Hard X-rays from the Galactic Center: Theory and Interpretation

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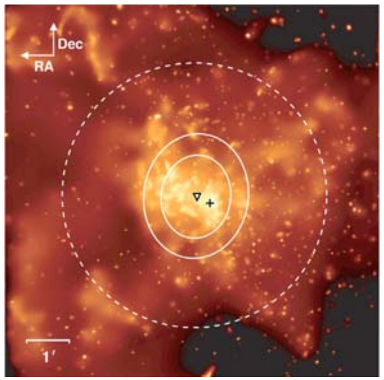
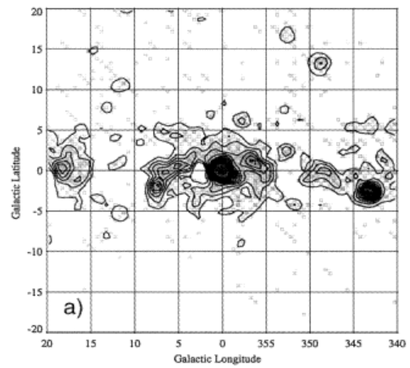
Galactic Center as a Harbour of High Energy Activity

TeV emission



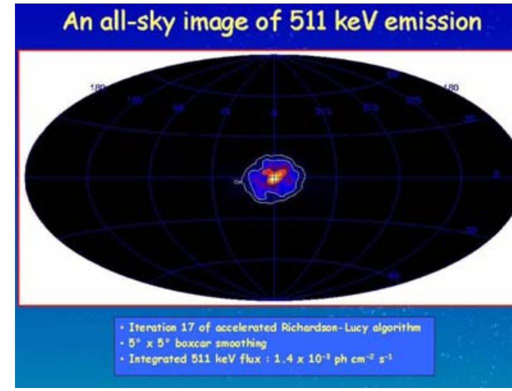
10^{35}erg/s

>100 MeV emission



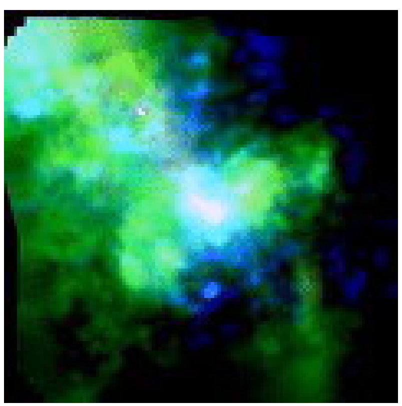
10^{37}erg/s

511 keV line emission



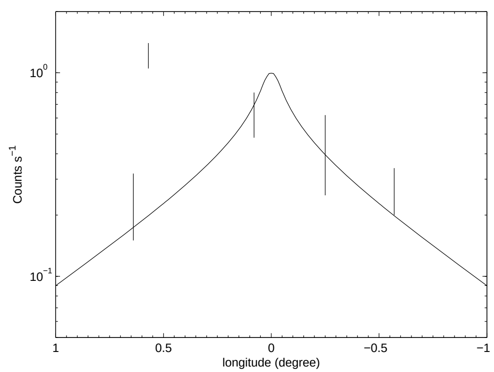
10^{37}erg/s

2-10 keV thermal emission



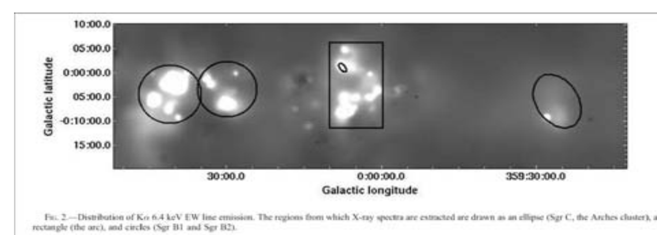
2 10^{36}erg/s

14-40 keV nonthermal emission



4 10^{36}erg/s

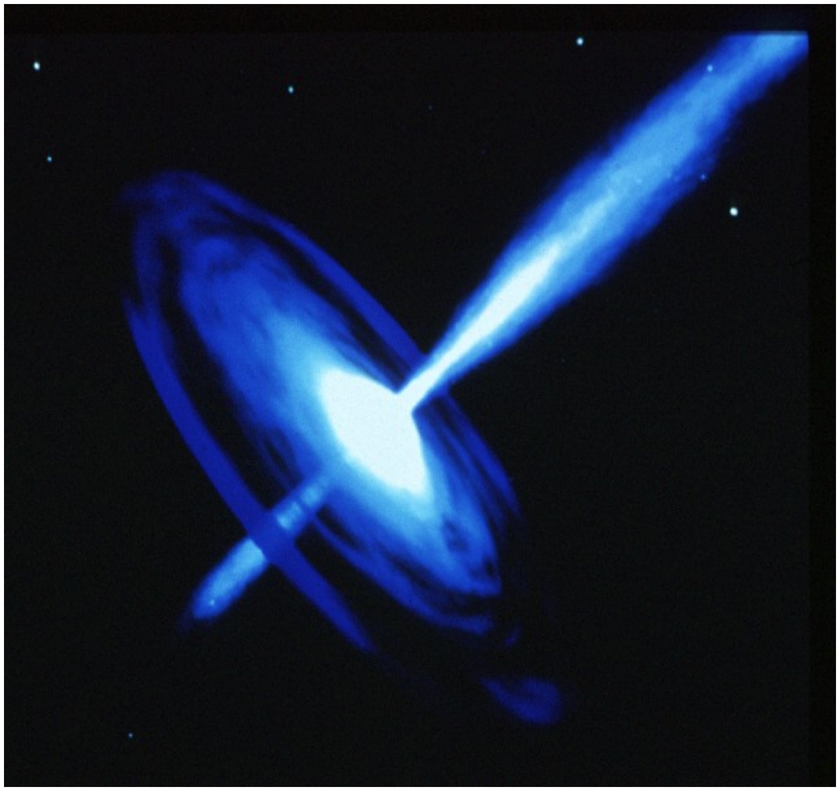
6.4 keV line emission



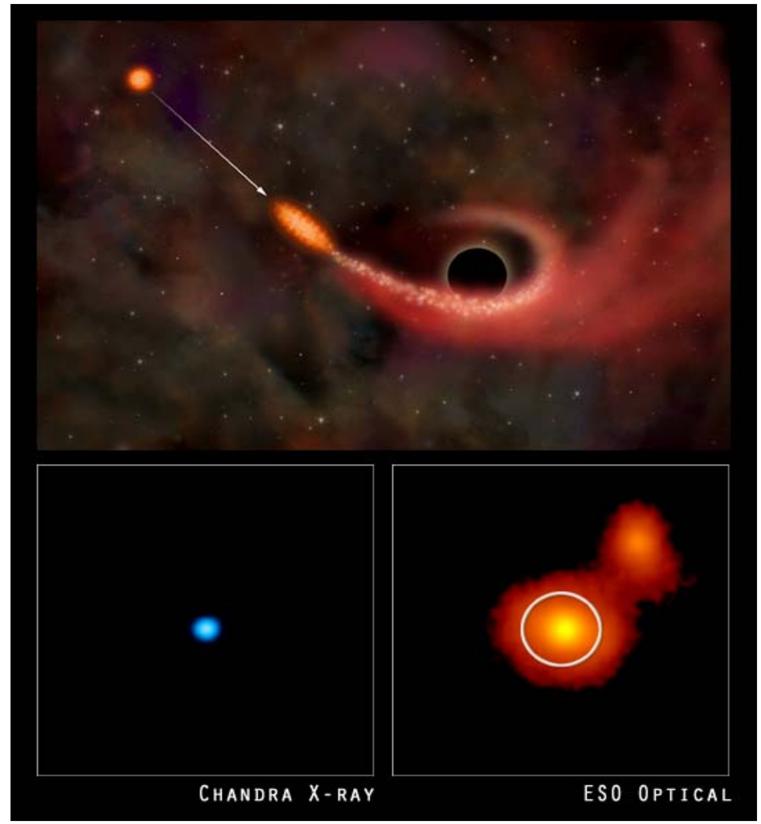
Origin of X-ray and Gamma-Ray Photons in the GC

- By occasion different processes generate this emission just in the GC;
- Point sources (X-rays)
- Emission ranging from X-rays to gamma-rays has a common origin due to star capture by the central massive blackhole

- Relativistic particles
  E>1 GeV

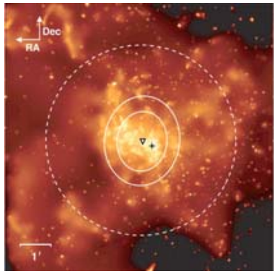


- Subrelativistic protons
  E<1 GeV



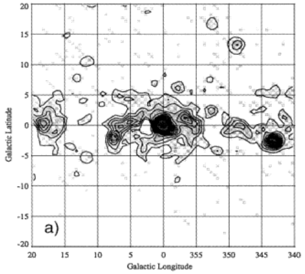
Gamma-Rays and X-rays Generated by Protons from Star Accretion Process

TeV emission



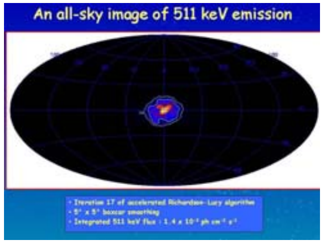
10^{35}erg/s

>100 MeV emission



10^{37}erg/s

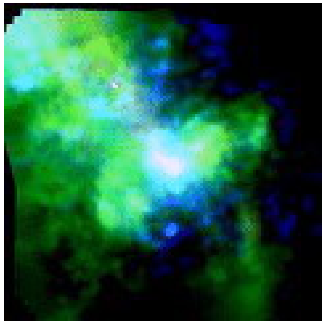
511 keV line emission



10^{37}erg/s

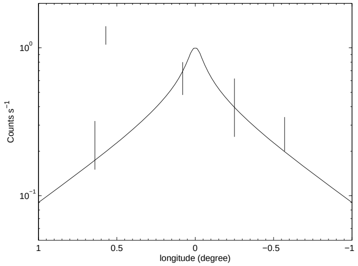
Gamma-rays are generated by relativistic protons

2-10 keV thermal emission



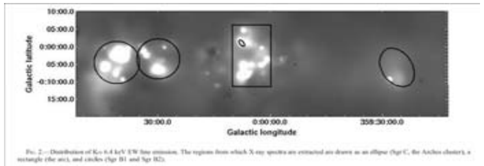
2 10^{36}erg/s

14-40 keV nonthermal emission



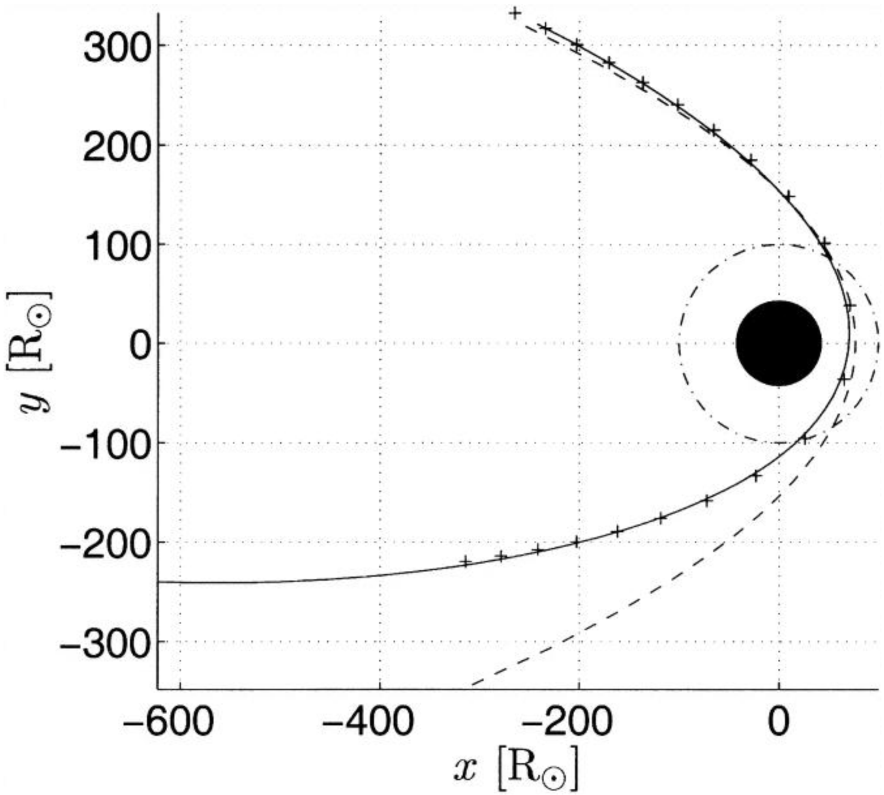
4 10^{36}erg/s

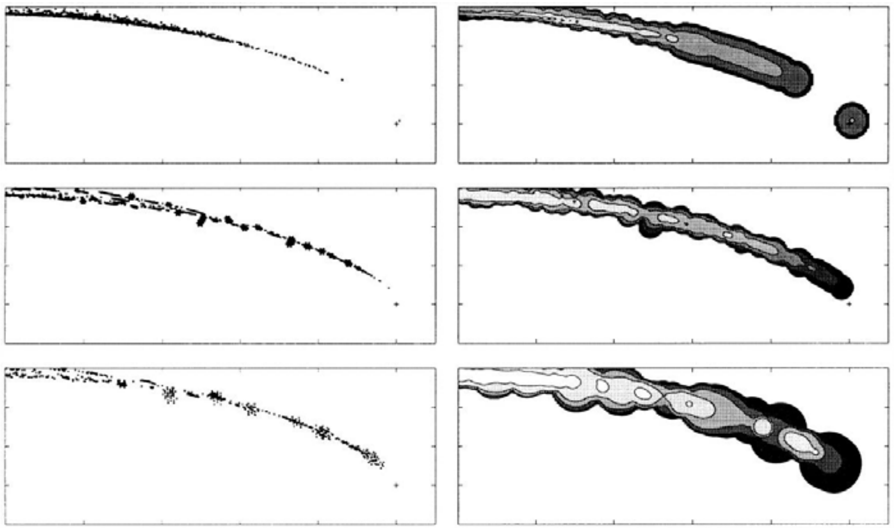
6.4 keV line emission



X-rays are generated by subrelativistic protons

Star capture (Diener et al. 1997, Ayal et al. 2000, Alexander 2005 etc.)





Frequency of star capture – 10^{-4} – 10^{-5} years^{-1}

A half of the star matter (i.e. ~ 10^{57} protons when a one solar mass star is captured) escapes with a subrelativistic velocity.

Energy Release from Tidal Disruption

$$E_{out} \sim 4 \cdot 10^{52} erg \left(\frac{M_*}{M_\odot}\right)^2 \left(\frac{R_*}{R_\odot}\right)^{-1} \left(\frac{m / M_*}{10^6}\right)^{1/3} \left(\frac{b}{0.1}\right)^{-2}$$

$$b = \frac{r_p}{r_t}$$

r_p – *radius of* periastron

r_p – *radius of* tidal *disruption*

dN/dt = N_{out}/τ =10^{45} prot/s; E~100 MeV/n; Q= E_{out}/τ ~10^{41}erg/s

Thermal Emission

T ~ 10^8 K

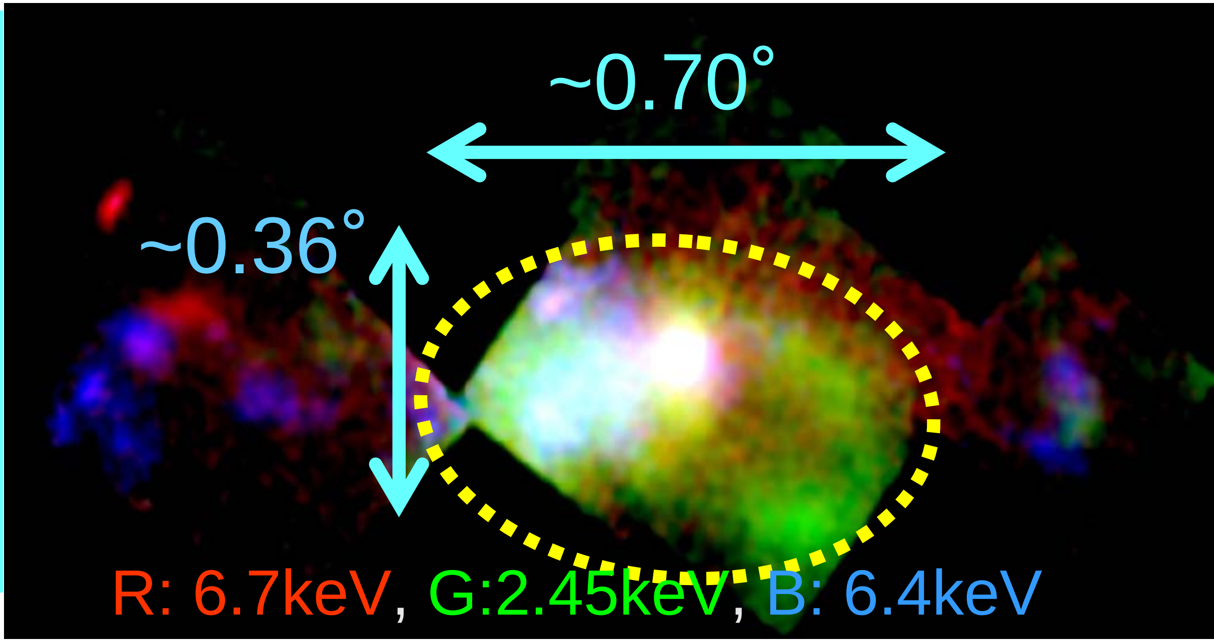
$L_{2\text{-}10}$ ~ 2×10^{36}ergs/s

Size ~ 50pc x 30pc

n_{ave} ~ 0.1cm^{-3}

n_{peak} ~ 0.4cm^{-3}

E_{gas} ~ 3×10^{52}ergs



- Escape Time scale: t_{esc} = Size/C_s = 2×10^4yr
- Heating Rate = E_{gas}/t_{esc}~5×10^{40}ergs/s~10^{-3} SN yr^{-1}

Very High !

(1) High SN rate ! Many SNRs in the GC

(2) Past Activities (Flares) of the Super massive black hole Sgr A*

(eg. Koyama+96)

Pro and Contra

Diffuse

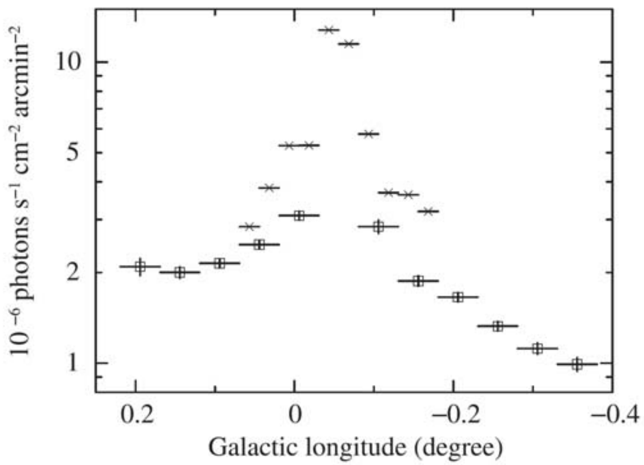
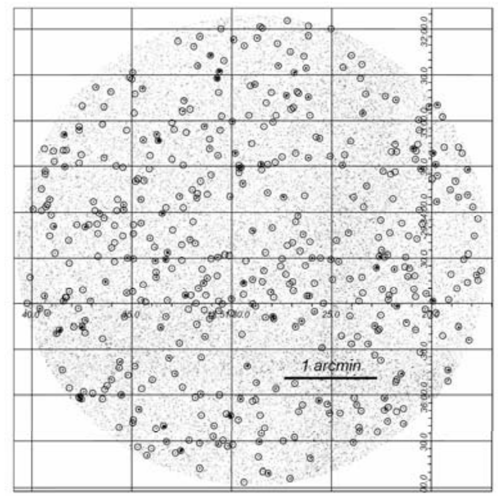


Fig. 6. The line fluxes of Fe XXV Kα are given by the squares, while the integrated point source fluxes in the 4.7–8 keV band are plotted by the crosses. The horizontal axis is the same as figure 5, but the vertical axis is a logarithmic scale.

Koyama et al. 2007

Resolved into point sources



Revnivtsev et al. 2009

Revnivtsev et al. (2009): Ridge emission is clearly explained by dim (and numerous) point sources. The summed point source spectrum shows prominent Fe line emission(s). Therefore, at least in the ridge emission, accreting white dwarfs and active coronal binaries are considered to be main emitters.

The X-ray source distribution derived from *Chandra* deep exposure of the <0:3±-radius central region does not show any correlation with the distribution of 6.7 keV line. The integrated flux of point sources contributed a rather small fraction of the total flux of GC X-rays and the major of emission from there is diffuse.

However, the Galactic latitude of this observation is 1.42 degree which is just at the edge of 200 pc circle from the Galactic center. Thus, the emission should be regarded as the ridge emission rather than GC emission

Pro and Contra (Cont.)

- Koyama et al. (1996, 2007, 2008): The GC emission has a temperature of ~6.5 keV and the ridge has lower temperature. This indicates that there could be different emission mechanism in these two regions.

- Yamauchi et al.(2009): the ratios of 6.9 to 6.7 keV lines (which traces the plasma temperature) and 6.4 to 6.7 keV lines are higher in GC than in GR, while in GR this ratio is almost constant along the plane.

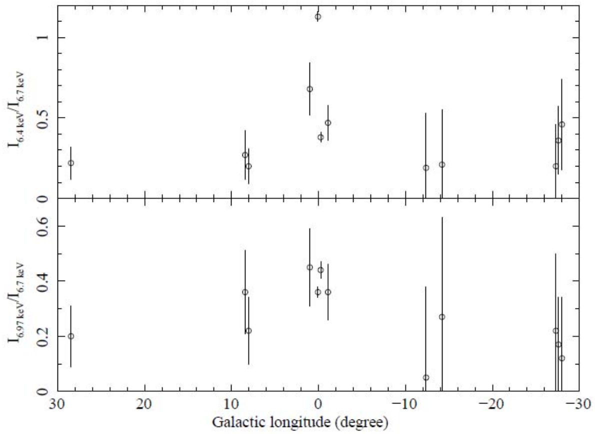


Fig. 4. The flux ratios of 6.4 keV/6.7 keV (upper) and 6.97 keV/6.7 keV (lower) lines as a function of the Galactic longitude. The error shows the 90 % confidence level.

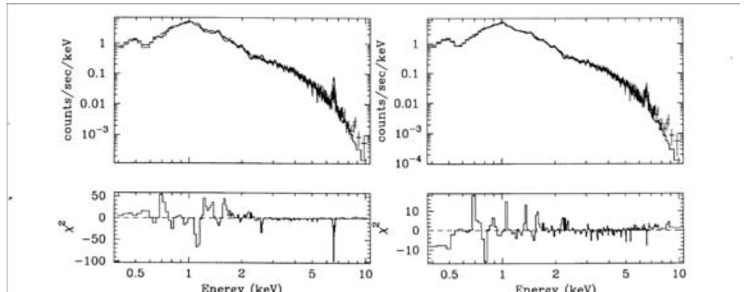
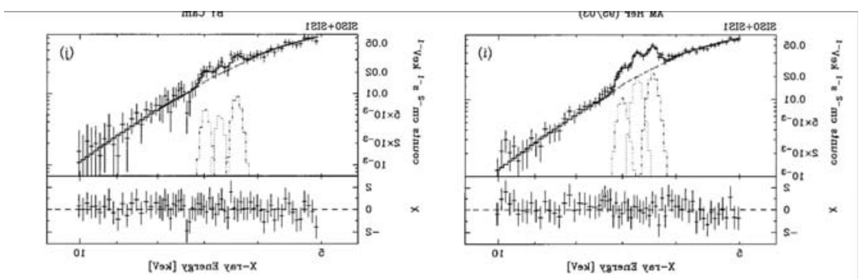


FIG. 2.—The spectral fits to the high-state SIS0 spectrum of Algol. The upper left-hand panel shows the fit to a solar photospheric abundance RS temperature model and the lower left panel the χ^2 residuals from the fit. The Upper right-hand panel shows the best-fitting two-temperature RS variable abun model and the lower right panel the χ^2 residuals from the fit. The best-fitting parameters are given in Table 1.



- This leaves an open possibility that the nuclear region of the Galaxy (within ~ 10’ - 1^o around Sgr A) may be somewhat different from the rest of the Galaxy, and, therefore, processes of radiation there have an origin which differs from other parts of the Galactic disk.


protons
Coulomb collisions
Gas heating

Subrelativistic Protons in GC

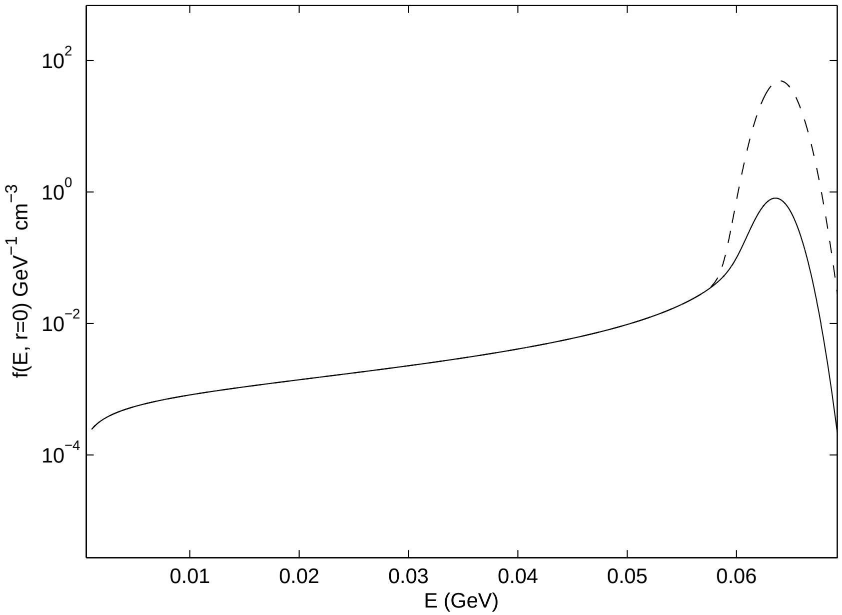
- Equation

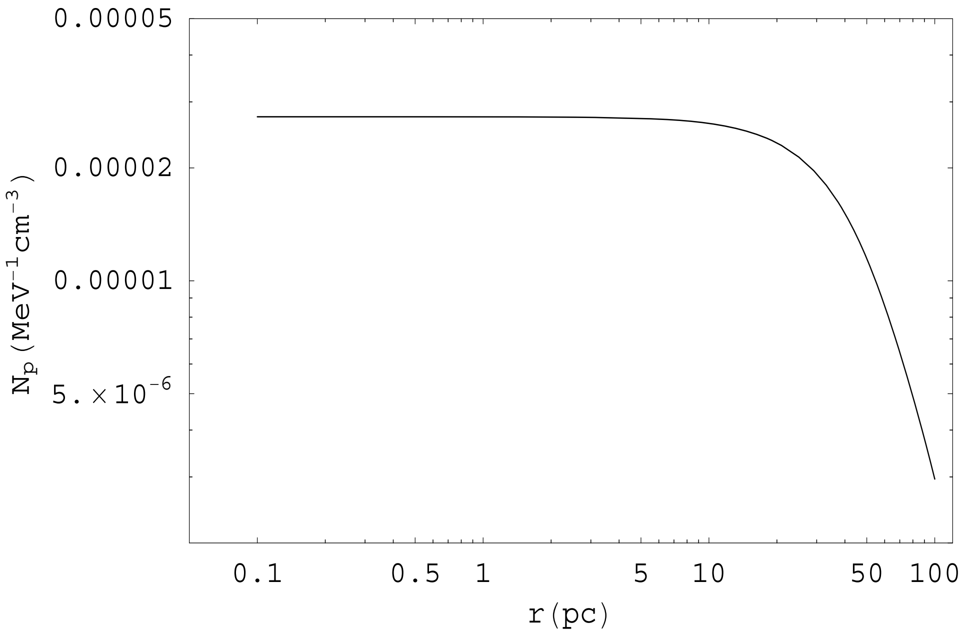
$$\frac{\partial f}{\partial t} - \nabla D \nabla f + \frac{\partial}{\partial E}\left(\frac{dE}{dt} f\right) = Q(E,t)$$

$$Q(E, \mathbf{r}, t) = \sum_{k=0} Q_k(E)\delta(t - t_k)\delta(\mathbf{r})$$

$$\tau_{ion} >> \tau_{cap}$$

- Energy distribution
- Spatial distribution



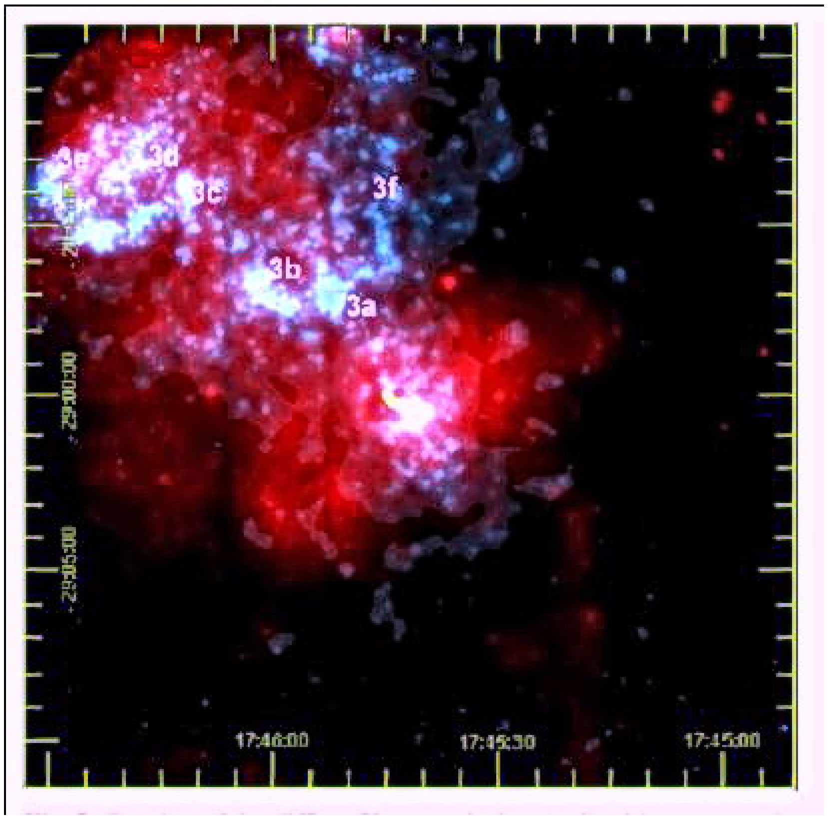


τ_i~3 10^6 years; τ_c <10^5 years

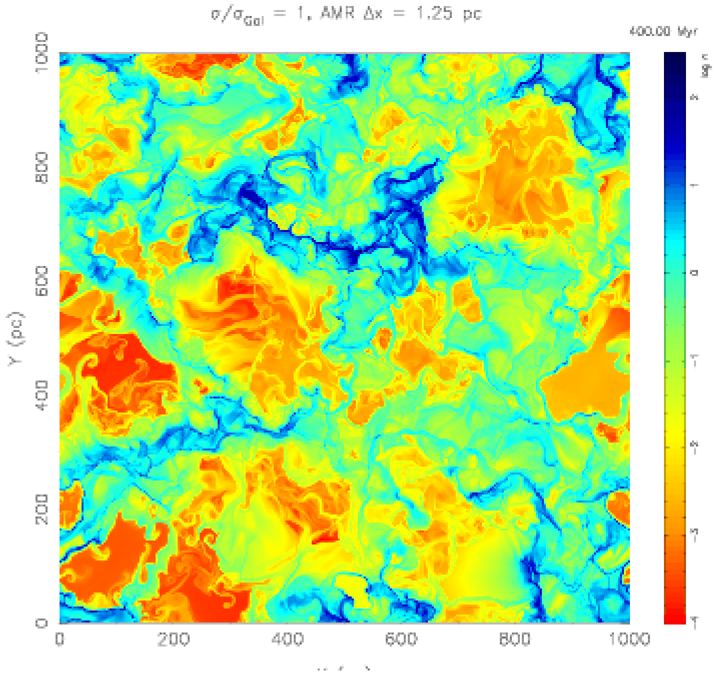
Quasi-stationary energy release in the GC in the form of subrelaivistic protons supplies just ~10^{41}-10^{42}erg/s that is necessary for the plasma heating!!!

Plasma Outflow?

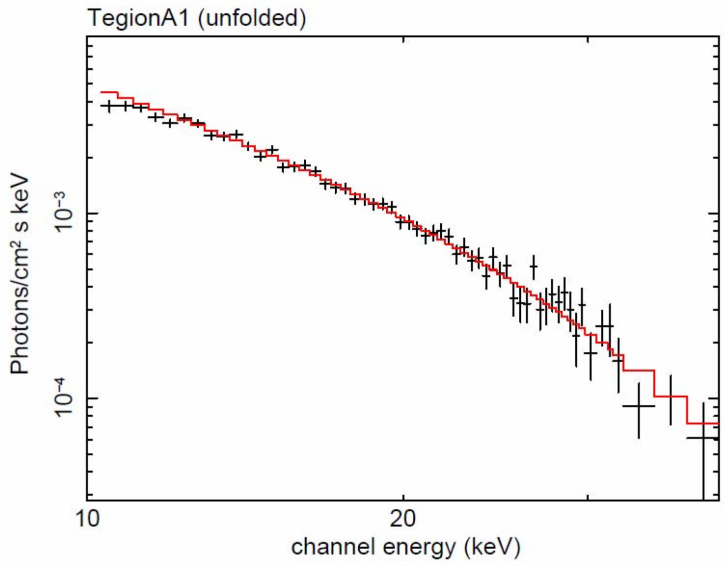
- Space structure near GC (Predehl et al. 2003)



- Space structure at star formation region (de Avillez and Breitschwerdt 2005)



Non-Thermal X-Ray Emision (Yuasa et al. 2008)



- Region

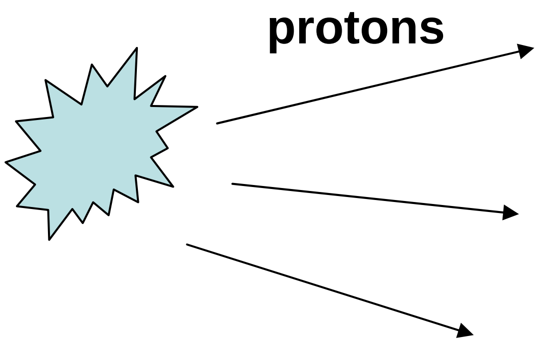
$l<2^o$, $b<2^o$

- Spectrum

$$f(E) = K(E/1\ keV)^{-\Gamma}\exp(-E/E_c)$$

ΔE=12-40 keV, Γ=1.4, E_c=19-50 keV

- Luminosity W~4 10^{36} erg/s



Bremsstrahlug losses ⇒ **Hard X-ray emission**

For $E_p=100$ MeV ⇒ $E_x<70$ keV

Inverse Bremsstrahlung?

- IB cross-section

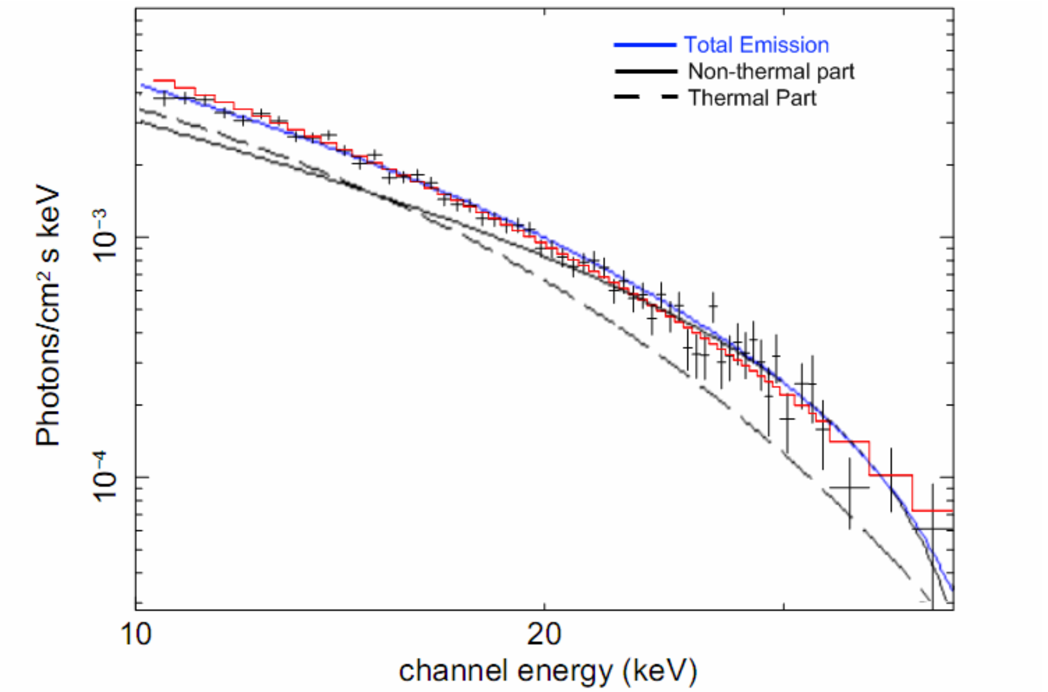
$$\frac{d\sigma_{br}}{dE_x} = \frac{8}{3} Z^2 \frac{e^2}{\hbar c} \left(\frac{e^2}{mc^2} \right)^2 \frac{mc^2}{E'} \frac{1}{E_x} \times \ln \frac{\left(\sqrt{E'} + \sqrt{E' - E_x} \right)^2}{E_x}$$

Here $E' = (m/M) E_p$

- IB intensity in the direction **l**

$$I_{\mathbf{l}} = \int\limits_{\mathbf{l}} N_p(E, \mathbf{r}, t) \frac{d\sigma_{br}}{dE_x} \mathrm{v}_p n \, d\mathbf{l}$$

Energy Spectrum of IB emission in GC

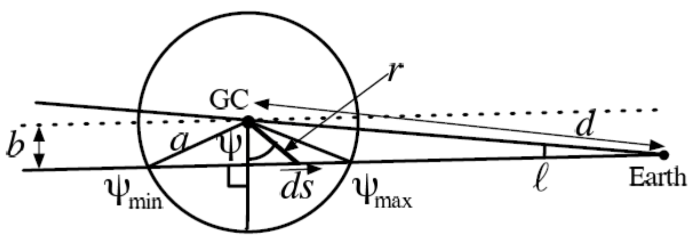


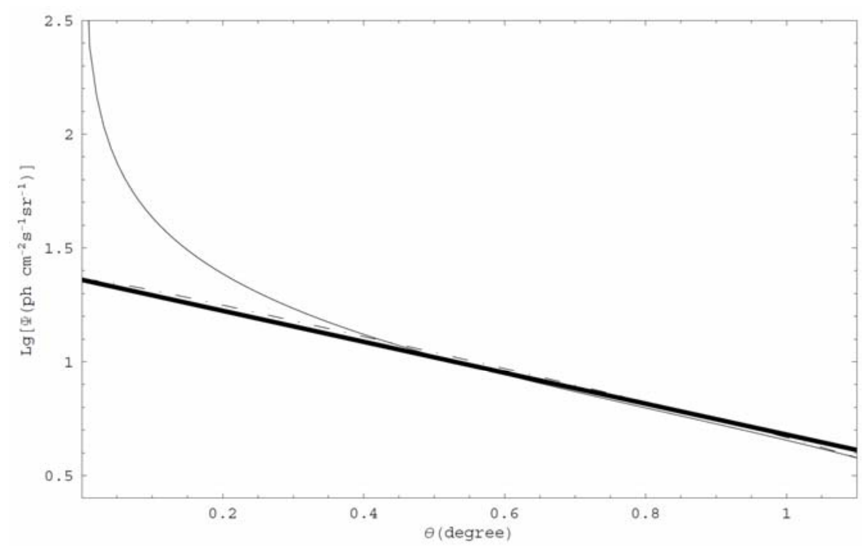
W_{IB}=3.4 10^{36}erg/s !

E_{max}~100 MeV

Gas Distribution in the GC

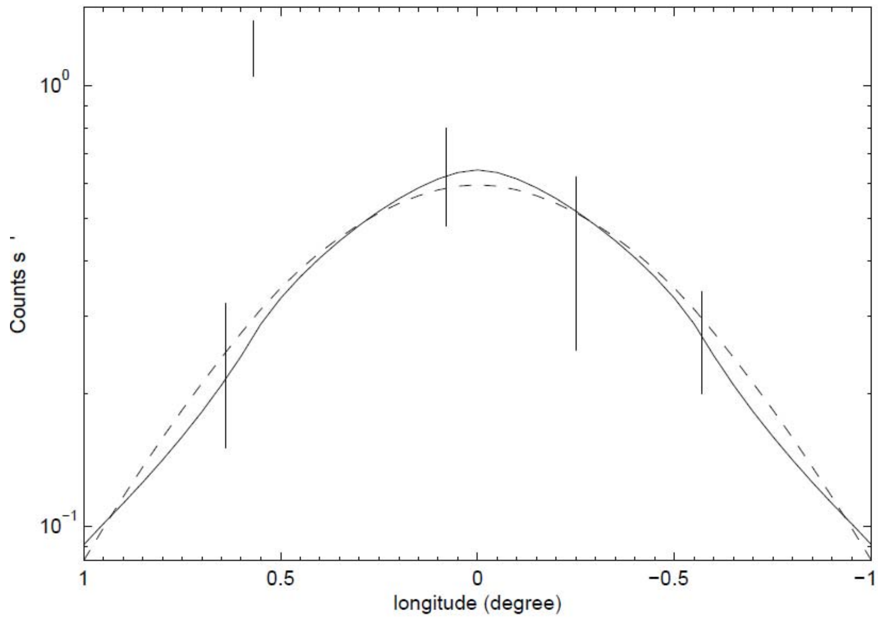
$$I_{6.7} \prec \int_s n^2(r)ds$$





Maeda 1998

Diffusion coefficient and necessary Power of Accretion



$$D \simeq 10^{26}\, cm^2 s^{-1}; \quad Q \simeq 2 \cdot 10^{45}\, prot\ s^{-1}$$

From Revnivtsev et al. (2009)

- Bad news: 100% of the GC emission may be due to faint sources;
- Good news: If a part of the GC X-ray emission is due to faint sources then parameters of star capture necessary for the rest (diffuse) emission are not so extreme

6.4 keV line from molecular clouds
(Yusef-Zadeh et al. 2007, Koyama et al. 2008)

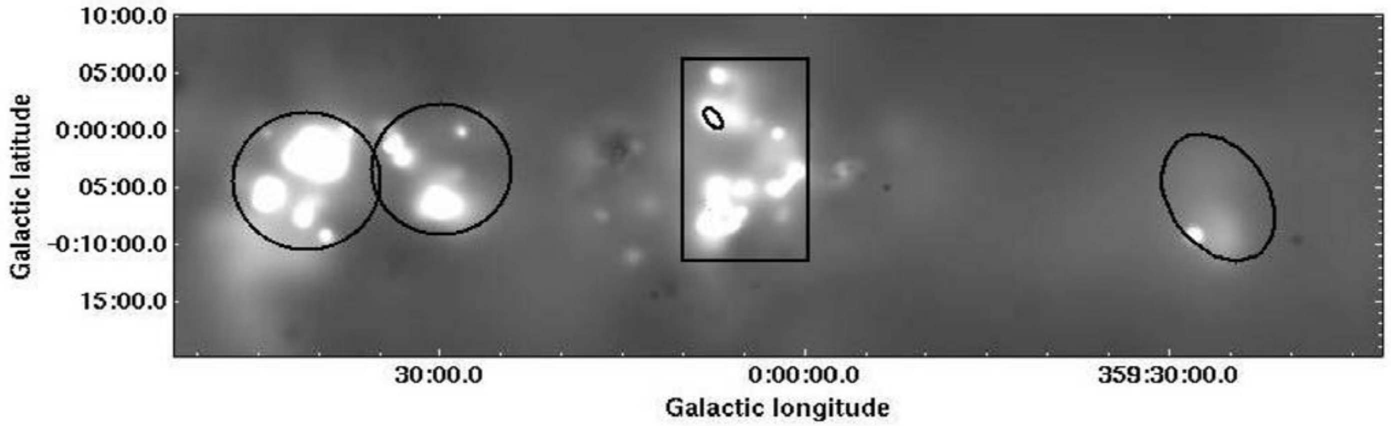
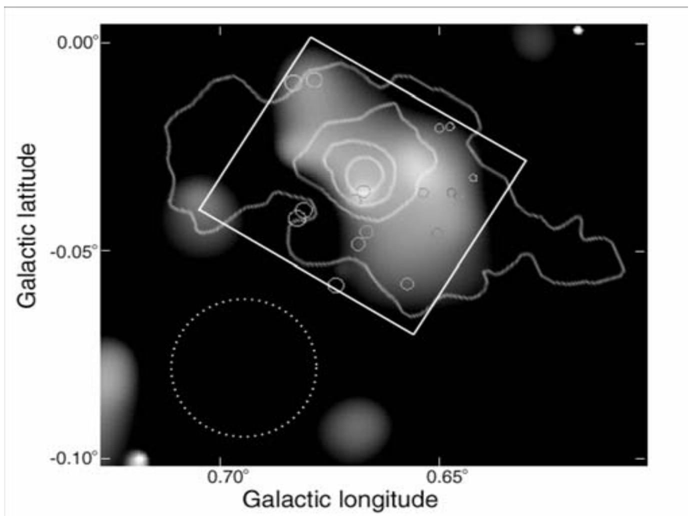
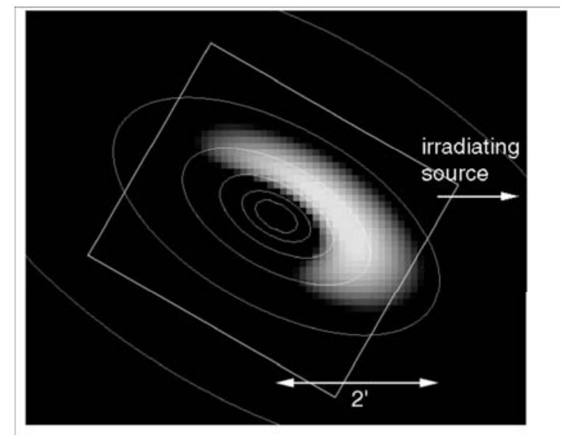


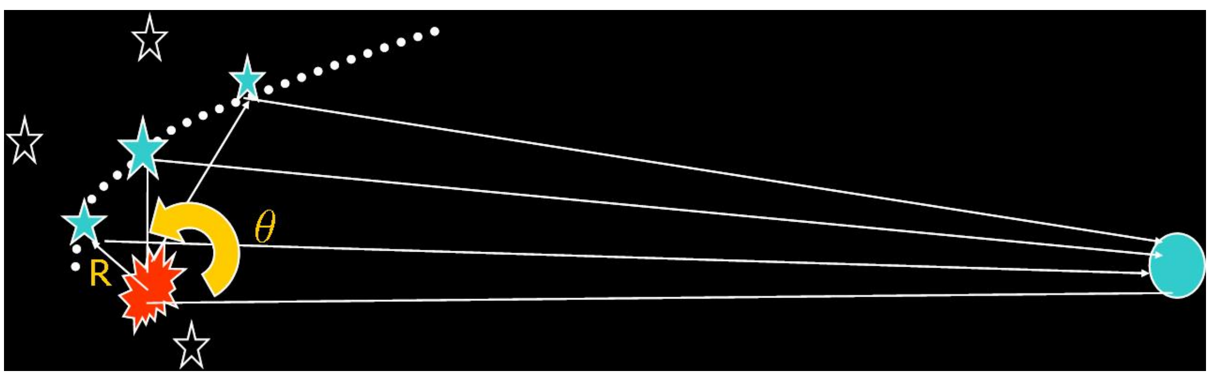
FIG. 2.—Distribution of Kα 6.4 keV EW line emission. The regions from which X-ray spectra are extracted are drawn as an ellipse (Sgr C, the Arches cluster), a rectangle (the arc), and circles (Sgr B1 and Sgr B2).

Origin: Reflection of X-ray flux produced in the past?
(Sunyaev et al. 1993, Koyama et al. 1996)





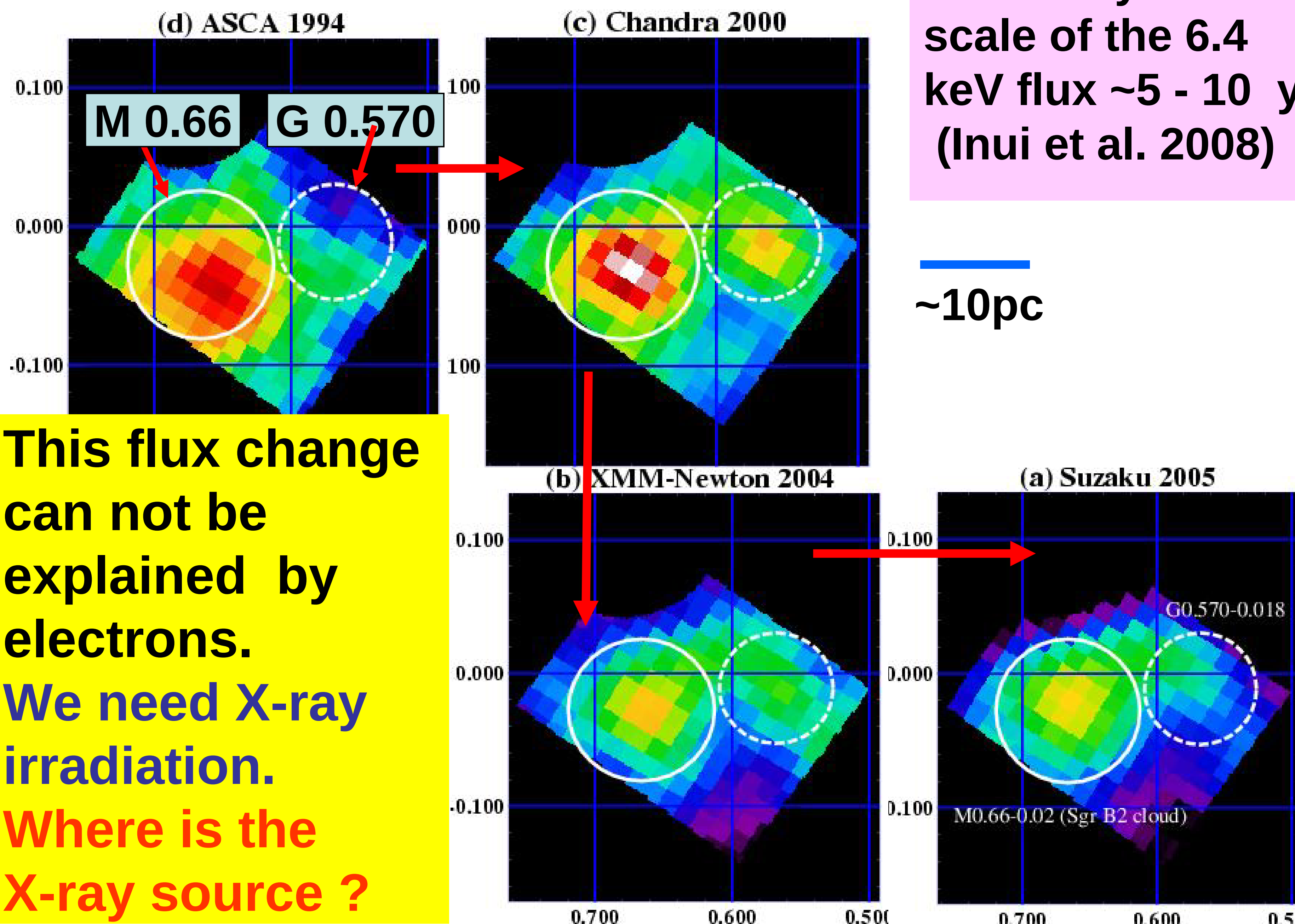
Sgr B2



Necessary flux of X-rays with E>7.1 keV – 10^{39}erg/s

The Sgr B2 Cloud

Variability time scale of the 6.4 keV flux ~5 - 10 ys (Inui et al. 2008)



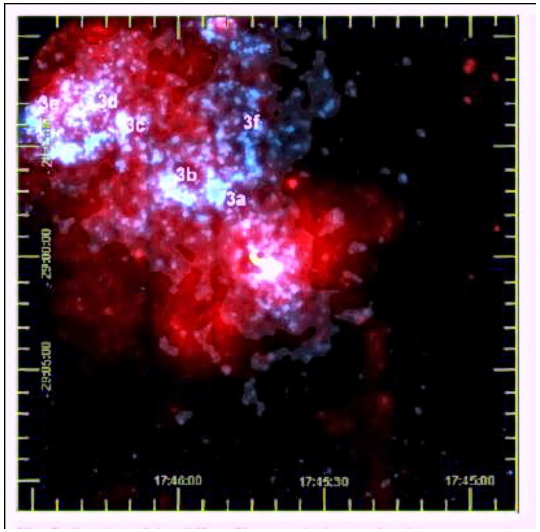
~10pc

This flux change can not be explained by electrons.

We need X-ray irradiation.

Where is the X-ray source ?

But: (Predehl et al.2003)



- Clouds show almost the same emissivity independently of distance from Sgr A

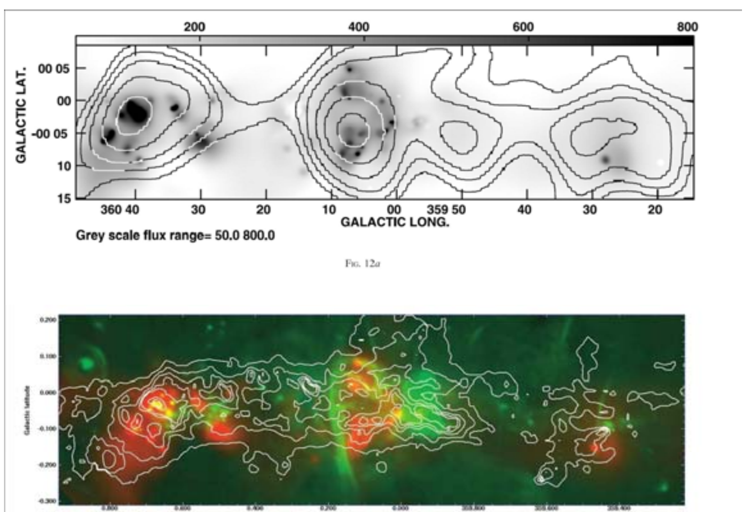


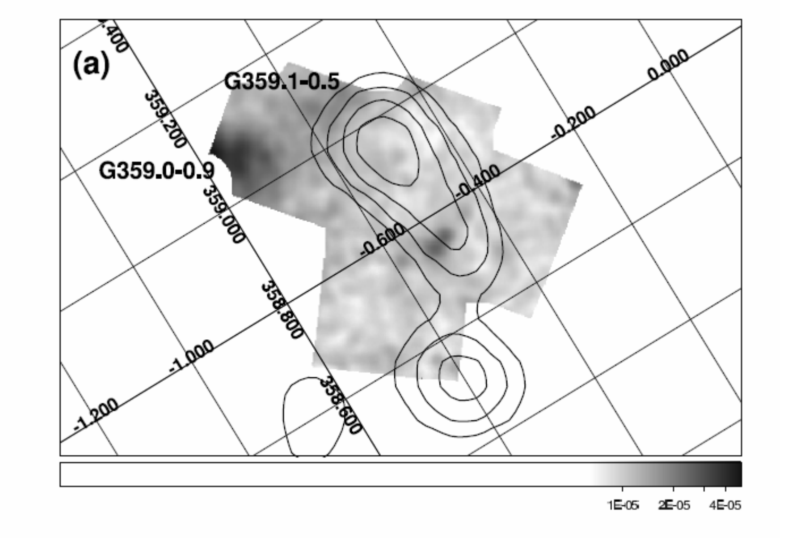
Fig. 12a

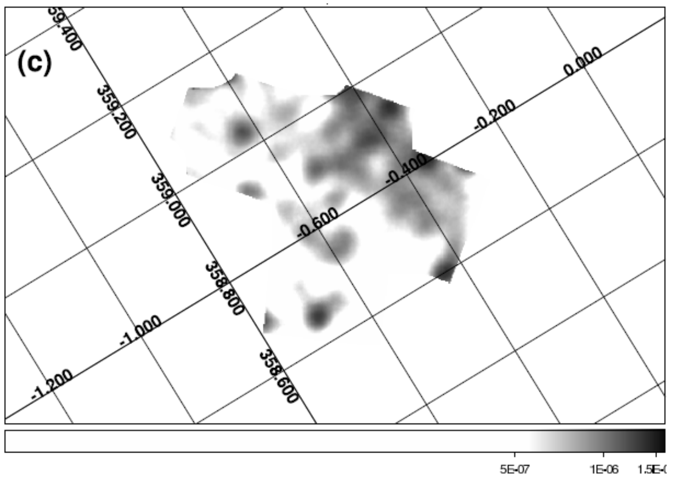
Fig. 12b

Fig. 12.—(a) Contours of HESS emission from the Galactic center (Aharonian et al. 2006) superimposed on the distribution of Kα 6.4 keV EW line emission. (b) Contours of 850 μm submillimeter emission superimposed on the distributions of Kα 6.4 keV EW line emission (*red*) and a 20 cm continuum emission (*green*).

- UHE gamma-ray distribution correlates with that of 6.4 keV
- Cosmic rays are inside clouds!!!

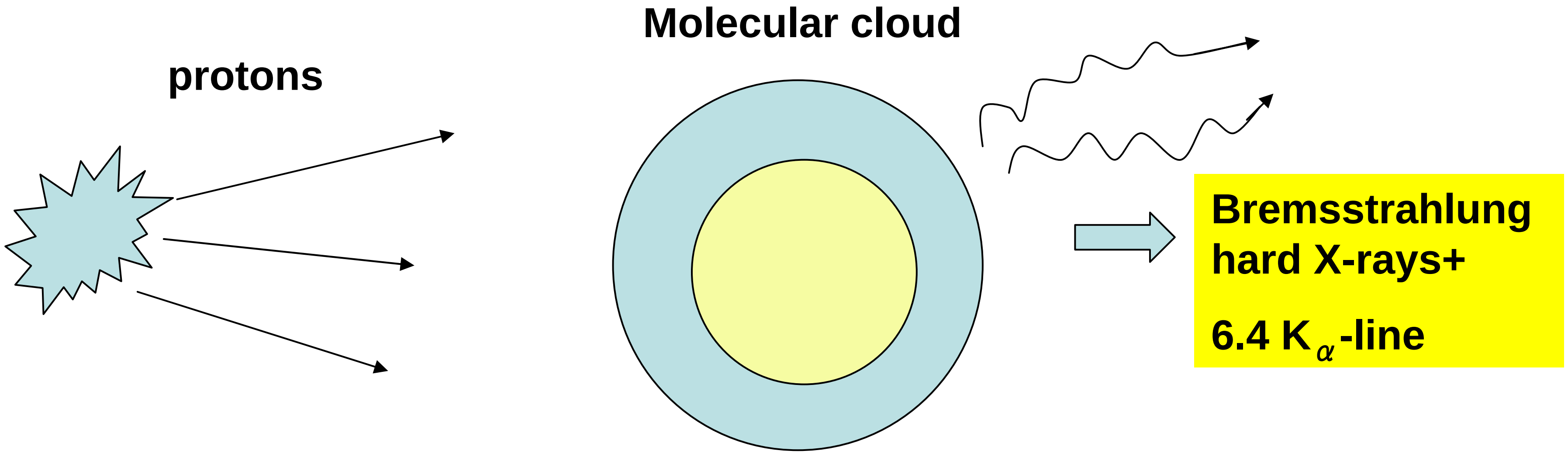
CRs Are Inside Molecular Clouds.
HESS Source **J1745-303** (Bamba et al 2009)





TeV and 0.5 – 2.0 keV emission

6.4 keV line emission



Molecular cloud
protons
Bremsstrahlung
hard X-rays+
6.4 K$_\alpha$-line

Molecular Clouds in the GC

Table 1. Characteristics of molecular clouds.

	Sgr B2	J1745-303
$M[M_\odot]$	$6 \cdot 10^6$	$5 \cdot 10^4$
Angular size[deg.]	0.05	0.3
Linear size[pc]	7	40
Distance[deg.]	0.7	1.2
Linear distance[pc]	~ 100	~ 200

Continuum and 6.4 keV line emission from the louds

Sgr B2

Telescope	$10^5 \cdot F_{6.4}$ (ph $cm^{-2}s^{-1}$)	$10^{-33} \cdot \Phi_{2(4)-10\ keV}$ (erg s^{-1})
ASCA	16.3	$110 - 140$
Chandra	13.7-17.1	$80 - 120$
Suzaku	11.4	97

HESS J1745-303

Telescope	$10^5 \cdot F_{6.4}$ (ph $cm^{-2}s^{-1}$)	$10^{-33} \cdot \Phi_{2-10\ keV}$ (erg s^{-1})
Suzaku	1.1	< 3.9 (< 80) 90% confidence limit
XMM -Newton	-	< 9.6 (< 226) 99% confidence limit

Parameters of proton propagation in the intercloud medium

Part.inj. numb.	Star capt. time	Part.inj. energy	Plasma dens.	Plasma temp.	Diff. coeff.
N_p	τ_k	E_m	n	T	D
10^{57} prot.	10^4 year	100 MeV	0.2 cm^{-3}	6.5 keV	10^{27} cm^2s^{-1}

Parameters of proton propagation inside molecular clouds

Gas dens.	Gas temp.	Fe Abund.	Diff. coeff.
$\bar{n}_c$	T_c	η_c	D_c
10^4 cm^{-3}	100 eV	$7.4 \cdot 10^{-5}$	10^{25} cm^{2}s^{-1}

Turbulence of neutral gas in giant molecular clouds (Larson, 1981, Myers, 1983, Solomon et al. 1987 etc.)

$$\Delta v(km/s) = 1.1\ L^{0.38}$$

$$0.01 < L < 300\ \ pc$$

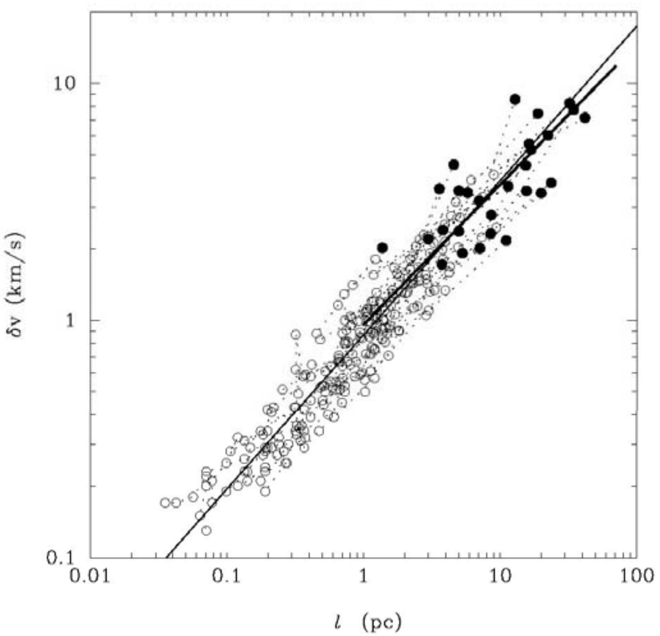


Fig. 1.— The composite $\delta v, l$ relationship from PCA decompositions of ^{12}CO J=1-0 imaging observations of 27 individual molecular clouds. The small scatter of points attest to the near invariance of interstellar turbulence within molecular clouds that exhibit a large range in size, environment, and star formation activity. The large filled circles are the global velocity dispersion and size for each cloud derived from the first principal component. These are equivalent to the global velocity dispersion and size of the cloud as would be measured in the cloud-to-cloud size-line width relationship (Larson 1981; Solomon et al. 1987). The light solid line show the bisector fit to all points from all clouds. The heavy solid line shows the bisector fit to the filled circles exclusively. The similarity of these two power laws explains the connection of Larson's cloud-to-cloud scaling law to the structure functions of individual clouds.

MHD-turbulence in a weakly ionized gas
(Gurevich, Dogiel, Istomin and Zybin 1985, 1987)

$$\frac{\partial \mathrm{u}}{\partial t} + (\mathrm{u}\nabla)\mathrm{u} = -\frac{1}{\rho}\nabla P_i + \frac{1}{4\pi\rho}(\nabla \times H)\times H + \nu_g \nabla^2 \mathrm{u} - \mu_{\mathrm{in}}(\mathrm{u} - \mathrm{v})$$

$$\frac{\partial \mathrm{H}}{\partial t} = \nabla \times (\mathrm{v} \times H) + \nu_m \nabla^2 \mathrm{H}$$

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathrm{u}) = 0, \qquad \nabla H = 0$$

✓External force in the form of friction between ionized and neutral gas

✓Back reaction of the ionized component and magnetic fluctuations on neutral component is neglected

✓In this approximation the system can be solved analytically

Particle Propagation and Acceleration

From the drift equations of particles propagation and the Boltzmann equation we can derive an equation for average distribution function of particles for magnetized $\gamma < \omega_H \tau$ and nonmagnetized $\gamma > \omega_H \tau$ particles where $\tau = L_{\min} / c$

$$\frac{\partial F}{\partial t} = \frac{\partial}{\partial x_i} \frac{\mathrm{v}}{c} D_x \frac{\partial F}{\partial x_i} + \frac{\partial}{\partial p} p \frac{\mathrm{v}}{c} D_p \frac{\partial F}{\partial p} - \frac{\partial}{\partial p}\left(\frac{dp}{dt} F\right)$$

where

$$D_x \propto \int_{-\infty}^{\infty} \int_{-\infty}^{t} \left\langle h(r,t)\, G(r,t \,|\, r',t')\, h(r',t') \right\rangle d^3 r'\, dt' \approx 10^{23} cm^2 / s$$

$$D_p \propto \int_{-\infty}^{\infty} \int_{-\infty}^{t} \left\langle V_i(r,t)\;\; V_j^{'}(r',t')\, G(r,t \,|\, r',t') h_\mu(r,t)\, h_\nu(r',t') \nabla_\mu \nabla_\nu^{'} h_i(r,t)\, h_j(r',t') \right\rangle d^3 r'\, dt' \approx 10^{-11} s^{-1}$$

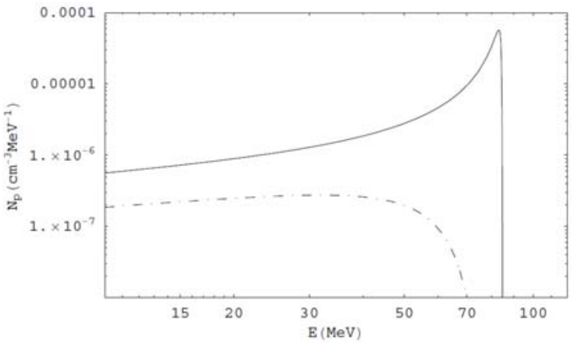
$$G(r,t \,|\, r',t') = \delta(r' - \rho(r,t,t')), \quad h = \vec{B} \Big/ \left|\vec{B}\right|$$

Subrelativistic Protons inside Clouds

- Equation in the intracloud medium

$$\frac{\partial f}{\partial t} - \nabla D \nabla f + \frac{\partial}{\partial E}\left(\frac{dE}{dt} f\right) = Q(E,t)$$

$$Q(E,\mathbf{r},t) = \sum_{k=0} Q_k(E)\delta(t-t_k)\delta(\mathbf{r})$$



- Equation inside clouds

$$\tilde{N}(E,x) = \frac{x}{\mid b_c(E) \mid} \int\limits_E^{E_m} \frac{dE_0 N_c(E_0)}{\sqrt{D_c} \cdot \tau_c(E,E_0)^{3/2}} \times$$

$$\times \exp\left[-\frac{x^2}{4D_c \cdot \tau_c(E,E_0)}\right].$$

Here $b_c(E)$ is the rate of ionization losses inside the cloud and

$$\tau_c(E,E_0) = \int\limits_{E_0}^{E} \frac{dt}{b_c(t)}.$$

Continuum and 6.4 keV Line Emission from Clouds in the GC

Cloud	$10^5 \cdot F_{6.4}$ (ph cm^{-2}s^{-1})	$10^{-33} \cdot \Phi_{2-10\ \mathrm{keV}}$ (erg s^{-1})
SGR B2	11	80
J1745-303	1.1	7.6

- The observed time-variations of the 6.4 keV flux from molecular clouds are strongly in favor of the XRN model, but they do not exclude simultaneous production of the 6.4 keV line by other processes;

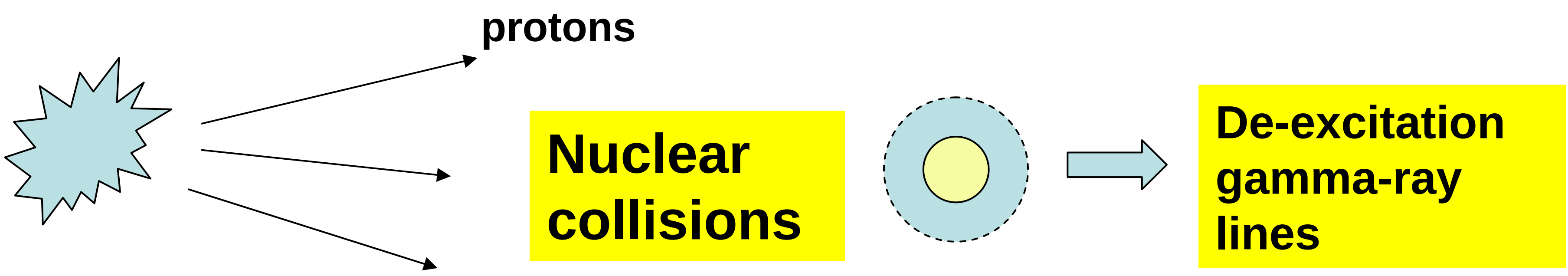
- Unlike other astrophysical problems, that of the 6.4 keV flux can be solved in the near future because of its fast time-variability. The 6.4 keV flux from Sgr B2 had dropped for the period from 2000 to 2005 to 60% of its maximum value. If Sgr B2 is an XRN source then one expects that this cloud will be almost unseen in several years;

- From the HESS observations it follows that Sgr A may be a source of high energy protons which penetrate into molecular clouds;

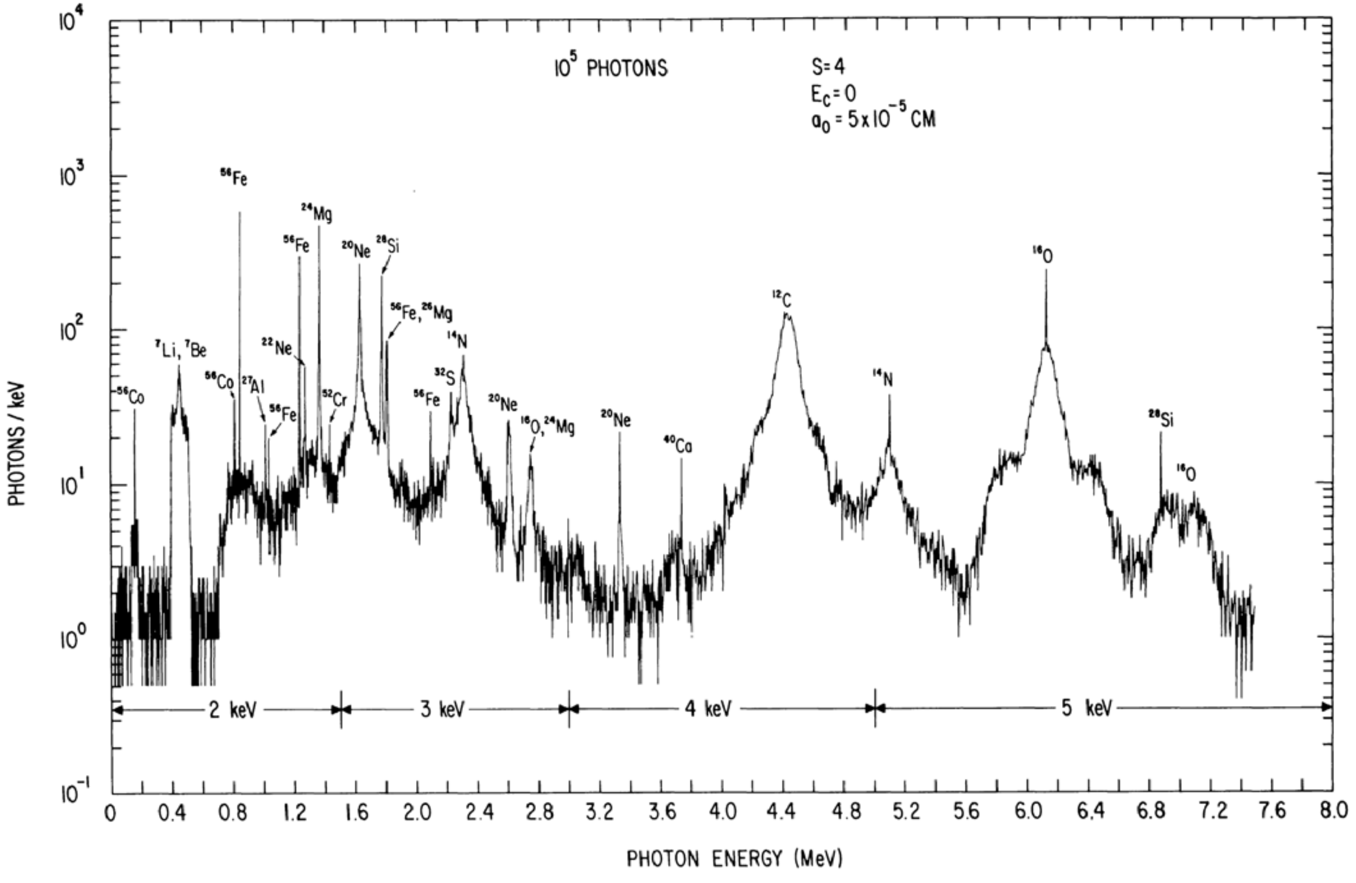
- The width of the 6.4 keV line produced by protons is about several tens of eV, which is about one order of magnitude wider than the natural width expected from that generated by subrelativistic electrons or X-ray refection. Future observations by *Astro-H*, whose energy resolution is supposed to be only 7 eV will be able to measure this parameter;

- It follows from our estimations that molecular clouds may contribute a signifcant part of the total hard X-ray flux from the GC.

Gamma-Ray Line Emission from the GC

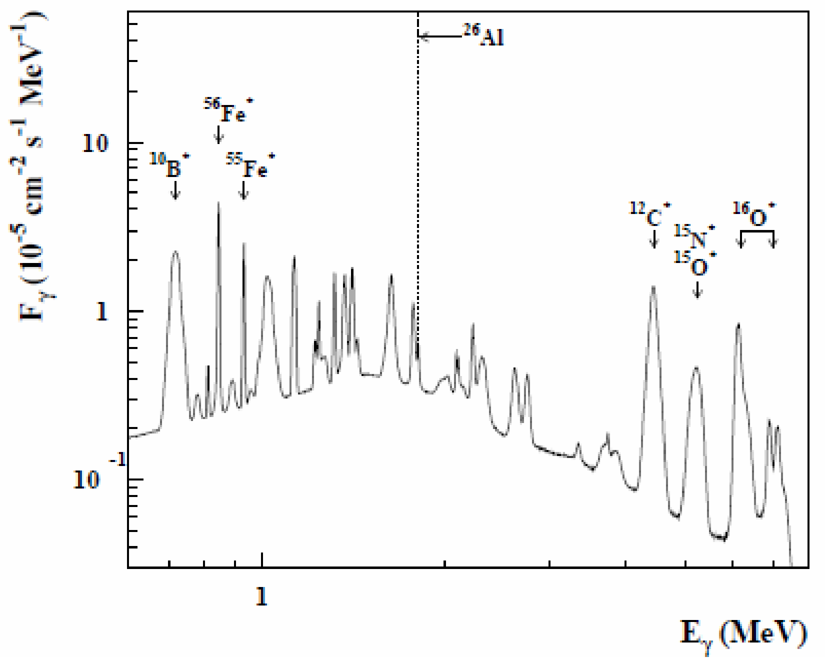


Gamma-Ray Line Emission from the GR (Ramaty et al., 1979)



Gamma-Ray Lines Produced by Subrelativistic Protons Ejected by Accrestion

$$F_\gamma(t) = \frac{n_H}{4\pi D^2}\sum_{ij}\frac{n_j}{n_H}\int_0^\infty f_i(E_i,t)v_i(E_i)\sigma_{ij}(E_i)dE_i$$



In the range E= 3 to 7 MeV the total gamma-ray line flux is 8.6 10^{-6} ph/cm^2/s

^{26}Al Line Emission from the GC

- Excited Al nuclei are thermilized long before gamma-ray photon emission, and the width of Al line are extremely narrow in comparison with others;
- Lifetime of radioactive ^{26}Al (~10^6 years) is much longer than the recurrence time of star capture (~ 10^4years). Therefore Al nuclei should accumulate in the GC region from several successive capture events:
- A saturation level of Al line emission from 1^{0}x1^{0} the GC region

$$F_{Al} \sim 3.1 \times 10^{-5}\, ph\ cm^{-1} s^{-1}$$

De-excitation gamma-ray line flux from the 1x1 degree central region

- The total flux from in prompt gamma-ray lines of energies below 8 MeV is about 2.3 10^{-5} cm^{-2} s^{-1},
- That in the 3-7 MeV range (carbon and oxygen de-excitation lines) is of the order of 8.6 10^{-6} cm^{-2} s^{-1}.
- The flux of ^{26}Al decay line is expected at the level 3.1 10^{-5} cm^{-2} s^{-1}.

Conclusion

- **Accretion processes in GC release in average 10^{42}erg/s in the form of subrelativistic protons with energies E>100 MeV;**
- **Protons lose almost all their energy by ionization and, thus, heat plasma up to the temperature ~ 10 keV;**
- **Inverse bremsstrahlung of these protons generates hard X-ray flux in the energy range above 10 keV with the total flux 3 10^{36}erg/s;**
- **Proton penetrating into dense molecular clouds produce Kα vacancies. The flux of 6.4 keV line at Earth from Sgr B2 is expected at the level 10^{-4} ph $cm^{-2}s^{-1}$, and the hard X-ray continuum flux due to proton bremsstrahlung is about 10^{35}erg/s;**
- **These protons heat molecular gas in GC up to the temperature about 100 K.**
- **The produce intensive de-excitation gamma-ray line which, in principle can be observed from the central 1^ox1^o region.**