Dark Matter clustering around Venya Berezinsky

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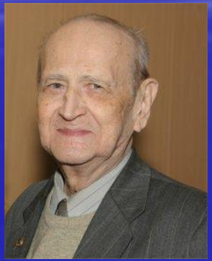
Gran Sasso Science Institute, L’Aquila - 2024







Clustering around Venya of dark matter and scientists throughout the multi-universe









LLNGS


GSSI



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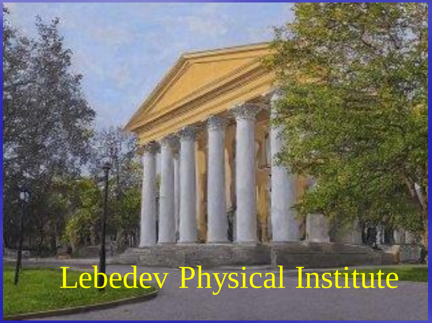

Lebedev Physical Institute


Baikal neutrino telescope


SUSY neutralino DM detection

- Direct neutralino χ detection
  - Recoil detectors: DAMA m_χ60 GeV?, Edelweiss, CDMS, XENON
  - LHC $m_\chi = \mathcal{O}(100)$ GeV?

- Indirect χ 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…

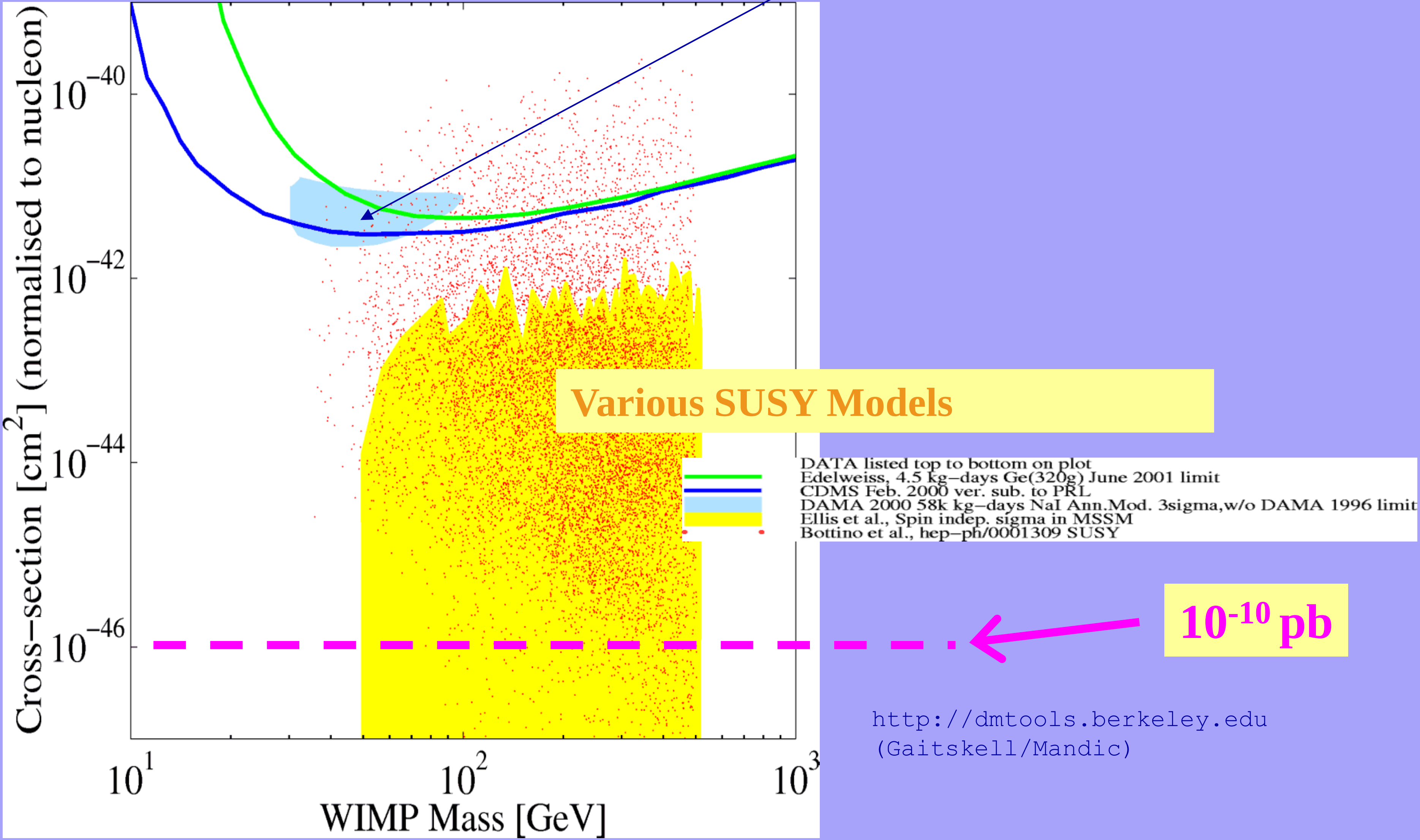
★ Halo clumpiness: mass fraction of clumps ξ

✦ Minimal mass of clumps M_{min}

⅄ Clump distribution function $\xi(M_{cl}, \rho_{cl}, r)$

Direct DM detection

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



Various SUSY Models

10^{-10} pb

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

Neutralino as WIMP

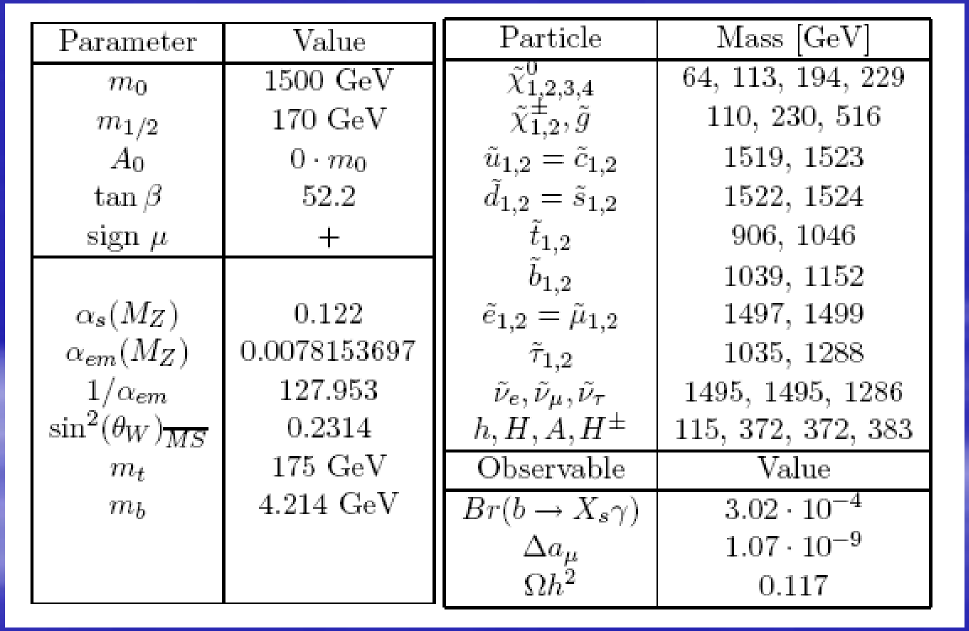
χ is LSP in mSUGRA: MSSM with SUGRA inspired breaking

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

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

Only 5 parameters:

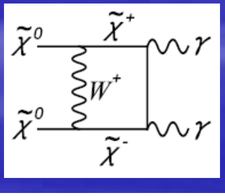


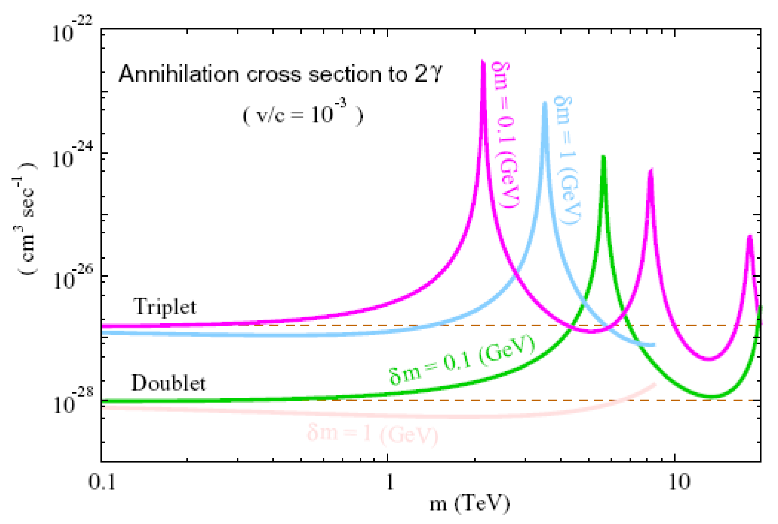
Parameter	Value
m_0	1500 GeV
$m_{1/2}$	170 GeV
A_0	$0 \cdot m_0$
$\tan\beta$	52.2
sign μ	+
$\alpha_s(M_Z)$	0.122
$\alpha_{em}(M_Z)$	0.0078153697
$1/\alpha_{em}$	127.953
$\sin^2(\theta_W)_{\overline{MS}}$	0.2314
m_t	175 GeV
m_b	4.214 GeV

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**
$Br(b \to X_s\gamma)$	$3.02 \cdot 10^{-4}$
Δa_μ	$1.07 \cdot 10^{-9}$
Ωh^2	0.117

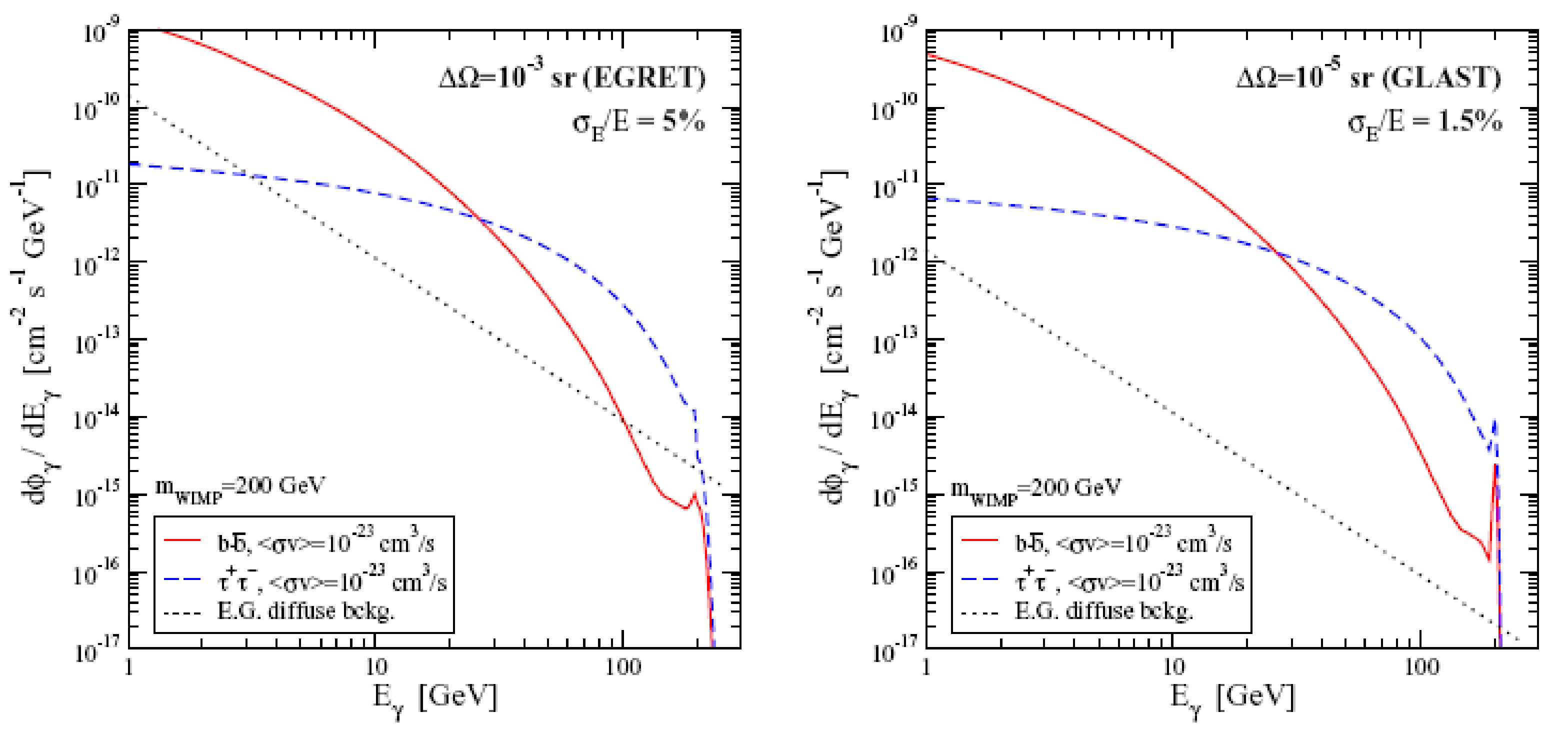
Dominant annihilation into quark pairs

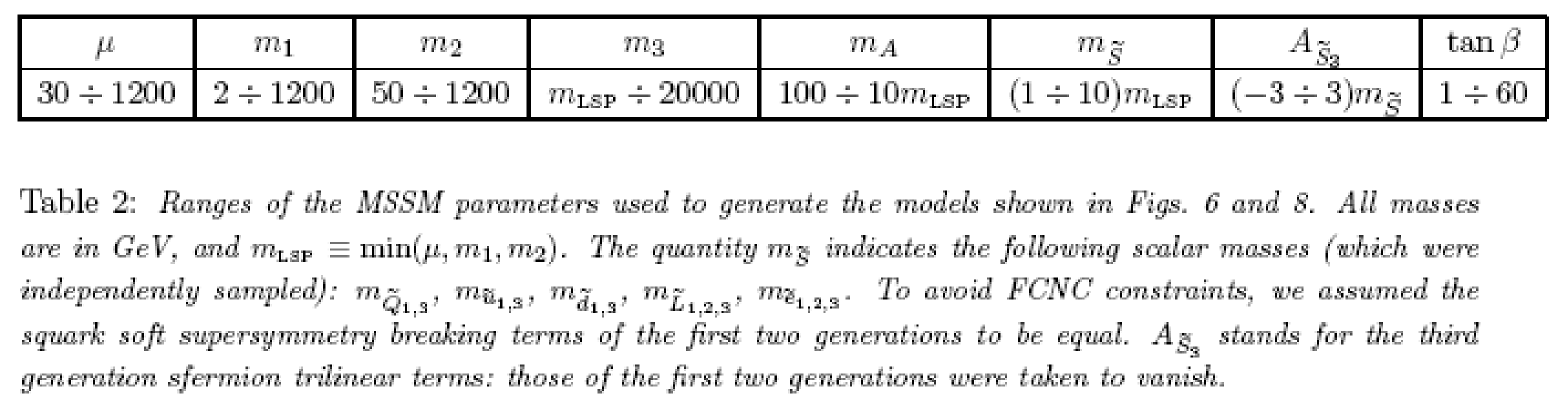
Annihilation to $\gamma\gamma$ is suppressed by a loop factor





Photon spectra of SUSY $\chi\chi$ annihilation





μ	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.*

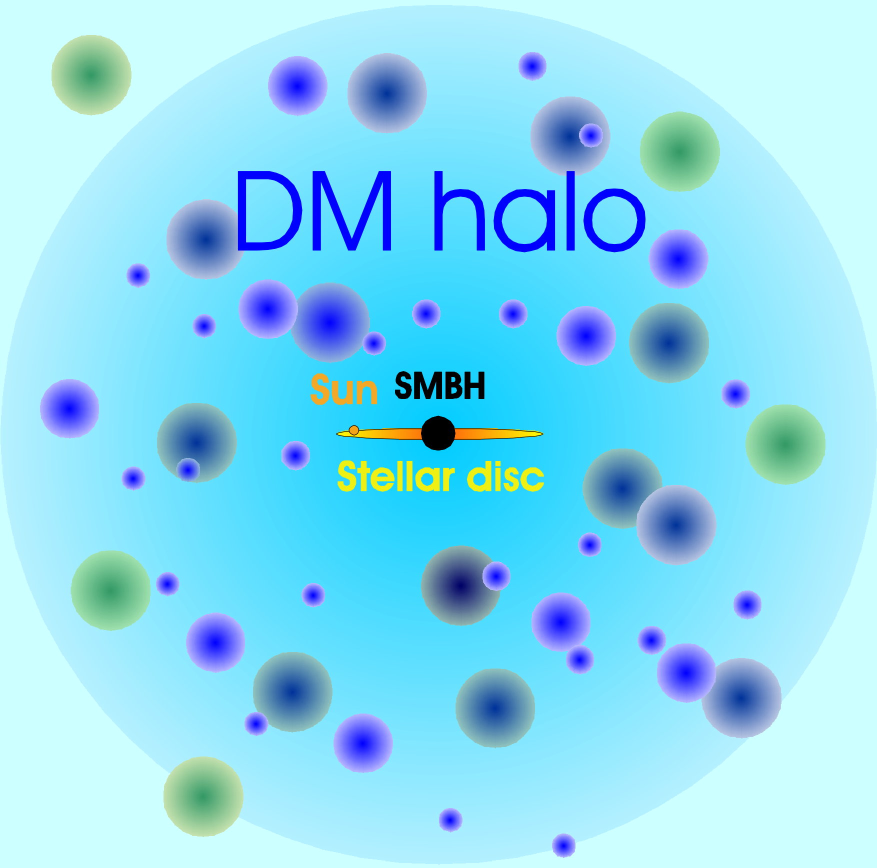
Profumo & Kamionkowski, 2006

Monochromatic gamma rays?

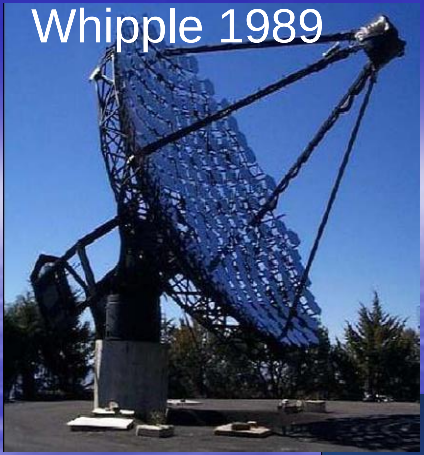
Boosting factor $\eta \sim 100$ is required!

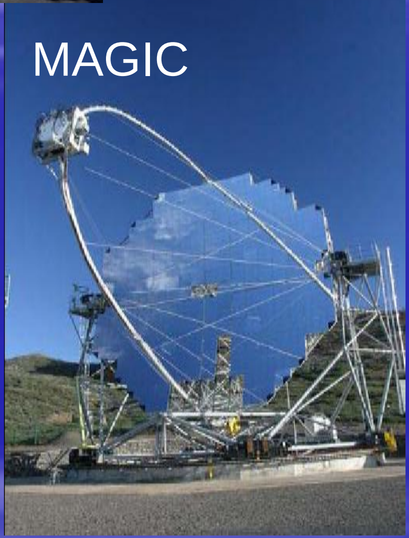
Clustering of DM!

Small-scale DM clumps in the Galactic halo



Atmospheric Cherenkov Telescopes





CACTUS Gamma-Ray Excess from Draco

CACTUS: Converted Atmospheric Cherenkov Telescope Using Solar-2

Solar 2 Heliostat Array CACTUS. Barstow, California, effective area 5×10^4 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

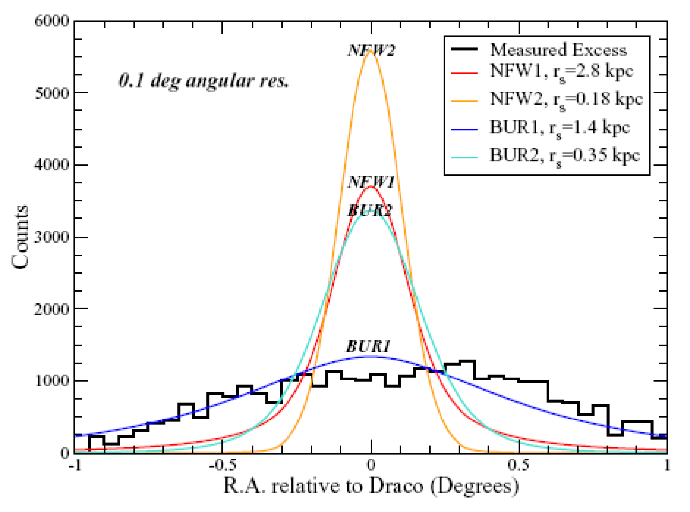
Draco heliocentric distance 75.8±0.7±5.4 kpc, R=0.5 kpc

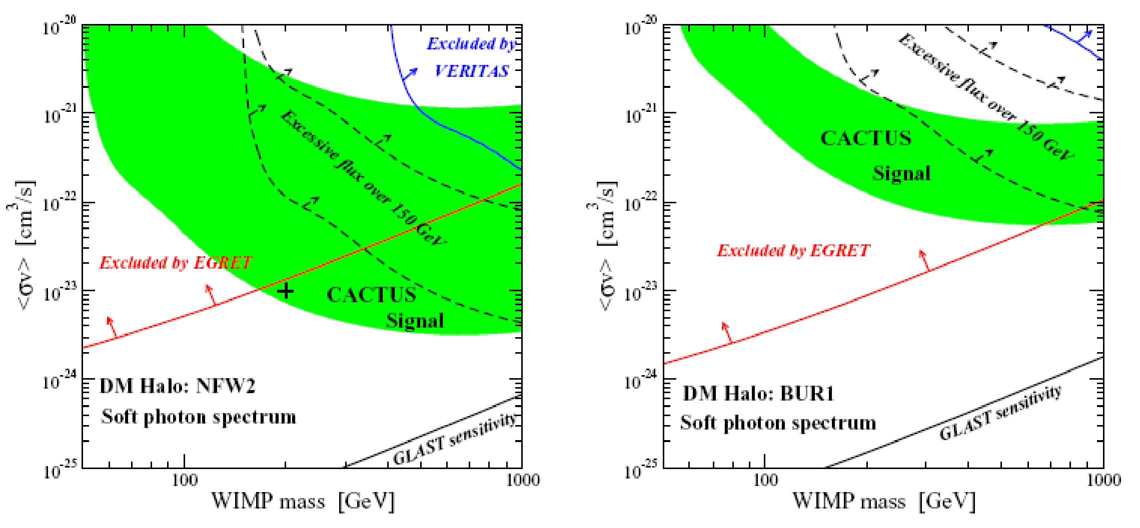
2004

Threshold: 50 GeV

Background: γ-like hadronic EASs, CR electrons, diffuse extragalactic background >50 GeV

Excess ~20% of the background >50 GeV



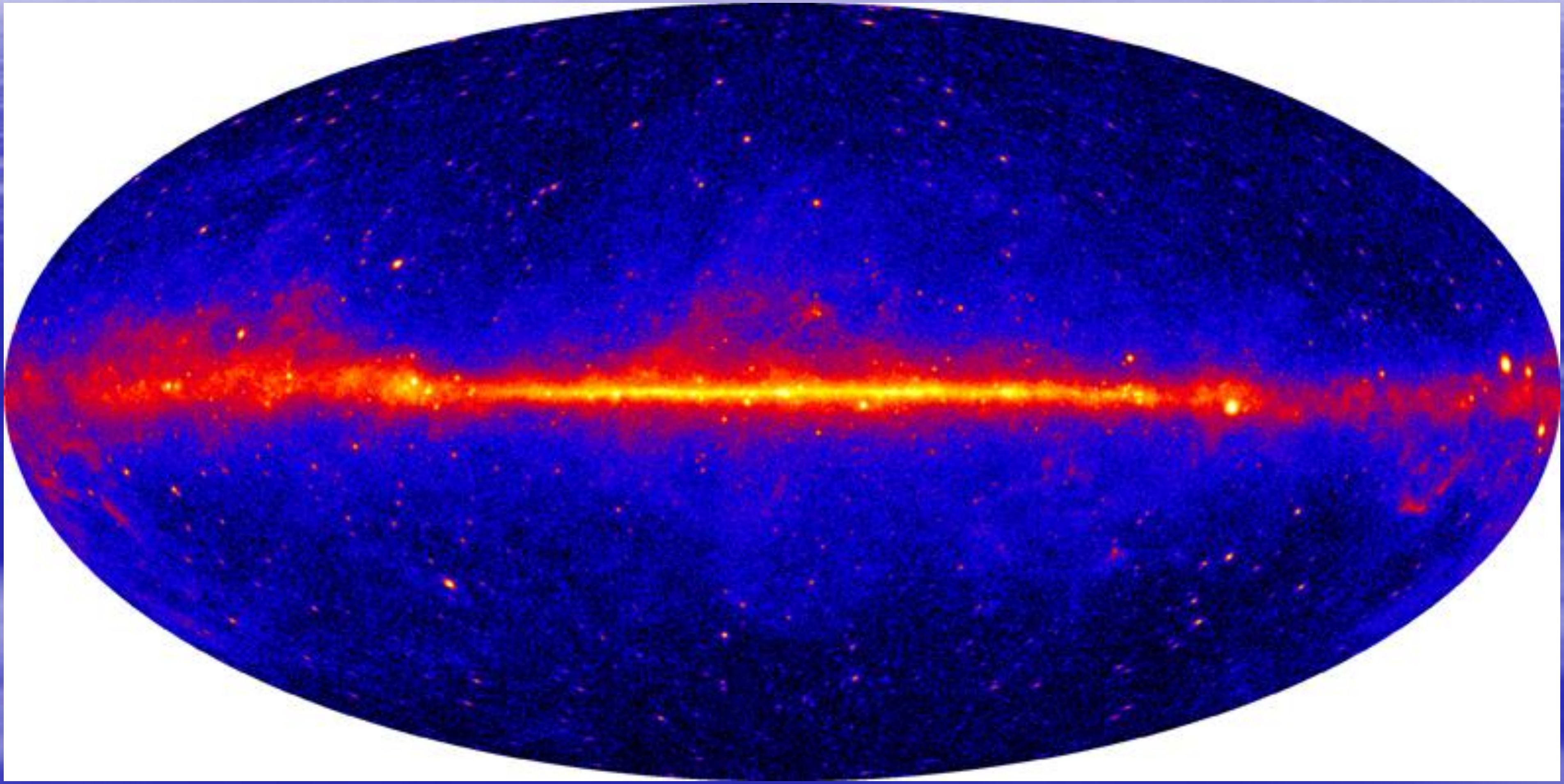


angular resopution Δθ=1°?

Profumo & Kamionkowski, 2006

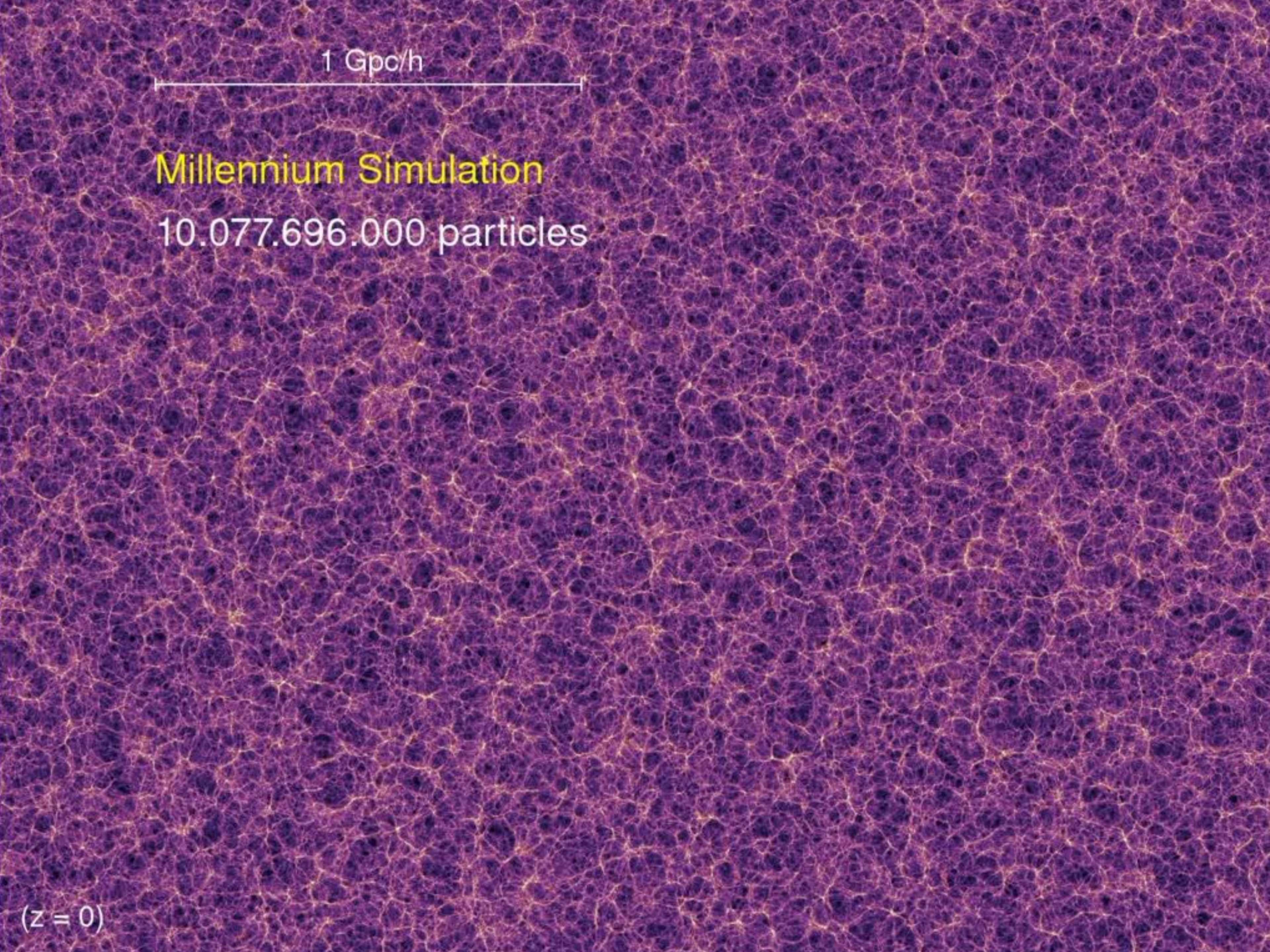
Opportunity for Fermi (formerly GLAST)?

All-sky view from Fermi



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

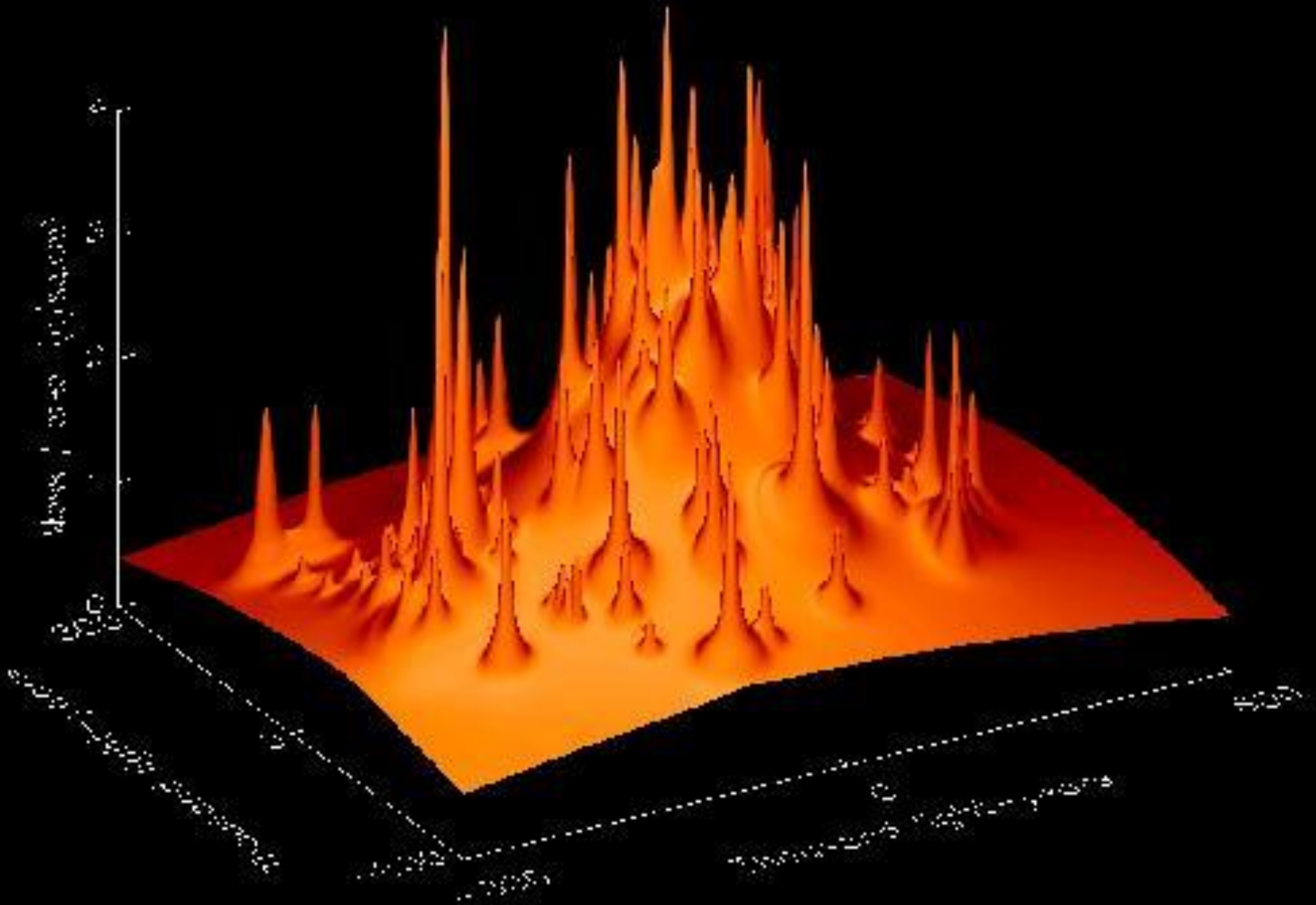
Project Columbia supercomputer (NASA)



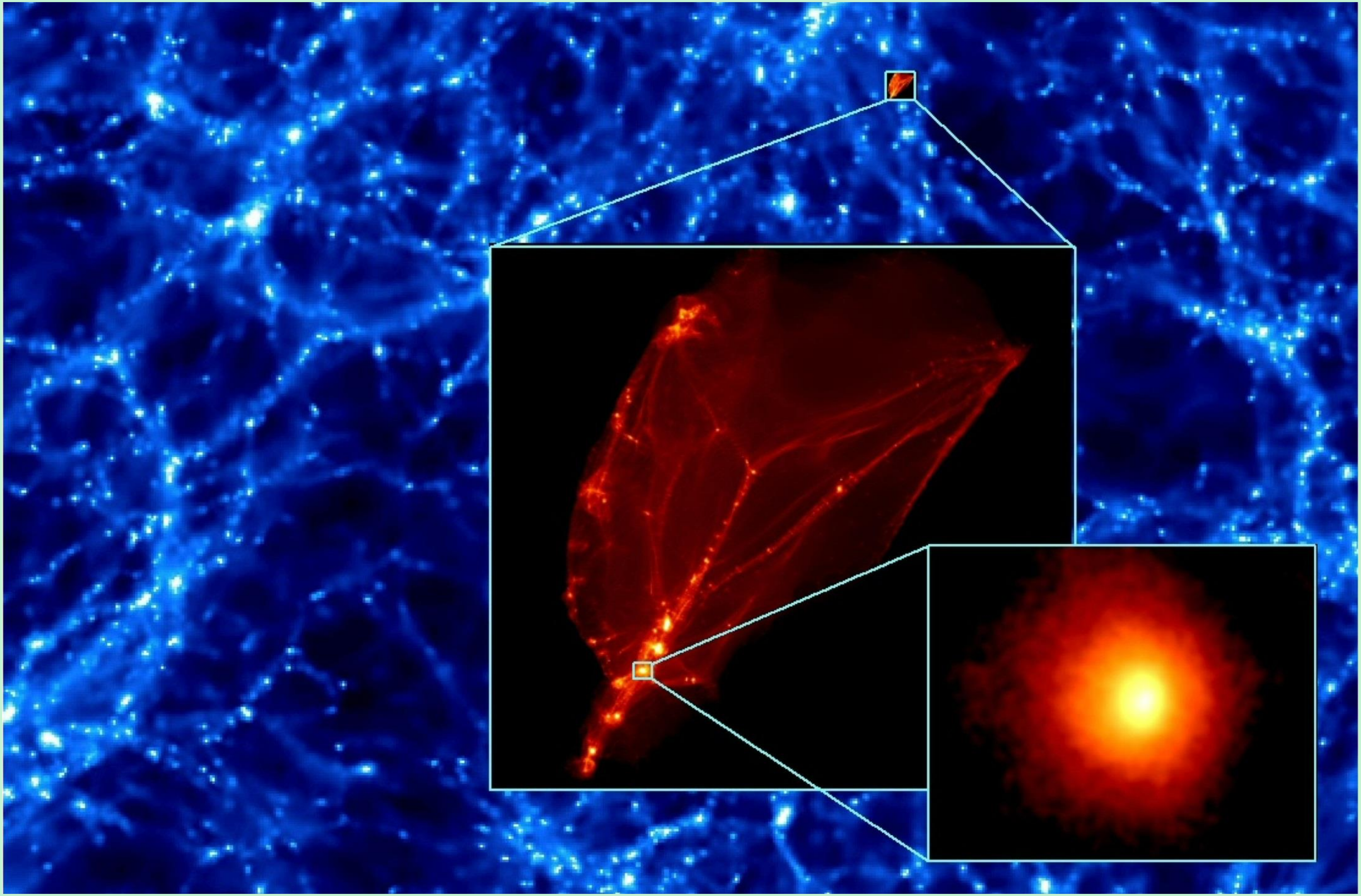
Millennium Simulation

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**

$N=62\ 10^6$, $m=1.2\ 10^{-10} M_\odot$ $z=350 \rightarrow z=26$, gravitational. 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

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

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

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

★ 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

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

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

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

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

⋆ Minimal mass of the clump

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

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

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

Power spectrum $P(k)$:

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

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

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

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

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

⋆ Core of a Dark Matter Clump

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

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

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

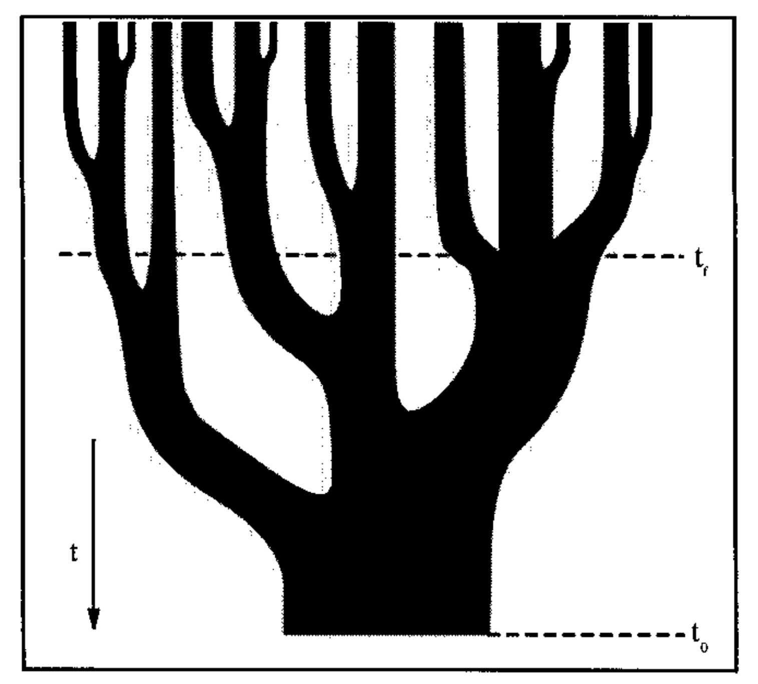
Tidal velocity $\frac{dv_{tid,i}}{dt} = -T_{ij}(t) r^j$

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

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

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

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

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

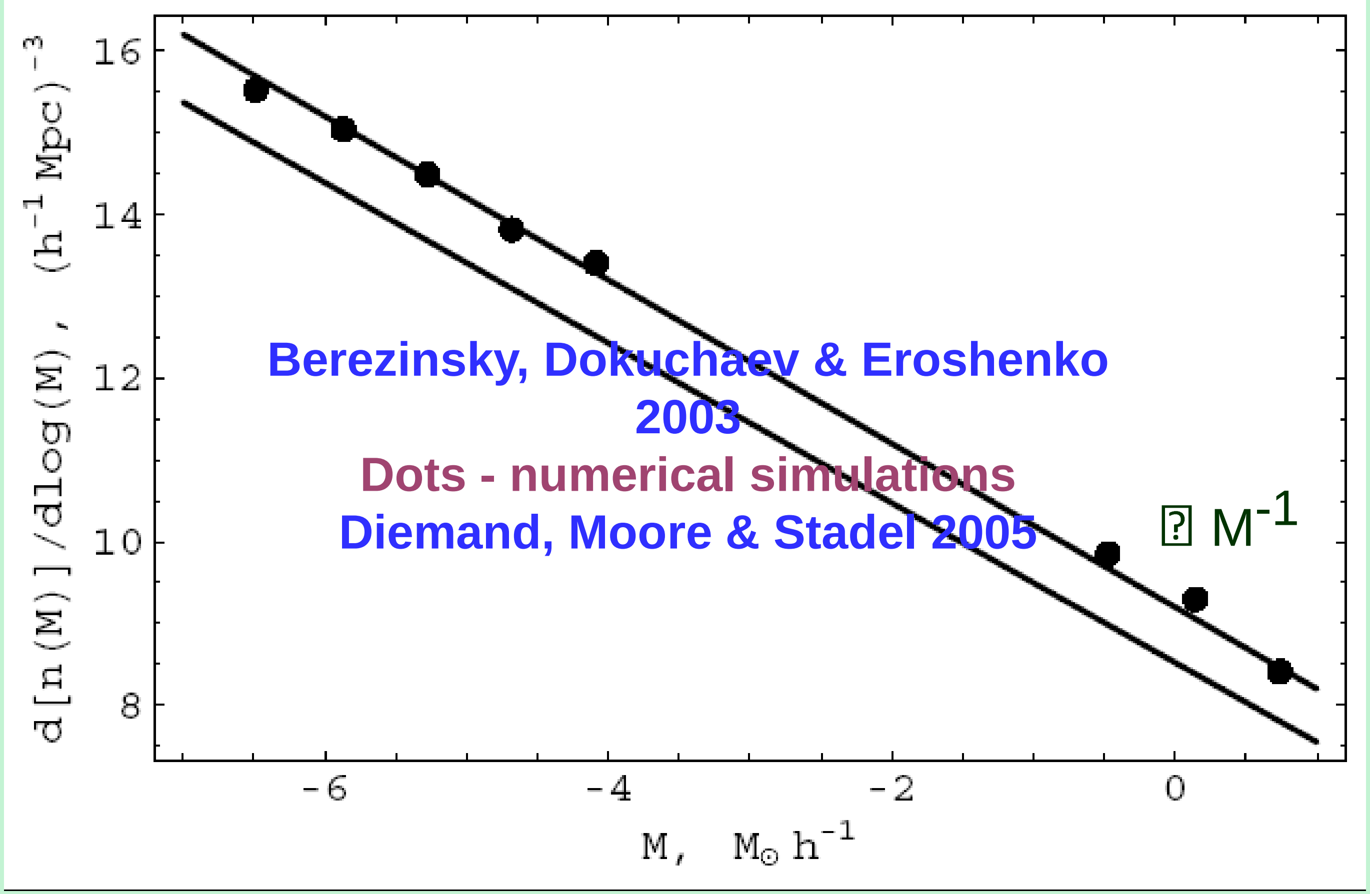
$$\phi_{PS} = \left(\frac{2}{\pi}\right)^{1/2} \frac{\rho}{M} \frac{\delta_c}{D_g(t)\sigma_{\rm eq}^2} \frac{d\sigma_{\rm eq}}{\rm DM} \exp\left[\frac{-\delta_c^2}{2D_g(t)^2\sigma_{\rm eq}^2}\right] dM$$

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



Berezinsky, Dokuchaev & Eroshenko 2003

Dots - numerical simulations

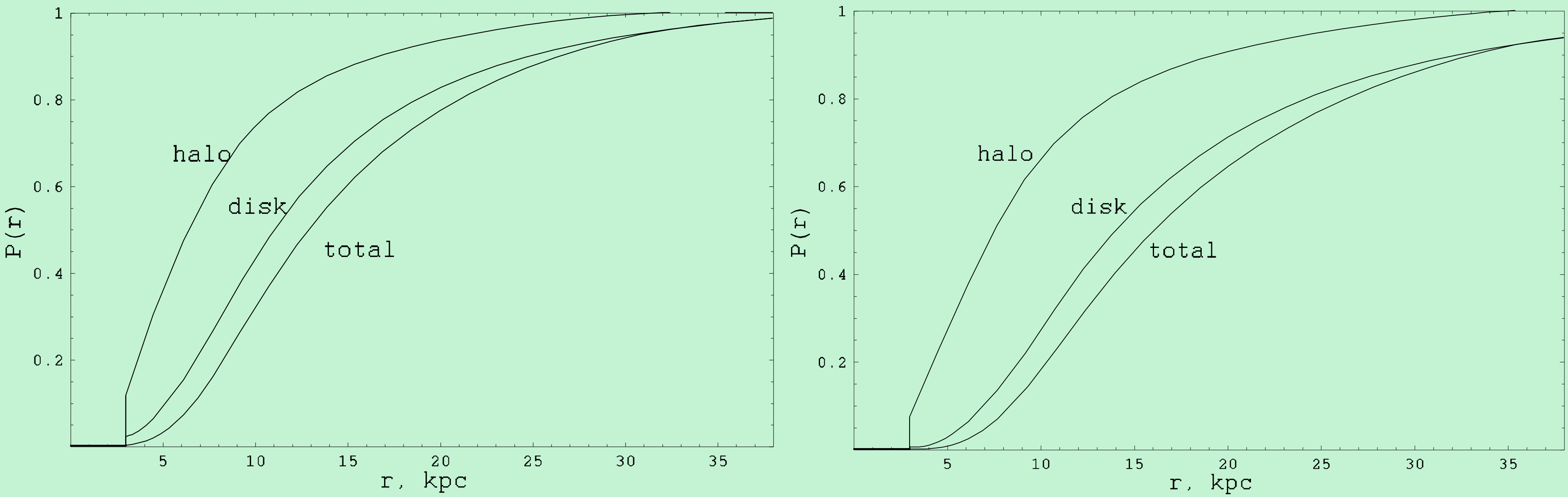
Diemand, Moore & Stadel 2005

$\propto M^{-1}$

Lower line – model calculation Berezinsky, Dokuchaev & Eroshenko 2003

Dots - numerical simulations Diemand, Moore & Stadel 2005

Fraction of survived clumps

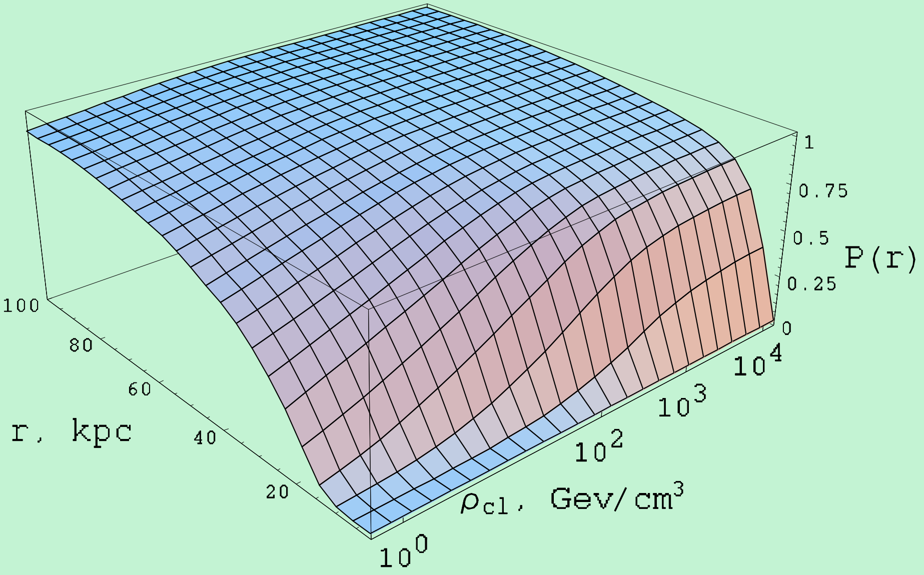


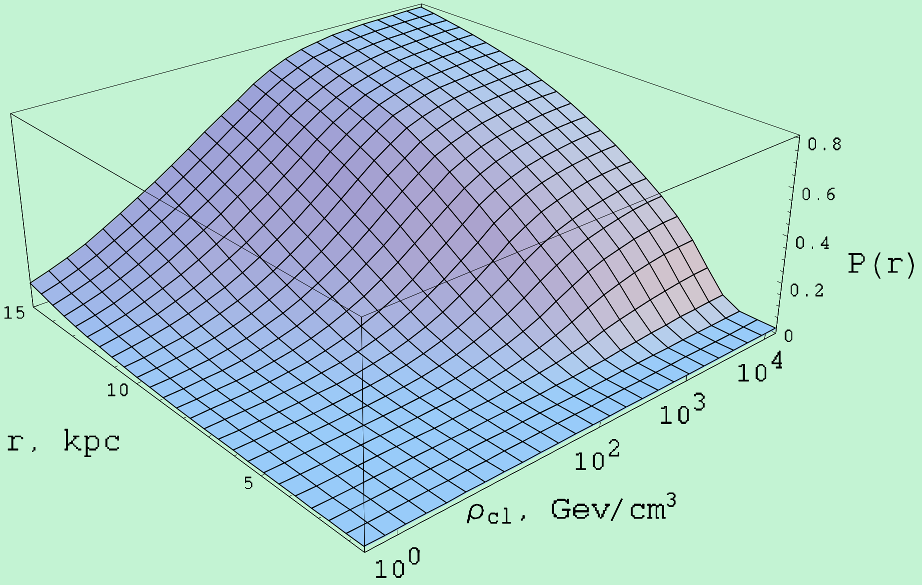
$M_{cl}=10^{-8}M_{\odot}$

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

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

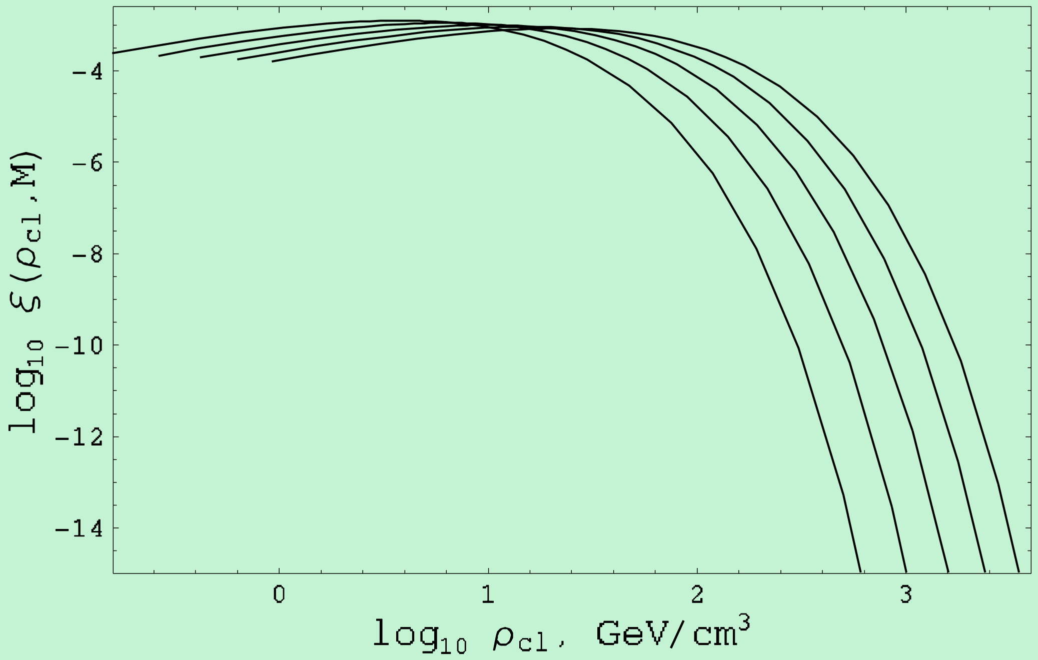




Radial galactocentric distance r in kpc

Mean internal density of clump ρ_{cl} in GeV/cm^3

Clump distribution function



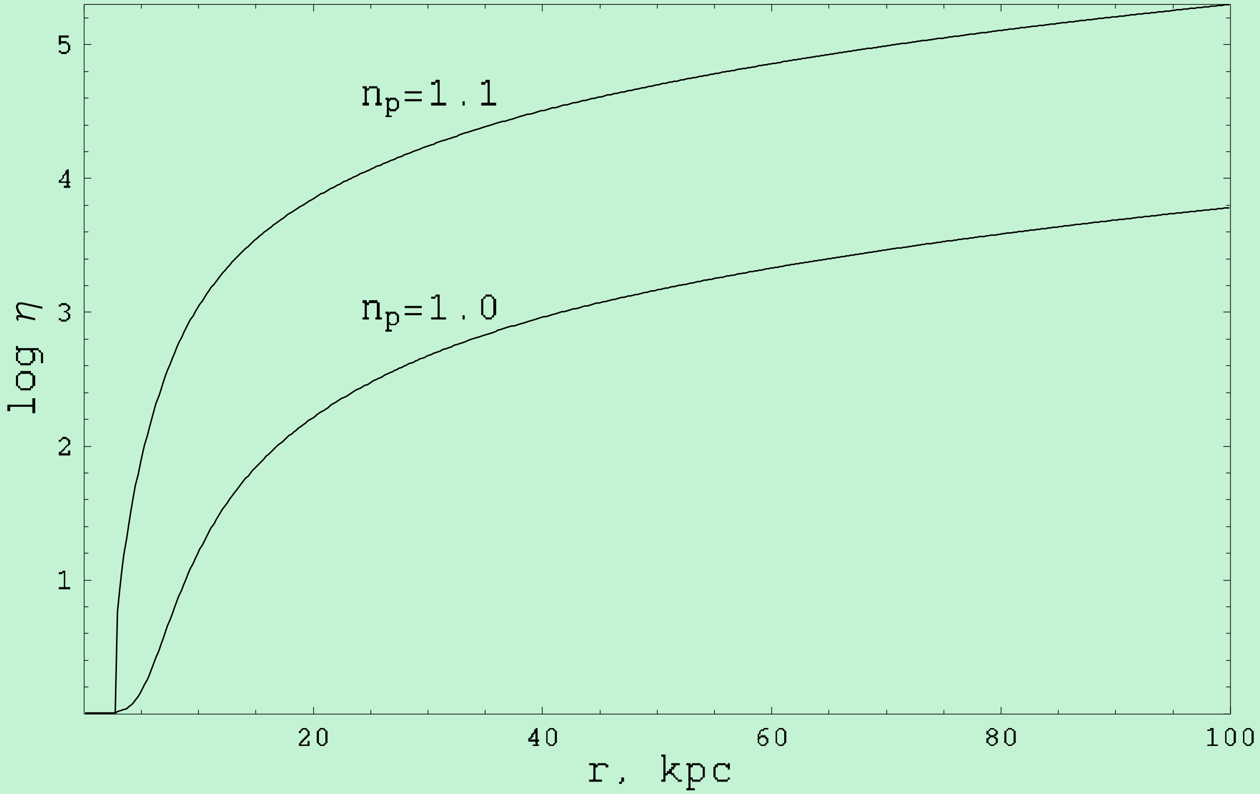
$$\xi(M,\nu)\,\frac{dM}{M}\,d\nu \simeq \frac{y(\nu)}{(2\pi)^{1/2}}\,e^{-\nu^2/2}\,\frac{d\log\sigma(M)}{dM}\,dM\,d\nu$$

Mean internal density of clump ρ_{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

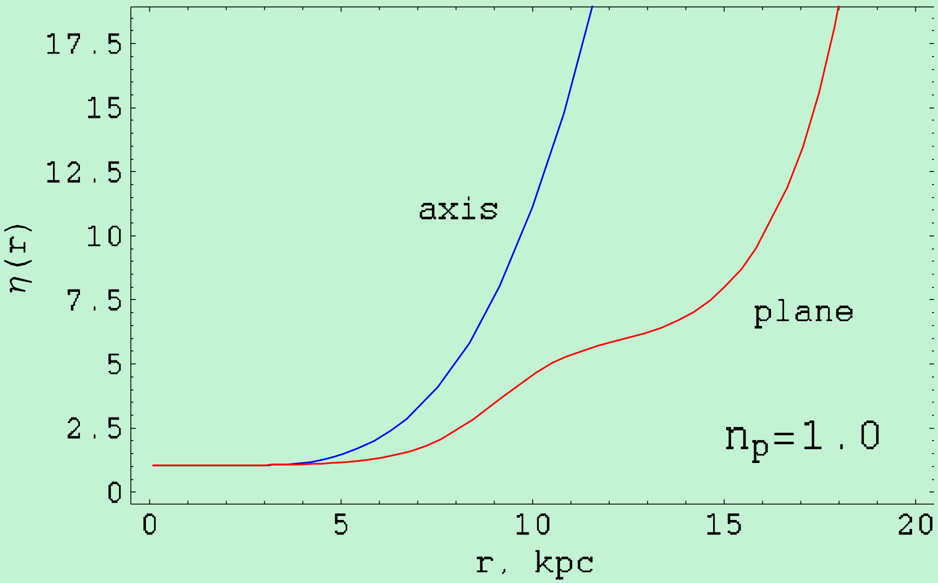
$$dI_{\rm dif} = \frac{\langle\sigma_{\rm ann}v\rangle}{4\pi l^2}\,\frac{\rho^2_{\rm DM}(r)}{m^2_\chi}\,d^3r$$

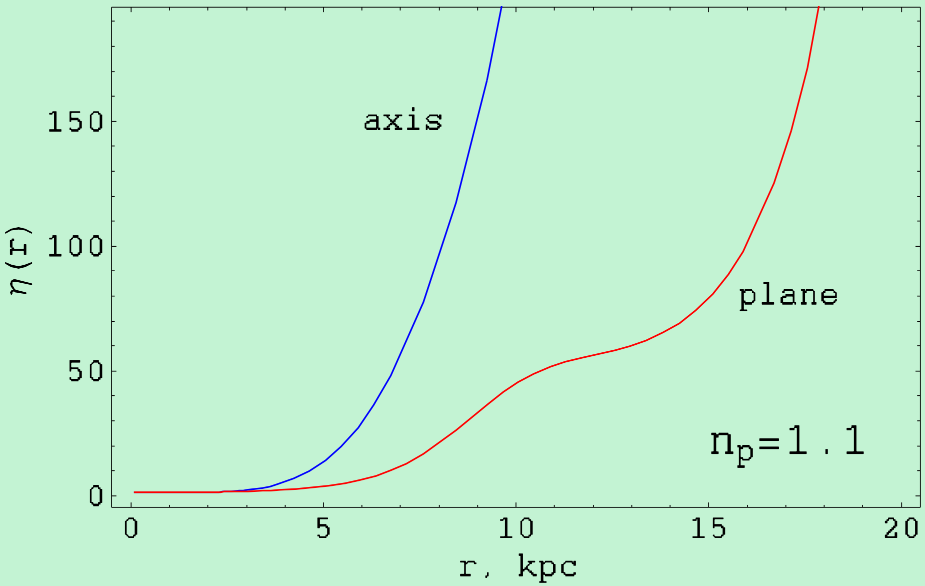
$$\bar\rho_{\rm cl,P}(r,n_p) = \frac{S(x_c,\beta)}{\xi_{\rm P}(r,n_p)}\int P(r,\rho_{\rm cl})\,\rho_{\rm cl}\,\xi(\rho_{\rm cl})\,d\rho_{\rm cl}$$

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

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

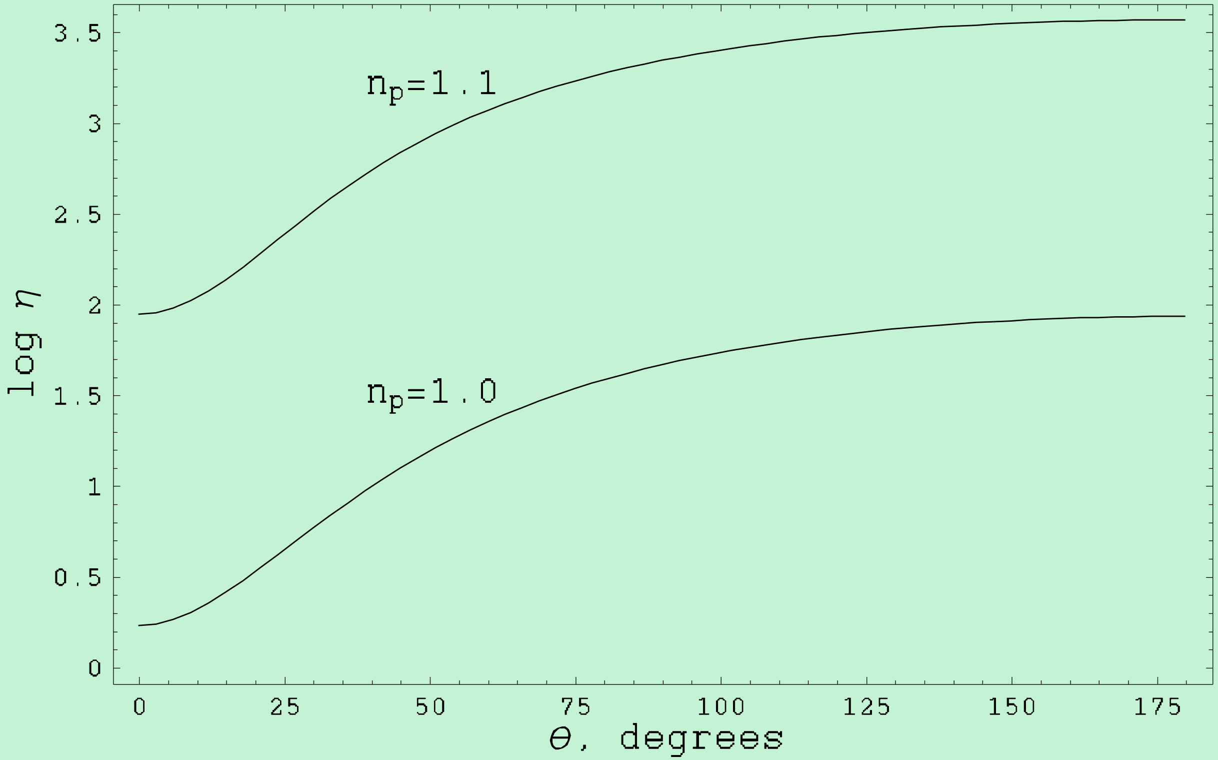
Local boosting in the Galactic plane and along z-axis





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)



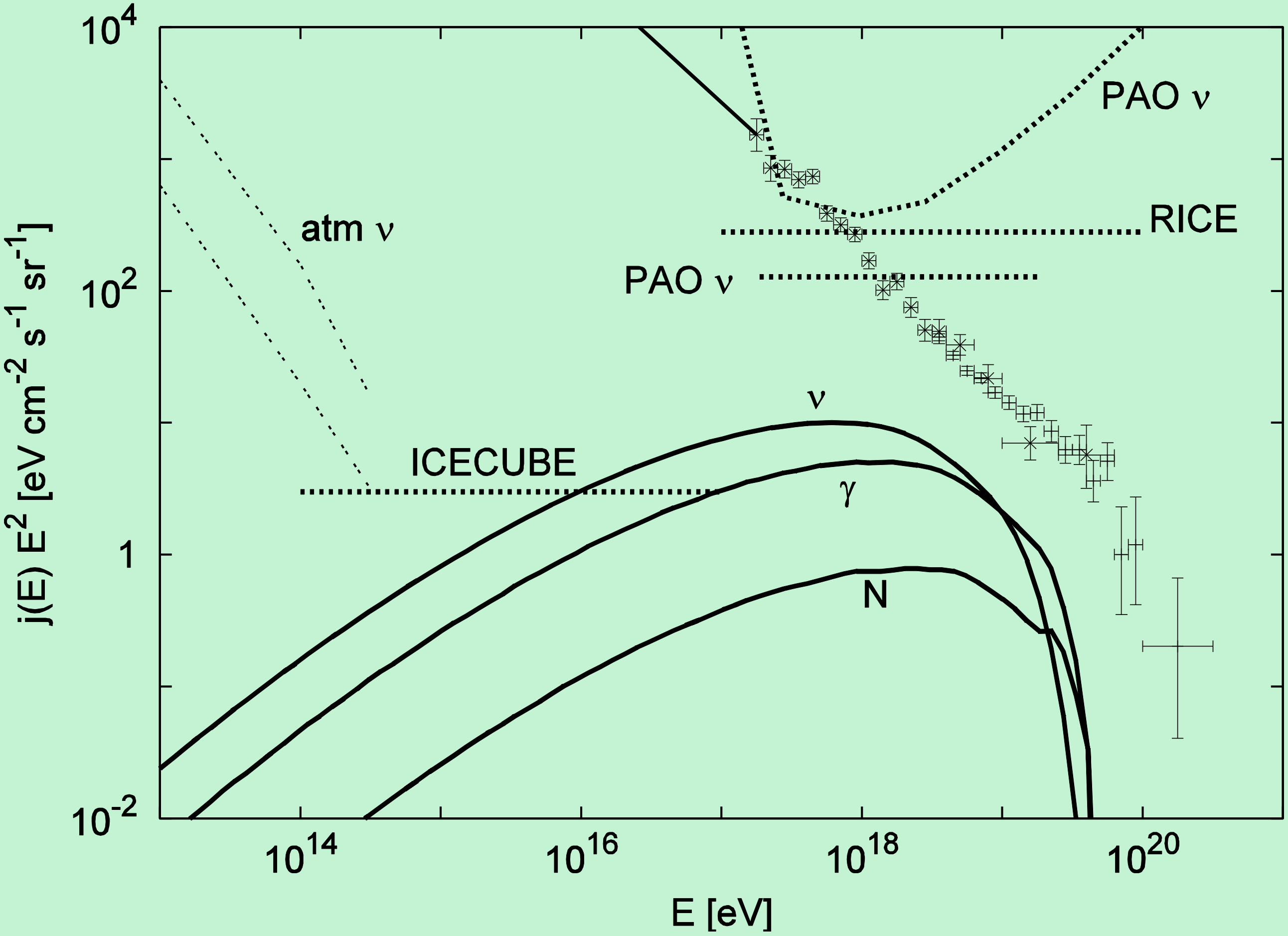
The case of isothermal spherically symmetric halo model

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

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

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

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 $n_p = 1, \quad \nu \sim 2.5$

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

$R \simeq 3.6 \cdot 10^{15}$ cm, $\quad R_c \simeq 1.8 \cdot 10^{14}$ 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 $\eta \sim 10 - 10^2$

Some publications by V. S. Berezinsky with co-arthors on Dark Matter clustering

1. Veniamin Berezinsky, Vyacheslav Dokuchaev and Yury Eroshenko. *SUSY dark matter annihilation in the Galactic halo* J. Phys.: Conf. Ser. **607**, 012015 (2015); arXiv:1506.03955 [astro-ph.HE]
2. V. S. Berezinsky, V. I. Dokuchaev, Yu. N. Eroshenko. *Small scale clumps of dark matter.* Phys. Usp.z **57** (1) (2014); arXiv:1405.2204 [astro-ph.HE].
3. V. S. Berezinsky, V. I. Dokuchaev, Yu. N. Eroshenko. *Formation and internal structure of superdense dark matter clumps and ultracompact minihaloes*. JCAP **11** (2013) 059; arXiv:1308.6742 [astro-ph.CO].
4 . V. Berezinsky, V. Dokuchaev and Yu. Eroshenko. *Superdense dark matter clumps from nonstandard perturbations*. Proc. 15th Lomonosov Conf. on Elementary Particle Phys., Particle Physics at the Tercentenery of Mikhail Lomonosov. Moscow State Univ. (Moscow, Russia) Aug. 18 --- 24, 2011, Ed. A. I. Studenikin (World Scientific, New Jersey, 2013), pp. 267--269.
5. V. Berezinsky, V. Dokuchaev and Yu. Eroshenko. *Dark matter annihilation in the Galaxy*. J. Phys.: Conf. Ser. **409**, 012117 (2013), Proc. of the 23rd European Cosmic Ray Symposium (and 32nd Russian Cosmic Ray Conference).
5. V. S. Berezinsky, V. I. Dokuchaev, Yu. N. Eroshenko. *Formation of superdense dark matter lumps at the radiation-dominated cosmological stage*. *Gravitation and Cosmology*, 2012, **18**, No. 1, pp. 57–60.
6. V. S. Berezinsky, V. I. Dokuchaev, Yu. N. Eroshenko, M. Kachelriess, M. Aa. Solberg. *Superdense dark matter clumps from superheavy particle*. Theor.Math.Phys. **170**(1), 83-89 (2012).
7. V. Dokuchaev, V. Berezinsky and Yu. Eroshenko. *Dark matter annihilation in the Galaxy*. Proc. 14th Lomonosov Conference on Elementary Particle Physics, Particle Physics on the eve of LHC, Moscow State University and JINR (Dubna), Russia, 19-25 August 2009. Ed. A. I. Studenikin, World Scientific, 2011, pp. 229-231.
8. V. S. Berezinsky, V. I. Dokuchaev, Yu. N. Eroshenko, *Dense DM clumps seeded by cosmic string loops and DM annihilation*, JCAP, **12**, 007 (2011); arXiv:1107.2751v1 [astro-ph.HE].
9. V. Berezinsky, V. Dokuchaev, Yu. Eroshenko, M. Kachelriess, M, .Aa. Solberg. *Superdense dark matter clumps from superheavy particles*. The International conference IDM2010 - identification of dark matter 2010, 26-30 July 2010, University 2, Montpellier, France. June 27 - July 2, 2011; Grav. Cosmol. 2012.
10. V. Berezinsky, V. Dokuchaev, Yu. Eroshenko, M. Kachelriess, M. Aa.Solberg. *Superdense dark matter clumps from superheavy particles*. 16th International Seminar on High Energy Physics QUARKS'2010 Kolomna, Russia, June 6-12, 2010.

The End

Thank you