# SUSY Dark Matter Annihilation in the Galactic halo

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Moscow – 2013

# SUSY neutralino DM detection

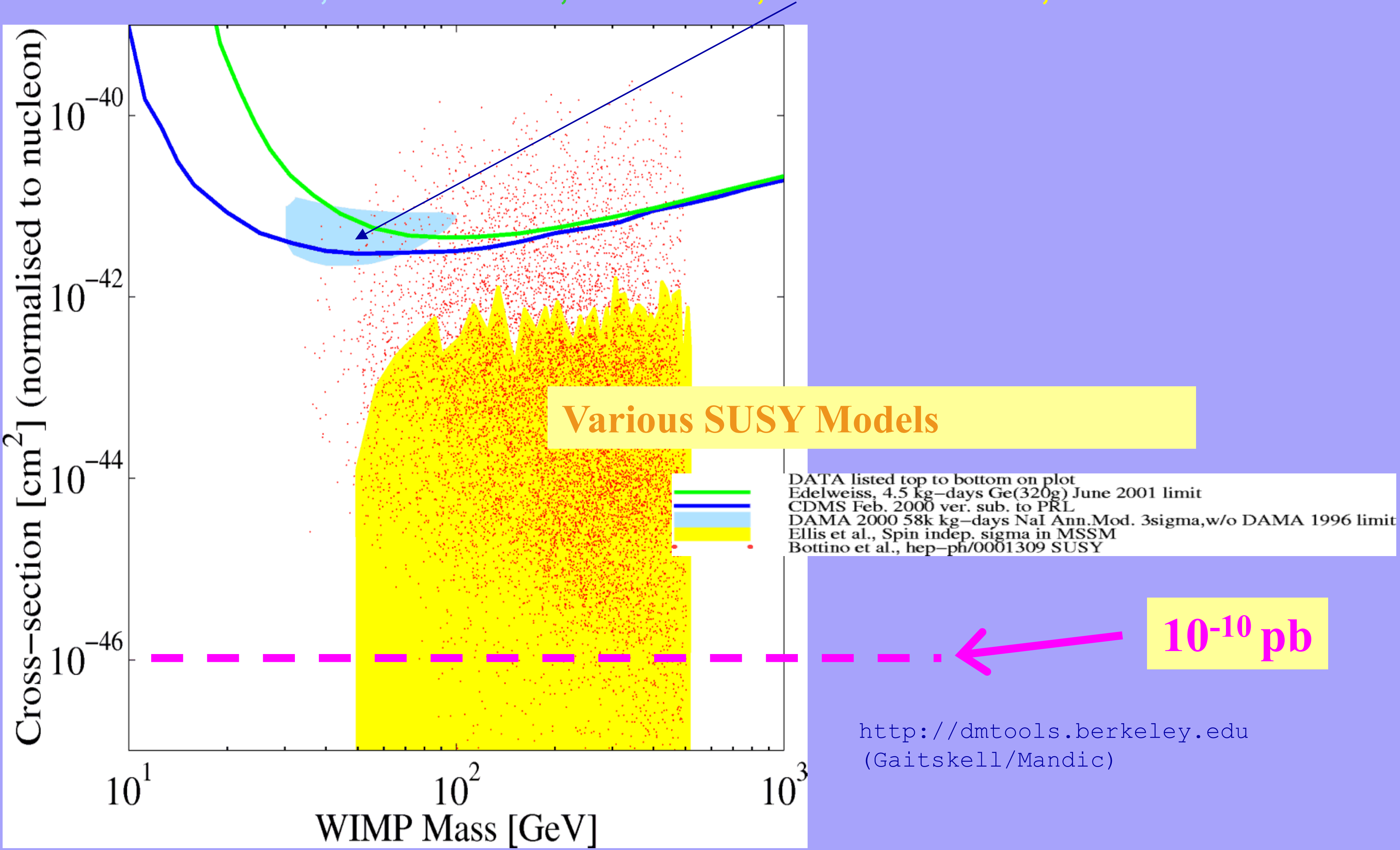
- Direct neutralino $\chi$ detection
  - Recoil detectors: DAMA $m_\chi \simeq 60$ GeV?, Edelweiss, CDMS, XENON
  - LHC $m_\chi = \mathcal{O}(100)$ GeV?

- Indirect $\chi$ detection
  - $\chi\ \chi$ annihilation in the galactic haloes
  - WIMP annihilation in the Sun, Earth, Moon…
  - …

- Gamma-rays, positrons, antiprotons, neutrino
- Halo structure: DM profile $\rho_{halo}(r)$ – NFW, Moore, Einasto…
- Halo clumpiness: mass fraction of clumps $\xi$
- Minimal mass of clumps $M_{min}$
- Clump distribution function $\xi(M_{cl}, \rho_{cl}, r)$

# Direct DM detection

Experiments: CDMS, CRESST, CUORE, **DAMA**, EDELWEISS, EUREKA, PICASSO, XENON, XMASS-DM, ZEPLIN…



**Various SUSY Models**

**$10^{-10}$ pb**

http://dmtools.berkeley.edu
(Gaitskell/Mandic)

# Neutralino as WIMP

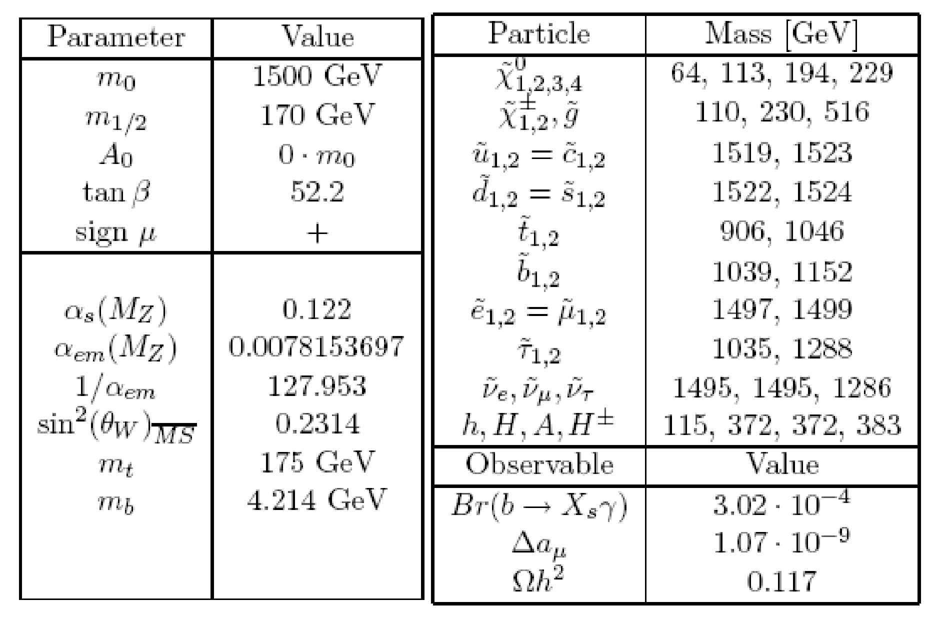
## $\chi$ is LSP in mSUGRA: MSSM with SUGRA inspired breaking

spin 1/2 Majorana particle: $|\chi\rangle = N_1|B_0\rangle + N_2\,|W_3\rangle + N_3\,|H_1\rangle + N_4\,|H_2\rangle$

$B_0$, $W_3$ – gauginos, $H_1$, $H_2$ - higgsinos

$\chi$ is almost pure bino: $(N_1,N_2,N_3,N_4) = (0.95,-0.10, 0.27,-0.09)$

Only 5 parameters:

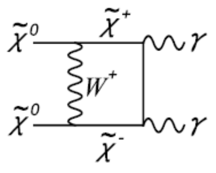


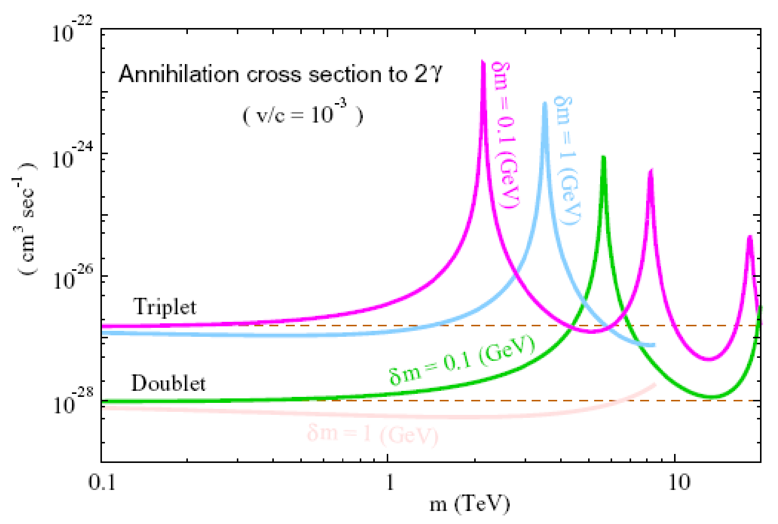
| Parameter | Value |
|---|---|
| $m_0$ | 1500 GeV |
| $m_{1/2}$ | 170 GeV |
| $A_0$ | $0 \cdot m_0$ |
| $\tan\beta$ | 52.2 |
| sign $\mu$ | + |
| $\alpha_s(M_Z)$ | 0.122 |
| $\alpha_{em}(M_Z)$ | 0.0078153697 |
| $1/\alpha_{em}$ | 127.953 |
| $\sin^2(\theta_W)_{\overline{MS}}$ | 0.2314 |
| $m_t$ | 175 GeV |
| $m_b$ | 4.214 GeV |

| Particle | Mass [GeV] |
|---|---|
| $\tilde{\chi}^0_{1,2,3,4}$ | 64, 113, 194, 229 |
| $\tilde{\chi}^{\pm}_{1,2}, \tilde{g}$ | 110, 230, 516 |
| $\tilde{u}_{1,2} = \tilde{c}_{1,2}$ | 1519, 1523 |
| $\tilde{d}_{1,2} = \tilde{s}_{1,2}$ | 1522, 1524 |
| $\tilde{t}_{1,2}$ | 906, 1046 |
| $\tilde{b}_{1,2}$ | 1039, 1152 |
| $\tilde{e}_{1,2} = \tilde{\mu}_{1,2}$ | 1497, 1499 |
| $\tilde{\tau}_{1,2}$ | 1035, 1288 |
| $\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$ | 1495, 1495, 1286 |
| $h, H, A, H^{\pm}$ | 115, 372, 372, 383 |
| **Observable** | **Value** |
| $Br(b \to X_s\gamma)$ | $3.02 \cdot 10^{-4}$ |
| $\Delta a_\mu$ | $1.07 \cdot 10^{-9}$ |
| $\Omega h^2$ | 0.117 |

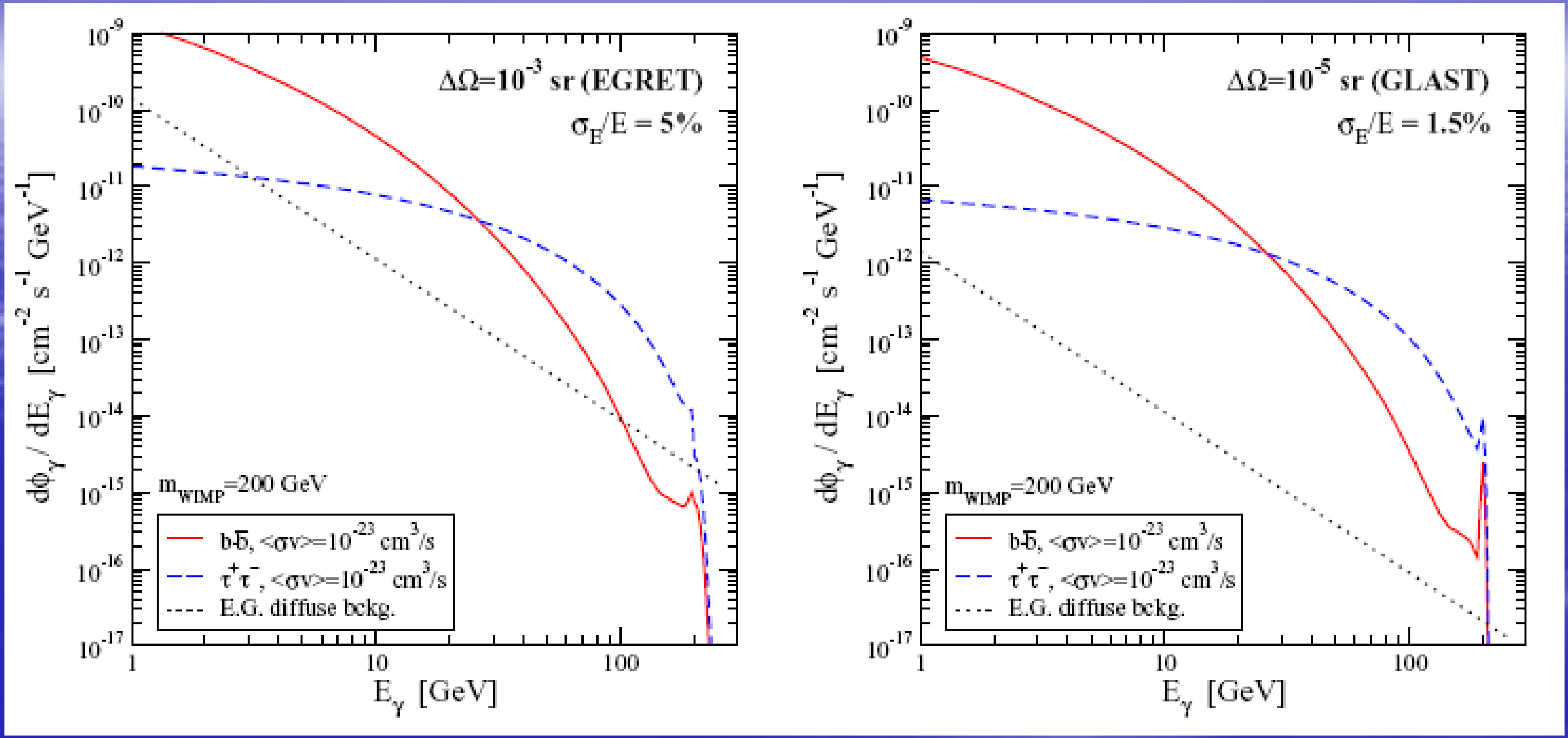
Dominant annihilation into quark pairs

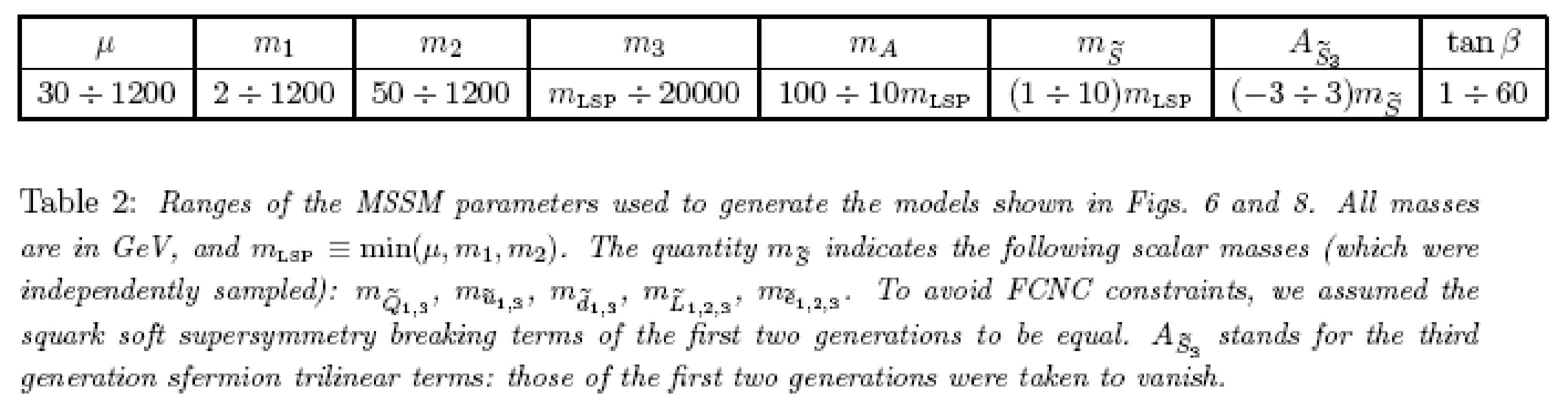
Annihilation to γγ is suppressed by a loop factor





# Photon spectra of SUSY $\chi\chi$ annihilation





| $\mu$ | $m_1$ | $m_2$ | $m_3$ | $m_A$ | $m_{\tilde{S}}$ | $A_{\tilde{S}_3}$ | $\tan\beta$ |
|---|---|---|---|---|---|---|---|
| $30 \div 1200$ | $2 \div 1200$ | $50 \div 1200$ | $m_{\rm LSP} \div 20000$ | $100 \div 10 m_{\rm LSP}$ | $(1 \div 10) m_{\rm LSP}$ | $(-3 \div 3) m_{\tilde{S}}$ | $1 \div 60$ |

Table 2: *Ranges of the MSSM parameters used to generate the models shown in Figs. 6 and 8. All masses are in GeV, and* $m_{\rm LSP} \equiv \min(\mu, m_1, m_2)$. *The quantity* $m_{\tilde{S}}$ *indicates the following scalar masses (which were independently sampled):* $m_{\tilde{Q}_{1,3}}$, $m_{\tilde{u}_{1,3}}$, $m_{\tilde{d}_{1,3}}$, $m_{\tilde{L}_{1,2,3}}$, $m_{\tilde{e}_{1,2,3}}$. *To avoid FCNC constraints, we assumed the squark soft supersymmetry breaking terms of the first two generations to be equal.* $A_{\tilde{S}_3}$ *stands for the third generation sfermion trilinear terms: those of the first two generations were taken to vanish.*

Profumo & Kamionkowski, 2006

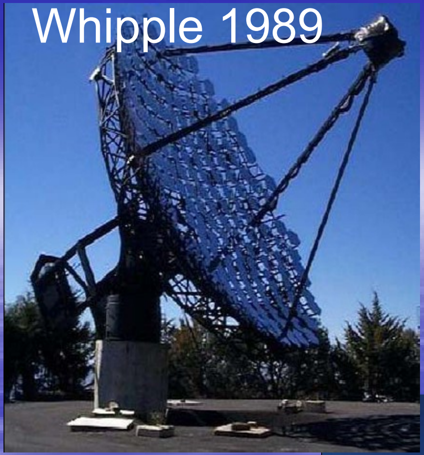
Monochromatic gamma rays?

# Boosting factor η~100 is required!

# Clumpiness of DM!

# Small-scale DM clumps in the Galactic halo

# Atmospheric Cherenkov Telescopes


Whipple 1989


CANGAROO III


MAGIC


H.E.S.S. 2002


HEGRA 1997


CELESTE


VERITAS
photomontage

# CACTUS Gamma-Ray Excess from Draco

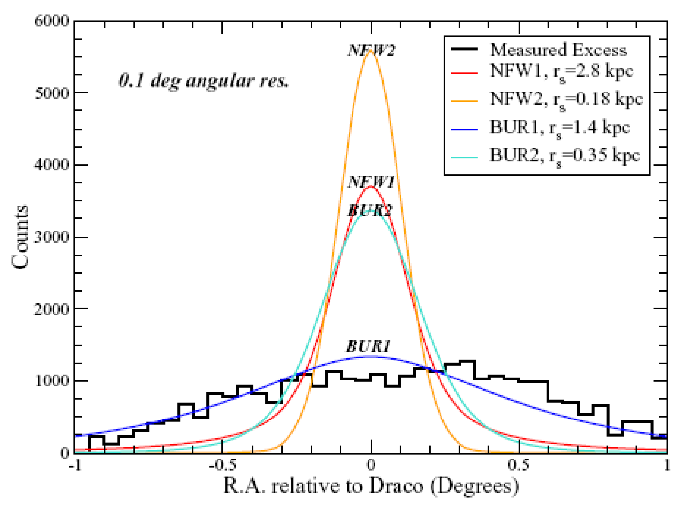
CACTUS: Converted Atmospheric Cherenkov Telescope Using Solar-2

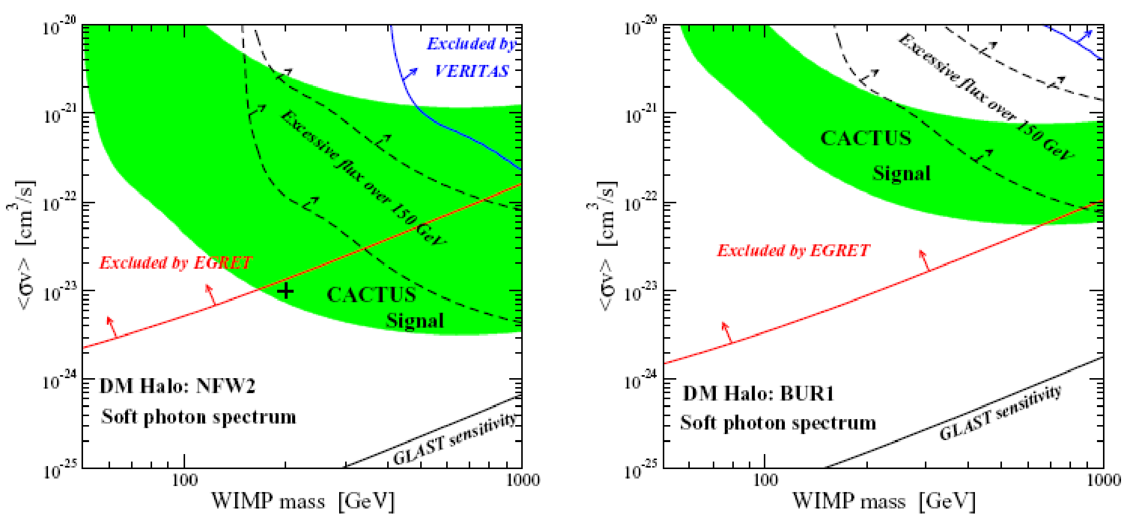
Solar 2 Heliostat Array CACTUS. Barstow, California, effective area $5\times10^4$ $m^2$, 144 heliostats, each 42 $m^2$

Dwarf spheroidal (dSph) galaxies within 100 kpc from the Milky Way center:
Carina, Draco, Ursa Minor and Sextans
Boosting factor ~40 insufficient for detection
Draco heliocentric distance 75.8±0.7±5.4 kpc, R=0.5 kpc


2004

Threshold: 50 GeV
Background: γ-like hadronic EASs, CR electrons, diffuse extragalactic background >50 GeV
Excess ~20% of the background >50 GeV



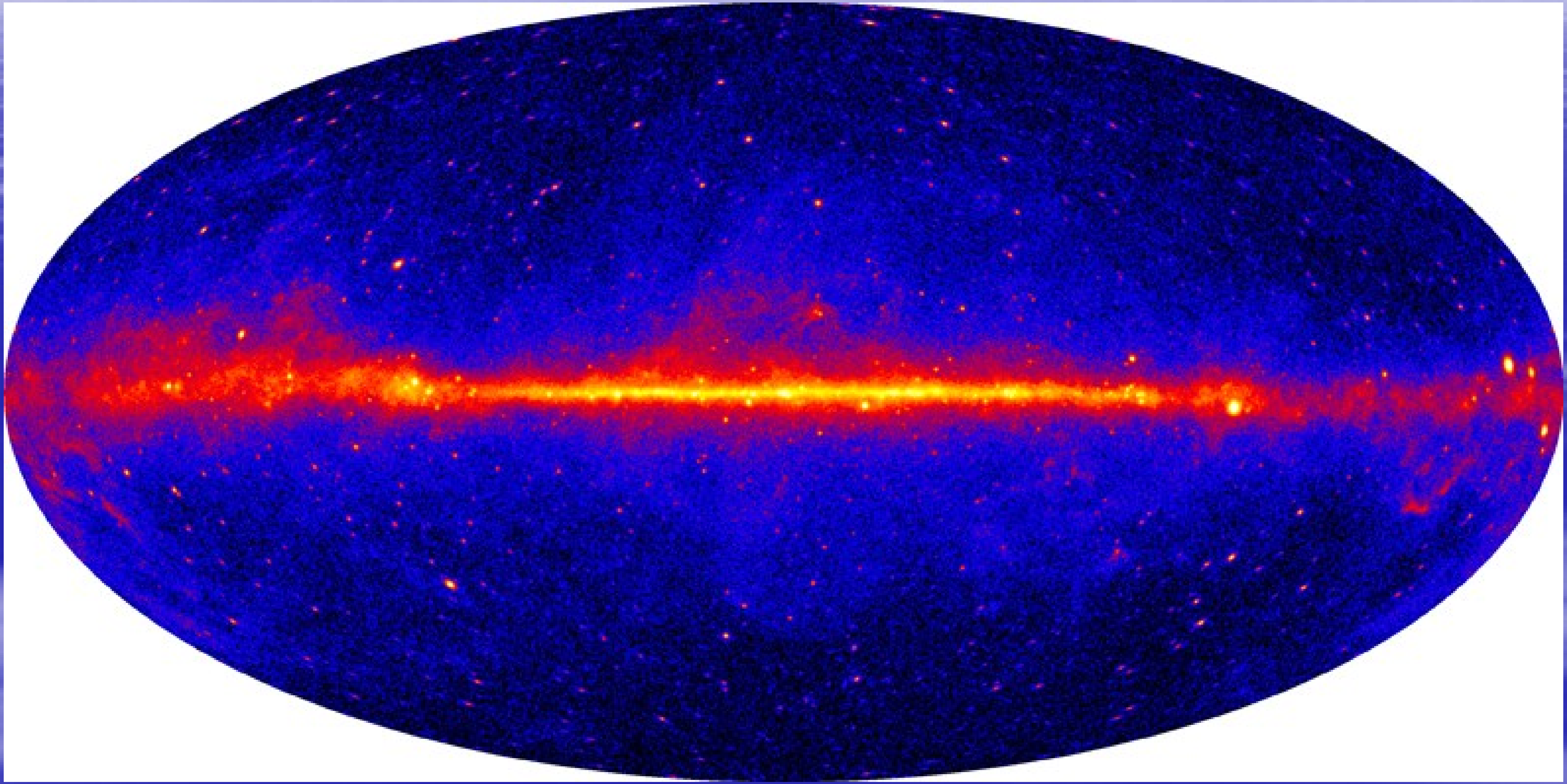


angular resopution Δθ=1°?

Profumo & Kamionkowski, 2006

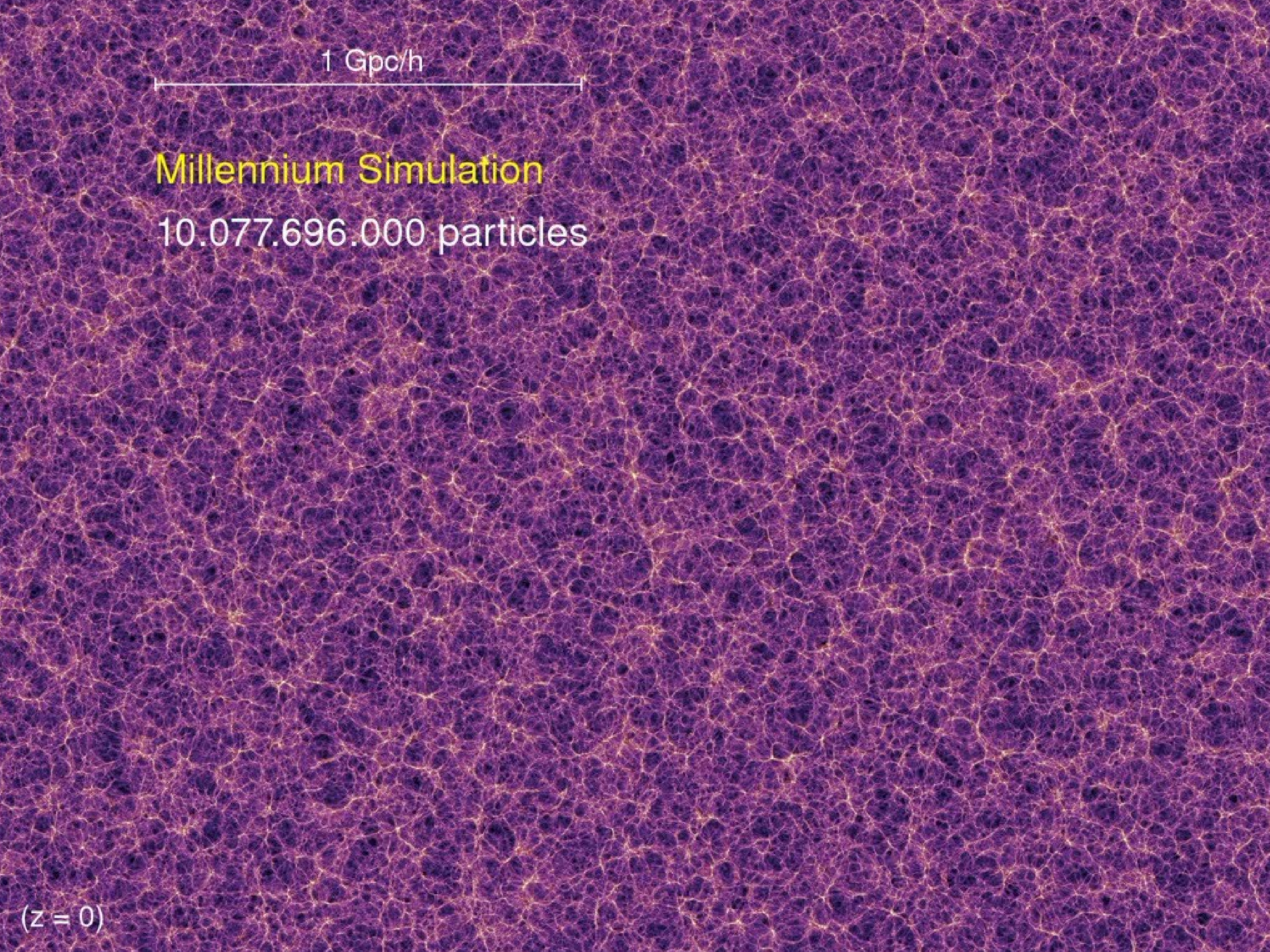
Opportunity for Fermi (formerly GLAST)?

# All-sky view from Fermi



http://fermi.gsfc.nasa.gov/ssc/

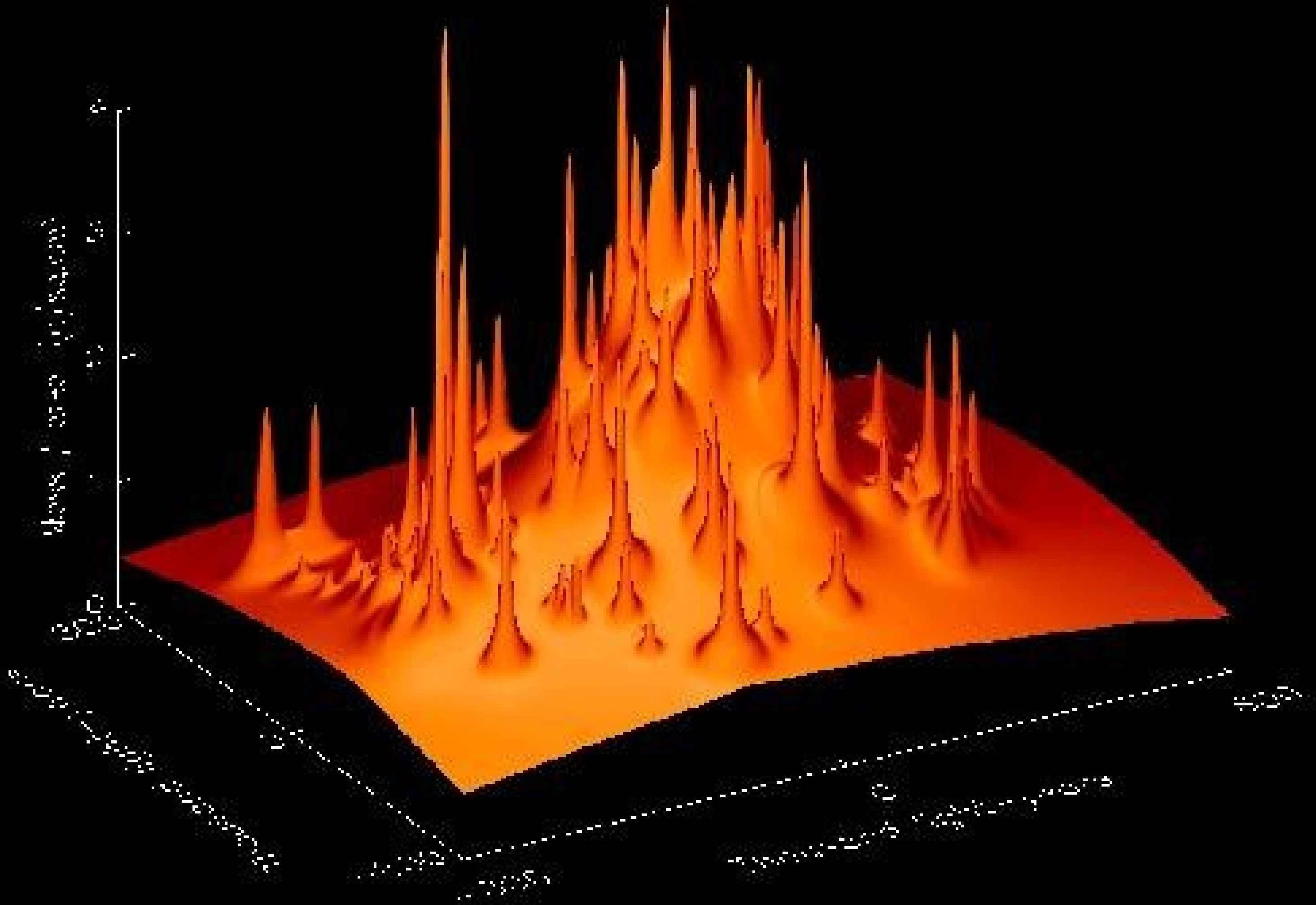
Project Columbia supercomputer (NASA)



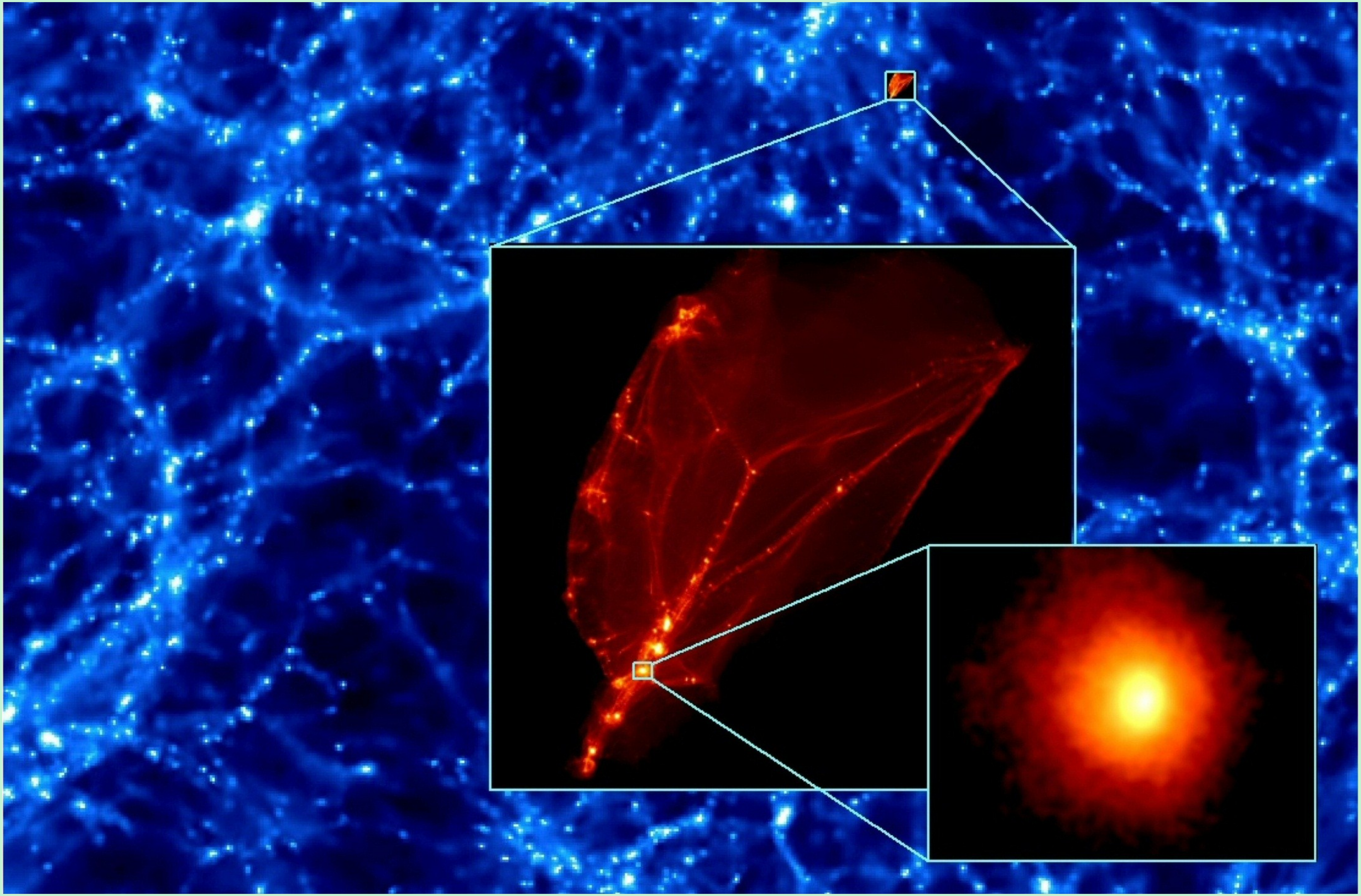
Millennium Simulation

10.077.696.000 particles


z=0.0
80 kpc



Mass reconstruction of the cluster. Note the large, smooth distribution of (apparently invisible) matter.



3 kpc 60 pc 0.024 pc

$N=62\ 10^6$, $m=1.2\ 10^{-10} M_\odot$ $z=350 \rightarrow z=26$, grav. softening of $10^{-2}$ pc

# ⋆ Clumps of Minimal Masses

$$M_{\min} \sim 10^{-12} M_{\odot}$$

Zybin Vysotsky Gurevich 99

$$M_{\min} \sim (10^{-7} - 10^{-6}) M_{\odot}$$

Schwarz Hofmann Stocker 01

Kinetic decoupling

$$\frac{1}{\tau_{rel}} \simeq H(t), \quad n_0(\omega) = \frac{1}{2\pi^2}\frac{\omega^2}{e^{\omega/T}+1}$$

Energy relaxation time

$$\frac{1}{\tau_{rel}} = \frac{1}{E_k}\frac{dE_k}{dt} = \frac{40}{2E_k m_\chi}\int d\Omega \int d\omega\, n_0(\omega) \left(\frac{d\sigma_{el}}{d\Omega}\right)_{fL\chi} (\delta p)^2$$

$$t_d = 3 \cdot 10^{-5} \left(\frac{m_\chi}{100\ \text{GeV}}\right)^{-1/2} \left(\frac{\tilde{M}}{1\ \text{TeV}}\right)^{-2} \left(\frac{g_*}{10}\right)^{-3/4} \text{s}$$

$$T_d = 150 \left(\frac{m_\chi}{100\ \text{GeV}}\right)^{1/4} \left(\frac{\tilde{M}}{1\ \text{TeV}}\right) \left(\frac{g_*}{10}\right)^{1/8} \text{MeV}$$

# ★ Diffusion cutoff of the mass spectrum

Diffusion equation

$$\frac{\partial \delta(\vec{x},t)}{\partial t} = \frac{D(t)}{a^2(t)} \Delta_{\vec{x}} \delta(\vec{x},t)$$

$$\delta_{\vec{k}}(t) = \delta_{\vec{k}}(t_f) \exp\left\{-k^2 C \tilde{M}^4 \left(t^{5/2} - t_f^{5/2}\right)\right\}$$

$$M_D = \frac{4\pi}{3} \rho_\chi(t_d) \lambda_D^3(t_d) = 10^{-13} \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^{-15/8} \left(\frac{\tilde{M}}{1\ \mathrm{TeV}}\right)^{-3/2} \left(\frac{g_*}{10}\right)^{-15/16} M_\odot$$

## ⋆ Free streaming cutoff of the mass spectrum

$$\vec{x} = \vec{f}(\vec{q}, \vec{v}_d, t) = \vec{q} + \int_{t_d}^{t} \frac{\vec{v}(t')\, dt'}{a(t')} = \vec{q} + g(t)\vec{v}_d$$

$$n(\vec{x}, t) = \int d^3 v_d\, \phi(\vec{v}_d) \sum_{\vec{q}_{\ddagger}} n(\vec{q}_*, t_d) \left| \frac{D\vec{f}}{D\vec{q}} \right|_{\vec{q}=\vec{q}_{\ddagger}}$$

$$= \int d^3 v_d\, \phi(\vec{v}_d) \int d^3 q\; n(\vec{q}, t_d)\, \delta^{(3)}(\vec{x} - \vec{f}(\vec{q}, \vec{v}_d, t))$$

$$n_{\vec{k}}(t) = n_{\vec{k}}(t_d) e^{-\frac{1}{2}k^2 g^2(t) \frac{T_d}{m_\chi}}, \qquad g(t) = a(t_d) \int_{t_d}^{t} \frac{dt'}{a^2(t')}$$

## ⋆ Minimal mass of the clump

$$M_{\min} = \frac{\pi^{1/4}}{2^{19/4} 3^{1/4}} \frac{\rho_{\rm eq}^{1/4} t_d^{3/2}}{G^{3/4}} \left(\frac{T_d}{m_\chi}\right)^{3/2} \ln^3 \left\{ \frac{24}{\pi G \rho_{\rm eq} t_d^2} \right\}$$

$$= 10^{-8} \left(\frac{m_\chi}{100\ \text{GeV}}\right)^{-15/8} \left(\frac{\tilde{M}}{1\ \text{TeV}}\right)^{-3/2} \left(\frac{g_*}{10}\right)^{-15/16} M_\odot$$

# ⋆ Density perturbation spectrum $\delta(\vec{r}) = (\rho(\vec{r}) - \bar{\rho})/\bar{\rho}$

Power spectrum $P(k)$:

$$\langle \delta^*_{\vec{k}} \delta_{\vec{k}'} \rangle = (2\pi)^3 P(k) \delta_D^{(3)}(\vec{k} - \vec{k}'),\ \delta_{\vec{k}} = \int \delta(\vec{r}) e^{i\vec{k}\vec{r}}\, d^3r$$

Transfer function $T(k)$ $\qquad P_{\rm eq}(k) = P_p(k) T^2(k)$

Moments of spectrum $P(k)$

$$\sigma^2_{(j)} = \frac{1}{2\pi^2} \int_0^\infty k^2\, dk\, P(k) k^{2j}, \quad \langle T_{ij} T_{ji} \rangle = \frac{2}{3} s^2_{(2)} = \frac{2}{3} (4\pi)^2 G^2 \bar{\rho}^2 \sigma^2_{(0)}$$

Power-law spectrum $P_{\rm eq}(k) \propto k^n, \quad \sigma_{\rm eq}(M) \propto M^{-(n+3)/6}$

Effective power-law index $n = -3 - 6\dfrac{\partial \ln \sigma_{\rm eq}(M)}{\partial \ln M}, \quad n_p \approx 1, \quad \boxed{n_p \approx 1 \pm 0.1}$

$$\sigma_{\rm eq}(M) \simeq \frac{2 \cdot 10^{-4}}{\sqrt{f_s(\Omega_\Lambda)}} \left[ \ln\left(\frac{k}{k_{\rm eq}}\right) \right]^{3/2} \left(\frac{k}{k_{h0}}\right)^{(n_p - 1)/2}$$

# ⋆ Core of a Dark Matter Clump

$$\phi(\vec{r},t) = \phi_0 + \left.\frac{\partial\phi}{\partial r^i}\right|_0 r^i + \frac{1}{6}\,\Phi_{ll}|_0\,\delta_{ij} r^i r^j + \frac{1}{2}\,T_{ij}|_0\, r^i r^j + \ldots$$

$$\Phi_{ij} = \frac{\partial^2\phi(\vec{r})}{\partial r^i \partial r^j}, \quad T_{ij} = \Phi_{ij} - \frac{1}{3}\Phi_{ll}\delta_{ij}$$

Peak height $\nu = \delta_{\rm eq}/\sigma_{\rm eq}(M)$

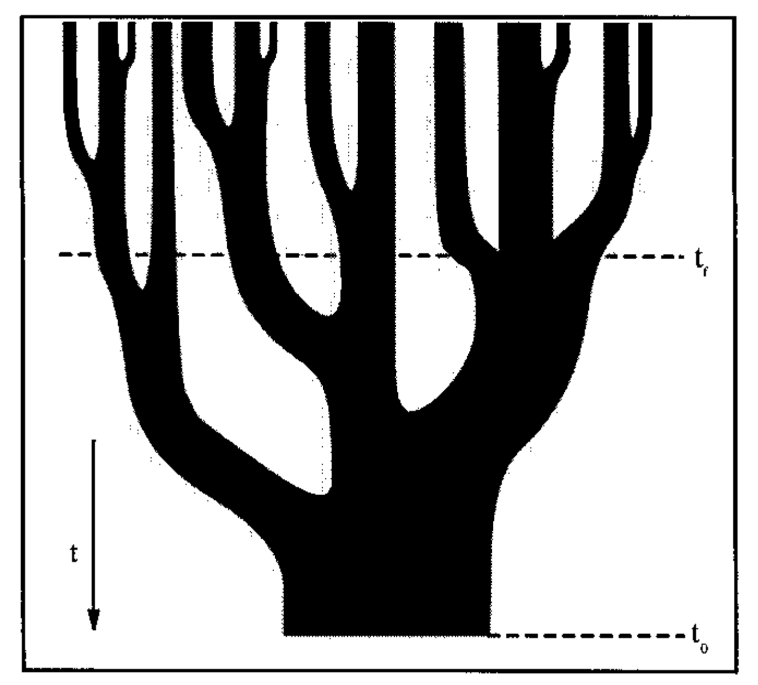
Tidal velocity $\frac{dv_{tid,i}}{dt} = -T_{ij}(t) r^j$

$\boxed{\Delta E \simeq \Delta V}$ $\Delta E \simeq \int d^3r\, \rho_{\rm int}(t_s) v_{tid}^2(t_s)/2, \quad \Delta V \simeq \frac{GMM_c}{R}$

Clump core radius

$$\frac{R_c}{R} \simeq \frac{\pi 2^{5/3} 3^{13/3}}{5^3} G\rho_{\rm eq} t_{\rm eq}^2 \frac{f^2}{\nu^2}(\delta_{\rm eq}) \simeq 0.3\nu^{-2} f^2(\delta_{\rm eq})$$

# Press-Schechter formalism:



`Merger tree'

## Mass function of unconfined clumps

$$\xi_{\rm PS}(t)\,\frac{dM}{M} = \frac{2\delta_c}{\sqrt{2\pi}\,\sigma_{\rm eq}^2 D(t)}\,\frac{d\sigma_{\rm eq}}{dM}\,\exp\left[-\frac{\delta_c^2}{2\sigma_{\rm eq}^2 D^2(t)}\right] dM,$$

$$\delta_c = 3\,(12\pi)^{2/3}/20 \simeq 1.686$$

## HIERARHICAL STRUCTURING

**Press & Schechter 1974**
**Lacey & Cole 1993**

# ⋆ Tidal destruction of clumps in hierarchical model

Clump destruction at $\Delta E \geq |E| \sim GM^2/2R, \quad \delta(M,t_f) = \delta_c$

Number density of unconfined (free) clumps

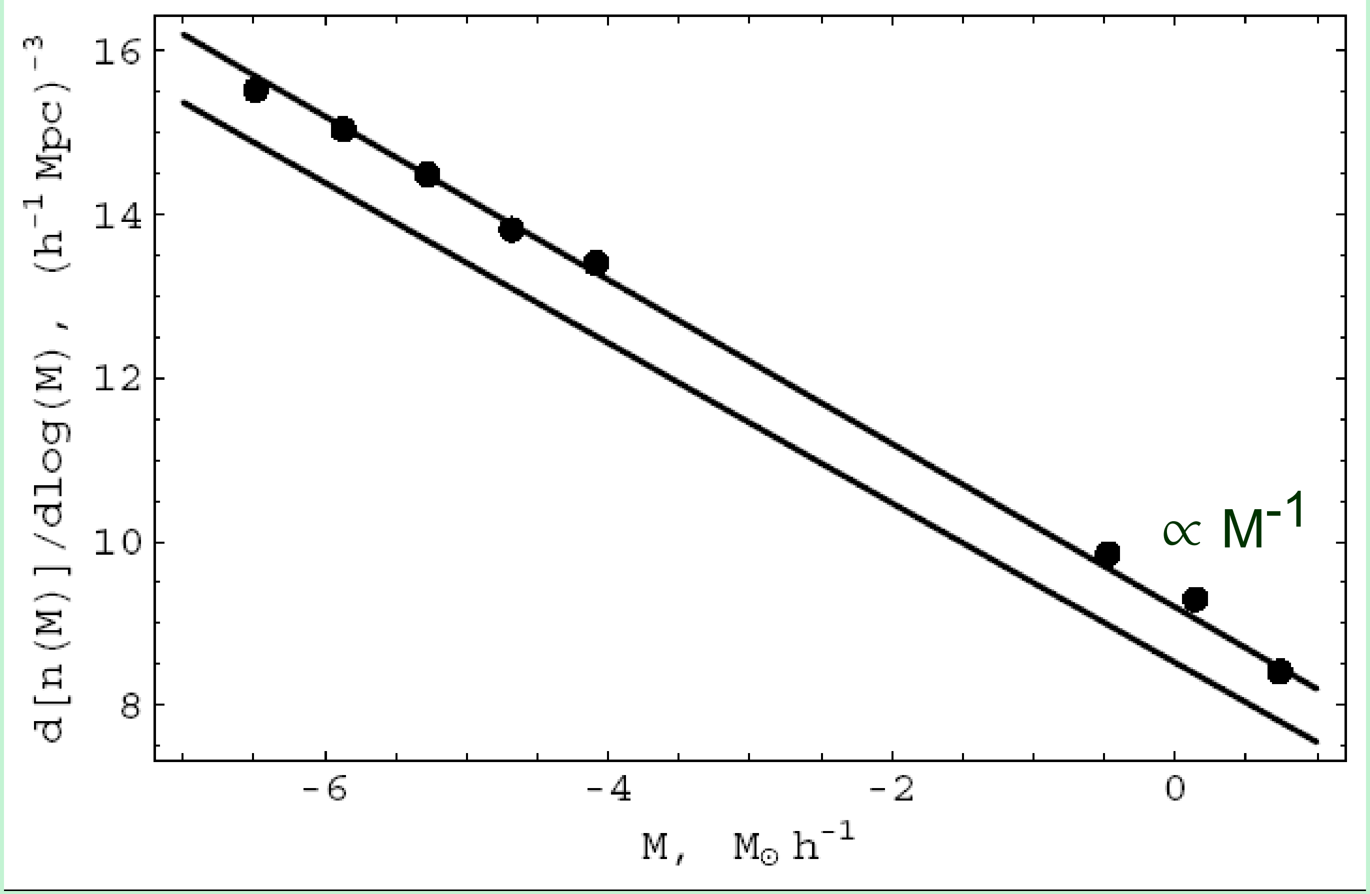
$$\phi_{PS} = \left(\frac{2}{\pi}\right)^{1/2} \frac{\rho}{M} \frac{\delta_c}{D_g(t)\sigma_{\rm eq}^2} \frac{d\sigma_{\rm eq}}{\rm DM} \exp\left[\frac{-\delta_c^2}{2D_g(t)^2\sigma_{\rm eq}^2}\right] dM$$

*Press, Shechter, 1974*

Energy increase during one fly-by

$$\Delta E = \frac{1}{2}\int d^3r\, \rho(r)(v_x - \tilde{v}_x)^2$$

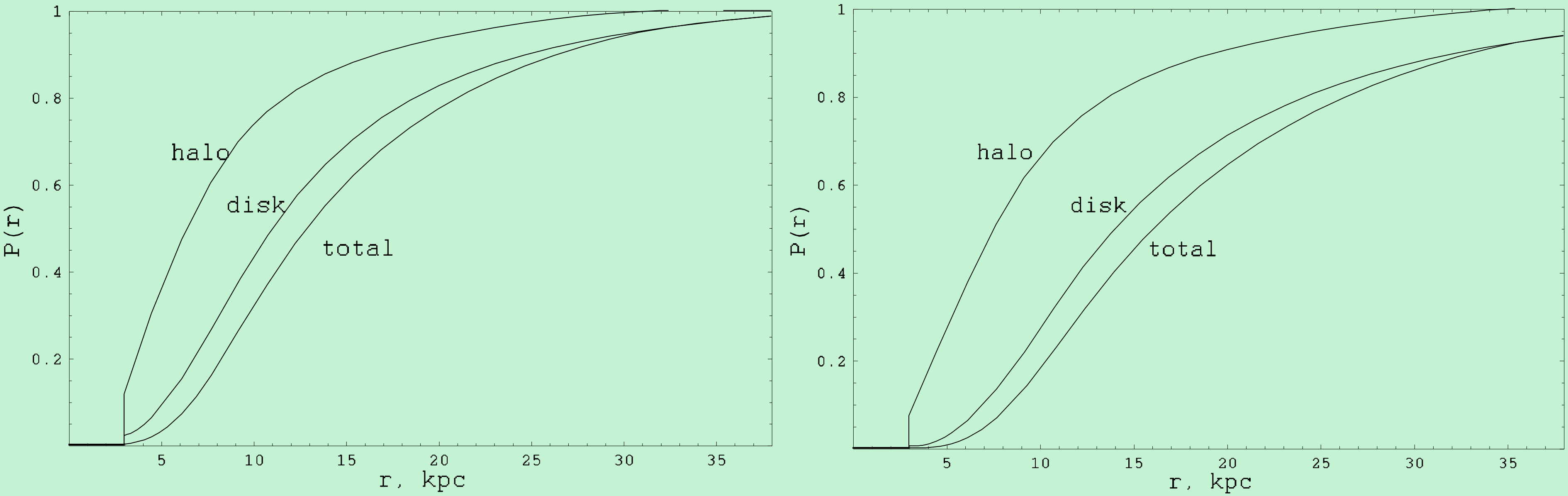
# Mass function of small-scale DM clumps



Lower line – model calculation    Berezinsky, Dokuchaev & Eroshenko 2003

Dots - numerical simulations    Diemand, Moore & Stadel 2005

# Fraction of survived clumps

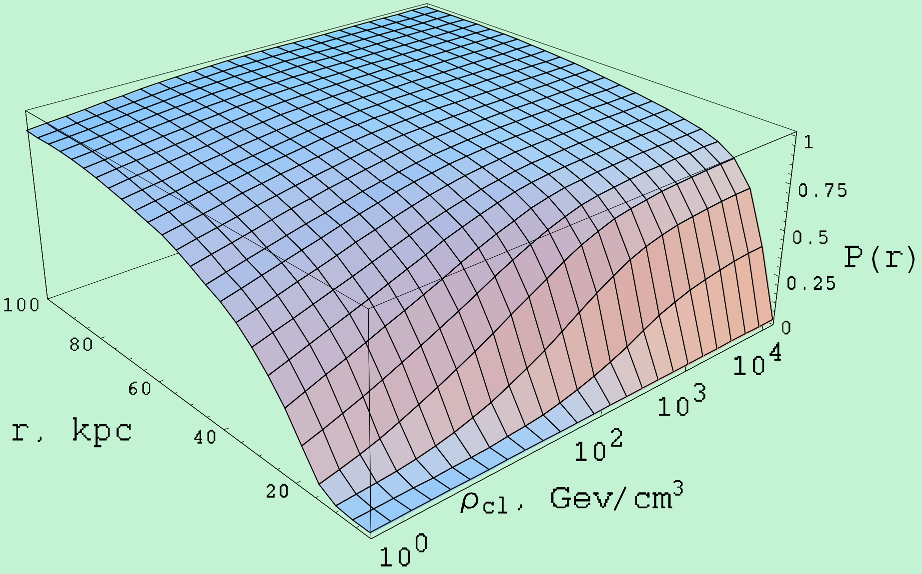


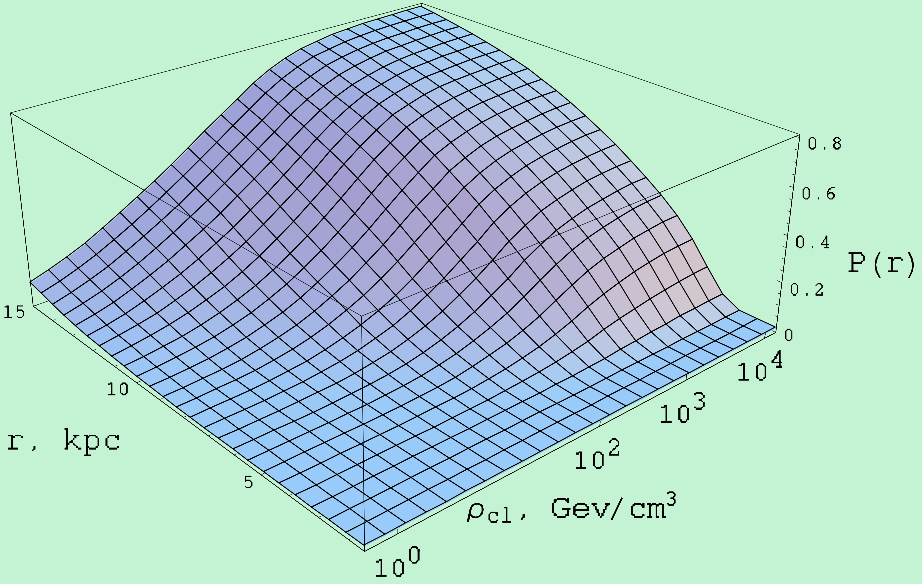
$M_{cl}=10^{-8}M_\odot$

$M_{cl}=10^{-3}M_\odot$

Tidal destruction of clumps in the Galactic bulge, disc, halo and the resulting total fraction of survived clumps with $M_{cl}=10^{-8}M_\odot$ and $10^{-3}M_\odot$

# Survived fraction of clumps P(r) in the Galaxy

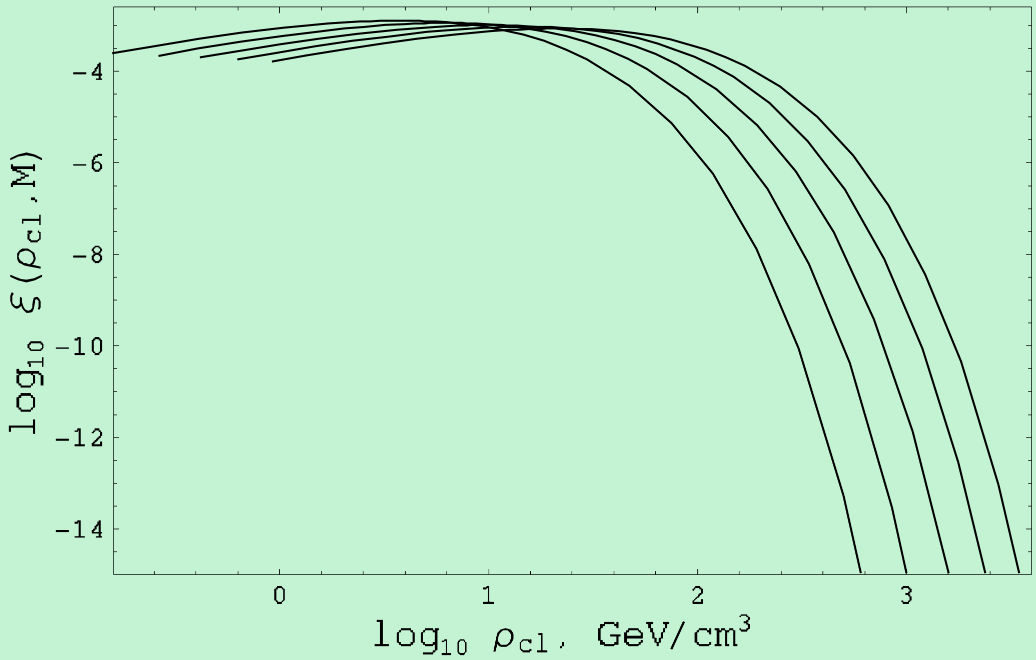




**Radial galactocentric distance $r$ in kpc**

**Mean internal density of clump $\rho_{cl}$ in GeV/cm$^3$**

# Clump distribution function



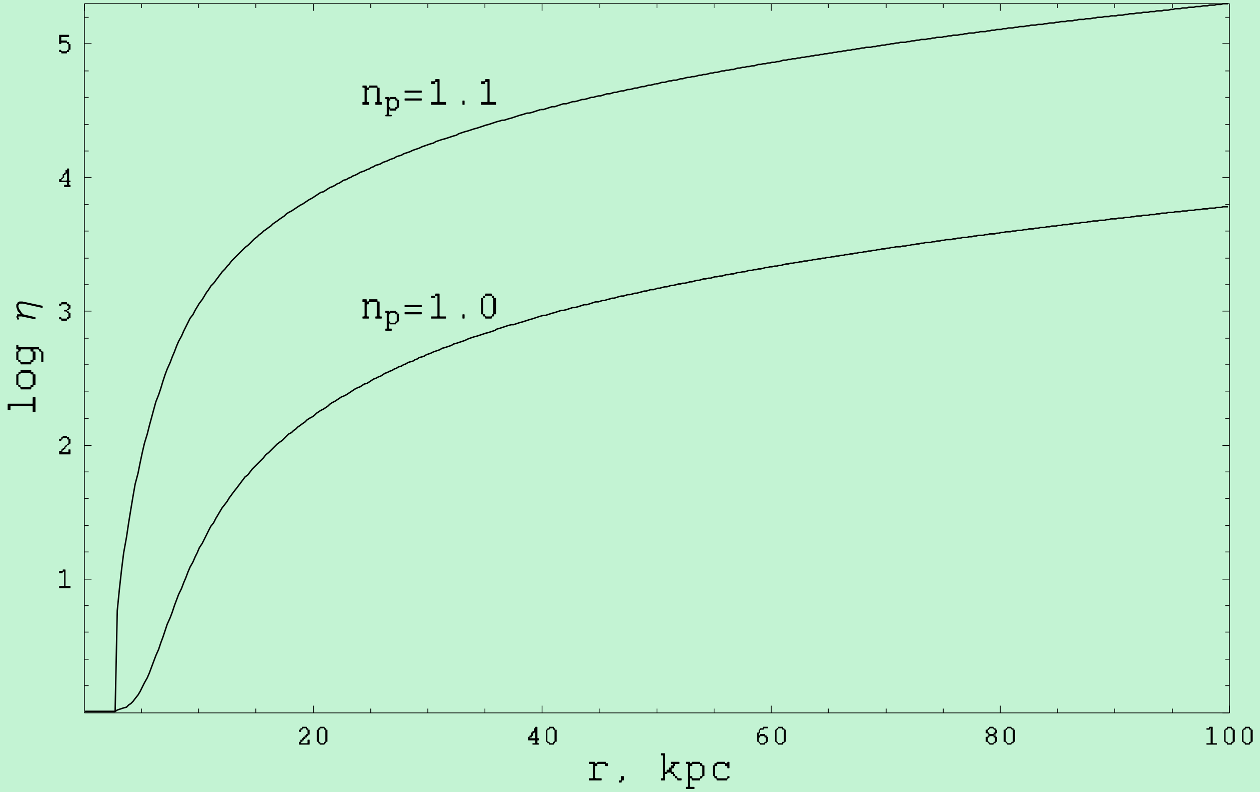
$$\xi(M,\nu)\,\frac{dM}{M}\,d\nu \simeq \frac{y(\nu)}{(2\pi)^{1/2}}\,e^{-\nu^2/2}\,\frac{d\log\sigma(M)}{dM}\,dM\,d\nu$$

**Mean internal density of clump $\rho_{cl}$ in GeV/cm$^3$**

**Right sides of curves correspond to**

**$M_{cl}$ / $M_{\odot}$=$10^{-8}$, $10^{-6}$, $10^{-4}$, $10^{-2}$, 1 from up to down**

# Annihilation enhancement in clumps



**Local annihilation enhancement factor (boosting) η(r)**
**in isothermal spherical symmetric halo**

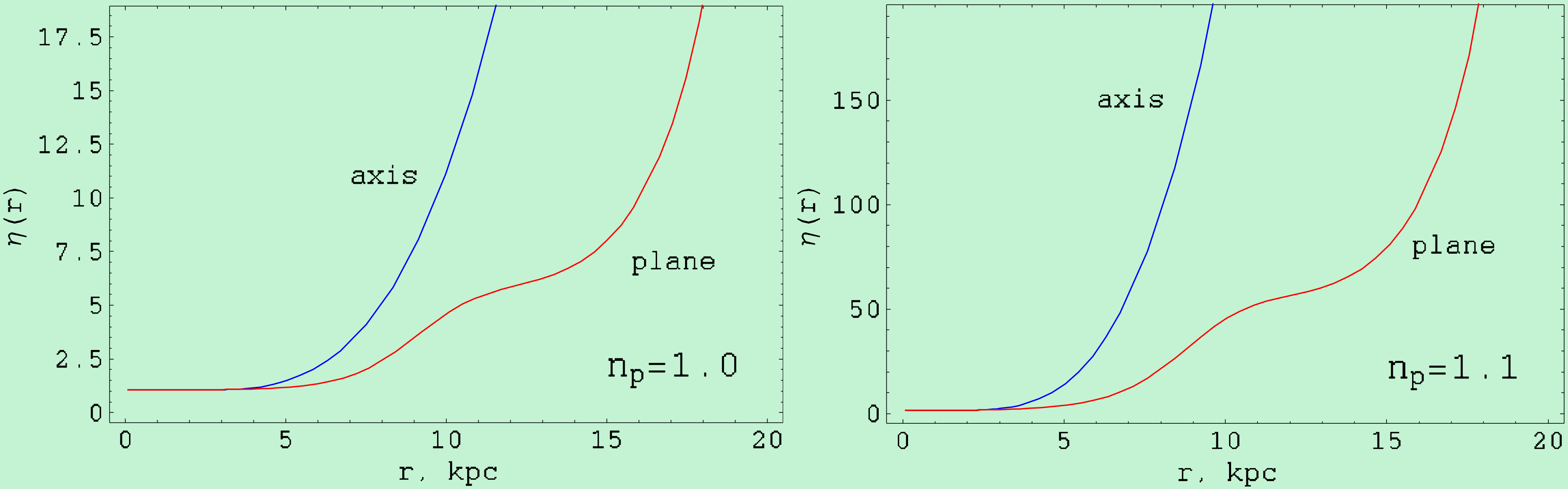
$$dI_{\rm dif} = \frac{\langle\sigma_{\rm ann} v\rangle}{4\pi l^2}\,\frac{\rho^2_{\rm DM}(r)}{m^2_\chi}\,d^3 r$$

$$\bar{\rho}_{\rm cl,P}(r,n_p) = \frac{S(x_c,\beta)}{\xi_{\rm P}(r,n_p)}\int P(r,\rho_{\rm cl})\,\rho_{\rm cl}\,\xi(\rho_{\rm cl})\,d\rho_{\rm cl}$$

$$\eta(r) = \frac{I_{\rm cl}+I_{\rm dif}}{I_{\rm dif}} = 1+\xi_{\rm P}(r,n_p)\frac{\bar{\rho}_{\rm cl,P}(r,n_p)}{\rho_\chi(r)}$$

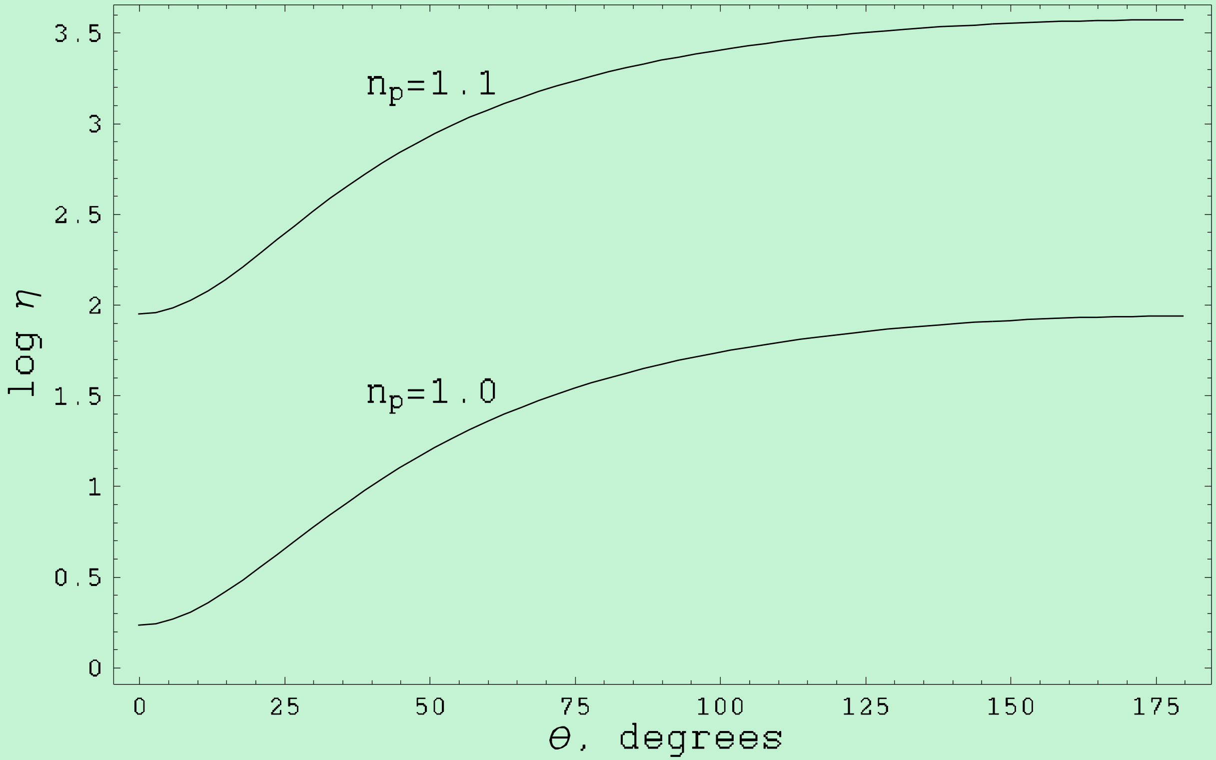
$$\xi_{\rm P}(r,n_p) = \int P(r,\rho_{\rm cl})\xi(\rho_{\rm cl})\,d\rho_{\rm cl},$$

# Local boosting in the Galactic plane and along z-axis



**Local annihilation enhancement factor (boosting) η(r) in NFW halo with ring at r=14 kpc**

# Integrated along the line of sight (observed) enhancement factor η(θ)



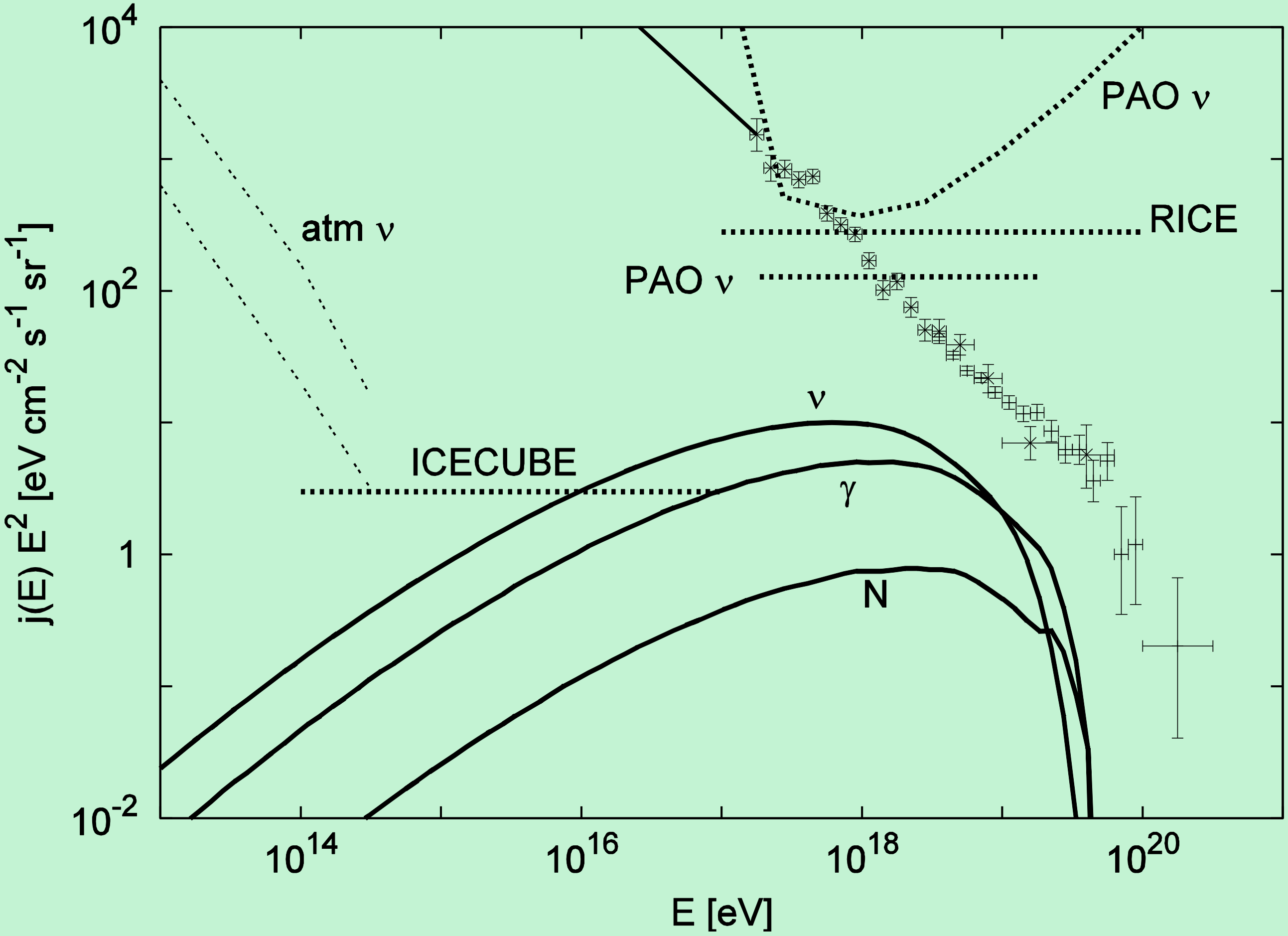
**The case of isothermal spherically symmetric halo model**

$$\eta(\theta,\phi) = 1 + \frac{\int \rho_\chi(r)\, dr\, \xi_{\rm P}(r)\, \bar{\rho}_{\rm cl,P}(r,n_p)}{\int \rho_\chi^2(r)\, dr}$$

$$\bar{\rho}_{\rm cl,P}(r,n_p) = \frac{S(x_c,\beta)}{\xi_{\rm P}(r,n_p)} \int P(r,\rho_{\rm cl})\, \rho_{\rm cl}\, \xi(\rho_{\rm cl})\, d\rho_{\rm cl}$$

$$\xi_{\rm P}(r,n_p) = \int P(r,\rho_{\rm cl}) \xi(\rho_{\rm cl})\, d\rho_{\rm cl},$$

# Annihilations of superheavy DM in superdense clumps



**Fluxes $I_i(E)$ of photons, nucleons and neutrinos from neutralino annihilations in the Galactic halo for neutralino with $m_\chi \sim 10^{11}$ GeV**

Berezinsky Dokuchaev Eroshenko Kachelrieß Solberg 2010

★ **Clumps with $M_{\rm min}$ give the dominant contribution to DM annihilation**

In the case of $n_p = 1, \;\; \nu \sim 2.5$

$M_{\rm min} \sim 10^{-8} M_{\odot}$

$R \simeq 3.6 \cdot 10^{15}$ cm, $\;\; R_c \simeq 1.8 \cdot 10^{14}$ cm

$\bar{\rho}_{\rm int} \simeq 2.5 \cdot 10^{-22}$ g cm$^{-3}$

Halo mass fraction in these clumps $\xi_{\rm int} \sim 0.002$

Mean number density in the halo $n_{\rm cl} \sim 25$ pc$^{-3}$

DM annihilation enhancement $\eta \sim 10 - 10^2$