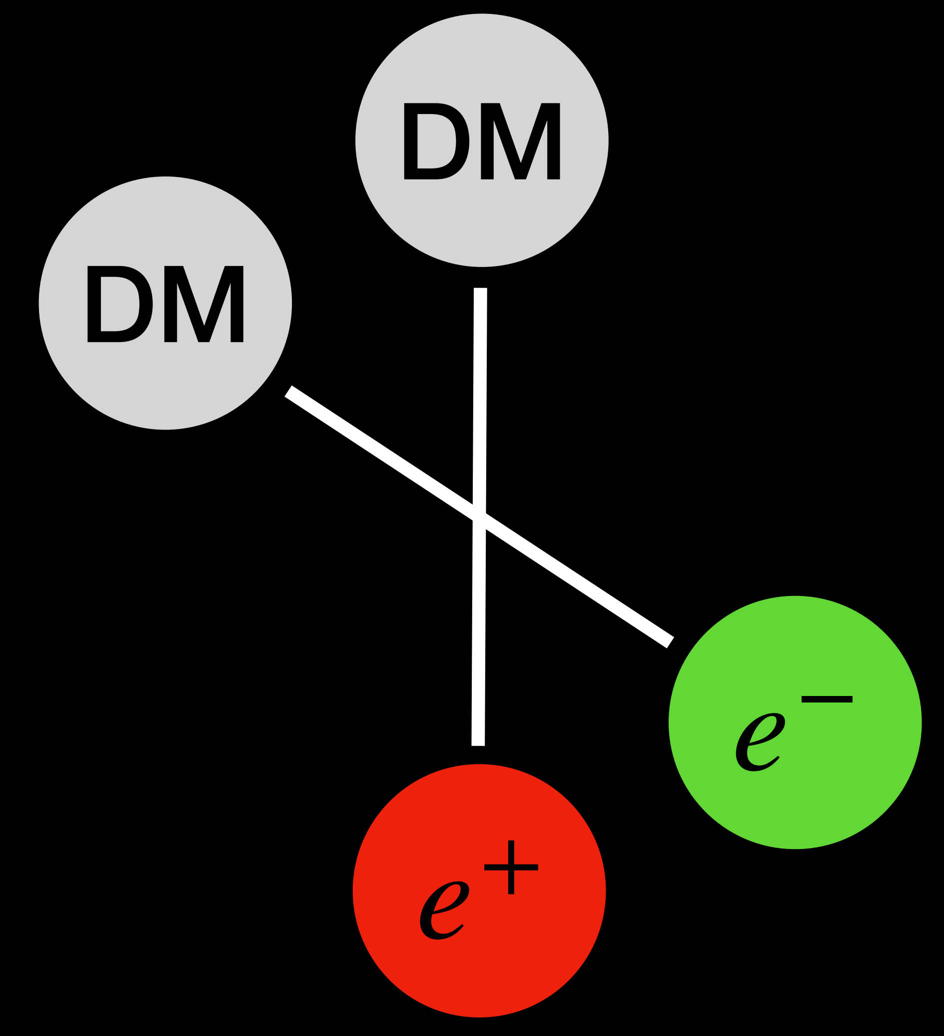
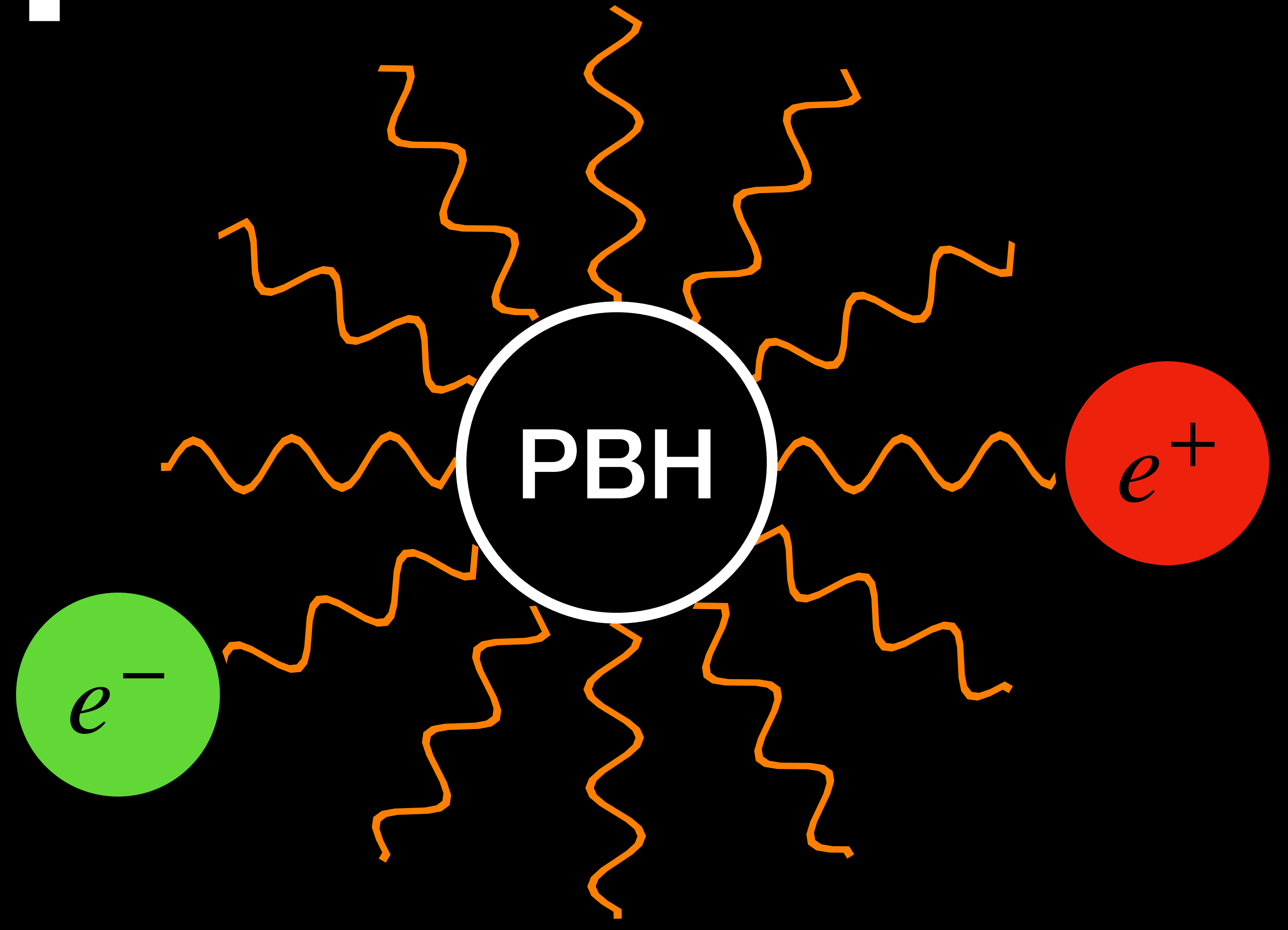
DRAGON School

Cosmic-ray theory, phenomenology, and beyond



Dark matter signals with DRAGON and HERMES

Hands-on session



Jordan Koechler (INFN Turin)

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Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

INFN TORINO

First things first…

Go to:

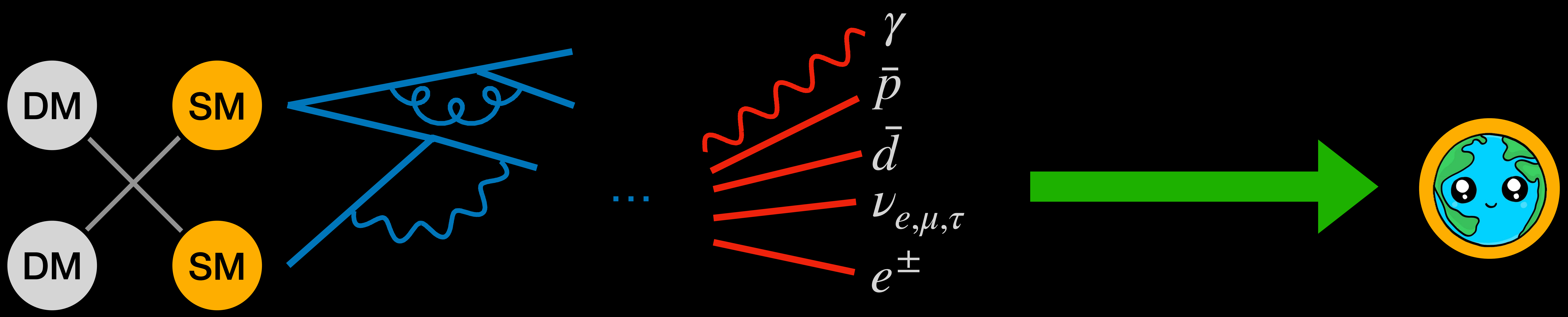
https://github.com/JordanKoechler/DRAGON-School-2025_HandsOn-DarkMatter

DRAGON/HERMES inputs, outputs

$e^{\pm}$ injection spectra for DRAGON

Some data and scripts…

Dark matter indirect detection



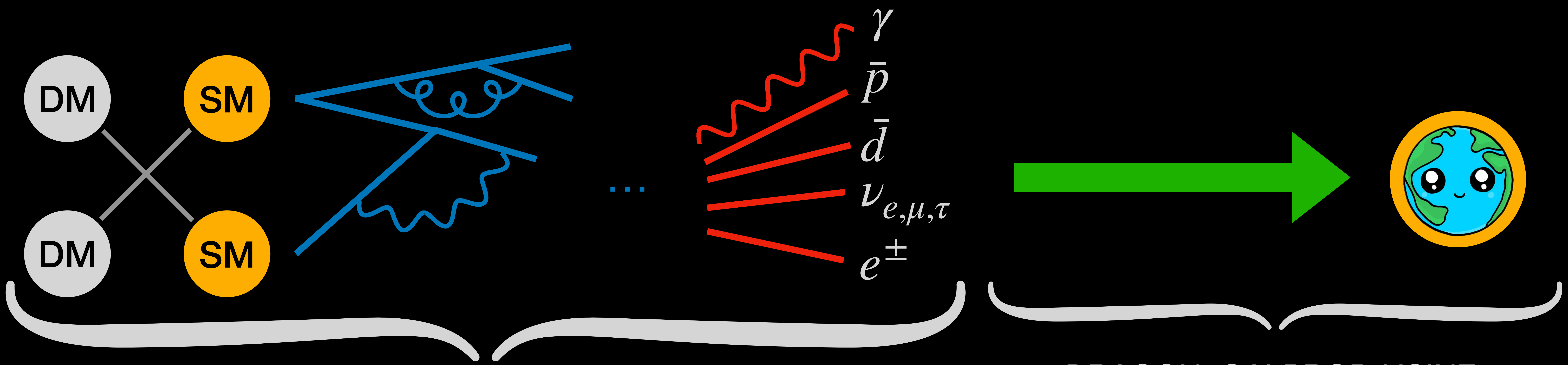
Annihilation (or decay)

Decay, hadronisation, coalescence, …

Stable particle flux

Propagation in the (extra-)galactic medium

Dark matter indirect detection



HDMSpectra: 500 GeV $< m_{DM} < M_{Pl}$

PPPC4DMID, CosmiXs: 5 GeV $< m_{DM} <$ 100 TeV

Hazma: $m_{DM} < 1$ GeV

Sometimes analytically…

DRAGON, GALPROP, USINE, HERMES, …

DM $\rightarrow \ldots \rightarrow \gamma$

DM $\rightarrow \ldots \rightarrow \gamma$

Differential flux of DM-produced photons

$$\frac{d\Phi_\gamma}{dE_\gamma d\Omega} = \frac{1}{4\pi}\frac{dN_\gamma}{dE_\gamma} \times \begin{cases} \dfrac{1}{2}\dfrac{\langle \sigma v \rangle}{m_{DM}^2}\displaystyle\int_{l.o.s.} \rho_{DM}^2(r,\Omega)\, ds & \text{(annihilation)} \\ \dfrac{\Gamma}{m_{DM}}\displaystyle\int_{l.o.s.} \rho_{DM}(r,\Omega)\, ds & \text{(decay)} \end{cases}$$

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e.g., PPPC4DMID

DM $\to \ldots \to \gamma$

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Free parameters

DM $\rightarrow \ldots \rightarrow \gamma$

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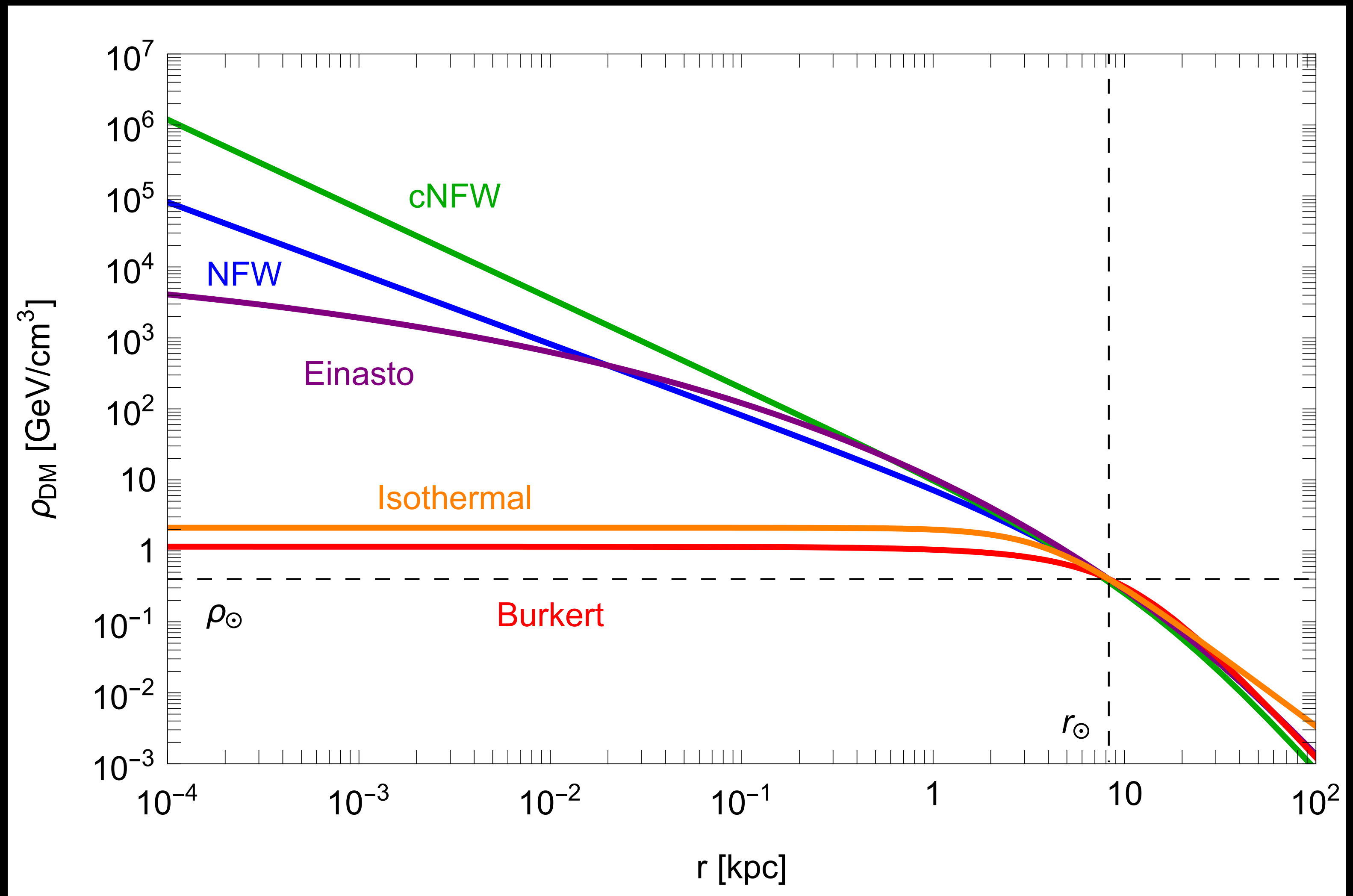
Free parameters

DM density profile



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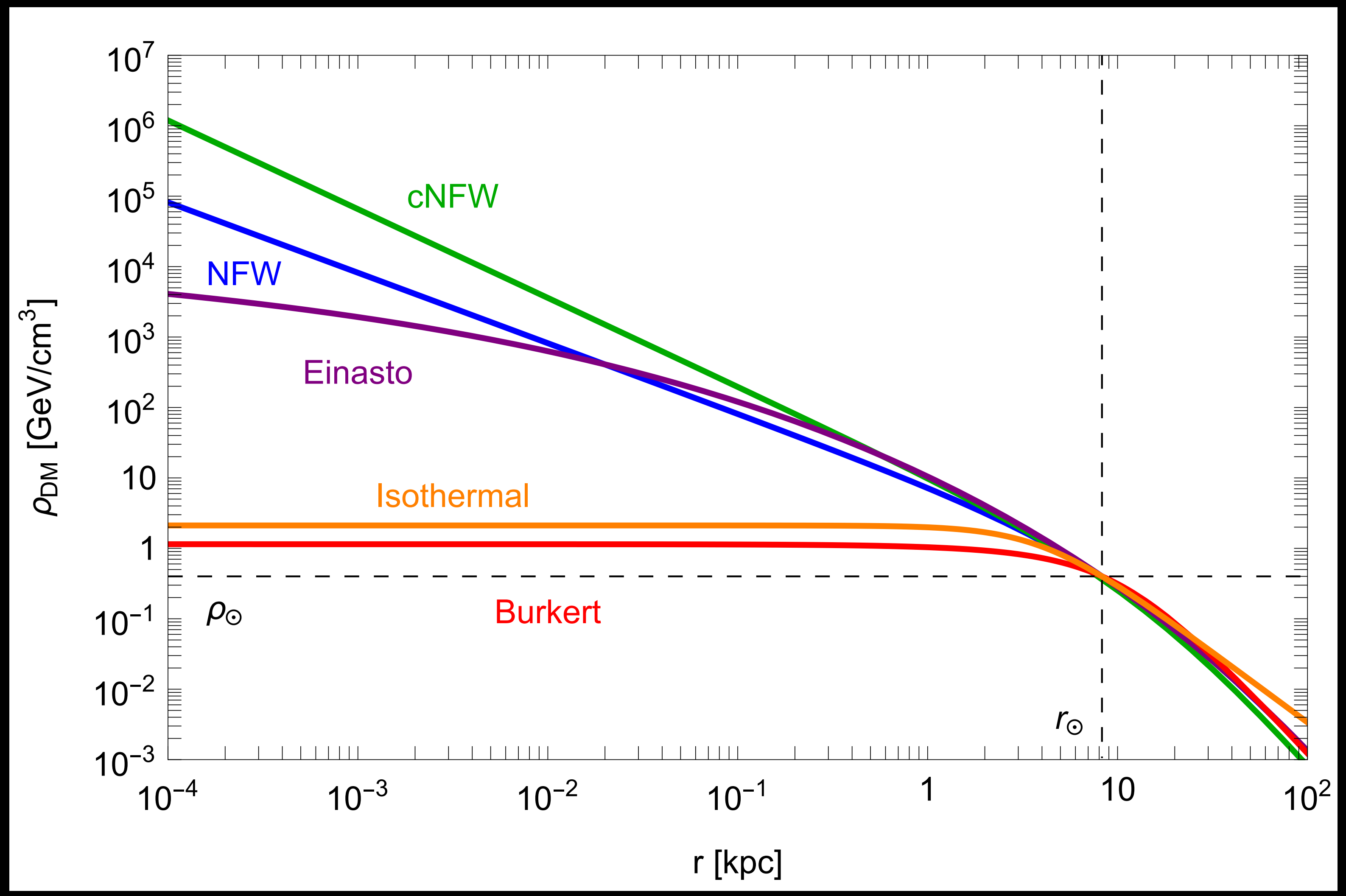
HERMES can do this computation using PPPC4DMID tables and the gNFW profile



$$\mathbf{DM} \rightarrow \ldots \rightarrow \gamma$$

DM density profile

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darkmatter.NFWGProfile(gamma, concentration, M_200)
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$$= 4\pi \int_0^{r_{200}} r^2 \rho_{gNFW}(r)\, dr \qquad c = \frac{r_{200}}{r_s}$$

r_{200} : radius for which the average DM density is $200\rho_c$

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DM annihilation spectrum

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Allowed primaries:

$e^+e^-, \mu^+\mu^-, \tau^+\tau^-$	e, mu, tau
$q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}$	q, c, b, t
W^+W^-, Z^0Z^0, hh	W, Z, h

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Allowed m_{DM} range:

5 GeV – 100 TeV (annihilation)

10 GeV – 200 TeV (decay)

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Allowed m_{DM} range:

5 GeV – 100 TeV (annihilation)
10 GeV – 200 TeV (decay)

For decaying DM, take the DM annihilation spectra for $m_{DM}/2$

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Allowed m_{DM} range:

5 GeV – 100 TeV (annihilation)
10 GeV – 200 TeV (decay)

Integrator:
```
DarkMatterIntegrator(darkmatter.DarkMatterSpectrum, darkmatter.GalacticProfile)
```

DM $\rightarrow \ldots \rightarrow \gamma$

Exercice: γ-ray galactic centre excess explained by DM?

- Step 1: run the HERMES_DMgamma.py script $t \sim 10$ s

DM DM $\rightarrow b\bar{b} \rightarrow \ldots \rightarrow \gamma$ for $m_{DM} = 40$ GeV

DM $\rightarrow \ldots \rightarrow \gamma$

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- Step 2: run the GCE_spec.py script

Extract the flux from a $40^\circ \times 40^\circ$ region
Compare it to Fermi-LAT data of the GCE
(background subtracted)

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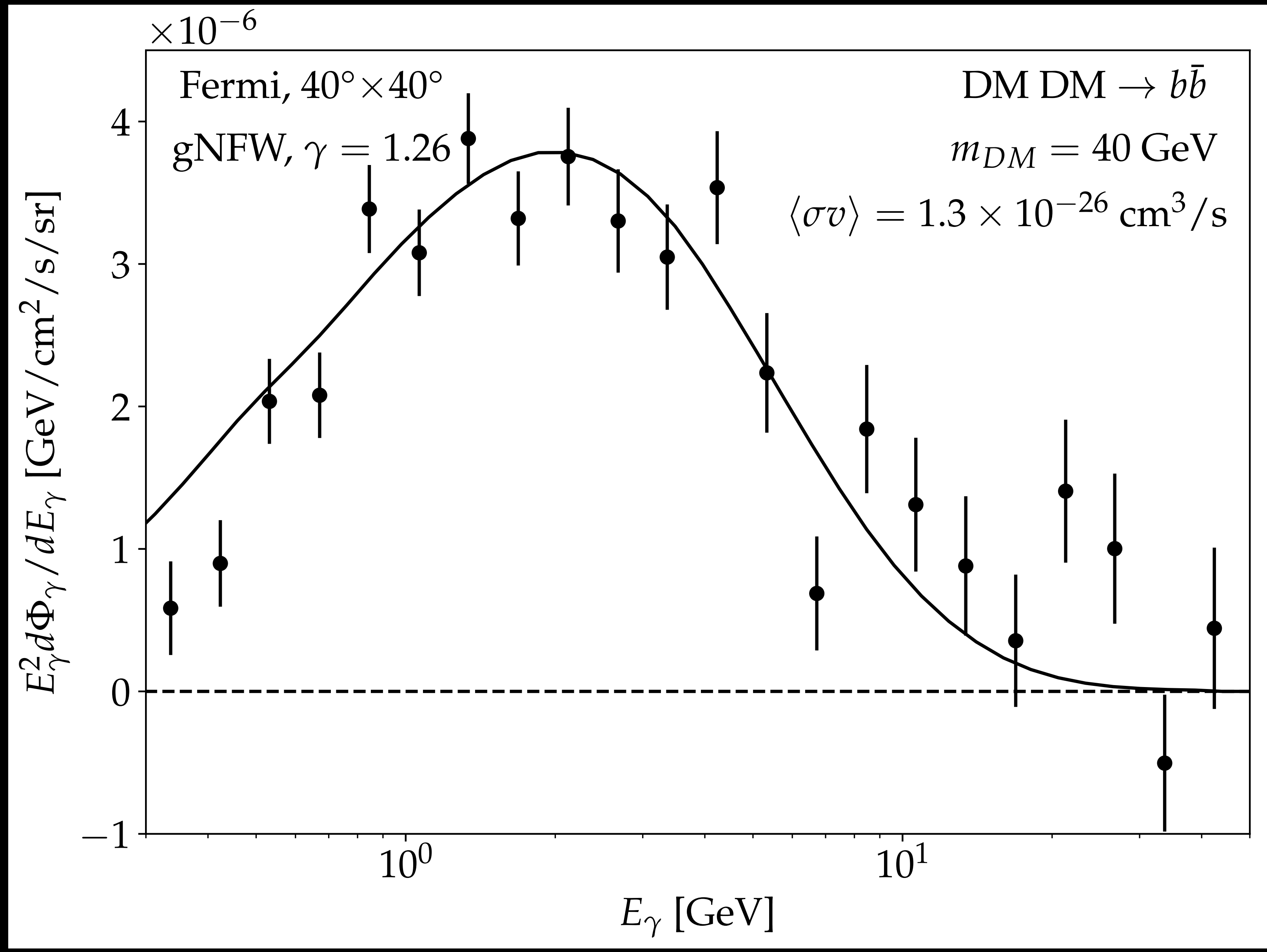

DM $\rightarrow \ldots \rightarrow e^{\pm}$

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$\mathbf{DM} \rightarrow \ldots \rightarrow e^{\pm}$

DM $\rightarrow \ldots \rightarrow e^{\pm}$ (cosmic-rays)

Diffusion-loss equation for DM-produced $e^{\pm}$:

$$\vec{\nabla}\left(D\,\vec{\nabla} f_{e^{\pm}} - \vec{v}_c f_{e^{\pm}}\right) + \frac{\partial}{\partial K_e}\left(b_{loss} f_{e^{\pm}} + \beta^2 D_{pp} \frac{\partial f_{e^{\pm}}}{\partial K_e}\right) + Q_{e^{\pm}}^{DM} = 0$$

spatial diffusion | convection | energy losses | momentum space diffusion | source

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$$D = D_0 \beta^n \frac{(R/R_0)^{\delta}}{\left[1 + (R/R_0)^{\Delta\delta/s}\right]^s}$$

(broken power-law)

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$$D_{pp} = \frac{4}{3}\frac{1}{\delta(4-\delta^2)(4-\delta)}\frac{v_A^2 p^2}{D}$$

(Alfvénic turbulence)

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spatial diffusion | convection | energy losses | momentum space diffusion | source

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Transport parameters ($D_0, \eta, R_0, \delta, \Delta\delta, s, v_A, L$) are set using CR fits

DM $\to \ldots \to e^{\pm}$ (cosmic-rays)

Source term (injection of DM-produced $e^{\pm}$):

$$Q_{e^{\pm}}^{DM}(E_e, \vec{x}) = \begin{cases} \dfrac{\langle \sigma v \rangle}{2} \left(\dfrac{\rho_{DM}(\vec{x})}{m_{DM}} \right)^2 \dfrac{dN_{e^{\pm}}}{dE_e} & \text{(annihilation)} \\ \Gamma \left(\dfrac{\rho_{DM}(\vec{x})}{m_{DM}} \right) \dfrac{dN_{e^{\pm}}}{dE_e} & \text{(decay)} \end{cases}$$

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$e^{\pm}$ injection spectrum

injec_spec/mm_105.7MeV_ann.txt
injec_spec/mm_1GeV_ann.txt

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DM DM $\rightarrow \mu^+\mu^-$: boosted Michel spectrum (DM $\rightarrow \mu^{\pm} \rightarrow e^{\pm}$)

Computed analytically (for $m_{DM} < 1$ GeV)

DM $\rightarrow \ldots \rightarrow e^{\pm}$ (cosmic-rays)

An important block of the input .xml file for DRAGON: <DarkMatter>

```
<DarkMatter Reaction="Annihilation" Model="SelfTable" Profile="NFW">
  <PropDMLepton />
  <Mass value="1" />                <!-- DM mass in GeV -->
  <SigmaV value="1e-26" />          <!-- DM annihilation cross section in cm3/s -->
  <SSDensity value="0.4" />         <!-- DM local energy density in GeV/cm^3 -->
  <LeptonDatafile value=« /Users/jordankoechler/Desktop/DRAGON_School/injec_spec/mm_1GeV_ann.txt" />
  <!-- File containing the e+e- spectrum from DM annihilation -->
</DarkMatter>
```

DM profiles: {NFW, ISO, Kra, Moore, Einasto}

```
<DarkMatter Reaction="Decay" Model="SelfTable" Profile="NFW">
  <PropDMLepton />
  <Mass value="1" />                <!-- DM mass in GeV -->
  <LifeTime value="1e26" />         <!-- DM lifetime in s -->
  <SSDensity value="0.4" />         <!-- DM local energy density in GeV/cm^3 -->
  <LeptonDatafile value=« /Users/jordankoechler/Desktop/DRAGON_School/injec_spec/mm_1GeV_dec.txt" />
  <!-- File containing the e+e- spectrum from DM decay -->
</DarkMatter>
```

DM $\rightarrow \ldots \rightarrow e^{\pm}$ (cosmic-rays)

Exercice: Effects of reacceleration (Alfvén speed)

- Step 1: Move the .xml files in the DRAGON_input directory to the dragon-3.1.0/examples

DM $\to \ldots \to e^{\pm}$ (cosmic-rays)

Exercice: Effects of reacceleration (Alfvén speed)

- Step 1: Move the .xml files in the DRAGON_input directory to the dragon-3.1.0/examples
- Step 2: Launch DRAGON with the run_2D_DMe_NFW_ann.xml file in the case of DM DM $\to \mu^+\mu^-$ for $m_{DM} = 1$ GeV

./DRAGON examples/run_2D_DMe_NFW_ann.xml $t \sim 100$ s

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- Step 3: Change v_A to 0 km/s in the <Reacceleration> sub-block and re-run

```
<Reacceleration type="Ptuskin94">
 <vA_kms value="13.4" />
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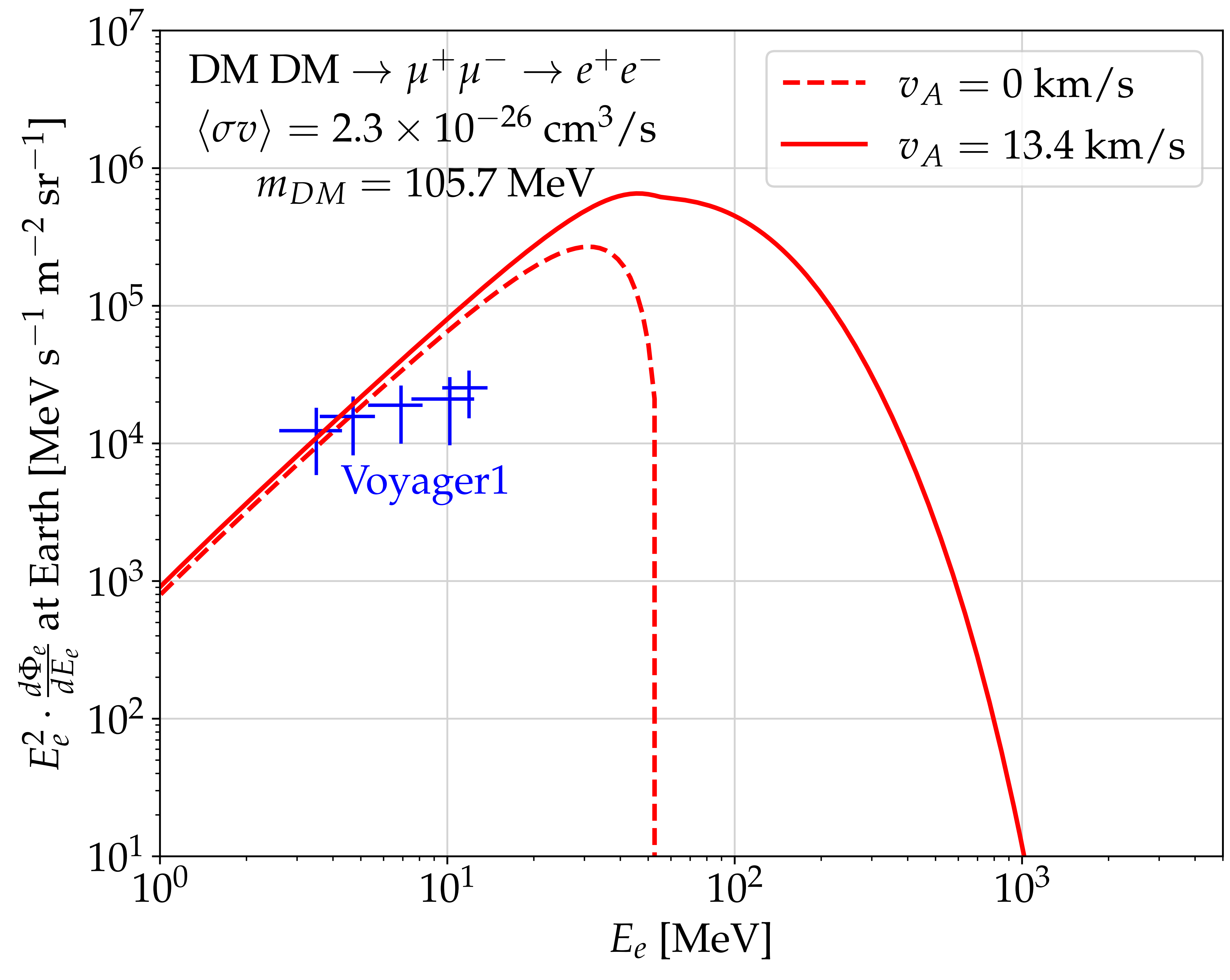
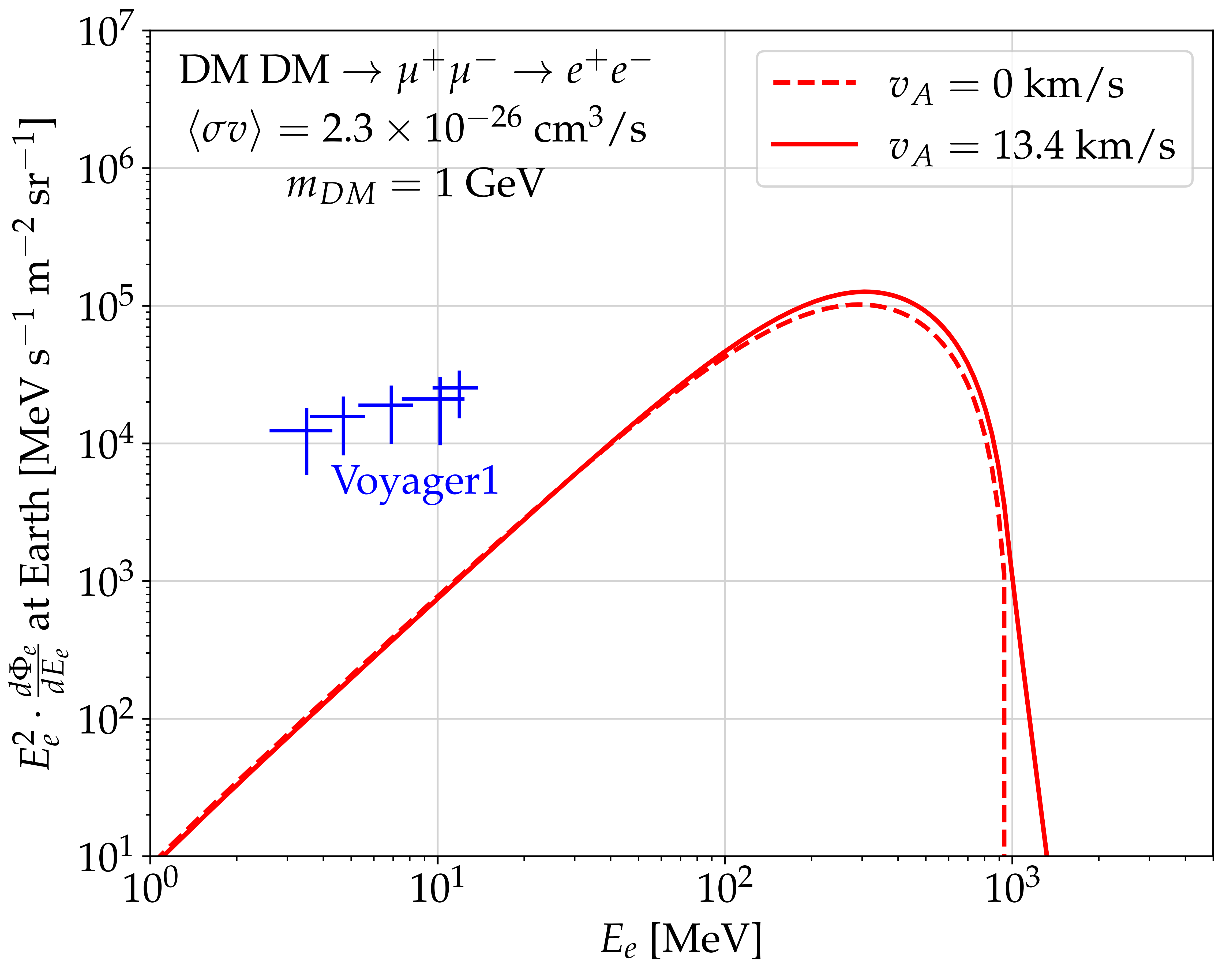
- Step 4: Re-run the two v_A cases for $m_{DM} = m_\mu = 105.7$ MeV
- Step 5: Run the extract_DRAGONfits.py script to plot the DM-produced $e^{\pm}$ flux at Earth

DM $\to \ldots \to e^{\pm}$ (cosmic-rays)





DM $\rightarrow \ldots \rightarrow e^{\pm}$ (secondary γ)

Differential flux of photons from secondary emissions:

$$\frac{d\Phi_\gamma^{sec}}{dE_\gamma d\Omega} = \frac{1}{E_\gamma}\int_{l.o.s.} ds \, \frac{j_{sec}(E_\gamma, \vec{x})}{4\pi}$$

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$$j_{sec}(E_\gamma, \vec{x}) = 2\int_{m_e}^{m_{DM}(/2)} dE_e \; \mathscr{P}_{sec}(E_\gamma, E_e, \vec{x})\, f_{e^\pm}(E_e, \vec{x})$$

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Radiating power

Density of DM-produced $e^{\pm}$ (DRAGON)

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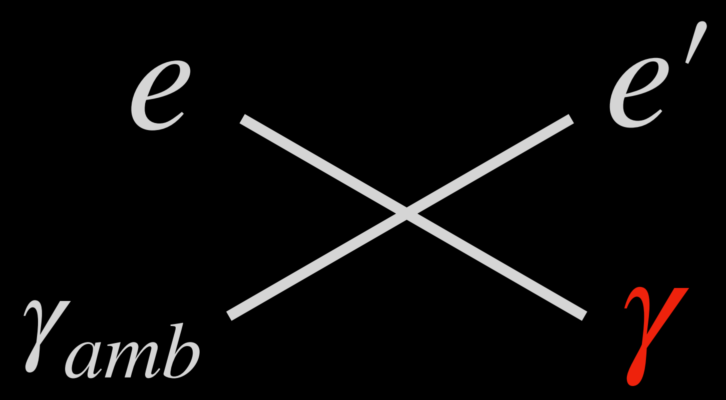
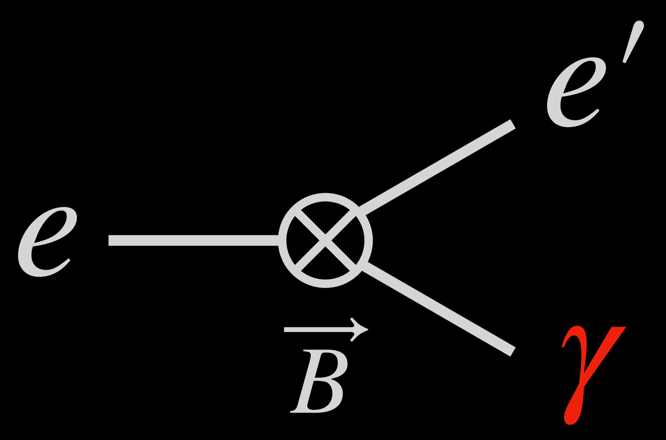
Radiating power

Density of DM-produced $e^{\pm}$ (DRAGON)

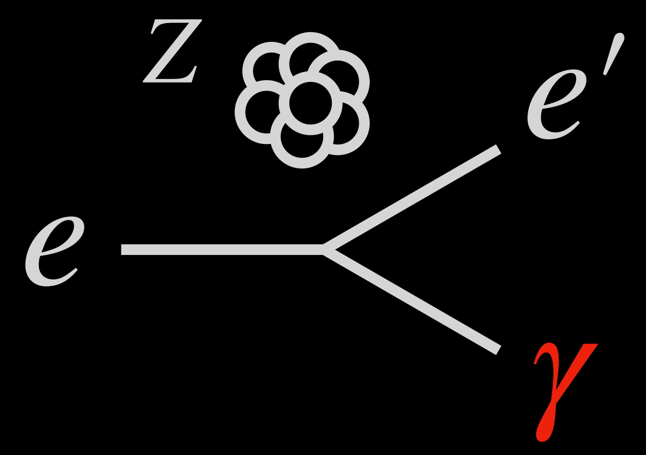
Inverse-Compton scattering



Synchrotron

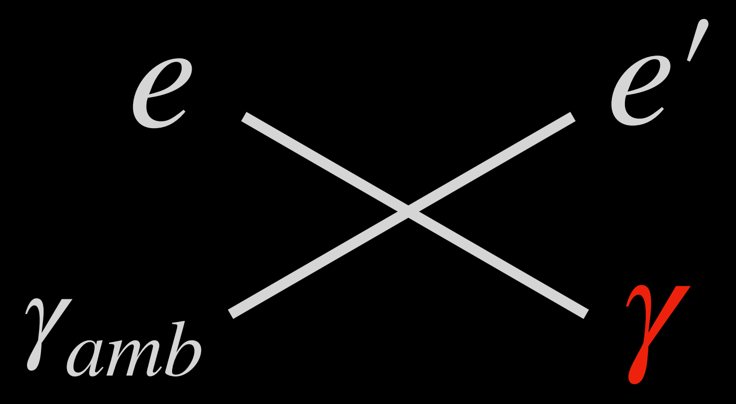


Bremsstrahlung



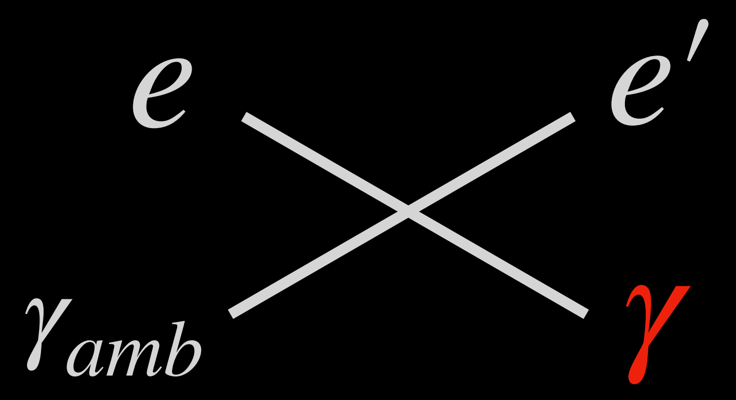
DM $\rightarrow \ldots \rightarrow e^{\pm}$ (secondary γ)

Inverse-Compton scattering



Implementation in HERMES

Inverse-Compton scattering



DM $\rightarrow \ldots \rightarrow e^{\pm}$ (secondary γ)

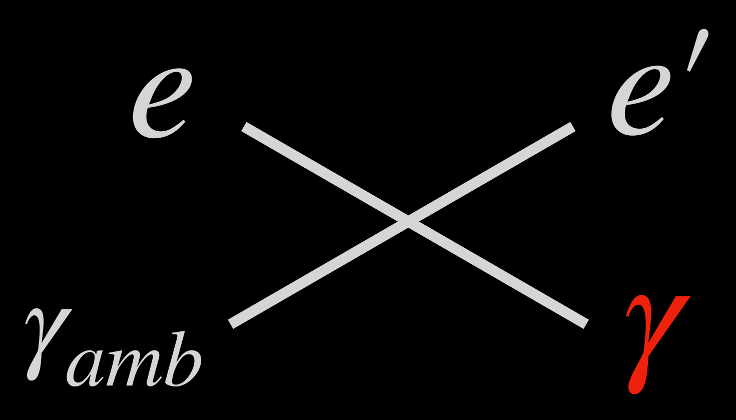
Implementation in HERMES

Integrator

```
InverseComptonIntegrator(cosmicrays.CosmicRayDensity, photonfields.PhotonField, interactions.DifferentialCrossSection)
```

DM $\rightarrow \ldots \rightarrow e^{\pm}$ (secondary γ)

Inverse-Compton scattering



Implementation in HERMES

Integrator

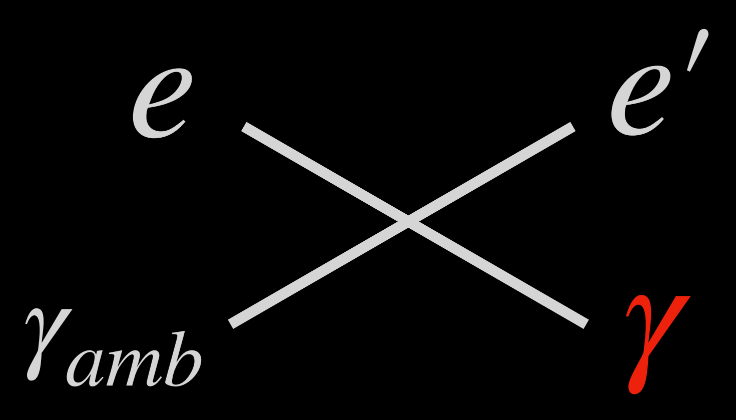
```
InverseComptonIntegrator(cosmicrays.CosmicRayDensity, photonfields.PhotonField, interactions.DifferentialCrossSection)
```

```
cosmicrays.Dragon2D(filename, [Electron, Positron])
```

Lepton map
from DRAGON

DM $\rightarrow \ldots \rightarrow e^{\pm}$ (secondary γ)

Inverse-Compton scattering



Implementation in HERMES

```
photonfields.CMB()
photonfields.ISRF()
```

Ambient photon fields

Integrator

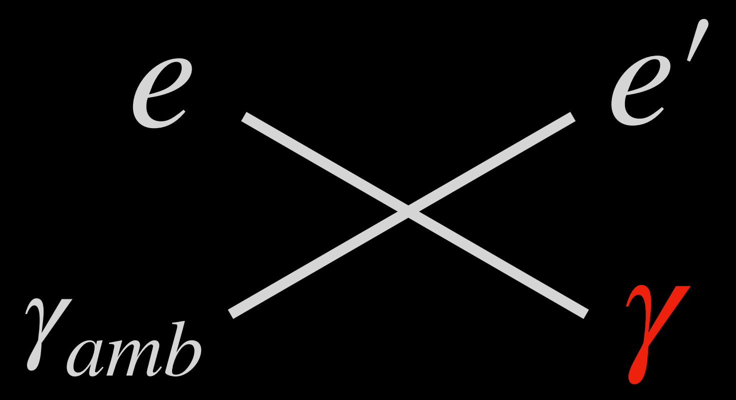
```
InverseComptonIntegrator(cosmicrays.CosmicRayDensity, photonfields.PhotonField, interactions.DifferentialCrossSection)
```

```
cosmicrays.Dragon2D(filename, [Electron, Positron])
```

Lepton map from DRAGON

DM $\rightarrow \ldots \rightarrow e^{\pm}$ (secondary γ)

Inverse-Compton scattering



Implementation in HERMES

Integrator

```
InverseComptonIntegrator(cosmicrays.CosmicRayDensity, photonfields.PhotonField, interactions.DifferentialCrossSection)
```

```
photonfields.CMB()
photonfields.ISRF()
```

Ambient photon fields

```
cosmicrays.Dragon2D(filename, [Electron, Positron])
```

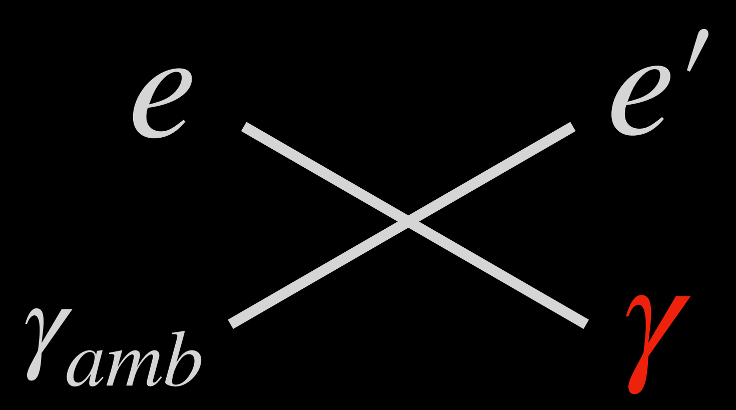
Lepton map from DRAGON

```
interactions.KleinNishina()
```

Klein-Nishina cross-section

DM $\rightarrow \ldots \rightarrow e^{\pm}$ (secondary γ)

Inverse-Compton scattering



Implementation in HERMES

```
photonfields.CMB()
photonfields.ISRF()
```

Ambient photon fields

Integrator

```
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```

```
cosmicrays.Dragon2D(filename, [Electron, Positron])
```

Lepton map from DRAGON

```
interactions.KleinNishina()
```

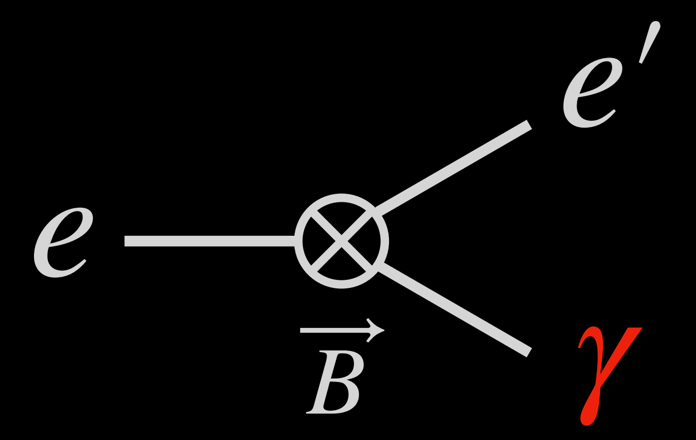
Klein-Nishina cross-section

And as always:

```
skymap_range = GammaSkymapRange(nside, MinEnergy, MaxEnergy, E_points)
skymap_range.setIntegrator(Integrator)
skymap_range.compute()
```

DM $\rightarrow \ldots \rightarrow e^{\pm}$ (secondary γ)

Synchrotron



Implementation in HERMES

Integrator

```
SynchroIntegrator(magneticfields.MagneticField, cosmicrays.CosmicRayDensity)
```

```
magneticfields.UniformMagneticField(Vector3QMField(Bx, By, Bz))
magneticfields.MagneticFieldList([MF1, MF2, …])
magneticfields.PT11(True, True, True)
. . .
```

Magnetic field model

```
cosmicrays.Dragon2D(filename, [Electron, Positron])
```

Lepton map
from DRAGON

And as always:

```
skymap_range = GammaSkymapRange(nside, MinEnergy, MaxEnergy, E_points)
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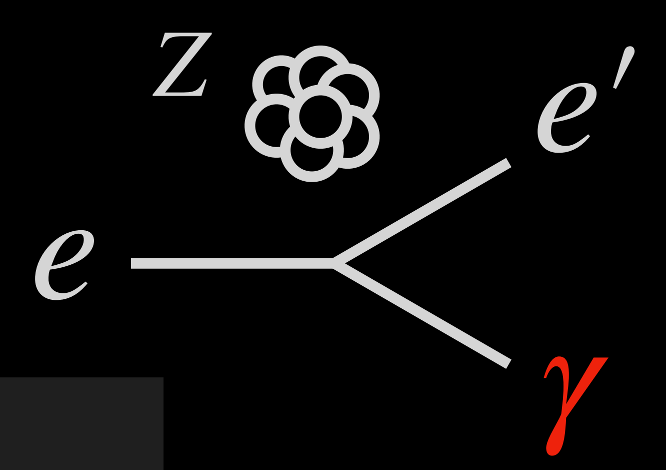
skymap_range.compute()
```

DM $\rightarrow \ldots \rightarrow e^{\pm}$ (secondary γ)

Bremsstrahlung



Implementation in HERMES

```
neutralgas.RingModel(neutralgas.GasType.HI)
neutralgas.RingModel(neutralgas.GasType.H2, XCOvalues)
```

HI and H2 maps

Integrator

```
BremsstrahlungIntegrator(cosmicrays.CosmicRayDensity, neutralgas.RingModel, interactions.BremsstrahlungAbstract)
```

```
cosmicrays.Dragon2D(filename, [Electron, Positron])
```

Lepton map
from DRAGON

```
interactions.BremsstrahlungTsai74()
interactions.BremsstrahlungGALPROP()
```

Bremsstrahlung
cross-section

And as always:

```
skymap_range = GammaSkymapRange(nside, MinEnergy, MaxEnergy, E_points)
skymap_range.setIntegrator(Integrator)
skymap_range.compute()
```

DM $\rightarrow \ldots \rightarrow e^{\pm}$ (secondary γ)

Exercice: Photon sky map of IC-scattered DM-produced $e^{\pm}$

- Step 1: run HERMES_IC_DMe.py, which computes the IC photon maps in the case of DM DM $\rightarrow \mu^+\mu^-$ for $m_{DM} = 1$ GeV (using the associated DM-produced $e^{\pm}$ maps computed with DRAGON)

$t \sim 15 \times 120$ s

DM $\rightarrow \ldots \rightarrow e^{\pm}$ (secondary γ)

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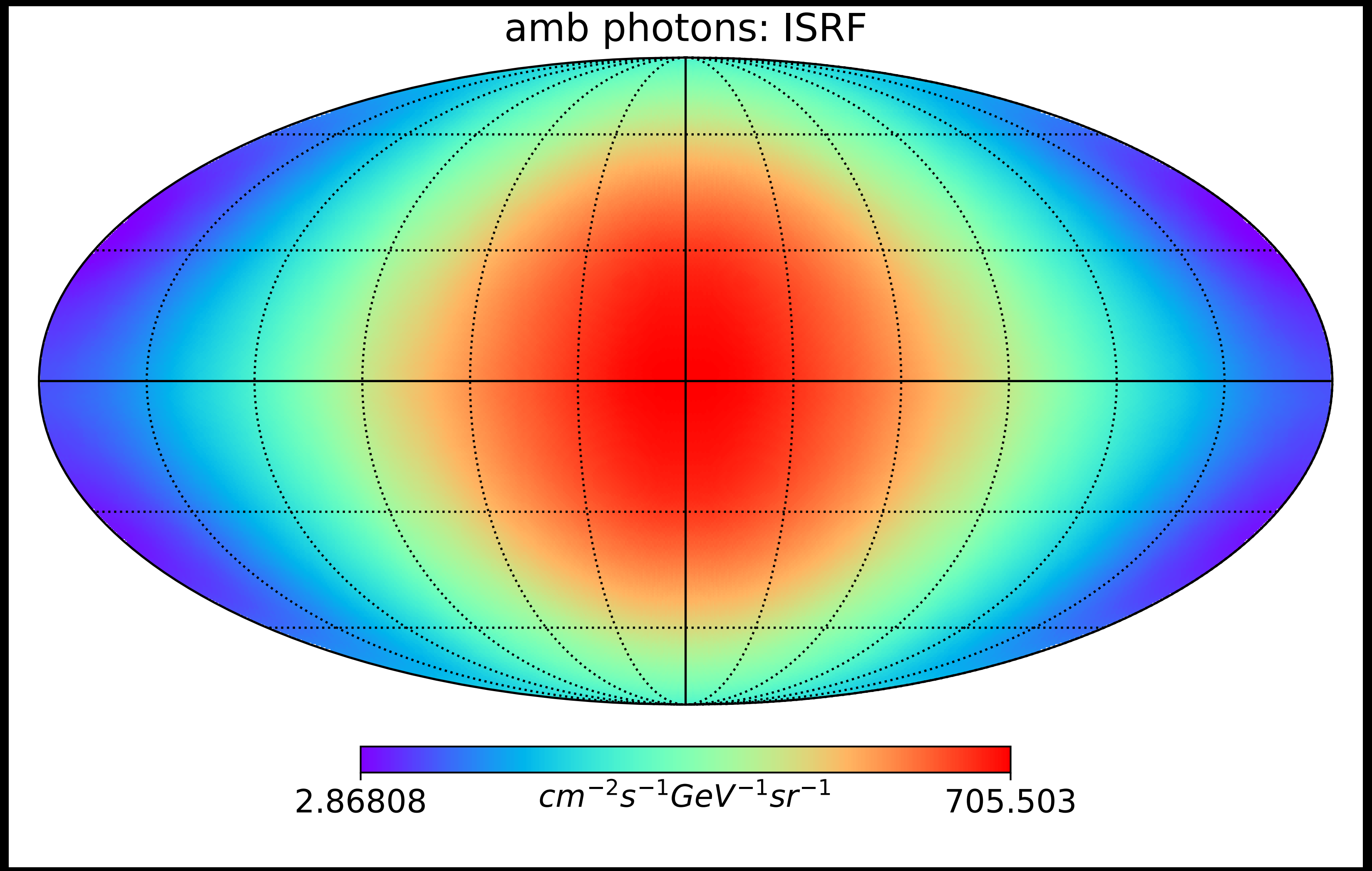

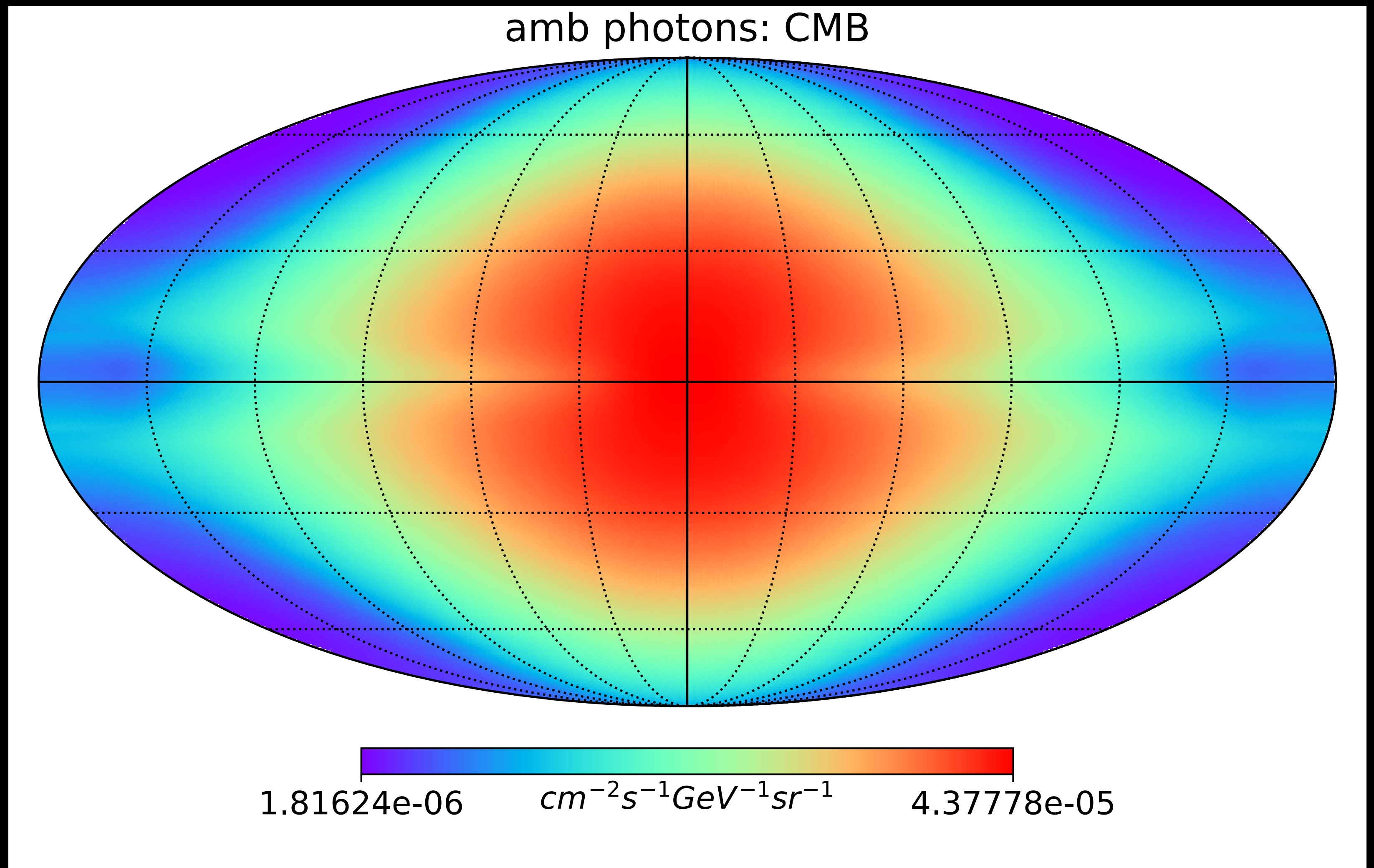

DM $\rightarrow \ldots \rightarrow e^{\pm}$ (secondary γ)

Exercice: Photon sky map of IC-scattered DM-produced $e^{\pm}$

- Step 3: run ICFlux_spec.py to see the IC photon flux compared to INTEGRAL data

DM $\rightarrow \ldots \rightarrow e^{\pm}$ (secondary γ)

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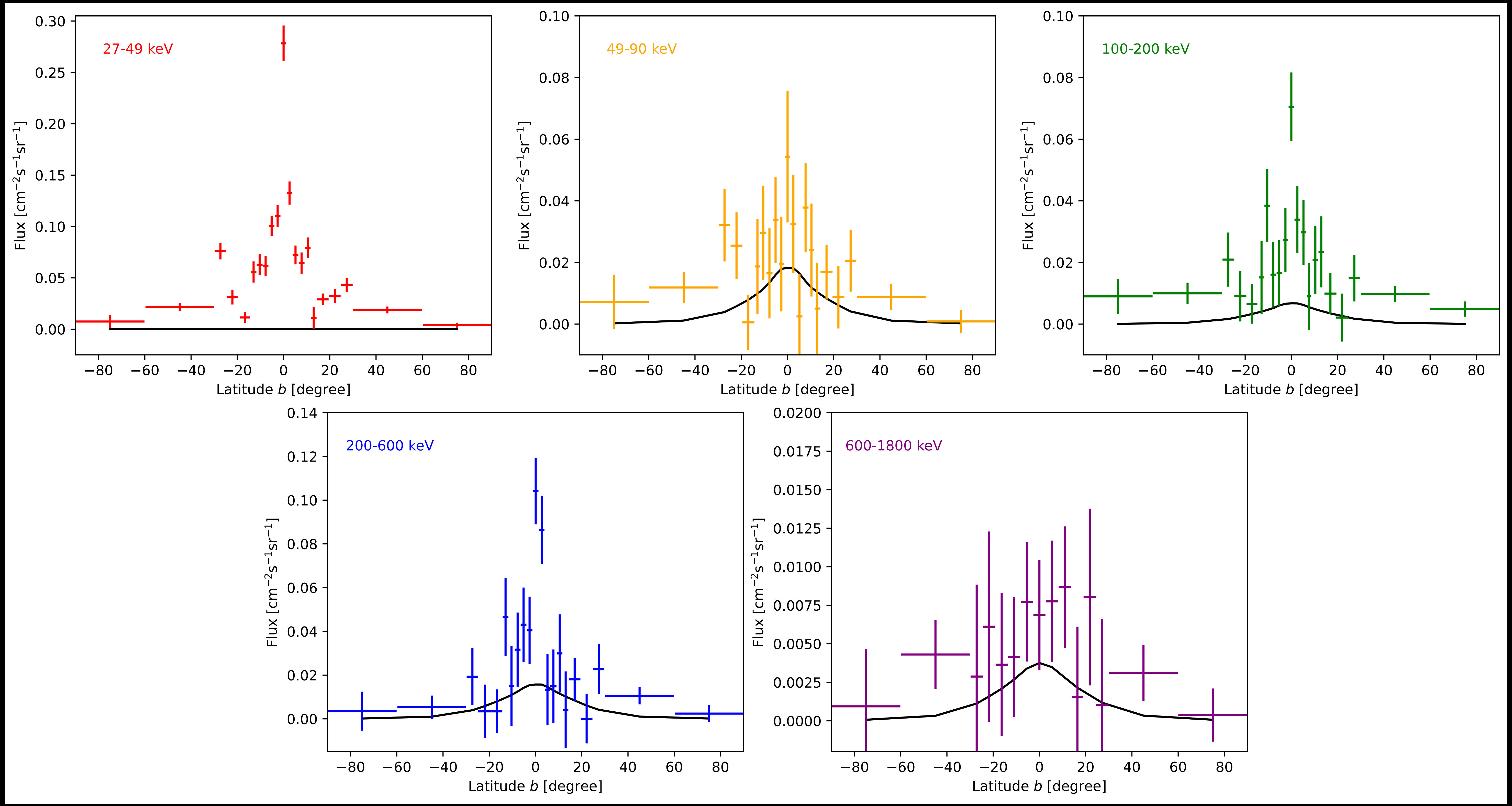
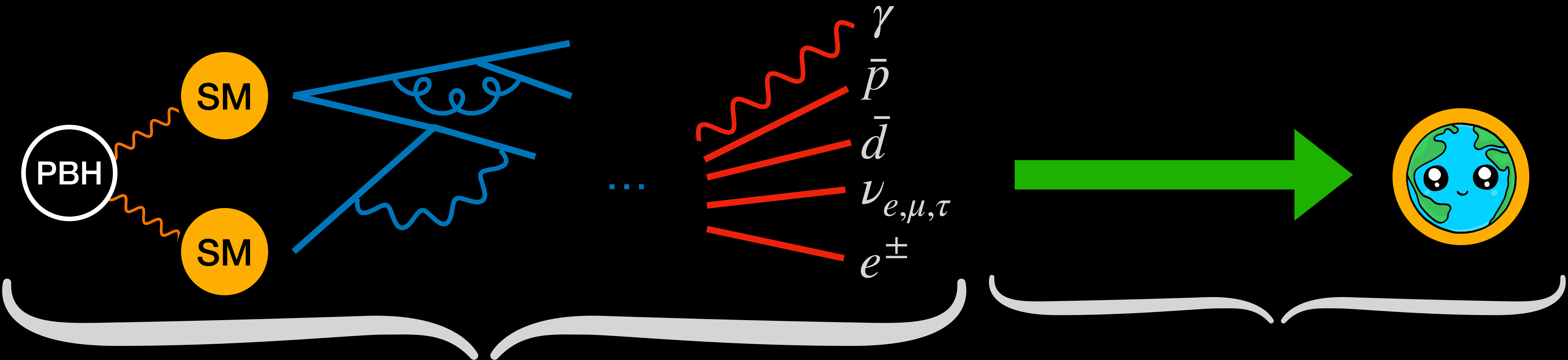


For $\langle \sigma v \rangle = 1 \times 10^{-27}$ cm^3/s

Thank for your attention!

PBH evaporation detection



DRAGON, GALPROP, USINE, HERMES, …

BlackHawk: $M_{BH} < M_{Pl}$

PBH $\to \ldots \to e^{\pm}$ (cosmic-rays)

Exercice: Adapting the .xml to PBH evaporation

- Try to write a .xml file in the case of PBH-evaporated $e^{\pm}$, knowing that the source term is:

$$Q_{e^{\pm}}^{PBH}(E_e, \vec{x}) = f_{PBH} \left(\frac{\rho_{DM}(\vec{x})}{M_{PBH}} \right) \frac{d^2 N_{e^{\pm}}}{dt dE_e}$$

PBH $\rightarrow \ldots \rightarrow e^{\pm}$ (cosmic-rays)

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$e^{\pm}$ injection spectrum

injec_spec/e_mBH_1e15g.txt
injec_spec/e_mBH_1e17g.txt

PBH $\to \ldots \to e^{\pm}$ (cosmic-rays)

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Hint: it looks similar to the DM decay one…

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$e^{\pm}$ injection spectrum

injec_spec/e_mBH_1e15g.txt
injec_spec/e_mBH_1e17g.txt

Hint: it looks similar to the DM decay one…

- Solution:

```
<DarkMatter Reaction="Decay" Model="SelfTable" Profile="NFW">
  <PropDMLepton />                <!-- fPBH = 1 -->
  <Mass value="1e15" />           <!-- PBH mass in g -->
  <LifeTime value="5.61e23" />    <!-- conversion factor: 1 g = 5.61e23 GeV -->
  <SSDensity value="0.4" />       <!-- DM local energy density in GeV/cm^3 -->
  <LeptonDatafile value="/Users/jordankoechler/Desktop/DRAGON_School/injec_spec/e_mBH_1e15g.txt" />
  <!-- File containing the e+e- spectrum from PBH evaporation -->
</DarkMatter>
```

PBH $\to \ldots \to e^{\pm}$ (cosmic-rays)