CRPropa

SORBONNE UNIVERSITÉ

the CRPropa framework for astroparticle propagation

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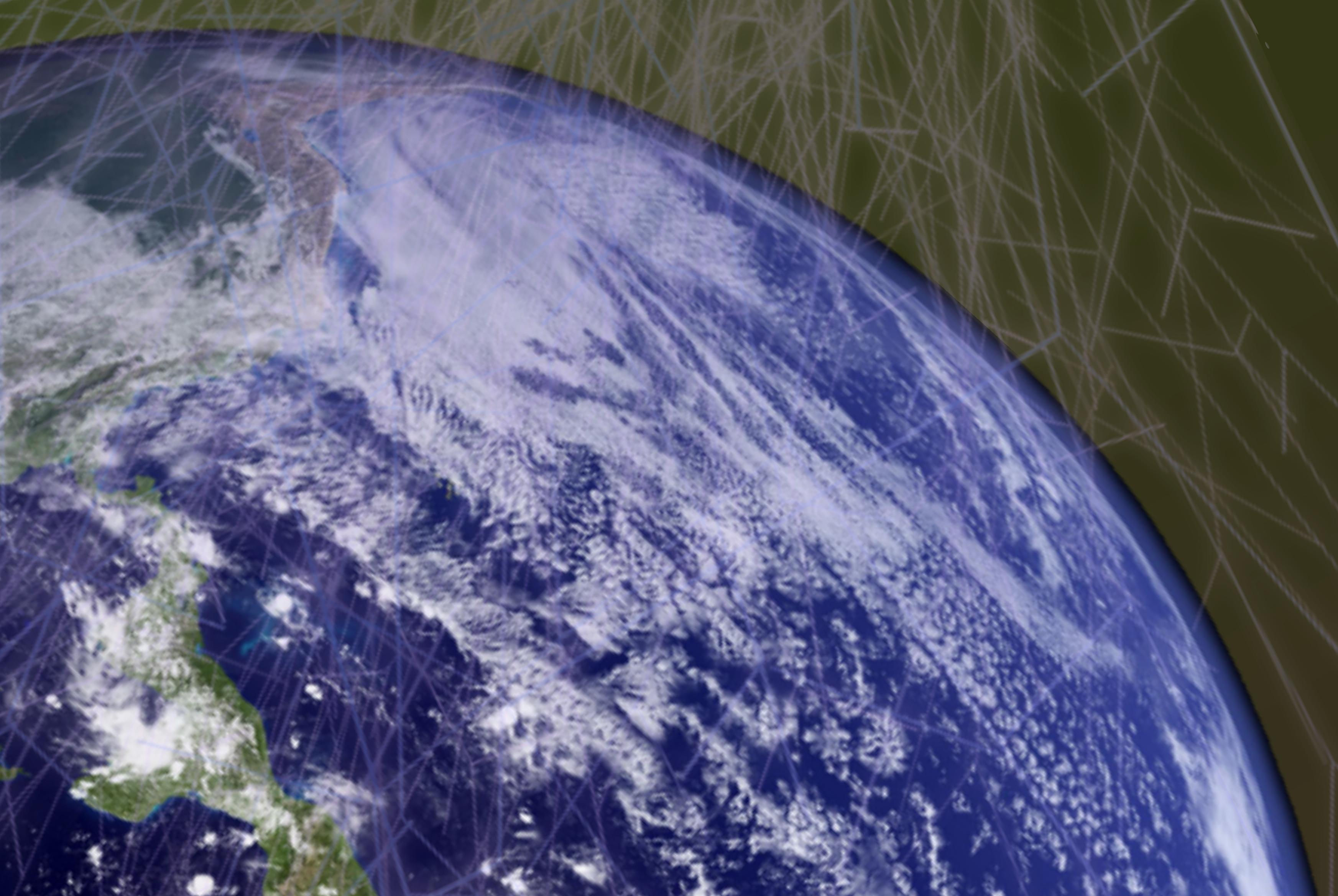
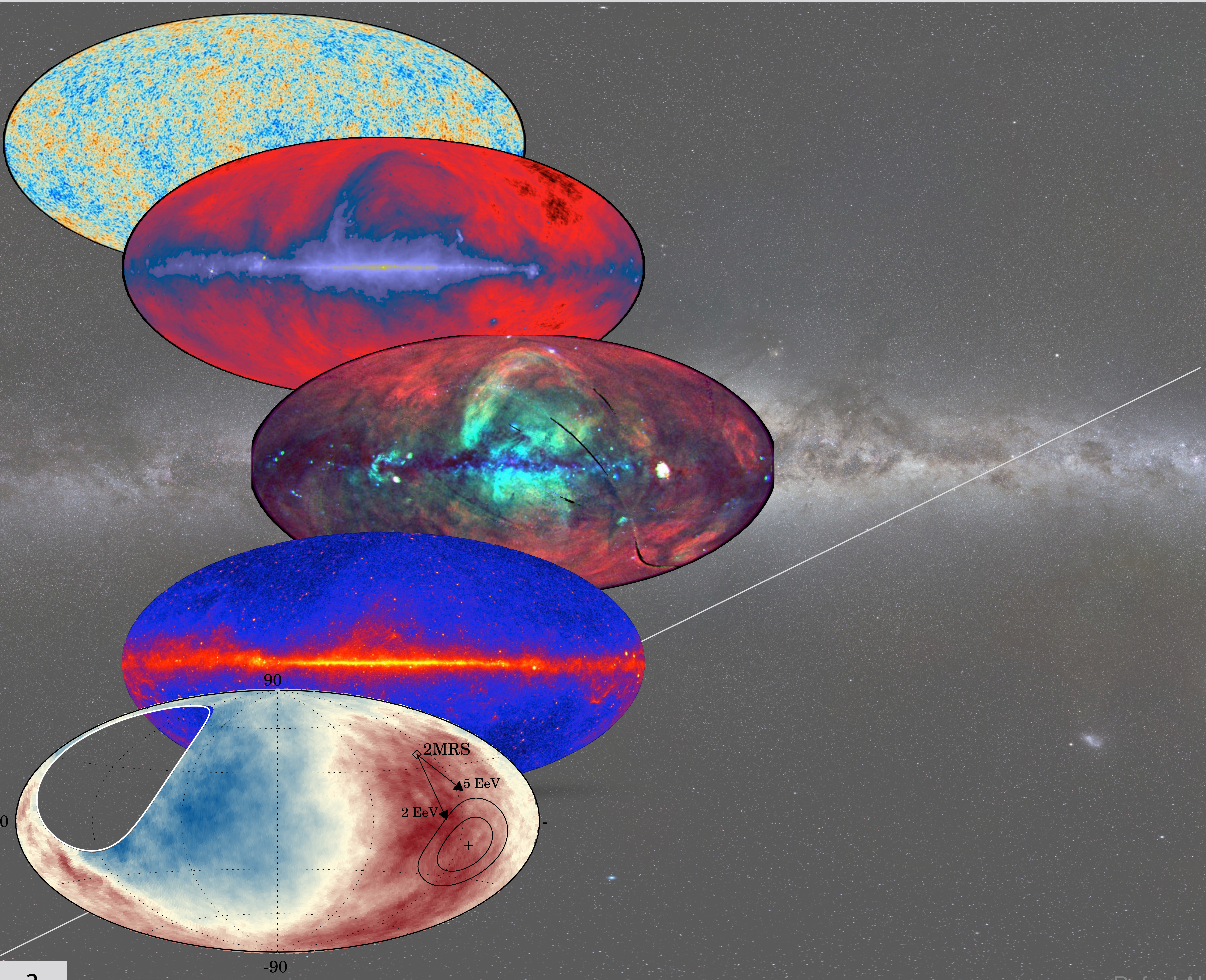
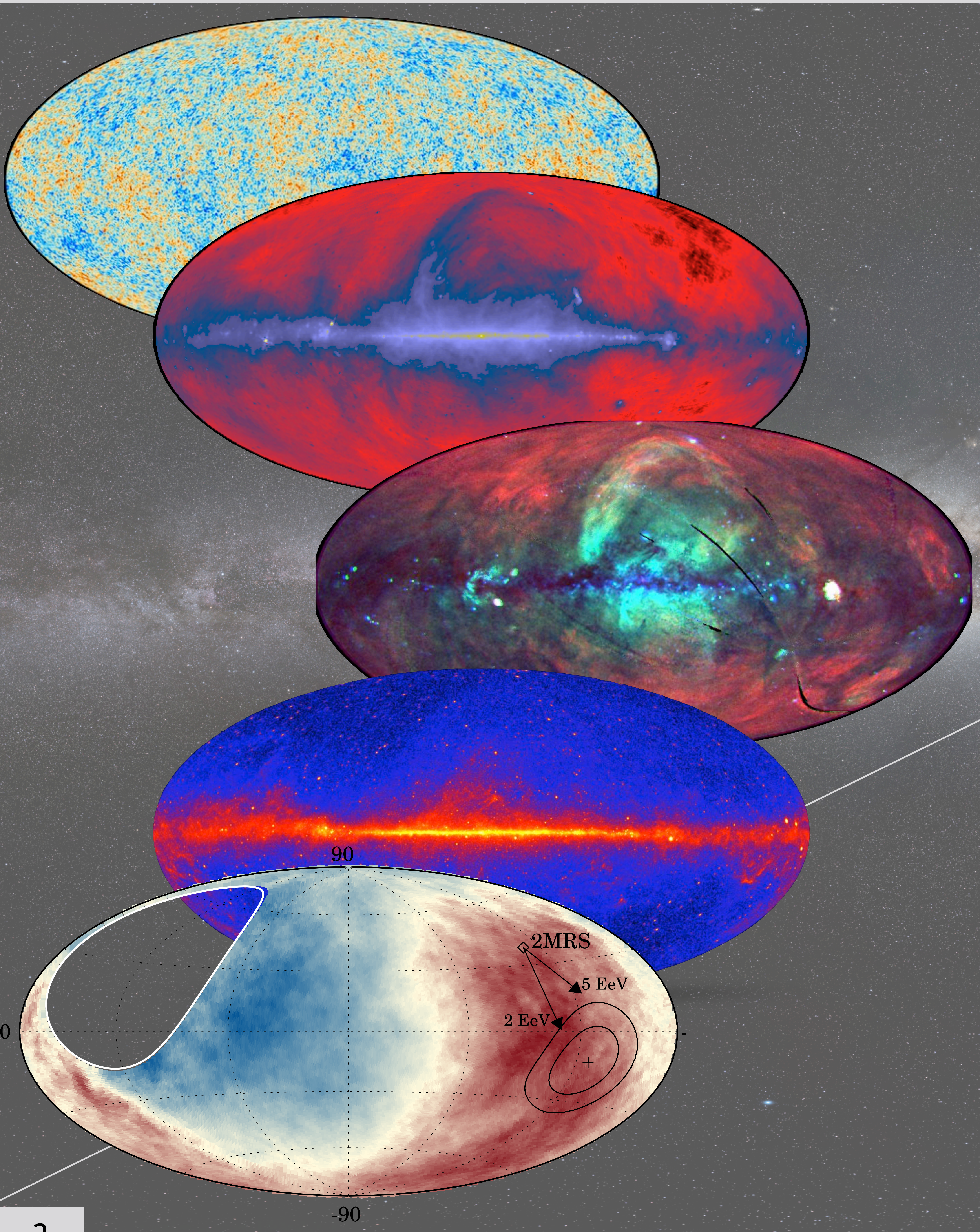


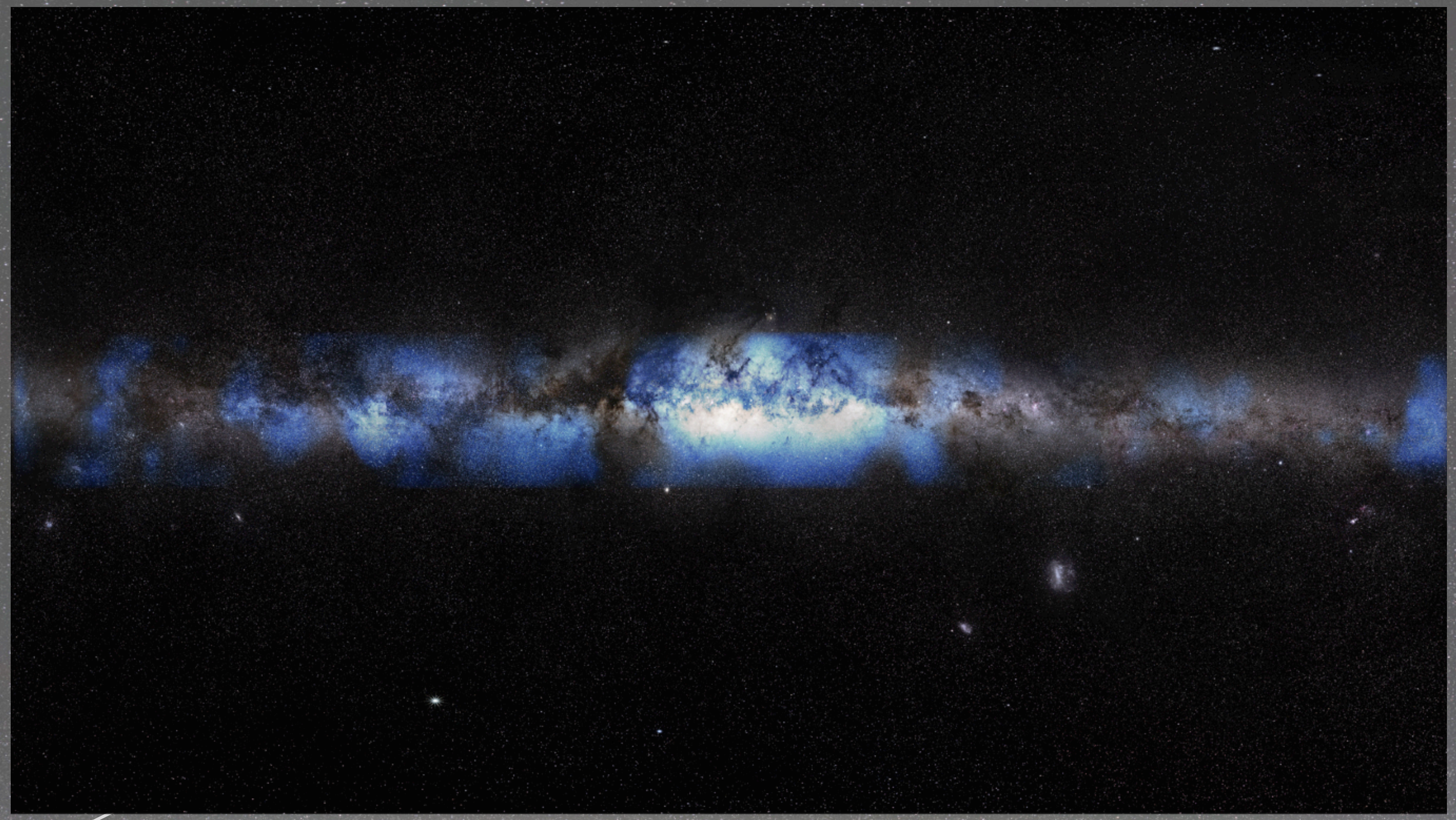
2nd VHEGam Meeting
28 May, 2025

motivation

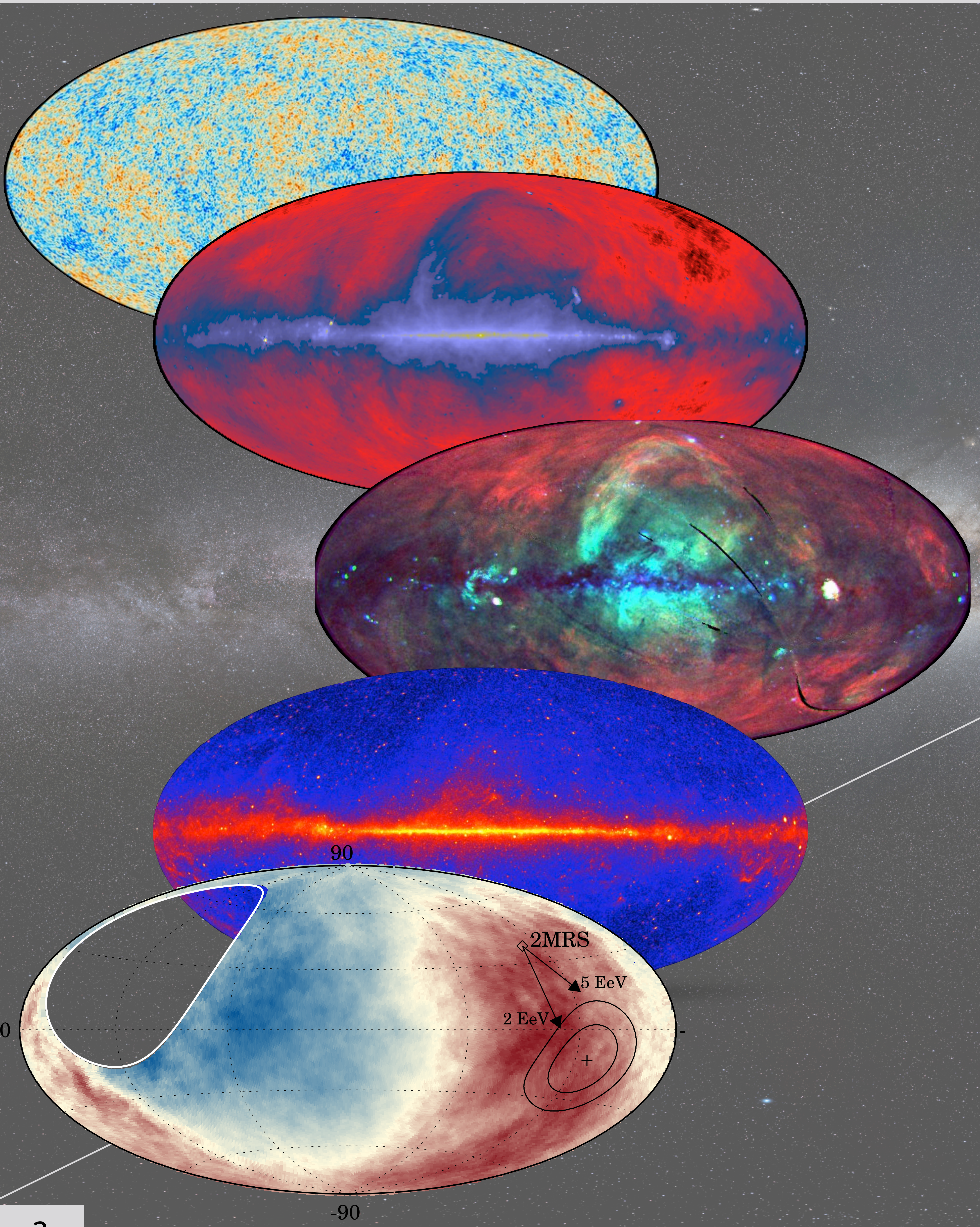

90
2MRS
5 EeV
2 EeV
-90

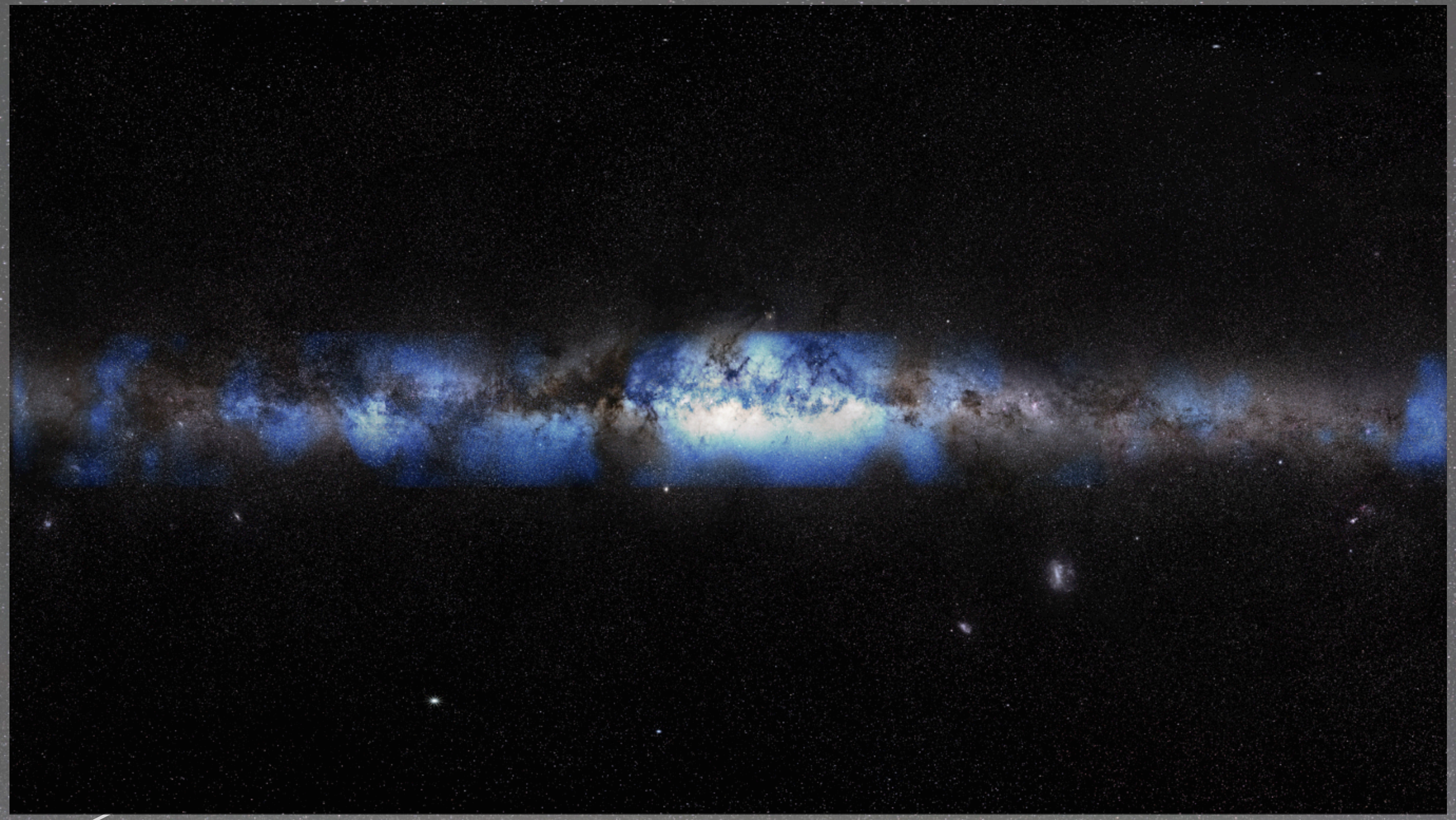

90
2MRS
5 EeV
2 EeV
-90



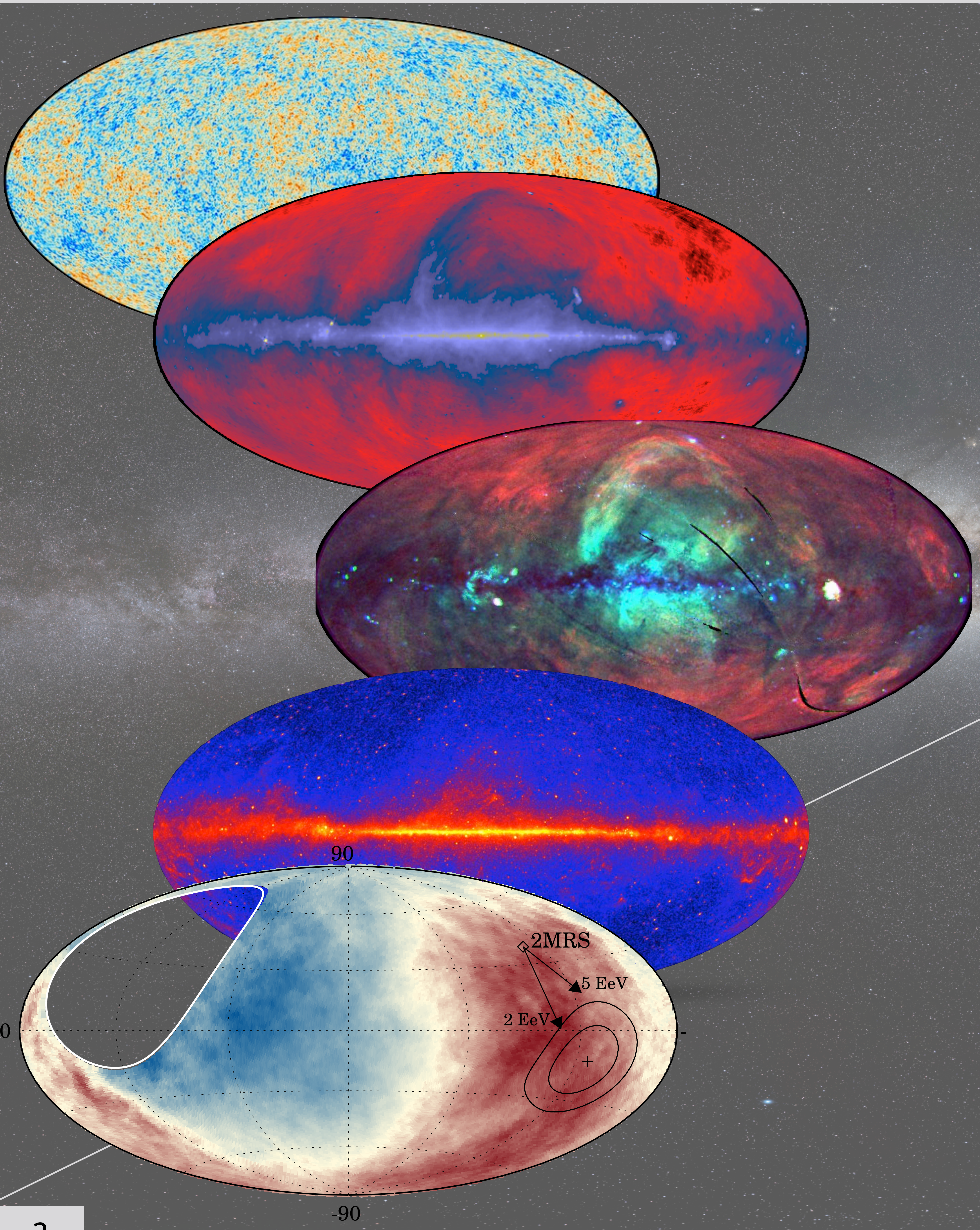


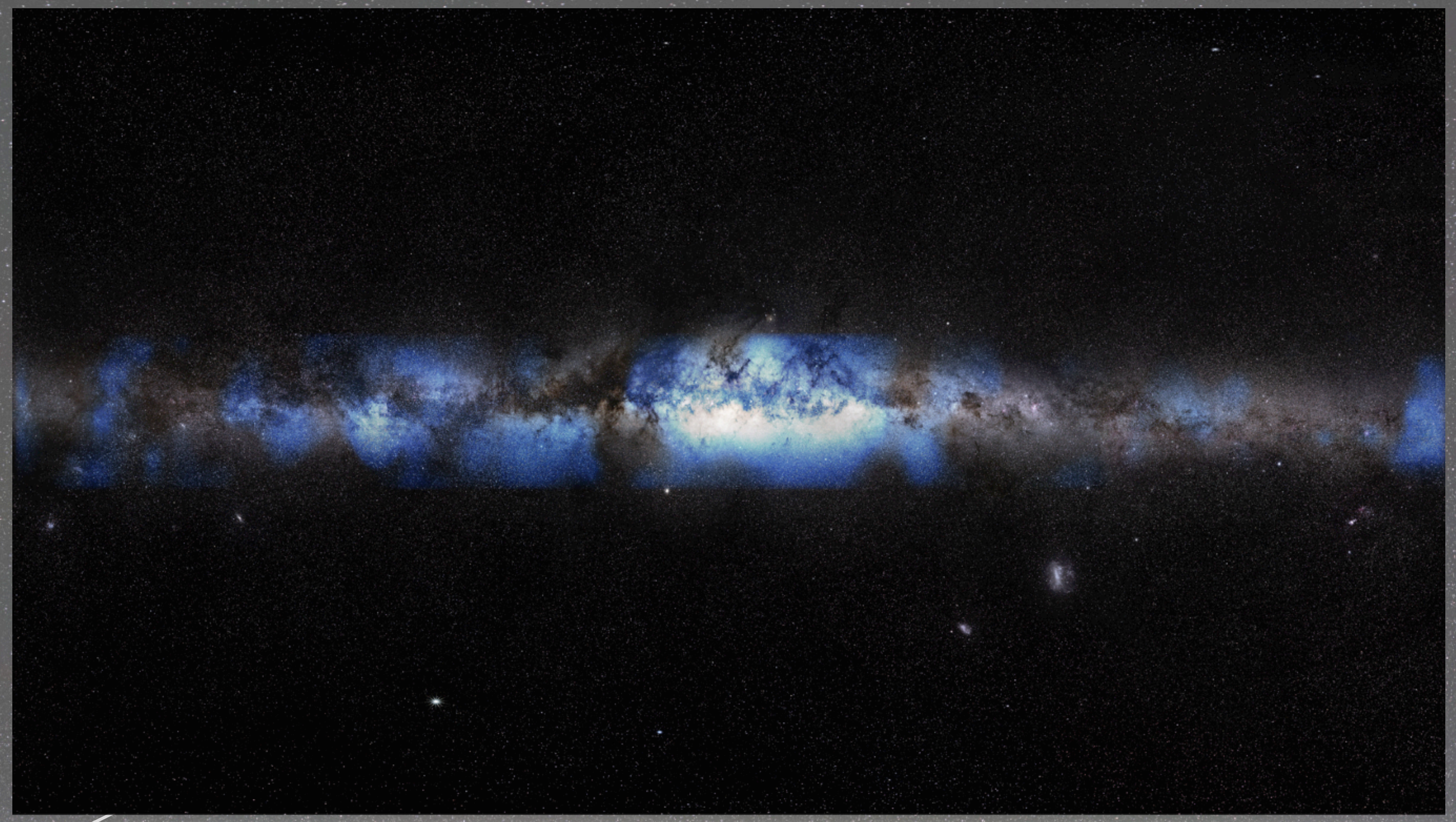
- do we **observe** high-energy cosmic messengers, or do we **detect** them?





- do we **observe** high-energy cosmic messengers, or do we **detect** them?
- "unobserved" processes in-between → **propagation**





- do we **observe** high-energy cosmic messengers, or do we **detect** them?
- "unobserved" processes in-between → **propagation**
- goal: build self-consistent picture of the universe

multimessenger propagation picture: cosmic rays


CR

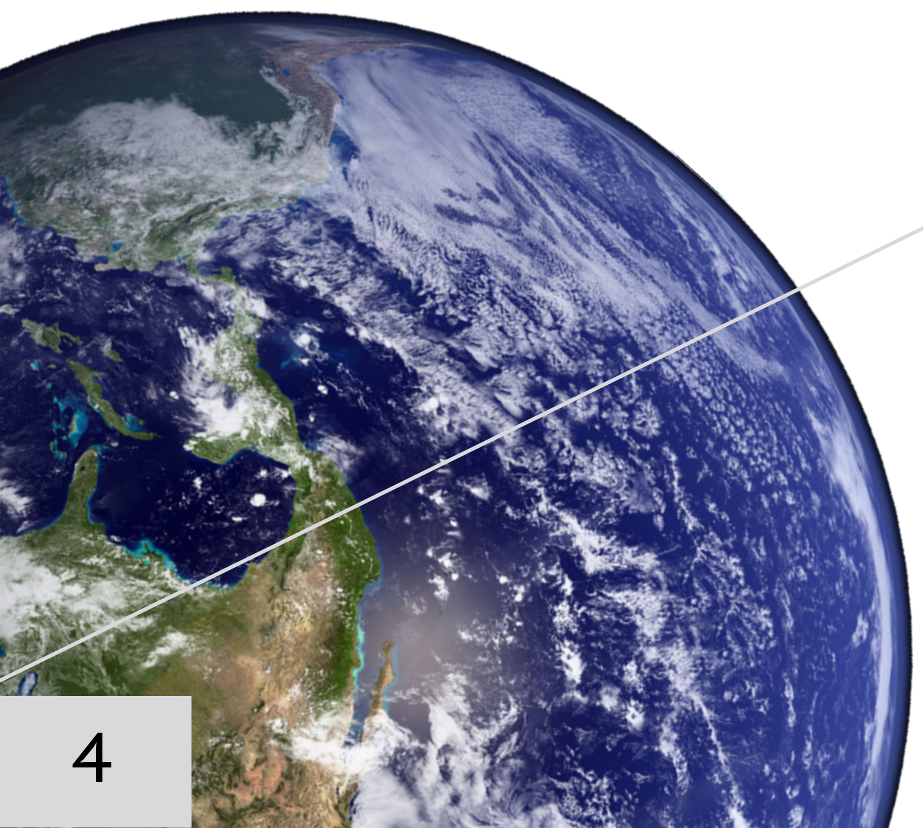

CR


CR
(secondary)
CR

multimessenger propagation picture: cosmic rays


CR
(secondary)
CR
cosmogenic ν
cosmogenic γ

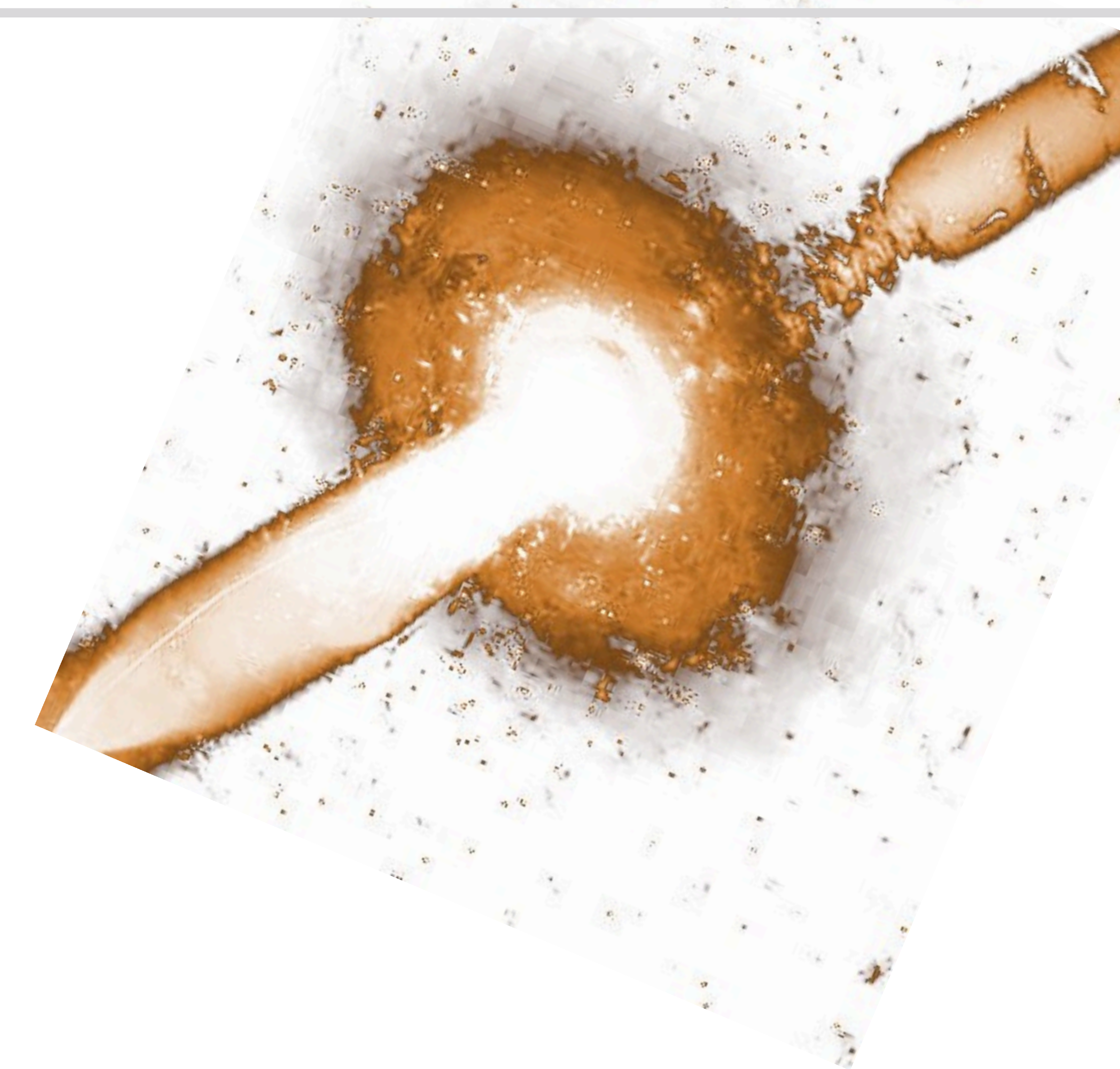
multimessenger propagation picture: neutrinos

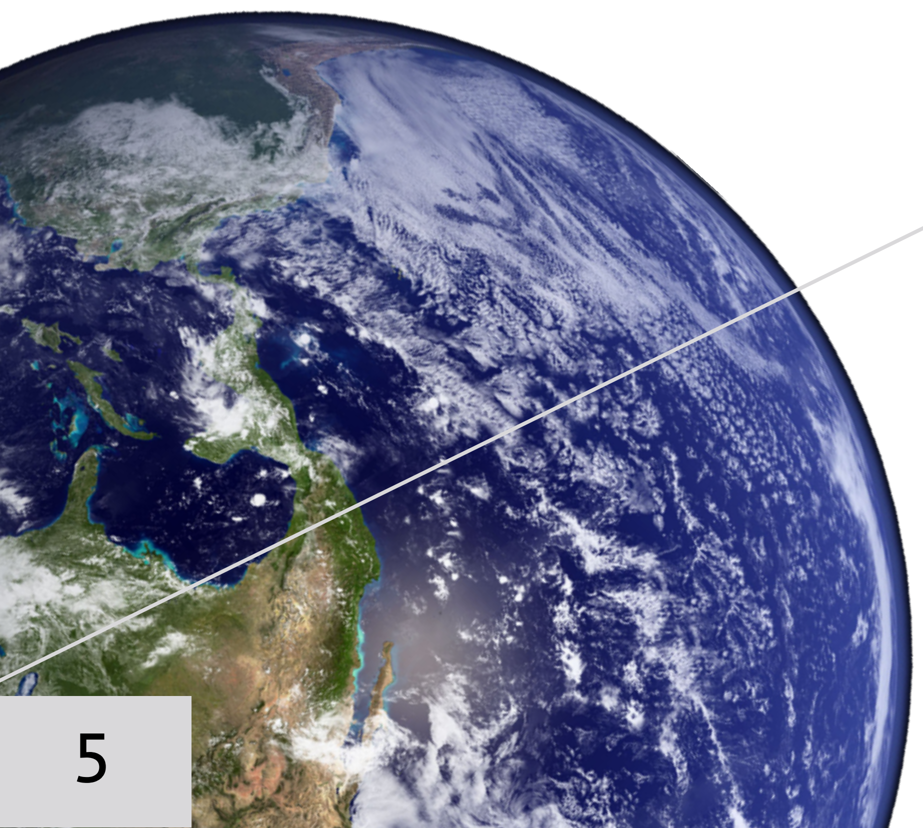



ν


ν
neutrino oscillations
τ
ν
e
μ

multimessenger propagation picture: gamma rays






γ

multimessenger propagation picture: gamma rays


γ
e-
e+
pair production
γ + γbg → e+ + e-


γ
e⁻
e⁺
pair production
$\gamma + \gamma_{bg} \rightarrow e^{+} + e^{-}$

multimessenger propagation picture: gamma rays

pair production

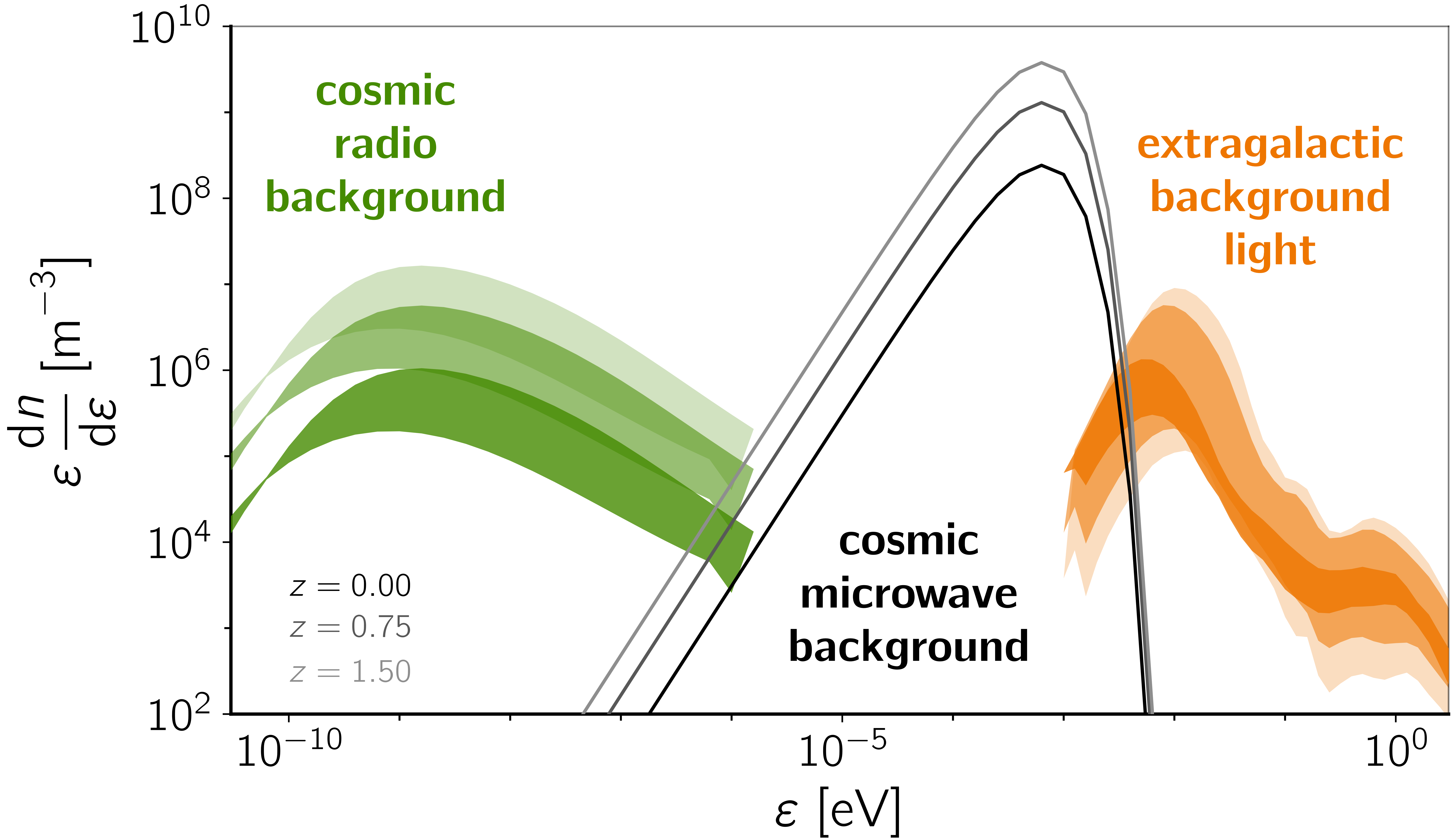
$\gamma + \gamma_{bg} \rightarrow e^+ + e^-$

inverse Compton scattering

$e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma$

multimessenger propagation picture: gamma rays

multimessenger propagation picture: gamma rays



cosmic radio background
extragalactic background light
cosmic microwave background
$z = 0.00$
$z = 0.75$
$z = 1.50$
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{-10}
10^{-5}
10^{0}
$\varepsilon \frac{dn}{d\varepsilon}$ [m^{-3}]
ε [eV]

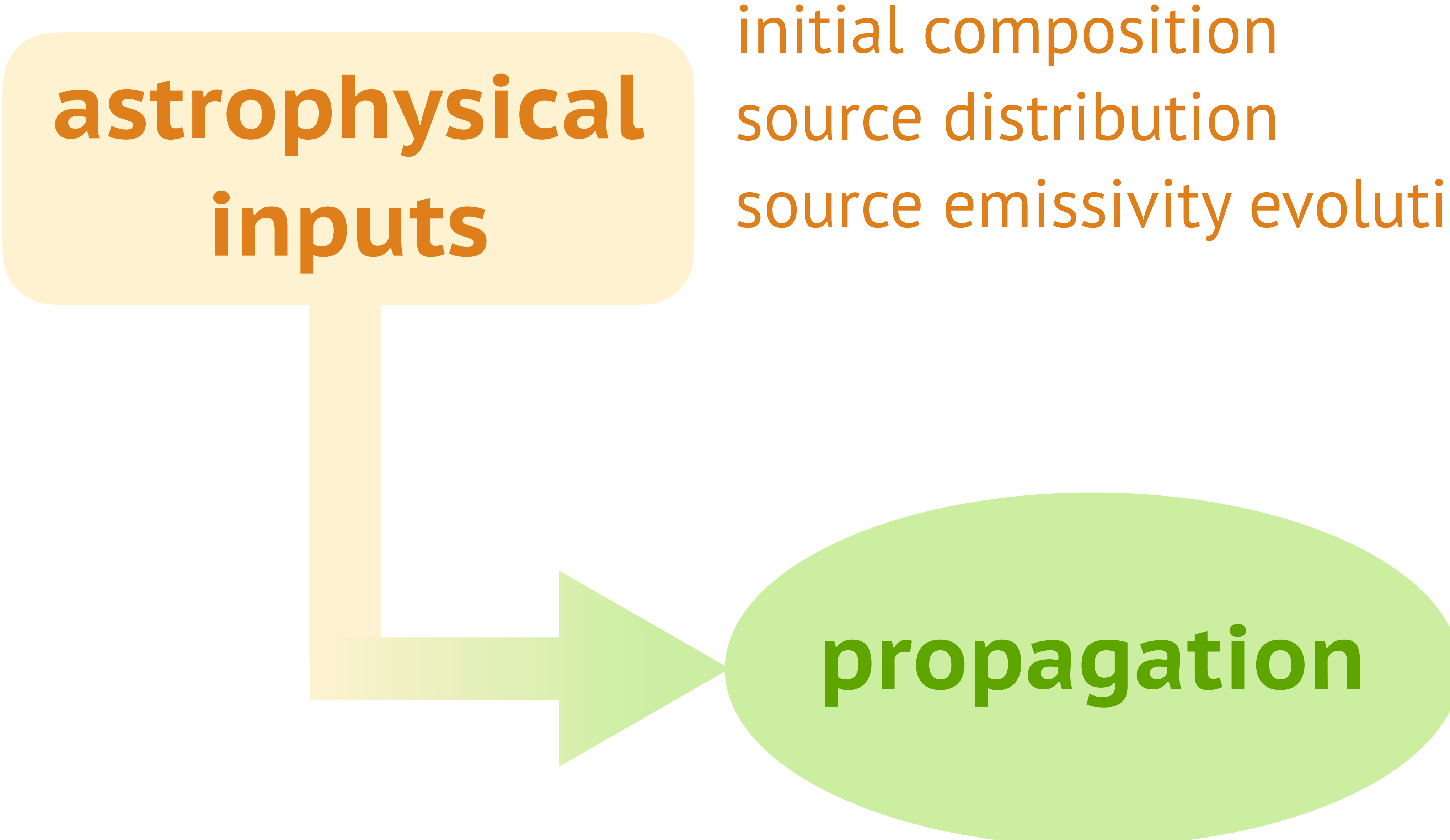
modelling the propagation

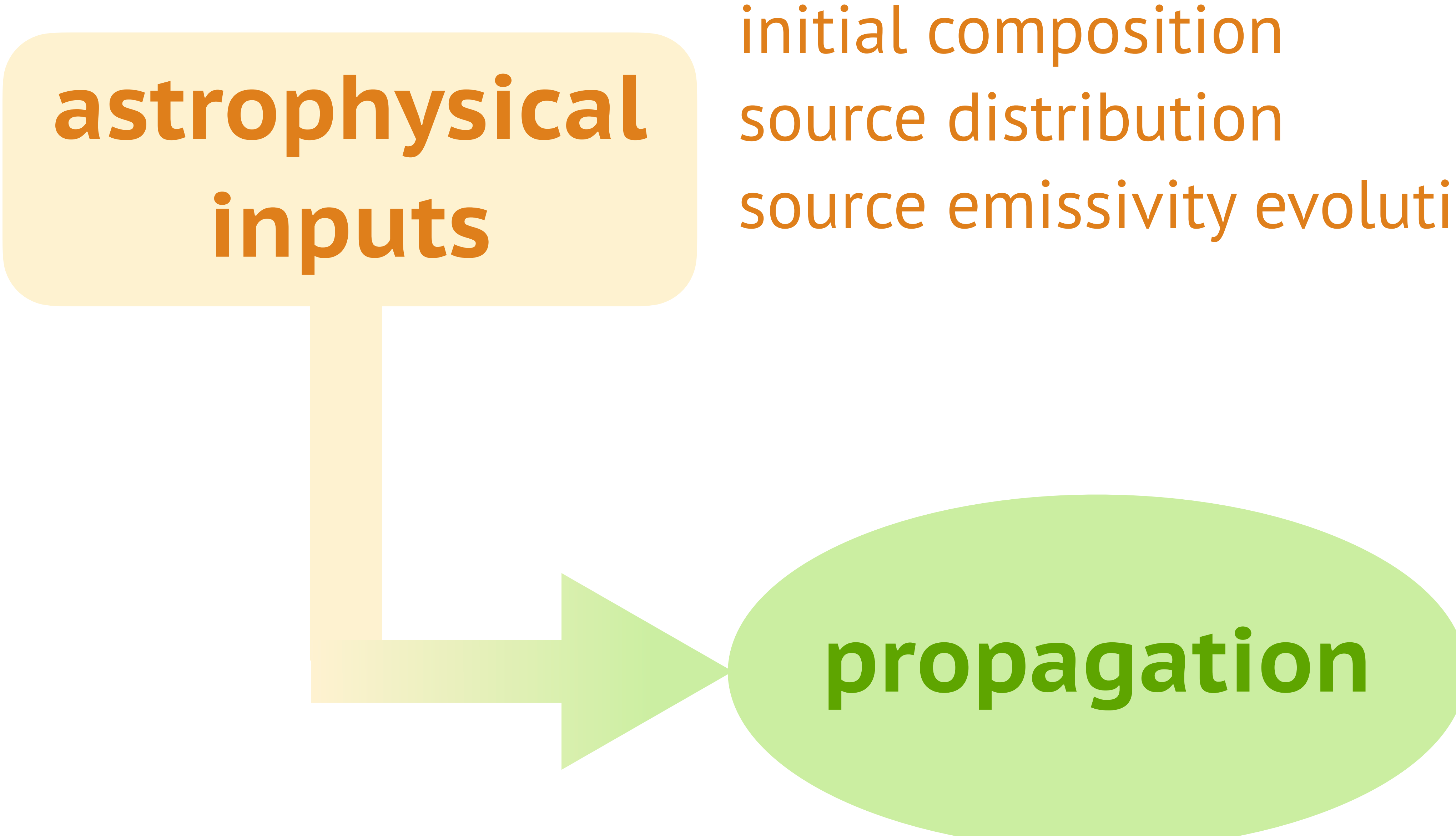
astrophysical inputs

astrophysical inputs

- injection spectrum
- initial composition
- source distribution
- source emissivity evolution

injection spectrum
initial composition
source distribution
source emissivity evolution





injection spectrum
initial composition
source distribution
source emissivity evolution

particle interactions
particle acceleration
background photon fields
background matter fields
magnetic fields

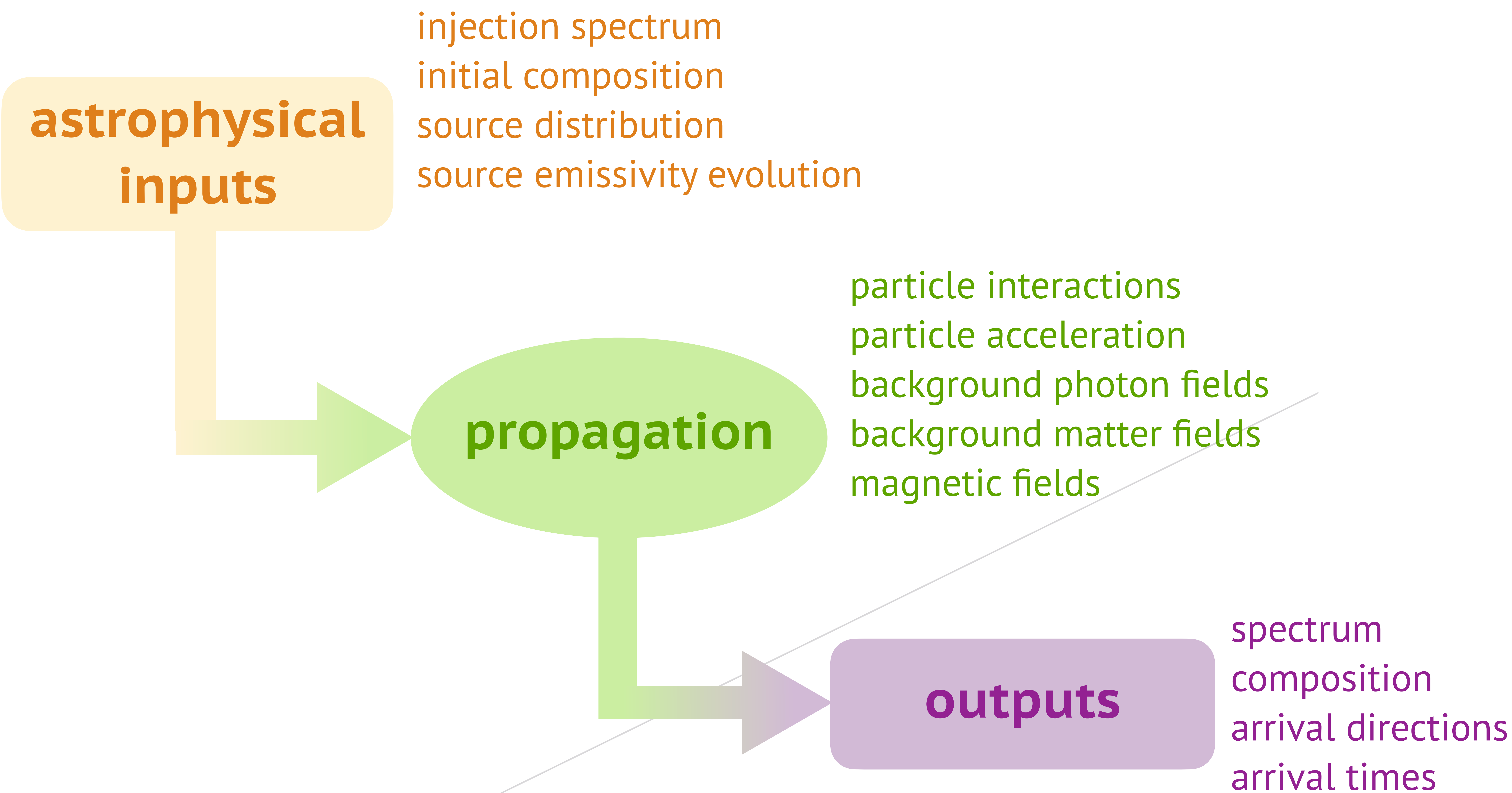
astrophysical inputs

- injection spectrum
- initial composition
- source distribution
- source emissivity evolution

propagation

- particle interactions
- particle acceleration
- background photon fields
- background matter fields
- magnetic fields

outputs


injection spectrum
initial composition
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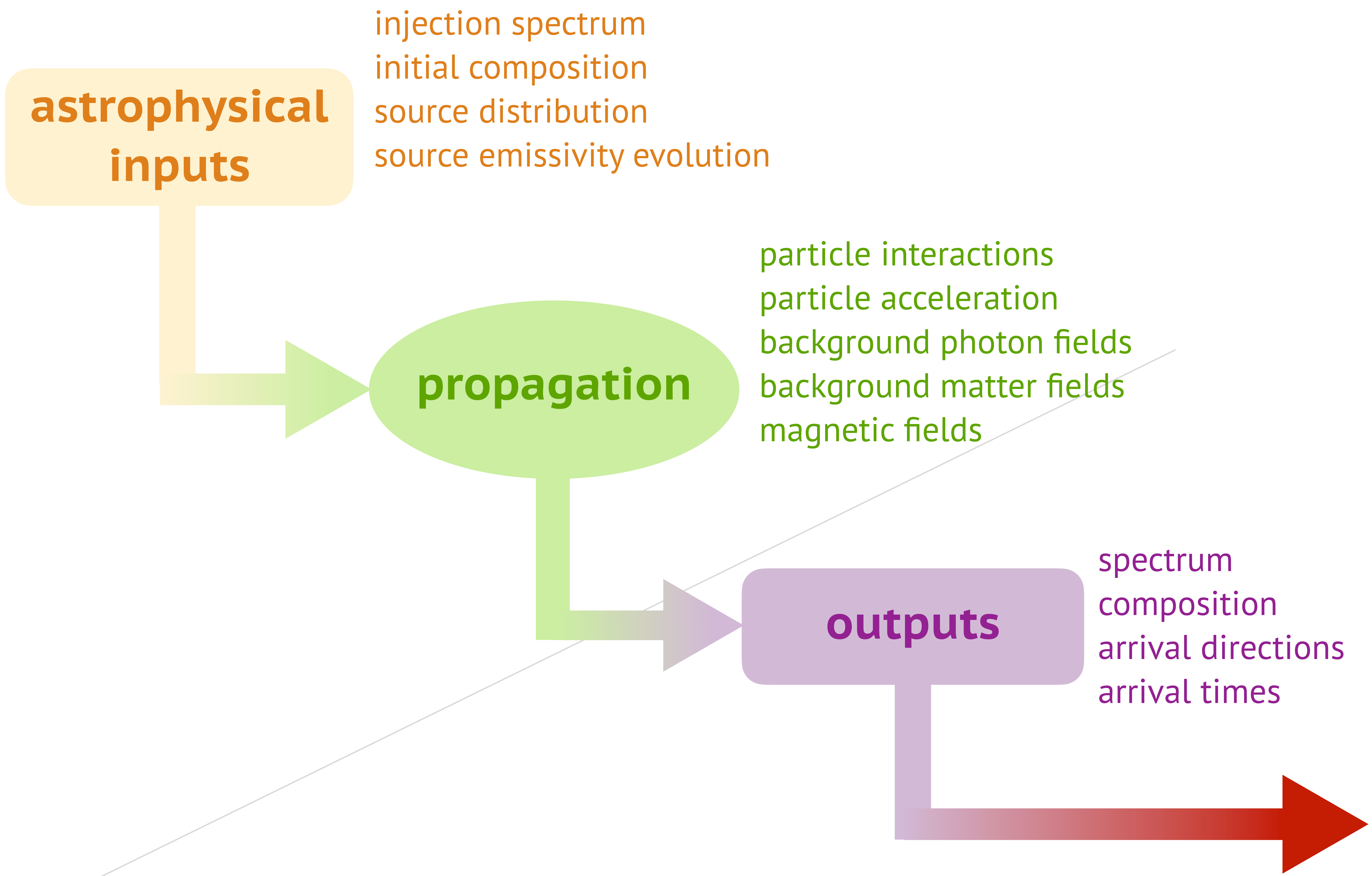
particle interactions
particle acceleration
background photon fields
background matter fields
magnetic fields
propagation
spectrum
composition
arrival directions
arrival times
outputs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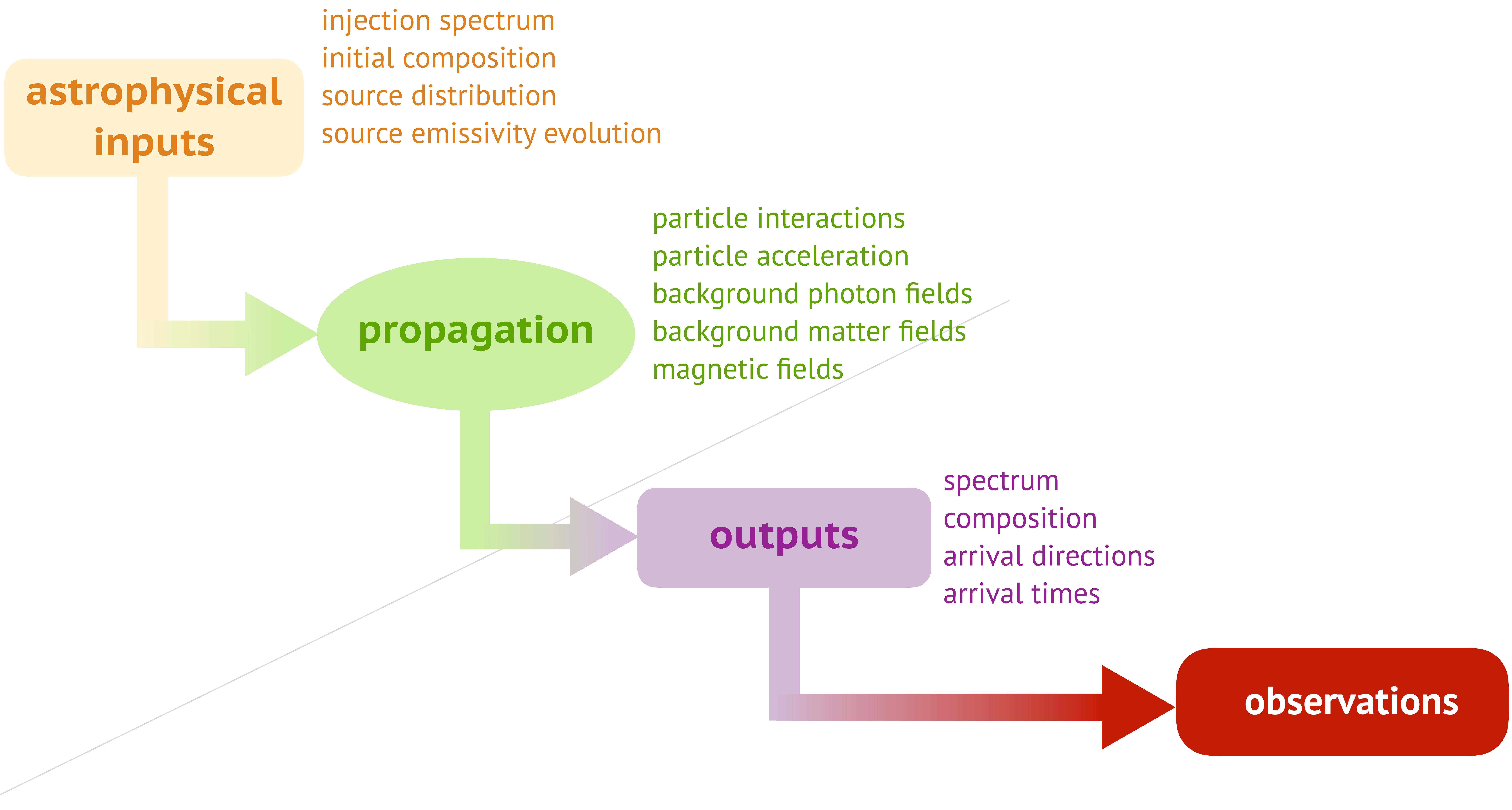
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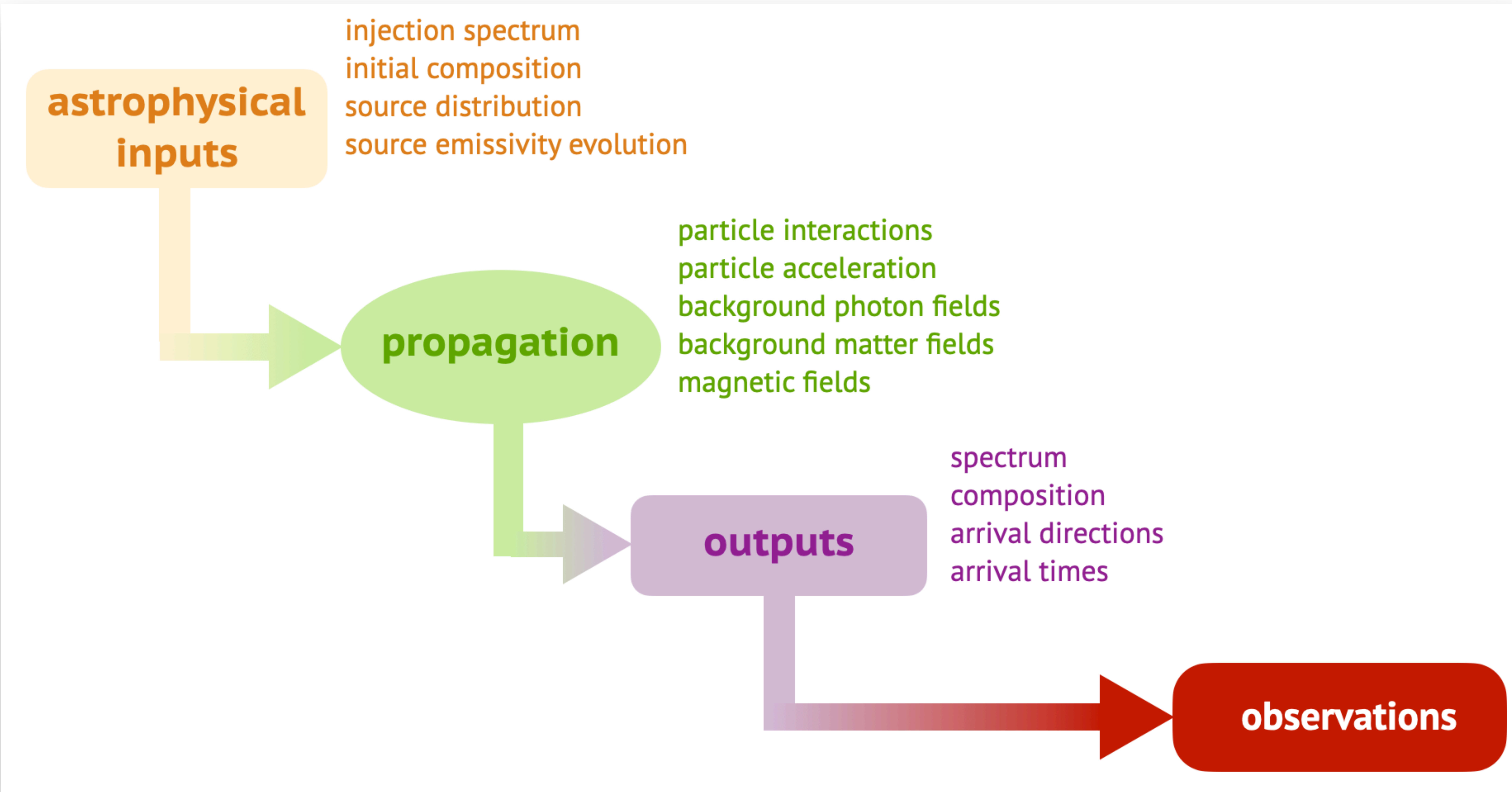
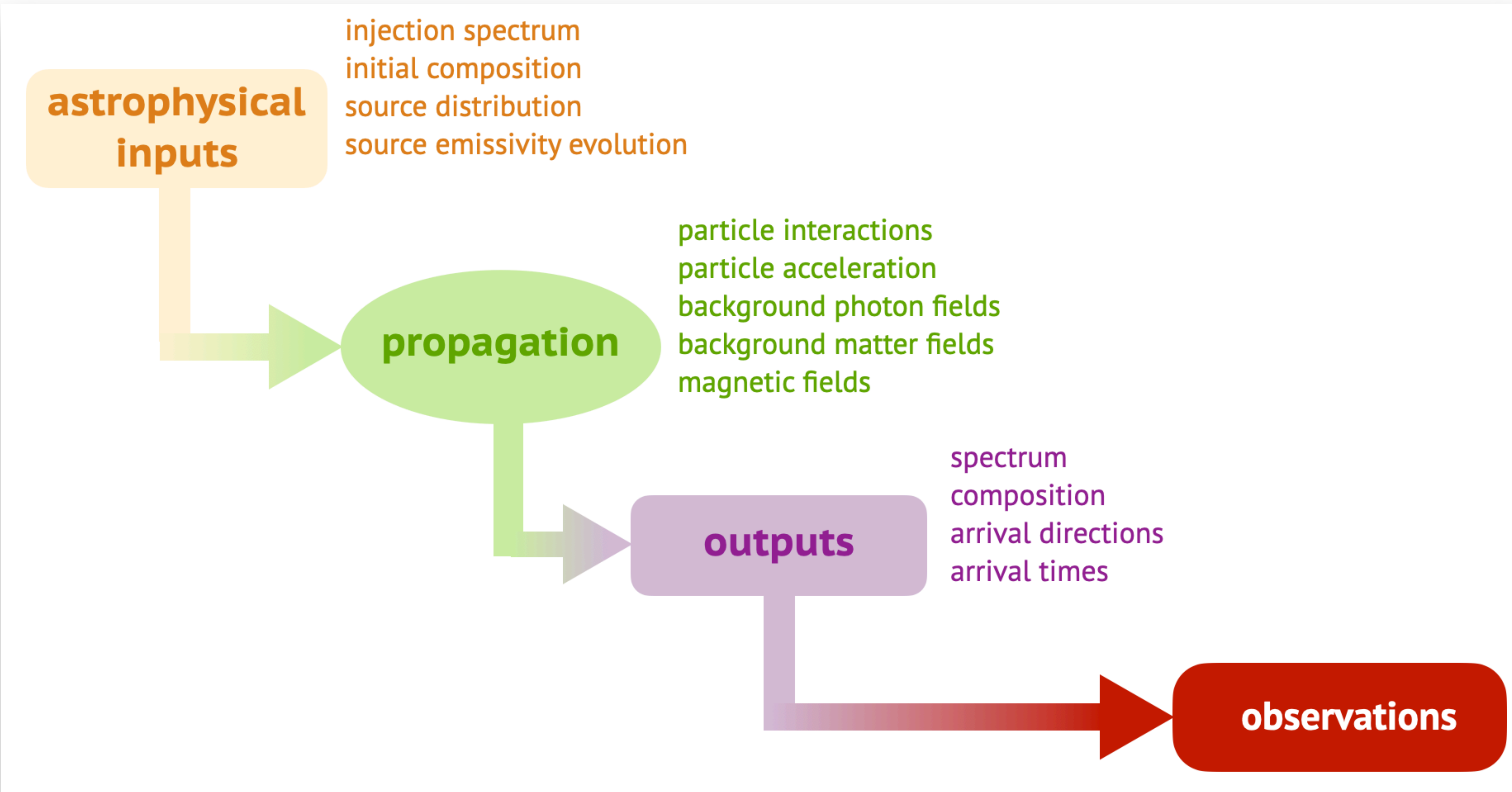
outputs
spectrum
composition
arrival directions
arrival times
observations

modelling the propagation of high-energy cosmic messengers

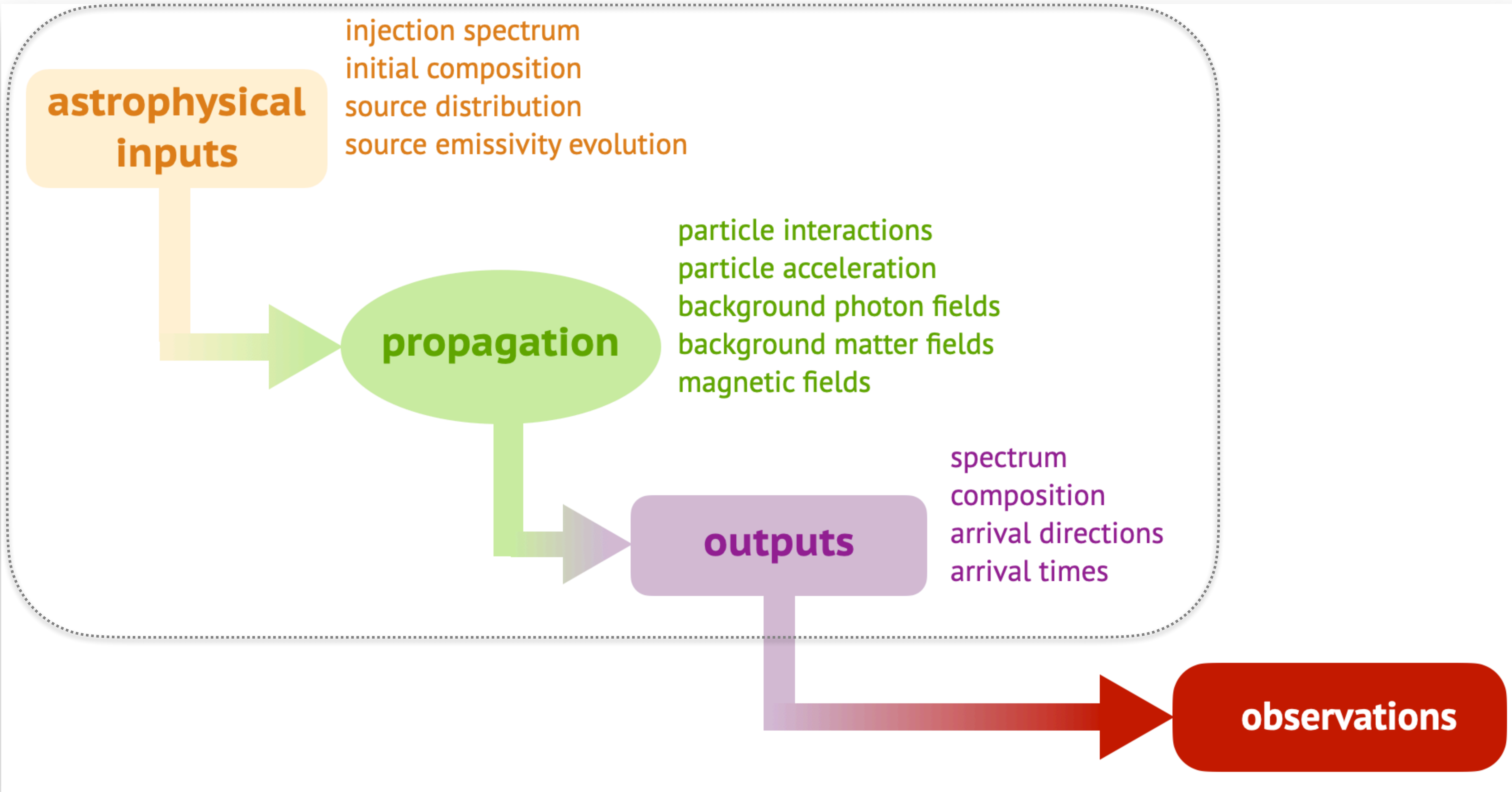


modelling the propagation of high-energy cosmic messengers



- mixing all ingredients → interpret (fit) observations based on models

modelling the propagation of high-energy cosmic messengers



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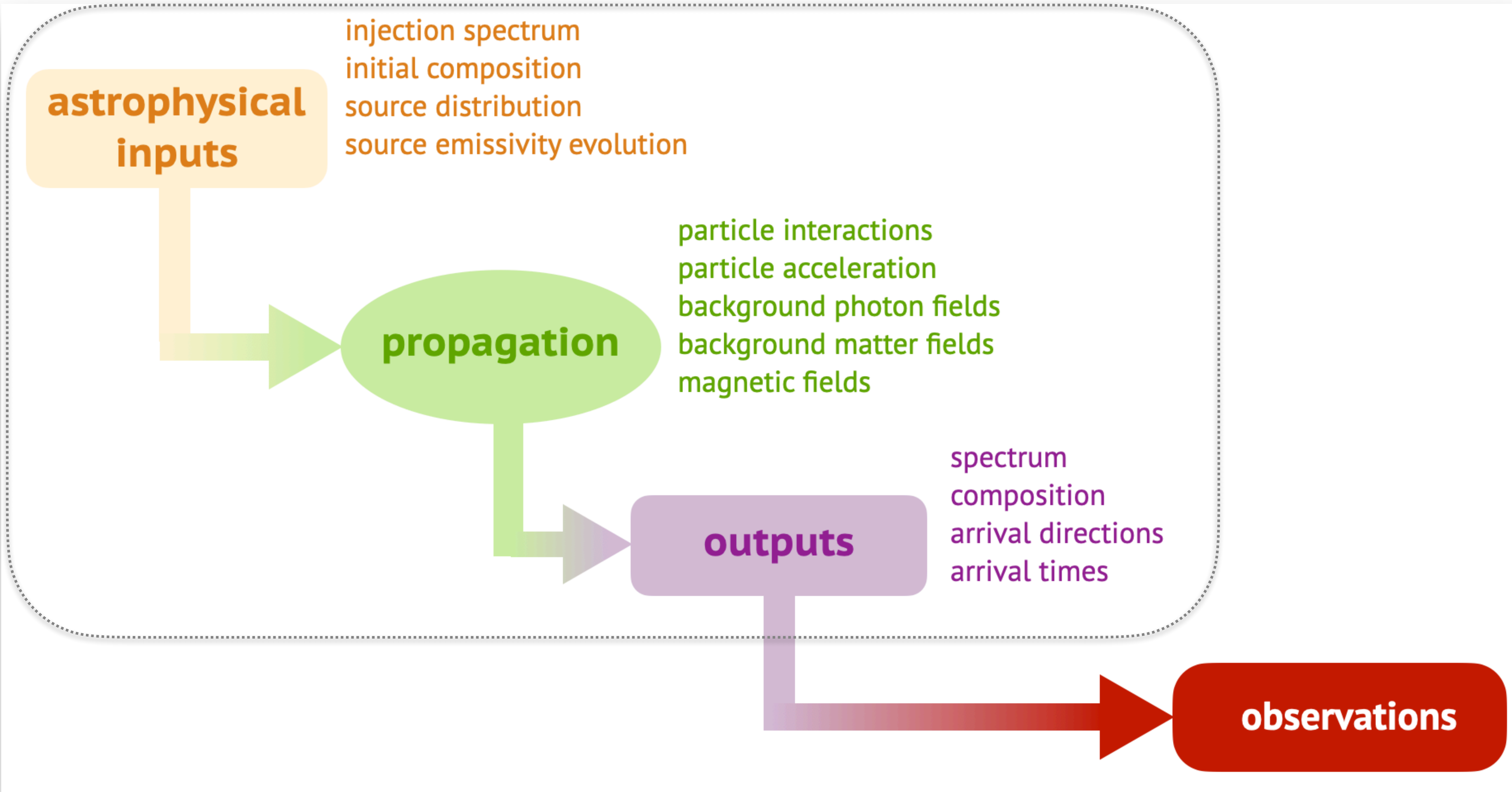

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- this should be done ***self-consistently for all messengers***

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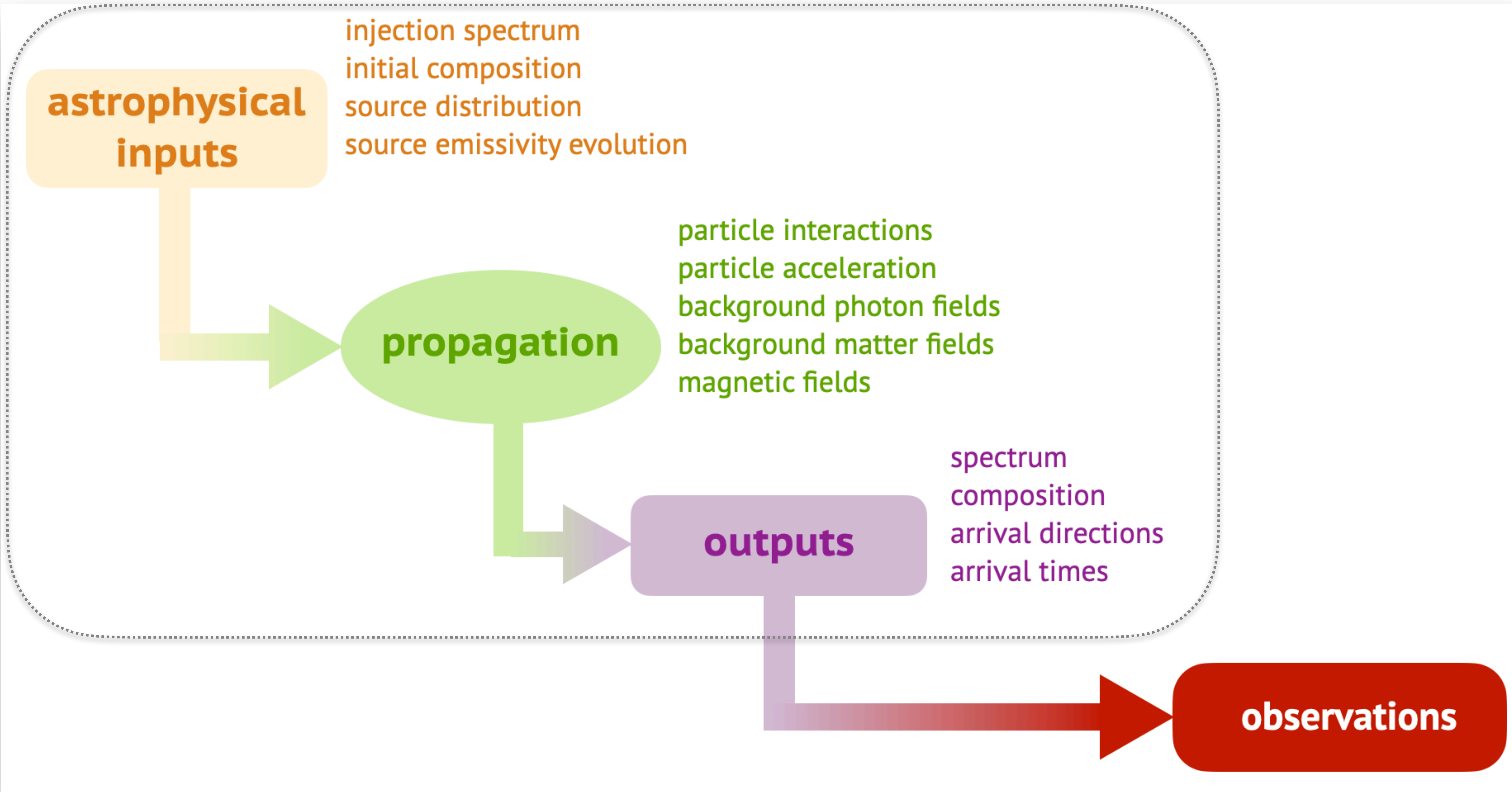

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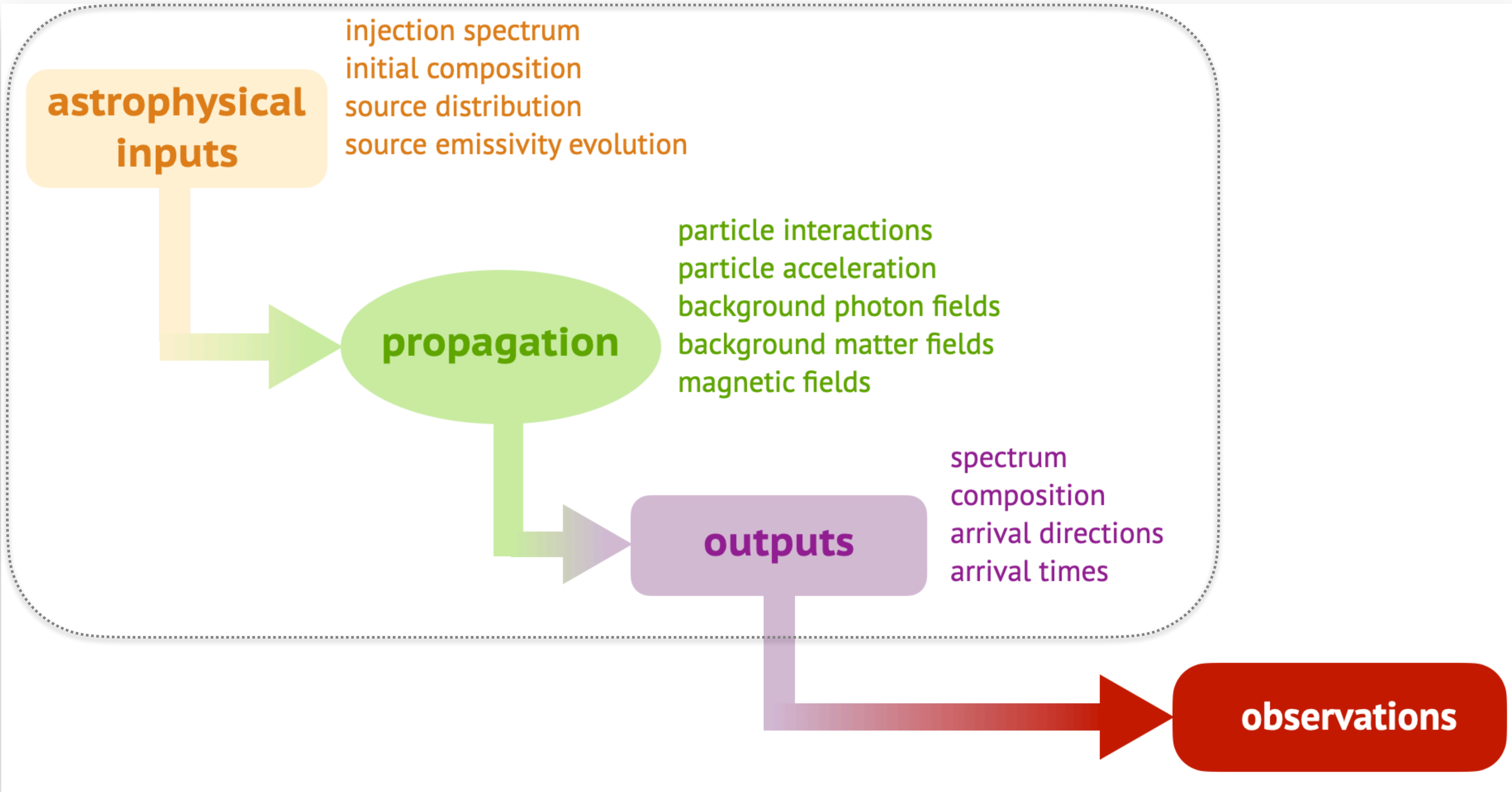
modelling the propagation of high-energy cosmic messengers



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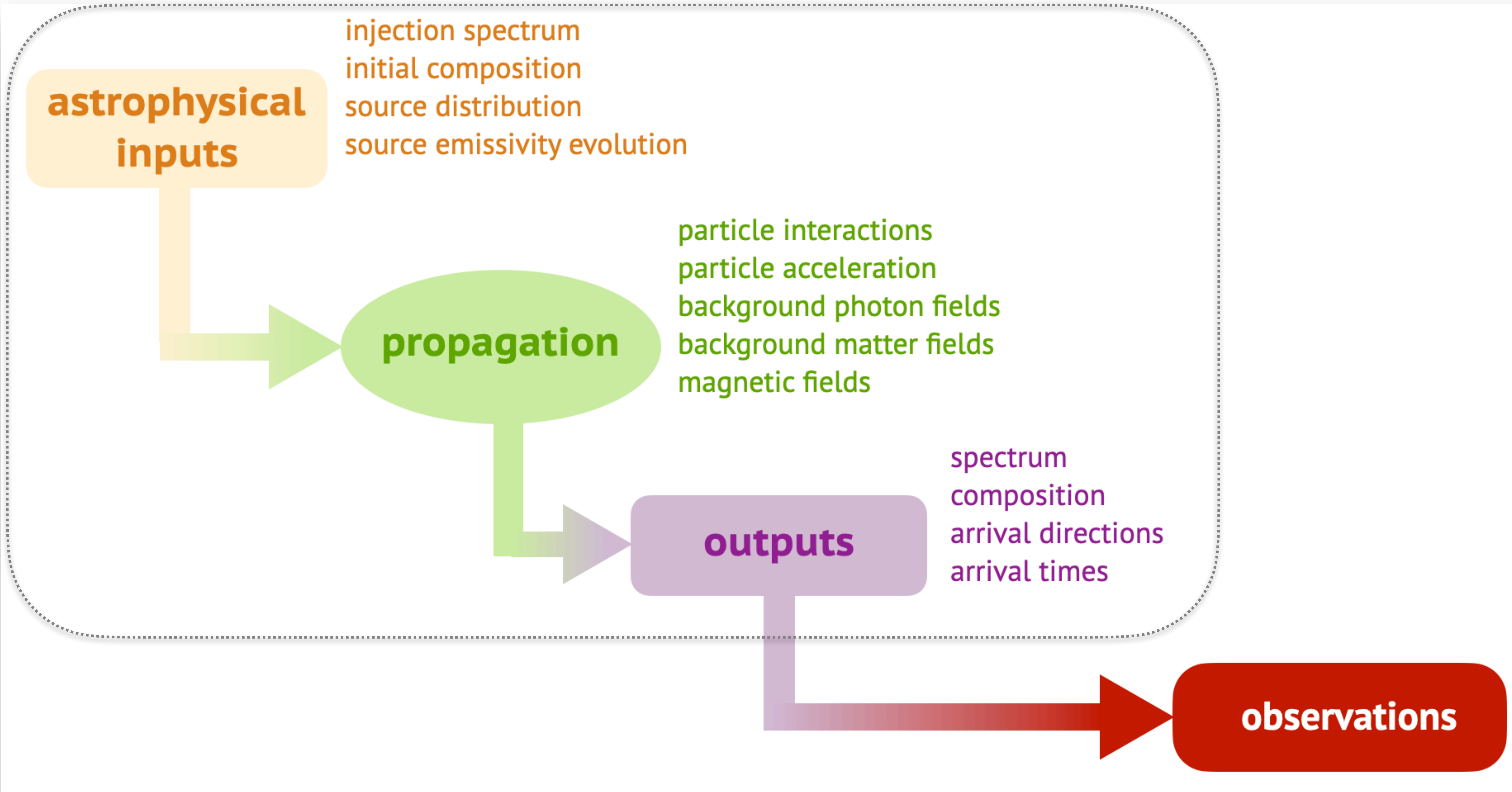

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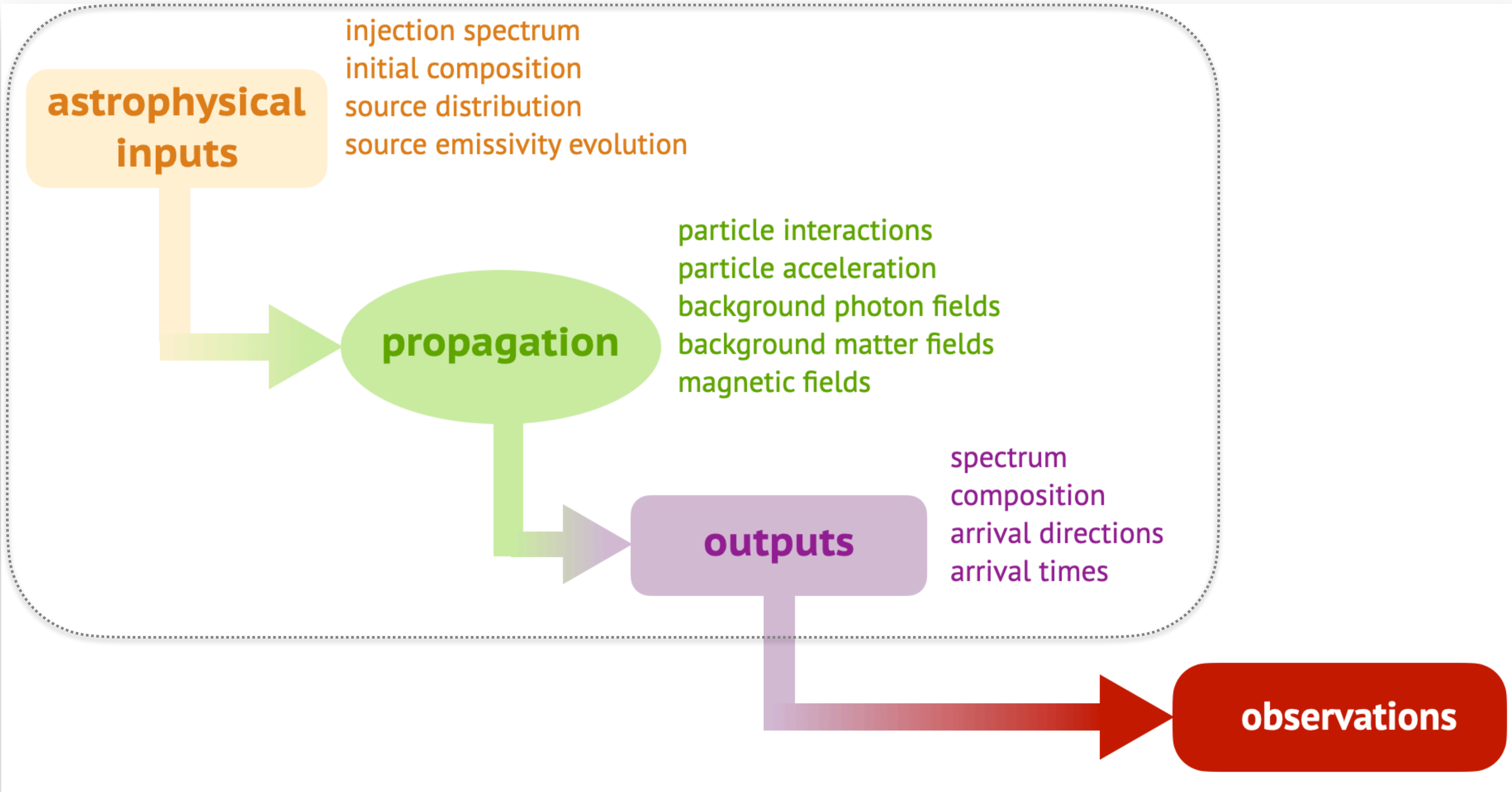
→ **multimessenger simulation framework**

modelling the propagation of high-energy cosmic messengers



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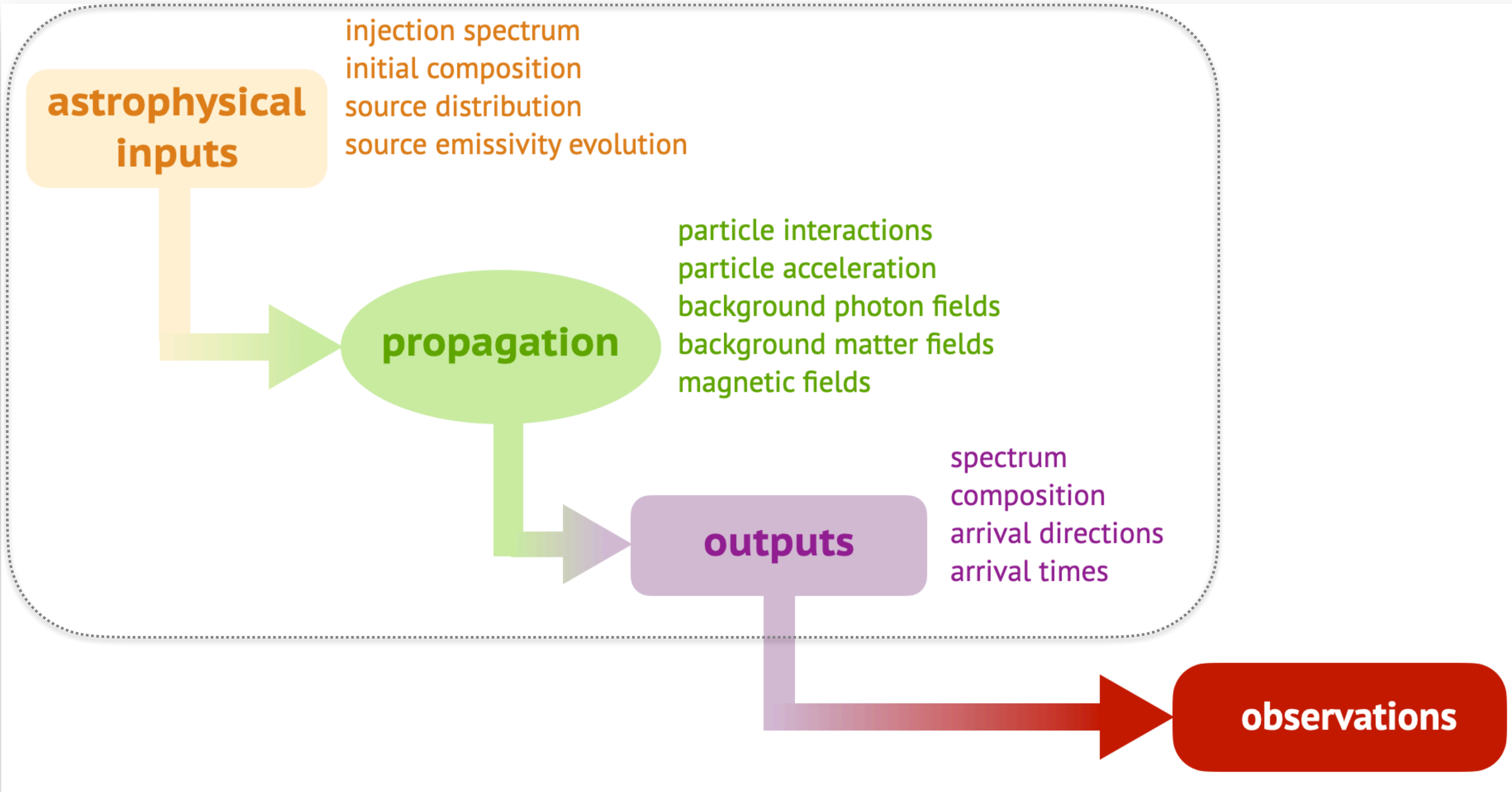
multimessenger simulation framework



CRPropa

- mixing all ingredients → interpret (fit) observations based on models
- this should be done ***self-consistently for all messengers***
- need to ***scan full parameter space*** of uncertainties

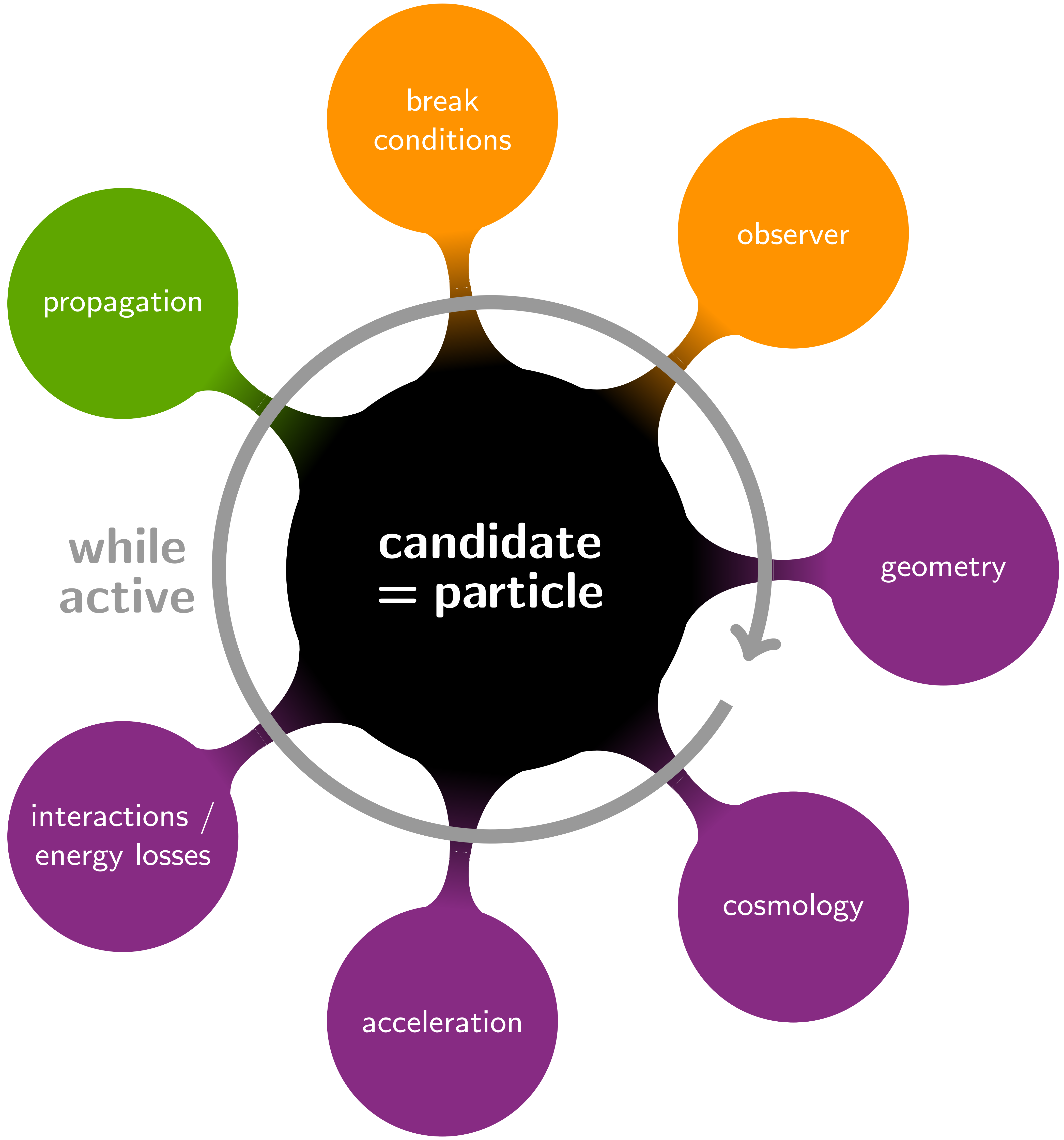
multimessenger simulation framework

the CRPropa framework

the CRPropa framework for astroparticle propagation

Alves Batista et al. JCAP 05 (2016) 038. arXiv:1603.07142
Alves Batista et al. JCAP 09 (2022) 035. arXiv:2208.00107

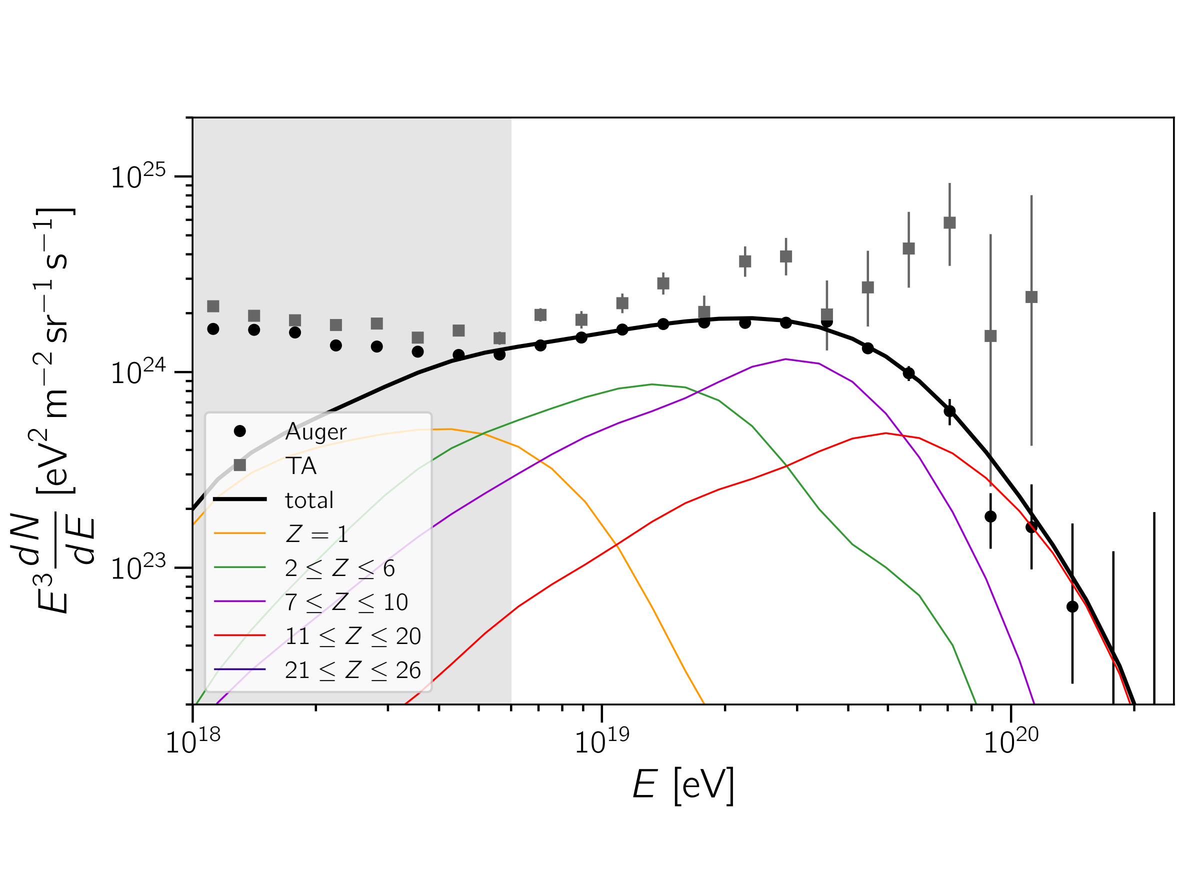
- publicly available Monte Carlo code
- propagation of high-energy cosmic rays, gamma rays, neutrinos, and electrons
- Galactic and extragalactic propagation
- modular structure
- parallelisation with OpenMP
- development on Github: https://github.com/CRPropa/CRPropa3



crpropa.desy.de

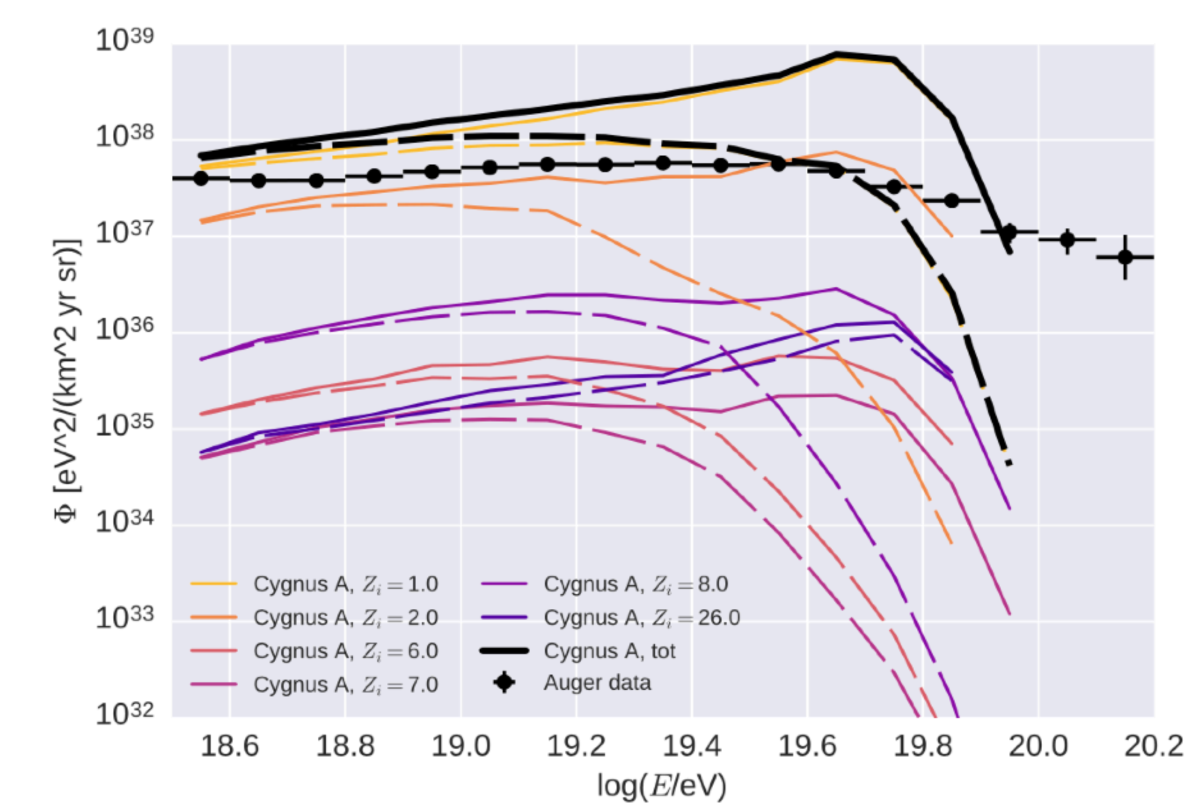
applications

fit UHECR measurements



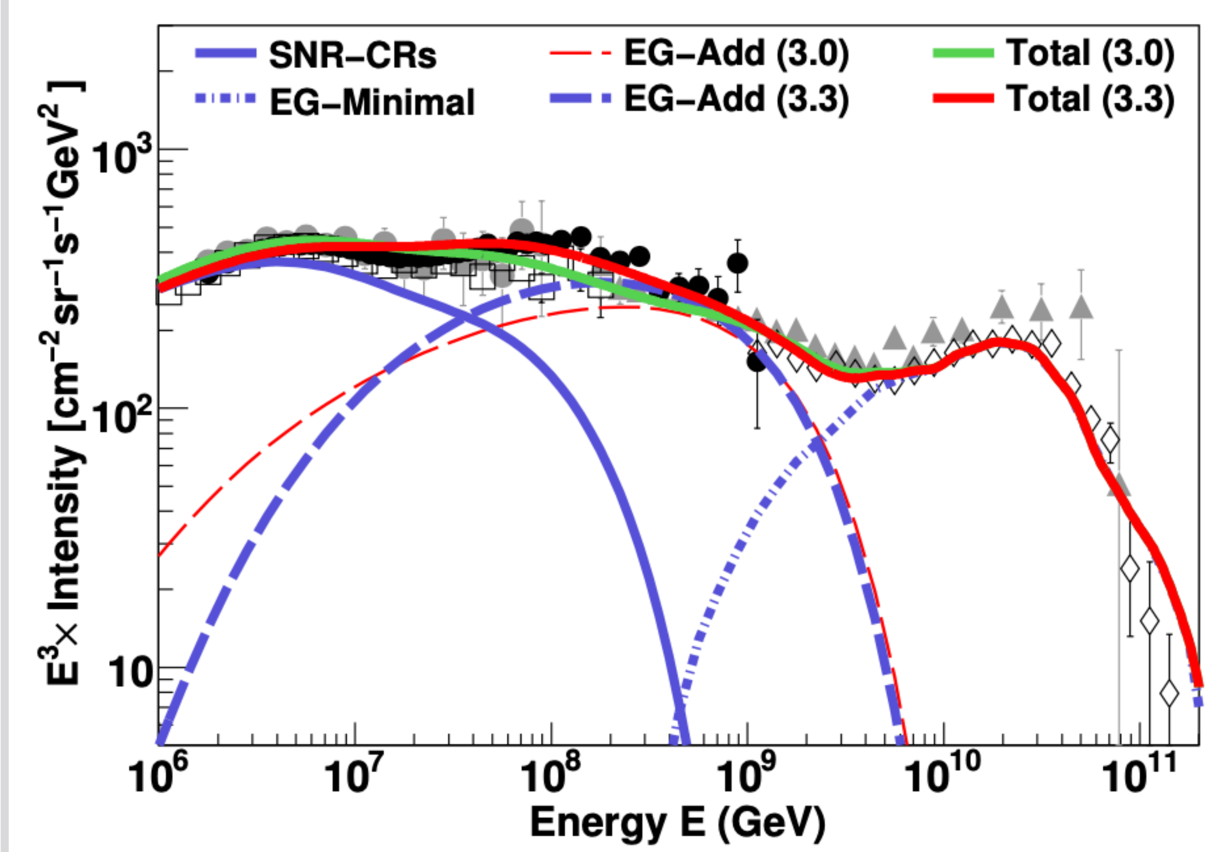
Alves Batista, de Almeida, Lago, Kotera. JCAP 01 (2019) 002. arXiv:1806.10879

test UHECR source models



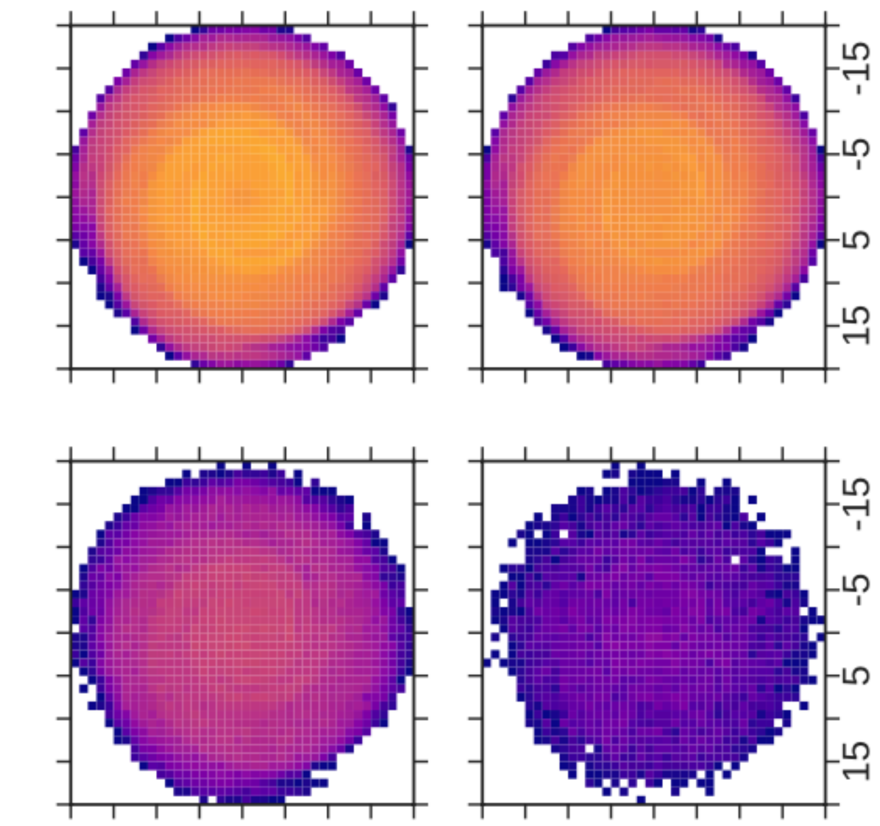
Eichmann et al. JCAP 02 (2018) 036. arXiv:1701.06792

transition G-EG CRs



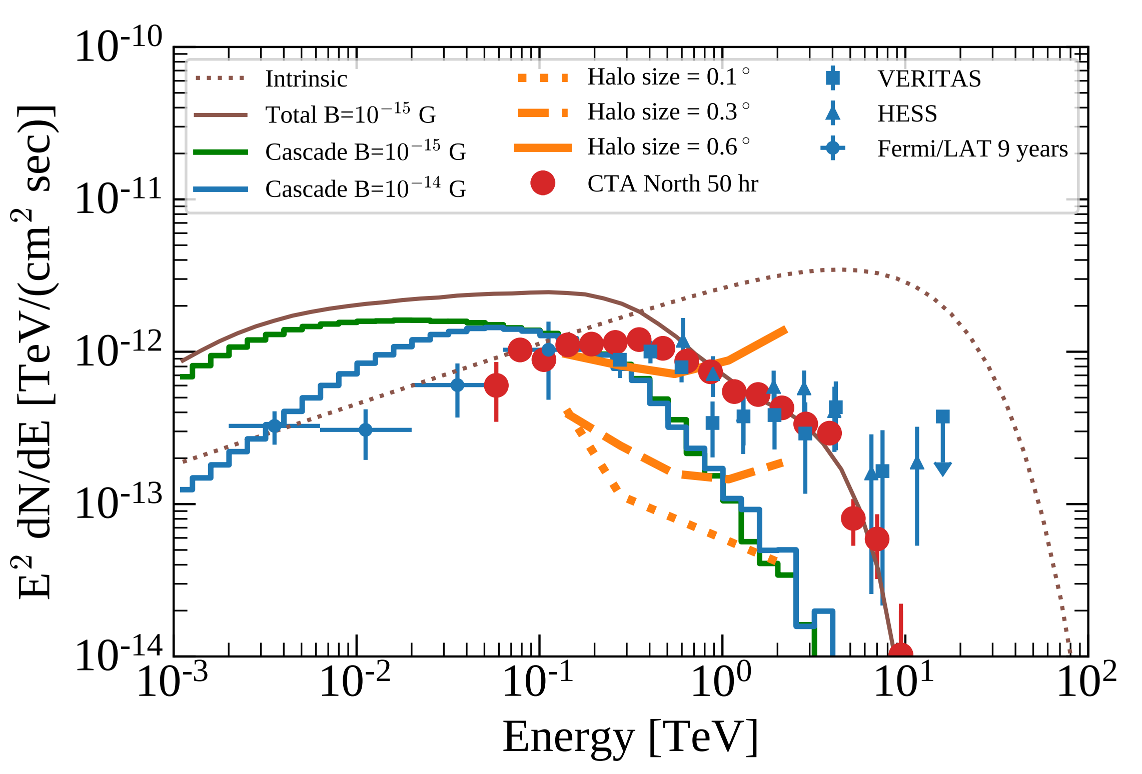
Thoudam et al. Astron. Astrophys. 595 (2016) A33. arXiv:1605.03111

diffusion of Galactic CRs



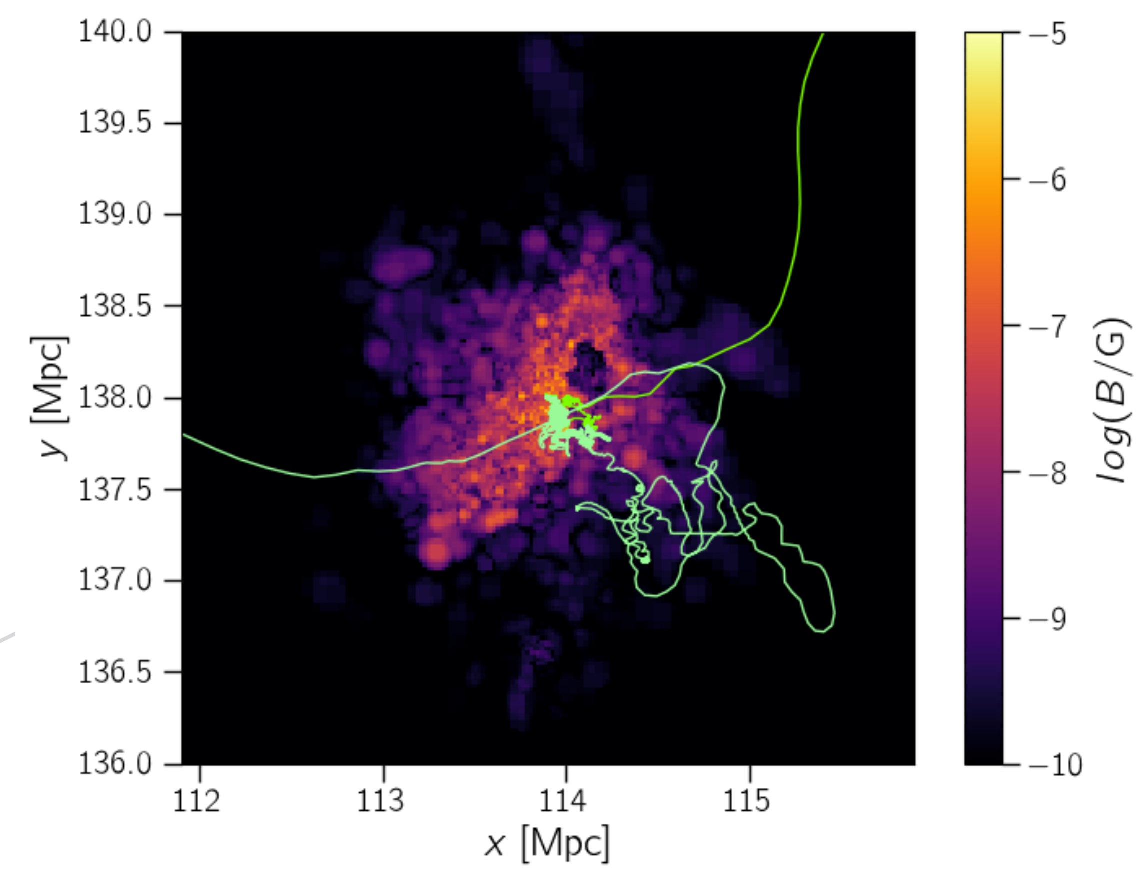
Merten et al. JCAP 06 (2016) 046. arXiv:1704.07484

gamma rays + IGMFs



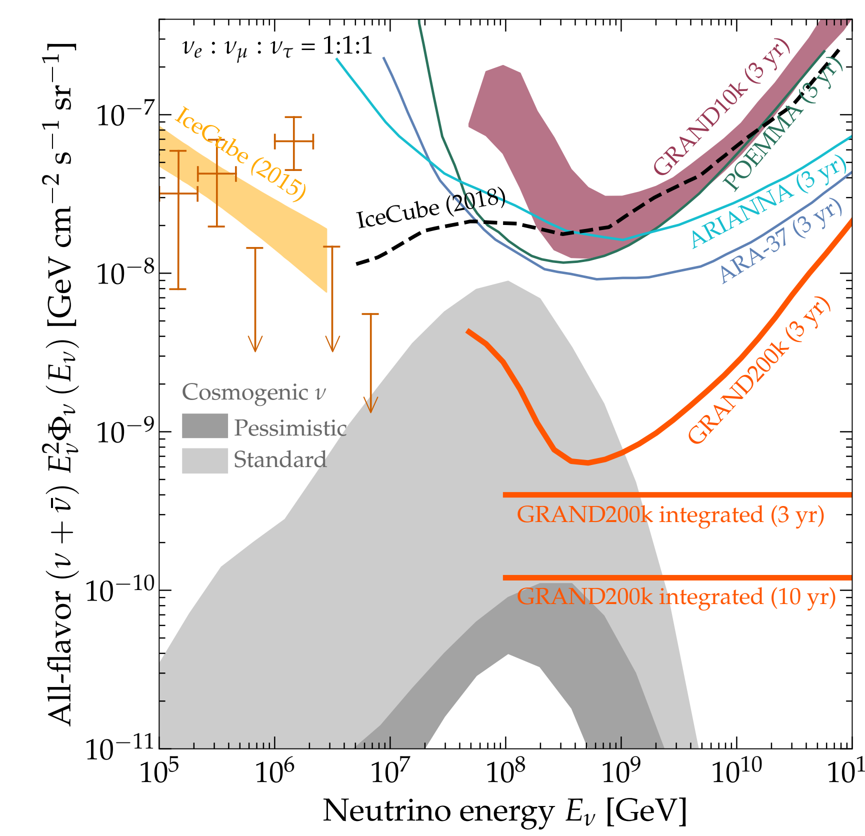
CTA Consortium. JCAP 02 (2021) 048. arXiv:2010.01349

neutrinos from galaxy clusters



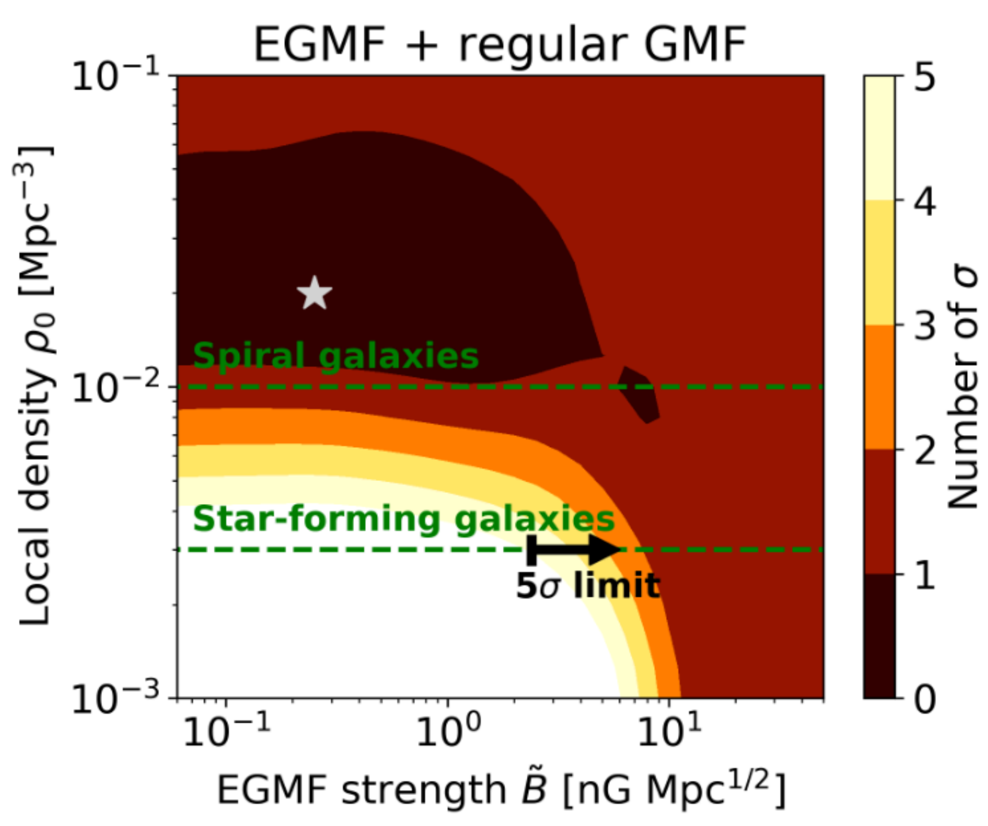
Hussain, Alves Batista, de Gouveia Dal Pino. Nature Comms 14 (2023) 2486. arXiv:2101.07702

cosmogenic neutrinos



GRAND Collaboration. Science China Phys 63 (2020) 219501. arXiv:1810.09994

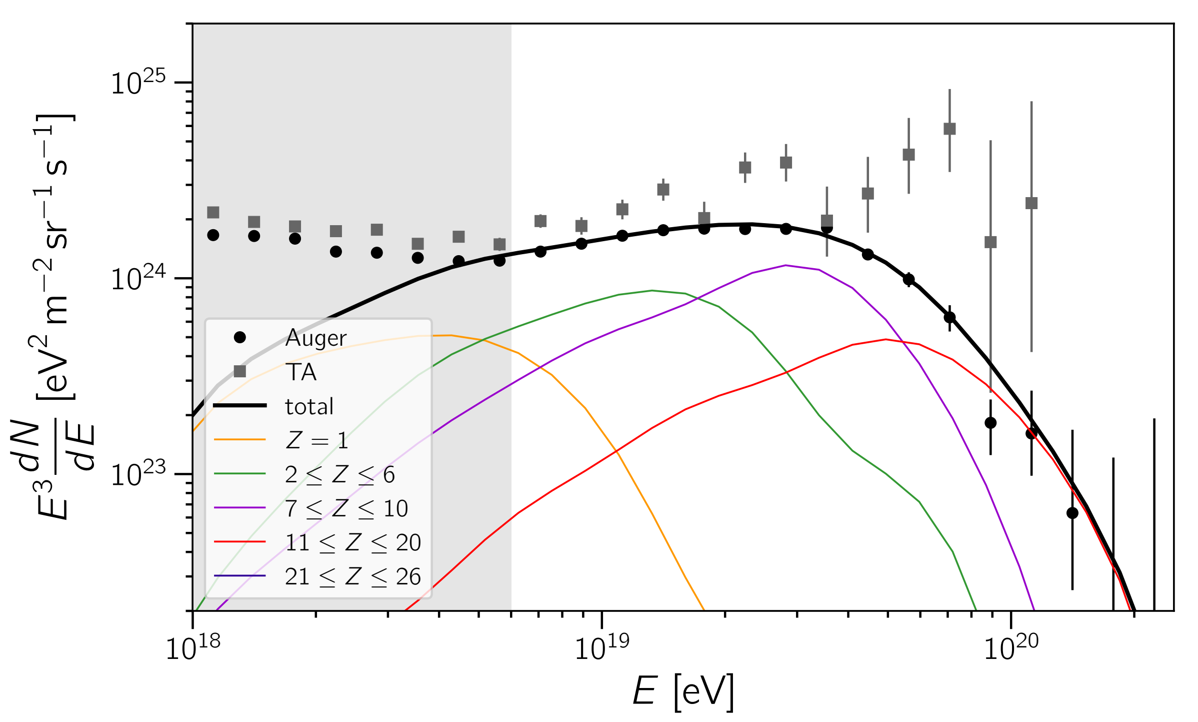
EGMF constraints



van Vliet, Palladino, Taylor, Winter. MNRAS 510 (2022) 1289. arXiv:2104.05732

applications

fit UHECR measurements



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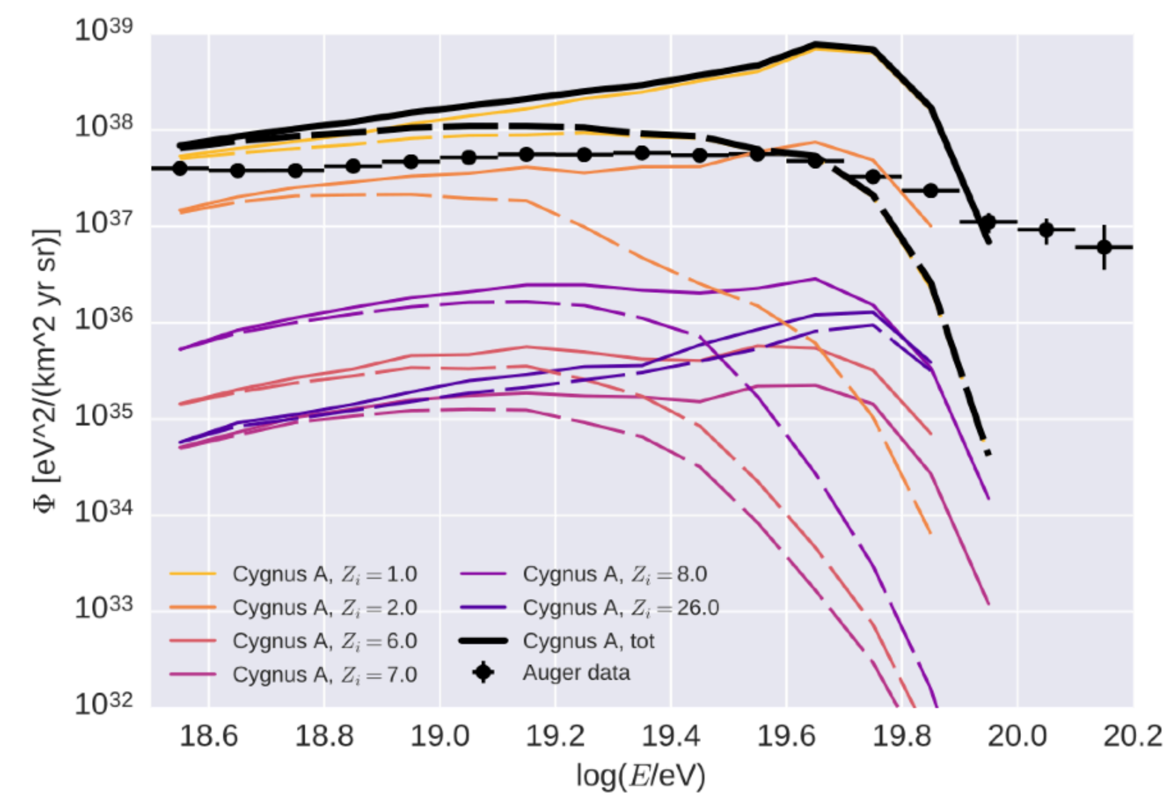

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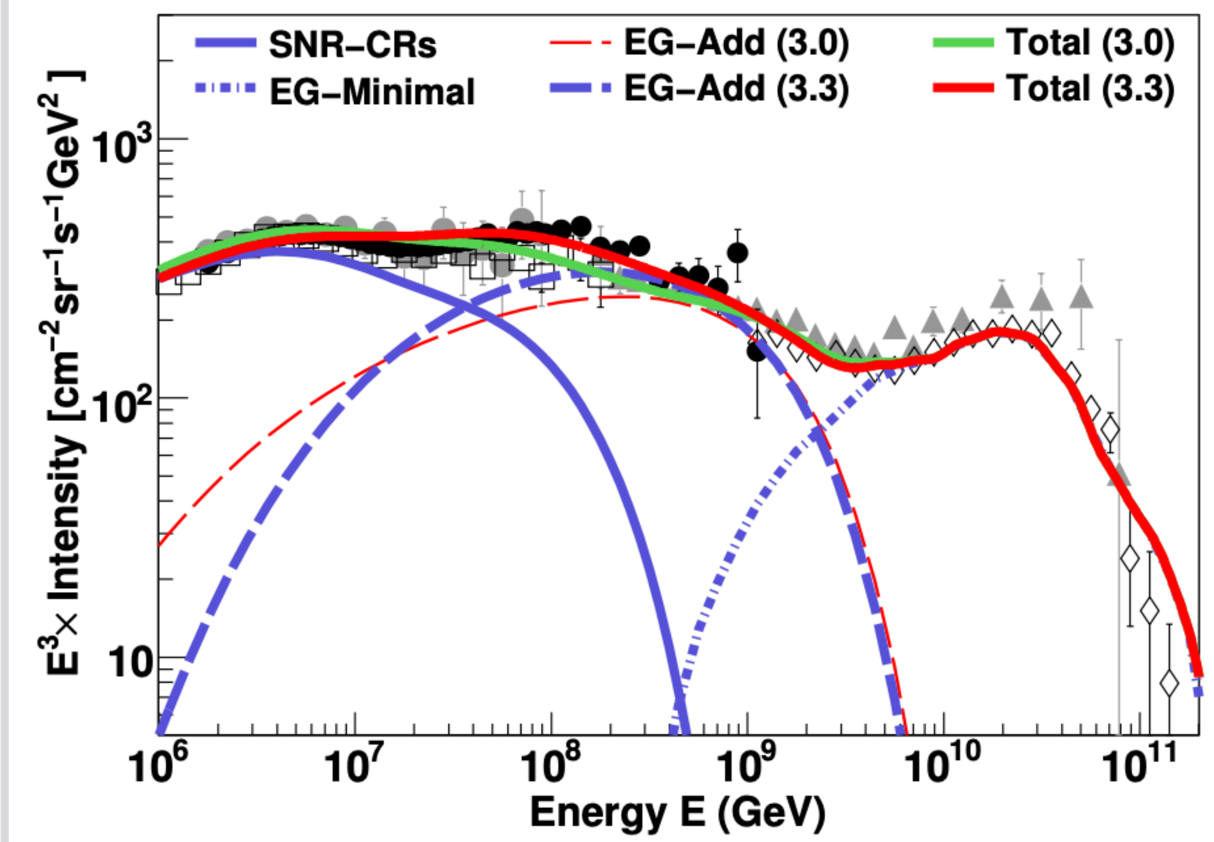

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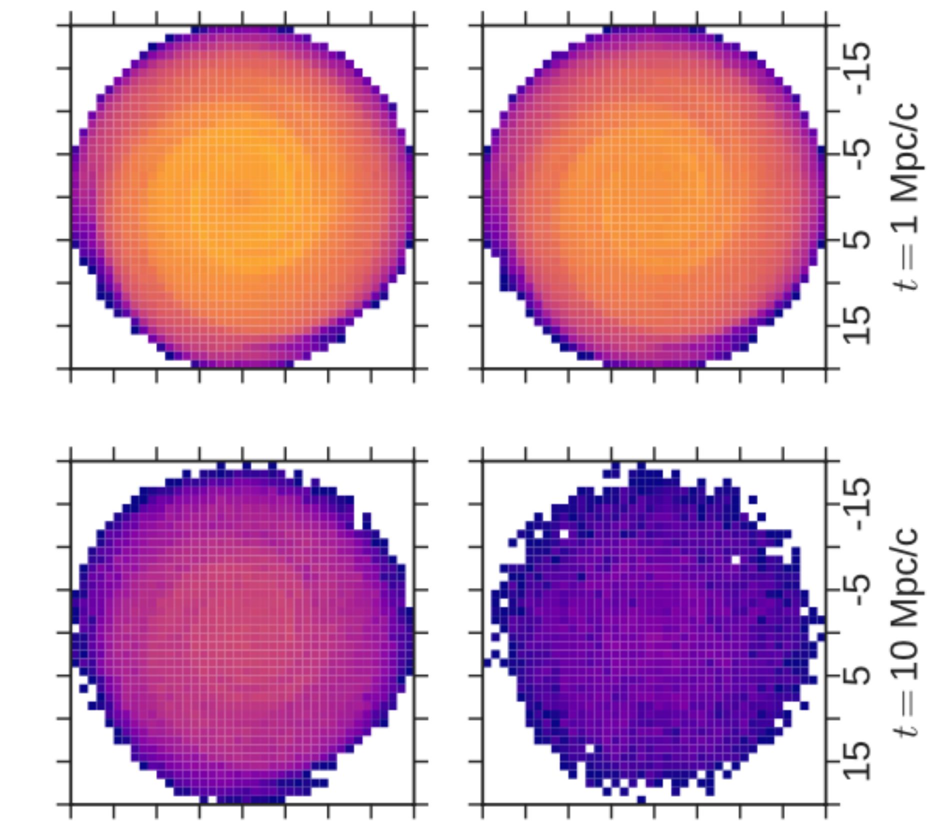

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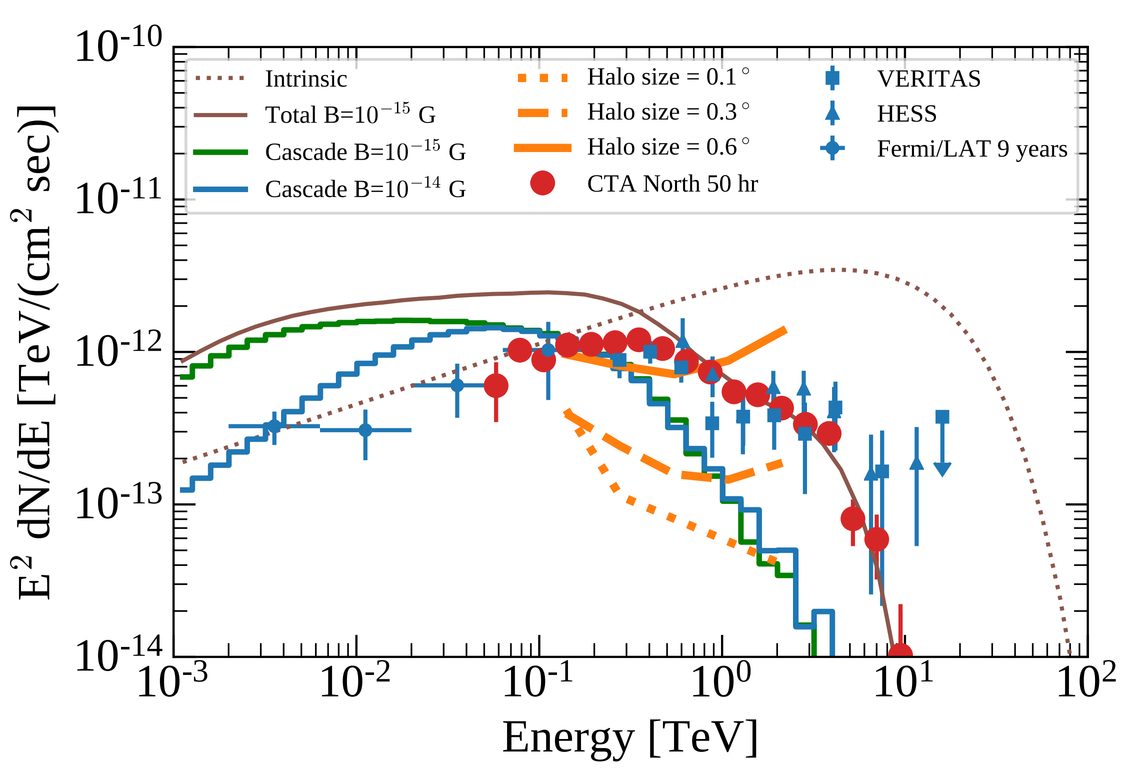

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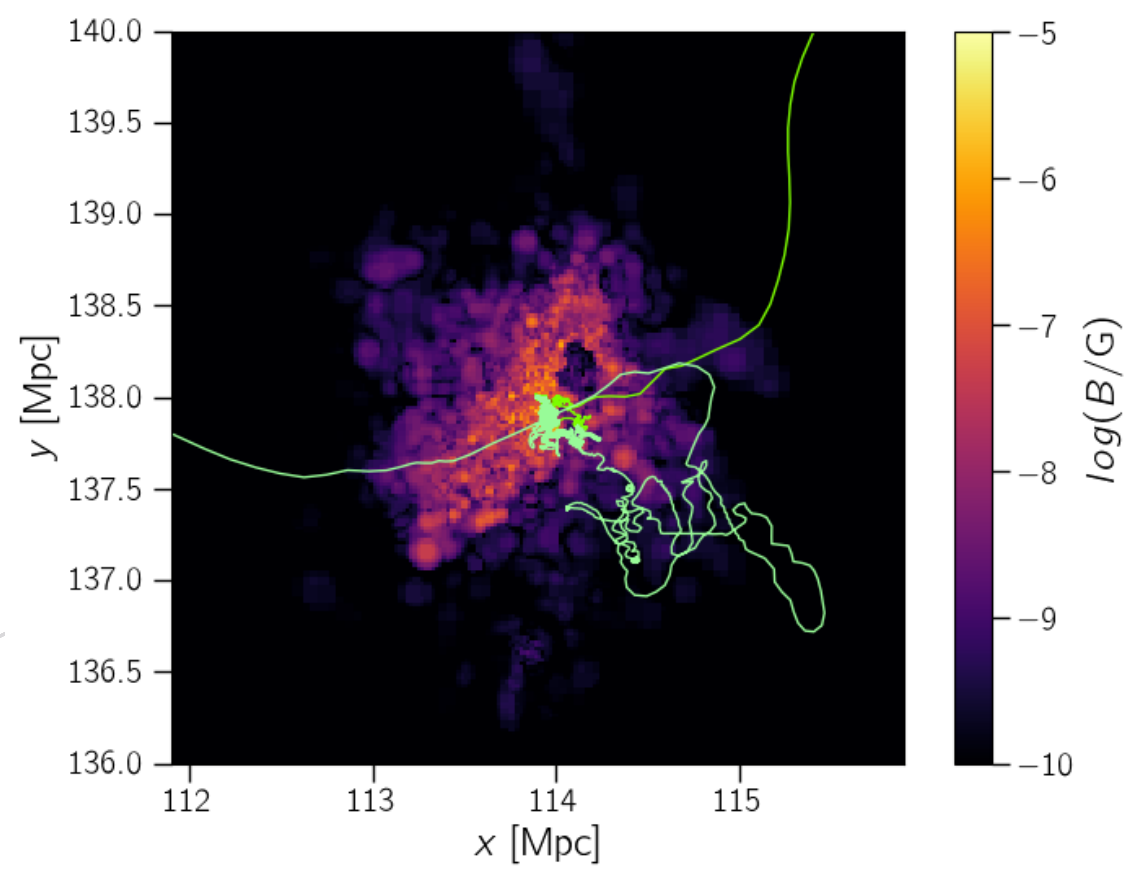

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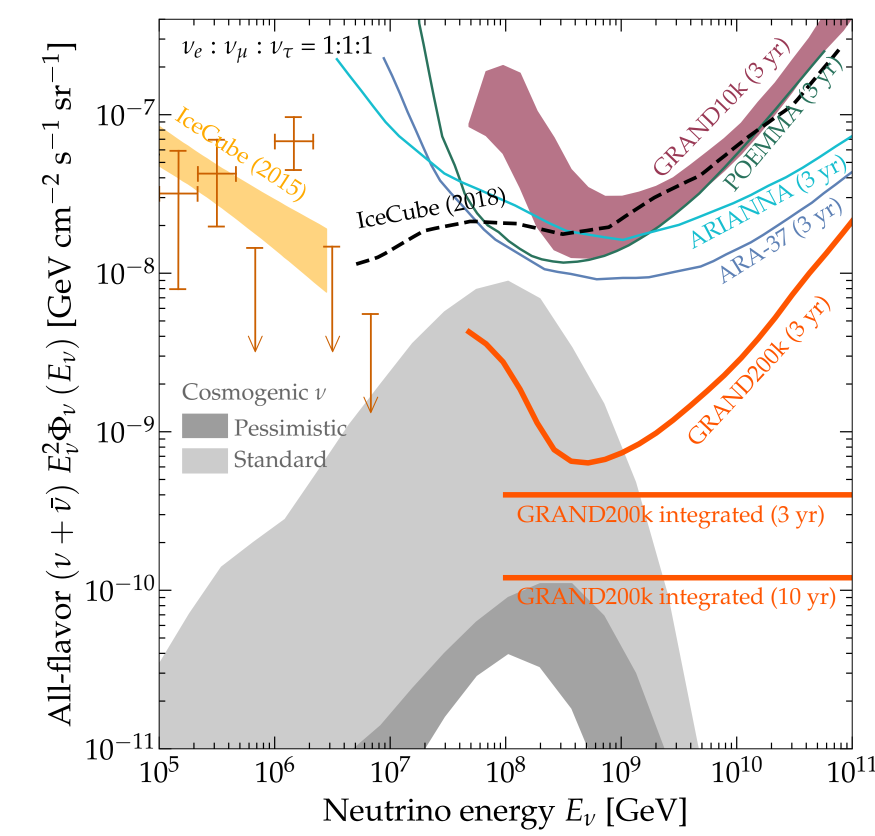

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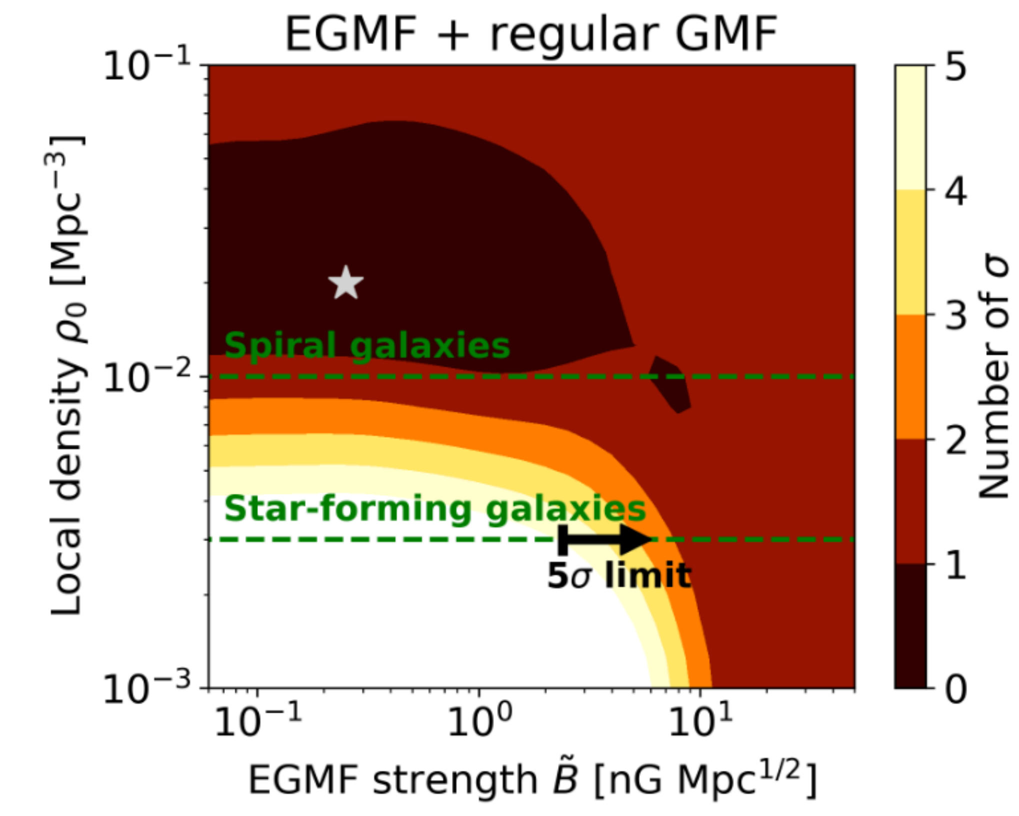

van Vliet, Palladino, Taylor, Winter. MNRAS 510 (2022) 1289. arXiv:2104.05732

... and much more!

CRPropa. propagation modes

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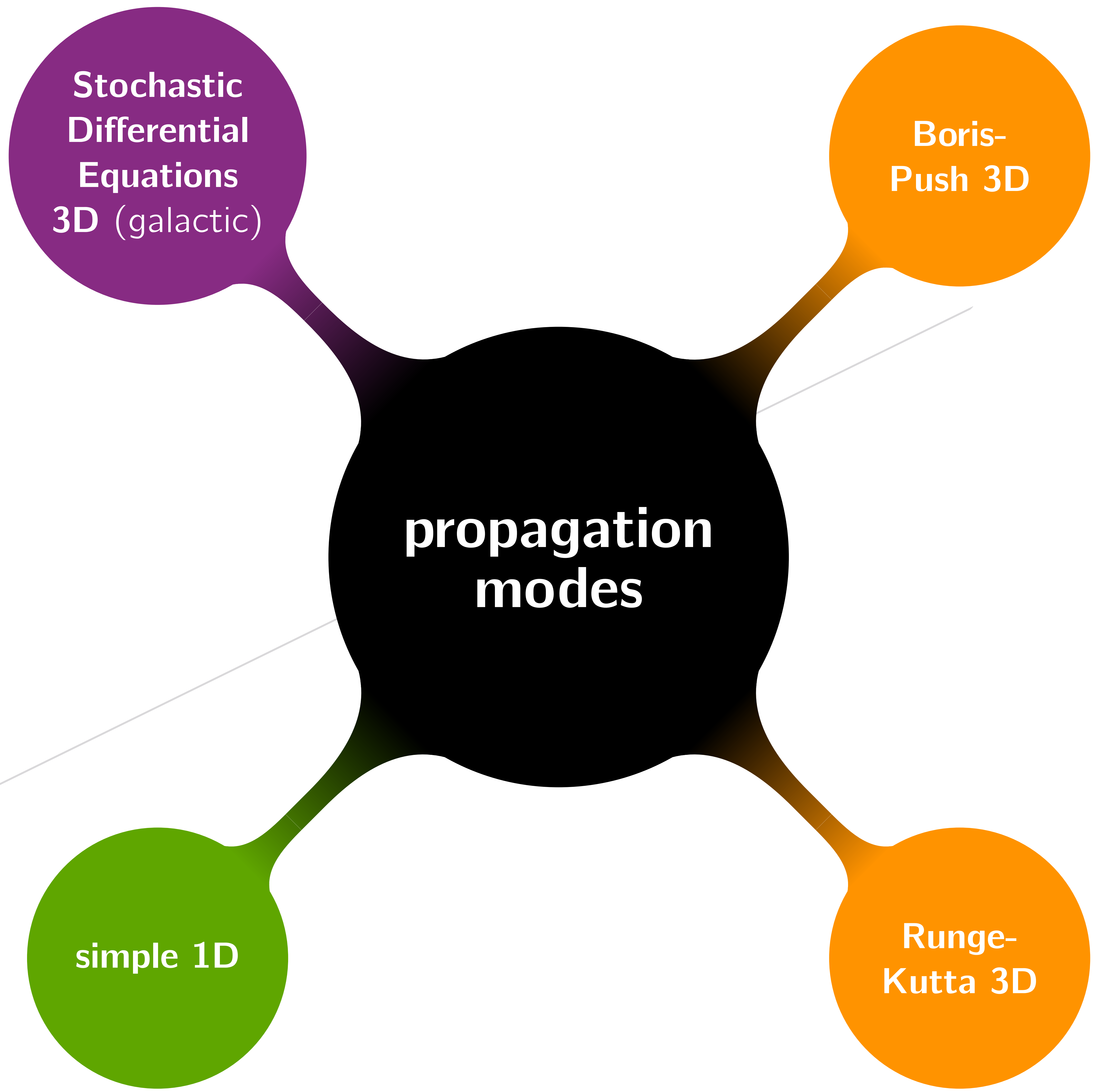
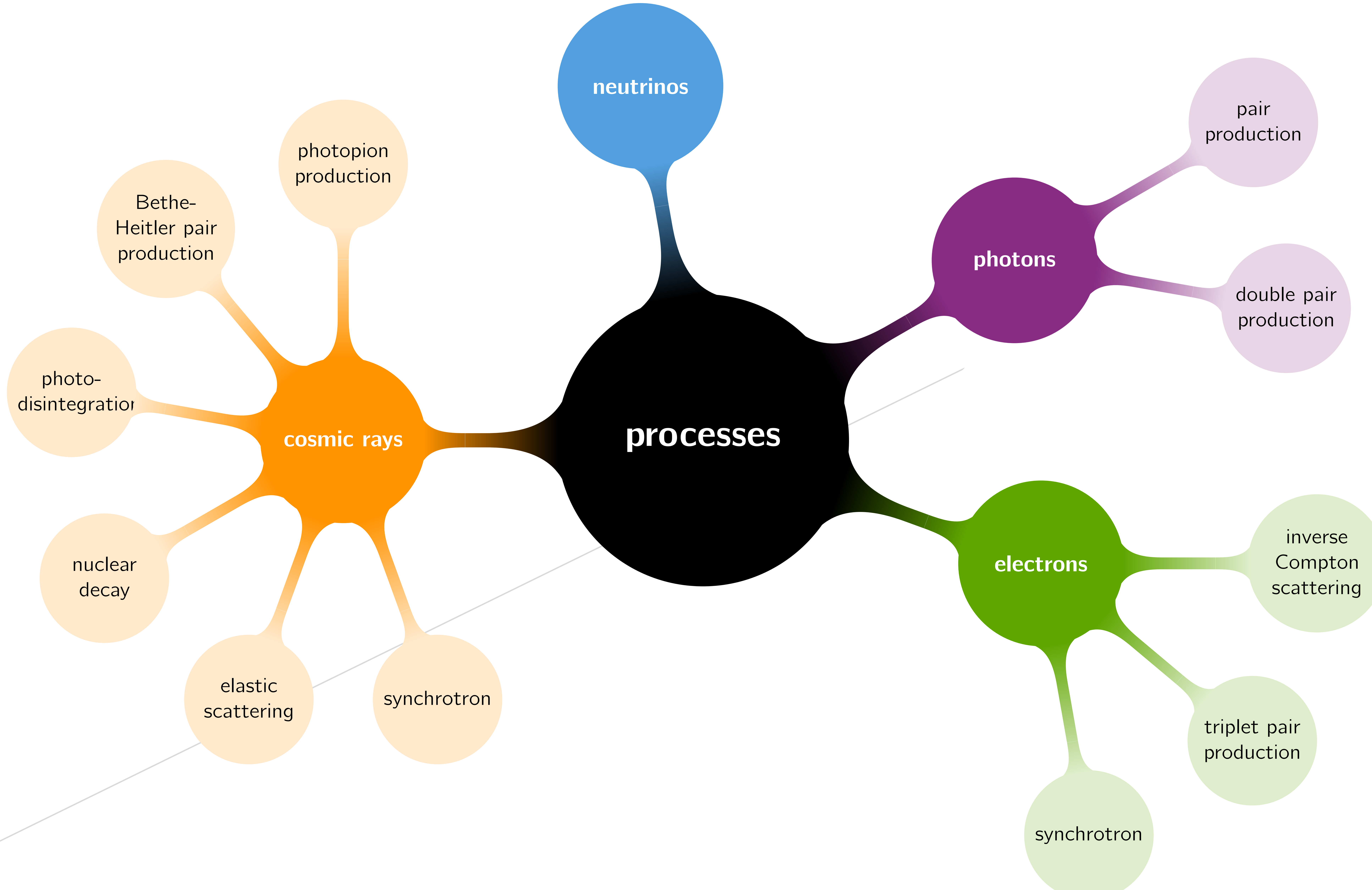
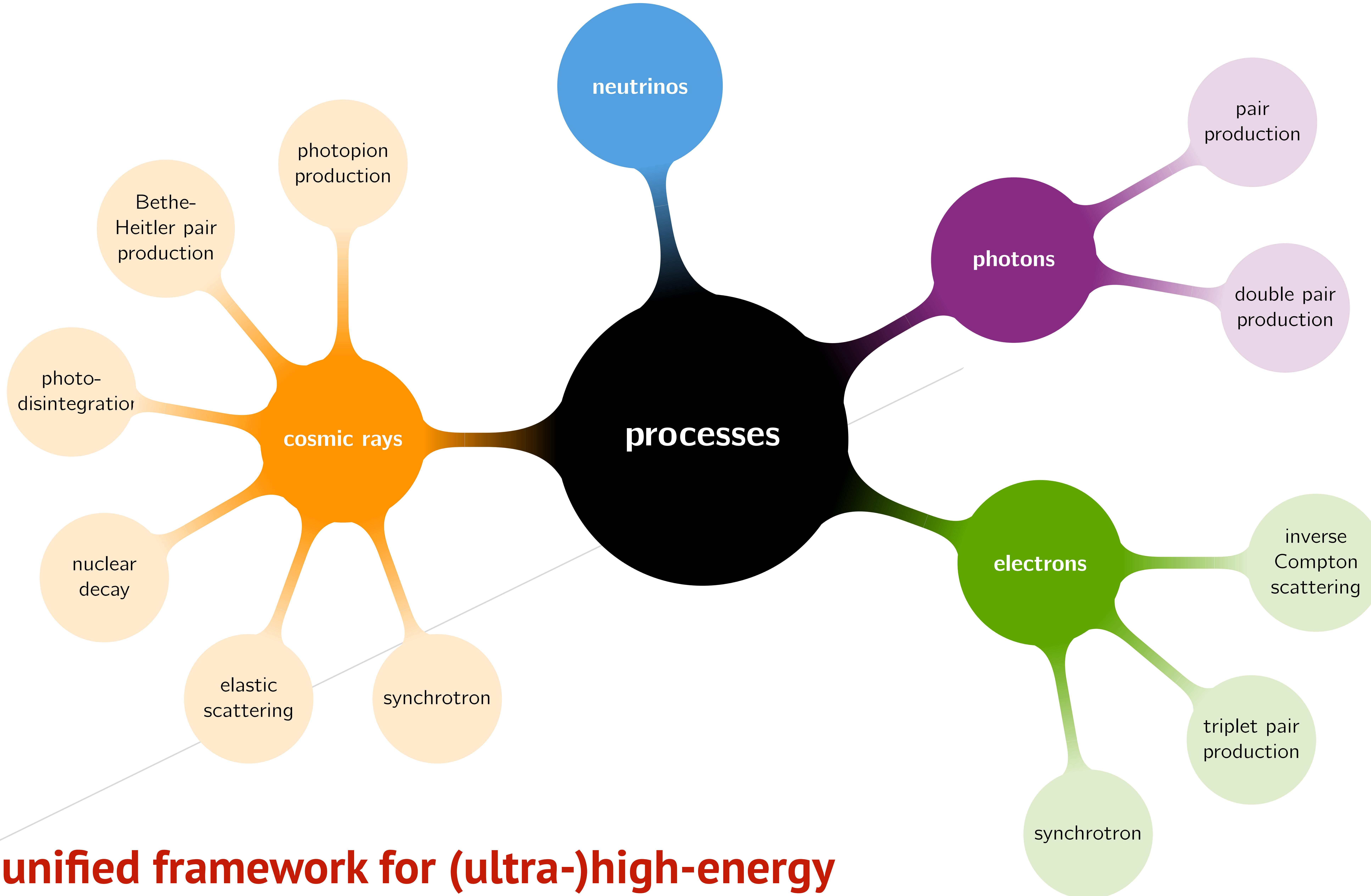


CRPropa. interaction processes





towards a unified framework for (ultra-)high-energy multimessenger studies

how does CRPropa work?

how does CRPropa work?

how does CRPropa work?

how does CRPropa work?


Δx
step
magnetic field

how does CRPropa work?

how does CRPropa work?

- does an interaction occur at this step?

- does an interaction occur at this step?
  - *no*: continue

- does an interaction occur at this step?
  - *no*: continue
  - *yes*: add by-products

how does CRPropa work?

- does an interaction occur at this step?
  - *no*: continue
  - *yes*: add by-products
- compute Lorentz force at each step

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how does CRPropa work?

- **resolution** (Δx)

- does an interaction occur at this step?
  - *no*: continue
  - *yes*: add by-products
- compute Lorentz force at each step

- **resolution** (Δx)
  - small: resolve interactions

- does an interaction occur at this step?
  - *no*: continue
  - *yes*: add by-products
- compute Lorentz force at each step

- **resolution** (Δx)
  - small: resolve interactions
  - large: speed up simulation

- does an interaction occur at this step?
  - *no*: continue
  - *yes*: add by-products
- compute Lorentz force at each step

- **resolution** (Δx)
  - small: resolve interactions
  - large: speed up simulation
- **magnetic field structure**

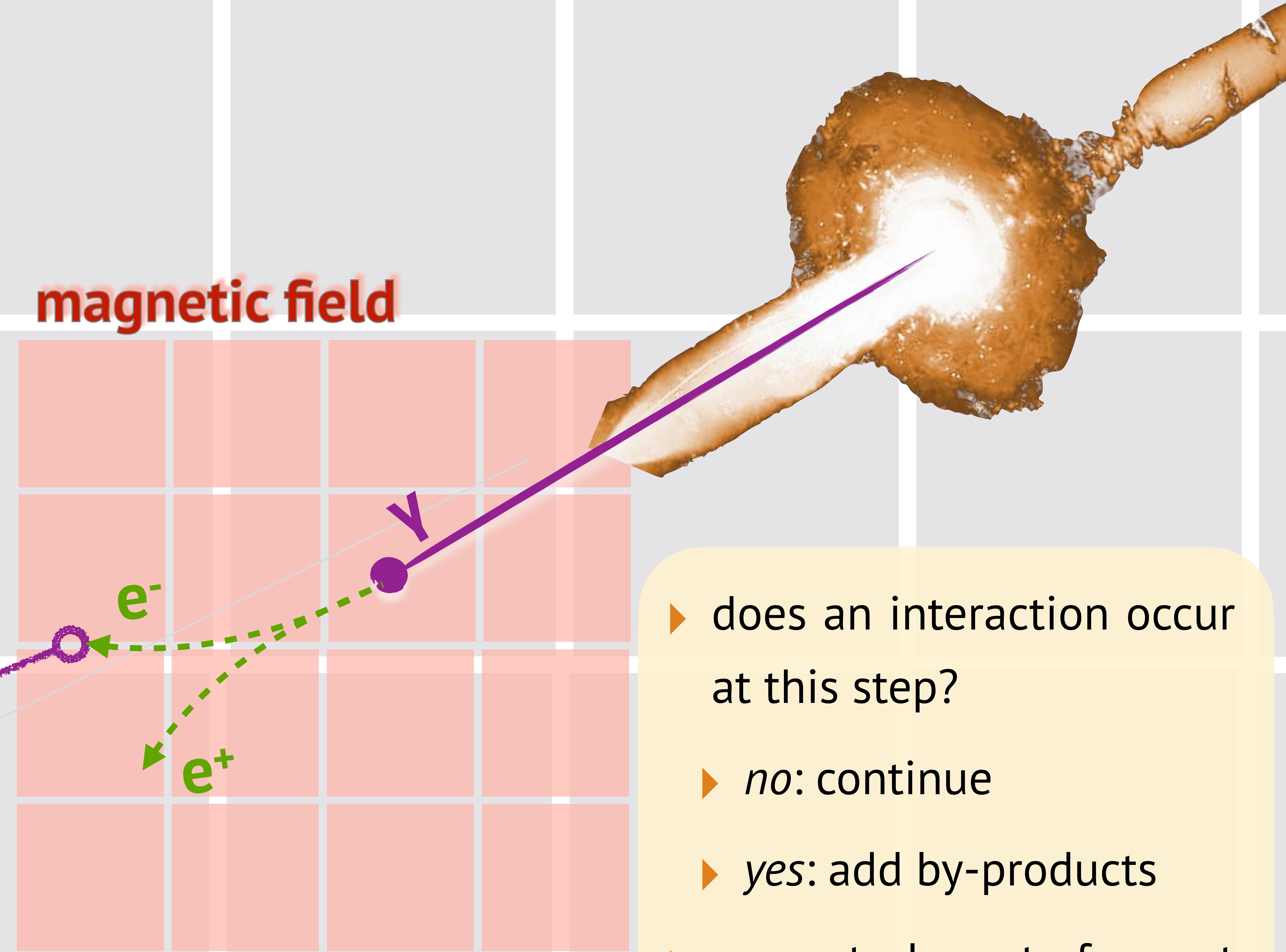
- does an interaction occur at this step?
  - *no*: continue
  - *yes*: add by-products
- compute Lorentz force at each step

how does CRPropa work?

Δx

step

- **resolution** (Δx)
  - small: resolve interactions
  - large: speed up simulation
- **magnetic field structure**
  - resolve propagation regime (diffusive vs. ballistic)



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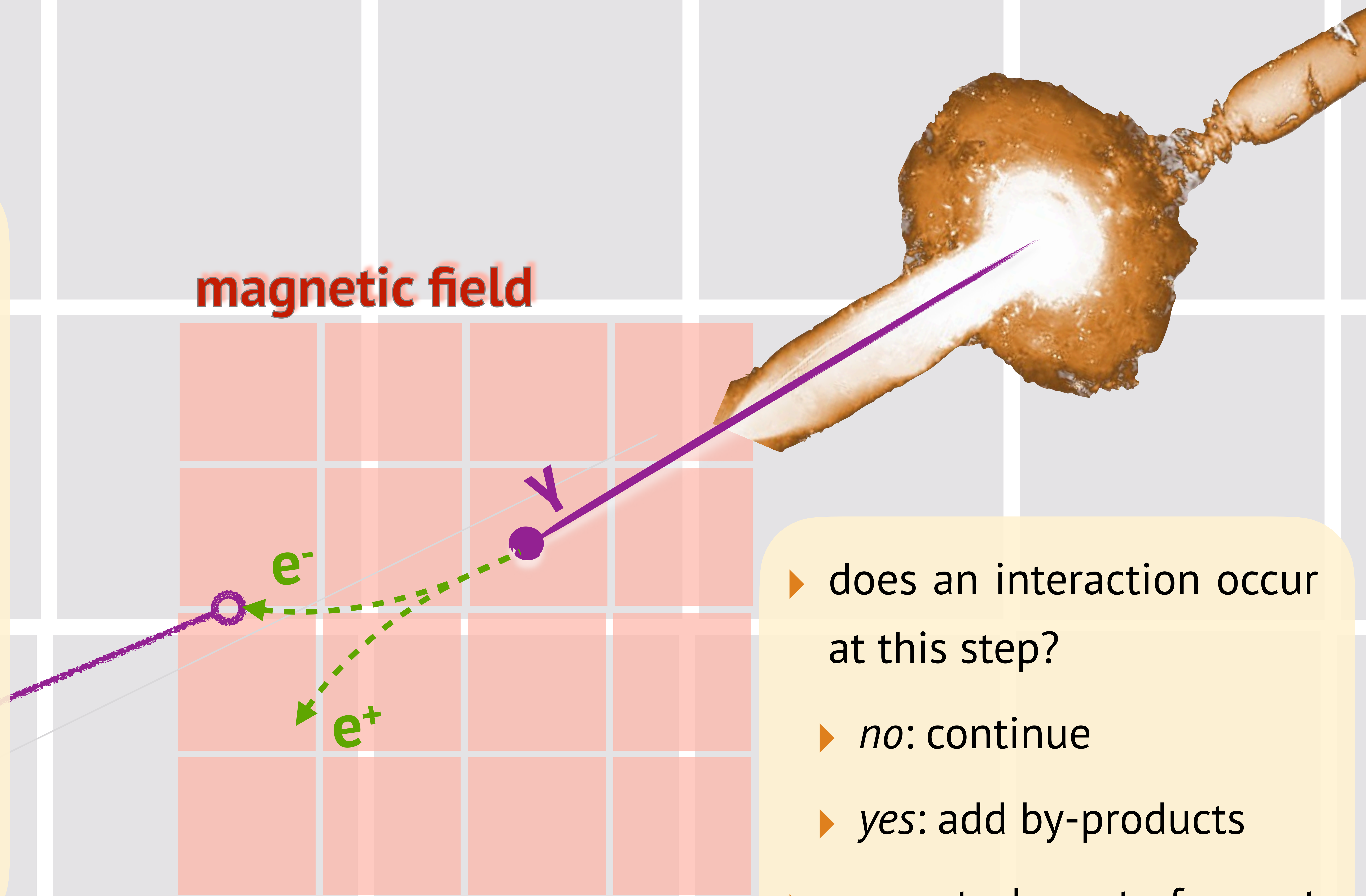
how does CRPropa work?

Δx
step



- **resolution** (Δx)
  - small: resolve interactions
  - large: speed up simulation
- **magnetic field structure**
  - resolve propagation regime (diffusive vs. ballistic)
- **geometry**

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  - *no*: continue
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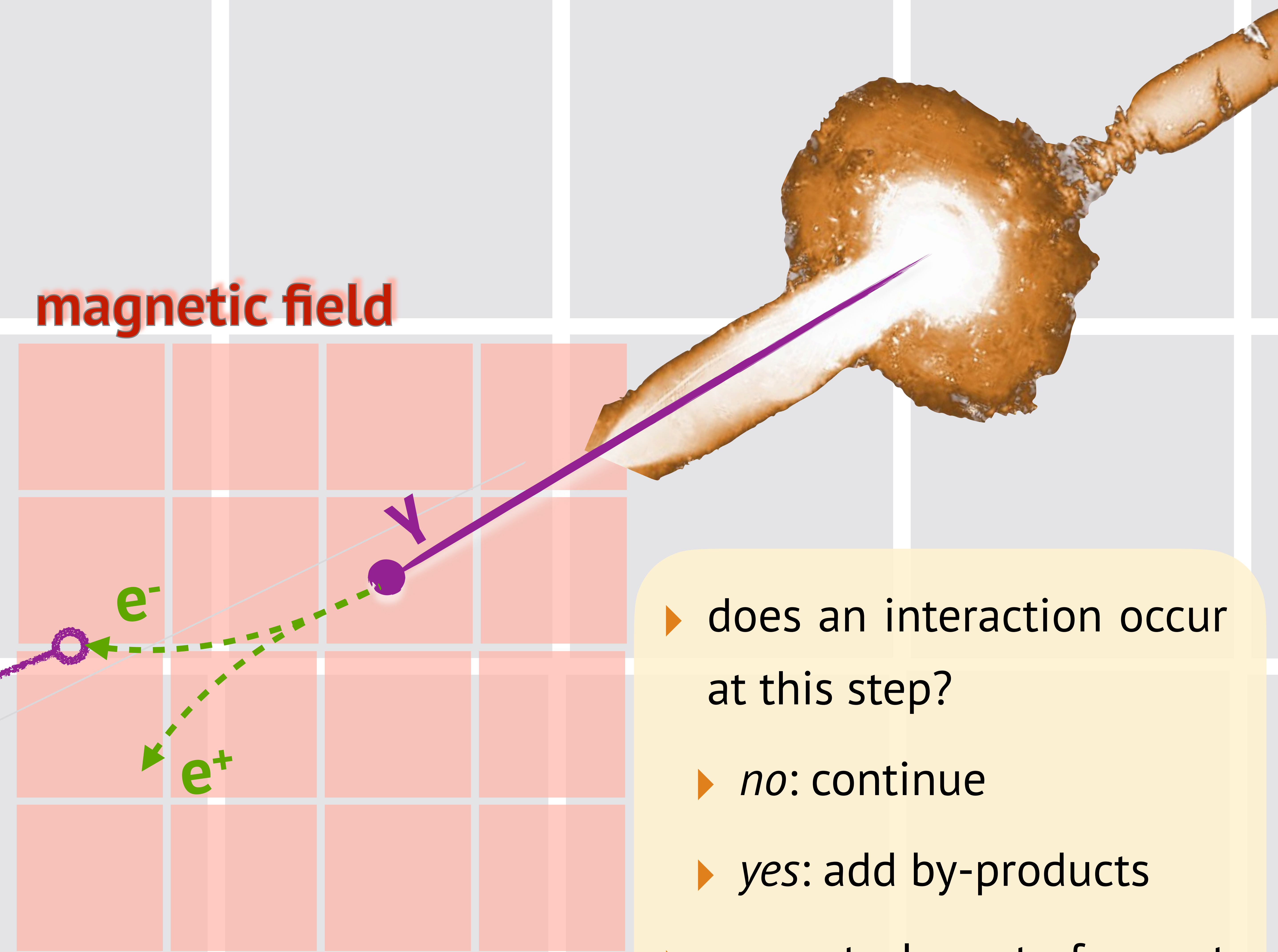
- compute Lorentz force at each step

Δx

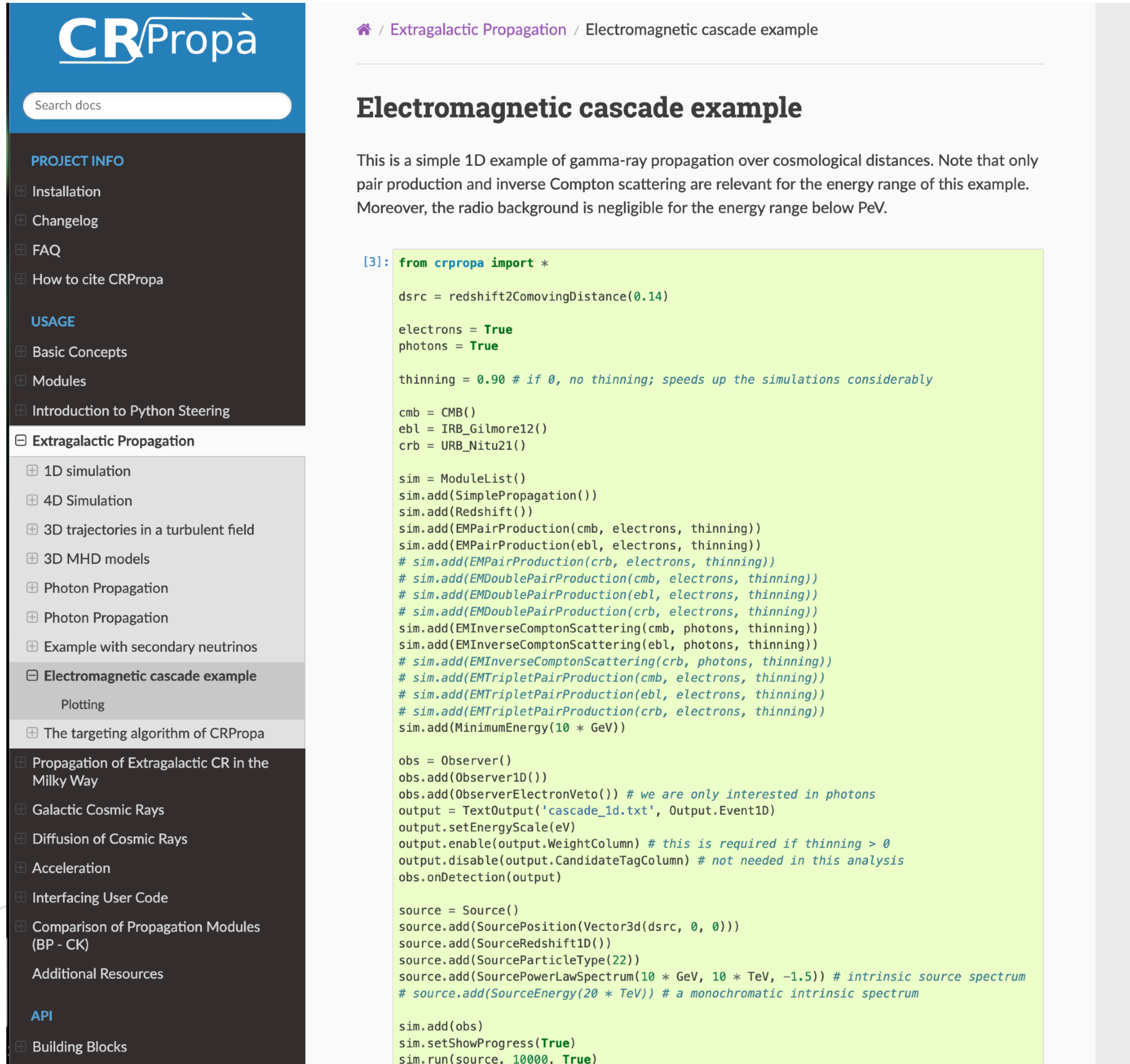
step

- **resolution** (Δx)
  - small: resolve interactions
  - large: speed up simulation
- **magnetic field structure**
  - resolve propagation regime (diffusive vs. ballistic)
- **geometry**
  - the "aiming" problem



- does an interaction occur at this step?
  - *no*: continue
  - *yes*: add by-products
- compute Lorentz force at each step

how to use CRPropa for gamma-ray studies?



Electromagnetic cascade example

This is a simple 1D example of gamma-ray propagation over cosmological distances. Note that only pair production and inverse Compton scattering are relevant for the energy range of this example. Moreover, the radio background is negligible for the energy range below PeV.

[3]:
```python
from crpropa import *

dsrc = redshift2ComovingDistance(0.14)

electrons = True
photons = True

thinning = 0.90 # if 0, no thinning; speeds up the simulations considerably

cmb = CMB()
ebl = IRB_Gilmore12()
crb = URB_Nitu21()

sim = ModuleList()
sim.add(SimplePropagation())
sim.add(Redshift())
sim.add(EMPairProduction(cmb, electrons, thinning))
sim.add(EMPairProduction(ebl, electrons, thinning))
# sim.add(EMPairProduction(crb, electrons, thinning))
# sim.add(EMDoublePairProduction(cmb, electrons, thinning))
# sim.add(EMDoublePairProduction(ebl, electrons, thinning))
# sim.add(EMDoublePairProduction(crb, electrons, thinning))
sim.add(EMInverseComptonScattering(cmb, photons, thinning))
sim.add(EMInverseComptonScattering(ebl, photons, thinning))
# sim.add(EMInverseComptonScattering(crb, photons, thinning))
# sim.add(EMTripletPairProduction(cmb, electrons, thinning))
# sim.add(EMTripletPairProduction(ebl, electrons, thinning))
# sim.add(EMTripletPairProduction(crb, electrons, thinning))
sim.add(MinimumEnergy(10 * GeV))

obs = Observer()
obs.add(Observer1D())
obs.add(ObserverElectronVeto()) # we are only interested in photons
output = TextOutput('cascade_1d.txt', Output.Event1D)
output.setEnergyScale(eV)
output.enable(output.WeightColumn) # this is required if thinning > 0
output.disable(output.CandidateTagColumn) # not needed in this analysis
obs.onDetection(output)

source = Source()
source.add(SourcePosition(Vector3d(dsrc, 0, 0)))
source.add(SourceRedshift1D())
source.add(SourceParticleType(22))
source.add(SourcePowerLawSpectrum(10 * GeV, 10 * TeV, -1.5)) # intrinsic source spectrum
# source.add(SourceEnergy(20 * TeV)) # a monochromatic intrinsic spectrum

sim.add(obs)
sim.setShowProgress(True)
sim.run(source, 10000, True)
```

example notebooks

CRPropa

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# sim.add(EMTripletPairProduction(cmb, electrons, thinning))
# sim.add(EMTripletPairProduction(ebl, electrons, thinning))
# sim.add(EMTripletPairProduction(crb, electrons, thinning))
sim.add(MinimumEnergy(10 * GeV))

obs = Observer()
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output = TextOutput('cascade_1d.txt', Output.Event1D)
output.setEnergyScale(eV)
output.enable(output.WeightColumn) # this is required if thinning > 0
output.disable(output.CandidateTagColumn) # not needed in this analysis
obs.onDetection(output)

source = Source()
source.add(SourcePosition(Vector3d(dsrc, 0, 0)))
source.add(SourceRedshift1D())
```

https://crpropa.github.io/CRPropa3/

```python
from crpropa import *

# general options
nEvents = 10000
energyMinimum = 1 * GeV
energyMaximum = 400 * TeV
redshift = 0.14
distance = redshift2ComovingDistance(redshift)
electrons = photons = True
thinning = 1.
cmb = CMB()
ebl = IRB_Gilmore12()
outputFile = 'sim/04-sim_gamma1D.txt'
```

- define SOURCE → initial conditions

```
from crpropa import *

# general options
nEvents = 10000
energyMinimum = 1 * GeV
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redshift = 0.14
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electrons = photons = True
thinning = 1.
cmb = CMB()
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outputFile = 'sim/04-sim_gamma1D.txt'
```

```
# source distribution: uniform with power-law spectrum
position = SourcePosition(Vector3d(distance, 0, 0))
direction = SourceDirection(Vector3d(-1, 0, 0)) # emit in the -x direction (1D simulation)
redshifts = SourceRedshift1D() # takes the positions and assign the corresponding redshifts
energySpectrum = SourcePowerLawSpectrum(energyMinimum, energyMaximum, -1)
particleType = SourceParticleType(22) # we are interested in gamma rays
source = Source()
source.add(position)
source.add(redshifts)
source.add(direction)
source.add(energySpectrum)
source.add(particleType)
```

- define SOURCE → initial conditions

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from crpropa import *

# general options
nEvents = 10000
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redshift = 0.14
distance = redshift2ComovingDistance(redshift)
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```

- define **Source** → initial conditions
- define **Observer** → region of interest, particle collector
  - saves outputs at a given time or position, …

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cmb = CMB()
ebl = IRB_Gilmore12()
outputFile = 'sim/04-sim_gamma1D.txt'
```

```python
# output
outputType = Output.Event1D
output = TextOutput(outputFile, outputType)
output.disable(output.CandidateTagColumn)
output.enable(output.WeightColumn) # since we are using thinning
output.setEnergyScale(eV)
output.setLengthScale(Mpc)

# observer
observerType = Observer1D()
observer = Observer()
observer.add(observerType)
observer.onDetection(output)
```

- define SOURCE → initial conditions
- define OBSERVER → region of interest, particle collector
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from crpropa import *

# general options
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  - e.g. pair production (with CMB, EBL, CRB), inverse Compton, …

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thinning = 1.
cmb = CMB()
ebl = IRB_Gilmore12()
outputFile = 'sim/04-sim_gamma1D.txt'
```

```python
# interactions
ppCMB = EMPairProduction(cmb, electrons, thinning)
ppEBL = EMPairProduction(ebl, electrons, thinning)
icsCMB = EMInverseComptonScattering(cmb, photons, thinning)
icsEBL = EMInverseComptonScattering(ebl, photons, thinning)
z = Redshift()
processes = [ppCMB, ppEBL, icsCMB, icsEBL, z]
```

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  - 1D, 3D (Boris push, Cash-Karp, diffusion, …)

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```

```
# propagator: one-dimensional
propagator = SimplePropagation(0.1 * kpc, 100 * kpc)
```

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- the **break conditions** → when to stop simulating?

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electrons = photons = True
thinning = 1.
cmb = CMB()
ebl = IRB_Gilmore12()
outputFile = 'sim/04-sim_gamma1D.txt'
```

```
# break conditions
breakEnergy = MinimumEnergy(1 * GeV)
```

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- define **interactions**
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- put everything in a **ModuleList**

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ebl = IRB_Gilmore12()
outputFile = 'sim/04-sim_gamma1D.txt'
```

```python
# assemble simulation components
sim = ModuleList()
sim.add(propagator)
for interaction in processes:
        sim.add(interaction)
sim.add(observer)
sim.add(breakEnergy)
sim.setShowProgress(True)
sim.run(source, nEvents, True)
```

an output example (1D simulation)

	D	ID	E	ID0	E0	W
10	81.1649	22	4.833030e+12	22	4.921480e+12	1.0000
11	81.1649	22	1.899920e+09	22	1.934690e+09	1.0000
12	81.1649	22	1.409820e+11	22	1.435620e+11	1.0000
13	81.1649	22	1.259420e+10	22	1.282470e+10	1.0000
14	81.1649	22	3.121590e+11	22	3.178720e+11	1.0000
...	...	...	...	...	...	...
95	81.1649	22	1.594810e+11	22	8.487520e+13	91.1634
96	81.1649	22	3.100800e+11	22	8.487520e+13	41.3962
97	81.1649	22	8.451480e+09	22	8.487520e+13	605.6770
98	81.1649	22	3.231870e+09	22	8.487520e+13	798.2140
99	81.1649	22	9.310190e+09	22	8.487520e+13	228.6540

90 rows × 8 columns

trajectory length

	D	ID	E	ID0	E0	W
10	81.1649	22	4.833030e+12	22	4.921480e+12	1.0000
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an output example (1D simulation)

detected
particle type

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90 rows × 8 columns

detected particle type

energy at detection

emitted particle type

trajectory length

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90 rows × 8 columns

detected
particle type

energy
at detection

emitted
particle type

energy
at emission

trajectory
length

	D	ID	E	ID0	E0	W
10	81.1649	22	4.833030e+12	22	4.921480e+12	1.0000
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14	81.1649	22	3.121590e+11	22	3.178720e+11	1.0000
...	...	...	...	...	...	...
95	81.1649	22	1.594810e+11	22	8.487520e+13	91.1634
96	81.1649	22	3.100800e+11	22	8.487520e+13	41.3962
97	81.1649	22	8.451480e+09	22	8.487520e+13	605.6770
98	81.1649	22	3.231870e+09	22	8.487520e+13	798.2140
99	81.1649	22	9.310190e+09	22	8.487520e+13	228.6540

90 rows × 8 columns

an output example (1D simulation)

detected particle type

energy at detection

emitted particle type

energy at emission

trajectory length

weights *(performance optimisation)*

	D	ID	E	ID0	E0	W
10	81.1649	22	4.833030e+12	22	4.921480e+12	1.0000
11	81.1649	22	1.899920e+09	22	1.934690e+09	1.0000
12	81.1649	22	1.409820e+11	22	1.435620e+11	1.0000
13	81.1649	22	1.259420e+10	22	1.282470e+10	1.0000
14	81.1649	22	3.121590e+11	22	3.178720e+11	1.0000
...	...	...	...	...	...	...
95	81.1649	22	1.594810e+11	22	8.487520e+13	91.1634
96	81.1649	22	3.100800e+11	22	8.487520e+13	41.3962
97	81.1649	22	8.451480e+09	22	8.487520e+13	605.6770
98	81.1649	22	3.231870e+09	22	8.487520e+13	798.2140
99	81.1649	22	9.310190e+09	22	8.487520e+13	228.6540

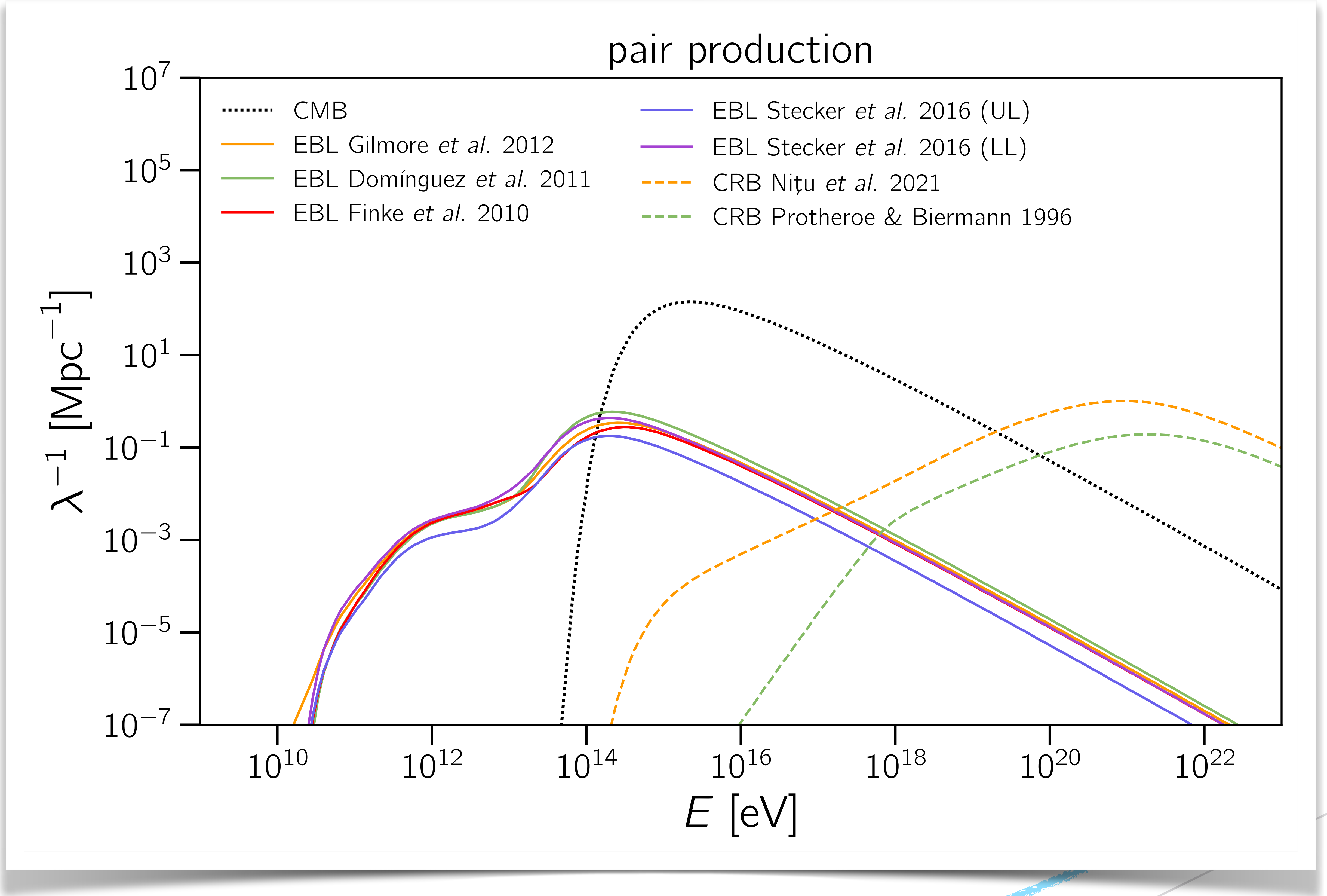
90 rows × 8 columns

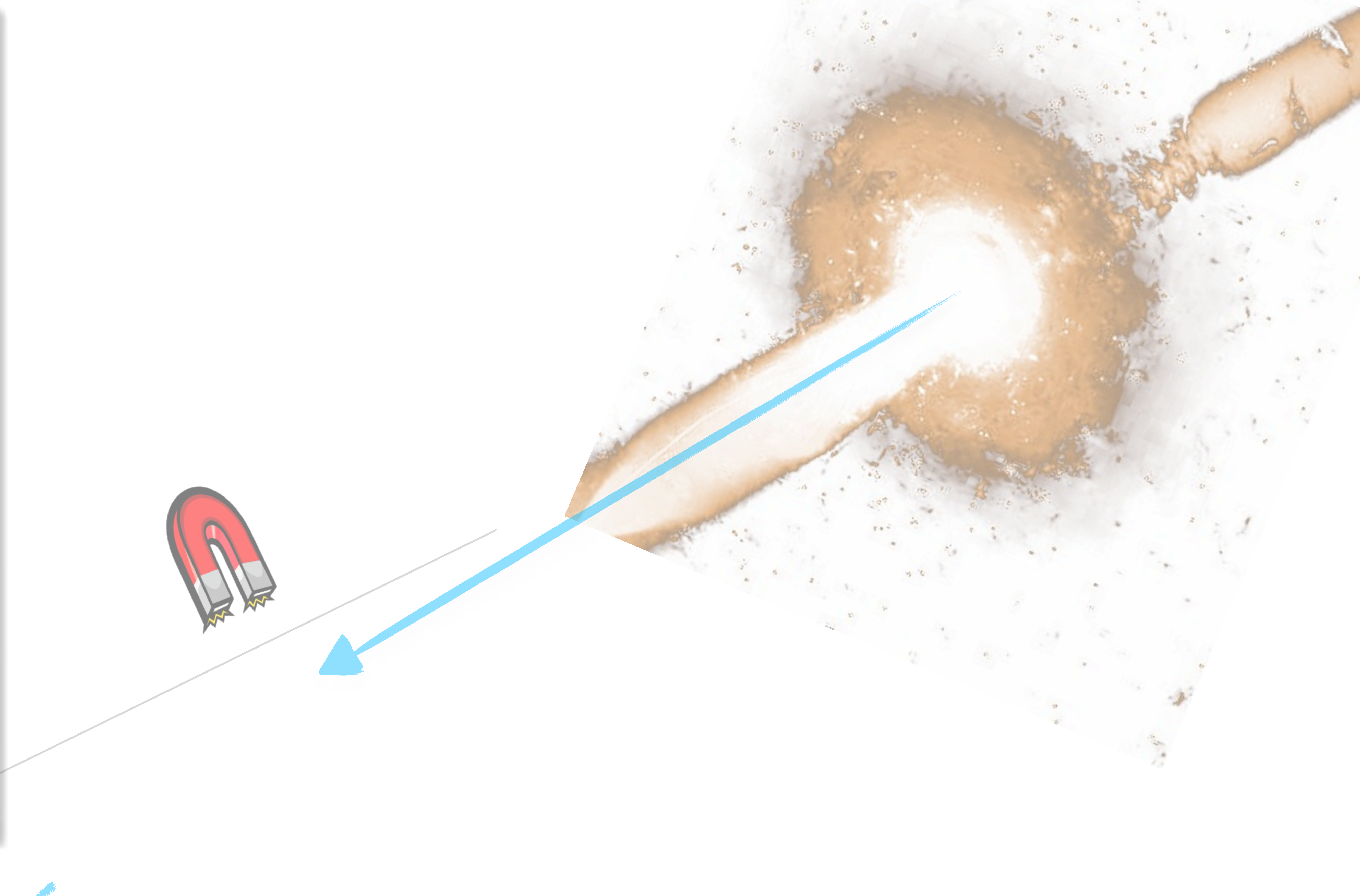
modelling the propagation of gamma rays

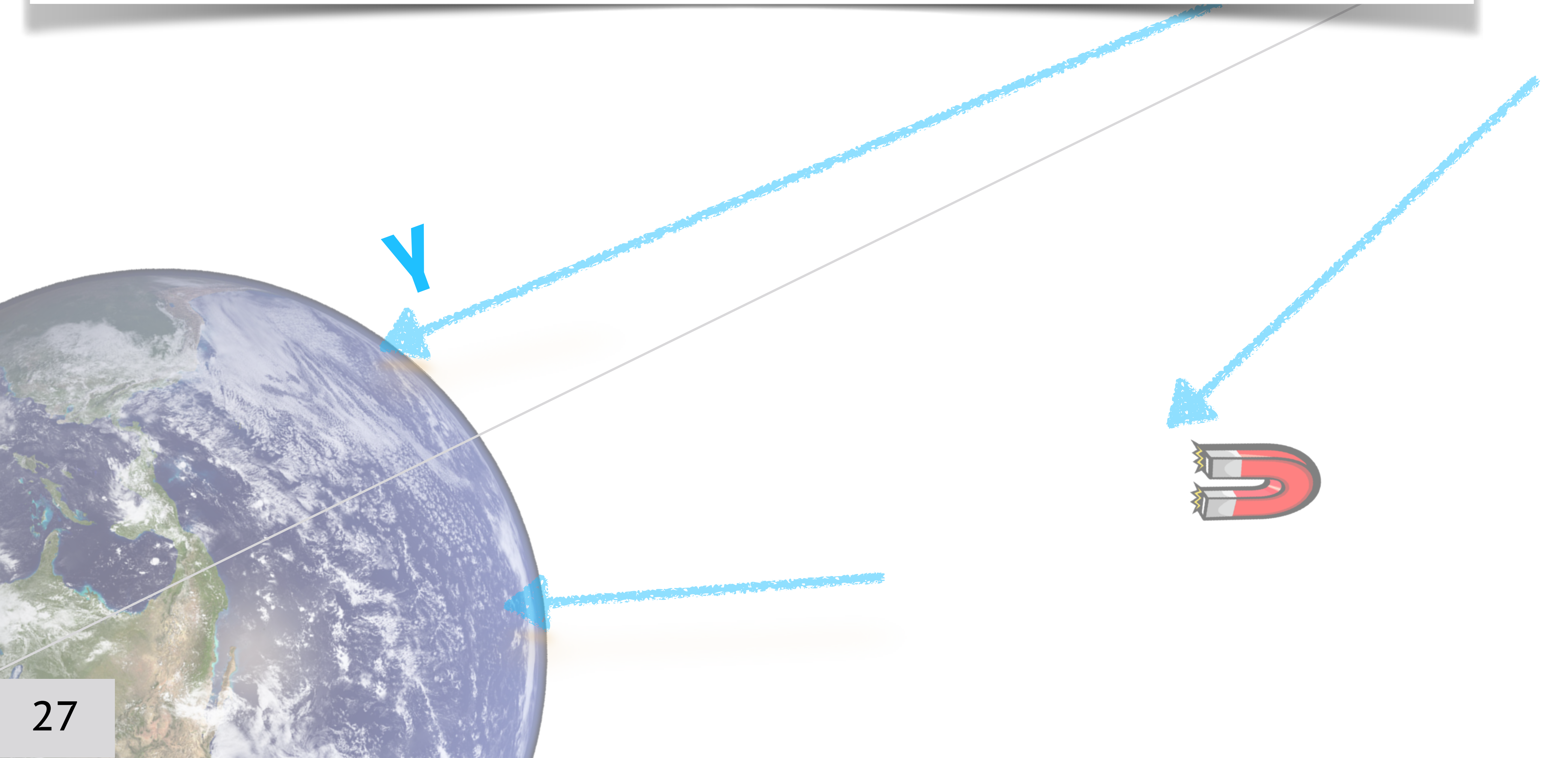
intergalactic propagation of gamma rays

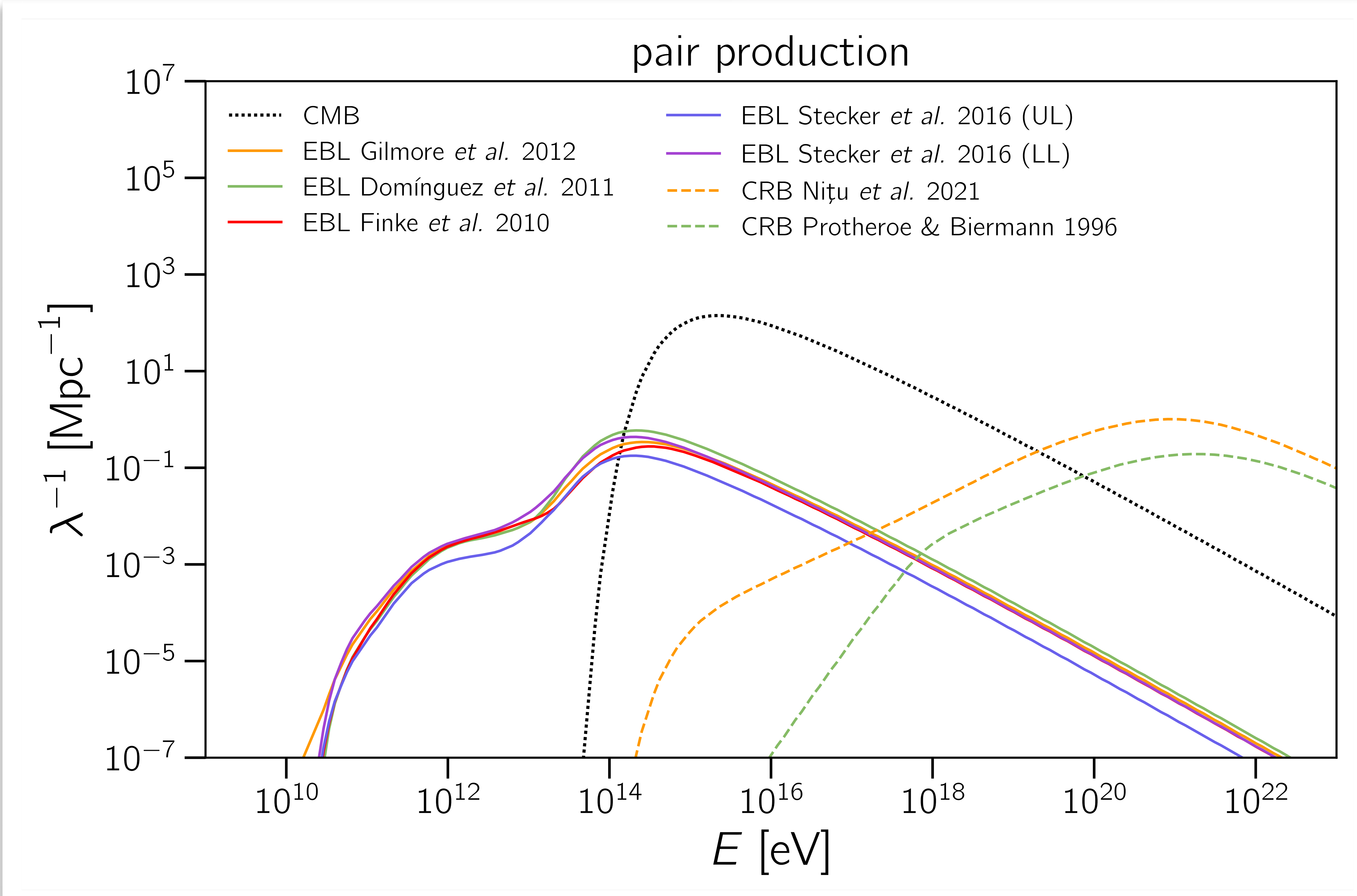

γ
e-
e+
γ
γ
e+
e-
pair production
$\gamma + \gamma_{bg} \rightarrow e^+ + e^-$
inverse Compton scattering
$e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma$


γ

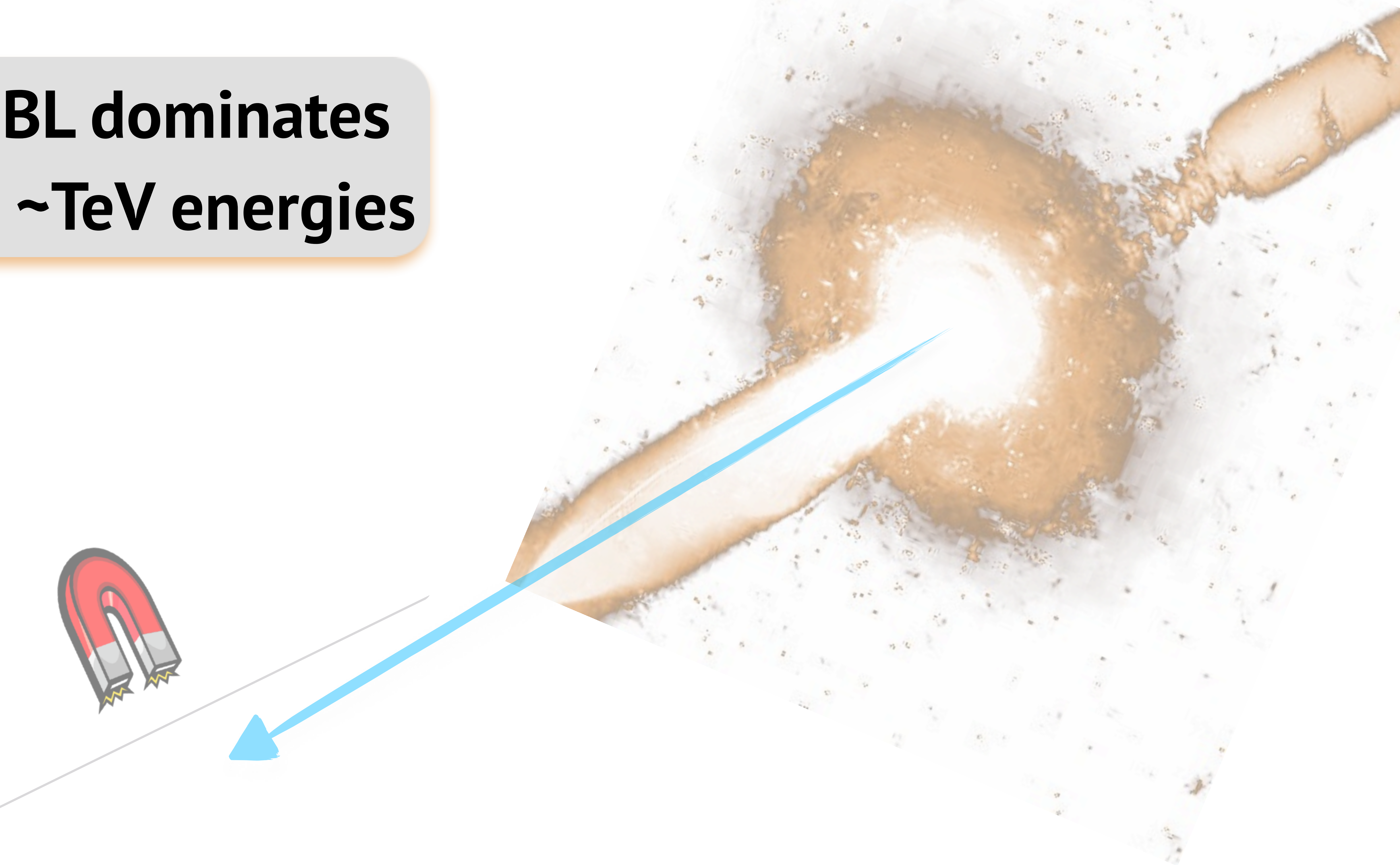

pair production
CMB
EBL Gilmore et al. 2012
EBL Domínguez et al. 2011
EBL Finke et al. 2010
EBL Stecker et al. 2016 (UL)
EBL Stecker et al. 2016 (LL)
CRB Nițu et al. 2021
CRB Protheroe & Biermann 1996
λ^{-1} [Mpc^{-1}]
10^{7}
10^{5}
10^{3}
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
10^{22}
E [eV]

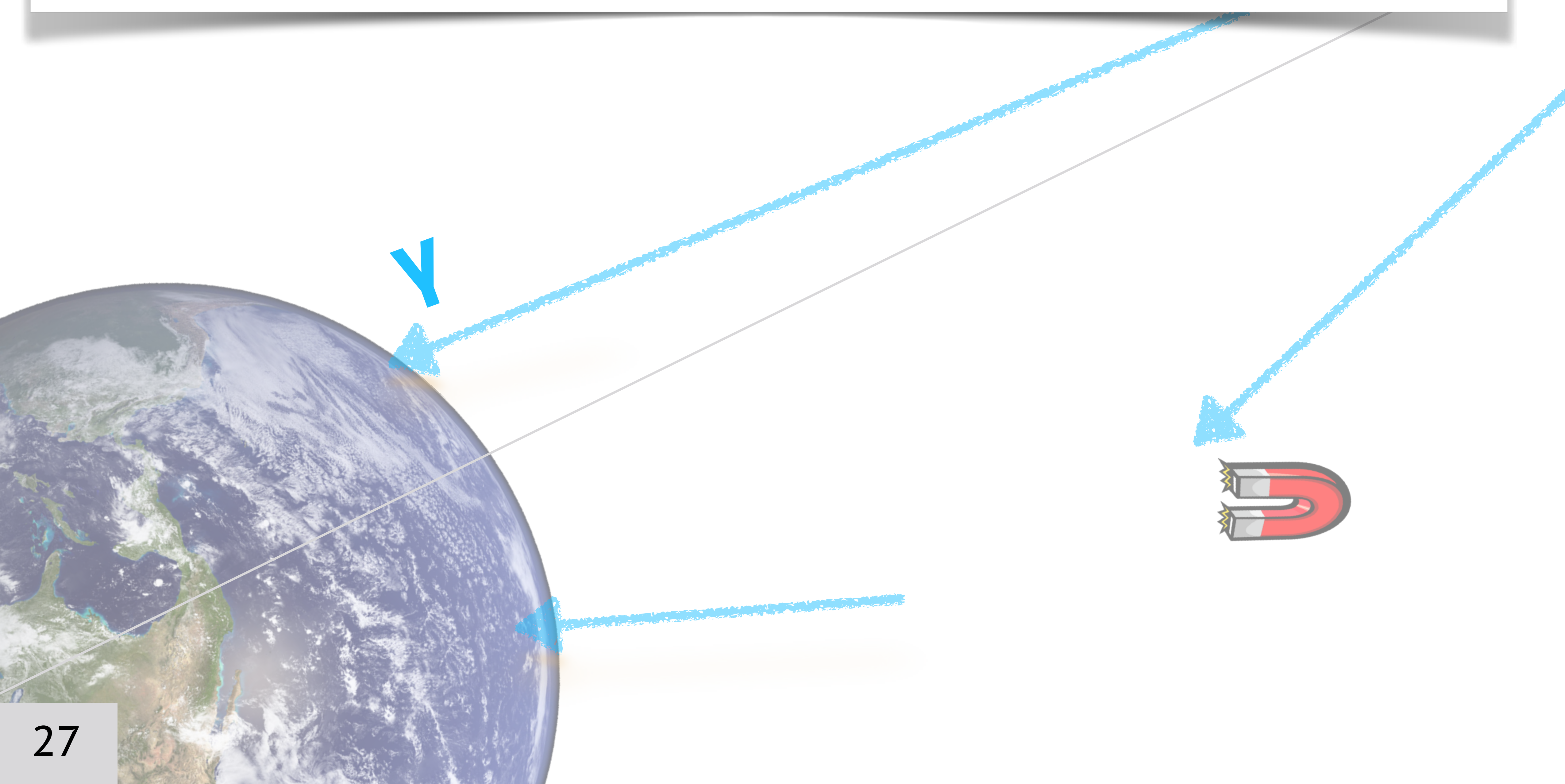



γ



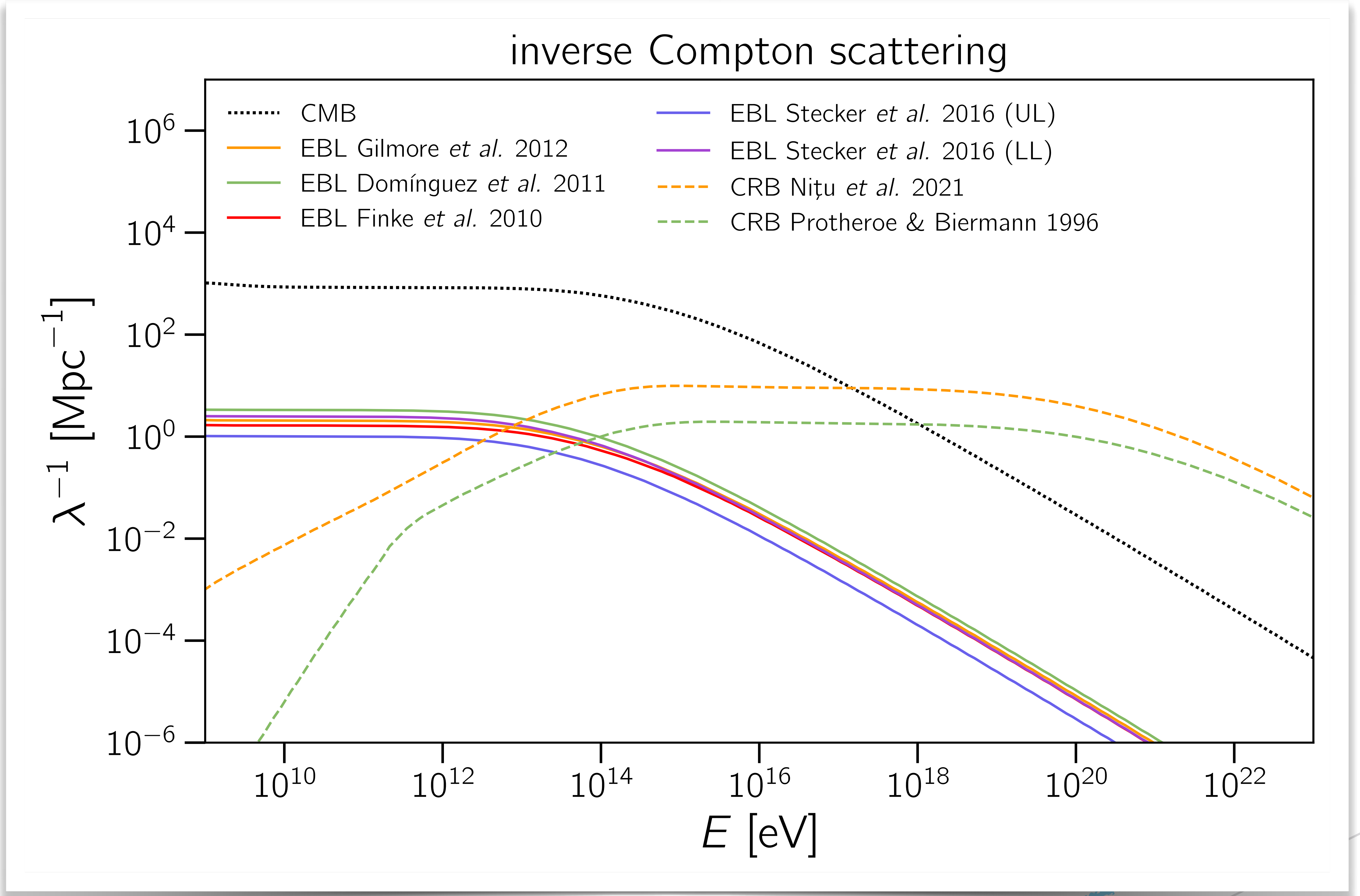
EBL dominates at ~TeV energies






pair production
$\gamma + \gamma_{bg} \rightarrow e^+ + e^-$
inverse Compton scattering
$e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma$
γ
e-
e+
γ
γ
e+
e-


γ


inverse Compton scattering
CMB
EBL Gilmore et al. 2012
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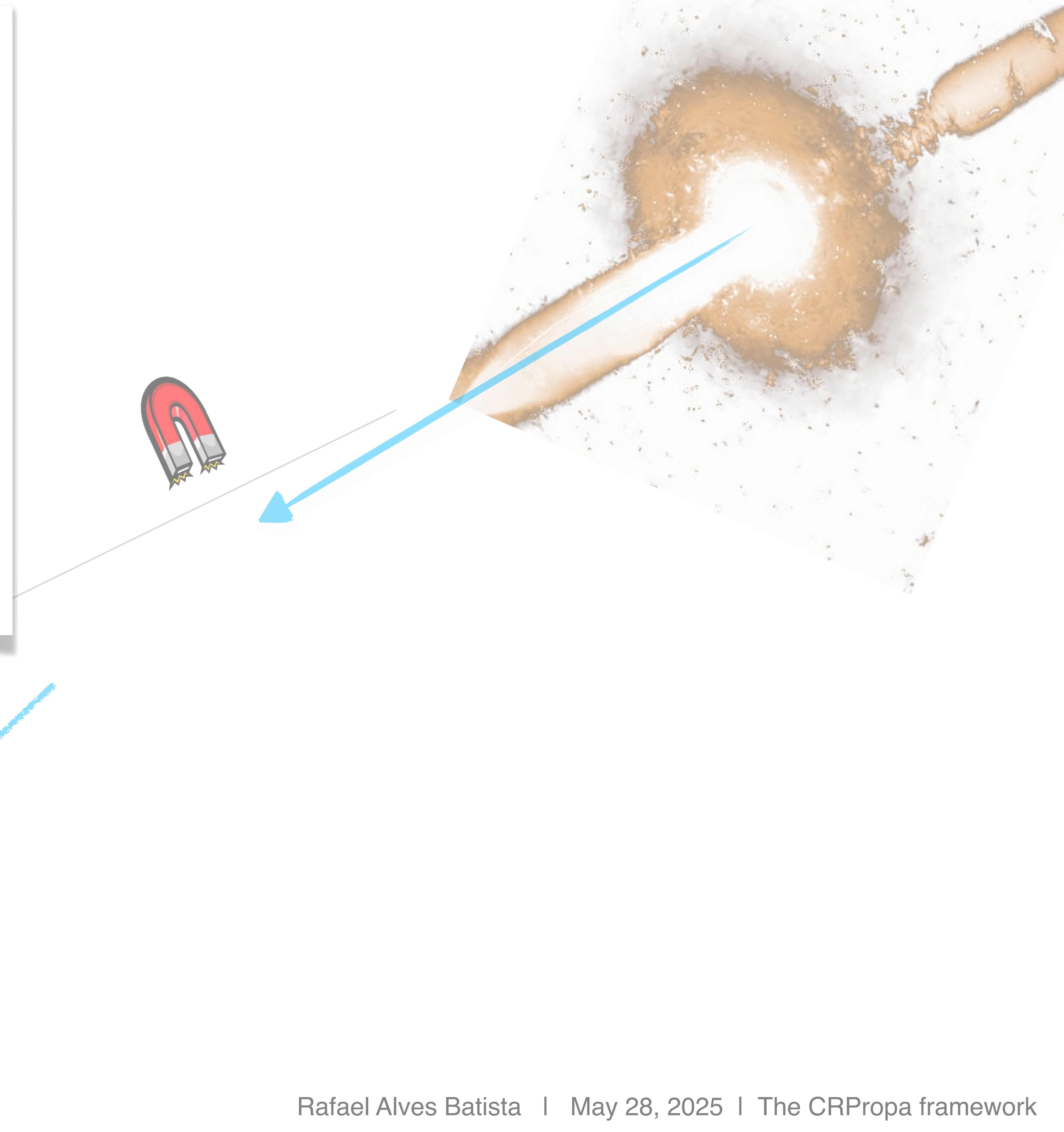
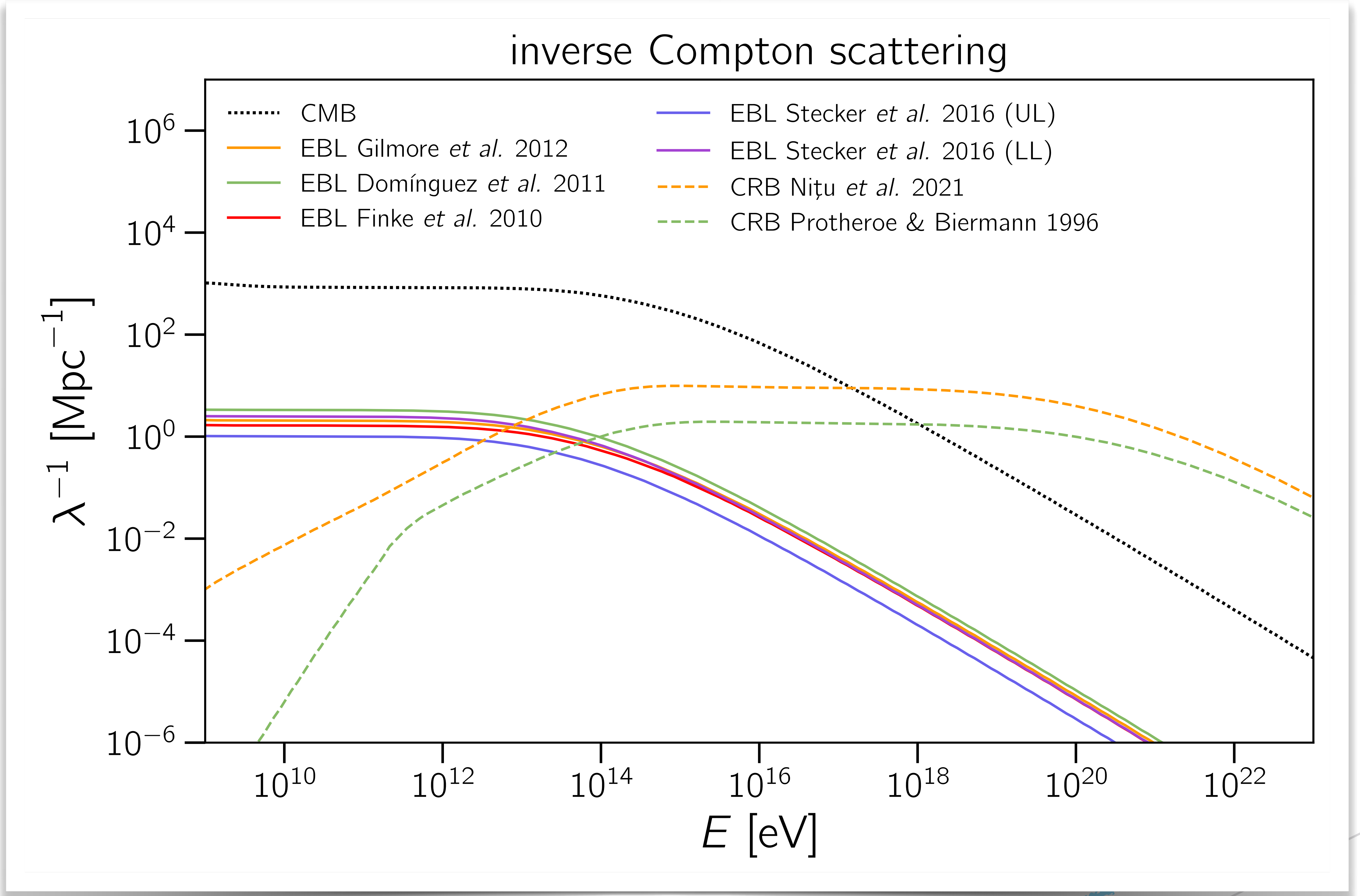
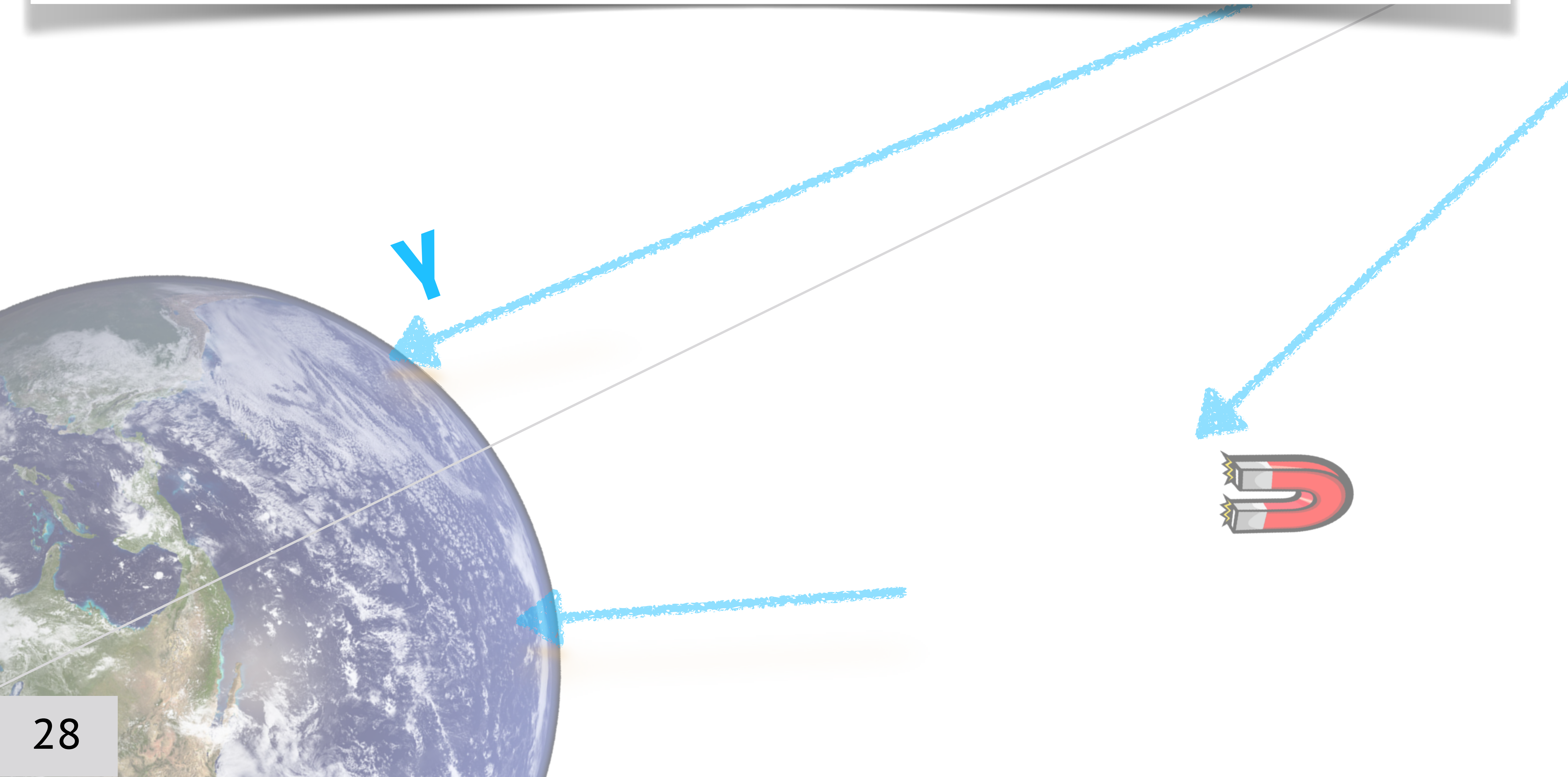
EBL Finke et al. 2010
EBL Stecker et al. 2016 (UL)
EBL Stecker et al. 2016 (LL)
CRB Nițu et al. 2021
CRB Protheroe & Biermann 1996
λ^{-1} [Mpc^{-1}]
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
10^{22}
E [eV]


γ

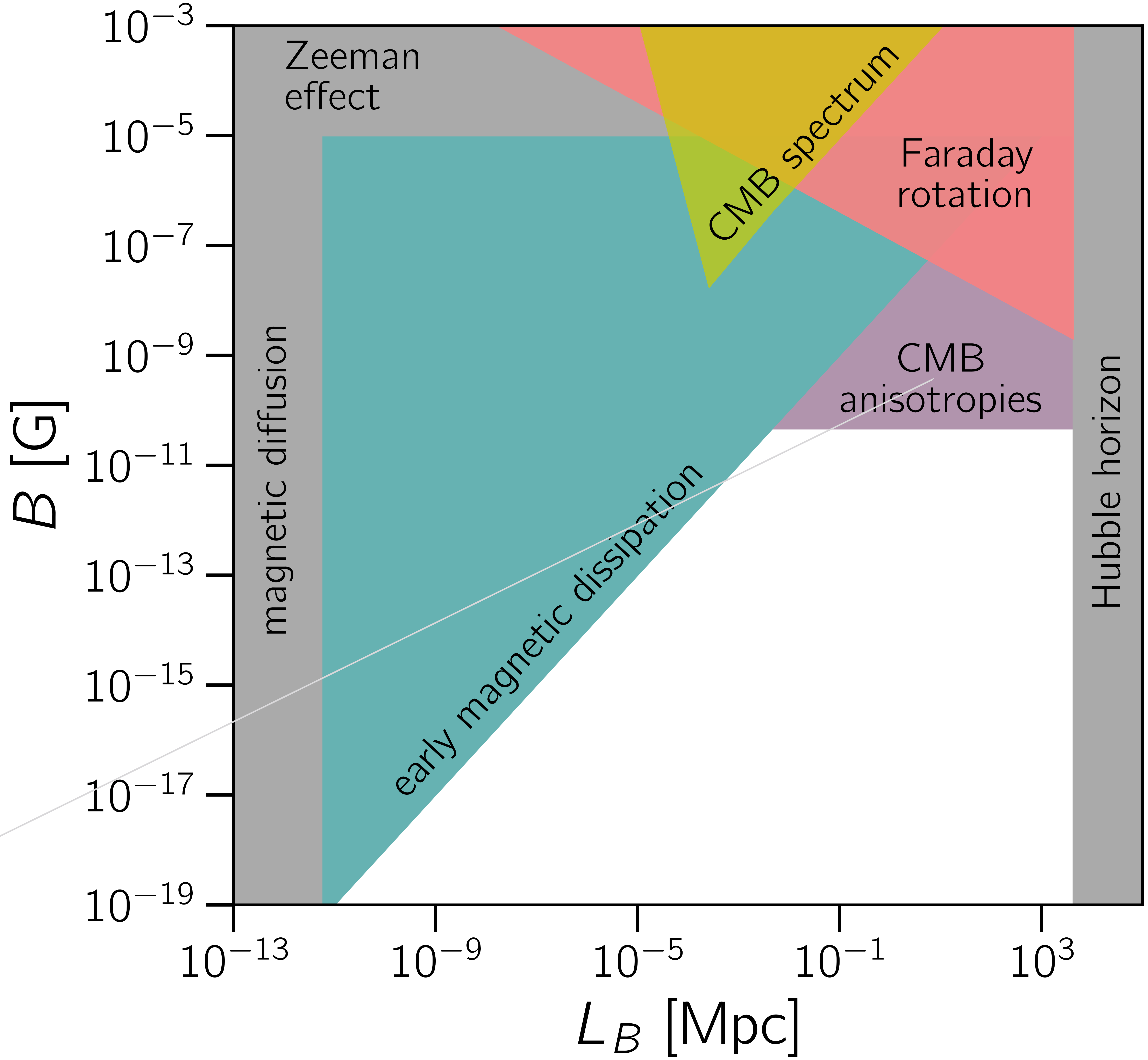


CMB dominates at ~TeV energies

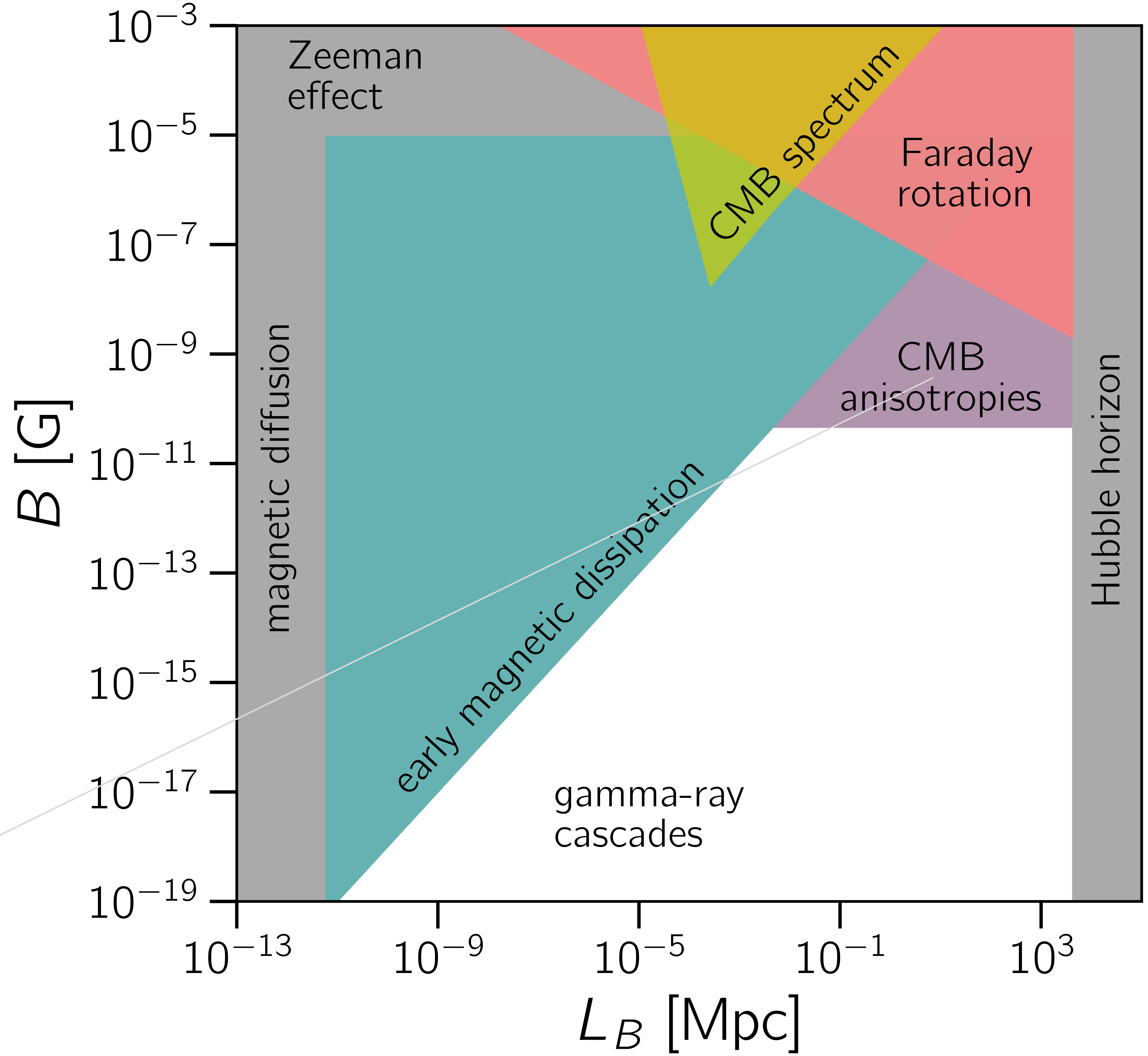


intergalactic magnetic fields (IGMFs)

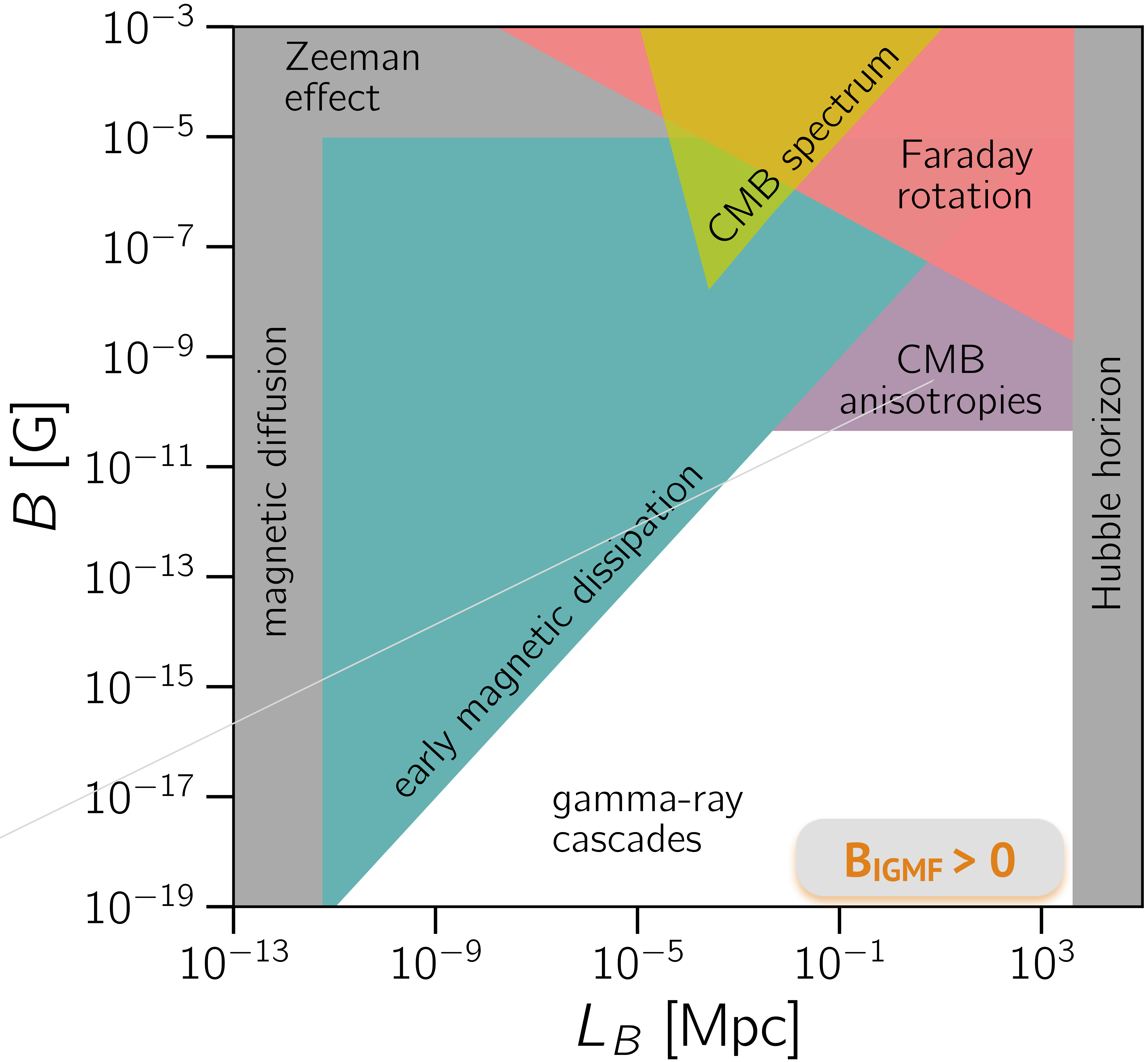
Alves Batista & Saveliev. Universe 7 (2021) 223. arXiv:2105.12020



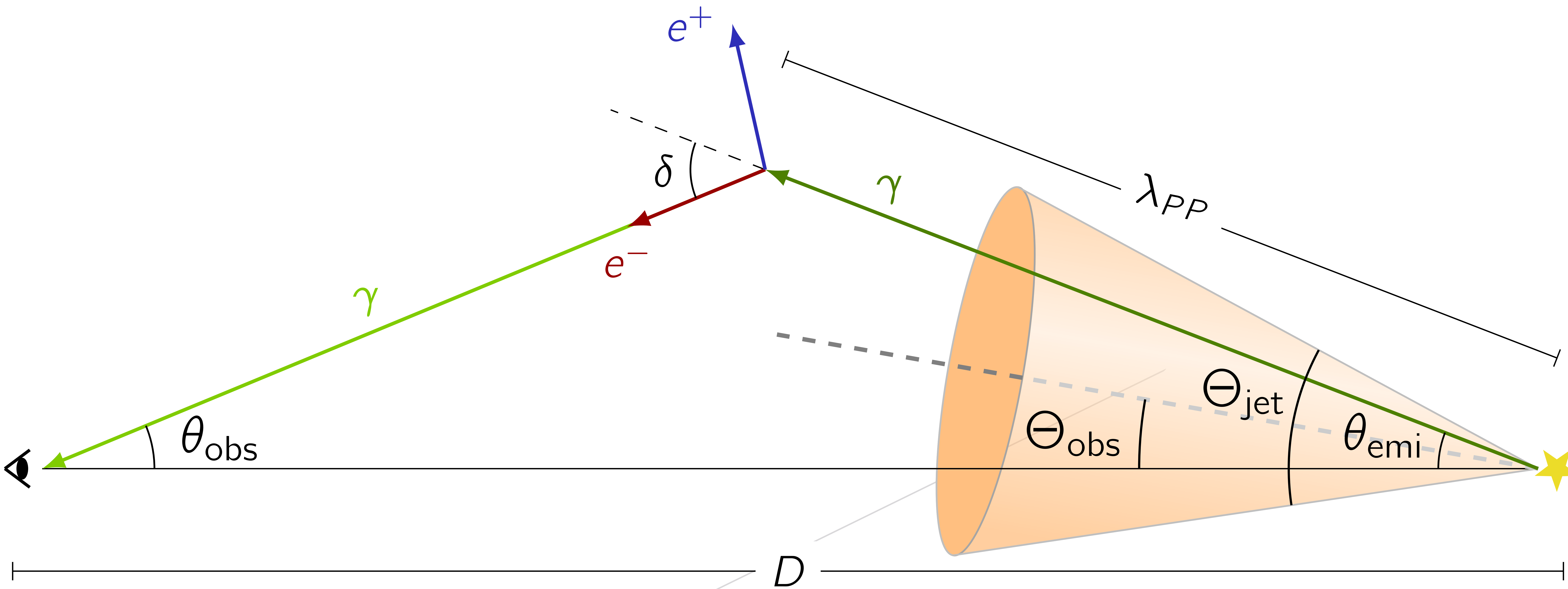
Alves Batista & Saveliev. Universe 7 (2021) 223. arXiv:2105.12020



Alves Batista & Saveliev. Universe 7 (2021) 223. arXiv:2105.12020



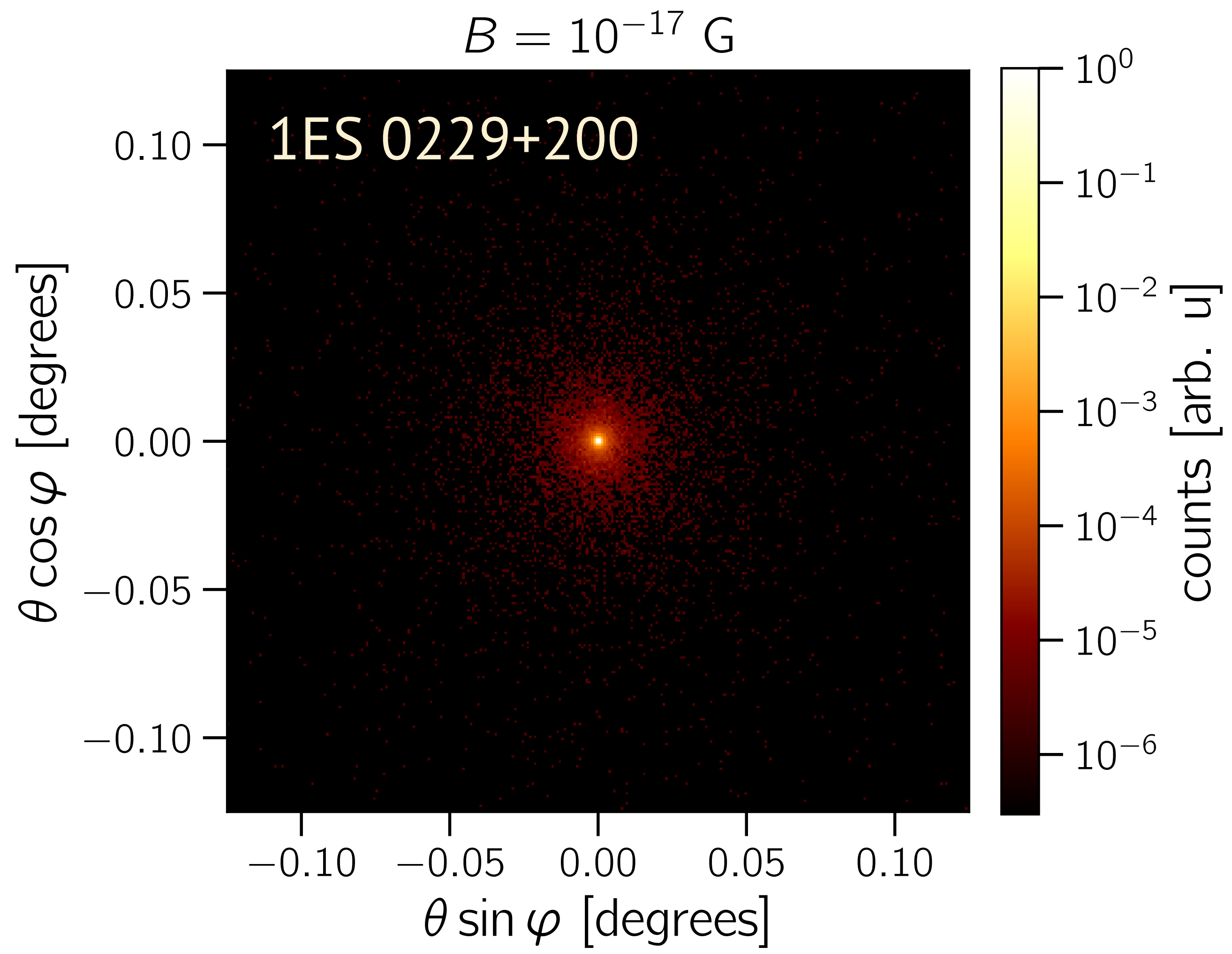
IGMF constraints with gamma rays. strategies



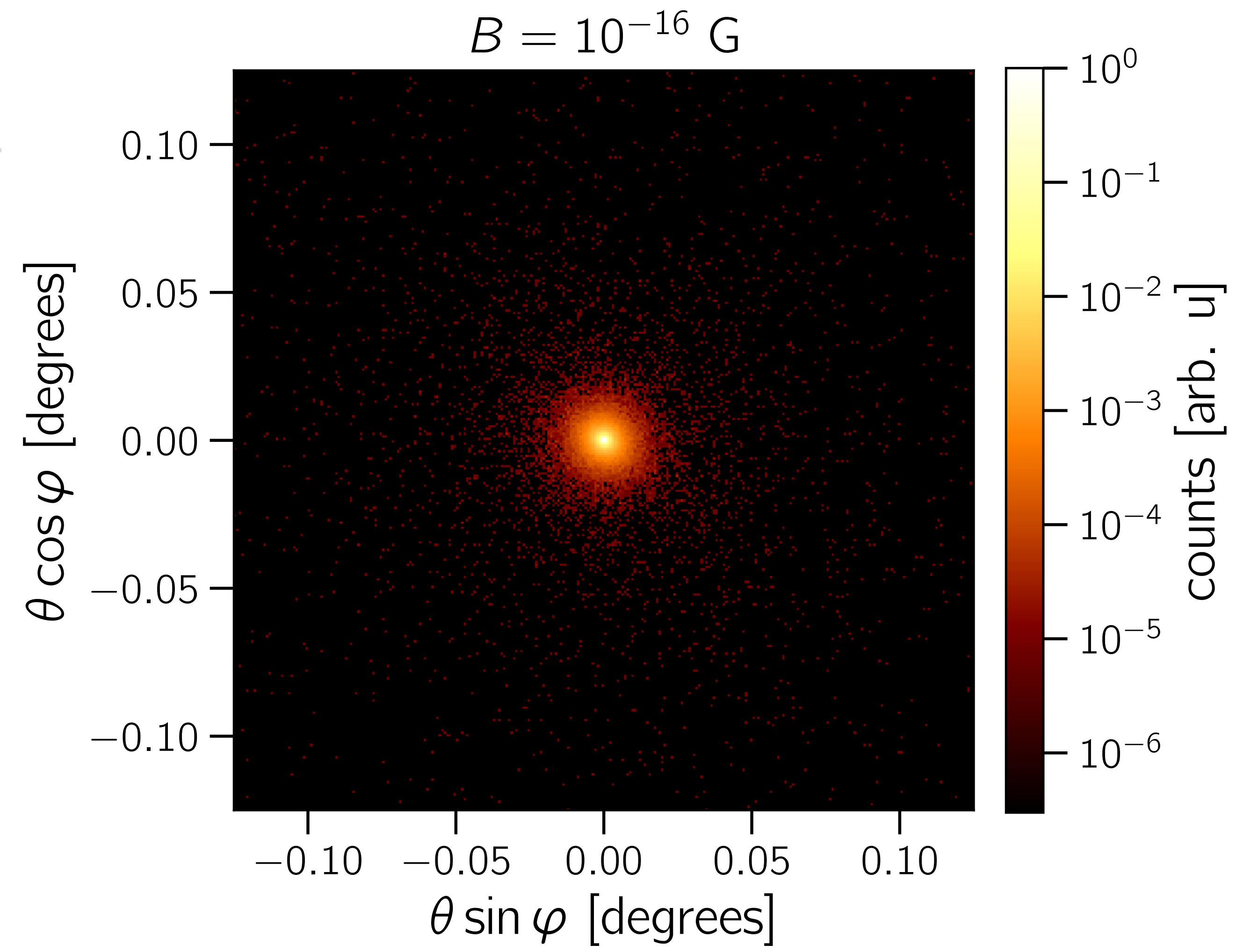
observational strategies

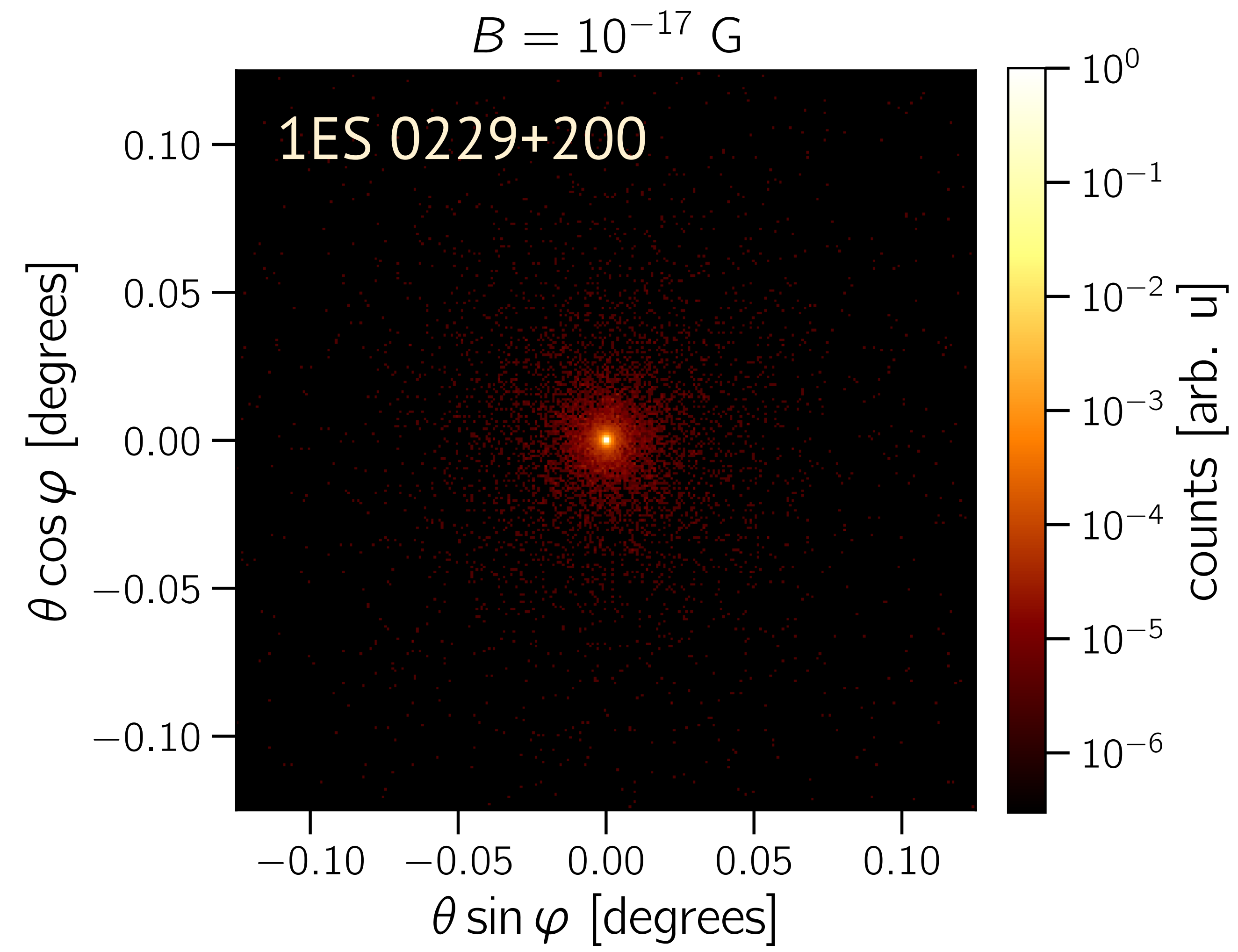
- **strategy 1:** point-like sources will appear extended
- **strategy 2:** secondary gamma rays will arrive with time delays
- **strategy 3:** combination of 1 and 2 → spectral changes

Alves Batista & Saveliev. Universe 7 (2021) 223. arXiv:2105.12020



Alves Batista & Saveliev. Universe 7 (2021) 223. arXiv:2105.12020





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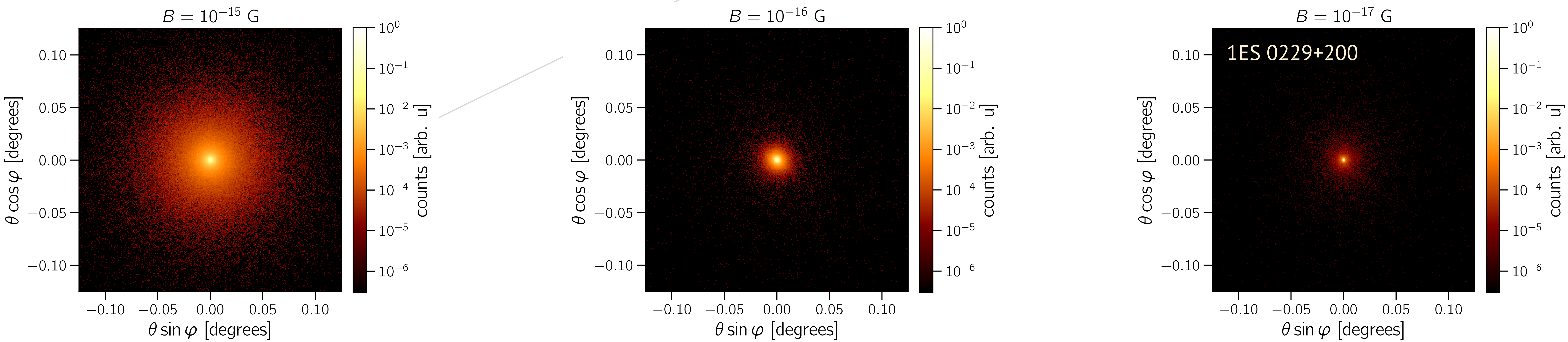

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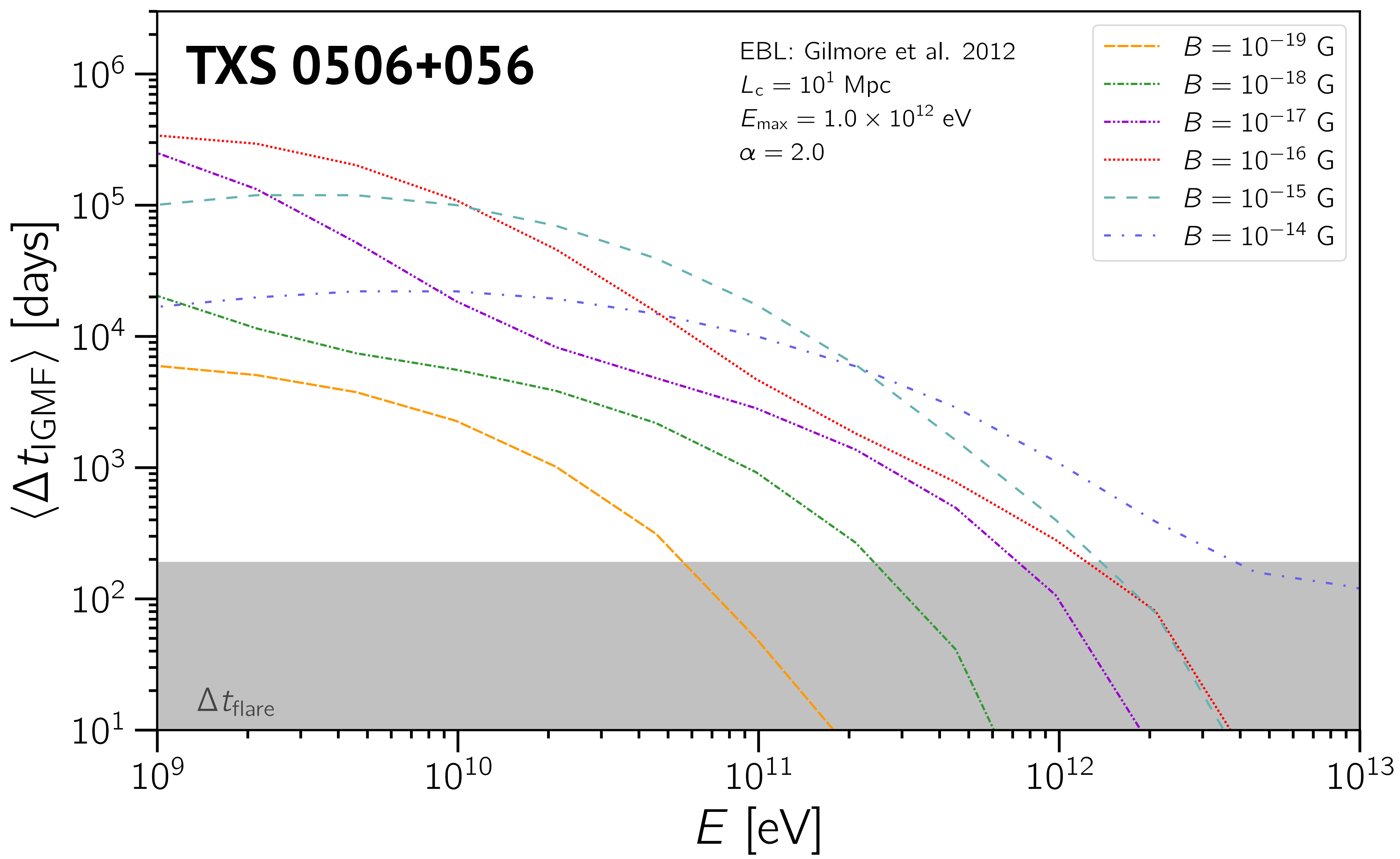

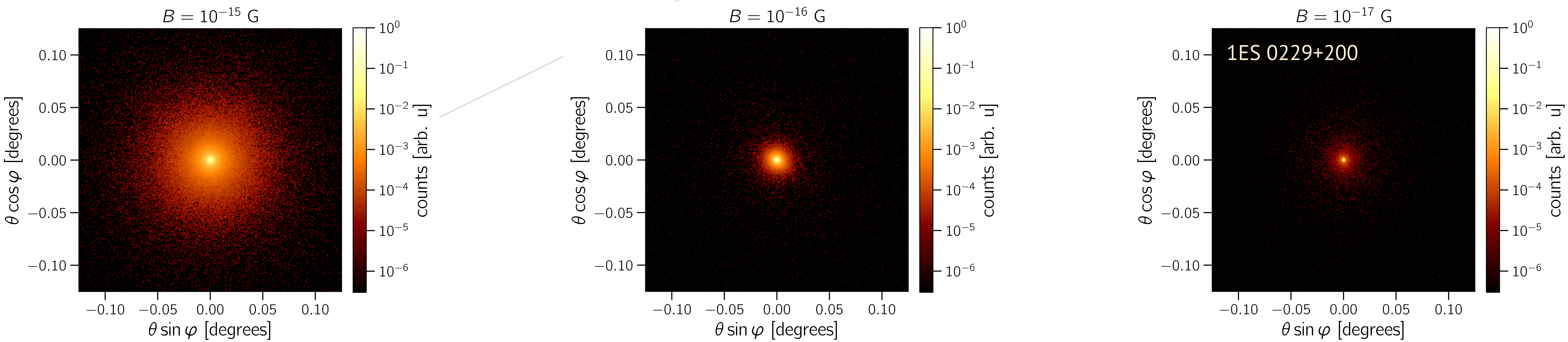

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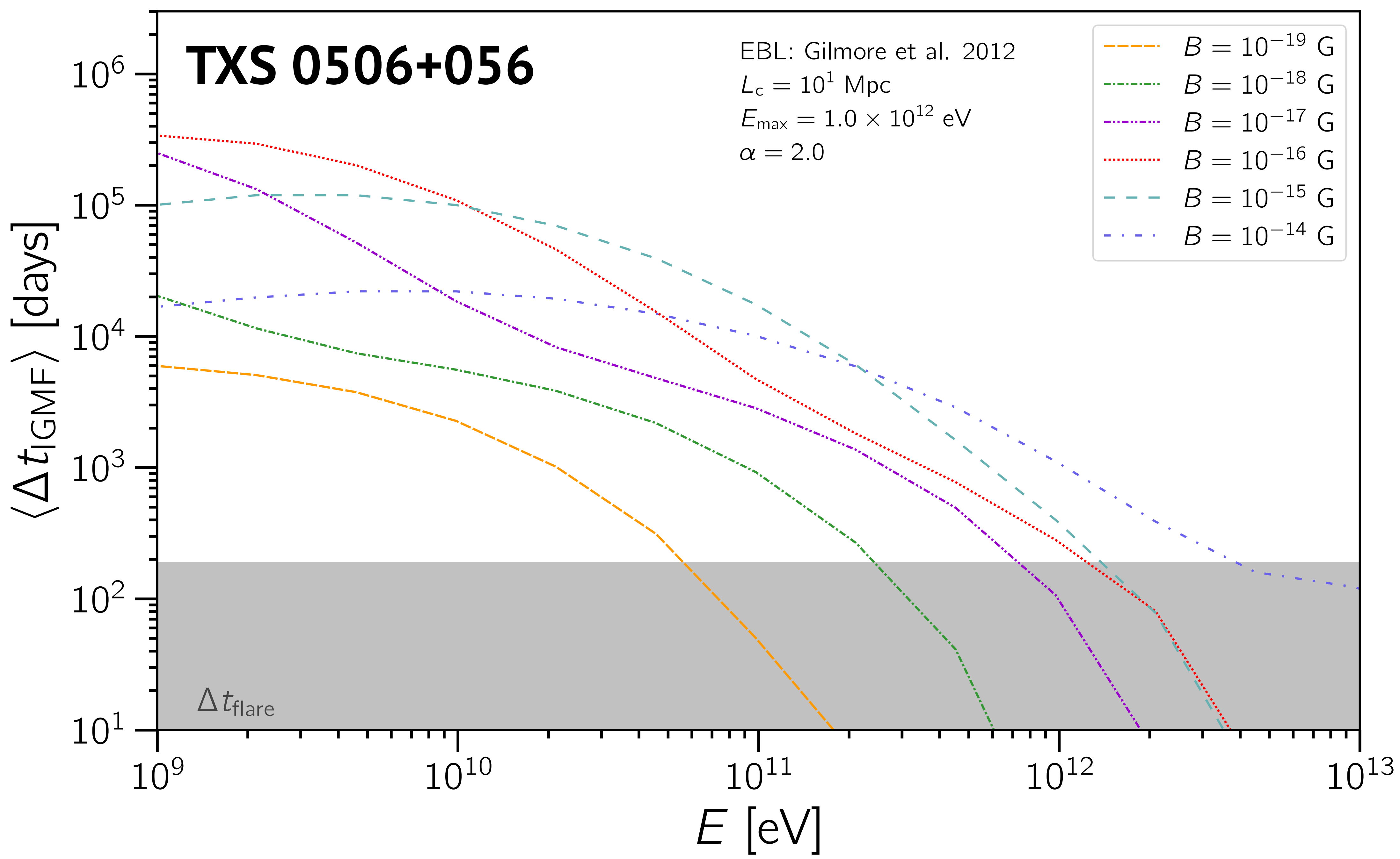
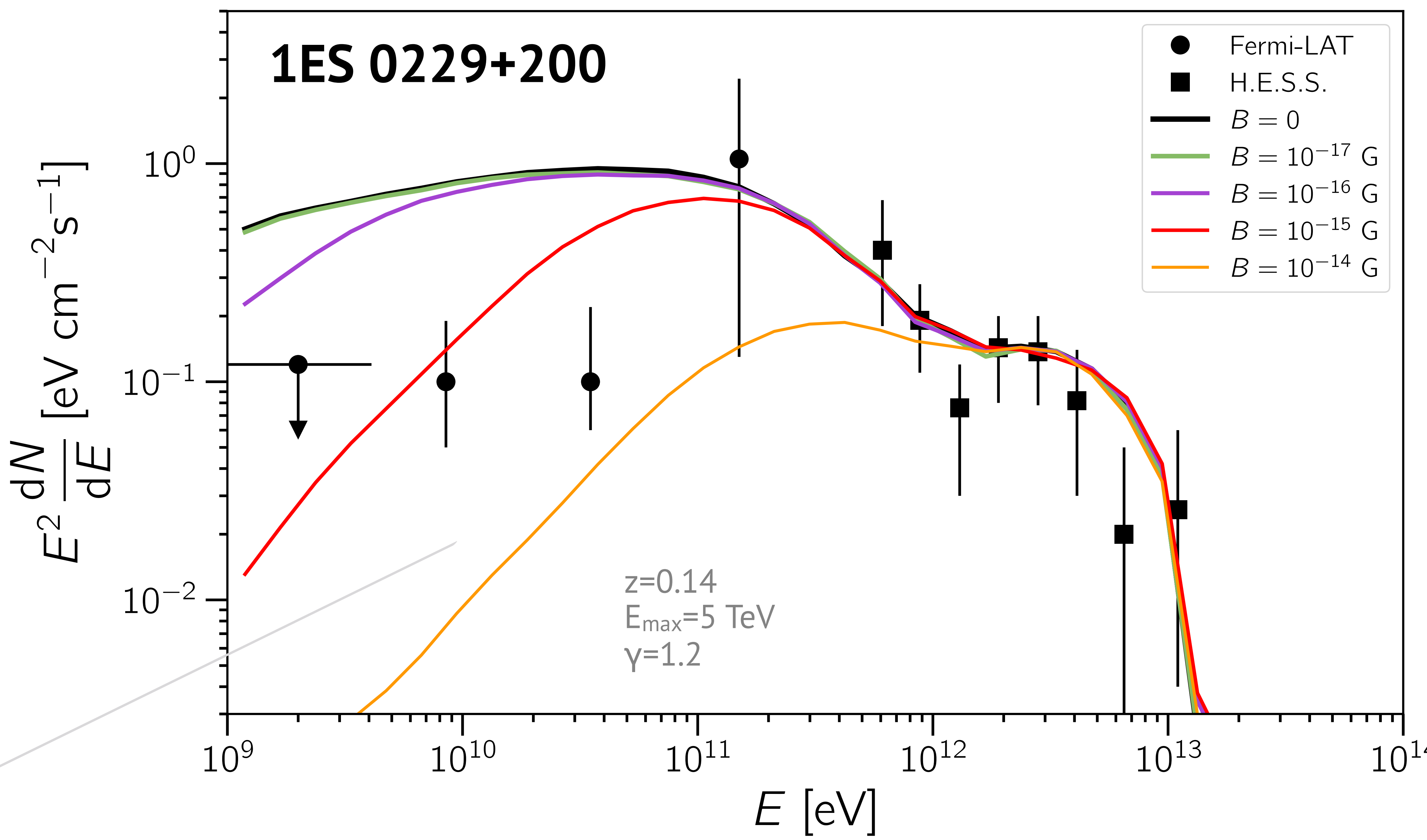
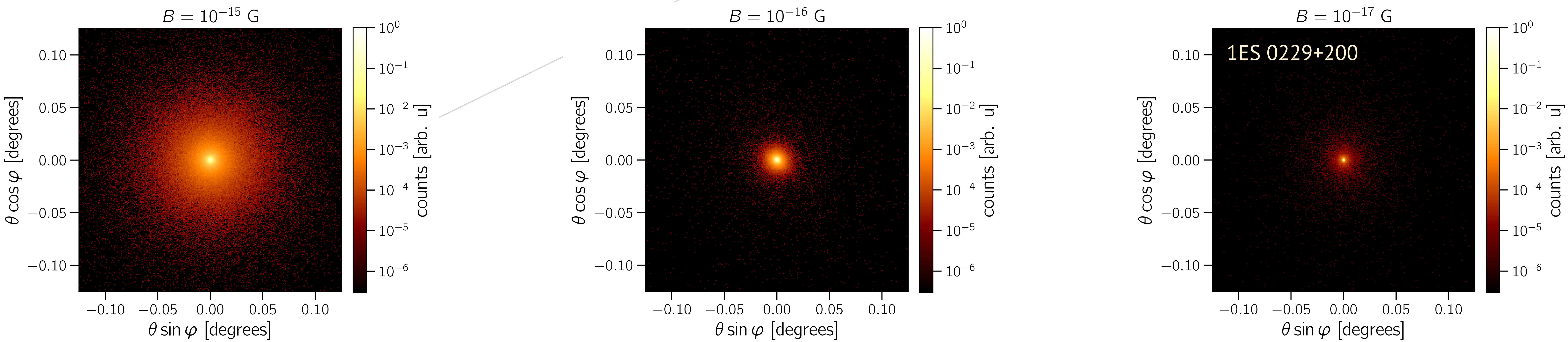
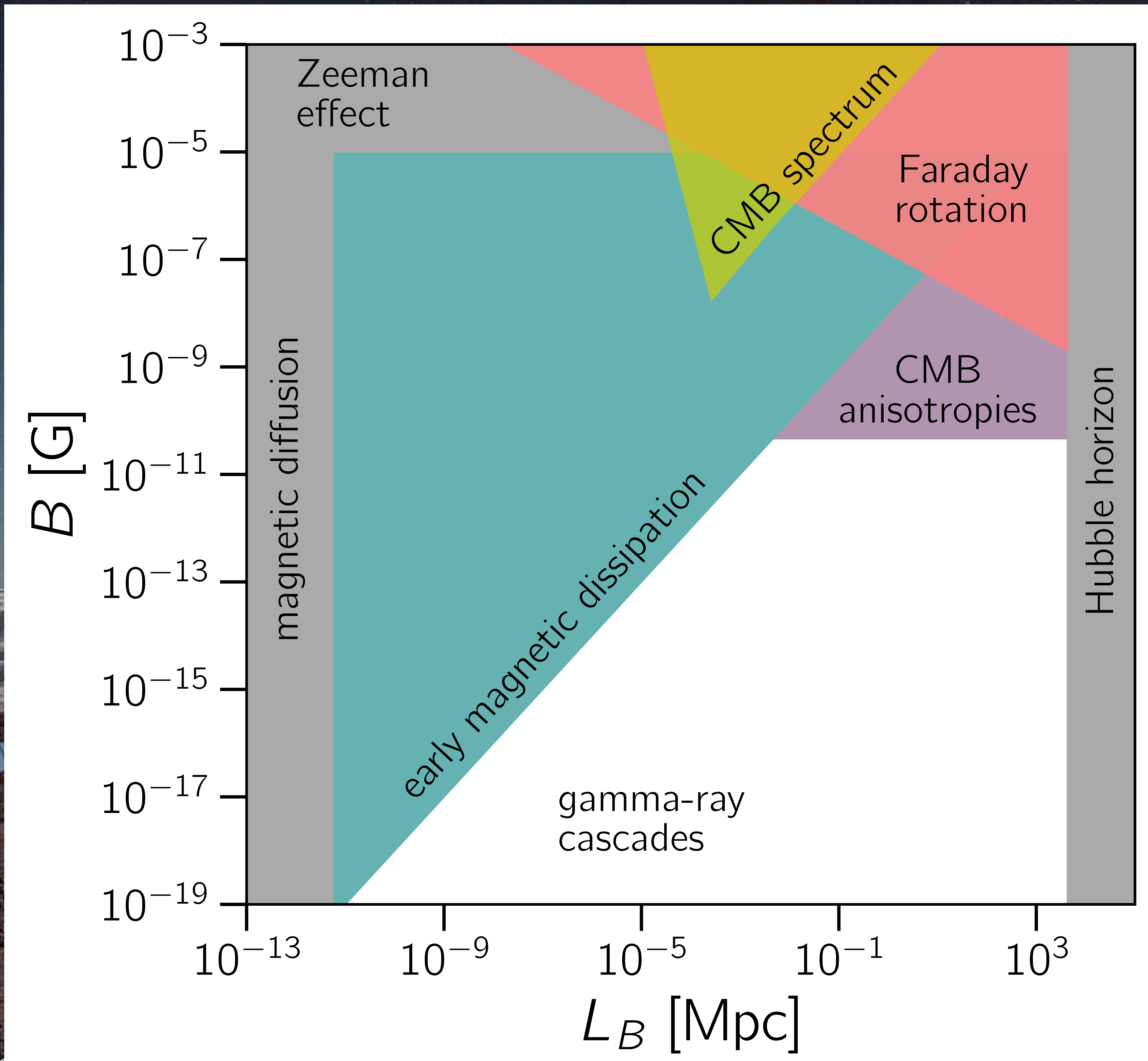






probing IGMFs with the Cherenkov Telescope Array Observatory

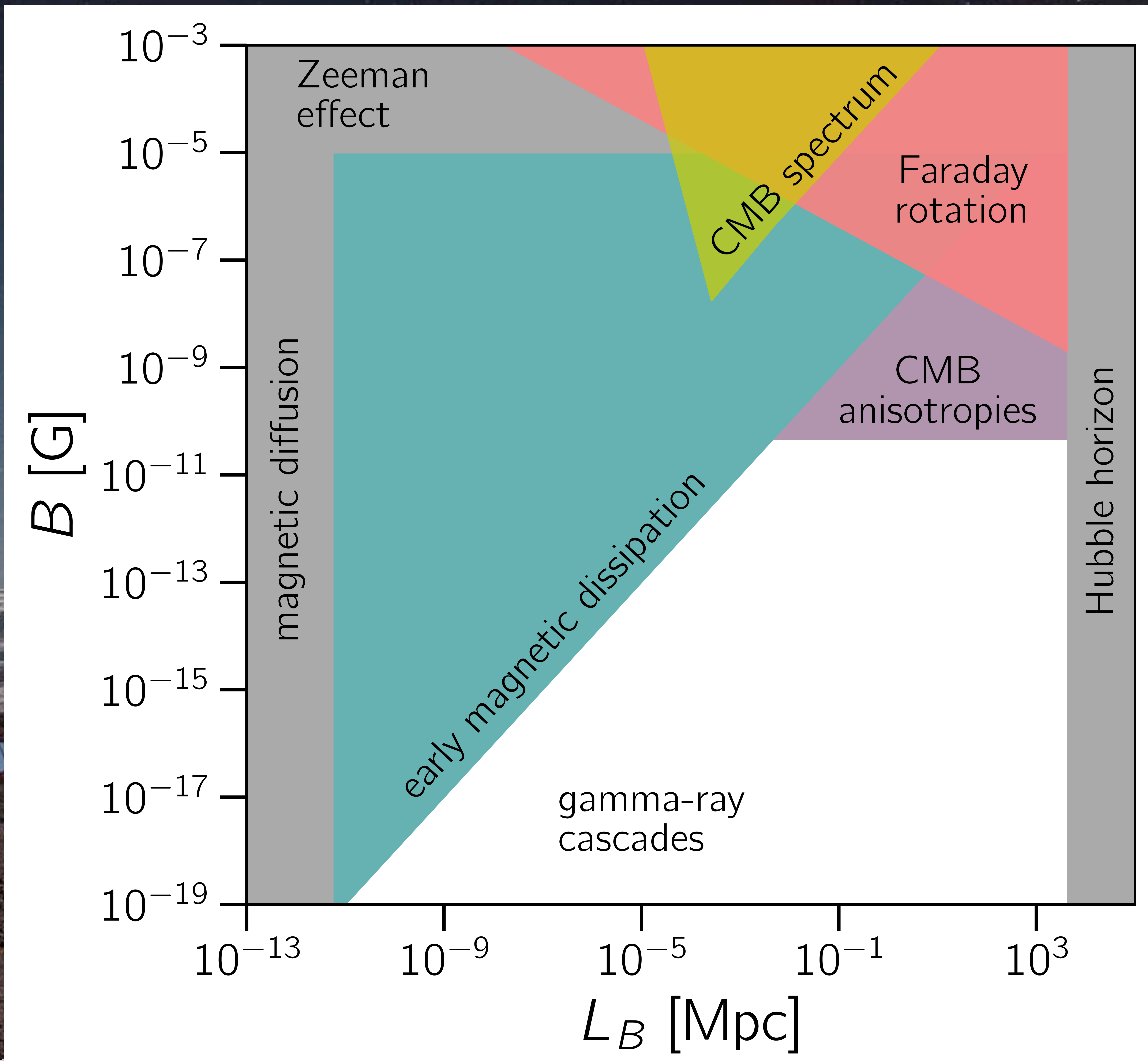
CTA Consortium. JCAP 02 (2021) 048. arXiv:2010.01349

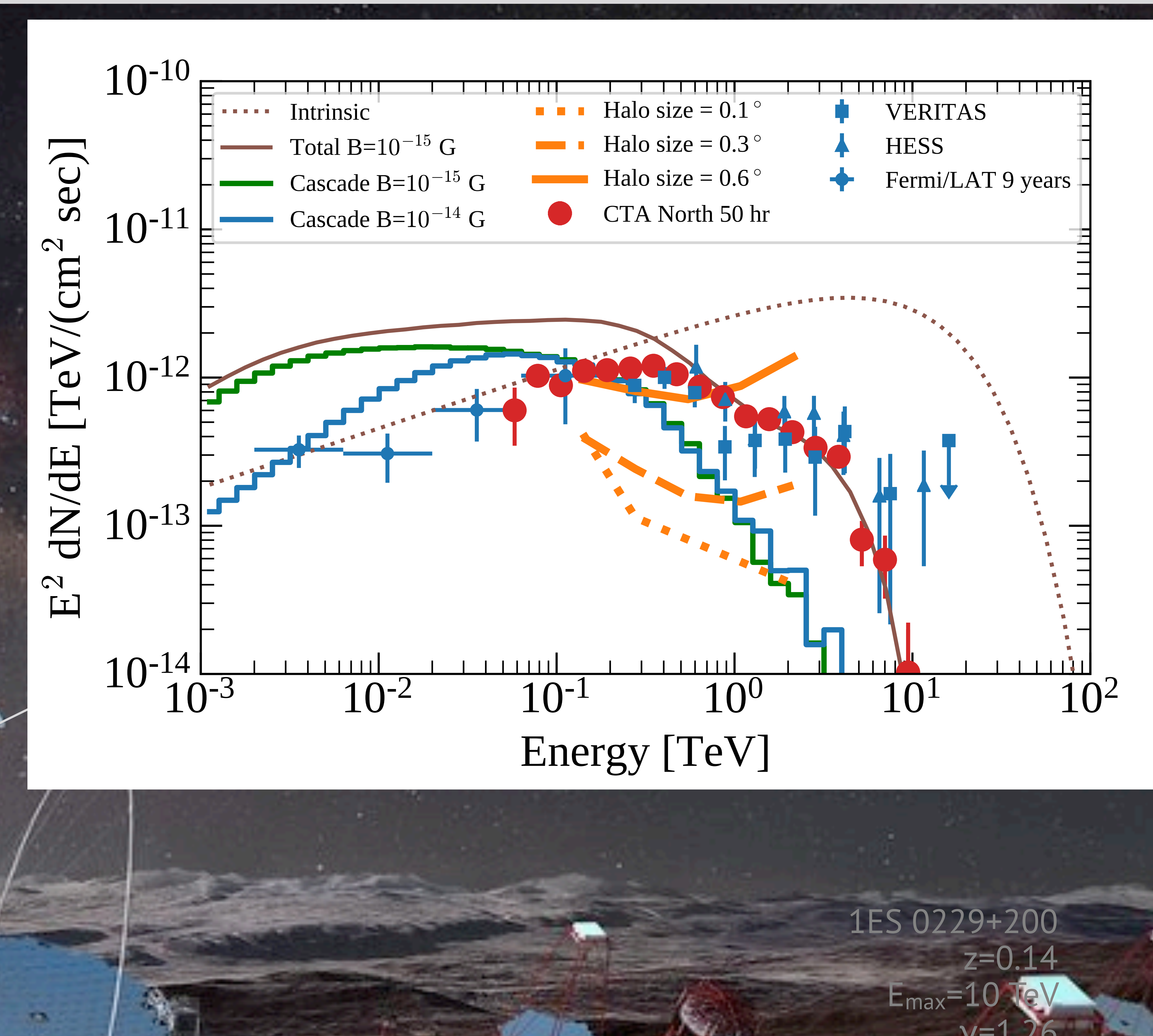


1ES 0229+200
z=0.14
E_{max}=10 TeV
γ=1.26

probing IGMFs with the Cherenkov Telescope Array Observatory

CTA Consortium. JCAP 02 (2021) 048. arXiv:2010.01349





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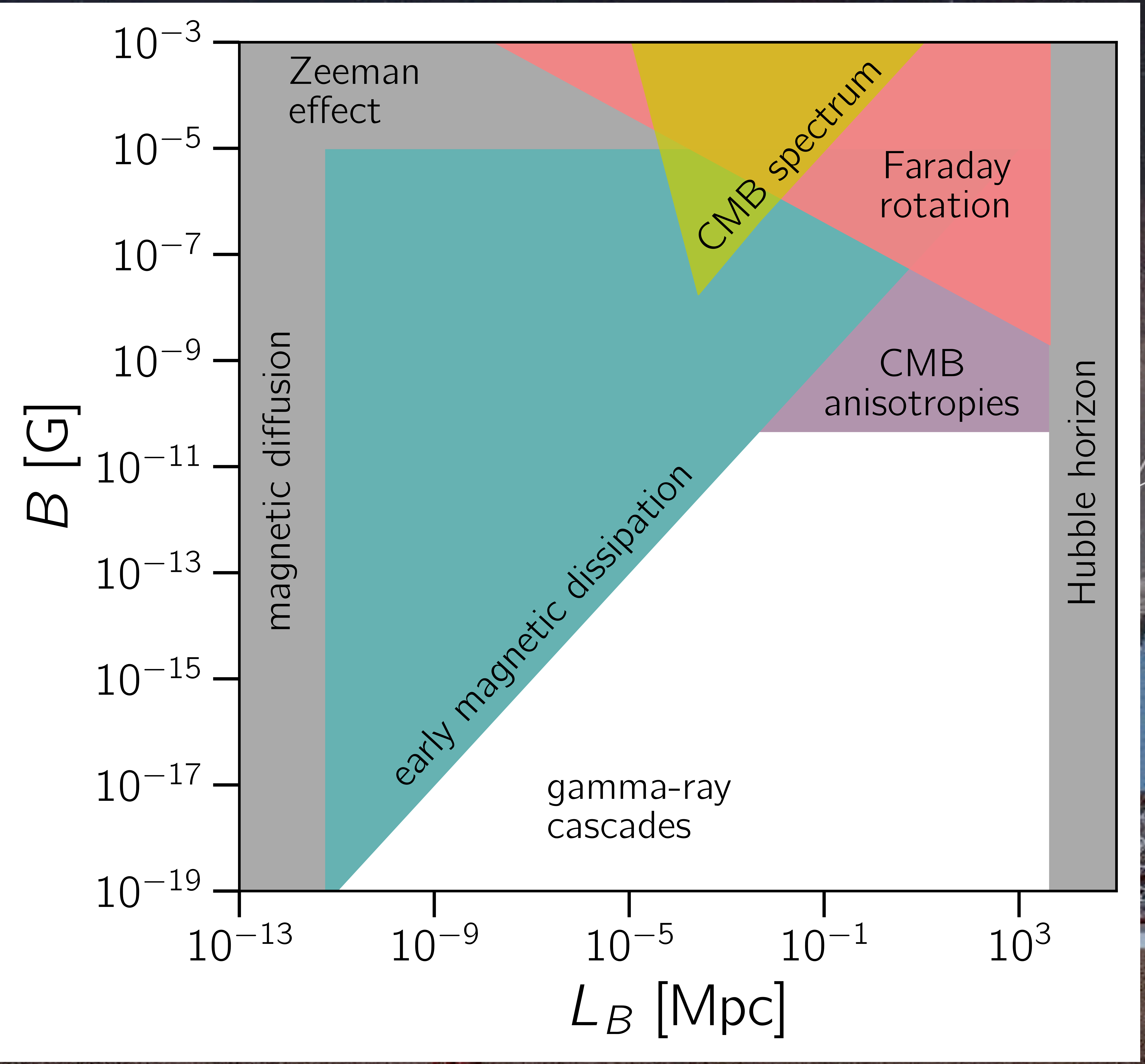

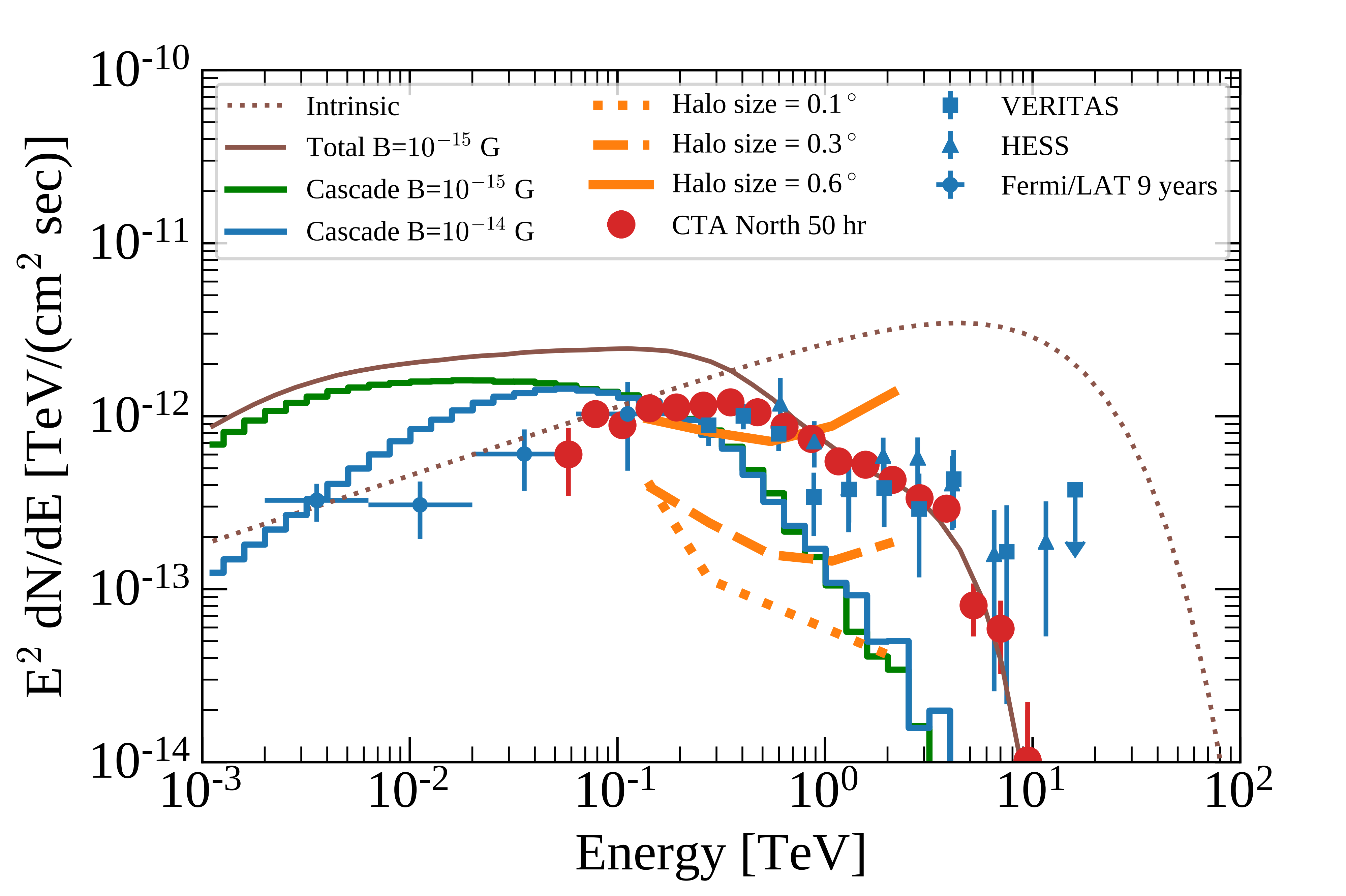

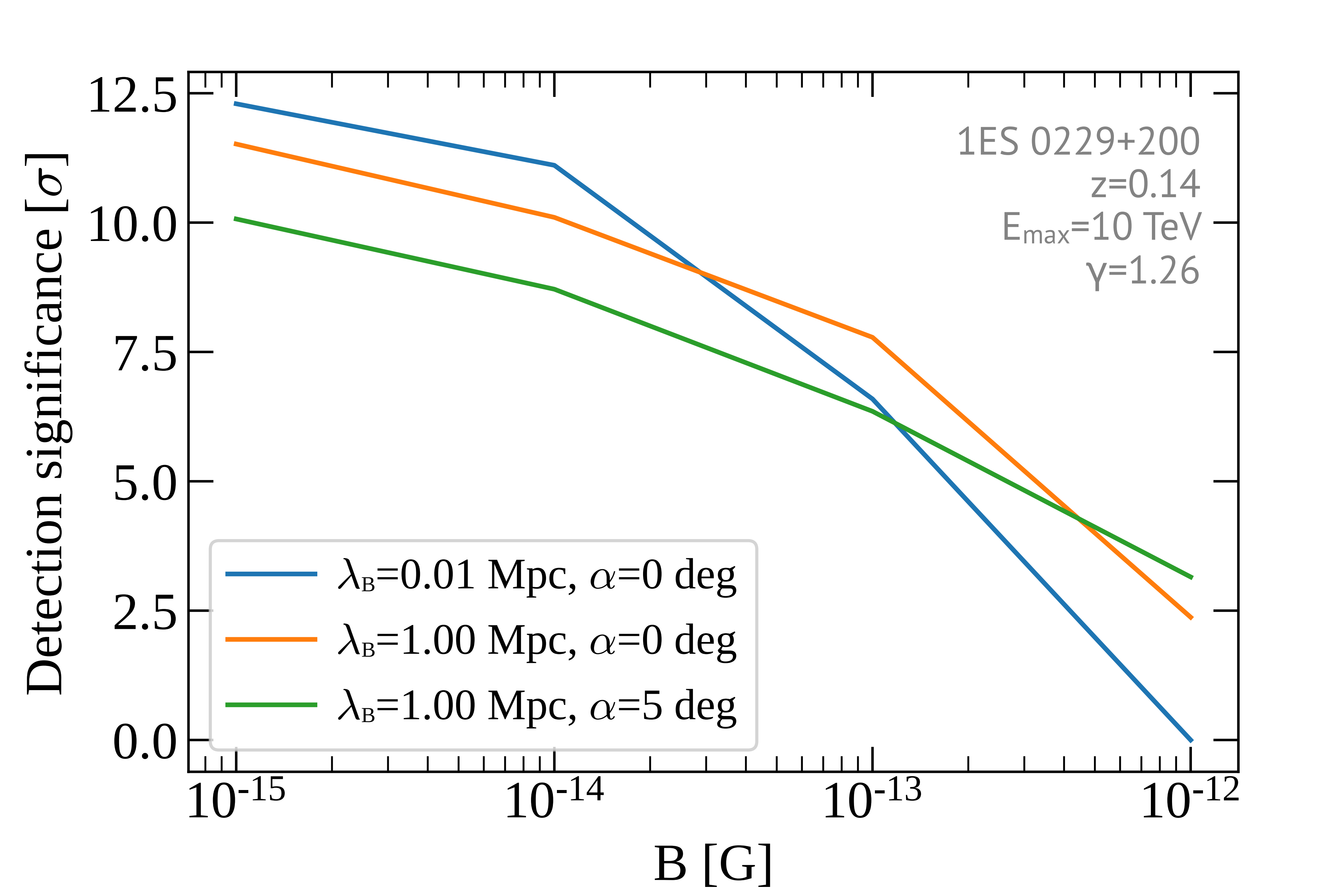

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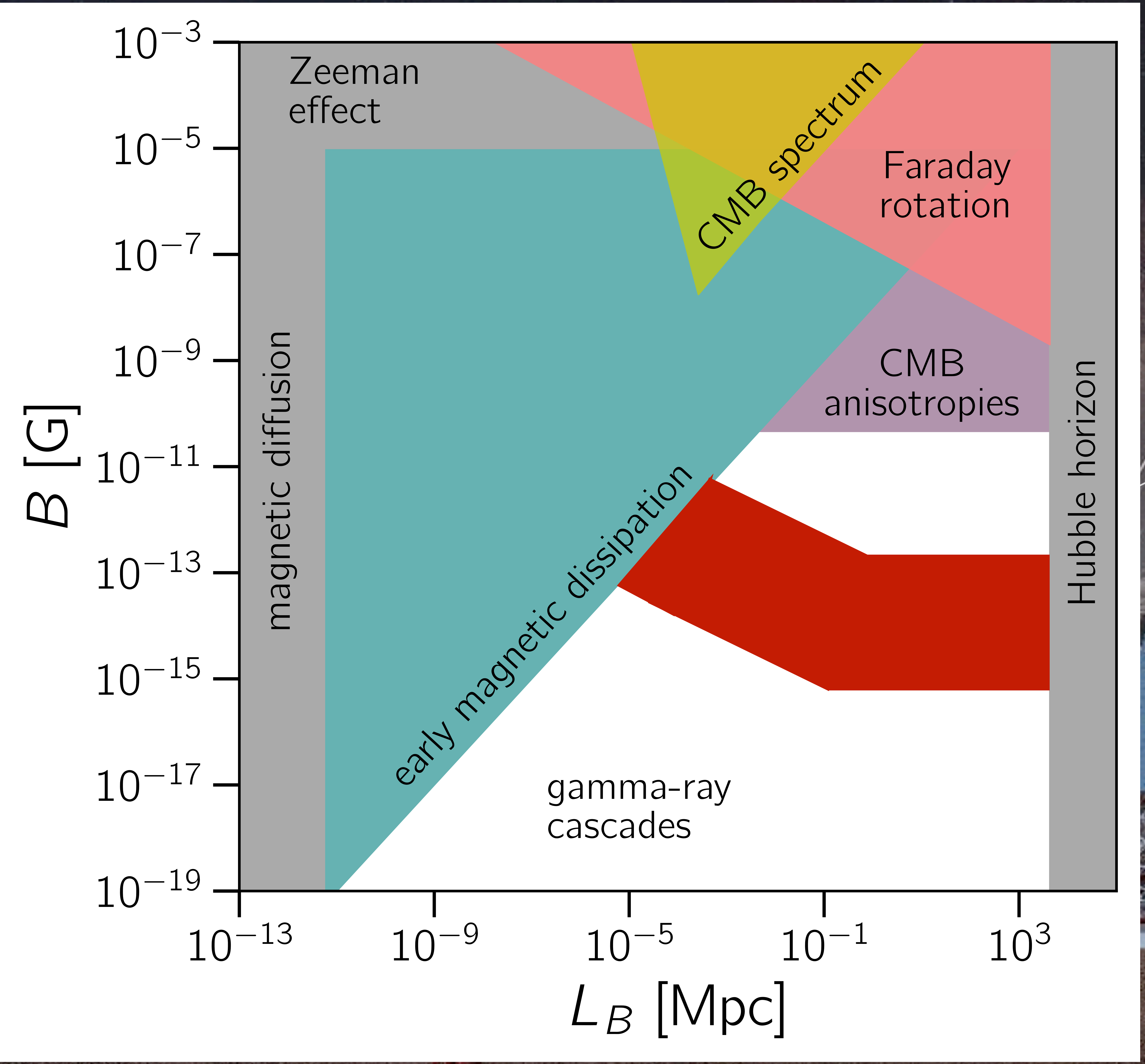

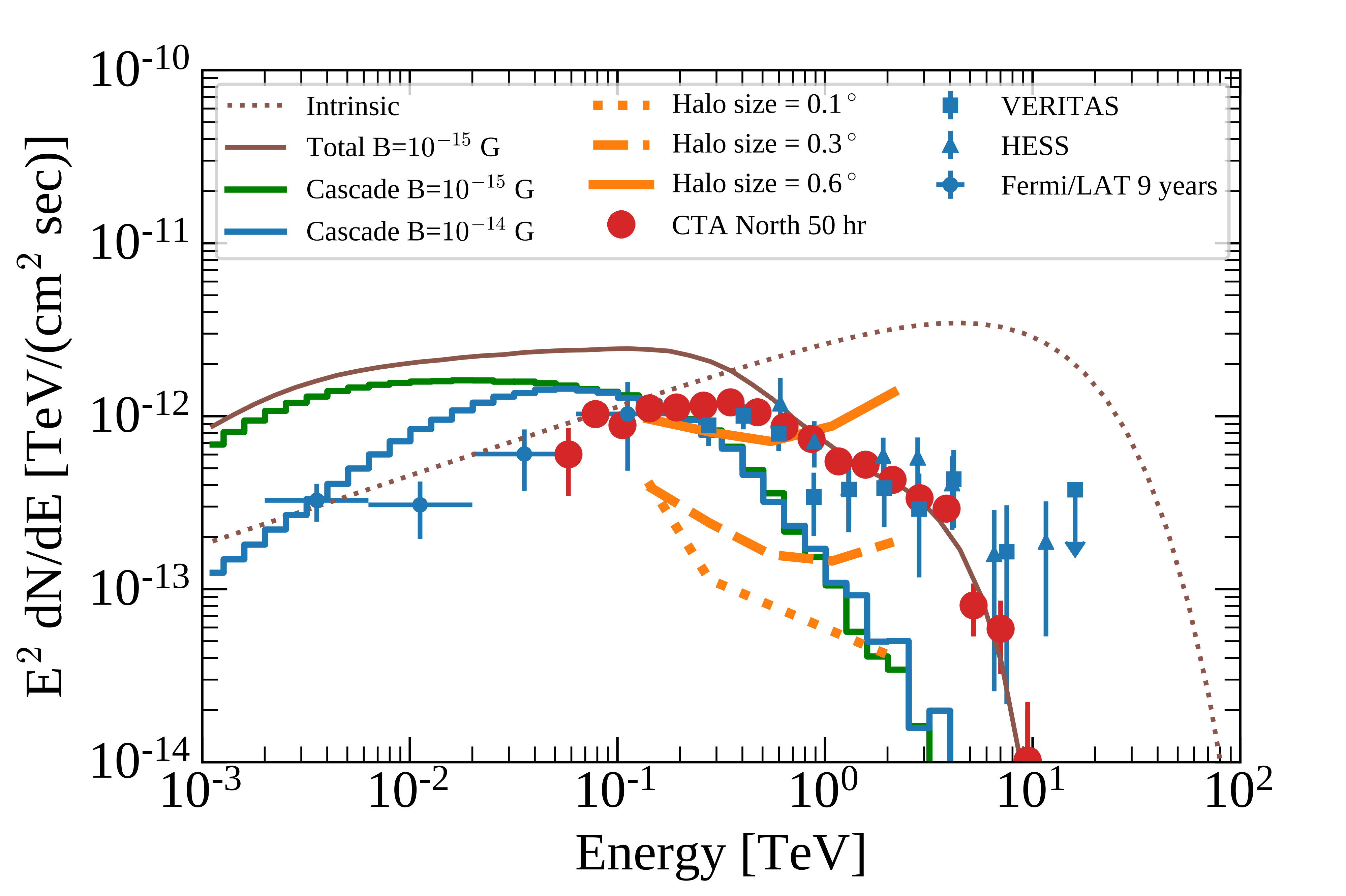

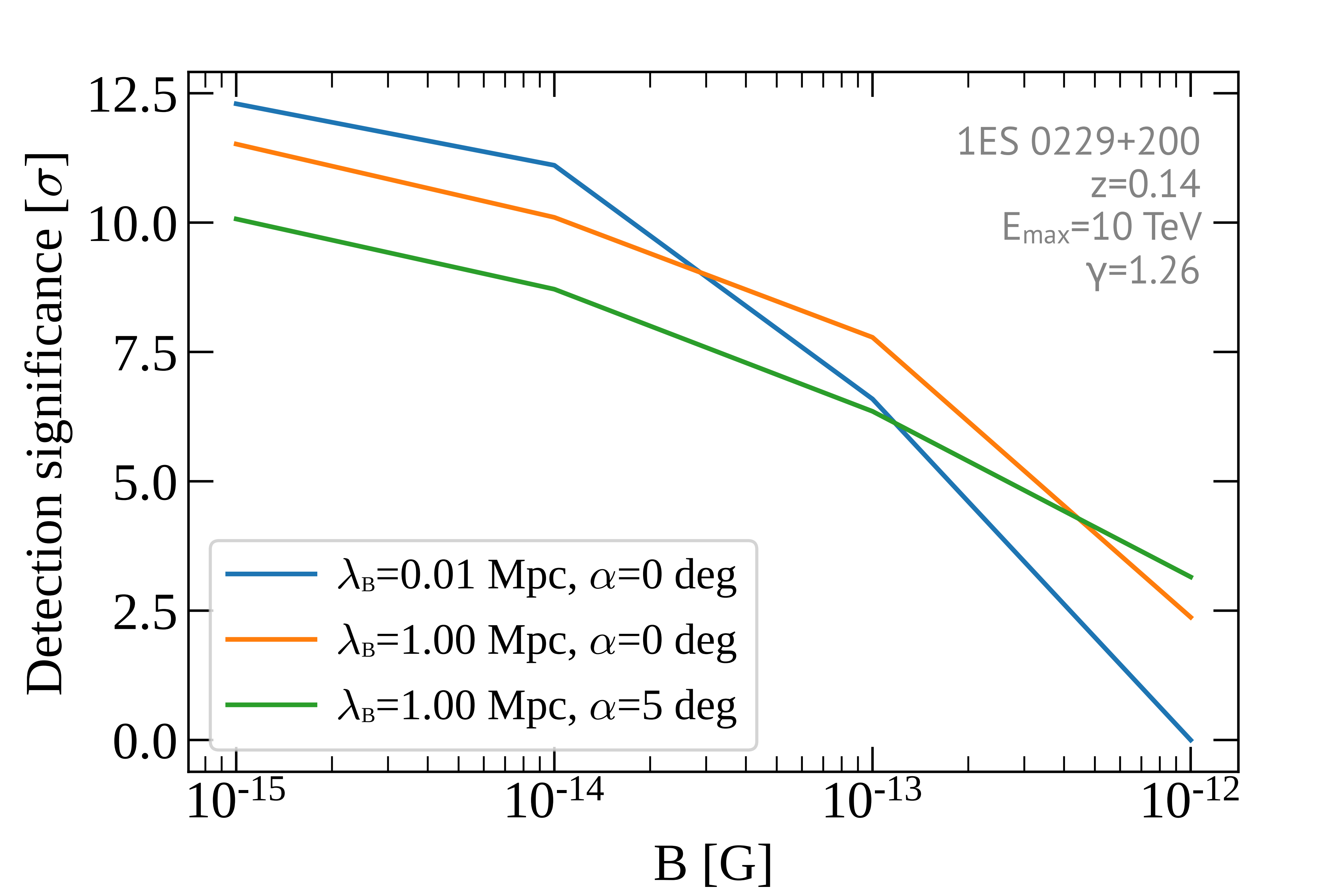

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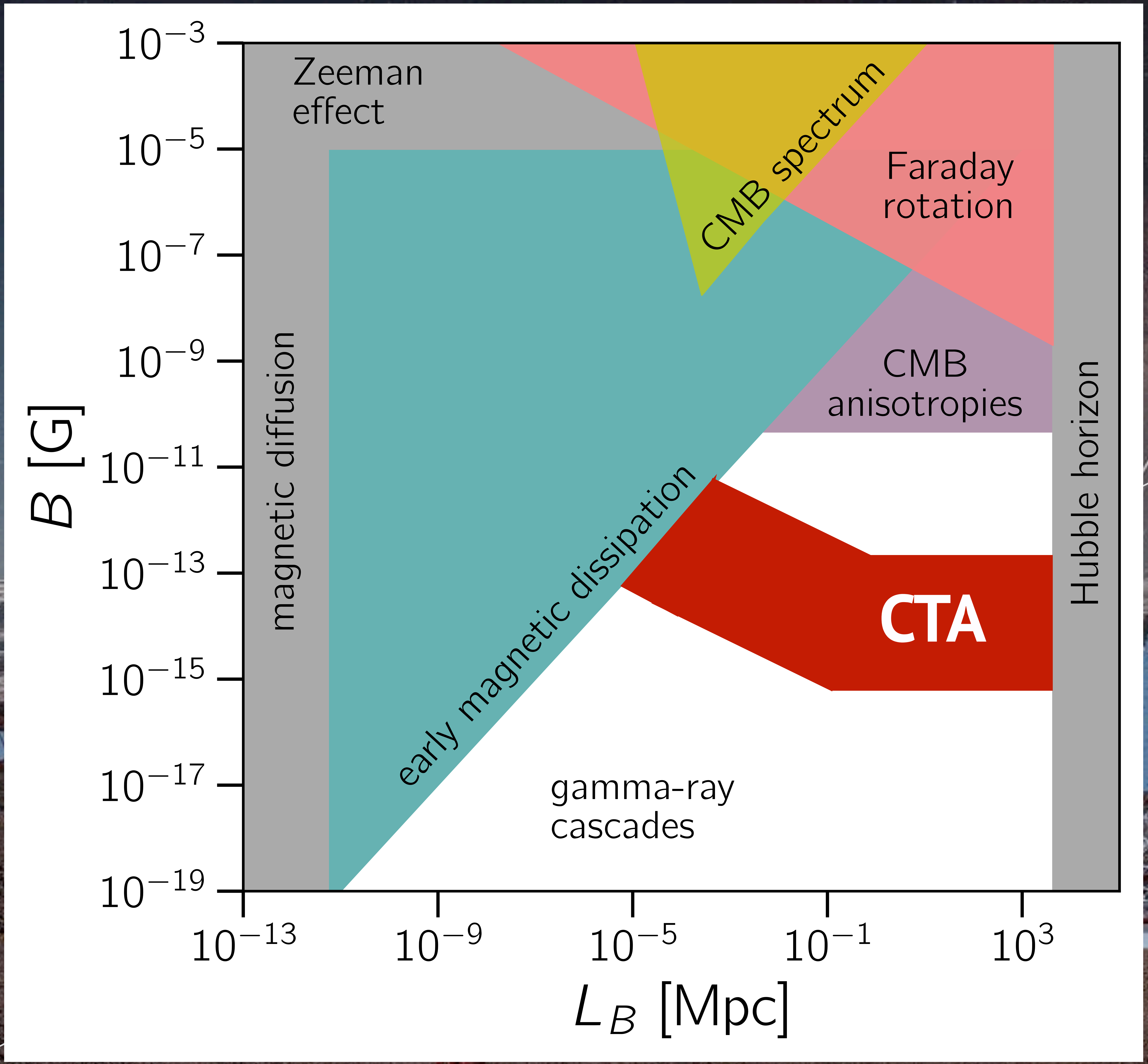

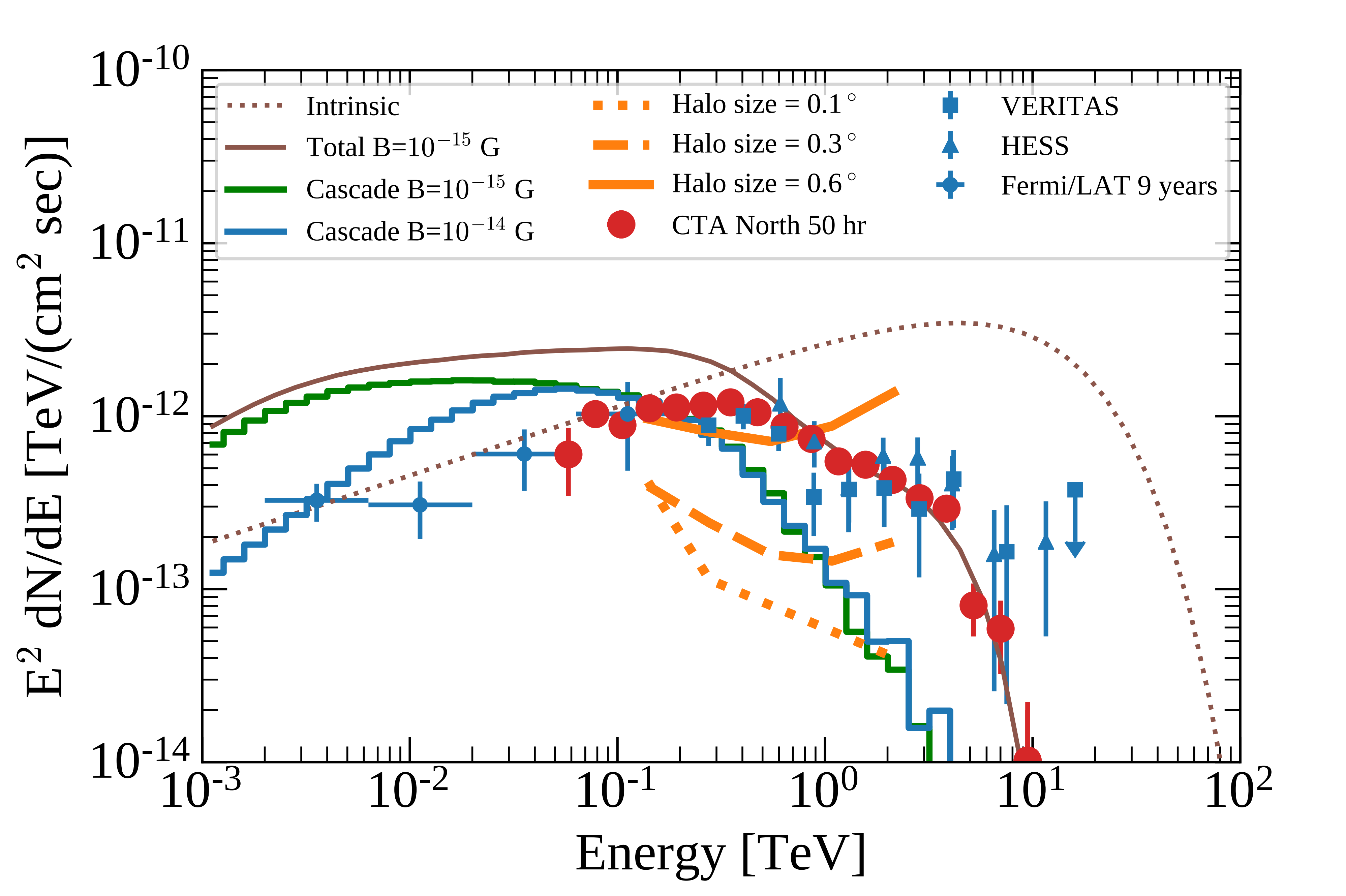

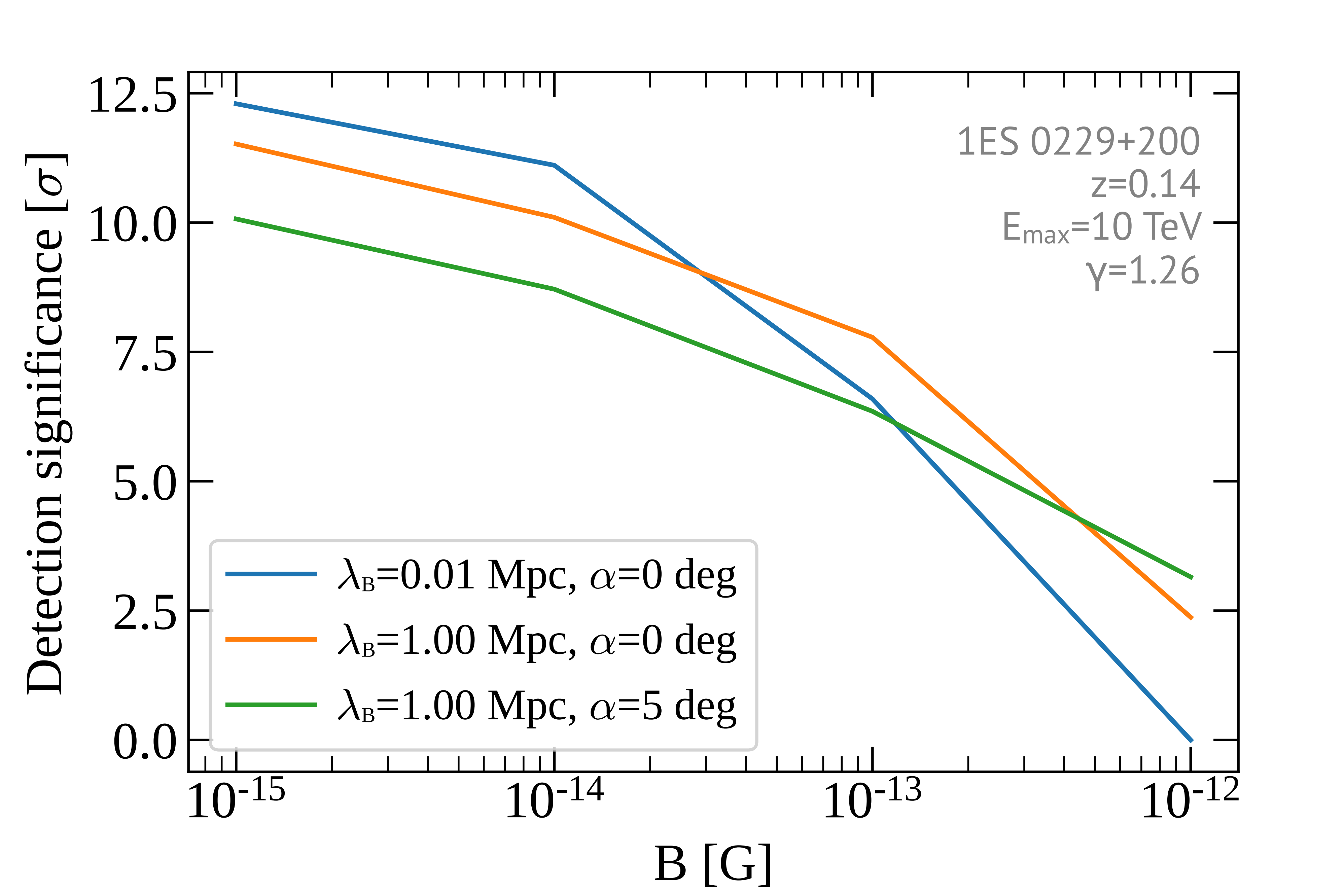

constraining IGMFs with the ASTRI Mini-Array

Vercellone et al. JHEAp 35 (2022) 1. arxiv:2208.03177

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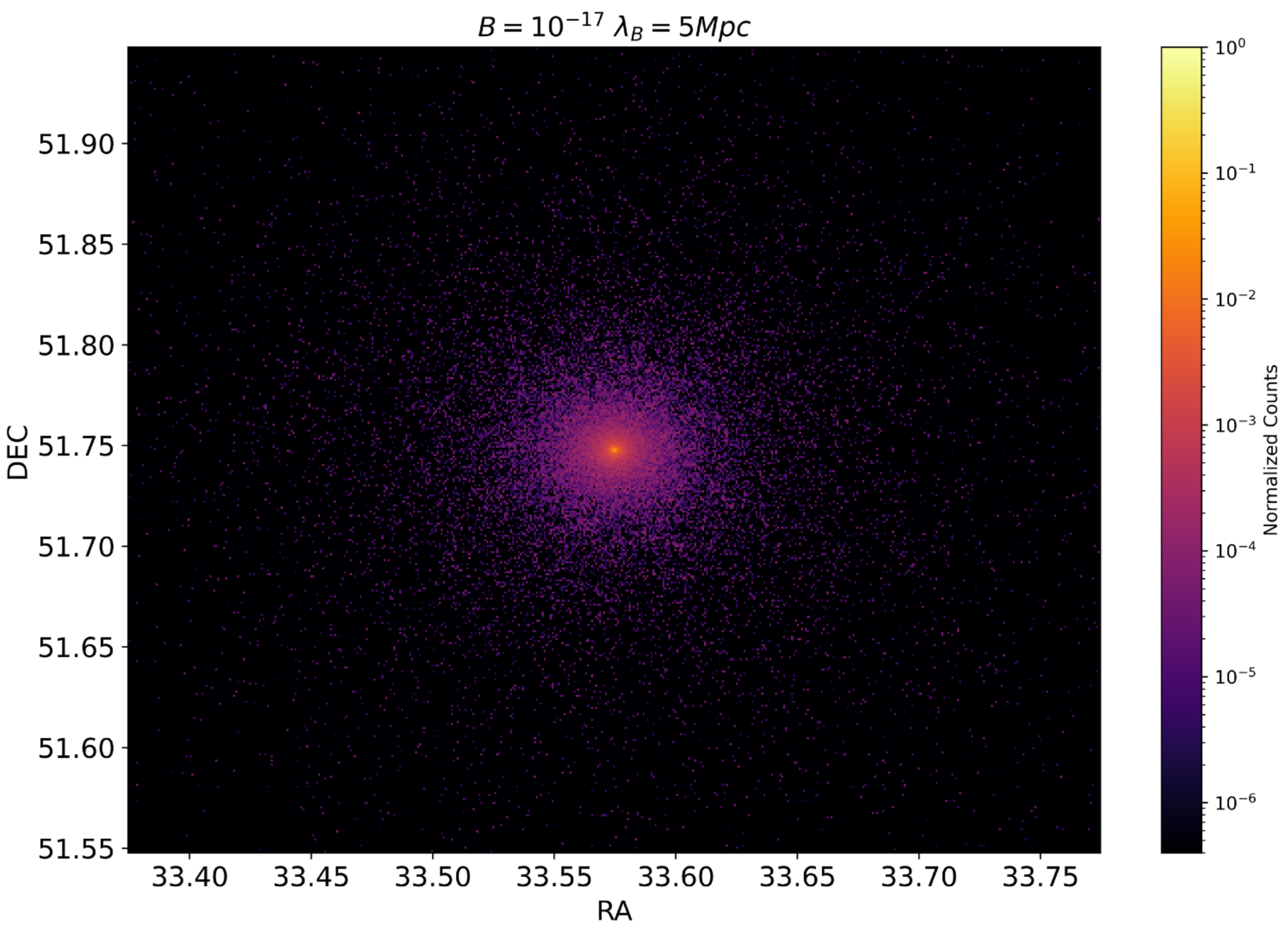
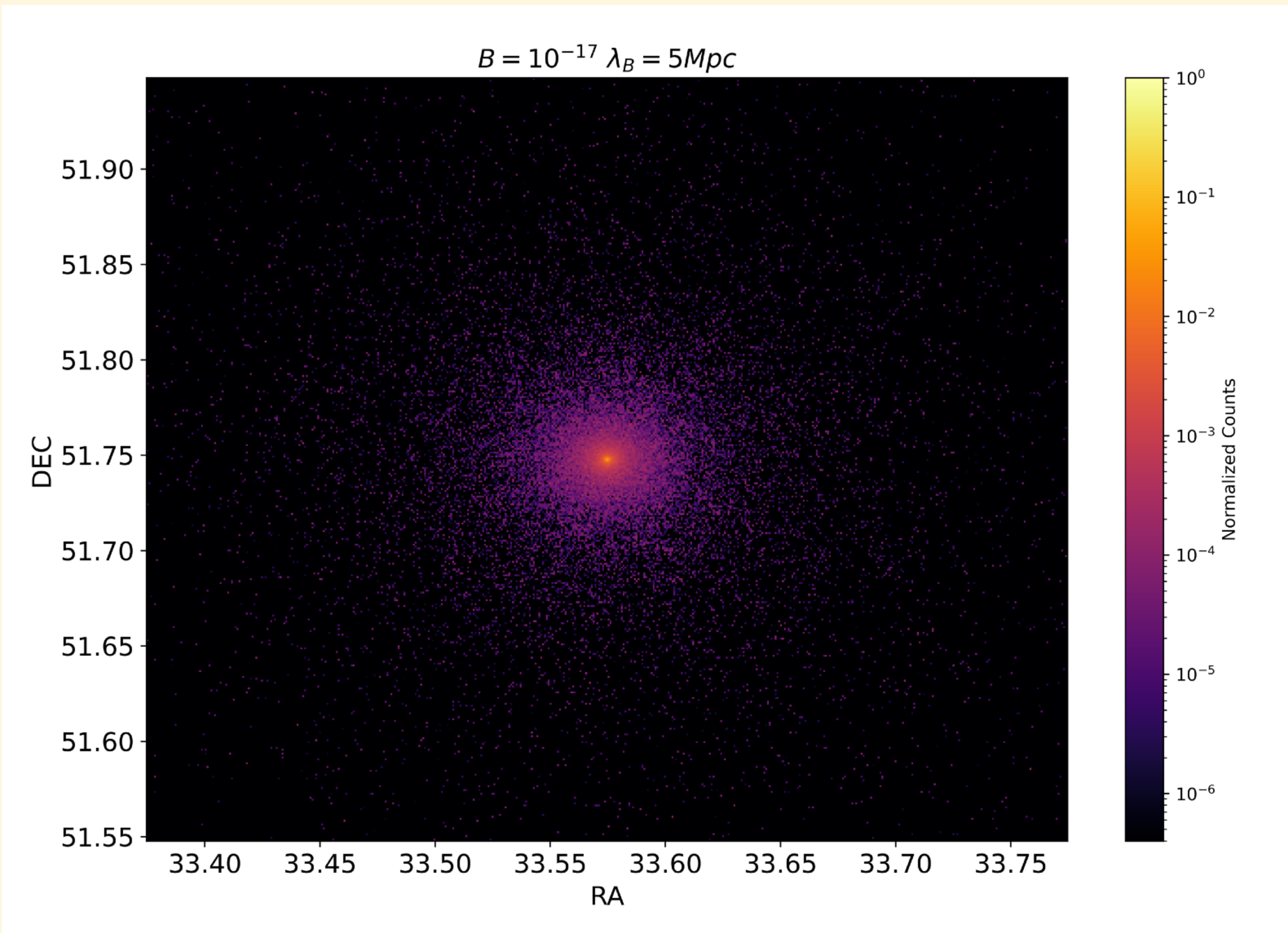
Vercellone et al. JHEAp 35 (2022) 1. arxiv:2208.03177

CRPropa-gammapy integration

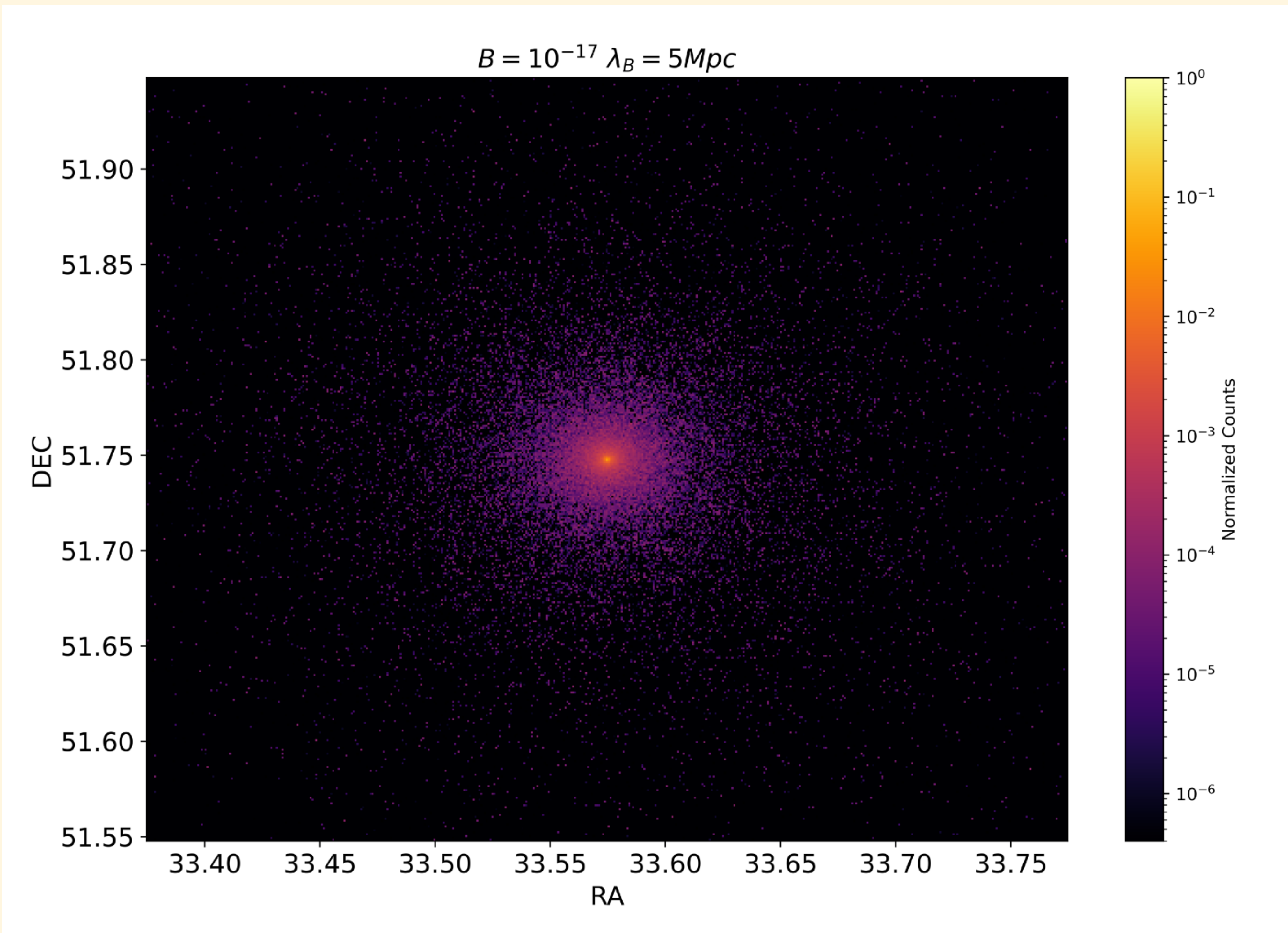
CRPropa-gammapy integration

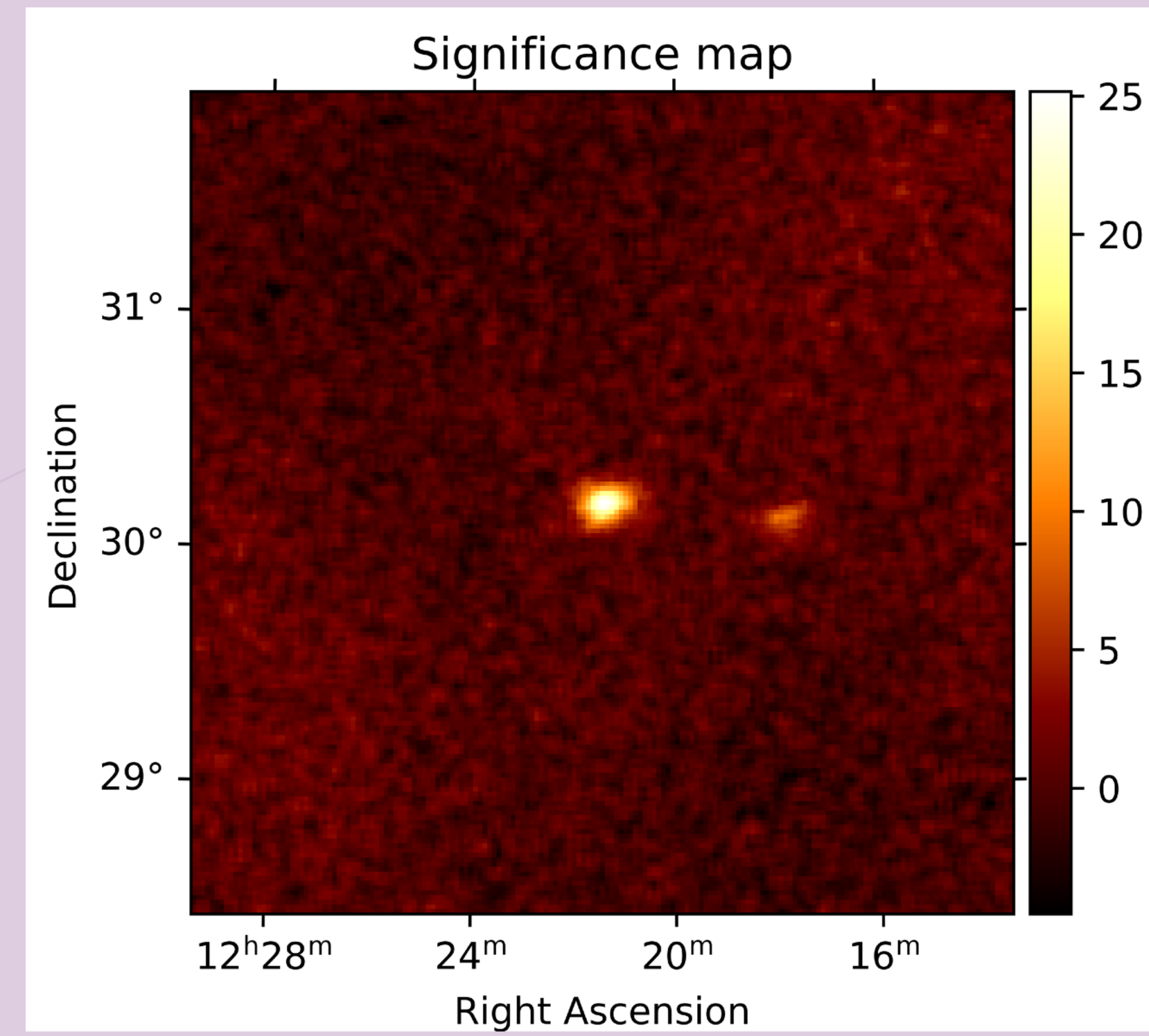


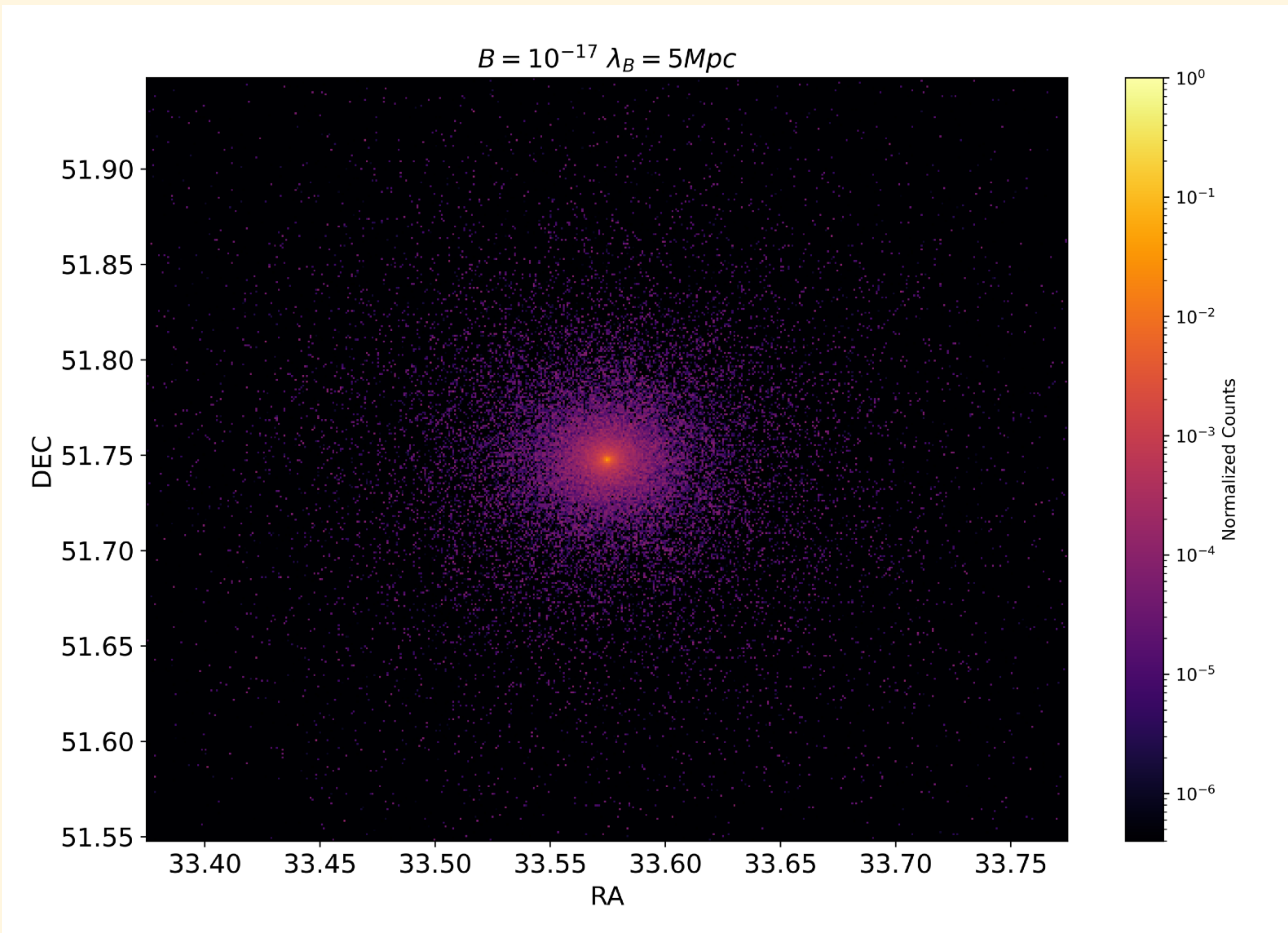
CRPropa-gammapy integration

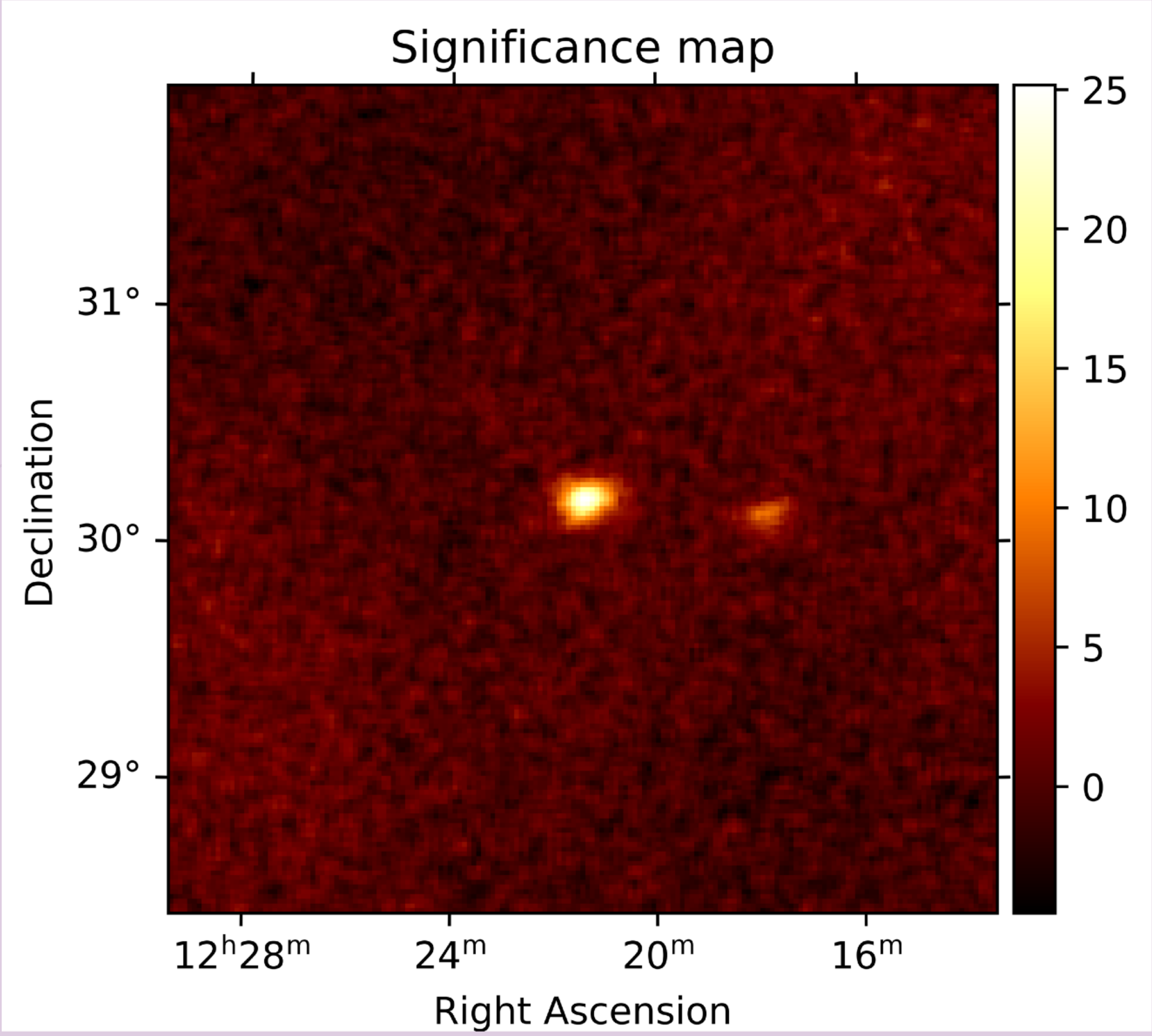


CRPropa-gammapy integration





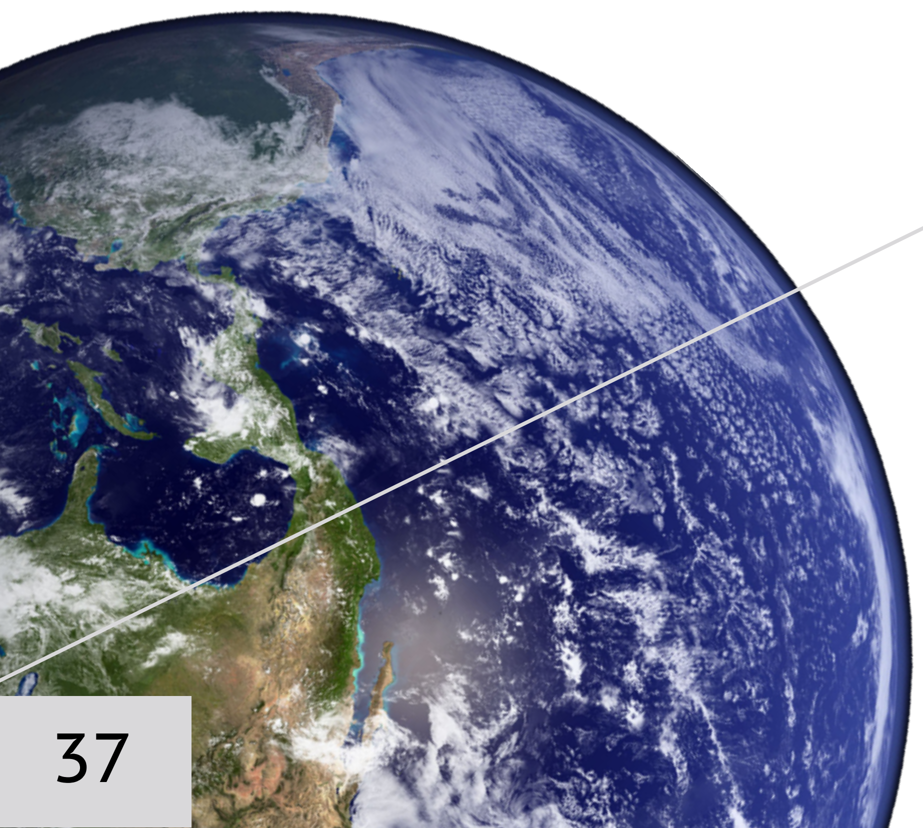




work by
Giuseppe Silvestri (Padova),
with J.-P. Lenain (Paris)

plasma instabilities

plasma instabilities: do they quench electromagnetic cascades?



plasma instabilities: do they quench electromagnetic cascades?


γ
e-
e+
pair production
$\gamma + \gamma_{bg} \rightarrow e^+ + e^-$
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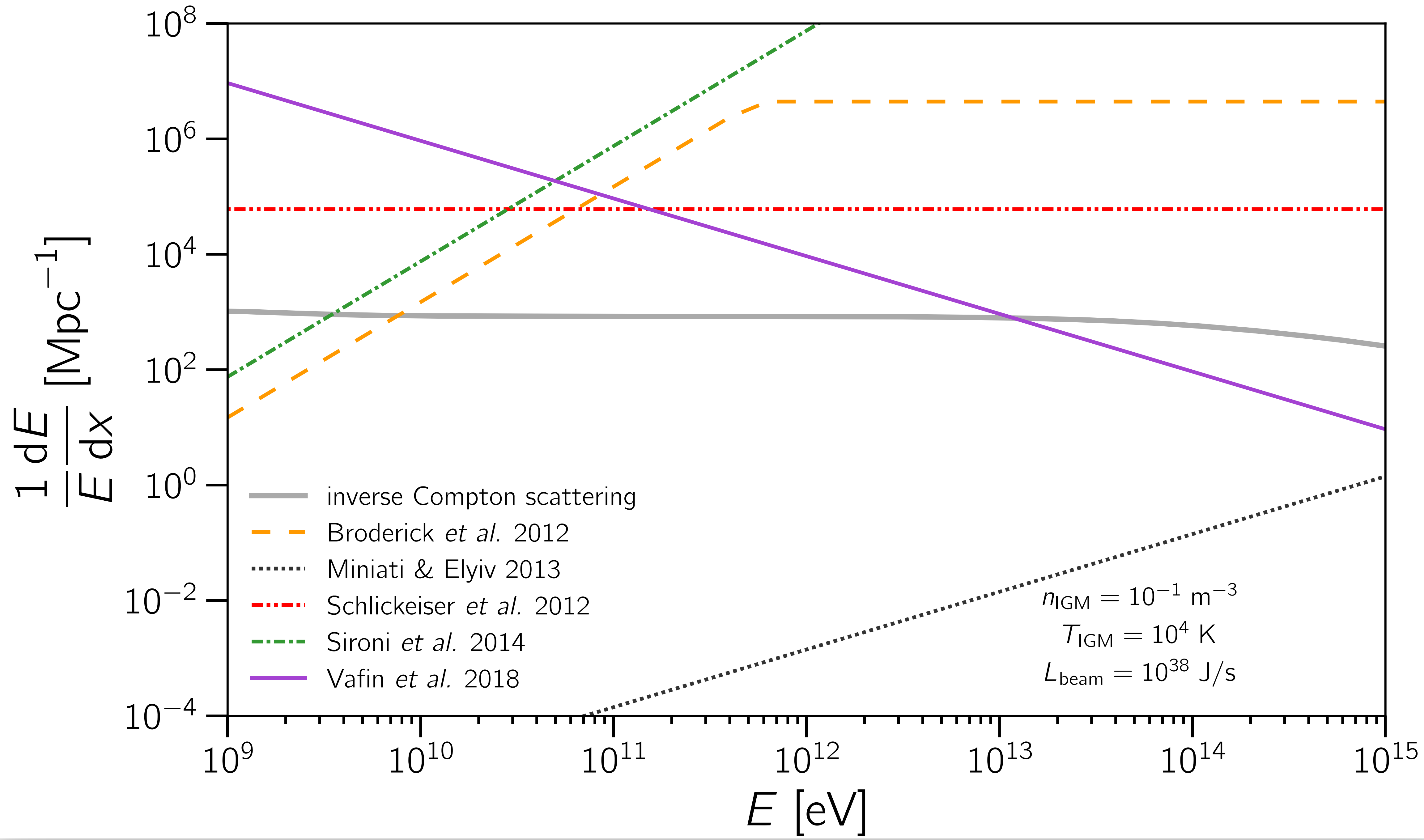
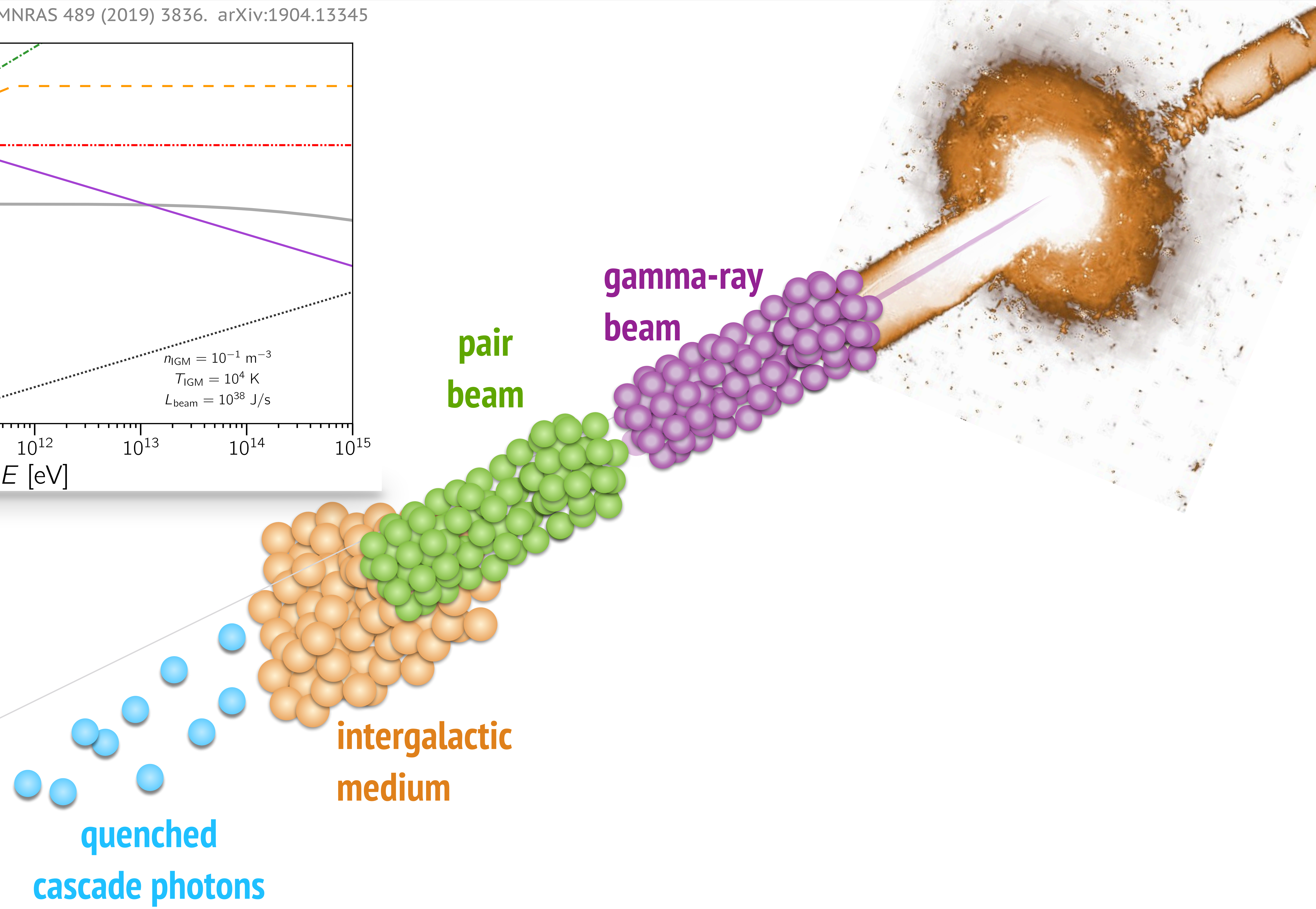
Alves Batista, Saveliev, de Gouveia Dal Pino. MNRAS 489 (2019) 3836. arXiv:1904.13345





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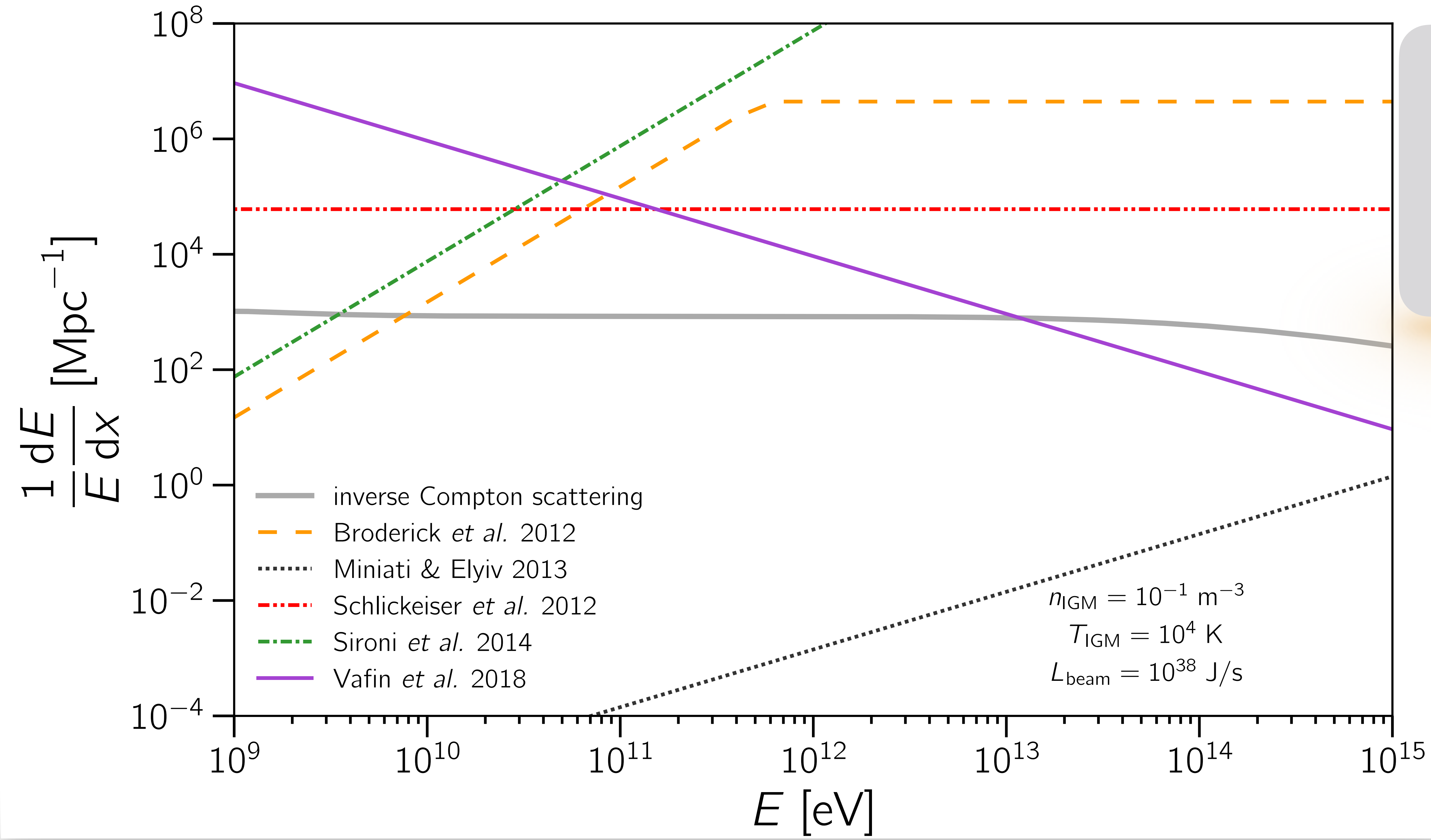
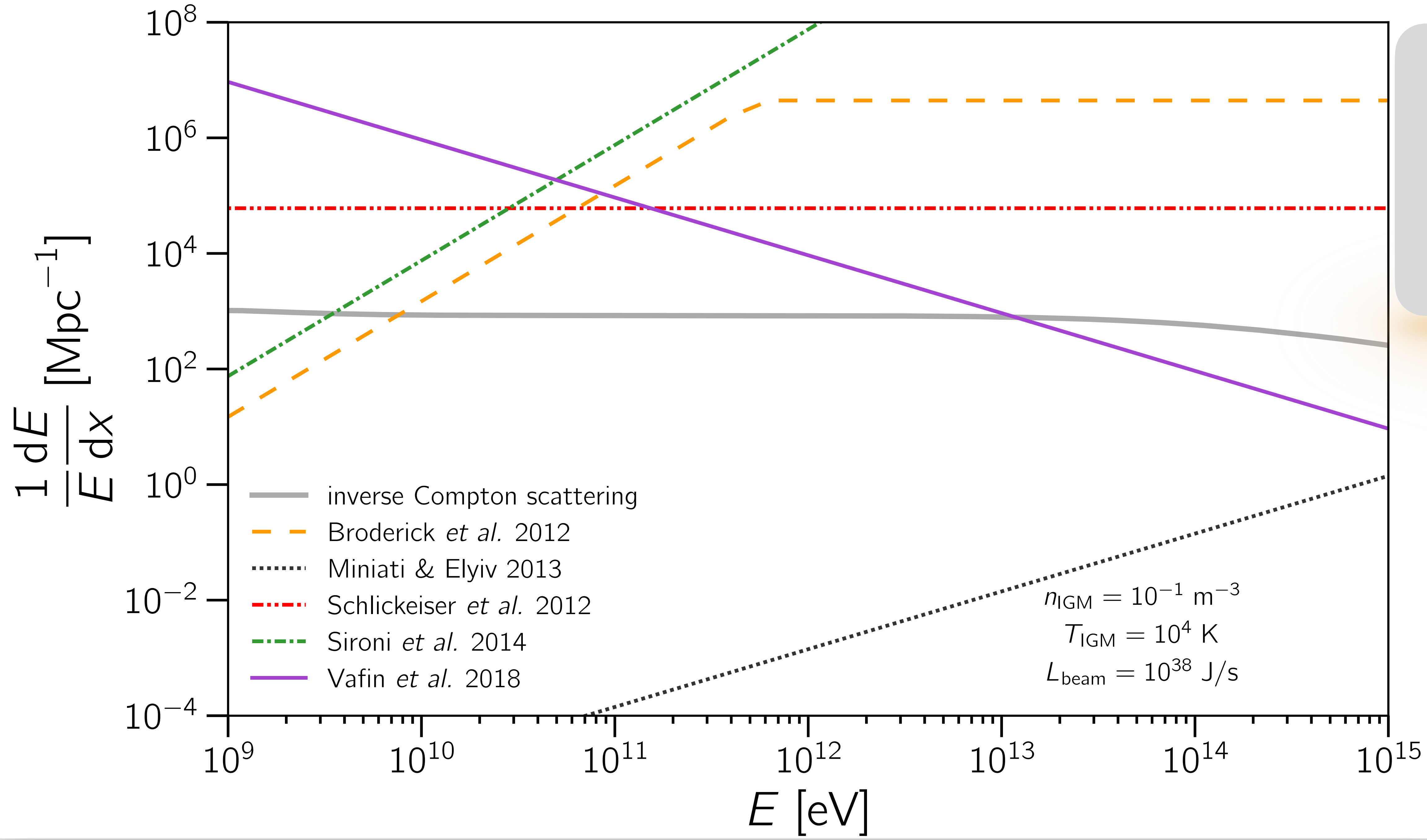


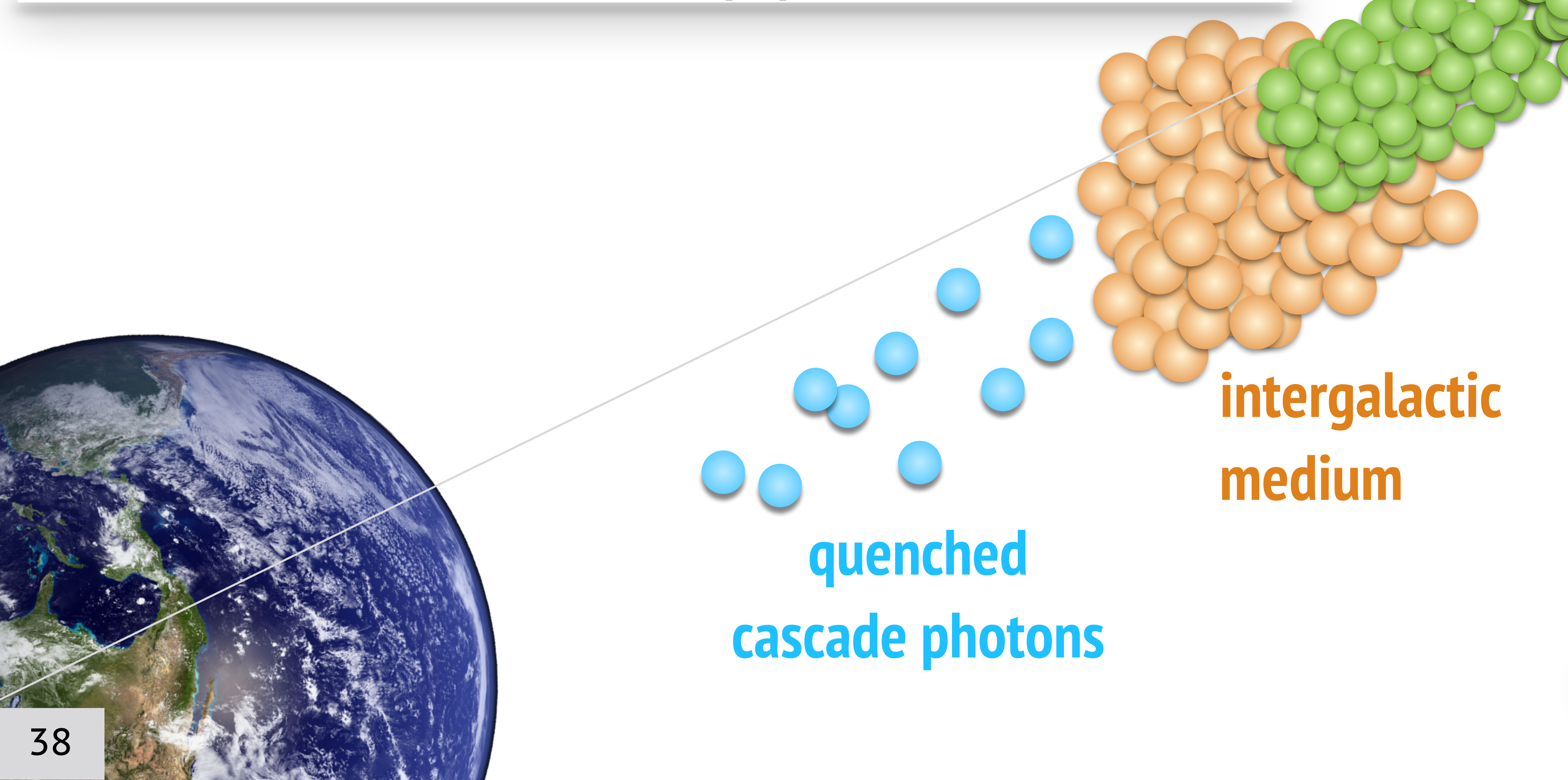
implemented in the GRPLINST module for CRPropa

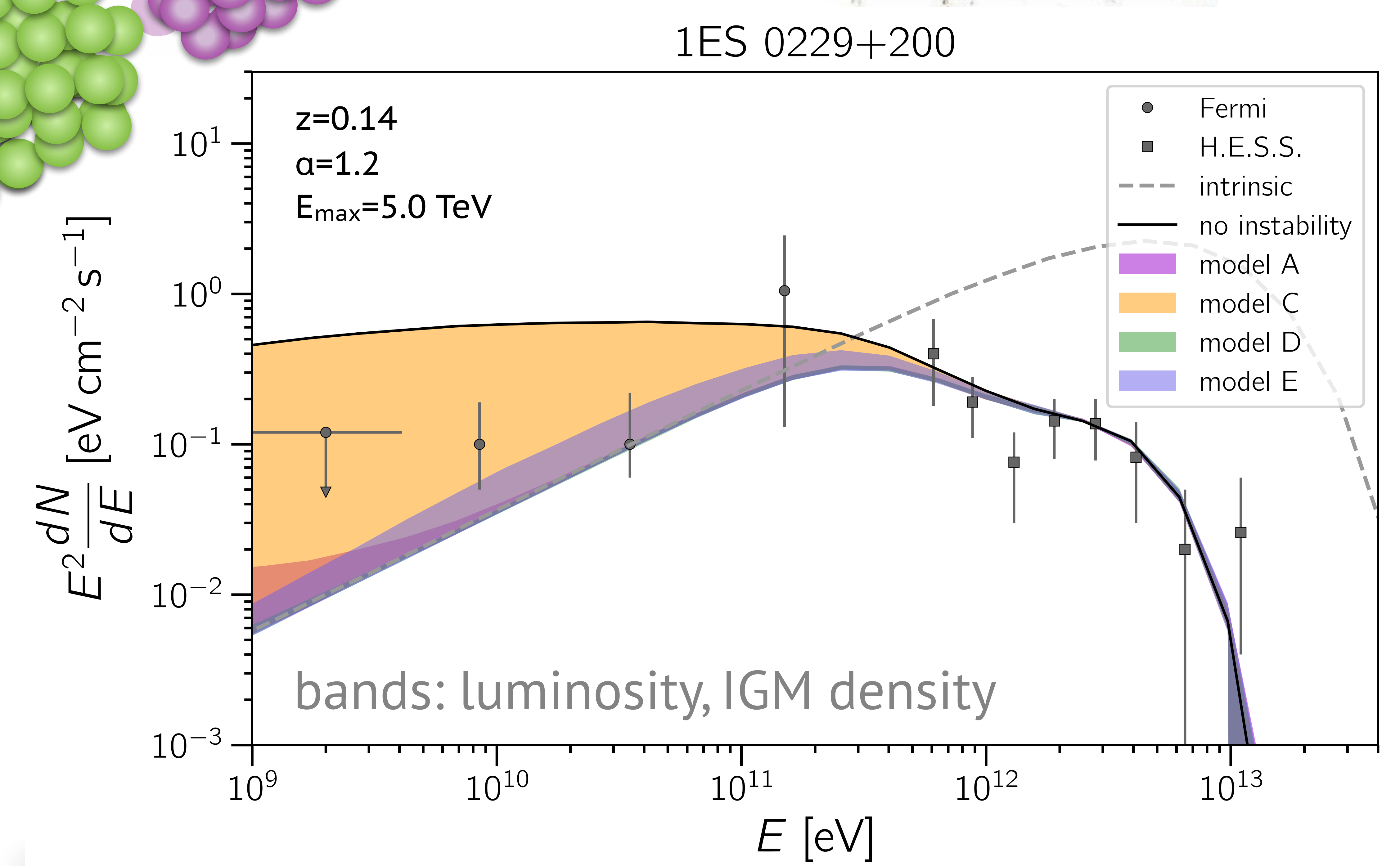
plasma instabilities: do they quench electromagnetic cascades?

Alves Batista, Saveliev, de Gouveia Dal Pino. MNRAS 489 (2019) 3836. arXiv:1904.13345

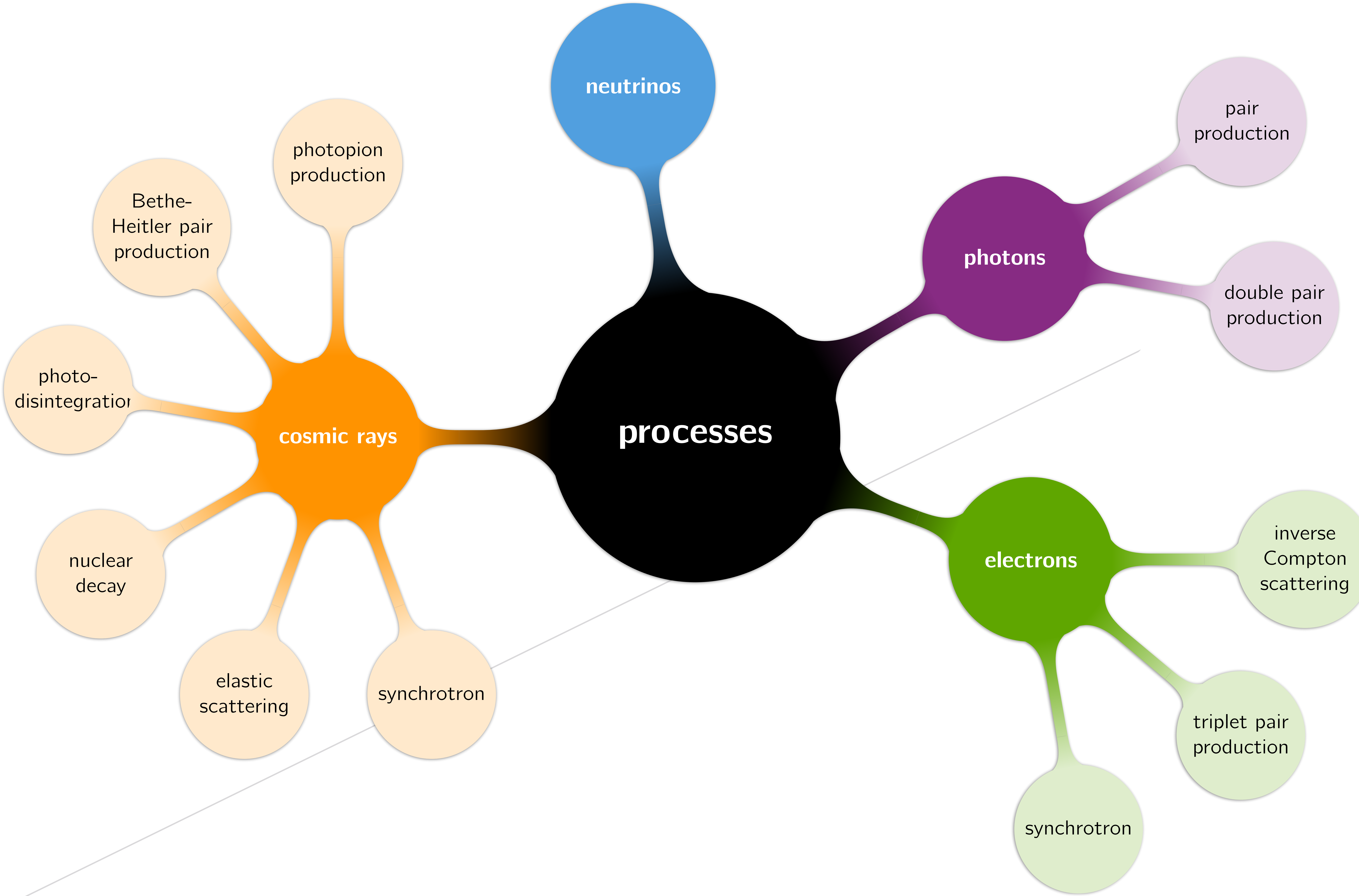


implemented in the GRPLINST module for CRPropa





the GRPLINST plugin for CRPropa



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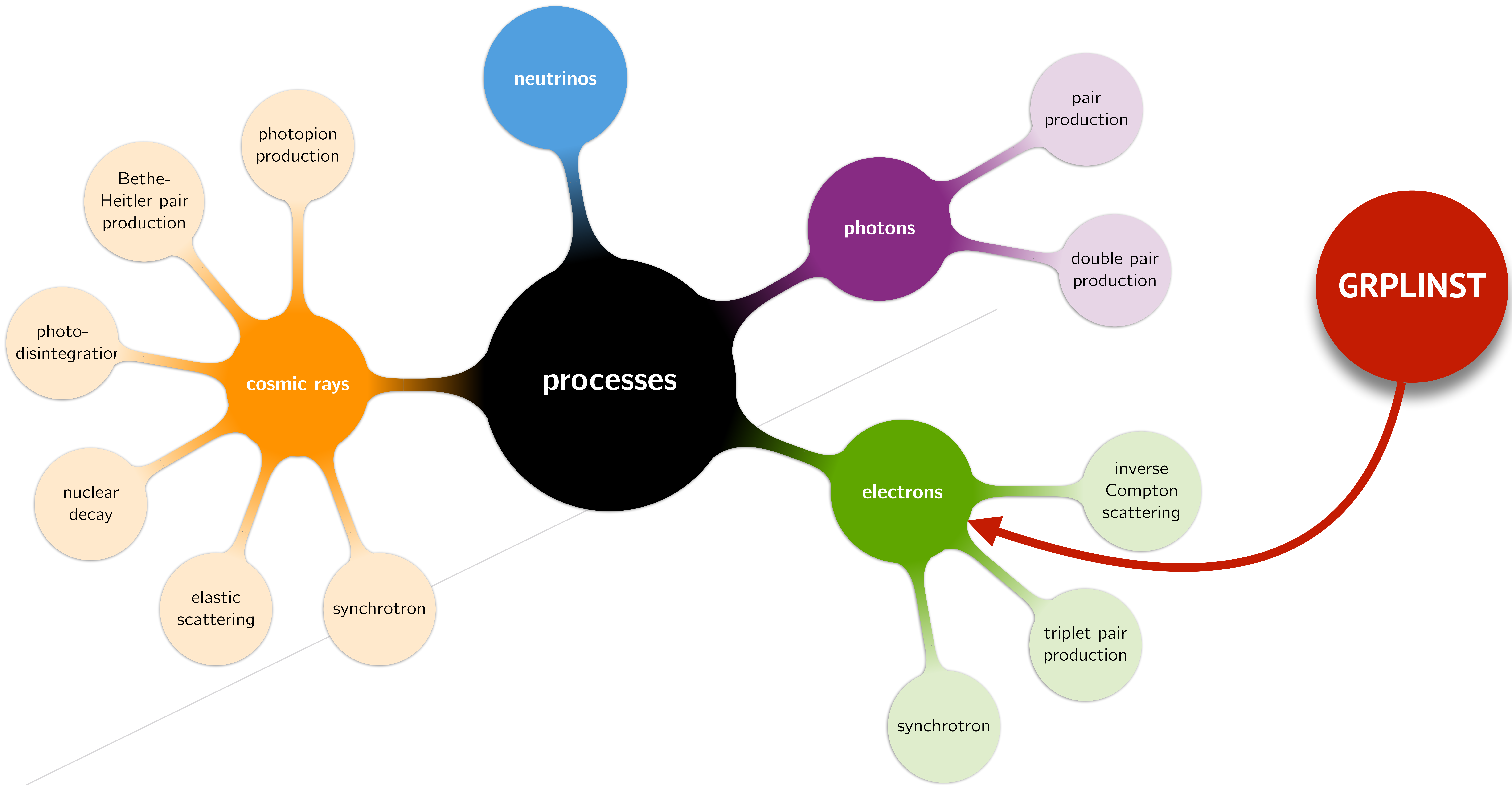
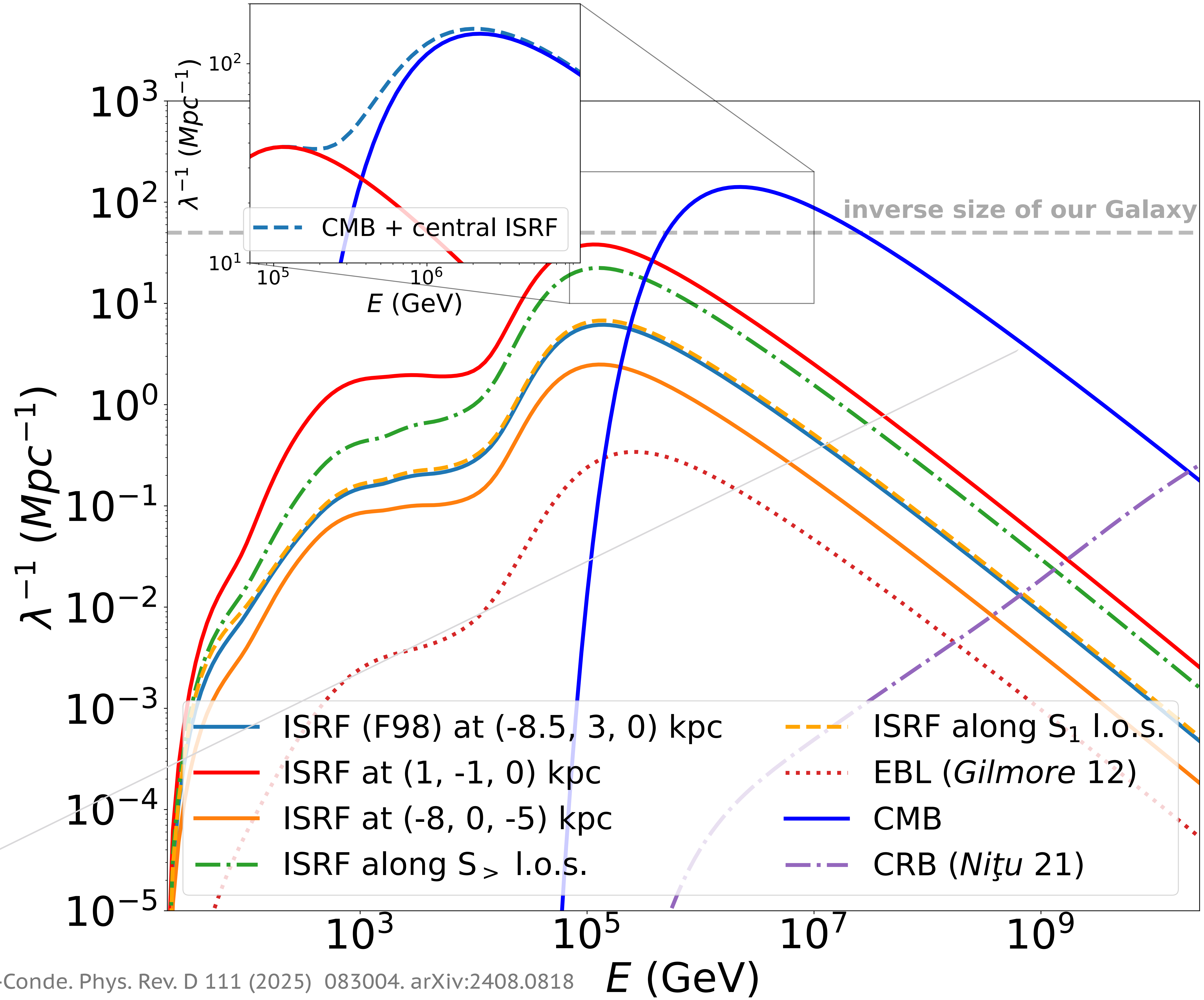


galactic propagation of gamma rays

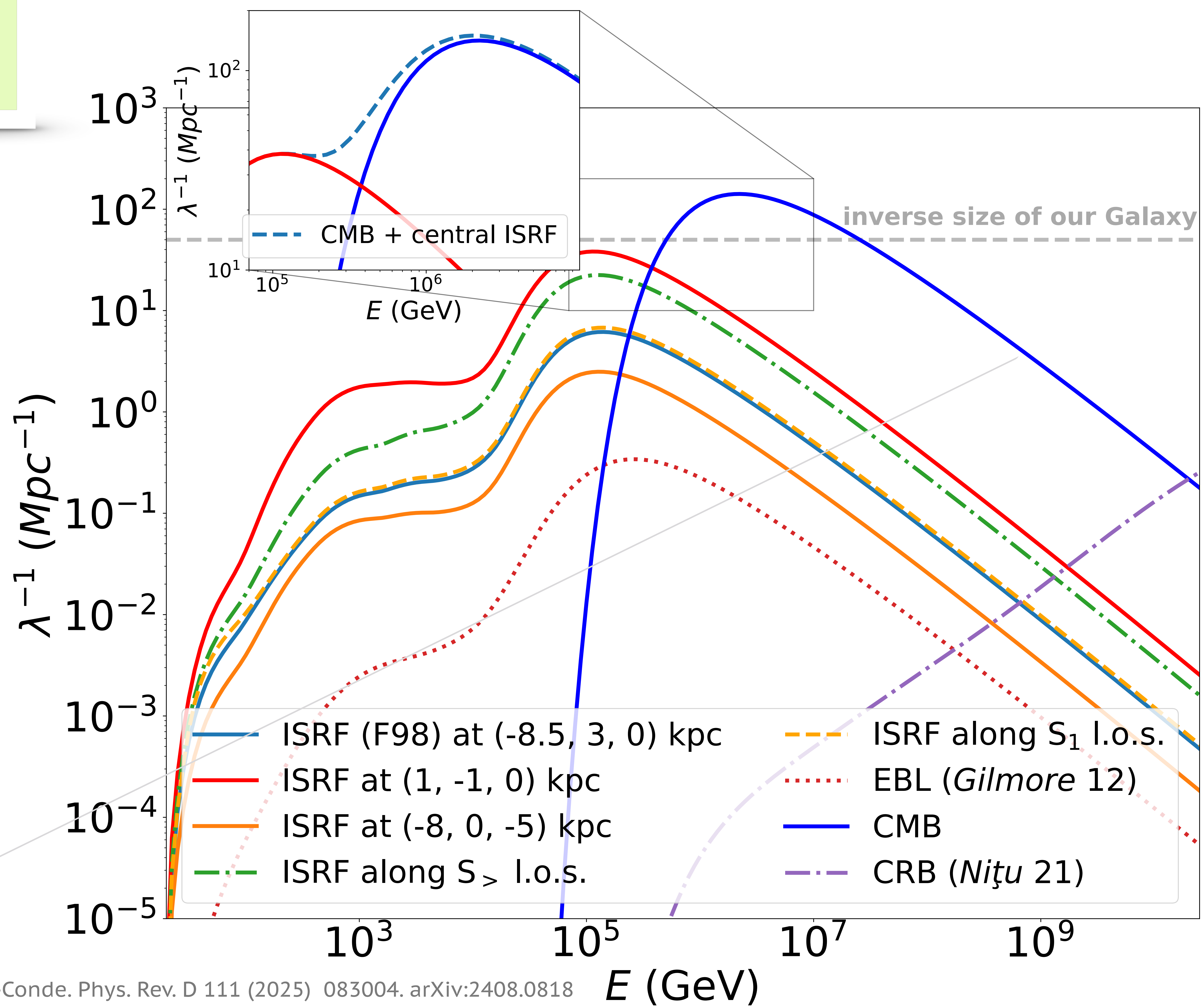
galactic propagation of PeV gamma rays



Di Marco, Alves Batista, Sánchez-Conde. Phys. Rev. D 111 (2025) 083004. arXiv:2408.0818

galactic propagation of PeV gamma rays

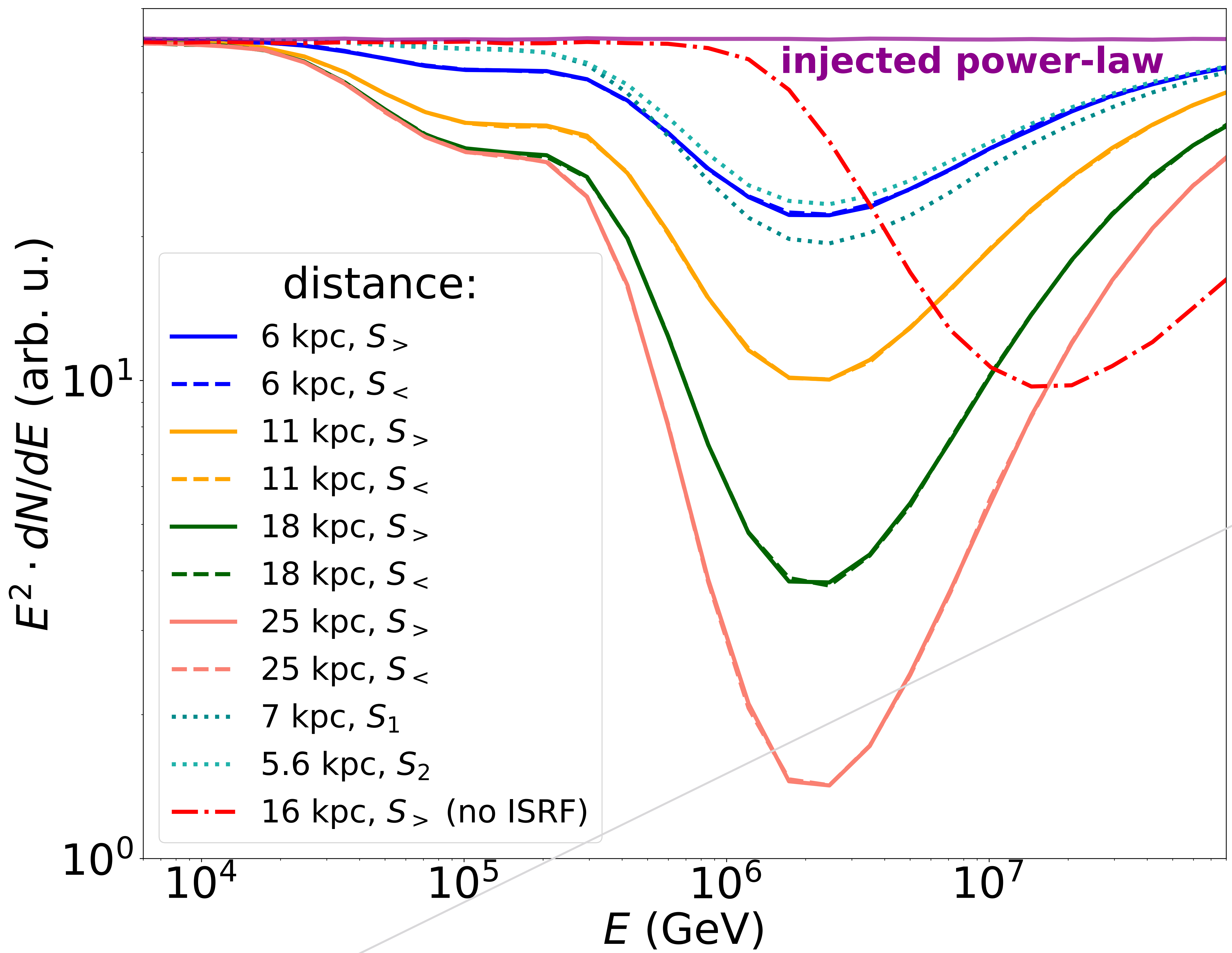
work by
Gaetano Di Marco
(Madrid)

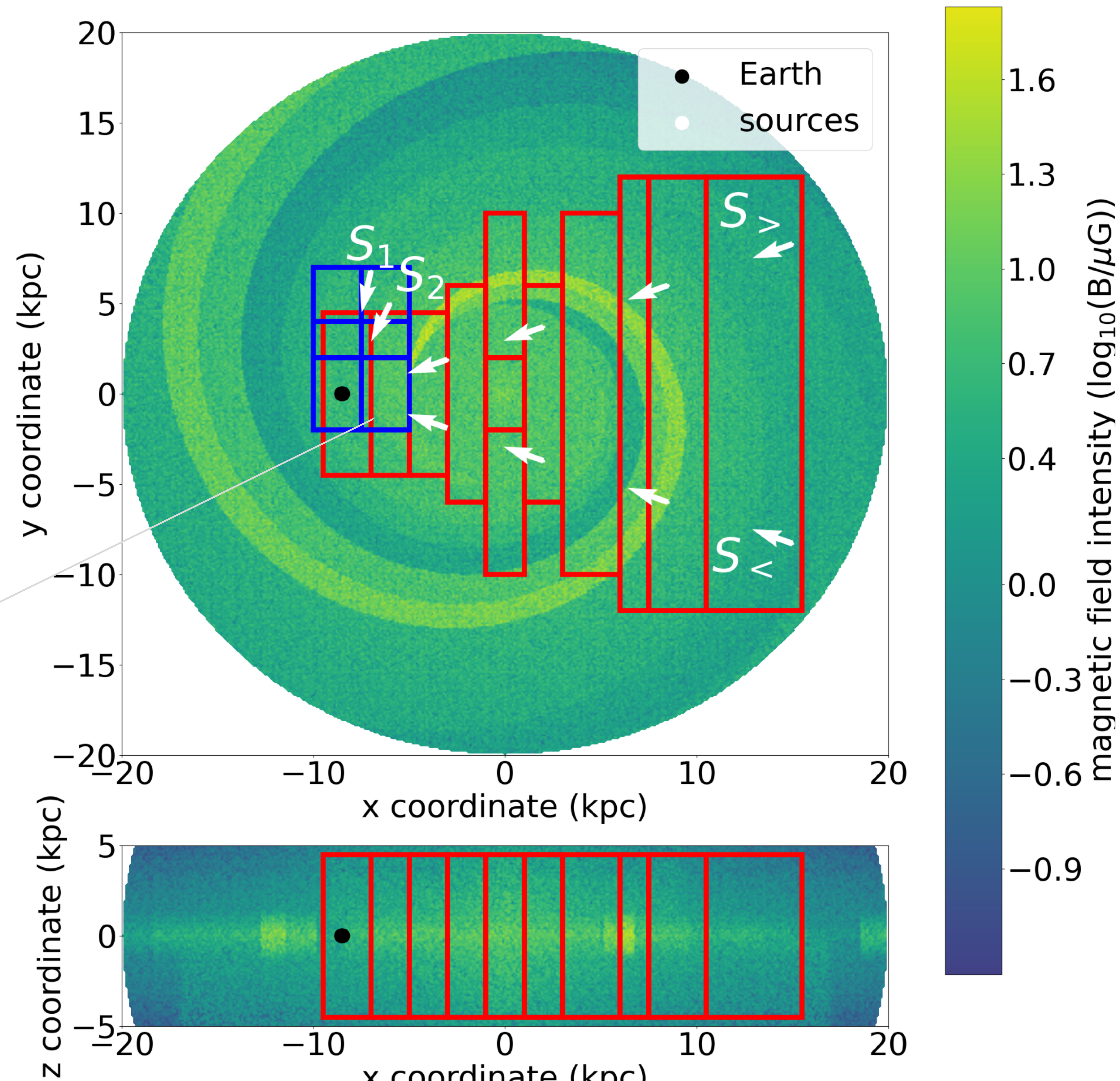


Di Marco, Alves Batista, Sánchez-Conde. Phys. Rev. D 111 (2025) 083004. arXiv:2408.0818

gamma-ray absorption in the interstellar radiation field

Di Marco, Alves Batista, Sánchez-Conde. Phys. Rev. D 111 (2025) 083004. arXiv:2408.0818





Lorentz invariance violation (LIV)

phenomenology of Lorentz invariance violation (LIV)

- Lorentz invariance is *the* pillar of special relativity

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- why LIV?
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modified dispersion relation

$$E_\alpha^2 = p_\alpha^2 \left[1 + \frac{m_\alpha^2}{p_\alpha^2} + \sum_{j=0}^{N} \chi_j^\alpha \left(\frac{p_\alpha}{E_{\mathrm{QG}}^\alpha} \right)^j \right]$$

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$$\Big\Downarrow \text{leading order}$$

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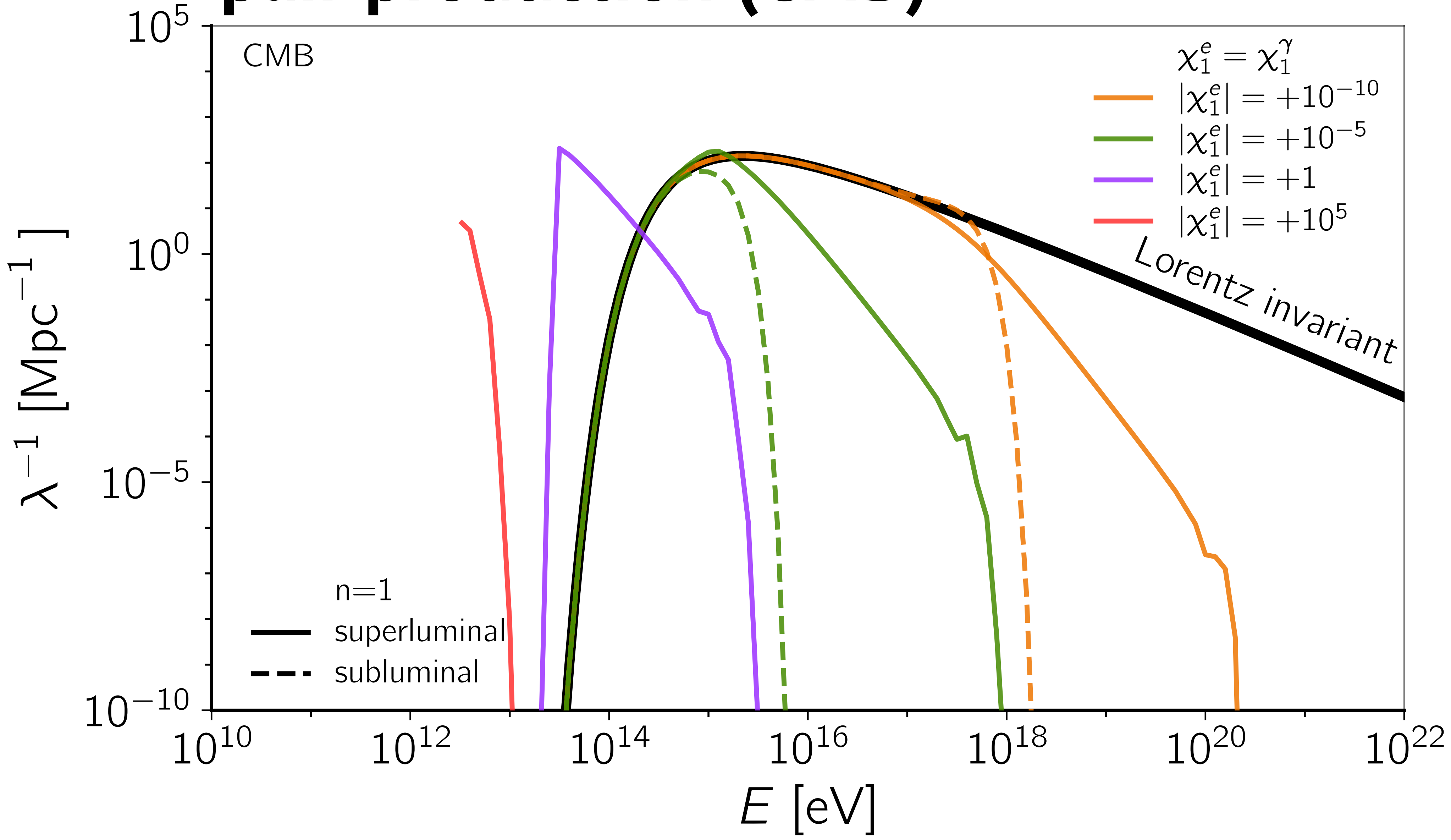
$$E_\alpha^2 \approx p_\alpha^2 \left[1 + \frac{m_\alpha^2}{p_\alpha^2} + \chi_n^\alpha \left(\frac{p_\alpha}{E_{\mathrm{QG}}^\alpha} \right)^n \right]$$

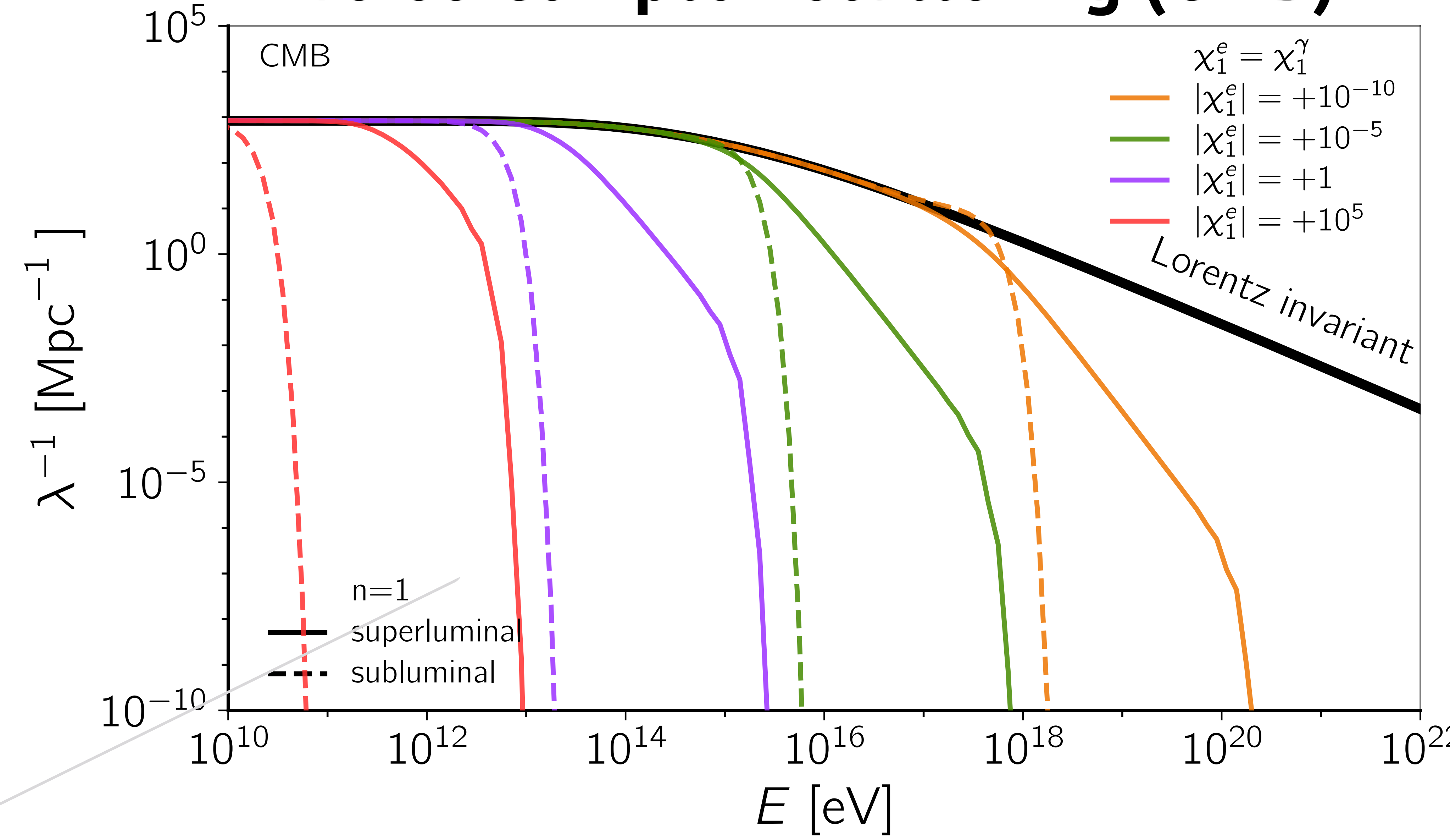
LIV. modified mean free paths

Saveliev & Alves Batista. Classical and Quantum Gravity 41 (2024) 115011. arXiv:2312.10803

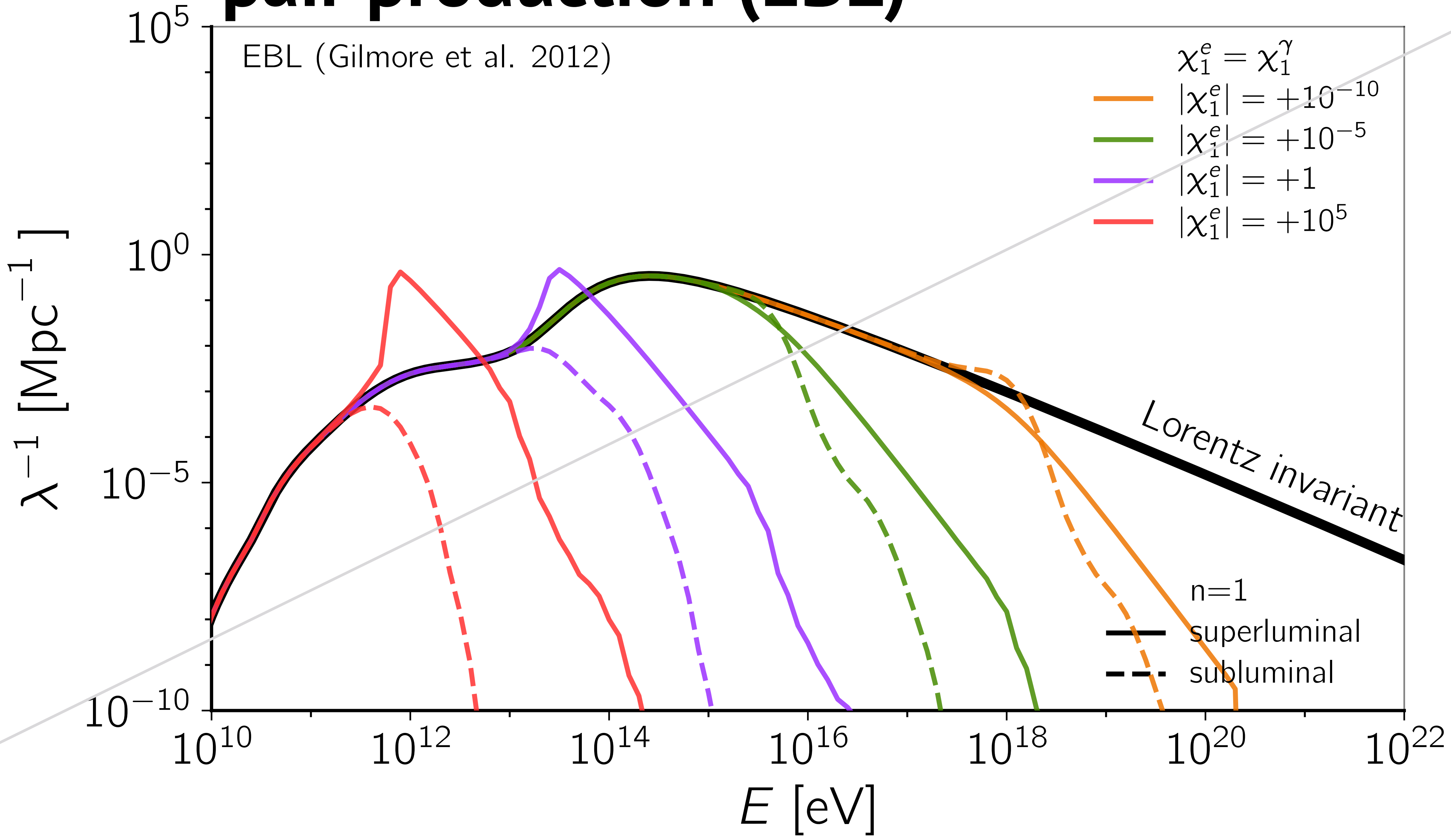
pair production (CMB)



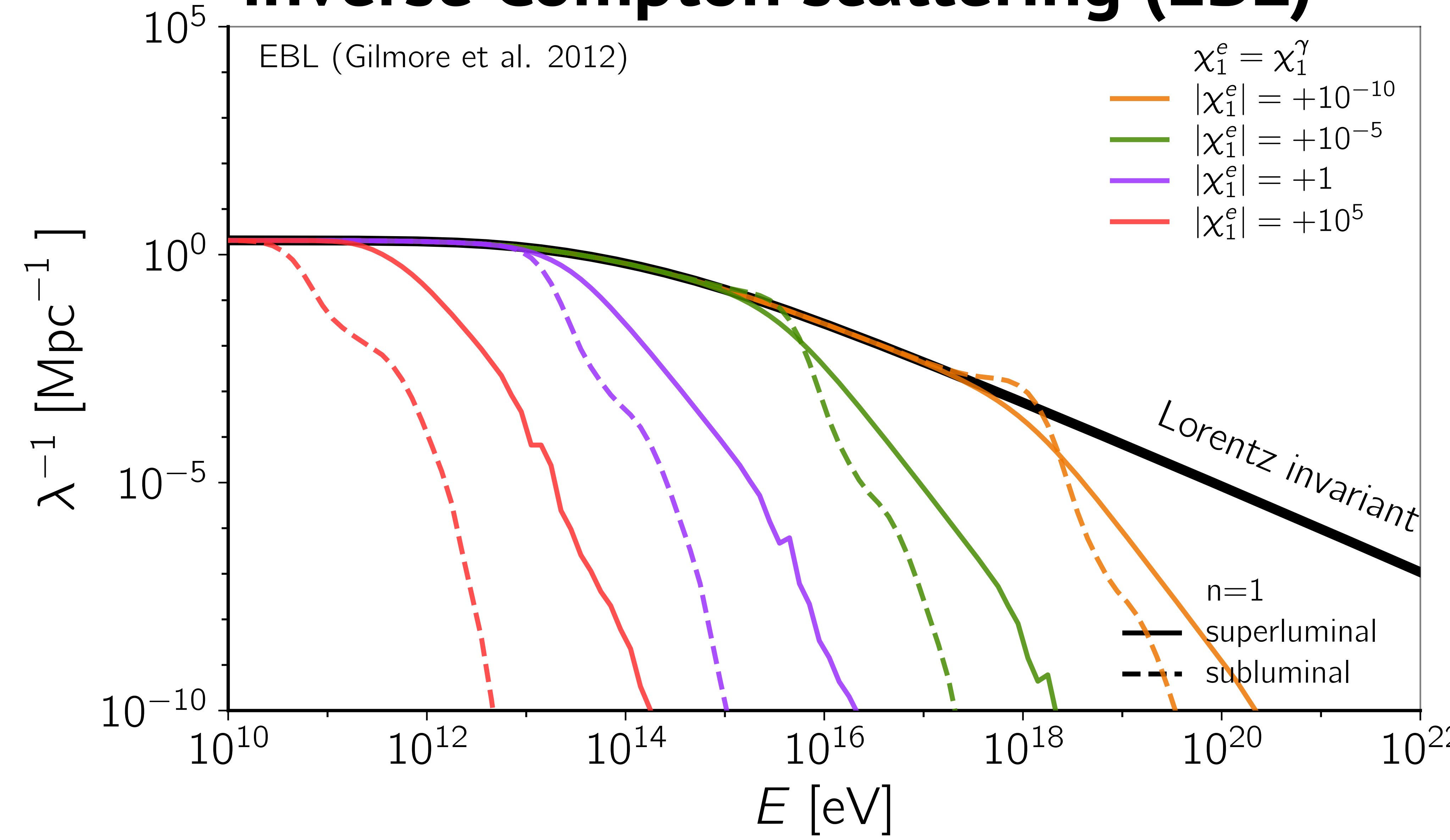
inverse Compton scattering (CMB)



pair production (EBL)



inverse Compton scattering (EBL)



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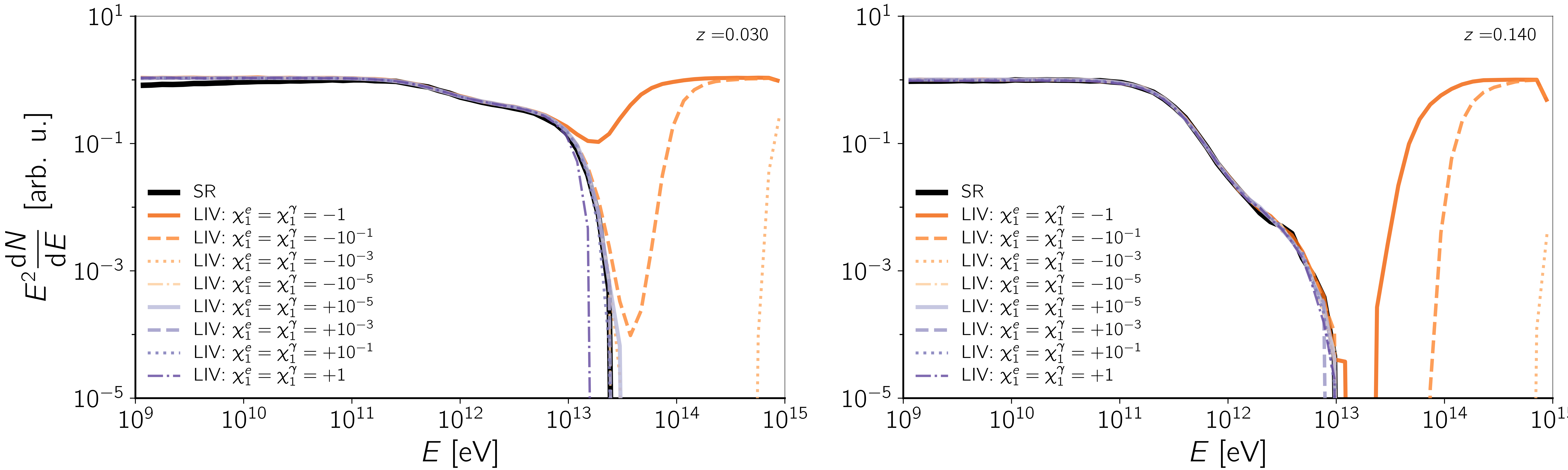

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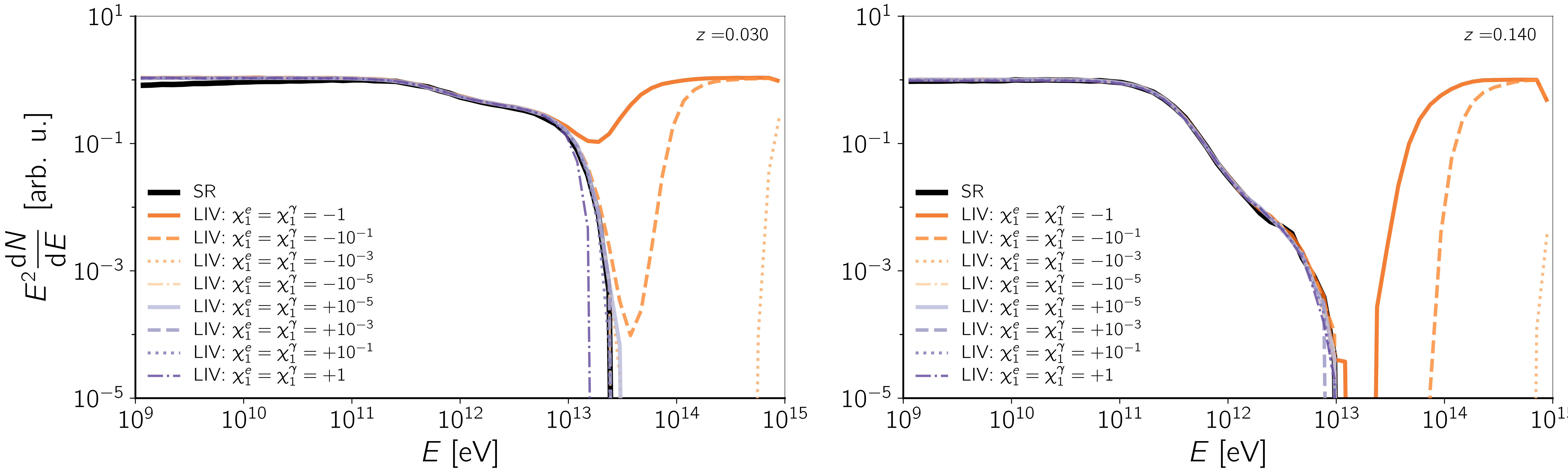
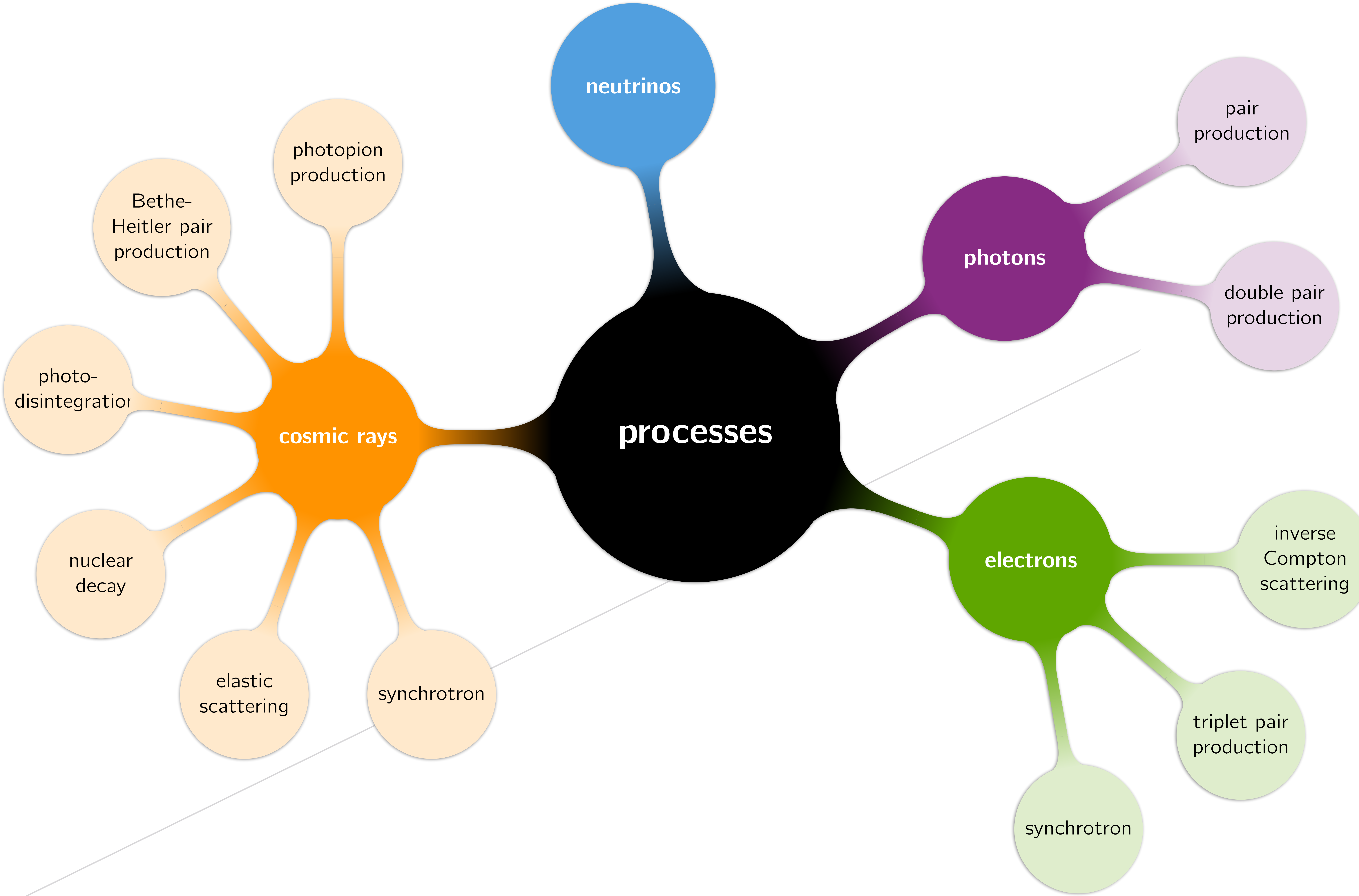
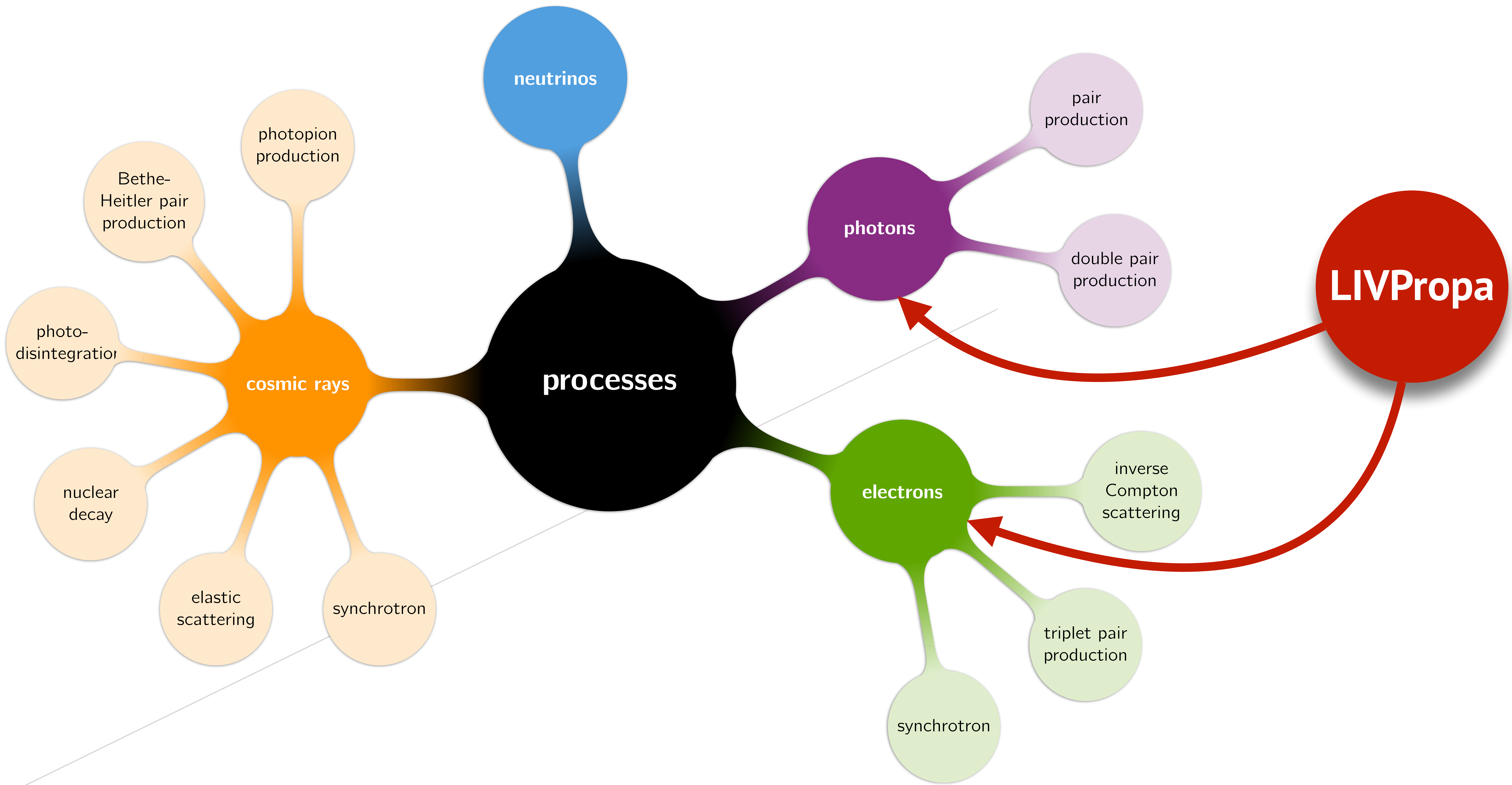


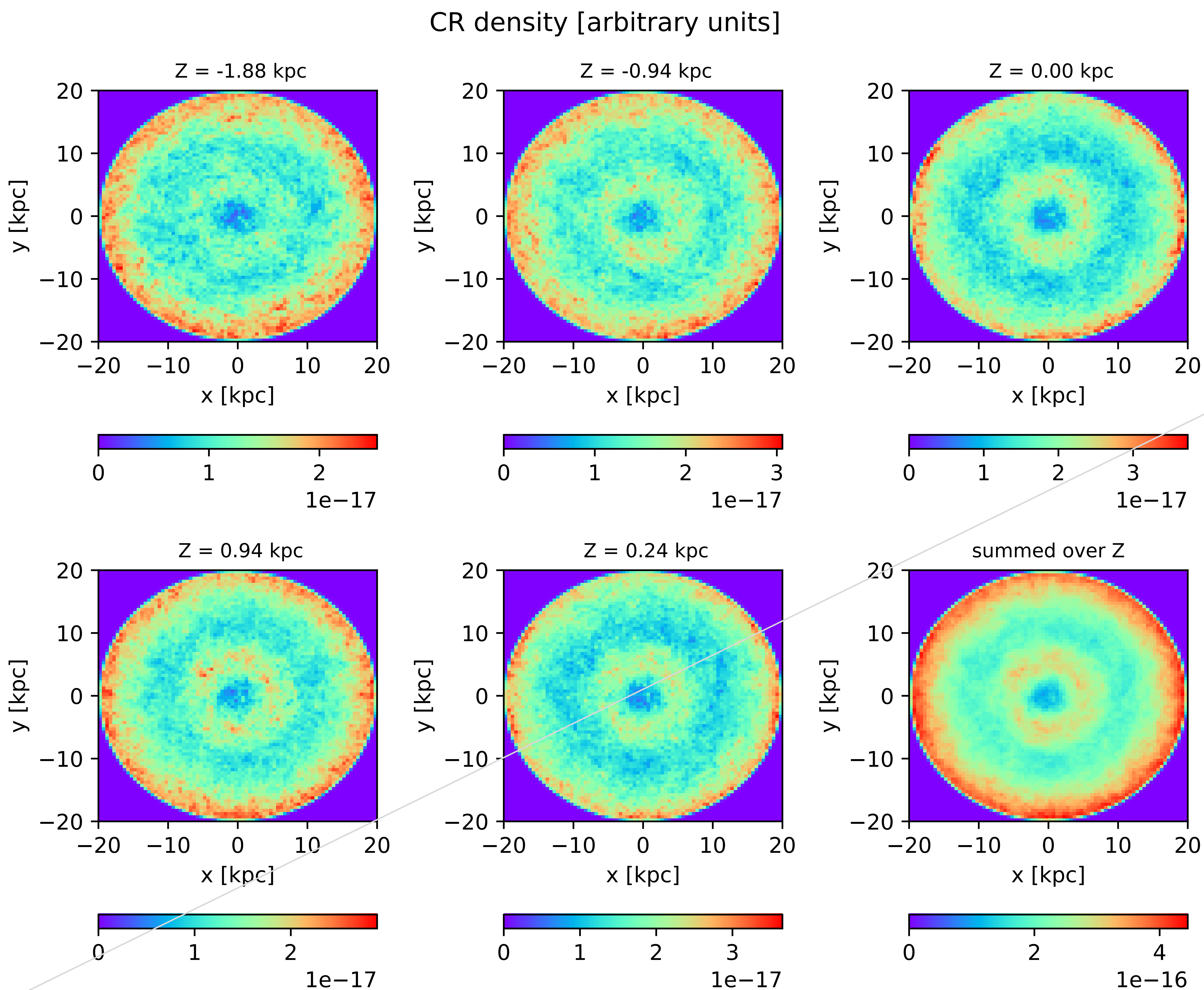
pair production + inverse Compton scattering + vacuum Cherenkov + photon decay

the LIVPROPA plugin for CRPropa



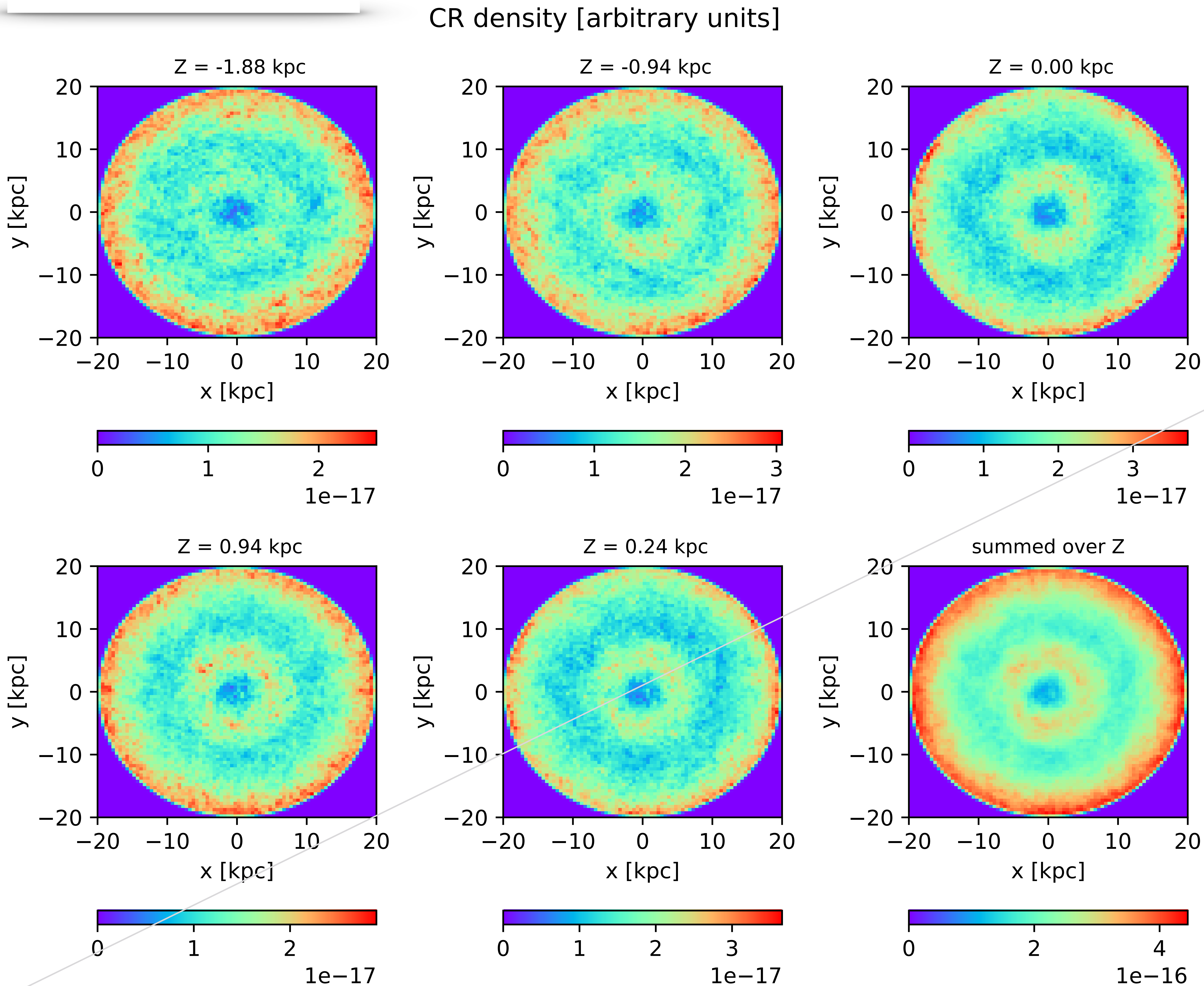

neutrinos
pair production
photopion production
Bethe-Heitler pair production
photons
double pair production
LIVPropa
photo-disintegration
cosmic rays
processes
nuclear decay
electrons
inverse Compton scattering
elastic scattering
synchrotron
triplet pair production
synchrotron

galactic diffuse emission


CR density [arbitrary units]
Z = -1.88 kpc
Z = -0.94 kpc
Z = 0.00 kpc
Z = 0.94 kpc
Z = 0.24 kpc
summed over Z
x [kpc]
y [kpc]
1e−17
1e−16

work by
Clément Prévotat
(Paris)

diffuse galactic emission from CRs



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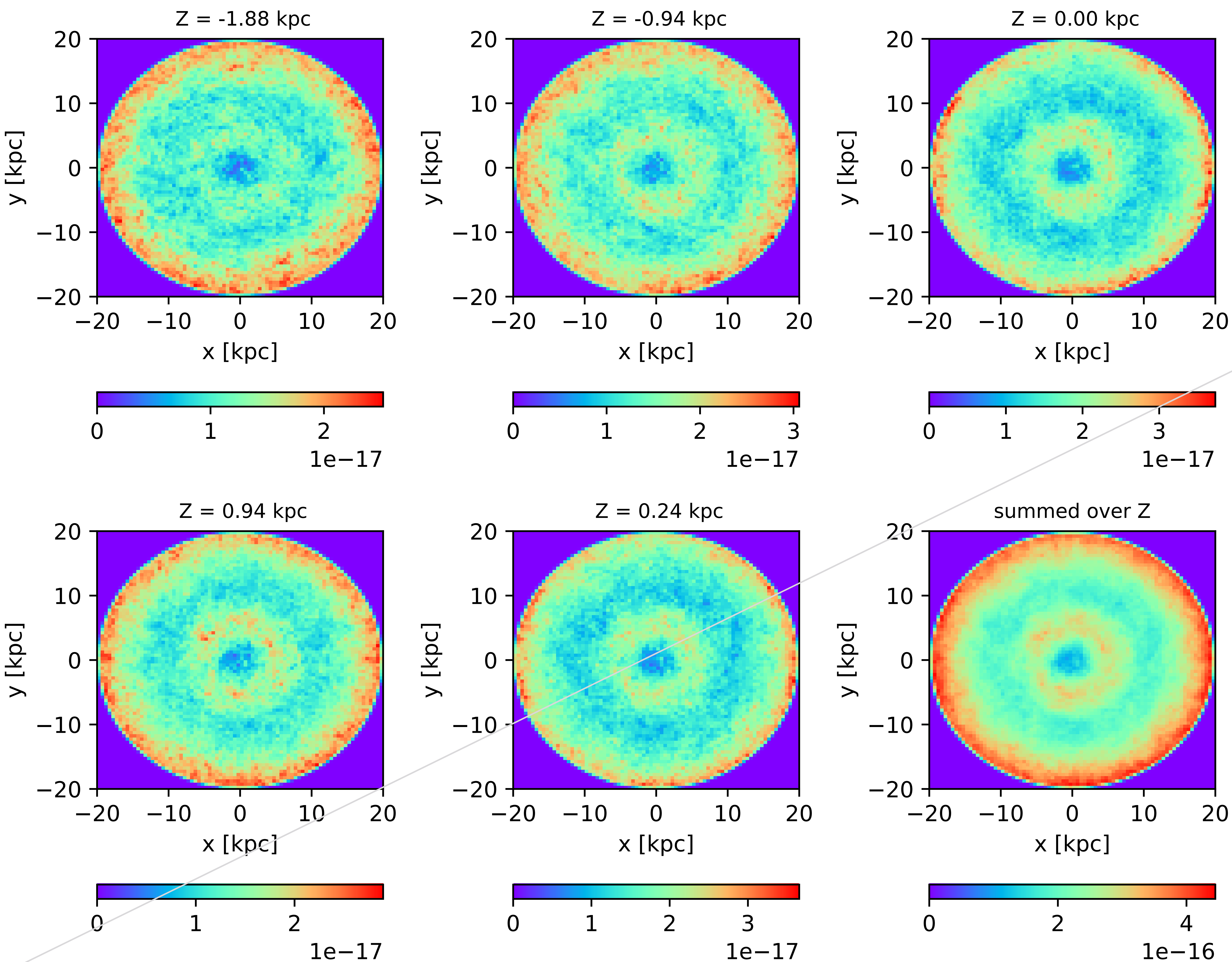
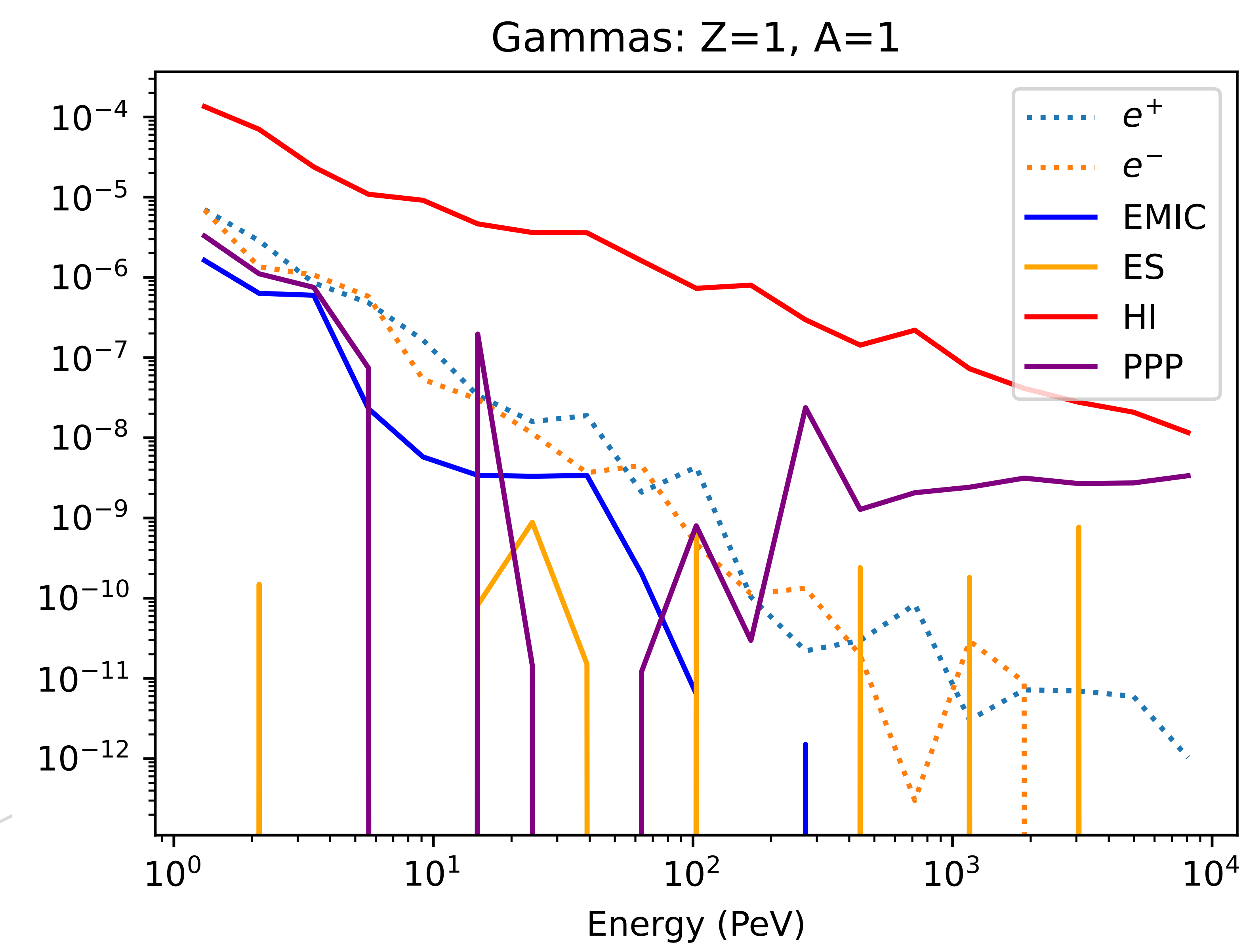
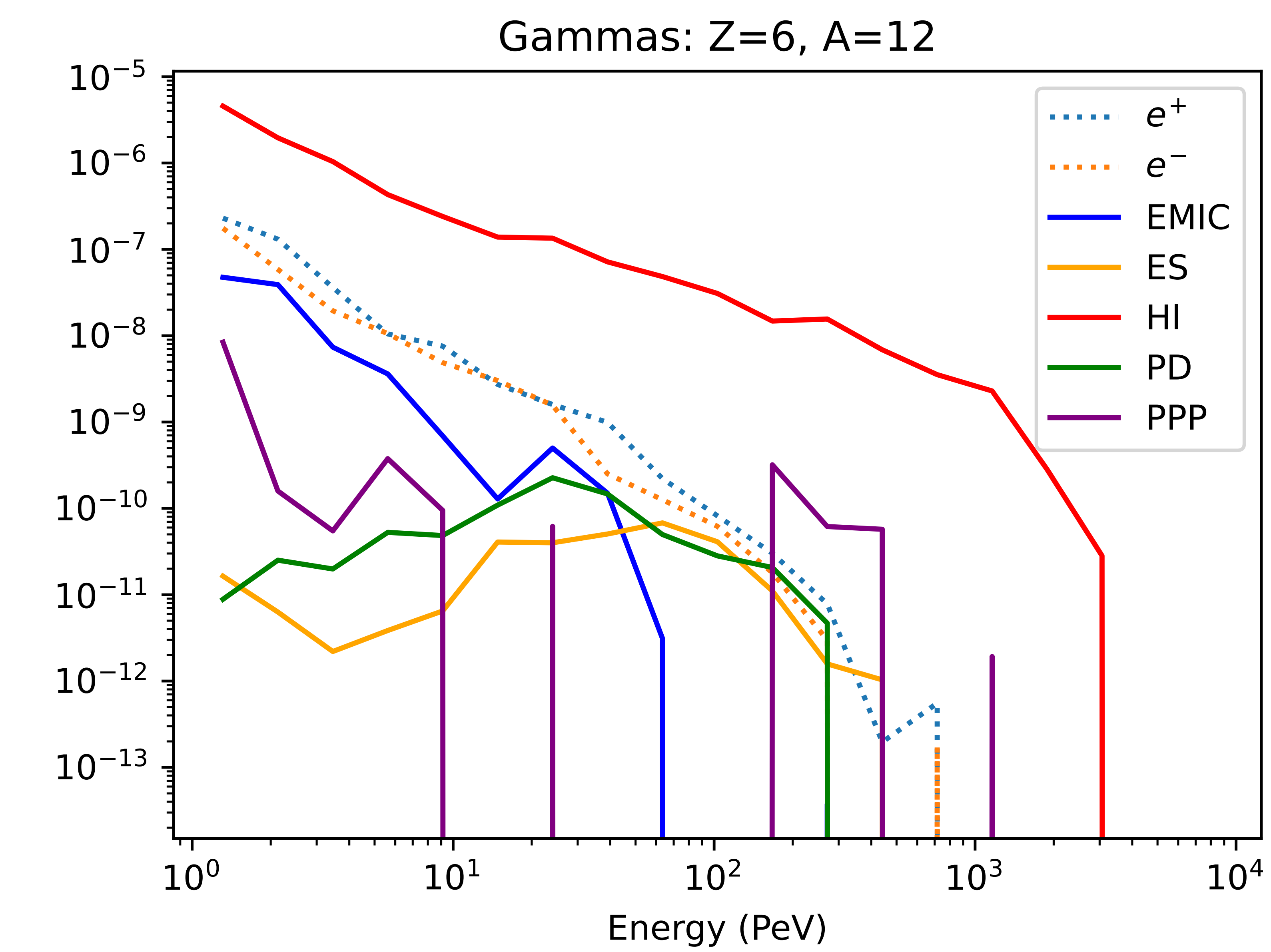
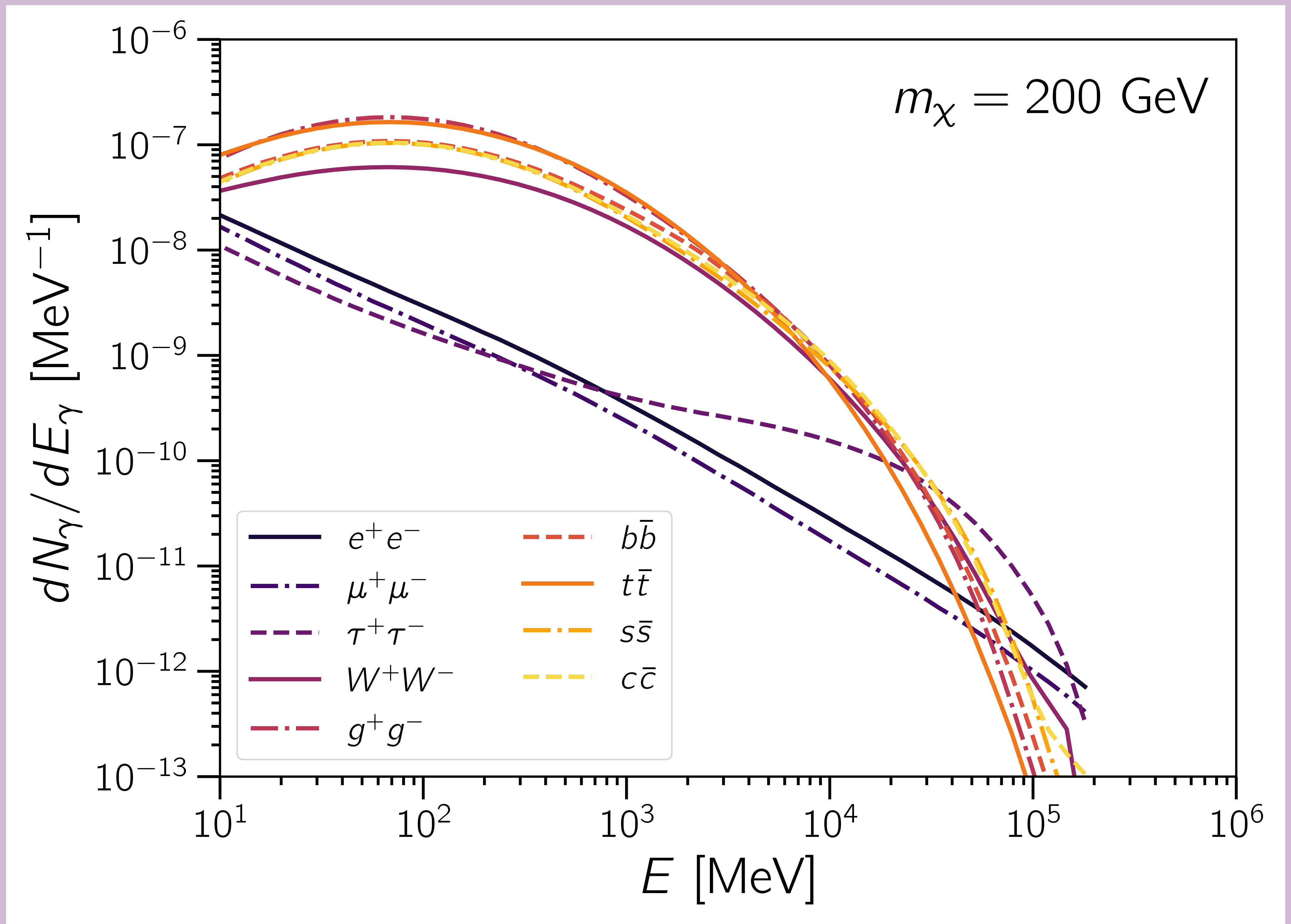




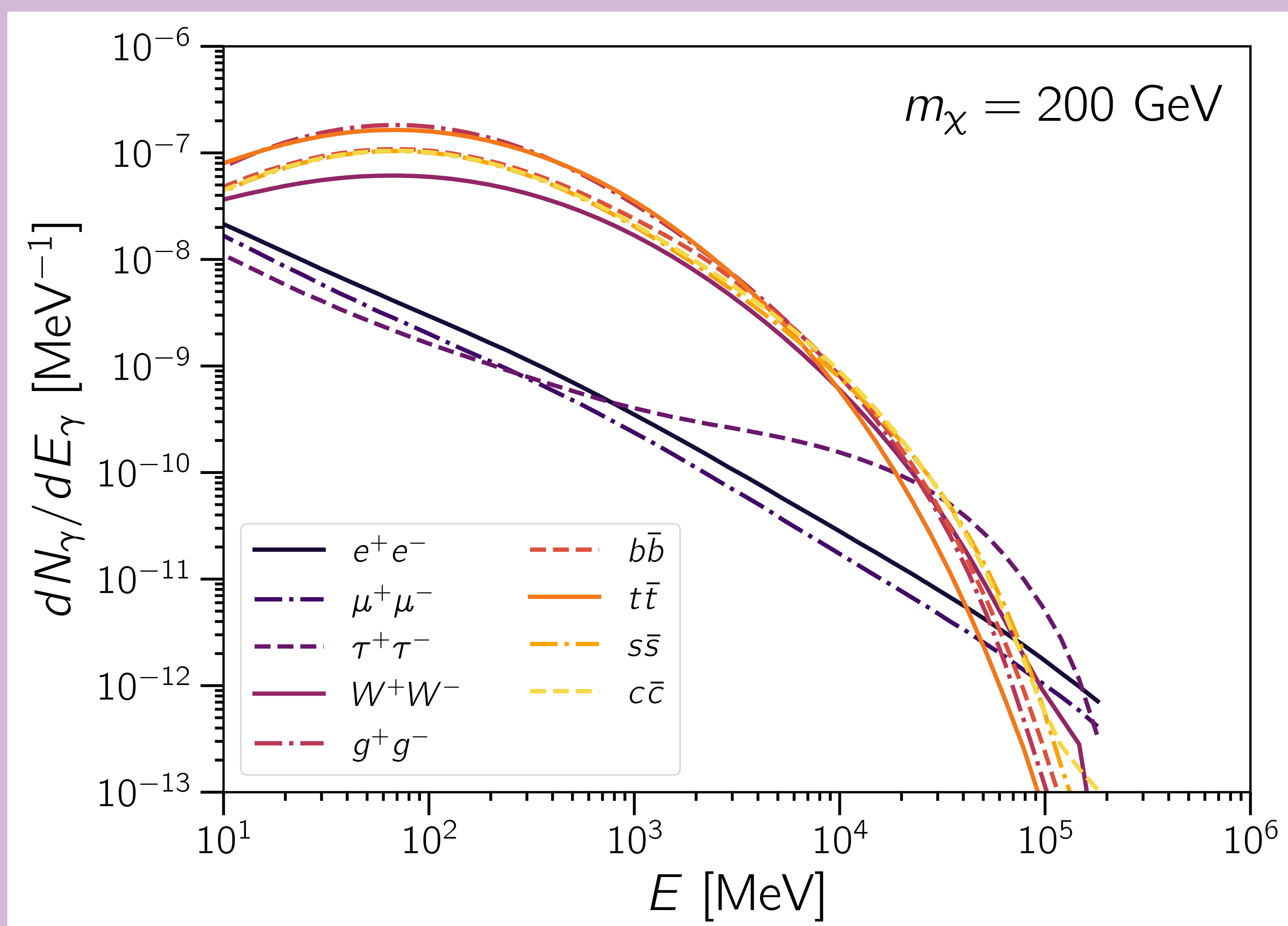


dark matter



Arina et al. JCAP 03 (2024) 035. arXiv:2312.01153

improving predictions: WIMP annihillation



CosmiXs

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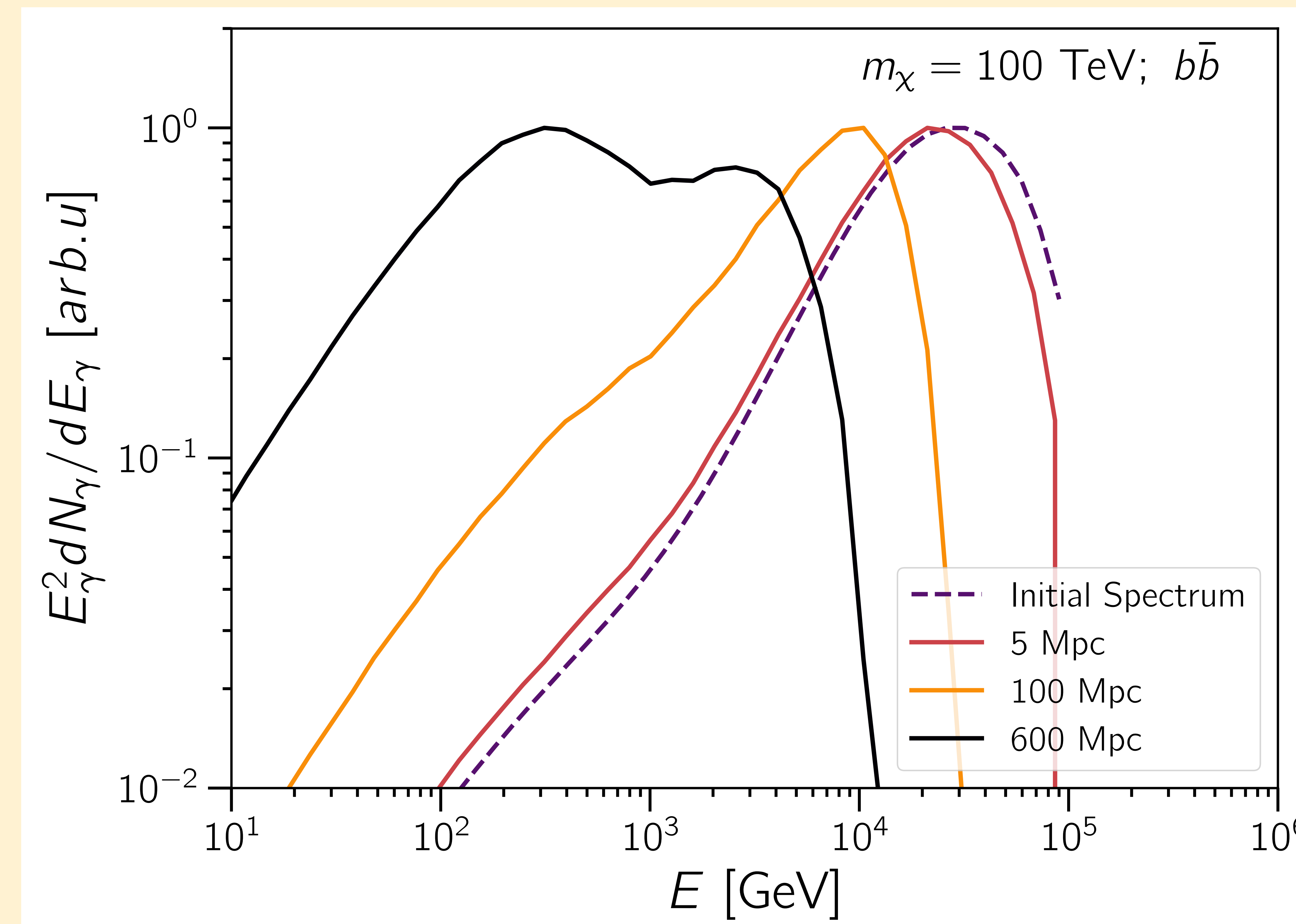
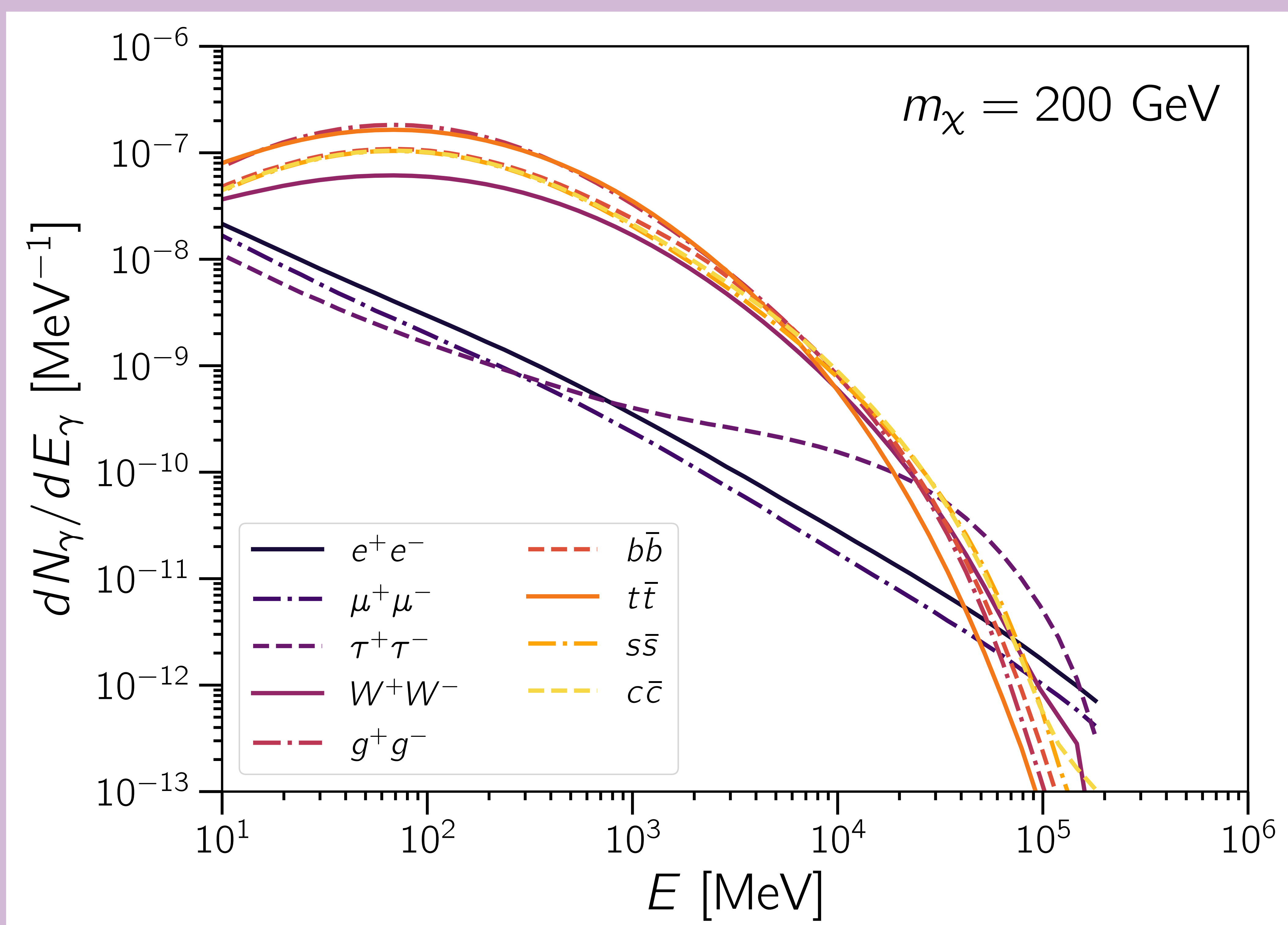


CRPropa

improving predictions: WIMP annihillation

work by
Ignacio Martínez López (Madrid), and
M. A. Sánchez-Conde (Madrid)



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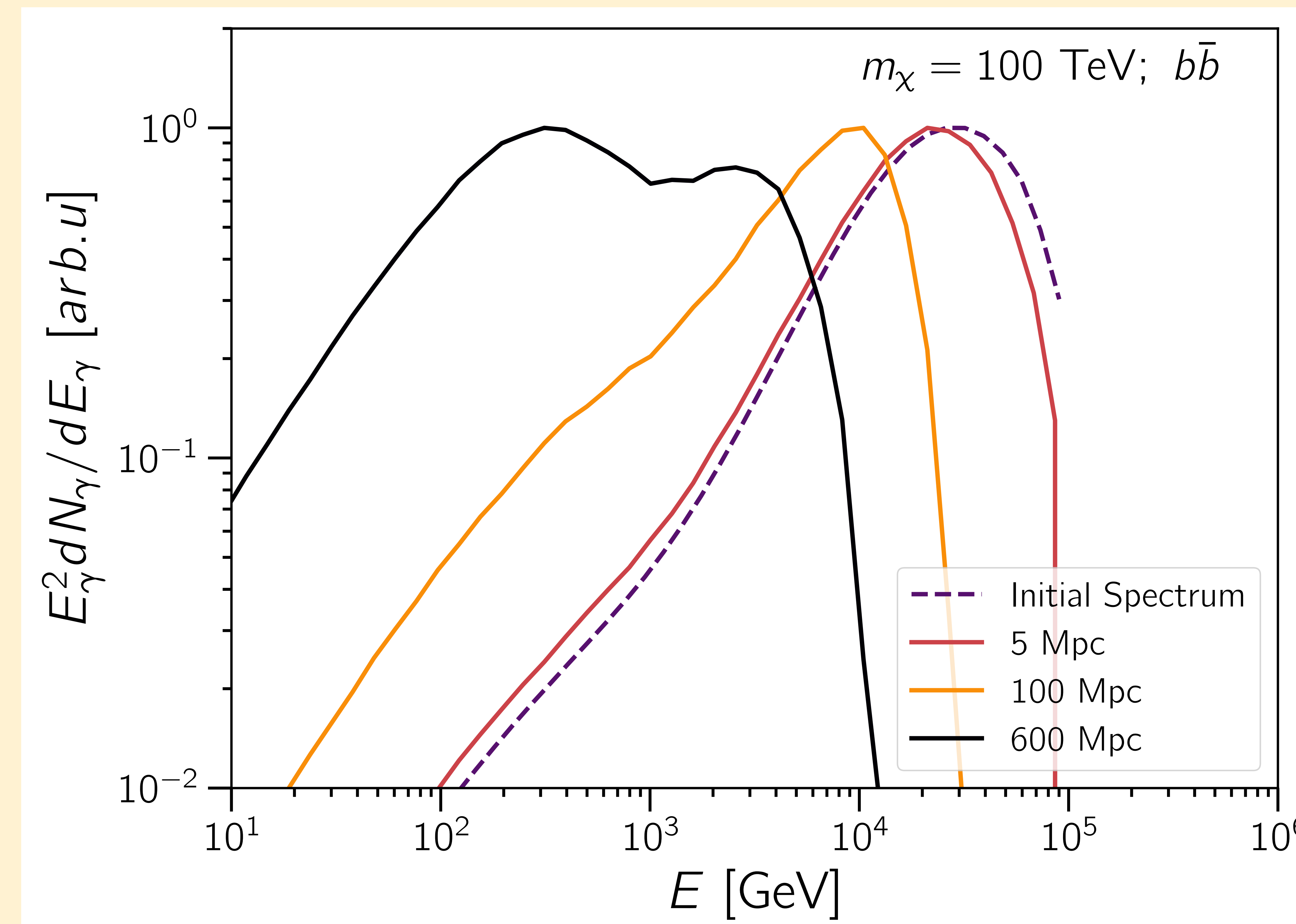
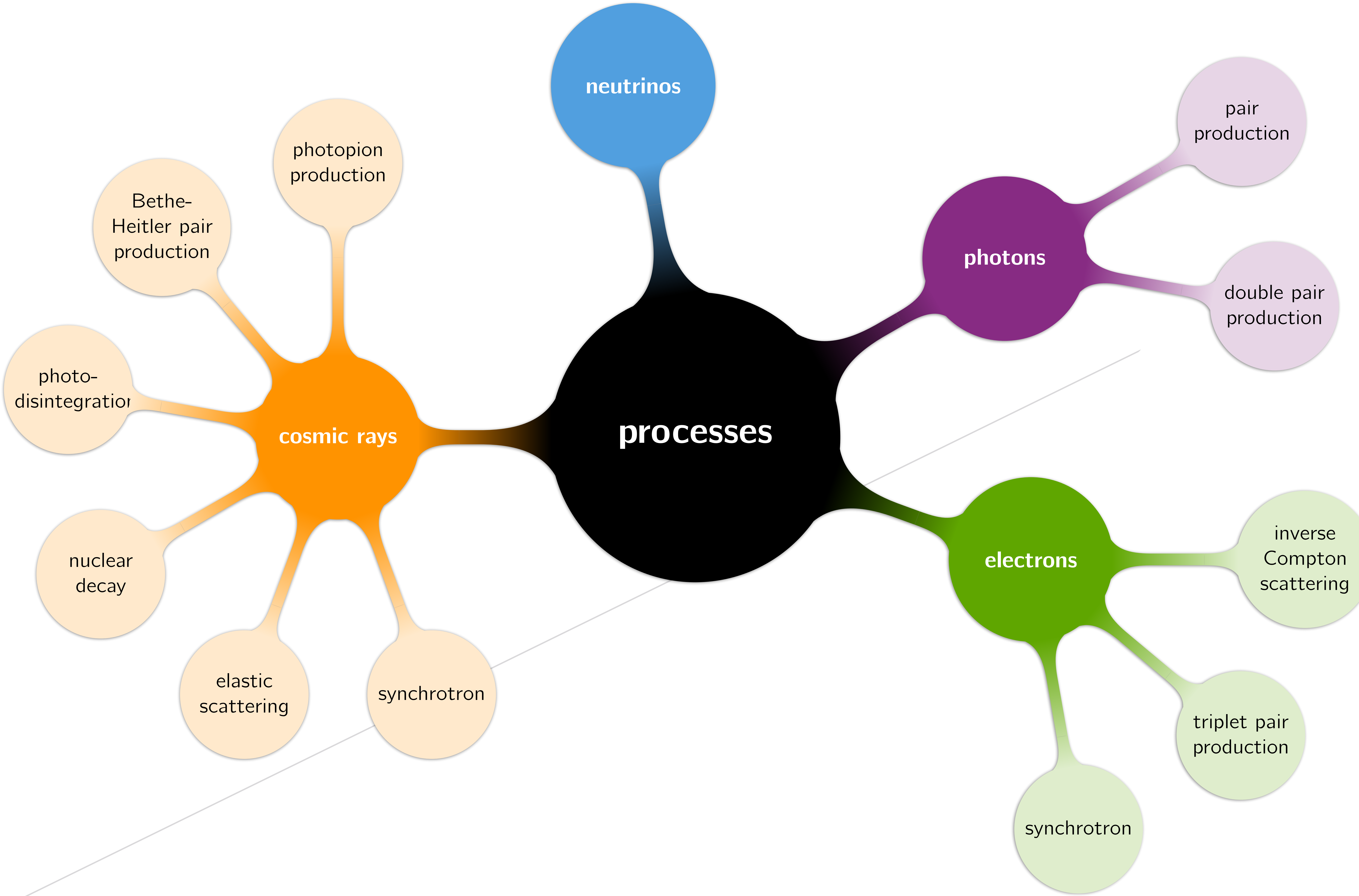


CRPropa


neutrinos
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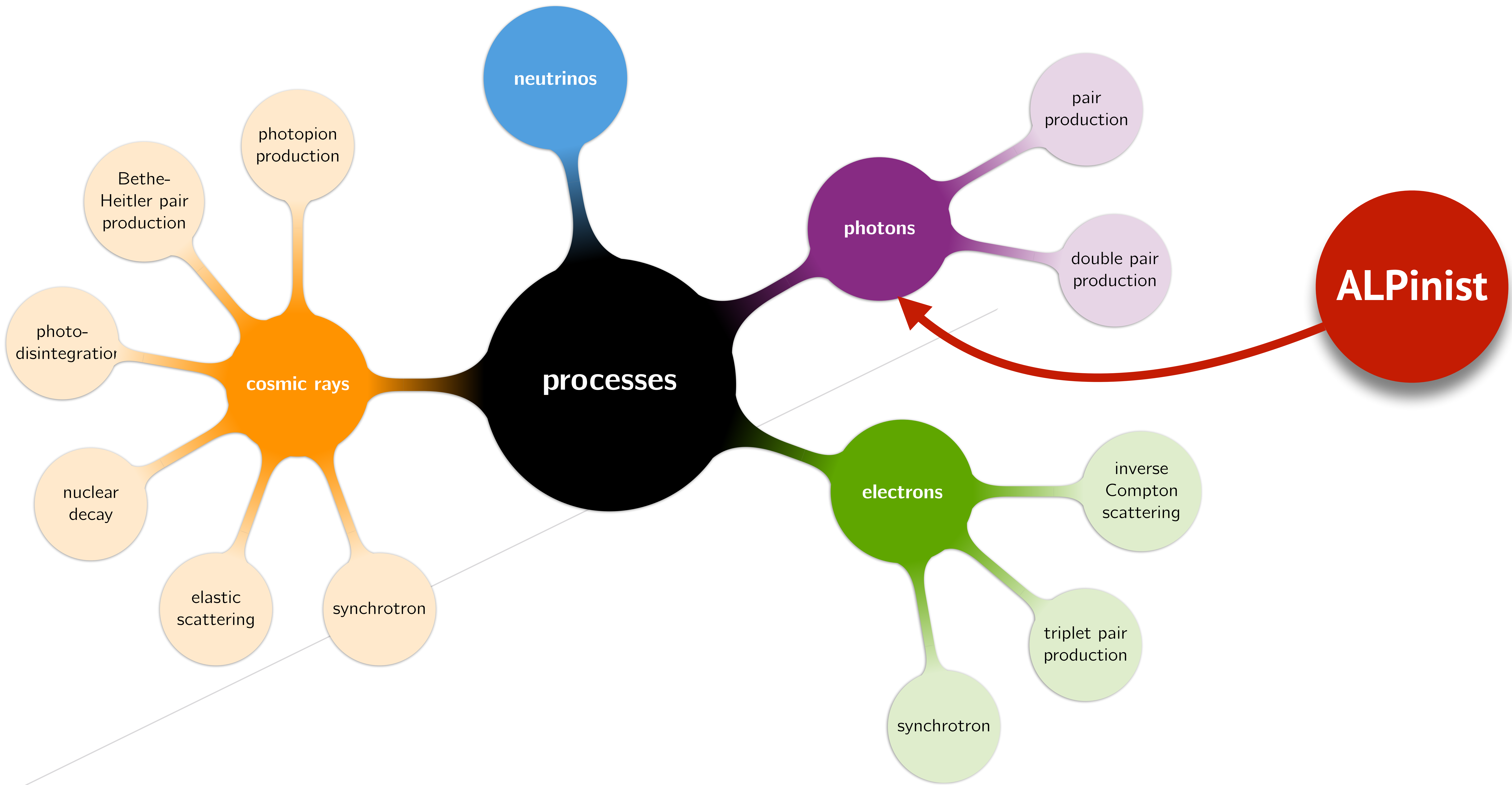
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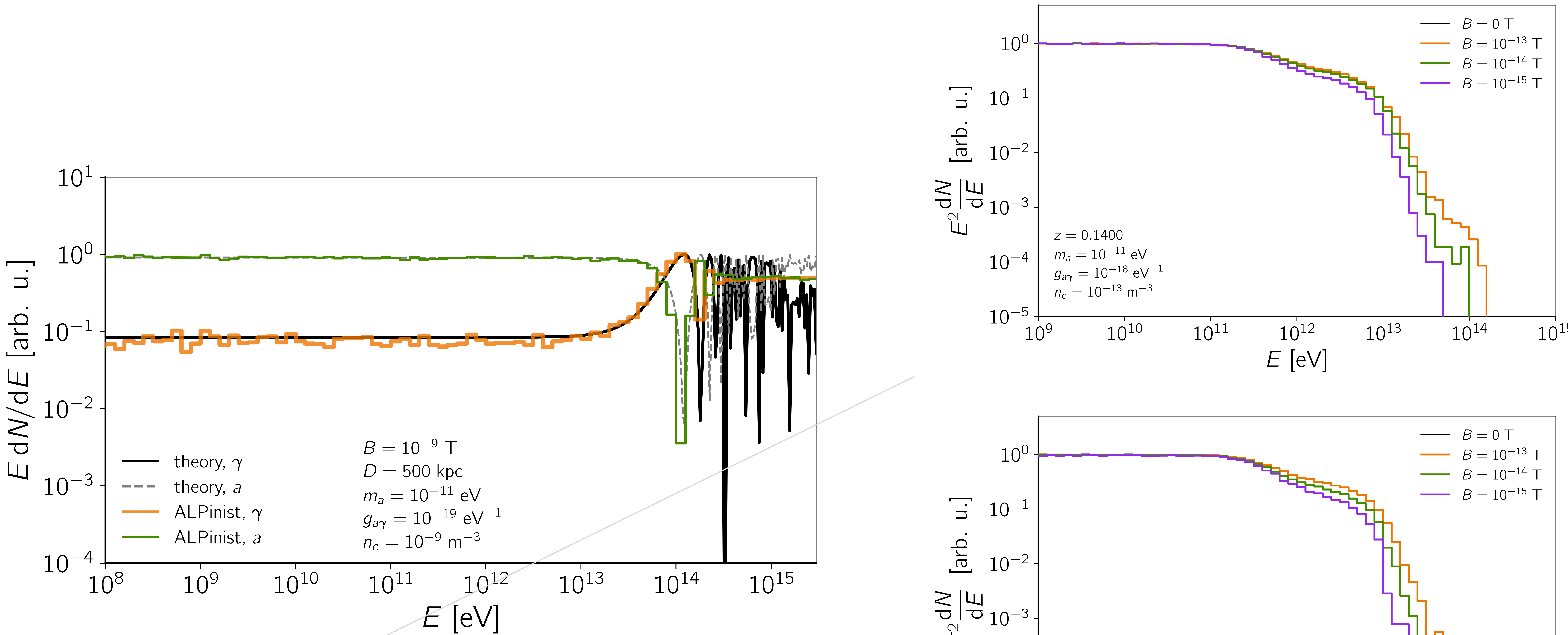
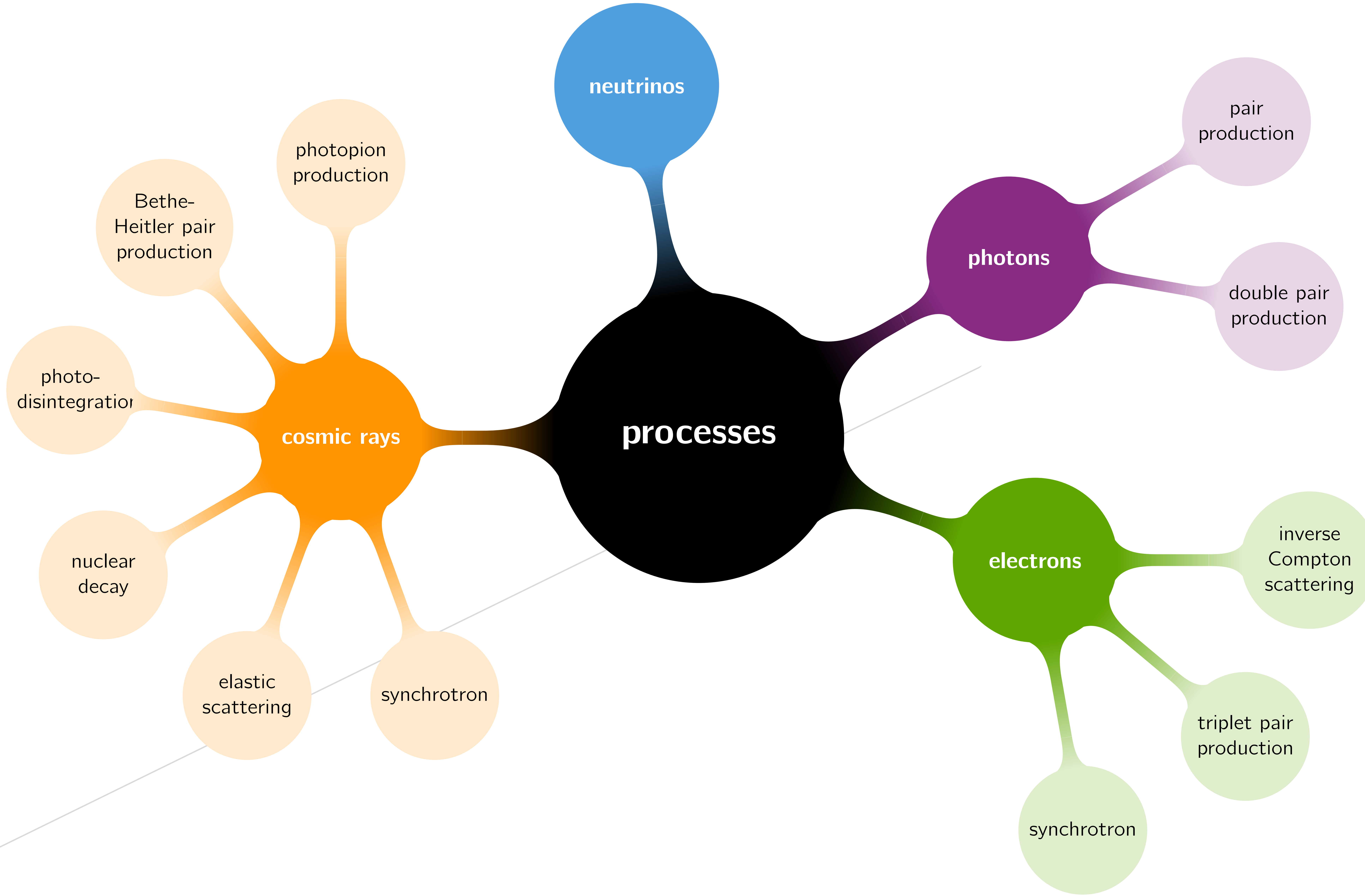
ALPinist. examples

Alves Batista, Viviente, Di Marco, Sánchez-Conde. PoS (ICRC2023) 1383. arXiv:2308.00935



summary & outlook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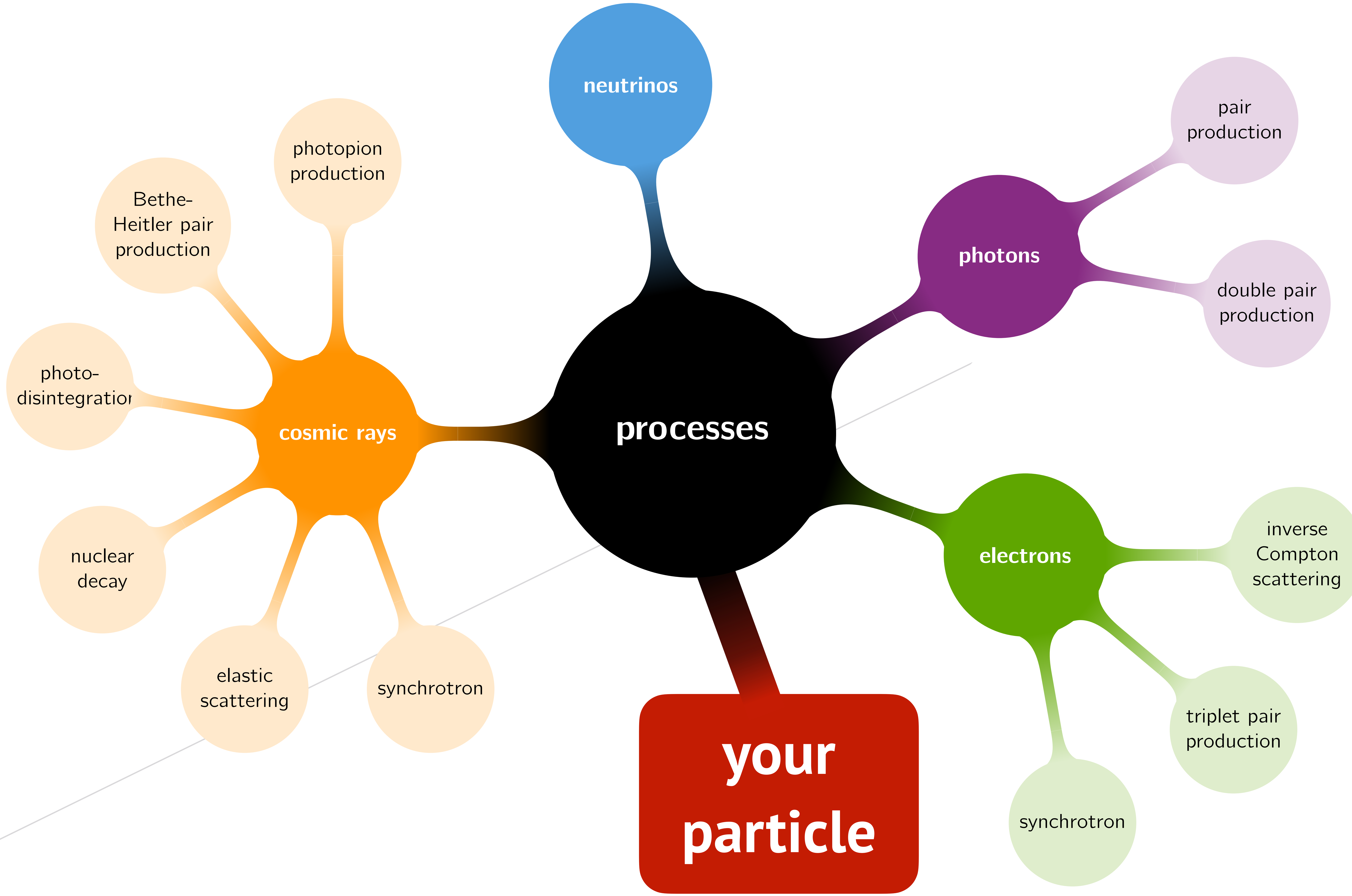
extending CRPropa: write your own plugin



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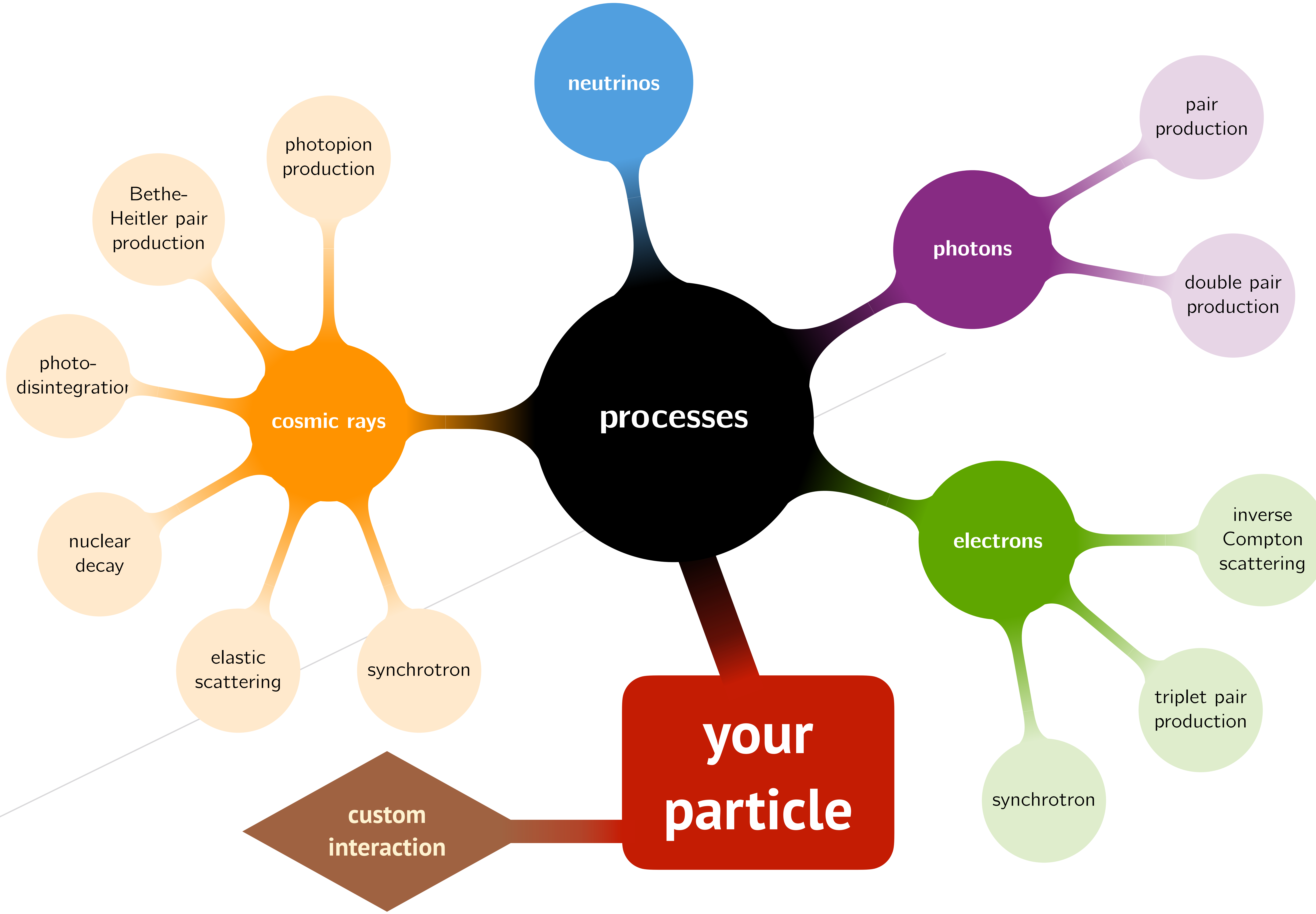

summary

- public *open-source* framework for the propagation of high-energy particles
- many photon background and magnetic-field models
- enables a self-consistent interpretation of observations with **multiple messengers**
- **modular design** enables easy customisation for various applications in astroparticle physics
- easy to extend: **write your own plugin!**
- moving towards **CRPropa 3.3** (and planning **CRPropa 4**)
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more information:

crpropa.desy.de

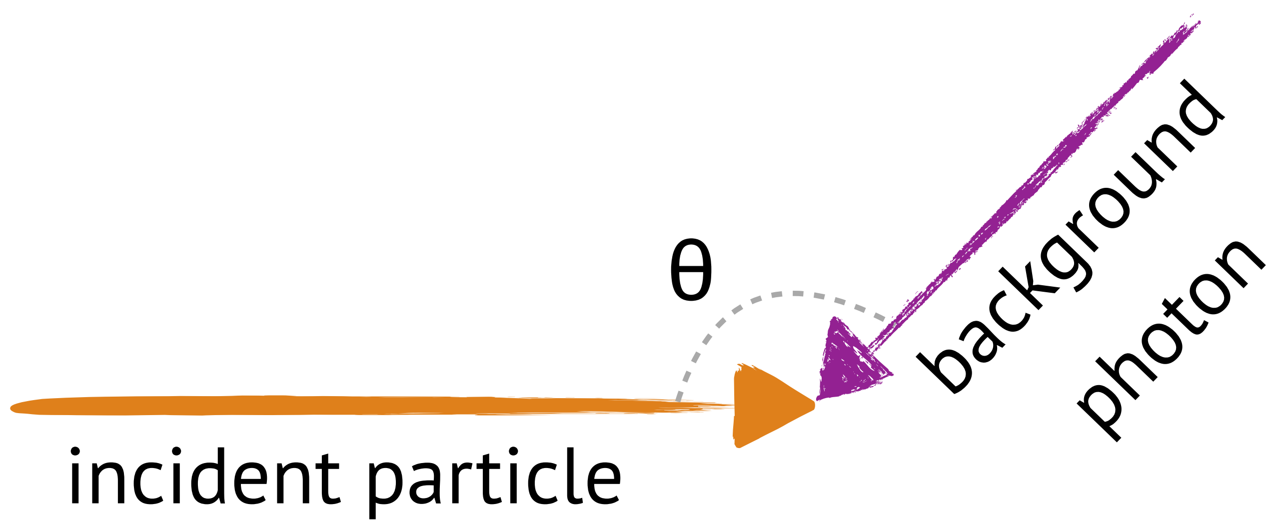
the developing team *(currently)*

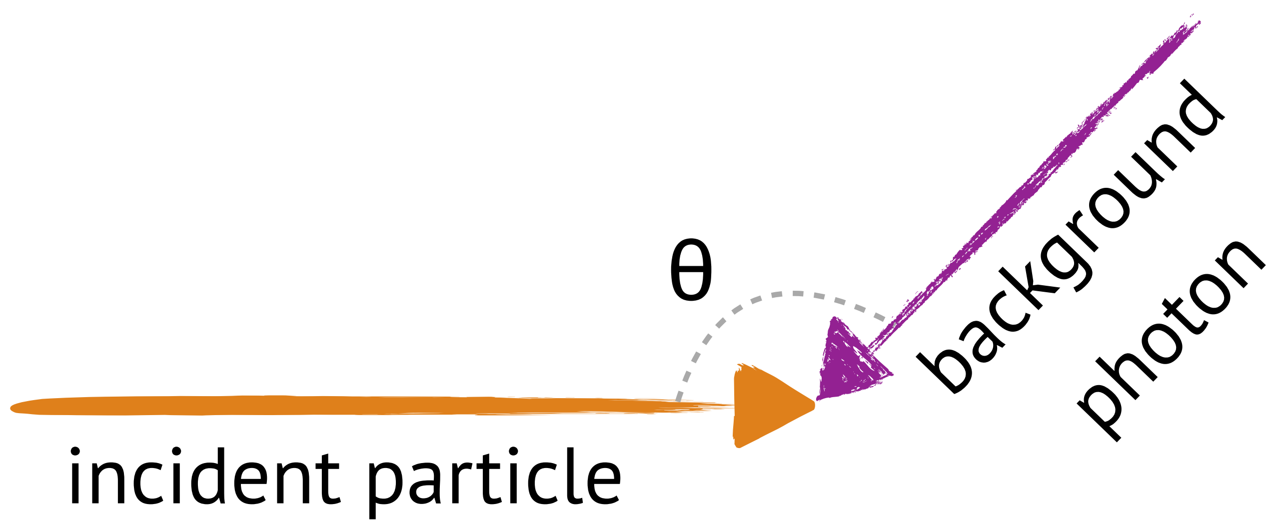
S. Aerdker (Bochum)
R. Alves Batista (Paris)
J. Becker Tjus (Bochum)
G. Di Marco (Madrid)
J. Dörner (Bochum)
K.-H. Kampert (Wuppertal)
L. Merten (Bochum)
L. Morejon (Wuppertal)
G. Müller (Aachen)
P. Reichherzer (Oxford)
A. Saveliev (Kaliningrad)
L. Schlegel (Bochum)
G. Sigl (Hamburg)
A. van Vliet (Abu Dhabi)

and MANY **contributors**

CRPropa users and developers.
CRPropa Workshop 2022 (Madrid)

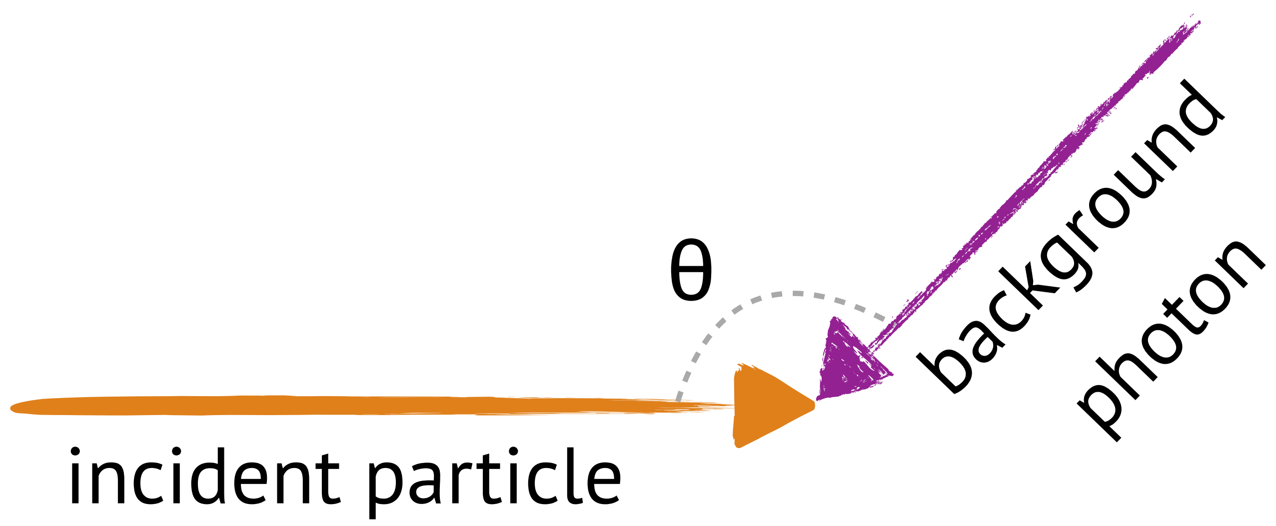
back-up slides


θ
background photon
incident particle



(squared) centre of mass energy

$$s = m^2 + E\varepsilon(1 - \beta \cos\theta)$$



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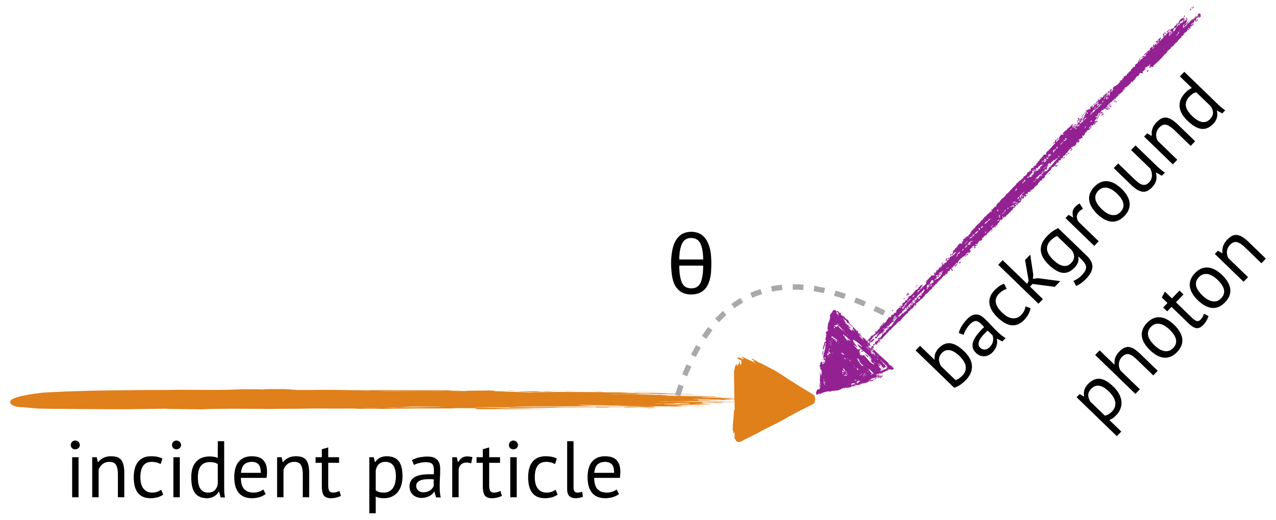
interaction length



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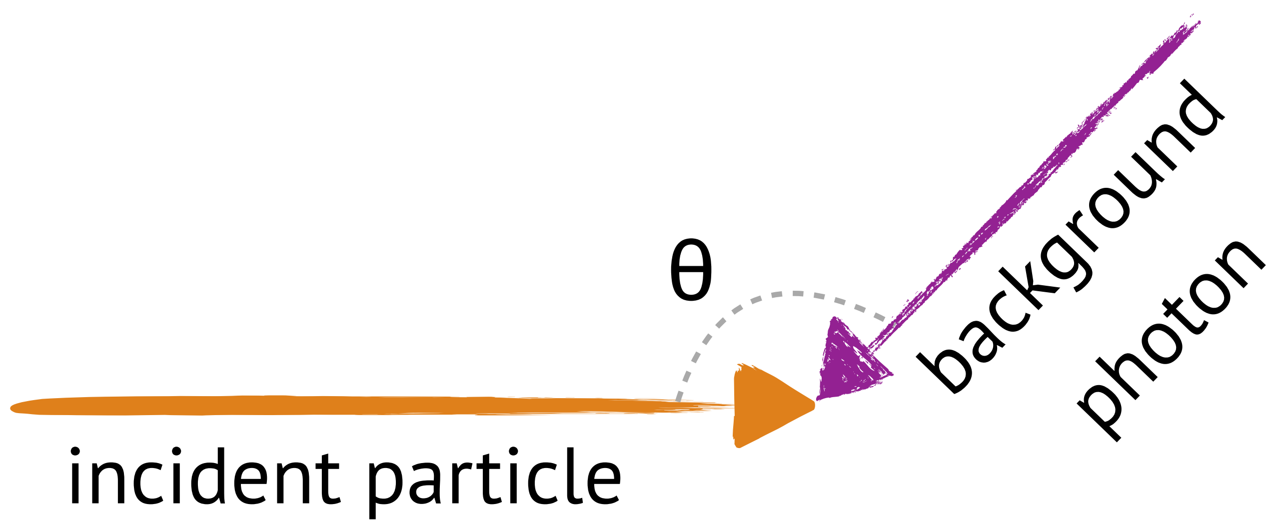
$$\lambda^{-1}(E,z) = \frac{1}{8\beta E^2} \int_{\varepsilon_{\min}(E)}^{+\infty} \frac{1}{\varepsilon^2} \frac{dn(\varepsilon, z)}{d\varepsilon} \int_{s_{\min}}^{s_{\max}(E,\varepsilon)} (s - m^2c^4)\sigma(s)\, ds\, d\varepsilon$$

cosmological propagation of high-energy messengers



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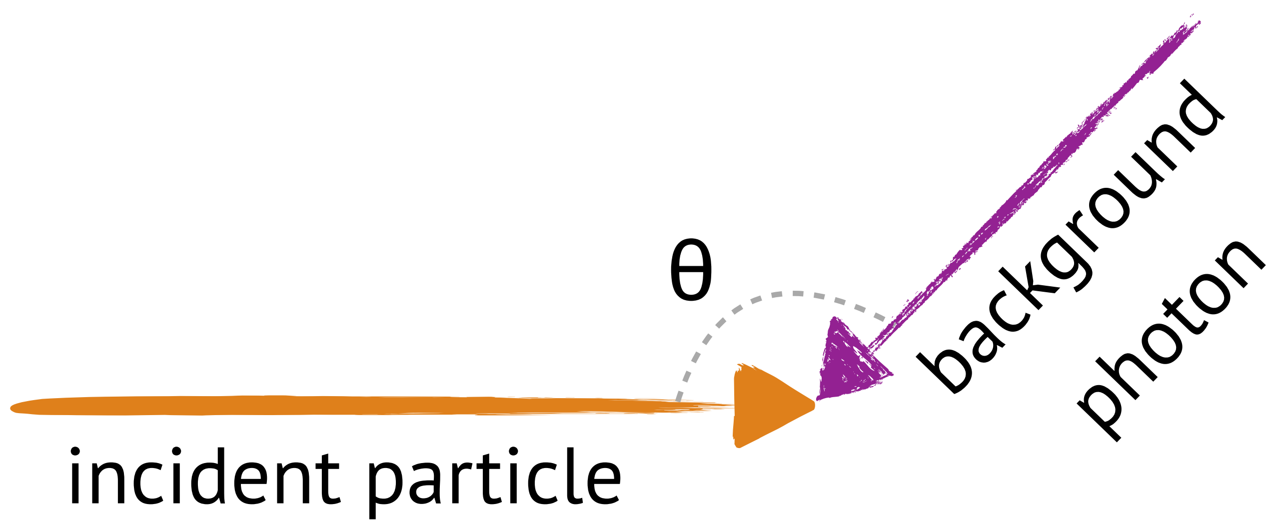
energy of incident particle

cosmological propagation of high-energy messengers



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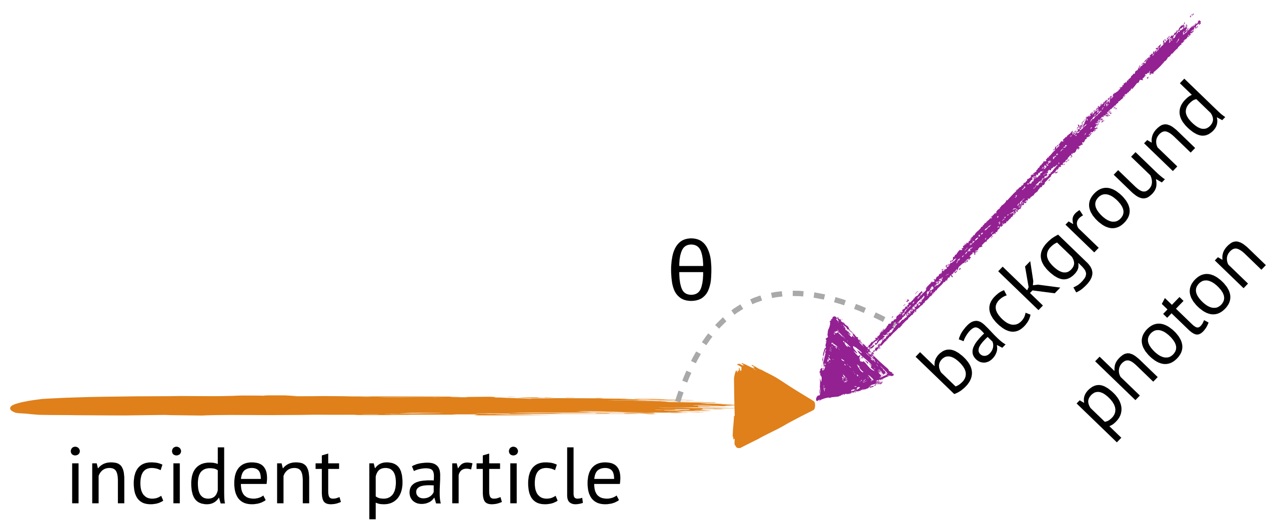
energy of incident particle

energy of background photon



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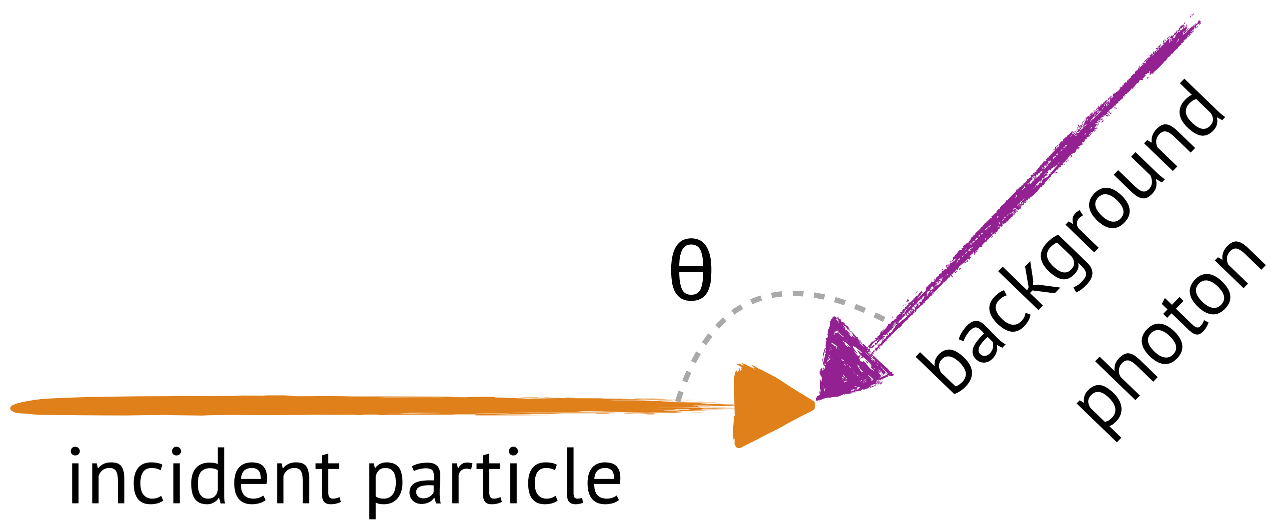

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flux attenuation

$$\Phi_o(E_o; z_s) = \Phi_s(E_o) \exp\left[-\tau(E_o, z_s)\right]$$

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$$\Phi_{\rm o}(E_{\rm o}; z_{\rm s}) = \Phi_{\rm s}(E_{\rm o}) \, \exp\left[-\tau(E_{\rm o}, z_{\rm s})\right]$$

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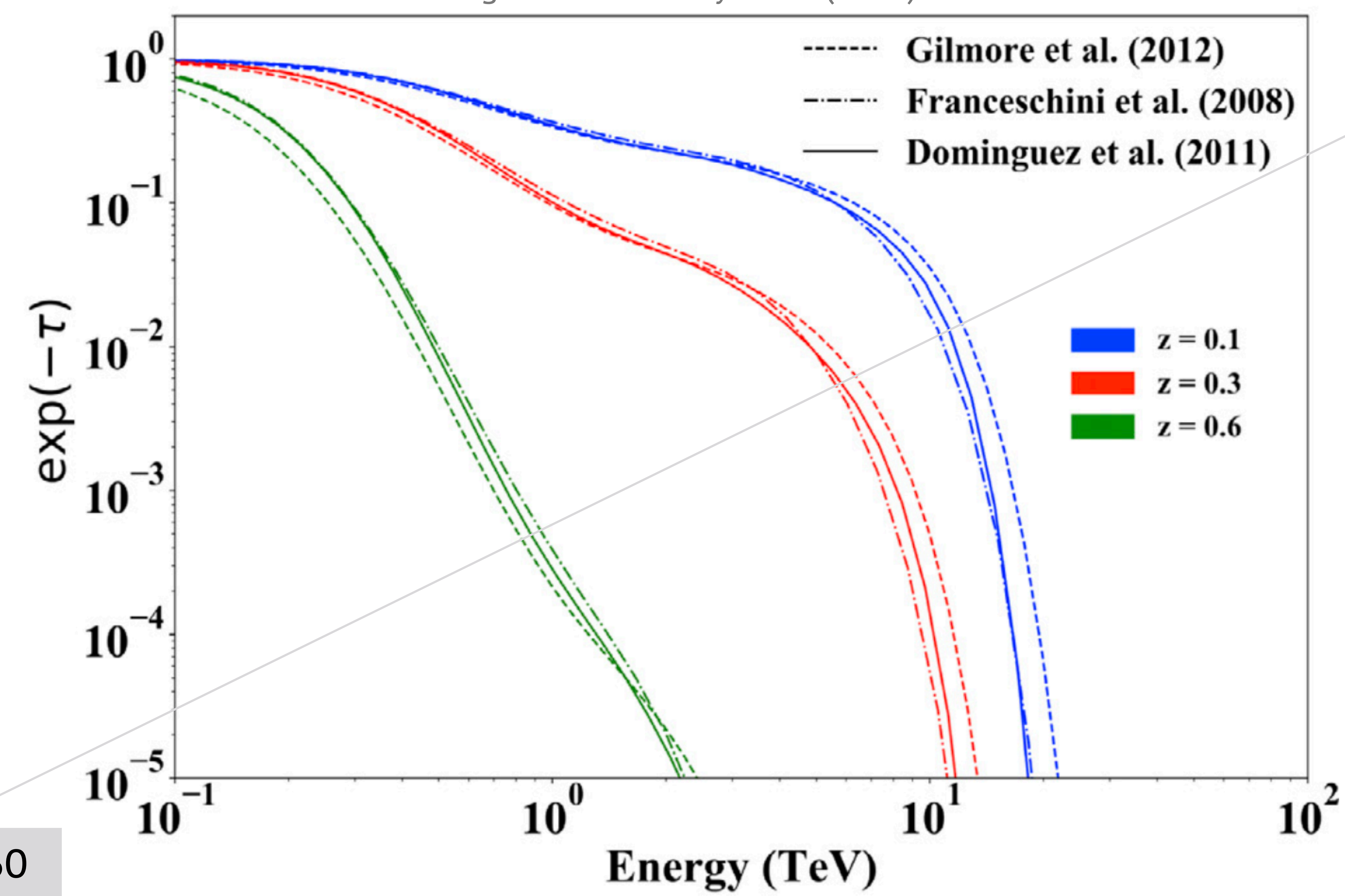
Addazi et al. Prog. Part. Nucl. Phys. 125 (2022) 103948. arXiv:2111.05659



the fate of the electrons

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how good is this approximation?

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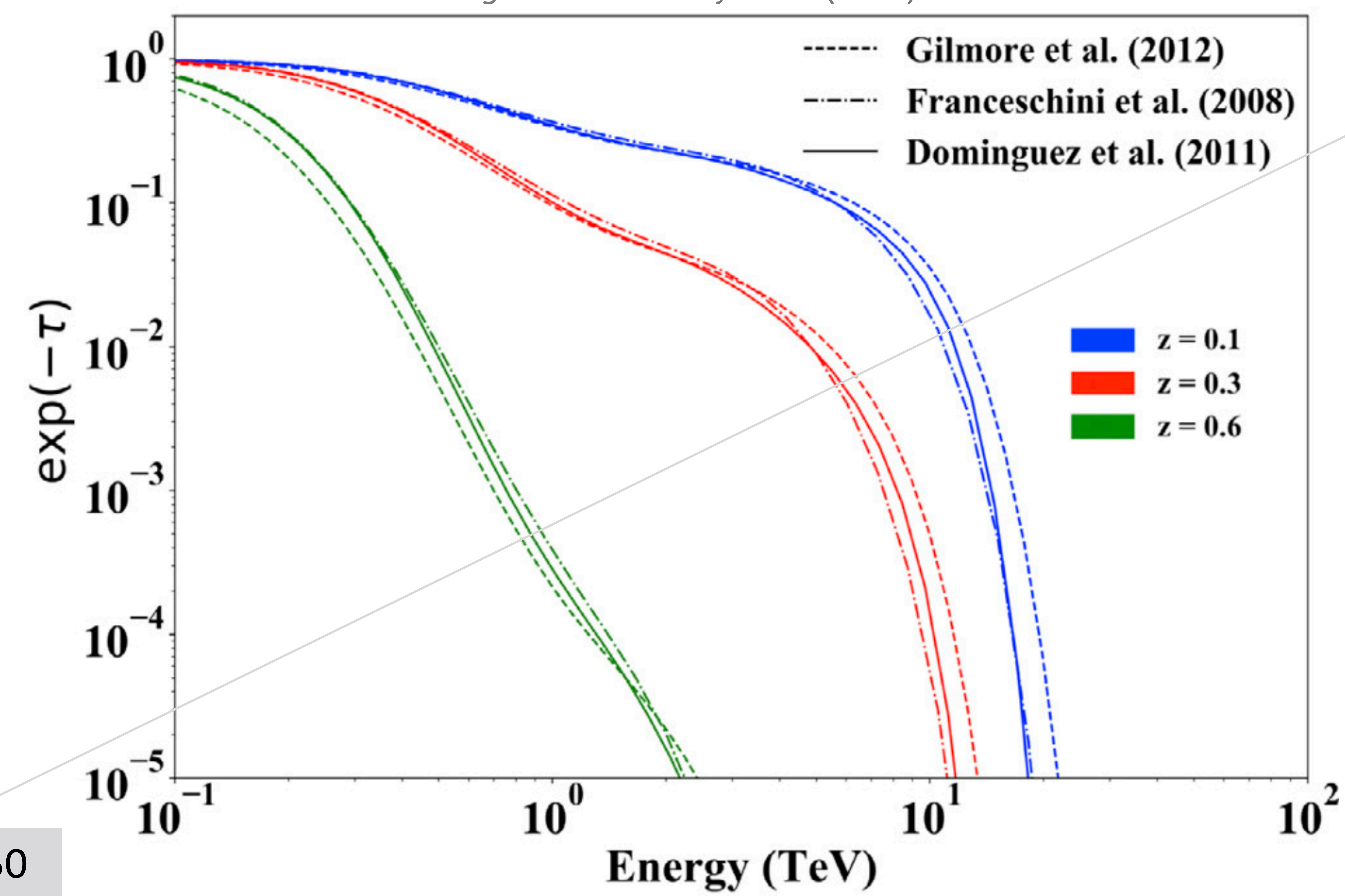

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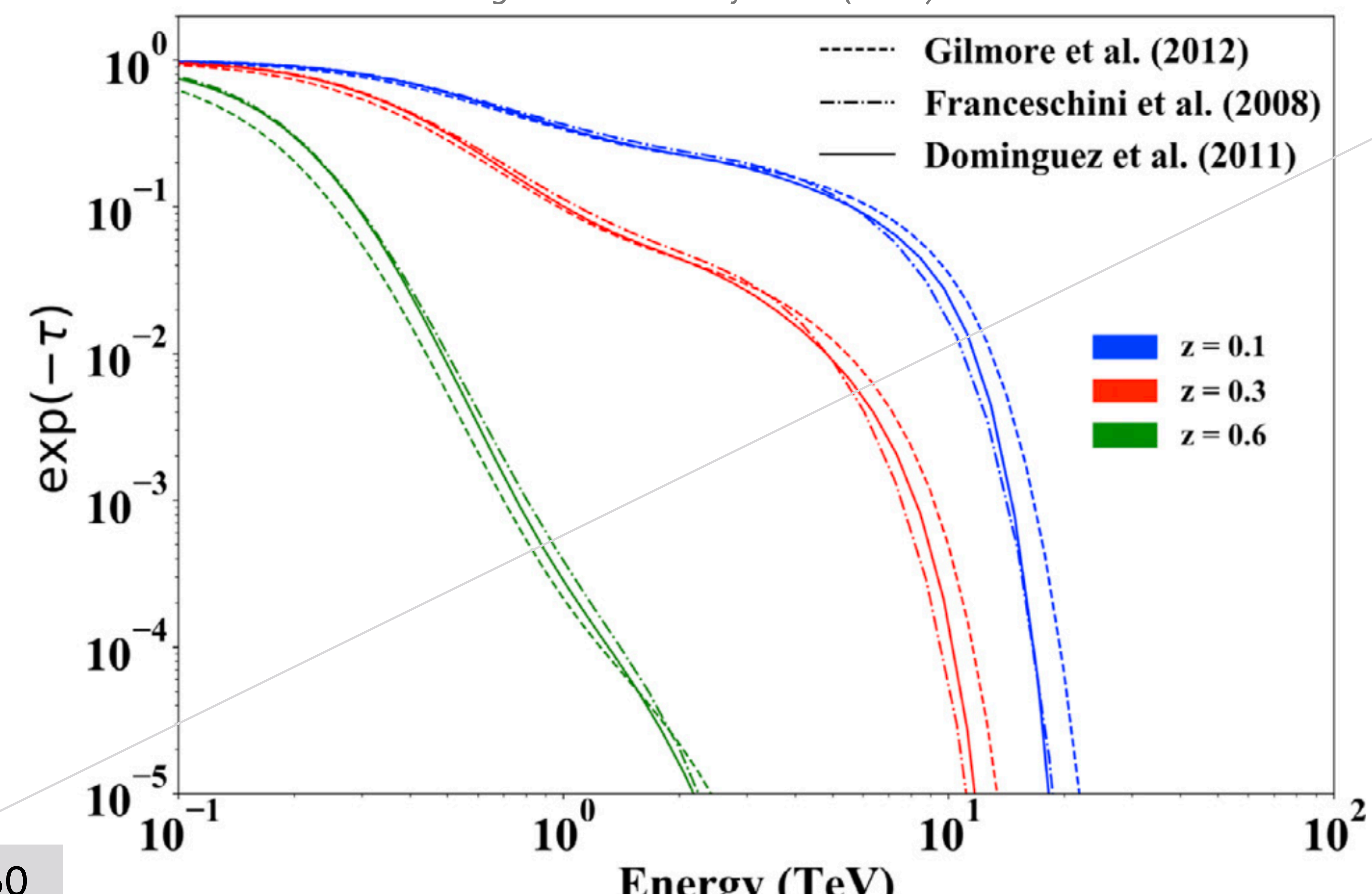

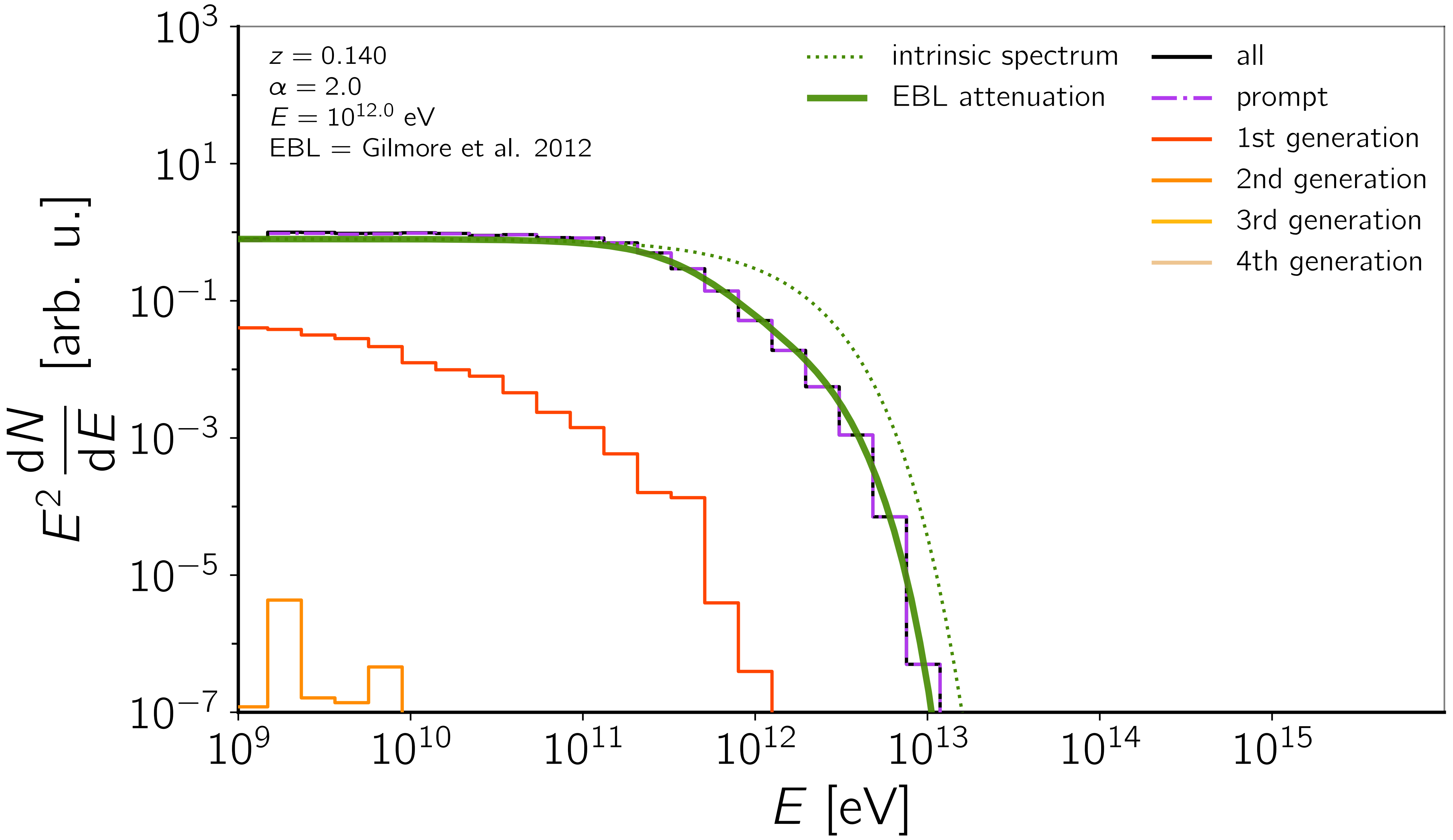

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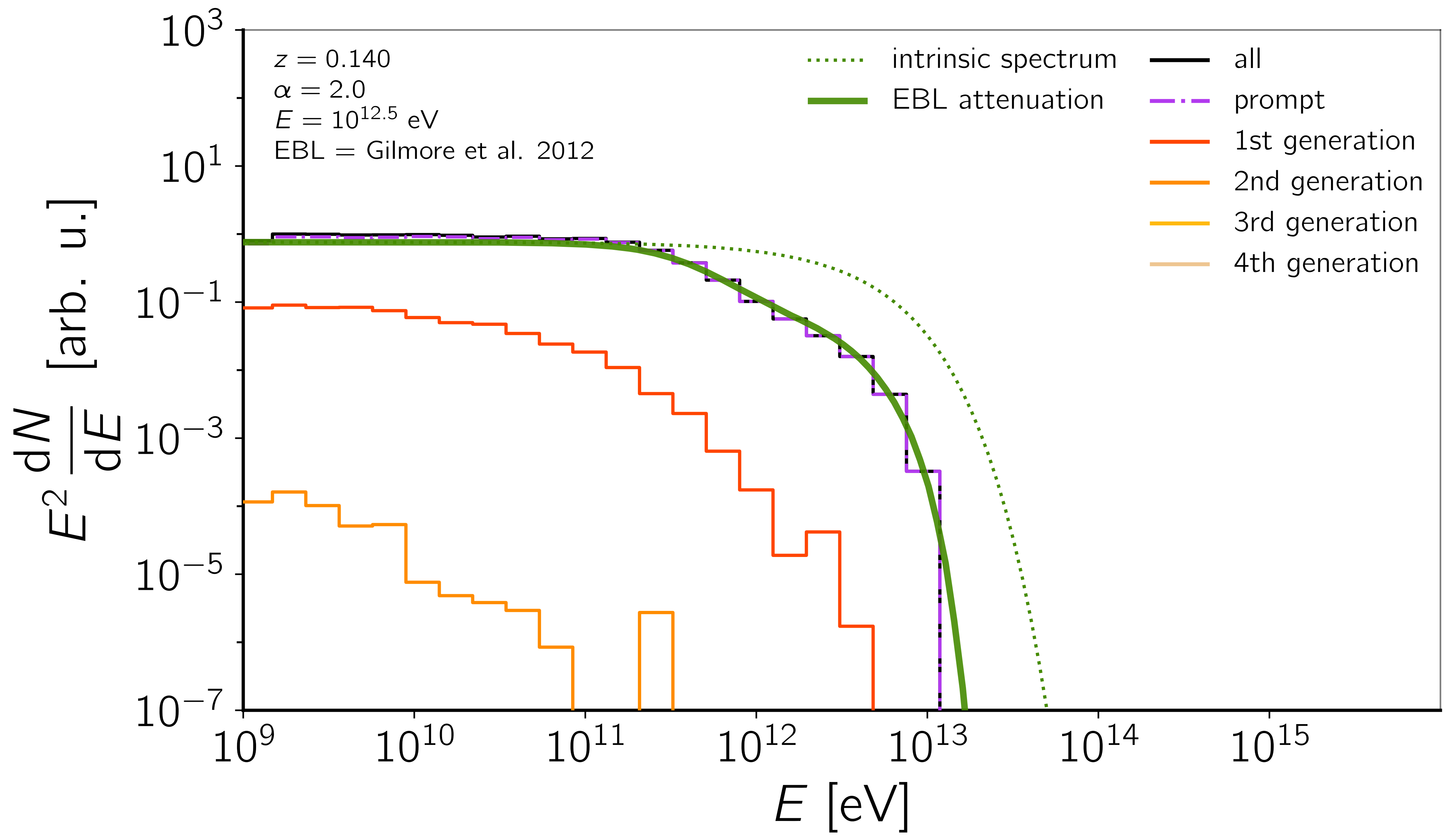

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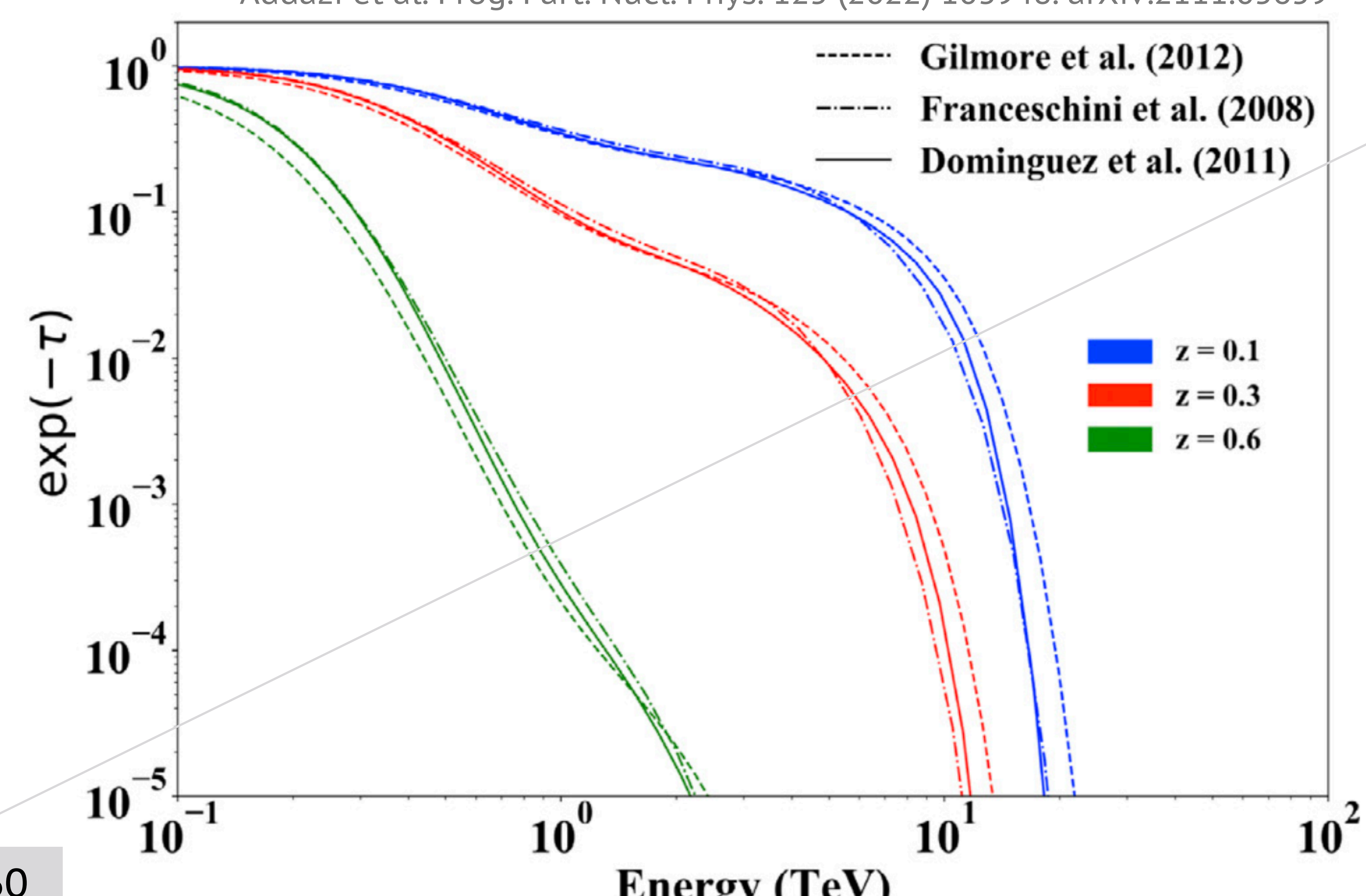

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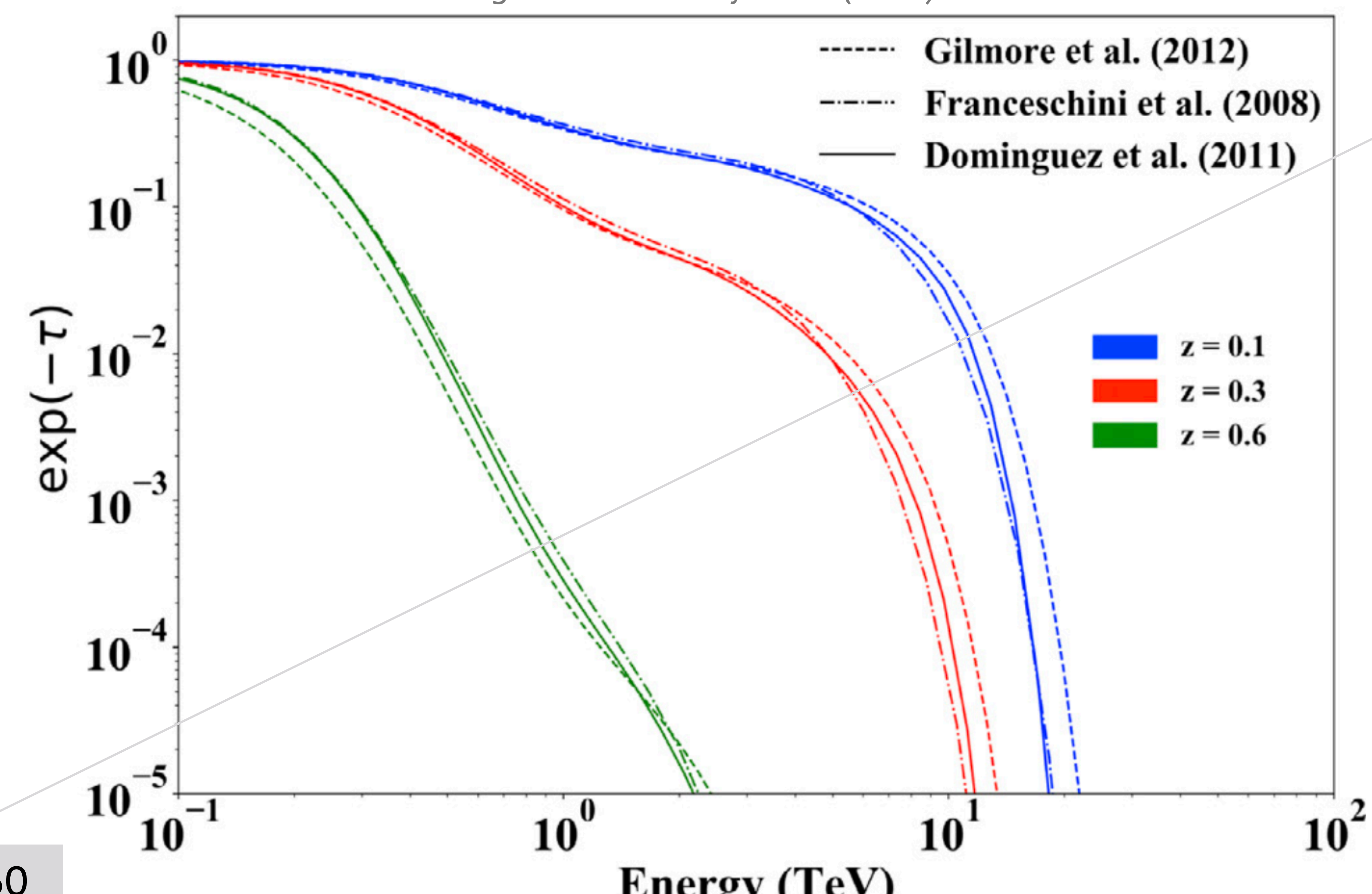

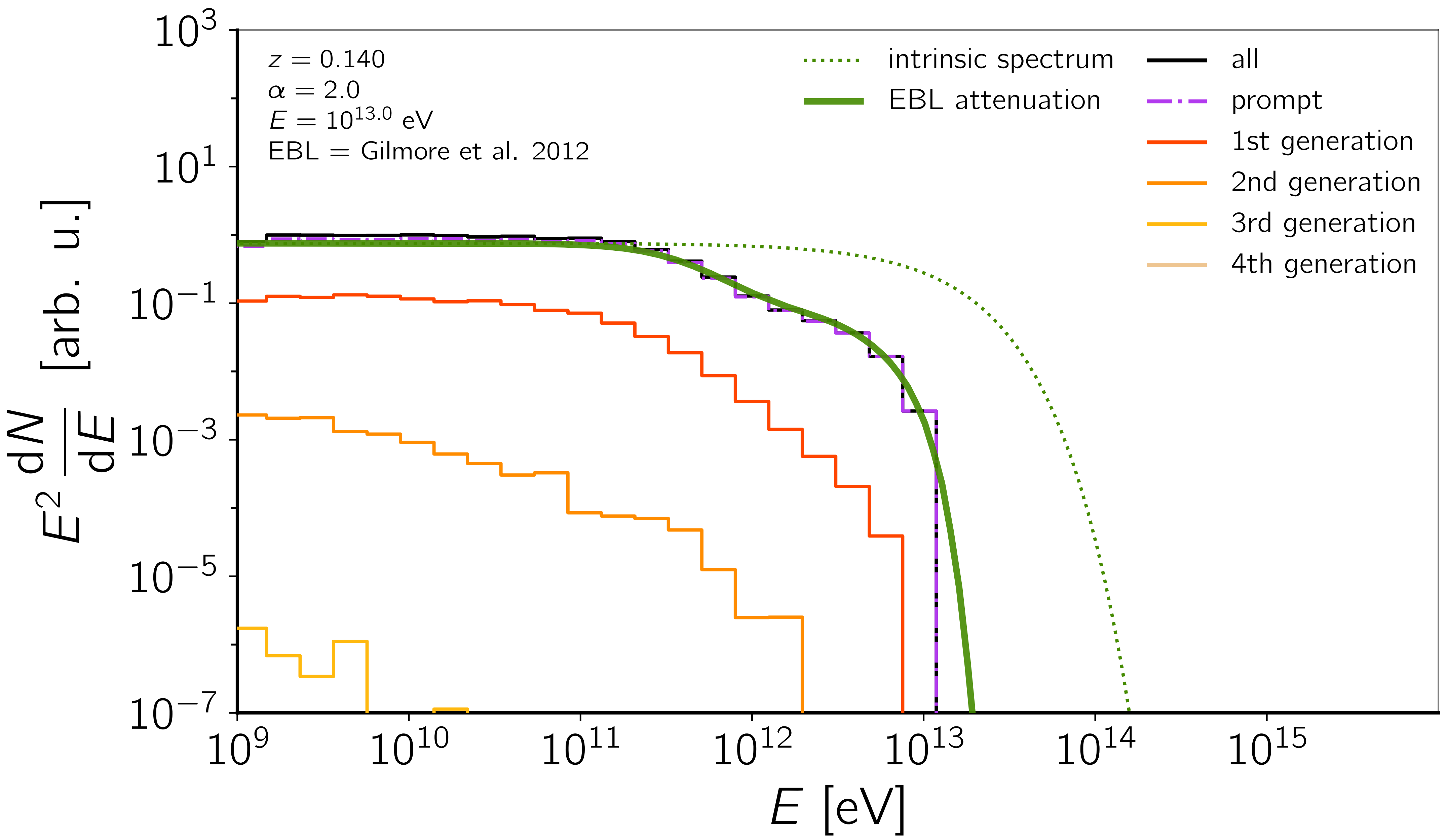

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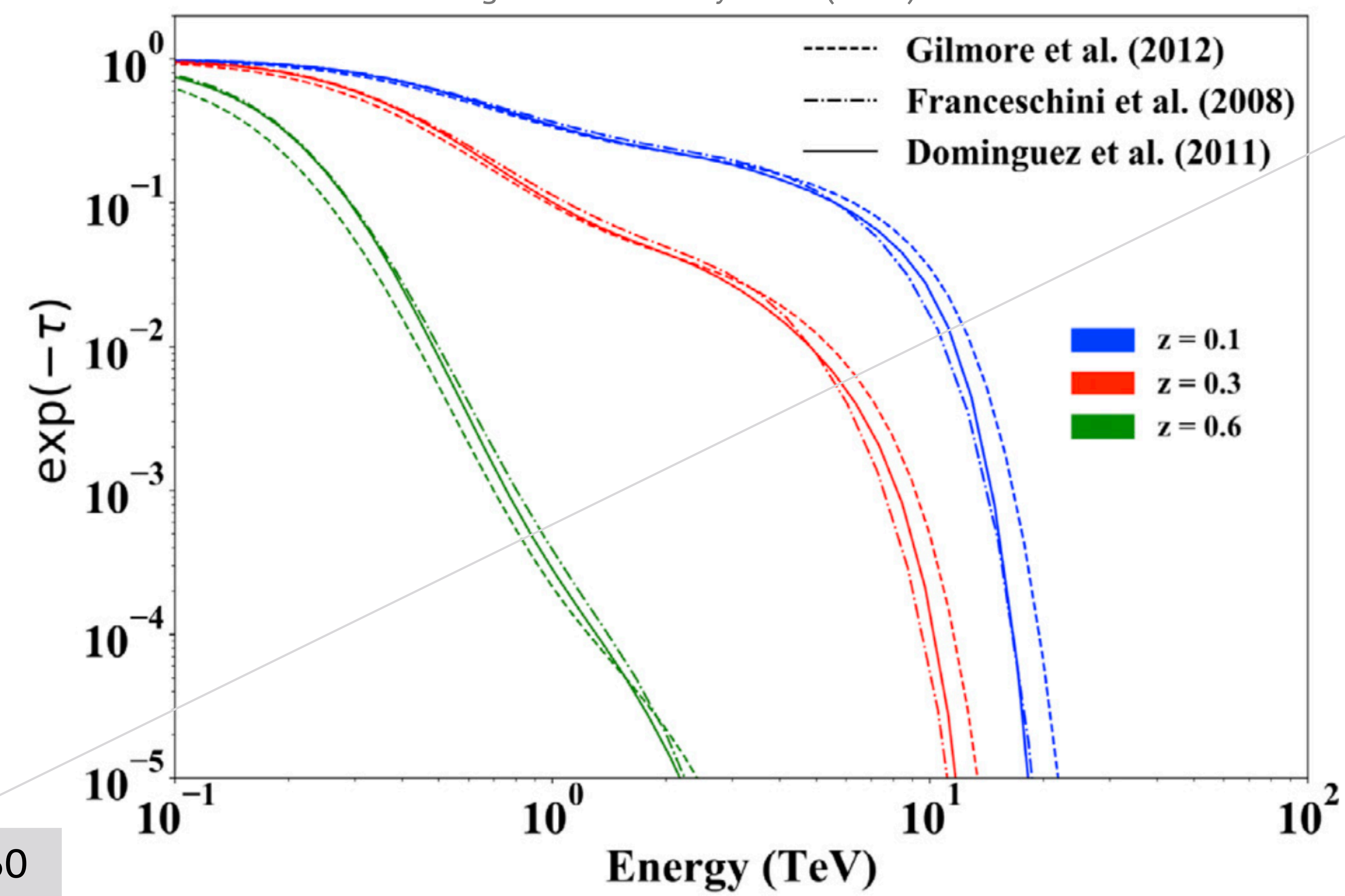
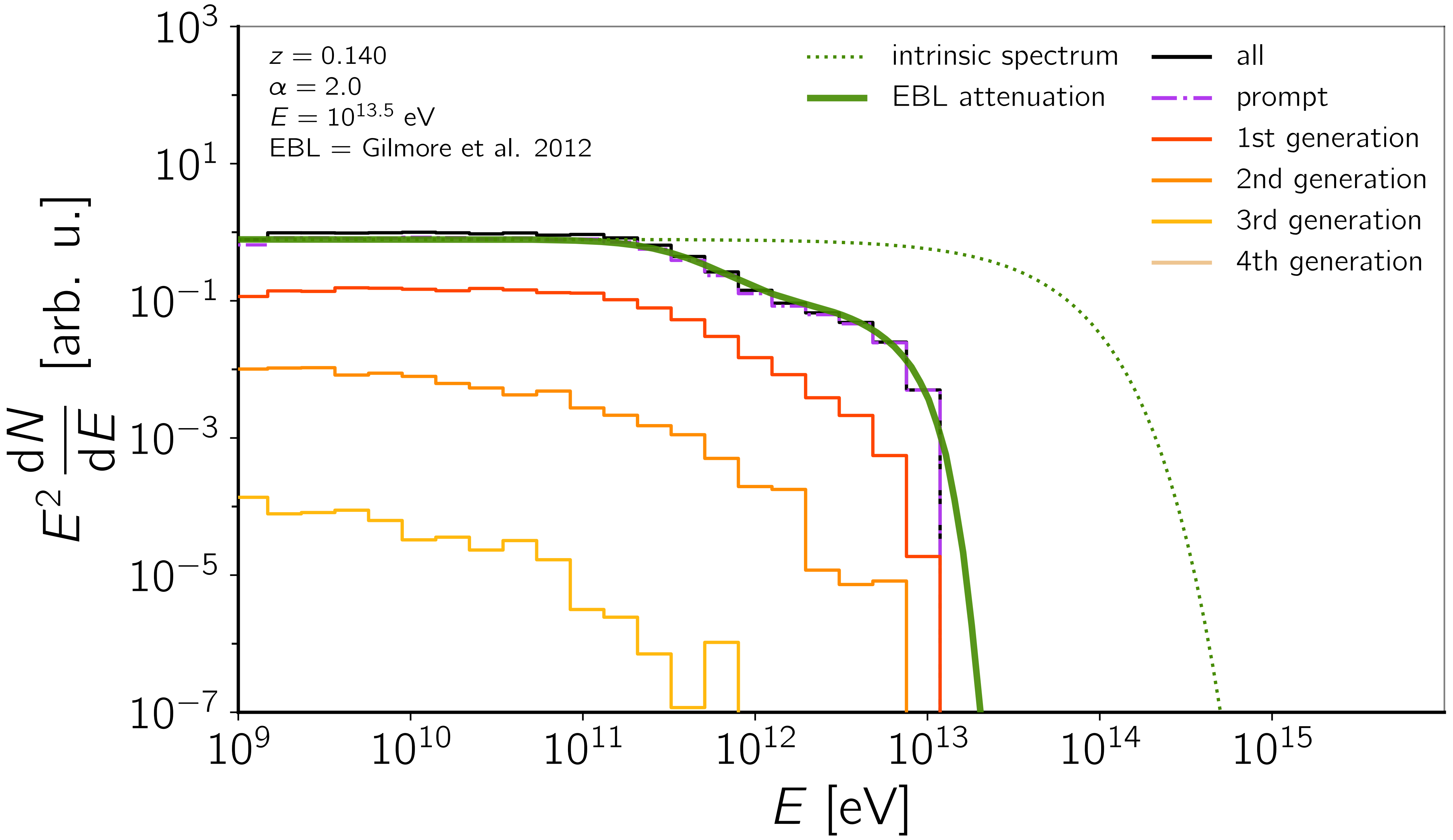
how good is this approximation?

Addazi et al. Prog. Part. Nucl. Phys. 125 (2022) 103948. arXiv:2111.05659





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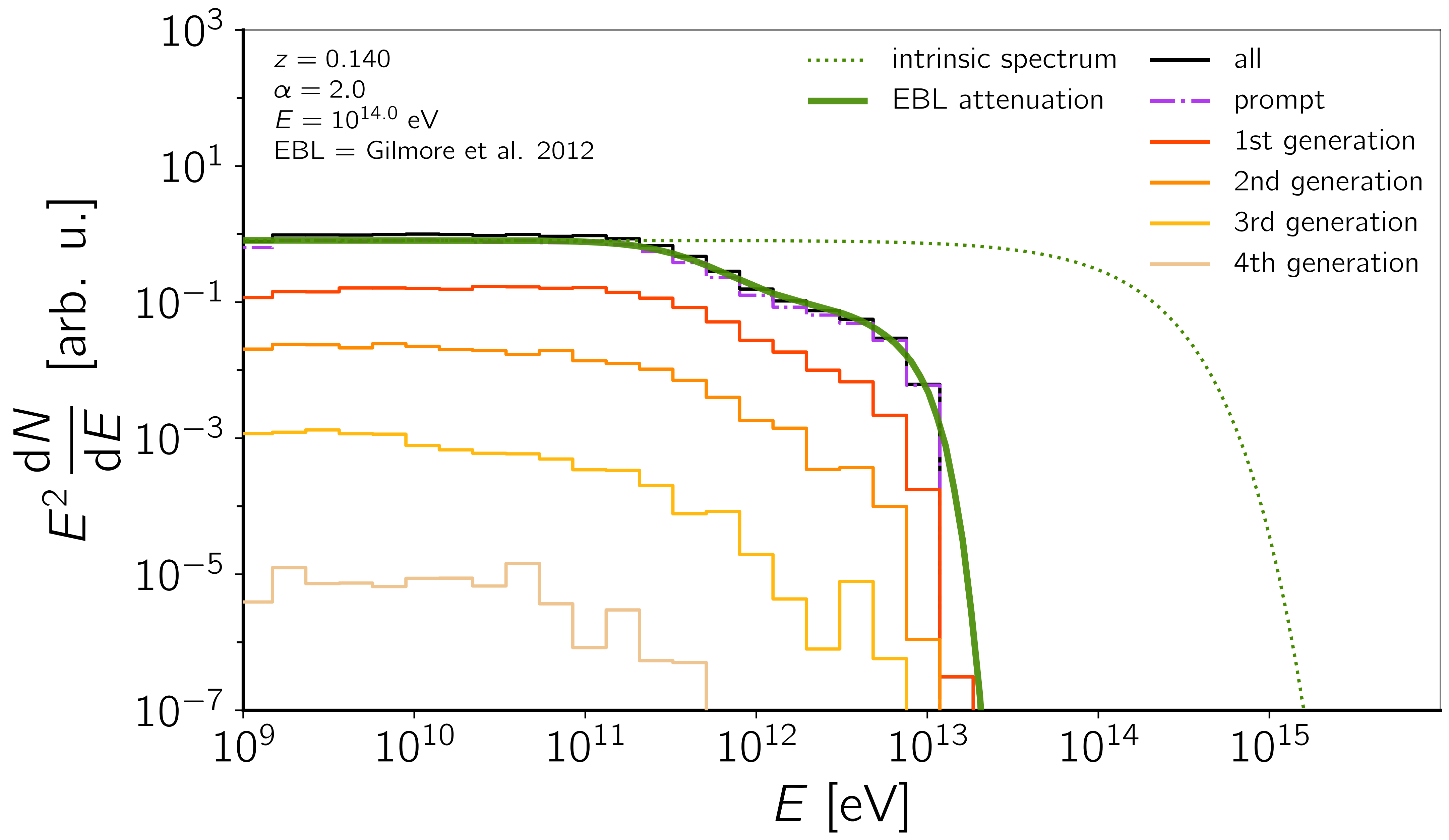

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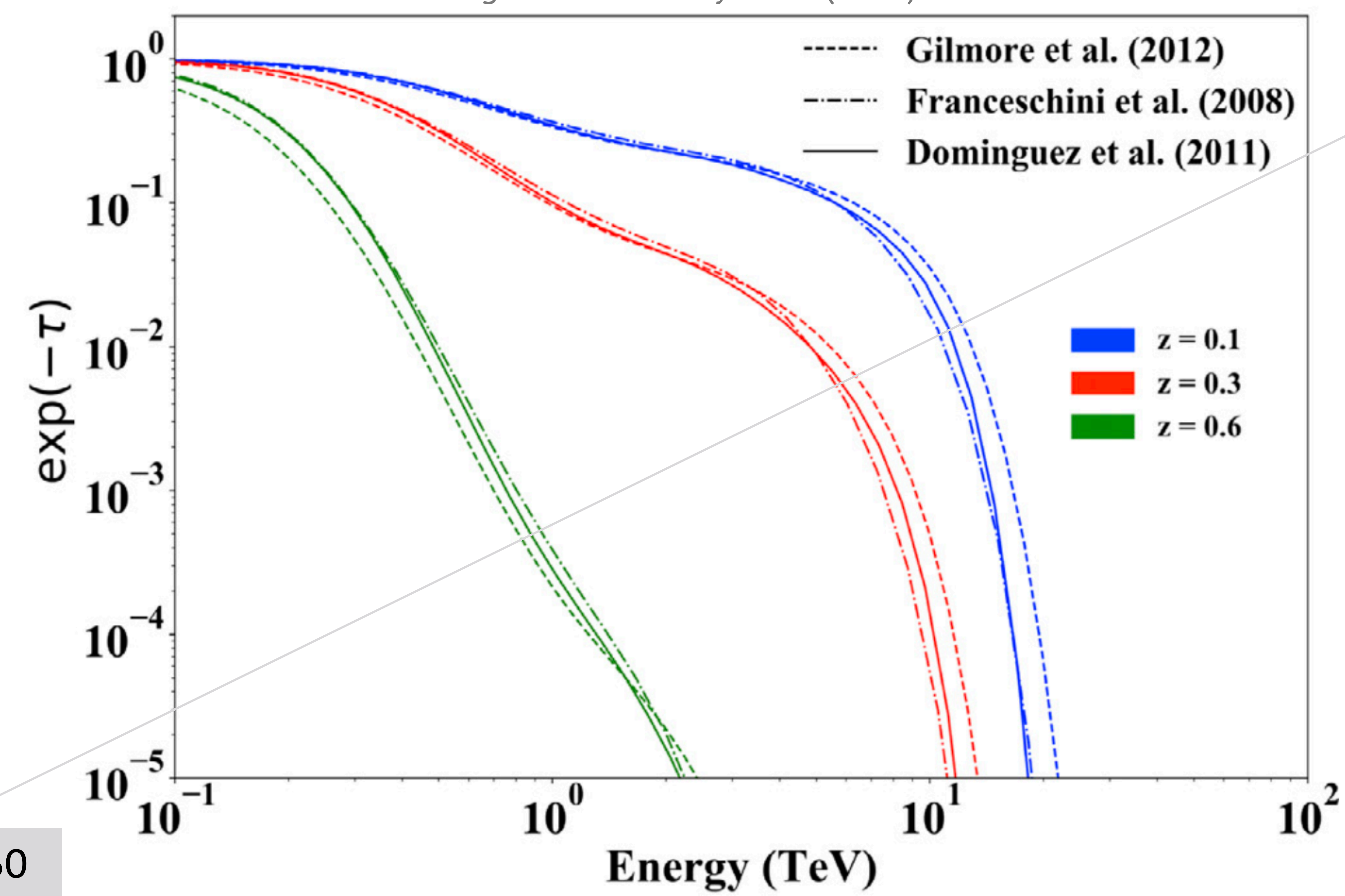

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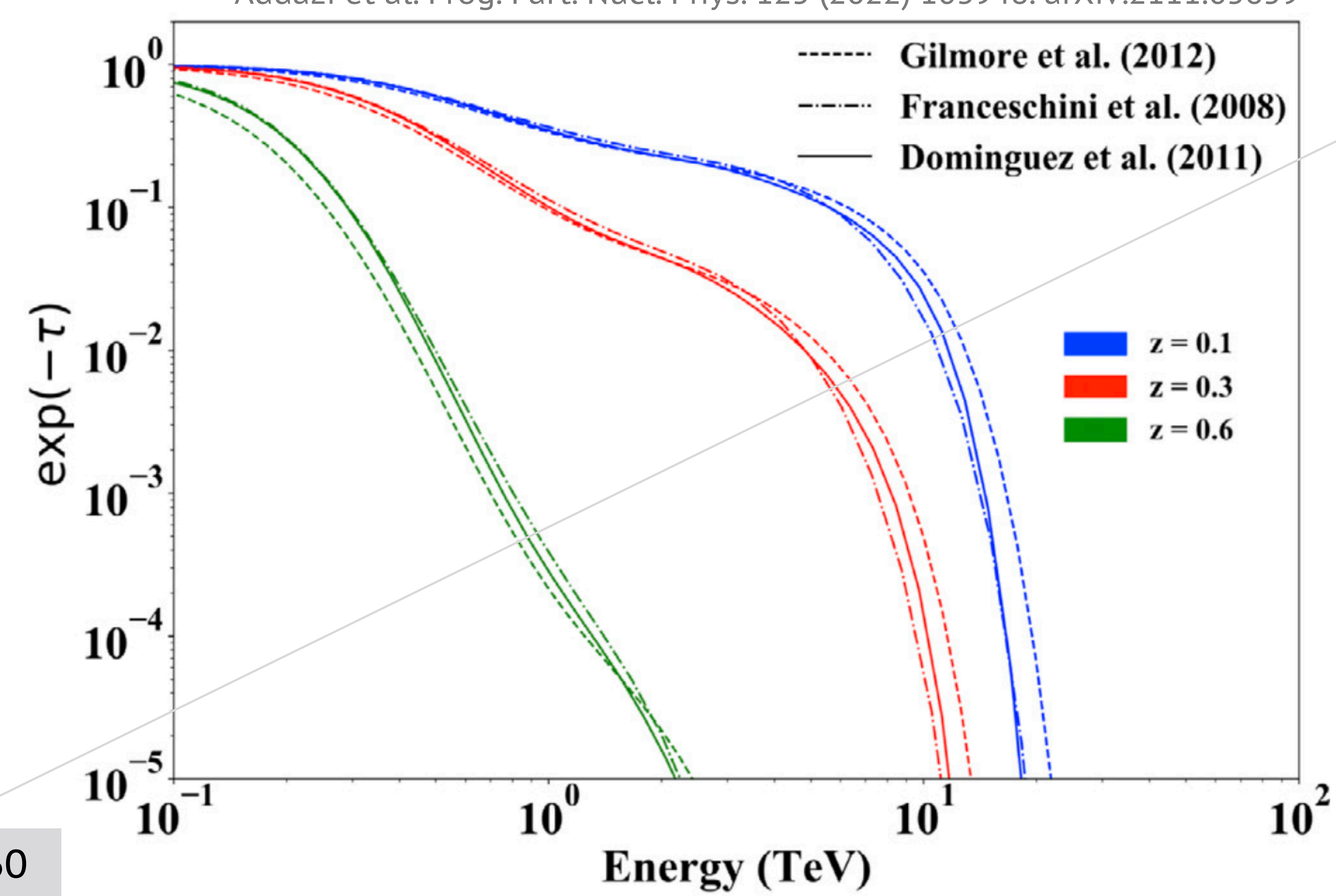

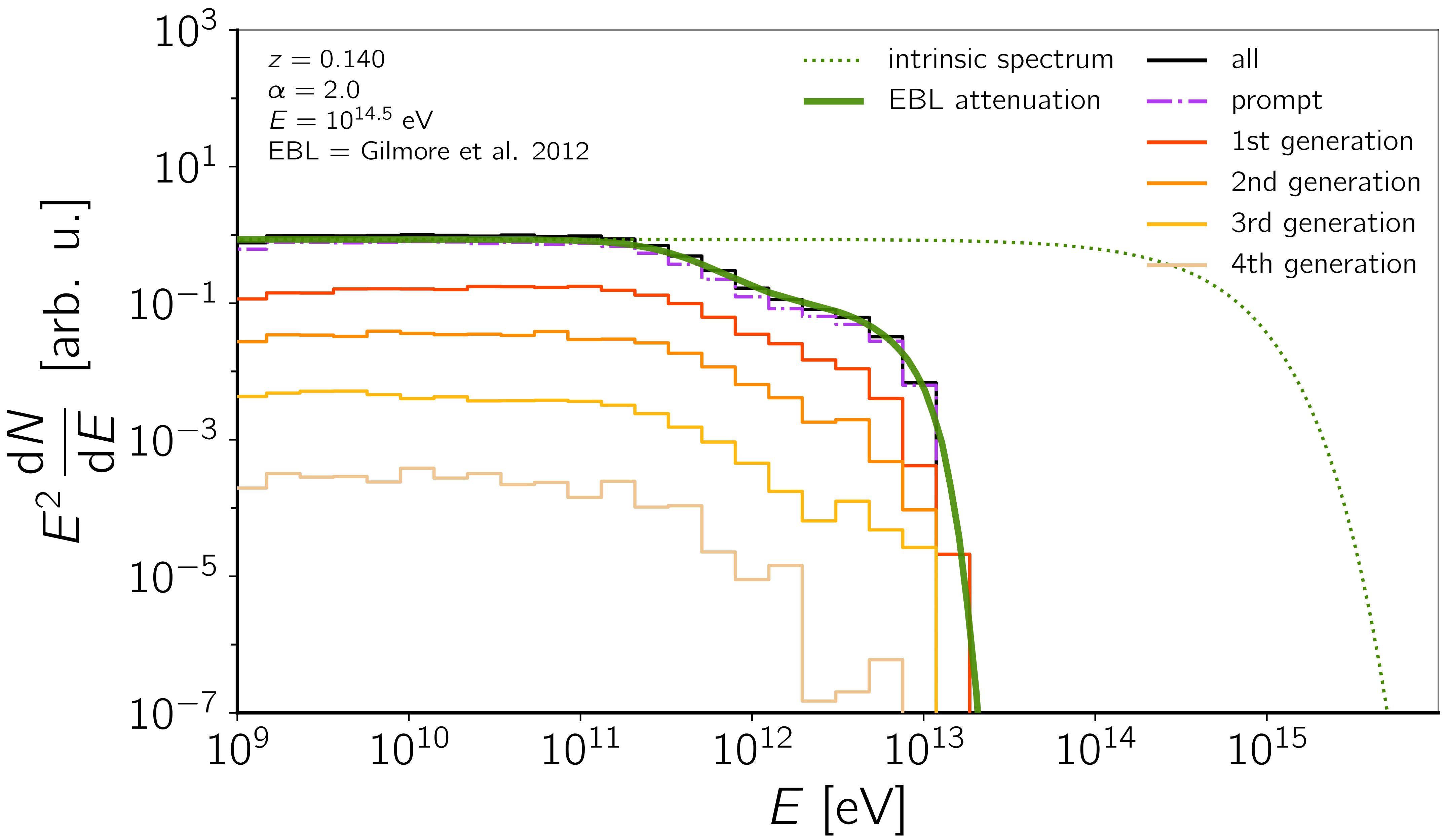

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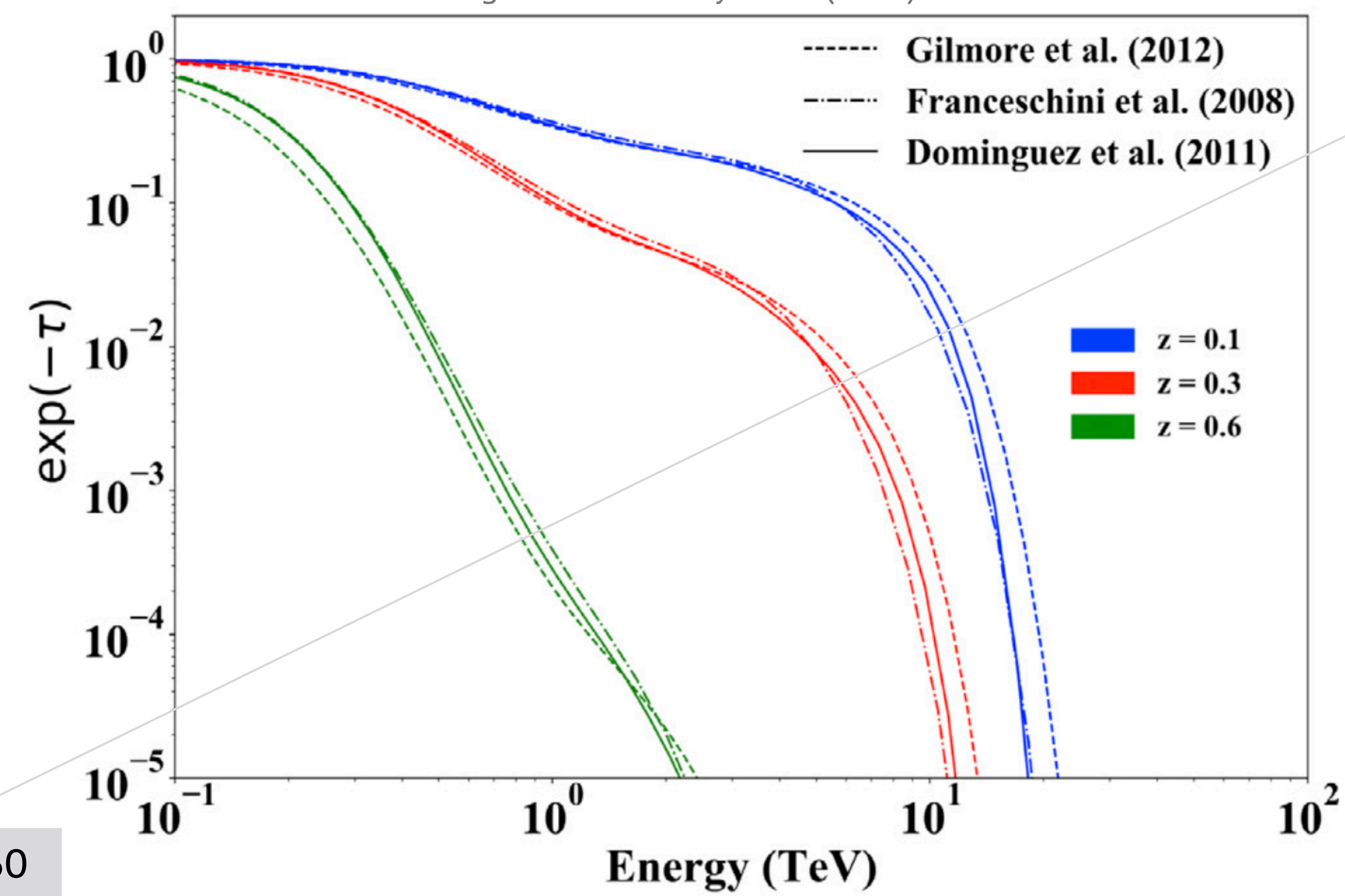

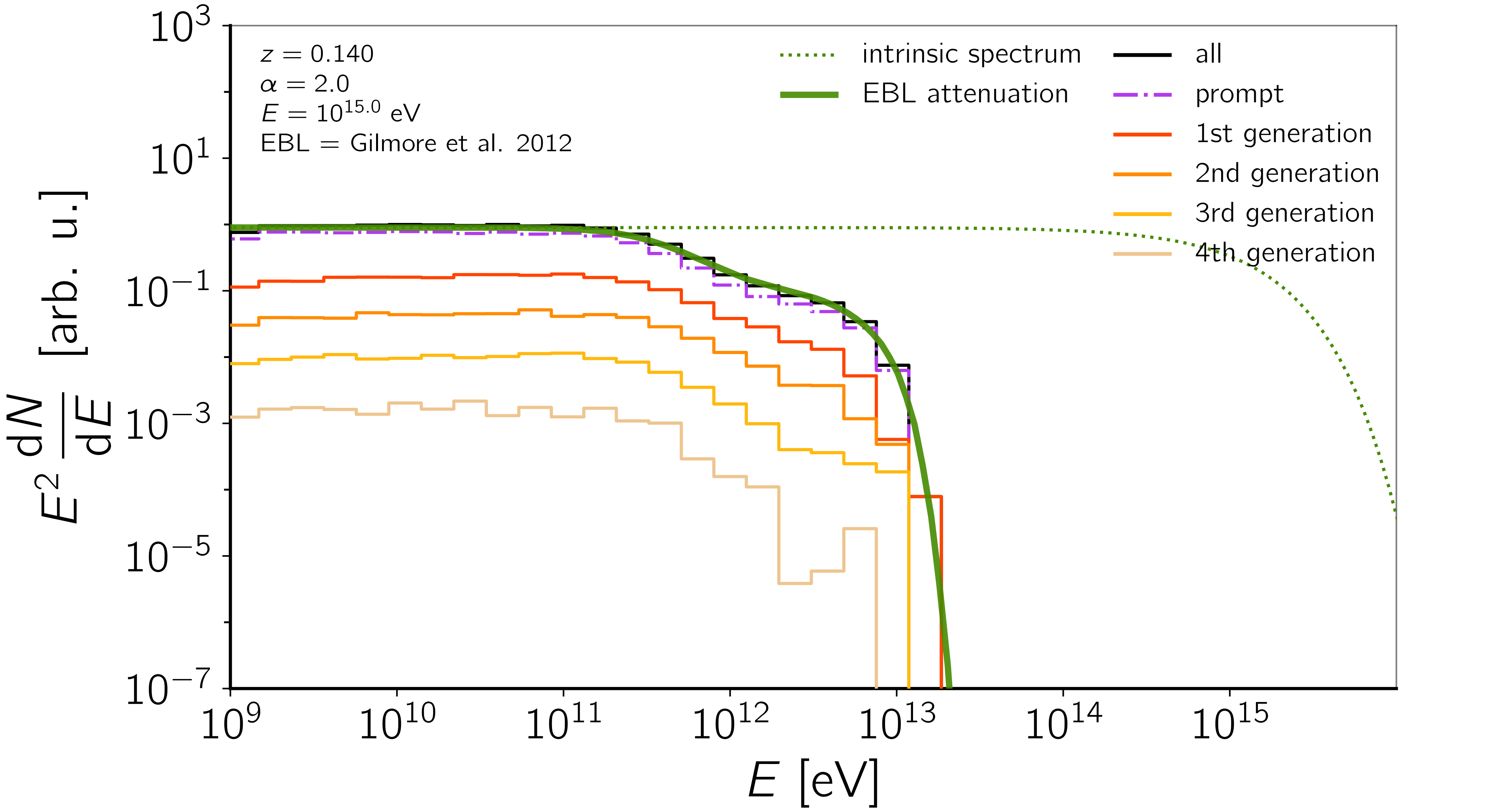

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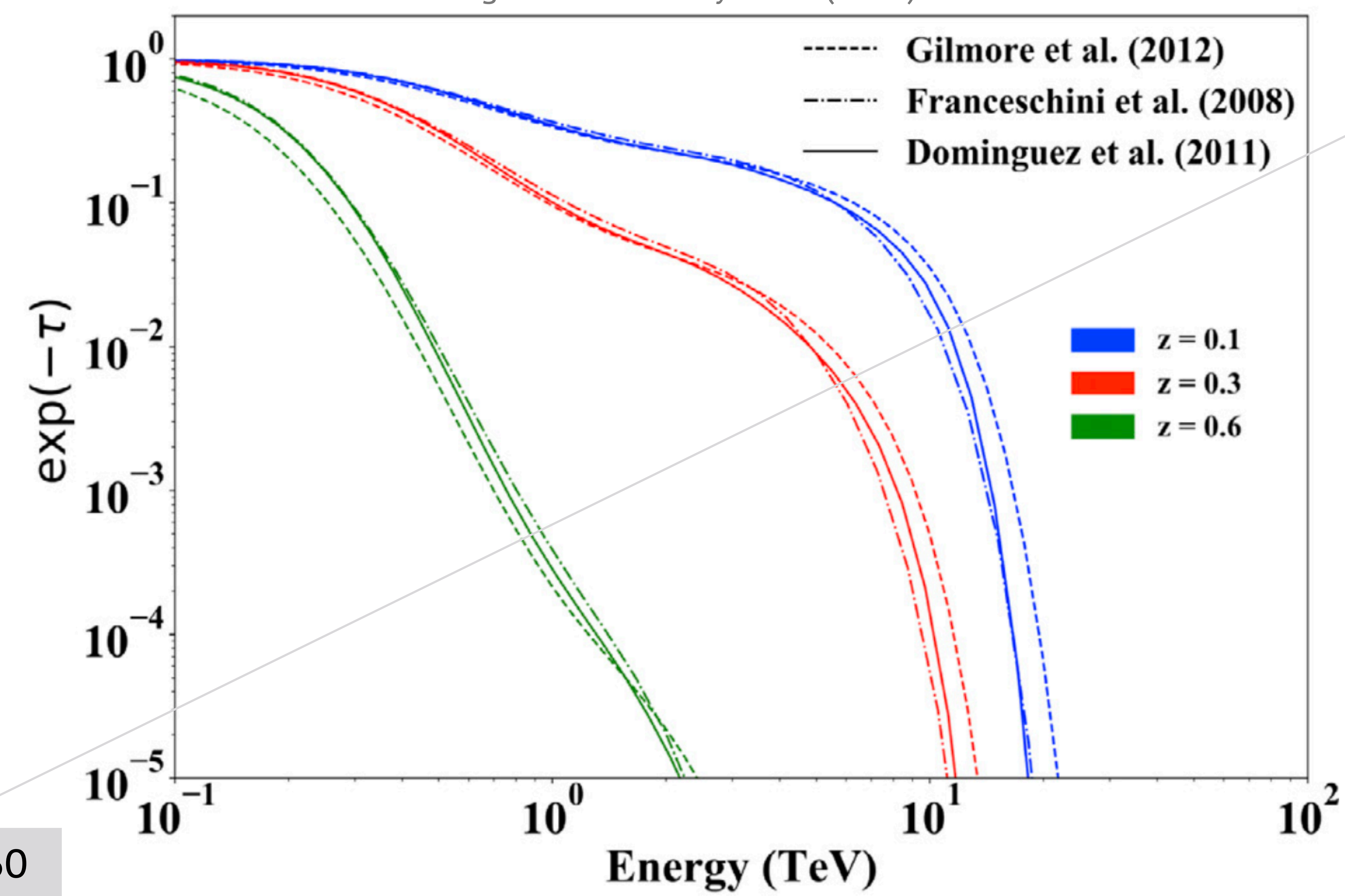

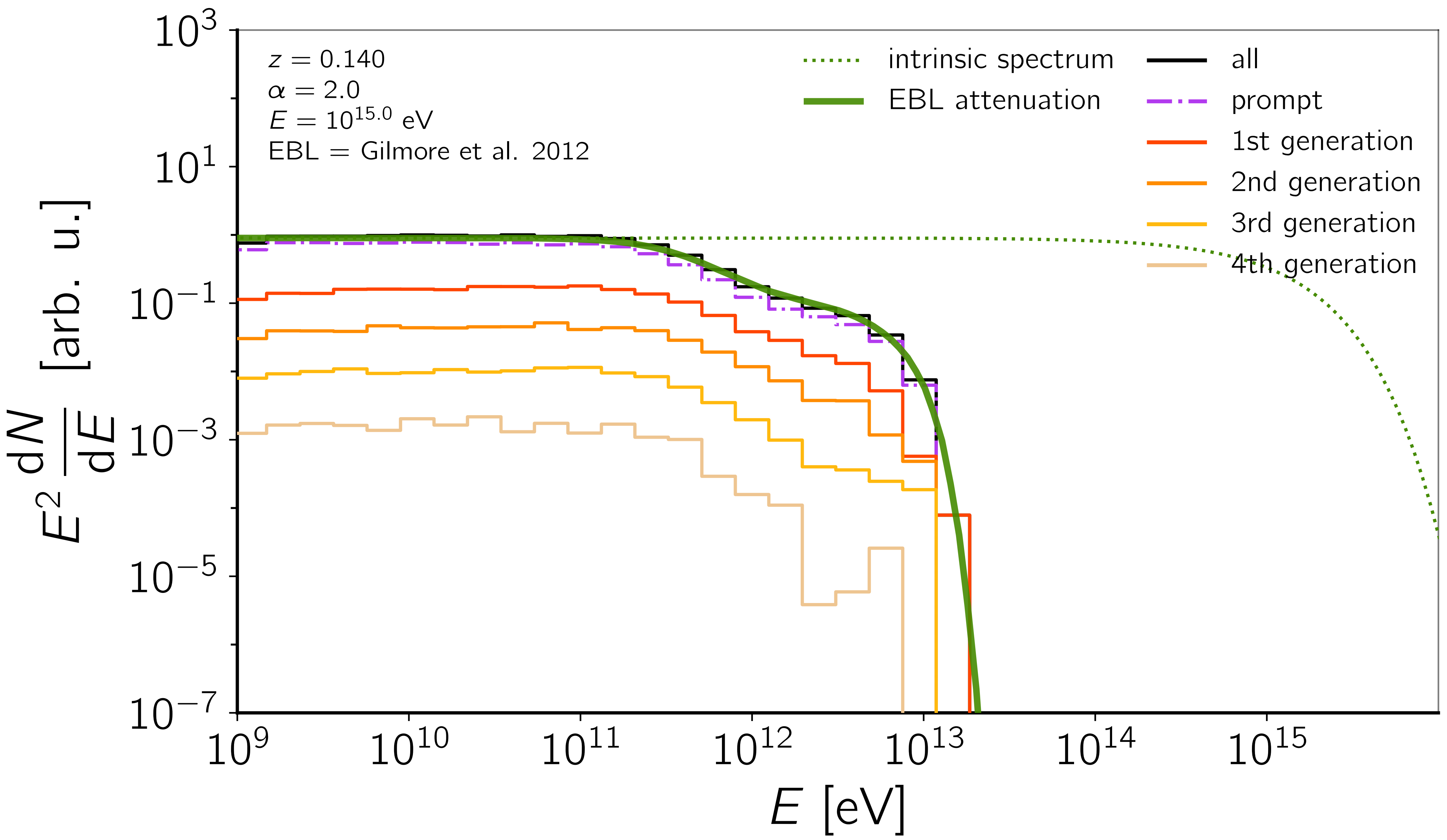

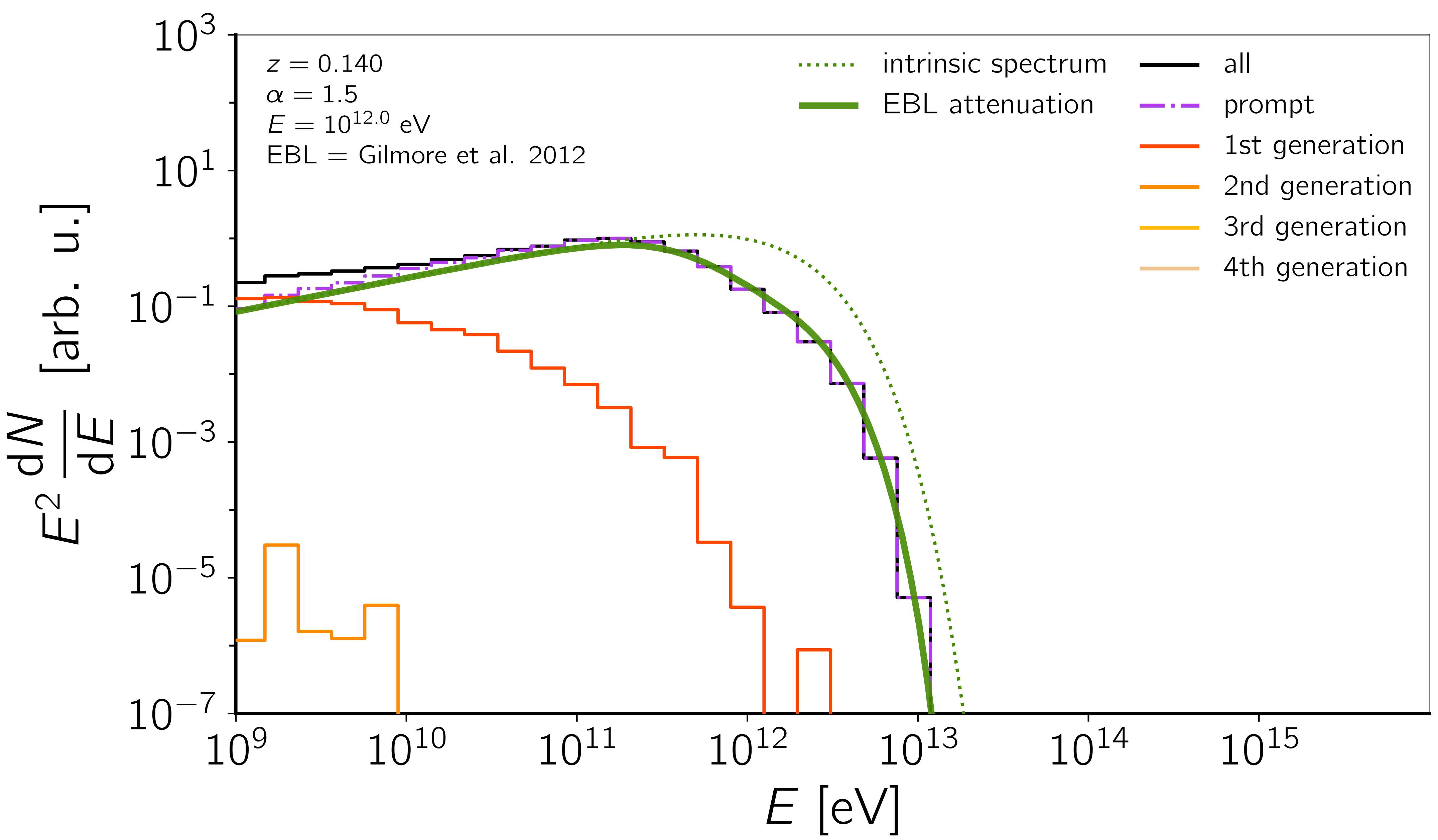

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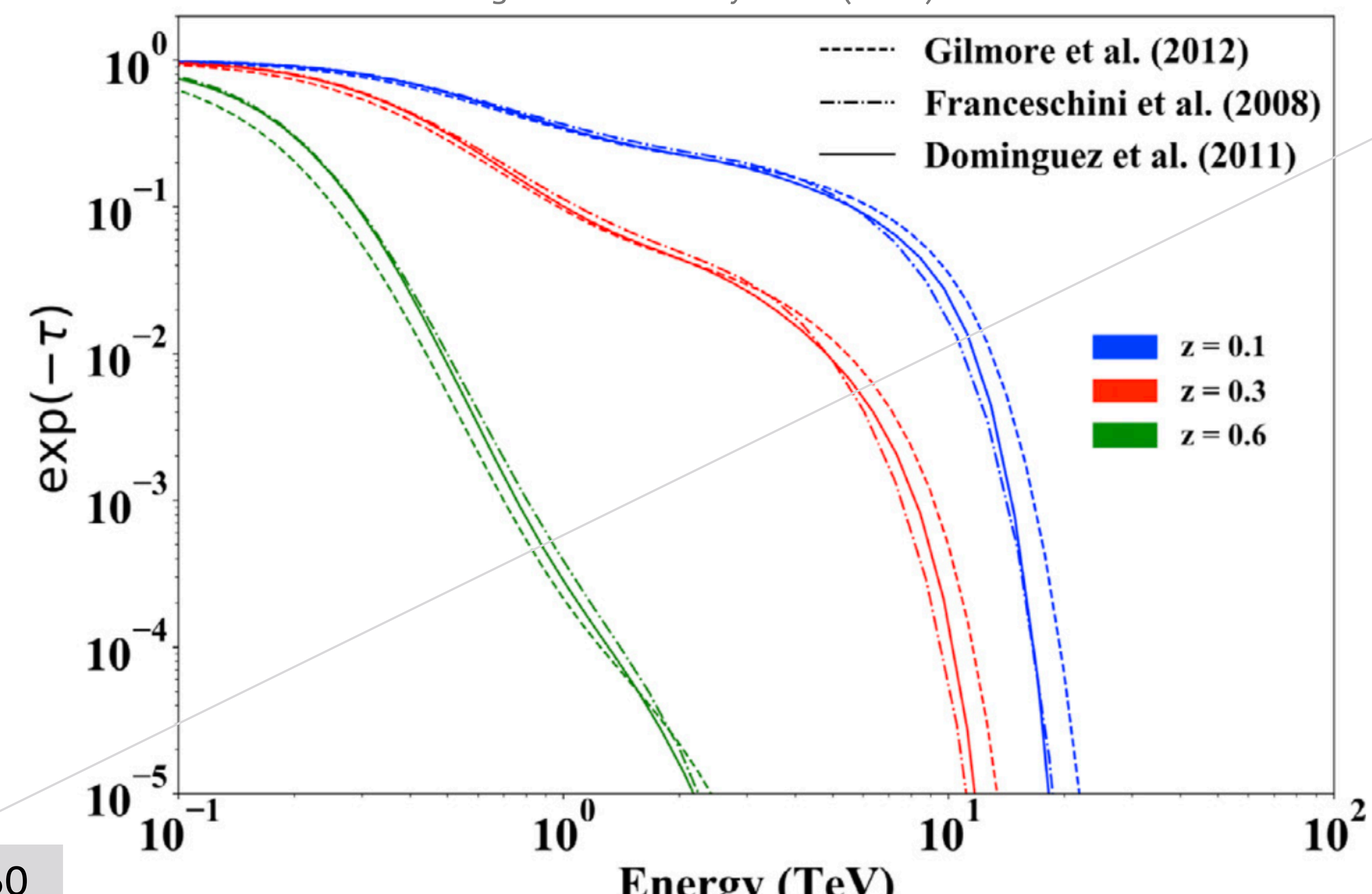

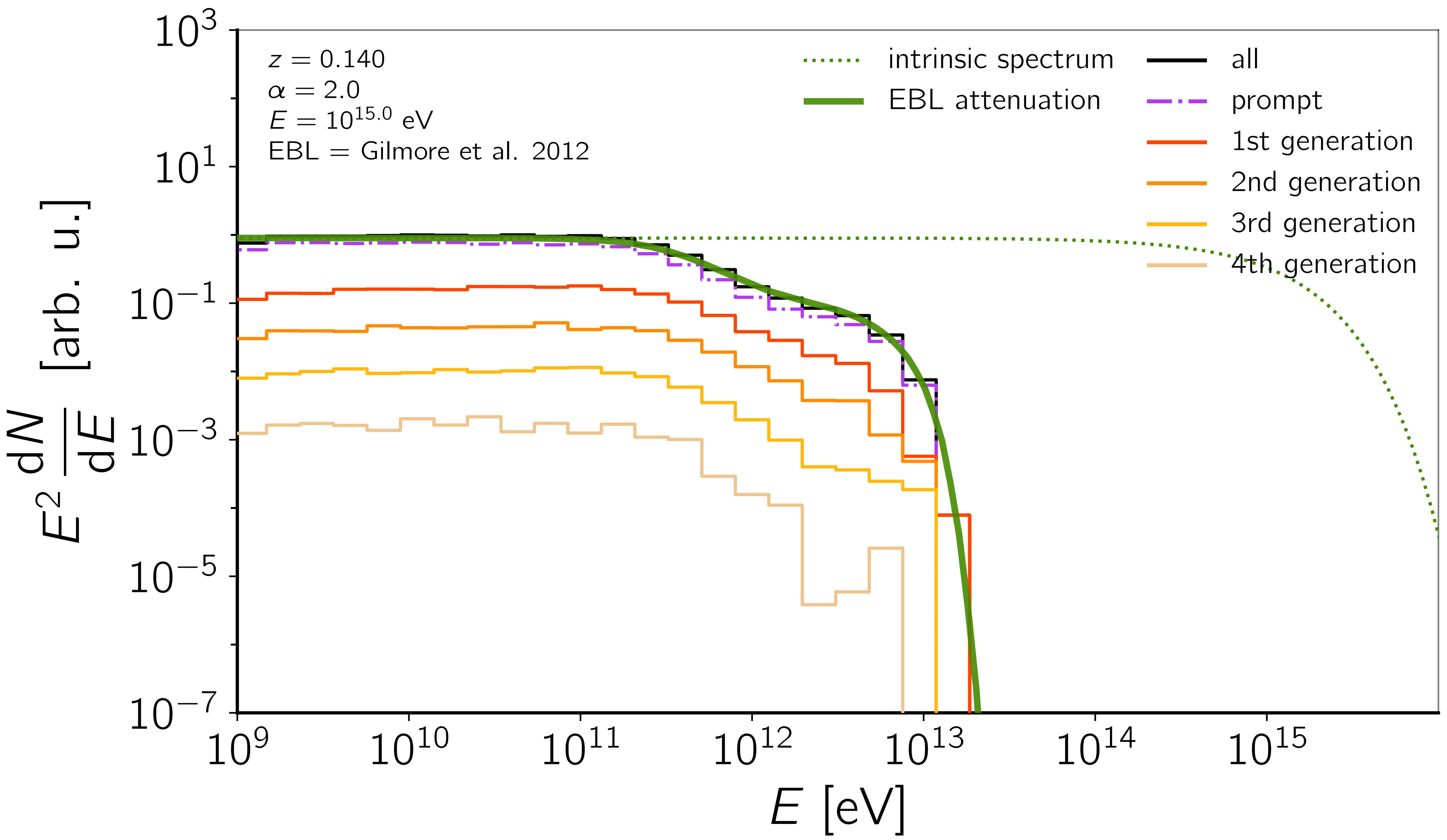

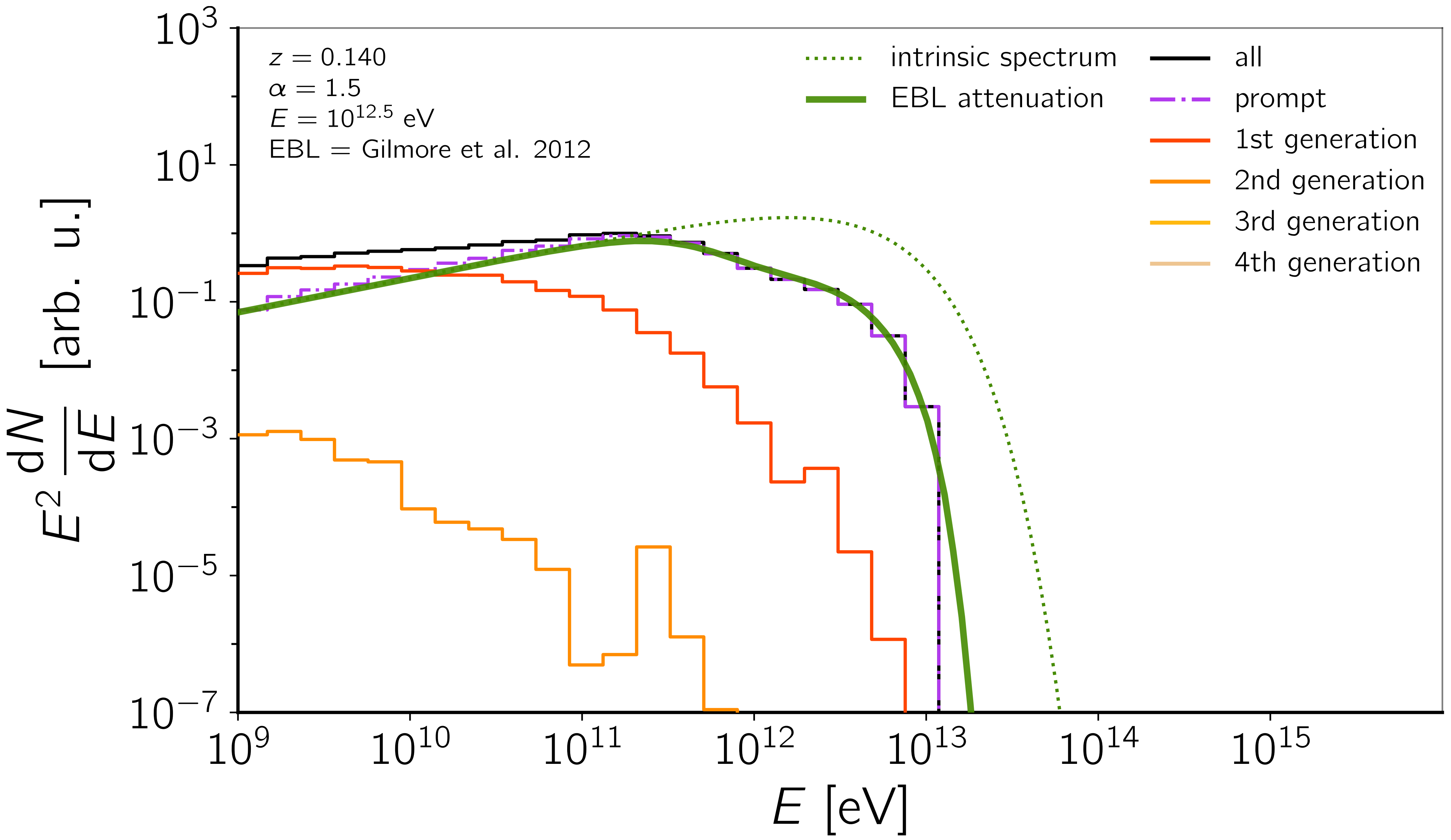

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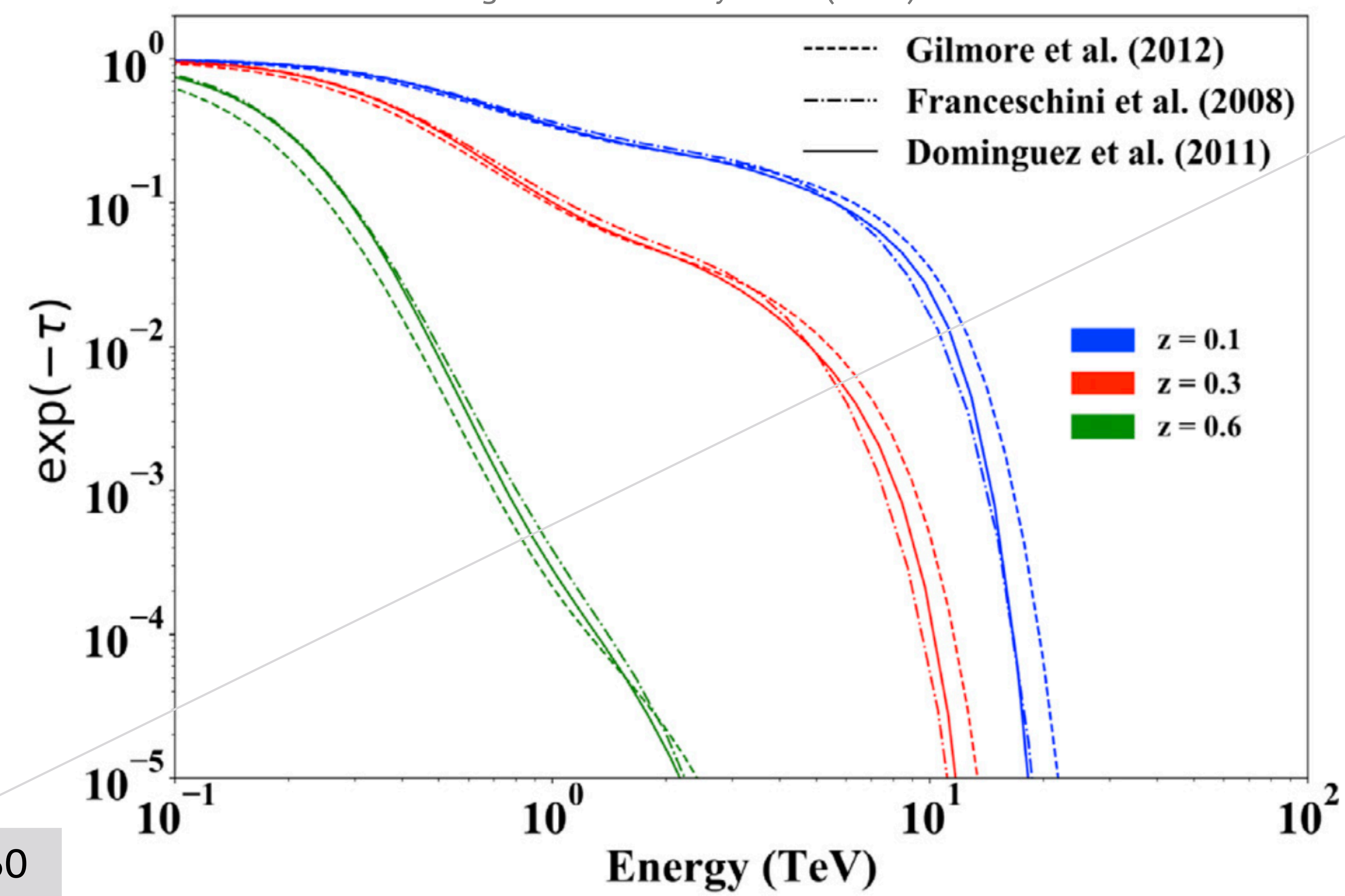

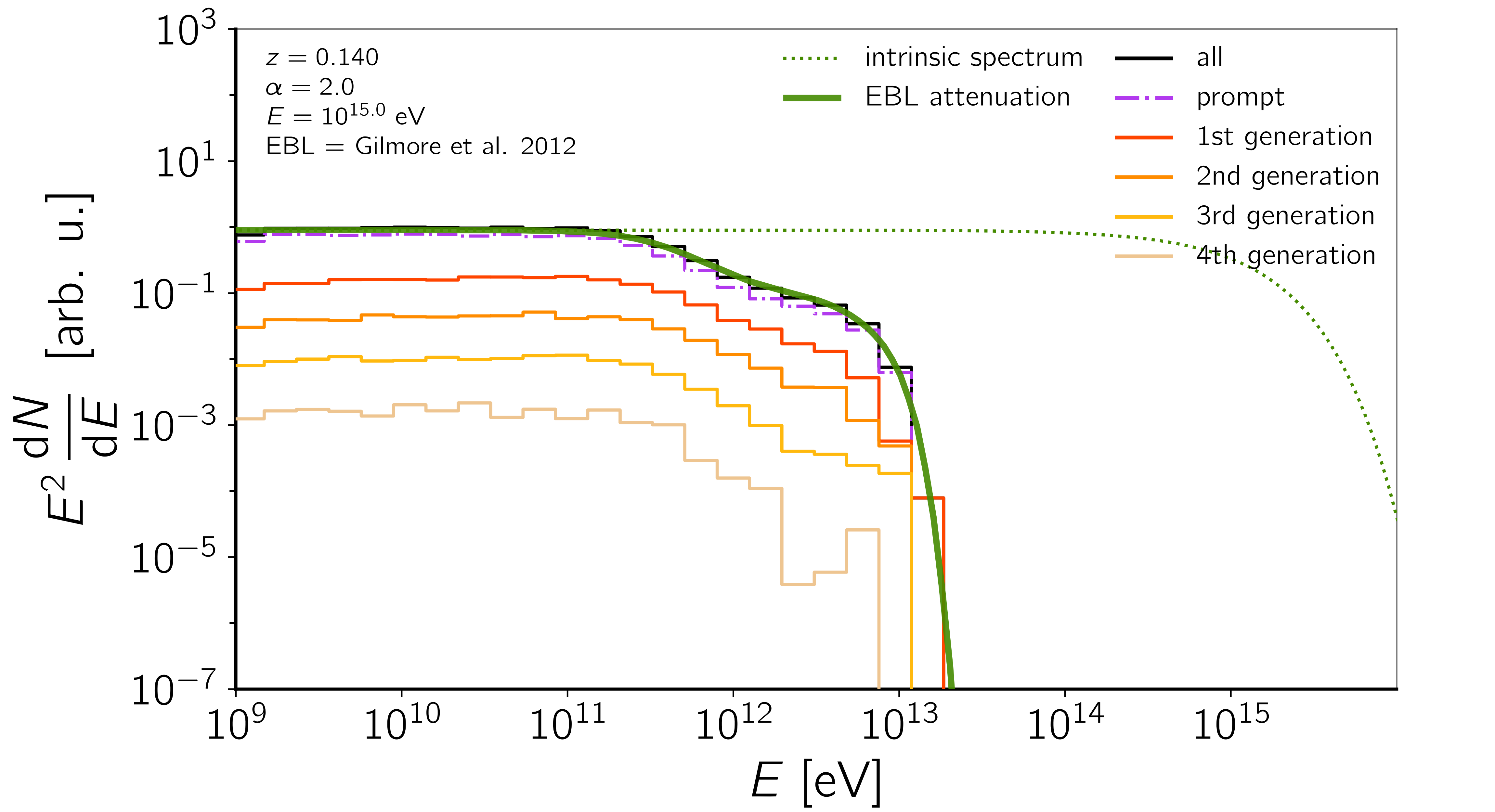

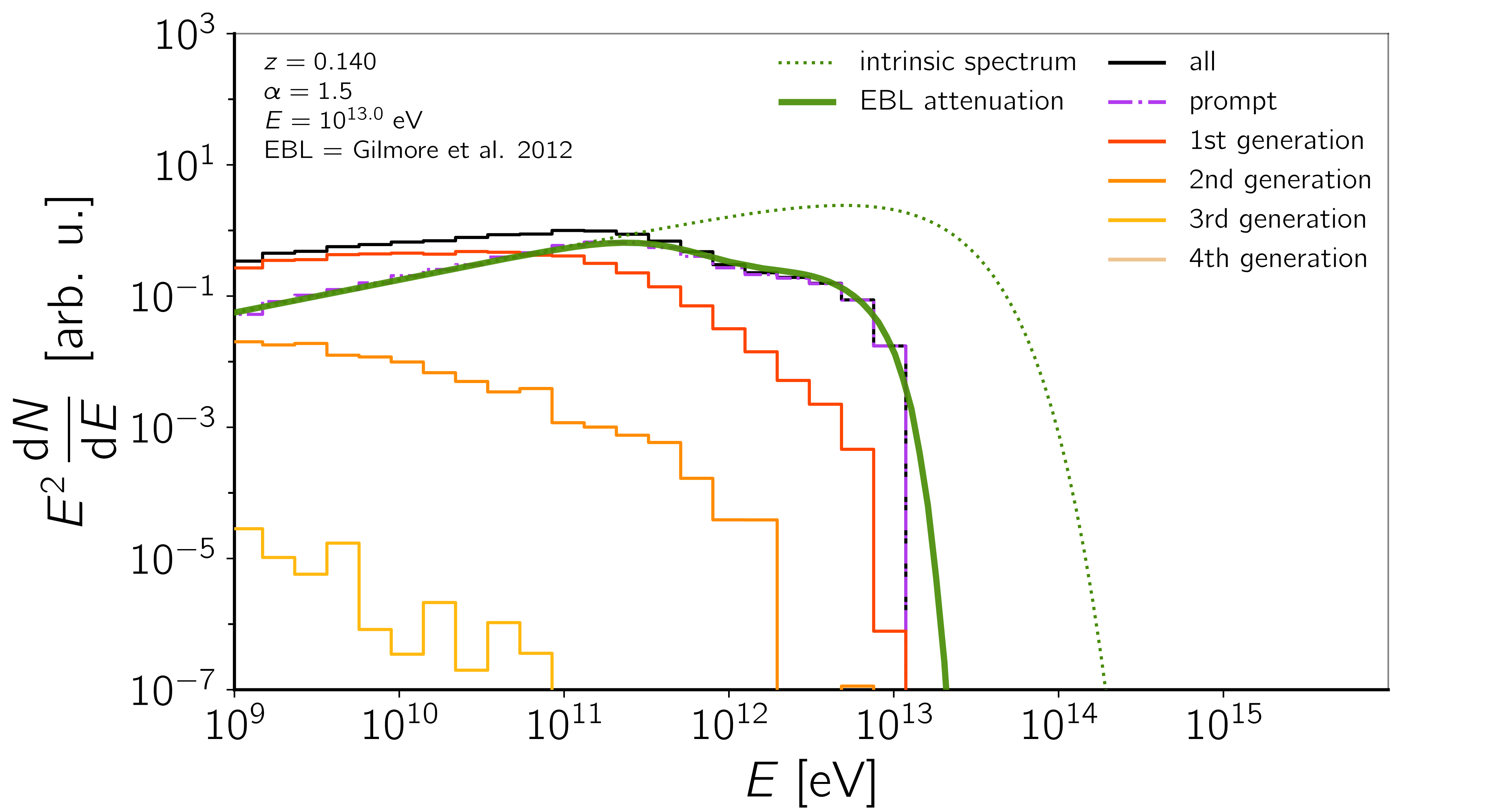

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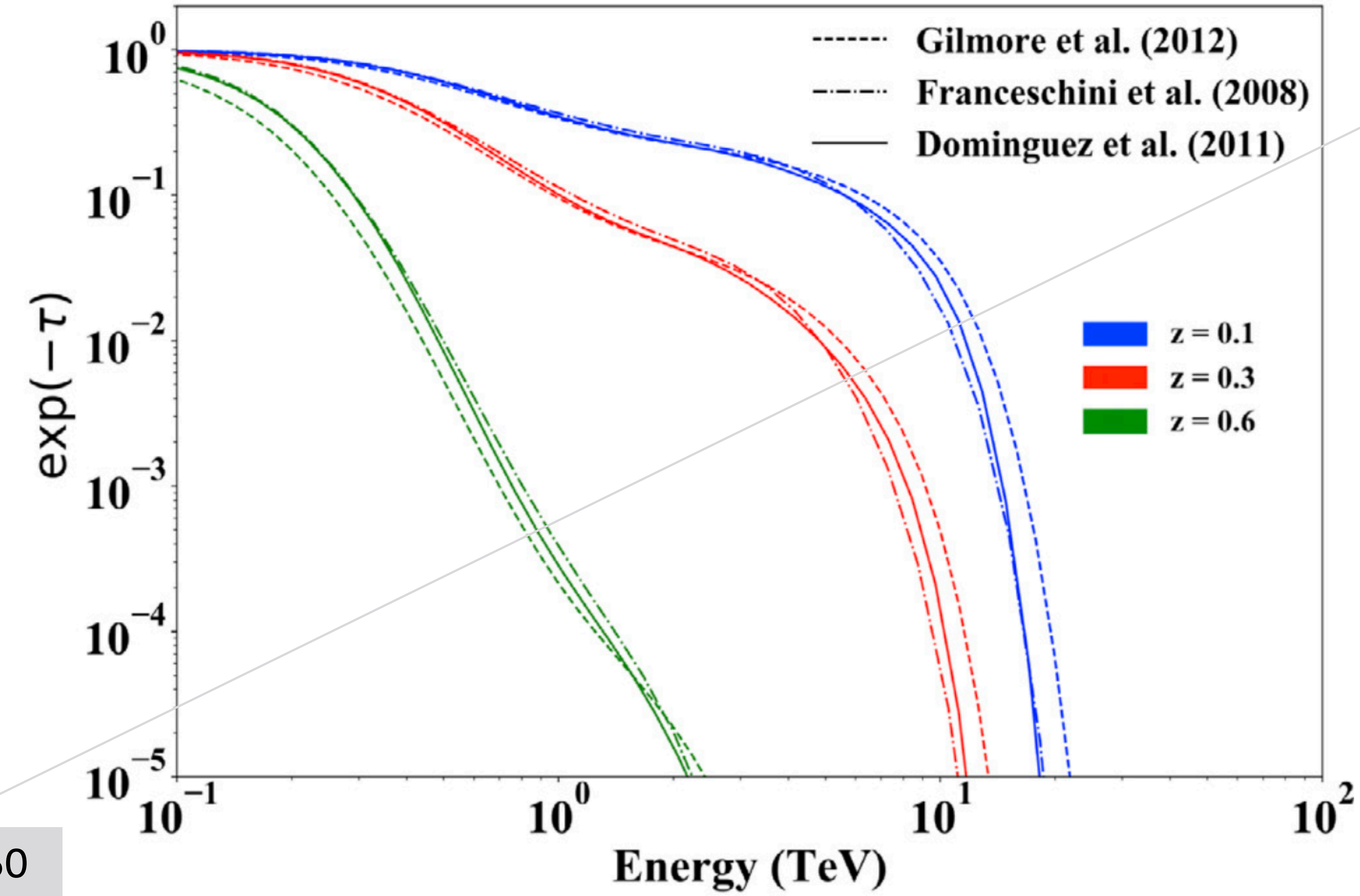

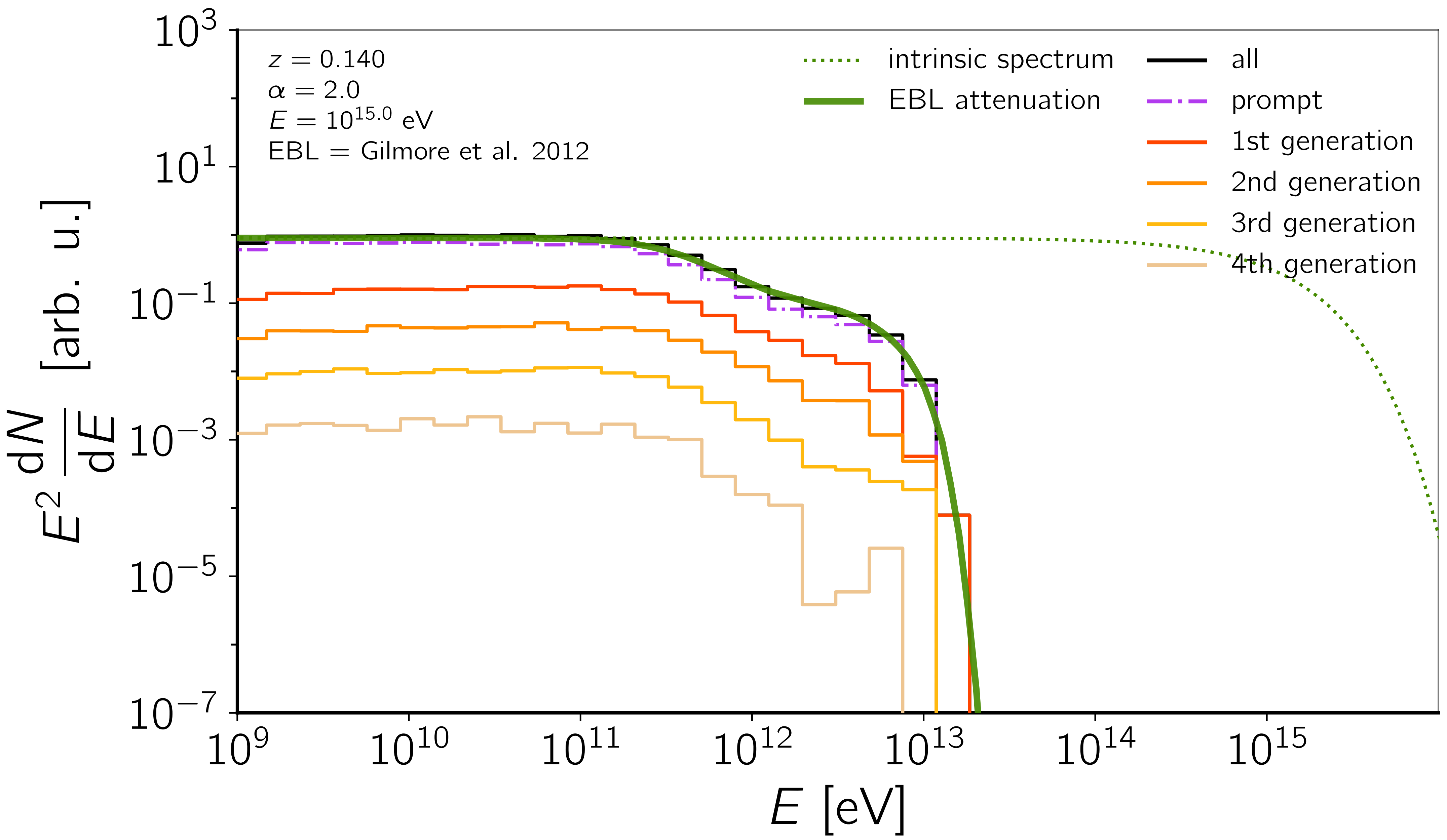

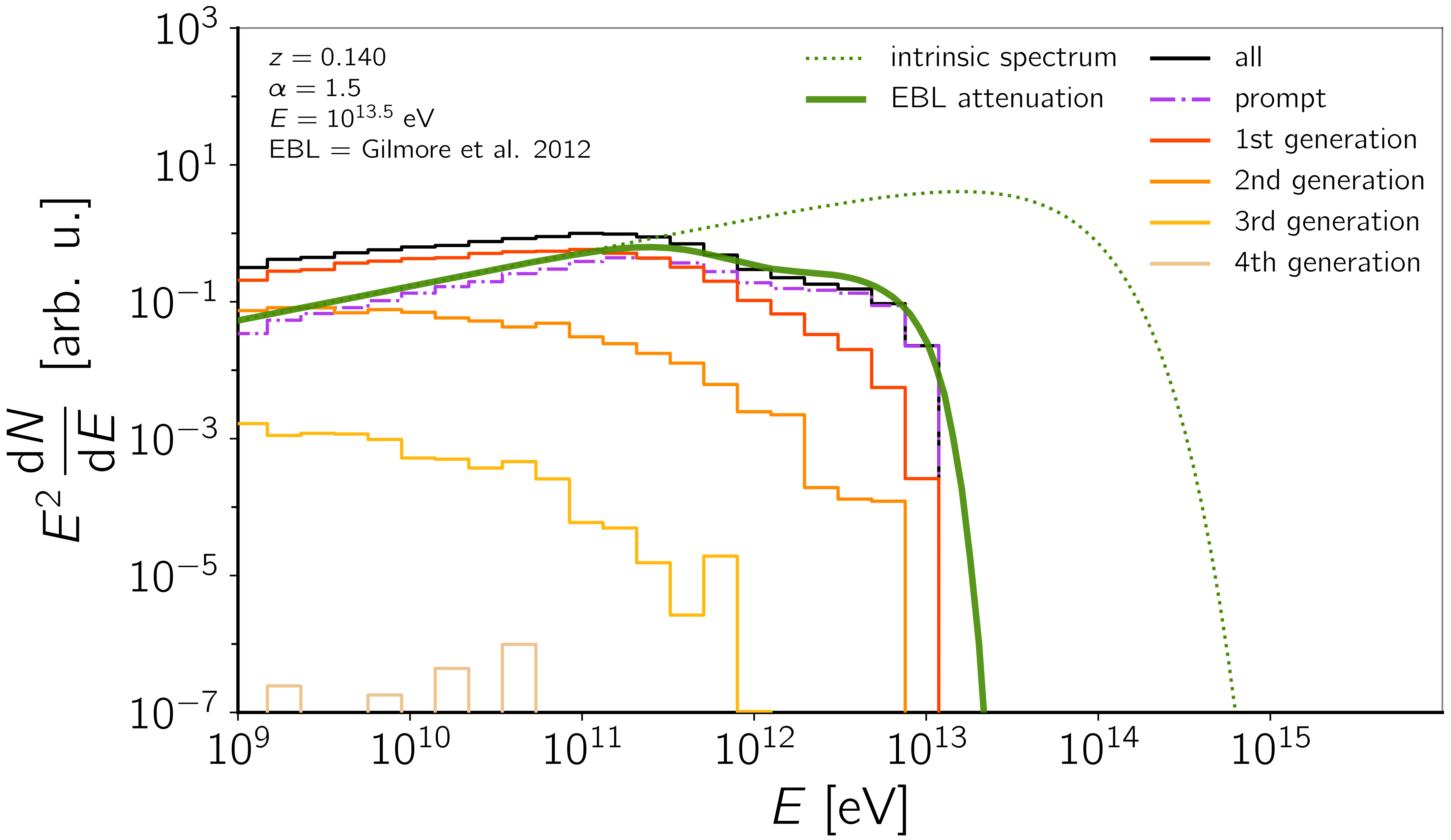

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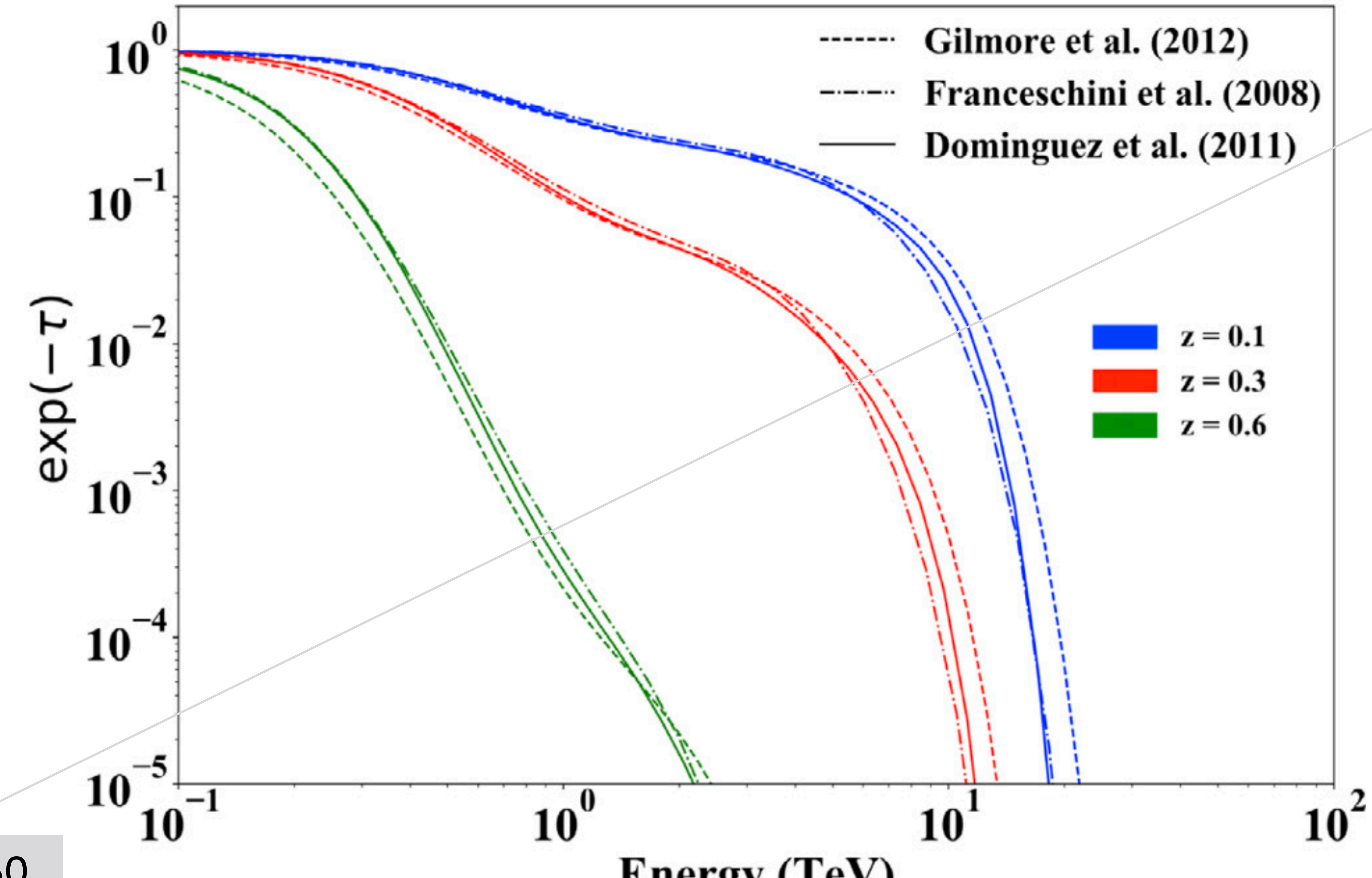

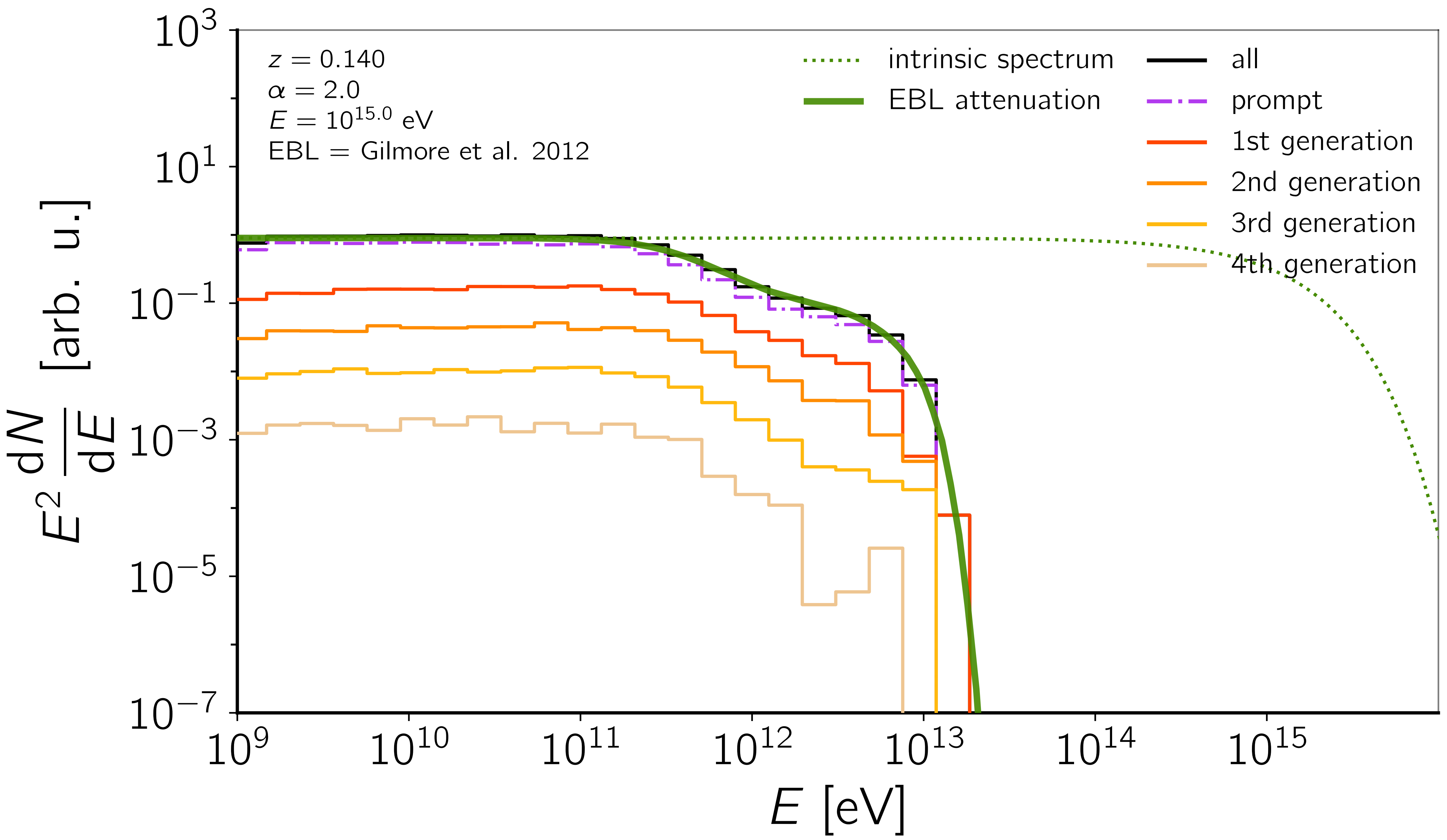

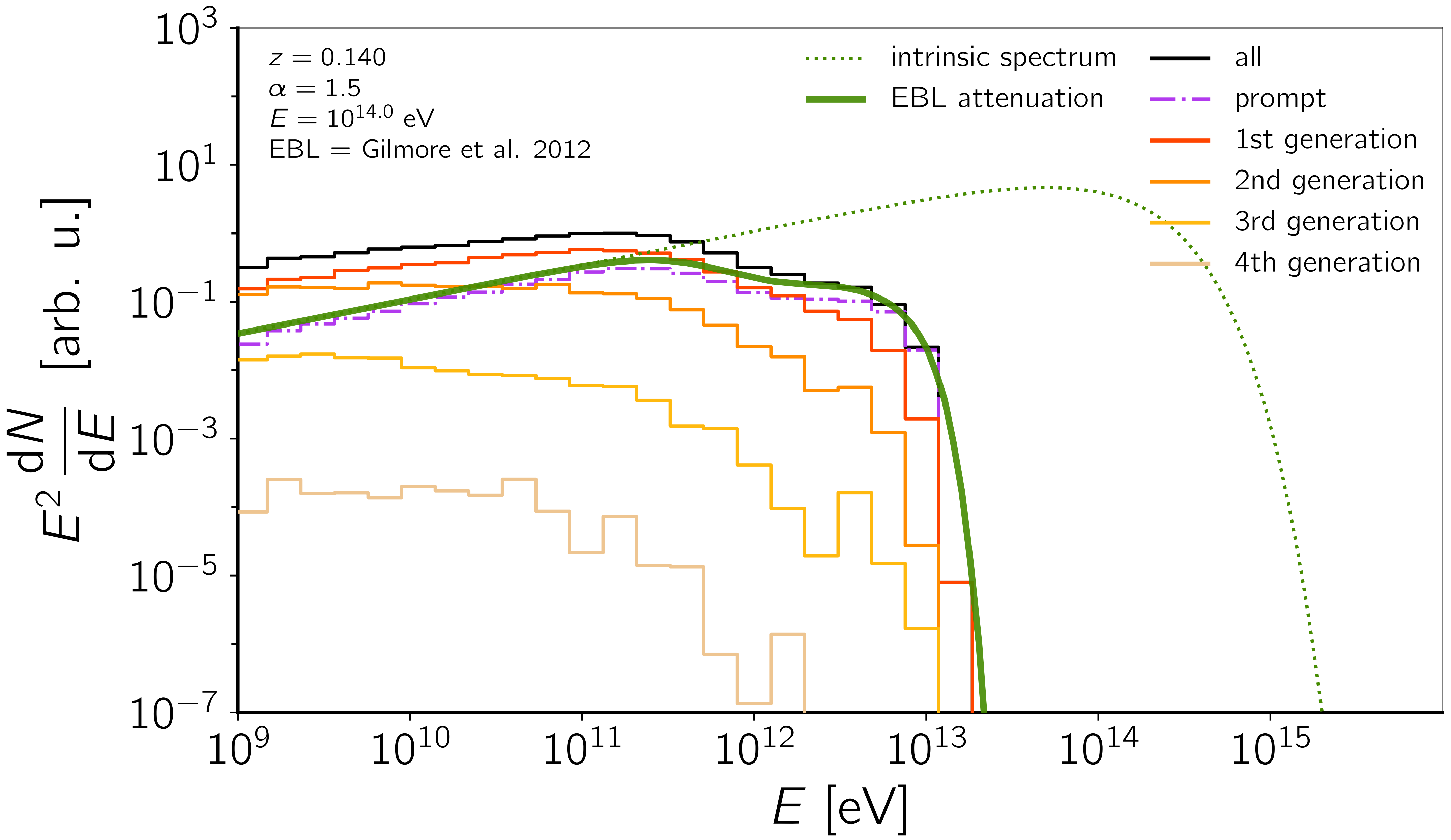

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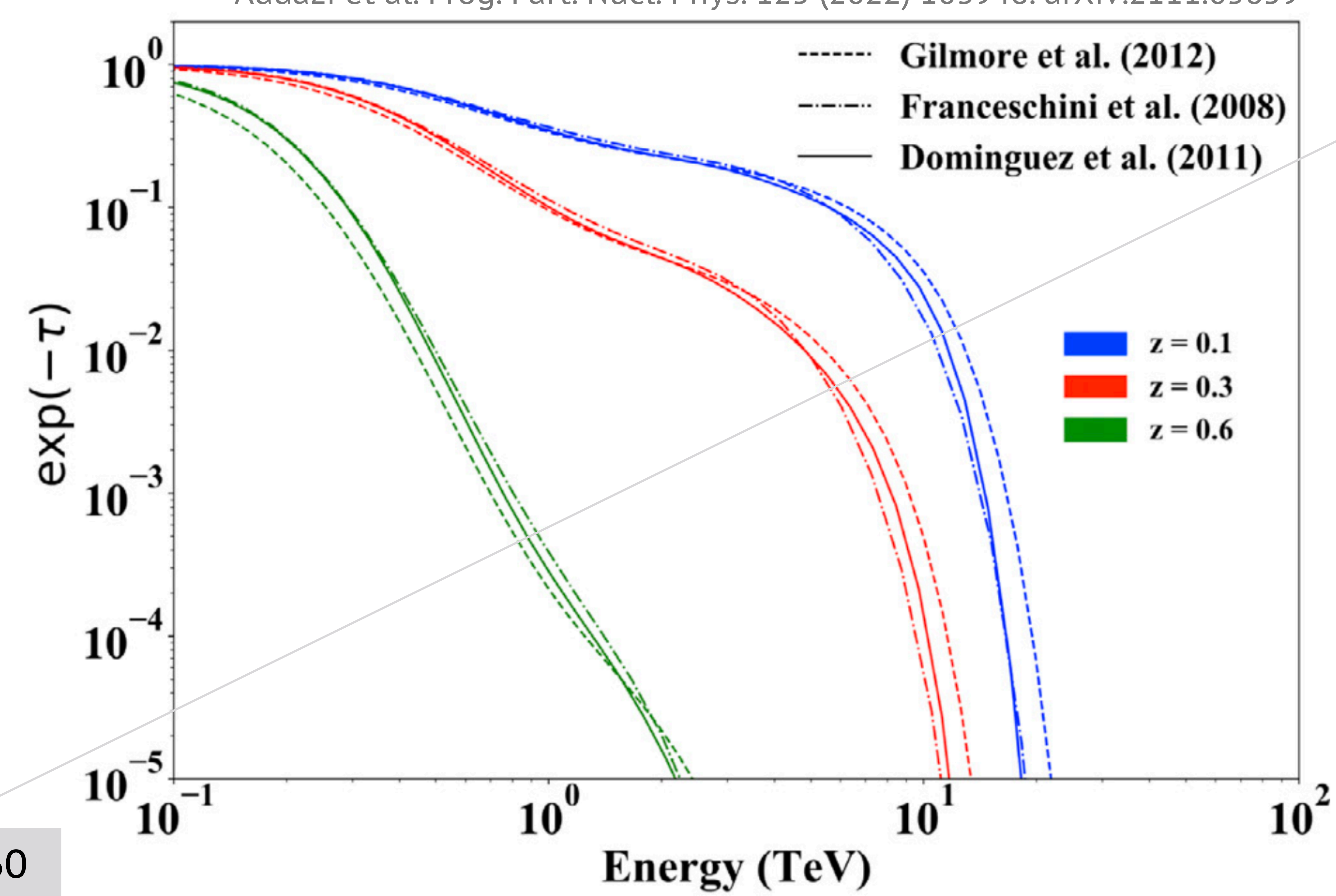

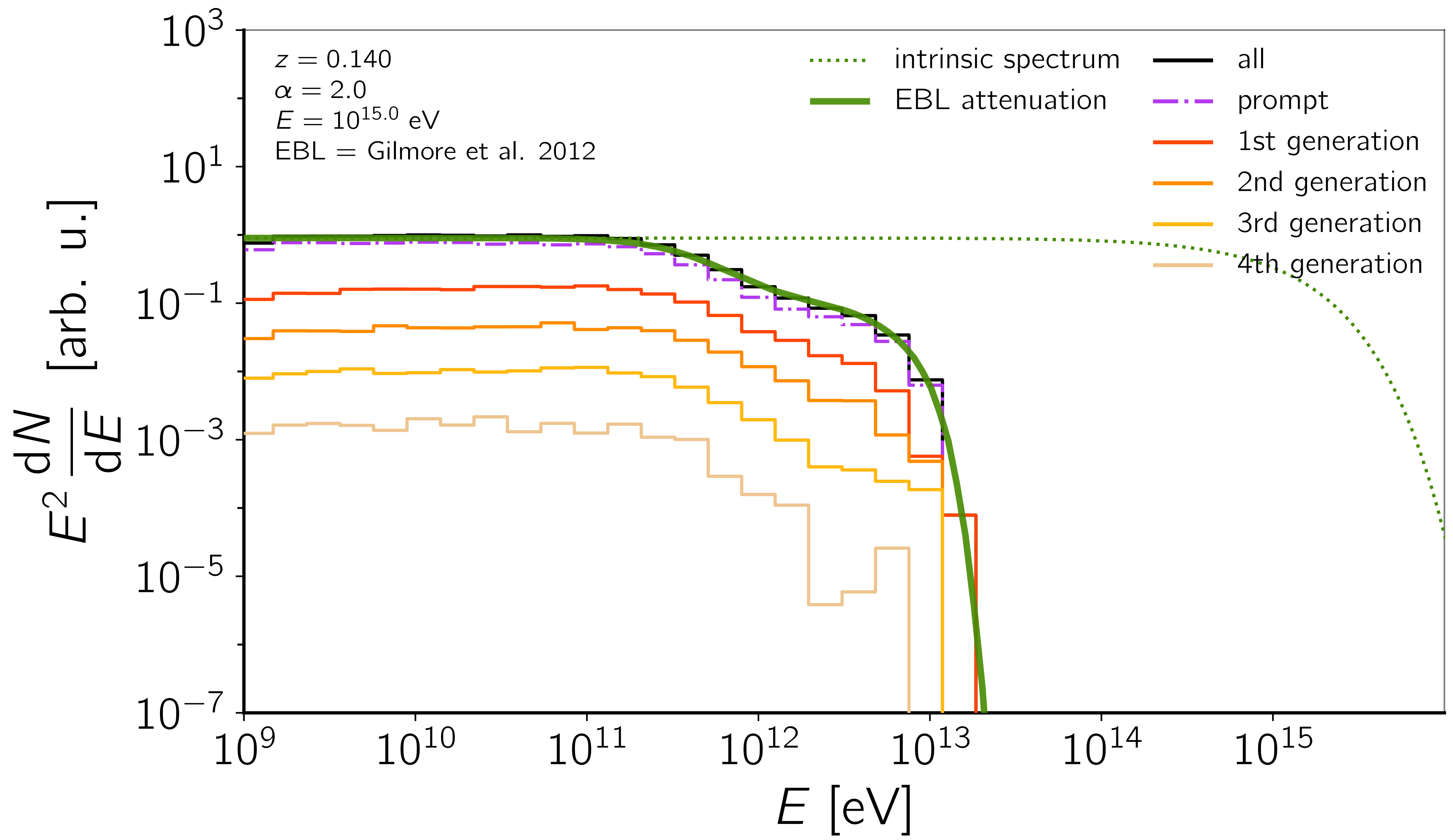

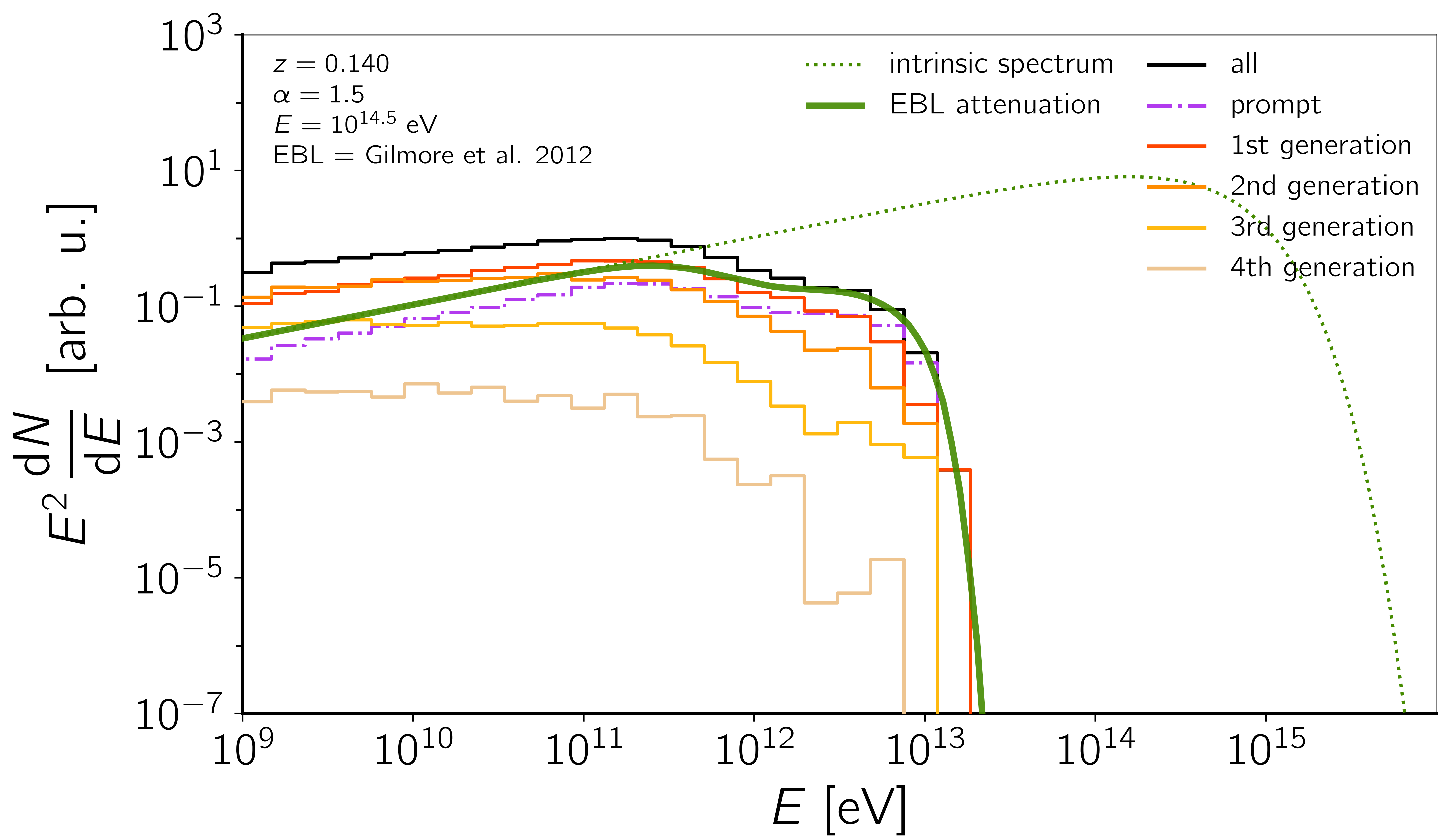

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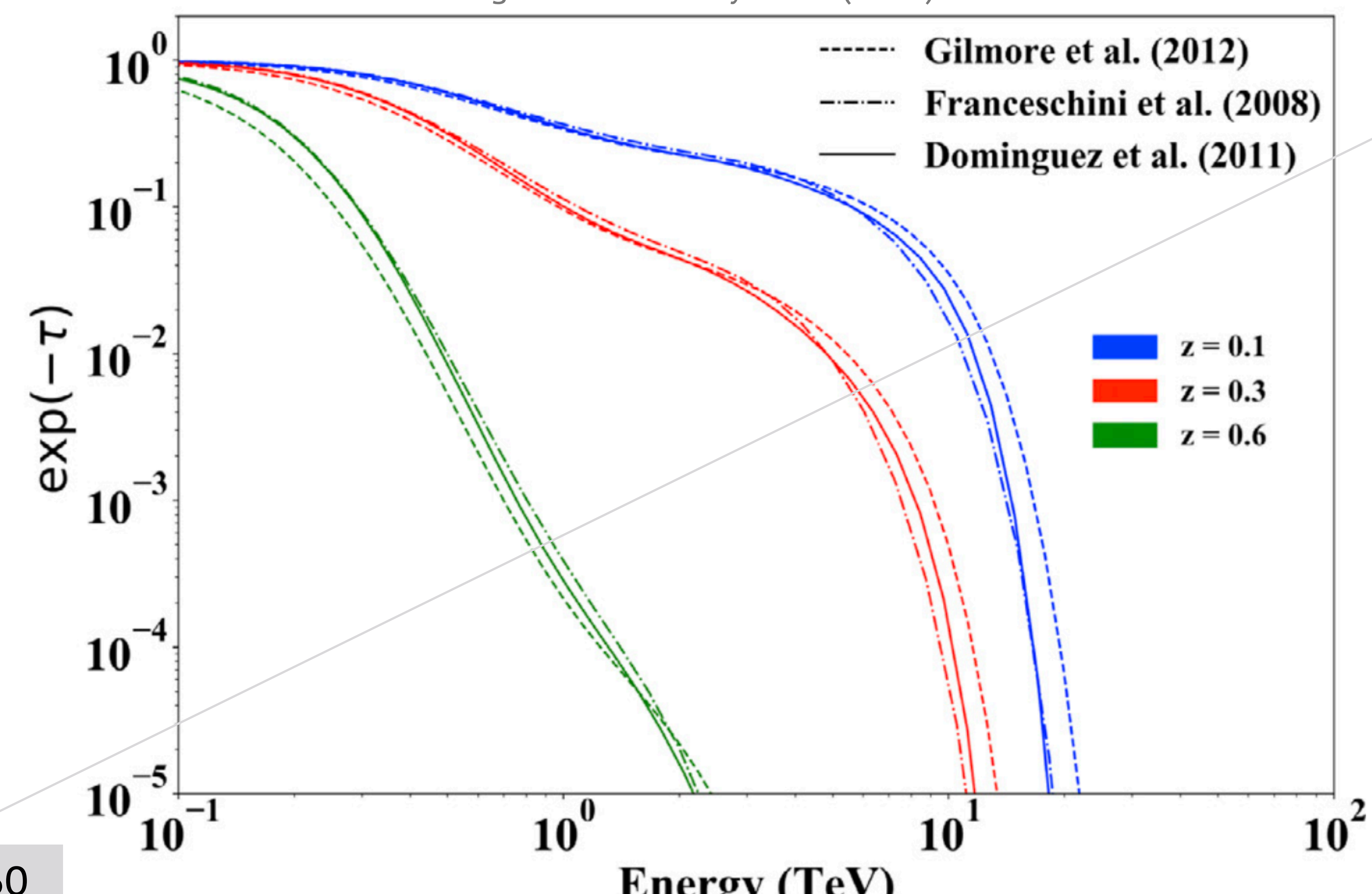
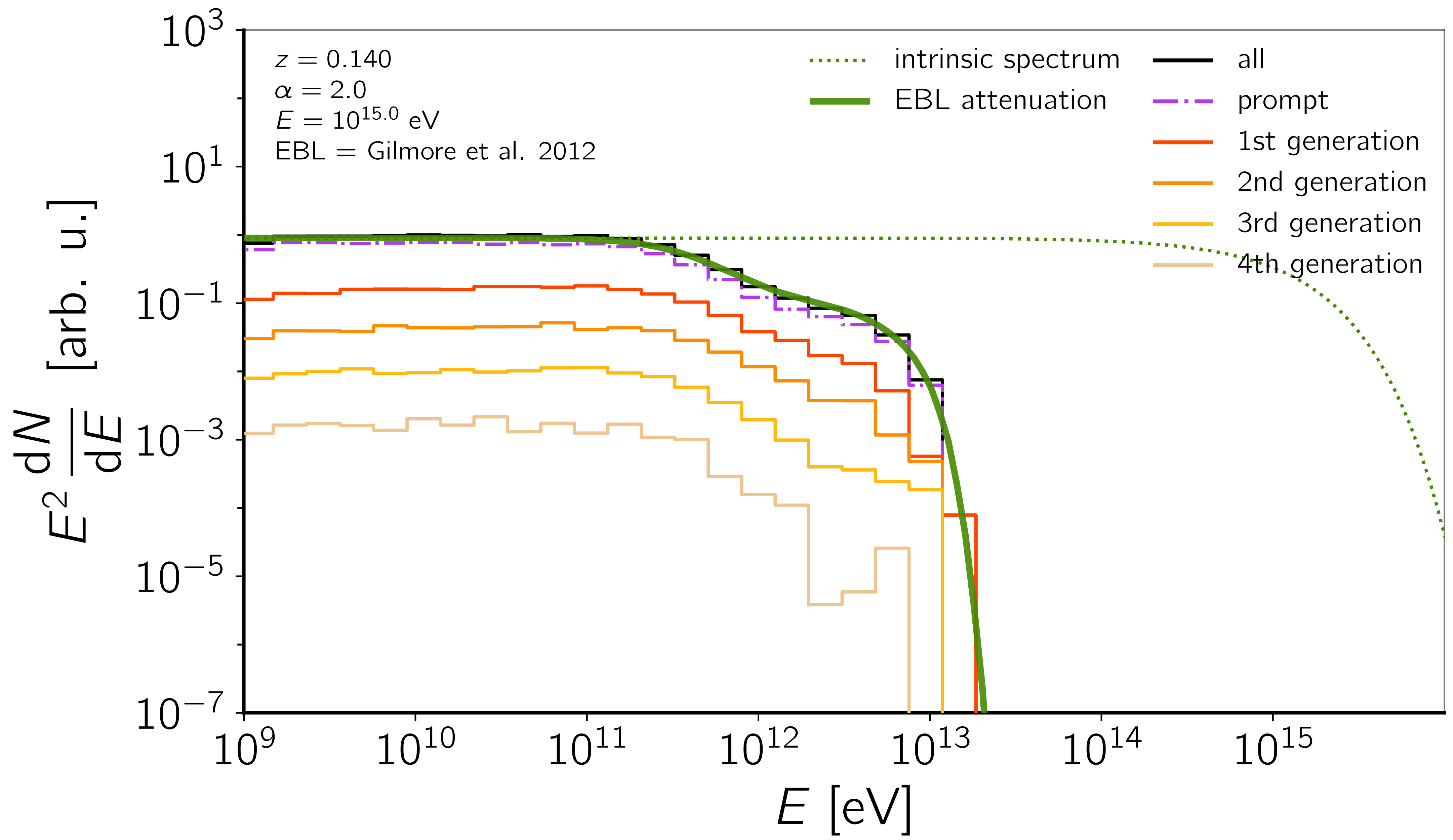
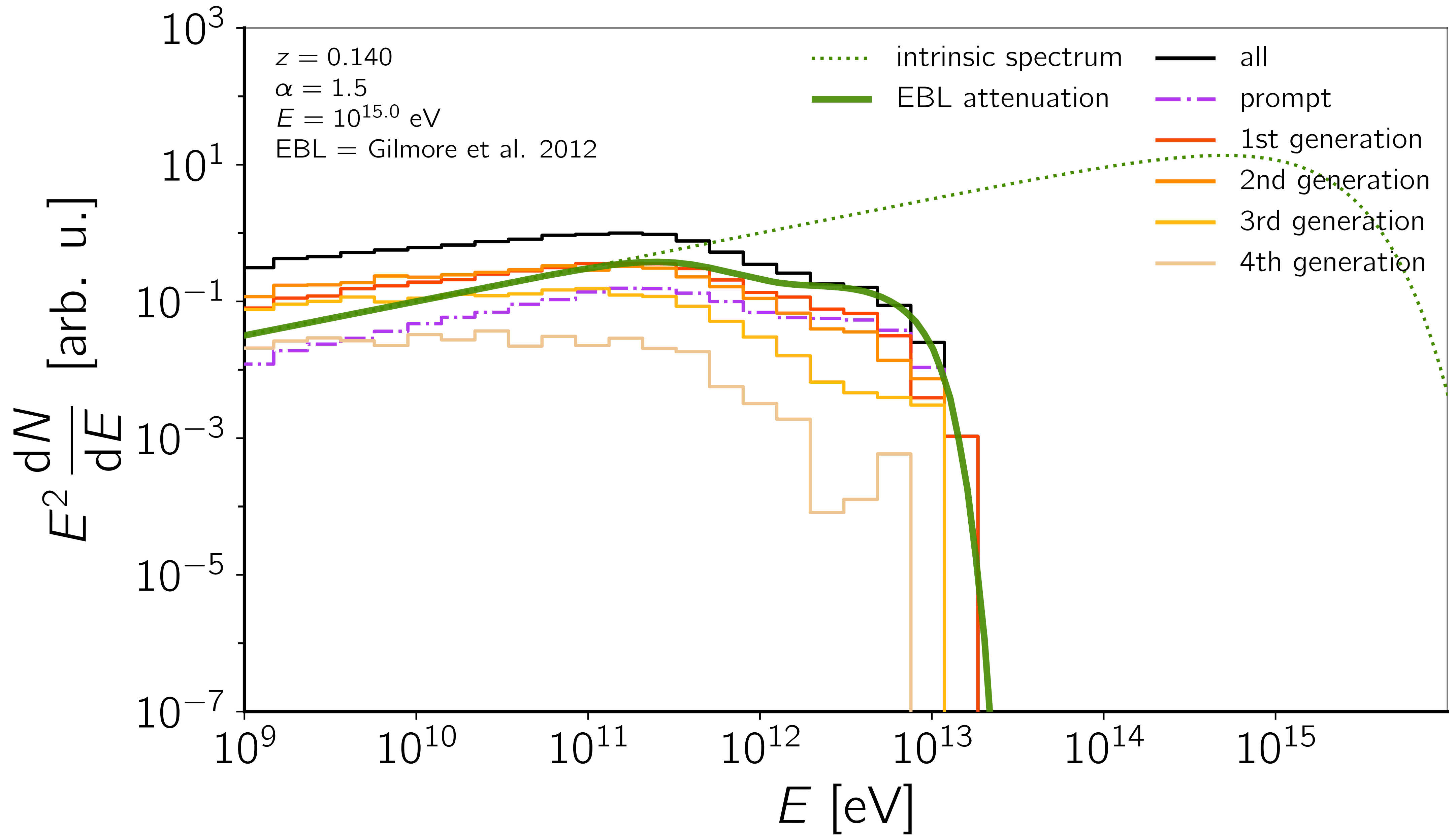
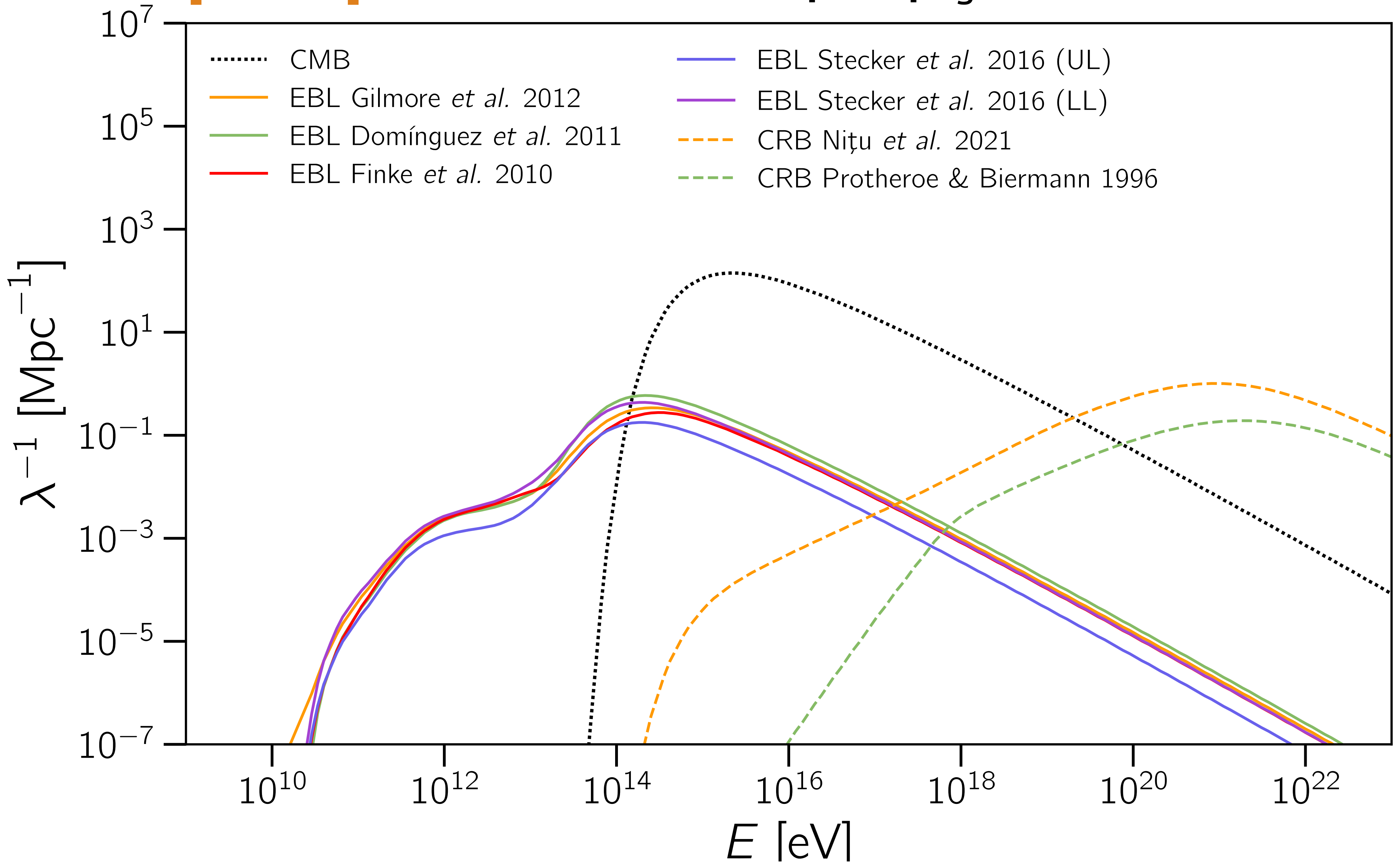




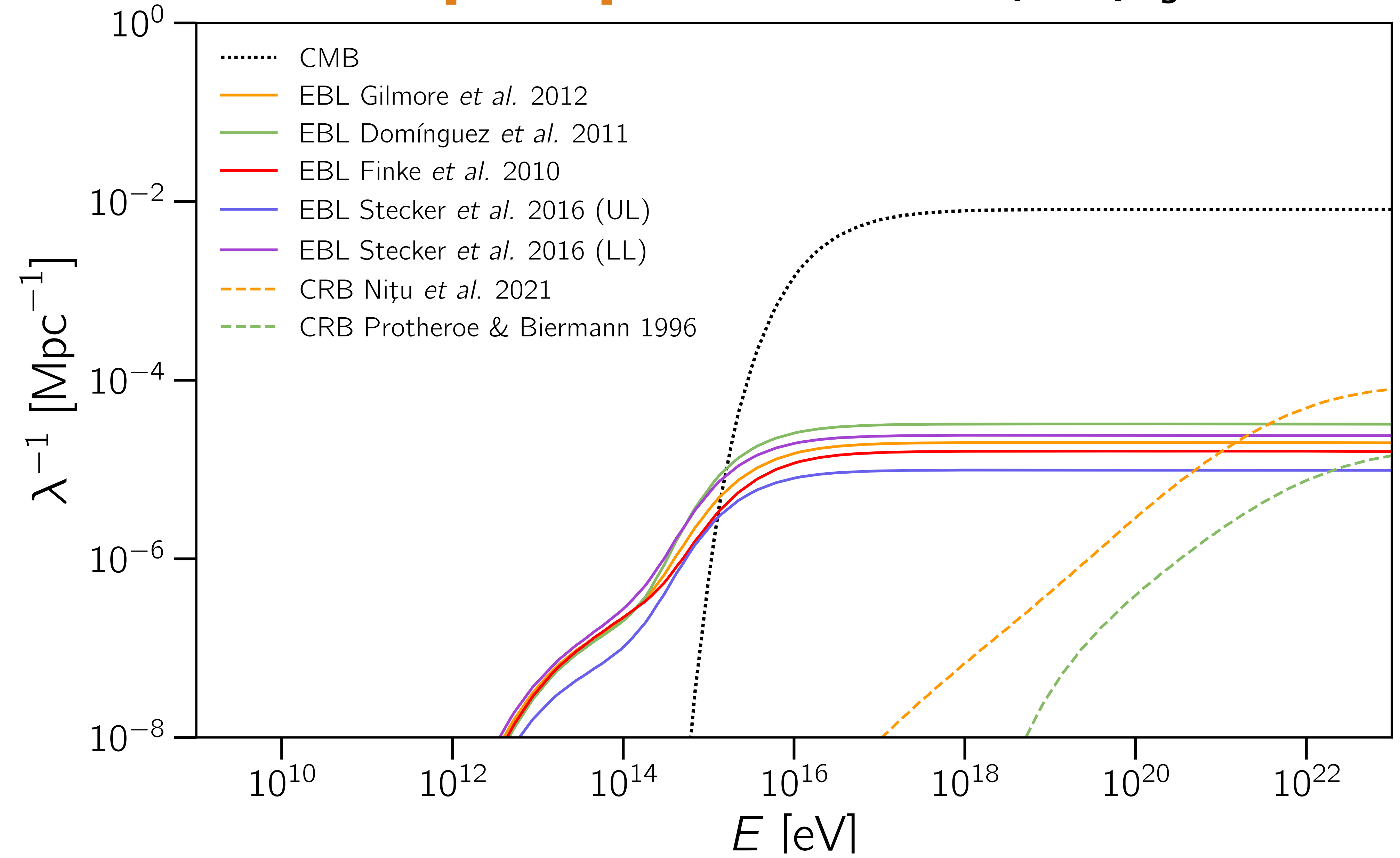


gamma rays. interactions during cosmological propagation

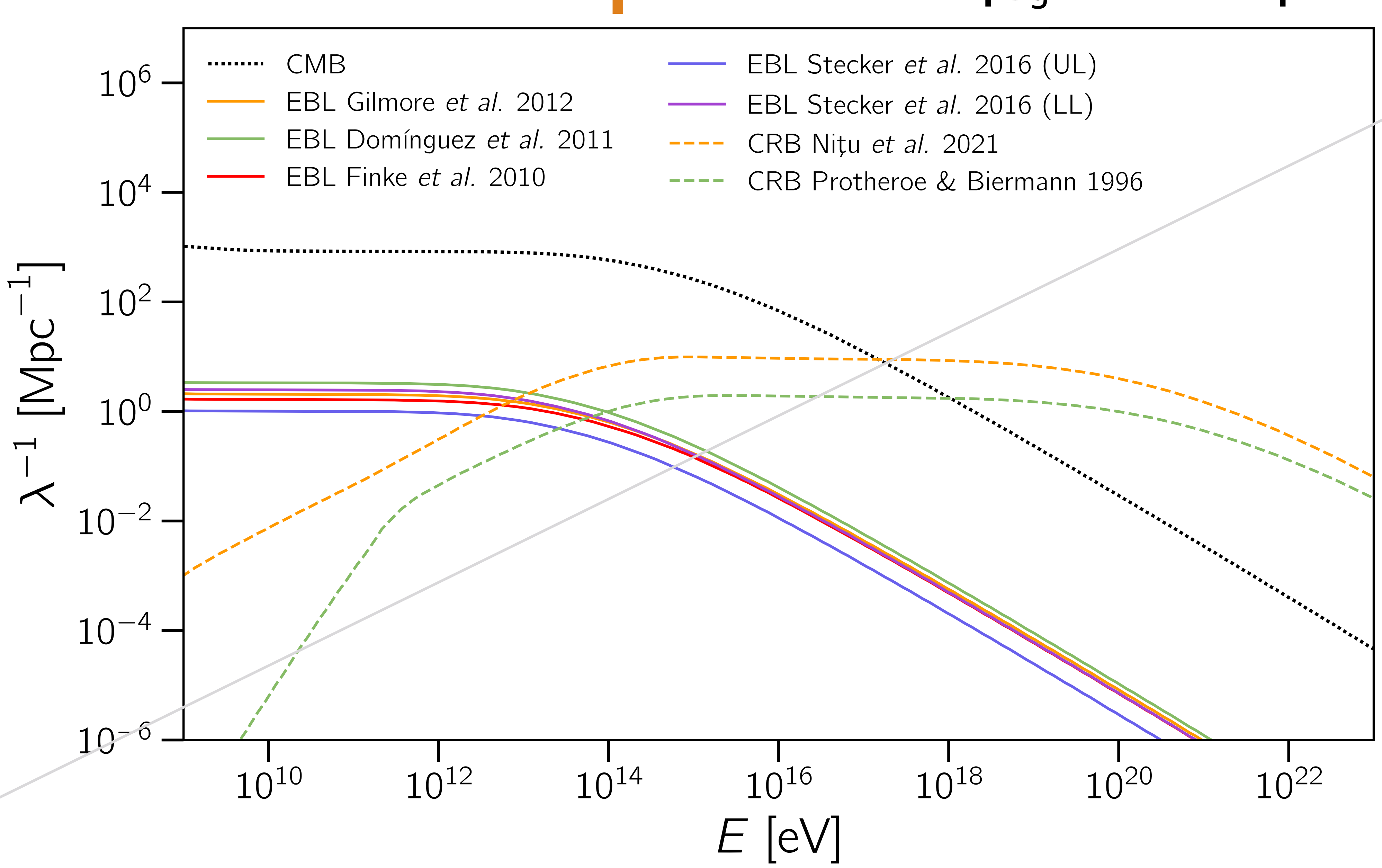
pair production $\gamma + \gamma_{bg} \rightarrow e^- + e^+$



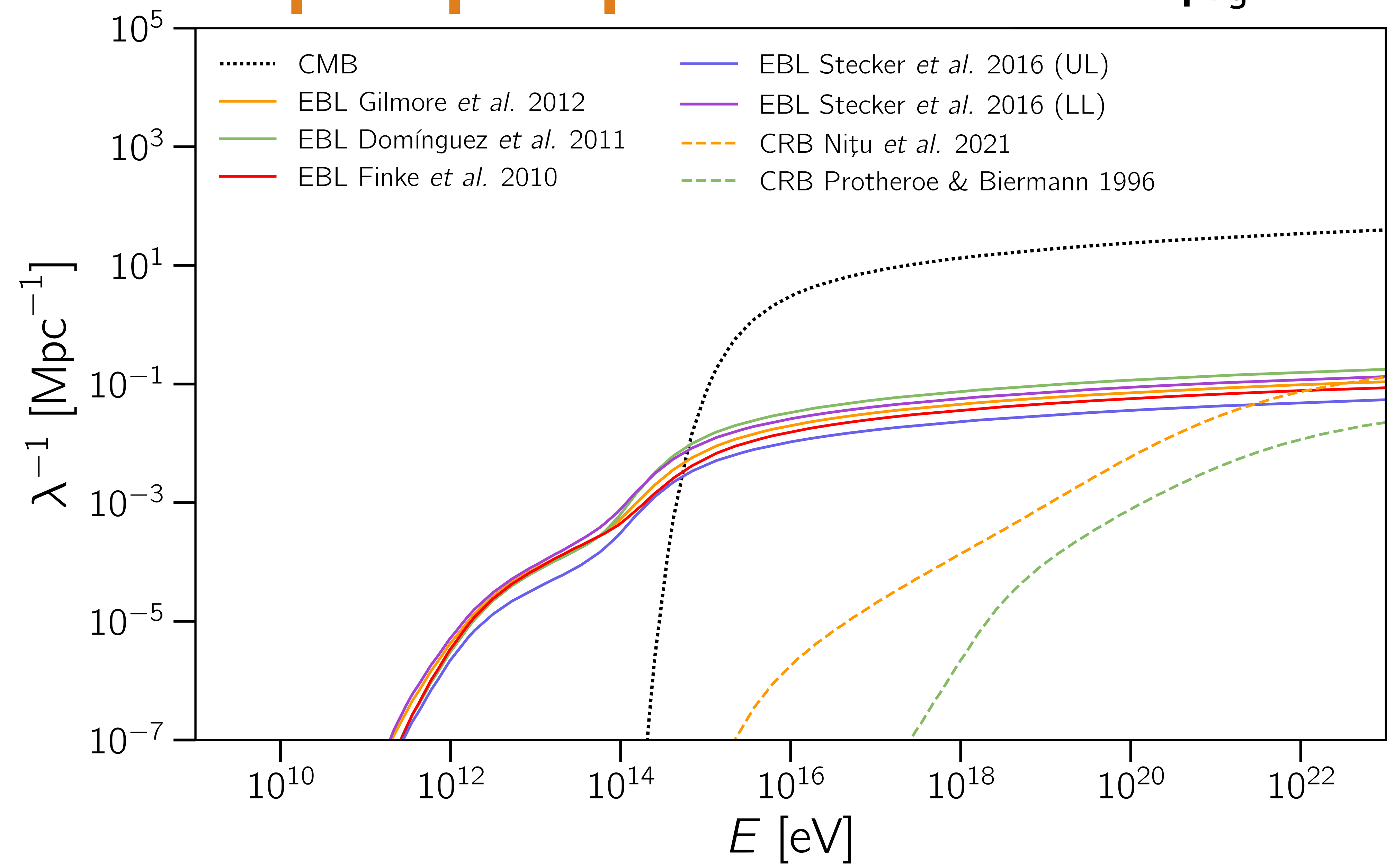
double pair production $\gamma + \gamma_{bg} \rightarrow e^- + e^+ + e^- + e^+$



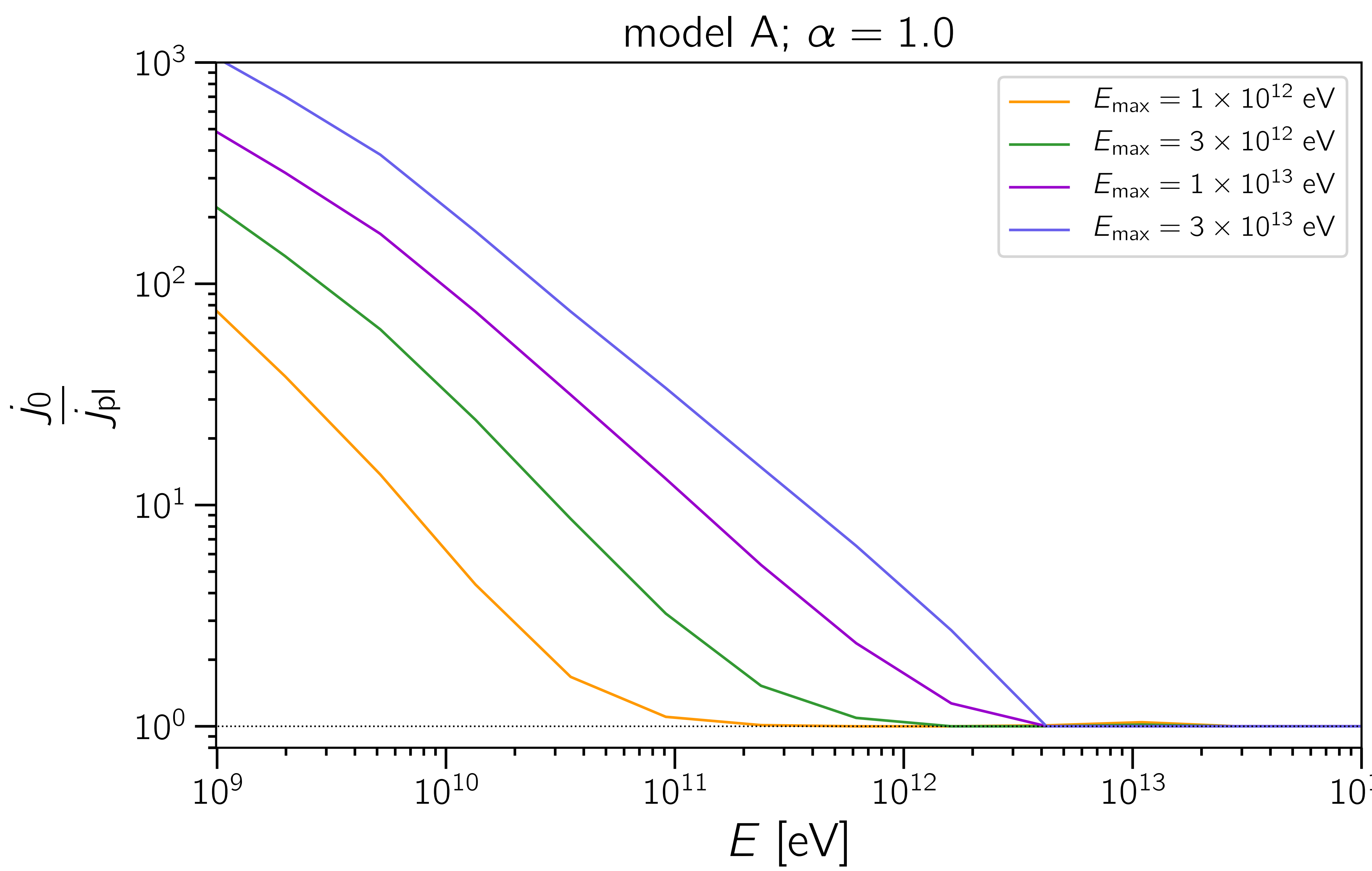
inverse Compton $e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma$



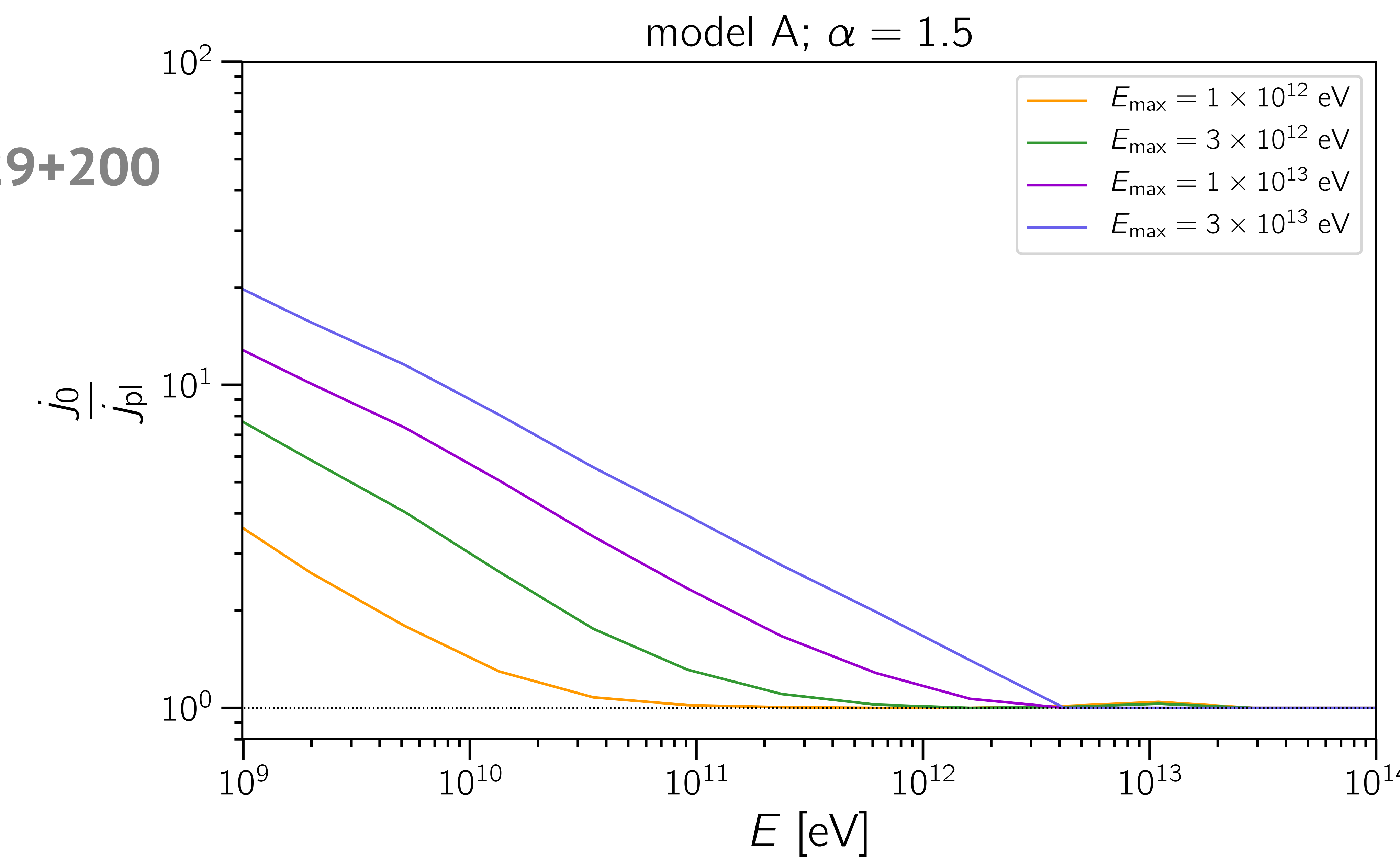
triplet pair production $e^\pm + \gamma_{bg} \rightarrow e^\pm + e^- + e^+$

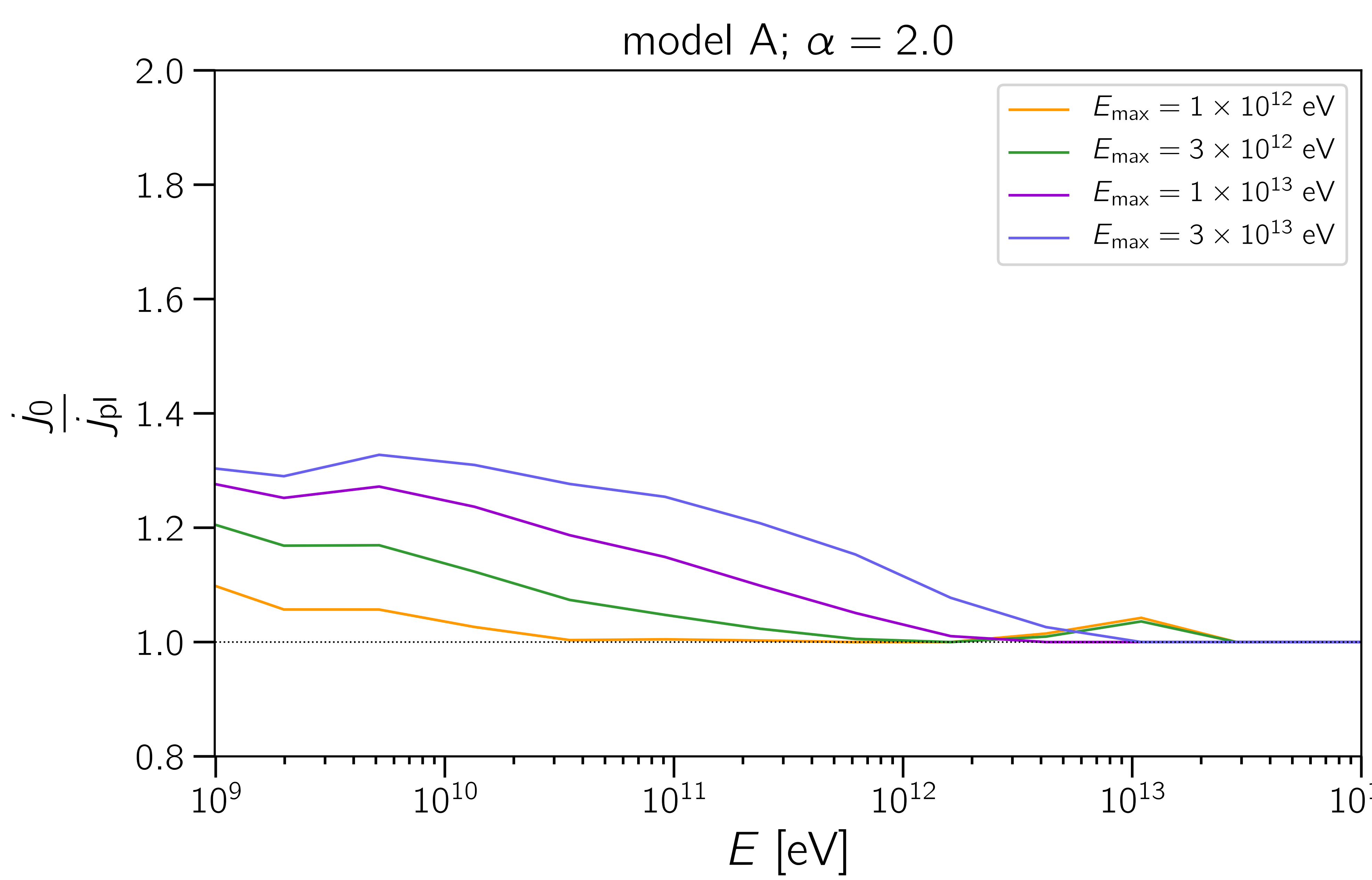


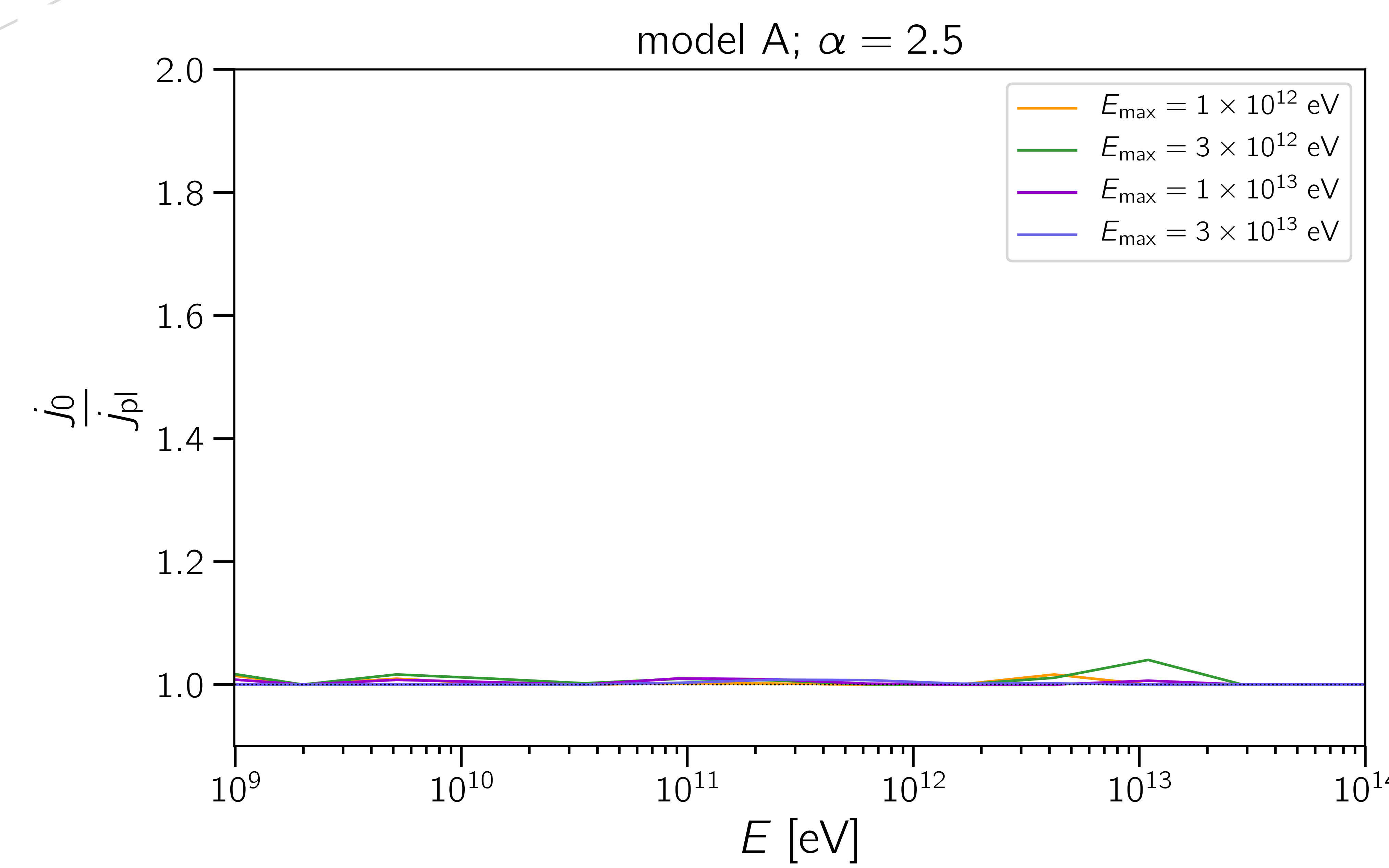
Alves Batista, Saveliev, de Gouveia Dal Pino. MNRAS 489 (2019) 3836. arXiv:1904.13345



1ES 0229+200
z=0.14







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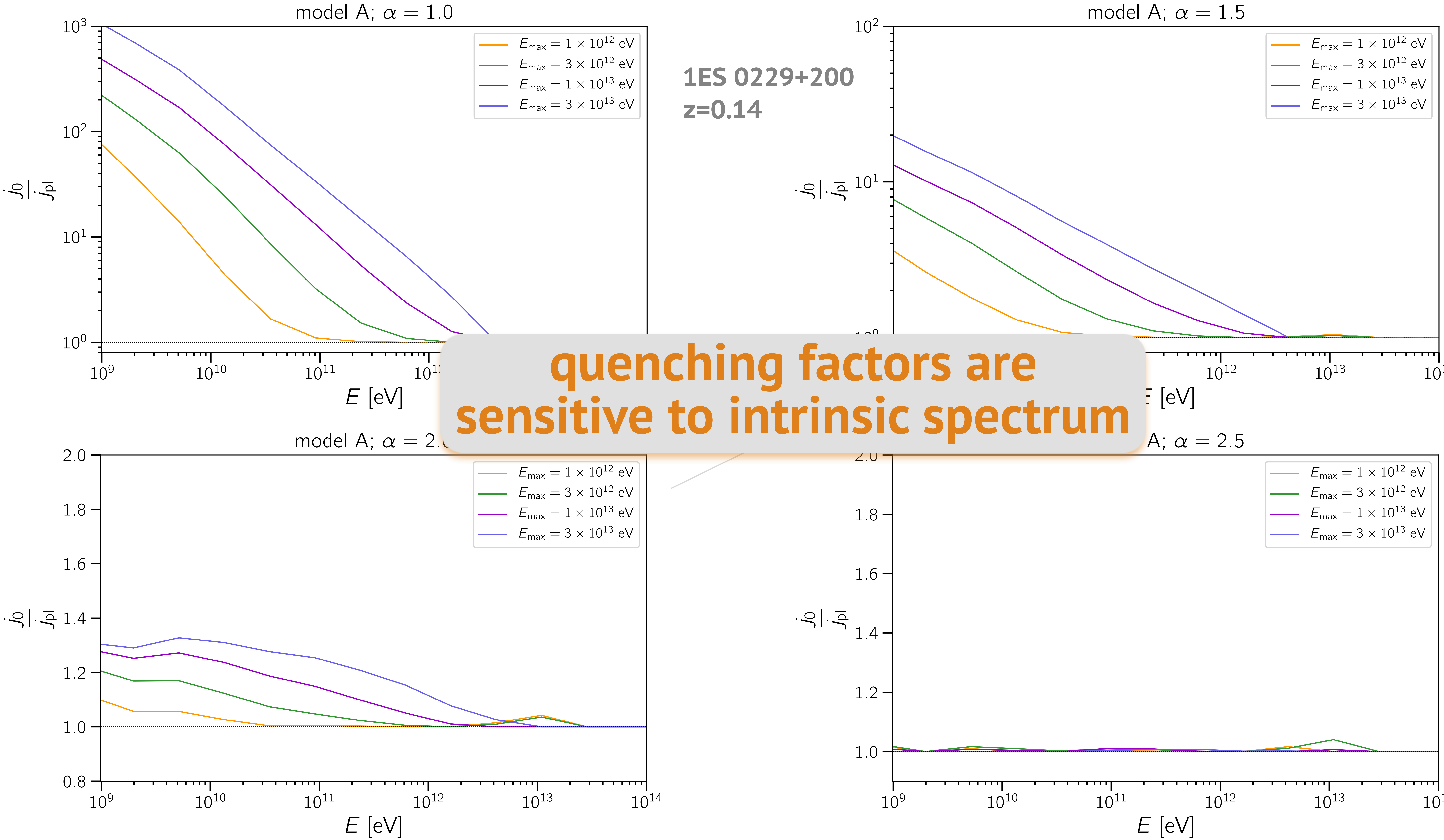

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quenching factors are sensitive to intrinsic spectrum

simulations of electromagnetic cascades with LIV

Saveliev & Alves Batista. Classical and Quantum Gravity 41 (2024) 115011. arXiv:2312.10803

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  - modification of pair production
  - including inverse Compton scattering
  - including vacuum Cherenkov
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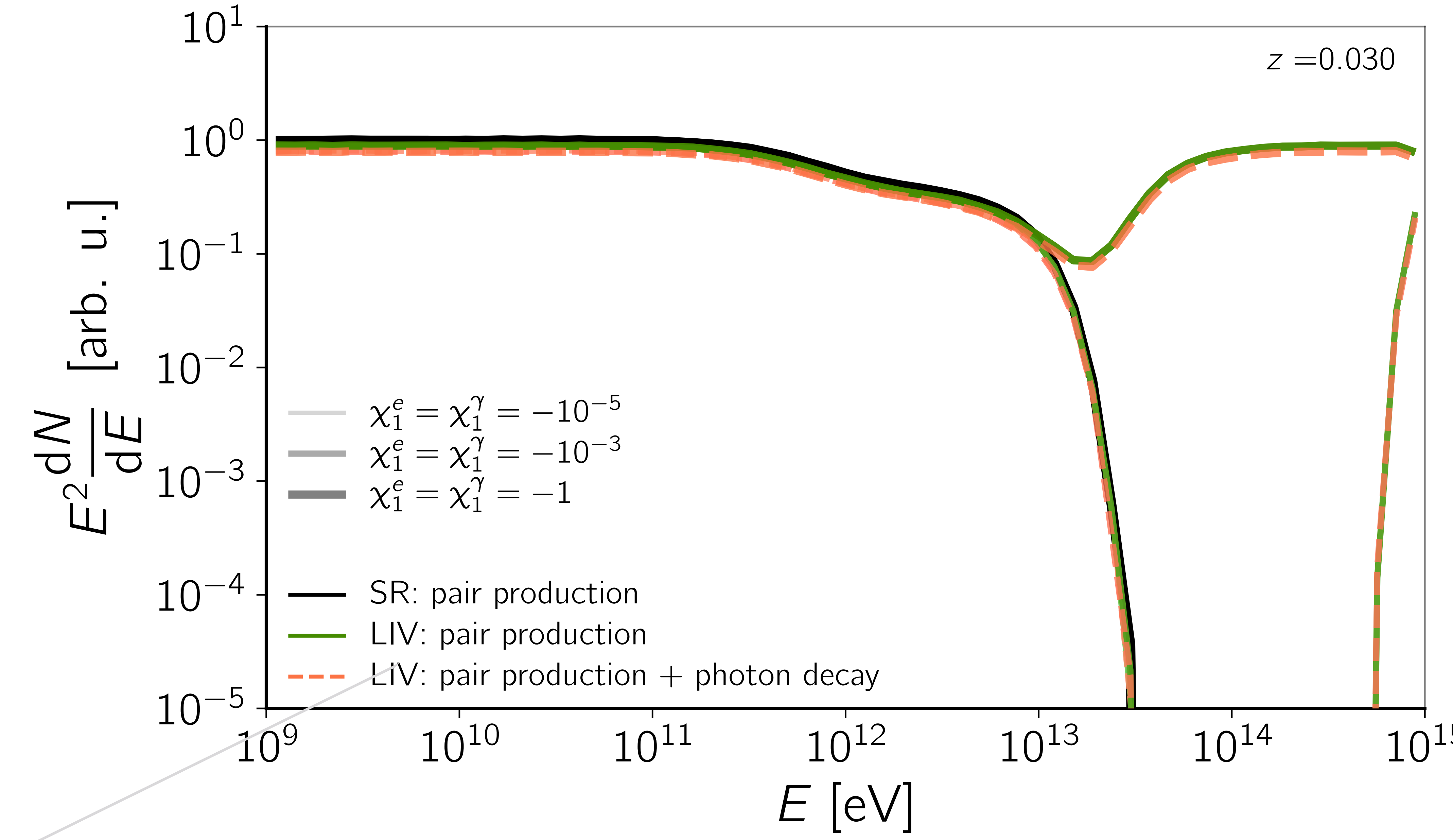

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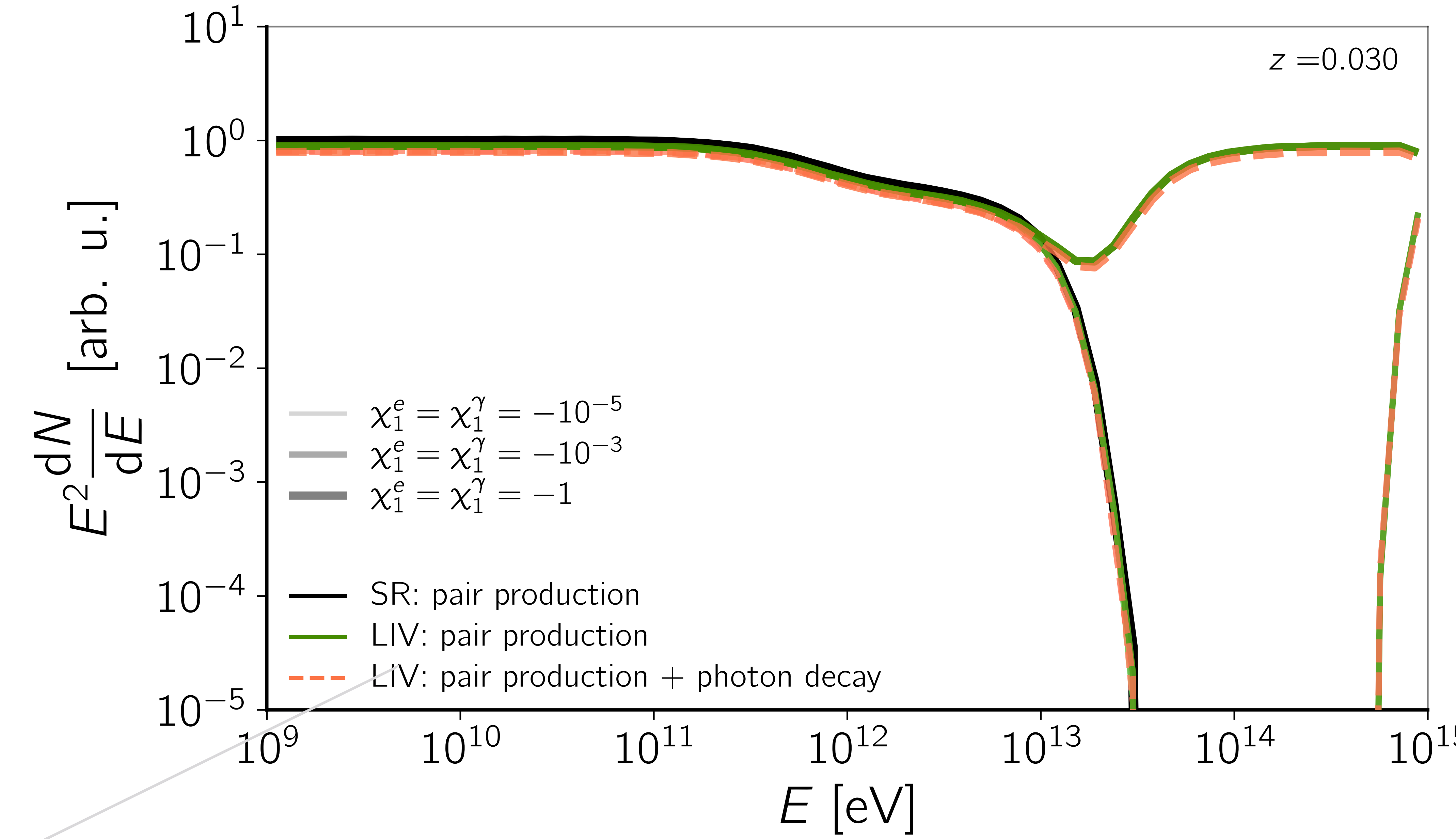

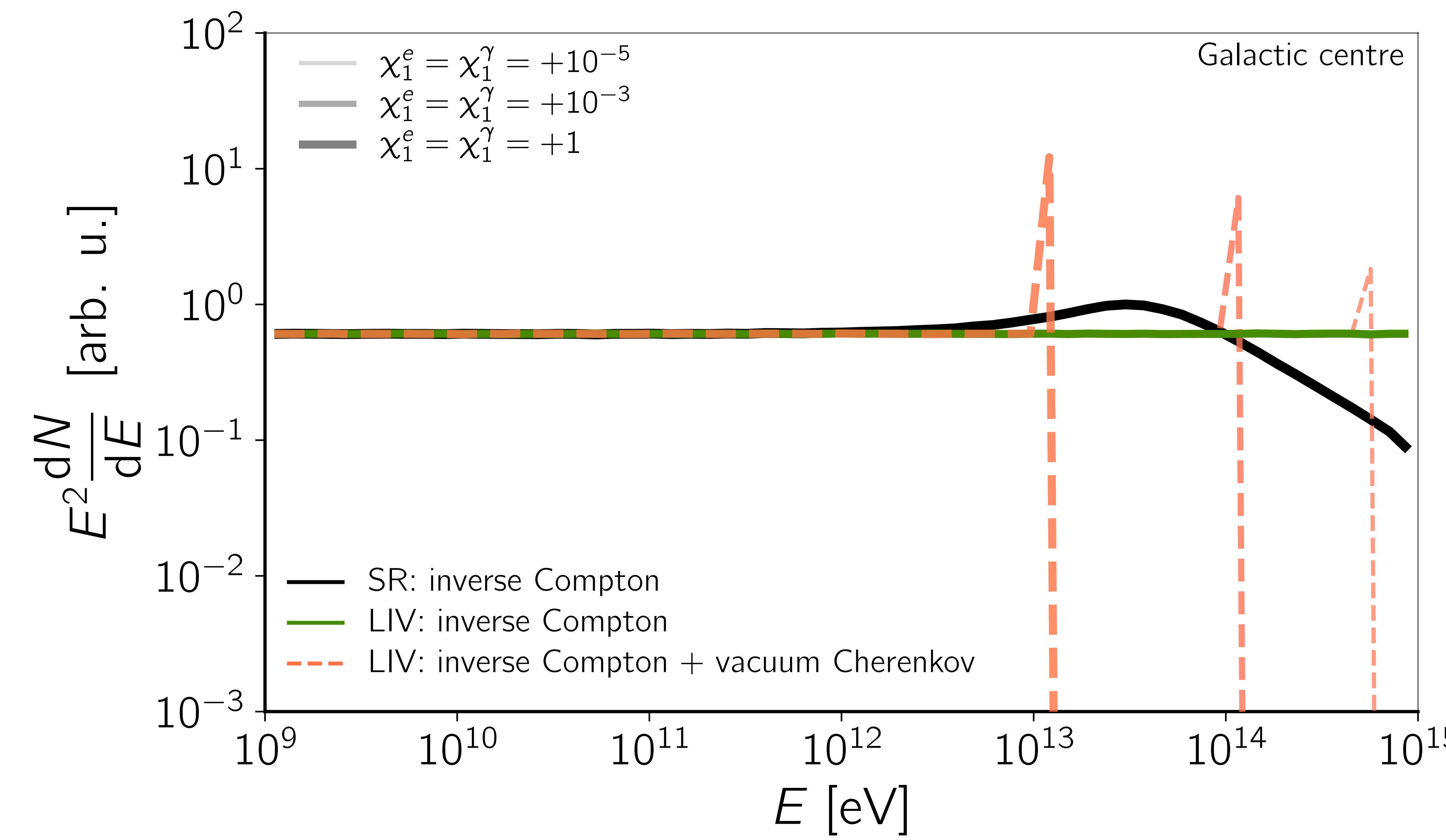

vacuum Cherenkov and photon decay

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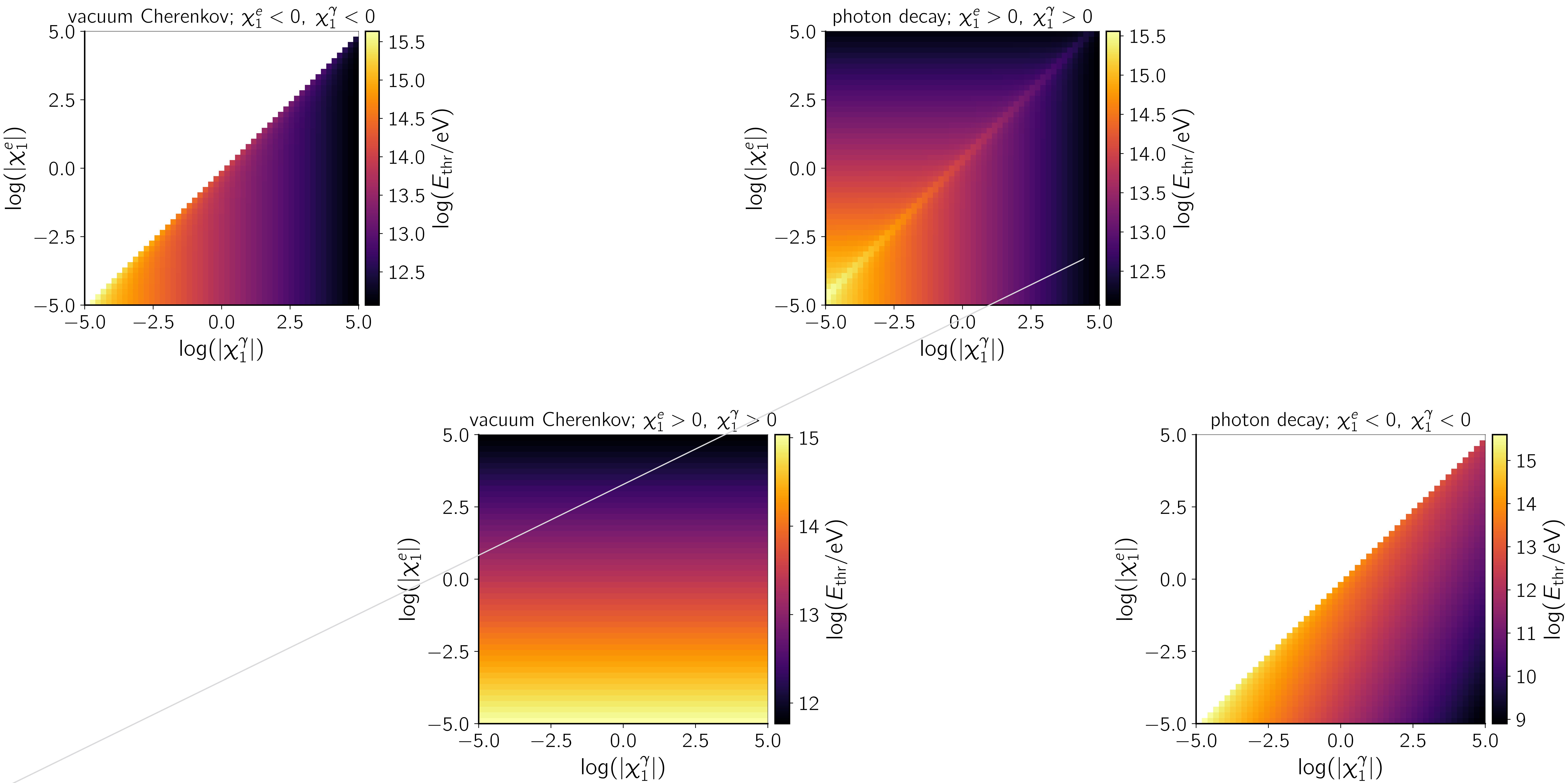

phenomenology of ALP-photon interconversion

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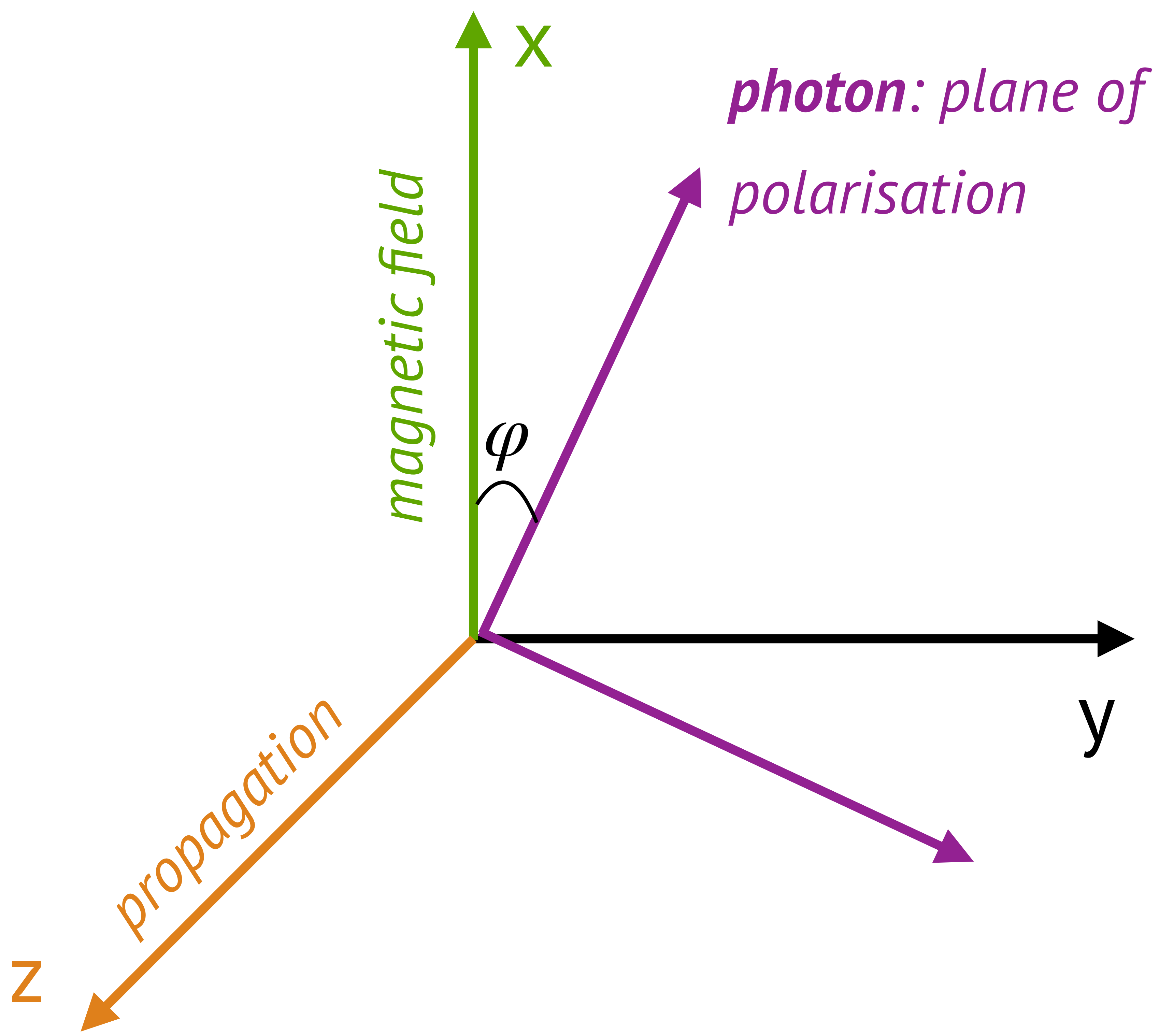
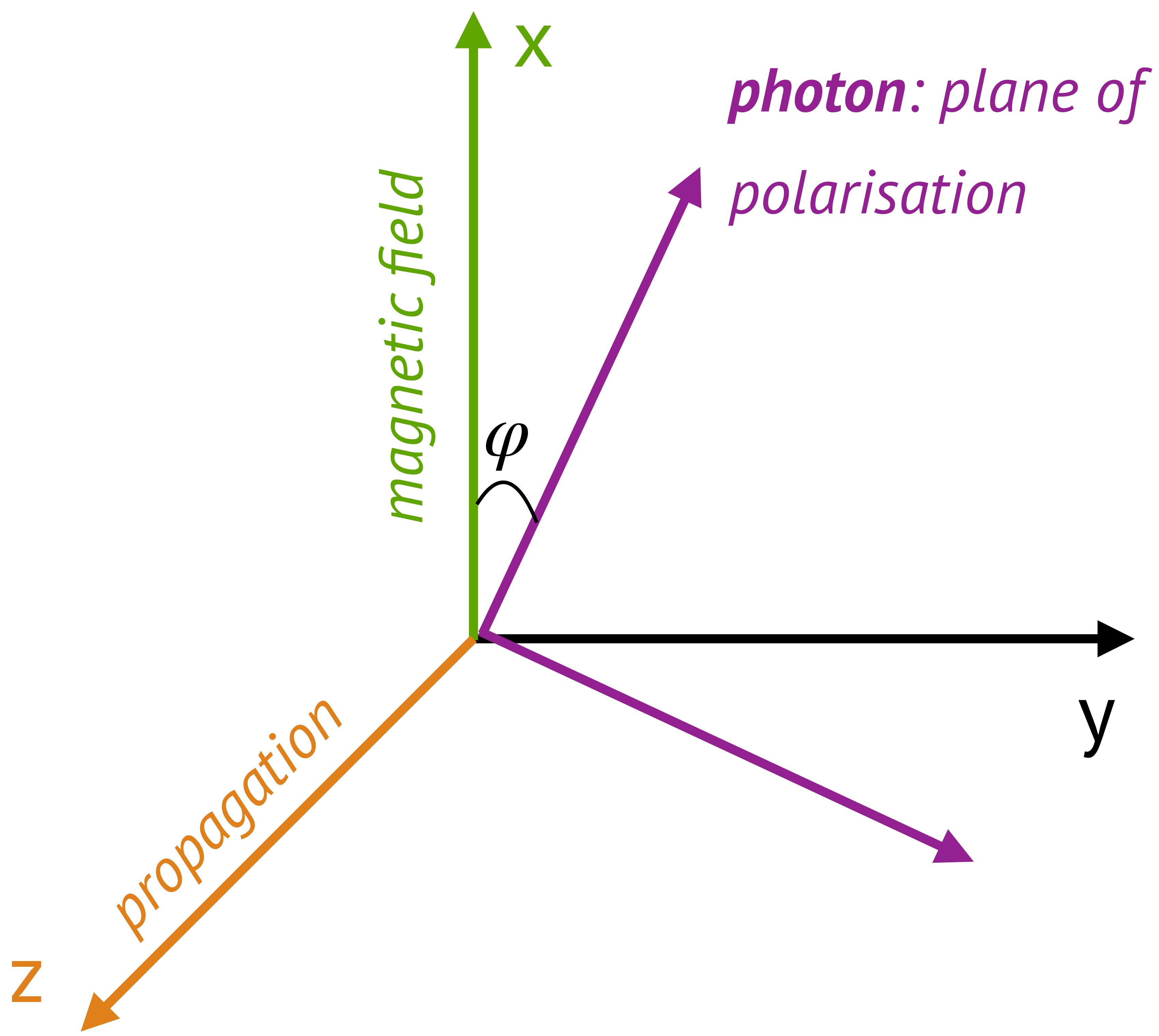
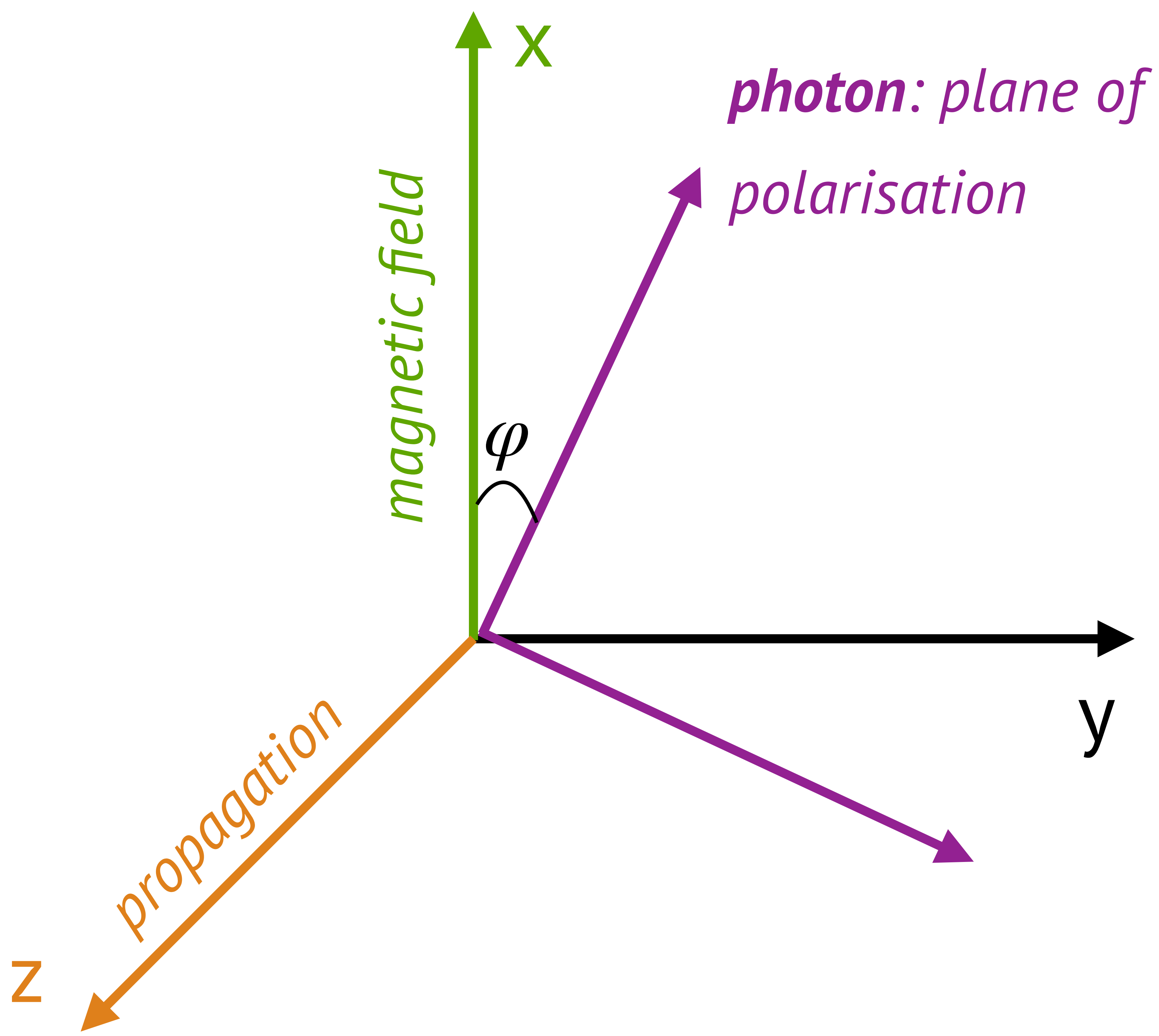


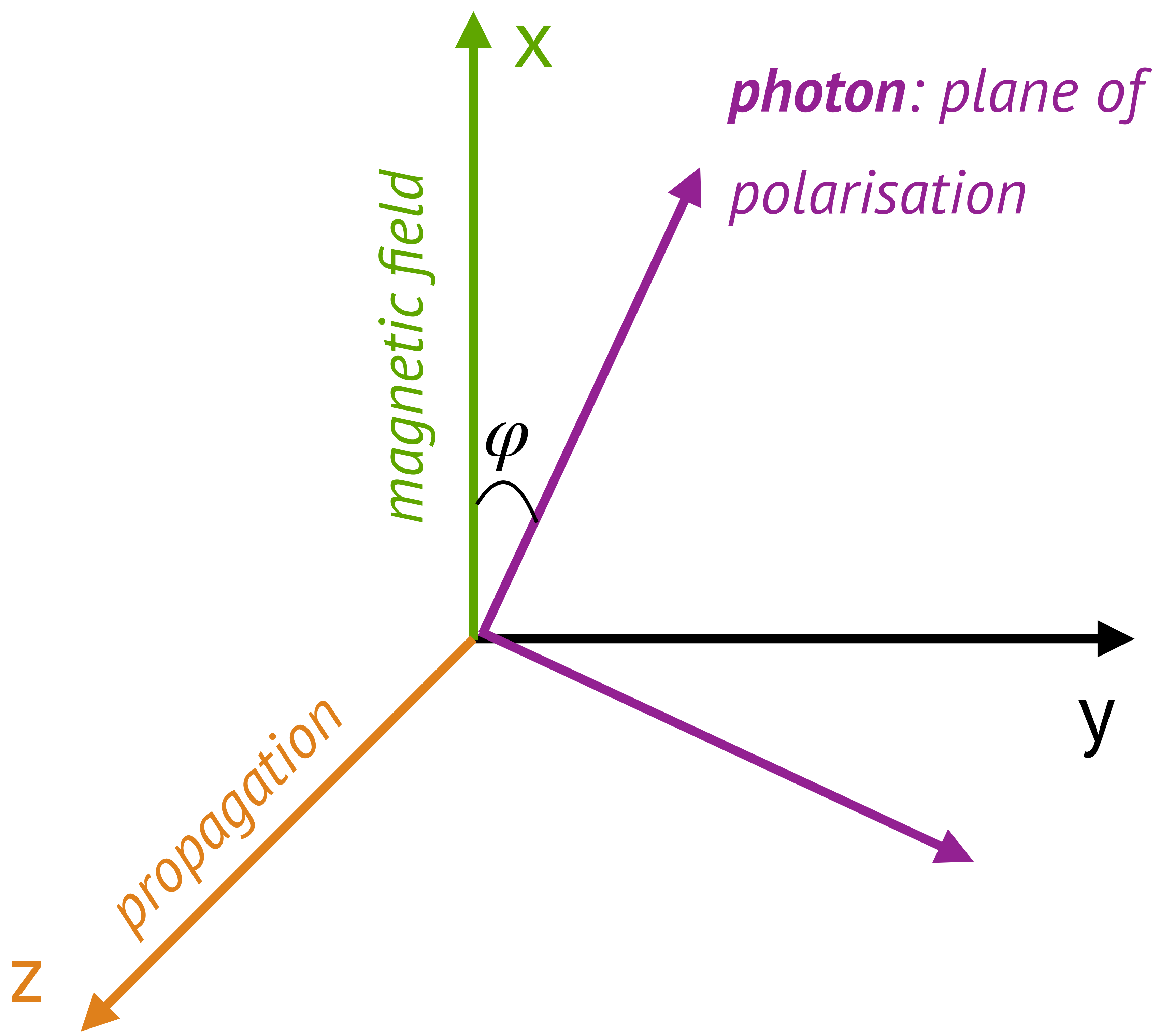


three-state quantum system



three-state quantum system

$$\mathscr{A}(z) = \begin{pmatrix} A_1(z) \\ A_2(z) \\ a(z) \end{pmatrix}$$



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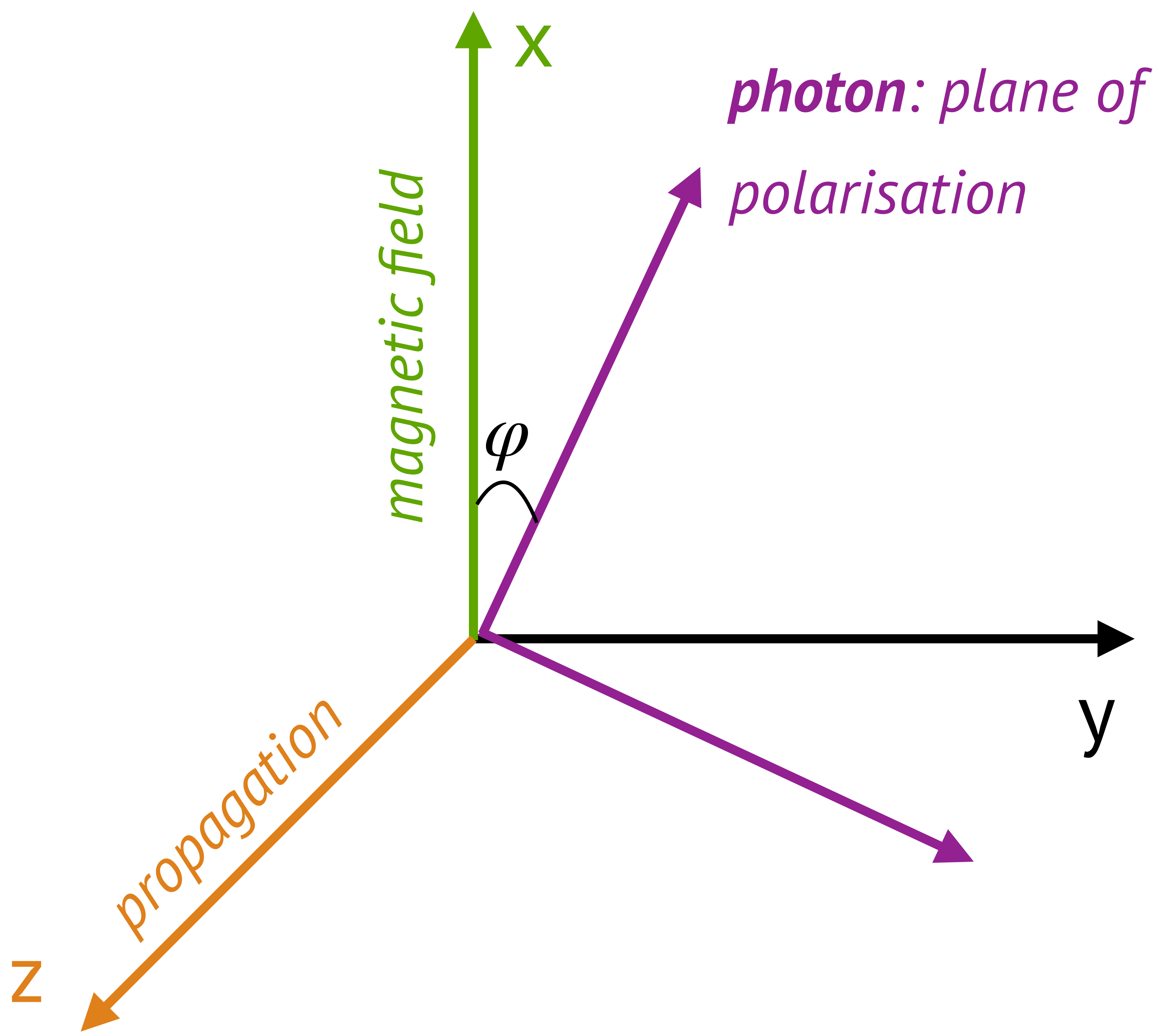

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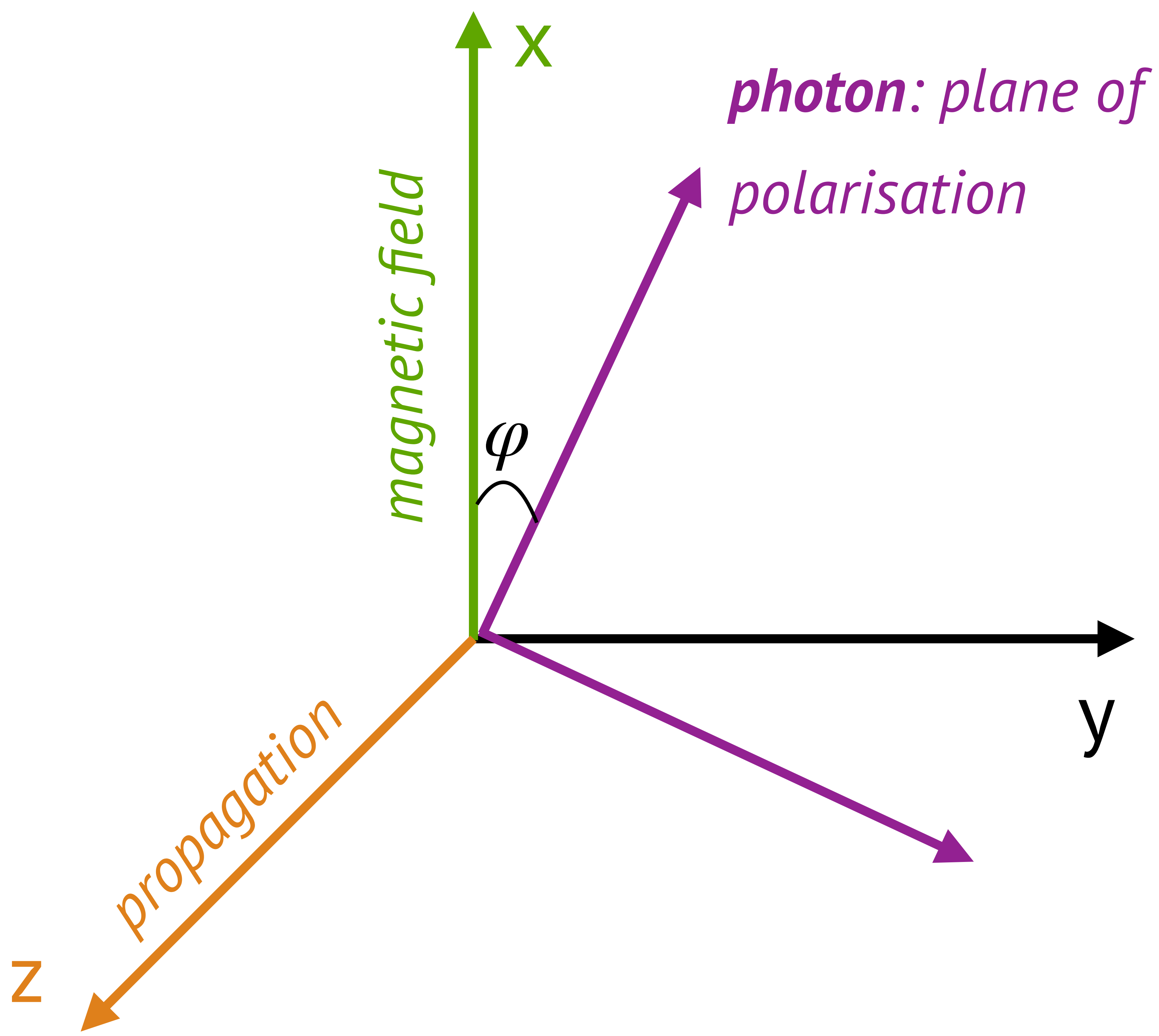
photon polarisations

ALP field



equation of motion

$$\left(E - i\frac{\partial}{\partial z} + \frac{1}{2E}\mathbb{M}\right)\vec{\mathscr{A}} = 0$$

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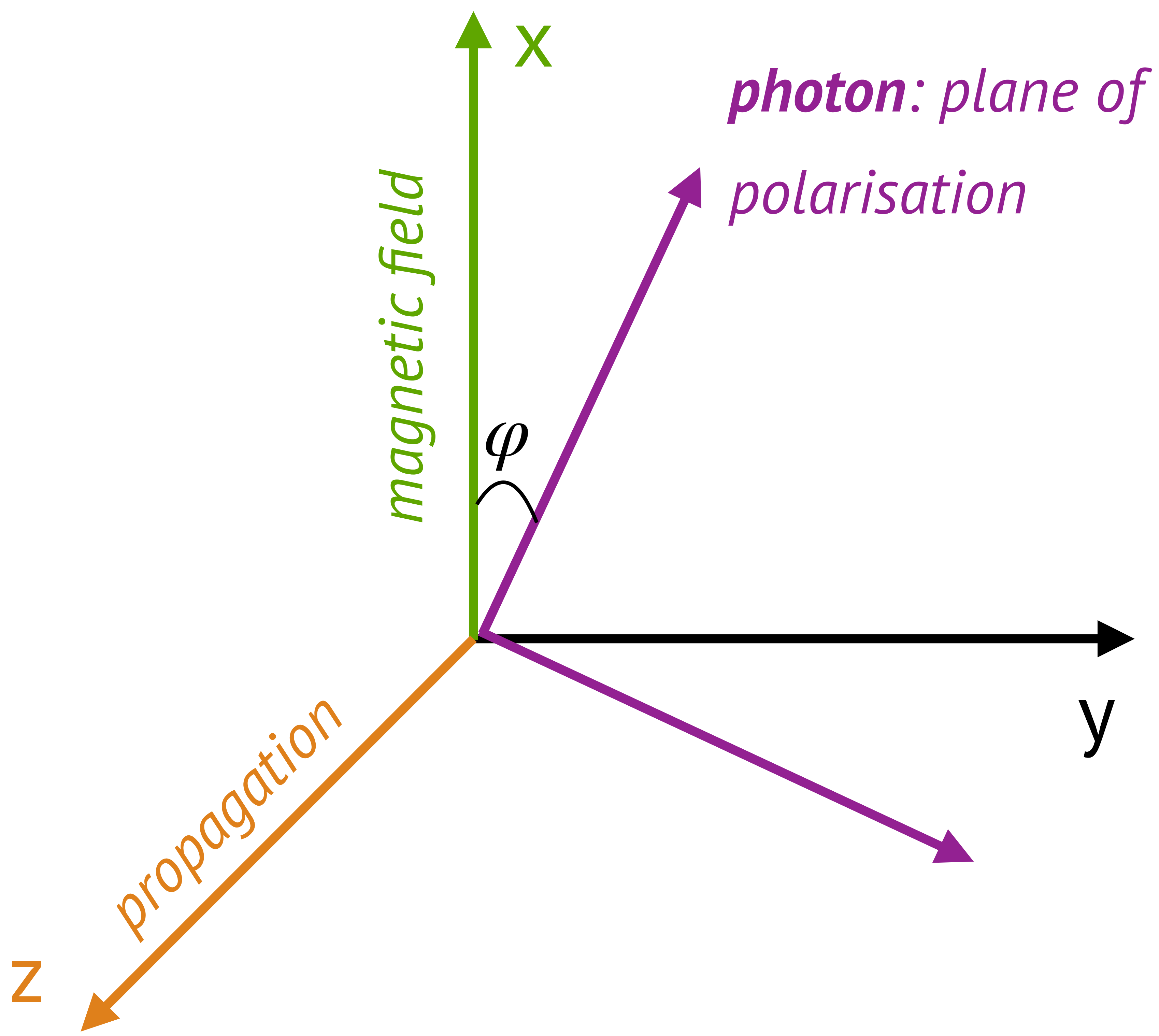
$A_1(z)$, $A_2(z)$ → photon polarisations

$a(z)$ → ALP field



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mixing matrix

$$\mathbb{M} = \begin{pmatrix} \Delta_{\parallel}\cos^2\varphi + \Delta_{\perp}\sin^2\varphi & \left(\Delta_{\parallel} - \Delta_{\perp}\right)\sin\varphi\cos\varphi & \Delta_{a\gamma}\cos\varphi \\ \left(\Delta_{\parallel} - \Delta_{\perp}\right)\sin\varphi\cos\varphi & \Delta_{\parallel}\sin^2\varphi + \Delta_{\perp}\cos^2\varphi & \Delta_{a\gamma}\sin\varphi \\ \Delta_{a\gamma}\cos\varphi & \Delta_{a\gamma}\sin\varphi & \Delta_a \end{pmatrix}$$

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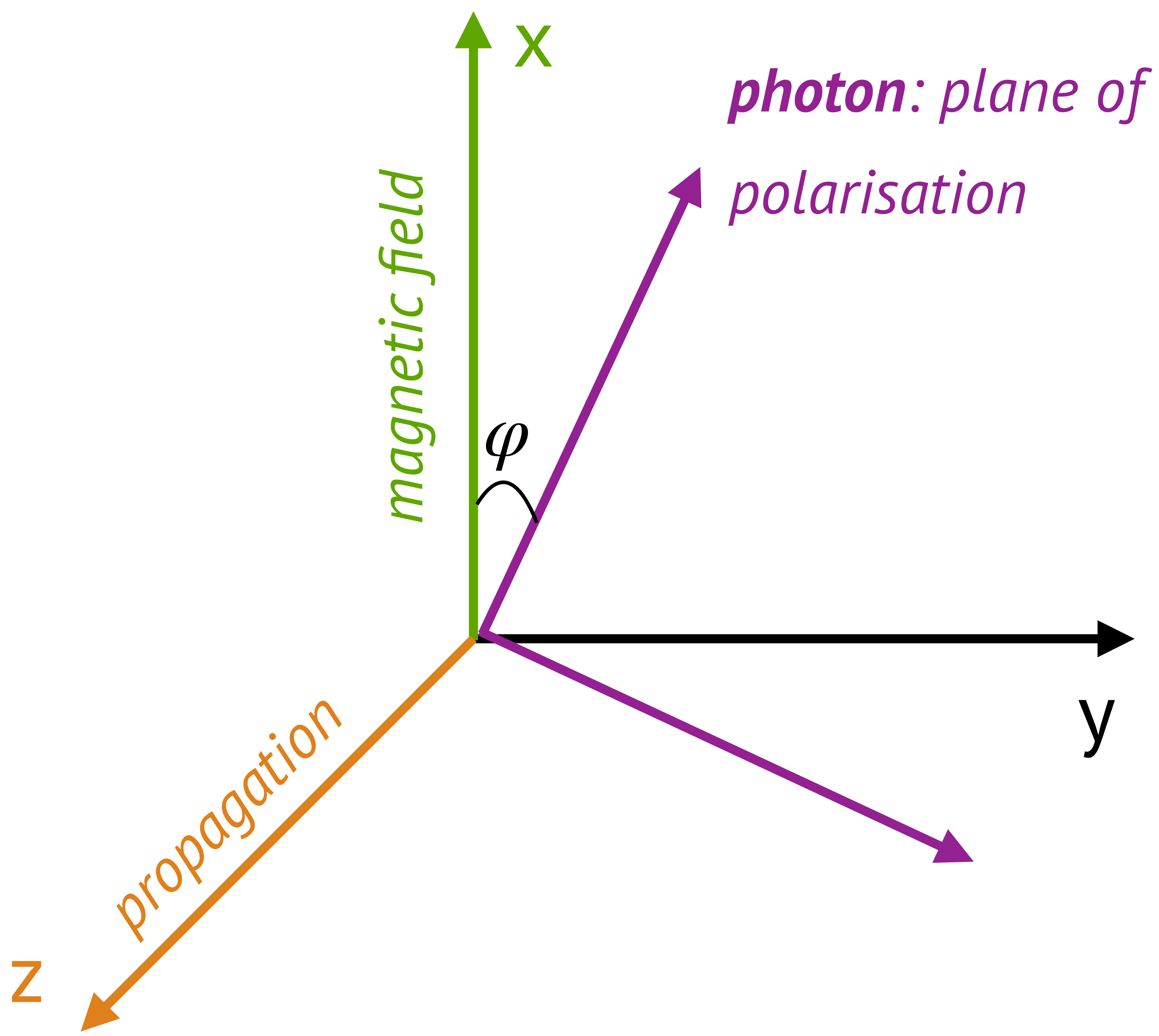
equation of motion

$$\left(E - i\frac{\partial}{\partial z} + \frac{1}{2E}\mathbb{M}\right)\vec{\mathscr{A}} = 0$$



mixing matrix

$$\mathbb{M} = \begin{pmatrix} \Delta_{\parallel}\cos^2\varphi + \Delta_{\perp}\sin^2\varphi & \left(\Delta_{\parallel} - \Delta_{\perp}\right)\sin\varphi\cos\varphi & \Delta_{a\gamma}\cos\varphi \\ \left(\Delta_{\parallel} - \Delta_{\perp}\right)\sin\varphi\cos\varphi & \Delta_{\parallel}\sin^2\varphi + \Delta_{\perp}\cos^2\varphi & \Delta_{a\gamma}\sin\varphi \\ \Delta_{a\gamma}\cos\varphi & \Delta_{a\gamma}\sin\varphi & \Delta_a \end{pmatrix}$$

depends on

$\Delta_{a\gamma}$ → B: external magnetic field, $g_{a\gamma}$: coupling constant

Δ_a → m_a: ALP mass, E: photon energy

$\Delta_{\perp}$ → E: photon energy, n_e: plasma density in medium

$\Delta_{\parallel}$ → E: photon energy

B: external magnetic field
gaγ: coupling constant
ma: ALP mass
E: photon energy
ne: plasma density in medium

three-state quantum system

$$\mathscr{A}(z) = \begin{pmatrix} A_1(z) \\ A_2(z) \\ a(z) \end{pmatrix}$$

$A_1(z)$, $A_2(z)$ → photon polarisations

$a(z)$ → ALP field