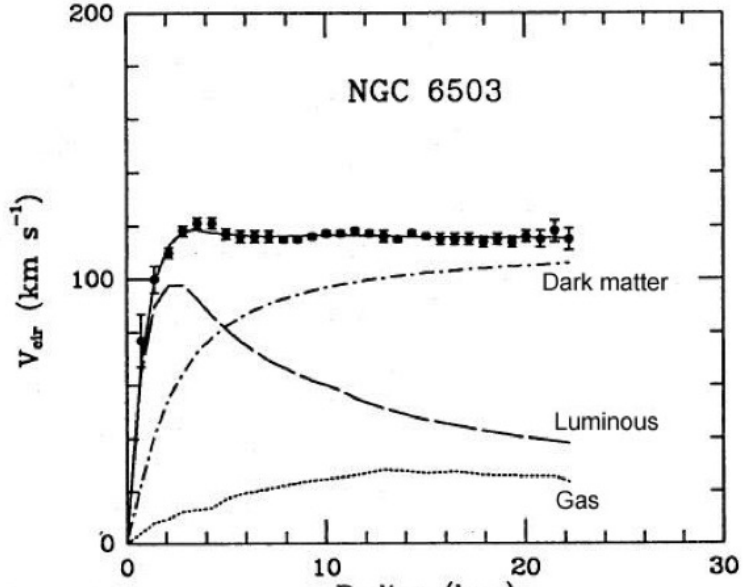
Novel Signatures of Dark Matter Clusters in Direct Detection Experiments

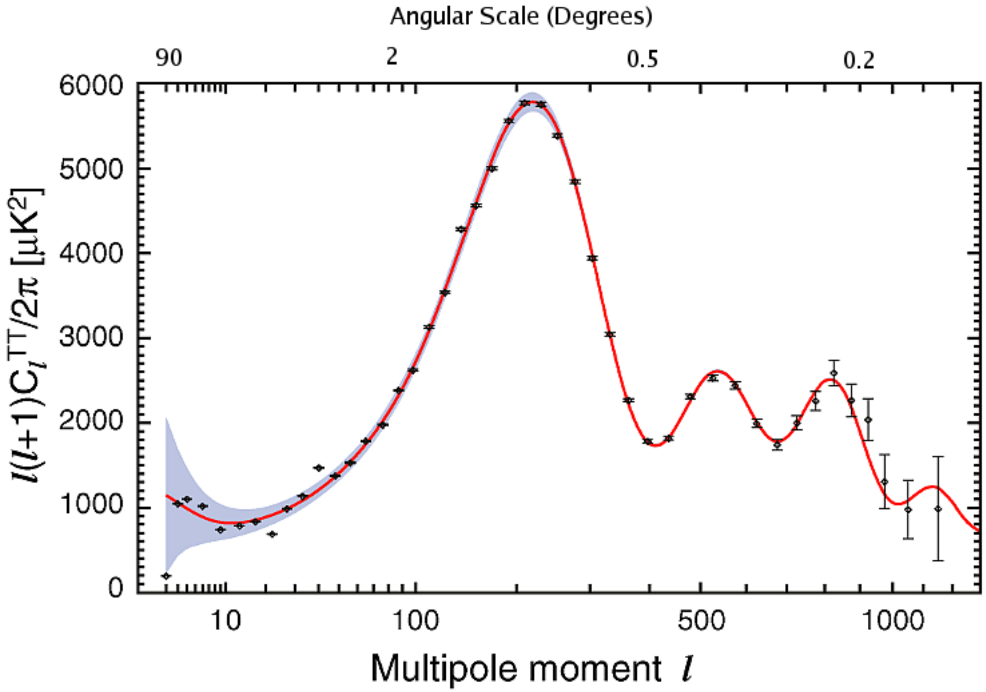
Yongchao Zhang
Washington University in St. Louis

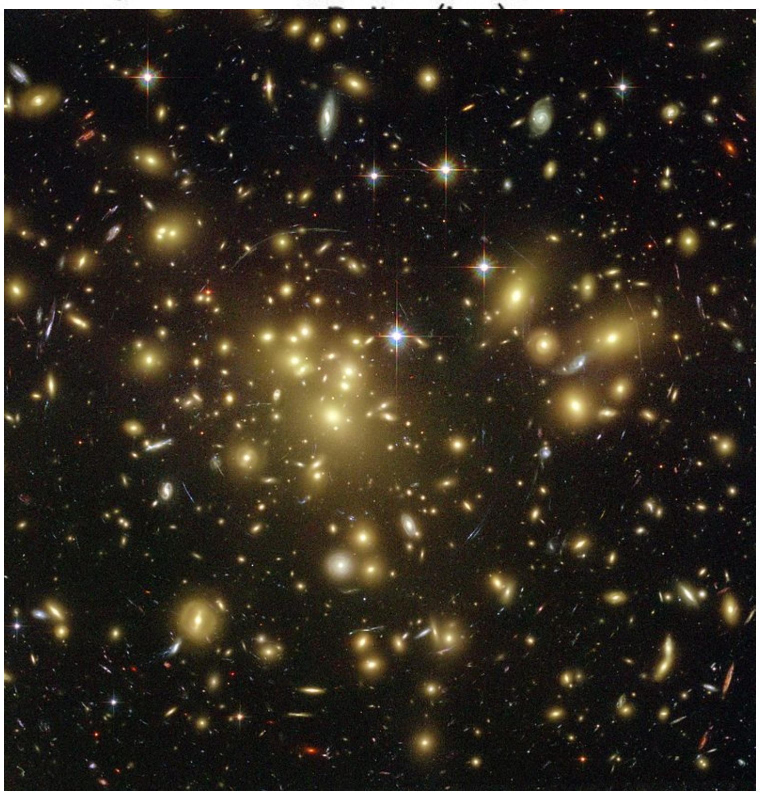
Based on:

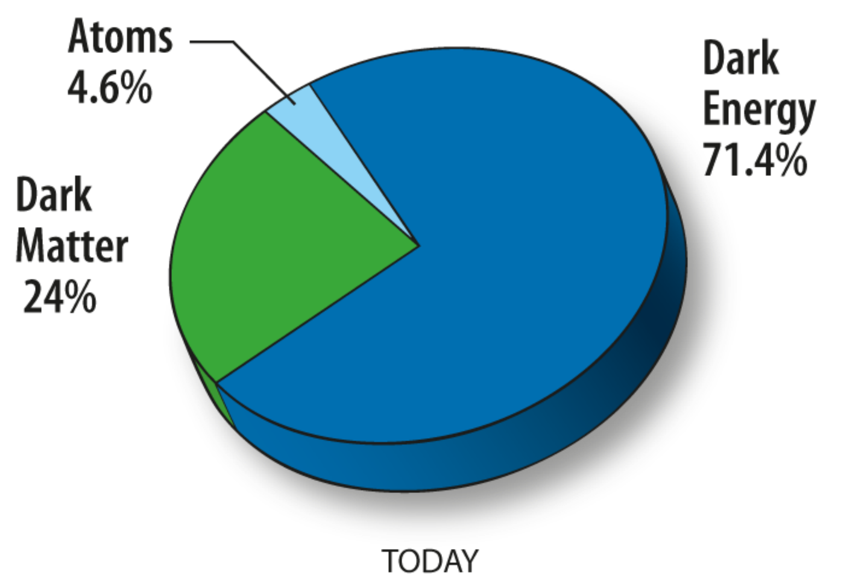
Shmuel Nussinov & YCZ, 1807.00846

Oct 6, 2018
6th PIKIO meeting, University of Notre Dame

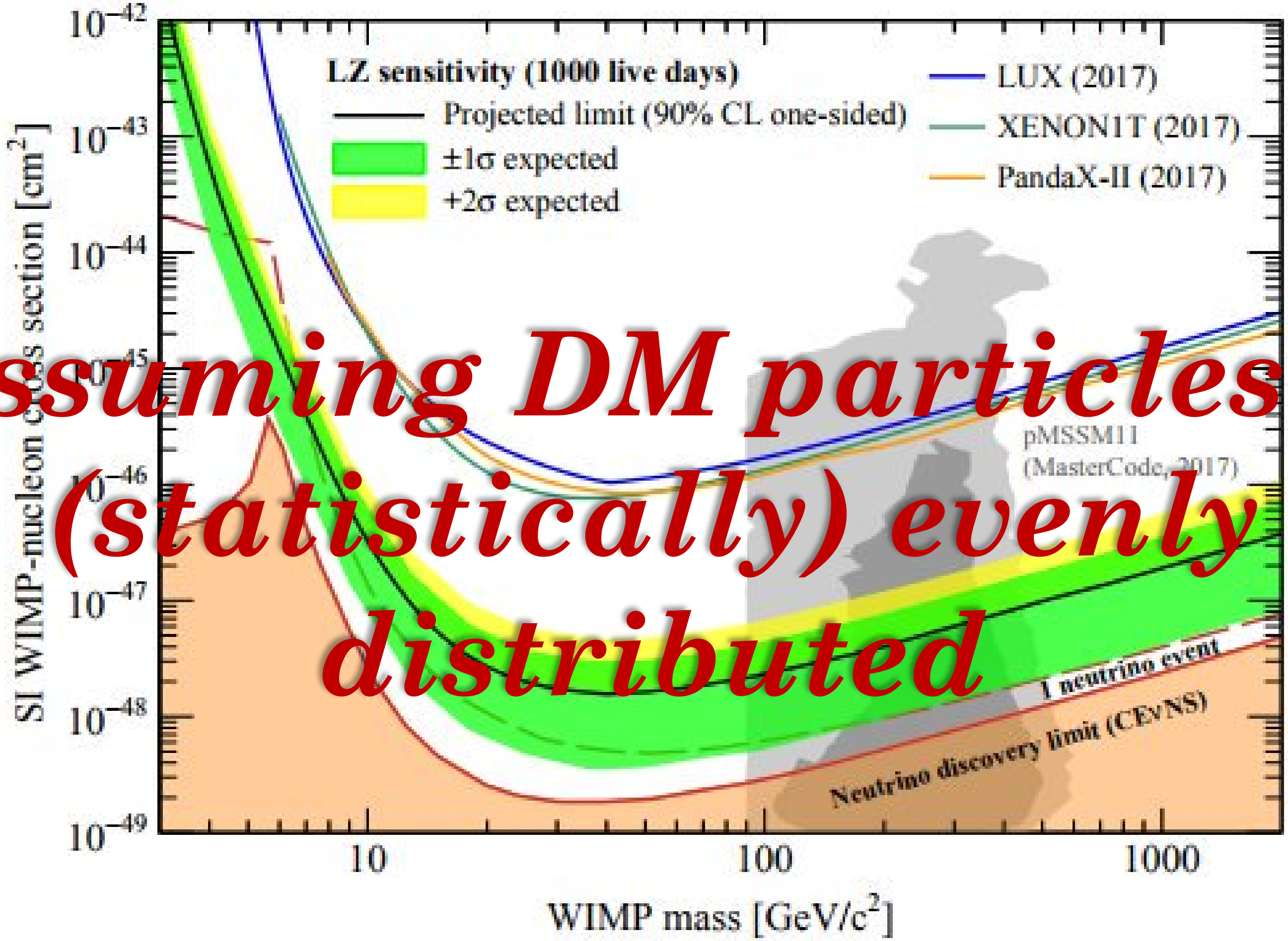

NGC 6503
Dark matter
Luminous
Gas
V_{cir} (km s^{-1})
200
100
0
0
10
20
30


Angular Scale (Degrees)
90
2
0.5
0.2
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l^{TT}/2\pi$ [μK^2]
10
100
500
1000
Multipole moment l




Atoms
4.6%
Dark
Energy
71.4%
Dark
Matter
24%
TODAY

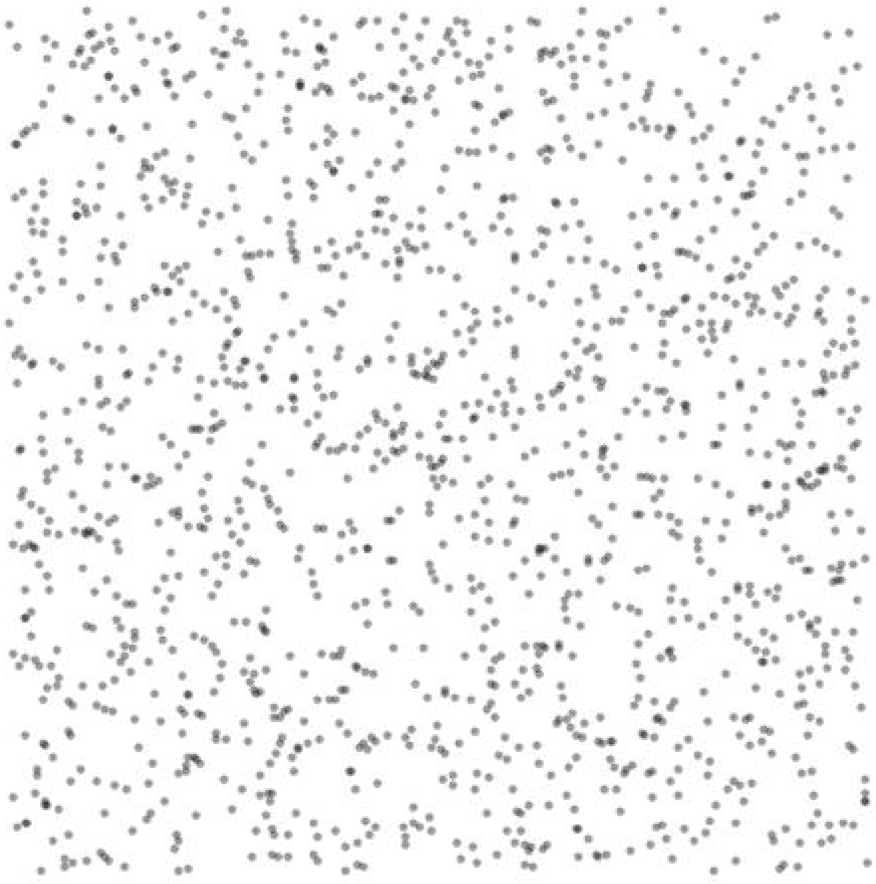
Direct detection of DM

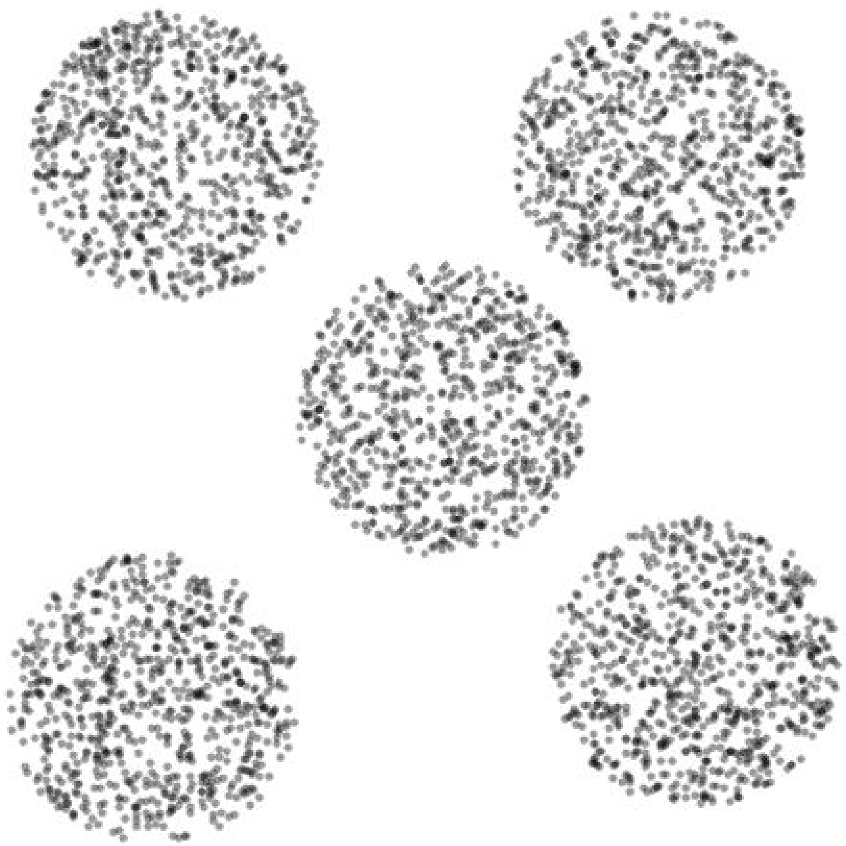


…assuming DM particles are (statistically) evenly distributed

From 1802.06039

DM clusters…





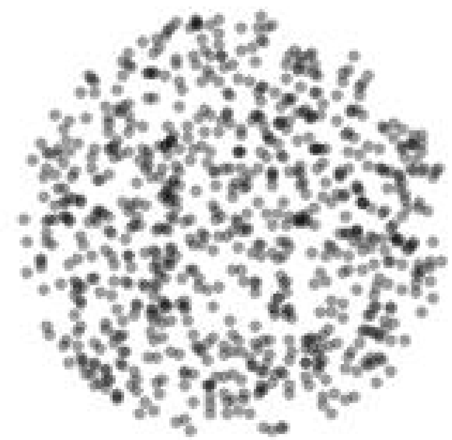
unclustered case

clustered case

Overall average density $\rho_{DM} \approx 0.3$ GeV/cm^3

Simplifying assumptions

- Single DM-particle component
  (*WIMP DM*)
- Spherical clusters with uniform DM number (or mass) density inside the cluster
- The same cluster radius R and enhancement factor E for all clusters
  It is possible that the clusters have hierarchical structures
- Most (or 100%) DM particles are inside the clusters
  It is also possible that only part of DM clusters



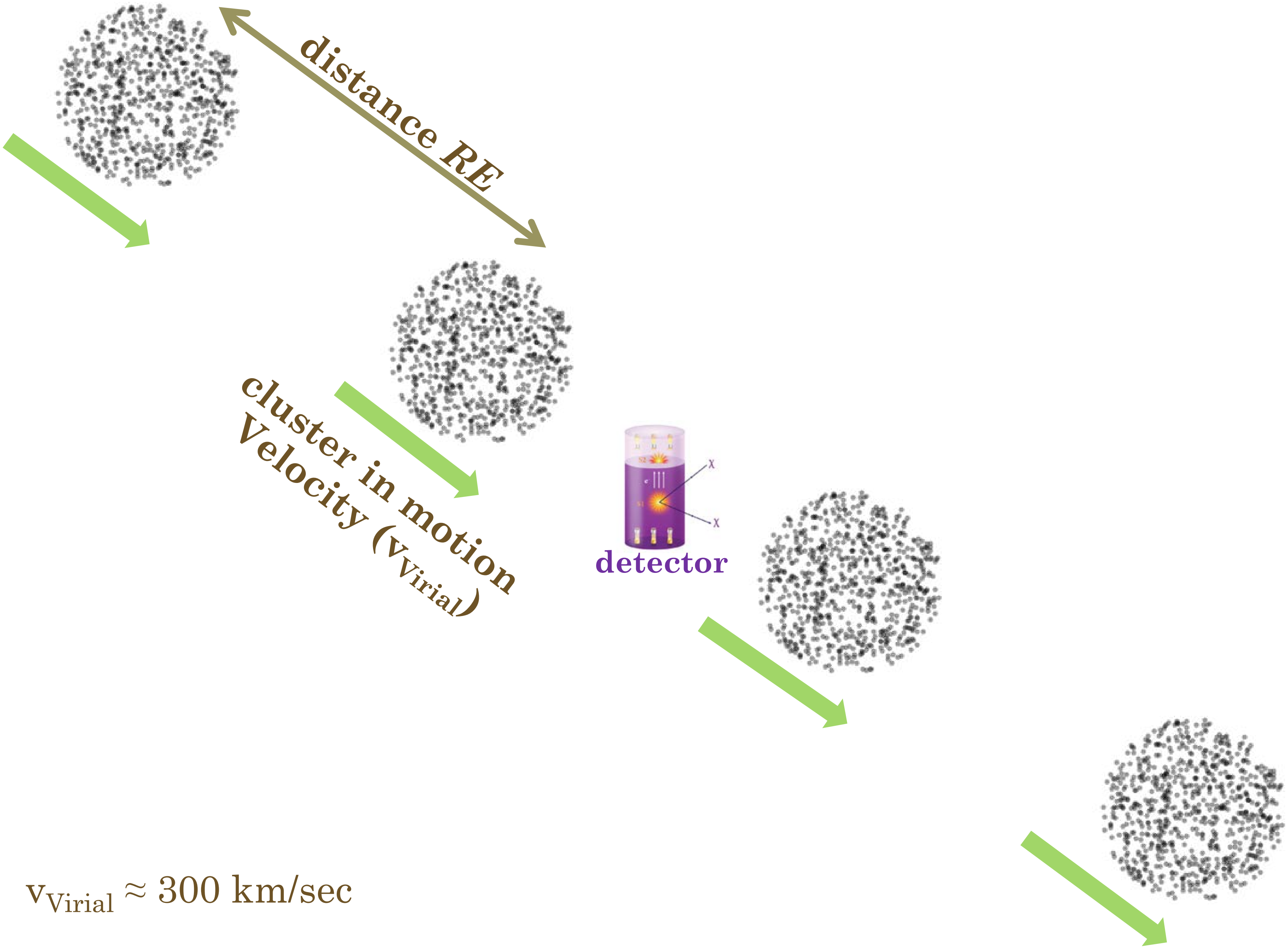
Implications for Direct detection
(liquid Xenon experiments)

- Two key parameters
  - DM cluster size R
  - Enhancement factor E
- The clusters occupy only a fraction $1/E$ of space so as to keep the average spatial density 0.3 GeV/cm^3 of DM
- A terrestrial detector is inside a cluster during only a fraction $1/E$ of the time.
- On average a distance RE has to be traversed before the detector encounters the next cluster
  Mean-free-path

$$l_{\rm MFP} \simeq \frac{1}{\sigma_{\rm cls} n_{\rm cls}} = RE$$

$$n_{\rm cls} = 1/ER^3 : \text{number density of clusters}$$

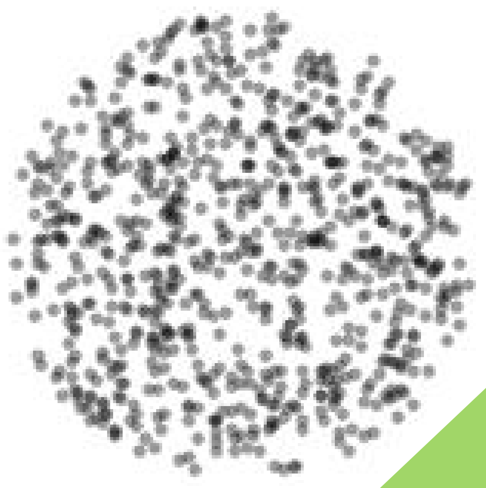
$$\sigma_{\rm cls} \simeq R^2 : \text{cross-section for colliding with a cluster}$$



$v_{Virial} \approx 300$ km/sec

“Large” clusters

Cluster go through the whole detector



Direct Detection of DM clusters

- Average "dry spells" during which the earth is outside any cluster:

$$\Delta t \ = \ \frac{RE}{v_{\rm cls}} \simeq \frac{RE}{v_{\rm Virial}} \simeq (1\,{\rm year}) \times \left(\frac{RE}{10^{15}\,{\rm cm}}\right)$$

- For one cluster-detector encounter, the number of DM which traverse the detector is

$$RE\, n_{\rm DM} A \ = \ 10^{16.5} \times \left(\frac{RE}{10^{15}\,{\rm cm}}\right) \left(\frac{m_{\rm DM}}{100\,{\rm GeV}}\right)^{-1} \left(\frac{A}{{\rm meter}^2}\right)$$

$n_{\rm DM}$: average DM density

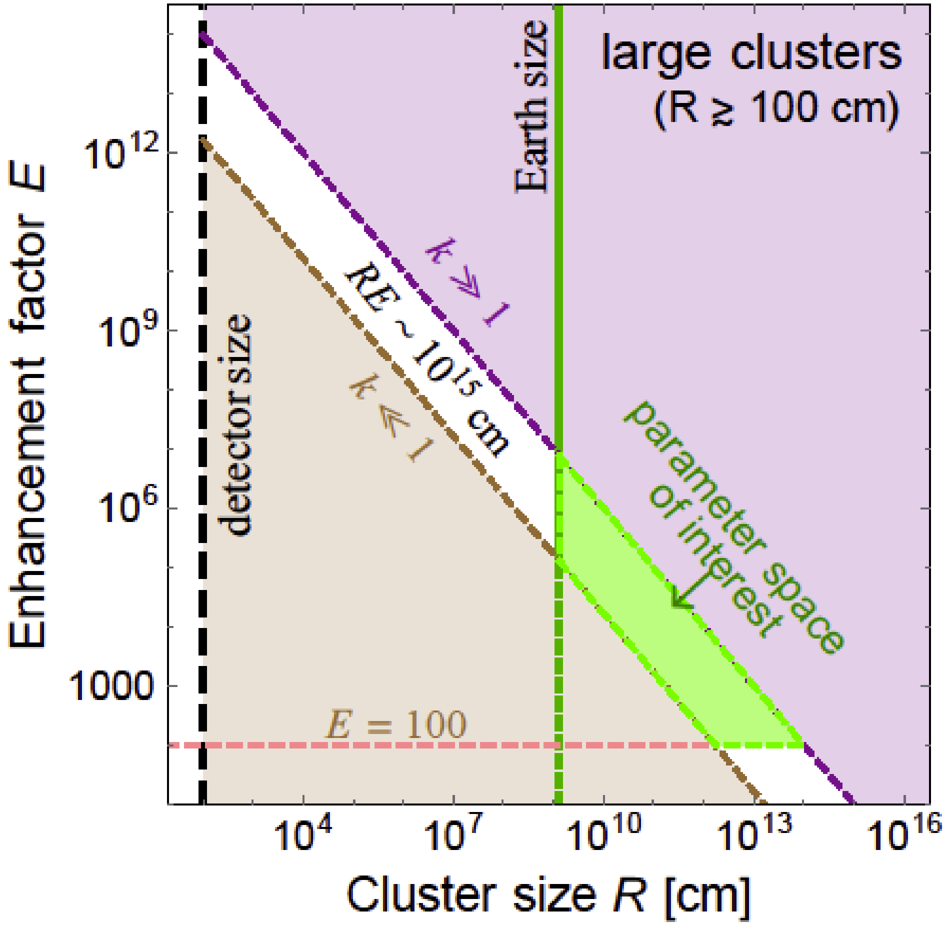
A : detector transverse area

- This is roughly the number of DM particles traversing it during a year in the unclustered case

Crucial scale $k = RE/(10^{15}\text{ cm})$

- If $k < 1/N_{\text{min}}$ …
  N_{min} the expected (minimal) number of DM events in one-year duration of DM experiment
  - $1/k$ clusters will be encountered during one-year duration of DM experiment; on average only kN_{min} events are expected in each encounter.
  - DM events tend to be randomly distributed over the year just as expected for the unclustered case.
- If $k > 1$ …
  - The failure of DM experiments may then simply reflect the fact that they run for less than k years.
  - The DM exclusion curves appropriate for unclustered DM are **no longer** justified.
  - The DM events would be rather “condensed”, occuring during less than 100 sec rather than be uniformly distributed over k years.

Parameter space of interest (large clusters)



- $RE \sim 10^{15}$ cm
- $R > 10^9$ cm (Earth size)
- $R < 10^{13}$ cm ($E > 100$)

$$\boxed{\begin{aligned} R &\simeq 10^9\,\mathrm{cm} - 10^{13}\,\mathrm{cm} \\ &= (1 - 10^4)\,R_\oplus\,, \end{aligned}}$$

Prime interest: $k \sim 1$

- Duration of encounter:

$$\delta t \simeq R/v_{\rm Virial} \simeq 30 - 3 \times 10^5 \, \mathrm{sec}$$

- For the unclustered case, the probability that all other events occur within ($10^{-6} - 10^{-2}$) fraction of a year near a reference time is, for $N_{\rm min} = 6$ & $N_{\rm det} = 2$

$$\begin{aligned} P &= 10^{-6[\mathcal{N}_{\rm det}\mathcal{N}_{\rm min}-1]} \quad \text{to} \quad 10^{-2[\mathcal{N}_{\rm det}\mathcal{N}_{\rm min}-1]} \\ &\simeq 10^{-66} \quad \text{to} \quad 10^{-22} \end{aligned}$$

- ...even if only 1/3 of DM clusters

$$\begin{aligned} P &= 10^{-6[\mathcal{N}_{\rm det}\mathcal{N}_{\rm min}/3-1]} \quad \text{to} \quad 10^{-2[\mathcal{N}_{\rm det}\mathcal{N}_{\rm min}/3-1]} \\ &\simeq 10^{-18} \quad \text{to} \quad 10^{-6} \end{aligned}$$

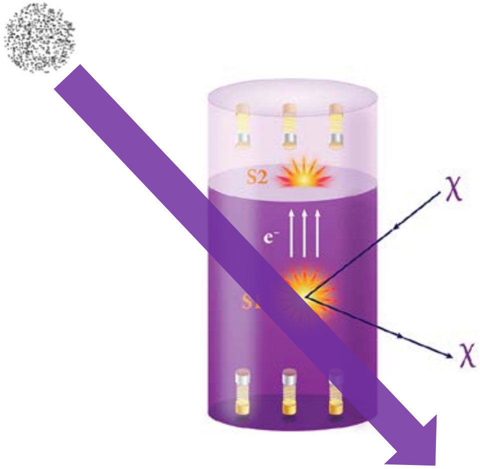
“Smoking-gun” signal of clustered DM

“***Coincident***” events during a time window of $(30 - 3 \times 10^5)$ sec from ***joint*** encounter of different DM experiments with the same DM cloud.

- DM events can be easily discriminated from the noises which are *not* correlated in different experiments.
- ***Minimal*** collaboration is required between DM experiments in different continents, … just like observation of the recent two neutron star merger.

“Small” clusters

Cluster goes through only a cylinder inside the detector, aligned along the moving direction



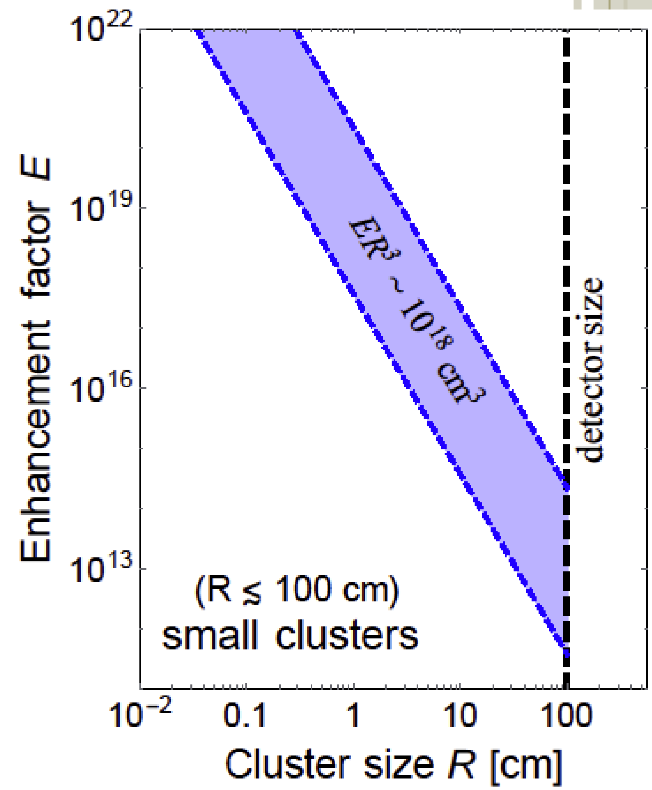
Small clusters (R < 100 cm)

- DM particles number (or mass) in the "grain" should equal that passing through the detector in the unclustered case
- Grain mass, indepenent of DM particle mass

$$M_{\rm grain} = \rho_{\rm DM}\, v_{\rm Virial}\, A\, t_{\rm run}$$
$$\simeq 5.1 \times 10^{-6}\,{\rm gram} \times \left(\frac{A}{10^4\,{\rm cm}^2}\right)\left(\frac{t_{\rm run}}{1\,{\rm year}}\right)$$

- Number of DM particles traversing the detector.

$$\mathcal{N}_{\rm DM} = 2.8 \times 10^{16} \times \left(\frac{m_{\rm DM}}{100\,{\rm GeV}}\right)^{-1}$$



Implications for direct detection

- DM events will ***not*** be ***uniformly*** distributed over the detector but rather will be within a cylinder, aligned along the moving direction of the grain, ***once $N_{event} \geq 2$***

$$f \simeq \frac{\pi R_{\rm eff}^2}{L^3} \simeq 3 \times 10^{-4} \times \left(\frac{R_{\rm eff}}{1\,{\rm cm}}\right)^2 \left(\frac{L}{100\,{\rm cm}}\right)^{-3}$$

- All the interactions induced by the "optimal" grain hit detector during a short time, which takes one year in the unclustered case.

$$\delta t = \frac{L}{v_{\rm Virial}} \simeq 3 \times 10^{-6}\,{\rm sec} \times \left(\frac{L}{100\,{\rm cm}}\right)$$

- All DM events should define a ***common*** velocity $v_{\rm Virial}$

$$\frac{|r_i - r_{i+1}|}{|t_i - t_{i+1}|} = v_i = v_{\rm Virial} \simeq 300\,{\rm km/sec}$$

The velocity information could…

- Eliminate/suppress the backgrounds, e.g. those due to penetrating relativistic muons and multiple neutron scattering.

- Indicates the direction and the source of DM clusters.

- Comparing with the WIMP wind (220 km/sec), confirm the ***cold*** DM nature

Are the clusters stable?

"breaking" effects smaller than g_{cls} or not important

- Galactic tidal acceleration

$$a_{\rm tidal}^{\rm (gal)} \simeq \frac{G_N M_{\rm gal} R}{l^3} \simeq (10^{-20} - 10^{-16})\,{\rm cm/sec}^2$$

- Tidal acceleration in cluster-stellar collision

$$a_{\rm tidal}^{\rm (str)} \simeq \frac{G_N M_\odot R}{l_{\rm str}^3} \simeq (10^{-21} - 10^{-17})\,{\rm cm/sec}^2$$

- Cluster-cluster collision

It needs 10^{18} to 10^{22} years to break the clusters!

$$a_{\rm tidal}^{\rm (cls)} = \frac{G_N M_{\rm cls}}{R^2} \qquad \frac{(\delta v)^2}{v_{\rm esc}^2} = \frac{v_{\rm esc}^2}{v_{\rm Virial}^2} \simeq 10^{-22} \text{ to } 10^{-18}$$

- Solar tidal acceleration

Fractional spreading $\delta R/R$ in the single solar passage is small

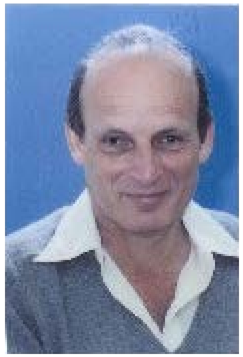
$$a_{\rm tidal}^{\rm (Sun)} = \frac{G_N M_\odot R}{{\rm Au}^3} \simeq (10^{-4.5} - 10^{-0.5})\,{\rm cm/sec}^2$$

$$\frac{\delta R}{R} = \frac{a_{\rm tidal}^{\rm (Sun)} (\delta t)^2}{2R} = \frac{G_N M_\odot}{\rm Au} \frac{1}{v_{\rm Virial}^2} \simeq 0.006$$

Conclusion

- We Propose the possibility of DM clustering and the novel implication for direct detection experiments.
- The non-trivial signature depends largely on the DM cluster size, compared to the detector size and Earth size.
- "Optimal" clusters with parameter $RE \sim 10^{15}$ cm and $R \sim (1 - 10^4)$ Earth size.
- Large cluster ($R > 100$ cm): the coincident events in different experiments during a time window of $(30 - 3 \times 10^5)$ sec is a "smoking-gun" signal of large clusters.
- Small cluster ($R < 100$ cm): The DM events are expcted to align within a cylinder of radius R_{eff}.
- The DM clusters are stable against the tidal accelerations and cluster-cluster and cluster-stellar collisions.

Acknowledgements



Shmuel Nussinov
(Tel Aviv Univ.)
Co-author

Zohar Nussinov
(Washington Univ.)

Robert Shrock
(Stony Brook)

Jordan Goodman
(Univ. of Maryland)

Ram Cowsik
(Washington Univ.)

Jim Buckley
(Washington Univ.)

Carter Hall
(Univ. of Maryland)

Backup slides

DM in clusters: symmetric?

- **Short Answer:**
  Yes, it could be (in the "optimal" clusters)!
- The mutual DM-DM annihilation required to establish the correct freeze-out residual DM density:

$$\frac{1}{n_{\rm DM}}\frac{{\rm d}n_{\rm DM}}{{\rm d}t} = c\sigma'_{\rm ann}\, n_{\rm DM}$$

$$\sigma'_{\rm ann} \sim \frac{\alpha^2}{m_{\rm DM}^2} \simeq 4\times 10^{-34}\,{\rm cm}^2 \times \left(\frac{\alpha}{0.01}\right)^2 \left(\frac{m_{\rm DM}}{100\,{\rm GeV}}\right)^{-2}$$

- The probability for DM to annihilate in the Universe age t_U is

$$P_{\rm ann} = c n_{\rm DM}\sigma'_{\rm ann} t_U$$

$$\simeq 1.5\times 10^{-7} \times \left(\frac{E}{100}\right)\left(\frac{\alpha}{0.01}\right)^2 \left(\frac{m_{\rm DM}}{100\,{\rm GeV}}\right)^{-3}$$

For $k = 1$ ($RE = 10^{15}$ cm), $P_{\rm ann} < 1\%$ ➔ $R > 10^8$ cm

Gravitational micro-lensing

- Gravitational acceleration at the surface of the cluster

$$\begin{aligned} g_{\rm cls} &= \frac{G_N M_{\rm cls}}{R^2} \simeq \frac{4}{3}\pi G_N\, RE\, \rho_{\rm DM} \\ &\simeq 1.5\times 10^{-16}\,{\rm cm/sec^2} \end{aligned}$$

- Escape velocity from the cluster (for the region of prime interest):

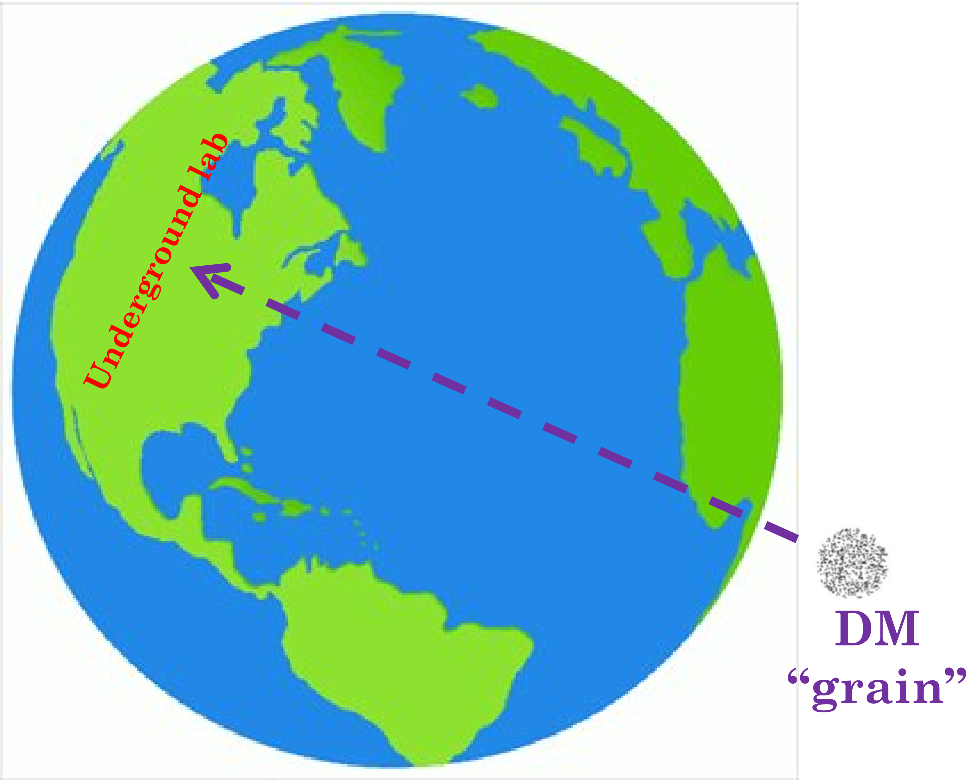
$$\begin{aligned} v_{\rm esc} &\simeq \sqrt{\frac{G_N M_{\rm cls}}{R}} = \sqrt{R g_{\rm cls}} \\ &\simeq (4\times 10^{-4} - 4\times 10^{-2})\,{\rm cm/sec} \end{aligned}$$

This ultra weak gravity of the clusters cannot induce any observable micro- or even femto-lensing effects

Efforts needed in direct detection experiments

- Such “multiple” events tends to be identified as noises and excluded in standard analysis
- Modified searches should then be done in the separate experiments to conclusively verify a DM source of such events.
- Such searches might be largely dictated by the spatial and temporal resolutions and other relevant features of these experiments.

Effect of passage in earth



Effect of passage in earth (negligible)

- The cluster will undergo $N_{col} \sim 10^8$ collisions while traversing the full earth en-route to the underground detector (assuming 6 collisions while traversing the ~ 1 meter size detector)
- These collisions will not modify our analysis if the recoiling DM particles simply leave the grain before the cluster reaches the detector.
- If, in the "worst" case, all DM particles which collided with nuclei (A, Z) in the Earth remain in the grain, then the deposited energy

$$
\begin{aligned}
W &= \mathcal{N}_{\rm col} E_{\rm recoil} \; < \; \mathcal{N}_{\rm col} \times \frac{1}{2} M_{\sf AZ}\, v^2_{\rm Virial} \\
&\simeq 3\,{\rm erg} \times \left(\frac{\mathcal{N}_{\rm col}}{10^8}\right)\left(\frac{M_{\sf AZ}}{30\,{\rm GeV}}\right)
\end{aligned}
$$

- This will heat up the grain by a temperature rise of 0.02deg Kelvin, if the specific heat of the DM grain is close to that of water.

Cluster Formation in the early universe

…for cold DM, almost scale free primordial density fluctuations lead to clustering on many different scales.

Cluster formation condition

- We *assume* the cluster collapse occurs before the galaxies and other structures form, say at redshift z = 100.

$$M_{\rm cls} = \frac{4}{3}\pi R_{\rm col}^3 \rho_{\rm DM}(z=100) = \frac{4}{3}\pi E R^3 \rho_{\rm DM} \simeq (10^9 - 10^{17})\,{\rm gram}$$

$$R_{\rm col} \simeq (10^{10} - 2\times 10^{13})\,{\rm cm}$$

- DM has to cool enough between the time of its freeze-out at a temperature of $T_{fo} \sim m_{DM}/20$ and z = 100, so that its final thermal energy $\sim T_{final}$ at z = 100 is lower than the gravitational binding energy:
  (a condition related to having imaginary plasma frequency in the more sophisticated Jeans instability criterion, see Weinberg, Gravitation and Cosmology)

$$T_{\rm final} \leq \frac{G_N M_{\rm cls} m_{\rm DM}}{R_{\rm col}}$$

Implications for DM

- Consider the simplest scenario without DM dissipation or dark photon.
- Collapse temperature

$$\frac{z_{\rm fo}}{100} = \frac{T_{\rm fo}}{T_{\rm CMB}|_{z=100}} \simeq \frac{5\,{\rm GeV}}{0.025\,{\rm eV}} \times \left(\frac{m_{\rm DM}}{100\,{\rm GeV}}\right)$$
$$= 2 \times 10^{11} \times \left(\frac{m_{\rm DM}}{100\,{\rm GeV}}\right) ,$$

$$T_{\rm final} = T_{\rm fo} \times \left(\frac{z_{\rm fo}}{100}\right)^{-2} \simeq 10^{-13}\,{\rm eV} \times \left(\frac{m_{\rm DM}}{100\,{\rm GeV}}\right)^{-1}$$

- Implication for DM mass

$$\boxed{m_{\rm DM} \geq 30 \ {\rm TeV}}$$

See the papers for unitarity bounds
Griest & Kamionkowski, PRL ***64****, 615 (1990),*
S. Nussinov, 1408.1157

…to model DM clusters with appreciable efficiency, we may need to invoke

- ***Short-range interactions between the DM particles, which is essential for grain formation;***
- ***Long-range attractive interaction helping form the desired large clusters.***

…to be detailed in a future paper.
(See also 1807.03788)