12th IDPASC School, Granada

Astrophysics and Dark Matter

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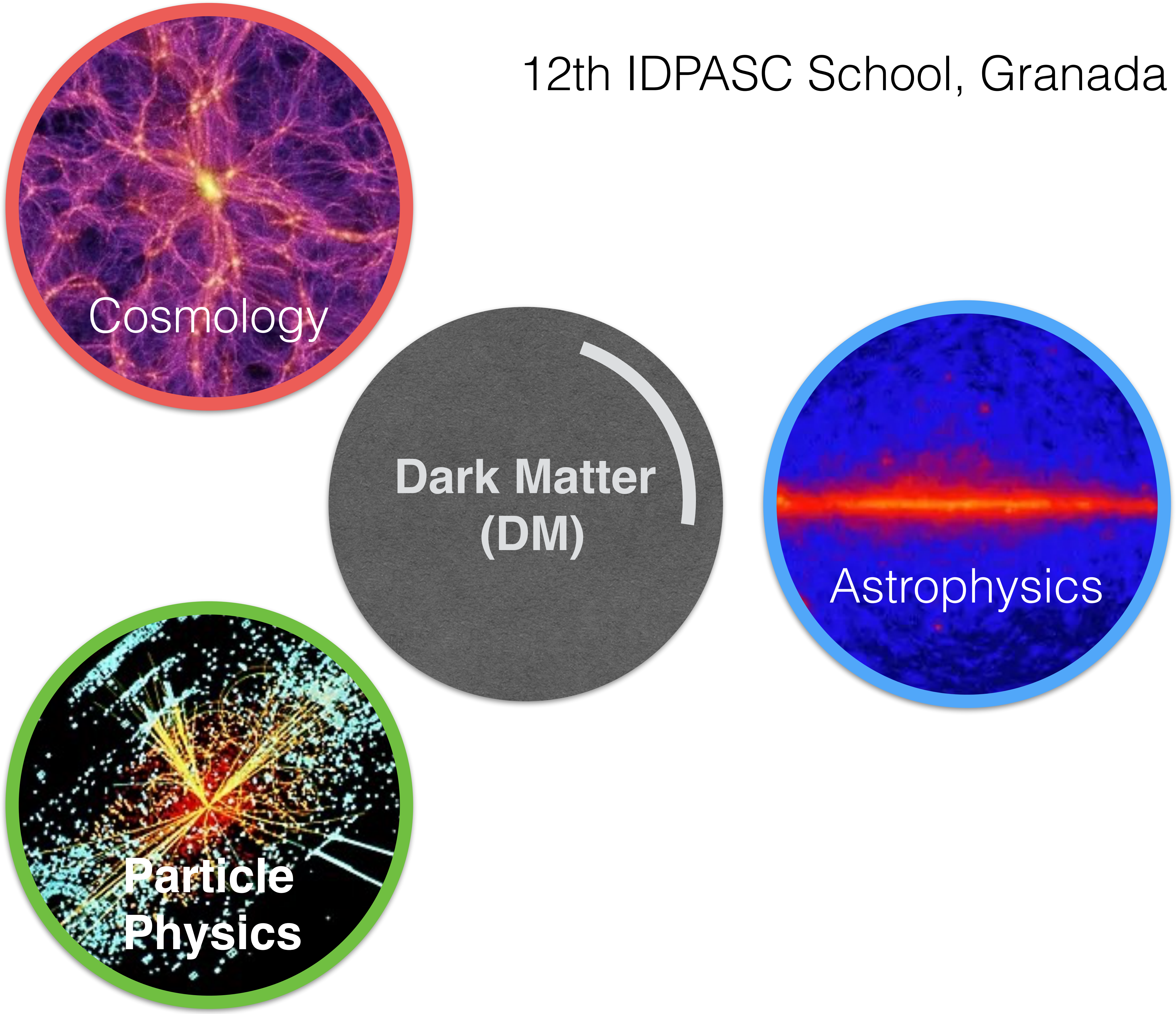


What do the properties of Galaxies tell us about the nature of Dark Matter?

What do astrophysical observations tell us about the nature of Dark Matter?

Lecture 1
Dark Matter evidence, properties, and hints from astrophysics of galaxies

Lecture 2
“Indirect detection” of Dark Matter: formalism and signals

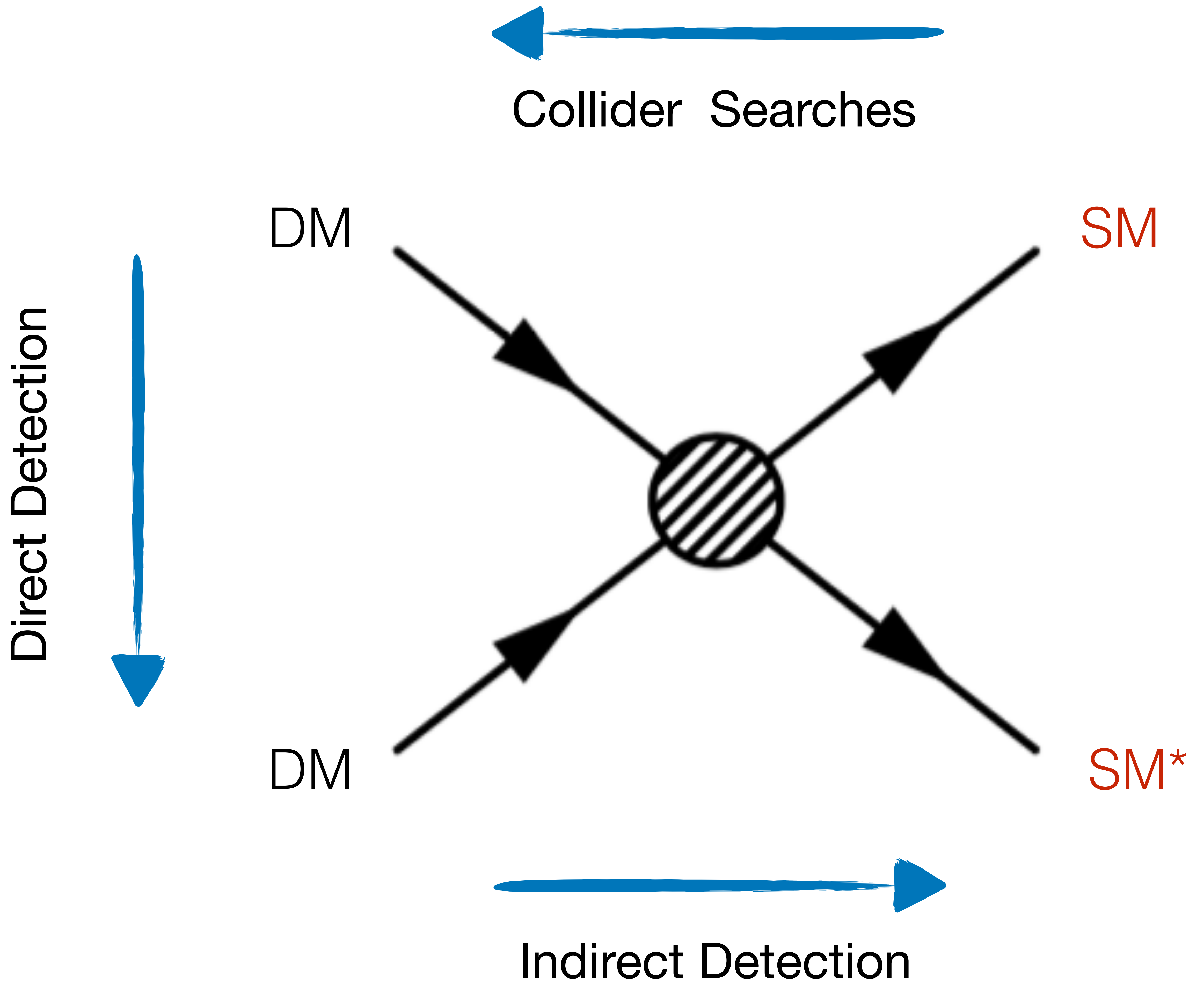
Lecture 3
Constraints and anomalies in indirect searches: gamma rays, cosmic rays, neutrinos, and more…

Detection of WIMPs

Collider searches: Searches for missing energy (and other signatures) in colliders, arising from the production (and escape) of Dark Matter

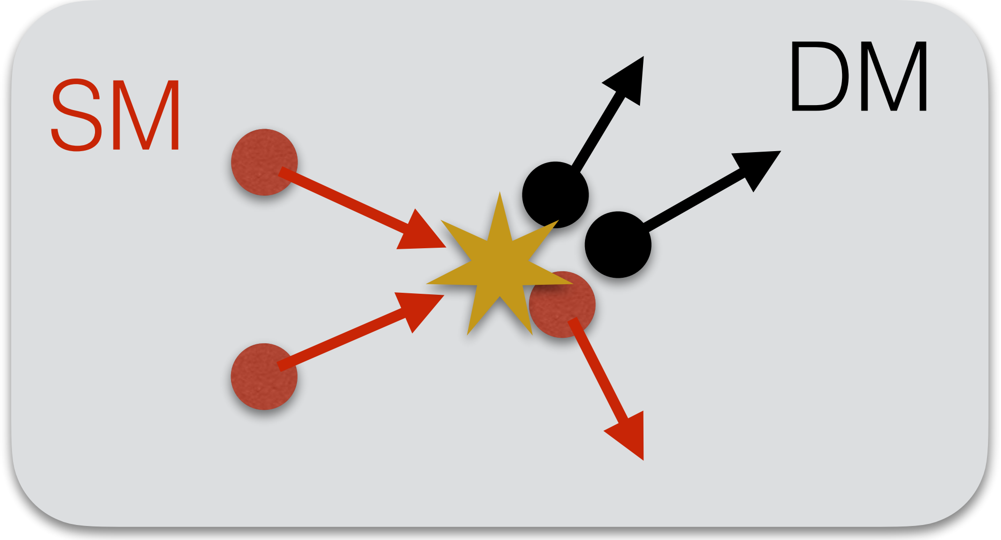
Direct detection: Searches for scattering events in low-background, low-threshold detectors, produced by Dark Matter in the Milky Way halo

Indirect detection: Searches for the Standard Model products of the self-annihilation of Dark Matter in the Milky Way and other galaxies

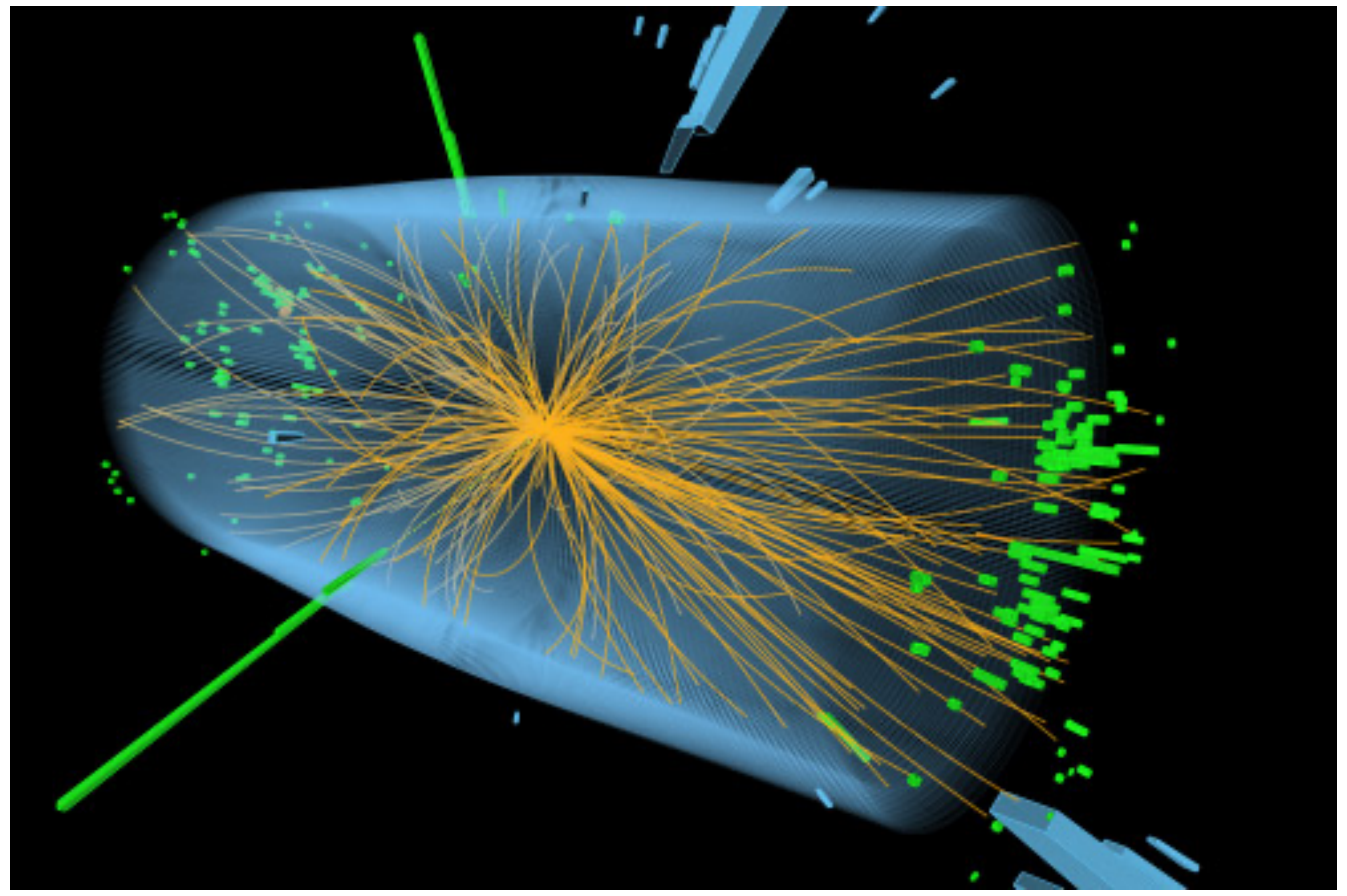


*Standard Model
(quarks, electrons, photons etc)

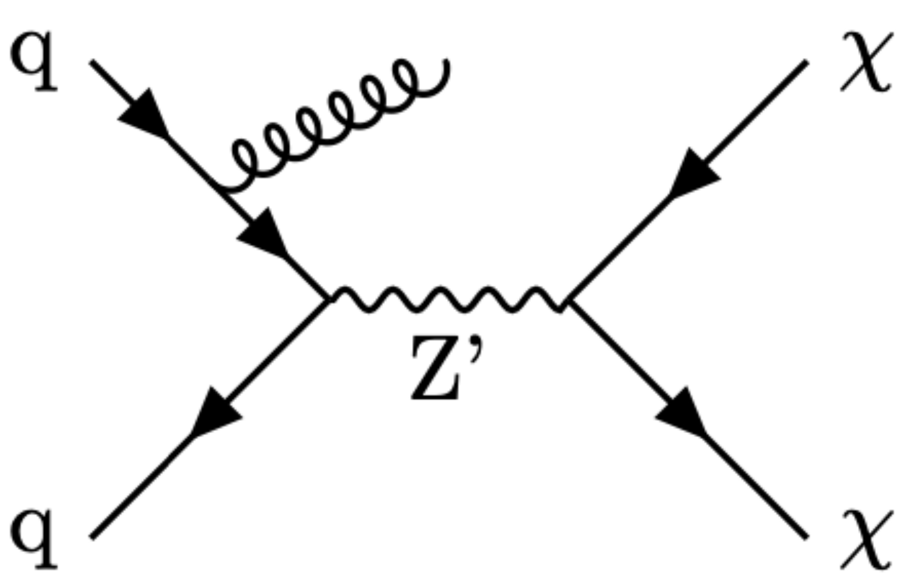
Collider Searches



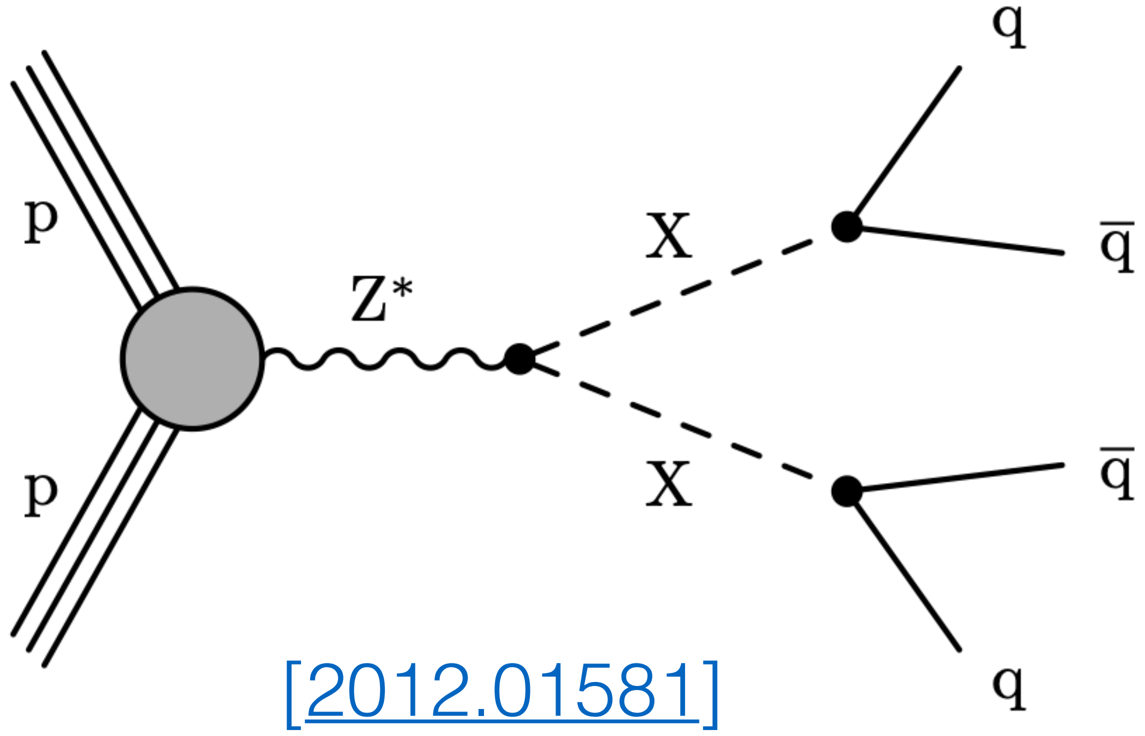
Look for the production of Dark Matter (tag on some final state SM particle with missing energy)



[Credit: CMS/CERN]

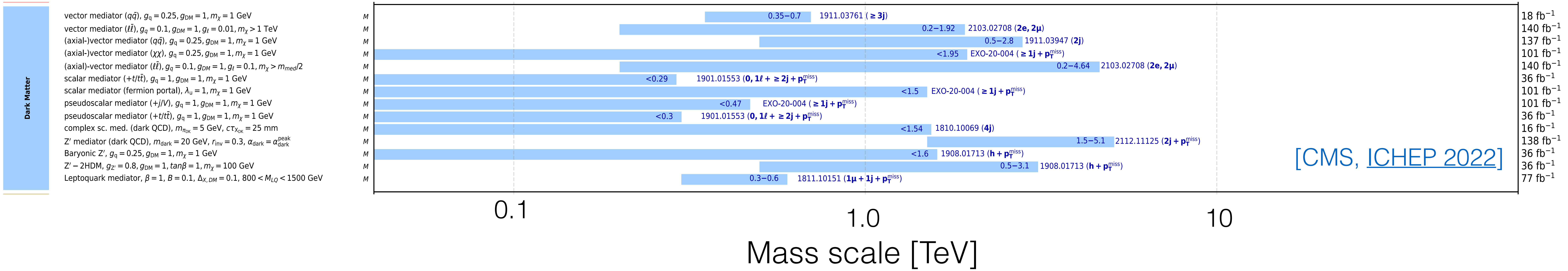


[2107.13021]



[2012.01581]

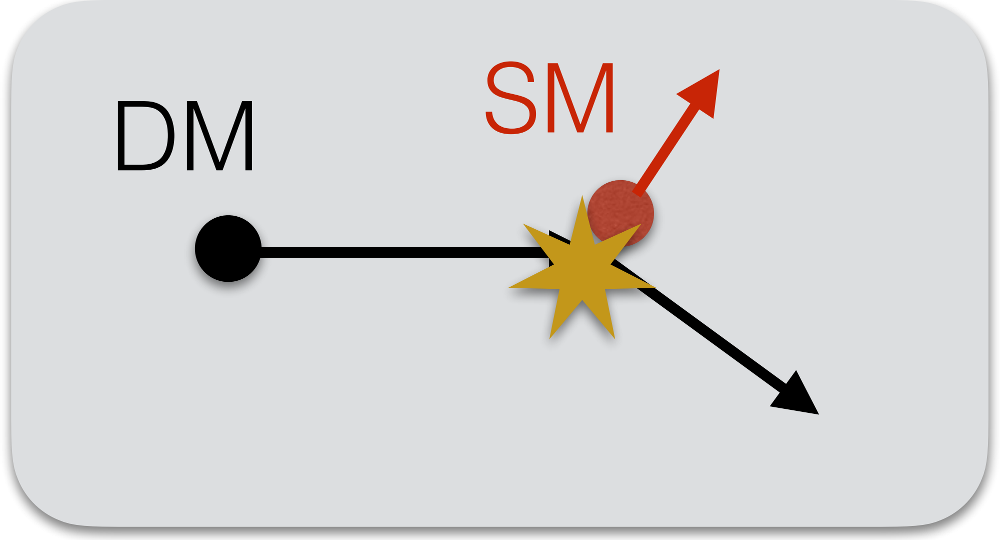
Summary of CMS constraints on the mass scale of new mediator particles coupling to DM:



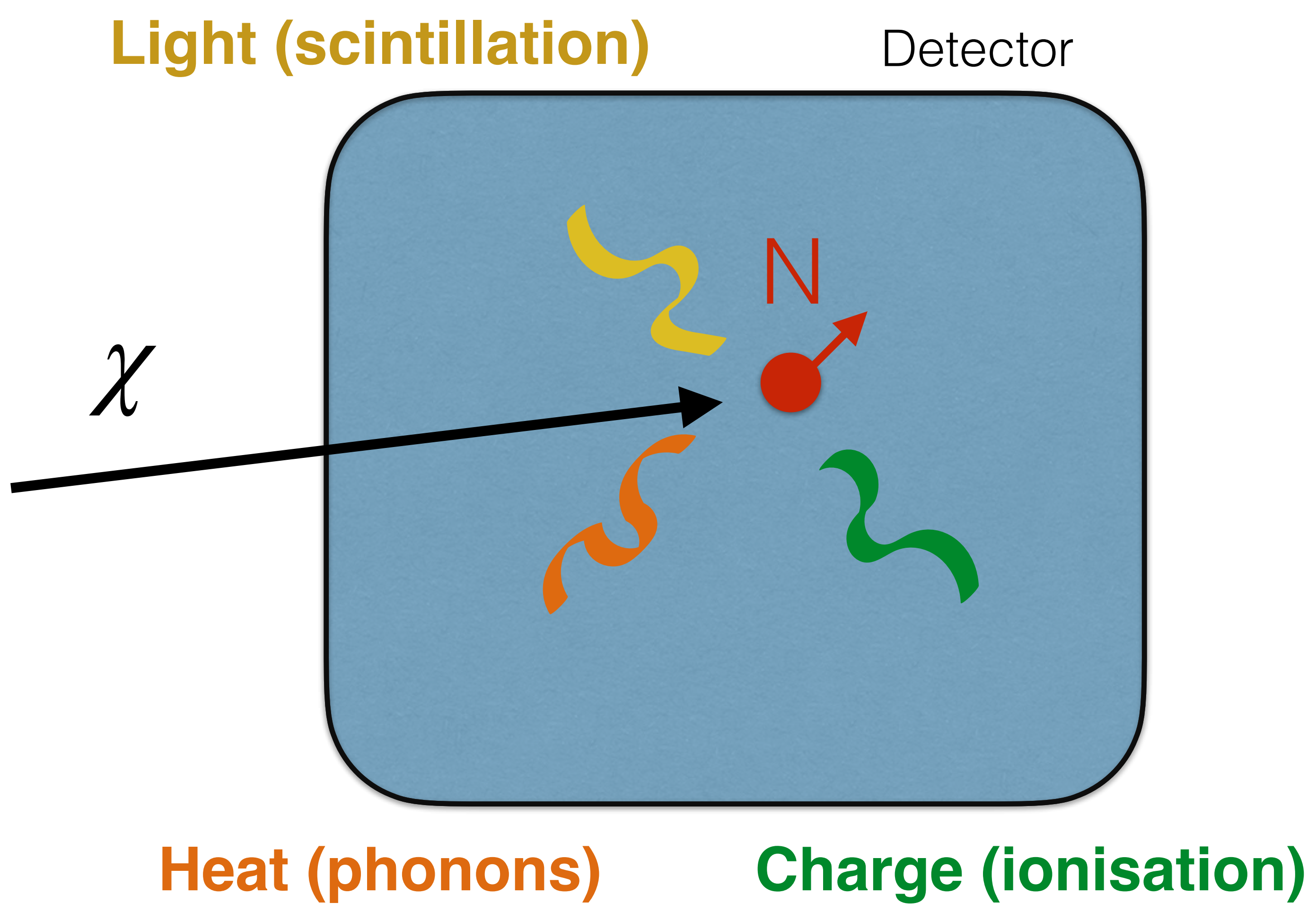
[CMS, ICHEP 2022]

LHC Run-3 (2022 - 2025) and High Luminosity LHC (2029+) will bring more data, but extending to a wider range of masses is challenging…

Direct detection of WIMPs on Earth

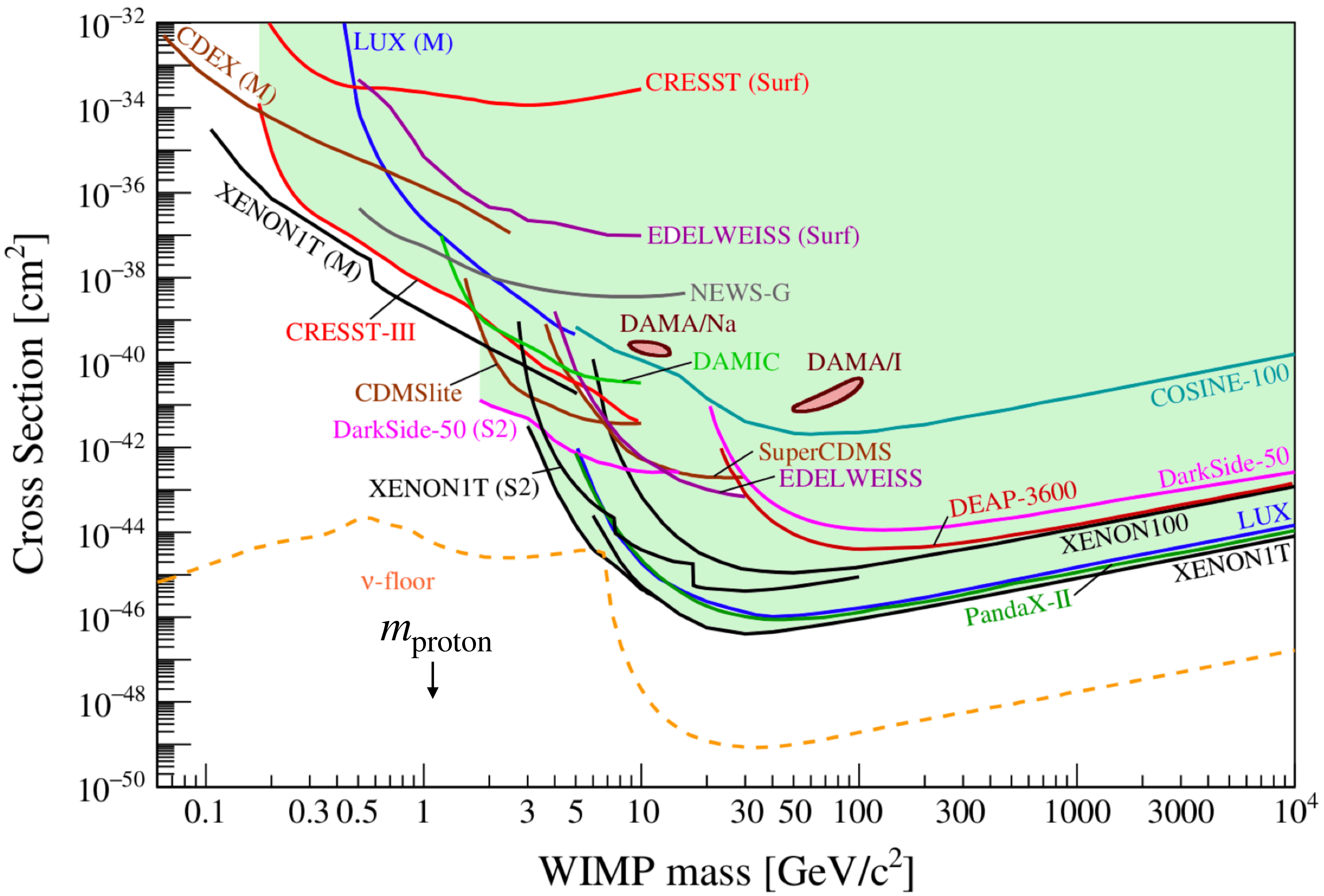


For WIMPs with GeV-scale masses, expect detectable nuclear recoils of energy O(keV)



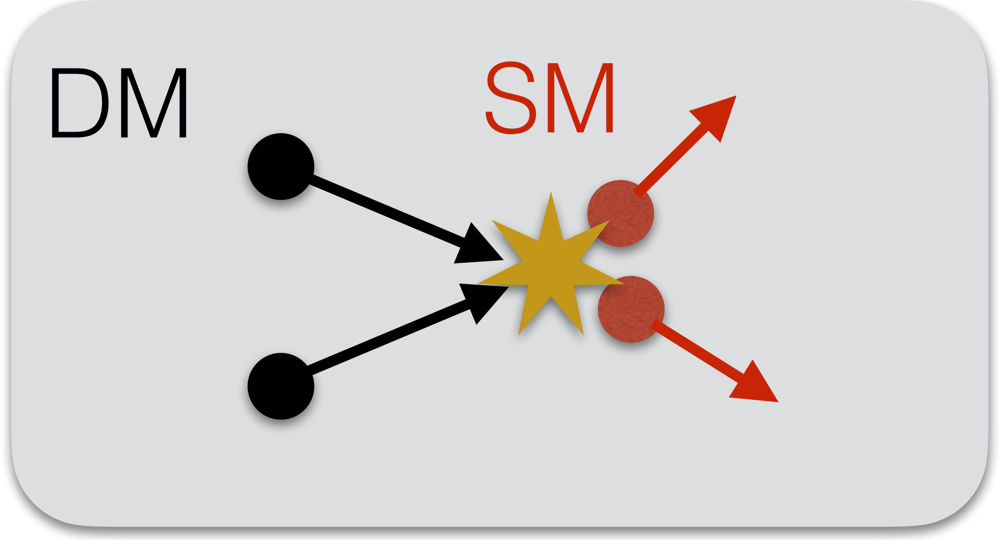
For sensible models, expect signal rates on the order of <1 event per kg per keV per day

No convincing signal yet!

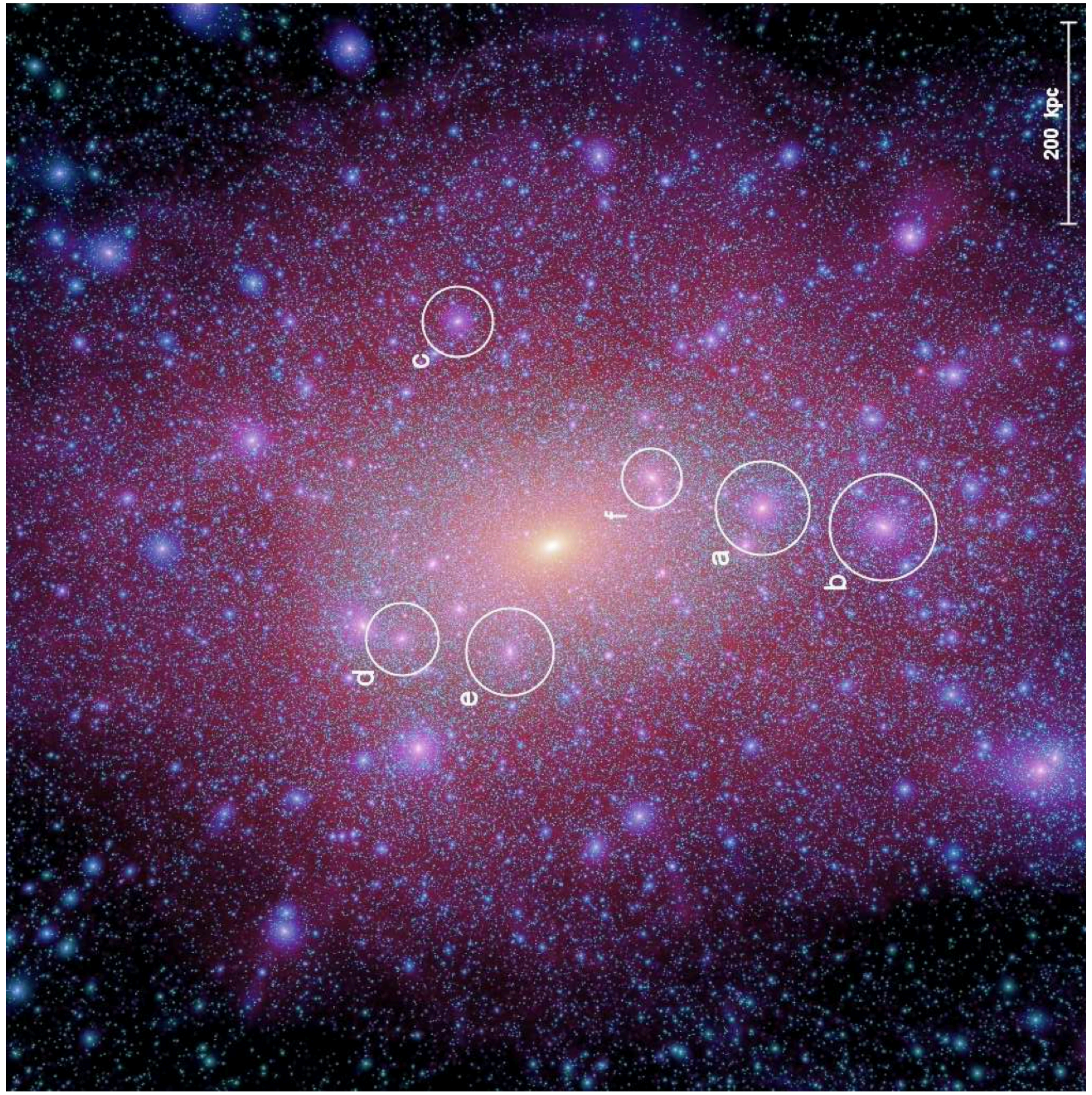


Also possible to look for DM-electron scattering, depending on the model.

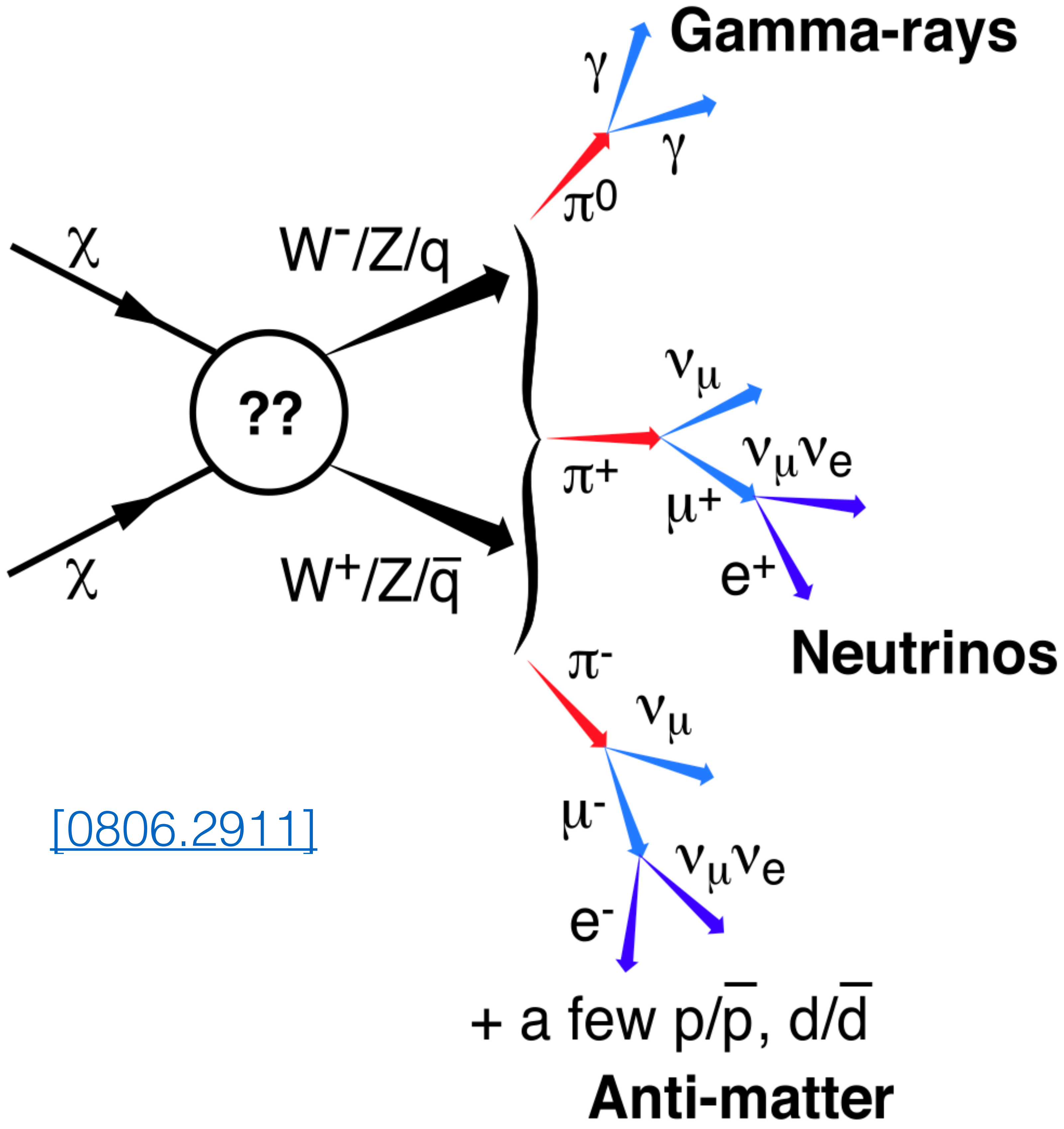
Indirect detection of Dark Matter



Search for the contribution of DM annihilation to the astrophysical flux of photons, neutrinos and charged particles.



[Aquarius simulation - 0809.0898]



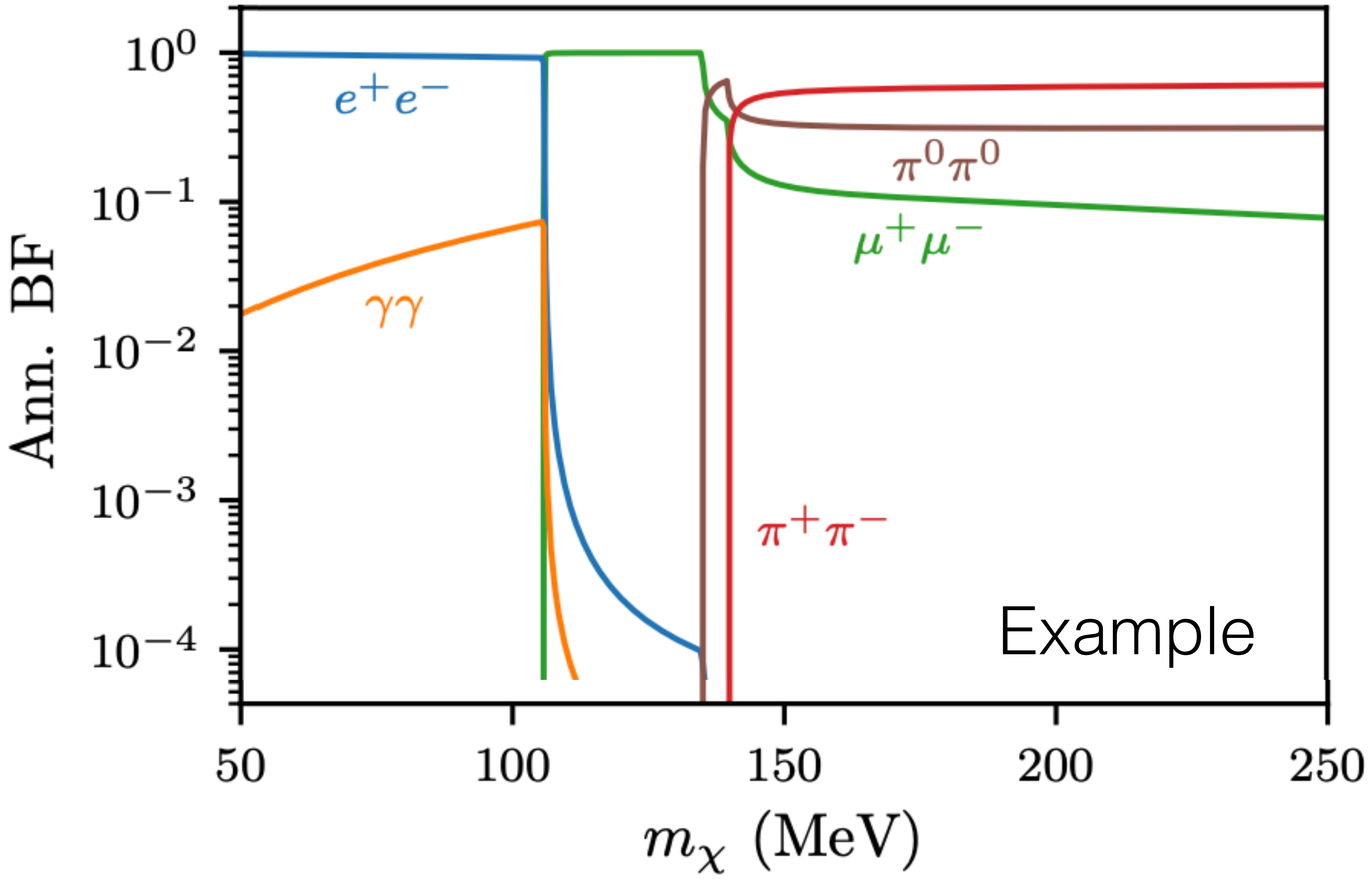
[0806.2911]

Primary Annihilation Spectra

For a specific WIMP model, we can calculate the total number of x particles produced per annihilation as:

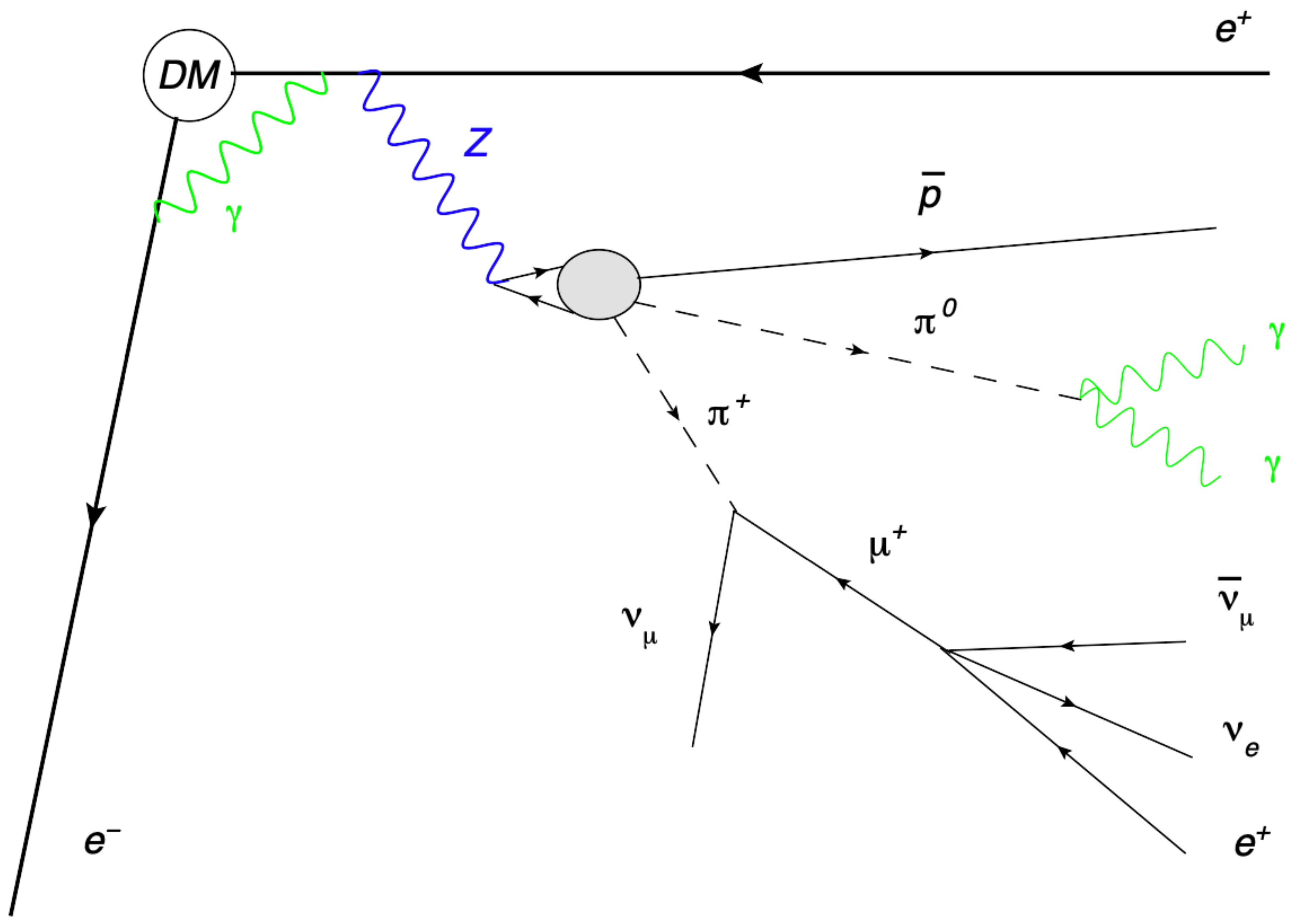
$$\frac{\mathrm{d}N_x}{\mathrm{d}E} = \sum_f B_f \frac{\mathrm{d}N_{x,f}}{\mathrm{d}E}$$

where B_f are the branching fractions into the various final states f, such that $B_f = \langle \sigma_{\chi\chi\to ff} v\rangle / \langle \sigma_{\mathrm{tot}} v\rangle$.



These branching fractions depend on the couplings and interactions of the DM model, so to be as model-independent as possible, we often constrain a single **annihilation channel** at a time.

Note that we write $\mathrm{d}N_{x,f}/\mathrm{d}E$ because annihilation into final state f can produce x particles through various processes (e.g. electroweak corrections):

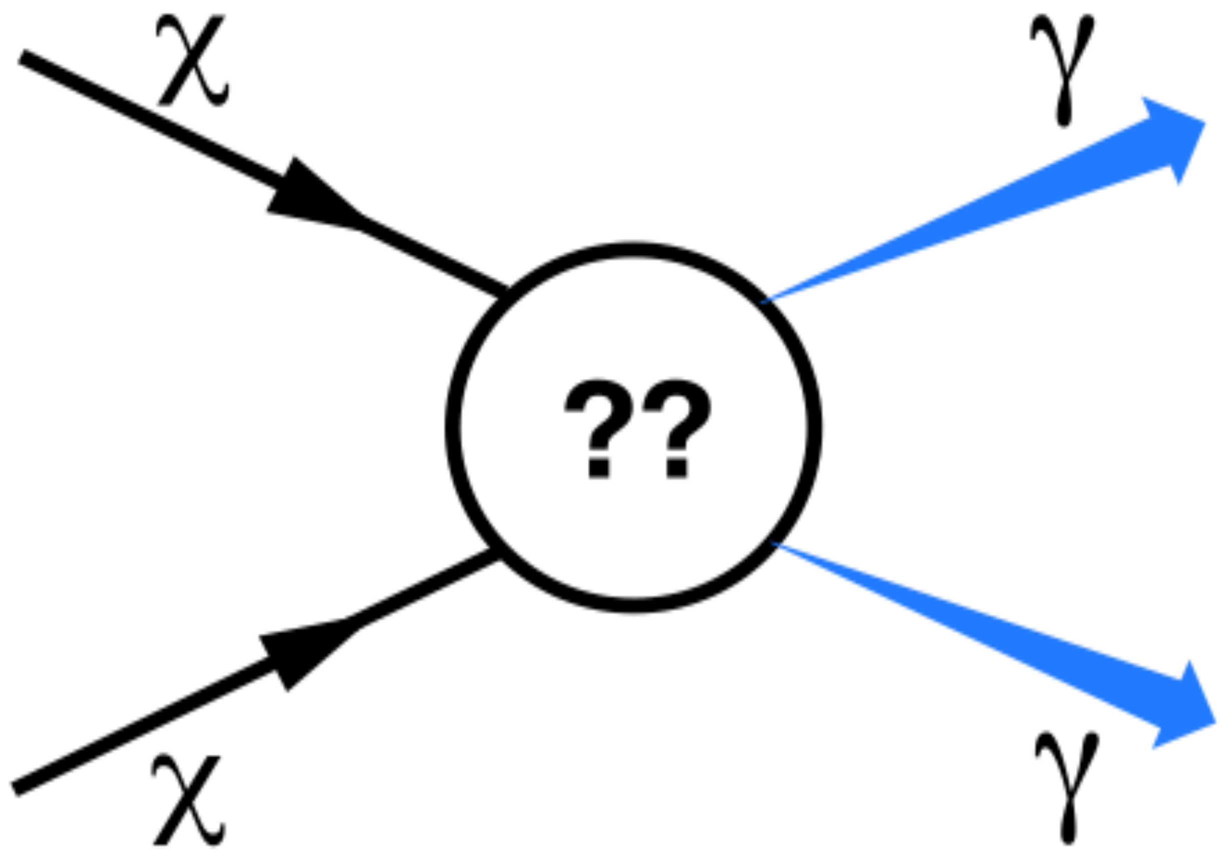


[1009.0224]

Gamma-ray Lines

Note: The prompt flux from neutrinos follows in a similar way as for photons

Perhaps the simplest annihilation spectrum is for annihilation into two gamma rays (or neutrinos). This gives rise to a mono-chromatic photon flux. Each photon carries the rest mass energy of the DM:



$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} = 2\delta(E_\gamma - m_\chi)$$

Considering DM in the mass range GeV-TeV, leads to a spectrum of gamma-rays.

Gamma-ray lines are hard to produce in nature. This would be a ‘smoking gun’ signal of Dark Matter!

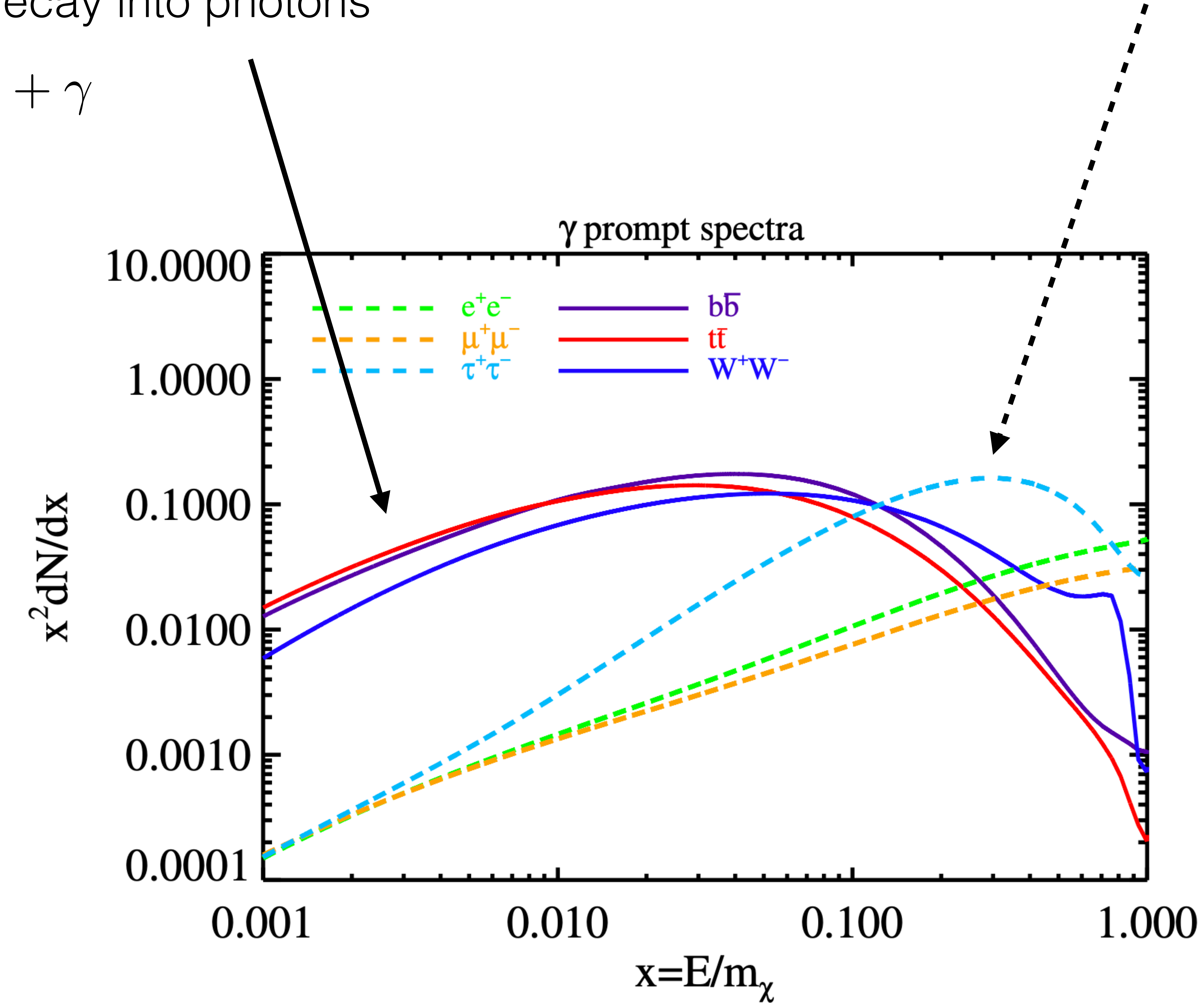
Other annihilation channels still produce gamma rays, but with a less distinctive ‘continuum’ spectrum…

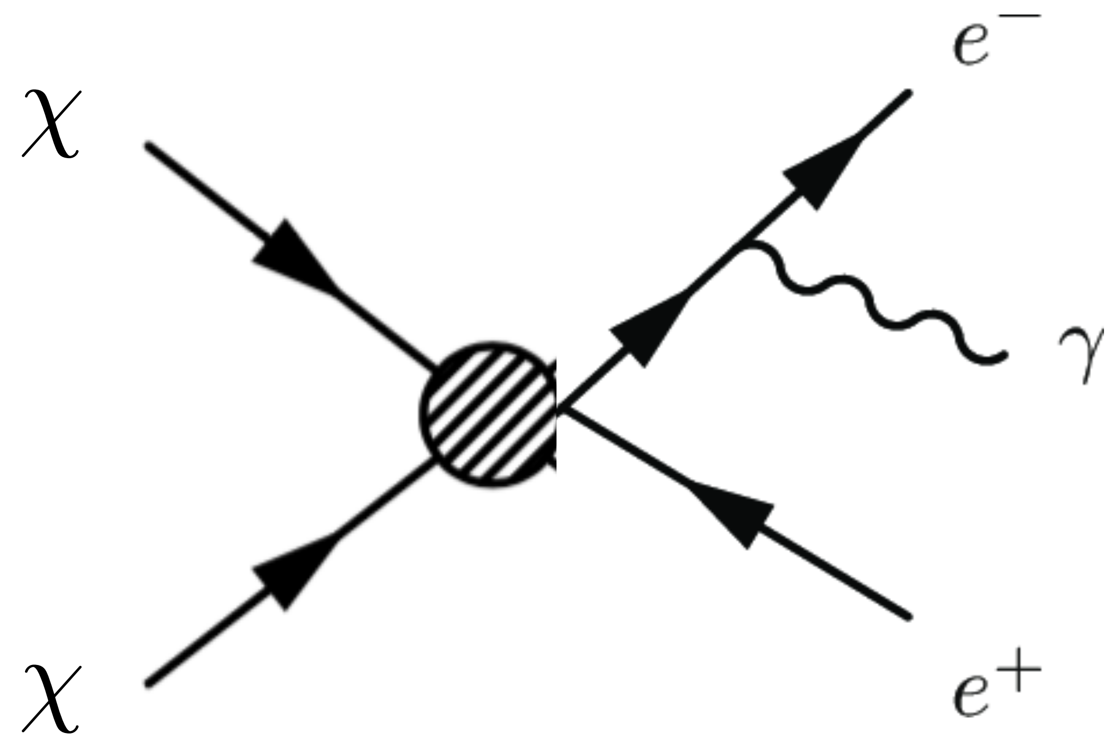
Gamma-ray spectra

Soft channels - hadronisation produces neutral pions which decay into photons

$\pi^0 \rightarrow \gamma + \gamma$

Hard channels - gamma rays from final state radiation

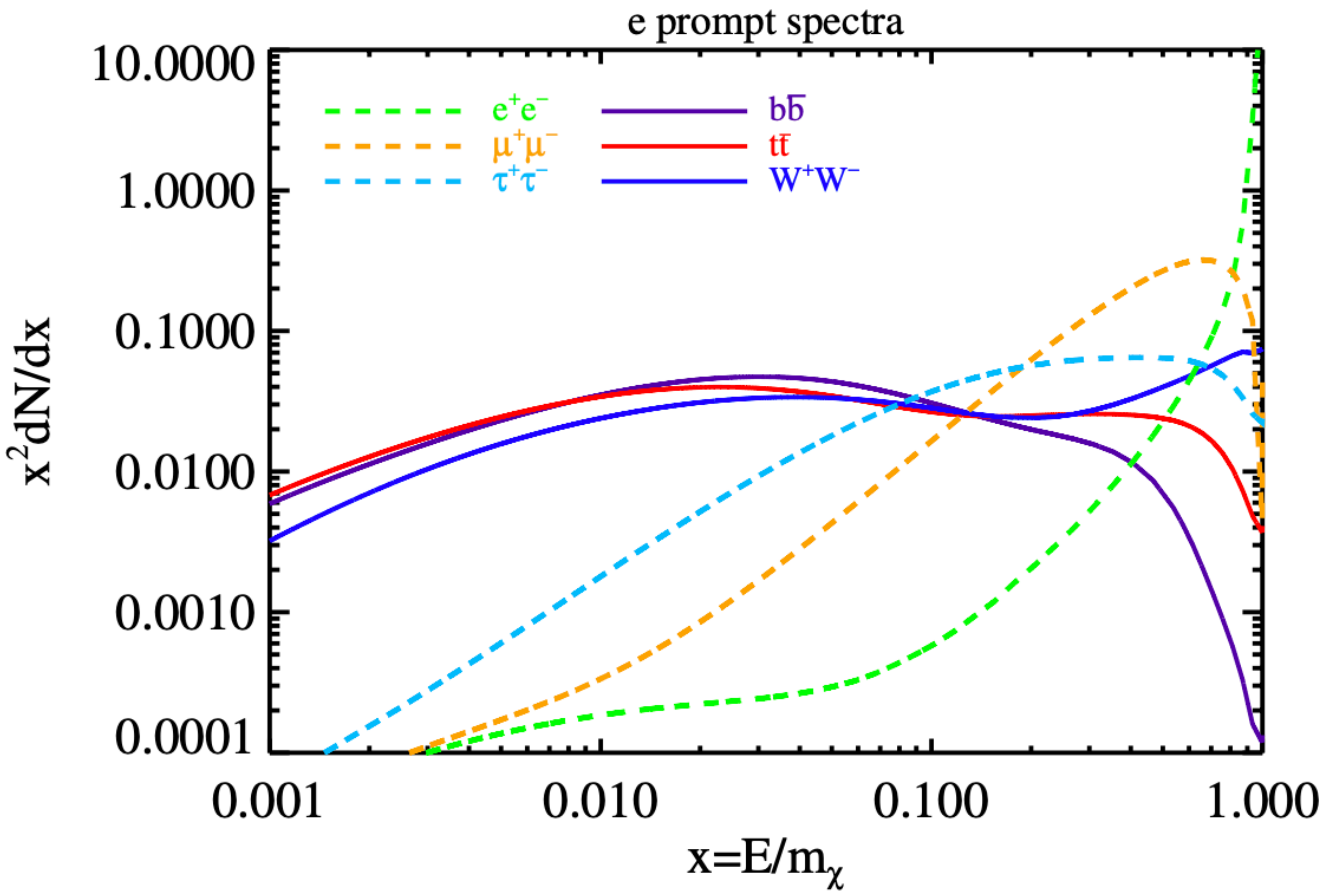


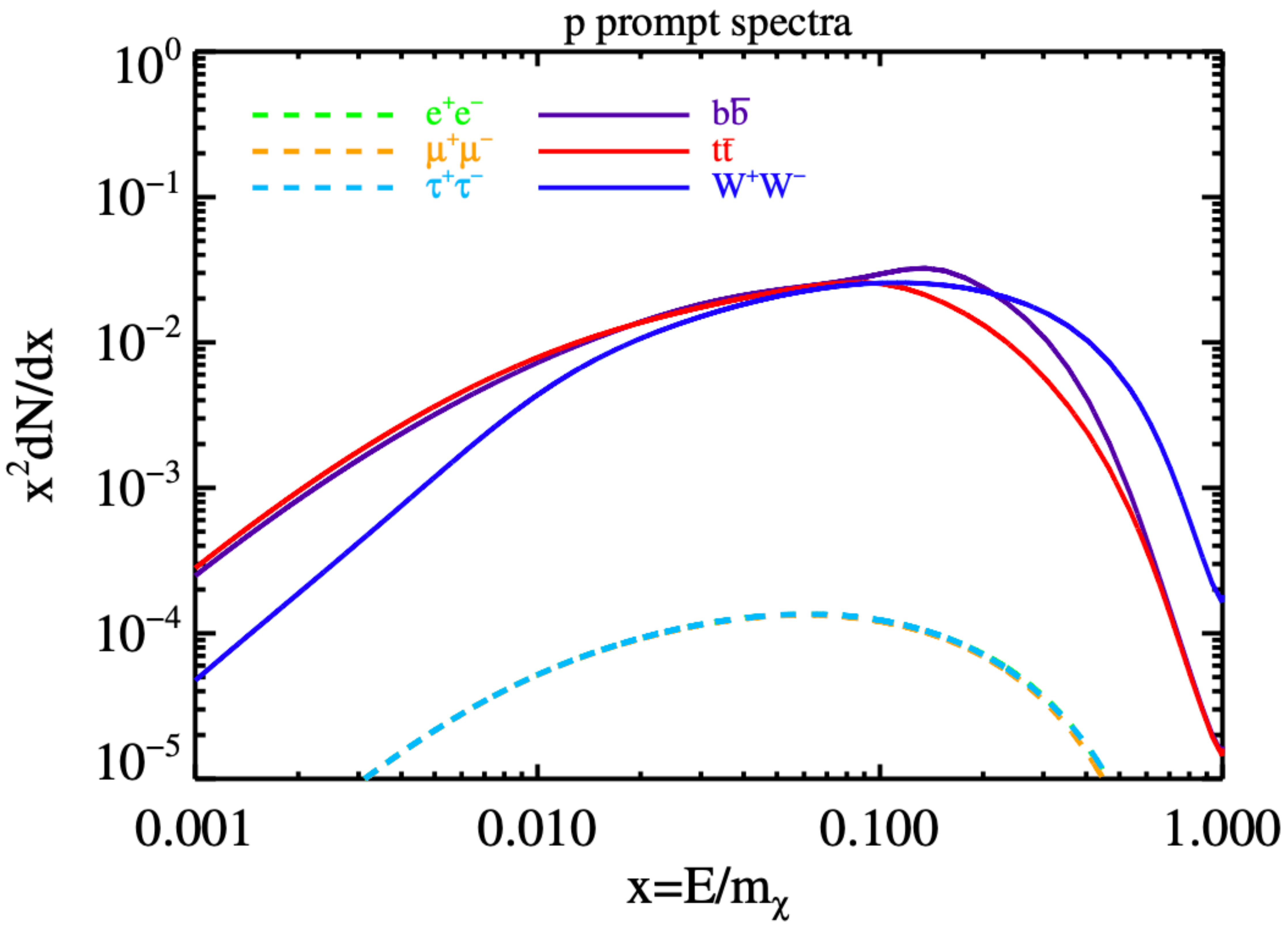


[Tools like PPPC4DMID, 1012.4515; Hazma, 1907.11846, 2207.07634]

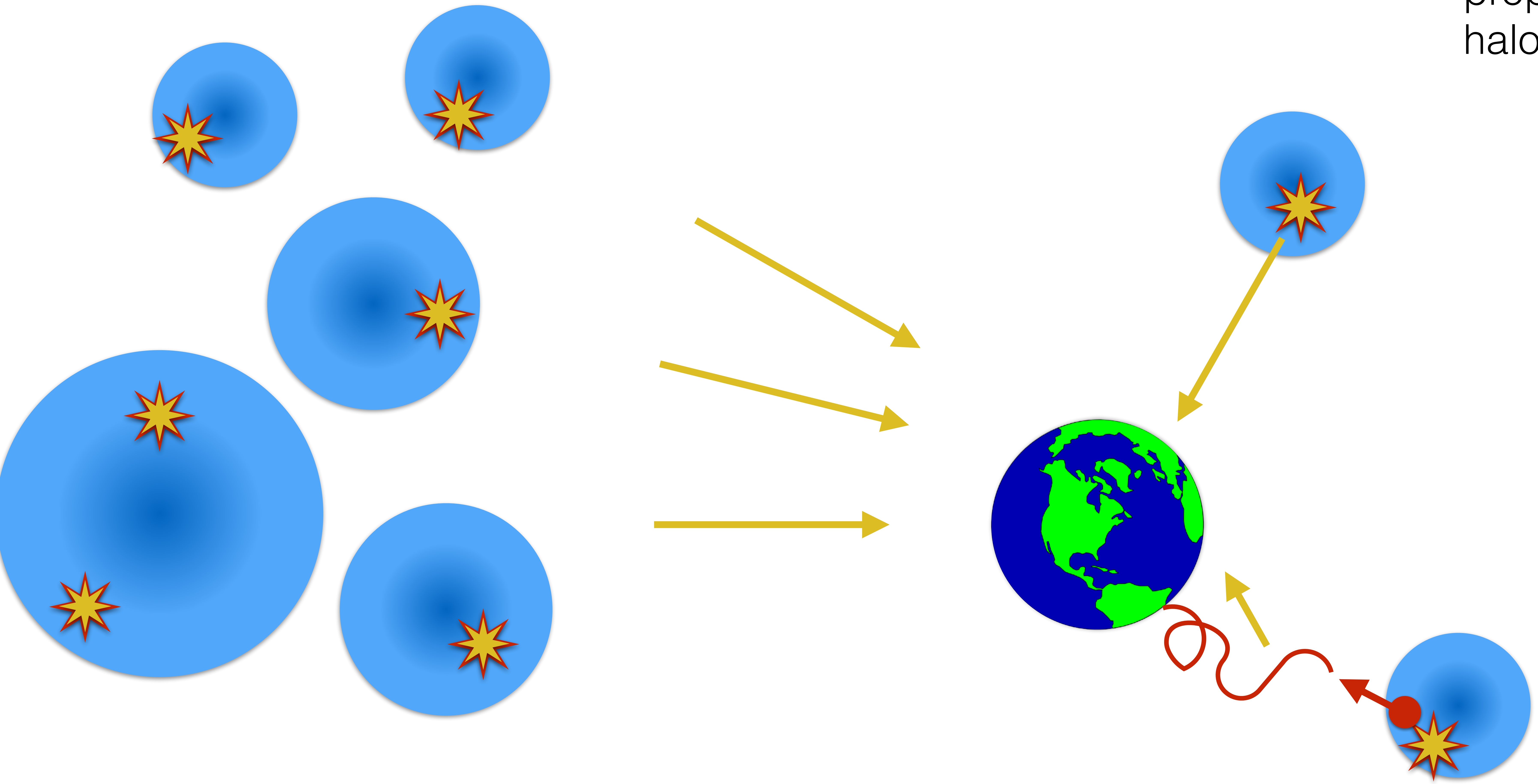
NB: Annihilation to light quarks can be more complicated, due to hadronic resonances.

Charged Particles





Types of Annihilation Signal



① **Prompt:** look for primary annihilation products (photons, neutrinos) which propagate directly to us from DM halos in the local Universe

② **Extragalactic:** look for photons and neutrinos coming from cumulative annihilation of DM across cosmic time

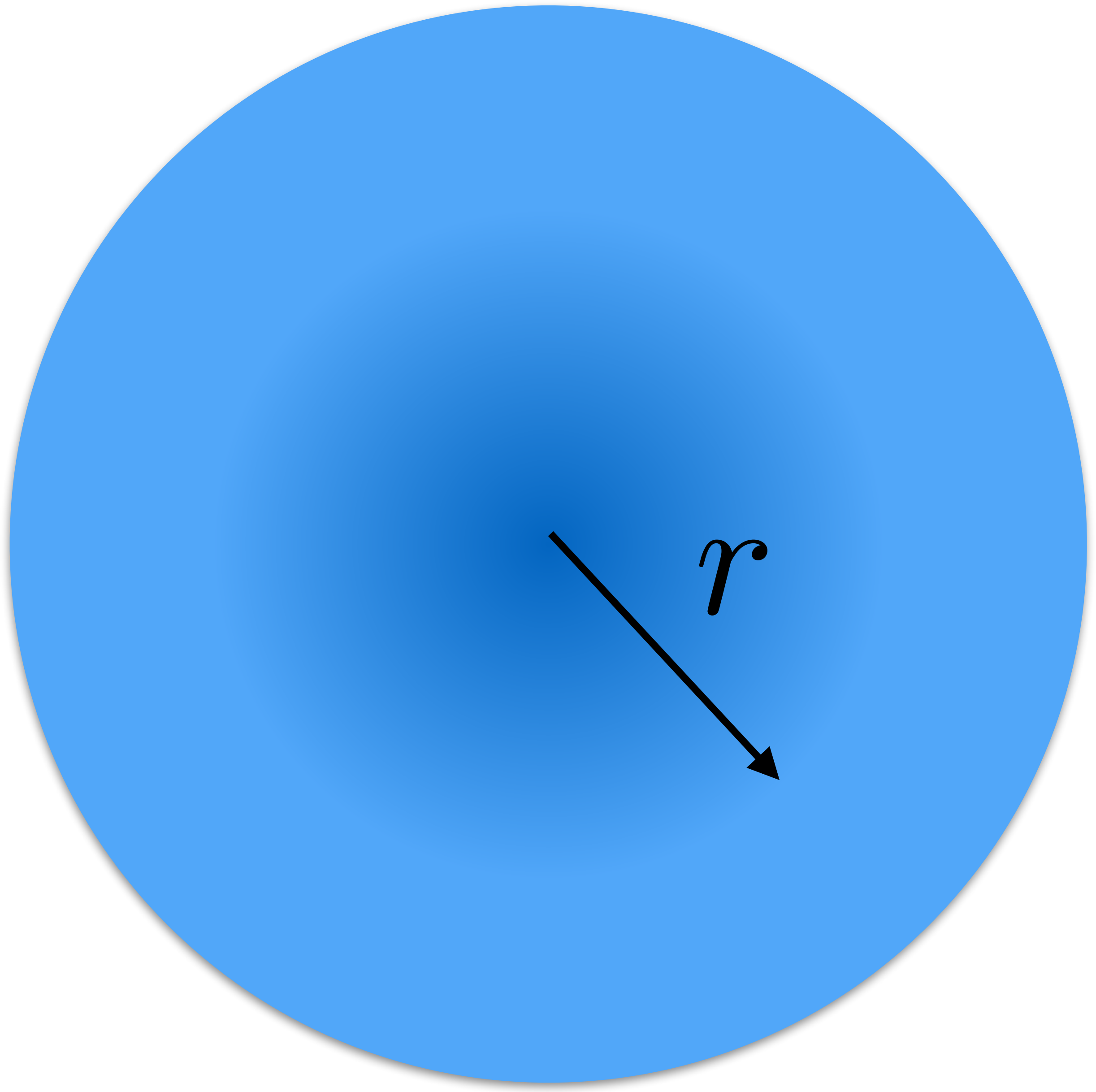
③ **Secondary:** look for annihilation products from the local Universe which undergo secondary effects such as scattering, diffusion,…

DM Annihilation Rates

*Need an extra factor of 1/2 if DM is not its own antiparticle.

Rate of DM annihilation per unit time:*

$$\begin{aligned}\Gamma_{\mathrm{ann}}(r,v) &= \Phi_\chi \times N_T \times \sigma \\ &= \frac{1}{2} n_\chi v \times n_\chi \times \sigma_{\mathrm{ann}}(v) \\ &= \frac{1}{2}\frac{\rho_\chi(r)}{m_\chi} v \times \frac{\rho_\chi(r)}{m_\chi} \times \sigma_{\mathrm{ann}}(v)\end{aligned}$$



Average over velocity distribution of DM particles:

$$\begin{aligned}\langle \Gamma_{\mathrm{ann}}(r)\rangle &= \frac{1}{2}\left(\frac{\rho_\chi(r)}{m_\chi}\right)^2 \times \int \sigma_{\mathrm{ann}}(v) v\, f(\mathbf{v})\,\mathrm{d}^3\mathbf{v} \\ &= \frac{1}{2}\left(\frac{\rho_\chi(r)}{m_\chi}\right)^2 \times \langle \sigma_{\mathrm{ann}} v\rangle\end{aligned}$$

Typical velocity dispersion in Galactic halos and sub-halos:

$$\begin{aligned}\sigma_v &\sim 20 - 200\,\mathrm{km/s}^2 \\ &\sim 10^{-4} - 10^{-3}\,c\end{aligned}$$

Typically, DM velocity dispersion is small, so only consider leading contribution σ_0 (“s-wave”) to annihilation cross section. “P-wave” $\propto (v/c)^2$ is typically suppressed.

$$\sigma(v)v \approx \sigma_0 + \sigma_1 (v/c)^2 + \ldots$$

Prompt photon flux from DM ann.

① **Prompt:** look for primary annihilation products (photons, neutrinos) which propagate directly to us from DM halos in the local Universe

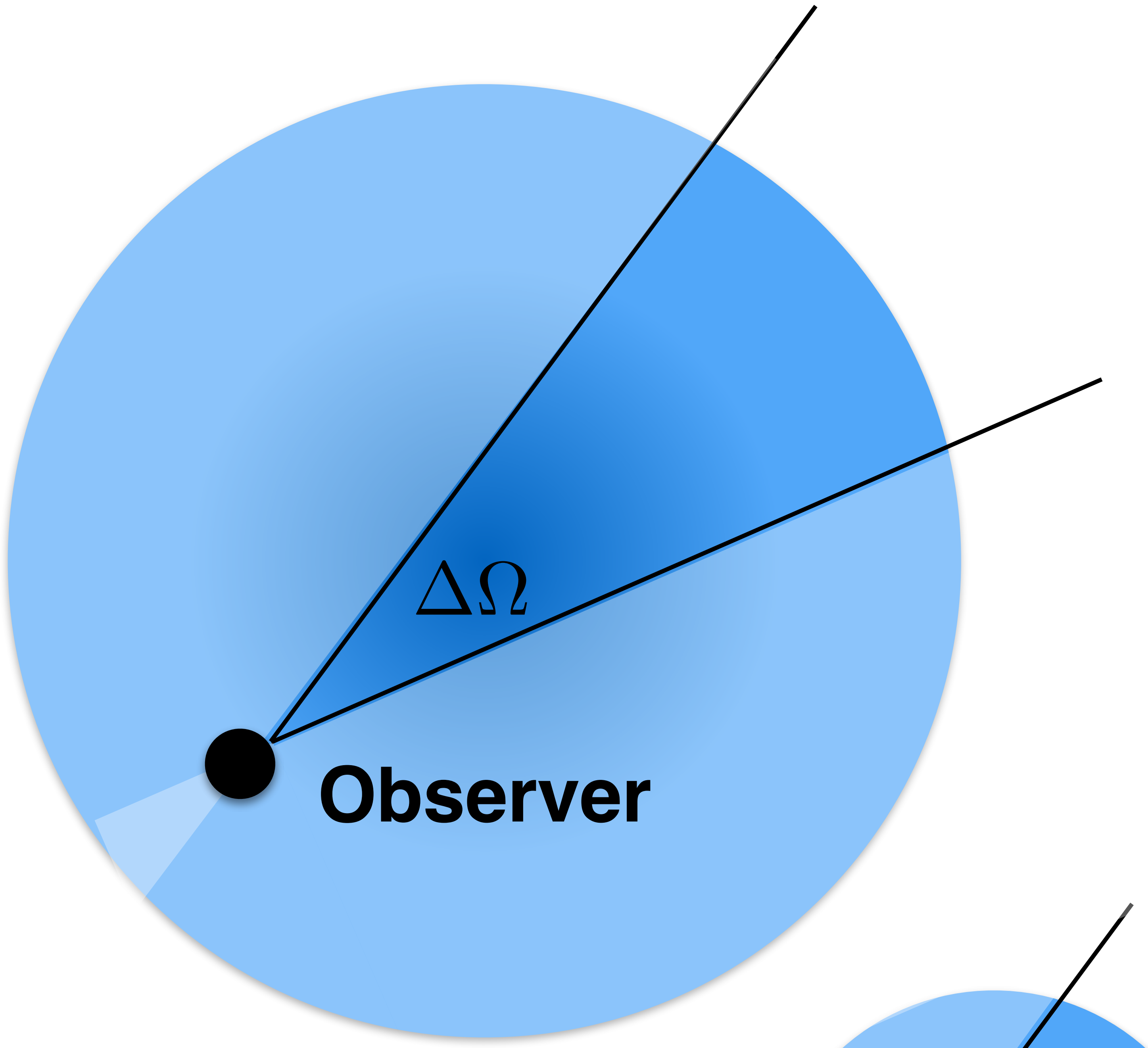
For neutral messengers (photons, neutrinos) from the local Universe.

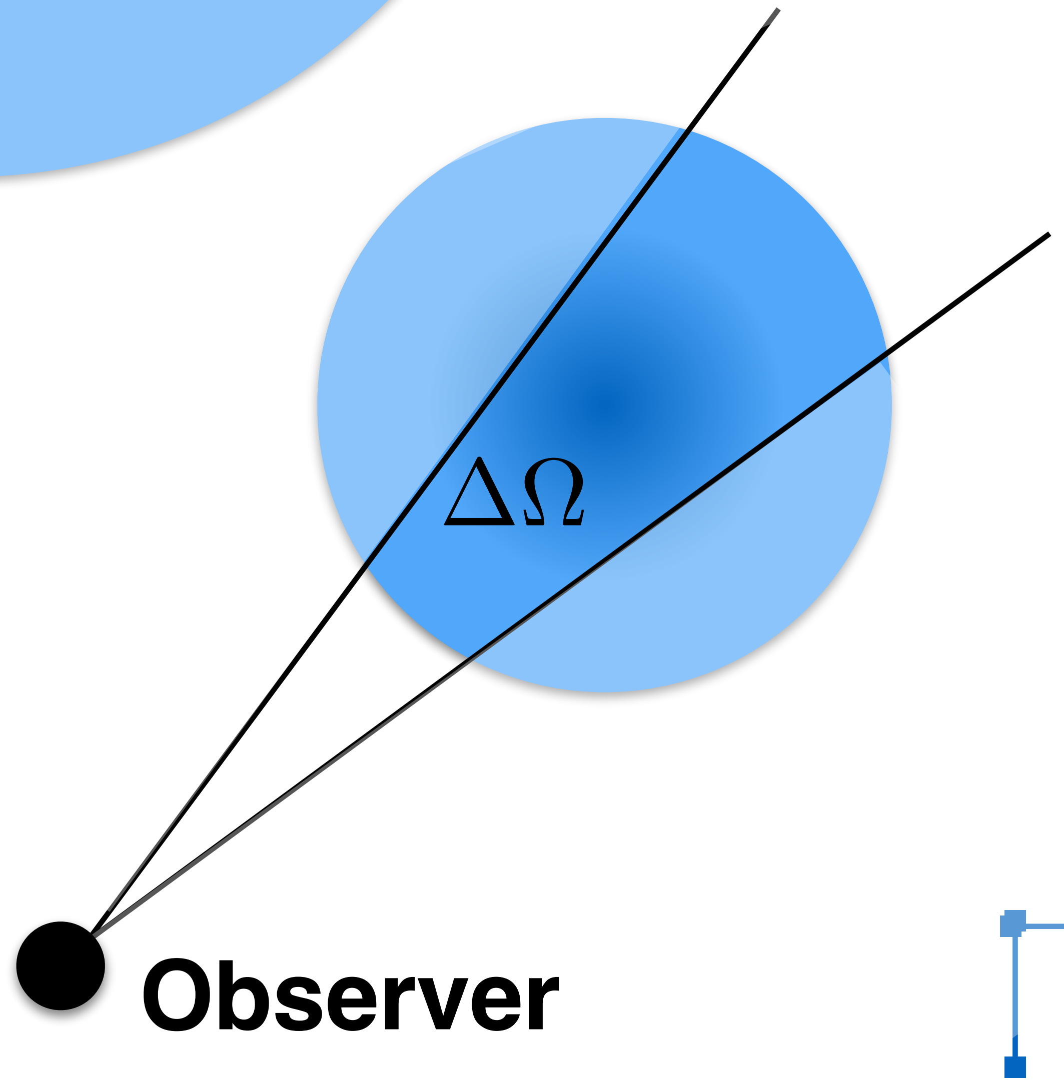
Flux from a single point at a line-of-sight distance ℓ is:

$$\frac{1}{4\pi\ell^2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\langle\Gamma_{\mathrm{ann}}(\mathbf{r})\rangle$$

For an observation over an angular region $\mathbf{\Delta\Omega}$, the total flux is:

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E_\gamma}=\int_{\Delta\Omega}\mathrm{d}^3\mathbf{r}\,\frac{1}{4\pi\ell^2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\langle\Gamma_{\mathrm{ann}}(\mathbf{r})\rangle$$





Annihilation cross section
(particle physics)

Gamma-ray spectrum
(annihilation channel)

DM density distribution
(astrophysics)

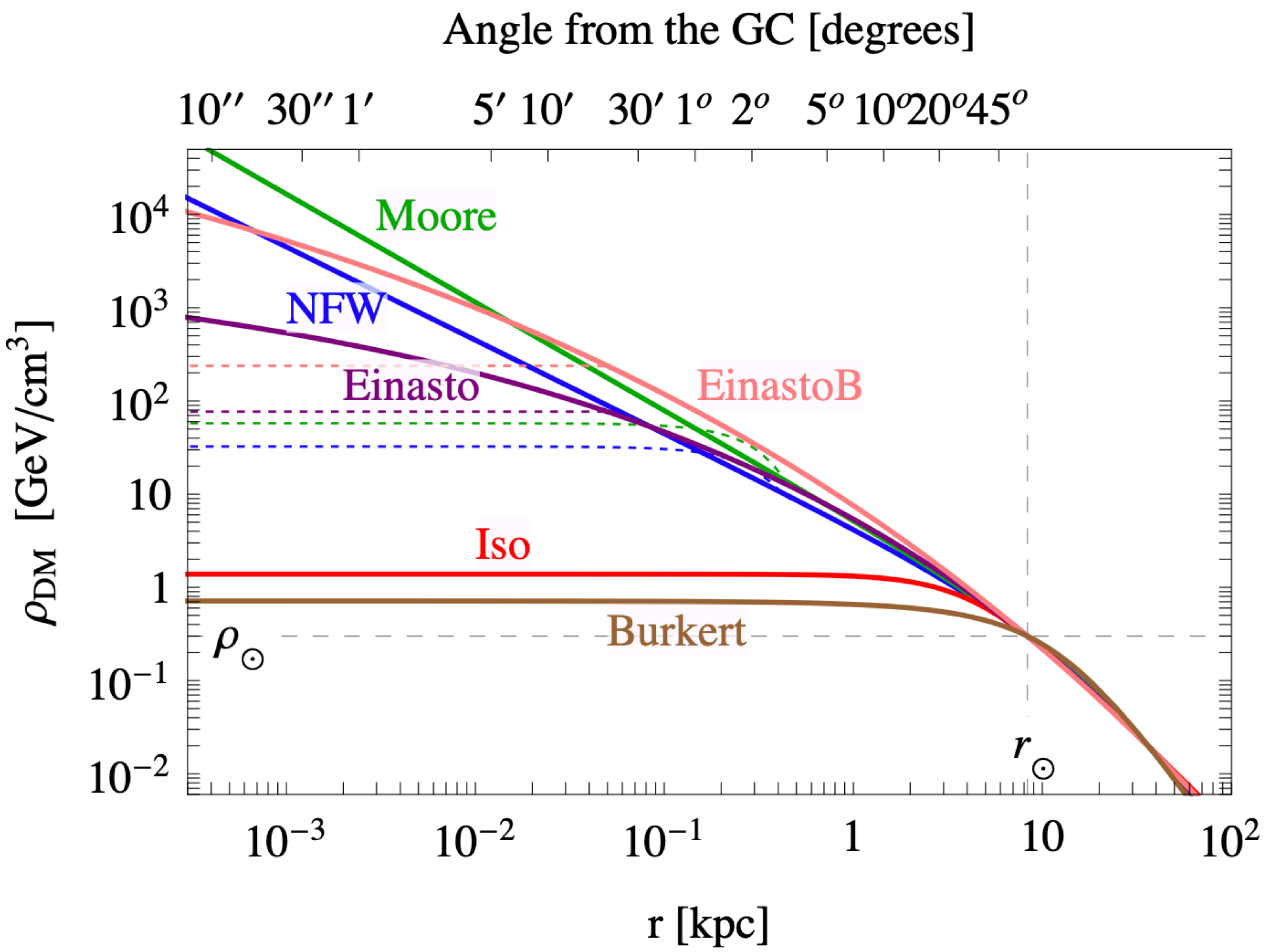
$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E_\gamma}=\frac{1}{4\pi}\frac{\langle\sigma_{\mathrm{ann}}v\rangle}{2m_\chi^2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\times\int_{\Delta\Omega}\mathrm{d}\Omega\int_{\mathrm{los}}\rho_\chi^2(\mathbf{r}(\ell,\theta)\,\mathrm{d}\ell$$

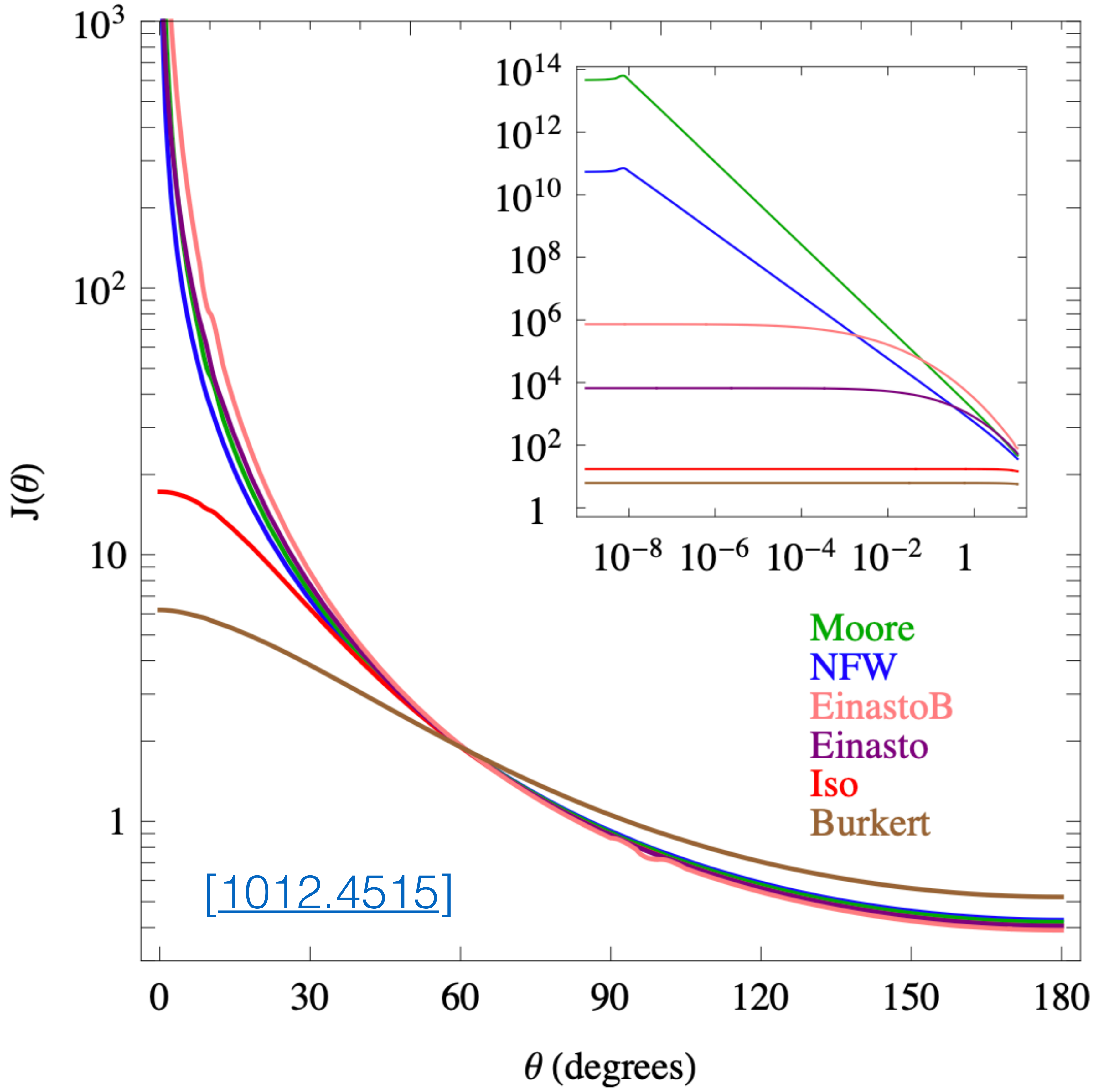
J-factors and Density Profiles

[astro-ph/9611107]

Dependence of photon flux on DM distribution is encapsulated in the **J-factor:**

$$J(\Delta\Omega) \equiv \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{los}} \rho_\chi^2(\mathbf{r}(\ell,\theta)\,\mathrm{d}\ell$$





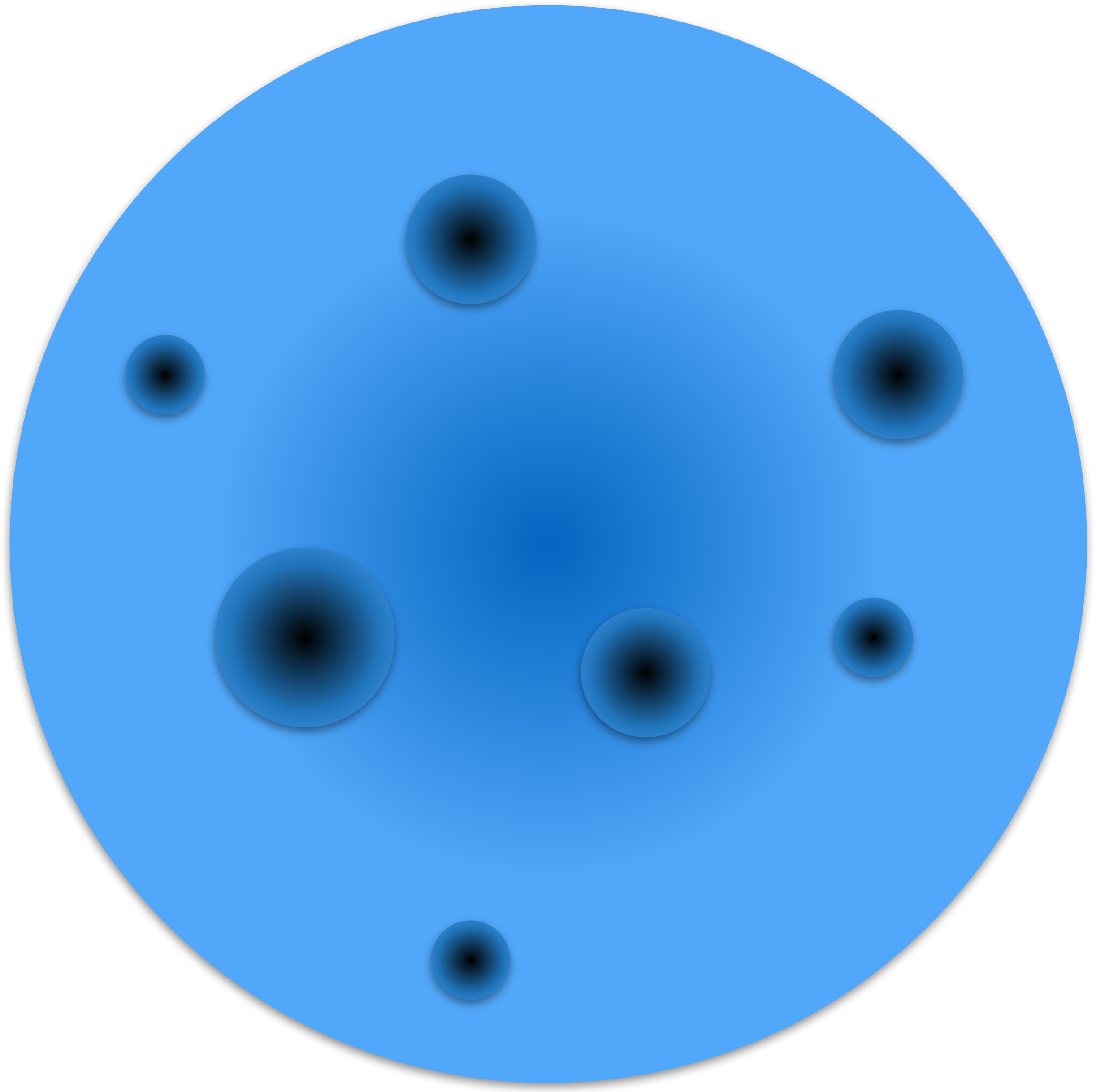
[1012.4515]

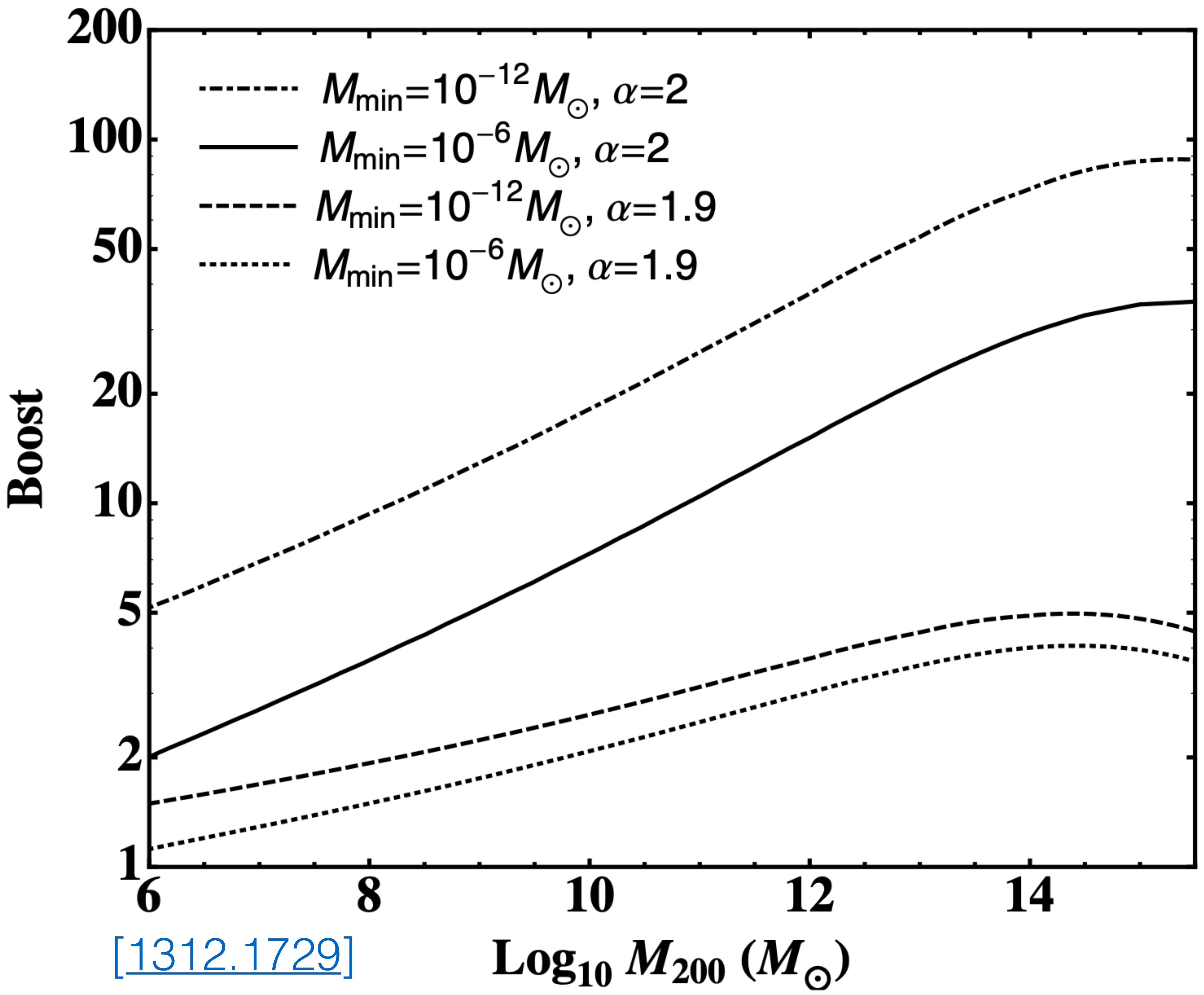
Tomorrow we'll discuss in more detail the estimation of J-factors in Milky Way Dwarf Galaxies…

Boost from Substructure

Because the DM annihilation cross section depends on $\rho_{\rm DM}^2$, it depends sensitively on how the DM is distributed.

Subhalos within larger halos can lead to an enhancement in the flux from DM annihilation (relative to smoothly distributed DM).





[1312.1729]

This Boost factor (ratio of DM luminosity with and without substructure) depends on the host halo mass, but may be substantial (~10).

But estimating the properties and distributions of sub-halos (and sub-sub-halos) is challenging (need to extrapolate to small scales, and include effects of tidal stripping).

[CLUMPY Code, 1201.4728]

Extragalactic Flux Calculation

② **Extragalactic:** look for photons and neutrinos coming from cumulative annihilation of DM across cosmic time

Isotropic background flux from DM annihilation in extragalactic halos.

$$\frac{\mathrm{d}\Phi_{\mathrm{EG}\gamma}}{\mathrm{d}E_\gamma} = \frac{1}{E_\gamma}\int_0^\infty \mathrm{d}z' \frac{c}{H(z')(1+z')} \frac{1}{(1+z')^3} j_{\mathrm{EG}\gamma}\left(E'_\gamma, z'\right) e^{-\tau\left(E_\gamma, z'\right)}$$

Conversion from time to redshift

Dilution of sources with redshift

Gamma-ray absorption

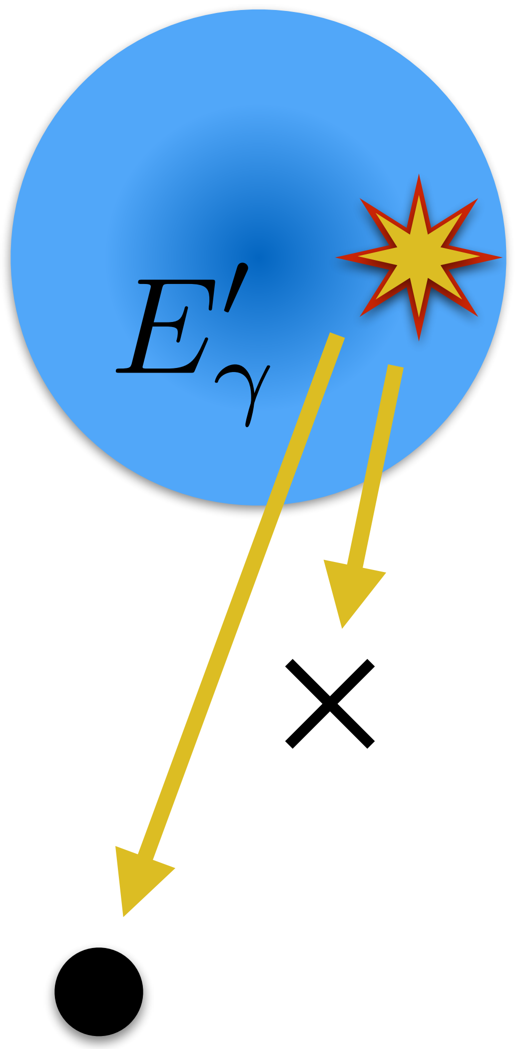
Extragalactic emissivity can be written in analogy with 'local' case:

$$j_{\mathrm{EG}\gamma}\left(E'_\gamma, z'\right) = E'_\gamma \frac{1}{2} B(z') \left(\frac{\bar{\rho}(z')}{M_{\mathrm{DM}}}\right)^2 \langle\sigma v\rangle \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\left(E'_\gamma\right)$$

Cosmological boost factor

Cosmic DM density

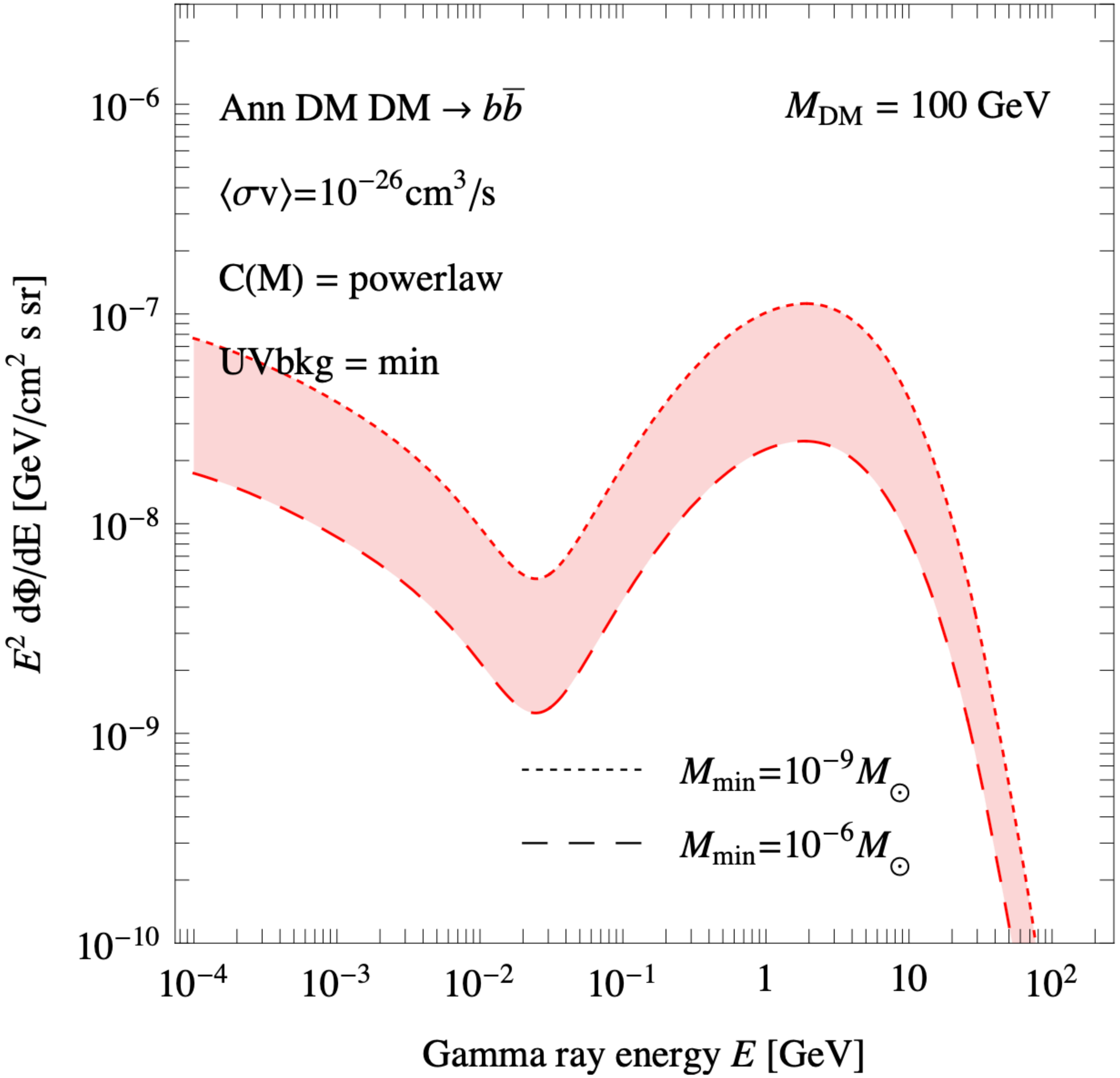
Extragalactic DM halo
$(z = z')$



Observer
$(z = 0)$

$$E_\gamma = E'_\gamma/(1+z')$$

Extragalactic Fluxes



Note that cosmological boost factor can be huge ($\sim 10^6$ at $z < 1$).

Secondary Effects and Propagation

③ **Secondary:** look for annihilation products from the local Universe which undergo secondary effects such as scattering, diffusion,…

DM annihilation can contribute to the local **Cosmic Ray** flux.
But need to worry about propagation!

One way to approach this problem is to write:

“Halo Function”

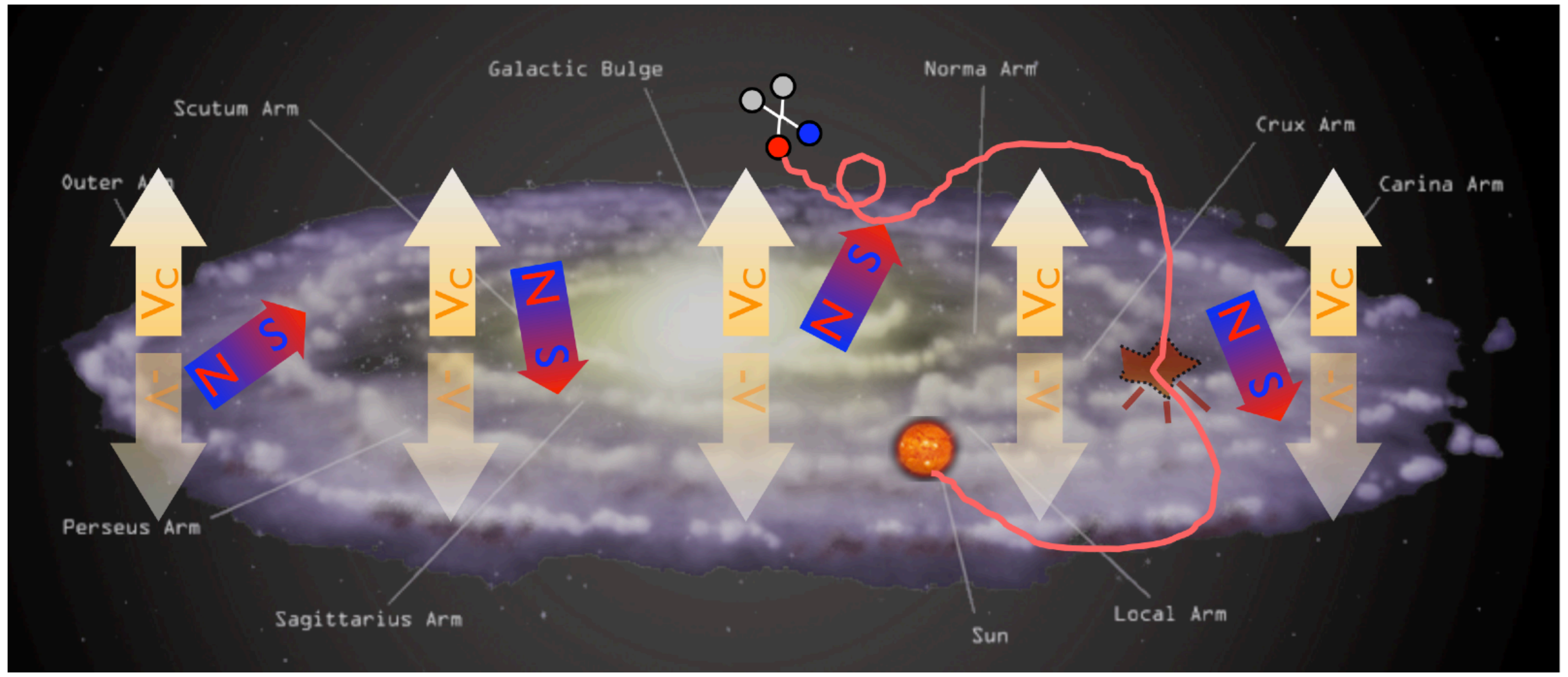
$$\frac{d\Phi_{e^\pm}}{dE}(E,\mathbf{r}) = \frac{v_{e^\pm}}{4\pi b(E,\mathbf{r})}\frac{1}{2}\left(\frac{\rho_\chi(\mathbf{r})}{M_{\rm DM}}\right)^2 \langle\sigma v\rangle \int_E^{M_{\rm DM}} dE_{\rm s}\frac{dN_{e^\pm}}{dE}(E_{\rm s})\, I\left(E,E_{\rm s},\mathbf{r}\right)$$

Energy losses

Injected electron spectrum

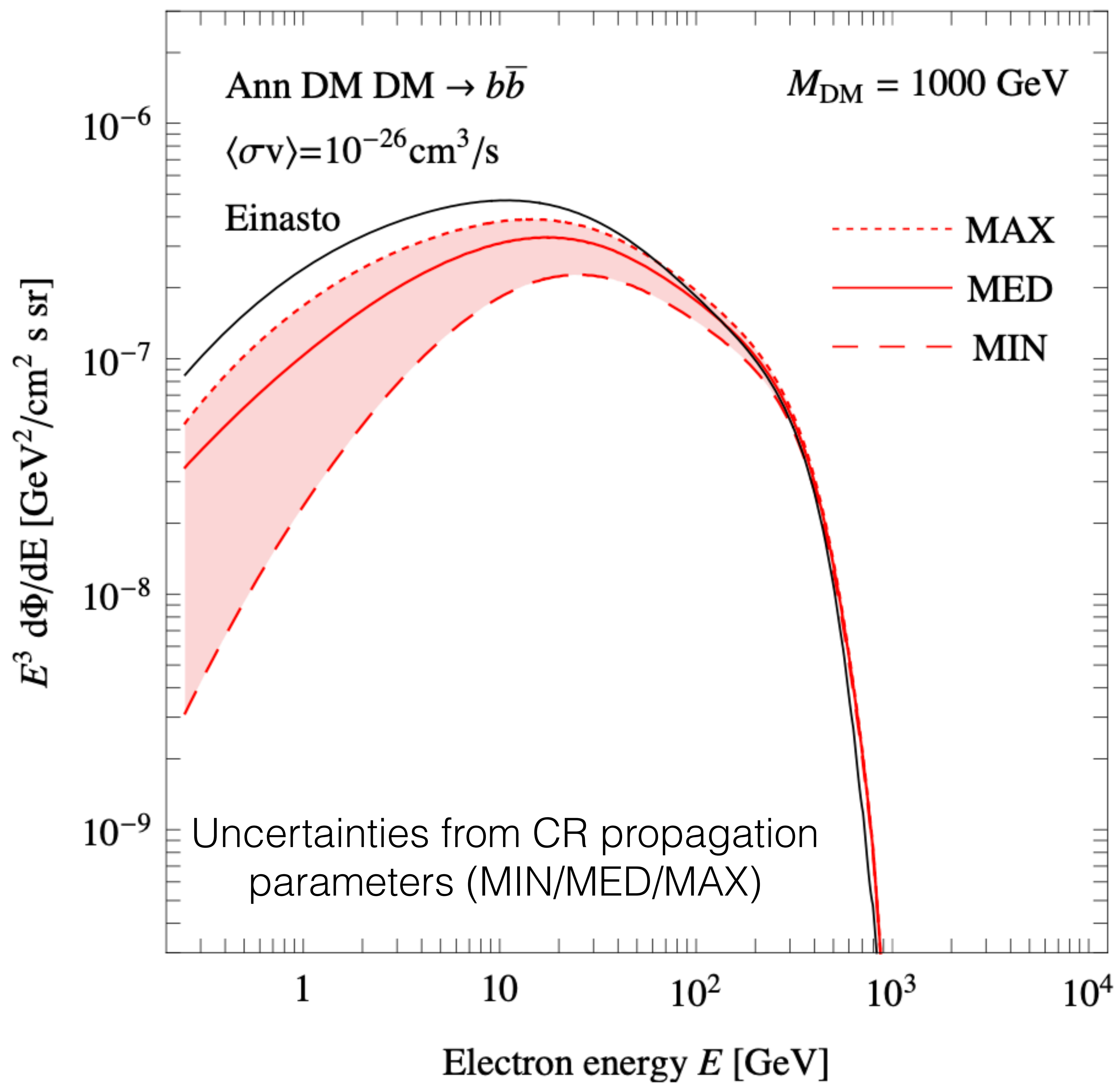
The Halo Function $I(E, E_s, \mathbf{r})$ is essentially a Green’s function, giving the probability of going from an initial ‘source’ electron energy E_s at production to a final energy E. This takes into account the (position-dependent) diffusion and propagation in the Cosmic Ray halo.

For a given CR model, these halo functions can be tabulated, or more detailed CR propagation modelling can be performed.

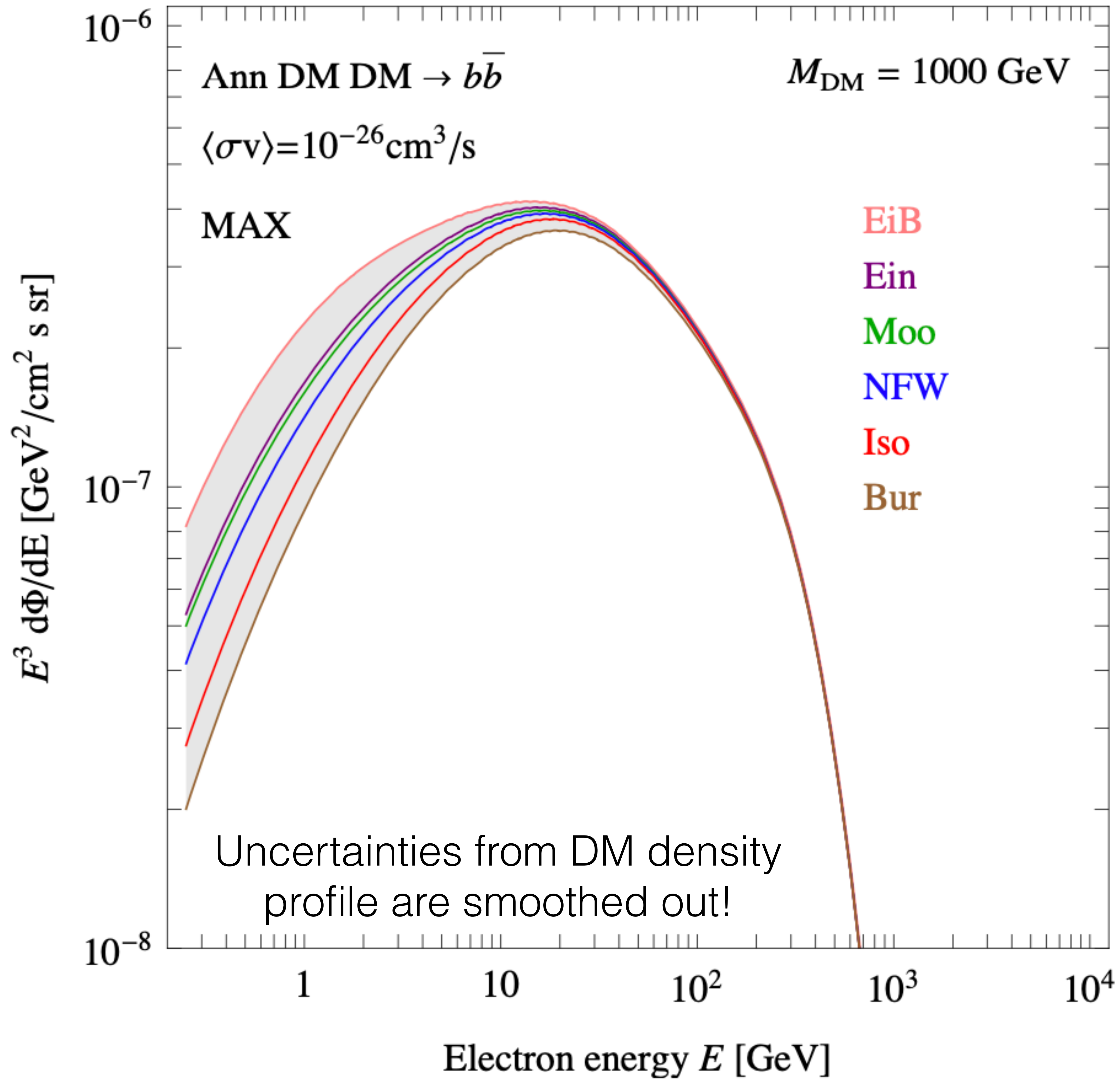


See Astroparticle physics Lecture 2

Electron Flux from DM annihilation



Uncertainties from CR propagation parameters (MIN/MED/MAX)

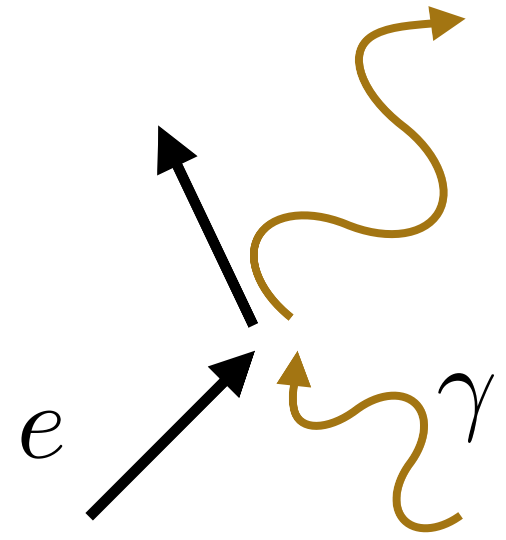


Uncertainties from DM density profile are smoothed out!

Synchrotron and Inverse Compton

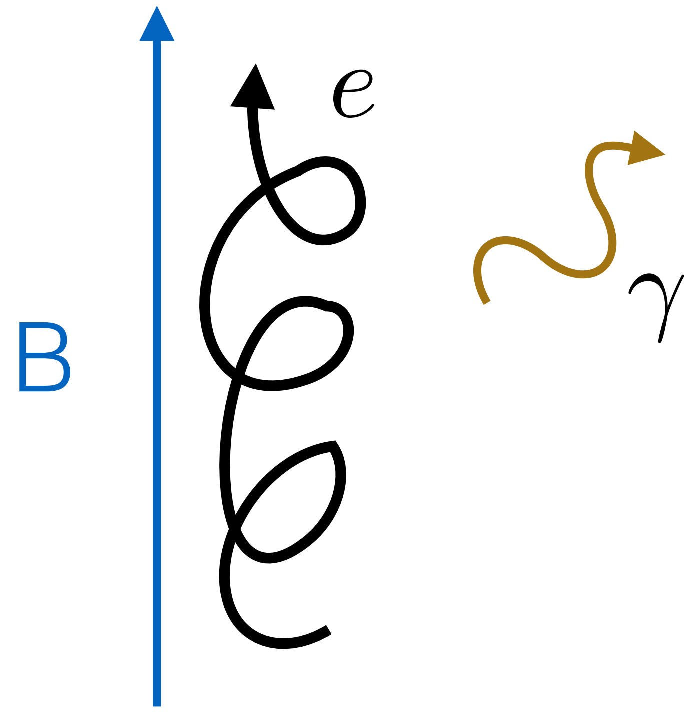
See Astroparticle physics Lecture 2

Energetic $e^{\pm}$ which are injected by Dark Matter annihilation can be 'reprocessed' to give a secondary photon signal:



Inverse Compton scattering (ICS) - Upscattering of background photons (e.g. CMB, starlight) by energetic $e^{\pm}$

For electrons with Lorentz factor $\gamma = E_e/m_e$, the upscattered photon goes from an energy $E_0 \to E \approx 4\gamma^2 E_0$.



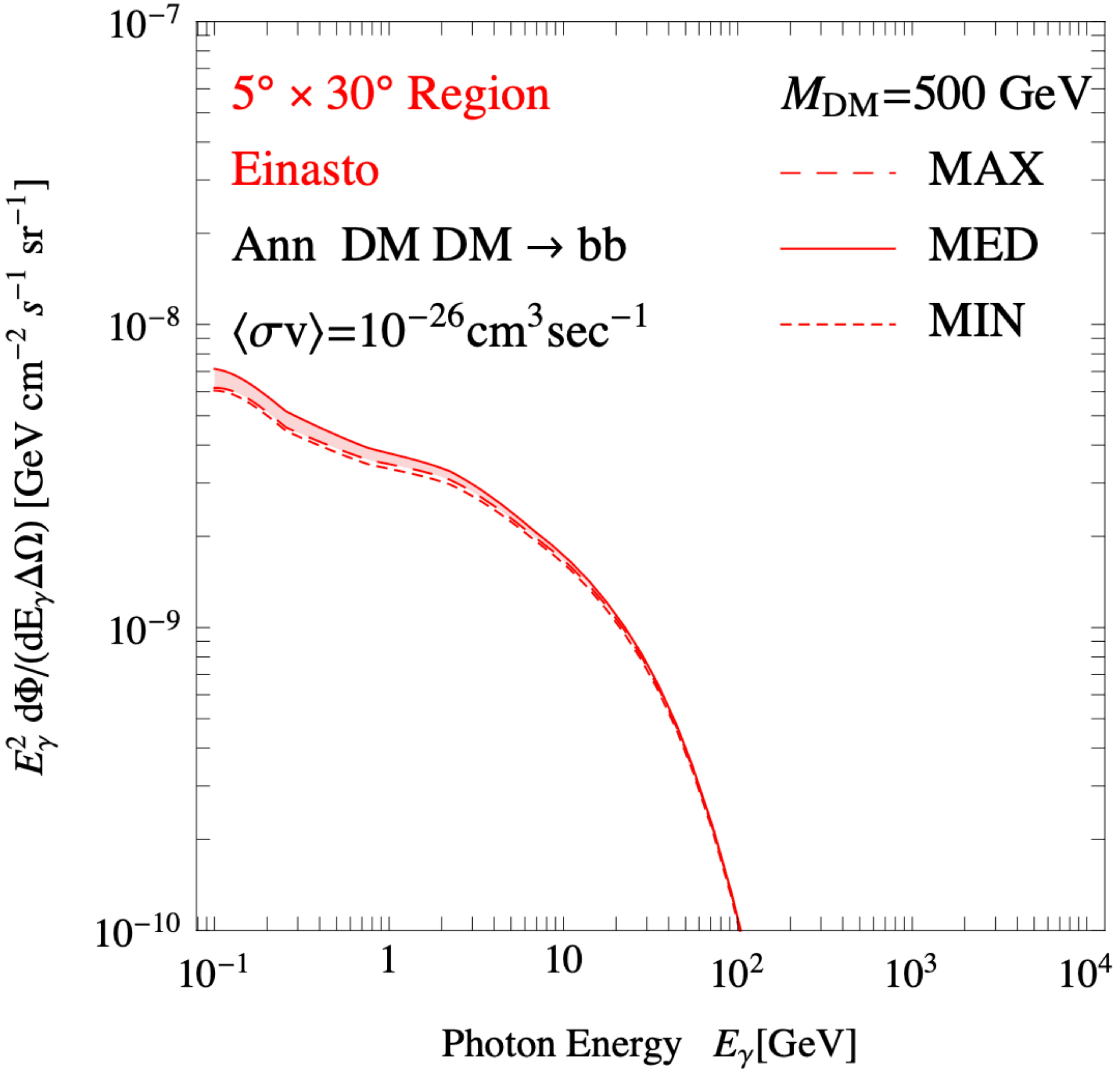
Electron synchrotron - Photon emission by energetic $e^{\pm}$ in a strong magnetic field

Calculation of fluxes is more complicated than for prompt emission: need to convolve the injected $e^{\pm}$ spectrum with the ICS/synchrotron power and then integrate over lines of sight.

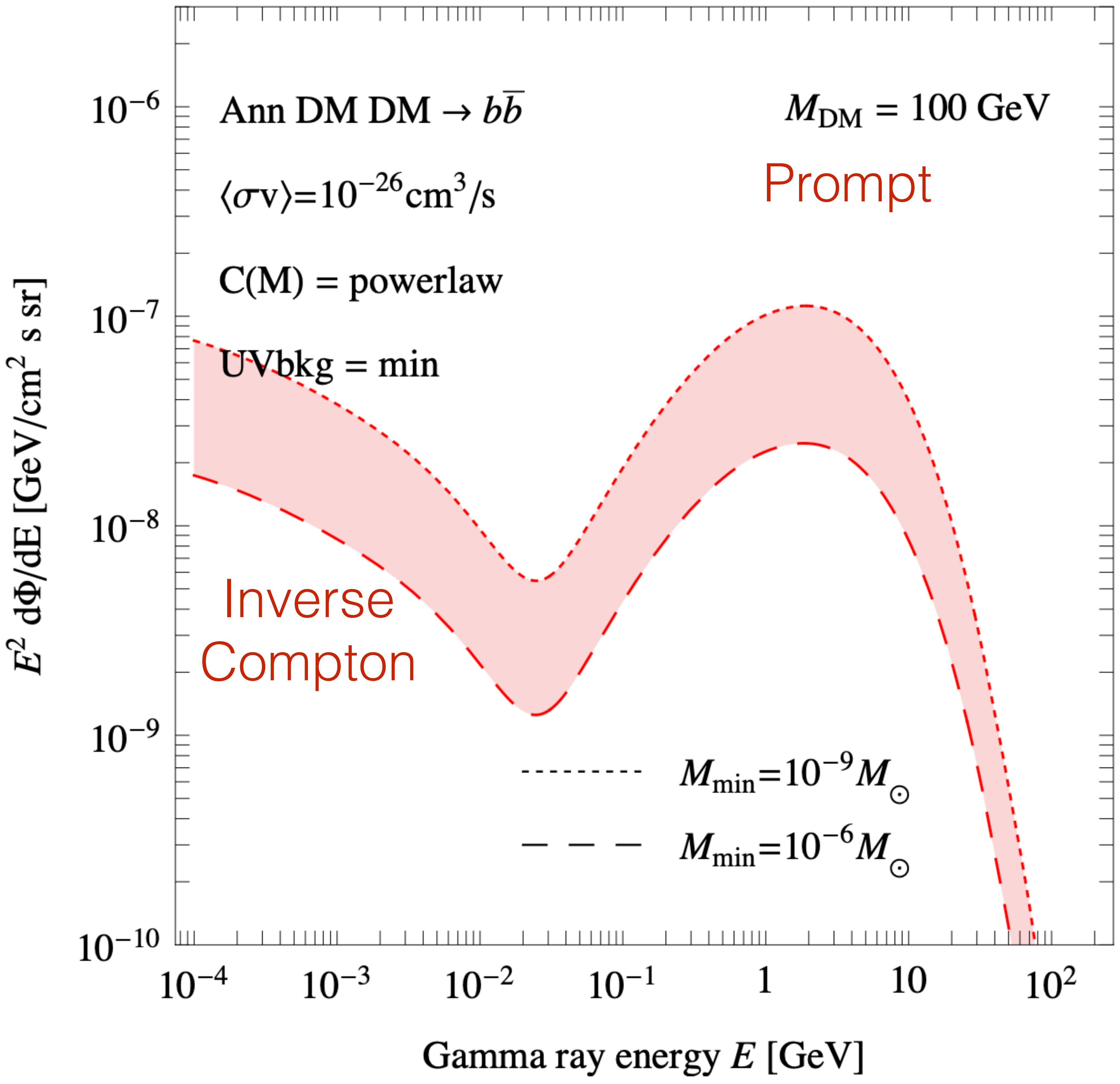
[See e.g. 1012.4515 for a detailed treatment]

ICS Gamma Rays

Relativistic electrons ($\gamma \sim 10^5$) can upscatter optical photons ($E_0 \sim \text{eV}$) to GeV energies



Extragalactic flux in fact also includes a contribution from Inverse Compton scattering (ICS)



Decaying Dark Matter

So far we have only considered DM annihilation: $\chi + \chi \to \mathrm{SM} + \mathrm{SM}$

In principle, DM may be unstable, with a long lifetime $\tau \gtrsim t_{\mathrm{Univ}}$. In that case, we could also look for signatures of **DM decay**: $\chi \to \mathrm{SM} + \mathrm{SM}$.

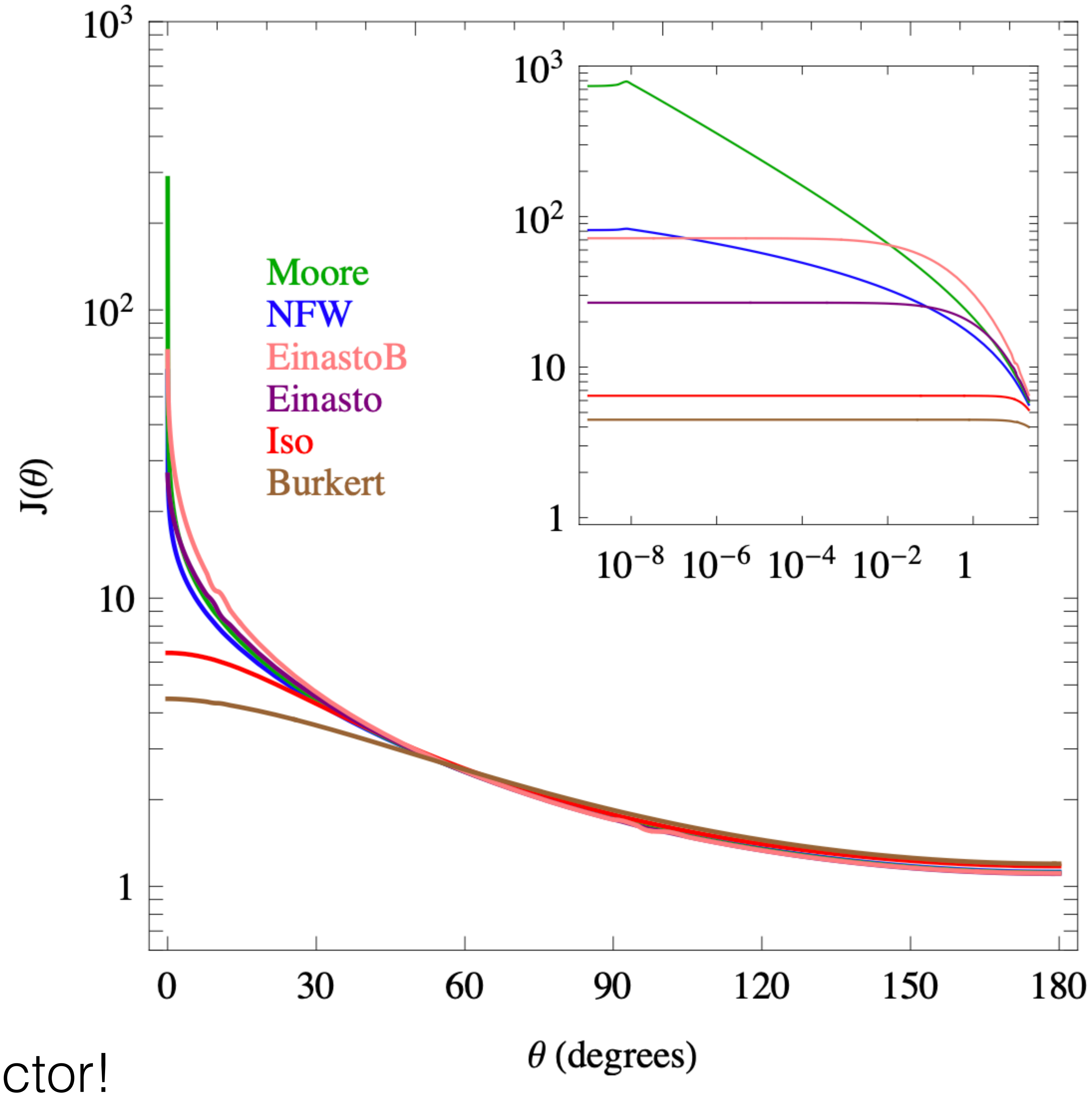
Indirect detection signatures for decaying DM are similar, but scale as ρ_χ / m_χ rather than $(\rho_\chi / m_\chi)^2$.

Relevant astrophysical quantity is now the D-factor:

$$D(\Delta\Omega) \equiv \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{los}} \rho_\chi(\mathbf{r}(\ell,\theta)\,\mathrm{d}\ell$$

C.f. J-factor:

$$J(\Delta\Omega) \equiv \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{los}} \rho_\chi^2(\mathbf{r}(\ell,\theta)\,\mathrm{d}\ell$$



No boost factor!

Summary

[Tools like PPPC4DMID, 1012.4515; Hazma, 1907.11846, 2207.07634]

① **Prompt:** look for primary annihilation products (photons, neutrinos) which propagate directly to us from DM halos in the local Universe

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\frac{\langle\sigma_{\mathrm{ann}}v\rangle}{2m_\chi^2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \times \int_{\Delta\Omega}\mathrm{d}\Omega\int_{\mathrm{los}}\rho_\chi^2(\mathbf{r}(\ell,\theta)\,\mathrm{d}\ell \equiv \frac{1}{4\pi}\frac{\langle\sigma_{\mathrm{ann}}v\rangle}{2m_\chi^2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\times J(\Delta\Omega)$$

② **Extragalactic:** look for photons and neutrinos coming from cumulative annihilation of DM across cosmic time

$$\frac{\mathrm{d}\Phi_{\mathrm{EG}\gamma}}{\mathrm{d}E_\gamma} = \frac{1}{E_\gamma}\int_0^\infty \mathrm{d}z'\,\frac{c}{H\left(z'\right)\left(1+z'\right)}\frac{1}{\left(1+z'\right)^3} j_{\mathrm{EG}\gamma}\left(E'_\gamma, z'\right) e^{-\tau\left(E_\gamma, z'\right)}$$

③ **Secondary:** look for annihilation products from the local Universe which undergo secondary effects such as scattering, diffusion,…

$$\frac{d\Phi_{e^\pm}}{dE}(E,\mathbf{r}) = \frac{v_{e^\pm}}{4\pi b(E,\mathbf{r})}\frac{1}{2}\left(\frac{\rho_\chi(\mathbf{r})}{M_{\mathrm{DM}}}\right)^2\langle\sigma v\rangle\int_E^{M_{\mathrm{DM}}} dE_{\mathrm{s}}\frac{dN_{e^\pm}}{dE}\left(E_{\mathrm{s}}\right) I\left(E, E_{\mathrm{s}}, \mathbf{r}\right)$$