International Conf. on Particle Physics & Cosmology dedicated to memory of V. Rubakov

On the contribution of cosmic-ray interactions in the Galactic halo to the observed neutrino flux

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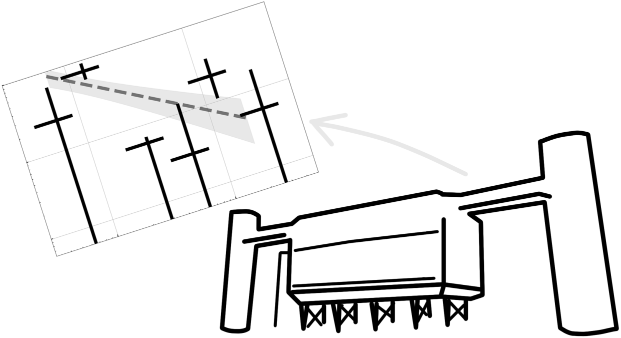
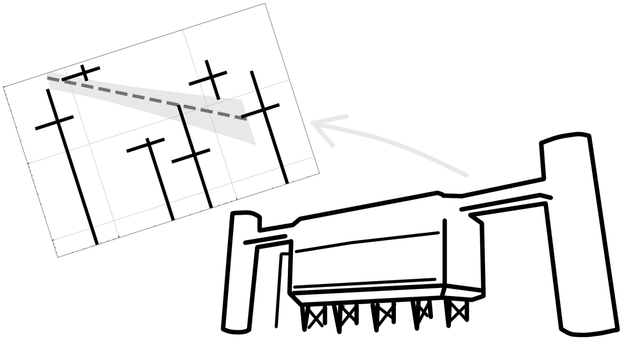
Yerevan, 2–7 October 2023



- Energies $\sim (10^4 ... 10^6)$ GeV
- IceCube $> 5\sigma$ / Baikal GVD $\sim 3\sigma$ / ANTARES $\sim 2\sigma$

Where do these neutrinos come from?



- Energies $\sim (10^4 ... 10^6)$ GeV
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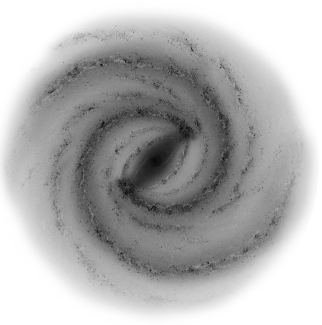
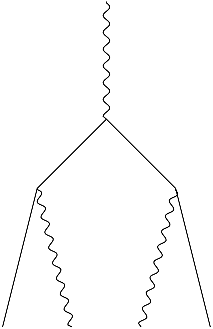
Galactic?..



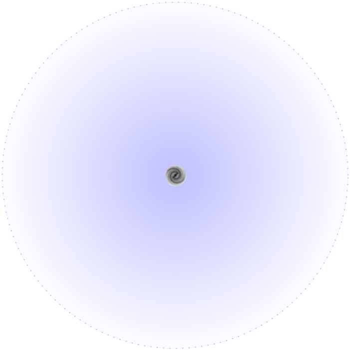
...for a long time: undetected anisotropy [arXiv:2208.08423]

Extragalactic?..



...accompanying γ-rays: e/m cascades on CMB, EBL

Circumgalactic!



$R \sim (200...300)$ kpc

[arXiv:1403.3206]

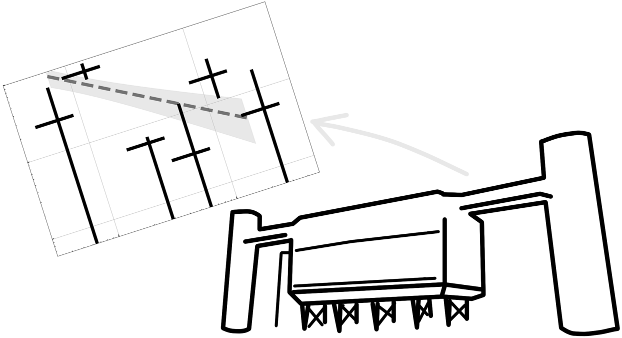
- ✓ not enough for e/m cascade to develop
- ✓ enough for (quasi-)isotropy

BUT

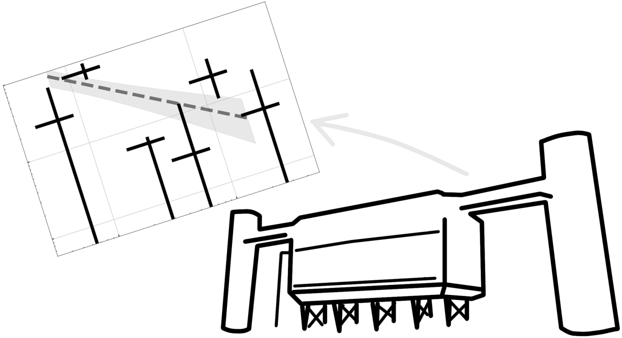
- ? significant neutrino production rate

Introduction. The main goal of this work

Where do these neutrinos come from?

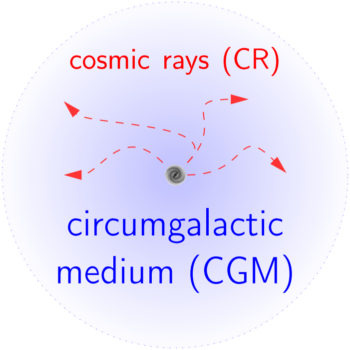


~~Where do these neutrinos come from?~~



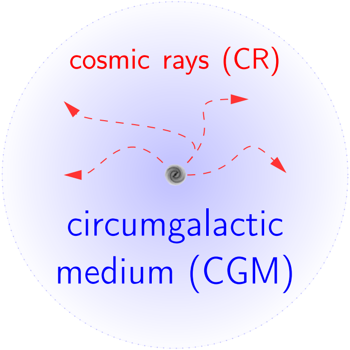
What is the circumgalactic contribution?

Circumgalactic high-energy ν. Model



[primary] CR + CGM gas $\rightarrow$
[secondary] CR $(\nu, \gamma, e^{\pm}$ etc.$)$

Circumgalactic high-energy ν. Model

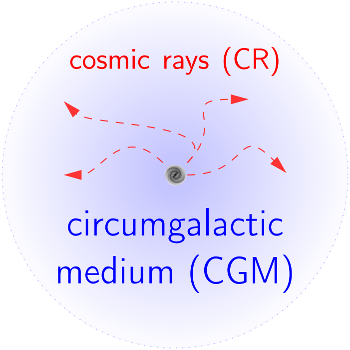


[primary] CR + CGM gas $\rightarrow$
[secondary] CR $(\nu, \gamma, e^{\pm}$ etc.$)$

CGM-to-total ratio:

- neutrinos:
  $\sim 1\%?$ [arXiv:1608.07421]
  $\sim 100\%?$ [arXiv:2101.05016]

Circumgalactic high-energy ν. Model



[primary] CR + CGM gas $\rightarrow$
[secondary] CR $(\nu, \gamma, e^{\pm}$ etc.)

CGM-to-total ratio:

- neutrinos:
  $\sim 1\%$? [arXiv:1608.07421]
  $\sim 100\%$? [arXiv:2101.05016]
- γ-rays: must be
  $\leq 100\%$ at all energies!

Circumgalactic high-energy ν. Outline of the calculation

```
input - - - -> TransportCR - - - -> output
```

[arXiv:1406.0735]

Circumgalactic high-energy ν. Outline of the calculation

`input - - - -> TransportCR - - - -> output`

[arXiv:1406.0735]

? CGM gas:

[number density]

$n_{\rm CGM}(r)$

? primary CR:

[spectral density]

$j_{\rm CR}(r, E')$

Circumgalactic high-energy ν. Outline of the calculation

input - - - -> TransportCR - - - -> output

[arXiv:1406.0735]

- only $\mathrm{p} + \mathrm{gas} \to \ldots$
- oscillations disabled
- 1D transport eq-s
- source term:

$$j_{\mathrm{CR}} \times n_{\mathrm{CGM}} \times \frac{d\sigma_{\mathrm{pp}}}{dE}$$

input - - - -> TransportCR - - - -> output

[arXiv:1406.0735]

- ✓ local $F_{\gamma/6\nu}(E)$ (not normalized)
- ✓ normalization to *Fermi*-LAT IGRB

[arXiv:1410.3696]

CGM gas density profile

input - - - -> TransportCR - - - -> output

[arXiv:1406.0735]

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CGM gas density profile

common-used parametrization: β–profile

$$n_{\rm CGM}(r) = n_0 \left(1 + r^2/r_c^2\right)^{-\frac{3\beta}{2}}$$

Satellite galaxies

- ram-pressure stripping: $n_{\rm CGM}$ is probed directly
- lack of data & detailed simulations in literature

Oxygen spectra

- absorption or blank-sky emission (OVII, OVIII)
- not $n_{\rm CGM}$ but $n_{\rm oxygen}$ is actually probed

CGM gas density profile

common-used parametrization: β–profile

$$n_{\rm CGM}(r) = n_0 \left(1 + r^2/r_c^2\right)^{-\frac{3\beta}{2}}$$

---

transition at $r \sim 30$ kpc, piecewise function is used

$r_c = 3$ kpc

$n_0 = 4.54 \times 10^{-3}\ {\rm cm}^{-3}$ $\beta = 0.337$ | $r^{\star}_{\rm kpc} \geq 30$ [arXiv:2105.02557]

$n_0 = 4.47 \times 10^{-1}\ {\rm cm}^{-3}$ $\beta = 1.000$ | $r_{\rm kpc} < 30$ [arXiv:1205.0249]

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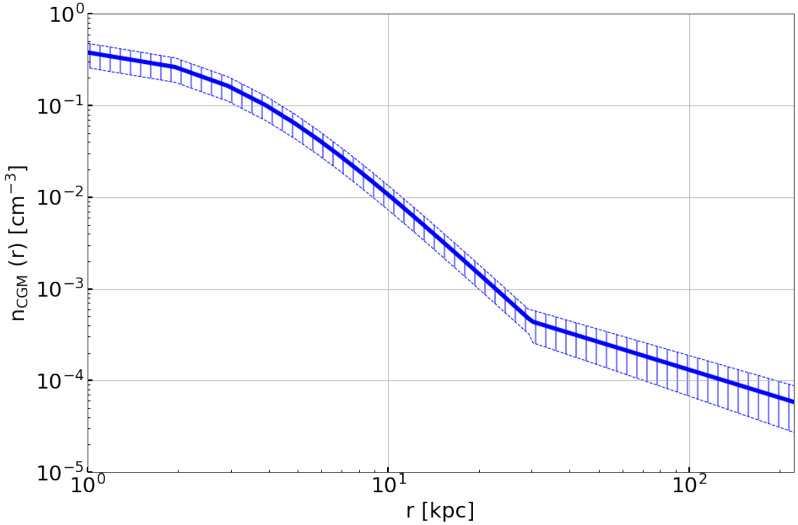
*hereafter $x_{\rm unit} \equiv x/{\rm unit}$

CGM gas density profile



Primary cosmic rays. Spectrum and density

```
input - - - -> TransportCR - - - -> output
```

[arXiv:1406.0735]

? CGM gas:

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$n_{\rm CGM}(r)$

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$j_{\rm CR}(r, E')$

Primary cosmic rays. Spectrum and density

$j_{\rm CR}(r, E)$ — depends on the assumed escape scenario!

Diffusive scenario

[arXiv:1608.07421]

- sources in the MW disc
- $j_{\rm CR}$ is the solution of the diffusion equation
- the injection spectrum and temporal evolution must be assumed

Non-diffusive scenario

[arXiv:2101.05016]

- observations of M31: tension with diffusion
- BUT: no well-described alternative scenario
  - additional acceleration in the CGM (shock waves?)
  - delivery of CR to the CGM inside bubbles?

Primary cosmic rays. Diffusive scenario

$$\frac{\partial}{\partial t} j_{\mathrm{CR}}(r, E', t) = D(E')\Delta_r j_{\mathrm{CR}}(r, E', t) - c\sigma_{pp}(E') n_{\mathrm{CGM}}(r) j_{\mathrm{CR}}(r, E', t) + Q(r, E', t)$$

Primary cosmic rays. Diffusive scenario

$$\frac{\partial}{\partial t} j_{\rm CR}(r, E', t) = D(E')\Delta_r j_{\rm CR}(r, E', t) - c\sigma_{pp}(E') n_{\rm CGM}(r) j_{\rm CR}(r, E', t) + Q(r, E', t)$$

$$j(r, E', t_0) = \; ?$$

the present-day CR profile and spectrum

Primary cosmic rays. Diffusive scenario

$$\frac{\partial}{\partial t} j_{\rm CR}(r, E', t) = D(E') \Delta_r j_{\rm CR}(r, E', t) - c\sigma_{pp}(E') n_{\rm CGM}(r) j_{\rm CR}(r, E', t) + Q(r, E', t)$$

$$D(E') = D_0 (E'_{\rm GeV})^{1/3}, \; D_0 = 1.2 \times 10^{29} \text{ cm}^2 \text{ s}^{-1}$$

[arXiv:1205.0249]

Primary cosmic rays. Diffusive scenario

$$\frac{\partial}{\partial t} j_{\mathrm{CR}}(r, E', t) = D(E') \Delta_r j_{\mathrm{CR}}(r, E', t) - c\sigma_{pp}(E') n_{\mathrm{CGM}}(r) j_{\mathrm{CR}}(r, E', t) + Q(r, E', t)$$

$$\sigma_{pp}(E') = \sigma_0 + \sigma_1 (\log E'_{\mathrm{GeV}}) + \sigma_2 (\log E'_{\mathrm{GeV}})^2$$

[PDG 2021], $E' > 10\ \mathrm{GeV}$

Primary cosmic rays. Diffusive scenario

$$\frac{\partial}{\partial t} j_{\mathrm{CR}}(r, E', t) = D(E') \Delta_r j_{\mathrm{CR}}(r, E', t) - c\sigma_{pp}(E') n_{\mathrm{CGM}}(r) j_{\mathrm{CR}}(r, E', t) + Q(r, E', t)$$

$$n_{\mathrm{CGM}}(r) = n_0 \left(1 + r^2/r_c^2\right)^{-\frac{3\beta}{2}}$$

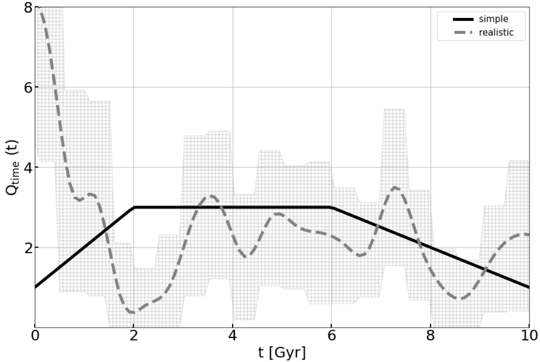
[arXiv:1205.0249] & [arXiv:2105.02557]

Primary cosmic rays. Diffusive scenario

$$\frac{\partial}{\partial t} j_{\rm CR}(r, E', t) = D(E')\Delta_r j_{\rm CR}(r, E', t) - c\sigma_{pp}(E') n_{\rm CGM}(r) j_{\rm CR}(r, E', t) + Q(r, E', t)$$

$$Q(r, E, t) \propto \theta(r_{\rm Q} - r) E'^{-\alpha} e^{-\frac{E'}{E_{\rm cut}}} \times Q_{\rm time}(t)$$

Primary cosmic rays. Diffusive scenario



$$r_{\mathrm{Q\,kpc}} = 15, \;\; \alpha = 2, \;\; E_{\mathrm{cut\,GeV}} = 10^8$$

[arXiv:1608.07421]

Primary cosmic rays. Diffusive scenario

$$\frac{\partial}{\partial t} j_{\rm CR}(r, E', t) = D(E')\Delta_r j_{\rm CR}(r, E', t) - c\sigma_{pp}(E') n_{\rm CGM}(r) j_{\rm CR}(r, E', t) + Q(r, E', t)$$

$$j_{\rm CR}(r, E', t = 0) = 0$$

$$\frac{\partial}{\partial r} j_{\rm CR}(r = 0, E', t) = j_{\rm CR}(r \to \infty, E', t) = 0$$

Primary cosmic rays. Non-diffusive scenario

Here we don't have any equations... :(

Here we don't have any equations... :(
...But we can obtain $j_{\rm CR}(r, E')$ phenomenologically!

Advantage: no need to assume a specific scenario, all* of them are taken into account

**non-diffusive* is just a conventional term, possible diffusion is also included

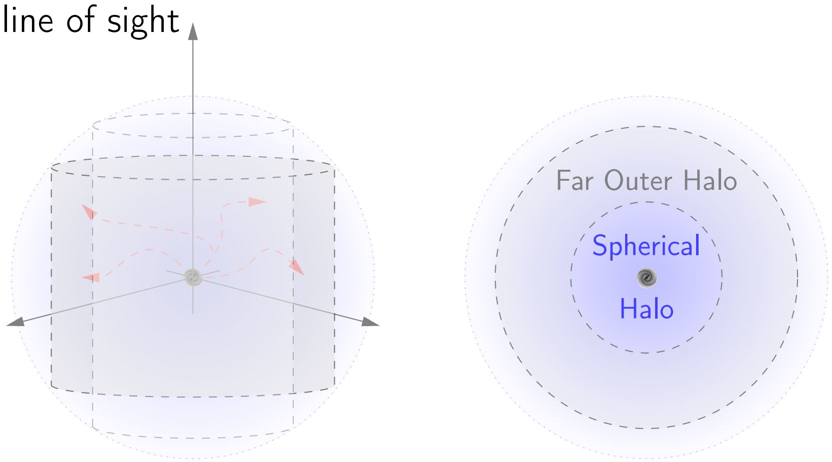
Primary cosmic rays. Non-diffusive scenario

- Reminder
  secondary CR source: $j_{\mathrm{CR}}(r, E') \times n_{\mathrm{CGM}}(r) \times \frac{d\sigma_{\mathrm{pp}}}{dE}$
- Assumptions (toy-model)
  - $n_{\mathrm{CGM}}(r) \times j_{\mathrm{CR}}(r, E') \propto r_{\mathrm{kpc}}^{-a} \times (E'_{\mathrm{GeV}})^{-2}$
  - $f_{\mathrm{M31}}(r) = f_{\mathrm{MW}}(kr)$, $k =$ M31-to-MW R_{vir} ratio

Idea: constrain the slope a from the observations of M31

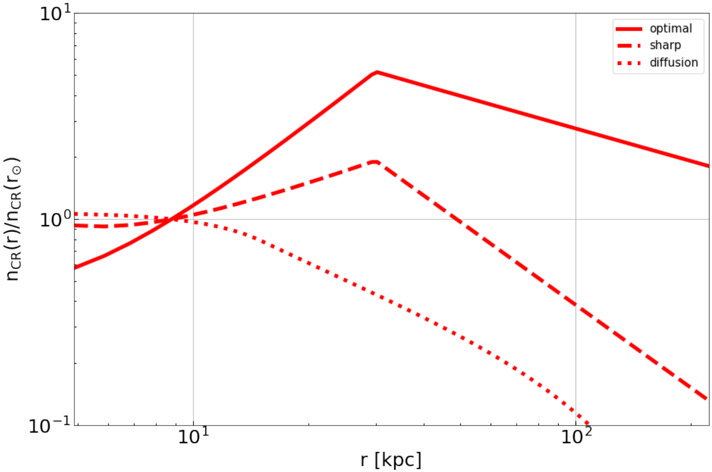
[arXiv:1903.10533]

Primary cosmic rays. Non-diffusive scenario



$I_{\mathrm{SH}} \div I_{\mathrm{FOH}}$ is an observable function of a!

Primary cosmic rays. Results



Secondary cosmic rays. Results

input - - - -> TransportCR - - - -> output

[arXiv:1406.0735]

✓ local $F_{\gamma/6\nu}(E)$ (not normalized)

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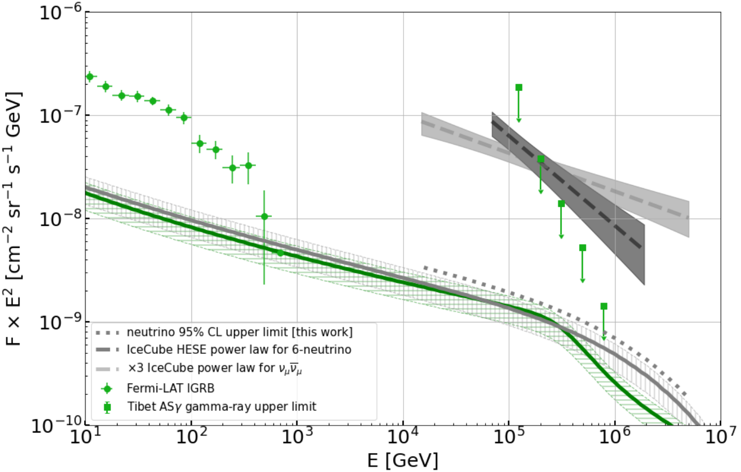
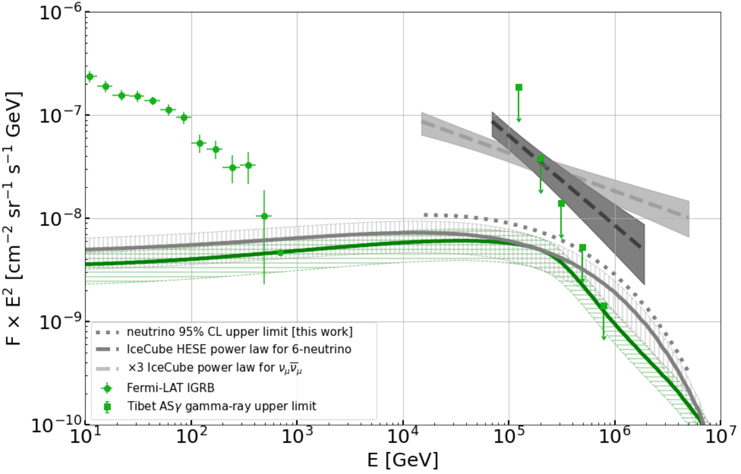
[arXiv:1410.3696]

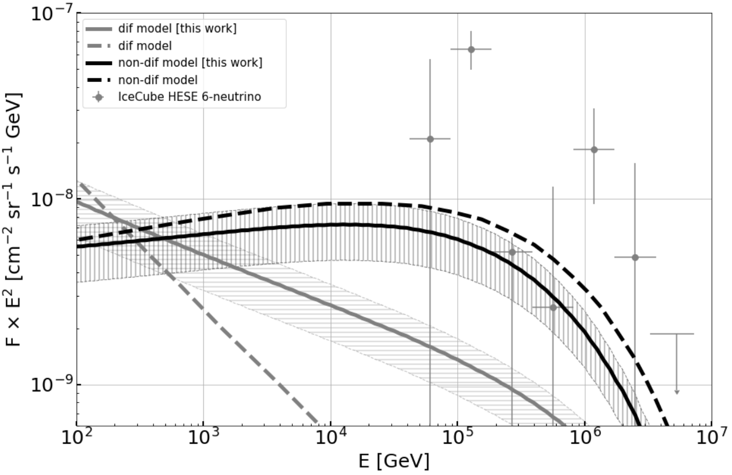
Secondary cosmic rays. Results for diffusive scenario



Secondary cosmic rays. Results for non-diffusive scenario



Secondary cosmic rays. Comparison with previous studies



Secondary cosmic rays. CGM-to-total ratio for ν

model \ scenario	diffusive	non-diffusive
IceCube HESE	$2.7\ (1.6 ... 3.7)\%$	$11.8\ (6.8 ... 16.6)\%$
IceCube $\nu_\mu \overline{\nu}_\mu \times 3$	$3.1\ (1.9 ... 4.1)\%$	$11.1\ (6.5 ... 15.1)\%$

What is the circumgalactic conrtribution?

We find that the CGM contribution to the observed neutrino flux is always subleading

Where do these neutrinos come from?

(Mostly) not from the CGM :)

For a detailed discussion, implications, etc.:

JCAP03 (2023) 053 [arXiv:2207.12458]

mail to: martynenko.ns18@physics.msu.ru

Backup. Numerical methods

$$r_{\text{kpc}} =: \varrho,\ t_{\text{Gyr}} =: \tau,\ D(E') \times \text{kpc}^{-2}\ \text{Gyr} =: D,$$
$$c\sigma_{\text{pp}}(E')n_{\text{CGM}}(r) \times \text{Gyr} =: f(\varrho),$$
$$E'^{-\alpha} \exp\left(\frac{-E'}{E'_{\text{cut}}}\right) r\theta(r_{\text{Q}} - r)Q_{\text{time}}(t) \times \text{GeV}^{\alpha}\ \text{kpc}^{-1} =: q(\varrho, \tau)$$

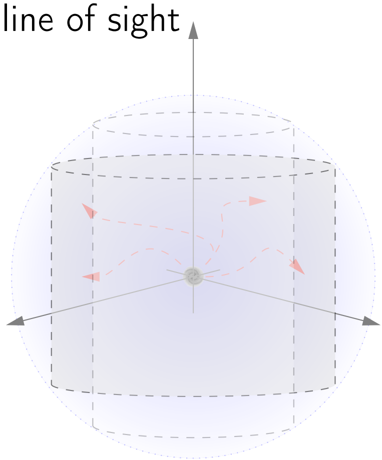
1024×256 (1024×2048) rectangular grid

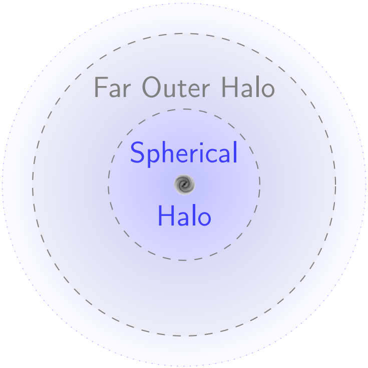
$$(\varrho_k, \tau_m) = (k\Delta\varrho, m\Delta\tau),\ (\varrho, \tau) \in [0, \varrho_{\text{bound}}] \times [0, 10]$$
$$\varrho_{\text{bound}} = 1000 \ \longleftrightarrow\ r = 1\ \text{Mpc} \gg r_{\text{gyr}}(E'_{\text{cut}})$$

$$u(r, E', t) = rj(r, E', t)/Q_0, \quad u_k^0 = u_0^m = u_{k_{\max}}^m$$

$$\frac{u_k^{m+1} - u_k^m}{\Delta\tau} = \frac{D\left(u_{k+1}^{m+1} - u_{k-1}^{m+1} - 2u_k^{m+1}\right)}{(\Delta\rho)^2} - f_k u_i^{m+1} + q_k^{m+1}$$

Backup. Observable function of a





Backup. Observable function of a

$$I(\eta_{in}, \eta_{out}|a) = \frac{I_0}{\eta_{out}^2 - \eta_{in}^2} \int\limits_{\eta_{in}}^{\eta_{out}} d\eta \left(\eta^2 \times \int\limits_0^{\sqrt{1-\eta^2}} d\xi \, \left(\xi^2 + \eta^2\right)^{-a/2} \right) =$$

$$= \frac{I_0}{\eta_{out}^2 - \eta_{in}^2} \times \int\limits_{\eta_{in}}^{\eta_{out}} d\eta \, \eta^{2-a} \sqrt{1-\eta^2} \; {}_2F_1\left(\frac{1}{2}, \frac{a}{2}, \frac{3}{2}, 1 - \frac{1}{\eta^2}\right)$$

$$\eta = r_\perp / R_{\text{vir}}, \; \xi = r_{||}/R_{\text{vir}}$$

$$a_{\text{optimal}} = 1.5, \; a_{\text{sharp}} = 2.3$$

Backup. Implications

parameter \ scenario	diffusive	non-diffusive
E'_{tot}, 10^{55} erg	2.9	3.1
P, 10^{41} erg s^{-1} $\times$ (T/Myr)	9.3	9.8