BIG BANG NUCLEOSYNTHESIS OF NUCLEAR DM (AND OTHER NON-STANDARD DM)

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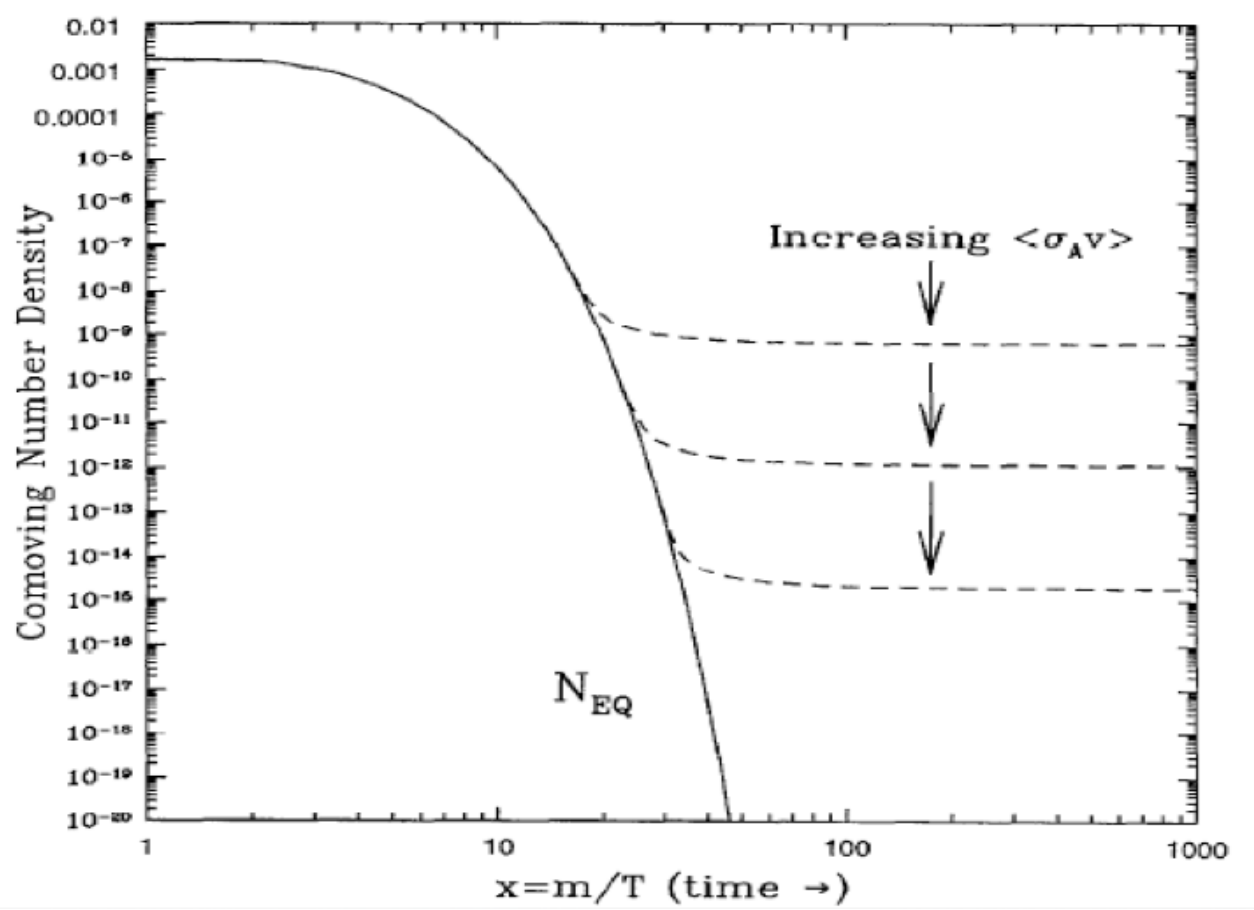
February 24th 2016

OUTLINE

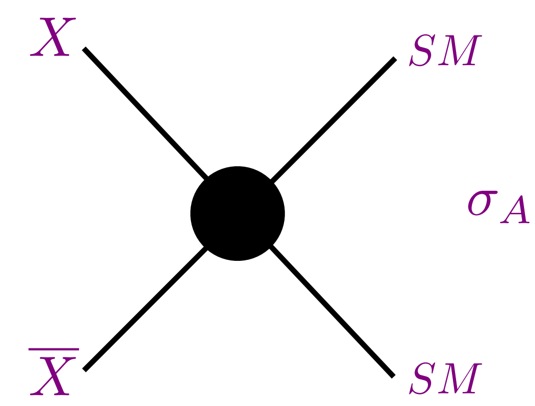
- PARTIAL OVERVIEW OF NON-STANDARD DM
  - FREEZE-OUT
  - ASYMMETRIC FREEZE-OUT
  - FREEZE-IN
- NUCLEAR DARK MATTER

STANDARD FREEZE-OUT

- STANDARD SCENARIO FOR WIMP DM...



KOLB AND TURNER



- SINGLE SPECIES OF DARK MATTER
- RADIATION DOMINATED UNIVERSE
- INITIALLY IN THERMAL EQUILIBRIUM
  $T > m_X$
- AS THE TEMP DECREASES $T < m_X$
  CREATION OF X BECOMES
  EXPONENTIALLY SUPPRESSED

- ANNIHILATION OF X STILL PROCEEDS, NUMBER DENSITY OF X GIVEN BY

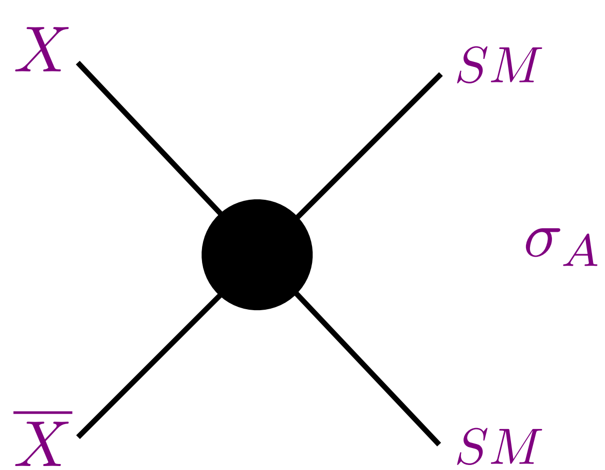
$$\mathrm{N_{EQ}} \approx g_X \left(\frac{m_X T}{2\pi}\right)^{3/2} e^{-m_X/T}$$

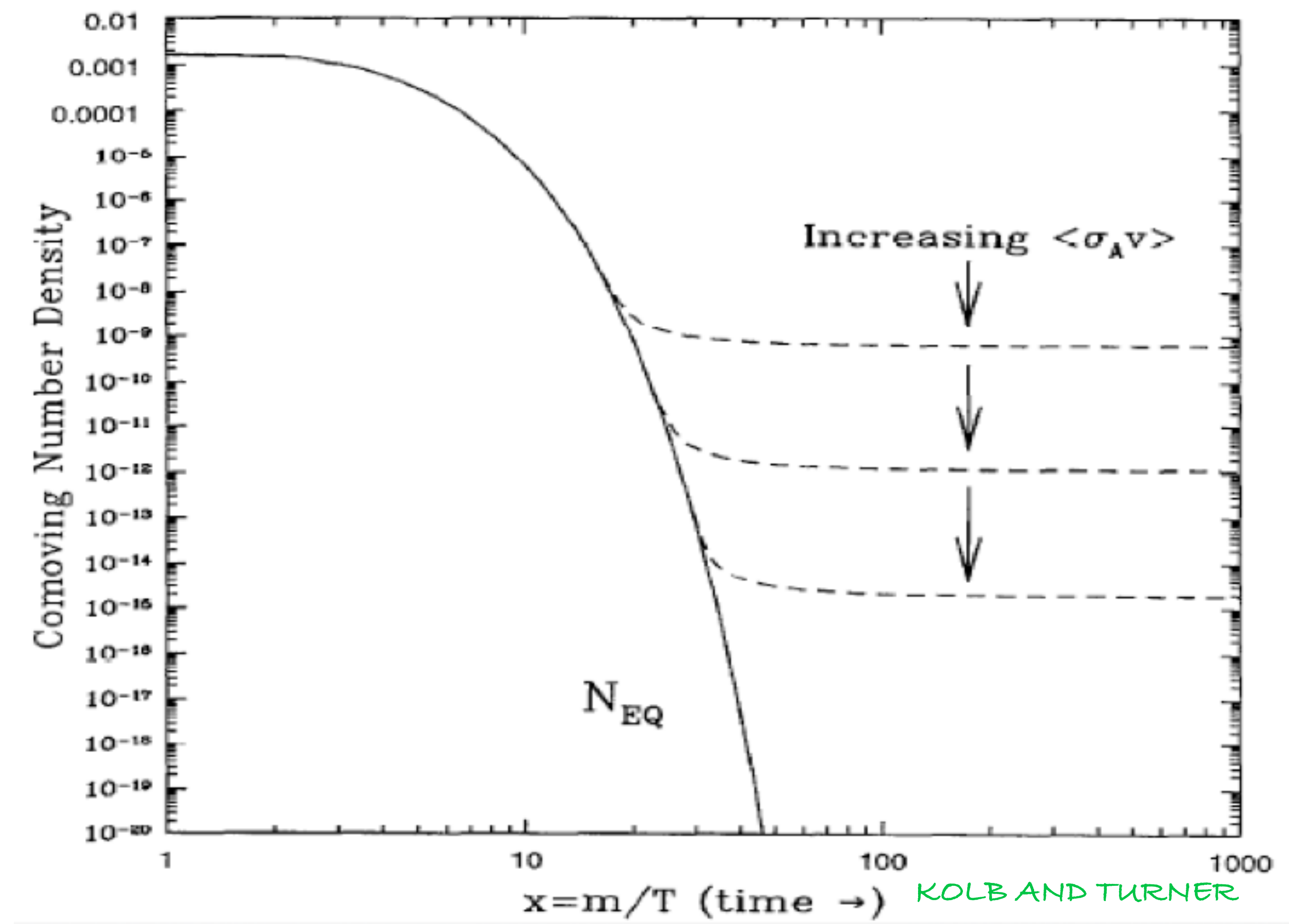
$n_{X,eq} \to 0$
as $T \to 0$

STANDARD FREEZE-OUT

- DUE TO EXPANSION, DARK MATTER NUMBER DENSITY FREEZES-OUT WHEN:

$$\Gamma = n_X \langle \sigma_A v \rangle < H$$





- YIELD SET AT FREEZE-OUT GIVES FINAL DARK MATTER ABUNDANCE.

$$\Omega h^2 \sim 0.1 \frac{3 \times 10^{-26} cm^3 s^{-1}}{\langle \sigma_A v \rangle}$$

MODIFYING FREEZE-OUT - ASYMMETRIC DM

- ONE VERY POPULAR OPTION - ASYMMETRIC DM χ (COMPLEX SCALAR OR DIRAC FERMION)

Nussinov '85; Gelmini, Hall, Lin '87; Barr '91; Kaplan '92;Thomas '95; Hooper, March-Russell, SW '04; Kitano and Low '04, Kaplan, Luty Zurek'09 ; Foadi, Frandsen, Sannino '09+...

VISIBLE SECTOR

$$q, e, W, Z, H, \tilde{q}, \ldots$$

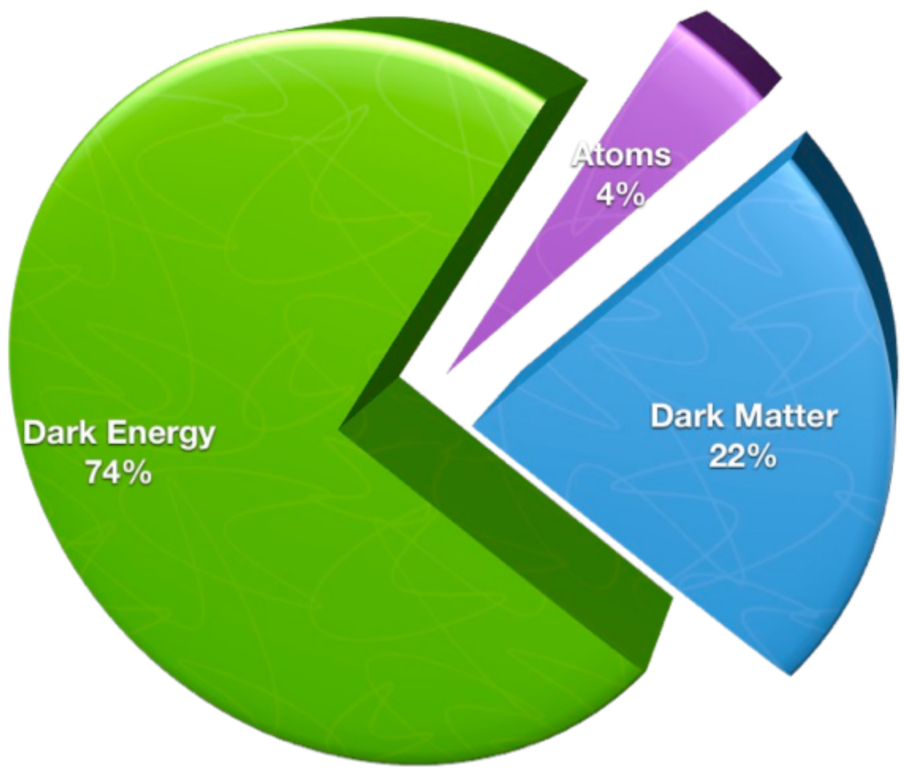
$$\chi, \overline{\chi}$$

- DYNAMICS GENERATE DARK MATTER POSSESSING A MATTER-ANTIMATTER ASYMMETRY

$$n_\chi - n_{\overline{\chi}} \neq 0$$

- FOR SUFFICIENTLY LARGE DM ANNIHILATION - DM ABUNDANCE IS DETERMINE BY ASYMMETRY

Asymmetric DM Motivation



$$\frac{\Omega_{dm}}{\Omega_B} \sim 5$$

- Standard picture:

Ω_{dm} — WIMP freeze-out - set when $\Gamma_{\rm ann} \lesssim H$

Ω_B — Set by CP-violating, baryon number violating out of equilibrium processes

- Given the physics generating each quantity, ratio is a surprise
- If not a coincidence - need to explain the closeness

$\Rightarrow$ Shared dynamics $\Rightarrow$ **Asymmetric Dark Matter**

MODELS OF ADM

$$\eta_{\rm dm} = n_{\rm dm} - n_{\overline{\rm dm}} \neq 0$$

OR

$$\eta_{\rm B} = n_{\rm B} - n_{\overline{\rm B}} \neq 0$$

OR BOTH

- RELATE THIS DM ASYMMETRY TO THE BARYON ASYMMETRY
- LEADING TO:

$$n_{\rm dm} - n_{\overline{\rm dm}} \propto n_{\rm B} - n_{\overline{\rm B}} \Rightarrow \eta_{\rm dm} = C\eta_{\rm B}$$

$$n_{\rm dm} \gg n_{\overline{\rm dm}}$$

$$\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \sim \frac{(n_{\rm dm} + n_{\overline{\rm dm}})m_{\rm dm}}{(n_{\rm B} + n_{\overline{\rm B}})m_{\rm B}} \sim \frac{(n_{\rm dm} - n_{\overline{\rm dm}})m_{\rm dm}}{(n_{\rm B} - n_{\overline{\rm B}})m_{\rm B}}$$

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$$\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \sim \frac{(n_{\rm dm} - n_{\overline{\rm dm}})m_{\rm dm}}{(n_{\rm B} - n_{\overline{\rm B}})m_{\rm B}} \sim \frac{\eta_{\rm dm}}{\eta_{\rm B}}\frac{m_{\rm dm}}{m_{\rm B}}$$

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$$\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \sim \frac{\eta_{\rm dm}}{\eta_{\rm B}} \frac{m_{\rm dm}}{m_{\rm B}} \sim C \frac{m_{\rm dm}}{m_{\rm B}}$$

- VALUE OF C IS DETERMINED BY HOW THE ASYMMETRIES ARE SHARED BETWEEN THE TWO SECTORS

ADM BASICS

$$\frac{\Omega_{dm}}{\Omega_B} \sim \frac{\eta_{dm}}{\eta_B}\frac{m_{dm}}{m_B}$$

If asymmetry sharing process drops out of thermal equilibrium when DM is still relativistic

$$\eta_{\rm dm} \sim \eta_{\rm B}$$

- Then we get a prediction for the mass of the dark matter

$$m_{\rm dm} \sim 5 m_{\rm B} \sim 5 \text{ GeV}$$

- This is the "natural" dark matter mass for ADM models.
- Not the only possible mass, more sophisticated models can allow for a large range of ADM masses

$\Rightarrow$ Depends on the way in which the asymmetry is shared (or generated)

HEAVY ADM

SEE E.G. BARR 91, BUCKELY, RANDALL '11

- Can have ADM with heavy masses
- X number violating processes only decouple after DM has become non-relativistic

$\Rightarrow$ Dark matter asymmetry gets Boltzmann suppressed

$$\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \approx \frac{m_{\rm dm}}{m_{\rm B}} x^{3/2} e^{-x}$$

with $x = \dfrac{m_{\rm dm}}{T_d}$

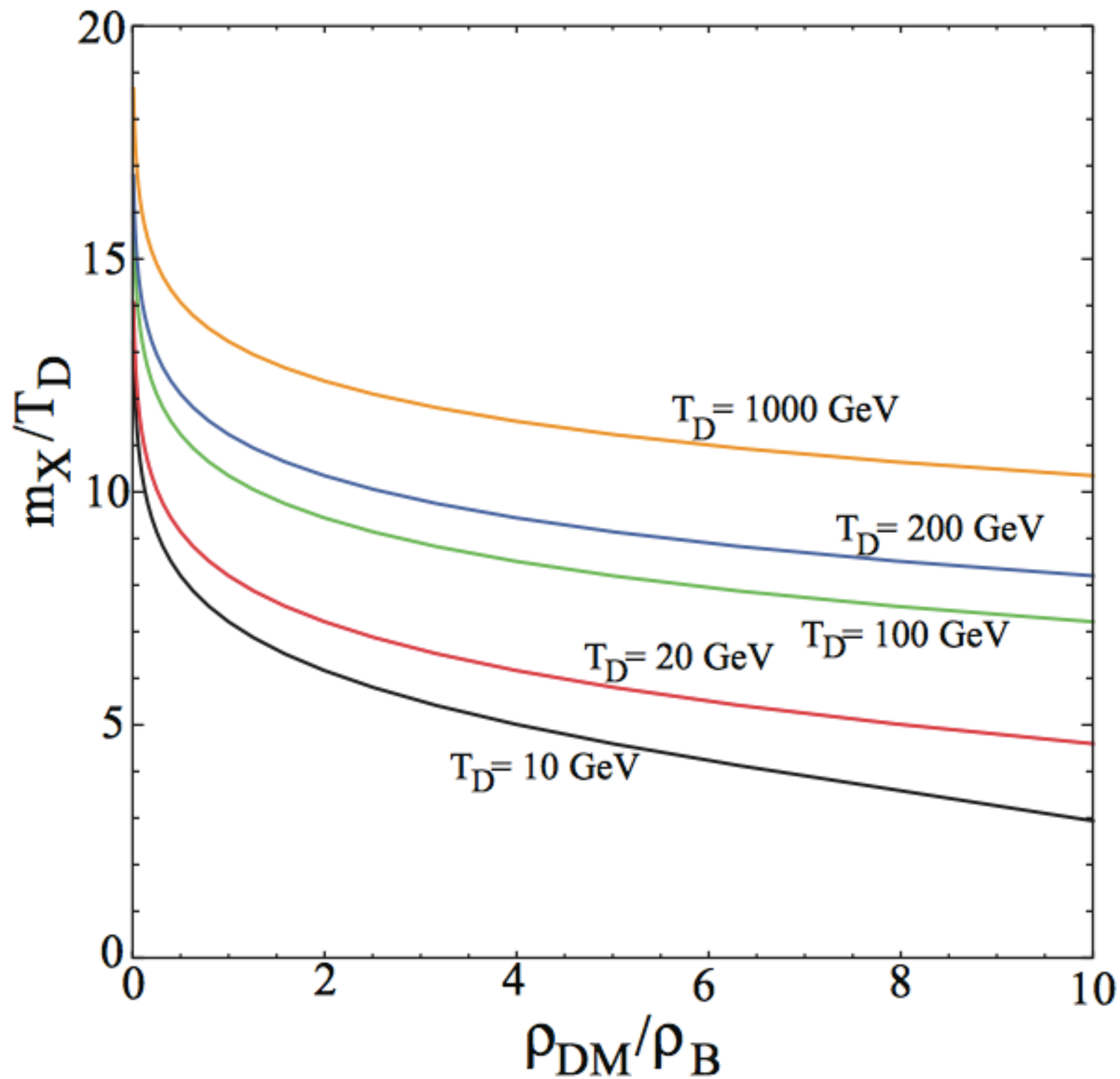
T_d — decoupling temp of X-number violating interactions

- Actual suppression is more complicated - see Barr '91

HEAVY ADM

Buckley, Randall; (2010)

- Large range of possible masses



HIDDEN SECTOR DM

VISIBLE SECTOR

$q, e, W, Z, H, \tilde{q}, \ldots$

PORTAL

HIDDEN SECTOR

$\phi_i, \chi_i, X_\mu \ldots$

- Hidden sector states have no SM gauge interactions
- Hidden sector may be linked, beyond gravity, to the visible sector

Portals: Higgs - $|H|^2|\phi_i|^2$

Neutrino - $LH\chi_i$

Kinetic mixing - $(\partial_\mu X_\nu - \partial_\nu X_\mu)F_Y^{\mu\nu}$ if X_ν is a $U(1)'$ gauge boson

plus D>4 operators $\frac{1}{M^{n-4}}\mathcal{O}_{\rm sm}\mathcal{O}_{\rm hs}$

- The form of this portal can play a major role in DM genesis

SINGLE SPECIES DM

- MUCH DEPENDS ON PORTAL - IF PORTAL INTERACTION IS STRONG ENOUGH FOR HIDDEN AND VISIBLE SECTORS TO BE IN THERMAL EQUILIBRIUM - USUAL FREEZE-OUT PICTURE

- IF PORTAL INTERACTION IS FEEBLE AND χ NOT IN THERMAL EQUILIBRIUM- CAN LOOK TO FREEZE-IN

HALL, JEDAMZIK, MARCH-RUSSELL, SW '09

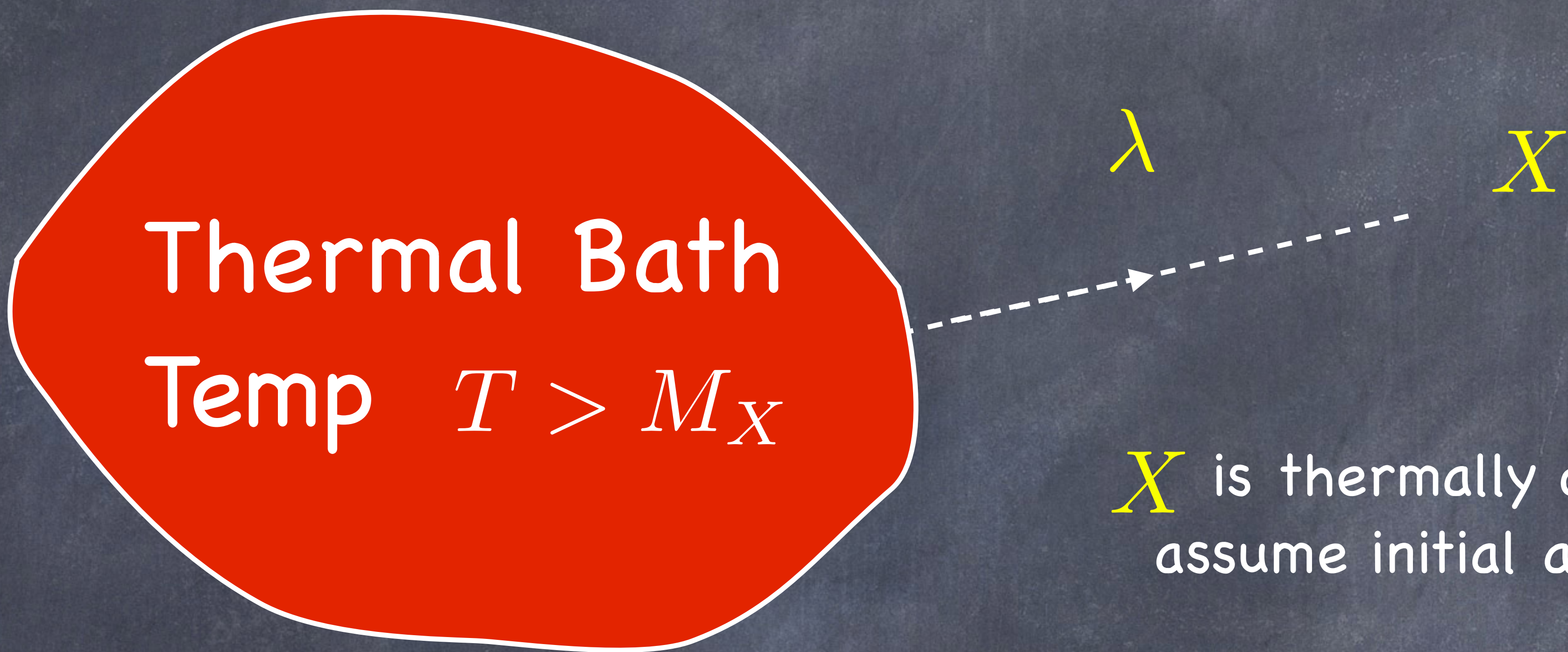
SEE EARLIER IMPLEMENTATION: MCDONALD '01, T. ASAKA, K. ISHIWATA, T. MOROI '05, '06

- FREEZE-IN - BATH PARTICLE SCATTERINGS OR DECAYS PRODUCE FIMPS THROUGH FEEBLE PORTAL INTERACTIONS

Freeze-in overview

- Freeze-in is relevant for particles that are feebly coupled (Via renormalisable couplings) - λ

  Feebly Interacting Massive Particles (FIMPs) X



X is thermally decoupled and we assume initial abundance negligible

- Although interactions are feeble they lead to some X production

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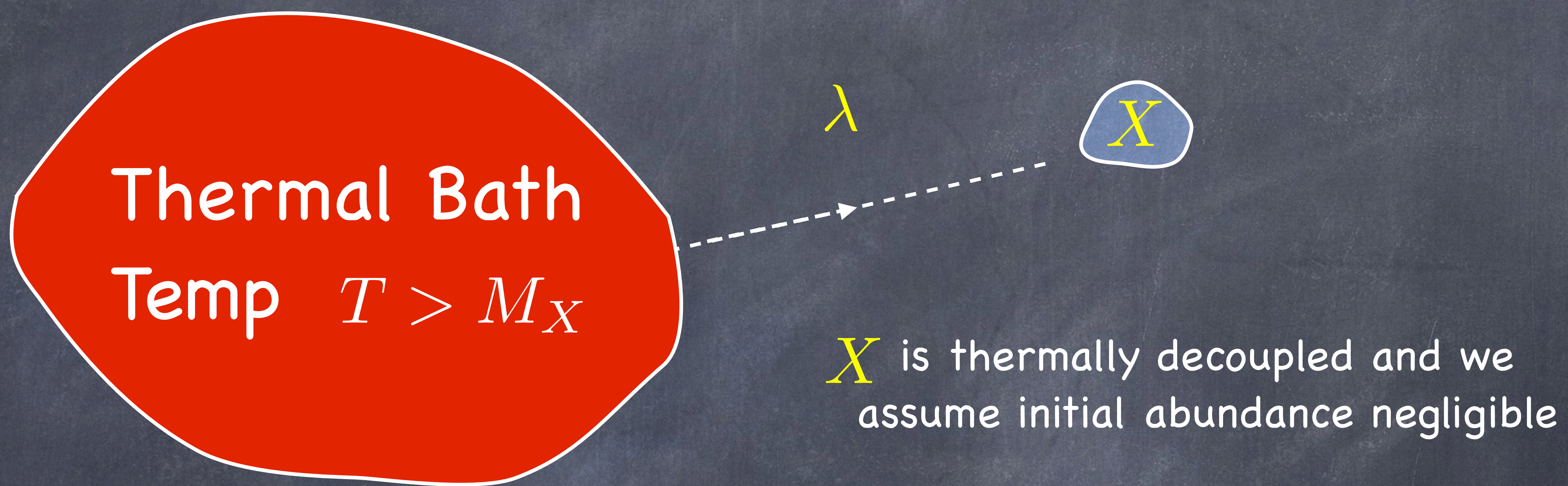

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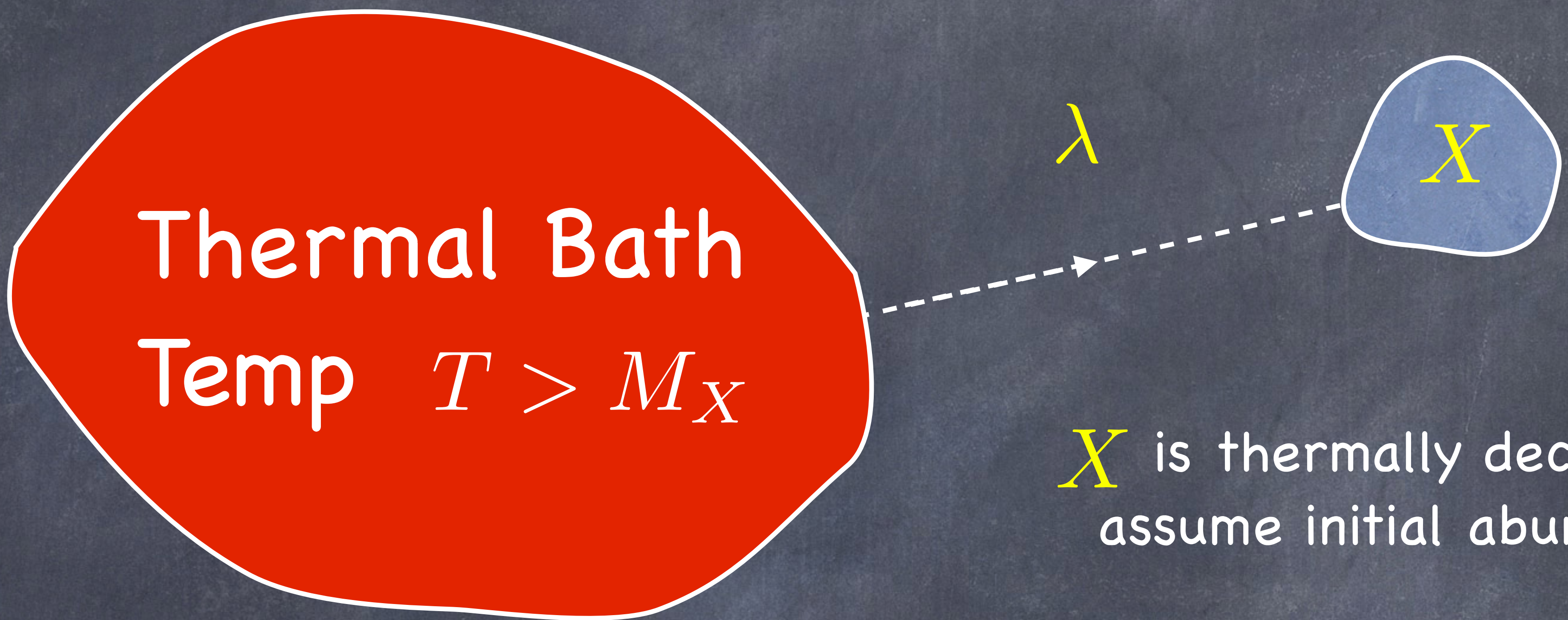

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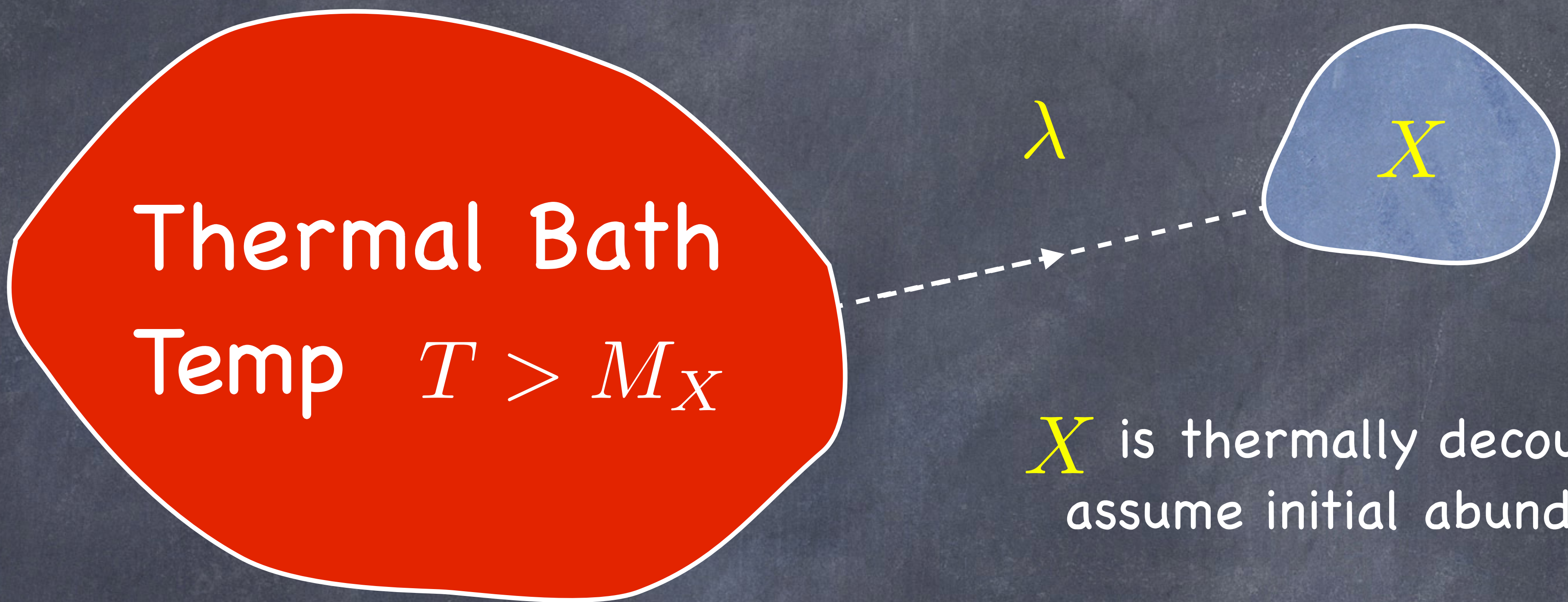


X is thermally decoupled and we assume initial abundance negligible

- Although interactions are feeble they lead to some X production
- Dominant production of X occurs at $T \sim M_X$ IR dominant
- Increasing the interaction strength increases the yield

opposite to Freeze-out...

Freeze-out vs Freeze-in

$$Y_{FO} \sim \frac{1}{\langle \sigma v \rangle \, M_{Pl} \, m'}$$

Using $\langle \sigma v \rangle \sim \lambda'^2 / m'^2$

$$Y_{FO} \sim \frac{1}{\lambda'^2} \left(\frac{m'}{M_{Pl}} \right)$$

Freeze-in via, decays, inverse decays or 2-2 scattering

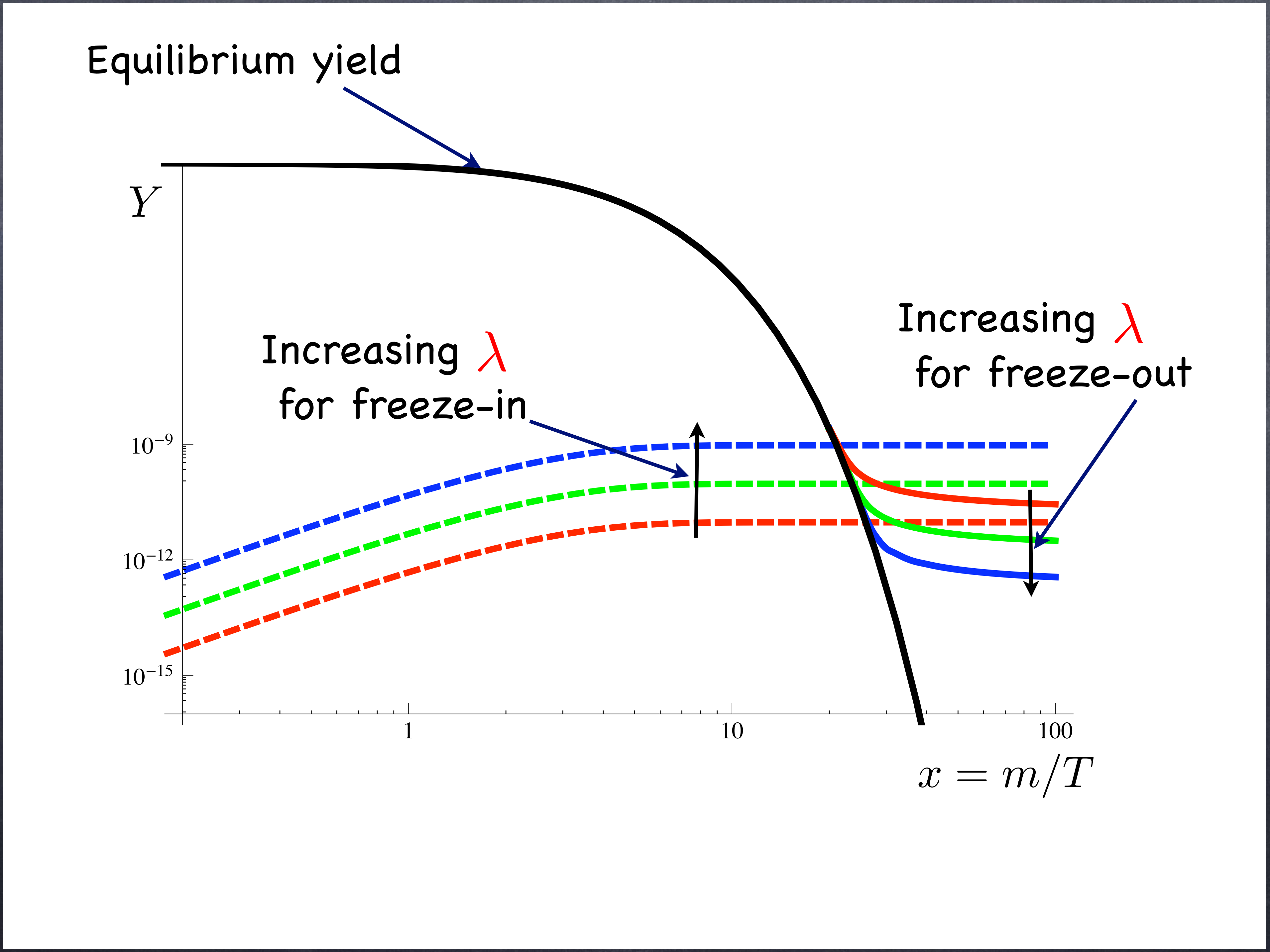
Coupling strength λ

m mass of heaviest particle in interaction

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

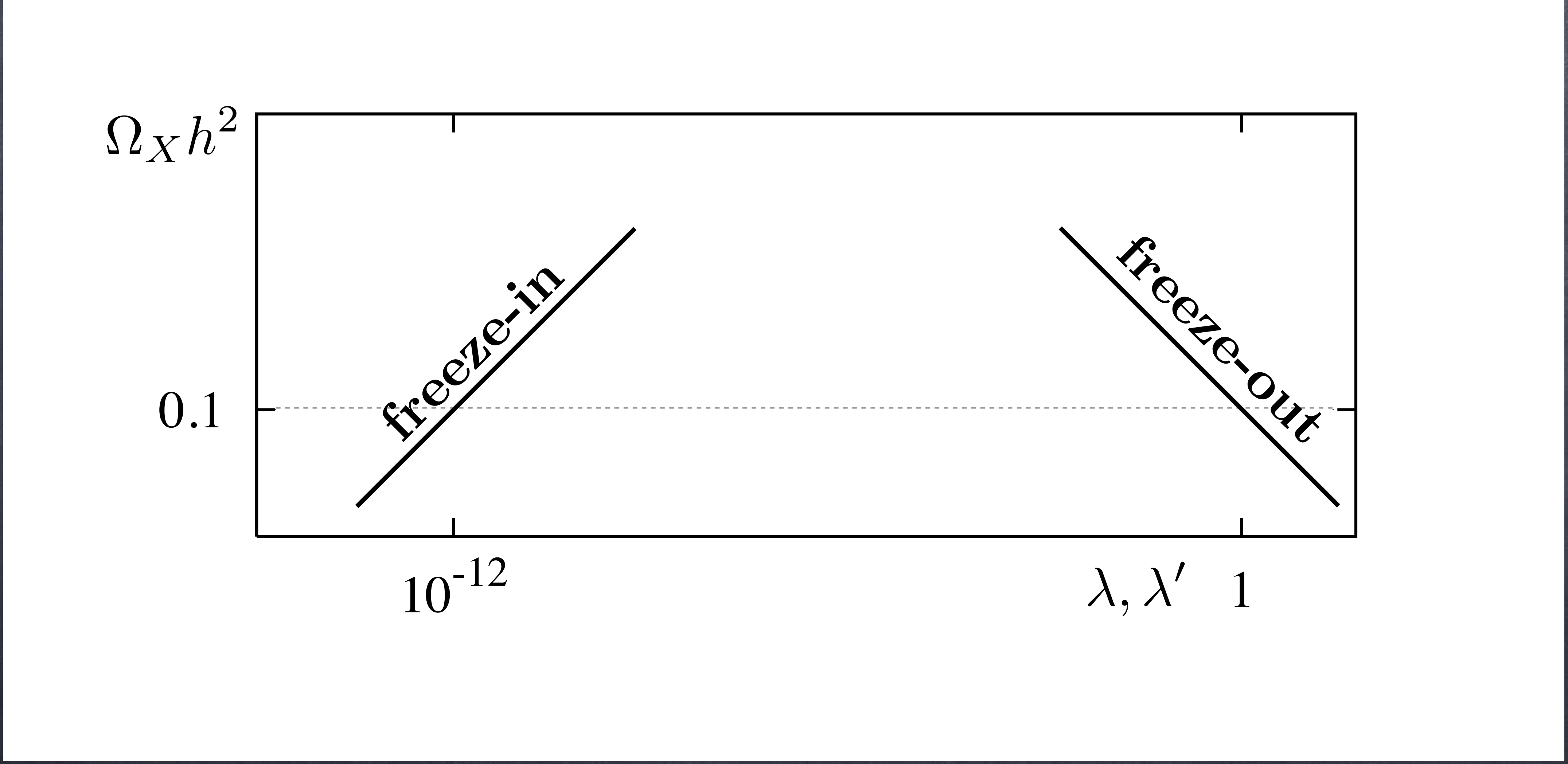
Freeze-in vs Freeze-out

- As T drops below mass of relevant particle, DM abundance is heading towards (freeze-in) or away from (freeze-out) thermal equilibrium



Freeze-in vs Freeze-out

- For a TeV scale mass particle we have the following picture.



FIMP miracle vs WIMP miracle

- WIMP miracle is that for $m' \sim v \quad \lambda' \sim 1$

$$Y_{FO} \sim \frac{1}{\lambda'^2}\left(\frac{m'}{M_{Pl}}\right) \sim \frac{v}{M_{Pl}}$$

- FIMP miracle is that for $m \sim v \quad \lambda \sim v/M_{Pl}$

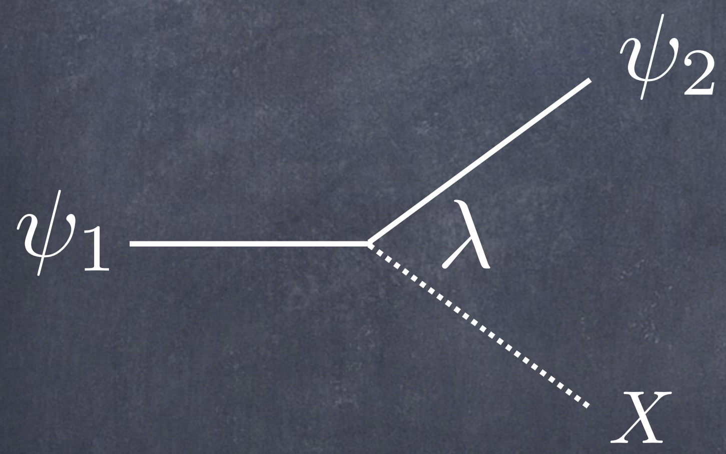
$$Y_{FI} \sim \lambda^2\left(\frac{M_{Pl}}{m}\right) \sim \frac{v}{M_{Pl}}$$

Example Toy Model I

- FIMPs can be DM or can lead to an abundance of the Lightest Ordinary Supersymmetric Particle (LOSP)
- Consider FIMP X coupled to two bath fermions ψ_1 and ψ_2

$$L_Y = \lambda \psi_1 \psi_2 X$$

- Let ψ_1 be the LOSP
- First case FIMP DM: $m_{\psi_1} > m_X + m_{\psi_2}$



$$\Omega_X h^2 \sim 10^{24} \frac{m_X \Gamma_{\psi_1}}{m_{\psi_1}^2}$$

Using $\Gamma_{\psi_1} \sim \frac{\lambda^2 m_{\psi_1}}{8\pi} \Rightarrow$

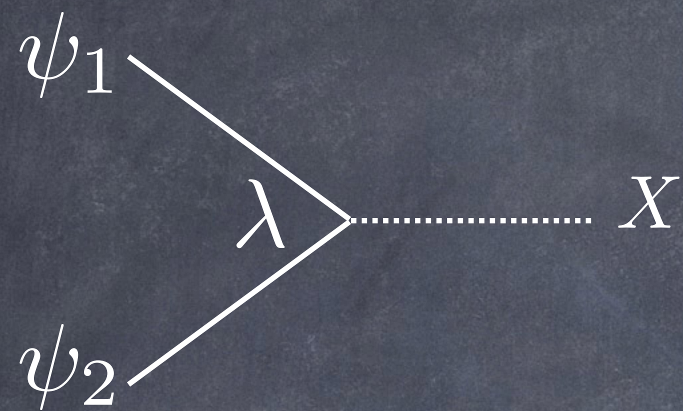
$$\Omega_X h^2 \sim 10^{23} \lambda^2 \frac{m_X}{m_{\psi_1}}$$

For $\frac{m_X}{m_{\psi_1}} \sim 1$ need $\lambda \sim 10^{-12}$ for correct DM abundance

- Lifetime of LOSP is long - signals at LHC, BBN...

Toy Model continued...

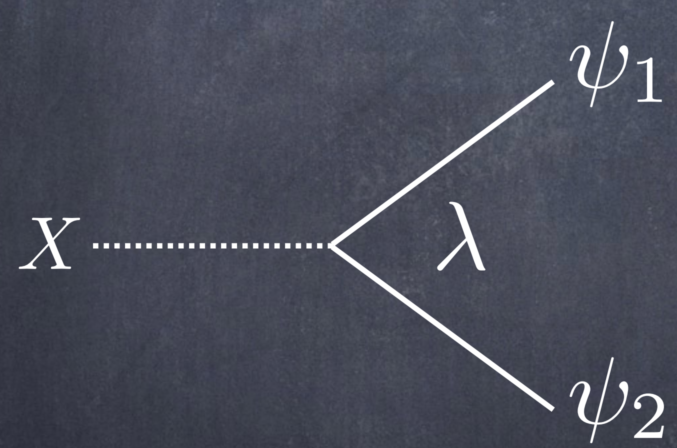
- Second case LOSP (=LSP) DM: $m_X > m_{\psi_1} + m_{\psi_2}$



$$\Omega_X h^2 \sim 10^{24} \frac{\Gamma_X}{m_X} \sim 10^{23} \lambda^2$$

Using $\Gamma_X \sim \frac{\lambda^2 m_X}{8\pi}$

- BUT X is unstable...



giving

$$\Omega_{\psi_1} h^2 = \frac{m_{\psi_1} \Omega_X h^2}{m_X} \sim 10^{23} \lambda^2 \frac{m_{\psi_1}}{m_X}$$

Again for $\frac{m_X}{m_{\psi_1}} \sim 1$ need $\lambda \sim 10^{-12}$ for correct DM abundance

- X lifetime can be long - implications for BBN, indirect DM detection

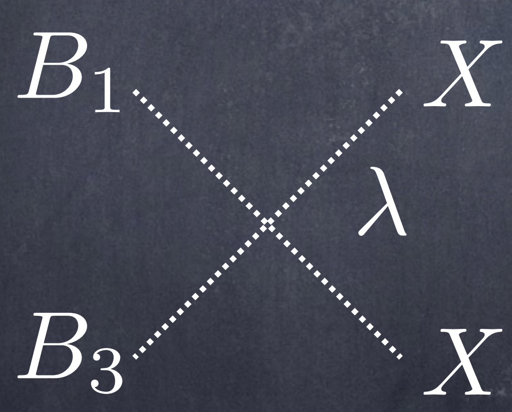
Another source of boost factors

Example Model II

- Many applications and variations of the Freeze-in mechanism
- Assume FIMP is lightest particle carrying some stabilising symmetry - FIMP is the DM
- Consider quartic coupling of FIMP with two bath scalars

$$\mathcal{L}_Q = \lambda X^2 B_1 B_2$$

Assuming
$m_X \gg m_{B_1}, m_{B_2}$



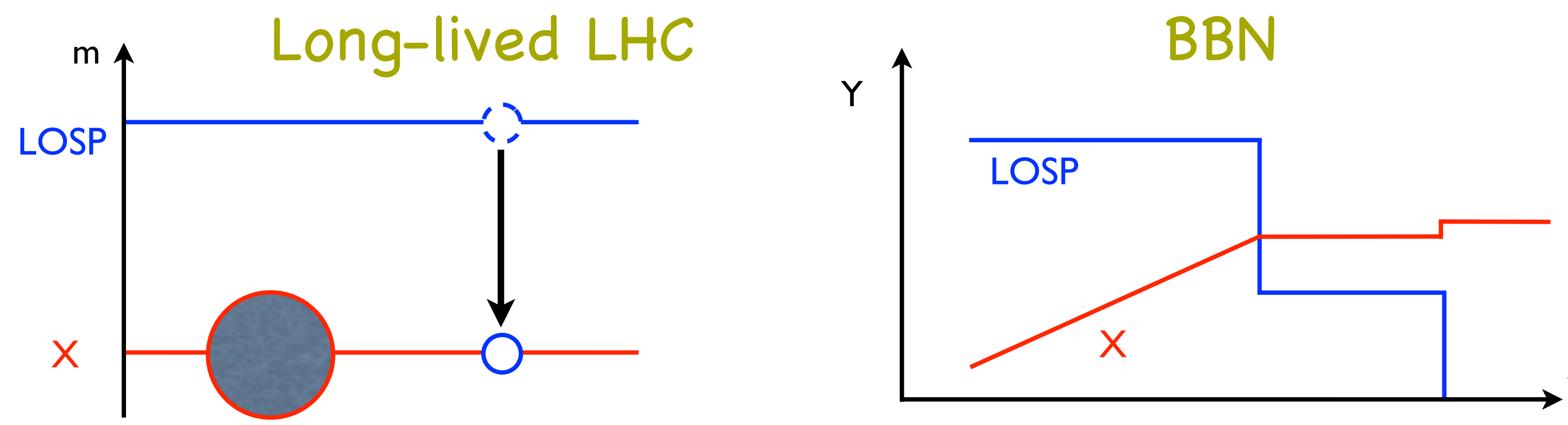
$$\Omega h^2_X \approx 10^{21} \lambda^2$$

For correct DM abundance $\Rightarrow \lambda \sim 10^{-11}$

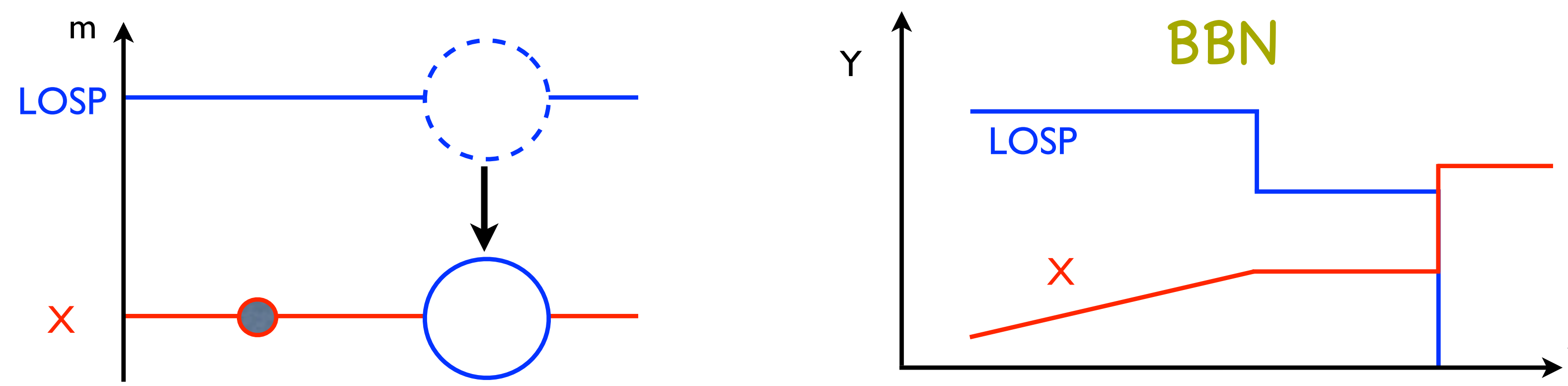
- NOTE: Abundance in this case is independent of the FIMP mass

Summary of Scenarios

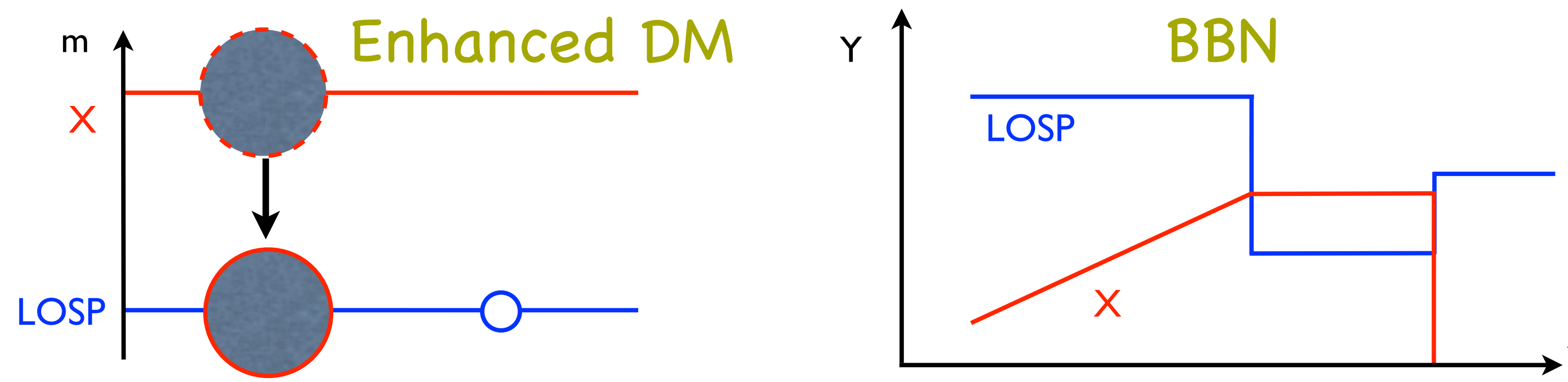
1 Freeze-in of FIMP DM



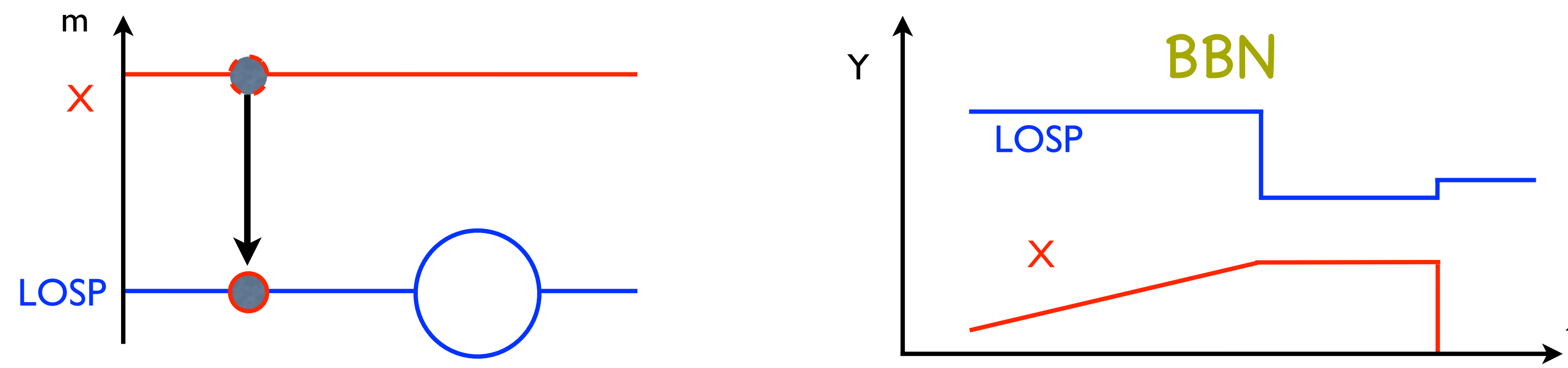
2 LOSP Freeze-out and decay to FIMP DM



3 FIMP Freeze-in and decay to LOSP DM



4 Freeze-out of LOSP DM



NUCLEAR DARK MATTER

NUCLEAR DARK MATTER

- CAN WE HAVE ANALOGY TO SM? RICH SPECTRUM OF COMPOSITE STATES
- CAN WE BUILD UP LARGE COMPOSITE STATES OF DM?
- OLD EXAMPLES OF BOUND STATES OF DARK STATES ARE:
  - WIMPONIUM (BOUND STATE OF TWO DM PARTICLES)

    M. POSPELOV AND A. RITZ '08; MARCH-RUSSELL, SW '08; SHEPHERDA, TAIT, ZAHARIJASB '09; PANOTOPOULOS '10, LAHA '13 '15; VON HARLING, PETRAKI '14, PETRAKI, POSTMA, WIECHERS '15
  - ATOMIC DARK MATTER

    KAPLAN, KRNJAIC, REHERMANN, WELLS '09, '11
- CAN WE GO BIGGER?

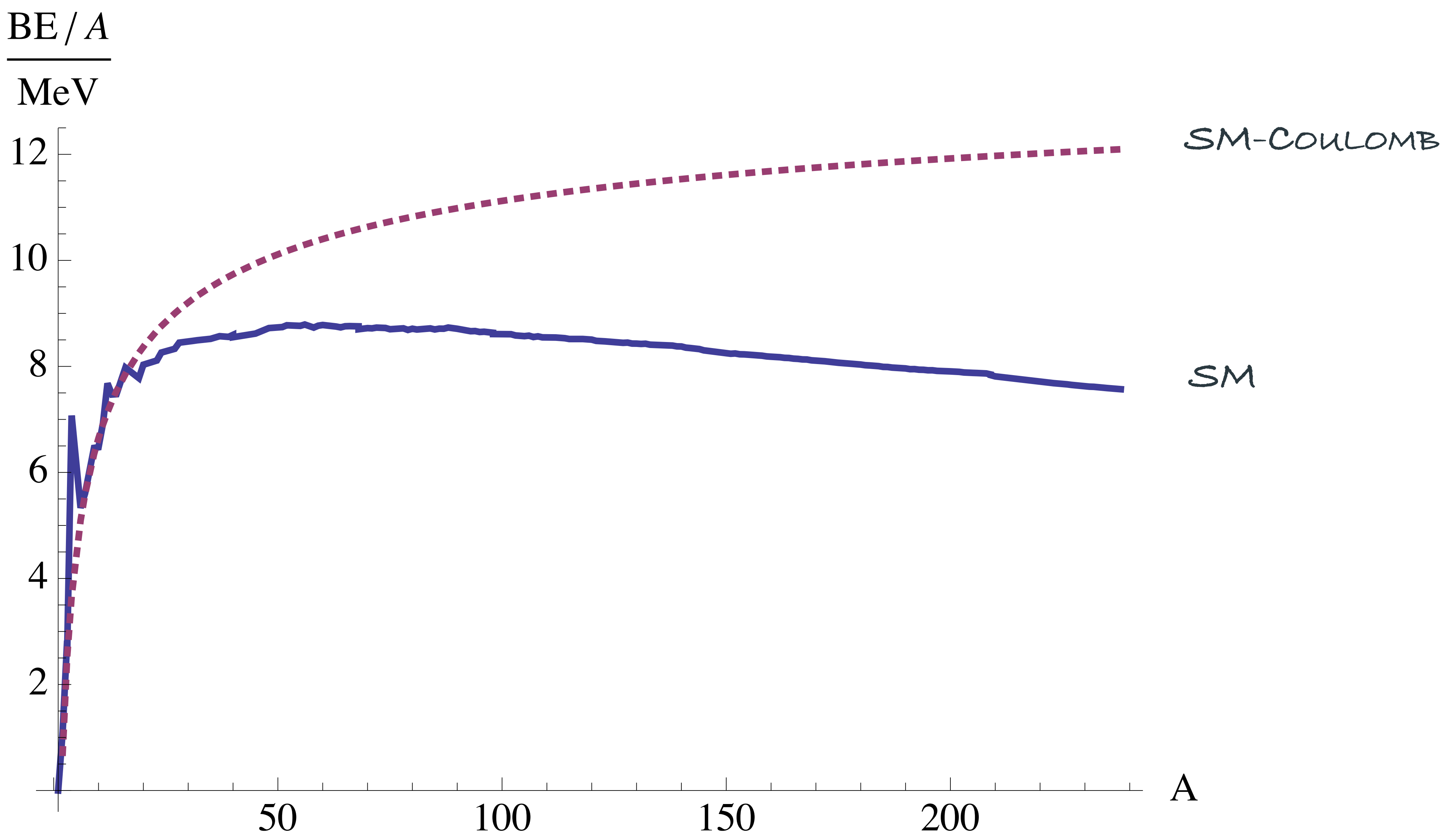
NUCLEAR DARK MATTER

G. Krnjaic and K. Sigurdson '14; Hardy, Lasenby, March-Russell, SW '14, '15

- Propose DM has short-ranged strong "nuclear" binding force with hard core repulsion - analogy with the SM
- DM or "dark nucleons" posses approximately-conserved quantum number, dark nucleon number (DNN) - analogous to baryon number
- Assume dark nucleons only - asymmetric DM
- No Coulomb force - binding energy per nucleon does not turn over at large DNN
- For minimality, only one type of dark nucleon present
- Dark nuclei exist with a range of DNNs, forming post freeze-out via dark nucleosynthesis

NUCLEAR DARK MATTER

- NO COULOMB FORCE - INCREASING BINDING ENERGY PER NUCLEON



NUCLEAR DARK MATTER

- RELATED WORKS
  - QCD-LIKE MODEL - NUCLEI WITH SMALL NUMBERS OF DARK NUCLEONS:

    DETMOLD, MCCULLOUGH, POCHINSKY '14

  - YUKAWA INTERACTIONS BETWEEN DARK NUCLEONS LEADING TO DARK NUCLEI (OR NUGGETS) WITH LARGE NUMBER OF NUCLEONS.
    - NO HARD CORE REPULSION LEADING TO INTERESTING RADIUS VS DNN BEHAVIOUR

    WISE AND ZHANG '14

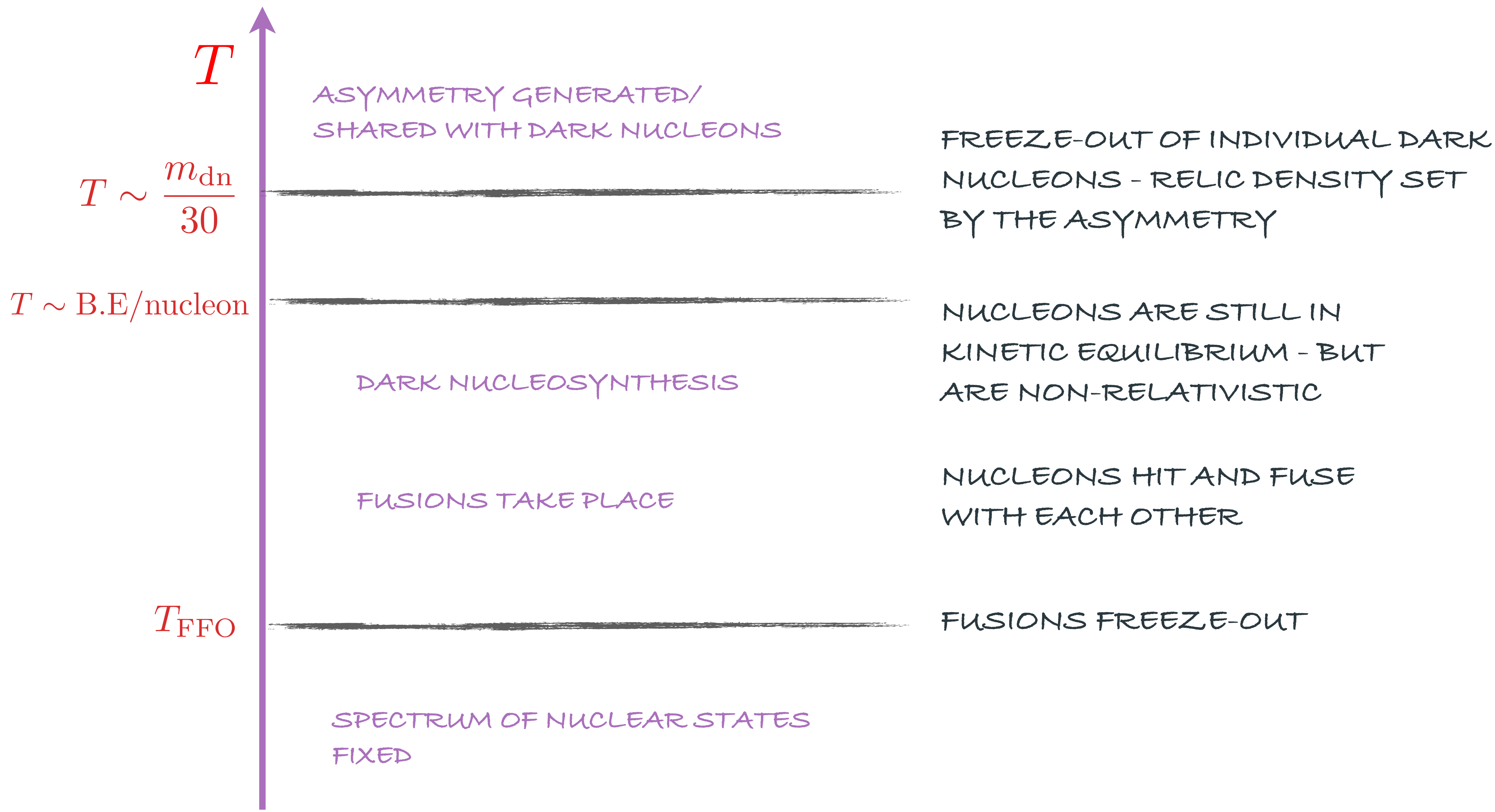
  - SIMILAR IN SOME WAYS TO Q-BALLS

    FRIEMAN, GELMINI, GLEISER, KOLB '88; FRIEMAN, OLINTO, GLEISER, AND C. ALCOCK '89 KUSENKO, SHAPOSHNIKOV '97;

NUCLEAR DARK MATTER

HARDY, LASENBY, MARCH-RUSSELL, SW '14, '15

- SCHEMATICALLY

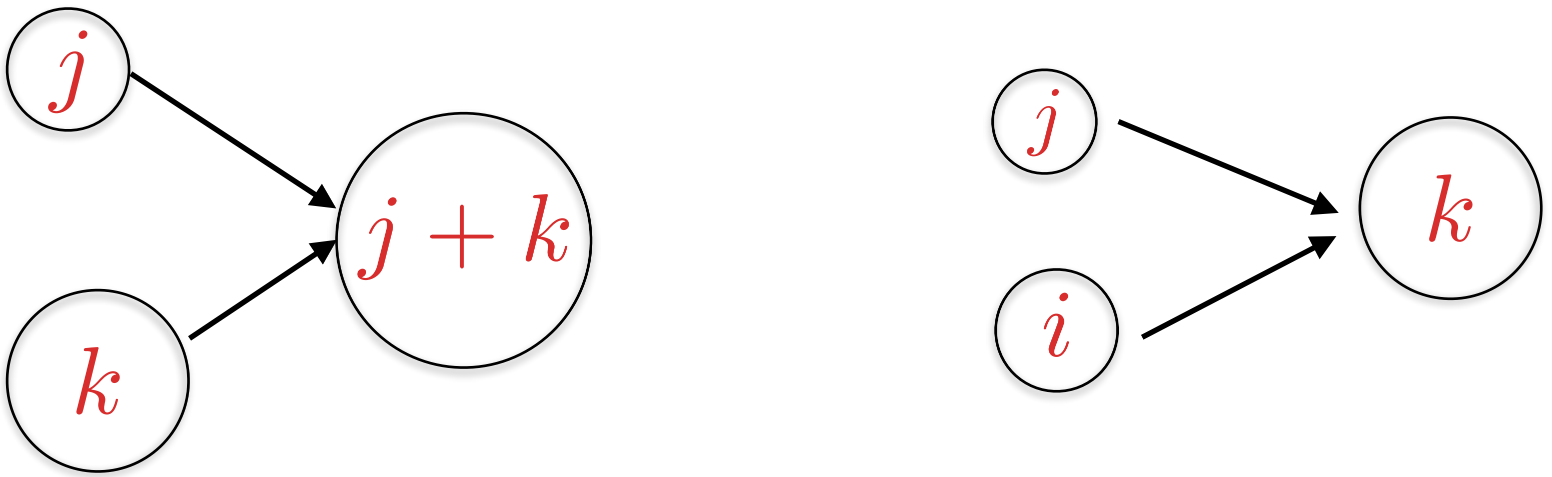


NUCLEAR DARK MATTER

HARDY, LASENBY, MARCH-RUSSELL, SW '14, '15

- AGGREGATION PROCESS - NEGLECTING DISSOCIATIONS
- WRITE BOLTZMANN EQUATION FOR A DARK NUCLEUS WITH K-DARK NUCLEONS

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



NEGLECTING DISSOCIATIONS

$k + (A-k) \leftrightarrow A$ DISSOCIATIONS NEGLIGIBLE IF

$$\frac{\langle \sigma v \rangle_{(k,A-k)\to A} n_k n_{A-k}}{\Gamma_{A\to(k,A-k)} n_A} \gg 1$$

SATISFIED FOR

$$n_0 \left(\frac{1}{m_1 T} \right)^{3/2} e^{\Delta B/T} \gg \text{const.}$$

TIME TAKEN FROM WHERE THE PROCESSES $k + (A-k) \leftrightarrow A$

ARE IN EQUILIBRIUM TO WHERE CONDITION ABOVE IS SATISFIED IS A FRACTION OF A HUBBLE TIME

OTHER DISSOCIATION PROCESSES ARE POSSIBLE BUT WE NEGLECT THEM HERE AS THEY ARE MODEL DEPENDENT

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

- REWRITING $y_k = Y_k/Y_0 = (n_k/sY_0)$

Y_0 IS TOTAL YIELD OF DARK NUCLEONS

AND $\langle\sigma v\rangle_{i,j} = \sigma_1 v_1 K_{i,j}$

WHERE σ_1 GEOMETRICAL CROSS SECTION OF INDIVIDUAL DARK NUCLEON

v_1 VELOCITY OF SINGLE NUCLEON

$K_{i,j}$ PARAMETERISES RELATIVE RATES OF DIFFERENT FUSION PROCESSES

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

WHERE WE CAN DEFINE A DIMENSIONLESS TIME VARIABLE

$$\frac{dw}{dt} = Y_0 \sigma_1 v_1(t) s(t)$$

SCALING SOLUTION

$$\langle \sigma v \rangle_{i,j} = \sigma_1 v_1 K_{i,j}$$

$$K_{i,j} \sim (i^{2/3} + j^{2/3}) \left(\frac{1}{i^{1/2}} + \frac{1}{j^{1/2}} \right)$$

RELATED TO GEOMETRICAL SIZE

RELATED TO RELATIVE VELOCITY

$$v^2 \sim T/m$$

RESCALING WE HAVE

$$K_{\lambda i, \lambda j} = \lambda^{1/6} K_{i,j}$$

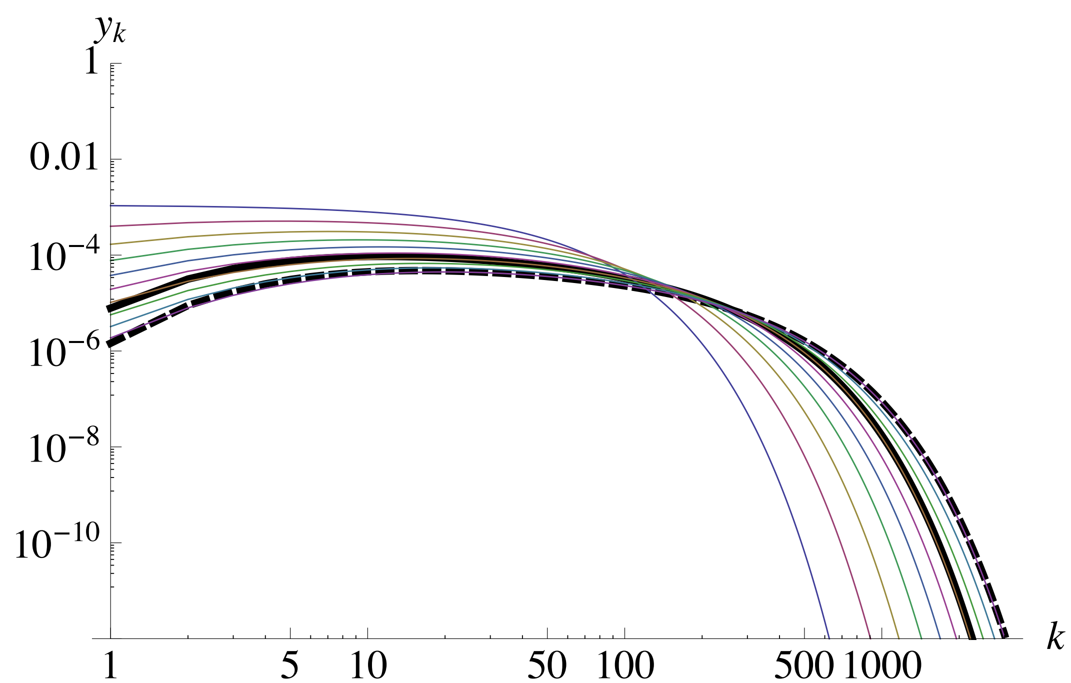
- FOR THIS CASE THERE IS AN ATTRACTOR SCALING SOLUTION FOR LARGE DNN (VALID FOR ALL INITIAL CONDITIONS WE CONSIDER)

SEE E.G. KRAPIVSKY, REDNER, BEN-NAIM, A KINETIC VIEW OF STATISTICAL PHYSICS, CUP, '10

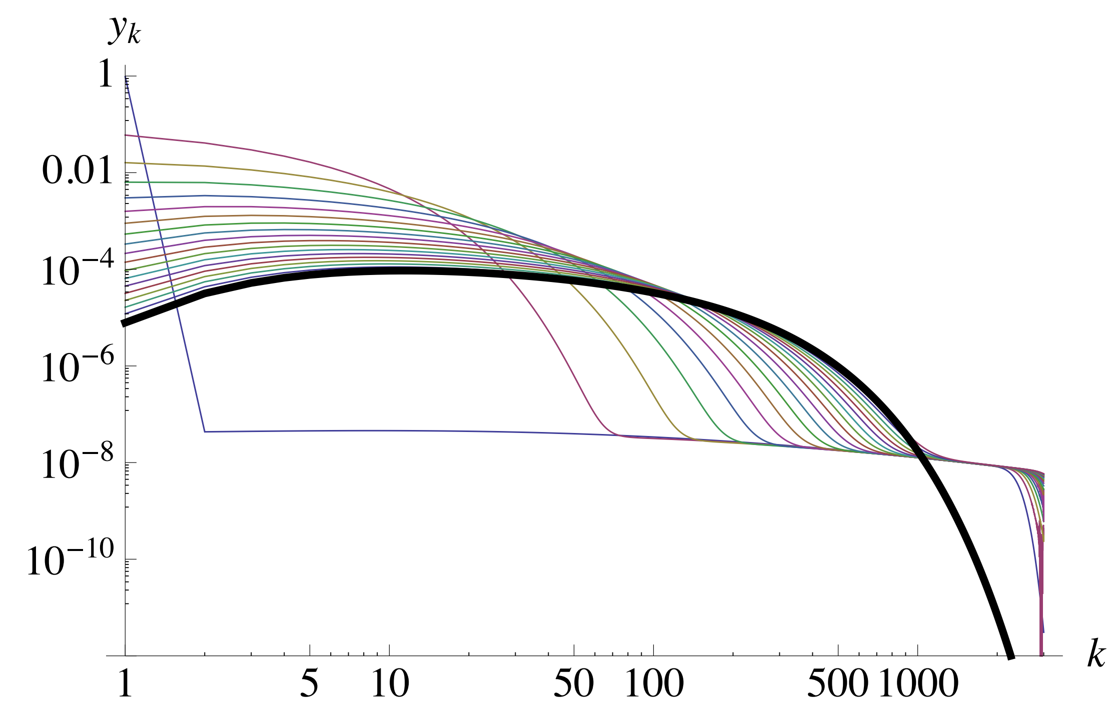
SCALING SOLUTION

HARDY, LASENBY, MARCH-RUSSELL, SW '14, '15

- FINAL DISTRIBUTION IS INDEPENDENT OF INITIAL CONDITIONS



$$y_k(0) = e^{-k/30}$$



INITIAL CON: MOSTLY IN SINGLE NUCLEONS, BUT WITH A SUB-DOMINANT TAIL

HOW BIG?

HARDY, LASENBY, MARCH-RUSSELL, SW '14, '15

- HOW BIG CAN WE GO?
  - FOR EQUAL SIZE FUSIONS $k + k \to 2k$

WITH $n_k = n_0/k \quad \sigma \sim \sigma_1 k^{2/3} \quad v_k \sim v_1 k^{-1/2}$

$$\frac{\Gamma}{H} \sim \frac{\langle \sigma v \rangle n_k}{H} \sim \frac{\sigma_1 v_1 n_0}{H} k^{-5/6}$$

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

WHERE PARAMETERS ARE SET TO SM VALUES - MOTIVATED BY ADM

$$\Rightarrow \quad k \sim 5 \times 10^8$$

IF WE HAVE SMALL-LARGE FUSIONS CAN ACTUALLY GO EVEN LARGER...

PHENOMENOLOGY OF NDM

- CHANGES FOR DIRECT DETECTION SIGNALS
  - DARK MATTER MOMENTUM DEPENDENT FORM FACTOR
  - COHERENT SCATTERING FROM DARK NUCLEI
  - INELASTIC PROCESSES
  - COLLECTIVE LOW ENERGY EXCITATIONS
- INDIRECT DETECTION SIGNALS
  - INELASTIC SELF-INTERACTIONS (MAY ALSO MODIFY DISTRIBUTION IN HALO)
- CAPTURE IN STARS
  - ASYMMETRIC IN NATURE SO CAN BUILD UP IN STARS
  - MODEL DEPENDENT CONSEQUENCES

Direct Detection - Standard WIMP

- Event rate:

Particle Physics	Nuclear structure	Local Astrophysics

$$\frac{dR}{dE_R} = \frac{\sigma_{XN}(0)}{m_X} \frac{F_N(q)^2}{\mu_{XN}^2} \rho_X g(v_{\min})$$

$\sigma_{XN}(0)$ .... DM-Nucleus zero-momentum-transfer cross section

$F_N(q)$ .... Nuclear form factor, q =momentum transfer

$g(v_{\min}) \equiv \frac{1}{2} \int_{v > v_{\min}} d^3\mathbf{v} \, \frac{f(\mathbf{v})}{v}$ .... Integral over local WIMP velocity distribution

$v_{\min} = \sqrt{E_R M_N / 2\mu_r^2}$ .... Minimum WIMP velocity for given E_R

DIRECT DETECTION - STANDARD WIMP

Coherent Enhancement

Spin Independent

$$\sigma^{\mathrm{SI}}_{XN}(0) = A^2 \frac{\mu^2_{XN}}{\mu^2_{Xp}} \sigma^{\mathrm{SI}}_{Xp}$$

(Assuming DM-p and DM-n interactions are equal)

A = Atomic number of target nucleus

DIRECT DETECTION - NDM

$$\frac{dR}{dE_R} = \frac{\sigma_{kN}(q)}{m_k \mu_{kN}^2} \rho_k g(v_{\min})$$

$$\sigma_{XN}(q) = \sigma_{XN}(0) F_N(q)^2 F_k(q)^2 \qquad m_X = k m_1 \qquad \sigma_{kN}(0) \propto k^2 A^2$$

$$\frac{dR_k}{dE_R} = g(v_{\min}) \frac{\rho_k}{2\mu_{kn}^2 m_1} A^2 k \, \sigma_0 F_N(q)^2 F_k(q)^2$$

σ_0 DN-SM Nucleus zero-momentum-transfer cross section

- Full recoil spectrum for a distribution of dark nuclei is the sum of k for all contributions - see later

DARK FORM FACTOR

- MOMENTUM DEPENDENT FORM FACTOR

  - FOR $\Delta q > R_k^{-1}$ WE WILL PROBE THE STRUCTURE OF THE DARK NUCLEUS

  - ASSUME A SPHERICAL TOP HAT DARK NUCLEON DISTRIBUTION

$$F(\mathbf{q}) = \int d\mathbf{r}\, e^{i\mathbf{q}\cdot\mathbf{r}} \rho(\mathbf{r}),$$

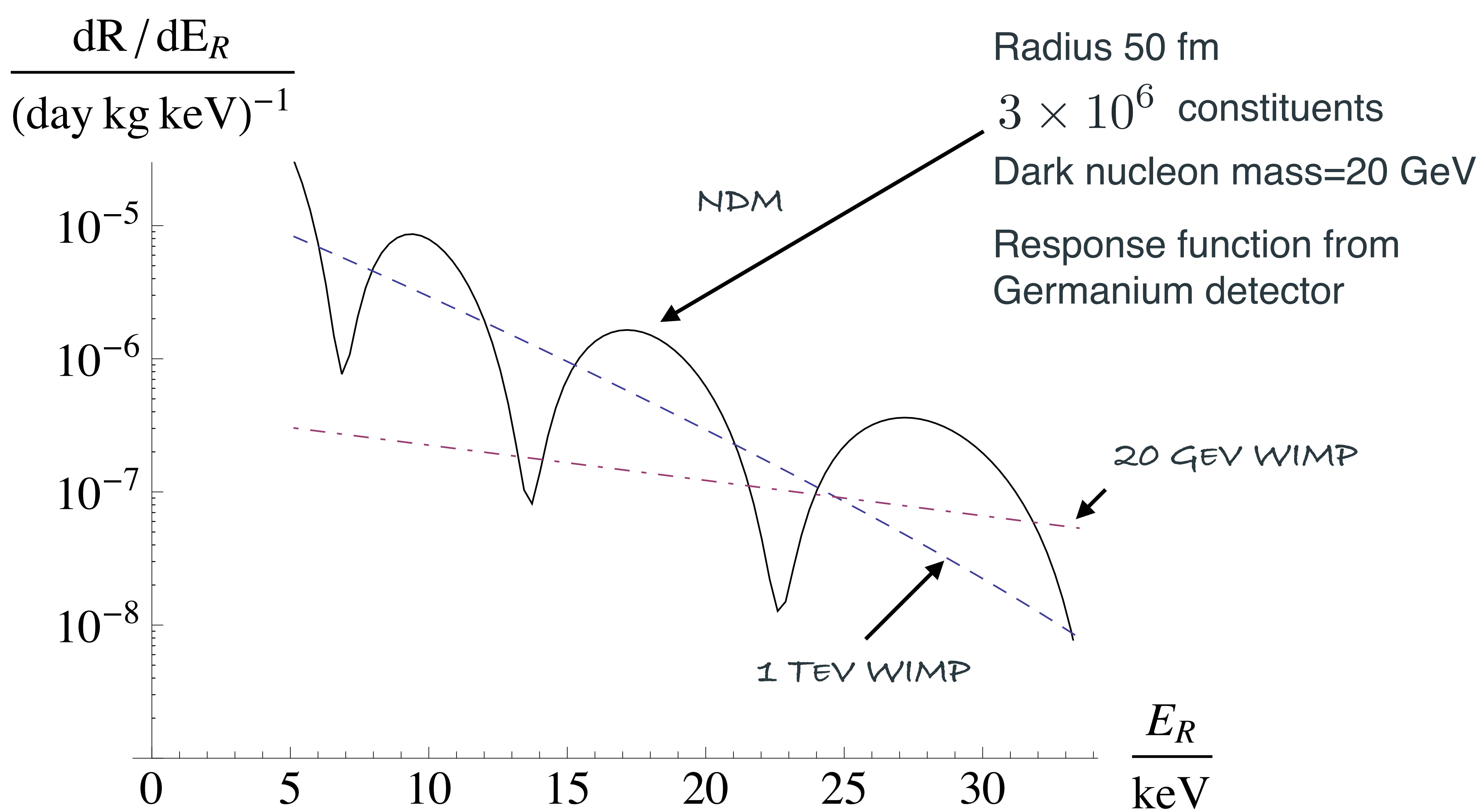
$$\Rightarrow F_k(q) = \frac{qR_k \cos(qR_k) - \sin(qR_k)}{(qR_k)^3}$$

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

  - PROVIDED THE DARK NUCLEUS IS LARGER THAN THE SM NUCLEUS WE WILL SEE EFFECT OF FORM FACTOR FIRST IN RECOIL SPECTRUM

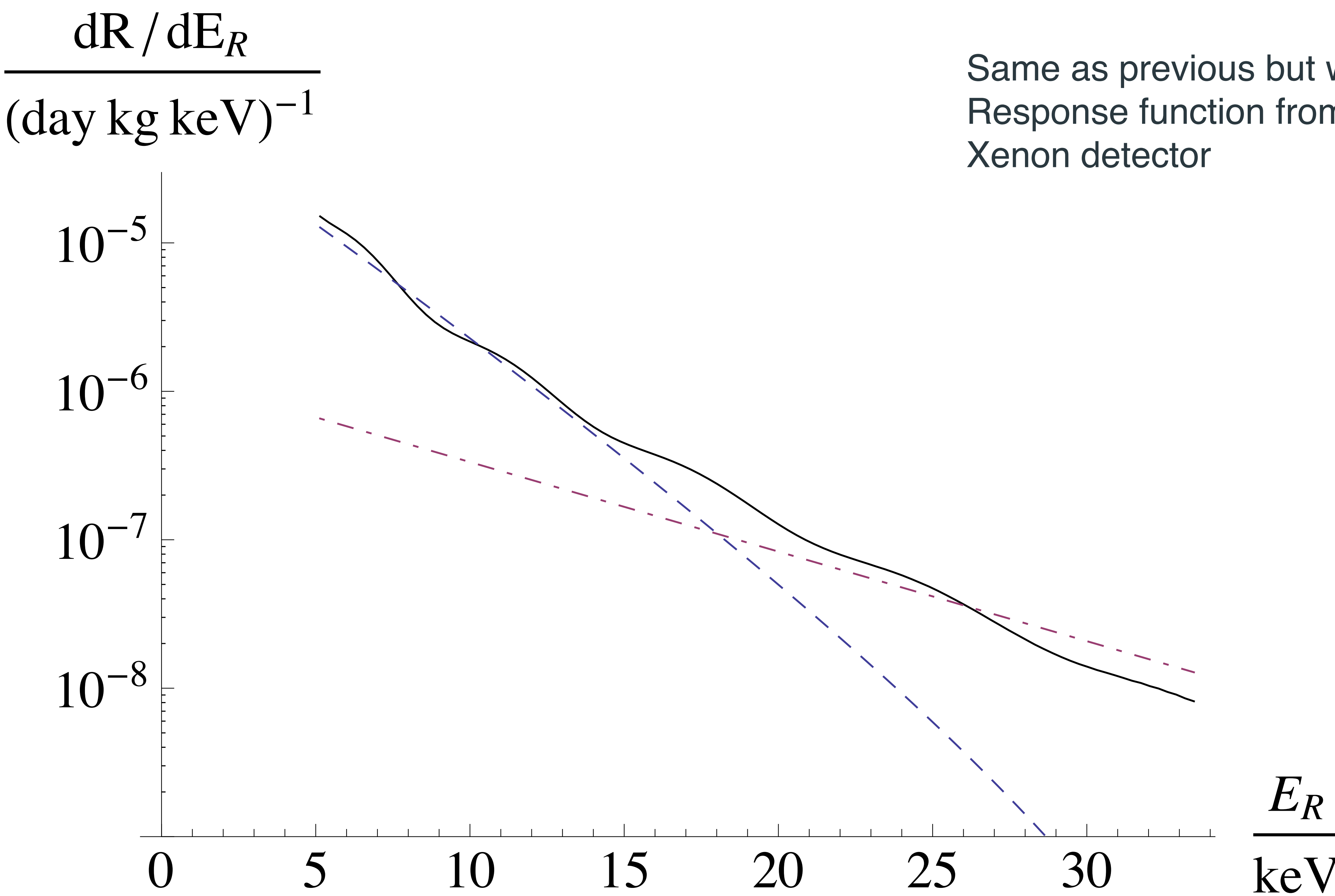
DIRECT DETECTION - SINGLE K

HARDY, LASENBY, MARCH-RUSSELL, SW '14, '15



- Easy to distinguish from WIMP, look for non-decreasing behaviour

DIRECT DETECTION - SINGLE K

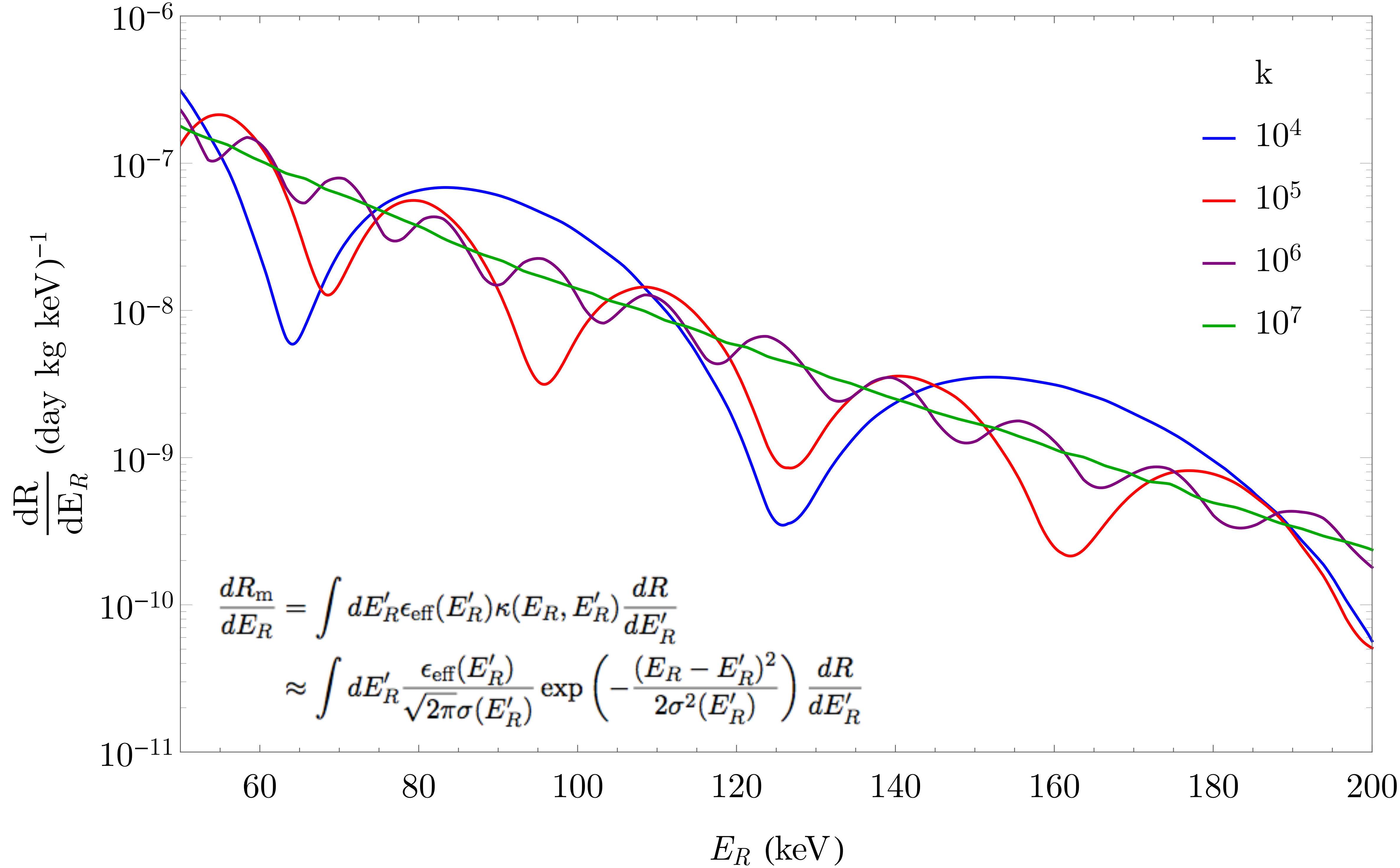


Same as previous but with Response function from Xenon detector

ENERGY RESPONSE FUNCTION

Butcher, Kirk, Monroe, SW '16

- Effect of energy response function on resolving form factor at high k



WIMP VS NDM

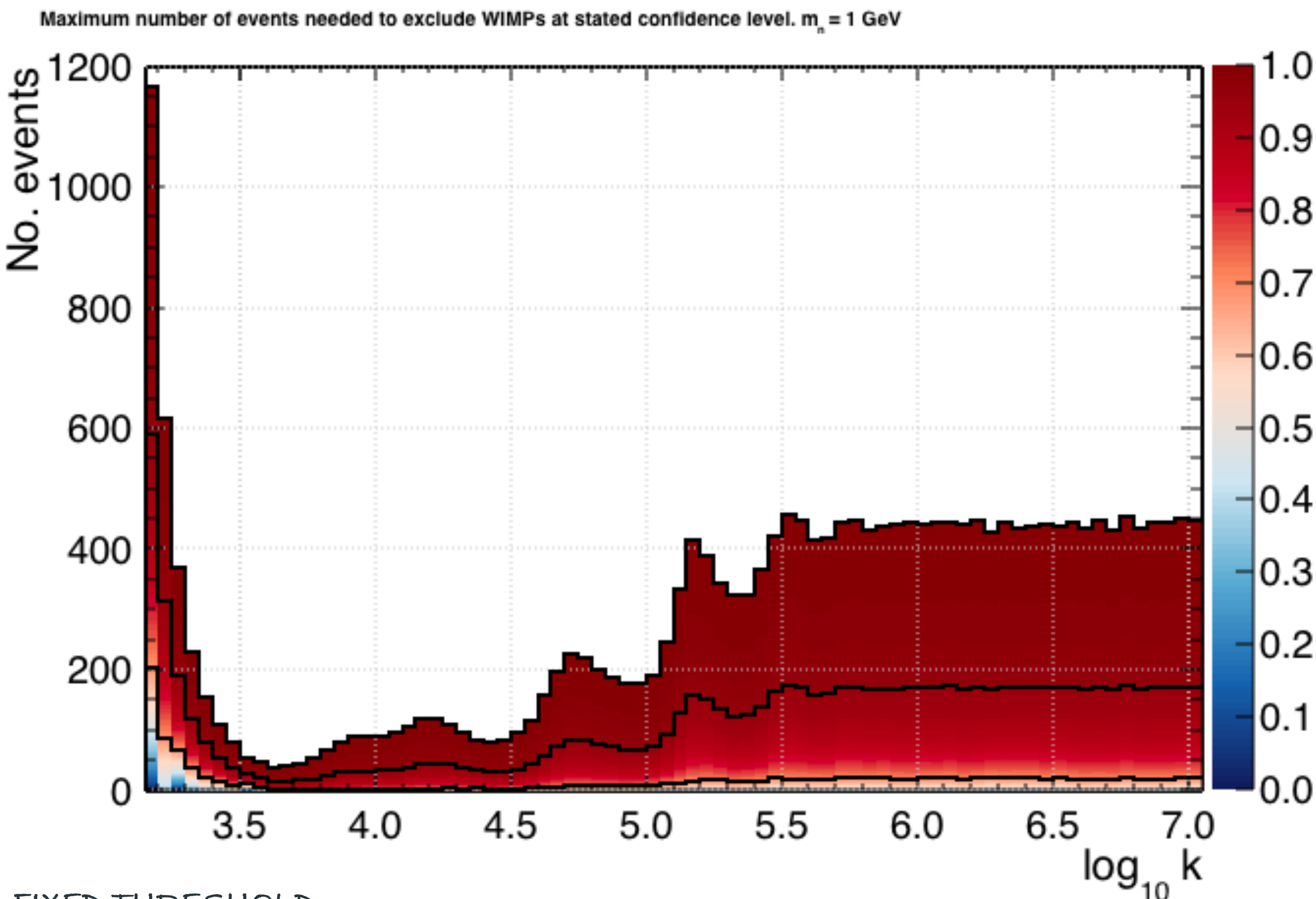
- IF WE HAVE EVENTS AT A DIRECT DETECTION EXPERIMENT, CAN WE DISTINGUISH BETWEEN A WIMP AND NDM?

- LOOK AT THE CASE OF A SINGLE K NDM STATE

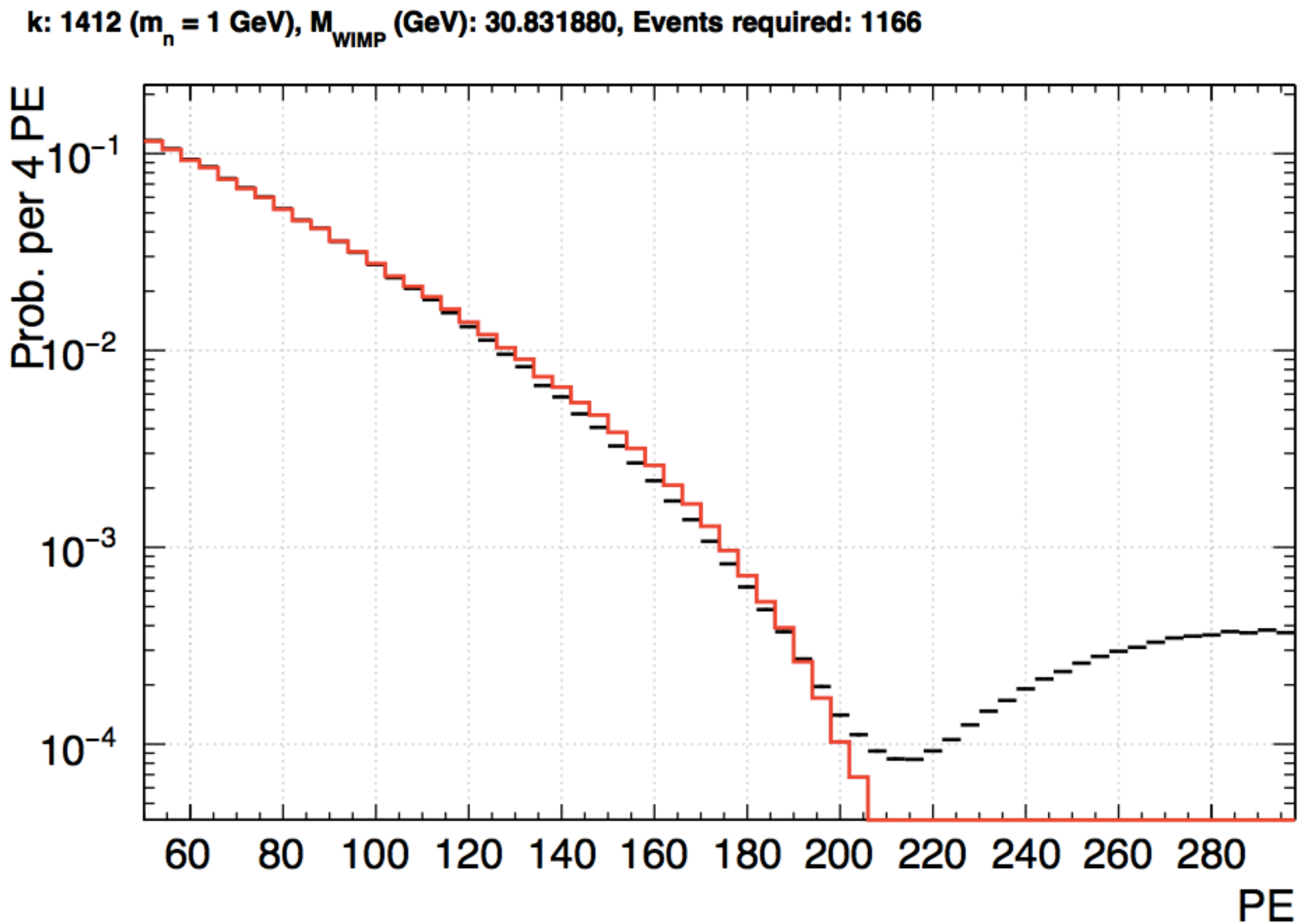
- SAMPLE EVENTS FROM NDM SPECTRUM AND TRY TO FIT A WIMP RECOIL SPECTRUM

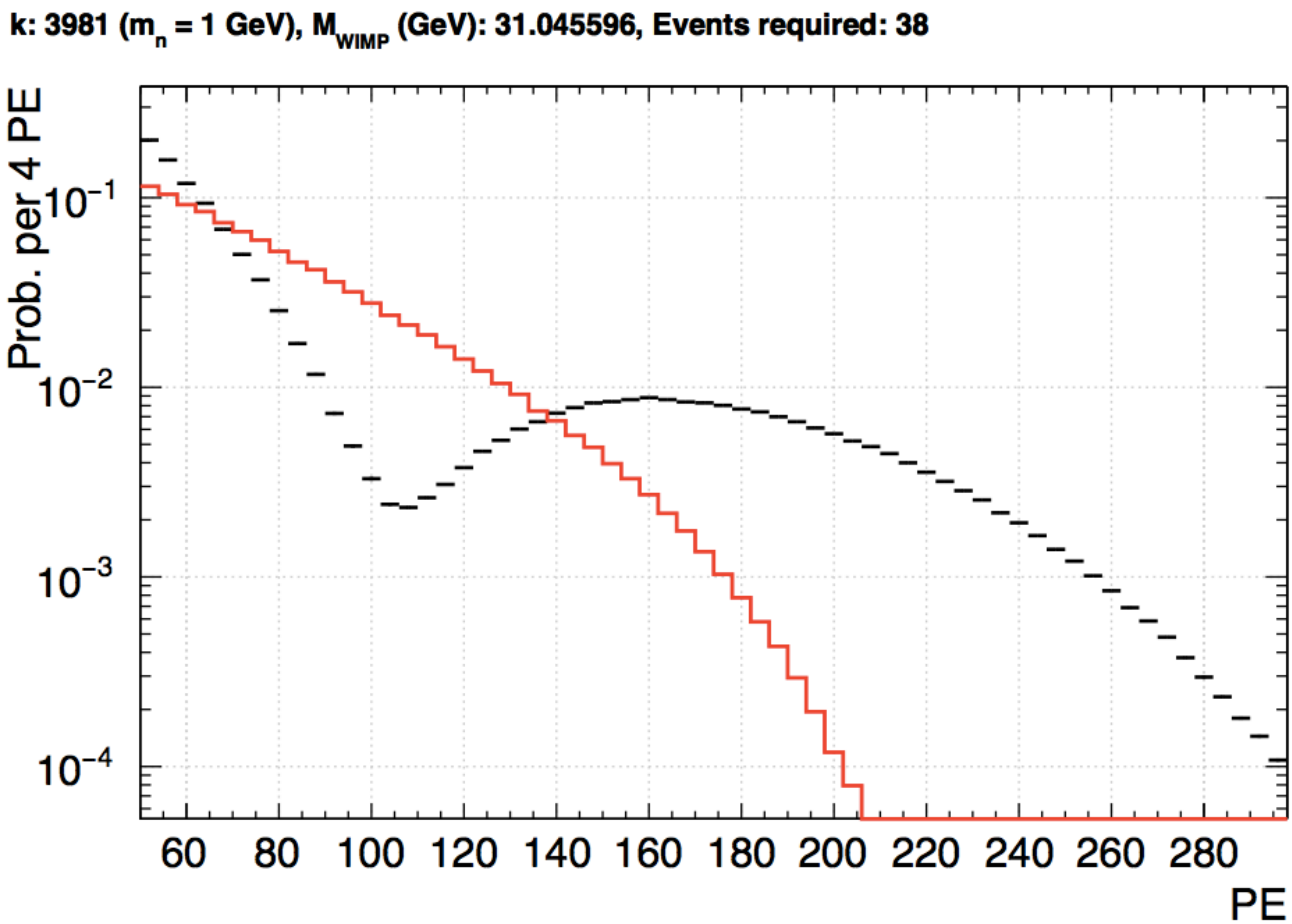
- KEEP SAMPLING EVENTS FROM NDM SPECTRUM UNTIL WE CAN REJECT THE WIMP HYPOTHESIS.

WIMP VS NDM



- FIXED THRESHOLD

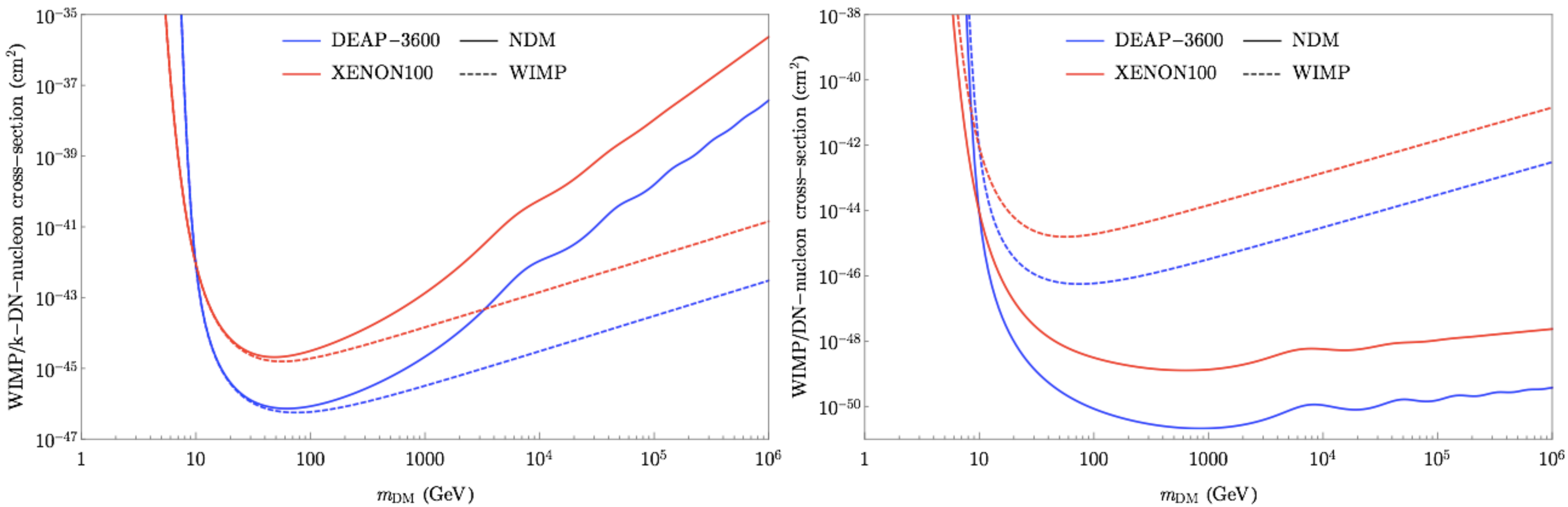

k: 1412 (m_n = 1 GeV), M_{WIMP} (GeV): 30.831880, Events required: 1166
Prob. per 4 PE
10^{-1}
10^{-2}
10^{-3}
10^{-4}
60
80
100
120
140
160
180
200
220
240
260
280
PE



k: 3981 (m_n = 1 GeV), M_WIMP (GeV): 31.045596, Events required: 38
Prob. per 4 PE
10^-1
10^-2
10^-3
10^-4
60
80
100
120
140
160
180
200
220
240
260
280
PE

DIRECT DETECTION - LIMITS

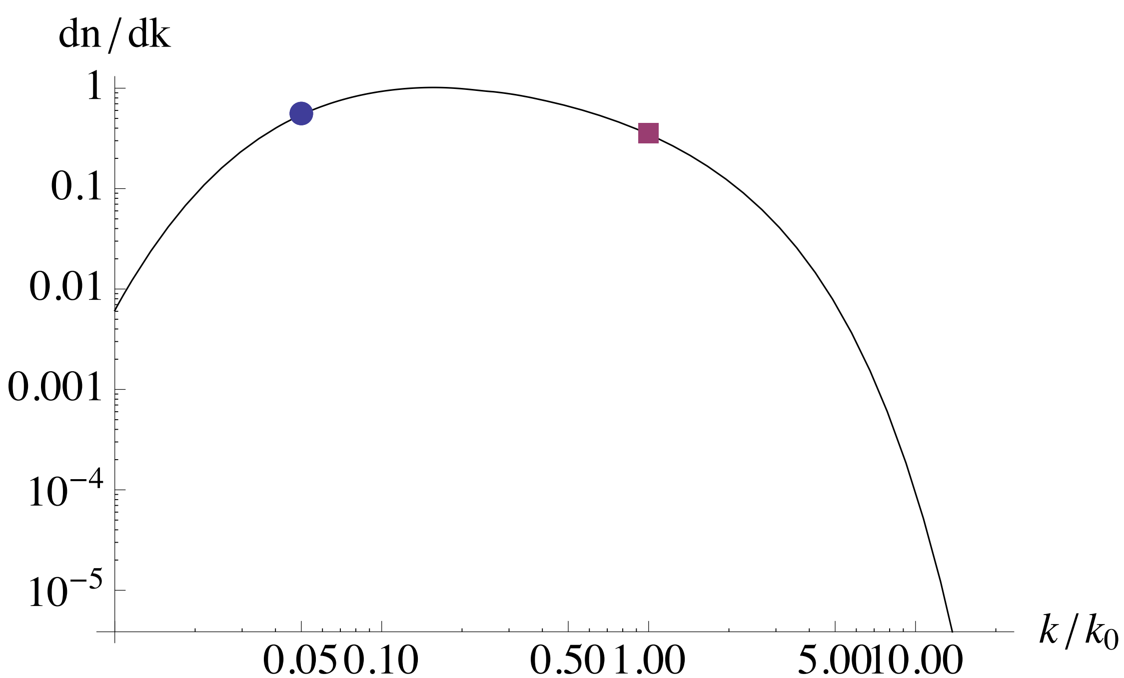
BUTCHER, KIRK, MONROE, SW '16

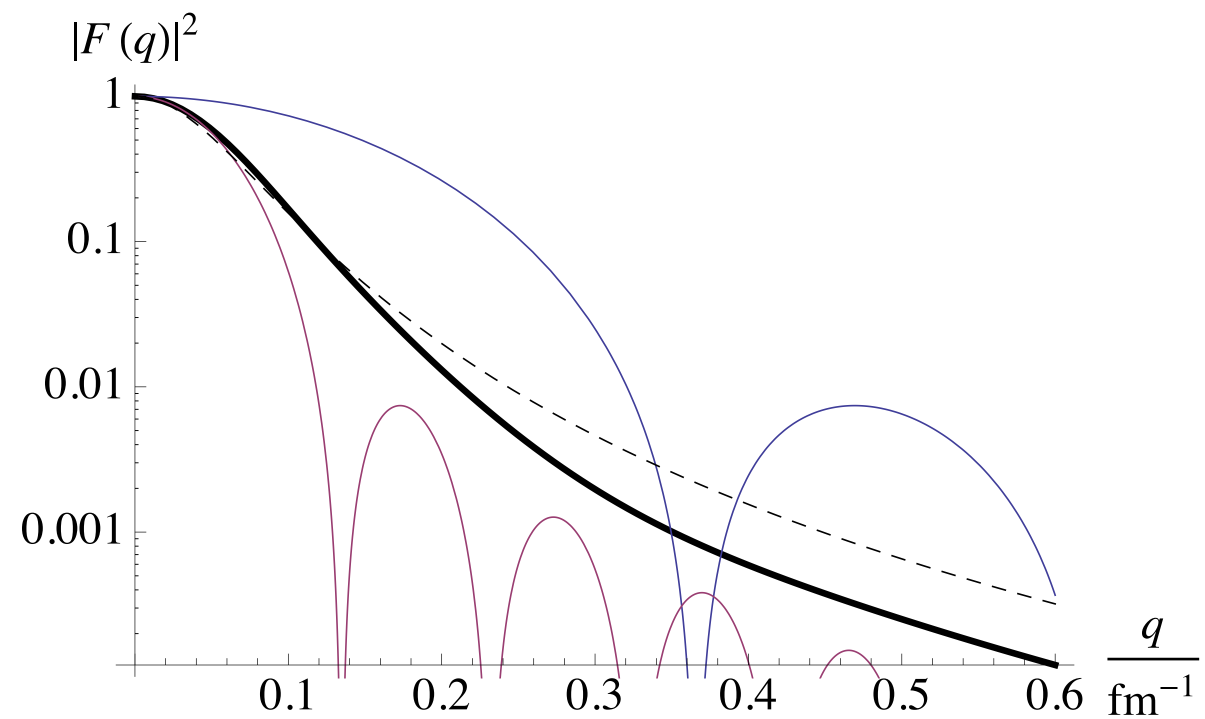


- CURRENT LIMITS FROM XENON100 (225 DAYS EXPOSURE) AND PROJECTED LIMITS FROM DEAAP-3600 (3 YEARS USING 3600KG MASS)

DIRECT DETECTION

- EFFECTIVE FORM FACTOR FROM DISTRIBUTION OF SIZES





- HARDER TO DISTINGUISH BETWEEN WIMP AND NDM - NEED TO DO HALO INDEPENDENT ANALYSIS

SUMMARY

- DARK MATTER COULD BE EXPLAINED IN A LARGE NUMBER OF WAYS BEYOND VANILLA WIMPS
- A RANGE OF DIFFERENT GENESIS MECHANISMS
- NUCLEAR DM POSSIBILITY ALSO A BIG DEPARTURE FROM WIMP FREEZE-OUT
  - THERMALLY PRODUCED DARK MATTER WITH MASSES IN EXCESS OF THE USUAL UNITARITY BOUND
  - DIRECT DETECTION RATES COHERENTLY ENHANCED BY DNN AND THE POSSIBILITY OF A MOMENTUM DEPENDENT FORM FACTOR
  - PRODUCE STATES WITH VERY LARGE SPIN?
  - INELASTIC INTERACTIONS IN BOTH DIRECT DETECTION AND IN ASTROPHYSICAL ENVIRONMENTS

LOTS OF POSSIBILITIES TO INVESTIGATE!