Title: Nuclear Dark Matter - Synthesis and Phenomenology

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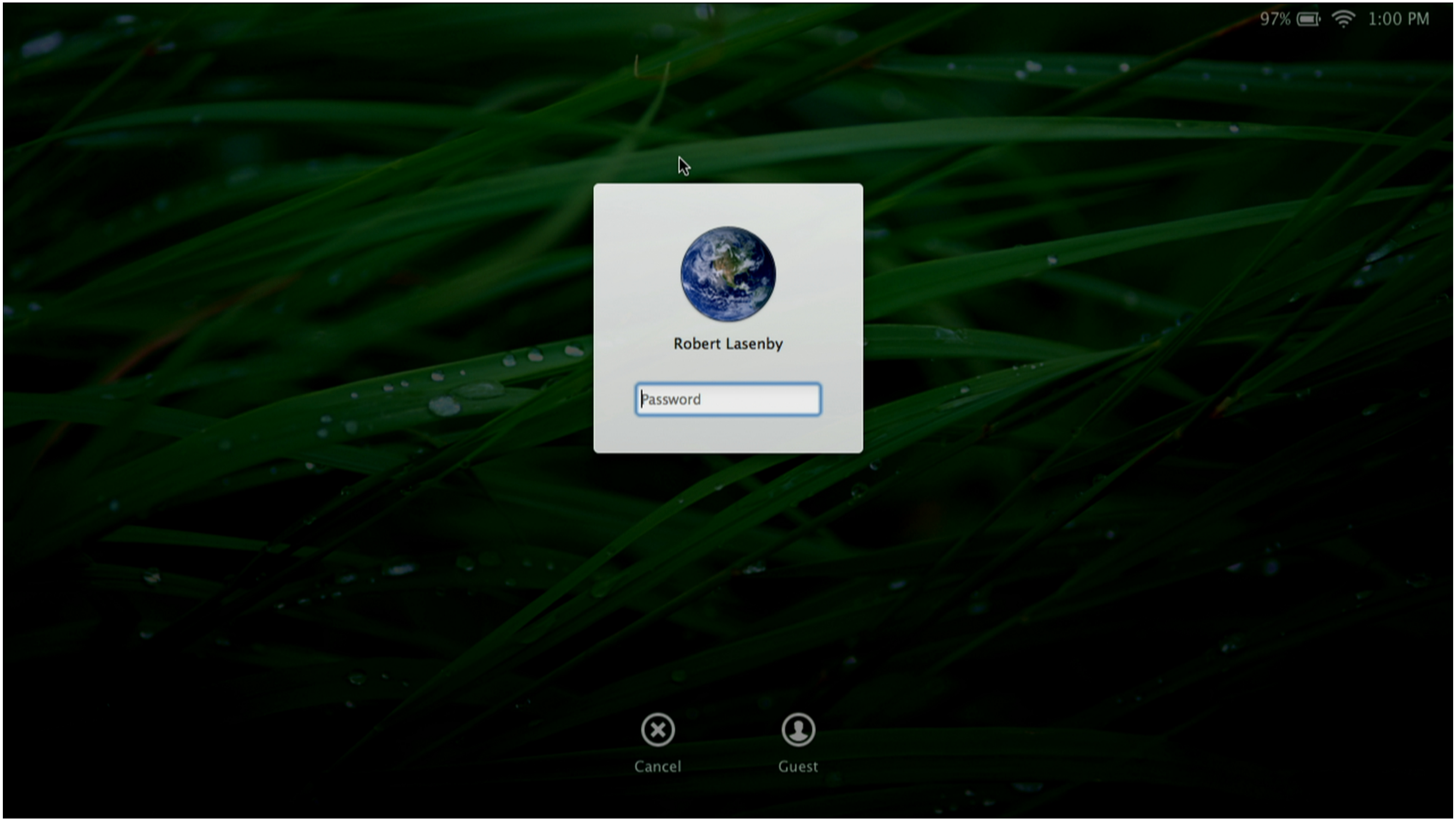
Abstract: <p>I will talk about the physics of models in which dark matter consists of composite bound states carrying a large conserved dark â€œnucleonâ€• number. The properties of sufficiently large dark nuclei may obey simple scaling laws, and this scaling can determine the number distribution of nuclei resulting from Big Bang Dark Nucleosynthesis. For plausible models of asymmetric dark matter, dark nuclei of large nucleon number, e.g. >~ 10^8, may be synthesised, with the number distribution taking one of two characteristic forms, which interestingly are broadly independent of initial conditions. A possible consequence of these scenarios is alterations to direct detection signals, which may be coherently enhanced (relative to collider signals), and could be modified by new momentum-dependent form factors. Inelastic interactions between dark matter states might also be important in astrophysical settings.</p>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Nuclear Dark Matter - Synthesis and Phenomenology

Robert Lasenby, University of Oxford

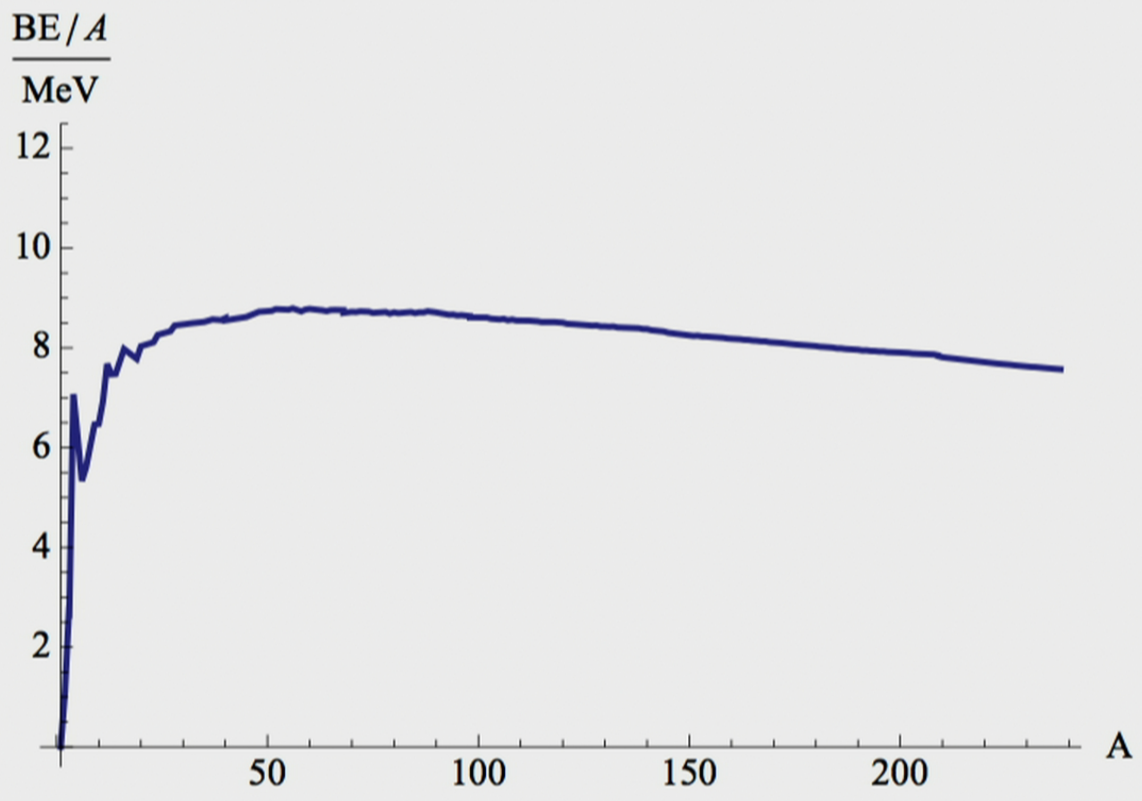
Work with E. Hardy, J. March-Russell, S. West
arXiv 1411.3739 and arXiv 1503.xxxxx

Perimeter Institute, 10/03/15

Large composite DM states

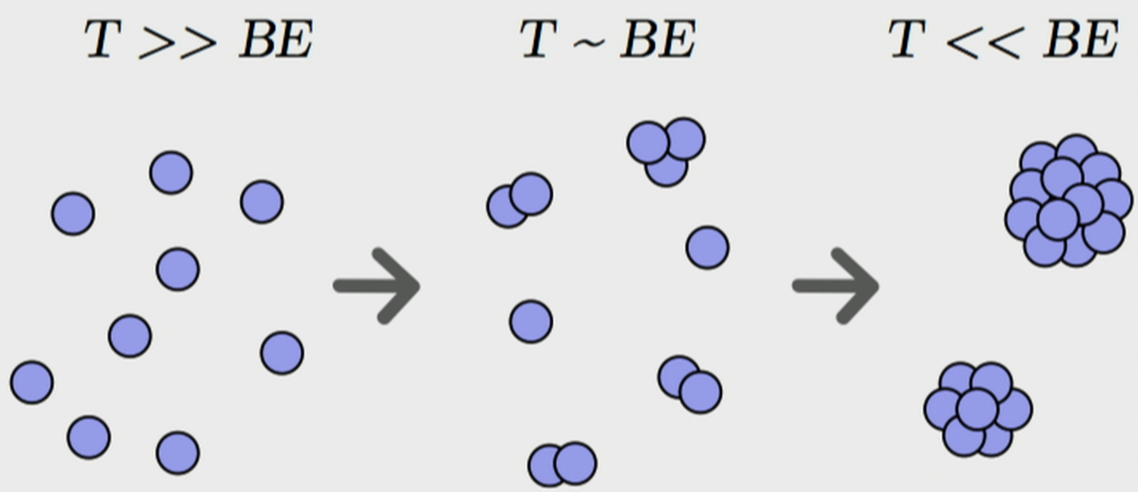
- Standard model: example of conserved baryon number, attractive interactions leading to multitude of large, stable bound states (nuclei)
- What if a similar thing happens for dark matter?
- Possibilities:
  - Number distribution over DM states
  - States with large spin
  - Structure on scales $\gg 1/m$ — form factors in scattering, possibility of larger cross sections
  - Coherent enhancement of interactions
  - Inelastic processes — fusions, fissions, excited states
  - 'Late-time' ($T \ll m$) synthesis — can achieve very heavy ($\gtrsim 100\,\mathrm{TeV}$) DM from thermal freeze-out
- Earlier example of Q-balls — non-topological solitons of scalar fields
- Related work: Krnjaic et al, Detmold et al, Wise et al

SM nuclei



Dark nucleosynthesis

Free energy $F = E - T\,S$:
large $T \Rightarrow$ everything dissociated
small $T \Rightarrow$ large states favoured
Assume asymmetric



Freeze-out of fusions

- Equal sizes: $A + A \to 2A$

$$\frac{\Gamma}{H} \sim \frac{\langle \sigma v \rangle n_A}{H} \sim \frac{\sigma_1 v_1 n_0}{H} A^{2/3} A^{-1/2} A^{-1} = \frac{\sigma_1 v_1 n_0}{H} A^{-5/6}$$

With $M_A = AM_1$,

$$\frac{\sigma_1 v_1 n_0}{H} \sim 2\times 10^7 \left(\frac{1\,\mathrm{GeV\,fm}^{-3}}{\rho_b} \right)^{2/3} \left(\frac{T}{1\,\mathrm{MeV}} \right)^{3/2} \left(\frac{M_1}{1\,\mathrm{GeV}} \right)^{-5/6}$$

so build-up to $A \sim 5 \times 10^8$ may be possible

- Small + large: $1 + A \to (1 + A)$. Rate for A of these is

$$\Gamma \sim \langle \sigma v \rangle n_k \frac{k}{A} \sim \sigma_1 v_1 n_0 \frac{1}{k^{1/2}} A^{2/3} A^{-1} = \frac{\sigma_1 v_1 n_0}{k^{1/2}} A^{-1/3}$$

Freeze-out of dissociations

- Overall forward rate for $k + (A - k) \leftrightarrow A$ is

$$\langle \sigma v \rangle_{(k,A-k)\to A} n_k n_{A-k} - \Gamma_{A\to(k,A-k)} n_A$$

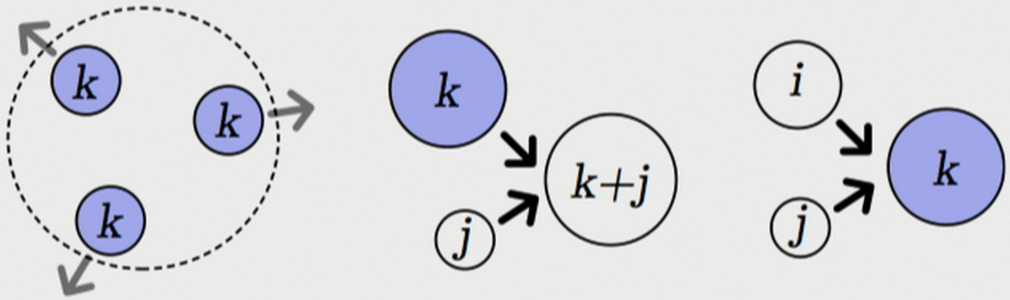
- Fusions dominate over dissociations if

$$\frac{\langle \sigma v \rangle n_k n_{A-k}}{\Gamma n_A} \gg 1 \quad \Leftarrow \quad n_0 \Lambda^3 e^{\Delta B/T} \gg (\text{const. wrt } T)$$

- Since $n_0 \Lambda^3 \ll 1$, equality is at $T \ll \Delta B$
- Go from equality to $n_0 \Lambda^3 e^{\Delta B/T} \gg$ const. within small fraction of Hubble time.

Aggregation process

$$\frac{dn_k}{dt} + 3Hn_k = -\sum_{j\geq 1} \langle \sigma v \rangle_{j,k} n_j n_k + \frac{1}{2} \sum_{i+j=k} \langle \sigma v \rangle_{i,j} n_i n_j$$



In terms of yields, $n_k(t)/s(t) \equiv Y_k(t) \equiv Y_0 y_k(w(t))$, $(\sum y_k = 1)$

where new 'time' w is $$\frac{dw}{dt} = Y_0 \sigma_1 s(t) f(T_d(t)) = n_0 \sigma_1 v_1$$

Then, $$\frac{dy_k}{dw} = -y_k \sum_j K_{k,j} y_j + \frac{1}{2} \sum_{i+j=k} K_{i,j} y_i y_j$$

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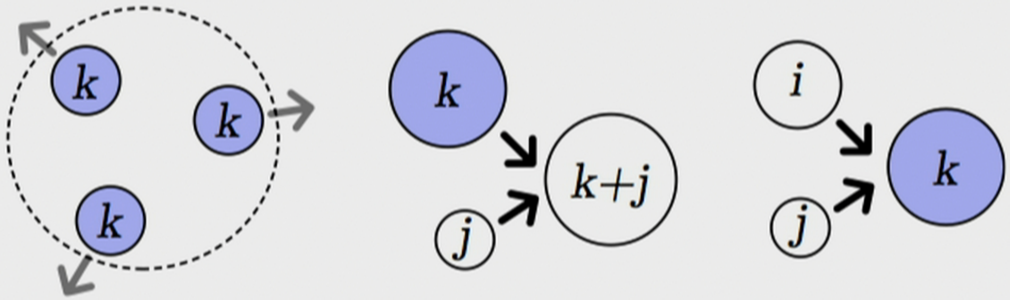

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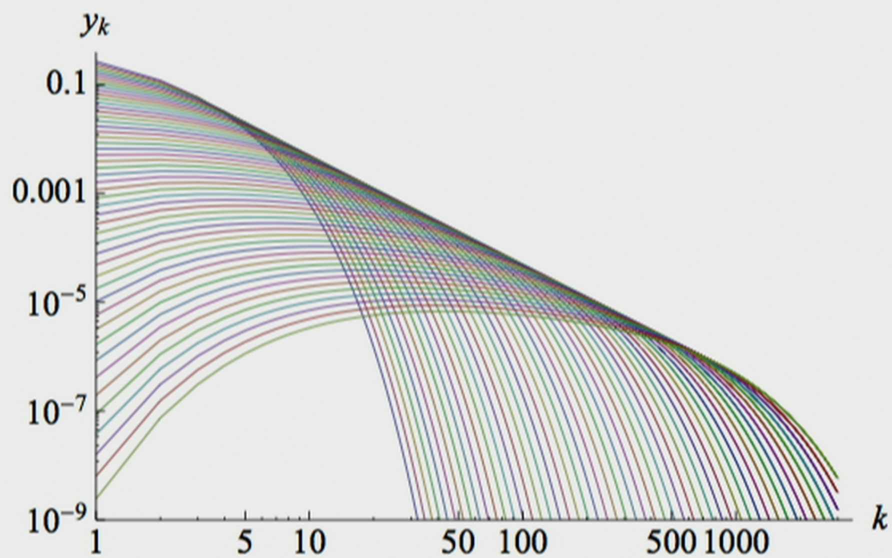
Scaling solution

$$\langle \sigma v \rangle_{i,j} \sim (\text{radius}_i + \text{radius}_j)^2 v_{\text{rel}}$$

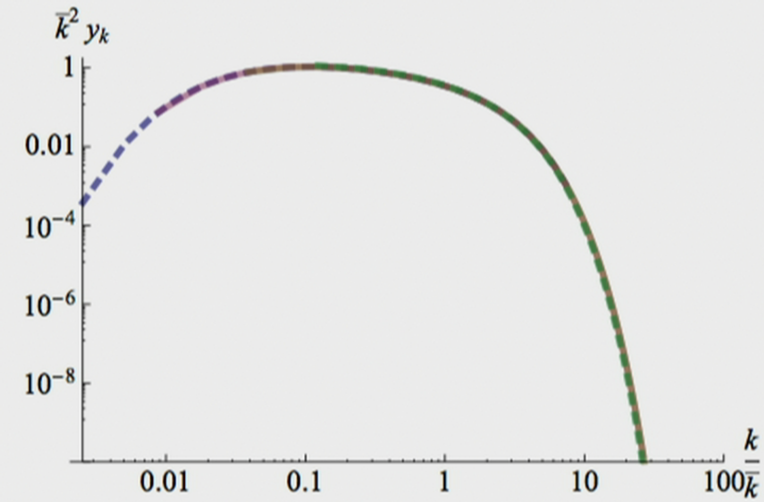
$$K_{i,j} = (i^{2/3} + j^{2/3})(i^{-1/2} + j^{-1/2}) \quad , \quad K_{\lambda i, \lambda j} = \lambda^{1/6} K_{i,j}$$



Number distributions at equally-spaced $\log w$ values, up to $w = 75$.

Scaling solution

- Shape stays the same, average size increases, $\bar{k}(w) \sim w^{6/5}$.



$\bar{k}^2 y_k$ versus $k/\bar{k}$, where $\bar{k} = 1/\sum_k y_k$.

- Attractor solution, depending only on large-k behaviour of kernel — reach this form (eventually) independent of initial conditions, small-k kernel.

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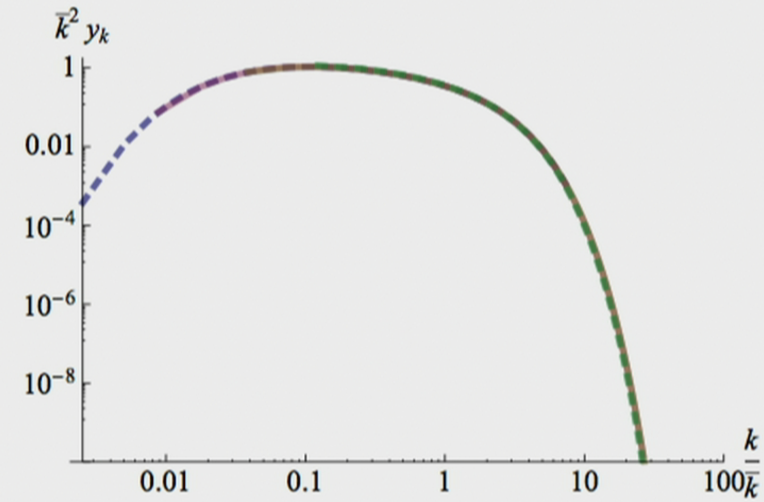

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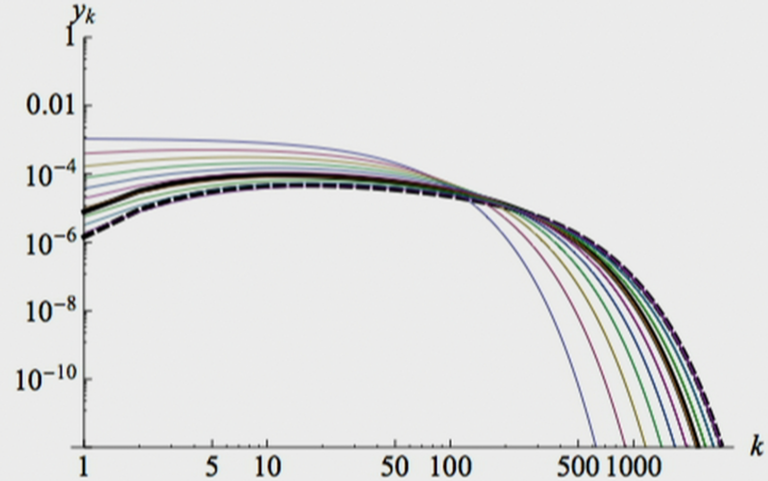
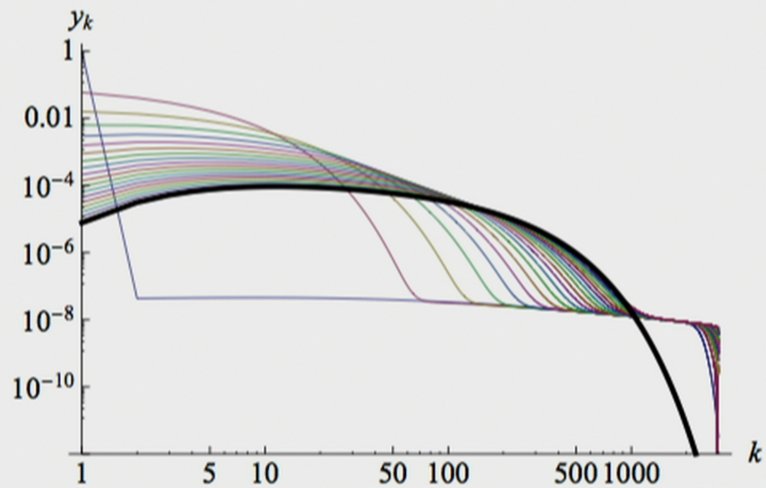
Independence of initial conditions

Exponentially-falling ICs,
$y_k(0) \propto e^{-k/30}$



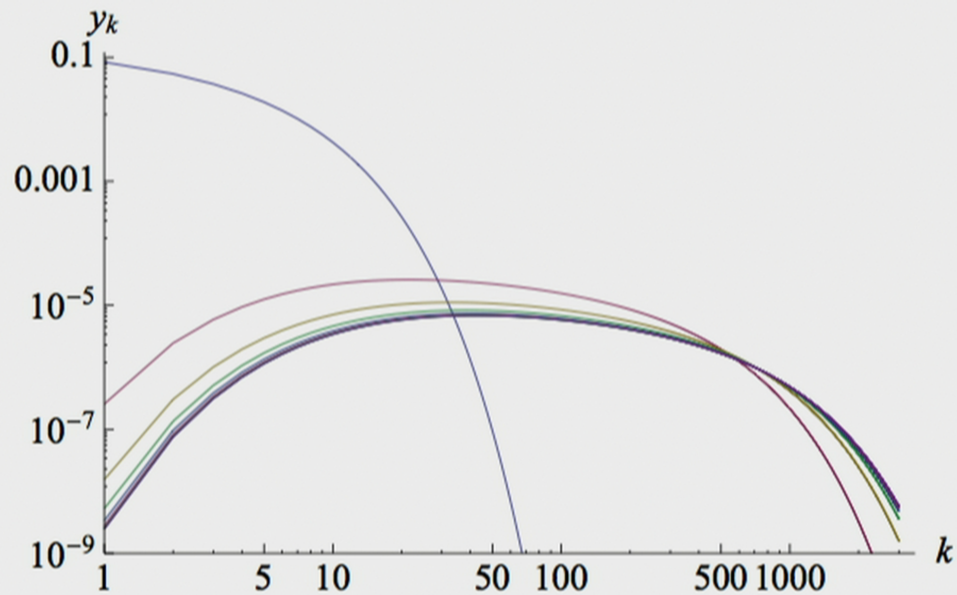


'Broad tail' ICs,
$y_1(0) = 0.97$

Real-time behaviour

$$T_d \propto 1/a \quad \Rightarrow \quad w(T) \simeq \frac{2}{3}\frac{n_0\sigma_1 v_1}{H_0}\left(1-\left(\frac{T}{T_0}\right)^{3/2}\right)$$

Most of build-up completes within one Hubble time.



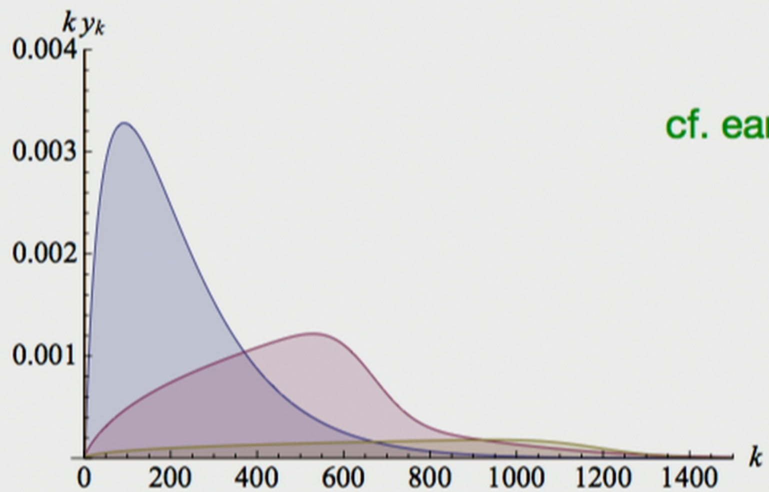
Number distributions at half e-folding time intervals

What if there's a bottleneck at small numbers? (cf. SM)

- If $K_{i,j}$ for small i, j is low enough, and $w_{\max}$ is small enough, never reach scaling regime
- Counter-intuitively, this can result in building up *larger* nuclei, since small + large fusions are less velocity-suppressed
- For $1 + k \to (k+1)$ fusions,

$$\frac{dk}{dw} \simeq K_{1,k} y_1 \propto k^{2/3} \Rightarrow k \sim \left(\int dw\, y_1\right)^3$$

cf. earlier 6/5



Mass distribution at $w = 25$ for $K_{1,1} = 4, 10^{-4}, 10^{-5}$

Summary: Synthesis of Nuclear Dark Matter

- Considered DM models with large bound states of strongly-interacting constituents
- Properties of sufficiently large 'dark nuclei' may obey geometrical scaling laws — this can determine number distribution from Big Bang Dark Nucleosynthesis
- If small-small fusions are fast enough, obtain universal scaling form of number distribution — may have $A \gtrsim 10^8$
- With a bottleneck at small numbers, may build up even larger nuclei, with power-law number distribution
- In both cases, most of build-up completes within a Hubble time
- Have assumed that deviations from geometrical cross sections are eventually unimportant — not necessarily the case!

Signatures of Nuclear Dark Matter

Most model-independent consequences:

- Soft scatterings coherently enhanced by A^2
  - Number density $\propto 1/A$, so total direct detection rate $\propto A$
  - For given direct detection rate, production at colliders etc. *suppressed*
- Possibility of new momentum-dependent form factors in direct detection
- Low-energy collective excitations may allow coherently enhanced inelastic scattering
- Inelastic self-interactions between DM may lead to indirect detection signals, or modify distribution in halos / captured distribution in stars

Many other model-dependent possibilities still to be investigated

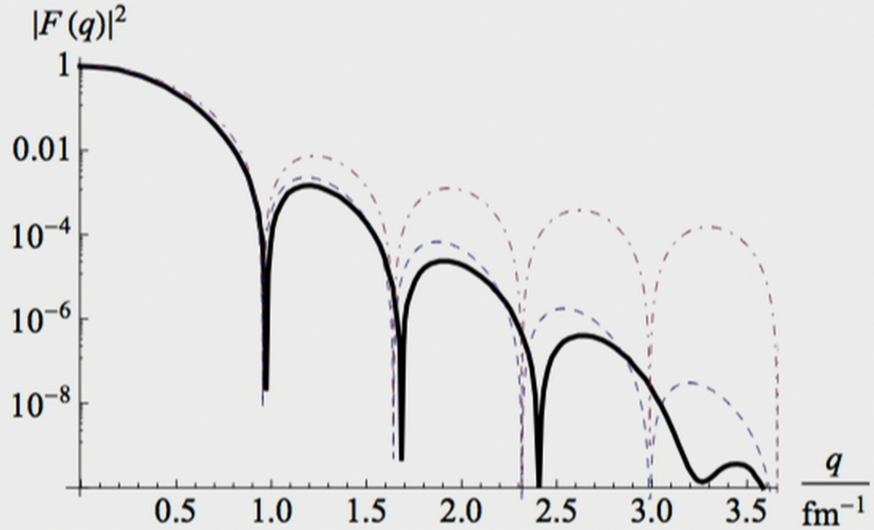
Form factors in scattering

If $R_{\mathrm{DM}} > (\Delta p)^{-1}$, probe DM form factor

Sharp boundary $\Rightarrow$ spherical Bessel function form factor

$$F(q) = \frac{qR\cos(qR) - \sin(qR)}{(qR)^3} \sim \frac{1}{(qR)^2}$$

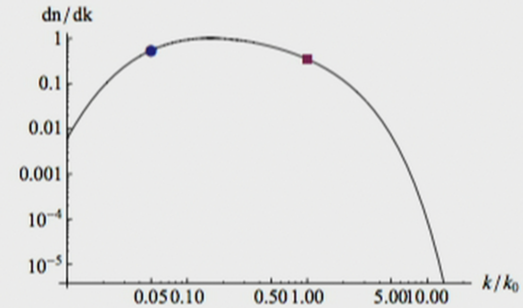
If skin depth etc of DM is smaller than SM nuclear scales, good approximation



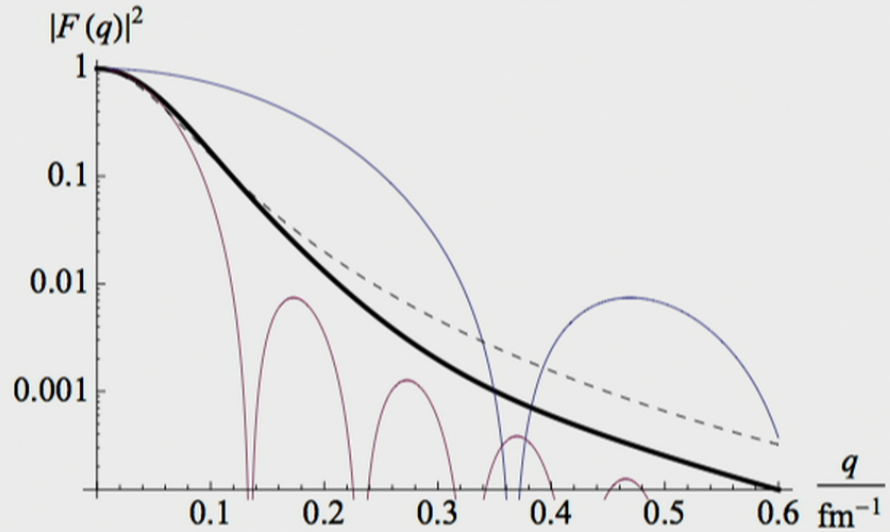
e.g. form factor for nuclear charge distribution of ^{70}Ge.

Effective form factor from distribution of sizes

Distribution over radii averages out peaks and troughs



Effective form factor similar to intermediate-mass mediator



Dependence on DM velocity distribution

Differential event rate:

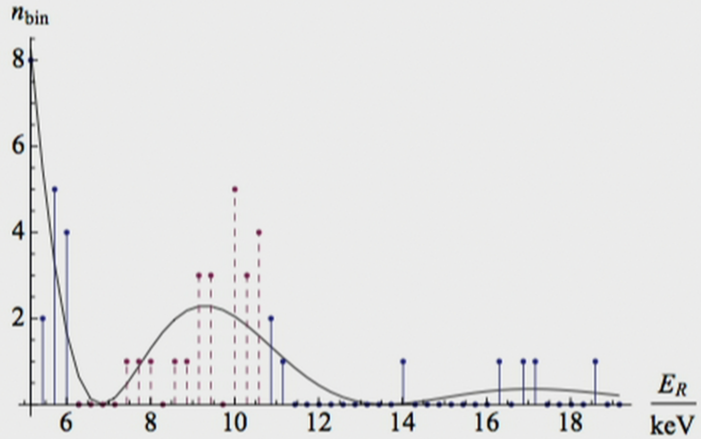
$$\frac{dR}{dE_R} \propto \left(\int_{|v|>v_{\min}} d^3v \frac{f(v)}{v} \right) F_N(q)^2 F_D(q)^2$$

with

$$v_{\min} \propto \sqrt{E_R}$$

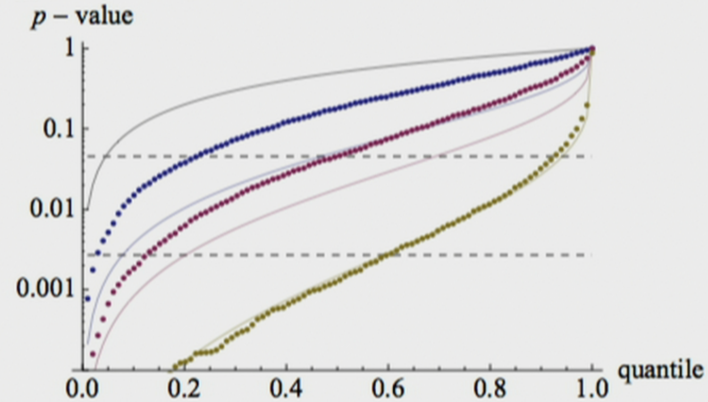
Consequence: ignoring $F_N(q), F_D(q)$, energy recoil spectrum is non-increasing with E_R.

Rising energy recoil spectrum



Samples from recoil spectrum,
$R_{\text{DM}} = 50\,\text{fm}$

p-value CDFs for 30, 50, 100 events



Astrophysical consequences

- Usual constraints wrt getting rid of abundances of other hidden sector states (large energy injections to SM safest before BBN)
- New features — release of binding energy from fusions, spectrum of inelastic modes
- Most binding energy released during dark nucleosynthesis — if inject significant energy to SM, should happen before BBN
- Post freeze-out fusions have rate scaling like v-suppressed annihilations $\Rightarrow$ strongest constraints from present-day ID observations, if injection is to sufficiently energetic SM particles other than neutrinos
- Rich ID phenomenology possible

Astrophysical consequences

- Self-interaction cross section & DM halo constraints?

$$\frac{\sigma_{AA}}{m_A} \simeq \frac{0.05\,\mathrm{barn}}{\mathrm{GeV}} A^{-1/3} \left(\frac{1\,\mathrm{GeV}}{M_1}\right)^{1/3} \left(\frac{1\,\mathrm{GeV\,fm^{-3}}}{\rho_b}\right)^{2/3}$$

Cross sections saturate at geometrical value, so can be safe from elastic-scattering constraints

- Proportion of DM mass density released by fusions:

$$\langle \sigma v \rangle n_A t_{\mathrm{gal}} \frac{\Delta BE}{M_A} \sim 10^{-3} A^{-2/3} \frac{\rho_{\mathrm{DM}}}{0.3\,\mathrm{GeV\,cm^{-3}}}$$

For comparison, annihilating symmetric DM has

$$\langle \sigma v \rangle n_X t_{\mathrm{gal}} \sim 3 \times 10^{-8} \left(\frac{100\,\mathrm{MeV}}{m_X}\right) \left(\frac{\langle \sigma v \rangle_X}{\mathrm{pb}}\right)$$

Possibility of detectable annihilation-type signal from fusions: depends on SM injection channels etc.

Inelastic DM-DM interactions

- Potentially important in areas of high DM density: galactic cores, inside stars
- Exothermic collisions: give DM a velocity kick, clear out high-density regions
- Dissipative collisions: remove KE, leading to contraction of DM distribution
- Within stars, estimates indicate that either dissipative collisions or fusions could lead to run-away contraction to very dense configuration at centre of star

Summary

- 'Nuclear dark matter' is an interesting possibility
- If properties of these states obey scaling laws, this can determine the number distribution from dark nucleosynthesis
- Possible to synthesis large-number ($\geq 10^8$) states, with either peaked (scaling) or power-law number distribution
- Potential consequences for direct detection, astrophysical signals
- Can weaken collider constraints relative to direct and indirect detection

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