

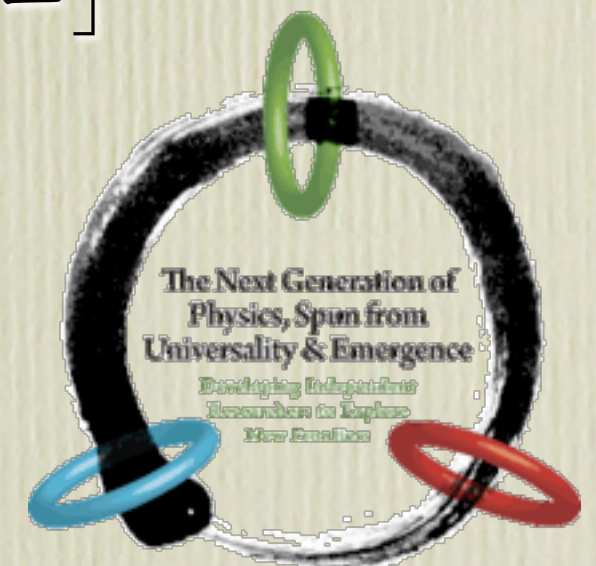
# 天文学とダークマター

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総研大短期スクール「銀河系とダークマター」

平成21年10月1日 軽井沢





# Contents

- 宇宙ガンマ線背景放射とダークマター
- 銀河系中心からの 511 keV 電子陽電子ガンマ線について
- MACHO 再考
  - 楕円銀河のサイズ進化の謎

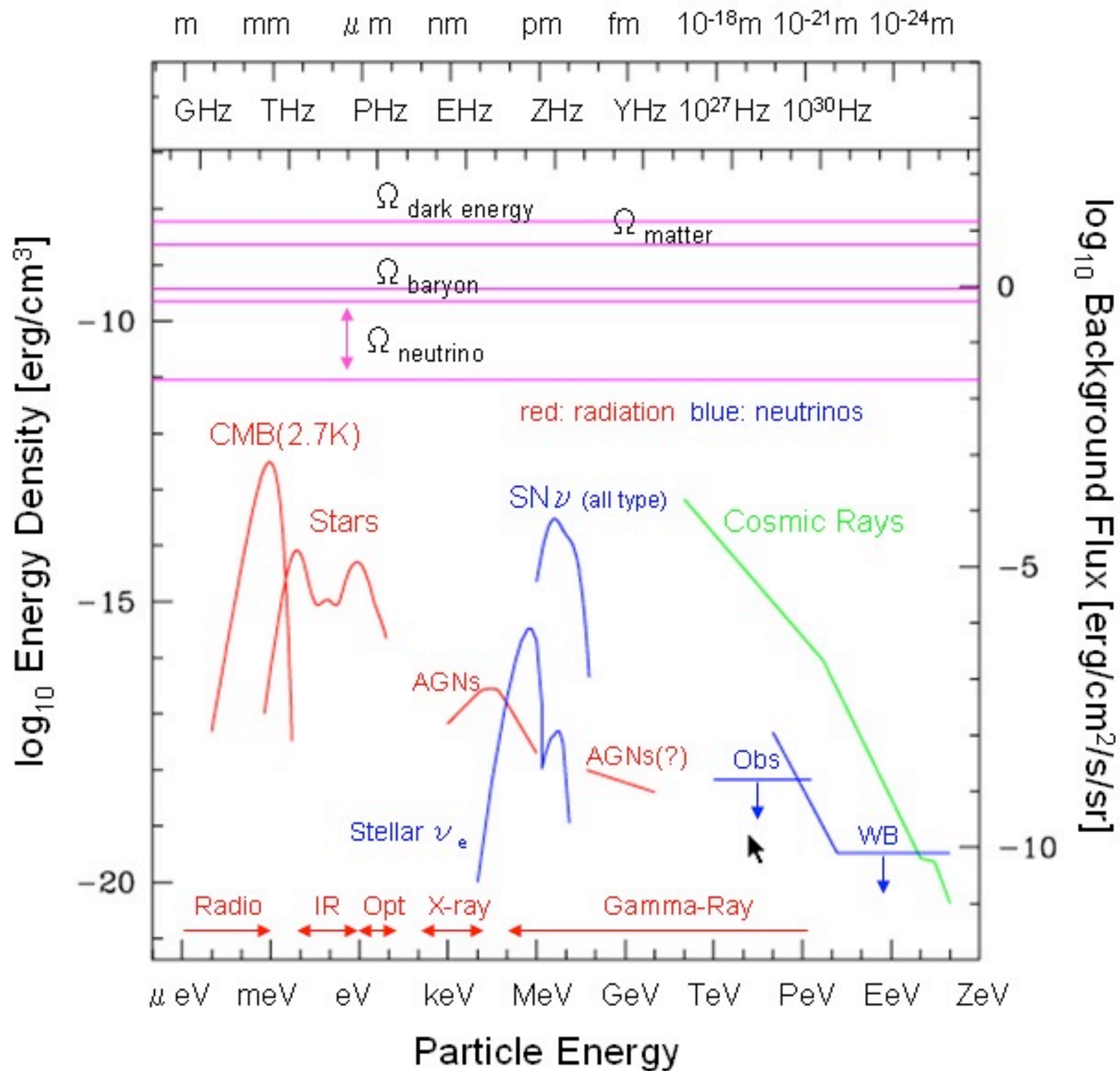


# 宇宙ガンマ線背景放射とダークマター





# The Cosmic Background Radiation





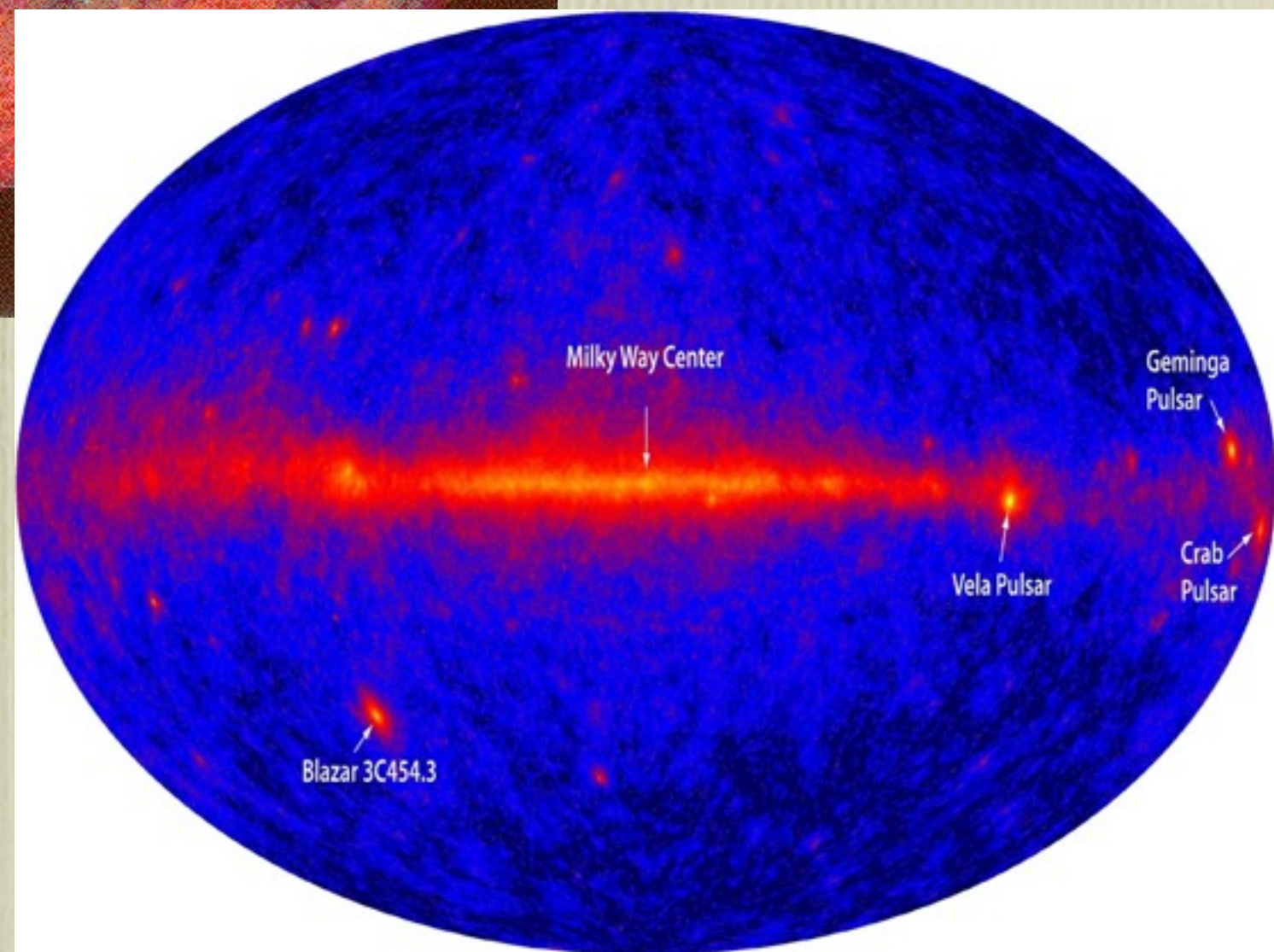
# X-ray and Gamma-Ray Sky

ROSAT PSPC  
MPE

All-Sky Survey

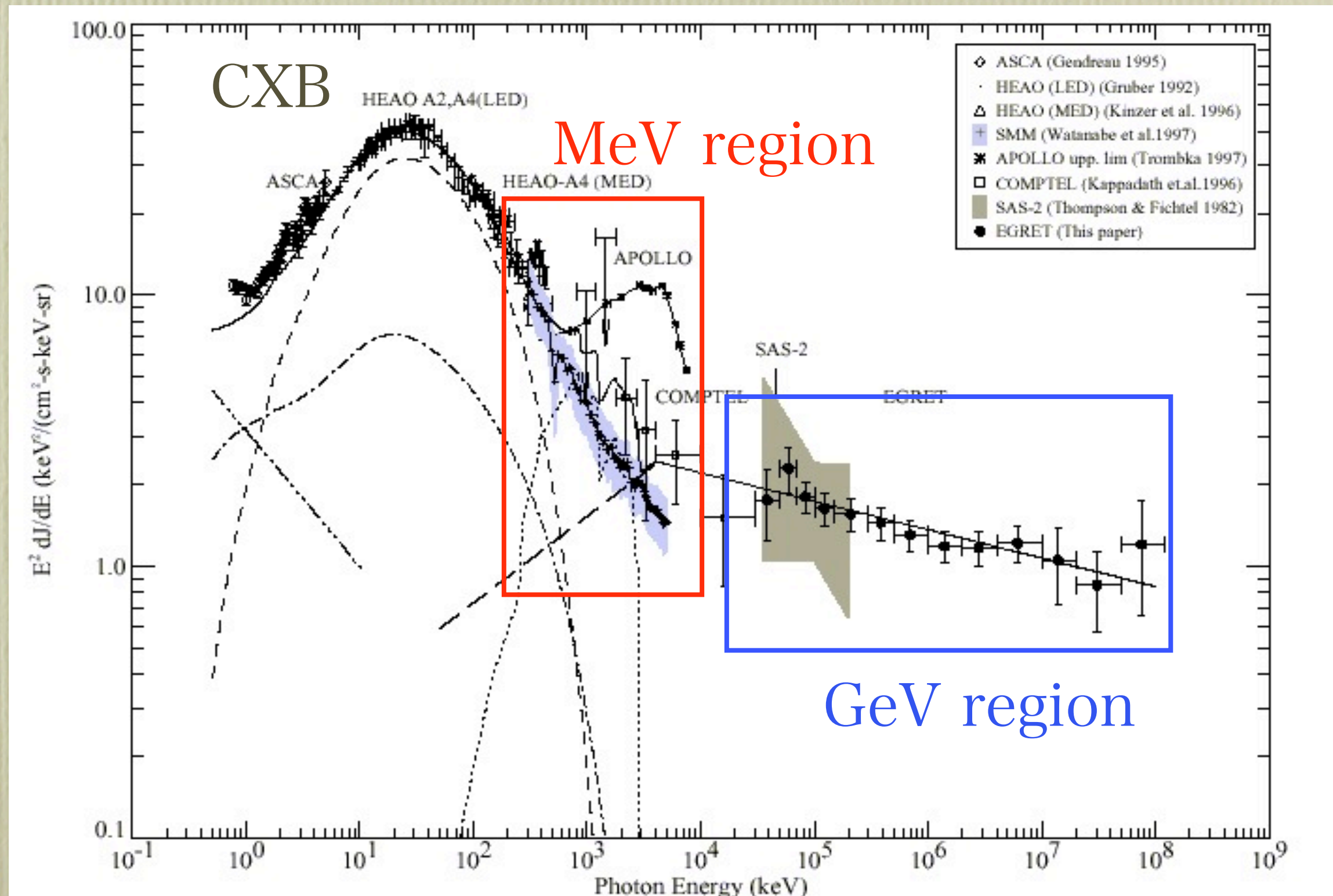
Multispectral

1,1,94  
point sources removed





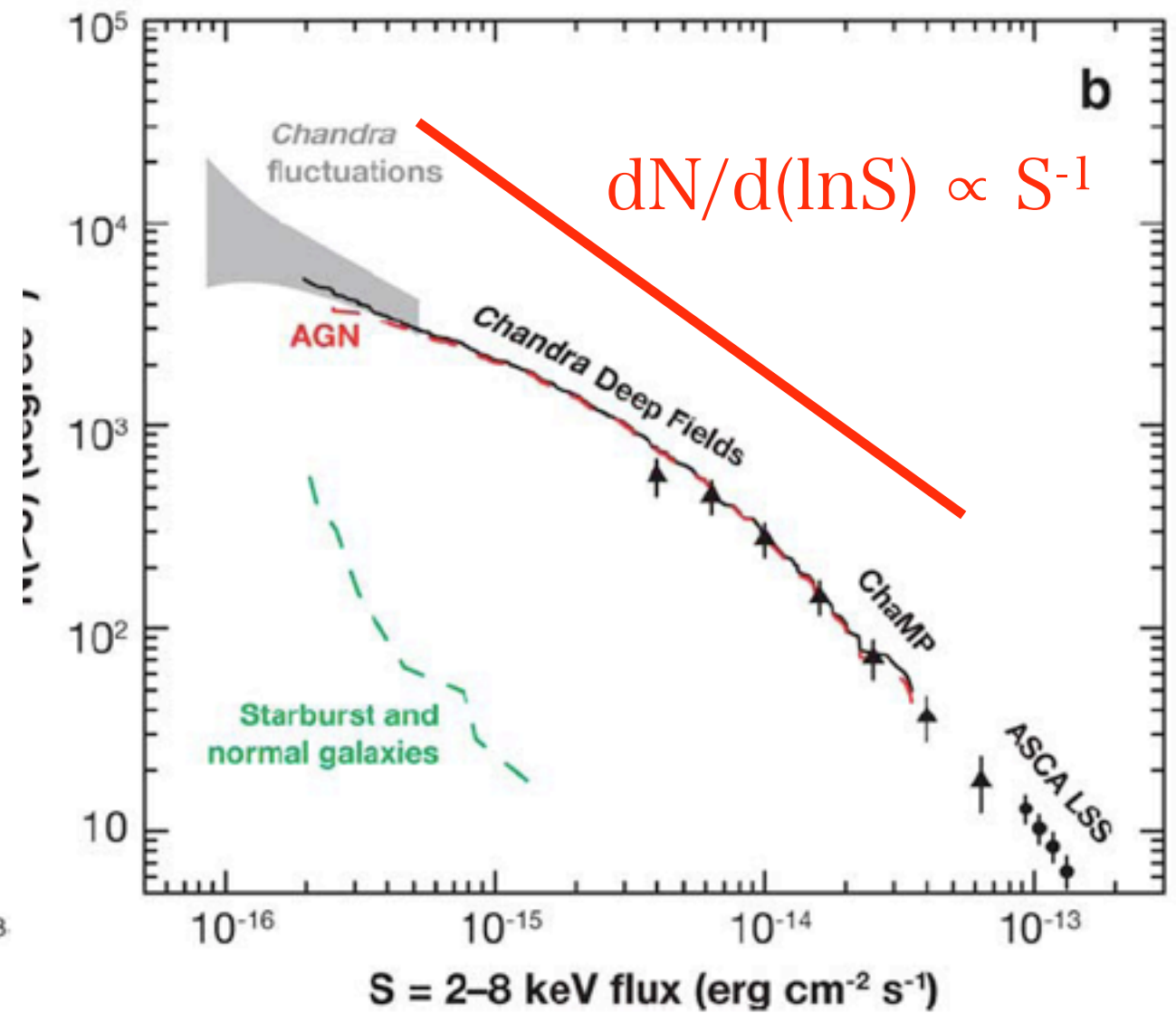
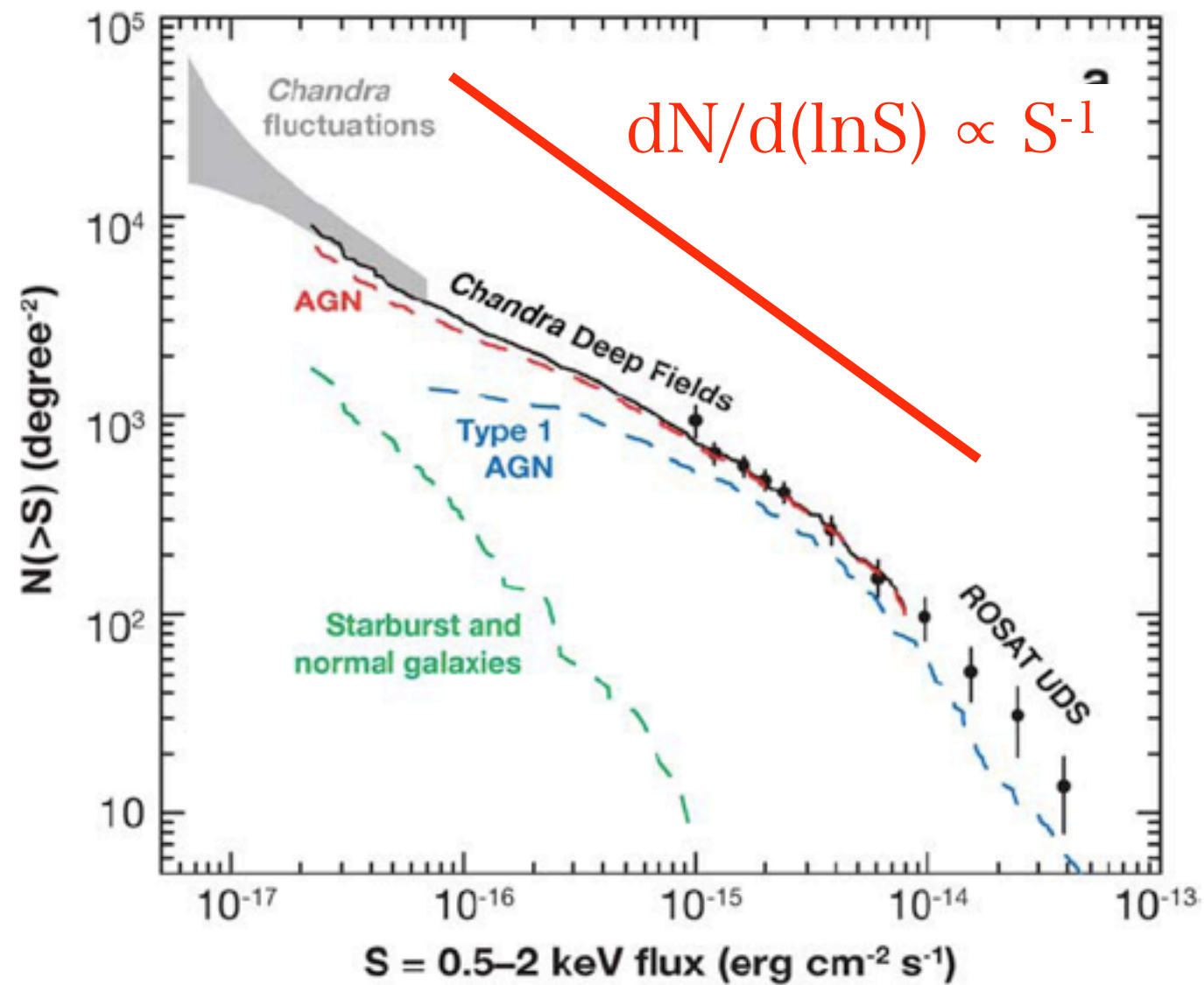
# Cosmic X-ray & gamma-ray background (CXB, CGB)



Sreekumar et al. 1998



# Source Counts in Deep X-ray Surveys





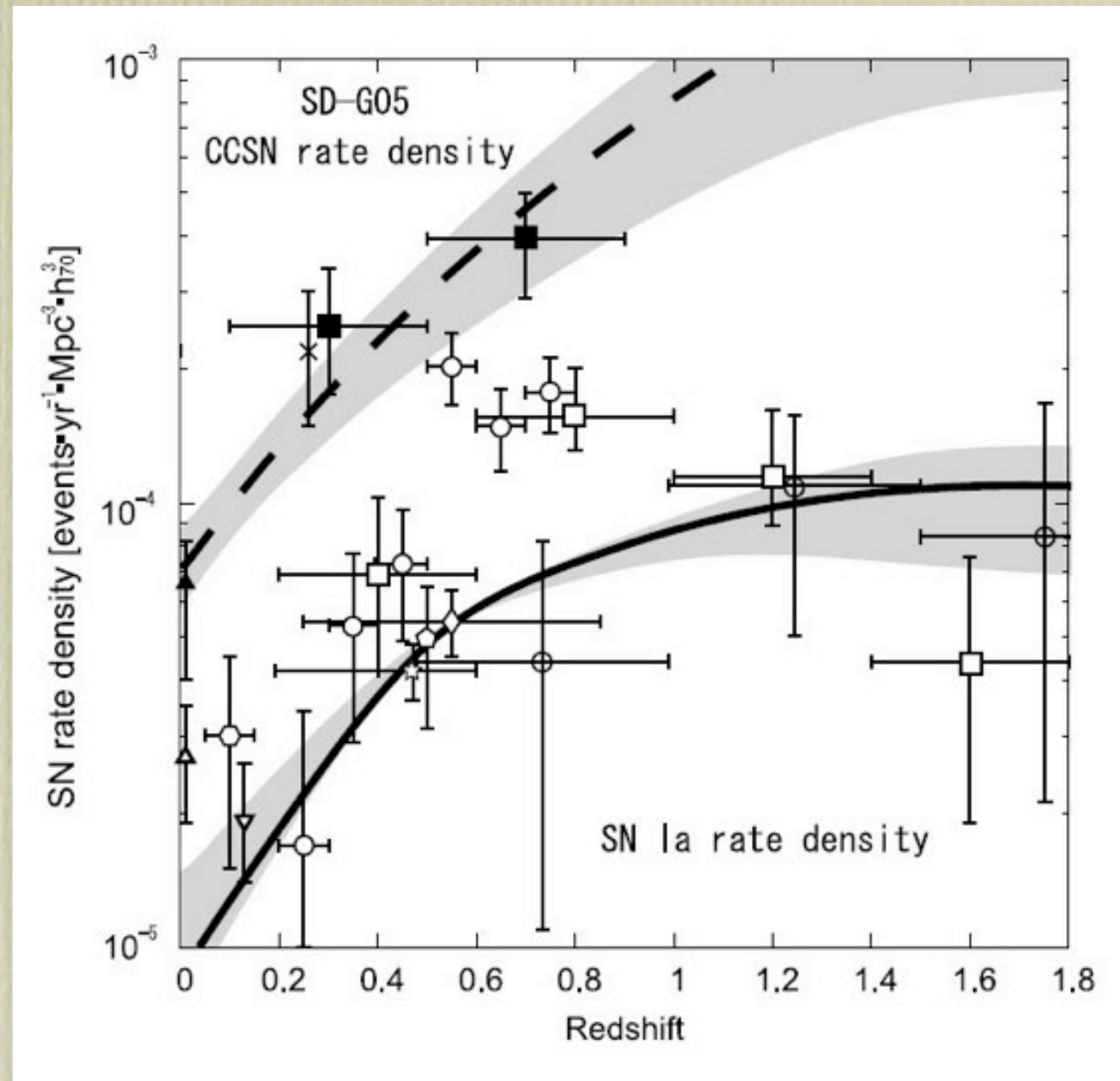
# Origin of MeV Background

- Cosmic X-ray background (CXB)
  - can be explained by integration of normal X-ray AGNs
  - has mostly been resolved into discrete sources
- MeV background
  - AGN? (“conventional” AGN models for CXB cannot explain)
  - SN Ia? (rate not sufficient)
    - Clayton & Ward ‘75; Zdziarski ‘96; Watanabe+’99
  - MeV-mass dark matter annihilation!?
    - Ahn+Komatsu ‘05a; Ramera+’06



# Cosmic SN Rate Evolution

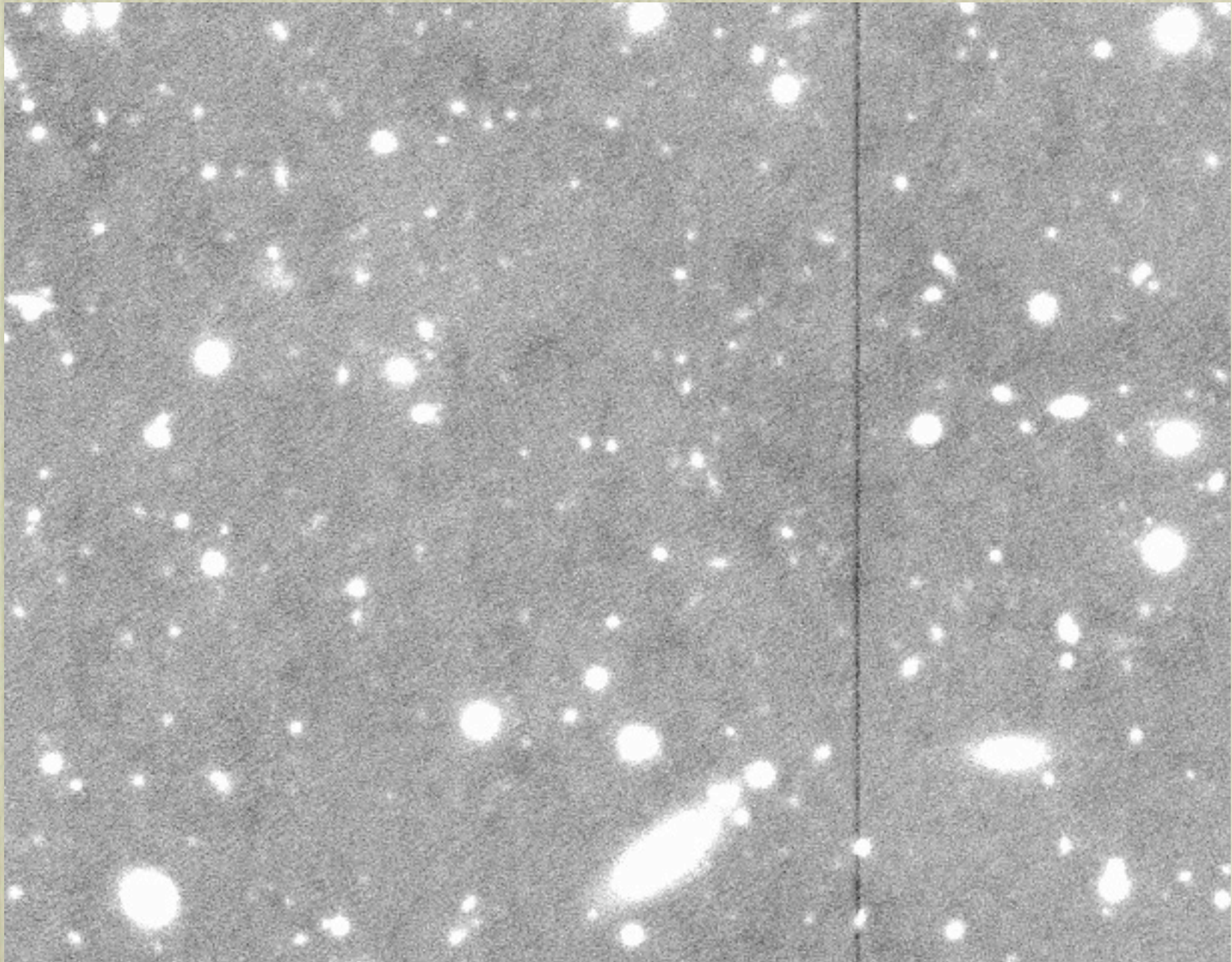
- SN Ia rate evolution to  $z \sim 1$  now well known
- ~10 times short to explain MeV background from SNe Ia (Ahn+ '05; Strigari+ '05)



Oda+'08

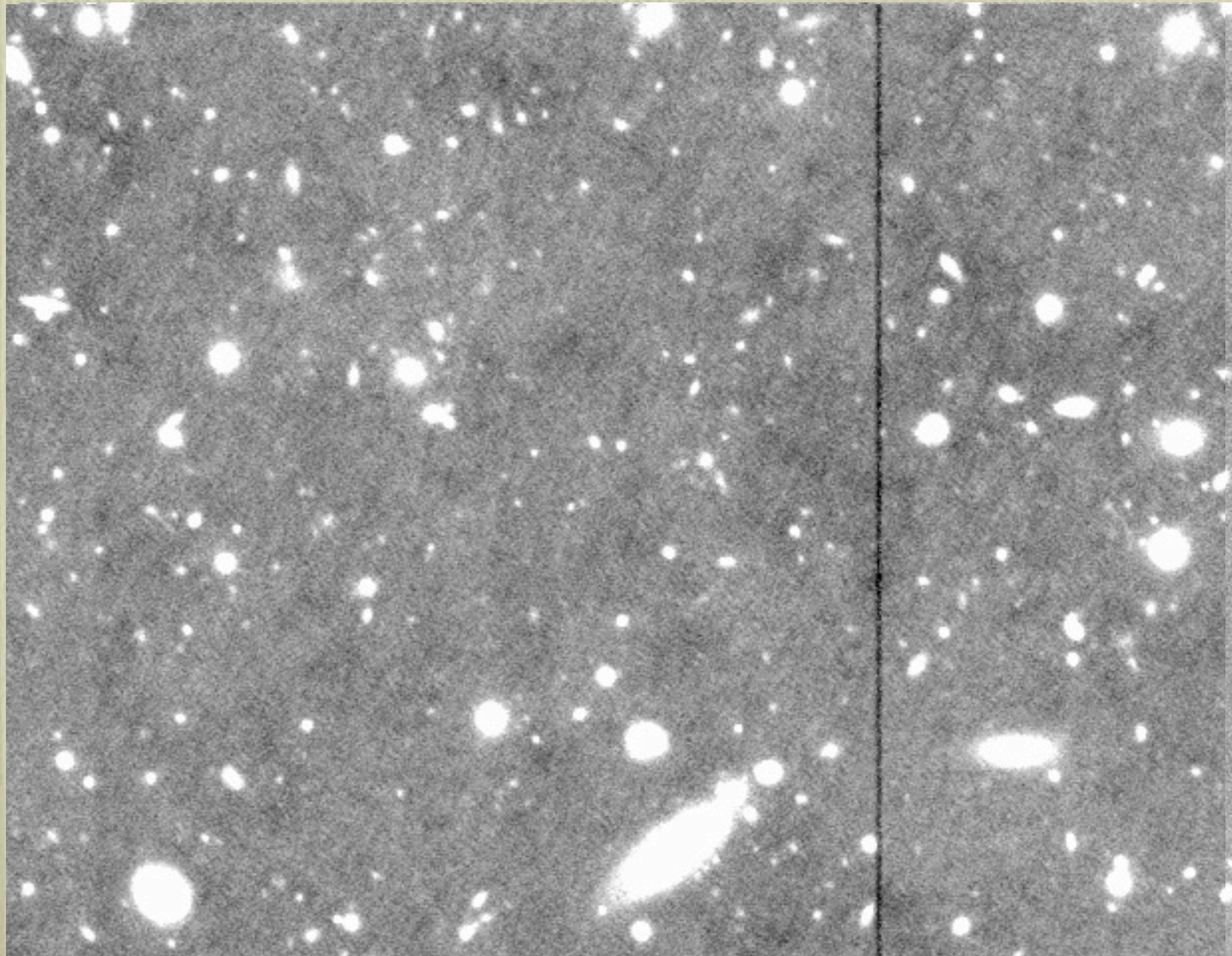


# High-z Supernova Searches



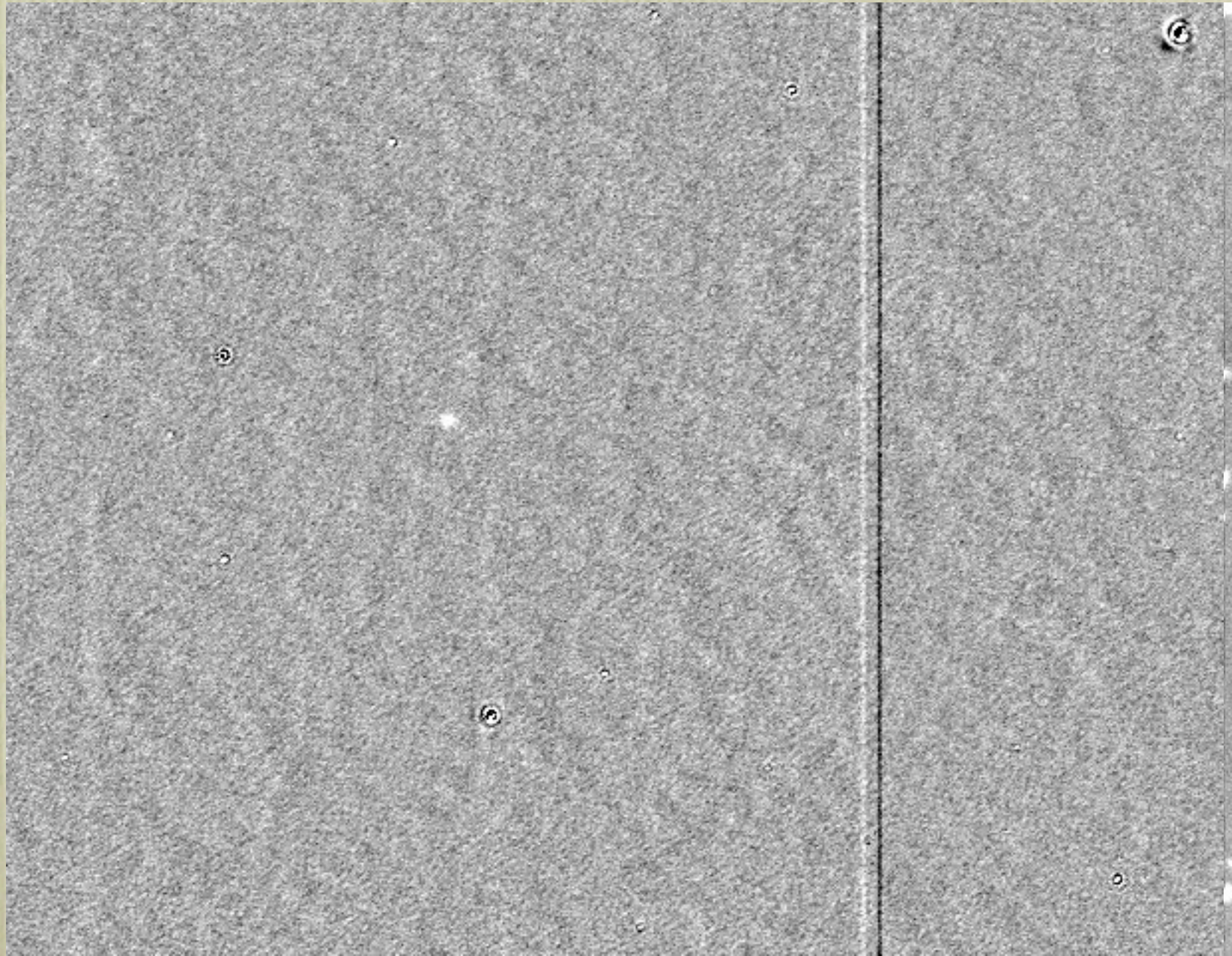


# High-z Supernova Searches





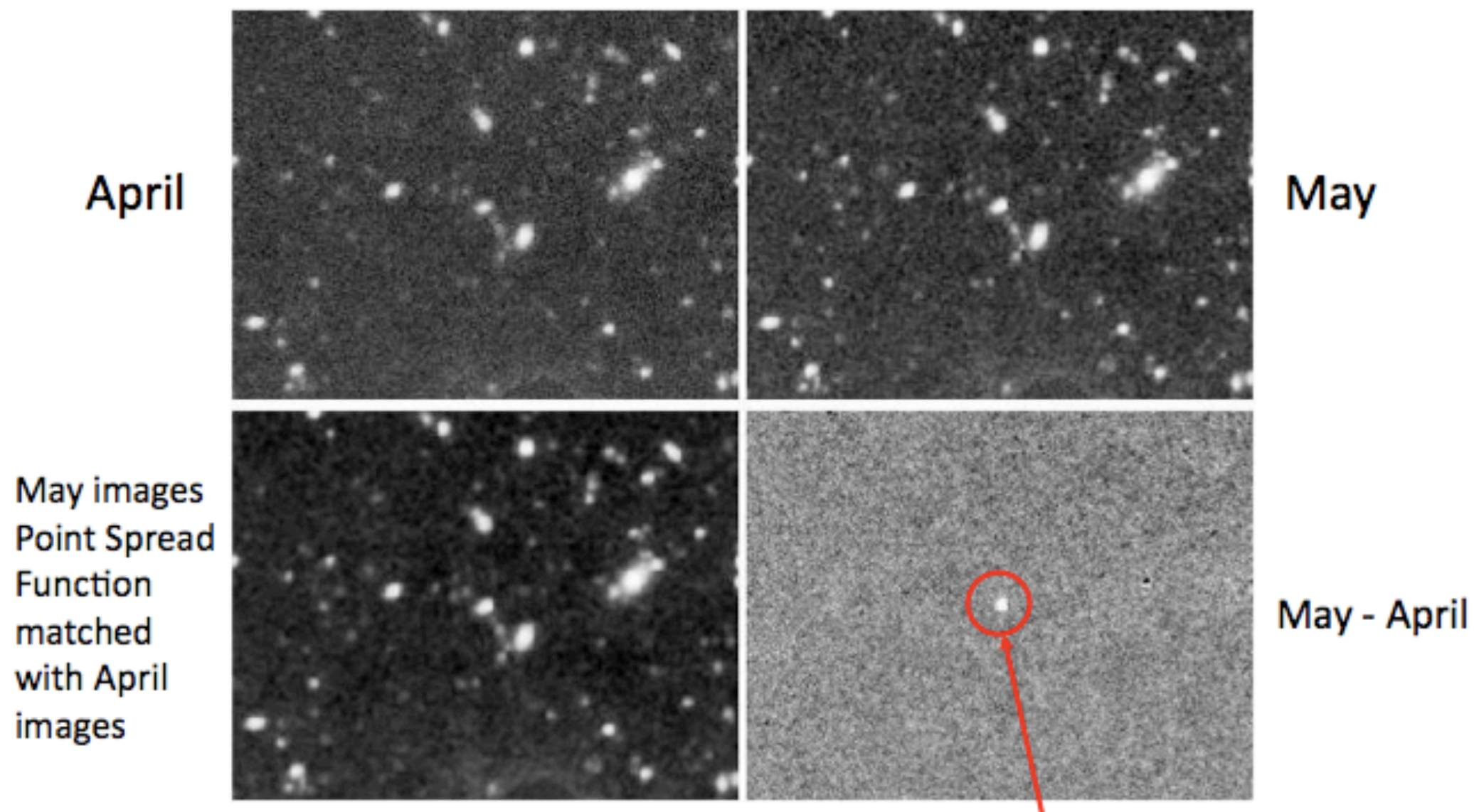
# High- $z$ Supernova Searches





# High-z Supernova Searches

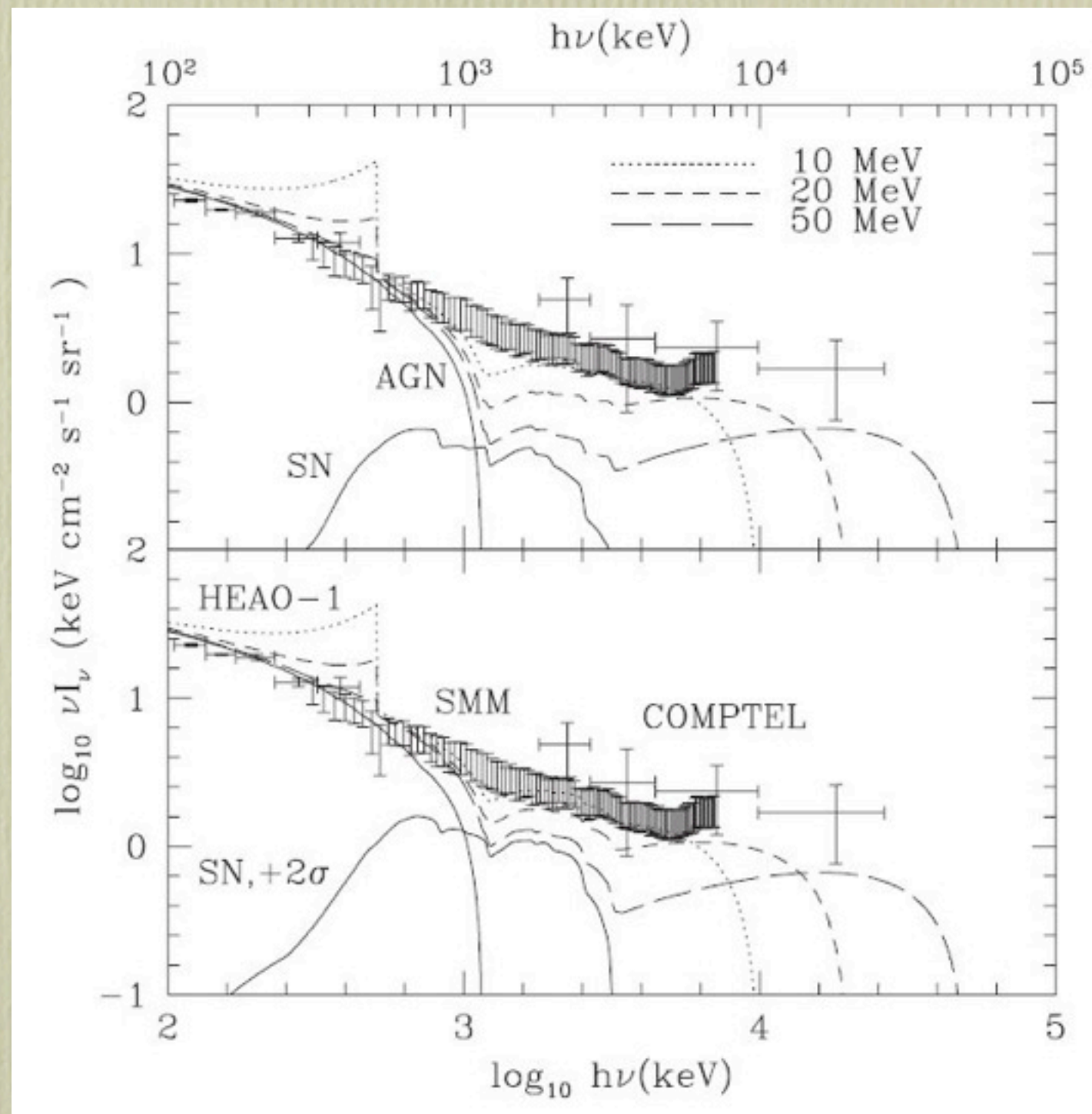
## Image Analysis (Subtraction)



(Ref. Alard, C. and Lupton, R. H. 1998)



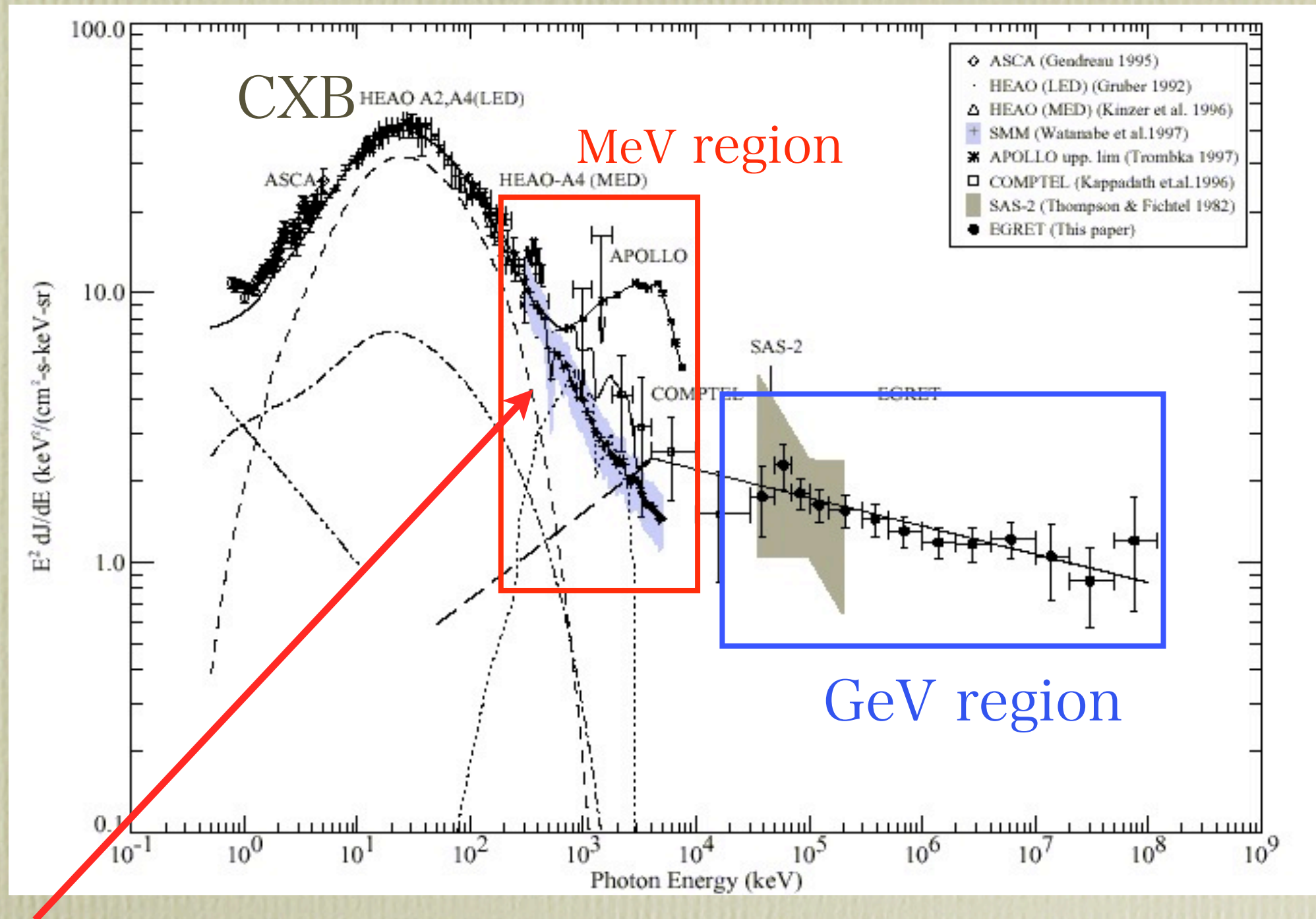
# MeV Dark Matter?



● Ahn+Komatsu '05



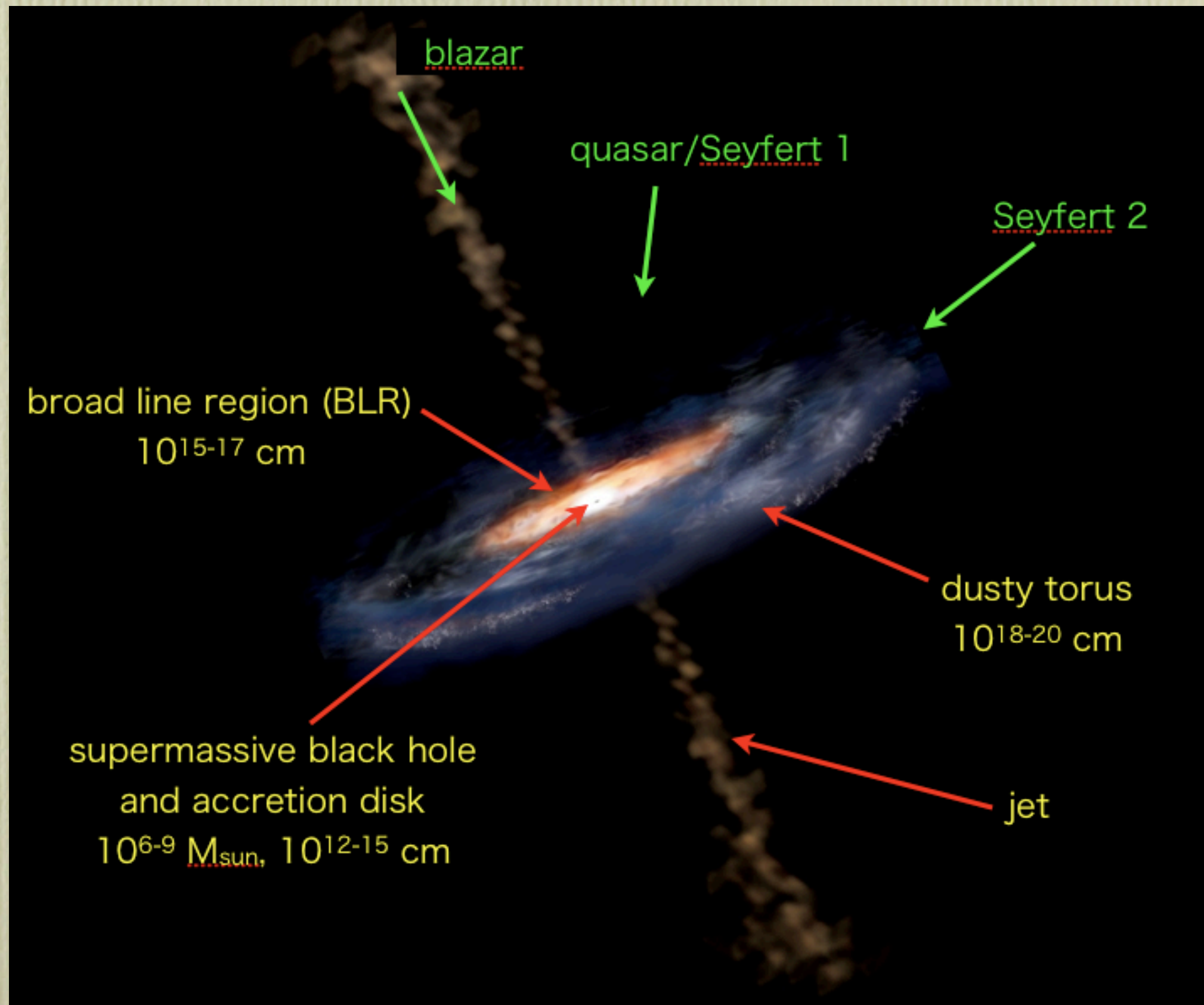
# Why not AGNs!?



- conventional AGN X-ray model predicts “exponential cut-off”
- However, MeV component “smoothly” connects to CXB!



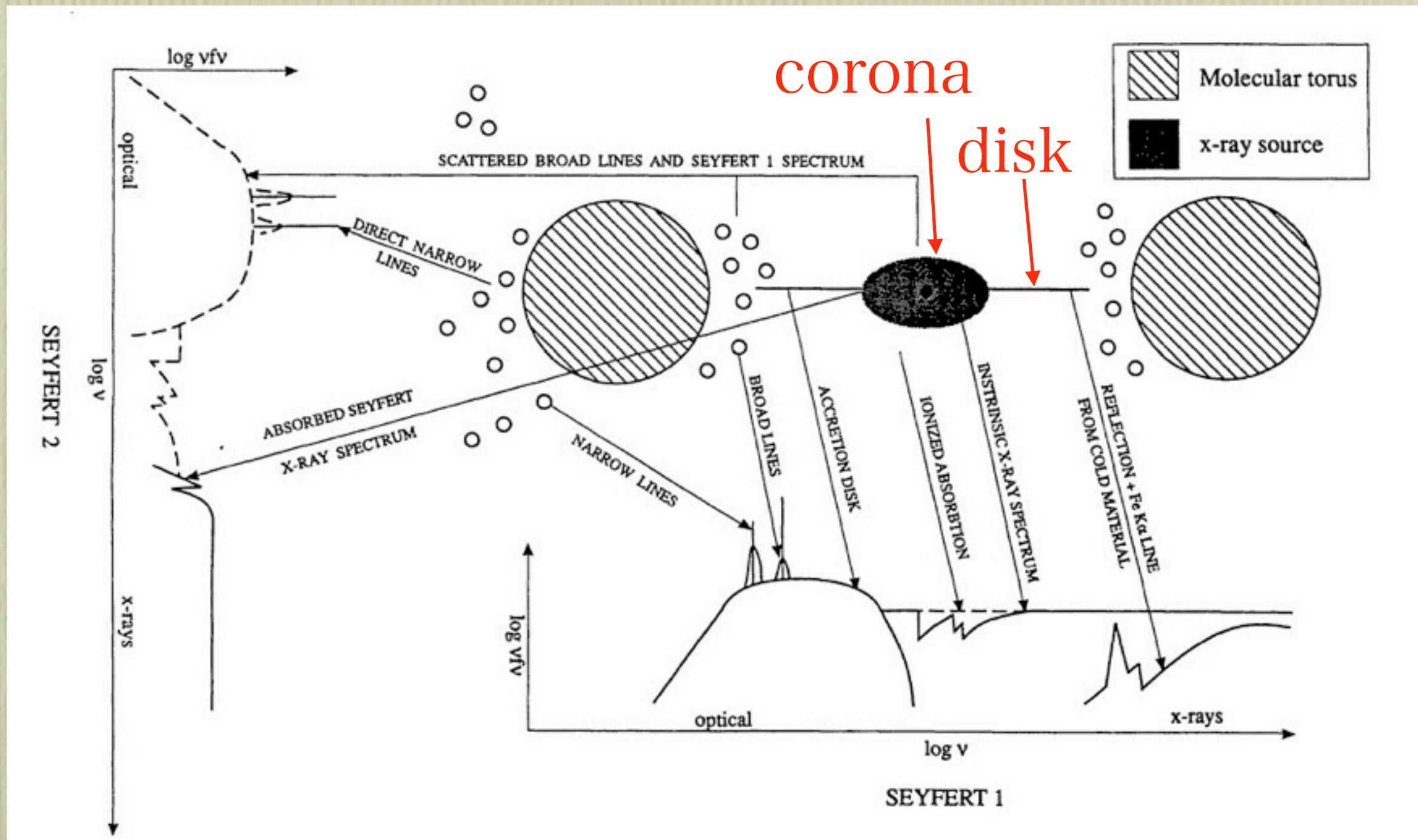
# Active Galactic Nuclei





# The Picture of AGN X-ray Spectra

☀ picture of normal X-ray AGNs (e.g., Seyferts)

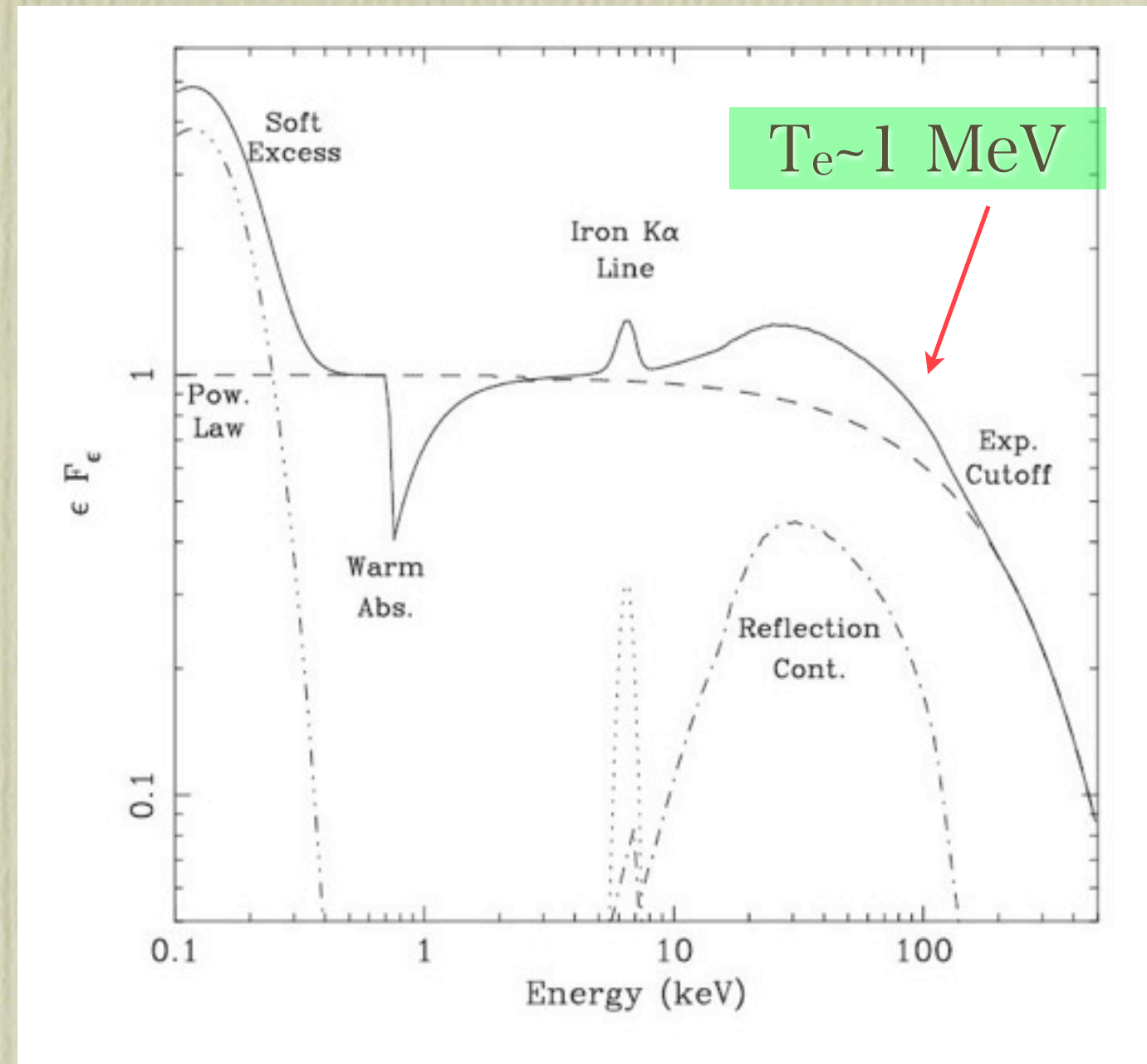


Mushotzky et al. 1993



# AGN X-ray Spectrum

- X-rays are produced by Compton up-scatter of UV disk photons by hot electrons in corona
- “the exponential cut-off” comes from “assumption” of thermal electron distribution in corona
- what if a small amount of non-thermal electrons exist?



schematic AGN spectrum  
Fabian 1998



# MeV background by AGNs with nonthermal coronal electrons

- Comptonization calculation by Yoshi Inoue, TT, & Y. Ueda 2008, ApJ, 672, L5
- Energy fraction 3.5%,  $dN_e/dE_e \propto E_e^{-3.8}$  will explain MeV background
- consistent with MeV upper limits on nearby AGNs

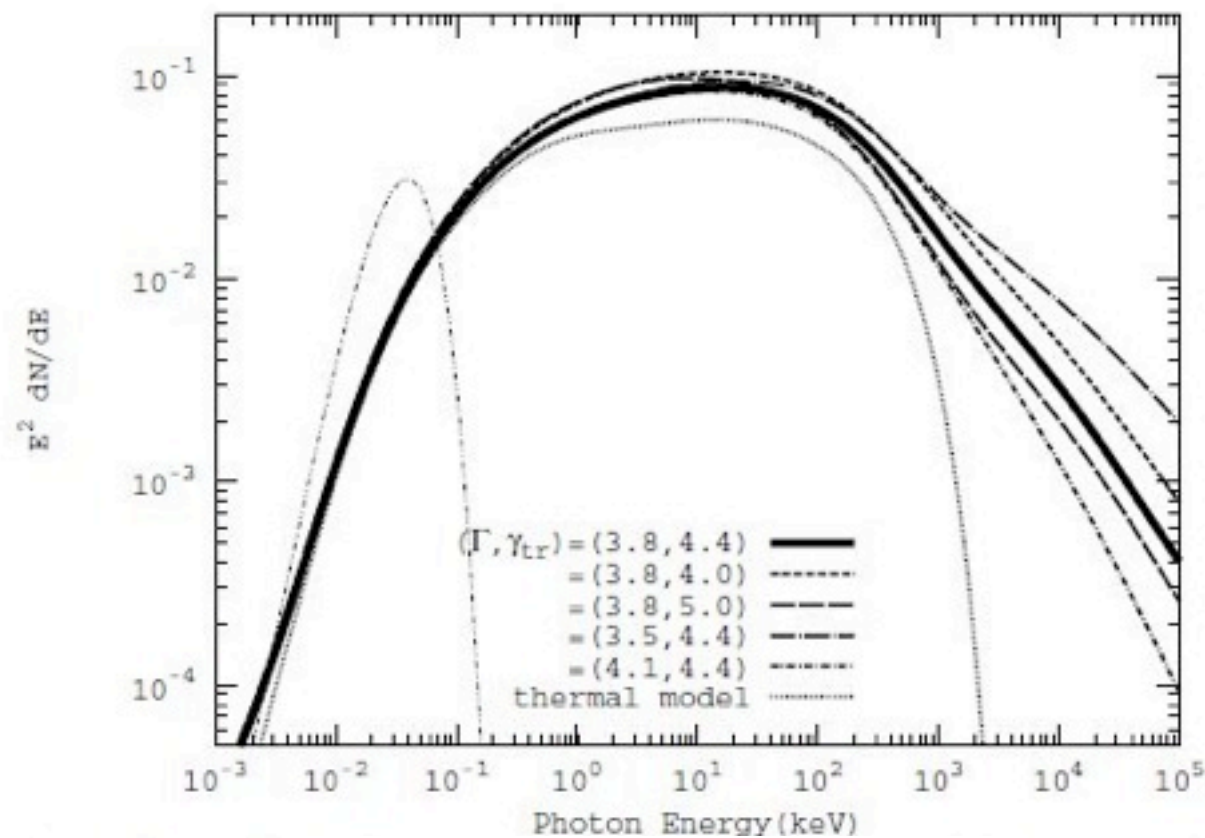


FIG. 1.— The AGN spectrum is calculated by our model. The curves show  $E^2 dN/dE$ , where  $dN/dE$  is a differential photon spectrum. They are Comptonization of UV seed photons without taking into account the reflection component and the absorption effect. The thick solid curve is our standard spectrum with  $\Gamma = 3.8$  and  $\gamma_{tr} = 4.4$ . The other thick curves are for the cases of different model parameters as indicated in the figure. The thick dotted curve is the spectrum only with the thermal component ( $kT_e = 256$  keV). The thin dotted curve is the input UV spectrum (a black body with  $T_d = 10$  eV).

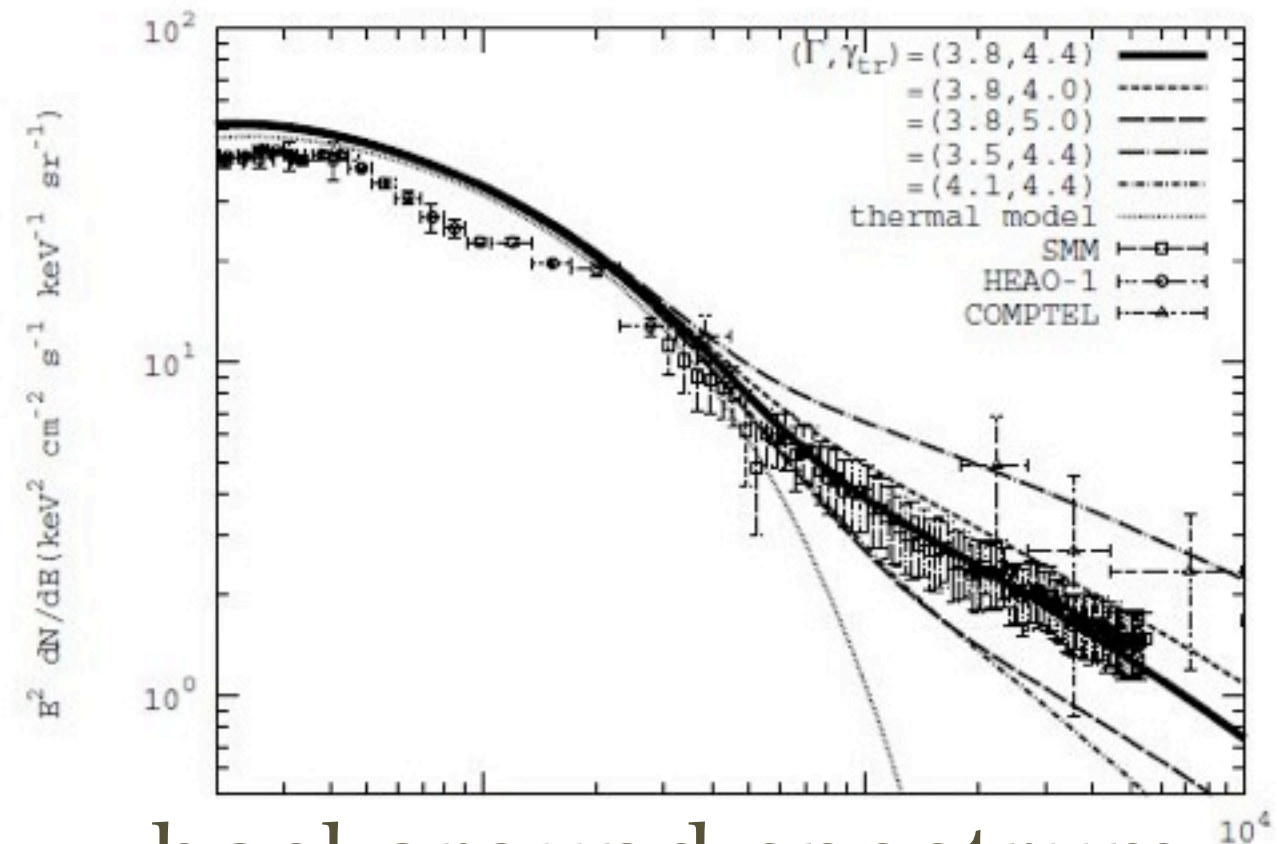
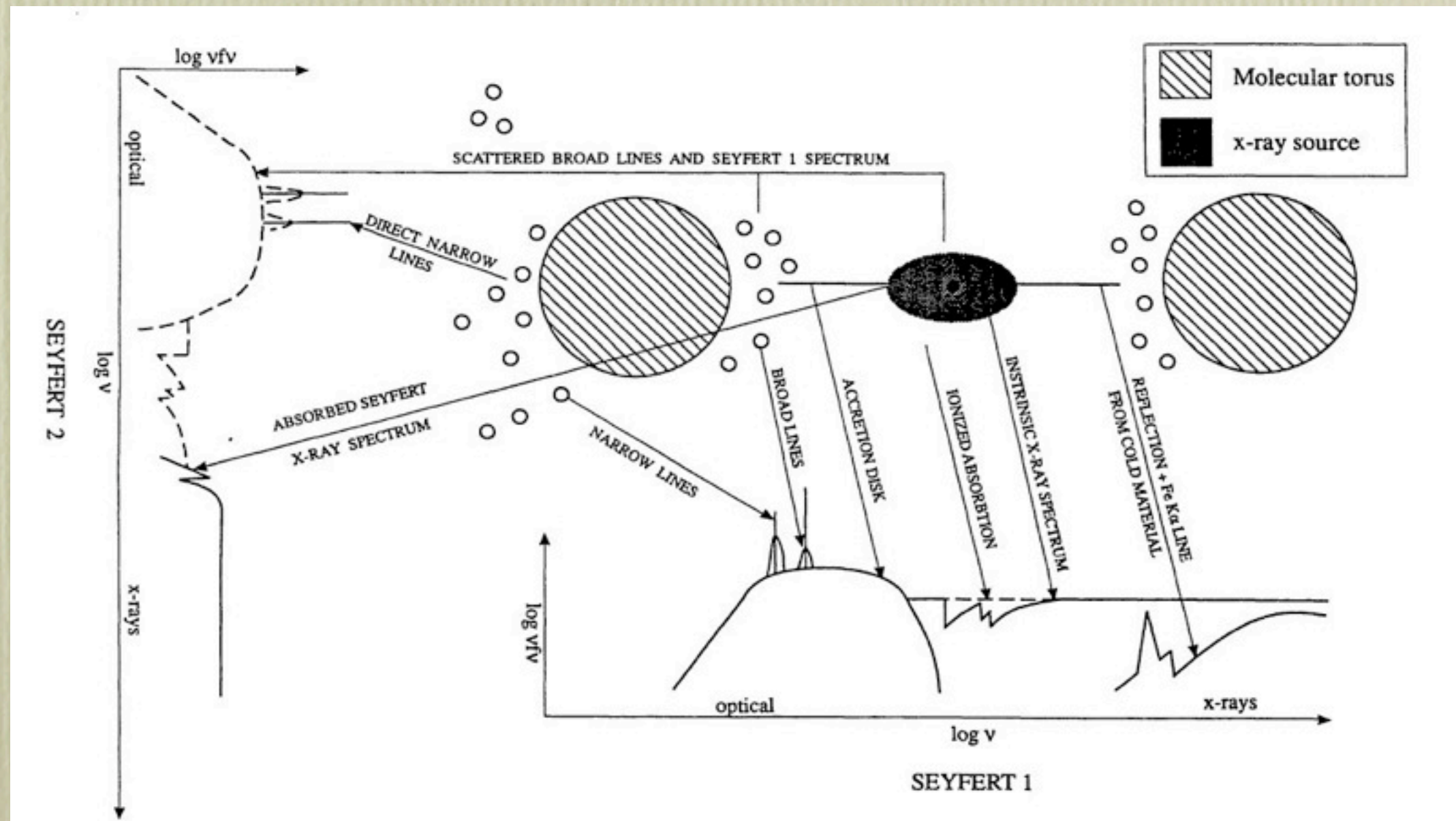


FIG. 2.— The spectrum of the cosmic background radiation in X-ray and gamma-ray bands, predicted by our model of AGN spectra shown in Fig. 1. For each line-marking, the corresponding AGN spectrum in Fig. 1 is used for the calculation. The data points of HEAO-1 (Gruber et al. 1999) SMM (Watanabe et al. 1999), and COMPTEL (Kappadath et al. 1996) experiments are also shown.



# The Origin of Non-thermal Electrons in Hot Coronae in AGNs?

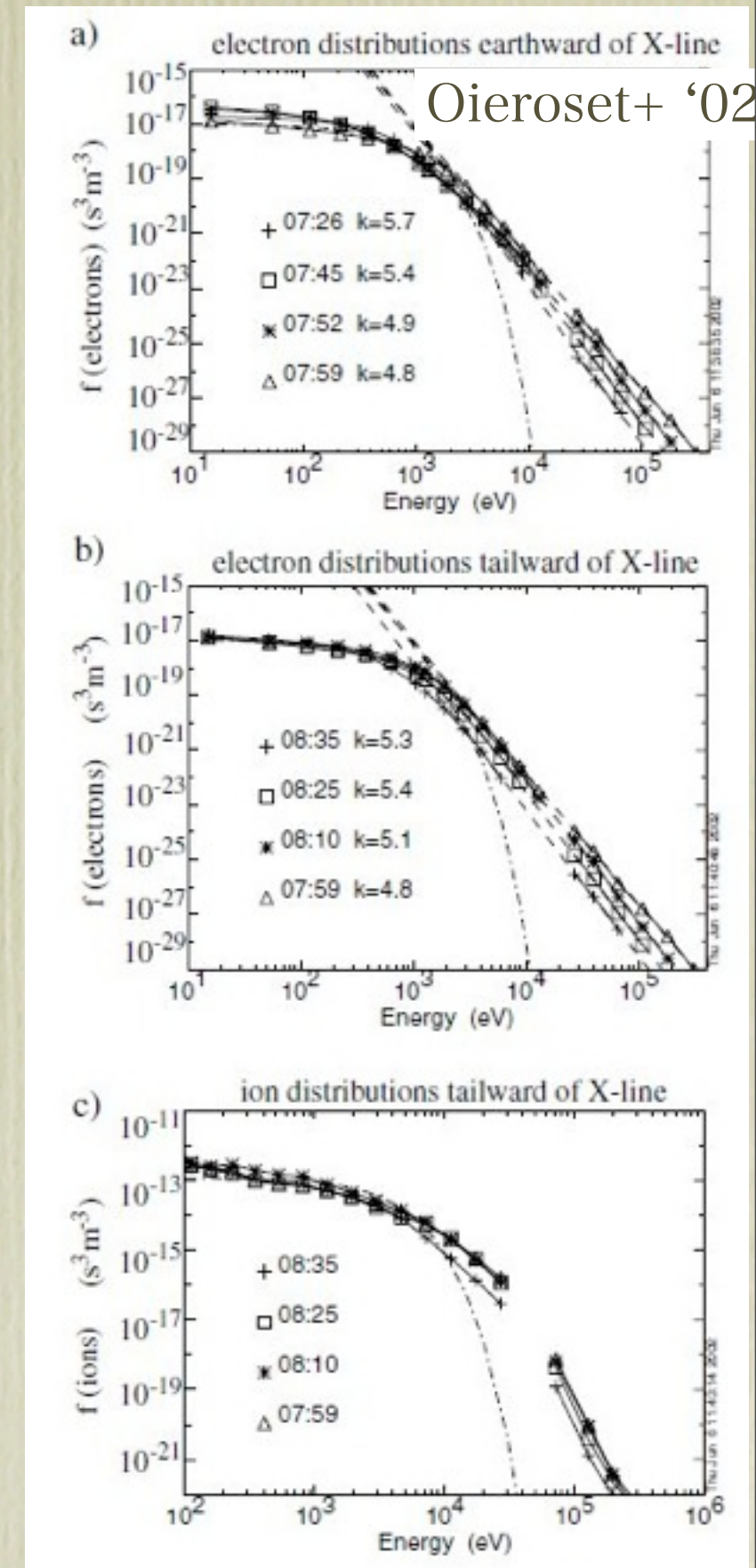
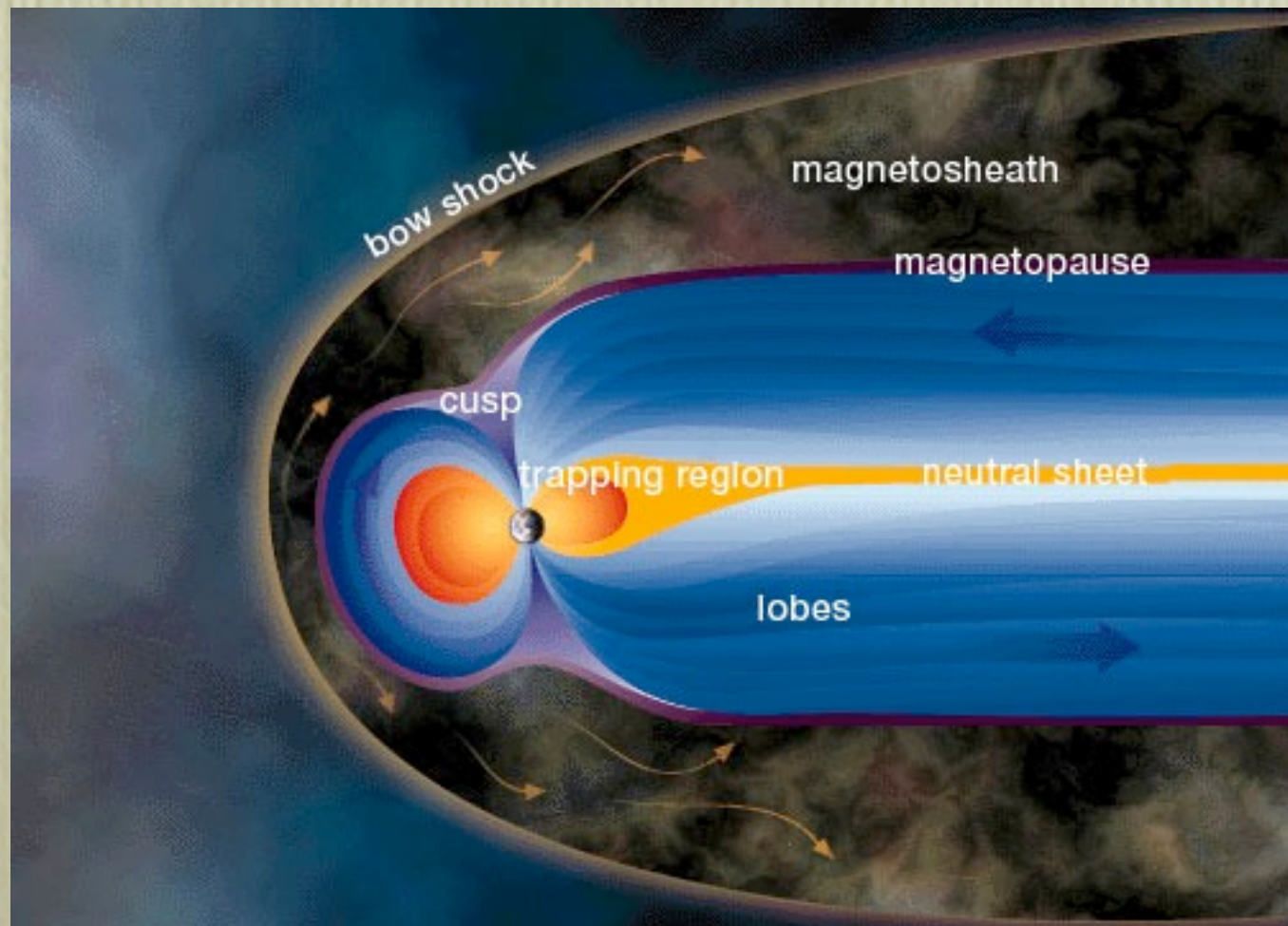
- The heat source of corona is still an open question
  - A popular scenario: magnetic reconnections (e.g. Liu+'02)
  - non-thermal particles are accelerated in reconnections!





# Particle accelerations in reconnections

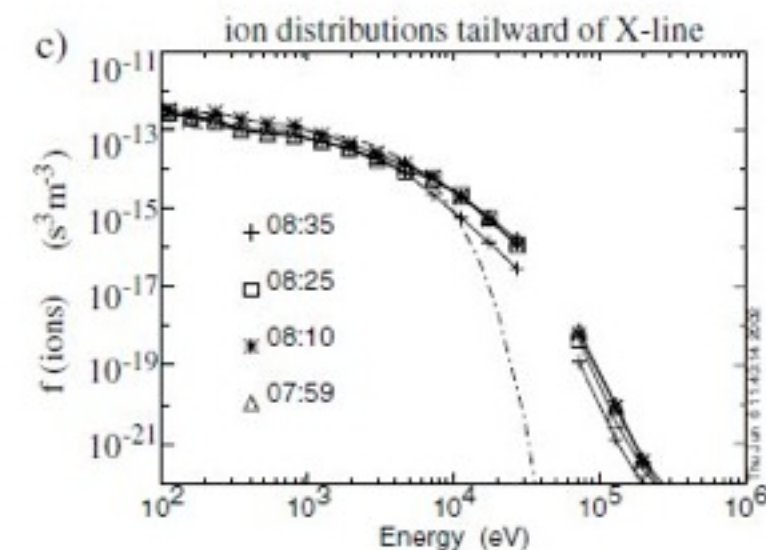
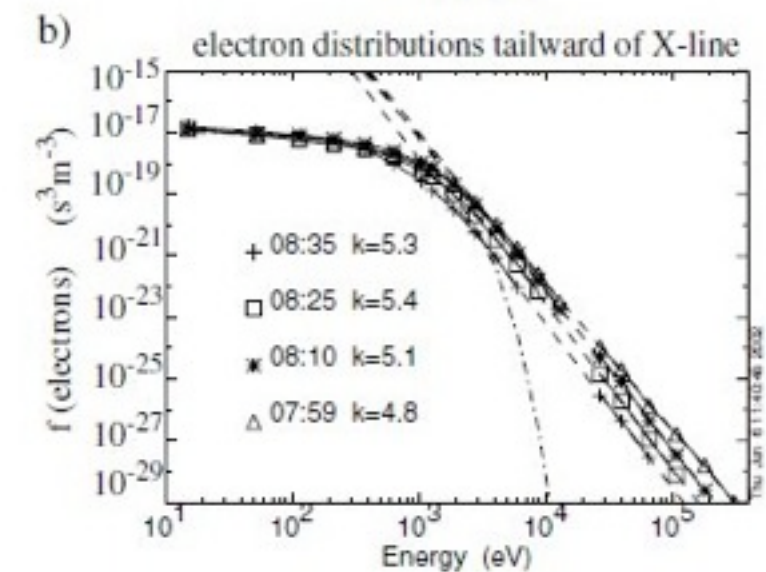
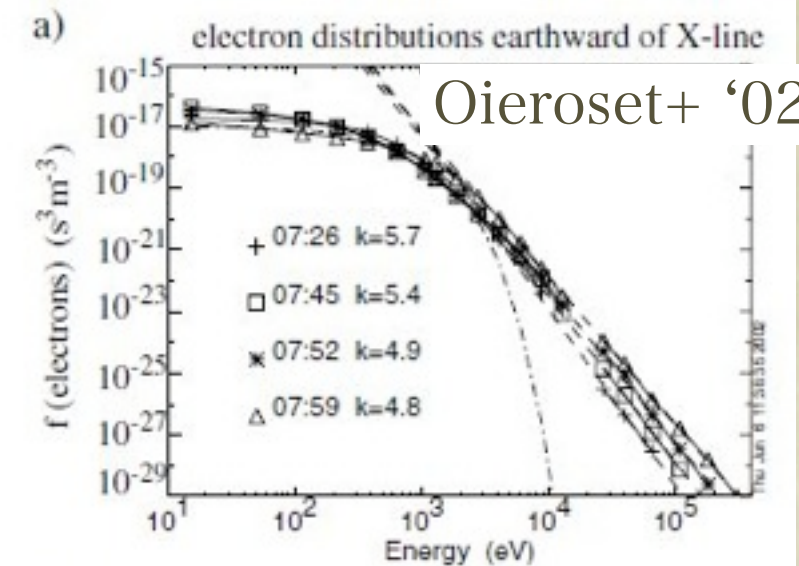
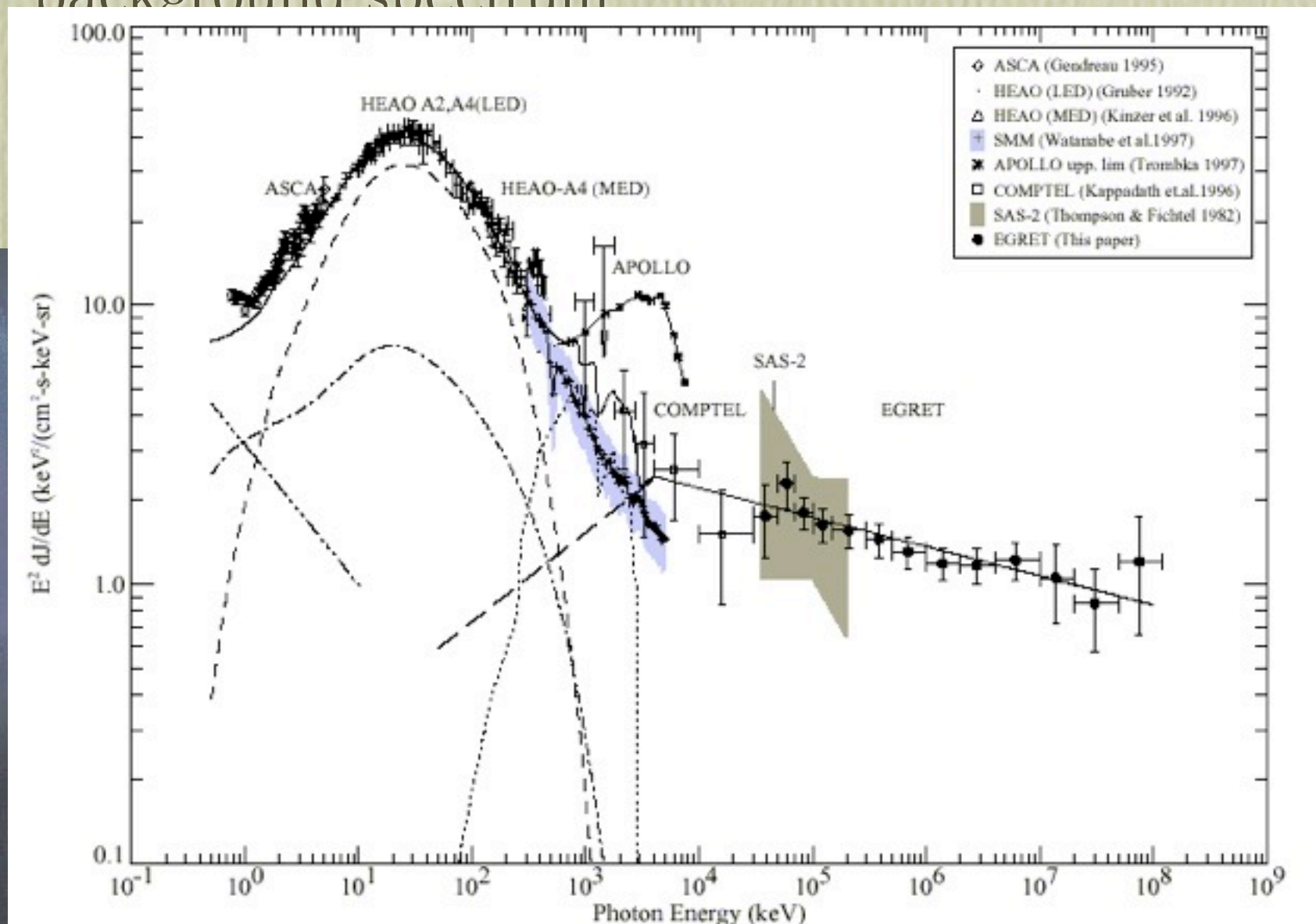
- soft power-law spectrum ( $dN/dE \sim E^{-4}$ ) is typically found in solar flares or Earth magnetosphere
- Interestingly very similar to X-ray-MeV background spectrum
  - A reasonable explanation, supporting the reconnection hypothesis for AGN coronae





# Particle accelerations in reconnections

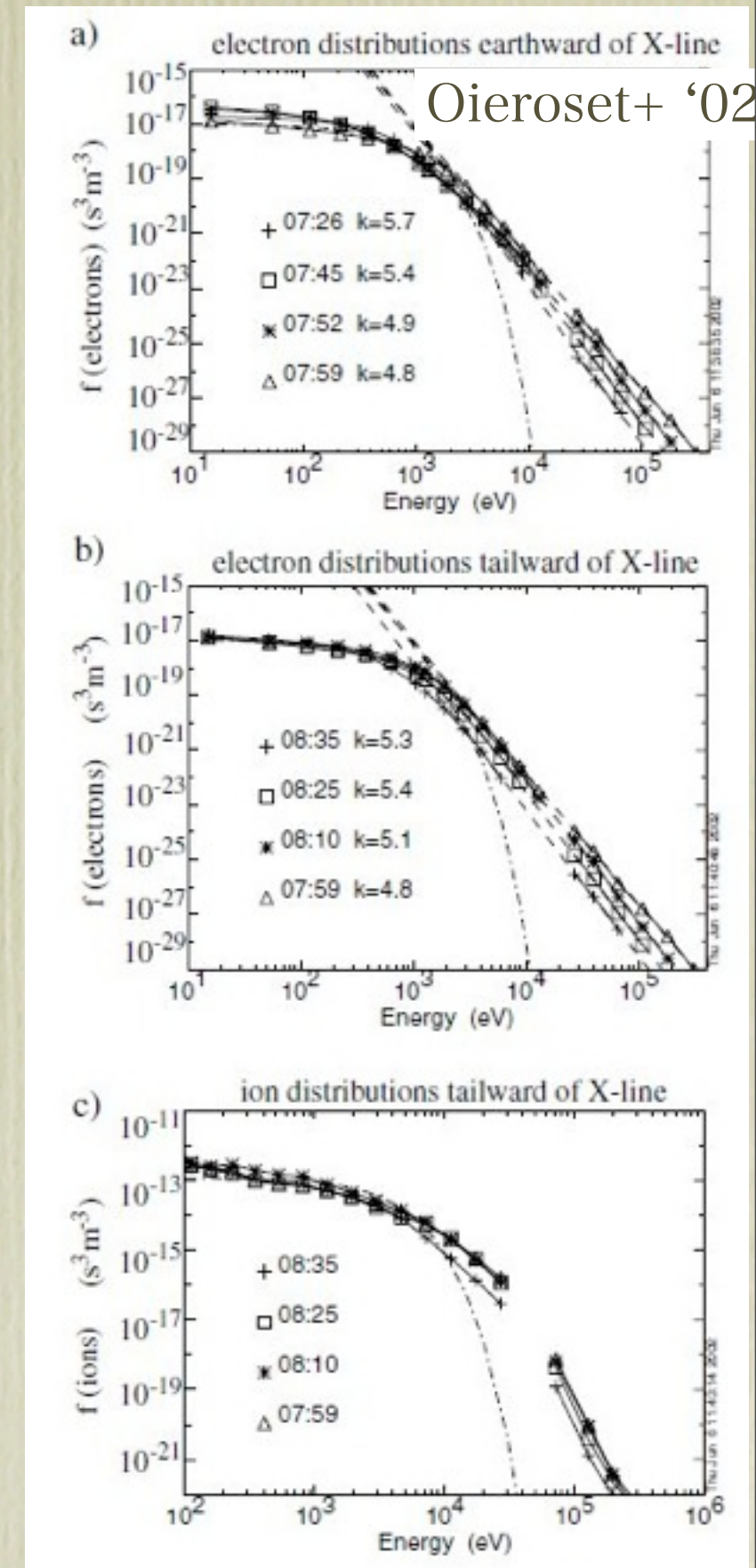
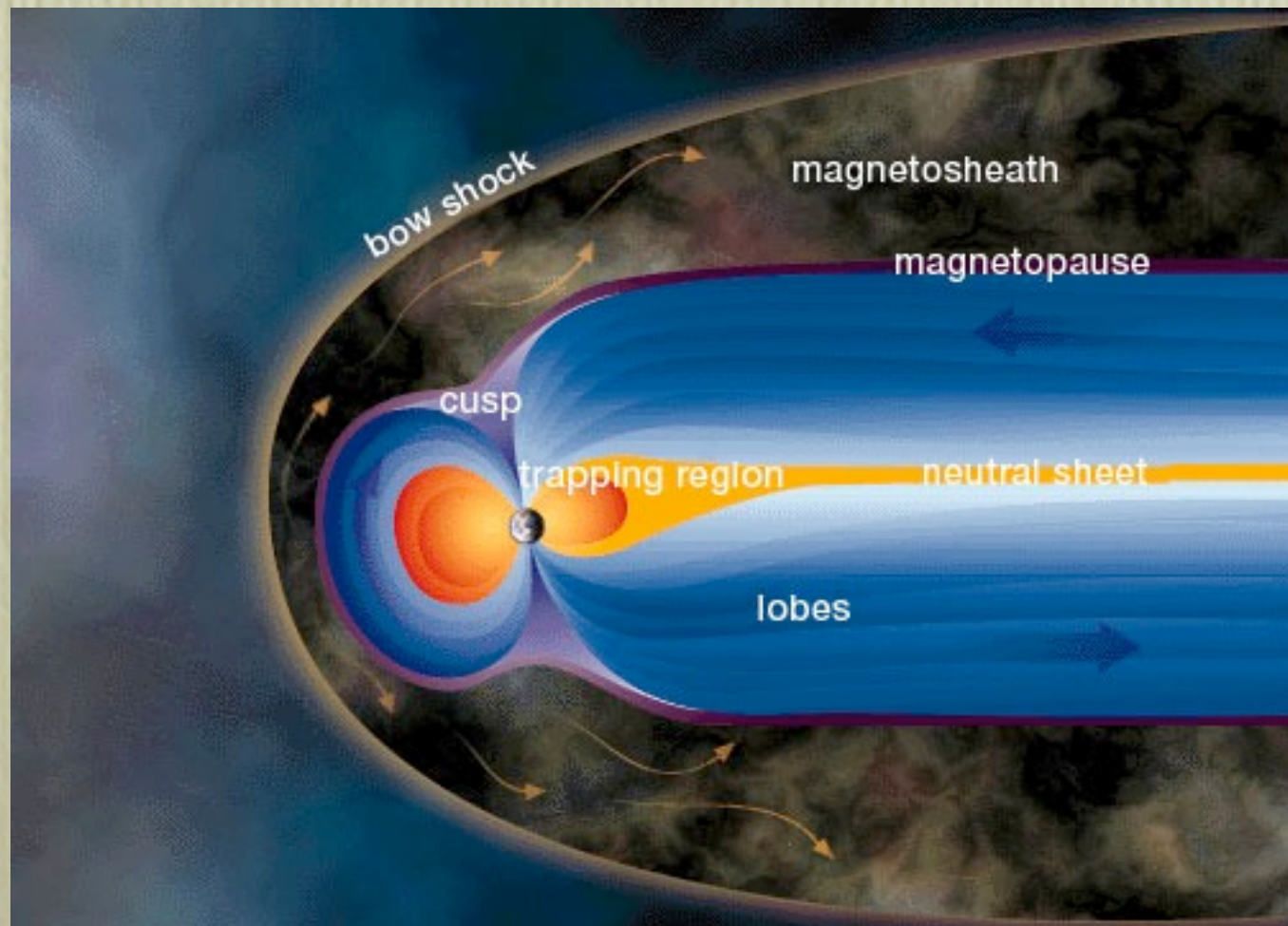
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# Particle accelerations in reconnections

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- Interestingly very similar to X-ray-MeV background spectrum
  - A reasonable explanation, supporting the reconnection hypothesis for AGN coronae



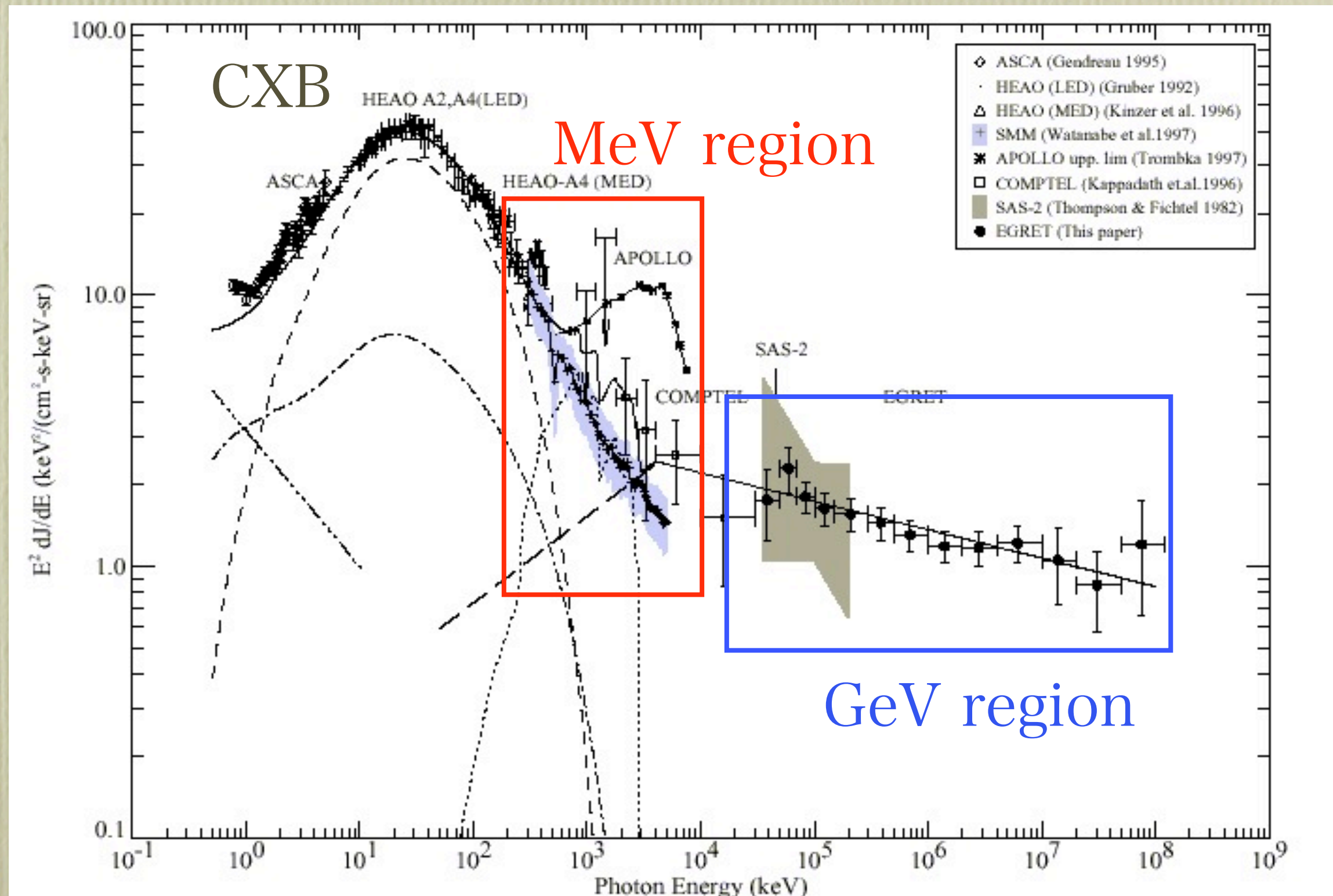


# MeV background: Summary

- Theoretically best explanation is “non-thermal tail” from normal AGNs
  - smooth power-law connection to CXB
  - non-thermal electrons naturally expected in AGN coronae
  - but, non-thermal electrons must be observationally confirmed from individual AGNs
    - Fermi?
    - future MeV missions?
- no strong motivation to consider about other sources
  - too small SN Ia rate
  - no good theoretical motivation for MeV DM
  - “MeV blazars” may have significant contribution? (Ajello+’09)



# Origin of the GeV background

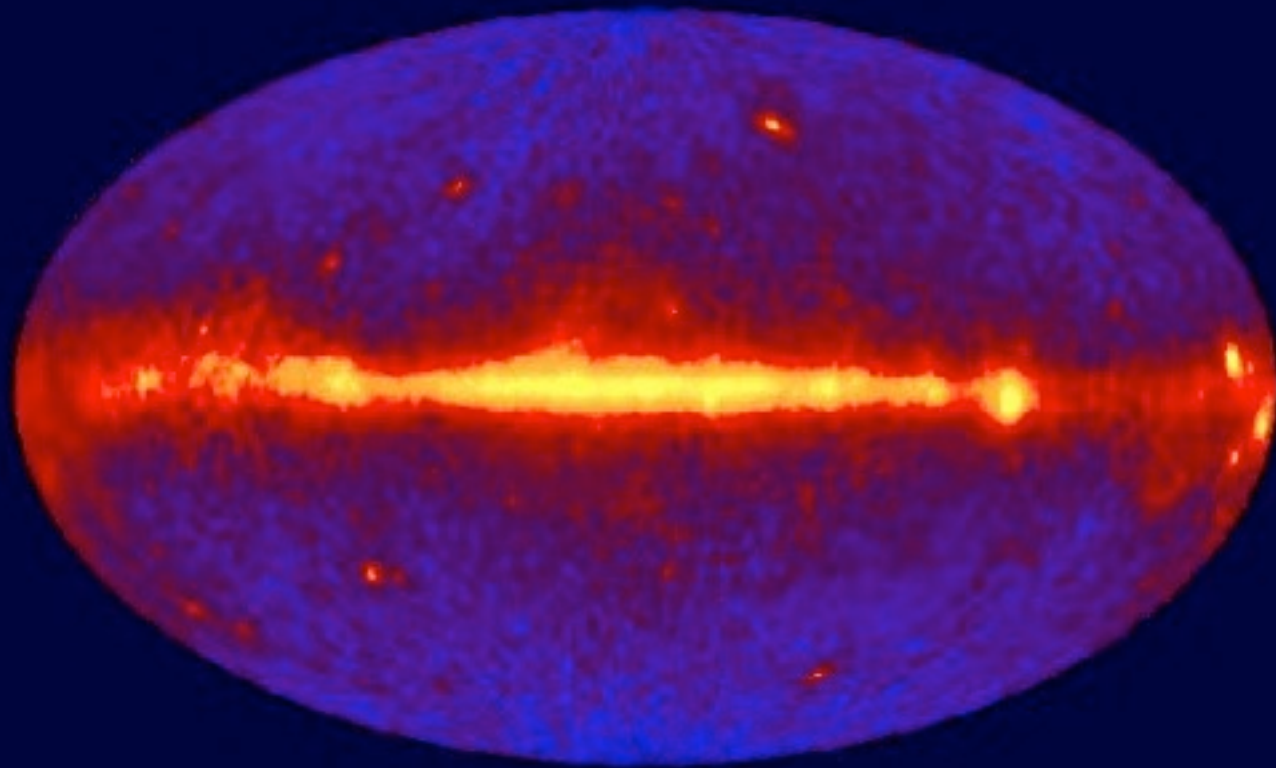




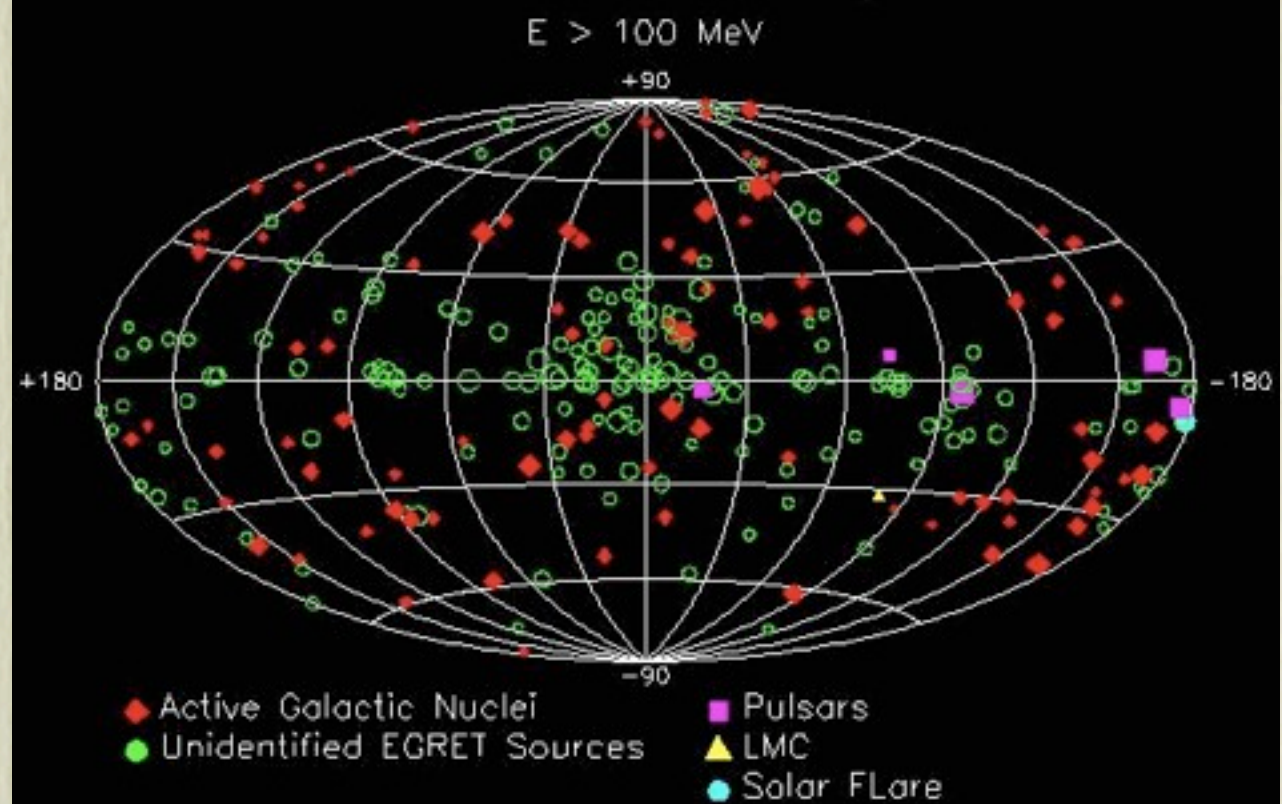
# the primary candidate: blazars

- almost all extragalactic EGRET sources ( $\sim 50$ ) are blazars
- blazars can account for at least  $> \sim 30\%$  of GeV background, but probably not 100% of the EGRET data
- new sources? DM? systematics in theory and/or data?

EGRET All-Sky Gamma-Ray Survey Above 100 MeV

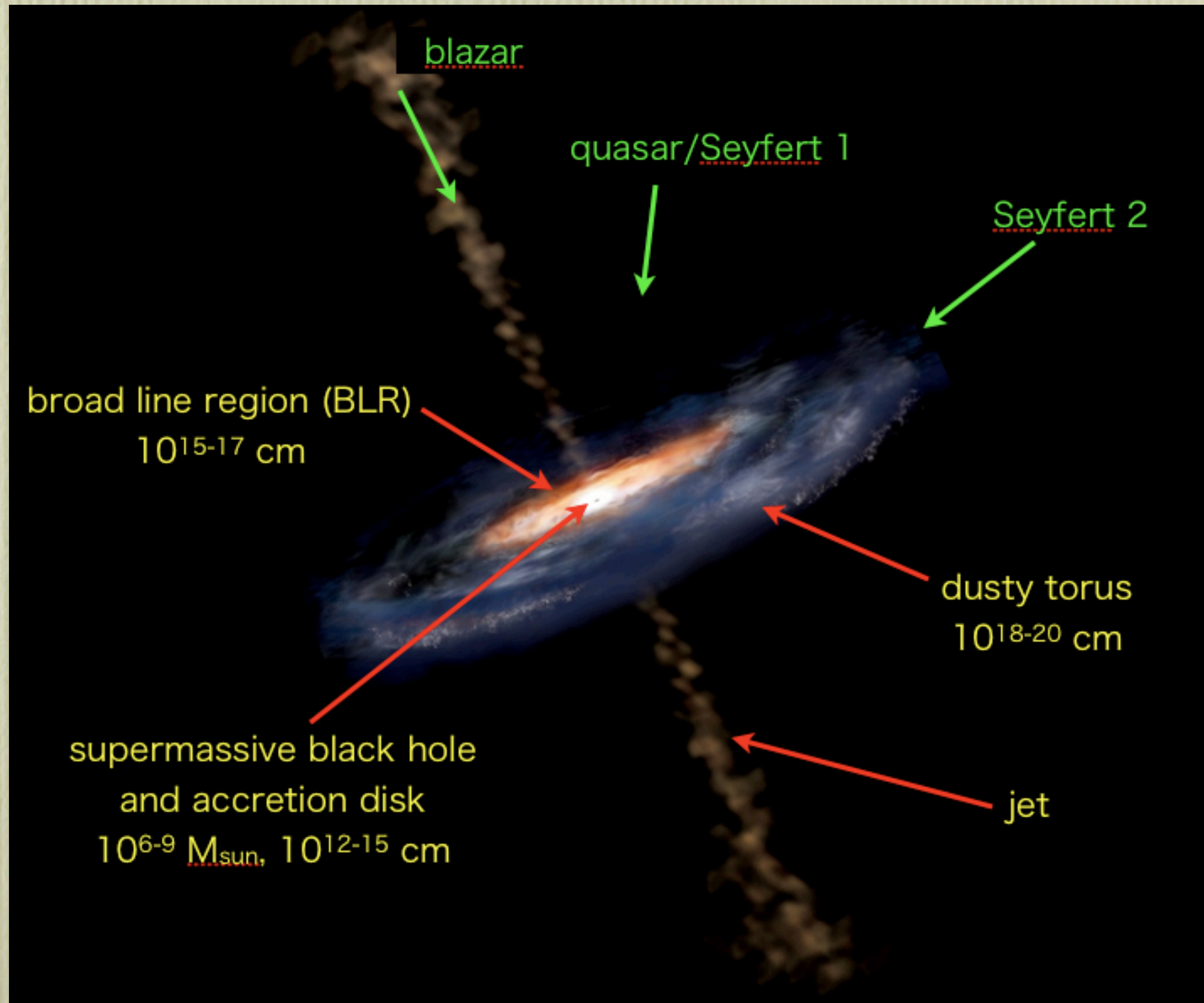


Third EGRET Catalog





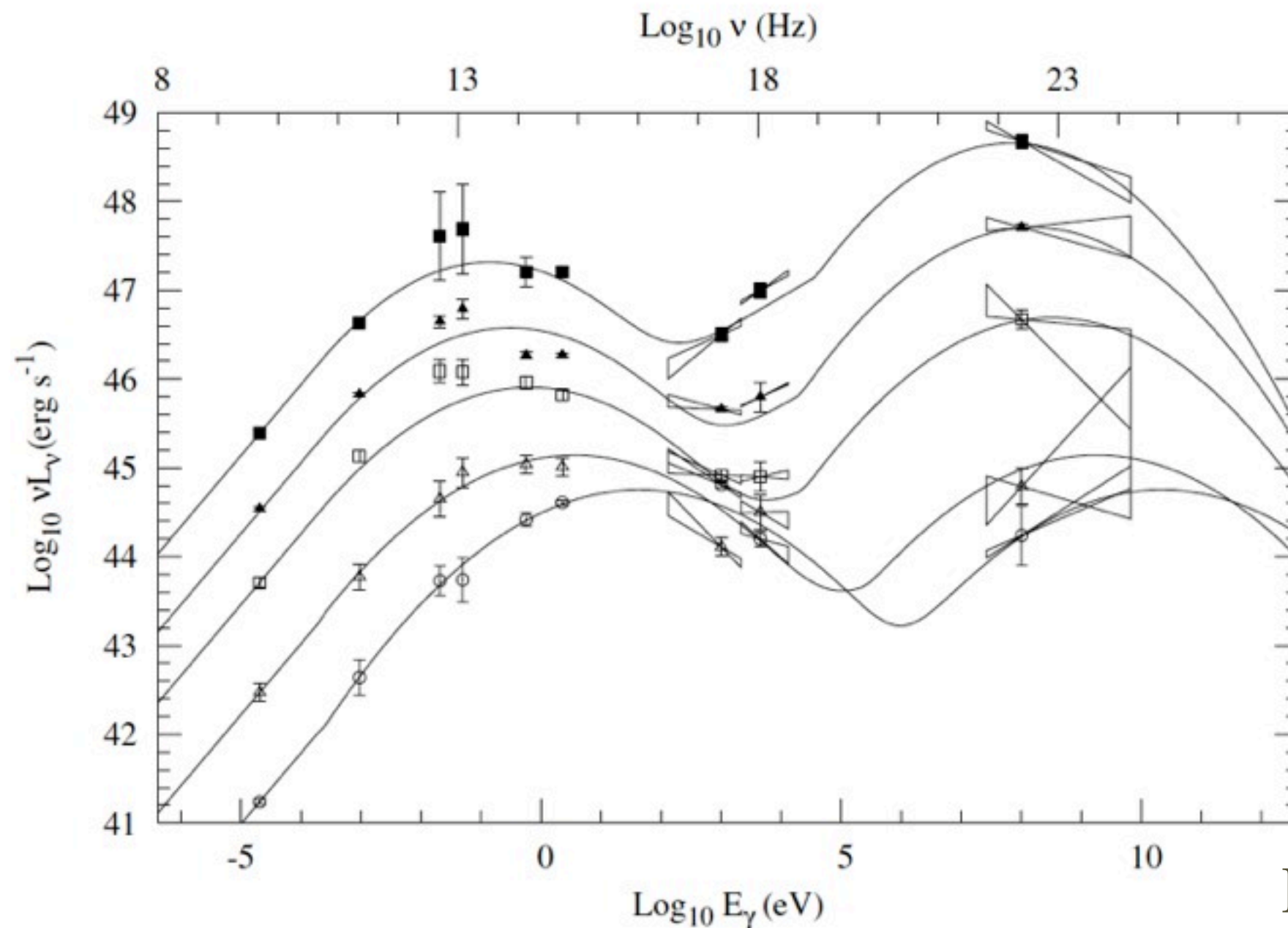
# blazars





# blazar spectral energy distribution (SED)

- two broad peak by synchrotron and inverse-Compton by non-thermal electrons
- the SED sequence (high peak frequency for lower luminosity)
- Fossati+'97, Donato+'01



Inoue+TT '09



# GeV background from Blazars

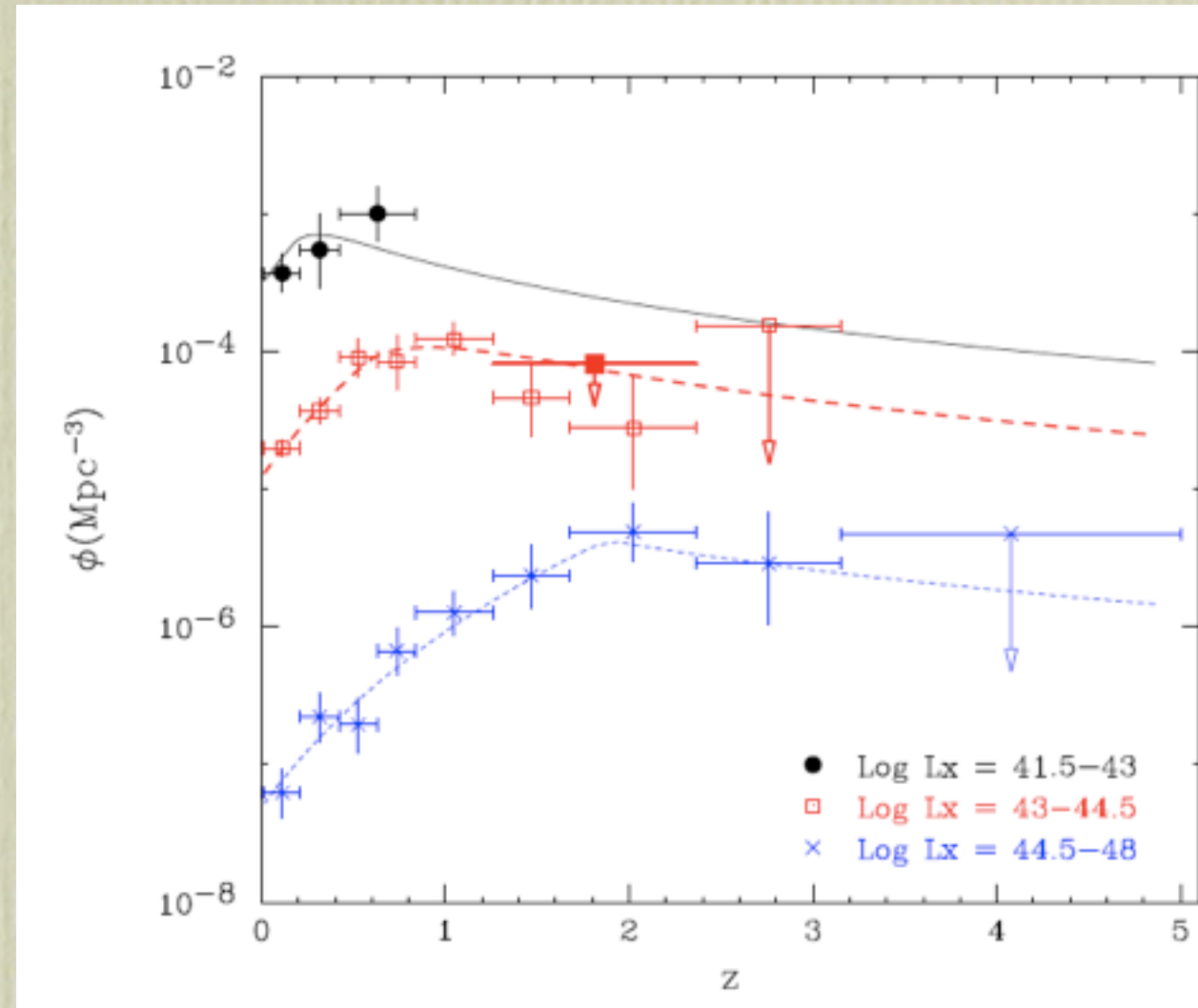
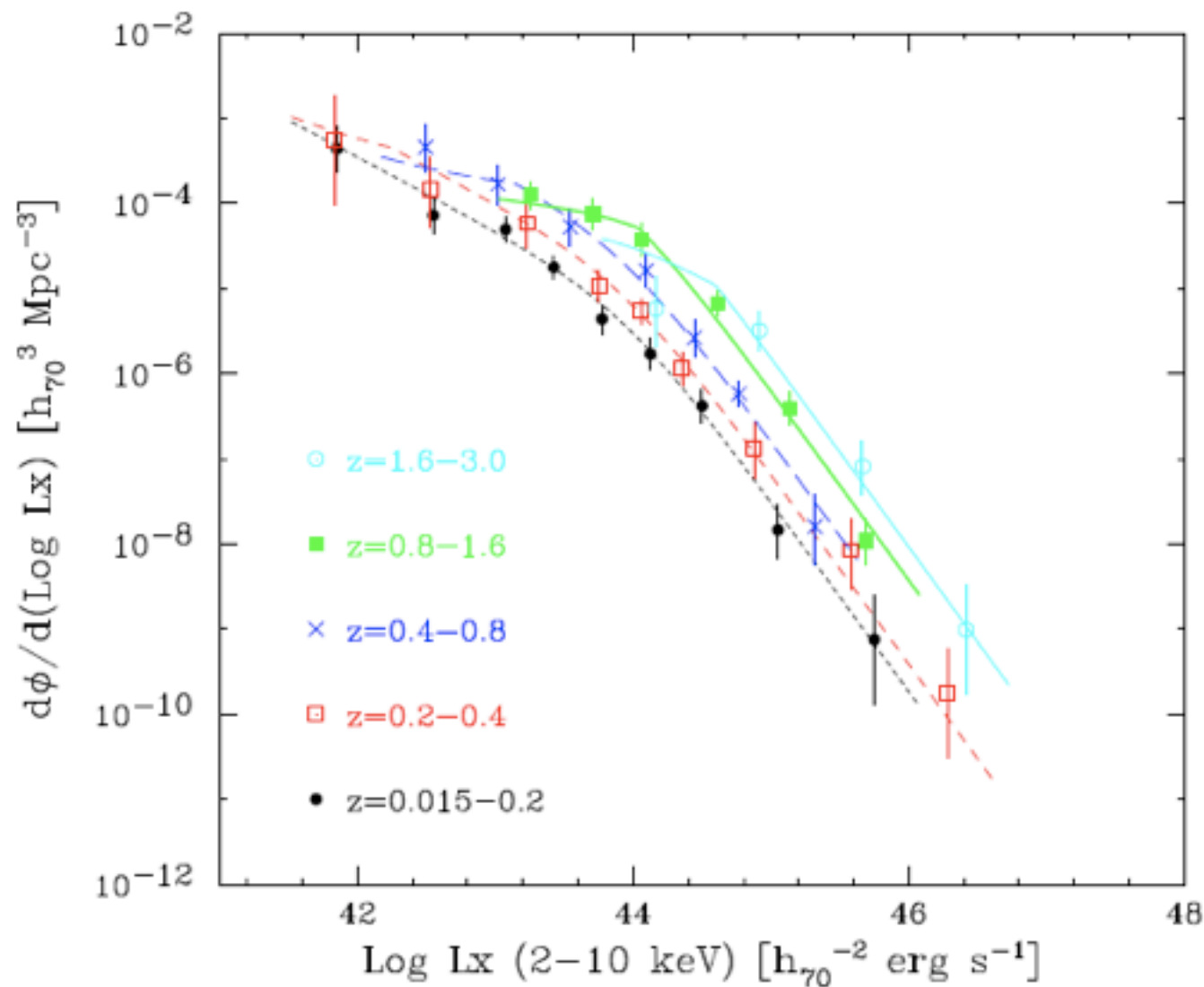
Padovani+'93; Stecker & Salamon '96; Chiang & Mukherjee '98; Mücke & Pohl '00;  
Narumoto & Totani '06; Giommi et al. '06; Dermer '07; Pavlidou & Venters '08;  
Kneiske & Mannheim '08; Inoue & Totani '09

- The basic scheme:
  - luminosity function (LF) evolution model (X, radio, etc.)
  - fitting to EGRET blazar distribution (flux & redshift)
  - spectral modeling of blazars
    - (power-law, SED sequence, theoretical model, ...)
- The latest model by Inoue+TT '09 (arXiv:0810.3580)
  - “LDDE” LF evolution based on X-ray surveys of AGNs
  - the SED sequence for blazar spectra
  - careful fitting to the EGRET data by likelihood analysis
    - likelihood analysis including radio counterpart detection probability



# AGN Luminosity Function Evolution

- LDDE (Luminosity Dependent Density Evolution)
- good fit to X-ray AGNs to  $z \sim 3$
- assume  $L_X \propto L_\gamma$  for blazar-AGN connection

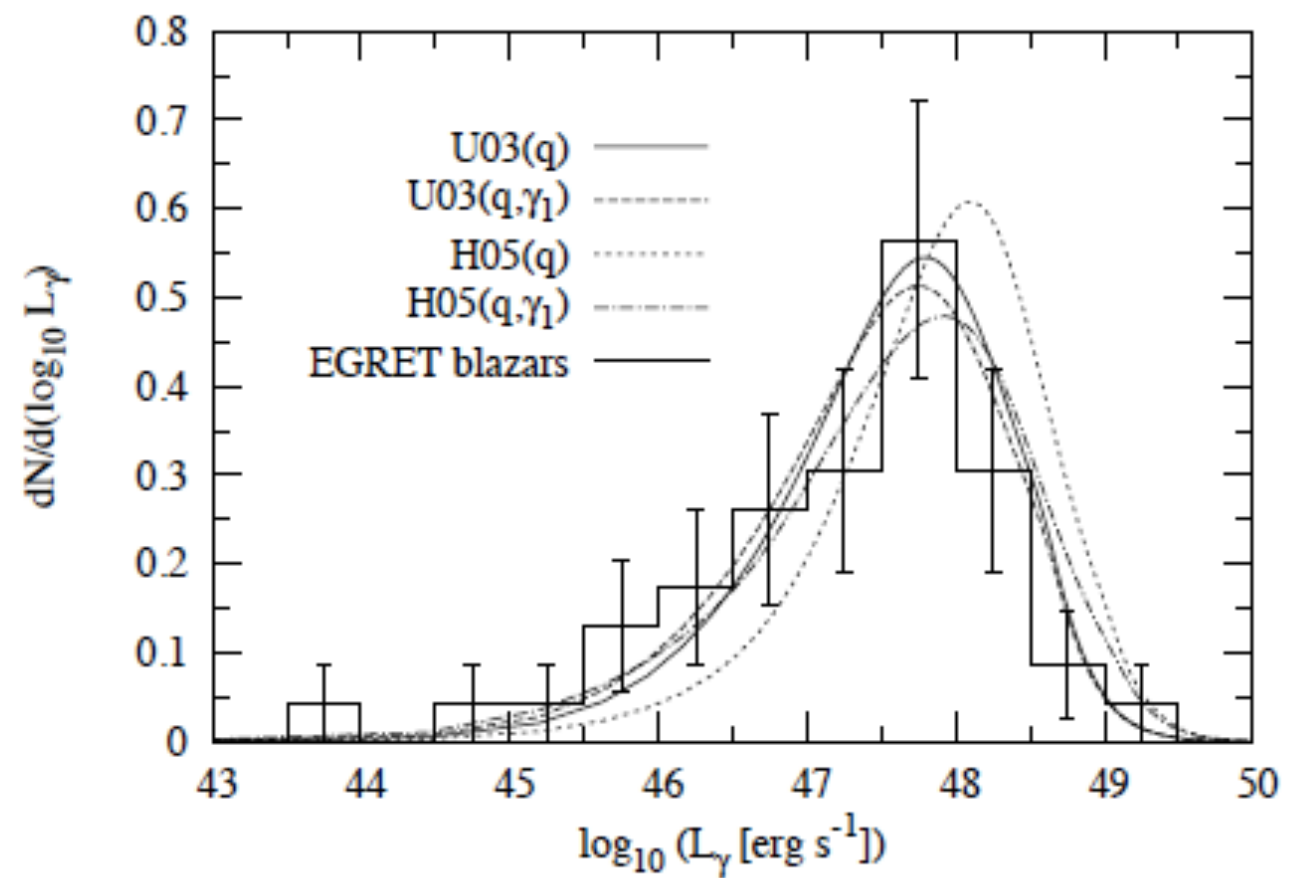
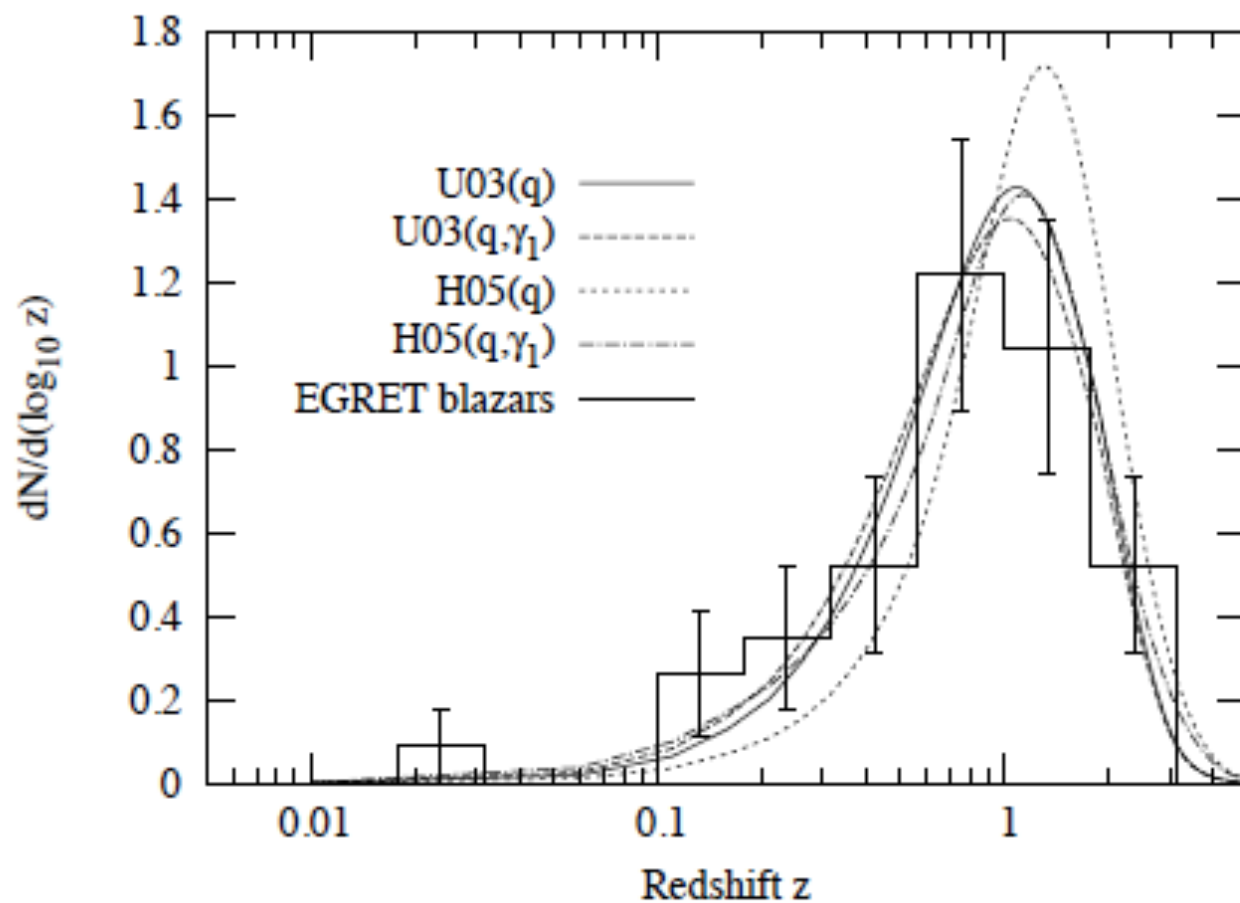


Ueda+'03



# L and z distribution of EGRET blazars

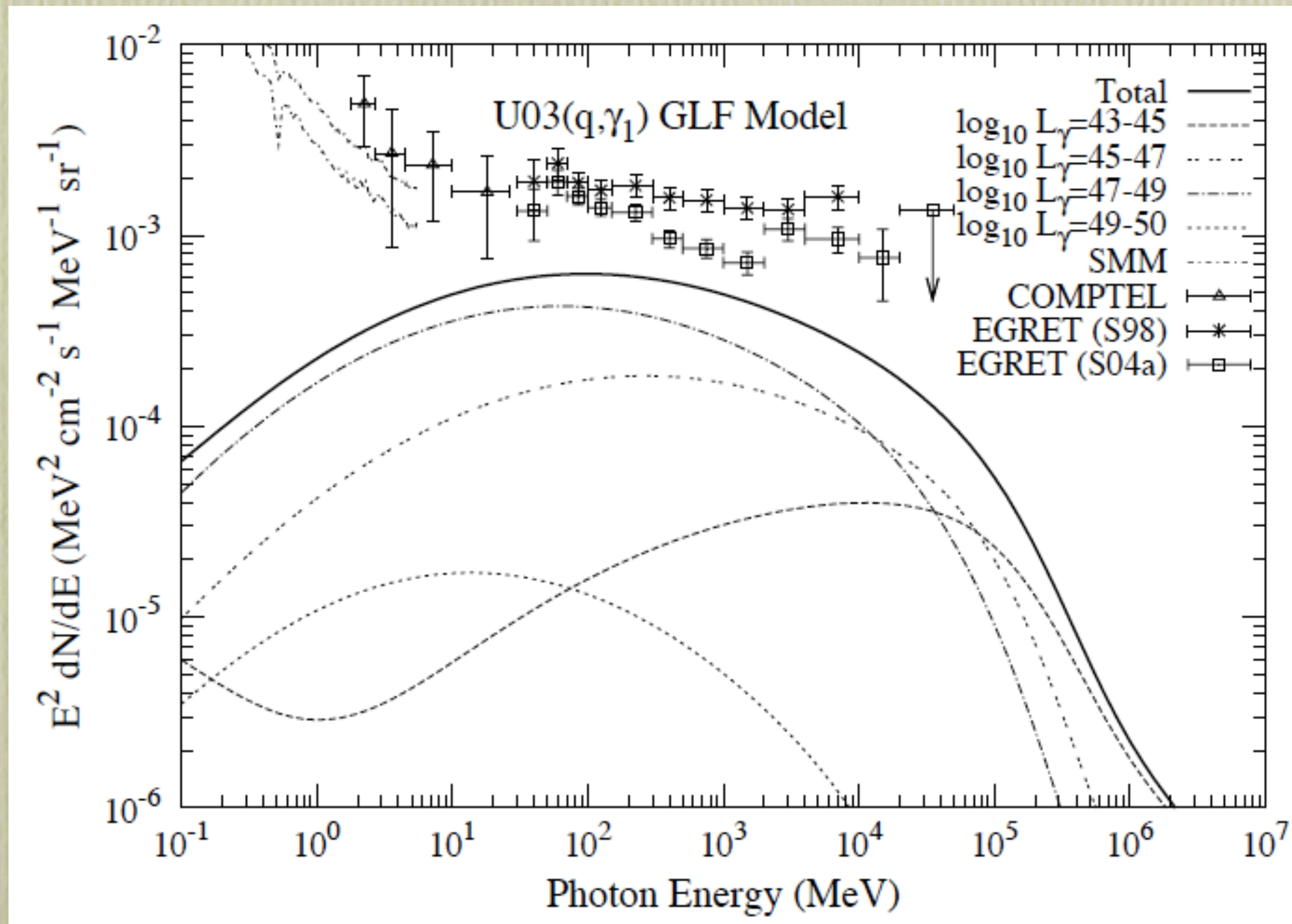
- good fit to 46 EGRET blazars up to  $z \sim 3$  (cosmologically significant!)
- LDDE better fits than “pure luminosity evolution” model
- not large uncertainty about evolution





# GeV background from blazars

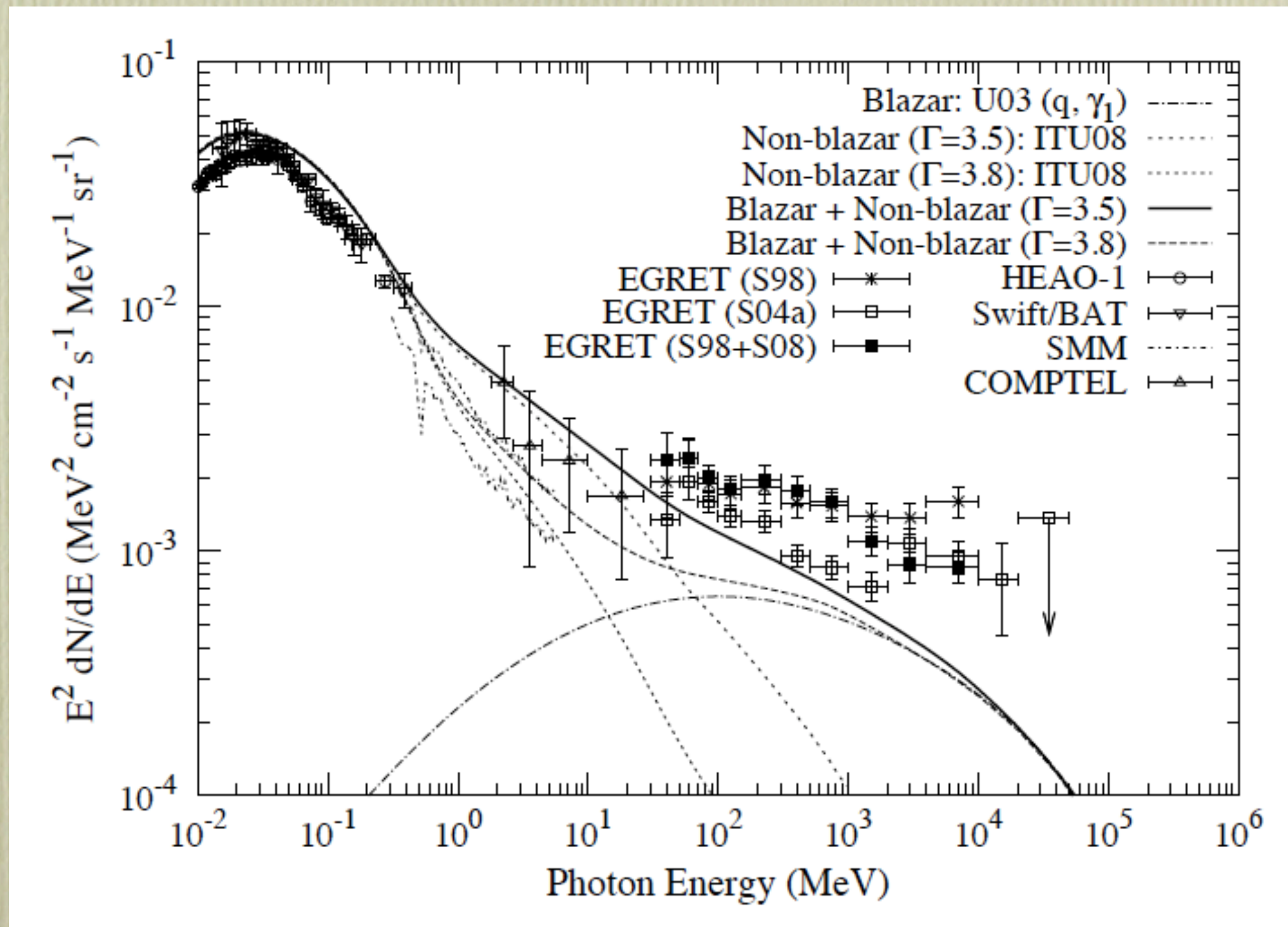
- can account for  $>\sim 50\%$  by blazars
- but difficult to explain  $\sim 100\%$





# Total gamma-ray background from normal+blazar AGNs

- the “minimum” contribution from the two populations
- normal AGNs in MeV and blazars in GeV

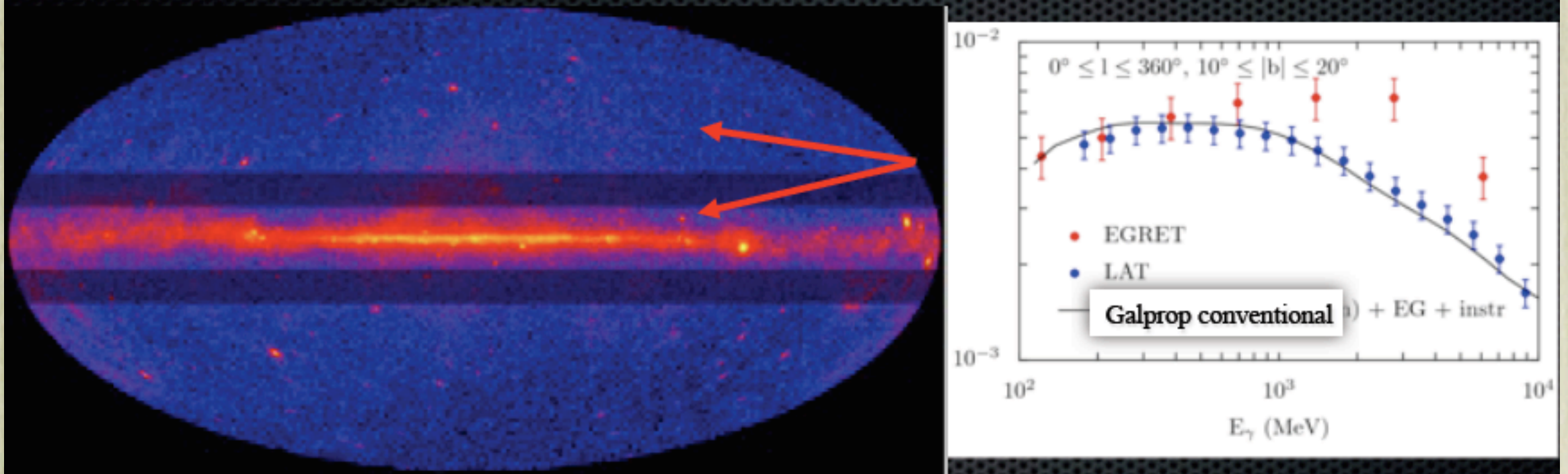




# Systematics in CGB measurements?

🌐 a slide by S. Funk

## The Fermi LAT View



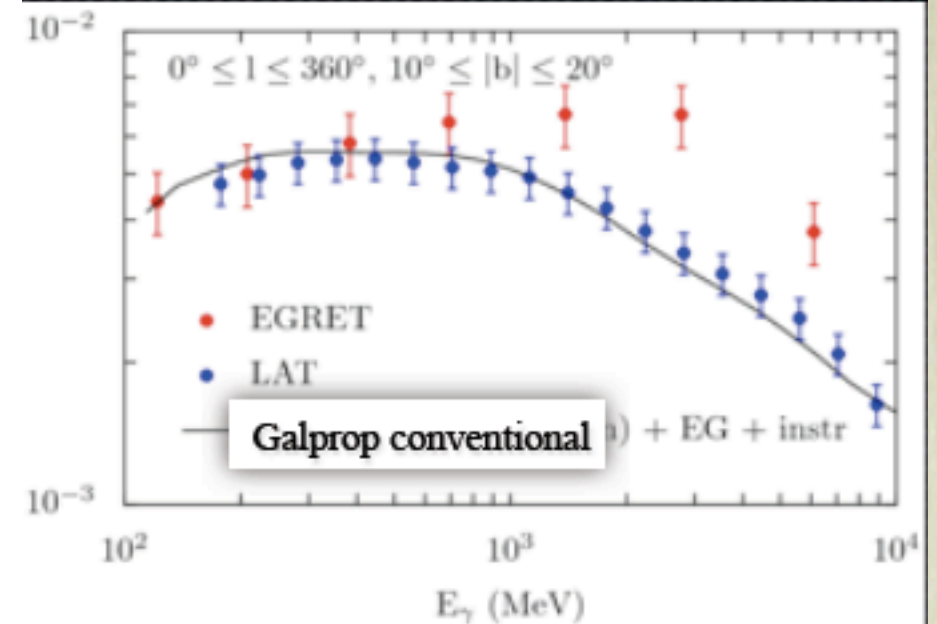
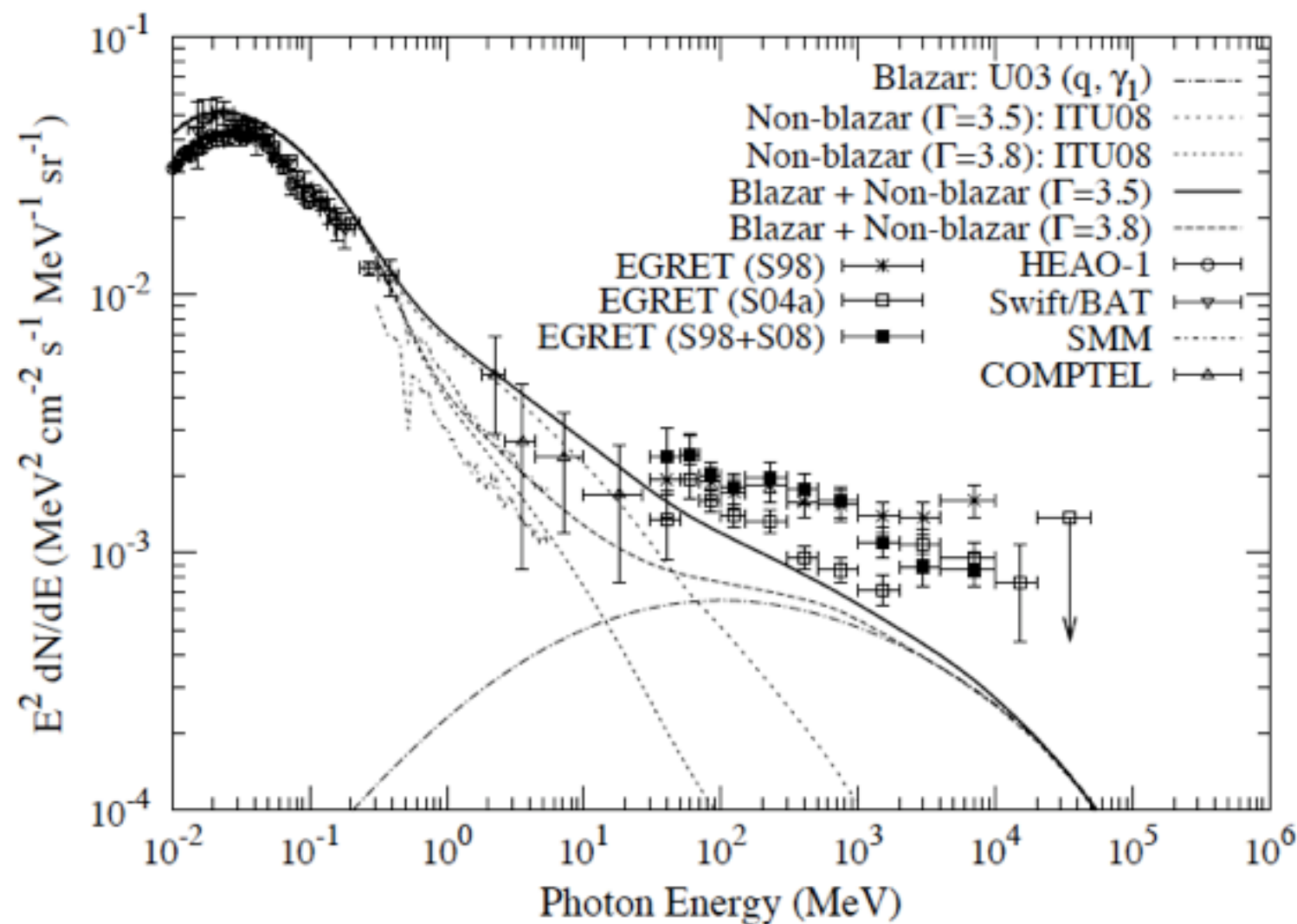
- Spectra shown for mid-latitude range → GeV excess in this region of the sky is **not** confirmed.
- Sources are not subtracted but are a minor component
- Diffuse emission matches very well expectation



# Systematics in CGB measurements?

☪ a slide by S. Funk

## The Fermi LAT View



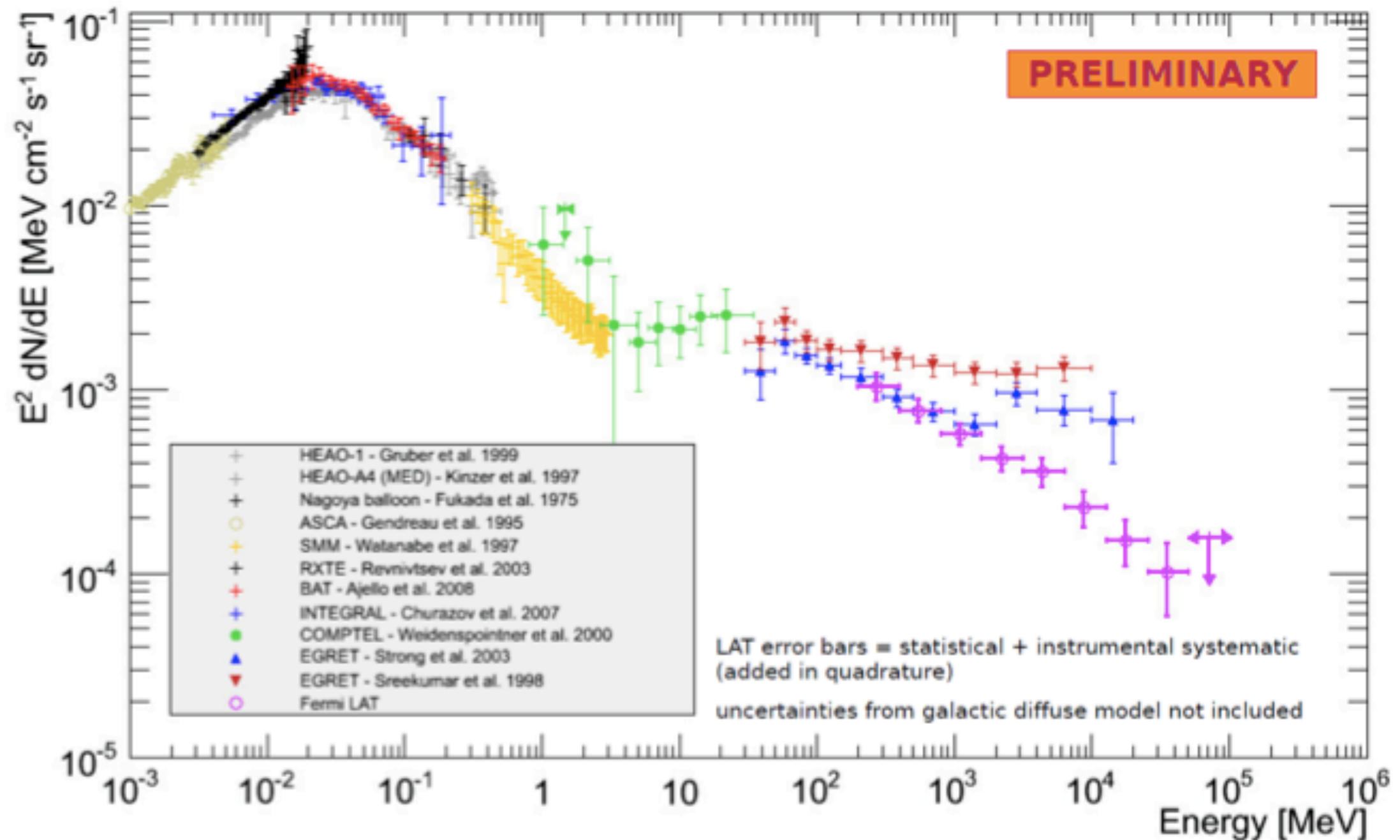
→ GeV excess in

- Sources are not subtracted but are a minor component
- Diffuse emission matches very well expectation



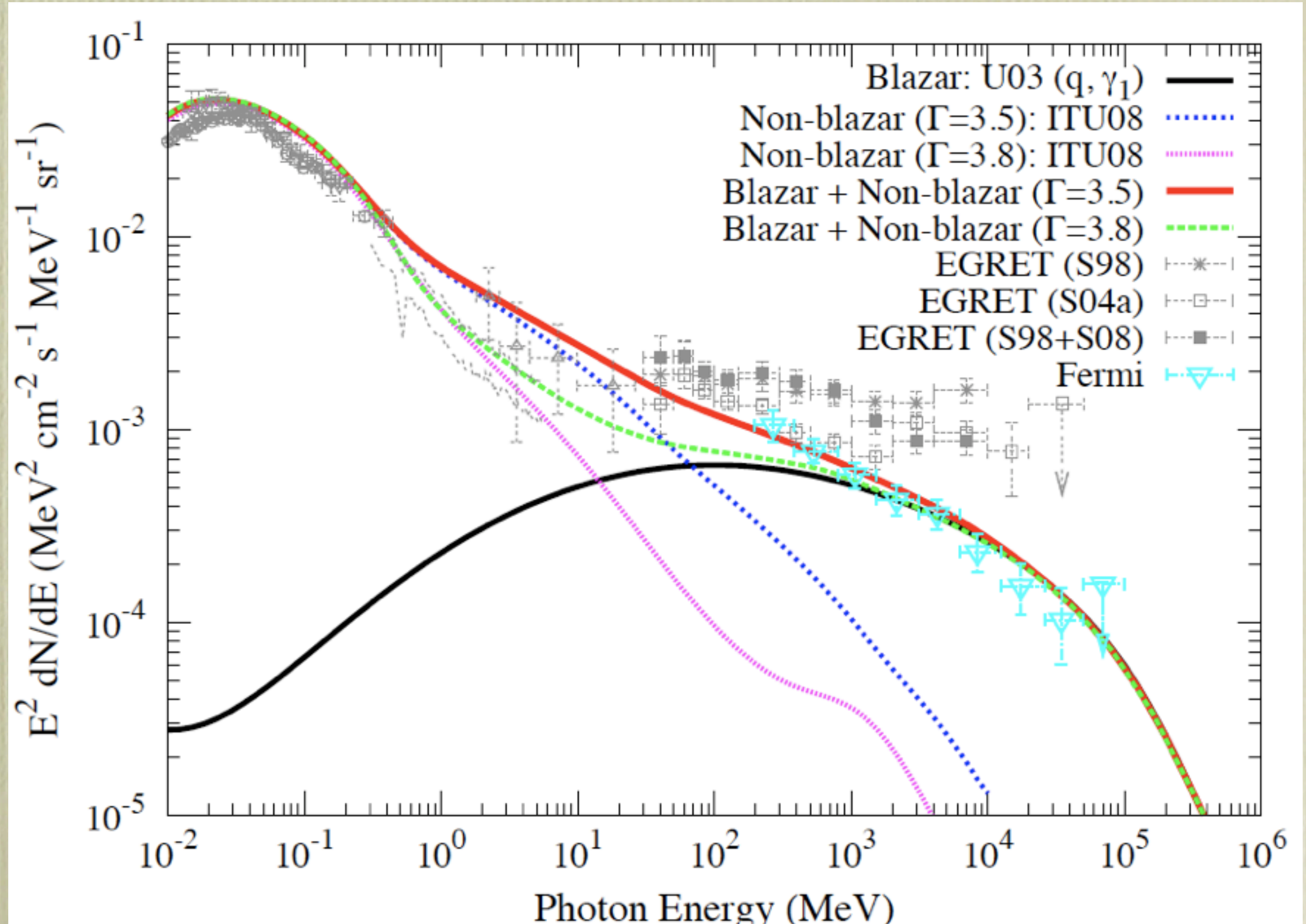
# New Measurement of GeV background by Fermi

## SED of the isotropic diffuse emission (1 keV – 100 GeV)



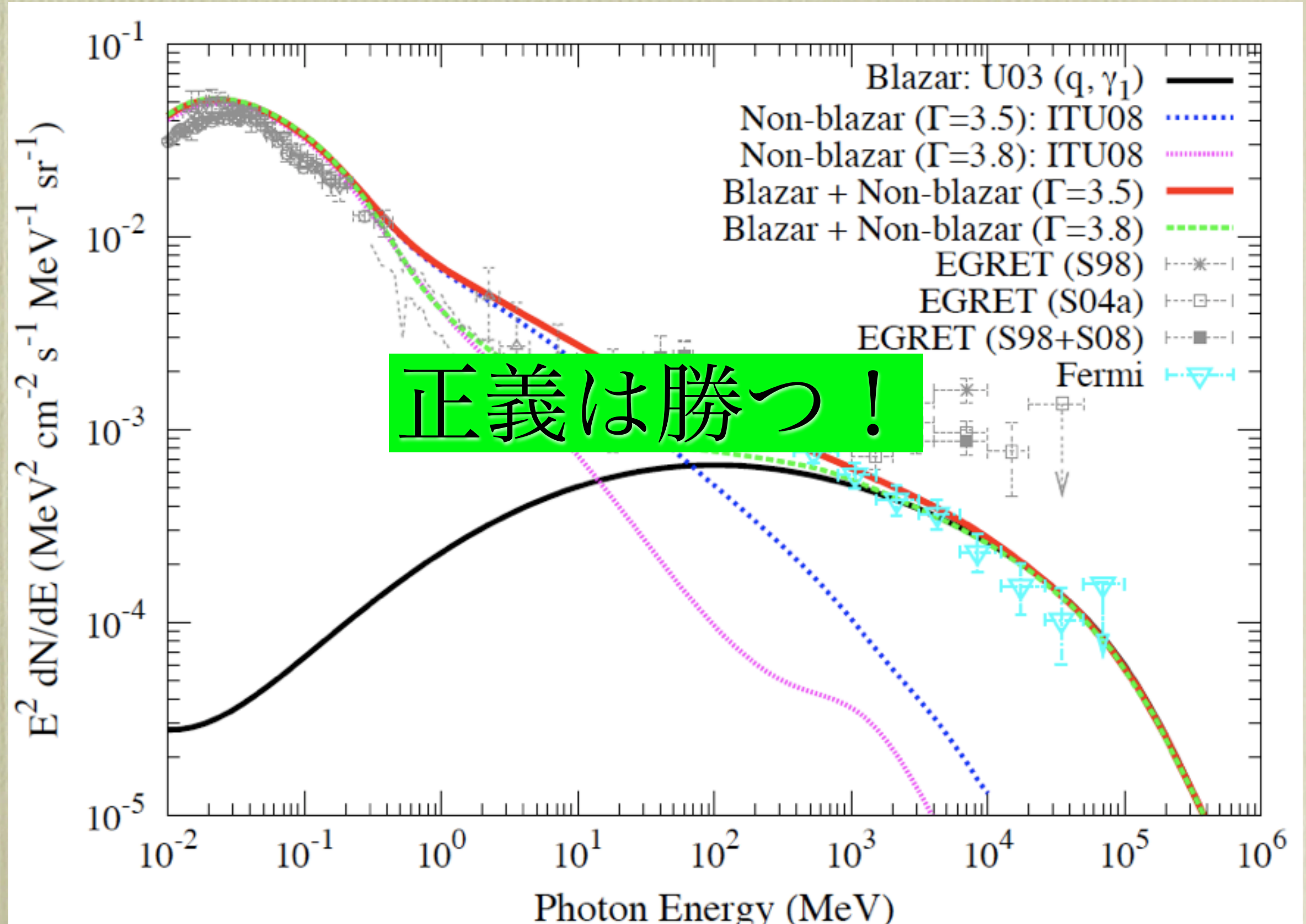


# Comparison with the Prediction by IT09





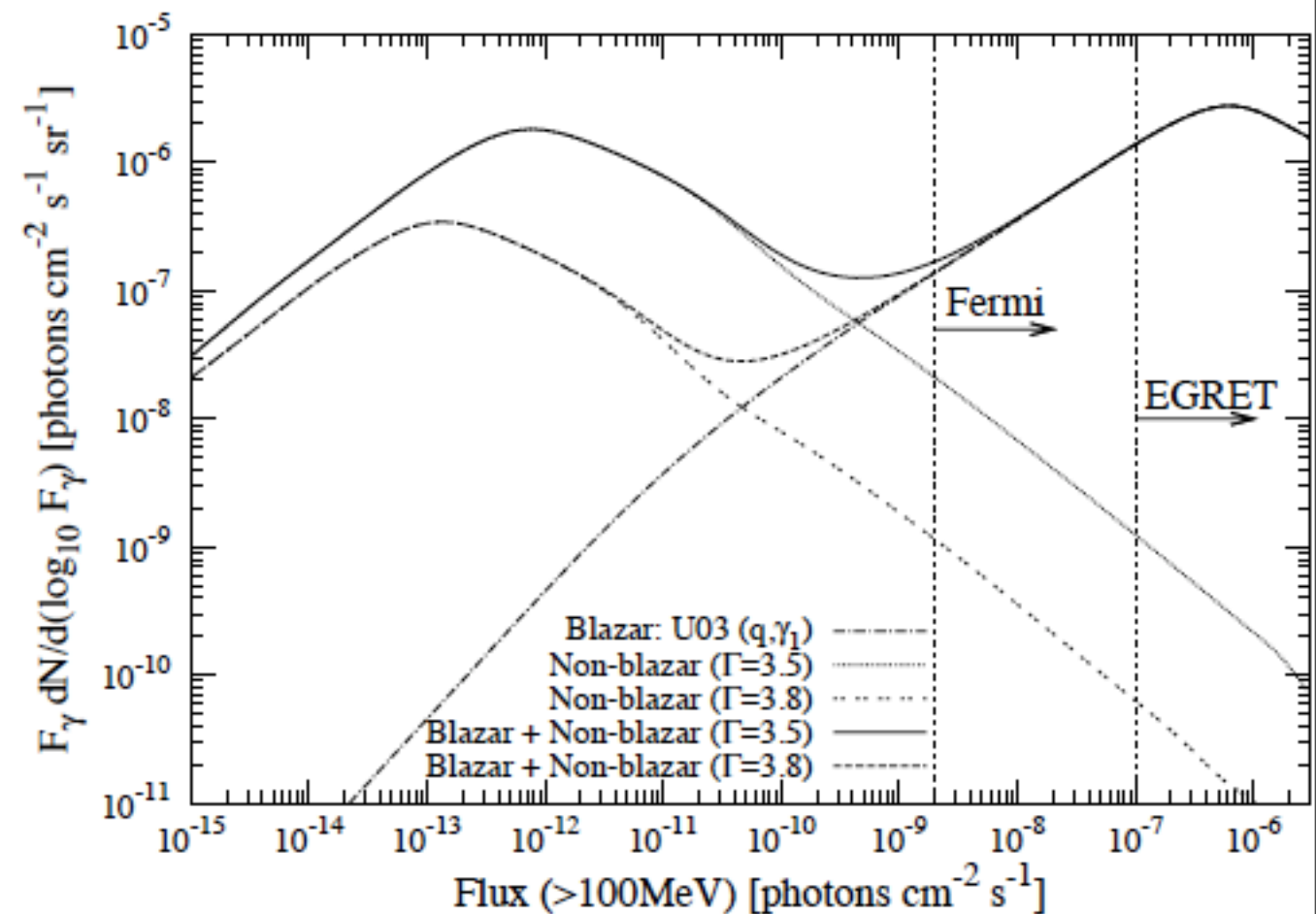
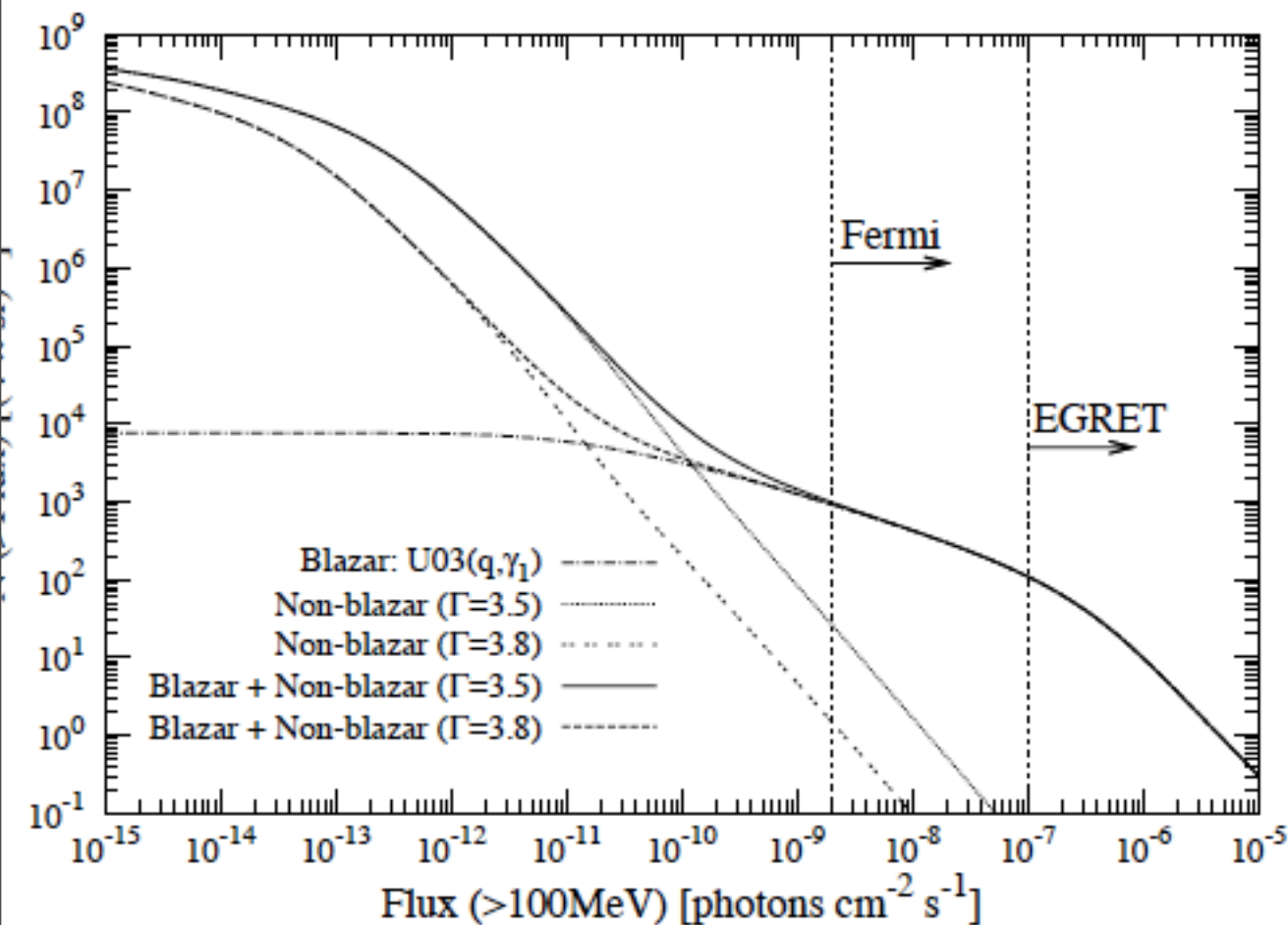
# Comparison with the Prediction by IT09





# Blazar Prediction for Fermi (1)

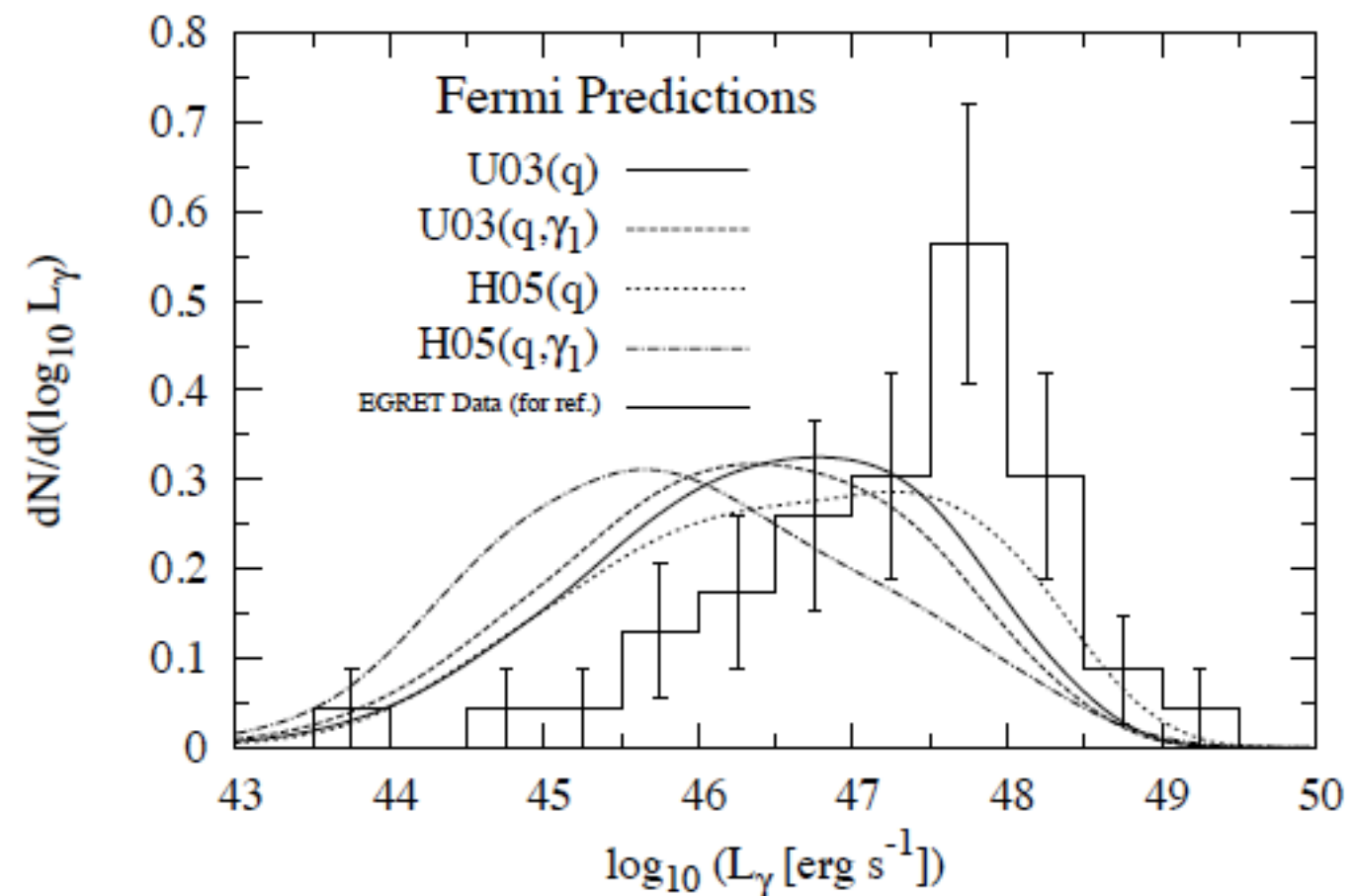
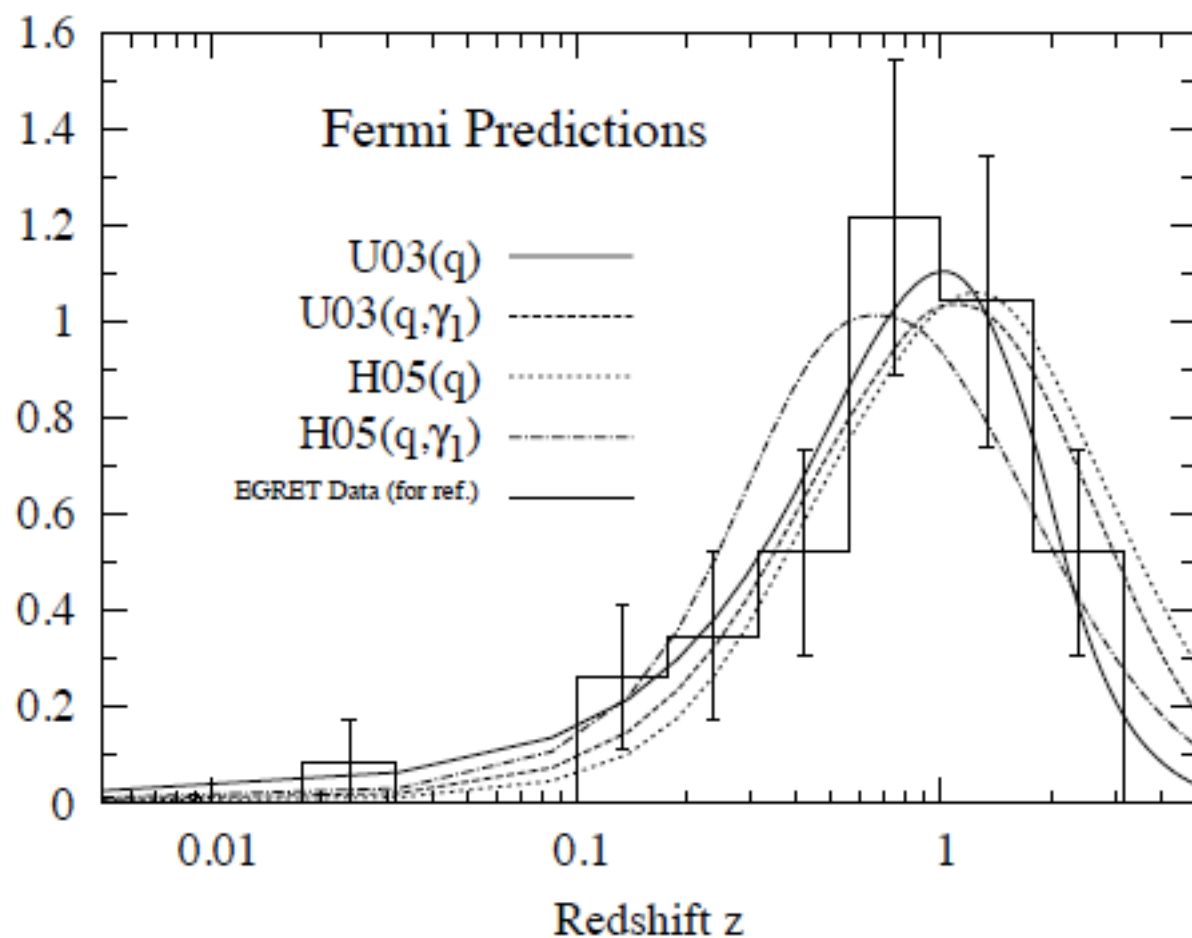
- ~1,000 blazars down to the expected final Fermi sensitivity
  - (considerably lower than many previous studies)
  - ~100 blazars in the current bright source catalog of Fermi
- Background from blazars will be resolved almost completely ( $>\sim 99\%$ )
  - background sources 100 times fainter could be probed
  - background from normal AGNs remain largely unresolved





# Blazar Prediction for Fermi (2)

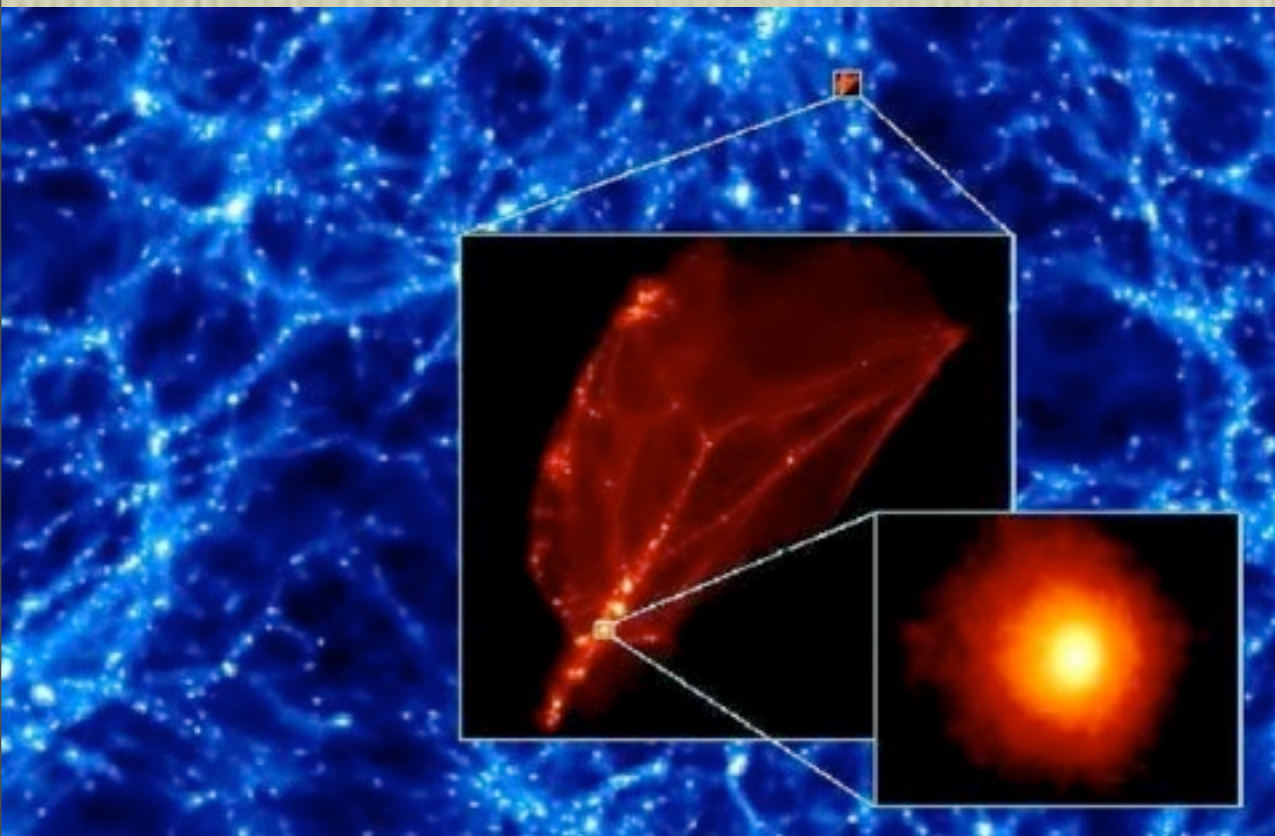
- redshift distribution not much different from EGRET
  - (but many more high-z blazars in absolute number than EGRET)
- probes lower luminosity range than EGRET
- $z > 7$  blazars may be found (expected number  $\sim 1$  from IT09 model)





# DM annihilation contribution to gamma-ray background?

- DM may contribute to gamma-ray background by
  - astrophysical/particle-physical boost factor
  - e.g., substructure down to  $\sim 10^{-6} M_{\text{sun}}$



Diemand+ '05

Oda, TT, Nagashima '05

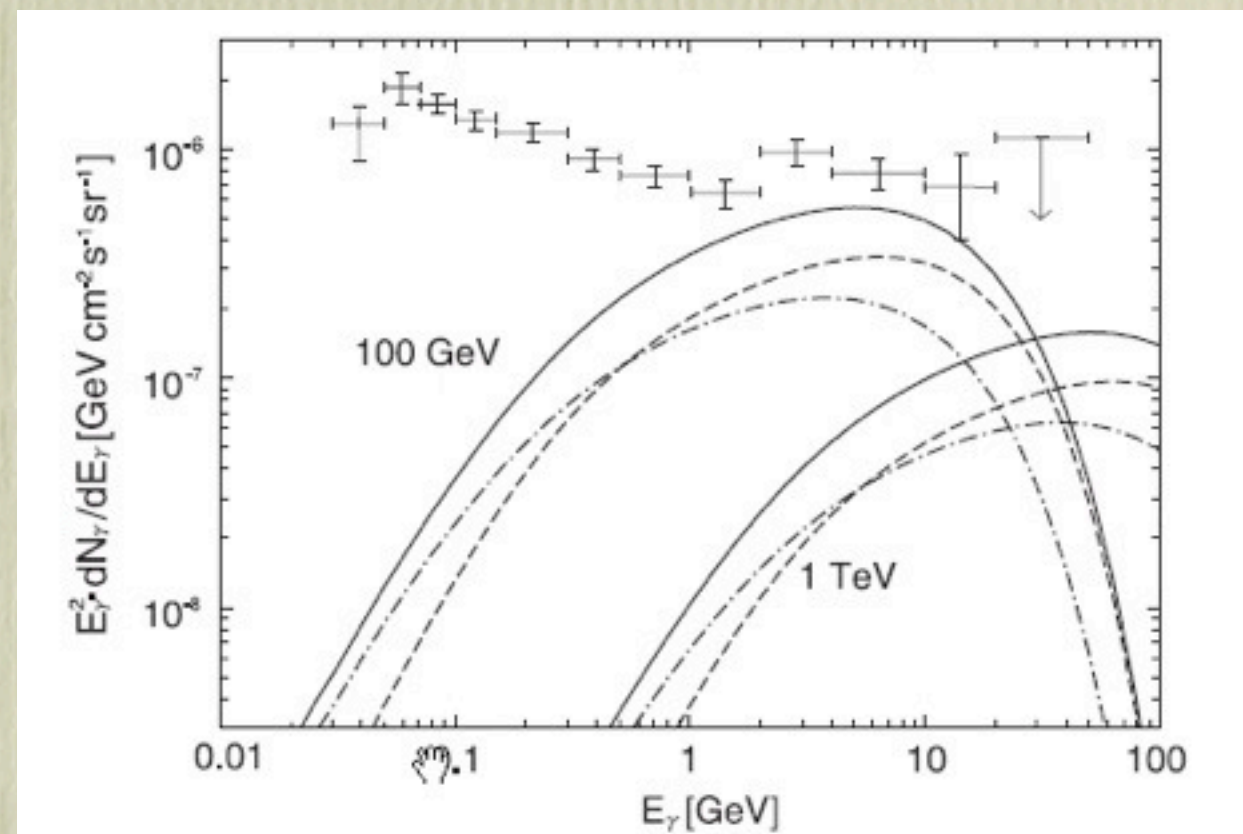
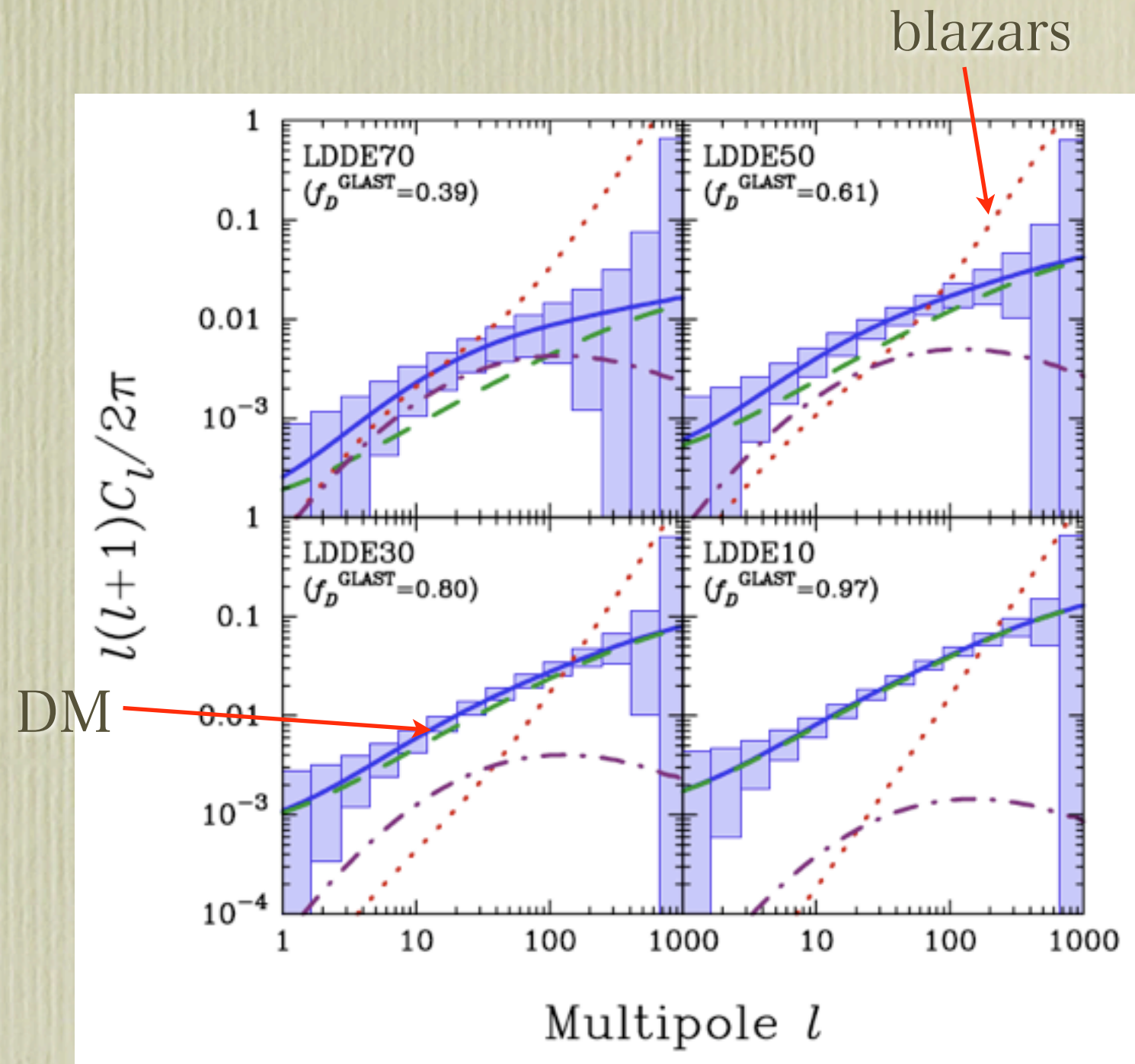


FIG. 1: The background gamma-ray flux from neutralino annihilation in the microhaloes. The GGRB (dashed), EGRB (dot-dashed), and the total (solid) components are shown. The two cases of  $m_{\chi} = 100$  GeV and 1 TeV are presented, with  $f_{\text{surv}} = 0.35$  and 1, respectively. The EGRET EGRB data points are from ref. [14]. The GGRB component assumes  $R_d = 5$  kpc and the baryon-compressed NFW profile for the Galactic halo. It is the mean of all sky except for the Galactic disk region, where the EGRB data are obtained.



# Anisotropy background signal from DM annihilation?

- (relatively) easy prediction:
  - blazars & other astro sources
  - DM annihilation from extragalactic halos
- Complication:
  - DM substructures in our Galaxy halo
- Challenge:
  - anisotropy in foreground Galactic diffuse (CR origin)
- see also Cuocco+'08, Miniati+'07, Hooper+'07, Fornasa+'09, Siegal-Gaskins+'08, Taoso+'09, Lee+'08

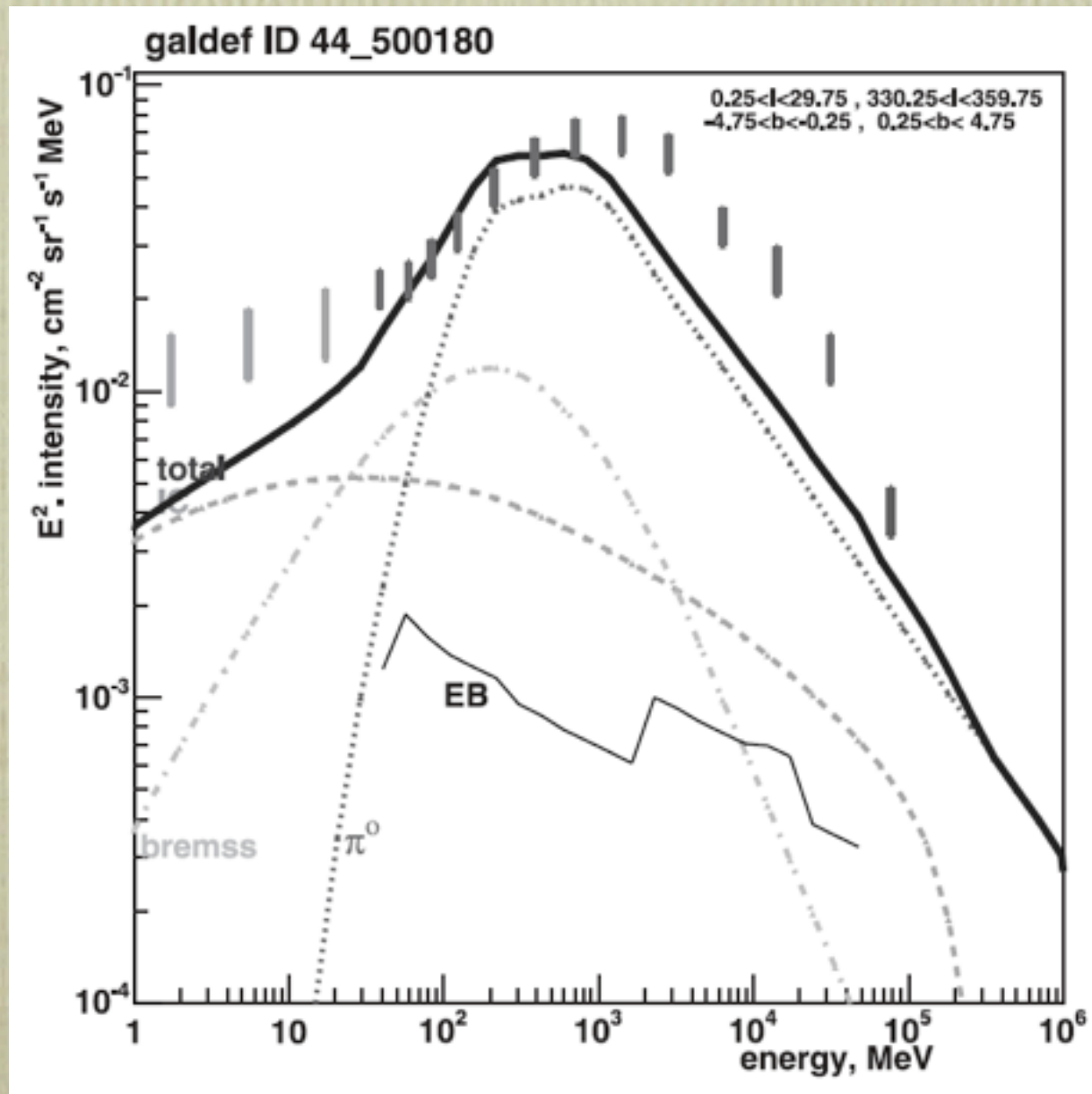


Ando, Komatsu, Narumoto & TT '07

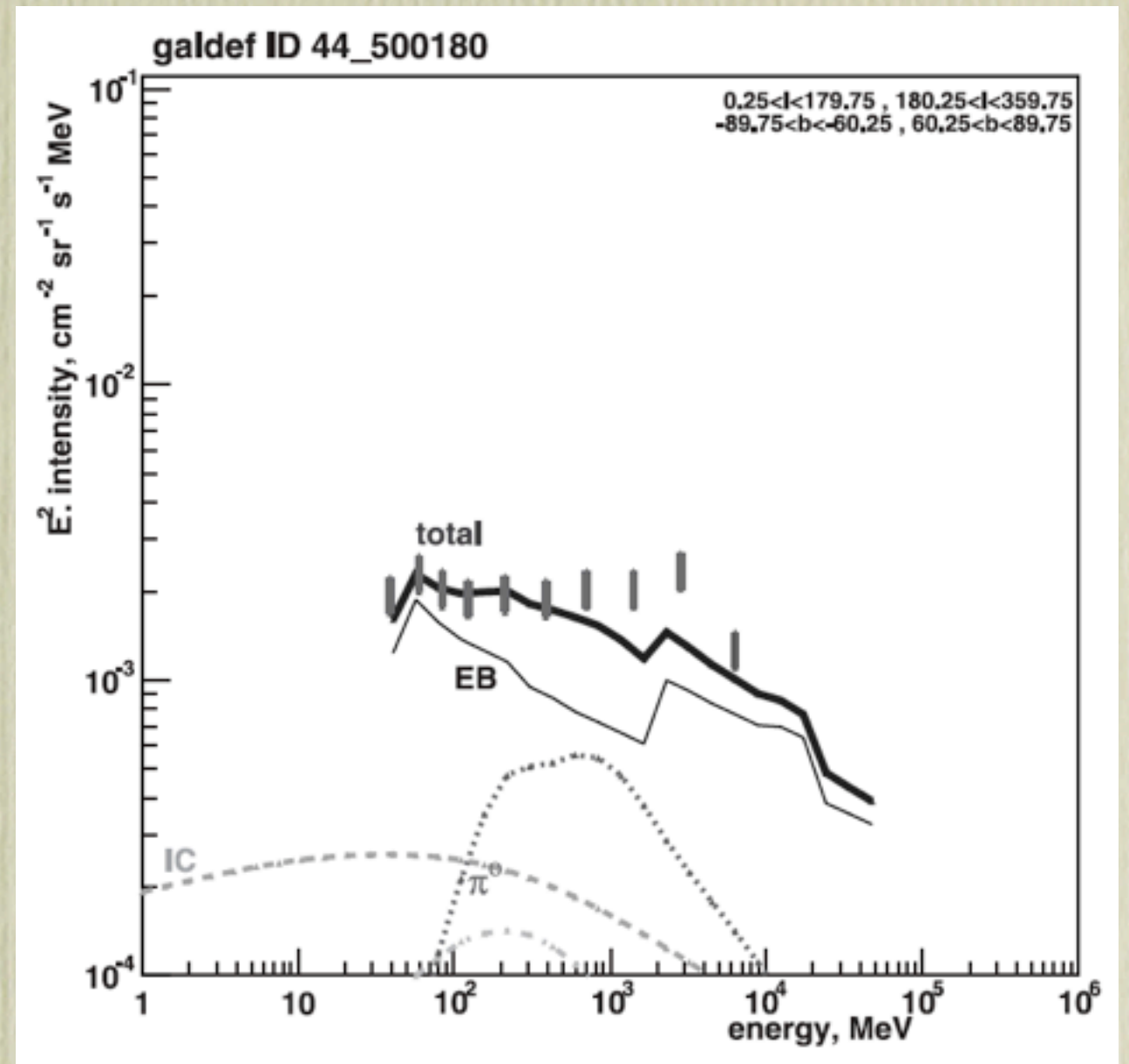


# Galactic vs. Extragalactic Diffuse

Galactic center region



Galactic pole region



Strong+'04



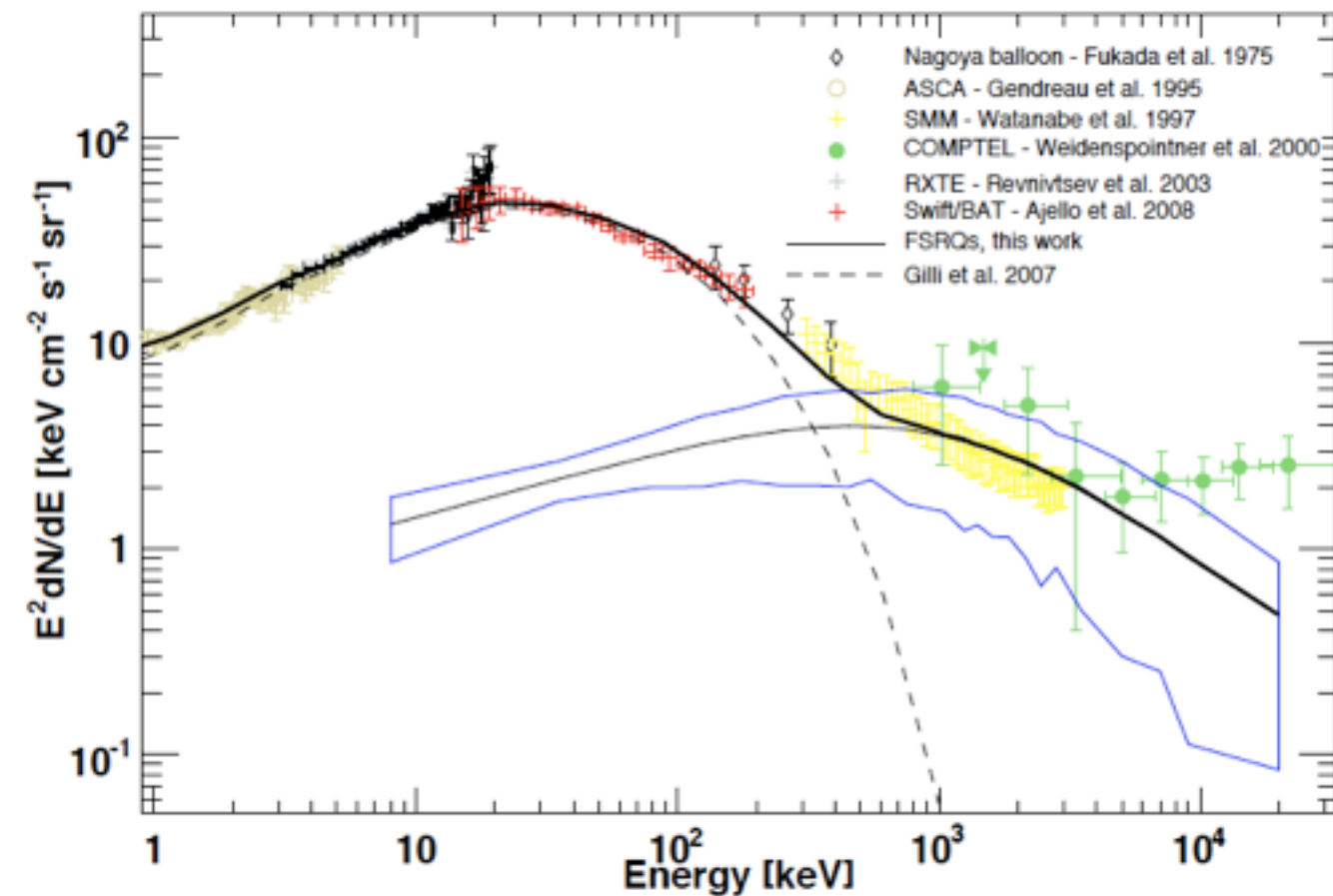
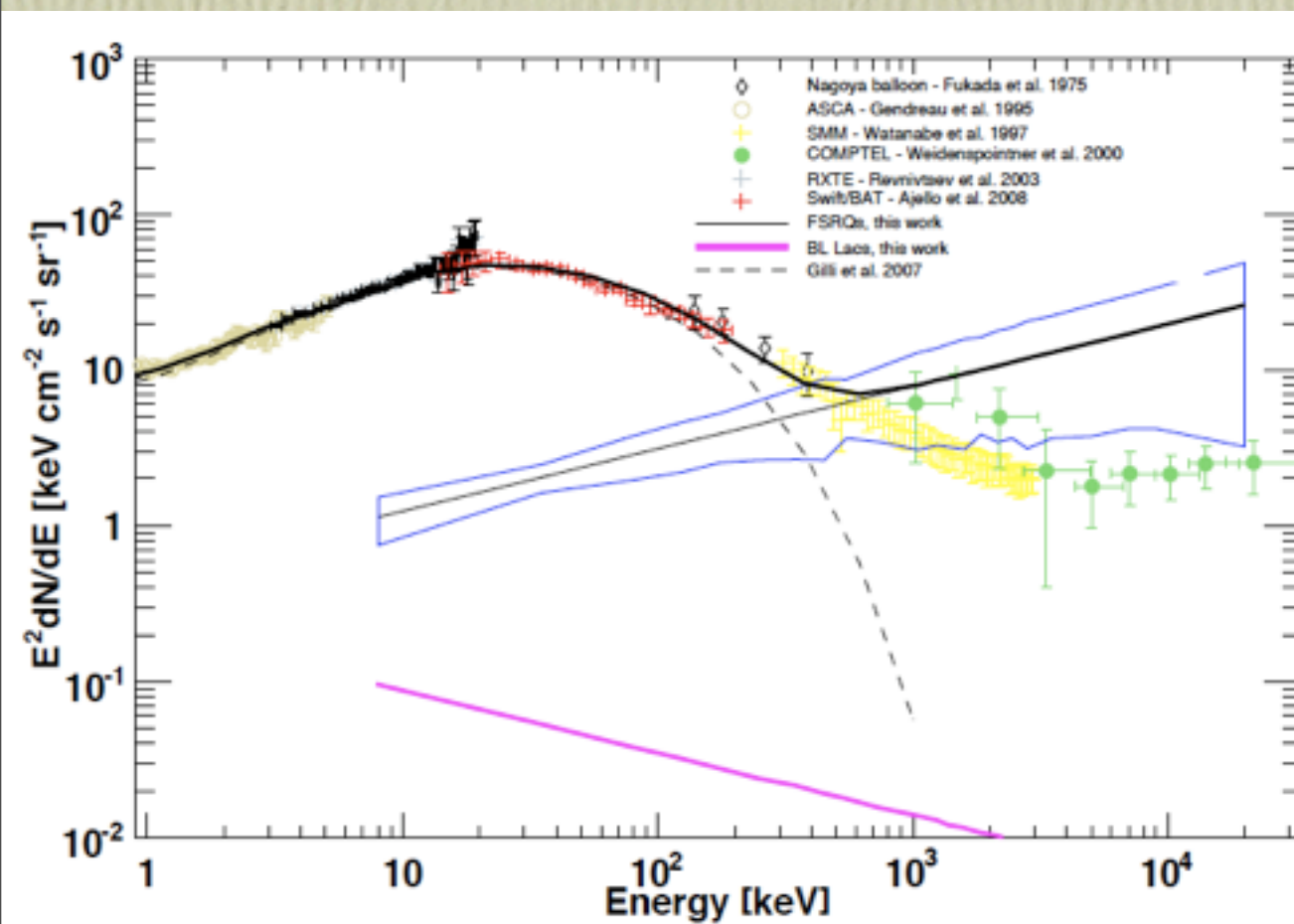
# GeV Background: Summary

- AGN's non-thermal tail + blazar can account for ~50-100% at  $< 1$  GeV
- A bump at  $> 1$  GeV in EGRET data?
  - DM annihilation?
  - systematic error in the EGRET detector (e.g. Stecker+'08)?
- New Fermi measurement in excellent agreement with IT09 model
  - Almost no room for exotic component
- Prospects for Fermi:
  - GeV background from blazars will be completely resolved
  - precise determination of LF evolution of blazars (AGN jets)
    - BH mass growth history vs. jet activity history of AGNs?



# MeV Blazars and MeV background

- blazars detected by Swift/BAT (10-55 keV) may significantly contribute to MeV background (Ajello+'09)
- しかし、CXB に滑らかにつなげるには SED の fine tuning が必要





# 銀河系中心からの 511 keV 電子陽電子対消滅ガンマ線



# The 511 keV Annihilation Line Emission from GC

- ☉ extended spherical bulge with  $\sim 8$  deg FWHM ( $\sim 1.1$  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  $\sim 1.5 \times 10^{43} \text{ s}^{-1}$

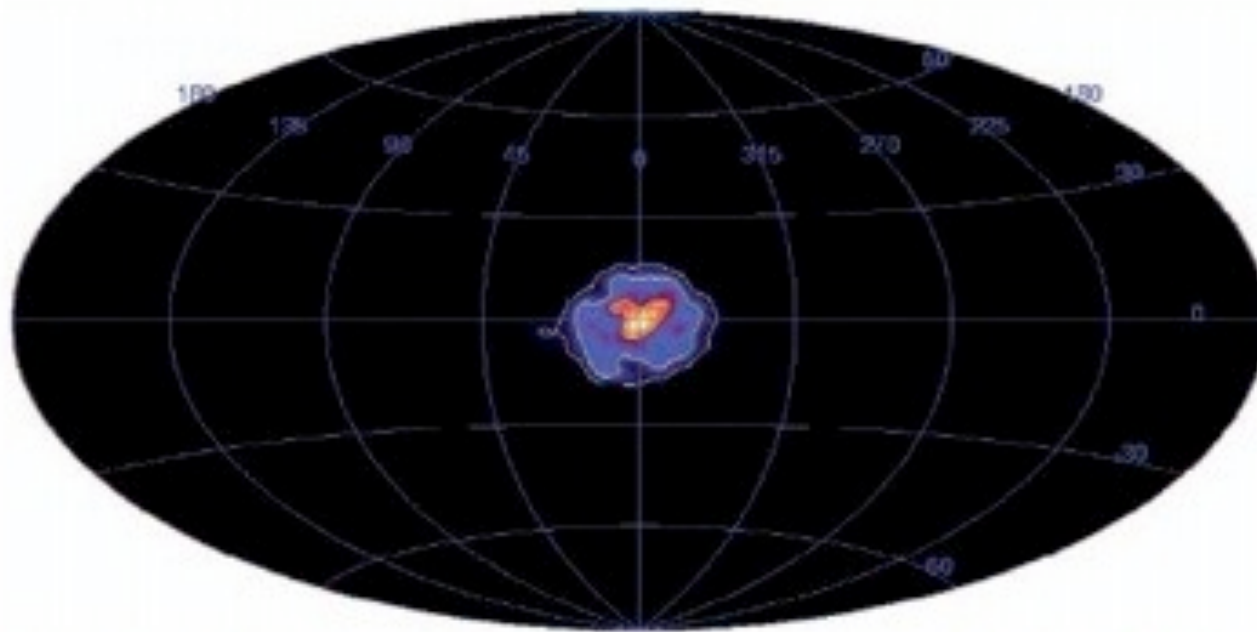


Fig. 4. Richardson-Lucy image of 511 keV gamma-ray line emission (iteration 17). Contour levels indicate intensity levels of  $10^{-2}$ ,  $10^{-3}$  and  $10^{-4} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$  (from the centre outwards).

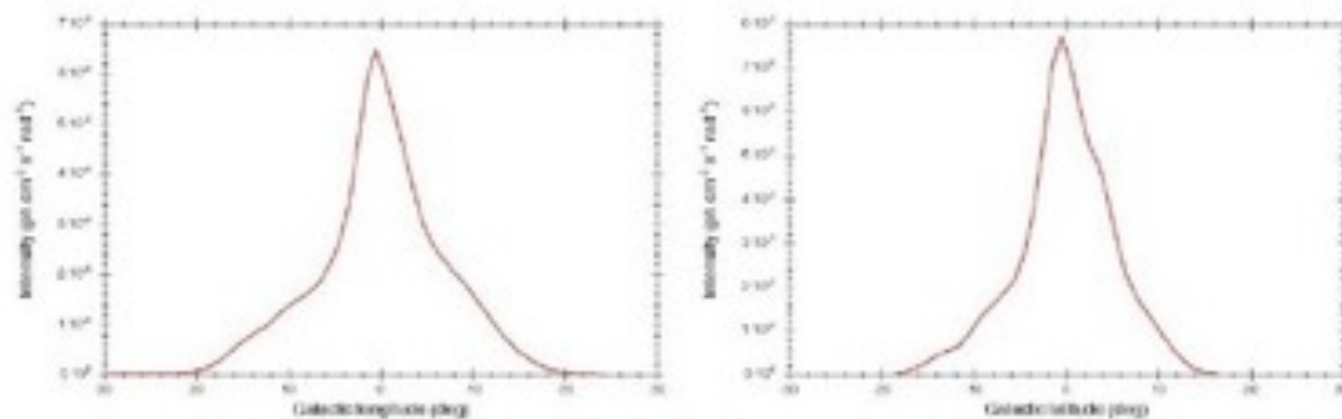
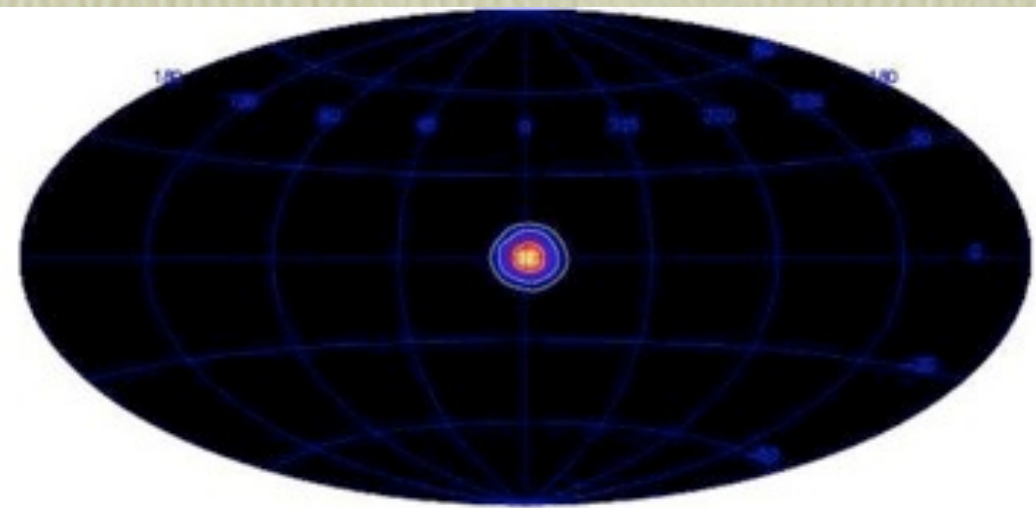


Fig. 5. Longitude and latitude profiles of the image shown in Fig. 4 (integration range  $|l| \leq 30^\circ$ ,  $|b| \leq 30^\circ$ ).

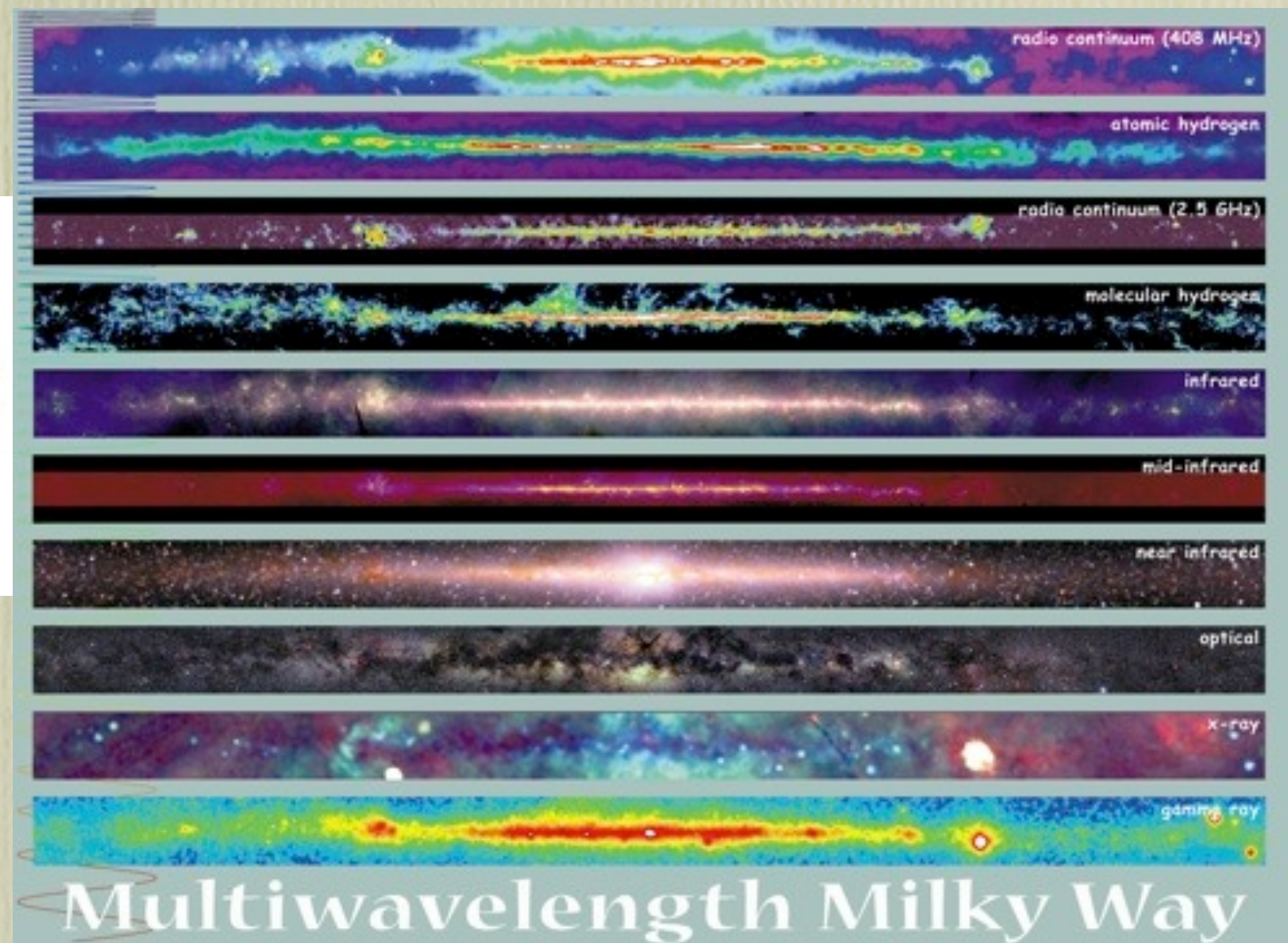
Knodlseder et al. 2005



# Unique Morphology!



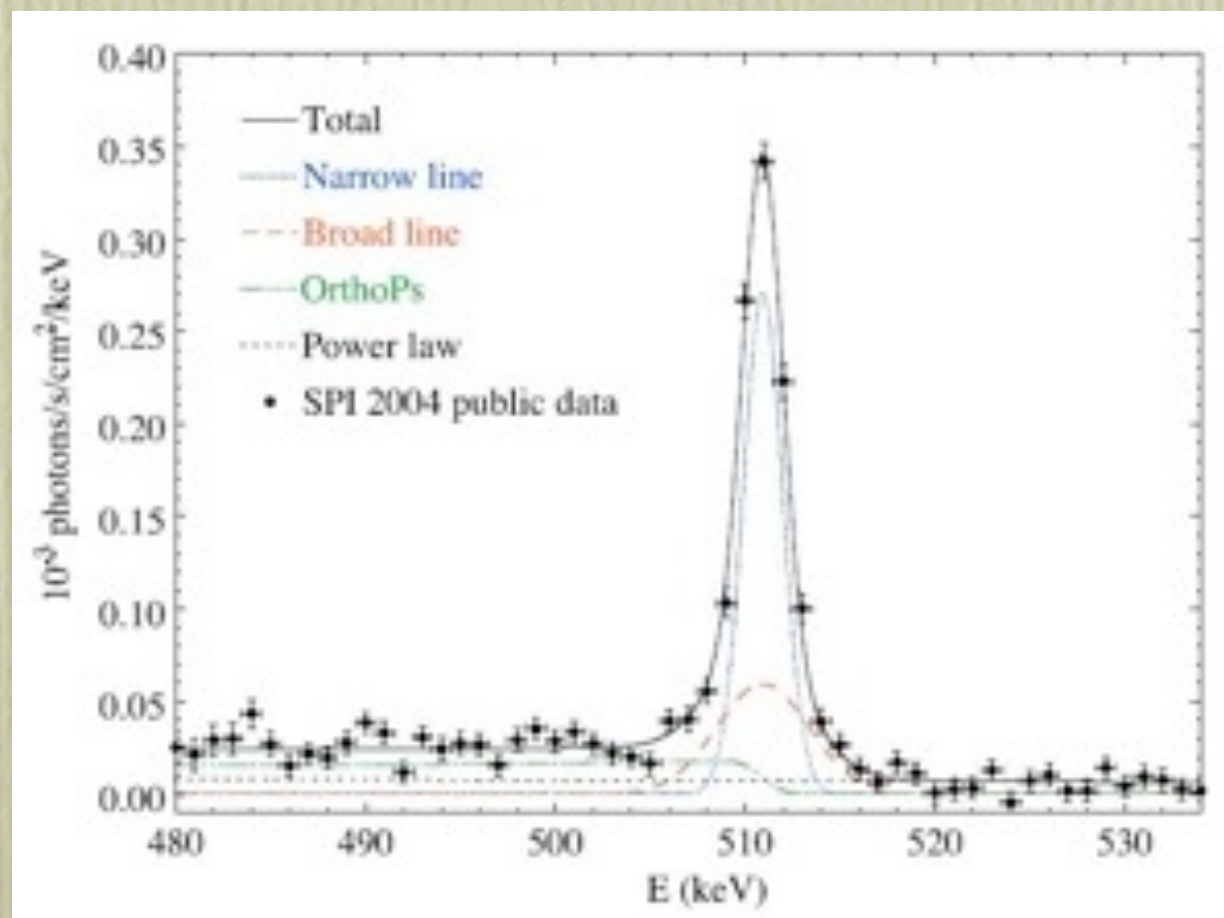
Weidenspointner+ '06



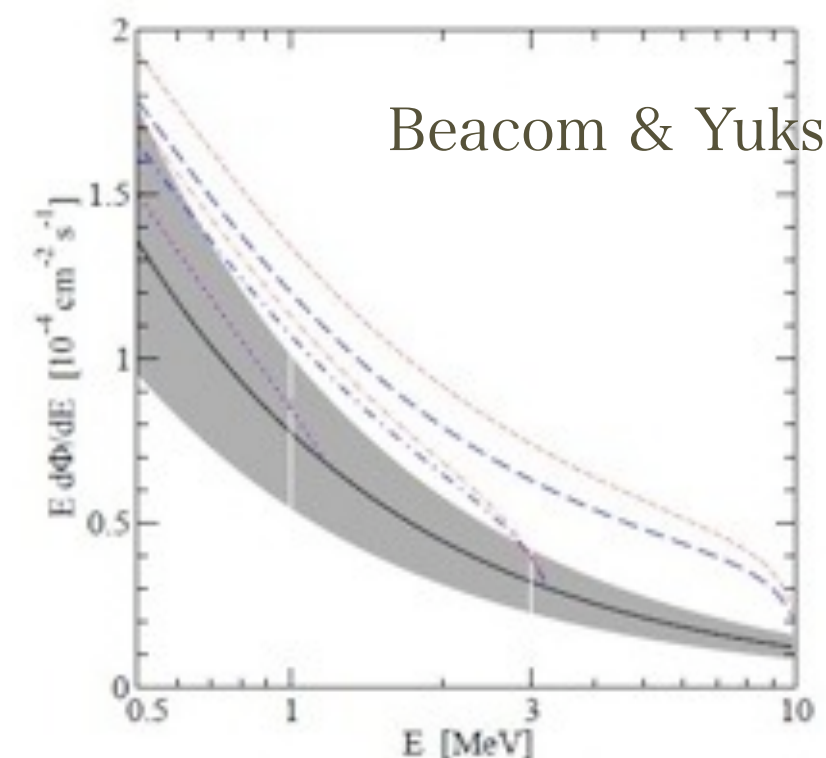


# The 511 keV Annihilation Line Emission from GC

- narrow line width
- positronium fraction:  $0.967 \pm 0.022$  (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  $\sim 10^7$  yr
- injection positron energy  $< \sim 3$  MeV (Beacom+'05)



Jean et al. 2006



Beacom & Yüksel '05

FIG. 2: The INTEGRAL and COMPTEL diffuse gamma ray flux measurements are shown with a black solid line, and their  $\pm 30\%$  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  $5^\circ$ -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、 $^{26}\text{Al}$  と consistent
- Bulge component:
  - type Ia SNe:
    - rate not sufficient ( $\sim 1/10$ ) (Prantzos 2006)
    - 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  $\sim 3-4$
  - production rate insufficient
- X-ray binaries / microquasars (Guessoum+ 06)
  - production rate uncertain
  - B/D  $\sim 1$
  - broad line 511 keV emission directly from sources



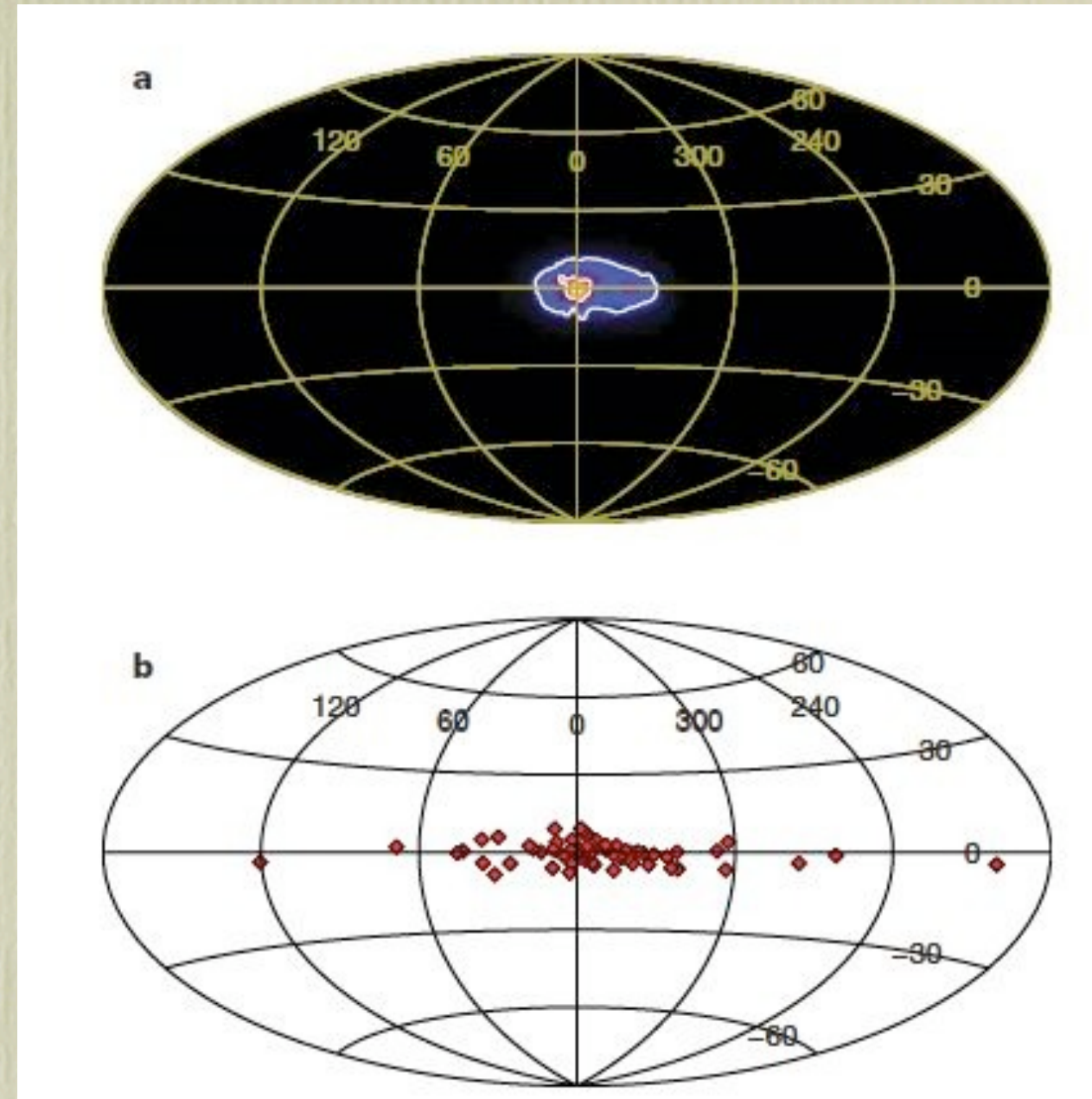
# Proposed Models for 511 keV Emission

- Bulge component (contd.):
  - propagation from disk positrons (Higdon+'09)
  - 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  $\sim 30$  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  $\sim$  MeV



# Asymmetry in the Disc component?

- Consistent with the hard LMXB distribution along the disk
- However, bulge component cannot be explained by the B/D ratio of LMXB
  - Sgr A\* or DM annihilation?
- LMXB asymmetry?
  - May be just a statistical fluctuation



Weidenspointer+2008



# 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\*

- Radiatively Inefficient Accretion Flow (c.f. standard accretion disk)

- Application to Sgr A\* (Yuan+ '03)

- Outer boundary at Bondi radius from X-ray observation

- quiescent X-ray emission spatially resolved by  $\sim 0.1$  pc)

- Bondi accretion rate  $\sim 10^{-6}$  Msun / yr

- Non-conserving mass accretion flow

- Faraday rotation 観測からの制限を満たす上で必要

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

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

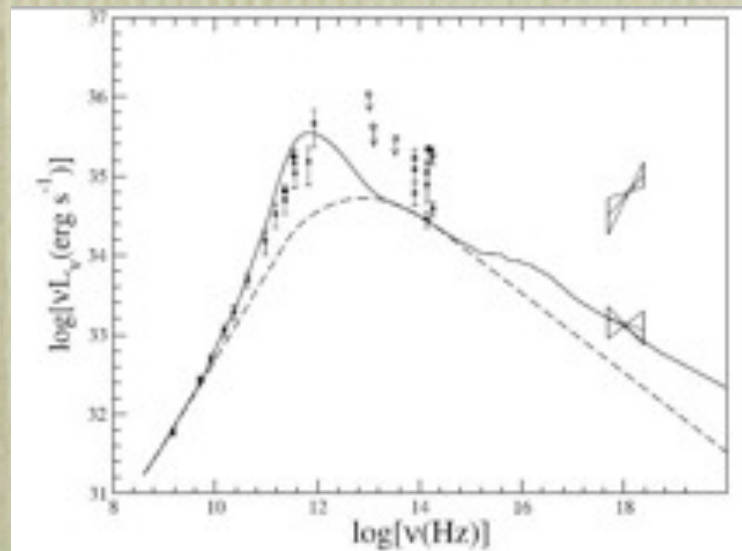


FIG. 1.—RIAF model for the quiescent state of Sgr A\*. The IR data with error bars are from Ghez et al. (2004) and Genzel et al. (2003), the radio data with error bars from Falcke et al. (1998, open circles) and Zhao et al. (2003, filled circles), the IR data with upper limits from Serabyn et al. (1997, 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  $p$  between the models shown for 2003/2001 (of  $p = 3$ ) is to fit the quiescent IR data better.

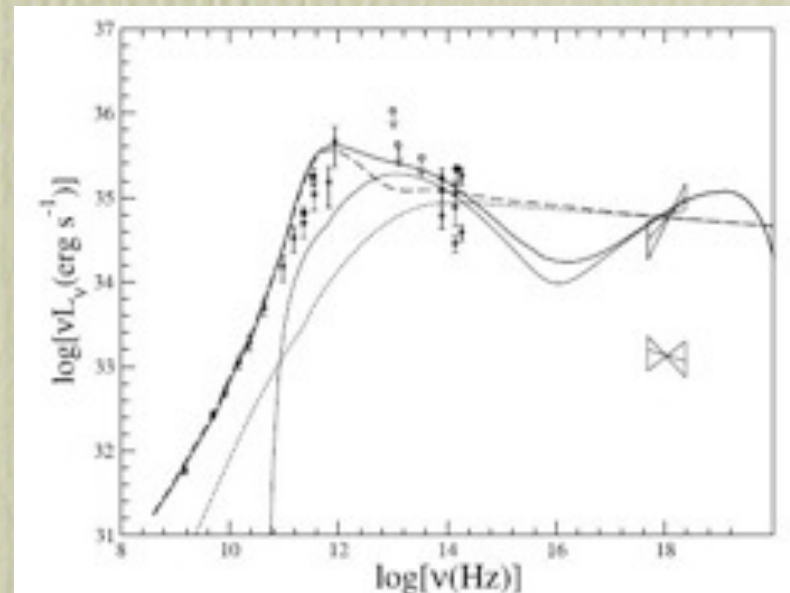


FIG. 3.—Pure synchrotron models for the IR and X-ray flares in Sgr A\*. The two dashed lines are models in which the electrons are assumed to have  $p = 2.1$ . The solid lines are for the broken power-law model (eq. [1]), with  $p_1 = 3$ ,  $p_2 = 1$ ,  $\eta = 7\%$ ,  $\gamma_{\text{max}} \sim 10^6$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

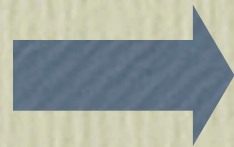
Yuan+ '04



# RIAF model は mass outflow を予言する

- non-conserving mass accretion rate  $\propto$  outflow
- e.g. Blandford & Begelman '99

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



Outflow from region around  $r \sim r_s$

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

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



# positron production from Sgr A\*

- 降着流の中で、
  - $e^-e^- \rightarrow e^-e^-e^-e^+$
  - $e^- \gamma \rightarrow e^-e^-e^+$
  - $\gamma \gamma \rightarrow e^-e^+$
  - 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 ( $10^{3-4}$  倍高い降着率が必要)
- 過去の活動性！？



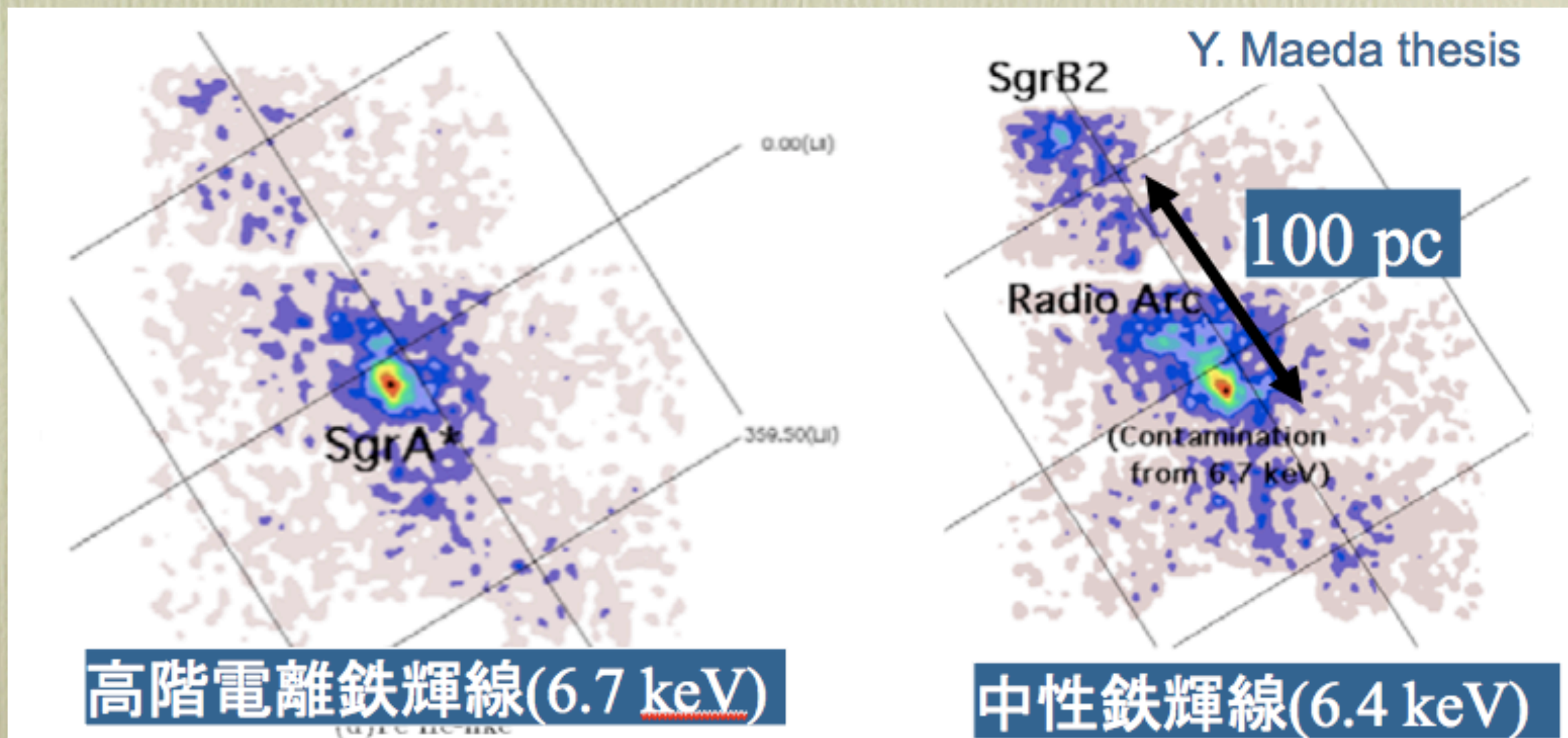
# Evidence for Past Higher Activity of the Galactic Center

- 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  $\sim 3 \times 10^{39}$  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  $10^{5-6}$  倍！





# Evidence for a Large Scale Outflow from GC

- estimated massive outflow energy:  
 $10^{55}$  erg in  $\sim 10^6$  yrs on the scale of  
the Galactic center lobe (GCL)

- $\sim 100$  km/s

- a few degree  $\sim 300$  pc

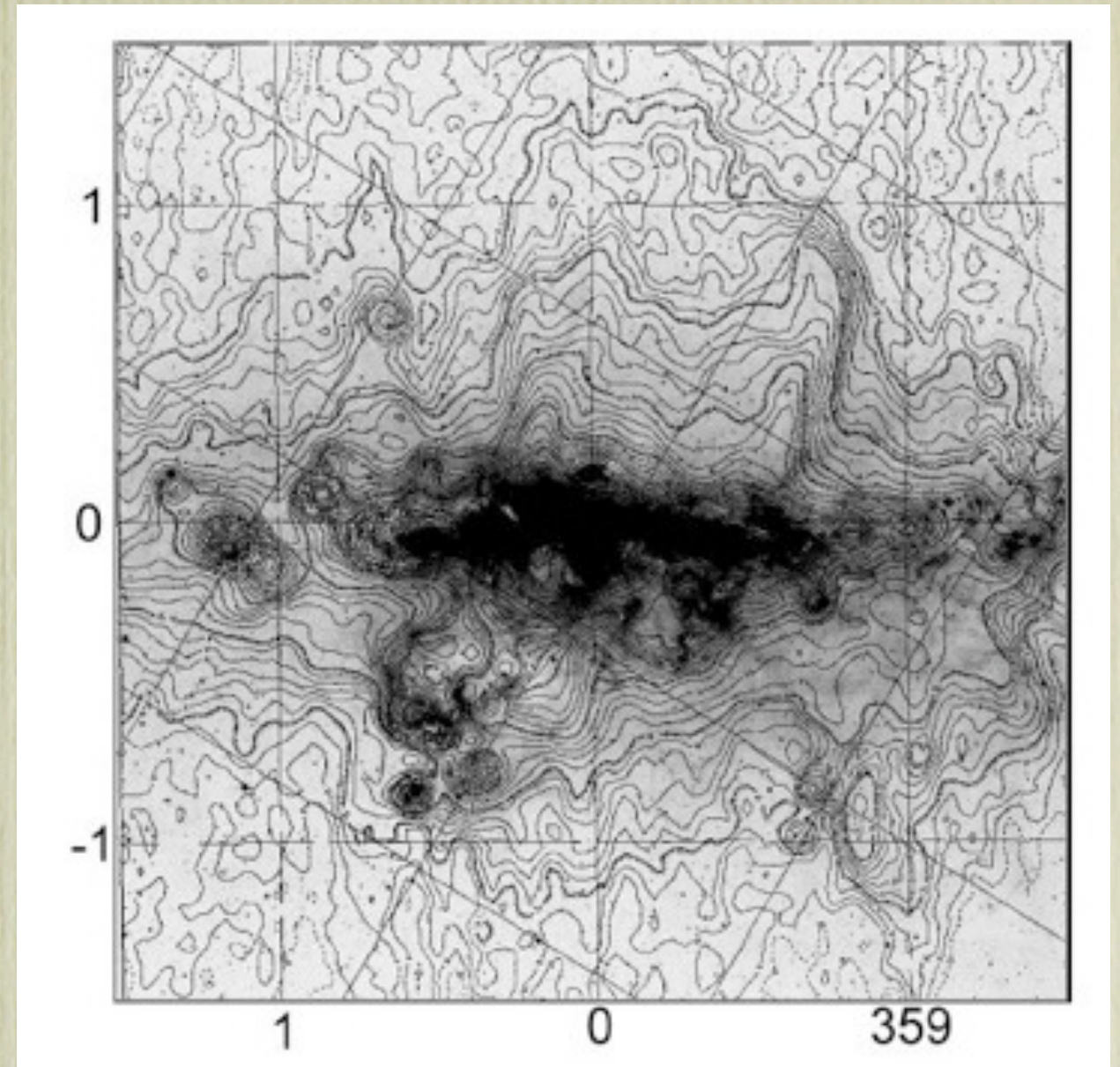
- Bland-Hawthorn & Cohen '04

- Other independent evidences:

- Expanding molecular ring (Kaifu et al. '72; Scoville '72)

- North Polar Spur (Sofue '00; Brand-Hawthorn+'04)

- Kinetic luminosity  $\sim 10^{41-42}$  erg/s



Bland-Hawthorn & Cohen '03

Image: MSX 8.3  $\mu$ m (dust)

Contour: 3 cm (thermal)

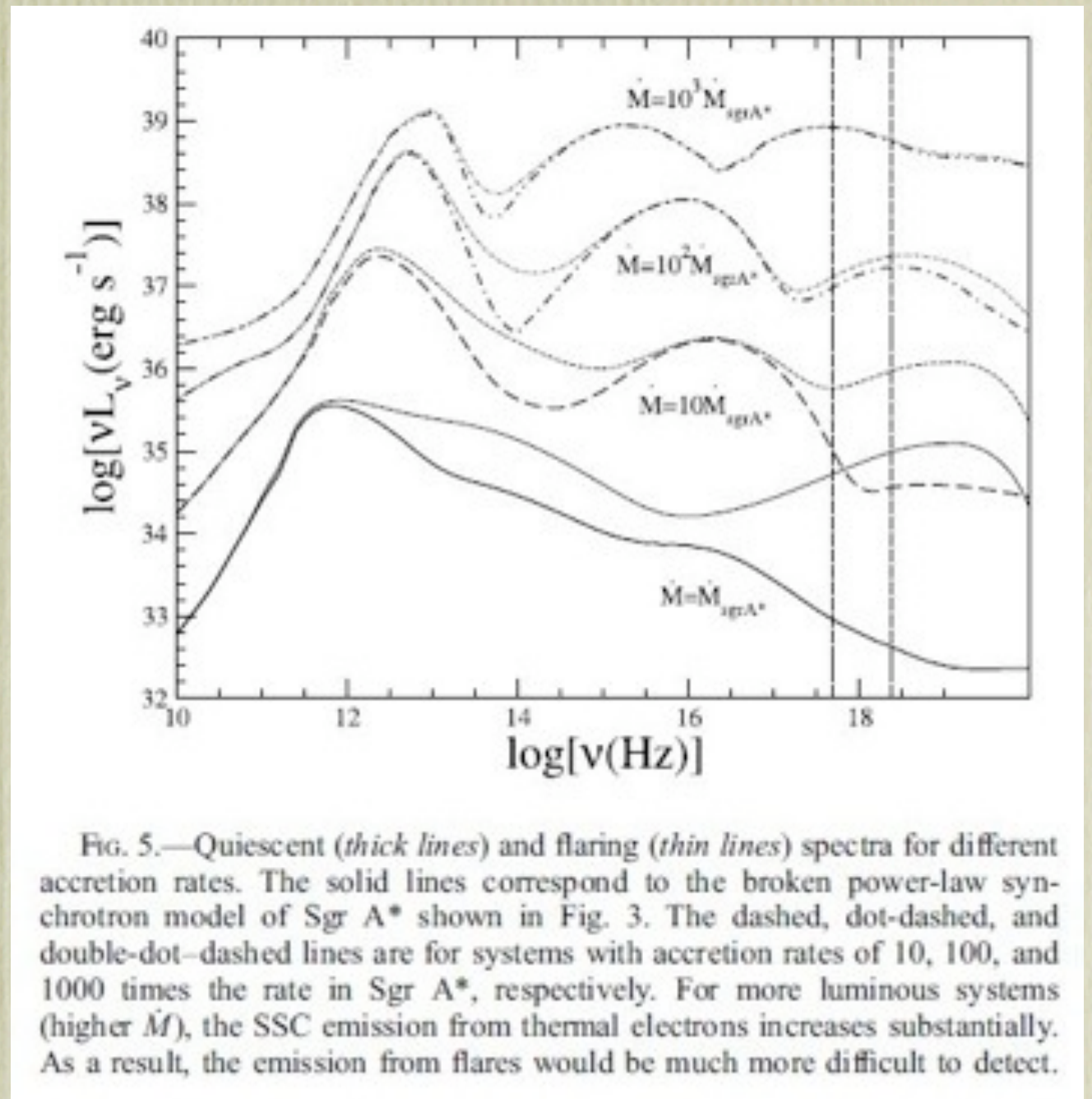


# Explaining Observational Evidence for the Higher Activity by the RIAF Picture

● RIAF では、一般に

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

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



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  $L_X \sim 3 \times 10^{39} \text{ erg/s}$
- Sgr A\* の RIAF model で、これを説明するには

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

$$\text{として、} f_B \sim 10^3 - 10^4$$

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

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

$$L_{wind} \sim 9.5 \times 10^{41} f_{3.5} \text{ erg/s}$$

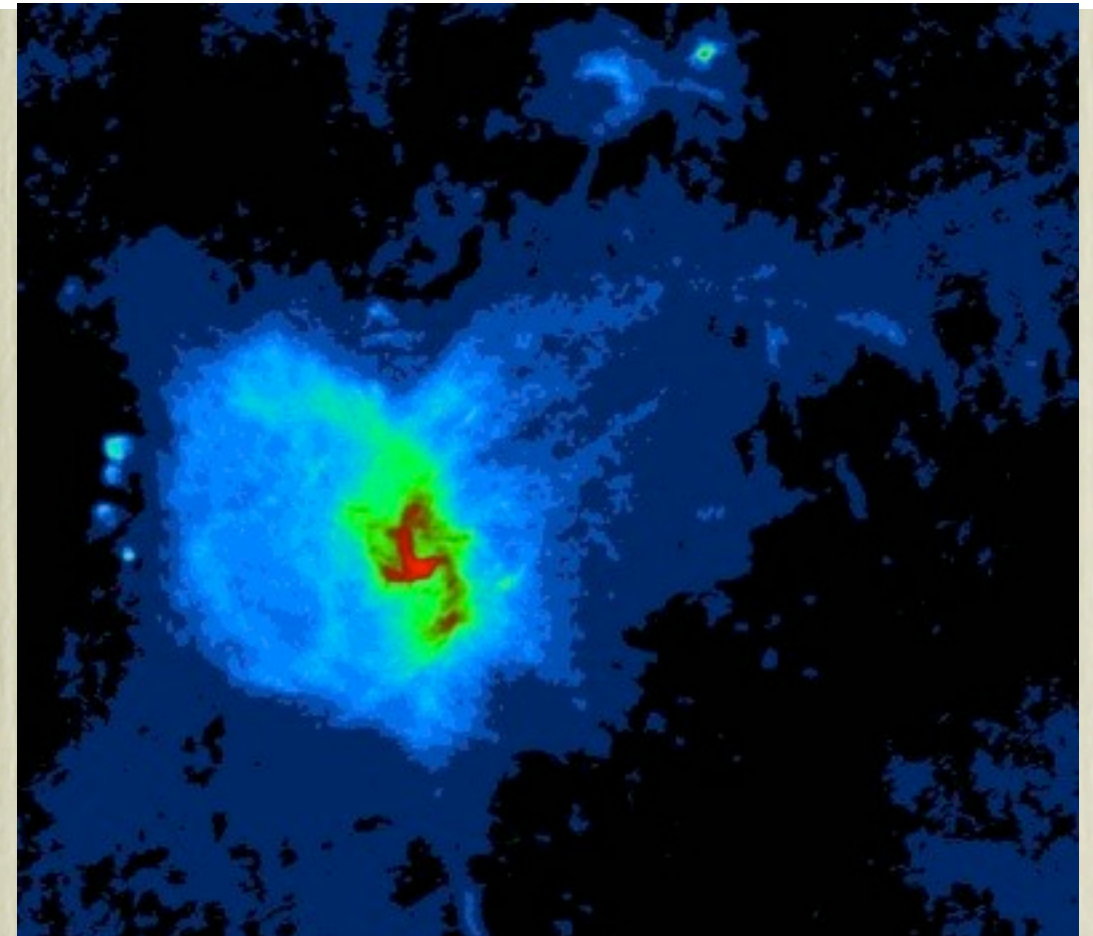
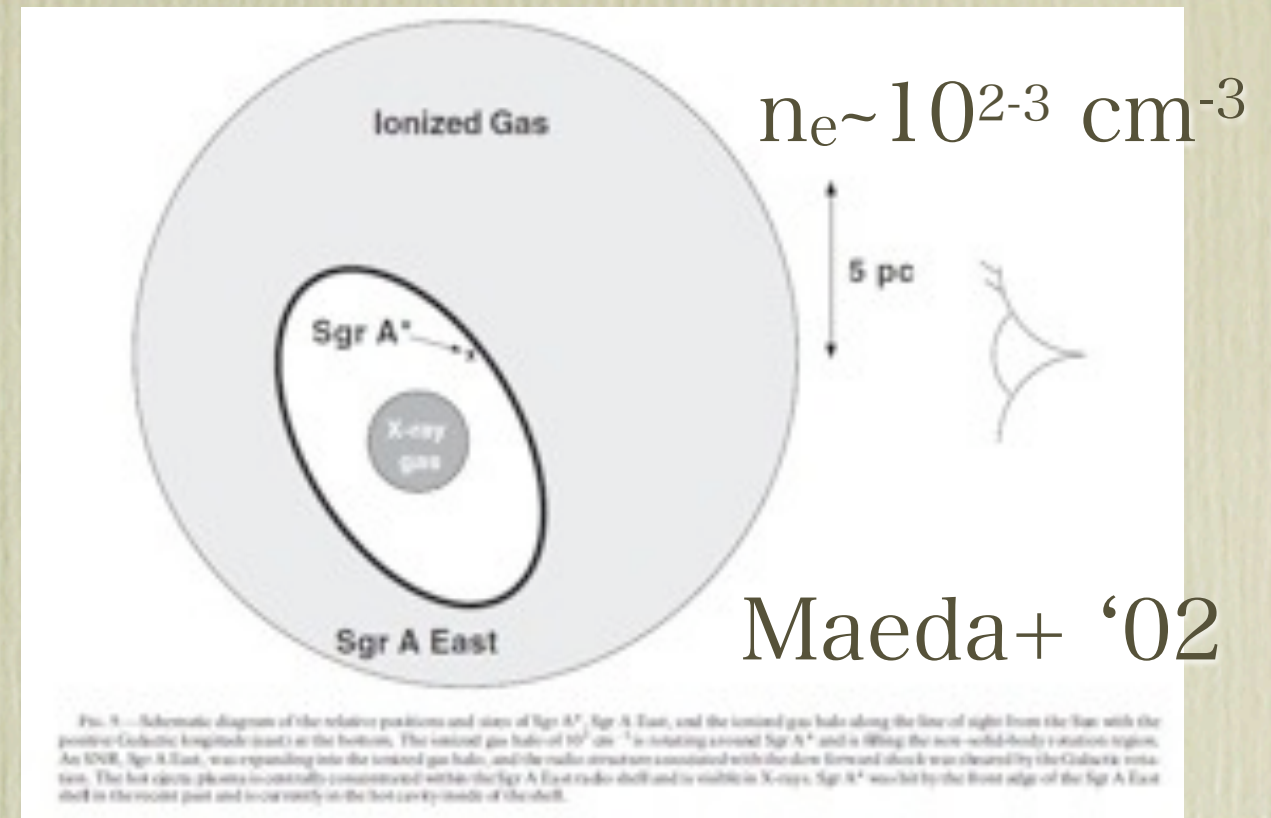
$$(f_{3.5} \equiv f_B / 10^{3.5})$$

- GCL, EMR, NPSなどから示唆される outflow kinetic luminosity  $\sim 3 \times 10^{41} \text{ erg/s}$
- ほぼ同じ boost factor で、X線光度も outflow kinetic luminosity も説明できる
- さらに、positron 生成も説明可能



# 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  $10^{3-4}$  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



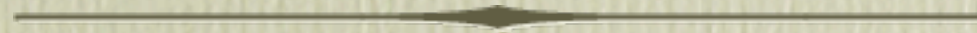


# Implications for 511 keV Emission

- positron production rate by Sgr A\* accretion flow  $\sim$  required from 511 keV observations ( $\sim 10^{43}$  /s) when  $f_B \sim 10^{3-4}$ 
  - $f_B \sim 10^{3-4}$  is consistent with observational evidence of GC past activity
- propagation:
  - 観測された広がり、 $\sim 10^7$  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
- 将来の MeV 観測による検証に期待
  - morphology による、Sgr A\* vs. propagation from disk の検証

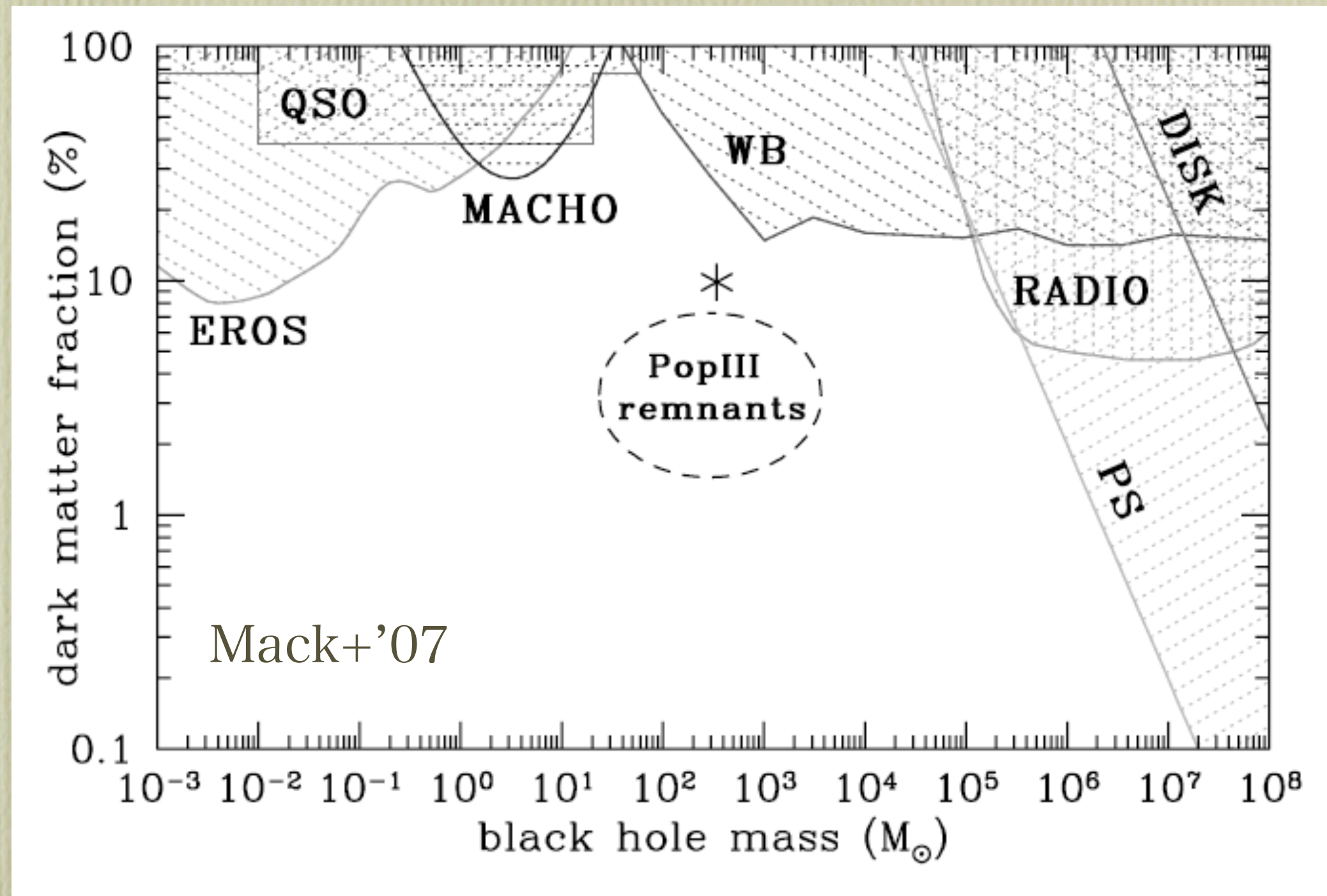


# MACHOs 再考： 楕円銀河のサイズ進化？





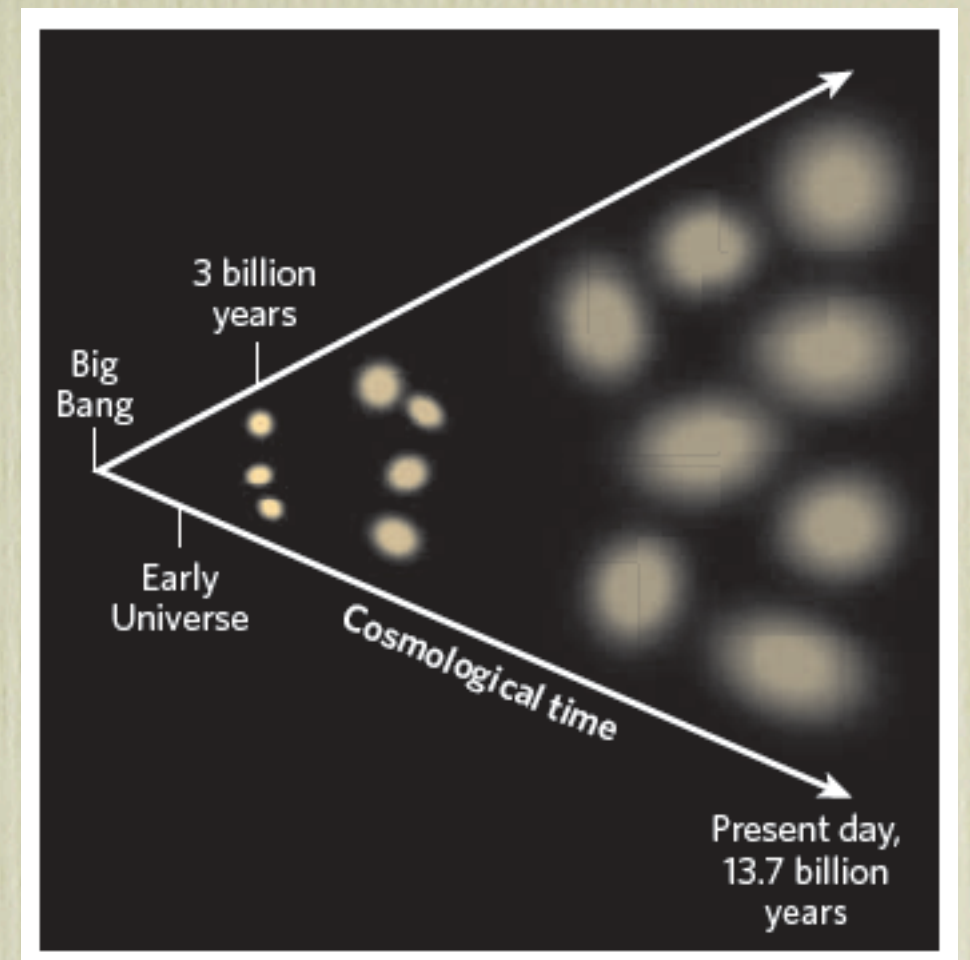
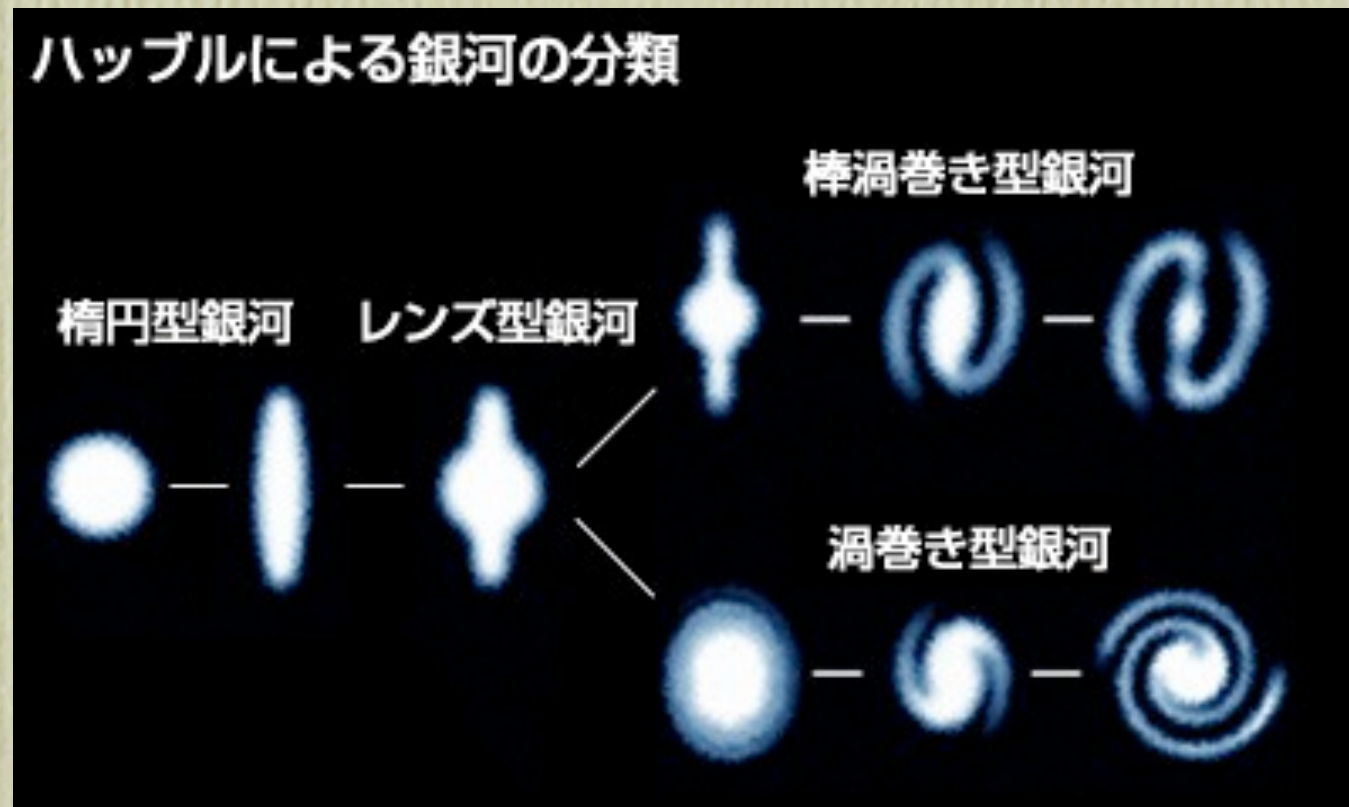
# MACHOs への観測的制限



- $10^{-10^5} M_{\text{sun}}$  付近に、まだ window が残っている
- 観測的兆候？



# 楕円銀河のサイズが進化している！？

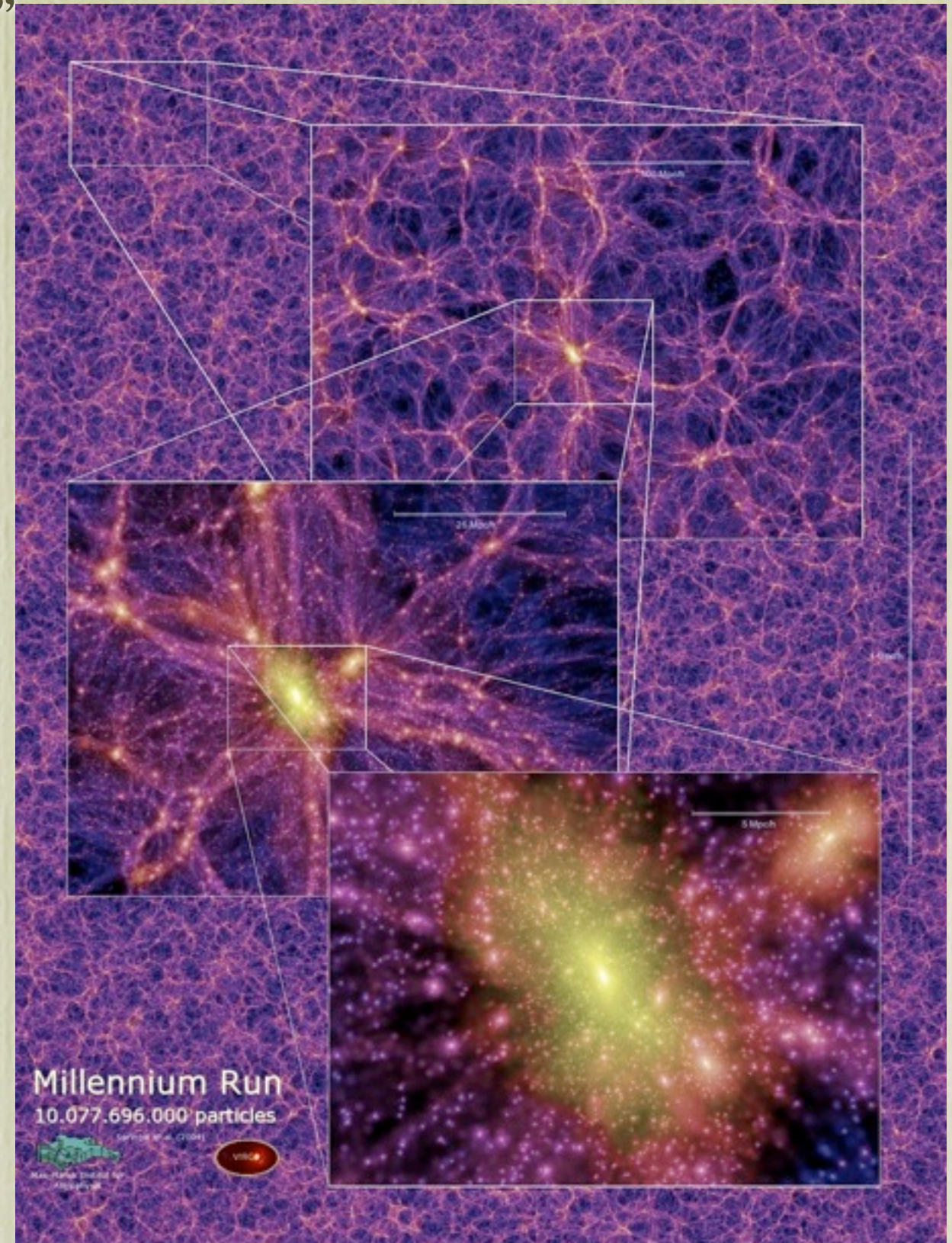
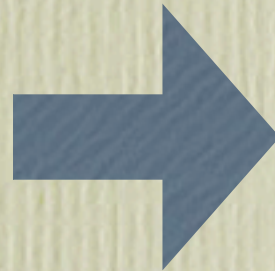
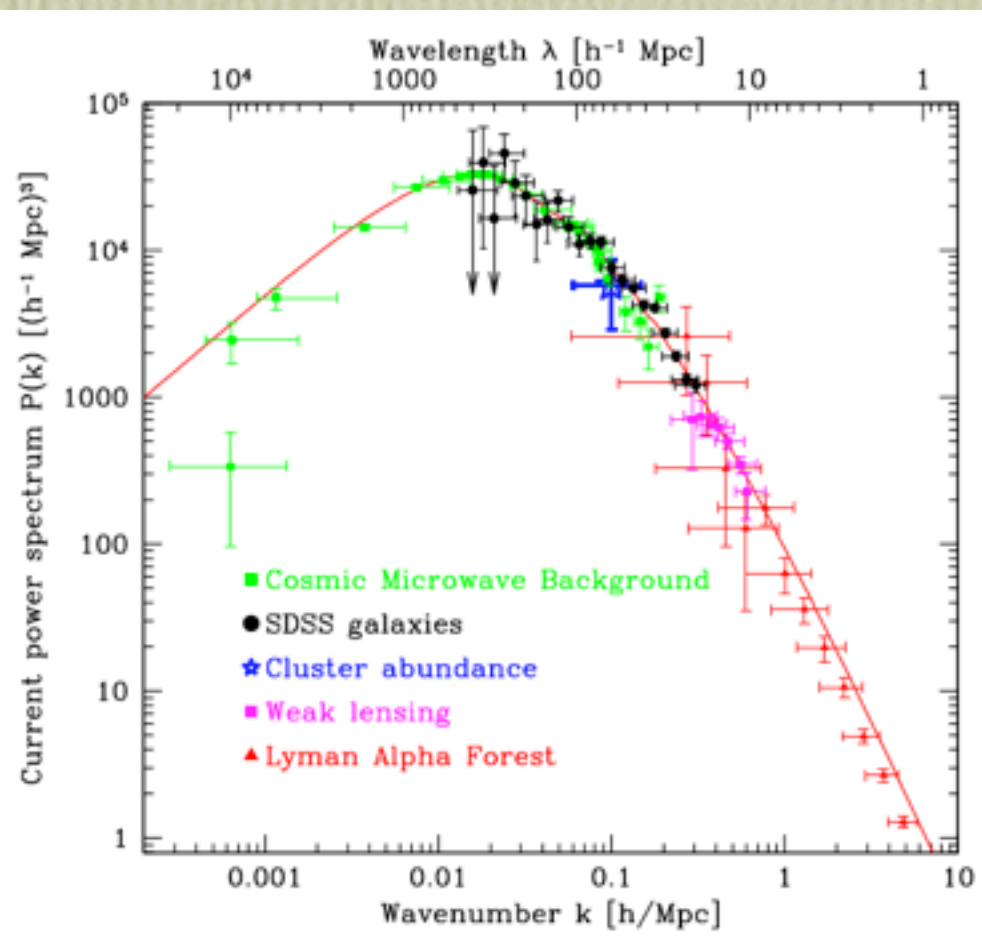
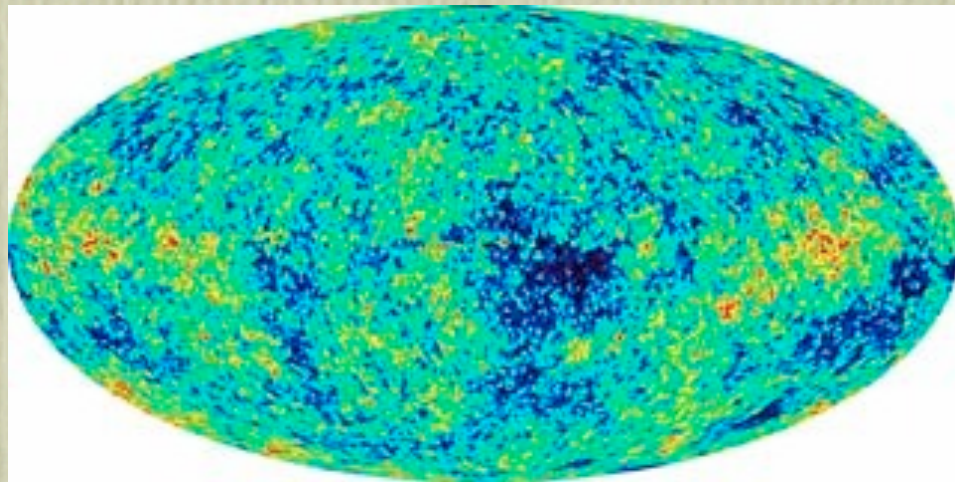


M87



# 銀河形成のシナリオ

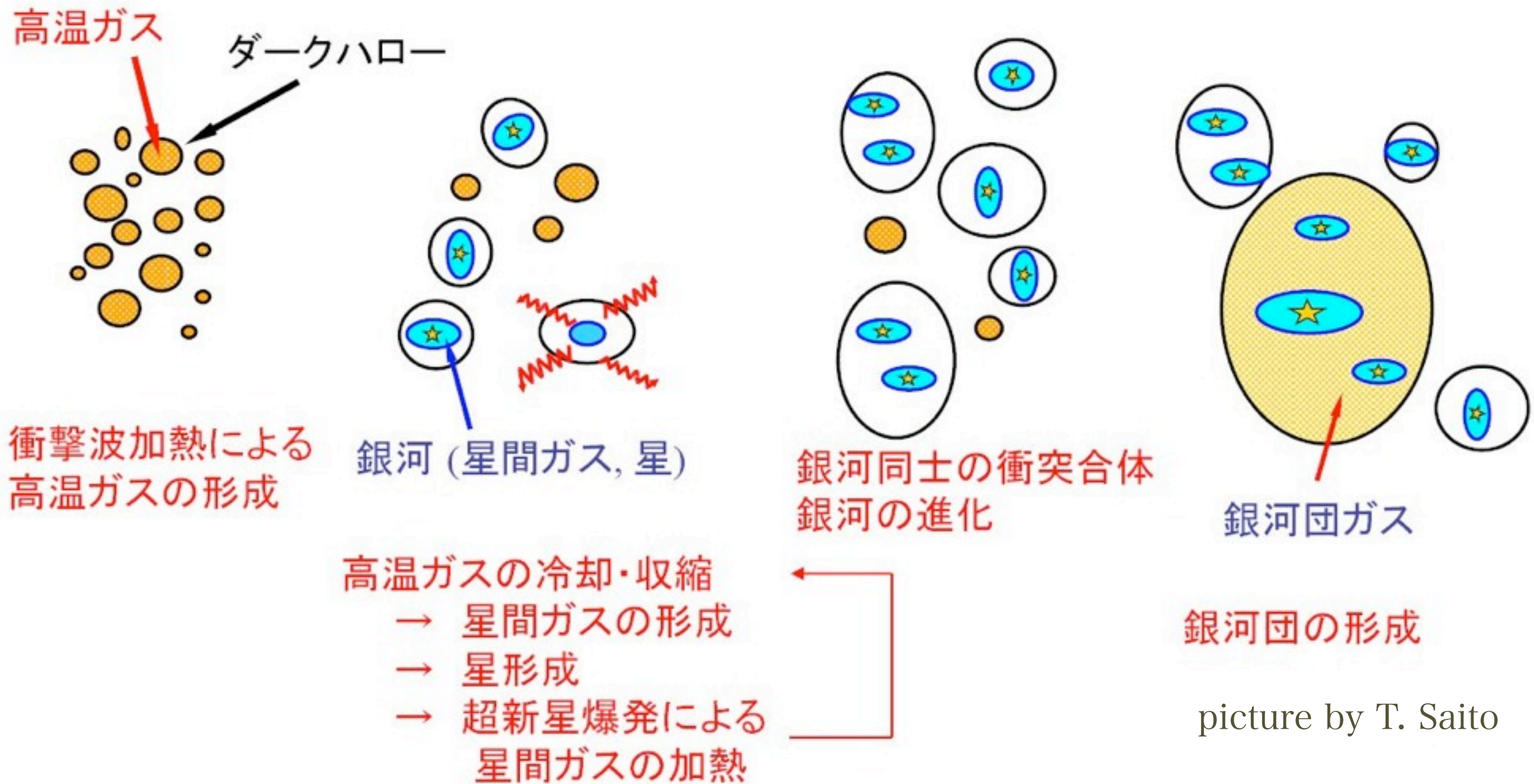
- cold dark matter の自己重力不安定によるダークハロー生成
- “hierarchical structure formation”





# 銀河形成のシナリオ

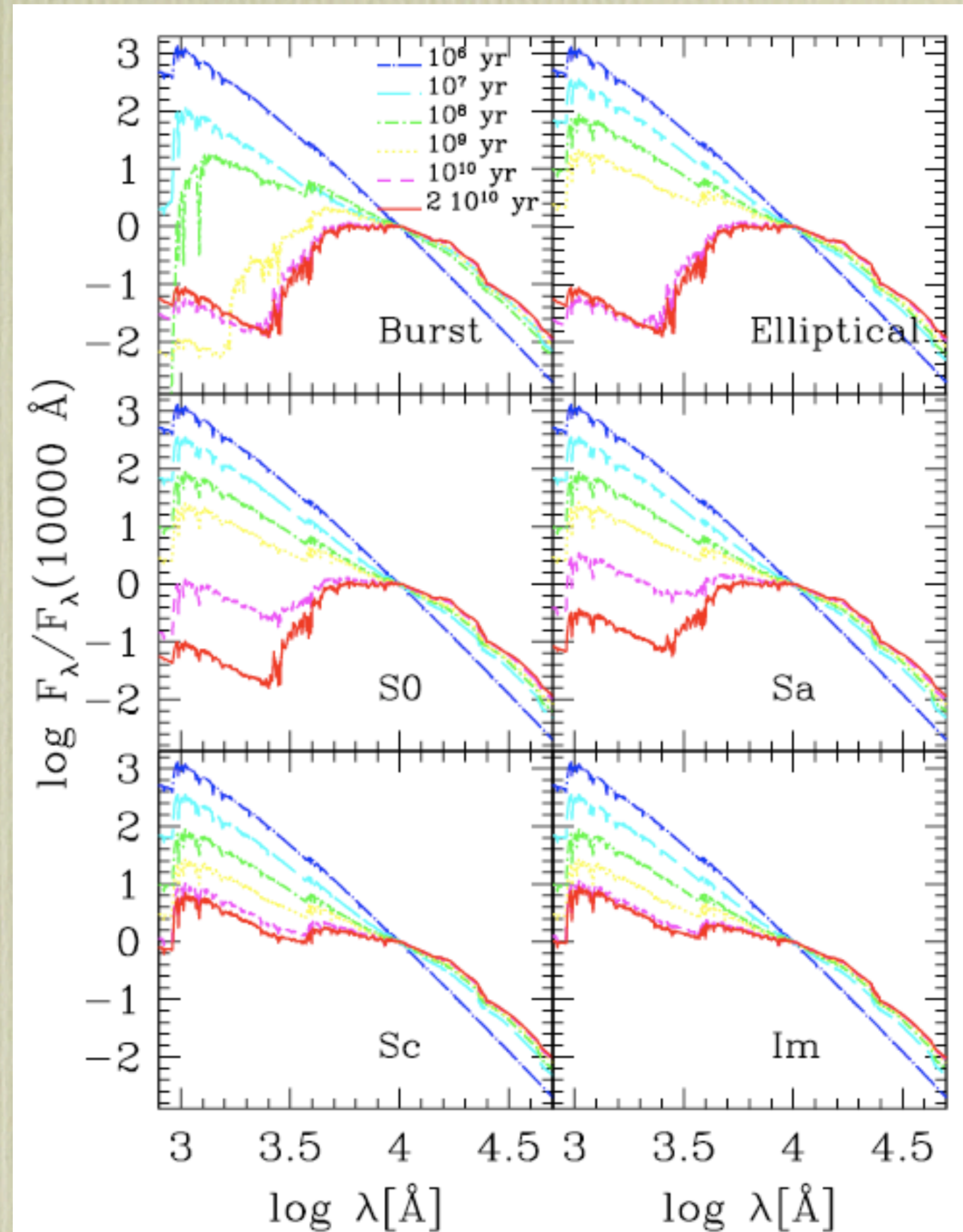
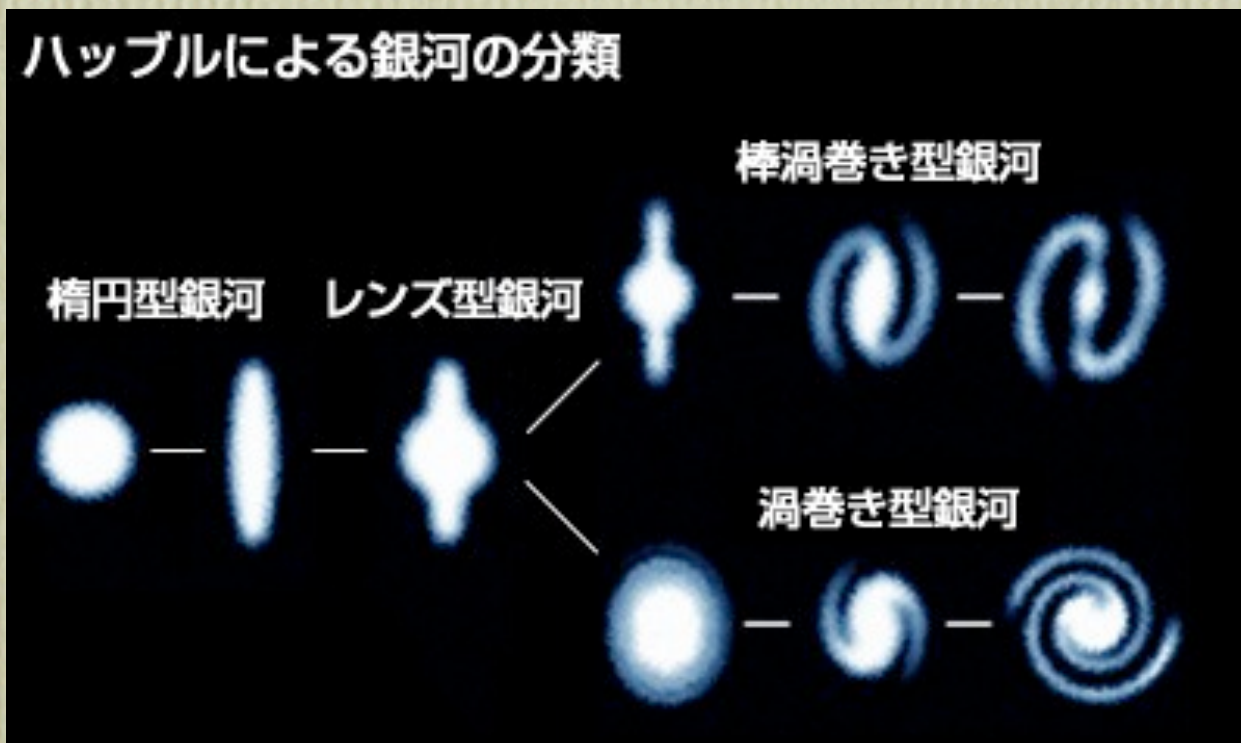
## ダークハローの集積



picture by T. Saito



# 星形成史とSED, morphology





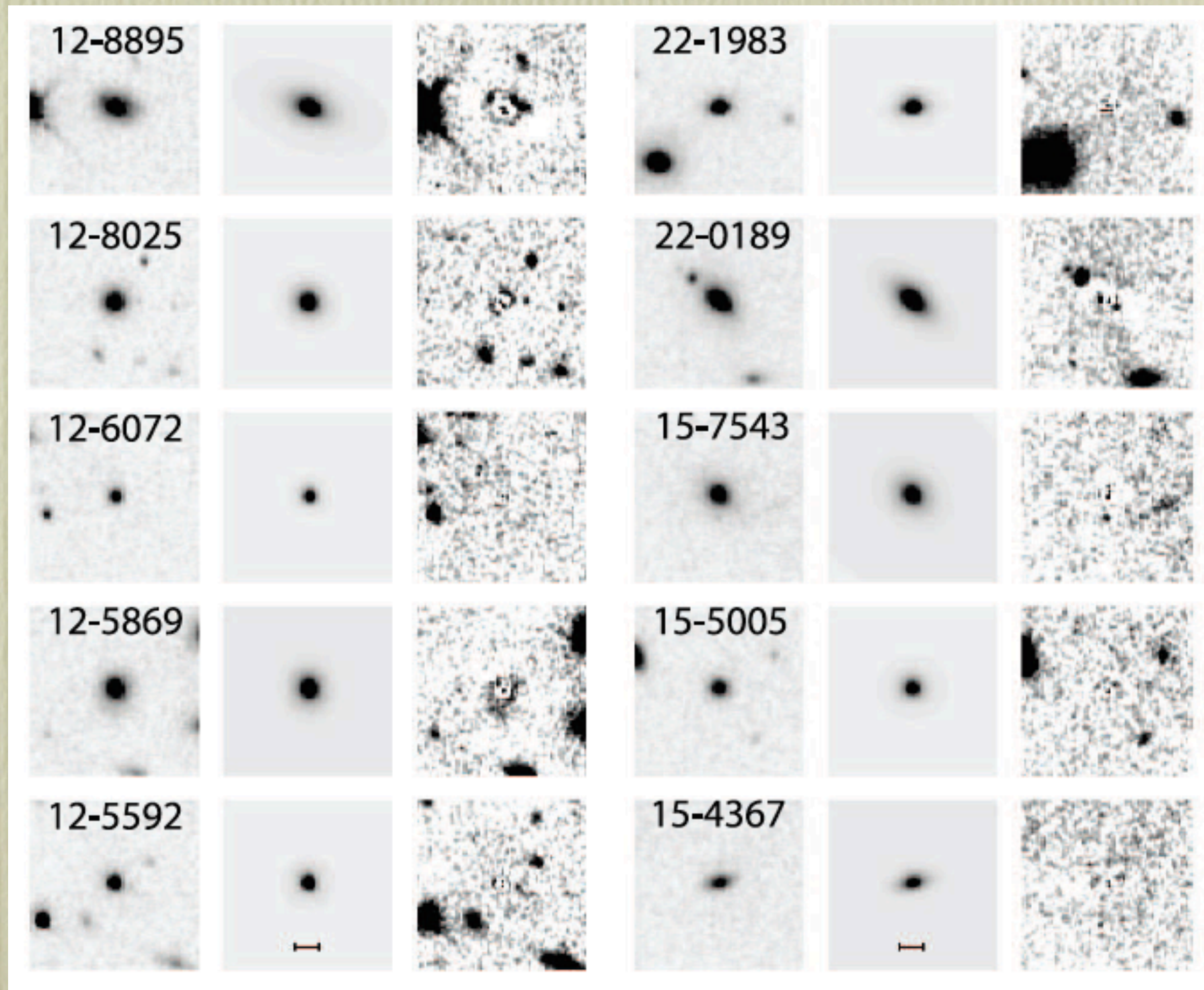
# Early-Type Galaxies 形成の描像

- 近傍 early-type galaxies の数密度の相当な割合が、 $z \sim 1-2$  で存在
- $z > 3$  で爆発的星形成、その後、星形成活動が無く、passive evolution で進化してきた
- 最初のスターバーストのトリガーは不明
  - merger?
  - monolithic collapse?
- いずれにせよ、 $z < 2$  で early type galaxies のサイズが進化することは考えにくい、しかし、、、



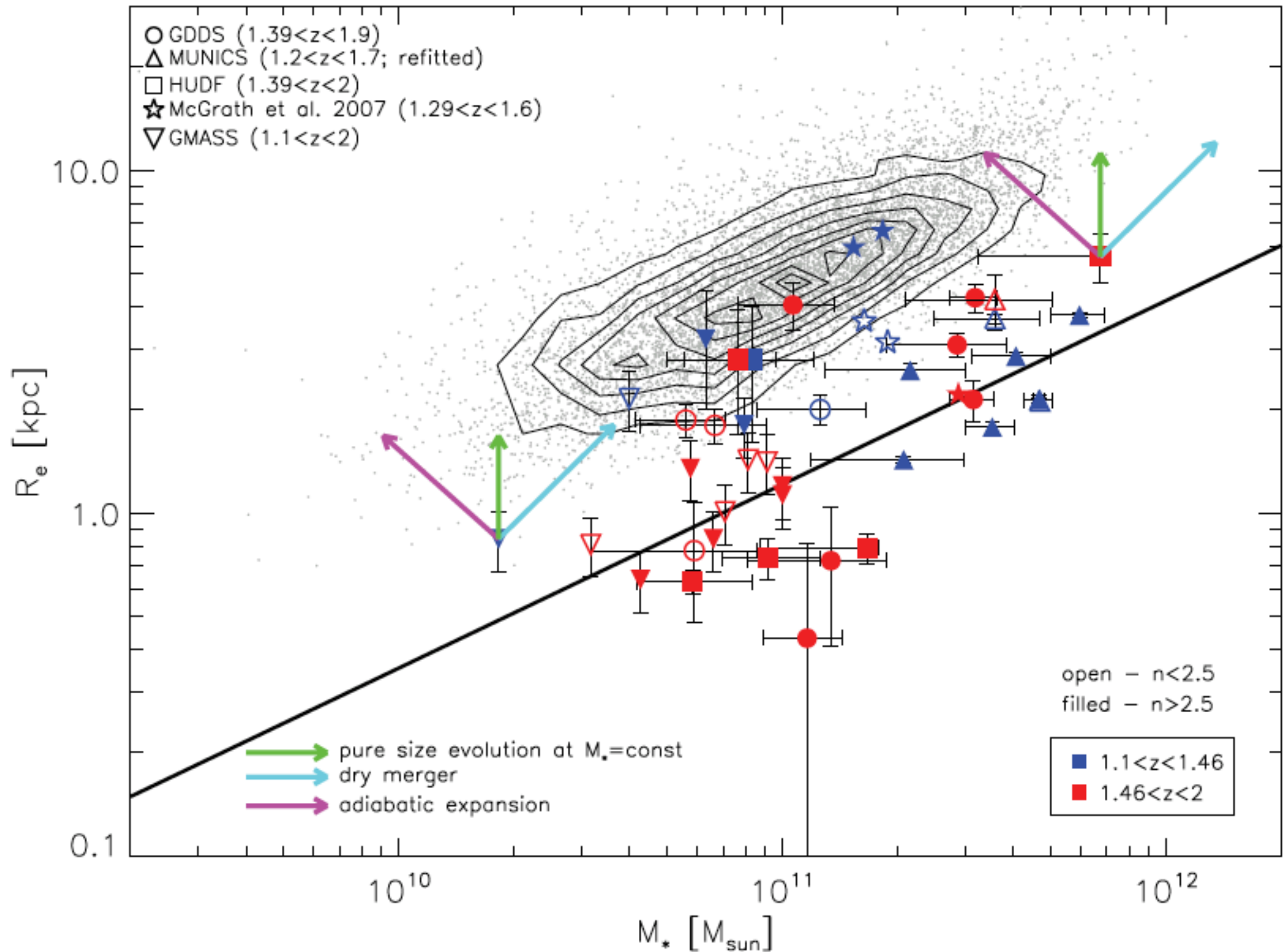
# サイズが変わっているみたい？

☉ early type galaxies at  $z \sim 1-2$  (Damjanov+'09)



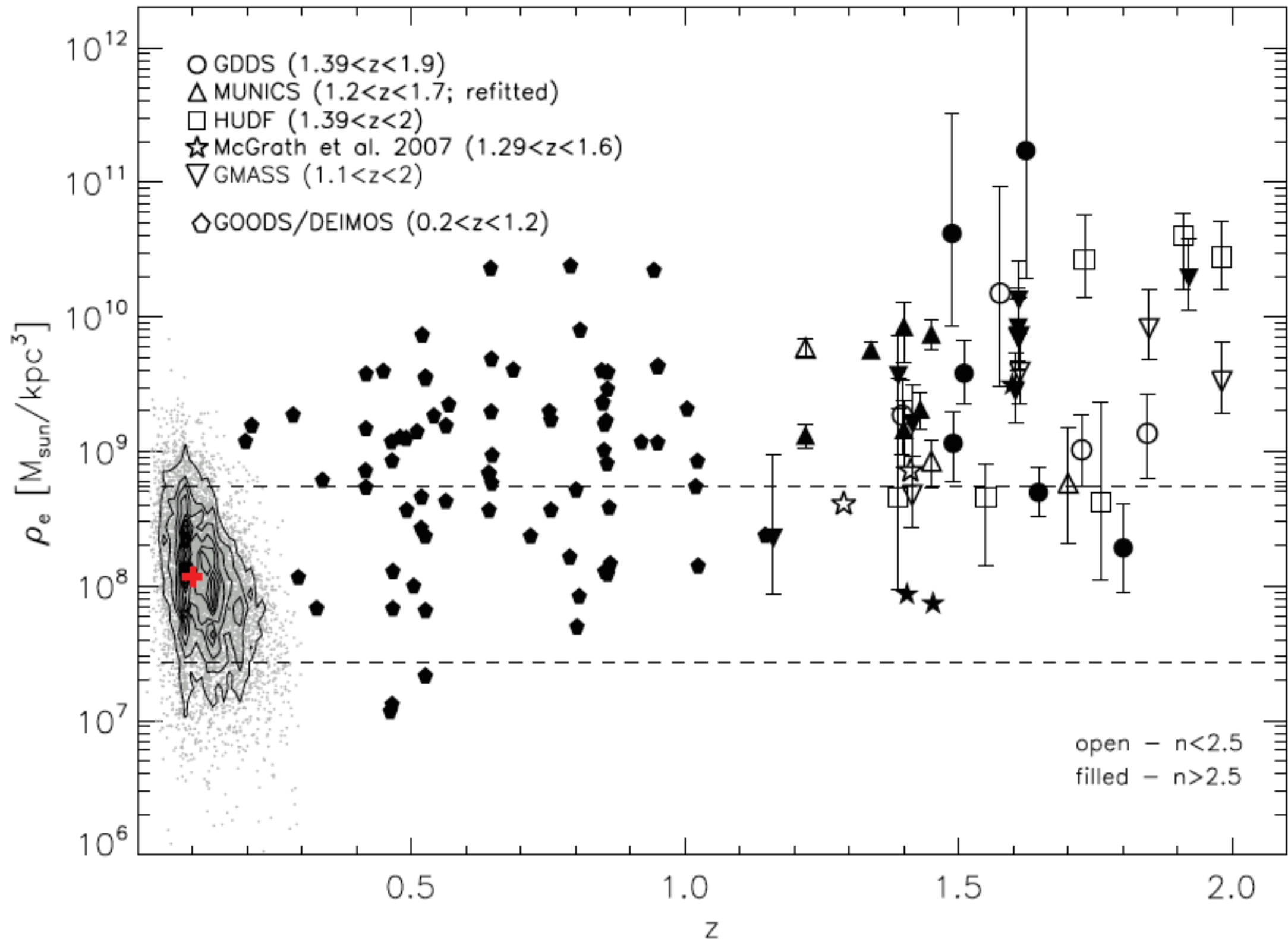


# サイズが変わっているみたい？ (2)





# サイズが変わっているみたい？ (3)





# サイズ進化の特徴

- 普遍的、ubiquitous に起きるらしい
  - $z \sim 1-2$  のコンパクトな early-type galaxies は、 $z=0$  で数密度  $1/5000$  以下に「消え去る」
- 宇宙論的な長いスケールで、主に質量を変えずにサイズだけがじわじわ進化しているように見える

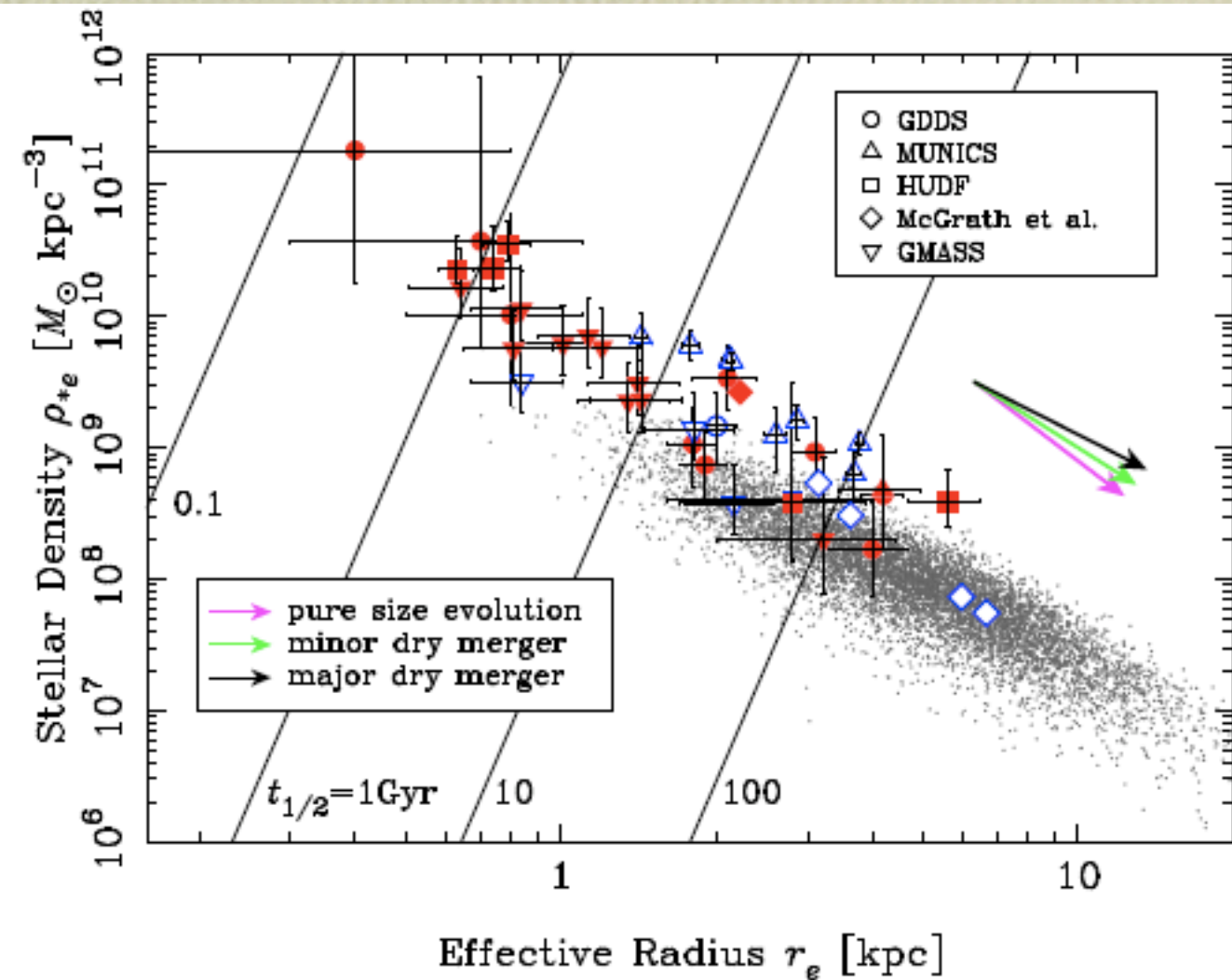
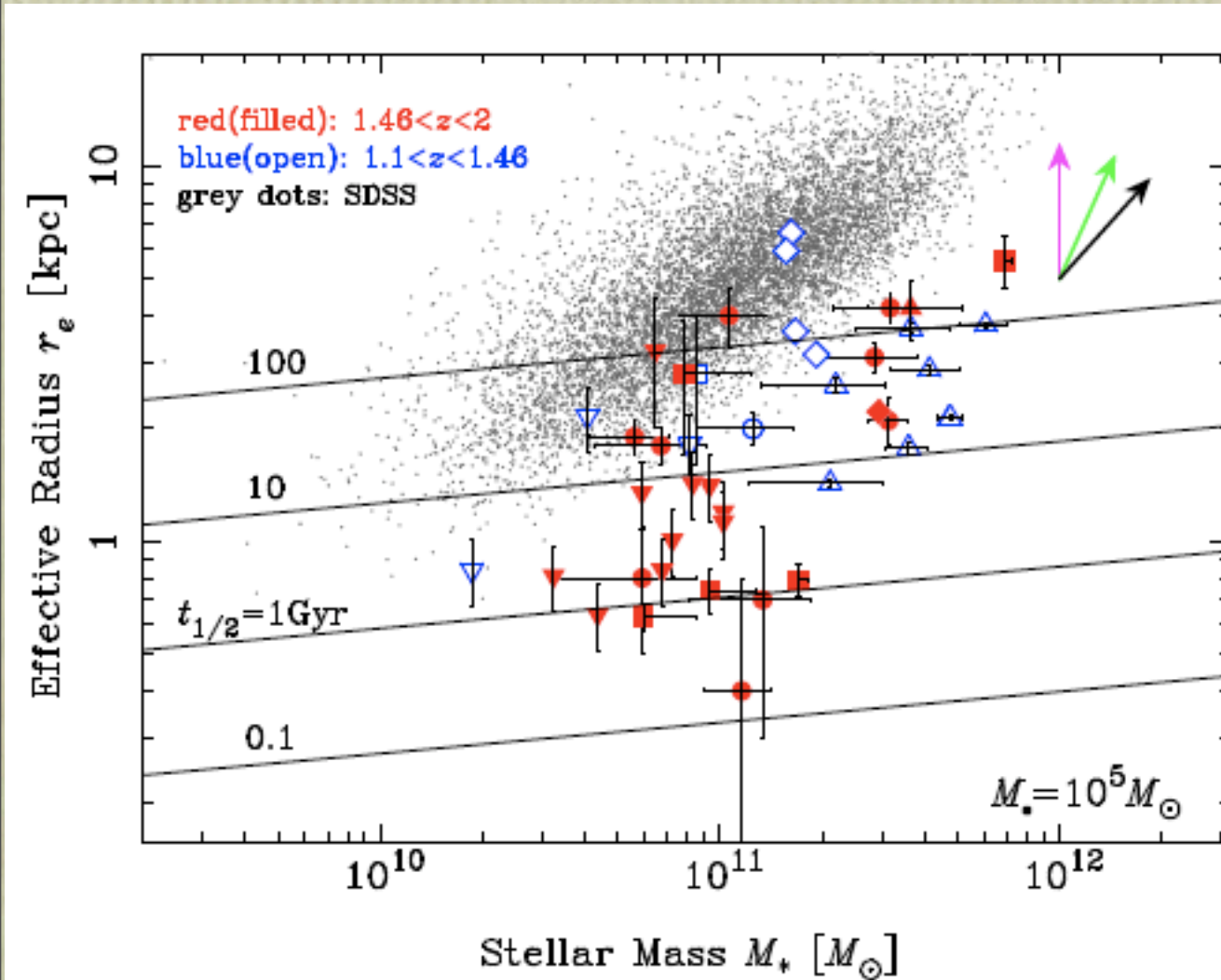


# サイズ進化のシナリオ？

- Dry mergers without star formation?
- Puff up by mass loss?
  - stellar mass loss
  - AGN activity
- Dynamical friction by  $10^5 M_{\text{sun}}$  dark matter compact objects
  - Totani 2009, arXiv:0908.3295



# Size Evolution by Compact Object Dark Matter





# $10^5 M_{\text{sun}}$ Compact Objects as Dark Matter?

- Primordial black holes (PBH)?
  - Horizon scale in the expanding universe  $\sim$  Schwarzschild radius of horizon mass
  - a modest density fluctuation results in PBHs
  - $10^5 M_{\text{sun}}$  corresponds to horizon mass of  $T \sim \text{MeV}$ ,  $e^\pm$  annihilation era
    - only a small portion ( $10^{-6}$ ) of universe needs to be locked up into PBHs to explain DM abundance
- Implications for AGN/supermassive black hole formation
  - all AGNs have BH mass  $> 10^6 M_{\text{sun}}$
  - $10^9 M_{\text{sun}}$  quasar BH at  $z=6$ !