暗黒物質ニュートラリーノの対消滅と宇宙物理・宇宙論的示唆

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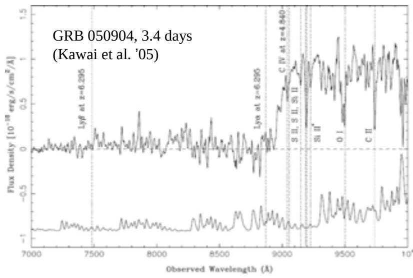
Outline

- 暗黒物質候補としてのニュートラリーノ: 概観
- Topic 1: 銀河団ガス加熱の可能性
- Topic 2:「宇宙最初の天体」マイクロハローからのガンマ線検出の可能性

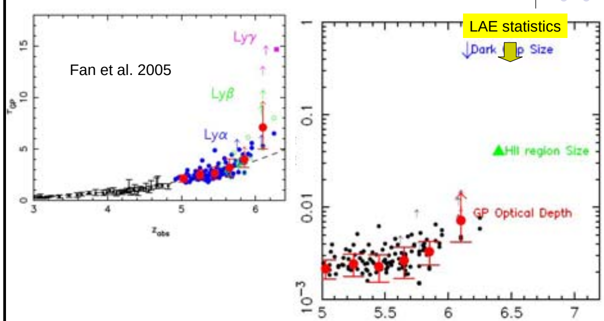
でもその前に、、、

GRB 050904 @ z=6.3

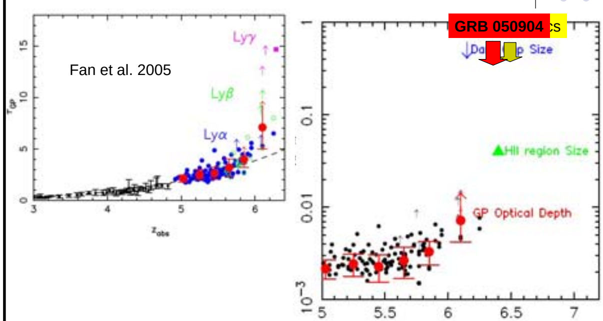
Constraint on Reionization:
$x_{HI} = n_{HI}/n_H = 0.00\pm0.17$, <0.60 (95%C.L.)



Constraints on Reionization

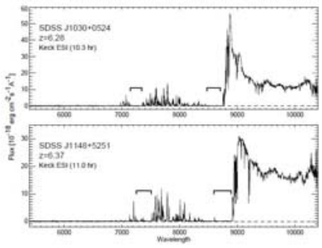


Constraints on Reionization



Only lower limits from quasars…

Gunn-Peterson optical depth
$\tau_{GP} = 2.1 \times 10^4 (1+z)^{3/2} x_{HI}$

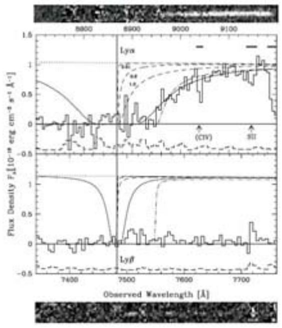


White et al. '03

First limit from Gunn-Peterson Damping Wing!

Totani et al. 2005

- direct method
- model-independent
- independent of IGM clumpiness
- robust limit on mass-weighted x_{HI} at z~6.1-6.3



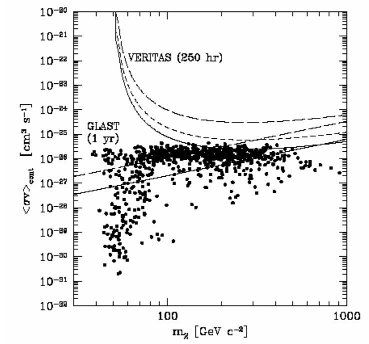
SUSY Dark Matter (WIMPs, Neutralinos)

- The most popular theoretical candidate for the dark matter
  - SUperSYmmetry: well motivated from particle physics
  - Neutralinos (l.c. of SUSY partners of photon, Z, and neutral Higgs): stable weekly interacting massive particles (WIMPs)
  - Relic abundance close to the critical density

$$\langle \sigma v \rangle_{\chi\chi \to ?} = 3\times10^{-27} / (\Omega_\chi h^2) \ \mathrm{cm^3\ s^{-1}}$$
$$\approx 3\times10^{-26}\ \mathrm{cm^3\ s^{-1}}$$

- Constraint on the neutralino mass
  - **50 GeV ~< m_χ <~ 10 TeV**
  - Lower bound from accelerator experiments
  - Upper bound from cosmic overabundance

Annihilation Cross Section

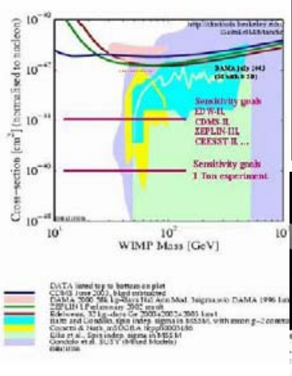


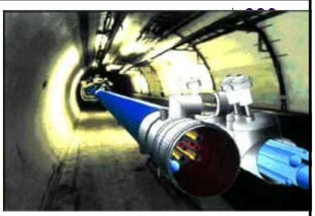
Stoehr et al. 2003

Searching for Neutralinos

- direct detection in underground experiments
  - CDMS, DAMA, …
- "make" neutralinos in accelerator experiments
  - LHC starts from 2007
- indirect detection of annihilation products in the sky
  - GLAST, ACTs, …

All these approaches have a reasonable chance to detect neutralinos in next 5-10 years!



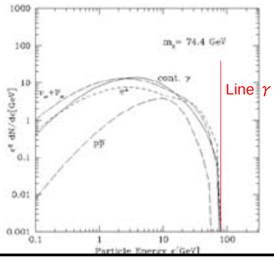


Annihilation Signals

- Continuum gamma-rays, e±, p, p-bar, ν's
- Line gamma-rays:
  - $\chi\ \chi \rightarrow 2\gamma$
  - $\chi\ \chi \rightarrow Z\gamma$
  - $(\sigma v)_{line} \sim 10^{-29}\ cm^3s^{-1} << (\sigma v)_{cont} \sim 10^{-26}\ cm^3s^{-1}$
- Search:
  - Line/continuum gamma-rays from GC, nearby galaxies, galaxy clusters
  - Positron/antiproton excess in cosmic-rays
  - …

Annihilation yields via hadron jets

- Annihilation energy goes to gammas, e±,p, p-bars, neutrinos as: ~1/4, 1/6, 1/15, 1/2
- Particle energy peaks at: 0.05, 0.05, 0.1, 0.05 $m_\chi c^2$.
  - (From DarkSUSY package, Gondolo et al. 2001)
  - Most energy is carried by ~1-10 GeV particles for m_χ~100GeV
  - photon flux peak at ~70 MeV (~m_π/2)



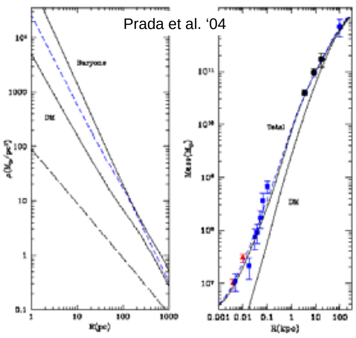
An example for yield Spectra from DarkSUSY

DM Halo Density Profiles

- Cosmological N-body Simulations
  - NFW (γ=1)
  - Moore (γ=1.5)

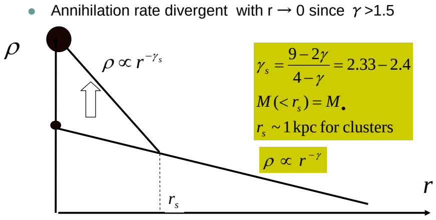
$\rho \propto r^{-\gamma}$ (in central part)

- Compression by baryons?
- Density spike by SMBH formation?



Density spike by SMBH formation?

- Density "spike" can be formed by the growth of supermassive black hole (SMBH) mass at the center.
  - Young (1980); for stellar density cusps in elliptical galaxies
  - Gondolo & Silk (1999); for DM cusps
  - "Adiabatic" = growth time scale > orbital period at r_s
  - Annihilation rate divergent with r → 0 since γ >1.5



$$\gamma_s = \frac{9-2\gamma}{4-\gamma} = 2.33 - 2.4$$

$$M(<r_s) = M_\bullet$$

$r_s \sim 1\,\text{kpc for clusters}$

$\rho \propto r^{-\gamma}$

Comparison for Various Cases

	Model	Gamma-Ray Flux [$cm^{-2}s^{-1}$]
	MW, as a whole (NFW)	2.3×10^{-7}
	MW, NFW, central 1°	2.3×10^{-9}
	MW, baryon compressed NFW, central 1°	2.3×10^{-8}
	MW, Moore, central 1°	1.6×10^{-6}
	MW, NFW+spike, core	3.2×10^{-7}
	MW, Moore+spike, core	1.6×10^{-4}
Obs	MW, EGRET observation	$\sim 10^{-6}$
	Draco, King	1.9×10^{-12}
	Andromeda, NFW	2.5×10^{-11}
	Perceus Cluster (CF equivallent)	$1.7 \times 10^{-7}(m_\chi/100\text{GeV})^{-2}$
Obs	Perceus Cluster (EGRET limit)	$< 3.72 \times 10^{-8}$

$$m_\chi = 100\,\text{GeV},\ \ \langle\sigma\upsilon\rangle = 3\times10^{-26}\ \text{cm}^3\text{s}^{-1}$$

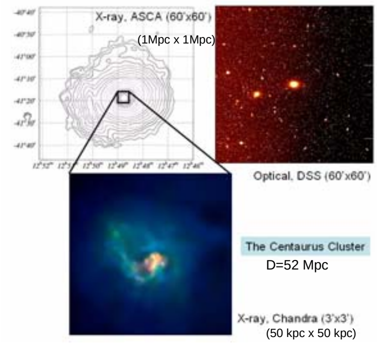
Topic 1

Cooling Flow Problem of Galaxy Clusters and DM Annihilation

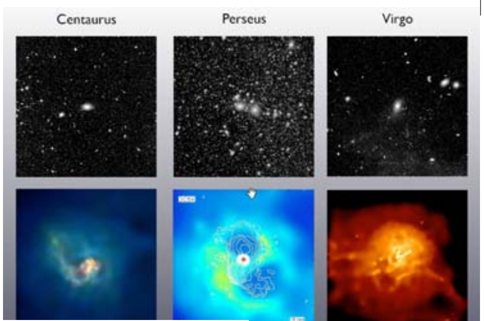
- Cooling time in cluster centers << cluster age
- No evidence for cooling
- cooling is compensated by feedback from the center
  - radio bubble formation observed in most cooling-core clusters
- Feedback mechanism?

X-rays from galaxy clusters

- thermal bremsstrahlung of hot gas:
  - kT ~ 5-10 keV
  - n ~ 10^{-3} cm^{-3} (virial)
  - n~10^{-1} cm^{-3} (central)
  - M_{tot}~10^{15} M_{sun}
    - M_{gas}/M_{tot} ~Ω_B/Ω_M~10%
    - M_{star}/M_{gas}~10%



Clusters seen in optical and X-rays



central part, NOT the same scale as above

Courtesy from K. Masai

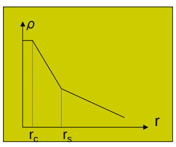
ニュートラリーノ対消滅による銀河団ガスの加熱

TT 2004, Phys. Rev. Lett. 92, 191301

- Density maximum determined by annihilation itself:

$$\rho_c \langle \sigma \upsilon \rangle / m_\chi = t_{cl} \equiv 10^{10} t_{10} \text{ yr}$$

$$r_c = 0.17 M_{\bullet,10}^{2/7} m_2^{-3/7} \langle \sigma \upsilon \rangle_{-26}^{3/7} t_{10}^{3/7} \text{ pc}$$



- The annihilation luminosity from $r<r_c$:

$$L_{\chi\bar{\chi}} = 2 m_\chi c^2 \langle \sigma \upsilon \rangle \left(\frac{\rho_c}{m_\chi} \right)^2 \left(\frac{4\pi r_c^3}{3} \right)$$

$$= 2 \times 10^{44} M_{\bullet,10}^{6/7} m_2^{-2/7} \langle \sigma \upsilon \rangle_{-26}^{2/7} t_{10}^{-5/7} \text{ erg/s}$$

- 銀河団ガスを加熱してクーリングフローを止めるに十分な熱量
- 初期の冷却によりSMBH成長、density spike ができるとすれば、冷却に対するフィードバックになっている
- 一度火がつけば宇宙論的時間スケールでほぼ一定の熱供給

銀河団ガスの加熱源は何か？

- 要求される条件
  - ガスの冷却に対するフィードバックになっている
  - 銀河団中心部において相対論的粒子によるバブルを形成する
    - AGN
    - density spike　形成によるニュートラリーノ対消滅
- AGN？
  - 安定性？
  - finely-tuned accretion?
  - anisotropic feed back from jet is not efficient in 3D simulation (Vernaleo & Reinolds 2005)
- AGNだとあたりまえすぎて面白くない

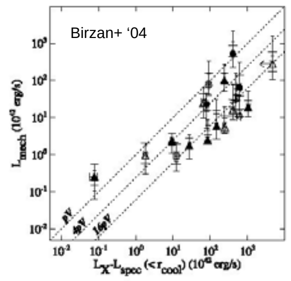


FIG. 2.—Mechanical luminosity vs. total luminosity minus the spectroscopic estimate of the cooling luminosity. Lines denoting $L_X - L_{spec} = L_{mech}$ are shown for the assumptions of pV, $4pV$, and $16pV$ energy in the bubbles. Symbols and error bars as in Fig. 1; the arrow denotes an upper limit.

加熱効率

- SMBH質量に対して要求される加熱効率

$$\varepsilon \equiv \frac{L_X\, t_{age}}{M_\bullet c^2}$$

$$\sim 0.017 \left(\frac{L_X}{10^{44}\,\mathrm{erg/s}}\right)\left(\frac{t_{age}}{10^{10}\,\mathrm{yr}}\right)\left(\frac{M_\bullet}{10^9 M_{SUN}}\right)^{-1}$$

- AGNで可能だろうか？
  - jet kinetic energy efficiency
  - particle acceleration
  - …
- Neutralino heating
  - ~0.007 for e$^\pm$ and p, p-bar s

ニュートラリーノによる銀河団ガス加熱: Predictions

- 対消滅ガンマ線はGLASTで受かるはず
  - 予言フラックスはEGRET限界のやや下
  - 他のプロセスのガンマ線と区別可能
    - 銀河団の中心から点源として見える
    - 時間変動なし(AGNと区別)
    - ラインが見えれば決定的
  - X線強度から推測すると、Perseus cluster が最も有望

Comparison for Various Cases

	Model	Gamma-Ray Flux $[\mathrm{cm^{-2}s^{-1}}]$
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Perseus Cluster からラインが見えれば俺は勝ち組

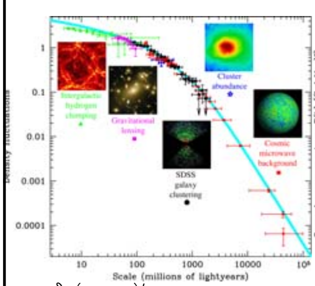
$$m_\chi = 100\,\mathrm{GeV}, \langle \sigma v \rangle = 3\times10^{-26}\ \mathrm{cm^3s^{-1}}$$

Topic 2

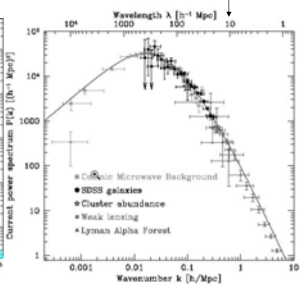
What is the mass of the first gravitationally bound objects in the early universe?

- density power-spectrum of the universe:

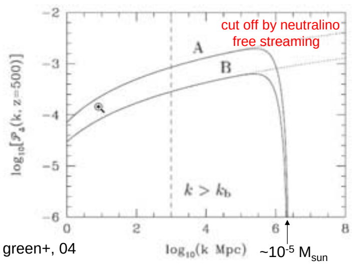
$10^{15} M_{sun}$



$\delta = (\rho - \rho_{av})/\rho$

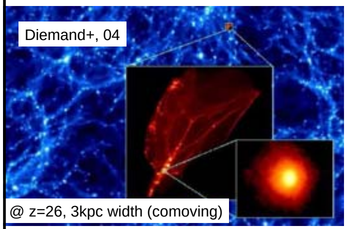


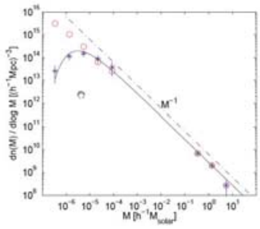
SDSS 3D P(k), Tegmark et al. 04



green+, 04

earth-mass sized microhaloes





- earth mass (10^{-6} Msun), 0.01 pc size objects forming z~60
  - Hofmann+, 01, Berezinsky+, 03, Diemand+, 04
- ~50% of mass in the Galactic halo may be in the substructure
- n~500 pc^{-3} around Sun, encounter to the Earth for every 1,000 yr.
- controversial whether or not they are destroyed by tidal disruption at stellar encounters

internal density profile of microhaloes

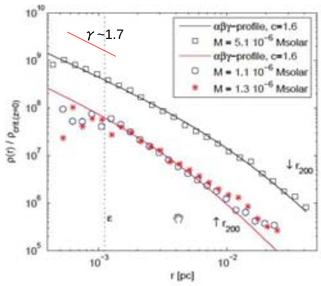
- annihilation signal enhancement

$$f_c = \frac{\text{mass-weighted } \bar{\rho}}{\text{volume-weighted density } \bar{\rho}\ (= \rho_{vir})}$$

- simulation:
  - concentration parameter c~1.6 in the simulation
  - (α, β, γ)=(1, 3, 1.2)
  - f_c = 6.1

$$\rho \propto \frac{1}{(r/r_s)^\gamma [1+(r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

$$r_s = r_{vir}/c$$



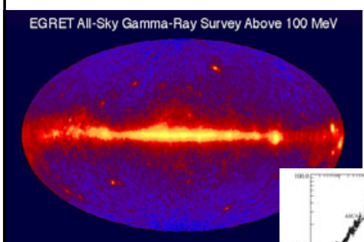
Diemand et al. '05

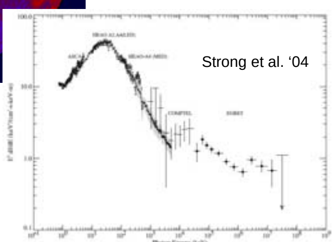
microhalo contribution to EGRB

Oda, Totani, & Nagashima, ApJ, 633, L65

- 一つ一つのマイクロハローからのガンマ線は極めて検出は難しい (see also Pieri et al. '05)
- しかし背景放射への寄与は結構でかい可能性がある
  - microhalos form at very high z~60, with high internal density $\propto (1+z)^3$

the cosmic gamma-ray background

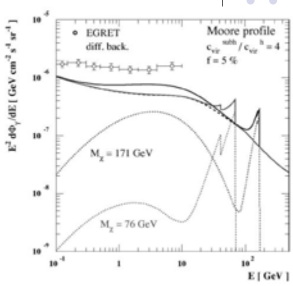




Strong et al. '04

Contribution to the cosmic gamma-ray background

- Ullio et al '02
  - substructures with M>~10^6 M_{sun}
  - model1:
    - M=171 GeV
    - σv=4.5x10^{-26} cm^3s^{-1}
    - b_{2gamma}=5.2x10^{-4}
  - model2:
    - M=76 GeV
    - σv=6.1x10^{-28} cm^3s^{-1}
    - b_{2gamma}=6.1x10^{-2}
- Assuming universal halo density profile, annihilation signal from GC exceeds if neutralinos have dominant contribution to EGRB (Ando 2005)



マイクロハローの破壊

- 銀河系内の破壊過程
  - 星との相互作用 （地球近傍で現在までに破壊されるかされないか、程度）
  - 銀河系の重力場による潮汐破壊 （銀河系中心～1kpc程度で破壊されると予想）
- 銀河系中心付近では強い潮汐力や星との相互作用で破壊される → 銀河系中心からのフラックス制限と無矛盾
- 一方、たとえ銀河系中心付近で破壊されても背景放射へはほとんど影響なし（mass within 10kpc is ~6% of MW halo）
  - extragalactic background flux hardly affected.

Galactic and extragalactic gamma-ray background from microhaloes

Oda et al. '05

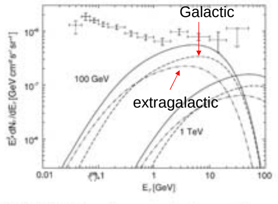


FIG. 1: The background gamma-ray flux from neutralino annihilation in the microhaloes. The GGRB (dashed), EGRB (dot-dashed), and the total (solid) components are shown. The two cases of m_χ = 100 GeV and 1 TeV are presented, with f_{surv} = 0.35 and 1, respectively. The EGRET EGRB data points are from 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.

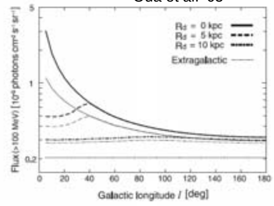
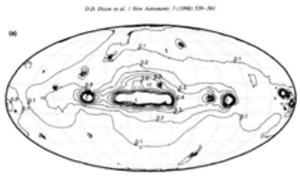


FIG. 2: The longitudinal distribution of the background flux (GGRB+EGRB). The neutralino mass is m_χ = 100 GeV and f_{surv} = 1. Three different values of disruption radius R_d are used as indicated. The two different density profiles of the Galactic halo are used: the baryon-compressed NFW (upper thick curves) and the original NFW (lower thin curves). The level of EGRB is indicated.

with standard annihilation cross section and microhalo abundance inferred from simulation

Gamma-ray halo around the GC?

Dixon et al. '98



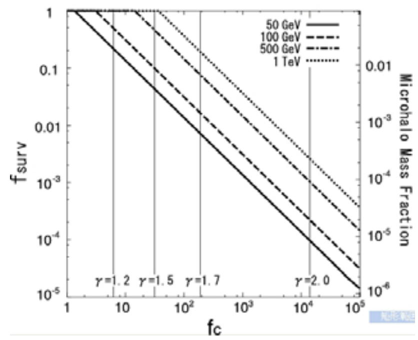
excess from the standard CR interaction model of the Galactic gamma-ray background

excess from the standard model x 1.2

gamma-ray halo?
Flux level ~ EGRB

limits in the f_{surv}-f_c plane

limits not to overproduce the observed gamma-ray background



まとめ

- 宇宙最初の天体、マイクロハローは一つ一つに分解しての検出は難しいが、背景放射には結構な寄与を持つ可能性がある
  - EGRETの系外背景放射全ては説明はできない（スペクトルが違う）
  - 近傍銀河（アンドロメダなど）のハローからも検出の可能性あり
- ガンマ線観測は、暗黒物質の正体だけでなく、構造形成理論の検証にも使える可能性がでてきた