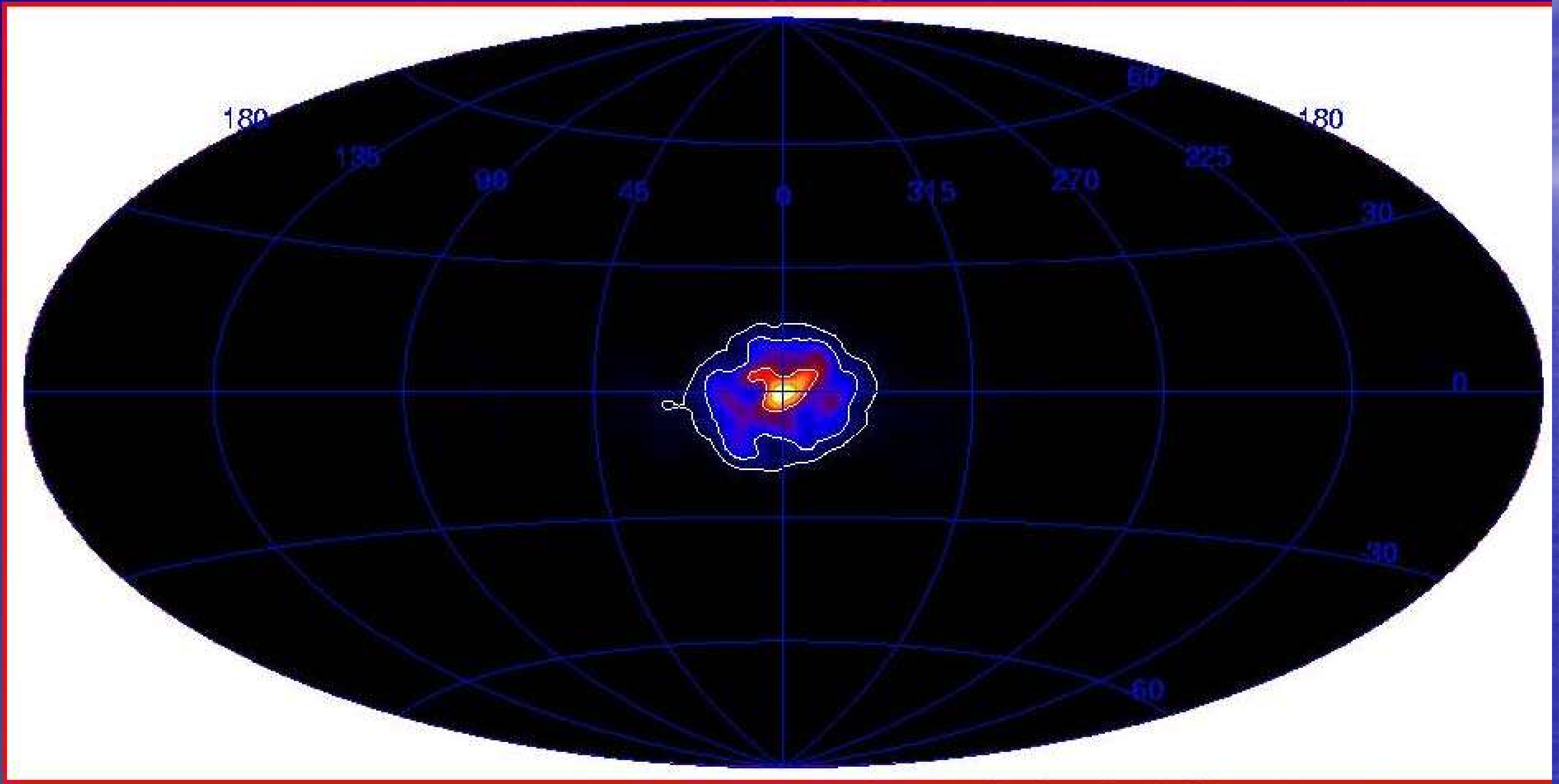
Annihilation Emission from the Supermassive Black Hole in the Galactic Center

V.A.Dogiel
I.E.Tamm Theoretical Physics Division P.N.Lebedev Institute, Moscow

Co-authors:
K.S.Cheng
Hong-Kong University
D.O.Chernyshov
Moscow Institute of Physics and Technology

An all-sky image of 511 keV emission

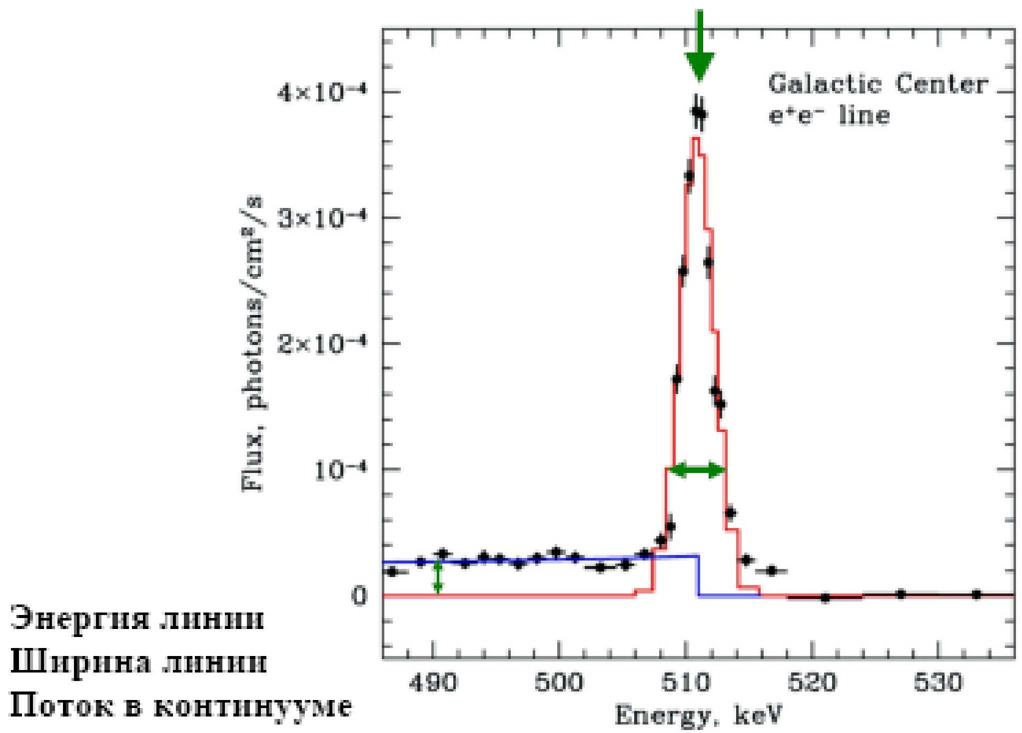


- Iteration 17 of accelerated Richardson-Lucy algorithm
- 5° x 5° boxcar smoothing
- Integrated 511 keV flux : 1.4×10^{-3} ph cm^{-2} s^{-1}

Spatial Characteristics of the Annihilation Emission

- Emissions appears to be diffuse. No evidence were found for significant emission from point sources in the Galactic Center;
- The bulge emission is centered on the Galactic Center with an extension of ~6º - 8° (FWHM).

Characteristics of the Annihilation Flux From the Galactic Center



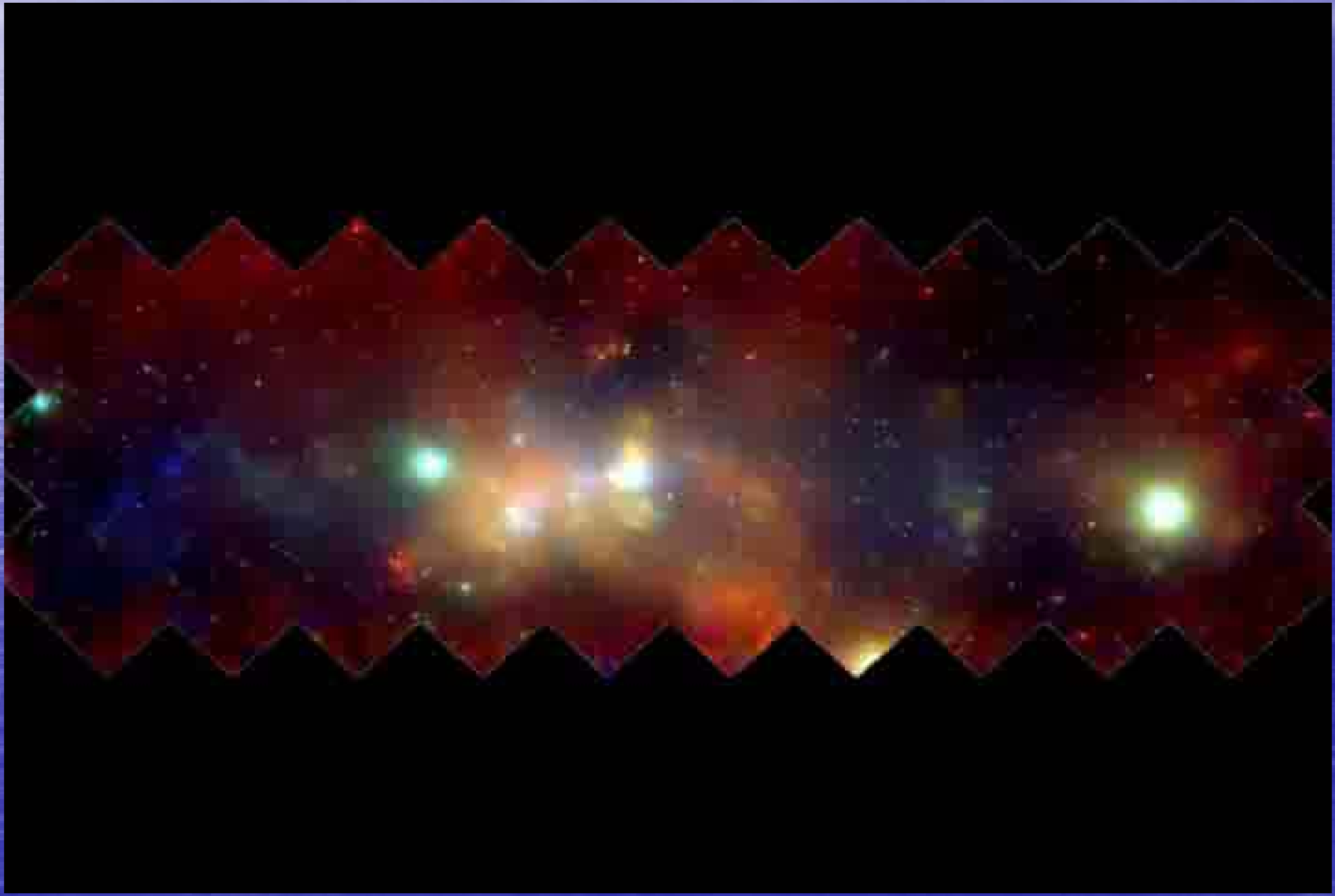
Spectral Analysis

(Churazov et al. 2005, Knoedlseder et al. 2005, Jean et al. 2006)

- Fraction of positronium - $(96.7 \pm 2.2)\%$
- Spectral parameters can be explained by a warm gas with the degree of ionization larger than a few % and the temperature $T_e \approx 7000 - 4 \cdot 10^4 K$
- 49% of emission comes from the warm neutral phase;
- 51% comes from the warm ionized phase
- It cannot be excluded that 23% of emission might come from cold gas
- The annihilation emission from hat gas and molecular clouds is less than 8% and 0.5%, respectively

Supermassive Black Hole in the Galactic Center

$$M_{BH} \sim 3.6 \cdot 10^{6} M_{\odot}$$

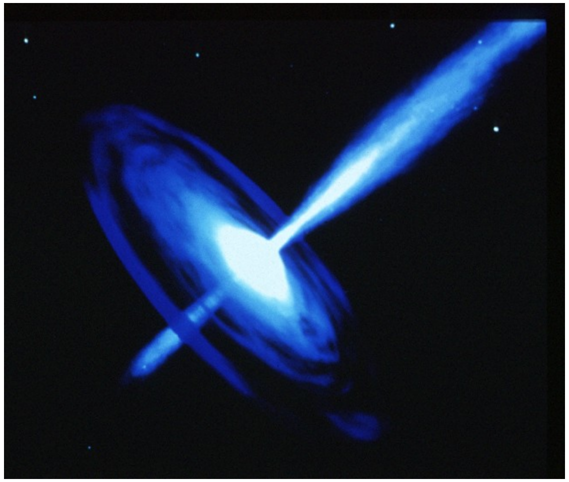


Energy Release in the Galactic Center

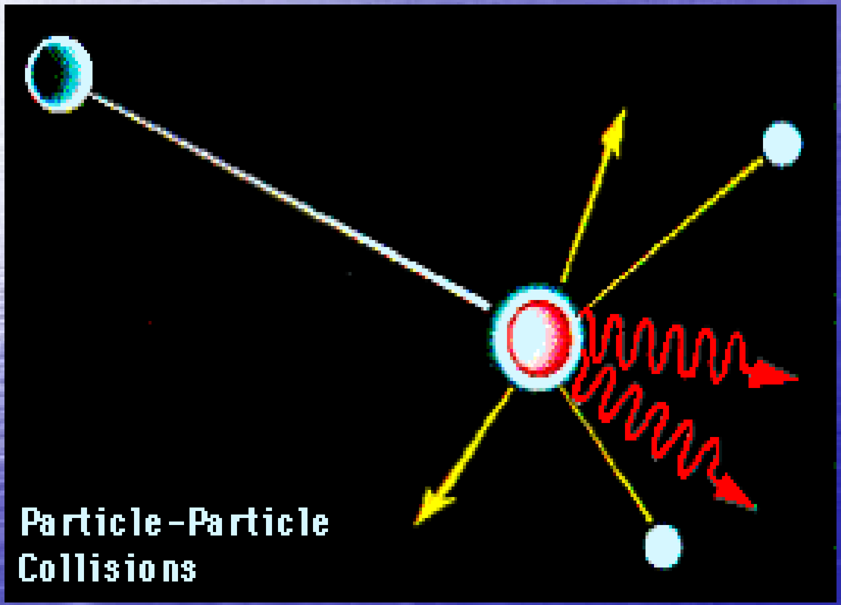
- Capture time of a star by the black hole in the Galactic Center – one in 10^4- 10^5years (Rees, 1988) ;
- Lu et al., 2005 - the energy star accretion converted into relativistic protons. The energy in relativistic protons is

$$\Delta E \approx 5\ 10^{51} (\eta / 10^{-2})(M_* / M_\otimes) erg$$

$$\leq 3 \cdot 10^{54} erg$$



Gamma-Ray Production by p-p Collisions



$$p + p \rightarrow p + p + a(\pi^+ + \pi^-) + b\pi^0,$$

$$p + p \rightarrow p + n + \pi^+ + c(\pi^+ + \pi^-) + d\pi^0,$$

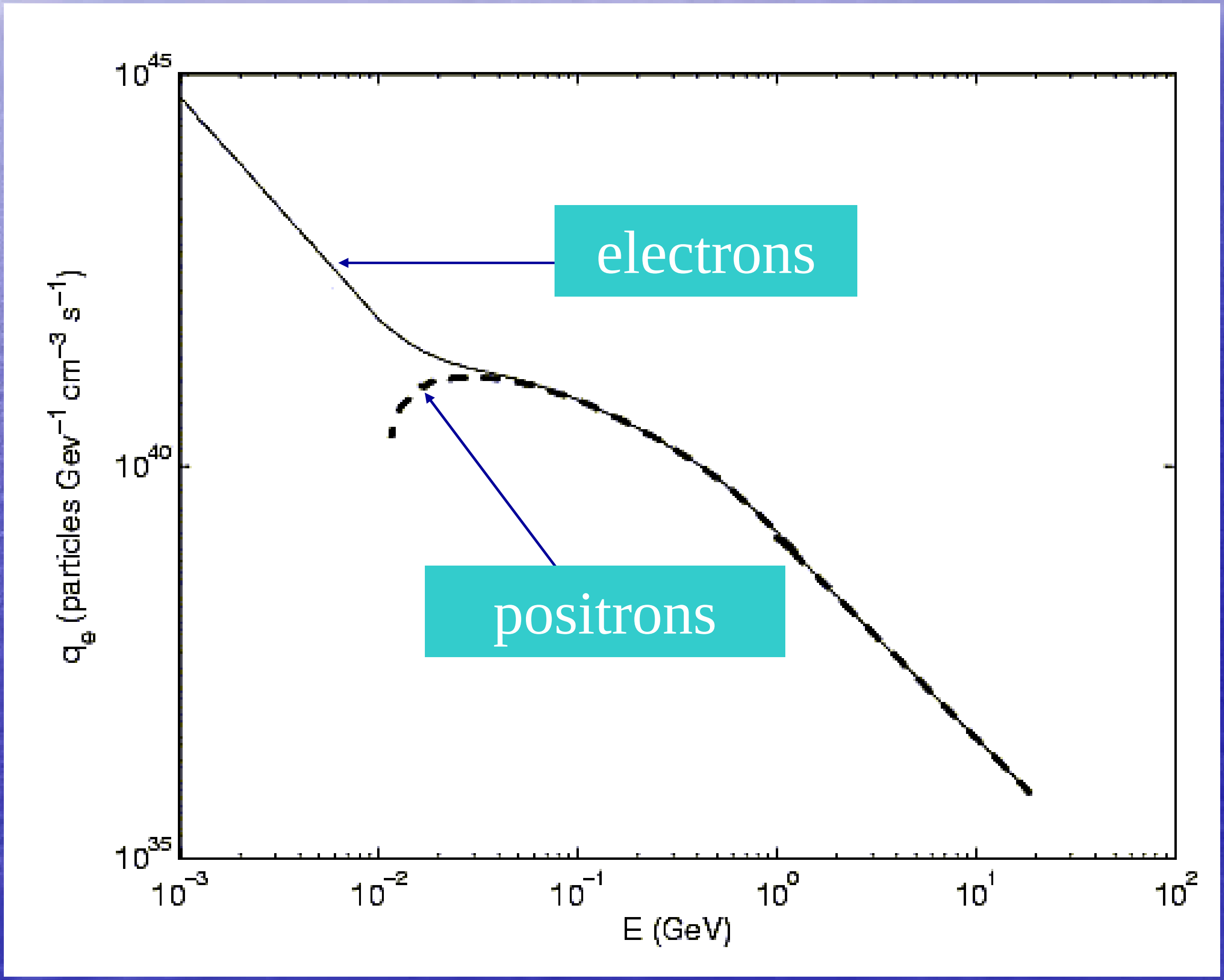
$$p + p \rightarrow n + n + 2\pi^+ + f(\pi^+ + \pi^-) + g\pi^0,$$

$$p + p \rightarrow D + \pi^+ + l(\pi^+ + \pi^-) + t\pi^0,$$

$$\pi^0 \rightarrow 2\gamma; \quad \pi^\pm \rightarrow \mu^\pm + \nu_\mu; \quad \pi^- \rightarrow \mu^- + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu; \quad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu,$$

Electron/Positron Production Spectrum



Thermalization of Positrons by Coulomb Collisions

$$\frac{\partial f}{\partial t}+\frac{vn(\sigma_{an}+\sigma_{ce})}{v_0}f-Q_{e^+}(p,t)=\frac{1}{p^2}\frac{\partial}{\partial p}p^2\cdot\left\{B(p,r)f+A(p,r)\frac{\partial f}{\partial p}\right\}+\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\cdot D(r,p)\frac{\partial f}{\partial r}\right)$$

$$v_0=\frac{2\pi nc^2r_e^2m_e}{\sqrt{mkT}}$$

$$B(p)=-p^2\left(\left(\frac{dp}{dt}\right)_i+\left(\frac{dp}{dt}\right)_{synIC}+\left(\frac{dp}{dt}\right)_{br}\right);\quad A(p)=-p^2\left[\left(\frac{dp}{dt}\right)_i\frac{\gamma}{\sqrt{\gamma^2-1}}\sqrt{\frac{kT}{mc^2}}\right]$$

Thermalization of Positrons in Low Ionized Gas

The general equation for positron distribution function in the low ionized medium has the form (see for details Gurevich et al. 2004)

$$\frac{\partial f(\varepsilon)}{\partial t} - q(\varepsilon, t) = -S(f) - \frac{\partial}{\partial \epsilon}\left(\frac{d\epsilon}{dt} f(\varepsilon)\right) - \hat{L} f(\varepsilon) \quad (1)$$

Here ε is the particle kinetic energy depended on the particle momentum p, and $S(f)$ is a full inelastic collision integral of positrons with atoms and molecules. It describes electron energy losses and birth rate due to ionization S_{ion}, excitation of optical S_{op}, vibrational S_v and rotational S_r levels, and dissociative attachment S_{at}

$$S(f) = \frac{2n_m}{mv}\left[S_{ion}(f) + S_{op}(f) + S_v + S_r + S_{at}\right] \quad (2)$$

$$S_{ion} = \varepsilon f(\varepsilon)\sigma_{ion} - (\varepsilon + \varepsilon_{ion} f(\varepsilon + \varepsilon_{ion})) \quad (3)$$

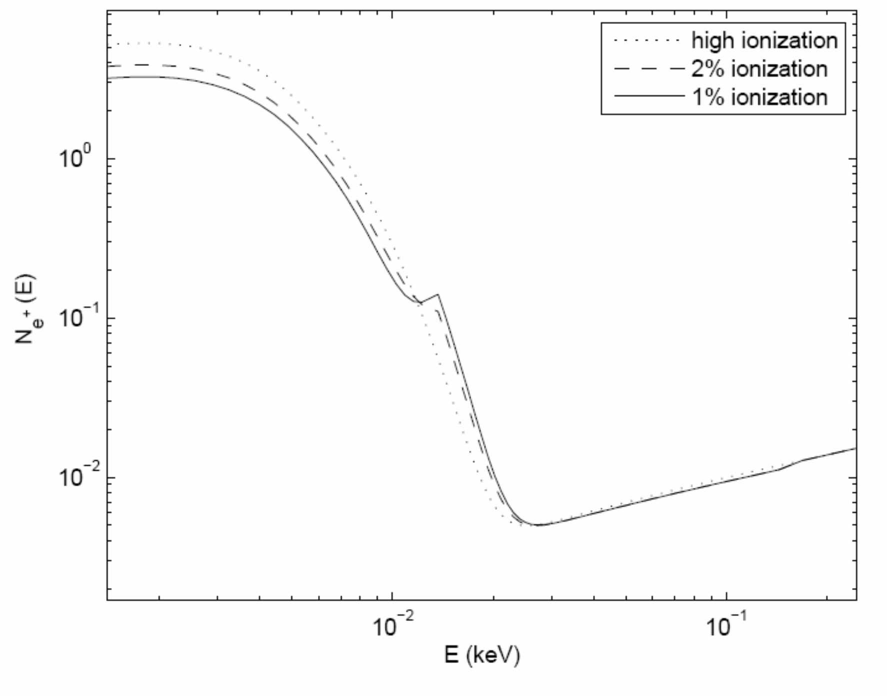
$$S_{op} = \varepsilon f(\varepsilon)\sum_{i=1}^{N_{op}} \sigma_i^{op}(\varepsilon) - \sum_{i=1}^{N_{op}} (\varepsilon + \varepsilon_{op} f(\varepsilon + \varepsilon_{op})\sigma_i^{op}(\varepsilon + \varepsilon_{op}) \quad (4)$$

$$S_v = \varepsilon f(\varepsilon)\sum_{i=1}^{N_v} \sigma_i^{v}(\varepsilon) - \sum_{i=1}^{N_v} (\varepsilon + \varepsilon_v f(\varepsilon + \varepsilon_v)\sigma_i^{v}(\varepsilon + \varepsilon_v) \quad (5)$$

$$S_r(f) = -\frac{1}{2v^2}\frac{\partial}{\partial v}\left[v^3 R_r(v) f(v)\right] \quad (6)$$

$$S_{at} = \frac{2N_m}{mv}\varepsilon\sigma_{at}(\varepsilon) f(\varepsilon) \quad (7)$$

Qausi-Stationary Spectrum of Positrons



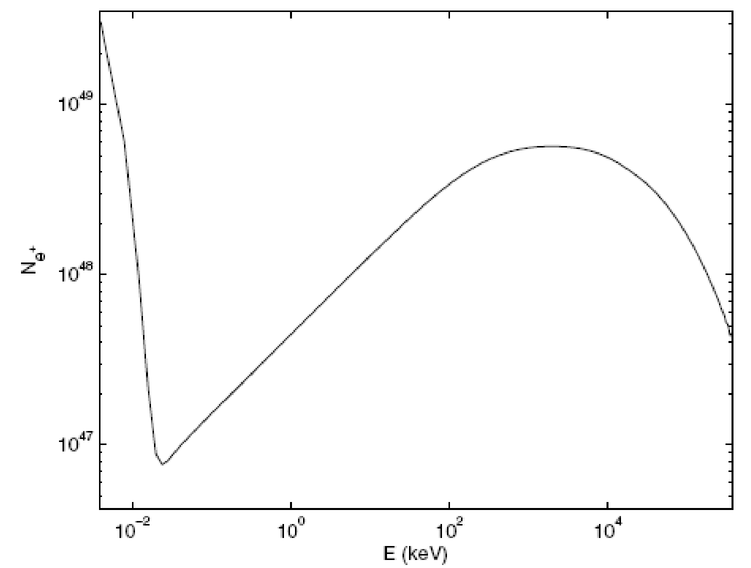


Fig. 2. The steady state distribution of positrons in the low density region (500 pc).

Spectrum near thermal energies

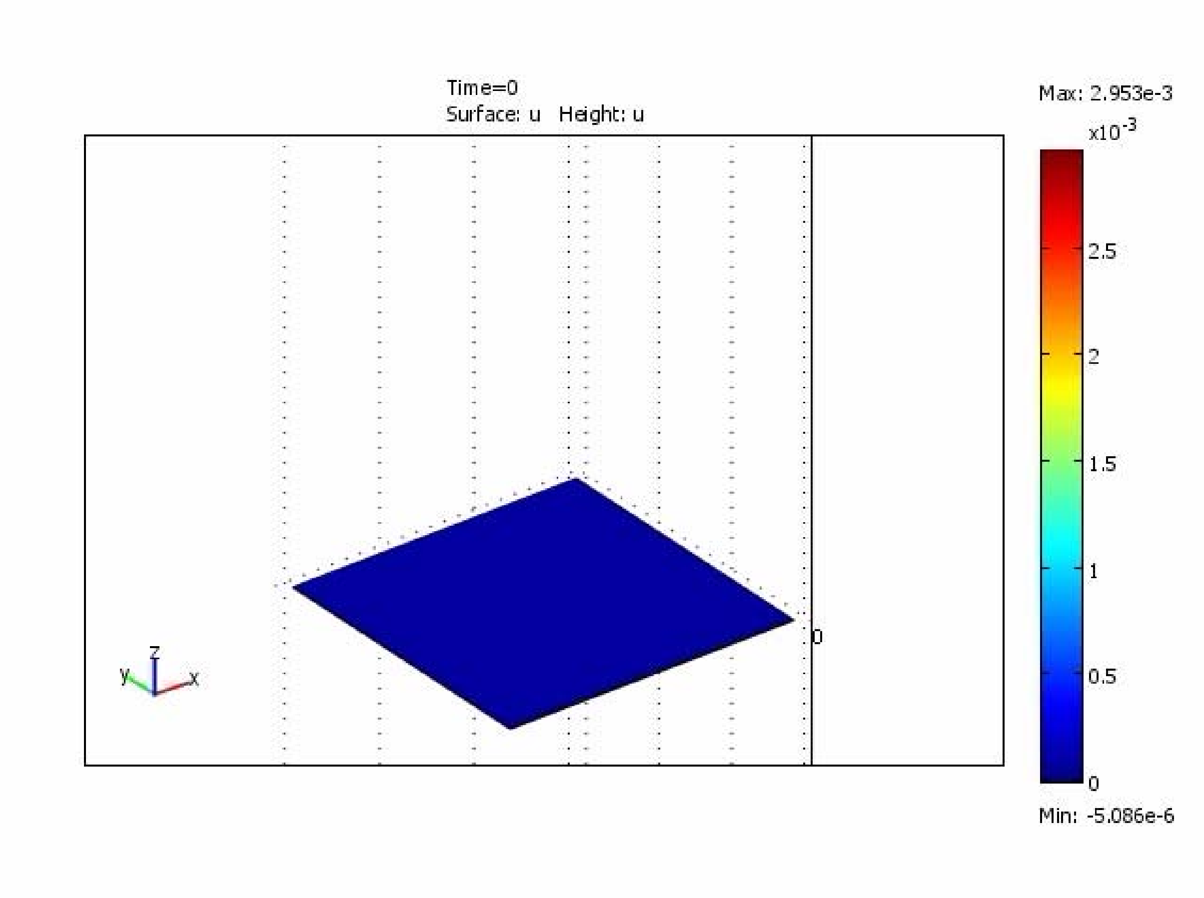
Total positron spectrum

Thermalization of Positrons by Coulomb Collisions

x – the radius of the emission region

y – the dimensionless momentum

z - the distribution function of positrons f(p); the number of positrons with the momentum p is $p^3 f(p)$



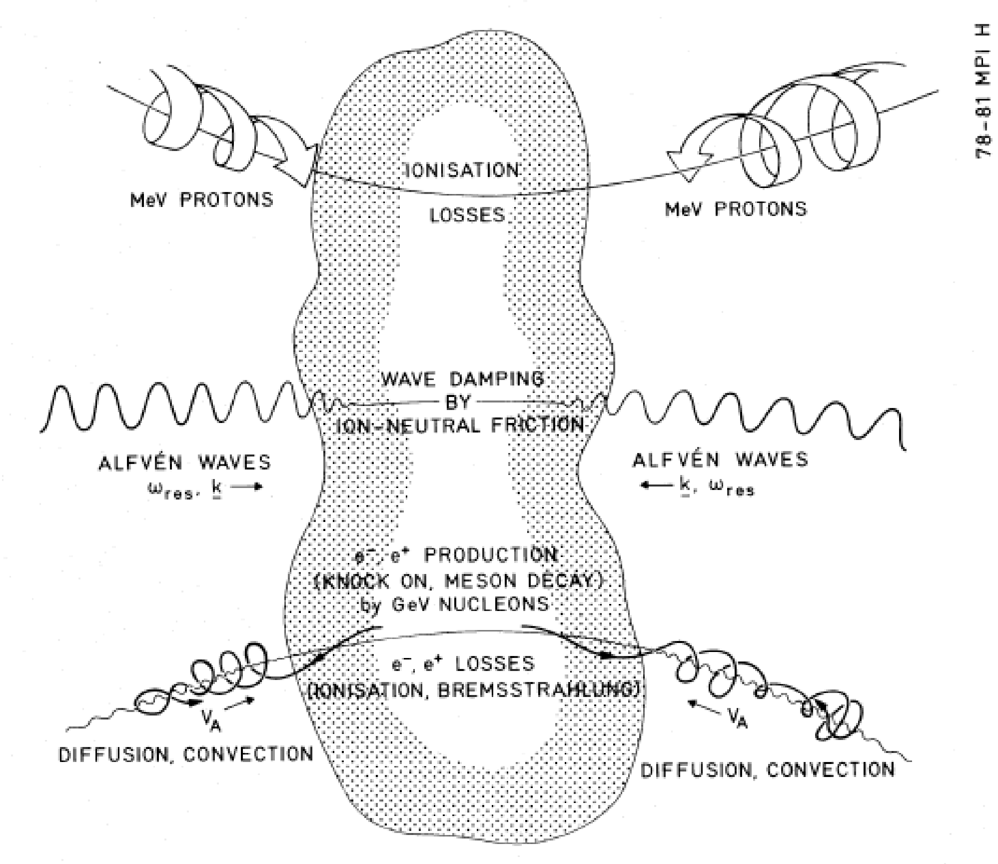
Parameters of the Interstellar Medium in the Galactic Bulge Region (Jean et al. 2005)

- The gas content in the center region is not well known
- The budge (region inside the radius ~230 pc and height 45 pc) contains $7 \cdot 10^{7} M_{\odot}$ of hydrogen gas
- 90% of this mass is trapped in small high density (~10^4 cm^{-3}) clouds while the remaining 10% is homogeneously distributed with the average density ~10 cm^{-3}.
- The rest of the gas in the bulge is contained in the region (like an ellipsoid) with the radius ~1.75 kpc. The H1 mass is about $4 \cdot 10^{7} M_{\odot}$ and it is equally distribute between cold and warm neutral gas
- The mass of warm and hot ionized gas is $2 \cdot 10^{6} M_{\odot}$ about 90% of this mass is in the warm phase and 10% is in the hot phase.

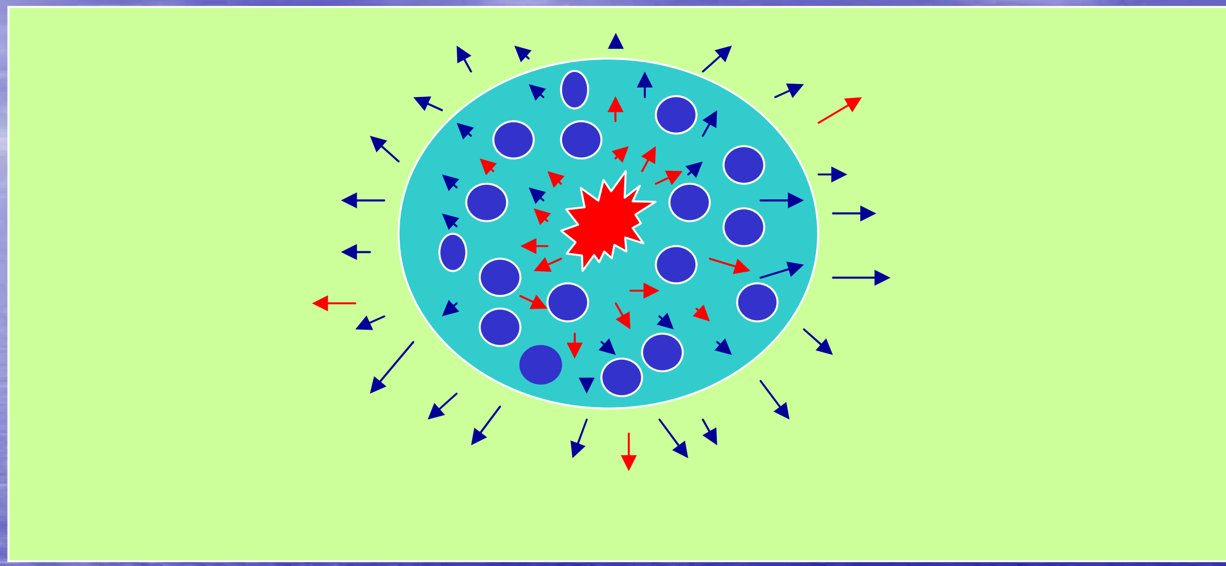
CR Penetration into Molecular Clouds (Skilling and Strong 1976, Dogiel and Sharov 1985)

- Alfven waves generated outside molecular clouds by the flux of cosmic rays are effective at excluding cosmic rays below a few hundred MeV;
- In the absence of waves the CR flux into clouds should be $j(E) \approx n_0(E)\mathrm{v}$.
- However, CRs of a few MeV excite the wave to such a high level that diffusion propagation becomes negligible and the flux reduces to $j(E) \approx n_0(E)\mathrm{V}_\mathrm{A}, \quad (V_A << \mathrm{v})$
- Cosmic rays of a few GeV freely penetrate into the clouds;
- The gamma-ray emissivity of the Orion molecular cloud measured with EGRET is consistent with electron and proton spectra in the intercloud space for energies above a few hundred MeV (Digel et al. 1999)

Morfill's Model (1982)



Particle escape from the Central region



Central region filled with molecular gas

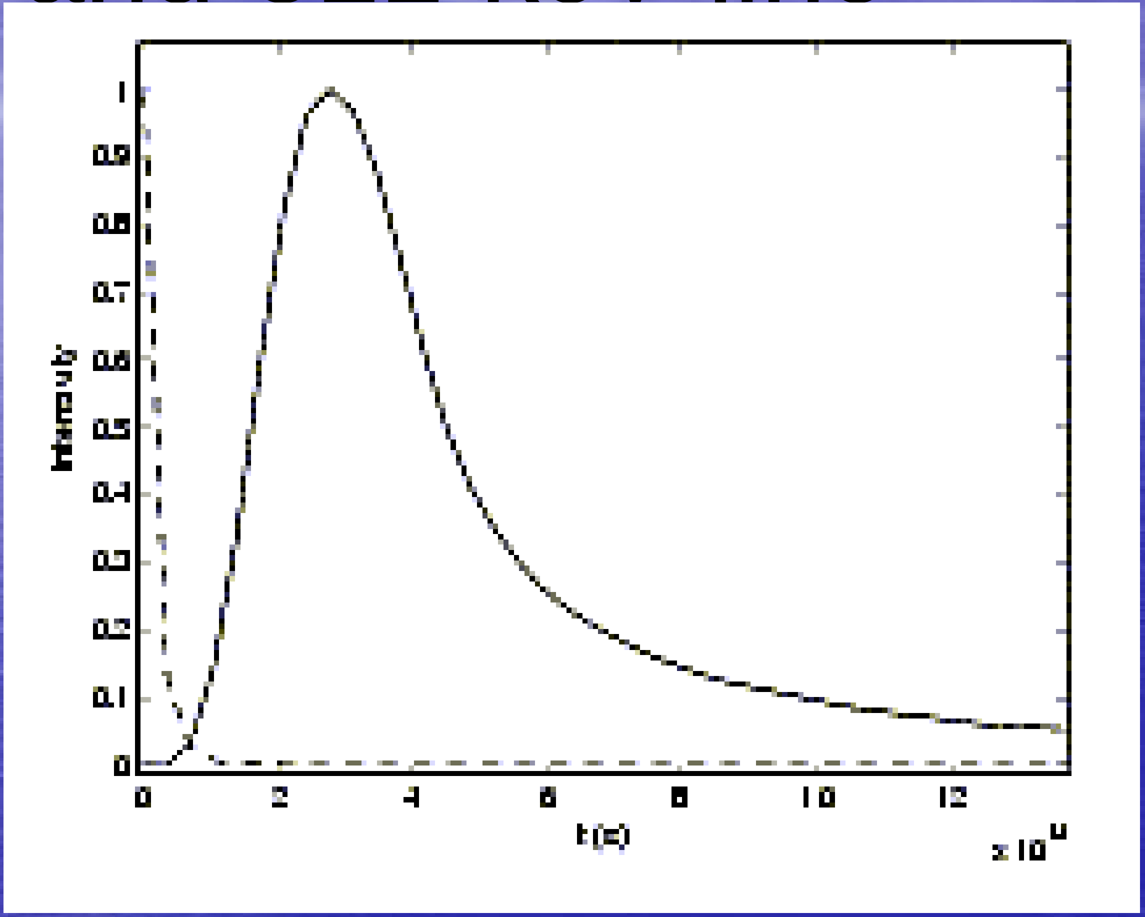
Dense clouds

Surrounding region filled with warm neutral and ionized fractions of the interstellar gas

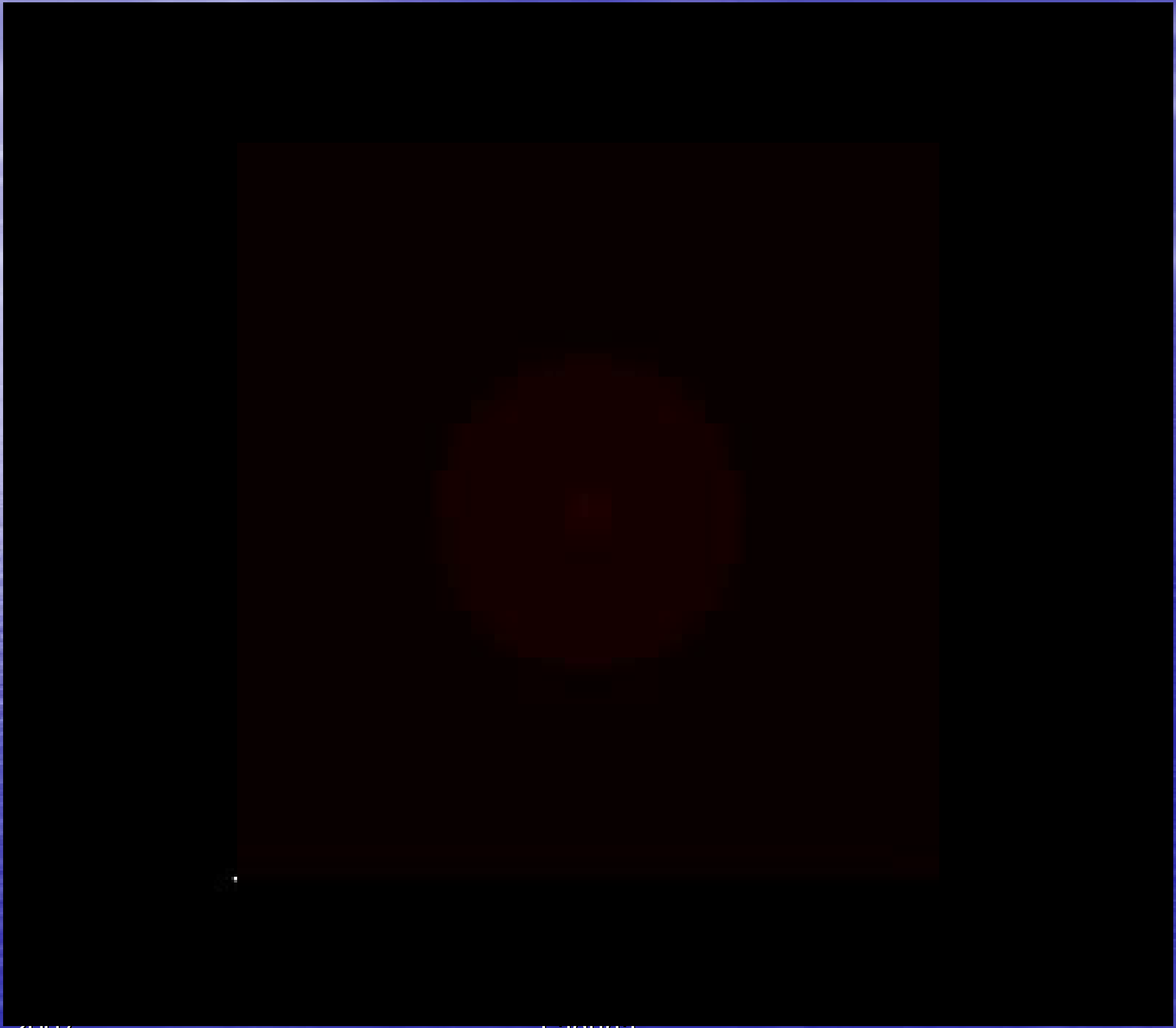
Flux of relativistic protons

Flux of 300-600 MeV secondary electrons

Time Variations of Gamma-rays and 511 keV line



$$W_p \sim 10^{54} erg$$



Frequency of star capture by the central black hole

- Syer and Ulman 1999: frequency of one solar mass star capture, $4.8 \cdot 10^{-5}\, yr^{-1}$
- Capture of red giants $\sim 8.5 \cdot 10^{-6}\, yr^{-1}$
- From observations (Donley et al. 2002)

$$\nu_{cap} \sim 10^{-5}\, yr^{-1}$$

- For the times of positrons thermalization about 100 capture events occur and positrons from many capture events are accumulated in the thermal region
- Therefore, the energy release about $W_p \sim 6 \cdot 10^{52}\, erg$ in each capture event is necessary in order to produce the observed annihilation flux

Time-Variations of Annihilation Fux and Gamma-ray emission from the Center and from 5º Region

511 keV Flux

Gamma-rays >100 MeV from the Galactic Center

Gamma-rays >100 MeV from 5º Region

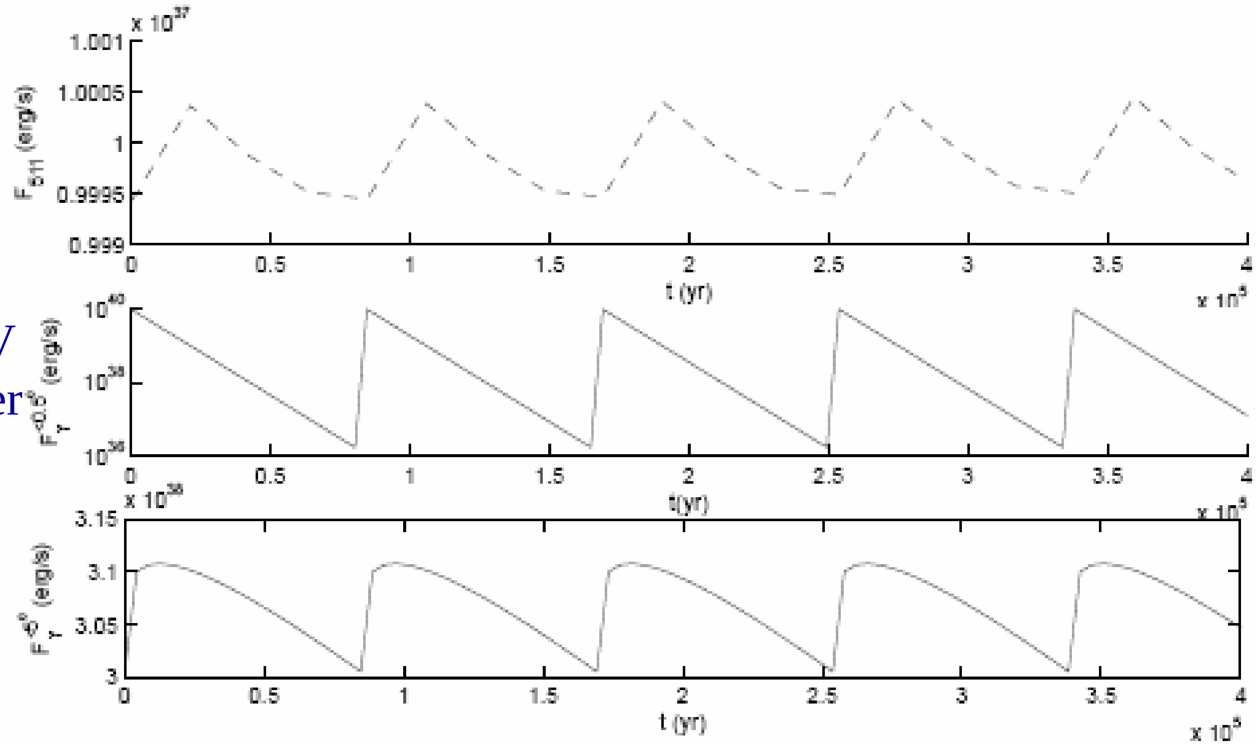
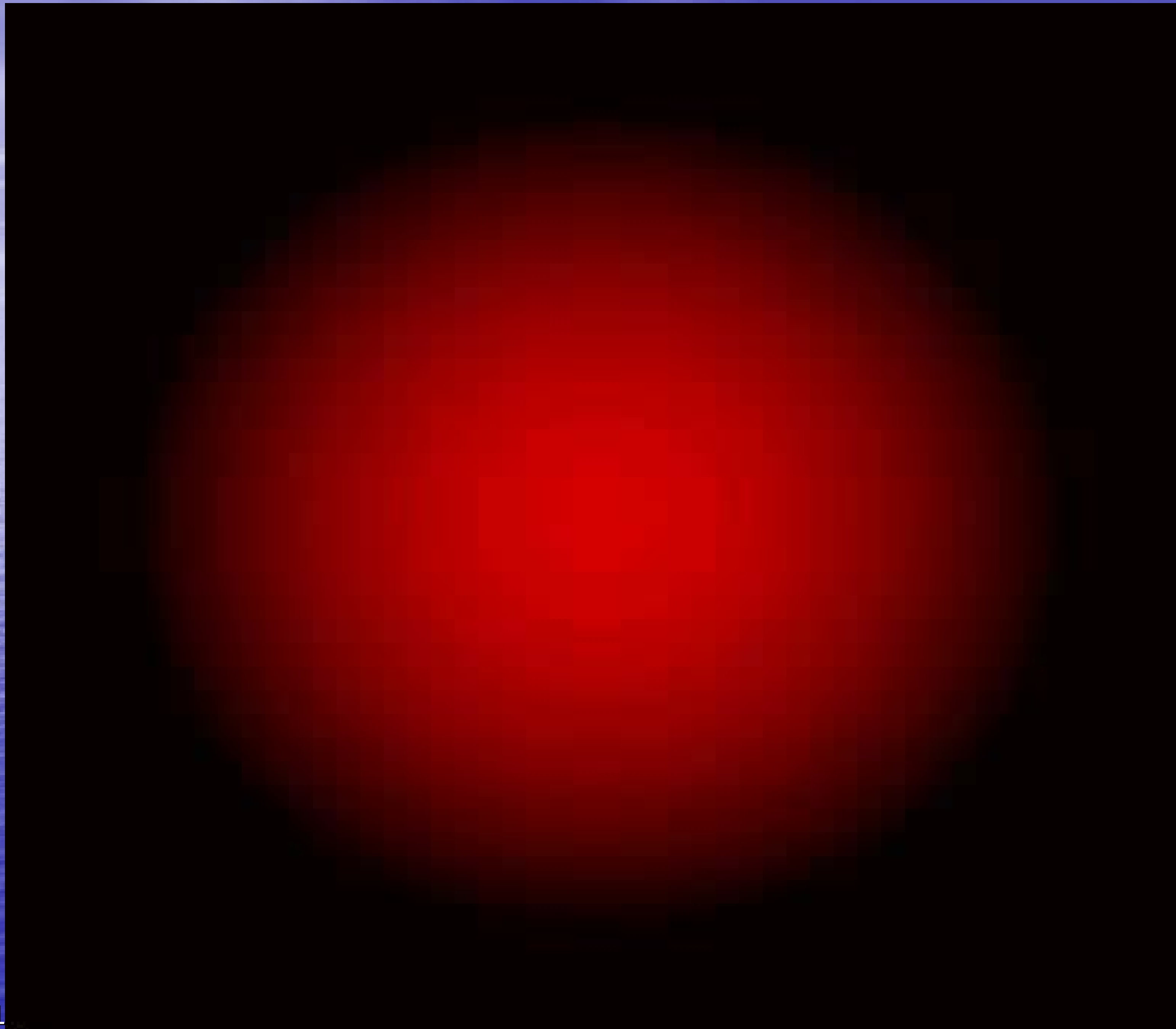


Fig. 1.— The time variations of annihilation emission, gamma-ray flux from the central high density region(50pc), and the flux of gamma-rays produced by protons escaping from the central core into the low density region (500pc).



Spectrum of Positrons in the Galactic Central Region

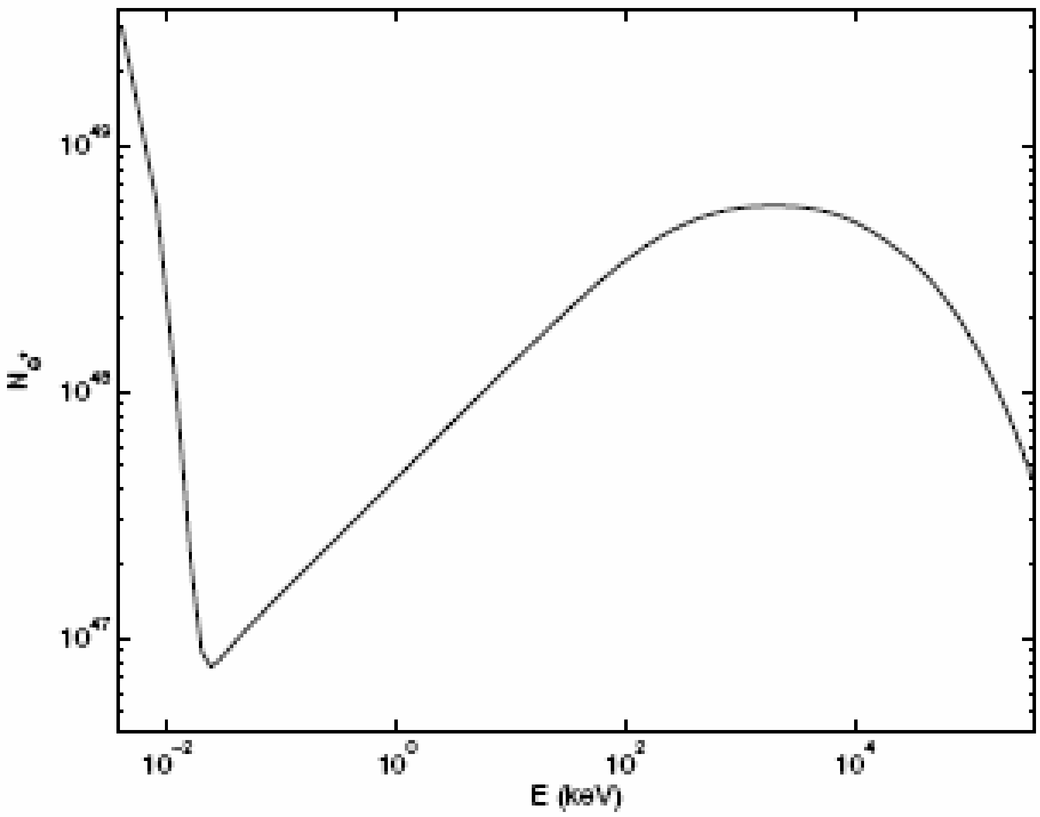


Fig. 2. The steady state distribution of positrons in the low density region (500 pc).

Spectrum of Gamma-ray Emission from the Galactic Center

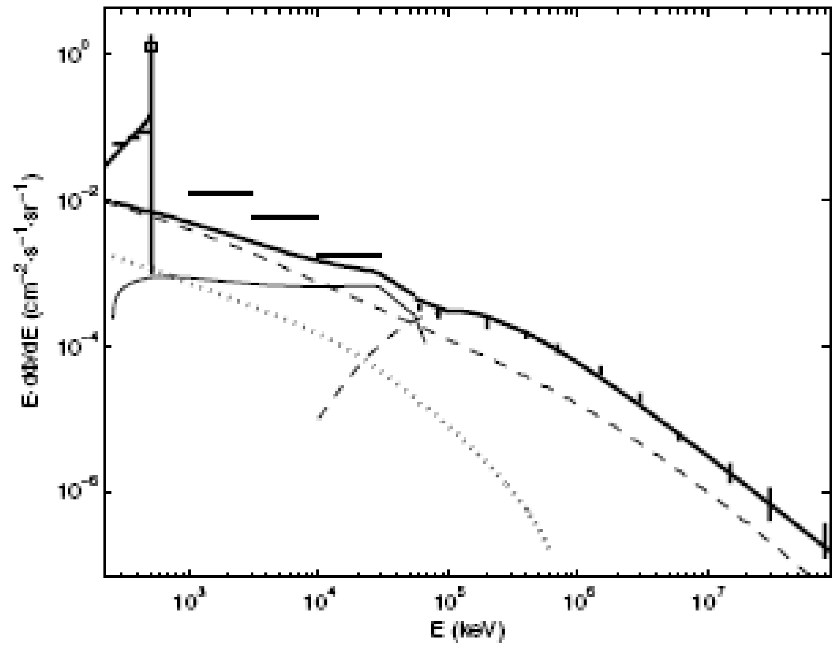


Fig. 3. The theoretical broad gamma-ray band spectrum and the observed data of EGRET, COMPTEL and INTEGRAL. Gamma-rays with energies from 30 MeV–100 GeV (EGRET range) are dominated by the decay of neutral pions (dashed thick line), gamma-rays with energies from 1–10 MeV (COMPTEL range) are dominated by in-flight annihilation (thin solid line) and inverse Compton scattering of relativistic electrons (thin dashed line); the IC data ware taken from Strong et al. (2005). The gamma-rays with energies about 500 keV are dominated by the electron-positron annihilation via positronium, in which two photon-decay produces the line spectrum and the three-photon decay produces the continuum. The dotted line presents the bremsstrahlung radiation of secondary electrons.

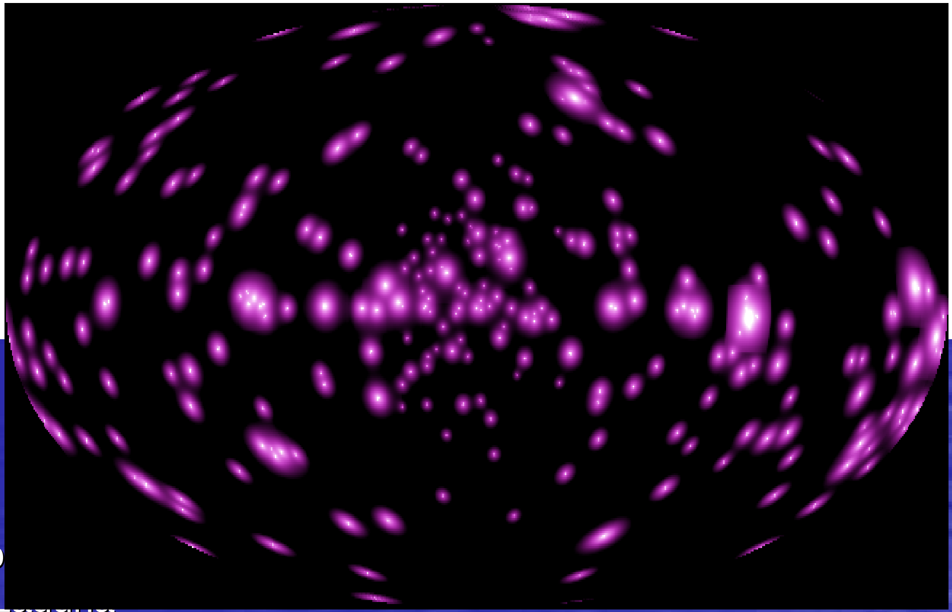
Gamma-Rays from Central Black Holes of External Galaxies

- For the EGRET sensitivity 10^{-8} ph/s at ~100 MeV these accretion processes can be seen at maximum of their activity from distances ~10 Mpc
- This model predicts that some nearby galaxies

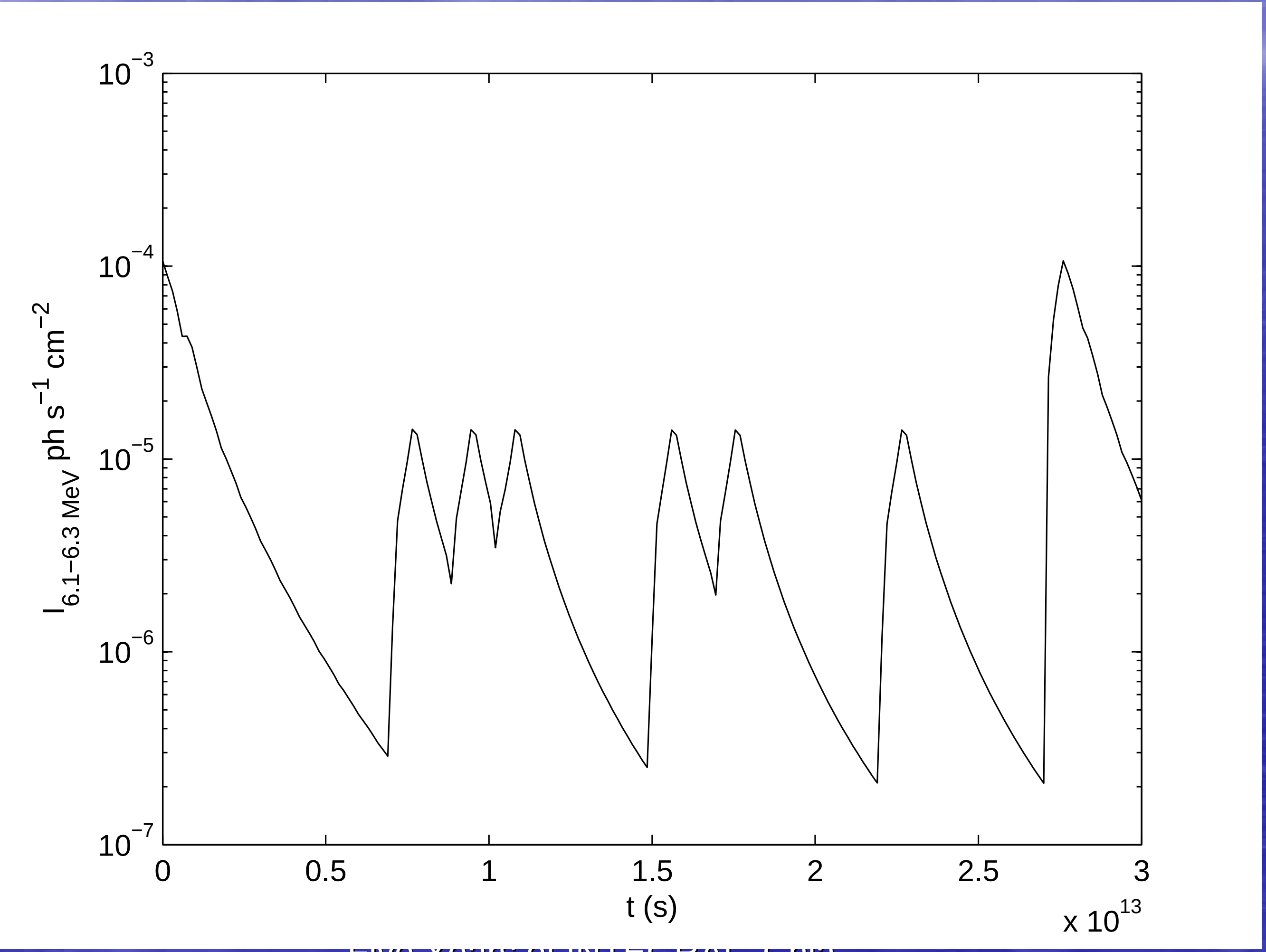
could be candidates

for the EGRET

unidentified sources



C and O De-Excitation Lines



Conclusion

- If captures of one solar mass stars produce a flux of relativistic protons then only 6 10^{52} erg in protons is needed in each capture event in order to explain the 511 keV flux by annihilation of secondary positrons;
- Due to long time of thermalization of secondary positrons the annihilation emission should be observed as an extended source;
- In-flight annihilation of relativistic positrons may generate a part of the gamma-ray continuum from the central region;
- We expect also a flux of de-excitation lines from the Galactic center produced by protons ejected by star captures.