Dark Matter: from 10^{-22} eV to 10^{67} eV

John March-Russell
Oxford University

The Dark Matter Landscape

~10^{-43} GeV

~10^{67}eV
(~solar mass)

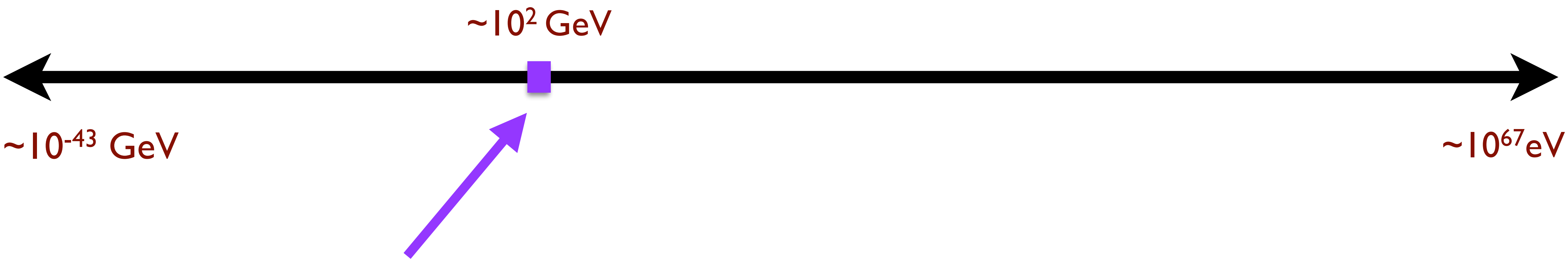
The Dark Matter Landscape

(in mass)

~10^{-43} GeV

~10^{67}eV
(~solar mass)

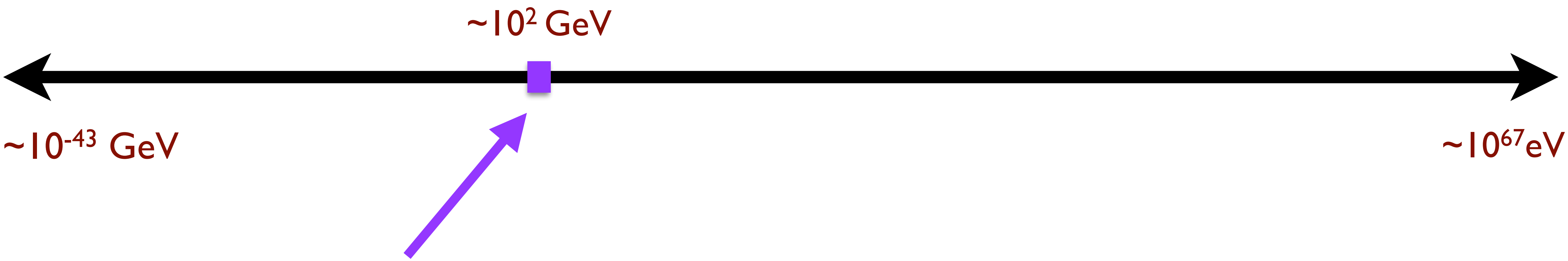
The Dark Matter Landscape



One Possibility: DM at same scale as SM - (WIMPs)

WIMPs heavy so low phase space density and looking for *particles*

The Dark Matter Landscape

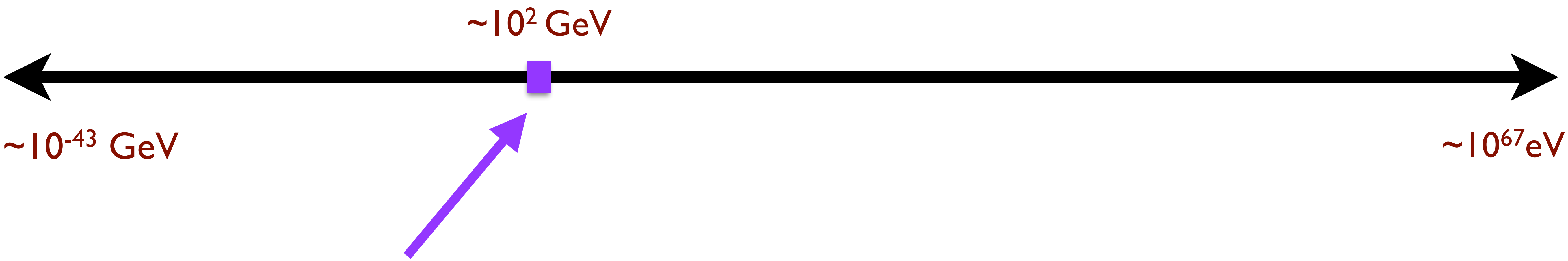


One Possibility: DM at same scale as SM - (WIMPs)

WIMPs heavy so low phase space density and looking for *particles*

“a simple, elegant, compelling explanation for a complex physical phenomenon”

The Dark Matter Landscape



One Possibility: DM at same scale as SM - (WIMPs)

WIMPs heavy so low phase space density and looking for *particles*

"For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation."
- *Tommy Gold*

The Dark Matter Landscape

(fermions)

The Dark Matter Landscape

(bosons)

Forbidden to be all DM since de Broglie wavelength > dwarf galaxy size

The Dark Matter Landscape

(bosons)

DM well-described as a *field (BEC)* as phase space density high (in galaxies now) as

$$\rho_{\mathrm{DM}} \approx 0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3} \approx (0.04\,\mathrm{eV})^4$$

The Dark Matter Landscape

(bosons)

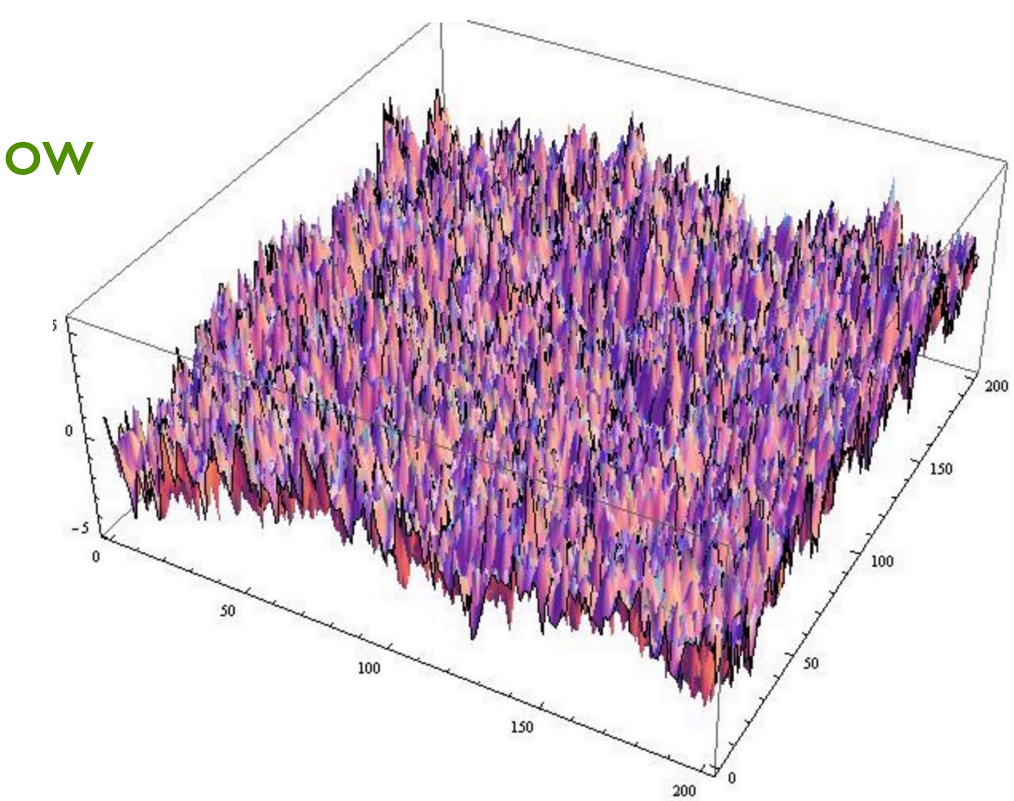
DM well-described as a *field (BEC)* as phase space density high (in galaxies now) as

$$\rho_{\rm DM} \approx 0.3\,\frac{\rm GeV}{\rm cm^3} \approx (0.04\,{\rm eV})^4$$

(phase) correlation length & time now

$$\ell_c \sim 1/(m_a v)$$

$$t_c \sim 1/(m_a v^2)$$



The Dark Matter Landscape

(bosons)

DM well-described as a *field (BEC)* as phase space density high (in galaxies now)

Much old & especially recent interest: super-light pNGBs (QCD Axion, ALPs), Hidden "Photon" DM,…

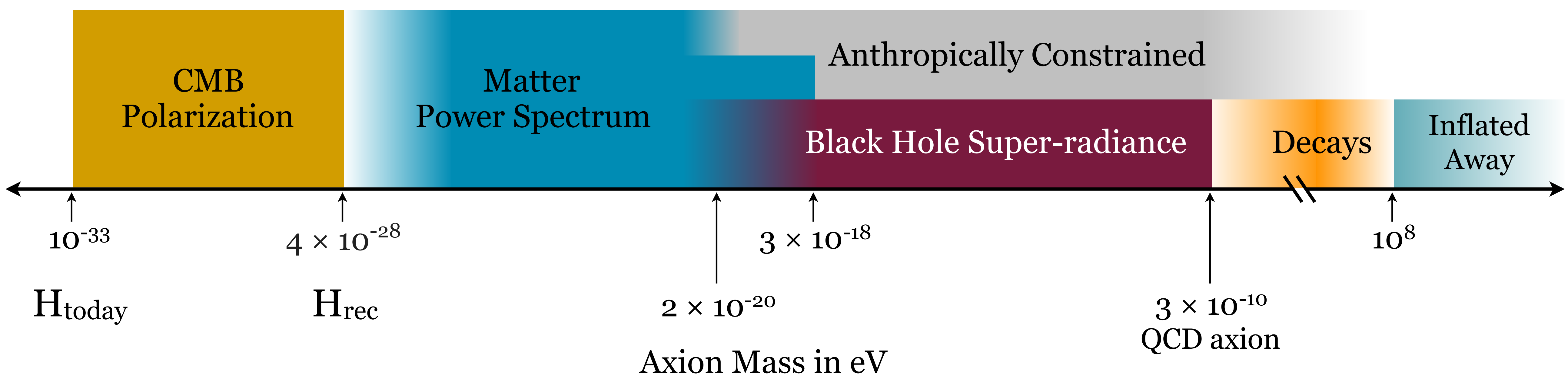
Peccei-Quinn-Weinberg-Wilczek
Kim-Shifman-Vainshtein-Zakharov
Dine-Fischler-Srednicki-Zhitnitsky

The Dark Matter Landscape

(bosons)

DM well-described as a *field (BEC)* as phase space density high (in galaxies now)

String Axiverse: A Plenitude of Axions:



Arvanitaki, Dimopoulos, Dubovsky, Kaloper, JMR; arXiv:0905.4720

Here they are...!

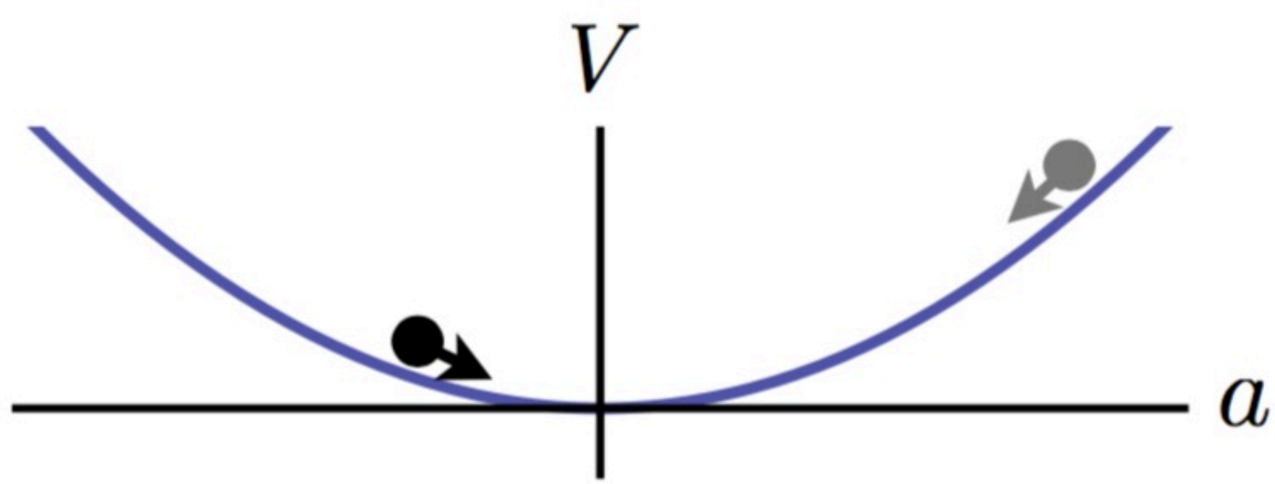
The Dark Matter Landscape

(bosons)

~10^{-22} eV ~10^{-2} eV ~10^{67}eV

DM well-described as a *field (BEC)*

Attractive production mechanism: misalignment (others possible)

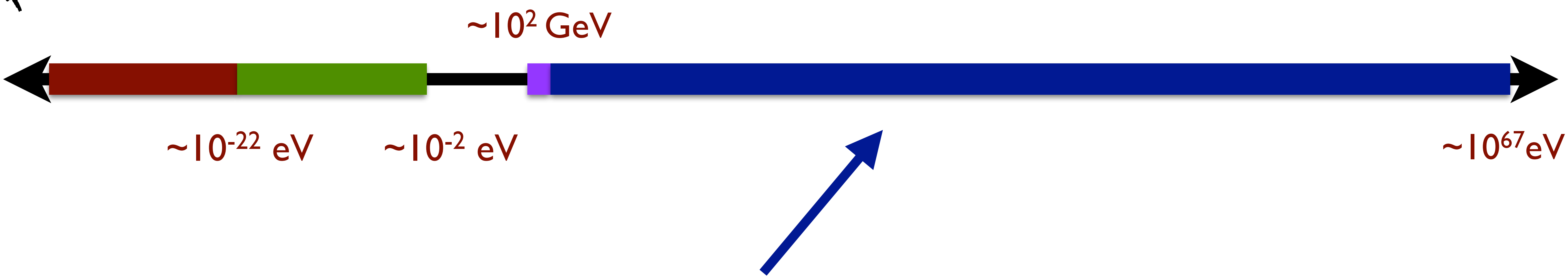


Focus today...

The Dark Matter Landscape

Focus today...

The Dark Matter Landscape



Question: Is this region also populated by interesting DM candidates with motivated production mechanisms??

Recall....

Freeze-In Production

Hall, Jedamzik, JMR, West; arXiv:0911.1120
McDonald; arXiv:hep-ph/0106249

- X only *feebly* coupled to visible-sector thermal bath particles V_i
- X never in thermal equilibrium with SM

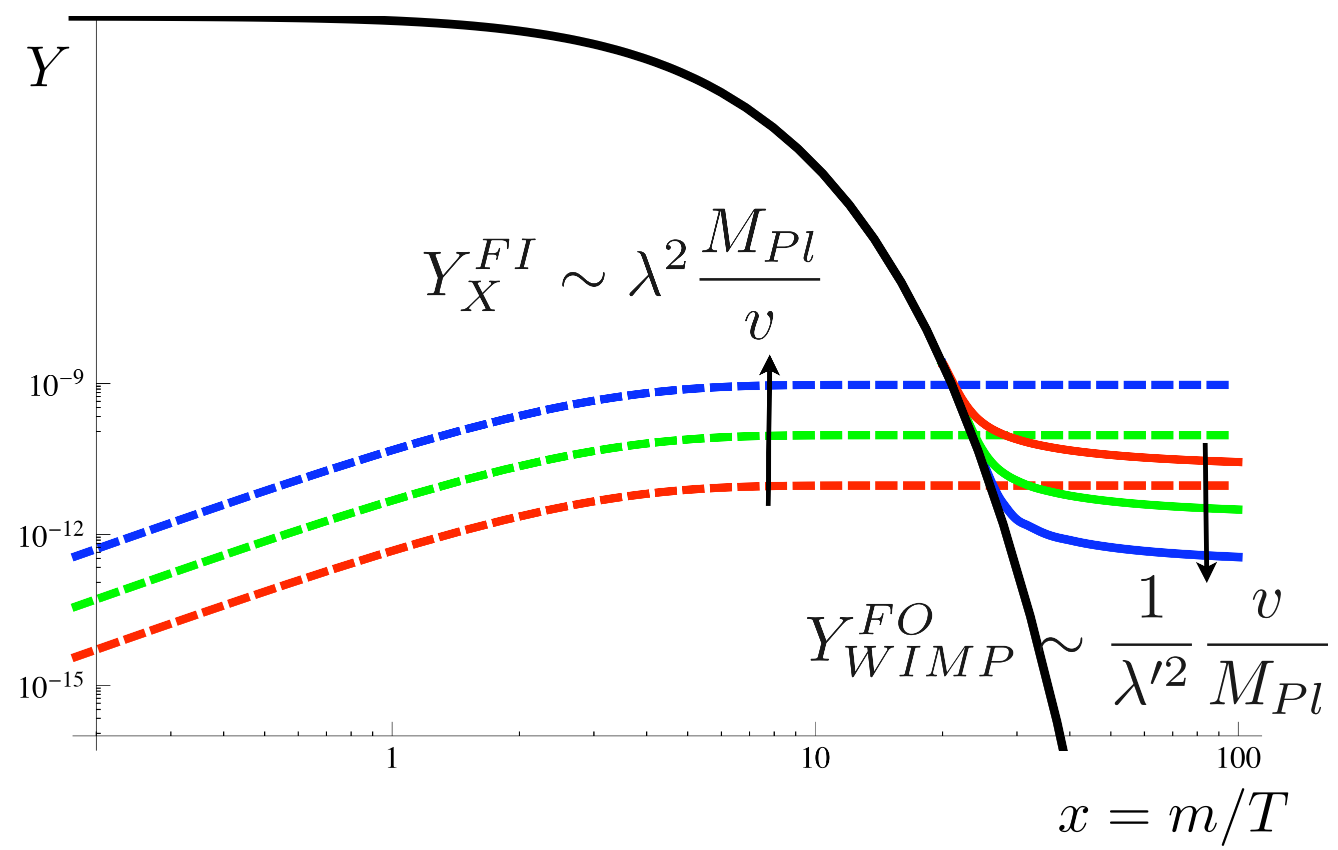
Recall....

Freeze-In Production

Hall, Jedamzik, JMR, West; arXiv:0911.1120
McDonald; arXiv:hep-ph/0106249

- X only *feebly* coupled to visible-sector thermal bath particles V_i
- X never in thermal equilibrium with SM

as universe evolves, a tiny X abundance is produced



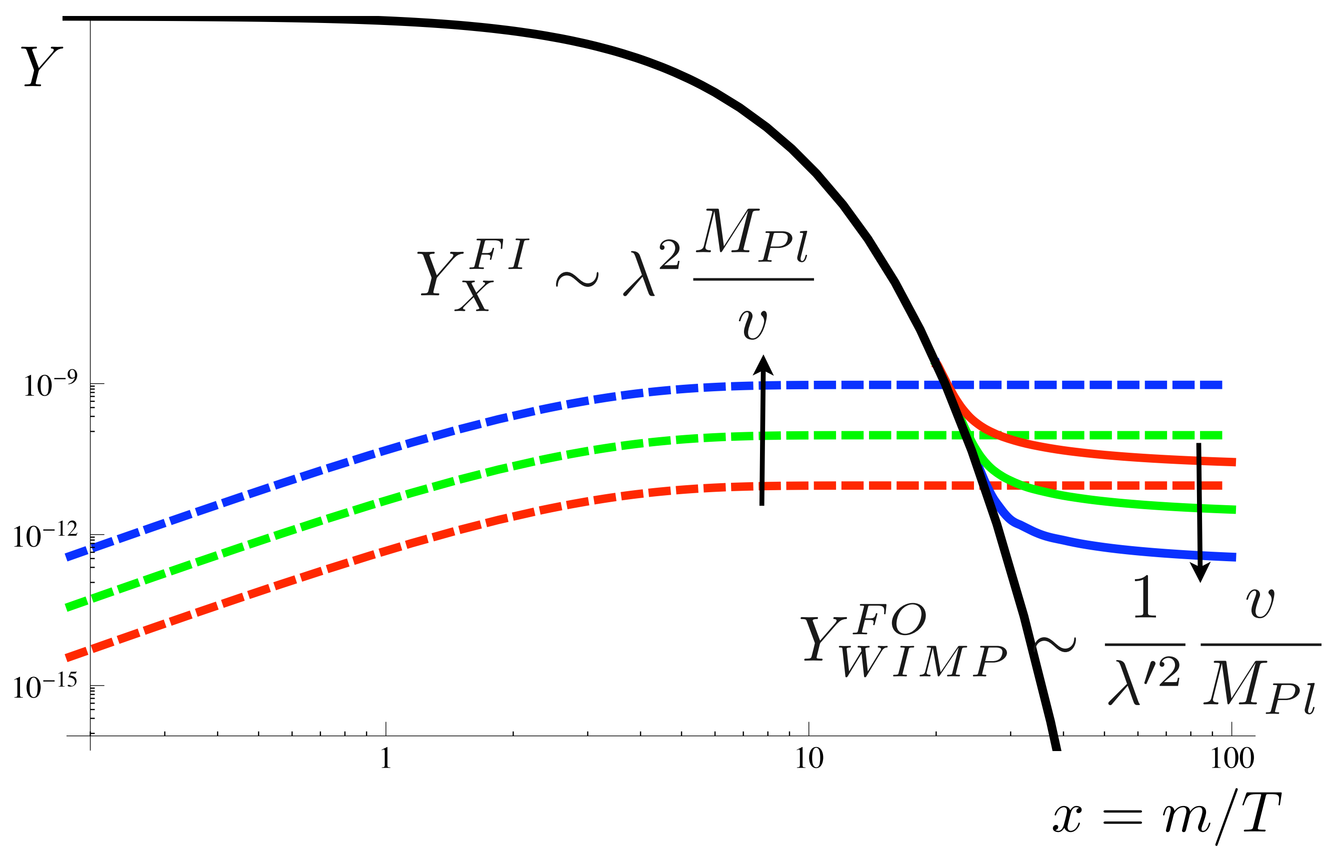
Recall....

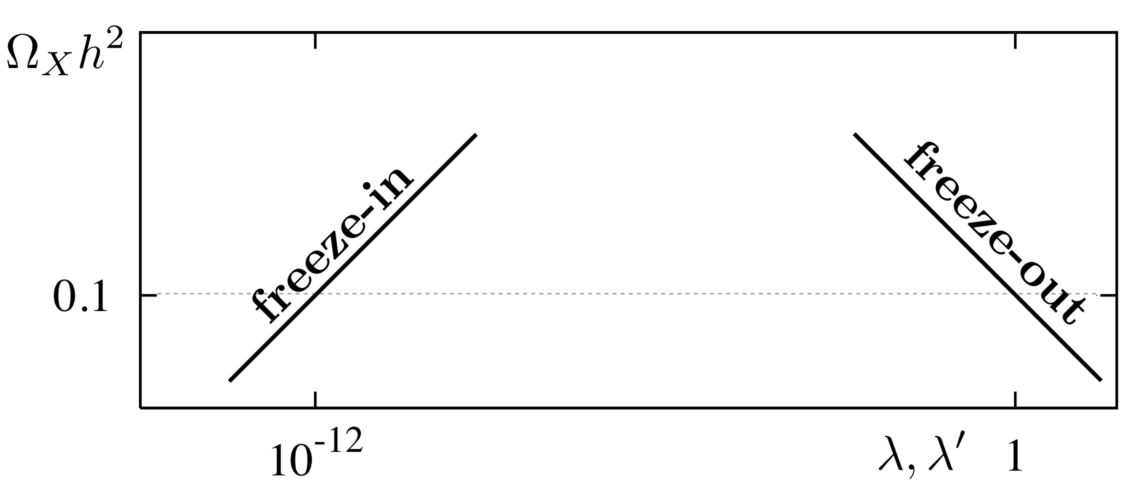
Freeze-In Production

Hall, Jedamzik, JMR, West; arXiv:0911.1120
McDonald; arXiv:hep-ph/0106249

- X only *feebly* coupled to visible-sector thermal bath particles V_i
- X never in thermal equilibrium with SM

as universe evolves, a tiny X abundance is produced





two calculable thermal mechanisms

(heading either in or out of equilibrium)

Freeze-In Production

Comments

- `Explains' why direct detection hasn't seen anything yet…

- FI yield is IR-dominated for renormalizable interactions

$$Y_X^{FI}(T) \sim \lambda^2 \frac{m^2 M_{Pl}}{T^3}$$

$\Delta L = \lambda X V_1 V_2$

dominant production occurs at $T \sim m$
(heaviest particle in vertex)

- Lightest ordinary-sector particle (LOSP) transforming under X-stabilising symmetry is automatically long-lived and interesting for future LHC searches if m~TeV

Freeze-In Production

Origin of Feeble Coupling?

The 'WIMP miracle' is that for $m' \sim v$ and $\lambda' \sim 1$

$$m' Y_{FO} \sim \frac{1}{M_{pl} \langle \sigma v \rangle} \sim \frac{m'^2}{M_{pl} \lambda'^2} \sim \frac{v^2}{M_{pl}}$$

gives the observed value of $\Omega_{DM} h^2$

Freeze-In Production

Origin of Feeble Coupling?

The 'WIMP miracle' is that for $m' \sim v$ and $\lambda' \sim 1$

$$m' Y_{FO} \sim \frac{1}{M_{pl}\langle \sigma v \rangle} \sim \frac{m'^2}{M_{pl}\lambda'^2} \sim \frac{v^2}{M_{pl}}$$

gives the observed value of $\Omega_{DM} h^2$

The 'FIMP miracle' is that for $\lambda \sim v/M_{pl}$

$$m Y_{FI} \sim m\ \lambda^2 \left(\frac{M_{pl}}{m} \right) \sim \frac{v^2}{M_{pl}}$$

Freeze-In Production

Origin of Feeble Coupling?

The 'WIMP miracle' is that for $m' \sim v$ and $\lambda' \sim 1$

$$m' Y_{FO} \sim \frac{1}{M_{pl} \langle \sigma v \rangle} \sim \frac{m'^2}{M_{pl} \lambda'^2} \sim \frac{v^2}{M_{pl}}$$

gives the observed value of $\Omega_{DM} h^2$

The 'FIMP miracle' is that for $\lambda \sim v / M_{pl}$

$$m Y_{FI} \sim m \, \lambda^2 \left(\frac{M_{pl}}{m} \right) \sim \frac{v^2}{M_{pl}}$$

Suggests that FIMPs occur where tiny couplings arise at linear order in weak scale eg...

Freeze-In Production

moduli of the SUSY-breaking sector giving SUSY-SM soft terms

$$m^2\left(1+\frac{T}{M}\right)(\phi^\dagger\phi+h^\dagger h) \qquad \mu B\left(1+\frac{T}{M}\right)h^2 \qquad Ay\left(1+\frac{T}{M}\right)\phi^2 h$$

$$m_{\tilde g}\left(1+\frac{T}{M}\right)\tilde g\tilde g \qquad \mu y\left(1+\frac{T}{M}\right)\phi^2 h^* \qquad \mu\left(1+\frac{T}{M}\right)\tilde h\tilde h,$$

or for modulini

$$\mu\,\frac{\tilde T}{M}\,\tilde h h \qquad \frac{m_{susy}}{M}\,\tilde T(q\tilde q^\dagger, l\tilde l^\dagger, \tilde h h^\dagger)$$

give tiny renormalizable couplings...

Freeze-In Production

eg...

moduli of the SUSY-breaking sector giving SUSY-SM soft terms

$$m^2\left(1+\frac{T}{M}\right)(\phi^\dagger\phi+h^\dagger h) \qquad \mu B\left(1+\frac{T}{M}\right)h^2 \qquad Ay\left(1+\frac{T}{M}\right)\phi^2 h$$

$$m_{\tilde g}\left(1+\frac{T}{M}\right)\tilde g\tilde g \qquad \mu y\left(1+\frac{T}{M}\right)\phi^2 h^* \qquad \mu\left(1+\frac{T}{M}\right)\tilde h\tilde h,$$

or for modulini

$$\mu\,\frac{\tilde T}{M}\,\tilde h h \qquad \frac{m_{susy}}{M}\,\tilde T(q\tilde q^\dagger, l\tilde l^\dagger, \tilde h h^\dagger)$$

give tiny renormalizable couplings…

$\lambda \sim 10^{-13}$ for either $m_{susy}\sim \mathrm{TeV}$ and $M\sim M_{GUT}$ (natural value of compactification scale & f_a in realistic string theories) or $m_{susy}\sim 10^{2-3}\mathrm{TeV}$ and $M\sim M_{pl}$

Freeze-In Production

So far assumed FIMP mass close to weak-scale. For WIMPs this must be so as unitarity limits size of annihilation cross-section

FIMPs completely different:

$$m Y_{FI} \sim m\ \lambda^2 \left(\frac{M_{pl}}{m} \right) \sim \lambda^2 M_{pl}$$

Remarkably this is independent of mass! (as long as $m < T_{\text{reheat,SM}}$)

Freeze-In Production

So far assumed FIMP mass close to weak-scale. For WIMPs this must be so as unitarity limits size of annihilation cross-section

FIMPs completely different:

$$mY_{FI} \sim m\ \lambda^2 \left(\frac{M_{pl}}{m}\right) \sim \lambda^2 M_{pl}$$

Remarkably this is independent of mass! (as long as $m < T_{\mathrm{reheat,SM}}$)

Calculable thermal production of superheavy FIMP DM possible

w/ apologies to Rocky: FIMPzilla's!

Freeze-In Production

So far assumed FIMP mass close to weak-scale. For WIMPs this must be so as unitarity limits size of annihilation cross-section

FIMPs completely different:

$$mY_{FI} \sim m\,\lambda^2 \left(\frac{M_{pl}}{m}\right) \sim \lambda^2 M_{pl}$$

Remarkably this is independent of mass! (as long as $m < T_{\mathrm{reheat,SM}}$)

Calculable thermal production of superheavy FIMP DM possible

w/ apologies to Rocky: FIMPzilla's!

however hard to see apart from indirect detection (annihilation or decay via d=6 ops)

The Dark Matter Landscape

Are there calculable very heavy DM objects with more signatures (not just indirect detection)?

Yes!

Asymmetric DM

Asymmetric DM allows for existence and formation of

very heavy composite objects (DM-"Nuclei", Q-balls,…)

with a wide variety of striking signatures in LHC, direct detection and indirect detection

Many novel possibilities…!

Recall...

Asymmetric DM

Similar physics underlies both Ω_B and Ω_{DM}

(Nussinov '85; Gelmini, Hall, Lin '87; Barr '91; Kaplan '92; Thomas '95; Hooper, JMR, West '04; explosion in last few yrs esp work of Zurek etal; JMR etal; Sarkar etal; Sannino etal; now many others...)

Baryons: $U(1)_B$ $\quad u, d, s...$ $\quad p$ stable $\quad \Omega_B \propto m_B \eta_B$

DM: $U(1)_X$ $\quad X_0, X_1, X_2...$ $\quad X_0$ stable $\quad \Omega_X \propto m_X \eta_X$

Recall...

Asymmetric DM

Similar physics underlies both Ω_B and Ω_{DM}

(Nussinov '85; Gelmini, Hall, Lin '87; Barr '91; Kaplan '92; Thomas '95; Hooper, JMR, West '04; explosion in last few yrs esp work of Zurek etal; JMR etal; Sarkar etal; Sannino etal; now many others...)

Baryons: $U(1)_B$ $u, d, s...$ p stable $\Omega_B \propto m_B \eta_B$

DM: $U(1)_X$ $X_0, X_1, X_2...$ X_0 stable $\Omega_X \propto m_X \eta_X$

At some era

Interactions violate B and X to yield related values for η_B and η_X

$$\frac{\Omega_X}{\Omega_B} = \frac{\eta_X}{\eta_B}\frac{m_X}{m_B}$$

Asymmetric DM

$$\frac{\Omega_X}{\Omega_B} = \frac{\eta_X}{\eta_B}\frac{m_X}{m_B}$$

only true if X density is determined by the asymmetric part otherwise

$$\frac{\Omega_X}{\Omega_B} = \frac{Y_X + Y_{\bar{X}}}{Y_B + Y_{\bar{B}}}\frac{m_X}{m_B}$$

need $Y_X + Y_{\bar{X}} = Y_X - Y_{\bar{X}} + \text{small corrections}$

Asymmetric DM

$$\frac{\Omega_X}{\Omega_B} = \frac{\eta_X}{\eta_B}\frac{m_X}{m_B}$$

only true if X density is determined by the asymmetric part otherwise

$$\frac{\Omega_X}{\Omega_B} = \frac{Y_X + Y_{\bar{X}}}{Y_B + Y_{\bar{B}}}\frac{m_X}{m_B}$$

need $Y_X + Y_{\bar{X}} = Y_X - Y_{\bar{X}} + \text{small corrections}$

non-trivial constraint as initially $$Y_X + Y_{\bar{X}} = \frac{Y_X - Y_{\bar{X}}}{\epsilon}$$

where expect $\epsilon \ll 1$ measures CP-violation

Asymmetric DM

$\Longrightarrow$ Must efficiently annihilate away symmetric part to light states

there has to be an efficient X-preserving freeze-out process

Options:

- direct FO to light SM dof

  $\Longrightarrow$ operators connecting X & SM sectors with strength bounded below

- direct FO to light dark sector dof

  $\Longrightarrow$ (potentially) new "long-range" DM interactions

- FO to (light) dark sector dof which then late decay to SM

  $\Longrightarrow$ late-time energy injection in early universe, as well as (potentially) new "long-range" DM interactions

Asymmetric DM

- direct FO to light SM dof

limits from direct detection experiments and monojet etc searches at LHC are very constraining

with slight exceptions if we want asymmetric DM in natural region $m_X < 10\ \mathrm{GeV}$ then direct FO to SM is disfavoured

eg, JMR, Unwin, West; arXiv:1203.4854
and many others….

$\Downarrow$

eliminating symm component likely implies new dark-sector dynamics

Asymmetric DM

Baryons:	$U(1)_B$	$u, d, s...$	p stable	$\Omega_B \propto m_B \eta_B$
DM:	$U(1)_X$	$X_0, X_1, X_2...$	X_0 stable	$\Omega_X \propto m_X \eta_X$

m_x ~ few GeV is favoured as O(1) ratio of asymmetries most "natural"
(but see, eg, JMR+McCullough, arXiv:1106.4319, and Sarkar etal for other possibilities)

major issue: *why* is DM mass near that of baryon?

(but see, eg, Garcia Garcia, Lasenby, JMR; arXiv:1505.07410 for automatic explanation *directly connected with naturalness*- the "Twin Higgs" mechanism: also see work on "mirror world" models, by Foot, Volkas, etal)

Nuclear DM

Hardy, Lasenby, JMR, & West; arXiv:1411.3739 & arXiv:1504.05419
Detmold, McCullough, Pochinsky; arXiv:1406.2276

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?

Nuclear DM

Hardy, Lasenby, JMR, & West; arXiv:1411.3739 & arXiv:1504.05419

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

Nuclear DM

Hardy, Lasenby, JMR, & West; arXiv:1411.3739 & arXiv:1504.05419

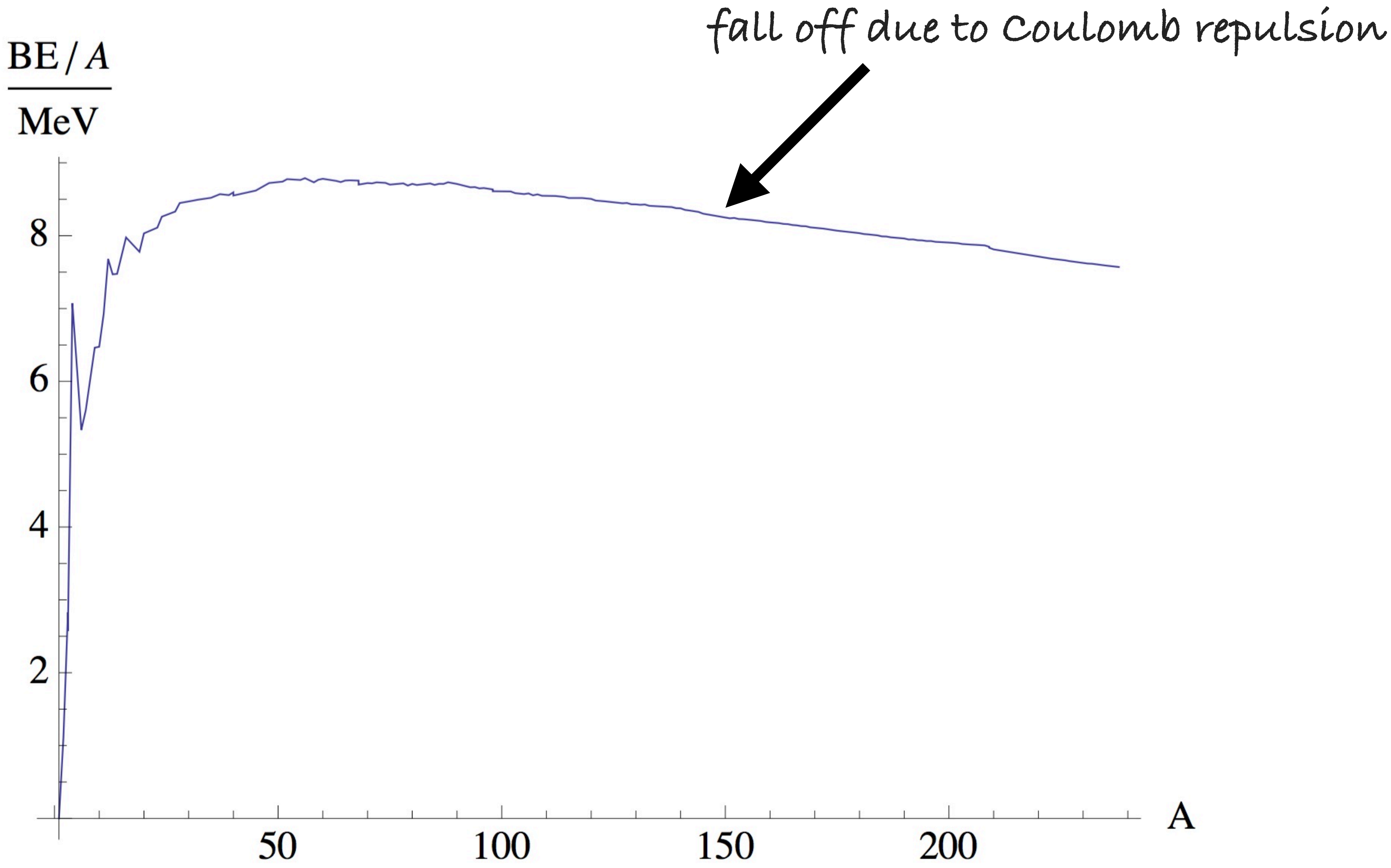
Large composite DM states

- 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
- Example of Q-balls — non-topological solitons of scalar fields

(will return to this at end if time...)

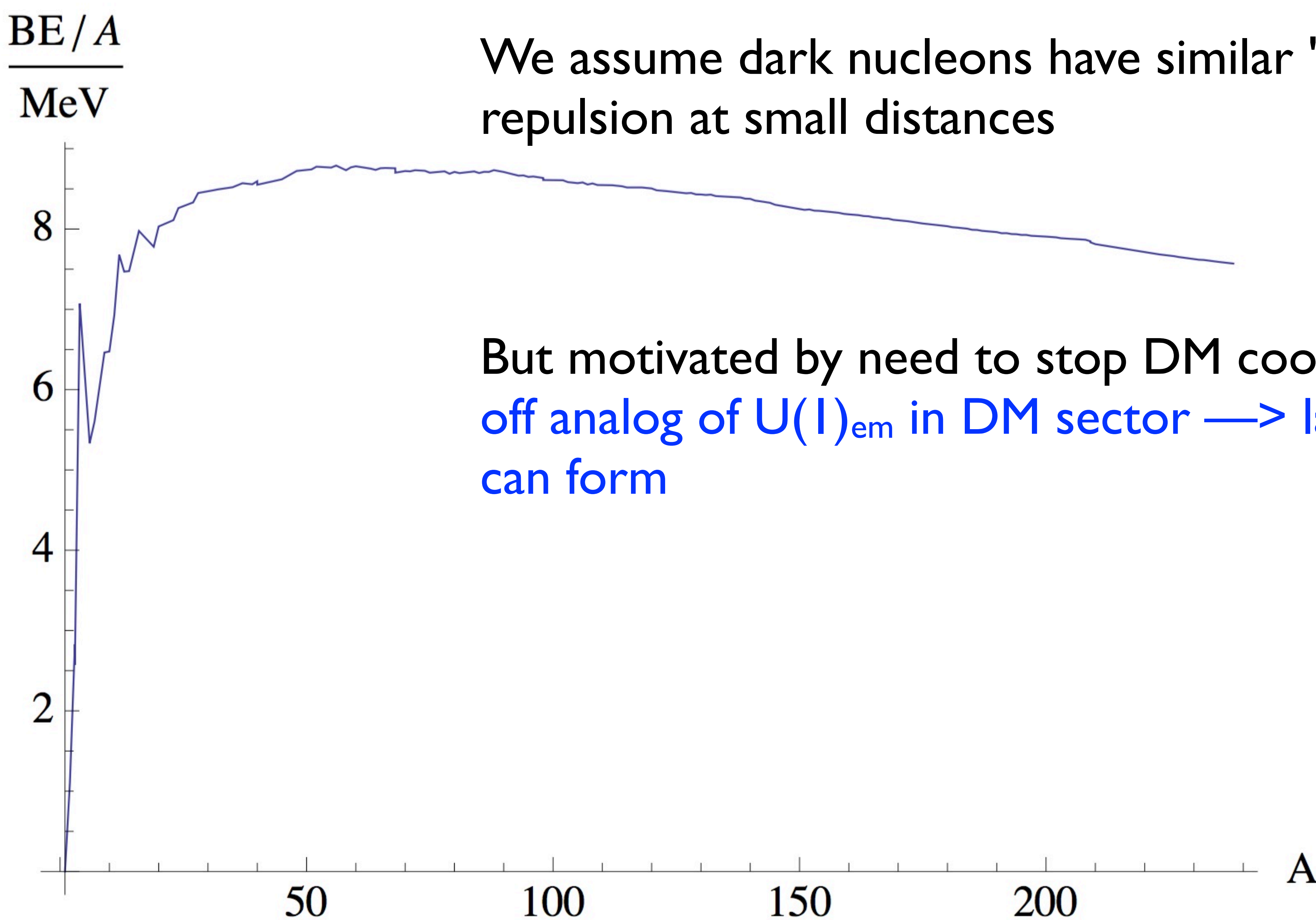
Nuclear DM

SM nuclei



Nuclear DM

SM nuclei



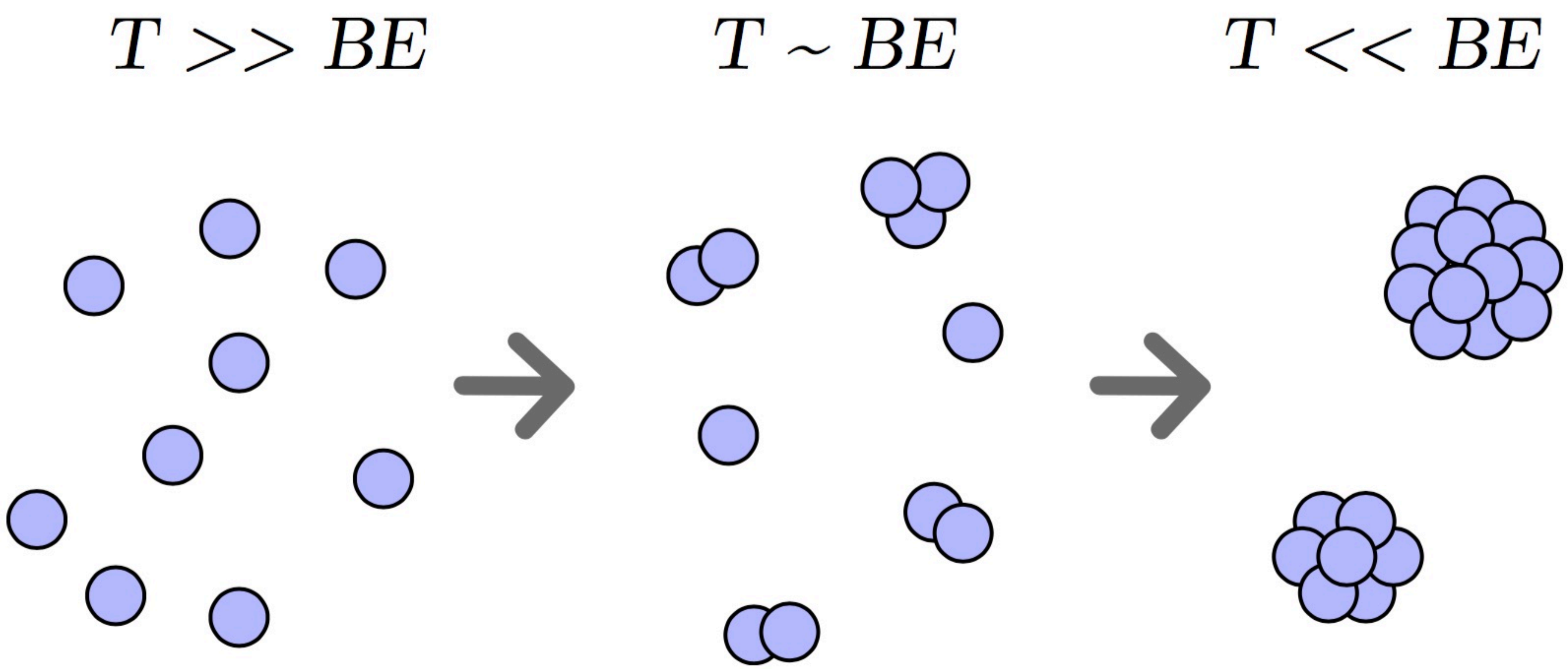
We assume dark nucleons have similar "hard core" repulsion at small distances

But motivated by need to stop DM cooling we turn off analog of $U(1)_{em}$ in DM sector —> large nuclei can form

Nuclear DM

Dark nucleosynthesis

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



Nuclear DM

Schematic thermal evolution

T

Asymmetry generated/
shared with dark nucleons

$T \sim \frac{m_{\rm dn}}{30}$

Freeze-out of individual dark nucleons
- relic density set by the asymmetry

$T \sim \mathrm{B.E/nucleon}$

Dark nucleons are still in kinetic equilibrium - but are non relativistic
Fusions start to dominate over dissociations

Dark Nucleosynthesis
takes place

$T_{\rm FFO}$

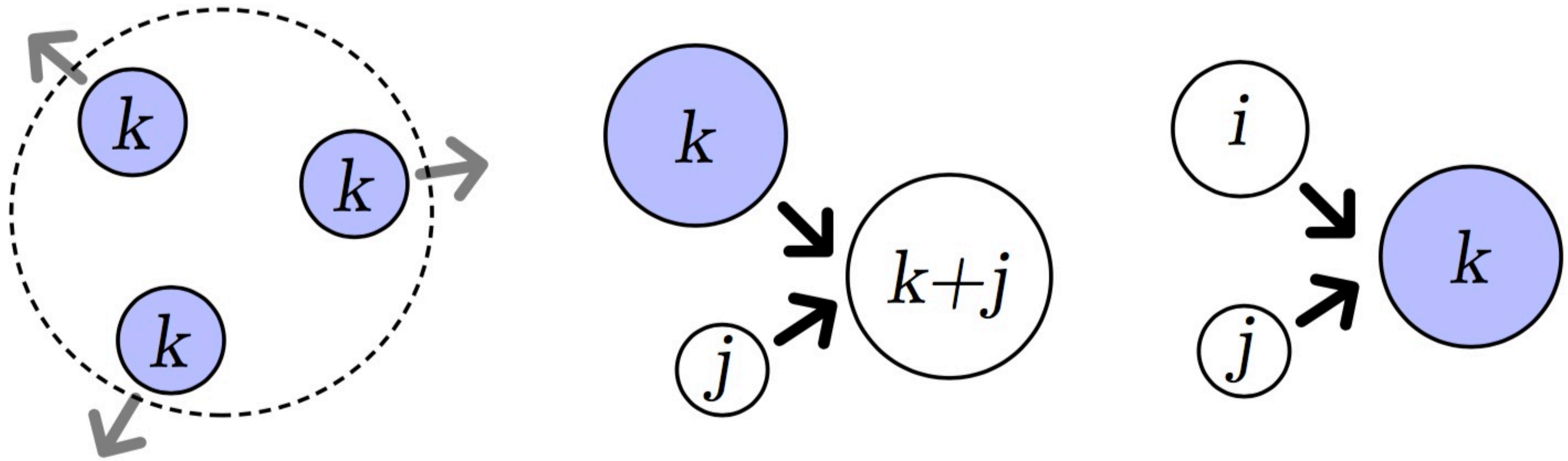
Fusions freeze-out

Spectrum of nuclear states fixed

Nuclear DM

Aggregation process after dissociations freeze-out

$$\frac{dn_k(t)}{dt} + 3H(t)n_k(t) = -\sum_{j=1}^{\infty}\langle\sigma v\rangle_{j,k} n_j(t) n_k(t) + \frac{1}{2}\sum_{i+j=k}\langle\sigma v\rangle_{i,j} n_i(t) n_j(t)\,,$$



Defining relative "yields" $y_k = Y_k/Y_0 = (n_k/s)/Y_0$

total dark nucleon yield

and scaled cross section $K_{i,j} = \dfrac{\langle\sigma v\rangle_{i,j}}{\sigma_1 v_1}$

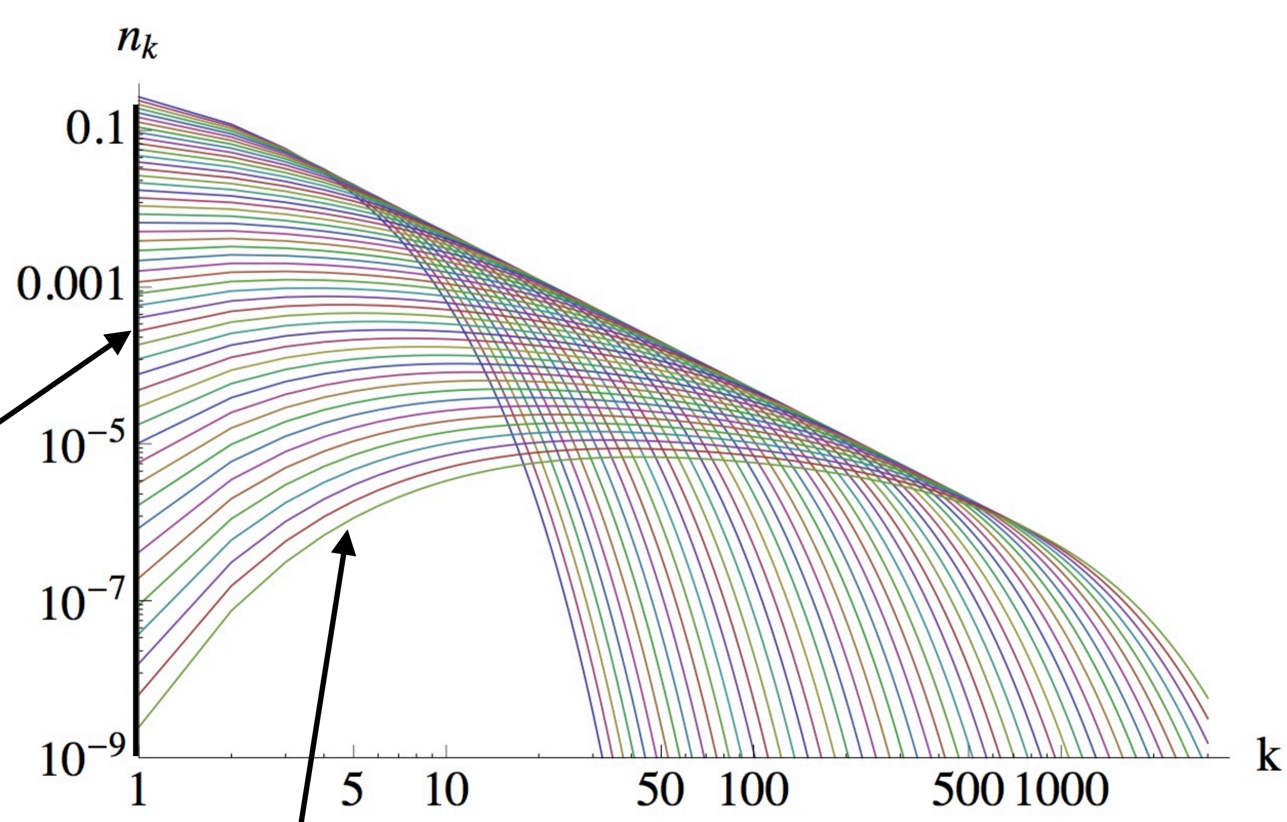
Nuclear DM

Scaling solution

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

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

Initial dist'n delta-fn at n_1



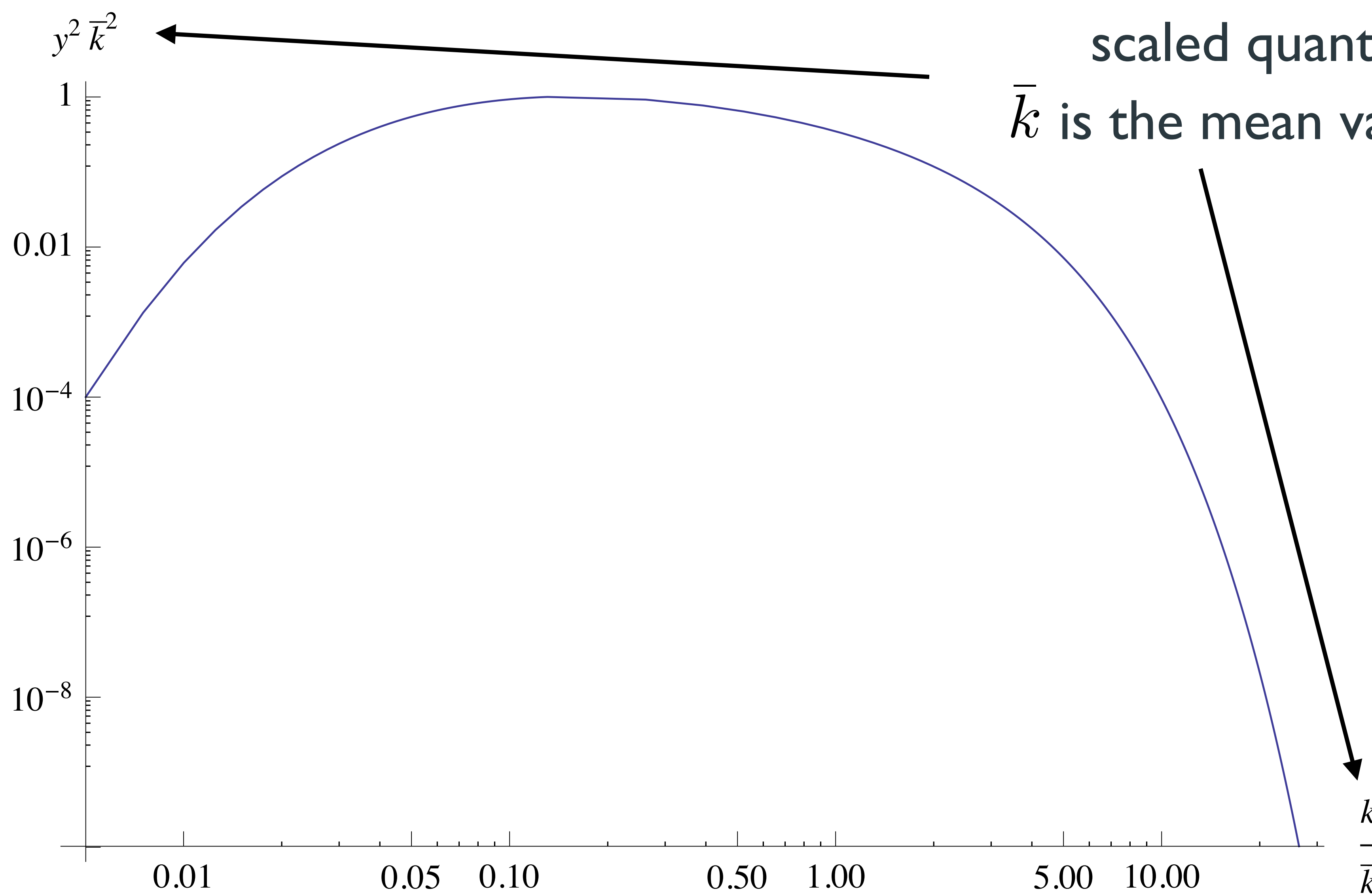
For this case there is an attractor scaling solution independent of details of initial conditions or small-k kernel (within limits)

See e.g. Krapivsky, Redner, Ben-Naim, A Kinetic View of Statistical Physics, CUP, '10

Nuclear DM

For most reasonable kernels and initial conditions scaling solution is reached within one Hubble time

From then on distribution shape stays same but average size of dark nuclei continues to increase until fusions finally freeze-out



scaled quantities

$\bar{k}$ is the mean value of k

Nuclear DM

Can estimate how big nuclei can be by looking at scaling of freeze-out of equal size fusions

Using $$\frac{\sigma_1 v_1 n_0}{H} \sim 2\times 10^7 \left(\frac{1\ \mathrm{GeV\ fm}^{-3}}{\rho_{darkB}}\right)^{2/3}\left(\frac{T}{1\ \mathrm{MeV}}\right)^{3/2}\left(\frac{m_1}{1\ \mathrm{GeV}}\right)^{-5/6}$$

(where motivated by ADM, dark parameters are scaled to SM values)

$$\sigma_{k,k} \sim \sigma_1 k^{2/3}$$
$$v_k \sim v_1 k^{-1/2}$$
$$n_k = n_0/k$$

freeze-out criterion $$\frac{\Gamma}{H} \sim \frac{\langle \sigma v\rangle_{k,k} n_k}{H} \sim \frac{\sigma_1 v_1 n_0}{H} k^{-5/6}$$

$$\Longrightarrow \quad k_{max} \sim 10^9 \quad !$$

(If we have severe bottle-neck at small k small-large fusions can, counter-intuitively, imply even larger final nuclei produced with different scaling solution…)

see Hardy, Lasenby, JMR, & West; arXiv:1411.3739 & arXiv:1504.05419

Nuclear DM

Can estimate how big nuclei can be by looking at scaling of freeze-out of equal size fusions

Using $$\frac{\sigma_1 v_1 n_0}{H} \sim 2\times 10^7 \left(\frac{1\ \mathrm{GeV\ fm^{-3}}}{\rho_{darkB}}\right)^{2/3} \left(\frac{T}{1\ \mathrm{MeV}}\right)^{3/2} \left(\frac{m_1}{1\ \mathrm{GeV}}\right)^{-5/6}$$

(where motivated by ADM, dark parameters are scaled to SM values)

freeze-out criterion $$\frac{\Gamma}{H} \sim \frac{\langle \sigma v\rangle_{k,k} n_k}{H} \sim \frac{\sigma_1 v_1 n_0}{H} k^{-5/6}$$

$$\sigma_{k,k} \sim \sigma_1 k^{2/3}$$
$$v_k \sim v_1 k^{-1/2}$$
$$n_k = n_0/k$$

$$\Longrightarrow \quad k_{max} \sim 10^9 \qquad !$$

(If we have severe bottle-neck at small k small-large fusions can, counter-intuitively, imply even larger final nuclei produced with different scaling solution…)

see Hardy, Lasenby, JMR, & West; arXiv:1411.3739 & arXiv:1504.05419

Thus Dark Nucleosynthesis can generate extremely large and massive composite dark nuclei, even if constituent dark nucleons are in usual ADM range

Rich Phenomenology!

Nuclear DM

Changes for direct detection signals

- Coherent enhancement of scattering from dark nuclei
- Dark matter momentum dependent form factor
- Inelastic processes
- Collective low energy excitations

Indirect detection signals

- Inelastic self-interactions (may modify distribution in Halo)

Capture in stars

- Asymmetric in nature so can build up in stars
- Model dependent consequences

Nuclear DM

- Coherent enhancement of scattering from dark nuclei

Nuclear DM

- Coherent enhancement of scattering from dark nuclei

For a k-dark-nucleus interactions with SM enhanced by k^2 x (form factor)

Number density ~1/k compared to single nucleons

$\Longrightarrow$ effective direct detection rate enhanced by k (could be ~10^9!)

$\Longrightarrow$ in other words, for given direct detection rate, collider production of kinematically accessible individual dark nucleons suppressed by k

Nuclear DM

- Dark matter momentum dependent form factor

  If momentum-transfer q in direction detection > $1/R_k$ (radius of k-dark-nucleus)
  probe DM form factor

Nuclear DM

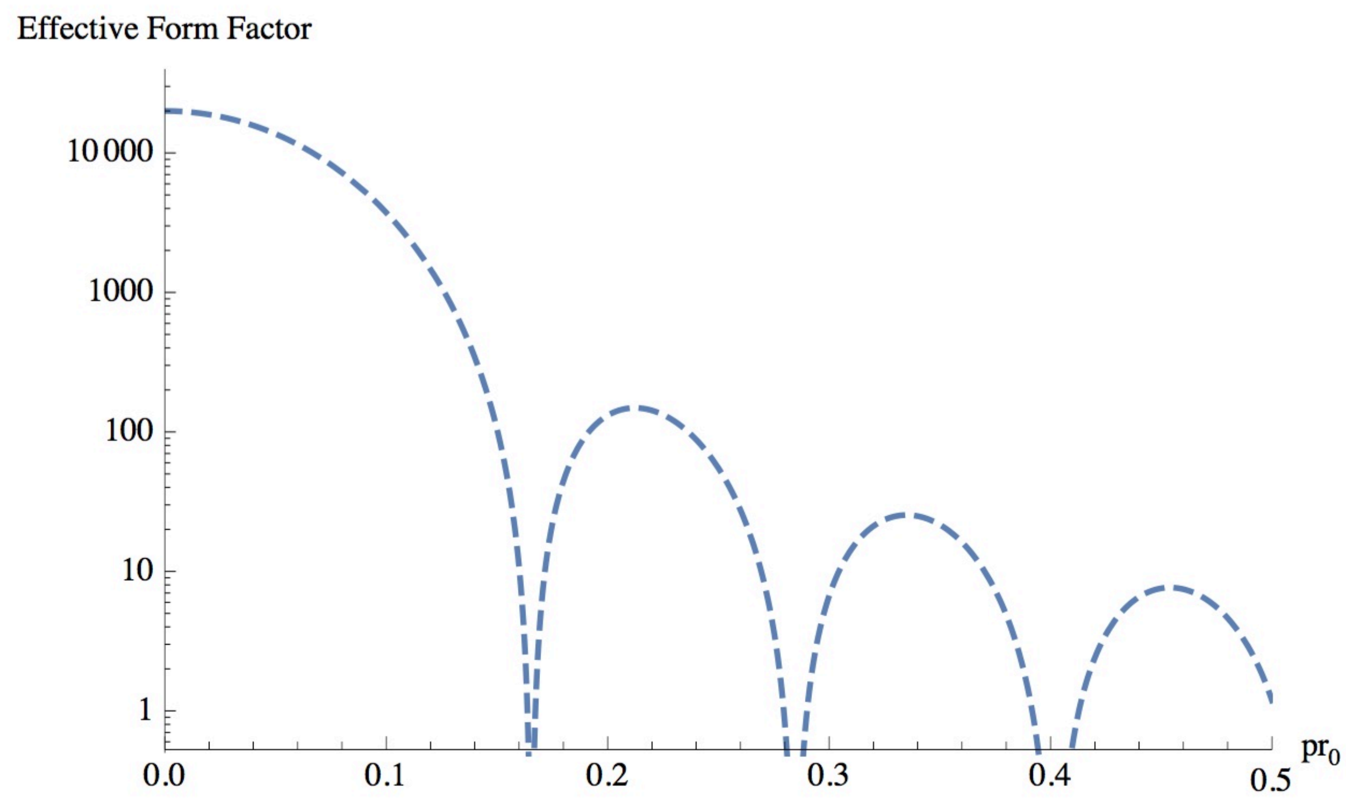
- Dark matter momentum dependent form factor

If momentum-transfer q in direction detection > $1/R_k$ (radius of k-dark-nucleus)
probe DM form factor

If skin-depth of DM-nucleus smaller than SM nuclear size then get "spherical top hat" form factor

$$F_k(q) = \frac{qR_k \cos(qR_k) - \sin(qR_k)}{(qR_k)^3}$$

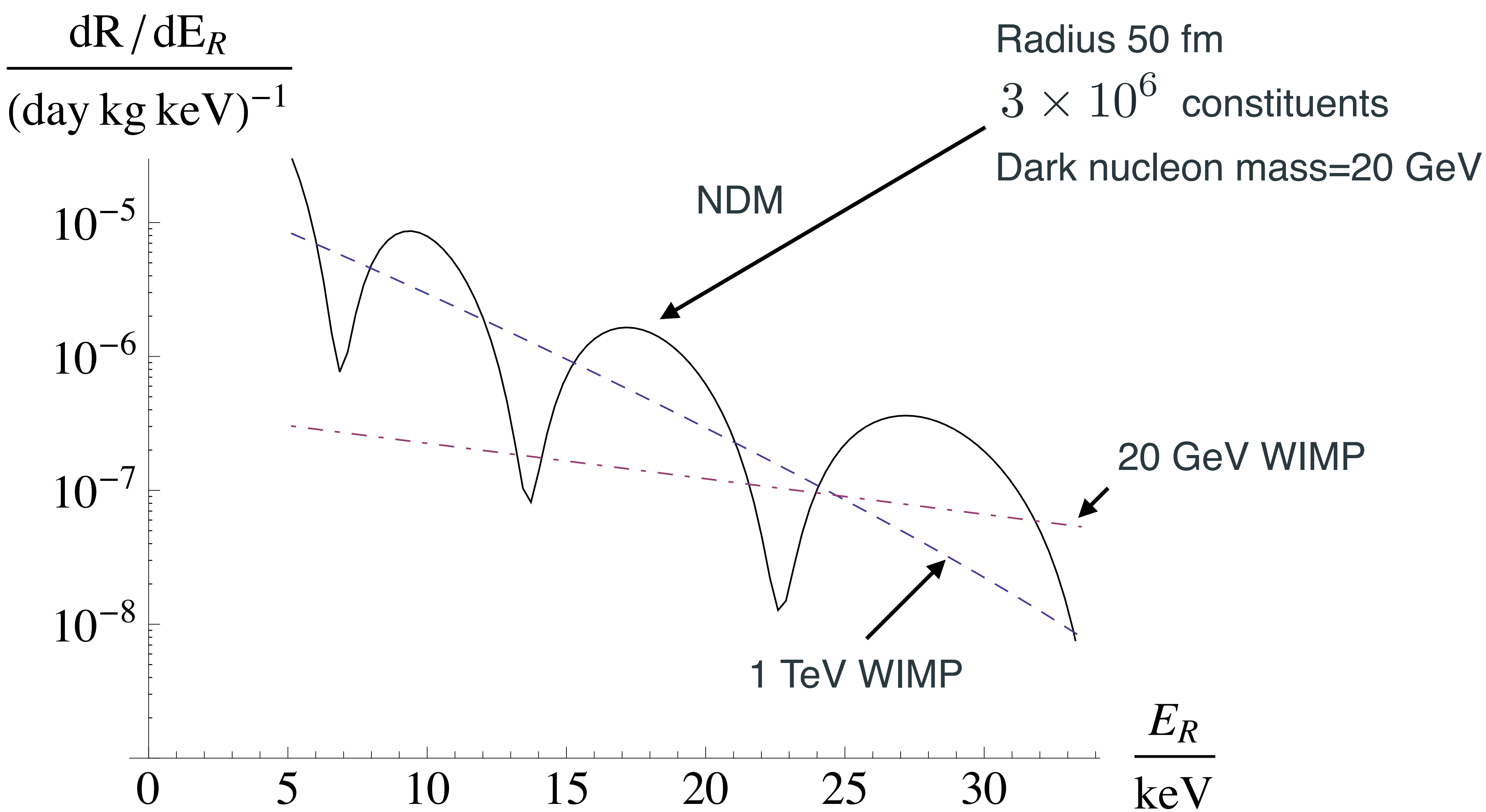
$$R_k \sim R_0 k^{1/3}$$



Nuclear DM

More generally with skin-depth of DM-nucleus and response function of detector included get modifications like, eg,

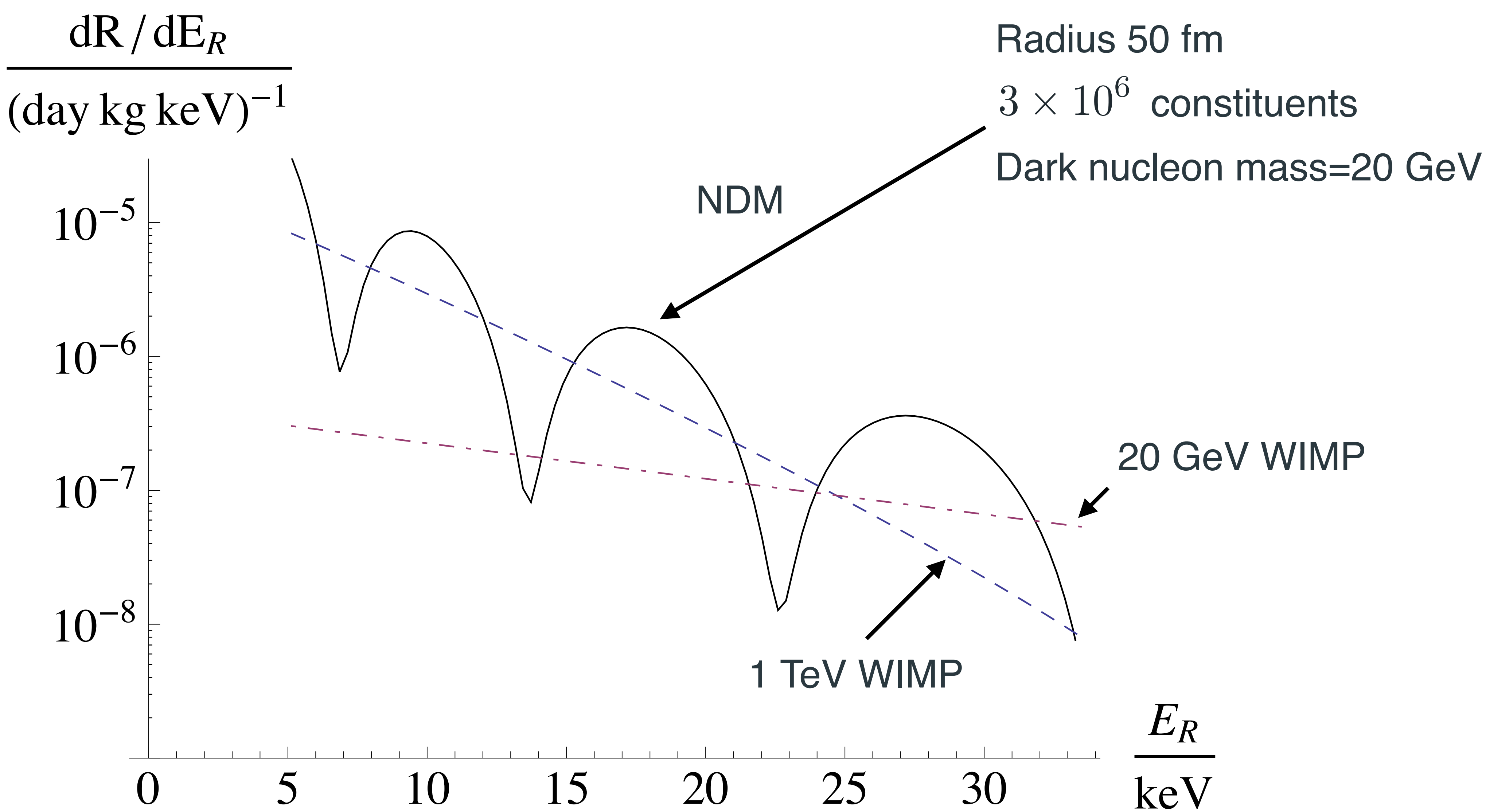
(Germanium detector response function)



Nuclear DM

More generally with skin-depth of DM-nucleus and response function of detector included get modifications like, eg,

(Germanium detector response function)



In principle can distinguish this scenario, and investigate some details of composite state

see Butcher, Kirk, Monroe, West; arXiv:1610.01840, for details of what is possible

Nuclear DM

There are *many* other striking, but largely unexplored consequences of Nuclear DM….

Finally…

Macroscopic DM

There are rich possibilities for getting "macroscopic" DM beyond just NuclearDM linked to Asymm DM

eg,

- Scalar solitons like Q-balls…
  Kusenko, Shaposhnikov, etal

- Primordial BHs…
  Carr; Bird etal; Garcia Bellido, etal

Macroscopic DM

There are rich possibilities for getting "macroscopic" DM beyond just NuclearDM linked to Asymm DM

eg,

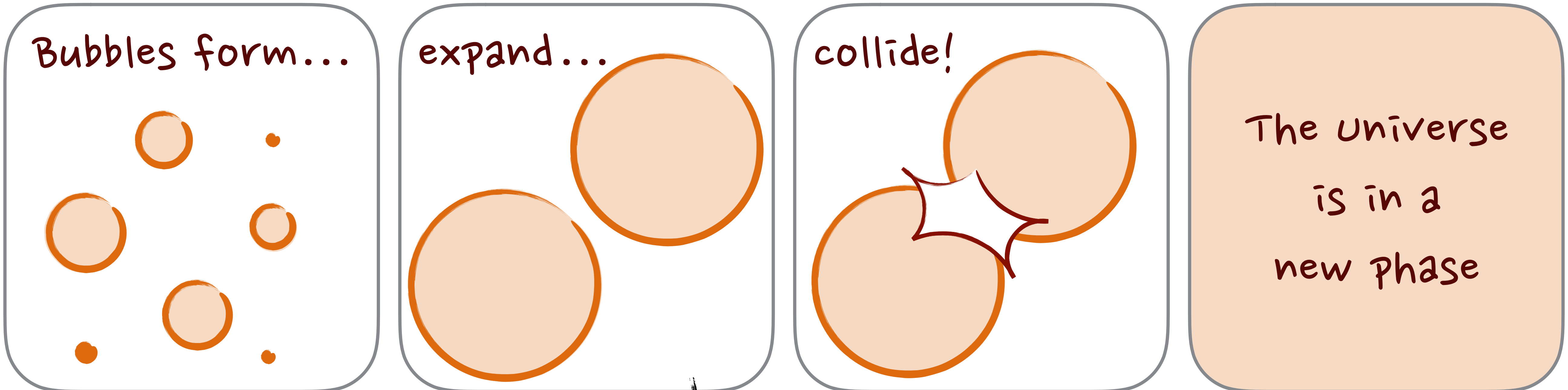
- Scalar solitons like Q-balls…
  Kusenko, Shaposhnikov, etal

- Primordial BHs…
  Carr; Bird etal; Garcia Bellido, etal

Crucial that we investigate both resulting (novel) phenomenology, and assess if there are calculable production mechanisms (ideally, not exponentially sensitive to parameters)

PBHs from T=0 (quantum) vacuum decay?

Garcia Garcia, Kripendorf, JMR; arXiv:1607.06813



They expand ultra-relativistically

Bubbles collide, emitting gravity waves and likely forming some PBHs too

Nobody has reliably computed resulting PBH mass spectrum…!

Garcia Garcia, JMR, work in progress…

Conclusions

Huge amount of exciting thy/expt awaits!