DM-induced electromagnetic signals:

from radio to gamma rays

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Outline

- Types of signals
- Targets
- Statistical correlations

Outline/1

Types of signals

- Prompt γ-ray emissions:
  - Production and decay of π^0
  - Final state radiation
  - Direct emission (monochromatic line)
  - Other (model dependent) features

- Radiative emissions of e^+-e^-:
  - Inverse Compton scattering
  - Synchrotron radiation
  - (Non-thermal) bremsstrahlung
  - Few words on other processes

- Multi-wavelength perspective

Outline / 2

Targets

- The Galaxy: - Galactic center
  - Milky-Way halo
  - Subhalos
- Dwarf spheroidal galaxies
- Clusters of galaxies
- Other galaxies
- Cosmological emission

Outline / 3

Statistical correlations

- Extragalactic multi-wavelength background

- Halo model

- 1-point correlation
- 2-point angular power spectrum

- Auto- and cross-correlations

Instructions

Huge topic, I had to do some selection.

Lectures trying to balance between **physical concepts** and latest results.

General references:

- Particle Dark Matter and signals:

  "Particle Dark Matter: Observations, Models and Searches", Edited by G. Bertone, Cambridge University Press 2010.

- Non-thermal emissions:

  G. Rybicki and A.P. Lightman, 1979, 'Radiative Processes in Astrophysics', John Wiley & Sons Inc.

  M. S. Longair, 2011, 'High Energy Astrophysics', Cambridge University Press.

- Halo model:

  A. Cooray abd R. Sheth, 'Halo models of large scale structure', Physics Reports, Volume 372, 2002.

Two key-assumptions

1) Dark Matter (DM) exists

and

is the main responsible for the gravitational potential inferred

in galaxies, clusters and cosmo.

2) Dark matter is non-gravitationally coupled

to standard matter

Indirect detection

Annihilations (or decays) of DM particles

in astrophysical objects

generate fluxes of "standard" detectable particles.

Energy of the process set by the **DM mass ~ GeV-TeV**

Indirect detection channels

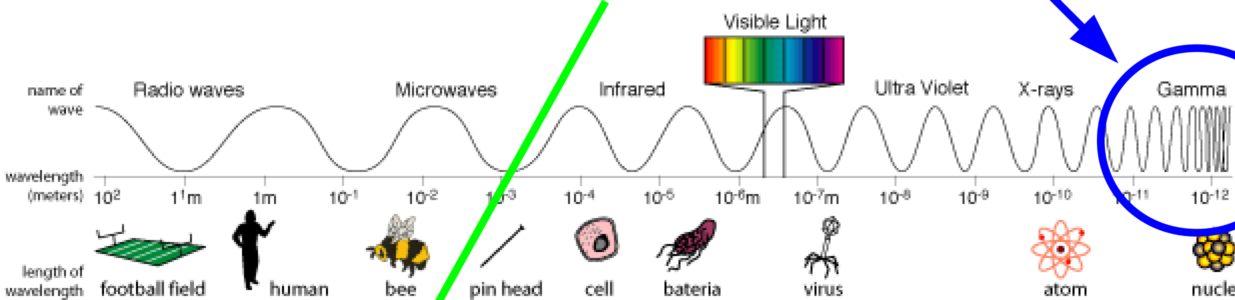
WIMPs are a primary source of

high-energy charged cosmic-rays,

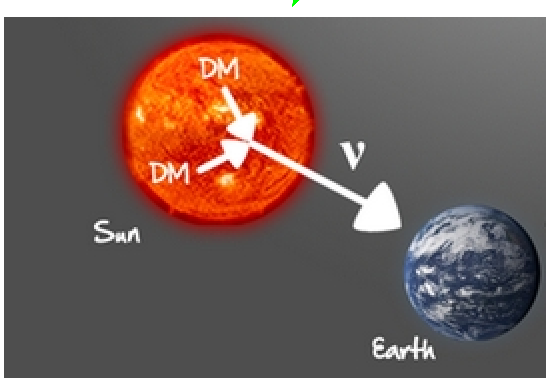
gamma-rays

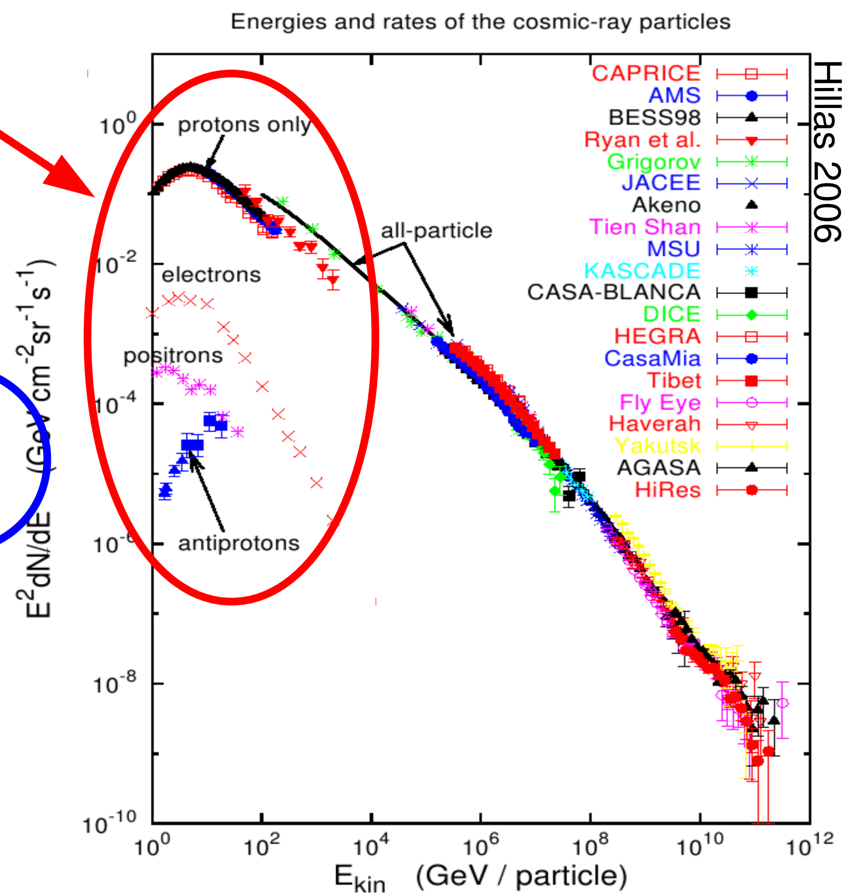
and

neutrinos



NASA image





Or of X-rays in case of keV dark matter (as e.g. sterile neutrinos)

DM source

Velocity averaged annihilation rate

Spectrum (number of particles i emitted per annihilation in the energy interval (E, E + dE))

Annihilating DM: $$Q_i^a(r,E) = \langle \sigma_a v \rangle \times \mathcal{N}_{pairs}(r) \times \sum_f B_f \frac{dN_i^f}{dE}(E)$$

DM spatial profile

$$\mathcal{N}_{pairs}(r) = \frac{\rho(r)^2}{2\,M_\chi^2}$$

DM mass

decay rate

Spectrum (number of particles i emitted per decay in the energy interval (E, E + dE))

Decaying DM: $$Q_i^d(r,E) = \Gamma_d \times \mathcal{N}_{DM}(r) \times \sum_f B_f \frac{dN_i^f}{dE}(E)$$

$$\mathcal{N}_{DM}(r) = \frac{\rho(r)}{M_\chi}$$

Indirect signals

What is the annihilation/decay rate we shoud aim to test?

Annihilating DM → WIMP miracle $\langle \sigma v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$

Decaying DM → no strongly compelling value but ...

(GeV-TeV)

GUT-scale suppressed DM number violating dimension-six operators

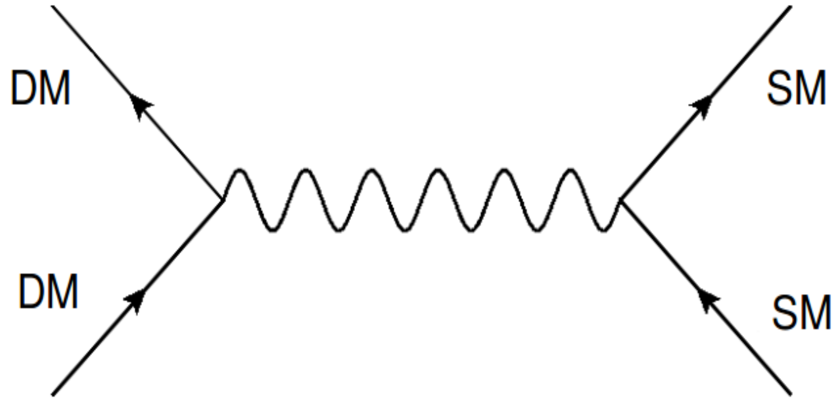
(which gained some attention in connection to the PAMELA excess):

$$\Gamma_6 \sim \frac{1}{M^4} m_\chi^5$$

$$\tau_6 \sim 10^{27}\ \mathrm{s} \left(\frac{1\ \mathrm{TeV}}{m_\chi}\right)^5 \left(\frac{M}{10^{16}\ \mathrm{GeV}}\right)^4$$

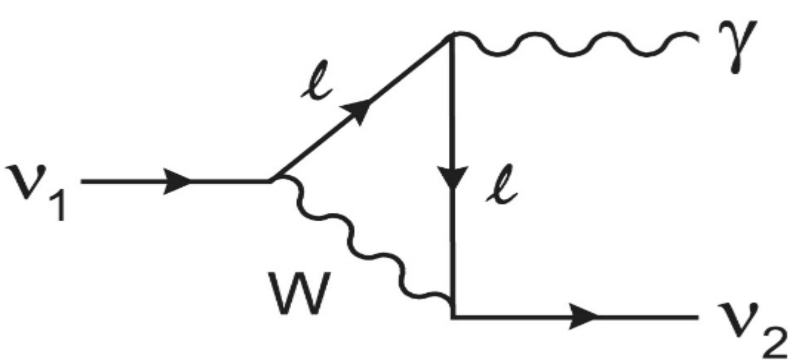
Indirect signals

First you need a theory or an effective description to set the **branching ratios** of annihilation/decay into lighter particles.



We will typically assume lighter states to be SM particles.

Decaying DM



At this level, kinematics is straightforward.

Types of electromagnetic signals

Type of signals

- Prompt γ-ray emissions:
  - Production and decay of π^0
  - Final state radiation
  - Direct emission (monochromatic line)
  - Other (model dependent) features

- Radiative emissions of e^+-e^-:
  - Inverse Compton scattering
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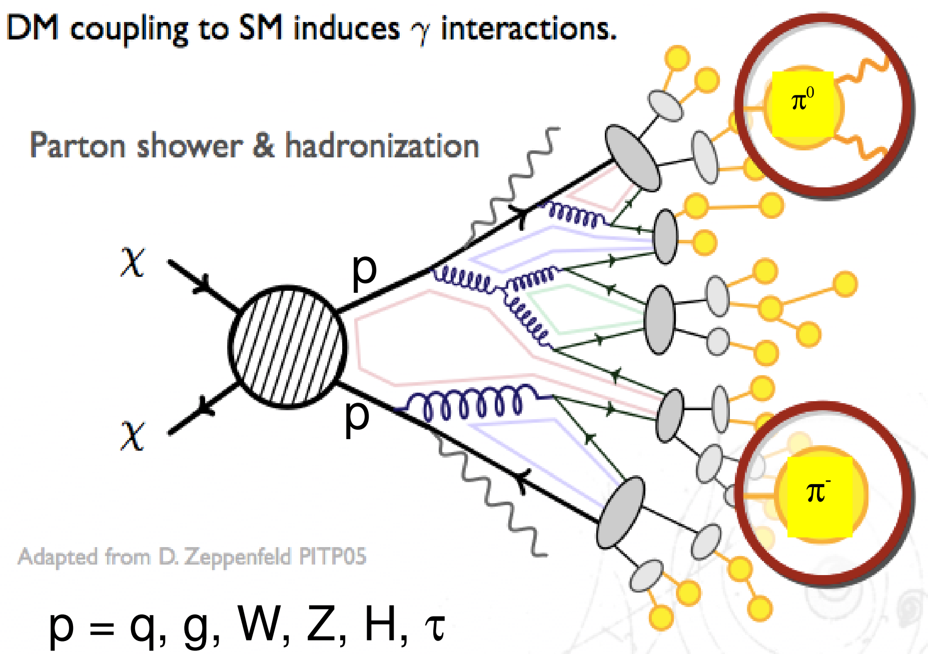
- Multi-wavelength perspective

Neutral pion production

If DM annihilates/decays into quarks, gauge or Higgs bosons particles then they produce colored partons (quarks and gluons) which shower and subsequently hadronize into color-neutral hadrons.

They in turn decay into light hadrons with the lightest being pions.

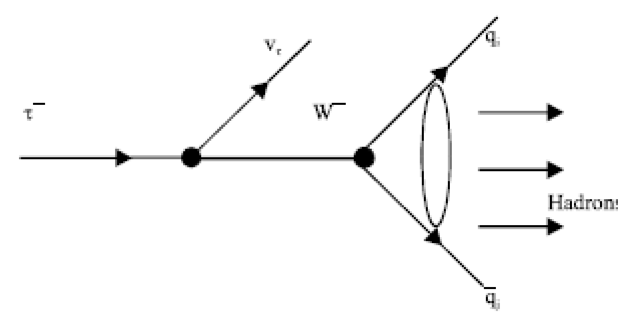


p = q, g, W, Z, H, τ

For the tau-lepton:

semi-hadronic decay

(P ~ 65%)

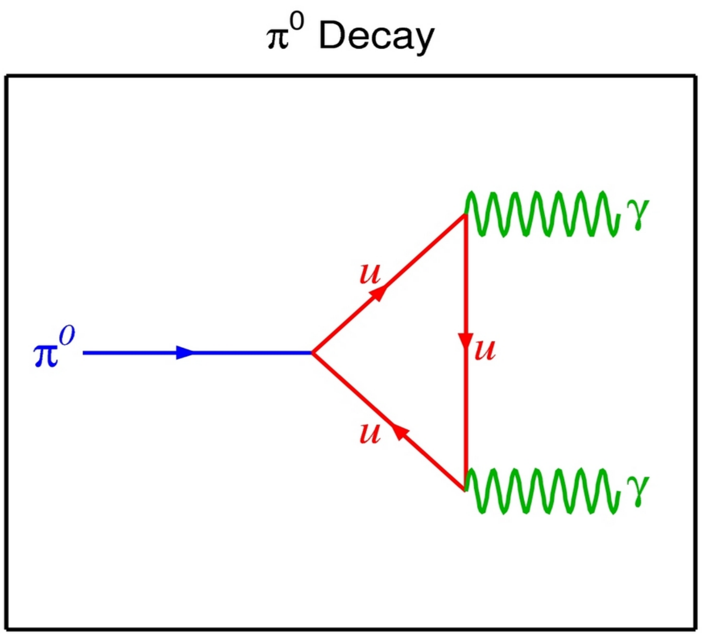


To compute showering and hadronization, better to use Monte-Carlo simulations (e.g. Pythia, Herwig)

Neutral pion decay

Main neutral pion decay mode is into two photons (P=98.798%): $\pi^0 \rightarrow \gamma\gamma$

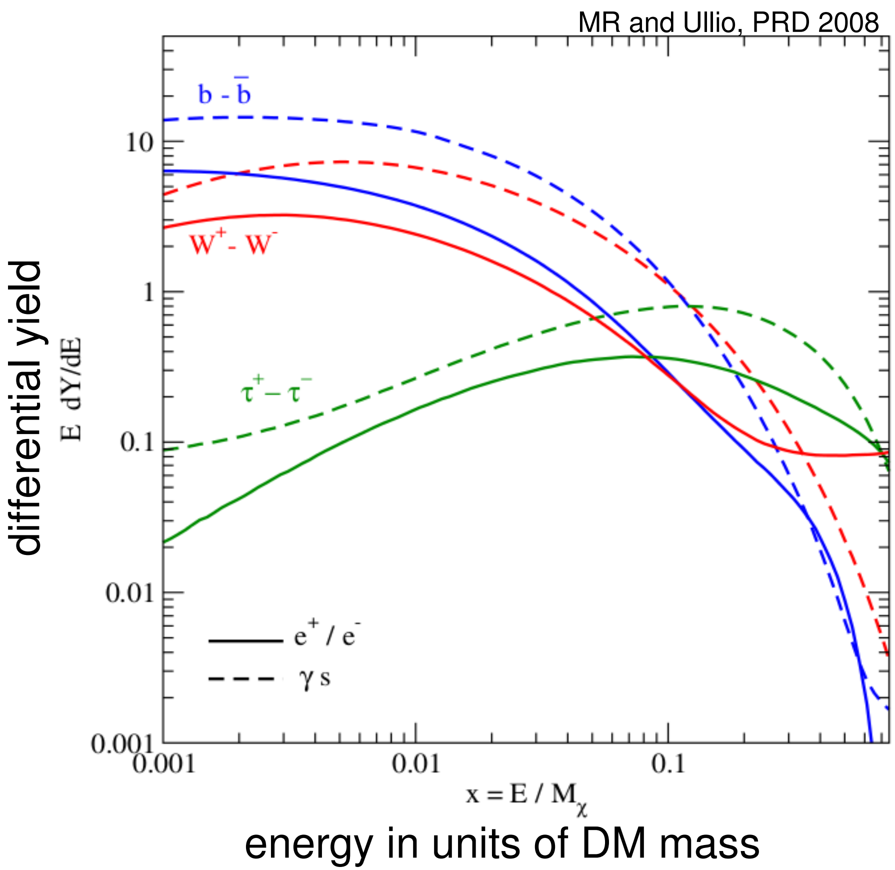
Lifetime ~ 10^{-16} s



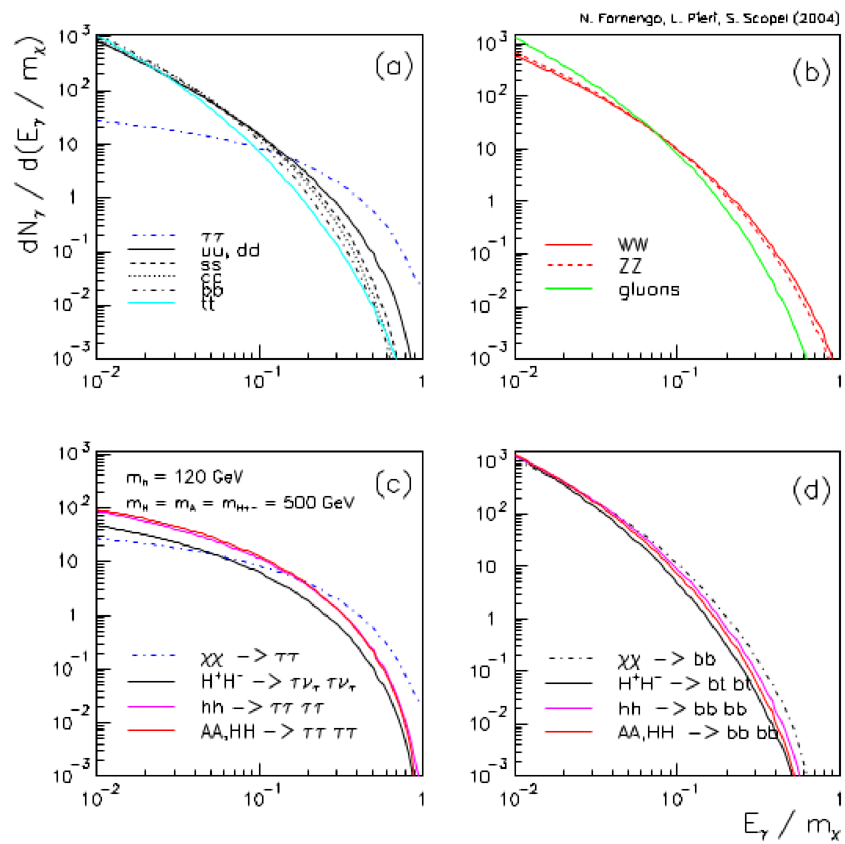
$$|\pi^0> = \frac{1}{\sqrt{2}}(|u\bar{u}> - |d\bar{d}>)$$

The contribution to the γ-ray DM-induced flux from production and decay of other mesons and of baryons is usually subdominant

Neutral pion decay

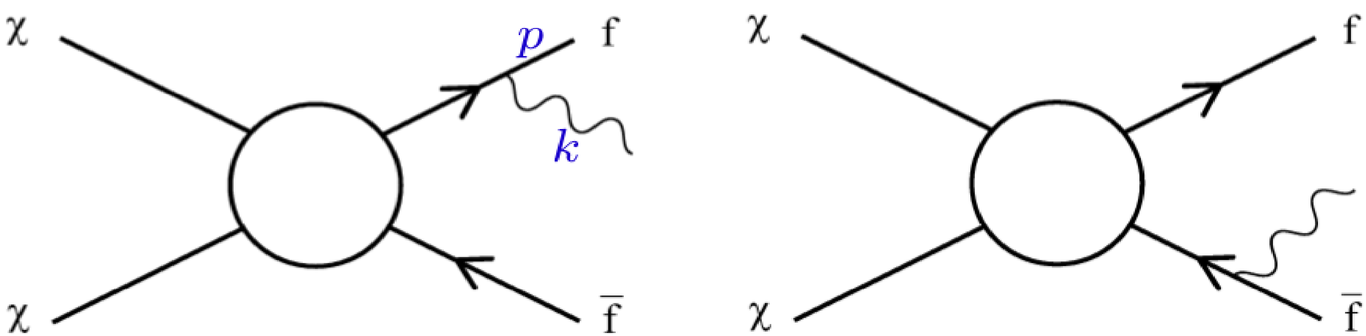


Hadronic channels are much softer than the tau case, with gauge and Higgs bosons somewhat in between (but much closer to the quark case)



Final state radiation

Radiation by charged particles originated from the DM annihilation/decay.
(Birkedal et al., 2005, Bergstrom et al., 2005)



propagator for f:

$$\propto \frac{1}{(k+p)^2 - m_f^2} = \frac{1}{2k \cdot p}$$

Bringmann IDM08

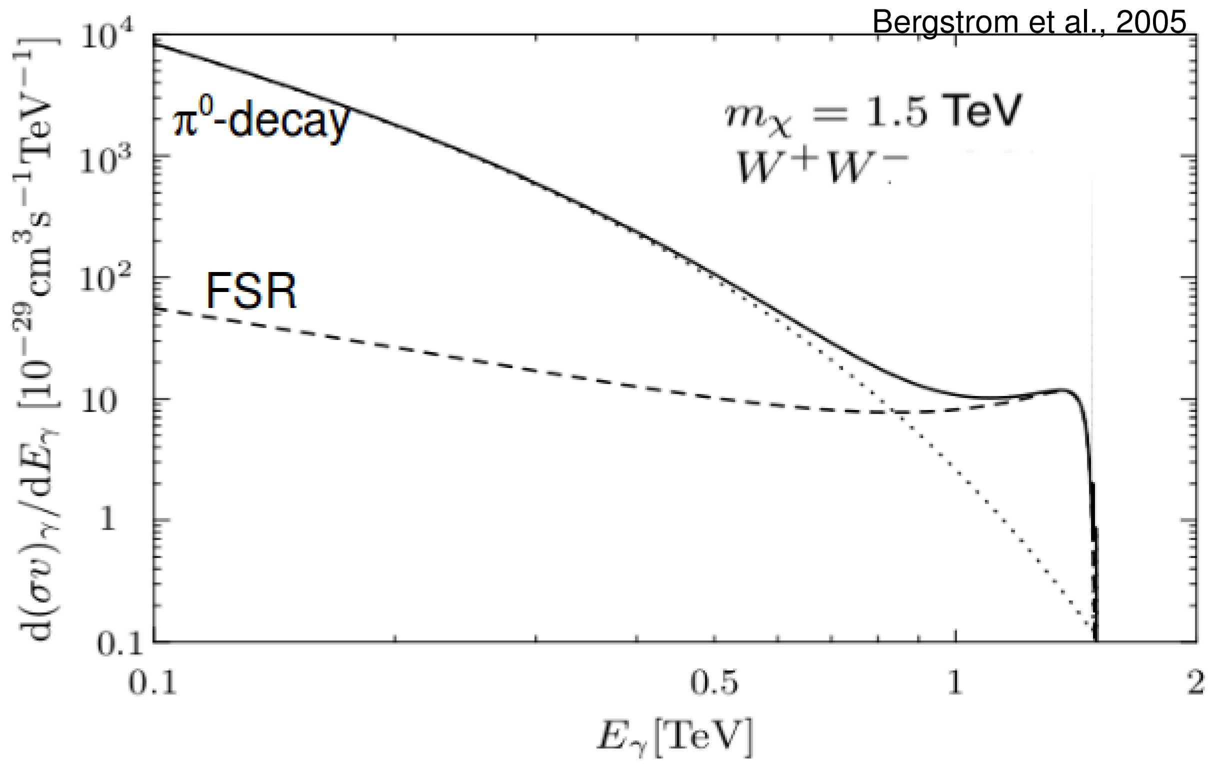
For collinear photons, the virtual f is almost on-shell

Model independent spectrum

Very important when $m_{DM} >> m_f$ (and especially for light leptons which do not decay into pions)

Logarithmic enhancement of the cross-section ~ $\log \frac{s}{m_f^2}(1-x)$

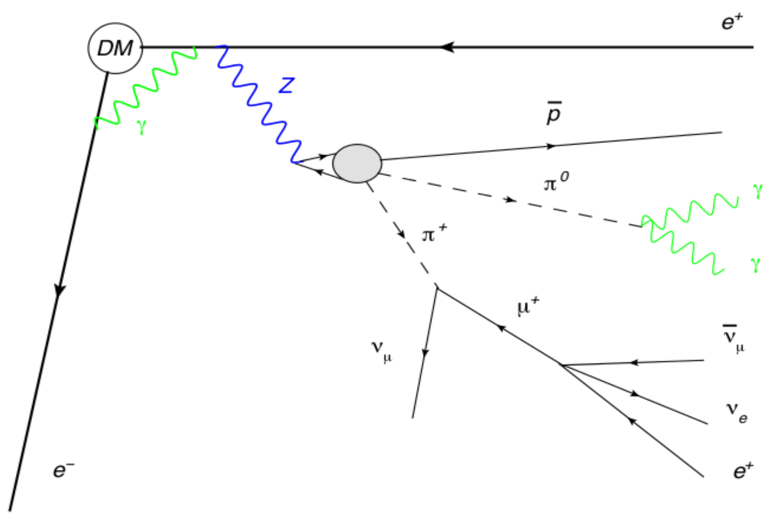
Final state radiation



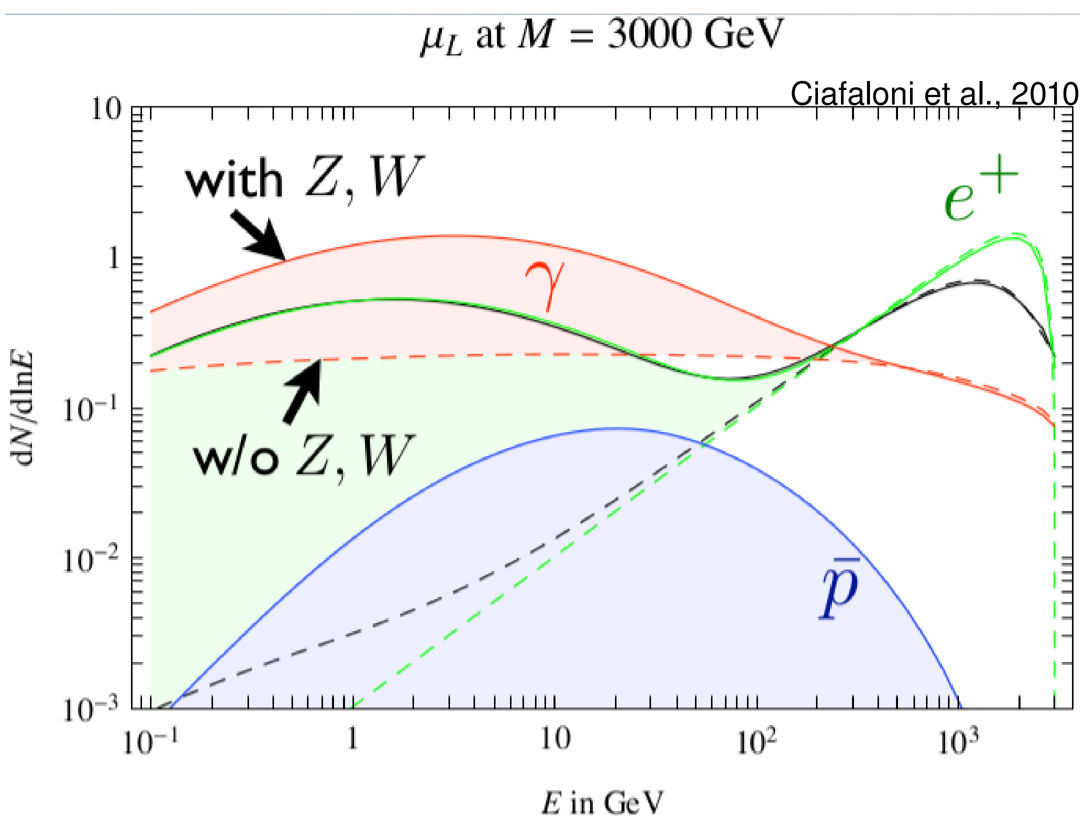
Possible spectral features (in particular, a sharp cutoff)

Electroweak corrections

Final state radiations of Z and W±



Significant contribution at small photon energy and for large DM mass.



Typically, no specific spectral features.

Monochromatic line

Direct annihilation into photons produces

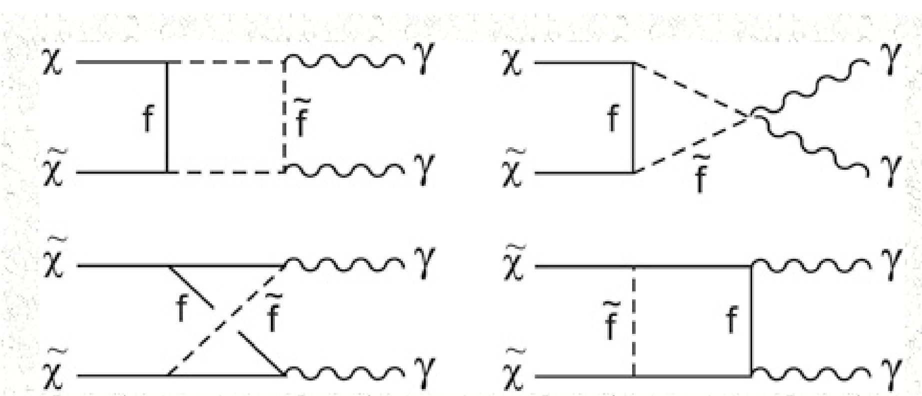
nearly **monochromatic spectral signatures**

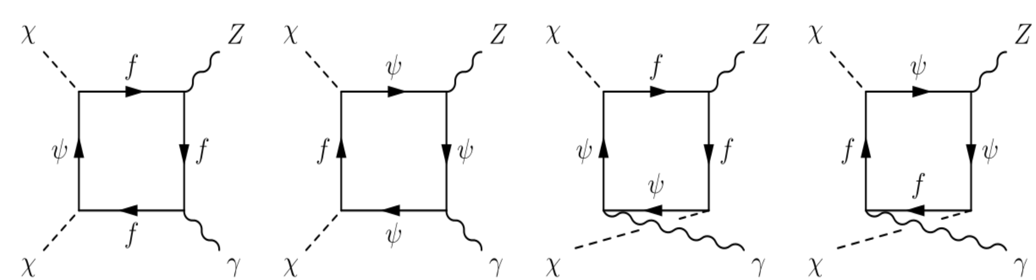
(width ~ v/c ~ 10^{-3} - i.e., Doppler broadening due to galactic rotation)

$$\chi\chi \rightarrow \gamma\gamma, Z\gamma, H\gamma$$

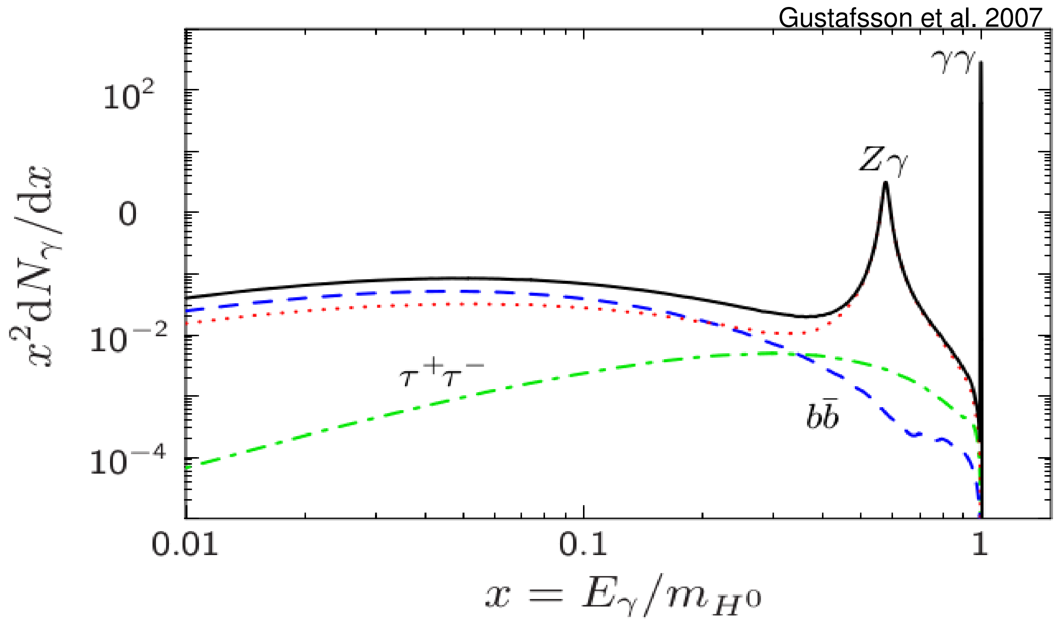
It has to be loop suppressed $$\frac{\langle\sigma v\rangle_{\gamma\gamma}}{\langle\sigma v\rangle_{\rm tot}} \sim \frac{\alpha^2}{16\pi^2}$$

Some examples:





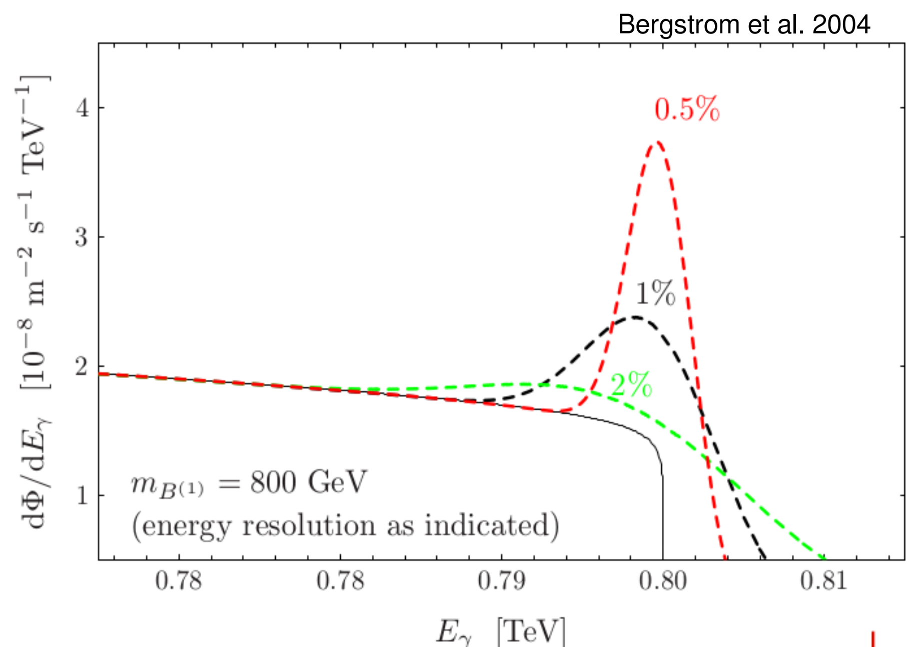
Monochromatic line



γγ line $E_\gamma \simeq M_\chi$

γP line $E_\gamma = M_\chi\left(1 - \frac{M_P^2}{4M_\chi^2}\right)$

Experimental energy resolution of current telescopes might be not sufficient



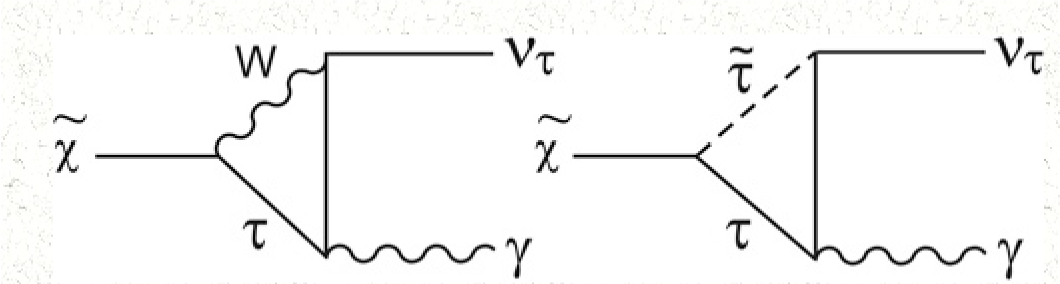
Monochromatic line

In case of decaying DM the line is at $E_\gamma = \frac{M}{2}\left(1 - \frac{M_P^2}{M^2}\right)$

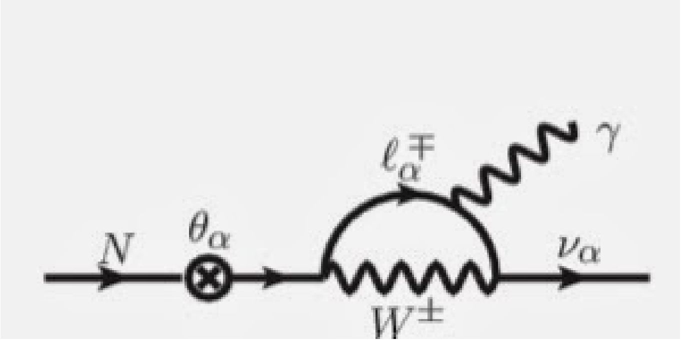
Examples:

R-parity violating neutralino

Berezinsky, Masiero, Valle, 1991



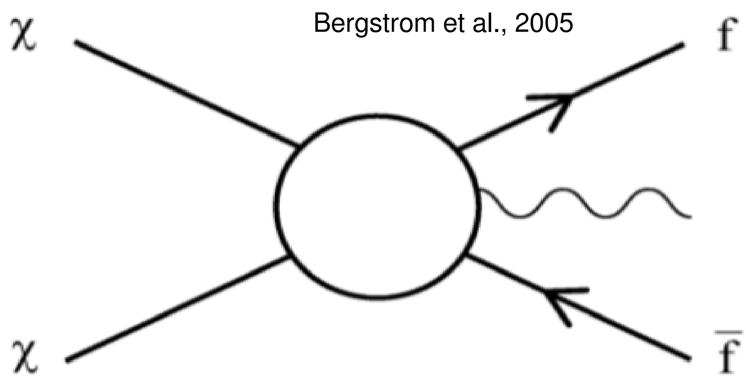
Sterile neutrino (→ keV-line)



Other spectral features

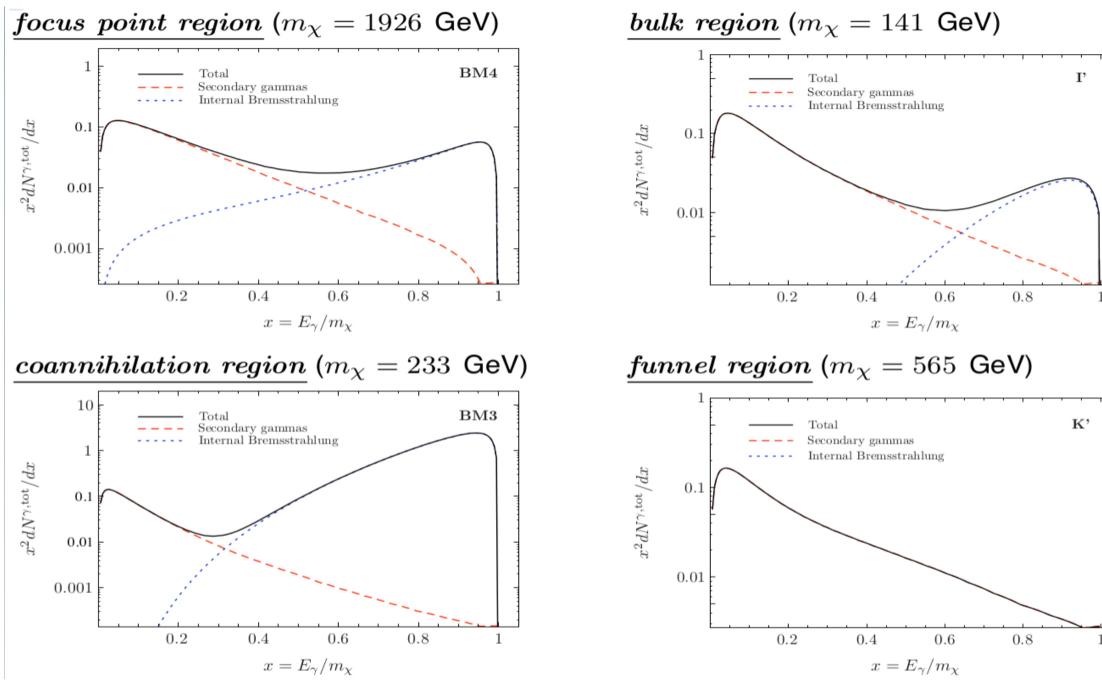
"Virtual" internal bremsstrahlung

Bergstrom et al., 2005



More **model-dependent** than final state radiation

It can be important for some models, namely for annihilations into charged bosons mediated by t-channel particles degenerate in mass with DM

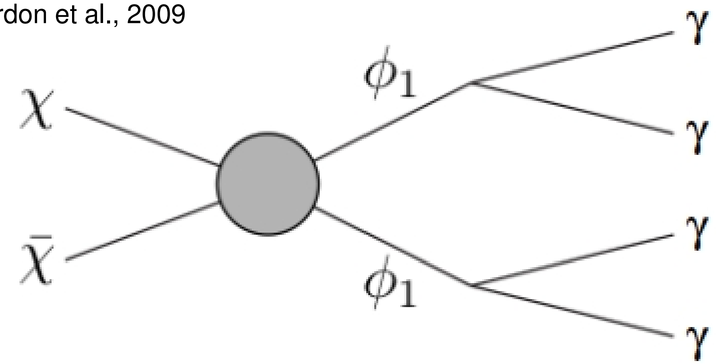


Bringmann et al., 2008

Other spectral features

Cascade decays

Mardon et al., 2009



Dark matter annihilates
into light degrees of freedom which
in turn decay into photons.
"Cascade annihilations"
(box-shaped features)

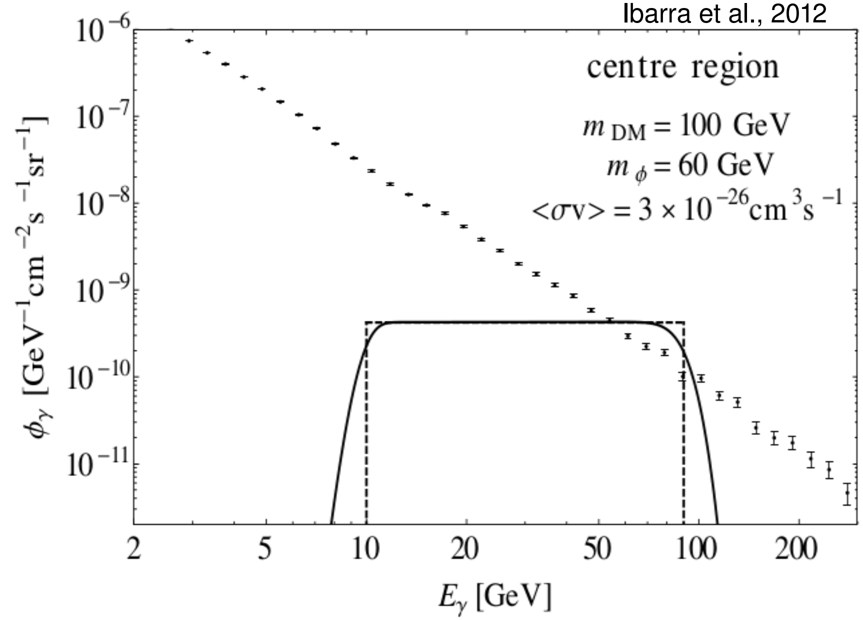
1 step

$$\frac{dN_\gamma}{dE_\gamma} = \frac{4}{\Delta E}\Theta(E - E_-)\Theta(E_+ - E)$$

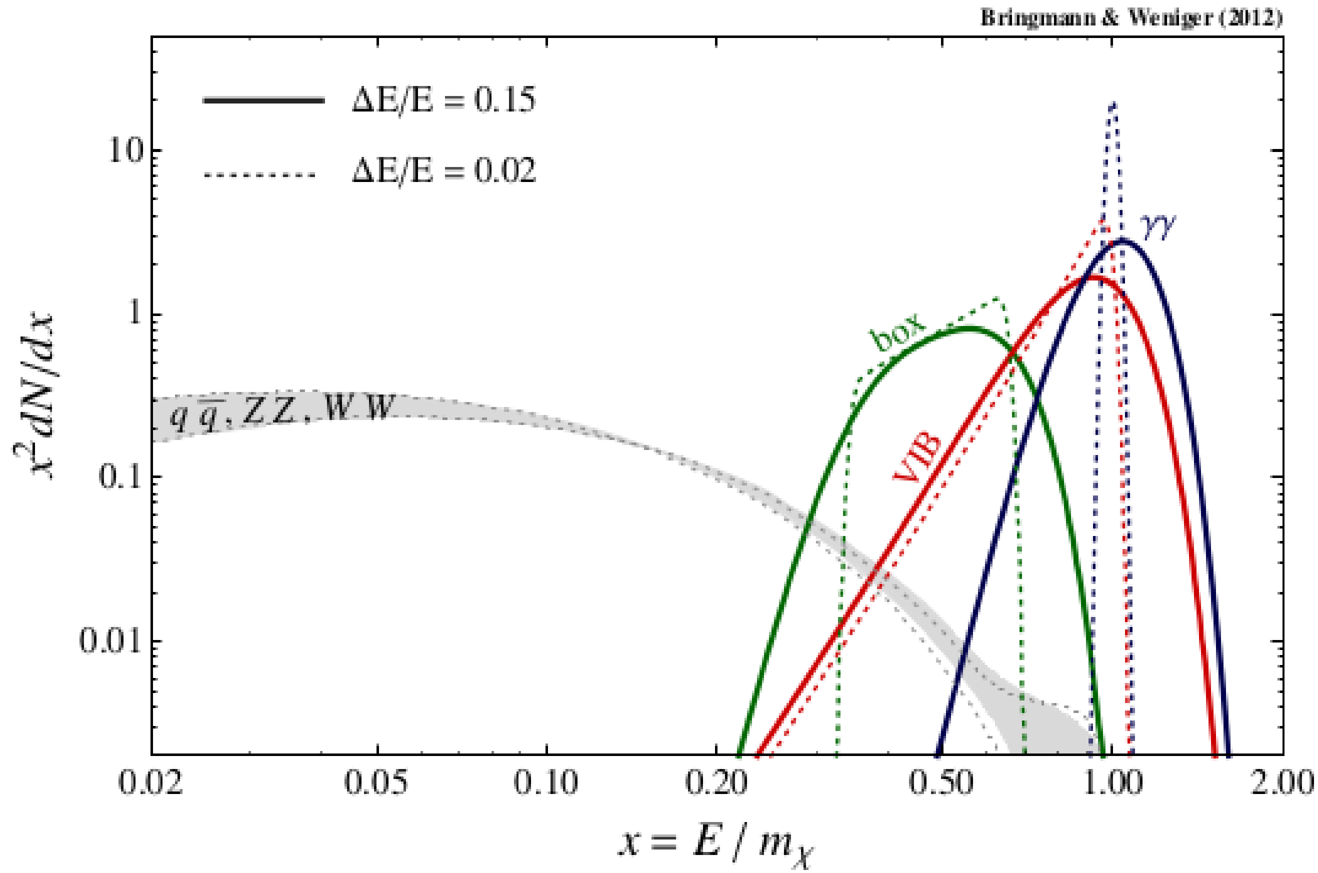
$$E_\pm = (m_{DM}/2)\left(1 \pm \sqrt{1 - m_\phi^2/m_{DM}^2}\right)$$

$$\Delta E = E_+ - E_- = \sqrt{m_{DM}^2 - m_\phi^2}$$

Ibarra et al., 2012



Prompt spectrum



Bulk of the emission typically smooth (i.e., hardly distinguishable from other astrophysical emission) but pronounced peaks near the kinematic endpoint.

Prompt spectrum

An incomplete list of references for computations of annihilation yields into photons including (most of) the mentioned effects:

$$\frac{dN_i^f}{dE}(E)$$

Fitting functions:

Fornengo, Pieri, Scopel, PRD 2004.

Cembranos et al., PRD 2011.

Numerical implementations:

DarkSUSY (Gondolo et al., JCAP 2004, http://www.fysik.su.se/~edsjo/darksusy/)

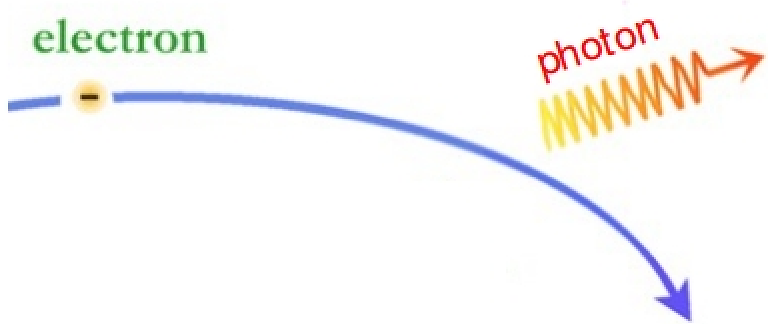
MicrOMEGAs (Belanger et al., JCAP 2005, https://lapth.cnrs.fr/micromegas/)

PPPC 4 DM ID (Cirelli et al., JCAP 2012)

Mostly based on PYTHIA.

Radiative emission

Ultra-relativistic electrons and positrons originated from DM annihilation or decay and then interacting with the interstellar medium can radiate photons at different frequencies.



We need to study the production of e^+-e^-.

Main channels:

- Production and decay of charged pions (for quarks, gauge bosons and tau)
- Decays of leptons and gauge bosons directly into e^+-e^- or into muons (with subsequent decay into e^+-e^-)

Higher order corrections (EW bremsstrahlung, etc..) similar to the photonic case but typically less considered since do not provide spectral features.

Charged pion decay

Production of charged pions proceeds in a similar way as for neutral pions.

Main decay mode (P=99.9877%) is leptonic: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

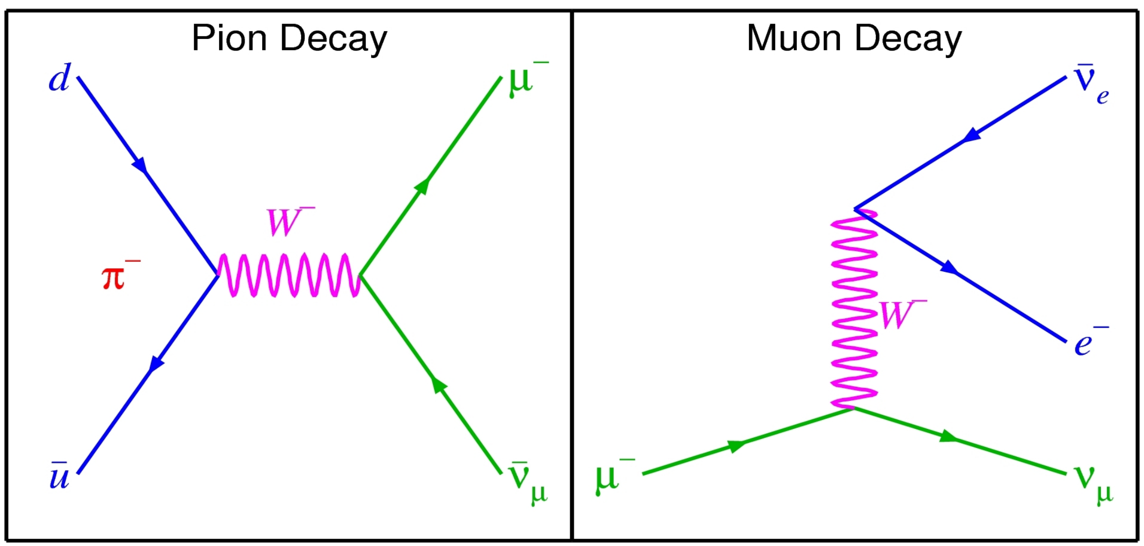
Lifetime ~ 2.6 10^{-8} s

$$\mu^+ \longrightarrow e^+ \ \nu_e \ \bar{\nu}_\mu$$

Subsequent decay of muons into electrons/positron (P~100%)

Lifetime ~ 2.2 10^{-6} s

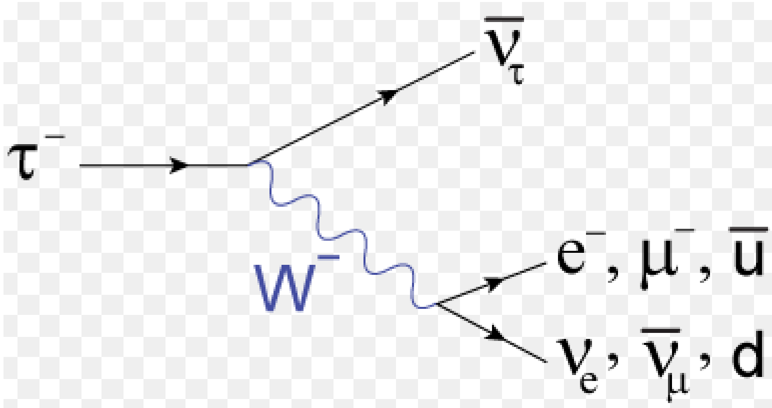
$$\mu^- \longrightarrow e^- \ \bar{\nu}_e \ \nu_\mu$$



Leptonic decays

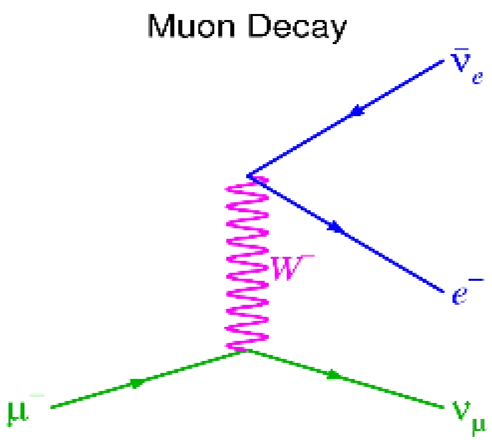
Decay into e^+-e^- for leptonic final states

TAU



Brancing ratios are
17.41% for $\mu^-\bar{\nu}_\mu\nu_\tau$
and
17.83% for $e^-\bar{\nu}_e\nu_\tau$
The rest are semi-hadronic decays (production of pions)

MUON



e^++e^-: e^++e^- line for direct emission (typically small but NOT loop suppressed)

Propagation

From the injection distribution of e^+-e^- one needs to compute the equilibrium distribution, taking into account various interactions with the interstellar medium.

TRANSPORT EQUATION

Spatial diffusion — Reacceleration — Energy losses — Source

$$\frac{\partial n_i(\vec{r},p,t)}{\partial t} = \vec{\nabla}\cdot(D_{xx}\vec{\nabla} n_i - \vec{v}_c n_i) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p}\frac{1}{p^2} n_i - \frac{\partial}{\partial p}\left[\dot{p} n_i - \frac{p}{3}(\vec{\nabla}\cdot\vec{v}_c) n_i\right] + q(\vec{r},p,t)$$

Convection

See e.g., Berezinski et al., 1990

$$n_i(p)dp = n_e(r,E)dE = 4\pi\, p^2 f(r,p)dp$$

$$-\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D \frac{\partial f}{\partial r}\right] + \frac{1}{p^2}\frac{\partial}{\partial p}(\dot{p} p^2 f) = q(r,p)$$

Stationarity

(radiative cooling of e^+-e^- < hundreds of Myr at the energy of interest)

Spherical symmetry

(collisionless and dissipationless DM)

$$n_e(E,r) = \frac{1}{b(E,r)}\int_E^\infty dE'\, Q_e(E',r)$$

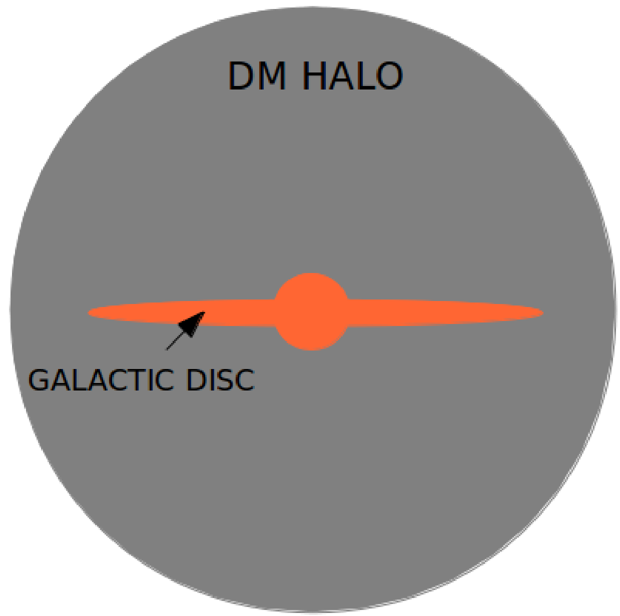
Radiative losses at injection place

(in case of **strong confinement**)

Disentanglement from "astro" sources

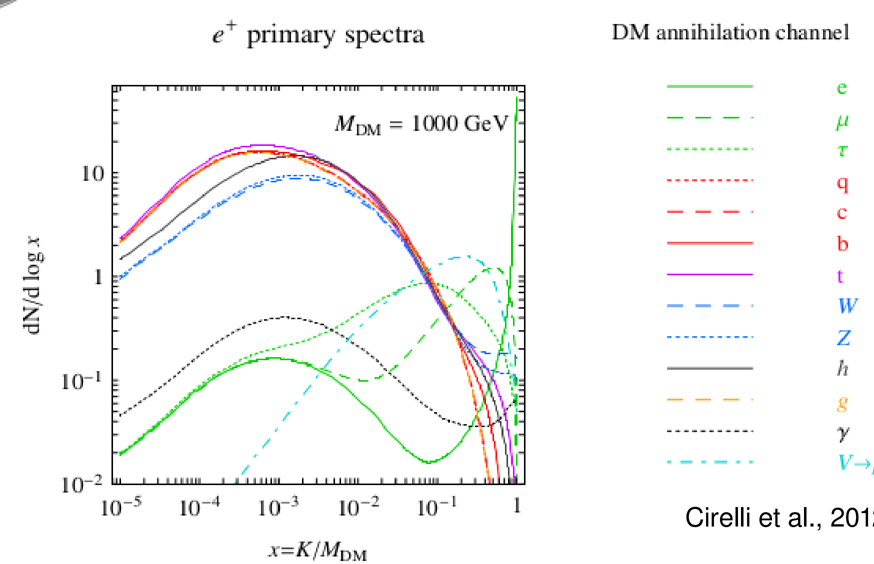
How can we distinguish the DM-induced electrons and positrons from the non-thermal components produced by astrophysical sources?

SPATIAL FEATURES



SPECTRAL FEATURES:

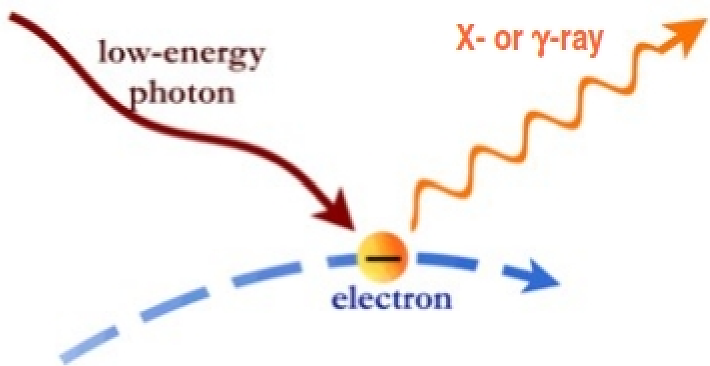
- spectral curvature
- cutoff at E = M_{DM}
- pronounced peaks



Cirelli et al., 2012

Inverse Compton scattering

Interacting with the interstellar radiation field, relativistic e^+-e^- upscatter photons producing an inverse Compton emission at X- and **γ-ray** frequency.



$$P_{IC}(r,E,\nu) = c\,h\nu \int d\epsilon\, n_\gamma(\epsilon,r)\,\sigma(\epsilon,\nu,E)$$

ε = energy of target photons

n_γ = energy spectrum of target photons

σ = Klein-Nishina cross-section

Radiative emissivity

$$j_i(\nu,r) = 2\int_{m_e}^{M_\chi} dE P_i(r,E,\nu) n_e(r,E)$$

Inverse Compton scattering

Loss rate $\left(\frac{dE}{dt}\right)_{IC} = \frac{4}{3}\sigma_T c u_{rad}\left(\frac{v^2}{c^2}\right)\gamma^2$

u_{rad} is the energy density of target photons

σ_T = Thomson cross-section

Valid only if $\gamma\hbar\omega \ll m_e c^2$

Otherwise Klein-Nishina corrections

Number of photons scattered per unit time

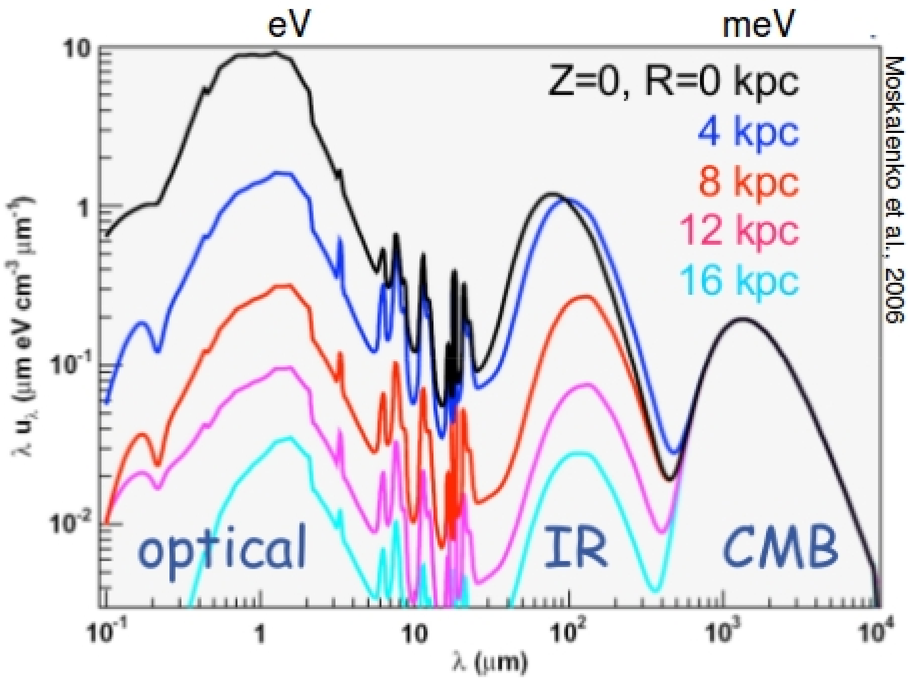
$$\sigma_T c u_{rad}/\hbar\omega_0$$

Average energy of the scattered photons

$$\hbar\overline{\omega} = \frac{4}{3}\gamma^2\left(\frac{v}{c}\right)^2\hbar\omega_0 \approx \frac{4}{3}\gamma^2\hbar\omega_0$$

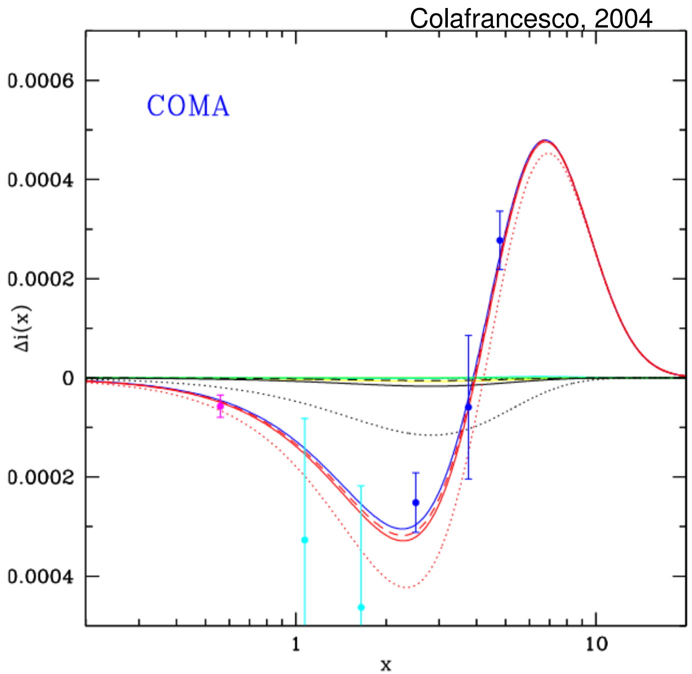
$$E_{IC} = 5.3\times 10^{-3}\left(\frac{E_e}{\text{GeV}}\right)^2\frac{\epsilon_0}{\text{eV}}\text{GeV}$$

Starlight in the Galaxy

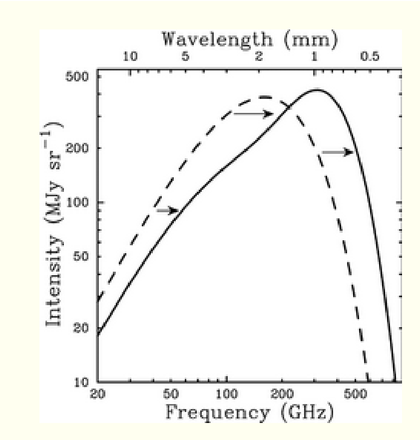


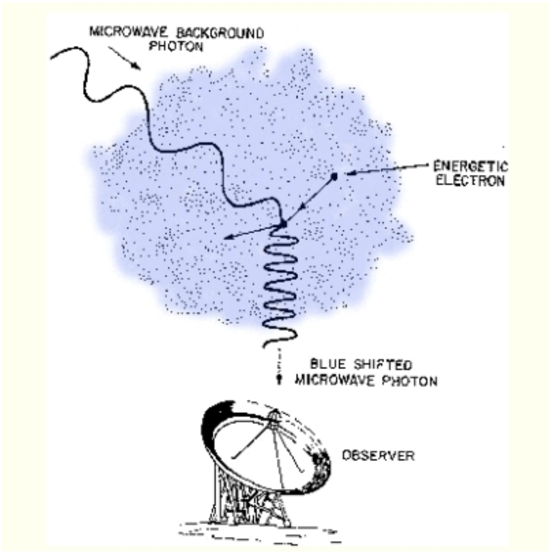
Sunyaev-Zel'dovich effect

When CMB photons encounter hot electrons, they can gain energy via IC scattering.



$$x \equiv h\nu/k_B T_0$$





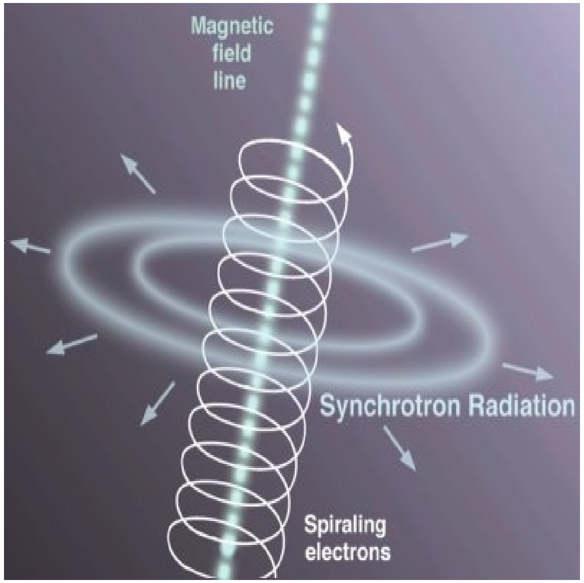
Non-thermal SZ effect associated to e^+-e^- originated from DM annihilation or decay

Synchrotron radiation

Emitted in a medium with **magnetic field**, high-energy electrons and positrons give raise to a radio continuum diffuse emission associated to synchrotron radiation.

Electron energy corresponding to the peak of synchrotron power (in the monochromatic approximation):

$$E \simeq 15\sqrt{\nu_{GHz}/B_{\mu G}}\ \mathbf{GeV}$$



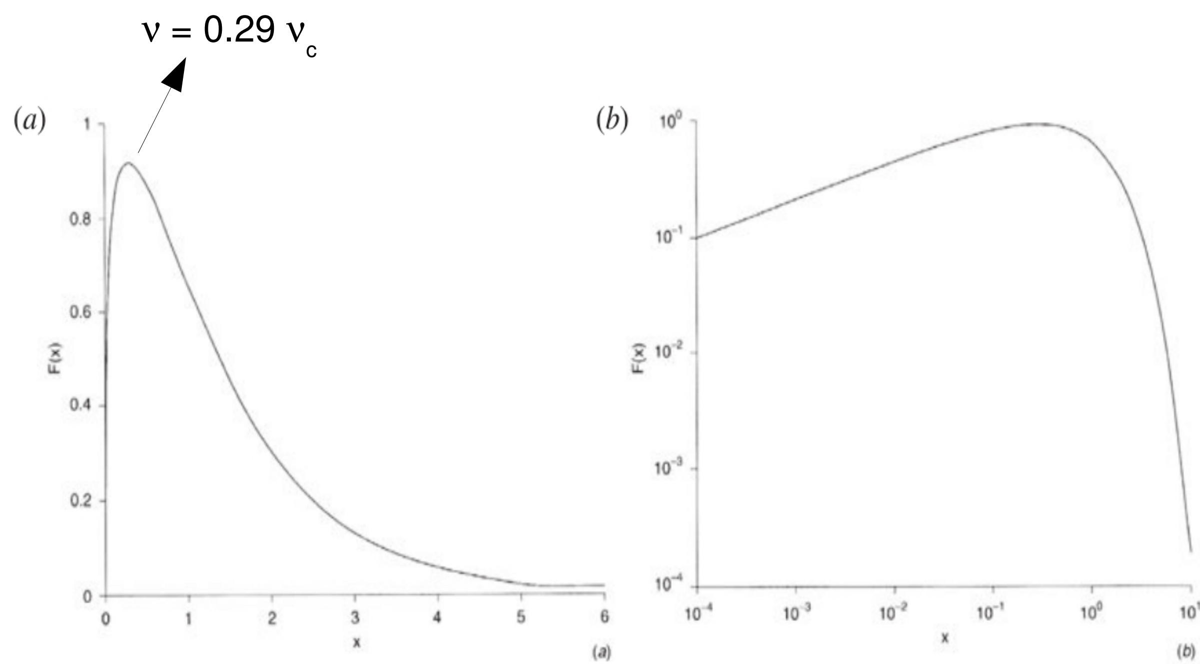
Credit: Sky & Telescope / Gregg Dinderman

Synchrotron radiation

$$P_{synch}(r,E,\nu) = \frac{\sqrt{3}\,e^3}{m_e c^2}\,B(r)F(\nu/\nu_c)$$

$$F(t) \equiv t\int_t^\infty dz K_{5/3}(z)$$

$$\nu_c \equiv 3/(4\,\pi)\cdot c\,e/(m_e c^2)^3 B(r) E^2$$



$$x = \omega/\omega_c = \nu/\nu_c$$

In the monochromatic approximation:

$$j_\nu(\nu,\vec{r}) = \frac{\mathrm{d}n_e}{\mathrm{d}E_e}(E_e(\nu),\vec{r})\,\frac{\mathrm{d}E_e(\nu)}{\mathrm{d}\nu}\,b_{\rm syn}(E_e(\nu),\vec{r})$$

with $b_{syn} = 0.0254\left(\frac{B}{\mu G}\right)^2 \frac{E}{\rm GeV}$

Synchrotron vs IC

LOSS RATE

(averaged over an isotropic distribution of pitch angles)

$$\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\mathrm{sync}} = \frac{4}{3}\sigma_{\mathrm{T}}\, c u_{\mathrm{mag}} \left(\frac{v^2}{c^2}\right)\gamma^2$$

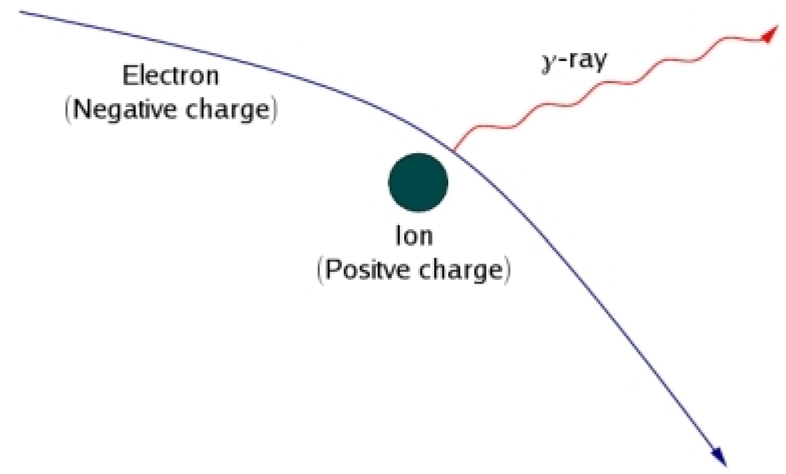
$$u_{mag} = \frac{B^2}{2\,\mu_0}$$

Comparison with IC loss-rate

$$\frac{(dE/dt)_{sync}}{(dE/dt)_{IC}} = \frac{u_{mag}}{u_{IC}} = 0.095\left(\frac{B}{\mu G}\right)^2\left(\frac{0.26\,\mathrm{eV\,cm^{-3}}}{u_{IC}}\right)$$

Bremsstrahlung

Relativistic (non-thermal) bremsstrahlung in ionized or neutral gas



The **loss rate** can be typically important at lower energy than for IC and synctrotron

The **emission** can be important in the range few MeV-few hundreds of MeV

$$\mathcal{L}_\nu = h\nu \int dE\ n_e(E) \sum_z n_z \frac{d\sigma(E, h\nu, Z)}{d(h\nu)}$$

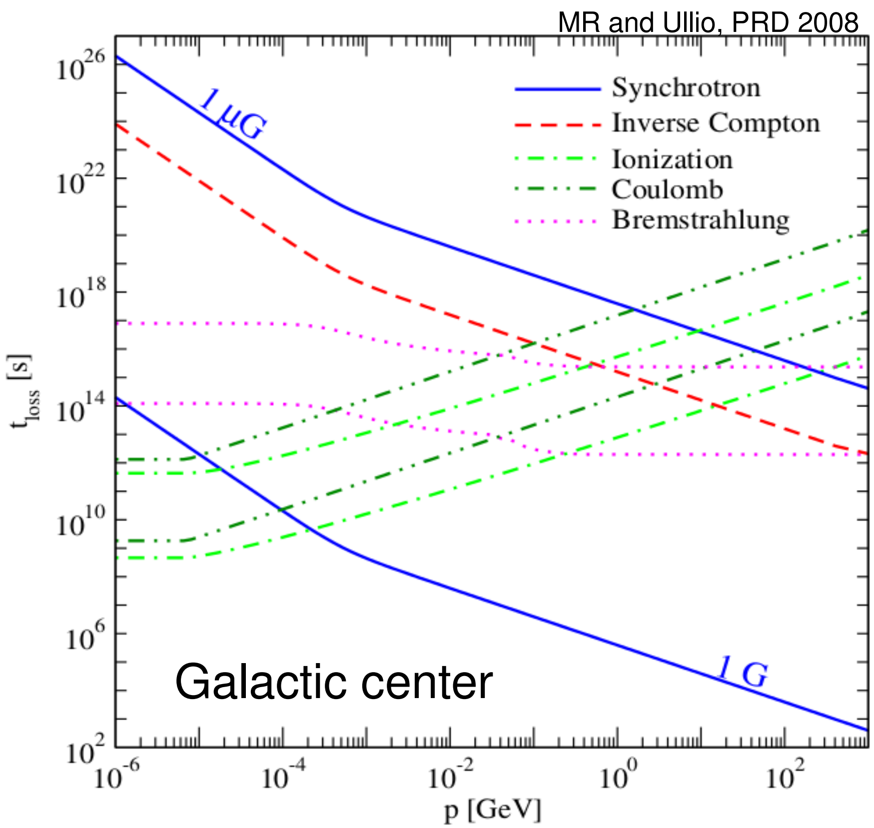
roughly, $d\sigma/d(h\nu) \propto E$

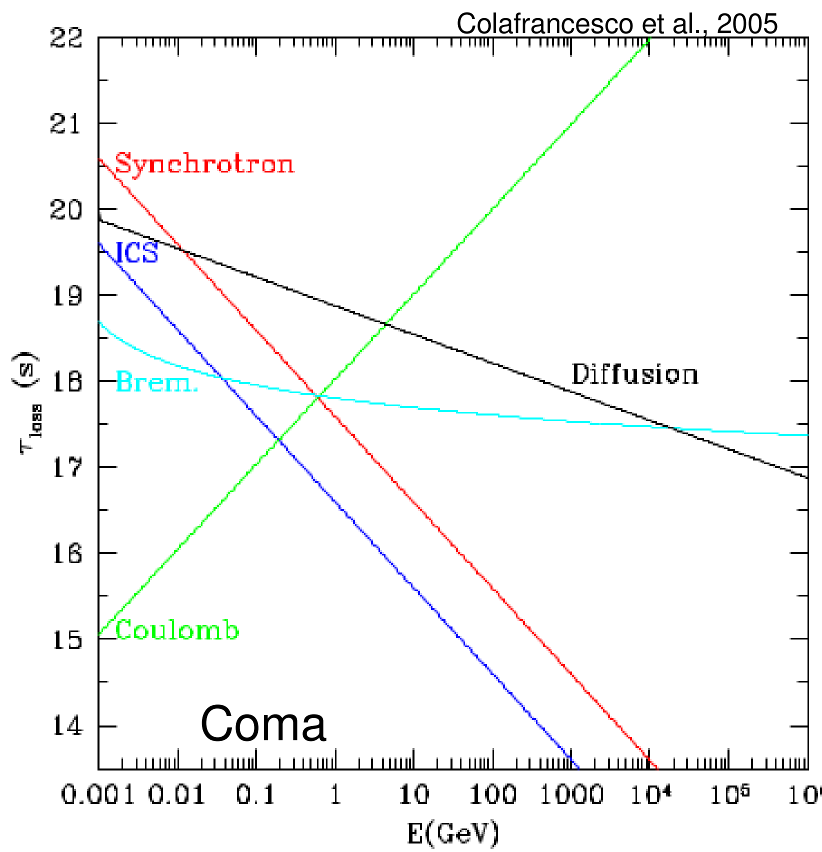
Other radiative processes

Heating of the ambient ionized plasma by means of Coulomb collision

$$\left(\frac{dE}{dt}\right)_{Coul} \propto \log \frac{E_e}{m_e c^2}$$

Loss rate important below few hundreds of MeV



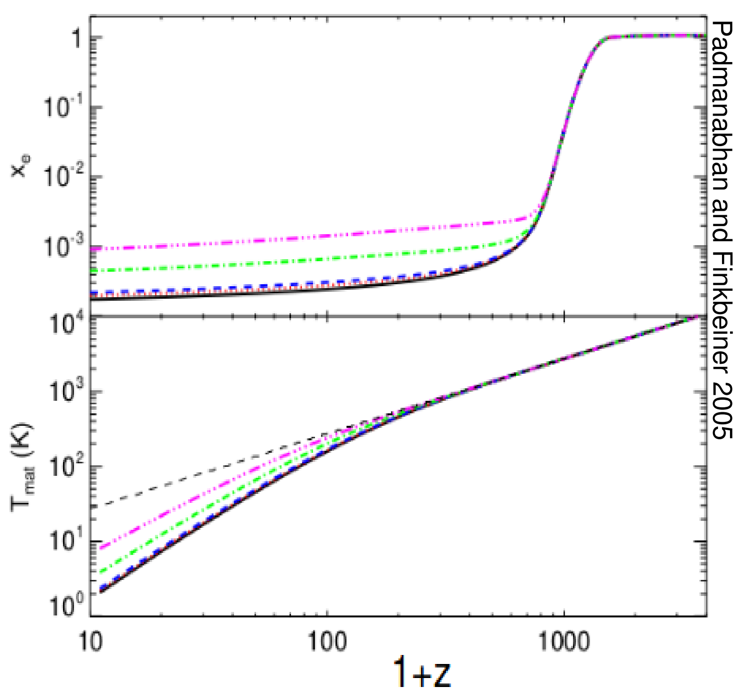


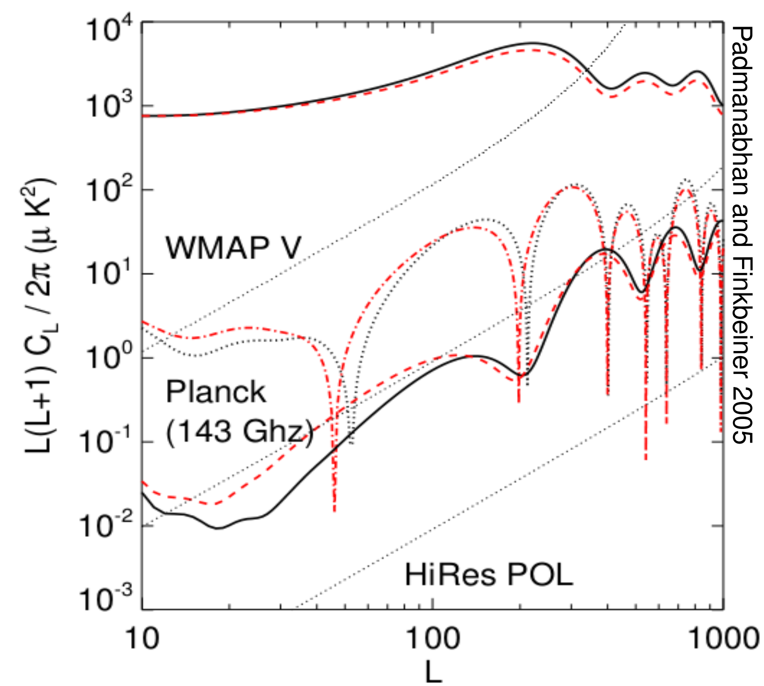
"Early-time" signals

DM annihilating/decaying during the recombination epoch and slightly after **injects energy which can be absorbed by the plasma** (e.g., Padmanabhan and Finkbeiner 2005, and Mapelli et al., 2006), via collisional heating, and atomic excitations and ionizations

changes the temperature of baryons

modify the evolution of **free electron fraction Xe** and consequently the anisotropy of the CMB

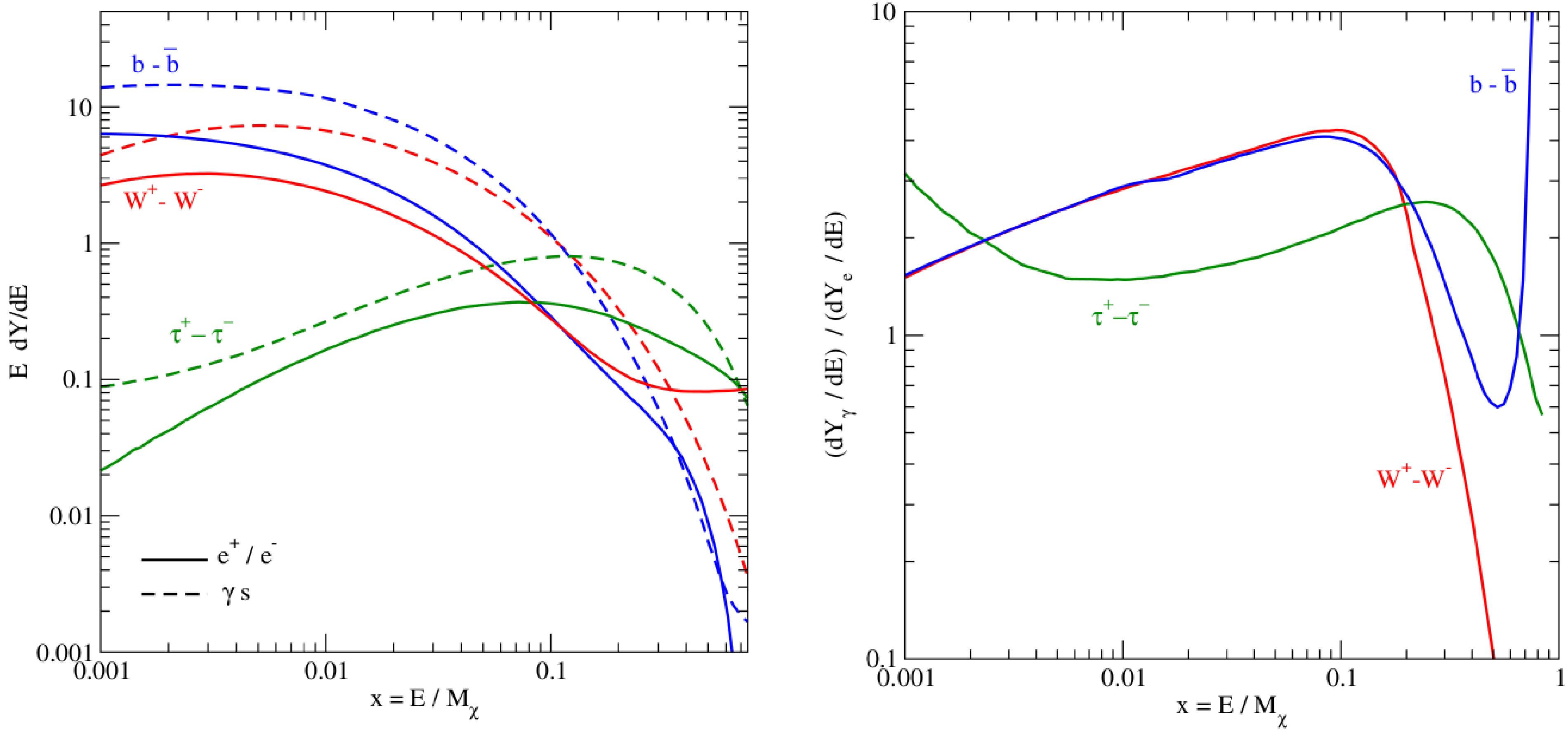




Multi-wavelength perspective

Sizable production of gamma-rays typically comes with a comparable e^+-e^- yield

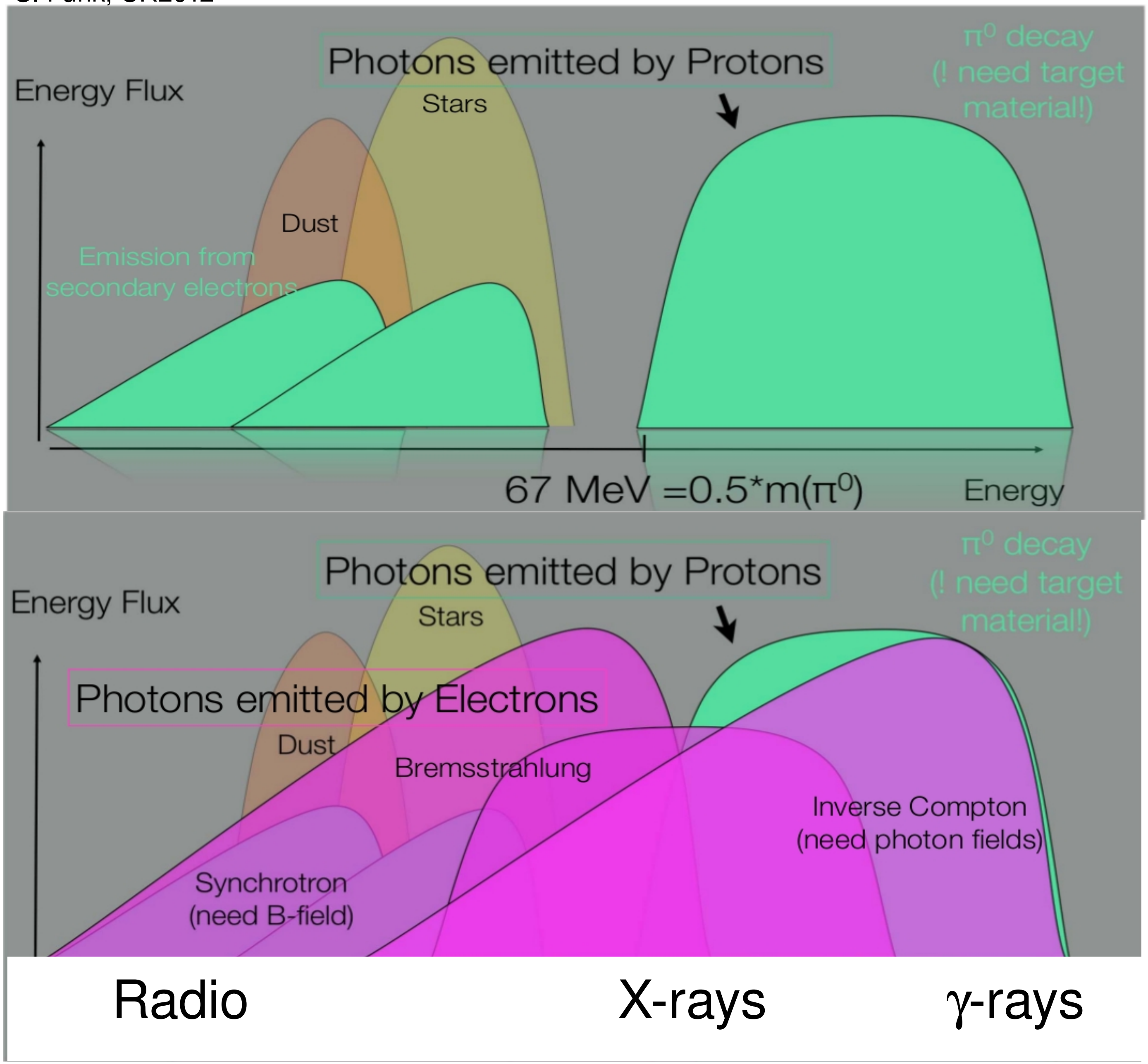
MR and Ullio, PRD 2008



Radiative emissions can play an important role → multi-wavelength strategy

Multi-wavelength signal of the background

S. Funk, CR2012



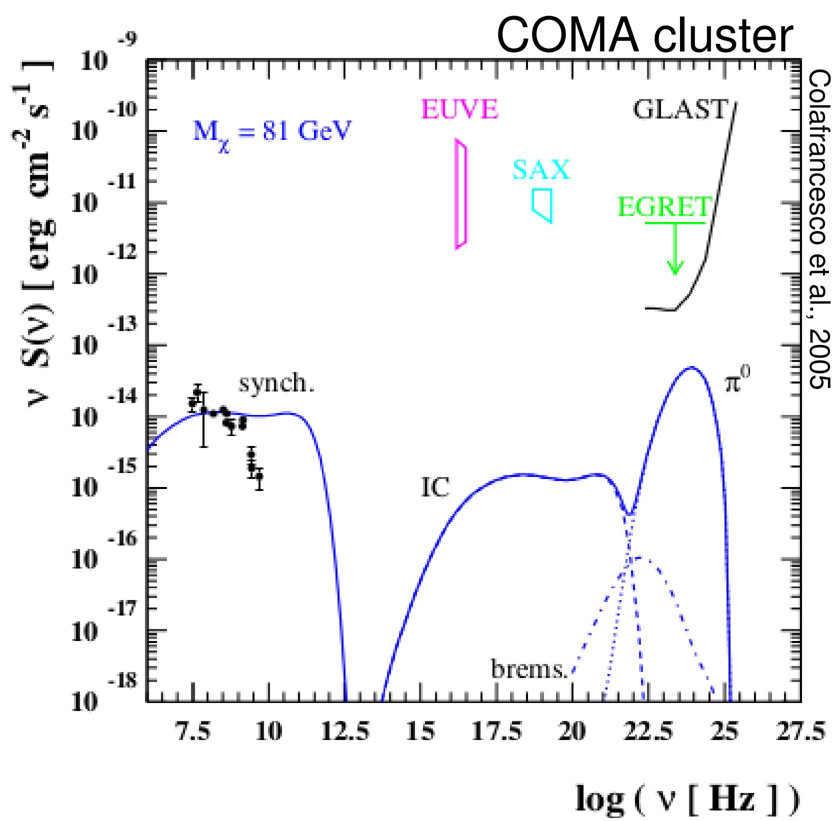
CR diffuse emissions

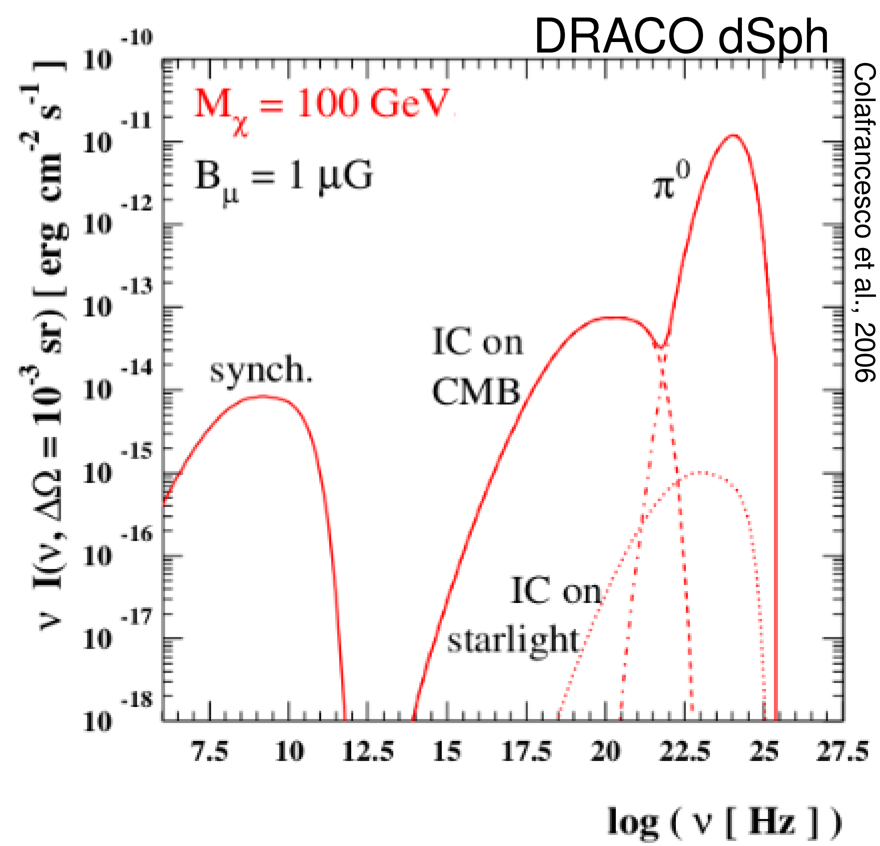
π^0-decay
produced by the interactions of protons with the ISM:
$p+H \to \pi^0 \to 2\gamma$

Radiative emissions:
Synchrotron and inverse Compton generated by
Primary: SNR e^- and pulsar e^+/e^-
Secondary: e^+/e^- produced by the interactions of protons with ISM:
$p+H \to \pi^\pm \to e^\pm$

Multi-wavelength signal of DM

Multi-wavelength spectrum from radio up to gamma-rays given by the described prompt and radiative DM-induced emissions.





Telescopes

Radio

Interferometers

Artist's impression
Credit: SPDO/TDP/DRAO/Swinburne Astronomy Productions.

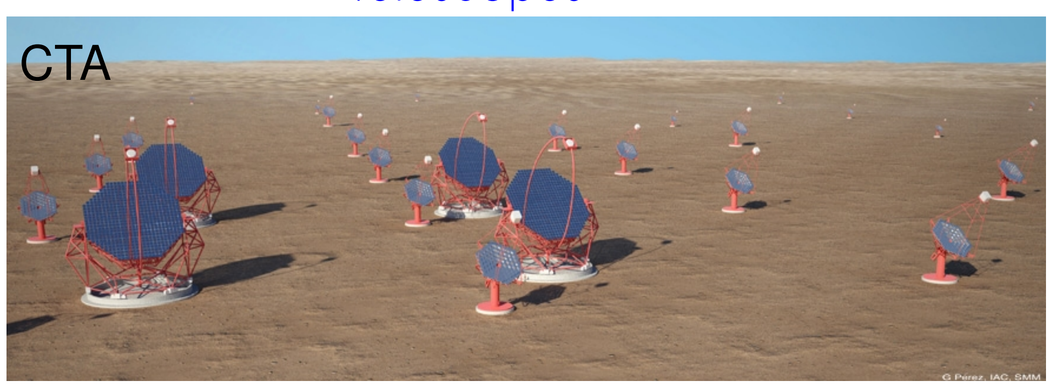
Single-dish

x-rays

Space satellites

gamma-rays

Ground based telescopes



Space satellites