Annihilation of positrons from AGN jets as a possible source of cosmic soft gamma-ray background

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Papers

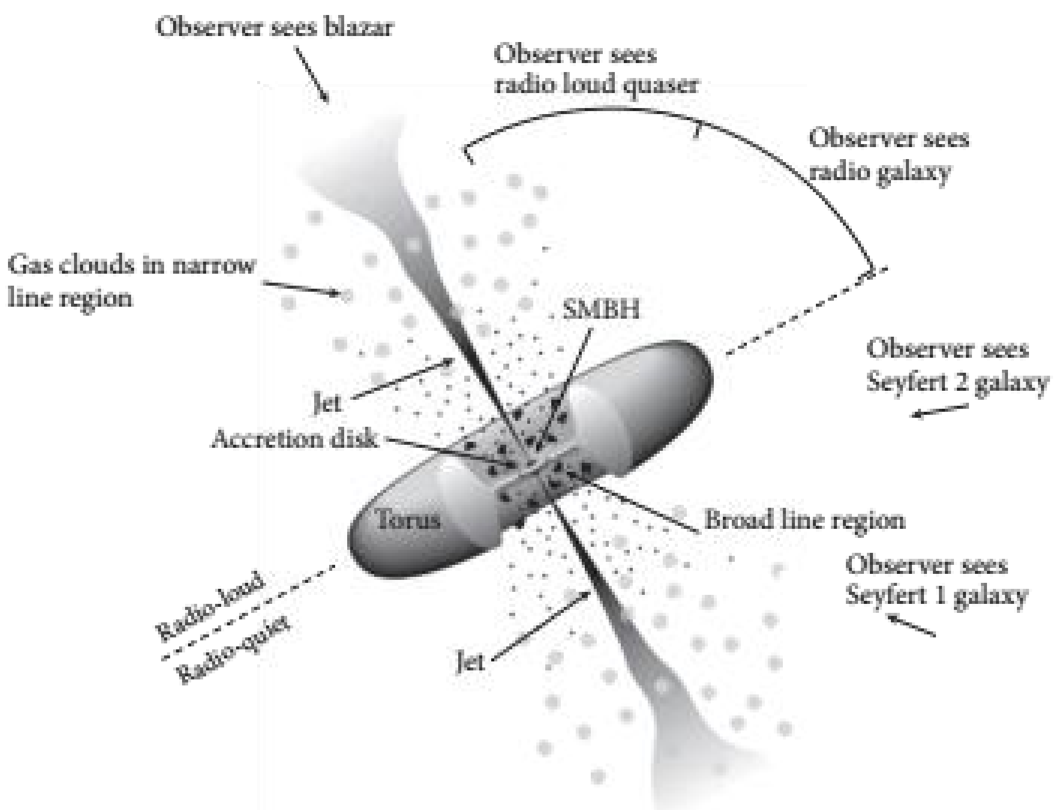
- B.A. Nizamov, M.S. Pshirkov, “Can Observations of 511 keV Line from the M31 Galaxy Shed Light on the AGN Jet Composition?”, arXiv:2303.0352

- B.A. Nizamov, M.S. Pshirkov, “Annihilation of positrons from AGN jets as a possible source of cosmic gamma-ray background at energies below 511 keV”, arXiv:2403.0827

AGN: unified model

- Matter is accreted on SMBH, releasing vast amount of energy: AGNs and relativistic jets are launched

- The Unified Model of AGNs: a supermassive black hole surrounded by a torus of dust. AGNs appear different because of their different oriention wrt. the line of sight.

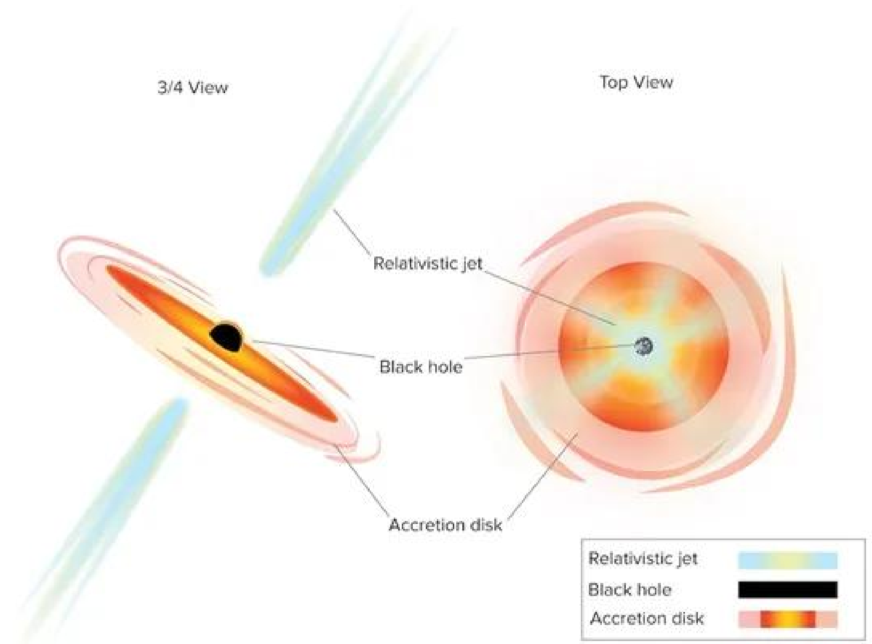


AGN: unified model

• Non-aligned AGNs -- we can observe radiation from both the accretion disk and the jet (sometimes from the host galaxy as well)

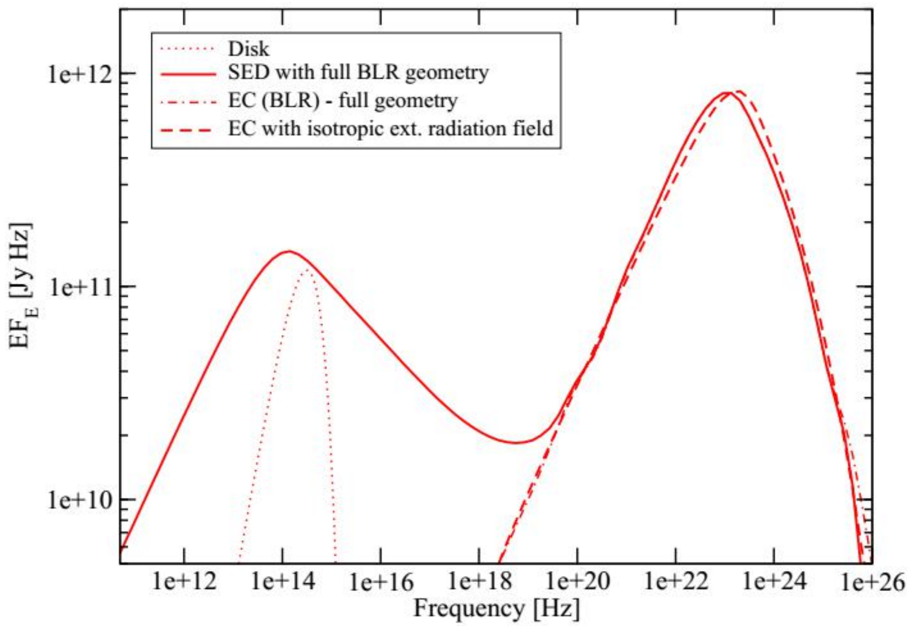
• Jet -- bulk relativistic motion, $\Gamma \sim 10$

• Extreme relativistic beaming for the aligned AGNs-- *blazars*. The jet dominates over all other sources of the radiation

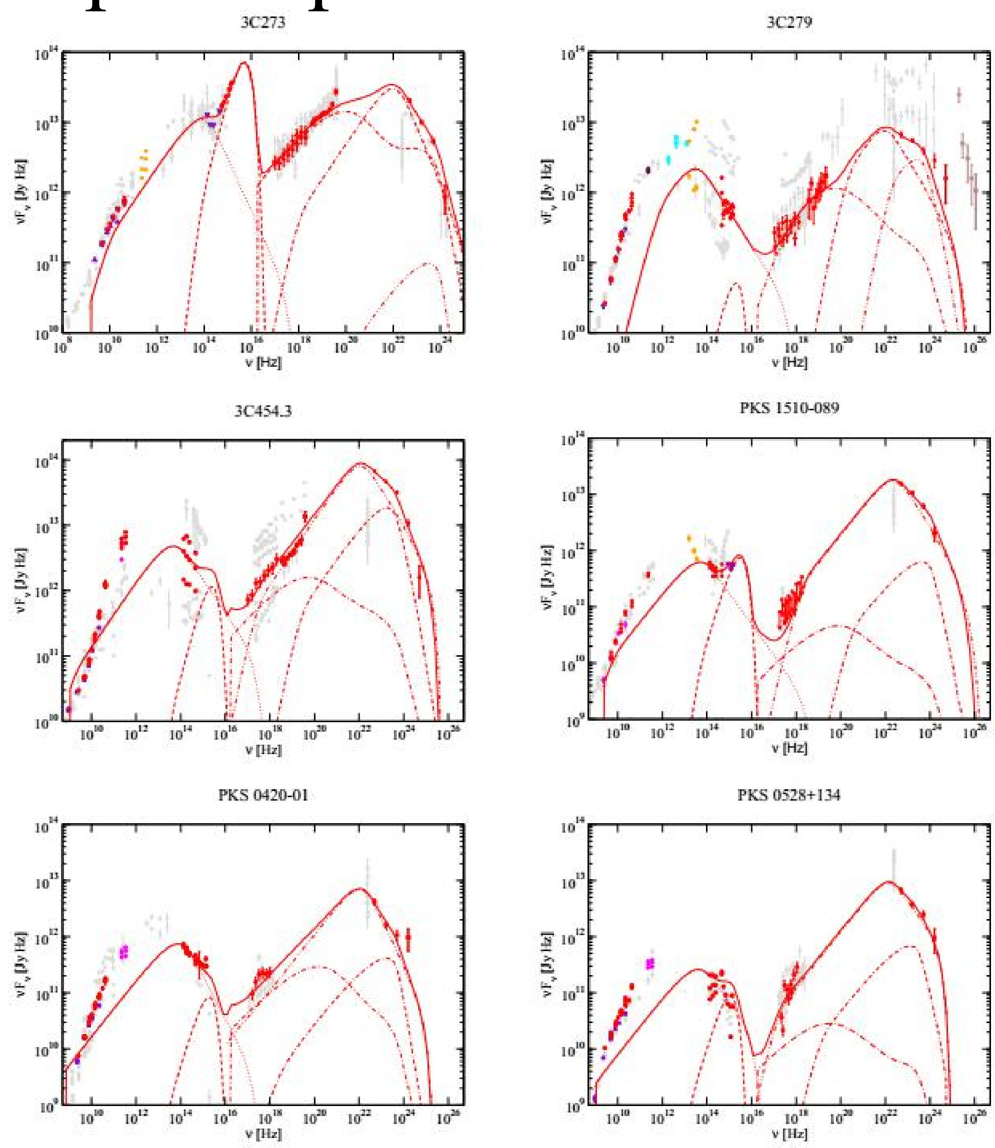


AGN jets: spectrum

- Two peaks: LE from synchrotron. HE -- ?
- Leptonic models -- IC
- Hadronic -- proton synchrotron/photo-pion



Bottcher et al, 2013



AGN jets: components

- We can be sure that there are electrons (from the first peak)

- +Protons: restore electroneutrality

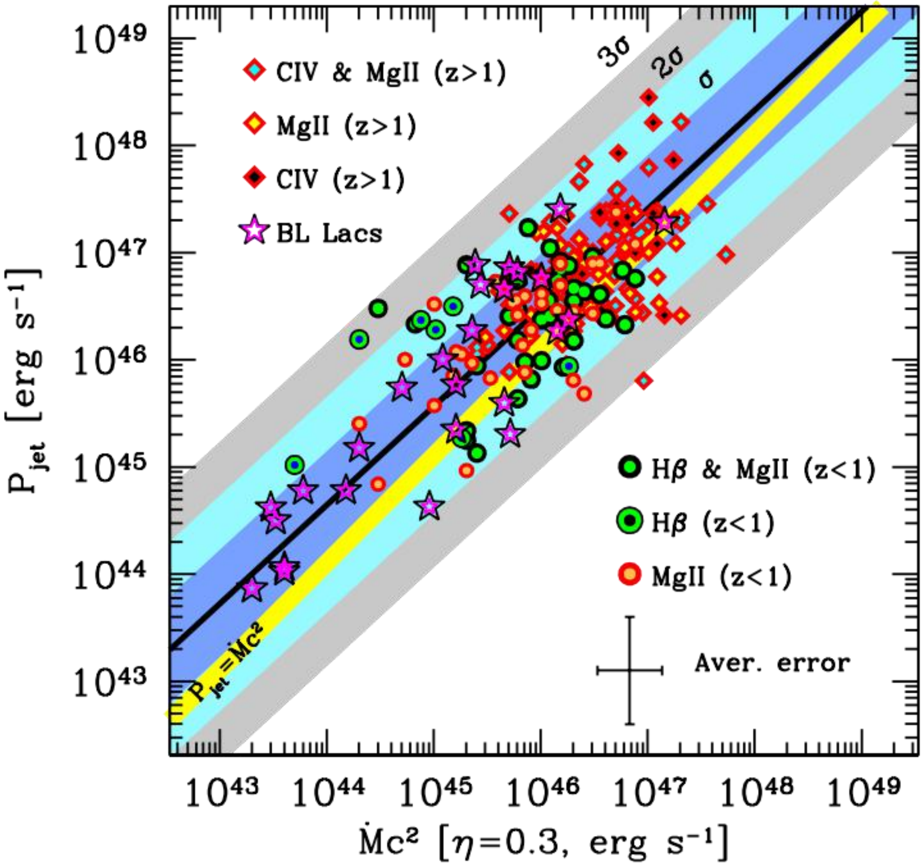
- Could be also some contribution from e^+e^- pairs

AGNs: energetis

- Accretion luminosity, $L = \epsilon \dot{M}_{acc} c^2$, ε~0.1
- Kinetic power of the jet, P_{jet}

- Several different methods to estimate the latter, some of them give $P_{jet} > \dot{M}_{acc} c^2$!

- Other more modest, $P_{jet}/\dot{M}_{acc} c^2$ ~(0.01-0.1)



Ghisellini et al, 2014

AGNs: pairs

- We can reconcile, adding 10-20 pairs for each proton.

- Also polarizational observations of jets are in line with presence of positrons.

- Jets are still energetically dominated by proton bulk motion, but numerically the protons are marginal constituent.

- Helps to lower needed jet energetics.

- Bottom line: we expect considerable amount of pairs to exist in the jets. They could have been originally created near the SMBH in the collisions of ~MeV photons.

Positrons: possible observational consequences

- Positrons eventually leave the jet

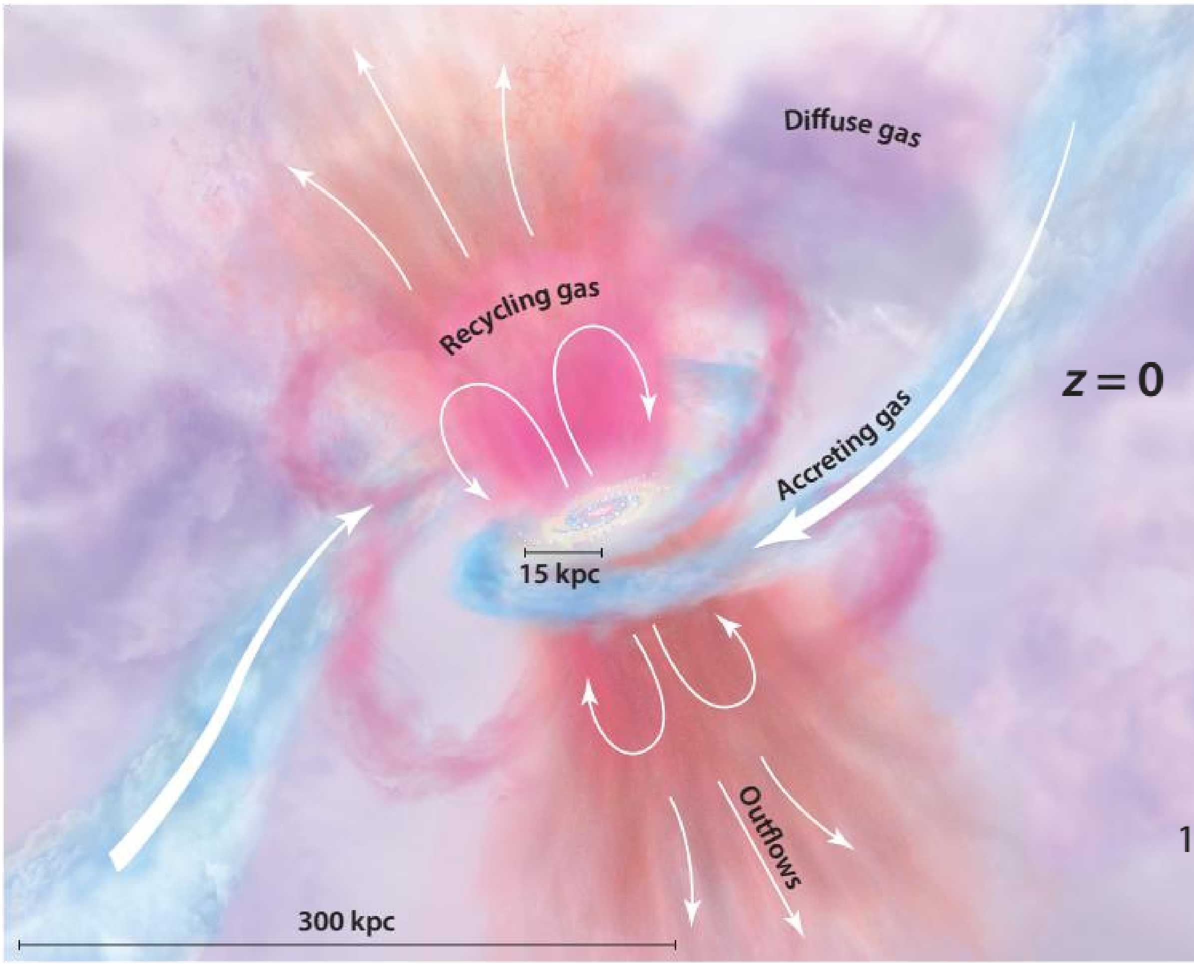
- They stay in the circum-galactic medium (CGM) of the galaxy (<100 kpc) and continuously annihilate there with tenuous CGM

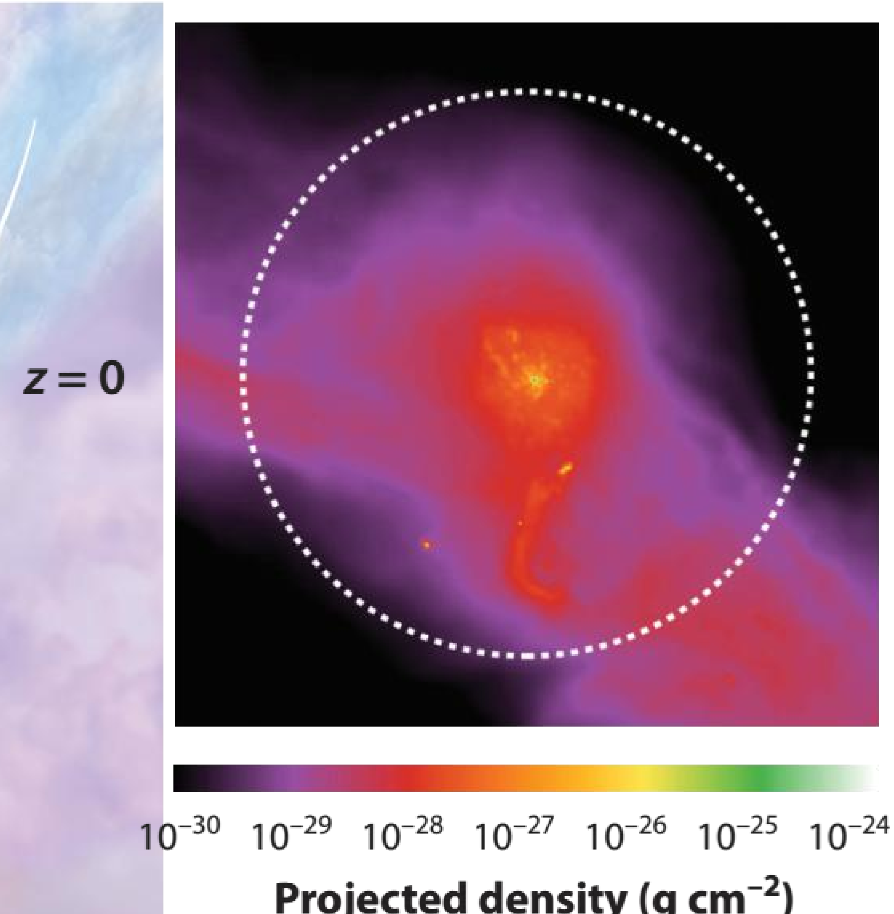
- We could potentially observe 511 keV line + soft-gamma ray continuum from 3-photon annihilation

- Caveat: we don’t know fraction of positrons leaving the halo for good

CGM

- Gas halo around the galaxy
- Inflow from the IGM, outflows to IGM -- baryon cycle





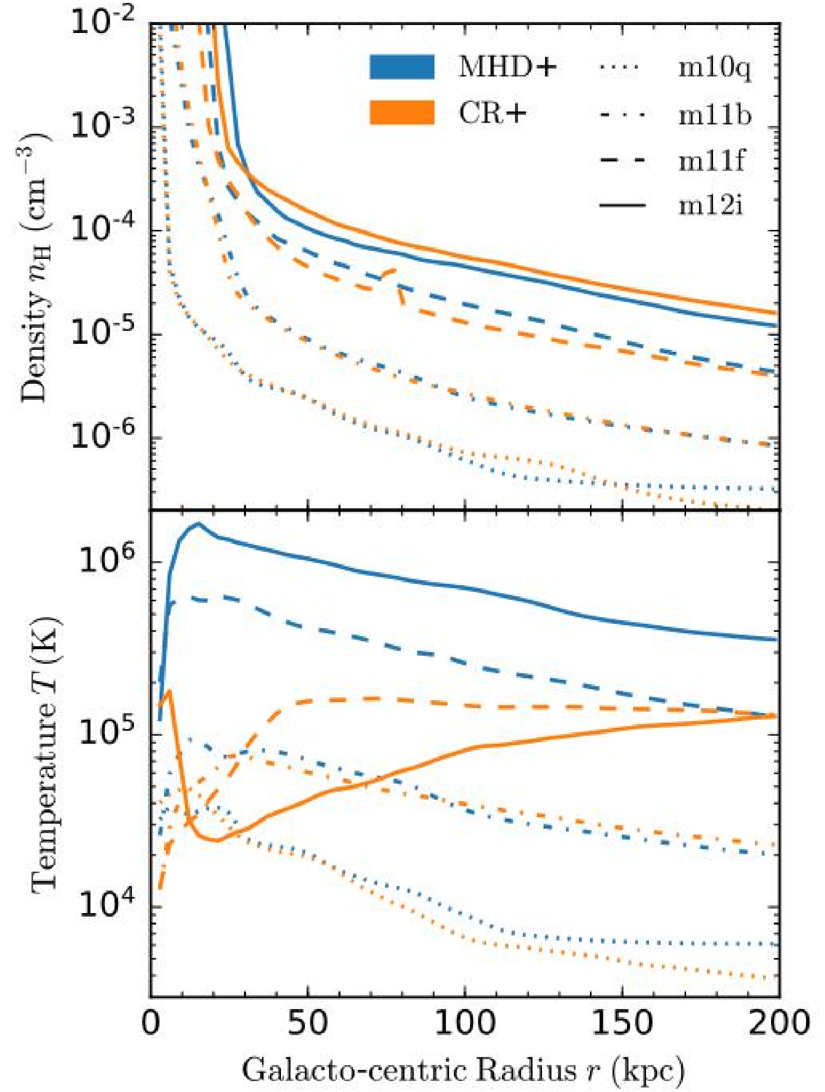
Tumlinson et al, 2017

CGM

- CGM is a complex multi-phase structure:
  - denser colder regions ($T=10^5$ K)
  - diluted hot regions ($T=10^6$ K)

- Characteristic density:

  $n \sim 10^{-4}$ cm^{-3}



Ji et al, 2020

Positron production

- As we have seen in the *Energetics* section, the jet power is tightly coupled to the accretion rate
- Assuming that $n_e = n_p$ (i.e., no positrons)

$$P_j = \eta \dot{M}_{acc} c^2 \quad , \eta \sim 1$$

- If $n_{pair} \neq 0$, this power is reduced

$$P_j = \eta \dot{M}_{acc} c^2 / 2 n_{pair}$$

- On the other hand, $P_j = \dot{N}_p \Gamma m_p c^2$, kinetic energy of proton bulk motion dominates
- We're interested in the positron production rate

$$\dot{N}_+ = n_{pair} \dot{N}_p \qquad\qquad \boxed{\dot{N}_+ = \frac{\eta \dot{M}_{acc}}{2 \Gamma m_p}}$$

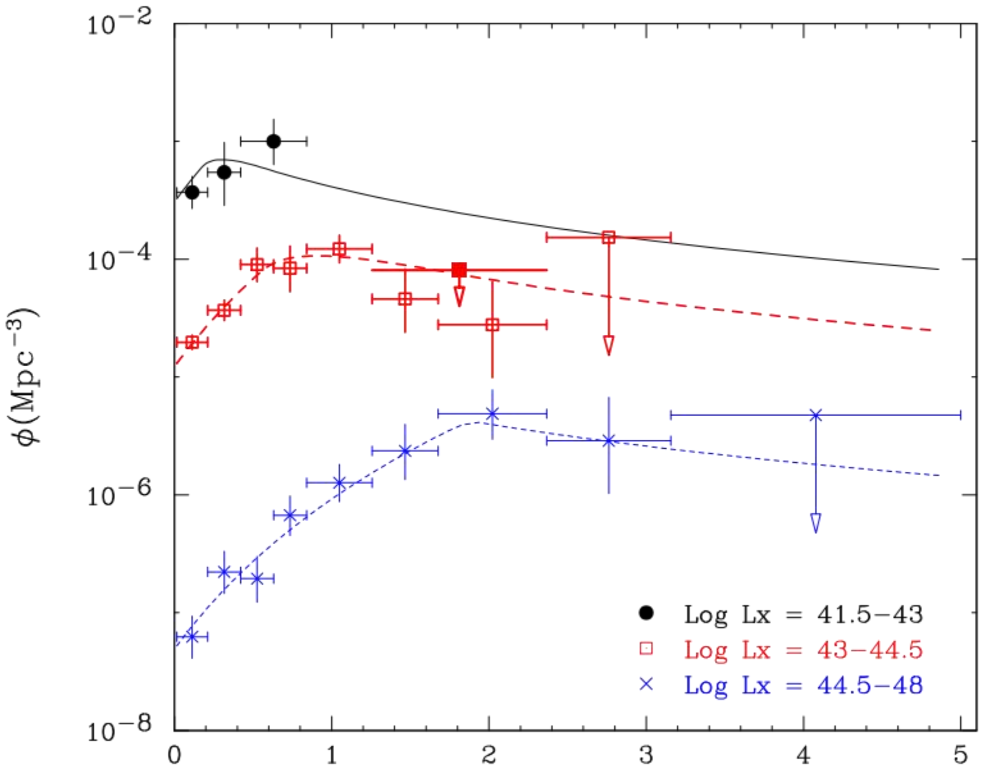
- Does not depend on n_{pair}! (If $n_{pair} \sim (10\text{-}20)$).
- Flux roughly proportional to M_{SMBH}/d^2. Sgr A*, M31, Cen A. The best candidate is M31.

Positron production

- We don't know accretion history $\dot{M}_{acc}(t)$ for any particular SMBH → we need mean evolution instead

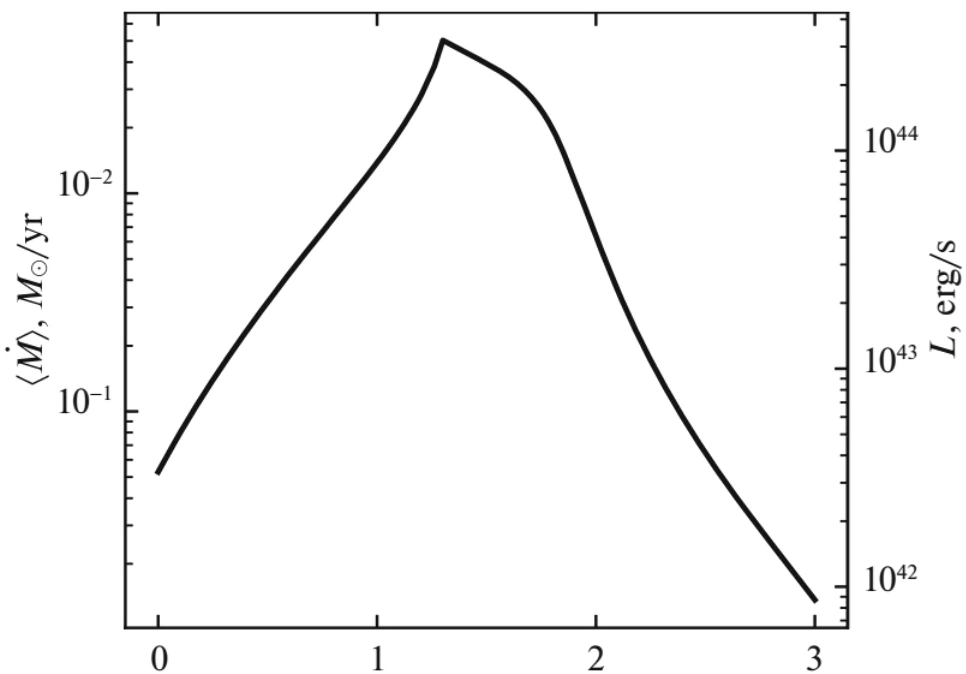
- Could be obtained from the luminosity functions at different redshifts. e.g. X-ray LFs (*Ueda et al, 2003*)

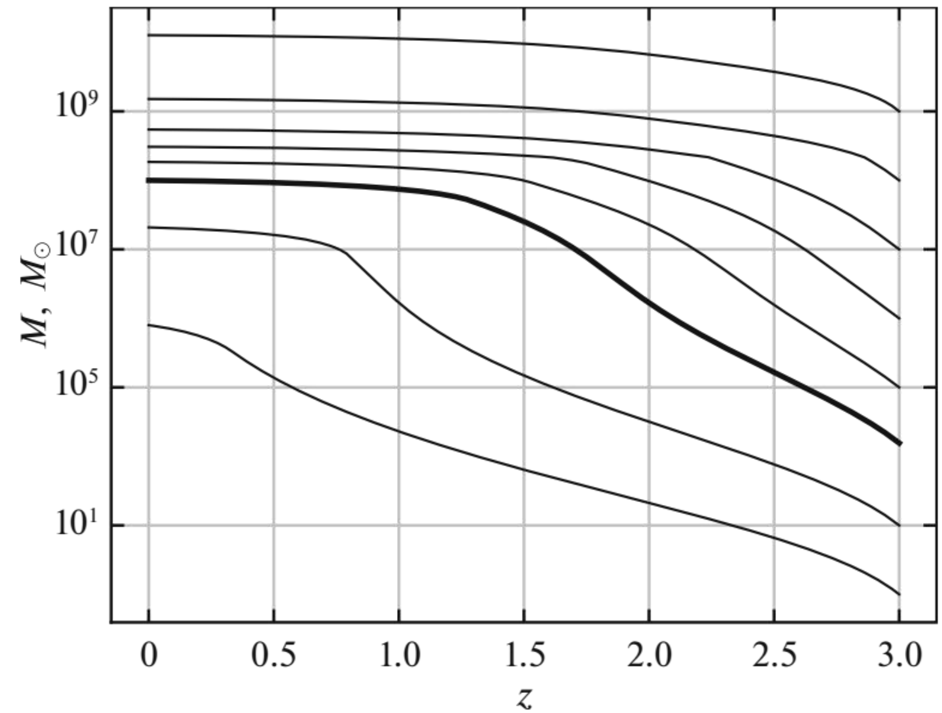
- Accretion tracks the X-ray luminosity



Positron production

- We normalize the rate, using the known present day SMBH mass (10^8 $M_\odot$)





Left: Average growth rate of an SMBH with the initial mass 1.56 × 104 Msol. On the right axis is shown the corresponding average AGN bolometric luminosity. *Right*: Growth history for SMBHs of various initial masses calculated by method of Marconi et al. (2004). The track used in the calculations is shown in bold.

Positron thermalization

- We need to know accumulated number of positrons in order to get the luminosity, $L(t) \sim N_+(t)$.
- Positrons could effectively annihilate only when "in rest", i.e. thermalized, due to the strong velocity dependence of the cross-section
- How to slow down initially relativistic particles (Γ)?
- Two ways:
  - Coulomb collisions (slow):

$$t_{\rm br} = (\Gamma - 1)mc^2 \left\{ 7.7 \times 10^{-9} \frac{n}{\beta} \left[\ln\left(\frac{\Gamma}{n}\right) + 73.6 \right] \right\}^{-1} \approx 2.2(\Gamma/10)(n/10^{-4}\ {\rm cm}^{-3})^{-1}\ {\rm Gyr.}$$

  - Adiabatic losses (fast):

$$t_{\rm ad} \sim r_{\rm halo}/v_{\rm wind}, \quad r_{\rm halo} = 50\ {\rm kpc},\ v_{\rm wind} = 300\ {\rm km/s} \qquad t_{\rm ad} \sim\ 200\ {\rm Myr.}$$

- Real $t_{\rm ad} < t_{\rm br} < t_{\rm coul}$, could be approximated as $0 < t_{\rm br} < t_{\rm coul}$

Positron annihilation

- Thermalized photons could annihilate either directly, or through formation of the bound state, so-called *positronium*, Ps

$2\frac{1}{2}$ roads to gamma:

Direct, $e^+ + e^- \rightarrow 2\gamma$, $E_\gamma = 511$ keV

Recombination, $e^+ + e^- \rightarrow$ Ps

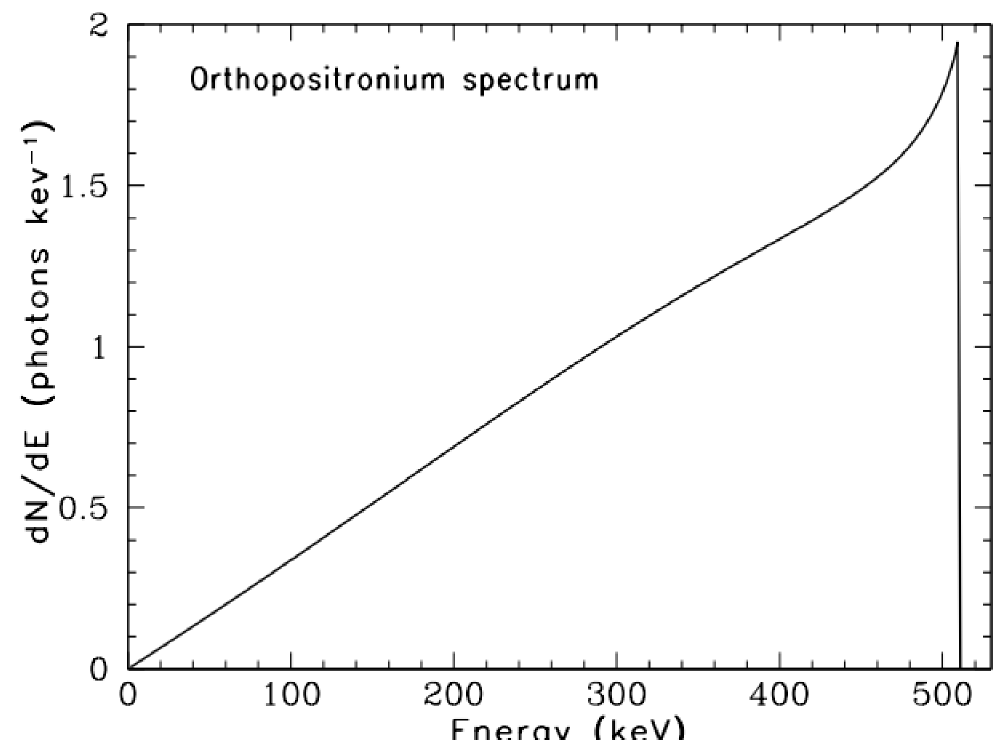
- Cross-sections and characteristic times has different n_e-dependences:

$$t_{\rm d} \approx 20 \times (T/10^6{\rm K})^{0.5}(n/10^{-4}{\rm cm}^{-3})^{-1} \quad {\rm Gyr}$$

$$t_{\rm r} \approx 27 \times (T/10^6{\rm K})^{1.1}(n/10^{-4}{\rm cm}^{-3})^{-1} \quad {\rm Gyr}$$

Positron annihilation

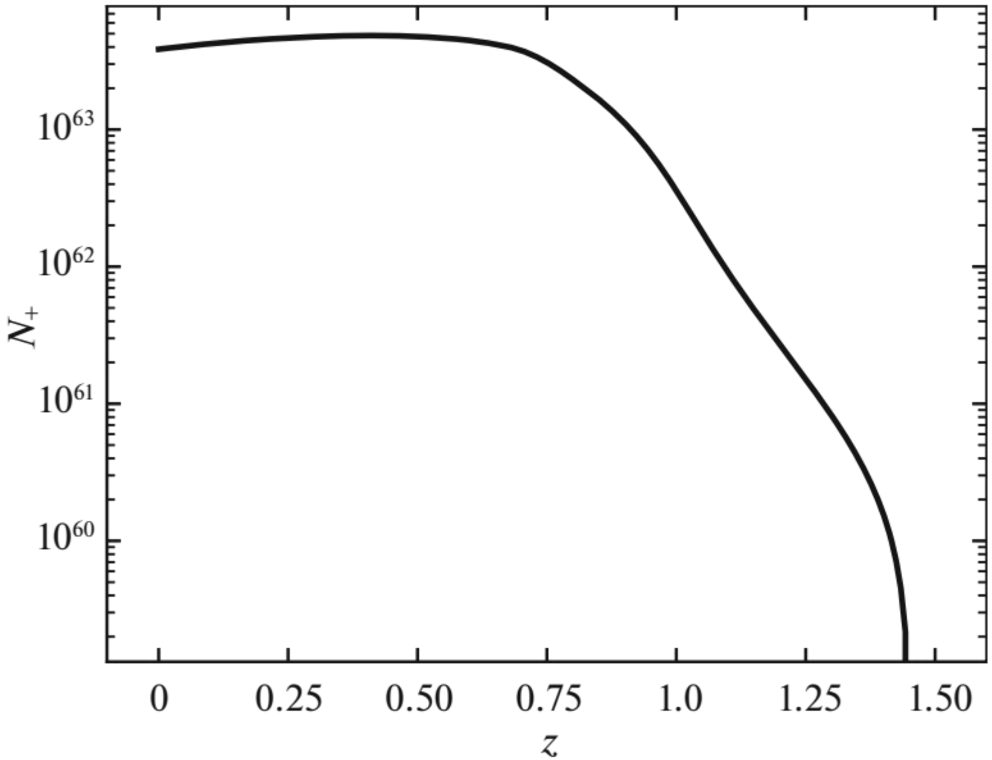
- Ps comes in two kinds. Singlet, with parallel spins, *para-positronium*, p-Ps. Triplet, with antiparallel spins, *ortho-positronium*, o-Ps.
- Branching ratio for Ps formation -- 1/4 for p-Ps, 3/4 for o-Ps.
- p-Ps annihilates in 2 photons, E=511 keV in 10^{-10} s. o-Ps lives longer, 10^{-7} s and decays into three photons, forming a continuum



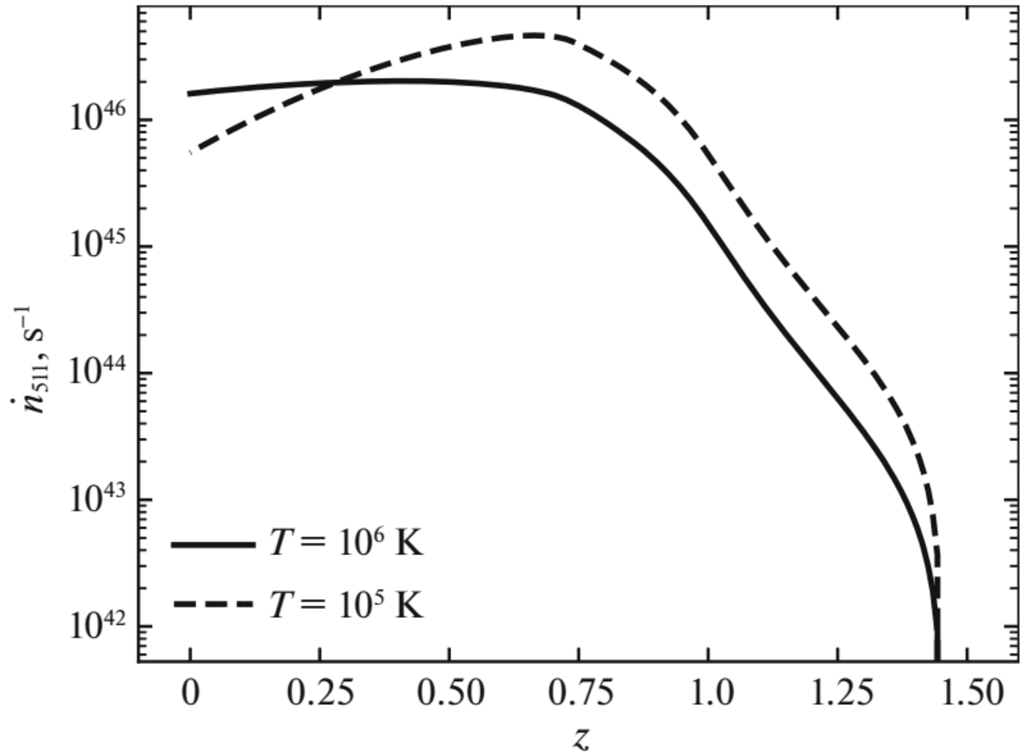
Positron annihilation

- Number of thermalized positrons could be calculated from the following equation:

$$\frac{dN_+(t)}{dt} = \dot{N}_+(t - t_{\rm br}) - nN_+(t)(\langle\sigma_{\rm a}v\rangle + \langle\sigma_{\rm r}v\rangle)$$



Evolution of the content of thermalized positrons in the halo of M31.



511 keV photon production rate in M31 halo for the halo temperature $T = 10^6$ and 10^5 K ($\Gamma = 10$)

511 keV line flux

- The flux at the Earth is: $$F = \frac{2nN_+(t_e)(\langle\sigma_a v\rangle + \frac{1}{4}\langle\sigma_r v\rangle)}{4\pi d^2}$$
- For the halo parameters $n = 10^{-4}$ cm^{-3}, $T = 10^6$ K, we obtain $F = 2.5 \times 10^{-4}$ photon cm^{-2} s^{-1}.
- For different values of T and Γ:

T, K	Γ		
	5	10	20
10^6	4.6×10^{-4}	2.5×10^{-4}	1.5×10^{-4}
10^5	1.1×10^{-4}	8.7×10^{-5}	1.1×10^{-4}

- Close to present-day ULs from *INTEGRAL*, 10^{-4} ph cm^{-2} s^{-1} obtained for a point-source M31.
- Near future missions, e.g. *COSI* will check.

Contribution to EDGRB

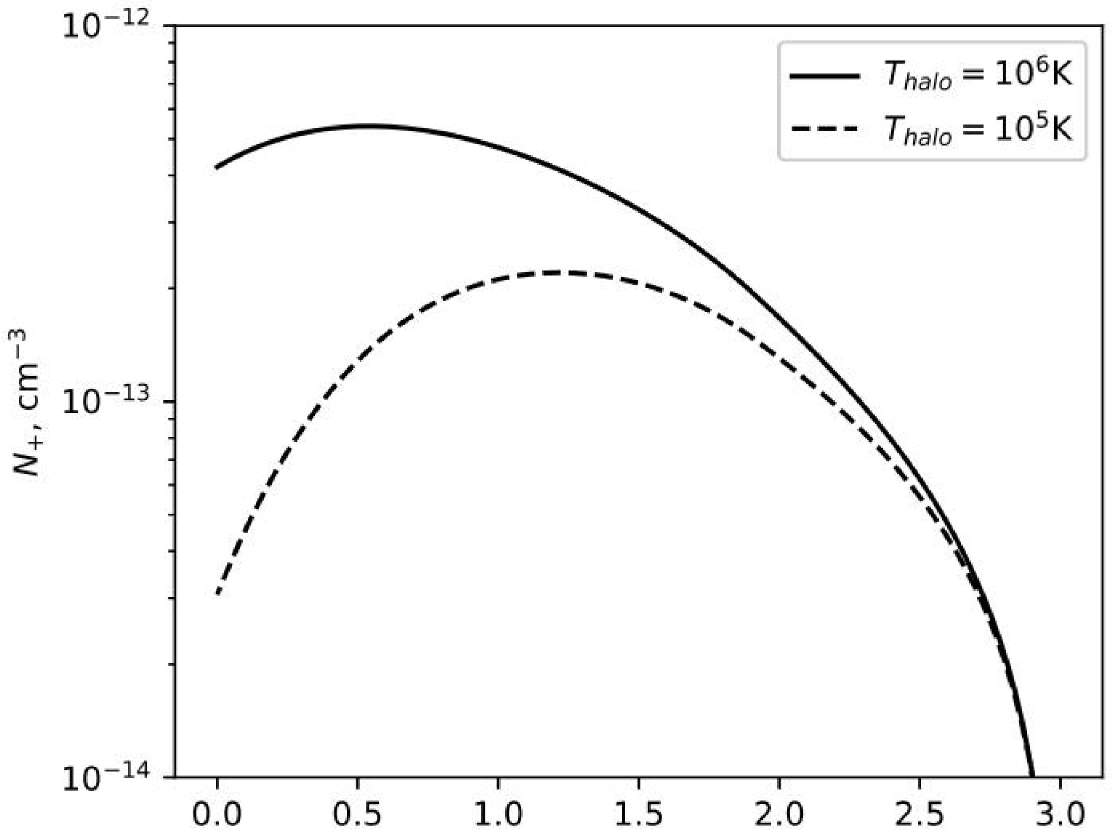
- Whole population of AGNs in the Universe could contribute to the observed extragalactic diffuse gamma-ray background
- 511 keV line would be redshifted. Also we now take into account 3-photon annihilation of o-Ps.
- Production rate could be directly extracted from the AGN luminosity function $\phi(L,t)$:

$$\dot{N}_+(t) = \frac{\eta \int L\phi(L,t) d\log L}{2\epsilon c^2 \Gamma m_{\rm p}}$$

- Number evolution

$$\frac{dN_+(t)}{dt} = \dot{N}_+(t - t_{\rm br}) - nN_+(t)(\langle\sigma_{\rm a} v\rangle + \langle\sigma_{\rm r} v\rangle)$$

Contribution to EDGRB



The mean comoving number density of positrons.

Contribution to EDGRB

- Comoving producton rates of 2- and 3-photons:

$$\varepsilon_{2\mathrm{phot}}(z) = 2nN_+(z)\left(\langle\sigma_{\mathrm{a}}v\rangle + \frac{1}{4}\langle\sigma_{\mathrm{r}}v\rangle\right) \qquad \varepsilon_{3\mathrm{phot}}(z) = \frac{3}{4}nN_+(z)\langle\sigma_{\mathrm{r}}v\rangle$$

- It is possible to obtain the radiation intensity of the sources with a known redshift distribution.

$$I_{\mathcal{E}} = \frac{c}{4\pi H_0}\int \frac{L[(1+z)\mathcal{E}, z]dz}{(1+z)E(z)}$$

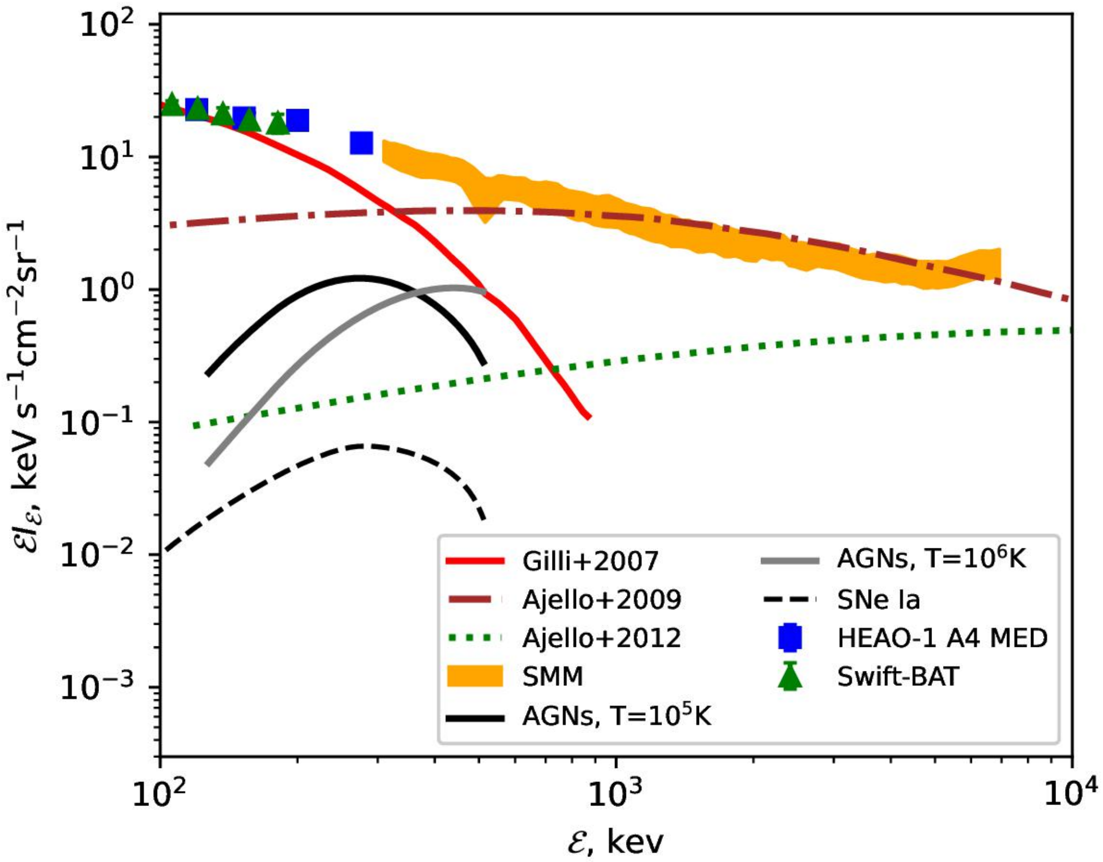
$$E(z) = \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}.$$

- In the case of two photon annihilation radiation, the luminosity is monochromatic and equals

$$L(\mathcal{E}, z) = \mathcal{E}_0\varepsilon_{2\mathrm{phot}}(z)\delta(\mathcal{E} - \mathcal{E}_0)$$

- 3-photons: $L(\mathcal{E}, z) = \mathcal{E}\varepsilon_{3\mathrm{phot}}(z)\varphi(\mathcal{E})$, $\varphi(\mathcal{E})$ --decay spectrum

Contribution to EDGRB



Diffuse GRB spectrum. The observation data are HEAO-1 A4, Swift-BAT , SMM . The model curves represent the contribution from AGNs (Gilli+2007) and FSRQs (Ajello+2009) and (Ajello+2012) . Our estimations from AGNs and SNe Ia are also shown.

Conclusions

- AGN jets are a viable source of positrons in the Universe.
- If they are produced in AGN jets and are trapped in galactic gaseous halos, they can survive for substantial amount of time
- We found that for a reasonable parameter combination, the present 511 keV photon flux at Earth from M31 can be as high as few times 10^{-4} cm^{-2} s^{-1} and can be potentially observed in the near future
- The possible annihilation component from the population of AGNs could make a subdominant contribution, providing up to ~ 20% of the total EDGRB in the 400–500 keV range

Thank you!

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