion of pulsar spin down power is required.
- 3.) Only 1D flux tubes were considered (CR density falls too fast in 3D space).
- 4.) Effects like pulsar motion were not considered.

A Super(nova) Solution?

Possible origin of the slow-diffusion region around Geminga

Kun Fang[1⋆] Xiao-Jun Bi[1,2]† Peng-Fei Yin[1]‡
[1] *Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[2] *School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China*

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ABSTRACT

Geminga pulsar is surrounded by a multi-TeV γ-ray halo radiated by the high energy electrons and positrons accelerated by the central pulsar wind nebula (PWN). The angular profile of the γ-ray emission reported by HAWC indicates an anomalously slow diffusion for the cosmic-ray electrons and positrons in the halo region around Geminga. In the paper we study the possible mechanism for the origin of the slow diffusion. At first, we consider the self-generated Alfvén waves due to the streaming instability of the electrons and positrons released by Geminga. However, even considering a very optimistic scenario for the wave growth, we find this mechanism DOES NOT work to account for the extremely slow diffusion at the present day if taking the proper motion of Geminga pulsar into account. The reason is straightforward as the PWN is too weak to generate enough high energy electrons and positrons to stimulate strong turbulence at the late time. We then propose an assumption that the strong

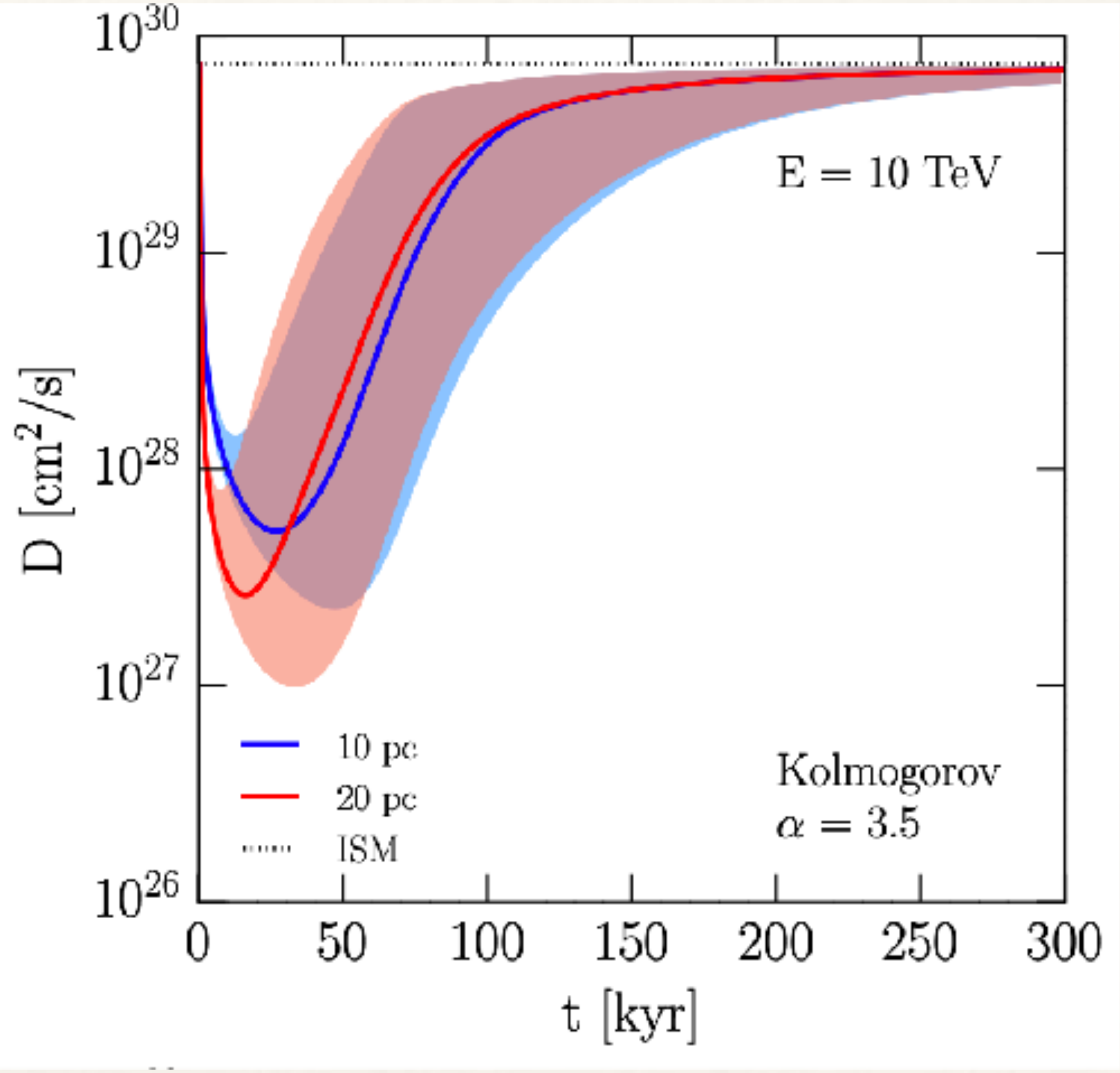
New Analysis

- Goal: Re-examine the Halo + SN Solution
  - Account for Pulsar Motion
  - Examine interactions of halos

New Analysis

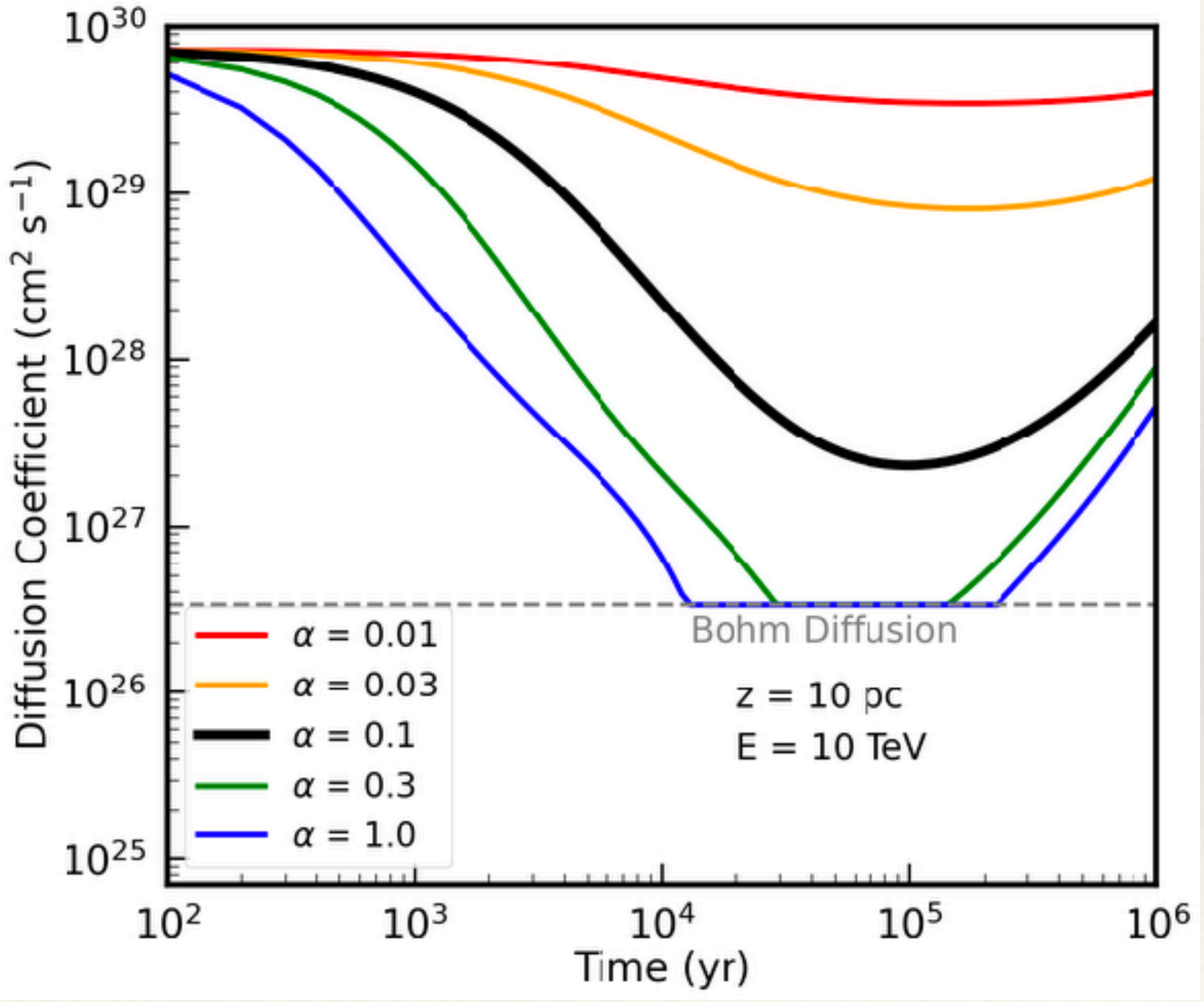
- Product: Found a bug in the previous analysis.

$$\Gamma_{NLD}(k) = c_k \, v_\alpha \begin{cases} k^{3/2} W^{1/2} & \text{Kolmogorov} \\ k^2 W & \text{Kraichnan} \end{cases}$$



Diffusion is More Inhibited

- Weak Relaxation leads to significant decrease in the diffusion coefficient.
- Models with a 10% e^+e^- production efficiency fit observations.
- Inhibited diffusion persists for ~10^6 yr, even with Kolmogorov diffusion.



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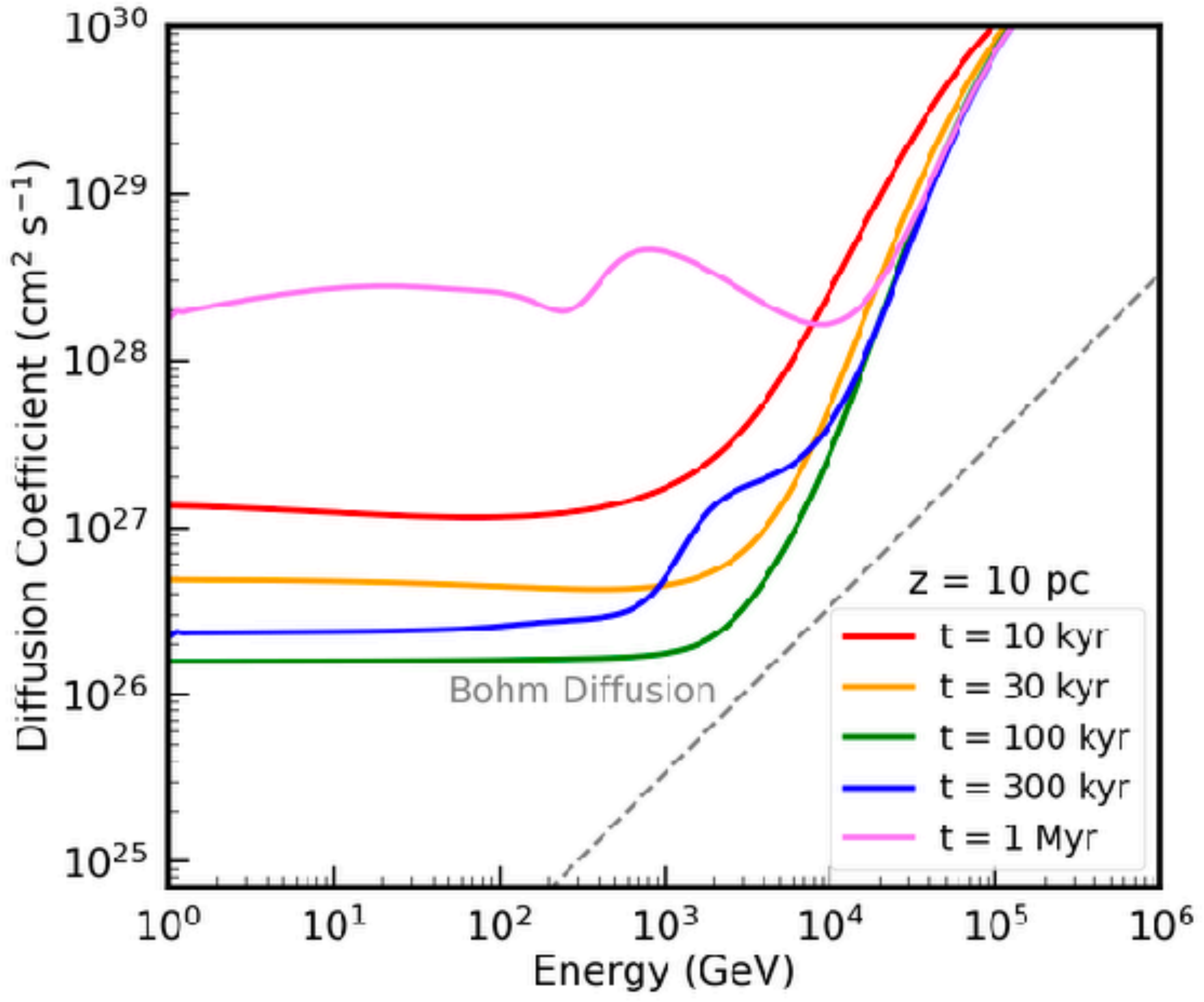

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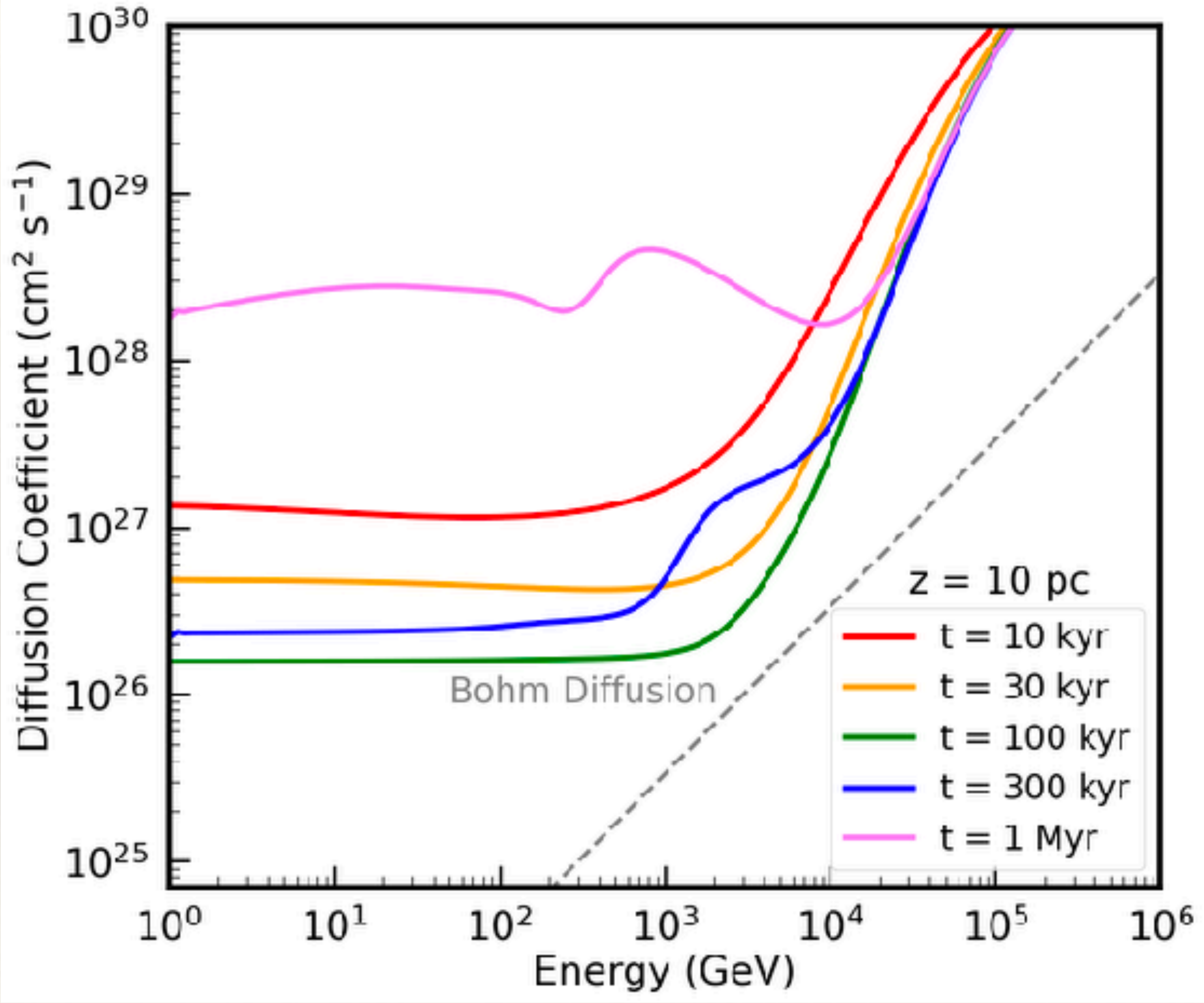
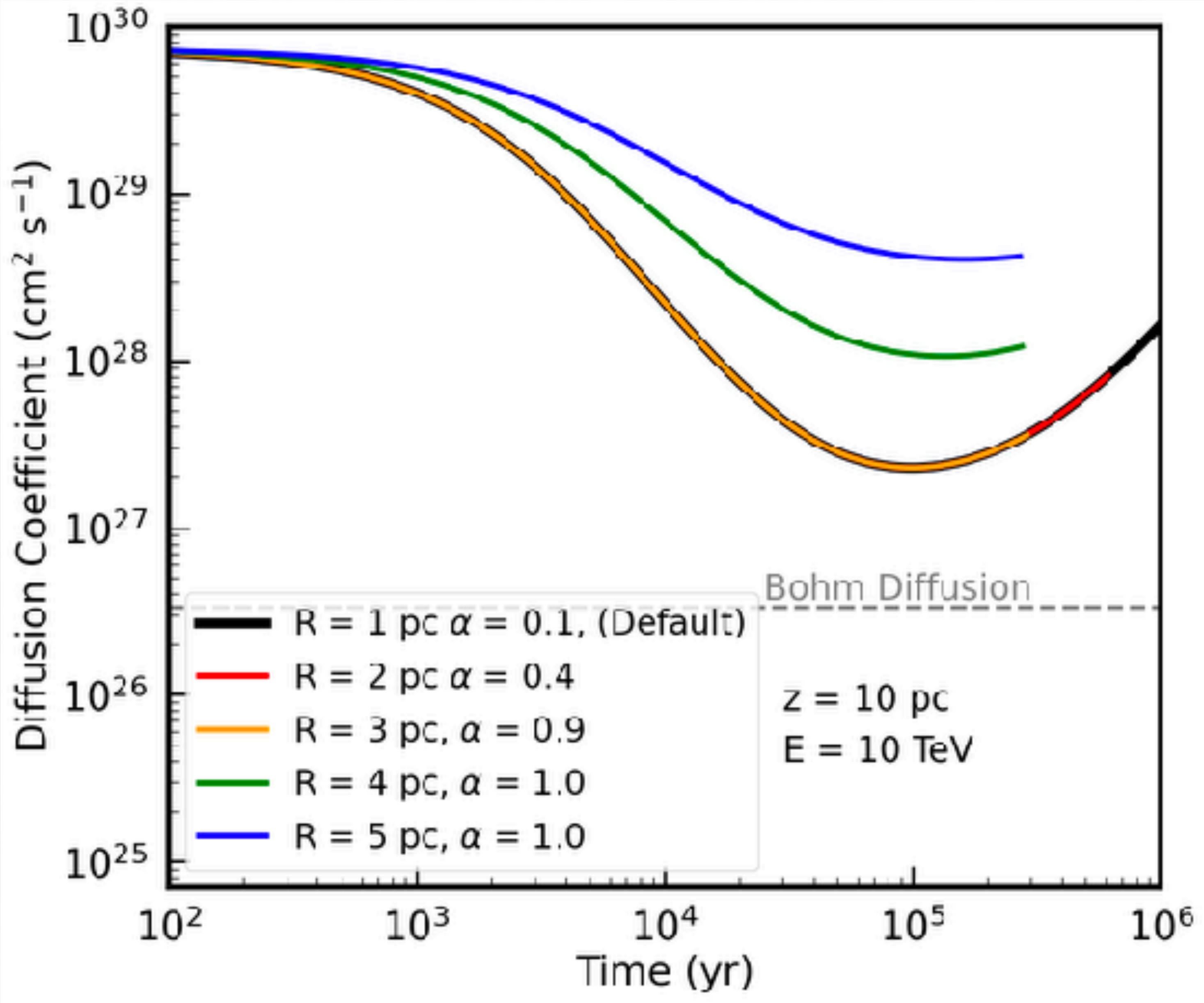


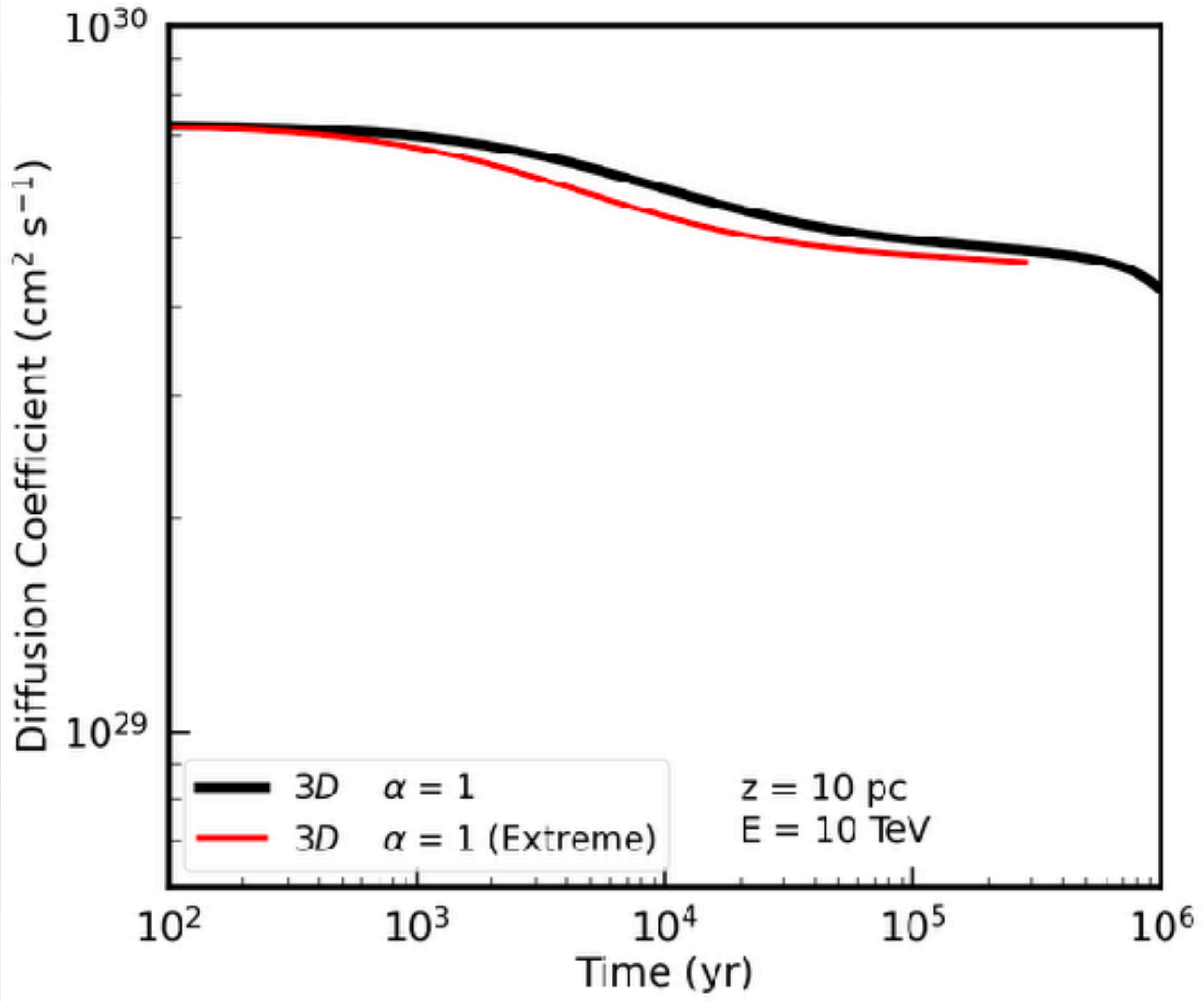
Simulation Can Continue with Wider Flux Tubes

- Degeneracy between pulsar efficiency and flux tube radius (until efficiency approaches 1)
- Can build significantly wider halos.



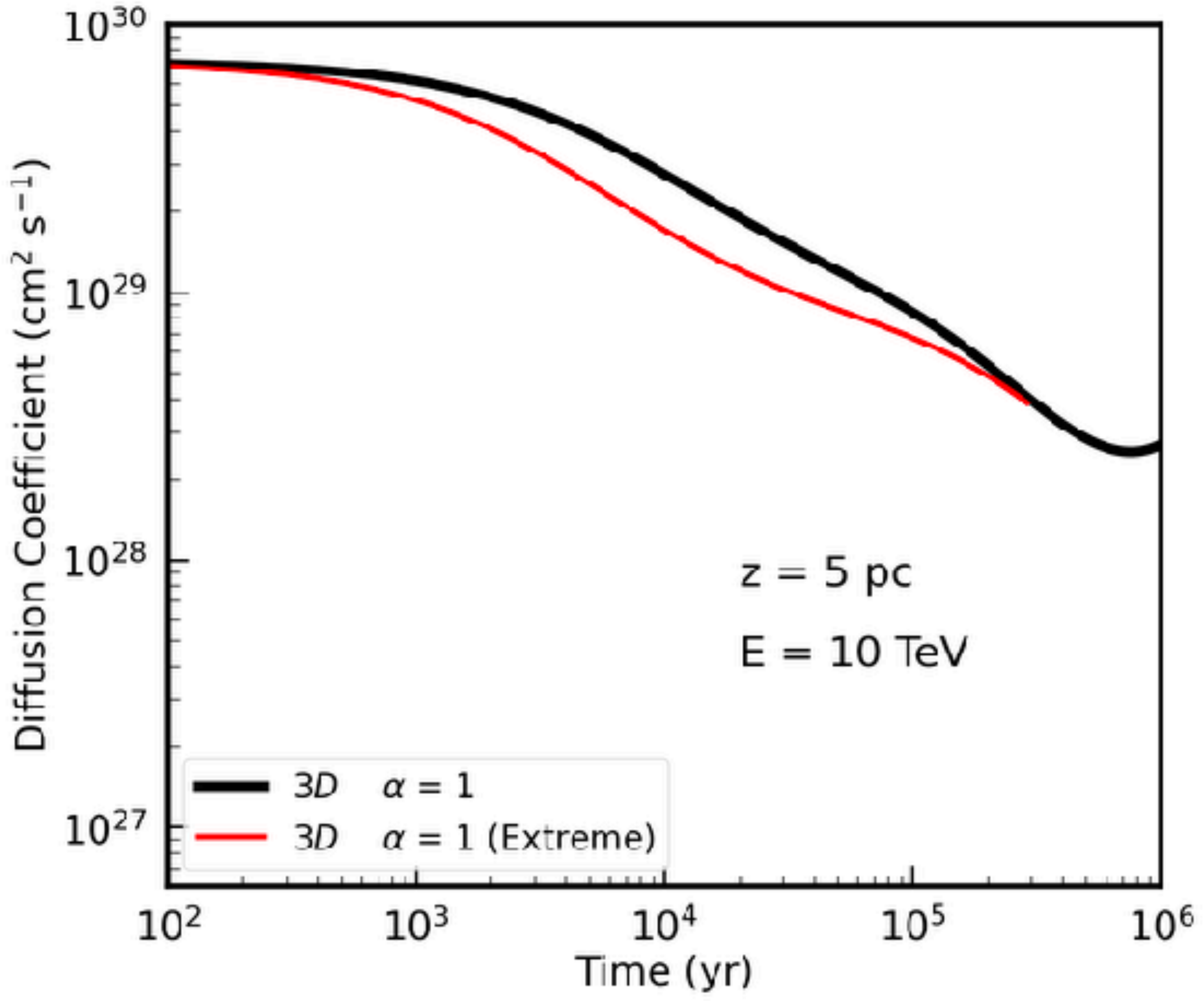
3D Diffusion Models

- In 3D, the pulsar power fails at 10 pc
- This is true even in relatively extreme models:
  - E^{-3} injection
  - 5 kyr spindown timescale
  - 0.5 muG B-field
  - Minimum energy 10 GeV.



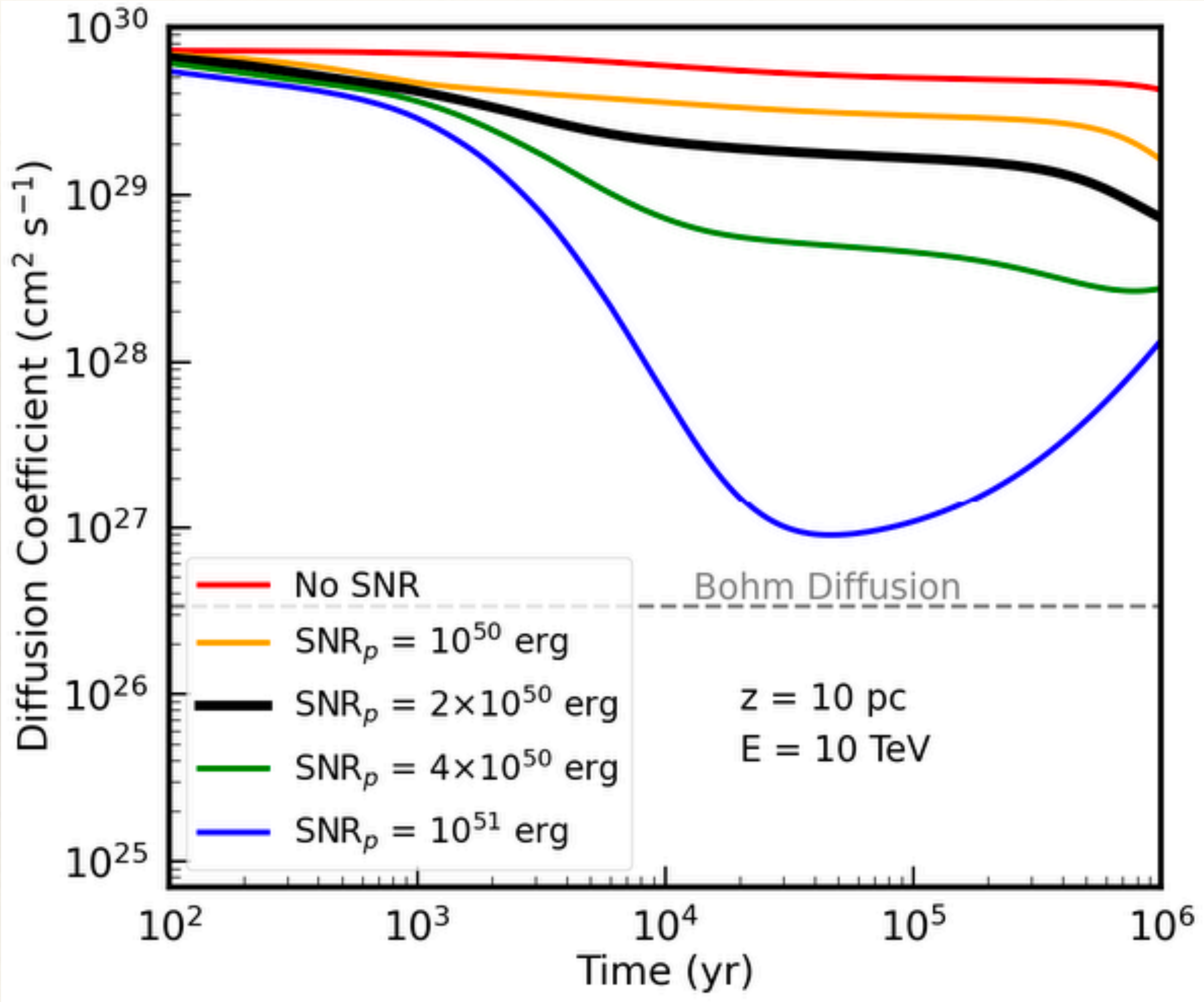
3D Diffusion Models (5 pc)

- The pulsar isn't doing nothing though — diffusion at 5 pc is highly inhibited.
- The inhibition of diffusion is non-linear — small changes to CR power can significantly affect result.



Possible Solution: Supernovae

- Gain more power by using a more powerful source.
- Model CR self-confinement stemming from both proton and lepton injection.
- Models require relatively high SNR power to inhibit diffusion at high energies.



Conclusion

- CR Self-Confinement Models are much more promising than previously thought.
    - Pulsar itself can easily power the necessary turbulence in 1D.
    - Pulsars cannot power the turbulence in 3D, but models that include SN contributions potentially can (energetically).
    - Modeling of the SN and PWN contributions is needed.