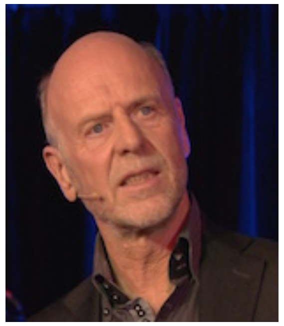
Nucleosynthesis for a Life: *A symposium in honour of R. Diehl*



Nuclear gamma-rays from hot accretion flows

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MPE, Munich, Feb 8, 2019

prompt de-excitation gamma-ray lines:

unique messengers of information about sub-relativistic Nonthermal Universe

initiated by suprathermal CRs - energy range 1 to 100 MeV

implications:

solar flares (main energy release)

star forming regions (ionisation, chemistry)

SNRs - problem of injection

ISM - pressure

……………

- realization - so far, not impressive (except for Solar Flares)

  the *status of "de-excitation gamma-ray line" astronomy - same as in the 1970s*

- reason - low efficiency of production (10^{-5} or less)
  and lack of sensitive MeV detectors

- future - ?? , partly eASTROGAM, …

100 MeV does not necessarily imply "nonthermal"

formation of hot 10^{10} K to 10^{12} K plasmas?

- *due to accretion on neutron stars and black holes*
- *termination of sub-relativistic shocks:* v ~ 0.03-0.3 c

typically two-temperature plasmas with $T_i >> T_e$

de-excitation lines - *the best carriers of information about two-temperature plasmas*!

radiation efficiency? - *somewhat better than in non thermal scenarios*!

my "entrance" to Astrophysics started with prompt gamma-ray lines

motivation *"rich" physics where I could use my knowledge in nuclear physics*

but also

disappointment *low radiation efficiency* + *low performance of MeV detectors*

=> shift of interest to (very) higher energies

35 years old almost unnoticed (only 48 citations!) paper

Mon. Not. R. astr. Soc. (1984) **210**, 257–277

Gamma-ray line emission, nuclear destruction and neutron production in hot astrophysical plasmas. The deuterium boiler as a gamma-ray source

F.A. Aharonian and R.A. Sunyaev

Summary. In hot astrophysical plasmas with ion temperatures high enough for nuclear excitation ($\geqslant 10^{11}$ K) inelastic spallation reactions can proceed at a higher or similar rate leading to nuclei destruction during the stationary high-temperature plasma formation time. Therefore the nuclei manage to be excited before destruction, but on the average not more than once. As a result the nuclear line luminosity is strongly depressed and does not exceed 10^{-3}–10^{-4} of the total luminosity which is associated mainly with the electron component of the plasma.

In the quasi-stationary sources of hard radiation (e.g. accretion discs) a proton–neutron plasma is formed due to nuclear destruction without a noticeable content of heavy nuclei. In the two-temperature plasma ($T_i > T_e$) the nucleons lose their energy mainly through elastic collisions. Besides, the nucleons radiatively cool due to neutron capture by protons (with deuterium production) and bremsstrahlung during the proton–neutron scattering.

The possibility of neutron evaporation from the two-temperature accretion discs is discussed.

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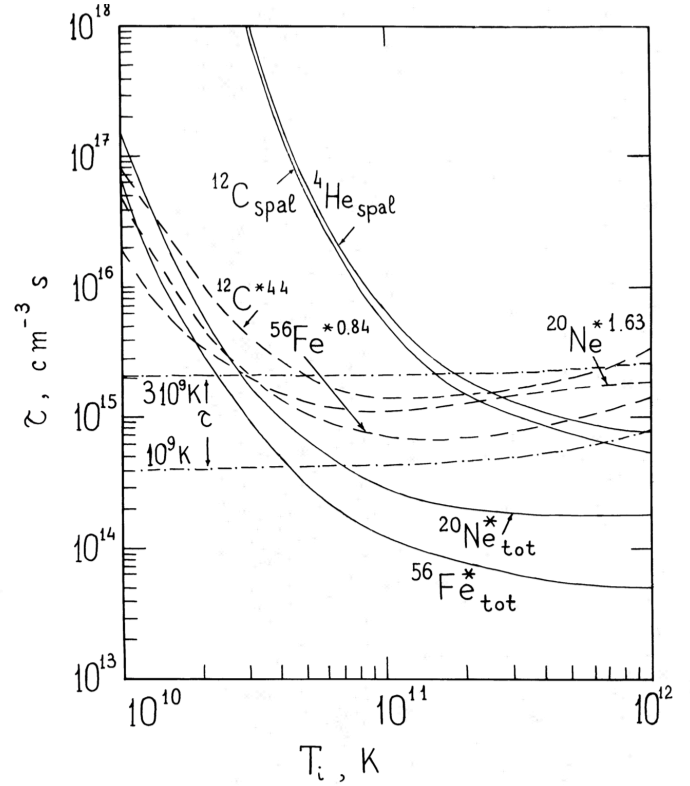


Figure 1. Nuclear excitation (– – –) and spallation (——) times in a Maxwellian plasma. The (p–e) relaxation times (– · – · –) at $T_e = 10^9$ K and $T_e = 3 \times 10^9$ K are also shown.

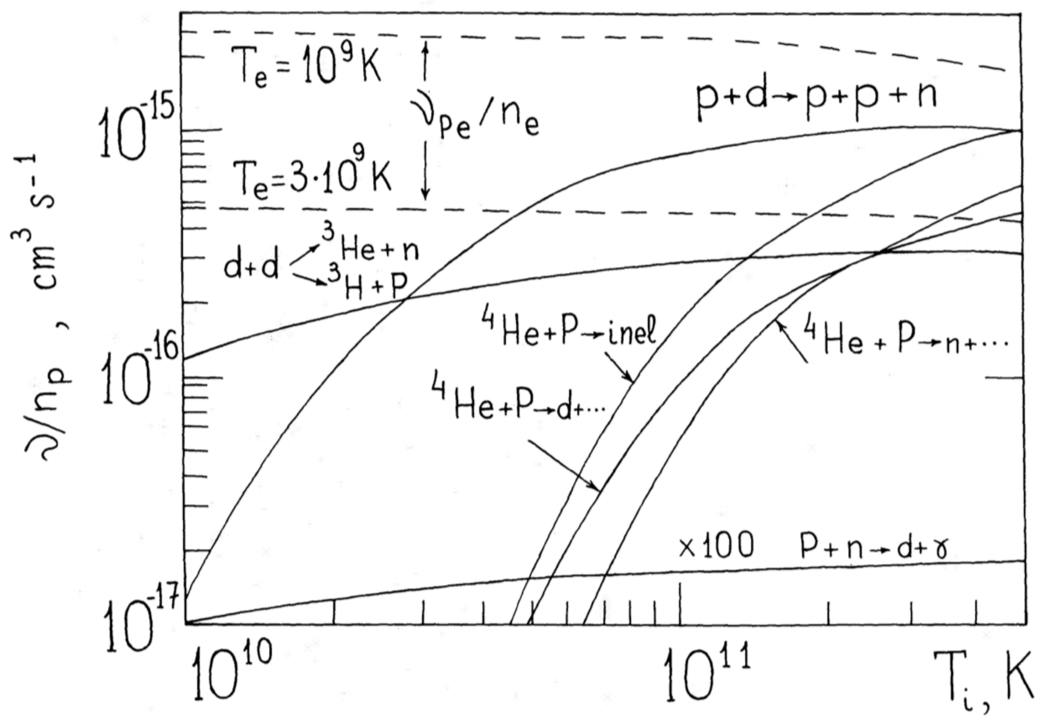
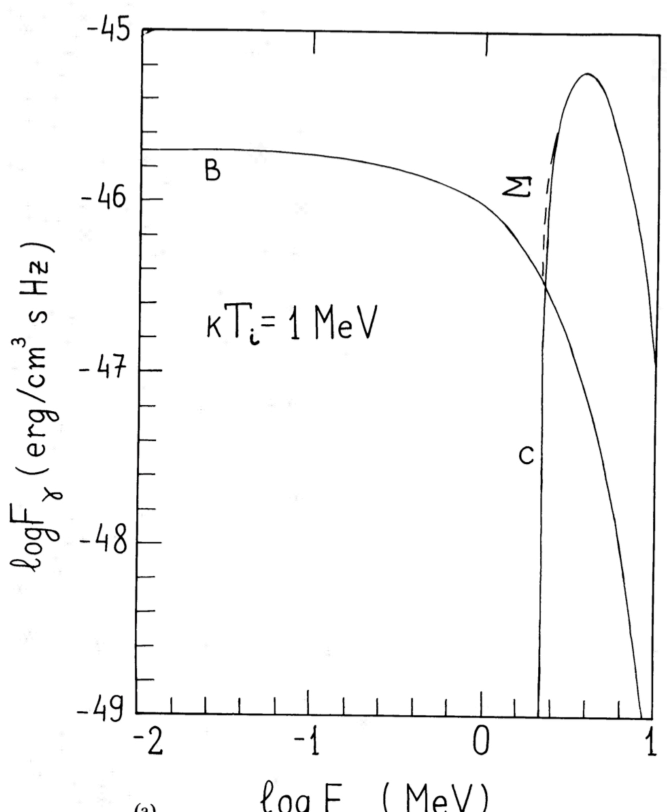


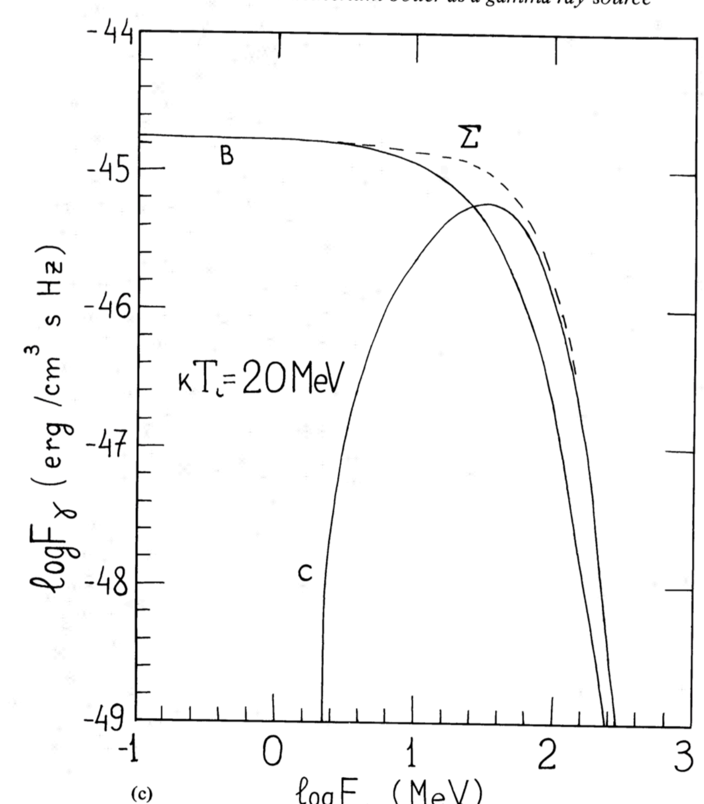
Figure 2. Reaction rates in Maxwellian plasma. The (p–e) energy exchange rates (– – –) at $T_e = 10^9$ K and $T_e = 3 \times 10^9$ K are also shown.



(a)

Figures 3a–c. The radiation spectra of proton–neutron plasma: B, bremsstrahlung; C, neutron capture; Σ = B + C. (a) $kT_i = 1$ MeV; (b) $kT_i = 5$ MeV; (c) $kT_i = 20$ MeV.

The deuterium boiler as a gamma-ray source



(c)

Figure 3 – *continued*

Mon. Not. R. astr. Soc. (1984) **210**, 257–277

5.4 NEUTRON EVAPORATION FROM ACCRETION DISC

The free path length of fast neutrons in the disc exceeds its half-thickness $[\lambda/h \simeq (\sigma_0 n_p h)^{-1} = (\sigma_T/\sigma_0)\,\tau_T^{-1} > 1$ at $E_n > 10\,\mathrm{MeV}]$; they are not confined by electrostatic forces or magnetic field. Therefore, an efficient neutron evaporation from the disc is possible. This problem is close to the classical problems of the atom evaporation from planetary atmospheres (J. Jeans, private communication) and the problem of star evaporation from star clusters (V. Ambartsumian & L. Spitzer, private communication).

A considerable part of them (~ 10 per cent) may be captured by internal regions of the accretion disc (Shakura & Sunyaev 1973) and by the companion star of the binary system. In dense cold regions neutrons are rapidly thermalized and at the proton capture give a deuteron and a narrow 2.22 MeV gamma-ray line. The deuterium atoms produced in the atmosphere of a companion star may be ejected into the interstellar medium by the stellar wind. In the limiting case of 100 per cent efficiency of the mechanism discussed and the assumption of a large number of black holes at the early stage of Galaxy, this mechanism might make a noticeable contribution to the interstellar abundance of deuterium.

Finally, the conditions in inner parts of accretion disks can allow neutrons to be produced by spallation of He, at the rate depending on the disk physical state. The neutrons produce 2.2-MeV photons when captured by protons, which can result in a broad line in black-hole accretion disks in the case of fast protons, at the estimated flux of $\sim 10^{-6}$ s^{-1} cm^{-2} at 1 kpc [709]. If neutron capture takes place in the upper atmosphere of an accreting neutron star, the line will be narrow and gravitationaly redshifted, and its redshift would yield the neutron star mass to radius ratio, and thus a constraint on the equation of state [710]. Neutrons can also escape the accretion disk and hit the companion star, where they slow down and get captured by ambient protons, resulting in a narrow line [711]. The flux in this case depends on many parameters, and a rough estimate is also $\sim 10^{-6}$ s^{-1} cm^{-2} for nearby (1–2 kpc) X-ray binaries [712].

Science with e-ASTROGAM
Journal of High Energy Astrophysics, Volume 19, p. 1-106

[709] Aharonian F. A., Sunyaev R.A., 1984, MNRAS, 210, 257
[710] Bildsten L., Salpeter E. E., Wasserman I., 1993, ApJ, 408, 615
[711] Jean, P., Guessoum, N., 2001, A&A, 378, 509
[712] Guessoum, N., Jean P., 2002, A&A, 396, 157

New interest to the topic:

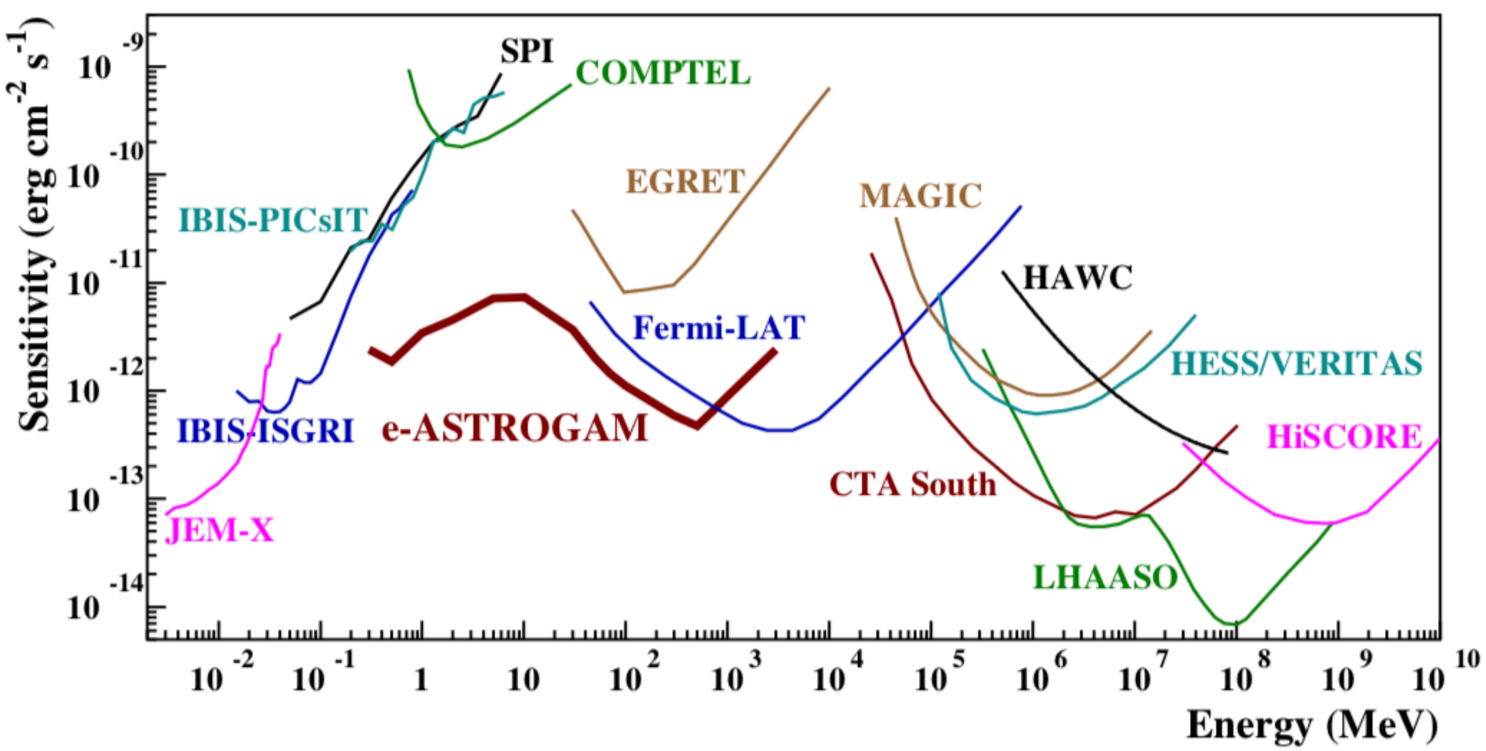
Gamma-ray line formation in hot plasmas - result of operation of large amount of excitation and spallation reactions in 1-100 MeV region

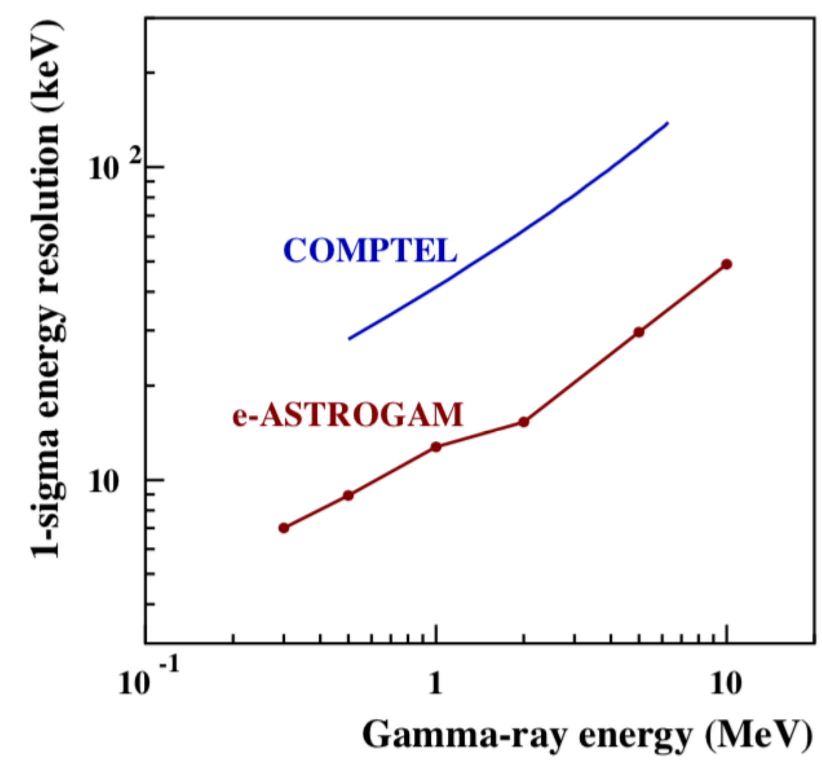
=> detailed nuclear reaction codes are required

now available (e.g. TALYS) !

New detectors: eASTROMAG

adequate performance for meaningful probes





$f_{\gamma,\min} \approx 10^{-11}\ \mathrm{erg/cm^2 s}$

$L_{\gamma,\min} \approx 10^{33} (d/1\mathrm{kpc})^{-2} \mathrm{erg/s}$

very good resolution for broad γ-ray lines!

Gamma-ray emission of hot astrophysical plasma

Ervin Kafexhiu,[1] Felix Aharonian,[2,1,3] and Maxim Barkov[4,5,6]

Very hot plasmas with ion temperature exceeding 10^{10} K can be formed in certain astrophysical environments. The distinct radiation signature of such plasmas is the γ-ray emission dominated by the prompt de-excitation nuclear lines and π^0-decay γ-rays. Using a large nuclear reaction network, we compute the time evolution of the chemical composition of such hot plasmas and their γ-ray line emissivity. At higher energies, we provide simple but accurate analytical presentations for the π^0-meson production rate and the corresponding $\pi^0 \rightarrow 2\gamma$ emissivity derived for the Maxwellian distribution of protons. We discuss the impact of the possible deviation of the high energy tail of the particle distribution function from the "nominal" Maxwellian distribution on the plasma γ-ray emissivity.

Phys. Rev D, 2019, accepted

Nuclear γ-ray emission from very hot accretion flows

E. Kafexhiu[1], F. Aharonian[1,2,3], and M. Barkov[4,5]

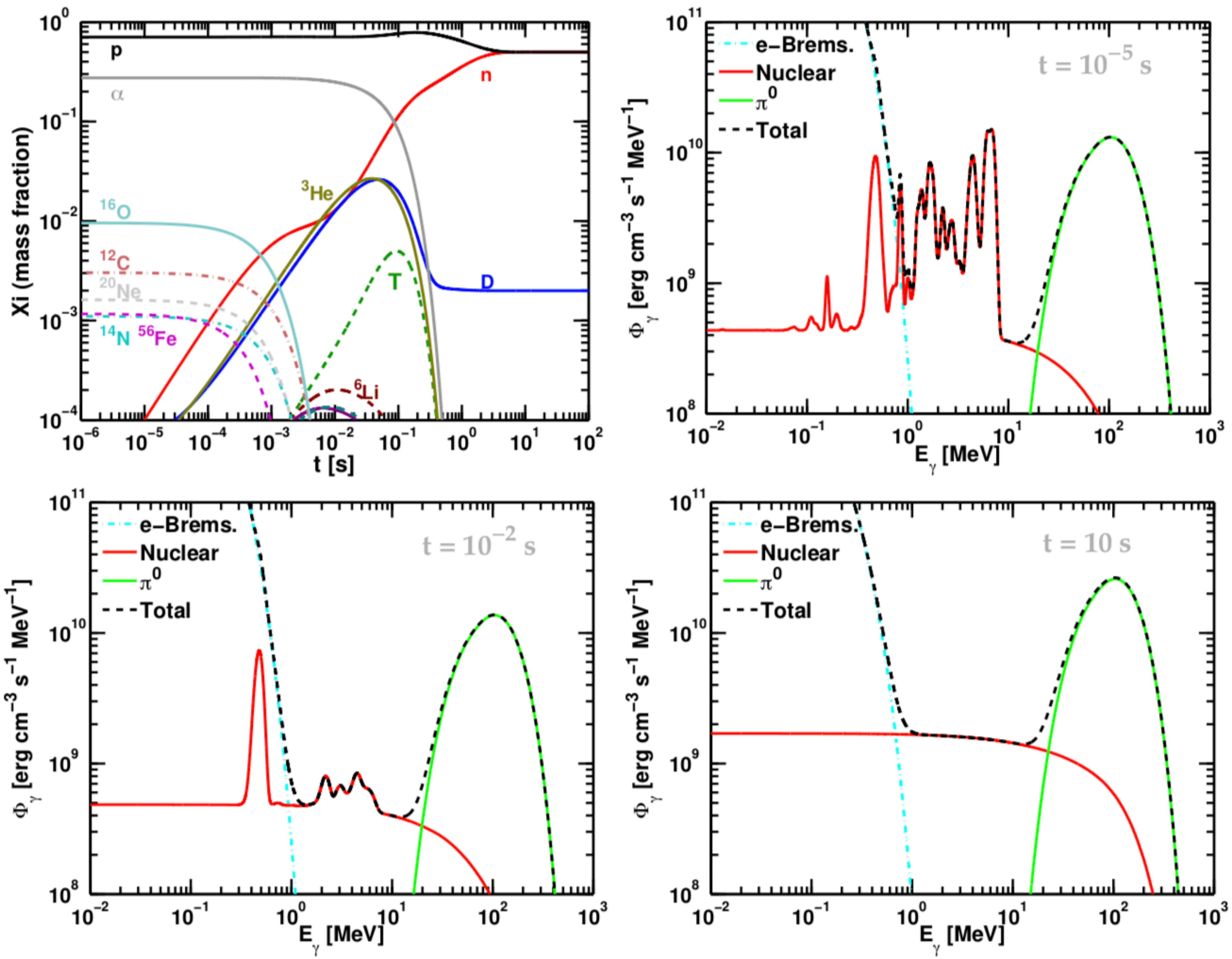
The optically thin accretion plasmas can reach ion temperatures $T_{\rm i} \geq 10^{10}$K, and thus trigger nuclear reactions. Using a large nuclear interactions network, we studied the radial evolution of the chemical composition of the accretion flow towards the black hole and computed the emissivity in nuclear γ-ray lines. In the Advection Dominated Accretion Flow (ADAF) regime, the CNO and heavier nuclei are destroyed before reaching the last stable orbit. The luminosity in γ-ray lines can be as high as 5×10^{-4} of the accretion luminosity. The efficiency of transformation of the kinetic energy of the outflow into high energy ($\geq$ 100 MeV) γ-rays through the production and decay of π^0-mesons, can be higher, up to 10^{-2} of the accretion luminosity. Neutrons that are produced in nuclear reactions can evaporate from the disk with a rate as large as 15 % of the accretion rate.

A&A, 2019, accepted

kTi=50 MeV, kTe=100 keV; n=10^{17} cm-3; solar composition

Evolution of Chemical composition

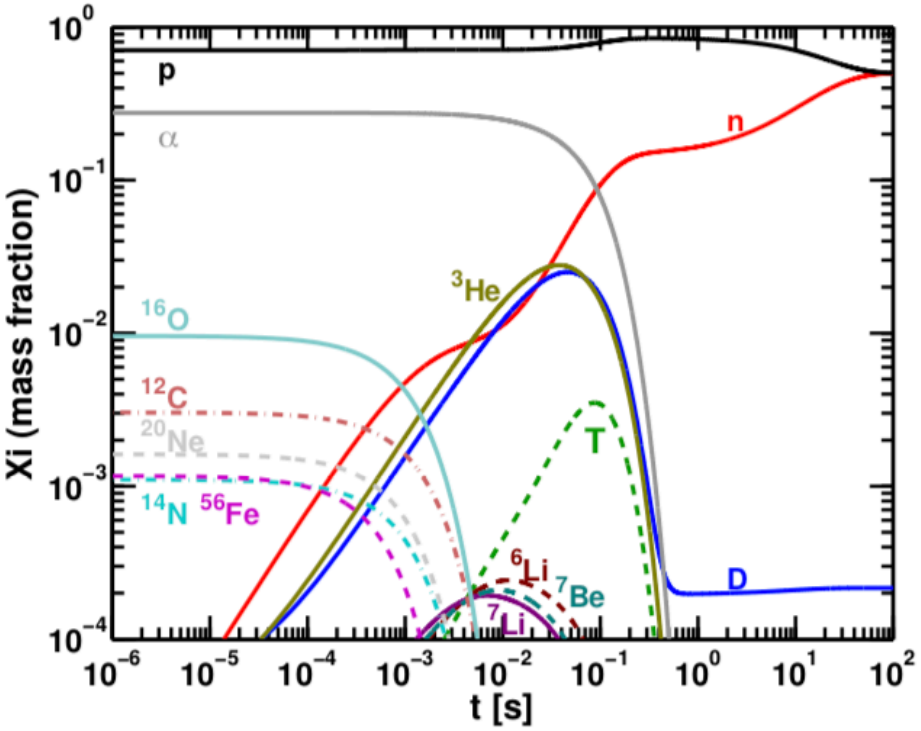
Emissivity of radiation at three different epochs: 10^{-5} s, 10^{-2} s, 1 sec

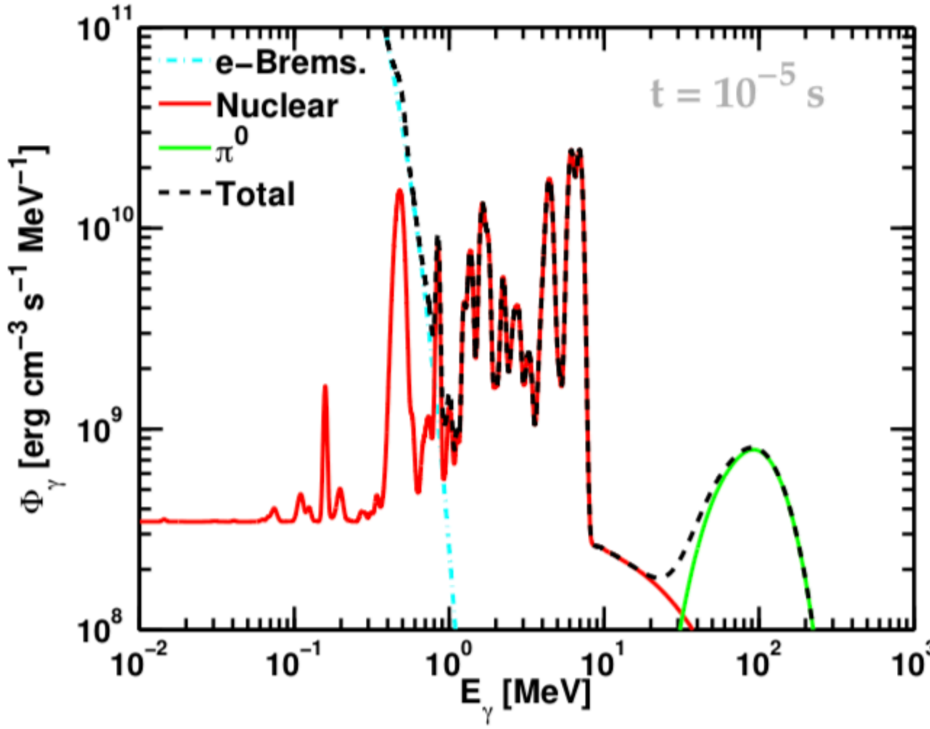


Evolution of Chemical composition

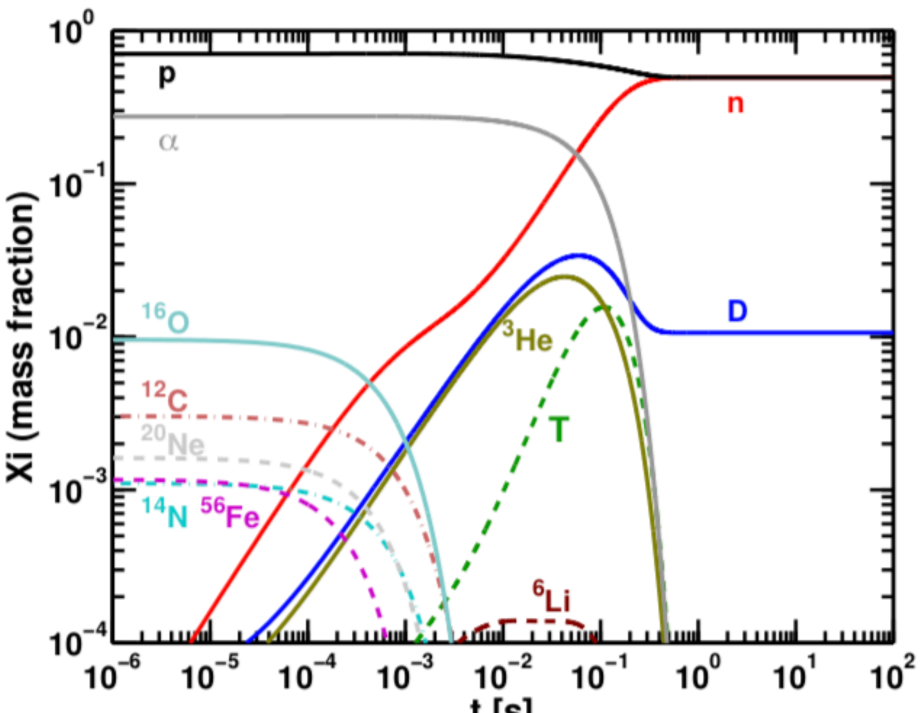
Emissivity of radiation at 10^{-5} s

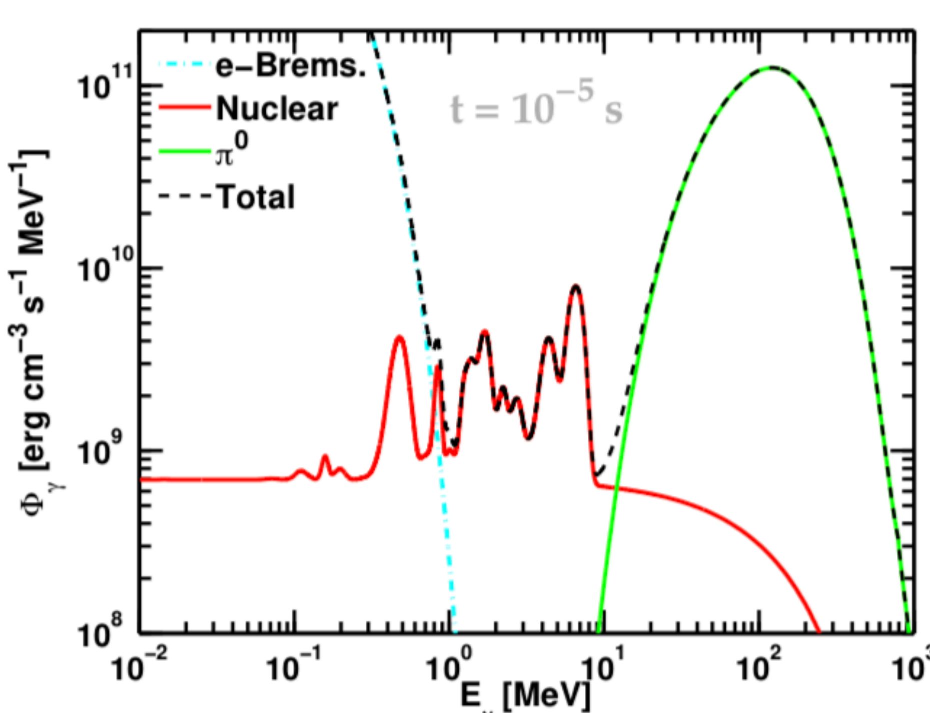
kTe=100 keV; n=10^{17} cm-3; solar composition





kTi=30 MeV





kTi=100 MeV

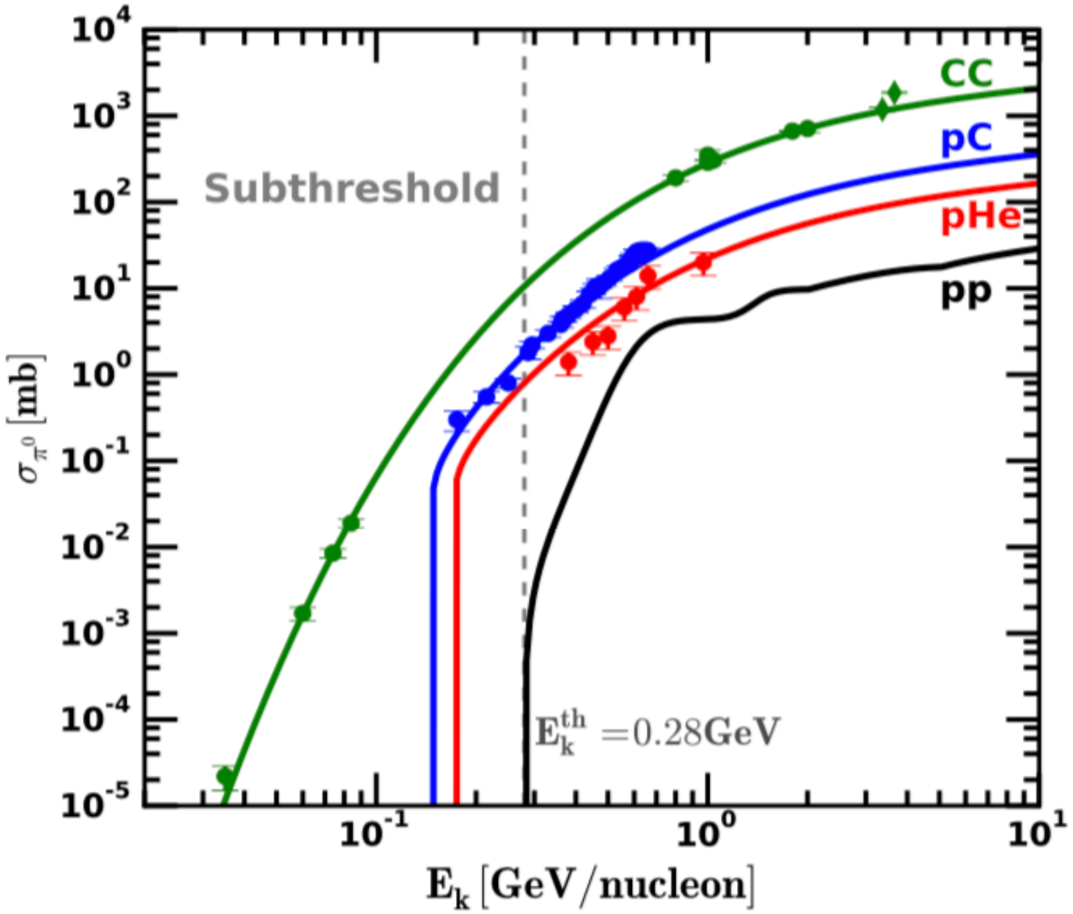


FIG. 3: π^0-meson production cross section as a function of the projectile kinetic energy per nucleon for reactions $p + p \to \pi^0$ (black), p $+^4$ He $\to \pi^0$ (red), p $+^{12}$ C $\to \pi^0$ (blue) and ^{12}C $+^{12}$ C $\to \pi^0$ (green). The experimental data points are from Refs. [29–37], whereas, the lines represent their analytical parametrisations given in Ref. [28, 38].

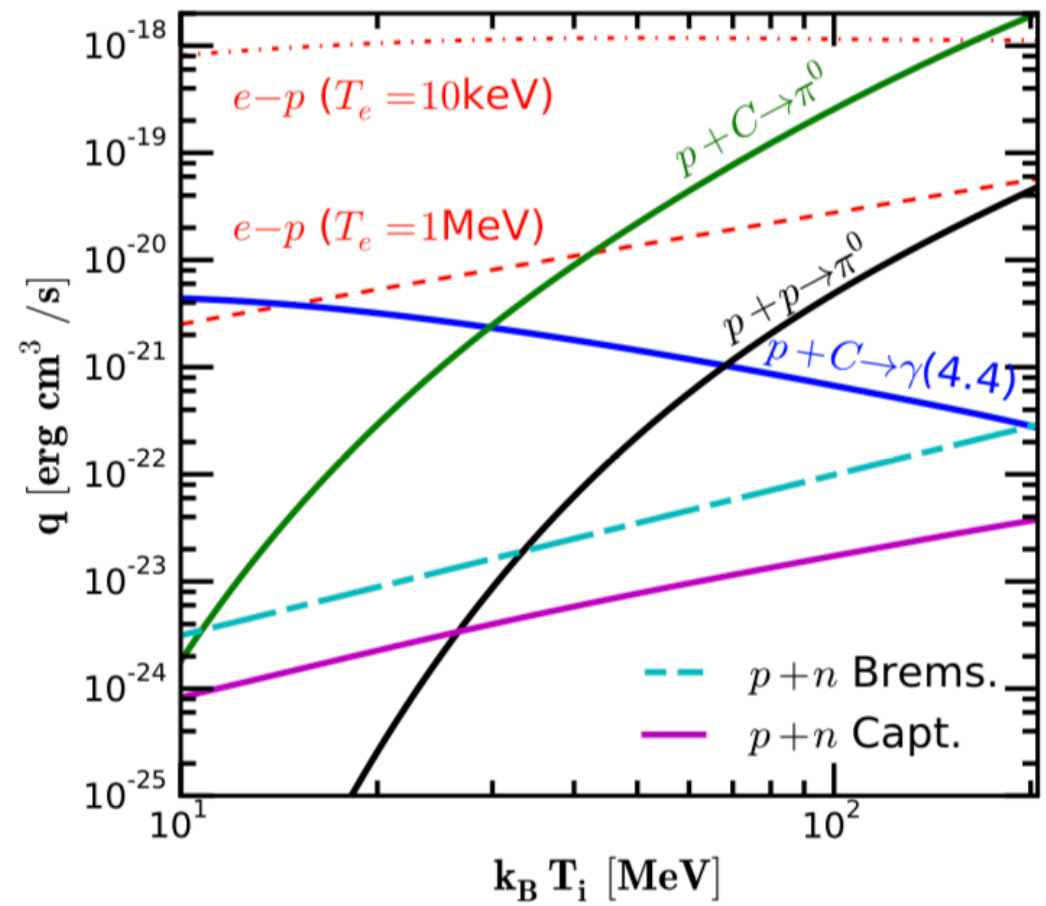


FIG. 9: Ion cooling rate as a function of the ion temperature for some important very hot plasma processes. The red dash-dot and dash lines represent the cooling rates from the Coulomb interaction with the electron gas of temperature $kT_e = 10$ keV and 1 MeV, respectively. The black solid line is the cooling rate from the $p + p \to \pi^0$ production. The green solid line is the cooling rate for $p+^{12}$C$\to \pi^0$ and the blue solid line is the cooling rate for $p+^{12}$C$\to \gamma(4.4)$ prompt γ-ray line. For both these lines a plasma with equal number of protons and ^{12}C was assumed. The long-dash cyan line and the solid magenta line represent the cooling rates for a neutron–proton plasma with equal number of neutrons and protons, due to the $n + p$ bremsstrahlung and the $n + p \to D + \gamma$(2.22MeV) radiative capture, respectively.

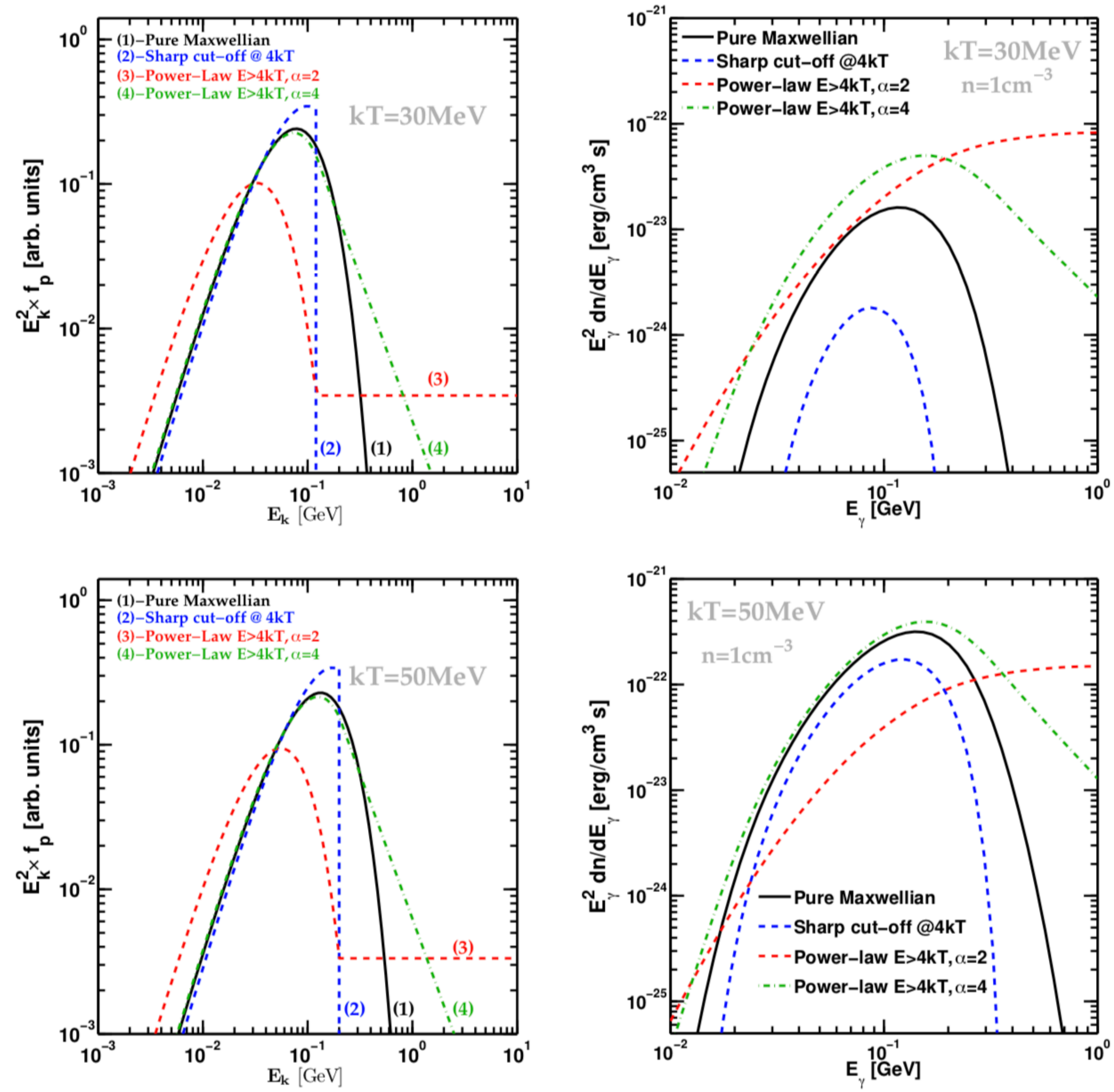


FIG. 10: Modified Maxwellian distribution functions and their π^0-decay γ-ray emissivities for two proton temperatures, $kT =$ 30 MeV (top) and 50 MeV (bottom). *Left panels*: four proton distribution functions (Maxwellian, Maxwellian with a sharp cutoff at $4kT$, Maxwellian with power-law tails starting at $E = 4kT$ with indices $\alpha = 2$ and 4). *Right panels*: the corresponding γ-ray luminosities. The plasma number density is set to $n_p = 1$ cm^{-3}. The distributions have been modified to conserve the total number of particles and the total energy of the original Maxwellian distribution as described in Eq. (9).

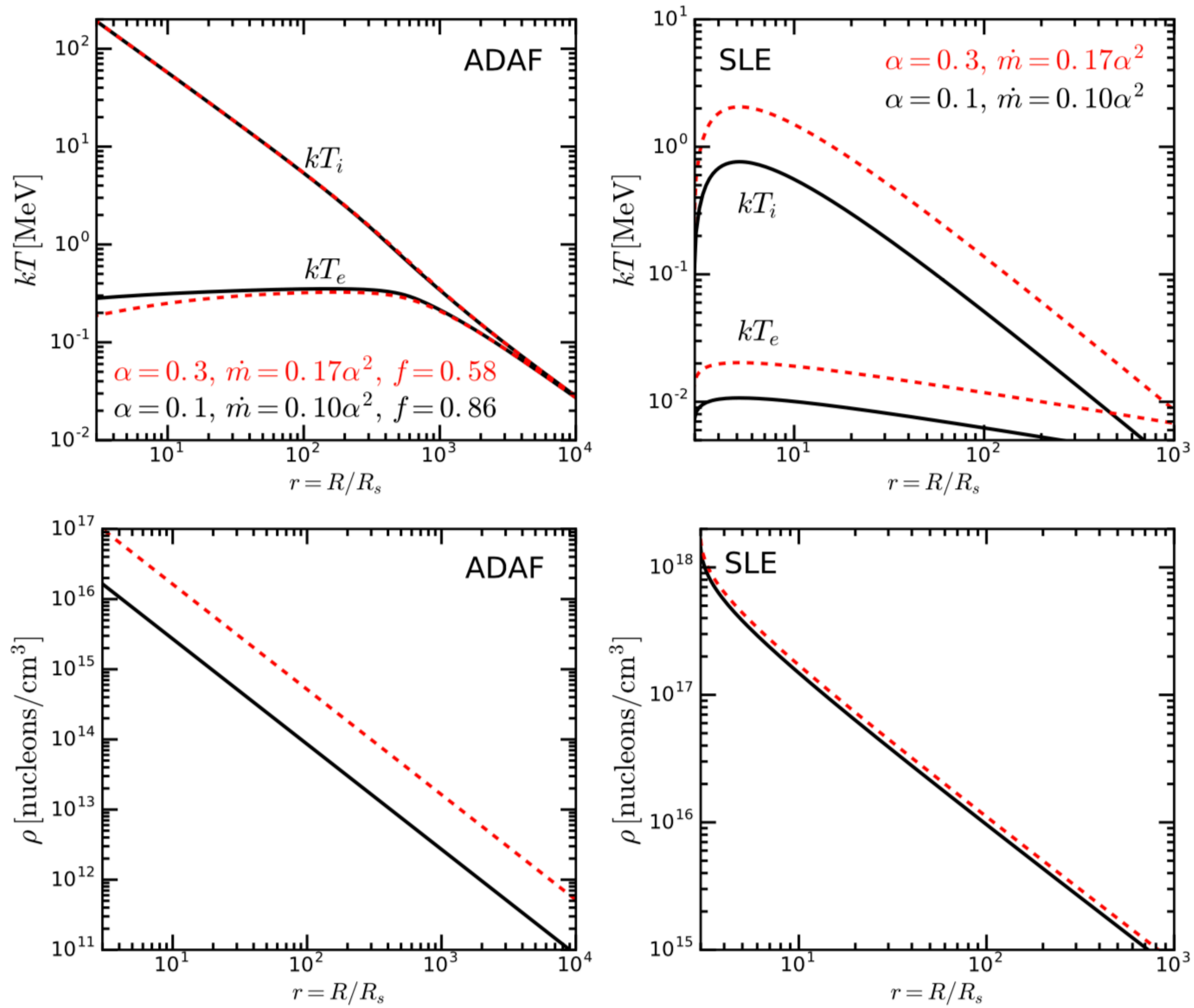
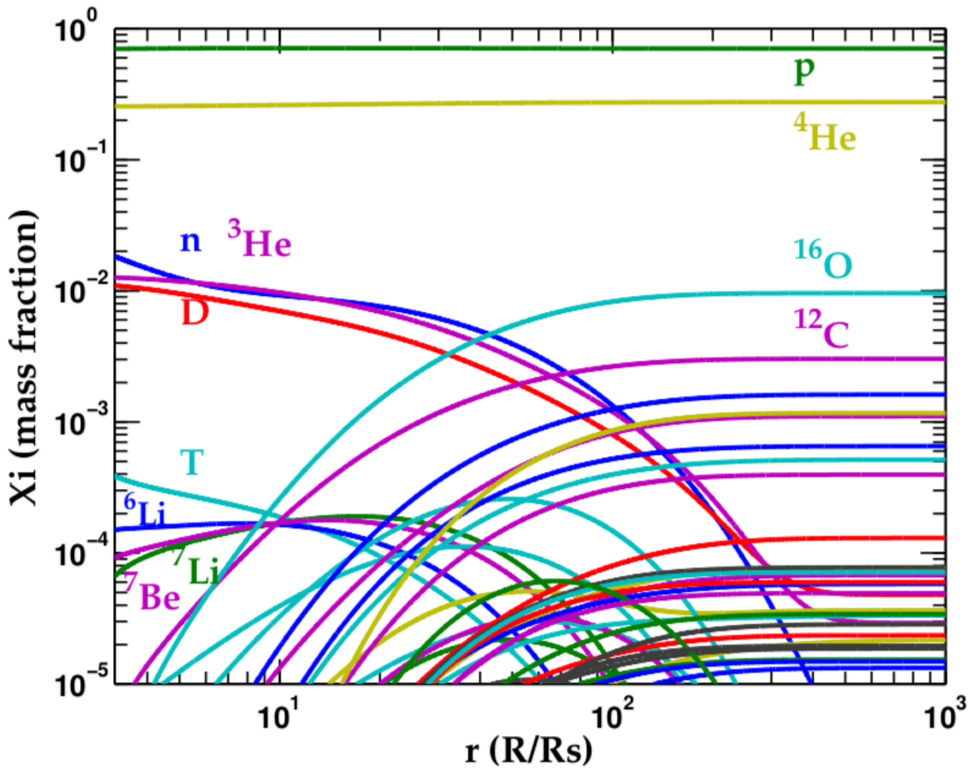
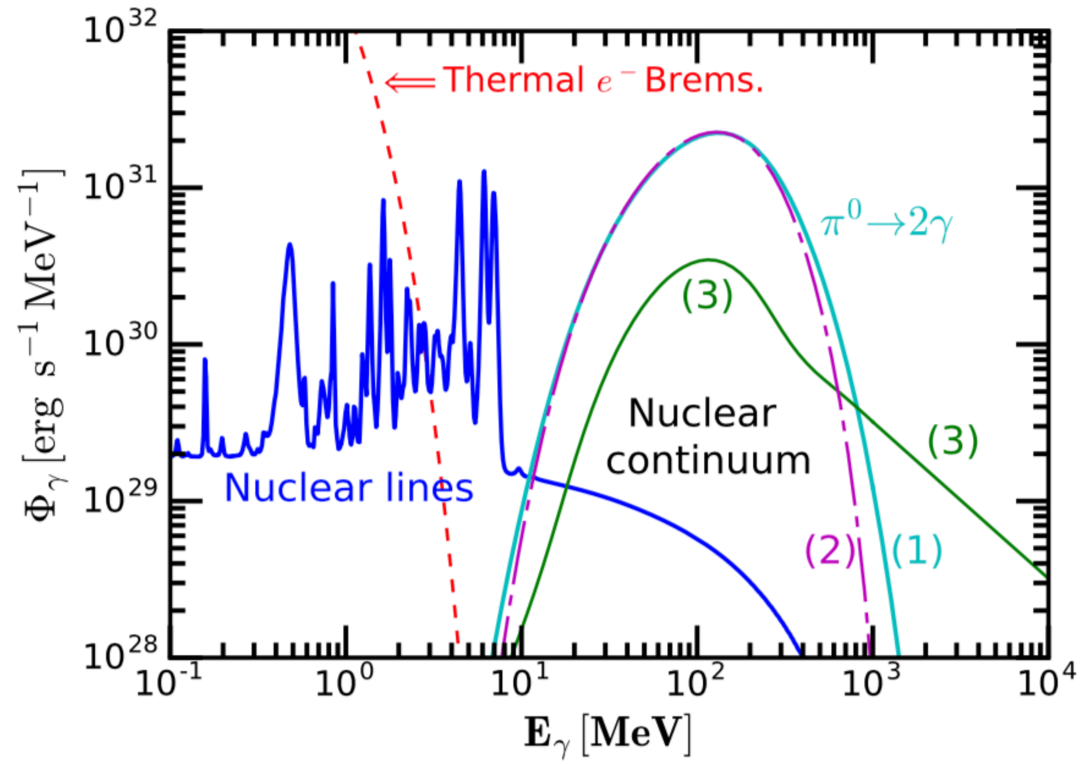


Fig. 1. The radial profiles of the temperature (top) and nucleon number density (bottom) profiles for the ADAF (left) and SLE (right) accretion disk models. The accretion disk parameters are α = 0.1 and $\dot{m}$ = 0.1α^2 (black lines) and α = 0.3 and $\dot{m}$ = 0.17α^2 (dash red lines); the mass m = 10 and β = 0.5.



chemical evolution with radius r=R/Rs



luminosity

π^0

Maxwell

sharp cutoff at 4kT

power-law after 4kT

$\dot{m} = 10^{-3}$ initial solar composition; $\alpha=0.1$; f=0.86

principal parameters:

viscosity α

BH mass $m=M/M_o=10$

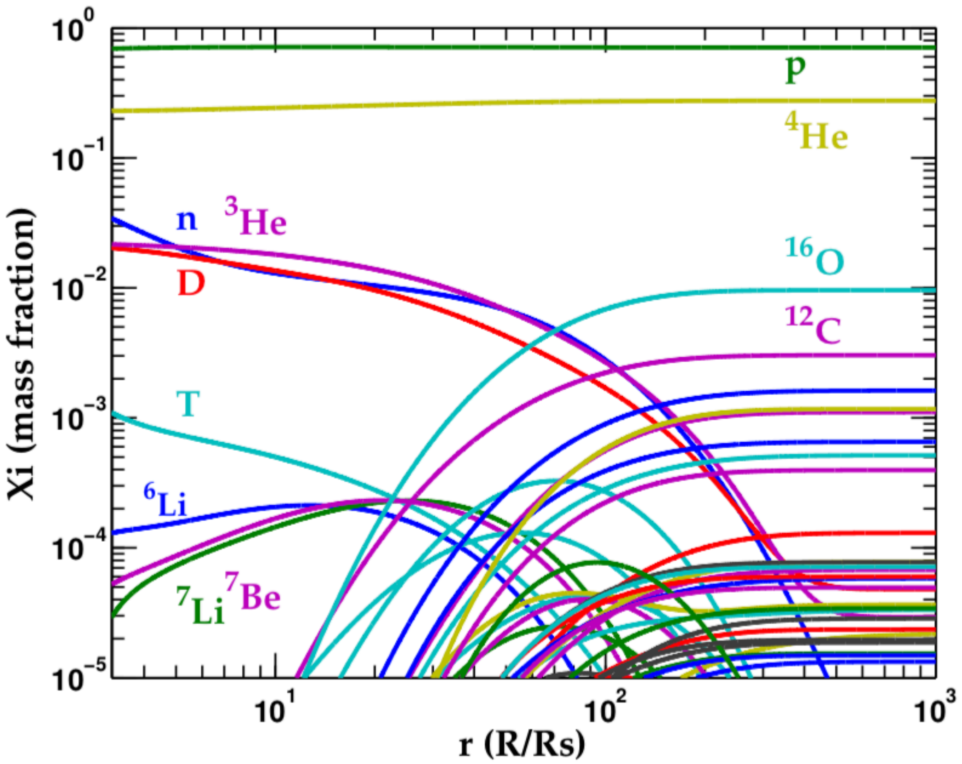
accretion rate $\dot{m} = \dot{M}/\dot{M}_{Edd}$

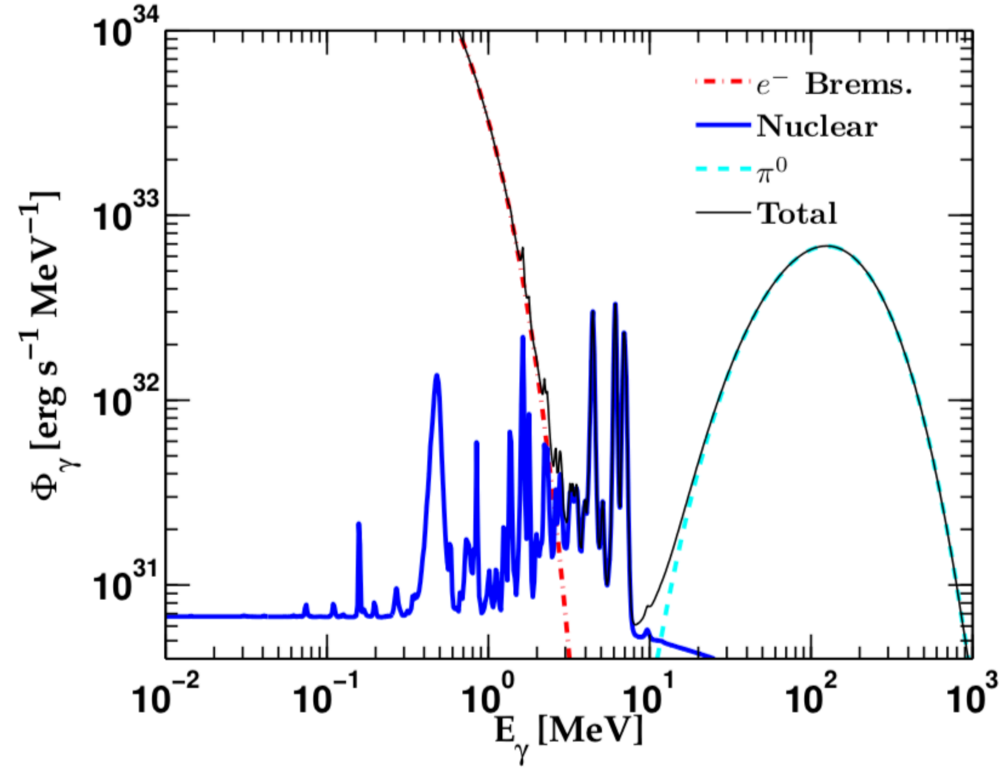
gas pressure/total pressure β;

adiabatic index γ;

electron heating/total heating δ;

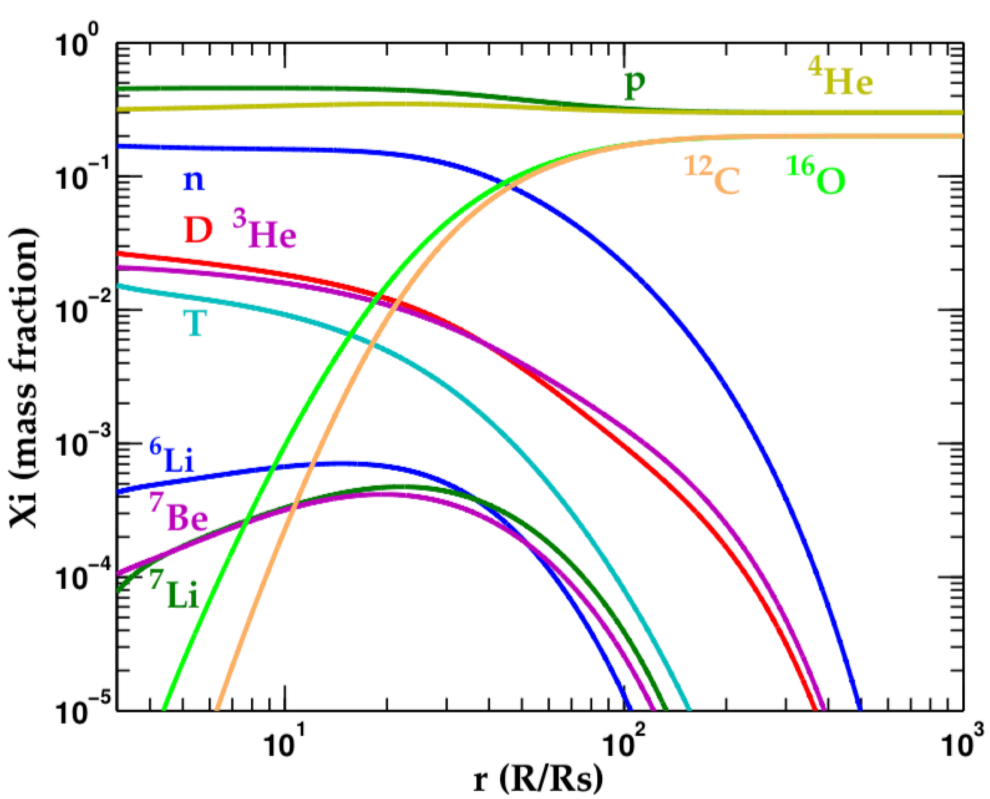
advection parameter f

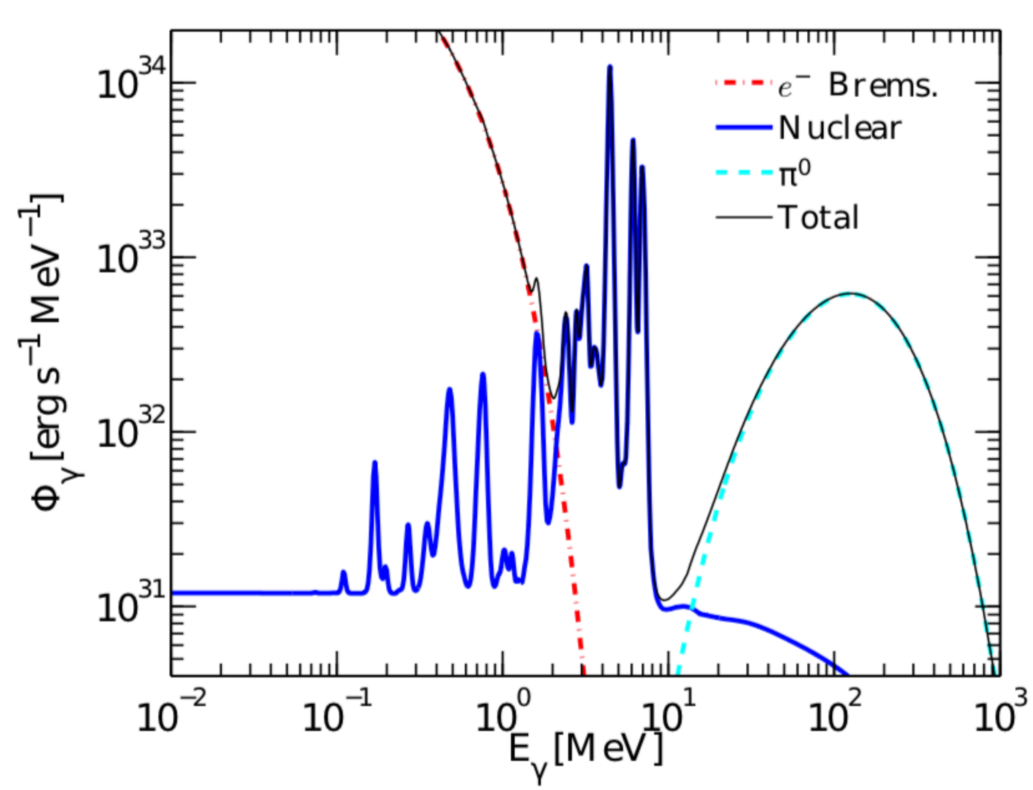




Solar composition

α=0.3 $\dot{m}$ =0.0153





$X_p = X_\alpha = 0.3$

$X_{C12} = X_{O16} = 0.2.$

In the ADAF regime, total gamma-ray line luminosity varies between 3×10^{31} - 10^{33} erg/s

in principle, can achieve 10^{34} erg/s for the “heavy initial composition

π^0 decay gamma-ray luminosities between 10^{34} - $3\ 10^{35}$ erg/s

sensitivity eASTROGAM:	at MeV energies	10^{33} (d/1kpc)^2 erg/s
	around 100 MeV	10^{32} (d/1kpc)^2 erg/s

detection of gamma-ray lines? *yes, if we are lucky*

detection of π^0 decay gamma-rays? *yes*

but why we did not detect so far with Fermi LAT?