# 銀河系中心からの 511 keV 電子陽電子対消滅ガンマ線

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- Slides for 511 keV observations were made many years ago. For more recent reviews, see, e.g.
  - http://galacticcentre.space/wp-content/uploads/2016/06/IAU2016_tsiegert_1.pdf

# The 511 keV Annihilation Line Emission from GC

- extended spherical bulge with ~8 deg FWHM (~1.1 kpc) + weak disk component (Knodlseder et al. 2005)
- bulge / disk flux ratio = 3-9 (c.f. mass ratio 0.3-1.0, Robin+'03)
- positron production rate ~$1.5 \times 10^{43}$ $s^{-1}$

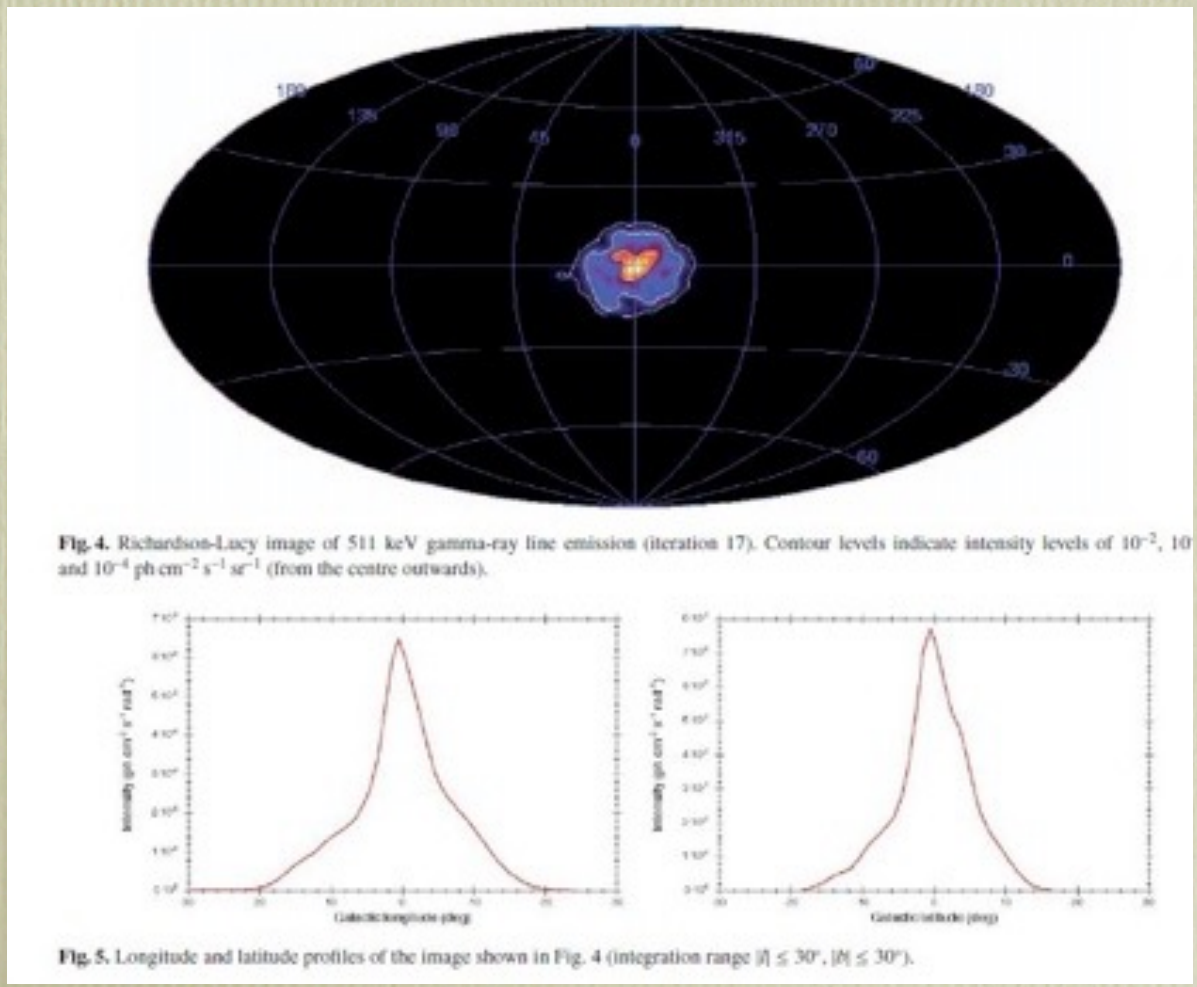
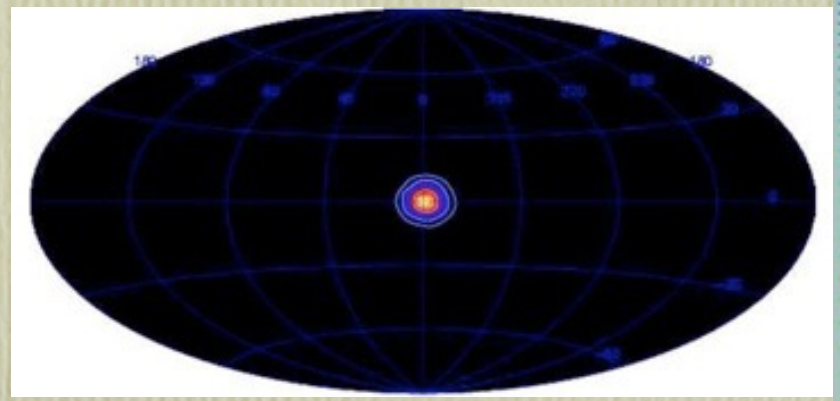


Fig. 4. Richardson-Lucy image of 511 keV gamma-ray line emission (iteration 17). Contour levels indicate intensity levels of $10^{-2}$, 10 and $10^{-4}$ ph cm$^{-2}$ s$^{-1}$ sr$^{-1}$ (from the centre outwards).

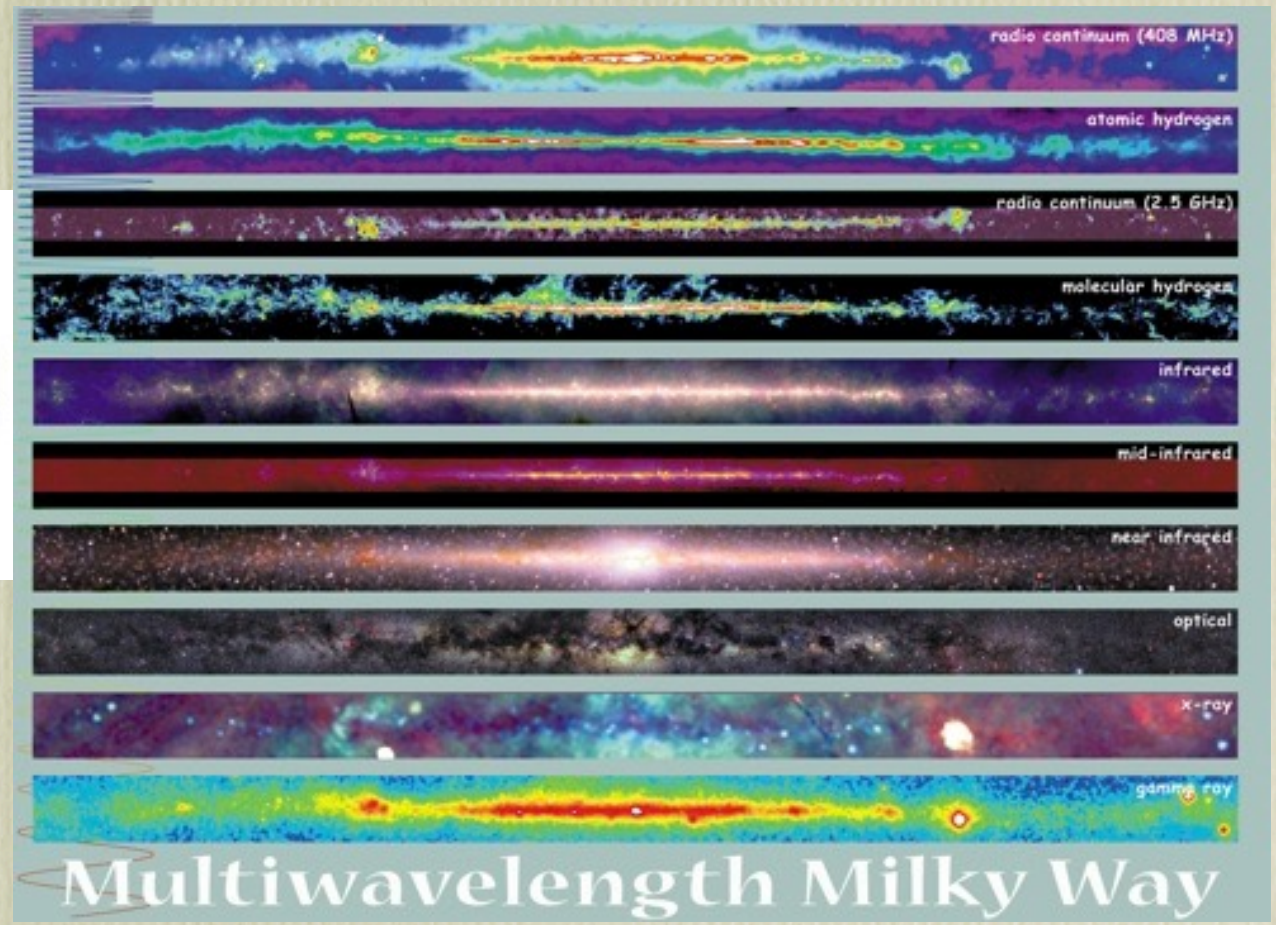
Fig. 5. Longitude and latitude profiles of the image shown in Fig. 4 (integration range $|l| \leq 30°$, $|b| \leq 30°$).

Knodlseder et al. 2005

# A Unique Morphology!

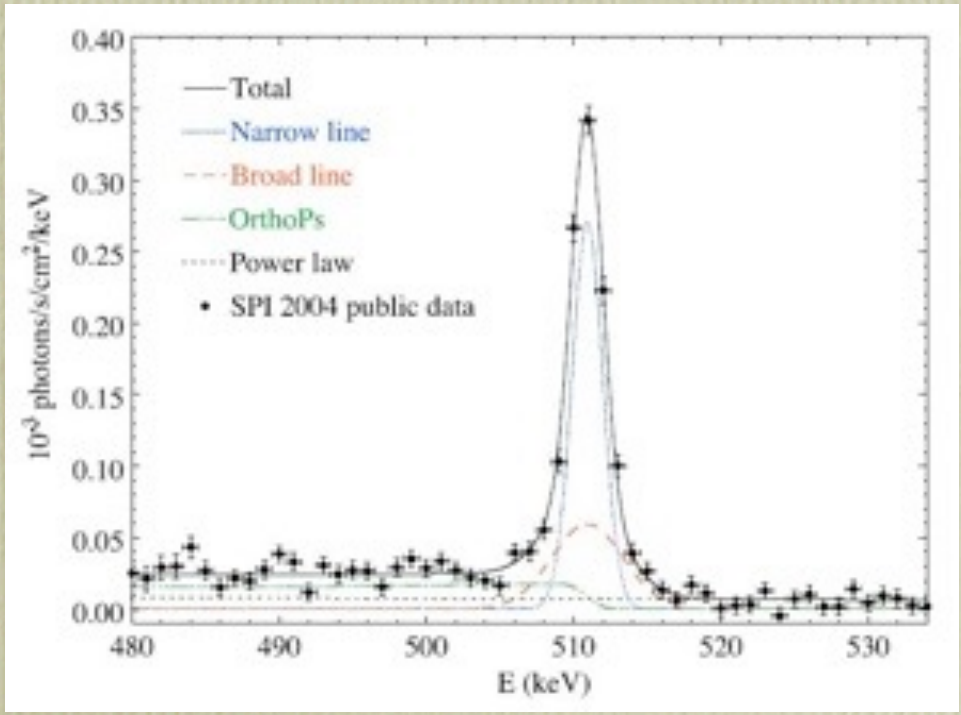


Weidenspointner+ ‘06



# The 511 keV Annihilation Line Emission from GC

- narrow line width
- positronium fraction: 0.967±0.022 (Jean et al. 2006)
  - ISM model との比較から、陽電子は ISM 中で減速、熱化され、warm medium の中で対消滅
  - 対消滅の time scale ~ $10^7$ yr
- injection positron energy <~ 3 MeV (Beacom+'05)




Jean et al. 2006

Beacom & Yuksel '05

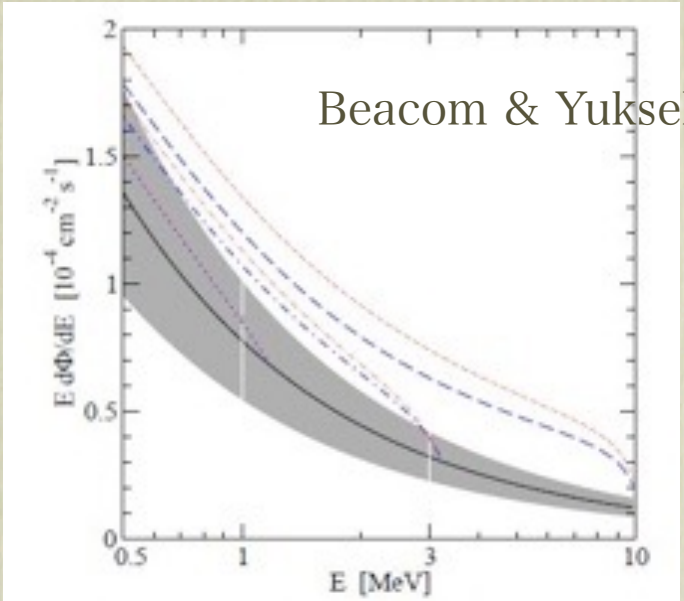



FIG. 2: The INTEGRAL and COMPTEL diffuse gamma ray flux measurements are shown with a black solid line, and their ±30% uncertainties by the gray shaded band. For positron injection energies of 1, 3, and 10 MeV (dotted, dot-dashed and dashed lines), the thick lines show how this would be increased by the inflight annihilation gamma ray flux (thin lines also include the internal bremsstrahlung flux). All results are for a 5°-diameter region at the Galactic Center. The 0.511 MeV line flux is not shown.

# Proposed Models for 511 keV Emission

- Disk component:
  - core-collapse SNe の元素合成起源、$^{26}$Al と consistent
- Bulge component:
  - type Ia SNe:
    - rate not sufficient (~1/10) (Prantzos 2006)
    - positron escape fraction likely << 100%
    - B/D ratio?
  - core-collapse SNe, GRBs, hypernovae, cosmic-rays, pulsars...
    - massive star origin inconsistent with the large B/D ratio
  - Novae
    - large B/D ~ 3-4
    - production rate insufficient
  - X-ray binaries / microquasars (Guessoum+ 06)
    - production rate uncertain
    - B/D ~1
    - broad line 511 keV emission directly from sources

# Proposed Models for 511 keV Emission

- Bulge component (contd.):
  - MeV-mass dark matter
    - B/D ratio OK, but not a natural candidate compared with SUSY particles
  - Sgr A*
    - Cheng+ 2006
      - stellar capture onto the SMBH, jet and cosmic-ray production, and pion-decay positrons
      - injection energy ~ 30 MeV
      - B/D ratio? compared with the gamma-ray background in EGRET band
    - Totani 2006:
      - standard RIAF framework + higher past activity
      - production rate consistent
      - injection energy ~ MeV
  - starburst around Galactic center (Alexis+2014)

# さらに最近の話: 特殊な超新星？

- Perets (2014, arXiv)
  - faint peculiar type Ia (“type .Ia”), prototype SN 2005E, originates from helium detonation on white dwarf
- Crocker et al. (2016, arXiv:1607)
  - sub-luminous thermonuclear SN (SN 1991bg-like)
  - helium WD + carbon-oxygen WD merger
- これらの超新星は長い delay time (>~ 5 Gyr) で起き、十分な量の陽電子を出すと主張
  - bulge 511 keV emission を説明出来る？

# Positrons from Sgr A*?

- 銀河系中心の観測
- Sgr A* への質量降着流からの positron 生成 (Totani '06)

# The RIAF Model for Sgr A*

- Application to Sgr A* (Yuan+ '03)
  - Outer boundary at Bondi radius from X-ray observation
    - quiescent X-ray emission spatially resolved by Chandra (~2"~0.03 pc)
    - Bondi accretion rate ~$10^{-6}$ Msun / yr

$$\dot{M} \propto r^{s}, \; s = 0.27$$

$$n_e \propto r^{-3/2+s}$$

  - Non-conserving mass accretion flow
    - Faraday rotation 観測からの制限を満たす上で必要

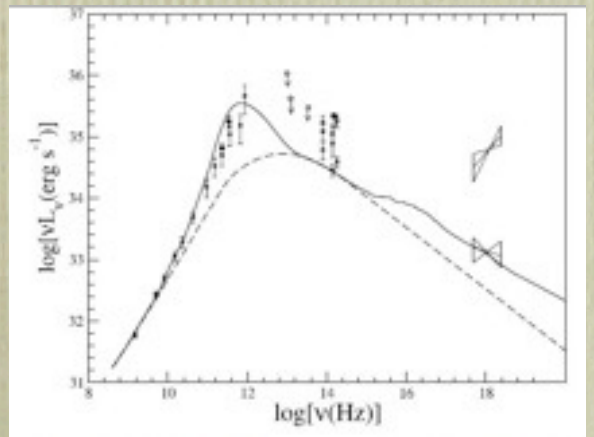



FIG. 1.—RIAF model for the quiescent state of Sgr A*. The IR data with error bars are from Ghez et al. (2004) and Genzel et al. (2003), the radio data with error bars from Falcke et al. (1998, *open circles*) and Zhao et al. (2003, *filled circles*), the IR data with upper limits from Serabyn et al. (1997, *open circles*) and Hornstein et al. (2002, *filled circles*), and the two "bow ties" in the X-ray for the quiescent (*lower*) and flaring (*higher*) states from Baganoff et al. (2003, 2001). The dashed line shows the synchrotron emission by power-law electrons with $p = 3$. The solid line shows the total quiescent emission, including that from thermal electrons. The slight difference in the value of $p$

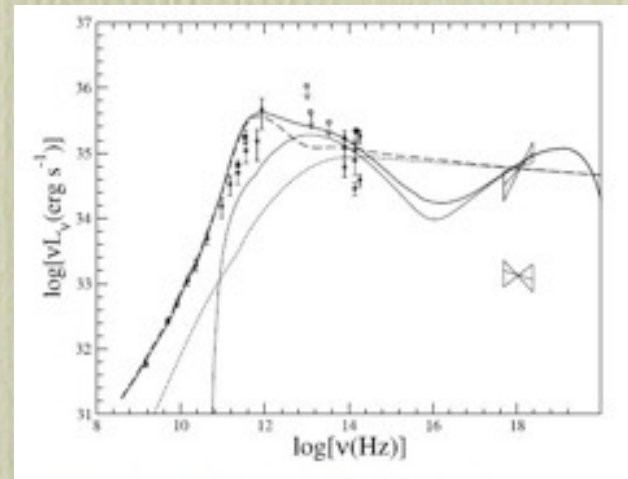



FIG. 3.—Pure synchrotron models for the IR and X-ray flares in Sgr A*. The two dashed lines are models in which the electrons are assumed to have $p = 2.1$. The solid lines are for the broken power-law model (eq. [1]), with $p_1 = 3$, $p_2 = 1$, $\eta = 7\%$, $\gamma_{\rm max} \sim 10^6$, and $\eta_{\rm BZC} = 1$. In each case, the thin lines correspond to the emission from only the power-law electrons, and the thick lines to the total emission, including the thermal electrons.

Yuan+ '04

# RIAF model は mass outflow を予言する

- non-conserving mass accretion rate ∝ outflow
  - ADIOS: Blandford & Begelman '99

$$\dot{M} \propto r^{s},\ s = 0.27$$
$$n_e \propto r^{-3/2+s}$$

Outflow from region around $r \sim r_s$

$$\text{mass outflow rate} : \sim \frac{d\dot{M}}{dr} r \sim 1.6 \times 10^{-8} M_{sun} / yr$$

$$\text{kinetic luminosity} : \sim \upsilon_{esc}^{2} \frac{d\dot{M}}{dr} r \sim 3 \times 10^{38} \text{erg/s}$$

# positron production from Sgr A*

- 降着流の中で、
  - e-e- → e-e-e-e+
  - e-$\gamma$ → e-e-e+
  - $\gamma$ $\gamma$ → e-e+
  - などのプロセスを考慮して、outflow に乗って放出される positron の量を計算することは straightforward

- ただし、現在の降着率では低すぎる（$10^{3\text{-}4}$ 倍高い降着率が必要）

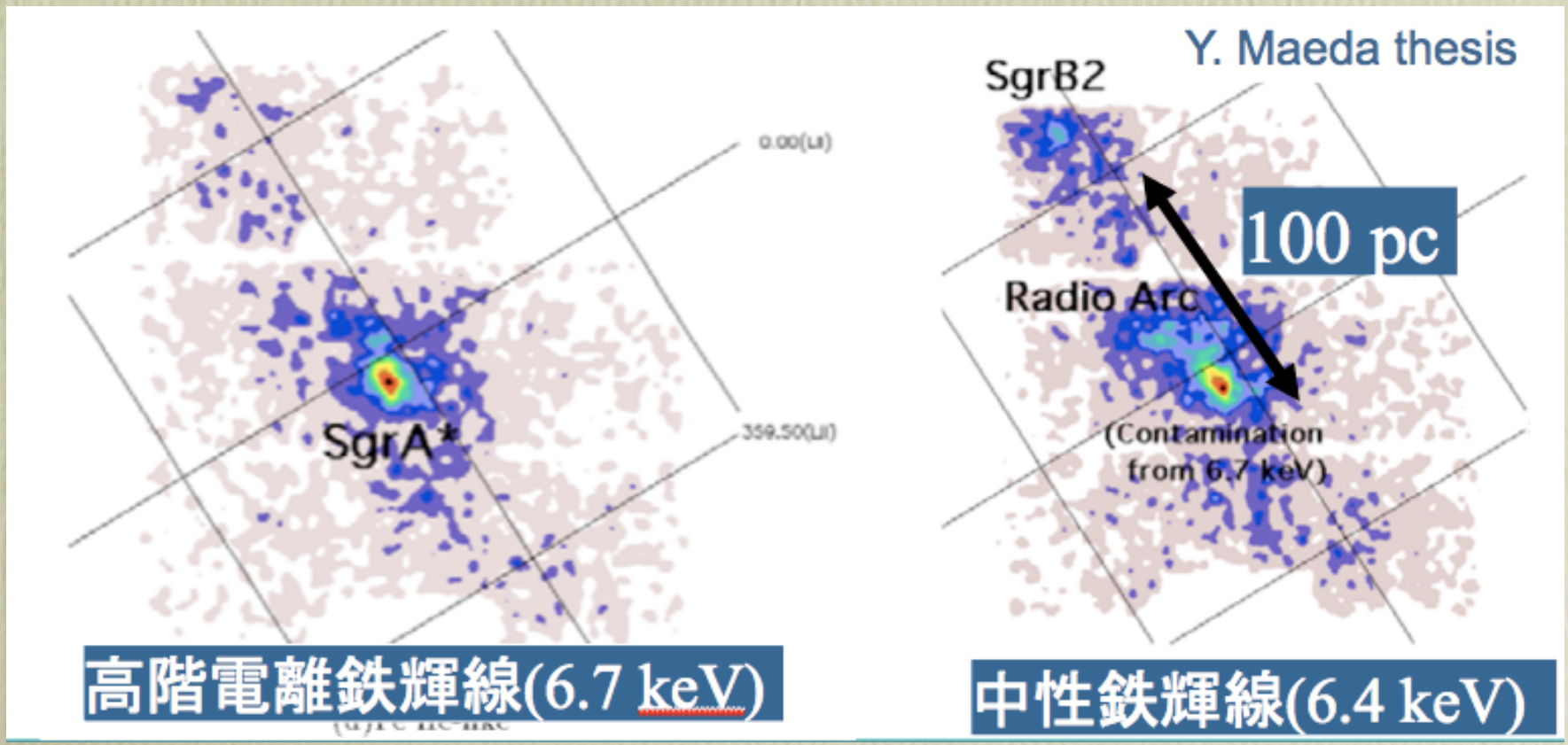
- 過去の活動性！？

# Evidence for Past Higher Activity of the Galactic Center

- Evidence for much brighter X-ray luminosity until ~300 yrs ago from Sgr A*
- Evidence for a large scale outflow from GC

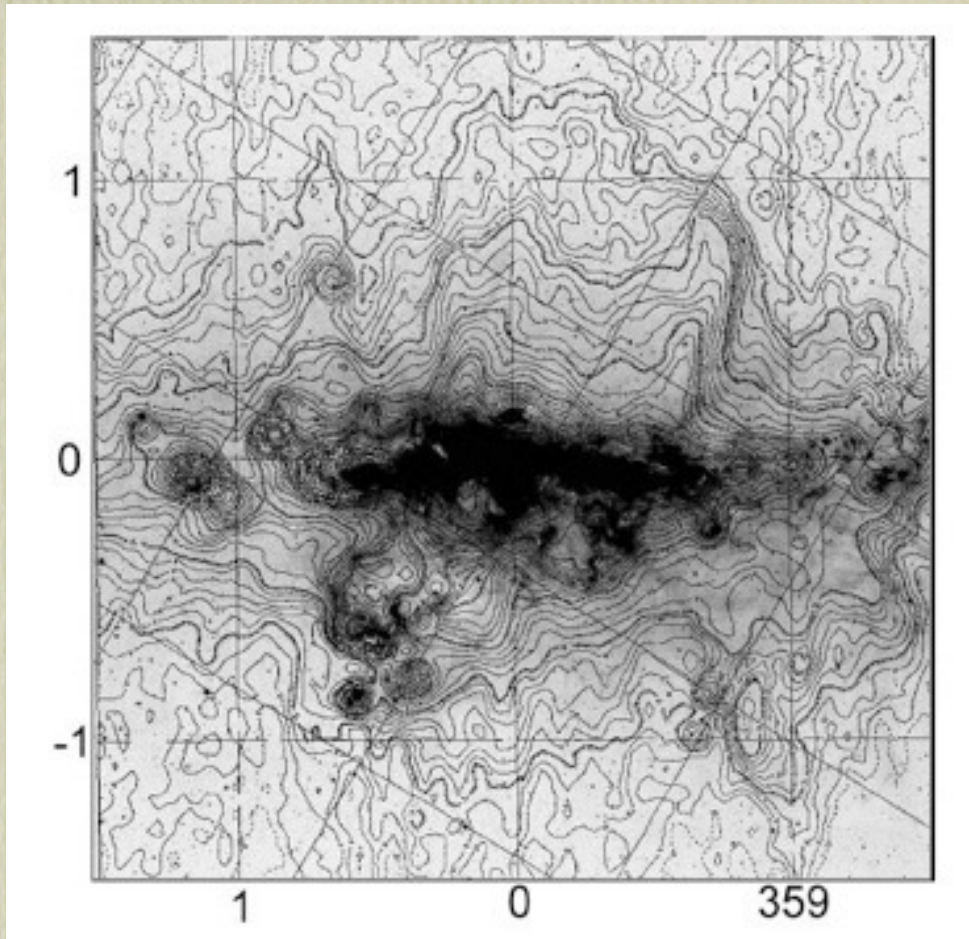
# Evidence for Brighter X-ray Luminosity of Sgr A*

- 巨大分子雲 Sgr B からの中性鉄輝線は、銀河中心からの放射の反射成分と考えられる
- 300 yr ほど前までは、Sgr A* のX線光度が ~3x$10^{39}$ erg/s で輝いていたと考えると説明できる (Koyama+'96; Murakami+'00)
  - 現在のX線光度の $10^{5\text{-}6}$ 倍！



# Evidence for a Large Scale Outflow from GC

- estimated massive outflow energy: $10^{55}$ erg in ~$10^{6}$ yrs on the scale of the Galactic center lobe (GCL)
  - ~100 km/s
  - a few degree ~ 300 pc
  - Bland-Hawthorn & Cohen '04
- Other independent evidences:
  - Expanding molecular ring (Kaifu et al. '72; Scoville '72)
  - North Polar Spur (Sofue '00; Brand-Hawthorn+'04)
- Kinetic luminosity ~ $10^{41\text{-}42}$ erg/s




Bland-Hawthorn & Cohen '03
Image: MSX 8.3 um (dust)
Contour: 3 cm (thermal)

# Explaining Observational Evidence for the Higher Activity by the RIAF Picture

- RIAF では、一般に

$$L_X \propto \dot{M}^2$$

$$L_{kin} \propto \dot{M}$$

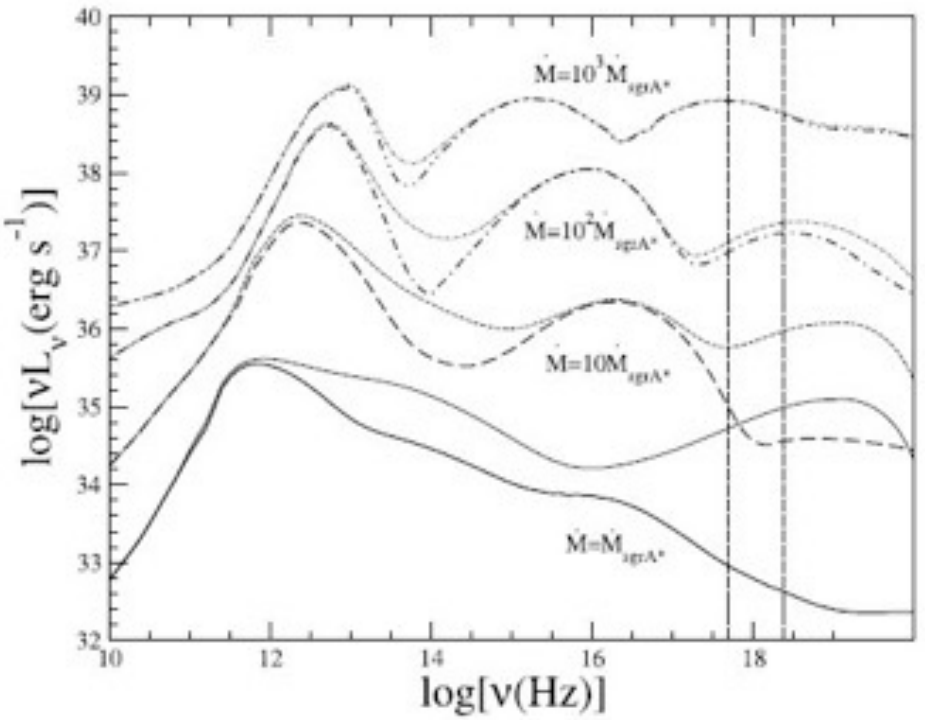



FIG. 5.—Quiescent (*thick lines*) and flaring (*thin lines*) spectra for different accretion rates. The solid lines correspond to the broken power-law synchrotron model of Sgr A* shown in Fig. 3. The dashed, dot-dashed, and double-dot–dashed lines are for systems with accretion rates of 10, 100, and 1000 times the rate in Sgr A*, respectively. For more luminous systems (higher $\dot{M}$), the SSC emission from thermal electrons increases substantially. As a result, the emission from flares would be much more difficult to detect.

Yuan et al. 2004

# Explaining Observational Evidence for the Higher Activity by the RIAF Picture

- X線反射星雲から示唆される過去の大光度は $L_X$~$3\times10^{39}$ erg/s
- Sgr A* の RIAF model で、これを説明するには

$$\text{boost factor } f_B \equiv \dot{M}_{past} / \dot{M}_{now}$$

として、$f_B \sim 10^3 - 10^4$

(このとき、$L_X \sim 10^{-5} L_{Edd}$, ちなみに現在は$L_X \sim 10^{-10} L_{Edd}$)

- このときに期待される outflow kinetic luminosity は

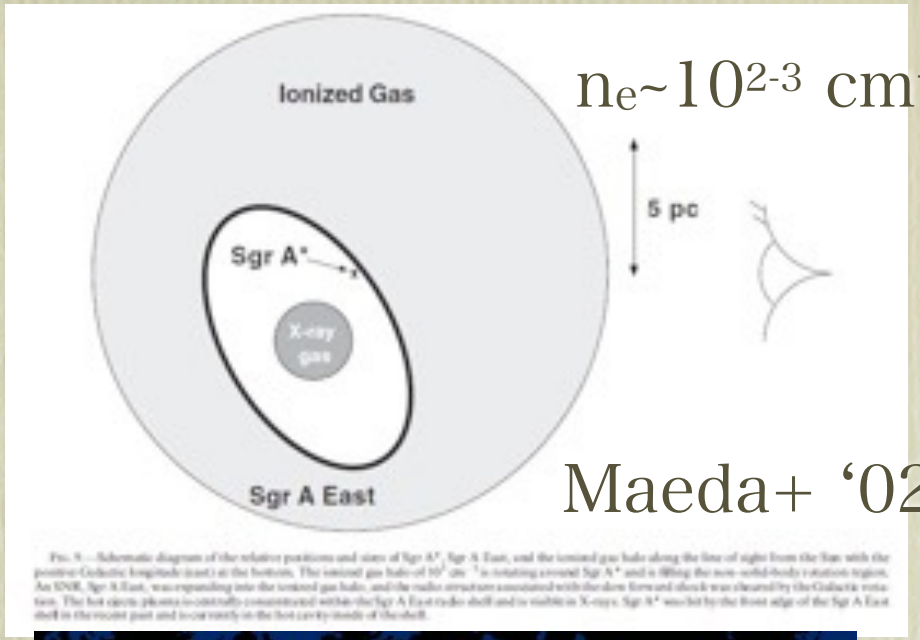
$$L_{wind} \sim 9.5\times10^{41} f_{3.5} \text{ erg/s}$$

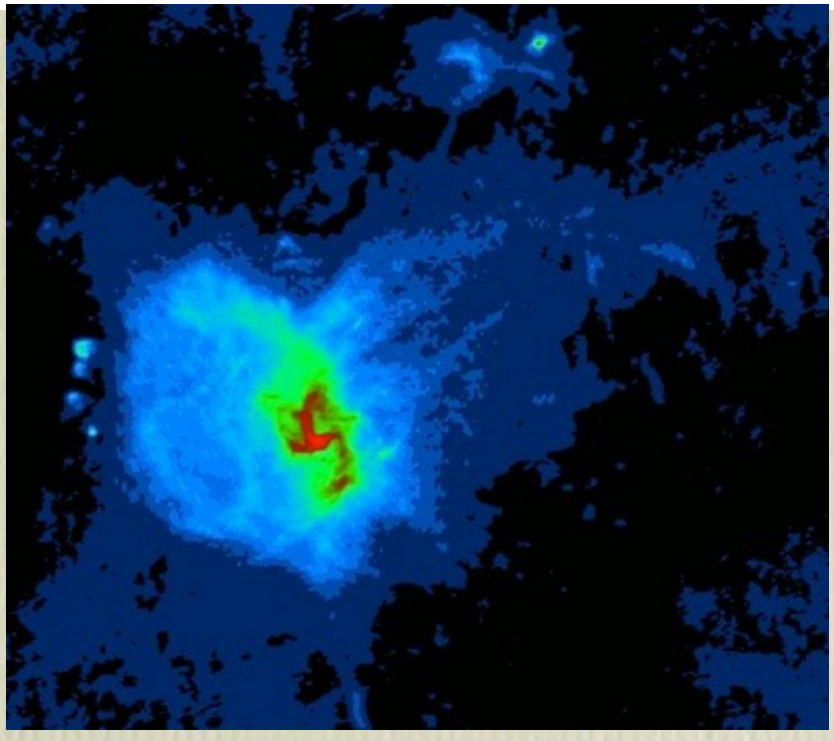
$$(f_{3.5} \equiv f_B / 10^{3.5})$$

- GCL, EMR, NPSなどから示唆される outflow kinetic luminosity ~$3\times10^{41}$ erg/s
- ほぼ同じ boost factor で、X線光度も outflow kinetic luminosity も説明できる

# Why Sgr A* Currently So Dim?

- 現在の低降着率は Sgr A East との相互作用のため
  - Sgr A East のシェル運動量はそれまでの降着流を破壊するに十分
- 現在より$10^{3\text{-}4}$倍高い降着率は、近傍の通常銀河では普通
  - むしろ現在の Sgr A* の降着率は異常に低い
- たまたま現在のように低い時期にあたる確率？
  - 銀河系中心付近の星形成率から類推すると、約１％程度



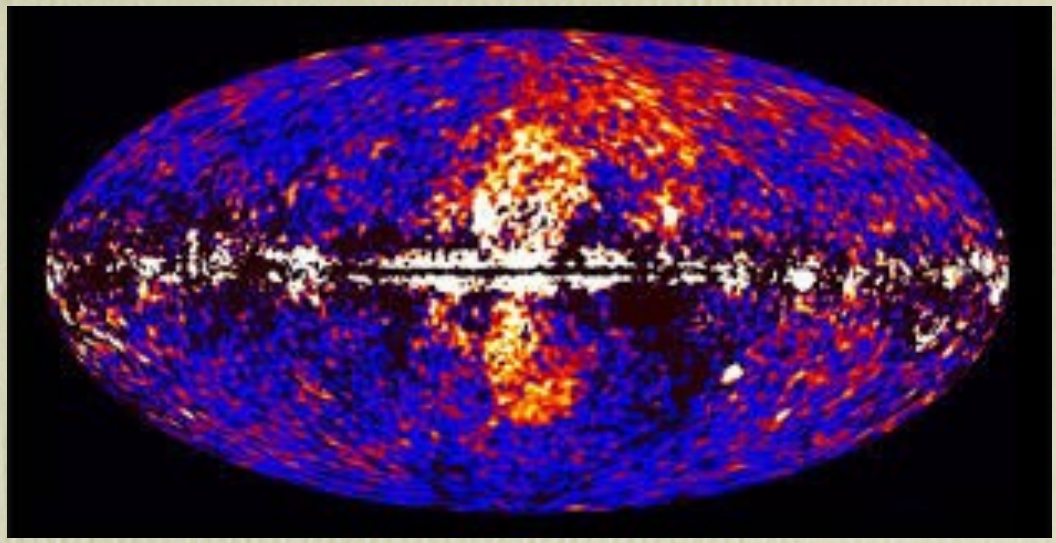



# Implications for 511 keV Emission

- positron production rate by Sgr A* accretion flow ～ required from 511 keV observations (~$10^{43}$ /s) when $f_B$ ~ $10^{3\text{-}4}$
  - $f_B$ ~ $10^{3\text{-}4}$ is consistent with observational evidence of GC past activity
- propagation:
  - 観測された広がりは、~$10^7$yr 程度の時間での拡散のスケールと無矛盾
- Sgr A* の過去の活動性は、511 keV 放射の high bulge-disk ratio の一つの無理の無い説明を与える

# そしてフェルミバブル

- Fermi bubble で議論されている時間、エネルギースケールは、Totani 2006で（Fermi bubble 発見前に）議論した銀河系中心の過去の活動性から推測していたものとよく合っている



# Concluding Remarks

- 銀河系中心からの 511 keV は50σ以上で受かっている
  - 起源を探るには、角分解能をあげたい
  - ただし、陽電子はバルジ程度の大きさに拡散してから対消滅
    - ソースの情報はかなり消えてしまう？
- 他の銀河？
  - 銀河中心核起源なら、同じ程度の銀河でも、最近の降着率によって大きく変わる
  - バルジの low mass star 起源なら、星質量にスケールするはず
  - M31 の距離 ~ 100 × 銀河系中心
    - 厳しそう…