Extagalactic Gamma-Ray Background Radiation (EGRB)

--- A Theorist's Point of View ---

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「高エネルギー宇宙現象の観測の最新成果と今後の展望」

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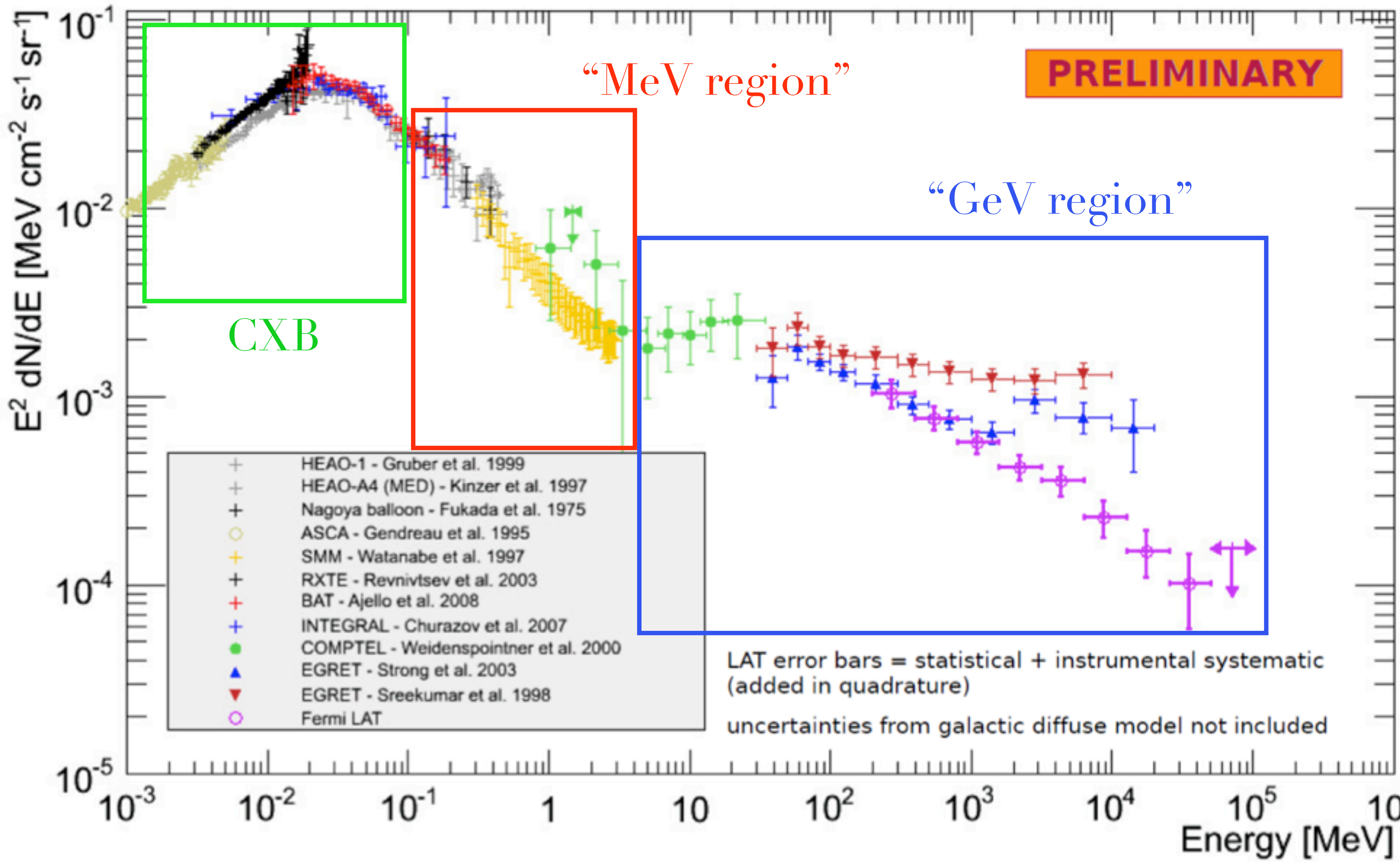
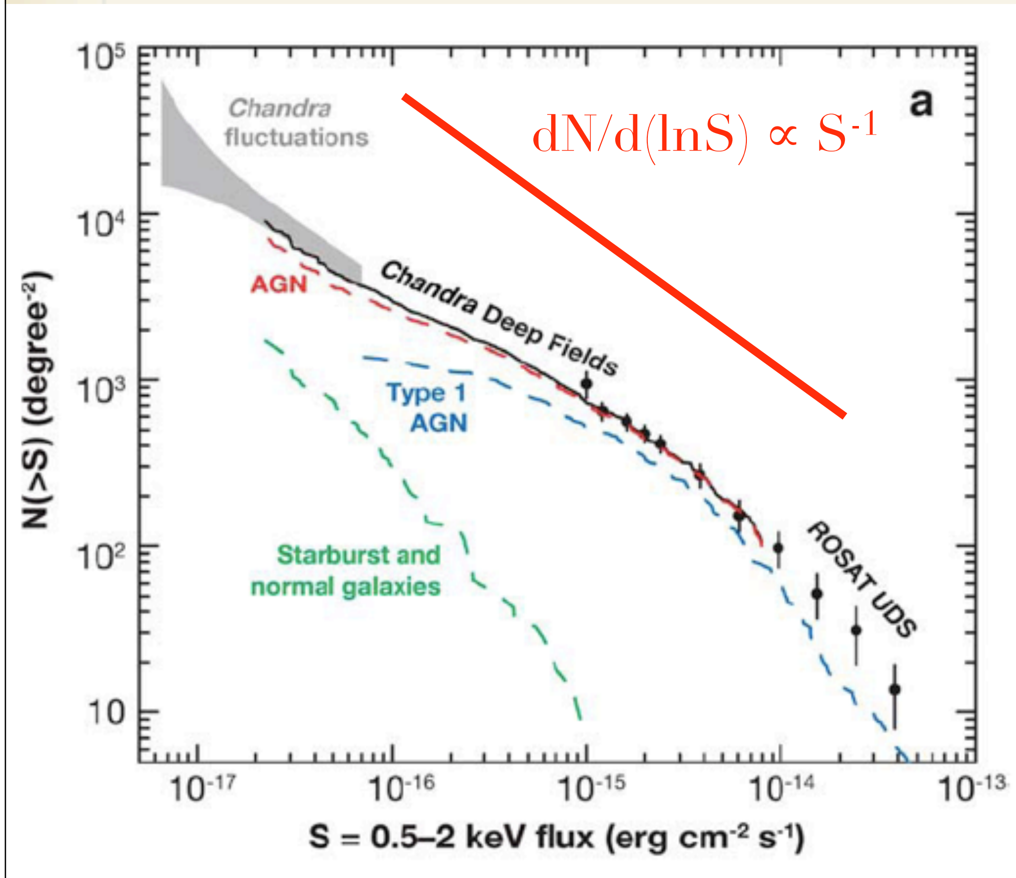
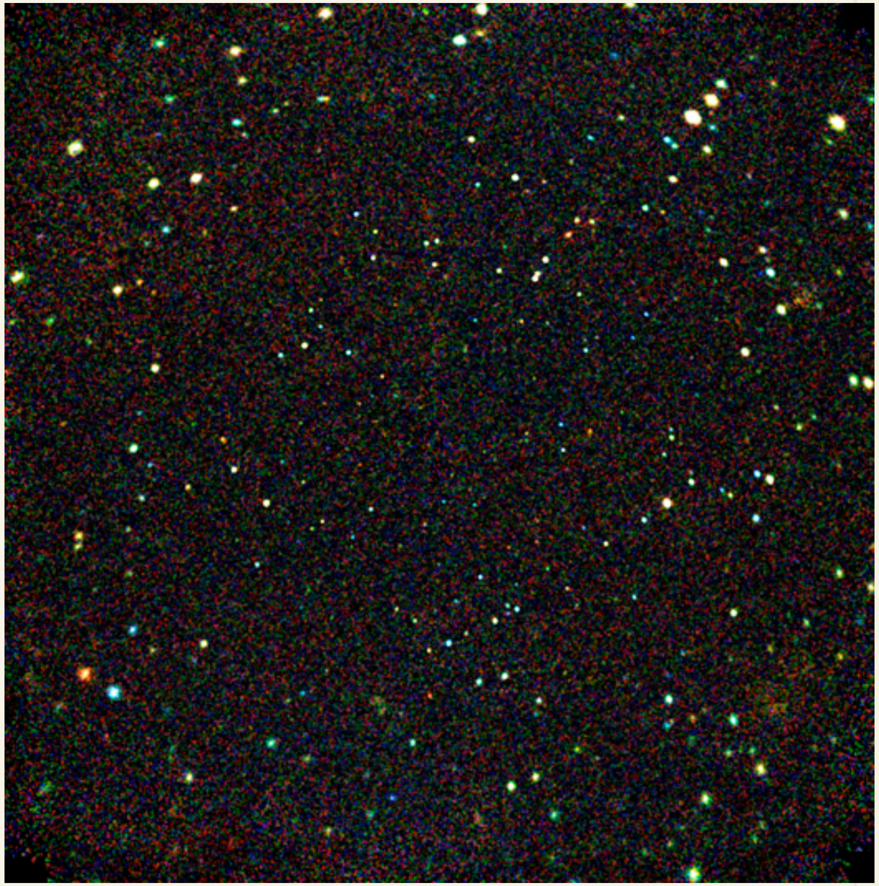
Cosmic X-ray & gamma-ray background



Cosmic X-ray Background (CXB)





Chandra Deep Field

CXB already resolved into AGNs

Importance of EGRB Study

- fossil record of the comic evolutionary history of contributing sources
  - blazars / AGNs → accretion and jet activity history of supermassive black holes
  - star-forming galaxies → cosmic-ray production and interaction with ISM

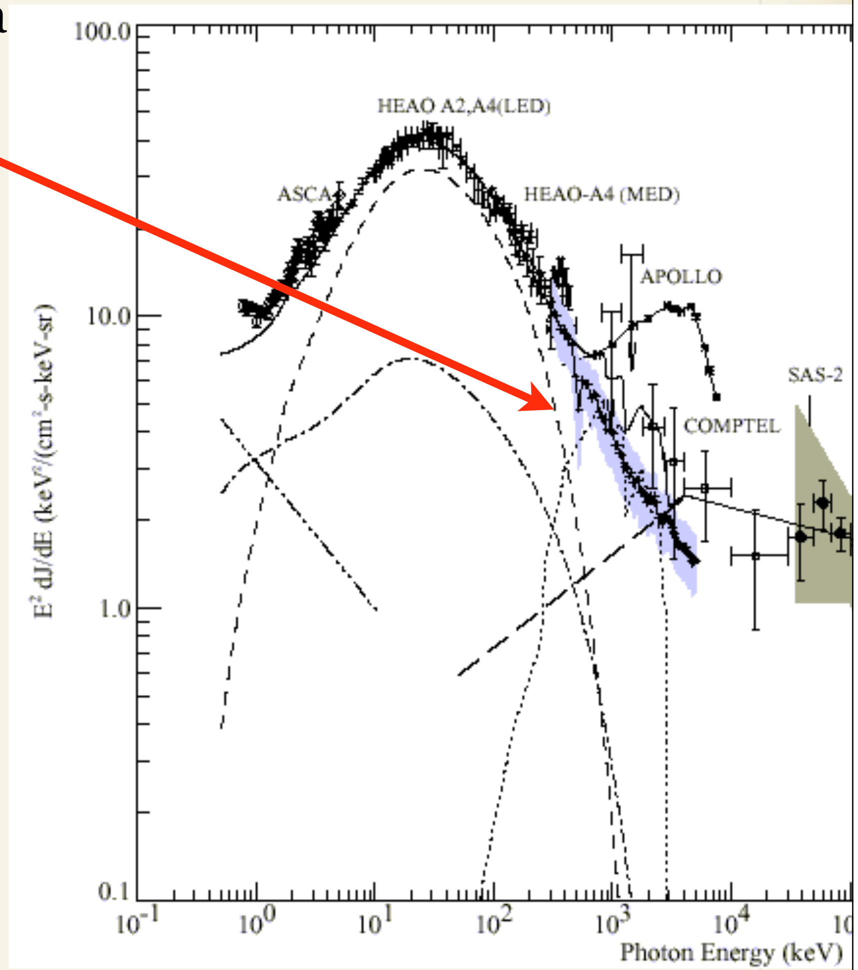
- Potential contribution from exotic sources
  - dark matter annihilation
  - SUSY predicts a natural DM candidate “neutralinos” with a mass range of ~100 GeV - 10 TeV
    - decay products in GeV band

Outline

- Origin of the MeV-region background
  - non-thermal tails of AGNs?
  - “MeV blazars?”
  - more!?
- Origin of the GeV-region background
  - blazars
  - star-forming galaxies
  - more!?

The "Mystery" of MeV Background

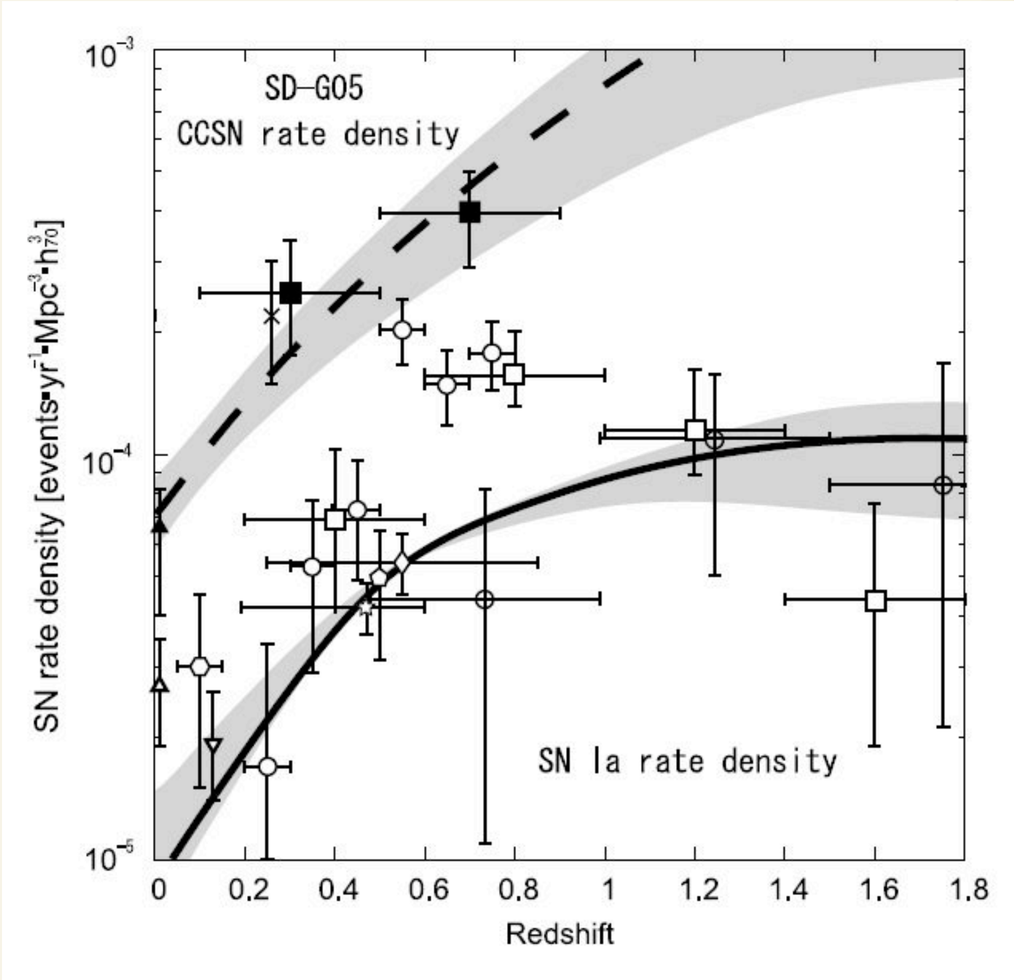
- "conventional" model of AGN X-ray spectra predict cut-off at ~MeV
- origin of MeV background?
  - SN Ia? (rate not sufficient)
    - Clayton & Ward '75; Zdziarski '96; Watanabe+'99
  - MeV blazars?
    - Ajello+'09
  - MeV-mass dark matter annihilation!?
    - Ahn+Komatsu '05a; Rasera+'06



Sreekumar+'98

Cosmic SN Rate Evolution

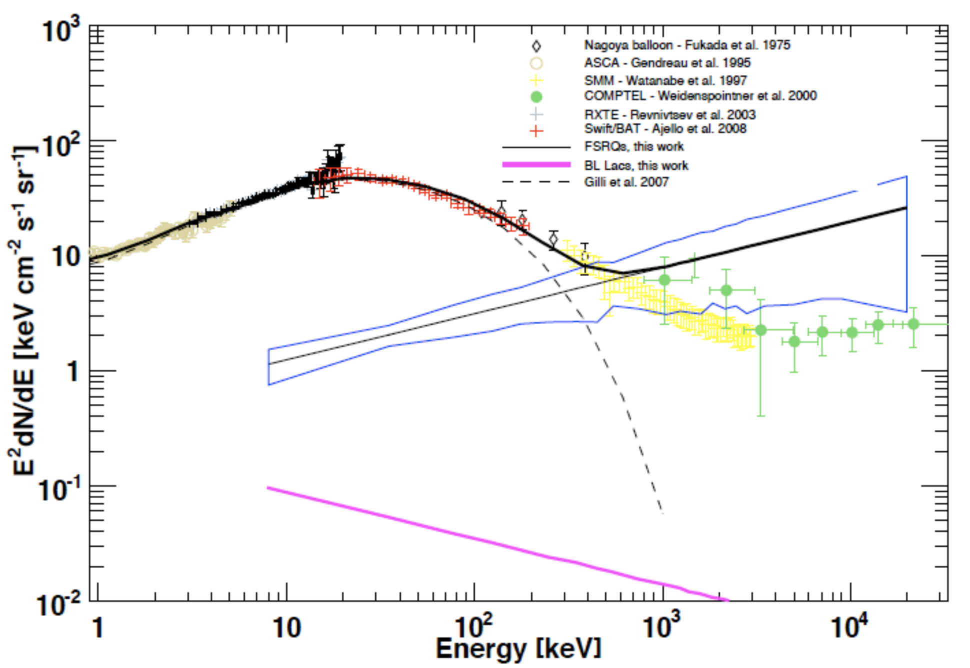
- SN Ia rate evolution to z~1 now well known
- ~10 times short to explain MeV background from SNe Ia (Ahn+ ’05; Strigari+ ’05)

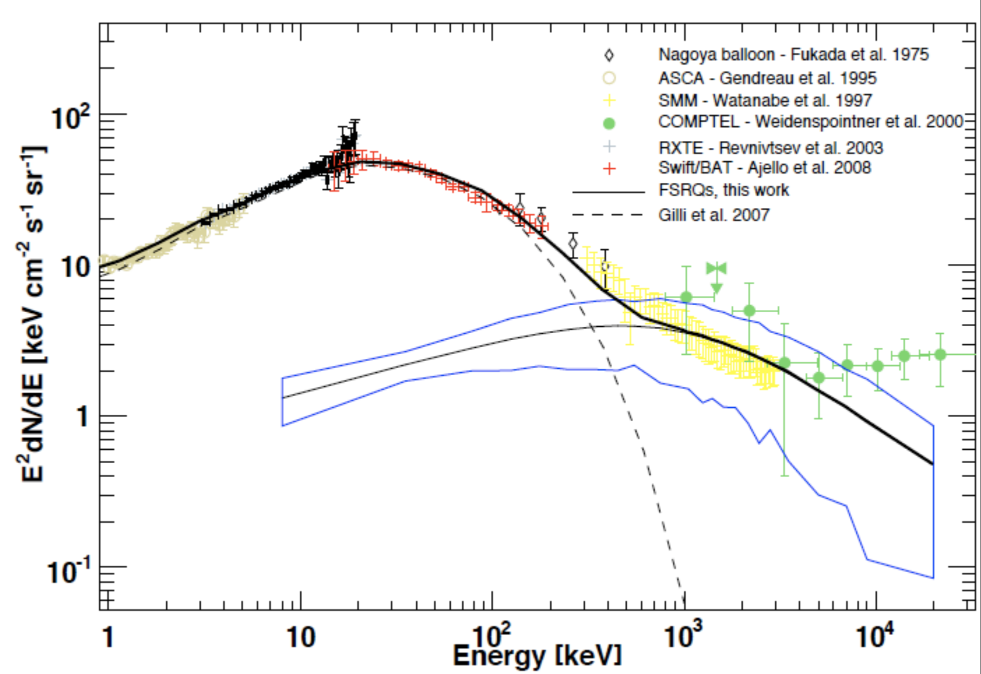


Oda+’08

“MeV Blazars” and MeV background

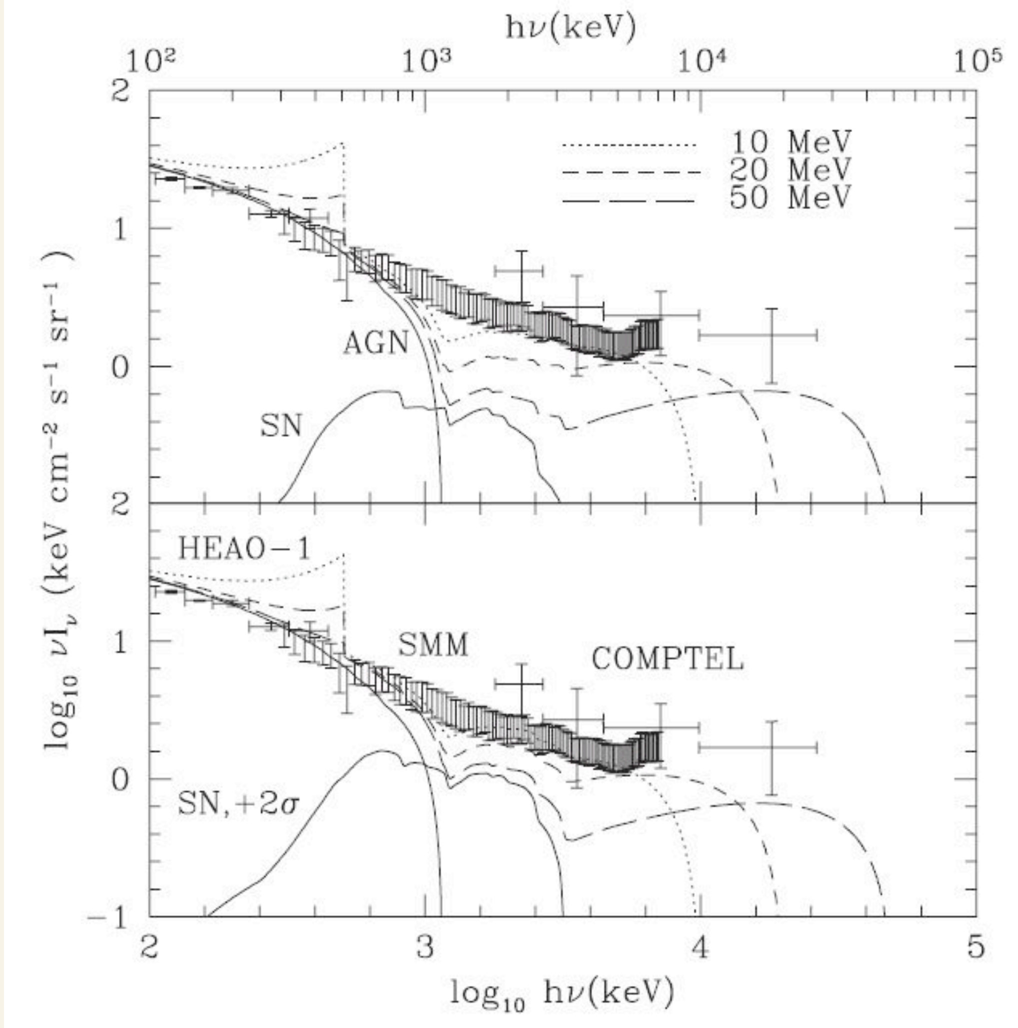
- blazars detected by Swift/BAT (10-55 keV) may significantly contribute to MeV background (Ajello+’09)
  - 26 FSRQ and 12 BL Lacs
- but depends on extrapolation from hard-X to MeV
- sample not large enough to reconstruct cosmological evolution of LF
- a fine-tuning required to reproduce a smooth power-law tail from CXB
- must be distinct population from blazars found in GeV





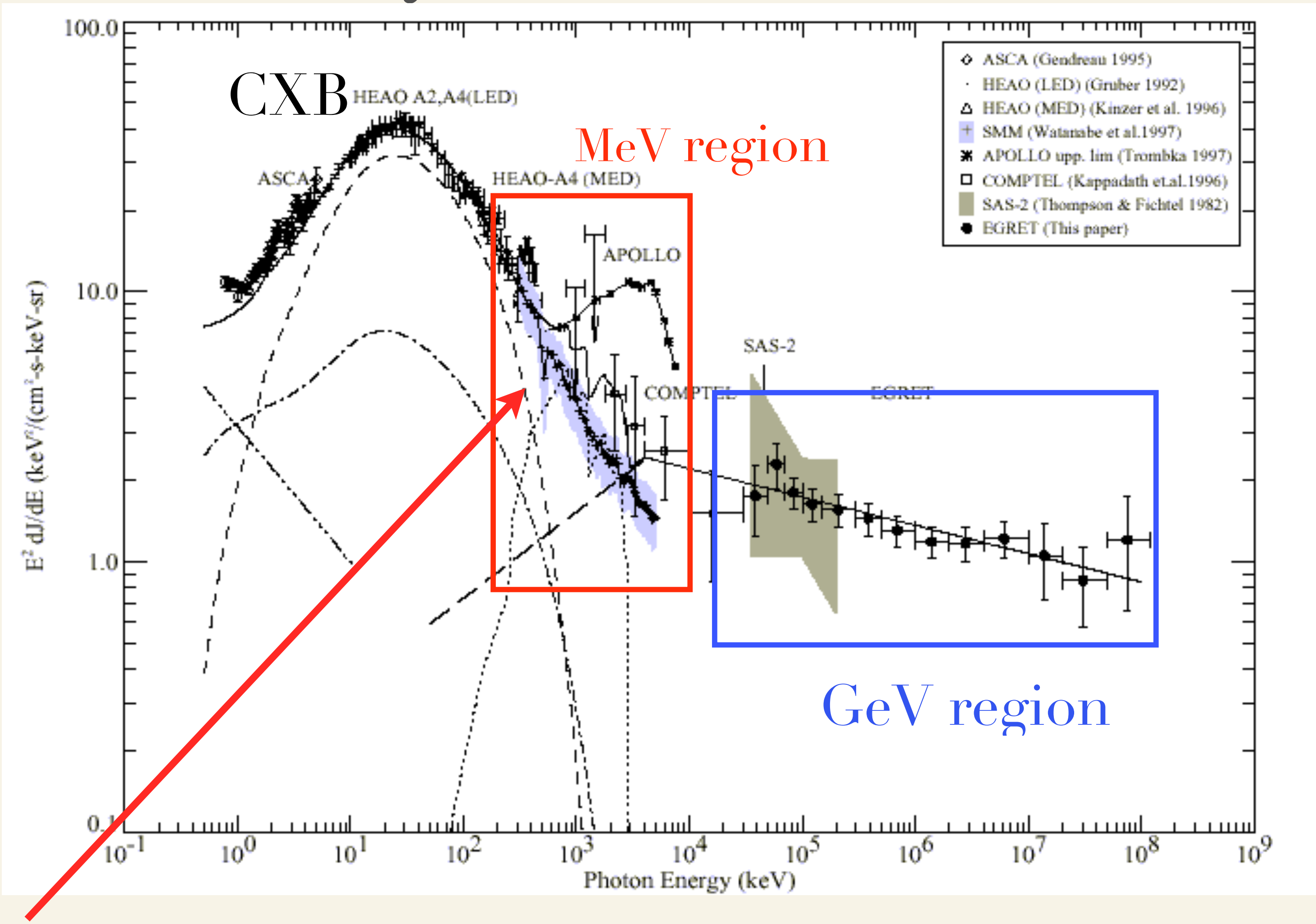
MeV Dark Matter?

- annihilation to MeV gamma-rays
- possible connection to the 511 keV emission from the Galactic Center
- No natural particle candidate
- the 511 keV emission may also be explained by astrophysical sources
  - Sgr A*
  - X-ray binaries



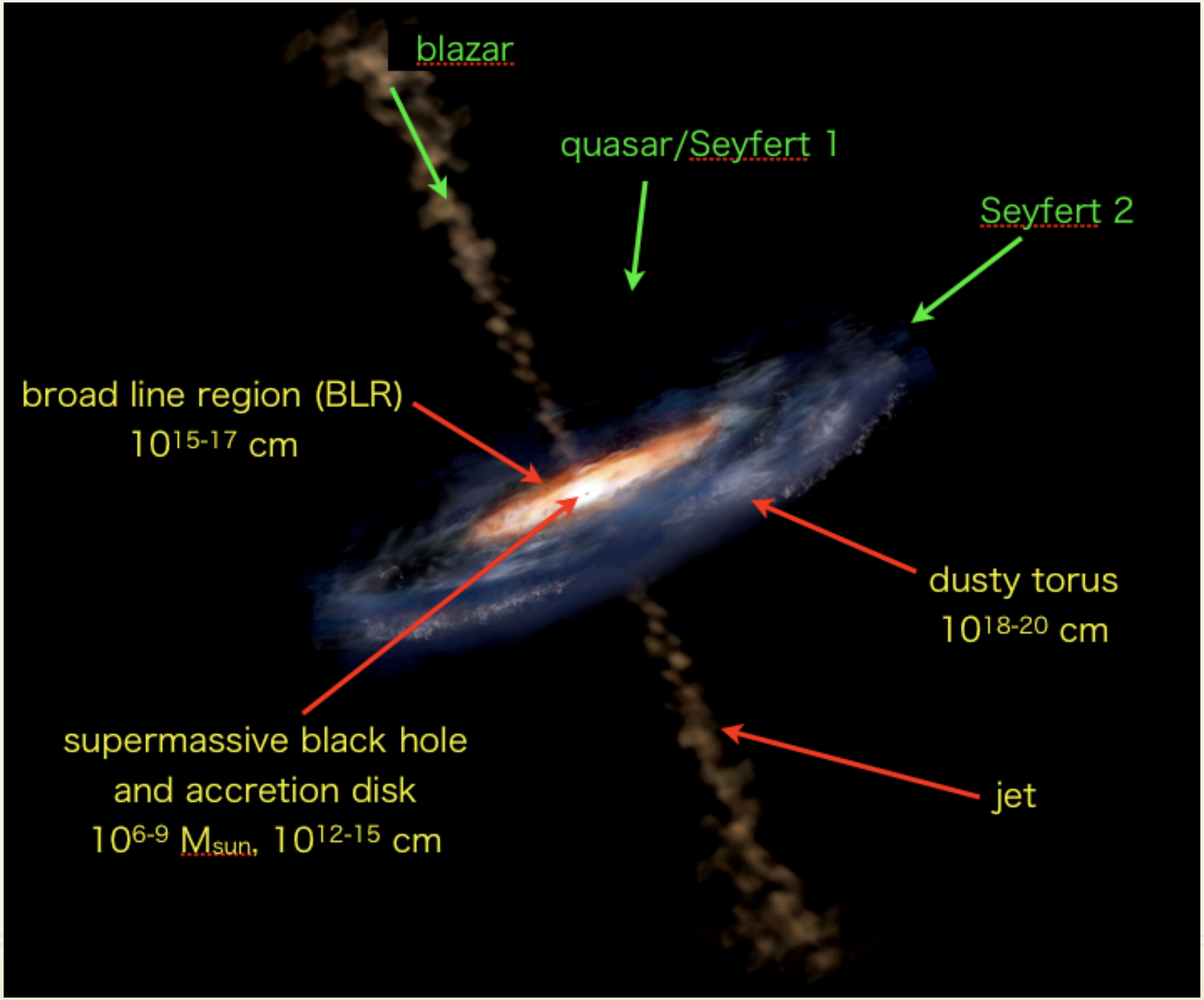
Ahn+Komatsu '05

Why not normal AGNs!?



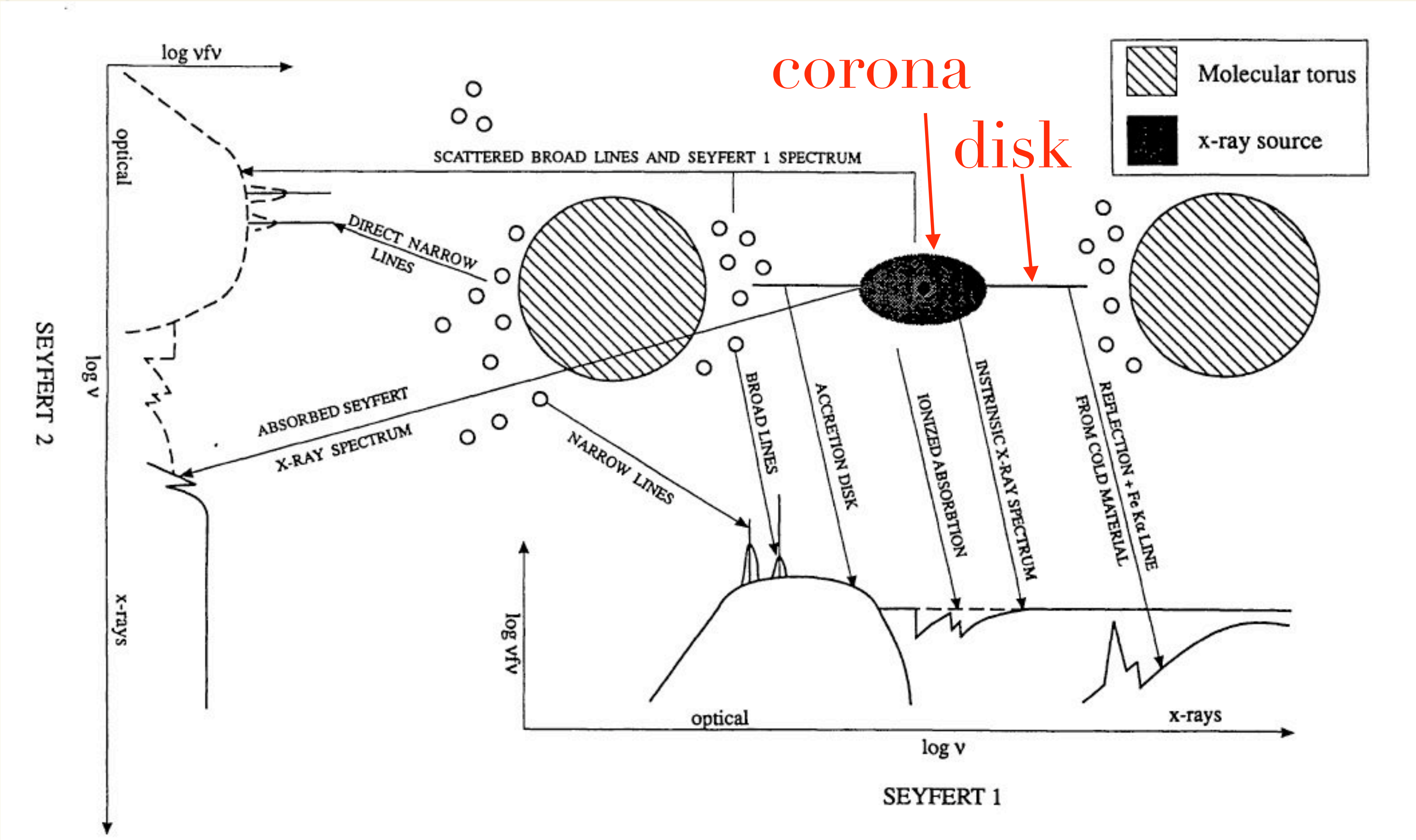
- conventional AGN X-ray model predicts “exponential cut-off”
- However, MeV component “smoothly” connects to CXB!

Active Galactic Nuclei



The Picture of AGN X-ray Spectra

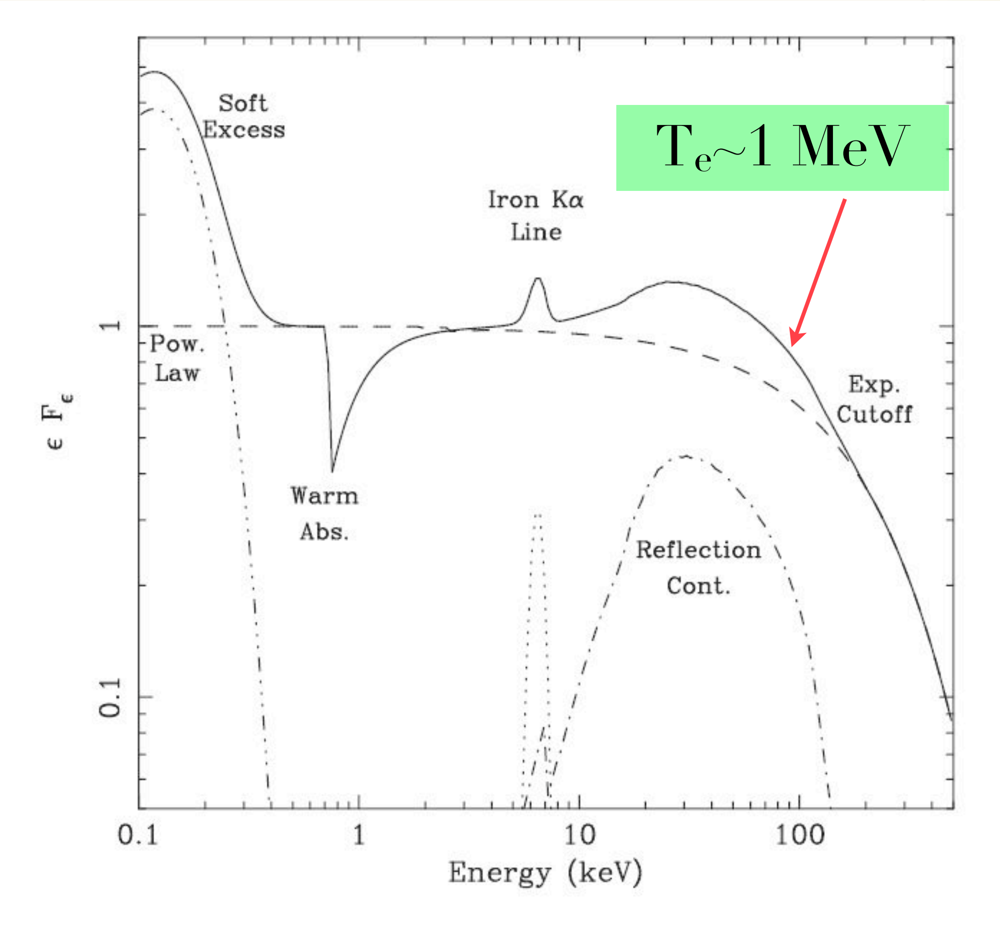
- picture of normal X-ray AGNs (e.g., Seyferts)



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 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

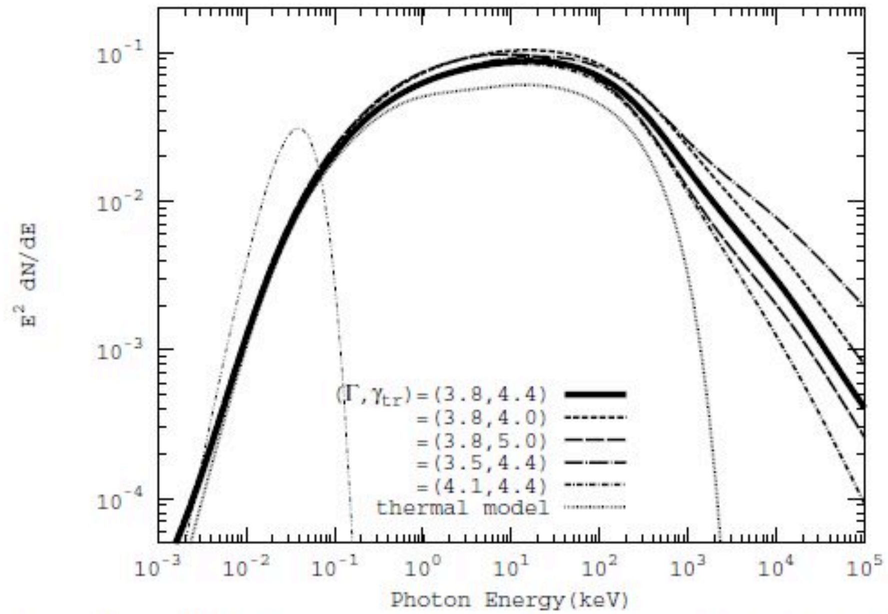
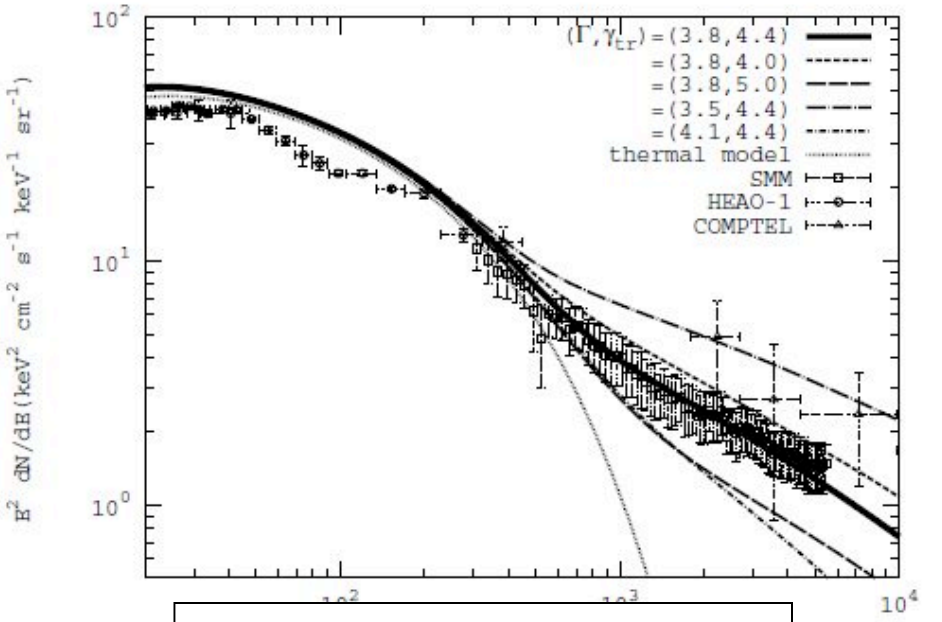


FIG. 1.— The AG

AGN spectrum

ray bands calculated by our model. The fl of E^2dN/dE, where dN/dE is a differenti omptonization 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).

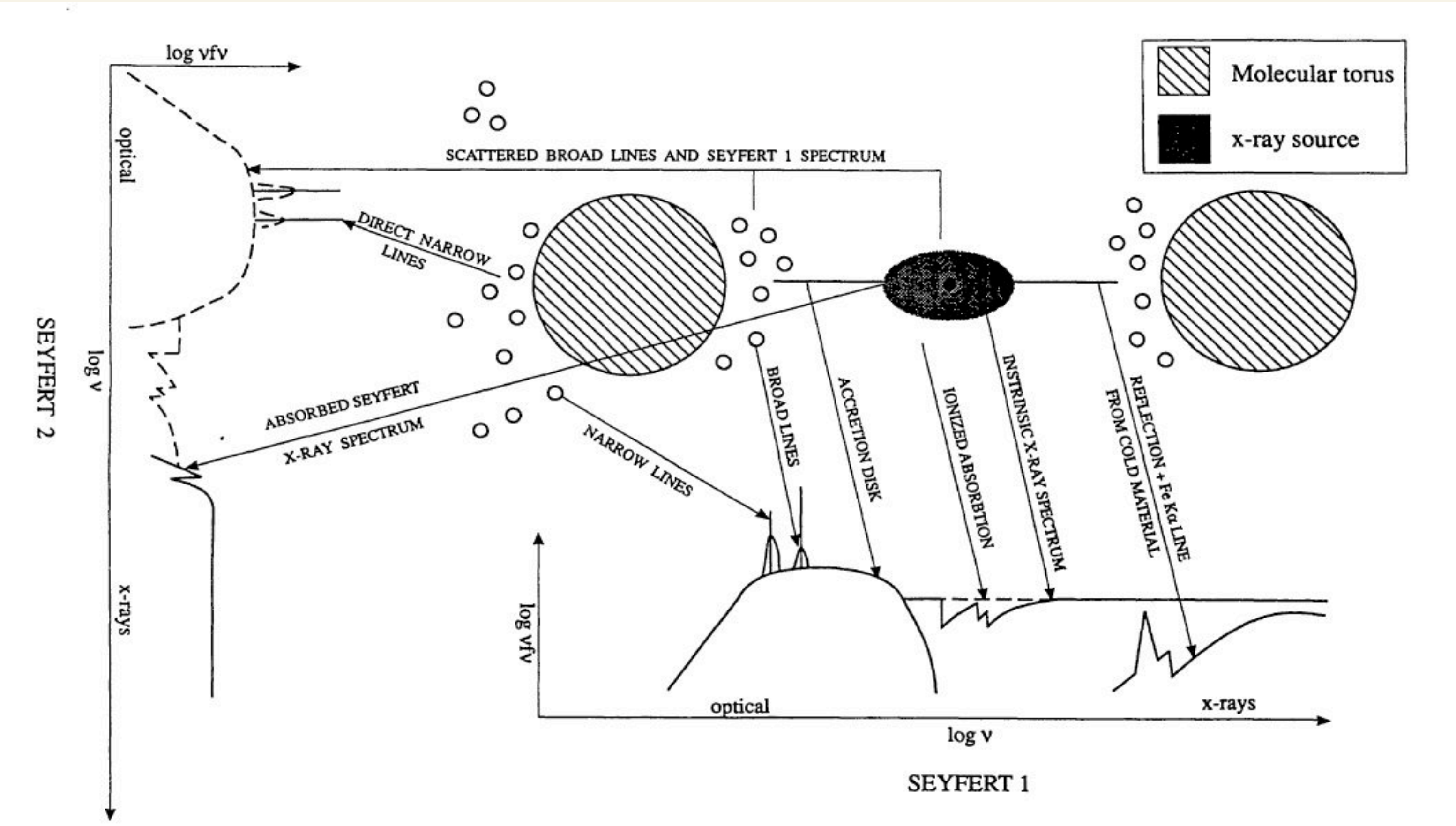


background spectrum

FIG. 2.— Th 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.

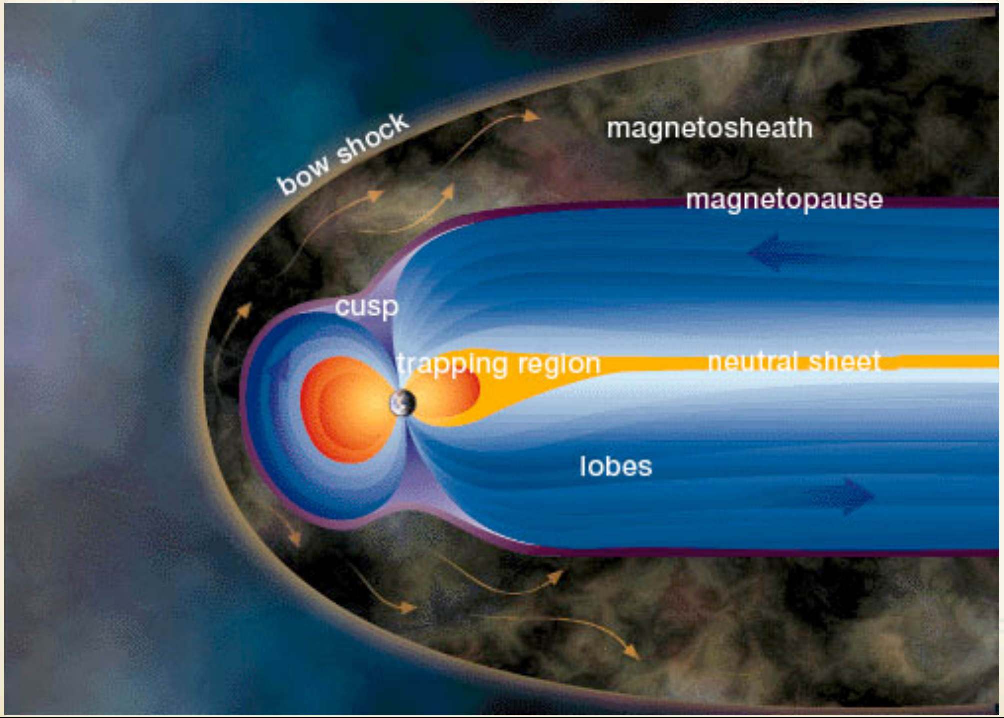
the Origin of Non-thermal Electrons in Hot Coronae in AGNs?

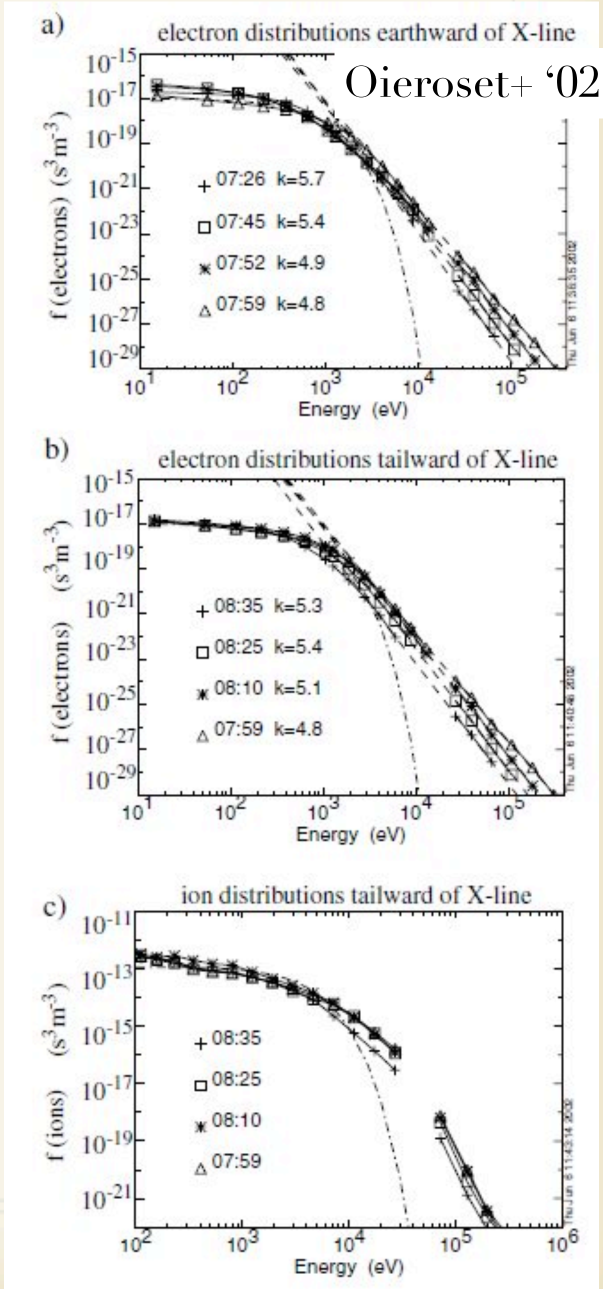
- The heat source of corona is still an open question
  - A popuIuar scenario: magnetic reconnections (e.g. Liu+’02)
  - non-thermal particles are accelerated in reconnections!



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





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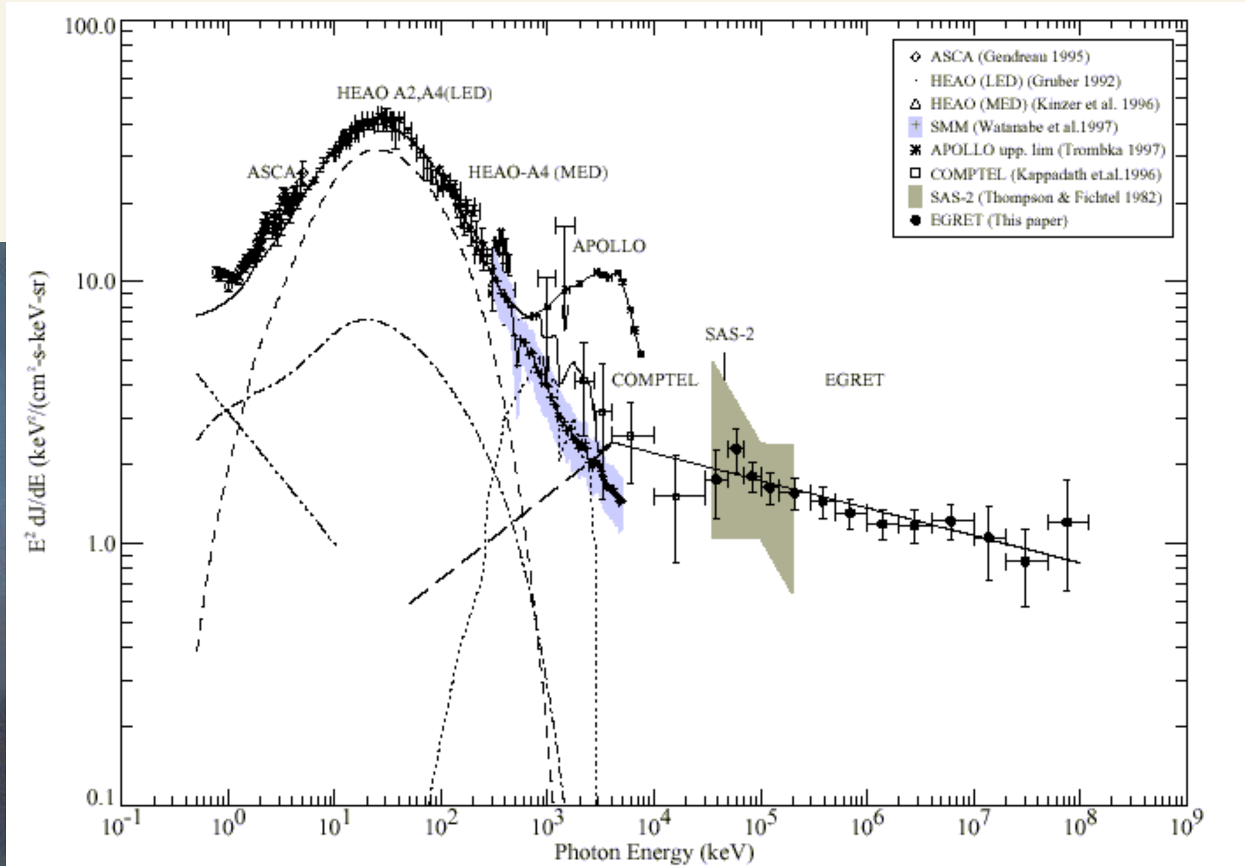

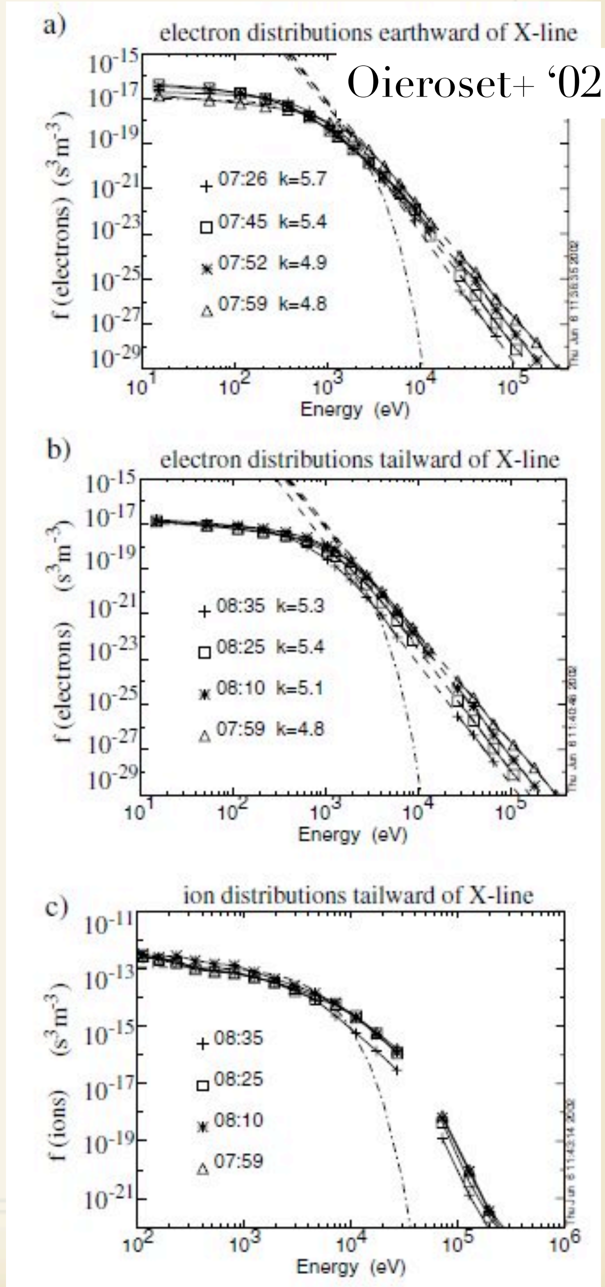

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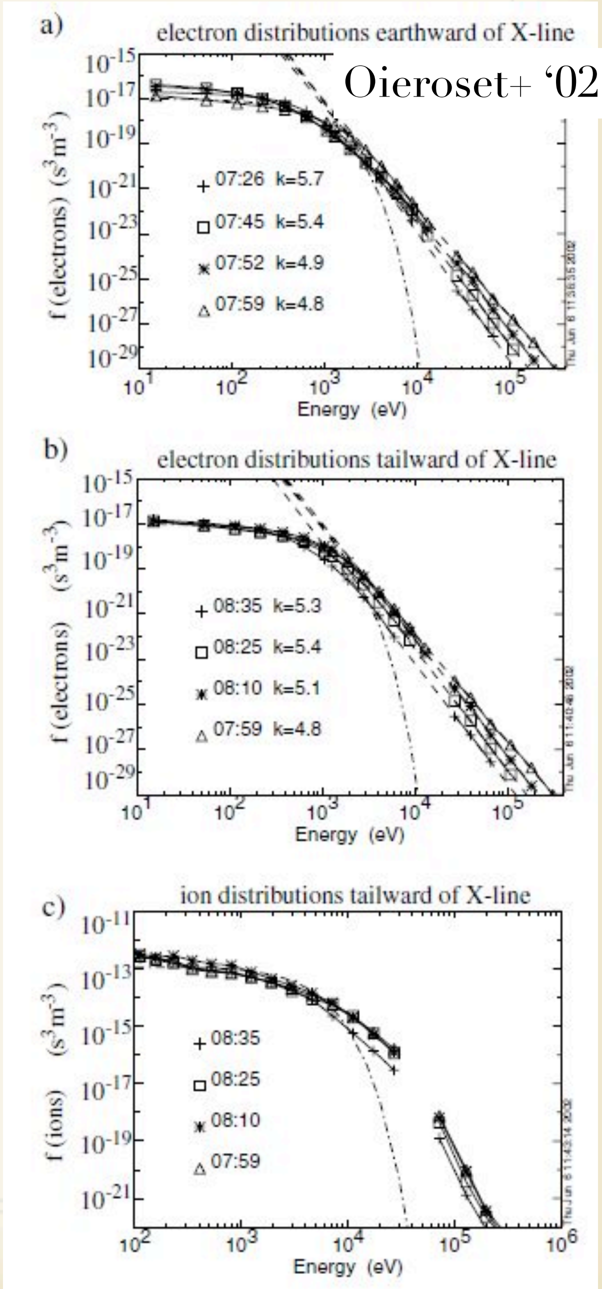
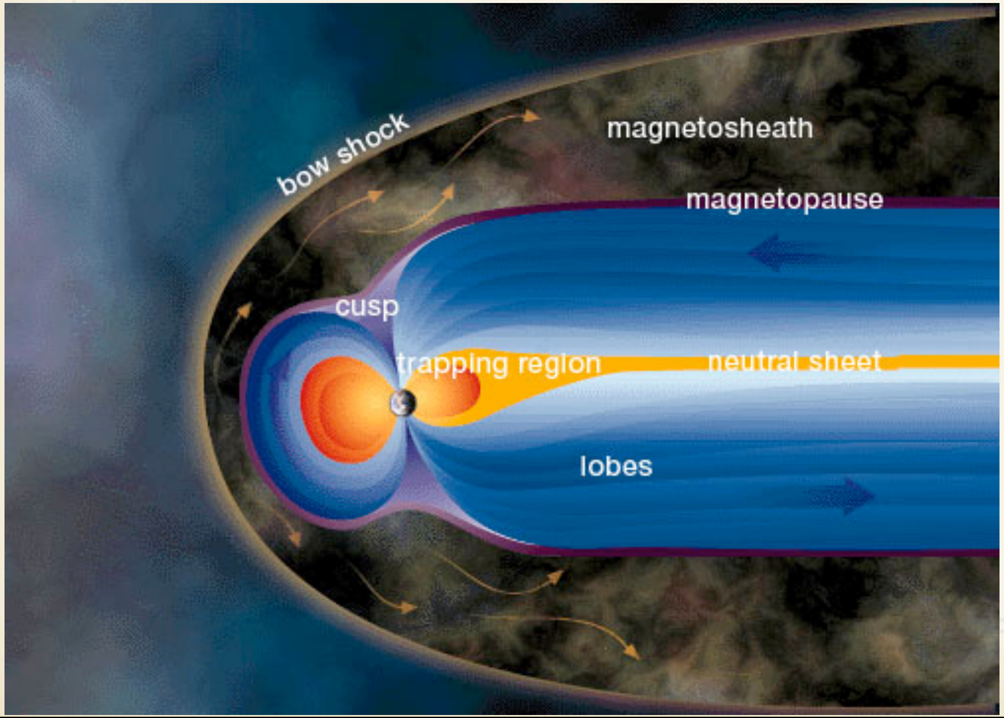
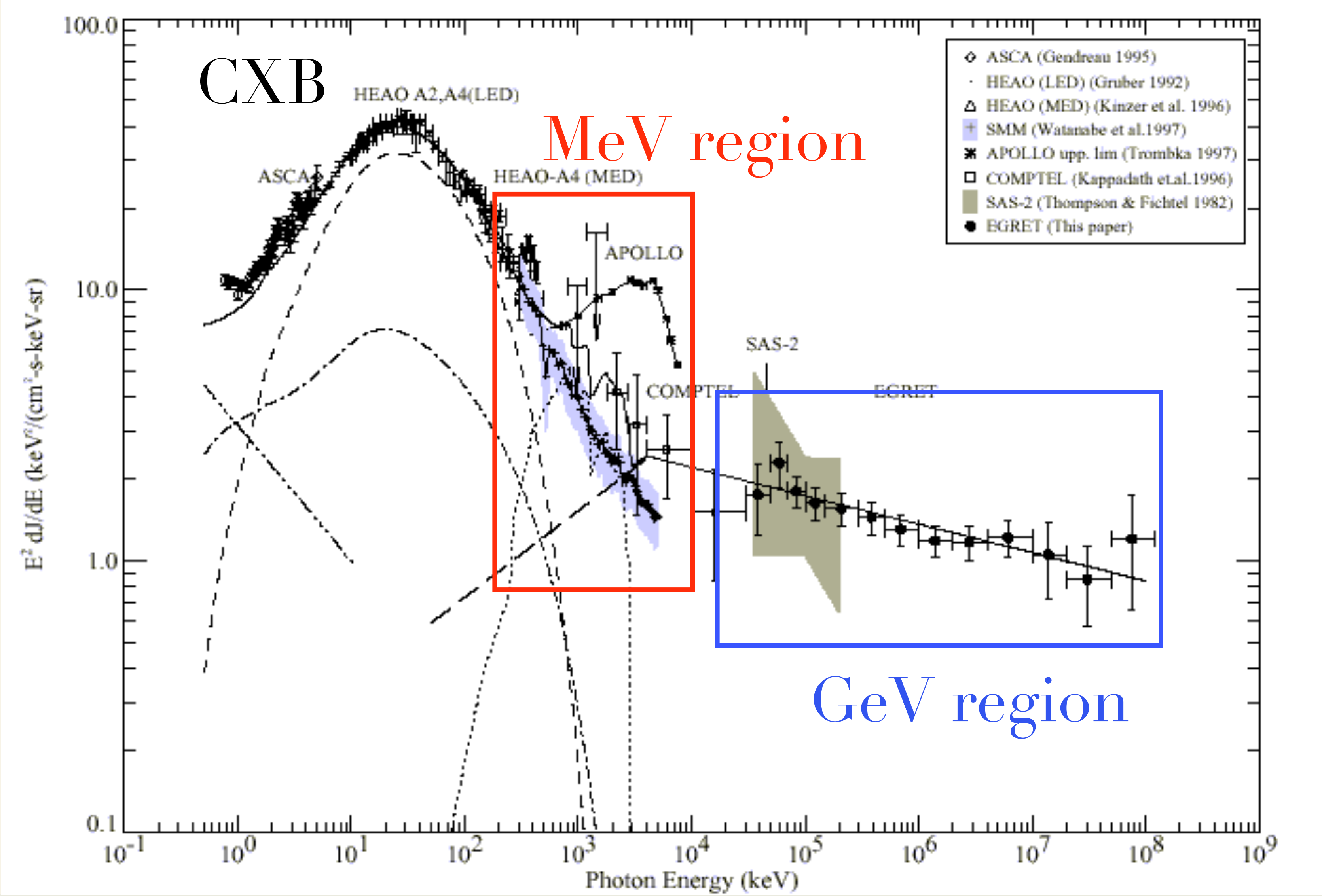




MeV background: Summary

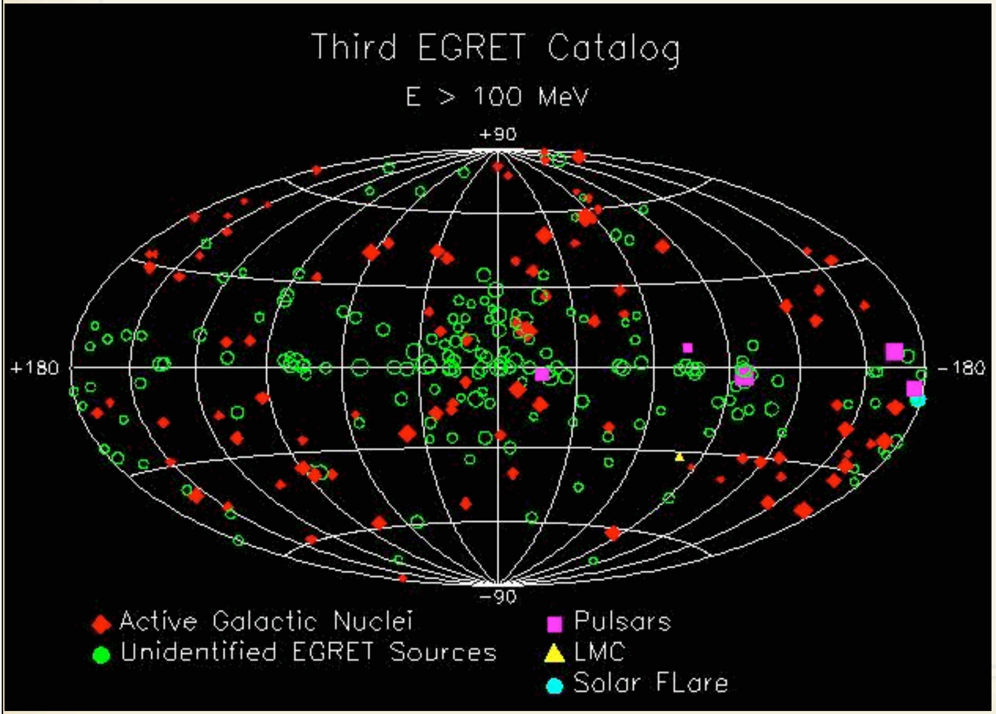
- The “theoretically best” explanation is “non-thermal tail” from normal AGNs
  - smooth power-law connection to CXB
  - non-thermal electrons naturally expected in AGN coronae
  - not confirmed by observation yet
- Possibilities of the contribution from completely different sources
  - SN Ia: too small rate from recent observations
  - MeV blazars: may have significant contribution suggested by Swift data
  - MeV dark matter: no good theoretical motivation for MeV DM
- We need deeper observations in MeV!

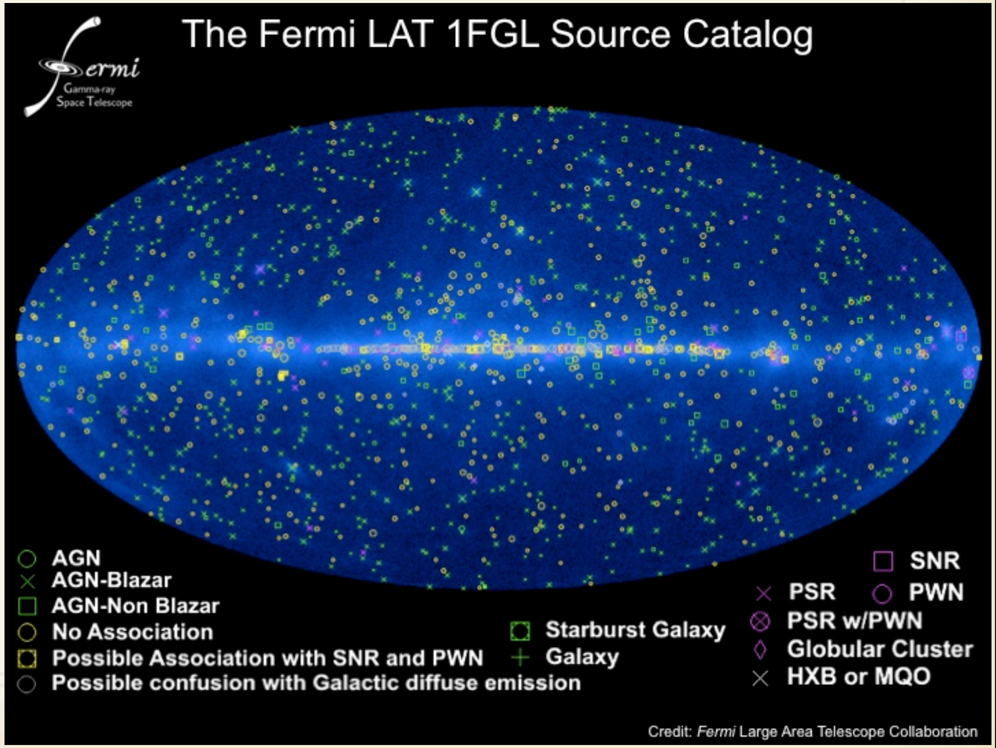
Origin of the GeV background



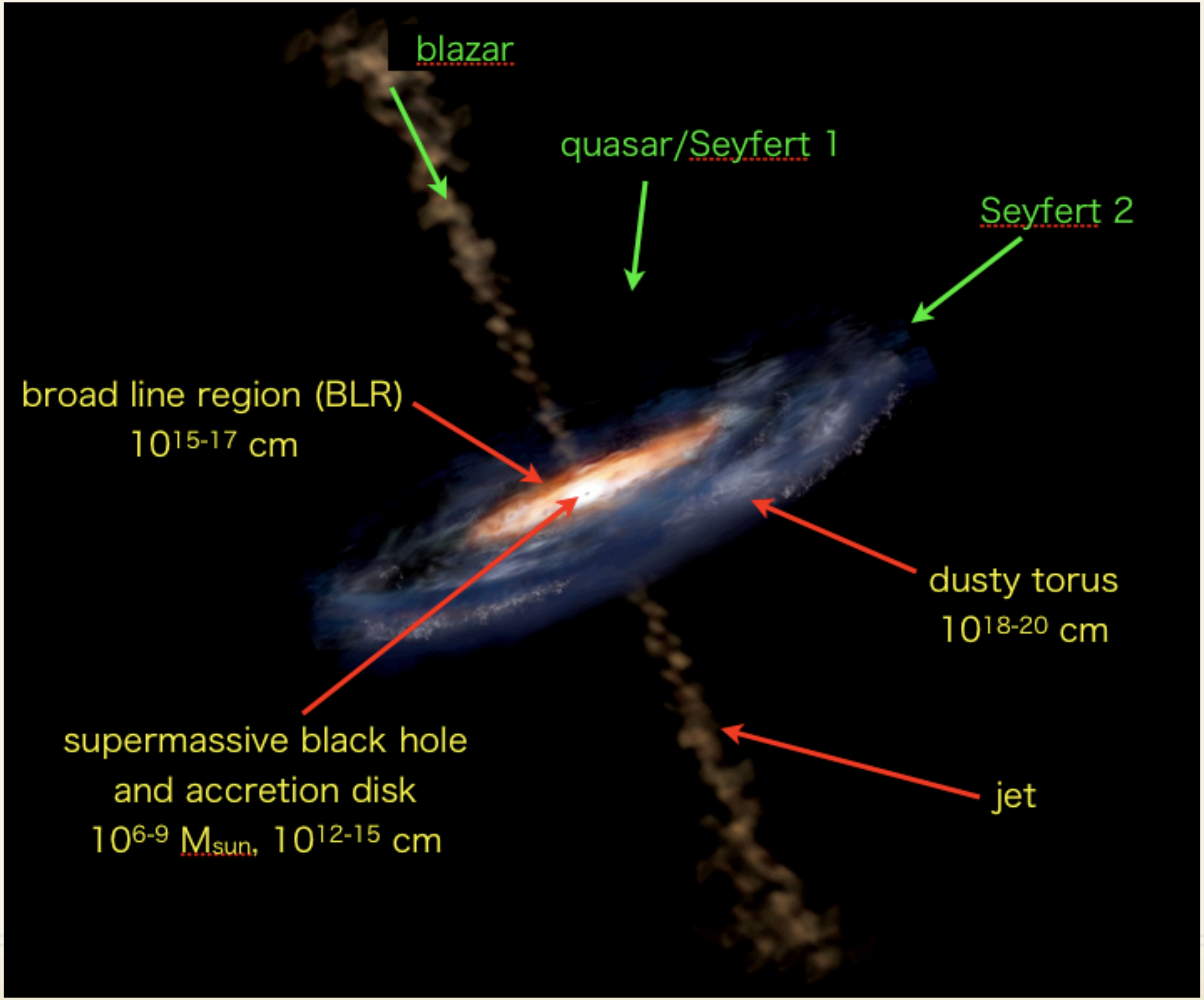
the primary candidate: blazars

- The majority of extragalactic GeV sources are blazars
- Blazars:
  - flat spectrum radio quasars (FSRQ) (in high luminosity regime)
  - BL lac objects (in low luminosity regime)





blazars


blazar
quasar/Seyfert 1
Seyfert 2
broad line region (BLR)
$10^{15\text{-}17}$ cm
dusty torus
$10^{18\text{-}20}$ cm
supermassive black hole
and accretion disk
$10^{6\text{-}9}$ M_{sun}, $10^{12\text{-}15}$ cm
jet

GeV background from Blazars

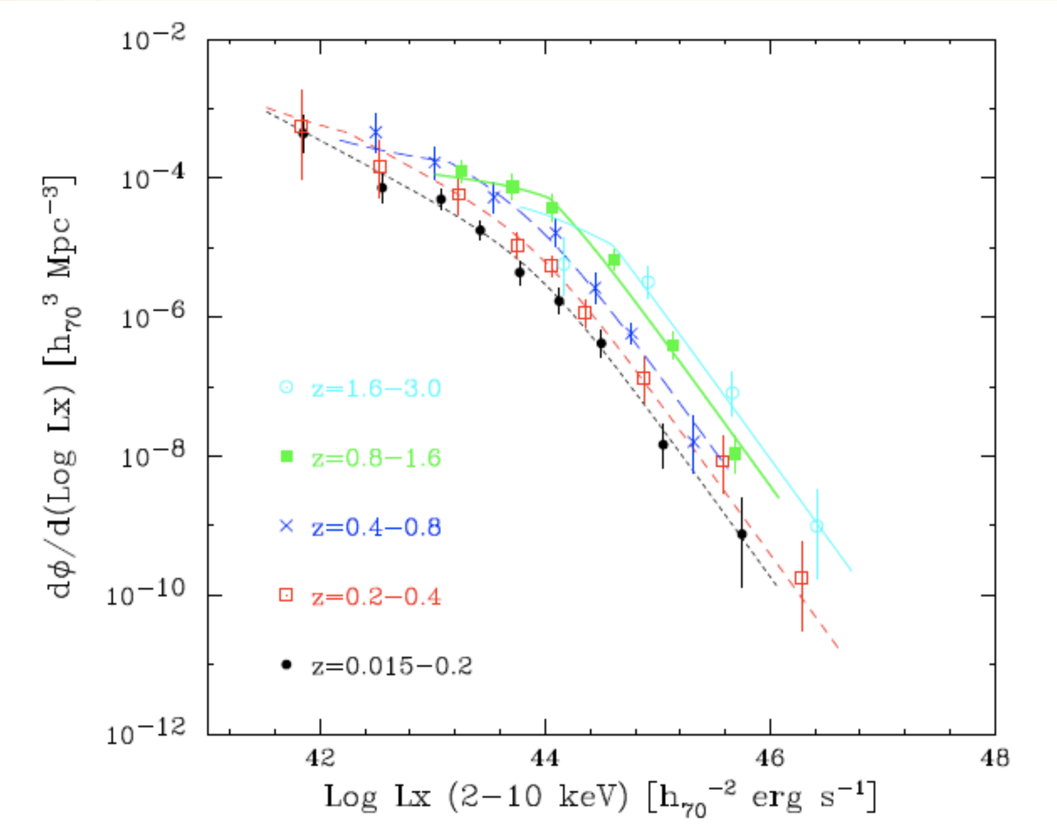
Padovani+'93; Stecker & Salamon '96; Chiang & Mukherjee '98; Mücke & Pohl '00; Narumoto & Totani '06; Giommi et al. '06; Dermer '07; Pavlidou & Venters '08; Kneiske & Mannheim '08; Inoue & Totani '09

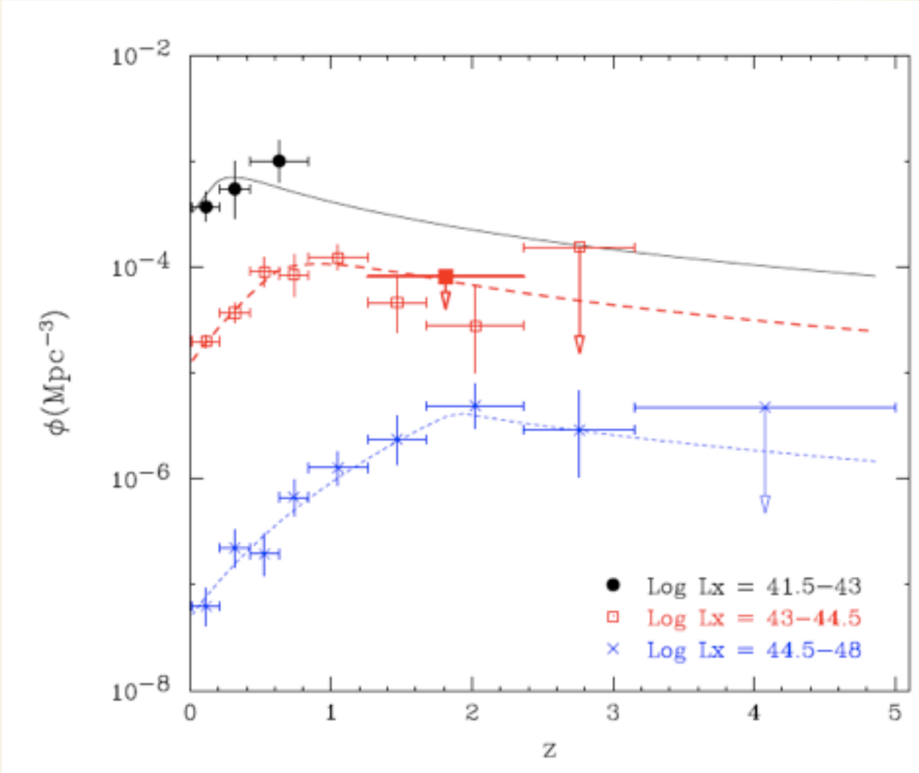
- The basic scheme:
  - luminosity function (LF) evolution model (X, radio, etc.)
  - fitting to EGRET blazar distribution (flux & redshift)
  - spectral modeling of blazars
    - (power-law, SED sequence, theoretical model, ...)

- The latest model by Inoue+TT '09 (ApJ, 702, 503)
  - "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 (LF) Evolution

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

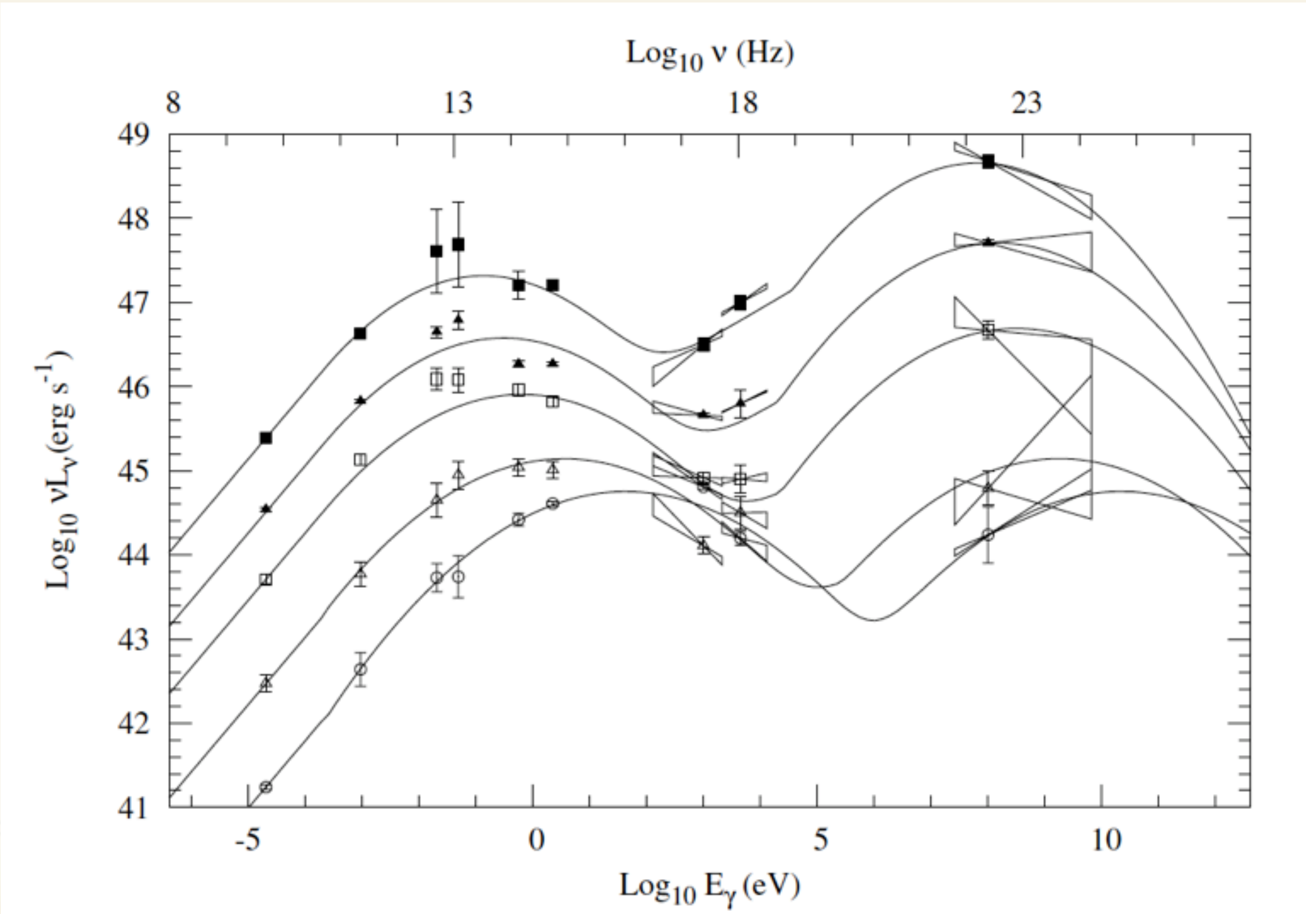




Ueda+'03

blazar spectral energy distribution (SED)

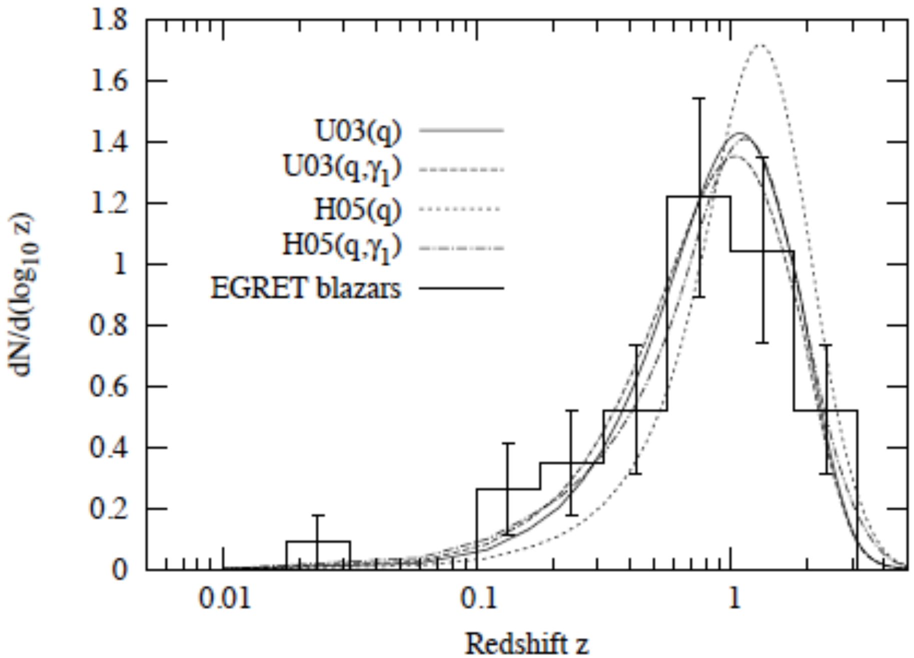
- two broad peak by synchrotron and inverse-Compton by non-thermal electrons
- the SED sequence (high peak frequency for lower luminosity)
  - Fossati+’97, Donato+’01

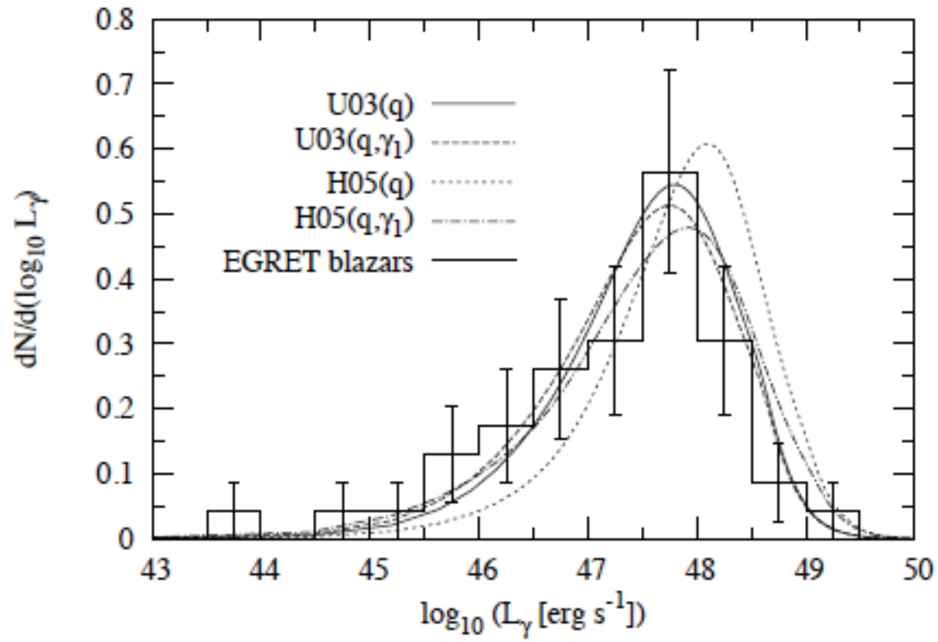


Inoue+TT ’09

Fit to EGRET blazars

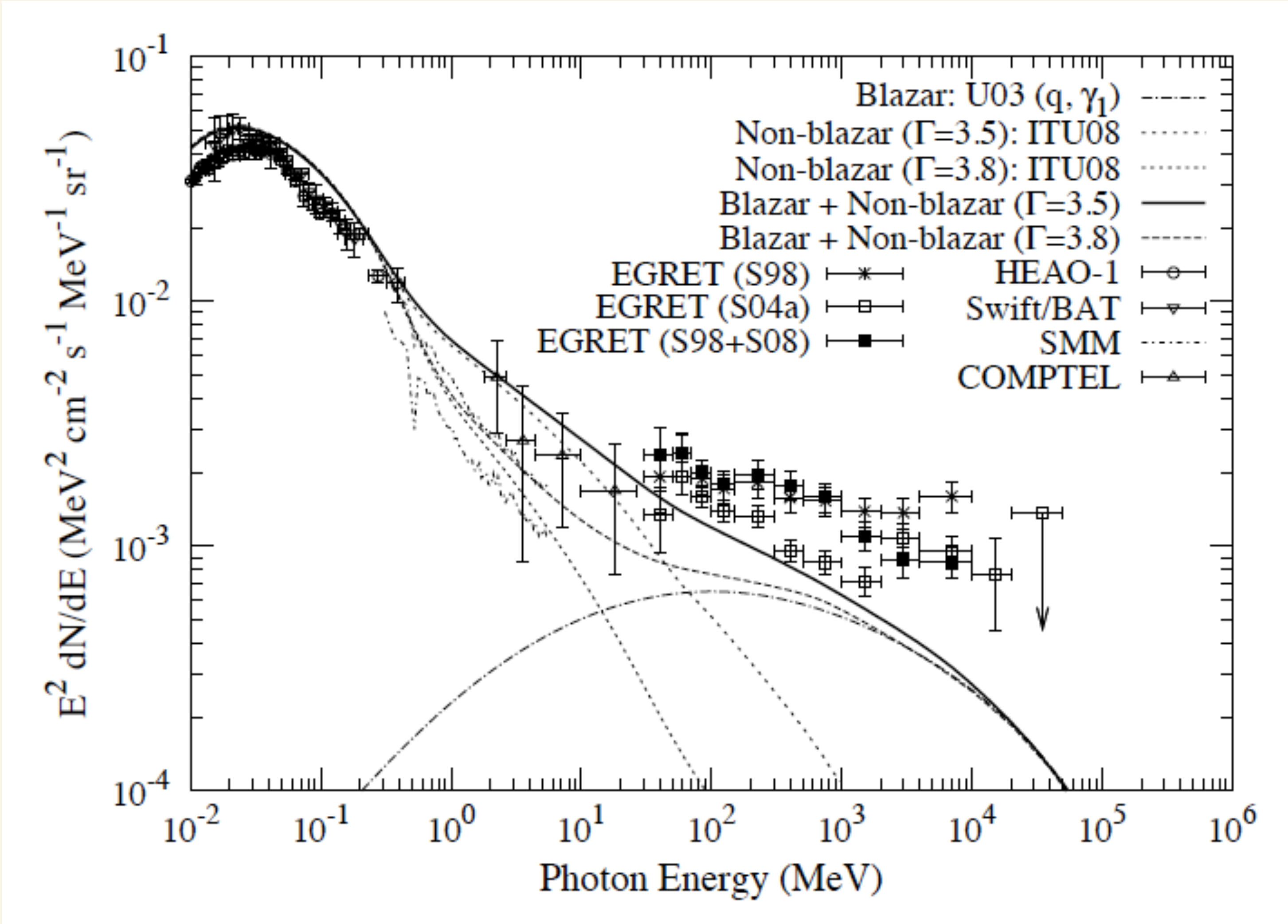
- Two basic parameters:
  - constant between luminosity L_X and L_γ
  - constant between number n_X and n_γ (beaming)
- good fit to 46 EGRET blazars up to z~3 (cosmologically significant!)
- LDDE better fits than "pure luminosity evolution" model
- not large uncertainty about evolution





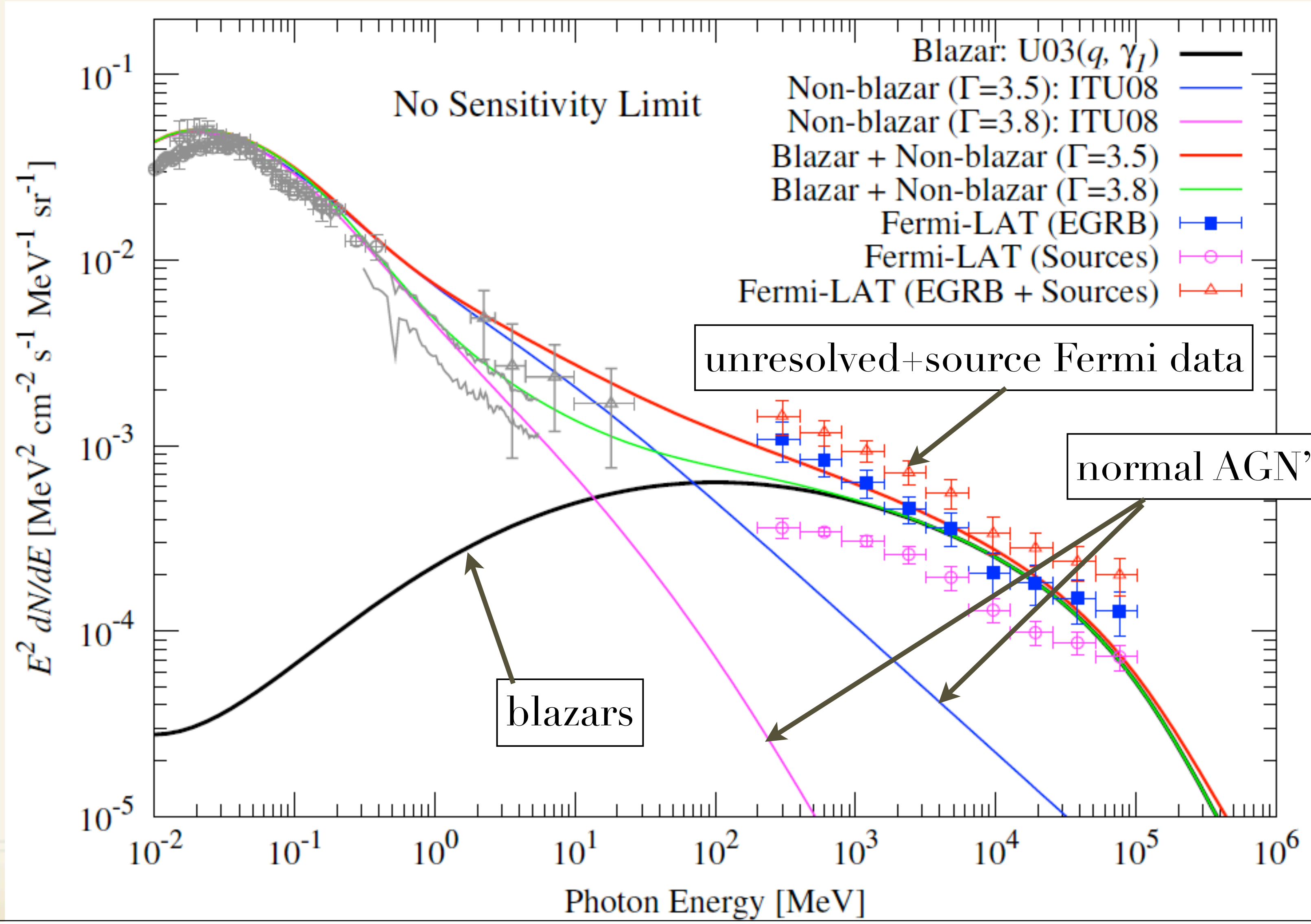
Prediction of Gamma-Ray Background

- prediction before the Fermi data came out



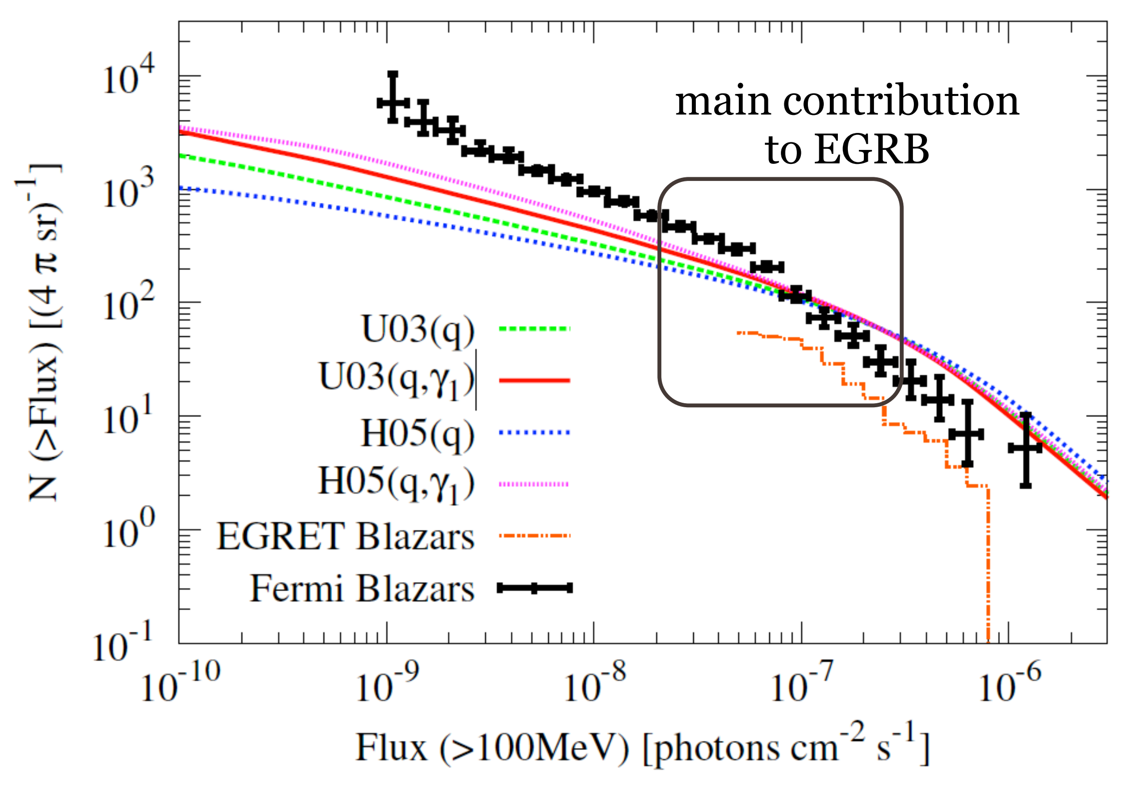
Comparison with the Fermi Data

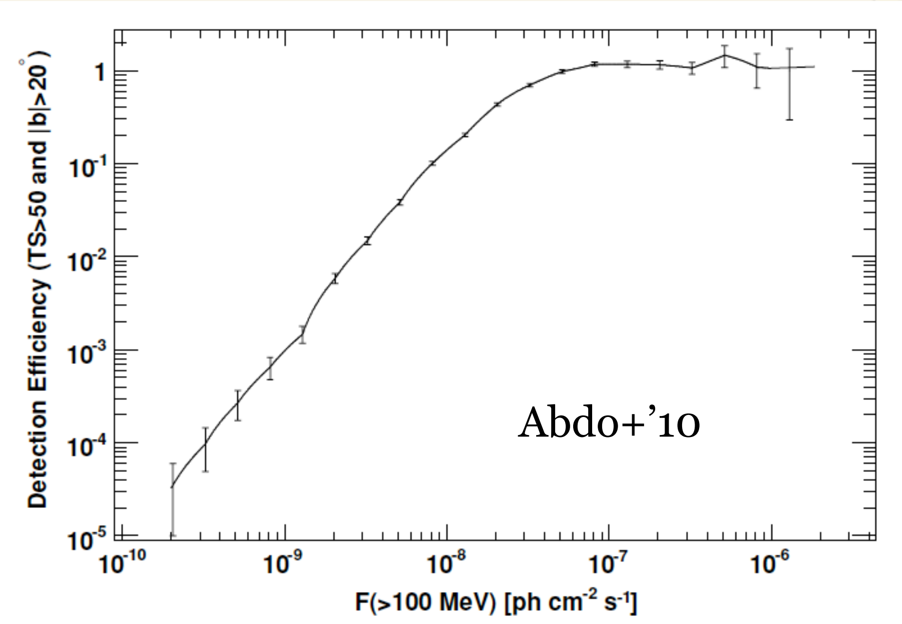
- model curves are for total EGRB including all sources in the universe
- should be compared with “unresolved+source” Fermi data



Source Counts

- model overestimates at bright end:
  - model uncertainty?
  - small number statistics?
  - cosmic variance/large scale structure?
- model underestimates at the faint end
  - model uncertainty?
  - detection efficiency uncertainty?
- break of logN-logF
  - rough agreement at 10^{-7} ph/cm^2/s
  - main contributer to EGRB
  - blazar EGRB mostly resolved
    - great success beyond EGRET





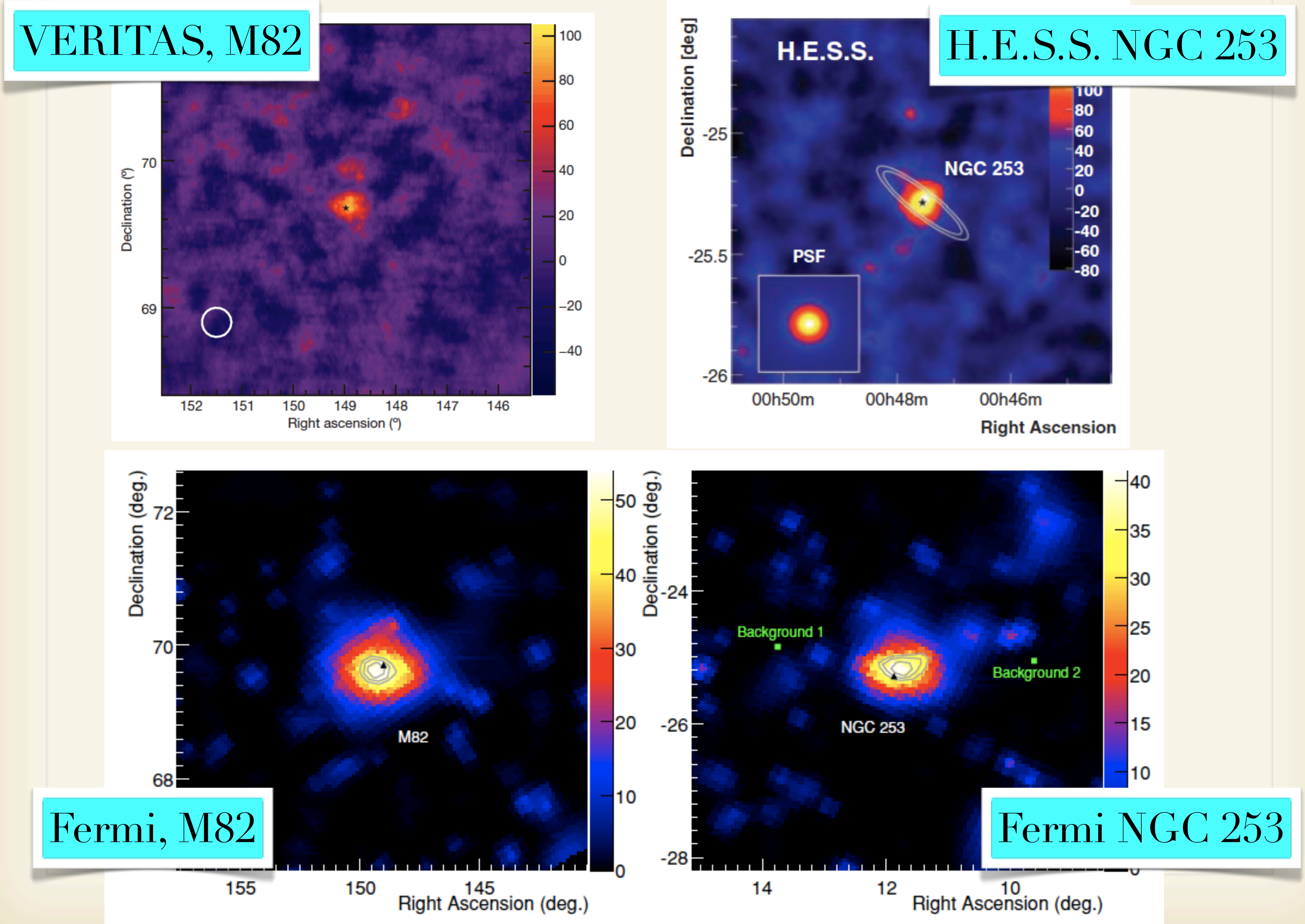
Blazars and EGRB in the Fermi Era

- Rough agreement between the model blazar LF and observation
  - good agreement in EGRB spectra and source counts around logN-logF break
  - the AGN unification scheme (blazar=jet of AGNs) and the blazar SED sequence paradigm consistent with observations

- fraction of all blazar (resolved+unresolved) in the total Fermi EGRB (resolved + unresolved) in terms of photon flux > 100 MeV
  - Fermi data estimate for blazars: ~43% (Abdo+'10)
    - 22.5% in "unresolved" EGRB flux (when logN-logS extrapolated to zero flux)
  - IT'09 prediction for blazars: ~45%
  - Both Fermi data and model indicate the blazar component has been resolved

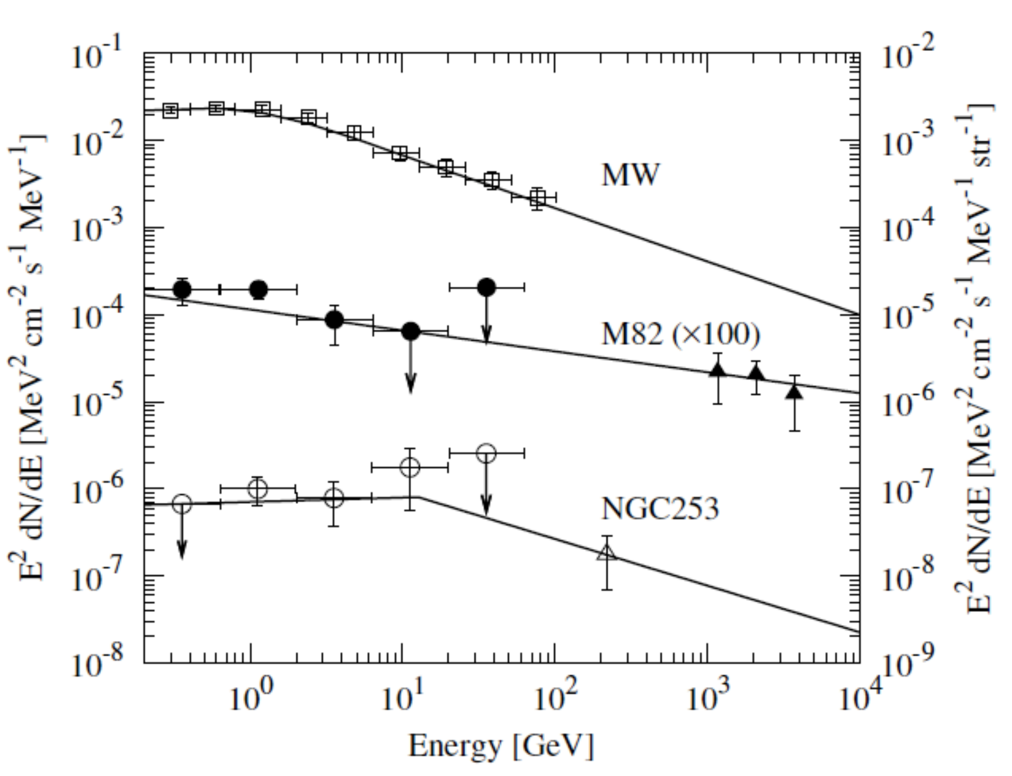
- How about the remaining component!?

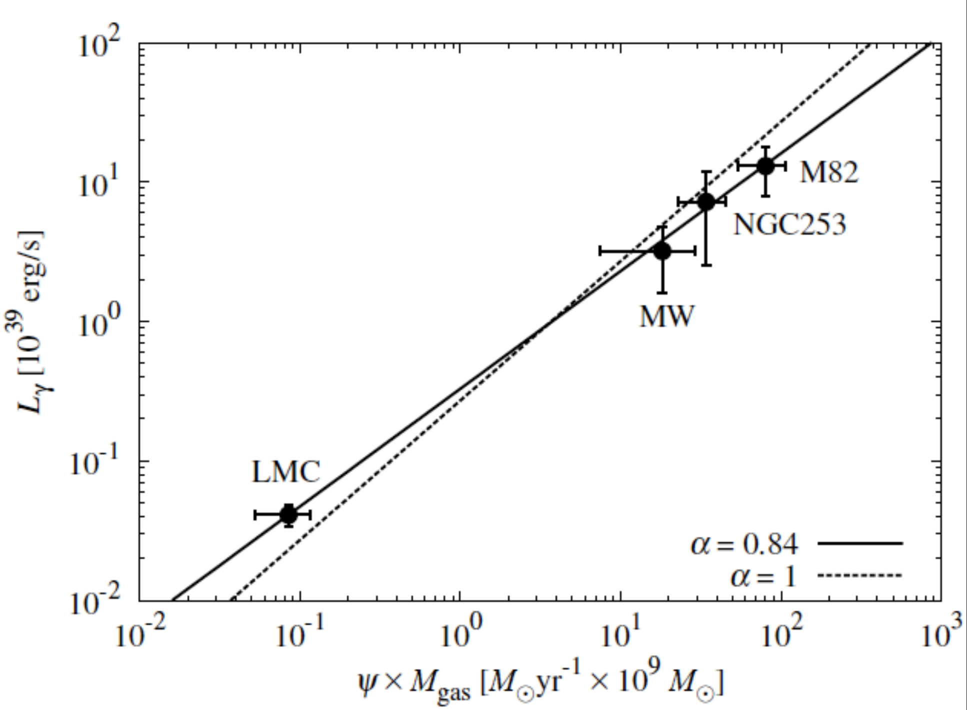
Gamma-rays from Star-forming Galaxies



Gamma-rays from Star-forming Galaxies

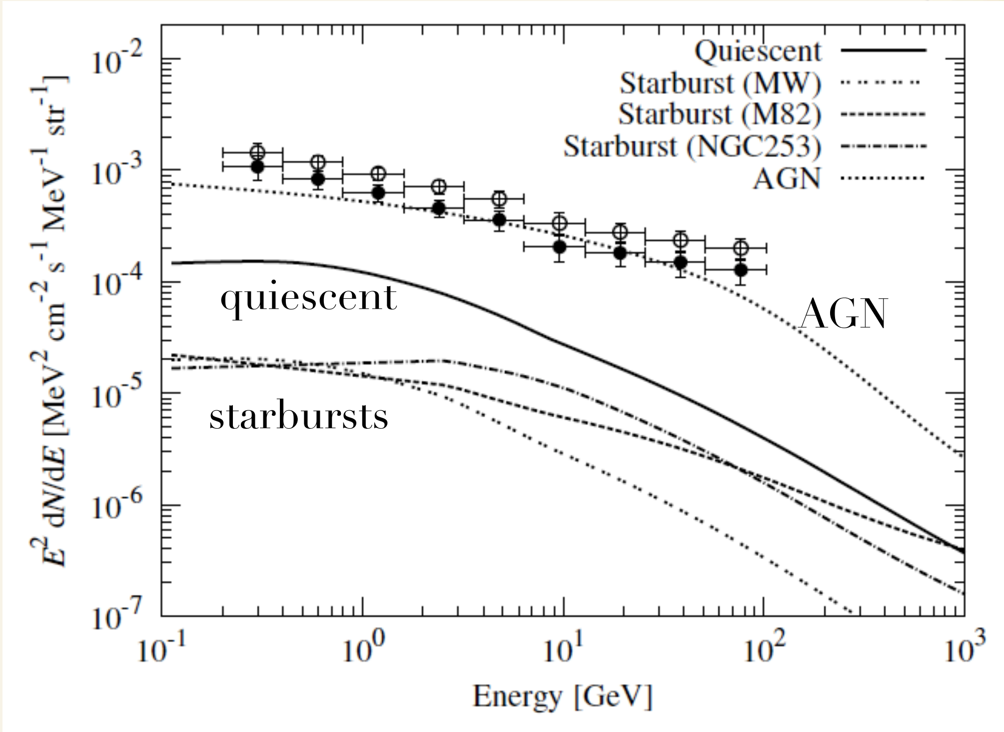
- harder spectra for starburst galaxies than MW
- good correlation with SFR×M_{gas}





gamma-ray background from star-forming galaxies

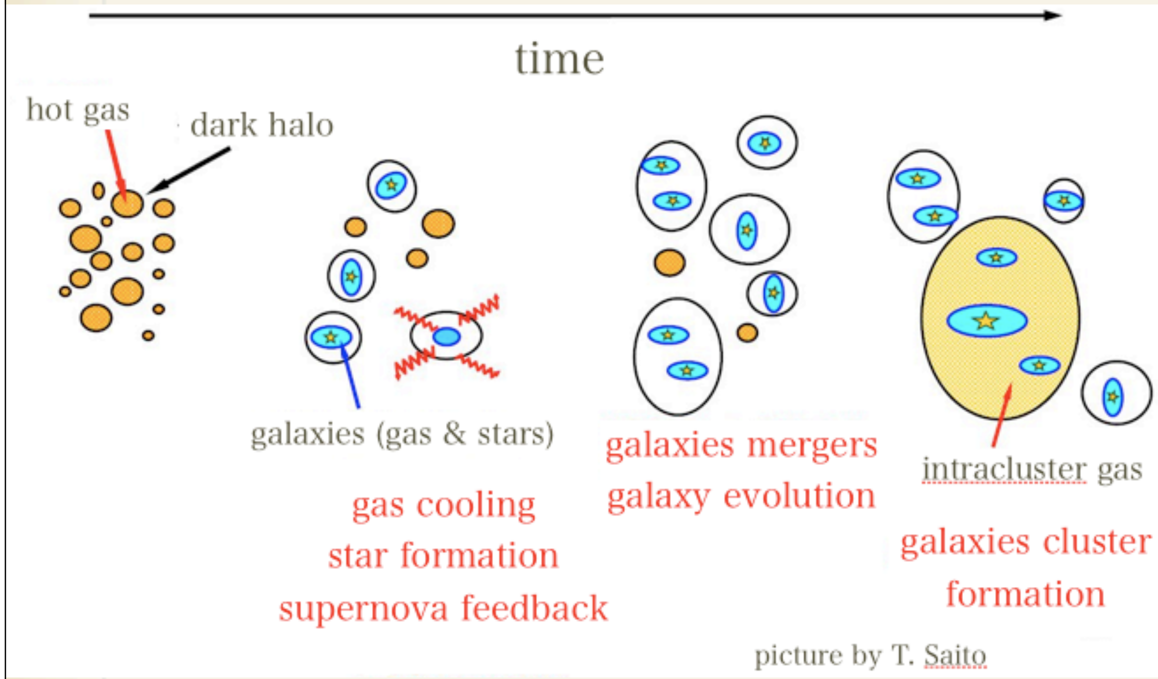
- Makiya, TT+'10, arXiv:1005.1390v1
  - see also Pavlidou+Fields '02; Thompson +'07, ...
- based on a detailed cosmological galaxy formation model that reproduce a number of galaxy observations
- $L_\gamma \propto (\mathrm{SFR}) \times M_{gas}$
- ~10% contribution to the total gamma-ray background
- predicted spectrum very similar to the observed EGRB

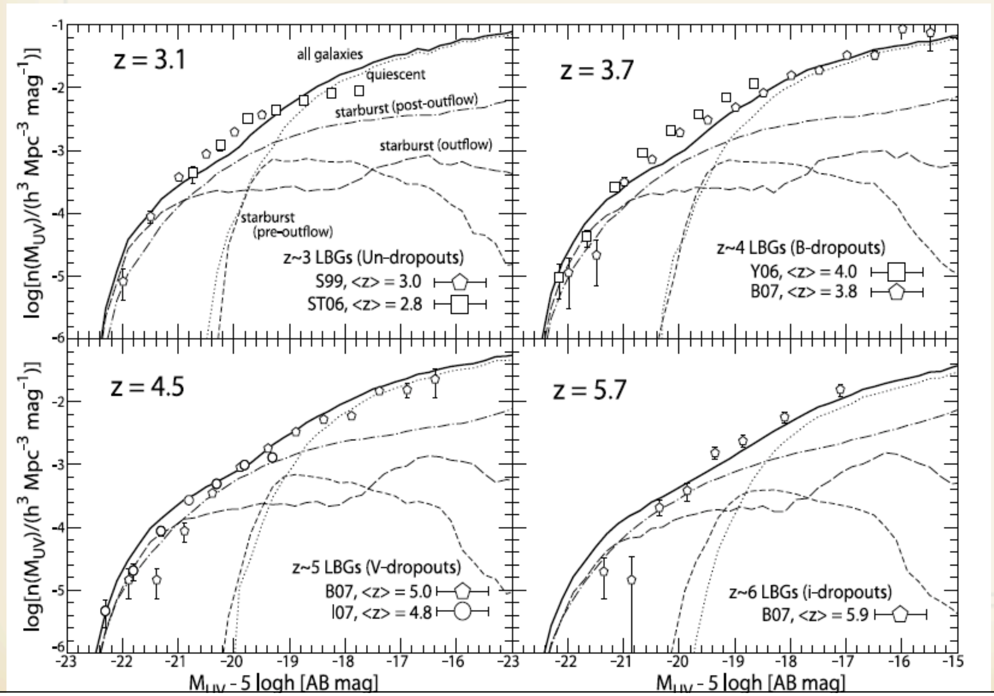


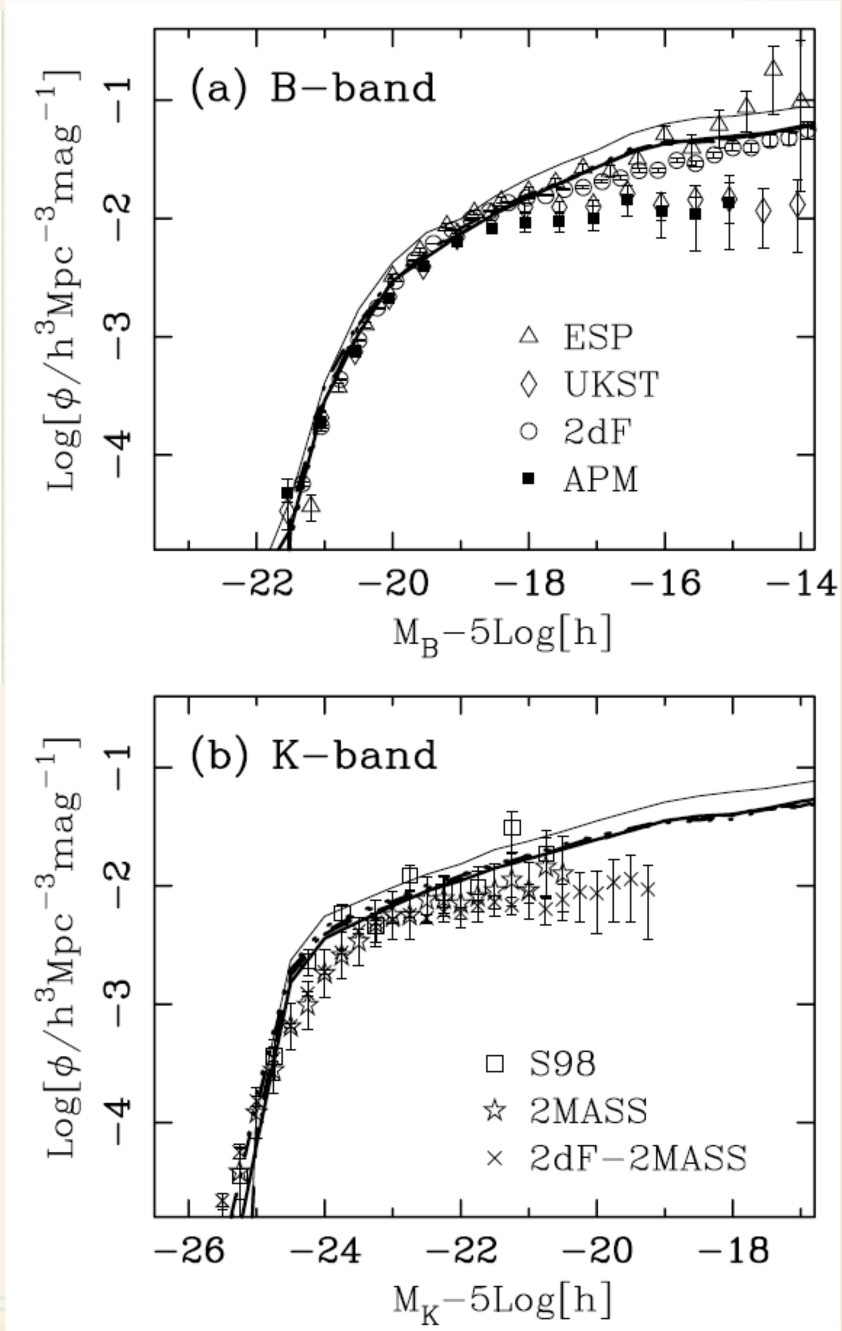
○ : total flux (incl. srcs)

● : diffuse at the Fermi limit

Cosmological Galaxy Formation Model







A semi-analytic model by Nagashima et al.

Origin of GeV EGRB: Concluding Remarks

- Contributions to EGRB from reasonable sources (in photon flux > 100 MeV)
- blazars: ~50% (confirmed both by observation and model)
- Star-forming galaxies: 10-20% (theoretical+local obs.)
- normal AGN's non-thermal tail: <~20% (theoretical)

- >~ 80% of EGRB can be explained by astrophysically reasonable source contributions
  - the predicted spectrum also in good agreement with observation
  - remaining <~20%? systematic uncertainties both in model and obs.?

- No evidence (sadly!) for exotic sources like dark matter annihilation
  - star-forming galaxy component difficult to resolve
  - direct DM detection impossible under ~10% of EGRB. Anisotropy?