Gamma-Ray Signal from Earth-Mass Dark Matter Halos

Toshikazu Ebisuzaki (Riken ASI)
Tomoaki Ishiyama and Jun Makino (NAOJ)
Venya Berezinsky (INFN)

Dark Matter Halo in CDM Scenario

- All the scales from Clusters of Galaxies (～Mpc) to the smallest size (～10μpc)
- Numerous number of Halos
- Hierarchy nature
  - Sub-halos in Halos
- Smallest halos
  - ←How cold is dark matter?
  - ←How massive they are?
- If dark matter Is the neutralino of several hundred GeV
  - Smallest halo ~ 10^{-6} Msun ~ Earth's mass
    (Zybin+1999, Hofmann+2001, Green+2004,
    Loeb & Zaldarriaga2005, Berezinsky+2003,2008)

Indirect Detection of Dark Matter: Theory

- Gamma-rays due to Annihilation of DM particles (Berezinsky+ 2003, 2008, Diemand+ 2005)
- Emisitivity per volume $\propto \rho^2$
- Core structure is important in the total luminosity
  - If $\rho \propto r^{-1.5}$, then

$$
\begin{aligned}
L(<r) &\sim \int_0^r \rho^2 dV \\
&\sim \ln(r/r_c)\rho_c^2 r_c^3
\end{aligned}
$$

$L \rightarrow \infty$ at $r \rightarrow 0$

Indirect Detection of Dark Matter: Obs

- Observation of Positron Anomaly: PAMELA and FERMI
  - Dark matter annihilation or Pulsar wind

PAMLA2009

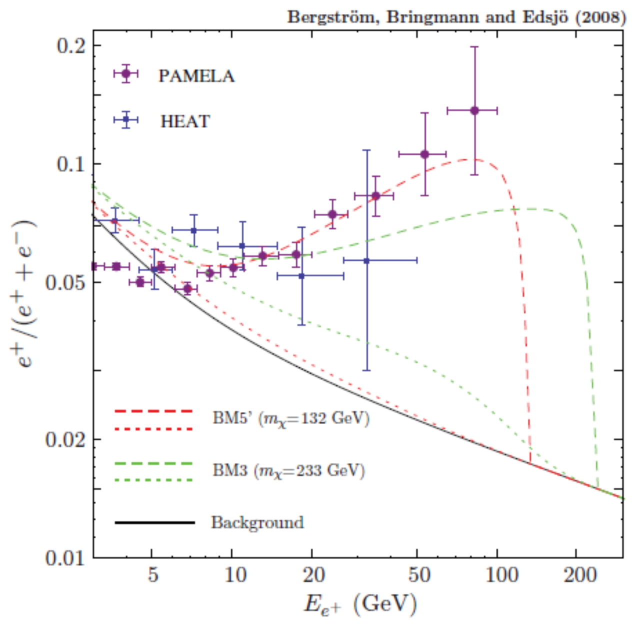


Figure 15. The solid line is the expected flux ratio $e^+/(e^+ + e^-)$ as calculated following [34]. The data points are the combined HEAT [40] and PAMELA data. The expected flux ratio is shown without (dotted lines) and after taking into account radiative corrections [51] (dashed lines).

FERMI2009

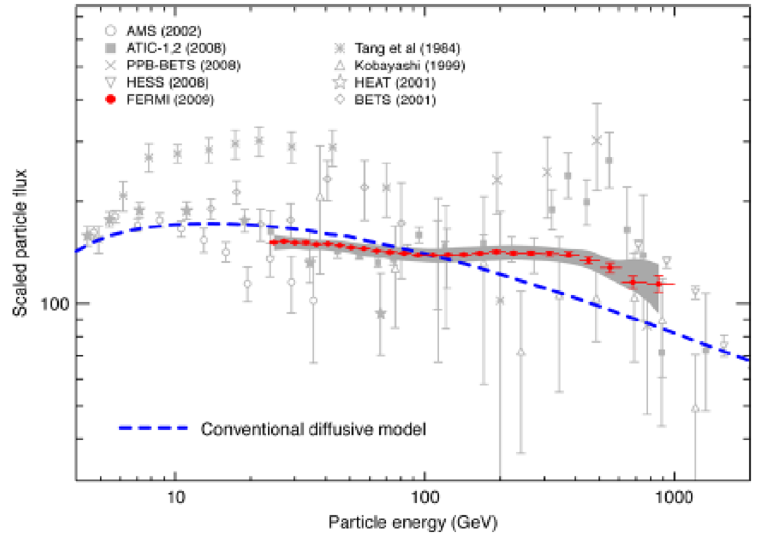
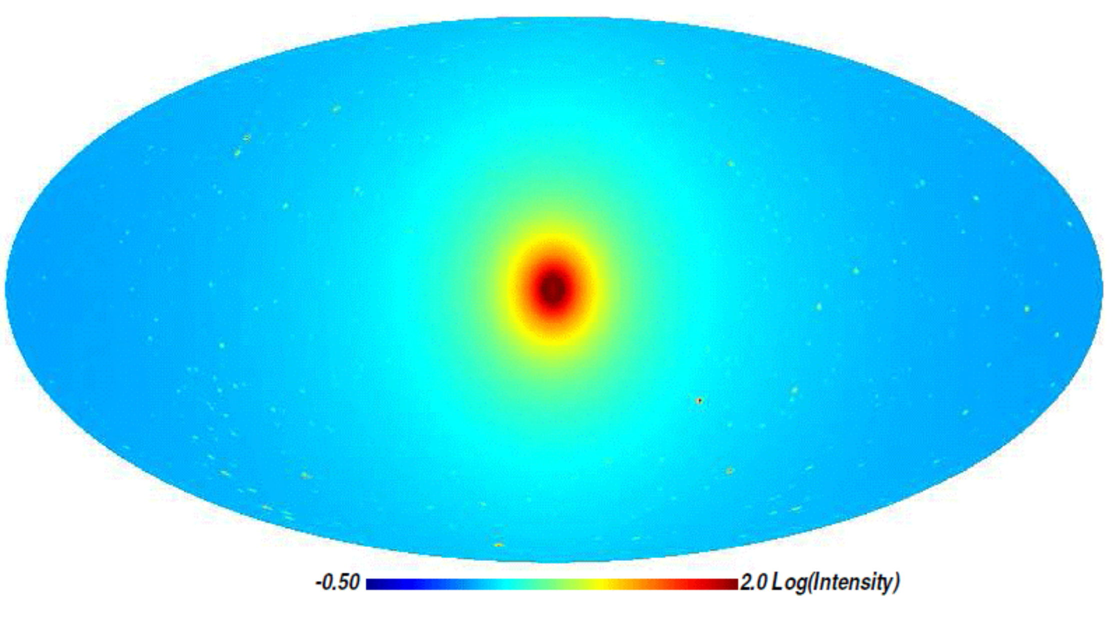


FIG. 2: Electron spectra from previous experiments (see [3] for sources listed in legend) and the results from the Fermi LAT (red circles with error bars), with systematic errors represented by the gray band. Dashed blue line shows spectrum from a conventional diffusive model [10]. (Illustration: adapted from Abdo *et al.*[3])

Springel et al. 2008, Nature



- Used NFW function for the density profile (PW ∼-1 at r→0)
- Annihilation signal is smooth
- Almost no contribution from micro-halo (sub halo)

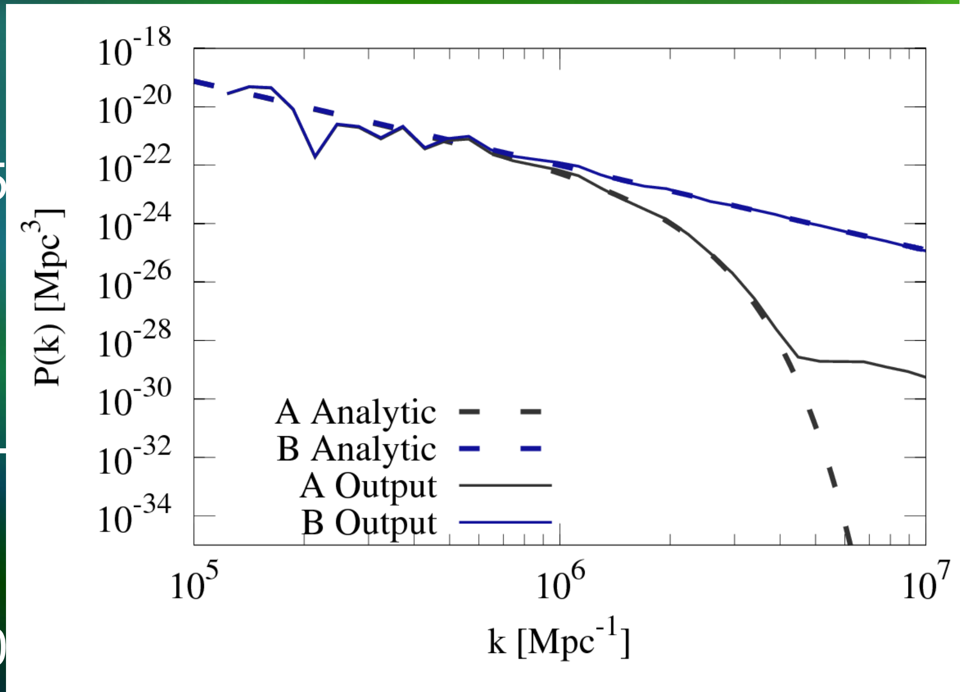
The results must be totally different, if density profiles are different from NFW

Objectives

- Determine the density structure of micro-halo by the simulations with ever highest resolution.
  - Resolve central cores of the smallest halos (it has not been done yet).
  - In previous works, NFW function is assumed, though it is likely to be different from NFW.
- Estimate the survival rate of micro-halos in the Galaxy
- Evaluate the gamma-ray flux from annihilation of DM particles.

Models simulated

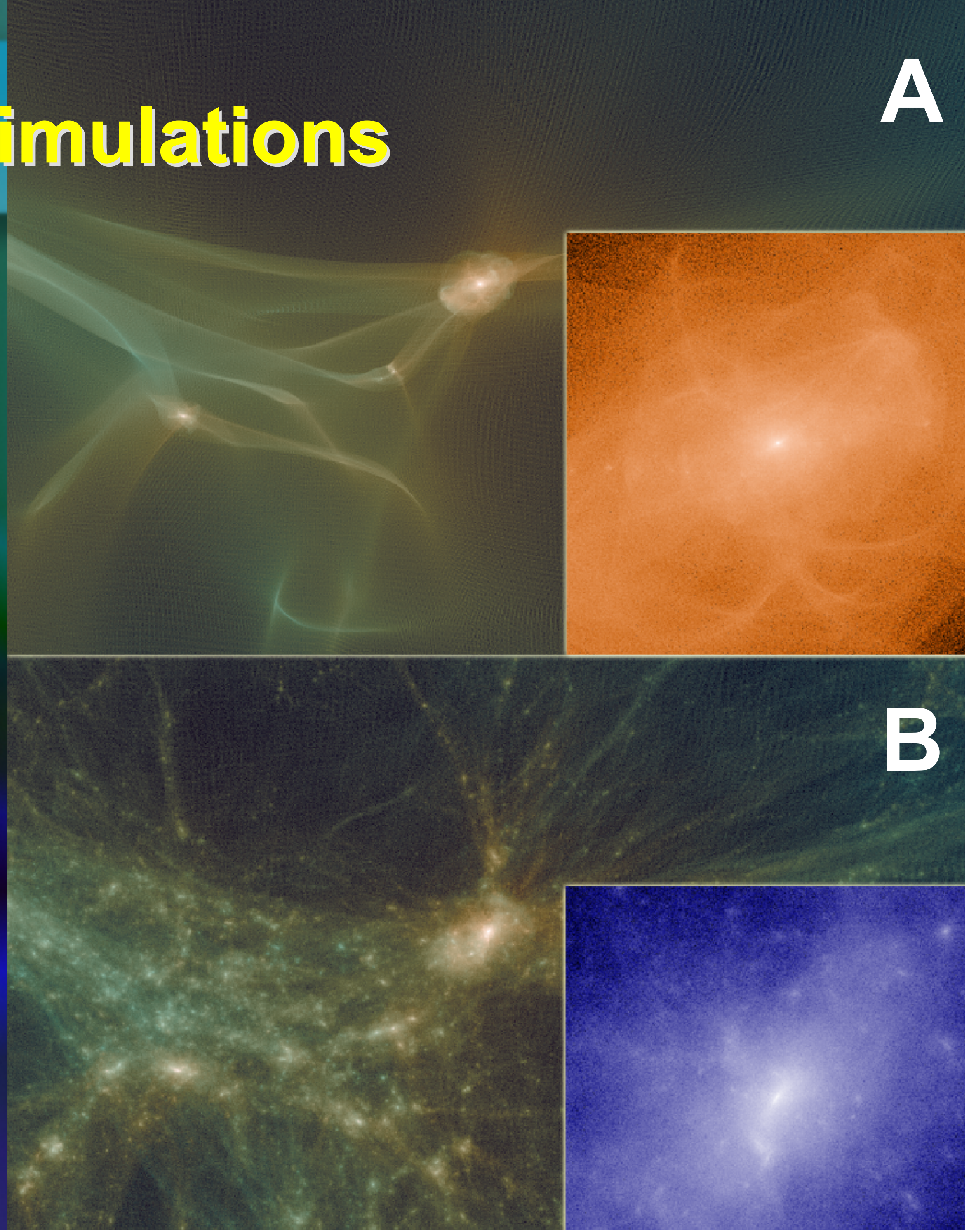
- Ω=0.3、h=0.71、σ_8=0.9
- Red shift at the start of the simulation: 5
- Number of particles= 1024^3
- Size of simulation BOX: 30 commoving-
- Mass resolution: 9.4×10^{-13} Msun
  - 100 times better than Diemand+200
- Softening parameter: 5×10^{-5} pc = 10AU
  - 20 times finer than Diemand+2005
- Simulation Code: GreeM
  (Ishiyama, Fukushige and Makino 2009, Parallel TreePM)



A : damping あり(Green+ 2004)
100GeV のニュートラリーノ
B : P(k) ∝ k^{-3}

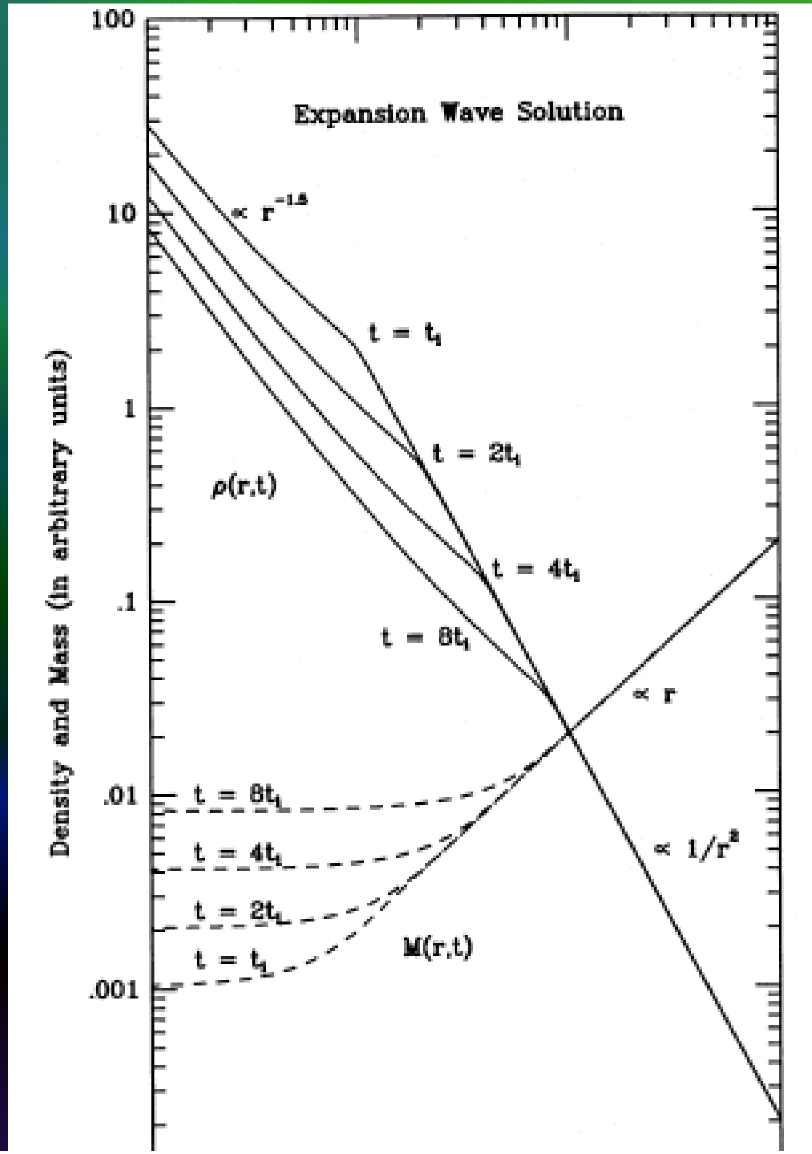
Snapshot of the simulations

- DM distribution at z=31
- above : with free streaming damping (realistic)
- bellow: without free streaming damping (comparison)
- Nature of cores
  - mass ~10^{-6} Msun
  - size ~10^{-2} pc
  - Velocity dispersion ~1m/s



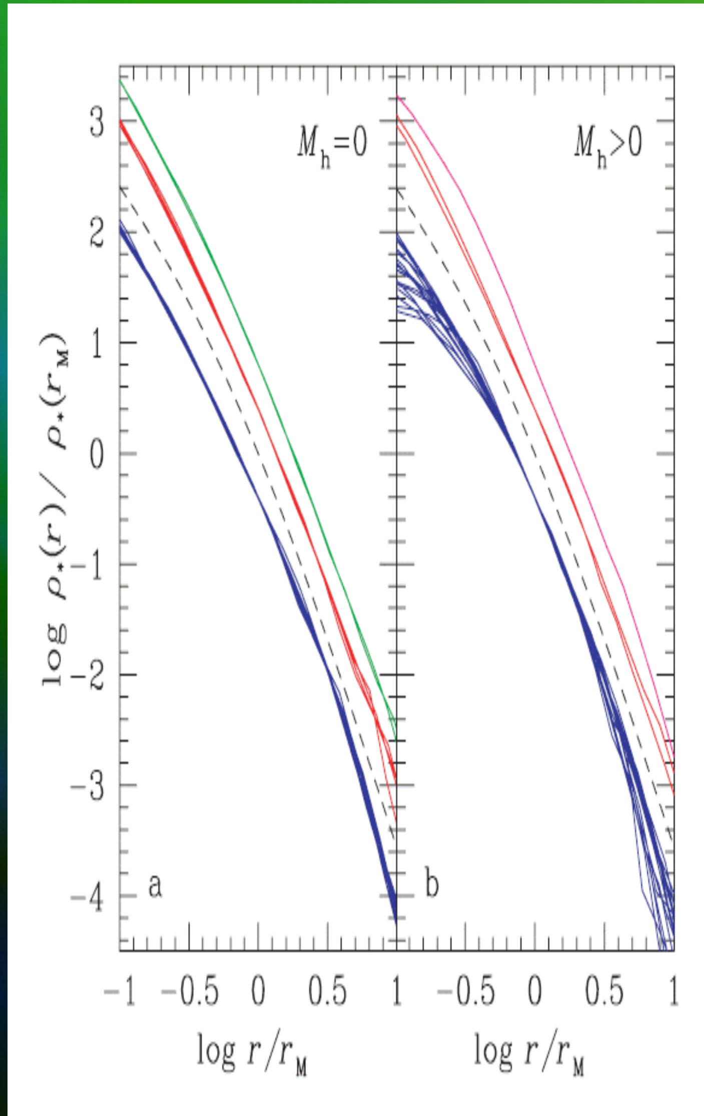
Density Structure of Zero Pressure Material (=Cold Dark Matter)

- Ever Lasting Free Fall
- Scale-free nature of Gravity
- Self-Similar Solution
- Inner region tends to $\rho \propto r^{-3/2}$ in all the possible cases
  - Silk and Suto 1988
  - Suto and Silk 1988



Core Structure

- Power law with an index of -1.5
- The results of high resolution cold collapse simulation also shows the asymptotic convergence to -1.5 (Nipoti+ 2006)
- Highest density is determined by the maximum phase space density of (Liouville Theorem)
- We can safely assume to be the maximum phase space density to be that at the kinematic decoupling
  - ~ 10^{15} Msun pc^{-3} $(km/s)^{-3}$

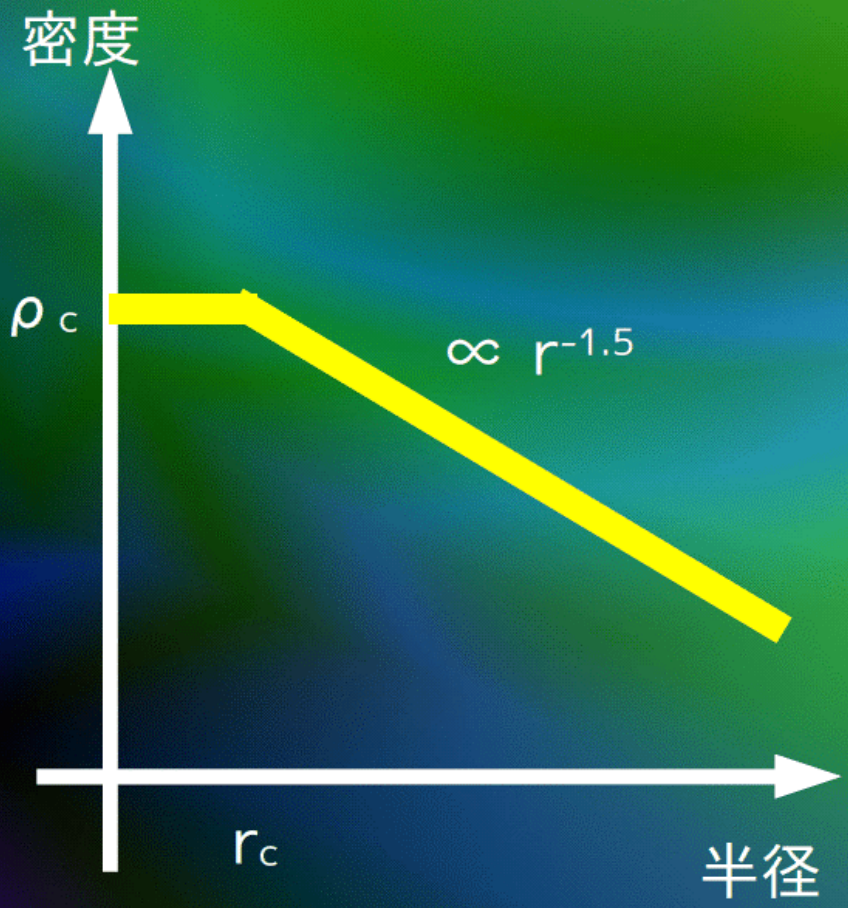


Actual density profile from these results

$$\rho(r) = \rho_c (r/r_c)^{-1.5} \quad \text{for} \quad 10^{-3}\text{pc} \geq r \geq r_c$$

$$\rho(r) = \rho_c \text{ for } r < r_c$$

$r_c \sim 10^{-5}$ pc
$\rho_c \sim 2 \times 10^4$ Msun pc^{-3}



- Tidal radius in the Galaxy

  0.082 (R/10kpc)$^{4/3}$ pc

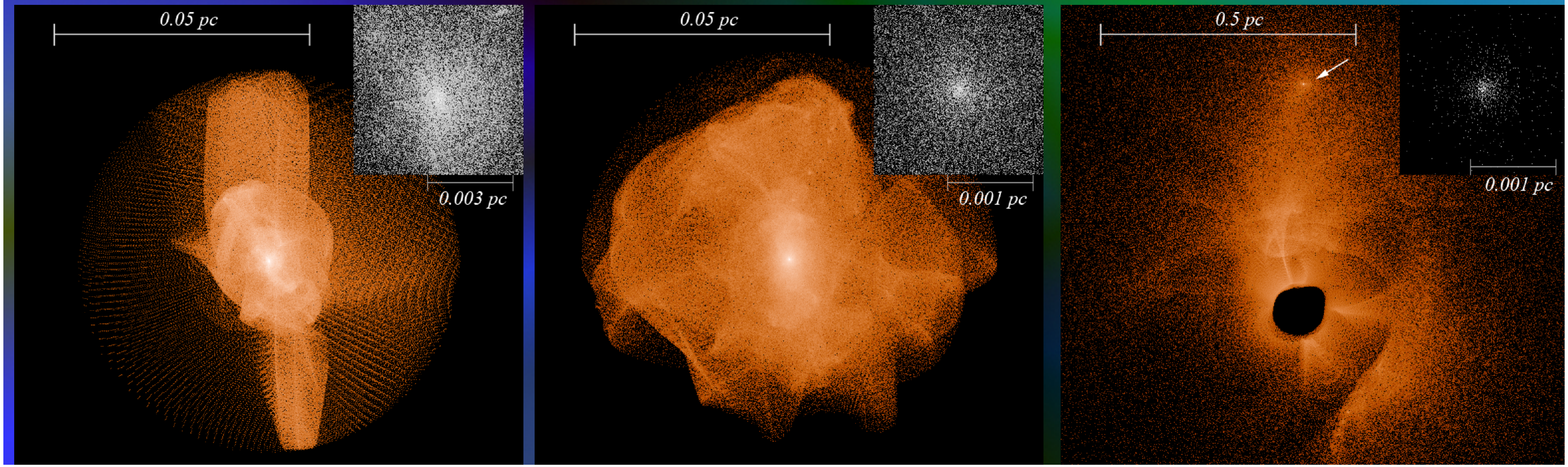
  0.06 pc at solar neighborhood

  3.8×10^{-3} pc at 1kpc

Tidal disruption is not significant except

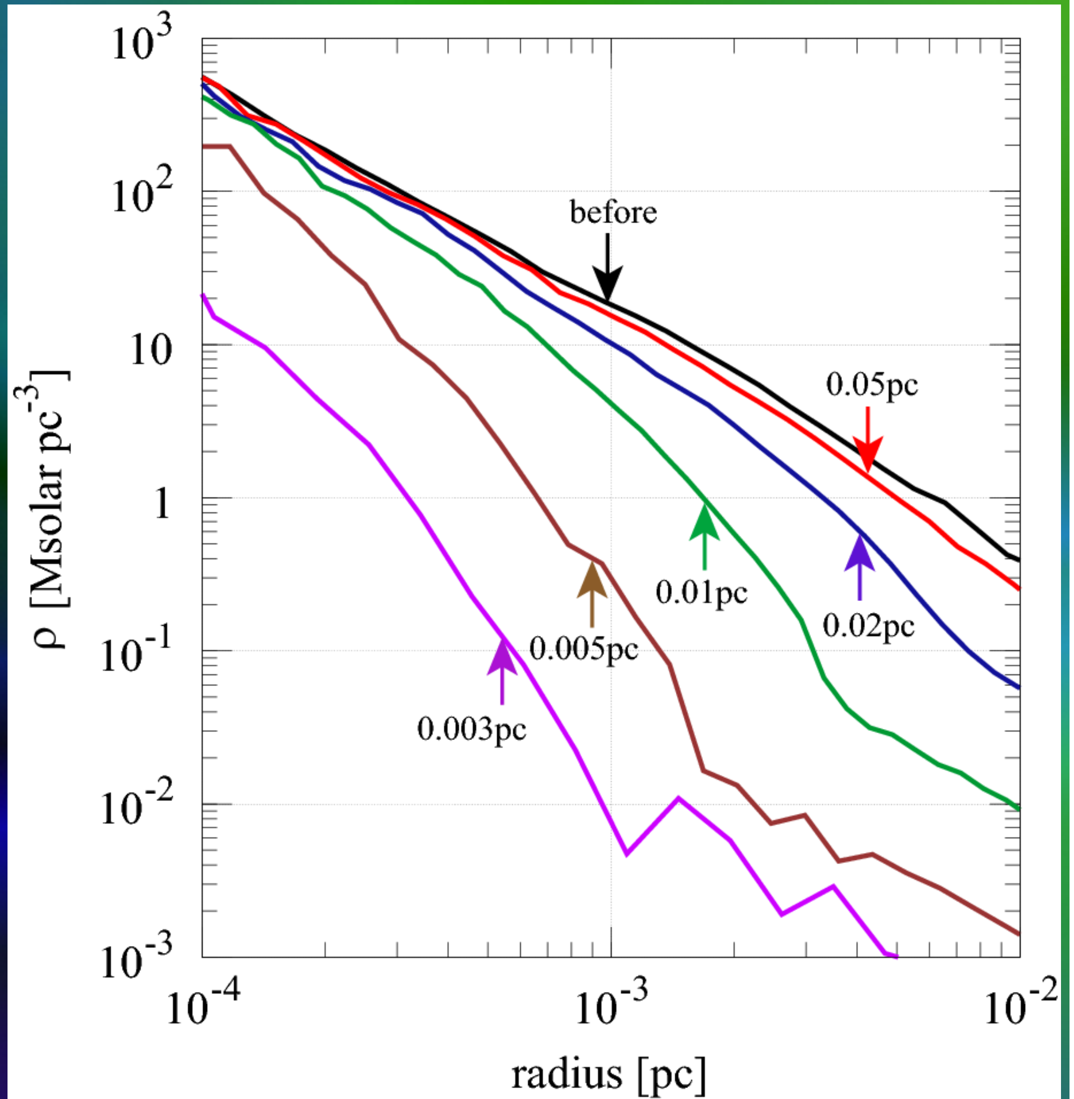
Disruption by the Star collision

- Expected impact parameter b~10^{-2}pc at solar neighborhood
- Core survives the stellar collisons, since it is much smaller than impact parameter



Profile changes by a stellar collision

- Core survives even if impact parameter as small as 10^{-3} pc
- Perfect disruption requires for the case of ~10^{-5} pc



Gamma-rays from one micro-halo

- Annihilation signal is proportional to the square of the local density

$$L(<r) \sim \int_0^r \rho^2 dV \\ \sim \ln(r/r_{\rm c})\rho_{\rm c}^2 r_{\rm c}^3$$

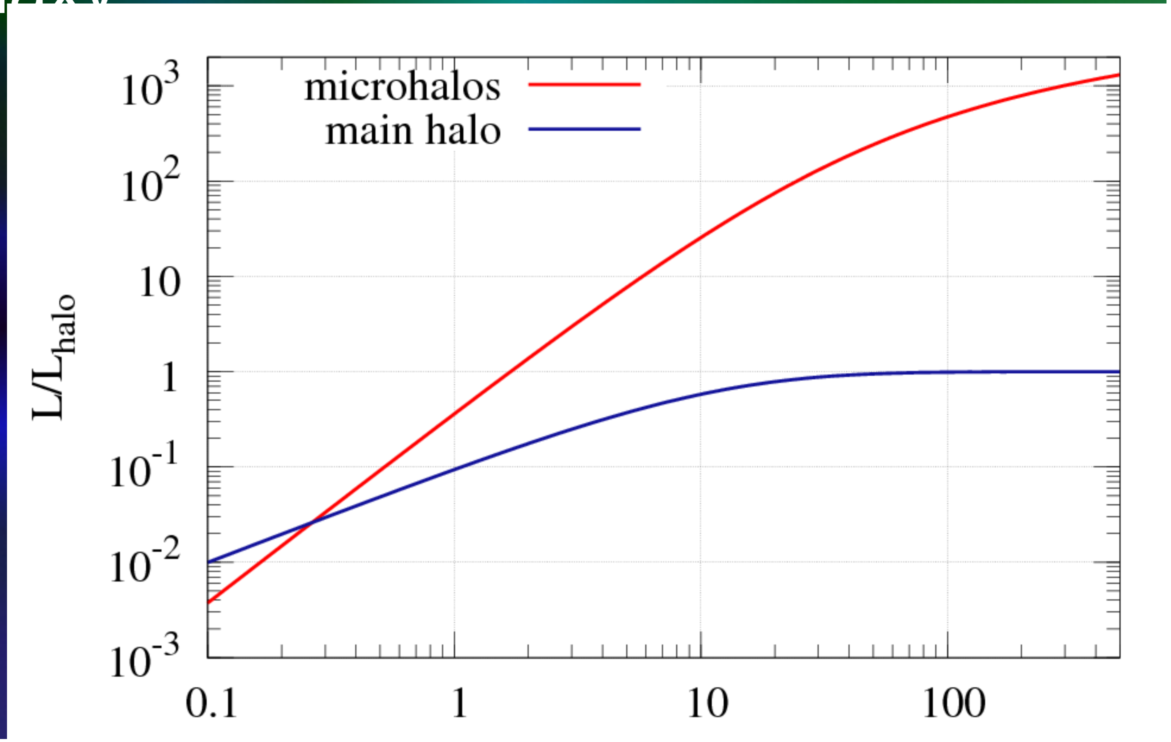
- Gamma-ray luminosity of a core does not change so much, if outskirt is heavily stripped
  - 50% of the total flux comes from inner 10%
  - 10% of the total flux comes from inner 1%

Micro-halo distribution in the Galaxy

- ~10^{16} micro-halos exists if all of them survived through the history of the Galaxy
- ~100 pc^{-3} in solar neighborhood
- In the regions where disruption is not important, the density distribution must be the same as the background dark matter.
  - It is true except very center of the Galaxy (within 1pc)

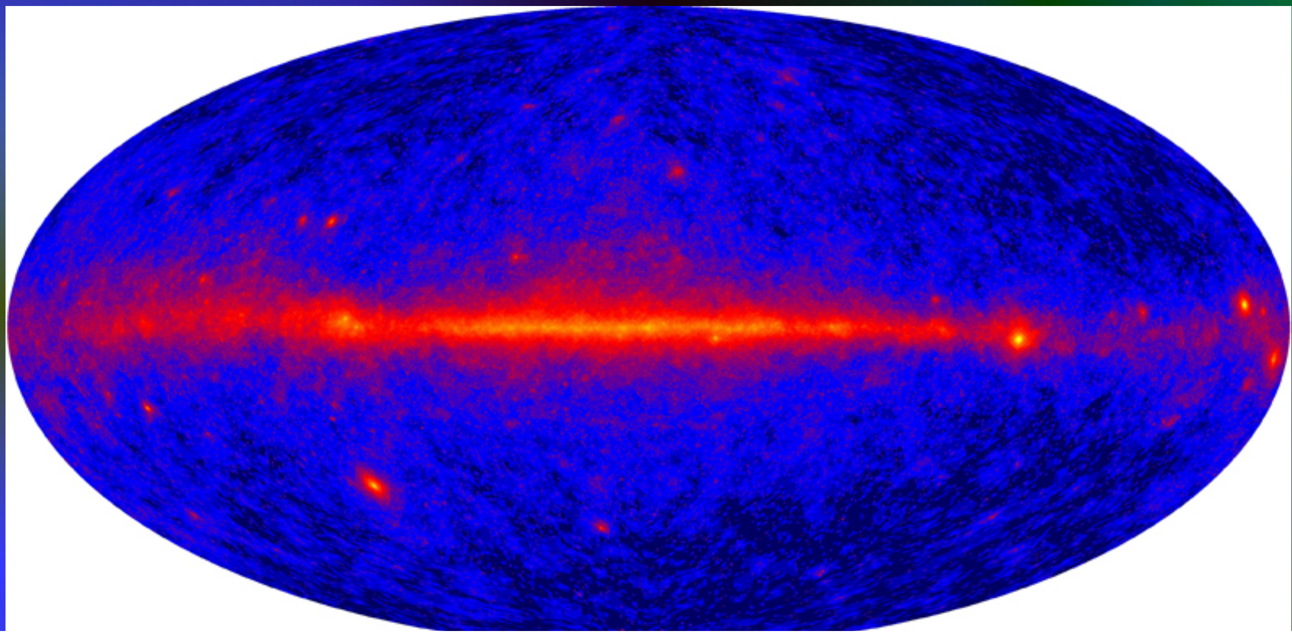
Profile of the gamma-ray flux

- All the micro-halos survives.
  - Same as NFW function
- Boost factor ~20 at solar neighborhood
- ~1000 for the entire galaxy



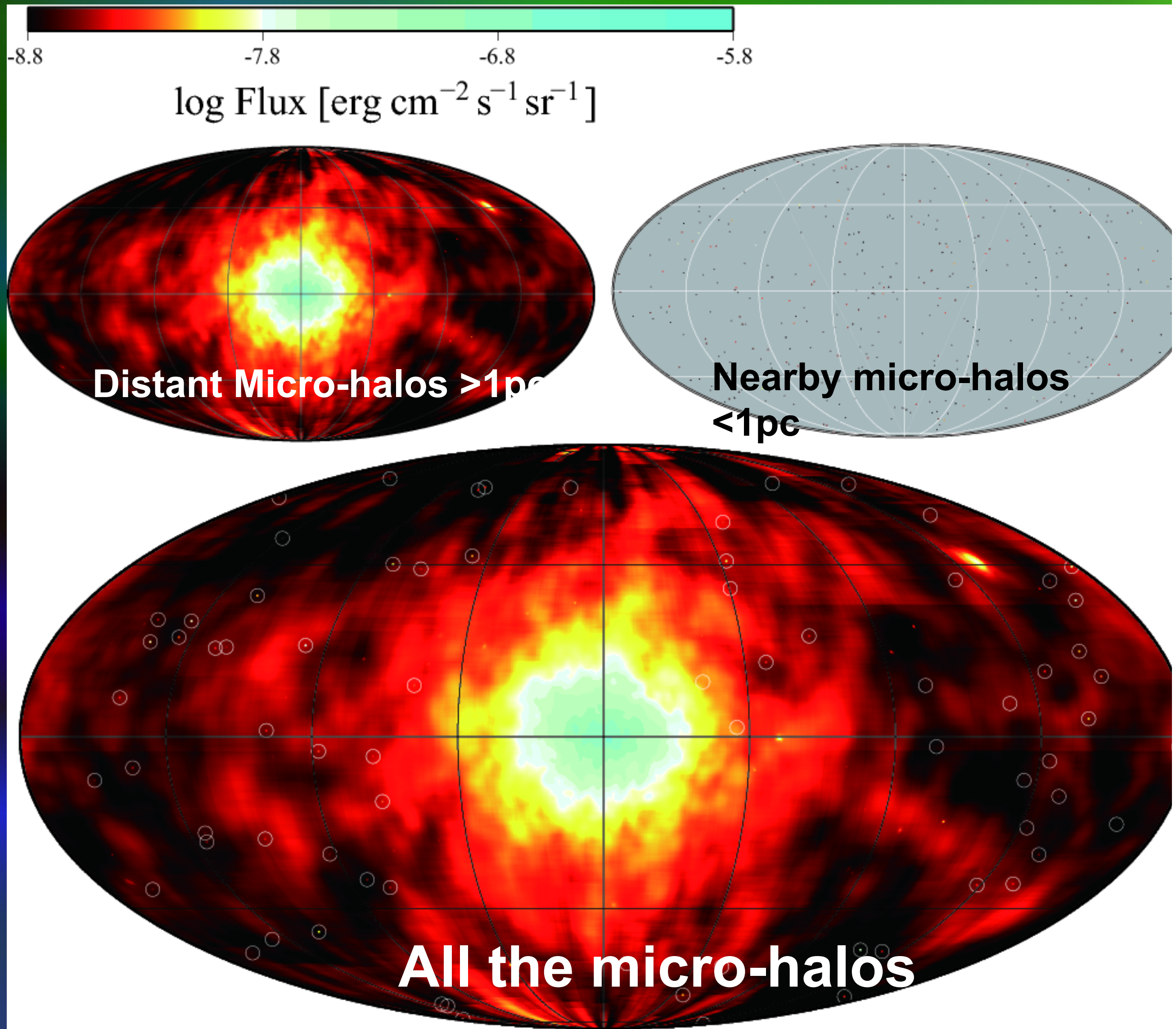
How would Fermi observe?

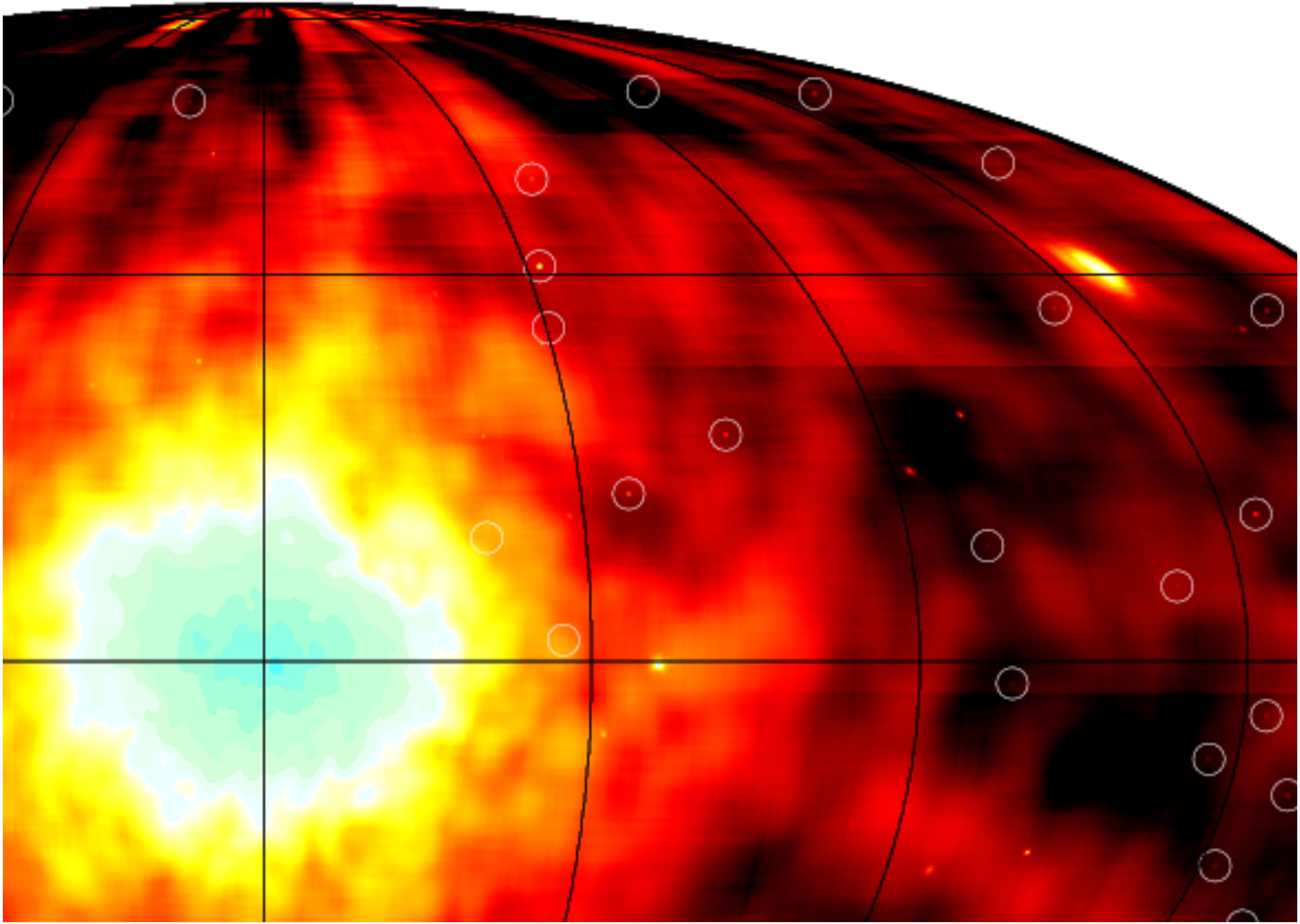
- Only micro-halo component take into account, since it is dominant in gamma-ray flux in the entire galaxy



All SKY MAP

- Galactic Center in the brightest source in the entire sky.
- Outer sub-halos are also prominent in the MAP.
- Individual micro-halos nearby can be observed as marginally resolved point sources.
  - Proper motion





Results of Fermi first year

- Tibaldo, Fermi/LAT Collaboration, 2009

  Observed gamma-ray spectra are consistent with the known sources beside of annihilation.

- Vitale, Morseli, Fermi/LAT Collaboration, 2009

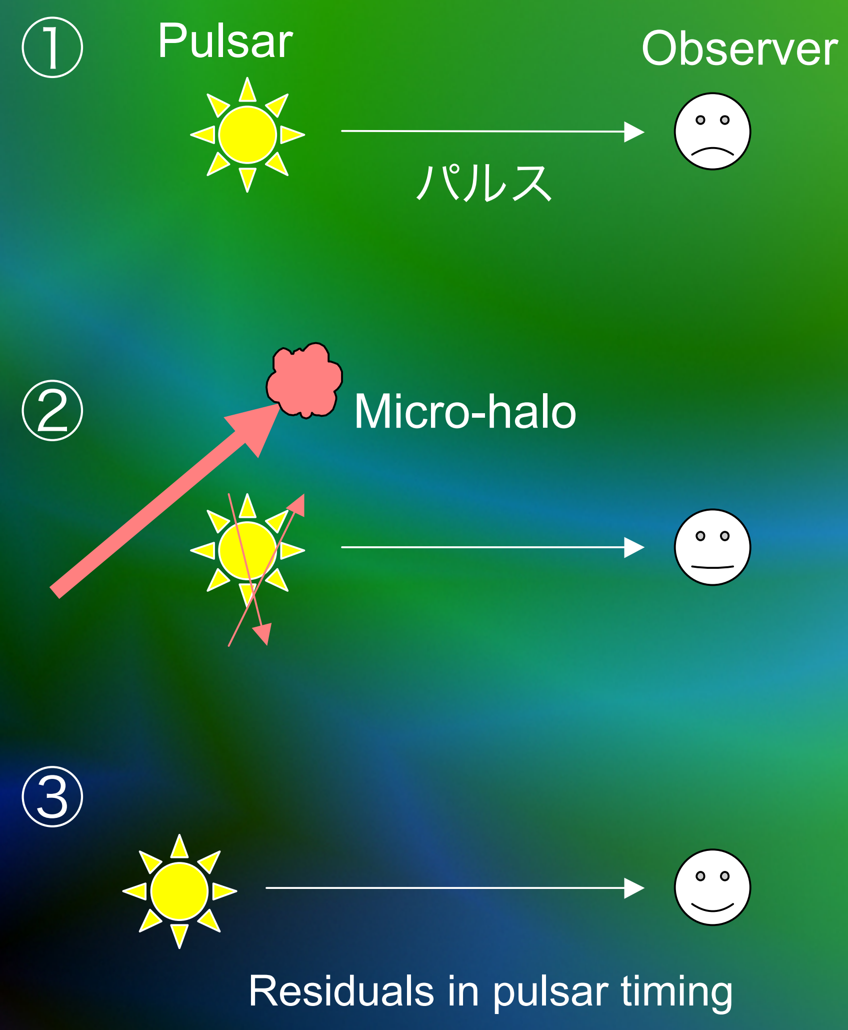
  Spectrum of the galactic center can be almost explained by the conventional models, though there are residuals that cannot be explained so far.

Huge proper motions are the key to distinguish them from the known sources

Perturbation to millisecond pulsar (MSPs)

- Micro-halo accelerates MPs when they pass nearby
- This makes the residuals in pulsar timing analysis
- MPs near the galactic center suffers from many such perturbation, since they are dense in number there
- ~5ns in 5 years observation
- A micro-halo moves ~1000AU in this 5 years

observable by PPTA



Summary

- Density profiles of the Earth-mass micro-halo is a single power law with -1.5.
  - Smallest micro-halos are different from other halos in density structure.
- The core survives through tidal disruption and stellar collision, since they are so dense (~10^4 Msun pc^{-3})
- Micro-halo enhance gamma-ray signal of DM signal by a large factor.
  - Individual halo shines in gamma-ray
  - Micro-halos nearby could be observed as point-like sources with huge proper motions.
- The perturbation onto millisecond pulsars could be observed by PPTA
- Direct DM signals may fluctuate in the time scale of month to year.