Superdense dark matter clumps from superheavy particles

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Superheavy dark matter particles

Thermal relic $\Omega_\chi \propto 1/\sigma_{ann}, \Omega_{CDM} h^2 \approx 0.1 \Rightarrow \langle \sigma_{ann} v \rangle \approx 3 \times 10^{-26} cm^3 s^{-1}$

Unitarity bounds $\sigma_{ann} \propto m_\chi^{-2} \Rightarrow m_\chi \leq 100\, TeV$ *(Griest, Kamionkowski 1990), (Hui 2001)*

Superheavy particles *(Berezinsky, Kachelries and Vilenkin 1997), (Kuzmin and Rubakov 1998)*

Gravitational production of superheavy particles at the end of inflation
(Chung, Kolb and Riotto 1999), (Kuzmin and Tkachev 1998), (Lyth and Roberts 1998)

Annihilation of superheavy DM particles $\dot{N}_{ann} \propto (\rho / m_\chi)^2 \langle \sigma_{ann} v \rangle \propto m_\chi^{-4}$, backgrounds $\propto E^{-\alpha}, \alpha \leq 3$

- dense central region of DM clumps *(Blasi, Dick, Kolb 2002)*
- formation of superdense clumps *(Kolb and Tkachev 1994), (Scott and Sivertsson 2009)*

Superheavy supersymmetry *(Berezinsky, Kachelries and Solberg, 2008)*

$$M_{SUSY} \gg m_Z \qquad \langle \sigma_{ann} v \rangle \approx 2 \times 10^{-42} (m_\chi / 10^{11}\, GeV)^{-2} cm^3 s^{-1}$$

Kinetic decoupling of superheavy DM particles

The mass spectrum of DM clumps has a low-mass cutoff $M_{\rm min}$ due to the leakage of particles from a clump. This mass is strongly model dependent.

Cutof the mass spectrum of DM clumps for standard (~100 GeV) neutralinos $M_{min} \sim 10^{-6} M_{\odot}$

Cutof for ultra-cold WIMPs *(Scott and Sivertsson 2009), (Gelmini and Gondolo 2008)*

$1/\tau_{rel} \sim H(t_d) \Rightarrow$ temperature T_d of kinetic decoupling

For $M_{\rm SUSY} = 10^{12}$ GeV:

$$T_d \simeq \begin{cases} 2\times 10^{11}\, GeV \\ 2\, GeV \end{cases} \qquad M_d \simeq \begin{cases} 6\times 10^{-12}\, g & bino \\ 6\times 10^{21}\, g & higgsino \end{cases}$$

The mass of DM inside horizon $M = 3.4\times 10^{16} (T/100\, GeV)^{-3} (N_{eff}/100)^{-3/4}\, g$

$$M \ll M_d, M \gg M_d$$

Peculiar velocities just after the horizon crossing $v_{pH} \simeq \delta_H c/3$

Free streaming. For bino $M_{fs} \simeq 4.6\times 10^{-11}\, g \simeq 260\, m_{\chi}$

In the case of a higgsino $M_{fs} \ll m_{\chi}$ and the free-streaming plays no role

Non-standard spiky density perturbation spectrum

$$\sigma_H(M) \simeq 9.5\times10^{-5}\left(\frac{M}{10^{56}}g\right)^{(1-n_p)/4}$$

(Green, Liddle 1997)

7-year WMAP data $n_p = 0.963 \pm 0.014$ $\Rightarrow$ the variance $\sigma_H(M)$ is too small for the formation of clumps at the RD stage.

<u>Clumps can be produced effectively at radiation dominated cosmological stage only from non-standard spectra</u>

Flat segment in the inflationary potential *(Starobinsky 1992), (Ivanov, Naselsky, Novikov 1994)*

$\delta_H \sim M_{Pl}^{-3} V^{3/2}/V'$ $V' = dV(\phi)/d\phi \to 0 \Rightarrow$ peak in the perturbation spectrum

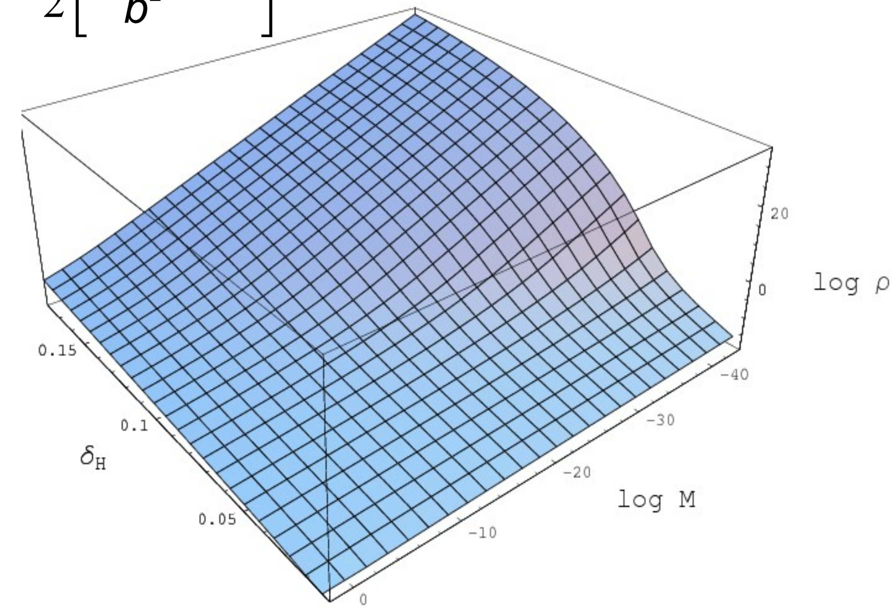
Inflationary models with several scalar fields *(Yokoyama 1995), (Garcia-Bellido, Linde, Wands 1996)*

Evidence for excess power at small scales ~10h^{-1} kpc
from the study of Lyman-α *(Demiansk, Doroshkevich 2003)*

Formation of superdense DM clumps at the RD epoch

Spherical model *(Kolb, Tkachev 1994)*: $y(y+1)\frac{d^2b}{dy^2}+\left[1+\frac{3}{2}y\right]\frac{db}{dy}+\frac{1}{2}\left[\frac{1+\Phi}{b^2}-b\right]=0$

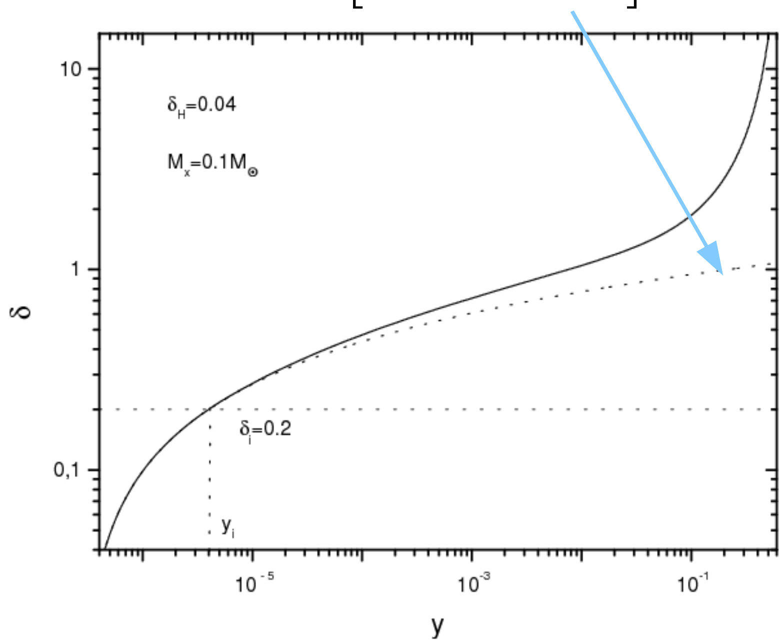
where $y=a(\eta)/a_{eq}$, $\eta=dt/da$, $\Phi=\delta\rho_{DM}/\rho_{DM}$; $r=a(\eta)b(\eta)\xi$

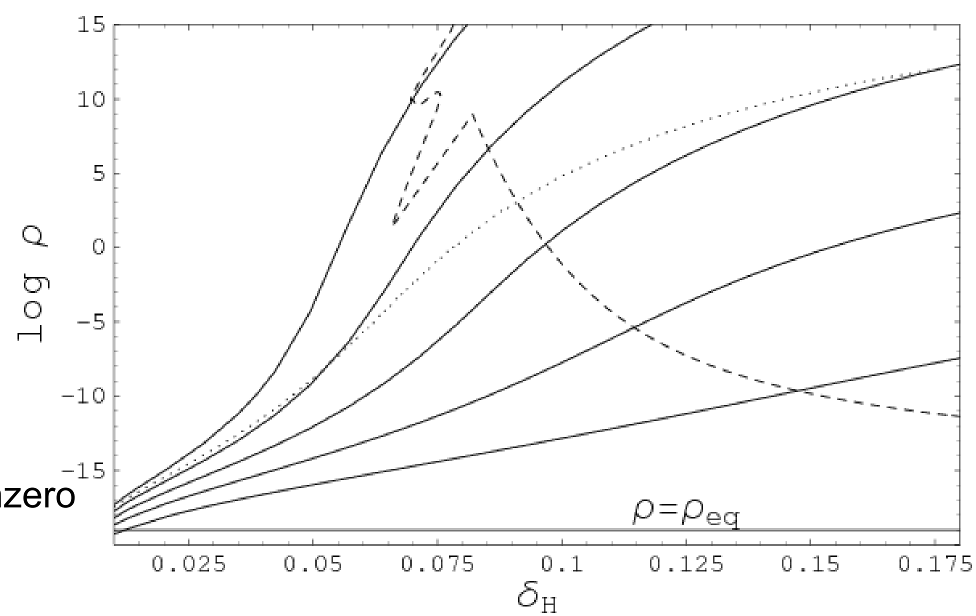


The formation of clumps from entropy perturbations *(Kolb, Tkachev 1994). db/dt=0,* $\rho\simeq 140\,\Phi^3(\Phi+1)\rho_{eq}$

$\Phi\sim 1-10^4$ in the case of axionic miniclusters with $M\sim(10^{-13}-0.1)M_\odot$

Linear evolution of adiabatic perturbations during the RD epoch: $\delta=\frac{3A}{2}\left[\ln\left(\frac{x}{\sqrt{3}}\right)+\gamma_E-\frac{1}{2}\right]$ where $x=k\,\eta$





Nonlinear evolution: $\Phi=0$, but the initial velocity db/dt is nonzero

Fraction of DM in the form of superdense clumps is $\xi\sim 1/2$

Relaxation in clumps, “gravithermal catastrophe”

Universal power-law density profile with exponent β=1.7 – 1.9 *(Gurevich, Zybin 1988)*

Core radius = ? Maximal central density = ?

EW scattering ~1/m². Gravitational two-body scattering ~m² may becomes the dominant process for the superheavy particles!

Two-body gravitational relaxation: $t_{rel,gr} \simeq \frac{1}{4\pi} \frac{v^3}{G^2 m^2 n \ln(0.4\mathrm{N})}$ *(Spitzer, Saslaw 1966)*

After the core collapsed, the singular profile $\rho \propto r^{-2}$ extends formally down to very small radius R_c

- EW elastic scattering of SHDM particles.
  The core remains transparent for superheavy neutralinos.

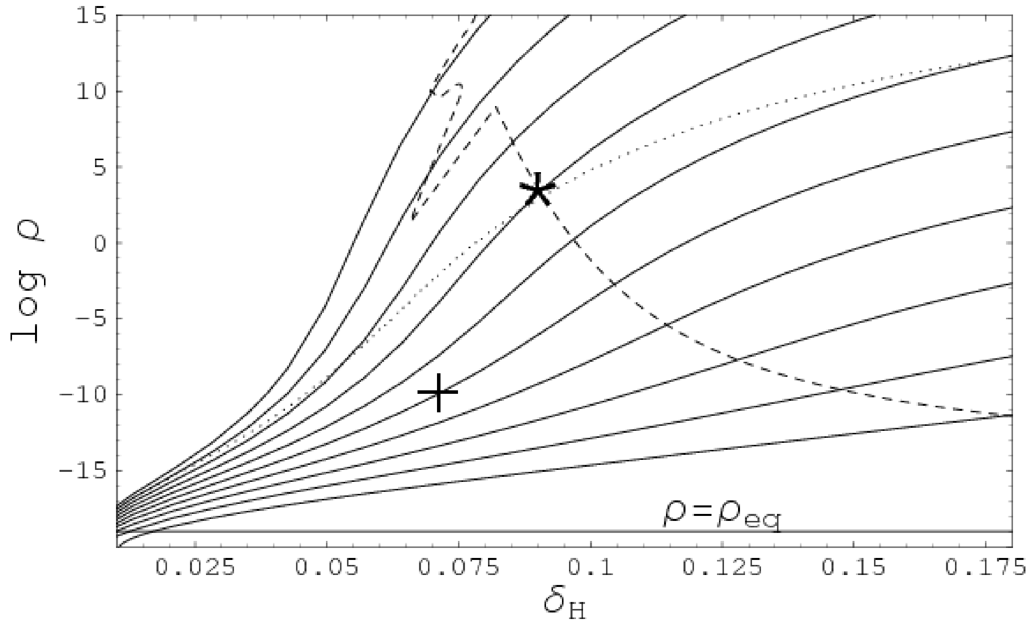
- Particle annihilation in core
  (Berezinsky, Gurevich, Zybin 1992)
  (Berezinsky, Bottino, Mignola 1997)

$$x_c^2 \equiv R_c/R \simeq \frac{\langle \sigma v \rangle \rho^{1/2}}{G^{1/2} m} \sim 7.4 \times 10^{-13}$$

- Fermi degeneration

$$p_F = (3\pi^2)^{1/3} (\rho_c/m)^{1/3} = m V_c$$

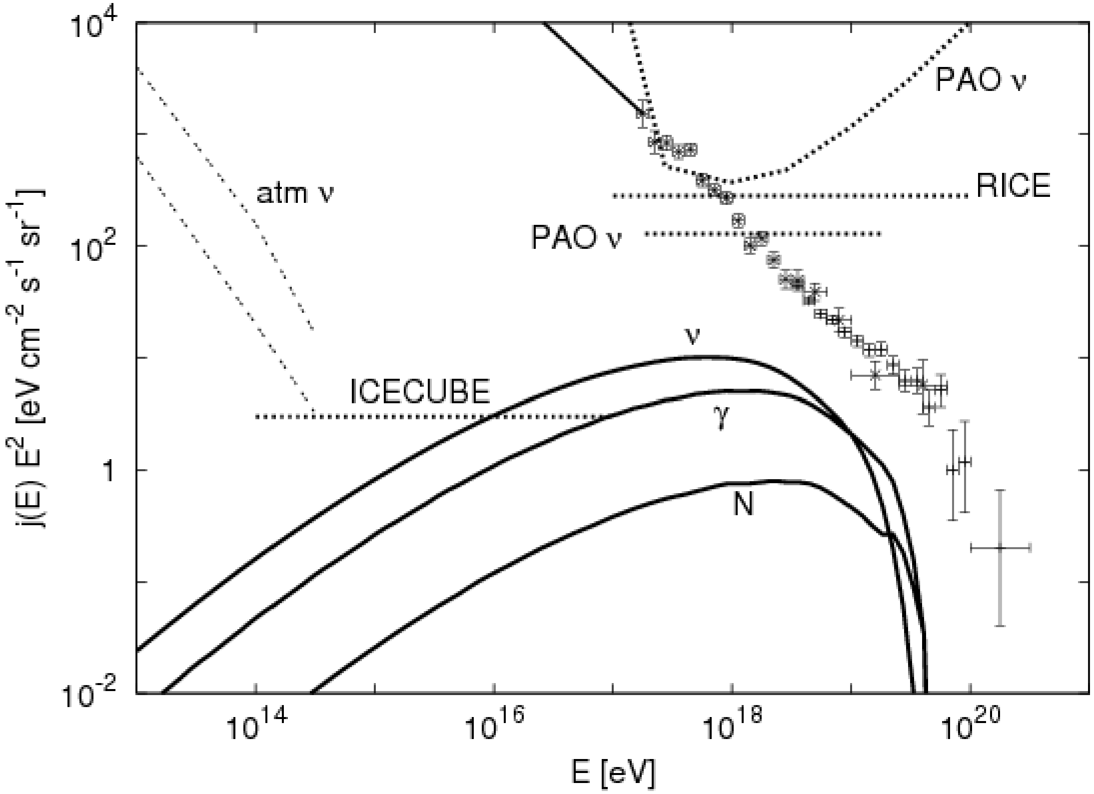
$$x_c^2 \simeq \pi^2 \frac{\bar{\rho}}{m^4} \left(\frac{GM}{R} \right)^{-3/2} \sim 10^{-11}$$



Annihiation signals

Flux $I_i(E)$ of particles $i = N, \gamma, \nu$ from DM annihilations summed over all DM clumps in the Galactic halo: $I_i(E) = \frac{1}{2} \dot{N}_{ann} F \frac{1}{m} \frac{dN_i}{dx}$

where dN_i / dx is the differential number of particles of type *i* produced per annihilation with energy *E=xm*



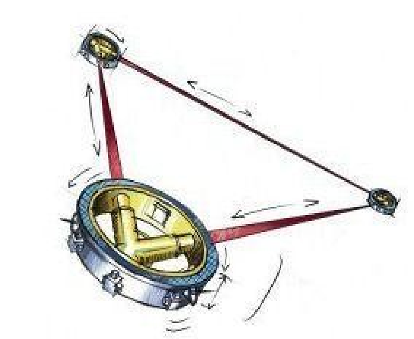
Spectra and fragmentation functions dN_i / dx *are* from *(Berezinsky, Kachelries 2001)* and *(Aloisio, Berezinsky, Kachelries 2004)*

Search for clumps by gravitational waves' detectors

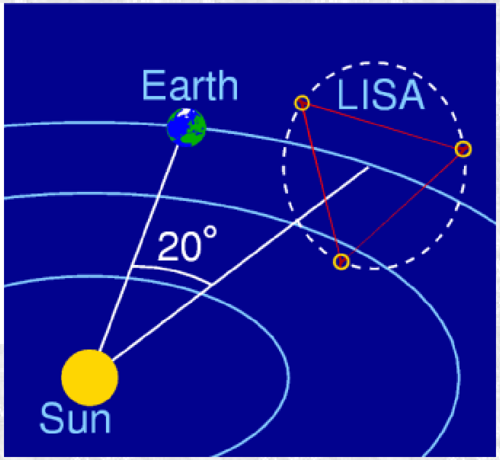
Primordial black holes *(Seto, Cooray 2004)*

Asteroids *(Tricarico 2009)*

Compact DM objects of unknown nature:
(Adams, Bloom, 2004,
"*Direct Detection of Dark Matter with Space-based Laser Interferometers*", arXiv:astro-ph/0405266v2)



lisa.nasa.gov

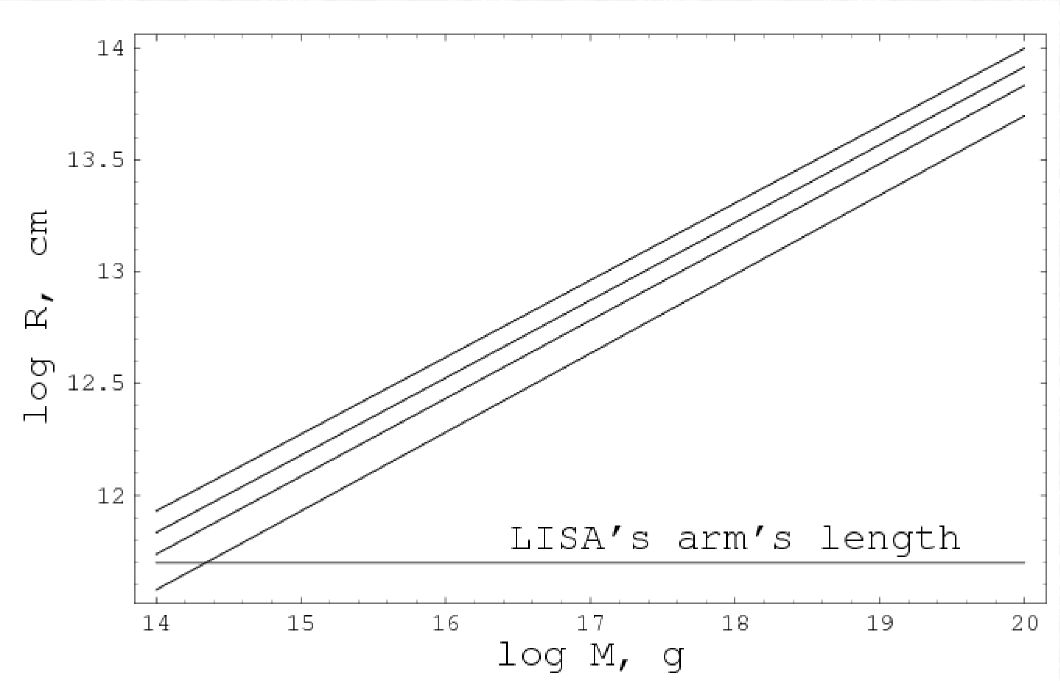


Superdense clumps should be included
in this list of objects.

Frequency range: 0.03 mHz–0.1 Hz

Mass interval for LISA 10^{16} g < M < 10^{20} g *(Seto, Cooray 2004)*
10^{14} g < M < 10^{20} g *(Adams, Bloom 2004)*

Standard power-law spectrum with
n_p=0.949,0.963,0.977 and 1



Conclusions

- Superdense clumps can be produced during the radiation dominated epoch from spikes in the spectrum of adiabatic perturbations.
- Being produced very early, superdense clumps do not belong to hierarchical structures for a long time, and therefore they are not destroyed during the formation of large-scale structures.
- Ordinary 100 GeV neutralinos are excluded as the constituents of superdense clumps, because they overproduce the diffuse gamma-ray spectrum.
- The limit on the superdense clumps is imposed by primordial black holes which originated from the same perturbation spectrum.
- For very heavy constituent particles and large intrinsic densities of the clumps a gravithermal catastrophe may develop in clumps. As a result the initial density profile turns into an isothermal one, and the large initial core collapses into a tiny, very dense new core.
- Superdense clumps can lead to detectable gamma radiation even in the case of superheavy DM particles.
- Superdense clumps can be in principle observed when the clumps are passing by gravitational wave detectors.

Details can be found in arXiv:1002.3444v2 and arXiv:1002.3445v2