An alternative solution to the Gradient problem

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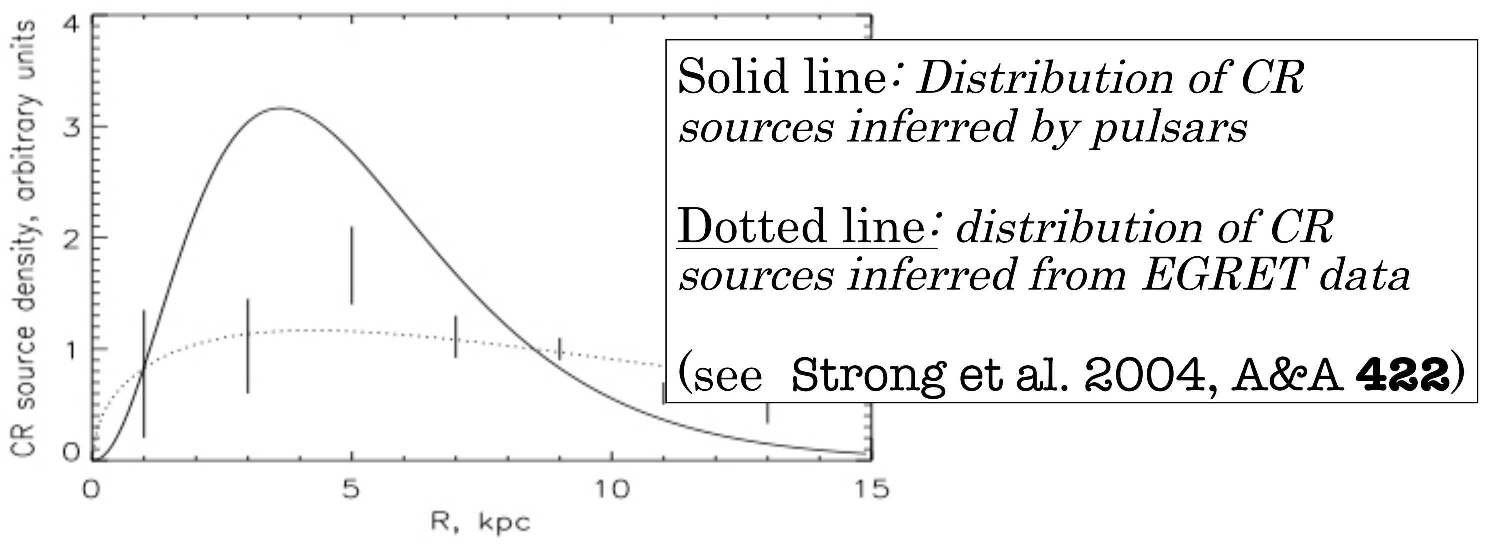
All CR propagation models considered so far in the literature adopt a spatially uniform diffusion coefficient. We show that a more physically reasonable diffusion coefficient that correaltes with the CR source function permits to solve the Gradient Problem, i.e. the discrepancy between the predicted CR emissivity gradient through the Galaxy and the observed one

Introduction: The Gradient problem

The Gradient problem has been known since EGRET era:



The Galactic distribution of emissivity per H atom, which is a measure of the cosmic-ray (CR) flux distribution, is much flatter than the observed pulsar distribution (which traces CR sources)

The problem is STILL PRESENT in Fermi-LAT data
(see e.g. Ackermann et al. 2010, ApJ **726**)

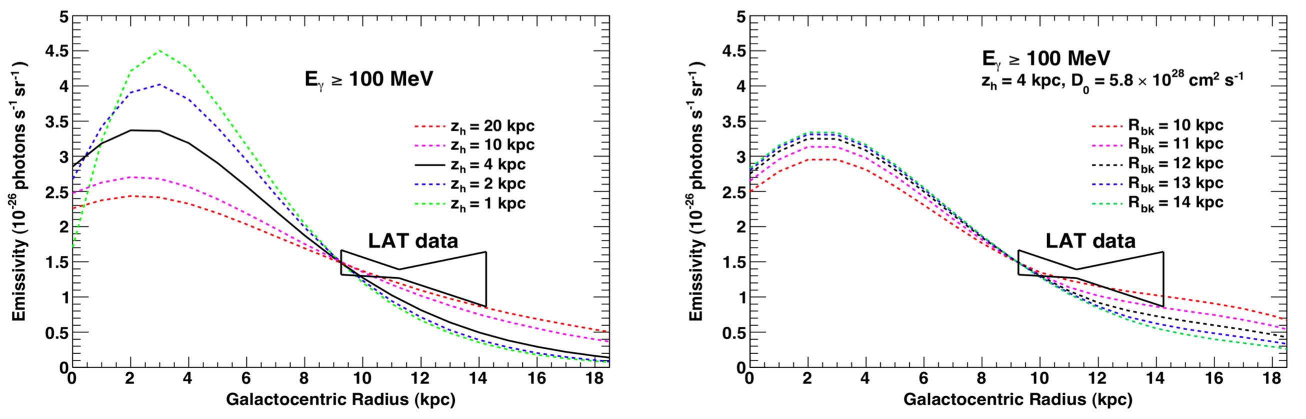


Fig. 13.— Comparison of the emissivity gradient obtained by the LAT and model expectations using GALPROP. The left panel shows models with different halo sizes and diffusion lengths: $(z_\mathrm{h}, D_0) = (1$ kpc, 1.7×10^{28} cm^2 s$^{-1})$, $(2$ kpc, 3.2×10^{28} cm^2 s$^{-1})$, $(4$ kpc, 5.8×10^{28} cm^2 s$^{-1})$, $(10$ kpc, 12×10^{28} cm^2 s$^{-1})$ and $(20$ kpc, 18×10^{28} cm^2 s$^{-1})$. The solid line is for $z_\mathrm{h} = 4$ kpc. The right panel shows different choices of the break distance beyond which a flat CR source distribution is assumed: $R_\mathrm{bk} = 10$–14 kpc with 1 kpc steps.

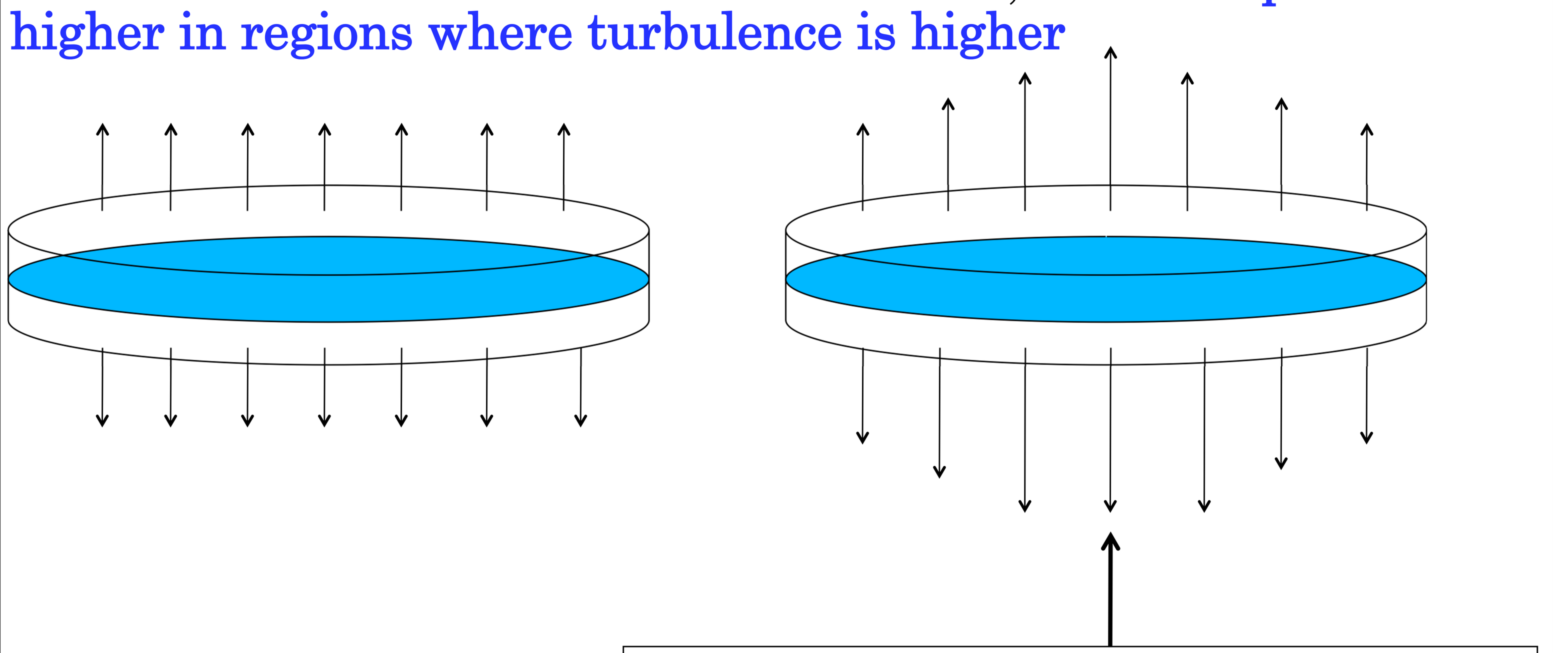
Although **less severe if a very large halo height is adopted in the model or a flatter source distribution in the outer Galaxy.**

Our idea:

All models considered so far adopt a spatially uniform diffusion coefficient.

However, the diffusion coefficient is not likely to be a constant throughout the Galaxy since in regions with an important ongoing star formation (e.g. the Molecular Ring) a higher level of turbulence is expected.

In our Galaxy the regular magnetic field is approximately directed along ϕ (in cylindrical coordinates).
Therefore, the diffusion coefficient that is important for CR escape is the perpendicular one, and the perpendicular diffusion coefficient increases with turbulence level, so it is expected to be higher in regions where turbulence is higher



In the regions where the diffusion coefficient is expected to be higher, **the CR escape is enhanced**. This effect decreases the CR flux and therefore helps to smooth the gradient!

Our models:

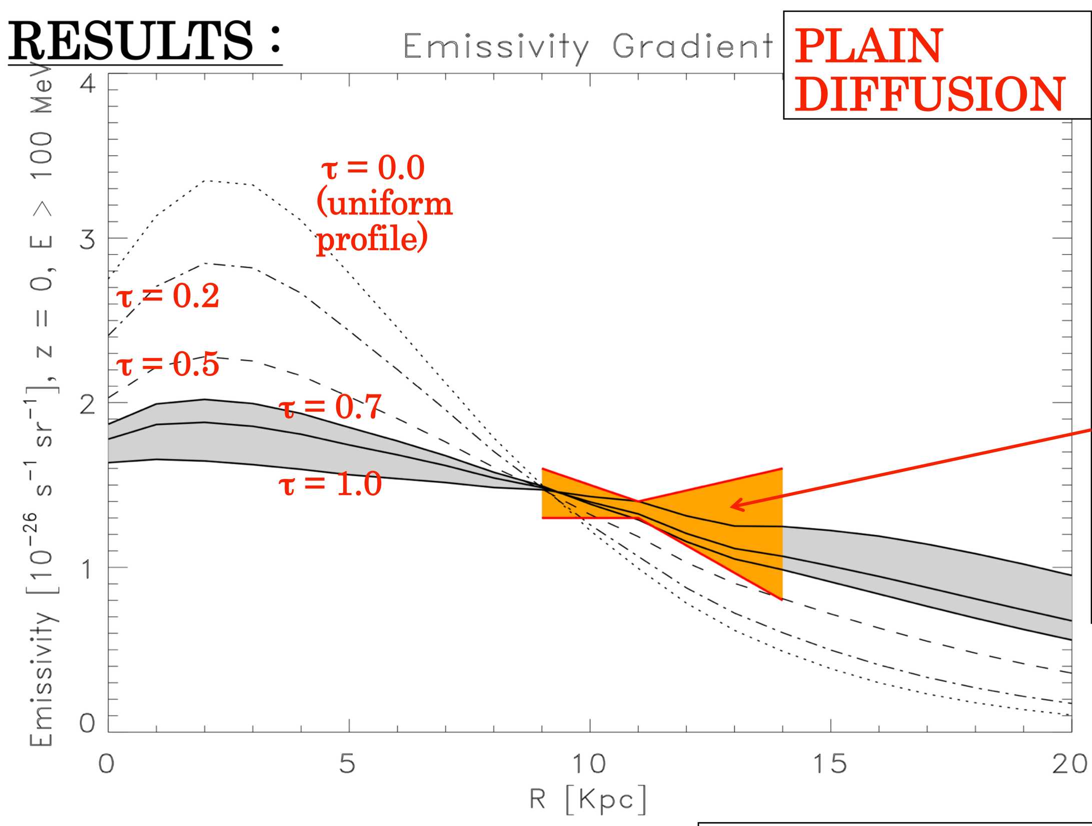
We considered models in which the diffusion coefficient is a function of position: D(r,z)

We started with a PLAIN DIFFUSION setup for simplicity (no reacceleration involved)

The D(p,r,z) is linked to the particle rigidity R and to the CR source term Q(r,z) in the following way:

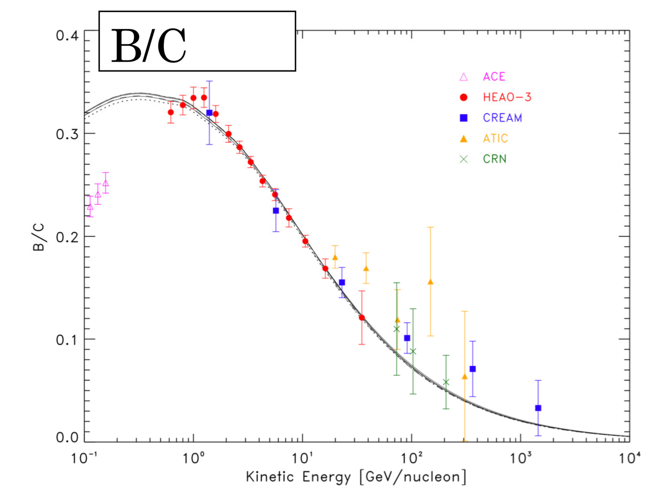
$$D(p,r,z) = D_0\, \beta^{\eta}\, R^{\delta}\, Q(r,z)^{\tau}$$

RESULTS :



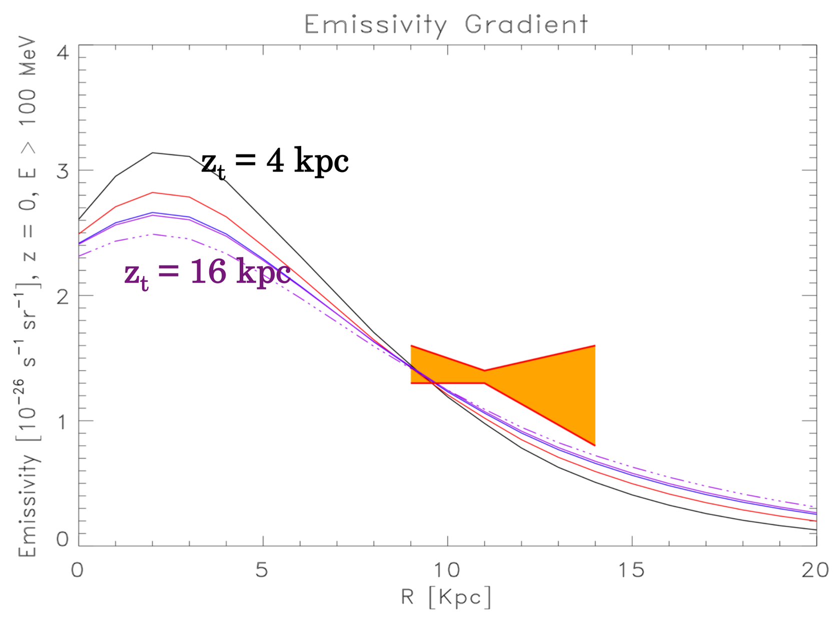
We considered a wide range from τ = 0.0 (uniform profile) to τ = 1.0

Values in the interval 0.7 – 1.0 nicely match the observed gradient!!



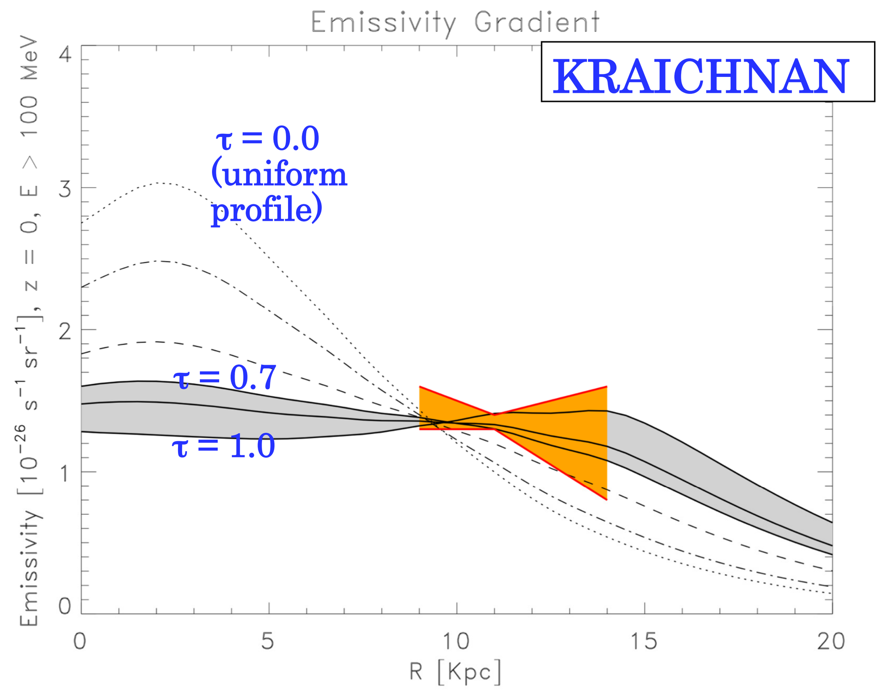
Notice that ALL models are compatible with B/C, C/O, N/O and proton flux. The propagation setup is a Plain Diffusion one (δ = 0.6; no reacceleration, no convection)

In all cases the diffusion coefficient does not change much (less than 1 order of magnitude) from the peak value to the solar value.



A similar effect is obtained with an increased scale height of the diffusion coefficient

But in order to obtain a noticeable flattening a very high value (z_t > 16 kpc) is required



The same effect is obtained with a Kraichnan diffusion setup
(δ = 0.5; v_A = 15 km/s, no convection)

In this case the reacceleration coefficient is taken spatially uniform through the Galaxy.

Conclusions

We found that a spatially variable diffusion coefficient correlated with the source function, which is more realistic from a physical point of view than a uniform one, leads naturally to a flat emissivity gradient compatible with recent Fermi-LAT observations. This effect does not depend on the diffusion setup and does not affect other observables.