NON-STANDARD DARK MATTER

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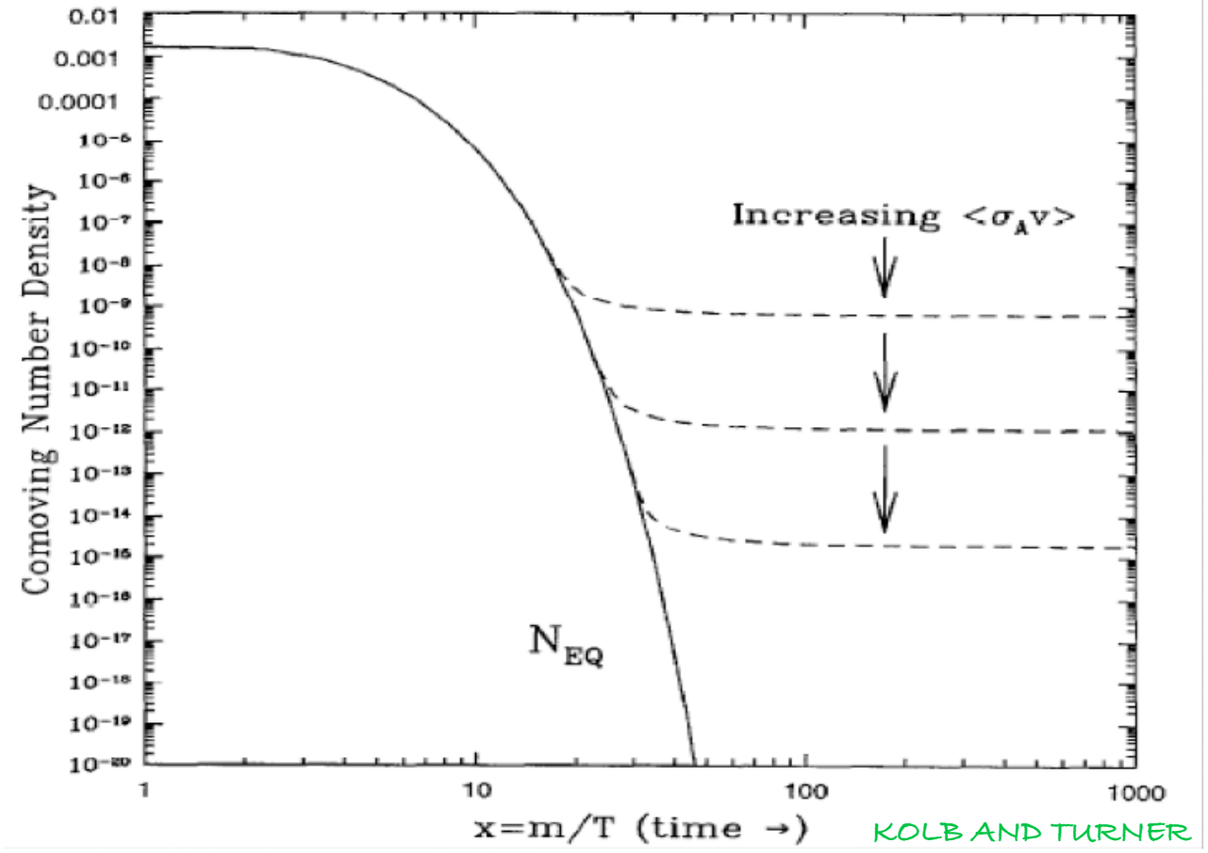
OUTLINE

- PARTIAL OVERVIEW OF ALTERNATIVE GENESIS MECHANISMS - TO INCLUDE...
  - MODIFIED FREEZE-OUT
  - FREEZE-IN
  - NON-THERMAL PRODUCTION
- 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
- FREEZES-OUT ABUNDANCE DETERMINED BY ANNIHILATION CROSS SECTION
- YIELD SET AT FREEZE-OUT GIVES FINAL DARK MATTER ABUNDANCE.

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

MODIFYING FREEZE-OUT - ASYMMETRIC DM

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

VISIBLE SECTOR

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

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

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+...

- 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

- MOTIVATION TO LINK TO THE BARYON ASYMMETRY TO EXPLAIN RELATIVE ABUNDANCES

$$\frac{\Omega_{\rm dm}}{\Omega_{\rm b}} = \frac{\eta_{\rm dm} m_{\rm dm}}{\eta_{\rm b} m_{\rm b}} \sim 5$$

HIDDEN SECTOR DM

- HIDDEN SECTOR STATES HAVE NO SM GAUGE INTERACTIONS

- HIDDEN SECTOR MAY BE LINKED, BEYOND GRAVITY, TO THE VISIBLE SECTOR

PORTALS: HIGGS - $|H|^2|\chi|^2$ OR $|H|^2|\chi'|^2$ ETC

NEUTRINO - $LH\chi$ OR $LH\chi'$

KINETIC MIXING - $(\partial_\mu \chi''_\nu - \partial_\nu \chi''_\mu) F_Y^{\mu\nu}$ IF χ''_μ 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
- IF BATH PARTICLE'S ONLY DECAY IS TO FIMP – LEADS TO LONG LIVED STATES IN COLLIDERS + BBN CONSTRAINTS

SINGLE SPECIES DM

- SIMPLE FREEZE-IN PICTURE TO JUST FREEZE-IN THE CORRECT ABUNDANCE OF χ
- VARIATIONS:
  - E.G. χ IS UNSTABLE, AFTER FREEZING IN DECAYS LATE TO REAL DM IN VISIBLE SECTOR, WHICH IS UNDER PRODUCED BY FREEZE-OUT
  - IMPLICATIONS AGAIN FOR BBN
- CAN PRODUCE ANYTHING FROM SUPERHEAVY FIMPS TO SUB-GEV
- IMPORTANT LAST POINT - PRODUCTION IS DOMINATED IN THE IR, NO DEPENDENCE ON THERMAL HISTORY

SINGLE SPECIES DM

- IF THE PORTAL INTERACTIONS ARE ONLY GRAVITATIONAL - STILL HAVE OPTIONS
- SUPERWIMPS: FENG, RAJARAMAN, TAKAYAMA '03
  - DM STATE NEVER IN THERMAL EQUILIBRIUM
  - ABUNDANCE IS GENERATED BY LATE DECAY OF ANOTHER PARTICLE THAT HAS FROZEN-OUT
  - PRIME EXAMPLE - GRAVITINO DM WITH LOSP FREEZING OUT AND DECAYING TO GRAVITINO
  - IMPLICATIONS FOR BBN + LONG LIVED STATES AT COLLIDERS
- SEE ALSO WIMPZILLAS KOLB, CHUNG, RIOTTO '98

MULTI-STATE HIDDEN SECTORS

- IN PARTICULAR THE IDEA OF SELF INTERACTING DARK MATTER (SIDM)

CARLSON, MACHACEK, HALL '92

- MOTIVATED BY SMALL SCALE STRUCTURE PROBLEMS E.G.

SPERGEL, STEINHARDT '99

* "CUSPS VS CORES" * "TOO BIG TO FAIL"

FOR SELF INTERACTING DM TO SOLVE, REQUIRES $\dfrac{\sigma}{m_\chi} \sim \dfrac{1\text{barn}}{\text{GeV}}$

ROCHA ET AL '12, PETER ET AL '12, VOGELSBERGER '12, ZAVALA ET AL '12

$\Rightarrow$ SUGGESTS SOME STRONGLY INTERACTING THEORY

$\Rightarrow$ CONFINING NON-ABELIAN GAUGE THEORY

SELF INTERACTING DARK MATTER

- MANY MODELS OF NON-ABELIAN THEORIES IN HIDDEN SECTORS E.G.
  - GLUEBALL DARK MATTER: PURE YANG-MILLS BODDY, FENG, KAPLINGHAT, SHADMI, TAIT '14
    + SUSY VERSION WITH GLUEBALLINOS
    - MAKES USE OF WIMPLESS MIRACLE FENG, KUMAR '08

$$\Omega h^2 \sim \frac{m_\chi^2}{g_\chi^4}$$

IF $m_\chi \propto g_\chi^2$ WE GET CORRECT SIZE

$\rightarrow$ LARGE RANGE OF POSSIBILITIES INCLUDING QCD-LIKE INTERACTIONS AND MASSES

LOTS OF OTHER EARLIER EXAMPLES E.G. FALKOWSKI, KUKNEVICH, SHELTON '09, ALVES, BEBNAHANI, SCHUSTER, WACKER '09, KRIBS, ROY, TERNING, ZUREK '09, LISANTI, WACKER '09, BUCKLEY, NEIL '12+...

SIMP MIRACLE

HOCHBERG, KUFLIK, VOLANSKY, WACKER '14
HOCHBERG, KUFLIK, MURAYAMA, VOLANSKY, WACKER '14

- INSPIRATION FROM THE CANNIBALISTIC MODEL OF CARLSON, MACHACEK, HALL '92

- FREEZE-OUT OF DARK MATTER DOMINATED BY $3 \to 2$ PROCESSES

- CRUCIAL PORTAL INTERACTION TO VISIBLE SECTOR ALLOWS EXCESS ENERGY FROM CANNIBALISATION OF DM STATES TO BE REDISTRIBUTED THROUGHOUT THERMAL BATH.

- ALLOWS FOR A STRONGLY INTERACTING MASSIVE PARTICLE WITH GEV OR BELOW MASS - APPLICATION TO SMALL SCALE STRUCTURE PROBLEM

NUCLEAR DARK MATTER

- A NATURAL EXTENSION OF THE DISCUSSION OF STRONGLY COUPLED HIDDEN SECTORS IS TO ASK
- CAN WE HAVE THE ANALOGY TO THE SM IN TERMS OF BUILDING 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

- FOR MINIMALITY, ONLY ONE TYPE OF DARK NUCLEON PRESENT AND NO DARK VERSION OF THE COULOMB FORCE

- ASSUME DARK NUCLEONS PRESENT ONLY - ASYMMETRIC

- NO COULOMB FORCE - BINDING ENERGY PER NUCLEON DOES NOT TURN OVER AT LARGE DNN

- DARK NUCLEI EXIST WITH A RANGE OF DNNS, FORMING POST FREEZE-OUT VIA DARK NUCLEOSYNTHESIS

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 NUCLEONS. NO HARD CORE REPULSION LEADING TO INTERESTING RADIUS VS DNN BEHAVIOUR

    WISE AND ZHANG '14

  * EARLY EXAMPLES IN TERMS OF Q-BALLS

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

NUCLEAR DARK MATTER

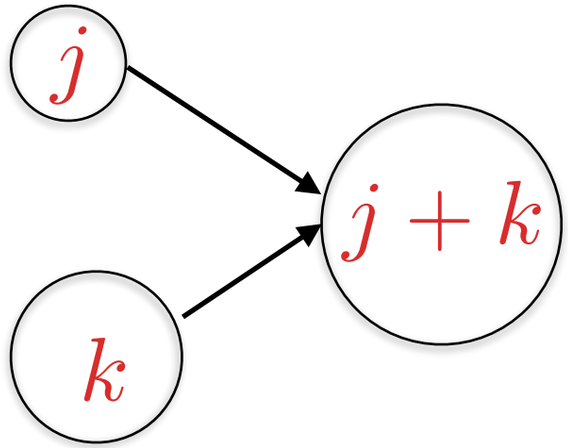
- INTERESTING POSSIBILITIES:
  - THERMALLY PRODUCED DARK MATTER WITH MASSES IN EXCESS OF THE USUAL UNITARITY BOUND GRIEST, KAMIONKOWSKI '90
  - DIRECT DETECTION RATES COHERENTLY ENHANCED BY DNN
  - POTENTIAL FOR INELASTIC INTERACTIONS IN BOTH DIRECT DETECTION AND IN ASTROPHYSICAL ENVIRONMENTS
  - POTENTIALLY PRODUCE STATES WITH VERY LARGE SPIN

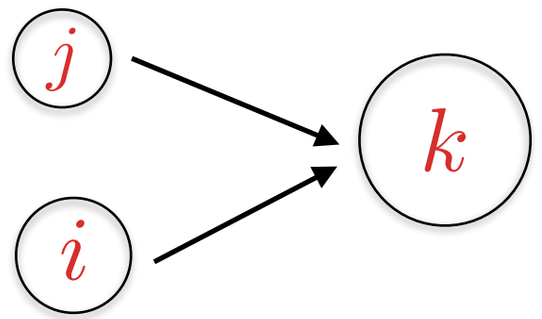
NUCLEAR DARK MATTER

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

- AGGREGATION PROCESS - NEGLECTING DISSOCIATIONS

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





- REWRITING $y_k = Y_k/Y_0$ AND $\langle \sigma v \rangle_{i,j} = \sigma_1 v_1 K_{i,j}$ WHERE

Y_0 IS TOTAL YIELD OF DARK NUCLEONS

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

σ_1 GEOMETRICAL CROSS SECTION OF INDIVIDUAL DARK NUCLEON

v_1 VELOCITY OF SINGLE NUCLEON

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

WHERE WE CAN DEFINE A DIMENSIONLESS TIME VARIABLE

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

- APPROXIMATING

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

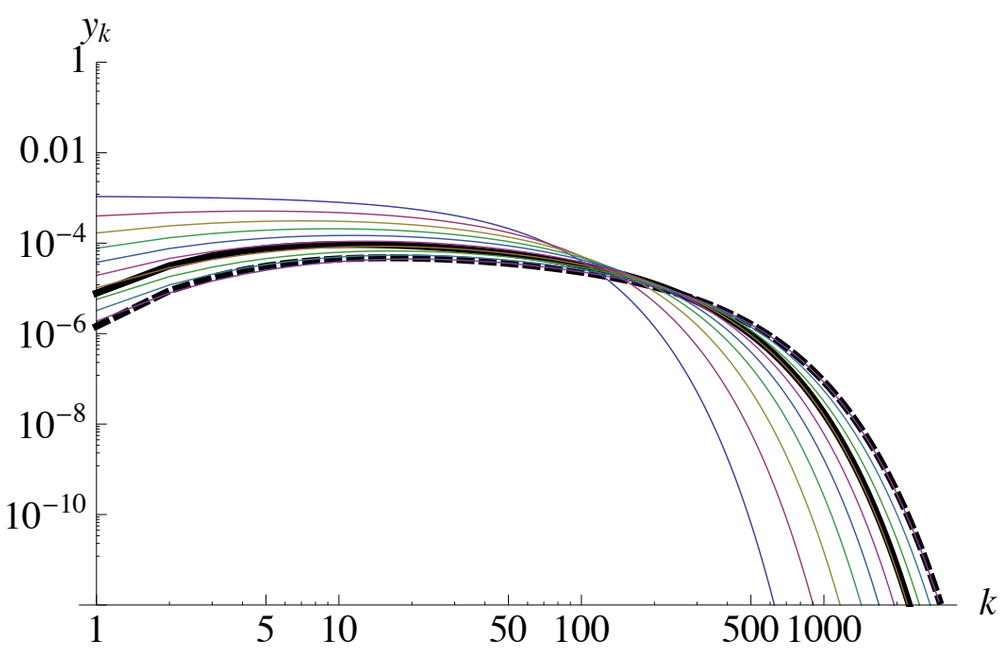
RELATED TO GEOMETRICAL SIZE

RELATED TO RELATIVE VELOCITY

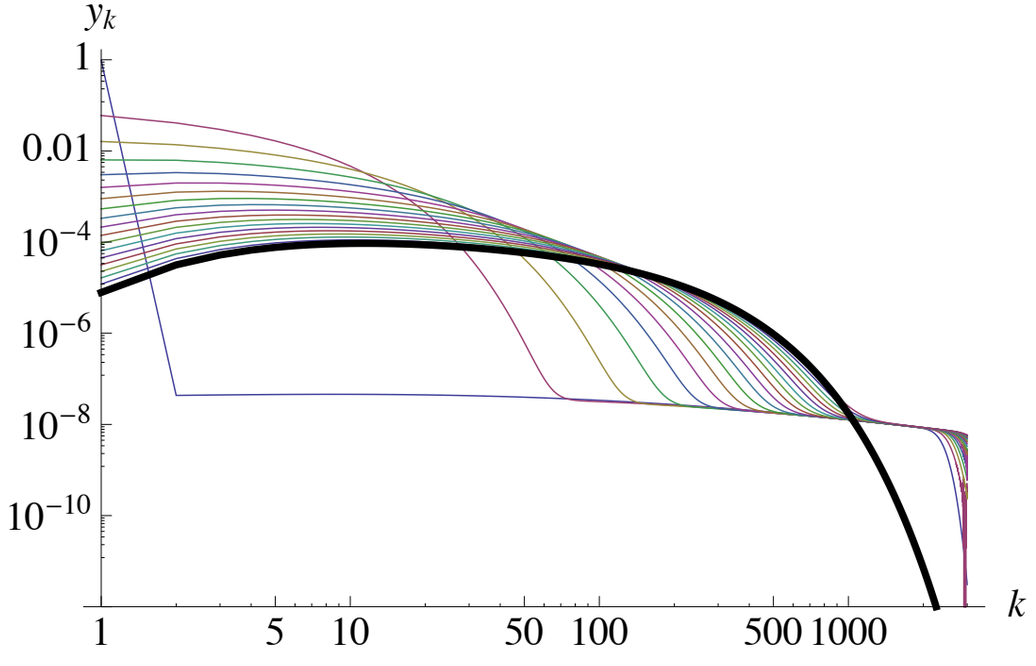
$$v^2 \sim T/m$$

- 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



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



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

NUCLEAR DARK MATTER IN DIRECT DETECTION

- SEVERAL INTERESTING POINTS

  - MOMENTUM DEPENDENT SCATTERING DUE TO DARK NUCLEI FORM FACTOR

  - FOR A LARGE RANGE OF THE MOMENTUM TRANSFER , ELASTIC SCATTERING (AND POSSIBLY INELASTIC) WILL BE COHERENTLY ENHANCE BY k^2

    * HOWEVER, OVERALL RATE WILL INCREASE AS k DUE TO $1/k$ DECREASE IN NUMBER DENSITY

  - DUE TO COHERENCE EFFECTS, UNDERLYING SIZE OF INDIVIDUAL DARK NUCLEON'-QUARKS INTERACTION REDUCED - - CONSEQUENCE FOR SEARCHES AT COLLIDERS

SUMMARY

- FREEZE-OUT IS BY NO MEANS THE ONLY WAY TO GENERATE DM IN THE EARLY UNIVERSE
- MANY DIFFERENT WAYS THAT DEPART FROM THE MAIN ASSUMPTIONS OF FREEZE-OUT, IN PARTICULAR
  - SINGLE SPECIES OF DARK MATTER
  - RADIATION DOMINATED UNIVERSE
  - YIELD SET AT FREEZE-OUT GIVES FINAL DARK MATTER ABUNDANCE.
  - INITIALLY IN THERMAL EQUILIBRIUM

MANY EXAMPLES OF MULTIPLE STATE HIDDEN SECTORS

NO TIME THIS TALK BUT EXAMPLES OF DM PRODUCTION DURING MATTER DOMINATED ERA - SEE TALKS BY KANE, CO AND QUEVEDO

FREEZE-IN, SUPERWIMPS, AND MANY OTHER NON-THERMAL MECHANISMS

- NUCLEAR DM POSSIBILITY ALSO A BIG DEPARTURE FROM WIMP FREEZE-OUT. MANY EXCITING CONSEQUENCES FOR A WIDE RANGE OF EXPERIMENTS

LOTS OF POSSIBILITIES TO INVESTIGATE!