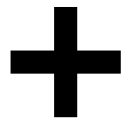# Vicissitudes in the propagation of highly-energetic gamma rays in our Galaxy

(arxiv:2408.08818 to JCAP)

Gaetano Di Marco (IFT UAM-CSIC)

Rafael Alves Batista (IAP SU)

Miguel A. Sánchez-Conde (IFT UAM-CSIC)

(F. J. Brown, «Inner Galactic Space», 1971)

Gamma24 Symposium – Milan, Italy – 04/09/2024

looking around...

- state-of-art & future gamma-ray observatories, e.g. **LHAASO**, **HAWC**, **CTA**
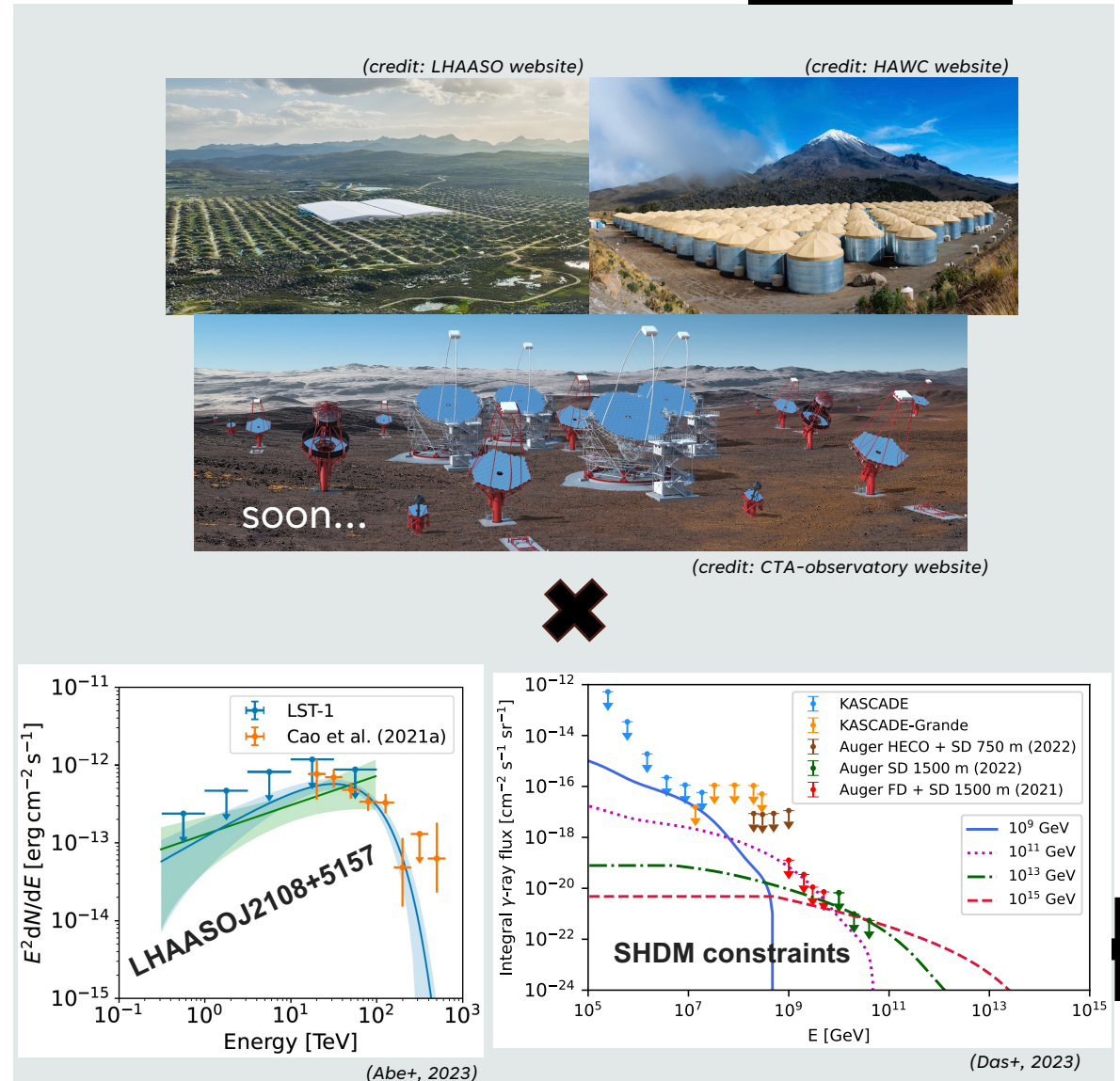
- recent **galactic PeVatrons** detections & indirect dark matter constraints

⬇
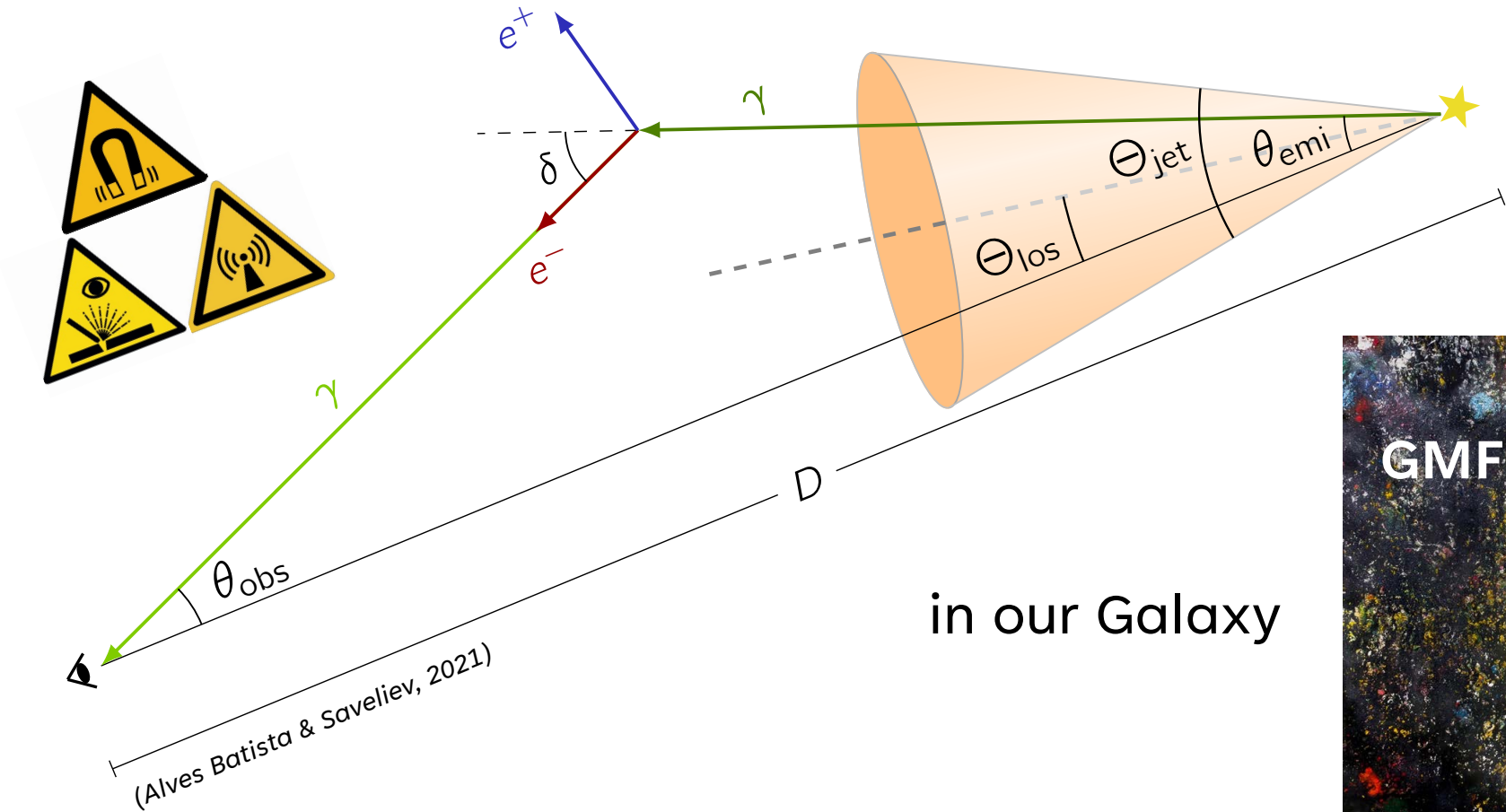
might galactic gamma-ray propagation effects be relevant?

⚠ "standard" astrophysics only!

(credit: LHAASO website)   *(credit: HAWC website)*

soon...

(credit: CTA-observatory website)

LHAASOJ2108+5157

(Abe+, 2023)

SHDM constraints

(Das+, 2023)

«deflection»/absorption of gamma rays

e^+

γ

δ

e^-

γ

Θ_{jet}

θ_{emi}

Θ_{los}

D

θ_{obs}

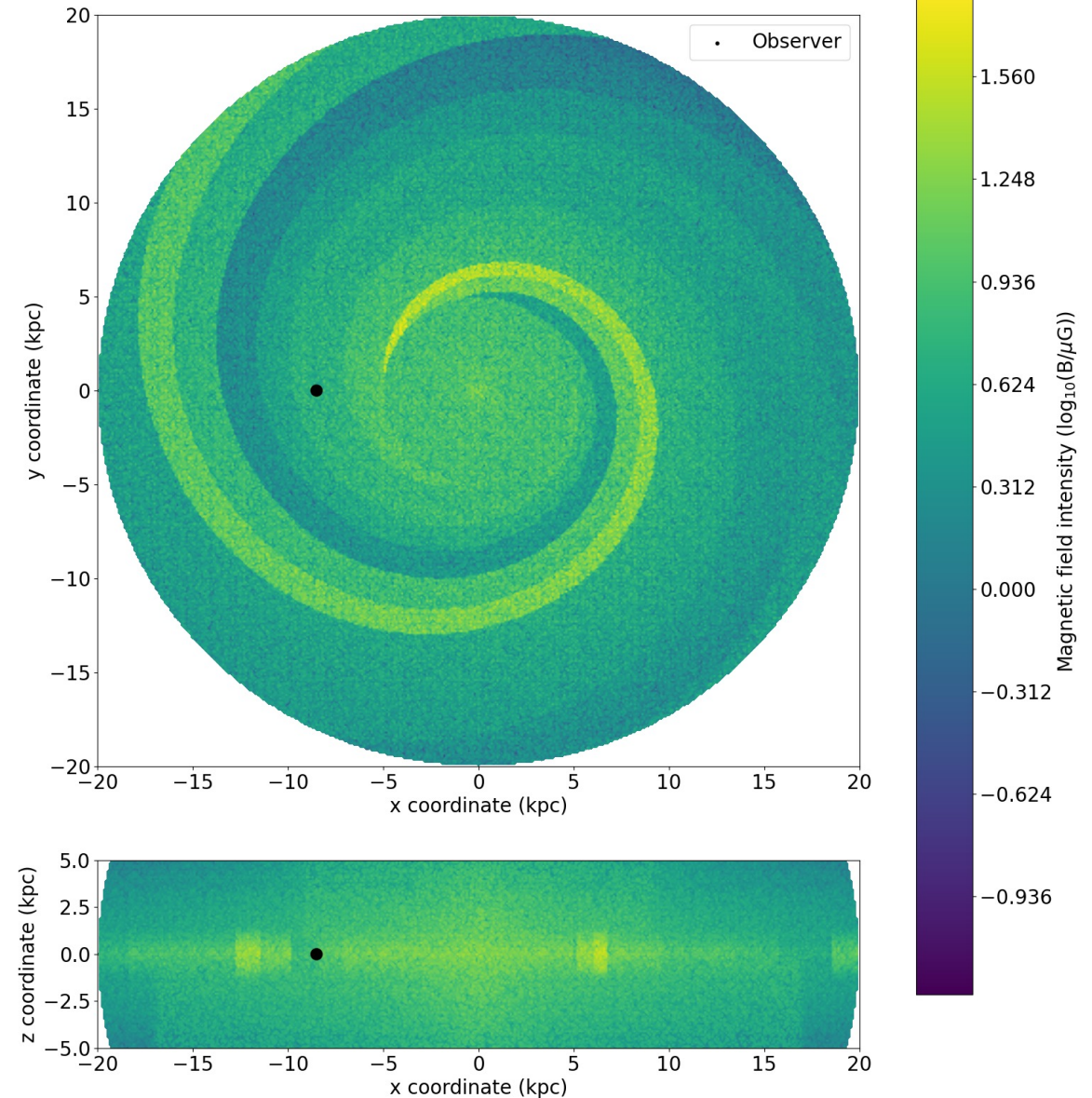(Alves Batista & Saveliev, 2021)

in our Galaxy

GMF ?

ISRF ?

(F. J. Brown, «Milky Way», 1977)

galactic magnetic field

three components:

- **regular large-scale** (disk + halo + X-field) follows thermal electron density

- **striated random** from hot plasma bubbles

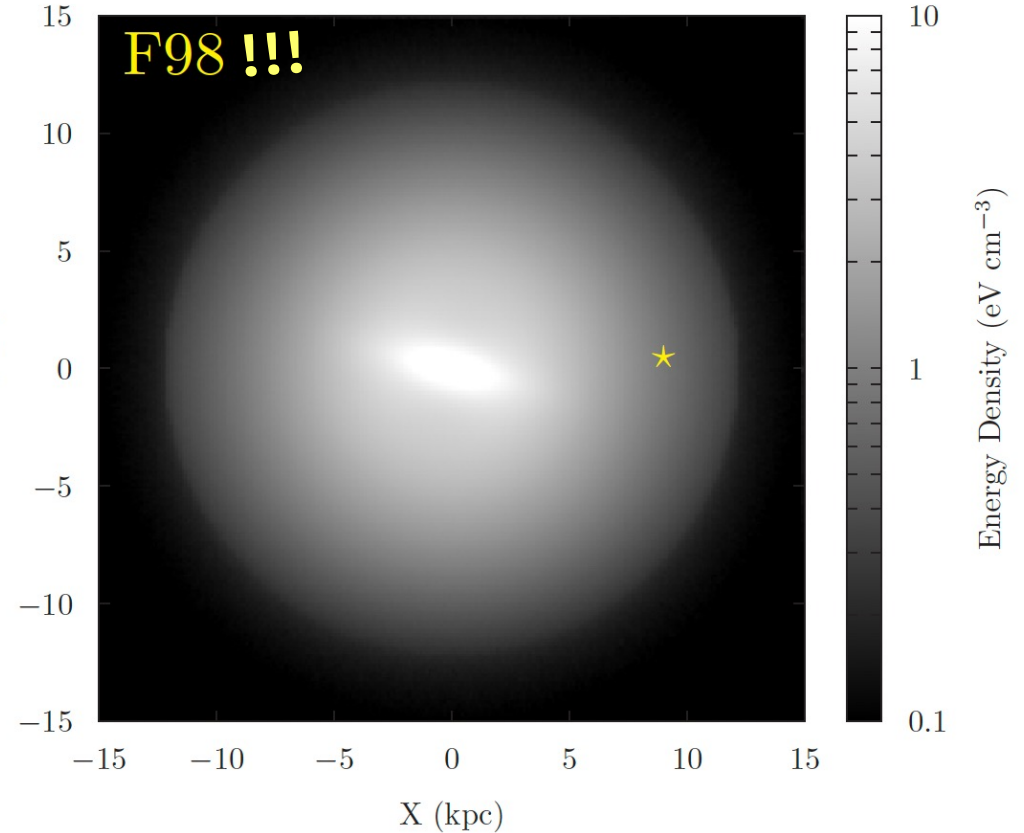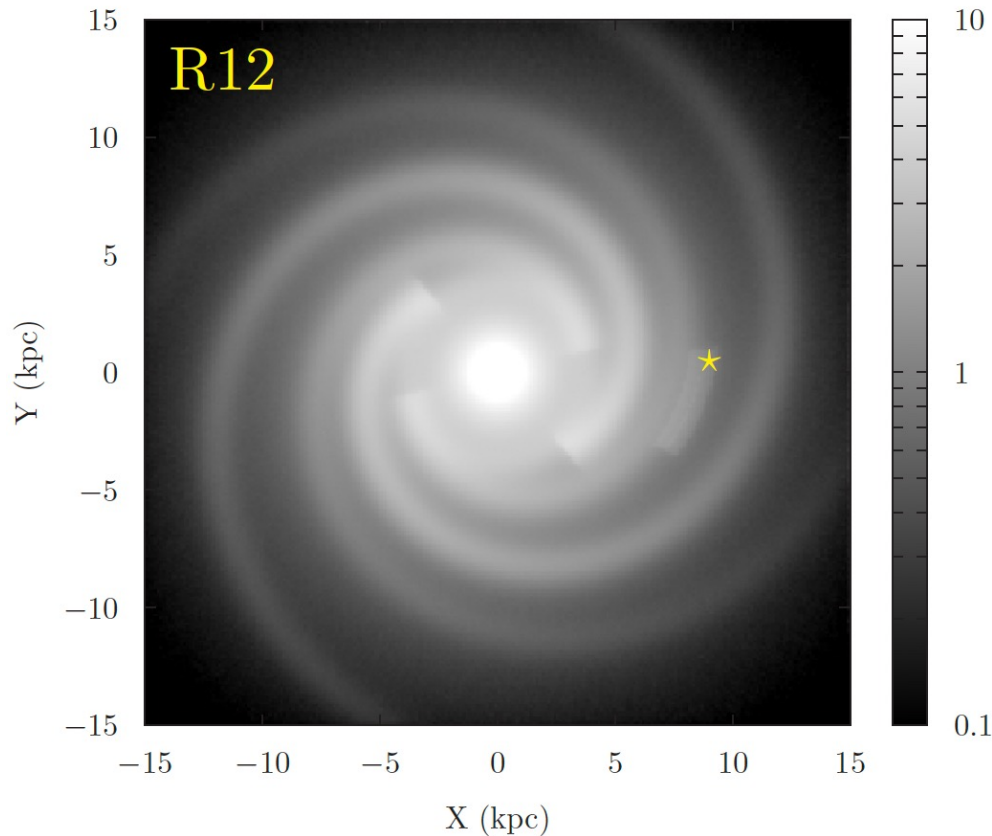- **turbulent small-scale** due to outflows, e.g. supernovae

CR Propa
(Alves Batista+, 2022)

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

interstellar radiation field (ISRF)

stars emission & starlight processed by dust ∈ [IR; UV]
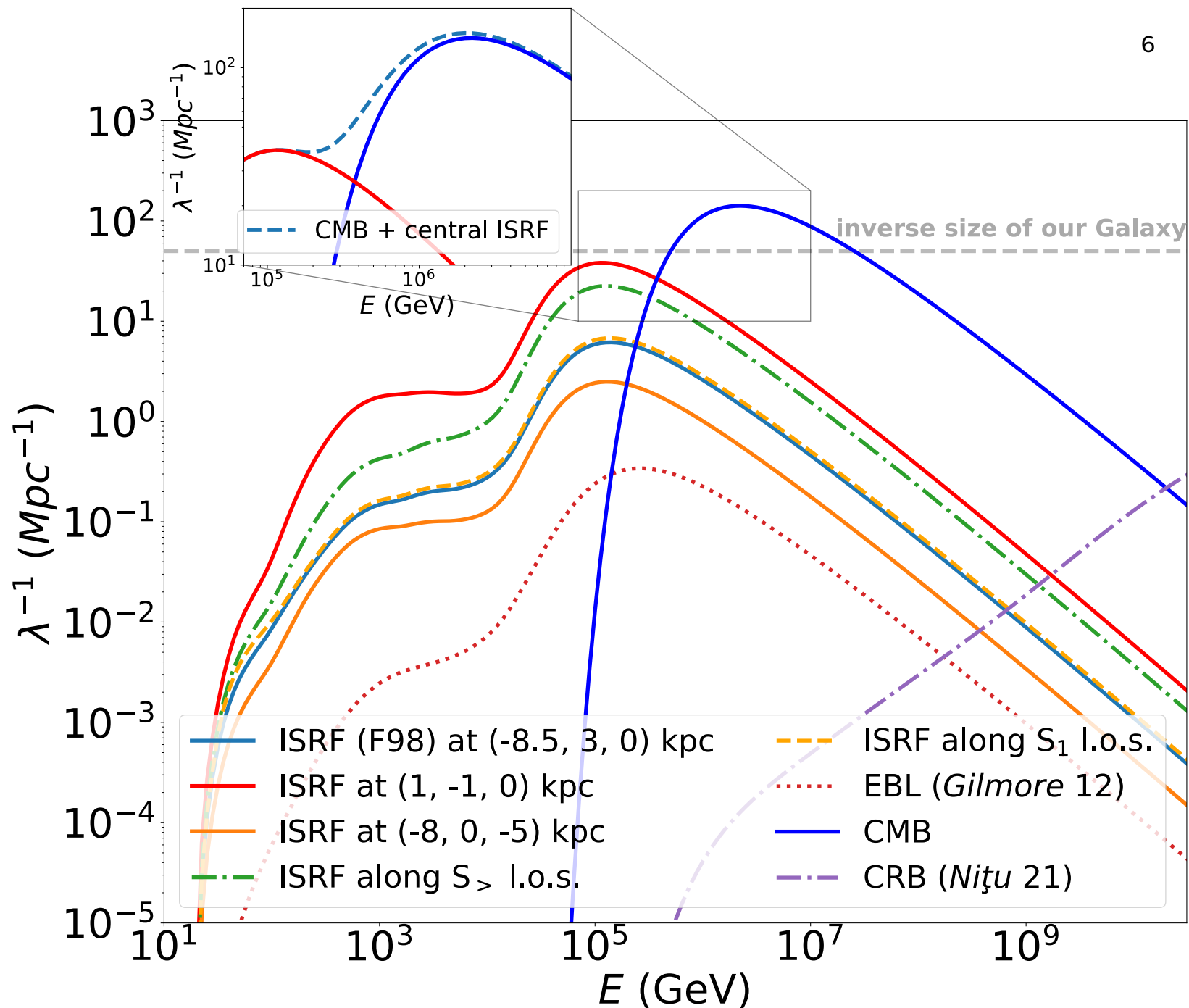
(arms' young stars averaged)

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

pair production

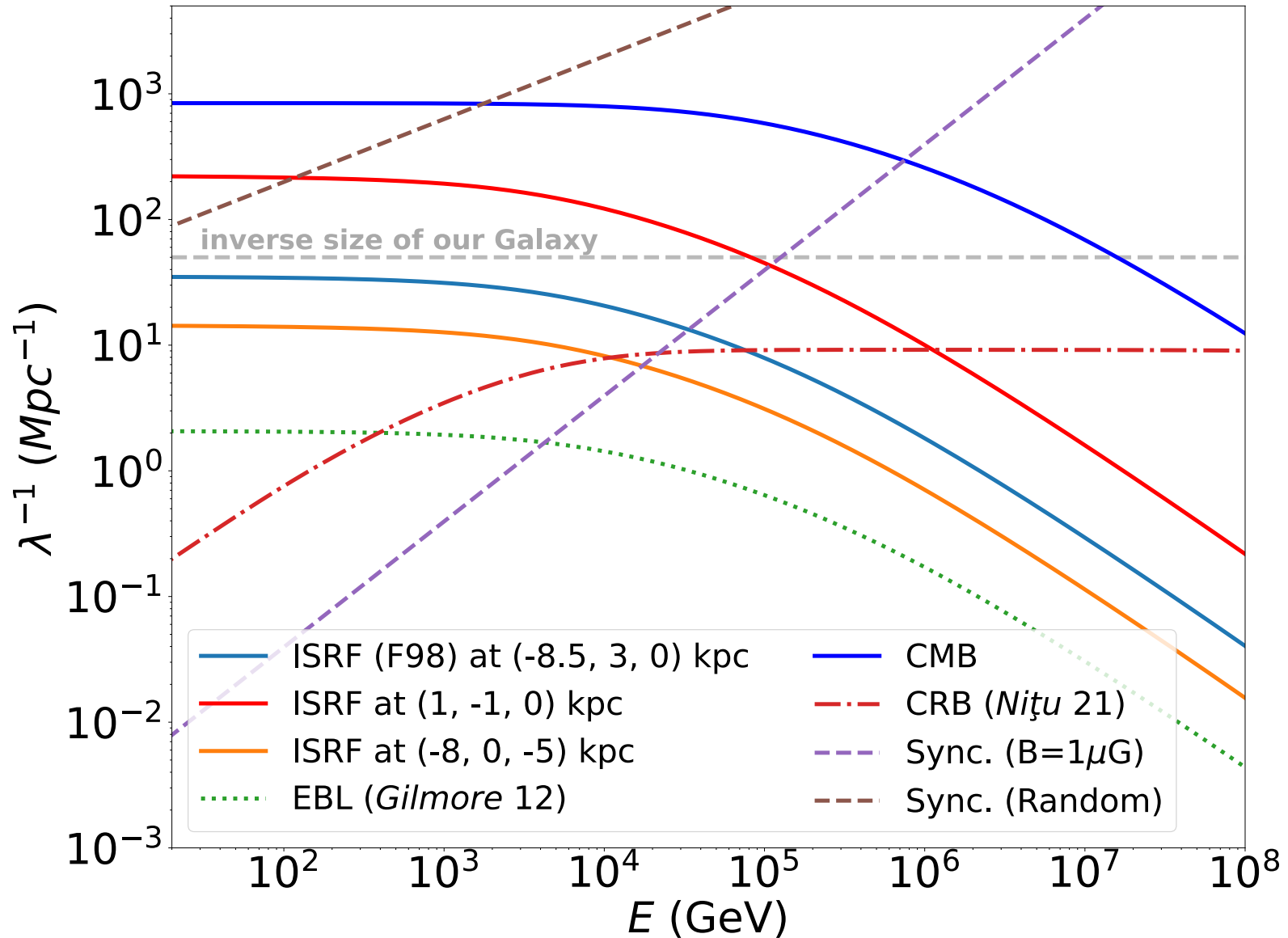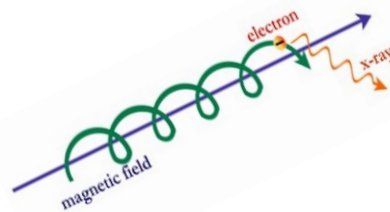- 1st ISRF maximum at 1 TeV

  - 2nd peak at 50 TeV

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

inverse Compton & synchrotron

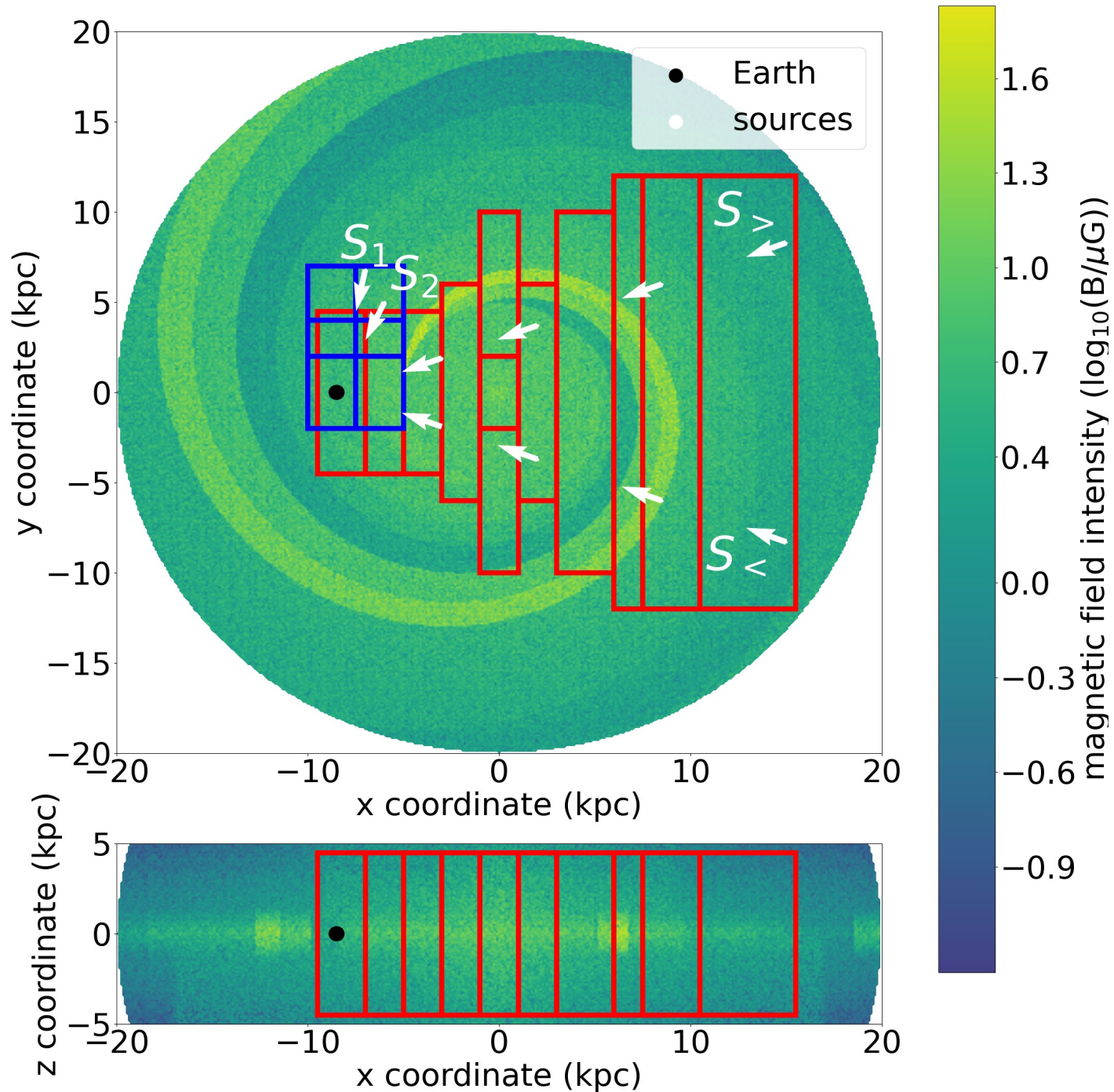inverse length scale of synchrotron energy loss:

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

simulation setup

- $S_{\lessgtr}$ datasets, distances:

    6, **11**, **18** and **25 kpc**
    (red ISRF domains)

    along the line of sight $\dfrac{B_{turb}}{B_{reg}} \gtrsim 10$

- S_1 & S_2, distances:

    7 and **5.6 kpc**
    (blue ISRF domains)

    along the line of sight $\dfrac{B_{turb}}{B_{reg}} \sim 2$
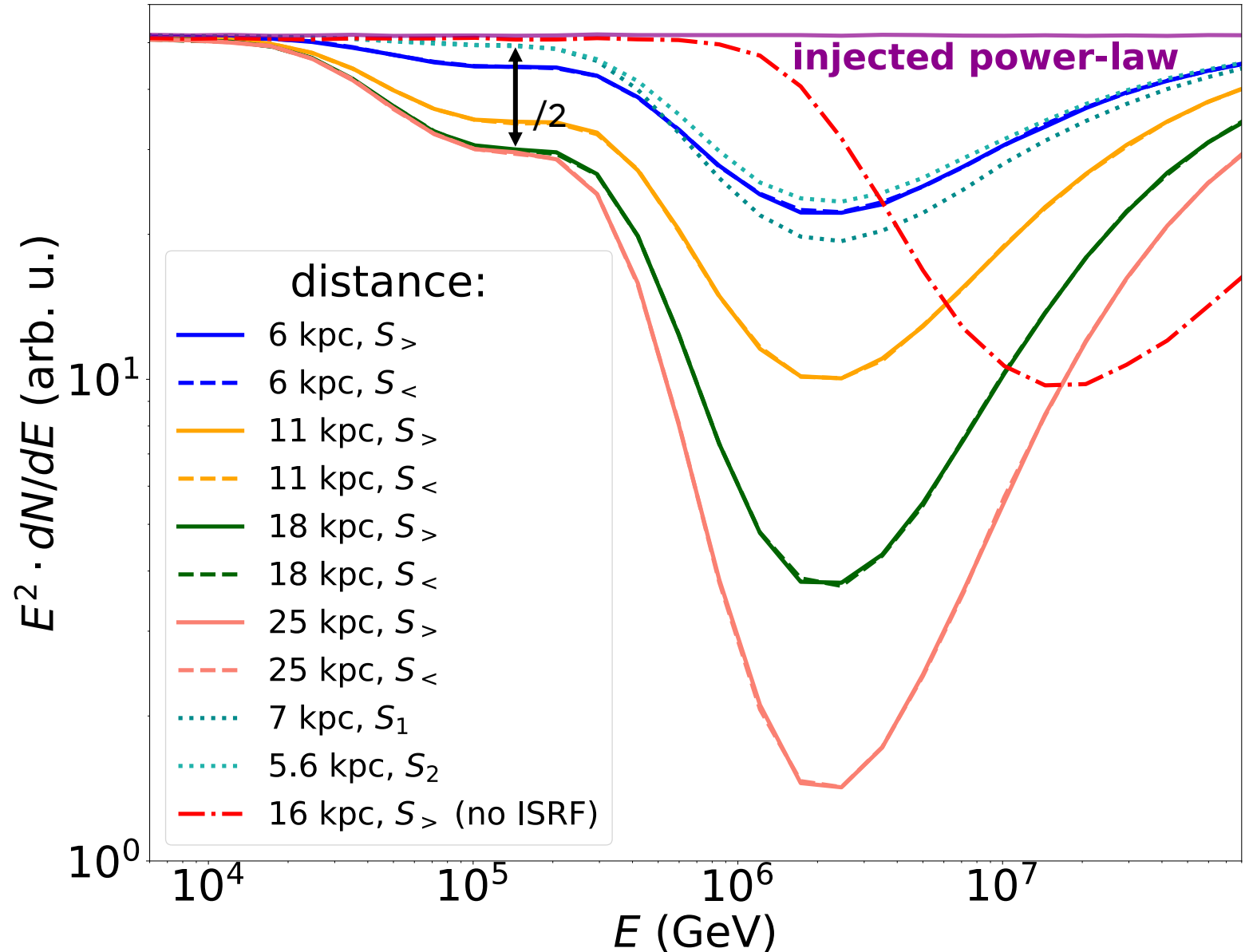
energy spectra

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

maximum absorption:

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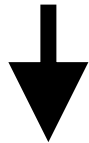
- **w ISRF** (approx.) **at 2 PeV**

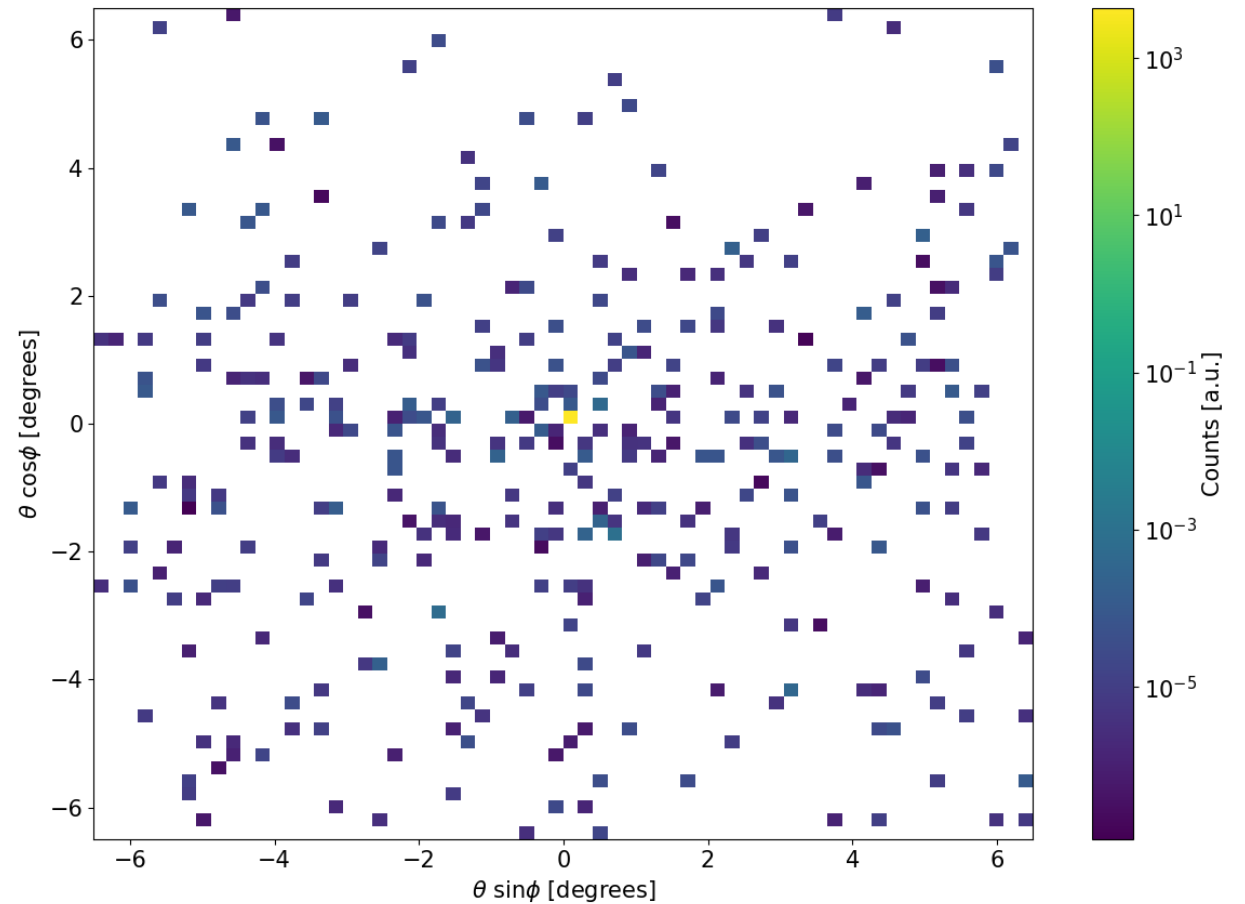**hints of combined CMB+central ISRF action**

injected power-law

distance:
- 6 kpc, $S_>$
- 6 kpc, $S_<$
- 11 kpc, $S_>$
- 11 kpc, $S_<$
- 18 kpc, $S_>$
- 18 kpc, $S_<$
- 25 kpc, $S_>$
- 25 kpc, $S_<$
- 7 kpc, S_1
- 5.6 kpc, S_2
- 16 kpc, $S_>$ (no ISRF)

count map w/o ISRF
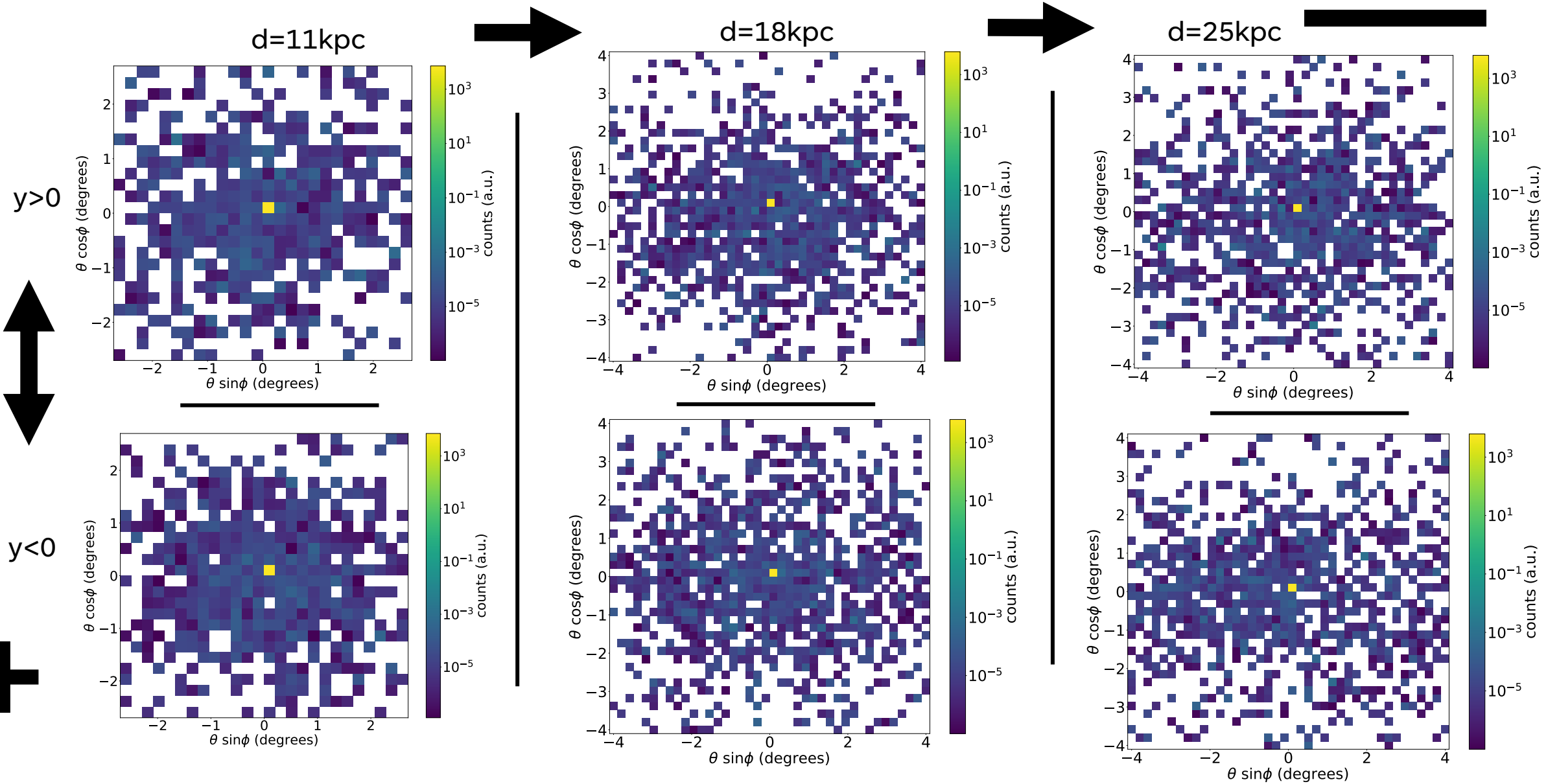
- filling galactic space with the EBL, apart from CMB and CRB

- $S_{\lessgtr}$ source at a distance of 16 kpc

NO haloes around the point-like source
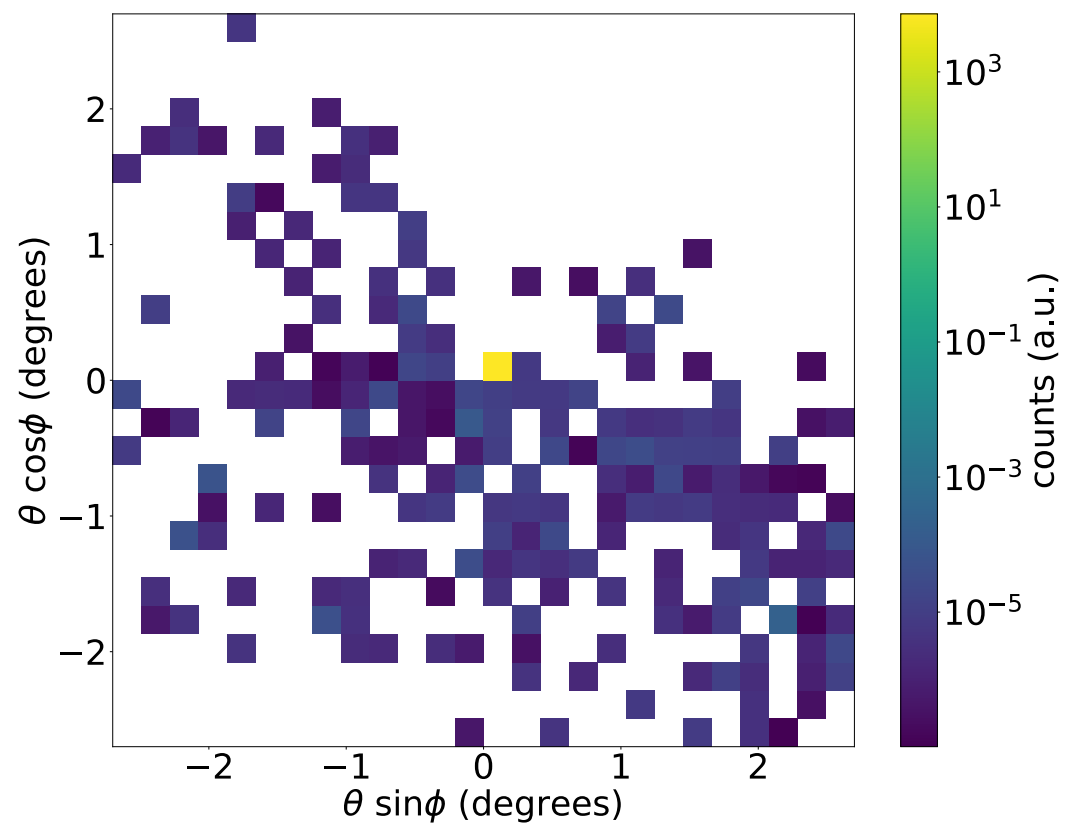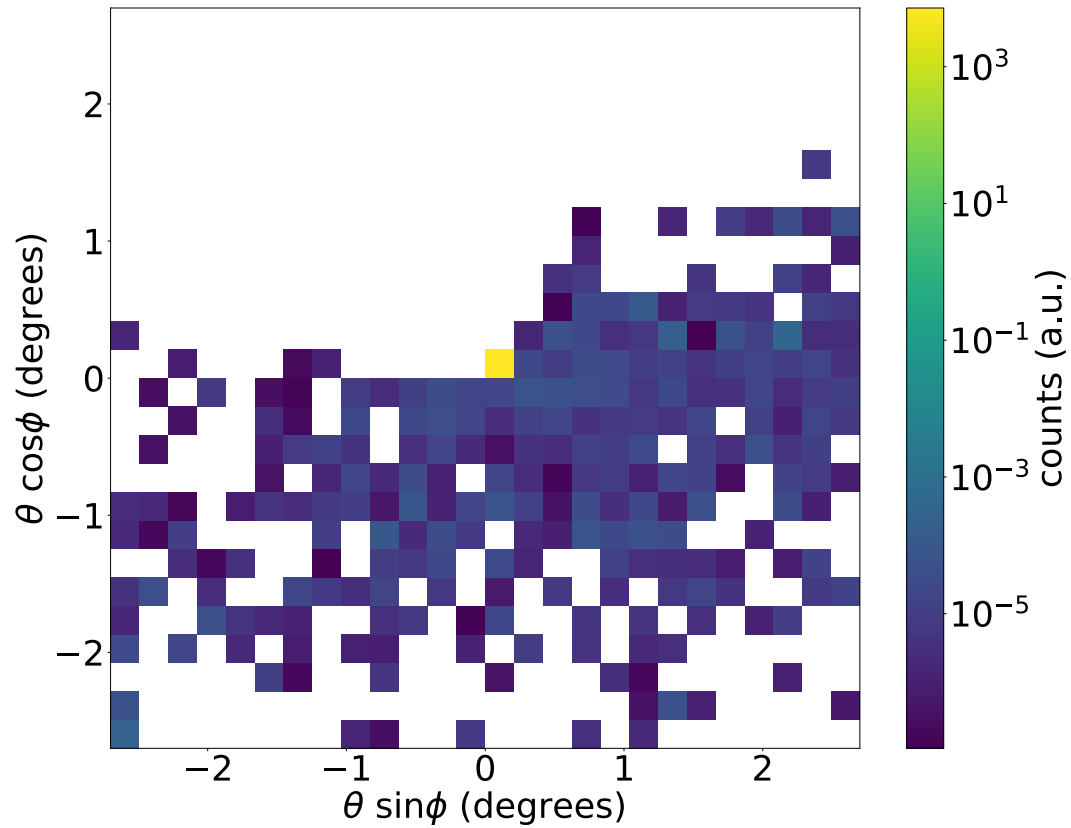
count maps w ISRF ($S_{\lessgtr}$ sources)

d=11kpc   d=18kpc   d=25kpc
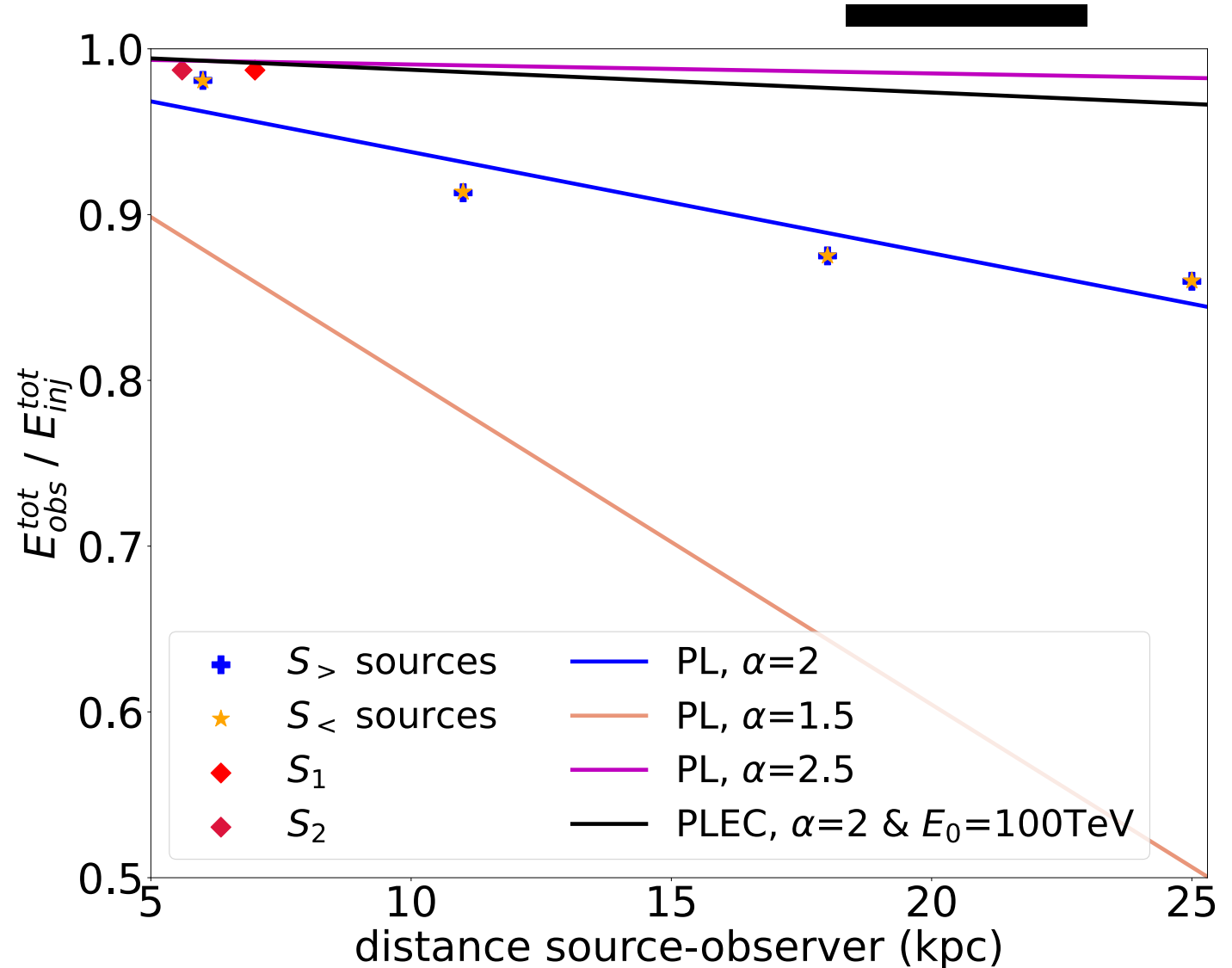
y>0

y<0

count maps w ISRF (S$_1$ & S$_2$ sources)

highly-shaped by the regular component of
the magnetic field!

on the total energy

❖ ISRF **spectral feature** depending on the distance and on the prompt spectrum

❖ the harder the spectrum, the larger *absorption per length*

❖ determinant the higher energy gamma rays, the *most impacted* by propagation effects

some prospects & conclusions

❖ **technical side**:

  ➢ close to implement position-dependent radiation fields in CRPropa

❖ **science side**:

  ➢ **detectability** of haloes and spectral features? **halo counts** are 10^{-4} less than those coming from the central point-like source, at least...

  ➢ contribution to the diffuse gamma-ray/electron background?

  ➢ revision of galactic gamma-ray observations, beyond tens of TeV? in light of position-dependent absorption and «deflection» features

  ➢ impact on dark matter constraints through gamma rays?
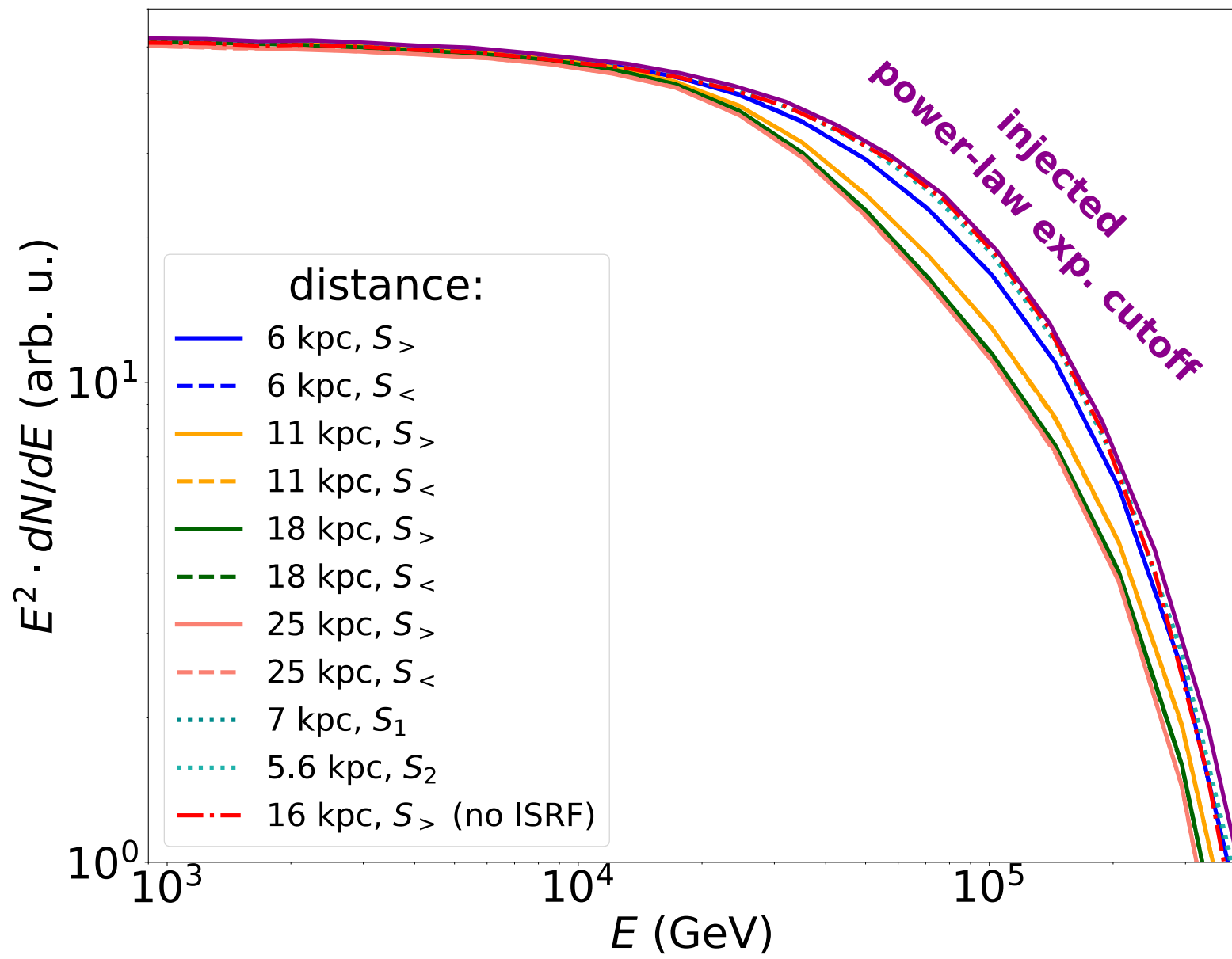
on **arXiv:2408.08818** (submitted to JCAP)

"Revisiting the propagation of highly-energetic gamma rays in the Galaxy"

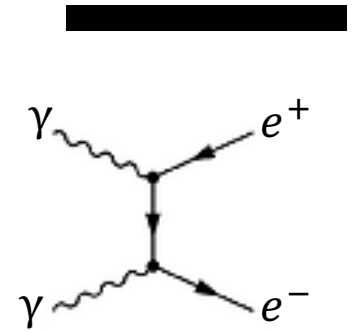Gaetano Di Marco (IFT UAM-CSIC), Rafael Alves Batista (IAP SU), Miguel A. Sánchez-Conde (IFT UAM-CSIC)

(F. J. Brown, «Study #427 Milky Way», 1977)

backup...

energy spectra

power-law exp. cutoff injected

distance:
- 6 kpc, $S_>$
- 6 kpc, $S_<$
- 11 kpc, $S_>$
- 11 kpc, $S_<$
- 18 kpc, $S_>$
- 18 kpc, $S_<$
- 25 kpc, $S_>$
- 25 kpc, $S_<$
- 7 kpc, S_1
- 5.6 kpc, S_2
- 16 kpc, $S_>$ (no ISRF)

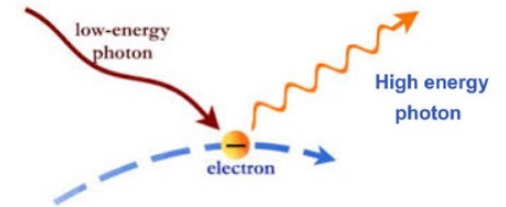$E^2 \cdot dN/dE$ (arb. u.)

E (GeV)

on gamma-ray propagation

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

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

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

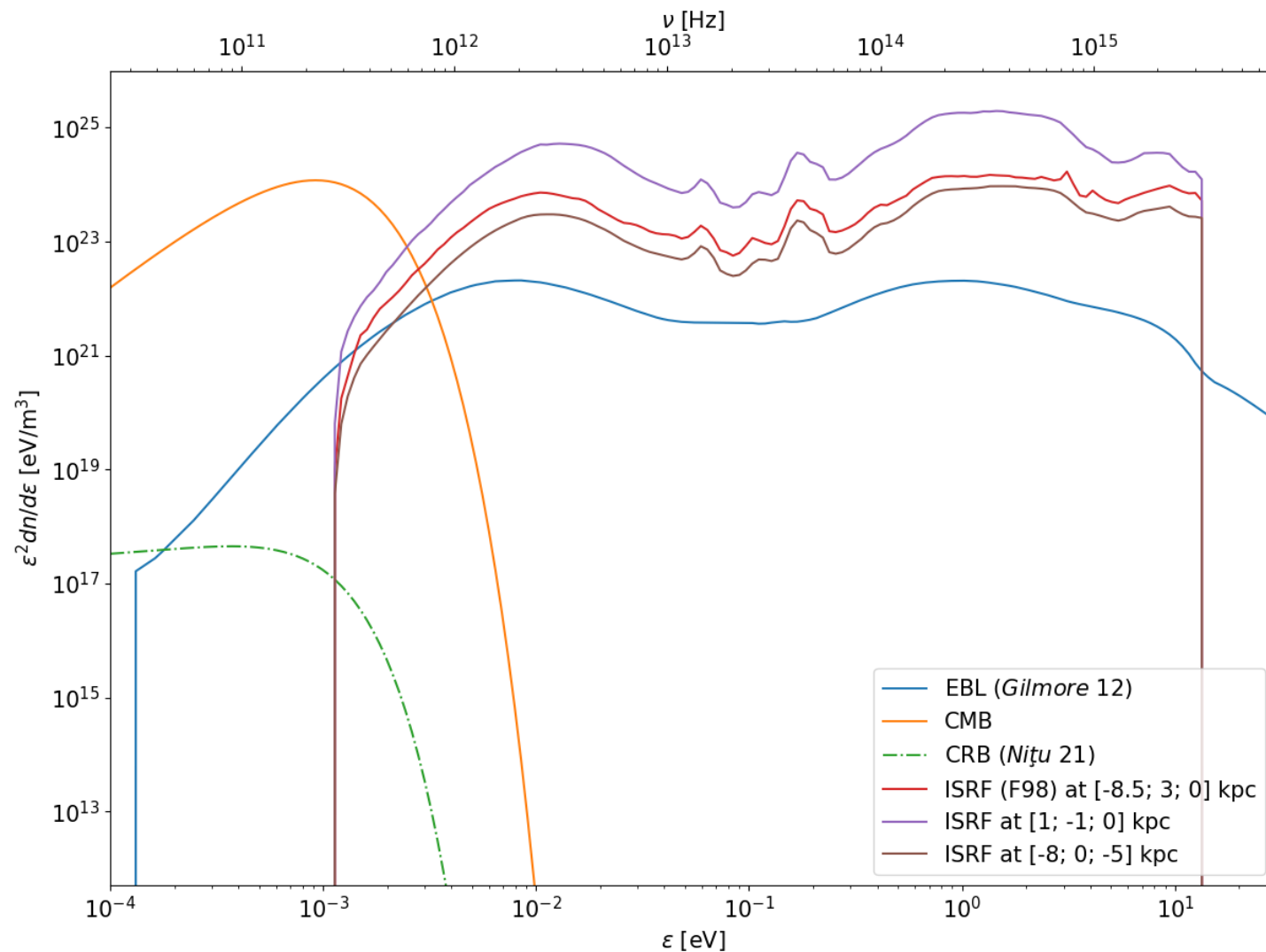 - triplet pair production: $e + \gamma_{BKG} \rightarrow e + e^- + e^+$

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

$\Longleftarrow$ **ISRF** $\rightarrow$ **IR, optical, UV**

photon background energy densities

three ISRF (from F98) as references:

- around the **galactic center**

- close to **Earth position**

- in Earth nearby, **out-of-plane**

inverse mean free path

photon background (volumetric) number density

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

process dependent!

particle energy

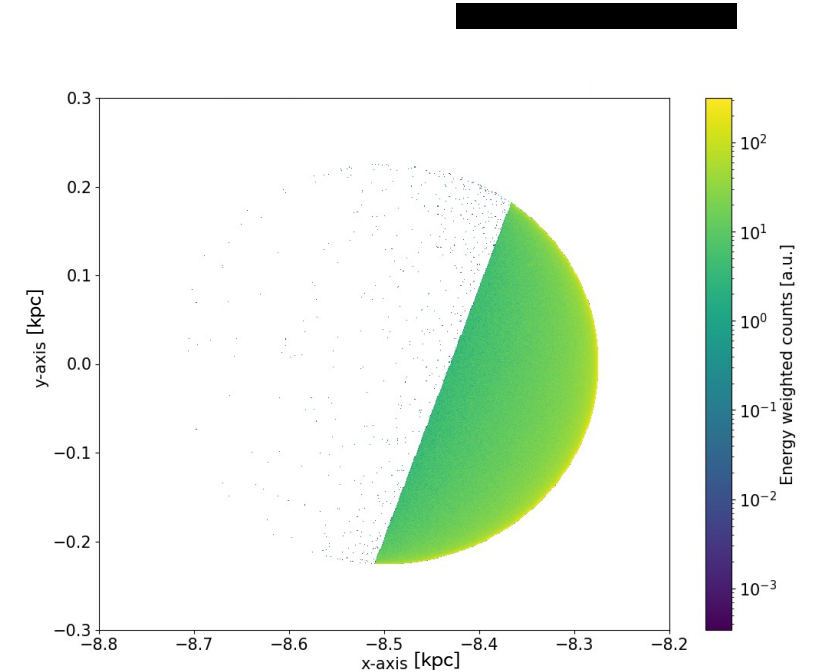# simulation setup

CR Propa

(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))
```

$$\begin{cases} \text{specIndex} = -2 \\ E = [100 \text{ GeV}; 100 \text{ PeV}] \\ \text{Scon} \sim 0.5° \end{cases}$$

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

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

restrictToRegion & sources
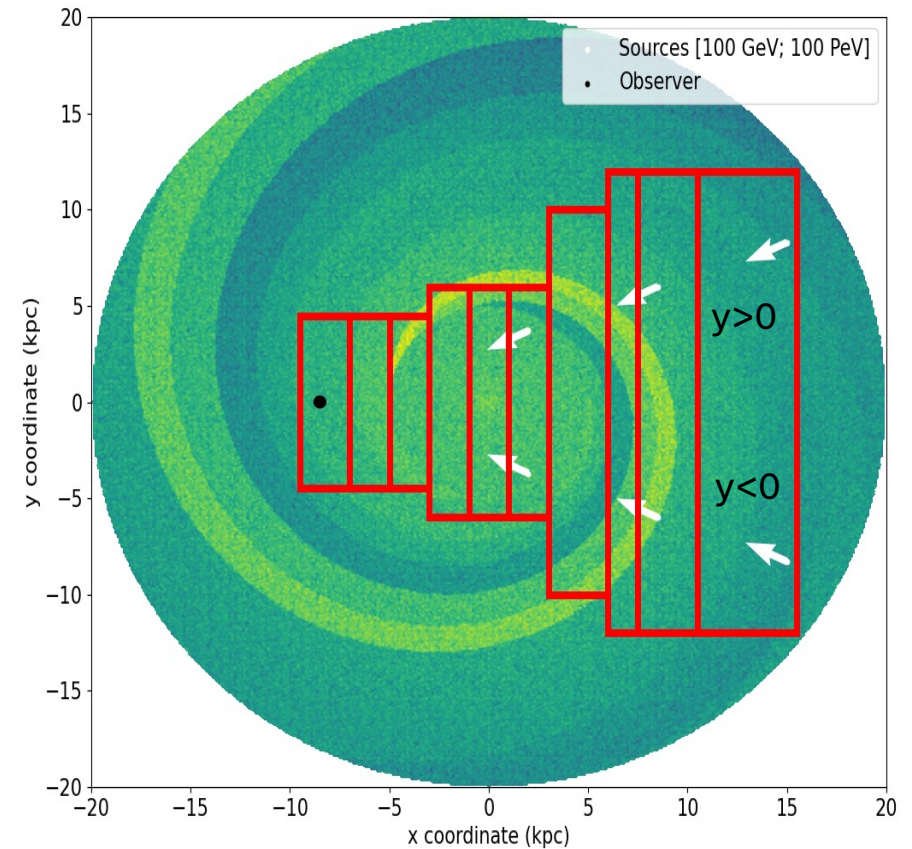
- (very) approximate ISRF spatial model, each region as:

```
isrf17 = TabularPhotonField("ISRF17", False)
sim.add(RestrictToRegion(EMPairProduction(isrf17, False, thinningEM),ParaxialBox(origin*kpc,ext*kpc)))
#... other interactions
```
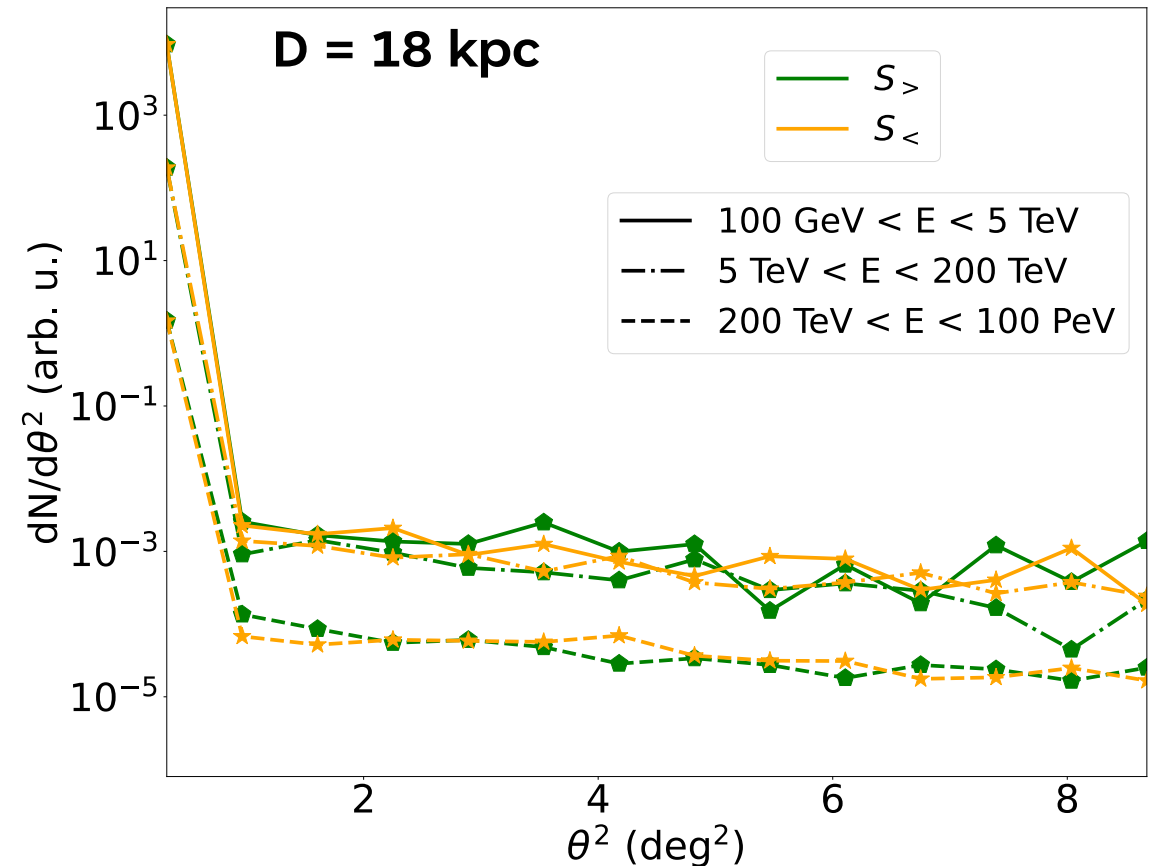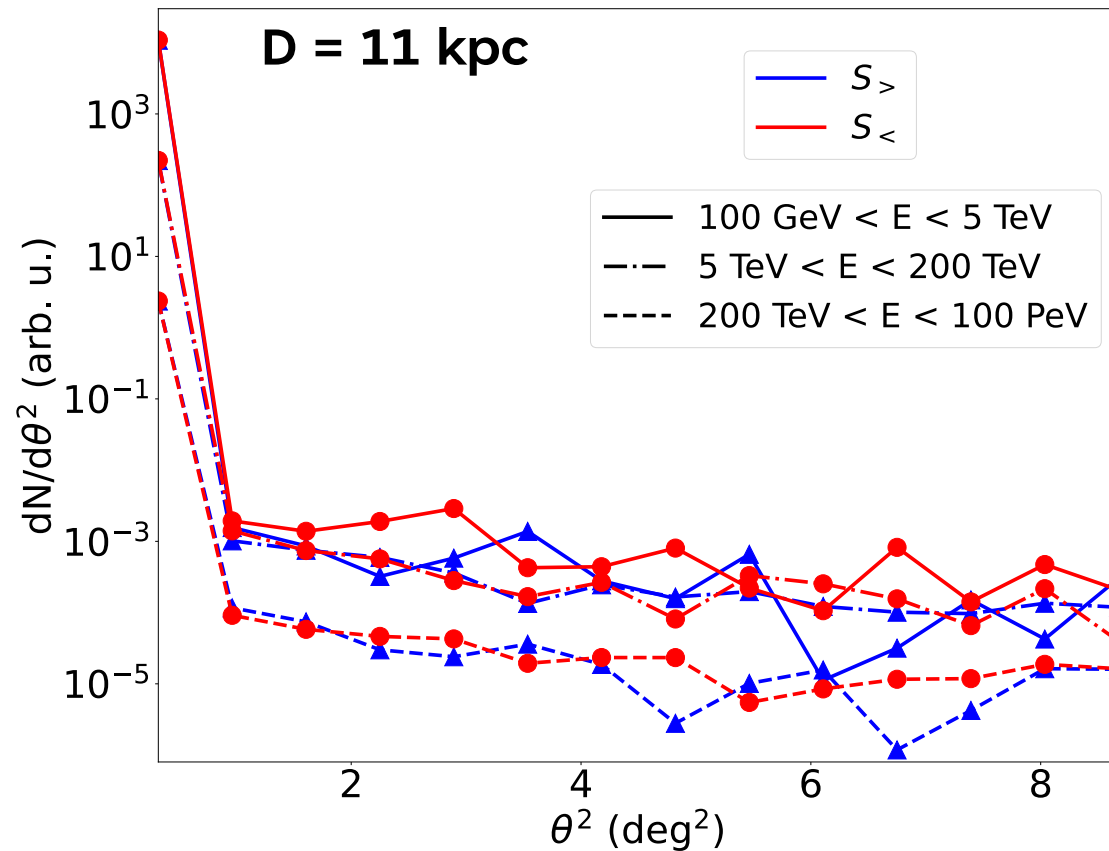
- six sources on galactic plane:

- 2 tests on **three different distances** (11 kpc, 18 kpc, 25 kpc)
- 3 on **two symmetric positions w.r.t. x-axis**

- observables: **energy spectra**
                    count maps
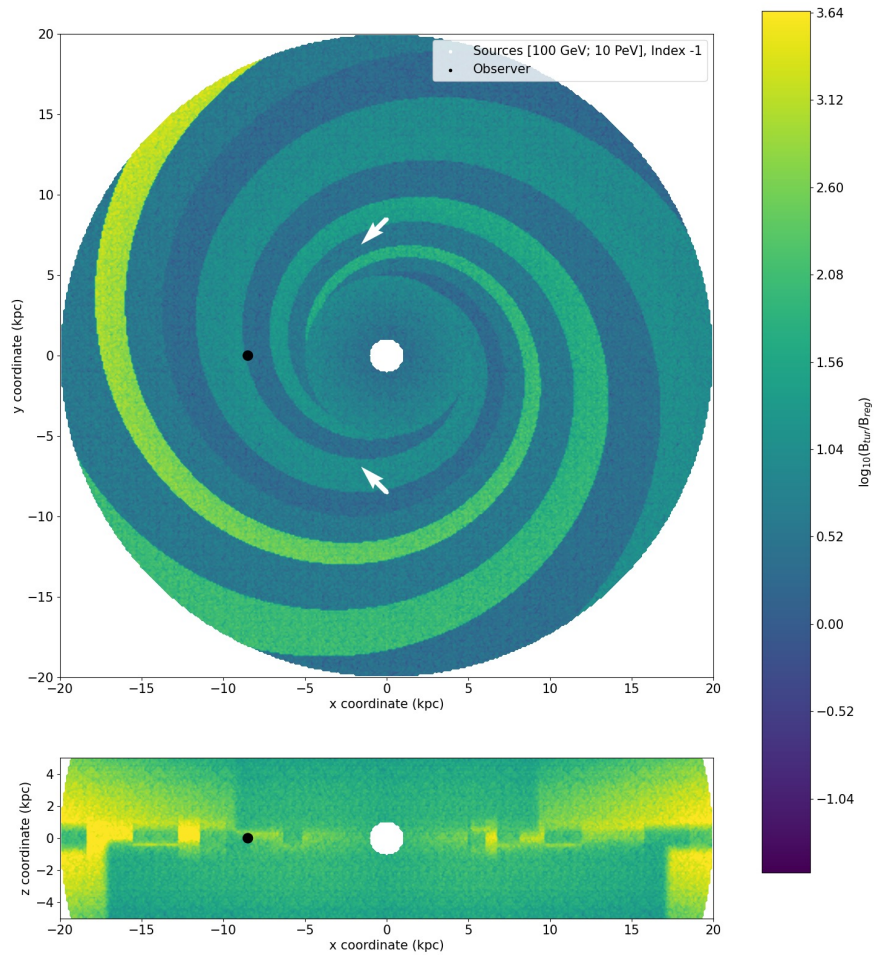   **surfaces brightness**
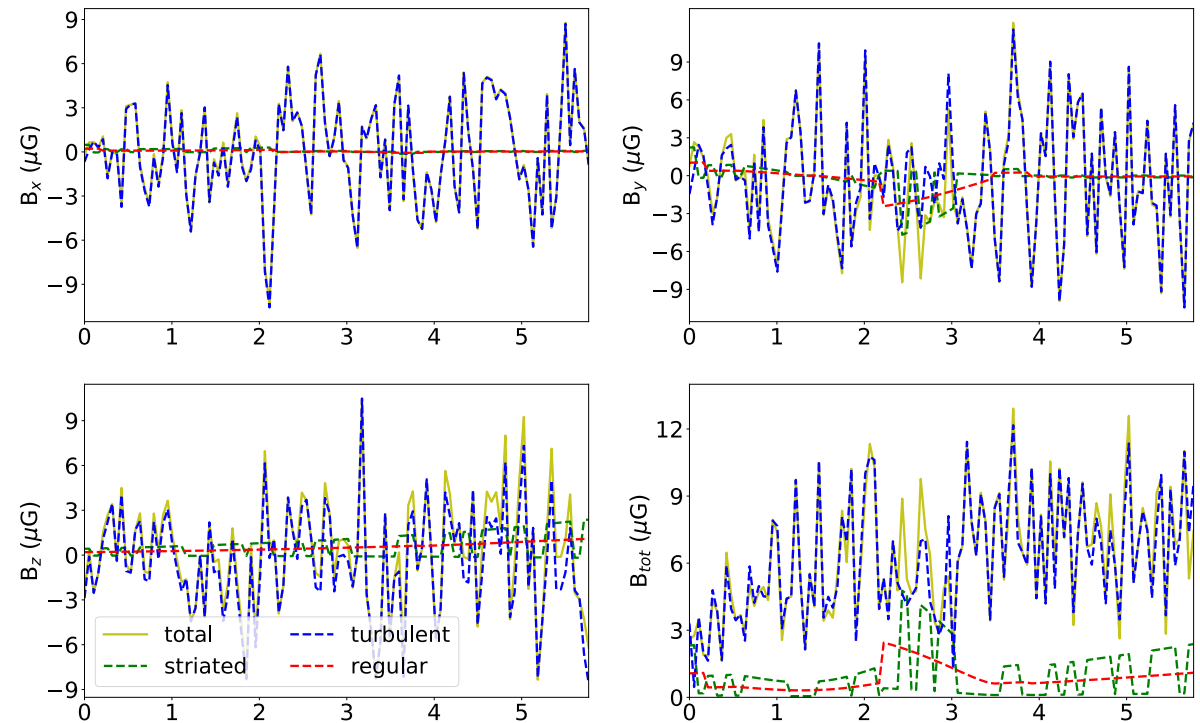
surface brightness (deflection angle, d=18kpc)

large contribution to the halo
from the intermediate energy
band!

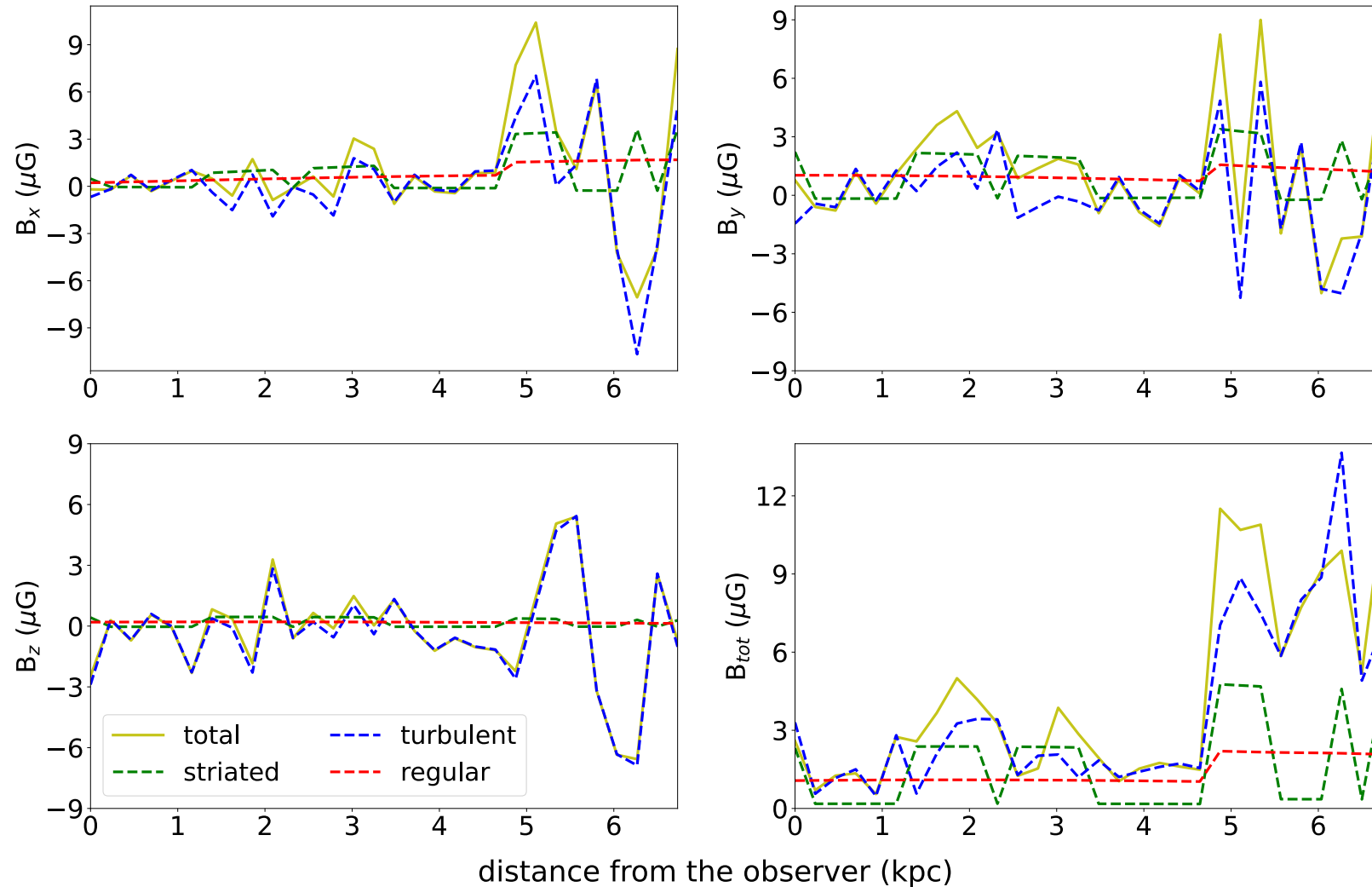# regular *vs* turbulent

S$_>$ source, 6 kpc distant

S$_1$ source, magnetic field along the line of sight

distance from the observer (kpc)

last scattering plot