Characterisation of γ-rays propagation in our Galaxy

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(J. Pollock, 1948-49)

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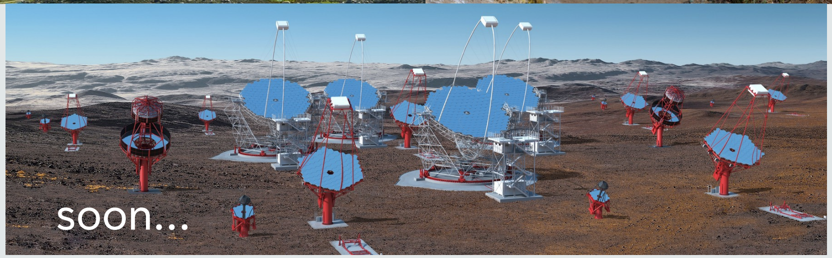
looking around...

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

(credit: LHAASO website)

(credit: HAWC website)

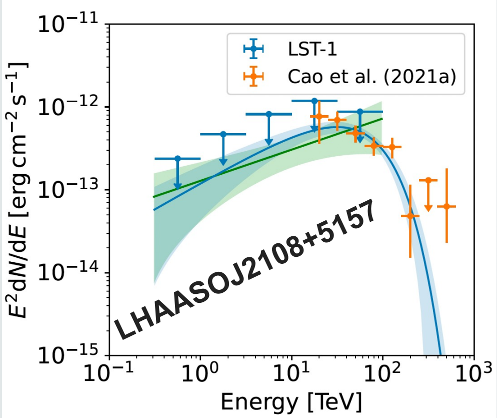


(credit: CTA-observatory website)

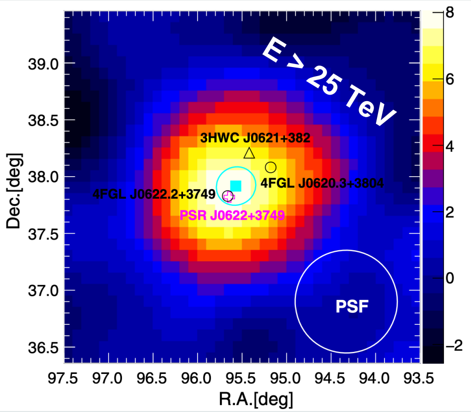
- recent **galactic PeVatrons** detections

might galactic propagation effects be relevant?

“standard” astrophysics only!



(Abe+, 2023)



LHAASO J0621+3755 from (Aharonian+, 2021)

outline

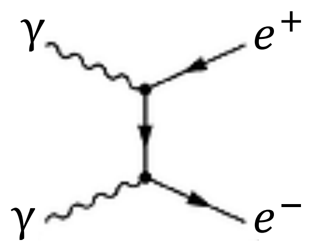
- gamma-ray propagation theory &
  galactic magnetic field (**GMF**) &
  interstellar radiation field (**ISRF**)

- simulation framework + results

goal: characterizing propagation in dependence to source position in the Galaxy

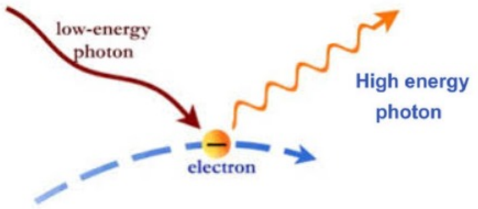
- conclusions & perspectives (implementations + science to address)

on gamma-ray propagation



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

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



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

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

+

$$\gamma_{BKG} \begin{cases} \mathrm{URB} \rightarrow \mathrm{Radio} \\ \mathrm{CMB} \rightarrow \mathrm{MicroWave} \\ \mathrm{EBL} \rightarrow \mathrm{IR, optical, UV} \end{cases} \Longleftarrow \quad \mathbf{ISRF \rightarrow IR, optical, UV}$$

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!

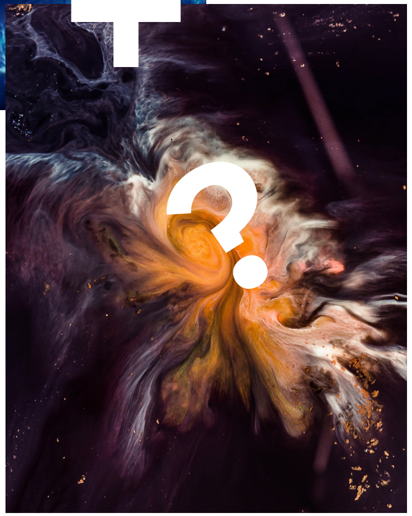
«deflection» of gamma rays

in our Galaxy:

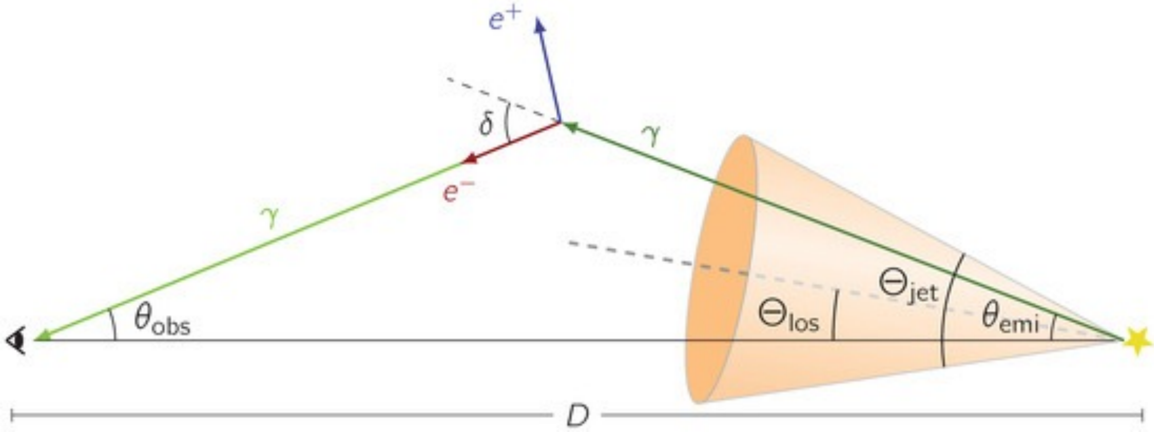
GMF

(credit: Pinterest)

ISRF



(credit: Unsplash)

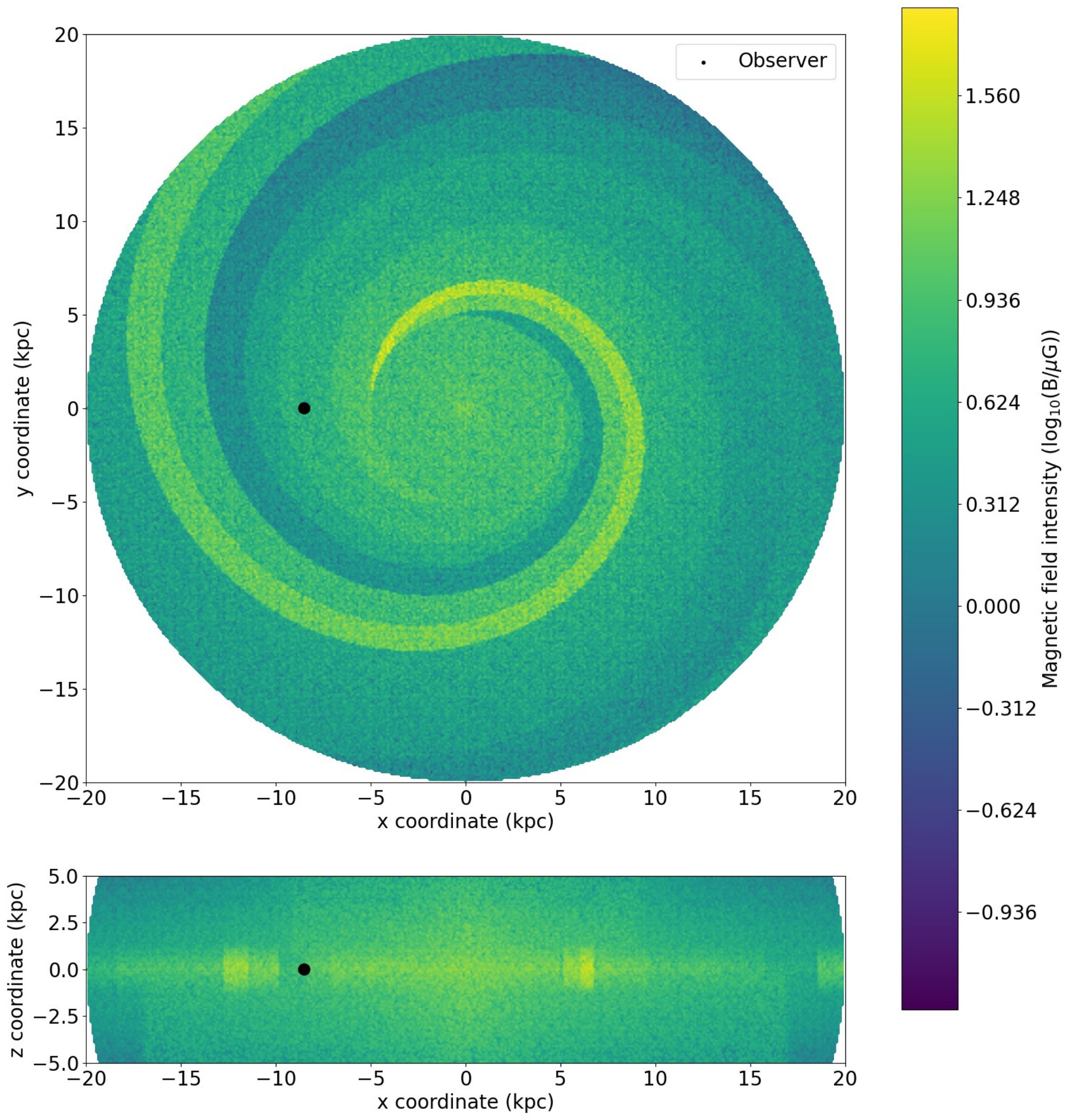


(Alves Batista & Saveliev, 2021)

galactic magnetic field

three components:

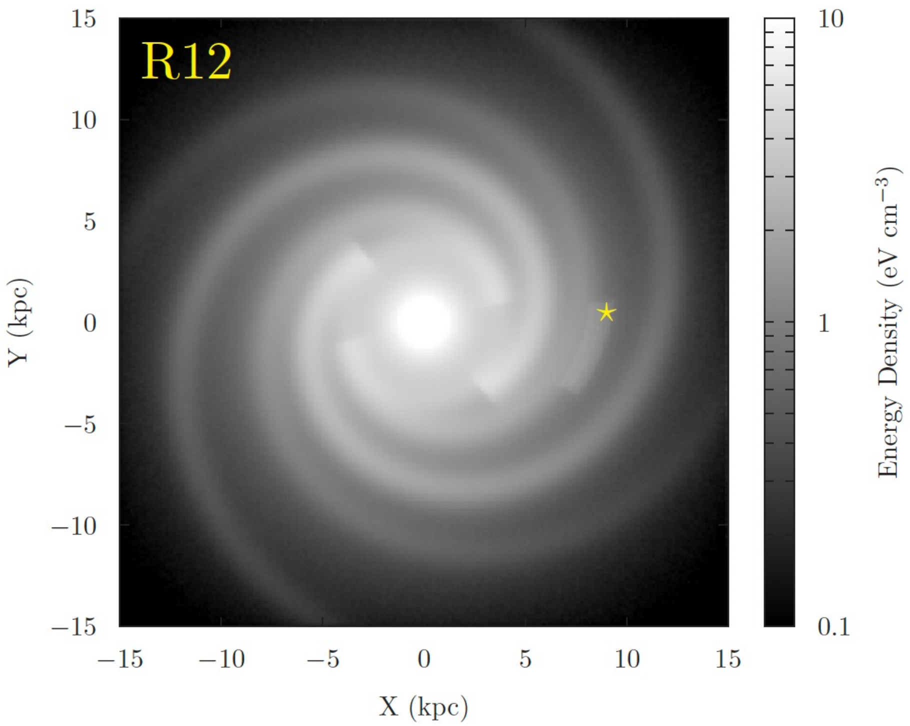
- **regular large-scale** (disk + halo + X-field) follows thermal electron density
- **striated random** from hot plasma bubbles
- **turbulent small-scale** due to outflows, e.g. supernovae



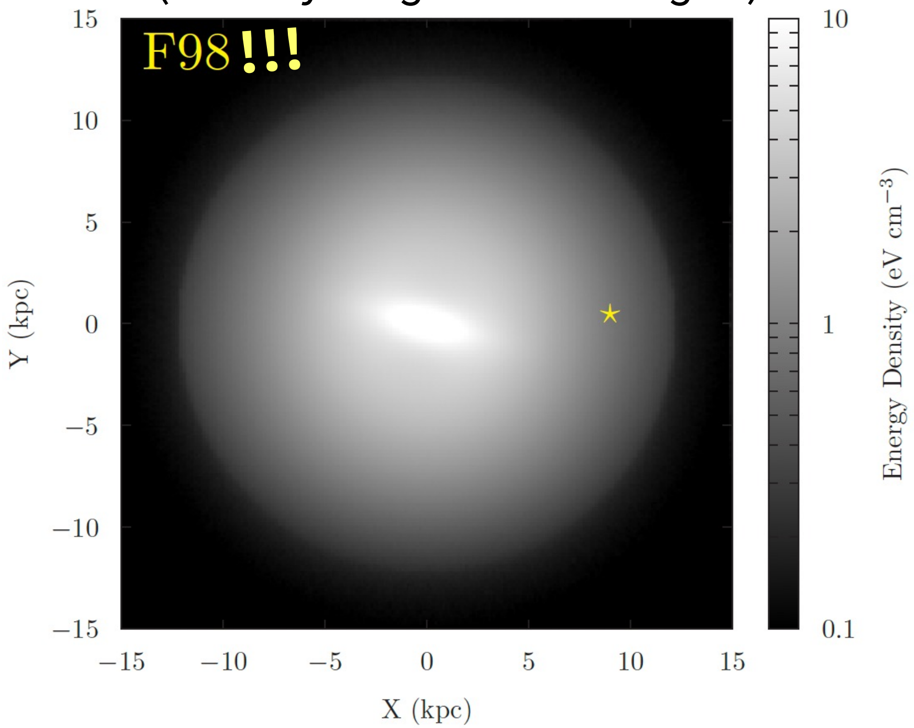
(Jansson & Farrar, 2012) implemented in (Kleimann+, 2019)

interstellar radiation field (ISRF)

stars emission & starlight processed by dust ∈ $[\mathrm{IR}; \mathrm{UV}]$



(arms' young stars averaged)

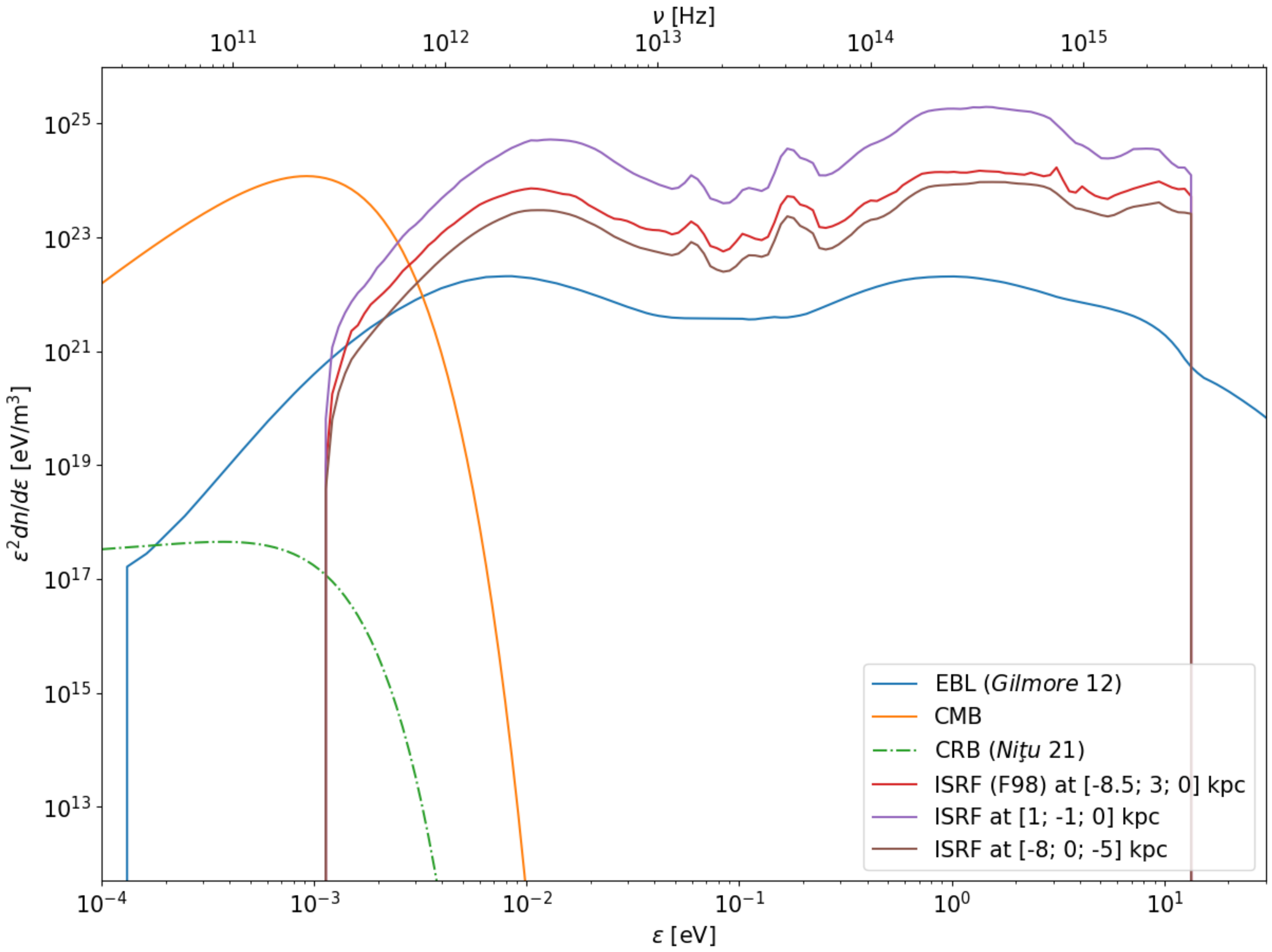


from (Porter+, 2017): R12 is (Robitaille+. 2012), **F98** (Freudenreich 1998)

photon background energy densities

three ISRF (from F98) as references:

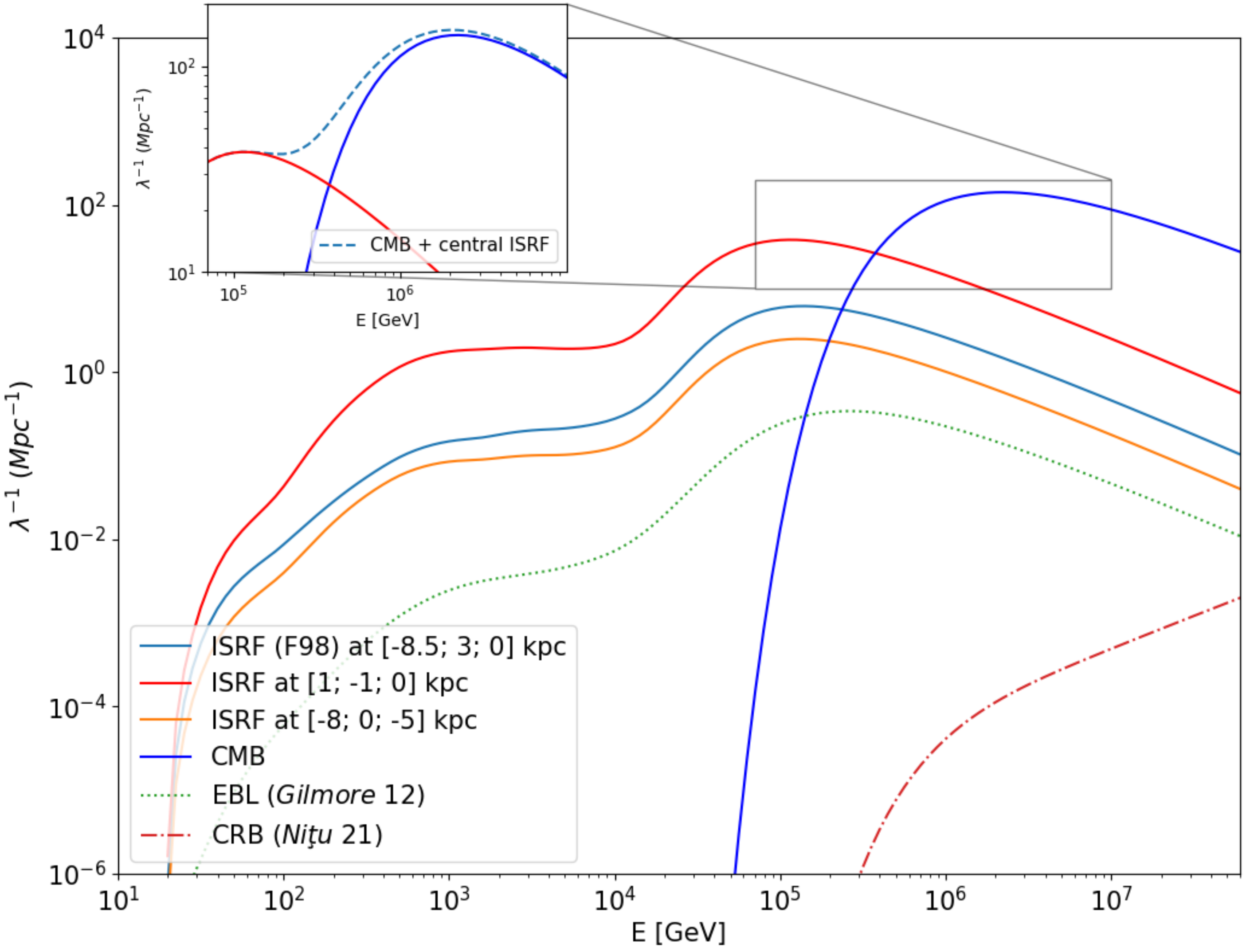
- around the **galactic center**
- close to **Earth position**
- in Earth nearby, **out-of-plane**



pair production

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

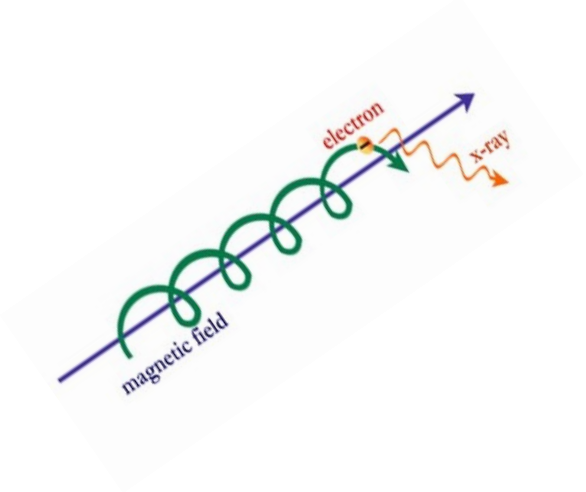
between **100 TeV & 1 PeV**:
central ISRF contribution ≲ CMB

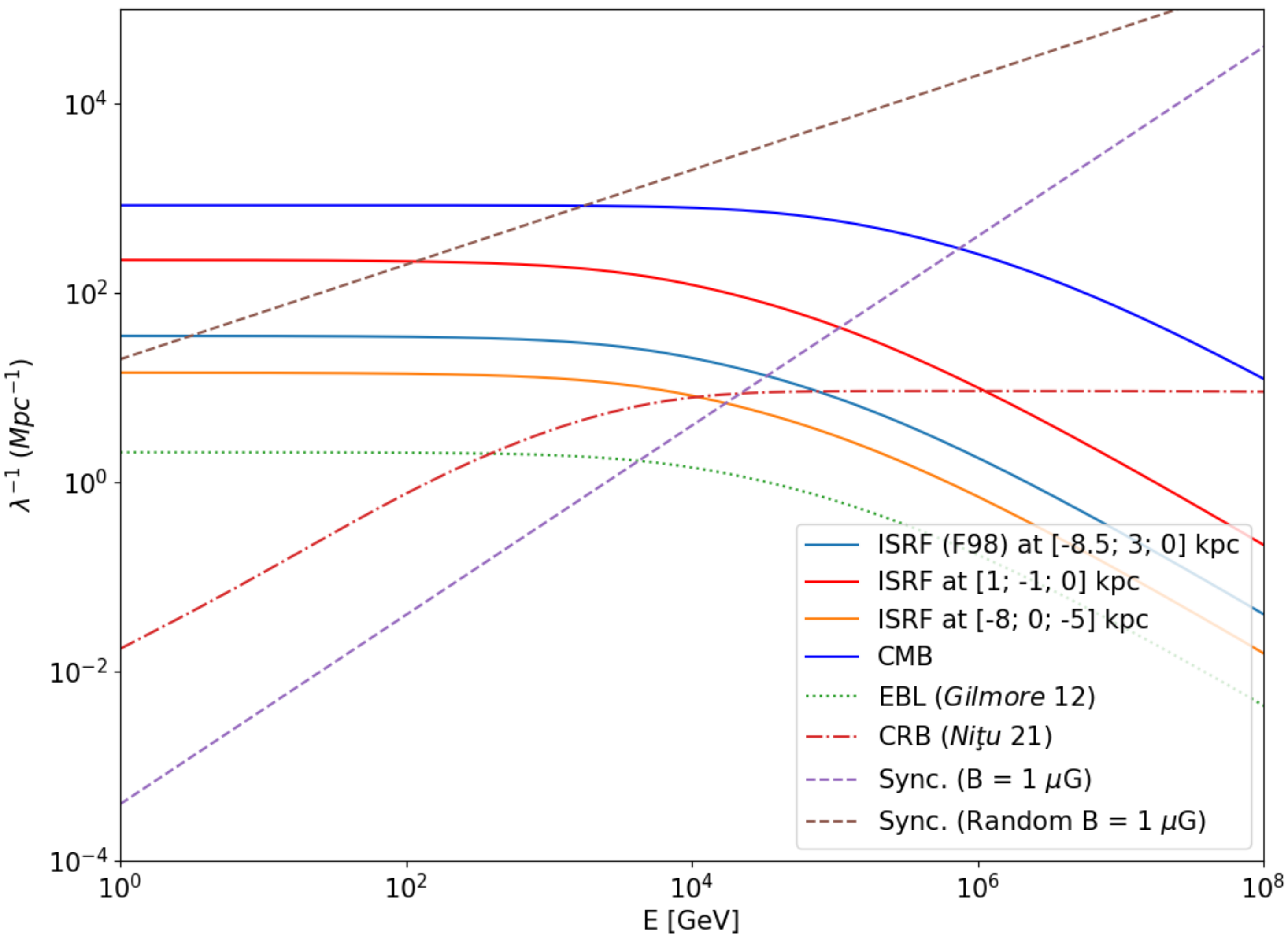


inverse Compton & synchrotron

inverse length scale of synchrotron energy loss:

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





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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, Orad * 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

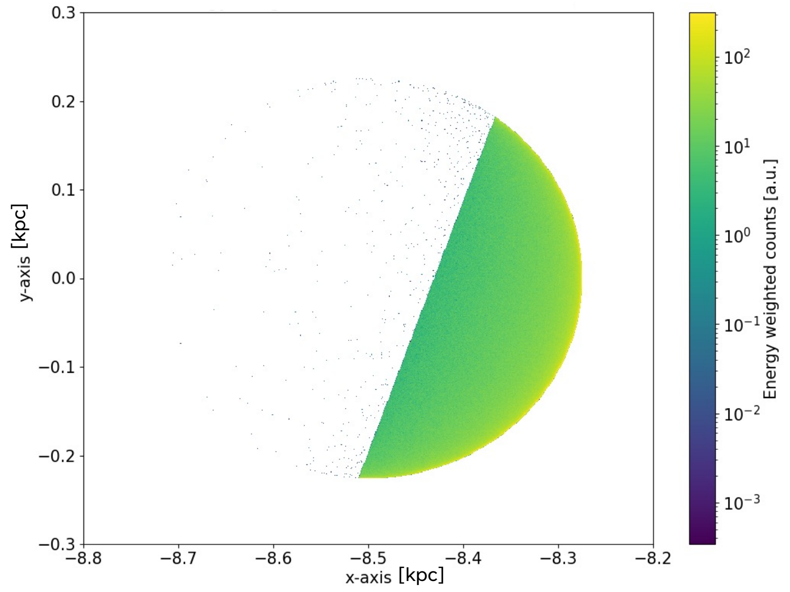
E = [100 GeV; 100 PeV]

Scon $\sim 0.5°$

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

```
sim.run(source, 500000)
```

x20 → total injected events: **1e7**



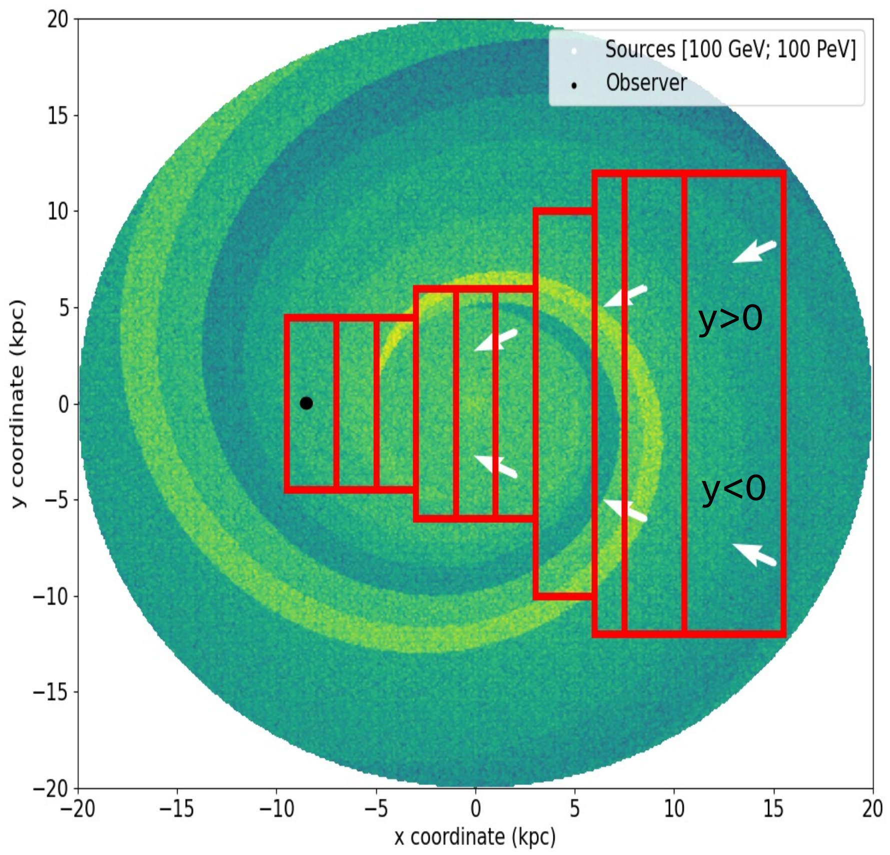
restrictToRegion & sources

- (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



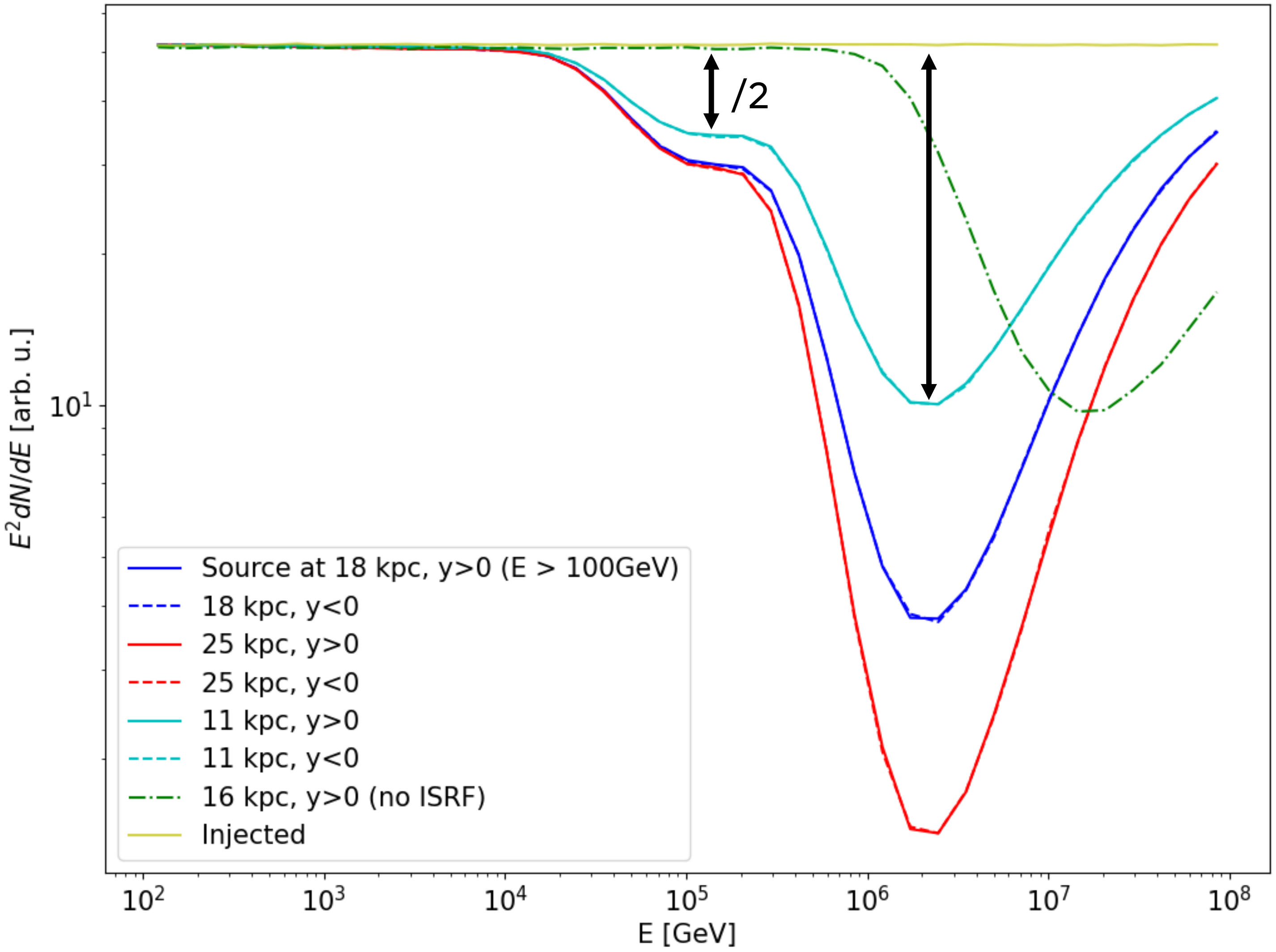
energy spectra

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 central action



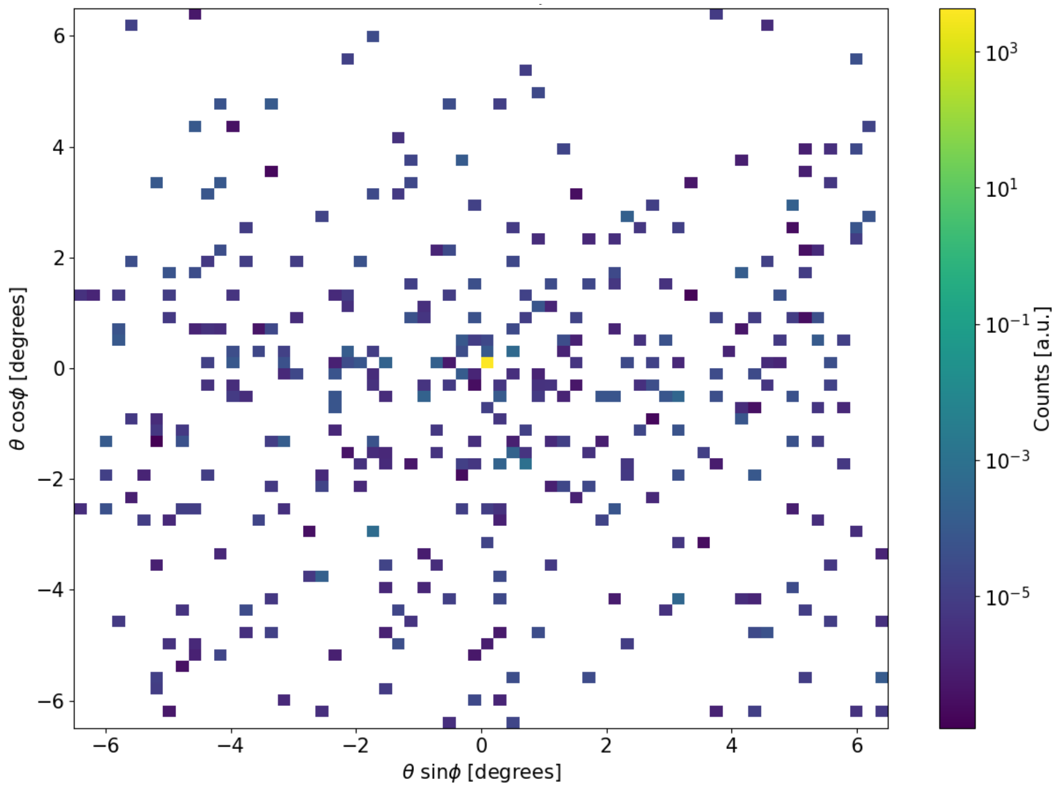
count map w/o ISRF

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

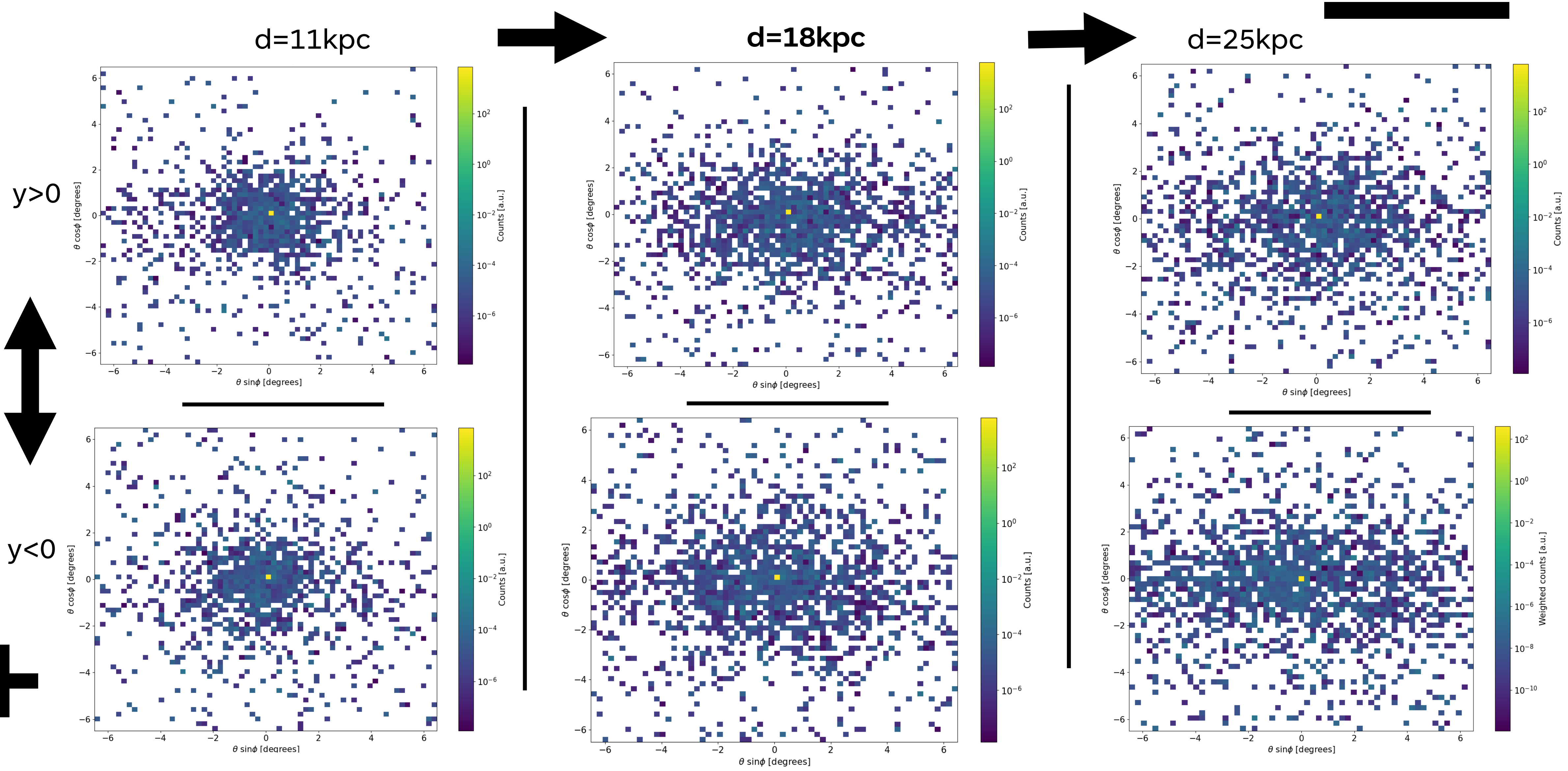
- source at a distance of 16 kpc

↓

NO haloes around the point-like source



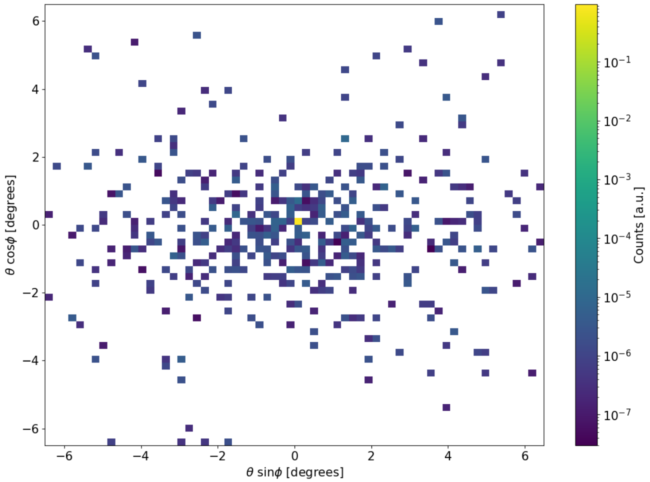
count maps w ISRF



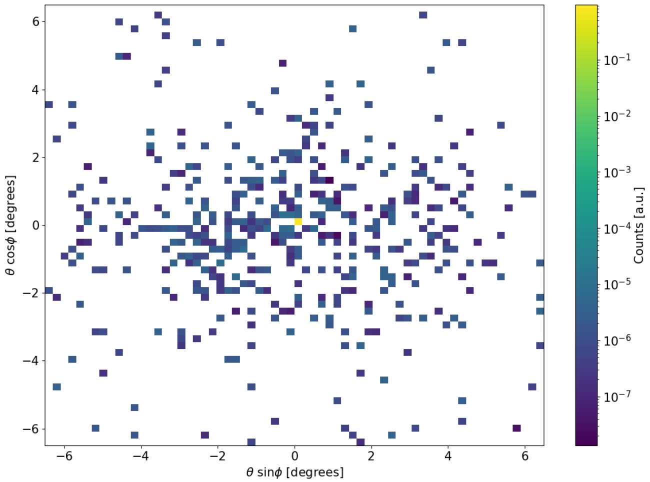
d = 18 kpc

100GeV<E<5TeV

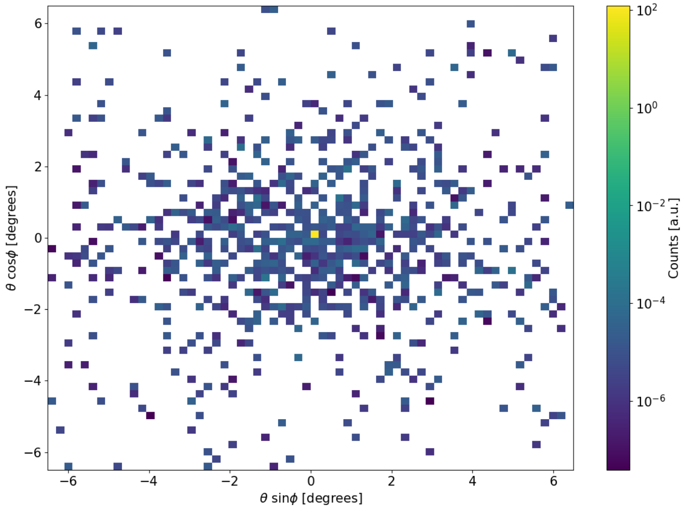
y>0

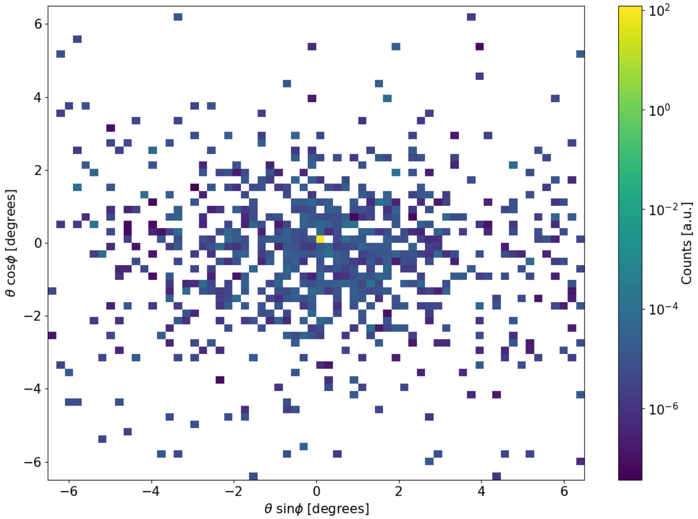


y<0

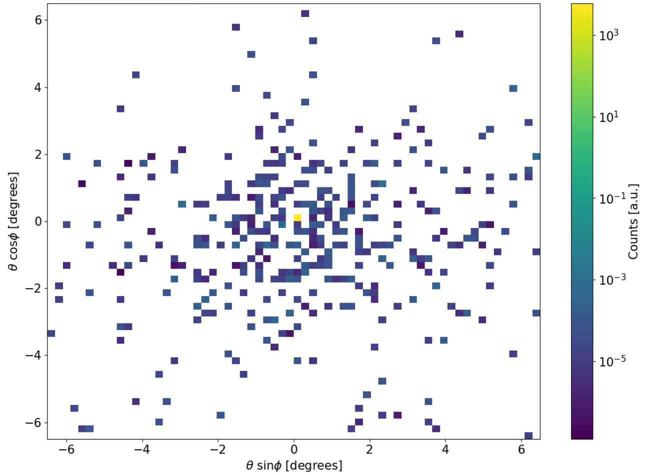


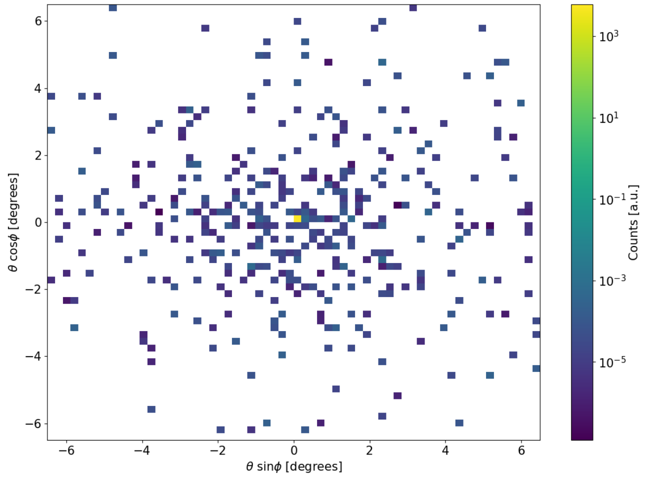
5TeV<E<200TeV



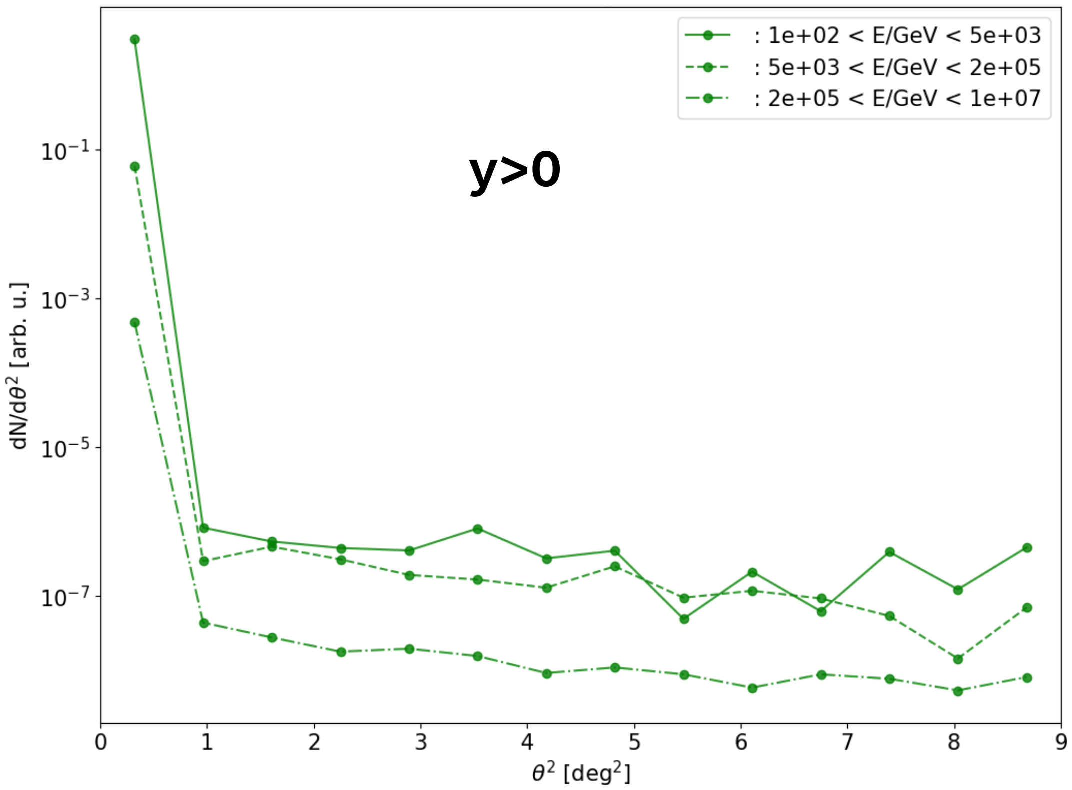


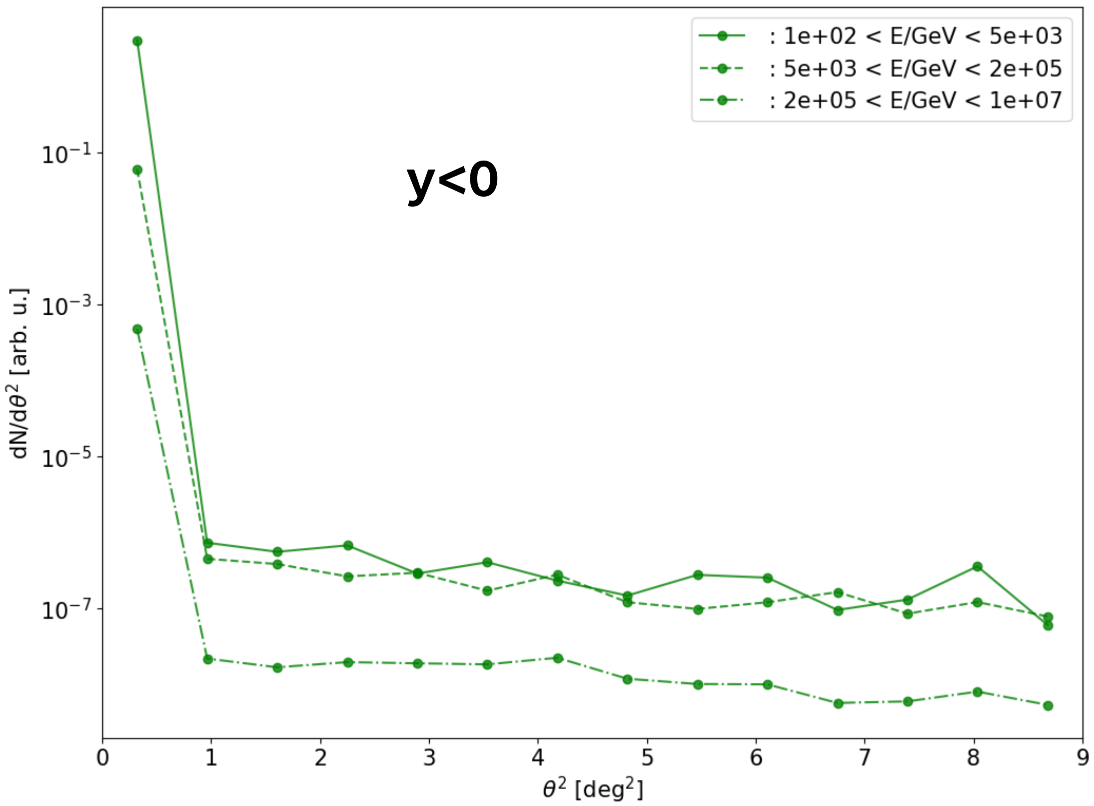
200TeV<E<100PeV





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≶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 ≳**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

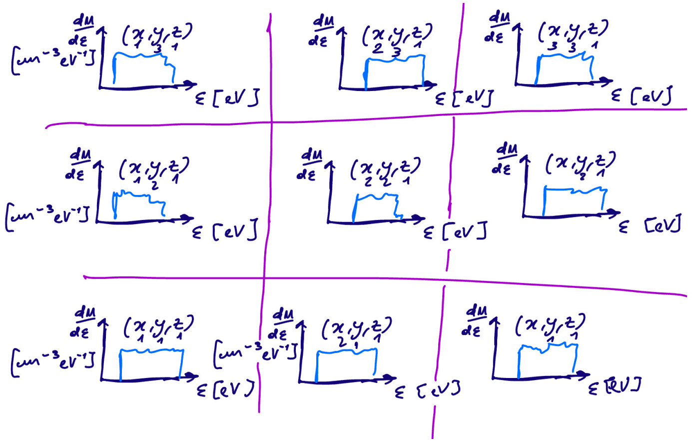
+ shape slightly position-dependent (comparing y≶0 cases)

❖ gamma rays between few tens and 200 TeV mainly contributes to the haloes

perspectives

❖ in CRPropa:

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



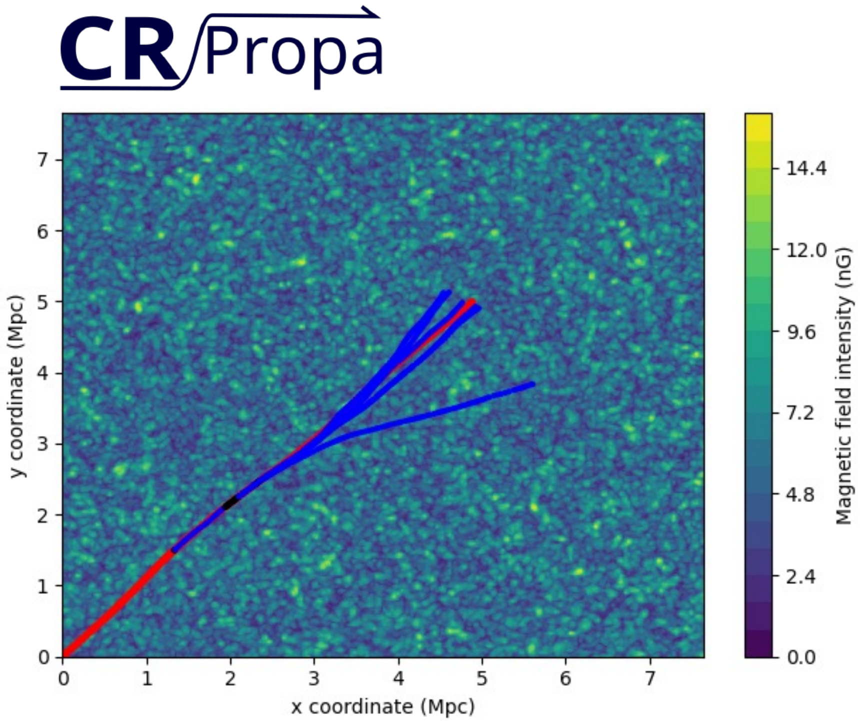
❖ in science:

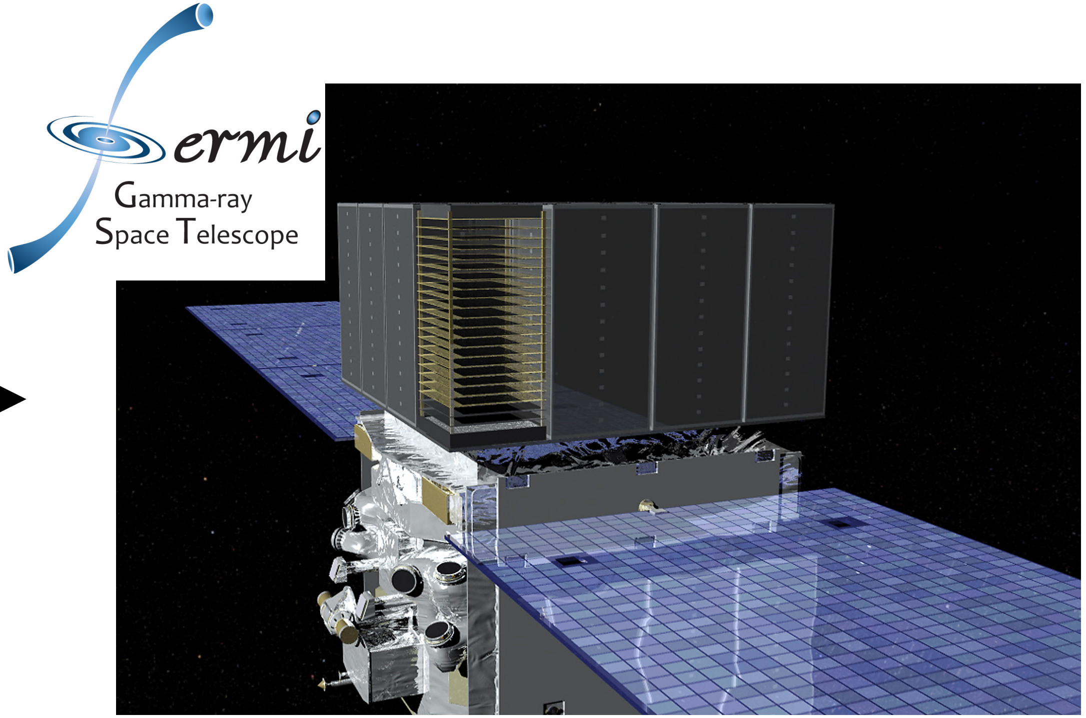
➢ role of **synchrotron** energy losses in the EM cascades?

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

➢ revision of galactic gamma-ray propagation?

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





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

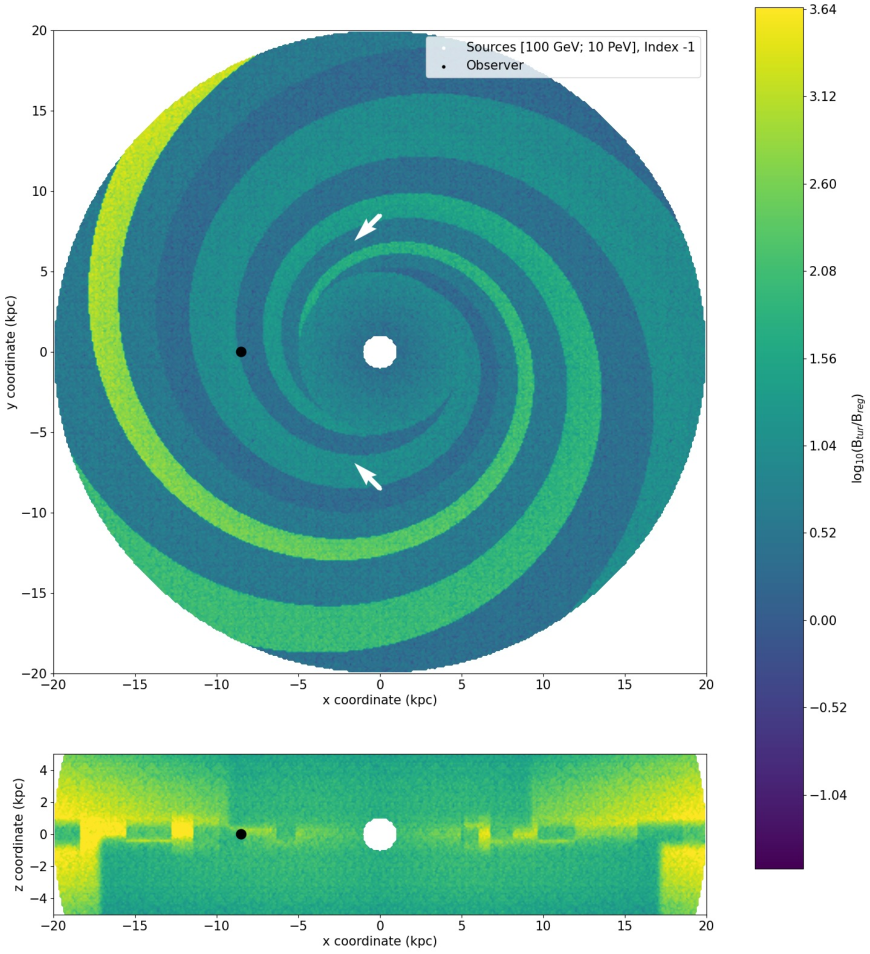
+ to constrain propagation **properties with gamma-ray data** (spectral distortion, spatial morphology...)

thanks!

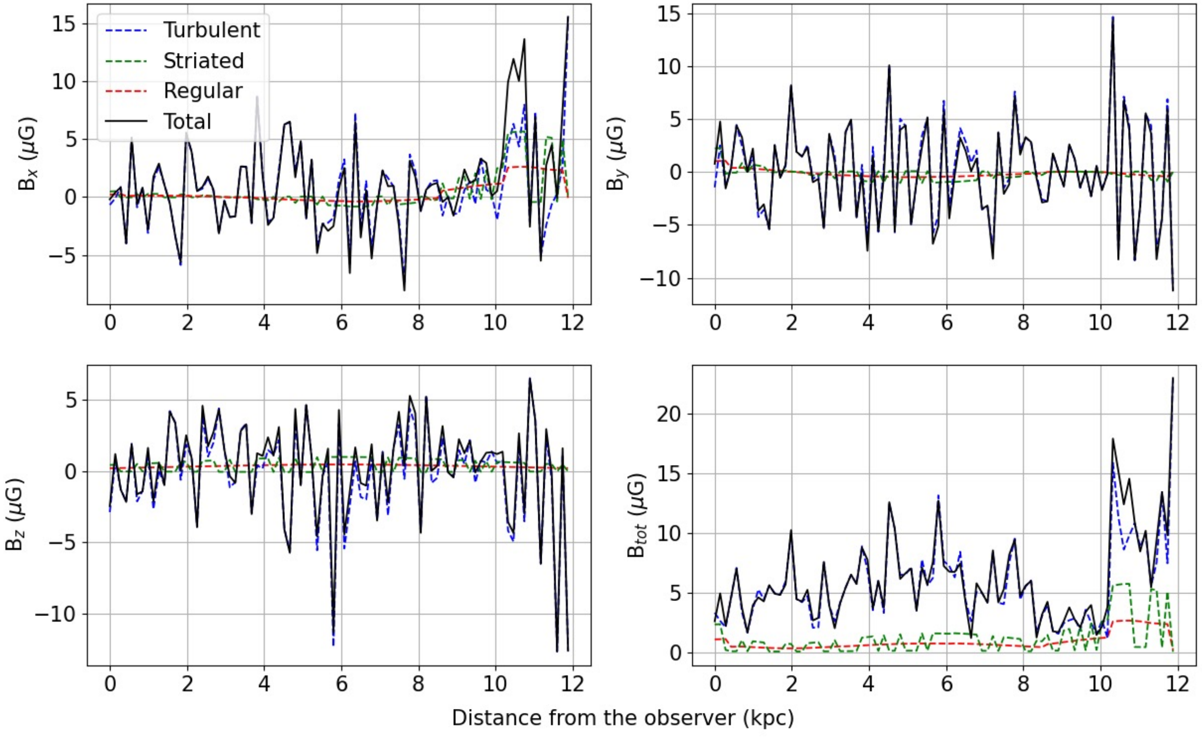
questions? comments?

backup...

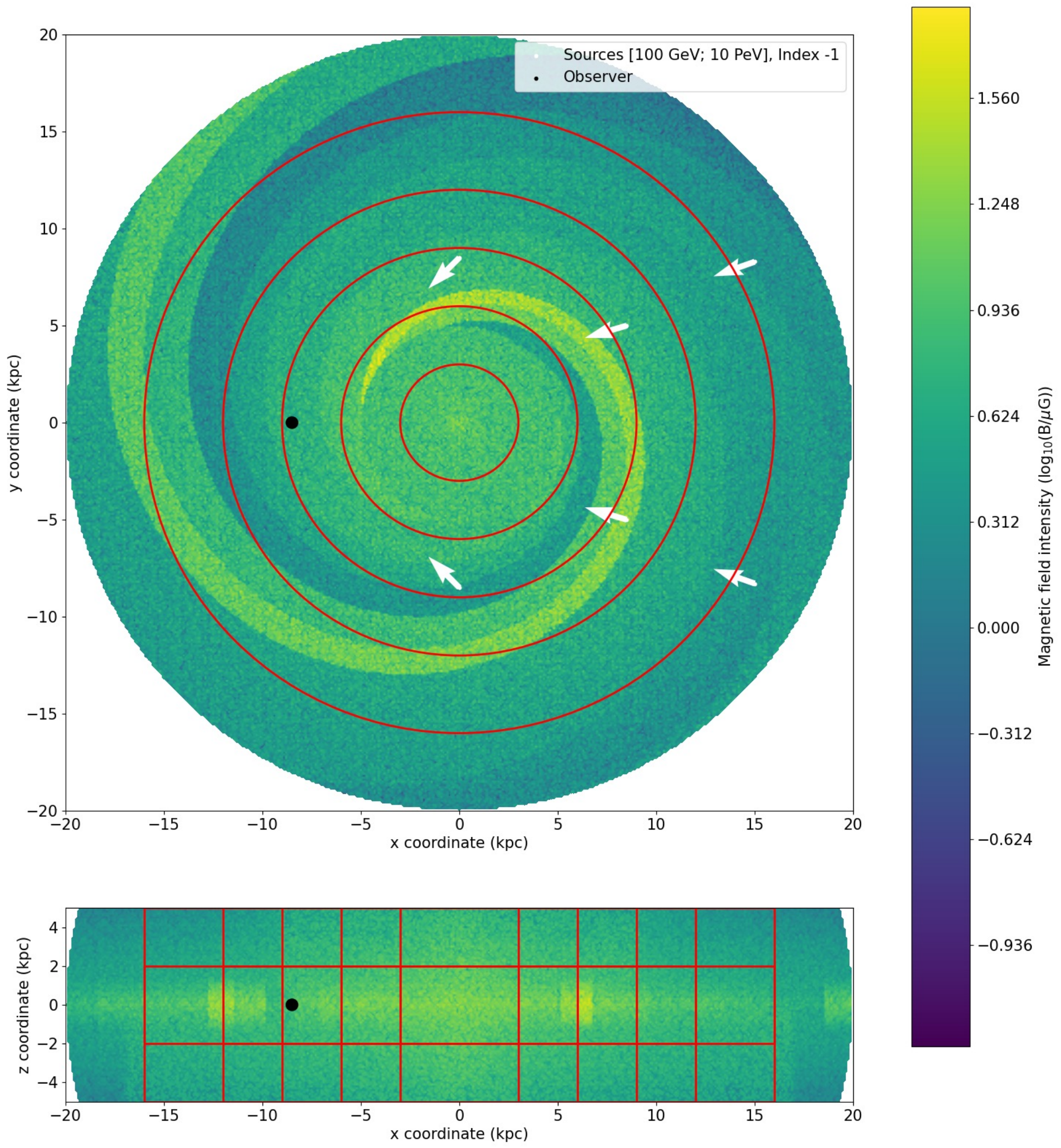
regular *vs* turbulent



along the l. o. s.



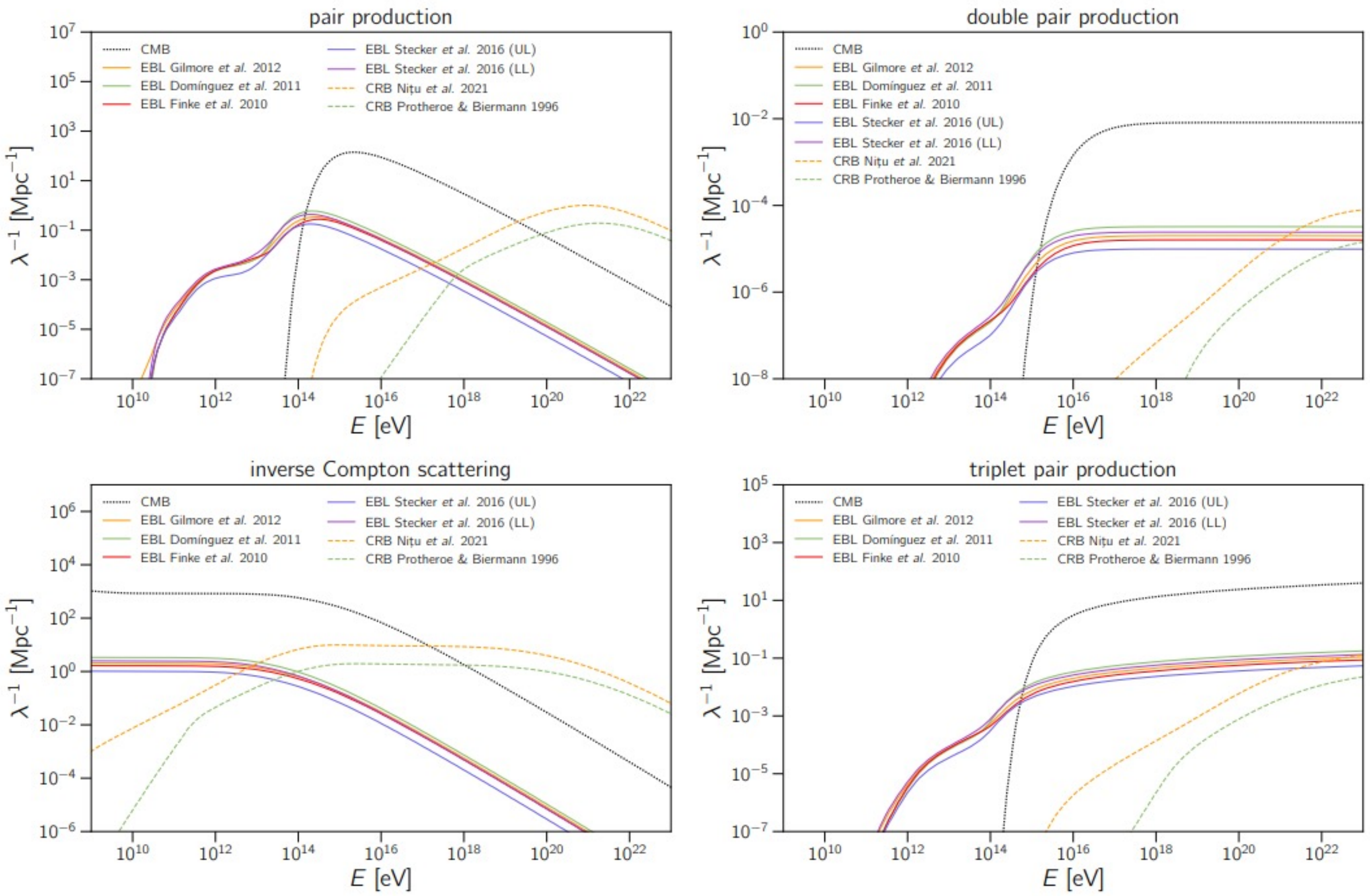
restrictToRegion_v2



Cylindrical (/Cylindrical hollowed) customized surfaces:

- easy to implement in python

- too expensive computationally



(Alves Batista & Saveliev, 2021)

last scattering plot