ガンマ線天文学と宇宙背景放射

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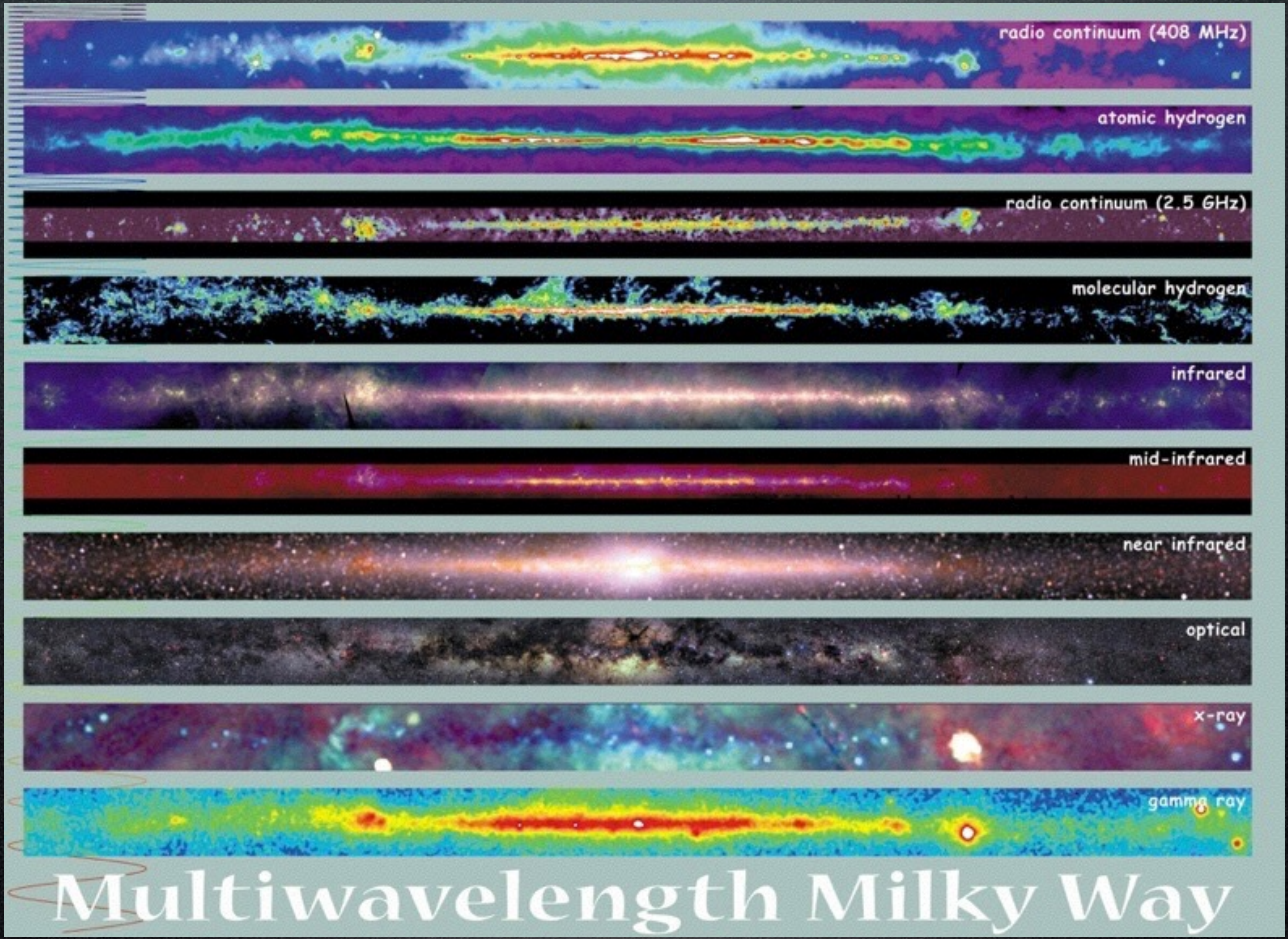
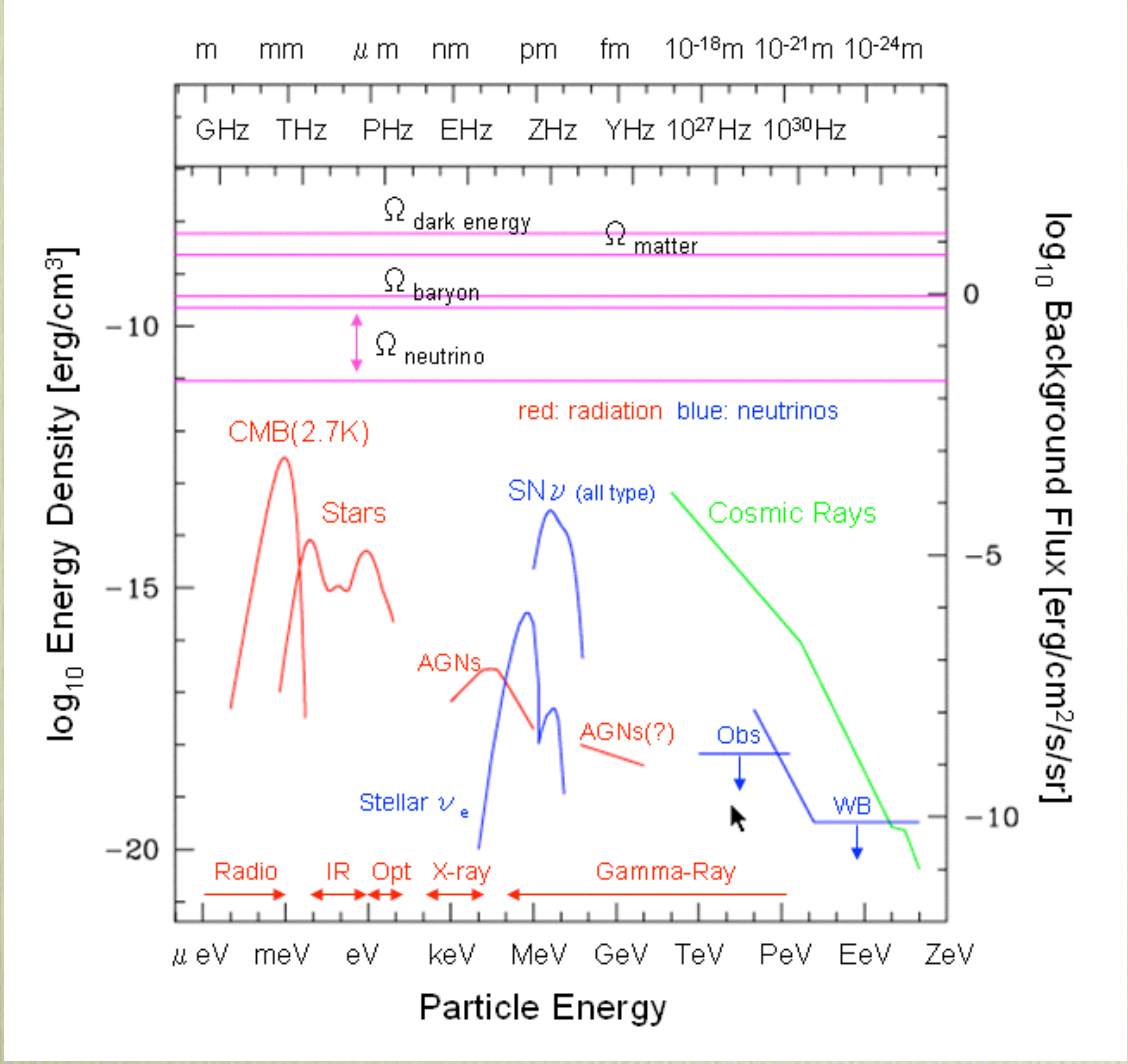
Outline

- 様々な波長における宇宙背景放射の起源
    - 特に、X線・ガンマ線の背景放射の起源は？

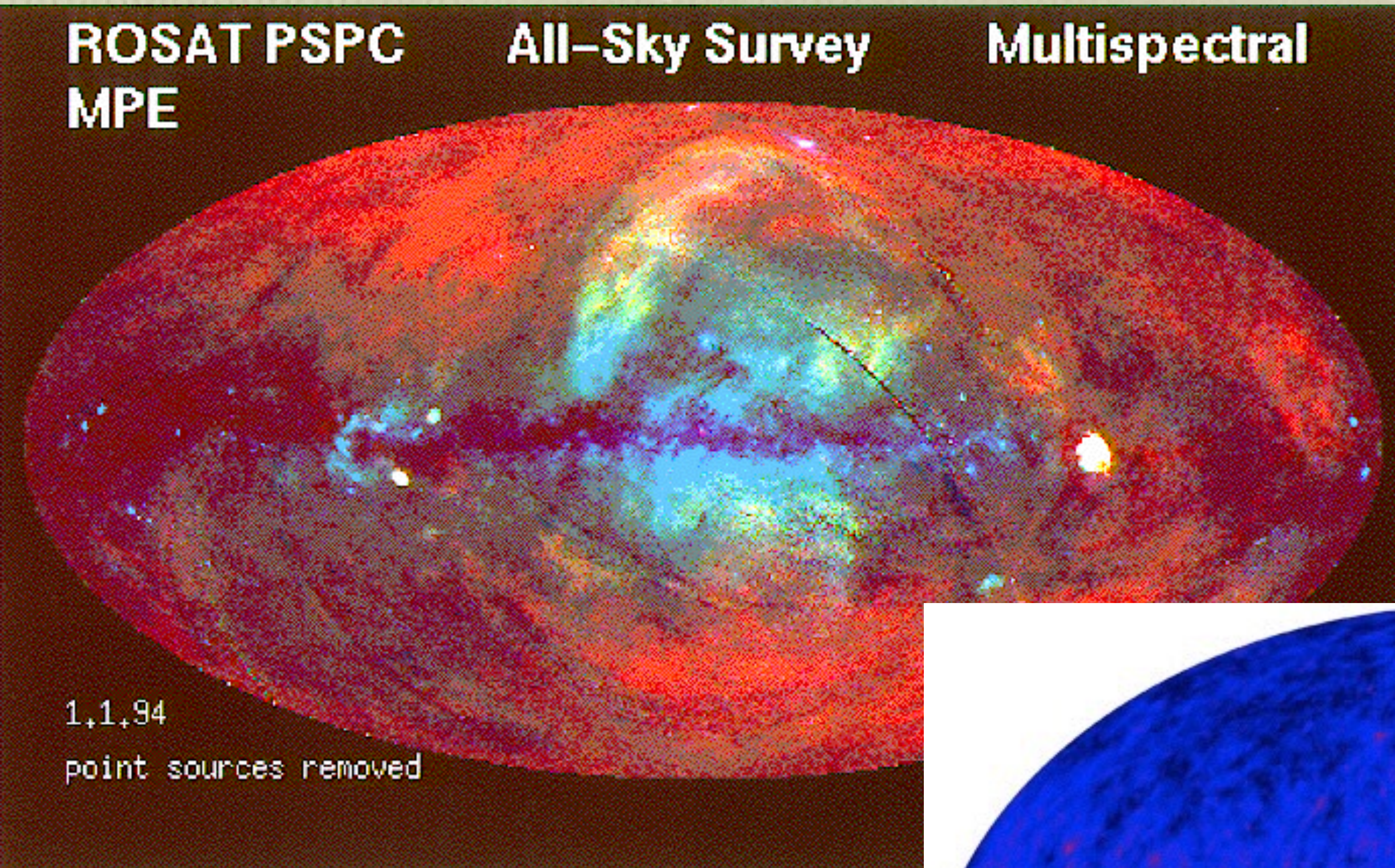
- 高エネルギーガンマ線と可視・赤外背景放射の相互作用
    - 可視赤外背景放射の理論モデル計算＝銀河形成理論

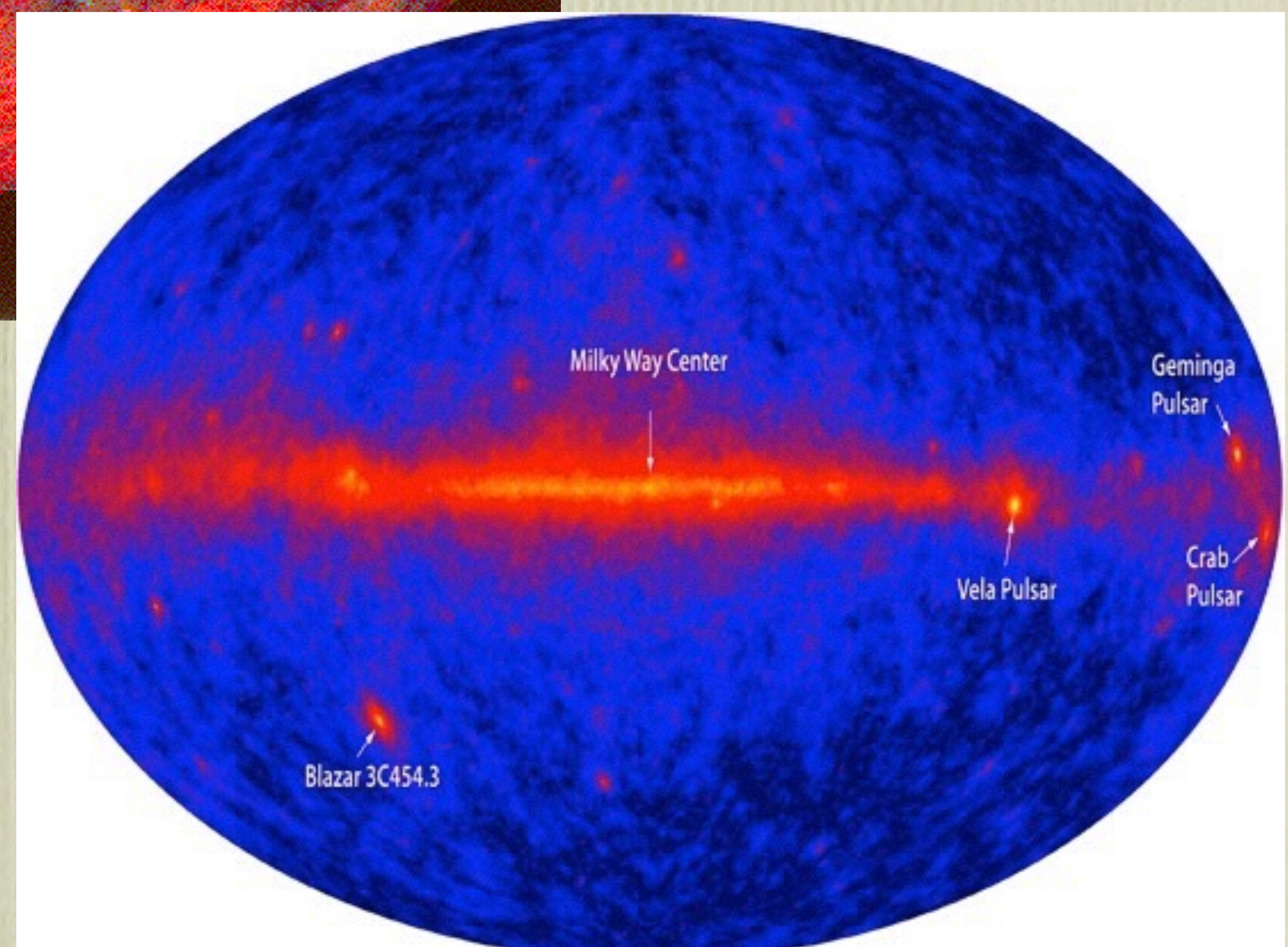

radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
Multiwavelength Milky Way

The Cosmic Background Radiation

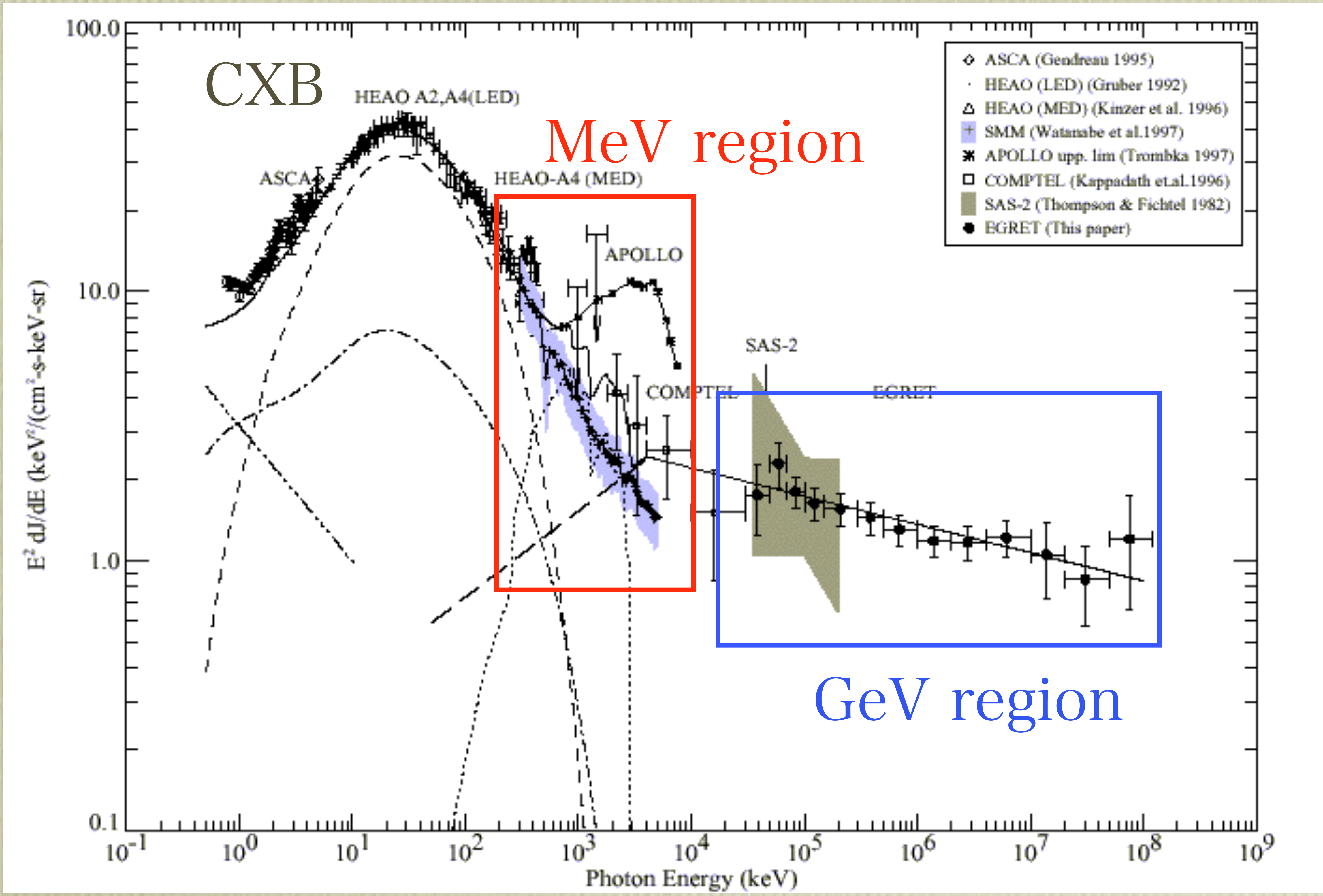


X-ray and Gamma-Ray Sky





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



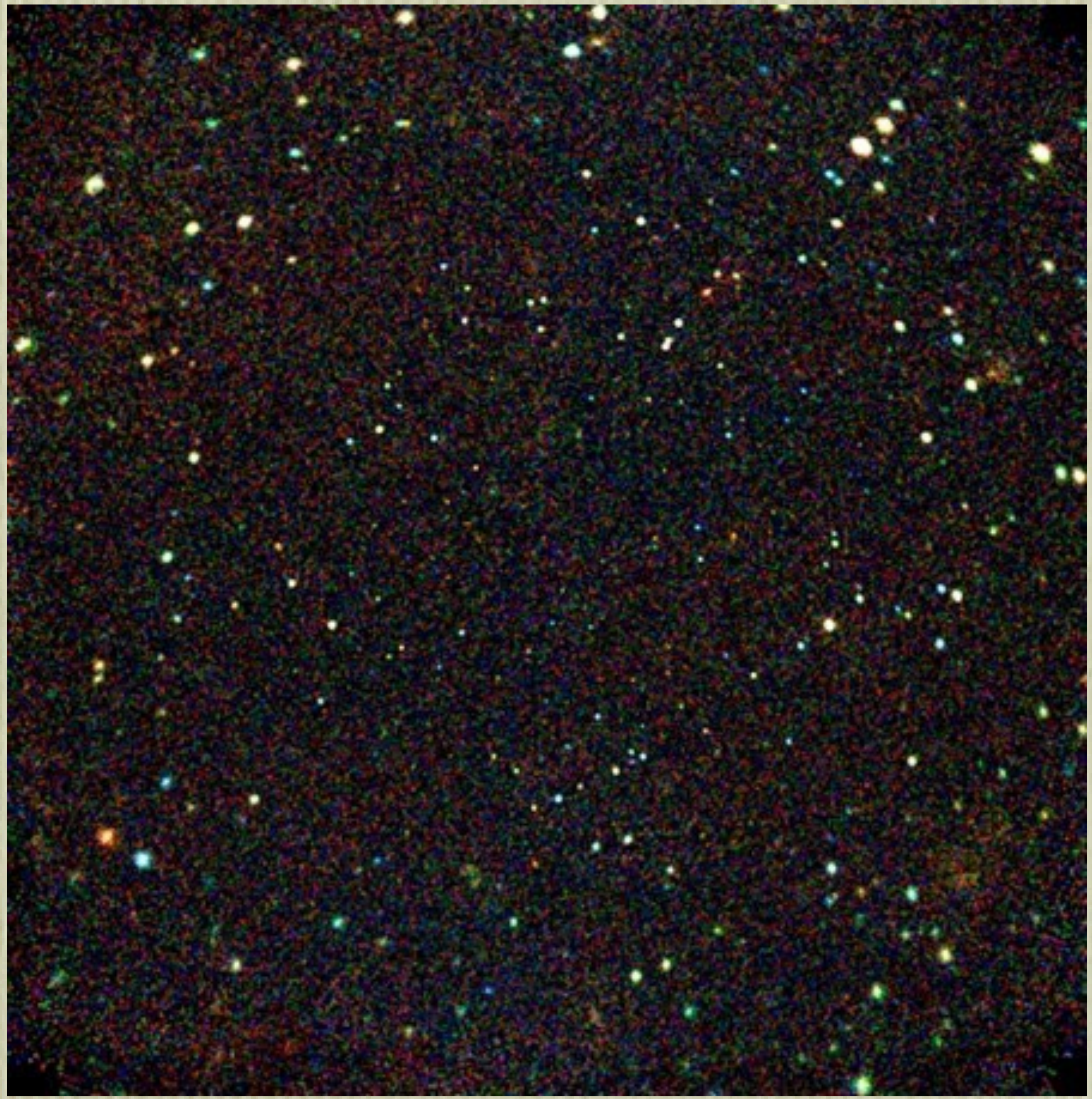
Sreekumar et al. 1998

Origin of X/MeV Background

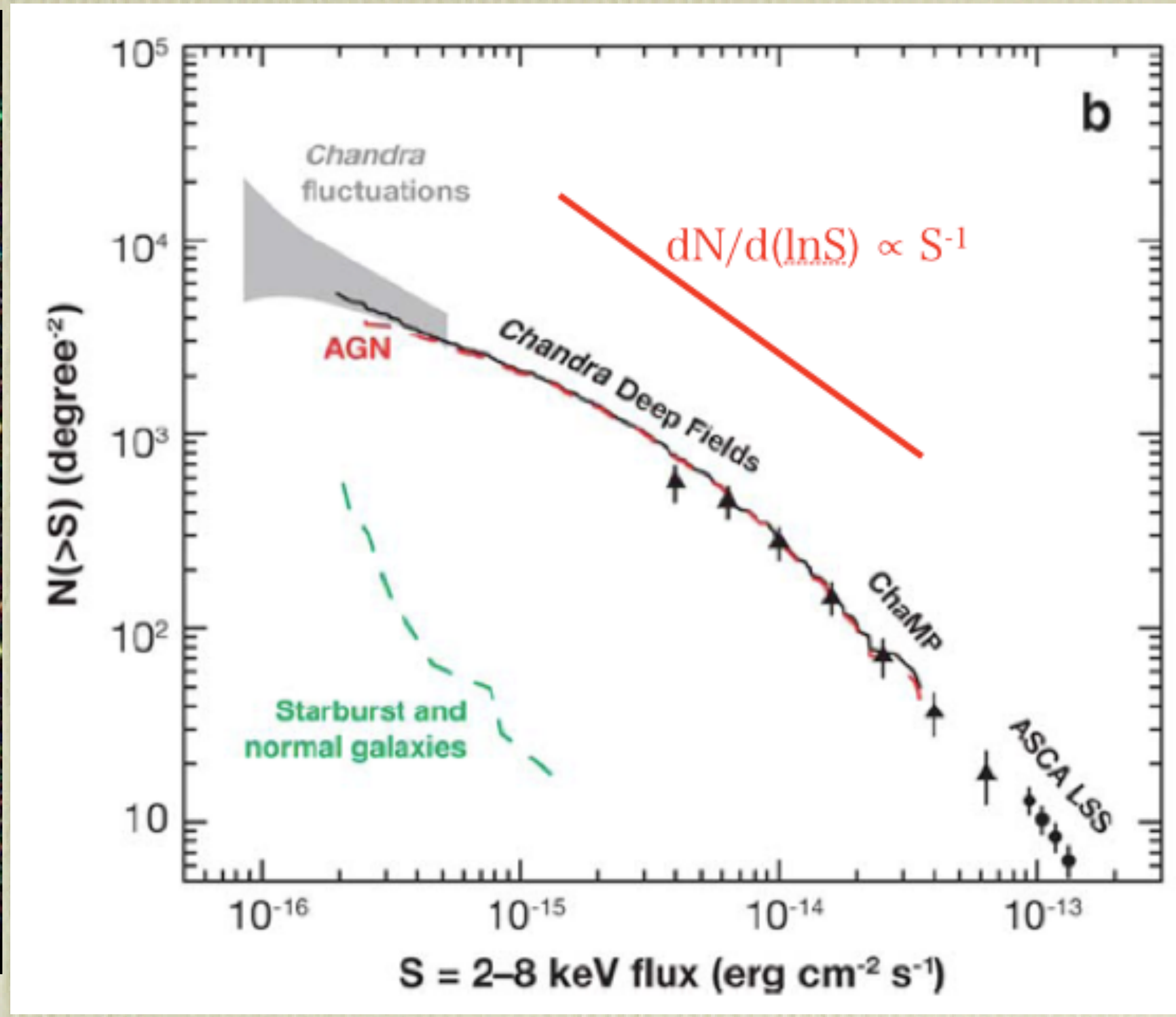
- Cosmic X-ray background (CXB)
  - can be explained by integration of normal X-ray AGNs
  - has mostly been resolved into discrete sources

- 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; Rasera+'06

Cosmic X-ray Background



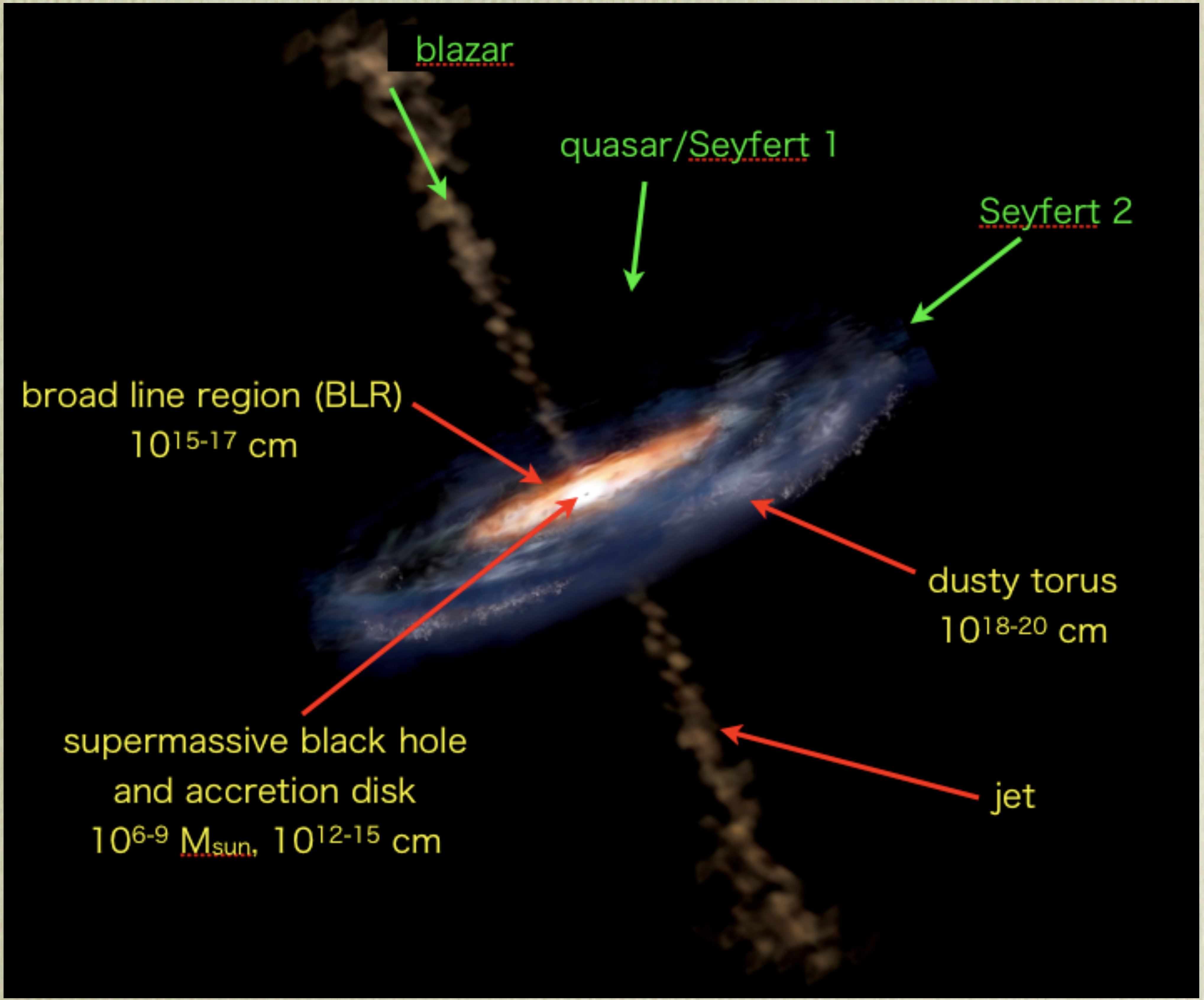
Chandra Deep Field



Brandt+Hasinger '05

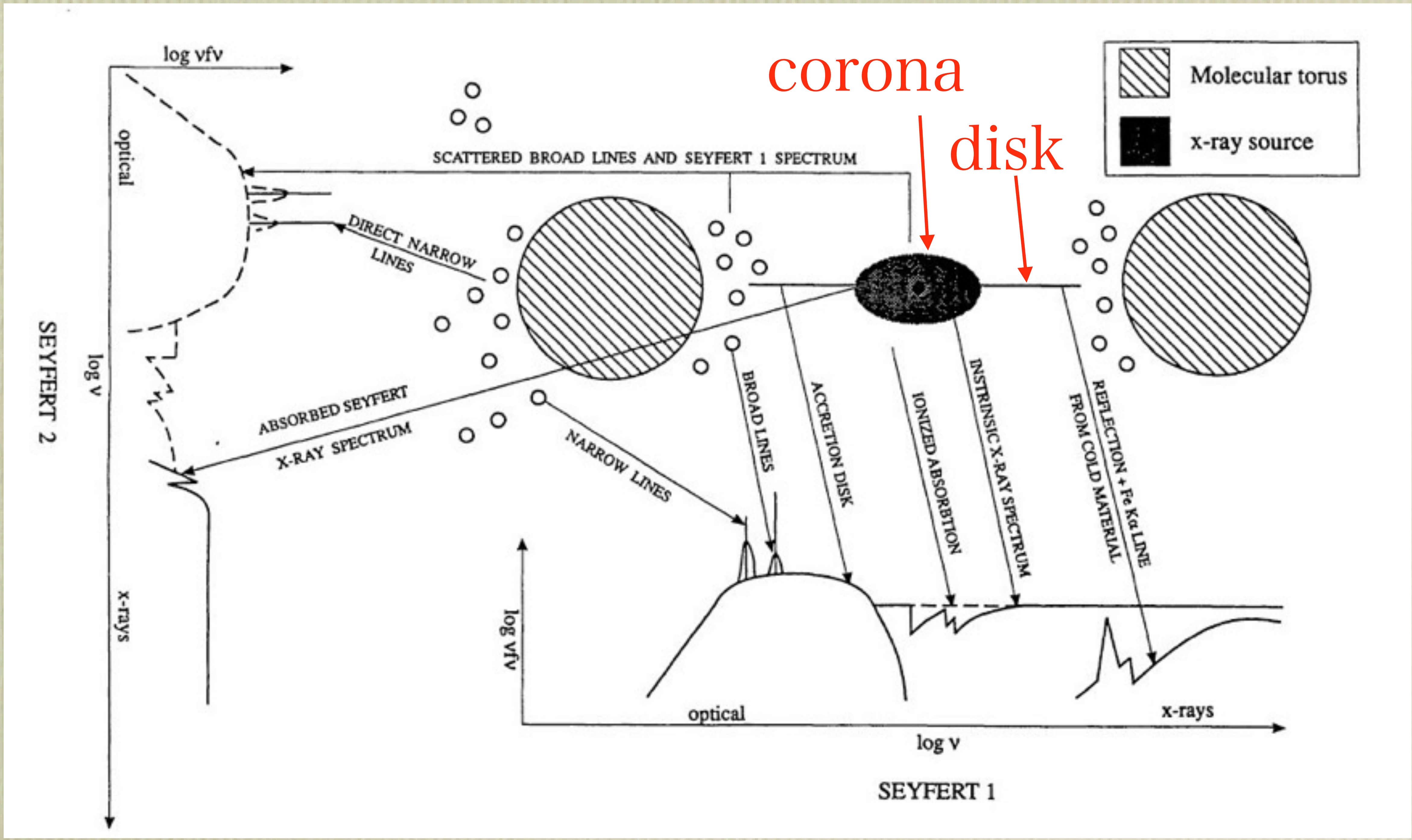
- CXB has mostly been resolved into discrete sources

Active Galactic Nuclei



The Picture of AGN X-ray Spectra

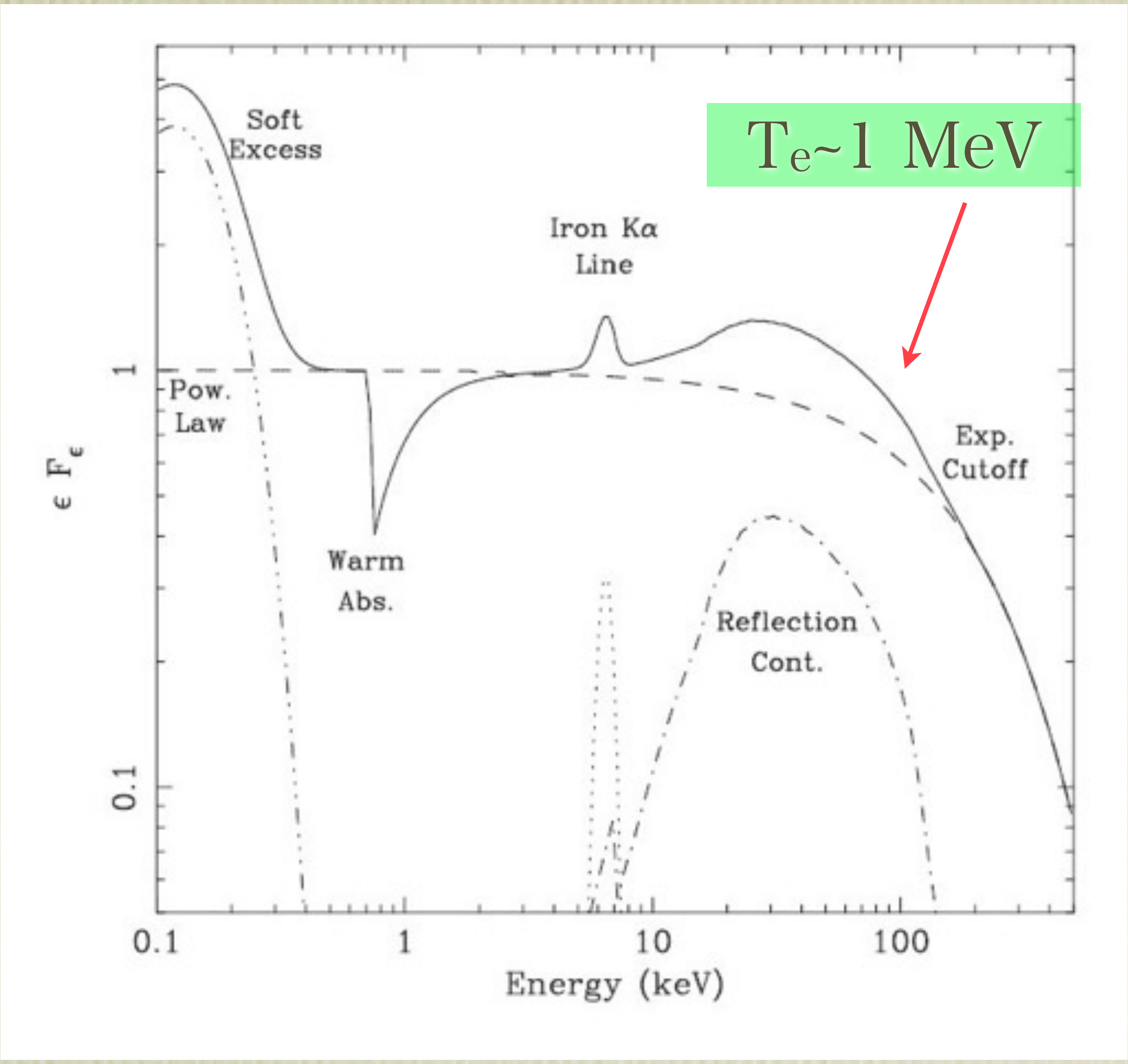
- picture of normal X-ray AGNs (e.g., Seyferts)



Mushotzky et al. 1993

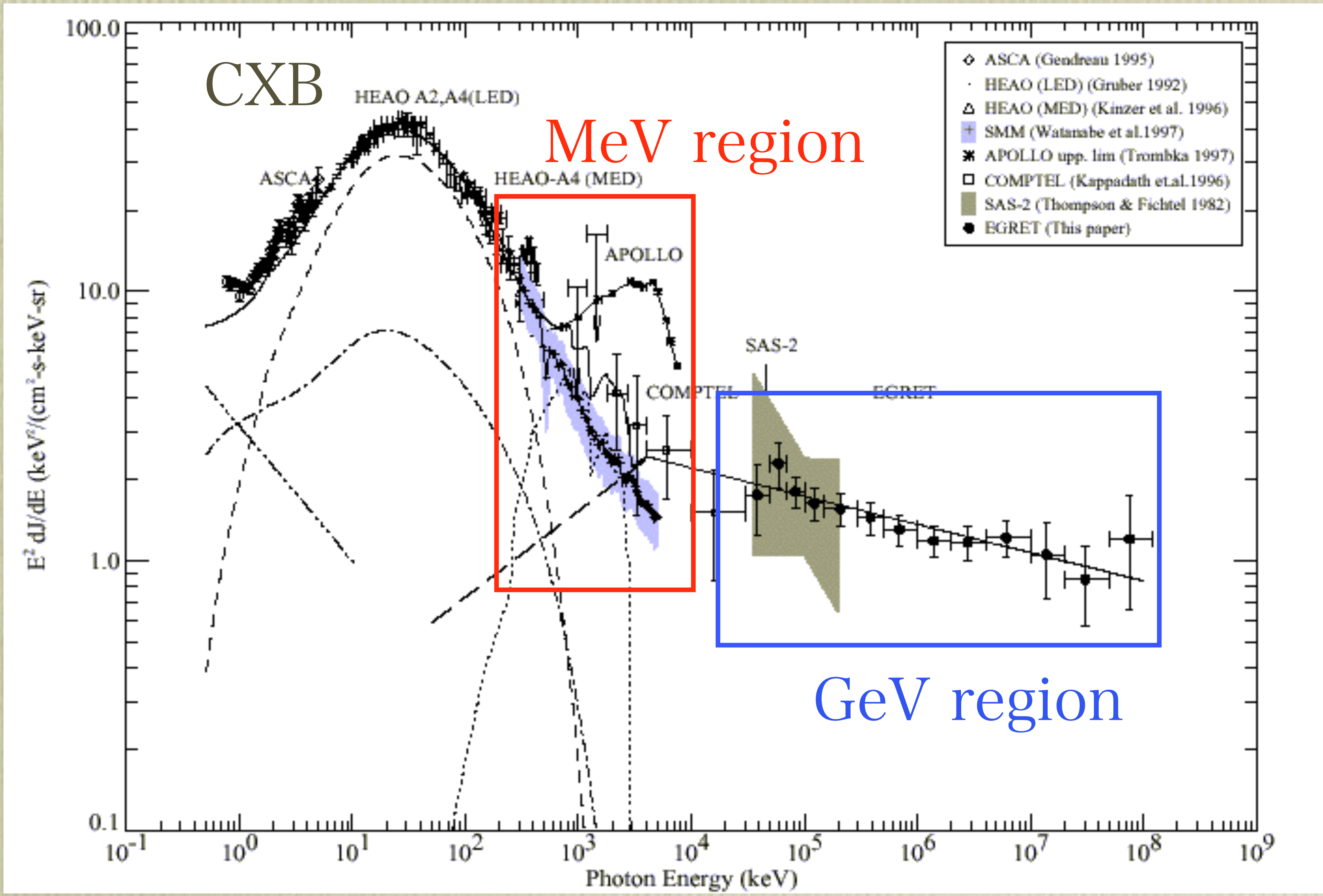
AGN X-ray Spectrum

- 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

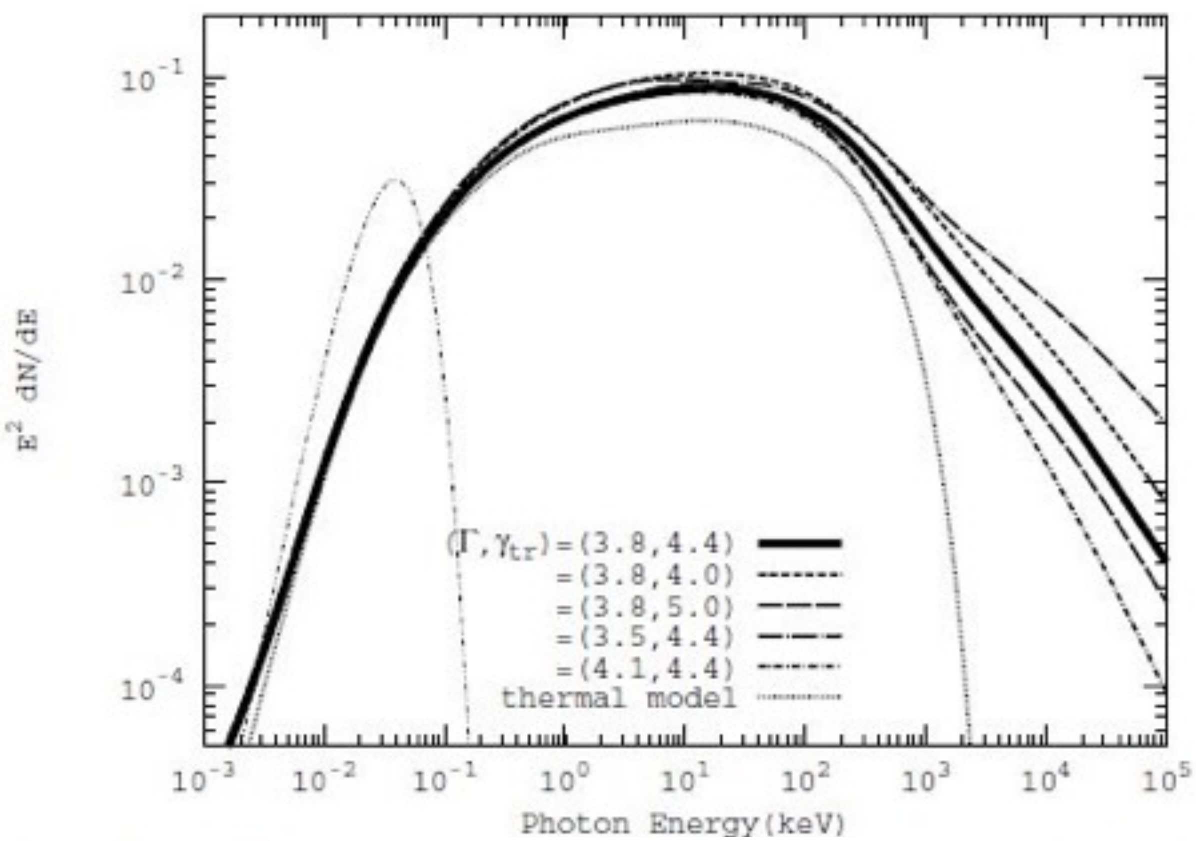
Cosmic X-ray & gamma-ray background (CXB, CGB)



Sreekumar et al. 1998

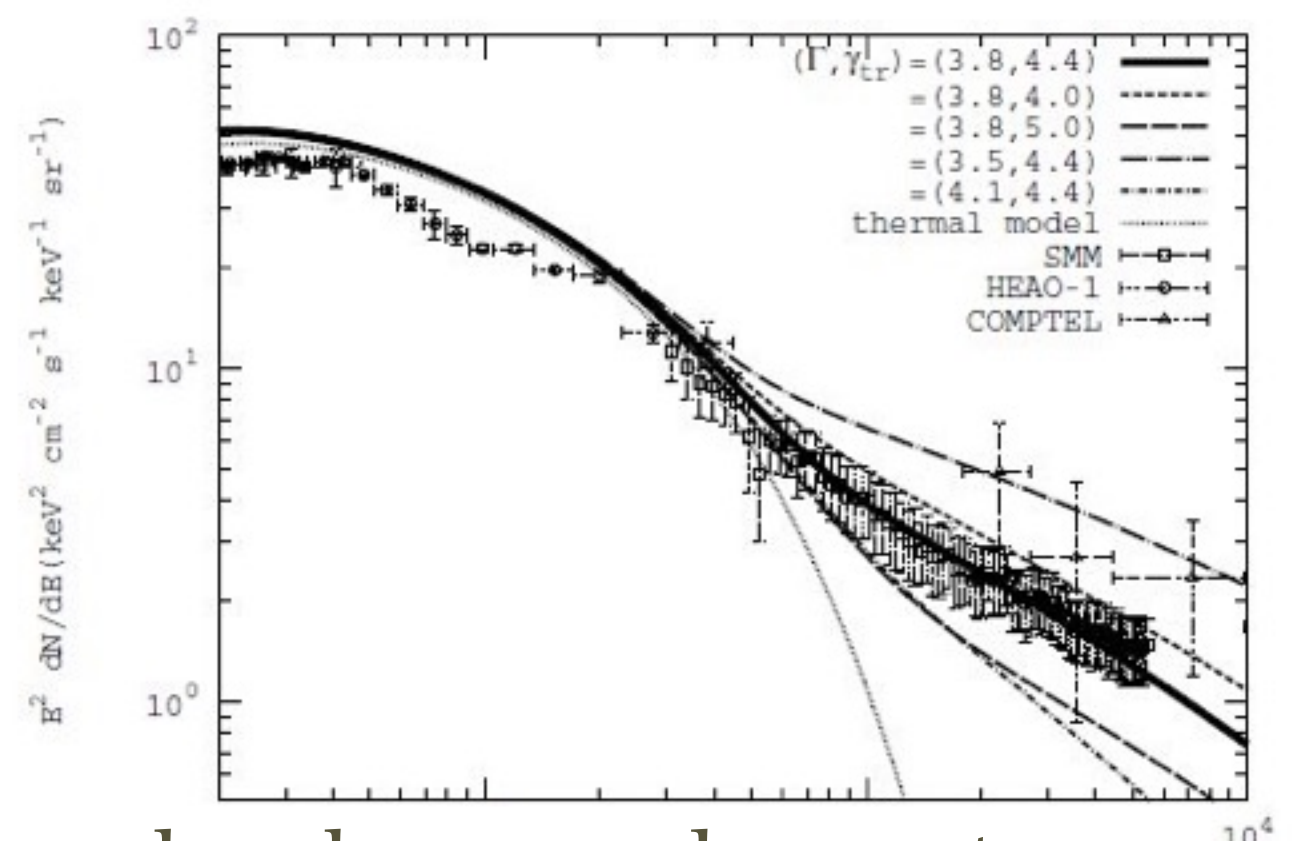
MeV background by AGNs with nonthermal coronal electrons

- 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



AGN spectrum

FIG. 1.— The ds calculated by our model. T /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).

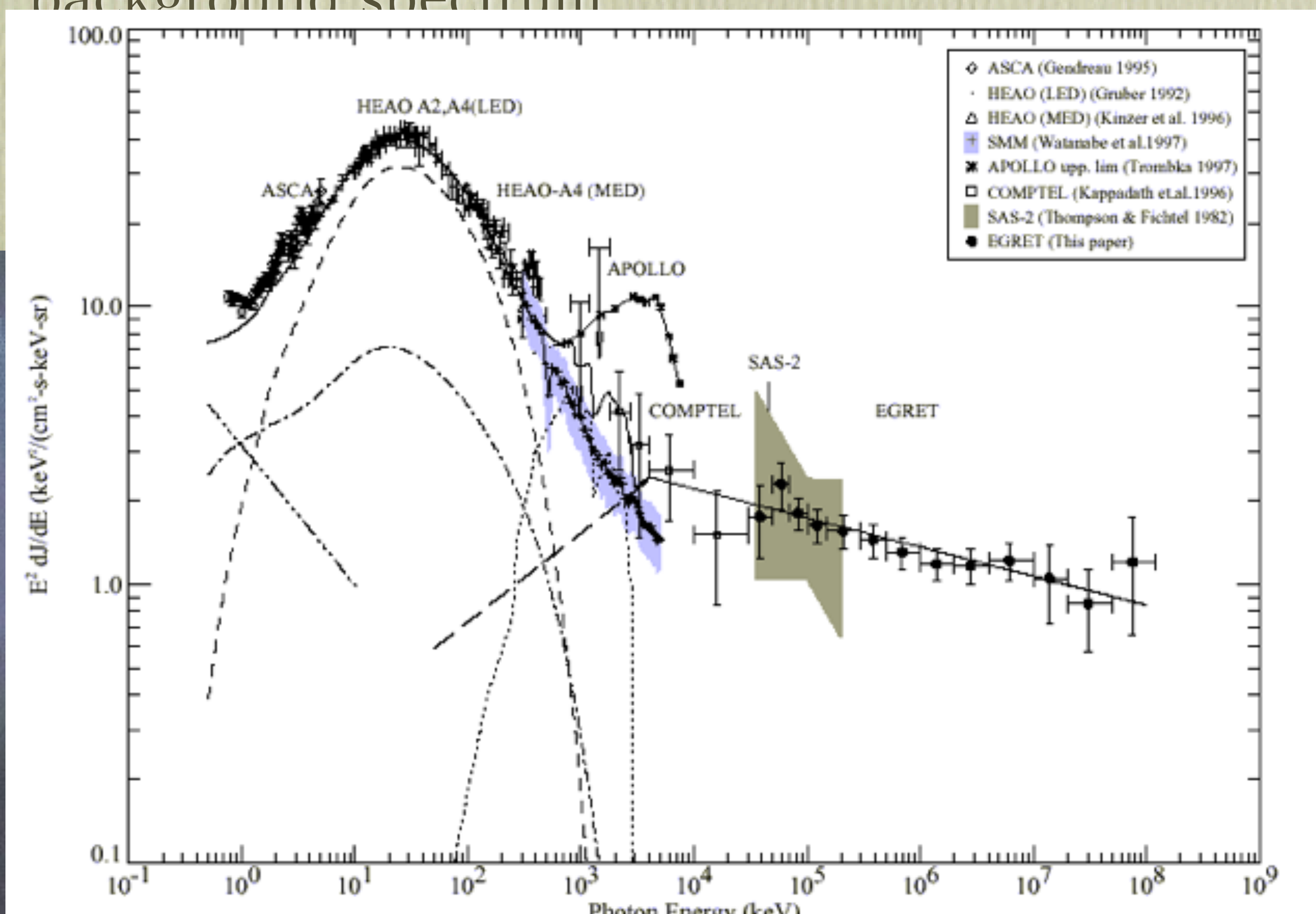


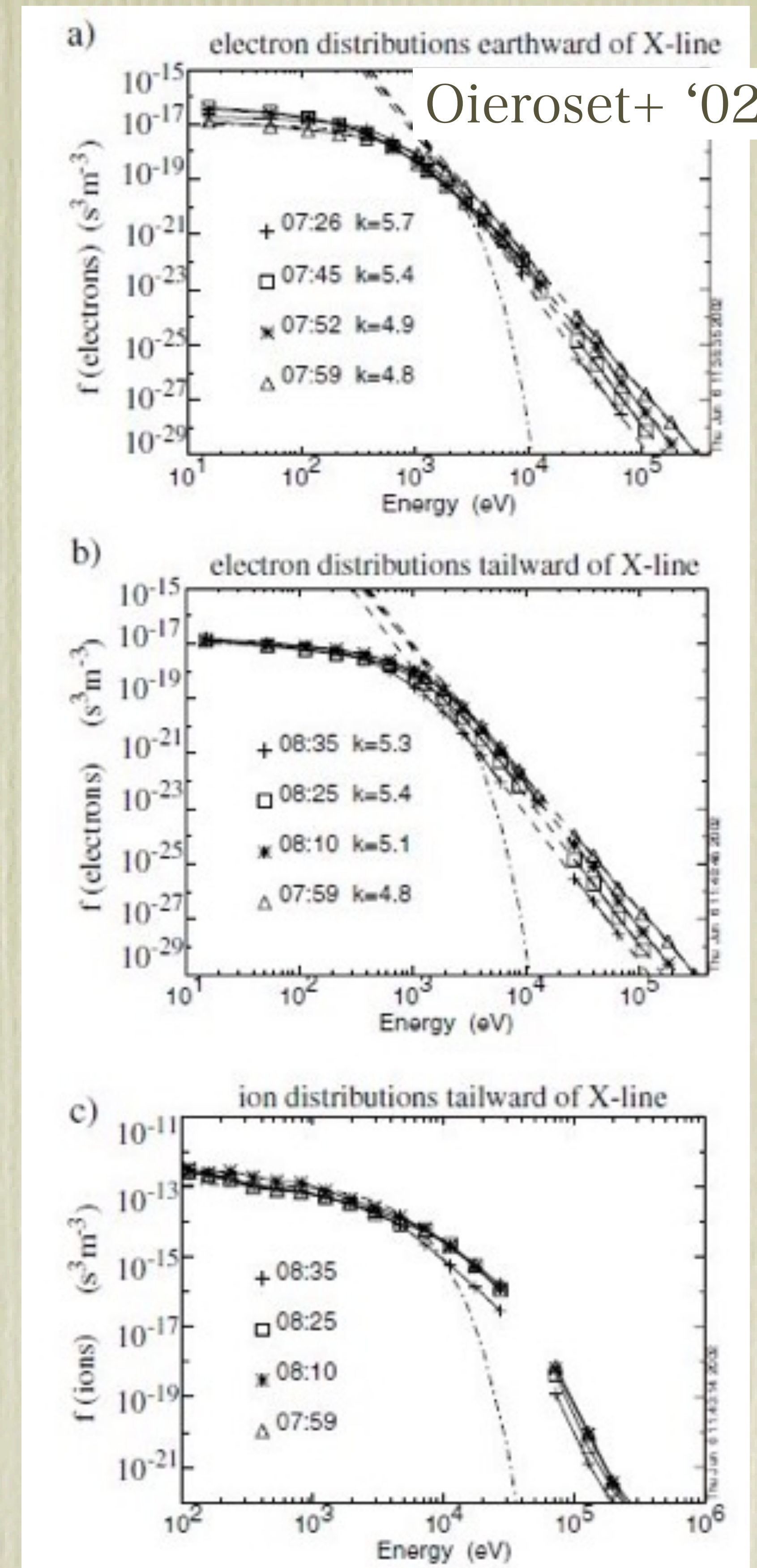
background spectrum

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.

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



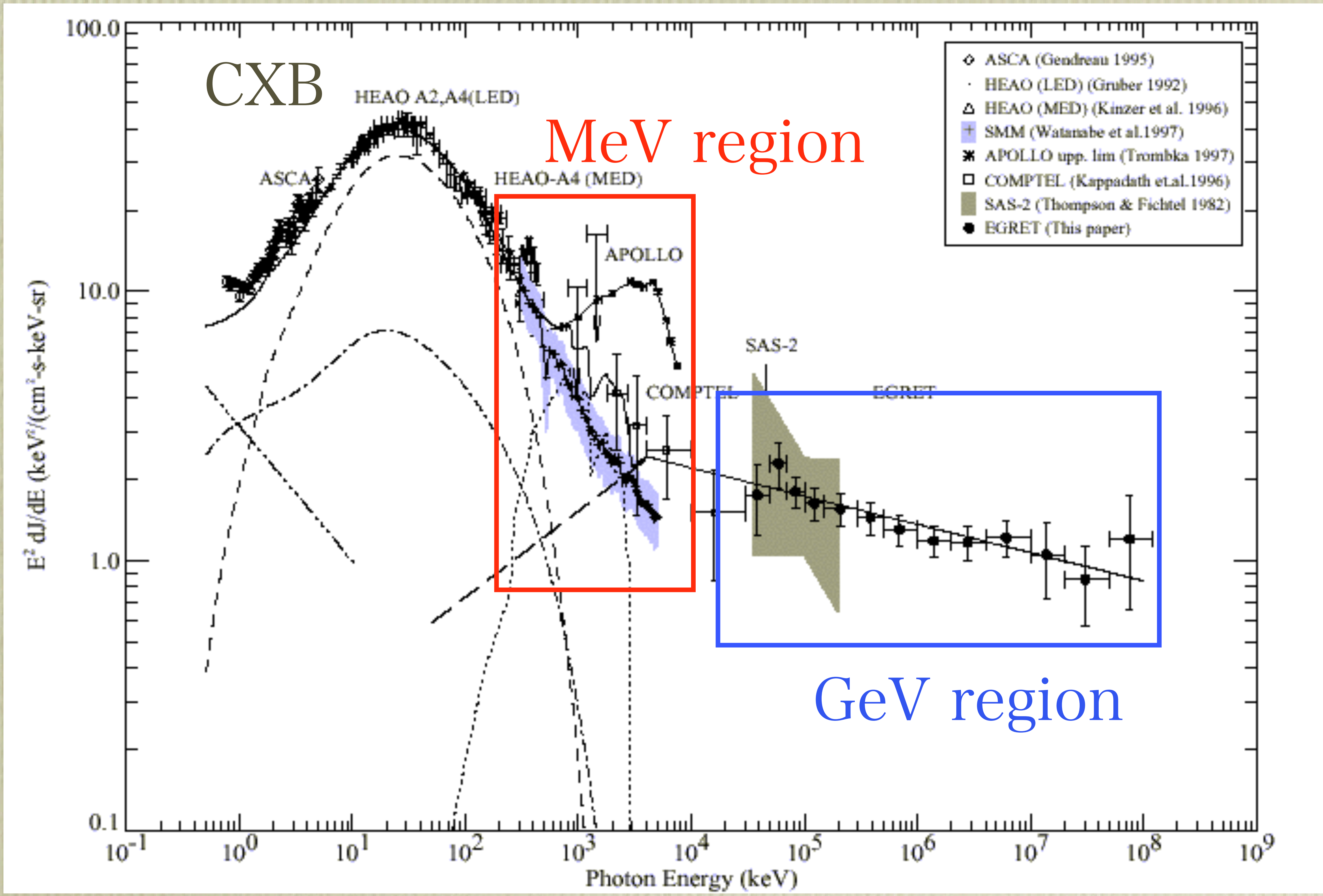


MeV background: Summary

- The best explanation is “non-thermal tail” from normal AGNs
  - smooth power-law connection to CXB
  - non-thermal electrons naturally expected in AGN coronae
  - ultimate confirmation would be direct observation from nearby normal AGNs

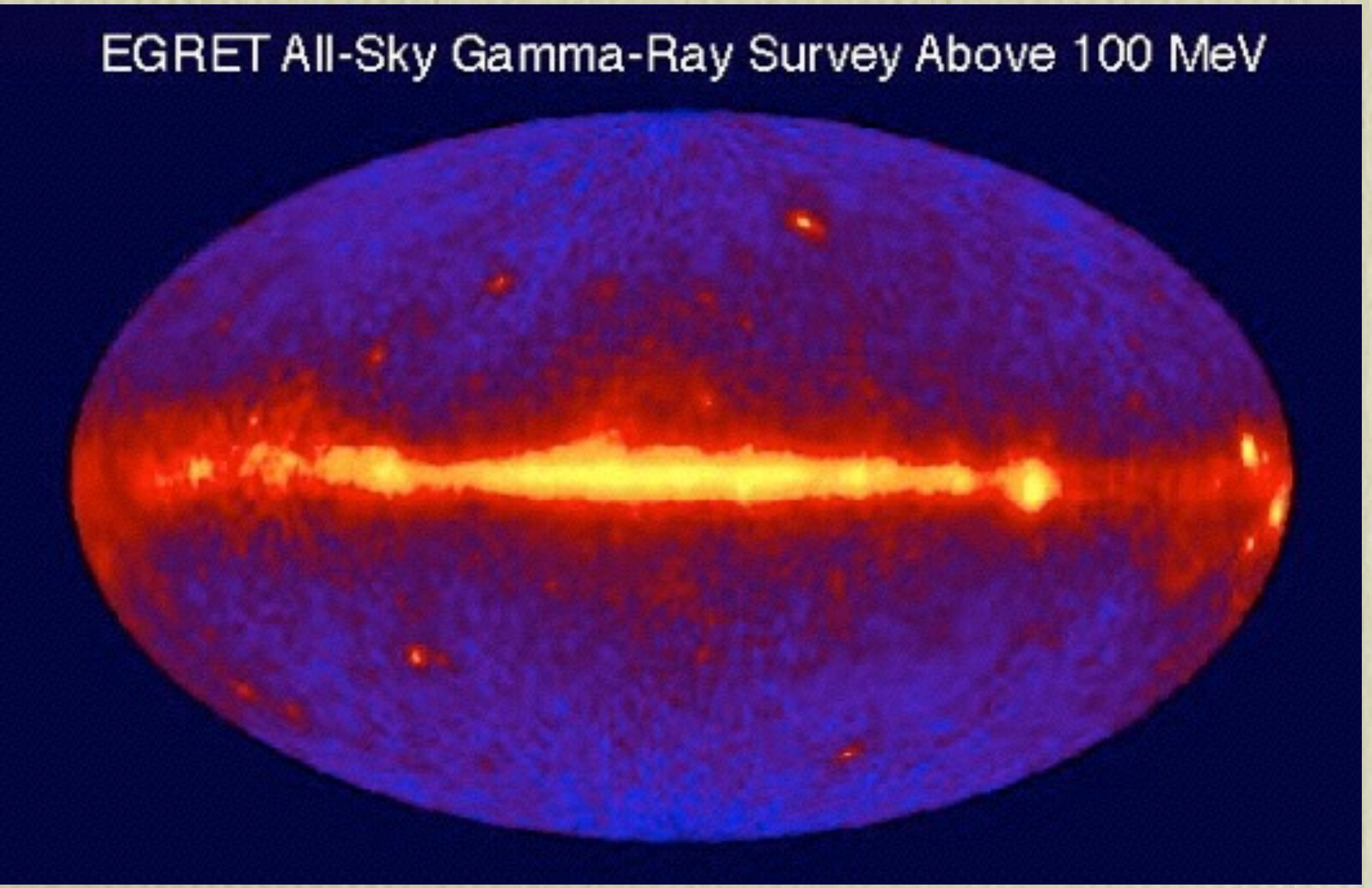
- no strong motivation to consider about other sources
  - too small SN Ia rate
  - no good theoretical motivation for MeV DM

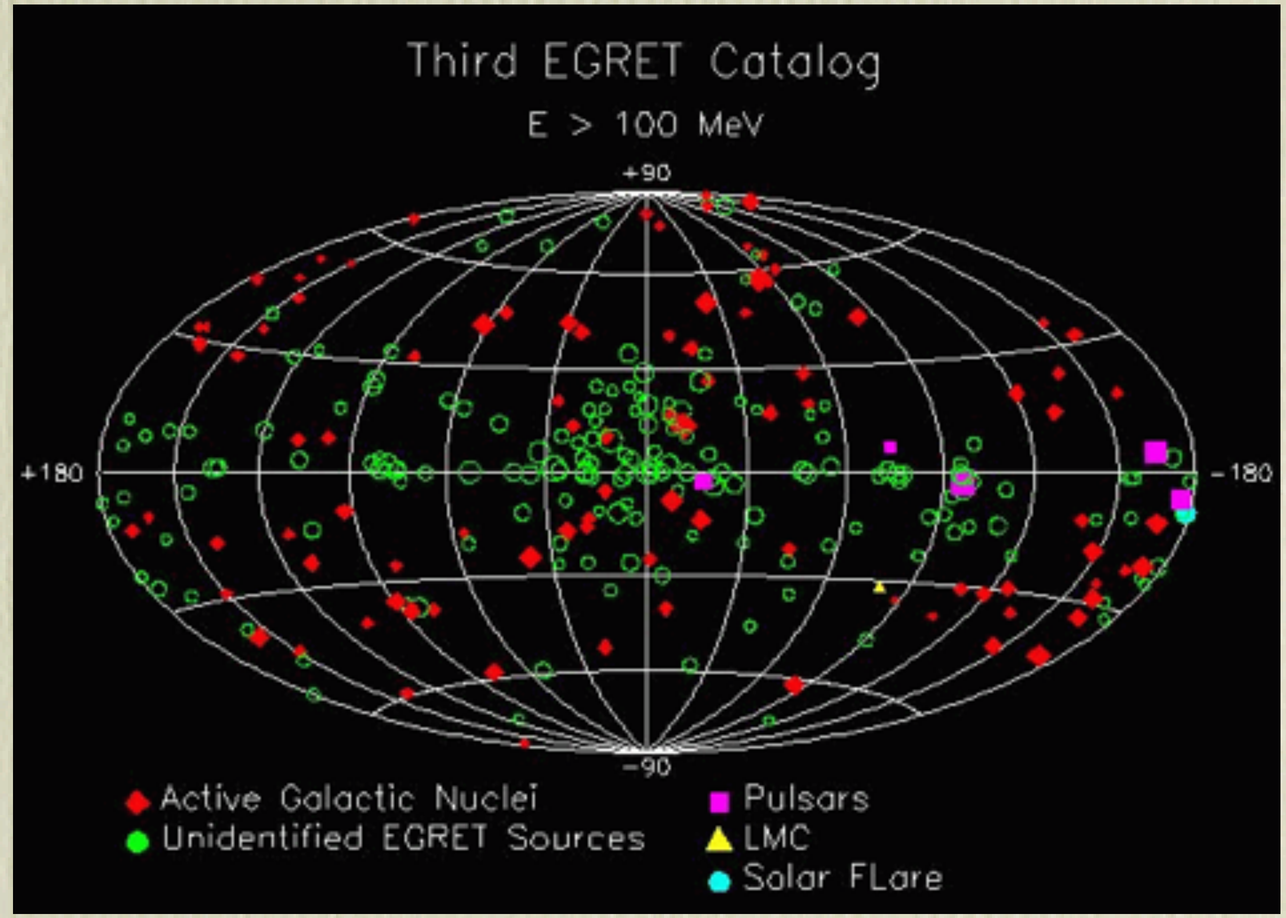
Origin of the GeV background



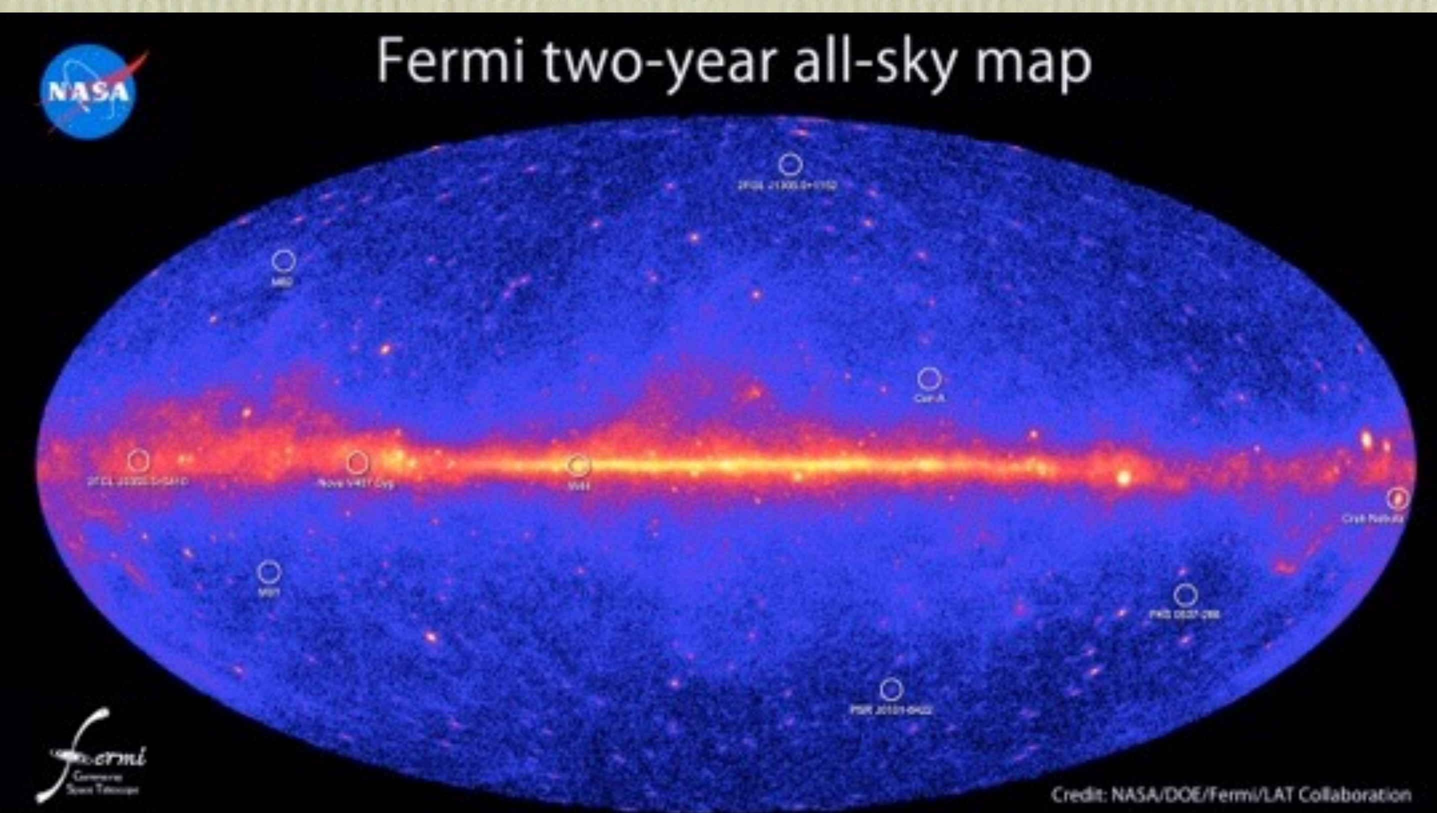
the primary candidate: blazars

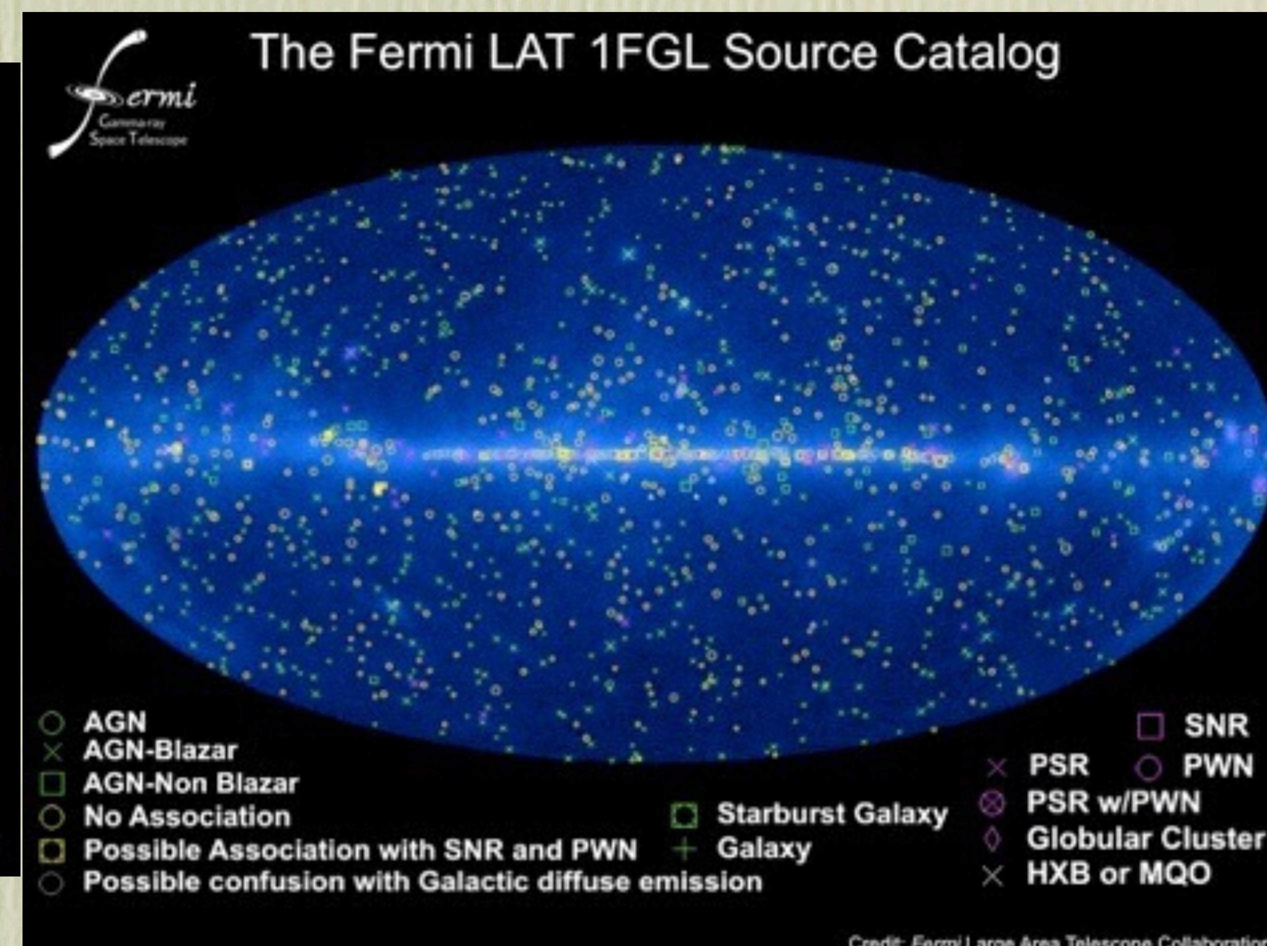
- almost all extragalactic EGRET sources (~50) are blazars
- blazars can account for at least >~30 % of GeV background, but probably not 100% of the EGRET data
  - new sources? DM? systematics in theory and/or data?



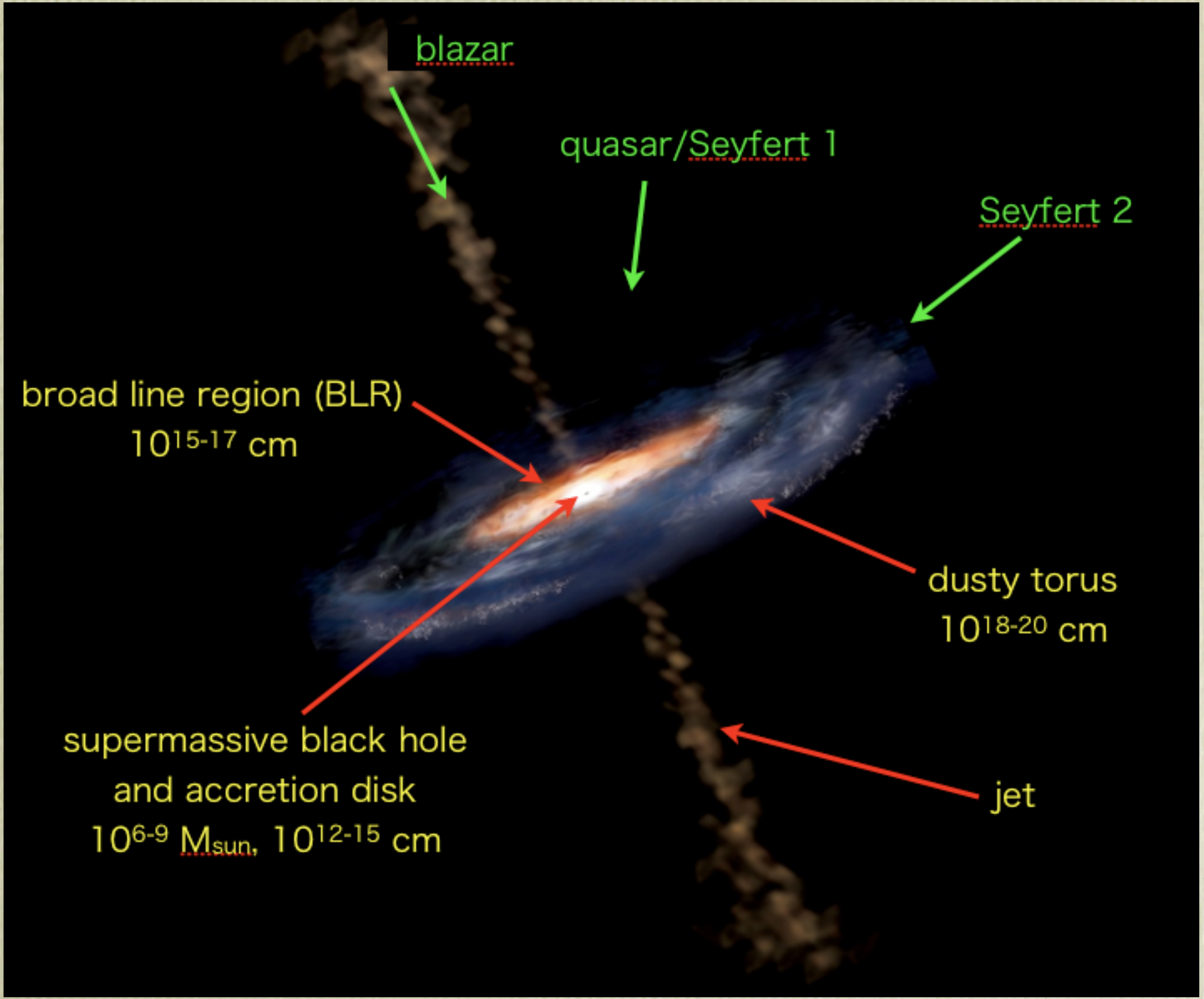


Fermi 衛星の成果


Fermi two-year all-sky map
NASA
Credit: NASA/DOE/Fermi/LAT Collaboration


The Fermi LAT 1FGL Source Catalog
AGN
AGN-Blazar
AGN-Non Blazar
No Association
Possible Association with SNR and PWN
Possible confusion with Galactic diffuse emission
Starburst Galaxy
Galaxy
SNR
PSR
PWN
PSR w/PWN
Globular Cluster
HXB or MQO
Credit: Fermi Large Area Telescope Collaboration

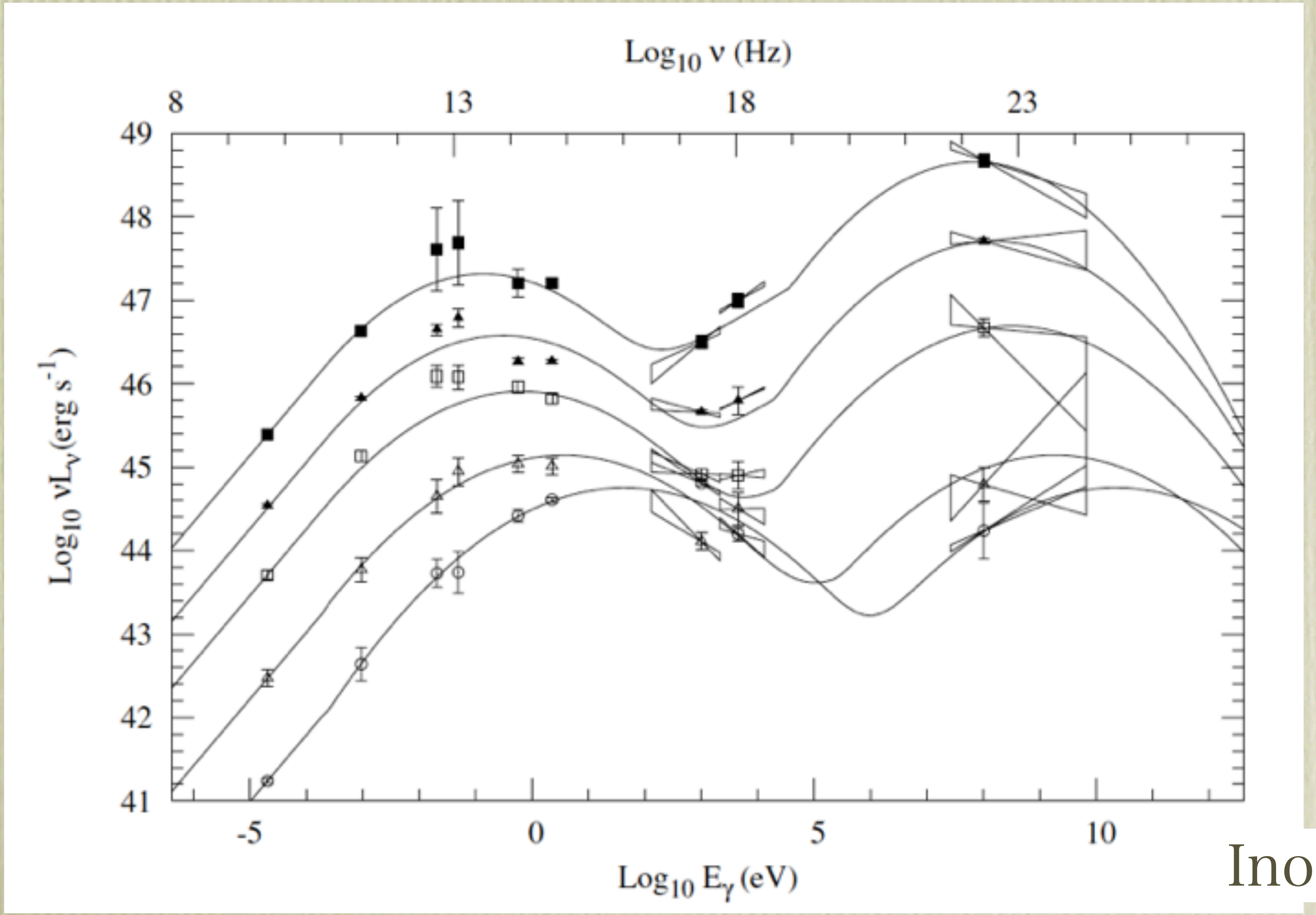
blazars



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

blazar spectral energy distribution (SED)

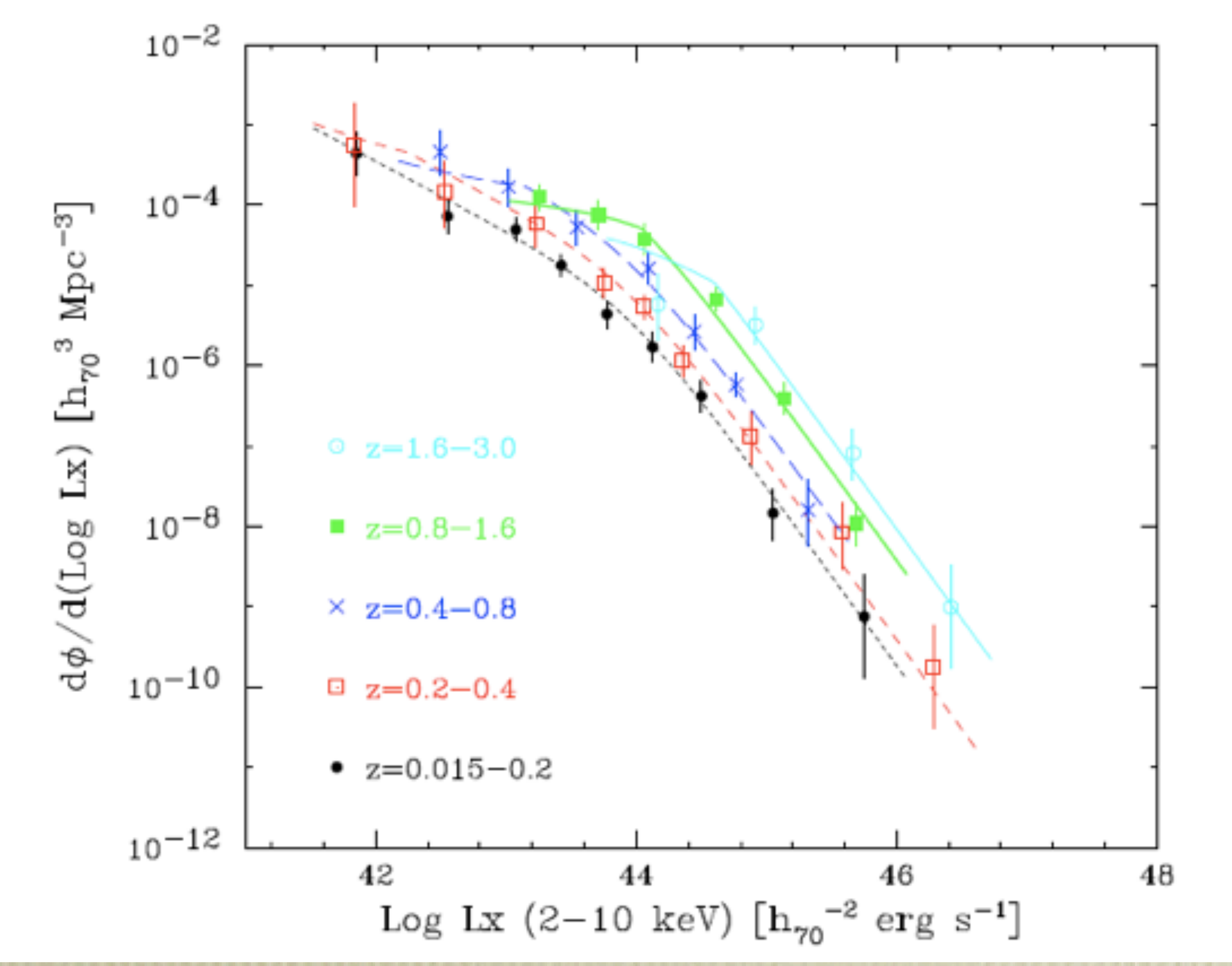
- two broad peak by synchrotron and inverse-Compton by non-thermal electrons
- the SED sequence (high peak frequency for lower luminosity)
  - Fossati+'97, Donato+'01

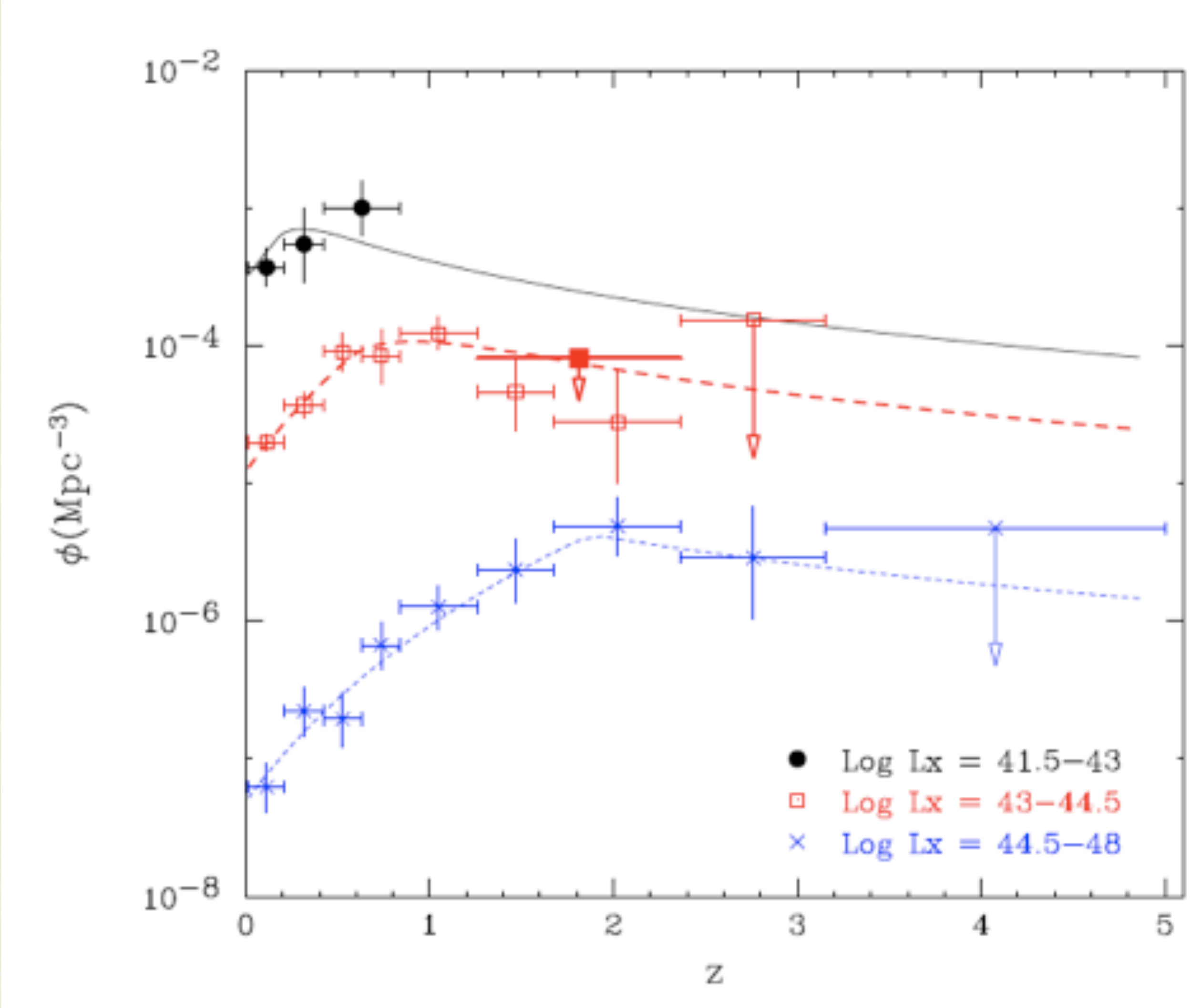


Inoue+TT '09

AGN Luminosity Function 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



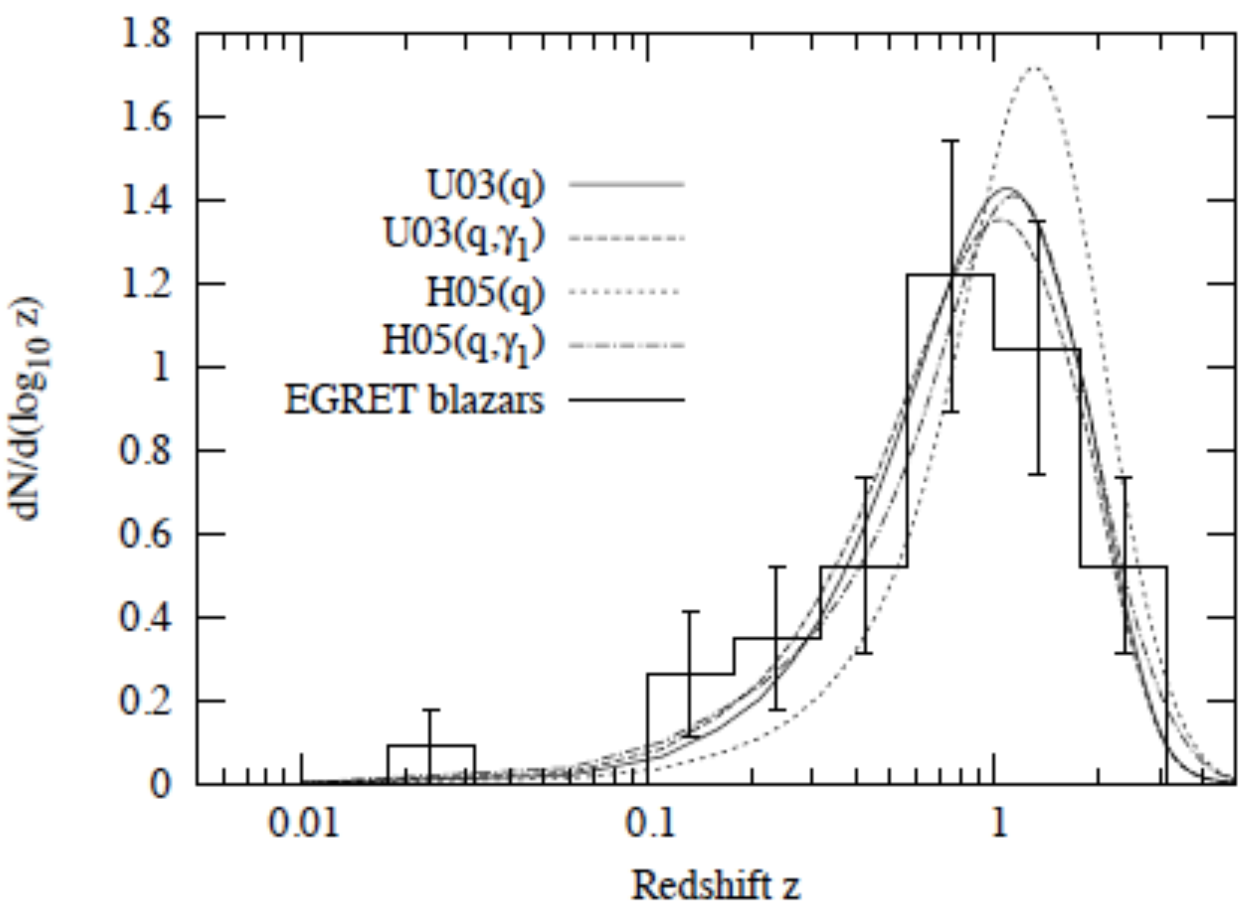


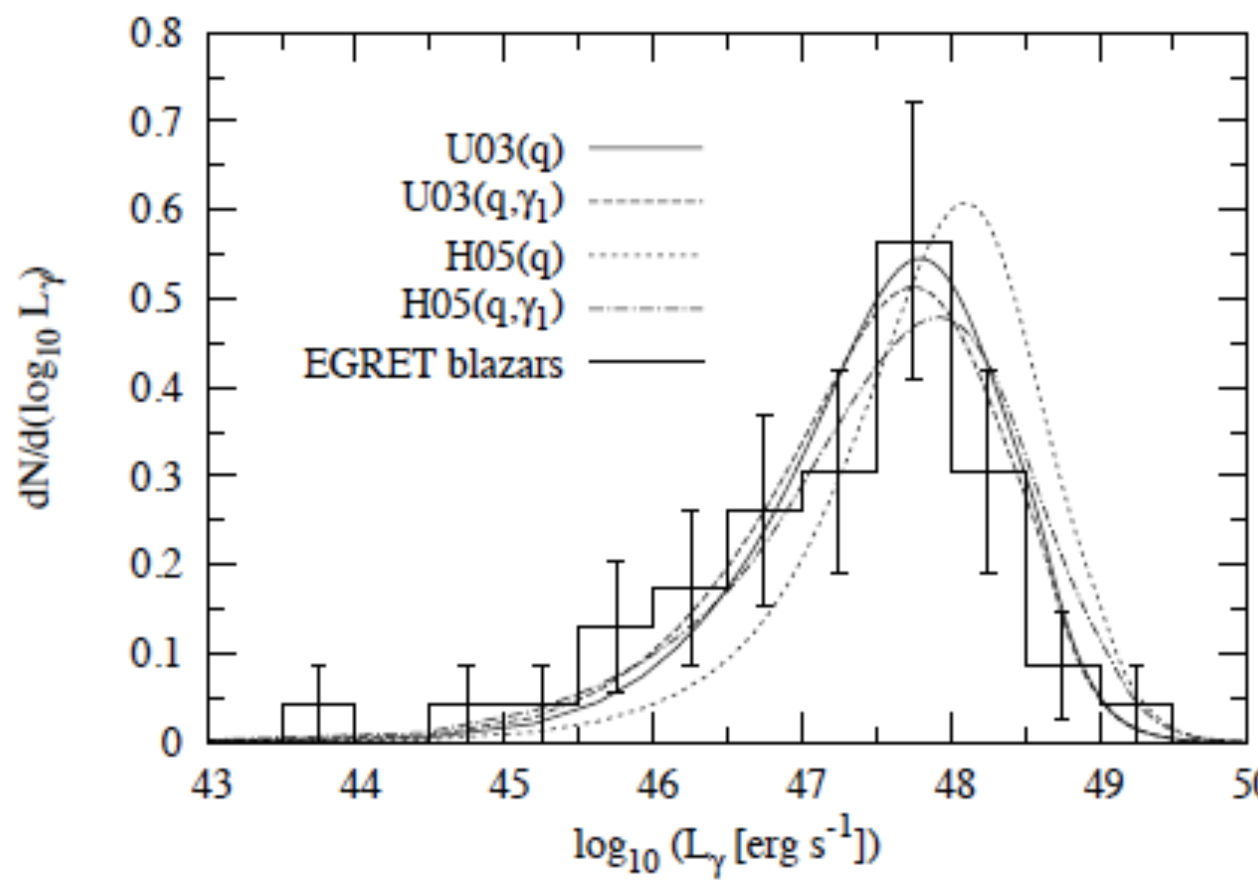
Ueda+'03

L and z distribution of EGRET blazars

- 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

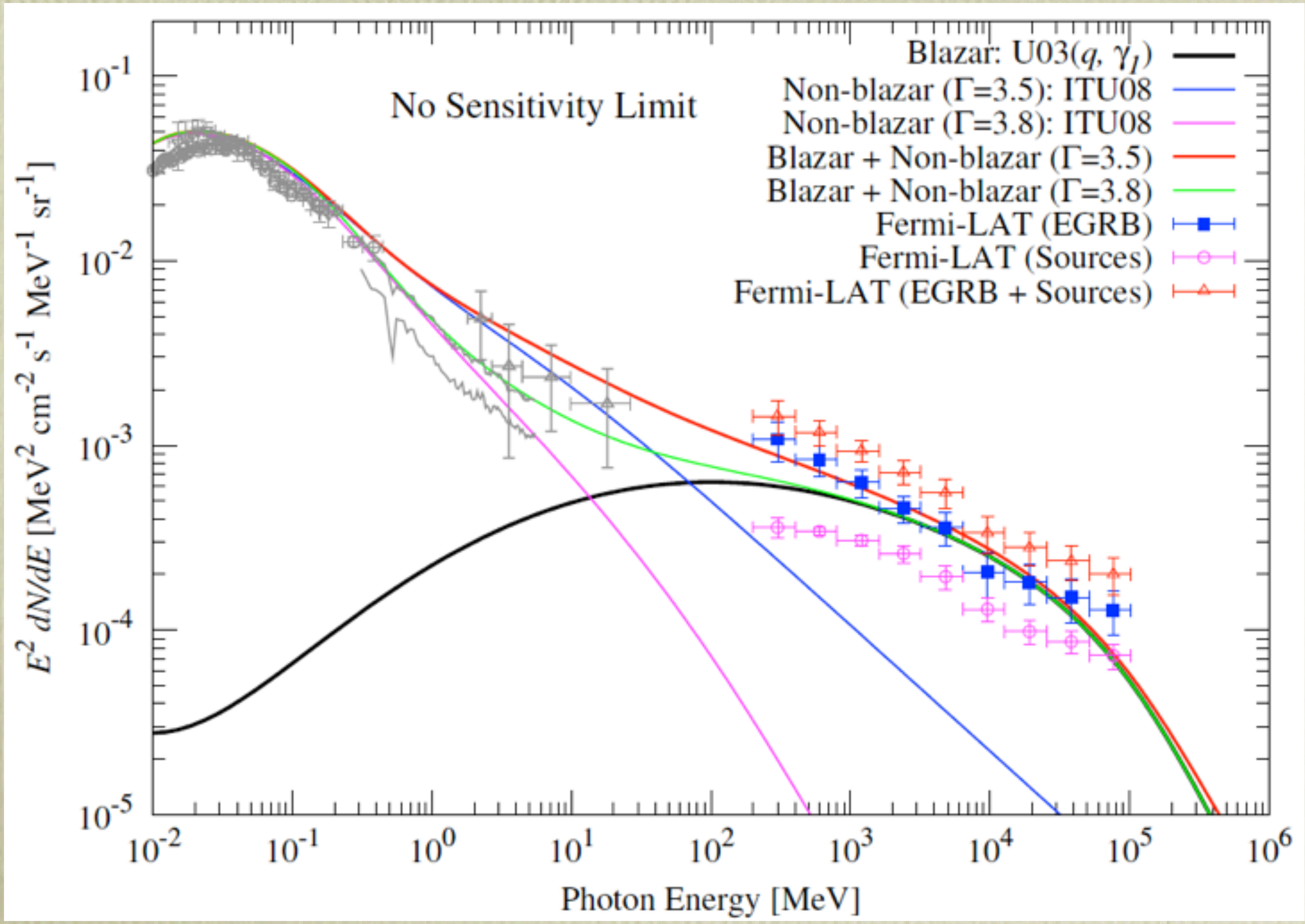
Inoue+’09





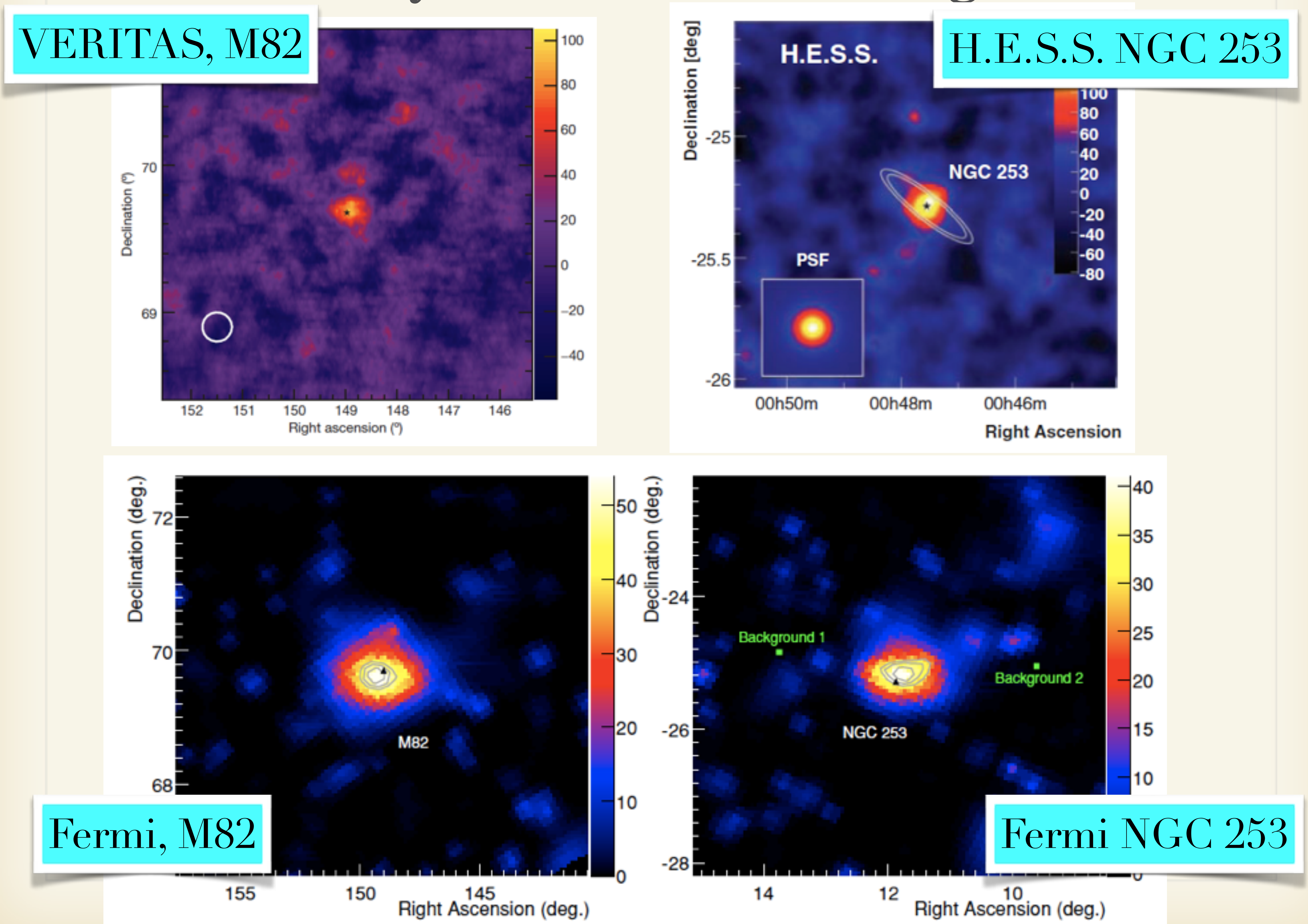
Total gamma-ray background from normal+blazar AGNs

- the "minimum" contribution from the two populations
  - normal AGNs in MeV and blazars in GeV
  - blazar model based on EGRET data, prediction in good agreement with new Fermi data!



Inoue+'09

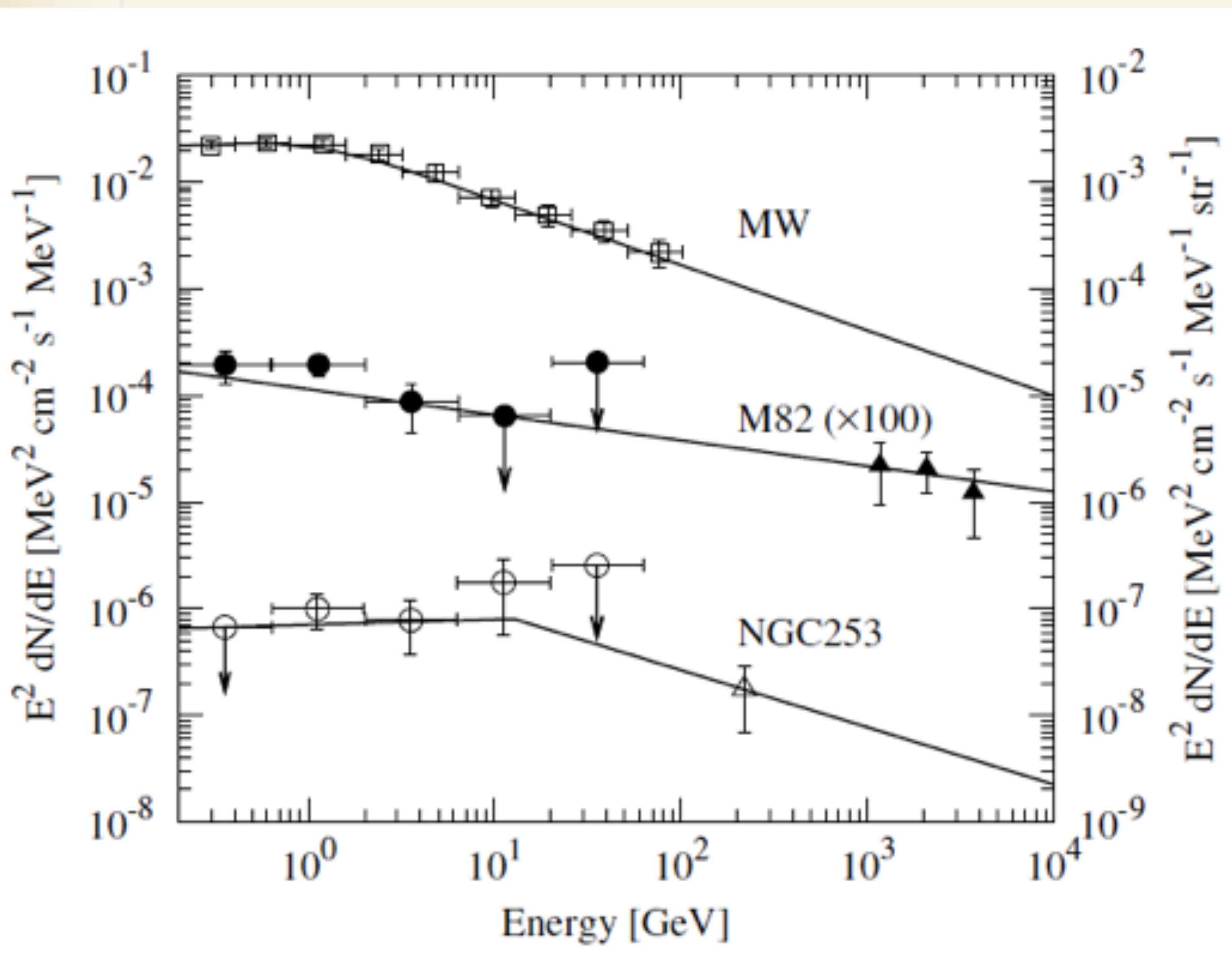
Gamma-rays from Star-forming Galaxies

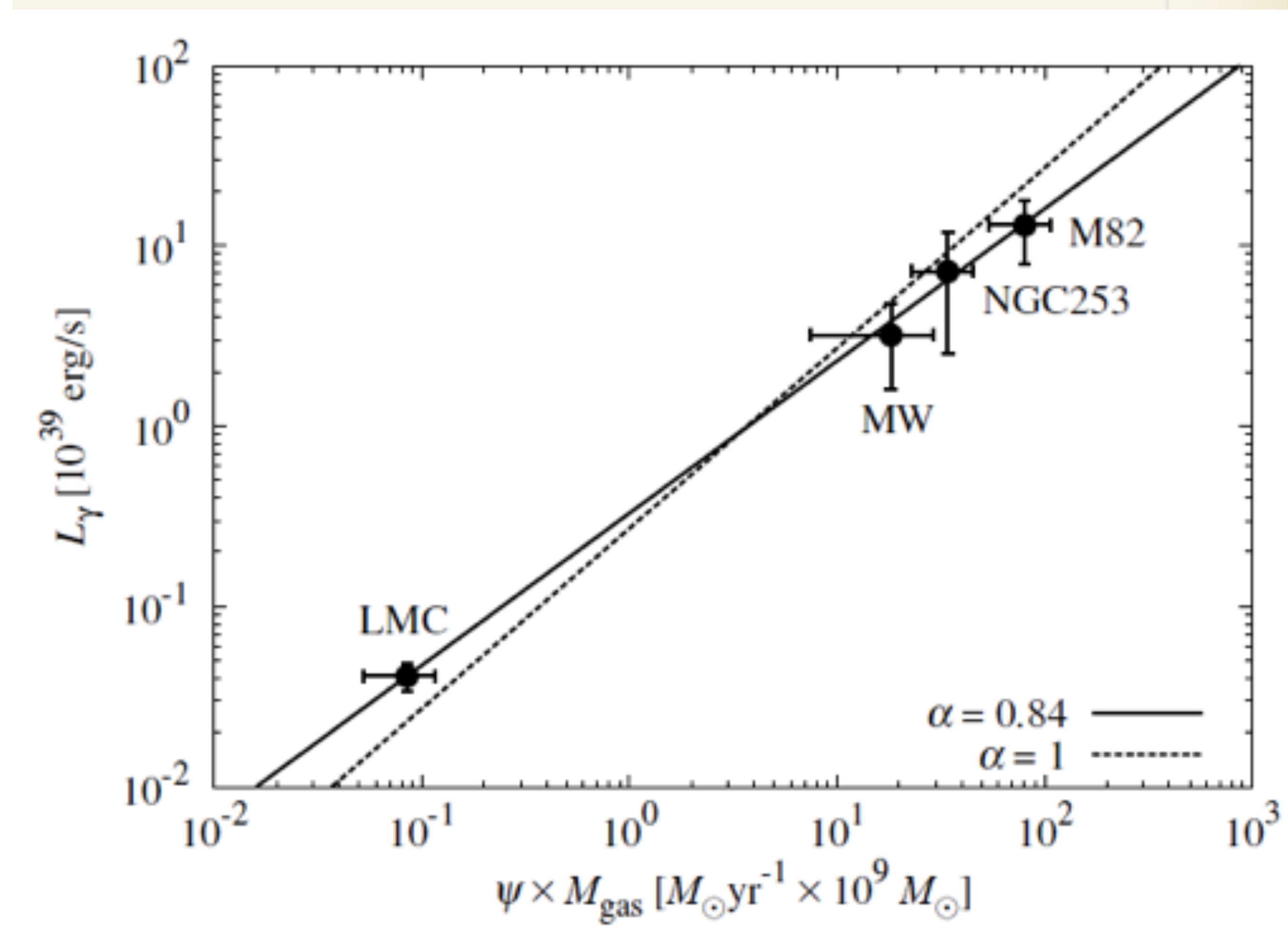


Gamma-rays from Star-forming Galaxies

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

Makiya+'11

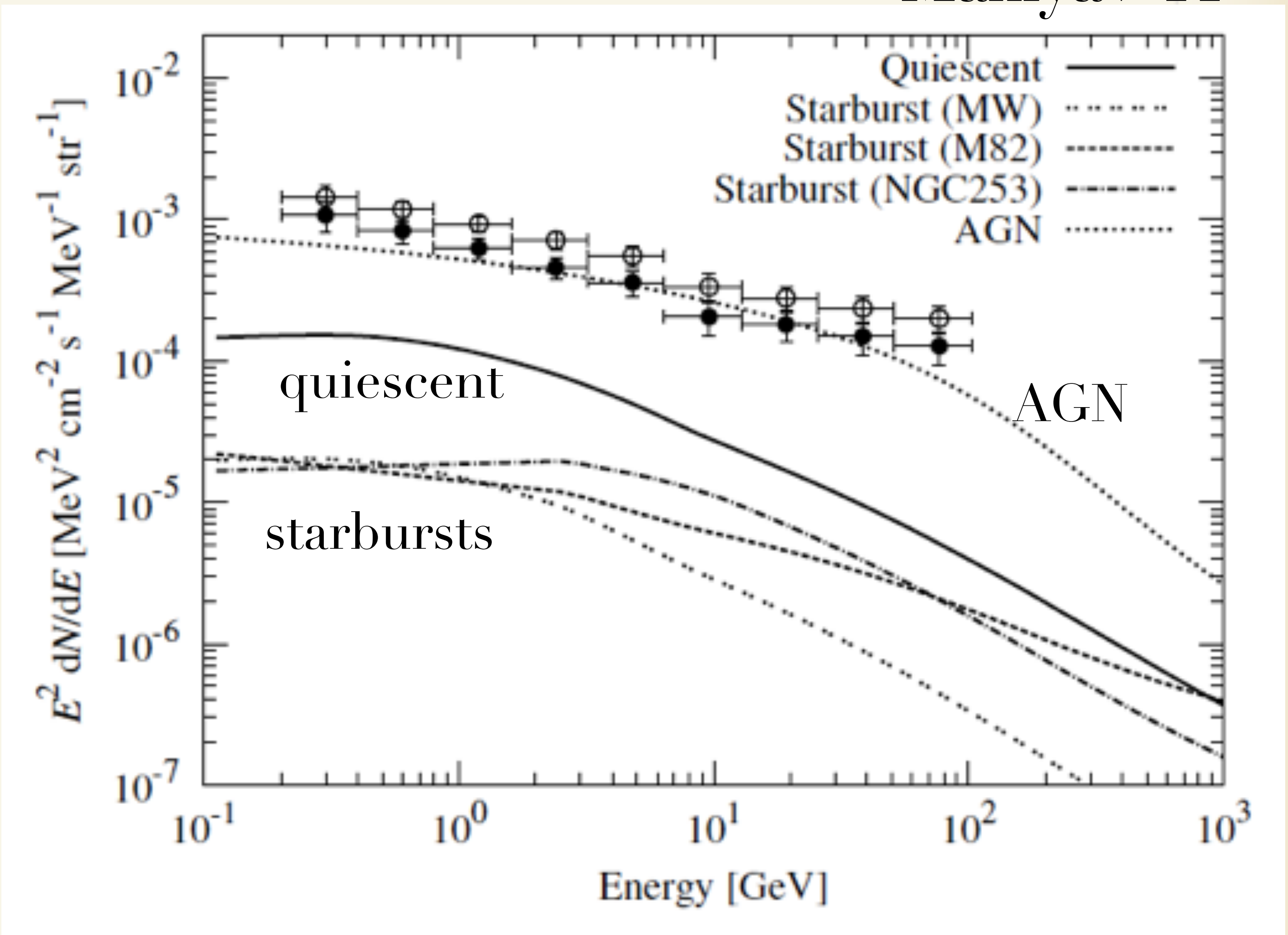




gamma-ray background from star-forming galaxies

- 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
- $L_\gamma \propto (SFR) \times M_{gas}$
- ~10% contribution to the total gamma-ray background
- predicted spectrum very similar to the observed EGRB

Makiya+'11



○: total flux (incl. srcs)

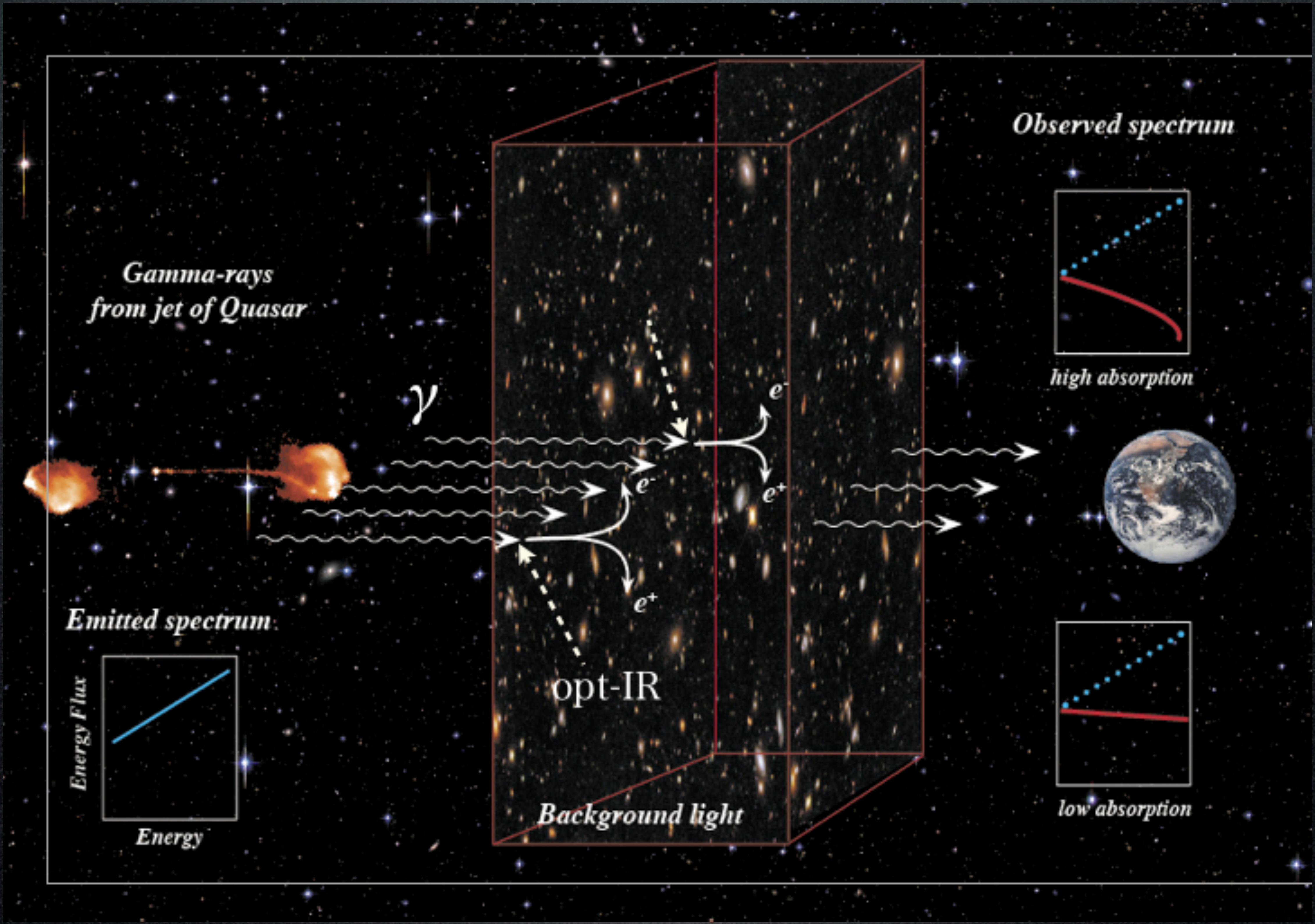
●: diffuse at the Fermi limit

X線・ガンマ線背景放射まとめ

- X線： normal AGN で OK
- MeV: X線から normal AGN の非熱電子テールが延びていると考えるのが自然
  - しかし、直接的な観測による検証が必要→ MeV 観測の発展に期待
- GeV:
  - ブレーザー、＋その他のAGN（電波銀河など）でかなりの部分を説明できる
  - 星形成銀河によるガンマ線も10%程度は寄与
  - 残りは？
    - その他の AGN 種族？ e.g. radio galaxies (Inoue '11)
    - exotic component? ダークマター対消滅？まだ強い兆候無し
    - Fermi のデータの蓄積で、銀河間ガンマ線吸収の兆候を捉えられるか？
    - ただし GeV 領域の観測は、Fermi が決定版か...将来は？

高エネルギーガンマ線の銀河間吸収と可視・赤外宇宙背景放射

intergalactic gamma-ray absorption by EBL



credit: HESS collab.

gamma-ray energy vs. EBL wavelength

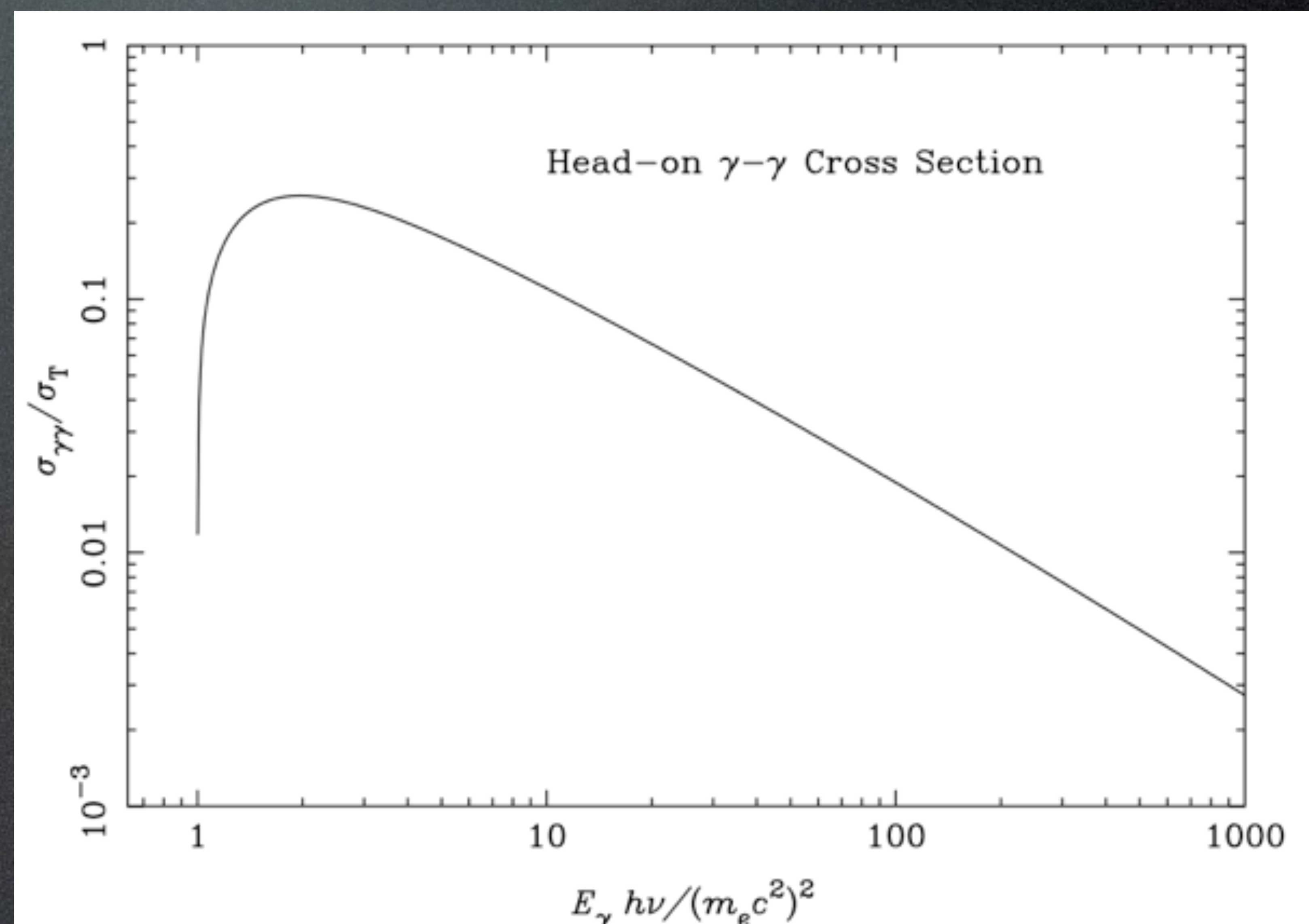
- center-of-mass energy >~ $m_e c^2$

gamma-ray energy ϵ_γ vs. target EBL photon frequency ν:

$$h\nu\,\epsilon_\gamma \gtrsim (m_e c^2)^2$$

$$\lambda \gtrsim 1.2\left(\frac{\epsilon_\gamma}{\mathrm{TeV}}\right)\,\mu\mathrm{m}$$

- most interaction occurs near the energy threshold



optical depth for gamma-rays

- larger optical depth for higher gamma-ray energy and higher z
- many calculations by different groups with different approaches

TT & Takeuchi '02

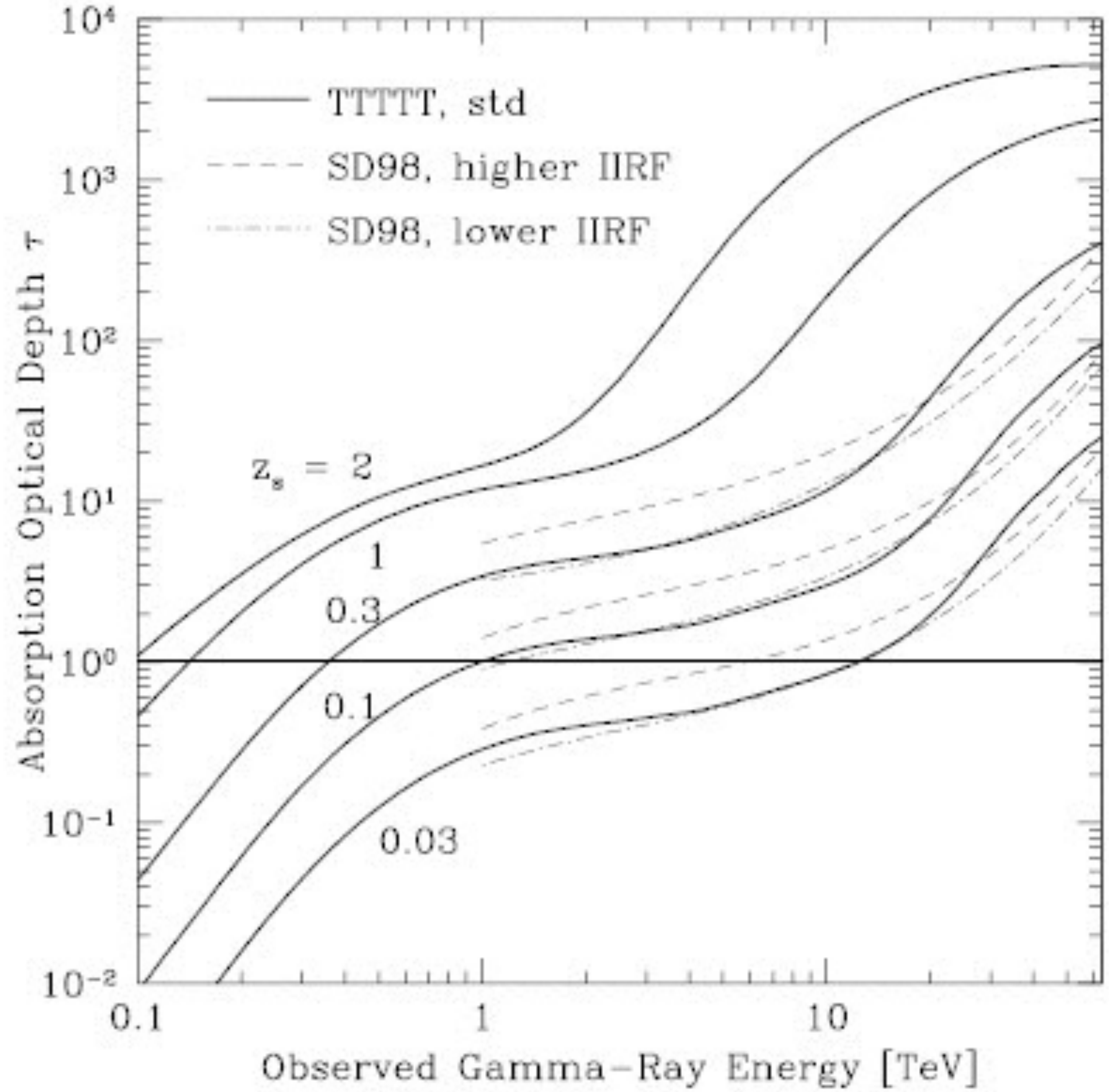
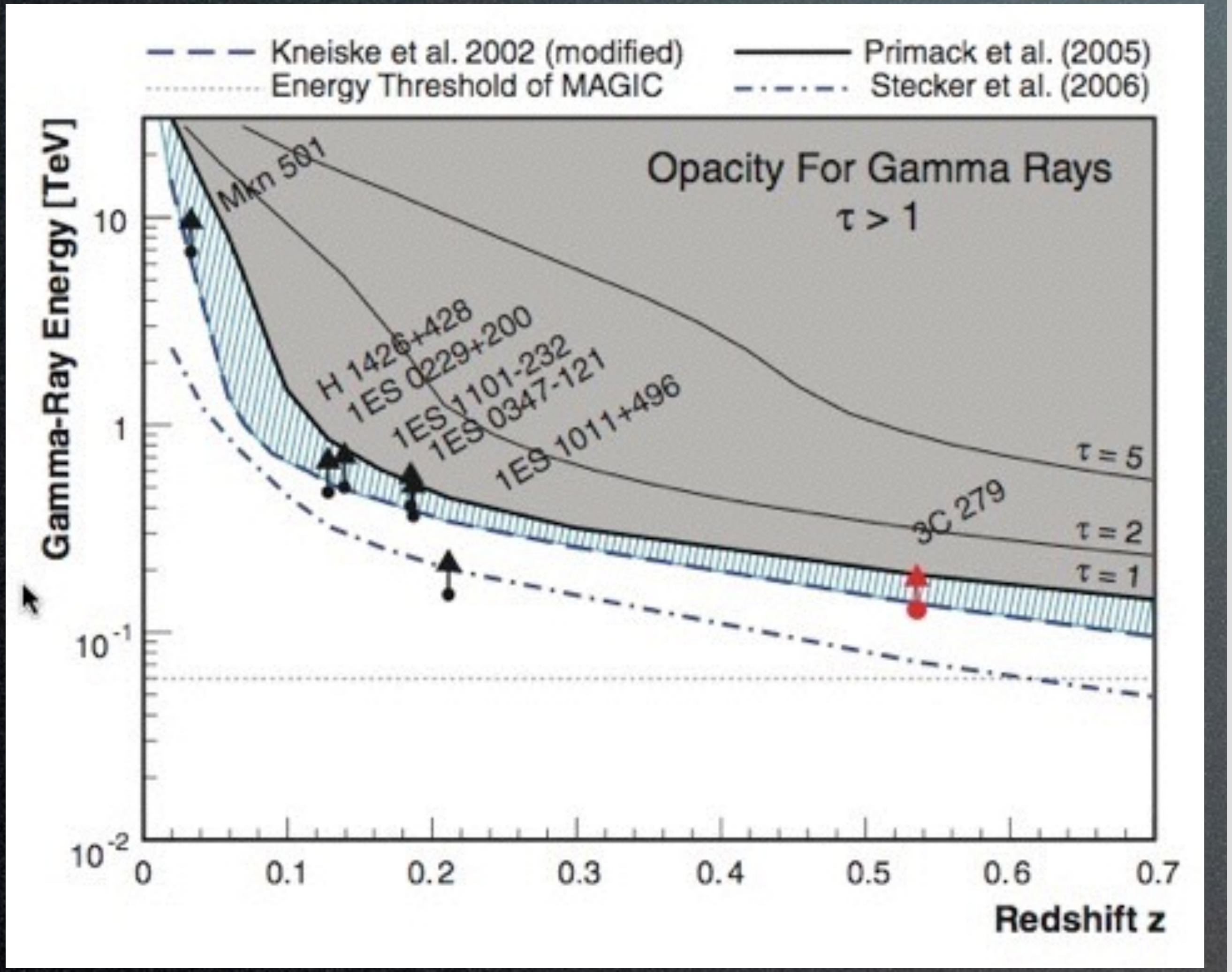
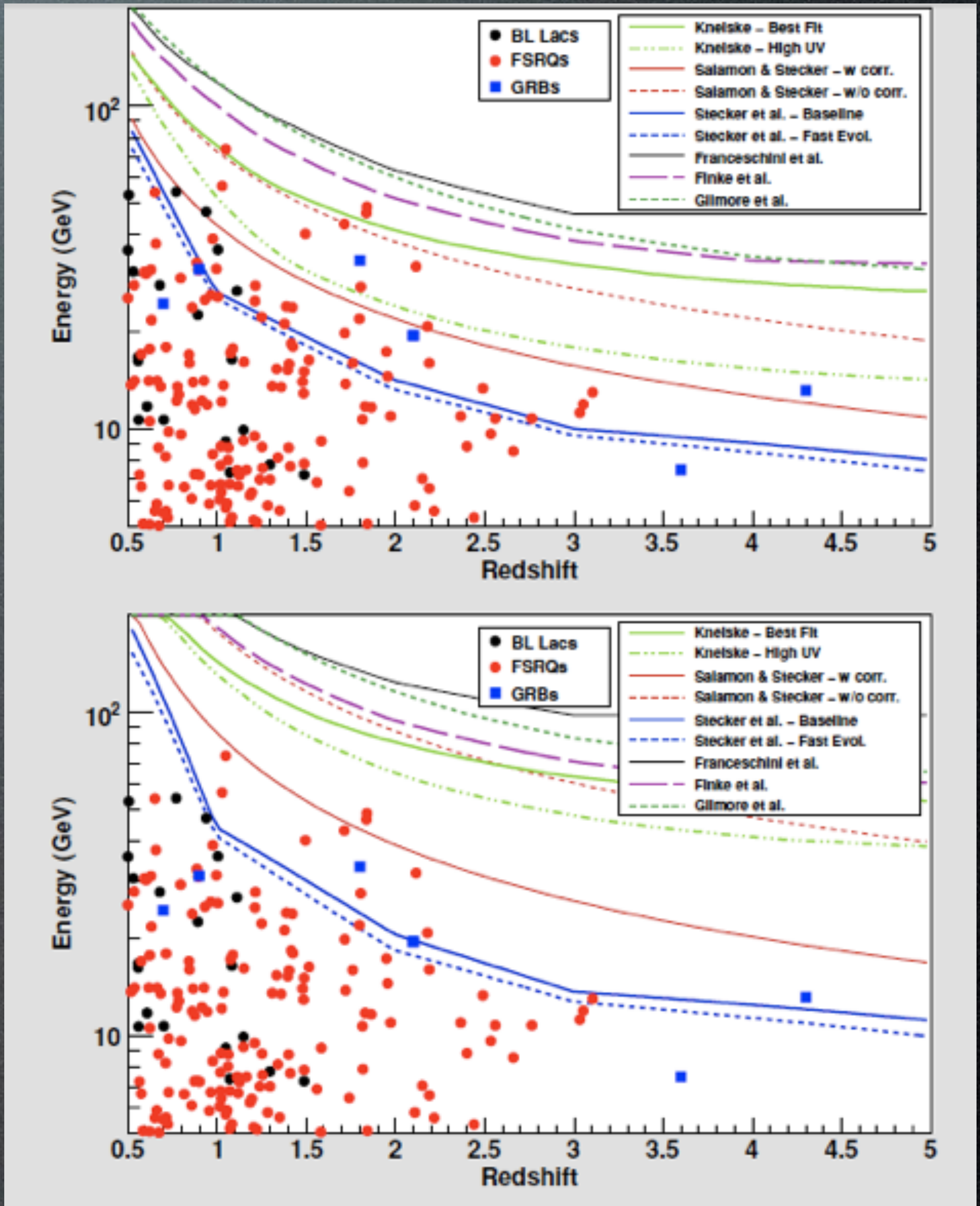


FIG. 19.— The intergalactic optical depth of very high energy gamma-rays to the absorption by interaction with optical/infrared cosmic background radiation, as a function of the source redshift (z_S) and the gamma-ray energy observed at $z = 0$. The solid lines are the calculation based on our baseline model, with the source redshifts indicated in the figure (indicated as TTTTT from the initials of the authors). For comparison, calculations with 'higher IIRF SED' (dashed line) and 'lower IIRF SED' (dot-dashed line) by Stecker & de Jager (1998) are plotted for z_S = 0.03, 0.1, and 0.3 (from the bottom to

data vs. theoretical predictions



Albert+'08



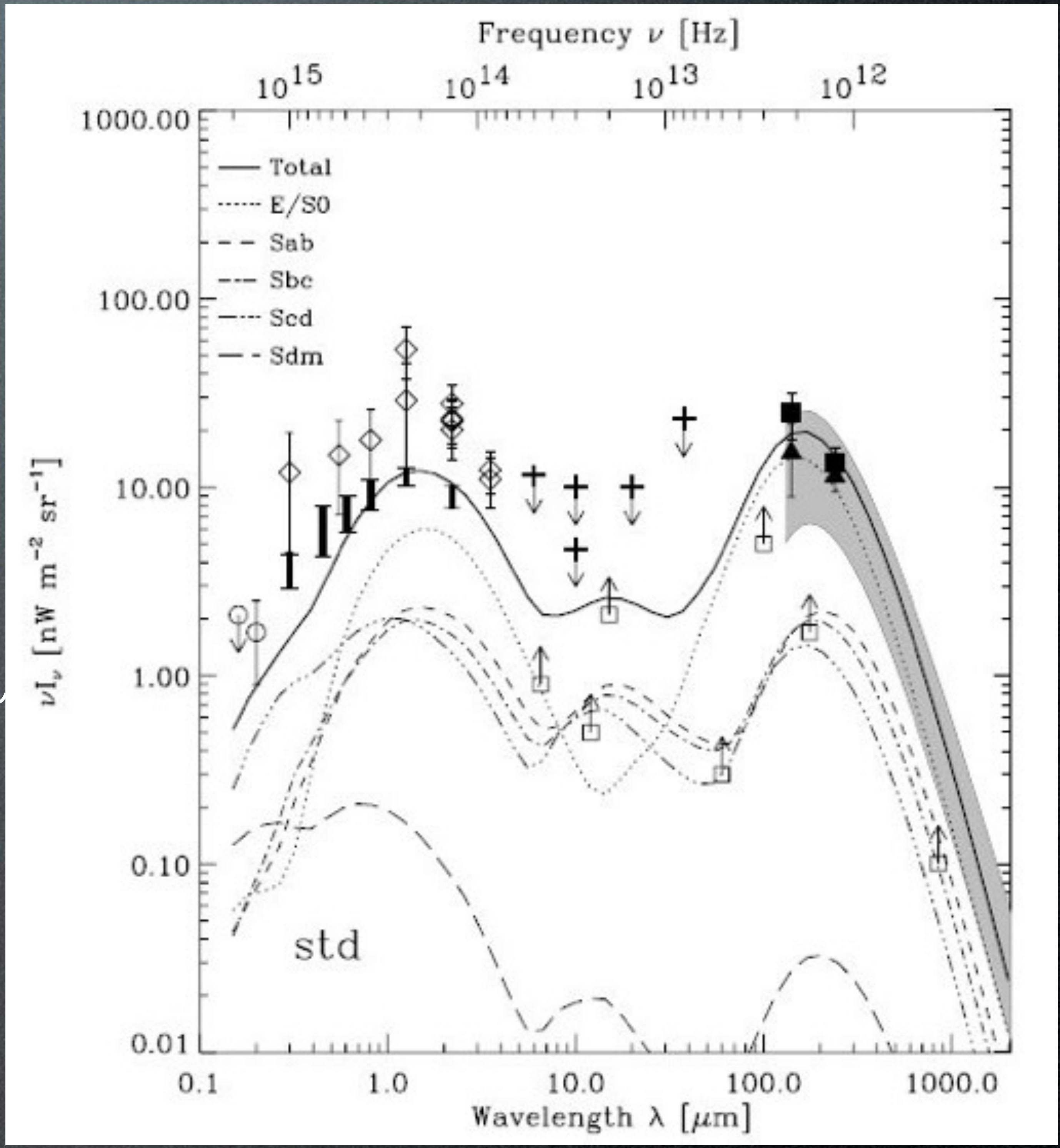
Fermi collab.+'10

cosmic optical/infrared background radiation (Extragalactic Background Light, EBL)

- fossil of galaxy formation
    - opt/near-IR: stellar radiation
    - mid/far-IR: reradiation from interstellar dust grains

- 何がわかる？
    - 宇宙の星形成史
        - 観測で受からない暗い銀河も含まれる
        - e.g., pop-III star formation activity

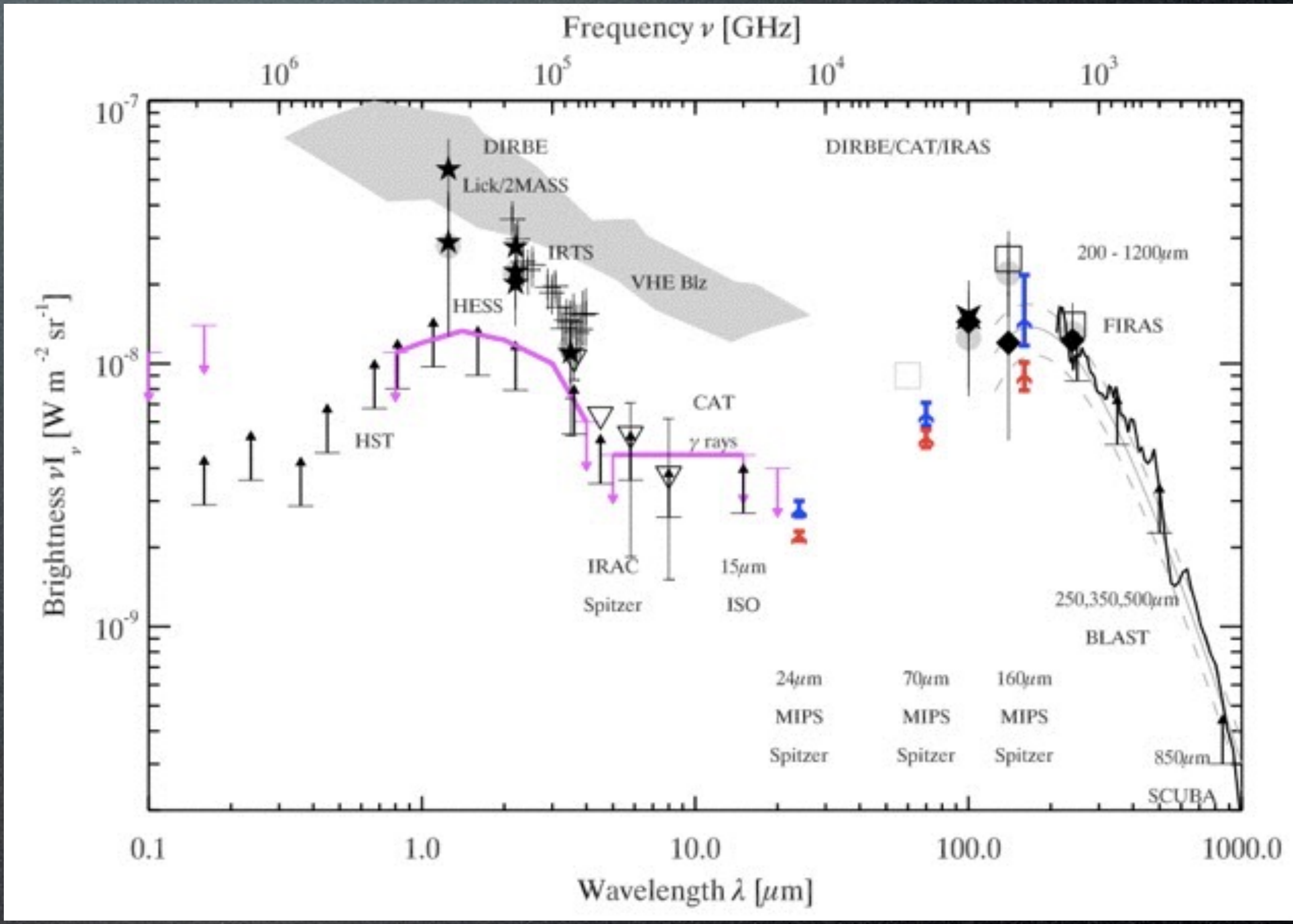
- 基本的には、普通の銀河の星形成史でだいたい決まる



TT & Takeuchi '02

observational constraints

- detection as a diffuse background light
  - λ>100 um
  - opt/near-IR (controversial)
- resolving EBL into discrete galaxies by deep surveys
  - strict lower limits
  - should be close to the total background flux in optical and near-IR



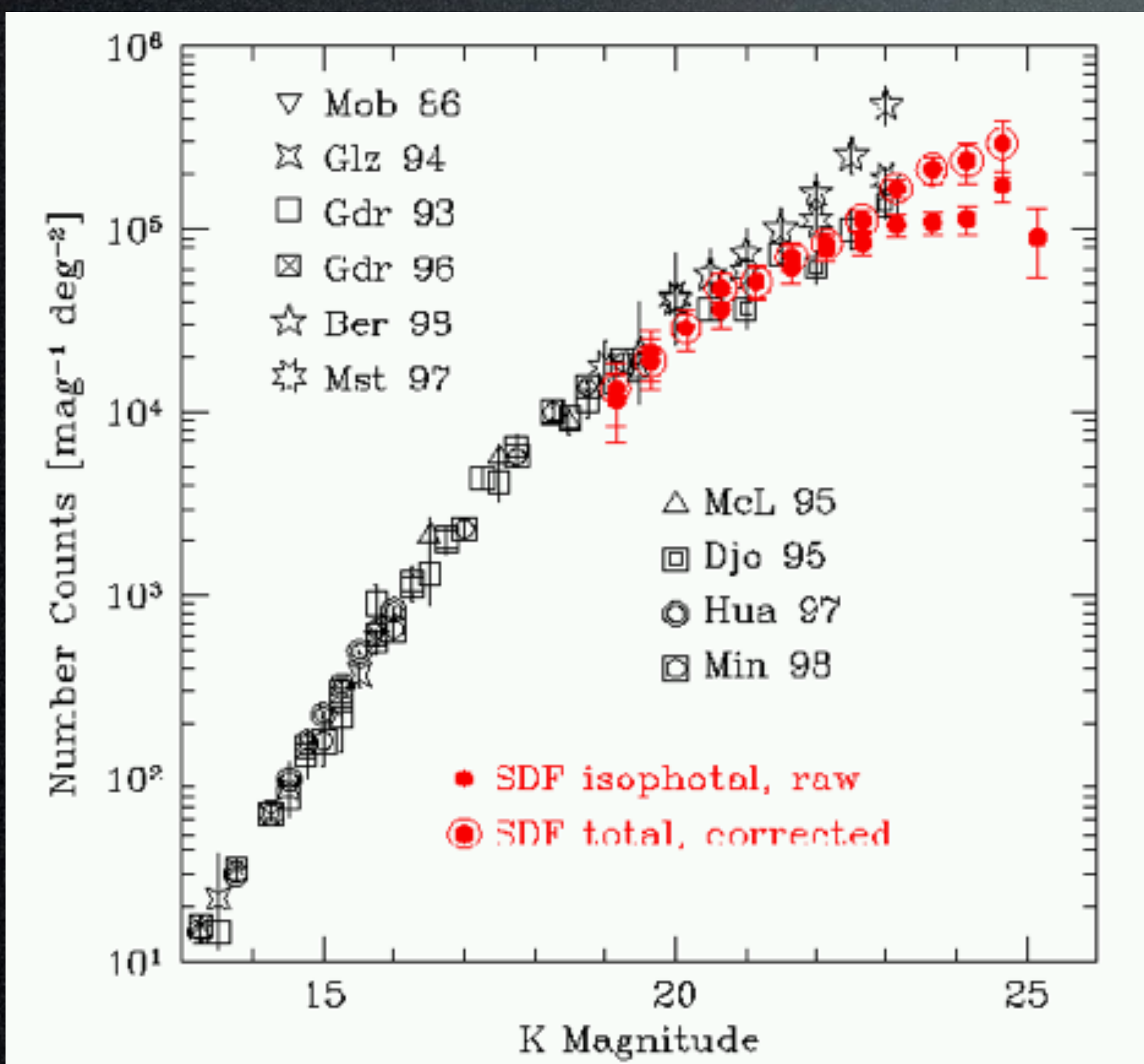
Bethermin+'10

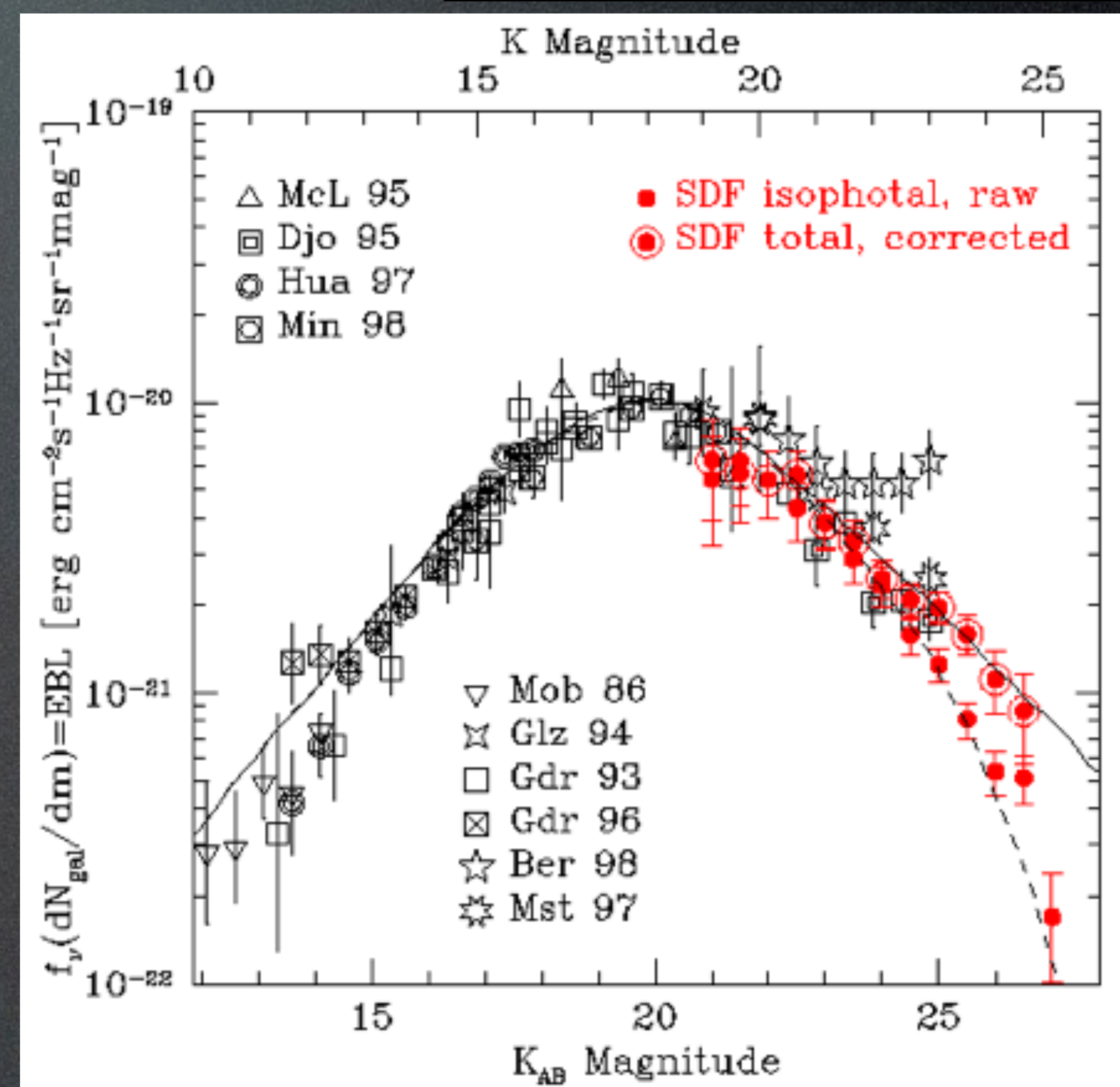
resolving EBL by deep surveys

- galaxy counts indicate more than >~90% of EBL already resolved in optical/near-IR

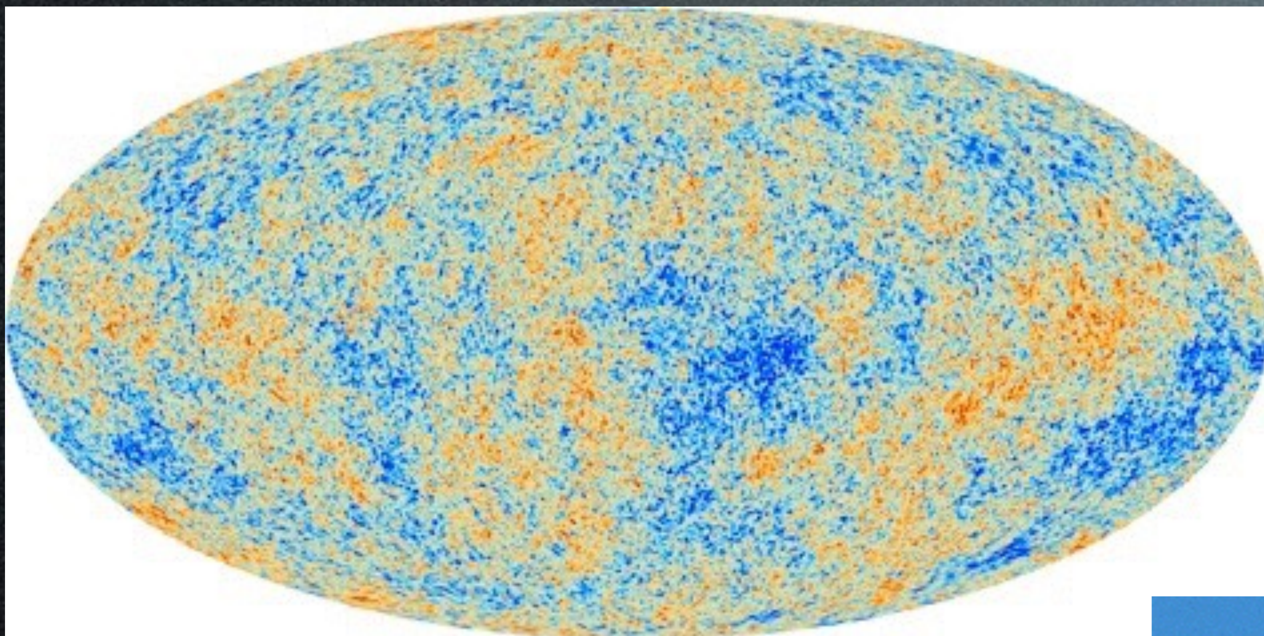
Subaru Deep Field (J,K)

TT + ’01

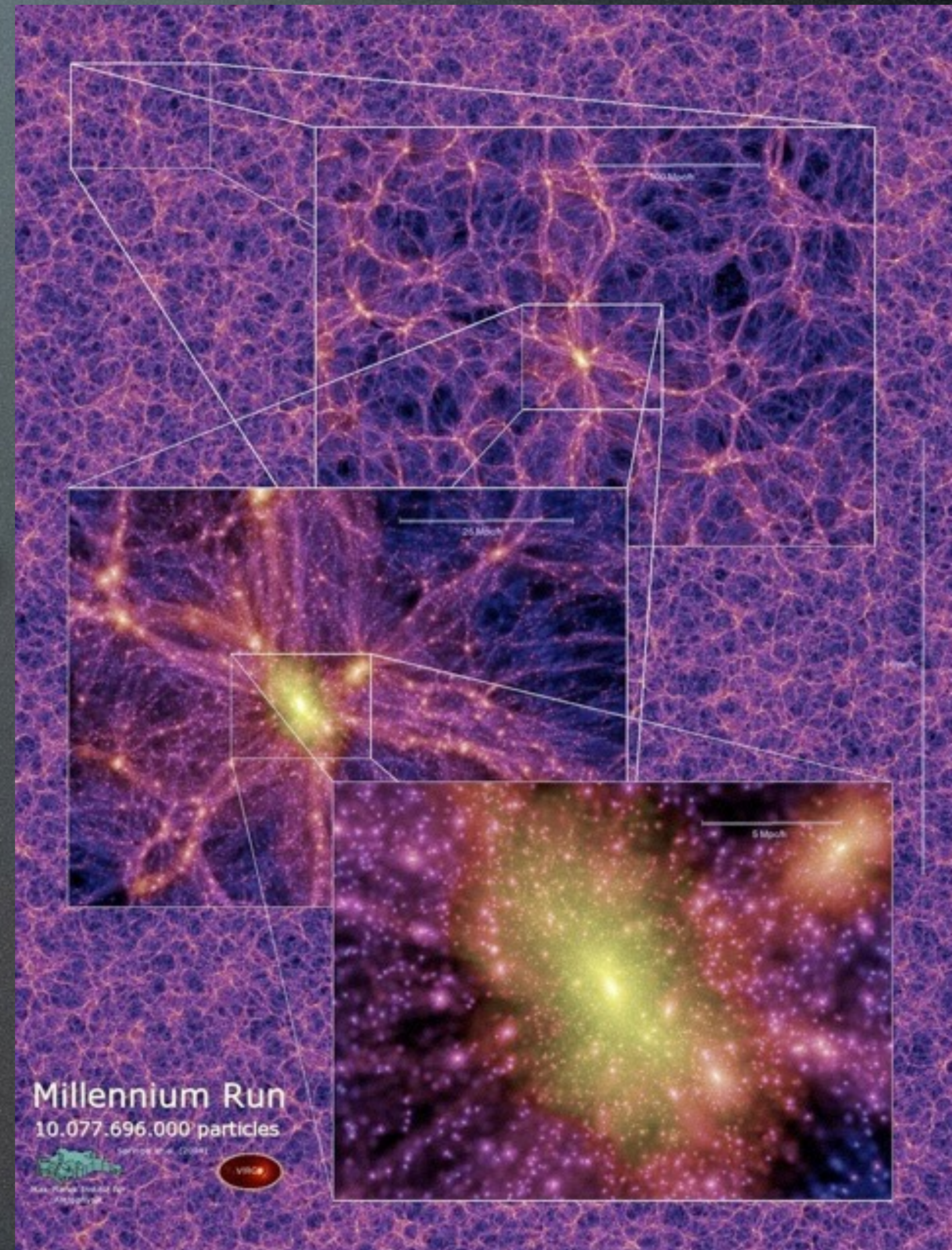




冷たい暗黒物質による階層的構造形成

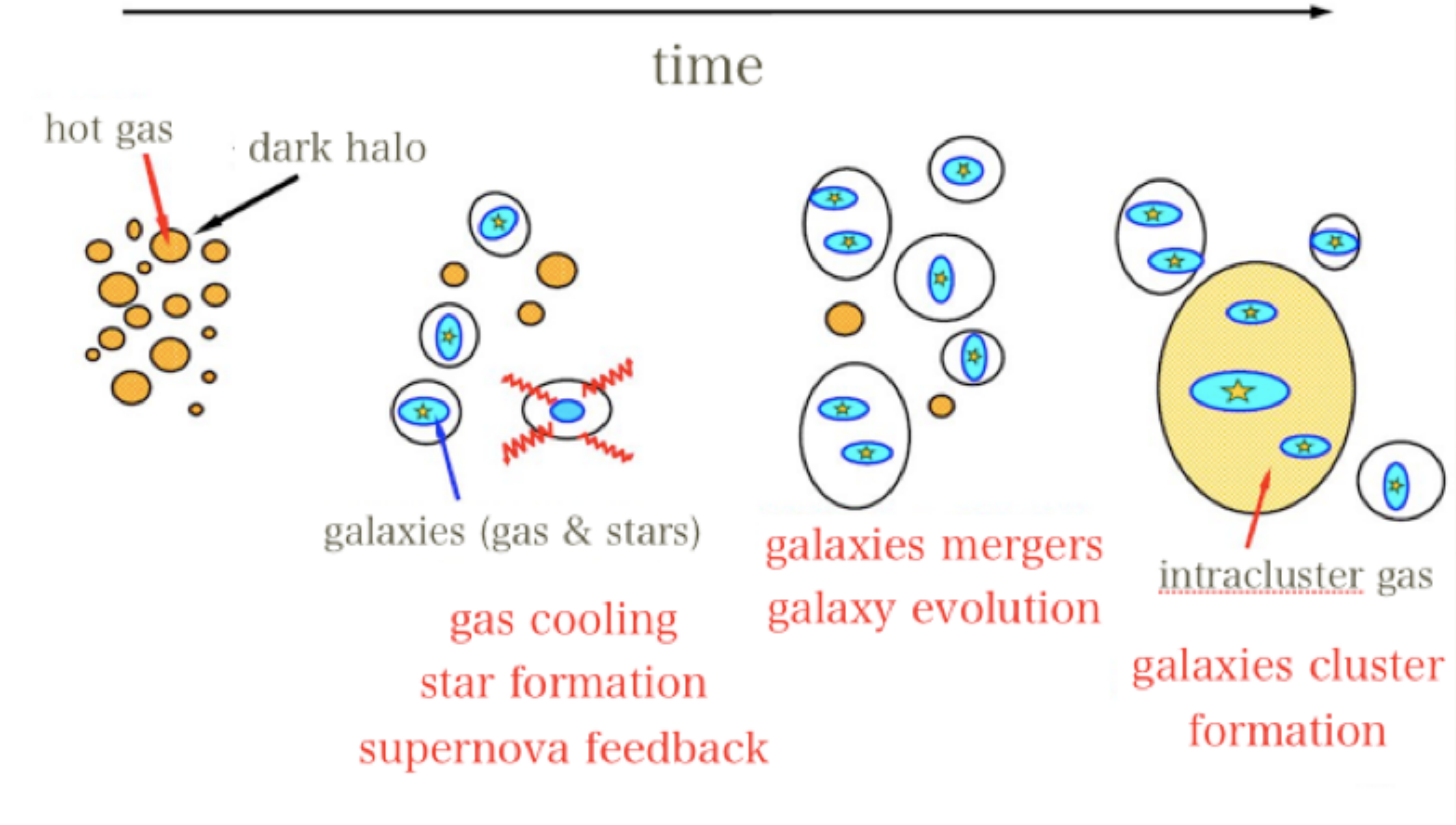


Planck CMB map



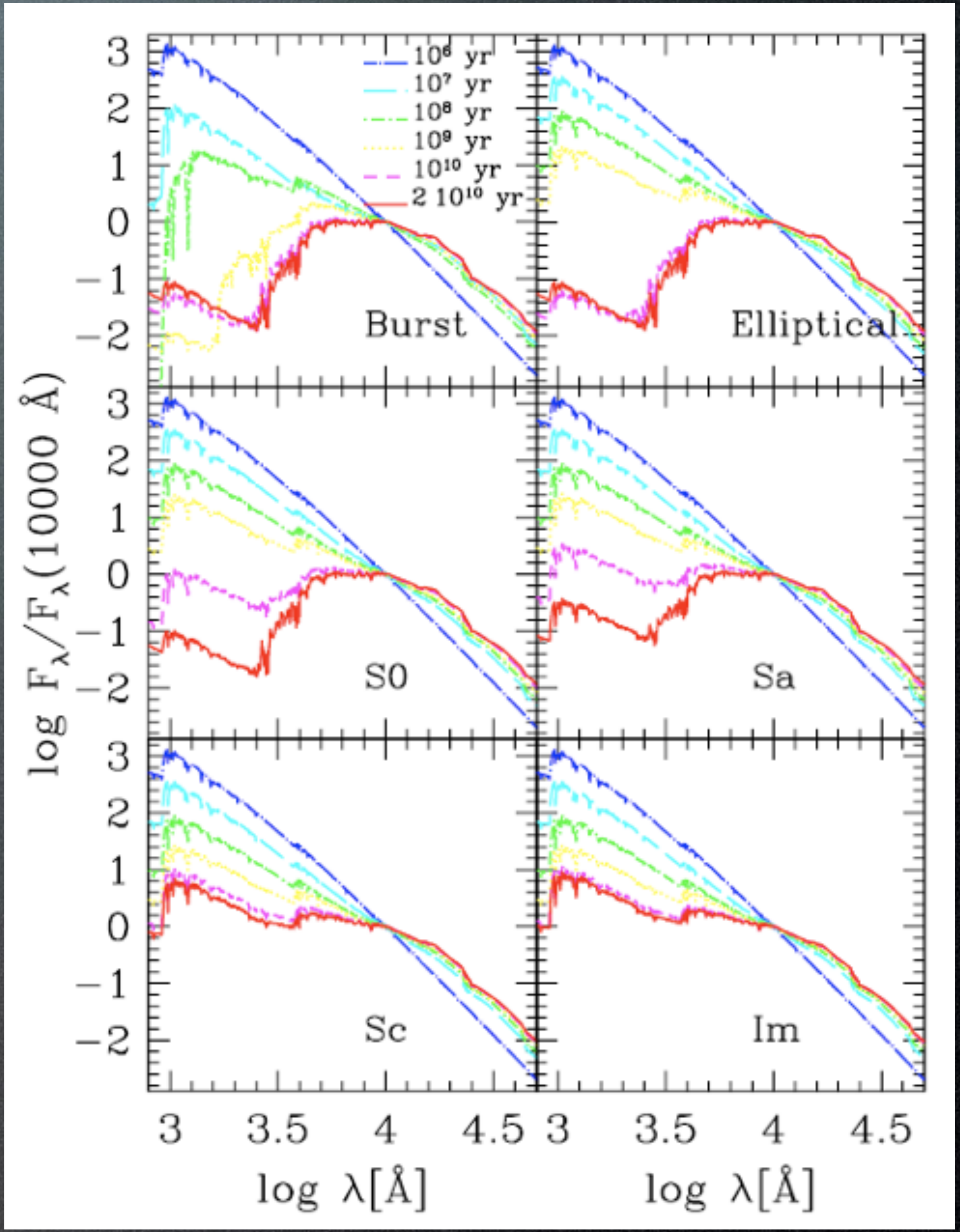
宇宙論的銀河形成の理論モデリング

- hierarchical galaxy formation in ΛCDM universe
  - star formation history can be predicted



Stellar Population Synthesis to predict opt/NIR SED

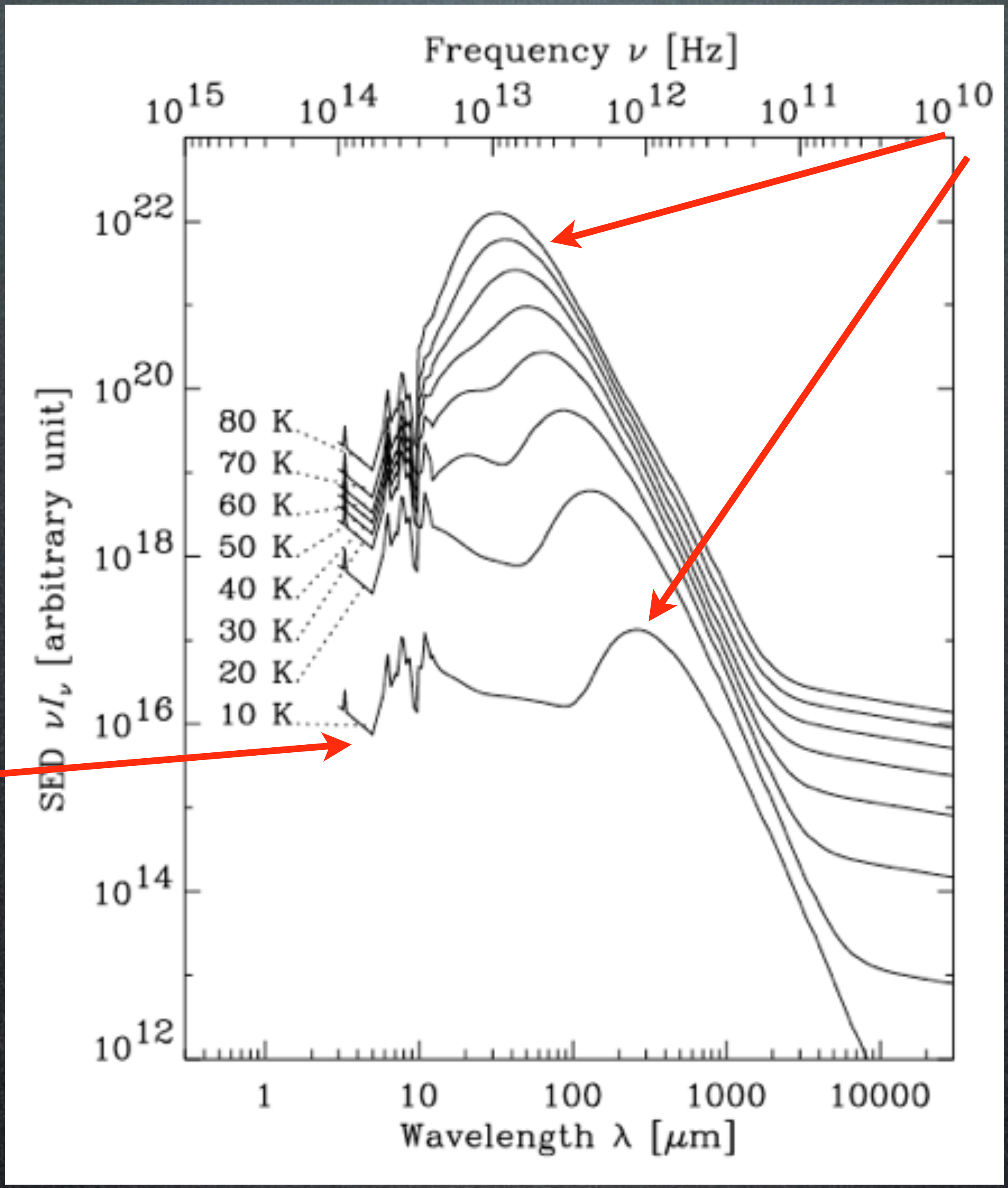
- ある銀河の星形成が分かれば、星のSED を合成して可視・近赤外の銀河のSED が出る
  - 星のスペクトルライブラリ
  - 星の初期質量関数（IMF）
  - 化学進化（金属量進化）



hyperz manual

Infrared SED of Galaxies: Emission from Dust

- physical dust model:
  - components
    - silicate
    - graphite
    - PAHs
  - size distribution
  - absorption coefficient
  - specific heat
  - ...
- non-equilibrium components:
  - small dust grains
  - stochasticly heated to high T by a single UV photon
  - PAH line features

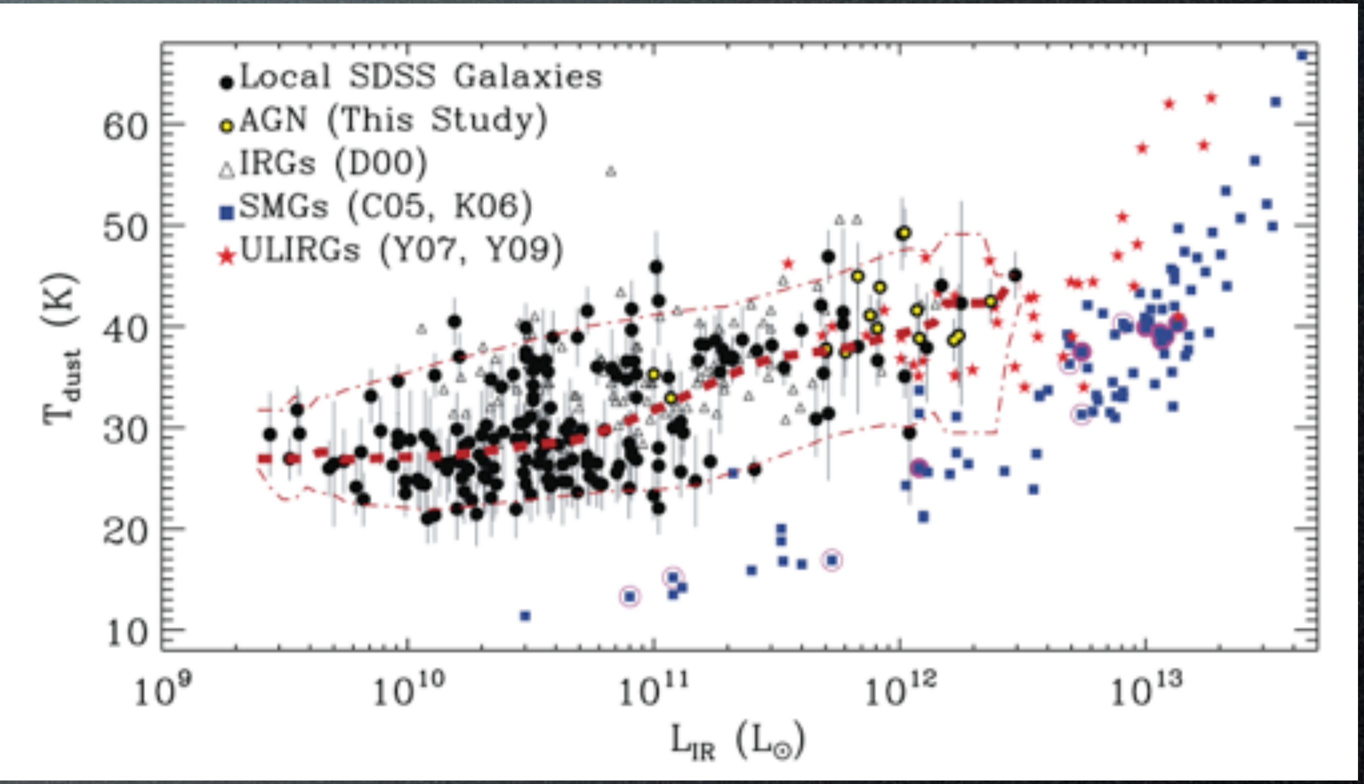


TT+Takeuchi '09

- "modified blackbody" peak:
  - thermal emission by large dust grains
  - modified blackbody by emissivity of dust
  - $F_\nu \propto \nu^\beta B_\nu(\nu, T)$, $\beta \sim$ 1-2
- heating radiation field determines the SED of dust emssion
  - denoted as U_h, in units of local ISRF
  - $U_h \Leftrightarrow T_{dust}$

銀河の IR SED / T_{dust} を決める物理?

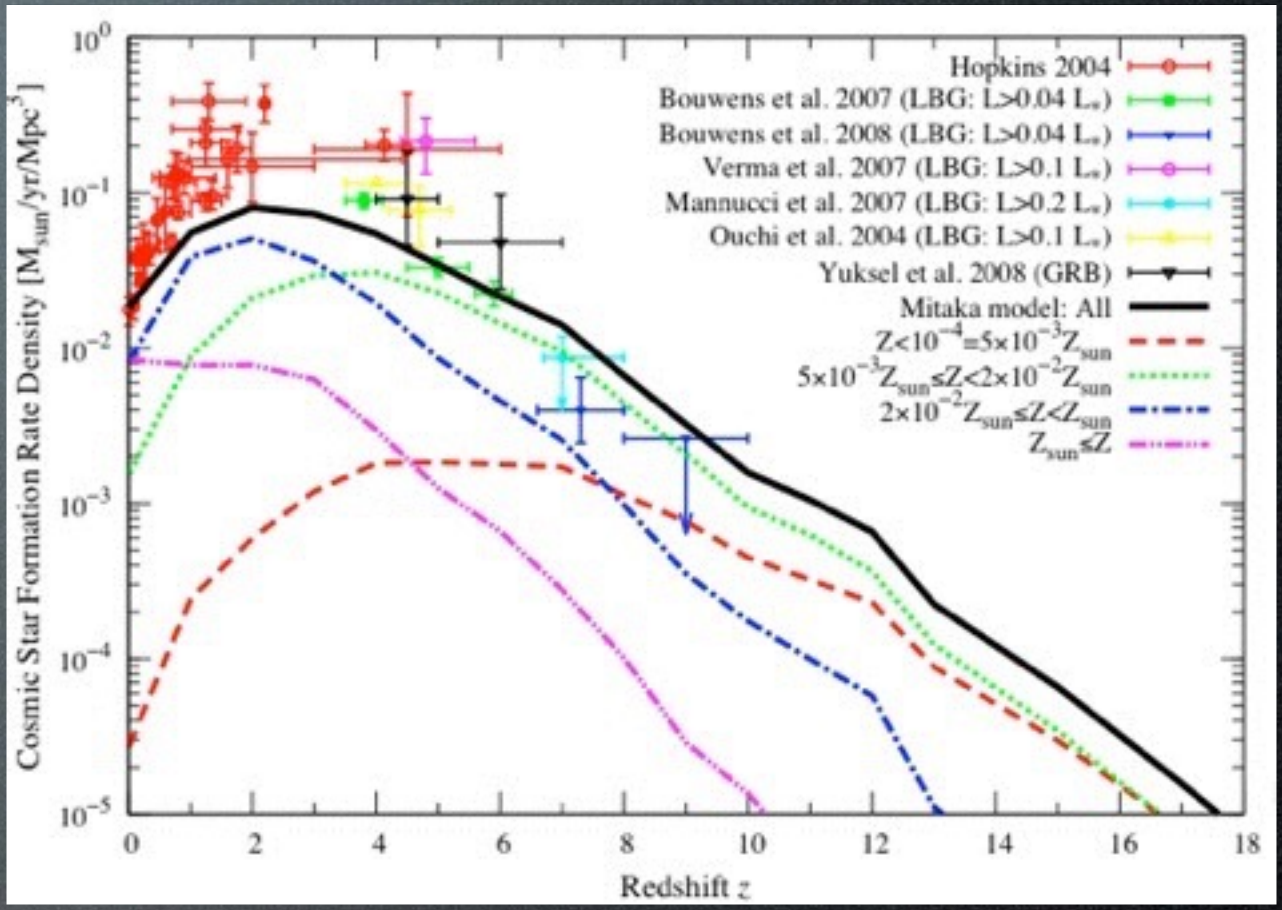
- T_{dust} は、dust heating radiation field との平衡で決まる
- trend of higher T_{dust} for larger L_{TIR}, but large scatter
- dust heating radiation field U_h (T_{dust} に対応) を決める要素
  - geometrical structure of galaxies
  - complicated radiative transfer in a galaxy
  - difficult to predict SED from the first princeple
- しかし、ダスト放射赤外SEDの理解は、隠された銀河形成の最終的な解明に不可欠

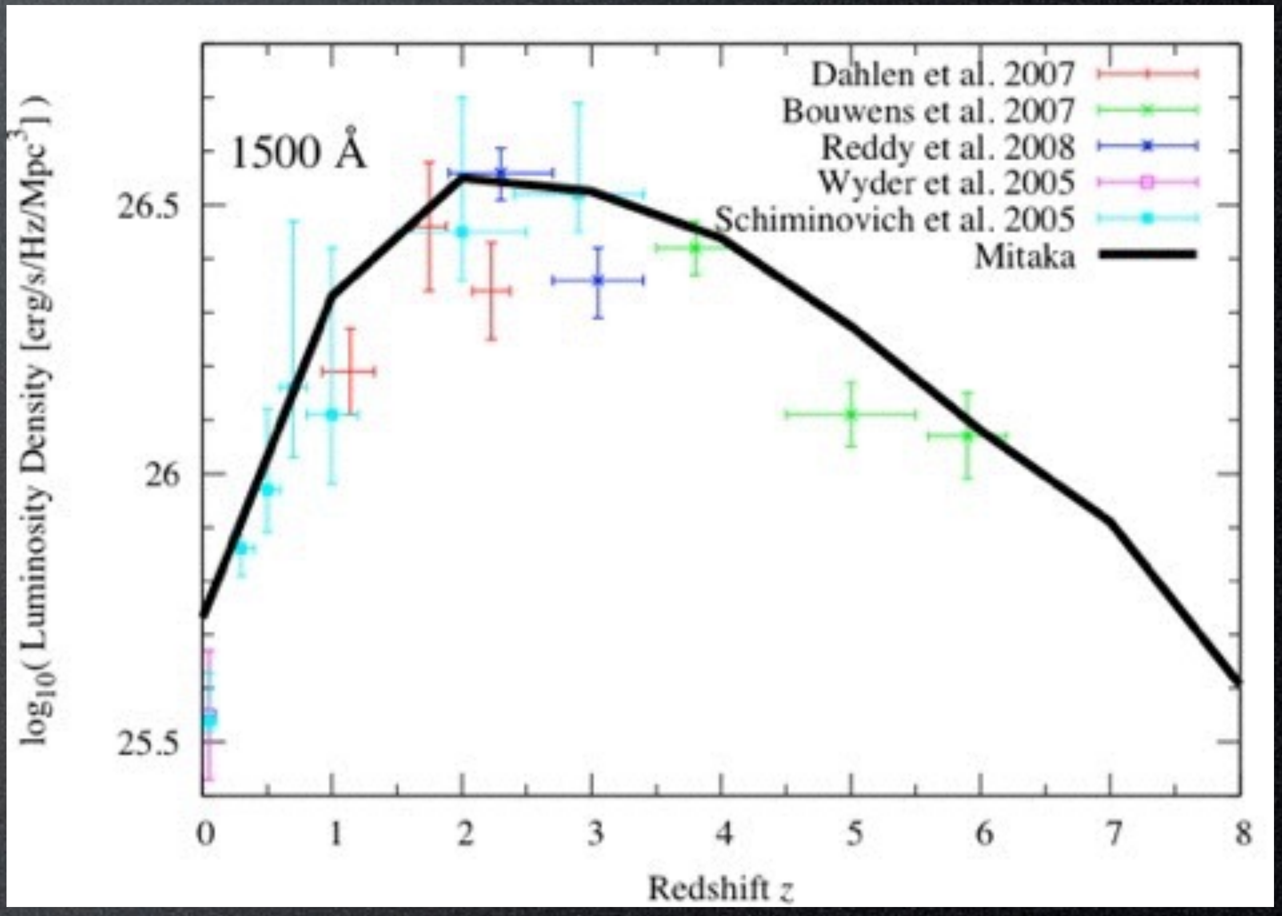


Hwang+ '10

theoretical prediction of EBL

- cosmic star formation history を銀河 SED で積分 → EBL
- CSFH データに関する注意ポイント
    - 様々な SFR indicator (UV, Hα, infrared, ...)
    - UV は特にダストによる吸収に弱い
    - IMF はもちろん仮定
    - 検出限界以下の暗い銀河は外挿
- CSFH plot ではなく、元の観測量でデータと一致しているかが重要
- 可視、近赤外の z=0 EBL は銀河カウントを積分したもののほうが精度がよい

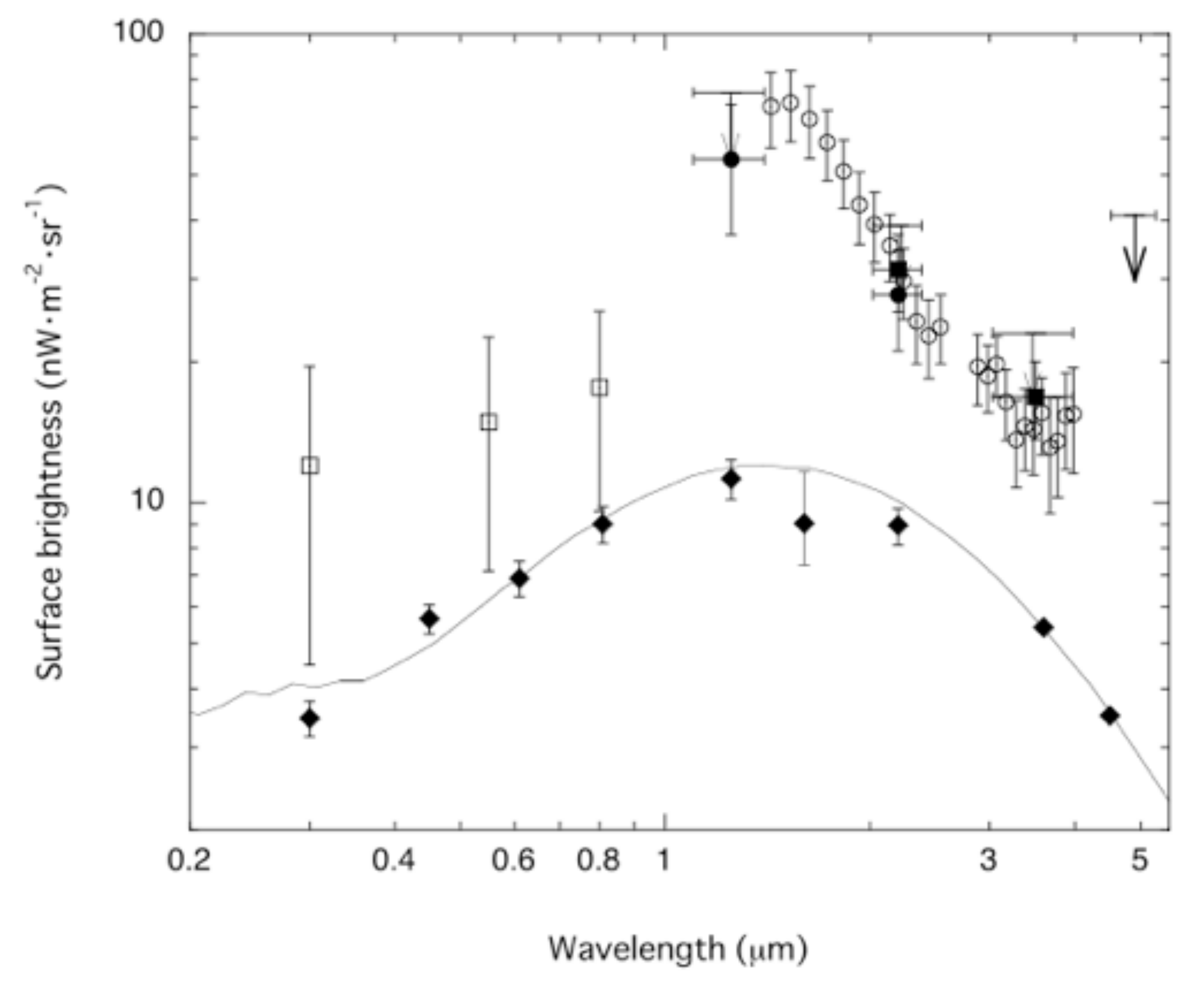




Y. Inoue+ '13

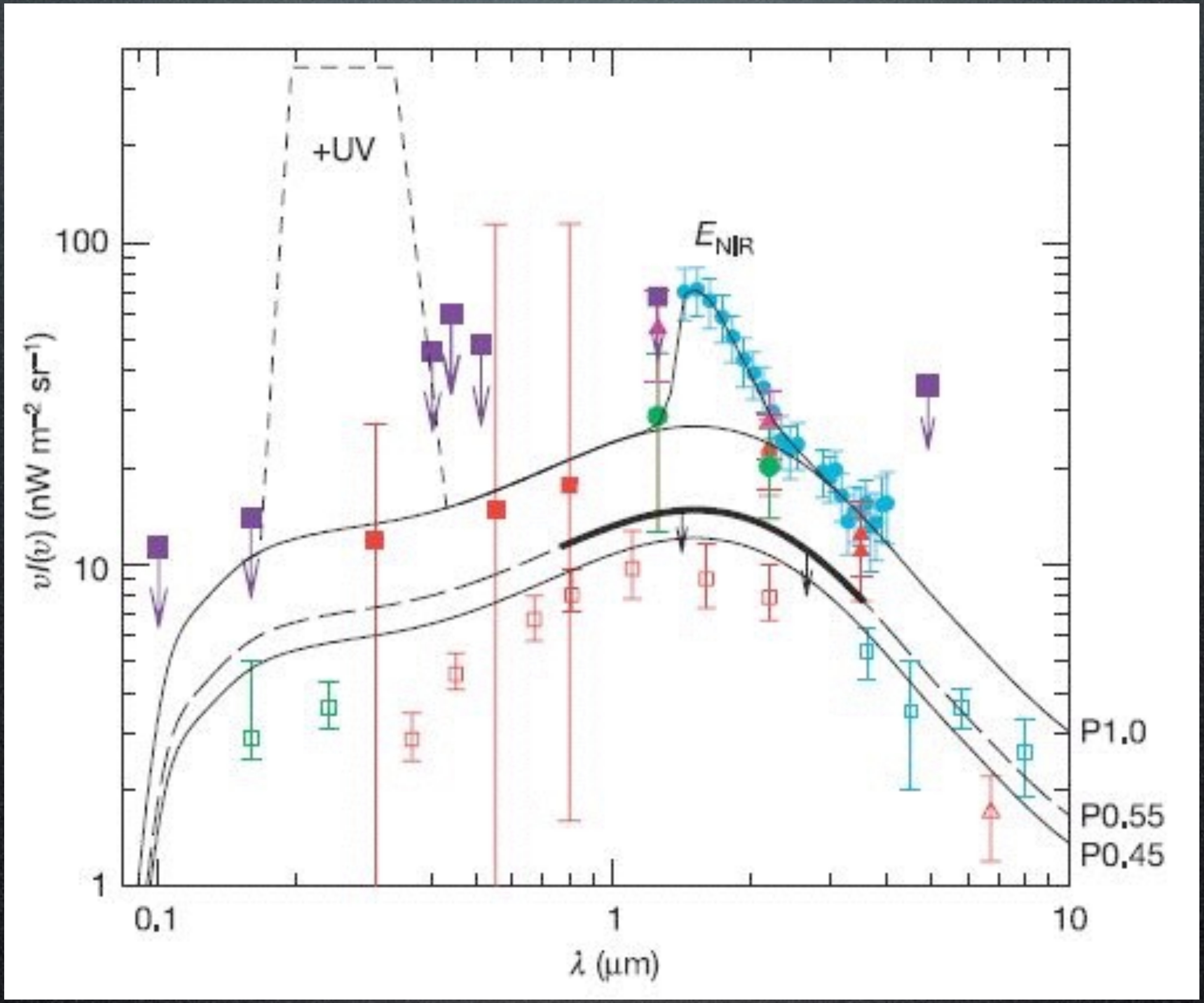
excess EBL in near-infrared?

- near-IR (2um 付近）の diffuse EBl 測定で、galaxy count の積分にくらべ ~5倍の超過
  - independent data from COBE and IRTS
- pop-III star formation!?
  - Lyman break at ~1-2 um ⇔ z~10
  - “extraordinary” amount
    - significant fraction of cosmi baryon goes to Pop III !!
    - leaving no other evidence (e.g. metal production) at all
      - Salpeter IMF では無理
- TeV data strongly disfavor
- systematic uncertainties in foreground subtraction, esp. zodiacal light?



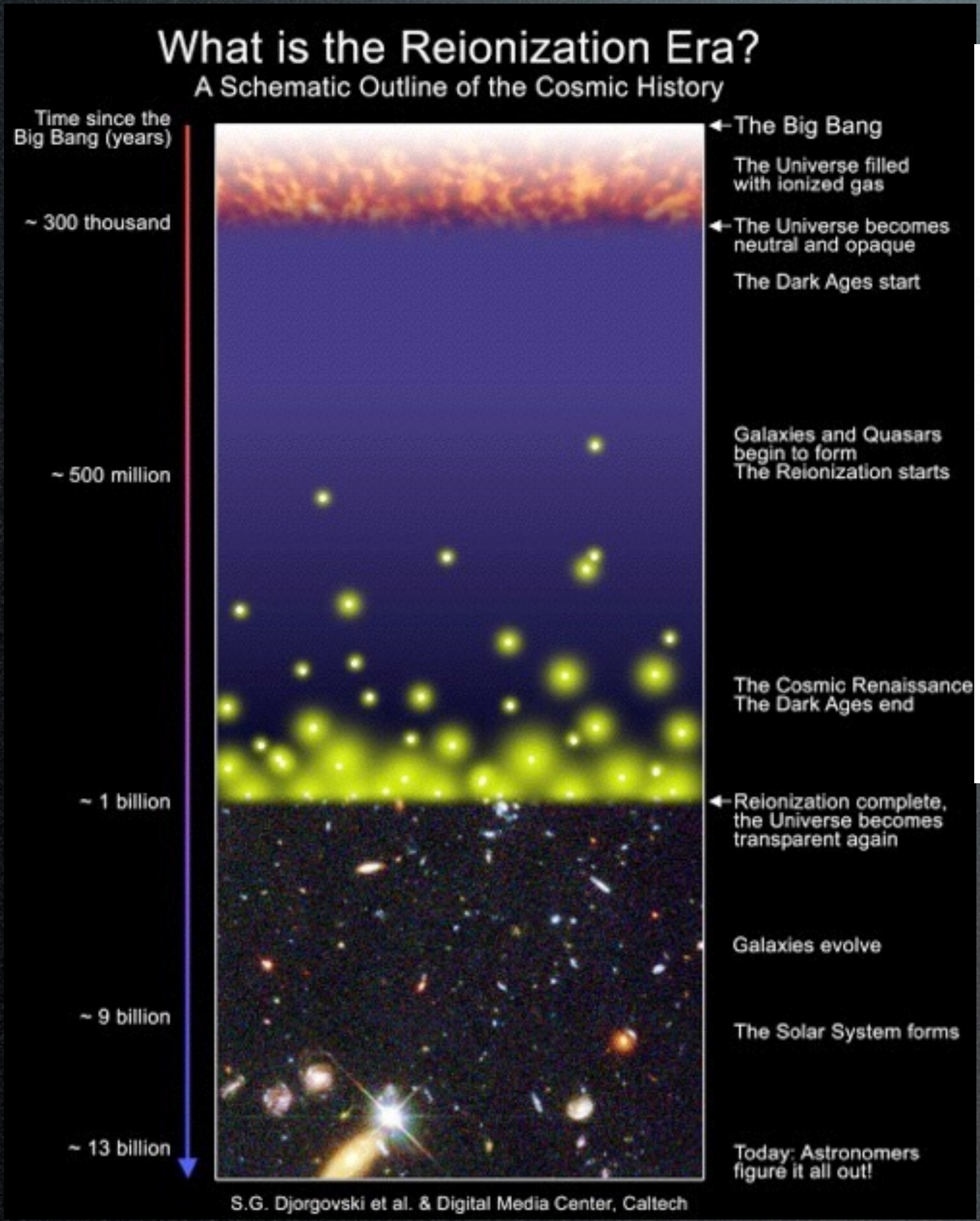
Matsumoto +’05

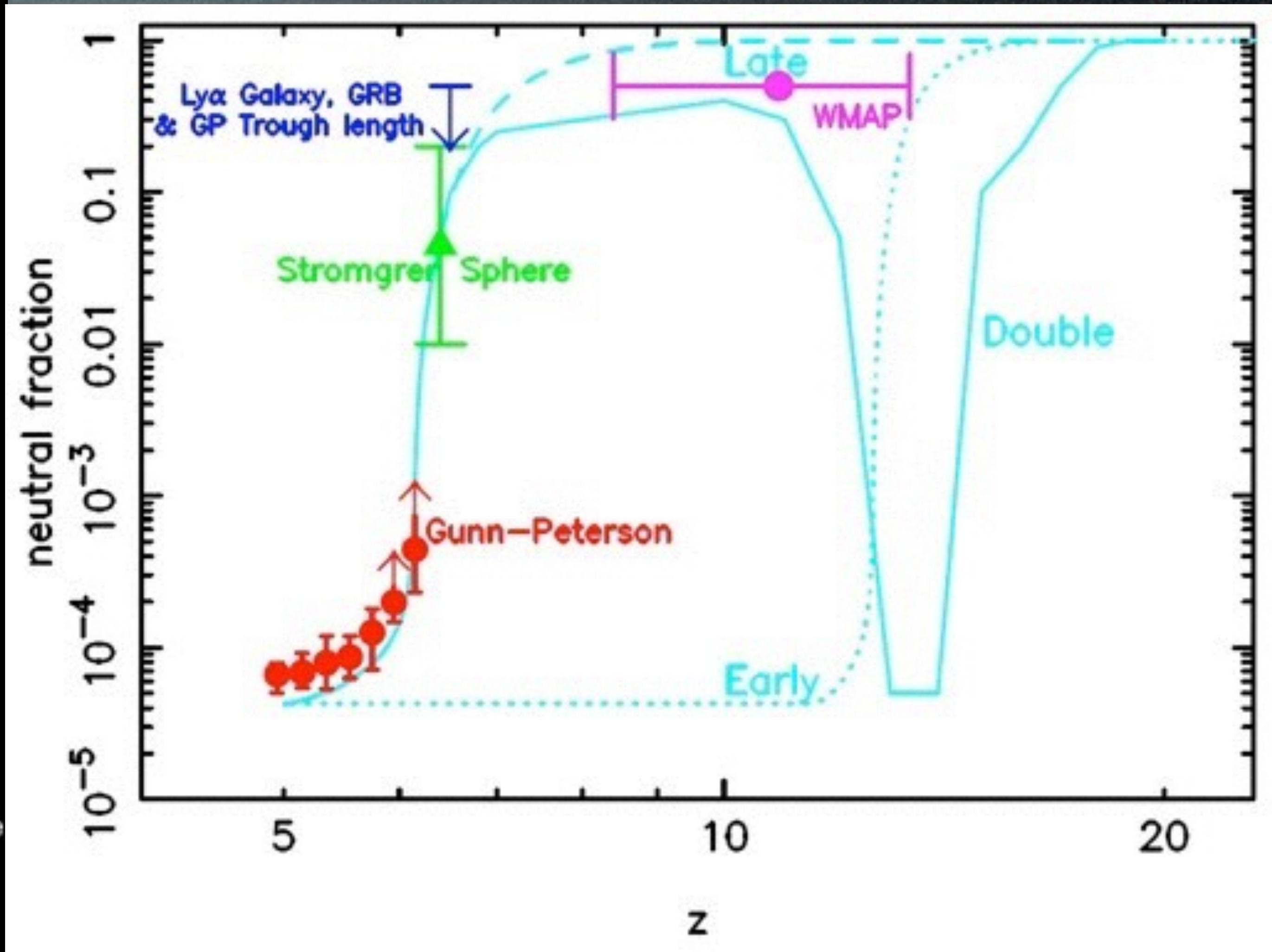
TeV gamma limit on cosmic NIR background



Aharonian+'06

宇宙の初代星形成と宇宙再電離



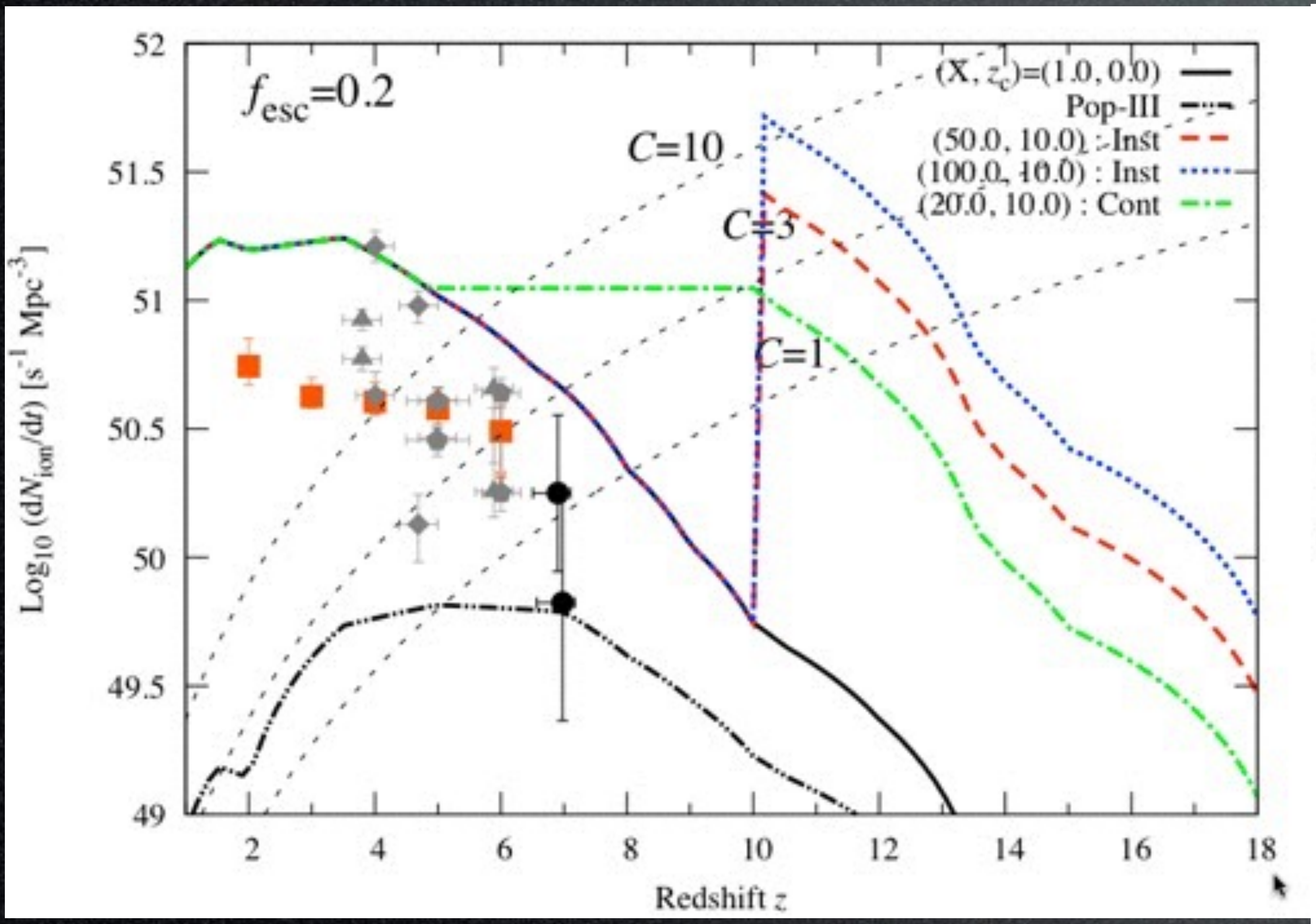


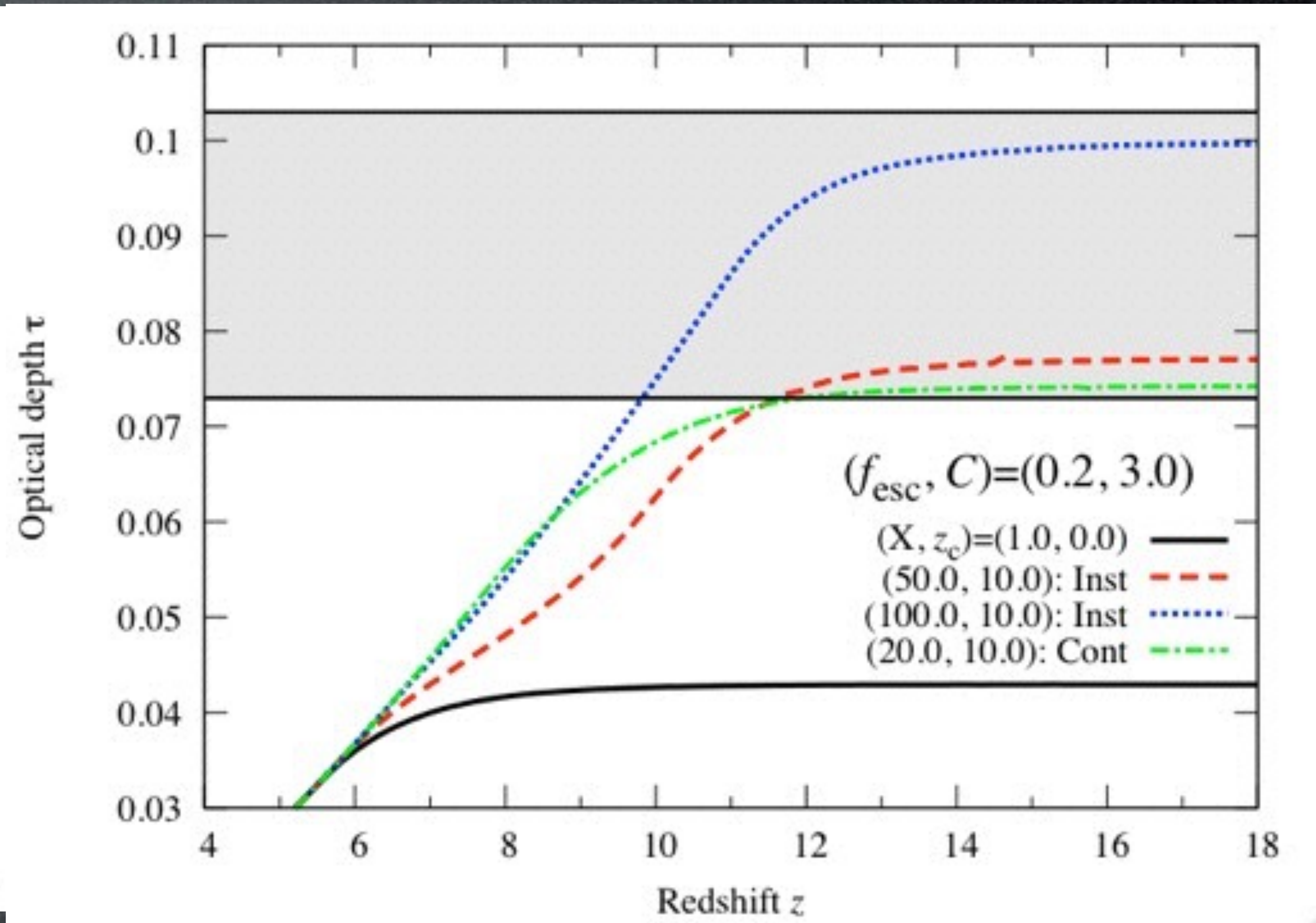
Fan+'06

Efficient Pop-III Star Formation? WMAP?

- WMAP 衛星の偏光観測より、z~10 で宇宙再電離の兆候
  - efficient Pop-III star formation?
- z < 7 の電離光子生成率は、標準的なモデルとデータはだいたい一致
- WMAP electron optical depth を説明するためには、z >~10 で標準的な銀河形成モデルの予言値に比べ、数十倍の電離光子が必要
  - 背景放射にはどれぐらい効く？

Y. Inoue+'13

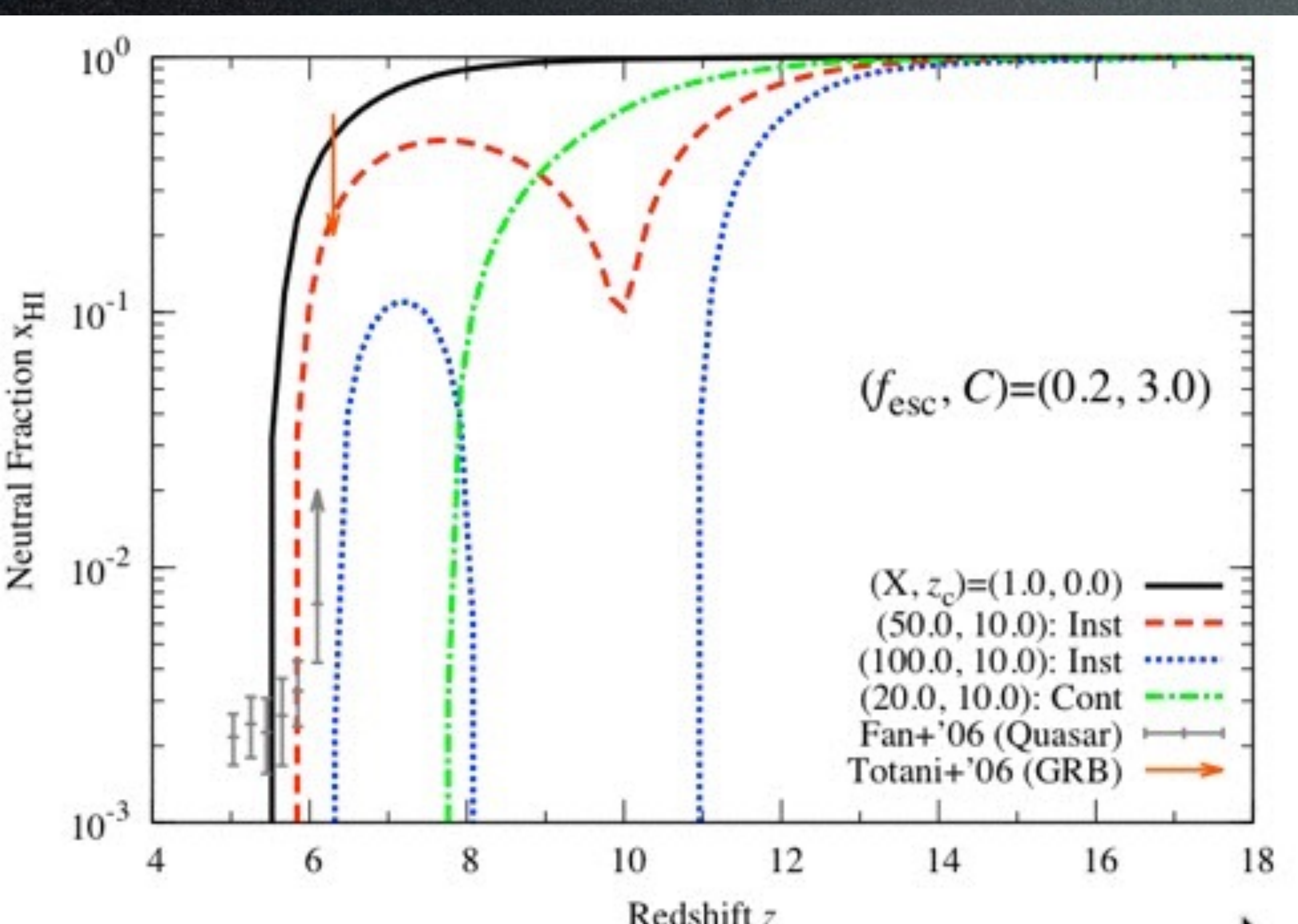


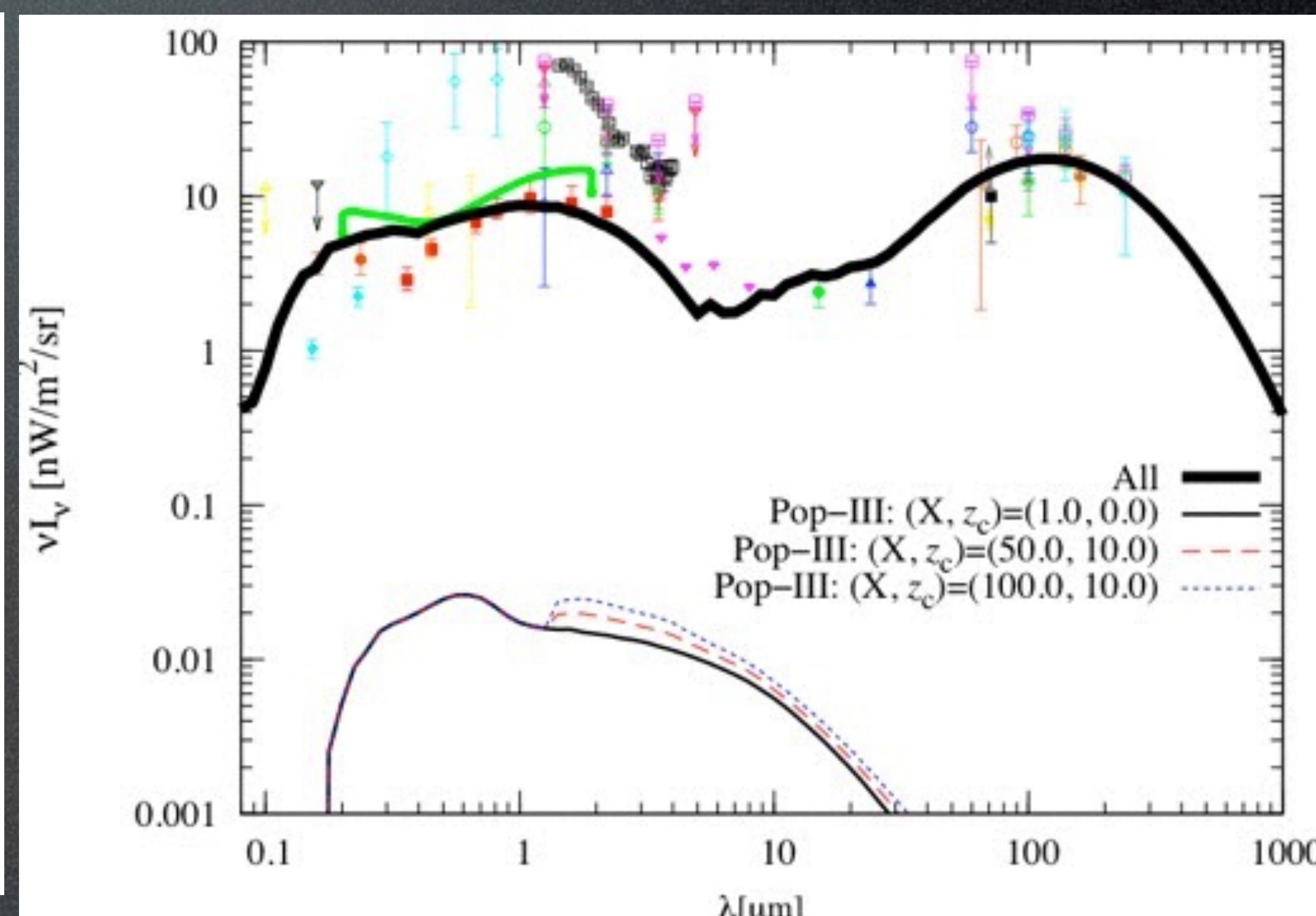


Pop-III contribution to EBL

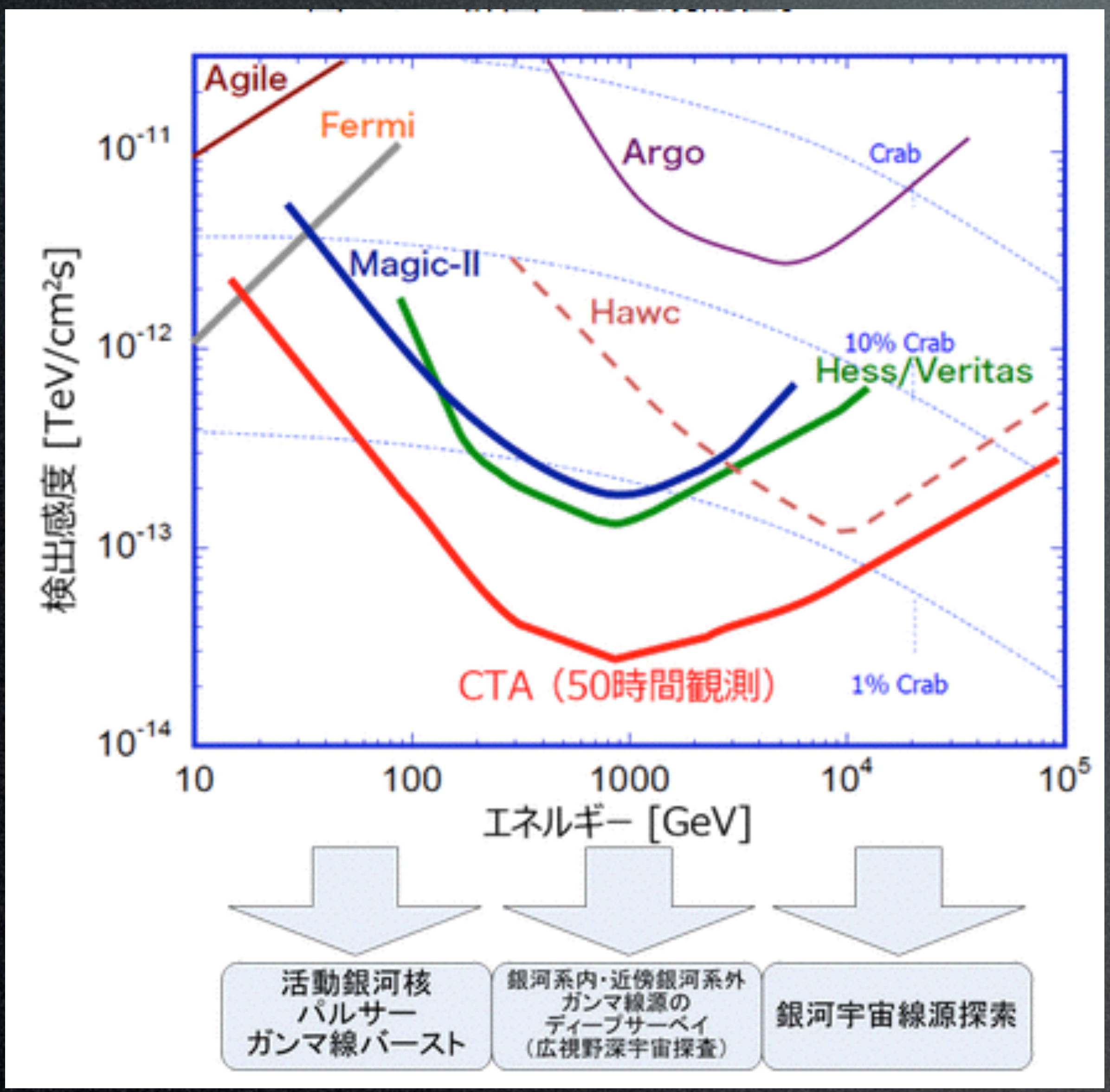
- WMAP を説明するのに必要なレベルの Pop-III star formation があったとして、その放射の背景放射成分の寄与は... 現在の EBL の 1/100 以下
- near-IR EBL excess が Pop-III だとすれば、WMAP から示唆される量の千倍の星形成が必要
    - 電離光子も大量に生成
    - それ以降の再電離史にそのような痕跡無し

Y. Inoue+'13.

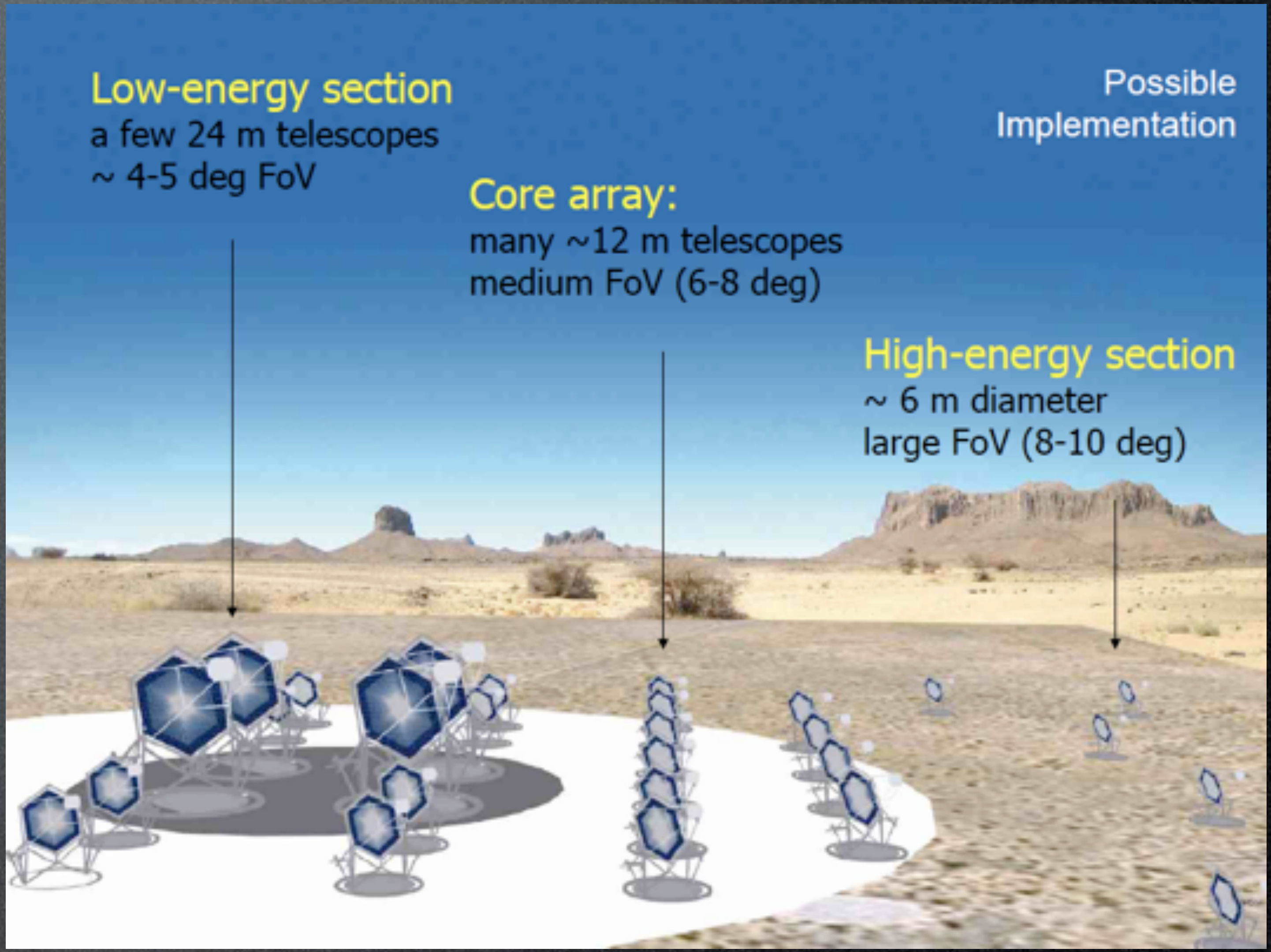




Future: CTA!



Agile
Fermi
Argo
Crab
Magic-II
Hawc
10% Crab
Hess/Veritas
CTA（50時間観測）
1% Crab
検出感度 [TeV/cm²s]
エネルギー [GeV]
活動銀河核
パルサー
ガンマ線バースト
銀河系内・近傍銀河系外
ガンマ線源の
ディープサーベイ
（広視野深宇宙探査）
銀河宇宙線源探索



Low-energy section
a few 24 m telescopes
~ 4-5 deg FoV
Core array:
many ~12 m telescopes
medium FoV (6-8 deg)
High-energy section
~ 6 m diameter
large FoV (8-10 deg)
Possible
Implementation