Diffuse flux of ultra-high energy photons from cosmic-ray interactions in the disk of the Galaxy and implications for the search for decaying super-heavy dark matter

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Motivations

Estimate of the expected photon flux above 10^{17} eV
from the interactions of UHECRs with the matter in the Galactic disk

<u>If this flux is detected :</u>

* possible probing of the cosmogenic flux originating from π_0 decay

UHECRs + photon fields

$$\phi_\gamma^{cosmo} + \phi_\gamma^{gal}$$

⇒ knowledge of the background hiding the emission of sources in the Galaxy

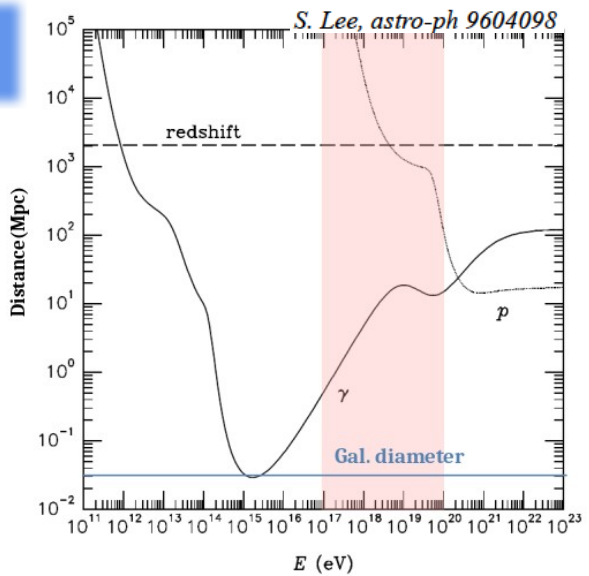
Galaxy gas irradiated by UHECRs

* detection of localized fluxes ⇒ discovery of CR sources

* highlight the presence of Super Heavy Dark Matter (SHDM) produced in the early Universe and decaying today

Procedure

Above 10^{17}eV : * CR flux = protons + heavier nuclei
* Galaxy transparent to photons



Computation of the directional flux = integration of emission rate along the line of sight

$$\phi_\gamma(E,\mathbf{n}) = \frac{1}{4\pi}\int_0^\infty \mathrm{d}s\; q_\gamma(E,\mathbf{x}_\odot + s\mathbf{n}).$$

emission rate

Isotropy of UHECRs ⇒ Isotropic irradiation ⇒ isotropic emission

Emission of UHE photons : inelastic interaction of UHECRs + interstellar gas → light mesons decaying into pions

$$q_\gamma(E,\mathbf{x}) = 4\pi \sum_{i,j} n_j(\mathbf{x}) \int_E^\infty \mathrm{d}E' \phi_i(E') \sigma_{ij}(E') \frac{\mathrm{d}N_{ij}^\gamma}{\mathrm{d}E}(E',E).$$

Local density of gas (j)

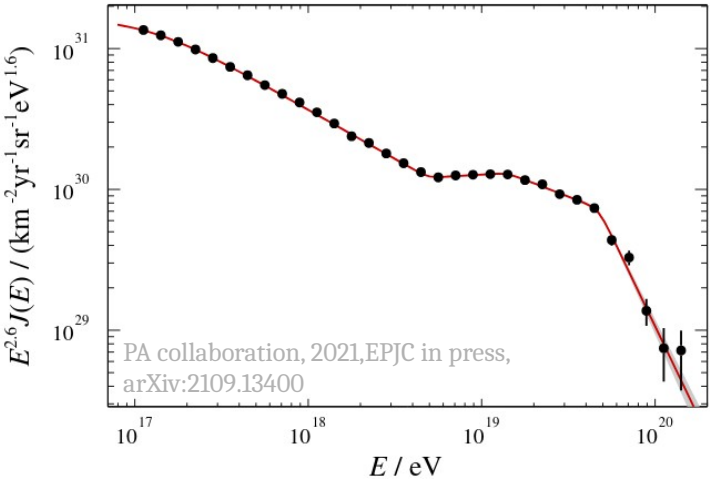
CR flux of (i)

Inel. Cross section

Number of photons produced during the interaction

Cosmic Ray Flux and Mass Composition

At UHE : CR flux and mass composition known by indirect mesurement of air showers produced in the atmosphere

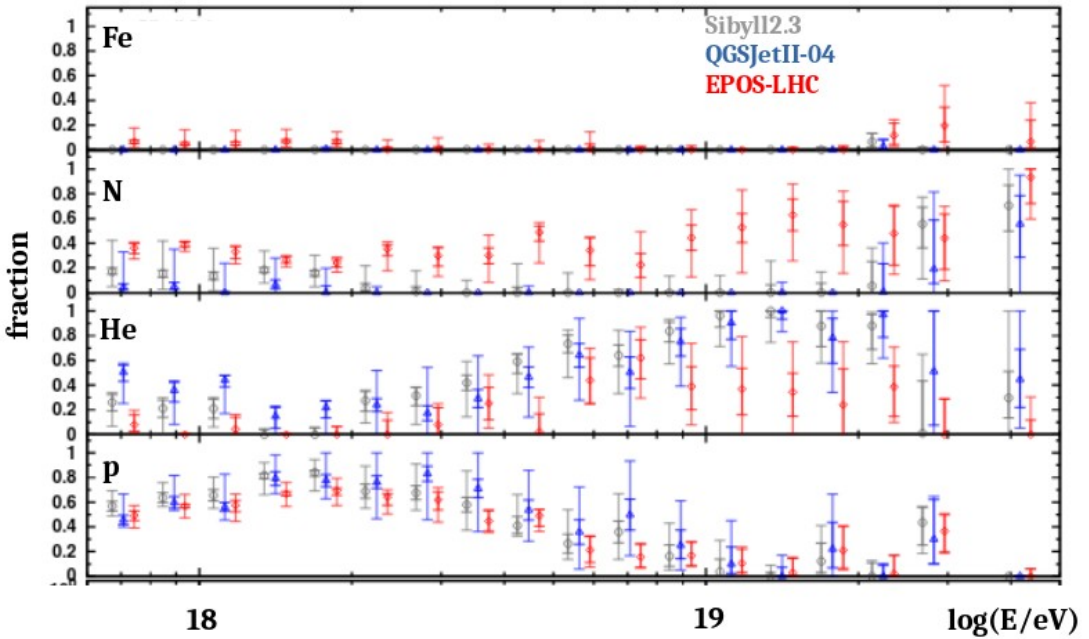


All particle spectrum above 10^{17}eV measured at the Pierre Auger Observatory :
largest cumulated exposure
+ single detector type

Energy-dependent mass composition
using the distribution of Xmax measurements from the Pierre Auger Observatory

With 3 hadronic interaction models
Sibyll2.3
EPOS-LHC
QGSJetII-04

PA Collaboration, Phys. Rev. D 90 (2014) 122006



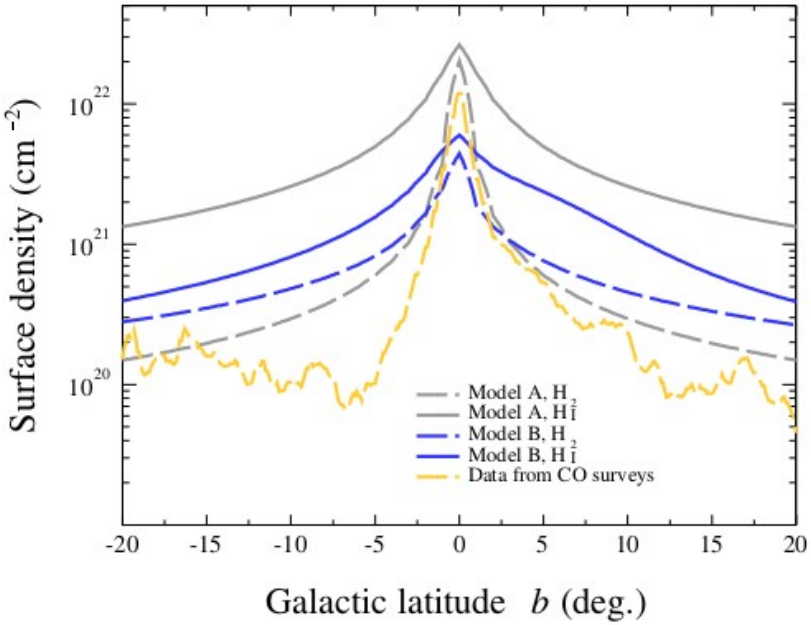
Interstellar gas density in the Milky Way

Interstellar medium = molecular and atomic **H (90%) + He (10%)**

Models of the gas distribution in the galaxy :

* Model A : large scale properties
  axial/up-down symmetric distribution
  [Lipari & Vernetto,Phys. Rev. D 98, 043003]

* **Model B** : smaller scale
  spiral arms and disk bulge modeled
  [Jóhannesson et al, 2018 ApJ 856 45]



Probing of the different gas elements :

* Atomic H : radio absorbtion line at 21 cm
  gas temperature → difference between the population of the singlet and triplet state –> absorbtion coefficient

* Molecular H : impossible to observe directly
  CO excited from its collisions with H_2 –> frequency of CO rotational transition –> calibration factor

* Helium : follows the H distribution (factor 10%)

Photon production

UHECRs irradiating interstellar matter result in the production of light mesons $(\pi_0, \rho, K, \eta...)$

$$\pi_0 \rightarrow 2\gamma$$

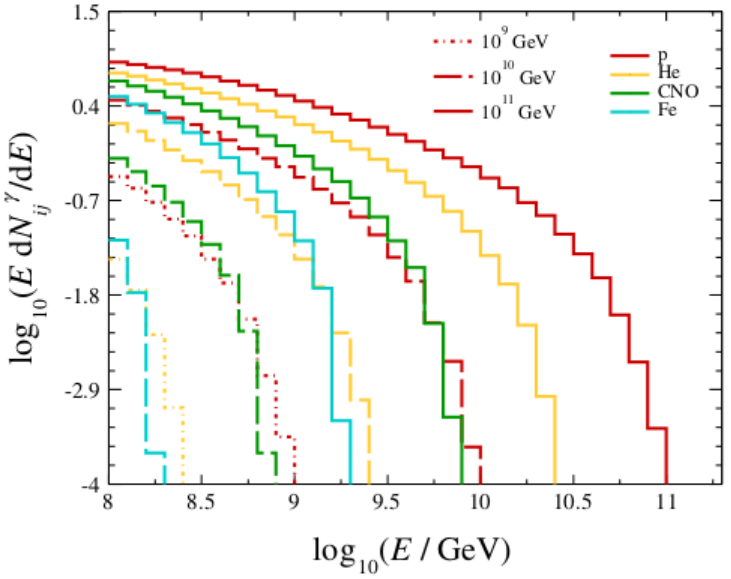
Inelastic cross sections and the energy spectra of photons : **Cosmic Ray Monte Carlo** (CRMC) package C. Baus, T. Pierog and R. Ulrich
https://web.ikp.kit.edu/rulrich/crmc.html

For each couple (i,j) :

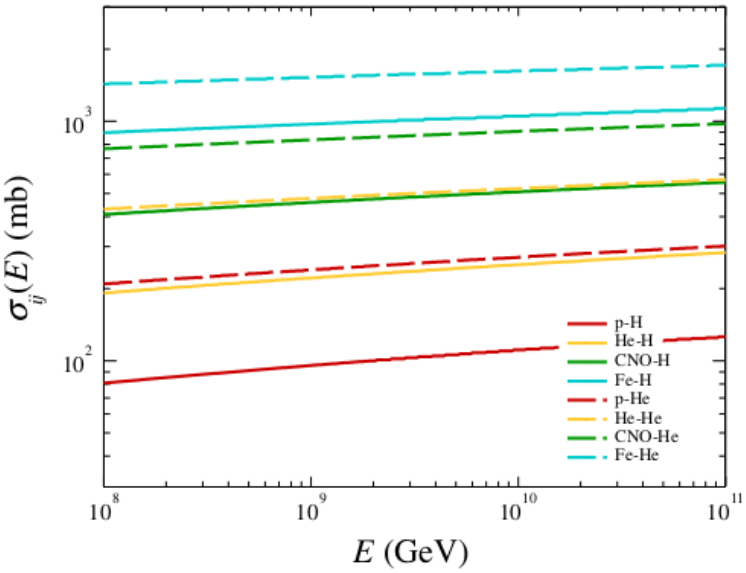
* 100,000 collisions simulated

* 7 primary CR energies

* Hadronic model : EPOS-LHC



Photon yields



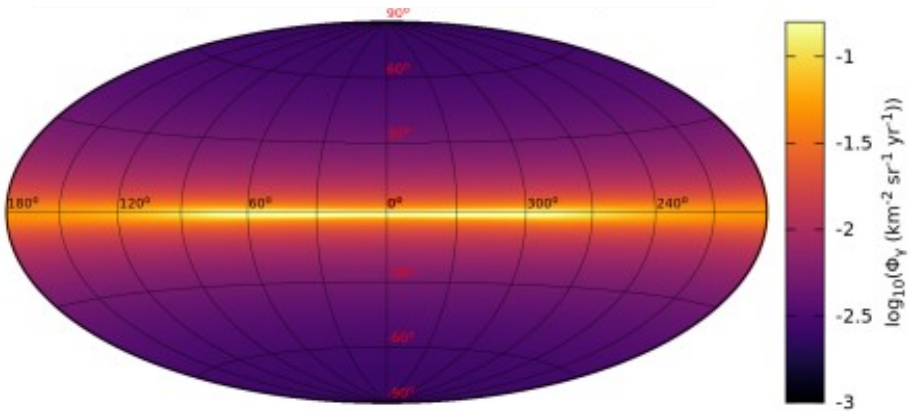
Cross sections

Diffuse flux of UHE photons

* the flux is concentrated around the galactic plane, as expected

* a factor 10^{-5} lower than the UHECRs spectrum, 10^{-6} at highest energy

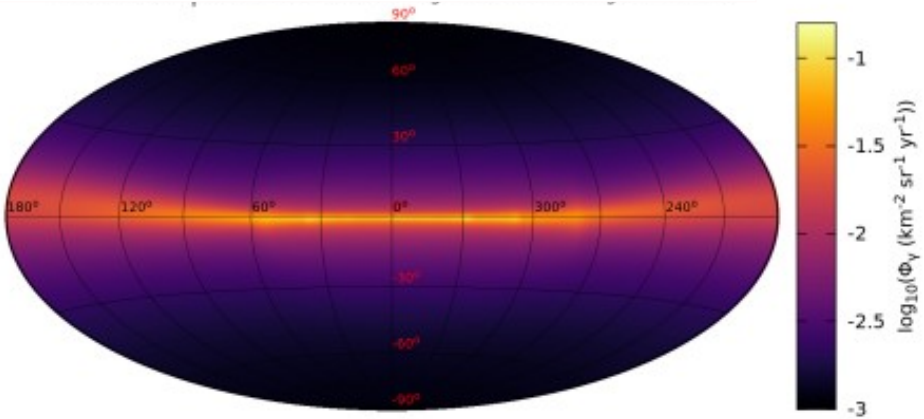
Model A



Smooth distribution along the longitude

Maximum value $\simeq 5.0 \times 10^{-1}$ /km²/yr/sr

Model B



Brighter in the innermost regions

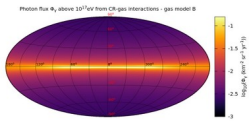
Maximum value (smaller than Model A) at $|l| \simeq 55°$

Comparison to current upper limits

Comparison to a search for point-like sources :

* upper limits taken from the Auger collaboration [ApJ, 789, 160 (2014)]

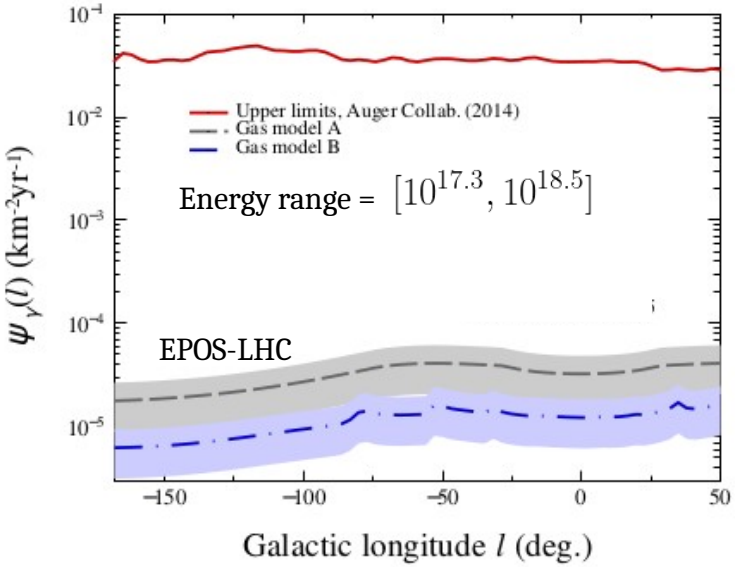
* converted our directional flux into a collection of point-like sources
(Averaged over a 5°-band over the galactic plane)



$$\rightarrow \phi(l) = \frac{1}{2.sin5°} \int dE_{CR} \int db.sinb \int d\mathbf{n}'.f(\mathbf{n}', \mathbf{n}).\phi(E_{CR}, \mathbf{n})$$

Directional photon flux

Point-spread function of the PAO
(gaussian filter)



Systematics =
all particle energy spectrum
+ hadronic models

Results :

* 3 orders of magnitude below current limits : unreachable with current detectors

* upper limits are reported for a E^{-2} photon flux and would be higher for steeper spectra

Comparison to current upper limits

Comparaison to other searches for a diffuse photon flux :

* performed by several other experiments : (**Auger**, **EAS-MSU**, **KASCADE-Grande**, **TA**)

* $\phi(E, \mathbf{n}) \rightarrow \phi(> E)$

* cosmogenic flux from π_0 decay : dependent on the primary UHECR mass

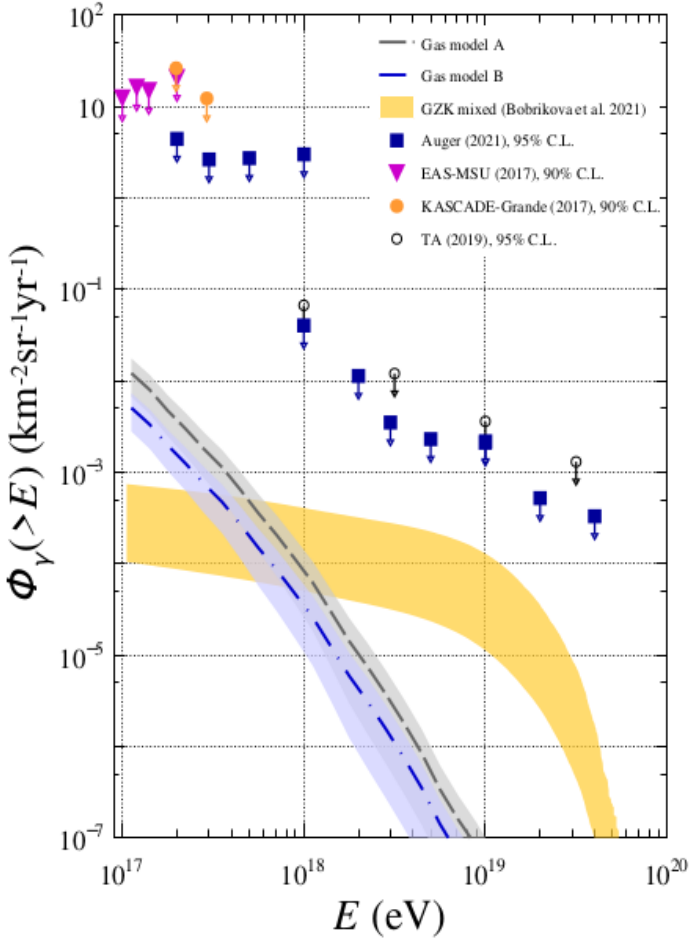
  ⇒ : a mix from p to Fe primaries that fits the Auger data
  [Bobrikova et al. , ICRC 2021, PoS]

Results :

* for energies $\approx (10^{17} \rightarrow 10^{18.5})$ eV : 2.5/3 orders of magnitude below other limits

* higher for larger energy thresholds

* the cosmogenic flux computed here is dominant between 10^{17} and 10^{18} eV



Implication for search of SHDM

* If dominant : could prevent the probing of sources and/or evidence of SHDM in the Galaxy

* ϕ^{DM} can be observed if SHDM particles have long enough lifetime τ_X

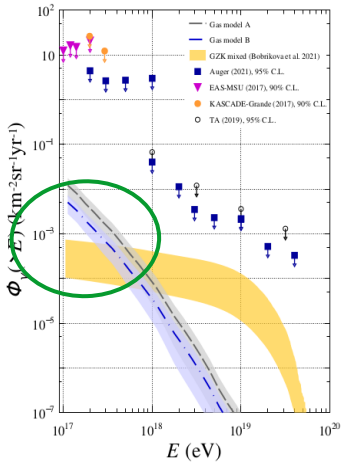
* SHDM particles X decays –> photons

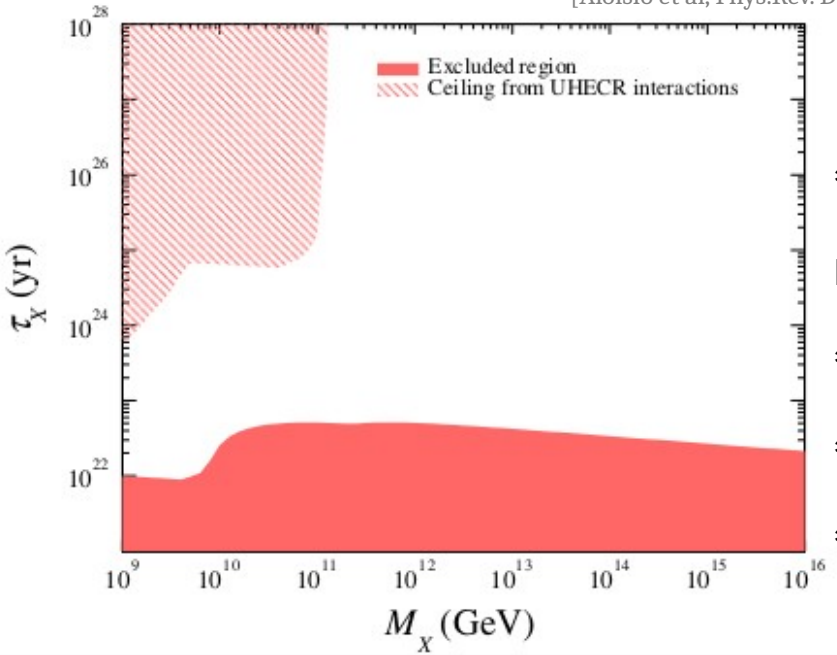
$$\phi_\gamma^{\mathrm{DM}}(E,\mathbf{n}) = \frac{1}{4\pi M_X \tau_X}\frac{\mathrm{d}N}{\mathrm{d}E}\int_0^\infty \mathrm{d}s\,\rho_{\mathrm{DM}}(\mathbf{x}_\odot + s\mathbf{n})$$

[Aloisio et al, Phys.Rev. D74 023516 (2006)]

Photons' fragmentation function

Energy-density profile of DM
[Navarro et al, ApJ. 462 563-575 (1996)]





* By scanning M_X we determine $\tau_X(M_X)$ for which $\phi^{DM}(E) < \phi^{\gamma}(E)$

Results :

* Ceiling affects masses up to $\approx 10^{11}$ GeV (cosmogenic flux cut-off)

* Ceiling more constrained by ϕ_γ^{gal} below 10^{10} GeV

* Above 10^{10} GeV the cosmogenic flux ϕ_γ^{cosmo} takes over

Summary and outlook

* the integrated UHE photon flux above 10^{17} eV amounts to 10^{-2} /km²/yr/sr (a few ° around the Galactic plane)

* it is the dominant cosmogenic flux between 10^{17} and 10^{18} eV

* out of reach with current observatories

* sets a floor below which other signals will be overwhelmed : relevant for SHDM searches

* Below $M_X \approx 10^{11}$ GeV : sets a ceiling region for the lifetime τ_X of SHDM particles

* Future study : UHE neutrino flux produced from charged pions and neutrons decay

Thank you for your attention