



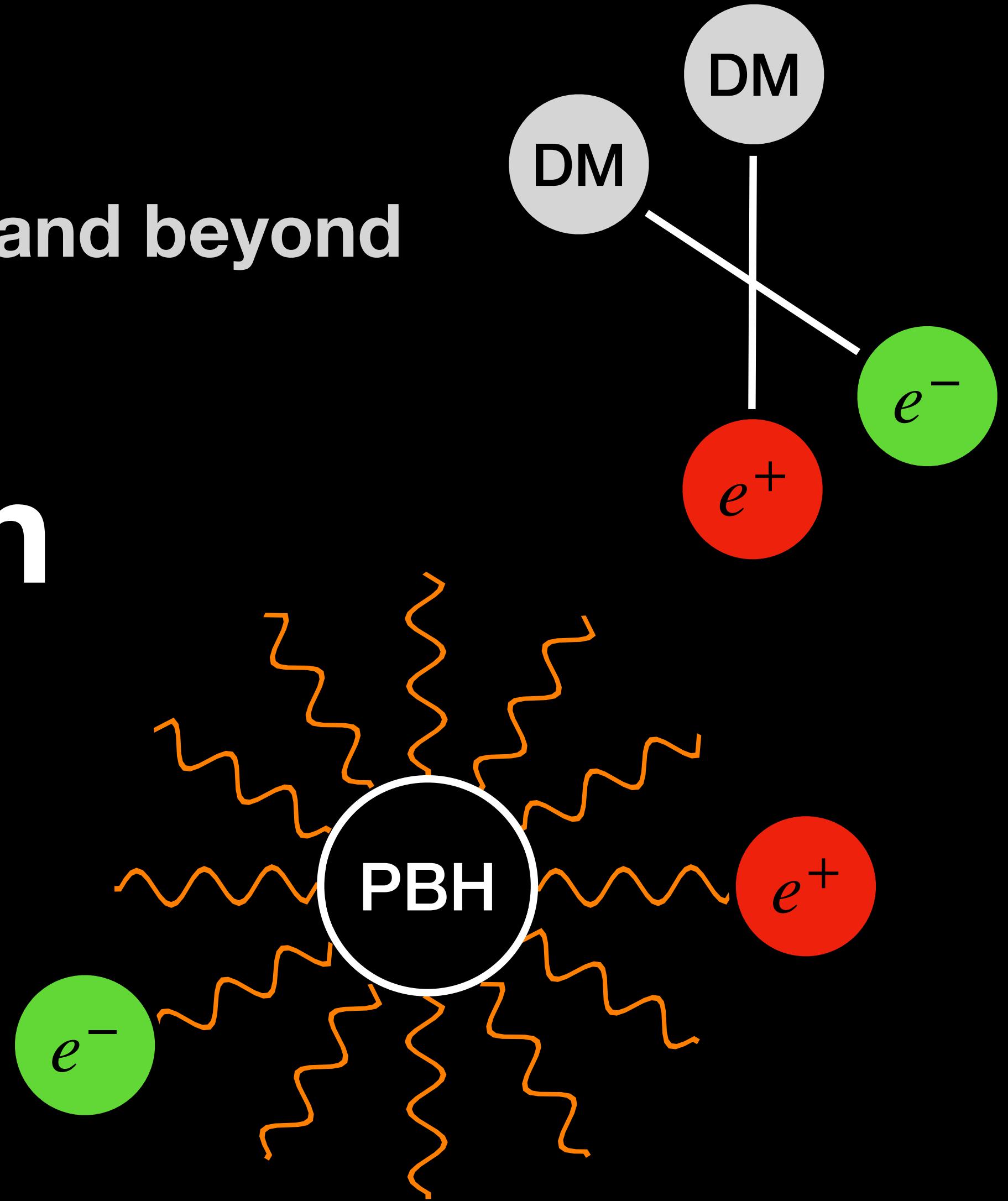
DRAGON School

Cosmic-ray theory, phenomenology, and beyond

Dark matter signals with DRAGON and HERMES

Hands-on session

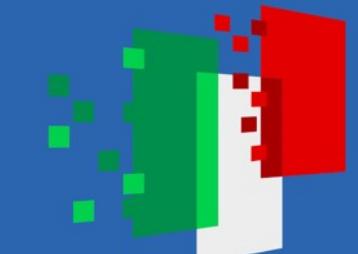
Jordan Koechler (INFN Turin)



Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



First things first...

Go to:

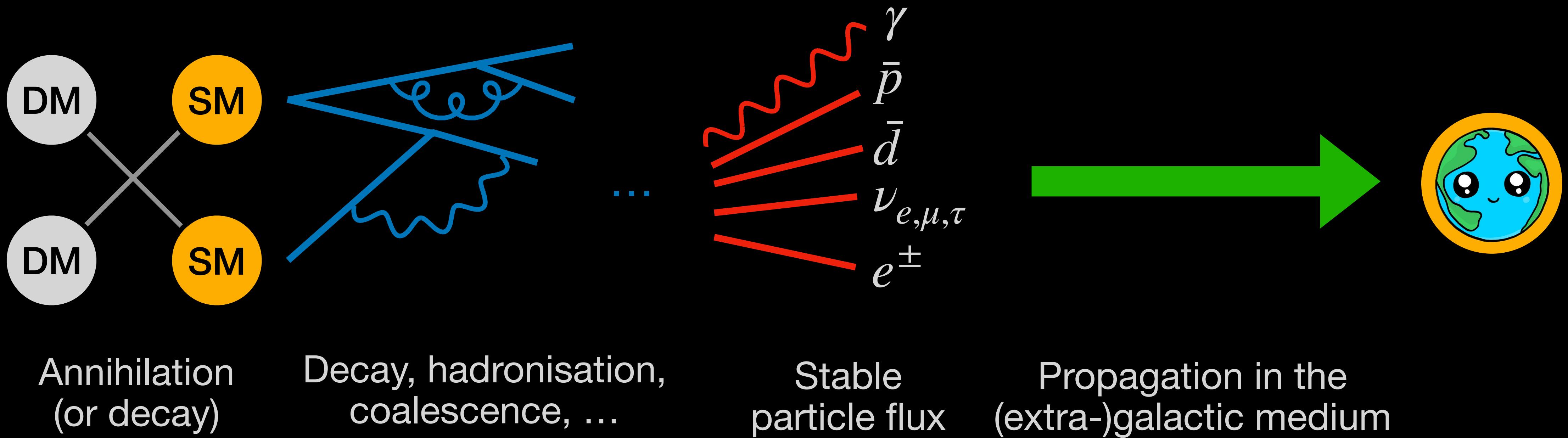
https://github.com/JordanKoechler/DRAGON-School-2025_HandsOn-DarkMatter

DRAGON/HERMES inputs, outputs

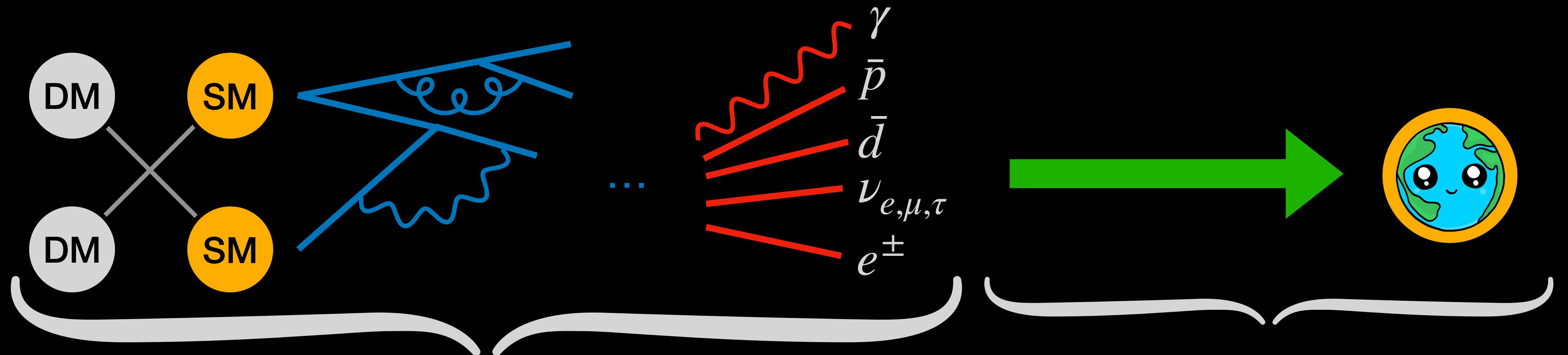
e^\pm injection spectra for DRAGON

Some data and scripts...

Dark matter indirect detection



Dark matter indirect detection



HDMspectra: $500 \text{ GeV} < m_{DM} < M_{Pl}$

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

Hazma: $m_{DM} < 1 \text{ GeV}$

Sometimes analytically...

DRAGON, GALPROP, USINE,
HERMES, ...

DM → ... → γ

Injection and propagation of DM-produced γ



DM → . . . → γ

Differential flux of DM-produced photons

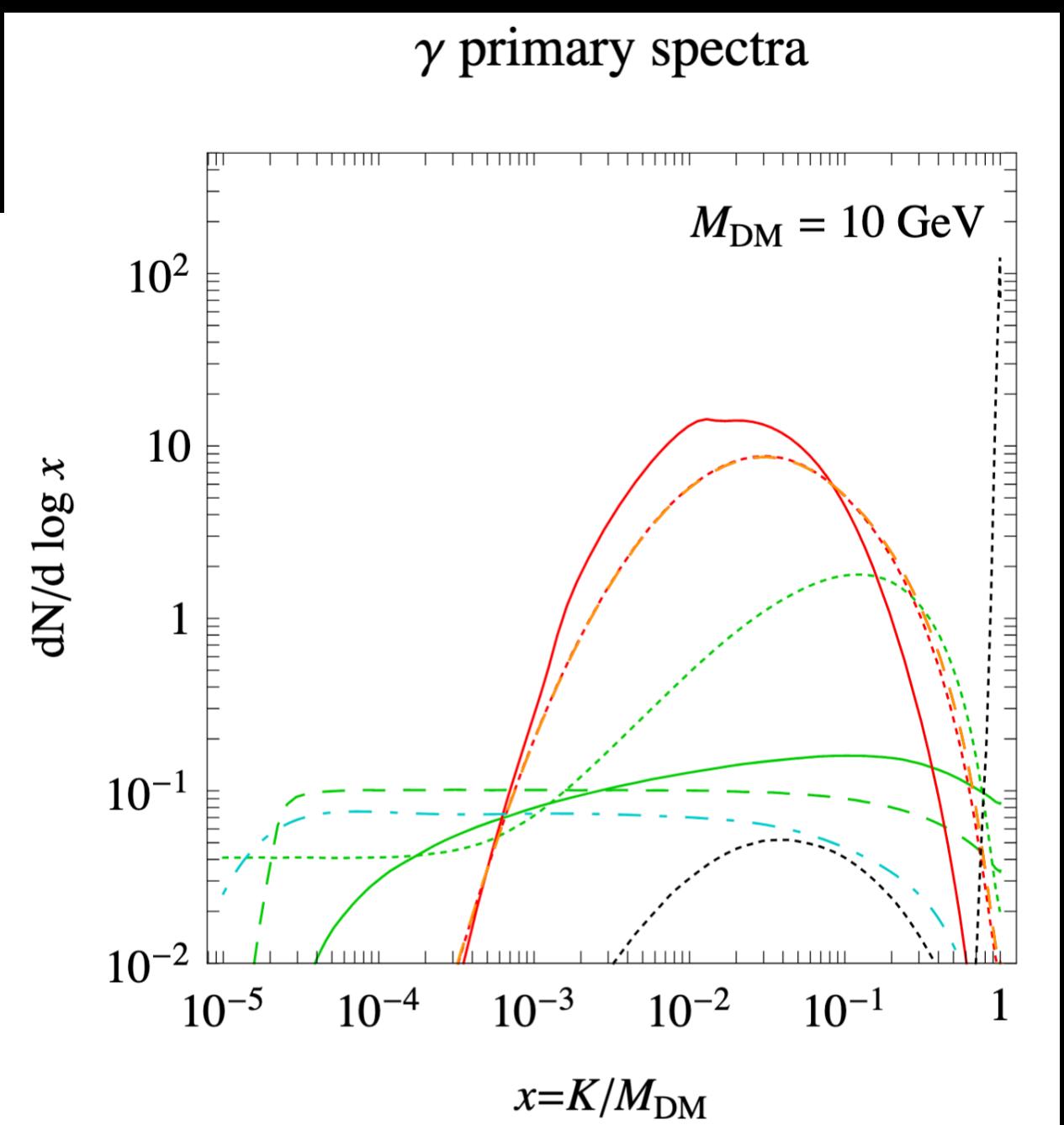
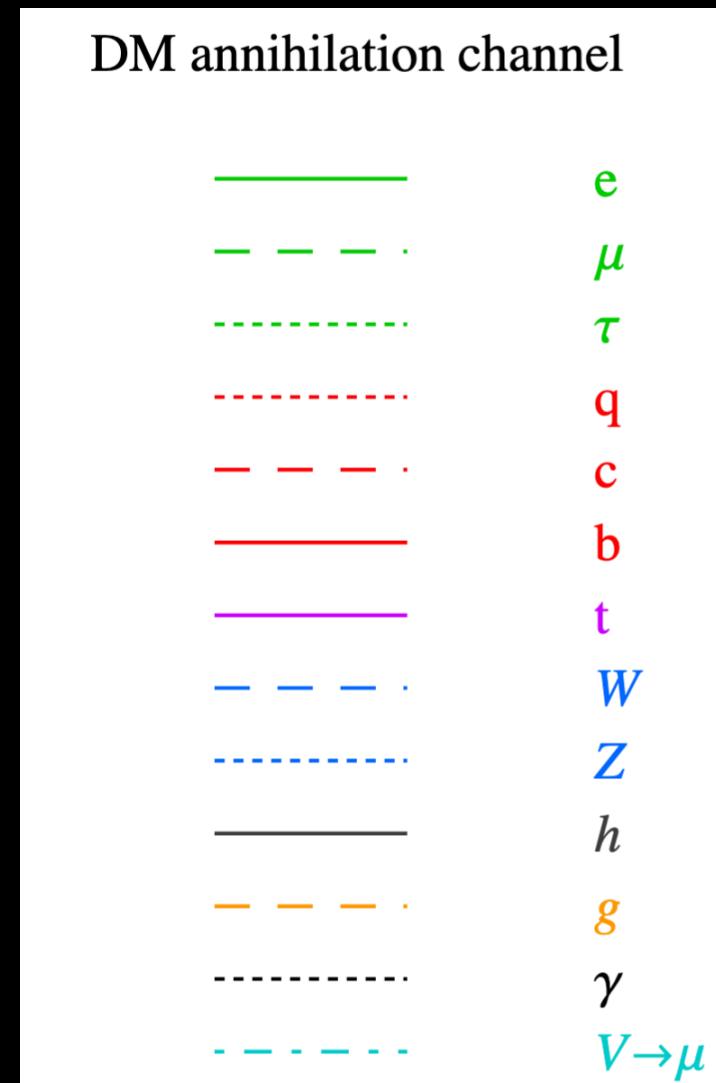
$$\frac{d\Phi_\gamma}{dE_\gamma d\Omega} = \frac{1}{4\pi} \frac{dN_\gamma}{dE_\gamma} \times \begin{cases} \frac{1}{2} \frac{\langle \sigma v \rangle}{m_{DM}^2} \int_{l.o.s.} \rho_{DM}^2(r, \Omega) ds & \text{(annihilation)} \\ \frac{\Gamma}{m_{DM}} \int_{l.o.s.} \rho_{DM}(r, \Omega) ds & \text{(decay)}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

DM → . . . → γ

Differential flux of DM-produced photons

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

e.g., [PPPC4DMID](#)



DM → . . . → γ

Differential flux of DM-produced photons

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e.g., [PPPC4DMID](#)

Free
parameters

DM → . . . → γ

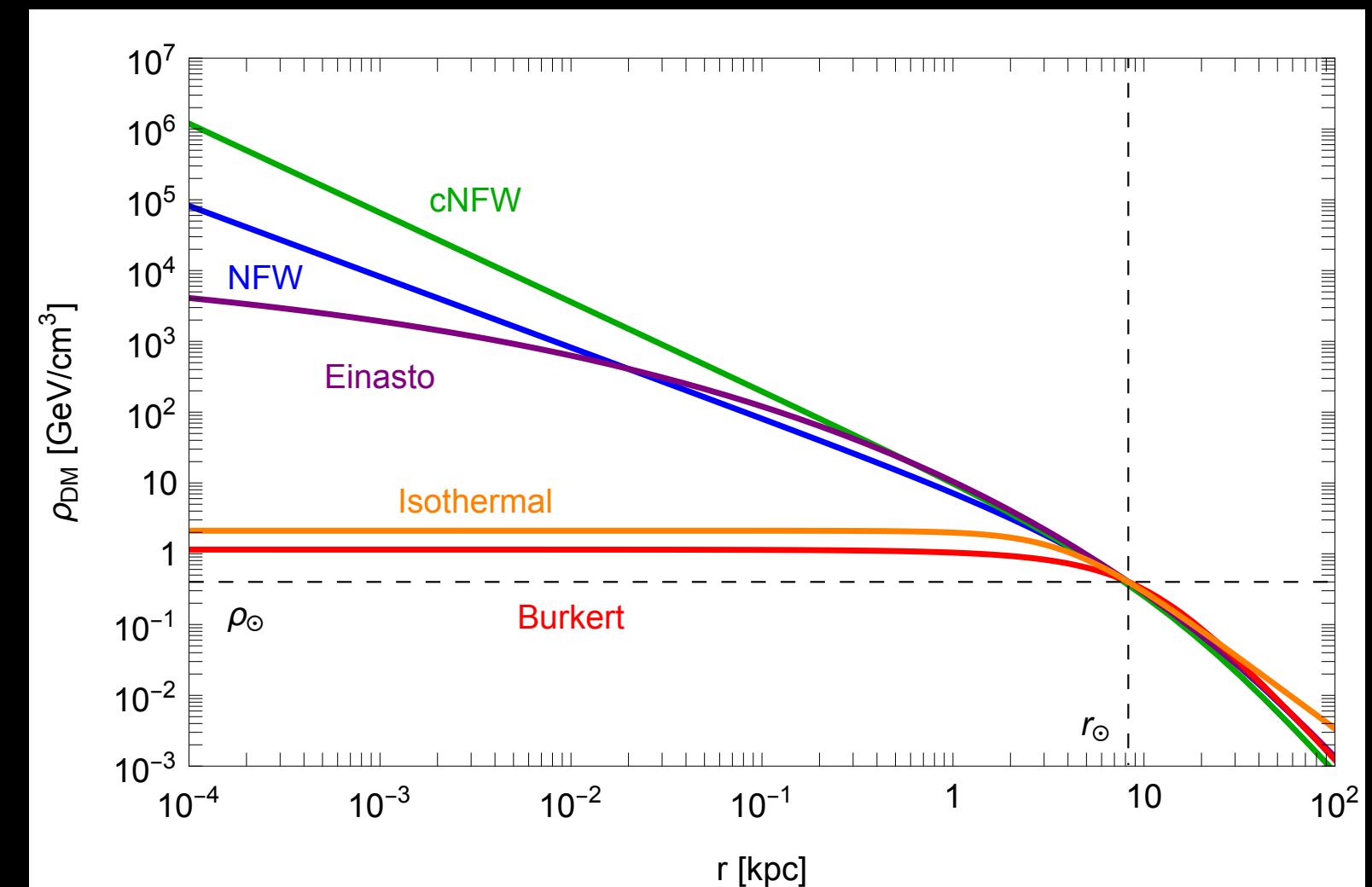
Differential flux of DM-produced photons

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e.g., PPPC4DMID

Free parameters

DM density profile



DM → . . . → γ

Differential flux of DM-produced photons

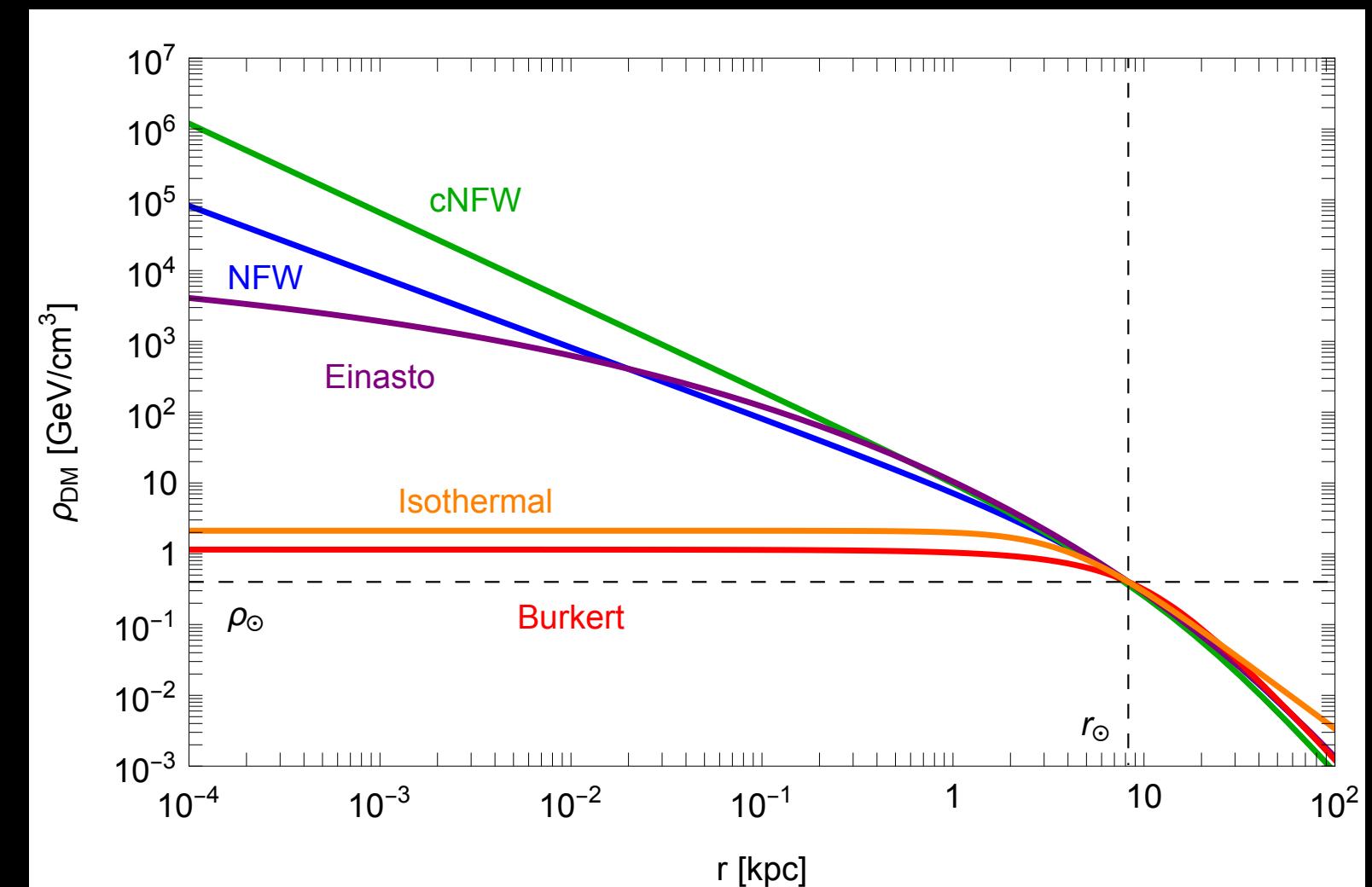
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e.g., PPPC4DMID

Free parameters

DM density profile

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



DM → . . . → γ

DM density profile

```
darkmatter.NFWGProfile(gamma, concentration, M_200)
```

DM → . . . → γ

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$$M_{200} = 200\rho_c \frac{4\pi}{3} r_{200}^3$$

$$= 4\pi \int_0^{r_{200}} r^2 \rho_{gNFW}(r) dr \quad c = \frac{r_{200}}{r_s}$$

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

DM → . . . → γ

DM density profile

DM annihilation spectrum

```
darkmatter.PPPC4DMIDSpectrum(darkmatter.Channel.b, darkmatter.Mass.m100GeV)
```

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Allowed primaries:

e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$

$q\bar{q}$, $c\bar{c}$, $b\bar{b}$, $t\bar{t}$

W^+W^- , Z^0Z^0 , hh

e, mu, tau

q, c, b, t

W, Z, h

DM → . . . → γ

DM density profile

DM annihilation spectrum

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Allowed m_{DM} range:

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

DM → . . . → γ

DM density profile

DM annihilation spectrum

`darkmatter.PPPC4DMIDSpectrum(darkmatter.Channel.b, darkmatter.Mass.m100GeV)`

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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 $m_{DM}/2$

DM → . . . → γ

DM density profile

DM annihilation spectrum

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darkmatter.PPPC4DMIDSpectrum(darkmatter.Channel.b, darkmatter.Mass.m100GeV)
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W^+W^- , Z^0Z^0 , hh	W, Z, h

Allowed m_{DM} range:

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

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

DM → . . . → γ

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

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

DM DM → $b\bar{b}$ → . . . → γ for $m_{DM} = 40$ GeV

DM → . . . → γ

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

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

DM DM → $b\bar{b}$ → . . . → γ for $m_{DM} = 40$ GeV

- 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)

DM → . . . → γ

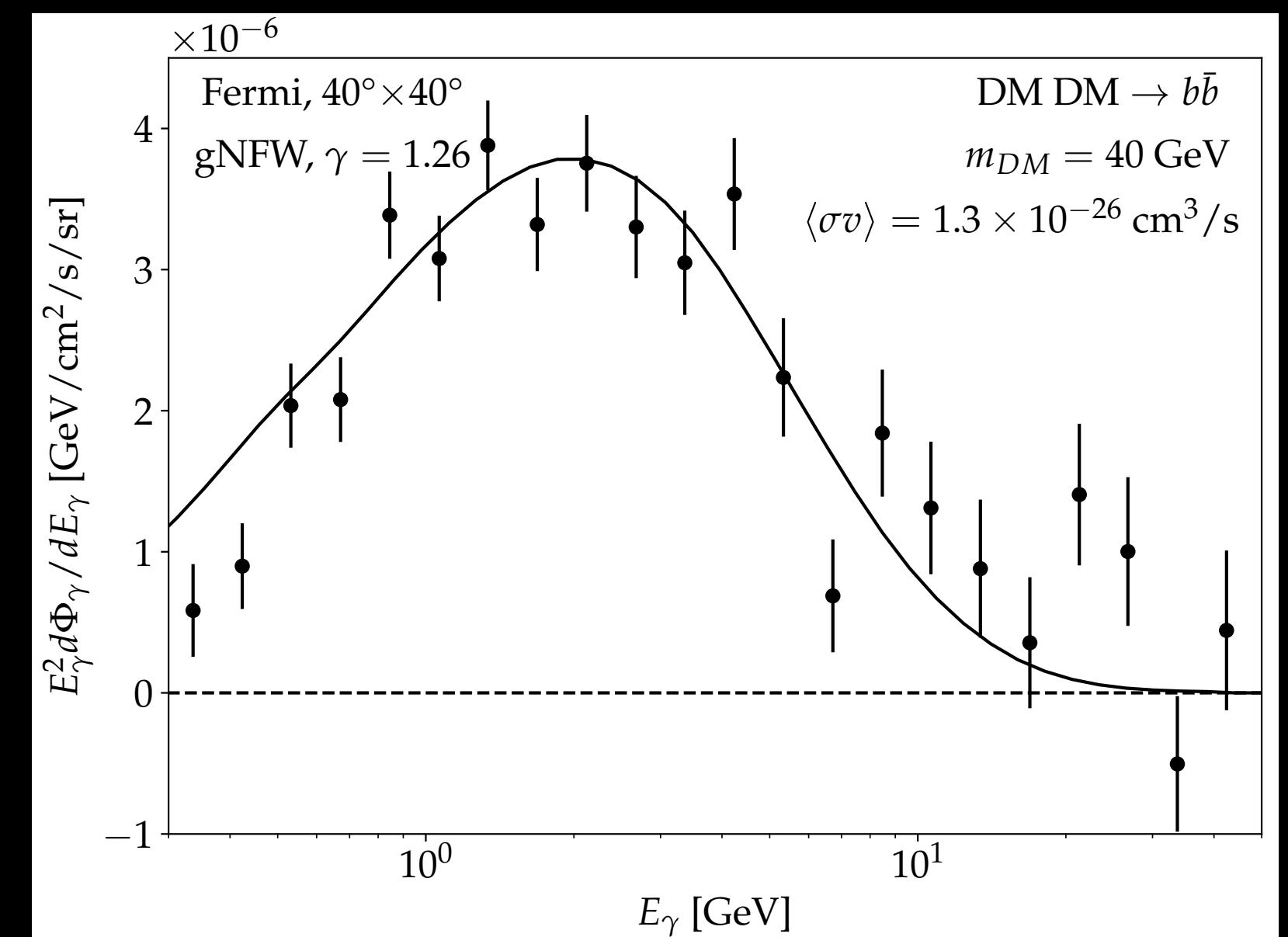
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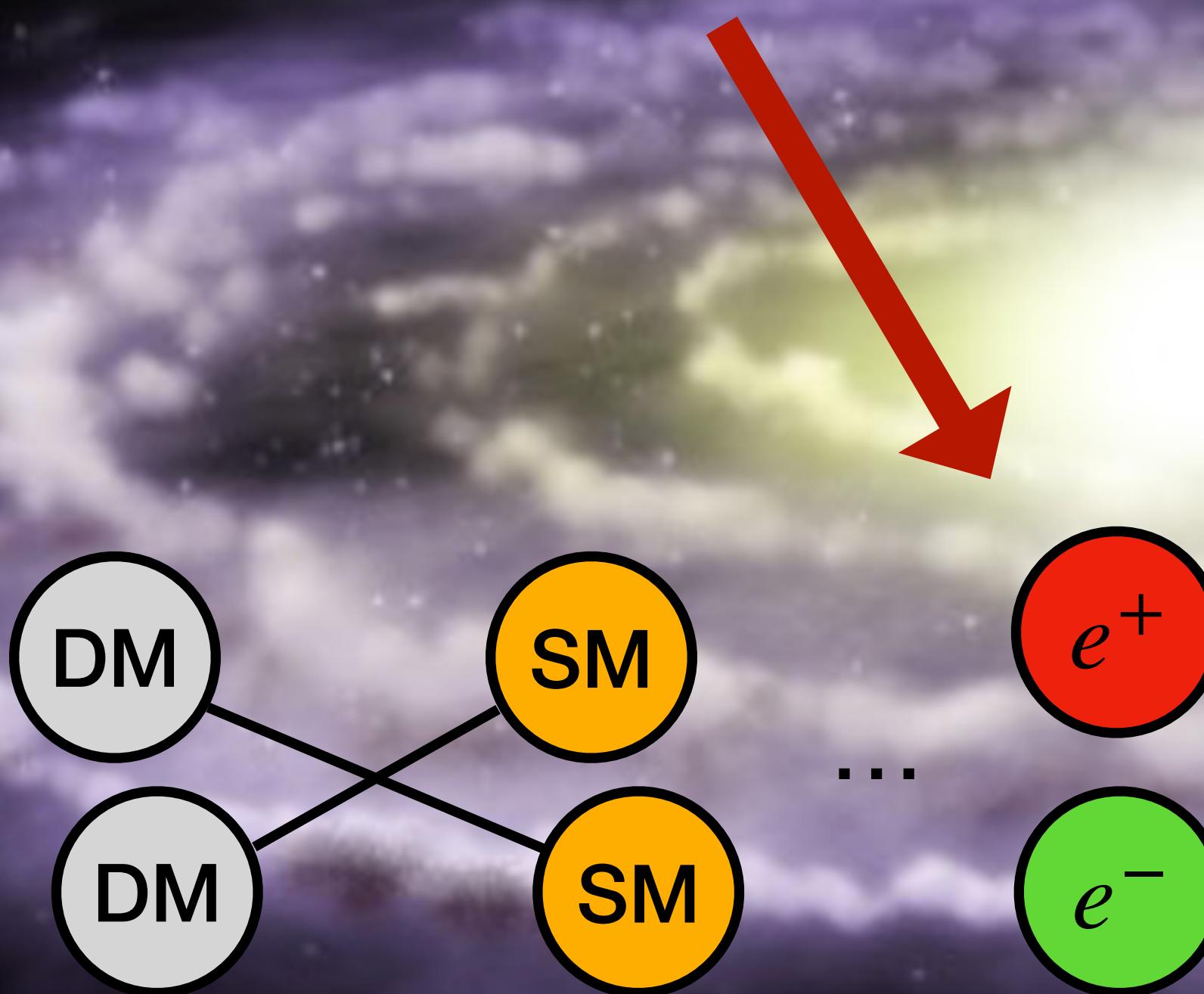
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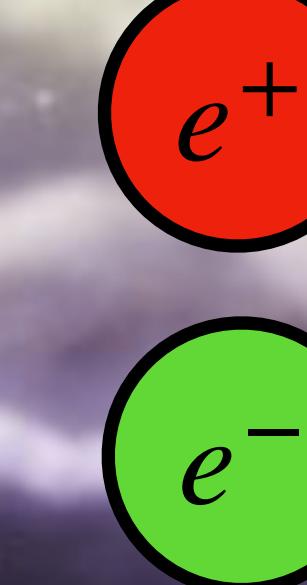
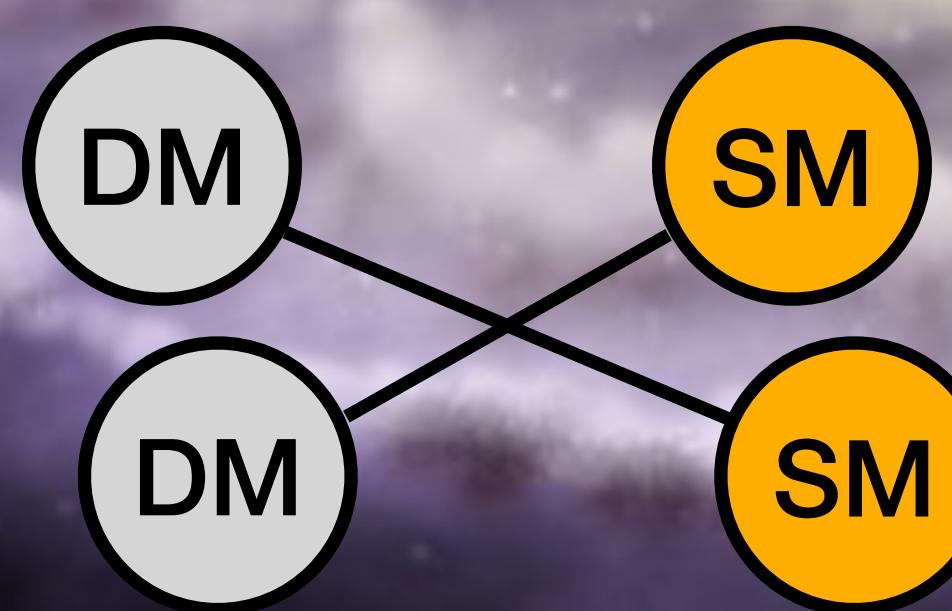
DM $\rightarrow \dots \rightarrow e^\pm$

Injection of DM-produced e^\pm



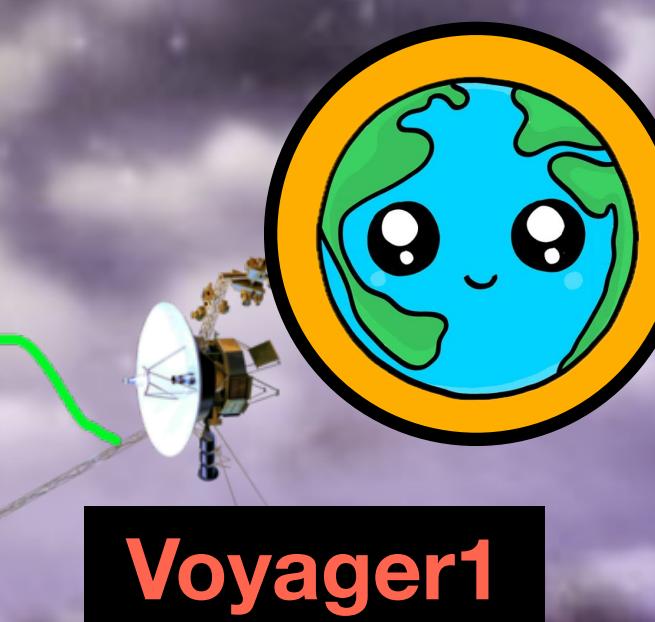
$$\text{DM} \rightarrow \dots \rightarrow e^\pm$$

Injection of DM-produced e^\pm



Cosmic-rays

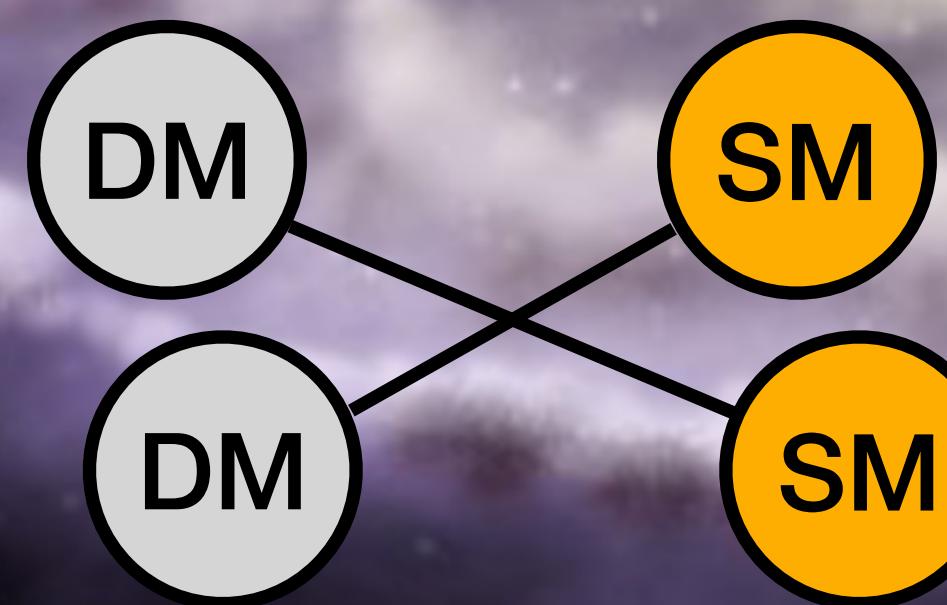
Propagation of DM-produced e^\pm
(DRAGON)



Voyager1

DM $\rightarrow \dots \rightarrow e^\pm$

Injection of DM-produced e^\pm



...



Interactions with the ISM
(HERMES)



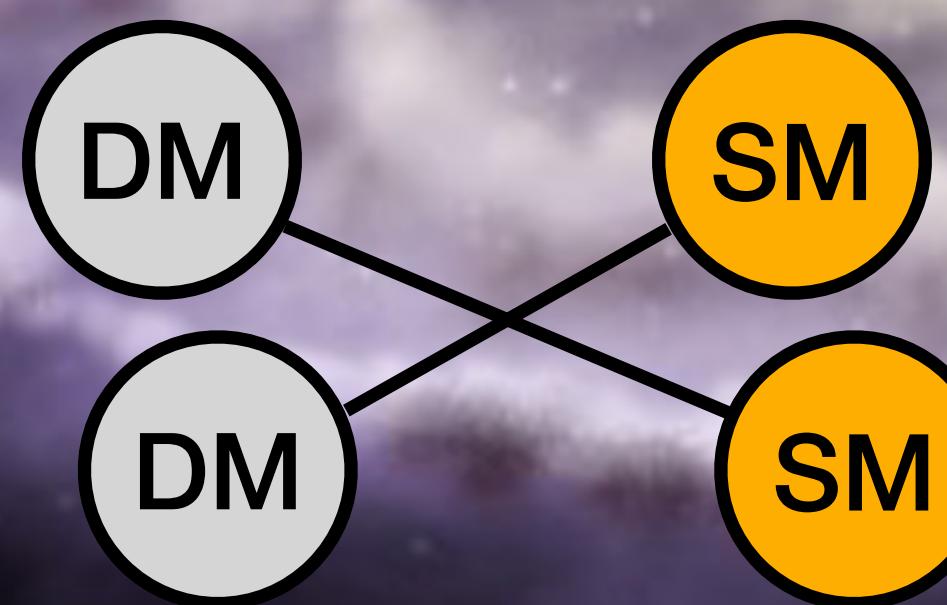
Cosmic-rays



Propagation of DM-produced e^\pm
(DRAGON)

DM $\rightarrow \dots \rightarrow e^\pm$

Injection of DM-produced e^\pm



...



Interactions with the ISM
(HERMES)



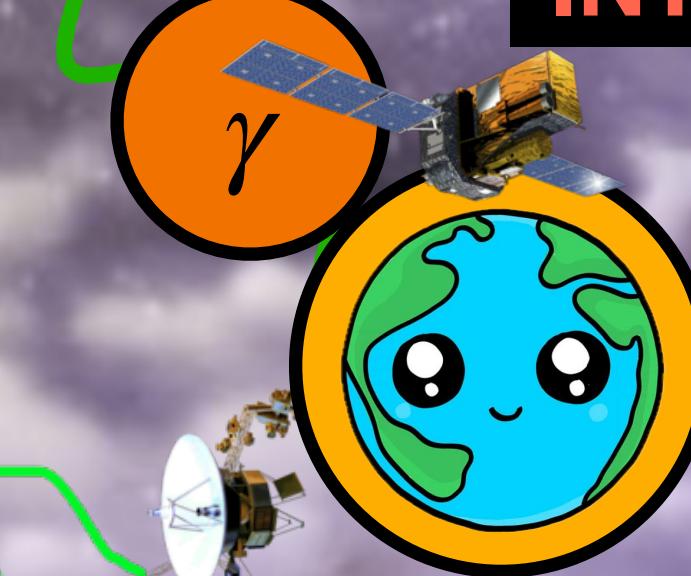
Secondary γ

INTEGRAL

Voyager1

Cosmic-rays

Propagation of DM-produced e^\pm
(DRAGON)



DM $\rightarrow \dots \rightarrow e^\pm$ (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

DM $\rightarrow \dots \rightarrow e^\pm$ (cosmic-rays)

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spatial diffusion convection energy losses momentum space diffusion source

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

(broken power-law)

DM $\rightarrow \dots \rightarrow e^\pm$ (cosmic-rays)

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

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spatial diffusion convection energy losses momentum space diffusion source

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

(broken power-law)

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

(Alfvénic turbulence)

DM $\rightarrow \dots \rightarrow e^\pm$ (cosmic-rays)

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

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(Alfvénic turbulence)

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

DM $\rightarrow \dots \rightarrow e^\pm$ (cosmic-rays)

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

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

DM $\rightarrow \dots \rightarrow e^\pm$ (cosmic-rays)

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e^\pm injection spectrum

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

DM $\rightarrow \dots \rightarrow e^\pm$ (cosmic-rays)

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

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

e^\pm injection spectrum

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

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

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

DM → . . . → 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 → . . . → 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 → . . . → 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 $\text{DM DM} \rightarrow \mu^+ \mu^-$ for $m_{DM} = 1 \text{ GeV}$

`./DRAGON examples/run_2D_DMe_NFW_ann.xml` $t \sim 100 \text{ s}$

DM → . . . → e^\pm (cosmic-rays)

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`./DRAGON examples/run_2D_DMe_NFW_ann.xml $t \sim 100 \text{ s}$`

- 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" />
</Reacceleration>
```

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

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`./DRAGON examples/run_2D_DMe_NFW_ann.xml` $t \sim 100 \text{ s}$

- Step 3: Change v_A to 0 km/s in the `<Reacceleration>` sub-block and re-run
- Step 4: Re-run the two v_A cases for $m_{DM} = m_\mu = 105.7 \text{ MeV}$

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<Reacceleration type="Ptuskin94">
  <vA_kms value="13.4" />
</Reacceleration>
```

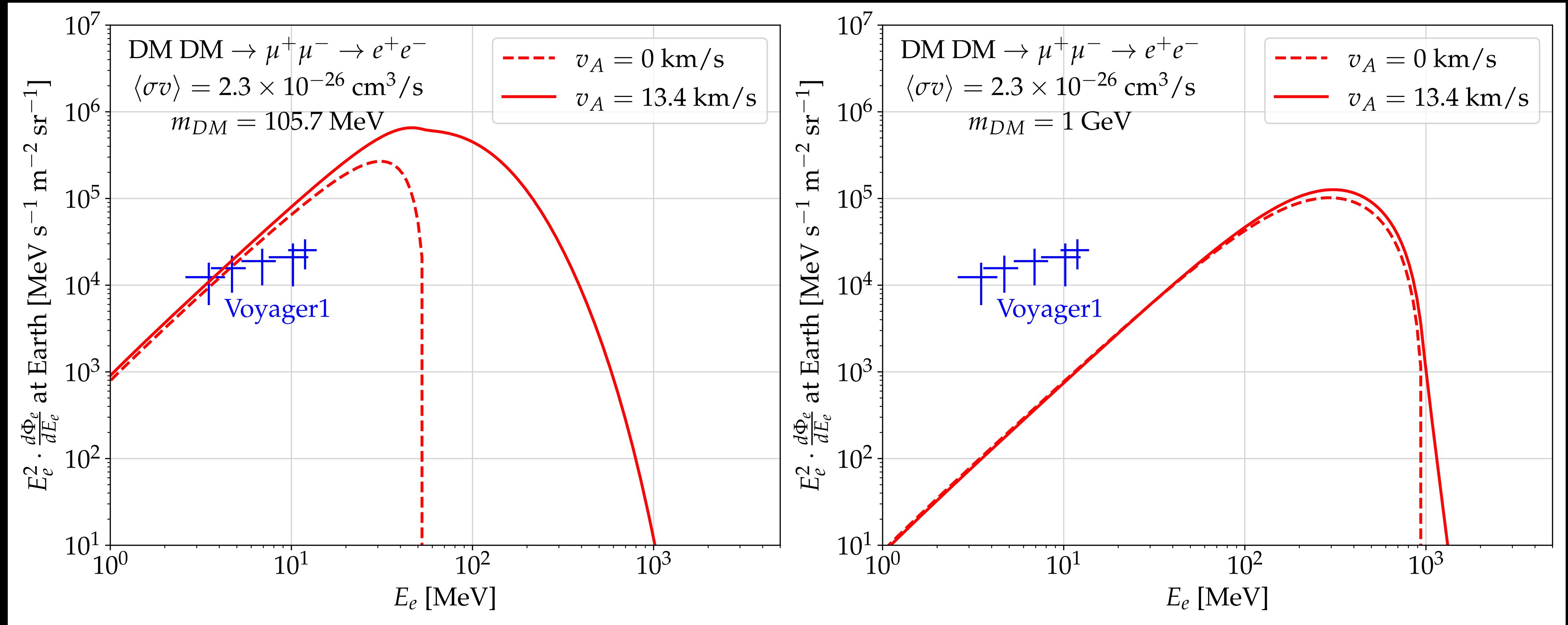
$\text{DM} \rightarrow \dots \rightarrow e^\pm$ (cosmic-rays)

Exercice: Effects of reacceleration (Alfvén speed)

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 $\text{./DRAGON examples/run_2D_DMe_NFW_ann.xml } t \sim 100 \text{ s}$
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```
- Step 4: Re-run the two v_A cases for $m_{DM} = m_\mu = 105.7 \text{ MeV}$
- Step 5: Run the extract_DRAGONfits.py script to plot the DM-produced e^\pm flux at Earth

DM $\rightarrow \dots \rightarrow e^\pm$ (cosmic-rays)



DM → . . . → e^\pm (secondary γ)

Differential flux of photons from secondary emissions:

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

DM → . . . → e^\pm (secondary γ)

Differential flux of photons from secondary emissions:

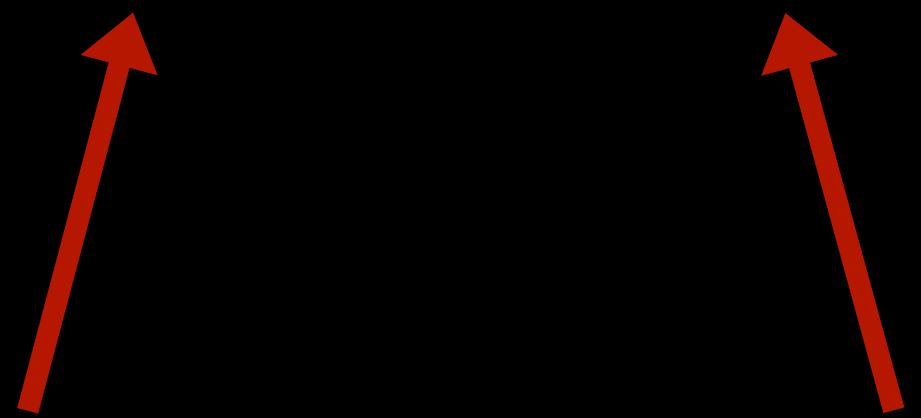
$$\frac{d\Phi_\gamma^{sec}}{dE_\gamma d\Omega} = \frac{1}{E_\gamma} \int_{l.o.s.} ds \frac{j_{sec}(E_\gamma, \vec{x})}{4\pi} \quad j_{sec}(E_\gamma, \vec{x}) = 2 \int_{m_e}^{m_{DM}/2) dE_e \mathcal{P}_{sec}(E_\gamma, E_e, \vec{x}) f_{e^\pm}(E_e, \vec{x})}$$

DM → . . . → e^\pm (secondary γ)

Differential flux of photons from secondary emissions:

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

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



Radiating power

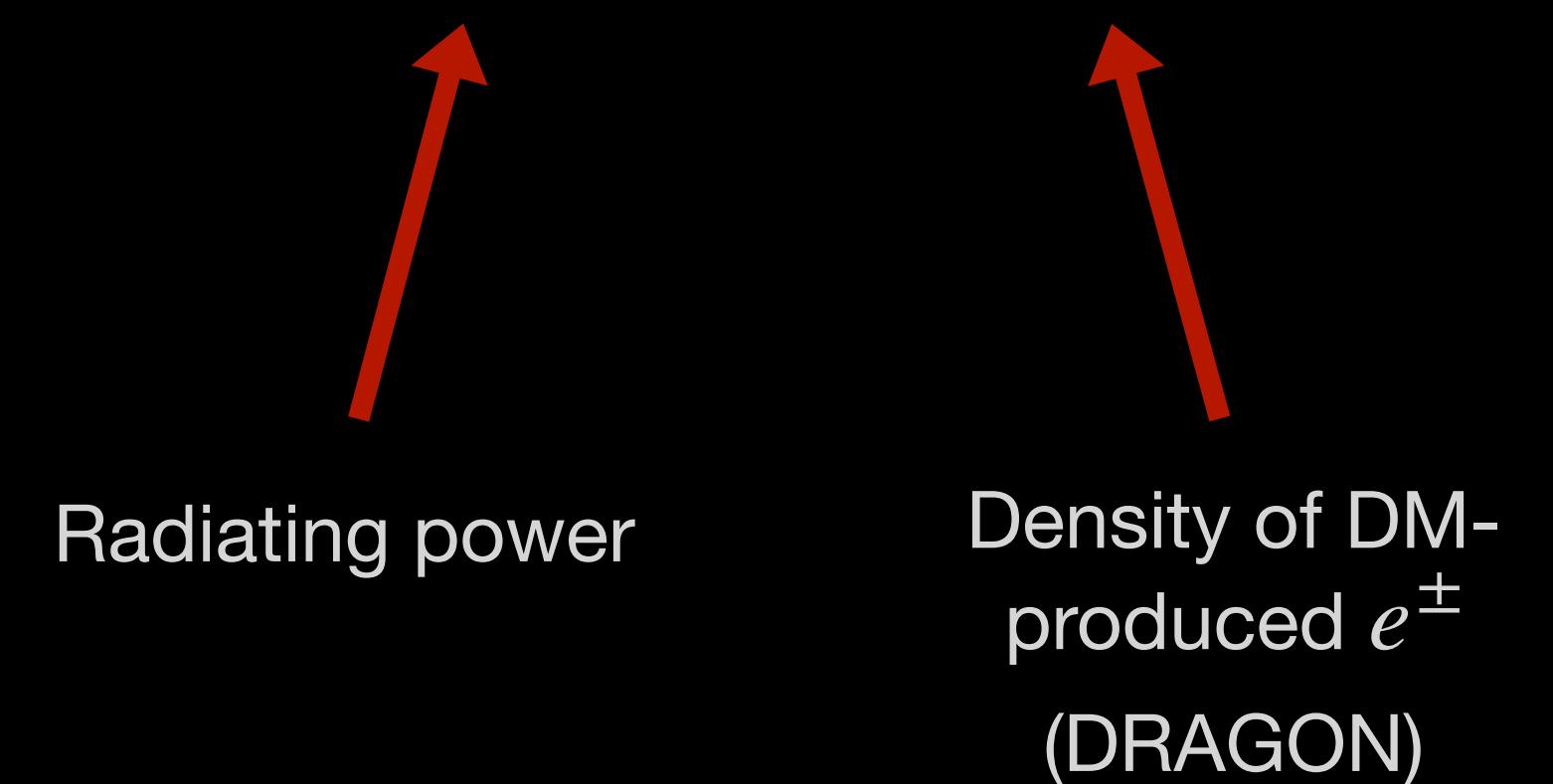
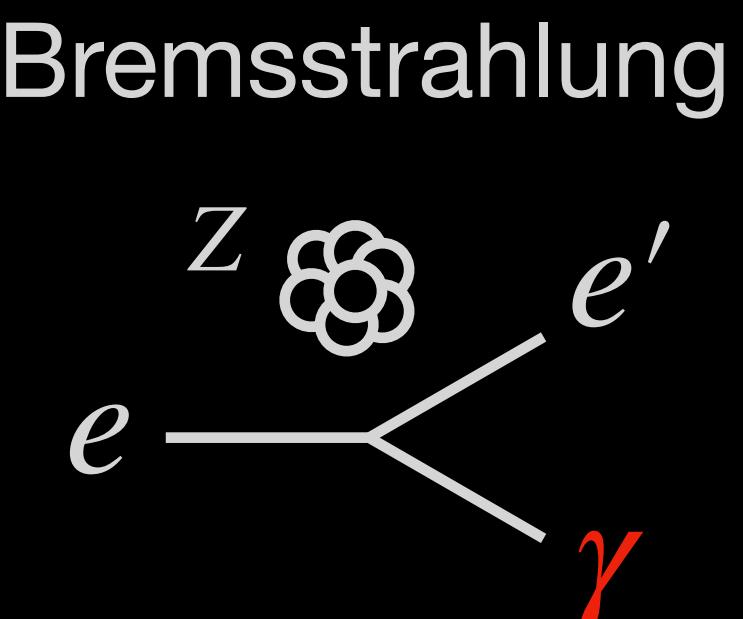
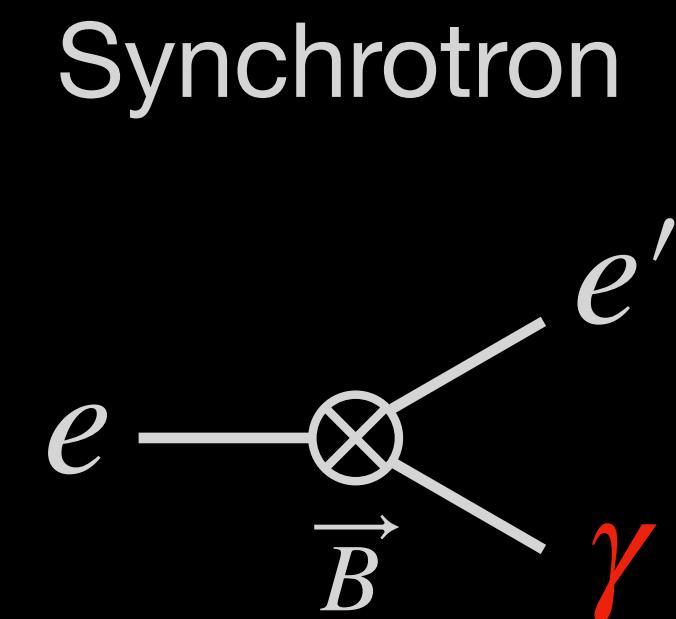
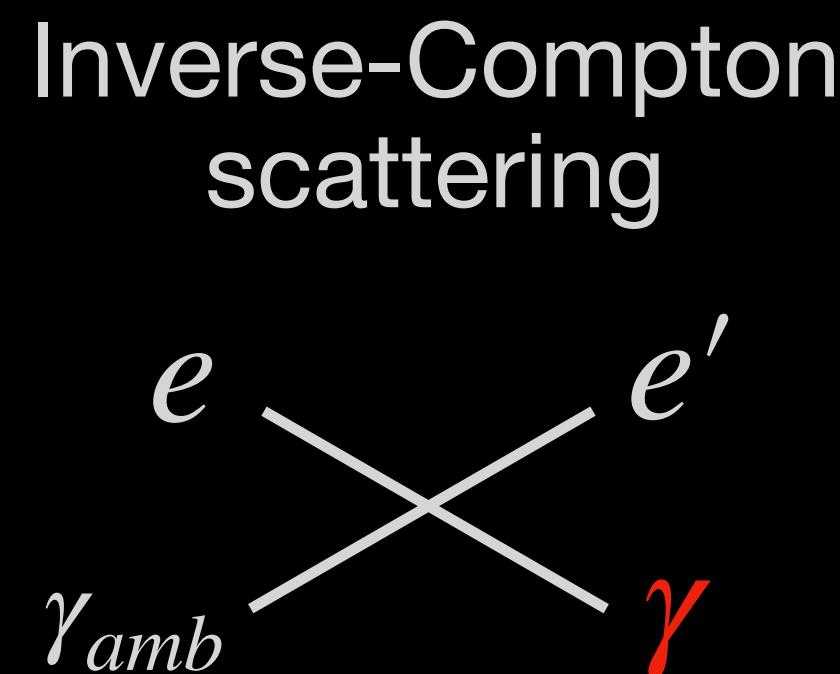
Density of DM-produced e^\pm
(DRAGON)

DM $\rightarrow \dots \rightarrow e^\pm$ (secondary γ)

Differential flux of photons from secondary emissions:

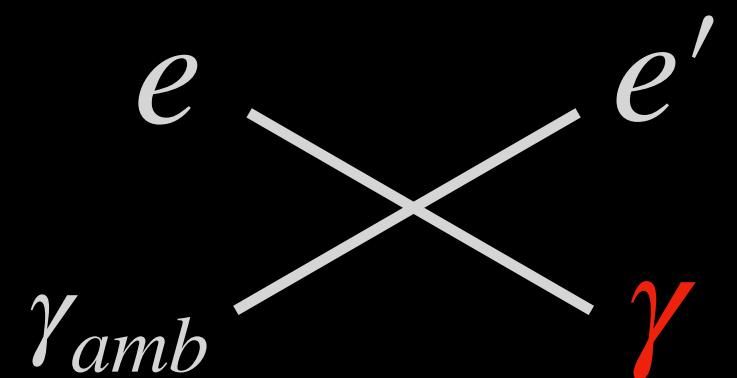
$$\frac{d\Phi_\gamma^{sec}}{dE_\gamma d\Omega} = \frac{1}{E_\gamma} \int_{l.o.s.} ds \frac{j_{sec}(E_\gamma, \vec{x})}{4\pi}$$

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Inverse-Compton
scattering

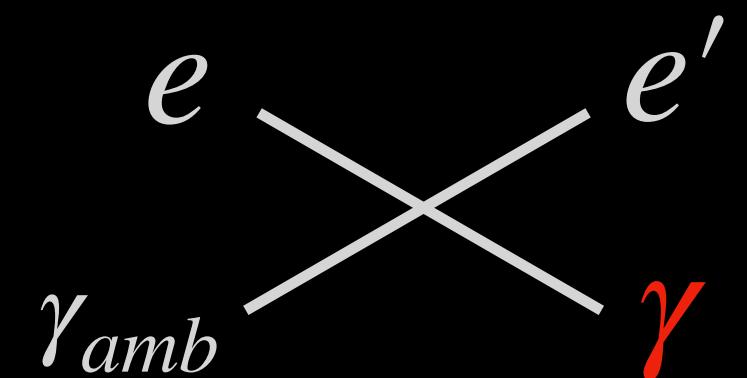
DM → . . . → e^\pm (secondary γ)



Implementation in HERMES

Inverse-Compton
scattering

DM → . . . → e^\pm (secondary γ)



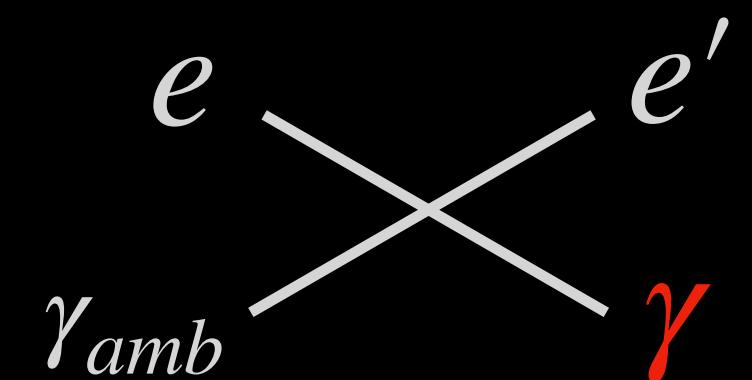
Implementation in HERMES

Integrator

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

Inverse-Compton
scattering

DM → . . . → e^\pm (secondary γ)



Implementation in HERMES

Integrator

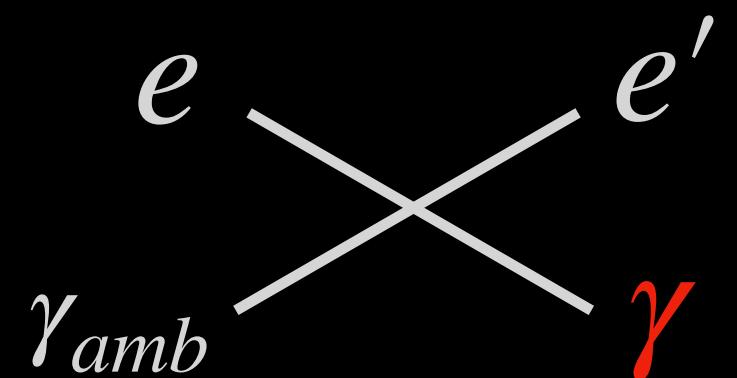
```
InverseComptonIntegrator(cosmicrays.CosmicRayDensity, photonfields.PhotonField, interactions.DifferentialCrossSection)
```



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

Lepton map
from DRAGON

Inverse-Compton
scattering



Implementation in HERMES

Integrator

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

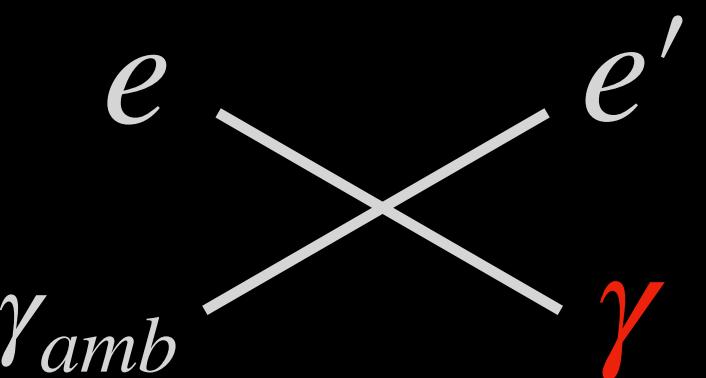
```
cosmicrays.Dragon2D(filename, [Electron, Positron])
```

Lepton map
from DRAGON

photonfields.CMB()
photonfields.ISRF()

Ambient
photon fields

Inverse-Compton
scattering



DM $\rightarrow \dots \rightarrow e^\pm$ (secondary γ)

Implementation in HERMES

Integrator

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



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

Lepton map
from DRAGON



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

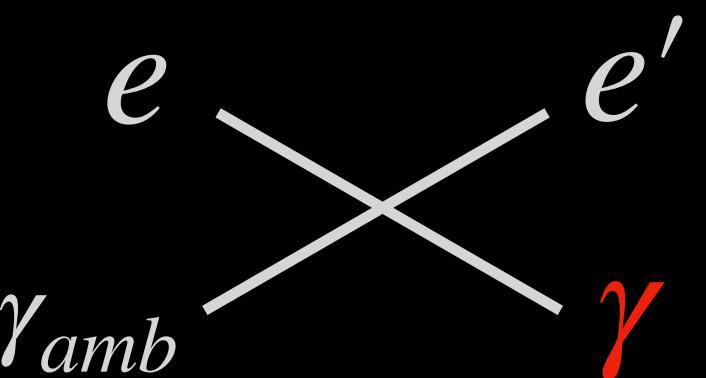
Ambient
photon fields



```
interactions.KleinNishina()
```

Klein-Nishina
cross-section

Inverse-Compton
scattering



DM → . . . → e^\pm (secondary γ)

Implementation in HERMES

Integrator

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



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

Lepton map
from DRAGON



Ambient
photon fields



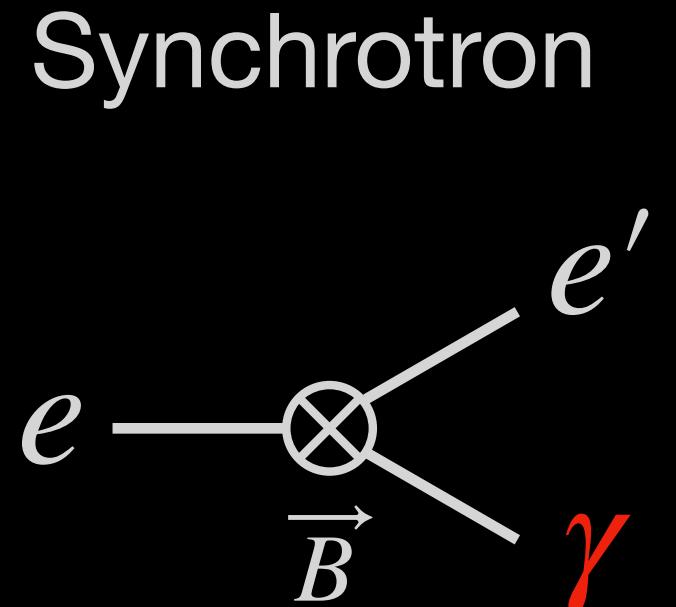
```
interactions.KleinNishina()
```

Klein-Nishina
cross-section

And as always:

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

DM → . . . → e^\pm (secondary γ)



Implementation in HERMES

Integrator

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



```
magneticfields.UniformMagneticField(Vector3QMFiel( Bx, By, Bz )  
magneticfields.MagneticFieldList([MF1, MF2, ...])  
magneticfields.PT11(True, True, True)  
...
```

Magnetic field model



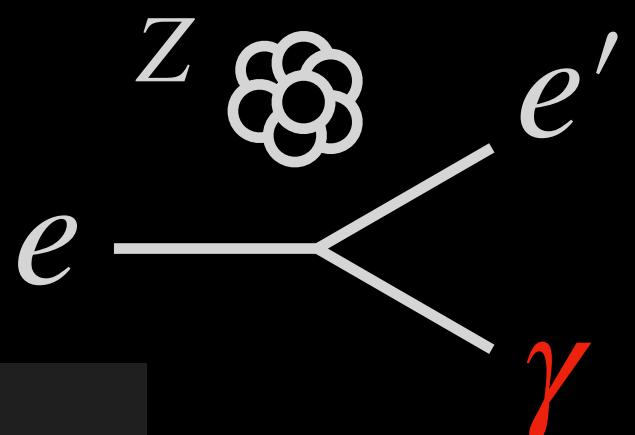
```
cosmicrays.Dragon2D(filename, [Electron, Positron])
```

Lepton map
from DRAGON

And as always:

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

Bremsstrahlung



DM → ... → e^\pm (secondary γ)

Implementation in HERMES

Integrator

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



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

Lepton map
from DRAGON



HI and H2 maps



```
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 → . . . → 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** $\text{DM} \rightarrow \mu^+ \mu^-$ for $m_{DM} = 1 \text{ GeV}$ (using the associated DM-produced e^\pm maps computed with DRAGON)
 $t \sim 15 \times 120 \text{ s}$

DM → . . . → e^\pm (secondary γ)

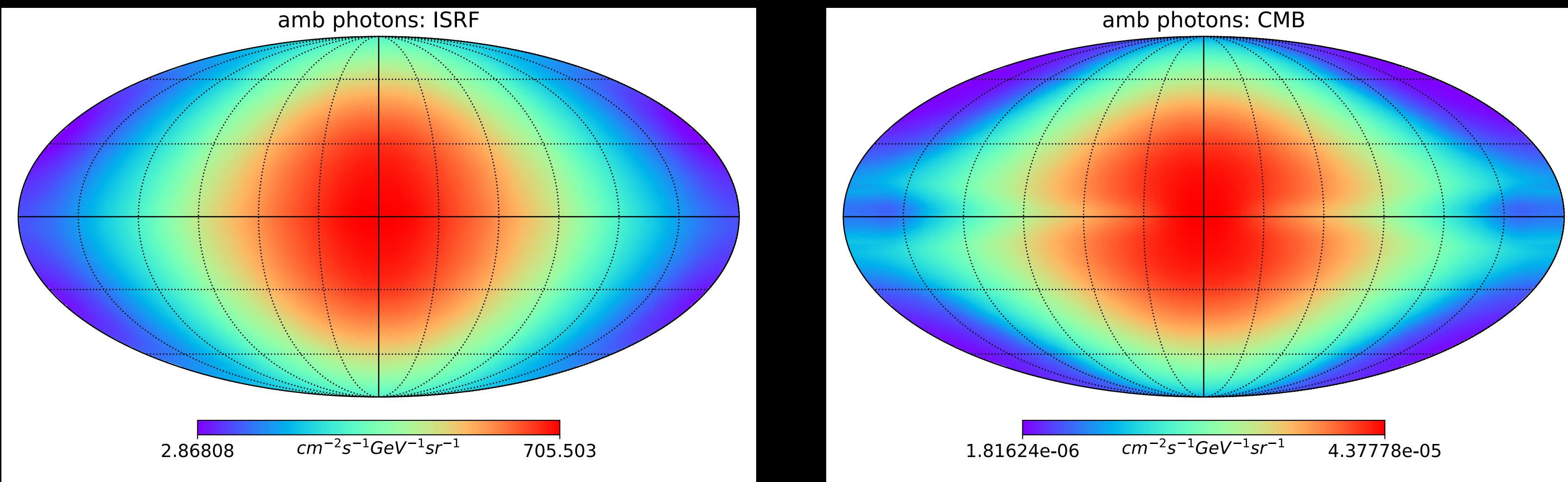
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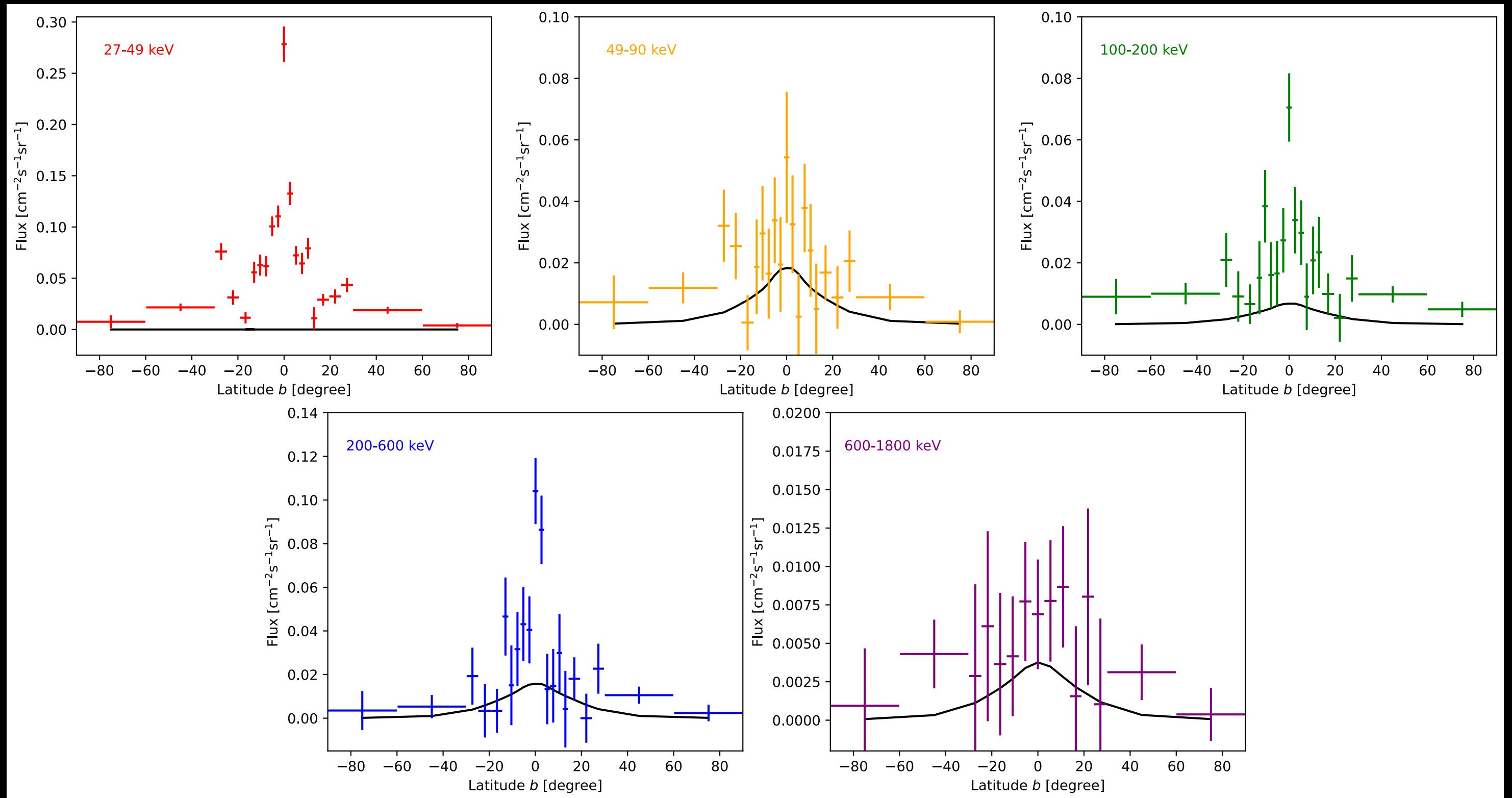
Exercice: Photon sky map of IC-scattered DM-produced e^\pm

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

DM $\rightarrow \dots \rightarrow e^\pm$ (secondary γ)

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

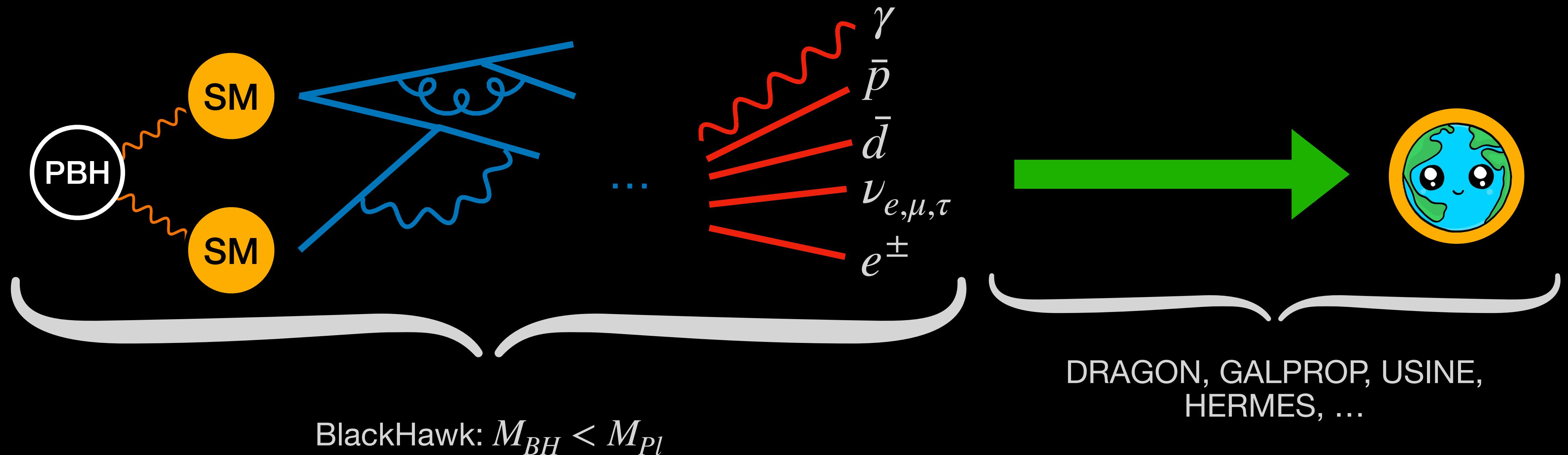
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For $\langle \sigma v \rangle = 1 \times 10^{-27} \text{ cm}^3/\text{s}$

Thank for your attention!

PBH evaporation detection



PBH → . . . → 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:

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

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e[±] injection spectrum

injec_spec/e_mBH_1e15g.txt
injec_spec/e_mBH_1e17g.txt

PBH → . . . → e^\pm (cosmic-rays)

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Hint: it looks similar to the DM decay one...

PBH → . . . → e^\pm (cosmic-rays)

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e[±] 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 → ... → e^+ (cosmic-rays)

