Characterisation of (ultrahigh-energy) γ-rays propagation in our Galaxy

student: **Gaetano Di Marco**

supervisors: **Rafael Alves Batista**

Miguel A. Sánchez-Conde

(J. Pollock, 1948-49)

MultiDark Workshop 2023 – Gandía, Spain – 27/10/2023

looking around...

- state-of-art & future gamma-ray observatories, e.g. **LHAASO**, **HAWC**, **CTA**

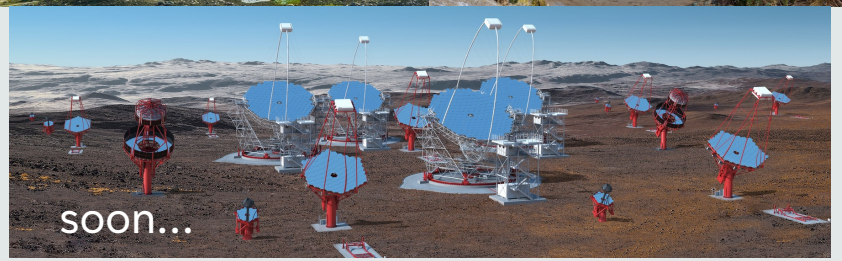
- recent **galactic PeVatrons** detections

might galactic propagation effects be relevant?

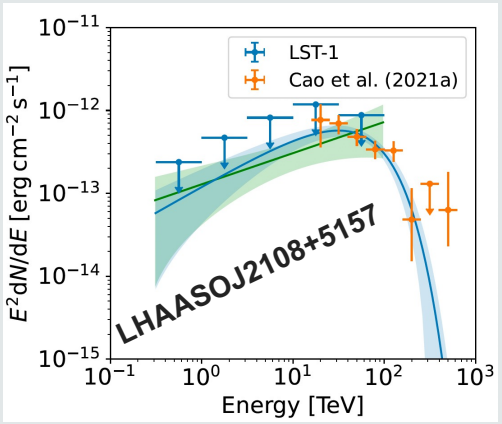
⚠ “standard” astrophysics only (**for now!**)

(credit: LHAASO website)

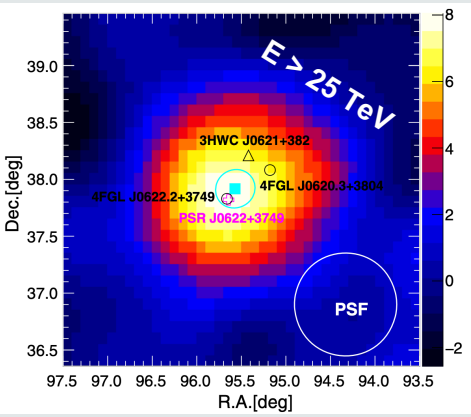
(credit: HAWC website)



(credit: CTA-observatory website)



(Abe+, 2023)



LHAASO J0621+3755 from (Aharonian+, 2021)

outline

- gamma-ray propagation theory

- simulation framework + results

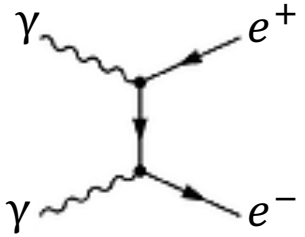
goal: characterise observables' dependence on galactic source position

- perspectives: dark matter searches?

Axion-Like Particles & **Super-Heavy Particles**

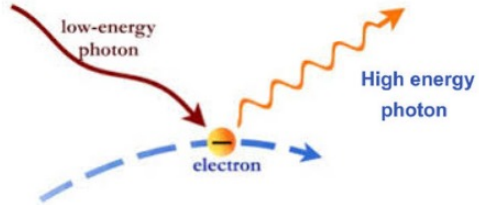
on gamma-ray propagation

- pair production: $\boldsymbol{\gamma + \gamma_{BKG} \rightarrow e^+ + e^-}$



  - double: $\boldsymbol{\gamma + \gamma_{BKG} \rightarrow e^+ + e^- + e^+ + e^-}$

- inverse Compton scattering: $\boldsymbol{e + \gamma_{BKG} \rightarrow e + \gamma}$



  - triplet pair production: $\boldsymbol{e + \gamma_{BKG} \rightarrow e + e^- + e^+}$

$$\gamma_{BKG} \begin{cases} \text{URB} \rightarrow \text{Radio} \\ \text{CMB} \rightarrow \text{MicroWave} \\ \text{EBL} \rightarrow \text{IR, optical, UV} \end{cases} \leftarrow \textbf{ISRF} \rightarrow \textbf{IR, optical, UV}$$

«deflection» of gamma rays

Galactic Magnetic Field (**GMF**)

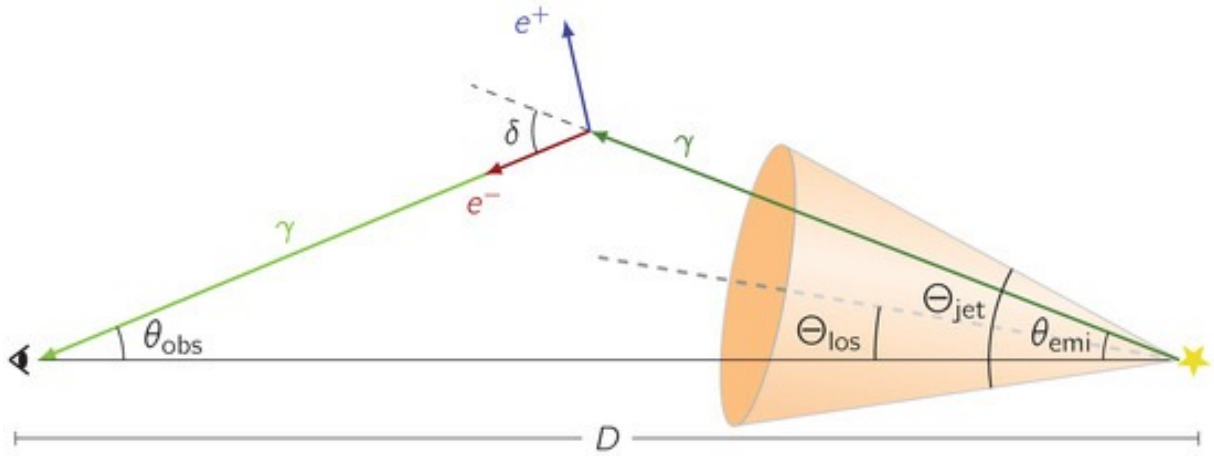
(credit: Pinterest)

+

(credit: Unsplash)

+

Interstellar Radiation Field (**ISRF**)



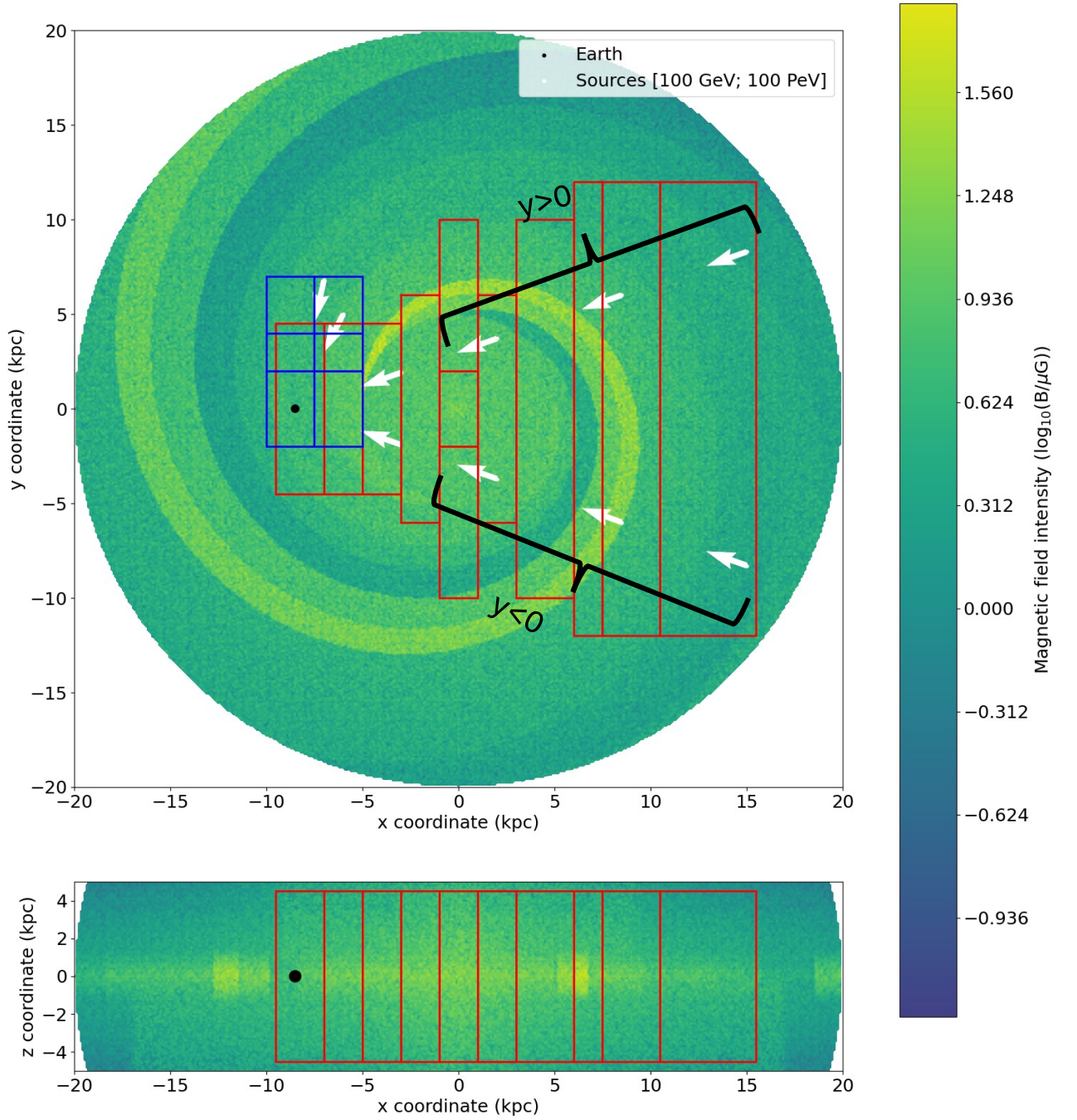
(Alves Batista & Saveliev, 2021)

CR Propa
(Alves Batista+, 2022)

galactic gamma rays simulation

- (very) approximate ISRF spatial model
from (Freudenreich 1998), implemeted in (Porter+, 2017)

- GMF model, as combination of regular and turbulent components
from (Jansson & Farrar, 2012), implemented in (Kleimann+, 2019)



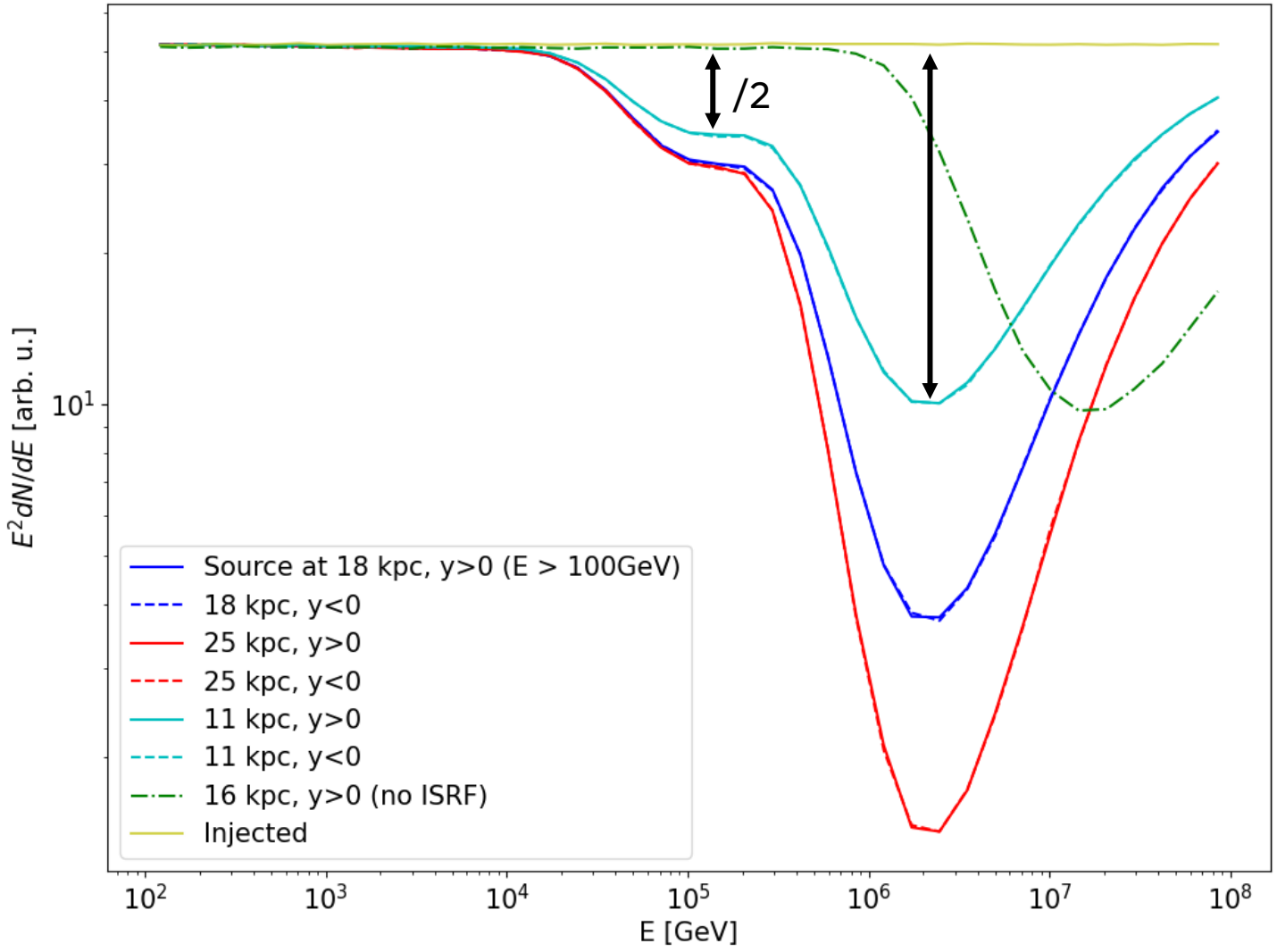
energy spectra

ISRF (approx.) starts absorbing **above 10 TeV**

maximum absorption:

- w/o ISRF at **10 PeV**
- **w ISRF** (approx.) **at 2 PeV**

hints of combined CMB+ISRF action



count maps w ISRF

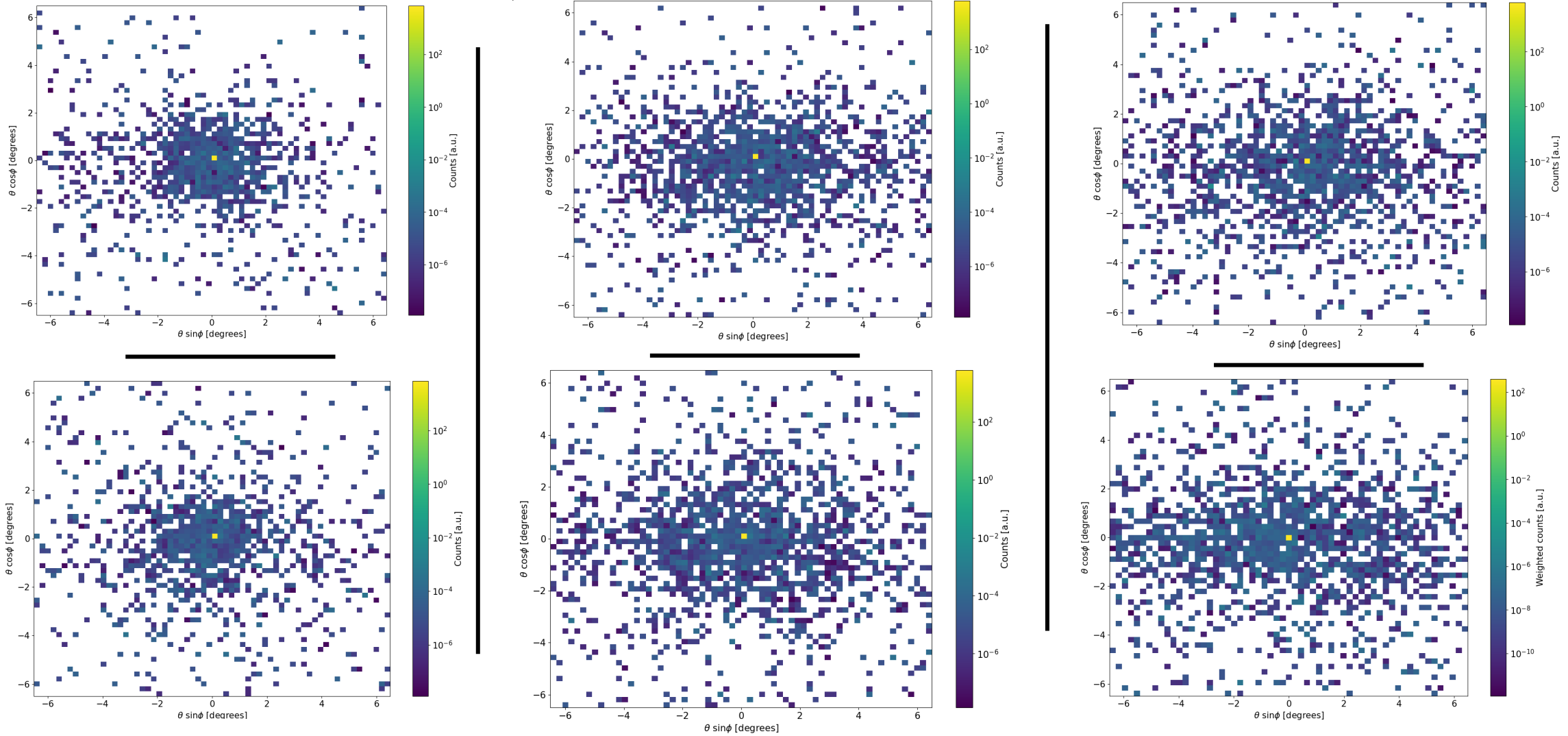
d=11kpc

d=18kpc

d=25kpc

y>0

y<0



conclusions (at this point!)

❖ISRF **spectral feature** distance-dependent

+ NO for slightly different positions (comparing y≦0 cases)

line of sight crossing the nearby of galactic center!

❖ **halo counts** are $\mathbf{10^{-3}}$ less than point-like source ones, at least

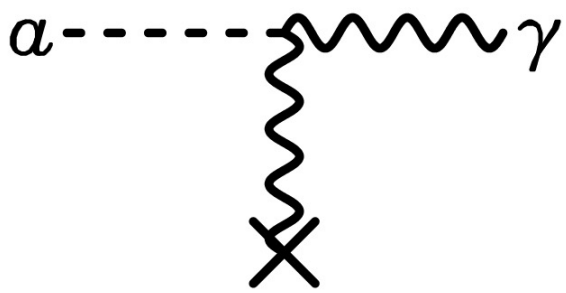
detectability? → **revision of galactic propagation beyond several TeVs?**

in dark matter gamma-ray searches

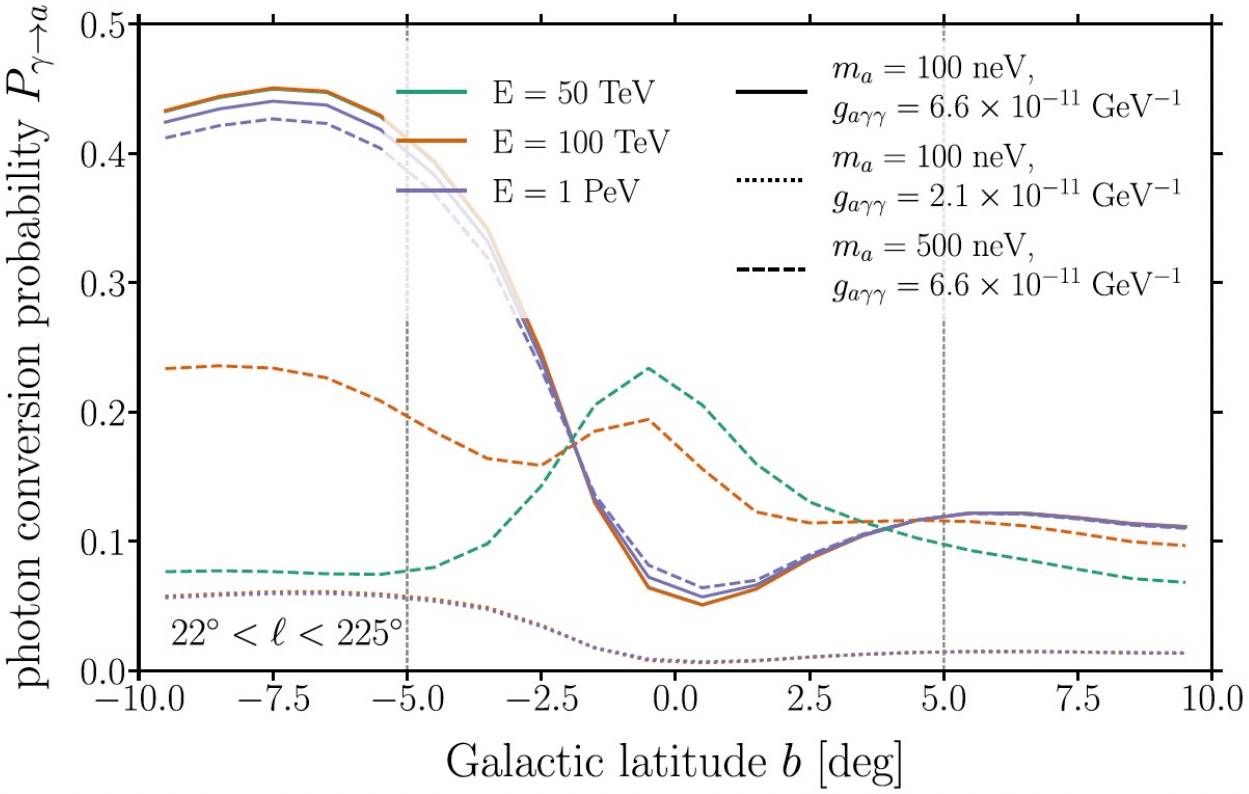
propagation effects in constraints on dark matter properties from gamma-rays beyond TeV?

axion-like particles (ALPs)

gamma rays **mixing with** low-mass **ALPs** in magnetized environments



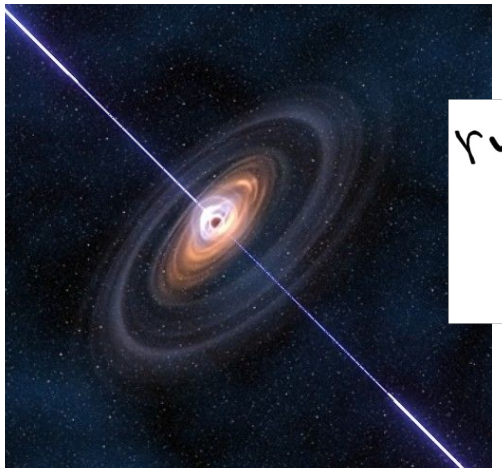
in Galactic Magnetic Field



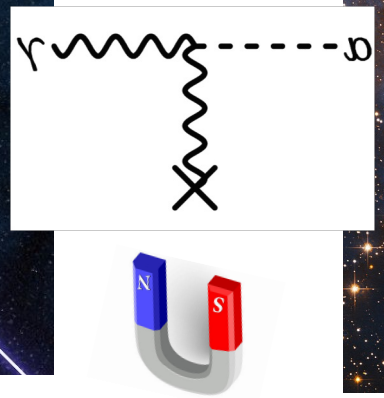
(Eckner & Calore, 2022)

interstellar «wall»?

(credit: Pinterest)

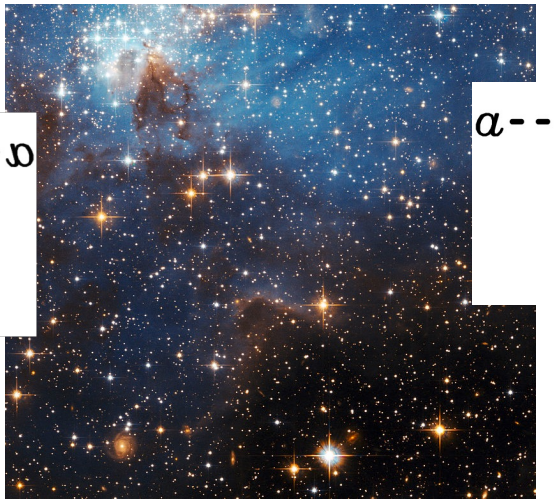


TeV-PeV gamma ray source

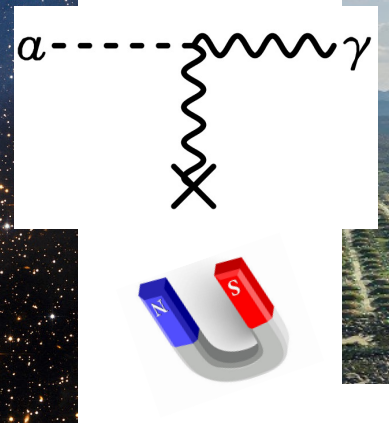


Primakoff or source magnetic field

(credit: Nasa website)



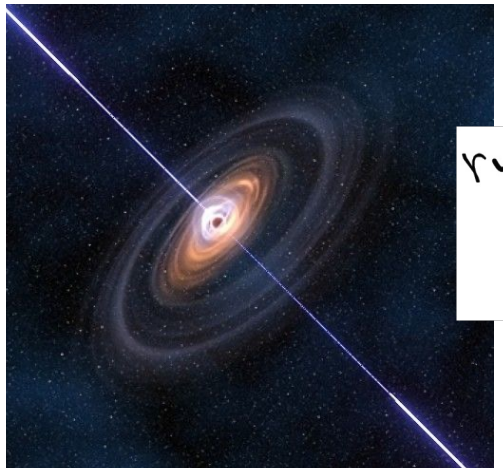
ISRF/CMB



GMF

on Earth observatories

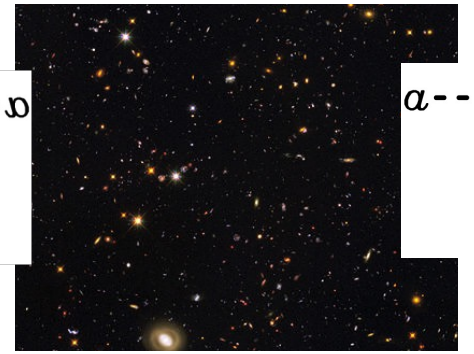
extragalactic PeV photons?



TeV-PeV extragalactic source

source or cluster magnetic field

(credit: Americaspace)



EBL/CMB

GMF

ISRF/CMB

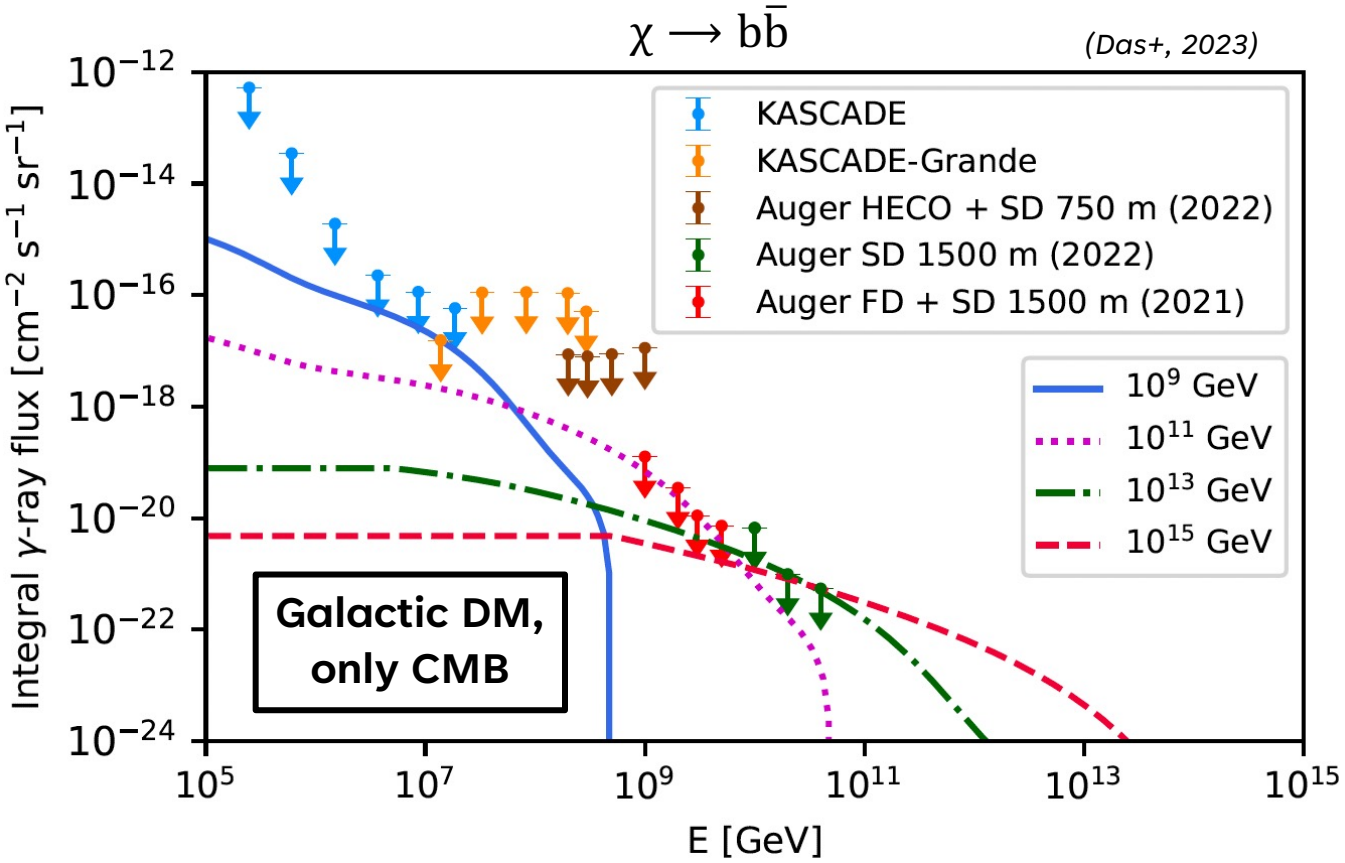
on Earth observatories

super heavy dark matter (SHDM)

lifetime $\tau_\chi \gg 10^{10}$ yr

mass $10^7 \lesssim M_\chi \lesssim 10^{16}$ GeV

$$\chi \longrightarrow \begin{cases} q\bar{q} \\ gg \\ \ldots \end{cases} \rightarrow p, e, \gamma, \nu$$



thanks!

questions? comments?

backup...

inverse mean free path

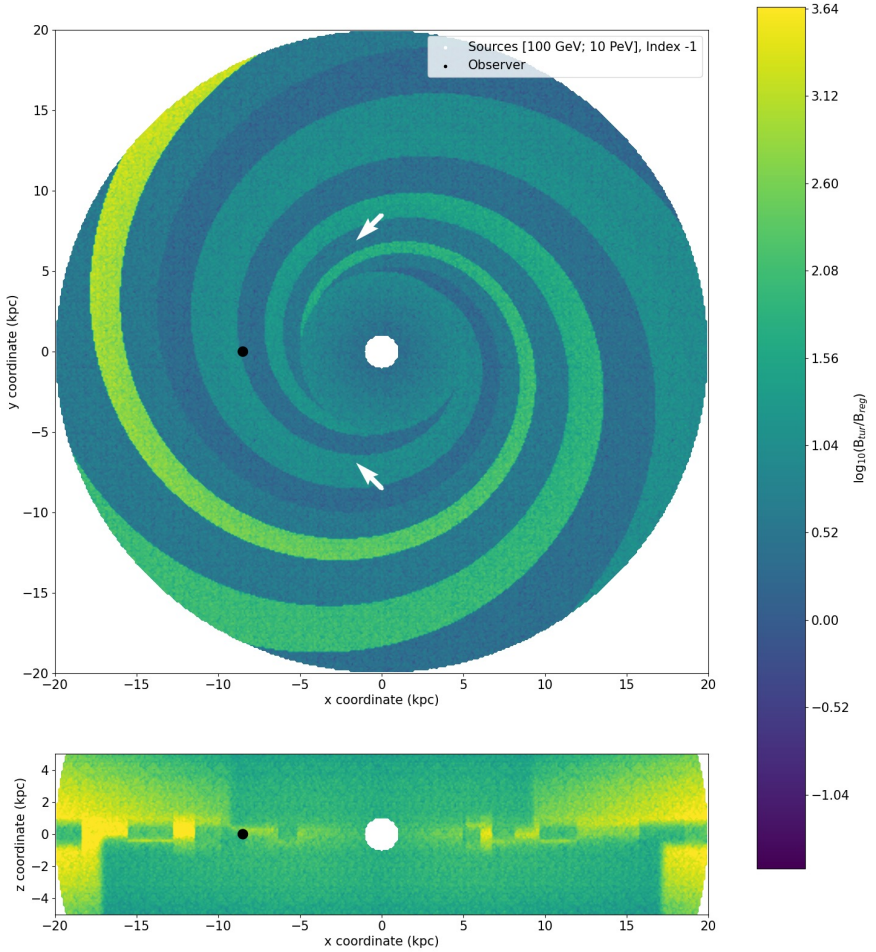
photon background (volumetric) number density

$$\lambda^{-1}(E,z) = \frac{1}{8E^2}\int_0^{\infty}\int_{s_{min}}^{s_{max}} \frac{1}{\varepsilon^2}\frac{\mathrm{d}n(\varepsilon,z)}{\mathrm{d}\varepsilon}\mathcal{F}(s)\,\mathrm{d}s\,\mathrm{d}\varepsilon$$

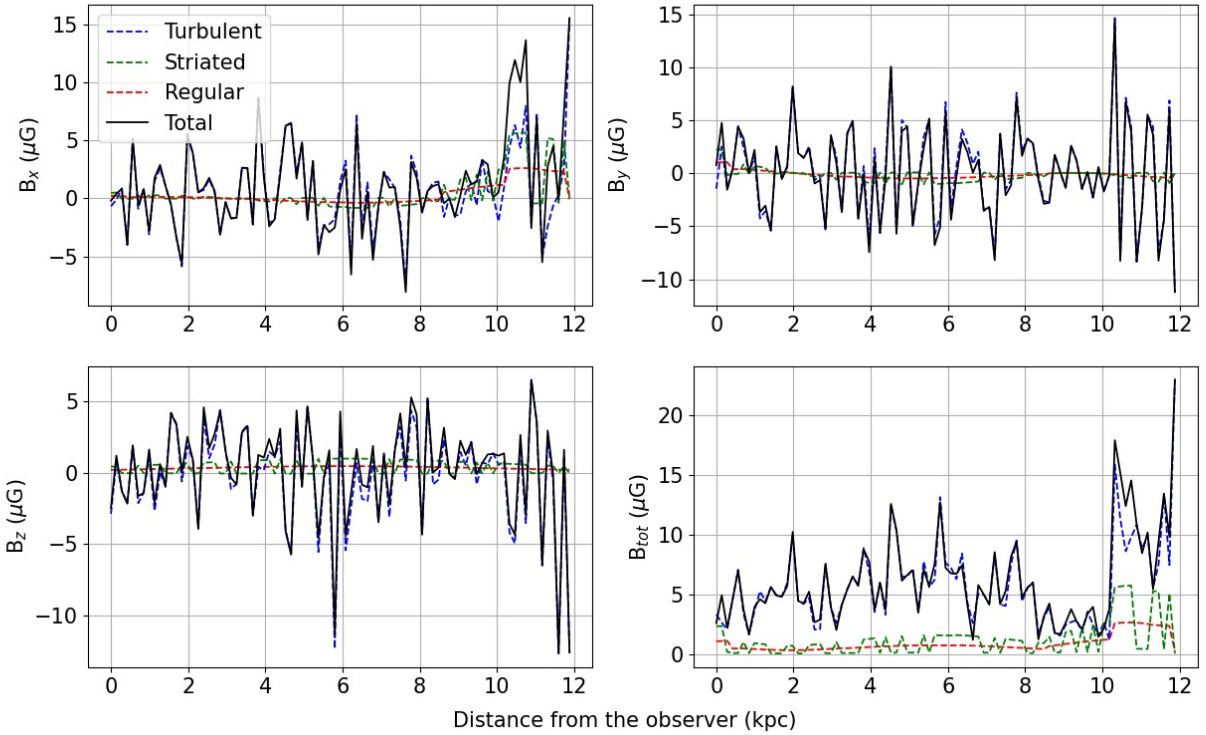
particle energy

process dependent!

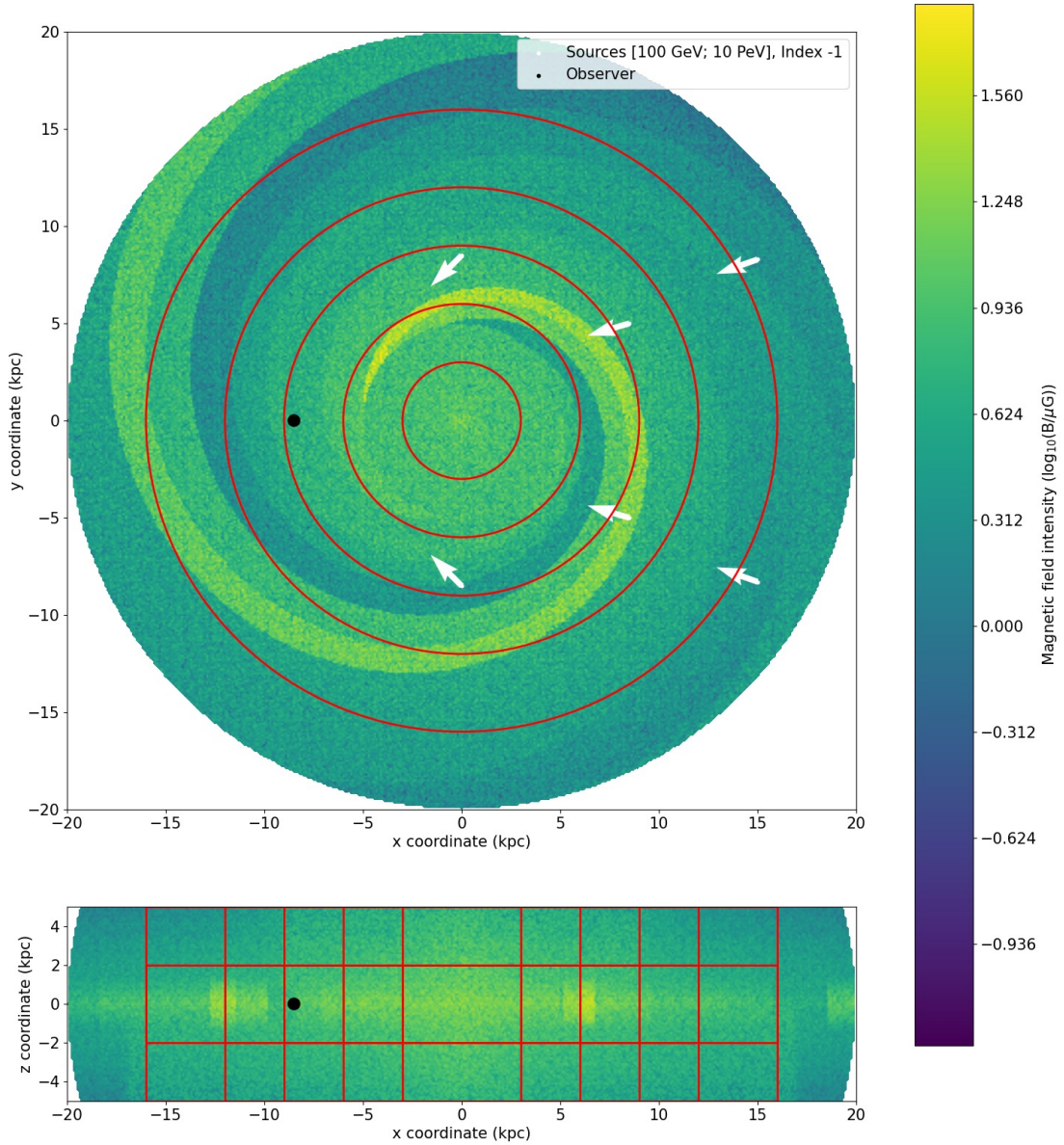
regular *vs* turbulent



along the l. o. s.



restrictToRegion_v2



Cylindrical (/Cylindrical hollowed) customized surfaces:

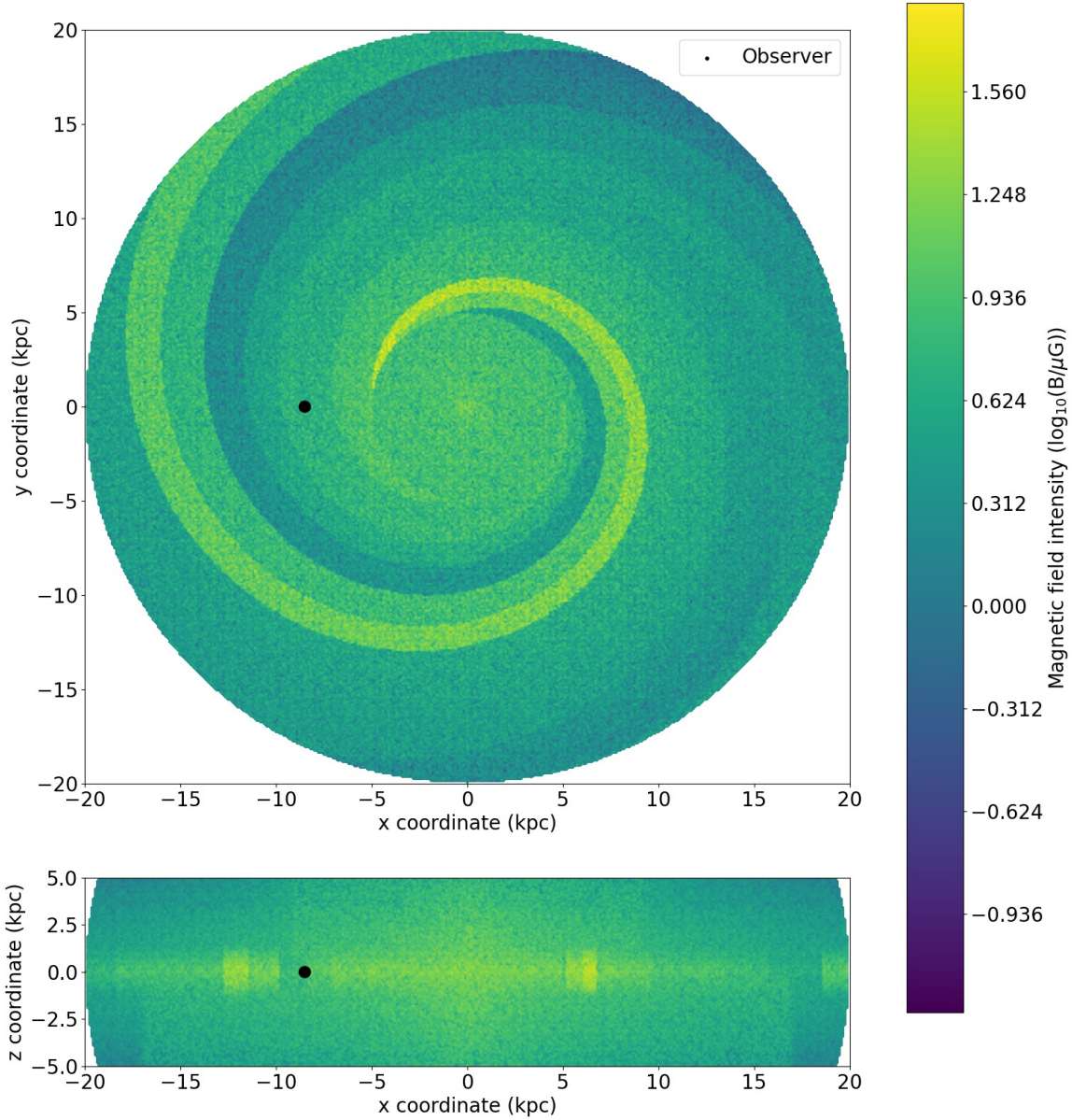
- easy to implement in python

- too expensive computationally

galactic magnetic field

three components:

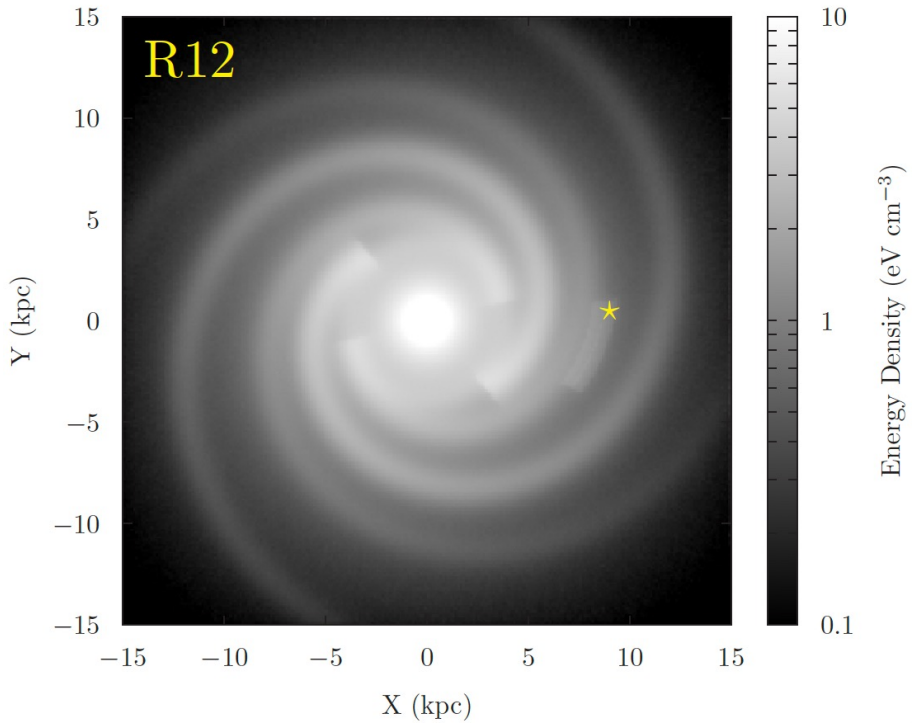
- **regular large-scale** (disk + halo + X-field) follows thermal electron density
- **striated random** from hot plasma bubbles
- **turbulent small-scale** due to outflows, e.g. supernovae



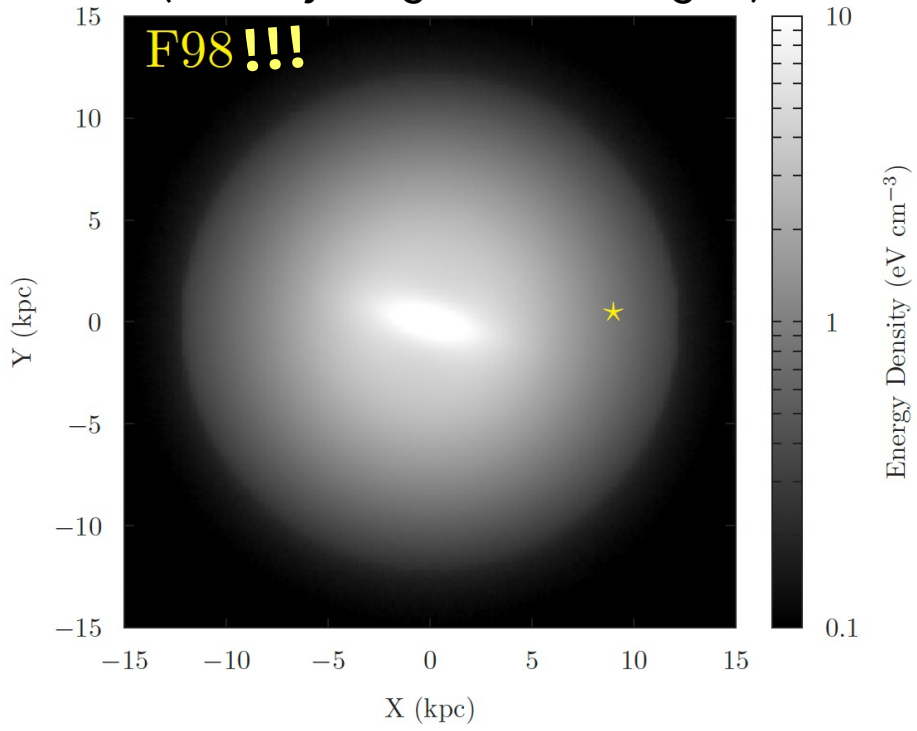
(Jansson & Farrar, 2012) implemented in (Kleimann+, 2019)

interstellar radiation field (ISRF)

stars emission & starlight processed by dust ∈ [IR; UV]



(arms' young stars averaged)

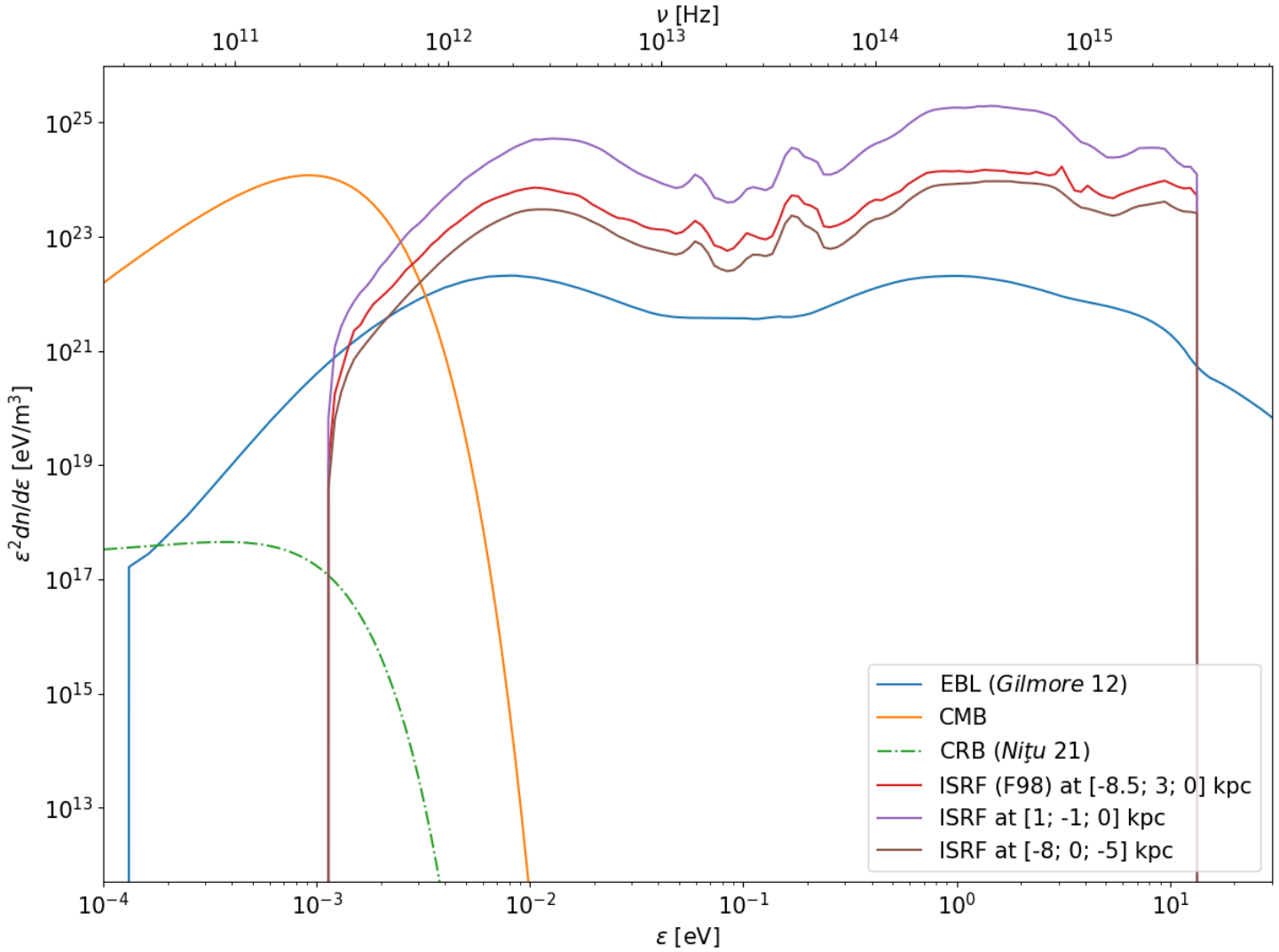


from (Porter+, 2017): R12 is (Robitaille+. 2012), **F98** (Freudenreich 1998)

photon background energy densities

three ISRF (from F98) as references:

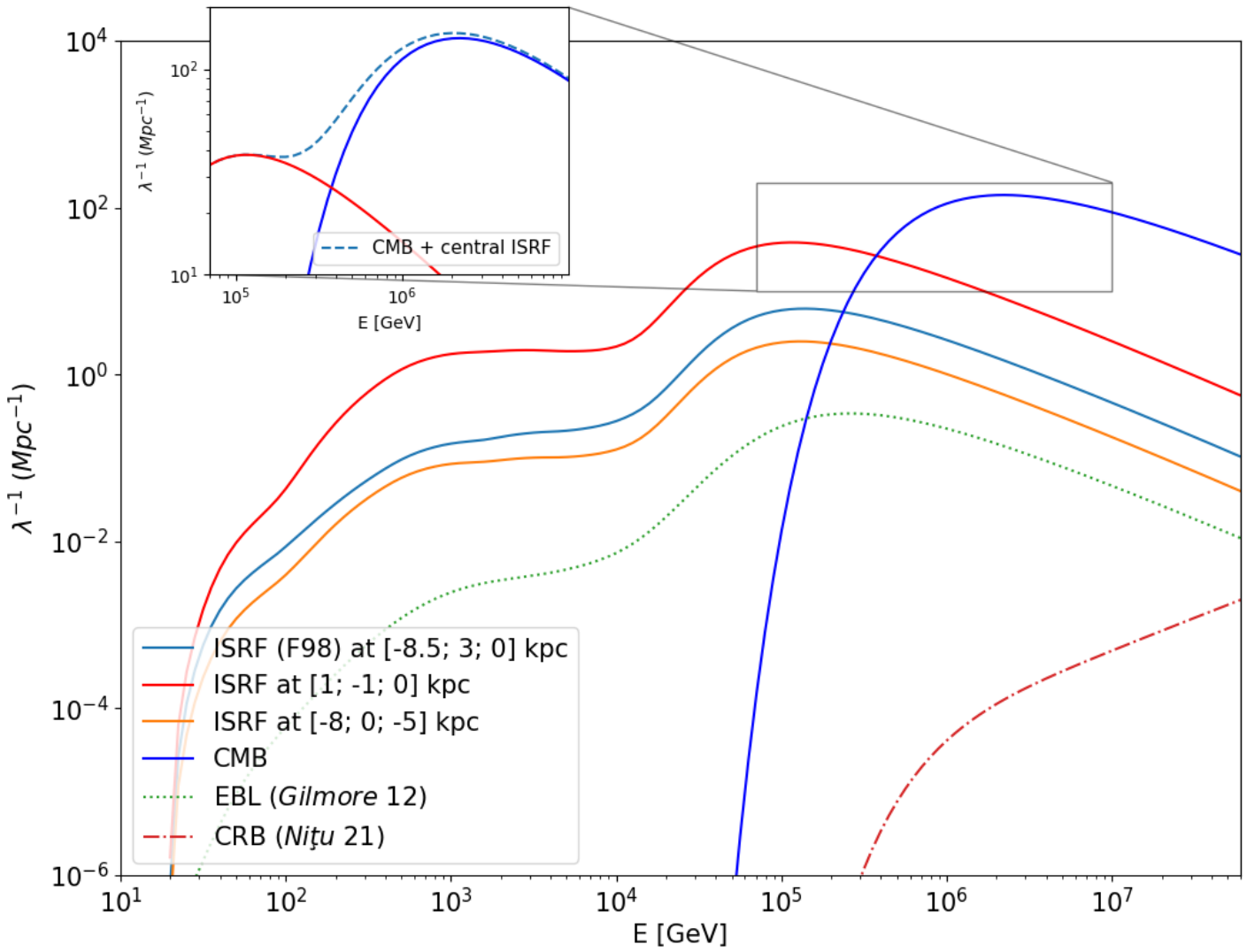
- around the **galactic center**
- close to **Earth position**
- in Earth nearby, **out-of-plane**



pair production

- 1st ISRF maximum: 1 TeV
  - 2nd peak: 50 TeV

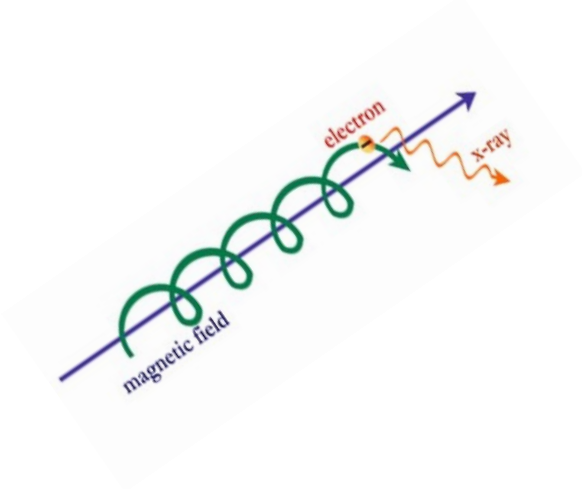
between **100 TeV & 1 PeV**:
central ISRF contribution $\lesssim$ CMB

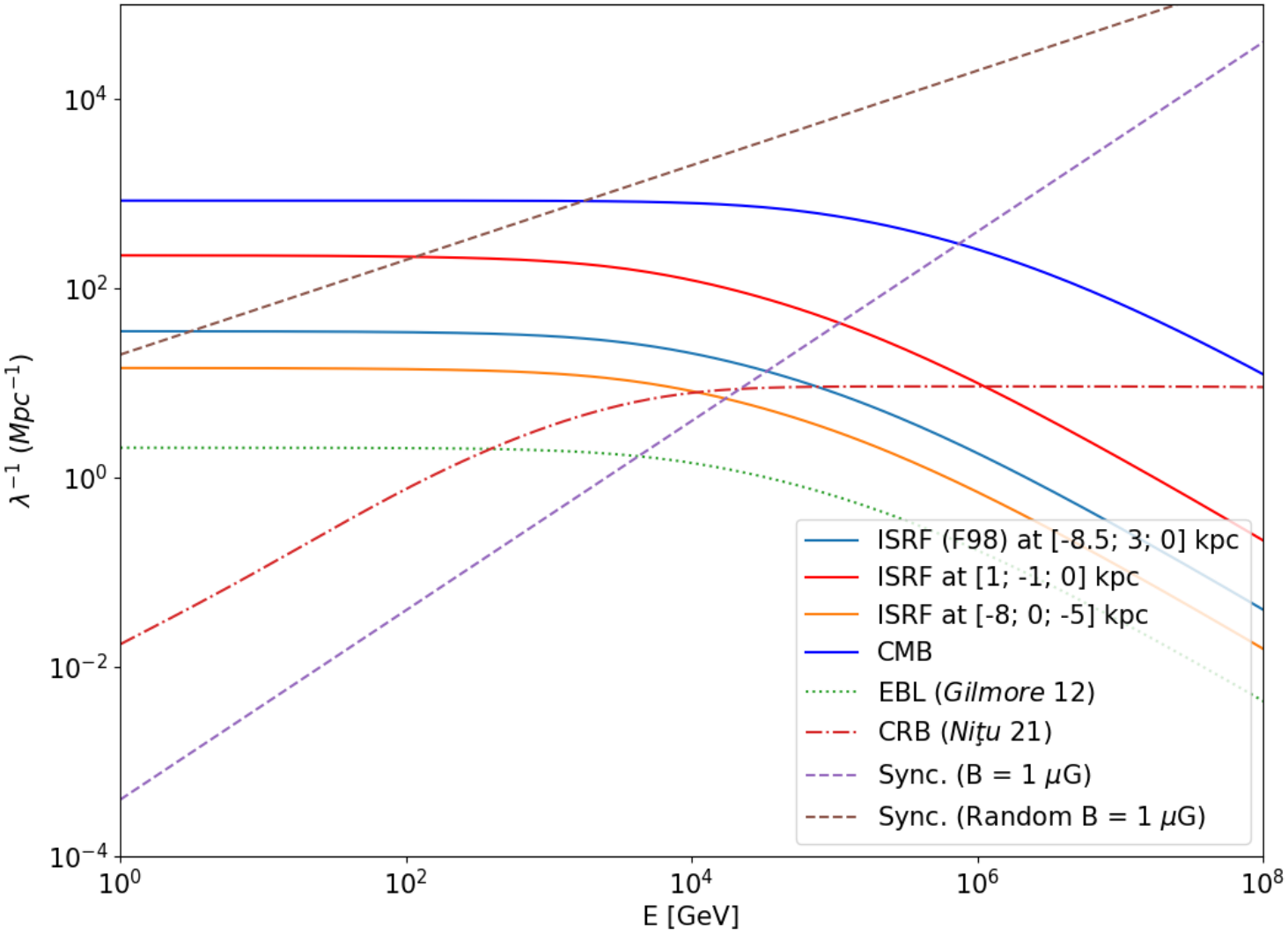


inverse Compton & synchrotron

inverse length scale of synchrotron energy loss:

$$\frac{1}{E}\left|\frac{\mathrm{d}E}{\mathrm{d}x}\right|(x) = \frac{\sigma_T\, B^2(x)}{4\pi m_e^2 c^4}\, E$$





simulation setup

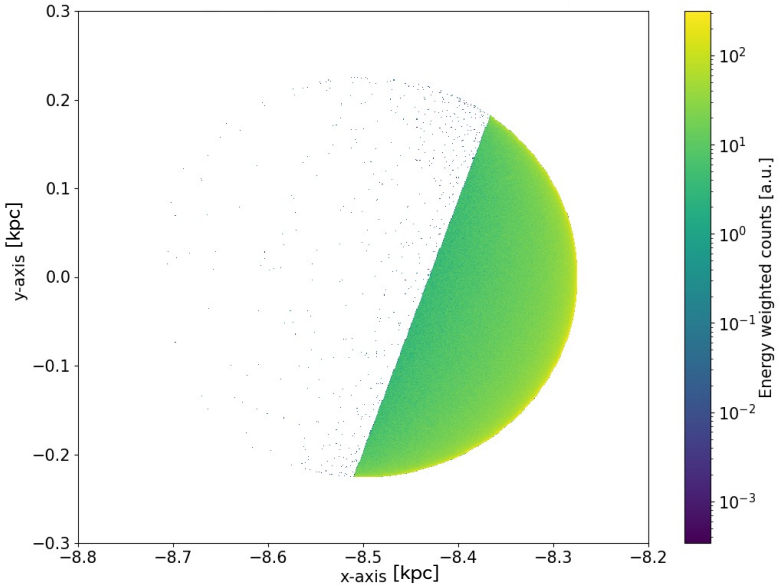
CRPropa
(Alves Batista +, 2022)

```
#Galactic Bfield
B = JF12FieldSolenoidal()
seed = runId
B.randomStriated(seed)
B.randomTurbulent(seed)
```

```
obs = Observer()
obs.add(ObserverSurface(Sphere(Vector3d(-8.5, 0., 0.) * kpc, 0rad * kpc)))
```

```
source = Source()
source.add(SourcePosition(Vector3d(x, y, z) * kpc))
source.add(SourceEmissionCone(v, Scon))
source.add(SourcePowerLawSpectrum(Emin * eV, Emax * eV, specIndex))
source.add(SourceParticleType(22))
```

→ specIndex = −2
E = [100 GeV; 100 PeV]
Scon ~ 0.5°




```
sim.add(PropagationBP(B,tol,minStep * kpc, maxStep * kpc))
```

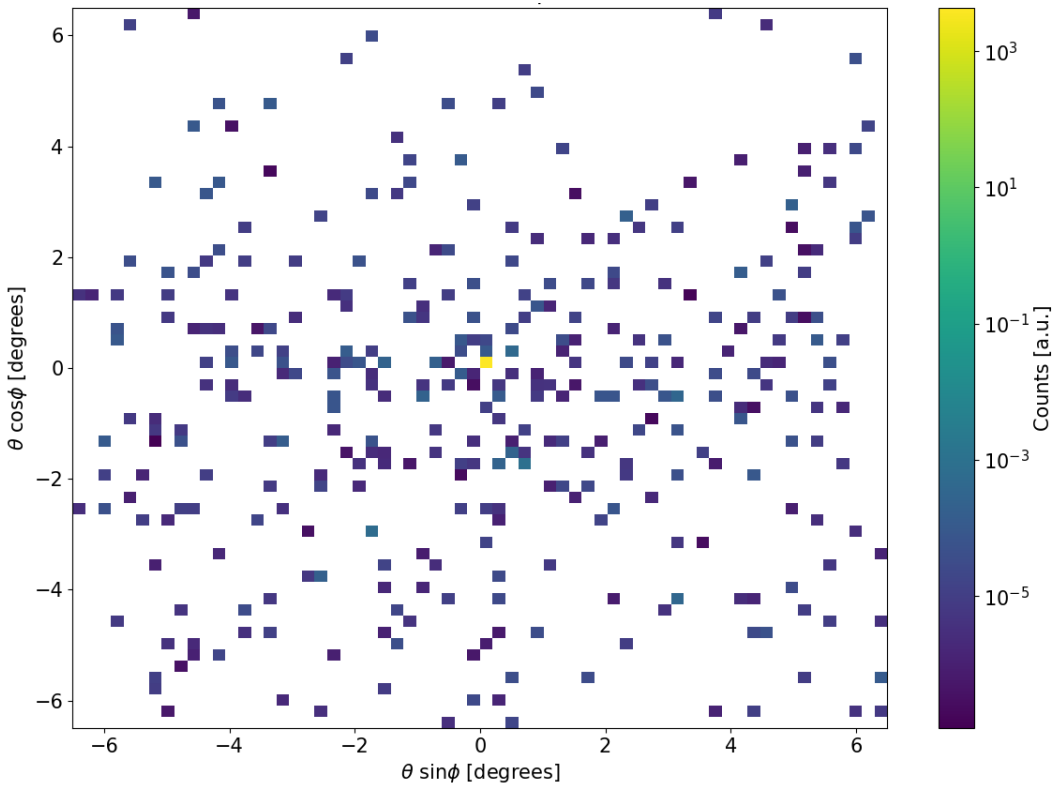
→ `sim.run(source, 500000)` x20 → total injected events: **1e7**

count map w/o ISRF

- filling galactic space with EBL, apart from CMB and CRB

- source 16 kpc far from Earth

NO haloes around the point-like source



d = 18 kpc

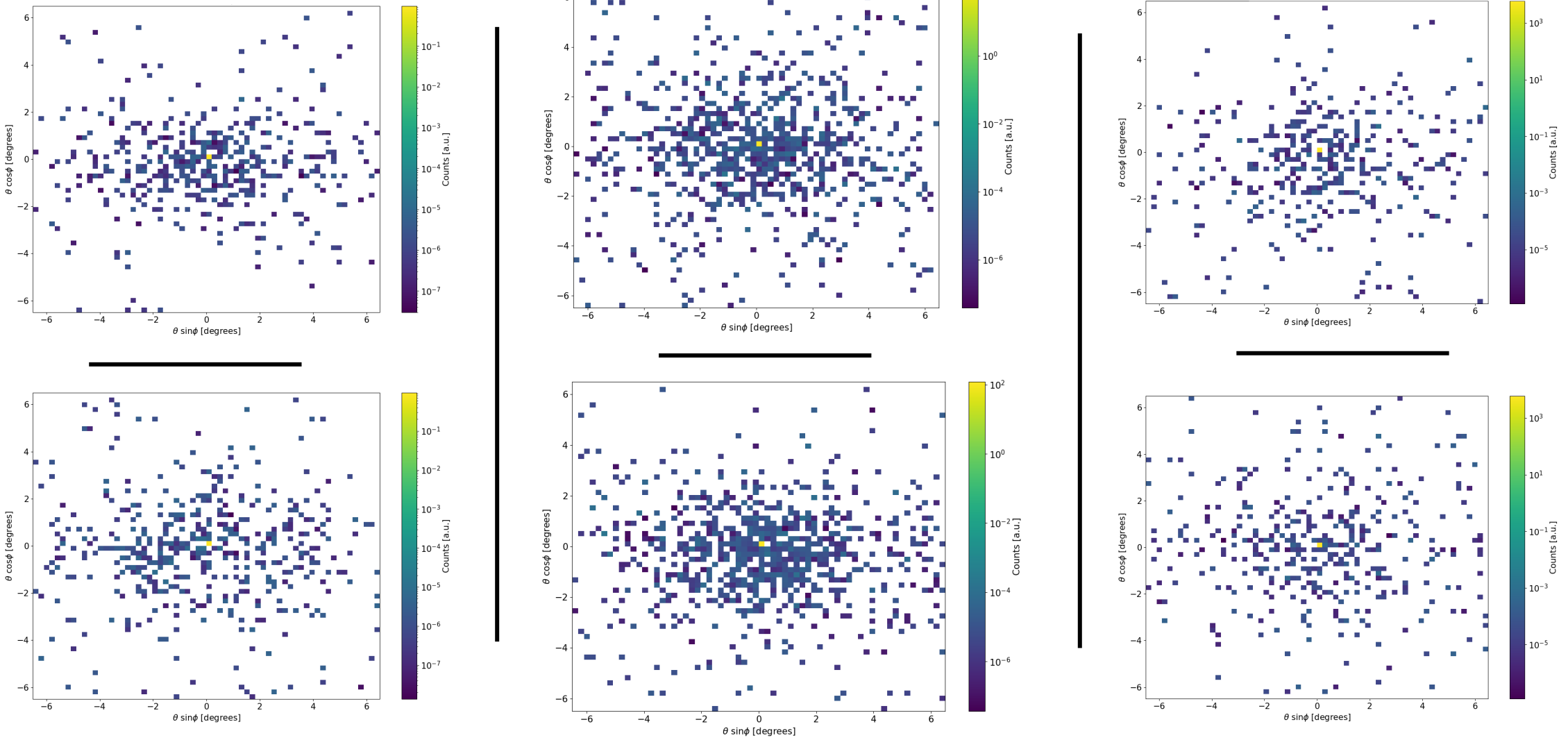
100GeV<E<5TeV

5TeV<E<200TeV

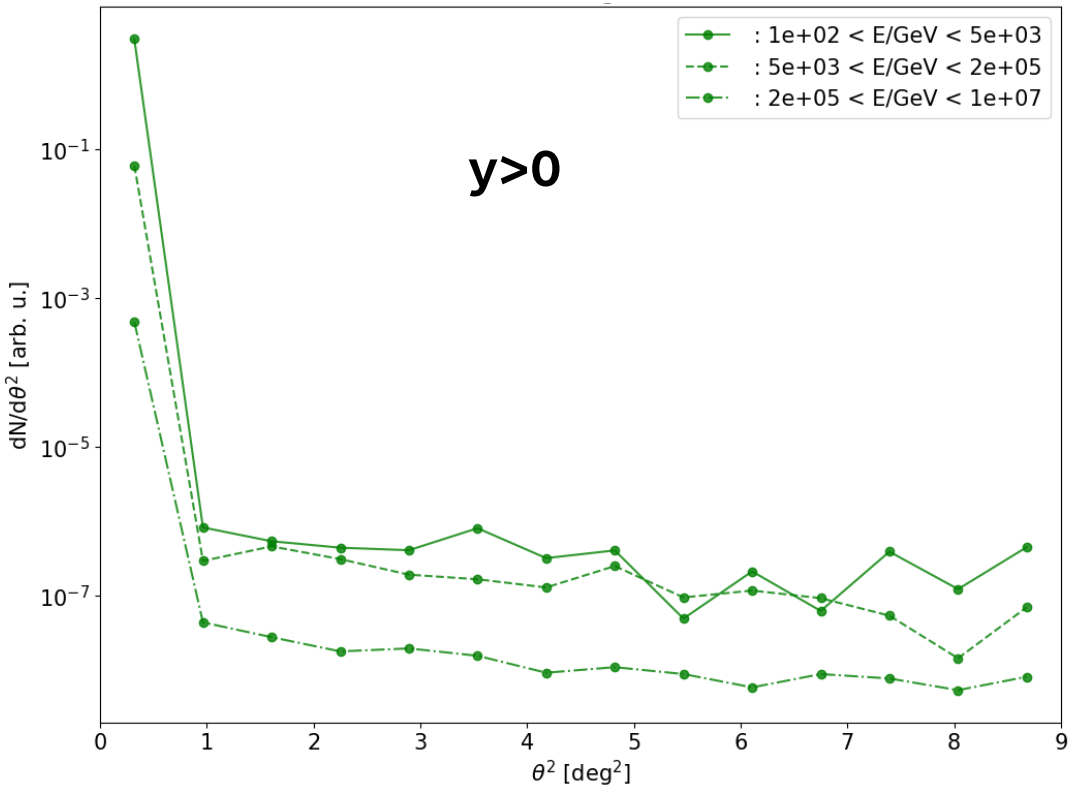
200TeV<E<100PeV

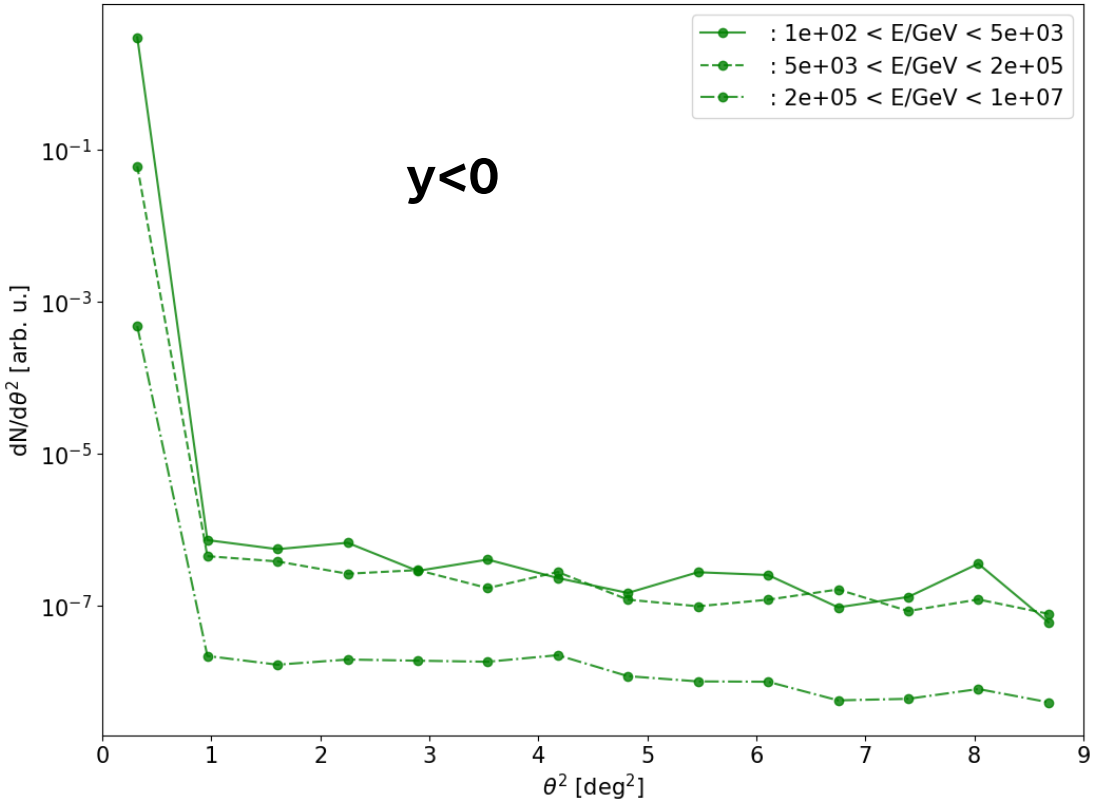
y>0

y<0



surface brightness (deflection angle, d=18kpc)





large contribution to the halo
from low energy photons!

conclusions (at this point!)

❖ ISRF **spectral feature** depending on the distance

+ NO for slightly different positions (comparing $y \lesssim 0$ cases)

line of sight crossing the galactic center!

❖ clear ISRF imprints on the energy spectrum from ~**10 TeV**, lowering up to a factor ~ 2

+ joint effect with CMB at energies $\gtrsim$**400 TeV**

❖ **halo counts** are $\mathbf{10^{-3}}$ less than point-like source ones, at least

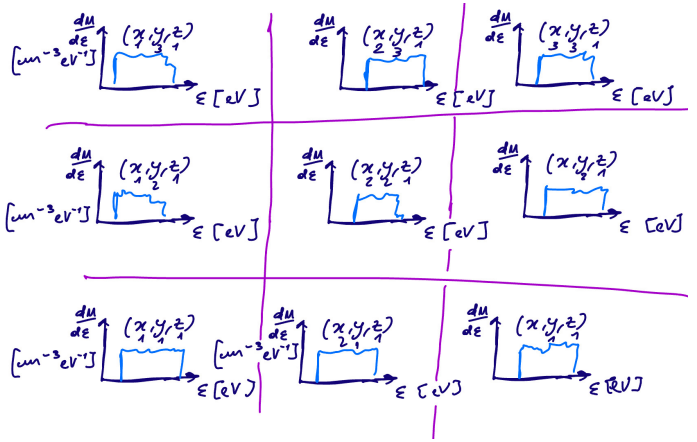
❖ the larger the distance, the more «interspersed» the halo is

+ shape slightly position-dependent (comparing $y \lesssim 0$ cases)

perspectives

❖ in CRPropa:

read ISRF density for each position? OR **Grid<std::vector<type>>?**



❖ in science:

➢ role of **synchrotron** energy losses in the EM cascades?

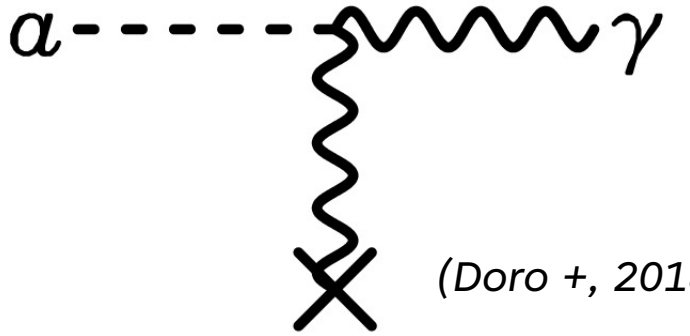
➢ **detectability** of haloes and spectral features?

➢ revision of galactic gamma-ray propagation?

ALPs-PHOTONS MIXING

$$\mathcal{L}_{ALP-\gamma} = g_{a\gamma}\, \boldsymbol{E} \cdot \boldsymbol{B}\, a$$

External B-field



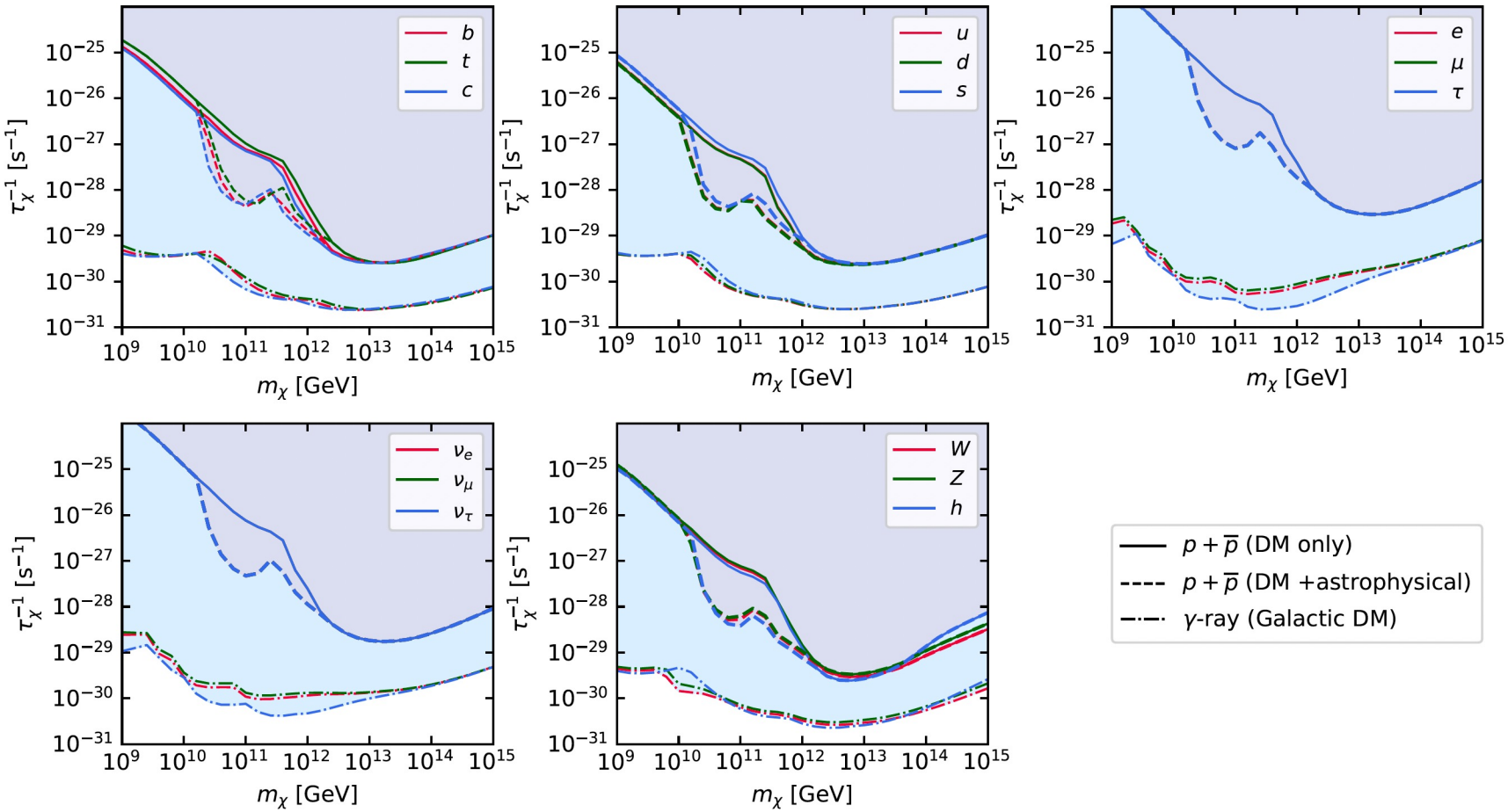
(Doro +, 2018)

$$P_{a\gamma}\left(E_\gamma, B, s \middle| m_a, g_{a\gamma}\right) = \frac{1}{1+\left(\frac{E_{crit}}{E_\gamma}\right)^2} \sin^2\left[\frac{B\ s\ g_{a\gamma}}{2}\sqrt{1+\left(\frac{E_{crit}}{E_\gamma}\right)^2}\right]$$

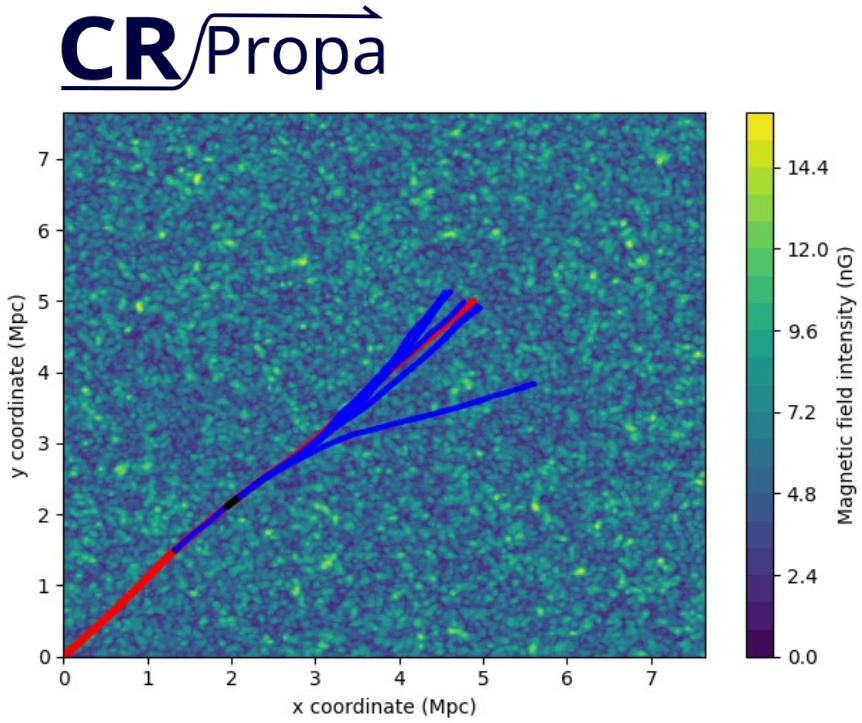
Relevant effects:

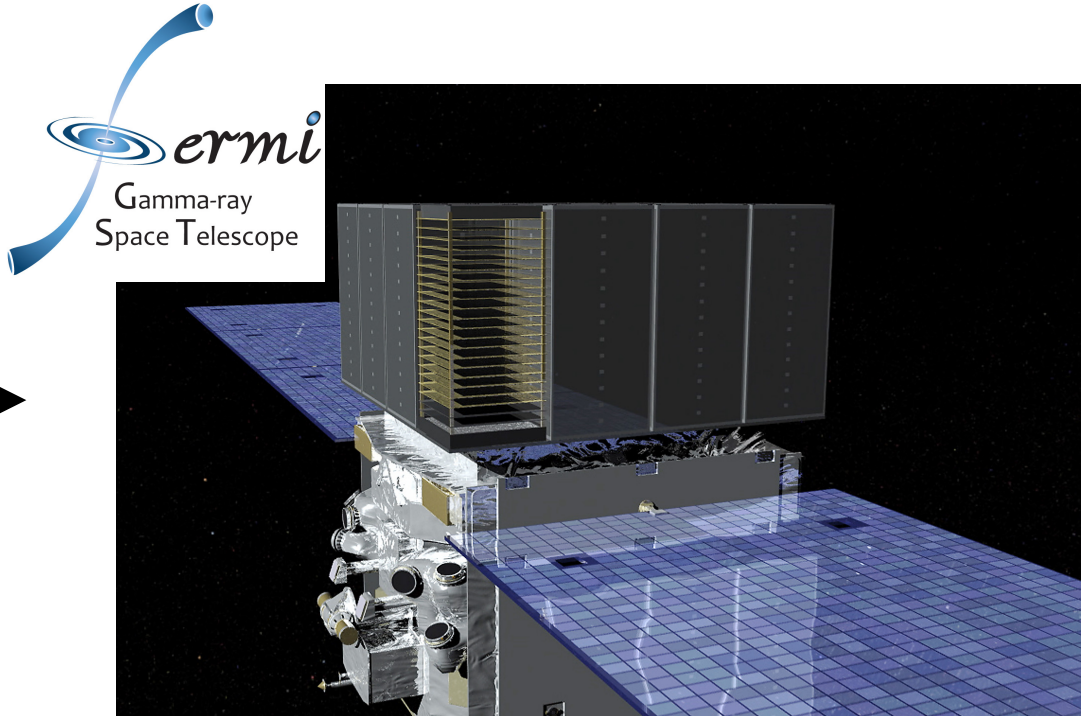
- **Birefringence**
- **γ-γ refraction**

Where: $\boldsymbol{E_{crit}} = \frac{|\boldsymbol{m_a^2} - \boldsymbol{\omega_{pl}^2}|}{2\, \boldsymbol{g_{a\gamma} B}}$


b
t
c
u
d
s
e
μ
τ
ν_e
ν_μ
ν_τ
W
Z
h
τ_χ^{-1} [s^{-1}]
m_χ [GeV]
$p + \bar{p}$ (DM only)
$p + \bar{p}$ (DM +astrophysical)
γ-ray (Galactic DM)

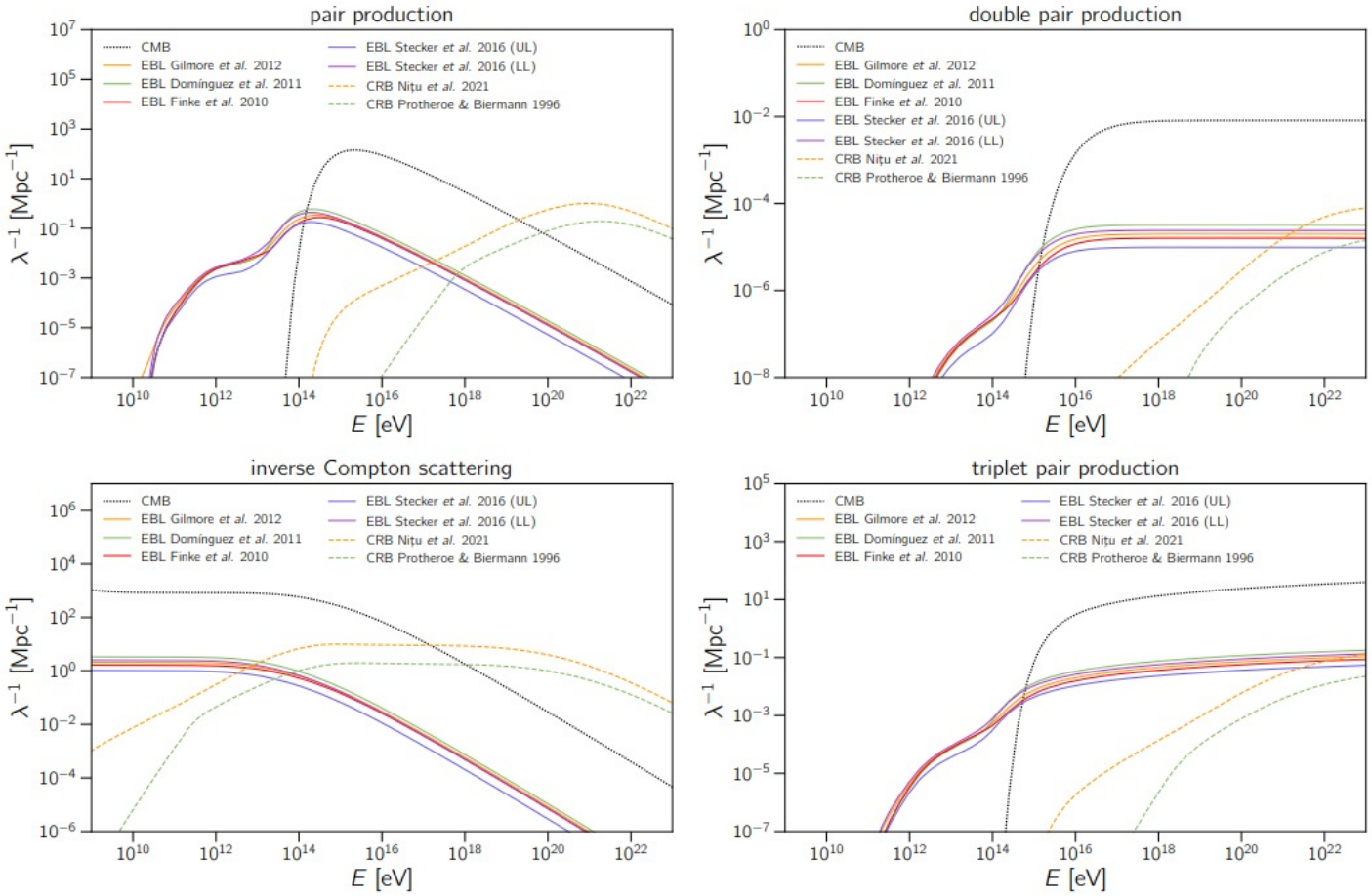
sinergy between gamma-ray simulations & observations (long-term)





Large Area Telescope: $20\ \mathrm{MeV} \lesssim \mathrm{E}_\gamma \lesssim 500\ \mathrm{GeV}$

to constrain propagation **properties with gamma-ray data** (spectral distortion, spatial morphology...)



(Alves Batista & Saveliev, 2021)

last scattering plot